Measurement of Jet Cross Sections in Deep-inelastic Scattering at HERA and Extraction of α_s at NNLO

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for the H1 Collaboration together with
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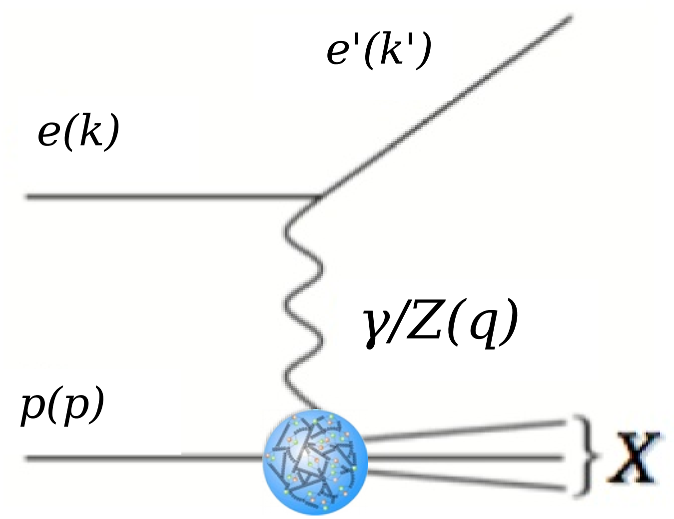
Deep-inelastic *ep* scattering

Neutral current scattering (NC)

$ep \to e'X$



Kinematic variables

Photon virtuality

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

Inelasticity

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

HERA *ep* collider in Hamburg

Data taking periods

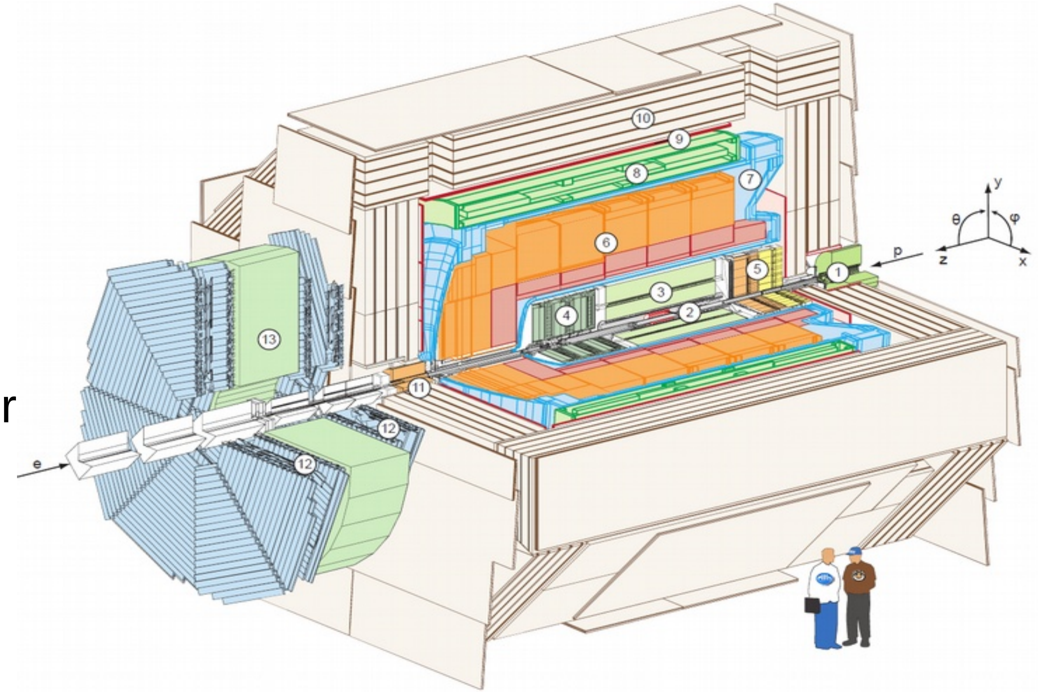
- HERA I: 1994 – 2000
- HERA II: 2003 – 2007

- $\sqrt{s}$ = 300 or 319 GeV

H1 Experiment at HERA

H1 multi-purpose detector

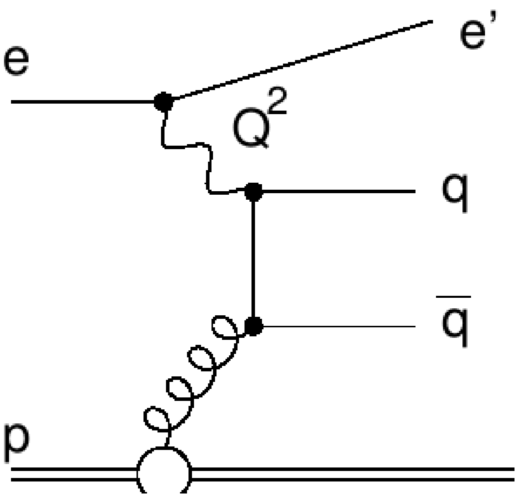
- Asymmetric design
- Trackers:
  - silicon tracker, jet chambers, proportional chambers, ...
- Calorimeters
  - Liquid Argon sampling calorimeter
  - SpaCal: scintillating fiber calorimeter
- Superconducting magnet: 1.15T
- Muon detectors

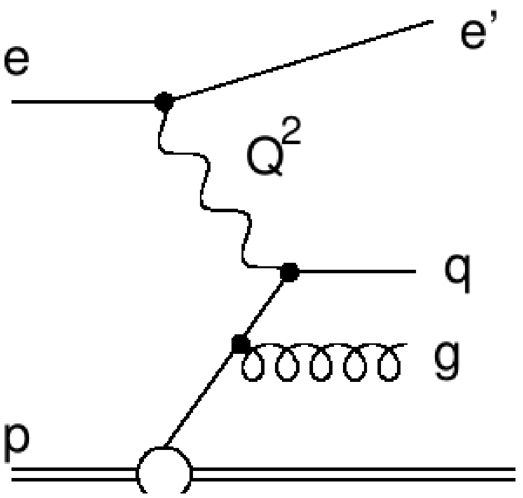


Excellent experimental precision

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

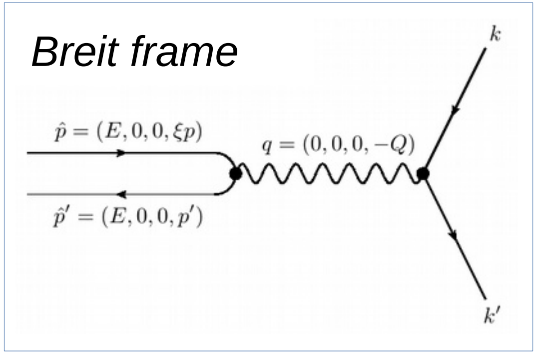
Jet production in *ep* scattering





Jet measurements are performed in Breit reference frame

- Virtual boson collides 'head-on' with parton from proton

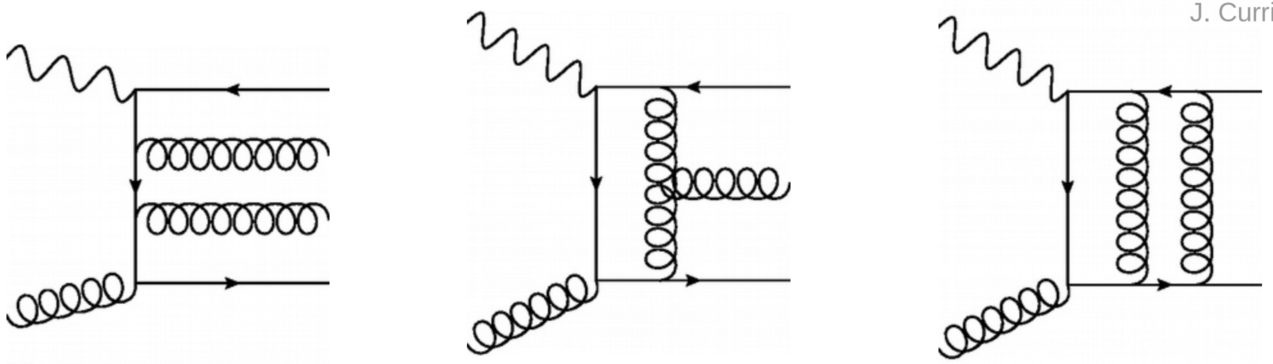


Jet measurements directly sensitive

- to α_s already at leading-order
- to gluon content of proton
- Trijet measurement at $O(\alpha_s^2)$ in leading-order

DIS jet production in NNLO

J. Curie, et al. [RPL 117 (2016) 042001]
J. Curie, et al. [arXiv:1703.05977]



Double-real Real-virtual Double-virtual

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

A bit of history

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
  [Phys. Rev. D49 (1994) 3291]
- 2016 NNLO corrections for DIS jets
  [Phys. Rev. Lett. 117 (2016) 042001], [arXiv:1703.05977]

Antenna subtraction

- Cancellation of IR divergences with local subtraction terms
- Construction of (local) counter terms
- Move IR divergences across different phase space multiplicities

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

H1 Collaboration

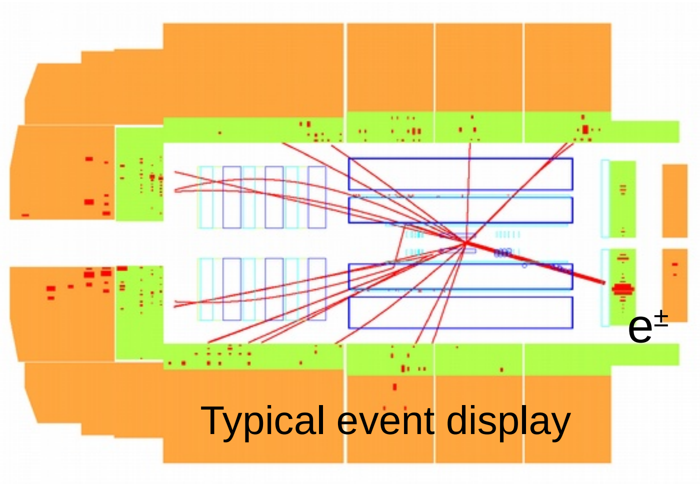
Eur.Phys.J. C77 (2017) 4, 215
[arxiv:1611.03421]

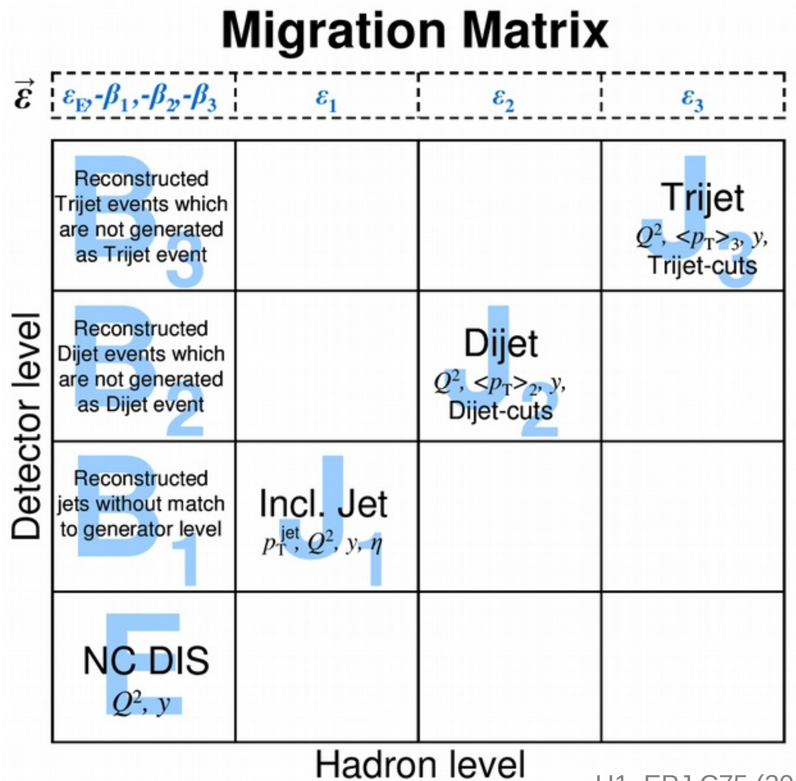
Analysis strategy and kinematic range

$5.5 < Q^2 < 80$ GeV^2
$4.5 < P_T^{jet} < 50$ GeV

Simultaneous measurement

- Inclusive jet, dijet trijet and NC DIS cross sections
- k_T jets with R=1, $-1 < \eta^{lab} < 2.5$





H1, EPJ C75 (2015) 2

Regularised unfolding optimised for accurate descripton of relevant 'migrations'

- 'extended phase space'
- Account for statistical correlations
- Matrix: 3381 x 12800 elements

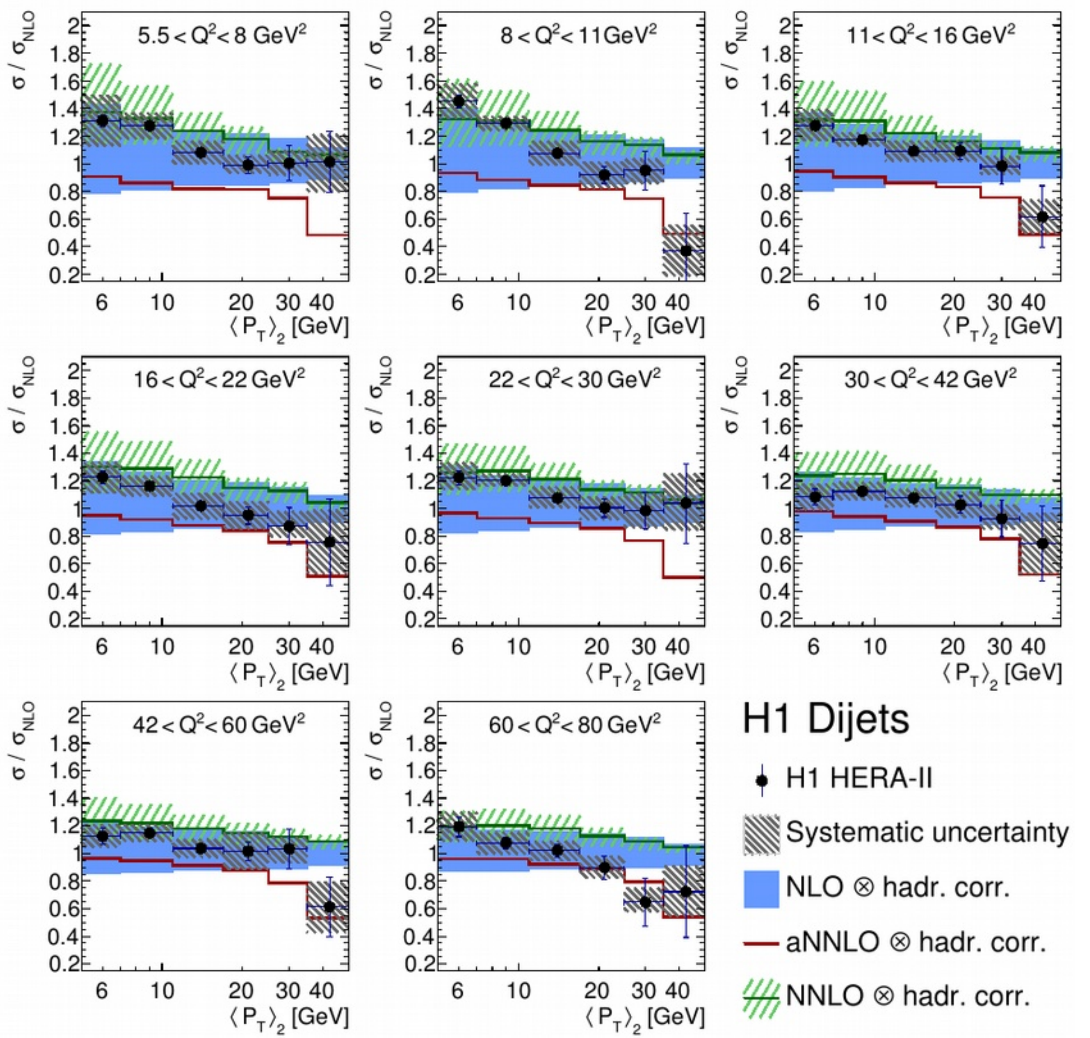
Dijet cross sections

Dijet cross sections
- as a function of Q^2 and $\langle p_T \rangle_2$
- $\langle P_T \rangle_2 = (P_T^{jet1} + P_T^{jet2})/2$
  with: $P_T^{jet} > 4$ GeV
- Ratio to NLO predictions shown

NLO *(nlojet++, NNPDF30_nlo)*
- reasonable description
- large scale uncertainties

approximate NNLO *(JetVip, NNPDF30_nnlo)*
- improved shape description

NNLO *(NNLOJET, NNPDF30_nnlo)*
- good description data
- NNLO predictions with reduced scale uncertainties than NLO



Inclusive jet cross sections

Inclusive jet cross sections

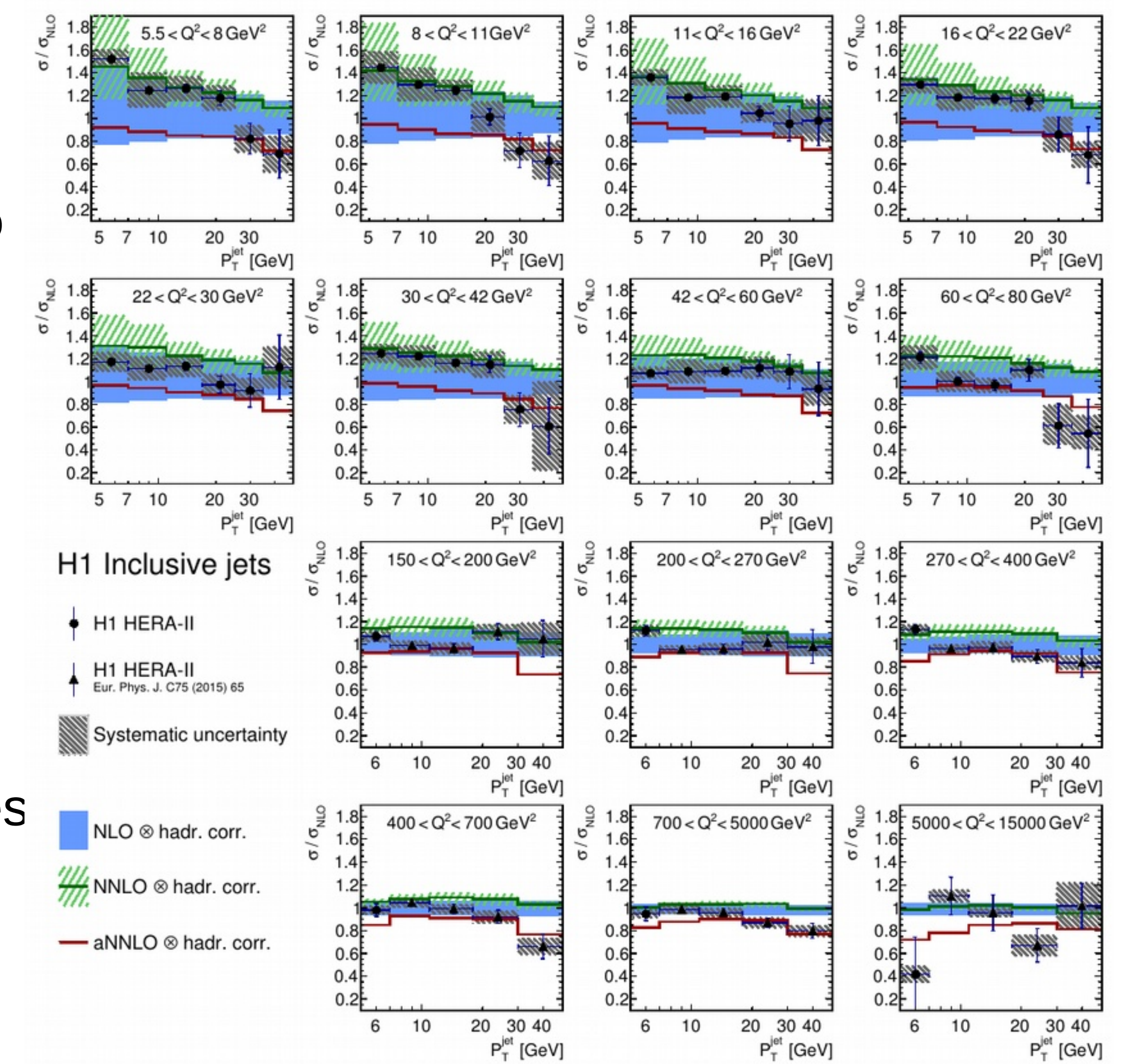
- low Q^2: $4.5 < P_T < 50$ GeV (new!)
- high Q^2: $5 < P_T < 7$ GeV (new!)
- high Q^2: $7 < P_T < 50$ GeV (EPJ C75 (2015) 2, 65)

- NLO with reasonable description within (scale) uncertainties
- aNNLO with somewhat improved shape

NNLO predictions

- NNLO provides improved shape and normalisation description
- NNLO with reduced scale uncertainties

Also normalised (inclusive) jet cross sections measured -> see backup

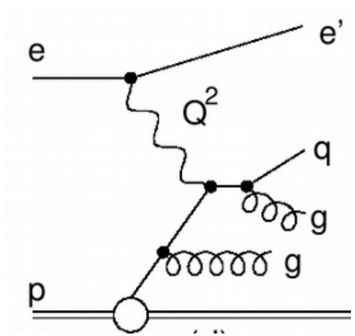


Trijet cross sections

Trijet cross sections

- Leading order $O(\alpha_s^2)$
- No NNLO predictions available yet

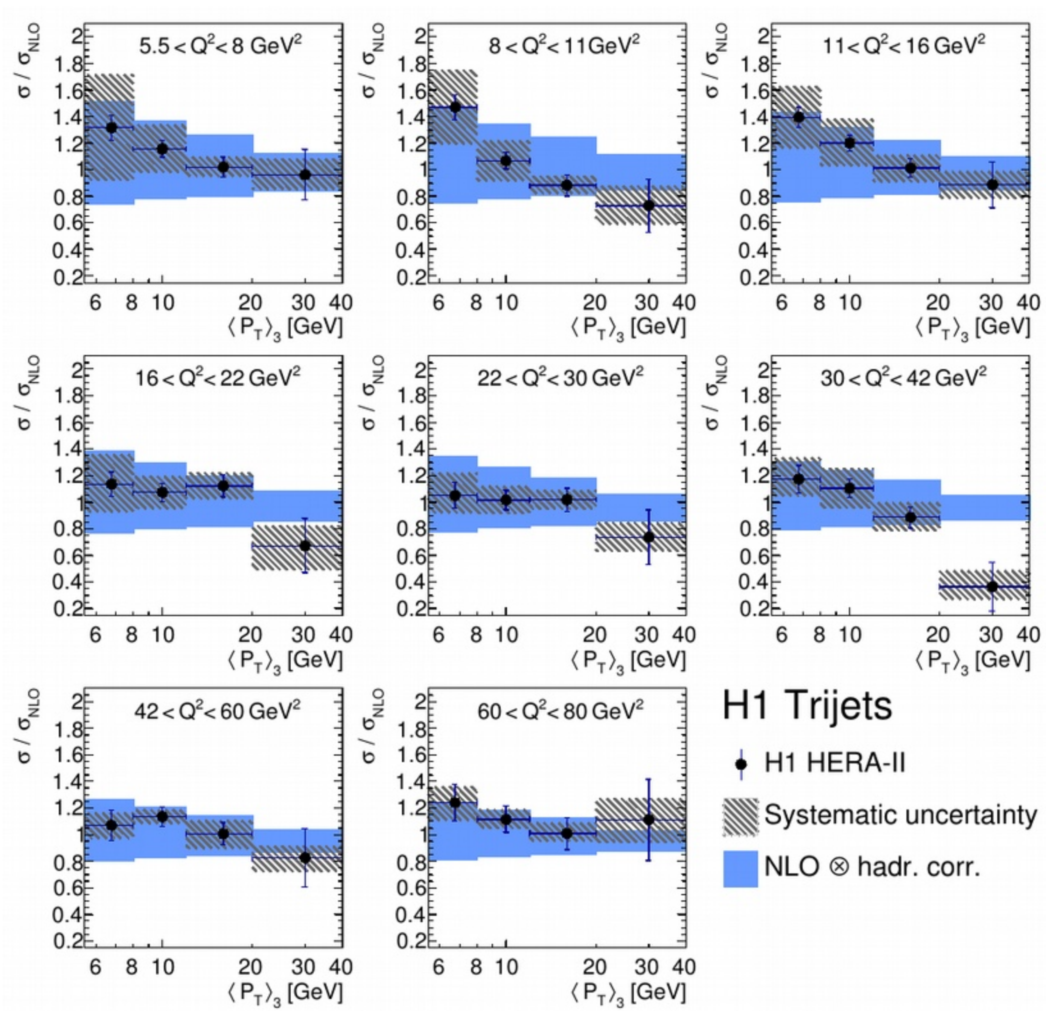
Example for LO matrix element



- Data well described by NLO (nlojet++)
- Data typically with smaller uncertainties than NLO theory

- Similar trend as dijets
  - low scales: NLO undershoots data
  - high $\langle P_T \rangle$: NLO overshoots data

- Normalised trijets also measured



Determination of $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements

H1prelim-17-031

H1 Collaboration together with
V. Bertone, J. Currie, C. Gwenlan, T. Gehrmann, A. Huss, J. Niehues, M. Sutton

[available at *https://www-h1.desy.de/publications/H1preliminary.short_list.html*]

Why α_s?

***Strong coupling α_s** enters in the calculation of every process that involves the strong interaction*

PDG world average (2016)

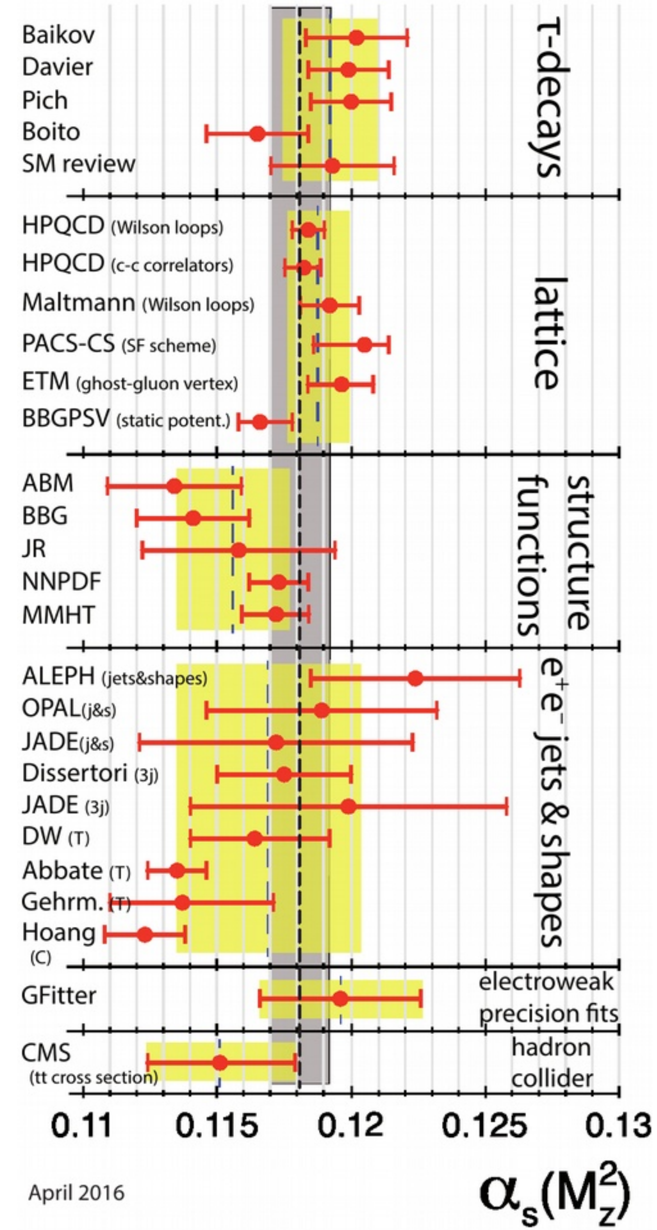
- $\alpha_s(m_Z) = 0.1181 \pm 0.0011$ [PDG2016]
- ~0.9% relative uncertainty

Uncertainty on α_s

- Important for precision phenomenology
- Notable examples: Higgs production cross sections, branching ratios

Jet measurements

- Direct constraint on α_s
- So far no NNLO results available



Inclusive jet and dijet cross sections at H1

Inclusive jet cross sections

- Measurements at HERA-I & HERA-II
- low-Q^2 and high-Q^2
- Differerent $\sqrt{s}$

Dijet cross sections

- as a function of Q^2 and $\langle p_T \rangle_2$
- HERA-I & HERA-II
- low-Q^2 and high-Q^2
- Different $\sqrt{s}$

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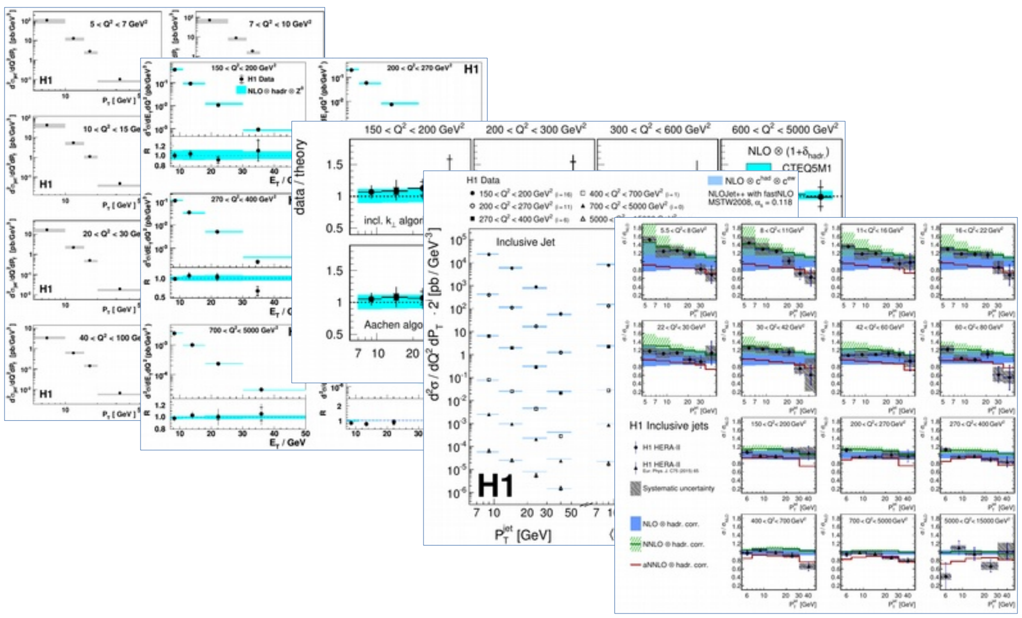
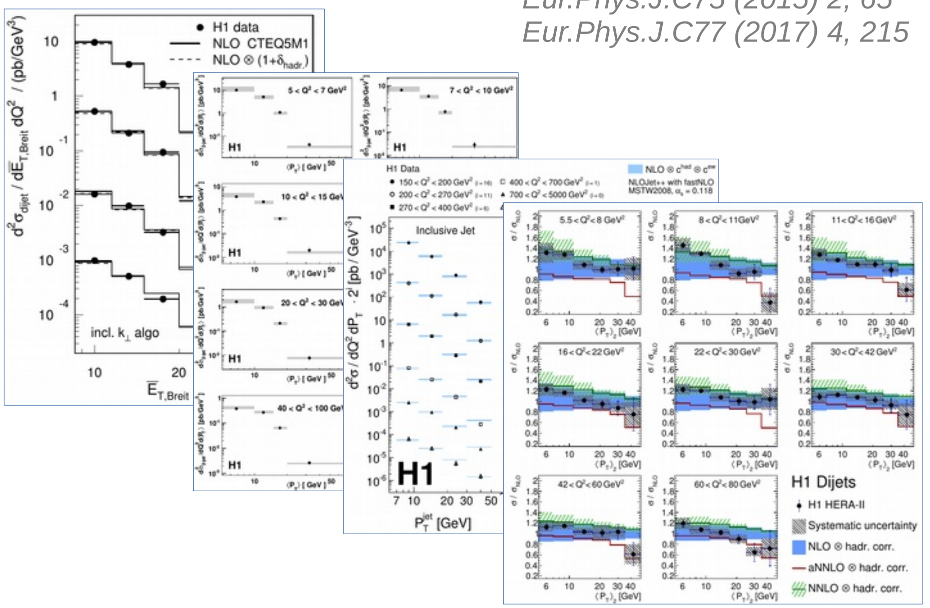




All H1 inclusive jet and dijet data is employed for α_s determination in NNLO

$\alpha_s(m_Z)$ dependence of cross sections

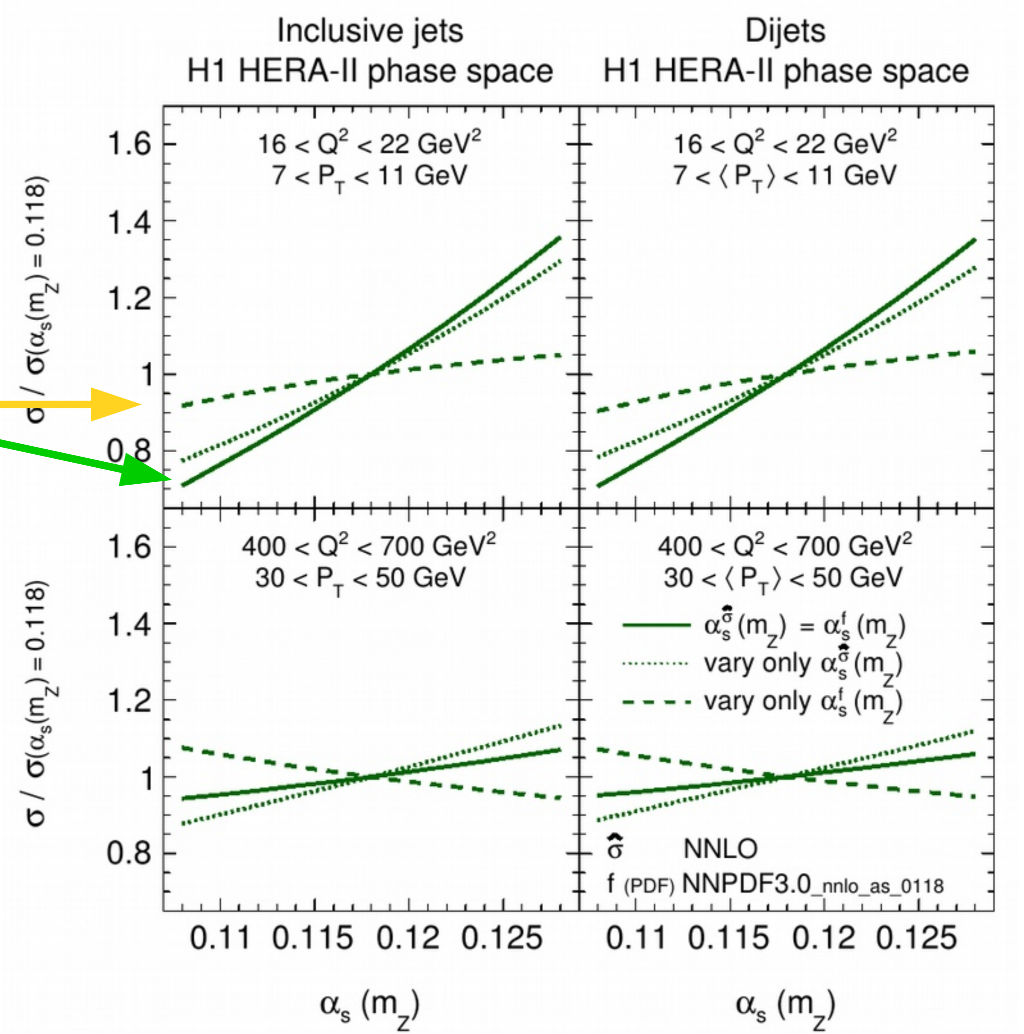
Jet cross sections directly sensitive to α_s

$$\sigma_i = \sum_{n=1}^{\infty} \sum_{k=g,q,\bar{q}} \int dx\, f_k(x, \mu_F) \hat{\sigma}_{i,k}^{(n)}(x, \mu_R, \mu_F) \cdot c_{\text{had}}$$

- *Two α_s-dependencies*

PDFs $\frac{\partial f}{\partial \alpha_s} = \frac{\mathcal{P} \otimes f}{\beta}$

Hard ME's
$\hat{\sigma}_{i,k}^{(n)} = \alpha_s^n(\mu_R) \tilde{\sigma}_{i,k}^{(n)}(x, \mu_R, \mu_F)$



At lower scales
- *Predominant α_s-sensitivity from hard coefficients*
- *PDF's provide increased sensitivity*

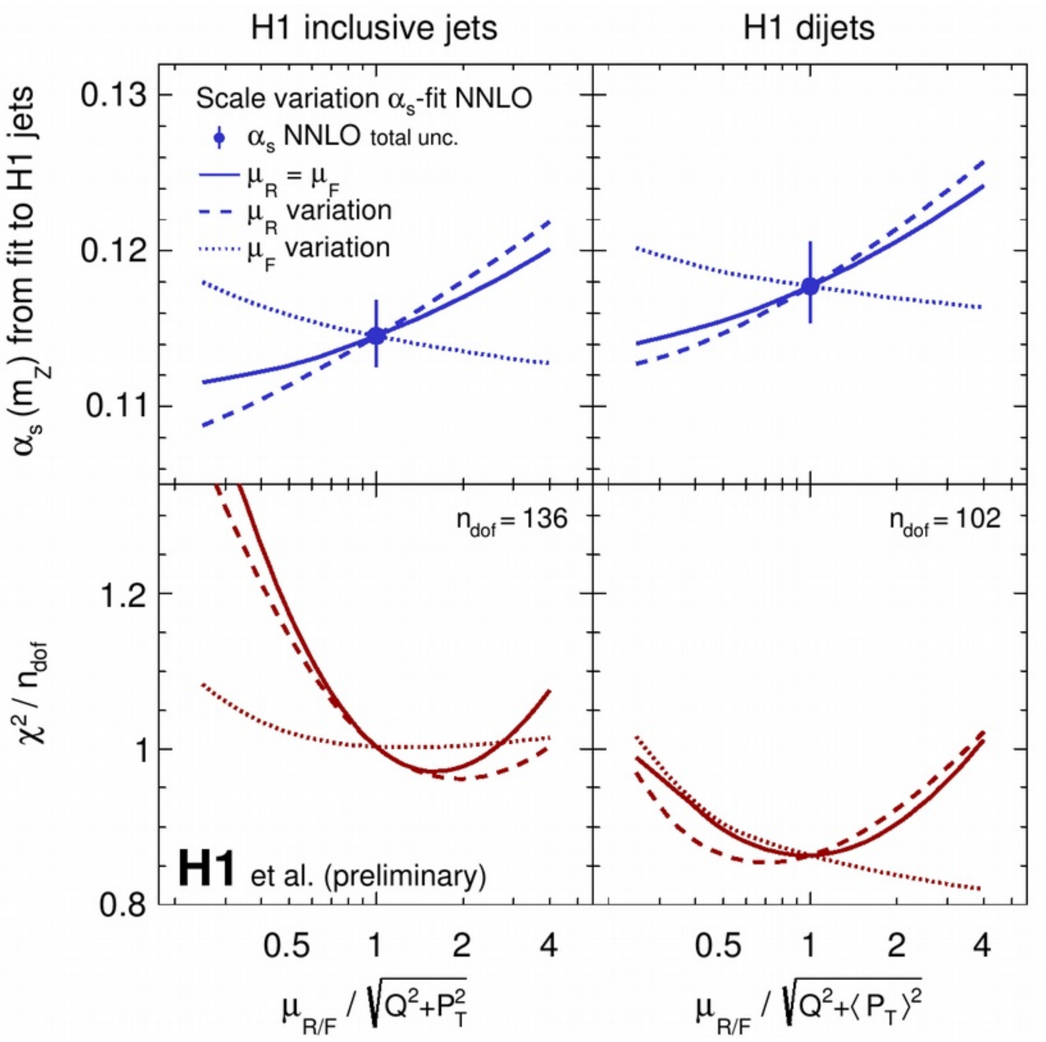
At higher scales
- *opposite dependence for hard coefficents and PDFs*

Scale dependence of α_s fit

- α_s results as a function of scale factors to nominal scale

$$\mu_R^2 = \mu_F^2 = Q^2 + P_T^2$$

- μ_r variation with more impact than μ_f
- χ^2 values as a technical parameter
  -> not intended to be a parabolas
- χ^2 values increase for large scale factors
  -> large scale factors disvafored
  -> A-priori chosen scale appears to be reasonable



Scale choice for α_s fit

- Study various definition for scales (μ_r, μ_f) built from Q^2 and p_T
  p_T denotes: p_T^{jet} or $\langle p_T \rangle$

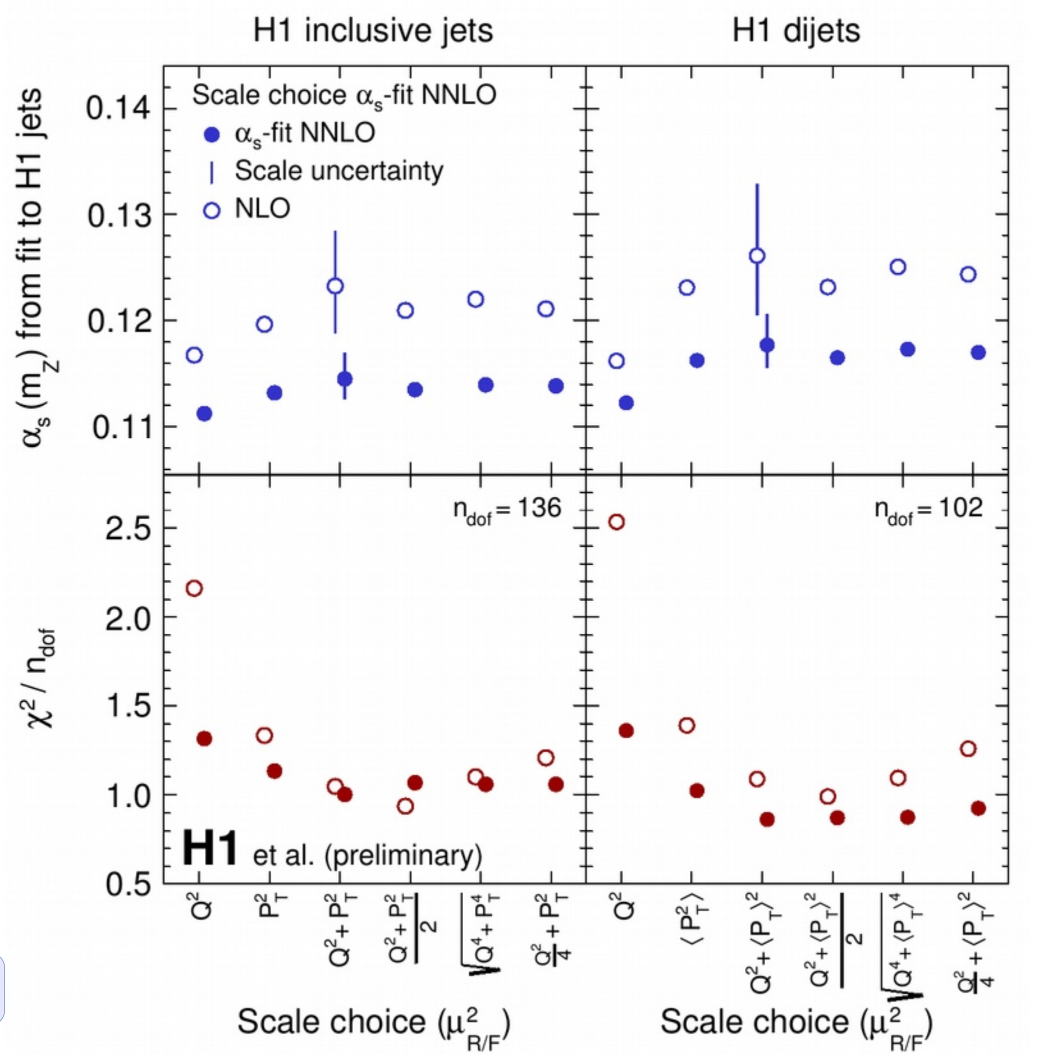
α_s results and χ^2 values

- Spread of results covered by scale uncertainty (variation by 0.5 & 2)
- χ^2 values are all reasonable for different choices

NLO vs. NNLO

- Reduced scale uncertainty in NNLO
- NNLO with reduced scale-dependence of α_s and χ^2 values
- NLO with larger χ^2 values

NNLO with reduced scale dependence



Strong coupling in NNLO from H1 jets

Uncertainty breakdown includes

- Experimental and hadronisation uncertainty
- Scale uncertainties (factors: 0.5, 2)
- (various) PDF uncertainties

α_s results from individual data sets

- High experimental precision
- All fits with good χ^2
  -> consistency of data

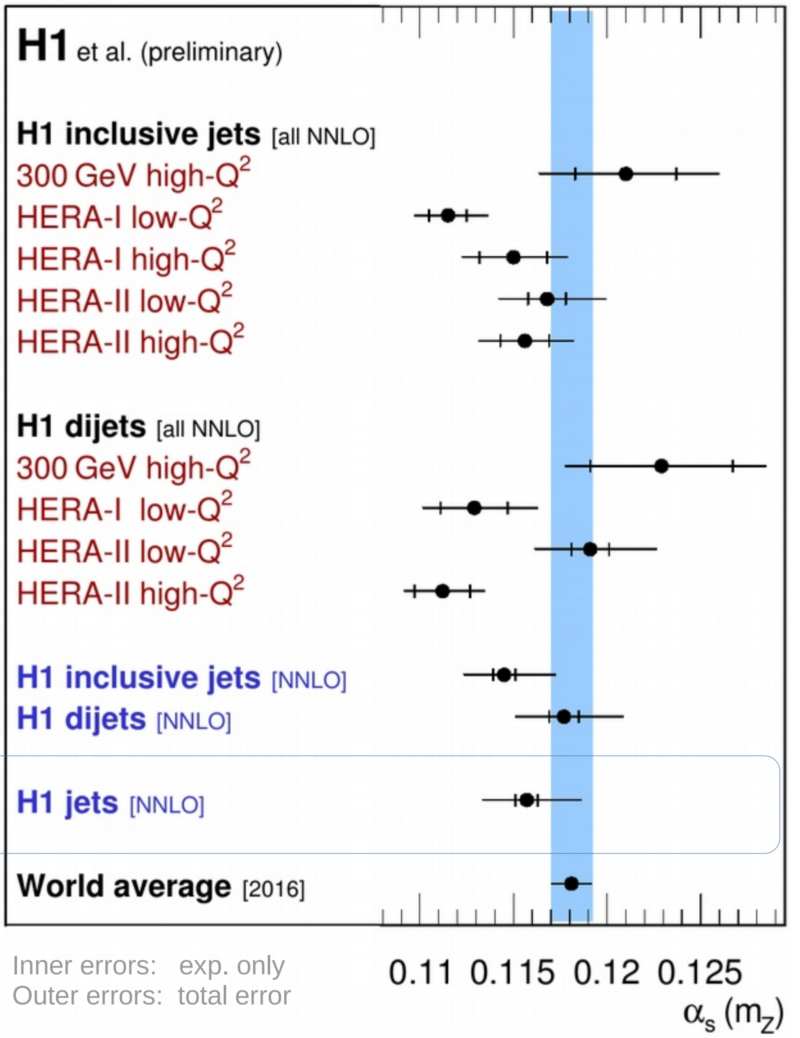
'H1 jets'

- Inclusive jet and dijet data taken together
- 203 data points

$$\alpha_s(M_Z) = 0.1157\,(6)_{\rm exp}\,(3)_{\rm had}\,(6)_{\rm PDF}\,(12)_{{\rm PDF}\alpha_s}\,(2)_{\rm PDFset}\,(^{+27}_{-21})_{\rm scale}$$

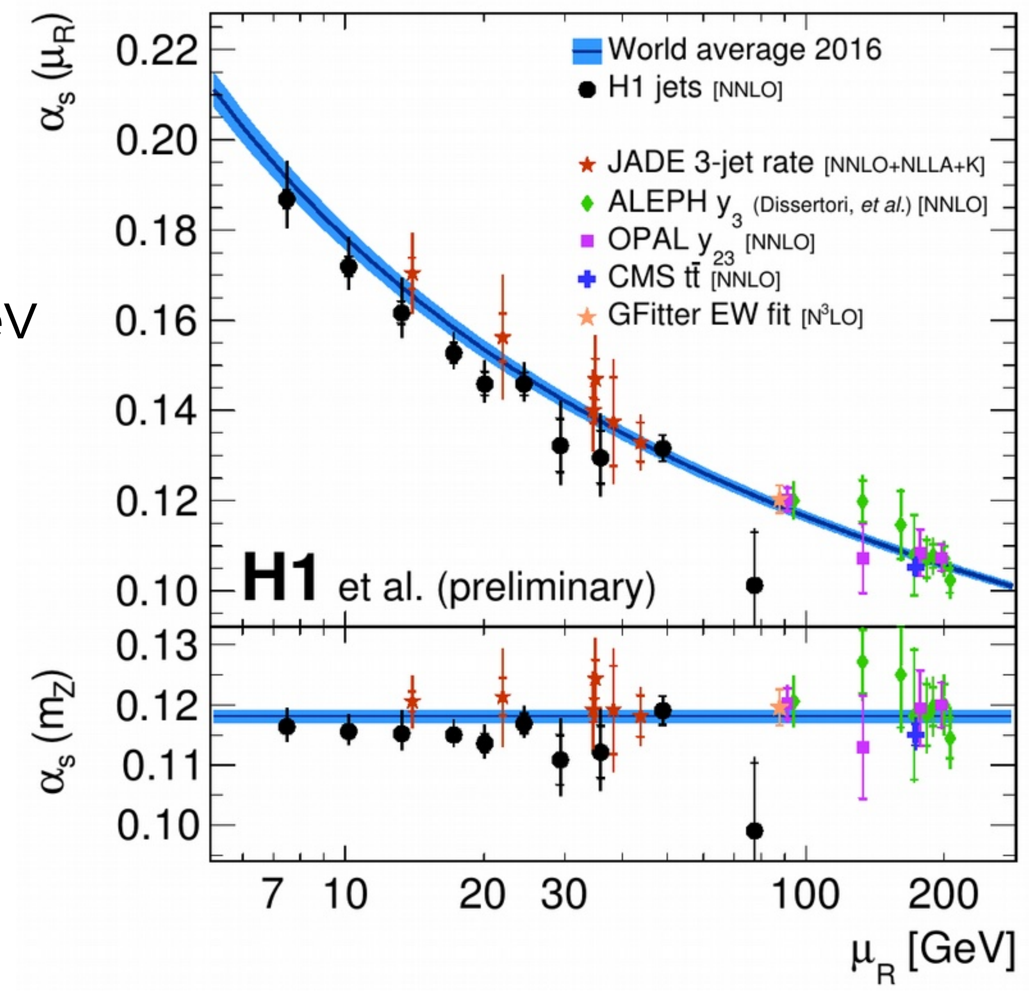
- High exp. precision
- Scale uncertainty dominates
- PDF uncertainties sizeable

$$\chi^2/n_{\rm dof} = 1.03$$



Test running of strong coupling in NNLO

- Repeat fits to groups of data points
- Theory uncertainty often larger than experimental uncertainty
- Confirmation of 'running' between 7–90 GeV
- Consistency with other extractions and with other processes
- Scale uncertainty is largest uncertainty for most intervals
- NNLO with small scale uncertainty (also) at lower scales



Summary

New measurement of jet cross sections in NC DIS *[EPJ C77 (2017) 4, 215]*

- *Inclusive jet, dijet and trijet cross sections*
- *Normalised jet cross sections with reduced experimental uncertainty*
- *Data well described by (new) NNLO predictions*
- *NNLO corrections are important at lower scales*

Strong coupling constant determined in NNLO *[H1prelim-17-031]*

- *Explore all H1 inclusive jet and dijet cross section measurements (1995 – 2007)*

$$\alpha_{\mathrm{s}}(m_{\mathrm{Z}}) = 0.1157(6)_{\mathrm{exp}}(^{+31}_{-26})_{\mathrm{theo}}$$

- *High experimental precision & competitive theoretical precision*
- *Probe running of α_s over one order of magnitude with H1 jet data*
- *https://www-h1.desy.de/publications/H1preliminary.short_list.html*
  Preprint ready in 5-7 weeks

H1 in collaboration with
V. Bertone, J. Currie, T. Gehrmann,
C. Gwenlan, A. Huss, J. Niehues, M. Sutton

Precision QCD phenomenology with jets in NNLO accuracy

- *Fruitful collaboration of theoreticians and experimentalists*

Fit methodology

α_s from χ_2-minimisation

- $\alpha_s(m_Z)$ is a free parameter to NNLO theory prediction σ_i
- χ^2 calculated as: (ς=Data, σ_i=NNLO, V=covariance matrices)

$$\chi^2 = \sum_{i,j} \log\frac{\varsigma_i}{\sigma_i}(V_{\rm exp} + V_{\rm had} + V_{\rm PDF})^{-1}_{ij} \log\frac{\varsigma_j}{\sigma_j}$$

Perform fits to

- All 9 individual data sets
- All 5 inclusive jet data sets (137 data points)
- All 4 dijet data sets (103 data points)
- All H1 jet data taken together (denoted as 'H1 jets')
  (exclude HERA-I dijet data as correlations to inclusive jets are not known)
- Data points at a similar scale μ
- Data points above a certain scale value μ_{min}

Additional cuts

- remove data below $\mu < 2m_b$, to avoid effects from heavy quark masses
- drop HERA-I, low-Q^2 dijets with $\langle p_T \rangle < 7$ GeV, because of IR issue

Selection of data sets

Kinematic range of H1 jet data

Data set [Ref.]	$\sqrt{s}$ [GeV]	int. $\mathcal{L}$ [pb^{-1}]	DIS kinematic range	Inclusive jets	Dijets $n_{\text{jets}} \geq 2$
300 GeV [1]	300	33	$150 < Q^2 < 5000\,\text{GeV}^2$ $0.2 < y < 0.6$	$7 < P_T^{\text{jet}} < 50\,\text{GeV}$	$P_T^{\text{jet}} > 7\,\text{GeV}$ $8.5 < \langle P_T \rangle < 35\,\text{GeV}$
HERA-I [2]	319	43.5	$5 < Q^2 < 100\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_T^{\text{jet}} < 80\,\text{GeV}$	$5 < P_T^{\text{jet}} < 50\,\text{GeV}$ $5 < \langle P_T \rangle < 80\,\text{GeV}$ $(\langle P_T \rangle > 7\,\text{GeV})^*$ $m_{12} > 18\,\text{GeV}$
HERA-I [3]	319	65.4	$150 < Q^2 < 15000\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_T^{\text{jet}} < 50\,\text{GeV}$	–
HERA-II [4]	319	290	$5.5 < Q^2 < 80\,\text{GeV}^2$ $0.2 < y < 0.6$	$4.5 < P_T^{\text{jet}} < 50\,\text{GeV}$	$P_T^{\text{jet}} > 4\,\text{GeV}$ $5 < \langle P_T \rangle < 50\,\text{GeV}$
HERA-II [5, 4]	319	351	$150 < Q^2 < 15000\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_T^{\text{jet}} < 50\,\text{GeV}$	$5 < P_T^{\text{jet}} < 50\,\text{GeV}$ $7 < \langle P_T \rangle < 50\,\text{GeV}$ $m_{12} > 16\,\text{GeV}$

Inclusive jet cross sections by H1

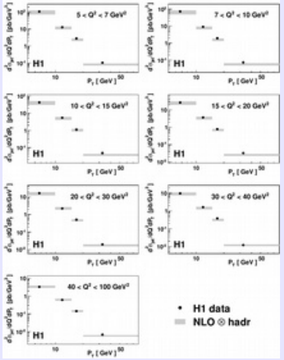
Inclusive jet cross sections

- $d\sigma/dQ^2dP_T^{jet}$
- 300 GeV, HERA-I & HERA-II
- low-Q^2 (<100 GeV^2) and high-Q^2 (>150 GeV^2) regions

Consistency

- kt-algorithm, R=1
- $-1.0 < \eta < 2.5$
- P_T ranges from 4.5 to 50 GeV

HERA-I low-Q^2



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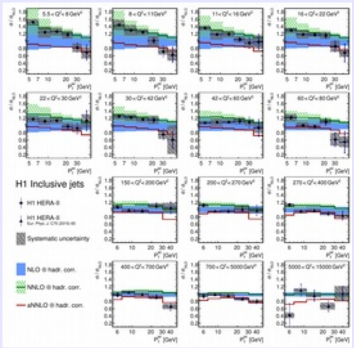
HERA-II low-Q^2



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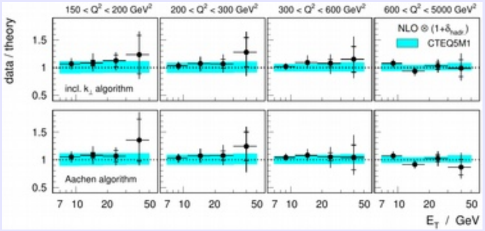
300 GeV high-Q^2



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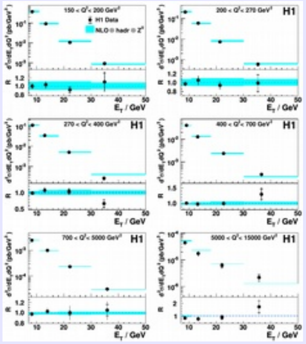
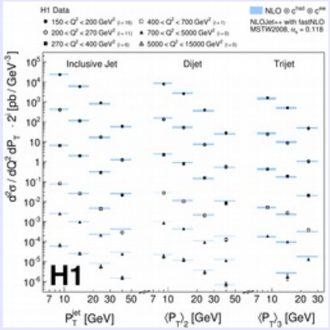
HERA-I high-Q^2



Phys.Lett.B653 (2007) 134

HERA-II high-Q^2



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arXiv:1611.03421

Dijet cross section by H1

Dijet cross sections

- $d\sigma/dQ^2 d\langle p_T \rangle$
- 300 GeV, HERA-I & HERA-II
- low-Q^2 and high-Q^2

Dijet definitions

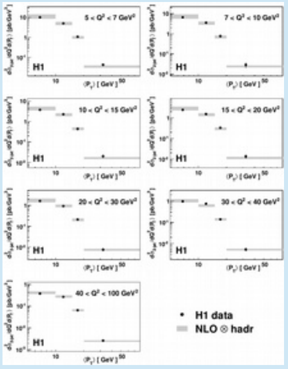
- $\langle p_T \rangle$ greater than 5,7 or 8.5 GeV
- P_T jet greater 4, 5 or 7 GeV
- Asymmetric cuts on p_T^{jet1} and p_T^{jet2}
- M_{12} cut for two data sets

Earlier studies

- All inclusive jet and dijet data have been employed for α_s extractions in NLO previously

-> Data and uncertainties well-understood
-> NNLO theory is new

HERA-I low-Q^2



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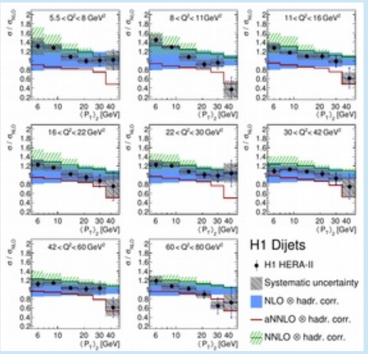
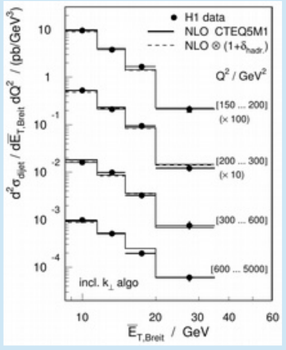
HERA-II low-Q^2



arXiv:1611.03421

300 GeV high-Q^2



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HERA-I high-Q^2

Dijet cross sections not statistically independent from HERA-II analysis

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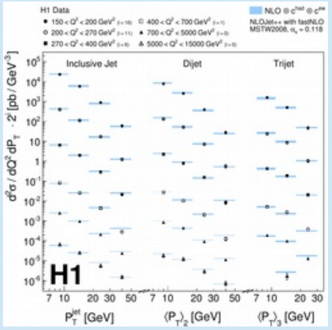
HERA-II high-Q^2



Eur.Phys.J.C75 (2015) 2

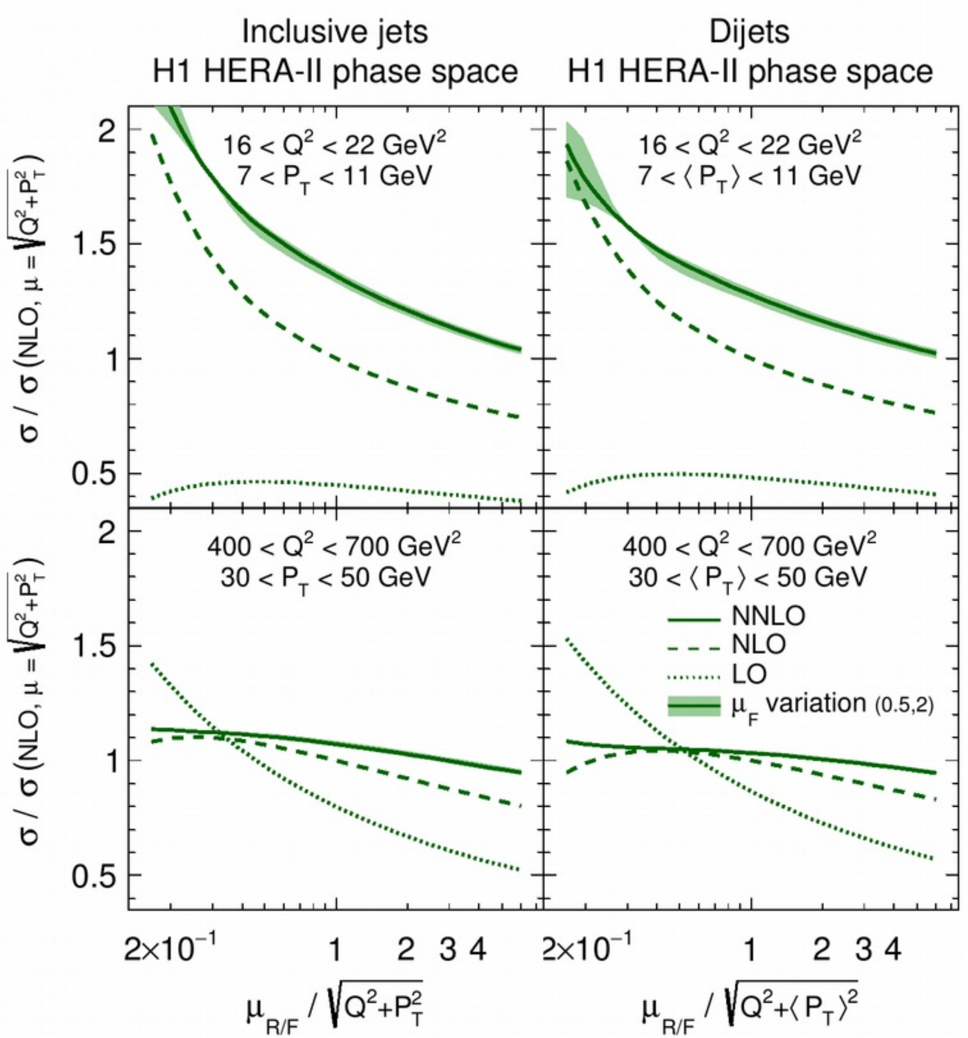
Scale dependence of NNLO cross sections

Scale dependence of NNLO cross sections

- Study simultaneous multiplicative variation of renormalisation and factorisation scale

Scale dependence

- At lower scales
  - NNLO reduced scale dependence w.r.t. NLO
  - Still relevant scale dependence in NNLO
- At higher scales
  - Scale dependence reduced w.r.t. NLO
- μ_f dependence small
- Inclusive jets with higher scale dependence than dijets at lower scales



α_s dependencies separately fitted

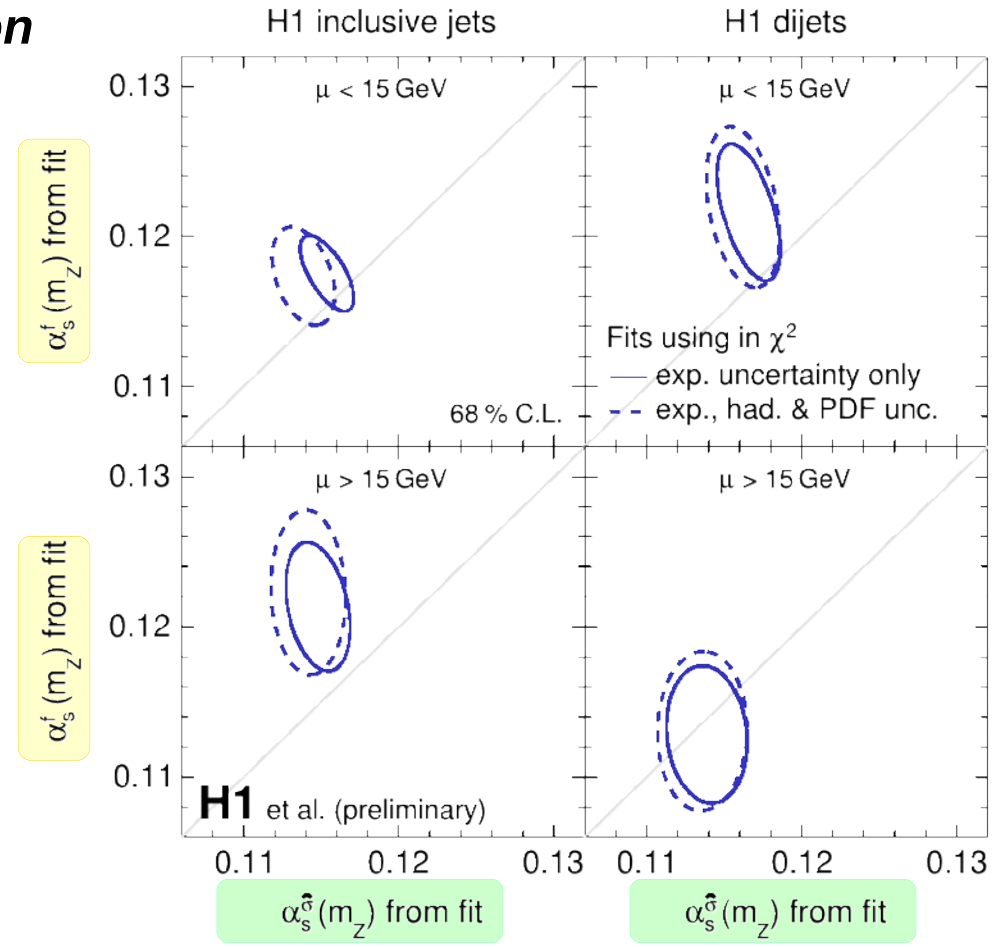
Fits with two free α_s parameters in calculation

$$\sigma_i = f(\alpha_s^f(m_Z)) \otimes \hat{\sigma}_k(\alpha_s^{\hat{\sigma}}(m_Z)) \cdot c_{\text{had}}$$

- Separate fits for low- and high-μ data points
- Fits to Inclusive jet or dijet data

Results

- Most sensitivity arises from matrix elements
- Best-fit α_s-values in PDF's and ME's are consistent
- Significant anti-correlation at lower scales -> Increased sensitivity if both α_s-values identified to be identical



Dependence on the PDF

PDF is external input NNLO calculation

Choice of PDF set

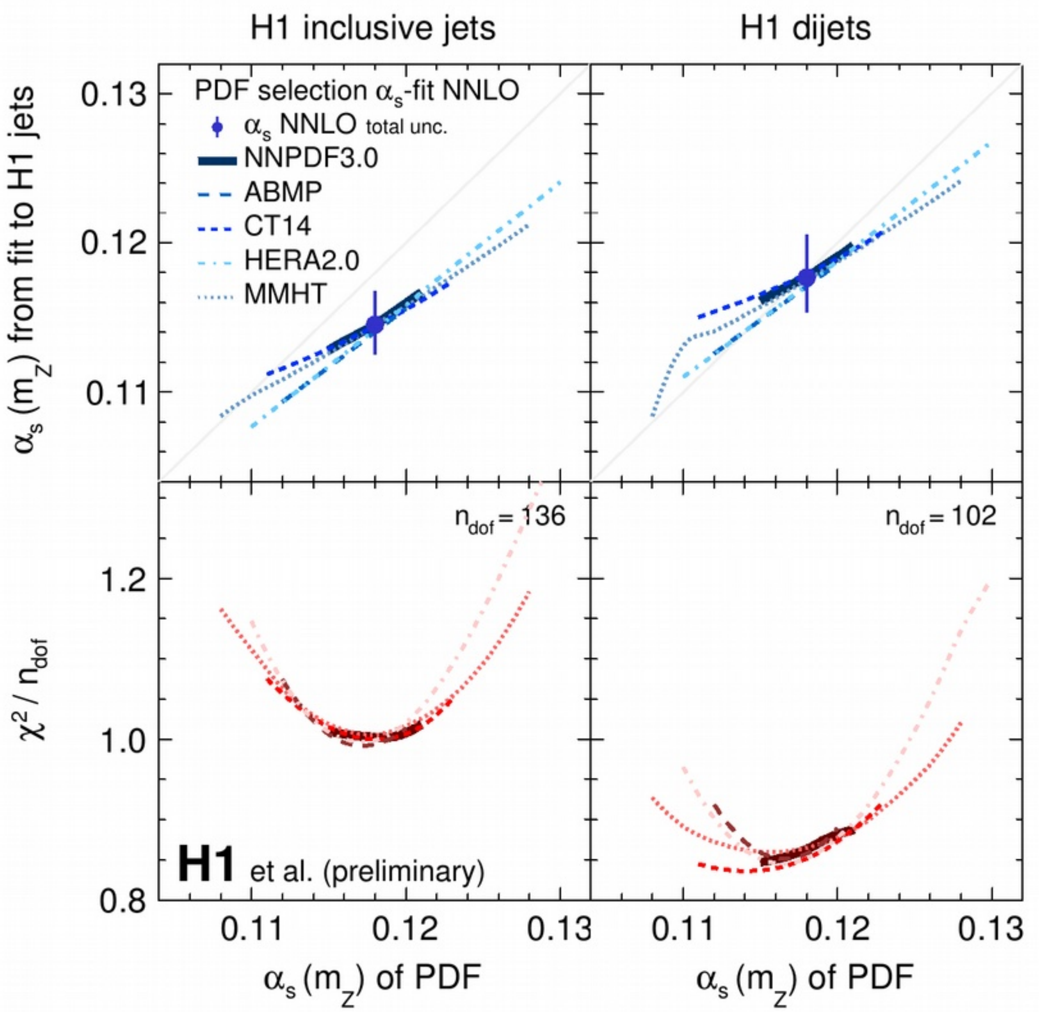
- Different PDF groups:
  different input data sets, PDF parameterisations, model parameters, fit methodology, etc...
- Different PDFs are consistent

Choice of α_s as input to PDF

- $\alpha_s(m_Z)$ important input parameter to PDF fit
- Relevant correlation with fitted results
- Differences among different PDF sets

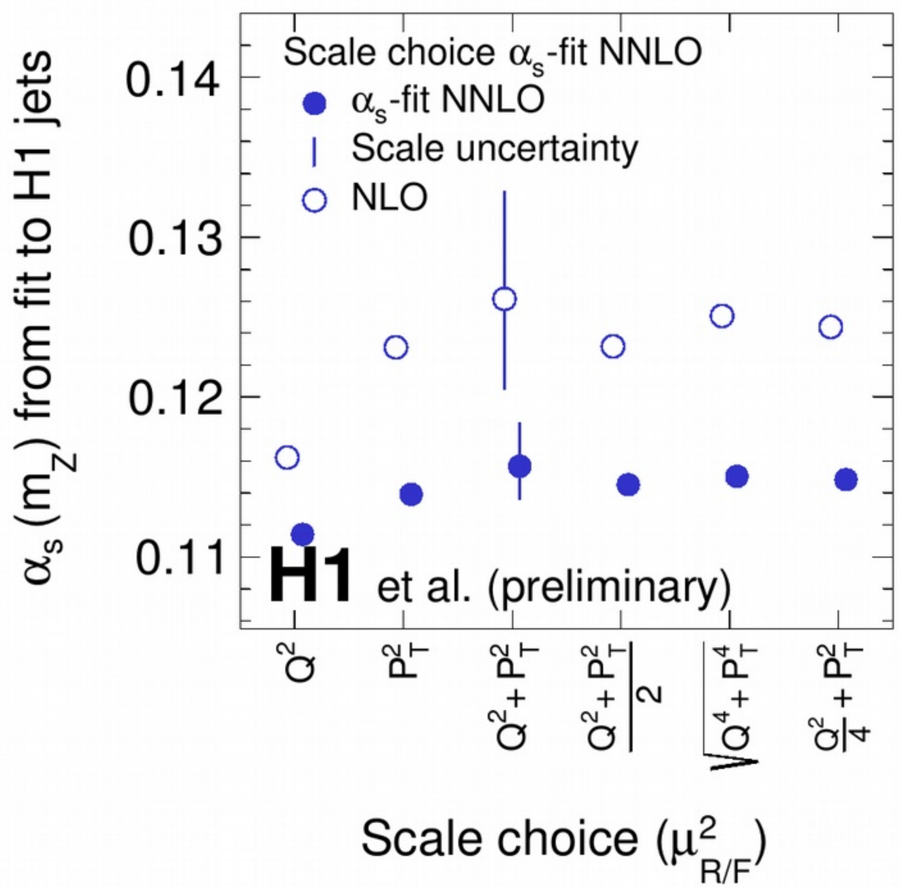
Additional PDF uncertainties on result

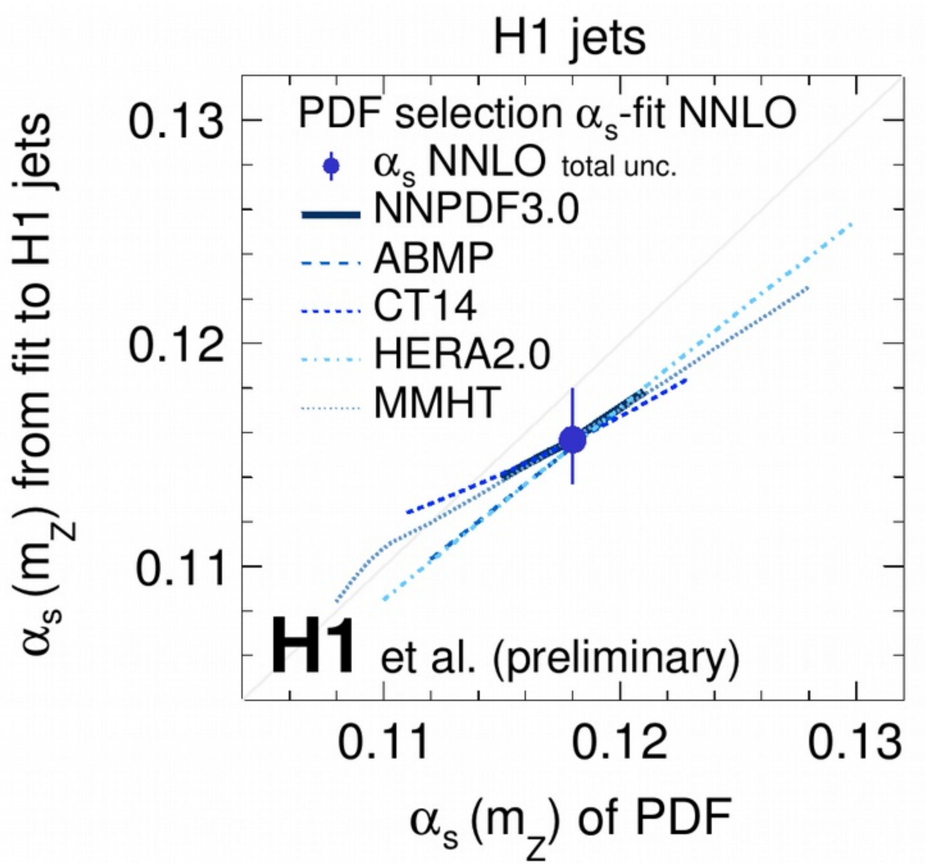
- 'PDFset': 1/2*max(Δ(all PDFs))
- 'PDFα_s': 1/2 ($\Delta\alpha_s$=0.004)



PDF dependence and scale choice

- Fits to 'H1 jets' (inclusive jets & dijet data taken together)

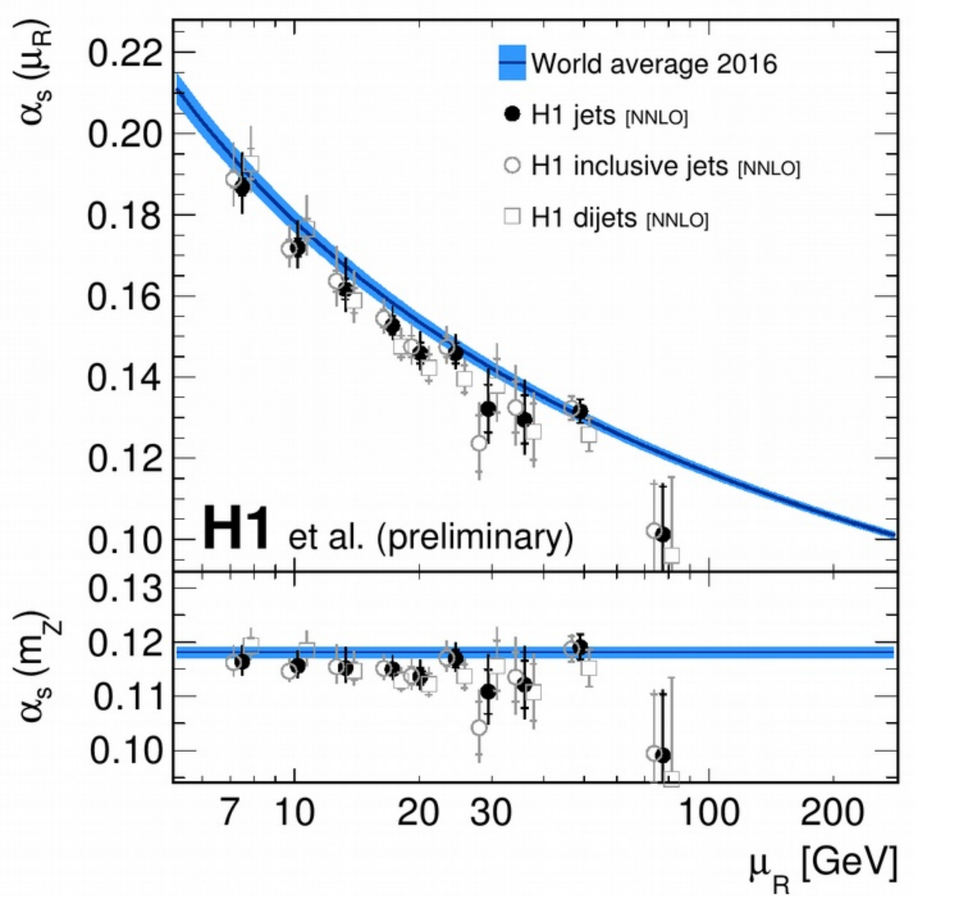




Running from inclusive jets and dijets

Test running of strong coupling

- Repeat fits to groups of data points at similar scales
- All fits with good χ^2
- Study assumes running to be valid only within limited range covered by an interval



Results

- Theory uncertainty often larger than experimental uncertainty
- Consistency of inclusive jets and dijets
- Consistency also down to lower scales (while otherwise data with $\mu<2m_B$ is excluded)
- Scale uncertainty almost 'constant' at all scales

-> NNLO with small scale uncertainty (also) at lower scales

Confirmation of 'running' between 7-90 GeV

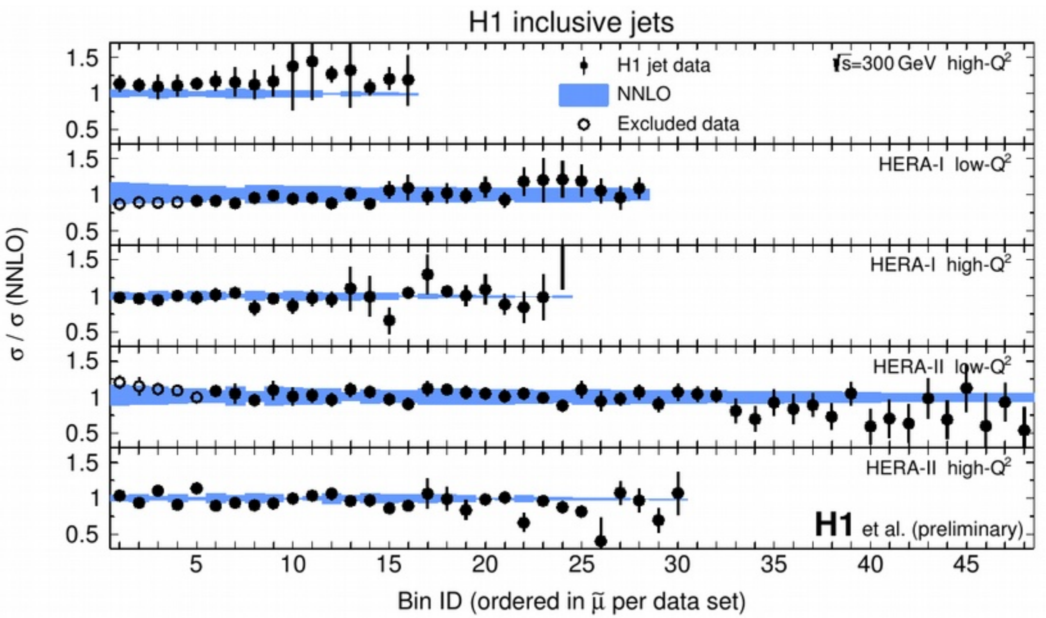
NNLO cross sections

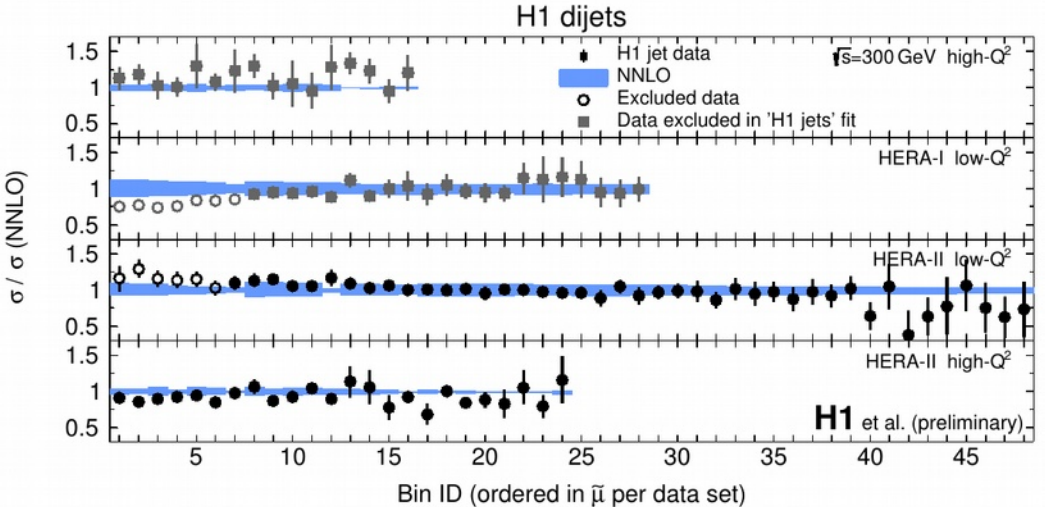
Ratio of data to NNLO predictions

- Using: $\alpha_s(m_Z) = 0.1157$
- Blue band: NNLO scale uncertianties
- Excluded data points (open symbols)
  - $\mu < 2m_b$
  - HERA-I low-Q2 dijets: 5 < <pT> < 7 GeV
    -> because of symmetric cuts
    -> Issues with NNLO

Conclusions

- Overall good agreement of NNLO predictions to H1 data
- Consistency of data
- All phase space regions in agreement with NNLO
  -> also confirmed by dedicated χ^2 studies





	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

Phase space of measurement
and
phase space of unfolding

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	✓		

Summary of
predictions

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

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

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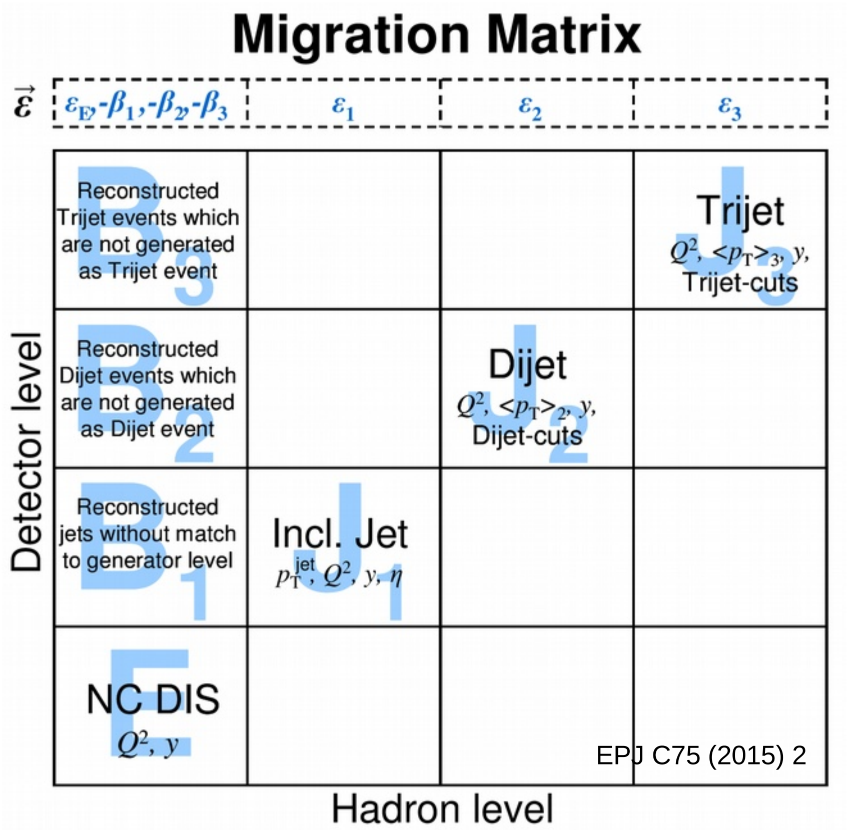

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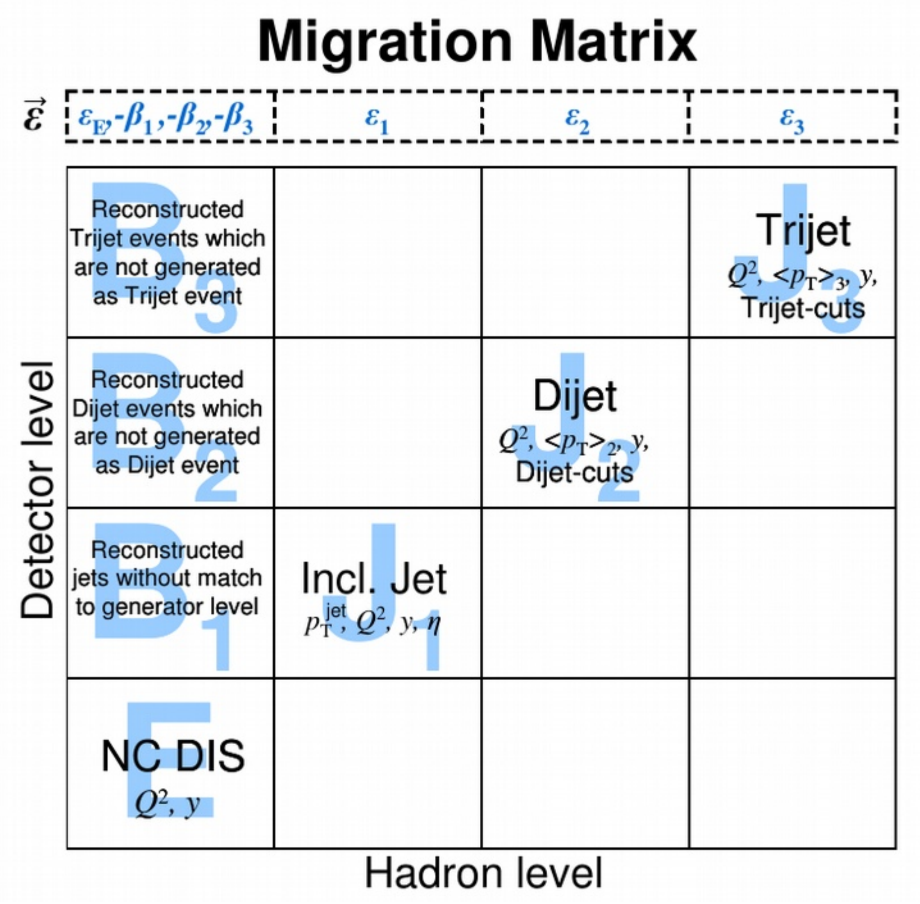
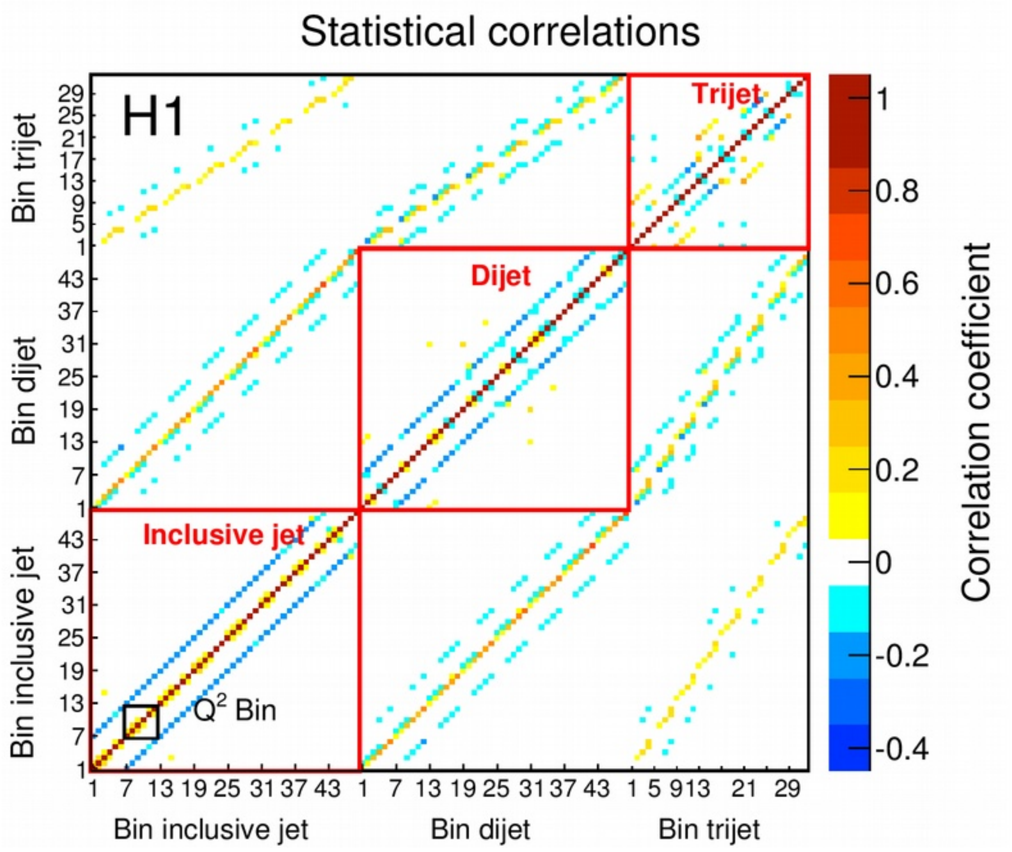
Unfolding matrix and resulting correlations





Dijet cross sections

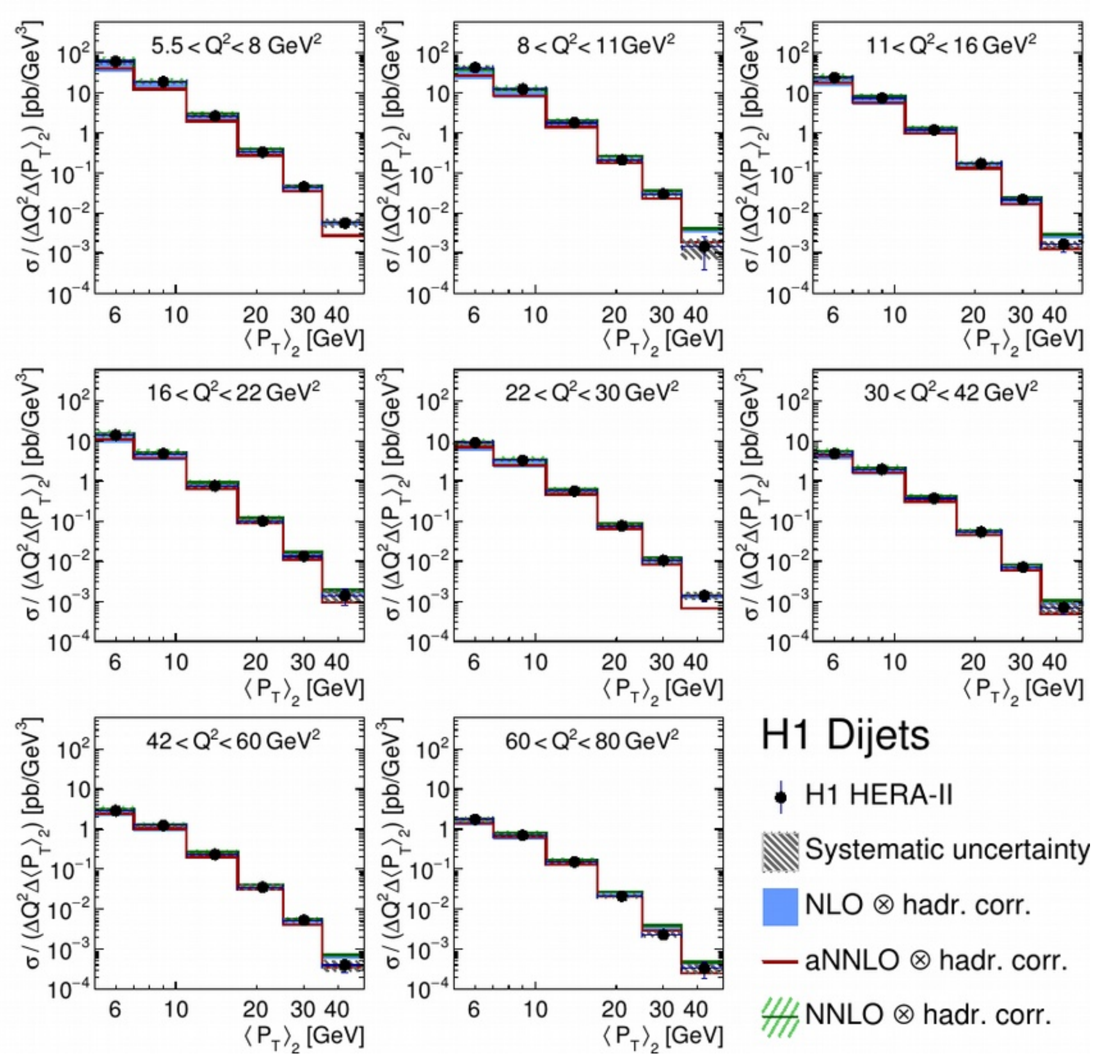
Dijet cross sections

- 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)

Predictions provide overall good description of data

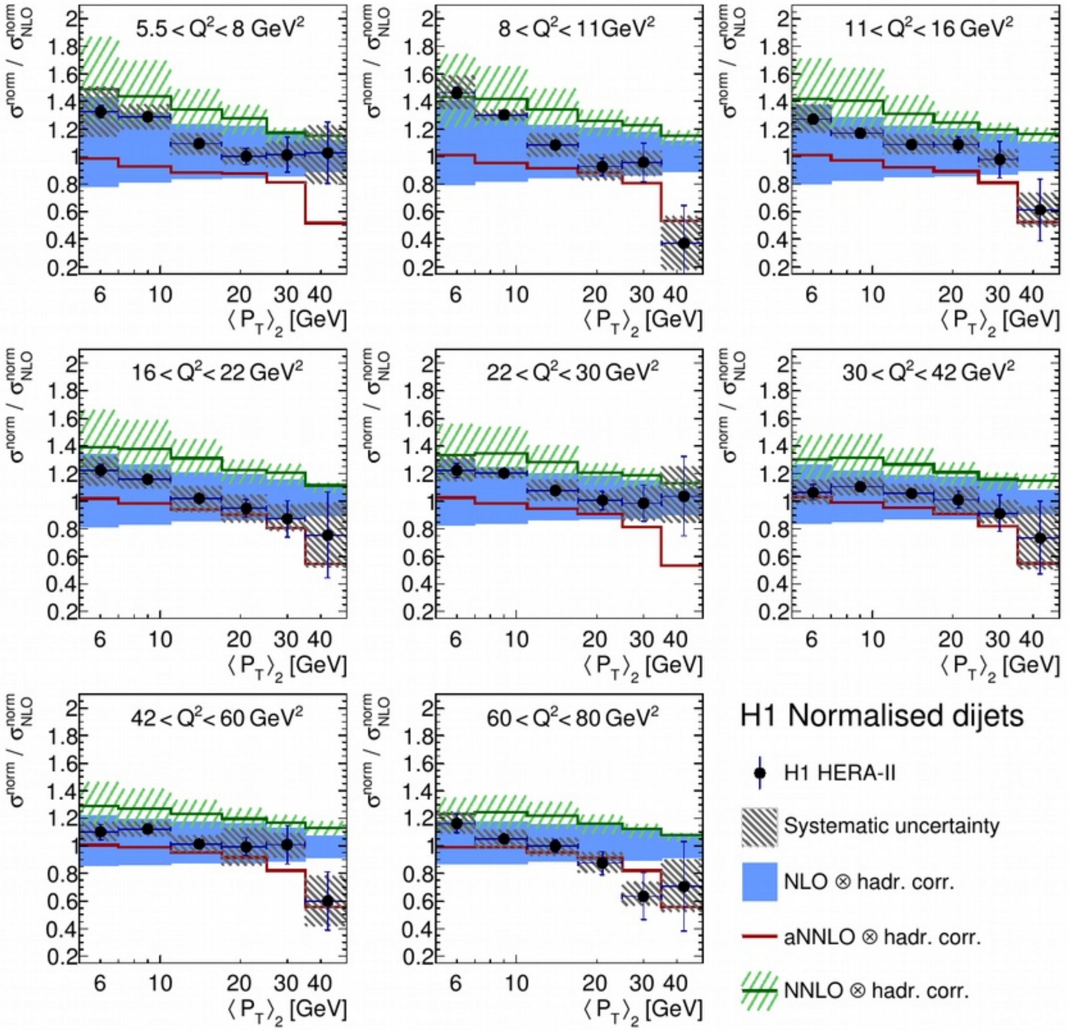


Normalised dijet cross sections

- Normalisation w.r.t. NC DIS cross section in given Q^2 range

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

- (partial) cancellation of exp. uncertainties
  smaller benefit at lower Q^2
- Overall good description by NLO, aNNLO and NNLO predictions
- NNLO slightly overshoots data
  -> Probably caused by normalisation of NC DIS predictions in NNLO



Normalised jet cross sections

Normalised jet cross sections

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

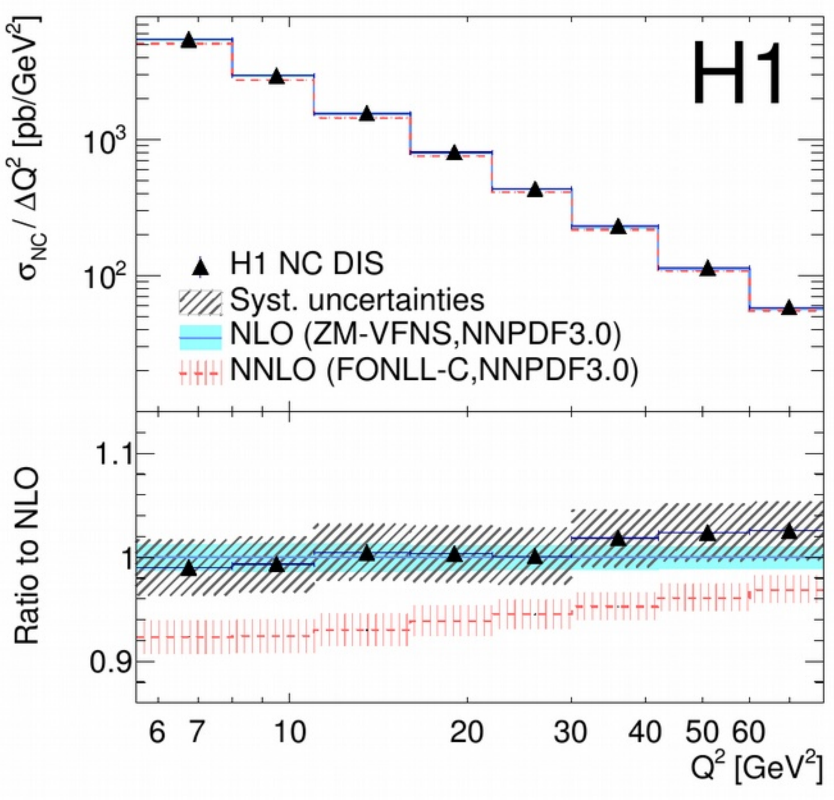
Advantages

- Reduced experimental uncertainties
- Cancellation of normalisation uncertainty

NC DIS predictions

- 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



Reminder: inclusive jets @ high-Q^2

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

Inclusive jets in range

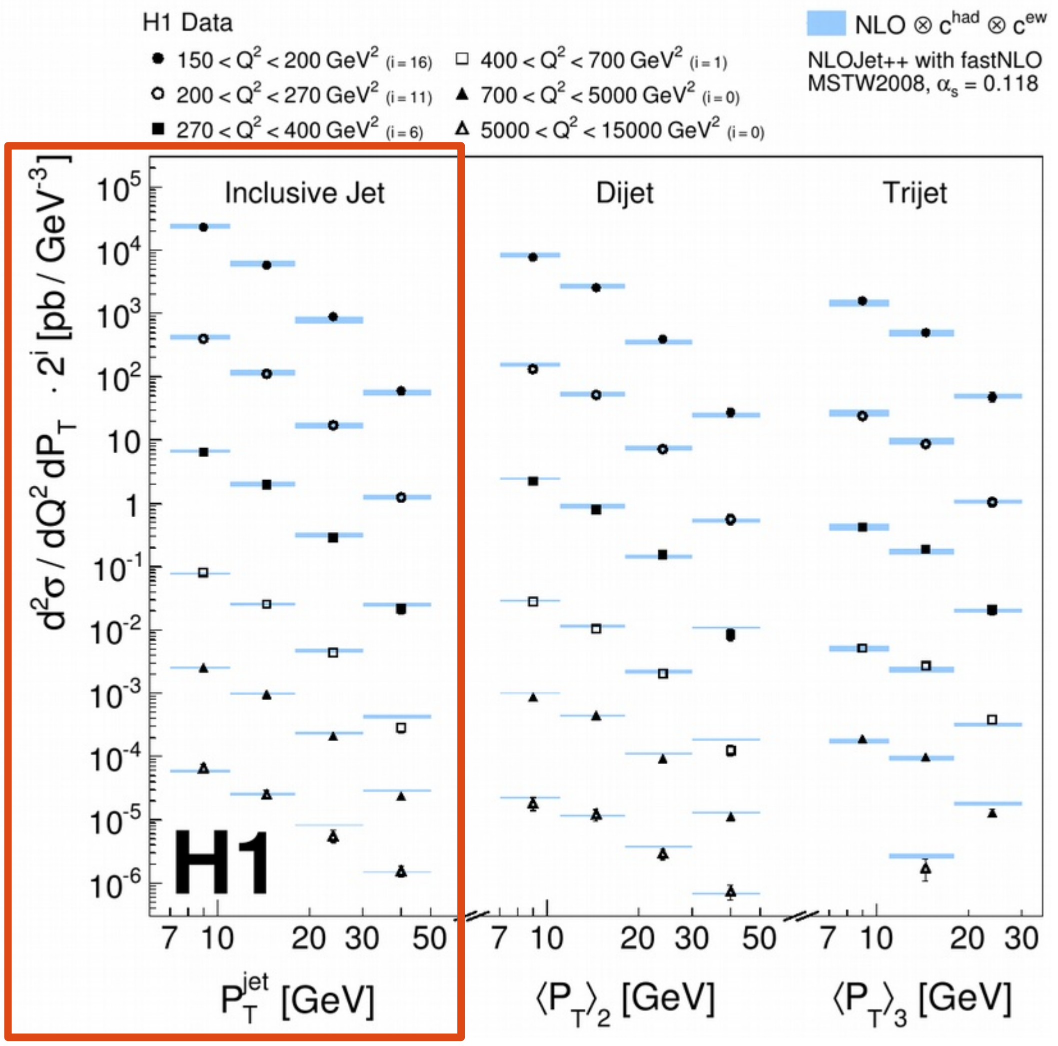
- $7 < p_T < 50$ GeV

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



Normalised inclusive jet cross sections

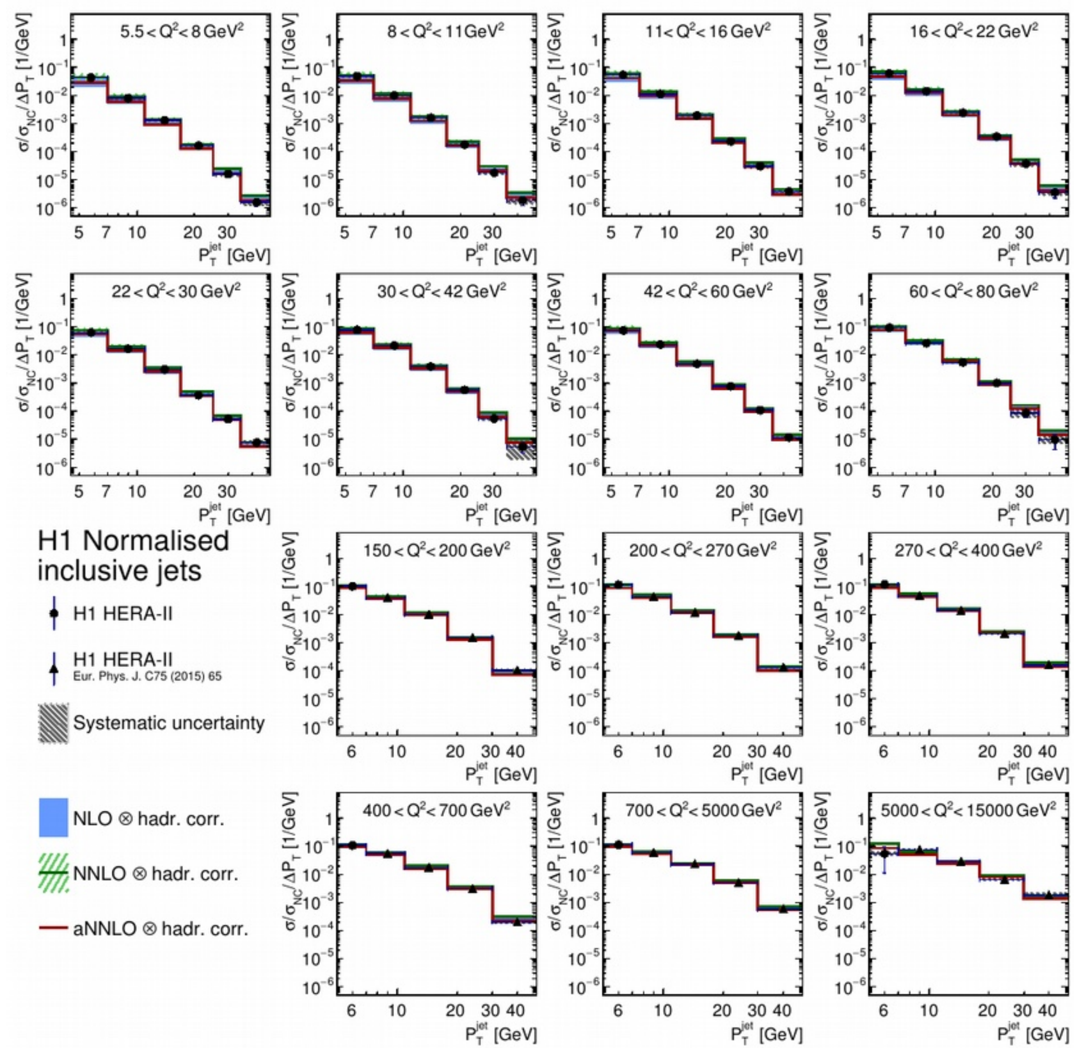
Normalised inclusive jets

- 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



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

$\alpha_s(M_Z)$ from H1 HERA-II jets

- Normalised jet cross sections
  correlations of uncertainties considered

Low- and high-Q^2 data

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

$\alpha_s(M_Z)$ in NLO

- χ^2 fit to all data points together: $\alpha_s(M_Z)$

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

- Very high experimental precision
- Future improvements on dominating theory uncertainties in NNLO

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