Forward hadron production at the LHC

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Nagoya University

“ISVHECRI 2014”
17-23 Aug, 2014, CERN
① Inelastic cross section (TOTEM and others)

② Forward energy spectrum \((\gamma/\pi^0, \text{hadron spectrum})\)

③ Inelasticity \(k = 1 - p_{\text{lead}}/p_{\text{beam}}\) (leading baryon / \(\gamma\) ratio)

④ Nuclear effect (shadowing, Cronin effect)

⑤ Secondary interactions (\(\sqrt{s}\) dependence)
Y. Itow, Forward production at LHC

2ndary particle productions

Figure by T. Pierog

<table>
<thead>
<tr>
<th>dN/dη</th>
<th>SPS low ~7 GeV</th>
<th>SPS high ~17 GeV</th>
<th>RHIC 200 GeV</th>
<th>LHC 7000 GeV</th>
</tr>
</thead>
</table>

remnant

Very forward

central

Projectile diffraction

LHCf sees

ATLAS/CMS

LHCf/ZDC

CASTOR

RPS
Very forward – connection to low-x physics

- Very forward region: collision of a low-x parton with a large-x parton
- Small-x gluon become dominating in higher energy collision by self interaction.
- But they may be saturated (Color Glass Condenstation)

Naively CGC-like suppression may occur in very forward at high energy

→ However situation is more complex (not simple hard parton collisions, but including soft + semi-hard)

[Diagram showing soft, hard, and semi-hard processes]
Particle density and energy flow for 7TeV pp
ATLAS and LHCf

Central detector (ATLAS)

LHCf, ZDC ($\eta \sim 8.5$)
**LHCf: location and detector layout**

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

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

**Detector I**
- Tungsten
- Scintillator
- Scintillating fibers
- Front Counter: 140 m
- 8 cm wide

**Detector II**
- Tungsten
- Scintillator
- Silicon μ strips
- Front Counter: 140 m
- 6 cm wide

**INTERACTION POINT**
- IP1 (ATLAS)
- 44X₀, 1.6 λᵢₙₜ

**NG NEUTRAL LE BEAM**
CMS forward and TOTEM

Forward Detectors

- Hadronic Forward (HF) (3<|η|<5)
- Inner Tracker
- Hadronic Forward (HF) (3<|η|<5)
- ZDC (|η|>8.4) (-6.6<η<-5.2)
- CASTOR
- ZDC (|η|>8.4)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic Forward (HF)</td>
<td>( \sigma_E \approx 20-40% ) High granularity, Steel absorb. and quartz fibres</td>
</tr>
<tr>
<td>CASTOR</td>
<td>( \sigma_E \approx 5-20% ) Quartz/tungsten calorimeter</td>
</tr>
<tr>
<td>TOTEM T2</td>
<td>( p_T &gt; 40 \text{MeV} ) Triple-GEM</td>
</tr>
</tbody>
</table>

Slide by C. Baus
E calib. is challenging.
So far calibrate to HF at 7TeV pp by $\eta$ extrapolation. (PbPb analysis, 20% uncertainty)
In future, Z->ee or UPC can give precise absolute E scale
Y. Itow, Forward production at LHC

TOTEM

TOTEM – Experimental Setup at IP5

T1, T2: CSC and GEM Inelastic telescopes; RP: Roman Pots
[Details: JINST 3 (2008) S08007 and F. Ferro’s talk at this meeting]
ALICE

The ALICE experiment at LHC

Central rapidity
Inner Tracking (ITS), Time
Projection Chamber (TPC),
Time-of-Flight, TRD, EMCAL
|\eta| < 0.9

Forward rapidity
Muon Spectrometer
-4 < \eta < -2.5

New FOCAL plan
3.3 < \eta < 5.3
LHCb

- Unique forward spectrometer $2 < \eta < 5$
- VELO (vertex locator) 8mm distance to beam
Outline of this talk

• Energy flow in pp
  – CMS
  – ATLAS
  – LHCf

• Multiplicity in pp
  – CMS+TOTEM
  – LHCb
  – ALICE

• Energy flow in PbPb
  – CMS

• Nuclear modification in pPb
  – ALICE
  – LHCf

• Future

Special thanks to
C.Baus,
R.Ulrich,
S.Ostapchenko,
T.Pierog,
Y.Yamazaki,
N.Sakurai
and more…
Forward energy spectra and energy flow
CMS HF: Forward energy flow


\[
\frac{dE}{d\eta} (\text{GeV})
\]

Minimum Bias

\[
\text{CMS}
\]

0.9 TeV

7 TeV

3.15 < \eta < 4.19
CMS hard-to-inclusive energy ratios

- Ratio of $E$ in $-6.6<\eta<-5.2$ btw two samples
  - Inclusive and hard samples (leading charged jet in central)
  - Large jet PT -> harder (more central) collisions
- 7 TeV; increase at large PT due to multi parton interactions (MPI)
- 0.9 TeV: decrease at large PT due to less proton remnant energy
Y. Itow, Forward production at LHC

Energy dependence of energy flow ratio (-6.6 < η < -5.2)

- Relative energy flow ratio to 2.76TeV pp collisions
- Larger slope for hard sample (central jet PT>10GeV/c)
- MPI is important to explain these trend

JHEP 04 (2013) 072
ATLAS ET for MB and hard $|\eta|<4.8$

- ET sum for charged $p>500\text{MeV}$ (neutral $>200\text{MeV}$)
- minimum bias and hard dijet samples
  - MB: 2 PT$>150\text{MeV}$ tracks in $|\eta|<2.5$
  - DIJET: 2 back-to-back jets w/ ET$>20\text{GeV}$ in $|\eta|<2.5$

\[\langle \delta^2 \Sigma E_T \rangle \text{[GeV]} \]

\[\frac{\delta^2 \Sigma E_T}{\delta \phi} \text{[GeV]} \]

\[\frac{MC}{Data} \]

\[\text{Data, Py6 AMBT1, Py6 AUET2B, CTEQ6L1, Py6 DW, Py8 4C, H++ UE7-2, EPOS LHC} \]

\[N_{ch} \geq 2 \left(p_T^{ch} > 250 \text{MeV}, |\eta^{ch}|<2.5\right) \]

\[p_T^{ch(\text{neutral})} > 500(200) \text{MeV} \]

\[N_{\mu} \geq 2 \left(E_T^{\mu,1,2} > 20 \text{GeV}, |\eta^{\mu}|<2.5\right)\]

\[|\Delta\phi| > 2.5, E_T^{\mu,1,2}/E_T^{\mu} > 0.5 \]

\[\text{Transverse region} \]

\[p_T^{ch(\text{neutral})} > 500(200) \text{MeV} \]
ATLAS DIJET/MB ET ratio

- EPOS reproduces MB ET, but less in DIJET
LHCf single $E_{\gamma}$ at 7 TeV and 0.9 TeV pp

7 TeV

$\eta > 10.94$

LHCf $\sqrt{s} = 7$ TeV

Gamma-ray like

$\eta > 10.94, \Delta \phi = 360^\circ$

3.5 TeV

0.9 TeV

LHCf $\sqrt{s} = 900$ GeV

Photon like

$\eta > 10.15 (\langle \theta \rangle = 39 \mu$rad)

$\eta > 10.15$

$8.77 < \eta < 9.46$

$\langle \theta \rangle = 234 \mu$rad

3.5 TeV

$8.81 < \eta < 8.99$

LHCf $\sqrt{s} = 7$ TeV

Gamma-ray like

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

DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

PLB 703 (2011) 128-134
PLB 715 (2012) 298-303
LHCf $\pi^0$ $P_T$ at 7TeV pp

PRD 86 (2012) 092001

Type-I

Type-II

$\sqrt{s}=7\text{TeV}$ $\pi^0$

$8.9 < y < 9.0$

$\int Ldt=2.53+1.90\text{nb}^{-1}$

$1/\alpha_{\text{inel}} E d^3\sigma/d^3p$ [GeV$^{-2}$]

Data 2010
DPMJET 3.04
QGSJET II-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

$9.4 < y < 9.6$

$\int Ldt=2.53+1.90\text{nb}^{-1}$

$1/\alpha_{\text{inel}} E d^3\sigma/d^3p$ [GeV$^{-2}$]

Type-I sample
Type-II sample

Type-I at LHCf-Arm1
Type-II at large tower
Type-II at small tower

$E \pi^0$(GeV) 3500
LHCf EM(\(\pi^0\)) energy flows vs rapidity (7TeVpp)

- Integrated p0 energy in LHCf acceptance
- Reasonably reproduced by QGSJET04 and EPOS-LHC
- Only tail covered for 7TeV, but peak covered for 13 TeV

Plot by N.Sakurai
Very forward neutron at 7TeV p-p

- $\eta > 10.76$: QGSJET03 good, $>\eta > 9.22$ DPMJET3 good
- Larger neutron / gamma ratio than expected

<table>
<thead>
<tr>
<th>Data</th>
<th>$n/\gamma$ ratio</th>
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<tr>
<td>DPMJET3.04</td>
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<td>EPOS 1.99</td>
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<tr>
<td>SYBILL 2.1</td>
<td>0.88</td>
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</tr>
</thead>
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<td>DPMJET3.04</td>
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<tr>
<td>EPOS 1.99</td>
<td>0.69</td>
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<td>PYTHIA 8.145</td>
<td>0.82</td>
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<tr>
<td>QGSJET II-03</td>
<td>0.65</td>
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<tr>
<td>SYBILL 2.1</td>
<td>0.57</td>
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LHCf neutron energy flow vs rapidity

Plot by N. Sakurai
Bump ? at XF=1 for 0 deg neutron


RHIC PHENIX (200GeV), ISR (30.6-62.7 GeV)

LHCf 7TeV neutron (Arm1 only)

0<P_T<0.11x_F GeV/c
Comparison to HERA 0 deg neutron (Y. Yamazaki @ LOWX2014)

Neutron XF for LHCf kinematical regions calculated based on HERA data (Nuc Phys B 776, (2007) 1) by Y. Yamazaki (Kobe)

Disagree: $\eta > 10.76$ non zero at $X_f = 1$
Agree: $9.22 > \eta > 8.81$

Comparison (2)

- Medium-$x_F$ behaviour: quite well reproduced
  - including the height of peaks, if appropriately normalised by a common factor
- Lack of events for $E > 2500$ GeV in the HERA parameterisation
- Low-$x_F$: slight deficit
  - Note that the exponential parameterisation may not be appropriate when the slope is small
Y.Itoh, Forward production at LHC

Low mass diffraction plays in $X_F=1$

- QGSJET03 (& EPOS also ?) reproduces 0 deg. neutron
- Low $\xi$ bump in low mass diffraction contributes neutron $X_F$ bump (c.f. Ostapchenko)

S.Ostapchenko@HESZ2014
Forward multiplicity
Charged multiplicity in CMS+TOTEM T2

- First attempt of CMS+TOTEM common plot
- Reasonable agreement wide $\eta$ range in $0 \sim 5.3-6.2$, while data may prefer less (more) in central (forward)

Inclusive, 8TeV pp

NSD enhanced, 8TeV pp
ALICE photon multiplicity in $2.3 < \eta < 3.9$

- Forward $N_\gamma$ by ALICE PMD
- Higher multiplicity than models.

arXiv:1103.1668
LHCb charged multiplicity

- $2 < \eta < 4.5$ and $-2.5 < \eta < -2$
- Data excess substantially
- Forward charm also available? (wish for atm prompt $\nu$ study)

Forward energy flow in PbPb
CMS forward energy flow in Pb-Pb

CMS PAS HIN-12-006

- Central: EPOS better
- Peripheral: QGSJET better

![Histograms showing energy flow in Pb-Pb collisions for different centralities: 20-30% and 70-80%.]
PbPb centrality dependence

$$R_{PC}(\eta, N_{\text{part}}) = \frac{\langle E \rangle(\eta, N_{\text{part}})}{\langle E \rangle(\eta, N_{\text{part}}^{\text{max}})} \cdot \frac{N_{\text{part}}^{\text{max}}}{N_{\text{part}}}$$

Forward energy flow
Weaker centrality dependence

CMS PRELIMINARY

---

PbPb, $\sqrt{s_{NN}}=2.76$ TeV

-6.60 < $\eta$ < -5.19
-4.89 < $\eta$ < -4.54
-0.35 < $\eta$ < 0.35

-6.60 < $\eta$ < -5.19

EPOS-LHC
QGSJetII.3
AMPT
HYDJet 1.8
Nuclear modification in pPb
Nuclear shadowing at very forward in p-A?

- Suppression and PT broadening due to gluon saturation
- Maybe large at very forward (small-x)

\[
R_{dAu}^Y = \frac{\sigma_{\text{inel}}^{pp}}{\langle N_{\text{bin}} \rangle \sigma_{\text{hadr}}^{dAu}} \frac{E d^3\sigma / dp^3(d + Au \rightarrow Y + X)}{E d^3\sigma / dp^3(p + p \rightarrow Y + X)}
\]

\(\langle N_{\text{bin}} \rangle\): Number of N-N binary collisions (from Glauber model)

\(\eta\) = 4.0

\(\pi^0 (\langle \eta \rangle = 4.00)\)

\(h^- (\eta = 3.2)\)

\(h^- (\eta = 2.2)\)

Gluon saturation

\(\sqrt{s_{\text{NN}}} = 200\) GeV

RHIC STAR d-Au, PRL 97, 152302 (2006)
ALICE pPb 5.02TeV $R_{pPb}$: central and forward

- Large suppression at low PT in pPb in central
- $J/\phi$ suppression in forward p side, but no in Pb side
- $\psi(2S)$ suppressed in both side of forward

PRL 110, 082302 (2013)
arXiv:1405.3796
LHCf nuclear modification factor (-11.0 > η > -8.9)

- Very large suppression (~ 0.1) at \( P_T \sim 100\text{MeV} \) region in p-side
- Models also reproduce large suppression, but PT dependence?

\[
R_{pPb} \equiv \frac{\sigma_{\text{inel}}^{pp}}{\langle N_{\text{coll}} \rangle \sigma_{\text{inel}}^{ppb}} \frac{E d^3 \sigma^{pPb}/dp^3}{E d^3 \sigma^{pp}/dp^3}
\]

\( \langle N_{\text{coll}} \rangle = 6.9 \pm 0.7 \)
Future
Possible future p-Oxygen run

- Important missing information; nuclear shadowing
- Large suppression 0.1 for p-Pb for very forward $\pi^0$ at low PT
- Less expected for p-Light Ion, but model dependent (~25%)
- Oxygen beam is technically feasible in LHC

By T. Pierog

Current largest diff. btw 2 models

By S. Ostapchenko

QGSJET II-04

EPOS LHC

O + p → All $\sqrt{s} = 4.9$ TeV

25% difference
Missing $\eta = 6.6-8.4$ coverage, how cover?

- Current LHCf acceptance limited by beam pipe vertical aperture at D1 exit
- CMS CASTOR Z=14.3m, $\eta = -5.2 - -6.6$
- Still large energy flow fraction here
- Interesting transition region from diffraction to string fragmentation.

Uncovered!
Summary

• Now various forward particle production data available at LHC for pp, pPb and PbPb at various energies.

• What we observed is:
  – None of models can reproduce perfectly
  – But CR models eventually work reasonably well

• We may start to see some trends in forward (personal view)
  – Less energy flow, softer spectrum of $\pi^0$
  – More abundant and larger energy flow of baryon (neutrons)
  – More harder MPI collisions to produce higher multiplicity
  – Larger suppression due to nuclear effect
  – These may suggest some new insight of QCD (saturation, etc..?)

• Need more data
  – 13 TeV! Higher energy density, larger forward collimation
  – Less knowledge for nuclear effect. Future p-O run?
Summary: forward spectra coverage

\[ \eta \]

\[ \sqrt{s} \]

\[ \theta = \frac{<P_T>}{P_{\text{beam}}} \]

\[ <P_T> \sim 0.4 \text{GeV/c} \]

\[ \text{ISR} \]

\[ \text{BRAHMS} \]

\[ \text{UA5} \]

\[ \text{CDF} \]

\[ \text{ATLAS} \]

\[ \text{CMS} \]

\[ \text{ALICE} \]
Parent particles relevant for LHCf observations

Gamma spectrum

Hadron spectrum

Fraction of $\pi^0$ and $\eta$ differs each model.

Sybill at 7TeV
7TeV pp energy flow summary

E flow vs. $\eta$ distr. of p-p $\sqrt{s}=7$[TeV]

- All
- $\pi^0$
- $\pi^\pm$
- $K^\pm, K^0_s, K^0_L$
- $p, \bar{p}$
- neutron
- $\Lambda$

QGSJET04
Elasticity ( $X_F$ of leading baryon)
pseudorapidity and interactions

Elastic

Single diffractive

Double diffractive

Non-diffractive

\( \sigma @7\text{TeV} \)

\(~25\text{mb}~\)

\(~10\text{mb}~\)

\(~10\text{mb}~\)

\(~50\text{mb}~\)
Forward E spectra forseen at 14TeV (MC for ~0.1nb^{-1})

Gamma Energy spectrum of 20mm square at Beam Center

single γ

DPMJET3
QGSJET
QGSJETII
SIBYLL

Neutrons (true energy)

QGSJET
QGSJETII
DPMJET3
SIBYLL

Neutrons (w/ 30% resolution)

30% Energy Resolution

ΔE/ΔN [1/100GeV/1.04x10^{7}col.]

Reconstructed
DPMJETIII
QGSJETII
SIBYLL
EPOS1.99

ΔE/ΔN [1/100GeV/1.04x10^{7}col.]

10^{-3}
10^{-2}
10^{-1}
1
10
10^{-3}
10^{-4}

E_{π^0} [GeV]
Rapidity vs Forward energy spectra

Gamma-rays @ $\sqrt{s}=7$TeV

Neutral Hadrons @ $\sqrt{s}=7$TeV

Projected edge of beam pipe

Viewed from IP1 (red:Arm1, blue:Arm2)
Contribution from very forward production

$5 \times 10^{19}$ eV proton showers
(60 deg zenith)

- No cut
- Low $X_F \gamma$ origin ($x_F < 0.05$)
- $\pi, K$ origin ($x_F < 0.1$)

Half of shower particles comes from large $X_F \gamma$

Measurement at very forward region is needed
Impact of parameters of interactions

- Cross section
- Multiplicity
- Elasticity

R. Ulrich et al., PRD83(2011)054026
Y. Itow, "Forward production at LHC"

ALICE $\sigma_{\text{diffraction}}$

LHC zero degree experimental site

- **Protons**
- **Charged particles (+)**
- **Neutral particles**
- **Beam pipe**
- **Charged particles (-)**

**LHCf/ZDC**

**96mm**

**ATLAS**

**TAN absorber**
Energy flow for $\sqrt{s}=14$ and 7TeV

14TeV

7TeV

Double diffractive $\pi^0$

Single diffractive $\pi^0$
LHCf $\pi^0$ $p_T$ for 5.02 TeV pPb ($-11.0 > \eta > -8.9$)

- Large suppression and PT broadening
- Irrelevant to $\eta$ region