Precise QCD predictions for the production of dijet final states in deep inelastic scattering.

Rencontres de Moriond 2017

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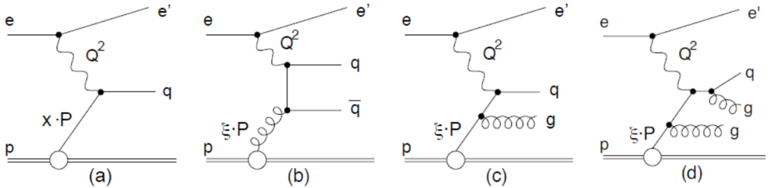
Overview

Topics

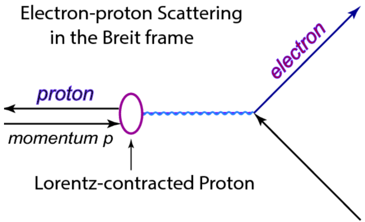
1. Neutral current deep-inelastic scattering
2. The NNLOJET program
3. Phenomenological applications

Neutral Current Deep-Inelastic Scattering

- Deep-inelastic scattering gives a clean probe of proton sub-structure.



a) Lab frame 1 jet, b)-d) Breit frame 2 jet.



Breit-frame

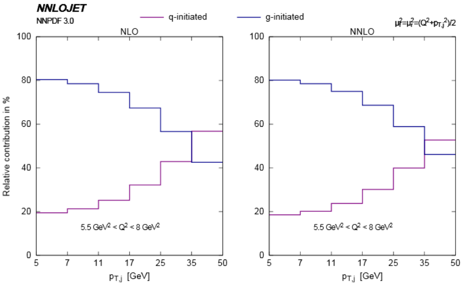
Frame in which the photon with completely space-like momentum is on collision axis with the proton → two final state jets of same P_T @ LO.

Starting Point

Applications

HERA jet measurements

- are sensitive to the value of α_s.
- provide a high constraint on the gluon content of the proton.

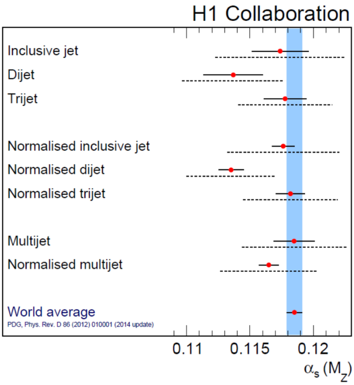


[Currie,Gehrmann,Huss,JN,arXiv:1703.05977(2017)]

Uncertainty on **NLO** prediction large

$\rightarrow$ **NNLO** calculation necessary!

HERA α_s measurement



[H1,Eur.Phys.J.C75(2015)no.2]

NNLOJET

NNLOJET is a semi-automated Monte Carlo program at NNLO accuracy that has grown into a process library.

Processes

Many processes are already included at NNLO:

- pp$\rightarrow$H($\gamma\gamma$)+0,1 jets
  [Chen,Gehrmann,Glover,Jaquier:Phys.Lett.B740(2015)],
- pp$\rightarrow$Z(l^+l^-)+0,1 jets
  [Gehrmann-DeRidder et.al:Phys.Rev.Lett.117(2016)no.2],
- NC DIS dijets
  [Currie,Gehrmann,JN:Phys.Rev.Lett.117(2016)no.4],
- Inclusive NC DIS (lp $\rightarrow$ l+1jet) Not published,
- pp$\rightarrow$dijets (Joao Pires' talk)
  [Currie,Glover,Pires:Phys.Rev.Lett.118(2017)no.7].

Antenna Subtraction

NNLOJET employs the antenna subtraction method. This is a local subtraction method that requires the construction of counter terms.

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 $\{p_X\} \subset \{p_{m+1}\}$:

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

[Gehrmann-DeRidder,Gehrmann,Glover:JHEP0509(2005)056]

Antenna Subtraction

Adding a zero

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

- Construction of local counter terms.
- Move IR divergences across different phase space multiplicities.

DIS Observables

DIS Variables

For scattering:

$$l(k) + p(P) \rightarrow l'(k') + X(p_X),$$

with l donating the lepton, p the proton and X the hadronic final state.

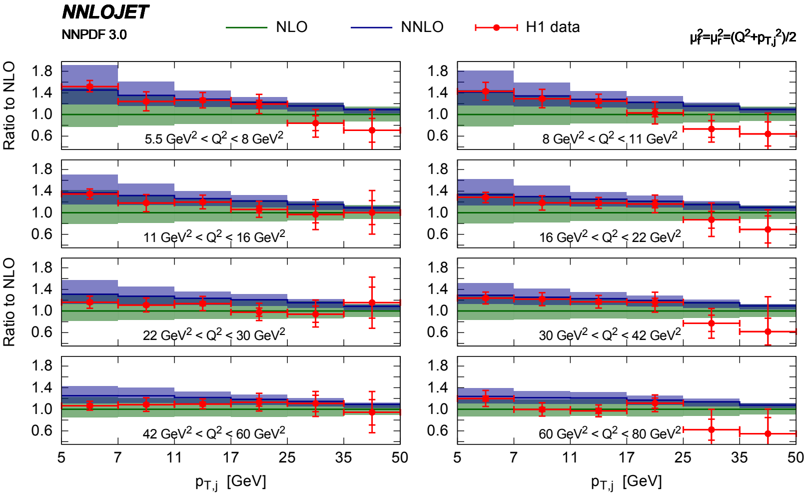
- $Q^2 = -q^2$, $x_{bj} = \frac{Q^2}{2q \cdot P}$, $y = \frac{q \cdot P}{k \cdot P}$

Measured observables

- $\xi_2 = x_{bj}(1 + M_{12}/Q^2) \rightarrow$ corresponds to Feynman x @ LO,
- $\langle p_T \rangle_2 = \left(p_T^1 + p_T^2\right)/2$,
- $p_{T,jet}$ for inclusive jets.

RESULTS

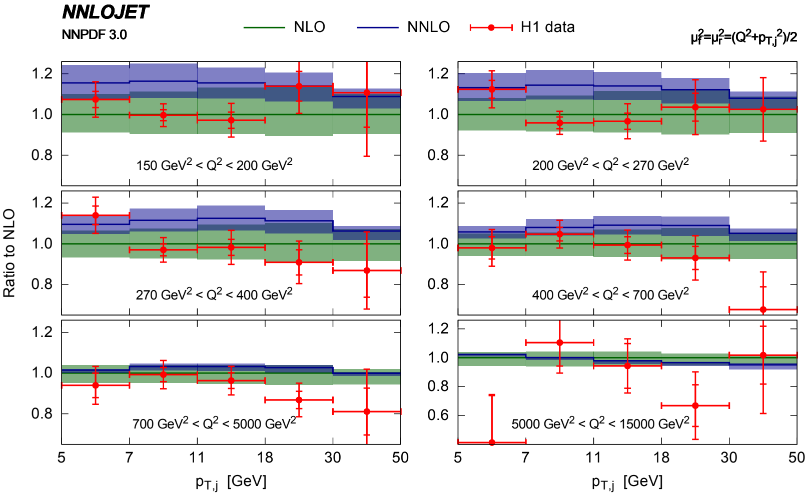
H1 Inclusive 1 Jet low Q^2



$5.5\mathrm{GeV}^2 < Q^2 < 80\mathrm{GeV}^2$, $-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$ [arXiv:1703.05977]

- Scale dependence still large for small scales (value of α_s large).
- NNLO describes data shape much better than NLO.

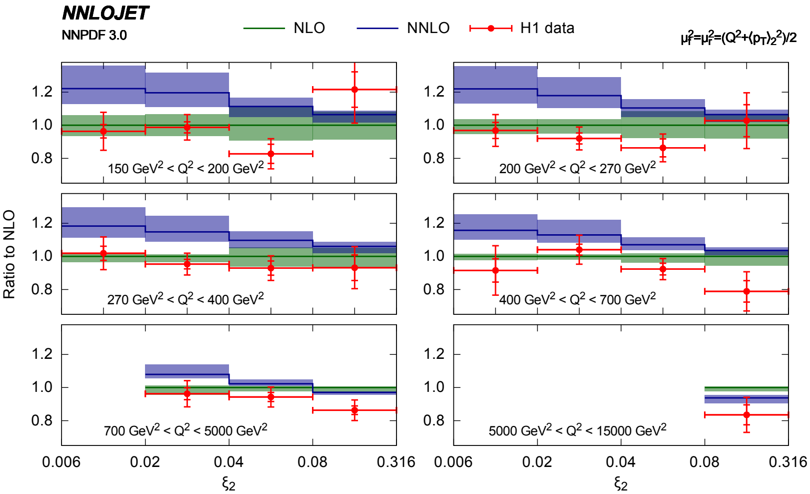
H1 Inclusive 1 Jet high Q^2



$$150\text{GeV}^2 < Q^2 < 15000\text{GeV}^2,\ -1.0 < \eta^{\text{jet}}_{\text{lab}} < 2.5$$ [arXiv:1703.05977]

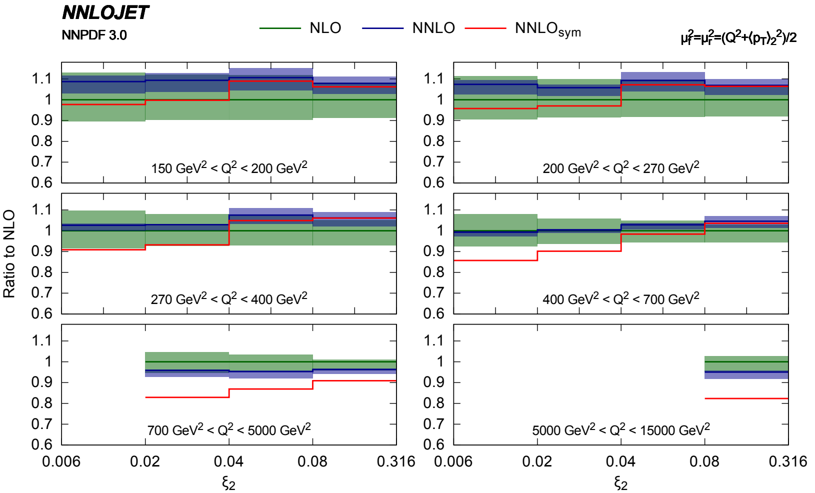
- Scale dependence reduces for NNLO prediction.
- Some predictions move away from the data $\rightarrow$ refit PDFs?!

H1 Dijets High Q^2



$150\mathrm{GeV}^2 < Q^2 < 15000\mathrm{GeV}^2$, $-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$, $p_{T,jets} > 5\mathrm{GeV}$, $M_{jj} > 16\mathrm{GeV}$ [arXiv:1703.05977]

H1 Dijets High Q^2 With Asymmetric p_T Cuts



$150\mathrm{GeV}^2 < Q^2 < 15000\mathrm{GeV}^2$, $-1.0 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.5$, $p_{T,jets} > 4\mathrm{GeV}$, $p_{T,j1} > 5\mathrm{GeV}$, $M_{jj} > 16\mathrm{GeV} \rightarrow M_{jj}$ **cut not sufficient to over come IR sensetivity introduced by symmetric p_T cut.** [arXiv:1703.05977]

Results Using The fastNLO Interface

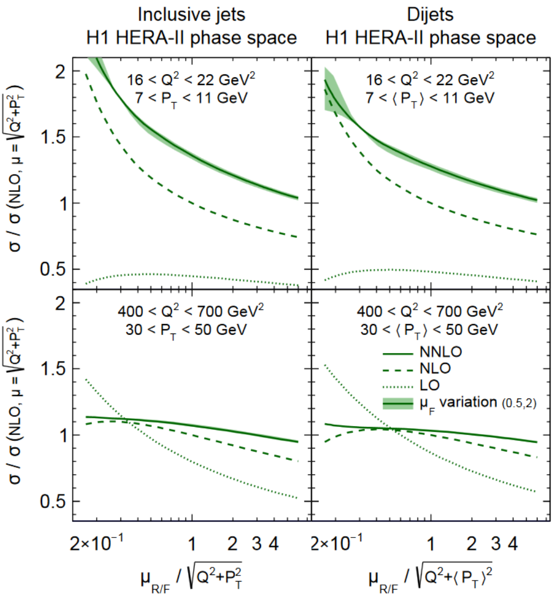
NNLOJET is now fully interfaced to fastNLO and Applgrid
$\rightarrow$ allows generation of PDF grids.

Using this interface the following results are obtained in collaboration with H1, V. Bertone, D. Britzger, J. Currie, T. Gehrmann, C. Gwenlan, A. Huss and M. Sutton.

Scale Dependence Of The Total Cross-Section

- Reduction in scale dependence from NLO → NNLO.
- Low scales → large value of α_s → more orders in pQCD needed.
- Convergence better at higher scales.

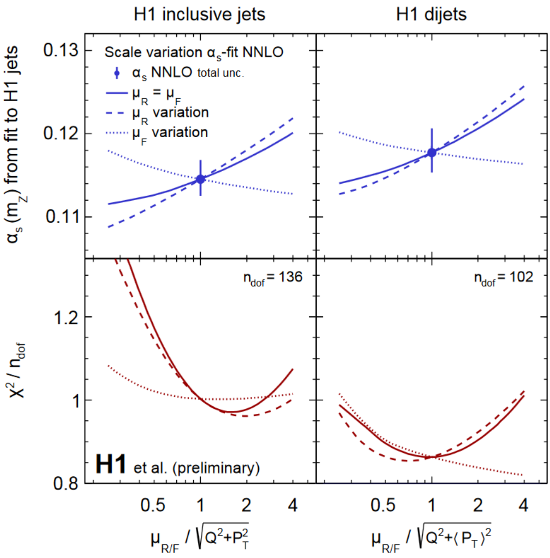
[H1prelim-17-031]



Scale Dependence Of The α_s Fit

- $\chi^2/n_{dof} \approx 1$ implies good agreement between data and theory.
- Theory uncertainty on α_s extraction more sensitive to μ_r than to μ_f.

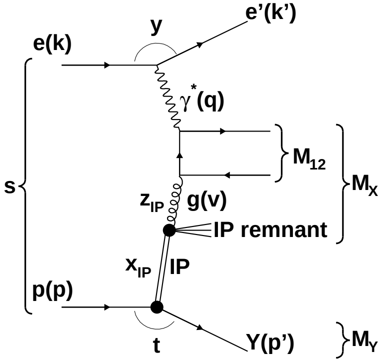
[H1prelim-17-031]



Diffractive Jets In DIS

Following results are obtained in collaboration with H1, D. Britzger, J. Currie, T. Gehrmann, A. Huss and R. Žlebčik.

Diffractive Scattering



At LO: The momentum fraction entering the hard subprocess is given by

$$z_{IP} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2}$$

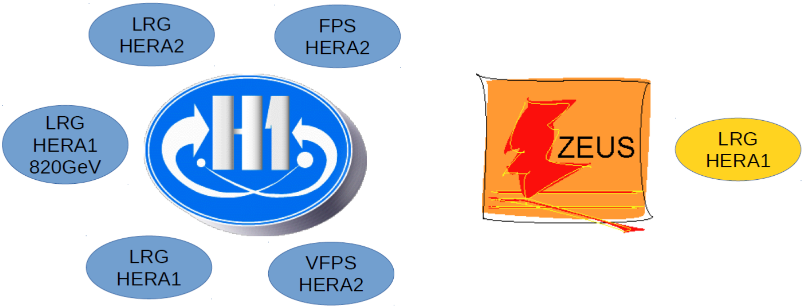
- In diffractive events the beam proton stays intact.
- Factorisation theorem proven for diffractive DIS. [Collins(1998)]
- Hard matrix elements calculated to NNLO using NNLOJET.
- DPDFs currently only available at NLO!

Diffractive variables:

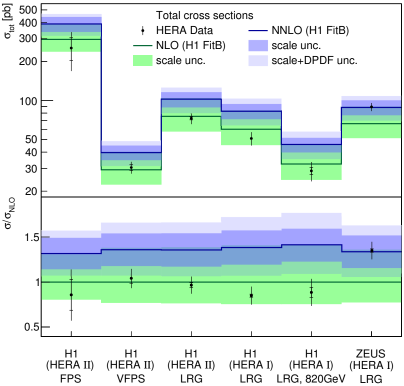
$$x_{IP} = 1 - \frac{E'_p}{E_p} \quad t = (p - p)^2$$

The DIS dijets measurement

- We analysed 5 HERA DIS dijets measurements with proton energies of 920GeV and one with 820GeV.
- In total 57 different distributions were compared to data.



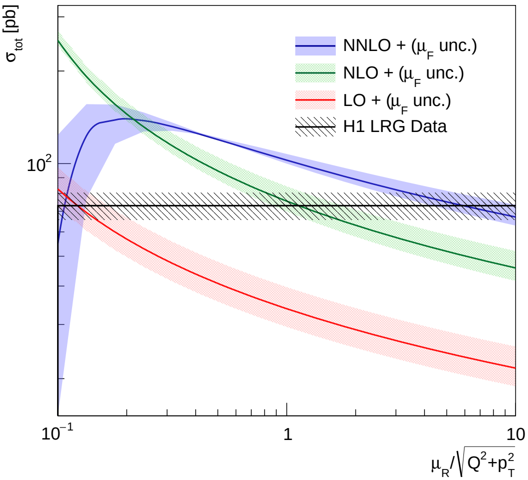
Predictions For The Total Cross Section



[PERLIMINARY: Britzger et al., Moriond 2017]

- NNLO normalisation seems to be off by a factor of 30%.
- Potentially a PDF effect as DPDFs are only available to NLO.

Scale Dependence Of The Total Cross Section

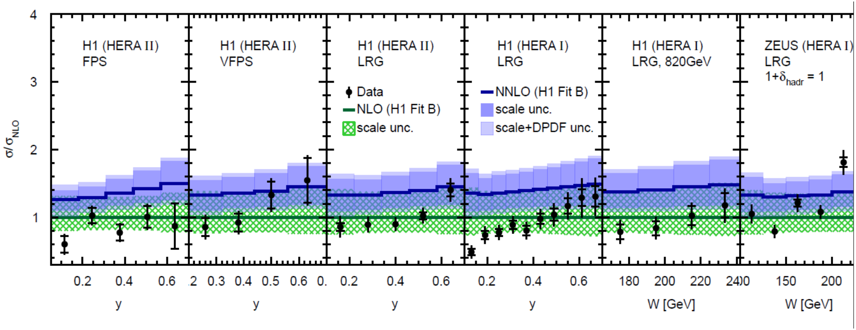


[Britzger et al., Moriond 2017]; LRG HERA 2

- Scale uncertainty is dominated by renormalisation scale.
- NNLO scale dependence is still sizable.

y Distributions

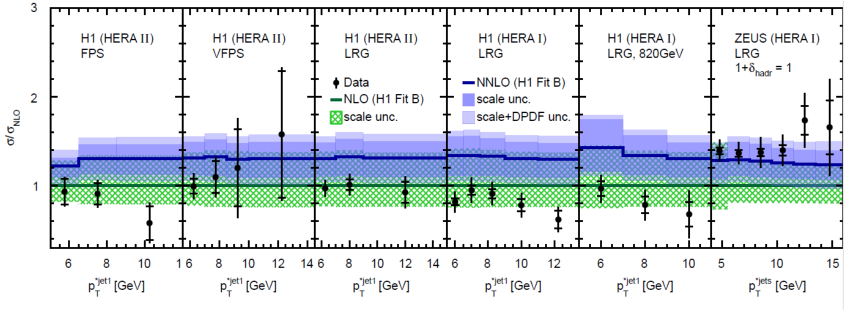
Comparison of y distributions between theory and data:



- Normalisation of NNLO prediction is off by a factor of 30%.
- NNLO tends to describe the data shape better than NLO.

$P_{T,j1}$ Distributions

Comparison of the leading jet's p_T against data:



- Similar conclusion as above.

Conclusions

- We calculated the ep$\rightarrow$ 2jets cross section to NNLO accuracy using the antenna subtraction formalism.
- The NNLOJET process library is growing with more processes to appear soon.
- NNLOJET is fully interfaced to APPLgrid and fastNLO!
- Phenomenology using NNLO calculations advanced significantly in recent years.