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- LHC @ 13 TeV
  - Upgraded detectors
  - Run conditions/DAQ strategy
  - Expected spectra

- Future @ LHC

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Introduction
The High Energy cosmic ray spectrum

- The spectrum falls very rapidly with energy (~$E^{-2.7}$)
- No direct measurements are possible for $E > 10^{15}$ eV (Flux < 1/m$^2$/year)
- We have to rely on the atmospheric showers measurements

Detailed knowledge of high energy hadronic interactions is necessary to reconstruct the primary CR type and energy!

$\sim 27 \ X_0$

$\sim 11 \ \lambda_{\text{int}}$
**Uncertainty of hadron interaction models**

**Uncertainty in the interpretation of the observables**

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**High Energy CR Showers main Observables**

- $X_{\text{max}}$: depth of air shower maximum in the atmosphere
- $\text{RMS}(X_{\text{max}})$: fluctuations in the position of the shower maximum
- $N_\mu$: number of muons in the shower at the detector level

- To go from these observables to the CR composition and energy determination passing through the hadronic interaction models is mandatory
The role of the accelerators experiments

Accelerator based experiments are the most powerful available tools to determine the high energy hadronic interactions characteristics

→ Hadronic interactions models tuning

LHC 13 TeV → $9 \times 10^{16}$ eV

Unique opportunity to calibrate the models in the ‘above knee’ region
How accelerator experiments can contribute?

1. **Inelastic cross section**
   - If large $\sigma$: rapid development
   - If small $\sigma$: deep penetrating

2. **Forward energy spectrum**
   - If softer: shallow development
   - If harder: deep penetrating

3. **Inelasticity** $k = 1 - E_{\text{lead}} / E_{\text{avail}}$
   - If large $k$ ($\pi^0$s carry more energy): rapid development
   - If small $k$ (baryons carry more energy): deep penetrating

4. **Secondary interactions**
   - nucleon, $\pi$
We may profit (and we are profiting) of the very broad coverage! 
Dedicated forward detectors for a better measurement of the energy flow.
Models tuning after the first LHC data (EPOS and QGSJET) (See talk by Engel)

Significant reduction of differences btw different hadronic interaction models!!!
LHC @ 13 TeV

Charged multiplicity

Energy flow

Forward neutral particles spectra
What is new in the detectors/trigger/analysis?

- LHCf completed an upgrade to improve radiation hardness

- Very forward proton tag to identify the event topology
  - ATLAS/Alfa
  - CMS/TOTEM

- ATLAS-LHCf combined data analysis
  - LHCf trigger will be used by ATLAS to trigger the detector
  - Offline synchronization of the events will be possible

- Some improvements in the trigger algorithms by big experiments
+ ATLAS upgraded forward region
**LHCf: location and detector layout**

**INTERACTION POINT**

- **IP1 (ATLAS)**
- **Front Counter**:
  - Detector I: Tungsten GSO, GSO bars
  - Front Counter: 140 m
  - Front Counter: 8 cm
- **Front Counter**:
  - Detector II: Tungsten GSO, Silicon μstrips
  - Front Counter: 140 m
  - Front Counter: 6 cm

### Detector Layout

- **Arm#1 Detector**
  - 20mmx20mm+40mmx40mm
  - 4 X-Y GSO Bars tracking layers

- **Arm#2 Detector**
  - 25mmx25mm+32mmx32mm
  - 4 X-Y Silicon strip tracking layers

### Performance

- **Energy resolution**:
  - < 5% for photons
  - 30% for neutrons

- **Position resolution**:
  - < 200 μm (Arm#1)
  - 40 μm (Arm#2)

- **Pseudo-rapidity range**:
  - η > 8.7 @ zero Xing angle
  - η > 8.4 @ 140μrad

### Interaction Parameters

- **44X₀, 1.6 λᵢₘₜ**

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O. Adriani

Cosmic rays and accelerators: future

Cortona, April 21st, 2015
Arm2 Energy Reconstruction

\[ \sigma_{E/E} = 2.1-2.7\% \]

100 & 150 GeV electron beam on small tower center

300 GeV proton beam on small tower center

\[ \sigma_{E/E} = 42-45\% \]
Arm2 silicon energy measurement (small tower)

- Sum of energy releases over all silicon layers
- Only strips with signal $> 3\sigma$ are considered
- Central events (5 mm x 5 mm square)

Resolution with old configuration:
- 8.4 % @100 GeV
- 8.2 % @150 GeV
LHCf/ATLAS common operation strategy

- Beam conditions:
  - Low luminosity ($L<6.10^{28} \text{ cm}^{-2}\text{s}^{-1}$), low pileup ($\mu<0.03$) at the beginning of the LHC run

- Very clean beam conditions

- LHCf trigger delivered to ATLAS + Offline matching of the events

- $>50.10^6$ commonly triggered events

- Excellent statistics for clean measurements of:
  - $\gamma$
  - Neutrons
  - $\pi^0$

for different conditions of central activity
Charged particles multiplicity

- Important for the longitudinal dependence of the showers: $X_{\text{max}}$

- ‘Standard measurements’ will be done at 13 TeV
  - $|\eta| < 2.5$ (Atlas, CMS, Alice)
  - $2 < |\eta| < 4.5$ (LHCb)
  - $3.1 < |\eta| < 6.5$ (TOTEM)

- For the first time the measurement could be correlated with the very forward proton tag!

From D. Salek
Energy flow

- Energy flow is the most important ingredient for the air shower development.

- This measurement can greatly profit of the forward proton tag.

- Energy flow is significantly affected by the presence of a leading very forward high energy particle.

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**Plot**: 

*ATLAS* and *CASTOR* Underlying Event, *CMS*

From D. Salek
**Very forward neutral particle spectra I: photons**

- LHCf is optimized for the very forward neutral particle detection
- $|\eta| > 8.4$
- Excellent performances in the $\gamma$ measurement (~2%)
- Large difference even with tuned models
Very forward neutral particle spectra II: neutrons

- Even larger differences wrt $\gamma$!
- 30% energy resolution is not taken into account
- .... But unfolding works well! (See Bonechi’s talk)
What happens if we off-line combine ATLAS and LHCf?

- ATLAS0: no charged particles in the $|\eta| < 2.5$ and $p_t > 0.1$ GeV/c
- ATLAS2: >1 charged particles in the $|\eta| < 2.5$ and $p_t > 0.1$ GeV/c
- Central activity selection enhance the differences btw models
- Could be used to tune different components of the models
The future....
The far future @ LHC

- The most promising future at LHC involve the proton-light ions collisions

- To go from p-p to p-Air is not so simple….
  - Comparison of p-p, Pb-Pb and p-Pb is useful, but model dependent extrapolations are anyway necessary

- Direct measurements of p-O or p-N could significantly reduce some systematic effects
A new idea!

- After the talk of F. Donato yesterday a new idea came to my mind

- The SMOG system has already been tested in 2012 in LHCb
  - Injection of noble gas atoms inside the beam pipe to:
    - Measure the beam profile
    - Measure the luminosity

- Why don’t use SMOG to measure cross section relevant for Cosmic Ray Physics???
  - P-He $\rightarrow$ Antiprotons+X

- We could make use of ‘perfect’ Particle Identification Detectors

- We could make use of the highest possible energies
  - Direct access to protons in the most interesting energy region
Fixed target physics at LHCb

SMOG: System for Measuring Overlap with Gas

→ injection of Ne gas into interaction region
Fixed target physics at LHCb

→ injection of Ne gas into interaction region

z-distribution of primary vertex

• increase of beam-gas interaction rate by two orders of magnitude
• accurate measurement of beam profile → precise luminosity determination
→ also allows to study pNe interactions at \( \sqrt{s} = 87 \) GeV
  shift of cm system by 4.5 units in rapidity in proton direction
→ LHCb is a central detector for fixed target collisions
The future @ RHIC: From the Large Hadron Collider to the Longisland Hadron Collider
$\sqrt{s}$ scaling: a key for extrapolation beyond the LHC

All $\pi^0$ expected from models (0.5TeV, 14TeV and 50TeV)

Comparison done in the **very limited phase space** of 900GeV collisions (green triangle in the phase space plot)

LHCf single photon data (900GeV pp, 7TeV pp)

Preliminary

All $\pi^0$ expected from models (0.5TeV, 14TeV and 50TeV)

Comparison done in the **very limited phase space** of 900GeV collisions (green triangle in the phase space plot)
• Detector is moved up-down; wide $p_T$ coverage
• $x_F$-$p_T$ coverage identical to LHC 7 TeV collision
• Wider coverage and higher resolution in $p_T$ than PHENIX ZDC+SMD measurements (joint analysis between ZDC and RHICf)
Expected Results (single photons)

- Photon spectra at 4 rapidity samples
- 12 hours statistics (12 nb\(^{-1}\) effective luminosity; 360nb\(^{-1}\) delivered)
- Statistical error is almost negligible except at the highest energy bins
Expected Results ($\pi^0$)

- $\pi^0$ spectra at 4 rapidity samples
- $<60\text{GeV}$ not detectable due to large opening angle of $\gamma \gamma$
- 24 min statistics (12 nb$^{-1}$ effective luminosity; 12 nb$^{-1}$ delivered)
- Statistical error will be negligible with a reasonable run time
Conclusions

In the last few years the importance of accelerator based measurements useful for Cosmic Ray physics came up very clearly

LHC is the ideal laboratory for these studies

Many important measurements have already been done
  - Significant improvement of EPOS_LHC and QGSJET-04 hadronic interaction models

Synergies between dedicated forward detectors and large acceptance central detectors are coming up
  - Next generation measurements, profiting of these synergies, will be soon performed, allowing further improvements of the models in their different components
Backup slides
LHCf-Atlas: photons

$\gamma$

$8.81 < \eta < 8.99 \Delta \phi = 20$

Energy (GeV)

$LHCf$

$\gamma$ with $8.81 < \eta < 8.99 \Delta \phi = 20$

Energy (GeV)

$LHCf$

$\gamma$

$\eta > 10.94$

Energy (GeV)

$\gamma$ with $\eta > 10.94$

Energy (GeV)
\[ \frac{\Delta E}{E} = \frac{65\%}{\sqrt{E\text{(GeV)}}} + 15\% \]

**PHENIX ZDC**

- **Energy resolution**:\[ \Delta E = \frac{65\%}{\sqrt{E\text{(GeV)}}} + 15\% \]
- **Position resolution**

**RHICf**

- **Hadronic shower (MC)**
  - **Position resolution**
  - **Energy resolution**
    - \[ \sigma_E/E \sim 40\% \text{ because of } 1.6\lambda \]
RHICf beam condition proposal

Constraints
- RHICf DAQ speed is limited to 1kHz
- Collision pile up cannot be resolved
- Small angular dispersion is preferred

Beam Proposal
- 510GeV p+p collisions
- $\beta^* = 10$m
- Radial (horizontal) polarization; 0.4-0.5
- $\varepsilon = 20$mm mrad, $I_b = 2 \times 10^{11}$, $n_{b\text{-colliding}} = 100$, $n_{b\text{-noncolliding}} = 20$ (nominal)
- Luminosity=$1.1 \times 10^{31}$ cm$^{-2}$s$^{-1}$

Operation
- Few days for physics and few days for contingency
- $\pi^0$ (double tower event) enhanced and single shower prescaled triggers are used simultaneously
- Trigger exchange with PHENIX
- Stay at the garage position not to interfere ZDC when RHICf does not take data
Motivations:

- Inelasticity measurement $k=1-p_{\text{leading}}/p_{\text{beam}}$
- Muon excess at Pierre Auger Observatory
  Cosmic rays experiment measure PCR energy from muon number at ground and florescence light
  20-100% more muons than expected have been observed

- Number of muons depends on the energy fraction of produced hadron
- Muon excess in data even for Fe primary MC!!!!
- EPOS predicts more muons due to larger baryon production, even if it is not sufficient to reproduce the experimental data

R. Engel

importance of baryon measurement!!!
Inclusive neutron spectra (7 TeV pp)

Very large high energy peak in the $\eta>10.76$ (predicted only by QGSJET)

$\Rightarrow$ Small inelasticity in the very forward region!
+ **Type II \( \pi^0 \) in pp 7 TeV collisions**

Present LHCf results are based on the Type-I \( \pi^0 \) events. Improved \( \pi^0 \) reconstruction, Type-II, is now ready for use in analysis.

Present LHCf results are based on the Type-I \( \pi^0 \) events. Improved \( \pi^0 \) reconstruction, Type-II, is now ready for use in analysis.

**Motivation of Type-II**
- extended \( p_T \) range
- applicable to \( \Lambda \) and \( K \)
- di-hadron.

**This analysis**

**Arm2 acceptance for Type-I \( \pi^0 \)**

PRD 86, 092001
PRC 89, 065209

**Arm2 acceptance for Type-II \( \pi^0 \)**

**Large Tower**

**Small Tower**

**σ ~4%**

Cosmic rays and accelerators: future
Cortona, April 21st, 2015
**π⁰ energy spectra (for different p_T bins)**

- **DPMJET** and **PYTHIA** are harder than LHCf p_T < 1.0 GeV, although compatible at low p_T and low E.
- **QGSJET II** gives good agreement at 0 < p_T < 0.2 GeV and 0.8 < p_T < 1.0 GeV.
- **EPOS 1.99** agrees with LHCf at 0.4 < p_T < 0.8 GeV. LHCf prefers EPOS 1.99 than EPOS LHC.
π⁰ p_T spectra (for different rapidity bins)
2015 updated LHC operation schedule

- **8 weeks beam commissioning**
- **5 days special physics at \( \beta^* = 19 \) m (VdM, LHCf, TOTEM & ALFA)**
- **Start TS1 – 15th June. 24 hour technical stop in SPS in parallel followed by SPS scrubbing.**

From M. Lamont, LMC Meeting, 15/04/15
DATA vs MC: comp. 900GeV/7TeV

- None of the model nicely agrees with the LHCF data
- Here we plot the ratio MC/Data for the various models
- > Factor 2 difference

\[ \eta > 10.94 \]

\[ 8.81 < \eta < 8.9 \]

LHCF \( \bar{\nu}_s = 900 \text{GeV}, \) Photon like
\( \eta > 10.15 \) (\( \langle \theta \rangle = 39 \mu \text{rad} \))

LHCF \( \nu_s = 900 \text{GeV}, \) Photon like
8.77 \( < \eta < 9.46 \) (\( \langle \theta \rangle = 234 \mu \text{rad} \))

MC/Data

\( \eta > 10.94 \)

\( 8.81 < \eta < 8.9 \)
DATA : 900GeV vs 7TeV

Coverage of 900GeV and 7TeV results in Feynman-X and $P_T$

- Normalized by the number of entries in $X_F > 0.1$
- No systematic error is considered in both collision energies.

Good agreement of $X_F$ spectrum shape between 900 GeV and 7 TeV.

$\frac{1}{\sigma_{inel}} \frac{d\sigma_{\gamma}}{dX_F} \bigg|_{\eta<\text{limited}} \propto \frac{1}{\sigma_{inel}} \frac{d\sigma_{\gamma}}{p_T dp_T dX_F} \langle p_T \rangle dp_T$
\( \pi^0 P_T \) spectra for various \( y \) bin: MC/data

- DPMJET 3.04
- QGSJETII-03
- SIBYLL 2.1
- EPOS 1.99
- PYTHIA 8.145

EPOS gives the best agreement both for shape and yield.
\[ \pi^0 \text{ analysis at } \sqrt{s}=7\text{TeV} \]

1. Thermodynamics

\[
\frac{1}{\sigma_{\text{inel}}} \frac{d^3\sigma}{dp^3} = A \cdot \exp(-\sqrt{p_T^2c^2 + m_{\pi^0}^2c^4/T})
\]

\[
\langle p_T \rangle = \sqrt{\frac{\pi m_{\pi^0}^2c^2T}{2}} \frac{K_2(m_{\pi^0}^2c^2/T)}{K_{3/2}(m_{\pi^0}^2c^2/T)}
\]

2. Numerical integration
actually up to the upper bound of histogram

- Systematic uncertainty of LHCf data is 5%.
- Compared with the UA7 data (\(\sqrt{s}=630\text{GeV}\)) and MC simulations (QGSJET, SIBYLL, EPOS).
- Two experimental data mostly appear to lie along a common curve
  \(\rightarrow\) no evident dependence of \(\langle p_T \rangle\) on \(E_{\text{CMS}}\).
- Smallest dependence on \(E_{\text{CMS}}\) is found in EPOS and it is consistent with LHCf and UA7.
- Large \(E_{\text{CMS}}\) dependence is found in SIBYLL.
Muon excess at Pierre Auger Obs.

Auger hybrid analysis
- event-by-event MC selection to fit FD data (top-left)
- comparison with SD data vs MC (top-right)
- muon excess in data even for Fe primary MC

EPOS predicts more muon due to larger baryon production
=> importance of baryon measurement

Pierog and Werner, PRL 101 (2008) 171101
**What LHCf can measure**

Energy spectra and Transverse momentum distribution of:

- Gamma-rays ($E > 100\text{GeV}, dE/E < 5\%$)
- Neutral Hadrons ($E > \text{a few } 100\text{ GeV}, dE/E \sim 30\%$)
- $\pi^0$ ($E > 600\text{GeV}, dE/E < 3\%$)

at pseudo-rapidity range $> 8.4$

**Energy Flux @14TeV**

- Low multiplicity !!
- High energy flux !!

Simulated by DPMJET3
Common trigger with ATLAS

- LHCf forced to trigger ATLAS
- Impact parameter may be determined by ATLAS
- Identification of forward-only events