Measurement of double-differential inclusive jet cross section @ energy $\sqrt{s}=13\text{TeV}$ with CMS

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HEP GREECE Conference  
Date: 29-31/03/2018
Contents

• CMS Detector
• Jet Energy Reconstruction and Corrections
• Measurements
• Conclusions
CMS Detector

Technical Details:

Magnetic Field: 3.8T

Tracker: $|\eta|<2.5$

Central Calorimeter: $|\eta|<3$

Forward Calorimeter: $3<|\eta|<5$

$$\eta \equiv -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$$

Graphical Depiction of CMS detector (Compact Muon Solenoid)
CMS Trigger

• LHC collides protons in each 25ns. (40 MHz, $10^9$ events/s)
• Demanding the quick selection of the interesting events

Level-1 Trigger (L1T)

40 MHz \rightarrow 100 kHz

High Level Trigger (HLT)

100 kHz \rightarrow 100 Hz
Jet Reconstruction

At CMS experiment, the Particle Flow algorithm is used, which both handles and implements the information from all of the sub-detectors’ systems as a result of the reconstruction and identification of particles.

After that, the 4-vector momentum of the particles are introduced to the anti-kt algorithm which combines the particles into jets.

**Particle Flow Algorithm (PF)**

**Anti-kt Algorithm**: \( p = -1 \)

\[
d_{ij} = \min \left( k_{T,i}^{2p}, k_{T,j}^{2p} \right) \frac{\Delta R_{ij}^2}{R^2}
\]
Jet Energy Correction

By the completion of the jets identification it is vital to correct their energy.

This correction is important due to the fact that:

The calorimeters have non-linear and non-uniform response in energy deposits by particles.
Data for Analysis

- The data for the following analysis collected with the CMS at 2016 in 25ns @ √s=13TeV

\[
\frac{d^2\sigma}{dp_T\,dy} = \frac{1}{\varepsilon \cdot L} \frac{N_{jets}}{\Delta p_T (2 \cdot \Delta |y|)}
\]

- Total integrated luminosity L = 30.1 fb⁻¹

- Demanding one good primary vertex, tight JetID and jet p_T>113 GeV

- Jets up to p_T 3 TeV and |y|<2.0 in four different rapidity regions with step at 0.5
Trigger Studies

High Level single Jet Triggers:

\[
eff_{\text{HLT \_AK8PFJet}X} = \frac{\text{Incl RecoJet \_O(trig \_ref + L1Obj \_p_T > Z + HLTObj \_p_T > Y)}}{\text{Incl RecoJet \_O(trig \_ref)}}
\]

<table>
<thead>
<tr>
<th>HLT Triggers</th>
<th>Lumi (pb(^{-1}))</th>
<th>Turn-on(GeV)</th>
<th>Phase Division(p_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_AK8PFJet40</td>
<td>0.043978</td>
<td>-</td>
<td>74-114</td>
</tr>
<tr>
<td>HLT_AK8PFJet80</td>
<td>0.851458</td>
<td>114.47</td>
<td>114-196</td>
</tr>
<tr>
<td>HLT_AK8PFJet140</td>
<td>8.54722</td>
<td>186.92</td>
<td>196-272</td>
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<tr>
<td>HLT_AK8PFJet200</td>
<td>70.6187</td>
<td>260.31</td>
<td>272-330</td>
</tr>
<tr>
<td>HLT_AK8PFJet260</td>
<td>442.356</td>
<td>330.34</td>
<td>330-395</td>
</tr>
<tr>
<td>HLT_AK8PFJet320</td>
<td>1310.37</td>
<td>381.33</td>
<td>395-468</td>
</tr>
<tr>
<td>HLT_AK8PFJet400</td>
<td>3924.74</td>
<td>461.54</td>
<td>468-548</td>
</tr>
<tr>
<td>HLT_AK8PFJet450</td>
<td>29464.1</td>
<td>501.76</td>
<td>&gt;548</td>
</tr>
</tbody>
</table>
Unfolding

• Unfolding is a way to pass from the detector level to the stable-parton level:

DETECTOR LEVEL  UNFOLDING  PARTICLE LEVEL

• This method is used owning to the fact that there is no "perfect" detector due to mainly finite precision and limited efficiency in the measurement procedure of events, like the measurement of energy.

• Iterative D’Agostini Bayesian with ROOUnfold Software package

• Construction of the Response Matrices:
  1. Events are generated with flat spectrum with regard to $p_T$
  2. These events are then weighted by the theoretical cross sections obtained from NLOJet++(FASTNLO) using CT14 PDF set and corrected for non-perturbative effects. In this way the Toy MC constructs the true $p_T$ cross section.
  3. The measured cross sections are generated by smearing the true cross sections with the resolution obtaining from JetMET group.
  4. Construction of the Response Matrices using the Toy MC a total of 100M events are generated for each rapidity bin.
Data Results: reconstructed and unfolded are now being presented for our observable for the four different regions of rapidity. The correction after the unfolding is 5-20%
Systematic Uncertainties

Experimental Systematic Uncertainties Studies:
1. Uncertainties due to jet energy scale (JES), $p_T = p_T(1 \pm 1\sigma)$
2. Uncertainties due to jet energy resolution (JER)
3. Uncertainties due to trigger efficiency curves (trigger efficiency corrections) and jet ID $\sim 1\%$
4. Uncertainties due to luminosity of 2016 data $\sim 2.6\%$

Theoretical Systematic Uncertainties Studies:
1. Scale uncertainties $\sim 1-8\%$
2. PDF uncertainties $\sim 1-12\%$
3. NP uncertainties

$$\sigma_{sys+} = \frac{|JES\_up|}{JES\_normal}$$

$$\sigma_{JER+} = \frac{JER\_up}{JER\_nominal}$$

$$C_0^{NP} = \frac{N^{PS+HAD+MPI}_{LO(NLO)}}{N^{PS}_{LO(NLO)}}$$
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic Effect</th>
<th>AK7 Jet Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>8-65 %</td>
</tr>
<tr>
<td>JER</td>
<td>1-2 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6 %</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>1 %</td>
</tr>
<tr>
<td>Pile-Up</td>
<td>-</td>
</tr>
<tr>
<td>PDF</td>
<td>1-8 %</td>
</tr>
<tr>
<td>Scale</td>
<td>1-12 %</td>
</tr>
<tr>
<td>NP Corrections</td>
<td>1 %</td>
</tr>
<tr>
<td>TOTAL</td>
<td>10 – 65 %</td>
</tr>
</tbody>
</table>
The results at the stable-particle level (unfolded spectra) for the large cone (AK7 R=0.7) for four different ranges of rapidity with step 0.5. are presented here.

The final results are compared with theoretical predictions at 2nd order perturbation theory (NLO) QCD.

At the left plot, the observable are compared with the software computing package NLOJet++ and at the right plot with the Monte Carlo Event Generator POWHEG+Pythia8 tune CUETM1.
Satisfactory adjustment with the different PDF+NLOJet++ for the barrel region of detector.
Sufficient description for the event generator PH+P8 for the barrel region of the detector.
Summary

➢ Measurement of the double differential cross section for inclusive jet at energy 13 TeV.
  – The data belongs to the 2016 statistics (30.1 fb⁻¹)
  – The observable is calculated
  – Unfolding using Toy MC
  – Systematic Uncertainties: JES, JER, NP corrections

➢ Comparison at a stable-parton level with:
  • NLOJet++ combining with different PDFs
  • Monte Carlo Event Generators (NLO)

➢ Sufficient description of the final results in the barrel region (|y|<1.5).

➢ Discrepancies in outer rapidity regions. From my point of view, it is not easy to say that H7 is promising. It fluctuates a lot. We need more MC statistics.
Thank you all both for your patience and attention
SPARE SLIDES
Cross Section - Detector Level

- Measurement of the double differential inclusive jet cross section.

\[
\frac{d^2\sigma}{dp_T^2\,dy} = \frac{1}{\varepsilon \cdot L \cdot \Delta p_T} \frac{N_{jets}}{2 \cdot \Delta |y|}.
\]

\[\text{anti-}\kappa, R=0.7\]

\[\begin{aligned}
|y|<0.5 (x10^6) \\
0.5<|y|<1.0 (x10^5) \\
1.0<|y|<1.5 (x10^5) \\
1.5<|y|<2.0 (x10^5)
\end{aligned}\]
Unfolding - Response Matrices
2. Systematic Uncertainties due to Jet Energy Resolution (JER)

➢ JER: the migrations of the events between the different bins inside the histogram

Scale Factors from JetMET

➢ The transverse momentum resolution is estimated by the «official» $p_T$ Resolution by JetMET for 12 different regions of rapidity and 5 bins of $\rho$

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_AKSPFJet10</td>
<td>0.07858</td>
<td>0.42870</td>
<td>0.36185</td>
<td>0.11092</td>
<td>0.01995</td>
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<tr>
<td>HLT_AKSPFJet40</td>
<td>0.06880</td>
<td>0.39839</td>
<td>0.38256</td>
<td>0.12838</td>
<td>0.02188</td>
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<tr>
<td>HLT_AKSPFJet60</td>
<td>0.08431</td>
<td>0.44050</td>
<td>0.35125</td>
<td>0.10463</td>
<td>0.01931</td>
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<tr>
<td>HLT_AKSPFJet80</td>
<td>0.09000</td>
<td>0.44824</td>
<td>0.34463</td>
<td>0.09934</td>
<td>0.01779</td>
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<td>HLT_AKSPFJet140</td>
<td>0.08829</td>
<td>0.44709</td>
<td>0.34703</td>
<td>0.09982</td>
<td>0.01777</td>
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<tr>
<td>HLT_AKSPFJet200</td>
<td>0.08770</td>
<td>0.44753</td>
<td>0.34781</td>
<td>0.09956</td>
<td>0.01740</td>
</tr>
<tr>
<td>HLT_AKSPFJet260</td>
<td>0.09406</td>
<td>0.44932</td>
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<td>0.09808</td>
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<tr>
<td>HLT_AKSPFJet320</td>
<td>0.08444</td>
<td>0.44427</td>
<td>0.35177</td>
<td>0.10186</td>
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<tr>
<td>HLT_AKSPFJet400</td>
<td>0.09147</td>
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<td>0.34449</td>
<td>0.09881</td>
<td>0.01703</td>
</tr>
<tr>
<td>HLT_AK3AKSPFJet50</td>
<td>0.06814</td>
<td>0.41302</td>
<td>0.37613</td>
<td>0.12030</td>
<td>0.02239</td>
</tr>
</tbody>
</table>
Systematic Experimental Uncertainties

Systematic Uncertainties due to Jet Energy Scale (JES)

Varying up and down the transverse momentum $p_T$ from all jets by the uncertainty: $p_T = p_T(1\pm1\sigma)$

The new observables are compared with the nominal distribution

Estimating the uncertainties due to Jet Energy Scale:

$$\sigma_{sys+} = \frac{|JES\_up|}{JES\_normal} \quad \sigma_{sys-} = \frac{|JES\_down|}{JES\_normal}$$
Systematic Experimental Uncertainties

➢ The uncertainty due to JER is as follows:

Varying the values of the transverse momentum $p_T$ up and down by the scale factors which appeared at the table in the previous slide and constructing three different curves (up, nominal, down) in the same plot. Finally, using the formulas at the middle of the slide, we calculate the JER uncertainties:

$$\sigma_{JER^+} = \frac{JER\_up}{JER\_no\_minimal}$$

$$\sigma_{JER^-} = \frac{JER\_down}{JER\_no\_minimal}$$

| $|y|\,$ | AK7 |
|-------|-----|
| 0.0-0.5 | 1%  |
| 0.5-1.1 | 1%  |
| 1.1-1.7 | 1%  |
| 1.7-2.3 | 1%  |
| 2.3-2.8 | 1.5%|
| 2.8-3.2 | 2%  |
| 3.2-5.0 | 2%  |
Non-Perturbative Corrections

- Corrections due to model assumptions used at QCD (fixed-order predictions as used in fits of SM). The formula for these corrections is displayed at the top right hand corner of the slide:

\[ C_{0}^{NP} = \frac{N_{PS+HAD+MPI}^{LO(NLO)}}{N_{PS}^{LO(NLO)}} \]

- For this calculation of non-perturbative factors the following Monte Carlo event generators were used:
  - POWHEG (CT14nlo) + PYTHIA8 CUETP8M1
  - POWHEG (CT14nlo) + PYTHIA8 CUETP8S1-CTEQ6L1
  - POWHEG (HERAPDF2.0NLO) + PYTHIA8 CUETP8S1-HERAPDF
  - PYTHIA8 CUETP8M1
  - HERWIG++ UE-EE-5C
  - HERWIG++ CUETHppS1

\(|y| < 0.5\)
Non-Perturbative Corrections

• The envelopes from the plots according to LO and NLO MC event generators are presented only for the first rapidity bin.
• The previous corrections (previous slide) are estimated on average for the final correction.
• For the procedure of fitting the relation $y=a+b^c x^c$ was used, where $a, b, c$, are considered free parameters.
• NPs are applied to the NLOJet++ predictions.

$|y| < 0.5$
Electroweak Corrections

- Arising from the virtual exchanges of massive gauge W and Z
- Become sizeable at high jet transverse momentum $p_T$ and central rapidity $y$.
- Electroweak corrections are applied to the NLOJet++ predictions (like NP)

![Graph showing Electroweak Correction Factor vs. $p_T$](image)

AK7 (R=0.7)
These corrections range between 0.96-1.05 depending on the jet
Transverse momentum and rapidity and are less 3% for $p_T<1$TeV.