Cosmic Ray International Seminar 2015
Gallipoli, 15\textsuperscript{th} Sep 2015

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\textbf{LHCf EXPERIMENT: PHYSICS RESULTS}
PHYSICS MOTIVATIONS

Impact on HECR Physics
THE HIGH ENERGY COSMIC RAY SPECTRUM

- The cosmic ray spectrum falls very rapidly with energy (~E^{-2.7})
- At high energies direct measurements are limited by the very low flux of particles (< 1/m^2/year)
- We have to rely on atmospheric showers measurements

Detailed knowledge of high energy hadronic interactions is needed in order to reconstruct the primary CR type and energy

Calorimetric measurement using Earth's atmosphere

\~ 27 \chi_0
\~ 11 \lambda_{\text{int}}

10^{19} \text{ eV proton}
HIGH ENERGY CR SHOWERS: MAIN OBSERVABLES

HECRs

- $X_{\text{max}}$: depth of 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

Uncertainty in hadron interaction models

Uncertainty in the interpretation of the observables

hadronic interaction models

CR composition and energy
Accelerator based experiments are the most powerful available tools for:

- studying the characteristics of high energy hadronic interactions
- tuning hadronic interaction models

**LHC**: 13 TeV \( \Rightarrow 9 \times 10^{16} \) eV

Unique opportunity to calibrate the models in the region beyond the "knee"
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 Nuclear effects CR-Air
A very broad phase space coverage is available
Dedicated forward detectors for a better measurement of the energy flow

\[ \eta = -\ln \tan \left( \frac{\theta}{2} \right) \]

\[ p_T^{\text{max}} = \sqrt{s}/2 \exp(-\eta) \]
Significant reduction of differences among hadronic interaction models

from D. D’Enterria
LHCf @ LHC

the experimental set-up
LHCF EXPERIMENTAL SET-UP

Arm1
Tungsten/GSO calorimeter
+ GSO bars

Arm2
Tungsten/GSO calorimeter
+ Silicon μ strips

INTERACTION POINT
IP1 (ATLAS)

Arm1 Detector
20mm x 20mm + 40mm x 40mm
4 X-Y GSO bars tracking layers

Arm2 Detector
25mm x 25mm + 32mm x 32mm
4 X-Y Silicon strip tracking layers

Position resolution:
< 200 μm (Arm1)
40 μm (Arm2)

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

Pseudo-rapidity range:
η > 8.7 @ zero X-ing angle
η > 8.4 @ 140 μrad

44 X₀
1.6 λₘₐₓ
THE LHCf COLLABORATION

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**BRIEF HISTORY OF LHCf**

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved
- Jul 2006 construction
- Aug 2007 SPS beam test
- Jan 2008 installation
  Sep 2008 1st LHC beam
- Dec 2009 - Jul 2010
  0.9TeV & 7TeV pp, detector removal
- Dec 2012 - Feb 2013
  5.02 TeV/n pPb & 2.76TeV pp (Arm2 only), detector removal
- May - June 2015
  13 TeV pp (dedicated run), detector removal
<table>
<thead>
<tr>
<th>Proton equivalent energy in the LAB (eV)</th>
<th>( \gamma )</th>
<th>( n )</th>
<th>( \pi^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-Pb 5.02 TeV</td>
<td>1.3x10^{16}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-p 13 TeV</td>
<td>9.0x10^{16}</td>
<td>Data taken in June 2015 after the restart of LHC</td>
<td></td>
</tr>
</tbody>
</table>
LATEST ANALYSES AND RESULTS
PREVIOUSLY PUBLISHED RESULTS

- comparison between data and expectation from different models
- inclusive energy spectra
- $p_T$ spectra in different rapidity bins

7 & 0.9 TeV pp photon

7 TeV pp $\pi^0$

5.02 TeV/n pPb $\pi^0$
**HED RESULTS**

- Comparison between data and expectation
- Inclusive energy spectra
- \( p_T \) spectra in different rapidity bins

**Previously Published Results**
INCLUSIVE NEUTRON SPECTRA (7 TeV pp)

Submitted to Phys. Lett. B

<table>
<thead>
<tr>
<th>n / γ ratio</th>
<th>η&gt;10.76</th>
<th>8.99&lt;η&lt;9.22</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCf data</td>
<td>3.05±0.19</td>
<td>1.26±0.08</td>
</tr>
<tr>
<td>DPMJET3.04</td>
<td>1.05</td>
<td>0.76</td>
</tr>
<tr>
<td>EPOS 1.99</td>
<td>1.80</td>
<td>0.69</td>
</tr>
<tr>
<td>PYTHIA 8.145</td>
<td>1.27</td>
<td>0.82</td>
</tr>
<tr>
<td>QGSJET II-03</td>
<td>2.34</td>
<td>0.65</td>
</tr>
<tr>
<td>SYBILL 2.1</td>
<td>0.88</td>
<td>0.57</td>
</tr>
</tbody>
</table>

More abundant neutron yield wrt photons, not expected from MC

Large high-energy peak in the η>10.76 region (predicted only by QGSJET) → small inelasticity in the very forward region

M. Bongi – CRIS2015– 14th Sep 2015
**ANALYSIS: TYPE-I AND TYPE-II EVENTS**

- **Type-I**: pair of photons each detected in one of the towers or both in the same tower.
- **Type-II**: multi-hit events excluded.
- \( p_T \) and \( p_Z \) of \( \pi^0 \) reconstructed from energy and incident position of photon pair.
- Invariant mass distribution to select \( \pi^0 \) candidates.
- Data are corrected for experimental effects:
  - background contamination
  - detector response and reconstruction efficiency (unfolding)
  - detector acceptance
  - multi-hit rejection efficiency
\( \pi^0 p_T \) SPECTRA (TYPE-I + TYPE-II): 2.76 TeV pp

- **QGSJETII-04**: best agreement
- **EPOS-LHC**: harder than data
- **SIBYLL**: smaller yield
- **DPMJET** and **PYTHIA**: larger yield

Submitted to Phys. Rev. D
$\pi^0 p_T$ SPECTRA (TYPE-I + TYPE-II): 7 TeV pp

- QGSJETII-04: best agreement
- EPOS-LHC: larger yield for high $p_T$
- SIBYLL: harder than data
\( \pi^0 p_Z \) SPECTRA (TYPE-I + TYPE-II): 7 TeV pp

Submitted to Phys. Rev. D

- **QGSJETII-04**: good agreement in the low \( p_T \) region
- **EPOS-LHC**: harder than data for high \( p_Z \)
- **SIBYLL**: smaller yield for low \( p_T \), larger yield for high \( p_T \)
- **DPMJET** and **PYTHIA**: ok for low \( p_Z \) (and low \( p_T \))
\( \pi^0 p_T \) SPECTRA (TYPE-I + TYPE-II): 5.02 TeV pPb

- QGSJETII-04 and EPOS-LHC: similar, good agreement
- DPMJET: good agreement for low \( p_T \), harder for high \( p_T \)
- characteristic bump at \( p_T \sim 0.2 \) GeV: Ultra Peripheral Collisions (UPC)

Submitted to Phys. Rev. D
\[ \pi^0 p_T SPECTRA \ (\text{TYPE-I} + \text{TYPE-II}): \ 5.02 \text{ TeV pPb} \]

- **QGSJETII-04**: good agreement for low \( p_T \)
- **EPOS-LHC**: compatible with data in some \( p_T \), \( p_Z \) intervals
- **DPMJET**: agreement for low \( p_T \) and low \( p_Z \)
- characteristic bump at \( p_Z \approx 1.2 \) TeV for \( p_T < 0.4 \) GeV: Ultra Peripheral Collisions (UPC)

Submitted to Phys. Rev. D
SOME TESTS OF SCALING HYPOTHESES

(for the first time in the forward region at E~TeV)
Average $p_T$ is inferred with 3 different methods:

- Gaussian distribution fit
- Thermodynamical approach
- Numerical integration of the histogram

- Test of independence of average $p_T$ (as a function of the rapidity loss $\Delta y$) in the very forward rapidity region wrt the c.m. energy $\sqrt{s}$

- **Scaling hypothesis holds at ±10% level**

\[ \Delta y = y_{\text{beam}} - y \]
LIMITING FRAGMENTATION IN FORWARD $\pi^0$ PRODUCTION

- Test of independence of rapidity distribution in the very forward rapidity region wrt the c.m. energy $\sqrt{s}$
- limiting fragmentation hypothesis holds at $\pm15\%$ level

submitted to Phys. Rev. D
Test of independence of cross section of secondary particles as a function of 
\[ x_F = \frac{2p_Z}{\sqrt{s}} \] in the very forward rapidity region wrt the c.m. energy \( \sqrt{s} \).

- Feynman scaling holds at \( \pm 20\% \) level
THE 13 TeV p-p RUN IN 2015
Detector upgrade in 2014: plastic scintillators $\rightarrow$ GSO, new silicon detectors

During Week24, June 9th-13th, **LHCf dedicated low-luminosity run**

Total of 26.6 hours with $L = 0.5 \div 1.6 \cdot 10^{29}$ cm$^{-2}$s$^{-1}$

~ $39 \cdot 10^6$ showers $\rightarrow$ $0.5 \cdot 10^6 \pi^0$ events

Trigger exchange with ATLAS

Detector removal on June 15th during TS1

Run was very successful!
AN IMPRESSIVE HIGH ENERGY $\pi^0$

LHCf Arm2 Detector
$\pi^0$ Candidate Event
LHC p-p, $\sqrt{s} = 13$ TeV Collisions

RUN: 44484
NUMBER: 3010
TIME: 1434152507
FILL: 3855
$E_{25mm}$: 1014 GeV
$E_{32mm}$: 1021 GeV
$M_{\gamma\gamma}$: 147 MeV

25mm Calorimeter
32mm Calorimeter

Silicon X
Silicon Y

SMALL TOWER  LARGE TOWER

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FIRST LOOK AT 13 TeV DATA

Preliminary

LHCf photon pair invariant mass (preliminary)
LHCf Arm2 detector
LHC 13TeV p-p collisions (fill 3855)
Very forward production of $\gamma$, $n$ and $\pi^0$ in $p$ - $p$ and $p$ - $Pb$ collision have been measured by LHCf at different c.m. energies

LHCf data provide a benchmark for hadronic interaction models and can contribute to improve their tuning

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

Detailed $\pi^0$ production studies in many different conditions
  + Reasonable agreement of LHCf $\pi^0$ data with QGSJET II-04 and EPOS-LHC

Very successful 13 TeV $p$ - $p$ run in June 2015 after detector upgrade

Stay tuned for future results at LHC:
  + $p$ - $Pb$ at 13 TeV in 2016-2017?
  + $p$ - light-ions?

510 GeV polarized $p$-$p$ RHIC run in 2017 has been accepted by RHIC PAC at BNL to increase the phase space coverage and for further checking the scaling laws