Monte Carlo study of diffraction in p-p collisions at $\sqrt{s}=13\text{TeV}$ with the LHCf detector

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on behalf of the LHCf collaboration

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Outline

❖ Introduction
  ‣ LHCf experiment: detector, results.

❖ A MC study about diffractive and non-diffractive interaction contribution to the LHCf spectrum.

❖ ATLAS-LHCf common operation (MC study).
  ‣ Detector acceptance
  ‣ Efficiency and purity of diffraction identification by common data
  ‣ Low mass diffraction selection

❖ Summary
The LHCf experiment

- Measure hadronic production cross section of neutral particles emitted in the very forward region of LHC.
- To afford the data for verifying and improving the hadronic interaction models.

LHCf and ATLAS are observing the particles from the same collisions, but different position.

LHCf detectors are sensitive to the *soft processes*.
The most energetic secondary particles emitted to the very forward region (LHCf sensitive region)

Most of secondary particles concentrate to the center

Particle density and energy flow at 13TeV

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The LHCf calorimeter

- Two imaging sampling shower calorimeters
- 44r.l. tungsten, 16 layers of GSO scintillators and 4 position sensitive layers
- The $\eta$ coverage of the calorimeter: $|\eta| > 8.4$

Energy resolution:
- $>100\text{GeV}$
- $<5\%$ for photons
- $40\%$ for neutrons

Position resolution:
- $<200\mu\text{m}$ for photons
- $<1\text{mm}$ for neutrons

Arm1 detector
- Position sensor: 4XY GSO-bar hodoscope + MAPAT

Arm2 detector
- Position sensor: 4XY silicon strip detectors
Operations and schedule at the LHC

• December 2009 ~ July 2010
  p+p @ 900GeV
  p+p @ 7TeV
• January, February~ 2013 (only arm2)
  p+Pb @ 5.02TeV
  p+p @ 2.76TeV
• June 2015
  p+p @ 13TeV
• November or December 2016
  p+Pb @ 8.1TeV (only arm2)
## Results

<table>
<thead>
<tr>
<th>Energy</th>
<th>Photon</th>
<th>Neutron</th>
<th>( \pi^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p 2.76TeV</td>
<td></td>
<td></td>
<td>arXiv:1507.08764</td>
</tr>
<tr>
<td>p+p 13TeV</td>
<td>Preparing</td>
<td>On-going</td>
<td></td>
</tr>
<tr>
<td>p+Pb 8.1TeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$\pi^0$ at $\sqrt{s}=7$ TeV, $p+p$

$\pi^0$ was reconstructed from the two decayed $\gamma$ observed by the LHCf

Type I $\pi^0$  Type II $\pi^0$

Good agreement with QGSJET-II-04
EPOS-LHC at $p_T<0.5$ is OK
Neutron at $\sqrt{s}=7$TeV, p+p

Forward neutron measurement can give constraint of forward baryon production in the models.

- No model can represent the data
- Models give a large discrepancy at $\eta>10.76$
- DPMJET3 represent the data better than the other models at $8.81<\eta<9.22$
Photon at $\sqrt{s}=13\,\text{TeV}$, p-p

$\eta>10.94$

$\eta<8.99$

$LHCf \sqrt{s}=13\,\text{TeV}$ photon

$\eta > 10.94$, $\Delta\phi=180^\circ$

$\int Ldt=0.191+0.191\,\text{nb}^{-1}$

Preliminary

$8.81<\eta<8.99$, $\Delta\phi=20^\circ$

$\int Ldt=0.191+0.191\,\text{nb}^{-1}$

Preliminary

MC/Data
What’s the source of the difference

- Hard interactions can be predicted by using perturbative QCD.
- Soft interactions dominate by non-perturbative QCD, \textit{phenomenological} models base on Regge theory proposed.
- Diffractive dissociation belong to soft process.

Diffraction measurement is difficult issue for experiment. especially, low mass diffraction.
Diffractive dissociation

Diffraction contribute 25%~30% of total cross sections.

Diffraction was described by pomeron based model, but the technic of calculation in each model is a little different

- EPOS-LHC : cut diagrams (pomeron)
- QGSJET-II-04: renormalized pomeron flux
- SIBYLL2.1 : eikonal picture
Monte Carlo study about diffractive and non-diffractive interaction contribution to LHCf spectrum
Investigation of photon spectrum

Total collisions:
- diffraction + non-diffraction

Diffraction = SD + DD + CD

The excess of PYTHIA8 at E > 3 TeV due to over contribution from diffraction
Photon spectrum comparison

$\eta > 10.94$

Model comparison
Total = diff. + non-diff.

<table>
<thead>
<tr>
<th>Model</th>
<th>Total</th>
<th>Non-diffraction</th>
<th>Diffraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPOS-LHC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QGSJET-II-04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIBYLL2.1</td>
<td></td>
<td></td>
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<tr>
<td>PYTHIA8212</td>
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<td></td>
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</tr>
</tbody>
</table>

Diffraction@PYTHIA8212
Diffraction@EPOS – LHC
Investigation of PYTHIA8 diffraction

E [GeV]
0 1000 2000 3000 4000 5000 6000

\( \eta > 10.94 \)

Pomeron flux options in PYTHIA

Regge trajectory: \( \alpha_{P}(t)=1.085+0.25t \) as default

PYTHIA8DL gives better agreement to ATLAS \( n_{(MBTS)} \) distribution [ATLAS-CONF-2015-038]. However, it gives too much diffraction at \( E > 3 \text{TeV} \) to LHCf spectra.
Neutron spectrum comparison

• Dominated by diff. or non-diff.?  
• Increased baryon pair production (SIBYLL2.1->2.3), non-diff. production increased.
Prospects for ATLAS-LHCf common analysis
Common data acquisition for the minimum bias measurement.

LHCf detectors were incorporated into ATLAS readout system.

LHCf triggers ATLAS with trigger rate ~400Hz.

The event matching was done offline by using ATLAS L1ID.

Event matching succeed, data analysis on going
Detector acceptance

\[ \xi = \left( \frac{M(x)}{\sqrt{s}} \right)^2 = 1 - X_F \sim e^{-\Delta \eta} \]

- Trigger efficiency (only with SD)
- Trigger condition of LHCf
  - Photon: \( E_\gamma > 200 \text{GeV} \)
  - Neutron: \( E_n > 500 \text{GeV} \)
- ATLAS
  - Pass track selection
  - \( N_{\text{hit}} > 2 \)
  - PYTHIA has different fragmentation function?

LHCf and ATLAS cover different diffractive mass range
LHCf event selection w/ ATLAS central trackers

- ATLAS Inner detector (tracking system)
  Condition:
  Charged particle \((P_T > 100\text{MeV})\) number at \(|\eta| < 2.5\)
  → Diffractive like (ATLAS veto)

<table>
<thead>
<tr>
<th>Tracks</th>
<th>Tracks (\leq 1)</th>
<th>Tracks (\leq 2)</th>
<th>Tracks (\leq 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.49</td>
<td>0.56</td>
<td>0.62</td>
</tr>
<tr>
<td>Purity</td>
<td>0.995</td>
<td>0.991</td>
<td>0.982</td>
</tr>
</tbody>
</table>

- Diffraction identification:
  No charged particle (tracks=0) at \(|\eta| < 2.5\) was employed in this analysis
LHCf photon spectrum w/ ATLAS veto

$\eta > 10.94$

Diffraction: MC true

ATLAS veto: tracks=0 @ $|\eta| < 2.5$

Diffraction@veto overlap ATLAS veto

high diff. selection purity

Miss selection

efficiency $= \frac{LHCf \_ event @ ATLASveto}{LHCf \_ Diff.}$

purity $= \frac{Diff. @ ATLASveto}{LHCf \_ event @ ATLASveto}$

- High purity model independently.
- Efficiency $\sim 50\%$, EPOS and QGSJET give almost consistent efficiency.
LHCf neutron spectrum w/ ATLAS veto

\[ \eta > 10.94 \]

\[ 8.81 < \eta < 8.99 \]
LHCf $\pi^0$ spectrum w/ ATLAS veto

0$<P_T[\text{GeV}]<$0.2

0.8$<P_T[\text{GeV}]<$1.0
Diffractive mass distribution

Pomeron flux options in PYTHIA

\[ \xi = \left( \frac{M(x)}{\sqrt{s}} \right)^2 = 1 - X_F \approx e^{-\Delta \eta} \]

- \( \log_{10}(\xi) \) distribution of SD represents the pomeron flux implemented in the model.
- Large discrepancy exists between models
- Pomeron flux is an extremely important parameter for modeling diffraction

arXiv:1005.3894v1
Low mass diffraction

- The inefficiency parts of ATLAS-veto are high mass diff.
- ATLAS-LHCf can access the low mass single diffraction region, with high efficiency, experimentally.
Summary

☀️ LHCf has taken data in p-p and p-Pb collisions at different energies, results have been published about photon, neutron and $\pi^0$

No models represent the data perfectly

☀️ The identification of diffraction can verify and improve the hadronic interaction models.

☀️ The efficiency and purity of diffractive event identification by ATLAS-LHCf common operation were estimated.
  - The efficiency of diffraction identification is approximately 50%, with 99% purity.

☀️ LHCf detectors have high sensitivity at $\log_{10}(\xi) < -6$

☀️ Application of ATLAS veto to the LHCf data purifies low mass diffraction event samples

Stay Tuned
Backup
What to be calibrated by accelerators

Hard interactions can be predicted by using perturbative QCD. Soft interactions dominate by non-perturbative QCD, Phenomenological models base on Regge theory proposed

Key parameters
- Inelastic cross section (interaction mean free path)
  TOTEM, ATLAS, CMS etc.
- Multiplicity
- Central detector
- Inelasticity ($k = 1 - P_{lead}/P_{beam}$)
  LHCf, ZDC, etc.
- Forward energy spectrum
  LHCf, ZDC, etc.
- Nuclear effect
  LHCf, ALICE, etc.
Hadronic interaction models

$\Delta X_{\text{max}}$ indicates the different primary mass composition

The issue to interpret the air shower data:
The limitations in modeling of hadronic interactions in air shower and largely unknown model uncertainties.
Detection efficiency of photon

- Threshold for Arm1 small tower and large tower are 176, 152 GeV, respectively.
- Threshold for Arm2 small tower and large tower are 100 and 101 GeV.
LHCf detector performance (Arm2)

Neutron

Energy resolution of 13TeV

Position resolution of 13TeV
Systematic uncertainties *(preliminary)*

p-p@13TeV

| Items                      | Arm1 $|\eta|<10.94$ | Arm1 $8.99<\eta<1.81$ |
|----------------------------|-----------|-------------|
| Energy scale               | -11%, +14%| -28%, +23%  |
| PID correction             | ±5%       | ±2.5%       |
| Beam center                | ±2%       | ±3%         |
| Multi hit performance      | ±2%       | ±3%         |
| Multi hit correction       | -3%, +20% | -9%, +34%   |
| Luminosity                 | ±5%       | ±5%         |

![Graph showing Systematic Errors (Arm1) for Rapidity-0 and Rapidity-1](image)
Ultra Peripheral Collisions (UPCs)

If \( b > R_p + R_{Pb} \), hadron interaction is strongly suppressed and proton collides with electromagnetic field of Pb, of which strength is proportional to \( Z^2 \). The EM interaction can be described as a collision between proton and quasi-photon.

Exp.) \( p + \text{Pb} \rightarrow X + \text{Pb} \Leftrightarrow p + \gamma^* \rightarrow X \)

In UPCs, what can we see at zero degree of collision?

= in LHCf

LHCf had operations with \( p + \text{Pb} \) collisions of \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) in 2013.

LHCf measured the energy spectra of \( \gamma, \pi^0, \) neutron inclusively.
Energy Spectra - Hadron like -(neutron)

Clear difference between spectra of $n_{\text{sel}}=0$ and of $n_{\text{sel}}>0$.
Harder spectrum of $n_{\text{sel}}=0$ due to contribution of $\Delta$ resonance at UPCs.
Scattering angle distribution

\[ dN/d\Omega = \text{events}/(10^{-12} \text{sr}) \]

\[ \text{Scattering angle [\(\mu\text{rad}\)]} \]

\[ = 5.02 \text{ TeV} \]

\[ p+\text{Pb}, \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

- w/o selection
- \( n_{\text{sel}} > 0 \)
- MC (UPC+QCD)
- MC (QCD)

Data with the event selection by number of tracks in ATLAS; \( n_{\text{sel}} \)

MC with the selection by process

- Clear concentration at zero degree with events of \( n_{\text{sel}} = 0 \).
- Similar distribution of \( n_{\text{sel}} > 0 \) as one of MC (QCD)

Note) The sum of UPC and QCD simulations was normalized to all data in the range from 0 \(\mu\text{rad}\) to 120 \(\mu\text{rad}\).

- The joint analysis clearly helps to study the forward particle production with categorizing the type of interaction.
Impact of diffraction collisions to $X_{\text{max}}$

- $K_{\text{inel}} = \Delta E/E_0 = \exp(-\Delta \eta) \ll 1$ (inelasticity)
  ($\Delta E$: the energy loss of the leading secondary nucleon).

→ Diffraction collision is relate to the $X_{\text{max}}$

- The higher rate of Diffractive collision, the deeper $X_{\text{max}}$

Impact of diffraction collisions to $X_{\text{u}}^{\text{max}}$

- Weak influence on EM Xmas
- Cumulative effect for $X_{\text{u}}^{\text{max}}$
- Neutron (baryon) and gamma (pair production from $\pi$ meson) are detectable for LHCf detectors

T. Pieorg, HESZ 2015
Photon at $\sqrt{s}=7\text{TeV}, p+p$
Consistence of Arm1 and Arm2

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

Preliminary

LHCf $\sqrt{s}=13$ TeV photon
$8.81<\eta<8.99$, $\Delta \phi=20^\circ$
$\int L dt=0.191+0.191$ nb$^{-1}$

Preliminary
LHCf-ATLAS Event matching

Consistent

<table>
<thead>
<tr>
<th>Events</th>
<th>( \mu = 0.01 ) (run 44299-44472)</th>
<th>( \mu = 0.03 ) (run 44482-45106)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCf events</td>
<td>4.168 M</td>
<td>14.194 M</td>
</tr>
<tr>
<td>Matched events</td>
<td>4.158 M</td>
<td>2.121 M</td>
</tr>
</tbody>
</table>
Phonon spectrum comparison II

\(8.81 < \eta < 8.99\)

Models:
- EPOS-LHC
- QGSJET II-04
- SIBYLL 2.1
- PYTHIA 8.212

Total, Non-diffraction, Diffraction comparisons for LHCf \(1\) TeV photon, \(8.81 < \eta < 8.99\), \(\Delta\phi = 20^\circ\)

\[\int L d\tau = 0.191 + 0.191 \text{nb}^{-1}\]

Preliminary
Photon spectrum comparison

$\eta > 10.94$

$8.81 < \eta < 8.99$
Neutron spectrum comparison

$\eta > 10.94$

$8.81 < \eta < 8.99$

Models:
- EPOS-LHC
- QGSJET-II-04
- SIBYLL2.3
- PYTHIA8

Total
Non-diffraction
Diffraction
π^0 spectrum comparison

$0 < p_T [\text{GeV}] < 0.2$

$0.8 < p_T [\text{GeV}] < 1.0$

Models:
- EPOS-LHC
- QGSJET-II-04
- SIBYLL2.3
- PYTHIA8212

$p-p, \sqrt{s} = 13 \text{ TeV}$

0 < $p_T$ [GeV] < 0.2

Total
Non-diffraction
Diffraction
Low mass diffraction (photon)

\[ \eta > 10.94 \quad M(x) < 5 \text{GeV} \]

\[ 8.81 < \eta < 8.99 \]
Low mass diffraction (neutron) 

\[ \eta > 10.94 \quad M(x) < 5 \text{GeV} \]

\[ 8.81 < \eta < 8.99 \]
Low mass diffraction ($\pi^0$)

$0<P_T[GeV]<0.2 \quad M(x)<5 GeV \quad 0.8<P_T[GeV]<1.0$