Latest LHCf physics results

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Physics Motivations

Impact on HECR Physics
Extensive air shower observation
- Longitudinal distribution
- Lateral distribution
- Arrival direction

Air shower development

Astrophysical parameters
- Spectrum
- Composition
- Source distribution

$X_{\text{max}}$ is the depth of air shower maximum in the atmosphere. An indicator of CR composition.

Uncertainty of hadron interaction models

Uncertainty in the interpretation of $\langle X_{\text{max}} \rangle$
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
Models tuning after the first LHC data

\( X_{\text{max}} \) as function of \( E \) and particle type

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

The experimental set-up
**LHCf: location and detector layout**

**Detector I**  
Tungsten  
Scintillator  
Scintillating fibers

**Detector II**  
Tungsten  
Scintillator  
Silicon μstrips

**INTERACTION POINT**  
IP1 (ATLAS)

Front Counter  
140 m

Front Counter  
140 m

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  
\( \eta > 8.4 \) @ 140urad

8 cm  
6 cm

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

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

44\(X_0\),  
1.6 \(\lambda_{int}\)
# LHCf ‘analysis matrix’

<table>
<thead>
<tr>
<th>Proton equivalent energy in the LAB (eV)</th>
<th>γ</th>
<th>Neutrons</th>
<th>π⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-Pb 5.02 TeV</td>
<td>1.3x10¹⁶</td>
<td></td>
<td>Phys. Rev. C 89, 065209 (2014)</td>
</tr>
<tr>
<td>p-p 7 TeV</td>
<td>9.0x10¹⁶</td>
<td>Waiting for LHC restart!</td>
<td></td>
</tr>
</tbody>
</table>
Latest analysis

Neutrons in 7 TeV pp collisions

$\pi^0$ in 5.02 TeV p-Pb collisions
The challenge of neutron analysis

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

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
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!
The 2013 p-Pb run at $\sqrt{s_{NN}} = 5.02$ TeV

- **2013 Jan-Feb for p-Pb/Pb-p collisions**
  - Installation of the only Arm2 at one side (silicon tracker good for multiplicity)
  - Data both at p-side (20Jan-1Feb) and Pb-side (1fill, 4Feb), thanks to the swap of the beams

- **Details of beams and DAQ**
  - $L = 1 \times 10^{29} - 0.5 \times 10^{29} \text{cm}^{-2} \text{s}^{-1}$
  - ~200,10$^6$ events
  - $\beta^* = 0.8$ m, 290 $\mu$rad crossing angle
  - 338p+338Pb bunches (min.$\Delta T = 200$ ns), 296 colliding at IP1
  - 10-20 kHz trig rate downscaled to approximately 700 Hz
  - 20-40 Hz ATLAS common trig. Coincidence successful!
  - p-p collisions at 2.76 TeV have also been taken
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

$\text{proton} \quad \rightarrow \quad \text{Pb}$

Peripheral collisions

$\text{proton} \quad \rightarrow \quad \text{impact parameter} : b$

$\text{Pb}$

Estimation of momentum distribution of the UPC induced secondary particles (Lab frame+Boost): 
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation
2. photon-proton collisions are simulated by the SOPHIA model ($E_\gamma > \text{pion threshold}$)

Dominant channel to forward $\pi^0$ is

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

About half of the observed $\pi^0$ originate from UPC
About half is from soft-QCD
Need to subtract UPC component

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π⁰ event reconstruction in p-Pb collisions

1. Search for two photons

2. BG subtraction by sideband

3. Unfolding the smeared p_T spectra and correction for geometrical inefficiency

4. Subtraction of the UPC component
Inclusive $\pi^0 p_T$ spectra in p-Pb at 5.02 TeV

- LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- LHCf spectra in p-Pb are clearly harder than the LHCf data in p-p at 5.02 TeV (shaded area, spectra multiplied by 5). The latter is interpolated from the results at 2.76 TeV and 7 TeV.
Nuclear modification factor in p-Pb at 5.02 TeV

- Both LHCf and MCs show strong suppression.
- NMF grows with increasing $p_T$, as can be expected by the $p_T$ spectrum that is softer in p-p 5 TeV than in p-Pb 5 TeV collisions.

\[
R_{pPb}(p_T) \equiv \frac{\sigma_{pPb}^{inel}}{\langle N_{coll} \rangle \sigma_{pp}^{inel}} \frac{Ed^3 \sigma_{Pb}^{pPb}/dp^3}{Ed^3 \sigma_{PP}^{pp}/dp^3}
\]

\[
\langle N_{coll} \rangle = 6.9
\]
Conclusions

- Very forward $\pi^0$ production in p-Pb collision has been measured by LHCf

- Soft-QCD component of the measured $\pi^0$ production overall agrees with DPMJET 3.04 and EPOS 1.99.

- Strong suppression of $\pi^0$ production is found in p-Pb collision which is consistent with predictions of DPMJET, EPOS and QGSJET II-03

- Large amount of high energy neutrons exists in very forward region of p-p collisions, leading to small inelasticity

- Detector setup for future runs is ongoing smoothly:
  - LHC@13 TeV in 2015
  - 510 GeV polarized p-p RHIC run in 2016 has been proposed to RHIC PAC. We are waiting for official answer
Backup slides
The LHCf Collaboration

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UPC subtraction

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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
Derivation of $\pi^0$ $p_T$ spectra in p-p at 5.02 TeV

1. Thermodynamics (Hagedorn model)

$$\frac{1}{\sigma_{\text{inel}}} \frac{E}{dp^3} = A \cdot \exp(-\sqrt{p_T^2 + m_{\pi^0}^2 / T})$$

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

2. Gauss distribution

$$\frac{1}{\sigma_{\text{inel}}} \frac{E}{dp^3} = A \cdot \frac{\exp(-p_T^2 / \sigma_{\text{Gauss}}^2)}{\pi \sigma_{\text{Gauss}}^2}$$

$$\langle p_T \rangle = \frac{\sqrt{\pi}}{2} \sigma_{\text{Gauss}}$$

The $p_T$ spectra in “p-p at 5.02 TeV” are obtained by the Gauss distribution with the above $\langle p_T \rangle$ and absolute normalization.

$$\langle p_T \rangle(y)_{5.02 \text{ TeV}} = 216.3 + 116.0(8.585 - y) \text{ [MeV]}$$

$(\Delta y \equiv y_{\text{beam}} - y)$. 

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The importance of neutrons in the very forward region

Motivations:

- Inelasticity measurement: \( k = 1 - p_{\text{leading}} / p_{\text{beam}} \)
- Muon excess at Pierre Auger Observatory
  - Cosmic rays experiment measure HECR 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 muon due to larger baryon production

R. Engel

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p-Pb run: $\pi^0$

Double photon events - invariant mass (p-remnant)

<table>
<thead>
<tr>
<th>h1ggmass</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>15.89 / 5</td>
</tr>
<tr>
<td>p0</td>
<td>1232 ± 23.0</td>
</tr>
<tr>
<td>p1</td>
<td>0.1354 ± 0.0001</td>
</tr>
<tr>
<td>p2</td>
<td>0.005017 ± 0.000072</td>
</tr>
<tr>
<td>p3</td>
<td>103.5 ± 12.9</td>
</tr>
<tr>
<td>p4</td>
<td>-402.4 ± 95.7</td>
</tr>
</tbody>
</table>

DATA (p-Pb 2013)

PRELIMINARY
Comparison wrt MC Models at 7 TeV

DPMJET 3.04  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145  QGSJET II-03

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None of the model nicely agrees with the LHCF data.

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

> Factor 2 difference

η > 10.94

8.81 < η < 8.9
**DATA : 900GeV vs 7TeV**

Coverage of 900GeV and 7TeV results in Feynman-\(X_F\) 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.

\[
\frac{1}{\sigma_{\text{inel}}} \left. \frac{d\sigma_{\gamma}}{dX_F} \right|_{\eta<\text{limited}} \propto \frac{1}{\sigma_{\text{inel}}} \frac{d\sigma_{\gamma}}{p_T dp_T dX_F} \langle p_T \rangle dp_T
\]

Data 2010 at \(\sqrt{s}=900\text{GeV}\)
(Normalized by the number of entries in \(X_F > 0.1\))
Data 2010 at \(\sqrt{s}=7\text{TeV} (\eta > 10.94)\)
$\pi^0$ $p_T$ 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.
\( \pi^0 \) Data vs MC at 7 TeV cm
**π^0 analysis at \sqrt{s}=7\,\text{TeV}**

1. Thermodynamics
   (Hagedorn, Riv. Nuovo Cim. 6:10, 1 (1983))
   \[
   \frac{1}{\sigma_{\text{inel}}} \frac{E}{dp^3} d^3 \sigma = A \cdot \exp(-\sqrt{p_T^2 c^2 + \frac{m_{\pi^0} c^4}{T}}) 
   \]
   \[
   \langle p_T \rangle = \sqrt{\frac{\pi m_{\pi^0} c^2 T}{2}} \frac{K_2(m_{\pi^0} c^2 / T)}{K_{3/2}(m_{\pi^0} c^2 / T)}
   \]

2. Numerical integration
   actually up to the upper bound of histogram
   \[
   \langle p_T \rangle = \frac{\int_0^\infty 2\pi p_T^2 f(p_T) dp_T}{\int_0^\infty 2\pi p_T f(p_T) dp_T}
   \]

- Systematic uncertainty of LHCf data is 5%.
- Compared with the UA7 data (\sqrt{s}=630\,\text{GeV}) 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_{CMS}.
- Smallest dependence on E_{CMS} is found in EPOS and it is consistent with LHCf and UA7.
- Large E_{CMS} dependence is found in SIBYLL

---

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- Two experimental data mostly appear to lie along a common curve → no evident dependence of \langle p_T \rangle on E_{CMS}.
- Smallest dependence on E_{CMS} is found in EPOS and it is consistent with LHCf and UA7.
- Large E_{CMS} dependence is found in SIBYLL
A very clear $\pi^0$ in Arm2

Longitudinal development measured by scintillator layers

- 25mm Tower
  - $\rightarrow 600\,\text{GeV}$ photon
- 32mm Tower
  - $\rightarrow 420\,\text{GeV}$ photon

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

- X-view
- Y-view

Reconstruction of $\pi^0$ mass $M_{\pi^0} = \sqrt{E_{\gamma 1}E_{\gamma 2}} \cdot \theta$

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

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**LHCf: future plan**

**p-p at 13TeV (2015)**
Main target: measurement at the LHC design energy.
Study of energy scaling by comparison with $\sqrt{s} = 900$ GeV and 7 TeV data
Upgrade of the detectors for radiation hardness.

**p-light ions (O, N) at the LHC (2019?)**
It allows studying HECR collisions with atmospheric nuclei.

**RHICf experiment at RHIC**
Lower collision energy, ion collisions.
LOI to the RHIC committee submitted

- **p-p collisions:**
  - Max. $\sqrt{s} = 500$ GeV
  - Polarized beams

- **Ion collisions:**
  - Au-Au, d-Au
  - Max. $\sqrt{s} = 200$ GeV
  - Possible, d-O,N (p-O,N)
  ➔ Cosmic ray – Air @ knee energy.
Physics of RHICf

- Physics of RHICf
  - Energy Scaling of Very Forward at p-p $\sqrt{s}=500\text{GeV}$
  - Measurement at p-light ion collisions (p-O) $\sqrt{s_{NN}}=200\text{GeV}$
  - Asymmetry of Forward Neutron with polarized beams

- LOI submitted to the RHIC committee and nicely appreciated
  - More news soon

*Nuclear modification factor at d-Au 200GeV*
**What LHCf can measure**

Energy spectra and Transverse momentum distribution of:
- Gamma-rays ($E > 100\text{GeV}, dE/E < 5\%$)
- Neutral Hadrons ($E > \text{a few 100 GeV}, dE/E \sim 30\%$)
- $\pi^0$ ($E > 600\text{GeV}, dE/E < 3\%$)

at pseudo-rapidity range $> 8.4$

**Multiplicity @ 14TeV**

- Low multiplicity !!
- ATLAS/CMS LHCf/ZDC CASTOR RPs

**Energy Flux @ 14TeV**

- High energy flux !!
- ATLAS/CMS LHCf/ZDC CASTOR RPs

simulated by DPMJET3
Common trigger with ATLAS

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

MC impact parameter vs. # of particles in ATLAS LUCID
Neutron identification

- Particle Identification with high efficiency and small contamination is necessary.

- A 2D method based on longitudinal shower development is used.

- \(L_{20\%}(L_{90\%})\): depth in \(X_0\) where 20\% (90\%) of the deposited energy is contained.

- \(L_{2D} = L_{90\%} - 0.25 L_{20\%}\)

- Mean purity in the 0-10 TeV range: 95\%.

- Mean efficiency: \(~90\%\).