NNLO QCD predictions for single jet inclusive production at the LHC

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Based on work in [Phys. Rev. Lett. 118, 072002 (2017)] and new results

Rencontres de Moriond QCD Session March 30, 2017
Jets 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

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

![Graph showing $d^2\sigma/dp_T dy$ vs Jet $p_T$](image)
Jets at the LHC

\[ \sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), s/\mu^2, s/\mu_F^2) \]

- Inputs from physical parameters
- PDF’s ; strong coupling
- Unphysical inputs
- renormalization and factorization scales
- Partonic cross section calculable in perturbation theory

\[ \hat{\sigma}_{ij} = \hat{\sigma}_{ij}^{LO} + \left( \frac{\alpha_s}{2\pi} \right) \hat{\sigma}_{ij}^{NLO} + \left( \frac{\alpha_s}{2\pi} \right)^2 \hat{\sigma}_{ij}^{NNLO} + O(\alpha_s^3) \]
Jets at the LHC

- Percent level experimental accuracy in jet production is a reality at the LHC
- Rigorous tests of pQCD dynamics across a huge range of kinematics
- Constrain PDF's
Jets at the LHC

- Percent level experimental accuracy in jet production is a reality at the LHC
- Rigorous tests of pQCD dynamics across a huge range of kinematics
- Constrain PDF’s
- Determine $\alpha_s(M_Z)$ and running coupling from a single experiment

CMS-SMP-14-001
Jets at the LHC

- Percent level experimental accuracy in jet production is a reality at the LHC
- Rigorous tests of pQCD dynamics across a huge range of kinematics
- Constrain PDF’s
- Background to high mass resonances decaying to dijet final states

[Graphs and data from CMS and ATLAS experiments]

arXiv:1703.09127
Theory state of the art

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

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

- **NLO EW**  [Dittmaier, Huss, Speckner ’13]
  [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro ’16]

- **NNLO QCD**  [Gehrmann-De Ridder, Gehrmann, Glover, JP ’13]
  [Currie, Gehrmann-De Ridder, Glover, JP ’13]
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New approach to look at jet data at the LHC (this talk)
Anatomy of an NNLO calculation

\[ d\hat{\sigma}_{NNLO} = \int d\phi_4 d\hat{\sigma}^{RR}_{NNLO} \]

\[ + \int d\phi_3 d\hat{\sigma}^{RV}_{NNLO} \]

\[ + \int d\phi_2 d\hat{\sigma}^{VV}_{NNLO} \]

- double-unresolved
- single-unresolved
- \( 1/\varepsilon^2 ; 1/\varepsilon \)
- \( 1/\varepsilon^4 ; 1/\varepsilon^3 ; 1/\varepsilon^2 ; 1/\varepsilon \)

- 6 parton tree level  [Berends, Giele '87] [Mangano, Parke, Xu '87] [Britto, Cachazo, Feng '06]

- 5 parton one-loop [Bern, Dixon, Kosower '93]

- 4 parton two-loop [Anastasiou, Glover, Oleari, Tejeda-Yeomans '01][Bern,De Freitas Dixon '02]

- non-trivial cancellation of infrared singularities at NNLO
NNLO antenna subtraction

\[ \sigma_{\text{NNLO}} = \int d\Phi_4 \left( \hat{\sigma}_{\text{NNLO}}^{\text{RR}} - \hat{\sigma}_{\text{NNLO}}^{S} \right) + \int d\Phi_3 \left( \hat{\sigma}_{\text{NNLO}}^{\text{RV}} - \hat{\sigma}_{\text{NNLO}}^{T} \right) + \int d\Phi_2 \left( \hat{\sigma}_{\text{NNLO}}^{\text{VV}} - \hat{\sigma}_{\text{NNLO}}^{U} \right) \]

- universal factorization properties in IR limits

- mimic RR, RV in unresolved limits

- analytically cancel the poles in RV and VV matrix elements

- phase space factorization

\[ d\Phi_{m+1}(p_1, \ldots, p_{m+1}; q) = d\Phi_{m}(p_1, \ldots, \tilde{p}_I, \tilde{p}_K, \ldots, p_{m+1}; q) \cdot d\Phi_{X_{ijk}}(p_i, p_j, p_k; \tilde{p}_I + \tilde{p}_K) \]
NNLO antenna subtraction

\[ d\hat{\sigma}_{NNLO} = \int d\Phi_4 \left( d\hat{\sigma}_{NNLO}^{RR} - d\hat{\sigma}_{NNLO}^S \right) \]
\[ + \int d\Phi_3 \left( d\hat{\sigma}_{NNLO}^{RV} - d\hat{\sigma}_{NNLO}^T \right) \]
\[ + \int d\Phi_2 \left( d\hat{\sigma}_{NNLO}^{VV} - d\hat{\sigma}_{NNLO}^U \right) \]

\[ d\hat{\sigma}_{NNLO}^S \quad d\hat{\sigma}_{NNLO}^T \]
- mimic RR, RV in unresolved limits

\[ d\hat{\sigma}_{NNLO}^T \quad d\hat{\sigma}_{NNLO}^U \]
- analytically cancel the poles in RV and VV matrix elements

For pp→jet +X

- all subprocesses included through leading colour \( \alpha_s^2 N^2, \alpha_s^2 N N_F, \alpha_s^2 N_F^2 \)

\[ \{ gg, qg, q\bar{q}, qq, qq', q\bar{q}' \} \]
- subleading colour contributions to the NNLO coefficient neglected
NNLOJET parton level generator


• parton level generator based on antenna subtraction to compute fully differential cross sections at NNLO in QCD

  • pp -> H+jet
  • pp -> Z+jet
  • pp -> 2 jets

• interface to applfast nnlo tables

  • pp->H,W,Z
  • ep-> 2 jets

Jan Niehues talk

Daniel Britzger’s talk
Single jet inclusive scale choice

two widely used scale choices:

• $\mu_R = \mu_F = \{p_{T1}, p_T\}$

  • leading jet $p_T$ in the event $p_{T1}$

  • individual jet $p_T$

• high $p_T$ jets are back to back $\Rightarrow p_T \rightarrow p_{T1}$
Single jet inclusive scale choice

two widely used scale choices:

• $\mu_R = \mu_F = \{p_{T1}, p_T\}$
  - leading jet $p_T$ in the event $p_{T1}$
  - individual jet $p_T$

• high $p_T$ jets are back to back $\Rightarrow p_T \rightarrow p_{T1}$

• $p_T \neq p_{T1}$ for:
  - 3jet events
  - 3rd jet outside fiducial jet cuts

$\Rightarrow$ with $p_T$ choice the real emission event with different $R$ gives rise to a different scale $\Rightarrow$ larger $R \Rightarrow$ harder scale $\Rightarrow$ $p_T \rightarrow p_{T1}$

• at NLO the $p_{T1}$ scale choice generates the same hard scale for the event independent of the value of $R$
ATLAS jets

Theory setup

- NNPDF3.0_nnlo
- anti-\(k_T\) jet algorithm
- \(\mu_R=\mu_F=\{p_{T1}, p_T\}\)
- vary scales by factors of 2 and 1/2

Comparison to data

- ATLAS 7 TeV 4.5 fb\(^{-1}\)
- \(R=0.4\)
Ratio to NLO

- asymmetric scale band variation

- underestimated at small pT due to turn over of the NLO coefficient

- 20% uncertainty for central high pT jets rising to 40% for forward jets

Comparison to data

- non perturbative effects < 2% effect [JHEP 1509, 141 (2015)]

- data favours the pT1 scale choice at NLO

[Currie, Gehrmann, Glover, Huss, JP (in preparation)]
Ratio to NNLO

- symmetric scale band variation
- pT1!=pT effects enlarged at NNLO
- 10% scale uncertainty at low pT and percent level scale uncertainty at high pT

Comparison to data

- data favours the pT scale choice at NNLO
- NLO EW effects around 15% for central high pT jets

[Currie, Gehrmann, Glover, Huss, JP (in preparation)]
K-factor plot

- $p_{T1}! = p_T$ effects enlarged at NNLO at low $p_T$
  - decrease for larger R values

Sensible criteria for scale choice for single jet inclusive production

- perturbative stability
- data driven scale choice

Future steps

- compare with CMS jet data; change R value; change $\sqrt{s}$

- Obtain consistent description of jet data at NNLO for all jet data sets at low and high $p_T$ in the central and forward regions for multiple R values

[Currie, Gehrmann, Glover, Huss, JP (in preparation)]
Summary

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

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

- Percent level theory scale uncertainty for high pT jet production at NNLO below PDF and $\alpha_s(M_Z)$ uncertainties on the cross section

- Observed significant ambiguity at small pT due to scale choice (underestimated at NLO) which requires further phenomenological studies

- In future: 8 TeV, 13 TeV, CDF data, different PDFs etc… gateway to NNLO jet phenomenology