Cosmic rays and accelerator physics at LHCf

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NPQCD 2017
Pollenzo, May 22nd, 2017
Contents

- Introduction
- LHCf @ different energies and different beams
  - Contribution to CR physics
  - Contribution to forward physics
- RHICf
- Future @ LHC
Introduction
The High Energy cosmic ray spectrum

- The spectrum falls very rapidly with energy ($\sim E^{-2.7}$)
- 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!

$\sim 27 \ X_0$

$\sim 11 \ \lambda_{int}$
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 → $9.10^{16}$ 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 $k = 1 - \frac{E_{\text{lead}}}{E_{\text{avail}}}$
   - If large $k$ ($\pi^0$s carry more energy) rapid development
   - If small $k$ (baryons carry more energy) deep penetrating

4. Secondary interactions nucleon, $\pi$
Impressive coverage of the central region

- The largest detectors for particle physics
- Surrounding the LHC Interaction Points
- Covering many fundamental physics items
- Designed for discoveries!

General purpose detectors (ATLAS, CMS,...) cover the spatial region at low rapidity.

Special detectors to access forward particles are necessary!
And also of the forward region!
LHC phase space coverage

We may profit (and we are profiting) of the very broad coverage!
Dedicated forward detectors for a better measurement of the energy flow
First models tuning after the first LHC data (EPOS and QGSJET)

Significant reduction of differences btw different hadronic interaction models!!!

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Cosmic rays and accelerator physics at LHCf
Second models tuning after the first LHC data (Sibyll 2.3)

New models: composition heavier than before

Change of model predictions understood
But not everything is perfect....
LHCf detector and performances
LHCf: location and detector layout

Detector I
- Tungsten
- GSO
- GSO bars

Front Counter: 140 m
- 8 cm thick

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

INTERACTION POINT
IP1 (ATLAS)

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

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

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

Pseudo-rapidity range:
- $\eta > 8.7$ @ zero Xing angle
- $\eta > 8.4$ @ 140µrad

Energy resolution: $44X_0$, $1.6\lambda_{int}$

Detector II
- Tungsten
- GSO
- Silicon µstrip

Front Counter: 140 m
- 6 cm thick
A brief LHCf photo-history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

Jul 2006 installation

Aug 2007 SPS beam test

Jan 2008 1st LHC beam

Dec- Jul 2010
0.9 TeV & 7 TeV pp
Detector removal

Dec 2012- Feb 2013
5 TeV/n pPb, 2.76 TeV pp
(Arm2 only)
Detector removal

May-June 2015
13 TeV dedicated pp
Detector removal

November 2016
8 TeV p-Pb
Event category in LHCf

- Leading baryon (neutron)
- Multi meson production
- LHCf calorimeters
  - Single hadron event
- Single photon event
- Pi-zero event (photon pair)
**Event category in LHCf**

**Responsible for air shower core (elasticity)**

Leading baryon (neutron)

LHCf calorimeters

- Single hadron event

**Multi meson production**

**Responsible for EM air shower component (inelasticity)**

- Single photon event
- Pi-zero event (photon pair)
+ $\pi^0$ reconstruction

Longitudinal development measured by scintillator layers

25mm Tower

\[ \text{600GeV photon} \]

32mm Tower

\[ \text{420GeV photon} \]

Transverse profile measured by silicon $\mu$–strip layers

\[ X\text{-view} \]

\[ Y\text{-view} \]

Reconstruction of $\pi^0$ mass:

\[ M_0 = \sqrt{E_1E_2} \times \]

Determination of energy from total energy release

PID from shape

Determination of the impact point

Measurement of the opening angle of gamma pairs

Identification of multiple hit
\( \gamma\gamma \) invariant mass distribution

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<td>RMS</td>
<td>82.81</td>
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<td>( \chi^2 / \text{ndf} )</td>
<td>112.1 / 11</td>
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<tr>
<td>( p_0 )</td>
<td>4466 ± 44.7</td>
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<td>( p_1 )</td>
<td>129.4 ± 0.1</td>
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<td>( p_2 )</td>
<td>6.632 ± 0.058</td>
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<tr>
<td>( p_3 )</td>
<td>400.3 ± 8.7</td>
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\( \gamma\gamma \) - invariant mass distribution

Fill5519
Run60971-61156

\( p\text{-Pb@8 TeV} \)
LHCf physics results
## LHCf Data Taking and Analysis matrix

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<tr>
<th></th>
<th>Proton $E_{\text{LAB}}$ (Ev)</th>
<th>Photon (EM shower)</th>
<th>Neutron (hadron shower)</th>
<th>$\pi^0$ (EM shower)</th>
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<td>$4.1 \times 10^{15}$</td>
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<td></td>
<td>Phys. Rev. D 86, 092001 (2012)</td>
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<td><strong>p-Pb at 5.02TeV</strong></td>
<td>$1.3 \times 10^{16}$</td>
<td></td>
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<td>Phys. Rev. D 94, 032007 (2016) Type II</td>
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<tr>
<td><strong>p-p at 13TeV</strong></td>
<td>$9.0 \times 10^{16}$</td>
<td>Submitted to PLB</td>
<td>Preliminary results</td>
<td></td>
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<td><strong>p-Pb at 8.1 TeV</strong></td>
<td>$3.6 \times 10^{16}$</td>
<td>Run completed in November 2016</td>
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<td></td>
</tr>
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</table>

*Run1, Run2, Run3, Run4*
γ energy spectra at 13 TeV

η > 10.94

QGSJET II-04: overall good agreement
EPOS-LHC: overall good agreement
DPMJET 3.06: overall higher flux
SIBYLL 2.3: overall lower flux
PYTHIA 8.212: higher flux above 3 TeV
γ energy spectra at 13 TeV

\[8.81 < \eta < 8.99\]

**QGSJET II-04**: overall lower flux

**EPOS-LHC**: higher flux above 3-4 TeV

**DPMJET 3.06**: overall higher flux

**SIBYLL 2.3**: higher flux above 2 TeV

**PYTHIA 8.212**: higher flux above 3 TeV
Feynman scaling: differential cross section as a function of $X_F$ independent of $\sqrt{s}$ for $X_F$

Feynman scaling holds within systematic uncertainties
Preliminary ARM2 unfolded neutron spectra @ 13 TeV

Differential production cross section

\[
d\sigma_n/dE = \frac{dN(\Delta \eta, \Delta E)}{E} \times \frac{2\pi}{L} \times d\phi
\]

Only **QGSJET II-04** qualitatively reproduces behavior of data in \(\eta > 10.76\)

**EPOS-LHC** has similar shape in \(8.81 < \eta < 9.22\), but lower yield
Feynman scaling in neutron production cross-section

\[ p_T < 0.15 \text{ GeV/c} \]

Feynman scaling hypothesis holds within the error bars
Consistency is good especially in the region \(0.2 < x_F < 0.75\)
**Measurement of interesting quantities for CR Physics**

**Inelasticity VS $\theta$**

- LHCf p+p $\sqrt{s} = 13$ TeV
- QGSJET II-04
- EPOS-LHC
- DPMJET 3.00
- PYTHIA 8.212
- SIBYLL 2.1

**$d\sigma/d\eta$ VS $\eta$**

- LHCf p+p $\sqrt{s} = 13$ TeV
- QGSJET II-04
- EPOS-LHC
- DPMJET 3.00
- PYTHIA 8.212
- SIBYLL 2.1

**$dE/d\eta$ VS $\eta$**

- LHCf p+p $\sqrt{s} = 13$ TeV
- QGSJET II-04
- EPOS-LHC
- DPMJET 3.00
- PYTHIA 8.212
- SIBYLL 2.1

---

All models overestimate inelasticity in the most forward region even if **QGSJET II-04** and **EPOS-LHC** are consistent within the error bars.

**EPOS-LHC** and **SIBYLL 2.1** reproduce enough well the measured total differential cross section except in the most forward region.

Where the energy flux is high, the agreement between experimental measurements and **SIBYLL 2.1/EPOS-LHC** is quite good.
LHCf @ pPb 5.02 TeV: $\pi^0$ analysis

(Soft) QCD: central and peripheral collisions

Ultra peripheral collisions: virtual photons from rel. Pb collides a proton

Central collisions

Periphereral collisions

Proton Pb

Proton Pb

$b \ll R_p + R_{Pb}$

$b \sim R_p + R_{Pb}$

Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model ($E_\gamma >$ pion threshold).
3. produced mesons and baryons by $\gamma$-p collisions are boosted along the proton beam.

Dominant channel to forward $\pi^0$ is

$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$

About half of the observed $\pi^0$ may originate in UPC, another half is from soft-QCD.

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LHCf @ pPb 5.02 TeV: $\pi^0$ $p_T$ spectra

- QGSJETII-04 and EPOS-LHC: similar, good agreement for $p_T > 0.4$ GeV
- DPMJET: good agreement for $-8.8 > y_{lab} > -10.0$ and $p_T < 0.3$ GeV
- Characteristic bump at $y > -9.6$ and $p_T \sim 0.2$ GeV: Ultra Peripheral Collisions
Nuclear modification factor

Strong suppression of the $\pi^0$ production from the nuclear target relative to that from the nucleon target.
LHCf & ATLAS
ATLAS-LHCf combined data taking

- Trigger sharing with ATLAS at ~100-500 Hz in p+p (500 Hz in 2016 p+Pb)
- Off-line event matching
- Internal note (p+Pb 2013)
  - ATL-PHYS-PUB-2015-038

Important to separate the contributions due to diffractive and non-diffractive collisions
- It makes more easy improving the hadronic interaction models
Diffractive studies

- MC studies
  - Contributions on forward photon/neutron spectra from diffractive/non-diffractive collisions.
  - Event-selection by the central particle production to separate these events

Very forward photon energy spectra predicted by four models with total/diffractive/non-diffractive

- Total: Very similar spectra in EPOS,QGSJET and SIBYLL (LHCf alone)
- Diffractive/Non-diffractive: Very big difference between models (ATLAS-LHCf)

Diffractive studies

- Event selection for Diffractive/Non-diffractive by using $N_{\text{charged}}$ with $p_T>100\text{MeV}$ in $|\eta|<2.5$

Expected efficiencies

By using ATLAS-tracker information, We can separate diffractive/non-diffractive events with high efficiency and purity

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Cosmic rays and accelerator physics at LHCf

Pollenz, May 22$^{nd}$, 2017
Physics cases with Atlas jointly taken data

- In p+p collisions
  - Forward spectra of Diffractive/ Non-diffractive events
  - Measurement of proton-π collisions

  Both are important for precise understanding of CR air shower development

- In p+Pb collisions
  - Measurement of UPC in the forward region.

  Leading neutron can be tagged by LHCf detectors
  -> total cross section multiplicity measurement

Khoze et al., arXiv:1705.03685
The future...
The future @ RHIC: From the Large Hadron Collider to the Longisland Hadron Collider

LHCf Arm2 detector in the LHC tunnel

Schematic view of the RHICf installation
RHICf detector acceptance

STAR IP

Cross section view from IP

Acceptance in E-$p_T$ phase space

- Widest and gapless $p_T$ coverage is realized by moving the vertical detector position.
- Beam pipes obscure photons but not neutrons.
\(\sqrt{s} \) scaling, or breaking?

LHCf 2.76TeV and 7TeV data shows scaling of forward \(\pi^0\) production at RHICf.

\[\pi^0\]

**neutron**

ISR (30-60GeV), PHENIX (200GeV) and LHCf (7TeV) data indicate scaling breaking of forward neutrons.

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Cosmic rays and accelerator physics at LHCf

Pollenzo, May 22nd, 2017
RHICf commissioning

- RHIC starts first RUN2017 collision on 20-Feb
- RHICf observed shower signal (PMT coincidence) and tuned timing
- Common operation (RHICf triggers STAR) tested and common data successfully recorded at STAR (analysis of physics correlation on going)
- Data taking: last week of June

Bunch ID of RHICf trigger recorded at “STAR”
Two abort gaps correctly identified
Diffractive vs. non diffractive at \( \eta > 8.2 \) with \( \sqrt{s} = 510 \text{GeV} \) \( p+p \) collisions

**PYTHIA 8 simulation**

**BLUE:** inclusive spectra expected by RHICf only

**RED:** diffractive only ("RHICf + no central track in STAR" will be similar => TBC)

**BLACK:** non diffractive ("RHICf + >=1 central track in STAR" => TBC)
The Near-Far Future at LHC

- The most promising future at LHC for LHCf involve the proton-light ion 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
- Still make sense to take data if intermediate ion (like Ar) will be available

Photon spectra p-p vs. O-O

Y. Okuno, Master thesis
Nagoya university (2016)
Conclusions

- In the last few years the importance of accelerator based measurements useful for Cosmic Ray physics came up very clearly, in addition to the ‘standard’ physics case

- LHC is the ideal laboratory for these studies

- Many important measurements have already been done
  - Significant improvement of EPOS_LHC, QGSJET-04 and Sibyll_2.3 hadronic interaction models

- LHCf provided many precise results on forward $\gamma$, $n$ and $\pi^0$ with different collision’s conditions

- Joint analysis with Atlas is on-going for diffractive/non diffractive events selection

- RHICf will take data next month
LHCf-Atlas: photons

- Energy (GeV)
- dN/dE

- 8.81 < η < 8.99 Δφ=20
- γ

- EPOS LHC ATLAS0
- QGSJETII-04 ATLAS0
- EPOS LHC ATLAS2
- QGSJETII-04 ATLAS2

- γ with 8.81 < η < 8.99 Δφ=20

- γ
- η > 10.94

- EPOS LHC ATLAS0
- QGSJETII-04 ATLAS0
- EPOS LHC ATLAS2
- QGSJETII-04 ATLAS2

- γ with η > 10.94
ZDC resolution @PHENIX vs RHICf

PHENIX ZDC

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

Energy resolution (%)

\begin{align*}
\text{Inverse square of incident energy } E^{-1/2} (\text{GeV}^{-1/2})
\end{align*}

RHICf

Hadronic shower (MC)

Position resolution

Black: X-plane

Red: Y-plane

Energy resolution

Small tower

Large tower

\[\sigma_{E/E} \sim 40\% \text{ because of } 1.6\lambda\]
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
- $\beta^* = 10m$
- Radial (horizontal) polarization; 0.4-0.5
- $\varepsilon = 20\text{mm mrad}$, $I_b = 2 \times 10^{11}$, $n_{b\text{-colliding}} = 100$, $n_{b\text{-noncolliding}} = 20$ (nominal)
- Luminosity $= 1.1 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$

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 fluorescence 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

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

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

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

This analysis

- PRD 86, 092001
- PRC 89, 065209

$\sigma \sim 4\%$
π⁰ energy spectra (for different pₜ bins)

- DPMJET and PYTHIA are harder than LHCf when pₜ < 1.0 GeV, although compatible at low pₜ and low E.
- QGSJET II gives good agreement at 0 < pₜ < 0.2 GeV and 0.8 < pₜ < 1.0 GeV.
- EPOS 1.99 agrees with LHCf at 0.4 < pₜ < 0.8 GeV. LHCf prefers EPOS 1.99 than EPOS LHC.
$\pi^0$ $p_T$ spectra (for different rapidity bins)

Preliminary

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Cosmic rays and accelerator physics at LHCf

Pollenzno, May 22nd, 2017
## 2015 updated LHC operation schedule

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**From M. Lamont, LMC Meeting, 15/04/15**

- 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.
None of the model nicely agrees with the LHCf data.

Here we plot the ratio MC/Data for the various models.

> Factor 2 difference

\[ \eta > 10.94 \]

\[ 8.81 < \eta < 8.9 \]
DATA : 900GeV vs 7TeV

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

- 900GeV vs. 7TeV with the same PT region

- 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. ➔ weak dependence of $<p_T>$ on $E_{CMS}$

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

**EPOS gives the best agreement both for shape and yield.**

- **DPMJET 3.04**
- **QGSJET II-03**
- **SIBYLL 2.1**
- **EPOS 1.99**
- **PYTHIA 8.145**
π⁰ analysis at √s=7TeV

1. Thermodynamics

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

\[
\langle p_T \rangle = \sqrt{\pi m_{\pi^0}^2 c^2 T \frac{K_2(m_{\pi^0}^2 c^4 / T)}{2 K_{3/2}(m_{\pi^0}^2 c^4 / T)}}
\]

2. Numerical integration

\[
\langle p_T \rangle = \frac{\int_0^\infty 2\pi p_T^2 f(p_T) dp_T}{\int_0^\infty 2\pi p_T f(p_T) dp_T}
\]

- Systematic uncertainty of LHCf data is 5%.
- Compared with the UA7 data (√s=630GeV) and MC simulations (QGSJET, SIBYLL, EPOS).
- Two experimental data mostly appear to lie along a common curve → 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>100GeV, dE/E<5%)
- Neutral Hadrons (E>a few 100 GeV, dE/E~30%)
- \( \pi^0 \) (E>600GeV, dE/E<3%)

at pseudo-rapidity range >8.4

Front view of calorimeters @ 100 μ rad crossing angle

Low multiplicity !!

High energy flux !!
Common trigger with ATLAS

- LHCf forced to trigger ATLAS
- Impact parameter may be determined by ATLAS
- Identification of forward-only events
Analysis of hadron production in p-p collisions at 13 TeV

Data set
12 July 2015, 22:32-1:30 (3 hours)
Fill # 3855
μ = 0.01
∫ L dt = 0.19 nb⁻¹
σ_{ine} = 78.53 mb

Event selection criteria:
- Software trigger: at least 3 consecutive layers with deposit above threshold dE > dE_{thr}
- PID selection: L_{2D} > L_{2D}^{thr}
  where L_{2D} is a variable related to shower longitudinal profile
- Pseudorapidity acceptance
  3 different pseudorapidity regions

Beam Center
Estimated using 2D fit on high energy hadron hitmap distribution
Charged particle distribution in pseudorapidity

Protons: $E_{\text{lab}} = 3 \times 10^{16}$ eV

(data exist from all LHC experiments)

Feb. 2016: tuned version of Sibyll (v2.3)
Photon reconstruction

Performance study for the photon measurements of the upgraded LHCf calorimeters with Gd$_2$SiO$_5$ (GSO) scintillators

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ΔE/E<2%

Δx<0.2 mm

Arm1 20 mm cal.

Arm2 25 mm cal.
$\Delta m_{\gamma\gamma}/m_{\gamma\gamma} \sim 3.5\%$

Additional content: $\pi^0$ mass peak

Graph showing the reconstructed $m_{\gamma\gamma}$ distribution with a peak at approximately 130 MeV, normalized to 3.5%.
Neutron reconstruction

Performance for 1.5 TeV neutrons:
\[ \Delta E/E \sim 35\%-40\% \]
\[ \Delta x \sim 1\text{mm} \]

And…. Detector performance is also interaction model dependent!

Unfolding is essential to extract physics results from the measured spectra

Physics measurement important to try to solve the ‘Muon excess’ observed from the ground based HECR experiments
Reconstructed ARM2 hadron energy spectra @ 13 TeV

- QGSJET II-04 and EPOS-LHC have similar shape but lower yield
- DPMJET 3.04 have very different shape and yield
LHCf @ pPb 5.02 TeV: $\pi^0$ spectra @ p-remnant side

LHCf data vs. UPC calculation

(0.5x) UPC calculation
LHCf @ pPb 5.02 TeV: π⁰ spectra @ p-remnant side

The LHCf results in p-Pb (filled circles) show good agreement with DPMJET and EPOS.

The LHCf results in p-Pb are clearly harder than the LHCf results in p-p at 5.02TeV (shaded area) which are interpolated from the results at 2.76TeV and 7TeV.
Very forward neutral particle spectra: neutrons

- Even larger differences wrt $\gamma$!
- 30% energy resolution is not taken into account
- .... But unfolding works well!
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 enhances the differences between models.

Could be used to tune different components of the models.

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![Graphs](From T.Pierog LHCf)

- Neutrons $\eta > 10.94$
- Neutrons $8.81 < \eta < 8.99$ $\Delta\phi=20$

![Graphs](From T.Pierog LHCf)

- EPOS LHC ATLAS0
- QGSJETII-04 ATLAS0
- EPOS LHC ATLAS2
- QGSJETII-04 ATLAS2
\[ \sqrt{s} \text{ scaling: a key for extrapolation beyond the LHC} \]

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

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

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

DPMJET3
QGSJET II

Preliminary

0.9TeV (\( \eta > 8.68 \))
7TeV scaled (\( \eta > 10.94 \))
\[ \sqrt{s} = 900 \text{GeV} \text{ Scaled to } \sqrt{s} = 7 \text{TeV} (\eta > 8.88) \]
Hard Diffractive Events

Diffractive events with high $p_T$ particles produced

Probing the hard structure of the Pomeron

$E_T > 10$ GeV

- $\sigma_{incl} \sim 1$ $\mu$b
- $\sigma_{excl} \sim 7$ nb

$M (j1,j2) = 120$ GeV

$\sigma_{excl} \sim 18$ pb / $\Delta M = 10$ GeV

Rates at $L = 2 \times 10^{29}$ cm$^{-2}$ s$^{-1}$

- 720/h
- 5/h

Rates at $L = 2 \times 10^{31}$ cm$^{-2}$ s$^{-1}$

- 30/day