ATLAS studies of diffraction, soft particle production and double parton scattering.

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On behalf of the ATLAS Collaboration
Overview

- Double Parton Interactions in $W \rightarrow l\nu + 2$ jet
  - Azimuthal Ordering
    - $\Lambda$ Properties & Two Particle Correlations
    - Transverse Energy Flow
      - Event Shapes
        - Track Jet Underlying Event
          - Forward-Backward Correlations
            - Inelastic & Diffractive Cross Sections
              - NeW!
Following analyses use a combination of Inner Detector Tracking and ATLAS calorimetry.
Non Diffractive Interaction at 7 TeV in Pythia 8
~75% of all inelastic interactions at the LHC are non-diffractive.

~25% of the time the inelastic interaction is diffractive which can result in a characteristic rapidity gap.

Many soft particles
Inelastic

- Inelastic \( pp \) cross section measured over acceptance of ATLAS Minimum Bias Trigger Scintillators.

\[ \sigma_{\text{inel.}} = 69.4 \pm 2.4(\text{exp.}) \pm 6.9(\text{extrap.}) \]

- MC model uncertainty dominates extrapolation to full phase space.
- Also measured the ratio of exclusively single sided MBTS triggered events.
- Sensitive to the magnitude of the diffractive component.
$\sigma_{\text{Inelas.}}$ as a function of $\Delta \eta^F$

$\Delta \eta_F = \text{largest, empty } \eta \text{ interval from edge of detector at } \eta = \pm 4.9$

Corrected to charged & neutral particles $p_T > 200, 400, 600 \& 800 \text{ MeV}$

Bayesian unfolding technique
Particle Correlations

- **Forward-Backward** multiplicity and $p_T$ correlations in $\eta$.

Deviations of $fwd(bkwd)$ multiplicities from their mean.

Sum over events:

$$\rho_{fb}^{n} = \frac{\sum x_f^n x_b^n}{N \sigma_f^n \sigma_b^n}$$

Standard deviation of $fwd(bkwd)$ distributions about their mean.

Detector level distributions are corrected to the hadron level using linear regression technique with different MC models.

$$\rho_{had} = \alpha + \beta \rho_{det}$$

Trigger & Vertex Eff. : $\alpha = 0.07 \pm 0.03$

Track Reconstruction Eff. : $\beta = 0.96-0.97$
Results for $\rho^n_{fb} \& \rho^{pT}_{fb}$

Centre of mass dependence

Multiplicty

Scalar Sum

$\rho^n_{fb}$

$\rho^{pT}_{fb}$

Minimum $p_T$ dependence

$\rho^n_{fb}$

$\rho^{pT}_{fb}$
Azimuthal Correlations

- Investigated as a function of $\eta$ region and fwd/bkwd correlation.
- Primarily looking at the `toward' region.
- Subtract away the `transverse' region plateau for data and MC.
- The difference $\Delta \phi$ is plotted here vs. the leading (highest $p_T$) track in the event.

$$N^T_{sub} = \frac{(N^T - N^T_{min})}{\sum \text{Bins}(N^T - N^T_{min})}$$

$$N^T_{SO} = \frac{(N^T_{same} - N^T_{opp.})}{\sum \text{Bins}(N^T_{same} - N^T_{opp.})}$$
Track-jet Underlying Event

Huge quantity of tuning data, much too much to show here.

- $N_{\text{ch}}, \Sigma|p_T|$ and $<p_T>$. Plus as a function of $p_T^{\text{jet}}$ in the range $4 < p_T^{\text{Jet}} < 100 \text{ GeV}$
- For Anti-$k_T$ Track jets with $R = 0.2, 0.4, 0.6, 0.8, 1.0$
- In the Transverse and Away regions.

Average of mean $p_T$ as function of $p_T^{\text{Jet}}$ for $R=0.2$

Average of Sum $p_T$ per unit $(\eta, \phi)$ as function of $p_T^{\text{Jet}}$ for $R=0.2-1.0$

Average of $N_{\text{ch}}$ per unit $(\eta, \phi)$ as function of $p_T^{\text{Jet}}$ for $R=0.2$
Differential Transverse Energy Density

MinBias
Mid $\eta$ dip from $p_T$ cuts.
Best soft model EPOS

Bayesian Unfolding Technique

Underlying Event
Transverse region to di-jet system only.
Best UE model Pythia 6 DW
Differential Transverse Energy Density

- **Diffractive** contributions halved and doubled.
- Affects the **amount of activity** (diffractive events are softer on average).
- Has **little effect on the shape**.

- **In MSTW2008 LO**, changes to the gluon PDF decreases central but increases forward energy.
Transverse Thrust:

$$\tau_\perp = 1 - T_\perp$$

For Thrust Axis, unit vec. $\hat{n}_T$ for which:

$$\max \frac{\sum_i |\vec{p}_T^i \cdot \hat{n}|}{\hat{n} \cdot \sum_i |\vec{p}_T^i|}$$

Di-jet Like

Circularly Symmetric $1-(2/\pi)=0.36$

AMBT2B not so good

Z1 best

`Pencil Like' in $\phi$

Isotropic

Thrust Minor:

Out of event plane energy flow.

$$\hat{n}_M = \hat{n}_T \times \hat{z}$$

Defined by thrust axis ($\hat{n}_T$) and beam axis ($\hat{z}$)

$$T_M = \frac{\sum_i |\vec{p}_T^i \cdot \hat{n}_M|}{\sum_i |\vec{p}_T^i|}$$
Event Shapes

**Transverse Sphericity:**
A measure of the transverse summed $p_T^2$ with respect to the event axis.
Shown here as a function of $p_{T}\text{lead}$
Derived from the eigenvectors ($\lambda_{xy_2} < \lambda_{xy_1}$) of the transverse components of the event momentum tensor:

$$S_{xy} = \sum_i \left[ \frac{p_{x_i}^2}{p_{x_i}p_{y_i}} \frac{p_{y_i}^2}{p_{x_i}p_{y_i}} \right] S_{\perp} = \frac{2\lambda_{xy}}{\lambda_{xy_2} + \lambda_{xy_1}}$$

Transverse thrust, thrust minor and transverse sphericity measured for leading particle.

$p_{T}\text{lead} > 0.5, 2.5, 5.0$ GeV

Along with average values as a function of $N_{ch}$ and $\Sigma p_T$
**Hard DPI: \( W \rightarrow l\nu+jj \)**

\[
\Delta_{\text{jets}}^n = \frac{|\vec{p}_{T1} + \vec{p}_{T2}|}{|\vec{p}_{T1}| + |\vec{p}_{T2}|}
\]

- **Direct Production**
- **Double Parton Scatter**

- **Alpgen+Herwig+Jimmy** (Also used: Sherpa)

- **Template A:** Non-DPI MC
- **Template B:** Di-jet Data

**Templated \( \chi^2 \) minimisation**

\( f_{\text{DPI}}^R = 0.16 \pm 0.01 \) (stat) \( \pm 0.03 \) (sys)

**Template extracted fraction of DPI**

**Subsequently evaluated DPI cross section:**

\( \sigma_{\text{DPI}}^{\text{eff}}(7 \text{ TeV}) = 11 \pm (stat) + 3_{-2} \) (sys) mb
Is the gluon field helical?

- An efficient way to pack soft gluons into a Lund string formalism under helicity conservation requirement is the formation of a helix structure at the end of the parton cascade. [Is there screwiness at the end of the QCD cascades? arXiv:hep-ph/9807541v1]
- Correlations in the break points of a helically ordered string will manifest as observables in the \( p_T \) distribution and azimuthal ordering of hadrons produced directly from string fragments.
- Assuming string breakup through tunneling, \( \phi \) direction of initial hadron \( p_T \) coincides with the phase of the helix string.
- \( \phi \) opening angle of two direct hadrons will then measures the phase difference between two corresponding points along the string.

Assumes helix winding is proportional to the rapidity difference between hadrons.

\[
S_\eta(\xi) = \frac{1}{N_{Ev}} \sum \frac{1}{n_{Ch}} \left| \sum_{j} n_{Ch} e^{i(\xi \eta_j - \phi_j)} \right|^2
\]

\( \xi \) is a scale parameter.
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- Correlations in the break points of a helically ordered string will manifest as observables in the $p_T$ distribution and azimuthal ordering of hadrons produced directly from string fragments.

- Assuming string breakup through tunneling, $\phi$ direction of initial hadron $p_T$ coincides with the phase of the helix string.

- $\phi$ opening angle of two direct hadrons will then measures the phase difference between two corresponding points along the string.

$S_{\eta}(\xi) = \frac{1}{N_{Ev}} \sum_{\text{Events}} \frac{1}{n_{Ch}} \left| \sum_{j} e^{i(\xi \eta_j - \phi_j)} \right|^2$

$\xi$ is a scale parameter.
$K^0_S$ and $\Lambda$

All tunes struggle to describe $\Lambda$ data at high $p_T$

Two Particle Correlations

- $\Delta\eta$ and $\Delta\phi$ correlations between all particles in an event.
- Background subtracted by combining two particles from different events.
- Normalised to be independent of per event particle multiplicity.

Corrected via HBOM [arXiv:1111.4896v2]

Most models (except Herwig++) reasonably predict the shape of the correlations.
Conclusion

- A wealth of data from ATLAS on event characteristics, particle properties and correlations are available at the hadron level.
- Measurement of charged-particle event shape variables in $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector [Coming soon!]
- Measurements of the pseudorapidity dependence of the total transverse energy in proton-proton collisions at $\sqrt{s}=7$ TeV with ATLAS [Coming soon!]
- Measurement of charged-particle event shape variables in $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector [Coming soon!]
- Measurement of the azimuthal ordering of charged hadrons with the ATLAS detector at the LHC [arXiv:1203.0419]
- Measurement of Inclusive Two-Particle Angular Correlations in pp Collisions with the ATLAS Detector at the LHC [arXiv:1203.3549]
- Forward-backward correlations and charged-particle azimuthal distributions in pp interactions using the ATLAS detector [arXiv:1203.3100]
- Rapidity Gap Cross Sections in pp Interactions at $\sqrt{s} = 7$ TeV measured with the ATLAS detector [arXiv:1201.2808]
- Kshort and Lambda production in pp interactions at $\sqrt{s} = 0.9$ and 7 TeV measured with the ATLAS detector at the LHC [arXiv:1111.1297]
- Measurement of the Inelastic Proton-Proton Cross-Section at $\sqrt{s} = 7$ TeV with the ATLAS Detector [arXiv:1104.0326]
- A measurement of hard double-partonic interactions in $W \rightarrow l \nu + 2$ jet events with the ATLAS detector at the LHC [ATLAS-CONF-2011-160]
BACKUP
Is the gluon field helical? Part II

- One possibility, a static, regular helix with helical phase difference $\Delta \varphi$ proportional to the stored energy in the string.

$$\Delta \varphi = \mathcal{L} \kappa \Delta l = \mathcal{L} \Delta E$$

- $\Delta E$ is not directly observable, but we can approximate the string as a chain of hadrons, ordered in $\eta$.

- Define a second power spectrum, based on $\varphi$ and the position in the chain, $X$ defined as:

$$X_j = 0.5 \ E_j + \sum_{k=0}^{k<j} E_k$$

$$S_E(\omega) = \frac{1}{N_{Ev}} \sum_{\text{Events}} \frac{1}{n_{Ch}} \left| \sum_{j}^{n_{Ch}} e^{i(\omega X_j - \phi_j)} \right|^2$$

- $\omega$ is a scale parameter.

$E_k$ is the energy of the $k_{th}$ hadron in the string.

$\Delta l$ & $\Delta E$ are length and energy separation in string rest frame.

Very similar form factor, but probing a different structure in the QCD field.

Helical ordering will appear as a peak in the power spectrum, location = winding density.
More results for $S_E(\omega) \& S_\eta(\xi)$

- Data corrected to hadron level via HBOM [arXiv:1111.4896v2]
  (Backward extrapolation from the parametrisation of repeated applications of the detector smearing matrix)

Lund string fragmentation model roughly reproduces the data.

$\omega$: Helix proportional to stored energy in string

$\xi$: Helix proportional to particle rapidity difference

Low $p_T$ Enhanced

Models unable to sufficiently describe the data.
More results for $S_E(\omega) \& S_\eta(\xi)$

**Low $p_T$ Depleted**

**Low $p_T$ Enhanced**

**Model Parameter Sensitivity**

**Inclusive**

$\mathcal{L} = 0.7 \text{ rad/GeV}$
Two Particle Correlations

- **Δη and Δφ correlations** between all particles in an event.
- **Background subtracted** by combining two particles from different events.
- **Normalised** to be independent of per event particle multiplicity.

Most models (except Herwig++) reasonably predict the shape of the correlations.

The strength of correlations is less well predicted.

Data corrected using HBOM method.
$K_0^S$ and $\Lambda$

All tunes struggle to describe $\Lambda$ data at high $p_T$

$K_0^S$: Flight distance between 4 - 450 mm
Decay to two charged pions with $|\eta| < 2.5$, $p_T > 100$ MeV

$\Lambda$: $p_T > 500$ MeV, flight distance between 17 mm - 450 mm
Decay to a proton and a pion with $|\eta| < 2.5$, $p_T > 100$ MeV
Track-jet Underlying Event

Ratio of mean $N_{ch}$ for $R=0.2/R=0.6$ and $R=1.0/R=0.6$ as function of $p_{T}^{\text{Jet}}$

Event normalised average $p_{T}$ for $R=0.2$ and $31 \leq p_{T}^{\text{jet}} < 50$ GeV
\[ \int \sigma_{\text{Inelas}}(\xi) \, d\xi \]

- Measure the total inelastic cross section which produces particles in the main ATLAS detector. Can integrate up to a cut point.
- Apply all correlated systematics symmetrically plus additional correction from \( \Delta \eta^F \) to \( \xi \) derived from MC, at most \( 1.1 \pm 1.1 \% \)
- Luminosity error dominates.
- Comparison with published ATLAS paper good to \( 0.8 \% \), this is the measured run-to-run lumi error.
- Also included, TOTEM.
- And Durham RMK prediction.

\[ \xi = \frac{M_X^2}{s} \]

\( M_X \) = Invariant mass of diffractive system
\[ \int \sigma_{\text{Inelas}}(\xi) \, d\xi \]

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**Tension of \(~7\) mb of low mass diffractive cross section.**
Particle Correlations

- **Forward-Backward** multiplicity and $p_T$ correlations in $\eta$.

Deviations of $\text{fwd(bkwd)}$ multiplicities from their mean.

$$\rho_{n fb} = \frac{\sum x^n_f x^n_b}{N \sigma^n_f \sigma^n_b}$$

Sum over events

$N$ events

Standard deviation of $\text{fwd(bkwd)}$ distributions about their mean.

Deviation of $\text{fwd(bkwd)}$ scalar $p_T$ sum of all accepted tracks from their mean.

$$\rho_{pT fb} = \frac{\sum x^{pT}_f x^{pT}_b}{N \sigma^{pT}_f \sigma^{pT}_b}$$

Deviations of $\text{fwd(bkwd)}$ scalar $p_T$ sum of all accepted tracks from their mean.

ATLAS

Data 2010

Following plots examine symmetric fwd/bkwd $\eta$ regions

$p_T > 100$ MeV

$\eta_{ch} \geq 2$

$|\eta| < 2.5$