Current theory status for jet production

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Jet production at the LHC

- Look at production of jets of hadrons with large transverse energy in proton-proton collisions

- For sufficiently high transverse momentum $p_T > 20$ GeV high rates and clean and simple cross section definition

- Anti-$k_t$ jet definition infrared and collinear safe used in experimental measurements and theory predictions

\[
\frac{d\sigma}{dp_T dy} = \frac{1}{L} \frac{N_{jets}}{\Delta p_T \Delta y} \propto \alpha_s^2
\]
Jet measurements have become very precise:

- dominant systematic uncertainty JES ~ 1-2% corresponds to < 10% uncertainty on single jet inclusive cross section
- similar for ATLAS and CMS: 5% systematic on a wide range, and sub-% statistical → allow jet precision physics at the LHC

Ideal testing ground for QCD:

- test perturbative QCD description of jet data at the LHC
- constrain PDFs (sensitive to gluon at LO)
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- determine $\alpha_s \rightarrow$ huge range in jet $p_T$ directly tests energy dependence/running of $\alpha_s$ from a single experiment

$\alpha_s$ running in the TeV range from LHC jet data
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- Test perturbative QCD description of jet data at the LHC.

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- A window to new physics e.g. $\rightarrow$ bumps in dijet mass distributions $\rightarrow$ precise BSM searches in dijet angular distributions.
Jet observables

- **Single jet inclusive cross section:** \( pp \rightarrow \text{jet} + X \)
  - inclusive sum of individual jet contributions in the event that pass the jet fiducial cuts
    - each jet in the event contributes separately, leading to multiple entries of a single event in distributions
  - differential in transverse momentum \( p_T \) and rapidity \( y \)
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  - differential in transverse momentum $p_T$ and rapidity $y$

- **Di-jet inclusive cross section: $pp \rightarrow 2 \text{ jet} + X$**
  - consider only the two leading jets (in $p_T$) in the event
    → single entry per event in distributions
  - multi-differential measurements possible ($M_{jj}, p_{T,\text{avg}}, y^*, y_{\text{boost}}, \ldots$)
Jet observables: theory status

- Much progress in **fixed-order calculations/resummation** and **parton shower predictions**
  - NLO QCD  
    [Ellis, Kunszt, Soper '92] [Giele, Glover, Kosower '94] [Nagy 02]
  - NLO QCD + PS  
    [Alioli, Hamilton, Nason, Oleari, Re '11] [Hoeche, Schonherr '12] [Herwig7 '15]
  - NLO QCD + Resummation (threshold+jet radius)  
    [Dasgupta, Dreyer, Salam, Soyez '14] [Liu, Moch, Ringer '17]
  - NLO EW  
    [Dittmaier, Huss, Speckner '13] [Campbell, Wackeroth, Zhou '16]
  - NLO QCD+EW  
    [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '17]
  - NNLO QCD  
    [Gehrmann-De Ridder, Gehrmann, Glover, JP '13]  
    [Currie, Glover, JP '16] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP '17]
NLO QCD + PS (POWHEG)

- hardest emission generated first according to:

\[ d\sigma = \bar{B}(\Phi_B) \, d\Phi_B \left[ \Delta_R(p_T^{\text{min}}) + \frac{R(\Phi_R)}{B(\Phi_B)} \Delta_R(k_T(\Phi_R)) \, d\Phi_{\text{rad}} \right] \]

- with the born cross section replaced with the NLO differential cross section at fixed Born kinematics integrated over single emission \(\rightarrow\) preserves NLO accuracy for inclusive quantities

\[ \bar{B}(\Phi_B) = B(\Phi_B) + \left[ V(\Phi_B) + \int d\Phi_{\text{rad}} \, R(\Phi_R) \right] \]

- probability of not having an emission harder than \(p_T\) \(\rightarrow\) POWHEG Sudakov

\[ \Delta_R(p_T) = \exp \left[ - \int d\Phi_{\text{rad}} \, \frac{R(\Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_R) - p_T) \right] \]

- interface with shower generator to develop the rest of the shower vetoing emissions harder than the first one
NLO QCD + PS (POWHEG)

Comparison to cross section data \( R = 0.4; 0.6 \) @ 8 TeV

POWHEG prediction lower than fixed-order NLO QCDxNPxEW

Ratio to data less sensitive to the jet radius in POWHEG
NLO QCD + Resummation (threshold+jet radius)


Double differential single jet inclusive cross section:

\[
\frac{p_T^2 d^2 \sigma}{dp_T^2 dy} = \sum_{i_1i_2} \int_0^V (1-w) \, dz \int_{\frac{1}{1-z}}^{1-\frac{1-v}{1-z}} dv \, x_1^2 f_{i_1}(x_1) x_2^2 f_{i_2}(x_2) \frac{d^2 \hat{\sigma}_{i_1i_2}}{dv \, dz}(v, z, p_T, R)
\]

- \( z = s_4/s \) invariant mass recoiling against the jet
- in the small \( R \)-limit and threshold limit \( z \to 0 \) cross section factorizes within SCET

\[
\frac{d^2 \hat{\sigma}_{i_1i_2}}{dv \, dz} = s \int ds_X \, ds_c \, ds_G \, \delta(zs - s_X - s_G - s_c) \text{Tr} \left[ H_{i_1i_2}(v, p_T, \mu_h, \mu) S_G(s_G, \mu_{sG}, \mu) \right] \\
\times J_X(s_X, \mu_X, \mu) \sum_m \text{Tr} \left[ J_m(p_TR, \mu_J, \mu) \otimes \Omega_s c_m(s_cR, \mu_{sc}, \mu) \right],
\]

- perturbative contributions know at least to NLO
- joint resummation at NLL accuracy \( \alpha_s^n \left( \ln^k(z)/z \right)_+ \); \( \alpha_s^n \ln^k(R) \)
- additive matching to fixed-order NLO QCD result

\[
\sigma_{\text{NLO+NLL}} = \sigma_{\text{NLO}} - \sigma_{\text{NLO}_{\text{sing}}} + \sigma_{\text{NLL}}
\]

- resummation scales \( \mu_i \) evolved through RGE equations to common hard scale \( \mu = \mu_h = p_T^{\text{max}} \)
NLO QCD + Resummation (threshold+jet radius)

- threshold logs lead to an enhancement of the cross section for large \( p_T \) \( \mu = \mu_h = p_T^{max} \)
- resummation of small R-logs lead to a decrease in the cross section in the entire range \( p_T \)

Liu, Moch, Ringer [arXiv: 1808.04574]
NNLO QCD

- Perturbative QCD expansion of the inclusive jet cross section at hadron colliders

\[ d\sigma = \sum_{i,j} \int \left[ d\hat{\sigma}_{ij}^{LO} + \left( \frac{\alpha_s}{2\pi} \right) d\hat{\sigma}_{ij}^{NLO} + \left( \frac{\alpha_s}{2\pi} \right)^2 d\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3) \right] f_i(x_1) f_j(x_2) dx_1 dx_2 \]

- NNLO gluonic contributions

\[ A_6^{(0)}(gg \rightarrow gggg) \quad A_5^{(1)}(gg \rightarrow ggg) \quad A_4^{(2)}(gg \rightarrow gg) \]

- tree-level 2→4 matrix elements
- one-loop 2→3 matrix elements
- two-loop 2→2 matrix elements
- NNLO DGLAP evolution
- NNLO PDF’s

[Berends, Giele '87] [Mangano, Parke, Xu '87]
[Britto, Cachazo, Feng '06]
[Bern, Dixon, Kosower '93] [Kunszt, Signer, Trocsanyi '94]
[Anastasiou, Glover, Oleari, Tejeda-Yeomans '01] [Bern, De Freitas, Dixon '02]
[Moch, Vermaseren, Vogt '04]
[ABMP, CT, NNPDF, MMHT]
NNLO antenna subtraction

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

\[ \hat{\sigma}_{\text{NNLO}}^{\text{S}} \quad \hat{\sigma}_{\text{NNLO}}^{\text{T}} \quad \hat{\sigma}_{\text{NNLO}}^{\text{U}} \]

• mimic RR, RV in unresolved limits
• analytically cancel the poles in RV and VV matrix elements

For inclusive jet and dijet production: \( pp \rightarrow \text{jet} + X \); \( pp \rightarrow 2\text{jet} + X \)

• NNLO corrections known \([\text{Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, JP '17}]\)
• all channels \( \{gg, gq, q\bar{q}, qq, q\bar{q}, q\bar{q}'\} \) at leading colour \( \alpha_s^2 N^2, \alpha_s^2 NN_F, \alpha_s^2 N_F^2 \)
• gg-channel with full colour
• sub-leading colour contributions: (suppressed by \( 1/N^2 \))
  • below two percent at NLO (all channels)
NNLO fully differential parton-level generator

- Based on antenna subtraction for the analytic cancellation of IR singularities at NNLO

**Infrastructure**

- Process management
- Phase space, histogram routines
- Validation and testing
- ApplFast interface in progress

**Processes implemented at NNLO**

- $Z^{\pm}(0,1)$ jet, $W^{\pm}(0,1)$ jet
- $H^{\pm}(0,1)$ jet
- DIS-2jet
- VBF $H^+$2jet
- Inclusive jet production

A thorough study of jet cross sections at the LHC [Bellm, Buckley, et.al., arXiv:1903.12563]

- PS MC's matched or merged to NLO accuracy and fixed-order LO,NLO,NNLO for:
  - $Higgs + jet$ ; $Z + jet$ ; inclusive jet production at the LHC

- Observe good agreement between different PS predictions for inclusive jet production reflecting the underlying fixed-order NLO results
A thorough study of jet cross sections at the LHC [Bellm, Buckley, et.al., arXiv:1903.12563]

- Complete analysis of Hadronization and MPI corrections as a function of the jet size for measurements in:
  - $Higgs+jet$; $Z+jet$; inclusive jet production at the LHC

- Compatible results for the combined hadronization and MPI corrections between Sherpa and HERWIG, small for $R=0.4$
Inclusive jet cross section $R$-dependence fits to the functional form $f(R) = a + b \log(R) + cR^2$

- larger slope at NNLO and NLO+PS compared to NLO
- lower panels show scale uncertainty $R$-dependence and alternative uncertainty estimates
  - ansatz 1 uncertainty estimate combines scale uncertainties in $\sigma(R) = \sigma(R_0) \frac{\sigma(R)}{\sigma(R_0)}$ in quadrature
  - ansatz 2 uncertainty estimate combines scale uncertainties of $a,b,c$ in quadrature
Single jet inclusive production: 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 → potentially large logs sensitive on IR effects; NNLO: large and positive

- **Stabilization of the predictions at NNLO** (in line with the LO) → functional form of the scale matters
Decomposition of events contributing to a single bin in $p_{T2}$:

- bin content above constrained to add up to one by construction
- instability in the second jet $p_T$ distribution from events when additional radiation is not recombined into the outgoing jet

→ **Large cancellations** between positive real emission and large negative virtual correction provide a guide to understand the behaviour of the scale choice

- worse for $\mu = pT_1$ that changes event-by-event in the distribution; $\mu = pT$ remains constant


$\mu = pT_1 \Rightarrow$ strongly disfavoured in NNLO predictions for single jet inclusive $p_T$ distributions
$\mu = p_T$ strongly disfavoured in NNLO predictions for single jet inclusive $p_T$ distributions.
• Conclusion in agreement with recent measurements from ATLAS $\sqrt{s}=13$ TeV

• NNLO theory from NNLOJET

• Theoretical understanding of the scale choice and precision phenomenology with jet observables at NNLO is just starting
Understanding single jet inclusive production at the LHC - first steps of the NNLO era

Results have appeared in the context of individual theory publications looking at published LHC data.
Today:

- tables of $k$-factors from NNLO runs, fixed binning, fixed PDF set and scale choice
- determination of $(PDF, \alpha_s)$ require NNLO predictions to be computed multiple times (varying PDF sets, scales, etc.)
- we would like to store the perturbative coefficients of the (N)NLO QCD calculations of final state observables in lookup tables or grids once and for all with very high statistical precision
Understanding single jet inclusive production at the LHC - dissemination of NNLO results

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Outlook/steps for the coming months:
• single jet inclusive grids generation using APPLFAST-NNLOJET interface in progress [D.Britzger, C.Gwenlan, K. Rabbertz, M.Sutton] cross sections at NNLO available in both formats
  • FASTNLO
  • APPLGRID
  → First application: H1 determination of $\alpha_s$ from jet production in DIS (H1: arXiv:1709.07251)
• grids hosted at CERN → ploughshare project: ploughshare.web.cern.ch
• many grids already available → source for NNLO grids from APPLfast
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Ultimate goal:
• have a consistent description of jet data at NNLO for all jet datasets (ATLAS, CMS, LHCb, ALICE) at low and high-$p_T$ in the central and forward rapidity regions for multiple jet R cone sizes
Dijet triple differential measurement - CMS

- Obtain the maximal sensitivity from the dijet cross section to the parton densities from multi-differential distributions.

- Explore the shape of the dijet cross section in triple differential form to constrain PDFs at small to moderate x-values: interplay between the parton luminosities and the scattering matrix elements.

- 2 jet observables built from the two-leading jets in the event, with the caveat that the assignment of the hardest jet in the event is not infra-red safe.

- Follow the setup of the 8 TeV CMS measurement that overcomes the problem.

\[ p_{T,\text{avg}} = \frac{p_{T,1} + p_{T,2}}{2} \]

\[ y^* = \frac{|y_1 - y_2|}{2} \]

\[ y_b = \frac{1}{2} |y_1 + y_2| \]
• density plot in the partonic fractions $(x_1, x_2)$ plane of the triple differential cross section as a function of $y^*$ and $y_b$ for the fiducial cuts of the CMS measurement $p_{T,\text{avg}} > 133$ GeV

• cuts on $y^*$ and $y_b$ directly map to surfaces on the $x$-$Q^2$ plane where the PDFs are determined; CMS setup

\begin{align}
    x_1 &= \frac{p_T}{\sqrt{s}} (e^{y_1} + e^{y_2}) = \frac{2 p_{T,\text{avg}}}{\sqrt{s}} e^{\pm y_b} \cosh(y^*), \\
    x_2 &= \frac{p_T}{\sqrt{s}} (e^{-y_1} + e^{-y_2}) = \frac{2 p_{T,\text{avg}}}{\sqrt{s}} e^{\mp y_b} \cosh(y^*). (1)
\end{align}
State of the art

Previously studied:

- The NLO inclusive two jet triply differential cross section
  

- Scale uncertainties and missing higher order corrections limit the achievable precision

- Measurement from CDF at 1.8 TeV based on an integrated luminosity of 86pb$^{-1}$
  
  CDF collaboration [hep-ex/0012013
  Phys.Rev.D64 (2001) 012001

Goal:

- Compute for the first time the triple differential observable at NNLO

- Detailed comparison with CMS 8 TeV data 19.7fb$^{-1}$ dataset at the percent level

- Include an assessment of NP and EW effects
CMS $\sqrt{s}=8$ TeV anti-$k_T$ $R=0.7$

- **NP correction** 10% in the lowest $p_{T,\text{avg}}$ bins, negligible above 1 TeV

  - center of the envelop of HERWIG, PYTHIA and POWHEG with and without hadronization and MPI

- **EW correction** relevant in the low $y^*$ and low $y_b$ rapidity slice reaching 8% at high $p_{T,\text{avg}}$

  - EW effects visible in the LHC measurements that reach percent-level precision
size of the corrections varies significantly as a function of $p_{T,\text{avg}}$ and the applied cuts on $y^*$ and $y_b$

NNLO correction changes both the shape and normalisation of the NLO result

QCD scale choice $\mu_R = \mu_F = m_{jj}$
CMS $\sqrt{s}=8$ TeV  $0 < y_b < 1$

- **NNLO** correction changes both the shape and normalisation of the NLO result

$\rightarrow$ good agreement with NNLO$\otimes$NP$\otimes$EWK for the central $y_b$ slice

**CMS $\sqrt{s}=8 \text{ TeV}$ $y_b > 1$**

- $y_b$ variation probes the scattering of a high-$x$ parton off a low-$x$ parton; $\rightarrow$ large PDF uncertainty

- data sits below the central value of the MMHT2014 NNLO central value

- PDF effect since matrix element contribution invariant under $y_b$ variation
Summary/Outlook

Summary:

• **Significant theoretical progress** in the description of inclusive jet and dijet production at the LHC

• Theoretical developments *driven* by the increase in precision of the experimental measurements

• New theoretical calculations available that can be used to *understand* the impact of the effects of higher order corrections in the description of jet data at hadron colliders

Outlook

• Perform further *quantitative comparisons* between data and theory (different energies, covering wide jet $p_T$ and rapidity and jet cone sizes) → APPLFAST interface in progress

• Use new data to understand effects in tuning of hadronization and underlying event parameters and respective uncertainties

• Extend existing phenomenological predictions to triple-differential measurements and angular observables and jet shapes

• Study sensitivity of jet-based observables to $\alpha_s$ and PDF extractions and assess ultimate reach in precision in a combined fit