MSSM Neutral Higgs Bosons searches at CMS in the $\mu^+\mu^-$ channel

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Introduction

The Standard Model (SM) of electro-weak interactions, comprising a Quantum Chromo Dynamics (QCD) sector for the strong interactions, is the accepted theory of the elementary particles and their interactions. The SM has been very successful in its predictions and has successfully passed many precision experimental tests, but one of the fundamental parts of the theory has still to be confirmed experimentally: the Higgs sector. Because the SM lagrangian has no mass terms for fermions and vector bosons, the particle masses are explained with the Higgs mechanism of Spontaneous Symmetry Breaking (SSB). This mechanism predicts a new particle, the Higgs boson, which is still to be discovered.

However, there are strong arguments (the problem of unification of interactions, the neutrino mass, the number of fermion families, the hierarchy problem) for the SM being the low energy limit of a more fundamental theory. The strongest candidate for such an extension is Supersymmetry (SUSY), a symmetry which relates masses and couplings of fermions and scalars. In the Minimal Supersymmetric extension of the Standard Model (MSSM), the electro-weak symmetry breaking is not put by hand, but can be generated radiately by quantum corrections. Nevertheless, the Higgs sector of the MSSM is more complex, because one has to take into account at least two complex Higgs doublets, rather than just one Higgs boson. After EW symmetry breaking, five Higgs scalar mass eigenstates remain, consisting of one CP-odd neutral scalar A, two charged scalars $H^\pm$, and two CP-even neutral scalars h and H.

The CMS experiment, that will be installed at the Large Hadron Collider (LHC, a proton-proton collider with a center of mass energy of 14 TeV) at CERN in 2005, has been designed with the aim of discovering the Higgs bo-
son and/or signatures of new physics (SUSY). The work performed for this thesis is part of the program of the physics performances evaluation and the development of tools for reconstruction and analysis of the CMS experiment. In particular, the discovery potential of a neutral Higgs boson of the MSSM has been evaluated, focusing on the $A/H b \bar{b} \rightarrow \mu^+\mu^- b\bar{b}$ channel. This channel poses very challenging requirements on the $b$-tagging and muon reconstruction performances. Hence, during this thesis, a track reconstruction method called Connection Machine, well suited for the reconstruction of secondary tracks, has been designed and implemented, and different strategies for muon reconstruction through the whole CMS detector have been developed.

In chapter 1, a brief description of the SM is given, with an eye to the Higgs mechanism. Supersymmetry is then introduced, and the Higgs sector of the MSSM is described in detail.

In chapter 2, the CMS detector and its components, in particular the tracker, are explained. The chapter also includes an overview of the simulation, reconstruction and analysis software used by the CMS collaboration.

In chapter 3, the track reconstruction algorithm developed during this thesis, the Connection Machine, is described in detail and its performance on single tracks and $b$-jets is evaluated. The muon reconstruction strategies are also presented in this section.

The Higgs searches at CMS are presented in chapter 4, analysing the Higgs production mechanism at LHC and the more promising decay channels that could lead to a possible discovery. The phenomenology of the $A/H b \bar{b} \rightarrow \mu^+\mu^- b\bar{b}$ channel is also described.

A in depth analysis of the signal signatures and of the main background processes is performed in chapter 5, and the selection strategy used to discriminate signal from backgrounds is presented.

In chapter 6, the results obtained on different MSSM scenarios are reported, and the discovery capabilities of CMS in the $A/H b \bar{b} \rightarrow \mu^+\mu^- b\bar{b}$ channel are studied over a large fraction of the $(m_A, \tan\beta)$ plane.
Chapter 1

Standard Model and beyond

1.1 Standard Model

The SM is an unified quantum gauge theory which describes electromagnetic and weak interactions, with a Quantum Chromo Dynamics (QCD) sector for the description of the strong interactions [1],[2]. The matter particles are fermions (particles with spin $S = \frac{1}{2}$), classified into leptons and quarks and divided in three families (see Table 1.1).

<table>
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<tr>
<th>Family</th>
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<th>Quarks</th>
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<tr>
<td>1</td>
<td>$\nu_e$ 0</td>
<td>u $\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>e -1</td>
<td>d $-\frac{1}{3}$</td>
</tr>
<tr>
<td>2</td>
<td>$\nu_\mu$ 0</td>
<td>c $\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>$\mu$ -1</td>
<td>s $-\frac{1}{3}$</td>
</tr>
<tr>
<td>3</td>
<td>$\nu_\tau$ 0</td>
<td>t $\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>$\tau$ -1</td>
<td>b $-\frac{1}{3}$</td>
</tr>
</tbody>
</table>

Table 1.1: Matter fermions.

The model for electroweak interactions is based on the gauge group $SU(2)_L \otimes U(1)_Y$. The generators of $SU(2)_L$ are $T_i = \frac{\sigma_i}{2}$, where $\sigma_i$ are the Pauli matrices, while the generator of $U(1)_Y$ is the hypercharge $Y = 2Q - I^3$, where $Q$ is the electric charge and $I^3$ the weak isospin. The group symmetry of the electromagnetic interactions ($U(1)_{em}$) appears as a subgroup of $SU(2)_L \otimes U(1)_Y$, and thus the electromagnetic and weak interactions are unified. The associated
gauge bosons are the hypercharge boson $B$ (from $U(1)_Y$) and the three weak bosons $W^i$ (from $SU(2)_L$).

The left-handed fermions transform as doublets under $SU(2)_L$:

$$f_L^i = \begin{pmatrix} \nu_L^i \\ \ell_L^i \\ u_L^i \\ d_L^i \end{pmatrix}, \quad i = 1, 2, 3$$

while right-handed fermions transform as singlets, $f_R^i = \ell_R^i, u_R^i, d_R^i$.

The SM electroweak lagrangian is obtained requiring invariance under a local gauge transformation, which implies the replacement of the field derivatives by the covariant derivatives:

$$D_f = \left( \partial_\mu - ig_1 \frac{Y}{2} B_\mu - ig_2 \vec{W}_\mu \right) f$$

where $g_1$ and $g_2$ are the coupling constants of $U(1)_Y$ and $SU(2)_L$. The total EW-lagrangian can be written as a sum of terms:

$$\mathcal{L}_{SU(2)_L \otimes U(1)_Y} = \mathcal{L}_{el} + \mathcal{L}_{weak} + \mathcal{L}_G$$

where $\mathcal{L}_{el}$ takes into account free fermions and electromagnetic interaction, $\mathcal{L}_{weak}$ the weak currents and $\mathcal{L}_G$ is the gauge term:

$$\mathcal{L}_{el} = \sum_f \bar{f} i \partial_\mu f - e \sum_f Q_f \bar{f} \gamma_\mu f A^\mu$$

$$\mathcal{L}_{weak} = -\frac{g_2}{2 \cos \theta_w} \sum_f \bar{f} \gamma_\mu (g_V - g_A \gamma_5) f Z^\mu +$$

$$-\frac{g_2}{2 \sqrt{2}} \sum_f \bar{f} \gamma_5 (\sigma^+ W^{\mu+} + \sigma^- W^{\mu-}) f_L$$

$$\mathcal{L}_G = -\frac{1}{4} W^i_{\mu \nu} W^{i \mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu}$$

$g_V = I_f^3 - 2Q_f \sin \theta_w^2$ is the coupling constant of the vector part of the weak neutral-current and $g_A = I_f^3$ is the coupling constant of the axial part. The physical gauge bosons are related to their electroweak interaction eigenstates by:

$$W^\pm = \frac{1}{\sqrt{2}} (W^1 \mp iW^2)$$

$$Z = \cos \theta_w W^3 - \sin \theta_w B$$

$$\gamma = \sin \theta_w W^3 + \cos \theta_w B$$
where \( \cos \theta_w = \frac{g_2}{\sqrt{g_1^2 + g_2^2}} \) is the weak mixing angle.

Strong interactions are described by QCD by mean of the non-abelian Lie group \( SU(3)_C \). The gluons \( g_i, i = 1, \ldots, 8 \) are the gauge bosons associated to the Gell-Mann matrices \( \frac{\lambda_i}{2} \), which are the eight generators of \( SU(3)_C \) group.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>boson</th>
<th>( Q )</th>
<th>( m )</th>
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<tr>
<td>Electromagnetic</td>
<td>( \gamma )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>( W )</td>
<td>( \pm 1 )</td>
<td>80.4 GeV</td>
</tr>
<tr>
<td></td>
<td>( Z )</td>
<td>0</td>
<td>91.2 GeV</td>
</tr>
<tr>
<td>Strong</td>
<td>( g )</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1.2: Gauge bosons.

The QCD lagrangian can be built in a similar way as the QED one, taking into account the particularities of the non-abelian symmetry group, thus:

\[
\mathcal{L}_{QCD} = \sum_q \bar{q} g_3 \frac{\lambda_i}{2} G^i_{\mu} \gamma^\mu q - \frac{1}{4} F_{\mu\nu}^i F^{\mu\nu}_i \tag{1.10}
\]

where \( g_3 \) is the strong coupling constant, \( G^i_{\mu} \) are the gluon fields and \( F_{\mu\nu}^i \) the gluon field strength:

\[
F_{\mu\nu}^i = \partial_\mu G^i_\nu - \partial_\nu G^i_\mu + g_3 f^{\alpha\beta\gamma}_i G^\alpha_\mu G^\beta_\nu G^\gamma_\gamma \tag{1.11}
\]

The first term in the lagrangian corresponds to the gauge interactions between quarks and gluons, the second to the kinetic term for the gluon fields.

### 1.2 Higgs Mechanism

The gauge symmetry of the SM forbids mass terms in the lagrangian, leading to massless fermions and bosons. On the other hand, we know from experiments that all particles, except the photon, have mass.

The simplest way to generate particle masses while preserving the renormalizability of the theory, is the Higgs mechanism of Spontaneous Symmetry Breaking (SSB) [3]. A field represented by a complex \( SU(2)_L \) doublet:

\[
\Phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{1.12}
\]
with hypercharge $Y(\Phi)=1$ and the potential given by the relation:

$$V(\Phi) = \mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

(1.13)

is defined. One finds that, if $\lambda > 0$ and $\mu^2 < 0$, the potential $V(\Phi)$ has a minimum for:

$$\Phi^\dagger \Phi = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}.$$  

(1.14)

The vacuum (i.e. the lowest energy state) corresponds to one of these minima. Because the scalar field is complex, the above relation has an infinite number of solutions. By choosing one particular solution the gauge symmetry is broken.

The coupling of this field (called Higgs field) to particles provides masses to bosons and fermions. The terms in the SM lagrangian that provide mass to the fermions are described by the Yukawa lagrangian:

$$\mathcal{L}_Y = \lambda_e \bar{\ell}_L \Phi e_R + \lambda_u \bar{q}_L \Phi^c u_R + \lambda_d \bar{q}_L \Phi d_R + \ldots$$

(1.15)

where $\lambda_i$ are the Yukawa coupling constants and $\Phi^c = i\sigma_2 \Phi^*$. The terms that provide mass to the gauge bosons are:

$$\mathcal{L}_{SSB} = (D_\mu \Phi)^\dagger (D_\mu \Phi) + \mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

(1.16)

By substituting the Higgs field expansion around the vacuum state:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

(1.17)

in the two previous expressions, one can obtain the mass terms for fermions, gauge bosons and Higgs boson:

$$m_u = \frac{1}{\sqrt{2}} \lambda_u v, \quad m_d = \frac{1}{\sqrt{2}} \lambda_d v, \quad m_e = \frac{1}{\sqrt{2}} \lambda_e v, \ldots$$

(1.18)

$$M_W = \frac{1}{\sqrt{2}} g_2 v, \quad M_Z = \frac{1}{\sqrt{2}} \sqrt{g_1^2 + g_2^2} v, \quad M_\gamma = 0$$

$$M_H = \sqrt{-2\mu^2},$$

as well as the trilinear Higgs self-coupling and the Higgs-gauge boson and Higgs-fermion interaction strengths:

$$\lambda_{HHH} = 3 \frac{M_H^2}{M_Z^2}, \quad \lambda_{HVV} = 2 \sqrt{2G_F} M_V^2, \quad \lambda_{Hff} = \sqrt{2G_F m_f}.$$  

(1.19)
where $\lambda_{HHH}$ is expressed in units of $\lambda_0 = M_Z^2/v$, and $V = W, Z$.

The SM has been very successful in its predictions: mass values of $W$ and $Z$ bosons were predicted well before their discovery in experiments. Moreover, there is a remarkable agreement between the SM predictions and the precision measurements of electroweak observables performed at LEP and SLC.

Notwithstanding its extremely successful description of elementary particle interactions, we have still to discover the Higgs boson itself. Also, as I will show in the next paragraphs, there are other shortfalls to the model.

### 1.3 Hierarchy problem

Although the SM has successfully passed many precision experimental tests, there are strong arguments for it not being the ultimate theory of elementary particles and interactions. Mainly, the arguments concern the number of free parameters of the theory, the problem of unification of all interactions, the neutrino mass, the number of fermion families, etc . . . Among these problems, one finds that one of the most serious drawbacks of the SM is the hierarchy problem [4], that arises when one tries to extend the validity of the SM to large masses and energy scales.

Calculating the one loop radiative corrections to the Higgs mass in a theory which contains massive scalars and fermions, one obtains:

\[
\delta M^2_H = \frac{g^2_F}{4\pi^2}(\Lambda^2 + m^2_F) - \frac{g^2_S}{4\pi^2}(\Lambda^2 + m^2_S) + \log \text{ terms} + \ldots
\]

(1.20)

where $\Lambda$ is a cut-off characteristic of the energy scale at which the radiative corrections are calculated. These corrections diverge quadratically and are many orders of magnitude greater than that of a plausible physical value for $M_H$ (we know that the consistency of the SM is broken if $M_H > \mathcal{O}(1 \text{ TeV}/c^2)$).

If one keeps a reasonably small $M_H$ value with respect to the largest mass scale, then the divergent terms must be cancelled by some counterterms, which must be fine tuned at each perturbative order, with unnatural precision.

A possible solution to this problem is offered by Supersymmetry (SUSY), a symmetry which relates masses and couplings of fermions and scalars. Because both fermions and scalars enter the mass corrections with opposite signs, if each
fermion (scalar) of the SM has a scalar (fermion) SUSY partner, the two terms tend to cancel each other, if the couplings are equal \( (g_S = g_F) \) and partners have equal masses:

\[
\delta M_{\mu}^2 \simeq \mathcal{O}(\alpha) (m_S^2 - m_F^2)
\]  

(1.21)

1.4 Supersymmetry

The particles of a supersymmetric theory are grouped in supermultiplets, each one containing both a fermion and a boson (called superpartners of each other). Particles in the same supermultiplet have equal masses and also identical electric charge, weak isospin and color degrees of freedom, because SUSY generators act independently of any internal symmetry. Moreover, the number of bosonic and fermionic degrees of freedom in a supermultiplet are equal.

The two simplest possible supermultiplets are:

- Chiral supermultiplets: it contains a single Weyl fermion and a complex scalar field.

- Gauge supermultiplets: it contains a spin 1 vector boson and a spin 1/2 Weyl fermion. These fermions, which have the same gauge transformation properties for right-handed and left-handed components, are called gauginos.

In a supersymmetric extension of the SM [6], each of the known fundamental particles must be in either a chiral or gauge supermultiplet, and have a superpartner with spin differing by 1/2. Only chiral supermultiplets can contain fermions whose left-handed component transform differently that their right-handed component, so all of the SM fermions (quarks and leptons) must be members of a chiral supermultiplet. Their superpartners are called squarks (scalar quarks) and sleptons (scalar leptons). The left-handed and right-handed parts of quarks and leptons are separate two-component Weyl fermions with different gauge transformation properties, so each one must have its own complex scalar partner: \( \tilde{f}_L \) and \( \tilde{f}_R \). In the SM, neutrinos are always left-handed, so the sneutrinos are denoted without appending a subscript for the helicity of
The Higgs scalar boson also must reside in a chiral supermultiplet, since it has spin 0. Actually, it turns out that one chiral supermultiplet is not enough, because, due to the structure of supersymmetric theories, only a $Y = +1/2$ Higgs chiral supermultiplet can give masses to charge $Q = +2/3$ quarks, and only a $Y = -1/2$ Higgs chiral supermultiplet can give masses to charge $Q = -1/3$ quarks. According to this, the two $SU(2)_L$-doublet complex scalar fields are called $H_u$ and $H_d$ (see Table 1.3). The neutral scalar that correspond to the physical SM Higgs Boson is a linear combination of $\tilde{H}_u^0$ and $\tilde{H}_d^0$.

The vector bosons of the SM must reside in gauge supermultiplets (see Table 1.4), and their superpartners are usually referred to as gauginos. The gluon superpartners are the gluinos; the electroweak gauge bosons superpartners are called winos ($\tilde{W}^\pm$, $\tilde{W}^0$, $\tilde{W}^0$) and bino ($\tilde{B}^0$). We saw in the previous section

<table>
<thead>
<tr>
<th>Names</th>
<th>spin 0</th>
<th>spin 1/2</th>
<th>$SU(3)_C$, $SU(2)_L$, $U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>squarks, quarks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(×3 families)</td>
<td>$Q$</td>
<td>$\tilde{u}_L$</td>
<td>(3, 2, $\frac{1}{2}$)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{u}_R^*$</td>
<td>$u_R$</td>
<td>(3, 1, $-\frac{2}{3}$)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{d}_R^*$</td>
<td>$d_R$</td>
<td>($\bar{3}$, 1, $\frac{1}{2}$)</td>
</tr>
<tr>
<td>sleptons, leptons</td>
<td>L</td>
<td>$\tilde{e}_L$</td>
<td>(1, 2, $-\frac{1}{2}$)</td>
</tr>
<tr>
<td>(×3 families)</td>
<td>$\tilde{e}_R^*$</td>
<td>$e_R$</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>Higgs, higgsinos</td>
<td>$H_u$</td>
<td>$(\tilde{H}_u^+ \tilde{H}_u^0)$</td>
<td>(1, 2, $+\frac{1}{2}$)</td>
</tr>
<tr>
<td></td>
<td>$H_d$</td>
<td>$(\tilde{H}_d^0 \tilde{H}_d^-)$</td>
<td>(1, 2, $-\frac{1}{2}$)</td>
</tr>
</tbody>
</table>

Table 1.3: Chiral supermultiplets in the Minimal Supersymmetric Standard Model.

<table>
<thead>
<tr>
<th>Names</th>
<th>spin 1/2</th>
<th>spin 1</th>
<th>$SU(3)_C$, $SU(2)_L$, $U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino, gluon</td>
<td>$\tilde{g}$</td>
<td>$g$</td>
<td>($8$, 1, 0)</td>
</tr>
<tr>
<td>winos, W bosons</td>
<td>$\tilde{W}^\pm$</td>
<td>$W^\pm$</td>
<td>(1, 3, 0)</td>
</tr>
<tr>
<td></td>
<td>$\tilde{W}^0$</td>
<td>$W^0$</td>
<td>(1, 1, 0)</td>
</tr>
<tr>
<td>bino, B boson</td>
<td>$\tilde{B}^0$</td>
<td>$B^0$</td>
<td>(1, 1, 0)</td>
</tr>
</tbody>
</table>

Table 1.4: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.
that, after electroweak symmetry breaking, $W^0$ and $B^0$ mix to give mass eigenstates $Z$ and $\gamma$; the corresponding gaugino mixtures are called zino ($\tilde{Z}^0$) and photino ($\tilde{\gamma}$). If supersymmetry were unbroken, they would be mass eigenstates with masses $m_Z$ and 0, but, as we will see in the next sections, this is not the case.

### 1.5 Minimal Supersymmetric Standard Model

Tables 1.3 and 1.4 summarize the particle content of the Minimal Supersymmetric Standard Model (MSSM) [7]. The next step in order to describe the model is to construct the supersymmetric lagrangian, remembering it should contain the SM lagrangian [6]. Requiring SUSY and gauge invariance, the lagrangian can be expressed as:

$$
\mathcal{L}_{SUSY} = \sum_{i} (D_\mu S_i)\dagger (D^\mu S_i) + \frac{i}{2} \sum_{i} \bar{\psi}_i \gamma^\mu D_\mu \psi_i + \\
-\frac{1}{4} \sum_{A} F_{\mu\nu A} F_{\mu\nu}^A + \frac{i}{2} \sum_{A} \bar{\lambda}_A \gamma^\mu D_\mu \lambda_A + \\
-\sqrt{2} \sum_{i,A} \left[ S_i^\dagger (g_{\alpha} t_{\alpha A}) \bar{\psi}_i \frac{1}{2} \gamma^5 \lambda_A + h.c. \right] + \\
+ \frac{1}{2} \sum_{A} \left[ \sum_{i} S_i^\dagger g_{\alpha} t_{\alpha A} S_i \right]^2 + \\
+ \mathcal{L}(W)
$$

(1.22)

where $S_i$ ($\psi_i$) is the scalar (fermion) component of the $i^{th}$ chiral superfield, $F_{\mu\nu A}$ is the Yang-Mills gauge field and $\lambda_A$ is the gaugino superpartner of the corresponding gauge boson. The sum over $i$ is intended over all fermions of the SM, their scalar superpartners and the two Higgs doublet. The sum over $A$ is performed over all gauge fields and their superpartners, the gauginos.

The first two lines are the kinetic energies of the components of chiral and gauge supermultiplets, the third describes the interactions of gauginos with matter and Higgs multiplets, while the fourth describes quartic couplings of scalar matter. All this terms are completely specified by the gauge symmetries and by supersymmetry, and all interaction strenghts are fixed in terms of the SM coupling constants.
The only freedom writing the SUSY lagrangian is in the definition of the \textit{superpotential} $W$ [8] (the last part of eq. 1.22), which expanded takes a form of this kind:

$$\mathcal{L}(W) = -\sum_i \left[ \frac{\partial W}{\partial \hat{S}_i} \right]_{\hat{S}_i = S_i}^2 +$$

$$-\frac{1}{2} \sum_{i,j} \left\{ \bar{\psi}_i \left[ \frac{1 - \gamma_5}{2} \right] \left( \frac{\partial^2 W}{\partial \hat{S}_i \partial \hat{S}_j} \right)_{\hat{S}_i = S_i} \psi_j + h.c. \right\} \quad (1.23)$$

In the MSSM, the invariant superpotential can be expressed as:

$$W = \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_e + \mu H_u H_d \quad (1.24)$$

The objects $H_u, H_d, Q, L, \bar{u}, \bar{d}, \bar{e}$ are chiral superfields corresponding to the chiral supermultiplets in Table 1.3. The dimensionless Yukawa coupling parameters $y_u, y_d, y_e$ are $3 \times 3$ matrices in family space. The first three terms give the Yukawa interaction of fermions with the Higgs bosons, the last one gives the mass terms for the Higgs bosons. It is worth to note here that all these coefficients are not free parameters, because they are determined in terms of fermion masses and vacuum expectation values (VEV’s) of the neutral members of the Higgs doublets. Up to this point, there is only one additional parameter with respect to the SM, $\tan \beta = \frac{v_u}{v_d}$, related to the vacuum expectation values of the neutral components of the two Higgs doublets: $v_d \equiv < H_d^0 >$ and $v_u \equiv < H_u^0 >$.

The superpotential in equation 1.24 is the minimal superpotential that produces a phenomenologically viable model. Its most general expression can contain others terms, which are gauge invariant and analytic in the chiral superfields, but violate either baryon number or total lepton number. The existence of such terms would be rather disturbing, because baryon number or total lepton number violating processes have never been observed experimentally. The usual approach is to eliminate these terms by introducing a new symmetry, which allows the terms in equation 1.24, while forbidding baryon number or total lepton number violating processes. This new symmetry is called \textit{R-parity} [6]. R-parity is defined as a multiplicative quantum number such that all SM particles have R-parity +1, while SUSY partners have R-parity -1:

$$P_R = (-1)^{3(B-L)+2s} \quad (1.25)$$

11
where $B$ ($L$) is the baryon (lepton) number, and $s$ the spin of the particle.

The exact conservation of the R-parity has three important phenomenological consequences:

- The lightest supersymmetric particle (LSP) must be absolutely stable.
- In collider experiments, sparticles can only be produced in even numbers.
- At the end of the decay chain of each sparticle, only SM particle(s) and an odd number of LSPs are produced.

### 1.6 SUSY breaking

The above description of MSSM is not yet complete. None of the superpartners of the SM particles has been discovered so far, therefore supersymmetry is a broken symmetry in the vacuum state chosen by Nature. In fact, if supersymmetry were unbroken, there would be two selectrons $\tilde{e}_L$ and $\tilde{e}_R$ with masses exactly equal to $m_e \sim 0.511$ MeV/$c^2$, etc., but such particles have not been observed.

To understand the nature of the SUSY breaking, it is important to return back to the hierarchy problem in the SM. Supersymmetry forced us to introduce two complex scalar fields for each SM fermion, which is what is needed to enable a cancellation of the quadratic divergent ($\Lambda^2$) terms in equation 1.20. This cancellation also requires that the associated dimensionless couplings should be related ($g^2 \sim g_5^2$). If a broken symmetry is still to provide a solution to the hierarchy problem, then the relation between dimensionless couplings must be maintained. This requirements lead to consider *soft* supersymmetry breaking, and to write the effective MSSM lagrangian as:

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$$

(1.26)

where $\mathcal{L}_{soft}$ violates supersymmetry but contains only mass terms and couplings with *positive* mass definition.

Soft supersymmetry breaking seems an arbitrary requirement, but theoretical models can indeed yield effective lagrangians with such terms for $\mathcal{L}_{soft}$. If the largest mass scale associated with the soft terms is $m_{soft}$, the additional
non-supersymmetric corrections to the Higgs mass must vanish in the limit $m_{soft} \rightarrow 0$, so they cannot be proportional to $\Lambda^2$. More generally, these models maintain the cancellation of quadratic divergent terms in the radiative corrections of all scalar masses, to all orders in perturbation theory. The remaining corrections diverge logarithmically:

$$\delta M_H^2 \simeq m_{soft}^2 \left[ \frac{\lambda}{4\pi^2} \ln(\Lambda/m_{soft}) + \ldots \right]$$

where $\lambda$ is a typical dimensionless coupling.

Since mass splittings between SM particles and their superpartners are determined by the parameter $m_{soft}$, the differences cannot be too large, otherwise SUSY would not solve the hierarchy problem. Moreover, the masses of at least the lightest few superparticles should be at most around 1 TeV/$c^2$, in order to have $m_W \simeq 80.4$ GeV/$c^2$ and $m_Z \simeq 91.2$ GeV/$c^2$ without unnatural cancellations.

The most general soft SUSY breaking lagrangian compatible with gauge invariance and R-parity is the following [8]:

$$\mathcal{L}_{soft} = -\frac{1}{2} \left( M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} \right) + c.c. +$$

$$\left( \tilde{u}_a Q H_u - \tilde{d}_a Q H_d - \tilde{e}_a L H_d \right) + c.c. +$$

$$-\tilde{Q}^\dagger m_Q^2 \tilde{Q} - \tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{u}_a^2 \tilde{u}^\dagger - \tilde{d}_a^2 \tilde{d}^\dagger - \tilde{e}_a^2 \tilde{e}^\dagger +$$

$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left( b H_u H_d + c.c. \right)$$

(1.28)

$M_1$, $M_2$ and $M_3$ are the bino, wino and gluino mass terms. The second line contains the scalar couplings: each of $a_u$, $a_d$ and $a_e$ is a $3 \times 3$ matrix in family space. The third line consists of squark and slepton mass terms: each $m_Q^2$, $m_u^2$, $m_d^2$, $m_L^2$ and $m_e^2$ is a $3 \times 3$ matrix in family space. The last line contains contributions to the Higgs potential. $\mathcal{L}_{soft}$ introduces 104 new parameters, as opposite to $\mathcal{L}_{SUSY}$ where only one new parameter ($\tan \beta$) is introduced.

Usually, it is assumed that SUSY breaking occurs in a hidden sector at a high energy scale, and this interacts with ordinary particles and their superpartners via superheavy particles. There are two main scenarios, the gravity-mediated and the gauge-mediated SUSY breaking. In gravity-mediated SUSY breaking [9], the hidden sector interacts with the visible MSSM sector via
gravitational interactions. In this case the SUSY breaking scale is of the order of $10^{10}$ GeV and the gravitino has a mass of the order of the electro-weak scale. In gauge-mediated SUSY breaking [10], the interactions are ordinary gauge interactions, and the SUSY breaking scale is much lower, of the order of $10^4 - 10^5$ GeV. In this case, the gravitino has a mass in the range from the eV/c^2 to keV/c^2, and it is the LSP.

1.7 SUSY Higgs sector

In MSSM, the description of the EW symmetry breaking has to take into account that there are two complex Higgs doublets, rather than just one Higgs boson as in the ordinary SM. However, while in the SM electro-weak symmetry breaking is put by hand, in SUSY it can be generated radiatively by quantum corrections [11].

Including the soft SUSY breaking terms, and after setting $H_u^+ = H_d^- = 0$ without loss of generality, the MSSM Higgs potential is given by:

$$V_H = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b H_u^0 H_d^0 + c.c.) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)$$

In this expression, only the $b$ term depends on the phase of the fields, but any phase in $b$ can be absorbed with a redefinition of the phases of $H_u$ and $H_d$. Moreover, $< H_u^0 >$ and $< H_d^0 >$ must have opposite phase, and a $U(1)_Y$ gauge transformation can be used to make them both real and positive, since $H_u$ and $H_d$ have opposite hypercharges. It follows that CP cannot be spontaneously broken by the Higgs scalar potential, then the Higgs scalar mass eigenstates can be assigned well defined eigenvalues of CP. The following inequality has to be satisfied:

$$b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2)$$

otherwise $H_u^0 = H_d^0 = 0$ will be a stable minimum of the potential, and electroweak symmetry breaking will not occur. In order for the MSSM scalar potential to be viable, the potential has to be bounded from below for arbitrary
large values of the scalar fields. This requirement leads to:

\[ 2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 \]  \hspace{1cm} (1.31)

It is worth to note that if \( m_{H_u}^2 = m_{H_d}^2 \) the previous constraints cannot both be satisfied. In models derived from minimal supergravity or gauge mediated boundary conditions, \( m_{H_u}^2 = m_{H_d}^2 \) holds at tree level, but the \( X_t \) contribution to the RG equation for \( m_{H_u}^2 \) pushes it to \( m_{H_u}^2 < m_{H_d}^2 \) at the EW scale. So in this models, EW symmetry breaking is actually driven by quantum corrections.

The VEVs at the minimum of the potential can be connected to the mass of the Z boson and the electroweak gauge couplings:

\[ v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \sim (174 \text{ GeV})^2 \]  \hspace{1cm} (1.32)

where \( <H_u^0>=v_u \) and \( <H_d^0>=v_d \). Usually the ratio of the two VEVs is written as \( \tan \beta = v_u/v_d \).

The conditions \( \partial \mathcal{V}_H/\partial H_u^0 = \partial \mathcal{V}_H/\partial H_d^0 = 0 \) under which the potential has a minimum satisfying the two previous constraints lead to:

\[ |\mu|^2 + m_{H_d}^2 = b \tan \beta - (m_Z^2/2) \cos 2\beta \]  \hspace{1cm} (1.33)

\[ |\mu|^2 + m_{H_u}^2 = b \tan \beta + (m_Z^2/2) \cos 2\beta \]

The Higgs scalar fields correspond to eight real, scalar degrees of freedom. Three of them, after EW symmetry breaking, become the longitudinal modes of the Z, and W\(^\pm\) massive vector bosons. The remaining five Higgs scalar mass eigenstates consist of one CP-odd neutral scalar \( A \), two charged scalars \( H^\pm \), and two CP-even neutral scalars \( h \) and \( H \). In terms of the original gauge-eigenstate fields, the mass eigenstates are given by:

\[
\begin{pmatrix}
G^0 \\
A
\end{pmatrix}
= \sqrt{2}
\begin{pmatrix}
\sin \beta & -\cos \beta \\
\cos \beta & \sin \beta
\end{pmatrix}
\begin{pmatrix}
\text{Im}[H_u^0] \\
\text{Im}[H_d^0]
\end{pmatrix}
\]  \hspace{1cm} (1.34)

\[
\begin{pmatrix}
G^+ \\
H^+
\end{pmatrix}
= \begin{pmatrix}
\sin \beta & -\cos \beta \\
\cos \beta & \sin \beta
\end{pmatrix}
\begin{pmatrix}
H_u^+ \\
H_d^{-}\ast
\end{pmatrix}
\]  \hspace{1cm} (1.35)
with $G^- = G^{++}$ and $H^- = H^{++}$, and

$$
\begin{pmatrix}
    h \\
    H
\end{pmatrix} = \sqrt{2} \begin{pmatrix}
    \cos \alpha & - \sin \alpha \\
    \sin \alpha & \cos \alpha
\end{pmatrix} \begin{pmatrix}
    Re[H_u^0] - v_u \\
    Re[H_d^0] - v_d
\end{pmatrix}
$$

(1.36)

which defines a mixing angle $\alpha$. The tree level masses of the Higgs bosons are:

$$
m_A^2 = \frac{2|\mu B|}{\sin 2\beta}
$$

(1.37)

$$
m_{H^\pm}^2 = m_A^2 + m_W^2
$$

(1.38)

$$
m_{h,H}^2 = \frac{1}{2} \left[ m_A^2 + m_Z^2 + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2m_Z^2\cos^2 2\beta} \right]
$$

(1.39)

In terms of these masses, the mixing angle $\alpha$ is determined at tree level by:

$$
\begin{align*}
\sin 2\alpha & = -\frac{m_A^2 + m_Z^2}{m_H^2 - m_H^2} \\
\cos 2\alpha & = \frac{m_A^2 - m_Z^2}{m_H^2 - m_H^2}
\end{align*}
$$

(1.40)

The masses of $A$, $prtH$ and $prtH^\pm$ can in principle be arbitrary large since they all grow with $c/\sin 2\beta$. On the other hand, the mass of $h$ is bounded from above and it is lighter than $m_Z|\cos 2\beta|$. However, Higgs masses are subject to large radiative corrections which have been calculated up to the two-loop level in the effective potential approach [12]. Fig. 1.1 shows the masses of the Higgs bosons $h$ and $H$ in the no-mixing scenario (described in chapter 3) taking into account these corrections.

The couplings of the MSSM Higgs particles can be derived from the Yukawa lagrangian and the kinetic term for the two Higgs doublets, and they are reported in Table 1.5, normalized to the SM couplings. An interesting limit

<table>
<thead>
<tr>
<th>$\Phi$</th>
<th>$g_{\Phi uu}$</th>
<th>$g_{\Phi dd}$</th>
<th>$g_{\Phi vv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>H</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MSSM</td>
<td>h</td>
<td>$\cos \alpha/\sin \beta$</td>
<td>$-\sin \alpha/\cos \beta$</td>
</tr>
<tr>
<td></td>
<td>$H,H^\pm$</td>
<td>$\sin \alpha/\sin \beta$</td>
<td>$\cos \alpha/\cos \beta$</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>$1/\tan \beta$</td>
<td>$\tan \beta$</td>
</tr>
</tbody>
</table>

Table 1.5: Higgs couplings in the MSSM normalized to the SM couplings.

(called decoupling limit) occurs when $m_A \gg m_Z$. In this case, $m_h$ can saturate
the upper limit, while $A$, $H$ and $H^\pm$ are much heavier and nearly degenerate. Moreover, the mixing angle $\alpha$ is fixed to be $\alpha = \beta - \pi/2$, and in this limit $h$ has the same couplings as would the Higgs boson of the ordinary Standard Model.

1.8 Constrained MSSM

In the most general framework, with minimal field content and R-parity conservation, the MSSM is a model with 124 free parameters. A deeper understanding of the mechanism of SUSY breaking will probably relate many of them to the others, but in the meanwhile, there are several experimental facts which point to some hints for the reduction of the number of free parameters. First of all, the observed behavior of gauge coupling constants: if SUSY particles have masses of the order of $O(10^2 - 10^3 \text{ GeV}/c^2)$, the constants meet at a scale about $10^{16}$ GeV. So, it is usually assumed that the gaugino masses unify at $M_{GUT}$:

$$M_1(M_{GUT}) = M_2(M_{GUT}) = M_3(M_{GUT}) \equiv m_{1/2}$$
In order to avoid lepton number violation, slepton mass matrices should be kept flavour diagonal. Furthermore, constraints on Flavour Changing Neutral Current (FCNC) also lead to flavour diagonal squarks mass matrices and trilinear couplings. Again, GUT inspired SUSY assumes that all squarks and sleptons have the same mass and the same trilinear couplings at GUT scale:

\[
\begin{align*}
M^2_Q(M_{GUT}) &= M^2_D(M_{GUT}) = M^2_U(M_{GUT}) = M^2_E(M_{GUT}) = m_0^2 \\
A_d(M_{GUT}) &= A_u(M_{GUT}) = A_e(M_{GUT}) = A_0
\end{align*}
\]

The SUSY model with this set of assumptions is called constrained MSSM. With respect to the SM, in the constrained MSSM there are only 6 new parameters:

- \( M_2 \) \( SU(2)_L \) gaugino mass at EW scale
- \( m_0 \) a universal scalar mass at GUT scale
- \( A_0 \) a universal trilinear coupling at GUT scale
- \( \tan \beta \) the ratio of the VEV’s of the two Higgs fields at EW scale
- \( \mu \) a higgsino mass parameter at EW scale
- \( M_A \) the mass of CP-odd Higgs boson

When these 6 parameters are specified, the entire particle spectrum at EW scale can be derived using the renormalization group equations.
Chapter 2

The CMS Experiment at LHC

The Large Hadron Collider (LHC) [15] is a proton-proton collider that will be housed in the 27 Km long LEP tunnel at CERN (see Fig. 2.1).

This project will provide proton-proton collisions with a center of mass energy of 14 TeV, as well as lead-lead collisions at $\approx 10^3$ TeV. The two beams will counterrotate in separated pipes, kept in a circular trajectory by supercon-
ducting magnets and accelerated by superconducting RF cavities. They will interact in four points, corresponding to the experimental sites approved by the LHC committee: CMS [16], ATLAS [17], LHCb [18], Alice [19].

Because of the large constituent energies and the low cross-sections and branching ratios for most of the interesting physical processes, a high machine luminosity is required to obtain statistically significant results. The LHC luminosity, after the first few years at $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (usually referred as low luminosity period), will reach the value of $10^{34}$ cm$^{-2}$s$^{-1}$ (high luminosity).

In order to achieve such a high luminosity, each beam will consists of 2835 closely spaced bunches filled with $\simeq 10^{11}$ protons. The bunch crossing rate will be as high as 40 MHz, corresponding to a 25 ns collision time. A serious drawback of this high rate could be the pile-up from more than one bunch crossing; to avoid this problem, a very fast detector response and readout electronic is required in the experiments design. Nevertheless, an average value of 25 minimum bias events piled up at each bunch crossing are expected (at high luminosity), due to the very large total proton-proton cross section (about 100 mb, as extrapolated from previous experiments). The minimum bias events are not only an unavoidable background for all physical processes at LHC, but also affects most of the detector design choices: radiation hard devices both for subdetectors and electronics are required in such a hostile environment.

2.1 The CMS Detector

The CMS detector (Fig. 2.2) has been designed to detect efficiently the different signatures of new physics. All the choices in the design of the experiment are focused on this task, and optimized to obtain the maximum possible coverage of the solid angle and precise identification and measurement of muons, electrons and photons over a large energy range (1% energy resolution).

Its structure is typical of a general purpose experiment designed for a collider: it is composed of cylindrical devices coaxial to the beam pipe in the central region (generally referred as barrel), while, at both ends of the cylinder, detector planes are installed perpendicular to the beam pipe (end-caps or forward region), ensuring a very high detector hermeticity.
All the subdetectors, with the exception of the muon chambers, are located inside a large superconducting solenoid, which provide the high magnetic field (4 T) needed to measure charged particle momenta.

From here onward, the coordinate system used is the standard CMS definition, a cartesian frame with the z-axis parallel to the beam pipe and the x-axis directed toward the center of LHC.

### 2.2 The Magnet

The choice of the magnet system was the first decision taken in the design of the CMS detector [16]. A superconducting solenoid 12.5 m long and with an inner diameter of 5.9 m, generating an uniform magnetic field of 4 T was chosen. The magnetic flux is closed in a loop via a 1.8 m thick saturated iron yoke, instrumented with four muon stations. The main result obtained using this configuration, due to the favourable aspect ratio and the high magnetic field, is that the provided bending power allows charged particle tracking and
efficient muon detection and measurement up to a rapidity of 2.5 without forward toroids. Hence the muon spectrometer uses a single magnet, simplifying the detector design.

The inner coil diameter is large enough to accommodate the tracker and the calorimeters. Moreover, because the magnet is the main element of CMS in terms of size, weight and structural rigidity, it is used as the principal structural element to support all other barrel components.

2.3 The Muon System

At LHC, the efficient detection of muons as a signature of new physics requires coverage over a large rapidity interval; the importance of a large rapidity acceptance is shown in Fig. 2.3 for the decay of a light Higgs in to four muons. The geometric coverage of the muon detector up to a pseudorapidity $|\eta| < 2.4$ is obtained with a barrel detector covering the region $|\eta| < 1.3$ and an endcap detector covering the region $0.9 < |\eta| < 2.4$.

Both barrel and endcap regions are equipped with four muon stations interleaved with the iron return yoke plates, which also serve as the absorber. Several different muon detection technologies were considered to provide the required measurement precision ($\approx 100 \mu$m) in the different detection regions (Fig. 2.4).

In the barrel, where the expected occupancies and rates are low ($< 10\text{Hz/cm}^2$) and there is no appreciable magnetic field in the vicinity of most of the muons stations, a system of 240 chambers of drift tubes (DTs) arranged in four concentric stations (MS1, MS2, MS3, MS4) is used. The barrel detector is divided in five wheels of twelve $30^\circ$ sectors each. Each DT module consists of twelve planar layers of drift cells: eight layers parallel (organized in two SuperLayers of four layers, providing measurements of the $\phi$ coordinate) and four layers perpendicular to the beam (one SuperLayer providing measurements of the $z$ coordinate). Stations MS1 and MS2 are arranged in such a way that a muon always crosses at least one of them, and the arrangement of MS3 and MS4 with respect to MS1 and MS2 ensures that every muon in the barrel region crosses at least three stations.
Figure 2.3: Differential acceptance for the muon with the maximum pseudorapidity among the four belonging to a Higgs decay. The shaded area corresponds to the fraction of events for which the Higgs mass can be fully reconstructed, having all the four muons in the acceptance region of the muon chambers.

In the endcap region, cathode strip chambers (CSCs) have been chosen because of their capability of functioning in a high non-uniform magnetic field. The CSCs, arranged in four muon stations (MF1 to MF4), containing six layers of wires sandwiched between cathode panels: therefore, each CSC provides six measurements of the $\phi$ coordinate (strips) and six measurements of $r$ coordinate (wires). In MF1, which experiences the full field of the solenoid, the wires will be strung at an angle to compensate for the Lorentz drift. As for the barrel, the muon stations are arranged in such a way that a muon in the endcap always crosses at least three stations.

Both barrel and endcap regions are equipped with resistive plate chambers (RPCs) to have additional, complementary trigger detectors with excellent timing capability and reasonable position resolution. Trigger signals coming from DTs, CSCs and RPCs will proceed in parallel until reaching the level of
the global trigger logic: this will provide redundancy for evaluating efficiencies, and should result in a higher efficiency and greater rate capability.

Comprehensive studies showed that such design of the muon system can fulfil the requirements needed to achieve the physics goals of the CMS experiment [20]:

- **Trigger**: the combination of muon chambers and dedicated trigger detectors provides unambiguous beam crossing identification and trigger on single and multimuons events with well defined $p_t$ threshold from a few GeV/c to 100 GeV/c up to $\eta = 2.1$.

- **Standalone momentum resolution**: from 8 to 15% $\delta p_t/p_t$ at 10 GeV/c and 20 to 40% at 1 TeV/c.

- **Global momentum resolution**: after matching with the Tracker, from 1 to 1.5% at 10 GeV/c, and from 6 to 17% at 1 TeV/c.

- **Charge assignment**: correct to 99% confidence up to the kinematic limit of 7 TeV/c.
2.4 The Calorimeters

The calorimetry system of the CMS detector is composed of an inner high resolution electromagnetic calorimeter (ECAL) and an outer sampling hadron calorimeter (HCAL), both subdivided in a barrel and an endcap region. In the endcap region, the ECAL extends up to $|\eta| = 2.6$ and the HCAL up to $|\eta| = 3.0$; this central calorimetry system is supported, to insure detector hermeticity for good resolution on missing transverse energy, by a very forward calorimeter that covers the pseudorapidity range $3.0 < |\eta| < 5.0$.

The CMS collaboration has chosen a homogeneous electromagnetic calorimeter, made of lead tungstate (PbWO$_4$) crystals, to optimize energy resolution of electrons and photons within the overall detector design. The main reasons to choose this kind of crystals are its short radiation length ($X_0 = 9$ mm) and small Molière radius ($\simeq 2.2$ cm), leading to a compact calorimeter; moreover, such crystals show a good radiation hardness, and a short scintillation decay time constant ($\simeq 10$ ns), which matches the LHC bunch crossing time. The low light-yield of this crystal can be effectively addressed by the use of a new generation large area silicon avalanche photodiodes. Crystals have a length of 23 cm ($25.8 \times X_0$) in the barrel and 22 cm in the endcap, while the front face granularity is respectively 22 mm$^2$ and 24.7 mm$^2$. A preshower device, 3$X_0$ thick, is placed in front of crystals to enhance neutral pion rejection in the endcap region. The expected energy resolution for such design has been parameterised as:

$$\frac{\sigma_{E}}{E}^{\text{ECAL}} = \frac{0.03}{\sqrt{E}} \oplus \frac{0.15}{E} \oplus 0.005$$  \hspace{1cm} (2.1)

where $E$ is in GeV.

The hadronic calorimeter surrounds the ECAL and, together with it, measures the energies and direction of jets, also providing hermetic coverage for measuring missing transverse energy. In the central region around $\eta = 0$ a hadron shower tail catcher is installed outside the solenoid coil to ensure adequate sampling depth and to reduce the hadron spill through in the muon chamber region. The active elements of the barrel and endcap HCAL consist of plastic scintillator tiles with wavelength-shifting fibre readout and copper absorbers.
The tiles are arranged in projective towers with fine granularity (lateral segmentation $\Delta \eta \times \Delta \phi \simeq 0.09 \times 0.09$) to provide good di-jet separation and mass resolution. Using the same expression as before, the energy resolution can be parameterised as:

$$\frac{\sigma_{E}^{H\text{CAL}}}{E} = 0.8 \sqrt{E} + 1.03$$

(2.2)

where $E$ is in GeV.

### 2.5 The Tracker

Robust tracking and detailed vertex reconstruction are expected to play an essential role for an experiment designed to address the multiplicity of the physics goals of LHC. The following considerations illustrate some of the requirements which the Tracker must satisfy:

- **Lepton momentum resolution.** The leptonic decays of gauge bosons can be a clean signature of several new physics process, so a good momentum measurement for energetic leptons is required.

- **Isolated lepton reconstruction.** Effective isolation criteria rely on the efficient reconstruction of all hadronic tracks down to $p_t \simeq 2\text{ GeV}/c$, and may be further improved by the reconstruction of tracks with a $p_t$ as low as 1 GeV/c.

- **B-jets tagging and reconstruction.** B-jets are a particularly useful signature for a broad spectrum of new physics, besides being an essential tag for top quark physics; also their detailed study may yield insights into the question of CP violation. As a signal for new physics, b-jets may results from the decay of a new particle, or in associated production via gluon-gluon fusion. In the first case, efficient b-tagging for high momentum tracks imposes several constraints on two track separation capability, while for the second case, good b-tagging efficiency is required up to $|\eta| = 2.4$. Moreover, in order to ensure a satisfactory performance of the b-tagging algorithms based on displaced vertices, it is mandatory
to keep under control the tails of the parameter distributions due to errors in pattern recognition.

- Photon conversion. In order to minimize the effect on tracking performances of electron bremsstrahlung and hadronic interactions, and in order to fully exploit the ECAL performances for channels like $H \rightarrow \gamma\gamma$, several constraints on the material budget need to be imposed.

Many of the most interesting physical processes require the highest luminosity achievable at LHC and therefore the stringent demands placed on the tracking system must continue to be satisfied up to $10^{34}$ cm$^{-2}$s$^{-1}$. In the volume covered by the tracker, this results in a background of $O(10^3)$ soft charged tracks, coming from $\sim 25$ minimum bias events, leading to a highly congested environment for pattern recognition. To isolate interesting events and overcome pattern recognition problems, low cell occupancy and large hit redundancy are required. Low occupancy can be obtained by working with small detection cell size (high granularity) and fast primary charge collection, while redundancy relies on the largest number of measured points per tracks, within an acceptable material budget.

The very high magnetic field of CMS affects events topology, by confining low $p_t$ charged particles to small radius helical trajectories. Coupled with the steeply falling $p_t$ spectrum characteristic of minimum bias events, this results in a track density which rapidly decreases with increasing radius. This has important implications for the architecture of the CMS tracker. Two detector technologies, each best matched to the task of satisfying the stringent resolution and granularity requirements in the higher and lower particle density regions, have been chosen. The inner part of the tracker is equipped with Pixel Detectors, while in the outer region a Silicon Microstrip Detectors will be used.

### 2.5.1 The Pixel Detector

The CMS pixel system [21] consists of two or three barrel layers and two end layers (end disks) on each side of the barrel (see Fig. 2.5). Because of the large fluence of charged particle near the interaction point, the barrel configuration
will be different for the low and high luminosity period, in order to prevent radiation damage. Two options are under evaluation for the low luminosity phase: the first, with two barrel layers at a radius of approximately 4 cm and 7 cm, and another one with an additional layer at 11.5 cm, to optimize pattern recognition and trigger capabilities. At high luminosity, two layers are foreseen, at 7 cm and 11.5 cm. Nevertheless, to provide full functionality, the layer at 7 cm must be replaced after 6 or 7 years of operation.

Figure 2.5: Perspective view of the pixel detectors.

The two end disk will be placed at \(|z| = 32.5\) cm and \(|z| = 46.5\) cm, covering radii from 6 cm to 15 cm, in order to complement the \(\eta\)-coverage for two pixel hits. Again, it is foreseen to replace the innermost end disks once during the experiment.

Each layer is composed of modular detector units, containing a thin (\(\sim 200-250\) \(\mu\)m) segmented sensor plate with highly integrated read-out chips connected to them using bump bonding technique. In finding and localising secondary decay vertices, accurate measurements of all three hit coordinates are needed. Therefore, a square pixel shape has been chosen (with a pixel size around \((150\mu m)^2\)), combined with analog signal read-out to profit from position interpolation, where effects of charge sharing among pixels are present. Charge sharing between pixels is mainly due to Lorentz drift, and, in this respect, sensors should be n-type pixels which collect electrons, because elec-
trons drift angle is three times larger than the holes one. Moreover, radiation hardness considerations lead to choose n+ pixels on n-type silicon substrate.

In the barrel, charge sharing in the $r\phi$ direction is large due to the very high magnetic field (the Lorentz drift angle for electrons in silicon is 32° at 4 T). Therefore barrel detectors are arranged such that the drift angle induces significant charge sharing across neighbouring cells, in order to improve resolution. In spite of using a pixel dimension of 150 μm, an intrinsic hit resolution of 10-15 μm can be obtained. Moreover, charge sharing along the $z$ direction is also present in barrel for inclined tracks, leading to similar hit resolution. In the end disks, detectors are rotated by 20° around their central radial axis to benefit of charge sharing: the induced Lorentz effect improves charge sharing among adjacent pixels both in $r$ and $r\phi$ directions. Although the amount of charge sharing is less than in the barrel, good resolutions at the level of 15 μm are expected for both $r$ and $r\phi$ coordinates at the start of CMS, degrading to around 20 μm with radiation damage.

2.5.2 The Silicon Tracker

Microstrip silicon detectors are the natural choice to instrument the intermediate and outer regions of the CMS tracker system, due to their spatial and time resolution characteristics, radiation hardness and high detection efficiency: the excellent spatial resolution required in the central tracking volume is ensured by the fine strip pitch that can be carried out in microstrip devices while the fast charge collection time in silicon allows single bunch crossing identification.

The CMS Silicon Strip Tracker (SST), [21],[22] extends to about 5.6 m along the $z$ axis, covering the pseudorapidity region $\eta \leq 2.5$, with a silicon active area of more than 230 m$^2$; beyond $\eta \sim 2.5$, the radiation level and the track density becomes too high to operate silicon detectors reliably.

The barrel region of the tracker consists of ten concentric layers providing $r\phi$ information; layers 1, 2, 5 and 6 also deliver stereo measurements for the $z$ coordinate, to improve pattern recognition and momentum resolution (see Fig. 2.6). The four innermost layers (inner barrel) extend from -65 to 65 cm along the $z$ axis, and are equipped with thin sensors (320 μm), tilted to
compensate the Lorentz angle. The six outermost layers (outer barrel) extend from -110 to 110 cm and are equipped with thick sensors (500 µm): in the outer part of the tracker, longer detectors are needed to reduce the number of electronic channels.

Each of the two end-cap regions consists of nine big disks, with $120 \leq |z| \leq 280$ cm, and three small disks (the inner endcaps) that close the inner barrel. The three outermost rings are equipped with thick sensors, the others with thin ones. All rings provide $z\phi$ measurements, while rings 1, 2 and 5 also deliver stereo measurements.

The total amount of Tracker material in units of radiation length is reported in fig. 2.7

A single hit resolution of better than 20 µm in the inner part (40 µm in the outer tracker) and a two track resolution better than 200 µm are required to allow an efficient overall pattern recognition. The actual design of SST sensors, with pitches ranging from 80 µm to 183 µm in the barrel, and from 81 µm to 205 µm in the forward, achieves such precision: the hit resolution is around 15 µm for the sensors with the smaller pitches, and approaches the digital limit ($\text{pitch}/\sqrt{12}$) for the larger pitches, where most of the charge is deposited on a single strip.
Another strong constraint in the SST design is the lifetime of the sensors in the LHC hostile environment. The survival of silicon detectors is strongly dependent on careful detector design and bulk properties, and a large program of studies and tests has been performed by the Tracker collaboration to achieve the required performances [23].

2.6 Reconstruction Software

In the previous sections, the CMS experiment has been shown as a challenging project as far as it concerns the physics goals and the hardware design of the detector. The same can be said for the CMS software requirements and needed computing resources [24], which will exceed by far those of any currently existing high energy physics experiment. From 1995, the CMS software group has been engaged in an extensive program to evaluate and prototype a software architecture to allow an efficient and reliable development of the reconstruction and analysis software. Several new technologies (object oriented programming, object data base management system, flexible software architecture, evolutionary software development process) have been used to provide a
reliable environment for developers and end-users.

An application framework (CARF, CMS Analysis & Reconstruction Framework), customisable for each of the computing environments, defines the top level abstractions, their behaviour and collaboration patterns. To achieve maximum flexibility, CARF implements an implicit invocation architecture: all the different modules (reconstruction, physics and utility modules) register themselves at creation time, and are invoked when required.

The CMS software is subdivided in packages, which group all classes required to perform a given operation. CARF provides a PackageInitializer class, which can be specialised in each package and can be statically constructed when the corresponding library is loaded. Such an object can be used to construct and register default versions of the modules contained in the package. Part of the work performed for this thesis regards the development of a track reconstruction algorithm, included as a module of the Tracker package in ORCA (Object Oriented Reconstruction for CMS Analysis).

Another important issue for CARF is the persistency service: the project is required to store and retrieve the results of computing intensive processes; this responsibility covers also raw-data storage, because the collaboration plans to use the same software framework in both offline reconstruction and online triggers. An Object Data Base Management System (ODBMS) responds to the requirements of the collaboration, and provides a coherent solution to the problem of persistent object management. At the moment, Objectivity/DB (a commercial product) has been identified as a possible candidate to be used as ODBMS for CMS, but the software group has anyway started a prototype effort to understand if an in house product matching the requirements can be developed.

At the moment, the evaluation of the detector performances on the various interesting physics channels are performed through a complex computational chain, from the generation of the physics process to the reconstruction of the event, through the simulation of the detector response. In the following, a few details about each step are given.
2.6.1 Event generator

The event samples studied in this thesis, both signal and backgrounds, have been generated at the kinematical level using the Monte Carlo simulation program PYTHIA 6.136 [31]. It generates the chosen processes picking up the colliding partons from the protons at the required center of mass energy (14 TeV), according to the parton distribution functions. The generated final states decay following the allowed modes, while the secondary quarks and gluons generate jets by hadronization process (a string model is used): the resulting hadrons and leptons are then allowed to decay into stable particles. The user can define the relevant decay modes for all particles.

The output of the simulation program is the list of the stable particles\textsuperscript{1}, containing all the relevant informations: momentum, energy and production vertex. Moreover, all the mother-daughter relations of the generated decay processes are stored in the output.

2.6.2 Detector response simulation

After the generation of the events, the final state particles have to be propagated in the CMS detector. The detector response is simulated with Monte Carlo techniques using the CMSIM 122 [32] program, which is based on the CERN GEANT package [33]. Within the program a detailed description of the full CMS detector is present, including all the subdetectors as well as the cables and the mechanical support structures. All the particles produced at the generator level are propagated through the CMS detector, calculating the energy deposit in each subdetector module, taking into account all the possible propagation effects, for example ionization energy loss in the detectors and in the support structures, or interactions leading to secondary decay products.

The data for each event are then stored in to a database, using the persistency services provided by CARF with Objectivity, ready to be processed by the reconstruction software and then by the physics analysis.

\textsuperscript{1}in this case \textit{stable} means particles which not decayed within the detector
2.6.3 Reconstruction and analysis

As already stated, the reconstruction and analysis is performed using ORCA, the reconstruction and analysis project integrated in the CARF framework. In the reconstruction phase, the signals coming from the different CMS subdetectors are processed to obtain high level quantities and objects to be used during analysis. For example, reconstruction in the tracker includes strip hit clusterization, track pattern recognition and fitting as well as vertex finding and reconstruction.

During this thesis, I developed a track finding method called Connection Machine, hence a particular emphasis will be placed on the description of the track reconstruction framework in the next chapter, where the Connection Machine is described.
Chapter 3

Track Reconstruction with the Connection Machine

Nearly all physics analysis that will be performed at LHC will require an efficient and reliable pattern recognition as one of the fundamental parts of the analysis of the data. Part of the work performed for this thesis regards the development and implementation of a track finding method, and its applications to several topics, like muon reconstruction through the whole detector.

3.1 Track reconstruction problematic

While the design of a reconstruction system is extremely dependent on the experimental apparatus, several common issues can be found as general properties of track finding algorithms. First of all, the data provided by a tracking device can always be divided in three classes:

- Hits produced by charged tracks coming from the primary vertex or secondary decay products.

- Hits produced by spurious particles not belonging to the event, or not relevant to the physics analysis (particles from beam pipe interactions, particles from pile-up events).

- Fake hits (i.e. those given by the intrinsic noise of the detectors).

Given the tracking detector data, the track finding algorithm should divide it in different classes so that:
• Each class contains all the measurements that come from the same particle.

• One class (ideally empty) contains all the measurements that cannot be associated to a particle with enough confidence (noise, spurious hits).

Most of the track finding and reconstruction methods try to achieve this goal by relying on two complementary strategies: first of all, *track candidates*, i.e. hits that could represent the trajectory of a charged particle, are looked for; then, they are tested with a fit to a given *track model*. The various track models depend on the experimental configuration and design; the definition for the CMS track model is derived from the equation of motion of a charged particle in a static magnetic field:

\[
m\gamma \frac{d^2 \vec{x}}{dt^2} = kq\vec{v} \times \vec{B}
\]  

(3.1)

where \( k \) is a proportionality factor dependent on the choice of units, \( q \) the charge, \( \vec{v} \) the speed, \( m \) the mass and \( \vec{B} \) is the magnetic field at the position \( \vec{x} \) of the particle.

This equation can be rewritten in the following form [25]:

\[
\frac{d^2 \vec{x}}{ds^2} = \frac{kq}{|\vec{p}|} \frac{d\vec{x}}{ds} \times \vec{B}
\]  

(3.2)

where \( s \) is the curvilinear arc length. In fact, in this case:

\[
\left( \frac{d^2 \vec{x}}{dt^2} \right) \times \left( \frac{d\vec{x}}{dt} \right) \equiv 0
\]  

(3.3)

therefore:

\[
\left| \frac{d\vec{x}}{dt} \right| = \text{constant} = \nu = \beta c
\]

\[
\frac{d\vec{x}}{dt} = \frac{d\vec{x}}{ds} \frac{ds}{dt} = \frac{d\vec{x}}{ds} \beta c
\]

\[
\frac{d^2 \vec{x}}{dt^2} = \frac{d^2 \vec{x}}{ds^2} \beta^2 c^2
\]

The eq.3.2 can be written as:

\[
\frac{d\vec{x}}{ds} = \vec{n} \quad \frac{d\vec{n}}{ds} = a\vec{n} \times \vec{B}
\]  

(3.4)
where \( \mathbf{n} \) is the unitary vector tangent to the trajectory at \( \bar{x} \) and \( a \) is the constant \( kq/|p| \). This system of differential equations has six integration constants plus the unknown parameter \( a \) or \( kq/|p| \), but with the identity:

\[
\left( \frac{dx}{ds} \right)^2 + \left( \frac{dy}{ds} \right)^2 + \left( \frac{dz}{ds} \right)^2 = 1 \tag{3.5}
\]

and an arbitrary choice of one coordinate (the reference surface), there are, in fact, only five free parameters defining the track, i.e. \( x_0, y_0, n_x, n_y \) at a given \( z_0 \) and \( a \) or \( kq/|p| \). In a homogenous magnetic field, the solution of eq.3.2 is a helix with axis parallel to the magnetic field direction, therefore parallel to the beam axis, given an experimental configuration like CMS. Having defined the track model, one can proceed to the implementation of the reconstruction method.

All reconstruction methods perform the analysis of the event in two steps: first, sets of hits are selected to identify the track candidates (this phase is usually called recognition); then, a discriminant criterion is applied in order to accept or reject the candidate as a track. The criterion is based on the track model used (usually the one described above) and on the a priori knowledge of the tracking detector performances: resolution, systematic and statistical errors. With the final fit of the data hits to the track model, the most common choice for the decision function, the reconstruction is completed, providing values and errors of the integration constants.

It may happen that two or more tracks are not compatible (for example, if they share too many hits), and that only one has to be chosen as the correct one. In this case a measurement of the track quality is needed. A classical way is to use a \( \chi^2 \) test, but, although \( \chi^2 \) is distributed with a well known law, a small value of \( \chi^2 \) is not a sure indication that the reconstructed track corresponds to the real particle trajectory more than another which has a greater \( \chi^2 \). In fact, if the track model is not exact (e.g. magnetic field inhomogeneity), short tracks tend to have a higher confidence level than longer tracks. Thus a good measurement of the track quality is, in reality, given by the number of hits and the lack of skipped detector planes. Such a choice leads naturally to a hierarchical search of the tracks: tracks are looked for in order of length.
The track finding algorithm may also be classified as global or local. In a local method, the two steps reconstruction is divided in several parts: a track candidate at a time is selected, usually starting with a few points (track candidate initialization), then, based on the track model, regions where to look for further hits are defined. If additional hits are found, these are added to the track candidate, otherwise the track candidate is discarded and another one is processed. On the other hand, a method is called global if all the hits are managed by the algorithm in the same way, and are treated simultaneously.

3.2 Track Reconstruction Framework

The track finding method that I have developed and will describe in the following paragraphs has been included in ORCA as one of the main track finders for data reconstruction and analysis. ORCA provides a general framework for the implementation of track finding algorithms, and a brief description of this framework is useful to point out the logical modules in which a track finding method can be splitted.

Taking into account the considerations in the previous section, the task of track finding using a local method approach can be divided in four different phases, that correspond, in the ORCA framework, to four different logical units (see appendix A for the software implementation):

• **Seed generation.** Because the track reconstruction has to be as fast as possible, it is impossible to exploit all the combinations of hits to identify the track candidates. Hence, the seed generation phase is performed on a reduced set of data in order to define a set of trajectory seeds. These seeds can be considered as preliminary track candidates, with a rough estimate of the trajectory parameters, useful in reducing the search space where to look for further hits that will be added to the track candidate.

• **Trajectory building.** Starting from each seed, track candidates are built finding compatible hits (the preliminary estimation of the track parameters allows to reduce the combinations). Compatible hits are added to the candidate incorporating all the information that the measurement
provides (position and errors).

- **Trajectory cleaning.** In this phase ambiguities are resolved: the set of mutually exclusive track candidates are identified, and only one (the best) candidate for each set is chosen.

- **Smoothing.** The trajectory parameters are not necessarily optimal after the previous phases. The smoothing stage is performed to obtain the optimal track parameters at every hit of the track candidate.

Having factorized the problem of track finding in various, and independent, sub-tasks, it is easier to implement a reconstruction method, and to test different strategies while solving each sub-task, in order to obtain optimal performances.

A track reconstruction method can be characterized by describing the strategies used in these four phases, and I will follow such an approach while describing the Connection Machine.

### 3.3 The Connection Machine

The reconstruction method that I have designed and implemented, called the Connection Machine (CM), has to deal with two main issues which are of extreme importance for any reconstruction software: reconstruction efficiency and execution time. A typical event at low (high) luminosity is predicted to have $O(10^2)$ ($O(10^3)$) charged tracks, resulting in $O(10^3)$ ($O(10^4)$) hits in the Tracker. Clearly, the combinatorial background of fake tracks from such a huge number of hits is large, and one has to exploit some properties of the events and/or of the detector in order to reduce it to a reasonable level.

Most of the tracks which have to be reconstructed in an environment like CMS have their origin in the primary interaction vertex, while the rest comes from the decays of long lived particles or interactions with the tracker media. It is easy to guess that the reconstruction of secondary tracks will be more difficult and challenging, being a less constrained case. Therefore, the CM contains a simple and efficient algorithm dedicated to the primary tracks finding, starting with primary vertex identification and then reconstructing tracks
from the pixel system towards the outer layers (*forward reconstruction*). After this stage, a more general pattern recognition is performed, from the outer layers back to the interaction point (*backward reconstruction*) which is well suited for secondary tracks reconstruction. With this approach, the second, more demanding, task will start in a simpler combinatorial environment, because most of the tracks will have been reconstructed in the first phase. Moreover, only primary tracks are sometimes needed for analysis, and in this case reconstruction can be stopped just after the first step.

Actually, the name Connection Machine stands for the second part of the algorithm. Nevertheless, it will be used from here onward to identify also the full reconstruction chain, including both forward and backward reconstruction.

### 3.3.1 The Tracker Model

The CM works with a simplified Tracker model (STM) geometry, and all layers are approximated with geometrical surfaces: cylinders (for barrel layers) and rings (for end-cap disks), both coaxial with respect to the beam pipe.

Both types of surfaces have to be further subdivided to define the optimal granularity needed for collecting hits compatible with a track candidate so that track propagation can be performed. This is a critical issue both for what concerns efficiency and computational time: all the compatible hits should be picked up in this phase, but checking all the hits provided by the Tracker would lead to an explosion of the combinatorial possibilities. A possible reduction of the number of combinations can be achieved by just checking the surfaces next to the one where the track candidate is actually sitting; but a single layer still has too many hits and too much time would anyway be spent in this operation. Another possibility is to use the detectors themselves (i.e. silicon modules) as the lowest level of granularity: in this case the algorithm checks if the detector is compatible with the track candidate, and only in this case will it extract compatible hits. Unfortunately, in this way one loses any azimuthal symmetry in the STM (Simplified Tracker Model), and azimuthal symmetry is a crucial feature which is used in the learning phase of the algorithm, as explained in the next section. The optimal choice found consists in dividing
the barrel cylinders and forward disks in rings, as it is shown in Fig. 3.1, called cells.

Figure 3.1: Cell definition in barrel (left) and forward (right).

Having defined the granularity of the STM, the collection of compatible hits acts as follow: starting from a track candidate, the cells compatible with the propagation of the candidate are considered, and asked to provide hits compatible with the track candidate itself.

3.3.2 Learning Phase

The next task to address is how the navigation through the STM is handled during track reconstruction: again, checking all the cells to see if they are compatible with the track candidate is a time consuming operation, because each test would require the extrapolation of the track parameters to the cell surface, involving intensive mathematical calculations. The problem is solved using a learning phase of the algorithm that is performed once and for all at the starting of the analysis program. After learning, each cell knows which are the neighbouring cells that should be checked for track candidate propagation (i.e. the cell contains a vector of pointers to those other cells), in both forward (from the interaction point to the outside) and backward (from the outer layers towards the interaction point) directions. If one cell has a pointer to another one, the two cells are considered linked; moreover, if, going from the first cell to the second, one is proceeding from the interaction point to the outside, the link is called a forward link, in the other case backward link. It is evident that, if cell A has a backward link to cell B, then cell B must have a forward link to
The complete set of links is generated, during the learning phase, propagating through the STM several simulated single trajectories, with random parameters in this ranges:

- \( p_t \) down to a configurable minimum (0.9 GeV/c typically)
- \( |\eta| < 2.5 \)
- \( |z_{\text{vertex}}| < 30 \) cm (nominal primary vertex is at \( z_{\text{vertex}} = 0 \pm 5.3 \) cm).

If one of the trajectories crosses two consecutive cells, then these two cells are linked in both directions, forward and backward. For redundancy reasons (e.g. hit inefficiency), also cells with only one layer in between are linked. Because of the azimuthal symmetry in the STM, only simulated trajectories with \( \phi = 0 \) are propagated. The propagation to cylinders and rings during learning is done analytically neglecting the material budget (i.e. multiple scattering, ionisation losses) and magnetic field inhomogeneity; moreover, only trajectories with zero transverse impact parameter are propagated. Nevertheless, the resulting link system is redundant enough to be valid also for tracks with a large impact parameter, thus covering the full spectrum of tracks of interest to the physics analysis.

Another task is also performed during the learning phase, i.e. the definition of the cells where the track candidate initialization is performed. As discussed in section 3.2, the track candidate initialization cannot be executed exploiting all the combinations of hits: at least two hits (using a vertex constraint) are needed to define an helix, hence taking into account all possible pairs of hits would lead to \( \mathcal{O}(10^6) \) trajectory seeds even at low luminosity. During the learning phase, the reduced set of data to be used in track candidate initialization is defined, i.e. the list of cells to be used when creating the trajectory seeds. For the forward reconstructor, the starting cells are taken to be the pixel cells with at least one backward link. For the backward reconstructor, starting cells are the last (or next to last) element of long enough sequences of connected cells, hence backward starting cells sit on the outermost tracker layers.
3.3.3 Track parametrization

Before discussing how the CM actually works, it would be useful to define the track parametrization used during the several phases of the reconstruction. In a constant magnetic field directed along the z-axis $(0,0,B_z)$, neglecting multiple scattering and ionization losses, the trajectory of a charged particle is a spiral, and the corresponding equations of motion are:

\[
\begin{align*}
x(t) &= x_o + [\sin(kt + \psi_o) - \sin(\psi_o)]/k \\
y(t) &= y_o + [\cos(kt + \psi_o) - \cos(\psi_o)]/k \\
z(t) &= z_o + ct
\end{align*}
\]

(3.6)

where $t$ is the radial trajectory length, $k = 1/\rho = qB/p_t$ is the track curvature, $\psi_o$ is the tangent angle in the transverse plane at $t = 0$ and $x_o$, $y_o$ and $z_o$ are the coordinates of the vertex of production. This track model is approximate because of multiple scattering, ionization losses and magnetic field inhomogeneity, but however it is good enough for small propagations. It is worth to note that eqs. 3.6 is over-parametrised to describe a spiral, and in fact different parameters are used depending on the tracker region where the evaluation of the track parameters is performed, because the resolution on the coordinate measurements depend on the region where it is performed (for example, in the barrel, $x$ and $y$ are measured with good resolution, while $z$ is measured with a worse resolution, unless the hit sits on a stereo layer).

Assuming that the track has zero impact parameter ($x_o = y_o = 0$), eqs. 3.6 can be furthermore simplified, leading to:

\[
\begin{align*}
\phi &= \phi_o + \delta t \\
r &= \sin(\delta t) \simeq t + O(\delta^2) \\
z &= z_o + ct
\end{align*}
\]

(3.7)

where $\delta = \frac{1}{2}k$ and $\phi_o$ is the azimuthal angle at the origin.

3.3.4 Forward Track Finding

The first stage of the reconstruction using the Connection Machine is dedicated to primary tracks finding using a forward track finder, called Forward Kalman Filter (FKF), that starts with a primary vertex finder: the a priori knowledge
of the position of the primary vertex is essential in making the first phase of track reconstruction fast and quite efficient for primary tracks.

For each pair of hits in two linked cells in the pixel system, the vertex position $z_o$ can be estimated with a histogram method, assuming that the hit pair belongs to some track with zero transverse impact parameter. In fact, using eqs. 3.7, at order $O(\delta^2)$:

$$c \simeq \frac{z_{out} - z_{in}}{r_{out} - r_{in}}$$

where the subscripts $out$ and $in$ stand, respectively, for the hit in the outer and in the inner pixel layer. Extrapolating to the beam pipe, one obtains the $z$ coordinate of the vertex position:

$$z_o = \frac{r_{out}z_{in} - r_{in}z_{out}}{r_{out} - r_{in}}$$

The primary vertex should appear as a bump or a cluster over combinatorial noise in a histogram filled with the $z_o$ value for each hit pair (see Fig. 3.2). The vertex finder, in fact, looks for clusters in the histogram, and returns a list of vertex candidates (the first is the one with more entries in the corresponding cluster); the candidate with more entries is always returned, and a few more

![Figure 3.2: Histogram of the extrapolated $z_o$ values of the pixel hit pairs for a minimum bias event. A zoom view centered on the reconstructed primary vertex candidate is shown to the right.](image)
in case there are more candidates with at least half of the entries of the heaviest candidate. Typically, just one vertex is reconstructed in low luminosity conditions, and a few more at high luminosity.

The $z$ coordinate of the vertices is calculated as a weighted mean of the bins involved in the corresponding clusters:

$$z_o = \frac{\sum_{i_1,i_2} W_i * z_i}{\sum_{i_1,i_2} W_i}$$

(3.10)

where $i_{1,2} = i_{max} \pm 3$: a six bins window centered on the bin with maximal weight ($i_{max}$) is used. The probability that the primary vertex is within the reconstructed ones is nearly 100% even at high luminosity, and the accuracy on vertex position is of the order of 100 $\mu$m (see Fig. 3.3).

![Figure 3.3: Primary vertex position resolution.](image)

After calculating the position of the primary vertex, the seed generation (track candidate initialization) can be performed. For each hit in a starting cell (pixel cell with at least one backward link) backward linked cells are considered. Given the position of the starting hit, and the estimate of the vertex position,
a $\phi$ window on each linked cell can be calculated assuming a minimal $p_T$ cut (typically 0.9 GeV/c).

![Diagram](image)

Figure 3.4: Triplets definition in the initialization of a track candidate.

For each hit in the $\phi$ window, a helix can be fitted using the triplet of hits: vertex, inner pixel hit, outer pixel hit. The fit provides a first estimate of the track parameters and errors, and hence all the informations needed to initialize the track candidates.

The seed generation phase is followed by trajectory building. Each trajectory seed is propagated through the Tracker, using the following steps until the trajectory leave the Tracker active volume:

- Take the cell where the last (outermost) hit of the track candidate is sitting, and consider all the cells forward linked to this one.

- Try to propagate the track candidate to the surface of the linked cells, and, if the propagated state contains the linked cell surface within its errors, extract hits from the cell.

- For each compatible hit, create a new track candidate adding this hit to the old track candidate.

- Update the track candidate estimate of trajectory parameters and errors using measurements and errors of the new hit.
The algorithm used in this phase is based on a Kalman Filter (KF). The KF is an attractive method for track reconstruction because it is a step by step method which performs simultaneously both track finding and fitting. In the following, a few features of the *gain matrix* schema for the KF are presented, to explain how the trajectory building phase progresses (for full computational details see [30]).

A track candidate state is defined by the state vector $P_k$ where $k$ is the number of steps performed including seed generation (basically it’s the number of hits of the track candidate), the covariance matrix $C_k$ and the total $\chi^2_k$. When the track candidate is propagated to the surface of one of the linked cells, parameters and errors are propagated:

$$ P_k \rightarrow P_{k+1}^k(P_k) \quad C_k \rightarrow C_{k+1}^k = J_{k+1}^T C_k J_{k+1} $$

where $J_{k+1}$ is the Jacobian matrix of the parameters transformation. During this step, ionisation losses and multiple scattering are taken into account.

All the hits in the cells within the errors of the propagated state are then used to create several new track candidates (one for each compatible hit) and the updated state is calculated for the new track candidates. First of all, the Kalman matrix is calculated:

$$ K_{k+1} = C_{k+1}^k H_{k+1}^T (V_{k+1} + H_{k+1} C_{k+1}^k H_{k+1}^T)^{-1} $$

where $H_{k+1}$ is the measurements matrix used to project state vectors onto the measurement space and $V_{k+1}$ is the inverse of the two dimensional hit errors covariance matrix. Then, parameters and errors are updated:

$$ P_{k+1} = P_{k+1}^k + K_{k+1} (m_{k+1} - H_{k+1} P_{k+1}^k) $$
$$ C_{k+1} = (1 - K_{k+1} H_{k+1}) C_{k+1}^k (1 - K_{k+1} H_{k+1})^T + K_{k+1} V_{k+1} K_{k+1}^T $$

where $m_{k+1}$ is the measured hit position.

The total $\chi^2$ is updated taking into account the residual of the measured hit position:

$$ r_{k+1} = m_{k+1} - H_{k+1} P_{k+1} $$
$$ R_{k+1} = V_{k+1} - H_{k+1} C_{k+1} H_{k+1}^T $$
$$ \chi^2_{k+1} = \chi^2_k + r_{k+1}^T R_{k+1}^{-1} r_{k+1} $$
It is worth to note that, if the $\chi^2$ increment is too big, the hit is discarded and the new track candidate is not created. The trajectory building phase starting from a seed is stopped when no more valid propagations are found.

The main drawback is that the KF predictions are rather poor during the first steps and this can lead to a severe combinatorial problem in a dense environment like the CMS Tracker. A highly constrained seed generation phase reduces the combinatorial background to $O(10^2)$ trajectory seeds at low luminosity (to be compared to $O(10^6)$ without constraints), and several tricks are used during trajectory building: only candidates with at most one lost hit are considered, and only a few best track candidates are propagated at each step.

Because the KF is a step by step method, the optimal parameters are estimated only at the end of the propagation, when the informations of all measurements are available. On the other hand, in a physics analysis accurate track parameters estimation is needed especially near the interaction point. This is the reason why a smoothing phase is implemented after trajectory building. A backward KF of the trajectory would provide precise parameters at the beginning, but the information at the end would be lost. The recipe to obtain optimal parameters (i.e. including information of all hits) at both ends and at all intermediate positions is to combine the results of the forward and backward fits on every layer, avoiding using twice the same measurement layer.

The reconstruction is completed by the trajectory cleaning phase. The mutually exclusive track candidates are defined to be the candidates that shares more than half of their hits. From this set, the track candidate with most hits is picked up. In case some mutually exclusive track candidates have the same number of hits, the one with the best normalised $\chi^2$ is choosen.

### 3.3.5 Backward Track Finding

As opposite to FKF, the backward phase of the CM algorithm starts the track reconstruction from the outer Tracker layers. The reconstruction steps can be factorized in the usual way (track candidate initialization, trajectory building, smoothing, cleaning), but the seed generation phase is more peculiar and sophisticated.
The main idea is to use the full tracking detector for track candidate initialization, instead of the typical approach that uses a reduced set of data. As already pointed out, two main issues need to be addressed, fast navigation in the tracker and fast hits retrieval, otherwise the seed generation phase would be unfeasible due to computational time. As for the FKF, the fast navigation problem is addressed by the learning phase: the links generated during learning allow to navigate through the whole detector without expensive calculations. Fast hit retrieval requires a simple mathematical criterium to define the compatibility of a set of hits with a trajectory; the approximated track model of eq. 3.7 allows to define it, avoiding the heavy mathematical formalism of KF. In fact, from eq. 3.7, two constants of motion of a particle trajectory can be extracted:

\[ k = 2\delta \]
\[ \Delta = \frac{\delta}{c} = \frac{\phi_{\text{out}} - \phi_{\text{in}}}{z_{\text{out}} - z_{\text{in}}} \]  

(3.15)

The choice of this two constants is due to the fact that at least one of them can be calculated with good accuracy, depending on the region of the detector where they are sitting. Three measurements in the barrel, where \( r \) and \( \phi \) coordinates are provided with good precision, allow to calculate the curvature \( k \). In the forward, where \( z \) and \( \phi \) have the best precision, \( \Delta \) can be estimated. Moreover, stereo layers ensure that in some cases both constants can be estimated, allowing some redundancy.

The seed generation phase is performed over each hit in the backward starting cells (last or next to last element of long enough sequences of connected cells). For each starting hit, a template (in CM algorithm this is the name for preliminary track candidate) containing only the starting hit is created, then the track candidate initialization is performed in a few basic repeated steps:

- Consider the cell where the last hit of the template is sitting, and extract all the compatible hits from the backward linked cells within a \( \phi \) window defined assuming a minimal \( p_t \) cut (0.9 GeV/c).

- For each compatible hit, create a new template adding this hit to the previous template.
Repeat this steps for each new template.

In this way, starting from one hit, a full tree of templates is created and the best ones are used for track candidate initialization (see Fig. 3.5 for a naive example of template propagation). Both the definition of compatibility of the hits with a template, and the definition of quality of the templates, are based on $k$ and $\Delta$. In the following, some aspects of template tree development are pointed out.

During the first steps, while there is no estimate of the constants of motions, all the hits within the $\phi$ window on the linked cell are considered compatible with the template. As soon as the minimal number of hits to calculate one of the propagation parameters (three hits in barrel for $k$, two in the forward for $\Delta$) is collected, a quantitative definition of compatibility can be given. If $P_{old}$ is the value of one of the two constants of the template, and $P_{new}$ is the value calculated adding a new hit, the hit is compatible with the template if:

$$|P_{old} - P_{new}| < \text{const} \sqrt{\sigma^2_{P_{old}} + \sigma^2_{P_{new}}} \quad (3.16)$$

Moreover, the new templates are created only for the few best compatible hits, extracted with the following definition of quality:

$$Q_{new} = \text{const} |P_{old} - P_{new}| \quad (3.17)$$

Figure 3.5: Naive example of a template tree creation process.
After the tree of templates is fully developed, only the best ones belonging to the longest templates are used to initialize track candidates; the template quality is just the sum of the quality of its hits.

The selected templates are used to initialize track candidates performing a fit to the track model using the innermost hit (usually a pixel hit), the outermost hit and one of the middle hits (preferentially a stereo hit) of the templates. Then all the next phases (trajectory building, smoothing, cleaning) are performed like for FKF, with the difference that the Kalman Filter starts from outer layers and proceeds towards the interaction point.

The time spent in the complex seed generation phase of the CM is recovered during trajectory building, because starting seeds are much more precise (much smaller errors) and the KF has to deal with a negligible amount of combinations.

### 3.3.6 Combined reconstruction

Forward Kalman Filter and Connection Machine can be combined to provide a really efficient and reliable track finder, exploiting at best the advantages of the two methods, while overcoming their drawbacks. The current implementation of the FKF is pretty fast: thanks to the excellent pixel hit resolution and to the additional preselection provided by the primary vertex finder, the number of seeds processed is quite modest. Moreover the FKF track finder performance for tracks which originate not too far from the primary vertex is reasonable. On the other hand, some inefficiency remains for two reasons: first, some pixel hits can be spoiled in the dense environment near the interaction vertex; second, there is a non negligible intrinsic inefficiency of the pixel layers. The CM can overcome both problems, because by starting from the outer layers, the pixel hits are not needed to reconstruct tracks. The main drawback of the CM is that the seed generation phase is slow, because it is performed over the whole detector, but running the CM after the FKF using a hit locking mechanism (removing from the pool of tracker hits those which are assigned to tracks reconstructed by FKF) reduces the time problem. In this case, the CM is much faster, having to deal with a low density environment, and its aim is to
reconstruct all the tracks which have not been reconstructed by the FKF.

The performances presented in the next section are always referred to the combined reconstructor, unless otherwise stated.

### 3.3.7 Performances

In the development process and testing phase of a track reconstruction algorithm, it is useful to have some quantitative estimators of its performances. A good track reconstruction method should have the maximal possible efficiency, defined as:

$$\epsilon = \frac{N \text{ associated reconstructed tracks}}{N \text{ simulated tracks}}$$

Not all the reconstructed tracks enter in the efficiency evaluation, but only the reconstructed tracks which satisfy the following cuts:

$$p_{t}^{rec} > 0.7 \text{ GeV/c} \quad |\eta^{rec}| < 2.5 \quad N_{hits}^{rec} \geq 8$$

Depending on which kind of efficiency one has to evaluate, the quality cuts on simulated tracks are different. If one is interested in the method performances only, then one has to select only the simulated tracks with:

$$p_{t}^{sim} > 0.9 \text{ GeV/c} \quad |\eta^{sim}| < 2.4 \quad N_{hits}^{sim} \geq 8$$

In this way, the efficiency is not affected, for example, by detector inefficiency (missing hits) or early conversion. With this filter on the simulated tracks, the algorithmic efficiency ($\epsilon_{algo}$) is evaluated.

On the other hand, if one is interested in global performances, taking into accounts all possible effects coming from physics (e.g. conversion), detector (e.g. intrinsic inefficiency) and reconstruction method, the global efficiency ($\epsilon_{glob}$) has to be evaluated, applying the following cuts on the simulated tracks:

$$p_{t}^{sim} > 0.9 \text{ GeV/c} \quad |\eta^{sim}| < 2.4 \quad \text{charged}$$

The association between reconstructed and simulated tracks is performed by hits: a reconstructed track is associated to a simulated one if they share more than 50% of their hits.
While the efficiency should be as high as possible, the track finding method should not create ghost tracks, i.e. tracks that cannot be associated to any simulated tracks and that are reconstructed using, mainly, noise hits. The level of ghost tracks generated by a track finding algorithm can be evaluated using the fake rate:

$$\epsilon_{\text{fake}} = \frac{N \text{ not associated reconstructed tracks}}{N \text{ reconstructed tracks}}$$

Efficiency and fake rate are related to the number of tracks belonging to the real event that are reconstructed, but, evaluating a pattern recognition method, the quality of the reconstructed tracks is also important. Two quantities can help in this respect, the resolution, defined for each interesting parameter of the tracks as the difference between the reconstructed and the simulated value, and the pull, defined as the resolution normalised to the error on the fitted parameter:

$$X_{\text{res}} = X_{\text{rec}} - X_{\text{sim}}$$

$$X_{\text{pull}} = \frac{X_{\text{rec}} - X_{\text{sim}}}{\sigma_{X_{\text{rec}}}}$$

The pulls distribution is very important in studying the quality of track reconstruction. In fact, if there were no bias in the reconstruction and errors were Gaussian, a pulls distribution with mean zero and $\sigma = 1$ is expected by definition.

The global efficiency in single muon track reconstruction is shown in fig. 3.6. The tracker is fully efficient for energetic muons in the whole pseudorapidity range (the drop in the last bin is, in fact, at the limit of the $\eta$ coverage of the detector). A small drop in efficiency is observed for muons of $p_t = 1$ GeV/c in the region around $\eta = 1$, due to the transition region between barrel and forward detectors. In this region the hermeticity of the Tracker deteriorates slightly and the track finding algorithm is penalized by the occasional loss of two subsequent hits. Moreover, a sizeable amount of material is present in the barrel-forward transition region.

For b-jets identification and lifetime measurements, the impact parameter resolution, both in the transverse plane and along the $z$-axis, is a highly relevant issue. These two quantities, as well as the accuracy of the other track...
Figure 3.6: $\epsilon_{glob}$ for single muons as a function of the muon $\eta$. Dashed line corresponds to $\epsilon_{glob} = 98\%$. Error bars are smaller than the symbols.

Parameter measurements, are estimated using muons with various $p_t$ values. The transverse impact parameter is defined as:

Figure 3.7: $d_0$ resolution as a function of $\eta$ for muons with various $p_t$ values.
\[ d_0 = y_{\text{imp}} \cos \phi_0 - x_{\text{imp}} \sin \phi_0 \]  

(3.19)

where \( x_{\text{imp}} \) and \( y_{\text{imp}} \) are the coordinates at the impact point and \( \phi_0 \) the azimuthal angle at the impact point. For high \( p_t \) tracks, the accuracy is dominated by the precision of the measurement in the innermost Pixel layer, hence the resolution is independent of \( \eta \) and is about 10 \( \mu m \) (see fig. 3.7). When the track transverse momentum is smaller than 10 GeV/c, the \( d_0 \) resolution is limited by multiple scattering, and the visible degradation at large pseudorapidity reflects the increase of the material transversed by the tracks.

The \( z_{\text{imp}} \) resolution shows a similar behaviour (see fig. 3.8): at low momenta, the multiple scattering degrades the resolution and a strong dependence on \(|\eta|\) is observed. For high \( p_t \) muons in the barrel, the \( z_{\text{imp}} \) resolution can be approximated, assuming that \( z_{\text{imp}} \) is measured using pixel hits only, by:

\[
\sigma_z \sqrt{r_1^2 + r_2^2} \quad r_2 - r_1
\]

(3.20)

where \( \sigma_z \) is the pixel \( z \)-hit resolution and \( r_1 \) and \( r_2 \) represent the radii of the pixel layers. The pixel \( z \)-hit resolution varies with \(|\eta|\) and the cluster size yields the best resolution at \(|\eta| \sim 0.5\), explaining the observed behaviour for \( z_{\text{imp}} \) in the barrel.

---

Figure 3.8: \( z_{\text{imp}} \) resolution as a function of \( \eta \) for muons with various \( p_t \) values.
The momentum resolution for high $p_t$ tracks (see fig. 3.9) has a small dependence on pseudorapidity in the interval $|\eta| < 1.7$, in which $\sigma_{p_t}/p_t \sim 1 - 2\%$, while at larger $|\eta|$ the resolution worsens due to the smaller lever arm of the tracker. For low $p_t$ muons, multiple scattering becomes significant and it induces a strong $\eta$-dependence on the resolution, reflecting the amount of mater-
The $\phi_0$ and $\cot \theta$ are shown in fig. 3.10. The $\phi_0$ resolution is fairly independent of $|\eta|$, due to the constant number of precision hits over the full pseudorapidity range, while the $\cot \theta$ resolution is dominated by the pixel detector, hence the behaviour is the same as for $z_{imp}$.

Figure 3.11: Pull of several variables as a function of $\eta$ for muons with $p_t = 100$ GeV.
The pulls distributions for $p_t$, $\phi_0$ and $\cot \theta$ (see fig. 3.11) confirm the quality of the track reconstruction method.

![Graph](image)

Figure 3.12: $\epsilon_{\text{glob}}$ with $b$-jets as a function of jet pseudorapidity.

In order to test the Connection Machine performances in the dense LHC environment, efficiency and ghost rate in high $E_t$ jets have been studied. The global track finding efficiency with $b$-jets is shown in Fig. 3.12. In the barrel, an efficiency of $\sim 93\%$ can be estimated, fairly independent of the jet $E_t$ within the errors. The efficiency decreases by nearly 8% at larger pseudorapidity values, obviously correlated to the amount of material that the particles transverse at different angles (see Fig. 2.7).

Anyway, if one considers the algorithmic efficiency, i.e. the efficiency for simulated tracks with at least 8 simulated hits, the efficiency (fig. 3.13) is higher than 95% over the full pseudorapidity range, reaching 98% in the barrel. The main source of inefficiency in jets is, therefore, the lack of eight hits per tracks; using looser cuts on the number of hits (the standard analysis cut on the number of hits per track is 6), the global efficiency is higher, and approaches the algorithmic one.
Figure 3.13: $\epsilon_{algo}$ with $b$-jets as a function of jet pseudorapidity. Dashed line corresponds to 95% efficiency.

Figure 3.14: $\epsilon_{fake}$ with $b$-jets as a function of jet pseudorapidity.
The number of ghost tracks generated by the CM using noise or wrong hits is low; in fact, the fake rate estimated on the same event samples is always lower than 1% (see fig. 3.14).

### 3.4 Muons Reconstruction

For many interesting physical processes, identification and measurement of the muons in the event is a fundamental issue. The muon system, where the occupancy is low and pattern recognition is relatively easy, can provide trigger and identification of muons, but parameter estimation (impact point and momentum) is too rough for accurate analysis. These situation arises, for example, for a Higgs decaying into muons (e.g. $H \rightarrow \mu^+\mu^-$ or $H \rightarrow ZZ^* \rightarrow \mu^+\mu^-\ell^+\ell^-$), when one need to carefully measure the muon momentum in order to reconstruct the Higgs mass. In these cases, the muon trajectory should be reconstructed through the full CMS detector, and especially in the inner tracker, in order to use its high spatial resolution and excellent momentum measurement in the 4T field. This is a very important and demanding task, particularly for muons in jets, for example in muon tagging of b-jets.

Before going into the details describing some approaches to the problem, a few words on reconstruction in the muon system are needed. Pattern recognition in the muon stations is done by building reconstructed hits separately in the $r\phi$ and $rz$ planes. The track segments in the same muon station and in the same or contiguous sectors are considered as a pair which is used for the Kalman filter. The KF starts from the outermost stations and proceeds towards the inner stations with a constrained fit to the impact point. All the performances reported in the following sections are normalised to the efficiency of the reconstruction in the muon system.

#### Track matching

The most obvious muon reconstruction strategy is to perform both muon station reconstruction and full track reconstruction, and to assign one by one all the track observed in the muon station to a candidate in the tracker given some matching quality criterium. Given two track candidates, one in the muon
system and the other in the tracker, one can extrapolate both candidates to a common plane or point, check the difference in momentum and position and select the best combination among the candidates.

A quantitative definition can be given, defining the matching quality $\chi^2$ as follow:

$$
\chi^2 = \sqrt{\frac{(1/p_{tr} - 1/p_{ms})^2}{\sigma_{p_{ms}}^2}} + \frac{(\phi_{tr} - \phi_{ms})^2}{\sigma_{\phi_{ms}}^2} + \frac{(\theta_{tr} - \theta_{ms})^2}{\sigma_{\theta_{ms}}^2}
$$

where the subscripts $tr$ and $ms$ stand for the quantities measured in the tracker and in the muon system, respectively. Given a track candidate in the muon system, the selected propagation is the track candidate in the tracker with the smallest $\chi^2$.

**Seeded track reconstruction**

The best solution in terms of speed is to use the track observed in the muon station as a trajectory seed for the trajectory building phase of the track reconstruction, i.e. to use the reconstruction in muon system as the seed generation phase of the track finding. In this way, track reconstruction is performed only in a small cone around the muon system prediction, while the rest of the tracker is ignored. The parameters of the track candidate from the muon system are propagated to an active surface of the tracker (usually the innermost or the outermost layer), and then the KF is performed, starting from this layer, and using the propagated state as an initial guess of the trajectory parameters and errors.

**Regional track reconstruction**

An alternative strategy is to mix the two previous approaches. Instead of using the candidate from the muon system to seed the track reconstruction, it is used to define a geometrical region (typically a cone) inside the tracker. The cone axis is determined by the momentum direction, while the size of the cone is proportional to the magnitude of the momentum and inversely proportional to the errors of the momentum direction. Inside the region defined by the cone, standard track reconstruction is performed, and then the best propagation in
the tracker of the candidate in the muon system is chosen using the track matching approach.

Using this method, the full muon reconstruction is fast, because most of the tracker is not checked for tracks, and the parameter estimation is not biased by the initial guess of the track candidate parameters from the muon system.

### 3.4.1 Performances

Because the main goal of this thesis work is to study the possibility of the discovery of a neutral MSSM Higgs boson in the channel \( H/A \rightarrow \mu \mu \), the performances presented in this section are obtained using the regional track reconstruction approach. A typical preselection cut for this channel is, in fact, to require two, high \( p_t \), isolated muons, and the regional reconstruction is the best approach in this case: the seeded reconstruction cannot check for isolation, while full reconstruction is a time expensive operation, and in fact it is performed only if two isolated muons are identified.

The \( p_t \) dependence of the matching efficiency is shown in fig. 3.15 for single muons. Above 10 GeV/c, the efficiency reaches a plateau above 95% (the dashed line correspond to 95% matching efficiency), while it decreases for low \( p_t \), reaching nearly 80% for very low \( p_t \).

![Matching efficiency vs Pt](image)

**Figure 3.15:** Matching efficiency for single muons as a function of the muon \( p_t \).
Figure 3.16: Matching efficiency for single muons as a function of the muon $\eta$.

Figure 3.17: Efficiency for muons from W decay as a function of the muon $\eta$, using only the muon system.

Looking to the $\eta$ dependence of the matching efficiency (fig. 3.16), it is clear that the inefficiency sources are confined in well defined regions: the region between the central and next-to-central rings ($|\eta| \sim 0.2$), the transition region between barrel and forward ($0.7 < |\eta| < 1.2$) and the very forward region. Because the coverage of the CMS tracker is limited up to $\eta \sim 2.4$, the inefficiency in the last region can be easily explained with the lack of hits in the tracker.
itself. The other two regions are problematic, but a clue comes from the efficiency plots for the muon system (see fig. 3.17). It turns out that regions where there is lower efficiency in the muon system are also the inefficiency regions for the matching algorithm. In these two regions, the resolutions provided by the muon system on the track parameters are a bit worse, making the matching procedure more difficult. Moreover, the region \((0.7 < |\eta| < 1.2)\) correspond to the transition region between barrel and forward in the tracker, hence the region where pattern recognition is more complicated and less reliable.

![1/Pt Resolution Diagram](image)

Figure 3.18: Single muon \(p_t\) resolution after tracker-muon matching.

As expected, the muon system-tracker matching improves the resolution on track parameters. The \(p_t\) resolution, for example, is improved by a factor of ten, when tracker information are used with respect to muon system only reconstruction (see fig. 3.19,3.18).
Figure 3.19: Single muon $p_t$ resolution using only the muon system.
Chapter 4

MSSM Neutral Higgs Bosons
Search at CMS

Searches on MSSM neutral Higgses have already been performed at LEP and LEPII, providing mass and parameter limits. Two benchmark scenarios were considered:

- **no mixing** scenario: it assumes that there is no mixing between the scalar partners of the left-handed and the right-handed top quarks.

- **$m_h$-max** scenario: it is designed to yield the maximal value of $m_h$ in the model. This scenario corresponds to the most conservative range of excluded tan $\beta$ values for fixed values of the mass of the top quark and $M_{\text{SUSY}}$.

The limits obtained assuming the mass of the top quark to be 174.3 GeV/c$^2$ are reported in table 4.1 [26]. In a more general scan, where the MSSM parameters are varied independently and the top quark mass is allowed to be larger, the limits on $m_h$, $m_A$, and tan $\beta$ are weaker [27]. For example, if the mass of the

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$m_h$ limit (GeV/c$^2$)</th>
<th>$m_A$ limit (GeV/c$^2$)</th>
<th>Excluded tan $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_h$-max</td>
<td>91.0</td>
<td>91.9</td>
<td>0.5 &lt; tan $\beta$ &lt; 2.4</td>
</tr>
<tr>
<td>no mixing</td>
<td>91.5</td>
<td>92.2</td>
<td>0.7 &lt; tan $\beta$ &lt; 10.5</td>
</tr>
</tbody>
</table>

Table 4.1: Limits at 95% CL on $m_h$ and $m_A$ and excluded region of tan $\beta$ in the two scenarios explained in the text. The median expected limits are listed in parentheses.
top quark is 179 GeV/c$^2$ (roughly 1σ higher than the central measured value), then tan β can no longer be excluded above 1.9 in the $m_h$-max scenario.

Although the LEP limits reduce the parameter space, the study of the Higgs sector of the MSSM is complex, because one has to deal with a rich spectrum of possible signals. In principle, if SUSY particles are light enough, decays of Higgs bosons to SUSY particles are kinematically allowed. In the following, it is assumed that the whole sparticle spectrum is heavy enough to be ignored in the decay of the MSSM Higgs bosons.

## 4.1 Production Mechanism

The main production mechanisms for the SM Higgs boson are:

- **gluon fusion**: $pp \rightarrow gg \rightarrow H$
- **vector – boson fusion**: $qq \rightarrow qqV^*V^* \rightarrow qqH$
- **Higgs – strahlung**: $q\bar{q} \rightarrow V^* \rightarrow VH$
- **associated production**: $q\bar{q}, gg \rightarrow Ht\bar{t}, b\bar{b}$

where $V = W, Z$.

The gluon fusion process is the dominant process over the full mass range up to 1 TeV/c$^2$, apart from vector-boson fusion which is of the same order of magnitude above 800 GeV/c$^2$.

Things are slightly different when considering MSSM Higgs bosons production. First of all, the production via vector-boson fusion or Higgs-strahlung is possible only for the CP-even Higgs bosons, because the CP-odd boson A does not interact with vector particles at tree level. Moreover, the scalar Higgs vector-boson couplings are suppressed by a factor $\sin(\beta - \alpha), \cos(\beta - \alpha)$ (see Table 1.5), hence the production cross sections in the vector-boson fusion channel are smaller than the corresponding SM ones. Likewise, Higgs-strahlung production is smaller than in the SM case.

Thus the dominant production mechanism in the phenomenologically relevant Higgs mass ranges for small and moderate values of tan β is the gluon fusion process, consisting of loops involving top and bottom quarks, as well as squarks. At large tan β, the associated production involving a $b\bar{b}$ pair is
Figure 4.1: Production cross sections, including all known QCD corrections, of h and H at LHC for the two values of $\tan\beta = 1.5, 30$. The vertical line separates the allowed mass regions.
Figure 4.2: Production cross sections of the Higgs boson $A$ at LHC for the two values of $\tan \beta = 1.5, 30$, including all known QCD corrections.
greatly enhanced by the large Yukawa couplings to down-type quarks, and so plays a crucial role. On the other hand, associated production involving a $t\bar{t}$ is suppressed at large $\tan \beta$, because the Yukawa couplings to up-type quarks are proportional to $1/\tan \beta$.

The cross sections of the various MSSM Higgs production mechanisms at LHC are shown in Figs. 4.1, 4.2. The results are obtained [28] using CTEQ4M parton density, taking into account all the known QCD corrections, up to the NLO. Only for the associated production mechanism, the leading order CTEQ4L parton densities have been used, because the NLO QCD corrections are still unknown.

4.2 Decay and Signature

The figs. 4.3, 4.4, 4.5 show the branching ratios of the MSSM neutral Higgs bosons for the most significant decay channels, calculated taking into account the contributions due to below threshold decay channels [14].

The dominant decay mode for the lightest CP-even Higgs boson is $h \rightarrow b\bar{b}$ but further evaluations on $b$-tagging capabilities are needed to judge its exploitability, especially connected to associated production of a $t\bar{t}$ pair, which presents the cleanest signature with respect to the QCD background.

The $\tau^+\tau^-$ decay mode, with a branching ratio of about $8\%$ over the full relevant part of the parameter space, is more interesting, providing a distinctive signature when at least one tau decays in one charged hadron.

Anyway, the most promising channel, from a detection point of view, is $h \rightarrow \gamma\gamma$, and preliminary studies show that the discovery range extends down to $m_A > 260$ GeV and $\tan \beta > 2.5$ for $10^5 \text{ pb}^{-1}$.

The branching ratios of the heavy CP-even Higgs boson $H$ have a rather complicated behaviour, mainly due to the $H \rightarrow hh$ decay; in fact, for $m_H < 2m_t$ and low $\tan \beta$, this decay mode is dominant when kinematically allowed.

A very interesting channel is $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$, the so-called *gold-plated* signature also for the SM Higgs boson. This channel has a very clean signature, but it is strongly suppressed with respect to the SM case. This is due to the suppression of the $g_{\Phi VV}$ coupling (see Table. 1.5), to the opening of the $H \rightarrow hh$
channel and to the enhancement of the $H \to t\bar{t}$ channel. These peculiarities limit the observability of this channel to the range $2m_h < m_H < 2m_t$ and to low values of $\tan\beta$.

By far, the most promising observation chance comes from the $H \to \tau^+\tau^-$ channel, because it is strongly enhanced over a large region of the parameter space with respect to the SM case. Moreover, for large values of $\tan\beta$, the production is dominated by the associated production $b\bar{b}H$, and the tagging of the spectator $b$-quarks allows to improve the background rejection.

The same channel is the most promising for the CP-odd Higgs boson $A$, also. In fact, the discovery potential for the two neutral heavy Higgses relies strongly on the detectability of the $H/A \to \tau^+\tau^-$ channel.

It is important to remind that for $m_A \geq 150$ GeV, the $H$ and $A$ bosons are almost degenerate in mass, so their signal rates in the $\tau\tau$-channel can be summed.
4.3 The $b\bar{b}H/A \rightarrow b\bar{b}\mu^+\mu^-$ channel

Although the branching ratio of the $H/A \rightarrow \mu^+\mu^-$ decays channel is small, nevertheless there are some factors that can provide an observable rate and make this channel appealing:

- At large $\tan \beta$, large enhancement of rates through associated production $b\bar{b}H$ and $b\bar{b}A$, and some enhancement of the branching ratio are present.

- To some extent, the reduction in signal rate with respect to the $\tau\tau$-channel is compensated by the much better identification efficiency that can be achieved in the $\mu\mu$-channel. Moreover, due to the very good muon momentum resolution at CMS, this channel enables a very precise Higgs mass reconstruction.

Part of the work of this thesis regards the study of the $H/A \rightarrow \mu^+\mu^-$ channel, in order to understand its discovery potential at CMS. The rates for this channel are determined by the same couplings as for the $\tau\tau$ channel, but the branching
Figure 4.5: Branching ratios for A as a function of $m_A$ for the two values of $\tan \beta = 1.5, 30$. 

ratio scales as:

\[
\frac{Br(H/A \rightarrow \mu^+\mu^-)}{Br(H/A \rightarrow \tau^+\tau^-)} \sim \left( \frac{m_{\mu}}{m_{\tau}} \right)^2 \sim 3.5 \times 10^{-3}
\]  

(4.2)

In this thesis, the attention is focused on the associated production mechanism, hence on the process $bbH/A \rightarrow bb\mu^+\mu^-$, because the tagging of the spectator $b$-quarks allows to improve the background rejection, for example of the huge $Z/\gamma^* \rightarrow \mu^+\mu^-$ Drell-Yan production.

In order to fully exploit the characteristics of this channel, two main tools are needed:

- An efficient and reliable track reconstruction method, with high b-tagging capability.

- A muon identification algorithm, able to match the informations coming from different sub-system (e.g., tracker and muon chambers) in order to obtain the best possible resolution on the muon momentum.
Thus, in order to fully evaluate the potential of this physics channel, part of the work of this thesis is devoted to the development of such tools, whose design, implementation and performance are described in the previous chapter.
Chapter 5

Analysis

5.1 Channel signatures

As already pointed out in the previous chapter, the analysis presented in this thesis regards the $H/A \rightarrow \mu^{+}\mu^{-}$ channel, with associated production of a $b\bar{b}$ pair.

![Feynman diagrams](image)

Figure 5.1: Complete gauge invariant set of Feynman diagrams for associated $b\bar{b}H/A$ production.

The two spectator $b$-quarks can provide a characteristic signature, like displaced secondary vertices or high transverse impact parameter tracks, due to the presence of long lived particles in the final state. Unfortunately, the two
spectator $b$-quarks are difficult to tag, because of two features: first of all, the spectator $b$-quarks are soft (see Fig. 5.2), and the resulting jets have low transverse energy. Such behaviour makes the b-jets hard to be identified, in fact an usual quality cut to avoid fake (ghost) jets produced by the jet reconstruction algorithm is $E_t > 10$ GeV.

Secondly, the $b$-quarks from associated production are mainly produced in the forward region, as one can see in Fig. 5.3. Hence, most of the tracks from $b$-particles have a pseudo-rapidity larger than the coverage of the CMS tracker ($|\eta| < 2.4$), making their reconstruction and identification impossible. Moreover, the $\eta$ distribution of the tracks from $b$-jets inside the tracker volume is flat, hence most of them are in the end-caps, where the track reconstruction is a bit less efficient than in the barrel region, as explained in the previous chapters. Overall, tagging the associated $b$-quarks can be a powerful tool to discriminate signal from background, but it is a very challenging one to implement.

On the other hand, the signature of the two muons coming from the Higgs decay is clear. In fact, the final state of this channel contains two isolated, high $p_t$ muons, mainly in the central region of the detector (see Figs. 5.4 and
Figure 5.3: $\eta$ distribution of the simulated $b$-quarks for $b\bar{b}H/A$ production, with $m_A = 150 \text{ GeV}/c^2$ and $\tan\beta=30$. Arbitrary normalization.

Figure 5.4: Transverse momentum of the muons from Higgs decay with $m_A = 150 \text{ GeV}/c^2$ and $\tan\beta=30$. Arbitrary normalization.

Both plots show a sharp cut (Fig. 5.4 at $p_t = 5 \text{ GeV}/c$ and Fig. 5.5 at $p_t = 79 \text{ GeV}/c$)
Figure 5.5: $|\eta|$ of the muons from Higgs decay with $m_A = 150 \text{ GeV}/c^2$ and $\tan \beta = 30$. Arbitrary normalization.

$|\eta| = 2.4$), due to the cuts used during simulation. In fact, only final states with two muons with $|\eta| < 2.4$ (the limit of coverage of the muon trigger) and $p_t > 5 \text{ GeV}/c$ (well below the trigger threshold on muon $p_t$) have been accepted; this introduces a minimal loss of generality on signal characterization.

Because the decay widths of the H and A Higgs bosons are in general much smaller than that of the SM Higgs bosons of the same mass (it is of the order of $\sim 1 \text{ GeV}/c^2$ for $\tan \beta = 10$ and $100 < m_A < 500 \text{ GeV}/c^2$, and varies between $6 - 25 \text{ GeV}/c^2$ for $\tan \beta = 50$), only a small window in the invariant mass of the muon pair should be considered (see Fig. 5.6). Moreover, for low values of $\tan \beta$, where the widths of the two Higgs bosons is smaller and are not completely degenerate in mass, the very good muon momentum resolution of the CMS experiment can in principle be used to decouple the H and A signals (see Fig. 5.7).

It is worth to note that the lower tails observed in the two mass plots are due to the internal bremsstrahlung of the two muons in the final state.
Figure 5.6: Invariant mass of the muon pair with $m_A = 150 \text{ GeV}/c^2$ and $\tan \beta=30$: with the given choice of parameters H and A are degenerate. Arbitrary normalization.

Figure 5.7: Invariant mass of the muon pair with $m_A = 150 \text{ GeV}/c^2$ and $\tan \beta=10$. Arbitrary normalization.

### 5.2 Signal rates

Because of the enhancement, at large $\tan \beta$, of both the $b\bar{b}H/A$ coupling and the $H/A \rightarrow \mu^+\mu^-$ branching ratio, the total rate for the $b\bar{b}H/A \rightarrow b\bar{b}\mu^+\mu^-$
channel is highly dependent on the choice of the MSSM parameters. Fig. 5.8 summarizes the event production rate, defined as the cross section of the associated production times the branching ratio in two muons as obtained from PYTHIA. The results show a rather strong enhancement at high $\tan \beta$. Fig. 5.9 shows the dependence of the event production rate on $m_A$.

![Event production rate](image)

Figure 5.8: $\sigma(gg \rightarrow H/A + b\bar{b}) \times BR(H/A \rightarrow \mu^+\mu^-)$ as a function of $\tan \beta$ for $m_A = 150$ GeV/c$^2$. Theoretical uncertainties are not shown.

As already discussed in section 4.1, the NLO QCD corrections to the associated production mechanism are still unknown. This implies large uncertainties on the correct value of the production rate, and, from here onward, a factor 2 will be assumed as the theoretical uncertainty [29]. Anyway, the full NLO corrections are under evaluation for the $gg \rightarrow H/A + b\bar{b}$ process, and this will reduce the theoretical uncertainties significantly.

Assuming a low luminosity phase at $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, the integrated luminosity during the first year of data taking will be $\mathcal{L}_{int} = 2 \times 10^4$ pb$^{-1}$. The corresponding number of expected events during the first year at low luminosity for a few benchmark choices of the parameters ($m_A$ and $\tan \beta$) are reported in Table 5.1. The total number of the events summing the contribution from the two Higgs bosons is also reported, when the choice of parameters leads A
Figure 5.9: $\sigma(gg \to H/A + b\bar{b}) \times BR(H/A \to \mu^+\mu^-)$ as a function of $m_A$ for $\tan\beta = 30$. Theoretical uncertainties are not represented.

and H to be degenerate.

<table>
<thead>
<tr>
<th>$m_A$ (GeV/$c^2$), $\tan\beta$</th>
<th>$Ab\bar{b} \to \mu^+\mu^-b\bar{b}$</th>
<th>$Hb\bar{b} \to \mu^+\mu^-b\bar{b}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>150, 10</td>
<td>$\sim 70$</td>
<td>$\sim 75$</td>
<td>-</td>
</tr>
<tr>
<td>150, 30</td>
<td>$\sim 740$</td>
<td>$\sim 750$</td>
<td>$1500^{+1500}_{-750}$</td>
</tr>
<tr>
<td>150, 50</td>
<td>$\sim 2500$</td>
<td>$\sim 2550$</td>
<td>$3000^{+3000}_{-1500}$</td>
</tr>
<tr>
<td>200, 30</td>
<td>$\sim 300$</td>
<td>$\sim 310$</td>
<td>$600^{+600}_{-300}$</td>
</tr>
<tr>
<td>130, 30</td>
<td>$\sim 1200$</td>
<td>$\sim 1100$</td>
<td>$2300^{+2300}_{-1200}$</td>
</tr>
</tbody>
</table>

Table 5.1: Number of events expected during the first year of data taking, within the acceptance range of CMS. Errors coming from theoretical uncertainties are reported for the total number of events only.

### 5.3 Background analysis

Given the signal signatures identified in the previous section, and the small event rate expected per year, several SM processes can act as possible back-
grounds, generating a sizable amount of events with a muon pair in the final state. The most important are presented in this section, with a few notes on the way they can be distinguished from the signal.

5.3.1 DY background

The dominant background process in the interesting mass range is the Drell-Yan muon pair production, i.e. the processes $\gamma^* / Z \rightarrow \mu^+ \mu^-$. With the constraint of an invariant muon mass pair $M_{\mu\mu} > 110 \text{ GeV}/c^2$, the expected cross section is $\sim 35 \text{ pb}$. The QCD corrections are known up to the NNLO order, hence the residual theoretical uncertainties are of the order of 10%. Assuming a cut on the muons $p_t$ at 5 GeV/c, the expected number of events inside the acceptance region of the detector is $320000 \pm 30000$. As one can see from Fig. 5.10, the DY background is huge, overwhelming the Higgs signal in the intermediate mass region also for high $\tan \beta$.

![Simulated dimuon system mass](image)

Figure 5.10: Invariant mass spectrum of the dimuon system for the DY background and Higgs signal ($m_A = 150 \text{ GeV}/c^2, \tan \beta = 30$), after one year low luminosity.

Because muons from DY process are isolated and have high transverse mo-
mentum, a strategy involving the spectator $b$-quarks has to be used to reject the DY background. The $b$-tagging method has to be highly reliable (very low mistagging rate) in order to effectively suppress such overwhelming background.

The $b\bar{b}Z \to b\bar{b}\mu^+\mu^-$ channel, which shows associated production of a $b\bar{b}$ pair through gluon-gluon fusion (the same production mechanism as the signal), is normally suppressed with respect to the standard DY background by a factor $10^{-3}$ and can be neglected if the mistagging rate is $\mathcal{O}(10\%)$. Anyway, if the mistagging rate can be kept of the order of $\mathcal{O}(1\%)$ or less, the $b\bar{b}Z \to b\bar{b}\mu^+\mu^-$ background becomes relevant.

5.3.2 $t\bar{t}$ background

While for $M_{\mu\mu} \lesssim 140$ GeV/$c^2$ the DY background (with or without associated $b\bar{b}$ production) is the only relevant background, for larger values of the invariant mass of the dimuon pair, the $t\bar{t}$ background starts to become competitive. In fact, the decay chain $t \to Wb \to \mu\nu_{\mu}b$ leads to a final state very similar to the signal: two isolated, high $p_t$, muons and two $b$-quarks. The expected cross section times the branching ratio for this process is $\sim 7.5$ pb, with a theoretical uncertainty of the order of 15%, due to available QCD corrections up to the NLO order. The expected number of events in the acceptance region of the detector is $120000 \pm 17000$, assuming a cut on the muons $p_t$ at 5 GeV/$c$.

The rejection strategy relies heavily on the presence of neutrinos in the final state. In fact, high missing transverse energy should be a pretty clean signature for this kind of events.

Anyway the spectator $b$-quarks, as for the DY background, play a crucial role in the signal-background discrimination. The spectator $b$-quarks produced in association with the Higgs bosons are produced mainly in the forward region, while the $b$-quarks coming from top decay are produced more centrally, as one can see from Fig. 5.11. Moreover, the $b$-quarks belong, in this case, to the hard interaction, hence having high transverse energy, while the spectator $b$-quarks of the signal are soft (see Fig. 5.12).
5.3.3 Minor backgrounds

There are several other potential backgrounds, like bosons pair production: \( W^+W^+ \rightarrow \mu^+\mu^- + X \) or \( ZZ \rightarrow \mu^+\mu^- + X \), but they are close to be negligible. In principle, a potential background source is also the \( b\bar{b} \rightarrow \mu^+\mu^- + X \) production, with a total cross section of \( 500\mu b \). Anyway, this background as been found to be negligible after requiring high \( p_t \) muons, and applying a muon isolation criteria. Similar considerations hold for \( c\bar{c} \rightarrow \mu^+\mu^- + X \) production.

5.4 Selection

The cuts used in this analysis can be grouped in three subsets, each one corresponding to one of the strategy described above for signal characterization and background rejection. In the following, the three subset of cuts are described, showing their performance on signal and backgrounds.
Figure 5.12: $E_t$ distribution of the $t\bar{t}$ decay $b$-quarks and for the signal ($m_A = 150$ GeV/$c^2$, $\tan \beta = 30$). Arbitrary normalization.

### 5.4.1 Muons identification

The muon identification is performed with the regional track reconstruction approach, described in section 3.4. In order to be accepted, an event should have two reconstructed muons having the following properties:

- **track quality**: $N_{hit} \geq 8$
- **high transverse momentum**: $p_{t\mu} > 10$ GeV/$c$
- **isolation**: no more tracks with $p_t > 2$ GeV/$c$ in a cone $\Delta r < 0.3$ around muon direction, where $\Delta r = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$

All the event samples, signal and main backgrounds, have high $p_t$ isolated muons in the final state, hence the selection efficiency is more or less the same for all of them, as reported, as an example, in Table 5.2. If two muons are successfully identified, the invariant mass of the muon pair is calculated:

$$M_{\mu\mu} = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - \|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\|^2}$$  \hspace{1cm} (5.1)
DY | signal \( m_A = 150 \text{ GeV}/c^2, \tan \beta = 30 \)  
| \( \epsilon \mu \) | .888 ± .005 | .813 ± .005 | .866 ± .005  

Table 5.2: Selection efficiency requiring two isolated, high \( p_t \) muons, with \( |\eta| < 2.4 \). Only statistical errors are reported.

In Fig. 5.13, the reconstructed invariant mass of the muon pairs from A and H Higgs bosons is reported, using the same set of parameters used to obtain the simulated masses plotted in Fig. 5.6.

![Reconstructed dimuon system mass](image)

**Figure 5.13:** Reconstructed invariant mass of the Higgs bosons decay muon pairs, using the same set of parameters as those of Fig. 5.6. Arbitrary normalization.

### 5.4.2 b-tagging

Because of the properties of the spectator \( b \)-quarks in signal events (small transverse energy, forward production), the \( b \)-tagging cannot rely on jet identification. Hence, some different strategies should be applied, like measuring the transverse impact parameter of tracks or reconstructing secondary vertices.

Track reconstruction is performed using the Connection Machine algorithm.
presented in chapter 3, in order to have maximum efficiency also for tracks coming from displaced secondary vertices. Moreover, since in both cases the quality of the tracks is a critical issues, only the reconstructed tracks that satisfy the following quality cuts are considered as well reconstructed:

- **Number of hits**: a good reconstructed track should have 6 or more hits of which at least one belonging to the pixel detectors;

- **Parameters**: only the tracks with $p_t > 0.9$ GeV/c and $|\eta| \leq 2.4$ are considered. Moreover, a transverse impact parameter smaller than $Tr_{IP} < 0.5$ cm is required, and a fit to the track model with $\chi^2/ndf < 5$. These two cuts, in fact, has been found very useful to avoid ghosts or badly reconstructed tracks.

Then, four different quantities are used for b-tagging, and results are combined requiring that at least two of the following conditions are true:

- **Track multiplicity**: signal events show a higher track multiplicity than DY background (see Fig. 5.14), hence events with more than 3 charged tracks with significance greater than 2 are tagged.

![Figure 5.14: Number of reconstructed tracks that satisfy the quality cuts. ($m_A = 150$ GeV/c$^2$ and $\tan \beta = 30$).](image)
• **Secondary vertices**: the presence of $b$-quarks in the final state provides a larger number of displaced secondary vertices (see Fig. 5.15). If at least two secondary vertices are reconstructed, or only one but with high multiplicity (number of tracks associated to the vertex greater than 3), the event is tagged.

![N secondary vertices](image)

Figure 5.15: Number of reconstructed secondary vertices. ($m_A = 150 \text{ GeV}/c^2$ and $\tan \beta = 30$).

• **Transverse impact parameter**: plotting the probability distribution of the transverse impact parameter ($T_{rIP}$) for tracks belonging to signal and DY background events (see Fig. 5.16), it is clear that tracks from signal events have more likely intermediate values of $T_{rIP}$. Combining this information with the higher track multiplicity of signal events, events are tagged when there are at least 2 reconstructed tracks with $0.01 < T_{rIP} < 0.1$.

• **3d impact parameter**: the same considerations can be applied studying the 3d impact parameter distribution (see Fig. 5.17), hence events are tagged when there are at least 2 reconstructed tracks with $0.02 < 3d_{IP} < 0.2$. 

90
Figure 5.16: Probability distribution of the transverse impact parameter of the reconstructed tracks. ($m_A = 150 \text{ GeV}/c^2$ and $\tan\beta = 30$).

Figure 5.17: Probability distribution of the 3-dimensional impact parameter of the reconstructed tracks. ($m_A = 150 \text{ GeV}/c^2$ and $\tan\beta = 30$).

The b-tagging efficiency and mistagging rate are summarized in Table 5.3, evaluated on DY background, $t\bar{t}$ background, and a signal sample for illustrative purposes.
Table 5.3: B-tagging efficiency and mistagging rates. The bottom line is the total $b$-tagging efficiency obtained combining the four algorithms as described in the text. Only statistical errors are reported.

<table>
<thead>
<tr>
<th></th>
<th>DY</th>
<th>$t\bar{t}$</th>
<th>signal ($m_A = 150$ GeV/$c^2$, $\tan \beta = 30$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{vertices}$</td>
<td>$0.030 \pm 0.002$</td>
<td>$0.386 \pm 0.007$</td>
<td>$0.118 \pm 0.005$</td>
</tr>
<tr>
<td>$\epsilon_{multiplicity}$</td>
<td>$0.096 \pm 0.004$</td>
<td>$0.898 \pm 0.004$</td>
<td>$0.317 \pm 0.006$</td>
</tr>
<tr>
<td>$\epsilon_{Tr_{IP}}$</td>
<td>$0.133 \pm 0.005$</td>
<td>$0.917 \pm 0.004$</td>
<td>$0.426 \pm 0.007$</td>
</tr>
<tr>
<td>$\epsilon_{3d_{IP}}$</td>
<td>$0.100 \pm 0.004$</td>
<td>$0.845 \pm 0.005$</td>
<td>$0.366 \pm 0.007$</td>
</tr>
<tr>
<td>$\epsilon_{b-tag}$</td>
<td>$0.120 \pm 0.005$</td>
<td>$0.918 \pm 0.004$</td>
<td>$0.402 \pm 0.007$</td>
</tr>
</tbody>
</table>

5.4.3 Jet rejection and missing $E_t$

Comparing the reconstructed jets in signal events and $t\bar{t}$ background (see Fig. 5.18), it is quite clear that the jets from $t$-quarks are much harder, and that an effective strategy to reject such background can rely on hard jet identification.

Figure 5.18: Probability distribution of the reconstructed jet transverse energy. ($m_A = 150$ GeV/$c^2$ and $\tan \beta = 30$).

The calorimeter system provides another useful information to reject $t\bar{t}$ events, i.e. missing transverse energy measurements, particularly useful due to
the presence of neutrinos in the final state of such events. The two strategies used to reject $t\bar{t}$ background can be summarized in the following way:

- **Jet rejection**: events with at least one jet with $E_t > 30$ GeV are discarded.
- **missing $E_t$**: if $E_t > 40$ GeV are rejected (see Fig. 5.19).

![Missing Et](image)

Figure 5.19: Reconstructed missing $E_t$ distribution in $t\bar{t}$ and signal events. ($m_A = 150$ GeV/$c^2$ and $\tan \beta = 30$).

In Table 5.4 the efficiencies on background events and on one of the analyzed signal samples are reported.

<table>
<thead>
<tr>
<th></th>
<th>DY</th>
<th>$t\bar{t}$</th>
<th>signal ($m_A = 150$ GeV/$c^2$, $\tan \beta = 30$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{anti-jet}}$</td>
<td>.796 ± .006</td>
<td>.091 ± .004</td>
<td>.798 ± .006</td>
</tr>
<tr>
<td>$\epsilon_{E_t}$</td>
<td>.853 ± .005</td>
<td>.309 ± .006</td>
<td>.856 ± .005</td>
</tr>
</tbody>
</table>

Table 5.4: Efficiency of the selection using calorimeter quantities. Only statistical errors are reported.
Chapter 6

Results

In this chapter, the analysis previously described is applied to different MSSM scenarios (different choices of the values of the relevant MSSM parameters), in order to understand the CMS discovery capability of a neutral MSSM Higgs boson in the channel $b\bar{b}H/A \rightarrow b\bar{b}\mu^+\mu^-$ during the first year of data taking (for an integrated luminosity of $L_{int} = 2 \times 10^4$ pb$^{-1}$) and up to the end of the low luminosity phase of the experiment (for a total integrated luminosity of $L_{int} = 6 \times 10^4$ pb$^{-1}$).

6.1 $m_A = 150$ GeV/c$^2$ and $\tan \beta = 30$

In the previous chapter, the MSSM scenario with $m_A = 150$ GeV/c$^2$ and $\tan \beta = 30$ has been taken as a sort of benchmark scenario in order to evaluate the efficiency of the different selection strategies. Table 6.1 summarizes the performances of the analysis, and reports the overall selection efficiency for the signal and the major backgrounds.

After one year of data taking, corresponding to an integrated luminosity of $L_{int} = 2 \times 10^4$ pb$^{-1}$, the total number of expected events, and the number of events surviving the analysis cuts are reported in Table 6.2.

Plotting the invariant mass of the muon pairs in the final state, the peak corresponding to the degenerate signal of the A and H Higgs bosons clearly emerges from background.

The significance of the signal can be estimated in a simple way using Poisson statistic. After defining a small window around the signal (in this case, $150 \pm$
Table 6.1: Overall efficiencies of the selection. Only statistical errors are reported.

<table>
<thead>
<tr>
<th></th>
<th>DY</th>
<th>( t\bar{t} )</th>
<th>signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon_\mu )</td>
<td>0.888 ± 0.005</td>
<td>0.813 ± 0.005</td>
<td>0.866 ± 0.005</td>
</tr>
<tr>
<td>( \epsilon_{b-tag} )</td>
<td>0.120 ± 0.005</td>
<td>0.918 ± 0.004</td>
<td>0.402 ± 0.007</td>
</tr>
<tr>
<td>( \epsilon_{anti-jet} )</td>
<td>0.796 ± 0.006</td>
<td>0.091 ± 0.004</td>
<td>0.798 ± 0.006</td>
</tr>
<tr>
<td>( \epsilon_{E_t} )</td>
<td>0.853 ± 0.005</td>
<td>0.309 ± 0.006</td>
<td>0.856 ± 0.005</td>
</tr>
<tr>
<td>( \epsilon_{tot} )</td>
<td>0.055 ± 0.003</td>
<td>0.042 ± 0.003</td>
<td>0.223 ± 0.008</td>
</tr>
</tbody>
</table>

Table 6.2: Expected number of events before and after analysis cuts after one year of data taking at low luminosity in the mass window 120 GeV/\( c^2 \) < \( M_{\mu\mu} \) < 180 GeV/\( c^2 \).

<table>
<thead>
<tr>
<th></th>
<th>DY</th>
<th>( t\bar{t} )</th>
<th>signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{tot}} )</td>
<td>76000 ± 7000</td>
<td>19000 ± 3000</td>
<td>( \sim 1500^{+1500}_{-750} )</td>
</tr>
<tr>
<td>( N_{\text{cuts}} )</td>
<td>4100 ± 400</td>
<td>800 ± 100</td>
<td>340^{+340}_{-170}</td>
</tr>
</tbody>
</table>

3 GeV/\( c^2 \), the significance of the excess is:

\[
S = \frac{S}{\sqrt{S + B}} \sim 6.6^{+7.0}_{-3.3} \tag{6.1}
\]

where \( S \) is the number of signal events, and \( B \) the number of background events in the chosen window. Due to the large theoretical uncertainties on the production cross sections, the significance upper limit is obtained considering the upper limit on the number of signal events and lower limit on the number of background events, the lower limit the opposite way.

Hence, it is possible to conclude that the 5 \( \sigma \) significance in this channel, with the given choice of parameters, can be achieved during the first year of data taking, and even in the most conservative scenario (signal production cross section overestimated by a factor 2) the significance would be higher than 3 \( \sigma \), thus resulting in a strong indication of a discovery.

The invariant mass spectrum of the dimuon system is fit using an exponential (for the background) with a superimposed gaussian (the signal), using the
Figure 6.1: Invariant mass spectrum of the dimuon system for backgrounds and Higgs signal ($m_A = 150 \text{ GeV}/c^2$, $\tan \beta = 30$), after one year low luminosity. The excess significance is $S \sim 6.6^{+7.0}_{-3.3}$.

Figure 6.2: Invariant mass spectrum of all the selected events after subtraction of the smooth part.
following parameterisation:

\[ f_{\text{fit}} = p_0 e^{-\frac{(m_{\mu\mu} - p_1)^2}{2p_2^2}} e^{p_3} e^{p_4 m_{\mu\mu}} \]

Hence, the Higgs mass value can be estimated from the fit:

\[ m_A \simeq m_H \simeq 150.8 \pm 3.7 \text{ GeV}/c^2 \]

### 6.2 \( m_A = 150 \text{ GeV}/c^2 \) and \( \tan \beta = 50 \)

At higher values of \( \tan \beta \), the signal rates are much higher, due to the large enhancement of the Yukawa coupling of the neutral MSSM Higgs boson with \( b \)-quarks. Such enhancement results in a more pronounced peak in the invariant mass plot, and the signal is clearly visible over the background fluctuations, despite the larger width of the Higgs bosons.

The significance of the excess in a mass window of \( 150 \pm 6 \text{ GeV}/c^2 \) after one year of data taking at low luminosity is, then:

\[ S \sim 14^{+11}_{-7}. \]

A few months of data taking can hence be enough to observe a MSSM Higgs signal, and the 5 \( \sigma \) excess can also be obtained in the most conservative scenario, at the end of the first year at low luminosity.

### 6.3 \( m_A = 200 \text{ GeV}/c^2 \) and \( \tan \beta = 30 \)

The production cross section of the \( A \) and \( H \) bosons falls when increasing the Higgs mass and the expected number of events is hence smaller than in the
Figure 6.3: Invariant mass spectrum of the dimuon system for backgrounds and Higgs signal ($m_A = 150\, \text{GeV}/c^2, \tan \beta = 50$), after one year low luminosity. The excess significance is $S \sim 14^{+11}_{-7}$.

previous case. Anyway, the DY background steeply falls at high values of the dimuon system invariant mass, and the signal remains observable.

The significance of the excess in a mass window of $200 \pm 6\, \text{GeV}/c^2$ after one year low luminosity is, then:

$$S \sim 5^{+5}_{-2}.$$ 

For $m_A, m_H > 200\, \text{GeV}/c^2$, the $t\bar{t}$ background becomes competitive with the DY background (see Fig. 6.4), and different approaches should provide better results: once the $t\bar{t}$ is the dominant background, the $b$-tag is not any more useful for the signal discrimination. The suppression of the DY background, in fact, does not justify anymore the efficiency loss on signal events. At high masses, better results can be obtained by considering both associated and direct production, and avoiding $b$-tagging.
Table 6.4: Cuts efficiency and expected number of events after analysis cuts with one year of data taking at low luminosity in the mass window $170 \text{ GeV}/c^2 < M_{\mu\mu} < 230 \text{ GeV}/c^2$.

<table>
<thead>
<tr>
<th></th>
<th>DY</th>
<th>$t\bar{t}$</th>
<th>signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{tot}}$</td>
<td>$0.055 \pm 0.003$</td>
<td>$0.042 \pm 0.003$</td>
<td>$0.191 \pm 0.008$</td>
</tr>
<tr>
<td>$N_{\text{cuts}}$</td>
<td>$440 \pm 50$</td>
<td>$280 \pm 40$</td>
<td>$120^{+120}_{-60}$</td>
</tr>
</tbody>
</table>

Figure 6.4: Invariant mass spectrum of the dimuon system for backgrounds and Higgs signal ($m_A = 200 \text{ GeV}/c^2, \tan \beta = 30$), after one year low luminosity. The excess significance is $S \sim 5^{+5}_{-2}$.

6.4 $m_A = 130 \text{ GeV}/c^2$ and $\tan \beta = 30$

While approaching the Z peak, the DY background increases; similarly, the signal event production rate increases up to a maximum at $m_A \sim 120 \text{ GeV}/c^2$ (see Fig. 5.9).

As one can see in Fig. 6.5, a discovery in this scenario is still achievable during the first year of data taking, and at least a strong indication of a signal can be obtained in case the signal production cross section were overestimated.
Table 6.5: Cuts efficiency and expected number of events after analysis cuts with one year of data taking at low luminosity in the mass window $110 \text{ GeV/}c^2 < M_{\mu\mu} < 170 \text{ GeV/}c^2$.

<table>
<thead>
<tr>
<th></th>
<th>DY</th>
<th>$t\bar{t}$</th>
<th>signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{tot}}$</td>
<td>.055 ± .003</td>
<td>.042 ± .003</td>
<td>.217 ± .008</td>
</tr>
<tr>
<td>$N_{\text{cuts}}$</td>
<td>7000 ± 700</td>
<td>970 ± 150</td>
<td>$500^{+500}_{-250}$</td>
</tr>
</tbody>
</table>

Figure 6.5: Invariant mass spectrum of the dimuon system for backgrounds and Higgs signal ($m_A = 130 \text{ GeV/}c^2, \tan \beta = 30$), after one year low luminosity. The excess significance is $S \sim 7.0^{+6.5}_{-3.6}$.

by a factor 2.

$$S \sim 7.0^{+6.5}_{-3.6}$$

The signal, in fact, clearly emerges above the background fluctuations after the smooth part of the background have been subtracted, and an estimate on the Higgs mass can be obtained (see Fig. 6.6):

$$m_A \simeq m_H \simeq 130.4 \pm 2.8 \text{ GeV/c}^2$$
Figure 6.6: Invariant mass spectrum of all the selected events after subtraction of the smooth part.

### 6.5 Scanning of the \((m_A, \tan \beta)\) plane

The overall discovery potential of the CMS experiment of a neutral MSSM Higgs boson in the \(b\bar{b}H/A \rightarrow b\bar{b}\mu^+\mu^-\) channel are shown in Figs. 6.7 and 6.8. In that figure, the 5\(\sigma\) discovery contour curves after 20 fb\(^{-1}\) and 60 fb\(^{-1}\) of integrated luminosity (roughly corresponding to one and three years of data taking at low luminosity) are reported. During the first year of data taking, a signal can be observed only in a region at relatively high \(\tan \beta\) in the \((m_A, \tan \beta)\) plane. The accessible region keeps increasing during the low luminosity data taking phase, and after three years a good sensitivity can also be achieved for intermediate values of \(\tan \beta\), thus covering an interesting fraction of the \((m_A, \tan \beta)\) plane. Moreover, promising sensitivity can be achieved for a signal near the Z mass peak, provided that \(\tan \beta\) is not too low.

While this analysis strategy obtains optimal results up to \(m_A < 200\) GeV/c\(^2\), for larger values of the Higgs mass, different approaches including direct Higgs production should obtain better results. In fact, for high values of the Higgs mass, the \(t\bar{t}\) background becomes competitive with the DY, and the \(b\)-tag is
no more an useful tool in the signal discrimination.
Figure 6.8: 5σ discovery contour curves for the $A/Hb\bar{b} \rightarrow \mu^+\mu^-b\bar{b}$ channel in the $(m_A, \tan \beta)$ plane. 20 fb$^{-1}$ and 60 fb$^{-1}$ correspond to one and three year of data taking at low luminosity.
Conclusions

In this thesis, I evaluated the discovery potential of a MSSM neutral Higgs boson at the CMS experiment in the $A/H \rightarrow \mu^+\mu^-$ channel. Since this channel is mostly interesting due to the possibility of an observation near the $Z$ mass peak, I developed a selection and analysis strategy dedicated to the associated production channel $gg \rightarrow A/Hb\bar{b}$, because it leads to a more identifiable final state.

This channel is a difficult one for various reasons. The signal final state is extremely similar to the final state of the main background, the Drell-Yan process $Z \rightarrow \mu^+\mu^-$. In the case of associated production, one can try to discriminate the signal from the background using the spectator $b$-quarks present in the final state. Unfortunately, the two spectator $b$-quarks are soft (they have low $E_t$), and refined track finding and reconstruction techniques are needed in order to correctly tag them. Hence, during this thesis, I developed a track reconstruction method, called Connection Machine, that has high quality performances also for tracks not coming from the primary vertex. This algorithm performs track reconstruction in two different phases: during the first stage, a simple and efficient algorithm dedicated to primary tracks finding is used, starting with primary vertex finding and then reconstructing tracks from the pixel system towards the outer layers of the tracker; after this stage, a more general pattern recognition is performed, from the outer layers back to the interaction point which is well suited for secondary tracks reconstruction. The backward stage, in fact, is less sensitive to kinks, interactions and decays in flight, since the track model used is very general. Due to the very good performances of this method (for example, an algorithmic efficiency above 95% over the full pseudo-rapidity range in $b$-jets), the Connection Machine became one of the
main track reconstruction methods used by the CMS collaboration. Another challenging aspect of this channel is the correct and accurate reconstruction of muons coming from the Higgs decay. In fact, the accurate estimation of the muon parameters, especially the momentum, determines the precision of the Higgs mass measurement. With this goal, I studied different strategies for muon reconstruction at CMS, and the most suitable have been used studying the channel under analysis. In particular, I investigated three different approaches: the *track matching*, the *seeded track reconstruction* and the *regional reconstruction*, and all of them provides good performances in terms of efficiency and muon momentum resolution.

The results obtained applying the developed strategy selection to the \( gg \rightarrow A/Hb\bar{b} \rightarrow \mu^+\mu^-b\bar{b} \) channel, summarized by the discovery contour curves in Figs. 6.7 and 6.8, show that this signal can be observed over a large region of the \((m_A, \tan \beta)\) plane, down to \(\tan \beta \sim 15\) in the studied mass range after three years at low luminosity. Moreover, the good rejection factor achieved for the DY background allows to push the discovery region towards values of the Higgs mass near the Z mass peak, provided that \(\tan \beta\) is not too low. Hence, the \( gg \rightarrow A/Hb\bar{b} \rightarrow \mu^+\mu^-b\bar{b} \) channel is a strong candidate to be a discovery channel, and, due to the excellent muon momentum resolution achievable at CMS, is one of the best channels for the Higgs mass estimation.
Appendix A

ORCA track reconstruction framework

The ORCA project (Object Oriented Reconstruction for CMS Analysis) has been underway since September 1998. Its goals is to provide the CMS collaboration with high quality tools to complete studies on design and optimization of the detector, and to prototype the software architectures and tools needed to satisfy the long term requirements of the collaboration. The implementation of the project is performed using the C++ language, to ensure easy code reusability and maintenance. This section is intended to give a brief overview of the design and implementation of the track reconstruction framework.

A.1 Base TrackFinder

All the track finding algorithms perform reconstruction in four basic steps: seed generation, trajectory building, smoothing and cleaning, which meaning is explained in section 3.2. The design of the ModularKfReconstructor class reflect this approach in the collaboration diagram (see Fig. A.1): the ModularKfReconstructor inherits from the TrackFinder class, and stores a reference to the classes responsible for each step.

Figure A.1: Collaboration diagram of the ModularKfReconstructor class.
The interface is pretty simple, and easy to understand for the end-users:

class ModularKfReconstructor : public TrackFinder {
public:
    virtual void reco(vector<RecTrack>&);
    void setSeedGenerator(SeedGenerator* sg);
    void setTrajectoryBuilder(TrajectoryBuilder* tb);
    void setTrajectorySmother(TrajectorySmother* ts);
    void setTrajectoryCleaner(TrajectoryCleaner* tc);
private:
    SeedGenerator* theSeedGenerator;
    TrajectoryBuilder* theTrajectoryBuilder;
    TrajectorySmother* theTrajectorySmother;
    TrajectoryCleaner* theTrajectoryCleaner;
};

A.2 TrackFinder components

SeedGenerator, TrajectoryBuilder, TrajectorySmother and TrajectoryCleaner are pure base classes which define an interface for each step to be performed during track finding:

class SeedGenerator {
public:
    typedef vector<TrajectorySeed> SeedContainer;
    typedef SeedContainer::iterator SeedIterator;
    virtual ~SeedGenerator() = 0;
    virtual SeedContainer seeds() = 0;
};
A track reconstruction algorithm can hence be implemented in ORCA just providing a concrete implementation for those pure interfaces. Moreover, because, for examples, all the concrete implementations of the TrajectoryBuilder
have to provide the same interface, one can easily create new track finders combining different implementation for each step, a very useful feature during developing, debugging and testing phases. The final goal of the track reconstruction is to provide a set of reconstructed tracks corresponding to the charged particle in the analyzed event, hence the Trajectory class is the object on which all the different phases act. The SeedGenerator provides a vector of TrajectorySeed that are processed one by one by the TrajectoryBuilder. The TrajectorySmooother and the TrajectoryCleaner complete the reconstruction returning the final set of track candidates as a vector of Trajectory.

A.3 Tracker geometry

In order to complete the overview of the track reconstruction framework, a few words on the tracker geometry description are needed. From the track reconstruction point of view, the layers objects provide the abstraction of the tracker. They implements two essential functions:

- Efficiency access to RecHits compatible with a given trajectory state.
- Navigation from a layer to the next layers that may contain the continuation of a given trajectory.

The abstract class that provides the interfaces to these functionalities is the DetLayer:
class DetLayer : public CompositeDet {
protected:
    typedef vector<DetUnit*>::iterator detunit_p_iter;
    typedef vector<Det*>::iterator det_p_iter;
public:
    virtual RecHitContainer recHits() const;
    virtual RecHitContainer recHits(const TrajectoryState&) const;
    NavigableLayer* navigableLayer() const { return theNavigableLayer;}
    virtual void setNavigableLayer( NavigableLayer* nlp);
    virtual vector<const DetLayer*> nextLayers( const FreeTrajectoryState& fts, PropagationDirection timeDirection) const;
    virtual vector<const DetLayer*> nextLayers( PropagationDirection timeDirection) const;
    virtual vector<TrajectoryMeasurement> fastMeasurements( const TrajectoryStateOnSurface&, const FreeTrajectoryState& fts, const Propagator&, const MeasurementEstimator&) const;
};

The DetLayer satisfies the request for RecHits or TrajectoryMeasurements using the *composite* design pattern [34]: a DetLayer is composed of other Dets,
and implements its interface by forwarding the request to its components. The navigation part of the DetLayer functionalities is handled by a separate class, the NavigableLayer, to which DetLayers forward the next layers request. A track reconstruction algorithm can provide its own navigation, if different from the default one, implementing a NavigationSchool.
Appendix B

Connection Machine geometry

B.1 Geometrical description

The Connection Machine uses a simplified geometrical description of the Tracker, as we already seen in section 3.3. The geometrical abstraction corresponding to the DetLayer of the standard ORCA Tracker description is the CmSurface, further specialized in CmBarrelSurface and CmForwardSurface. The CmSur-
face is an extended interface of the abstract DetLayer class, needed because the STM description has to handle the level of granularity of the CmCell, that was not foreseen in DetLayer design.

![Collaboration diagram of the CmBarrelSurface class.](image)

Figure B.2: Collaboration diagram of the CmBarrelSurface class.

The two concrete implementations, in fact, (CmBarrelSurface and CmForwardSurface), not only provide geometrical and material properties of the tracker layers, but also the access to the new level of granularity of the tracker.

### B.2 Reconstruction functionalities

The reconstruction functionalities, that the DetLayer provides in the standard ORCA tracker description (access to RecHits and navigation), are addressed, in the Connection Machine framework, by the CmCell. In order to keep the interfaces clean, and to clearly separate the different responsibilities, an additional level of inheritance is added, declaring the CmRingCell.

The CmCell is in charge for navigation through the tracker, providing, after learning, the correct behaviour of the next layers request during the different phases of track reconstruction. The request for TrajectoryMeasurement and RecHit are implemented in the CmRingCell class, that keeps track of the Det’s associated to each geometrical CmCell.
Figure B.3: Collaboration diagram of the CmRingCell class.
Appendix C

Connection Machine seed generation

Because, in the ORCA framework, the various track reconstruction methods mainly differ in the seed generation phase, a few more details on the Connection Machine seed generator are needed. The CmSeedGenerator class implements the SeedGenerator interface performing a loop on the reconstructed hits in the starting backward CmCells (see section 3.3 for a definition) and forwards to the CmTreeSeedGenerator the request of the list of templates that can be constructed starting with the given hit. Then, the CmSeedFitter fits an helix using the hits from each templates, and the fitted parameters and errors are used to initialize a TrajectorySeed.

The CmTreeSeedGenerator class is responsible for the creation of the template tree. From the starting hit, a template with only one hit and without parameter estimation is created, and then the full tree is generated in a few basic repeated steps:

- Consider the cell where the last hit of the template is sitting, and extract all the backward linked cells.

- For each backward link, forward to the CmPropagator the request for hits compatible with the template under analysis.

- For each compatible hit, create a new template obtained adding the new hit to the template under analysis.

- Repeat this steps for each new template.
At the end, the tree of templates is analyzed by the CmTreeSeedFilter, that selects the templates to be returned to the CmSeedGenerator. Two selection criteria are applied: first of all, only the longest templates are considered, then, among them, only the templates with highest quality are returned.

All the computational details of the template tree generation are handled in the CmPropagator class. The first responsibility of the CmPropagator is
the definition of the $\phi$ window where to look for hits compatible with the template under analysis. During the first steps of the template propagation, when neither $k$ or $\Delta$ have been evaluated, the $\phi$ window is defined as a fixed fiducial range around the $\phi$ coordinate of the last hit of the template. As soon as one of the two parameters have been evaluated, the $\phi$ window is calculated using the following formulas, depending on the region where the template is sitting:

$$
\phi = \phi_{old} - \frac{1}{2} k(r_{old} - r_{new})
$$

$$
\delta \phi = \max (\delta \phi_{1 \text{ GeV}/c/p_t, \delta \phi_{\text{min}}})
$$

where the $old$ subscript stands for measured quantities of the last hit of the template, the $new$ subscript stands for geometrical coordinates of the linked cell, $p_t$ is the template transverse momentum, $\delta \phi_{1 \text{ GeV}/c}$ is the $\phi$ window for a template with $p_t = 1 \text{ GeV}/c$ and $\delta \phi_{\text{min}}$ is a configurable optimised parameter.

Then, for each hit in the $\phi$ window, the evaluation of the constants of motion of the template under analysis plus the new hit is performed, using the approximated eqs 3.7, 3.16. If the new values of the constants are compatible with the values obtained at the previous step of propagation, the hit is returned to the CmTreeSeedGenerator, together with the new estimation of the constants of motion and their errors, in order to be added to the template under analysis.
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