Forward Physics Results from ATLAS and CMS

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On behalf of the CMS and ATLAS Collaborations

Hadron Structure 2013, VYSOKÉ TATRY, SLOVAKIA
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• **Forward Detectors at ATLAS and CMS**

• **Diffractive Dissociation**
  

  Measurement of diffraction dissociation cross sections at sqrt(s)=7 TeV at the LHC, CMS-PAS-FSQ-12-005, (2013).

  CMS+TOTEM event displays of high-p_T jets with two leading protons at sqrt(s)=8 TeV. CMS-DP-2013-004, CMS-DP-2013-006.

• **Transverse Energy Density and Underlying Events at Forward Rapidities**
  
  Study of the underlying event at forward rapidity in pp collisions at sqrt(s) = 0.9, 2.76, and 7 TeV, JHEP 04 (2013) 072, arXiv:1302.2394 [hep-ex].


  The underlying event in jet events at 7 TeV with the ATLAS experiment, ATLAS-CONF-2012-164.

• **Forward Jets**
  
  Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at sqrt(s) = 7 TeV, CMS PAS FSQ-12-002 (2013).

  Measurement of the inclusive jet cross-section in pp collisions at sqrt(s) = 2.76 TeV and comparison to the inclusive jet cross-section at sqrt(s) = 7 TeV using the ATLAS detector, arXiv:1304.4739 [hep-ex], submitted to Eur. Phys. J. C.

• **Summary**
ATLAS Forward Detectors

on both sides

- $2.1 < |\eta| < 3.8$
- $5.6 < |\eta| < 5.9$
- $|\eta| > 8.3$
- $10.6 < |\eta| < 13.5$

MBTS

Minimum bias triggers

LUCID

LUminosity Cherenkov Integrating Detector

counts number of interactions bunch-by-bunch

Zero Degree Calorimeter detects neutrals (n, γ)

Forward Calorimeter (FCAL), Liquid Argon (ionization)

3.1 < |\eta| < 4.9

Absolute Luminosity For ATLAS.

Roman Pots at 240m.
Zero Degree Calorimeter detects neutrals (n, γ) | | > 8.1

Roman Pots: detection of very forward protons

- TOTEM
  - Roman Pots
  - ±147m, ±220m

- CMS Forward Detectors
  - FSC
    - ~6 < |η| < 8
    - |η| > 8.1
  - BSC
    - 3.23 < |η| < 4.65
  - HF (Hadron Forward)
    - 3 < |η| < 5
  - T1
    - 3.1 < |η| < 4.7
  - T2
    - 5.3 < |η| < 6.5
  - CASTOR
    - -6.6 < η < -5.2

- Triggering minimum bias events with BSC.
- CASTOR is only at minus side.
Diffractive Dissociation

1. Forward rapidity gap cross section. (ATLAS).


3. Event displays of high-\(p_T\) jets with two leading protons. (CMS + TOTEM).
$\Delta \eta^F$: Largest empty $\eta$ interval from the edge of the detector.

$\Delta \eta^F = \max(\Delta \eta^\text{backward}, \Delta \eta^\text{forward})$

- Corrected back to hadron level for different $p_T$ cuts on stable final particles in $|\eta| < 4.9$. $p_T^{\text{cut}} > 200, 400, 600$ and $800$ MeV

- Exponential falling non-diffractive contribution.

- Diffractive plateau at $\Delta \eta^F > 3$

- Diffractive plateau corresponds to a mixture of SD and DD events with $\xi_Y < 10^{-6}$.

- The differential cross-section rises slowly with increasing $\Delta \eta^F$ for $\Delta \eta^F \gtrsim 5$. **What will the slope be at larger $\Delta \eta^F$?**
Described by Triple Pomeron-based approach, PYTHIA8, Donnachie-Landshof with

\[ \alpha_{IP}(0) = 1.058 \pm 0.003^{\text{stat.}} + 0.034^{\text{syst.}} - 0.039^{\text{syst.}} \]

CMS preliminary results extends the measurement by 0.4 unit of gap size. The rise still continues.

- Different hadron level definitions $|\eta| < 4.9$ (ATLAS) and $|\eta| < 4.7$ (CMS), up to 5% effect.
- Unfolding with a different model, PYTHIA8-MBR ($\varepsilon=0.08$), up to 10% effect.
- Agreement with ATLAS within uncertainties.
Difficult to distinguish SD and low-mass DD events in the limited $\eta$ coverage.

CASTOR

-6.6 < $\eta$ < -5.2

undetected particles in $|\eta| < 4.7$

SD1 type, gap on plus side

SD2 type, gap on plus side

DD type, central gap

$\eta_{\text{max}}$ ($\eta_{\text{min}}$) = $\eta$ of most forward (backward) particle

$\eta_{\text{o,max}}$ ($\eta_{\text{o,min}}$) = closest-to-zero positive (negative) $\eta$ of the rec. par.

measure SD and DD cross sections

$\eta_{\text{min}} > -1$ and CASTOR to separate SD and DD events

measure DD cross section

$\Delta \eta^o > 3$ selection

$\Delta \eta^o = \eta_{\text{o,max}} - \eta_{\text{o,min}}$
SD and DD cross sections as a function of $\xi$

PYTHIA8-MBR describe SD and DD cross sections. Better description of DD with smaller $\epsilon$.

PYTHIA6/8 Good description of DD but not describes the falling behavior of SD.

\[ \sigma_{SD} = 4.27 \pm 0.04 \text{(stat.)}^{+0.65}_{-0.58} \text{(syst.)} \text{ mb} \]

integrated over $-5.5 < \log_{10}\xi < -2.5$.

Multiplied by 2 to to account for both $pp \rightarrow Xp$ and $pp \rightarrow pX$ processes.

proton fractional momentum loss.

$\xi^\pm = \frac{\sum(E_i \pm p_{z}^i)}{\sqrt{s}} \sim \frac{M_X^2}{s}$
DD cross section as a function of $\Delta \eta$

The DD cross section predictions of PYTHIA8-MBR, PYTHIA8 and PYTHIA6 are in agreement with data.

The dominant source of uncertainties:
- Energy scale of HF (Hadron Forward)
- Hadronization and diffraction model.

$\sigma^{DD}_{\text{vis}} = 0.93 \pm 0.01(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$ mb

integrated over $\Delta \eta > 3$, $M_X > 10$ GeV and $M_Y > 10$ GeV
high-p$_T$ jets with two leading protons

3 jets event display – CMS
Run 198903 – Event 3478279

- At least two jets with p$_T$ > 20 GeV at CMS.
- FSC empty, 6<|\eta|<8.
- Reconstructed (non-elastic) proton tracks at TOTEM Roman Pots on both sides of IP.

Leading three jets E$_T$ = 65, 45, 27 GeV
proton \Delta p/p = -0.01 (z+)
proton \Delta p/p = -0.1 (z-)
M(pp, TOTEM) = 244 GeV
M(CMS) = 219 GeV
$\Sigma$ p$_T$ (CMS) = 3.4 GeV
FSC empty in both sides

ECAL/HCAL E$_T$ > 200 MeV
Track p$_T$ > 1 GeV
high-$p_T$ jets with two leading protons

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ECAL/HCAL $E_T > 200$ MeV
Track $p_T > 1$ GeV
high-$p_T$ jets with two leading protons

3 jets event display – TOTEM T2
Run 198903 – Event 3478279

- At least two jets with $p_T > 20$ GeV at CMS.
- FSC empty, $6 < |\eta| < 8$.
- Reconstructed (non-elastic) proton tracks at TOTEM Roman Pots on both sides of IP.
high-$p_T$ jets with two leading protons

3 jets event display – TOTEM RP
Run 198903 – Event 3478279

- At least two jets with $p_T > 20$ GeV at CMS.
- FSC empty, $6<|\eta|<8$.
- Reconstructed (non-elastic) proton tracks at TOTEM Roman Pots on both sides of IP.
Transverse Energy Flow and Underlying Events at Forward Rapidities

1. Underlying Events (UE) at forward rapidities at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. (CMS).
2. $\eta$ dependence of the total transverse energy at $\sqrt{s} = 7$ TeV. (ATLAS).
3. UE in jet events -- including full-$|\eta|$ range up to $|\eta| < 4.8$, $\sqrt{s} = 7$ TeV. (ATLAS).

**Inclusive**: Inelastic pp collisions (Minimum bias), non-diffractive or non-single-diffractive (NSD),...

**Hard scale**: usually requiring a dijet system with certain $p_T$ at central rapidities, $|\eta| < 2.5$. 

![Diagram of Transverse Energy Flow and Underlying Events at Forward Rapidities]
The UE activity at Forward Rapidity

**hard-to-inclusive ratio vs leading jet $p_T$**

-6.6 < $\eta$ < -5.2

$\sqrt{s} = 7$ TeV: Fast rise at low $p_T$ followed by a plateau at $p_T > 8$ GeV. *Typical UE behavior.*

$\sqrt{s} = 0.9$ TeV: *Ratio* < 1. Higher UE activity depletes the proton remnant which fragments into CASTOR.

- need MPI to describe the data.

- **Best model** PYTHIA tunes (4C, $Z^*$) fitted to the LHC data on UE at central rapidity.

- The SIBYLL and EPOS over estimates the turn-on but have good description at large $p_T$.

- DIPSY (BFKL dipole picture + MPI between dipoles) fails to describe the data.
Inclusive events

(UE contribution is expected to be small)

- The predictions differ little.

- QGSJETII-03 describes the data while other models underestimate the relative increase at $\sqrt{s} = 7$ TeV.

Events with hard scale

(lead. charged jet $p_T > 10$ GeV/c, $|\eta| < 2$)

- The predictions vary widely.

- QGSJETII-03, PYTHIA6-D6T and PYTHIA8-4C close to data. The other tunes/models underestimate the relative increase at $\sqrt{s} = 7$ TeV.
Differential Transverse Energy Density

$|\eta| < 4.8$, Inelastic pp collisions (Minimum Bias), Dijet events with $E_T^{\text{jet}} > 20$ GeV, $|\eta^{\text{jet}}| < 2.5$, back-to-back.

Good agreement in central region but not in forward.

Best soft model
EPOS LHC

Forward flow underestimated

Best UE model
PYTHIA6-DW
(Tevatron-era tune with virtuality ordered shower)
Diffractive contribution **doubled** or **halved** with constant non-diffractive cross section.

Increasing diffraction contribution:
- $E_T^{\text{density}}$ decreases.
- but **little effect on the shape**.

Change from CTEQ6L1 to MSTW2008 LO PDFs: (increasing gluon PDF both at low-x and high-x w.r.t. mid-x fraction). **Less energy in the central but more in forward.**
Underlying Event in jet events

$|\eta| < 2.5$

Inclusive

$|\eta| < 4.8$

Inclusive

$|\eta| < 2.5$

Exclusive

$|\eta| < 4.8$

Exclusive

Extending measurement to $|\eta| < 4.8$.

Exclusive dijet requirement removes contributions from extra jets (vetoing additional radiations).

very similar UE activity in central and forward regions for exclusive event selection.

Full $|\eta|$-range:

• Models undershoot the observed level of activity at low $p_T$ in both the inclusive and exclusive selections.

• Larger deviations from MC predictions than in the central region.
Forward Jets

1. Azimuthal angle decorrelations of Mueller-Navelet jets at $\sqrt{s} = 7$ TeV. (CMS)

2. Measurement of the inclusive jet cross section at $\sqrt{s} = 2.76$ TeV and comparison to the inclusive jet cross section at $\sqrt{s} = 7$ TeV. (ATLAS).

Mueller-Navelet jets:
the most forward and backward jets in rapidity.
Azimuthal decorrelations – $\Delta \phi$

- At least two jets, $p_T > 35$ GeV, $|\eta| < 4.7$.
- MN dijets (most forward and backward jets in rapidity)

**Observables:**

- \[
\frac{1}{\sigma} \frac{d\sigma}{d(\Delta \phi)}, \text{ rad}^{-1}
\]
- Fourier coefficients, $C_N = <\cos(N(\pi - \Delta \phi))>$; $N = 1, 2, 3$
- Ratios $C_2/C_1$ and $C_3/C_2$

**3 bins** of rapidity separation between jets

- $0 < \Delta y < 3$
- $3 < \Delta y < 6$
- $6 < \Delta y < 9.4$ (azimuthal decorr. never measured before)

- Larger azimuthal decorrelation with increasing $\Delta y$.
- Best description with Herwig++ (DGLAP and built-in AO).
- AO and MPI improve the description of the data, particularly at high $\Delta y$.
Azimuthal decorrelations – $C_{N+1}/C_N$

$C_2/C_1$ and $C_3/C_2$ ratios.

$C_N = \langle \cos(N(\pi - \Delta \phi)) \rangle$ ; $N = 1,2,3$

**Suppression of DGLAP contributions. Sensitive to BFKL–effects.**

**at low $\Delta y$:**
- $C_{N+1}/C_N$ described well by LL DGLAP based generators, PYTHIA6/8, Herwig++, Sherpa.
- Cascade–2 (CCFM) strongly underestimate $C_{N+1}/C_N$.

**at large $\Delta y$:**
- PYTHIA6/8 overestimate $C_2/C_1$.
- Herwig underestimate $C_{N+1}/C_N$.
- Sherpa $C_2/C_1$ but close to data for $C_3/C_2$.

**BFKL NLL analytical calculation at parton level, only for $\Delta y > 4$, describes $C_2/C_1$ within uncer.**
Inclusive Jet Cross Section

\( \sqrt{s} = 7 \text{ TeV} \) (\textit{Phys.Rev. D86 (2012) 014022})

\( \sqrt{s} = 2.76 \text{ TeV} \)

\( \sqrt{s} = 7 \text{ TeV} \)

\( \sqrt{s} = 2.76 \text{ TeV} \)

\( L = 0.20 \text{ pb}^{-1} \)

- Compared to NLO pQCD predictions, including non-perturbative corrections. 5 different PDF sets.
- The incl. jet cross section ratio of \( \sqrt{s} = 2.76 \text{ TeV} \) to \( \sqrt{s} = 7 \text{ TeV} \). Reduction of sys. uncer.

Good agreement with the data in general. Particularly, in the forward region, the central value of the prediction describes the data well.
jet cross section ratio (2.76 TeV / 7 TeV) vs $p_T$

- Small dependency to PYTHIA parton shower tunes. Only visible in the forward region for large-$p_T$.
- Like NLO pQCD ⊗ non-perturbative corrections, POWHEG has a different trend (up to 10%) at central rapidity but describes the data at forward rapidity.
Summary

Diffractive Dissociation

- ATLAS **forward rapidity gap cross section data** can be used to investigate and tune the Pomeron based MC models. CMS (preliminary results) extends the ATLAS measurement by 0.4 unit of gap size.

- **Inclusive SD and DD cross sections measured at 7 TeV:**
  \[
  \sigma_{SD}^{\text{vis}} = 4.27 \pm 0.04(\text{stat.})^{+0.65}_{-0.58}(\text{syst.}) \text{ mb for } -5.5 < \log_{10}\xi < -2.5 \\
  \sigma_{DD}^{\text{vis}} = 0.93 \pm 0.01(\text{stat.})^{+0.28}_{-0.22}(\text{syst.}) \text{ mb for } \Delta\eta > 3, M_X > 10 \text{ GeV}, M_Y > 10 \text{ GeV}
  \]

- CMS+TOTEM high-p_T jet event displays with two protons detected in the TOTEM RP.

Underlying Events at Forward Rapidities

- More complete picture of UE with the data in the forward region. Almost all models/tunes underestimates the UE activity in the forward. All models fail to reproduce the dependence on the \( \sqrt{s} \) simultaneously for inclusive events and events with a hard scale.

Forward Jets

- **Azimuthal angle decorrelations of Mueller-Navelet dijets** as a function of rapidity separation are measured for the first time up to \( \Delta y = 9.4 \) at \( \sqrt{s} = 7 \text{ TeV} \) pp collisions. Herwig++ and analytical BFKL NLL calculations demonstrate a better description of the data than the other DGLAP based MCs. **No sufficient evidence for or against BFKL effects. Data at higher energies are needed** to have a conclusion.

- **Inclusive jet double-differential cross section** is measured for jets up to rapidities of 4.4 at \( \sqrt{s} = 2.76 \text{ TeV} \). The ratio to the previously measured cross section at 7 TeV (ATLAS) is calculated. **Precise test of NLO pQCD** due to the reduced uncertainties. The predictions are in good agreement with the data in general. **POWHEG has the best description of the forward data.**

For all public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ
Backup
Comparion with published ATLAS paper (inelastic pp cross section at $\sqrt{s} = 7$ TeV)
good to 0.8%. The small difference explained by run-to-run lumi error which is the dominant source of the uncertainty for both measurements.
**Data/Trigger:** 2012 Low-PU 90m $\beta^*$ runs with common TOTEM-CMS trigger. TOTEM RP and T2 triggers to CMS, CMS combined di-jet and lepton/gamma trigger to TOTEM. CMS 'L1_DoubleJet20'.

**Event Selection:**
- At least two jets with $p_T > 20$ GeV, anti-$k_T$, R=0.5.
- Forward Shower Counters (FSC) empty, $6<|\eta|<8$.
- Reconstructed (non-elastic) proton tracks at TOTEM Roman Pots on both sides of IP.

**high-$p_T$ jets with two leading protons**

**very large rapidity coverage!**
Average cosines are sensitive to the parton ordering scheme in the parton shower and to the MPI.

A good description of the data requires polar angle ordering in parton showering.

C2/C1 and C3/C2 are more sensitive to AO and MPI conditions.
\[ C_N = \langle \cos(N(\pi - \Delta \phi)) \rangle ; \ N = 1, 2, 3 \]

The averages cosines are expected to be sensitive to the properties of non-collinear dynamics.

HERWIG++ 2.5 shows a satisfactory agreement with the data on the average cosine.

SHERPA overestimates the data.

CCFM based CASCADE predicts too weak angular correlation.

BFKL NLL analytical calc. at parton level: too strong angular correlation compared to the data.
Momentum distribution of the gluon $x_g$ and sea quarks $x_S = 2(x\bar{u} + x\bar{d} + x\bar{s})$ at the scale $Q^2 = 1.9 \text{ GeV}^2$

After the inclusion of the ATLAS jet data:

- The gluon momentum distribution tends to be harder.
- **The uncertainty in $x_g$ is reduced.**
- Being smaller in the high-$x$ region, the sea quark momentum distribution tends to be softer.