DIS Dijets @ NNLO

10^{th} Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"

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in collaboration with the NNLOJET collaboration.

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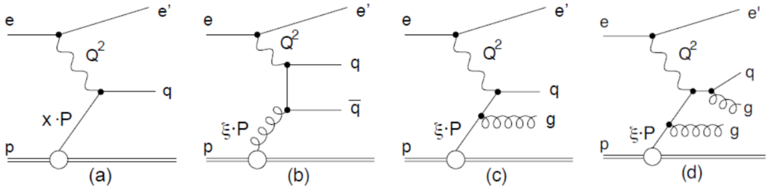
Overview

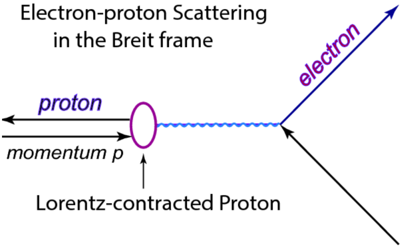
Topics

1. DIS and dijet observables
2. Antenna subtraction formalism
3. The NNLOJET program
4. Predictions for jet cross sections in NC DIS at NNLO
5. Outlook

Neutral Current Deep-Inelastic Scattering

- Deep-inelastic scattering gives a clean probe pf proton structure.





Breit-frame

Frame in which the photon momentum is completely space-like $\rightarrow$ two jets of same P_T @LO.

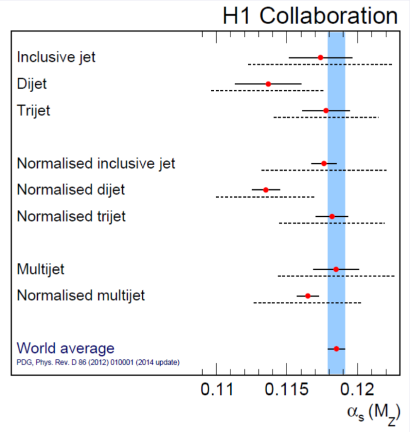
HERA Status

Applications

HERA measurements can be used to:

- Determination of strong coupling constant α_S: Experimental uncertainty (solid line) is much smaller than theoretical error (dashed line) $\rightarrow$ **NNLO calculation needed!**
- Dominant process for jet production is boson-gluon fusion $\rightarrow$ Precise HERA jet data provide high constraint on gluon PDFs.

HERA α_S measurement

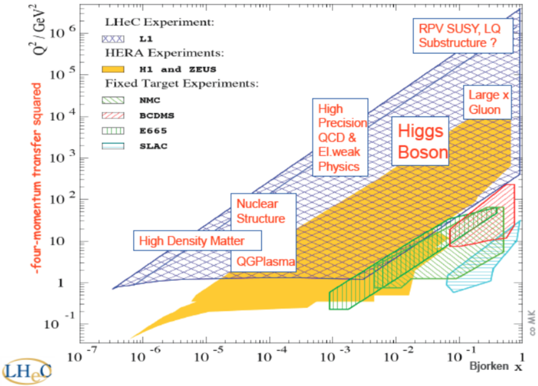


[arXiv:1406.4709]

A Future e-p Collider (LHeC or EIC)

Precision QCD

- With $Q^2 > 1$ TeV, $x \sim 0.5$.
- Higgs measurements in clean environment.
- Determination of $\alpha_S \sim 0.1\%$.
- Determination of PDF uncertainties to $\sim 1\%$.



Jet Cross Sections

Cross sections at different orders:

$$\mathrm{d}\sigma_{\mathrm{LO}} = \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{B}},$$

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma_{\mathrm{NLO}}^{\mathrm{real}} + \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{NLO}}^{\mathrm{virtual}} + \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{NLO}}^{\mathrm{mass-factorisation}},$$

$$\begin{aligned} \mathrm{d}\sigma_{\mathrm{NNLO}} &= \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma_{\mathrm{NNLO}}^{\mathrm{double-real}} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma_{\mathrm{NNLO}}^{\mathrm{real-virtual}} + \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{NNLO}}^{\mathrm{double-virtual}} \\ &+ \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{NNLO}}^{\mathrm{mass-factorisation,1}} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma_{\mathrm{NNLO}}^{\mathrm{mass-factorisation,2}}. \end{aligned}$$

Subtraction method I

Adding a zero

$$\overbrace{d\sigma_{\text{NNLO}}}^{\text{IR finite}} = \int\limits_{d\Phi_{m+2}} \overbrace{\left[d\sigma_{\text{NNLO}}^{\text{doube}-\text{real}} - d\sigma_{\text{NNLO}}^{\text{doube}-\text{real,S}}\right]}^{\text{IR finite}}$$
$$+ \int\limits_{d\Phi_{m+1}} \underbrace{\left[d\sigma_{\text{NNLO}}^{\text{real}-\text{virtual}} - d\sigma_{\text{NNLO}}^{\text{real}-\text{virtual,T}}\right]}_{\text{IR finite}}$$
$$+ \int\limits_{d\Phi_{m}} \underbrace{\left[d\sigma_{\text{NNLO}}^{\text{doube}-\text{virtual}} - d\sigma_{\text{NNLO}}^{\text{doube}-\text{virtual,U}}\right]}_{\text{IR finite}} .$$

Subtraction method II

Construction principle

Subtraction terms are constructed according to **factorisation** of infrared divergences in unresolved limits as well as the factorisation of phase space under suitable momentum maps from $\{p_{m+1}\} \to \{\widetilde{p_m}\}$ with $\{p_X\} \subset \{p_{m+1}\}$:

$$\mathrm{d}\sigma_{NNLO}^{RR,S} \approx \underbrace{X(\{p_X\})}_{\text{antenna}} \overbrace{\mathrm{d}\Phi_3(\{p_X\})}^{\text{Antenna PS}} \times \underbrace{|\mathcal{M}(\{\widetilde{p_m}\})|^2}_{\text{reduced ME}} \overbrace{\mathrm{d}\Phi_m(\{\widetilde{p_m}\})}^{\text{reduced PS}} \times \underbrace{\mathcal{J}(\{\widetilde{p_m}\})}_{\text{jet function}}$$

[arXiv:hep-ph/0505111]

Subtraction method III

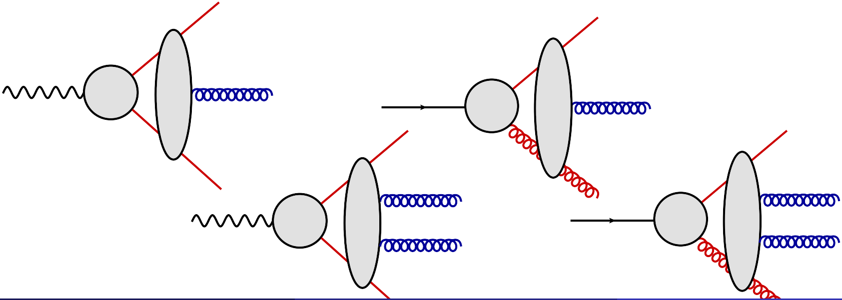
This allows:

- Cancellation of infrared divergences against matrix elements in numerical phase space integration.
- Analytic integration of antenna functions over the antenna phase space:
  1. Move subtraction terms across phase spaces of different multiplicities.
  2. Check explicit cancellation of poles between subtraction term and virtual matrix element.

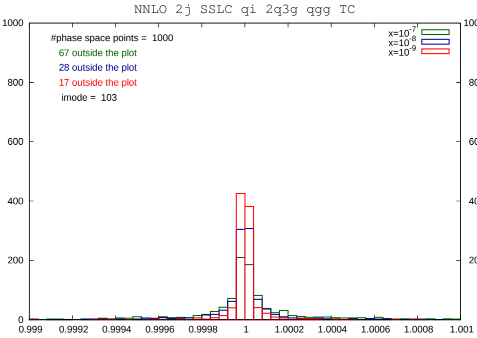
Subtraction method IV

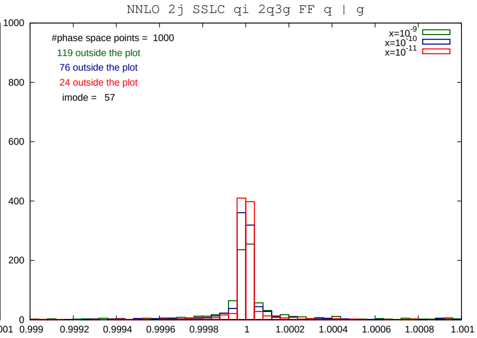
Antenna functions

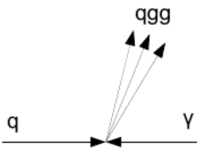
- Antennae have two hard radiators and are derived from physical processes.
- Antennae mimic all soft/collinear divergences of real emissions.
- Reproduce ϵ-poles of virtual corrections.
- Have all been analytically integrated over antenna phase space!

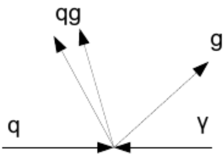


Validation Of The Subtraction / Spike Plots









Validation II

Consistency checks

- Subtraction gives right limits in all singular regions / spike plots,
- $\sigma^{\text{RR,RV}} + \sigma^{\text{S,T}}$ is stable under variation of technical phase space cut,
- Analytic pole cancellation against virtual matrix elements.

SHERPA

Validated LO and NLO 2- and 3-jet cross sections against SHERPA, including validation of differential distributions. Results also agree with NLOJET++.

Scale variation

Dependence of the total cross section on the scales was checked against analytic expressions.

NNLOJET

NNLOJET is a semi-automated Monte Carlo for NNLO phenomenology.

Processes

Many processes are already included at NNLO:

- pp→H($\gamma\gamma$)+ 0,1 jets [arXiv:hep-ph/0505111],
- pp→Z(l^+l^-) + 0,1 jets [arXiv:1607.01749],
- NC DIS dijets [arXiv:1606.03991],
- Inclusive NC DIS (ep → e + 1jet) To appear,
- pp→jets[arXiv:1611.01460].
- \+ More to follow.

Current priority is to generate **grids** for phenomenological studies (Daniel's talk)!

HERA High-Q2 Analysis

The H1 collaboration measured dijet and inclusive 1 jet distributions as described in [arXiv:1406.4709] in the following kinematic ranges:

Cuts in Breit frame

- $5\ \mathrm{GeV} < \mathrm{p}_{\mathrm{jet}}^{\mathrm{T}}$,
- $M_{12} > 16\ \mathrm{GeV}$, for di and trijet measurements only,
- Using the kt/anti-kt jet algorithm.

Cuts in HERA frame

- $-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$,
- $0.2 < y < 0.7$.

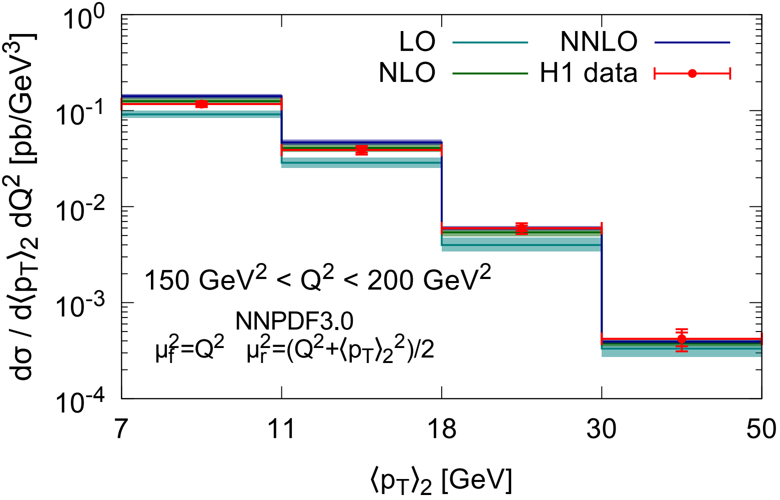
Observables

Dijet observables:

- $\xi_2 = x_{bj}(1 + M_{12}/Q^2)$,
- $\langle P_T \rangle_2 = \left(P_T^1 + P_T^2 \right)/2$,

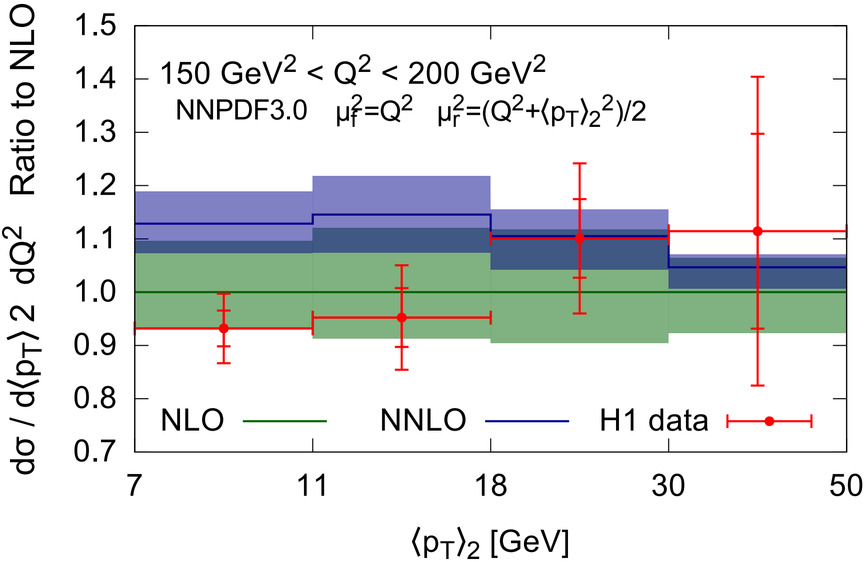
Inclusive jets measure individual jet P_T.

High-Q2 Results I



[PhysRevLett.177.042001]

High-Q2 Results II

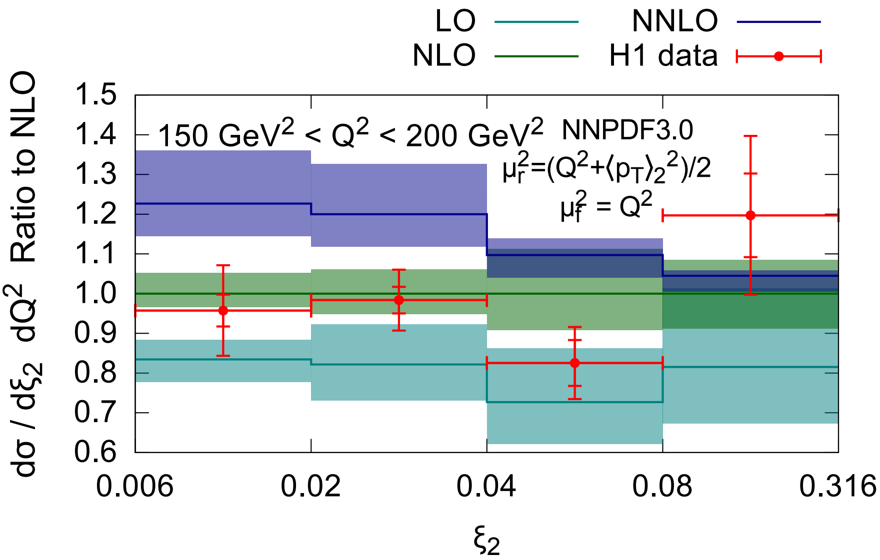


Discussion

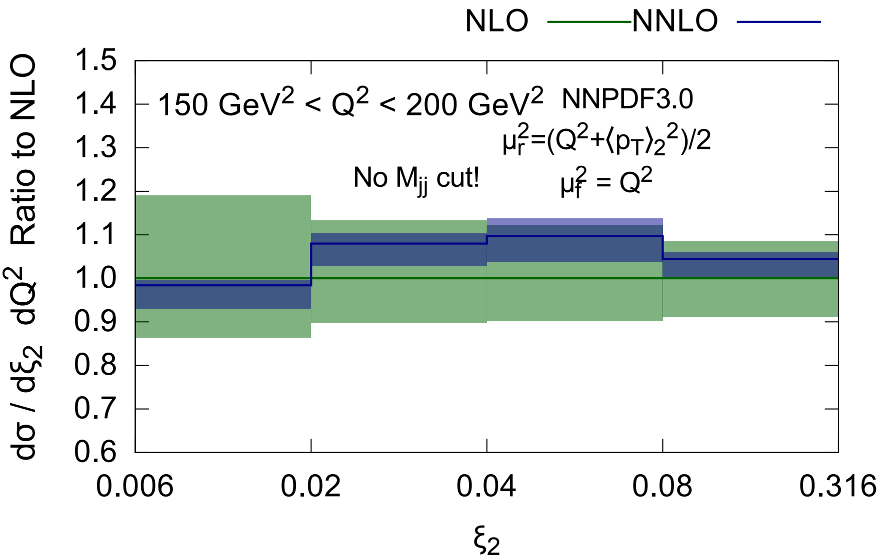
HERA cuts

- H1 uses $P^T_{\text{jet}} > 5$ GeV on all jets.
- $M_{\text{jj}} > 16$ GeV cuts (minimally) into first bin.
- Phase space opens up at NLO
  $\rightarrow$ large NLO/LO factor!
  $\rightarrow$ large NNLO correction $+$ large NNLO scale uncertainty.
- Should use asymmetric P^T_{jet} cuts for leading and subleading jet and no M_{jj} cut!

Results With Symmetric Cuts



Results With Asymmetric Cuts



HERA Low-Q2 Analysis

The H1 collaboration measured dijet and inclusive 1 jet distributions as described in [arXiv:1611.03421] in the following kinematic ranges:

Cuts in Breit frame

- $4\ \mathrm{GeV} < \mathrm{p}_{\mathrm{jet}}^{\mathrm{T}}$,
- kt jet algorithm.

Cuts in HERA frame

- $-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$,
- $0.2 < y < 0.6$.

And examined the following distributions:

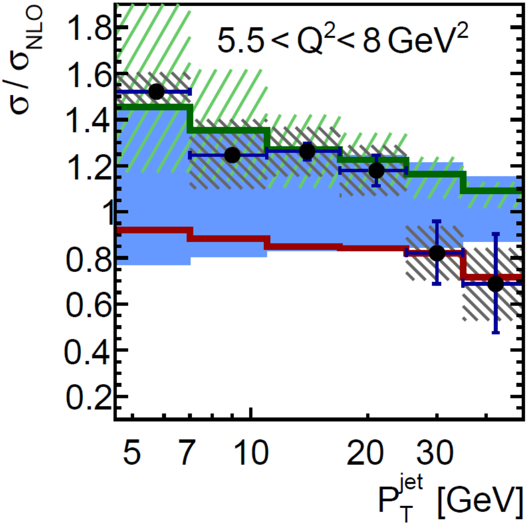
Observables

Dijet observables

- $\langle P_T \rangle_2 = \left(P_T^1 + P_T^2\right)/2$,

Inclusive jets measure individual jet P_T.

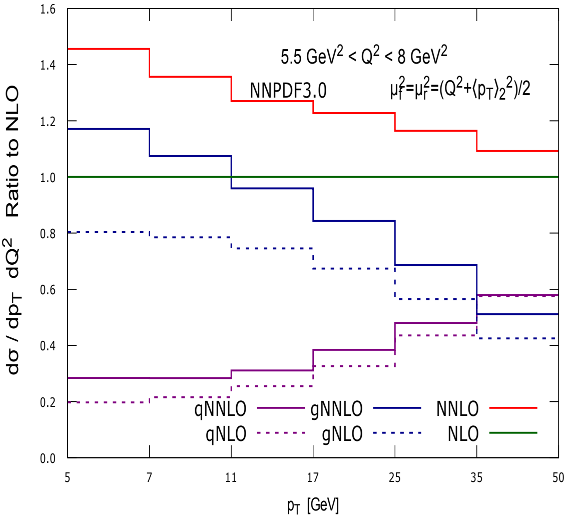
Low Q2 inclusive jets



[arXiv:1611.03421]

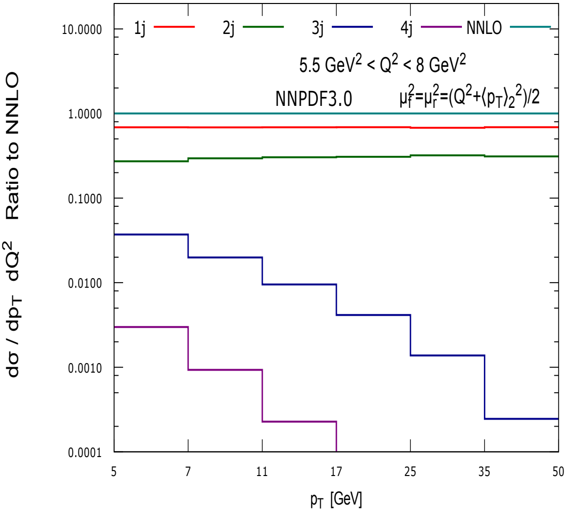
- Scale uncertainty significantly reduced at high-pT.
- Large NNLO correction at low scales.
- NNLO predictions within NLO uncertainties.
- Scale uncertainty still sizeable at low pT.

Relevance of subprocesses



- Gluon contribution dominates at low p_T.
- Quark contribution increases with p_T and is of similar size as the gluonic contribution in highest p_T bin.

Jet multiplicities in inclusive production



- 1^{st} and 2^{nd} jets dominate the contribution to the cross sections.
- 3^{rd} jet contribution is smaller by an order of magnitude.
- 4^{th} jet contribution is negligible particularly at high p_T.

Outlook

Future

- The program is ready and part of NNLOJET $\rightarrow$ interfaces to APPLGRID and FASTNLO are implemented.
- Program can now be applied to:
  1. Extract α_S from DIS jet data.
  2. Incorporate disjets into NNLO PDF fits
     $\rightarrow$ This may have a significant effect for parton distributions.
- Work on charged current DIS.