Results from forward detectors @ LHC and their impact in the study of High Energy Cosmic Rays

L. Bonechi – INFN Firenze
On behalf of the LHCf Collaboration
Outline

INTRODUCTION
  i. Forward physics and VHECR

FORWARD DETECTORS IN LHC EXPERIMENTS

CASE I: IP5 → TOTEM & CMS – some results
  i. Measurement of cross section
  ii. Measurement of particle pseudorapidity distrib.

CASE II: IP8 → LHCb
  i. Measurement of the forward energy flow

FOCUS ON CASE III: IP1 → LHCf & ATLAS
  i. Introduction to the LHCf experiment
  ii. Details of detectors
  iii. Physics program
  iv. Main results

SUMMARY
Observation at ground level of the products of extensive air showers

- Longitudinal distribution
- Lateral distribution
- Arrival direction

Reconstruction of particle params and astrophysical quantities

- Energy spectrum
- Composition
- Source distribution

CR @ E > 100 TeV requires studying EAS development

Example: study of the composition of primary CR with the variable $X_{\text{max}}$

(depth of air shower maximum in the atmosphere)

Before LHC data

After LHC data

Uncertainty of hadron interaction models

Uncertainty in the interpretation of $<X_{\text{max}}>$ data

Courtesy of Pierog Tanguy
KIT, Institut für KernPhysik
Karlsruhe, Germany
Atmospheric Showers

- Cross section for interaction at extreme energies
  - If large $\sigma_{\text{ine}}$: rapid development
  - If small $\sigma_{\text{ine}}$: deep penetrating

- Very forward energy spectrum
  - If softer: shallow development
  - If harder: deep penetrating

- Elasticity $k = \frac{E_{\text{lead}}}{E_{\text{avail}}}$
  - If small $k$ ($\pi^0$s carry more energy): rapid development
  - If large $k$ (baryons carry more energy): deep penetrating

- Secondary interactions ($n, p, \pi$)

- Secondary particle multiplicity
- Forward angular emission

Contributions by HE accelerator experiments

Study of Very High Energy Cosmic Rays

L. Bonechi - INFN Firenze

1) Introduction
2) LHC fwd detectors
3) CASE I: IP5
4) CASE II: IP8
5) CASE III: IP1

NPQCD, 20-22 April 2015
General purpose detectors (ATLAS, CMS,...) cover the spatial region at low rapidity.

Special detectors to access forward particles are necessary!

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!
Fwd detectors: instrumentation at two IPs

**IP1**
- **ATLAS**
  - ATLAS LUCID: $5.5 < |\eta| < 6$
  - LHCf and ATLAS ZDC: $(\pm 140 \text{ m}); |\eta| > 8.4$
  - ATLAS ALFA RPs: $(\pm 240 \text{ m})$
    - $10.6 < \eta < 13.5$
  - ATLAS FCAL: $3 < \eta < 5$

**IP5**
- **CMS**
  - **TOTEM T1 (CSC)**: $3.1 < |\eta| < 4.7$
  - **TOTEM T2 (GEM)**: $5.3 < |\eta| < 6.5$
  - CMS ZDC: $(\pm 140 \text{ m})$
    - $|\eta| > 8.4$
  - CMS HF: $2.9 < |\eta| < 5.2$
  - CMS CASTOR: $5.1 < |\eta| < 6.6$

**W/quartz Cherenkov calo**
• High particle multiplicity in the central region

• High energy flux is in the forward region
  - Central detectors lose the peak of the energy flow

LHCf acceptance cover the region for $|\eta| > 8.4$
TOTEM MAIN TOPICS

- total cross section
- elastic scattering
- diffraction

CMS
General purpose detector

TOTEM tracking components installed during LS1
ELASTIC CROSS SECTION:
- Events triggered by RPs in coincidence on both sides

INELASTIC CROSS SECTION:
- Events triggered by the T2 tracker on either arm

Triggers taken in random bunch crossings used for calibration.

Compilation of the total ($\sigma_{\text{tot}}$), inelastic ($\sigma_{\text{inel}}$) and elastic ($\sigma_{\text{el}}$) cross-section measurements: the TOTEM measurements are highlighted. The continuous black lines (lower for $pp$, upper for $\bar{p}p$) represent the best fits of the total cross-section data by the COMPETE collaboration. The dashed line results from a fit of the elastic scattering data. The dash-dotted lines refer to the inelastic cross section and are obtained as the difference between the continuous and dashed fits.
• Totem trigger – at least a charged particle in $5.3 < |h| < 6.5$ (T2).

• Inclusive sample, 91–96 % of the total inelastic proton–proton cross section.

• Totem trigger – at least a charged particle only in $5.3 < h < 6.5$ or only in $-6.5 < h < -5.3$.

• Single diffractive enhanced sample.
NSD-enhanced pp

**EPJC 74 (2014) 3053**

- **Totem trigger** – at least a charged particle in $5.3 < \eta < 6.5$ and in $-6.5 < \eta < -5.3$.

- Non Single Diffractive enhanced sample.

Value of $dN/d\eta$ at $\eta=0$ as a function of the centre-of-mass energy in $pp$ and $\bar{p}p$ collisions. Shown are measurements performed with different NSD event selections from UA1, UA5, CDF, ALICE, CMS. The dashed line is a power-law fit to the data.
• Data were collected in a low intensity LHC run with collisions occurring **11.25 m far from the nominal interaction point**.
• The data sample is expected to include 96–97 % of the inelastic pp interactions.
• The measurement considers charged particles with $p_T > 0$ MeV/c, produced in inelastic interactions with at least one charged particle in the regions $-7 < \eta < -6$ or $3.7 < \eta < 4.8$. 

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**Introduction**

**LHC fwd detectors**

**CASE I: IP5**

**CASE II: IP8**

**CASE III: IP1**

**TOTEM+CMS: measurement of pseudorapidity distrib.**

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**Inclusive pp, $\sqrt{s} = 8$ TeV**

- TOTEM: $N_{ch} \geq 1$ in $3.7 < \eta < 4.8$ or $-7 < \eta < -6.0$
- CMS-TOTEM: $N_{ch} \geq 1$ in $5.3 < \eta < 6.5$ or $-6.5 < \eta < -5.3$

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Upper figure: total measured energy flow as a function of $|\eta|$ compared with predictions by hadronic interaction models.

The error bars represent the systematic uncertainties. The statistical uncertainties are negligible.

Lower figure: ratios of MC predictions to data.
LHCf MAIN TOPICS

Calibration of hadronic interaction models used in CR physics:
• fwd study of neutral particles
• energy and pt spectra
• pseudorapidity dependencies

ATLAS
General purpose detector
The LHCf detectors measure energy and impact point of $\gamma$ and $n$.

Two independent detectors on both sides of IP1:
- Redundancy
- Coincidence
- Background rejection (esp. beam-gas)
Details and performance of the LHCf detectors

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Sampling and imaging E.M. calorimeters

- **Absorber**: W layers (44 r.l., 1.55λ_i in total)
- **Energy measurement**: plastic scintillator tiles
- **4 tracking layers** for imaging:
  - XY-SciFi(Arm1) and XY-Silicon μ-strip(Arm2)
- Each detector has two independent calorimeter towers
  → reconstruction of π⁰ → γγ events

**Performance**

- **Energy resolution** (> 100 GeV)
  - < 5% for γ and ~ (35 ÷ 40)% for n
- **Position resolution**
  - < 200μm (Arm1) and ~ 40μm (Arm2)

**Front Counter scintillators**

- thin scintillators 80x80 mm fixed upstream the main detectors
- monitoring of beam condition
- background rejection
- Van der Meer scan
The LHCf detectors for phase I

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SciFi-layer

W-layer

Arm#1 installation

Arm2 Detector

Tracker read-out

Silicon μ-strip layer

Arm1 Detector

Arm#2 installation
Overview of the LHCf experiment

Example:

**pp @ 13 TeV**

- **LHC frame**
  Detecting a 1 TeV neutron hitting one LHCf calorimeter tower at **3 cm from beam line**. Angle wrt the interaction line = $2 \cdot 10^{-4}$ rad.

- **LAB frame** (CR interaction in the atmosphere)
  Going from LHC to the LAB frame it corresponds to a **$1.3 \cdot 10^{16}$ ev neutron**. Angle wrt to the interaction line = $1.5 \cdot 10^{-8}$ rad. After 100 m in atmosphere it would be $1.5 \mu$m from the interaction line.

We are studying very high energy secondary particles emitted in a really narrow angular region of the central core of an atmospheric shower. LHC works as a powerful angular amplifier or microscope.
<table>
<thead>
<tr>
<th>Year</th>
<th>Proton Energy</th>
<th>Equivalent Proton Energy in LAB (eV)</th>
<th>γ</th>
<th>n</th>
<th>π^0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>p-p 2.76 TeV</td>
<td>4.1x10^{15}</td>
<td>PLB 703 128 (2011)</td>
<td>PRD 86 092001 (2012)</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb 5.02 TeV</td>
<td>1.3x10^{16}</td>
<td></td>
<td>Phys. Rev. C 89, 065209 (2014)</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>p-p 13 TeV</td>
<td>9.0x10^{16}</td>
<td>Upgraded detectors / waiting for low mu run in June</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016 (?)</td>
<td>p-p 500 GeV</td>
<td>1.3x10^{14}</td>
<td>Run @ RHIC under discussion (RHICf)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results


• O. Adriani, et al., “Transverse-momentum distribution and nuclear modification factor for neutral pions in the forward-rapidity region in proton-lead collisions at √ s_{NN} = 5.02 TeV”, PRC 89 (2014) 6, 065209

SOME RECENT RESULTS

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**Results**

**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**
  - $1\text{st}$ Layer
  - $2\text{nd}$ Layer
  - $3\text{rd}$ Layer
  - $4\text{th}$ Layer

- **Y-view**
  - $1\text{st}$ Layer
  - $2\text{nd}$ Layer
  - $3\text{rd}$ Layer
  - $4\text{th}$ Layer

**Reconstruction of $\pi^0$ mass:**

$$M_0 = \sqrt{E_1 E_2} \times$$

**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**
Comparison of single $\gamma$ data for pp @ 900 GeV with hadronic interaction models (pre-LHC versions)

No strong evidence of $\eta$-dependence

DPMJET and SYBILL show reasonable agreement of shape

None of the models reproduces the data within the error bars
Comparison of single $\gamma$ data for $pp @ 7$ TeV with hadronic interaction models (pre-LHC versions)

- No model can reproduce the LHCf data perfectly.
- DPMJET and PYTHIA are in good agreement at high-$\eta$ for $E_\gamma<1.5$TeV, but harder in $E>1.5$TeV.
- QGSJET and SIBYLL shows reasonable agreement of shapes in high-$\eta$ but not in low-$\eta$
- EPOS has less $\eta$ dependency against the LHCf data.
Identification of events with two particles hitting the two towers

- **EPOS1.99** show the best agreement with data in the models.
- **DPMJET** and **PYTHIA** have harder spectra than data ("popcorn model")
- **QGSJET** has softer spectrum than data (only one quark exchange is allowed)
More recent analysis: neutron energy spectra before and after unfolding (pp @ 7 TeV)

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

$\rightarrow$ Small inelasticity in the very forward region!

Preprint submitted to PLB

L. Bonechi - INFN Firenze

NPQCD, 20-22 April 2015
**Motivation:** study of nuclear effects for CR interactions

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**

- $L = 1 \times 10^{29} - 0.5 \times 10^{29} \text{cm}^{-2}\text{s}^{-1}$
- $\sim 200 \times 10^6$ 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
E.M. contribution to fwd particle production (p-Pb)

(Soft) QCD:
central and peripheral collisions

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

Central collisions                                      Peripheral collisions

proton  
\(b \ll R_p + R_{Pb}\)                                  \(b \sim R_p + R_{Pb}\)

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 \(\pi^0\)s originate from UPC
About half is from soft-QCD
Need to subtract UPC component
• LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
• LHCf spectra in p-Pb are clearly less steep 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.
Both LHCf and MCs show strong suppression.

NMF grows with increasing $p_T$, as can be expected by the $p_T$ spectrum that is steeper in p-p 5 TeV than in p-Pb 5 TeV collisions.

\[
R_{ppb}(p_T) \equiv \frac{\sigma_{\text{inel}}^{pp} E d^3 \sigma_{\text{inel}}^{PbPb} / d^3}{\langle N_{\text{coll}} \rangle \sigma_{\text{inel}}^{pp} E d^3 \sigma_{\text{pp}} / d^3}
\]

\[
\langle N_{\text{coll}} \rangle = 6.9
\]
• During the 2013 p-Pb run LHCf trigger was used for triggering the ATLAS detector. Combined data taking is foreseen also for the next run (pp @ 13 TeV).

• Activity in the central detector can be used to separate diffractive and non diffractive events. It will be used also to remove the UPC events (which give no activity in ATLAS) for the analysis of p-Pb data.

• Important for improving the quality of the hadronic interaction models, where diffractive and non diffractive events have completely separate treatments.

![Graphs showing energy distribution for γ and γ with η > 10.94](image)

- ATLAS0 = no charge particle particle with |η|<2.5 and p_t>0.1 GeV/c
- ATLAS2 = at least 2 charged particles particle with |η|<2.5 and p_t>0.1 GeV/c

Courtesy of Tanguy Pierog
• Improving hadronic interaction models: still necessary after years of LHC

• Many aspects of the study of EAS still require more reliable models for a clear interpretation of experimental data

• All LHC experiments produce information on different aspects which are relevant for EAS simulations

• In particular LHCf is a dedicated experiment which measures neutral secondary particles for $|\eta|>8.4$ (many results already published)

• In June 2015 a special low luminosity and low pile-up special run is scheduled for LHCf

• Combined data taking with ATLAS already performed in p-Pb 2013 will be done also in p-p 2015
  - Important to separate diffractive from non-diffractive events

I would like to thank Simone Giani, Beatrice Bressan and Mirko Berretti for providing material for the TOTEM experiment.