Differential jet cross sections at CMS

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on behalf of the CMS Collaboration

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Why jets?

• Jets allow to test perturbative predictions at the highest energy scales → the $\alpha_S$ running

• Jets allow to probe proton structure at the smallest distances ($\sim 10^{-19}$ m) → PDFs (Juan Rojo’s talk)

• Jets allow to test:
  Fixed order predictions
  Resummation effects
  ME + PS matching
  MPI + non. pert. effects

(Simon Platzer’s talk)
Jet detection at CMS – Particle flow (PF) algo

- Using all CMS components to reconstruct the jet kinematics

Better energy resolution

Better angular resolution

[arXiv:1706.04965]

Tracker
ECAL
HCAL
Magnet
Muon
The CMS jet analyses

- Inclusive jets at 8 TeV (20 fb\(^{-1}\))*
- Inclusive jets at 13 TeV (71 pb\(^{-1}\))
- Triple differential dijets at 8 TeV (20 fb\(^{-1}\))*
- \(R_{32}\) at 8 TeV (20 fb\(^{-1}\))*
- Azimuthal correlations at 13 TeV (36 fb\(^{-1}\))
- Azimuthal correlations for back-to-back jets at 13 TeV (36 fb\(^{-1}\)), new!

*Includes QCD analysis
Inclusive jets at 8 TeV

- The jet ($\text{anti-k}_T \ R=0.7$) spectrum between 20 GeV - 2000 GeV
- Forward region $3.2<|y|<4.7$ only for low-$p_T$
- Compared to fixed order NLO predictions (by NLOJET++)
Inclusive jets at 8 TeV – Power of Ratios

- Partial cancellation of:
  → Theoretical unc. (e.g. QCD scale)
  → Exp. systematic unc.
- Improved PDF sensitivity

$\frac{g(x = 200/2760, \mu = 200)}{g(x = 200/8000, \mu = 200)} \propto \frac{d^2\sigma}{dp_T^2}(7\,\text{TeV}) \div \frac{d^2\sigma}{dp_T^2}(8\,\text{TeV})$

2.76 TeV / 8 TeV

7 TeV / 8 TeV
Inclusive jets at 8 TeV – QCD Analysis

- A significant constrain of gluon PDF w.r.t. HERA-only fit

\[ \alpha_S \text{ running scanned up to 1.5 TeV} \]

Gluon PDF at \( \mu = 320 \text{ GeV} \)

- \( \alpha_S \) unc. dominated by scale

\[ \alpha_S^{\text{NLO}}(M_Z) = 0.116^{+0.006}_{-0.004} \]
Inclusive jets at 8 TeV – QCD Analysis

- Overall chi2/ndf ~ 1.2
- Slightly worse values for forward jets 1.5<|y|<2.5

<table>
<thead>
<tr>
<th>Data sets</th>
<th>Partial $\chi^2 / N_{dp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA I+II neutral current</td>
<td>376/332</td>
</tr>
<tr>
<td>e$^+$p, $E_p = 920$ GeV</td>
<td>61/63</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>197/234</td>
</tr>
<tr>
<td>e$^+$p, $E_p = 820$ GeV</td>
<td>204/187</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>219/159</td>
</tr>
<tr>
<td>e$^+$p, $E_p = 575$ GeV</td>
<td>41/39</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>50/42</td>
</tr>
<tr>
<td>e$^-$p</td>
<td></td>
</tr>
<tr>
<td>HERA I+II charged current</td>
<td></td>
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<td>e$^+$p</td>
<td></td>
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<td>HERA I+II charged current</td>
<td></td>
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<tr>
<td>e$^-$p</td>
<td></td>
</tr>
<tr>
<td>CMS inclusive jets 8 TeV</td>
<td></td>
</tr>
<tr>
<td>$0 &lt; y &lt; 0.5$</td>
<td>53/36</td>
</tr>
<tr>
<td>$0.5 &lt; y &lt; 1.0$</td>
<td>34/36</td>
</tr>
<tr>
<td>$1.0 &lt; y &lt; 1.5$</td>
<td>35/35</td>
</tr>
<tr>
<td>$1.5 &lt; y &lt; 2.0$</td>
<td>52/29</td>
</tr>
<tr>
<td>$2.0 &lt; y &lt; 2.5$</td>
<td>49/24</td>
</tr>
<tr>
<td>$2.5 &lt; y &lt; 3.0$</td>
<td>4.9/18</td>
</tr>
<tr>
<td>Correlated $\chi^2$</td>
<td>94</td>
</tr>
<tr>
<td>Global $\chi^2 / N_{dof}$</td>
<td>1471/1216</td>
</tr>
</tbody>
</table>
Inclusive jets at 13 TeV

- Early 13 TeV jet data (anti-k_\text{T} R=0.4, 0.7) from 2015 with limited lumi
- Data precision not sufficient for detailed QCD analysis

A legacy analysis of 2016, 2017 & 2018 data (~140 fb\textsuperscript{-1}) in progress

3D scan of the dijet events

Low-x + high-x

3D scan of the dijet events

- The 8 TeV jet data (anti-$k_T$, $R=0.7$) of lumi 20 fb$^{-1}$

  PDF sensitivity
  + PS matching effects.
  (POWHEG vs HERWIG7 vs NLOJET++)

**CMS**

2 forward jets

- dominated by PDF unc.

$p_T^\text{jets} > 50$ GeV

$19.7 \text{fb}^{-1}$ (8 TeV)

$\frac{d^3\sigma}{dp_T^\text{avg}dydy^*}$

$\mu = p_{T,\text{max}}^{1.3}$

NLOJET++ (NLO@EW@NP)

NNPDF 3.0
3D scan of the dijet events

- A reduction of PDF uncertainty at high-$x$

\[ \alpha_S \text{ unc. dominated by scale} \]
\[ \alpha_S^{\text{NLO}}(M_Z) = 0.120^{+0.004}_{-0.003} \]
The $R_{32}$ measurement

- The $R_{32}$ is the fraction of dijet events where an extra jet is “emitted”
  \[ R_{32} = \left. \frac{d\sigma}{dH_{T,2}/2} \right|_{N_{\text{jets}} > 3} / \left. \frac{d\sigma}{dH_{T,2}/2} \right|_{N_{\text{jets}} > 2} \]
  where $p_T^{\text{jet}} > 150$ GeV

- Partial cancellation of the exp. & theor. uncertainties in the ratio

\[ \alpha_S^\text{NLO}(M_Z) = 0.115^{+0.005}_{-0.002} \]

\[ H_{T,2}/2 = \left( p_T^{\text{jet}_1} + p_T^{\text{jet}_2} \right)/2 \]
Jet-based Strong Coupling extractions

- All $\alpha_s$ jet extractions based on 8 TeV data and NLO fixed order predictions

<table>
<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Lumi</th>
<th>$\alpha_s(M_Z)$</th>
<th>exp. unc.</th>
<th>theor. unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive jets</td>
<td>8 TeV</td>
<td>20 fb$^{-1}$</td>
<td>0.116</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>3D dijets</td>
<td>8 TeV</td>
<td>20 fb$^{-1}$</td>
<td>0.200</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>$R_{32}$</td>
<td>8 TeV</td>
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<td>0.001</td>
<td>0.004</td>
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</tbody>
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Uncertainty dominated by the QCD scale → NNLO predictions?

All $\alpha_s(M_Z)$ values compatible with world average 0.118±0.001
Azimuthal correlations

- Azimuthal angle between leading and sub-leading jet in $p_T$
  $$\Delta \phi_{1,2}$$

- The smallest azimuthal angle between any 2 jets
  $$\Delta \phi_{\text{2j}}^{\text{min}}$$
Azimuthal correlations

\[ \frac{1}{d\sigma_{1,2}} \frac{\sigma_{1,2}}{d\Delta\phi_{1,2}} \]

• For inclusive 2-jet 3-jet and 4-jet events \( p_T^{\text{jet}} > 100 \text{ GeV} \)
• 13 TeV 2016 data \( (R=0.4) \), 36 fb\(^{-1}\)
• Sensitive to the QCD resummation effects \( (\Phi_{1,2} \sim 180^\circ) \), as well as to higher orders & multi-leg ME (lower \( \Phi_{1,2} \))
Azimuthal correlations
(>= 2 Jets vs LO)

• Best description by 
  MadGraph + Pythia8
  (CUETP8M1)
  up to 4 jets in ME, MLM matching

• Pythia8 & Herwig++ have both
  “flatter” spectrum than in data for
  $\Phi_{1,2} \sim \pi$

• At smaller dphi Pythia8 agrees
  better than Herwig++
Azimuthal correlations
(>= 4 Jets vs LO)

- Best description again by Madgraph + Pythia8 (CUETP8M1), where ME itself contains topologies $\Phi_{1,2} > 90^\circ$

- Pythia8 (Heriwig++) sightly below (above) data
Azimuthal correlations (>= 2 Jets vs NLO)

- **HERWIG7 NLO** (MC@NLO like matching) provides the best description
- **Powheg-2J + Herwig++** performs significantly worse
Azimuthal correlations in back-to-back region

\[ 170^\circ < \Phi_{1,2} < 180^\circ \]
Azimuthal correlations in back-to-back region

- The normalized spectra for various $p_T$ ranges differ mostly in the back-to-back region.
- Higher $p_T$ enhances $\Phi_{1,2} \sim \pi$.

\[ p_T^{\text{jet}} > 100 \text{ GeV} \]
\[ 170^\circ < \Phi_{1,2} < 180^\circ \]
Azimuthal correlations
(\(\geq 2\) Jets vs LO)

- **Best** description by MadGraph + Pythia8 (CUETP8M1)
  up to 4 jets in ME, MLM matching
- **Pythia8** not steep enough
Azimuthal correlations
(>= 3 Jets vs LO)

- The worst description by MadGraph + Pythia8 (CUETP8M1) up to 4 jets in ME, MLM matching
Azimuthal correlations
(>= 3 Jets vs NLO)

- **Worst** description by POWHEG-3J+Pythia8 (CUETP8M1)
- **POWHEG-2J** performs better for 3-jet topologies!
Conclusions

- Inclusive jet measurements at 8 and 13 TeV
  → Scan of $\alpha_S$ running up to the TeV-scale
  → Reduction of PDF unc. at high-x & scales

- Triple differential jet x-section & $R_{32}$ measurement
  → Enhance $\alpha_S$ + PDF sensitivity by going more differential
    (but lower statistics)

- Azimuthal correlations between leading jets
  → Testing PS & ME matching
    e.g. MC@NLO (Hg7) found to perform better than POWHEG