Very forward particle production at colliders LHCf and RHICf

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for the LHCf and RHICf collaborations
Outline

• Forward detectors and LHCf/RHICf
• LHCf results (mainly from 7TeV p-p collisions)
  • $\pi^0$
  • Neutron
  • (preliminary) photon result at 13 TeV
• Origin of LHCf measured particles in models, and prospect for LHCf-ATLAS joint analysis
• $\sqrt{s}$ scaling
• Single-spin asymmetry at RHIC
• Future O-O collision at LHC
2\textsuperscript{ry} particle flow at colliders

multiplicity and energy flux at LHC 14TeV p-p collisions

- LHCf covers the peak of energy flow
- \( \sqrt{s} = 14 \text{ TeV} \) pp collision corresponds to \( E_{\text{CR}} = 10^{17} \text{eV} \)
• ZDCs (including LHCf/RHICf) are sensitive to neutral particles including zero degree
### Comparison of ZDC and LHCf/RHICf

<table>
<thead>
<tr>
<th></th>
<th>ZDC</th>
<th>LHCf/RHICf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original purpose</strong></td>
<td>determination of centrality in A-A collisions =&gt; number of spectator neutrons</td>
<td>measurements of $\pi^0$ cross section =&gt; position sensitive EM calorimeter</td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>thick</td>
<td>thin</td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>good</td>
<td>good in EM showers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>poor in hadronic showers</td>
</tr>
<tr>
<td><strong>Position resolution</strong></td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td><strong>Single particle identification</strong></td>
<td>poor</td>
<td>good</td>
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</table>
The LHC forward experiment

- Neutral particles (photons and neutrons) emitted around 0 degree arrive at LHCf
From the LHC forward (LHCf) to the RHIC forward (RHICf)

LHCf Arm1 detector in the LHC tunnel

Schematic view of the RHICf installation@STAR

18m
(140m at LHC)

Data taking in RUN17 is approved
Zero degree detector and acceptance

\[ p_T = p \sin \theta \leq \frac{1}{2} \sqrt{s} \sin \theta \]

\[ x_F = 2 \frac{p_z}{\sqrt{s}} \]

Phase space coverages at:
- LHC 7TeV p+p collision
- RHIC 500GeV p+p collision
- RHIC 200GeV p+p collision
- LHC 900GeV p+p collision
LHCf/RHICf Detectors

• Imaging sampling shower calorimeters
• Two calorimeter towers in each of Arm1 (RHICf) and Arm2
• Each tower has 44 r.l. of Tungsten, 16 sampling scintillator and 4 position sensitive layers
Event category of LHCf

- Single photon event
- Single hadron event
- Pi-zero event (photon pair)

Leading baryon (neutron)
Multi meson production
\(\pi^0\) photon
\(\pi^0\) photon
Detector performance

Hadronic shower (MC)
- Position resolution
  - Black: X-plane
  - Red: Y-plane
- Energy resolution
  \[ \frac{\Delta E}{E} \approx 40\% \]
  \[ \sigma_{E} / E \sim 40\% \text{ because of } 1.6\lambda \]

EM shower (MC)
- Position resolution
  \[ \text{Position Resolution[\mu m]} \]
  \[ 10^{-2} \]
- Energy resolution
  \[ \text{Resolution[\%]} \]
  \[ \Delta E / E < 5\% \]

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

\[ m_{\gamma} \sim m_{\pi^0} \]
Cosmic-ray spectrum and collider energy

(D’Enterria et al., APP, 35,98-113, 2011)

End of galactic CR and transition to extra-gal CR

Knee: end of galactic proton CR

Ankle

(GZK) cutoff: end of CR spectrum
## Publications

<table>
<thead>
<tr>
<th></th>
<th>Photon (EM shower)</th>
<th>Neutron (hadron shower)</th>
<th>$\pi^0$ (limited acceptance)</th>
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|physics results|
|performance results|
## Publications

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<td>preliminary</td>
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Physics results

Performance results
$\pi^0 p_z$ spectra in 7TeV p-p collisions

(PRD submitted, arXiv:1507.08764 [hep-ex])

• DPMJET3 and PYTHIA8 overestimate over all E-$p_T$ range
$\pi^0$ in 7TeV p-p collision
LHCf and models
\( \pi^0 \) in 7TeV p-p collision
LHCf and models (ratio to data)
\[ \pi^0 \quad \text{SIBYLL 2.1} \]

- Underestimate in low \( p_T \), overestimate in high \( p_T \)
- Totally overestimate because of larger phase space in high \( p_T \)
• Not bad, slightly overestimate in high energy
- Perfect in shape, slightly underestimate in higher $p_T$
- Totally slightly underestimate
Neutron
($\sqrt{s}=7\text{TeV}$ p-p; PLB 750 (2015) 360-366)

- DPM and PYTHIA under production at zero degree
- DPM and PYTHIA not bad at off-zero degree. DPM is best.
Neutron SIBYLL 2.1

- Lowest neutron yield, especially at zero degree
Neutron QGSJET II-03

- Qualitatively nice agreement, only model, at zero degree
- Lower yield at non-zero angle
Neutron EPOS 1.99

- Generally low yield
Energy flow

- Post-LHC models (EPOS-LHC and QGSJET II-04) well explain the $\pi^0$ results, but not for neutrons
- DPMJET3 explains the neutron results, but it is not recently used for CR simulations

\[ \pi^0 \]

neutron

Black solid circle: LHCf data ($\pi^0$, LHCf 2012)
Dotted lines: $\pi^0$ energy flow distribution of each model
Thick horizontal line: Energy flow calculation after $p_T$ cut

to be covered in 13TeV
Energy share between $\pi^0$ (photon) and neutron

<table>
<thead>
<tr>
<th></th>
<th>$\pi^0$</th>
<th>neutron</th>
<th>neutron/$\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCf</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DPMJET 3.04 (PYTHIA)</td>
<td>$\gg1$</td>
<td>$\sim1$</td>
<td>$&lt;&lt;1$</td>
</tr>
<tr>
<td>SIBYLL 2.1</td>
<td>$&gt;1$</td>
<td>$&lt;&lt;1$</td>
<td>$&lt;&lt;1$</td>
</tr>
<tr>
<td>QGSJET II-03, 04</td>
<td>$\sim1$</td>
<td>$&lt;1$</td>
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</tr>
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<td>EPOS 1.99, LHC</td>
<td>$\sim1$</td>
<td>$&lt;1$</td>
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</table>

Elasticity:

$$K_{ela} = \frac{E_{lead}}{E_{lead} + \sum E_\pi}$$

is important for air showers

"pseudo"-elasticity

Neutron/photon “number” ratio in the same angular ranges

<table>
<thead>
<tr>
<th>$N_n/N_\gamma$</th>
<th>Small ($\eta&gt;10.76$)</th>
<th>Large A ($9.22&gt;\eta&gt;8.99$)</th>
<th>Large B ($8.99&gt;\eta&gt;8.81$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$3.05 \pm 0.19$</td>
<td>$1.26 \pm 0.08$</td>
<td>$1.10 \pm 0.07$</td>
</tr>
<tr>
<td>DPMJET 3.04</td>
<td>1.05</td>
<td>0.76</td>
<td>0.74</td>
</tr>
<tr>
<td>EPOS 1.99</td>
<td>1.80</td>
<td>0.69</td>
<td>0.63</td>
</tr>
<tr>
<td>PYTHIA 8.145</td>
<td>1.27</td>
<td>0.82</td>
<td>0.79</td>
</tr>
<tr>
<td>QGSJET II-03</td>
<td>2.34</td>
<td>0.65</td>
<td>0.56</td>
</tr>
<tr>
<td>SYBILL 2.1</td>
<td>0.88</td>
<td>0.57</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Photon spectra, $\sqrt{s}=13$ TeV

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

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

$\int Ldt=0.191 \pm 0.191$ nb$^{-1}$

Preliminary

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

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

$\int Ldt=0.191 \pm 0.191$ nb$^{-1}$

Preliminary
Photon 7TeV vs. 13TeV

$\eta > 10.94$

$\sqrt{s} = 7\,\text{TeV}$

$LHCF \sqrt{s} = 13\,\text{TeV}$ photon
$\eta > 10.94, \Delta \phi = 180^\circ$

$L_\text{int} = 0.191\pm0.191\,\text{nb}^{-1}$

Preliminary

$8.81 < \eta < 8.99$

$\sqrt{s} = 13\,\text{TeV}$ acceptance

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

$LHCF \sqrt{s} = 13\,\text{TeV}$ photon
$8.81 < \eta < 8.99, \Delta \phi = 20^\circ$

$L_\text{int} = 0.191\pm0.191\,\text{nb}^{-1}$

Preliminary

$\sqrt{s} = 7\,\text{TeV}$ acceptance

$\sqrt{s} = 7\,\text{TeV}$

$LHCF \sqrt{s} = 7\,\text{TeV}$
$\eta > 10.94, \Delta \phi = 360^\circ$

$X_F = \frac{E_Y}{E_{\text{beam}}}$

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

$X_F = \frac{E_Y}{E_{\text{beam}}}$
Diffraction/non-diffraction tagging by ATLAS (prospect for 13TeV analysis)
Diffraction or Non-diffraction?

$\pi^0$

![Graphs showing diffraction and non-diffraction for various models at 13 TeV]
Diffraction or Non-diffraction?

neutron
Tagging by ATLAS
(no track=diffraction-like)
Technical feasibility

• Common Event ID was already tested using 5TeV p-Pb collision data in 2013

Timing and bunch ID matching

hadron spectrum@ 0 degree (folded energy)
vs scaling
$\sqrt{s}$ scaling ; $\pi^0$

- $(630\text{GeV} -) 2.76\text{TeV} - 7\text{TeV}$
  good scaling within uncertainties
- Wider coverage in $y$ and $p_T$ with 13TeV data
- Wider $\sqrt{s}$ coverage with RHICf experiment in 2017 at $\sqrt{s}=510\text{GeV}$
Vs scaling in EPOS-LHC, $\pi^0$

510GeV (RHIC)
7TeV (LHC)
100TeV (FCC)

(14x each step)
**Vs scaling; Neutron**

**PHENIX, PRD, 88, 032006 (2013)**

- $p_T < 0.11 \times x_F$ GeV/c
- $\sqrt{s} = 30-60$ GeV @ISR
- $\sqrt{s} = 200$ GeV @RHIC

- PHENIX explains the result by 1 pion exchange
- More complicated exchanges at >TeV?

**RHICf takes data at 510GeV p+p in RUN17**
Single-Spin Asymmetry at RHIC
Single spin asymmetry by PHENIX

(PRD, 88, 032006, 2013)

✓ strong asymmetry in forward neutrons was discovered at RHIC
✓ scaled with $p_T$ at $\sqrt{s} = 62, 200, 500$ GeV?
✓ position resolution $\approx 1\text{cm}$

ZDC

ZDC+BBC

PHENIX results at 200GeV

position resolution by SMD inserted in the PHENIX ZDC
Single spin asymmetry by RHICf

- Excellent position resolution allows to cover wide $p_T$ in a single $\sqrt{s}$ condition
- With horizontal polarization, covering $p_T<1\text{GeV/c}$
Very Future
LHC O-O collisions ($\sqrt{s_{NN}}=7$TeV)

- LHC is TECHNICALLY able to accelerate and collide Oxygen beams
- Is nuclear effect in light ion collisions well understood?
- In A-A collisions, high multiplicity in the very forward region => new detector is required.

Event sample
Photon hit in 9cmx9cm (neutron is not yet considered)
All pixelarized “Super ZDC”

- Perfect electronics (no BG, perfect linearity, no saturation) are assumed
Summary

• LHCf/RHICf measure neutral particles at very characteristic phase space – zero degree – where a large fraction of collision energy is carried

• LHCf tests interaction models at LHC
  • EPOS-LHC and QGSJET II-04 are two best models to describe $\pi^0$ production
  • All models under produce neutrons

• $\sqrt{s}$ scaling
  • Marginally scaling in $\pi^0$ between 2.76 and 7TeV is observed
  • Indication of scaling violation in neutron between 0.2 and 7TeV is observed
  • LHCf continues analysis of 0.9, 2.76, 7, and 13 TeV p-p collision data
  • RHICf will take data at 0.51TeV in 2017

• RHICf is expected to test $p_T$ scaling of single-spin asymmetry

• Detector design for future LHC O-O collision is on going

[not mentioned today: we have 5TeV p-Pb data and will have 8.2TeV p-Pb]