Recent QCD results from ATLAS

Javier Llorente, on behalf of the ATLAS Collaboration

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Outline of the talk

1. Measurements of soft QCD phenomena:
   1. Underlying event in $Z$ boson events.
   2. Polarisation of the $\Lambda$ hyperons produced in minimum bias events.

2. Measurements of hard scattering processes:
   1. Di-jet production with large rapidity gaps in the hadronic activity.
   2. Inclusive (1,2,3)-jet differential cross sections.
   3. Isolated, high-$p_T$ inclusive photon cross section.
   4. Jet shapes in $t\bar{t}$ events.
1. Soft QCD phenomena

1. Soft QCD measurements

- **UE**: All additional hadronic activity not arising from the hard scattering.
- Measured track observables: $\sum p_T, N_{ch}$ per $\delta \eta \times \delta \phi$ unit, average mean $p_T$.
- Three regions considered depending on $\Delta \phi$ to the direction of the $Z$ boson: Toward, away, transverse.

![Diagram of $Z$ boson event regions](image)

![Graph of $\langle \sum p_T, \delta \eta, \delta \phi \rangle$ vs $p_T^Z$](image)

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Recent QCD results from ATLAS 4 / 15
The distribution of \( t = \cos \theta^* \) follows 
\[
g(t, P) = \frac{1}{2} (1 + \alpha Pt). 
\]

- Signal and background fractions obtained from invariant mass fits.
- The extraction of the polarisation follows the method of moments:

\[
\chi^2(P, E_{bkg}) = \sum_{i=1}^{3} \left[ \frac{E_i - E_i^{\text{exp}}(P, E_{bkg})}{\sigma_{E_i}^2} \right]^2 
\]

where 
\[
E_i^{\text{exp}} = f_i^{\text{sig}} \{ E_i^{\text{MC}}(0) + [E_i^{\text{MC}}(1) - E_i^{\text{MC}}(0)]P \} + (1 - f_i^{\text{sig}})E_{bkg}
\]

- Correlations in $Q^2 = -(p_1 - p_2)^2$
- $R_2(Q) = \frac{\rho^{++}(Q)}{\rho^{+-}(Q)} \left( \frac{\rho^{++}(Q)}{\rho^{+-}(Q)} \right)_{MC}$
- Parameterisation in terms of the function $\Omega(Q; R, \lambda) = \lambda e^{-RQ}$
- Data corrected for Coulomb effects
  
  \[ G(Q) = \frac{2\pi \zeta}{e^{2\pi \zeta} - 1}; \quad \zeta = \pm \frac{\alpha m_\pi}{Q} \]
- Bins in $n_{ch}$ and $k_T = |\vec{p}_{T1} + \vec{p}_{T2}|/2$

- $\sqrt{s} = 900$ GeV and 7 TeV data.
2. Hard QCD phenomena

2. Hard QCD measurements

- Observables: Gap fraction $\frac{\sigma_{jj}(Q_0)}{\sigma_{jj}}$, $\langle N_{jet} \rangle$ in rapidity gap, $\langle \cos(\pi - \Delta \phi) \rangle$. Dependence on $\Delta y$ and the average $\overline{p_T} = (p_{T1} + p_{T2})/2$.
- Kinematics: $p_{T1} > 60$ GeV, $p_{T2} > 50$ GeV for the dijet system.
- BFKL-sensitive for large $\Delta y$.
- Comparisons with Powheg and HEJ.
The amount of decorrelation is increased at high $\Delta y$ and low $p_T$.
Double-differential cross section as a function of the jet $p_T$ and rapidity. $\sqrt{s} = 7$ TeV, $\int L dt = 4.5 \text{ fb}^{-1}$.

Two jet radii are used: $R = 0.4$ and $R = 0.6$. Jets with $p_T \geq 100$ GeV, $|y| < 3$ considered.

Comparison with NLO predictions corrected for EW and NP effects. Several PDFs investigated.
Double-differential cross section as a function of $m_{12}$ and $y^* = |y_1 - y_2|/2$. $\sqrt{s} = 7$ TeV, $\int L dt = 4.5$ fb$^{-1}$.

Kinematical requirements: $p_{T1} \geq 100$ GeV, $p_{T2} > 50$ GeV and $|y| < 3$

Comparison with NLO predictions corrected for EW and NP effects. Several PDFs investigated.
2.4 Three-jet cross sections. arXiv:1411.1855 [hep-ex]

- Double-differential cross section as a function of $m_{jjj}$ and $|Y^*| = |y_1 - y_2| + |y_2 - y_3| + |y_1 - y_3|$. $\sqrt{s} = 7$ TeV, $\int L dt = 4.5$ fb$^{-1}$.
- Asymmetric kinematics: $p_T^1 > 150$ GeV, $p_T^2 > 100$ GeV and $p_T^3 > 50$ GeV.
- NLO predictions corrected for NP effects. Several PDFs used.
Cross section for isolated, high-$p_T$ photons ($E_T^{iso} \leq 7$ GeV, $E_T^\gamma > 100$ GeV). $\sqrt{s} = 7$ TeV, $\int L dt = 4.6 \text{ fb}^{-1}$.

- Background estimation from 2-dimensional sideband method.
- Comparison with NLO predictions by Jetphox, corrected for NP effects.
- Fraction of transverse momentum in concentric rings from the jet axis.
- Comparison of $b$-jets from $t \rightarrow Wb$ and light jets from $W \rightarrow q\bar{q}'$.
- $b$-jets have a wider distribution due to the heavier mass of the $b$-quark.
Conclusions

- QCD phenomena has been explored at ATLAS on a large energy range.
- Underlying event measurements are useful inputs for tuning the MC predictions.
- $\Lambda$ polarisation and Bose-Einstein correlations follow the expectations from previous experiments.
- Jet cross-sections have been measured to a high precision for large energy ranges.
- Hard QCD measurements are well described by NLO calculations, corrected for NP (and EW) effects.
- Inclusive photon production is also well described by NLO calculations, and has sensitivity to PDF.
- Jet shapes in $t\bar{t}$ events are well described by MC expectations. Light jets have a narrower energy flow distribution than that of $b$-jets.
- New data at $\sqrt{s} = 13$ TeV coming soon. Stay tuned!
Backup Slides
UE in $Z$ boson events. Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{ch}$ vs $p_{T}^{Z}$</th>
<th>$\sum p_{T}$ vs $p_{T}^{Z}$</th>
<th>Mean $p_{T}$ vs $p_{T}^{Z}$</th>
<th>Mean $p_{T}$ vs $N_{ch}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton selection</td>
<td>0.5 - 1.0</td>
<td>0.1 - 1.0</td>
<td>&lt; 0.5</td>
<td>0.1 - 2.5</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>1.0 - 2.0</td>
<td>0.5 - 2.0</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>0.5 - 1.0</td>
<td>1.0 - 2.0</td>
<td>0.1 - 2.0</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Pile-up removal</td>
<td>0.5 - 2.0</td>
<td>0.5 - 2.0</td>
<td>&lt; 0.2</td>
<td>0.2 - 0.5</td>
</tr>
<tr>
<td>Background correction</td>
<td>0.5 - 2.0</td>
<td>0.5 - 2.0</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.5 - 3.0</td>
<td>0.5 - 3.0</td>
<td>&lt; 0.5</td>
<td>0.2 - 2.0</td>
</tr>
<tr>
<td>Electron isolation</td>
<td>0.1 - 1.0</td>
<td>0.5 - 2.0</td>
<td>0.1 - 1.5</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Combined uncertainty</td>
<td>1.0 - 3.0</td>
<td>1.0 - 4.0</td>
<td>&lt; 1.0</td>
<td>1.0 - 3.5</td>
</tr>
</tbody>
</table>
The distribution of the $\Lambda$ decay angle from which the moments $E_i$ are extracted for the $\chi^2$ fit is shown below for both $\Lambda$ and $\bar{\Lambda}$ baryons.
The invariant mass distribution is parameterised as a function of 11 free parameters

\[ M(m_{p\pi}) = f_{\text{sig}} M_{\text{sig}}(m_{p\pi}) + (1 - f_{\text{sig}}) M_{\text{bkg}}(m_{p\pi}) \]

- The signal component is

\[ M_{\text{sig}}(m_{p\pi}) = f_1 G(m_{\Lambda}, \sigma^L_1, \sigma^R_1) + 
\quad + (1 - f_1) \left[ f_2 G(m_{\Lambda}, \sigma^L_2, \sigma^R_2) + 
\quad + (1 - f_2) G(m_{\Lambda}, \sigma^L_3, \sigma^R_3) \right] \]

- The background component is

\[ M_{\text{bkg}}(m_{p\pi}) = \frac{1}{\Delta m} [1 + b(m_{p\pi} - m_c)] \]

- Signal fraction in the interval \( I_i \)

\[ f_{i}^{\text{sig}} = \frac{\int_{I_i} M_{\text{sig}}(m)dm}{\int_{I_i} M(m)dm} \]
The absolute systematic uncertainties for the $\Lambda/\bar{\Lambda}$ polarisation measurement are summarised below

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Lambda$</th>
<th>$\bar{\Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC statistics</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Mass range</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Background</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Kinematic weighting</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Other contributions</td>
<td>$&lt; 5 \times 10^{-4}$</td>
<td>$&lt; 5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Total</td>
<td>0.004</td>
<td>0.004</td>
</tr>
</tbody>
</table>

- **MC statistics**: Estimated using 10 gaussian pseudoexperiments for the values of $E(0)$ and $E(1)$ in MC.
- **Mass range**: The signal region is varied up and down by 2 MeV.
- **Background**: Different background model - Uncertainties on $f_i^{sig}$.
- **Kinematic weighting**: Different weighting function for the Data - MC agreement, constructed without background subtraction.
- **Other**: Track momentum scale, efficiency, trigger, uncertainty in $\alpha$...
Bose-Einstein correlations. $\lambda$ and $R$ versus $n_{ch}$ and $k_T$. 

**ATLAS**

$\lambda$

$p_T \geq 100$ MeV, $|\eta| < 2.5$

- ATLAS pp 900 GeV
- ATLAS pp 7 TeV
- ATLAS pp 7 TeV HM
- ATLAS pp 7 TeV MB + HM Exponential fit

$R$ [fm]

$p_T \geq 100$ MeV, $|\eta| < 2.5$

- CMS pp 900 GeV
- CMS pp 7 TeV
- UA1 pp 200 GeV
- ATLAS pp 900 GeV
- ATLAS pp 7 TeV
- ATLAS pp 7 TeV HM
- ATLAS pp 7 TeV MB + HM Constant fit

**ATLAS**

$\lambda$

$p_T \geq 100$ MeV, $|\eta| < 2.5$

- ATLAS pp 900 GeV
- ATLAS pp 7 TeV
- ATLAS pp 7 TeV HM
- ATLAS pp 7 TeV MB + HM Exponential fit

$R$ [fm]

$p_T \geq 100$ MeV, $|\eta| < 2.5$

- CMS pp 900 GeV
- CMS pp 7 TeV
- UA1 pp 200 GeV
- ATLAS pp 900 GeV
- ATLAS pp 7 TeV
- ATLAS pp 7 TeV HM
- ATLAS pp 7 TeV MB + HM Constant fit

- STAR pp 200 GeV
- E735 pp 1.8 TeV

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Recent QCD results from ATLAS
The main systematic uncertainties for the BEC measurement are shown below.

<table>
<thead>
<tr>
<th>Source</th>
<th>900 GeV</th>
<th>7 TeV</th>
<th>7 TeV (HM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$</td>
<td>$R$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Track efficiency</td>
<td>0.6%</td>
<td>0.7%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Splitting and merging</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MC samples</td>
<td>14.5%</td>
<td>12.9%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Coulomb correction</td>
<td>2.6%</td>
<td>0.1%</td>
<td>5.5%</td>
</tr>
<tr>
<td>Fitted range</td>
<td>1.0%</td>
<td>1.6%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Starting $Q$</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Bin size</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Exclusion interval</td>
<td>0.2%</td>
<td>0.2%</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14.8%</strong></td>
<td><strong>13.0%</strong></td>
<td><strong>9.6%</strong></td>
</tr>
</tbody>
</table>
Uncertainties on the gap fraction as a function of $\Delta y$ and $\langle \cos(\pi - \Delta \phi) \rangle$ as a function of $p_T$

![Graph 1](image1.png)

![Graph 2](image2.png)
Inclusive jet cross section. Uncertainties

Experimental and theoretical uncertainties

\[ \int L \, dt = 4.5 \, \text{fb}^{-1} \text{ anti-}k, \text{ jets, } R=0.6 \]
\[ \sqrt{s} = 7 \, \text{TeV} \quad |y| < 0.5 \]

\[ \int L \, dt = 4.5 \, \text{fb}^{-1} \text{ anti-}k, \text{ jets, } R=0.6 \]
\[ \sqrt{s} = 7 \, \text{TeV} \quad 2.5 \leq |y| < 3.0 \]

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Recent QCD results from ATLAS
Electroweak correction factors for the cross sections with $R = 0.4$ and $R = 0.6$
Inclusive jet cross section. NP corrections

NP correction factors for $R = 0.4$ and $R = 0.6$ in the different $y$ bins
Dijet cross section. EW and NP corrections

Non-perturbative correction

1.0 ≤ y∗ < 1.5

- ATLAS Simulation
- PYTHIA 6.425 (AUET2B MRST LO**)
- PYTHIA 6.425 (AUET2B CTEQ6L1)
- HERWIG++ 2.5.2 (UE-EE-3 CTEQ6L1)
- HERWIG++ 2.5.2 (UE-EE-3 MRST LO**)
- Uncertainty

Electroweak correction

Dittmaier, Huss, Speckner

- ATLAS Simulation
- PYTHIA 6.425 (AUET2B MRST LO**)
- PYTHIA 6.425 (AUET2B CTEQ6L1)
- HERWIG++ 2.5.2 (UE-EE-3 CTEQ6L1)
- HERWIG++ 2.5.2 (UE-EE-3 MRST LO**)
- Uncertainty

Recent QCD results from ATLAS
Dijet cross section. $\chi^2$ and CIs

The agreement of the data with NLO pQCD predictions is tested using a $\chi^2$ with asymmetric uncertainties.

$$
\chi^2(d; t) = \min_{\beta_a} \left\{ \sum_{i,j} [d_i - F_i(\beta_a)] \left[ C_{su}^{-1}(t) \right]_{ij} [d_j - F_j(\beta_a)] + \sum_a \beta_a^2 \right\}
$$

$$F_i(\beta_a) = \left( 1 + \sum_a \beta_a (\epsilon_a^\pm (\beta_a))_i \right) t_i$$

The level of agreement is quantified and contact interactions are excluded in the region $\Lambda < 7.1$ TeV.
Three-jet cross section. NP corrections

**ATLAS**
- anti-$k_t$ jets, $R = 0.4$
- $\sqrt{s} = 7$ TeV, $|Y^*| < 2$

**Pythia 6**
- Perugia 2011
- AUET2B CTEQ6L1

**Pythia 8**
- 4C
- AU2 CTEQ6L1
- Herwig++
- UEE3 CTEQ6L1

**Uncertainty**
- ATLAS = 0.4
- $R_{\text{jets}}$, $t_{\text{anti}}$, $s = 7$ TeV, $|Y^*| < 2$

**ATLAS**
- anti-$k_t$ jets, $R = 0.6$
- $\sqrt{s} = 7$ TeV, $|Y^*| < 2$

**Pythia 6**
- Perugia 2011
- AUET2B CTEQ6L1

**Pythia 8**
- 4C
- AU2 CTEQ6L1
- Herwig++
- UEE3 CTEQ6L1

**Uncertainty**
- ATLAS = 0.6
- $R_{\text{jets}}$, $t_{\text{anti}}$, $s = 7$ TeV, $|Y^*| < 2$
The observed $p$-values obtained in the comparison between data and NLO pQCD are shown below

<table>
<thead>
<tr>
<th>PDF set</th>
<th>$y^*$ ranges</th>
<th>mass range (full/high)</th>
<th>$R = 0.4$</th>
<th>$R = 0.6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT10</td>
<td>$y^* &lt; 0.5$</td>
<td>high</td>
<td>0.742</td>
<td>0.785</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>high</td>
<td>0.080</td>
<td>0.066</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>full</td>
<td>0.324</td>
<td>0.168</td>
</tr>
<tr>
<td>HERAPDF 1.5</td>
<td>$y^* &lt; 0.5$</td>
<td>high</td>
<td>0.688</td>
<td>0.504</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>high</td>
<td>0.025</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>full</td>
<td>0.137</td>
<td>0.025</td>
</tr>
<tr>
<td>MSTW 2008</td>
<td>$y^* &lt; 0.5$</td>
<td>high</td>
<td>0.328</td>
<td>0.533</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>high</td>
<td>0.167</td>
<td>0.183</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>full</td>
<td>0.470</td>
<td>0.352</td>
</tr>
<tr>
<td>NNPDF 2.1</td>
<td>$y^* &lt; 0.5$</td>
<td>high</td>
<td>0.405</td>
<td>0.568</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>high</td>
<td>0.151</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>full</td>
<td>0.431</td>
<td>0.242</td>
</tr>
<tr>
<td>ABM11</td>
<td>$y^* &lt; 0.5$</td>
<td>high</td>
<td>0.024</td>
<td>$&lt; 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>high</td>
<td>$&lt; 10^{-3}$</td>
<td>$&lt; 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$y^* &lt; 1.5$</td>
<td>full</td>
<td>$&lt; 10^{-3}$</td>
<td>$&lt; 10^{-3}$</td>
</tr>
</tbody>
</table>
Three-jet cross sections. Uncertainties

Experimental and theoretical uncertainties

- **ATLAS** $\sqrt{s} = 7$ TeV
  - anti-$k_t$ jets, $R=0.6$
  - $|Y^*| < 2$

- **ATLAS** $\sqrt{s} = 7$ TeV
  - anti-$k_t$ jets, $R=0.6$
  - $4 < |Y^*| < 6$

- **CT10(NLO)** $(0<|Y^*|<2)$
  - anti-$k_t$, $R=0.6$ jets. Theoretical uncertainties:
    - Renormalisation+factorisation scales
    - PDF
    - $\alpha_s$
    - Total

- **CT10(NLO)** $(4<|Y^*|<6)$
  - anti-$k_t$, $R=0.6$ jets. Theoretical uncertainties:
    - Renormalisation+factorisation scales
    - PDF
    - $\alpha_s$
    - Total
The $b$-jet sample is selected using $b$-tagging, while light jets are selected as the pair with closest mass to $m_W$. 

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