STUDIES OF THE UNDERLYING EVENT AND PARTICLE PRODUCTION WITH THE ATLAS DETECTOR.

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ATLAS has measured particle production and the underlying event

- using various different hard processes
- at several centre-of-mass energies

Too much to discuss in full, so I will show only most recent results:

13 TeV! Detector-level underlying event distributions
Underlying event in jet events
Underlying event in inclusive Z-boson production
Dijet production with large rapidity gaps
Exclusive dilepton production
Transverse polarisation of $\Lambda$ and $\bar{\Lambda}$ hyperons

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Underlying event
What is the underlying event?

Any **hadronic** activity not associated with **hard scattering** process

- Unavoidable **background** to collision events
- **Non-perturbative** effects dominate → not well-predicted

Typically modelled with

- Multiple parton interactions
- Initial/final-state radiation
- Colour reconnection with beam remnants

**Impossible to unambiguously assign particles to hard scatter or UE**

- Measurements must not be dependent on **details of model** used
Underlying event topology

- Identify a “hard scatter” using a reference object (e.g., jet/Z/track)
- Define azimuthal regions with respect to this leading object

- **Toward** and **transverse** regions most sensitive to the underlying event
- High $p_T$ recoil important in **away** region $\rightarrow$ perturbative QCD
- **Transverse** region can be further divided into **trans-max** and **trans-min** depending on the amount of activity
Reconstruct kinematics: calorimeter deposits and charged tracks

**Densities and averages**

- Average $p_T$ of charged particles: $\langle p_T \rangle$
- Number density of charged particles: $N_{ch}/\delta \eta \delta \phi$
- $p_T$ density of charged particles: $\sum p_T/\delta \eta \delta \phi$
- $E_T$ density of all particles: $\sum E_T/\delta \eta \delta \phi$

**Particle spectra**

- Charged particle $p_T$ spectrum
- Charged particle multiplicity spectrum
\( \geq 1 \) jet

\[ \delta p_T / \delta \eta \delta \phi / T \sum < 0.5 \]

\[ \delta p_T / \delta \eta \delta \phi / T \sum < 1 \]

\[ \delta p_T / \delta \eta \delta \phi / T \sum < 1.5 \]

\[ \delta p_T / \delta \eta \delta \phi / T \sum < 2 \]

\[ \delta p_T / \delta \eta \delta \phi / T \sum < 2.5 \]

Trans-min flat (at hard enough scales) \( \rightarrow \) treat UE activity as constant

Increasing activity for trans-max \( \rightarrow \) pQCD

Both trans-max and trans-min regions flat in \( p_T \)

Veto on extra hard activity lessens sensitivity to pQCD
Inclusive jet selection

Exclusive dijet selection

Similar distributions for $\sum E_T$ from calorimeter clusters

Compare to different Monte Carlo models and tunes

Best agreement given by PYTHIA 6 with Perugia 2011 tune
Underlying event in 7 TeV Drell-Yan events

Measurement of toward UE!
- Tune non-perturbative models with low $p_T$ region
- Away region dominated by $Z+j$
- Toward and transverse regions sensitive to higher $N_{jets}$
Double differential charged particle multiplicity and $p_T$ spectra

Provide further discrimination between Monte Carlo models

Current models do not describe these observables well
Universality of MPI model

- Compare UE measurements with different hard scatters
- Qualitative test of MPI universality in different hard processes

Good agreement between jet and Z-boson measurements → especially for trans-min (most sensitive to MPI)

How well does the MPI model extrapolate to higher energies?...
Leading track underlying event at 13 TeV

Detector-level only (preliminary result)

Good agreement with data in toward region
Leading track underlying event at 13 TeV

ATLAS Preliminary

\( \sqrt{s} = 13 \text{ TeV} \)

\begin{align*}
\text{Transverse region} & \quad p_T > 0.5 \text{ GeV, } |\eta| < 2.5 \\
p_T^{\text{lead}} > 1 \text{ GeV}
\end{align*}

\begin{align*}
\langle d^2 \Sigma p_T / \text{d}n / \text{d} \phi \rangle & \quad [\text{GeV}] \\
\langle d^2 N / \text{d}n / \text{d} \phi \rangle & \quad [\text{GeV}]
\end{align*}

- Greater discriminating power in transverse region
- Still only minor discrepancies from the data
  \[ \rightarrow \] MPI energy extrapolation working well
Particle Production
Dijet production with rapidity gaps

- Use tracks and calorimeter deposits to identify activity
- Rapidity gap is largest empty $\eta$ span from detector edge
- Decomposition into diffractive components
- Non-negligible contribution from ND even at large $\Delta \eta^F$
Cross sections as a function of diffractive mass

Consider $\xi = \frac{M^2_{\chi}}{s}$

In region $\Delta \eta^F > 2$

- ND contribution from PYTHIA or POWHEG+PYTHIA 8 not enough
- PYTHIA 8 DD contribution also falls short of the data
- POMWIG SD-only overshoots $\rightarrow$ need gap survival factor
Scaling by gap survival probability

Scale **POMWIG** to lowest log $\xi$ bin $\rightarrow S^2 = 16\%$

**PYTHIA 8** for three different Pomeron flux choices
$\rightarrow$ compatible without needing gap survival factor
Exclusive $\gamma\gamma \rightarrow ll$ production

$\sqrt{s} = 7$ TeV, 4.6 fb$^{-1}$

- Large backgrounds dominate
- Complex selection to extract signal
- Irreducible SD and DD contributions important

Baseline selection + 2 tracks associated with di-muon vertex
Extracting single-diffractive fraction

- Agreement with world average
- For $e^+e^-$ and $\mu^+\mu^-$ channels

- Fit acoplanarity distributions
- Subtract DD and Drell-Yan backgrounds
- Template fit allows extraction of SD fraction
Corrected for interactions between elastically scattered protons
Transverse polarization of $\Lambda$ and $\bar{\Lambda}$ hyperons

$\Lambda$ hyperon: spin $\frac{1}{2}$ particle

Polarisation, $P$, defined as:

$$P = \frac{N_{+\frac{1}{2}} - N_{-\frac{1}{2}}}{N_{+\frac{1}{2}} + N_{-\frac{1}{2}}}$$

$\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decays

Angular distribution given by:

$$w(\cos \theta^*) = \frac{1}{2} (1 + \alpha P \cos \theta^*)$$

$\alpha = 0.642 \pm 0.013$ (parity-violating decay asymmetry) is well-known

No theoretical model exists!

Angular distribution for polarization measured normal to production plane:

- as function of $p_T$ and $\chi_F = p_z/p_{beam}$
- in region $\chi_F < 0.0025$
Signal extraction

- Kinematic cuts to reduce **background**
- **Signal** from long-lived two-prong decays

- **ATLAS**
  - \( L = 760 \mu b^{-1} \)
  - \( \sqrt{s} = 7 \text{ TeV} \)

\[ \Lambda \to p\pi^- \]

- Divide invariant mass range into **signal region** and **sidebands**
- **Multi-parameter** fit to \( \Lambda \) candidate distribution
  → allows extraction of signal fractions, \( f_{\Lambda}^{\text{sig}} \) in each region
Polarisation of background contribution

- Expectation value (first moment) of decay angle linear in $P$

- Use $P = 0, 1$ templates

- Assume polarisation of background events $[E_{bkg}]$ independent of mass

- Calculate moments separately in the signal region and sidebands

- Signal fractions already known

- Simultaneously fit signal and sidebands to extract $E_{bkg}$ and $P$
Measurement binned in \( x_F \) and \( p_T \)

- Polarization \(< 2\%\) in all bins
- Consistent with zero in full fiducial phase space

\[
P(\Lambda) = -0.010 \pm 0.005\text{(stat)} \pm 0.004\text{(syst)}
\]

\[
P(\bar{\Lambda}) = 0.002 \pm 0.006\text{(stat)} \pm 0.004\text{(syst)}
\]
Comparison to previous results

- ATLAS tests different kinematic phase space → direct comparison of results non-trivial
- No theoretically motivated prediction, only empirical models

Propose introduction of energy dependence
- about half the $\Lambda$ produced in ATLAS come from decays
- dilutes polarisation → smaller than extrapolation
Conclusions

Underlying Event

- NEW measurements of underlying event [first Run II results]
- Large variety of multiplicity and energy density distributions
- MC models tuned to previous LHC data working well
  → particularly MPI energy extrapolation

Particle Production

- Complex measurements extracting small signals
- Measurements provided in well-defined fiducial regions for easy comparison with theory
- Many more Run II results on the way
Reconstructed decay angle distribution

\[ w(t) \propto \epsilon(t) \left[ (1 + \alpha Pt) \right] \otimes R(t', t) \]

where \( t' \) and \( t \) are true and reconstructed decay angles (\( \cos \theta^* \)), \( \epsilon(t) \) is the efficiency function and \( R(t', t) \) the resolution function.

Method of moments

- The expectation value (first moment) of \( w(t) \) is linear in \( P \):

\[ E(w|P = p) \equiv E(p) = C_0 + C_1 p = E(0) + [E(1) - E(0)]p \]

- \( E(0) \) and \( E(1) \) estimated from MC with polarisation set to 0 and 1

\[ E_i^{\text{exp}}(P, E_{\text{bkg}}) = f_i^{\text{sig}} \left[ E_i^{\text{MC}}(0) + \left[ E_i^{\text{MC}}(1) - E_i^{\text{MC}}(0) \right] P \right] + (1 - f_i^{\text{sig}})E_{\text{bkg}} \]
Many possible parametrisations

B. Lundberg [PRD 40 (1989) 3557] is a popular choice

Assumes energy independence and neglects detector effects

\[ P = \left( -0.268x_F - 0.338x_F^3 \right) \times \left( 1 - e^{-4.5p_T^2} \right) \]

ATLAS: \( \langle p_T \rangle \sim 1.8 - 2.1 \) GeV and \( \sqrt{s} = 7 \) TeV

HERA-B and E799: \( \langle p_T \rangle \sim 0.67 - 2.2 \) GeV and \( \sqrt{s} \sim 40 \) GeV