Overview of the forward measurement by the LHCf detector at LHC

Lorenzo Bonechi (INFN Firenze) on behalf of the LHCf Collaboration
Outline...

• Introduction
  – Cosmic rays and forward physics
  – The LHCf experiment
    – Purpose, Method, Collaboration and Apparatus

• Data analysis
  – Overview of the achieved results
  – Status of the on-going analysis and preliminary results

• Future activities
  – 2016 p+Pb collisions @ LHC
  – 2017 RHICf run @ RHIC
  – 20?? p+Light Ion @ LHC
Introduction
Spectrum of cosmic rays

- **RHIC**:
  - End of galactic CR and transition to extra-gal CR

- **LHC**:
  - Knee: end of galactic proton CR

- **FCC**:
  - Ankle
  - (GZK) cutoff: end of CR spectrum

**Indirect observation through air shower**

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Energy (eV/particle)

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

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Cosmic ray shower

- 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

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

- Forward angular emission
- Secondary particle multiplicity

- Secondary interactions ($n, p, \pi$)
Study of the composition of CR

Estimation of chemical composition:
- From Knee to Ankle: $N_\mu$
- From Ankle to the highest energies: $<X_{\text{max}}>$

Interpretation is based on predictions by MC using a particular hadronic interaction model.


PAO, PRD, 90, 122005 (2014)
**LHCf and Cosmic Ray Physics**

- Possibility to study particles in the **forward direction** at LHC (neutrals: $\gamma, \pi^0, n$)
  - Forward secondary particles carry a **great fraction** of the primary energy

- 6.5 TeV + 6.5 TeV in the LHC frame $\rightarrow \sim 10^{17}$ eV in the laboratory frame (LAB)

- Calibration of **hadronic interaction models** used for the simulation of atmospheric showers

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**COSMIC RAYS**

- Energy up to $10^{19} \div 10^{20}$ eV
- Nitrogen atom
- Observer standing outside and looking to cosmic rays...

**LHC**

- $E = 6.5 \times 10^{12}$ eV
- Observer sitting comfortably in LHC
- $E = \sim 10^{17}$ eV !!
- Observer riding a proton (LAB frame)!!

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**LHC phase space coverage**

We profit of the very broad coverage!
LHCf is a dedicated forward detector for a better measurement of the energy flow.
Position resolution: < 200 μm (Arm1) and 40 μm (Arm2)

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

Pseudo-rapidity range:
η > 8.7 @ zero X-ing angle
η > 8.4 @ 290 μrad (total)

**Arm1 Detector**
2cm x 2cm + 4cm x 4cm
GSO tiles (e.m. calo)
4 X-Y tracking layers (GSO bars)

**Arm2 Detector**
2.5cm x 2.5cm + 3.2cm x 3.2cm
GSO tiles (e.m. calor)
4 X-Y tracking layers (silicon microstrip)
Details of detectors

**ARM1**
- 2 towers 24 cm long stacked vertically with 5 mm gap
- Lower: 2 cm x 2 cm area
- Upper: 4 cm x 4 cm area

**ARM2**
- 2 towers 24 cm long stacked on their edges and offset from one another
- Lower: 2.5 cm x 2.5 cm
- Upper: 3.2 cm x 3.2 cm

4 pairs of scintillating fiber/GSO bars layers for tracking purpose

4 pairs of silicon micro-strip layers for tracking purpose (X and Y directions)

Absorber
- 22 tungsten layers 7mm – 14 mm thick (2-4 r.l.)
- (W: $X_0 = 3.5$mm, $R_M = 9$mm)
The LHCf collaboration today  (32 members)

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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

Dec- Jul 2010
0.9TeV & 7TeV pp (detector removal)

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

May-June 2015
13 TeV dedicated pp (detector removal)

Sept. 2016
Preparation to p+Pb @ 8 TeV
Overview of the LHCf results
Relevant type of events in LHCf

Responsible for air shower core (elasticity)

Leading baryon (neutron)

Multi meson production

LHCf calorimeters

Single hadron event

Responsible for EM air shower component (inelasticity)

Single photon event

$\pi^0$ photon

Pi-zero event (photon pair)
### Achieved results & others

<table>
<thead>
<tr>
<th>RUN</th>
<th>Proton $E_{LAB}$ (eV)</th>
<th>$\gamma$</th>
<th>$n$</th>
<th>$\pi^0$ limited acceptance</th>
<th>$\pi^0$ full acceptance</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p 7 TeV</td>
<td>$2.6 \times 10^{16}$</td>
<td>PLB 703, 128 (2011)</td>
<td>PLB 750 (2015) 360-366</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p+p 2.76 TeV</td>
<td>$4.1 \times 10^{15}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p+Pb 5 TeV</td>
<td>$1.4 \times 10^{16}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p+p 13 TeV</td>
<td>$9.0 \times 10^{16}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Data taken in June 2015 - Preliminary analysis</td>
</tr>
<tr>
<td>p+Pb 8.1 TeV</td>
<td>$3.6 \times 10^{16}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Scheduled in November 2016</td>
</tr>
</tbody>
</table>
Old LHCf results: single $\gamma$ energy - $p+p @ 900$ GeV

No strong evidence of $\eta$-dependence

EPOS and SIBYLL show reasonable agreement of shape

None of the models reproduces the data within the error bars

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

Syst. + Stat.
Old LHCf results: single $\gamma$ energy - p+p @ 7 TeV

- 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.
Old LHCf results: $\pi^0 p_t - p+p @ 7\,\text{TeV}$

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)

Reconstruction of the invariant mass of two-photon events

7 TeV pp $\pi^0$
Old LHCf results: $\pi^0 p_t - p+pB$ 2013 @ 5 TeV

- 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.
Most recent results
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 muon due to larger baryon production

Importance of baryon measurement!
Inclusive hadron spectra (LHCf @ 7 TeV pp)

Very large high energy peak in the $\eta > 10.76$ (predicted only by QGSJET) → Small inelasticity in the very forward region!

**Data ($\eta > 10.76$)**

<table>
<thead>
<tr>
<th>Model</th>
<th>n/γ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPMJET3.04</td>
<td>1.05</td>
</tr>
<tr>
<td>EPOS 1.99</td>
<td>1.80</td>
</tr>
<tr>
<td>PYTHIA 8.145</td>
<td>1.27</td>
</tr>
<tr>
<td>QGSJET II-03</td>
<td>2.34</td>
</tr>
<tr>
<td>SYBILL 2.1</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**Data (8.99 < $\eta$ < 9.22)**

<table>
<thead>
<tr>
<th>Model</th>
<th>n/γ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPMJET3.04</td>
<td>0.76</td>
</tr>
<tr>
<td>EPOS 1.99</td>
<td>0.69</td>
</tr>
<tr>
<td>PYTHIA 8.145</td>
<td>0.82</td>
</tr>
<tr>
<td>QGSJET II-03</td>
<td>0.65</td>
</tr>
<tr>
<td>SYBILL 2.1</td>
<td>0.57</td>
</tr>
</tbody>
</table>
LHCf Type-I and Type-II $\pi^0$ analysis

Type-I

Type-II

(c) Arm2 Type-I
$\pi^0$

(d) Arm2 Type-II
$\pi^0$

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\( \pi^0 p_T \) spectra in 7 TeV pp collisions

- **QGSJETII-04**: best agreement
- **EPOS-LHC**: harder than data for large \( p_T \)
- **SYBILL**: good agreement only for small \( y \)
$\pi^0 p_z$ spectra in 7 TeV pp collisions

DPMJET and Pythia overestimate over all E-$p_T$ range
\( \pi^0 p_z \) spectra in 7 TeV pp collisions \( \rightarrow \) QGSJET

- Very good agreement in shape, slightly underestimate at high \( p_T \)
- Totally slightly underestimate
Neutral pions in p+Pb @ 5 TeV (2013 run)
Scaling for neutral pions

- Scaling laws are a fundamental tool to safely extrapolate predictions to the UHECR regime
- Tested $<p_T>$, limiting fragmentation and feynman scaling @ 2.76TeV — 5.02 TeV – 7TeV
- Good scaling within uncertainties
- Wider coverage expected in y and $p_T$ with 13TeV data
- Wider vs coverage with RHICf experiment in 2017 at $\sqrt{s}=510$GeV
- RHICf results useful also to understand discrepancies with UA7 results

Reasonable scaling can be inferred from the data ~ 10-20%
Estimation of contributions from UPC:

- STARLIGHT to simulate the virtual photon flux
- SOPHIA for the low energy photon-proton interactions
- PHYTIA and DPMJET for the low energy photon-proton interactions
Last LHCf run: p+p @ 13 TeV (2015)

1) Single Photon analysis

2) Hadron analysis

- During Week 24, June 9-13 2015, LHCf dedicated low-lumi run
- Total 26.6 hrs with L=0.5~1.6.10^{29} cm^{-2}s^{-1} (16 nb^{-1})
- ~39 M showers, 0.5 M \pi^{0} obtained
- Trigger exchange with ATLAS
- Detector removal on June 15^{th} during TS1
- Run was very successful!!!!
Single photon analysis for pp 13 TeV

• Data set:
  - 12 June 22:32-1:30 (3 hours)
  - Fill # 3855, $\mu \sim 0.01$
  - $\int L dt = 0.191 \text{ nb}^{-1}$ for both detectors

• On-going analysis
  - Event Selection
    • Photon/hadron selection
    • Multi-Hit event rejection
  - Corrections
    • PID correction
    • Multi-Hit correction
    • Unfolding
  - Combination of Arm1 and Arm2 spectra considering all the systematics

Acceptance selection

$\eta > 10.94$

Beam center was estimated from the hit-map of high energy hadron events

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Very high energy pions!
Photon pairs - invariant mass

- Mandatory tool for energy scale calibration
- Importance of $\eta$ due to also charged decay mode
- We proposed to use also to calibrate models for muon-neutrino flux
- Big interest from model developers
Preliminary photon energy spectra in pp 13 TeV

LHCf $\sqrt{s}=13$ TeV photon
$\eta > 10.94$, $\Delta\phi = 180^\circ$
$\int Ldt=0.191+0.191\text{nb}^{-1}$

Preliminary

LHCf $\sqrt{s}=13$ TeV photon
$8.1<\eta<8.99$, $\Delta\phi = 20^\circ$
$\int Ldt=0.191+0.191\text{nb}^{-1}$

Preliminary

$1/N_{ne} \, dN/dE [\text{GeV}^{-1}]$

Data
QGSJET II-04
EPOS-LHC
DPMJET 3.06
SIBYLL 2.1
PYTHIA 8.212

MC/Data

Energy [GeV]

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ATLAS-LHCf combined data analysis

- Trigger sharing with ATLAS at ~100 Hz in 2015 p+p (10 Hz in 2013 p+Pb)
- Off-line event matching
- **Status** (p+p 2015)
  - Event matching successfully verified
- 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 for developers improving the hadronic interaction models

... + ALFA !!!
A commonly triggered event
The far future @ LHC

• The most promising future at LHC for LHCf 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
Conclusions

- LHCf has measured precisely very forward $\gamma$, n and $\pi^0$ production in p-p and p-Pb collision at $E_{CM} \leq 7$ TeV
  - Improving the knowledge of hadronic interaction models for HECR Physics
  - Results with hadrons interesting for the muon excess “problem” in EAS
  - Verification of scaling hypothesis important for extrapolating at higher energy
  - p+Pb results important to understand nuclear medium effects

- Very successful 13 TeV pp run in June 2015
  - Preliminary photon spectra ready, other analyses are on going

- Intensive 2016-2017 program:
  - 8.1 TeV (and 5 TeV) p+Pb collisions at LHC in November 2016
  - 510 GeV p+p with polarized beam at RHIC in May-July 2017

- More results will come in the next years... while waiting for p+Light Ion run at LHC
Backup slides
Tuning of hadronic interaction model with LHCf data

R. Engel
CRIS2016

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**Absolute energy scale uncertainty (pp 13 TeV)**

The uncertainty of energy scale is the largest contribution to the systematic uncertainty of the final spectra. The energy scale of detector is checked by using $M_{\gamma\gamma}$ peak of $\pi^0$.

**Table: shift of $\pi^0$ mass peak**

<table>
<thead>
<tr>
<th></th>
<th>New detector</th>
<th>Old detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm1</td>
<td>-3.4%</td>
<td>+7.8%</td>
</tr>
<tr>
<td>Arm2</td>
<td>-2.1%</td>
<td>+3.7%</td>
</tr>
</tbody>
</table>

Thank to the careful energy-calibration of detector by the CERN-SPS beam test, the shift of $\pi^0$-mass-peak is reasonable compared to the uncertainty of calibration, 3.5%. The systematic error is expected to be smaller than at the previous result at $\sqrt{s}=7$ TeV.
Corrections: particle ID and multiple hits

The correction factor was driven from the template fitting method of L90% distribution

![L90% distribution graph](image)

### PID correction

**Photon**

**Neutron**

Correlation Factor

- Photon
- Neutron

Effect of the multi-hit event cut is estimated based on MC with QGSJET2 model

A Multi-hit event identified by the Arm1 GSO bar hodoscope.

Multi-hit correction

Difference due to the different geometrical shape of calorimeters

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Comparison Arm1/Arm2

The evaluation of the systematic uncertainties is in progress.

We would like to acknowledge the ATLAS collaboration for providing the measurement of the luminosity and of the cross section.
Preliminary comparison with models

**LHCf Preliminary**

- **p-p, \( \sqrt{s} = 13 \text{ TeV} \)**
- Photon
- \( \eta > 10.94, \Delta\phi = 180^\circ \)

**LHCf Preliminary**

- **p-p, \( \sqrt{s} = 13 \text{ TeV} \)**
- Photon
- \( 8.81 < \eta < 8.99, \Delta\phi = 20^\circ \)

Error bars show only the statistical errors.
Impact of common ATLAS-LHCf trigger

PYTHIA MC study @ 14 TeV. Diffractive event selection efficiency and purity: dropping events with \((p_T > 100 \text{ MeV/c} \& \text{ Nch}>1 \text{ in } |\eta|<2.5)\) @ATLAS

All events in MC true, Non-diffractive Diffractive

\(\sim 13\%\)

w/ event selection (not ND)

key: low mass diffraction (Ostapchenko)

For diff. events, 35-40% efficiency
99% purity
Ony ARM2 Detector

Motivations:

- **Statistics:**
  - Measure $\pi^0$ with increased statistics wrt 2013 run
  - Possibility to detect the $\eta$ meson
  - Combined ATLAS-LHCf data taken (very limited in 2013)

- **Phase space**
  - extend up to $p_T > 1$ GeV/c
  - deviations from models suggested from 2013 data at high $p_T$
  - investigate pQCD phase-space region

- **Scaling properties**
  - Factor $\sim 3$ in energy (LAB ref.)
  - Extrapolation at extreme CR energies
  - Feynman scaling: spectra in $x_F$
p-Pb at 8.1 TeV: γ & n spectra

Expected **photon** distribution

Expected **neutron** distribution (35% energy resolution)

(CRMC)* framework has been used to simulate $10^7$ collisions with 4 different hadronic interaction models:

- DPMJET 3.0-6 p+Pb
- EPOS-LHC p+Pb
- QGSJET II-04
- HIJING 1.383

Small calorimeter tower centered on the beam spot
Only p-remnant side considered

* We acknowledge T. Pierog, C. Baus and R. Ulrich for support
**p-Pb at 8.1 TeV: run conditions**

**Beam conditions**
- $L=10^{28}-10^{29}\text{cm}^{-2}\text{s}^{-1}$
- filling scheme will be chosen after PS and SPS beam commissioning
- proton bunch spacing 100 ns (we can afford!)
- Pb bunch spacing 100 ns but not all bunches will collide
- $\beta^* \sim 0.6\text{ m}$ same as in high luminosity 8 TeV run
- crossing angle in IP1 (IP5) changed from 370 $\mu\text{rad}$ to $\sim 280\ \mu\text{rad (up2down)}$

**Data Taking request based on simulation estimates**
- Minimum integrated luminosity to detect $4\times10^4\ \pi^0$ ATLAS-LHCf common events for physics and energy calibration
- Data acquisition time depends on the bandwidth allowed by ATLAS for common data taking
  - 100 Hz common rate $\rightarrow \sim 1\text{ day}$
  - 400 Hz common rate $\rightarrow \sim 12\text{ h taking data in two different acceptance region}$
**p-Pb run schedule**

- **31/10 – 04/11:** technical stop  
  → installation of Arm2 detector

- **10/11 – 15/11:** 5 TeV operations  
  → possible run for LHCf

- **20/11 – 26/11:** 8 TeV operations  
  → LHCf dedicated run between 25/11 and 26/11

Common acquisition with ATLAS during all operation:
- 100% of LHCf triggers acquired by ATLAS
- rate of 400 Hz (maximum rate for LHCf: 500-600 Hz)
**p-Pb at 8.1 TeV: preparation**

- ARM2 electronics reconditioned
- Setup in USA15 ready
  - all the cabling done
  - tuning of DAQ logic with 100 ns bunch spacing done
  - test of common operation with ATLAS successful
- Detector ready to be installed
  - cabling completed
  - test of silicon readout done
  - PMT signals checked

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