Differential Cross Section for Inclusive Jets in CMS Experiment

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Jets: What are they?

- Surrogates of quark & gluon in detectors appears in a collimated fashion
- Encodes information from different scales
- Essential tool to understand dynamics of strong interaction
- Much higher probability than any other process at LHC
Unserstanding Jets

- Information from all sub-detectors are combined to reconstruct and identify particles \( \rightarrow \) PF candidates
- Jets, in CMS, are reconstructed using PF candidates using anti-kT algoirthm
- Charged hadrons not from primary vertex are rejected \( \Rightarrow \) CHS jets (neutral pile-up is removed by area-subtraction)

### Choice of jet size:
Interplay between loosing radiation vs adding pile-up

- Higher \( P_T \) \( \Rightarrow \) Larger shower depth
- \( \Rightarrow \) Larger EM fraction

Excellent tracking performance even in ~ TeV scale
Jet Energy Calibration & Resolution

- Cross-section measurement depends crucially on energy calibration and resolution (steep spectra → mis-measurement leads to bin migration)
- Factorised approach to match energy scale of detector level jets to particle level jets (on average)
  
  (Details of calibration in Robin’s talk)

- Effect of energy resolution appears through unfolding ⇒ leads to systematic uncertainty
- Jet energy resolution (JER) in MC is obtained (after applying JEC) by matching detector level jets to particle level jets, Data/MC scale factor is derived using photon+jet balance, di-jet asymmetry
- Uncertainty in JER comes from ISR+FSR, pile-up contamination, OOC showering, difference in flavour response ...

Effect of Pile up below pt <100 GeV
Selection for Cross-section Measurement

- Measurement for AK5 & AK7 jets @ $\sqrt{s} = 7$ & $8$ TeV
  for AK4 & AK7 jets @ $\sqrt{s} = 13$ TeV

- Events must pass:
  Single Jet trigger criteria (seeded by calorimeter based L1 trigger)
  $\text{MET} / \Sigma E_T < 0.3$ (to remove EW background & noise)

- Jets must pass:
  Identification criteria depending on energy fraction & # of particles (to reject noise in calorimeter read-outs faking as jet)

- Phase space is divided in bins of the leading jet $p_T$ and the lowest prescale trigger is used in each bin to use statistical power of data

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\mathcal{L}} \frac{N_j}{\Delta p_T \Delta y}$$

- Efficiency of selection
- Integrated Luminosity

$\#$ of jets in $p_T$ bin of width $\Delta p_T$ & rapidity bin of width $\Delta y$
Unfolding (Journey of Jets from Detector to Particle)

- Particle level prediction from NLO calculation (using NLOJet++), after non-perturbative & electroweak correction, is smeared using JER to obtain detector level spectra

- Construct response matrix relating detector level & particle level information

- Resolution factor is varied to measure the uncertainty due to unfolding (usually small)

Used D’Agostini method in RooUnfold package to unfold detector-level spectra, thus remove detector effects (inefficiency & resolution)!

Difference between unfolded and detector level spectra: 5-20%

CMS QCD-11-004
## Systematics in Cross-Section Measurement

<table>
<thead>
<tr>
<th>Experimental Sources</th>
<th>Theoretical Sources</th>
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<tr>
<td>Jet Energy Scale (JES) (8-65% for AK4 &amp; AK7)</td>
<td>Scale choice (AK7: 1-12%, AK4: 1-10%)</td>
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<tr>
<td>Jet Energy Resolution (JER) (1-2%)</td>
<td>PDF (AK7: 1-8%, AK4: 2-10%)</td>
</tr>
<tr>
<td>Pile-up (~0.1%)</td>
<td>Non-perturbative cor (AK7: 1%, AK4: 2%)</td>
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<tr>
<td>Uncertainty in Luminosity (4.8%)</td>
<td>Uncertainty in $\alpha_s$ (~1%)</td>
</tr>
<tr>
<td>Unfolding (~1%)</td>
<td>Values quoted for 13 TeV Measurement (50 ns data)</td>
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</tbody>
</table>

JES dominates exp uncertainty

Scale choice & PDF control theory systematics

NP Correction for fixed order prediction to take into account effect of hadronisation and MPI Uncertainty: PYTHIA8 - HERWIG++
Inclusive Jet Cross-Section at 13 TeV

Two different jet sizes to understand parton evolution

Fixed order (NLO) prediction * NP * EW correction

Good agreement between Data and NLO prediction over 8 orders of magnitude

NLO + PS (parton shower)
Comparison to Fixed Order Prediction at 13 TeV

- Overall good agreement with NLO prediction for AK7 jets (with larger fluctuation in data in forward region)
- Cross-section is little overestimated for AK4 jets (resummation of radiated soft gluons is absent in NLO prediction: more important for jets of small sizes)

Sensitive to PDF

CMS SMP-2015-007
Comparison to NLO + Parton Shower at 13 TeV

- For AK4 jets, NLO+PS provides better description compared to fixed order calculation.
- For AK7 jets, prediction is quite similar to the one from fixed order NLO calculation.

Two LO predictions are in opposite directions w.r.t. data.
NLO is between PYTHIA8 & HERWIG++, describes data quite well.

CMS SMP-2015-007
Non-perturbative correction is evident to be essential to complement fixed order prediction.

NNLO prediction (effectively NLO for ratio) improves the agreement with data.
Cross-Section Ratio of Two Jet Sizes at $\sqrt{s} = 7$ TeV

- Better modelling of data by using parton shower, best with NLO generator followed by PS
- Shows the importance of final state radiation to describe the ratio

CMS SMP-2013-002
Impact of Inclusive Jets on PDF

- Dominated by $gg \rightarrow gg$ at low $p_T$, $qg \rightarrow qg$ at medium $p_T$ & $qq \rightarrow qq$ at high $p_T$ => quark & gluon PDFs are sensitive

- Significant reduction in uncertainty band for gluon both at low and high $x$

- Improvement in valence $d$ quark PDF in low $x$ region

Using HERAFitter 1.1.1

arXiv:1609.05331
Impact of Inclusive Jets on PDF

- Dominated by gg -> gg at low $p_T$, qg -> qg at medium $p_T$ & qq -> qq at high $p_T$ => quark & gluon PDFs are sensitive

- Description of gluon improves at large $x$

  .... Useful for BSM search ;)

arXiv:1609.05331
Determination of Strong Coupling Constant using Inclusive Jets

\frac{d\sigma}{dp_T} = \alpha_s^2(\mu_R) \hat{X}^{(0)}(\mu_F, p_T) [1 + \alpha_s(\mu_R)K1(\mu_R, \mu_F, p_T)]

NLO prediction

- $\chi^2$ has been computed between NLO prediction (with CT10 PDF) and measured data in both exclusive and inclusive $p_T$ & $y$ bins with different choices of $\alpha_s(M_Z)$ (in steps of 0.001 with range 0.112-0.127)

- $\alpha_s$ is determined in 9 bins in $p_T$ range 74-2500 GeV (uncertainty from $\Delta\chi^2 = 1$)

$Q$: cross-section reweighted bin centre ($\alpha_s(M_Z)$ evolved to $Q$ scale using 2 loop 5F RG)

arXiv:1609.05331
Jet Mass at 13 TeV: Massive Story

- Jet mass is the most commonly used observable to discriminate jets containing heavy objects from QCD & in BSM searches
- In QCD, jet mass arises from radiation:
  Sensitive to dynamics of QCD evolution starting from a parton
- Radiation from partons exited from jet cone adds NGL:
  hard to compute => Use Soft Drop grooming to get rid of NGL

**Event Selection:**
At least 2 AK8 jets, $p_T > 200$ GeV, $|y| < 2.4$ &

$$\frac{p_{T_1} - p_{T_2}}{p_{T_1} + p_{T_2}} < 0.3 \quad \Delta(\phi_1 - \phi_2) > \pi/2$$

With grooming, PU sensitivity is reduced
Also modelling uncertainty is reduced
as Soft Drop removes soft gluons (hard to model)
Jet Mass at 13 TeV: Massive Story

- Sudakov peak disappears in soft drop mass distribution

- Powheg + PYTHIA8 is unable to describe jet mass dist in data (for absolute x-section)

- PYTHIA8 seems to be the best to predict distribution both for ungroomed & groomed jet mass

- Analytic calculation can describe jet mass dist in data (for normalised x-section)

LO + NNLL (using SCET)  
NLO + NLL
Conclusion

- CMS has a wealth of results on inclusive jets (many more to come)
- Inclusive jets have been established as a powerful tool to understand QCD, measure $\alpha_s$, constrain PDFs, ...
- Better calibration helps to make measurements more precise
- Experimental uncertainty is similar or less than theoretical uncertainty
- Fixed order NLO prediction (with NP & EW correction) describes large jets almost all over the phase space
- NLO+PS are found to make better prediction for small R jets and also for the cross-section ratio of two jet sizes
- Motivates higher order calculation with resummation to be the state-of-the-art
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THANK YOU!
More Material ..
Determination of Strong Coupling Constant
using Inclusive Jets

\[ \chi^2(\alpha_s(M_Z)) = \left( D - T(\alpha_s(M_Z)) \right)^T C^{-1} \left( D - T(\alpha_s(M_Z)) \right) \]

\[ C = C^{\text{stat}} + C^{\text{unfolding}} + \sum C^{\text{JES}} + C^{\text{uncor}} + C^{\text{lumi}} + C^{\text{PDF}} + C^{\text{NP}} \]

- JES, unfolding, lumi, PDF, NP are taken to 100% correlated among all pT and y bins
- Systematic uncertainty for each source is derived by removing covariance matrix for that source in \( \chi^2 \) and taking the difference with as dervied using full covariance matrix

| \(|y| \) bin | Fitted \( \alpha_s(M_Z) \) | PDF unc. | scale unc. | NP unc. | exp unc. | \( \chi^2_{\text{min}} / N_{\text{Bins}} \) |
|-----------|----------------|---------|-----------|---------|---------|------------------|
| 0.0–0.5   | 0.1155         | +0.0027 | +0.0070   | +0.0003 | +0.0025 | 48.6 / 37        |
| 0.5–1.0   | 0.1156         | +0.0025 | +0.0069   | +0.0003 | +0.0026 | 28.4 / 37        |
| 1.0–1.5   | 0.1177         | +0.0024 | +0.0027   | +0.0002 | +0.0024 | 19.3 / 36        |
| 1.5–2.0   | 0.1163         | +0.0025 | +0.0040   | +0.0002 | +0.0023 | 65.6 / 32        |
| 2.0–2.5   | 0.1164         | +0.0020 | +0.0046   | +0.0002 | +0.0019 | 38.3 / 25        |
| 2.5–3.0   | 0.1158         | +0.0029 | +0.0049   | +0.0006 | +0.0036 | 14.3 / 18        |
| Combined  | 0.1164         | +0.0025 | +0.0053   | +0.0001 | +0.0014 | 186.5 / 185      |

arXiv:1609.05331
Impact of Inclusive Jets on PDF

\[ xg(x) = A_g x^{B_g} (1 - x)^{C_g} (1 + E_g x^2) - A'_g x^{B'_g} (1 - x)^{C'_g}, \]
\[ xu(x) = A_{u,x} x^{B_{u,x}} (1 - x)^{C_{u,x}} (1 + D_{u,x} x + E_{u,x} x^2), \]
\[ xd(x) = A_{d,x} x^{B_{d,x}} (1 - x)^{C_{d,x}} (1 + D_{d,x} x), \]
\[ x\bar{U}(x) = A_{\bar{U},x} x^{B_{\bar{U},x}} (1 - x)^{C_{\bar{U},x}} (1 + D_{\bar{U},x} x), \]
\[ x\bar{D}(x) = A_{\bar{D},x} x^{B_{\bar{D},x}} (1 - x)^{C_{\bar{D},x}} (1 + D_{\bar{D},x} x + E_{\bar{D},x} x^2). \]

- Result simultaneous fit of PDF and \( \alpha_s \):
  \[ \alpha_s(M_Z) = 0.1185^{+0.0019}_{-0.0021} \text{(exp)} + 0.0002 (\text{model}) + 0.0000 (\text{param}) + 0.0022 (\text{scale}) \]

- For PDF
  Experimental uncertainty using Hessian method
  Modelling uncertainty from b-mass, c-mass, \( Q_{\text{min}} \)
  Parameterisation uncertainty from additional terms in function

arXiv:1609.05331
Jet Energy Calibration: Prep for Measurement

- Cross-section measurement depends crucially on energy calibration (steep spectra → mis-measurement leads to bin migration)
- Factorised approach to match energy scale of detector level jets to particle level jets (on average)
- Pile-up subtraction by removing tracks coming from secondary vertices and neutrals by hybrid area-subtraction using pile-up simulation and random cone method
- Correction as a function of jet pseudorapidity and $p_T$ based on simulation

Stable response
In barrel,
Requires $p_T$ dependent
Correction in EC & HF

CMS DP-2018/028
Jet Energy Calibration & Resolution

- Response correction as a function of $\eta$ by balancing dijet / minimisig MET (MPF)
- Absolute scale correction using photon+jet, $Z$+jet balance
- Additional correction for data using combination of photon+jet, $Z$+jet, multijet sample

Effect of Pile up below $p_T < 100$ GeV

CMS DP-2018/028
Uncertainty Jet Energy Calibration

- Normally below 1-2% in the phase space used for differential cross-section measurement

- Response difference between uds, b, c, gluon is crucial (gluon radiation pattern is less tuned in parton shower)

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**Uncertainty Components:**
- Combined $\gamma$, $Z\rightarrow$ ee, $Z\rightarrow$ mumu reference scale & ISR-FSR
- JER SF & ISR-FSR
- Bias from residual offset
- PYTHIA8 / HERWIG++ difference for parton response after data-based JEC
- Closure of lumi weighted correction per era

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**CMS DP-2018/028**

*Graphs showing JEC uncertainty and response comparisons.*

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**CMS JME-2013-004**

*Graphs showing jet response and parton flavor comparisons.*