Probing perturbative QCD at the ATLAS experiment

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Jet production at LHC understood to proceed via

$$\sigma_{pp\rightarrow jets} = \sum_{i,j} \int dx_{p_1} f_{i/p_1}(x_{p_1}, \mu_F) \int dx_{p_2} f_{j/p_2}(x_{p_2}, \mu_F) \hat{\sigma}_{ij\rightarrow jets}(\mu_R, \alpha_s, x_{p_1}, x_{p_2})$$

(1)

- Extension of previous studies at much higher scales $\Rightarrow$ test bed for long and short distance behaviour of QCD as well as for MC modelling
- Aim: compare unfolded data to pQCD predictions
Three topics.


- Measurement of transverse energy-energy correlations (TEEC) at $\sqrt{s} = 8$ TeV and determination of $\alpha_s$, Eur. Phys. C77 (2018) 892.

Inclusive jet and dijet production: anti-\(k_t\) with \(R = 0.4\).

- \(d^2\sigma/dp_Tdy = N_{\text{jets}}/\mathcal{L}.\Delta p_T.\Delta y\).
  - single-jet triggers with thresholds varying between 55 GeV and 360 GeV
  - 100 GeV < \(p_T\) < 3.5 TeV and \(|y| < 3.0\)
  - Data unfolded and EW corrected, compared to NLO and NNLO predictions
  - Several PDFs and scale choices: \(\mu_R = \mu_F = p_T^{\text{max}}\) or \(p_T^{\text{jet}}\)

- \(d^2\sigma/dm_{ij}dy^* = N_{\text{dijets}}/\mathcal{L}.\Delta m_{ij}.\Delta y^*\) with \(y^* = |y_1 - y_2|/2\)
  - pairing of jet triggers
  - 300 GeV < \(m_{ij}\) < 9 TeV; \(y^* < 3.0\); \(H_T^2 > 200\) GeV
  - Data unfolded and EW corrected, compared with NLO predictions
  - Scale choice: \(\mu_R = \mu_F = p_T^{\text{max}}.e^{0.3y^*}\)
- JES is the dominant source,
- inclusive : total uncertainty increases with rapidity and in the $p_T$ tails,
- dijets : it increases with increasing dijet mass only in the central rapidity bins
- Uncertainty due to renormalization and factorization scale is dominant
- PDF uncertainties vary from 2 to 12% while that due to $\alpha_s$ is below 2%
Comparison with NLO and NNLO predictions.

Inclusive: \( \frac{d^2 \sigma}{dp_T dy} \); Dijets: \( \frac{d^2 \sigma}{dm_{jj} dy^*} \), with \( y^* = \frac{1}{2} |y_1 - y_2| \)
Fair agreement between data and pQCD predictions in individual bins

Some tension when considering all data points, which calls for good understanding of correlations of experimental and theoretical syst uncertainties

Decorrelation scenarios applied to largest two point uncertainties: JES flavour response-multijet $p_T$ balance-PU as well as theoretical uncertainties like scale choice and variations and NP corrections

<table>
<thead>
<tr>
<th>$\chi^2$/dof</th>
<th>CT14</th>
<th>MMHT 2014</th>
<th>NNPDF 3.0</th>
<th>HERAPDF 2.0</th>
<th>ABMP16</th>
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<tbody>
<tr>
<td>all $</td>
<td>y</td>
<td>$, bins</td>
<td>419/177</td>
<td>431/177</td>
<td>404/177</td>
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<tr>
<td>$p_T^{\text{max}}$</td>
<td>419/177</td>
<td>431/177</td>
<td>404/177</td>
<td>432/177</td>
<td>475/177</td>
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<td>$p_T^{\text{jet}}$</td>
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<td>405/177</td>
<td>384/177</td>
<td>428/177</td>
<td>455/177</td>
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</table>
Inclusive dijet production: Comparison with NLO pQCD

ATLAS

\( L = 81 \text{ nb}^{-1} - 3.2 \text{ fb}^{-1} \)
\( \sqrt{s} = 13 \text{ TeV} \)
\( \text{anti-}k_t \, R=0.4 \)

Data
NLO QCD
\( \otimes k_{\text{EW}} \otimes k_{\text{NP}} \)
\( \mu = p_T \exp(0.3y^*) \)

CT14
HERAPDF 2.0
ABMP16

\( y^* \) ranges

<table>
<thead>
<tr>
<th>( y^* ) ranges</th>
<th>CT14</th>
<th>MMHT 2014</th>
<th>NNPDF 3.0</th>
<th>HERAPDF 2.0</th>
<th>ABMP16</th>
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<tbody>
<tr>
<td>( y^* &lt; 0.5 )</td>
<td>79%</td>
<td>59%</td>
<td>50%</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>( 0.5 \leq y^* &lt; 1.0 )</td>
<td>27%</td>
<td>23%</td>
<td>19%</td>
<td>32%</td>
<td>31%</td>
</tr>
<tr>
<td>( 1.0 \leq y^* &lt; 1.5 )</td>
<td>66%</td>
<td>55%</td>
<td>48%</td>
<td>66%</td>
<td>69%</td>
</tr>
<tr>
<td>( 1.5 \leq y^* &lt; 2.0 )</td>
<td>26%</td>
<td>26%</td>
<td>28%</td>
<td>9.9%</td>
<td>25%</td>
</tr>
<tr>
<td>( 2.0 \leq y^* &lt; 2.5 )</td>
<td>43%</td>
<td>35%</td>
<td>31%</td>
<td>4.2%</td>
<td>21%</td>
</tr>
<tr>
<td>( 2.5 \leq y^* &lt; 3.0 )</td>
<td>45%</td>
<td>46%</td>
<td>40%</td>
<td>25%</td>
<td>38%</td>
</tr>
<tr>
<td>all ( y^* ) bins</td>
<td>8.1%</td>
<td>5.5%</td>
<td>9.8%</td>
<td>0.1%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

- Fair overall description of the data

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Analogue of the EEC in $e^+e^-$ annihilation is the transverse EEC (TEEC) in hadronic collisions: [A. Ali, E. Pietarinen, J. Stirling, PL B141 (1984) 447]

\[
\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} = \frac{\int_{E_{T \text{min}}}^{\sqrt{s}} dE_T d^2\Sigma(E_T, \eta)/dE_T d\phi}{\int_{E_{T \text{min}}}^{\sqrt{s}} dE_T d^2\sigma(E_T, \eta)/dE_T d\phi} = \frac{1}{N} \sum_{A=1}^{N} \frac{1}{\Delta \phi_{\text{pairs}} \Delta \phi} \sum_{b_1, b_2, b_3} \frac{2E_{T_a}E_{T_b}}{(E_{T}^A)^2} \tag{2}
\]

In the LO in $\alpha_S(\mu)$, the l.h.s. is calculated by the following expression

\[
\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} = \frac{\sum_{a_i, b_i} f_{a_1/p}(x_1, \mu)f_{a_2/p}(x_2, \mu) \otimes \hat{\Sigma}^{a_1 a_2 \rightarrow b_1 b_2 b_3}}{\sum_{a_i, b_i} f_{a_1/p}(x_1, \mu)f_{a_2/p}(x_2, \mu) \otimes \hat{\sigma}^{a_1 a_2 \rightarrow b_1 b_2 b_3}} \tag{3}
\]

The r.h.s. above is approximately independent of the structure functions, yielding

\[
\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \sim \frac{\alpha_S(\mu)}{\pi} F^{pp}(\phi) \tag{4}
\]

NLO corrections, A.Ali, F.B., J. Llorente, W. Wang [PRD 86 (2012) 114017], found to be moderate with scale choice: $p_T^{\text{max}}$ or $H_{T2}$


End results: PDF uncertainty $O(1\%)$; scale uncertainty $O(6\%)$

ATEEC is defined as the F-B asymmetry in the TEEC function
For this measurement, multijet events in 2012 data sample at $\sqrt{s} = 8$ TeV have been selected with following criteria:

- **Trigger**: single jet trigger with $p_T > 360$ GeV $\Rightarrow L_{\text{eff}} = 20.2$ fb$^{-1}$
- **At least one primary vertex with 2 or more tracks with** $p_T > 400$ MeV
- **Jet selection**: anti-$k_T$ ($R = 0.4$) jets
- **Azimuthal resolution of jet axis is** 10 mrad
- **$p_T > 100$ GeV, $|\eta| < 2.5$**
- **Two leading jets should fulfil** $H_{T2} = p_{T1} + p_{T2} > 800$ GeV $\Rightarrow 6.2 \times 10^6$ events selected
- **TEEC and ATEEC measured in six bins in** $H_{T2}$
- **Jet energy scale (JES)**: MC based correction in $(p_T, \eta)$ bins obtained from the relation of reconstructed and particle level jets
- **JES uncertainty given by a set of 67 independent sources, correlated in** $p_T$
PYTHIA 6 and SHERPA give a fair description of the data, HERWIG needs better tuning.

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- Bayesian unfolding, representative transfer matrices shown below

![Graphs showing TEEC unfolding for different energy ranges](image)
Dominant uncertainties due to modelling and JES
**TEEC : Comparison to NLOJET++ calculations**

- Unfolded data \((x_i \pm \Delta x_i)\) fitted to NLOJET++ predictions \((\psi_i \pm \Delta \tau_i)\)
- Definition of \(\chi^2\):
  \[
  \chi^2(\alpha_s, \vec{\lambda}) = \sum_i \frac{(x_i - F_i(\alpha_s, \vec{\lambda}))^2}{\Delta x_i^2 + \Delta \tau_i^2} + \sum_k \lambda_k^2,
  \]
- NLOJET++ predictions are varied using nuisance parameters \(\lambda_k\)
  \[
  F_i(\alpha_s, \vec{\lambda}) = \psi_i(\alpha_s) \left(1 + \sum_k \lambda_k \sigma_k^{(i)}\right).
  \]
- Here, \(\sigma_k^{(i)}\) denotes the k-th source of systematic uncertainty in bin i-th.
- And \(\psi(\alpha_s)\) are analytical expressions parameterising the dependence of the observable (TEEC or ATEEC) on the strong coupling constant
- NP correction factors deviate from unity by less than 1%

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![Graphs showing non-perturbative corrections for ATLAS data sets](image-url)
Fair agreement between unfolded data and pQCD
Fitted values for $\alpha_s(M_Z)$ in good agreement with PDG average

Scale uncertainties are dominant ⇒ need for NNLO calculations for jet cross-sections

$\alpha_s(M_Z) = 0.1162 \pm 0.0011^{+0.0076}_{-0.0061} (\text{scale}) \pm 0.0018 (\text{PDF}) \pm (0.0003)(NP)$

$\alpha_s(M_Z) = 0.1196 \pm 0.0013^{+0.0061}_{-0.0013} (\text{scale}) \pm 0.0017 (\text{PDF}) \pm (0.0004)(NP)$
Azimuthal decorrelations: definition and event selection

  \[
  R_{\Delta \phi}(H_T, y^*, \Delta \phi_{max}) = \frac{\frac{d^2 \sigma_{dijet}(\Delta \phi_{dijet} < \Delta \phi_{max})}{dH_T dy^*}}{\frac{d^2 \sigma_{dijet(\text{inclusive})}}{dH_T dy^*}}
  \]

- Full 2012 data set corresponding to 20.2 $fb^{-1}$ at $\sqrt{s} = 8$ TeV
- Anti-$k_T$ (R=0.6) jets selected with $p_{T\text{min}} > 100$ GeV and $|\eta| < 2.5$
- At least two jets with $H_T = \sum_i p_{Ti} > 450$ GeV and $p_{T1}/H_T > 1/3$
- Constrain on phase space: $y^* = |y_1 - y_2|/2 < 2.0$
- Further constrain: $y_{\text{boost}} = (y_1 + y_2)/2 \Rightarrow |y_i - y_{\text{boost}}| < 0.5$
- $\Delta \phi_{dijet} = |\phi_1 - \phi_2| < \Delta \phi_{max}$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<td>$p_{T\text{min}}$</td>
<td>100 GeV</td>
</tr>
<tr>
<td>$y_{\text{max}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$y_{\text{boost}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$y^*$</td>
<td>2.0</td>
</tr>
<tr>
<td>$p_{T1}/H_T$</td>
<td>$&gt; 1/3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T$ bin boundaries (in TeV)</td>
<td>0.45, 0.6, 0.75, 0.9, 1.1, 1.4, 1.8, 2.2, 2.7, 4.0</td>
</tr>
<tr>
<td>$y^*$ regions</td>
<td>0.0-0.5, 0.5-1.0, 1.0-2.0</td>
</tr>
<tr>
<td>$\Delta \phi_{max}$ values</td>
<td>$7\pi/8$, $5\pi/6$, $3\pi/4$, $2\pi/3$</td>
</tr>
</tbody>
</table>
Azimuthal decorrelations

- At fixed \((y^*, \Delta \phi_{\text{max}})\) \(R_{\Delta \phi}\) decreases with increasing \(H_T\)
- At fixed \((H_T, \Delta \phi_{\text{max}})\) \(R_{\Delta \phi}\) increases with increasing \(y^*\)
- At fixed \((H_T, y^*)\) \(R_{\Delta \phi}\) decreases with decreasing \(\Delta \phi_{\text{max}}\)
- Inner (outer) error bars indicate statistical (stat+syst) uncertainties

\[ R_{\Delta \phi}(H_T, y^*, \Delta \phi_{\text{max}}) \]

\[ H_T \quad [\text{TeV}] \]

\[ \mu_R = \mu_F = H_T / 2 \]

\[ \text{MMHT2014 PDFs} \]

\[ \text{NLO pQCD} \]

\[ \text{LO pQCD} \]

\[ + \text{non-perturb. correct.} \]

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

\[ L = 0.010-20.2 \text{ fb}^{-1} \]

\[ 0.0 < y^* < 0.5 \]

\[ 0.5 < y^* < 1.0 \]

\[ 1.0 < y^* < 2.0 \]
Azimuthal decorrelations

- Ratios of unfolded data to NLO pQCD predictions are shown below for MMHT2014 PDF
- Inverse of NLO K-factor also shown ⇒ convergence of pQCD expansion good at large $\Delta \phi_{\text{max}}$

![Graph showing data ratios to NLO pQCD predictions for different y* regions and HT values.](chart)

MMHT2014 PDFs

$\alpha_s(m_Z) = 0.118$

$\mu_R = \mu_F = \frac{H_T}{2}$

Theory uncert.
PDF uncert.

$\Delta \phi_{\text{max}} = \frac{7\pi}{8}$
$\Delta \phi_{\text{max}} = \frac{5\pi}{6}$
$\Delta \phi_{\text{max}} = \frac{3\pi}{4}$
$\Delta \phi_{\text{max}} = \frac{2\pi}{3}$
Azimuthal decorrelations: fits to NLO predictions

- Data for $\Delta \phi_{\text{max}} = 7\pi/8$ integrated over $y^*$ fitted to pQCD predictions

\[
\begin{array}{c|cccccc}
\alpha_s(m_Z) & \text{Total} & \text{Statistical} & \text{Experimental} & \text{Non-perturb.} & \text{MMHT2014} & \mu_{r,f} \\
& \text{uncert.} & \text{correlated} & \text{corrections} & \text{uncertainty} & \text{PDF set} & \text{variation} \\
0.1127 & +0.3 & +1.8 & -0.1 & +0.6 & -0.6 & +2.9 & +5.2
\end{array}
\]
Azimuthal decorrelations: strong coupling constant determination

![Graph showing the running of the strong coupling constant, $\alpha_s(m_Z)$, as a function of $Q$.[1]](image)

- Running of strong coupling constant probed up to scales $\sim 2$ TeV

\[ \alpha_s(m_Z) = 0.1127^{+0.0063}_{-0.0027} \]

[1] Fernando Barreiro On behalf of the ATLAS Collaboration

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Summary

- Inclusive jet and dijet cross sections at $\sqrt{s} = 13$ TeV
  - Overall fair agreement with fixed order pQCD in individual bins, tension observed when the fit is carried out over the complete $p_T$ and $y$ coverage
  - NNLO predictions overestimate measurements when using $p_T^{\text{max}}$ as the scale
- TEEC and ATEEC measurements at $\sqrt{s} = 8$ TeV: precision test of QCD
  - Good agreement with pQCD predictions, running of $\alpha_s$
- First measurements of azimuthal decorrelations at $\sqrt{s} = 8$ TeV
  - Data corrected for NP effects well described by pQCD for $\Delta\phi_{\text{max}} = 7\pi/8$
EW correction factors for inclusive jet and dijet production

Dittmaier, Huss, Speckner
anti-$k_t$, $R=0.4$

Electroweak correction factor

$0.95$
$1$
$1.05$
$1.1$
$1.15$

Dittmaier, Huss, Speckner
$=0.4 R_t k_{anti}$

$|y| < 0.5$
$0.5 \leq |y| < 1.0$
$1.0 \leq |y| < 1.5$
$1.5 \leq |y| < 2.0$
$2.0 \leq |y| < 2.5$
$2.5 \leq |y| < 3.0$

$p_T [\text{GeV}]$

$m_{jj} [\text{GeV}]$
### TEEC: results of the fits

<table>
<thead>
<tr>
<th>⟨Q⟩ (GeV)</th>
<th>α_s(m_Z) value (NNPDF 3.0)</th>
<th>χ^2/N_{dof}</th>
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<tbody>
<tr>
<td>412</td>
<td>0.1171 ± 0.0021 (exp.) +0.0081</td>
<td>24.3 / 21</td>
</tr>
<tr>
<td></td>
<td>−0.0022 (scale) ± 0.0013 (PDF) ± 0.0001 (NP)</td>
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<tr>
<td>437</td>
<td>0.1178 ± 0.0017 (exp.) +0.0073</td>
<td>28.3 / 21</td>
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<td>−0.0017 (scale) ± 0.0014 (PDF) ± 0.0002 (NP)</td>
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<tr>
<td>472</td>
<td>0.1177 ± 0.0017 (exp.) +0.0079</td>
<td>27.7 / 21</td>
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<td>−0.0023 (scale) ± 0.0015 (PDF) ± 0.0001 (NP)</td>
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<tr>
<td>522</td>
<td>0.1163 ± 0.0017 (exp.) +0.0067</td>
<td>22.8 / 21</td>
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<td>−0.0016 (scale) ± 0.0016 (PDF) ± 0.0001 (NP)</td>
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<td>604</td>
<td>0.1181 ± 0.0017 (exp.) +0.0082</td>
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<tr>
<td>810</td>
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<td>23.7 / 21</td>
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<tr>
<th>⟨Q⟩ (GeV)</th>
<th>α_s(m_Z) value (NNPDF 3.0)</th>
<th>χ^2/N_{dof}</th>
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<td>10.9 / 10</td>
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