Astroparticle Physics with the LHCf Detector at LHC

Alessia Tricomi
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Physics Motivations
- The link between HECR Physics and LHC
- "Il vino buono sta nella botte piccola" or "good things comes in small packages"

Physics Results
- what we have done so far

Future Plans
- what's next...
What do cosmic rays consist of? What particles do they have?

Primary cosmic rays, the cosmic rays coming from outer space, are mostly protons. They collide with the Earth’s atmosphere and decay into secondary cosmic rays.

Cosmic rays on the Earth’s surface are tiny particles produced by energetic protons.

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Ultra High Energy Cosmic Rays

Studying the properties of primary High Energy Cosmic Rays based on observation of EAS

MC Simulation to describe hadronic interaction with atmosphere

Model-originated uncertainties or even discrepancies

- Energy
  - $E_{SD} > E_{FD}$: discrepancy
  - missing energy ($\mu, \nu$) in FD: uncertainty

- Mass
  - Mass vs. $X_{max}$ in FD: uncertainty
  - Mass vs. $e/\mu$ or $\mu$ excess in SD: discrepancy
HECR Physics at LHC: LHCf Physics

- **Inelastic cross section**
  - If large \( \sigma \), rapid development
  - If small \( \sigma \), deep penetrating

- **Forward energy spectrum**
  - If softer, shallow development
  - If harder, deep penetrating

- **Inelasticity \( k \)**
  - If large \( k \), rapid development
  - If small \( k \), deep penetrating

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**Example of a longitudinal air shower development** as measured with

\[
\begin{align*}
\text{Inelastic p-p cross section} & \quad \text{such as the shower peak position } X_{\text{max}} \\
\text{Forward energy spectrum} & \quad \text{2ndary interactions}
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HECR Physics at LHC: LHCf Physics

- **p-p + p-Pb**
  1. Inelastic cross section
  2. Forward energy spectrum
  3. Inelasticity k
  4. Nuclear effects

- Extrapolation to high energy precise measurements in lower energies are crucial

- model error

- **LHCf → use LHC**
  - 7 TeV+7 TeV → $E_{lab}=10^{17}$ eV
  - 3.5 TeV+3.5 TeV → $E_{lab}=2.6\times10^{16}$ eV
  - 450 GeV+450 GeV → $E_{lab}=2\times10^{14}$ eV
  - to calibrate MCs

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HECR Physics at LHC: LHCf Physics

- **p-p + p-Pb**
  1. Inelastic cross section
  - If large $\sigma$
    - rapid development
  - If small $\sigma$
    - deep penetrating

- **p-Pb**
  4. Nuclear effects

- **Extrapolation to high energy precise measurements in lower energies are crucial**

- **Inelasticity $k$**
  - If large $k$
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  - If small $k$
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**LHCf $\rightarrow$ use LHC**

- **7 TeV + 7 TeV**
  $\Rightarrow E_{lab} = 10^{17}$ eV

- **3.5 TeV + 3.5 TeV**
  $\Rightarrow E_{lab} = 2.6 \times 10^{16}$ eV

- **450 GeV + 450 GeV**
  $\Rightarrow E_{lab} = 2 \times 10^{14}$ eV

**to calibrate MCs**

- **In addition: p-Pb collision at 5.02 TeV to study nuclear effect**
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The LHCf detectors
- “Il vino buono sta nella botte piccola” or “good things comes in small packages”

Physics Results
- what we have done so far

Future Plans
- what’s next...
Two independent electromagnetic calorimeters equipped with position sensitive layers, on both sides of IP1

7 TeV + 7 TeV proton collisions at LHC correspond to $E_{\text{LAB}} = 10^{17}$ eV

Measure energy and position for $|\eta|>8$ of $\gamma$ from $\pi^0$ decays and neutrons produced in pp interaction at LHC

International Collaboration mainly Japan-Italy (about 30 members)
Experimental Set-up

**INTERACTION POINT**

**Detector I**
- Tungsten
- Scintillator
- Scintillating fibers

**Detector II**
- Tungsten
- Scintillator
- Silicon μstrips

**Front Counter**
- 140 m

**Impact point (η)**

**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

**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

**Absorber**
- 22 tungsten layers
  - 7mm - 14 mm thick (2-4 r.l.)
  - (W: X₀ = 3.5mm, Rₘ = 9mm)

**4 pairs of silicon micro-strip layers**
- (6, 12, 30, 42 r.l.) for tracking purpose (X and Y directions)

**4 pairs of scintillating fiber layers for tracking purpose**
- (6, 10, 32, 38 r.l.)

**16 scintillator layers**
- (3 mm thick)

**Trigger and energy profile measurements**
Detector Performance

Hadronic shower (MC)

Position resolution

Black: X-plane
Red: Y-plane

Energy resolution

σE/E ~ 40% because of 1.6λ and small transverse size

EM shower (MC)

Position resolution

PID technique
400 GeV photon
1 TeV neutron
Identification of incoming particle by shower shape

π⁰ reconstruction

LHCf Performance at LHC

E vs. sum of particles (Arm1)

A brief LHCf photo-history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved
- Jul 2006 construction
- Jan 2008 Installation
- Aug 2007 SPS beam test
- Dec 2009 1st 900GeV run
- Mar 2010 1st 7TeV run
- Jul 2010 Detector removal
- Gen-Feb 2013 p-Pb run
- Apr 2013 Detector removal and upgrade
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LHCf Data Taking and Analysis overview

<table>
<thead>
<tr>
<th></th>
<th>Photon (EM shower)</th>
<th>Neutron (hadron)</th>
<th>Π (EM shower)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p at 7TeV</td>
<td>Phys. Lett. B 703, 128-134</td>
<td>New Results</td>
<td></td>
</tr>
<tr>
<td>p-p at 2.76TeV</td>
<td></td>
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</tr>
<tr>
<td>p-Pb at 5.02TeV</td>
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</tbody>
</table>

Run1:
- p-p at 900GeV
- p-p at 7TeV
- p-p at 2.76TeV

Run2:
- p-Pb at 5.02TeV

New Results
- arXiv:1403.7845
LHCf @ pp 7TeV:
Single photon spectra MC vs Data

Around 0 degree (On axis)

Off axis

Adriani et al., PLB, 703 (2011) 128-134

DPMJET 3.04  QGSJET II-03  SIBYLL 2.1  EPOS 1.99  PYTHIA 8.145
LHCF @ pp 7 TeV vs 900 GeV

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

Normalized by the number of entries in $X_F > 0.1$

Comparison in the same $p_T$ range ($p_T < 0.13 x_F \text{ GeV/c}$)

No systematic error is considered in both collision energies.

Good agreement of $X_F$ spectrum shape between 900 GeV and 7 TeV.

More checking for the Feynman scaling with 2.76 TeV, 13 TeV and RHIC planned.
LHCf @ pp 7 TeV & p-Pb 5 TeV: \( \pi^0 \) analysis

Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter.

\[
M_{\pi^0} = \sqrt{E_{\gamma_1} E_{\gamma_2} \theta^2}, \\
E_{\pi^0} = E_{\gamma_1} + E_{\gamma_2}, \\
P_{T\pi^0} = P_{T\gamma_1} + P_{T\gamma_2}
\]

Analysis Procedure

Standard photon reconstruction

Event selection
- one photon in each calorimeter
- reconstructed invariant mass

Background subtraction
by using outer region of mass peak

Unfolding for detector response.

Acceptance correction.

Dedicated part for \( \pi^0 \) analysis
dpmjet 3.04 & pythia 8.145
overall agreement with LHCf
data for 9.2 < y < 9.6 and pt < 0.25 GeV/c
the expected π⁰ production
rates by both models exceed
the LHCf data as pt becomes
large

qgjet II-02
predicts harder pion spectra
than data
the expected π⁰ yield is
generally small

qgsjet II-03
predicts π⁰ spectra softer
than LHCf data

epos 1.99
shows the best overall
agreement with the LHCf
data:
behaves softer in the low ptegion, pt < 0.4 GeV/c in
9.0 < y < 9.4 and pt < 0.3 GeV/c
in 9.4 < y < 9.6
behaves harder in the large
pt region.

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LHCf @ pPb 5.02 TeV: π⁰ analysis

(Soft) QCD:
central and peripheral collisions

Central collisions ↓ Peripheral collisions ↑
proton Pb Pb

0 → 0

impact parameter: \( b \)

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

Dominant channel to forward \( \pi^0 \) is

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

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

Comparison with soft-QCD

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

Need to subtract UPC component

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Astroparticle Physics with the LHCf Detector at LHC
LHCf @ pPb 5.02 TeV: π° spectra @ p-remnant side

LHCf data vs. UPC calculation

(0.5x) UPC calculation
LHCf Data (UPC subtracted) vs Models

- 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 5.02 TeV (shaded area) which are interpolated from the results at 2.76 TeV and 7 TeV.
Both LHCf and MCs show strong suppression

But LHCf grows as increasing $p_T$, understood by the softer $p_T$ spectra in $p-p$ at 5 TeV than those in p-Pb.

$$R_{pPb}(p_T) \equiv \frac{d^2N^{pPb}_{\pi^0}/dydp_T}{\langle N_{coll} \rangle d^2N^{pp}_{\pi^0}/dydp_T}$$

$$\langle N_{coll} \rangle = 6.9$$
Nuclear modification factor

$\sqrt{s_{NN}}=200$ GeV

- $\pi^0$ ($<\eta>=4.00$)
- $h^-$ ($\eta=3.2$)
- $h^-$ ($\eta=2.2$)

$\eta=2.2$

$\eta=3.2$

$\eta=4.0$

Normalization Uncertainty = 17%

RHIC 200GeV d-Au, STAR Collaboration
LHCf @ pPb 5.02 TeV vs RHIC: Nuclear modification factor
LHCf @ pp 7 TeV: neutron analysis

**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**

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Astroparticle Physics with the LHCf Detector at LHC
Neutron energy reconstruction

- Neutron energy is reconstructed by a sum of energy deposits.
- Detector simulation based on QGSJET2 for hadronic shower reproduces the test beam data better than that on DPMJET3.
- Difference between QGSJET2 and the test beam data is taken into account as a systematic error in the latter analysis.

Particle identification

- With two variables, L90% and L20%, PID performance is improved to reduce the photon contamination in neutron events.
- PID efficiency and purity are >90%.
- Energy spectra are corrected for PID inefficiency and BG contamination.
LHCf @ pp 7 TeV: neutron spectra

- LHCf Arm1 and Arm2 agree with each other within systematic error, in which the energy scale uncertainty dominates.
- In \( \eta > 10.76 \) huge amount of neutron exists. Only QGSJET2 reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.

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Astroparticle Physics with the LHCf Detector at LHC
The impact of LHC measurements

- Difference of $<X_{\text{max}}>$ in p-air among pre LHC models is about 50 g/cm$^2$ at $10^{20}$ eV wrt. difference between p-air and Fe-air is about 100 g/cm$^2$.

- Still several measurements to be included but yet difference between p and Fe is reduced to 20 g/cm$^2$.
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LHCf Future Plans

2013-2014: Detector upgrade for 13 TeV run
- Replaced plastic scintillators with Rad Hard GSO
- Modify the silicon layers positions to improve silicon-only energy resolution and improve the dynamic range of silicon
- Test beam at SPS to calibrate ARM1/2
- Re-installation of the detector

2015: run at 13 TeV p-p collision at LHC

2016 ... Operation at RHIC, p-p at $\sqrt{s}=500\text{GeV}$, p-Ne at $\sqrt{s_{NN}}=200\text{GeV}$ (proposal presented at BNL PAC)

2019?? Run at LHC in p-light A
LHCf run-3 @ LHC pp 13 TeV collisions

Other considerations: first rough vdM Scan + LHCf

- Combined run for vdM and LHCf at 19 m $\beta^*$ early 2015

LHCf:
- 40 low intensity bunches $\sim 1 \times 10^{10}$, low luminosity ($6 \times 10^{28}$ cm$^{-2}$s$^{-1}$)
- Integrate 5 – 20 nb$^{-1}$
- Pilot run a week before the main run
- Runs at different energies: 13 TeV, 7 TeV and 3.5 TeV

vdM Scan:
- $\sim 2$ fills at 19 m $\beta^*$

- Will commission 19 m $\beta^*$ unsqueeze during initial beam commissioning
From LHCf to RHICf

Why RHIC?

LHC

RHIC

Letter of intent: Precise measurements of very forward particle production at RHIC

Y. Itoh, H. Menjo, G. Mitsuka, T. Sako
Solar-Terrestrial Environment Laboratory / Kobayashi-Maskawa Institute for the Origin of Particles and the Universe / Graduate School of Science, Nagoya University, Japan

K. Iwashita, T. Suzuki, S. Torii
Waseda University, Japan

O. Adriani, A. Trisciu
INFN, Italy

Y. Goto
Riken BNL, Japan

K. Tanida
Seoul National University

Energy resolution

$E_m = 25\%$

Neutron spectrum (Small Tower)

Energy spectrum (Small Tower)
Summary

- LHCf has succeeded to take data in p-p collisions at 900 GeV, 2.6 TeV and 7 TeV and in p-Pb collisions at 5.02 TeV.
- LHCf zero degree results are significantly contributing to improve our knowledge of hadronic interaction model for HECR Physics.
- New results with hadrons are particularly interesting to understand the muon excess.
- p-Pb results give important hints to understand nuclear medium effect.
- The detector upgrade is ongoing to improve performance for the 13 TeV run in early 2015.
- We are also planning to take data at RHIC in 2016 and later on come back for light ion run at LHC.
- Still a lot of results will come in the next years so... stay tuned!
LHCf @ pp 900 GeV: Single photon spectra MC vs Data
LHCf @ pp 7 TeV and 2.76 TeV: \( \pi^0 <p_T> \)
Ultra peripheral collisions:
virtual photons from rel. Pb collides a proton

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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