Measurement of low energy observables in proton-proton collisions at ATLAS

Andrew Foster
University of Birmingham
On behalf of the ATLAS Collaboration

QCD17, July 2017
Unable to calculate low energy effects with perturbative QCD. Monte Carlo generators use phenomenological models with parameters tuned to data.

1. **Track-based Underlying Event, 13TeV**
   - Analysis method
   - Monte Carlo models & tunes
   - Distributions of UE-sensitive parameters

2. **Bose–Einstein Correlations, 0.9TeV, 7TeV**
   - BEC with ATLAS
   - Effective radius measurement

3. **Ordered Hadronic Chains, 7TeV**
   - 3D QCD helix string model
   - Theoretical predictions
   - Observations Track-based Underlying Event

4. **Proton tagging with AFP**
   - Diffraction enriched sample using proton tagging
Underlying Event

- The underlying event is everything other than the main hard scattering process.

- Includes initial and final state QCD radiation, multiple parton interactions (MPI) and remnants from the interacting proton.

- Influenced by physics not currently calculable, thus measurements provide understanding of mechanisms involved and empirical tuning for Monte Carlo free parameters.
Underlying Event at ATLAS

- $\sqrt{s} = 13$ TeV, very low pile-up
- Minimum Bias trigger
- $|\eta| < 2.5$ particles reconstructed in inner tracking detector with $p_T > 500$ MeV
- Events with leading charged particles, $p_T > 1$ GeV
- No additional vertices with $\geq 4$ tracks
- Particles separated into three regions with respect to leading track
- Transverse side with least activity (left) most sensitive to UE
Monte Carlo Generators & Tunes

<table>
<thead>
<tr>
<th>Generator</th>
<th>Version</th>
<th>Tune</th>
<th>PDF</th>
<th>Focus</th>
<th>From</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia 8</td>
<td>8.185</td>
<td>A2</td>
<td>MSTW2008 LO</td>
<td>MB</td>
<td>ATLAS</td>
</tr>
<tr>
<td>Pythia 8</td>
<td>8.185</td>
<td>A14</td>
<td>NNPDF2.3 LO</td>
<td>UE</td>
<td>ATLAS</td>
</tr>
<tr>
<td>Pythia 8</td>
<td>8.186</td>
<td>Monash</td>
<td>NNPDF2.3 LO</td>
<td>MB/UE</td>
<td>Authors</td>
</tr>
<tr>
<td>Herwig 7</td>
<td>7.0.1</td>
<td>UE-MMHT</td>
<td>MMHT2014 LO</td>
<td>UE/DPS</td>
<td>Authors</td>
</tr>
<tr>
<td>EPOS</td>
<td>3.4</td>
<td>LHC</td>
<td>—</td>
<td>MB</td>
<td>Authors</td>
</tr>
</tbody>
</table>

- Pythia 8:
  - A2: Tuned using ATLAS minimum-bias data
  - A14: Tuned to ATLAS UE and jet radiation observables. Emphasis on high-scale events.
  - Monash: Tuned using data from other LHC and Tevatron experiments as well as ATLAS.

- Herwig 7: Default Herwig tune, with data input from LHC and Tevatron UE measurements

- EPOS: 3.4 is ‘LHC tune’ of EPOS; a specialist soft-QCD/cosmic-ray air-shower MC generator. Good minimum-bias description but lacks dedicated hard scattering component
EPOS performs best for $p_T^{\text{lead}} > 1$ GeV, but worst for $p_T^{\text{lead}} > 10$ GeV.

Herwig 7 and Pythia 8 Monash describes both variables the best for $p_T^{\text{lead}} > 10$ GeV, but the worst for $p_T^{\text{lead}} > 1$ GeV.
Transverse region with least activity

- **Trans-min** region most sensitive to MPI, while trans-max also contains hard scattering contamination
- Observe plateau, validating that this region is insensitive to the hard process
- No models describe well the region $p_T^{\text{lead}} < 5 \text{ GeV}$
- Pythia 8 Monash and Herwig provide best description of plateaus in both observables
Difference between transverse regions

- **Trans-diff** = **Trans-max** minus **trans-min**

- Region most sensitive to contamination of transverse region from the hard process (no plateau at high $p_T^{\text{lead}}$)

- Appears to be systematic mis-modelling in MC
  - These data can be used in future tunes to aid Run-2 physics analyses
Bose–Einstein Correlations

- BEC effect corresponds to enhanced emission of two identical bosons that are near in momentum space - dependent on effective radius, R, and a strength parameter

- Enables probing of geometry of hadronisation region

- Density functions ($C_2$ & $\rho$) parameterised in terms of $Q$, the 4-momentum difference the bosons

\[
C_2(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} = \frac{\text{2-particle density function}}{\text{2-particle density function, excluding BEC effects}}
\]

\[
Q^2 = -(p_1 - p_2)^2
\]
BEC in ATLAS

- Track based analysis ($p_T > 100$ MeV) comparing pairs of like and opposite signed charged hadrons at $\sqrt{s} = 0.9$ and 7 TeV

- MC does not simulate BEC, thus ATLAS uses 2-particle double-ratio correlation function $R_2(Q)$

- Excluded region due to MC overestimate of $\rho \rightarrow \pi^+ \pi^-$

- BEC observed when particles have similar momentum (low $Q$)

$$R_2(Q) = \frac{C_2(Q)}{C_2^{MC}(Q)} = \frac{\rho^{++}, --}{\rho^{+-}} \frac{\rho^{MC}(+-)}{\rho^{MC}(+-)}$$
Effective Radius

- Rise at low multiplicity independent of $\sqrt{s}$. Plateau at high multiplicities, implying a constant source size.

- $k_T$ dependence of $R$ also observed to be independent of $\sqrt{s}$, within uncertainties.
Ordered Hadron Chains

- Approximation of QCD field as narrow strings due to self-interaction of gluons (Lund string model used in Pythia)
- String fragmentation results in hadronisation, with hadrons also formed by the string, in-between the separating quarks
- Quantised 3D helix string results in two parameters: $kR$ (string tension, ~1 GeV/fm, multiplied by radius of helix) and $\Delta\Phi$
Observable model predictions

<table>
<thead>
<tr>
<th>Pair rank differences r</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q expected [MeV]</td>
<td>266±8</td>
<td>91±3</td>
<td>236±7</td>
<td>171±5</td>
<td>178±5</td>
</tr>
</tbody>
</table>

- QCD string breaks, forming an ordered chain of hadrons (pions). Order = ‘rank’.
- Low Q region should be dominated by equal sign pions (rank 2, 4)
- Rank 2 particles closer in Φ than rank 1
- Quantum threshold in Q for production of adjacent (rank 2) hadrons
- Mass of chain of ground state hadrons (under assumption of local field homogeneity):
  \[ M_{nh} < n \ kR \ \Delta \Phi \quad ; \quad M_{3h} < 575 \pm 20 \ MeV \]
Charge Combination Asymmetry

- Define $\Delta(Q)$ as correlation function of opposite and like sign pairs

- Observe Q threshold in data, as predicted
  - Typically attributed to BEC effect

- Not predicted by Lund string fragmentation model (Pythia) or the cluster hadronisation model (Herwig++)

\[
\Delta(Q) = \frac{1}{N_{ch}} [N(Q)^{-+} - N(Q)^{++,-+}]
\]
Diffraction Prospects with AFP

• AFP (ATLAS Forward Proton) Roman Pot detector system
  ‣ For identifying protons very close to the LHC beam, typically originating from diffractive scattering

• Compare AFP triggered sample with minimum-bias triggered sample
  ‣ Observe diffractive peak and minbias peak
  ‣ Validates AFP’s ability to select diffractive protons

• Early 2017, other side of AFP completed and time-of-flight detectors added for vertex discrimination

\[ \xi_{\text{cal}} = \frac{1}{\sqrt{s}} \sum p_i^i e^{-\eta_i} \]

2016. Low pile up, \( \mu = 0.3 \)
Summary

• 13 TeV Underlying Event:
  ‣ Analysis important for tuning of Monte Carlo generators for LHC Run 2 and beyond

• Bose–Einstein Correlations:
  ‣ BEC effect observed at low–Q
  ‣ Effective radius observed to plateau at high multiplicities

• Ordered Hadron Chains:
  ‣ Data supports prediction of Q threshold for production of adjacent hadrons
  ‣ 3D helix QCD string model also predicts enrichment of low–Q region, typically described by BEC

• Proton tagging with AFP:
  ‣ Demonstrated ability of AFP to select diffractive scattering enriched sample
Backup Slides
- Observe plateau in transverse region

- Implies independence from hard scattering process
Dependence on centre of mass energy
Two particle double correlation function for 0.9TeV, 7TeV, 7TeV High Multiplicity
• Strength parameter as function of multiplicity and $k_T$
Ordered Hadron Chains

Effect of three-hadron chains

- Chains selected by:
  - Finding like signed particle with minimal Q
  - Add opposite charged particle which minimises triplet mass

- $R^A$ and $R^B$ have contribution from low-mass 3-hadron chains subtracted
  - $R^A$ considers long uninterrupted chains
  - $R^B$ considers disconnected triplet chains

- 3D helix QCD string model can describe Bose–Einstein effect region

\[
R = \frac{N(Q)^{++,-\cdot}}{N(Q)^{+-}}
\]

![Graph showing the effect of three-hadron chains with data from ATLAS Preliminary.](image-url)
AFP Proton Tagging

• Rapidity gap from calorimeter edge in minimum-bias and in diffraction enriched samples

• Part of AFP’s physics programme