Measurement of Jet Production Cross Sections in Deep-inelastic ep Scattering at HERA

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Deep-inelastic scattering

Neutral current deep-inelastic scattering

Process: $ep \to e'X$
Electron or positron

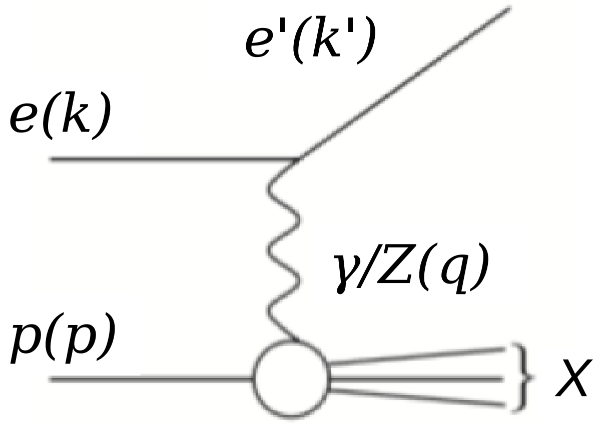
Kinematic variables

Virtuality of exchanged boson Q^2

$$Q^2 = -q^2 = -(k - k')^2$$

Inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$



$$\sigma_{ep \to eX} = f_{p \to i} \otimes \hat{\sigma}_{ei \to eX}$$

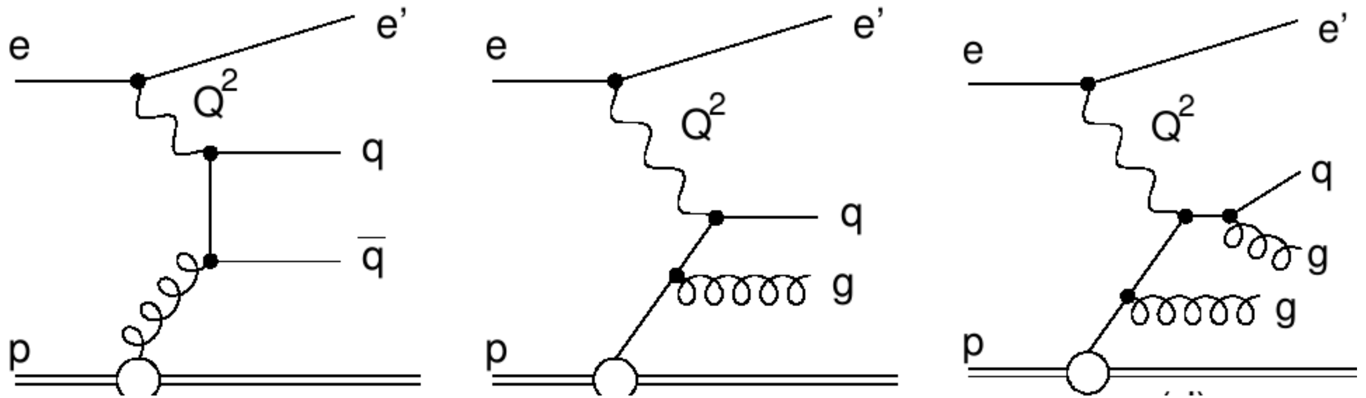
NC and CC DIS cross sections (HERA-II) are mandatory ingredients for PDF fits

- Only one proton involved
  -> lepton directly probes (charged) constitutents of proton

Gluon is mainly indirectly constrained by DGLAP and sum-rules

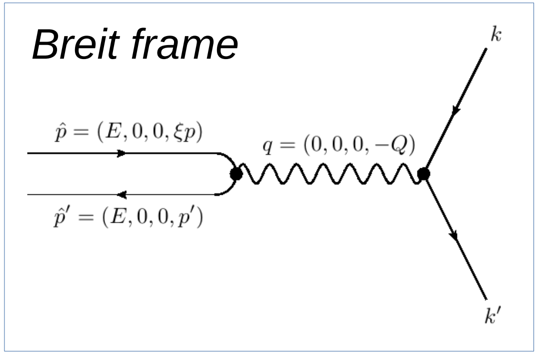
-> Measurement of *ep -> 2j+X* will allow direct access of gluon content

Jet production in *ep* scattering



Boson-gluon fusion   QCD Compton   Trijet leading-order

Jet measurements are performed in Breit reference frame
- Exchanged virtual boson collides 'head-on' with parton from proton ('brick-wall' frame)



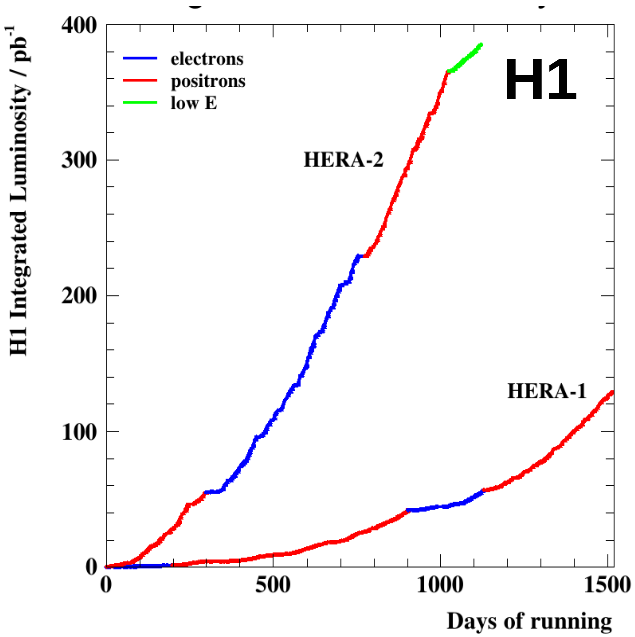
Jet measurements directly sensitive
- to α_s already at leading-order
- to gluon content of proton

Trijet measurement
- More than three jets with significant transverse momenta
- Leading-order already at $O(\alpha_s^2)$

The HERA ep collider

HERA *ep* collider

Integrated luminosity



HERA ep collider in Hamburg

- Data taking periods
  - HERA I: 1994 – 2000
  - HERA II: 2003 – 2007
- Delivered integrated luminosity ~ 0.5 fb^{-1}

HERA-II period

- Electron and positron runs
- $\sqrt{s}$ = 319 GeV
  - E_e = 27.6 GeV
  - E_p = 920 GeV
- Analysed int. Luminosity: L = 290 pb^{-1}

H1 Experiment at HERA

H1 multi-purpose detector

Asymmetric design

Trackers

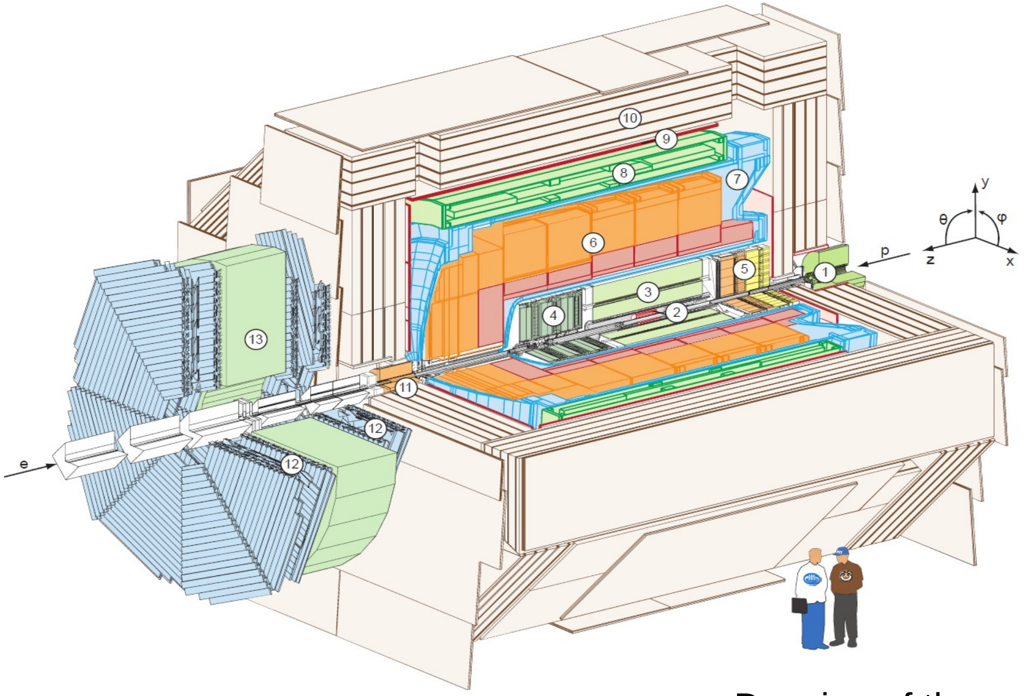
- Silicon tracker
- Jet chambers
- Proportional chambers

Calorimeters

- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid, 1.15T

Muon detectors



Drawing of the H1 experiment

Excellent control over experimental uncertainties

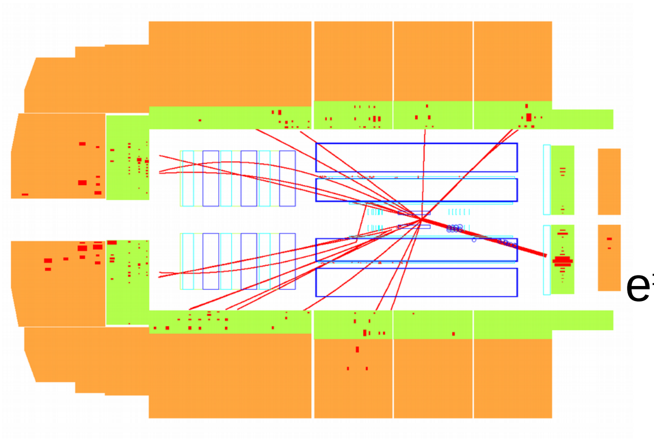
- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 1.5 - 2.5%
- Continuous upgrades with time

Analysis strategy and kinematic range

Data must be corrected for detector effects
- Kinematic migrations
- Acceptance and efficiency effects

Regularised unfolding
- For accurate descripton of migrations consider an '*extended phase space*'

Typical event display



	Extended phase space for unfolding	Cross section phase space
NC DIS	$Q^2 > 3$ GeV^2	$5.5 < Q^2 < 80$ GeV^2
	$y > 0.08$	$0.2 < y < 0.6$
(inclusive) Jets	$P_T^{jet} > 3$ GeV	$P_T^{jet} > 4.5$ GeV
	$-1.5 < \eta^{lab} < 2.75$	$-1.0 < \eta^{lab} < 2.5$
Dijet and Trijet		$P_T^{jet} > 4$ GeV
	$\langle P_T^{jet} \rangle > 3$ GeV	$\langle P_T^{jet} \rangle > 5$ [5.5] GeV

Regularised unfolding

Regularised unfolding using TUnfold

- Calculate unfolded distribution *x* by minimising

$$\chi^2(x,\tau)=(y-Ax)^T V_y^{-1}(y-Ax)+\tau L^2$$

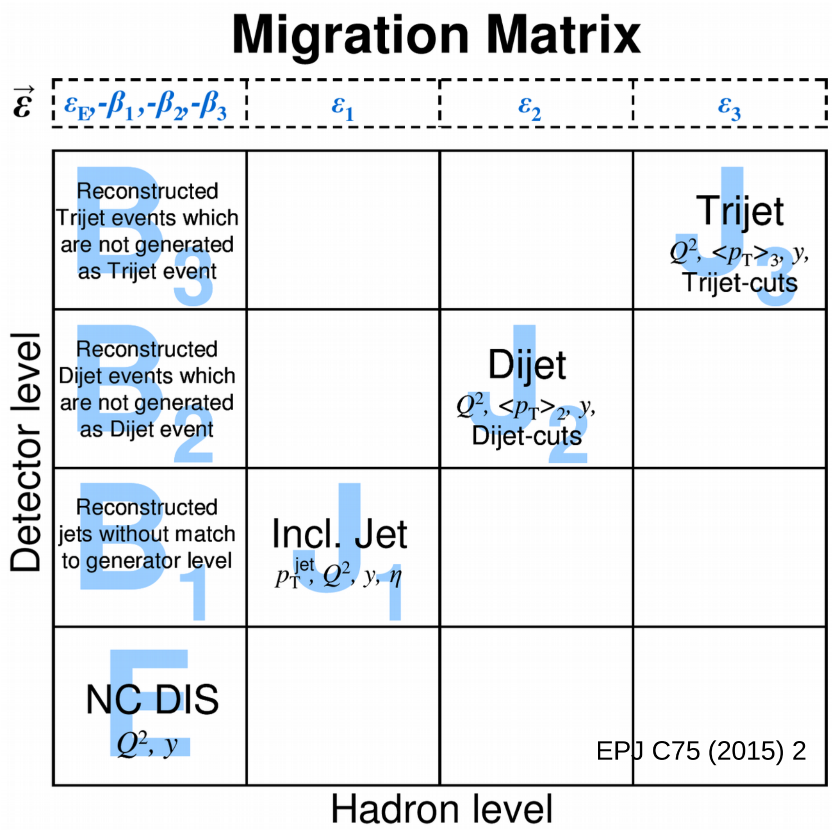
  - Linear analytic solution
  - Linear error propagation
  - Statistical correlations are considered in V_y

x	Hadron level
y	Detector level
V_y	Covariance matrix
A	Migration matrix
τL^2	Regularisation term

JINST 7 (2012) T10003

Simultaneous unfolding of Inclusive jet, Dijet, Trijet, NC DIS

- Statistical correlations are considered
- Matrix constituted from O(10^6) entries
  - Two generators used
  - Difference between the two -> model uncertainty
- Up to 6 variables considered for migrations
- 'detector-level fake jets' (or events) are constrained with NC DIS data



Control distributions

Acceptance of NC DIS events

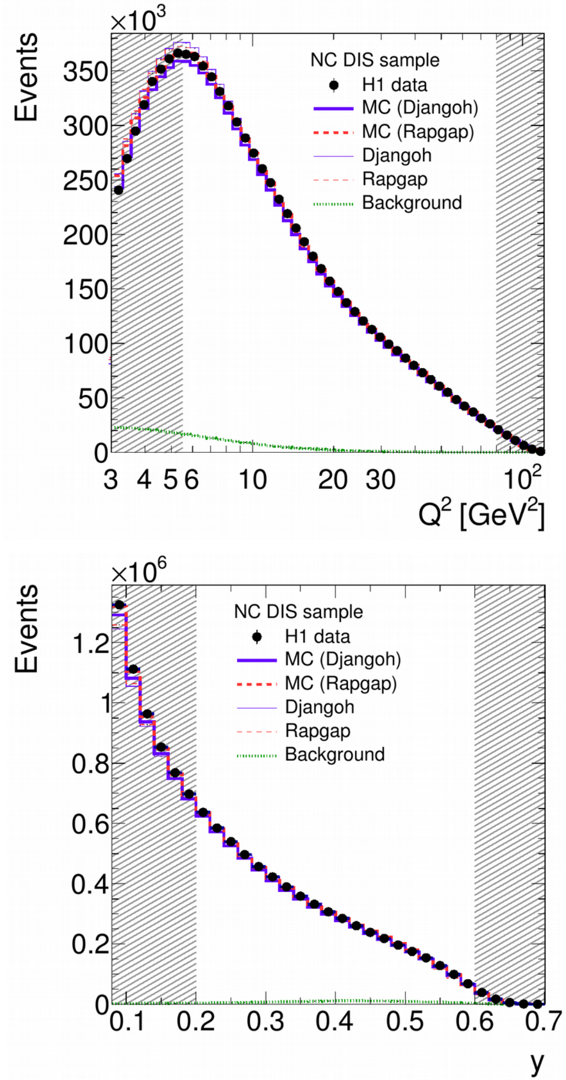
- Scattered lepton is found in SpaCal
- Lepton energy E_e > 10.5 GeV
- Selection based on un-prescaled SpaCal electron trigger

Monte Carlo generators

- Rapgap: LO matrix elements + PS
- Djangoh: Color-dipole model
- String fragmentation for hadronisation

Background

- Photoproduction simulation using Pythia
- Normalised to data using dedicated event selection
- Background for jet quantities almost negligible



Detector-level distributions for jets

Jet reconstruction

- k_T jet algorithm with R=1
- Jets built from tracks and clusters
- Jet energy calibration using neural networks
  Approx. 1% Jet-energy-scale uncertainty

Monte Carlo predictions

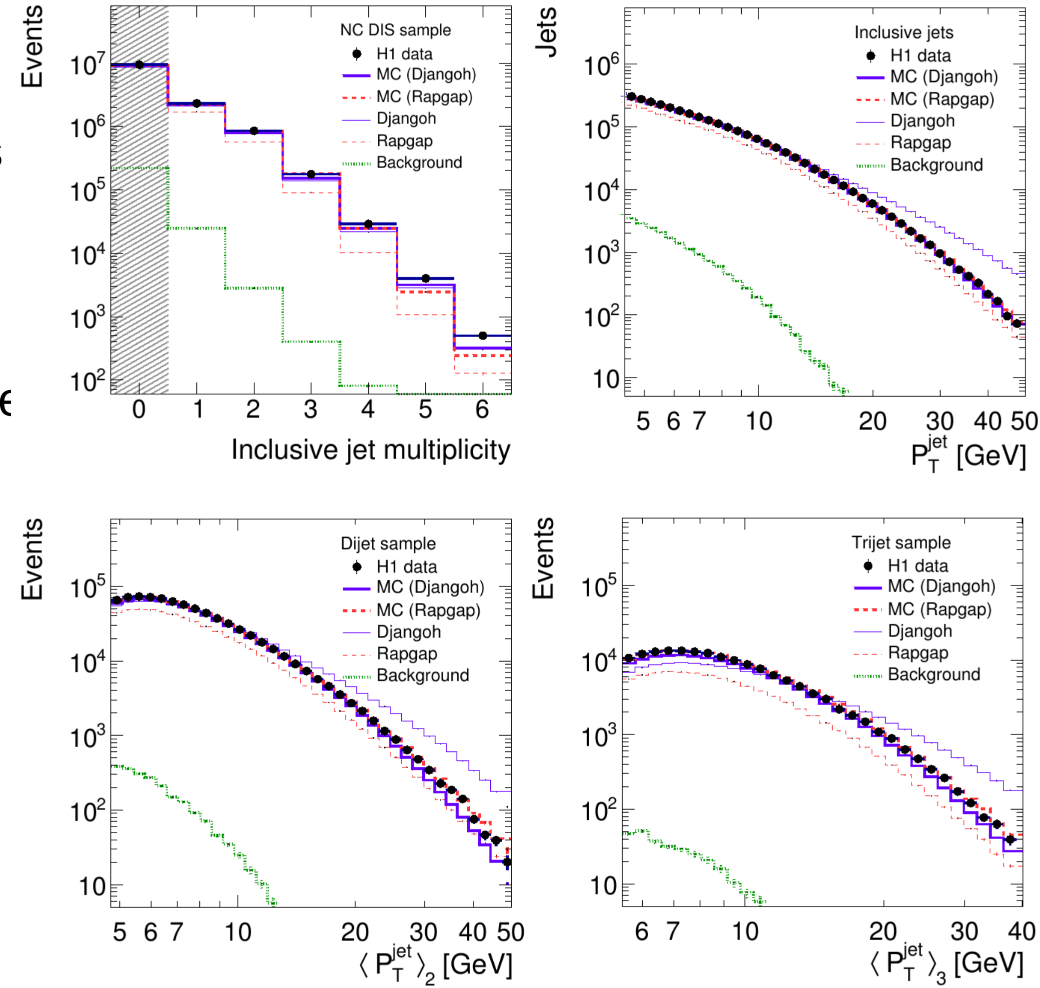
- MC simulations used for unfolding
- Jet multiplicities and spectra not well modelle
  - Djangoh: p_T^{jet} spectra too hard
  - Rapgap: Jet multiplicity underestimated
  - Both generators tend to have too few jets in forward direction

-> MC is weighted to describe data

Dijet and Trijet

- Distributions raise steeply due to p_T^{jet} > 5 GeV requirement

-> Extended phase space important for migrations



Comparisons to Predictions

Recently improved prediction became available for DIS jets

- approximate NNLO (Phys. Rev. D92 (2015) 7, 074037)
- NNLO (Rev. Lett. 117 (2016) 042001)

- Both theory groups have extended their calculations for our data

Predictions	**NLO**	**aNNLO**	**NNLO**
Program for jet cross sections	nlojet++	JetViP	NNLOJET
pQCD order	NLO	approximate NNLO	NNLO
Calculation detail	Dipole subtraction	Phase space slicing NNLO contributions from unified threshold resummation formalism	Antenna subtraction
Program for NC DIS	QCDNUM	APFEL	APFEL
Heavy quark scheme	ZM-VFNS	FONLL-C	FONLL-C
Order	NLO	NNLO	NNLO
PDF set	NNPDF3.0_NLO	NNPDF3.0_NNLO	NNPDF3.0_NNLO
$\alpha_s(M_Z)$	0.118	0.118	0.118
Hadronisation corrections	Djangoh and Rapgap		
Available for			
(Normalised) Inclusive jet	✓	✓	✓
(Normalised) Dijet	✓	✓	✓
(Normalised) Trijet	✓		

Dijet cross sections

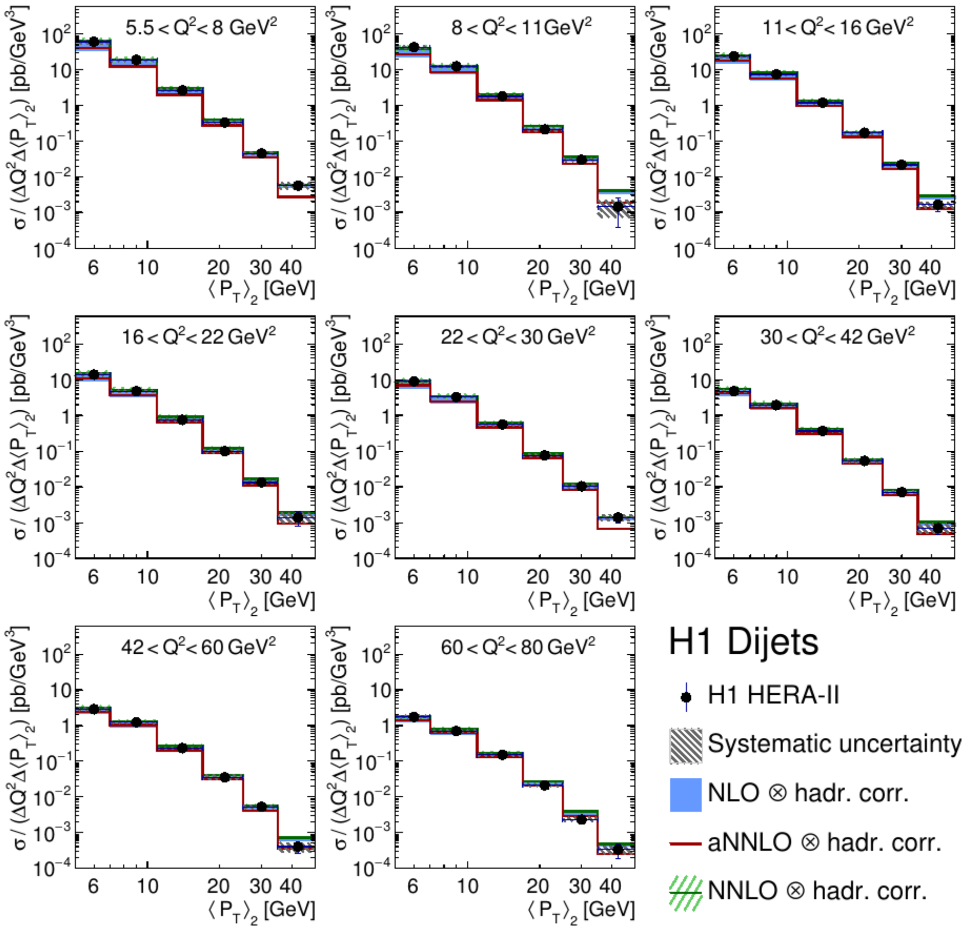
Dijet cross sections in NC DIS as a function of Q^2 and $<p_T>_2$

- $<P_T>_2 = (P_T^{jet1} + P_T^{jet2})/2$
  with: $P_T^{jet} > 4$ GeV

Comparison to Predictions

- NLO (nlojet++, NNPDF30_nlo)
- approximate NNLO (JetVip, NNPDF30_nnlo)
- NNLO (NNLOJET, NNPDF30_nnlo)

- Overall: predictions give reasonable description of data



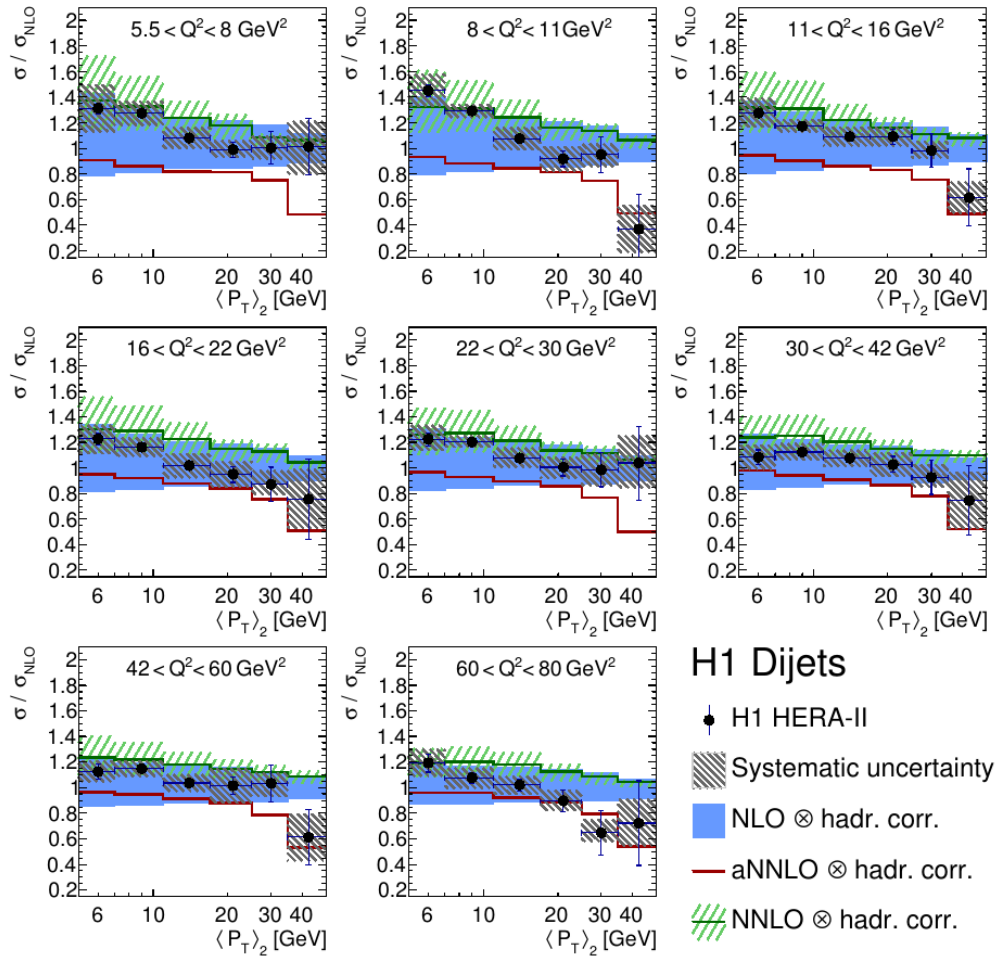
Ratio of dijet cross sections to NLO

Scale uncertainty: 7-point variation

- Vary μ_r and μ_f with factors of 2 and 0.5
- Exclude variations in 'opposite' directions
- Assign largest and smallest variations as uncertainty

Ratio to NLO prediction

- NLO give reasonable descriptions within large scale uncertainties
- aNNLO improves shape
  - aNNLO expected to improve description at high <p_T>
- NNLO improves shape dependence
  - NNLO predictions have smaller scale uncertainties than NLO at high-<p_T>



Normalised jet cross sections

- Jet cross sections are normalised to 'inclusive neutral-current DIS cross section' in respective Q^2 bin

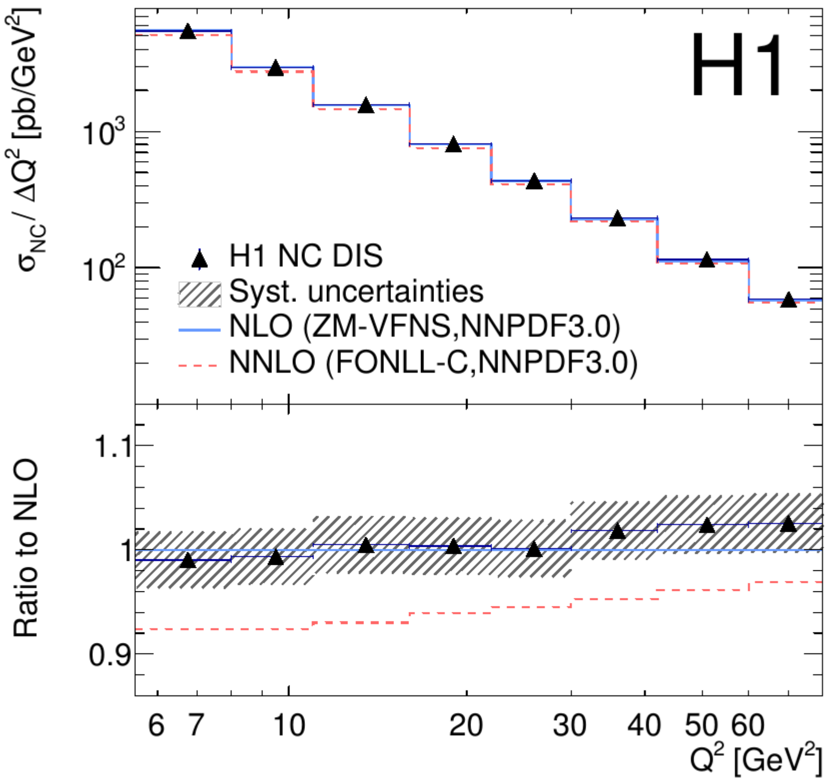
Advantage

- Reduced experimental uncertainties: Cancellation of normalisation uncertainty
  (in our case: only partial cancellation, because NC DIS cross sections are measured only with a subset of the jet data because of trigger reasons)

NC DIS cross sections

- NLO (ZM-VFNS) and NNLO (FONLL-C) predictions provide good description of data
- PDFs are fitted to NC DIS cross sections

Inclusive neutral-current DIS cross sections



Normalised dijet cross sections

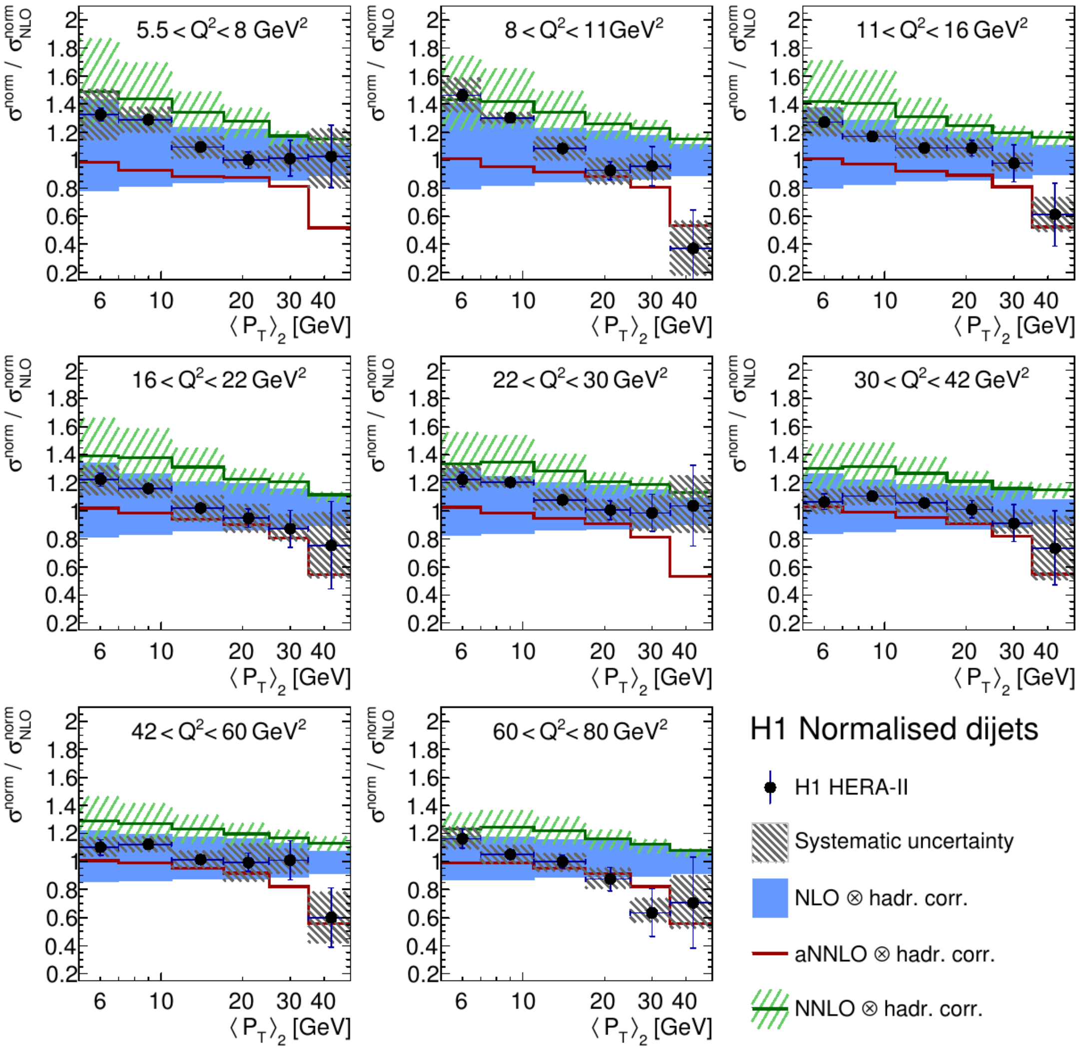
Normalised dijet cross sections

$$\sigma_i^{\text{norm}} = \frac{\sigma_i}{\sigma_{i_q}^{\text{NC}}}$$

- Predictions obtained as ratio jet and NC DIS calculations
- Scale uncertainties are obtained by varying jet cross sections only (because NC DIS are fitted to data)

Data to theory agreement

- Overall good description by NLO, aNNLO and NNLO predictions
- Somewhat reduced experimental uncertainties
- NNLO slightly overshoots data -> partially caused by normalisation w.r.t. NC DIS



Reminder: inclusive jets @ high-Q^2

Eur. Phys. J. C75 (2015) 2:

- Jet cross sections at high-Q^2
- Inclusive jet, dijet and trijet cross sections
- $150 < Q^2 < 15000 \mathrm{GeV}^2$

Inclusive jets previously published

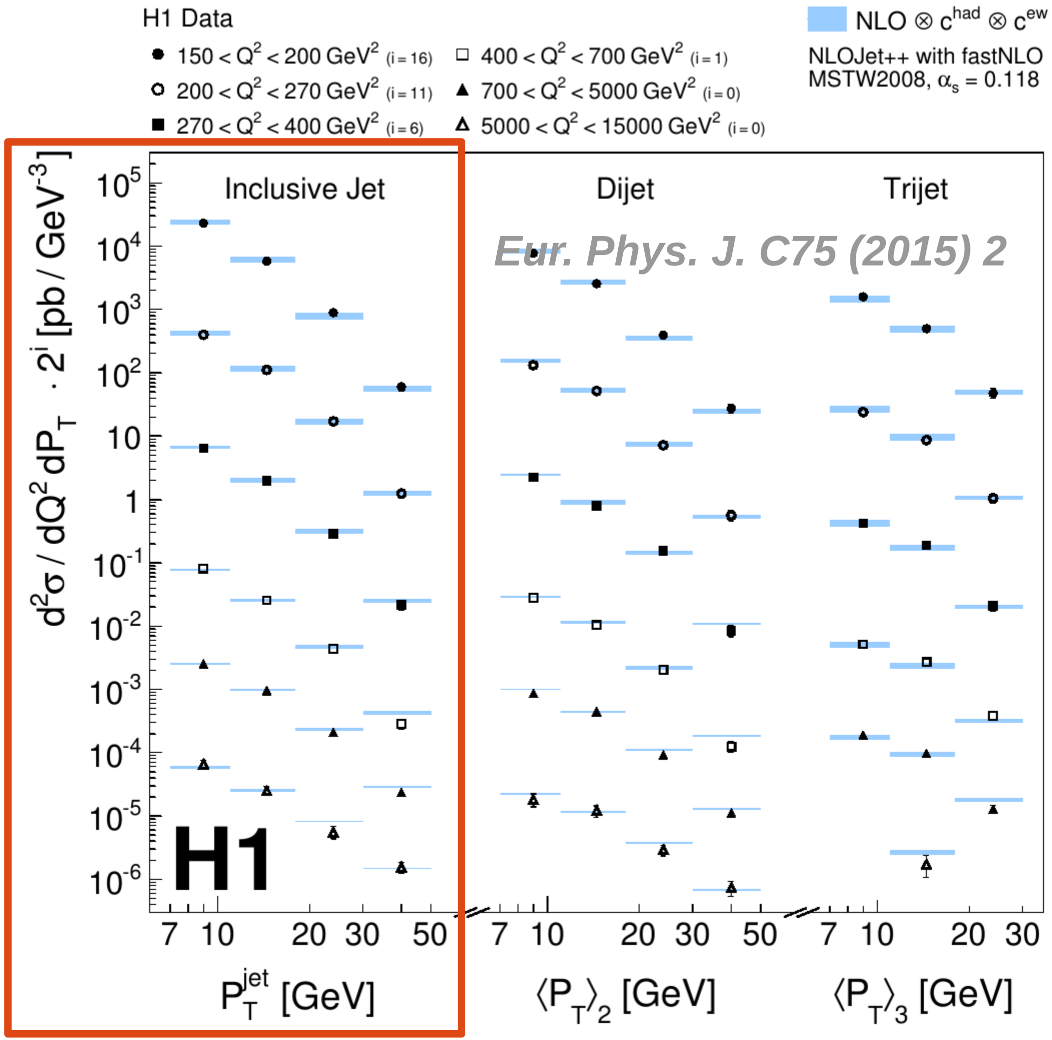
- $7 < p_T < 50$ GeV

Recent studies showed

- Inclusive jets are well measurable down to $p_T = 4$ GeV
- The original 'high-Q^2 '-analysis contained a cross section bin for inclusive jets for:

  $5 < p_T < 7$ GeV

- These additional bins are now provided (for each Q^2 range)
- Absolute and normalised cross sections



Inclusive jet cross sections

Inclusive jet cross sections

- low Q^2: $4.5 < P_T < 50$ GeV
- high Q^2: $5 < P_T < 50$ GeV

Predictions

- NLO, aNNLO & NNLO

NLO

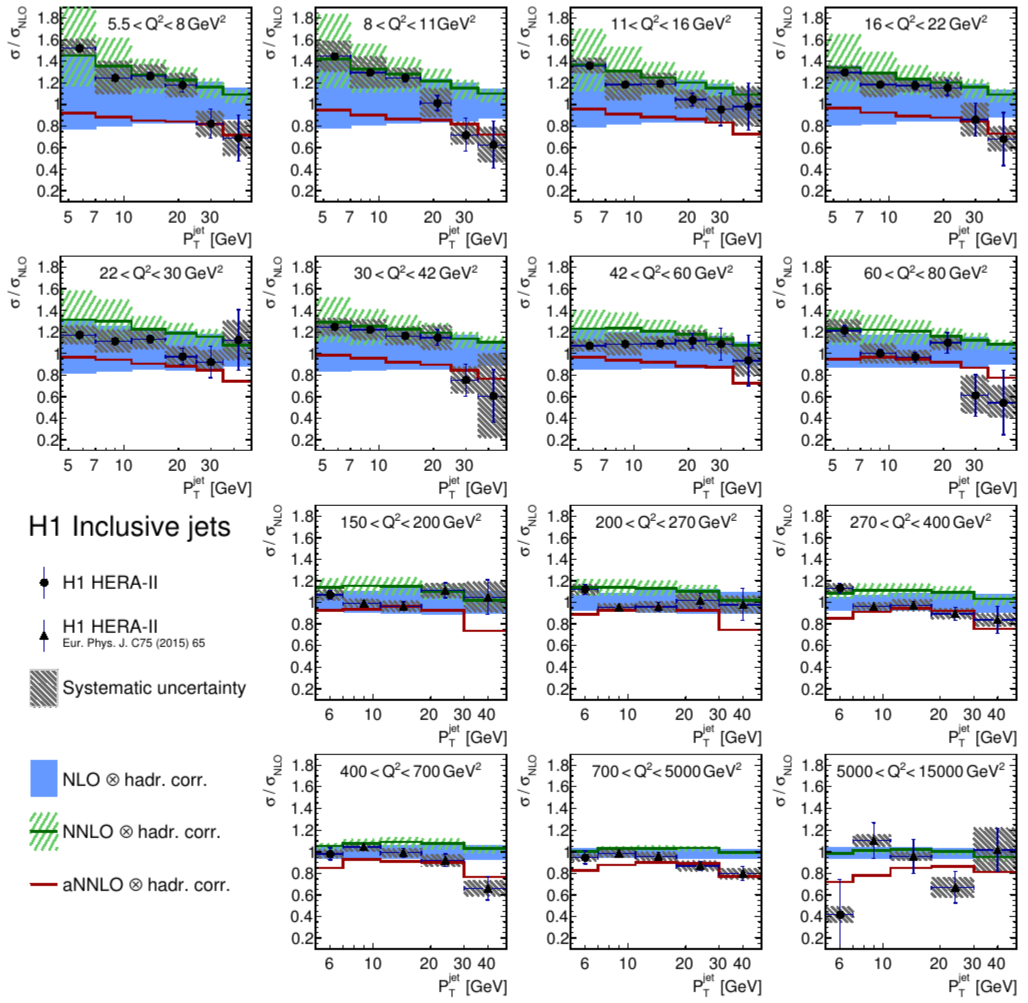
- Data well described within uncertainties

aNNLO

- Somewhat improved shape description

NNLO

- Improved shape and normalisation
- Reduced scale uncertainties for larger values of μ_r



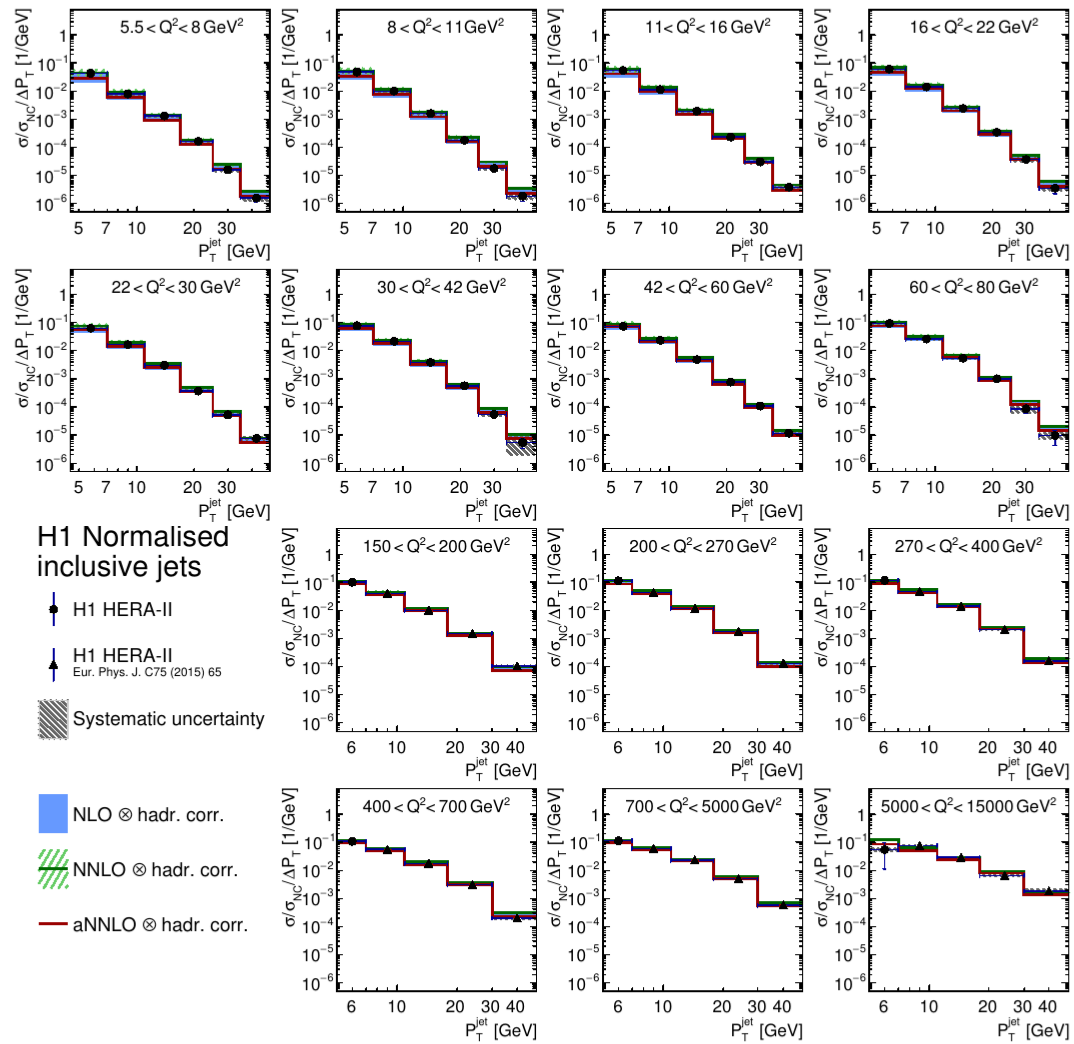
Normalised inclusive jet cross sections

Normalised inclusive jets

- Normalisation w.r.t. inclusive NC DIS cross section in respective Q^2 bin
- Significant reduction of uncertainties at higher values of Q^2

Normalised jet cross sections

- Increase as a function of Q^2 for a given P_T interval

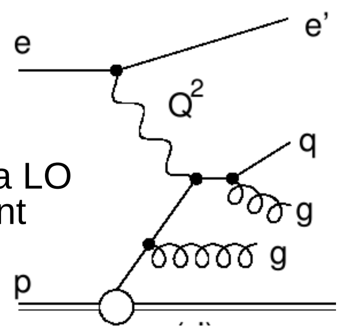


Trijet cross sections

ep -> 3jets

- Leading order O(α_s^2)

Exemple for a LO matrix element

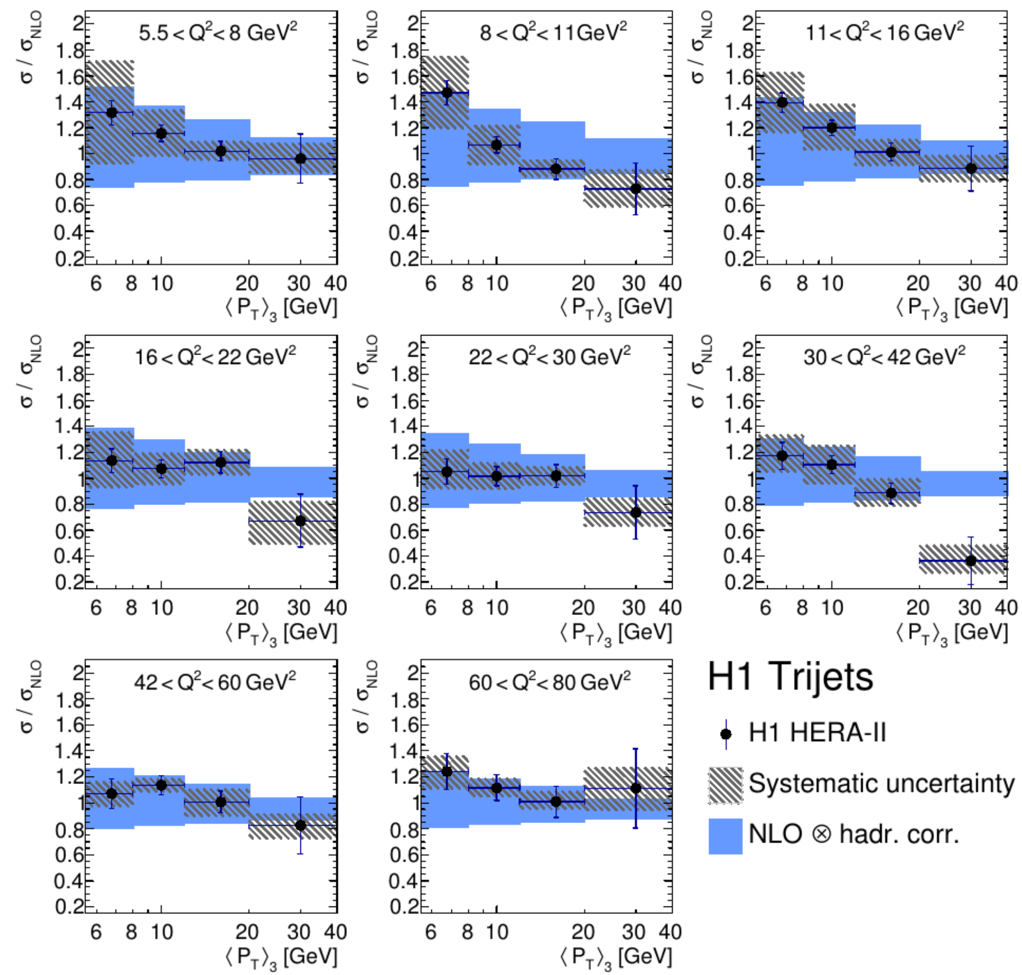


- No NNLO predictions available yet
- NLO(trijets) of same order in α_s than NNLO inclusive jet or dijet

Description by NLO

- Data well described by NLO
- Data precision mainly higher than scale uncertainties
- Similar trends than for dijets observed:
  low scales: NLO undershoots data
  high <P_T> : NLO overshoots data

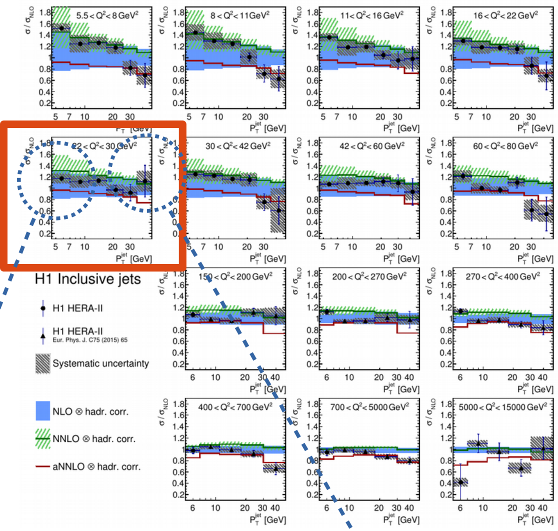
Normalised trijets also measured

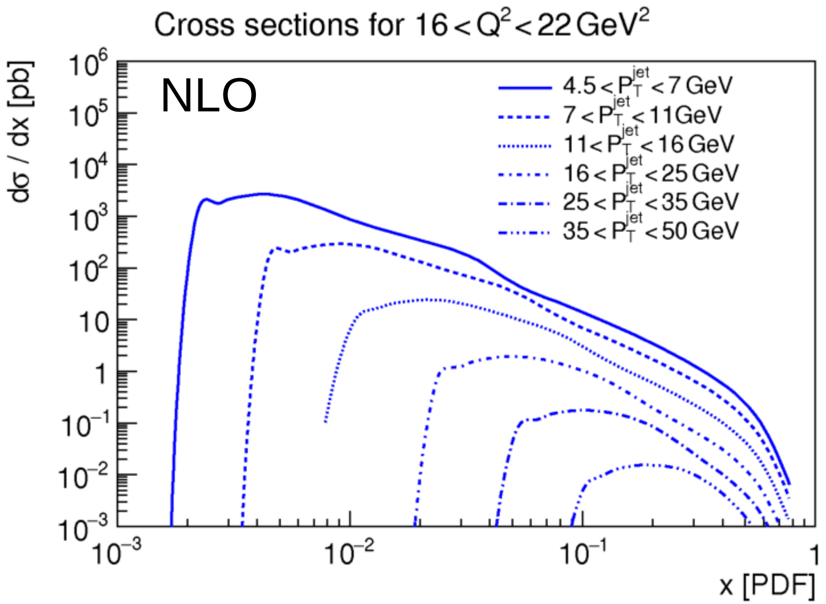


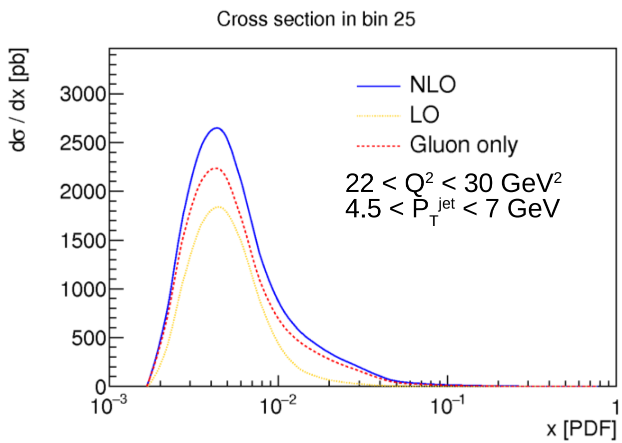
Phenomenological application

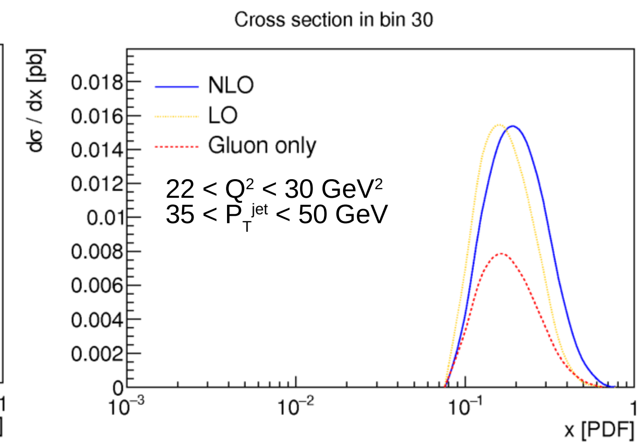
PDF dependence of <u>inclusive jet</u> cross sections

- Cross sections of single data points as a function of x(PDF)
- P_T-binning probes different x-regions
- Lowest x-values: $x \sim 10^{-3}$
- High-P_T cross sections: $x > 10^{-1}$
  -> H1 Jets may become important for high-x gluon
  -> Advantage: No convolution with second hadron in DIS
- x-dependence shows little dependence on Q^2









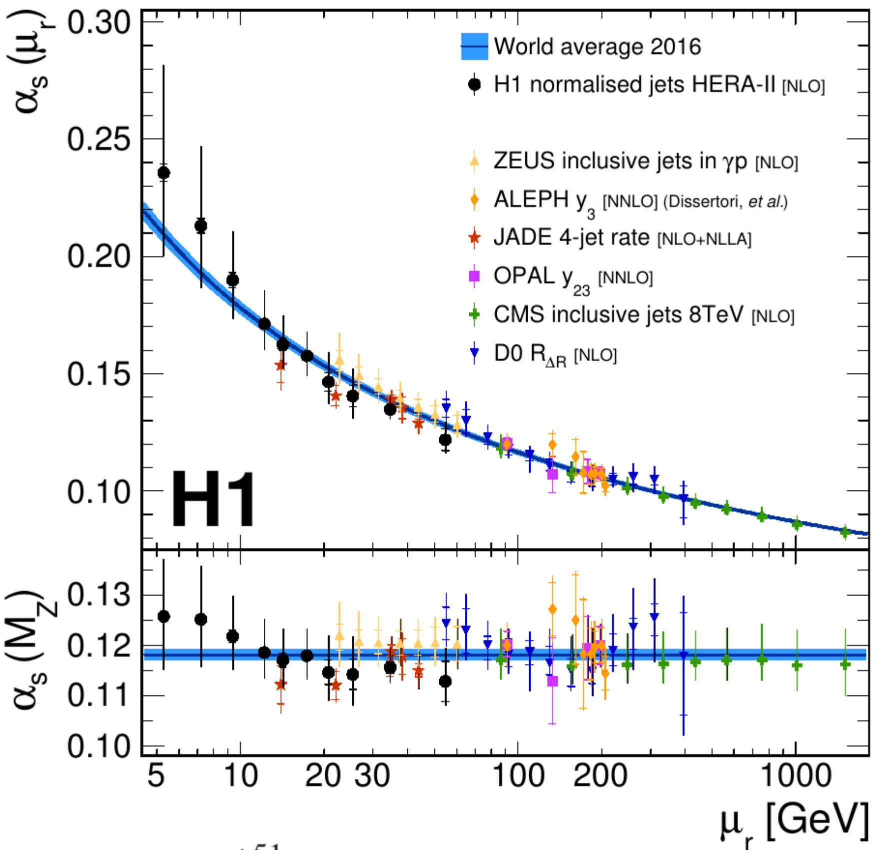
Determination of the strong coupling $\alpha_s(M_Z)$

Use low- and high-Q2 data

- Low-Q2 jets [arxiv:1611.03421]
- high-Q2 jets (Eur.Phys.J.C75 (2015) 2)

All normalised jet cross sections

  - Normalised inclusive jet
  - Normalised dijets
  - Normalised trijets
  - Correlations of uncertainties are known
- Fit $\alpha_s(M_Z)$ in χ^2-minimization procedure



Two results (NLO)

- Probe running of $\alpha_s(\mu_r)$
  Group data points with similar value of μ_r
- One fit to all data points together: $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1173\,(4)_{\rm exp}\,(3)_{\rm PDF}\,(7)_{{\rm PDF}(\alpha_s)}\,(11)_{\rm PDFset}\,(6)_{\rm had}\,(^{+51}_{-43})_{\rm scale}$$

World average (PDG2016)
$\alpha_s(M_Z) = 0.1181 \pm 0.0011$

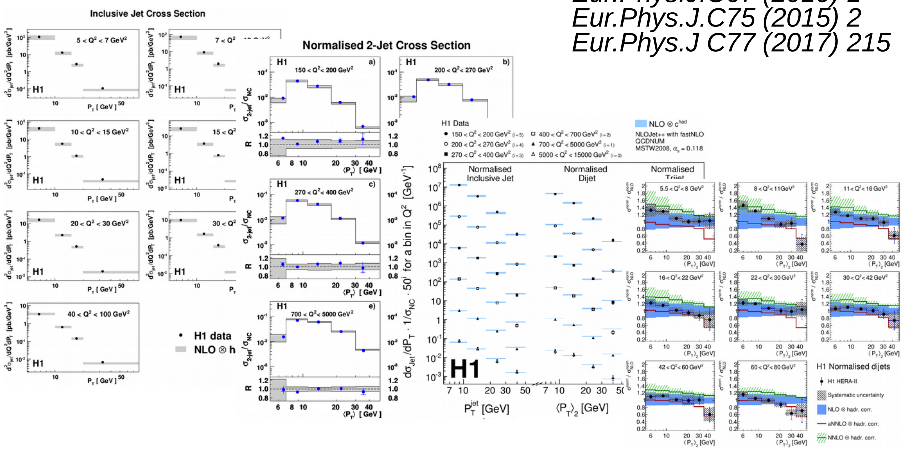
- Very high experimental precision
- Using NNLO: dominating theory uncertainties is reduced → see talk this afternoon

Conclusion

Eur.Phys.J.C65 (2010) 363
Eur.Phys.J.C67 (2010) 1
Eur.Phys.J.C75 (2015) 2
Eur.Phys.J C77 (2017) 215

Last missing piece of H1 jet legacy

Process		HERA-I	HERA-II
Low Q^2	Inclusive jet Dijet Trijet	EPJ C 67 (2010) 1	EPJ C 77 (2017) 215 (this presentation)
High Q^2	Inclusive jet Dijet Trijet	EPJ C 65 (2010) 363	EPJ C 75 (2015) 2

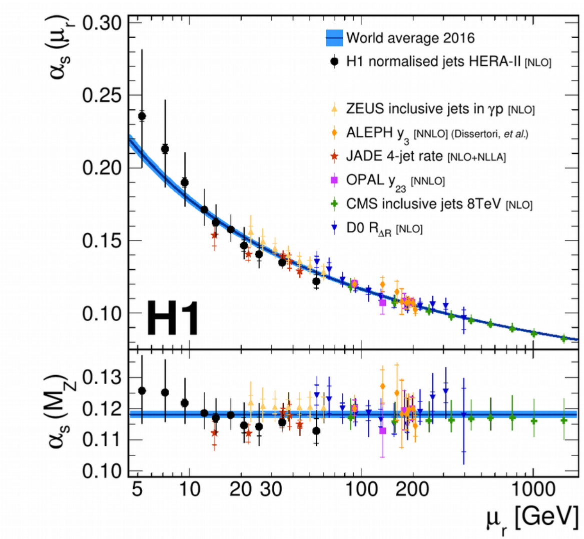


High precision jet cross sections

- Inclusive jet, dijet and trijets
- Also available: normalised w.r.t. inclusive NC DIS

Probe running of α_s over one order of magnitude

- Very high experimental precision on $\alpha_s(M_Z)$
- Challenging regime: $5 < \mu_r < 70$ GeV



Future applications PDFs with H1 jet data

- Very high sensitivity to gluon density

Finally we arrived: High-precision jet data together with NNLO predictions

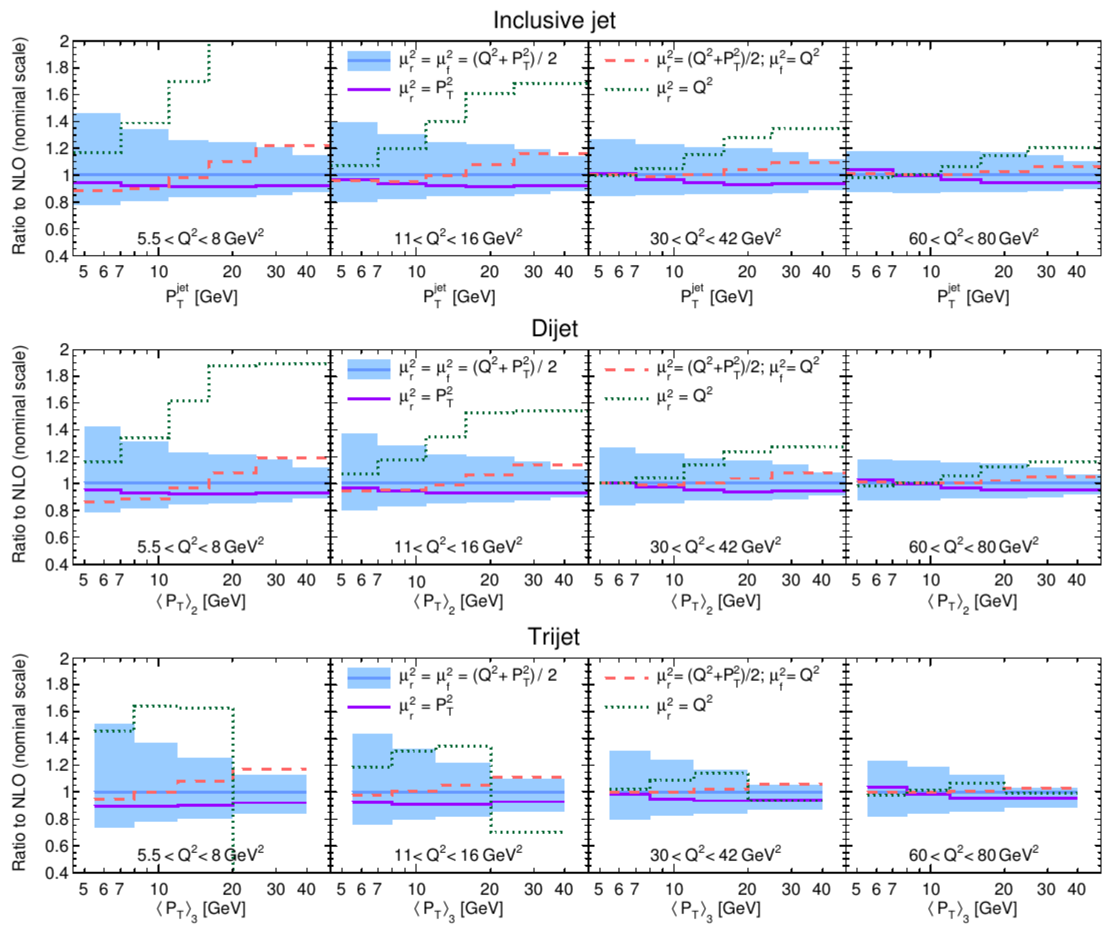


Figure 6: Comparison of NLO predictions obtained with scale choices of $\mu_r^2 = \mu_f^2 = \frac{1}{2}(Q^2 + P_T^2)$, $\mu_r^2 = \mu_f^2 = P_T^2$, $\mu_r^2 = \mu_f^2 = Q^2$, and $\mu_r^2 = \frac{1}{2}(Q^2 + P_T^2)$ with $\mu_f^2 = Q^2$ for selected Q^2 bins of the inclusive jet, dijet and trijet cross sections. The shaded area around the theory predictions indicates the scale uncertainty on the nominal scale choice of $\mu_r^2 = \mu_f^2 = \frac{1}{2}(Q^2 + P_T^2)$ as described in the text.

Statistical correlations

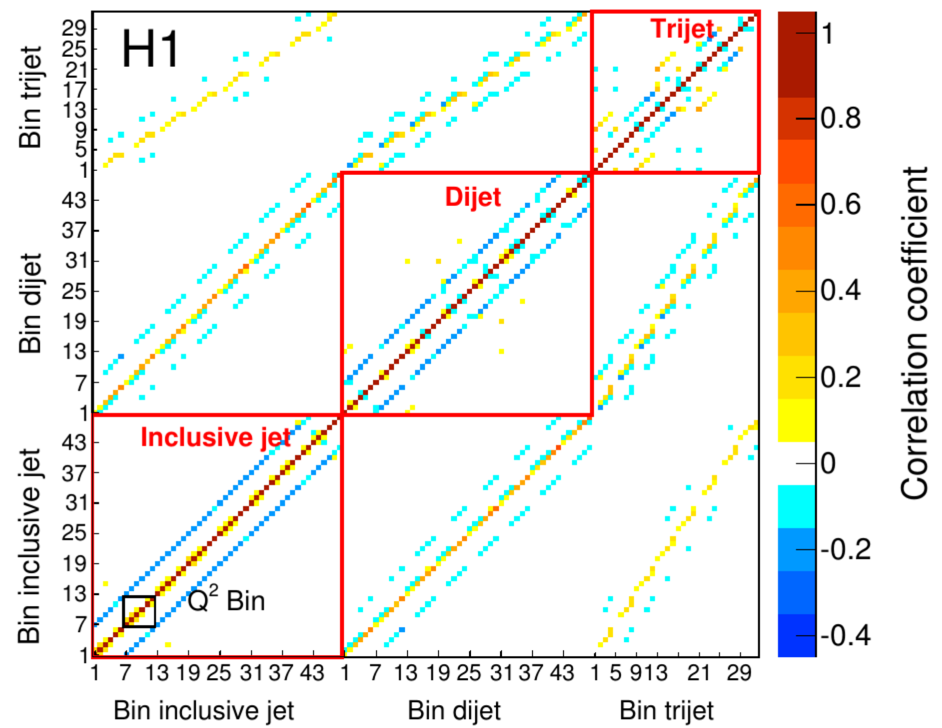


Figure 7: Matrix of statistical correlation coefficients of the unfolded cross sections. The bin labels are specified in table 5.

PDF dependence

Studies using different PDF sets

- Study various NNLO PDF sets
  - NNPDF3.0
  - CT14
  - MMHT
  - HERAPDF2.0
- All PDFs determined with $\alpha_s(M_Z) = 0.118$
- Technical aspect:
  Convolute with NLO matrix elements because NNLO matrix elements are too time-consuming to recalculate

Effect of different PDFs

- Very small
- All studied NNLO PDF sets are quite consistent
- Different PDFs mainly covered by NNPDF30 PDF uncertainty
- Increased PDF uncertainty for high values of P_T
- -> Future PDFs may have lower high-x gluon