Physics results of the LHCf experiment

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- Physics motivation and the LHCf detector
- Forward spectra at $\sqrt{s} = 7$ TeV and 900 GeV $p$-$p$ collisions
- $p$-$Pb$ run
- Detector upgrade
- Prospects for new data taking

EPS-HEP 2013, July 18-24 2013, Stockholm, Sweden
p-p interactions in the very forward region

- LHC gives a unique opportunity to calibrate the hadronic interaction models up to
  - $6.5\text{TeV} + 6.5\text{TeV} \Rightarrow E_{\text{lab}} = 10^{17}\text{eV}$
  - $3.5\text{TeV} + 3.5\text{TeV} \Rightarrow E_{\text{lab}} = 2.6 \times 10^{16}\text{eV}$
  - $450\text{GeV} + 450\text{GeV} \Rightarrow E_{\text{lab}} = 2 \times 10^{14}\text{eV}$

- Forward region is very effective on air shower development

**Key Parameters**
- Inelastic Cross Section
  - $\Rightarrow$ TOTEM, ATLAS, CMS, ALICE
- Forward Energy Spectrum
  - $\Rightarrow$ LHCf, ZDC and etc.
- Inelasticity $k = 1$-plead/pbeam
  - $\Rightarrow$ LHCf, ZDC and etc.
- Secondary interactions
LHCf: location and detector layout

Detector I
Tungsten
Scintillator
Scintillating fibers

Detector II
Tungsten
Scintillator
Silicon μstrip

INTERACTION POINT
IP1 (ATLAS)

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

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

Front Counter
140 m

8 cm

6 cm

44X₀
1.6 λₙₐₜ
LHCf: a brief photo-history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved
- Jul 2006 construction
- Jan 2008 Installation
- Aug 2007 SPS beam test
- Mar 2010 1st 7TeV run
- Dec 2009 1st 900GeV run
- Jul 2010 Detector removal
- Gen-Feb 2013 p-Pb run
- Apr 2013 Detector removal and upgrade
- Dec 2012 ARM2 re-installation

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Physics results of the LHCf experiment
Single photon spectra at 7 TeV p-p

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

No Model able to reproduce LHCf data especially in the high-energy region.

Magenta hatch: MC Statistical errors
Gray hatch: Systematic Errors
Photons: 900GeV vs 7TeV spectra

Coverage of the photon spectra in the plane Feynman-X vs $P_T$

- 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.

- Weak dependence of $<p_T>$ on $E_{CMS}$

Data 2010 at $\sqrt{s}=900$GeV (Normalized by the number of entries in $X_F > 0.1$)
Data 2010 at $\sqrt{s}=7$TeV ($\eta>10.94$)

Preliminary
7 TeV $\pi^0$ analysis

- No model able to reproduce LHCf data
- Best overall agreement with EPOS 1.99

Same conclusions as for photons results
Three different approaches used to derive the average transverse momentum, \( \langle p_T \rangle \)

1. By fitting an empirical function to the \( p_T \) spectra in each rapidity range (exponential distribution based on a thermodynamic approach)

1. By fitting a Gaussian distribution

2. By simply numerically integrating the \( p_T \) spectra

Results of the three methods are in agreement and are compared with UA7 data and hadronic model predictions.
Playing a game with air shower
(effect of forward meson spectra)

- DPMJET3 always over-predicts production
- Filtering DPMJET3 mesons
  - according to an empirical probability function, divide mesons into two with keeping $p_T$
  - Fraction of mesons escape out of LHCf acceptance
- This process
  - Holds cross section
  - Holds elasticity/inelasticity
  - Holds energy conservation
  - Changes multiplicity
  - Does not conserve charge event-by-event

\[ E = E_1 + E_2 \]

\[ x_F = E/E_0 \]

\[ P(X_F) = A \exp \left( -\frac{X_F}{\alpha} \right) + B \exp \left( -\frac{1-X_F}{\beta} \right) \]

\[ P(0) = P_1 \]

\[ P(1) = P_2 \]
An example of filtering

9.2 < y < 9.4

π^0 spectrum

DPMJET3+filter

2.5 \times 10^{16} \text{ eV prot}

~30 g/cm^2

AUGER, ICRC 2011
Motivations:

- Inelasticity measurement $k=1-p_{\text{leading}}/p_{\text{beam}}$
- Muon excess at Pierre Auger Observatory
- EPOS predicts more muons due to larger baryon production ((T. Pierog and K. Warner PRL 101, 171101, 2008)
- => importance of baryon measurement

Performance for neutrons

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>~70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Res.</td>
<td>35-40%</td>
</tr>
<tr>
<td>Position Res.</td>
<td>a few mm</td>
</tr>
</tbody>
</table>
Neutron spectra

Small Tower

Large Tower

Estimations of systematic uncertainties
Study of unfolding
ARM2 analysis

Only Arm1

Large beam center

On going
Operation in Jan-Feb 2013

- **p-Pb/Pb-p operation**
- **One arm (Arm2) observation**
- **p-remnant side (little Pb remnant)**
- **Common trigger with ATLAS**

- **2.76 TeV p-p operation**
Photon spectra at different $\eta$ in p-p, p-N, and p-Pb collisions
Enhancement of suppression for HI (Courtesy of S.Ostapchenko)

Nuclear effect in the forward particle production
Photon spectra for different impact parameters

QGSJET II-04
All $\eta$
8.81$<\eta<$8.99
$\eta>$10.94
LHCf p-Pb run: Photon spectra

Energy distrib. in small tower (p-remnant side)

Energy distrib. in big tower (p-remnant side)

EPOS over DPMJET-III ratio (small tower)

EPOS over DPMJET-III ratio (big tower)
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-N at $\sqrt{s_{NN}}=200\text{GeV}$ (proposal presented at BNL PAC)

2019?? Run at LHC in p-light A
The first LHCf data taking at LHC was very successful

- 7 TeV and 900 GeV inclusive photon spectra and $\pi^0 p_T$ spectra published
- First comparison of various hadronic interaction models with experimental data in the most challenging phase space region ($8.81 < \eta < 8.99$, $\eta > 10.94$)
- Large discrepancy especially in the high energy region with all models
- Comparisons with models gives important hints for HECR and soft QCD Physics
- Neutron spectra in p-p and photon spectra in p-Pb analyses are ongoing

We have clearly demonstrated the importance of a calibration of hadronic interaction models used in HECR Physics

- Implications of our data in UHECR Physics under study in strict connection with relevant theoreticians and model developer

We are upgrading the detectors to improve their radiation hardness

We are also planning a possible run at RHIC with lighter ions (2016?) and waiting for LHC p-Light A(2019?)

And of course...We are looking forward for the 13 TeV run with upgraded detector!!!
Backup slides

Some additional material
Single photon spectra at 900 GeV p-p

Results in agreement with 7 TeV spectra
No Model able to reproduce LHCf data especially in the high-energy region
7 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
7 TeV $\pi^0$ spectra

- *dpmjet 3.04 & pythia 8.145* show overall agreement with LHCf data for $9.2 < y < 9.6$ and $p_T < 0.25$ GeV/c, while the expected $\pi^0$ production rates by both models exceed the LHCf data as $p_T$ becomes large.

- *sibyll 2.1* predicts harder pion spectra than data, but the expected $\pi^0$ yield is generally small.

- *qgsjet II-03* predicts $\pi^0$ spectra softer than LHCf data.

- *epos 1.99* shows the best overall agreement with the LHCf data.
  - behaves softer in the low $p_T$ region, $p_T < 0.4$ GeV/c in $9.0 < y < 9.4$ and $p_T < 0.3$ GeV/c in $9.4 < y < 9.6$
  - behaves harder in the large $p_T$ region.
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
Neutron at LHCf phase-space

By Tanguy Pierog,
Modelists waiting for LHCf!!
Neutron Detection Efficiency and energy linearity

Efficiency at the offline shower trigger
Flat efficiency >500GeV
Energy and Position Resolution

We are trying to improve the energy resolution by looking at the ‘electromageticity’ of the event.

Neutron incident at (X,Y) = (8.5mm, 11.5mm)
~1mm position resolution
Weak dependence on incident energy
LHCf operations @900 GeV & 7 TeV

- With Stable Beam at 900 GeV Dec 6th – Dec 15th 2009
- With Stable Beam at 900 GeV May 2nd – May 27th 2010
- With Stable Beam at 7 TeV March 30th - July 19th 2010
- We took data with and without 100 µrad crossing angle for different vertical detector positions

<table>
<thead>
<tr>
<th></th>
<th>Shower</th>
<th>Gamma</th>
<th>Hadron</th>
<th>n^0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm1</td>
<td>46,800</td>
<td>4,100</td>
<td>11,527</td>
<td></td>
</tr>
<tr>
<td>Arm2</td>
<td>66,700</td>
<td>6,158</td>
<td>26,094</td>
<td></td>
</tr>
<tr>
<td>Arm1</td>
<td>172,263,255</td>
<td>56,846,874</td>
<td>111,971,115</td>
<td>344,526</td>
</tr>
<tr>
<td>Arm2</td>
<td>160,587,306</td>
<td>52,993,810</td>
<td>104,381,748</td>
<td>676,157</td>
</tr>
</tbody>
</table>
Data Set for inclusive photon spectrum analysis at 7 TeV

Data
- Date: 15 May 2010 17:45-21:23 (Fill Number: 1104) except runs during the luminosity scan.
- Luminosity: \((6.5-6.3) \times 10^{28} \text{cm}^{-2}\text{s}^{-1}\),
- DAQ Live Time: 85.7% for Arm1, 67.0% for Arm2
- Integrated Luminosity: 0.68 nb\(^{-1}\) for Arm1, 0.53 nb\(^{-1}\) for Arm2
- Number of triggers: 2,916,496 events for Arm1, 3,072,691 events for Arm2
- Detectors in nominal positions and Normal Gain

Monte Carlo
- QGSJET II-03, DPMJET 3.04, SYBILL 2.1, EPOS 1.99 and PYTHIA8.145: about \(10^7\) pp inelastic collisions each
Main systematic uncertainty due to energy scale
- Energy scale can be checked by $\pi^0$ identification from two tower events.
- Mass shift observed both in Arm1 (+7.8%) and Arm2 (+3.7%)
- No energy scaling applied, but shifts assigned in the systematic error in energy

Uncorrelated uncertainties between ARM1 and ARM2
- Energy scale (except $\pi^0$ error)
- Beam center position
- PID
- Multi-hit selection

Correlated uncertainty
- Energy scale ($\pi^0$ error)
- Luminosity error

$$M = \theta \sqrt{E_1 E_2}$$
An example of $\pi^0$ events

$\pi^0$ reconstruction

measured energy spectrum @ Arm2

Silicon strip-X view

$\gamma_1(E_1) \quad \theta = \frac{R}{140 \text{ m}}$

$\gamma_2(E_2)$

Reconstructed mass @ Arm2

- $\pi^0$'s are the main source of electromagnetic secondaries in high energy collisions.
- The mass peak is very useful to confirm the detector performances and to estimate the systematic error of energy scale.
Calorimeters viewed from IP

- Geometrical acceptance of Arm1 and Arm2
- Crossing angle operation enhances the acceptance

Projected edge of beam pipe
Luminosity for the analysis is calculated from Front Counter rates:

\[ L = CF \cdot R_{FC} \]

The conversion factor CF is estimated from luminosity measured during Van der Meer scan.

Beam sizes \( \sigma_x \) and \( \sigma_y \) measured directly by LHCf

BCNWG paper

https://lpc-afs.web.cern.ch/lpc-afs/tmp/note1_v4_lines.pdf
When the circulated bunch is 1x1, the probability of N collisions per Xing is

\[ P(N) = \frac{N \exp[-l]}{N!} = \frac{L \times f_{rev}}{f_{rev}} \]

The ratio of the pile up event is

\[ R_{\text{pileup}} = \frac{P(N \geq 2)}{P(N \geq 1)} = \frac{1}{1} \left( 1 + \frac{1}{e} \right) \]

The maximum luminosity per bunch during runs used for the analysis is 2.3x10^{28} \text{cm}^{-2}\text{s}^{-1}

So the probability of pile up is estimated to be 7.2% with \( \sigma \) of 71.5mb

Taking into account the calorimeter acceptance (~0.03) only 0.2% of events have multi-hit due to pile-up. It does not affect our results.
p_T distribution dependence

\[ \frac{dN_\gamma(E_\gamma)}{dE_\gamma} \bigg|_{8.81 \leq \eta \leq 8.99} = \frac{dN_\gamma(E_\gamma)}{dE_\gamma} \times \frac{dN_\gamma[8.81 \leq \eta \leq 8.99]}{dN_\gamma[all \ \eta]} \]

\[ \frac{dN_\gamma(E_\gamma)}{dE_\gamma} \bigg|_{\eta > 10.94} = \frac{dN_\gamma(E_\gamma)}{dE_\gamma} \times \frac{dN_\gamma[\eta > 10.94]}{dN_\gamma[all \ \eta]} \]

Directly relevant for UHECR shower development

The p_T distribution a sqrt[s] = 7 TeV is not a Gaussian of energy independent width.

Courtesy P. LIPARI
Interplay of LHCf data with HECR Physics Workshop, Catania, July 6 2011
Backgrounds

1. Pileup of collisions in one beam crossing
   - Low Luminosity fill, \( L = 6 \times 10^{28} \text{cm}^{-2}\text{s}^{-1} \)
   - 7% pileup at collisions, 0.2% at the detectors.

2. Collisions between secondary's and beam pipes
   - Very low energy particles reach the detector (few % at 100GeV)

3. Collisions between beams and residual gas
   - Estimated from data with non-crossing bunches.
   - \(<0.1\%\)

Beam-Gas backgrounds

Secondary-beam pipe backgrounds

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Systematic error from Energy scale

- Two components:
  - Relatively well known: Detector response, SPS => 3.5%
  - Unknown: $\pi^0$ mass => 7.8%, 3.8% for Arm1 and Arm2.

- Please note:
  - 3.5% is symmetric around measured energy
  - 7.8% (3.8%) are asymmetric, because of the $\pi^0$ mass shift
  - No ‘hand made’ correction is applied up to now for safety

- Total uncertainty is
  - -9.8% / +1.8% for Arm1
  - -6.6% / +2.2% for Arm2

Systematic Uncertainty on Spectra is estimated from difference between normal spectra and energy shifted spectra.
Arm1 Data

Peak at 145.8 ± 0.1 MeV

7.8 % shift

Arm2 Data

Peak at 140.0 ± 0.1 MeV

Arm2 MC (QGSJET2)

Peak at 135.0 ± 0.2 MeV

3.8 % shift

• Disagreement in the peak position
• No ‘hand made correction’ is applied for safety
• Main source of systematic error → see later

Many systematic checks have been done to understand the energy scale difference
π⁰ mass vs π⁰ energy

Arm2 Data
No strong energy dependence of reconstructed mass
Signal window: $[-3\sigma, +3\sigma]$
Sideband: $[-6\sigma, -3\sigma]$ and $[+3\sigma, +6\sigma]$

Remaining background spectrum is estimated using the sideband information, then the BG spectrum is subtracted from the spectrum made in the signal window.

$$\text{Signal} = f(E, P_T)^{\text{signal}} - \frac{f(E, P_T)^{\text{BG}} \int_{M-3\sigma_l}^{M+3\sigma_u} L_{BG} dM}{\int_{M-3\sigma_l}^{M-6\sigma_l} L_{BG} dM + \int_{M+3\sigma_u}^{M+6\sigma_u} L_{BG} dM}$$

Validity check of unfolding method

Detector responses are corrected by an unfolding process that is based on the iterative Bayesian method.

(G. D’Agostini NIM A 362 (1995) 487)

Detector response corrected spectrum is proceeded to the acceptance correction.
DATA-MC: comp. 900GeV/7TeV

**LHCf \( \sqrt{s} = 900\text{GeV} \), Photon like**

- \( \eta > 10.15 \) (\( <\theta> = 39 \mu\text{rad} \))
- \( 8.77 < \eta < 9.46 \) (\( <\theta> = 234 \mu\text{rad} \))
LHCf p-Pb run: Neutron spectra

Energy distrib. in small tower (p-remnant side)

Energy distrib. in big tower (p-remnant side)

EPOS over DPMJET-III ratio (small tower)

EPOS over DPMJET-III ratio (big tower)
Arm2 detector, all runs with zero crossing angle

True $\eta$ Mass: 547.9 MeV

MC Reconstructed $\eta$ Mass peak: 548.5 $\pm$ 1.0 MeV

Data Reconstructed $\eta$ Mass peak: 562.2 $\pm$ 1.8 MeV (2.6% shift)
Comparison of EJ260 and GSO - Radiation Hardness -

- EJ260 (HIMAC* Carbon beam)
  10% decrease of light yield after exposure of 100Gy

- GSO (HIMAC Carbon beam)
  No decrease of light yield even after 7\times10^5Gy exposure,
  BUT increase of light yield is confirmed

- The increase depend on irradiation rate (~2.5%/100Gy/hour)

*HIMAC : Heavy Ion Medical Accelerator in Chiba