Jet production at NNLO

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Jet production at the LHC

- look at production of jets of hadrons with large transverse energy
- for sufficiently high transverse momentum $p_T > 20$ GeV high rates and clean and simple cross section definition

$$\frac{d\sigma}{dp_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y}$$

Phenomenology of jet production at the LHC:

- test perturbative QCD
  - wide kinematical range in jet $p_T$ and rapidity covers 7 orders of magnitude in cross section
- determine structure of the proton $\rightarrow$ PDFs (sensitivity to the gluon medium to high-$x$)
- determine $\alpha_s$ and running of $\alpha_s$ from a single experiment
- search for BSM physics

Single jet inclusive: (pp $\rightarrow$ jet+X)
ATLAS@13 TeV (arXiv:1711.02962)
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Gluon PDF fractional uncertainty with LHC jet data included CMS (arXiv:1609.5331)
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$\alpha_s$ running in the TeV range from LHC jet data
Jet observables: theory status

- **NLO QCD**
  [Ellis, Kunszt, Soper '92] [Giele, Glover, Kosower '94] [Nagy 02]

- **NLO EW**
  [Dittmaier, Huss, Speckner '13]
  [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '17]

- **NLO QCD + PS (POWHEG)**
  [Alioli, Hamilton, Nason, Oleari, Re '11]

- **NLO QCD + Resummation (threshold+jet radius)**
  [Dasgupta, Dreyer, Salam, Soyez '14] [Liu, Moch, Ringer '17]

- **NNLO QCD**
  [Gehrmann-De Ridder, Gehrmann, Glover, JP '13]
  [Currie, Glover, JP '16]
  [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP '17]
Jet observables: uncertainties

**Experimental uncertainties:**

- observables measured differentially with percent level uncertainties, dominated by systematics, jet energy scale

**Theoretical uncertainties:**

- parametric dependence on PDF and $\alpha_S$
- perturbative uncertainty: truncation of the fixed order calculation to NLO and NNLO

Scale choice for inclusive jets at NNLO (this talk)

dominant exp. systematic uncertainty jet energy scale: ±5-10%

NLO scale uncertainty ~10% NNLO needed
Numerical setup - LHC $\sqrt{s} = 13$ TeV

*Theory setup: single jet inclusive production* \((pp->jet + X)\)

- NNLO pQCD predictions calculated with the NNLOJET* parton level event generator
- PDF4LHC15nnlo PDF set (for LO,NLO,NNLO cross sections)
- anti-\(k_T\) jet algorithm, cone sizes \(R=0.4\) and \(R=0.7\)
- theory uncertainty: vary renormalization \(\mu_R\) and factorization \(\mu_F\) scales by factors \([1/2,2]\) around pre-defined central scale

*Comparison with LHC data:*

- CMS $\sqrt{s} = 13$ TeV 71 pb$^{-1}$ \([CMS, arXiv:1605.04436]\)

- \(R=0.4\) and \(R=0.7\)

Scale choices $\mu_R, \mu_F$

- $p_T \rightarrow$ transverse momentum of the individual jets
- $p_{T1} \rightarrow$ transverse momentum of the leading jet
- $H_T \rightarrow$ scalar sum of the transverse momenta of the reconstructed jets
- $\hat{H}_T \rightarrow$ scalar sum of the transverse momenta of all partons
- $\mu_R, \mu_F$ are arbitrary and unphysical parameters and are absent from the true result $\rightarrow a$ priori each scale above is an equally valid scale choice

However, a suitable scale choice would

- minimize ratios of $Q^2/\mu^2$, i.e., faster perturbative convergence and smaller scale uncertainties
- avoid scales that introduce pathological behaviours in the prediction, i.e., $\sigma < 0$
- avoid scales that are discontinuous on the phase space of the observable, i.e., no kinks in k-factors

$\rightarrow$ recently derived NNLO predictions for inclusive jet production allow for the first time a robust study on scale setting, making use of the knowledge of three orders in the perturbative expansion of the observable
Individual jet contributions and jet fractions

- Single jet inclusive observable receives contributions from all jets in the event, at $O(\alpha_s^4)$

\[
\frac{d\sigma}{dp_T} (\mu = p_T) = \frac{d\sigma}{dp_{T1}} (\mu = p_{T1}) + \frac{d\sigma}{dp_{T2}} (\mu = p_{T2}) + \frac{d\sigma}{dp_{T3}} (\mu = p_{T3}) + \frac{d\sigma}{dp_{T4}} (\mu = p_{T4})
\]

**NLO:**

- leading jet dominates
- third jet negligible
- second jet sizeable at high $p_T$ negligible at low $p_T$

**NNLO:**

- leading and second jet fractions similar over the whole $p_T$ range
- significant increase in second jet $p_T$ contribution to the inclusive jet sample at NNLO with respect to NLO
Second jet transverse momentum distribution

Corrections to second jet distribution integrated over rapidity $R=0.4$

- NLO: large and negative with huge uncertainty $\rightarrow$ potentially large logs sensitive on IR effects; emissions not recombined with outgoing jets lead to imbalance between $p_{T1}$ and $p_{T2}$ and incomplete cancellations between real and virtual corrections (worse for small $R$)

- NNLO: large and positive

- Stabilization of the predictions at NNLO (in line with the LO) $\rightarrow$ functional form of the scale matters

\[ \mu = p_{T1} \quad \mu = p_T \quad \mu = 2p_T \quad \mu = \hat{H}_T \]
Differential corrections for leading and subleading jet

- large cancellations between corrections to first (blue) and second jet (red) at NLO (solid), NNLO (dashed)

- smaller perturbative coefficients for $\mu = 2p_T$ $\mu = \hat{H}_T$ for leading and subleading jet
On pure theoretical grounds for $\mu = \hat{H}_T$ and $\mu = 2p_T$ we observe:

- smaller NNLO/NLO k-factors on the inclusive jet sample
- NNLO prediction inside the NLO scale band
Comparison with LHC CMS data $R=0.7$

- small positive NNLO corrections improve the agreement with CMS data with respect to NLO
- significant reduction in scale uncertainty from NLO to NNLO $\rightarrow$ roughly more than a factor of 2 in a wide range of $p_T$ and rapidity $\rightarrow$ paves the way for precision physics with inclusive jets at the LHC
Comparison with LHC CMS data R=0.4

- improved agreement with data at NNLO with respect to NLO

- both scale choices are stable and provide reasonable predictions for R=0.7 and R=0.4
Conclusions

• Presented a new approach to look at jet data at the LHC with NNLO QCD corrections using antenna subtraction implemented in a new parton level generator NNLOJET

• Percent level experimental accuracy in jet production is a reality at the LHC

• Theoretical uncertainties include renormalization and factorization central scale choice and scale variation

• The knowledge of 3 orders in the perturbative expansion of the observable allows for the first time a robust study on scale setting for inclusive jet production at the LHC (soon to be on the arXiv)

• Contribution from second jet perturbatively unstable and typically harder scale choices show better convergence

• Improved agreement between the CMS $\sqrt{s}=13$ TeV jet data and predictions at NNLO in QCD

• Precision phenomenology with NNLO jet observables is just starting
Backup Slides
$p_T$ versus $p_{T1}$: similarities and differences

$p_T=p_{T1}$

- for leading order kinematics (2→2 kinematics)
- for high-$p_T$ jets (back to back)

$p_T \neq p_{T1}$

- for events with three or more jets
- for events with jets outside the fiducial cuts
Dijet inclusive production

\( pp \rightarrow 2\text{jets} + X: \)

- cross section measured differentially in:
  \[ m_{jj}^2 = (p_{j1} + p_{j2})^2 \]
  \[ y^* = \frac{1}{2} (y_{j1} - y_{j2}) \]

- requires observation of a dijet system in the final state
  \[ \mu = m_{jj} ; \quad \langle p_T \rangle = \frac{1}{2} (p_{T1} + p_{T2}) \]

**small \(|y^*|\):**

- both scales give reasonable predictions

**large \(|y^*|\):**

- stable prediction with \( \mu = m_{jj} \)
  - large negative NLO corrections, non-overlapping scale bands and residual NLO, NNLO scale uncertainties of \( \sim 100\% \), \( \sim 20\% \) with \( \mu = \langle p_T \rangle \)
Dijet inclusive production

- good theoretical motivation to use $\mu = m_{jj}$

Comparison with ATLAS data:

- NLO does not adequately capture the shape nor the normalization at low $m_{jj}$ and low $|y^*|$.
- good agreement with the NNLO prediction across the entire dynamical range in $m_{jj}$ and $|y^*|$.
- generally observe large reduction in the scale variation and small NNLO corrections.