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

Daniel Britzger
for the H1 Collaboration

DIS 17
25th International Workshop on Deep Inelastic Scattering and Related Topics
Birmingham, UK
05.04.2017

Deep-inelastic scattering

Neutral current deep-inelastic scattering

Process: $ep \rightarrow e'X$

Electron or positron

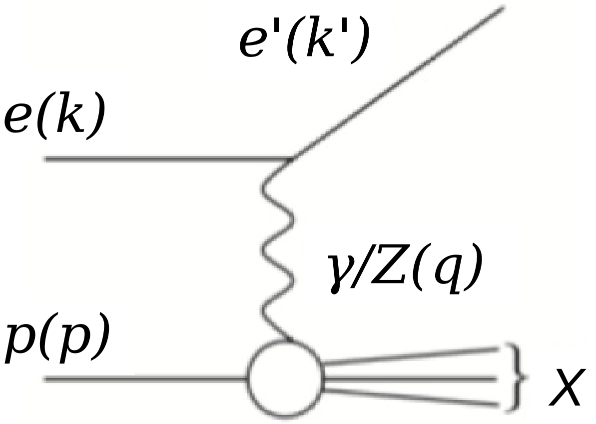
Kinematic variables

- Virtuality of exchanged boson Q^2

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

- Inelasticity

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



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

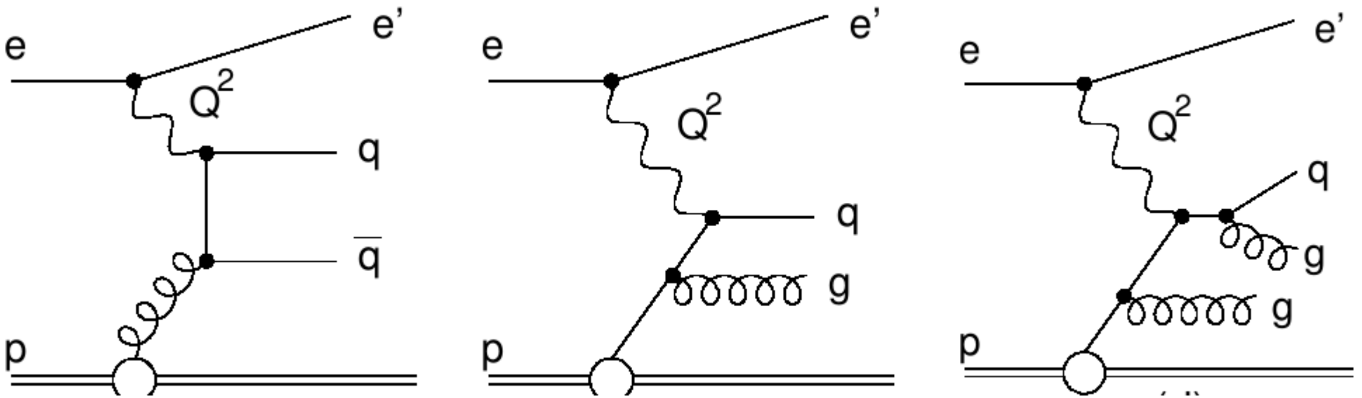
NC and CC DIS cross sections (HERA-II) are mandatory ingredients for PDF fits

- 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



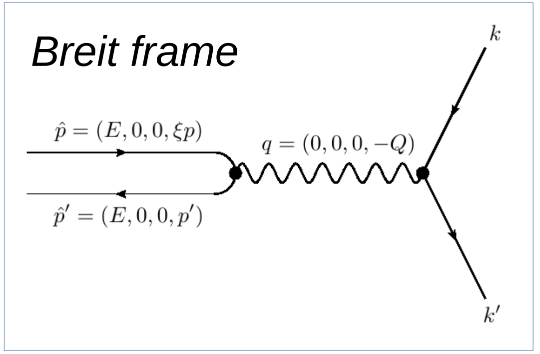
Boson-gluon fusion　　QCD Compton　　Trijet leading-order

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



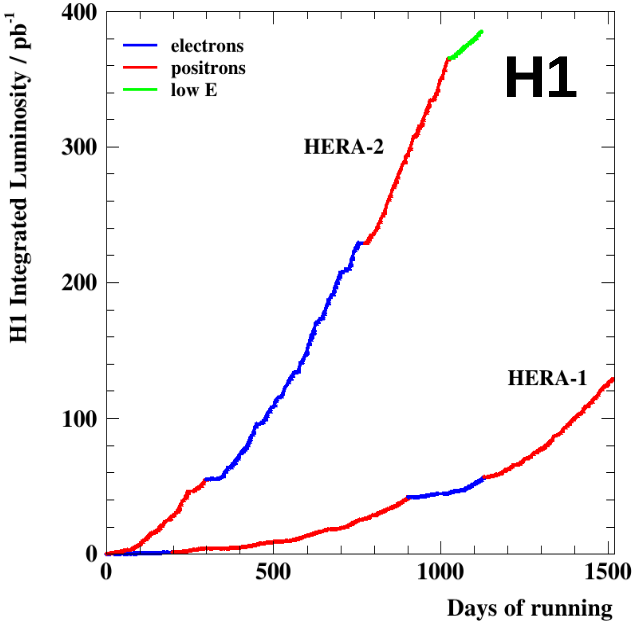
Trijet measurement

- 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}

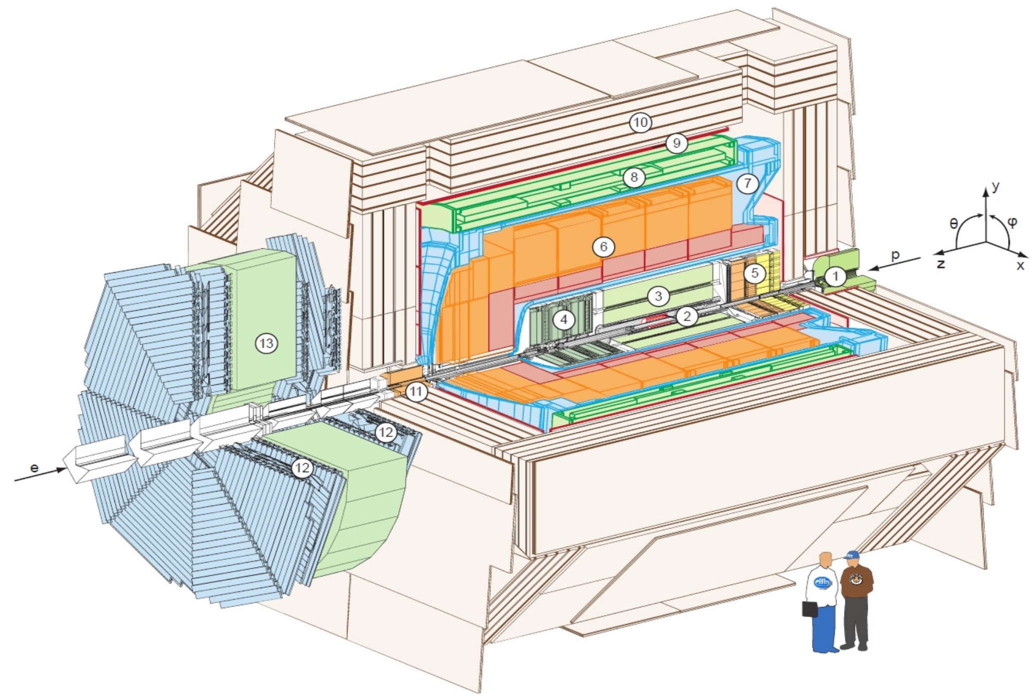
HERA-II period

- 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 magnet: 1.15T
- Muon detectors



Drawing of the H1 experiment

Excellent experimental precision

- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 2.5%

Analysis strategy and kinematic range

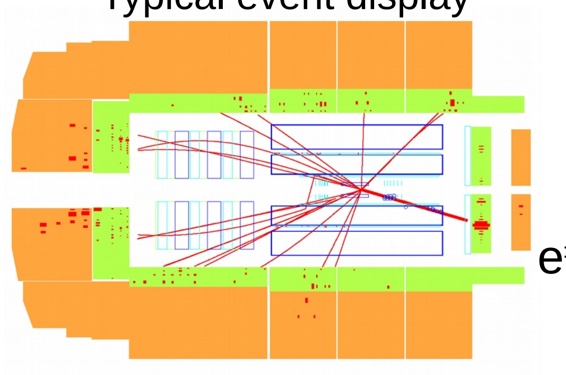
Data must be corrected for detector effects

- 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

- Dijets/trijets: asymmetric cuts on p_T^{jet1} & p_T^{jet2} avoid IR sensitive regions in NNLO

Regularised unfolding

Regularised unfolding using TUnfold

- Calculate unfolded distribution *x* by minimising

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

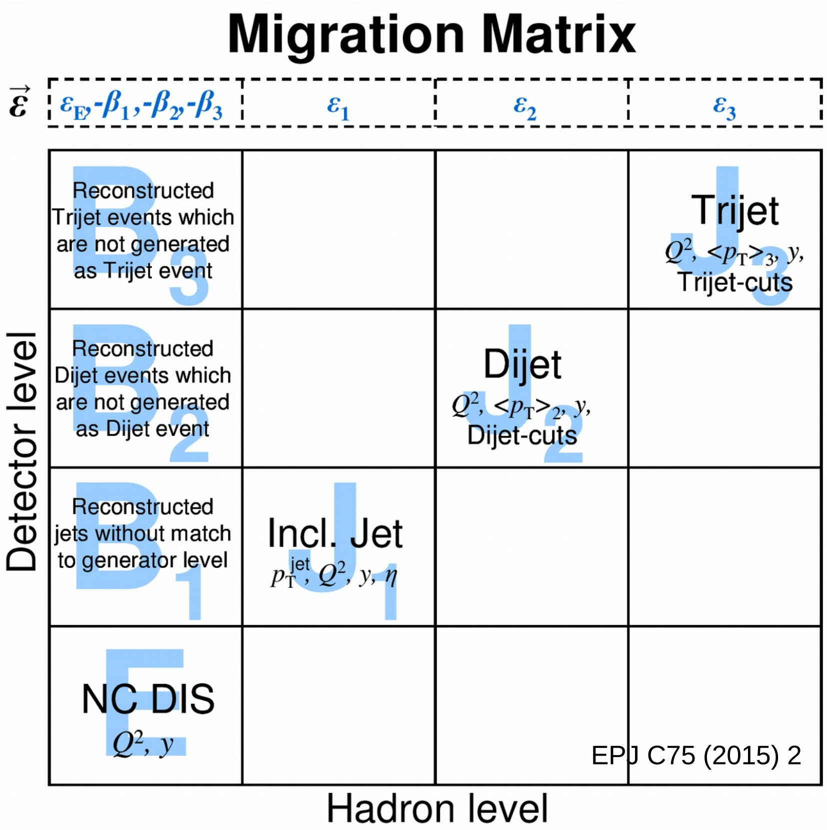
  - Linear analytic solution
  - Linear error propagation
  - Statistical correlations are considered in V_y

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

JINST 7 (2012) T10003

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



Control distributions

Acceptance of NC DIS events

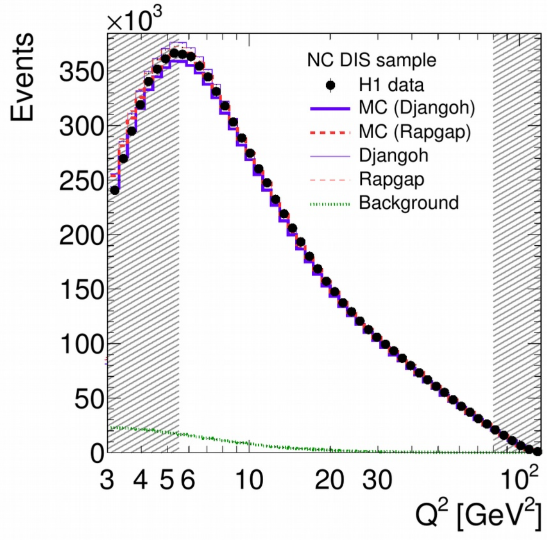
- Scattered lepton is found in SpaCal
- Lepton energy E_e > 10.5 GeV
- Selection based on un-prescaled SpaCal electron trigger

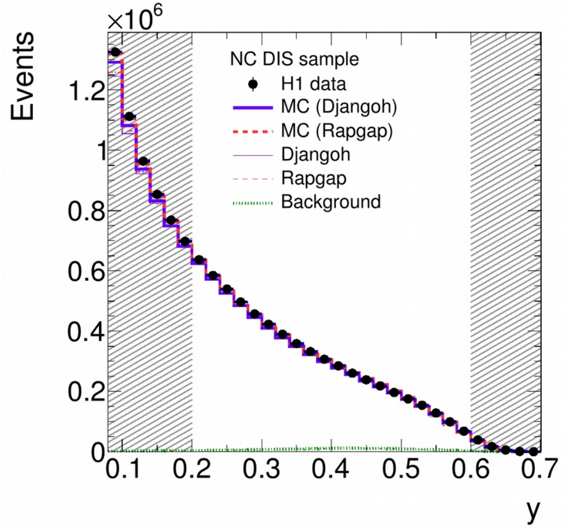
Monte Carlo generators

- 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

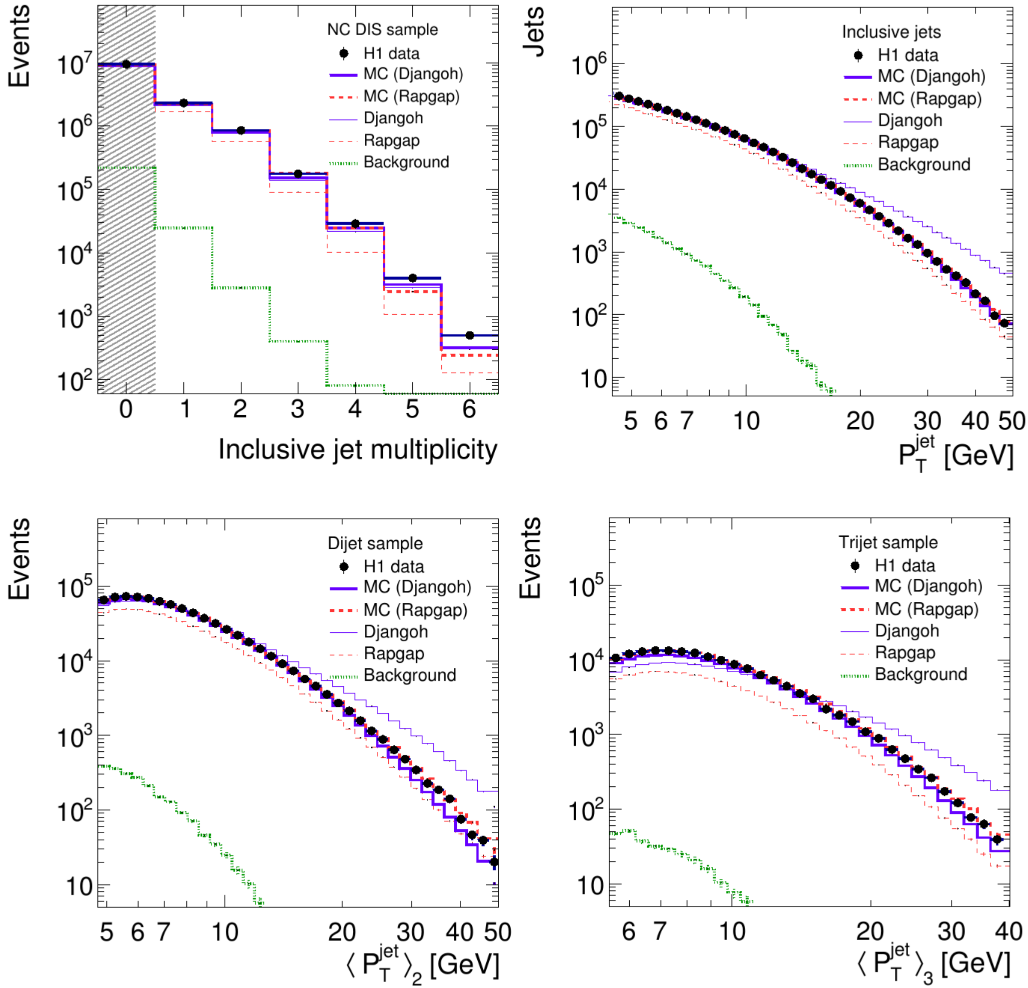
Jet reconstruction
- k_T jet algorithm with R=1
- Jets built from tracks and clusters
- Jet energy calibration using neural networks
  Approx. 1% Jet energy scale uncertainty

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

-> MC generators are 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) and [arXiv:1703.05977]

- 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

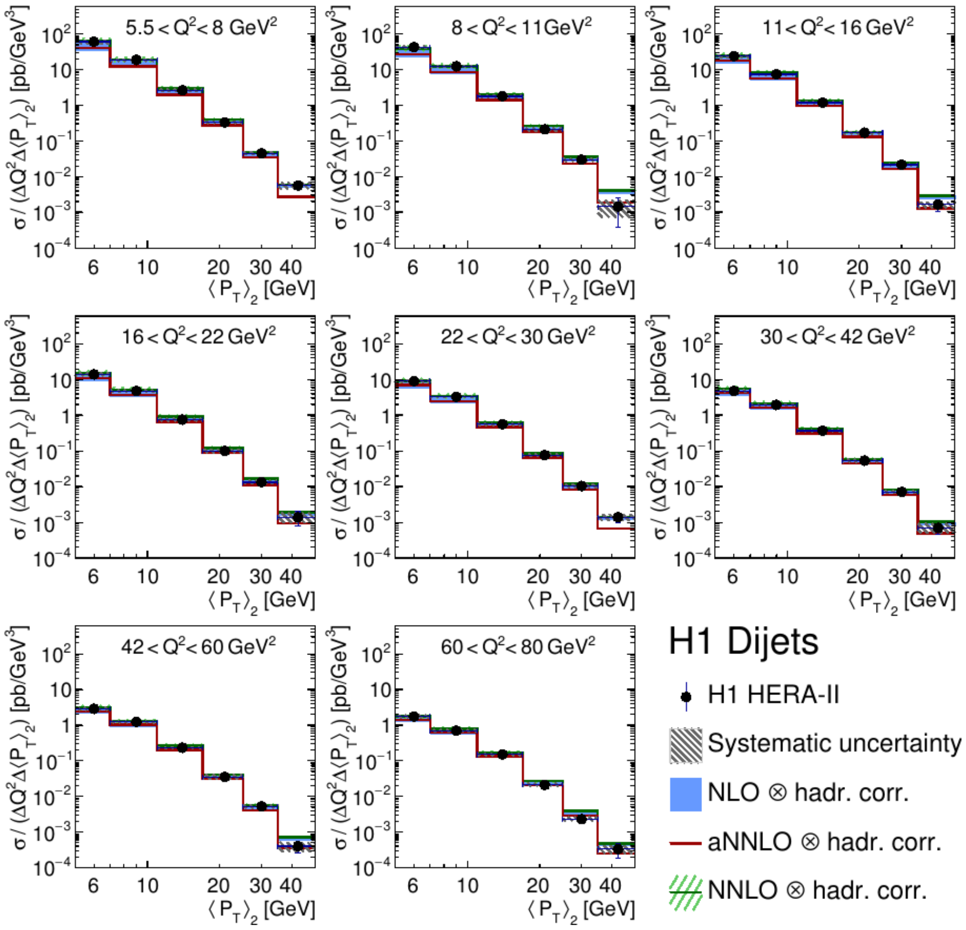
Dijet cross sections in NC DIS as a function of Q^2 and $<p_T>_2$

- $<P_T>_2 = (P_T^{jet1} + P_T^{jet2})/2$
  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



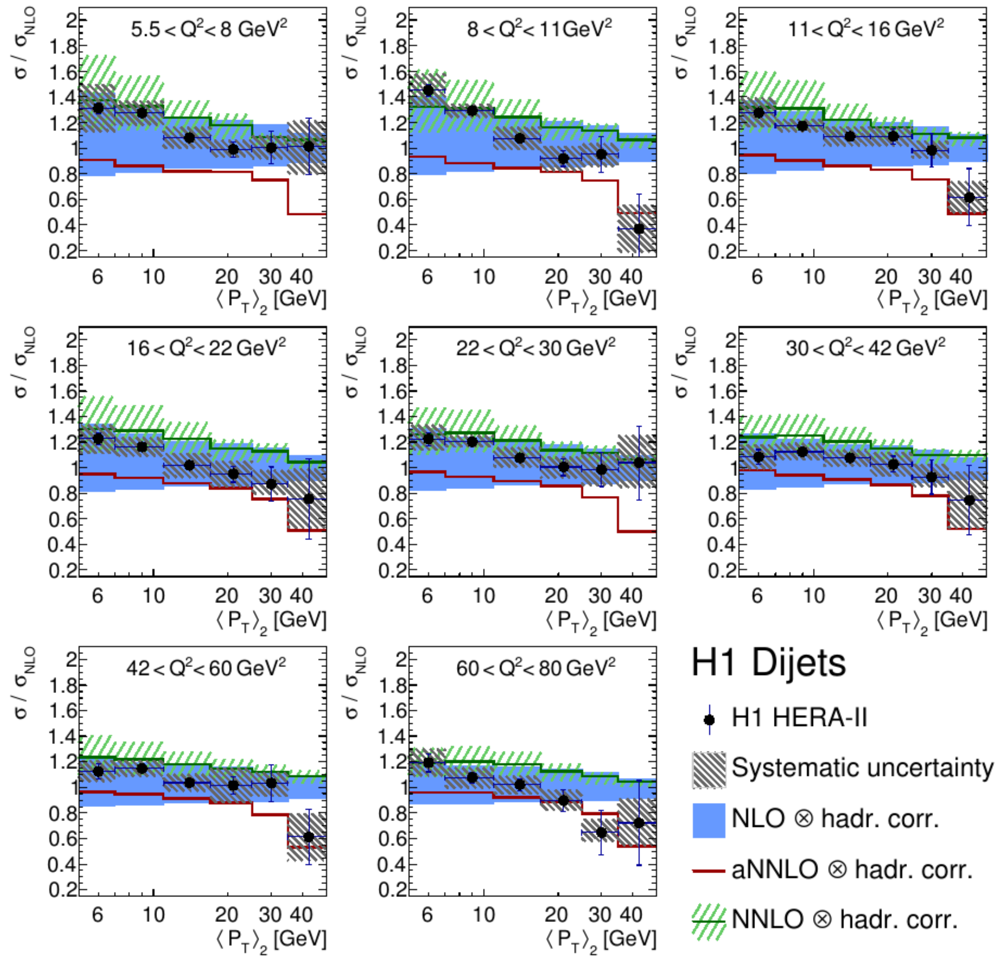
Ratio of dijet cross sections to NLO

Scale uncertainty

- So-called '7-point scale variation':
  Vary μ_r and μ_f independently by factors of 2 and 0.5, but exclude variations in 'opposite' directions

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

Normalised jet cross sections

- Normalised to:
  'inclusive neutral-current DIS cross section' in respective Q^2 bin

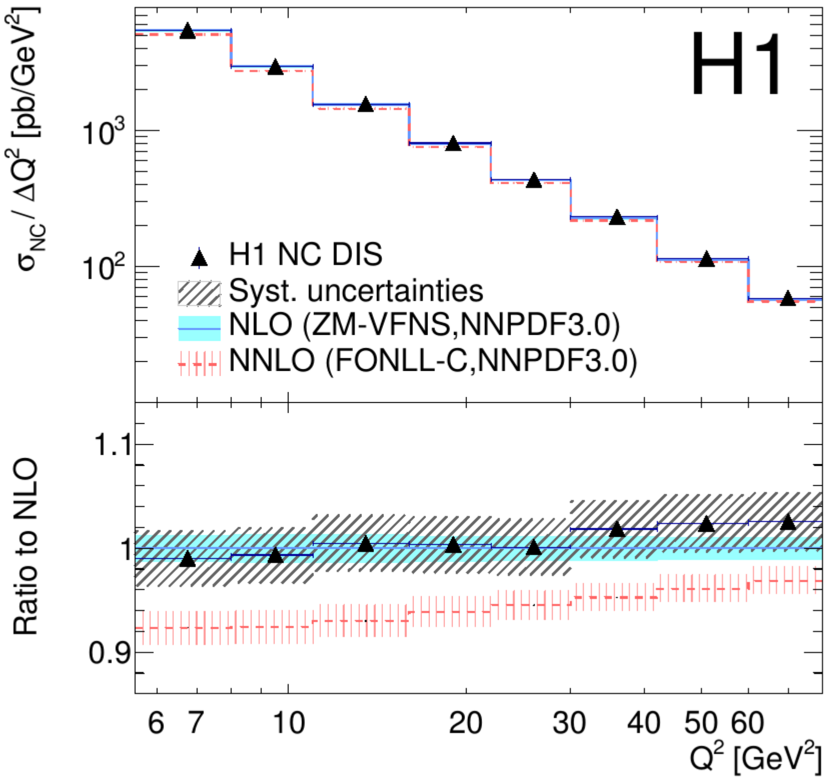
Advantages

- 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 a good description of the data
- PDFs are fitted to NC DIS cross sections

Inclusive neutral-current DIS cross sections



Normalised dijet cross sections

Normalised dijet cross sections

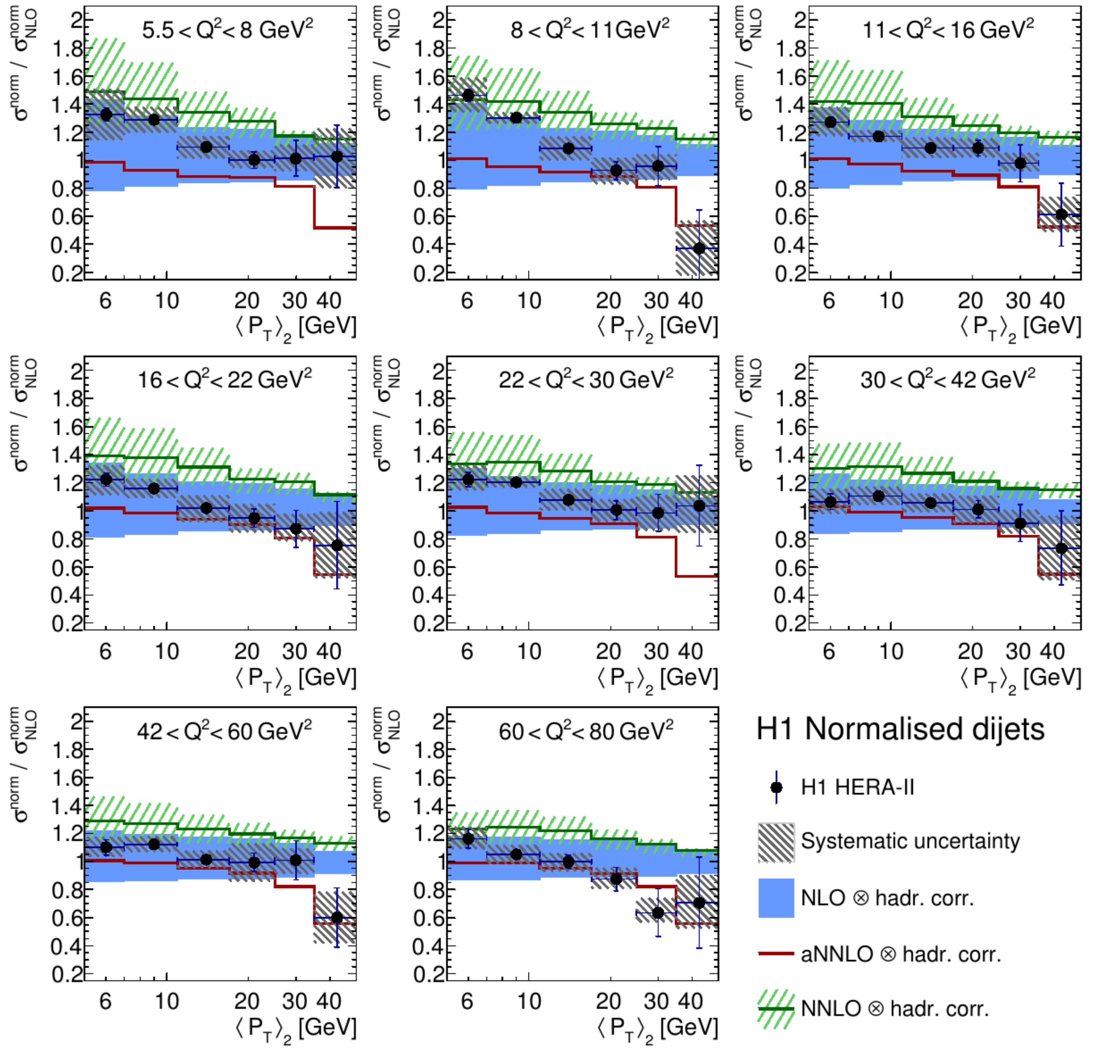
$$\sigma_i^{\text{norm}} = \frac{\sigma_i}{\sigma_{i_q}^{\text{NC}}}$$

Predictions

- Predictions obtained as ratio of jet to NC DIS calculations
- Scale uncertainties 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
- (only) 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

- H1 HERA-II jet cross sections at high-Q^2
- Inclusive jet, dijet and trijet cross sections
- $150 < Q^2 < 15\,000 \mathrm{GeV}^2$

Inclusive jets in range

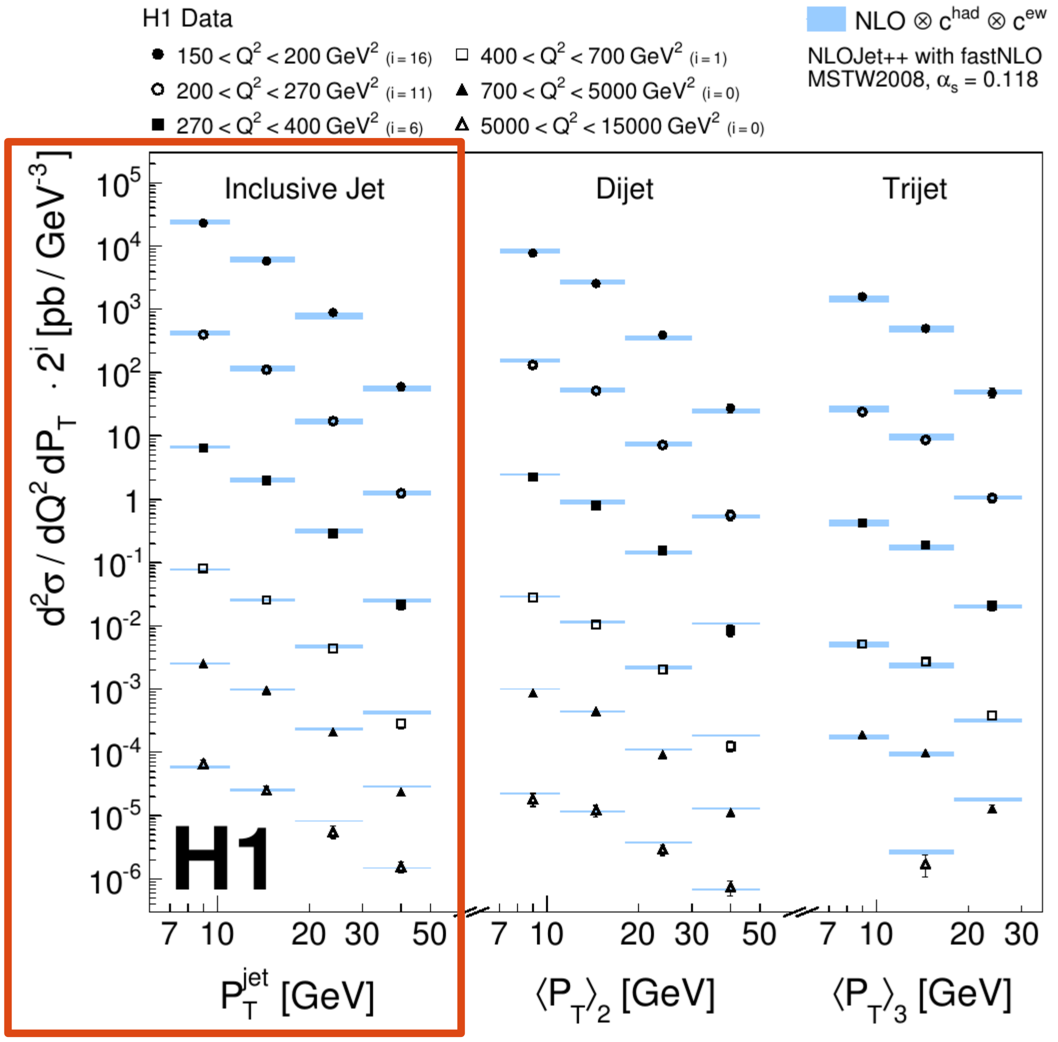
- $7 < p_T < 50$ GeV

Recent studies showed

- Inclusive jets are well measurable down to $p_T \sim$ 4 GeV
- The original 'high-Q^2 '-analysis contained a cross section bin for inclusive jets for $5 < p_T < 7$ GeV

Extension to low-p_T : $5 < p_T < 7$ GeV

- for each Q^2 range
- Absolute and normalised cross sections



Inclusive jet cross sections

Inclusive jet cross sections
- low Q²: 4.5 < P_T < 50 GeV
- high Q²: 5 < P_T < 50 GeV

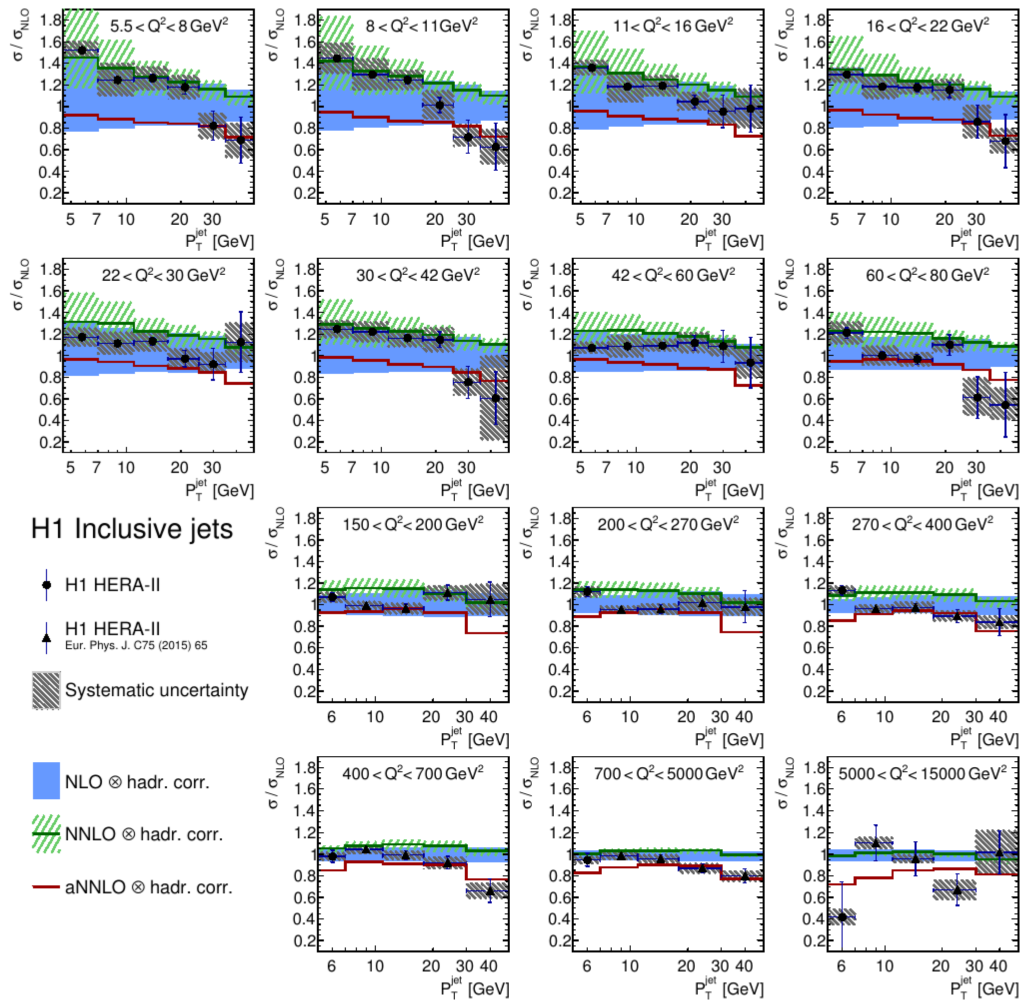
Predictions
- NLO, aNNLO & NNLO

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

Also measured
- Normalised inclusive jet cross sections



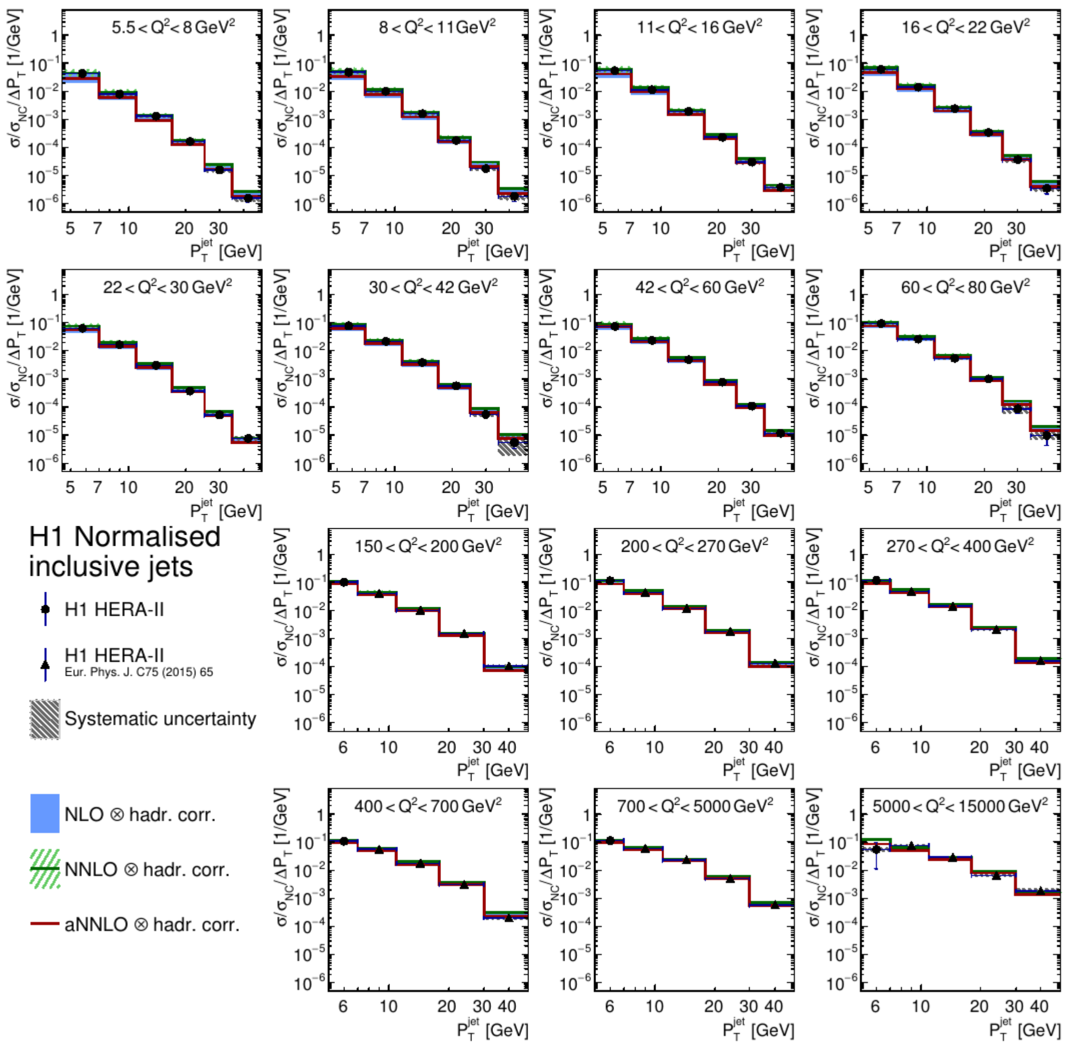
Normalised inclusive jet cross sections

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
- Q^2 and p_T are both important scales for inclusive jet production

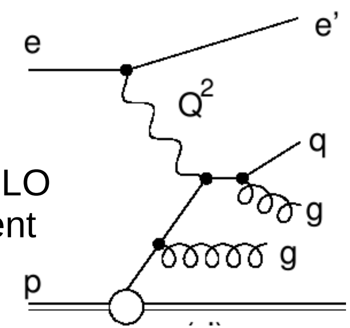


Trijet cross sections

Trijet cross sections

- ep -> 3jets
- Leading order $O(\alpha_s^2)$

Exemple for LO matrix element

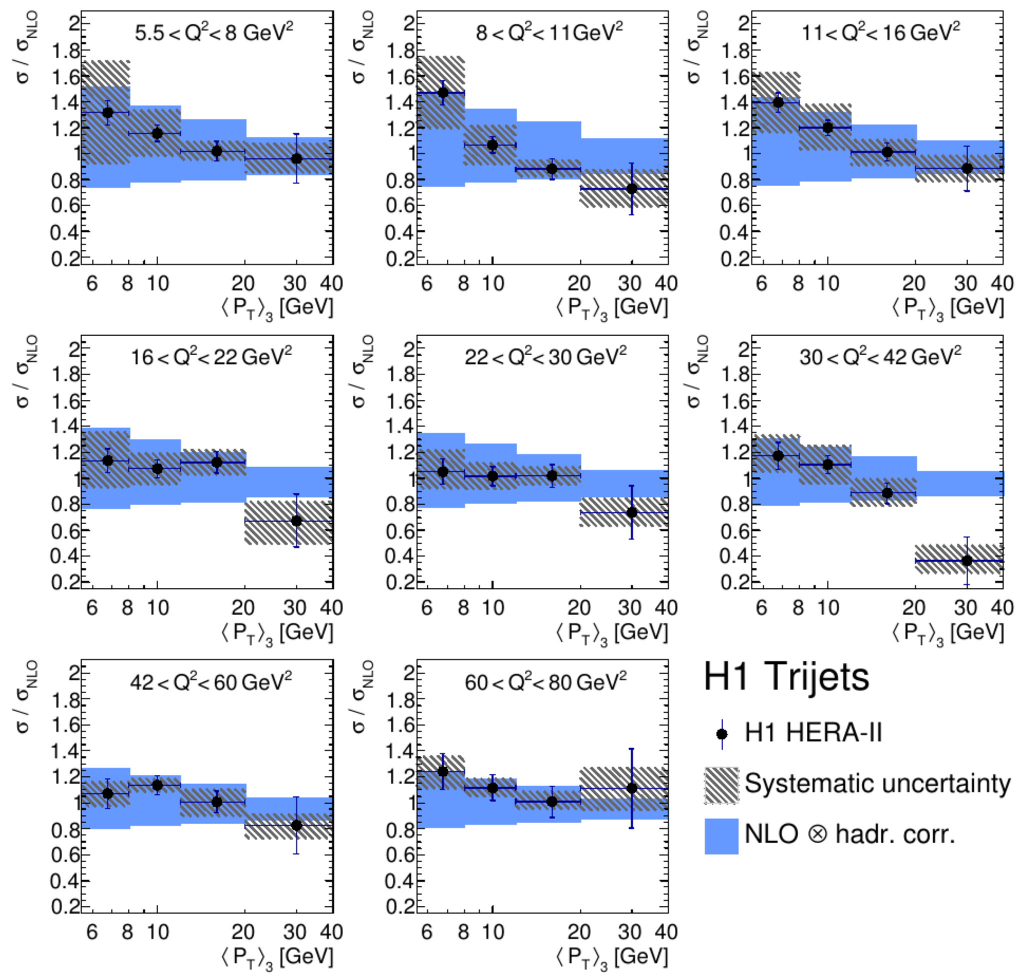


- No NNLO predictions available yet

Description by NLO

- Data well described by NLO (nlojet++)
- Data precision mainly higher than scale uncertainties
- Similar trends than observed for dijets
  low scales: NLO undershoots data
  high $\langle P_T \rangle$: NLO overshoots data

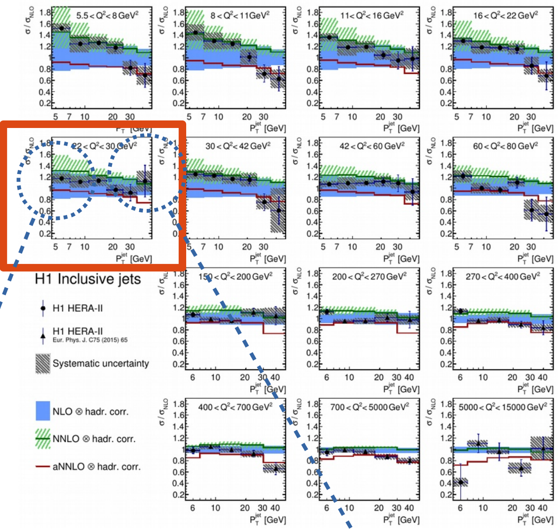
Normalised trijets also measured



Phenomenological application

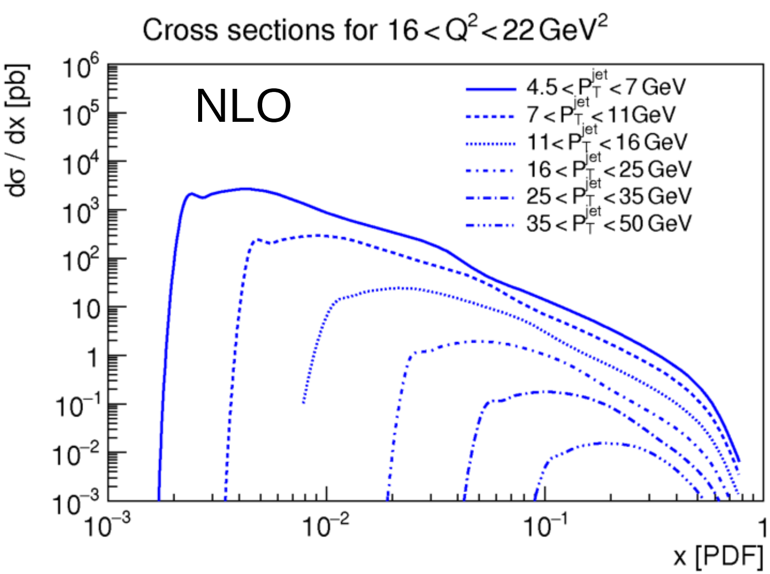
PDF dependence of <u>inclusive jet</u> cross sections

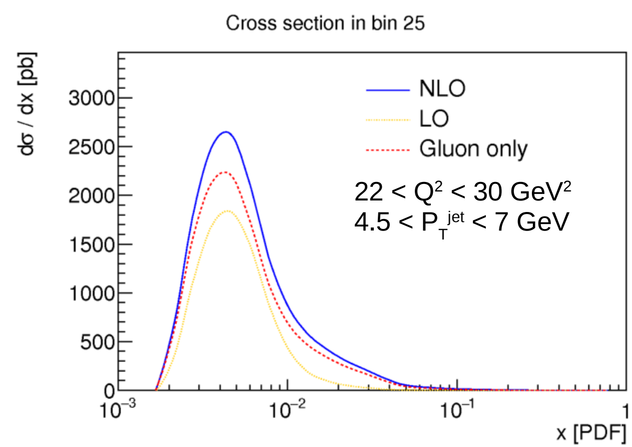
- Cross sections as a function of x_{PDF}
- P_T-bins probe different x-regions
  - Lowest x-values: $x \sim 10^{-3}$
  - High-P_T cross sections: $x > 10^{-1}$
- x-dependence shows little dependence on Q^2

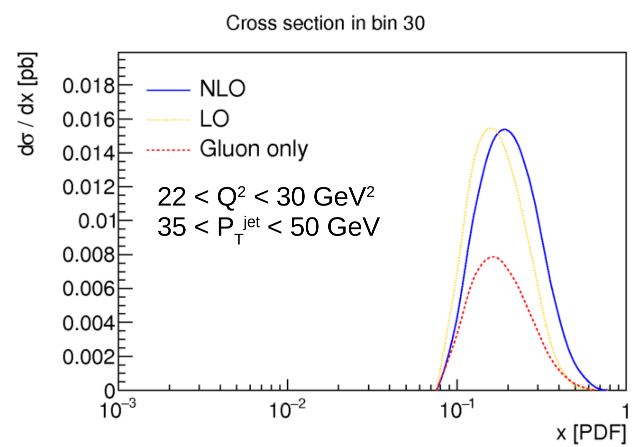


H1 jets may become important for PDFs

- high-x gluon
- only a single hadron involved (decorrelate high-x <--> low-x)



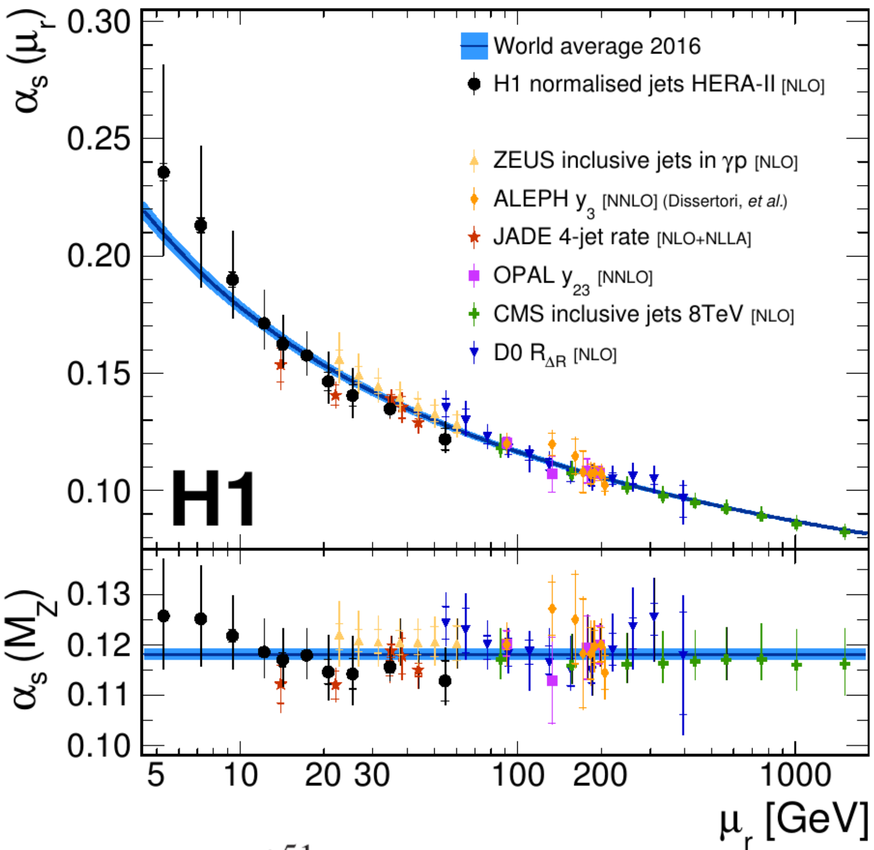




Determination of the strong coupling $\alpha_s(M_Z)$

Determination of $\alpha_s(M_Z)$ in a fit to H1 HERA-II jets

- Use low- and high-Q2 data
  - Low-Q2 jets [arxiv:1611.03421]
  - high-Q2 jets (Eur.Phys.J.C75 (2015) 2)
- Use all normalised jet cross sections
  - All correlations of uncertainties are known
- Fit $\alpha_s(M_Z)$ in χ^2-minimization procedure



Two results (NLO)

- Probe running of $\alpha_s(\mu_r)$
- 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
- Future improvements on dominating theory uncertainties in NNLO

Strong coupling $\alpha_s(M_Z)$ in NNLO

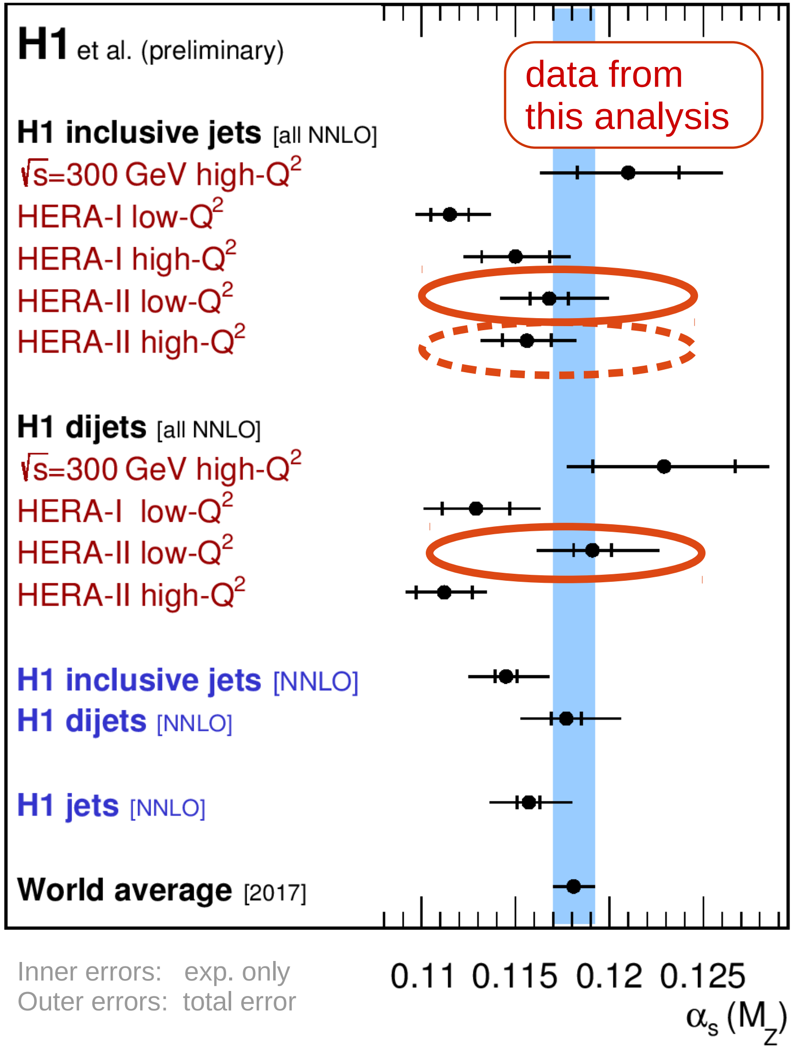
H1-prelim-17-031
- See talk on tuesday morning

NNLO predictions available for
- Inclusive jets
- Dijets

First extractions of strong coupling constant in NNLO precision
- Excellent agreement of theory and data
- Data at lower values of μ_R have an increased sensitivity to $\alpha_s(M_Z)$

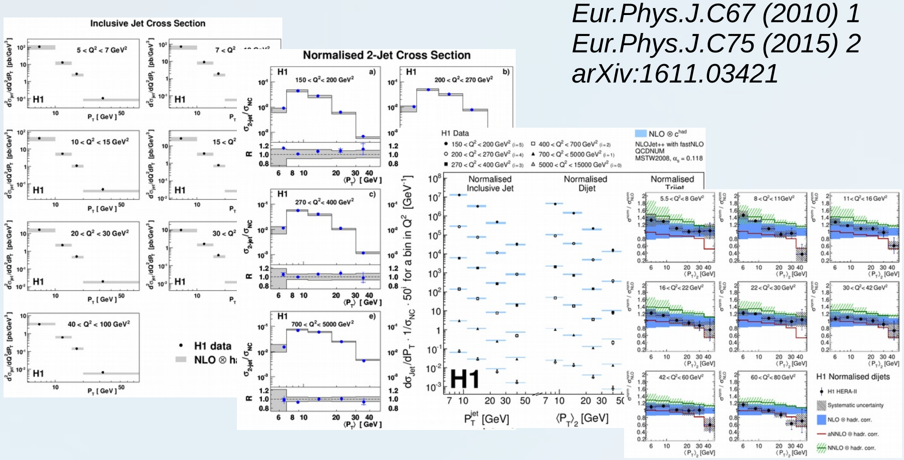
Scale uncertainty in NNLO
- reduction by approx. factor 2-3 compared to NLO
- Scale uncertainty remains dominant uncertainty

H1-prelim-17-031



Conclusion

Eur.Phys.J.C65 (2010) 363
Eur.Phys.J.C67 (2010) 1
Eur.Phys.J.C75 (2015) 2
arXiv:1611.03421

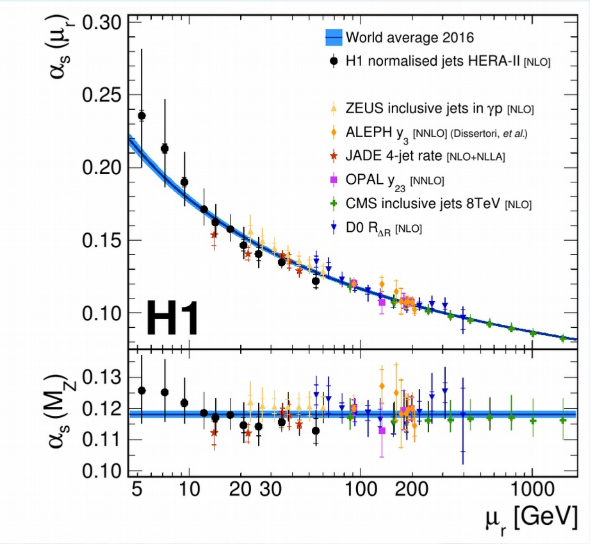


Last missing piece of H1 jet legacy

Process		HERA-I	HERA-II
Low Q^2	Inclusive jet Dijet Trijet	EPJ C 67 (2010) 1	arXiv:1611.03421 acc. by EPJ C
High Q^2	Inclusive jet Dijet Trijet	EPJ C 65 (2010) 363	EPJ C 75 (2015) 2

Probe running of α_s over one order of magnitude with H1 jet data

- Very high experimental precision on $\alpha_s(M_Z)$



Constrain PDFs with H1 jet data

- Very high sensitivity to gluon density

Outlook

- First extractions of $\alpha_s(M_Z)$ in NNLO on the way

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

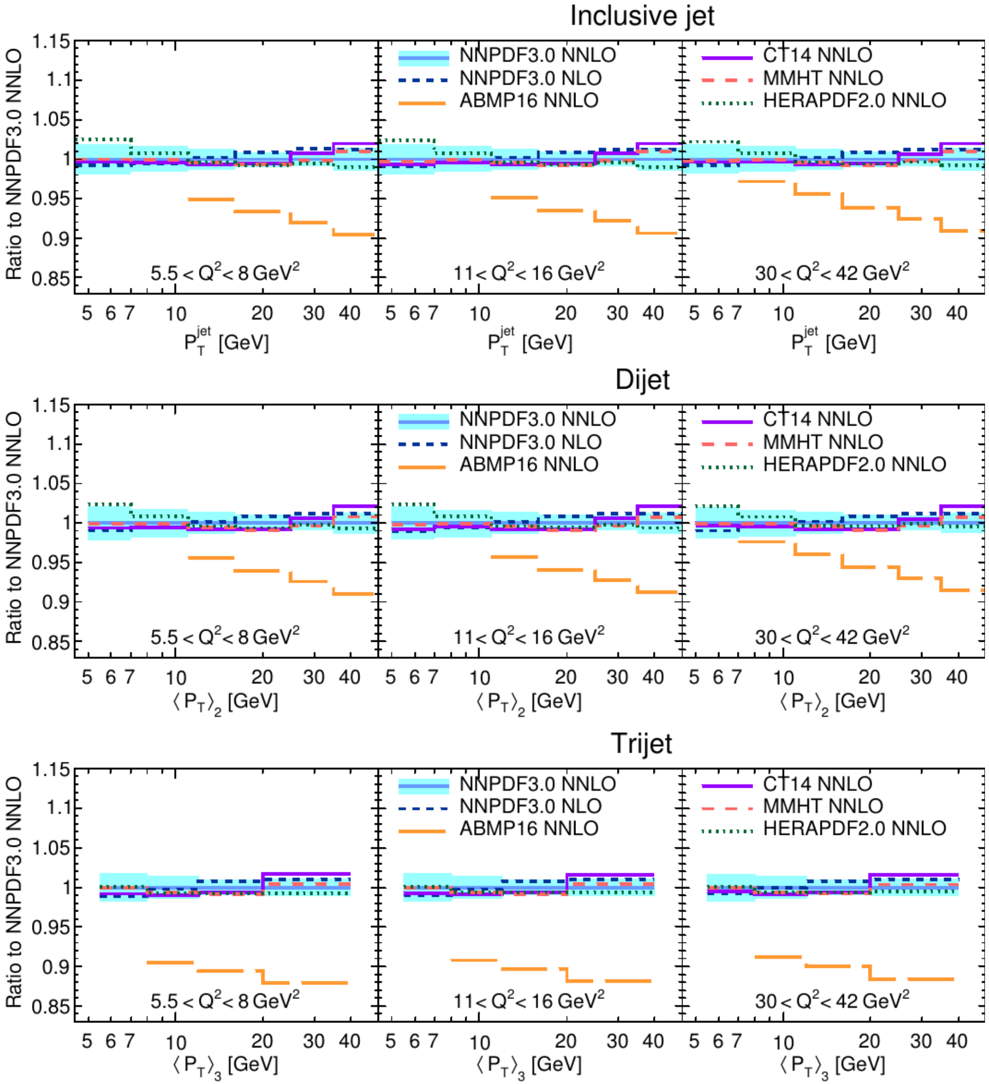
PDF dependence

Study different (NNLO) PDF sets

- NNPDF3.0
  - CT14
  - MMHT
  - HERAPDF2.0
  - ABMP
- Technical remark: convolution with NLO matrix elements because NNLO matrix elements are too time-consuming to recalculate

Different PDFs

- Mosy studied NNLO PDF sets are quite consistent
- Different PDFs mainly covered by NNPDF30 PDF uncertainty
- only ABMP with difference (due to $\alpha_s(m_Z)$?)



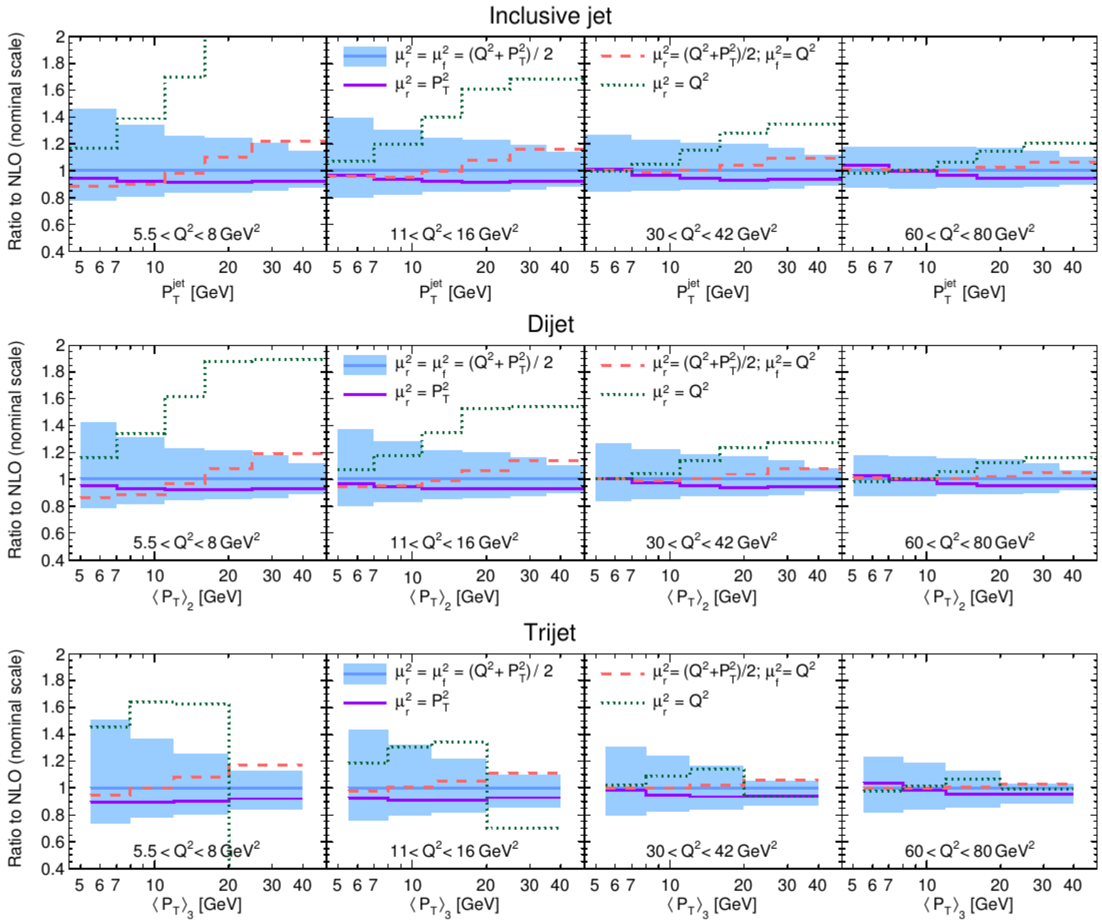


Figure 6: Comparison of NLO predictions obtained with scale choices of $\mu_r^2 = \mu_f^2 = \frac{1}{2}(Q^2 + P_T^2)$, $\mu_r^2 = \mu_f^2 = P_T^2$, $\mu_r^2 = \mu_f^2 = Q^2$, and $\mu_r^2 = \frac{1}{2}(Q^2 + P_T^2)$ with $\mu_f^2 = Q^2$ for selected Q^2 bins of the inclusive jet, dijet and trijet cross 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.

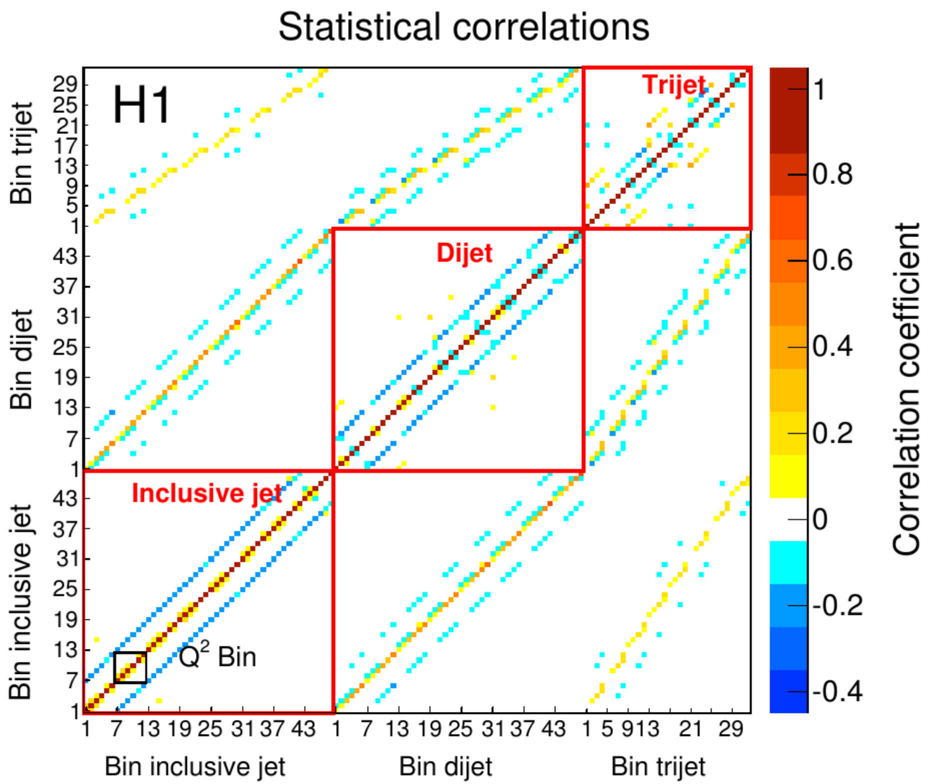


Figure 7: Matrix of statistical correlation coefficients of the unfolded cross sections. The bin labels are specified in table 5.

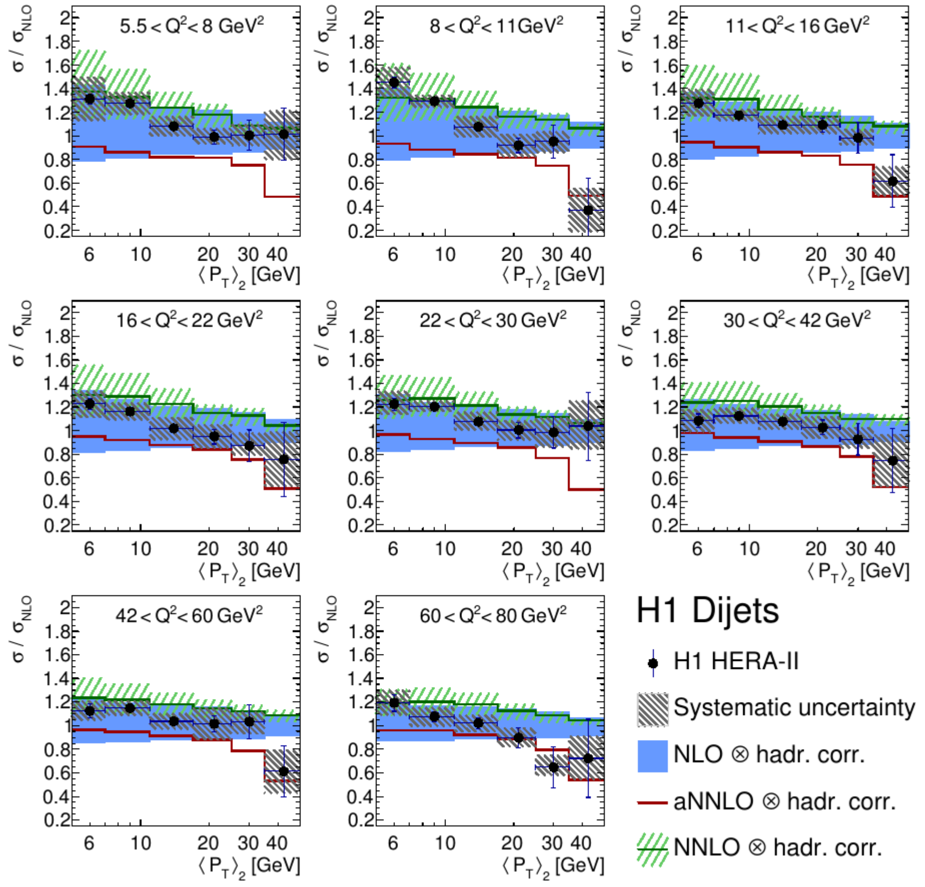
Normalised dijets

Normalised 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 NLO and <u>NNLO</u> predictions

- NLO give reasonable descriptions within large scale uncertainties ('6-point' variation)
- NNLO improves shape dependence
- NNLO slightly overshoots data -> partially caused by normalisation w.r.t. NC DIS
- high-pT region difficult to describe



Inclusive jet cross sections

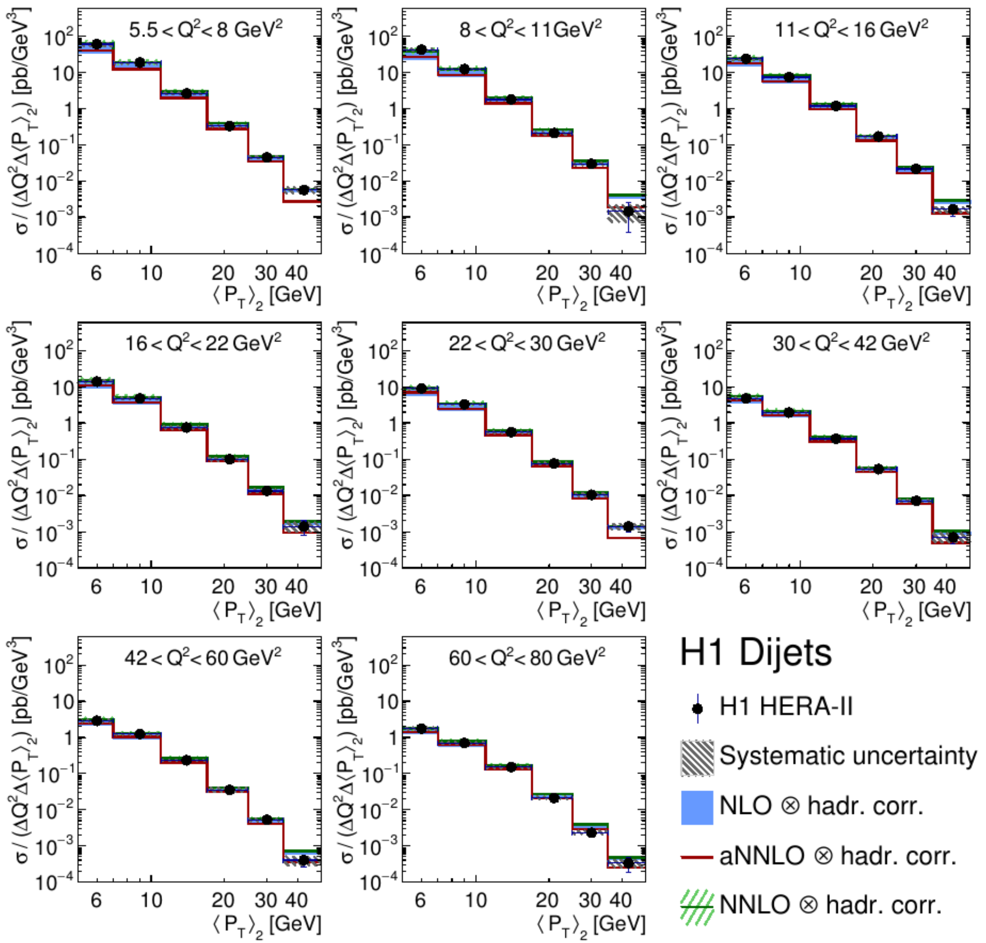
Double-differential inclusive jet cross sections as function of Q^2 and p_T^{jet}

Inclusive jets

- Count each jet in an NC DIS event
- Stat. uncertainty and correlations are measured
- Well described by NLO

Compared to H1 HERA-I

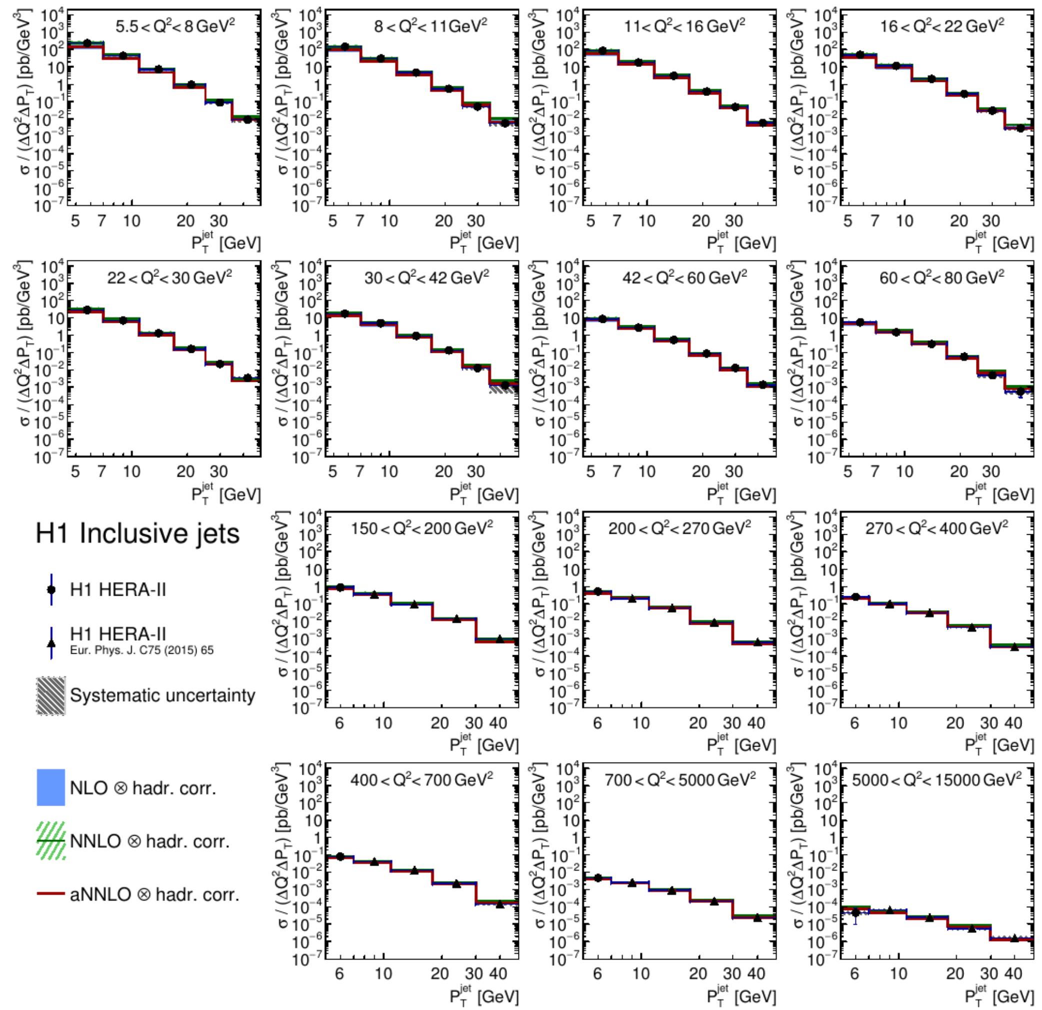
- Largely independent measurement
- HERA-II data with comparable precision
- Benefit from refined experimental methods
- Statistical uncertainty reduced for high P_T and high Q^2



Inclusive jets production in NC DIS

'Normalised' jet cross sections

- H1prelim-16-062
- Normalise jet cross sections w.r.t. inclusive NC DIS cross section
  - Full/partial cancellation of uncertainties



<u>New Data</u>

HERA-II low-Q^2

HERA-II high-Q^2, $5 < p_T < 7$GeV

Inclusive jets for major part of HERA NC DIS phase space

<u>New predictions</u>

aNNLO from JetViP

- Approximate NNLO using threshold resummation
  PR D 92 (2015) 074037 & work in progress

NNLO

- Full NNLO
  PRL 117 (2016) 042001 & work in progress
  See talk by J. Currie @ QCD@LHC2016
- Improved description of data by NNLO

Normalised Inclusive Jets

H1prelim-16-062

Detailed ratio to NLO prediction

- Data reasonably described by NLO theory, but NLO scale uncertainty large

Normalisation w.r.t. NC DIS for predictions

- NNLO & aNNLO predictions normalised with NC DIS predictions from APFEL using FONLL-C [V. Bertone et al.]
- NLO predictions normalised with ZM-VFNS using QCDNUM

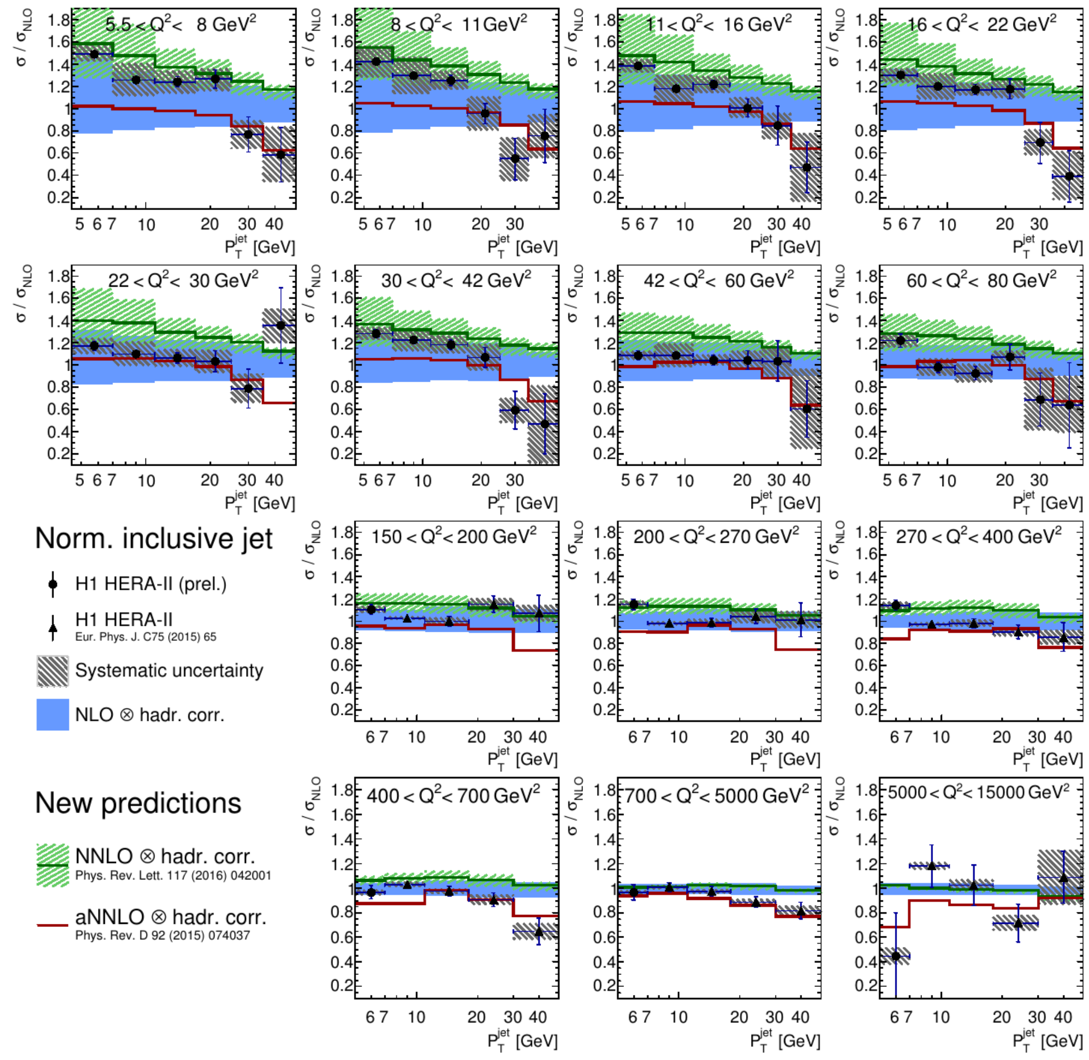
PDF: *NNPDF30_(n)nlo_0118*
Scale $\mu_r = \mu_f = (Q^2+P_T^2)/2$

aNNLO

- Improved data description at high-pT
- At low-pT aNNLO similar to NLO

NNLO

- Improved description of data by NNLO
- Significantly reduced scale uncertainty (particularly for higher scales)



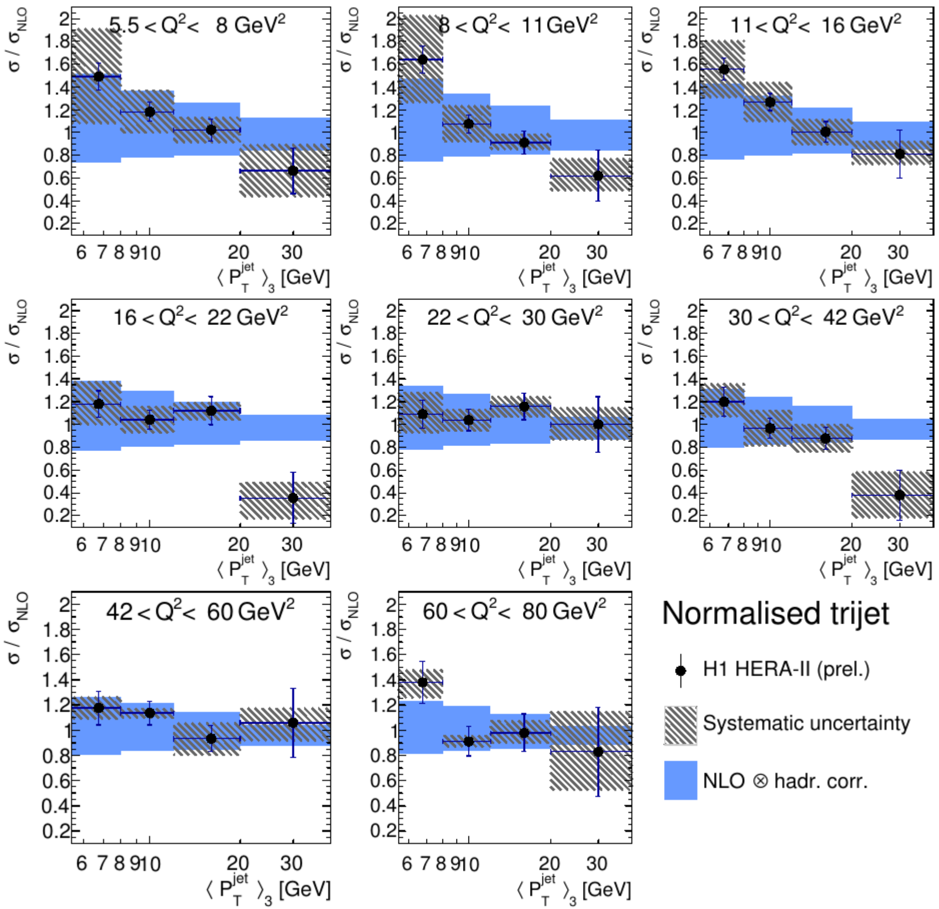
Trijet cross sections

H1prelim-16-062

Double-differential (normalised) Trijet cross sections as a function of Q^2 and $\langle p_T \rangle_3$

- Precision limited by systematic uncertainties over whole kinematic range
- 4 x 8 data points
  -> Excellent measurement of shape and dependence
- dominated by: Jet energy scale and model uncertainty
- Data precision overshoots NLO precision
- NLO has similar problems in describing the shape at low-Q2 as for dijet cross sections

No NNLO calculations available yet



History and Outlook

Eur.Phys.J.C65 (2010) 363
Eur.Phys.J.C67 (2010) 1
Eur.Phys.J.C75 (2015) 2
H1prelim-16-061 & H1prelim-16-062

Last missing piece of H1 jet legacy

Process		HERA-I	HERA-II
Low Q^2	Inclusive jet Dijet Trijet	EPJ C 67 (2010) 1	H1prelim 16-061 H1prelim 16-062
High Q^2	Inclusive jet Dijet Trijet	EPJ C 65 (2010) 363	EPJ C 75 (2015) 2

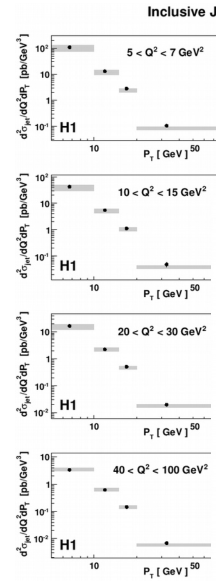
Probe running of α_s over one order of magnitude with all H1 jet data

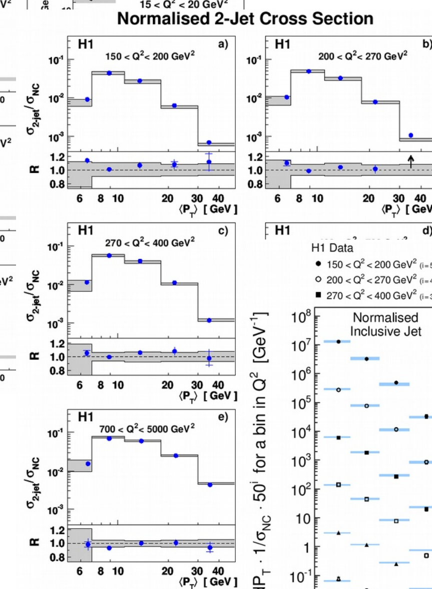
- Very high experimental precision on $\alpha_s(M_Z)$

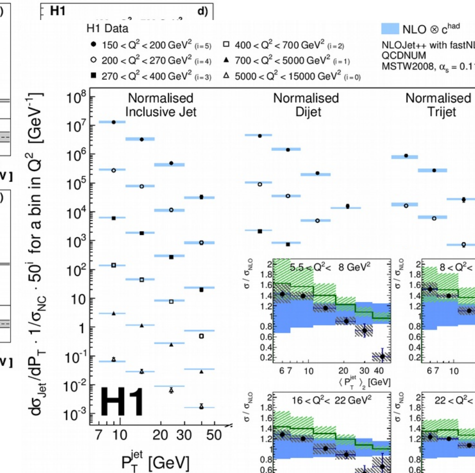
Contrain PDFs with H1 jet data

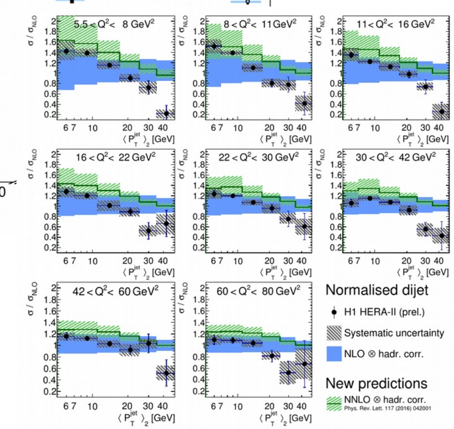
- Very high sensitivy to gluon density
  Particularly at low μ_f

HERA-I and HERA-II data can be used together for PDF fits









Finally we arrived: High-precision jet data and NNLO calculations

Backup

Predictions	**NLO**	**aNNLO**	**NNLO**
Jet cross sections			
Program	nlojet++	JetViP	NNLOJET
pQCD order	NLO [8]	approximate NNLO [12]	NNLO [15]
Calculation detail	Dipole subtraction	NLO plus NNLO contributions from unified threshold resummation formalism	Antenna subtraction
NC DIS cross sections			
Program	QCDNUM	APFEL	APFEL
Heavy quark scheme	ZM-VFNS	FONLL-C	FONLL-C
Order	NLO	NNLO	NNLO
PDF	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	✓		

Table 2: Summary of the theory predictions for the normalised jet cross sections. All predictions are corrected for hadronisation effects with multiplicative corrections factors obtained from Djangoh and Rapgap.

The H1 experiment

H1 multi-purpose detector

Asymmetric design

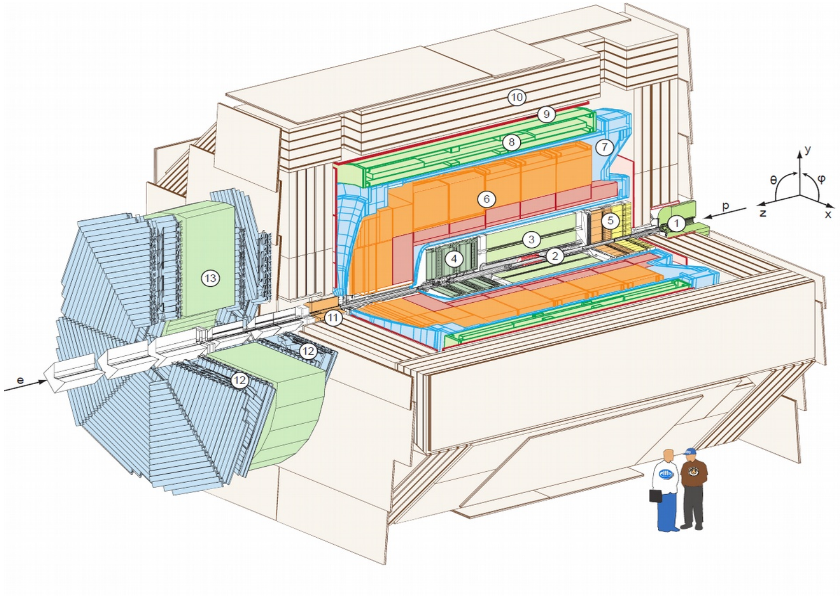
Trackers
- Silicon tracker
- Jet chambers
- Proportional chambers

Calorimeters
- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid
- 1.15T magnetic field

Muon detectors

Drawing of the H1 experiment



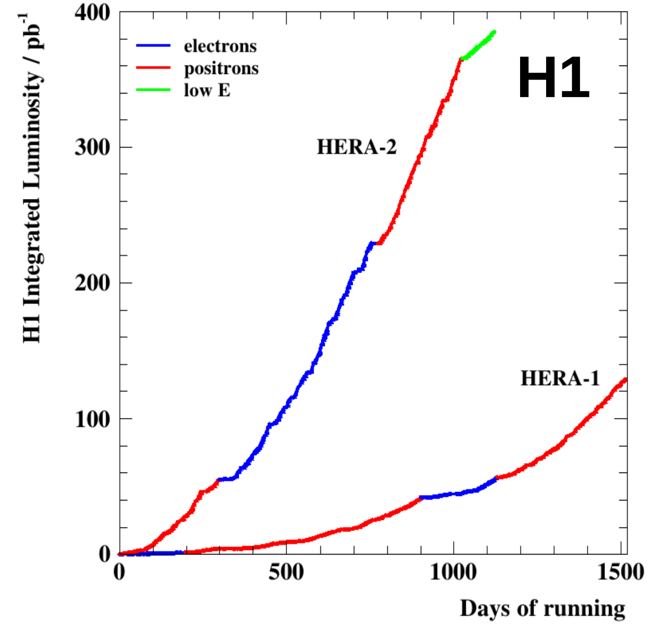
Excellent control over experimental uncertainties

- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet-calibration with neural networks as functions of η and p_T
  - Jet energy scale: 1%
- Luminosity: 2.5%

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
  - Special runs with reduced E_p in 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 = 184 pb^{-1}