Measurement of Diffraction and Underlying Event at ATLAS

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Analyses presented:

- “Measurement of differential cross sections for single diffractive dissociation in $\sqrt{s} = 8 \text{ TeV}$ pp collisions using the ATLAS ALFA spectrometer”
  - Accepted by JHEP

- “Measurement of distributions sensitive to the underlying event in inclusive Z boson production in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector”
Measurement of differential cross sections for single diffractive dissociation in $\sqrt{s} = 8$ TeV pp collisions using the ATLAS ALFA spectrometer
Total pp cross section

- Single Diffraction
- Non-diffraction
- Central Diffraction
- Double Diffraction
- Elastic
**Analysis variables**

Rapidity gap size

\[ \Delta \eta \]

Fractional energy loss of proton

\[ \xi = 1 - \frac{E_3}{E_2} = \frac{M_X^2}{s} \]

\[ \xi_{EPz} \approx \frac{\Sigma_i(E_i^z \pm p_i^z)}{\sqrt{s}} \]

Mandelstam t exchange

\[ t = (p_3 - p_2)^2 \]

\[ t \approx -p_T^2 \]
ALFA

Use requires:
• High $\beta^*$
• Low luminosity & pile-up

For the data in this analysis, $\beta^* = 90\text{m}$ & $\mu = 0.08$

Same run as used by elastic cross-section analysis
Event selection

- Online trigger
  - ALFA signal
  - MBTS on opposing side

- Offline selection:
  - Exactly one proton reconstructed in ALFA with additional selection
  - At least 5 MBTS counters above threshold
  - At least 1 ID track with $P_T > 200$ MeV
  - Only one reconstructed vertex
Backgrounds

• Single source backgrounds are small
  • CD biggest contribution

• ‘Overlay background’ is largest background
  • Due to uncorrelated ALFA activity (beam halo) and pile-up events
  • Estimated through data-driven model & ND-enriched sample
  • Provides t distributions
  • Provides normalisation to ξ & Δη MC distributions

• Performance of models assessed using control regions
Reconstructed level distributions

Nominal selection with $\sigma_{SD}$ scaled by 0.64

Background subtracted from data before iterative Bayesian unfolding
Integrated $\sigma_{SD}$

- Cross section integrated over fiducial region ($0.016 < |t| < 0.43$ GeV$^2$, $-4.0 < \log_{10} \xi < -1.6$):
  
  $$\sigma_{SD}(\xi, t \text{ fiducial}) = 1.59 \pm 0.13 \text{ mb}$$

- Small extrapolation (factor 1.18) for $0 < |t| < 0.016$ GeV$^2$ and $0.43$ GeV$^2 < |t| < \infty$ yields integrated $\sigma$ for $-4.0 < \log_{10} \xi < -1.6$:
  
  $$\sigma_{SD}(\xi \text{ fiducial}) = 1.88 \pm 0.15 \text{ mb}$$

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$\sigma_{SD}^{\text{fiducial}(\xi, t)}$ [mb]</th>
<th>$\sigma_{SD}^{t-\text{extrap}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$1.59 \pm 0.13$</td>
<td>$1.88 \pm 0.15$</td>
</tr>
<tr>
<td>PYTHIA8 A2 (Schuler–Sjöstrand)</td>
<td>$3.69$</td>
<td>$4.35$</td>
</tr>
<tr>
<td>PYTHIA8 A3 (Donnachie–Landshoff)</td>
<td>$2.52$</td>
<td>$2.98$</td>
</tr>
<tr>
<td>HERWIG7</td>
<td>$4.96$</td>
<td>$6.11$</td>
</tr>
</tbody>
</table>
Unfolded $\Delta \eta$

- Gap defined by charged particles with $P_T > 200$ MeV within $|\eta| < 2.5$

- Cross-section lower than predicted by MC:
  - PYTHIA8 A3 $\sim 1.5$
  - PYTHIA8 A2 $\sim 2.3$
  - HERWIG7 $\sim 3$

![Graph showing the ratio of data to MC for different models.](image)
Unfolded $|t|$

- Data consistent with expected exponential form

$$B = 7.65 \pm 0.26 \text{ (stat.)} \pm 0.22 \text{ (syst)} \text{ GeV}^{-2}$$

- Dominant uncertainty on $B$ is from overlay background and statistics
- Compare with:
  - PYTHIA8 A2 $B = 7.82 \text{ GeV}^{-2}$
  - PYTHIA8 A3 $B = 7.10 \text{ GeV}^{-2}$

$$\frac{d\sigma}{dt} = Ae^{Bt}$$
Unfolded $\xi$

- Follows $\frac{d\sigma}{d\xi} \propto \frac{1}{\xi}$ approximate relationship

- Also interpreted in triple Pomeron model with
  - $B = B_0 - 2\alpha' \ln \xi$
  - Fixed $B_0$
  - $\alpha(t) = \alpha(0) + \alpha' t$

$\alpha(0) = 1.07 \pm 0.02$ (stat.) $\pm 0.06$ (syst) $\pm 0.06$ ($\alpha'$)

- Dominant uncertainty is from extrapolation from lower $\sqrt{s}$ when using $\alpha' = 0.25 \pm 0.25$ GeV$^{-2}$

- Compare with:
  - PYTHIA8 A2 $\alpha(0) = 1.00$
  - PYTHIA8 A3 $\alpha(0) = 1.14$

- Data compatible with CMS result

\[ \frac{d\sigma_{SD}}{d\log_{10}\xi} \propto \left( \frac{1}{\xi} \right)^{\alpha(0) - 1} \frac{1}{B} \left( e^{B_{\text{high}} t} - e^{B_{\text{low}} t} \right) \]
Measurement of distributions sensitive to the underlying event in inclusive Z boson production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
The Underlying Event

• Activity accompanying the hard scatter
• The UE:
  • Can be in the soft QCD regime
  • Is not distinguishable from the hard scatter on an event-by-event basis
  • Can be probed using topological observable
  • Can include contributions from additional hard parton scatters (MPI)

• Using Drell-yan $Z \rightarrow \mu \mu$ events, the transverse regions should have little activity from the hard scatter
  • Particularly in trans-min, the region with the smaller (scalar) $\Sigma p_T$
Transverse thrust

- Transverse thrust describes the event topology

- $\hat{n}$ is unit vector which maximises thrust
- Events with lower thrust are more sensitive to MPI

\[
T_\perp = \frac{\sum_i |p^{T,i} \cdot \hat{n}|}{\sum_i |p^{T,i}|}
\]

Isotropic Event

Balanced Event

\[
T_\perp = \frac{2}{\pi}
\]

\[
T_\perp = 1
\]
Analysis variables

- Charged particle multiplicity
- Scalar sum of transverse momenta
- Mean transverse momentum of charged particles
- Normalised charged particle transverse momentum distribution
- All in bins of thrust, $P_T$ of Z boson & transverse / toward regions
Event selection

• Online trigger, either:
  • Single high-\(p_T\) (> 40 GeV) muon
  • Single, isolated lower-\(p_T\) (> 20 GeV) muon

• Offline selection:
  • Primary vertex
  • Exactly 2 muons with \(p_T > 25\) GeV & \(|\eta| < 2.4\)
  • Muons must be from PV & not from heavy quark decays
  • \(66\) GeV < \(m_{\mu\mu}\) < \(116\) GeV to reduce backgrounds

• Tracks:
  • \(p_T > 0.5\) GeV & \(|\eta| < 2.5\)
  • Come from PV
Backgrounds

- Assessed using MC:
  - $Z \rightarrow \tau\tau$
  - $Z \rightarrow tt$
  - $WW \rightarrow \mu\nu \mu\nu$
- Contribute to \(~0.7\%) of data events
**Differential distributions**

**All thrust**

![Graphs showing differential distributions](image)

- **ATLAS**
  - $\sqrt{s}=13$ TeV, 3.2 fb$^{-1}$
  - $10 \text{ GeV} < p_T^Z < 20 \text{ GeV}$
  - trans-min region

![Graph showing ratio and mean $p_T$](image)
Differential distributions

Different thrust

PowhegPythia8 shows good agreement at low thrust, but not at high

Sherpa & Herwig++ constantly across both thrust regions
Underlying event activity as a function of $p_T$

\begin{align*}
\Delta N_{\text{ch}} / \Delta \phi &\quad \text{ATLAS} \\
\text{trans-max region} &\quad \text{transverse region} \\
\text{trans-min region} &\quad \text{trans-\text{min} region}
\end{align*}

$\sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1}$

\begin{align*}
\Delta N_{\text{ch}} / \Delta \phi &\quad \text{ATLAS} \\
\text{powhegpythia8} &\quad \text{sherpa} \\
\text{herwig++} &\quad \text{stat. error} \oplus \text{syst.}
\end{align*}

Data 2015
Comparison with other \( \sqrt{s} \)s

Comparable, but slightly different, event selection
Growing UE activity with higher \( p_{T}^{z} \)

\[ \frac{N_{\text{ch}}}{\delta \eta / \phi} \]

ATLAS
\( \sqrt{s}=13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
trans-min

\[ \frac{<p_{T}^{z}>}{[\text{GeV}]} \]

ATLAS
\( \sqrt{s}=13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
trans-min

- Data 2015
- 7 TeV (4.6 fb\(^{-1}\))
- 1.96 TeV, CDF(p\(\bar{p}\), 2.7 fb\(^{-1}\))

syst. \( \oplus \) stat. error
Summary

- All tested generators significantly over predict the SD cross-section
- $B \& \alpha(0)$ are consistent with PYTHIA8
- All tested generators show significant deviations with data for predicting UE activity
- Herwig++ qualitatively performs best
Backup slides
Previous ATLAS result

- Previous ATLAS publication:
  - Measured inclusive rapidity gap spectra
  - Lack of proton tagging led to DD / SD / ND ambiguity
\[ \bar{x} = \frac{x_{\text{near}} + x_{\text{far}}}{2} \]
\[ \theta = \frac{x_{\text{far}} - x_{\text{near}}}{z_{\text{far}} - z_{\text{near}}} \]

- SD distribution is centred on (0,0)
- Only accept events within 3σ of SD MC fit parameters
- Removes beam backgrounds & restricts ξ range

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**ATLAS Simulation**

\[ \sqrt{s} = 8 \text{ TeV} \]

- 2 sigma
- 3 sigma
- 4 sigma
- No cuts

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**ATLAS Simulation**

\[ \sqrt{s} = 8 \text{ TeV} \]
MC & Acceptance

- Main MC sample is PYTHIA8 A3 tune $\alpha(0) = 1.08$
- Also:
  - PYTHIA8 A2 with $\alpha(0) = 1$
  - HERWIG7
- Lower limits in $\xi$ determined by MBTS requirements
- Upper limit in $\xi$ & t range determined by ALFA acceptance

**Fiducial range**

$0.016 < |t| < 0.43 \text{ GeV}^2$

$-4.0 < \log_{10} \xi < -1.6$
Control region: Overlay background
Nominal selection except 2 protons in ALFA
Control region: CD background

Nominal selection except 2 protons in ALFA & 2 < MBTS < 10

Reweighting applied
Response matrices

- $t$ & $\Delta \eta$ are approx. diagonal
- Linear calibration applied to $\xi$ corrects for:
  - Charged particles outside ID range
  - Missing neutrals
- Iterative Bayesian unfolding used to remove detector effects
Systematic uncertainties

- Plots show dominant sources
- Many more evaluated & not shown
- Overlay background is largest uncertainty in many bins
ξ comparison with CMS result

- Results scaled by 1.18 to cover full t range
- Shown to be compatible with similar CMS result:
  - Gap based
  - Small DD contribution
  - 7 TeV
  - *Phys. Rev. D* 92, 012003