Determination of the strong coupling at NNLO from jet production in DIS

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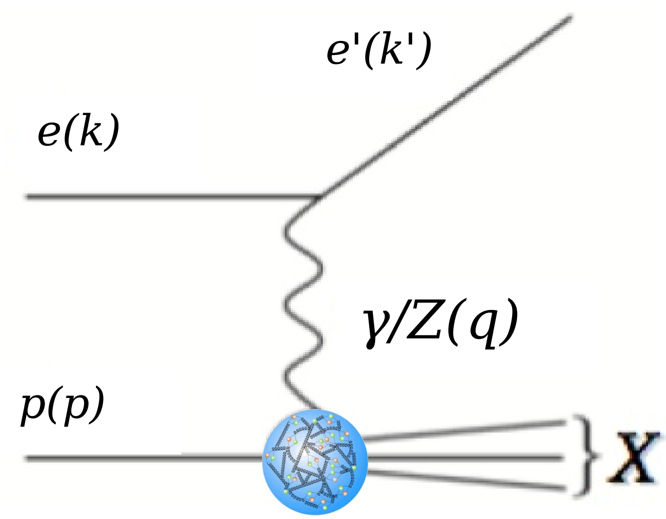
Deep-inelastic *ep* scattering

Neutral current scattering (NC)

$$ep \rightarrow e'X$$



Kinematic variables

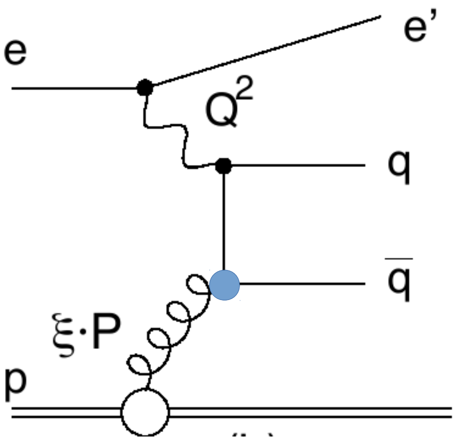
Photon virtuality	Inelasticity	Bjorken-x
$Q^2 = -q^2 = -(k-k')^2$	$y = \frac{p \cdot q}{p \cdot k}$	$x = \frac{Q^2}{2\, p \cdot q}$

HERA *ep* collider in Hamburg

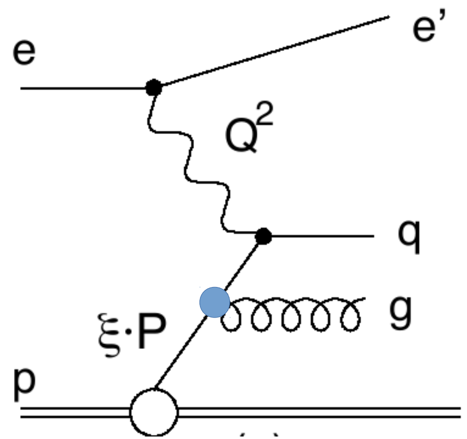
Data taking periods

- HERA I: 1994 – 2000
- HERA II: 2003 – 2007
- √s = 300 or 319 GeV

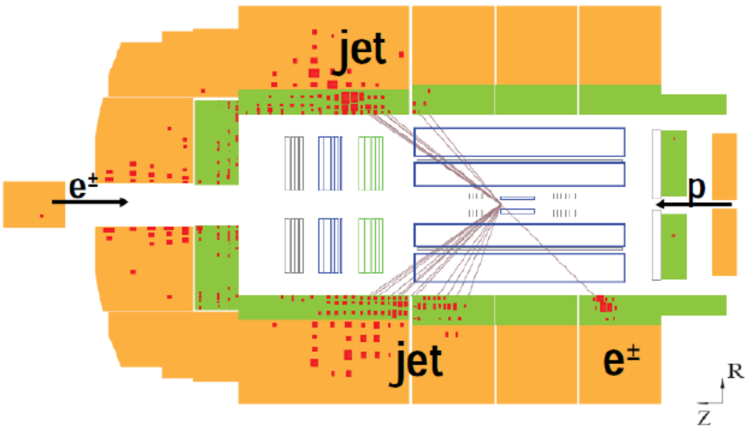
Jet production in DIS



Boson-gluon fusion



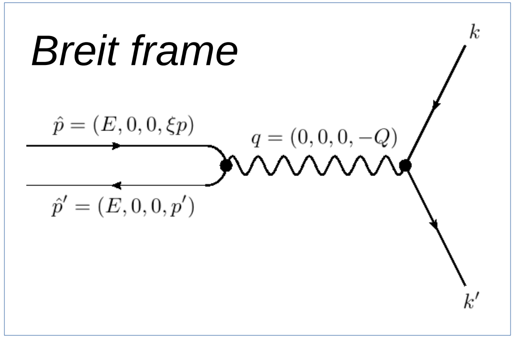
QCD Compton



Exemplary event display

Jets in DIS measured in Breit frame

- Virtual boson collides 'head-on' with parton from proton
  -> Process: ep -> 2jets
- Boson-gluon fusion dominant process in most phase space regions
- QCD compton important for high-p_T jets (high-x)



Jet measurement sensitive to α_s and gluon density

H1 Experiment at HERA

H1 multi-purpose detector

Asymmetric design

Trackers

- Silicon tracker
- Jet chambers
- Proportional chambers

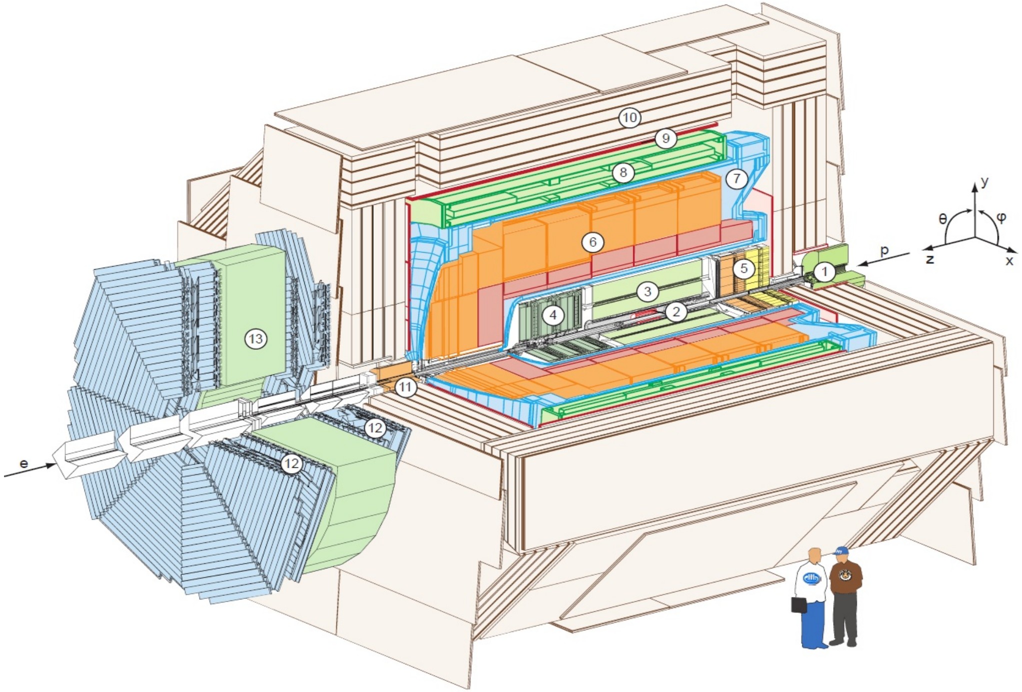
Calorimeters

- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid

- 1.15T magnetic field

Muon detectors



Drawing of the H1 experiment

High experimental precision

- 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

Inclusive jet cross sections by H1

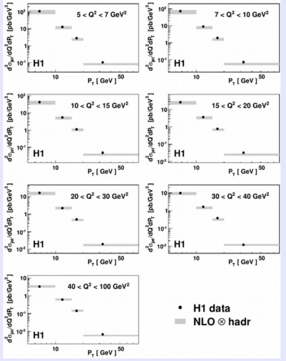
Inclusive jet cross sections

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

Consistency

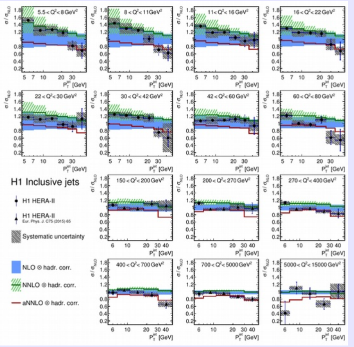
- kt-algorithm, R=1
- $-1.0 < \eta < 2.5$
- P_T ranges from 4.5 to 50 GeV

HERA-I low-Q^2



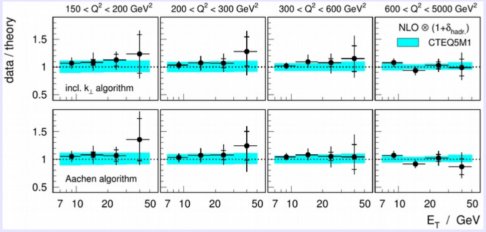
Eur.Phys.J.C67 (2010) 1

HERA-II low-Q^2



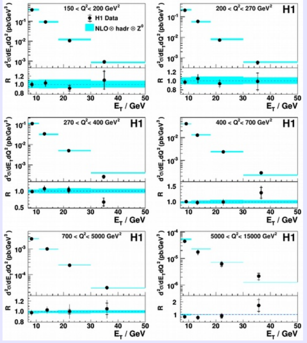
arXiv:1611.03421

300 GeV high-Q^2



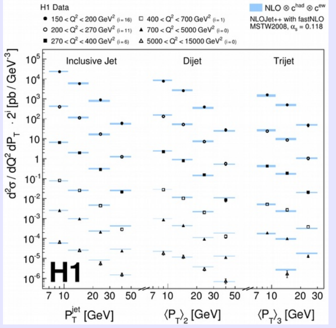
Eur.Phys.J.C19 (2001) 289

HERA-I high-Q^2



Phys.Lett.B653 (2007) 134

HERA-II high-Q^2



Eur.Phys.J.C75 (2015) 2
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

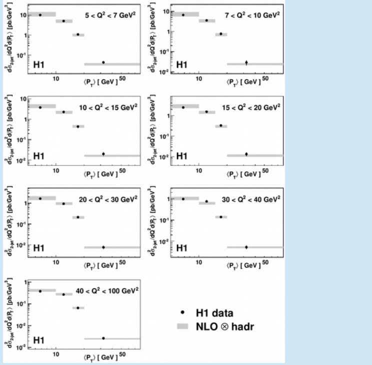
- $\langle p_T \rangle$ greater than 5,7 or 8.5 GeV
- P_T jet greater 4, 5 or 7 GeV
- Asymmetric cuts on p_T^{jet1} and p_T^{jet2}
- M_{12} cut for two data sets

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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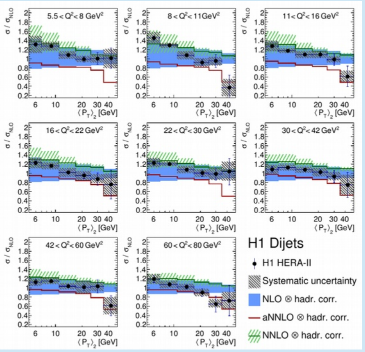
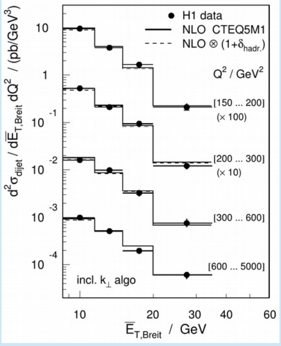
HERA-II low-Q^2



arXiv:1611.03421

300 GeV high-Q^2



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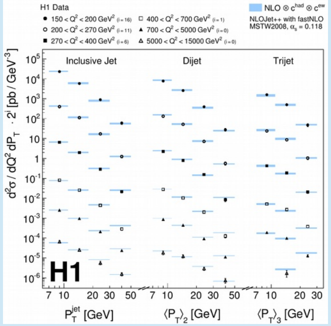
HERA-I high-Q^2

Dijet cross sections not statistically independent from HERA-II analysis
Eur.Phys.J.C65 (2010) 363

HERA-II high-Q^2



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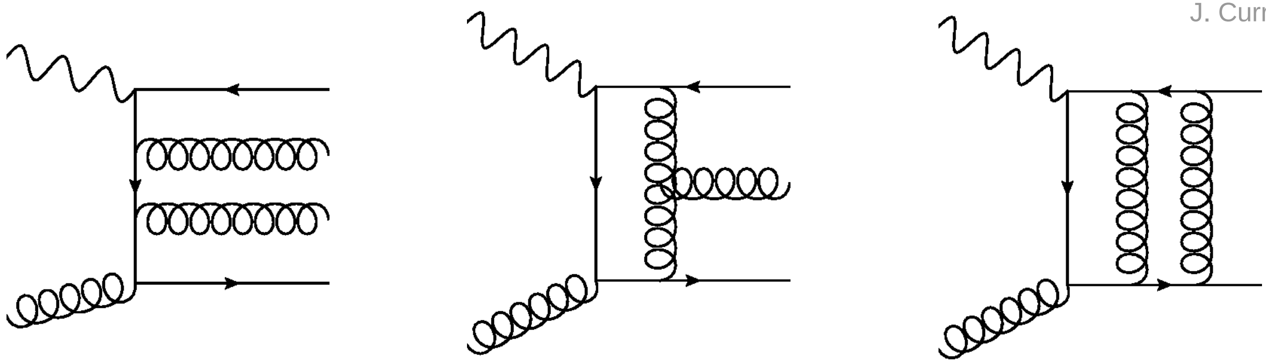
DIS jet production in NNLO

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



Double-real Real-virtual Double-virtual

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

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

NNLO predictions confronted with data

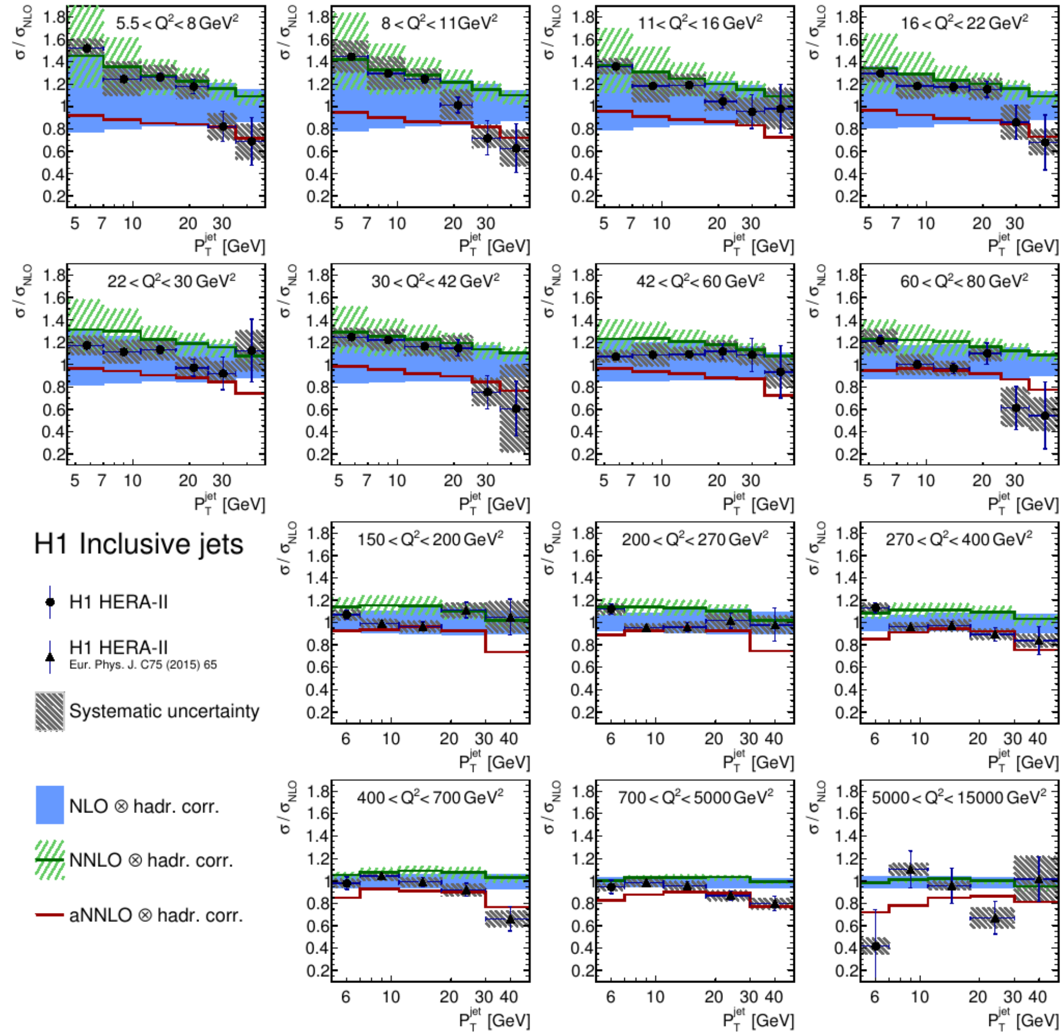
J. Currie, et al. [arXiv:1703.05977]
H1 Collab, accepted by EPJC [arxiv:1611.03421]

NNLO predictions

- NNLO PDF NNPDF3.0
- Improved description of data in NNLO as compared to NLO
- Sizeable NNLO corrections in some phase space regions
  -> NNLO important at lower scales (low-Q^2, low-p_T)

- Scale uncertainties significantly reduced at higher scales

- Scale uncertainties reduced at lower scales



New difficulties for dijets in NNLO

J. Currie, et al. [arXiv:1703.05977]

Dijet cross section

- Event counts with specified event topology
- pQCD: IR sensitive regions present for 'back-to-back' topologies at higher orders

H1 & ZEUS dijet measurements

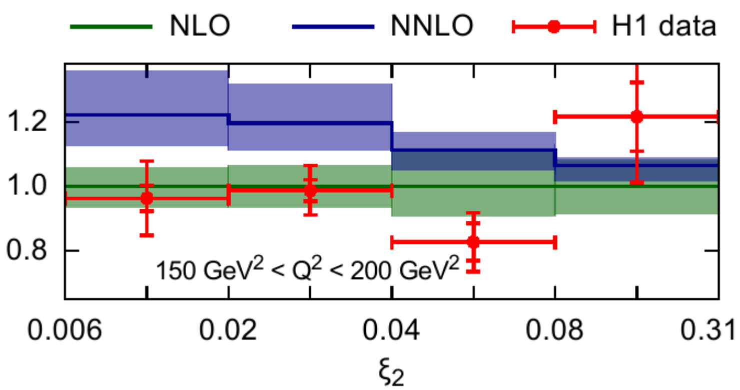
- IR sensitive regions avoided by imposing
  - cut on M_{12}
  - and/or asymmetric cuts for p_T^{jet1} & p_T^{jet2}

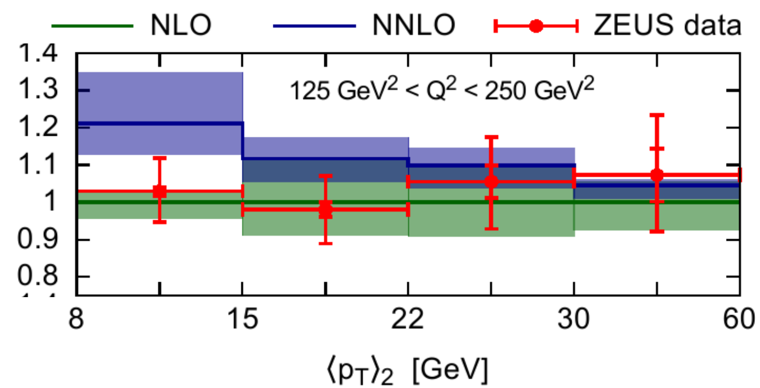
NNLO

- M_{12} cut not sufficient, and sometimes too 'hard'
  - -> LO diagrams are excluded
    -> pQCD calculation degenerates
- Asymmetric cuts are preferred

Dijet measurements with difficulties

- H1 HERA-II high-Q^2: $d\sigma/dQ^2d\chi_2$
- ZEUS HERA-I+II
- H1 HERA-I low-Q^2: lowest $<p_T>$ bins
  -> these 7 data points are excluded in this α_s-fit





All H1 measurements of $d\sigma/dQ^2d<p_T>$ are IR safe because of an asymmetric cut due to the binning

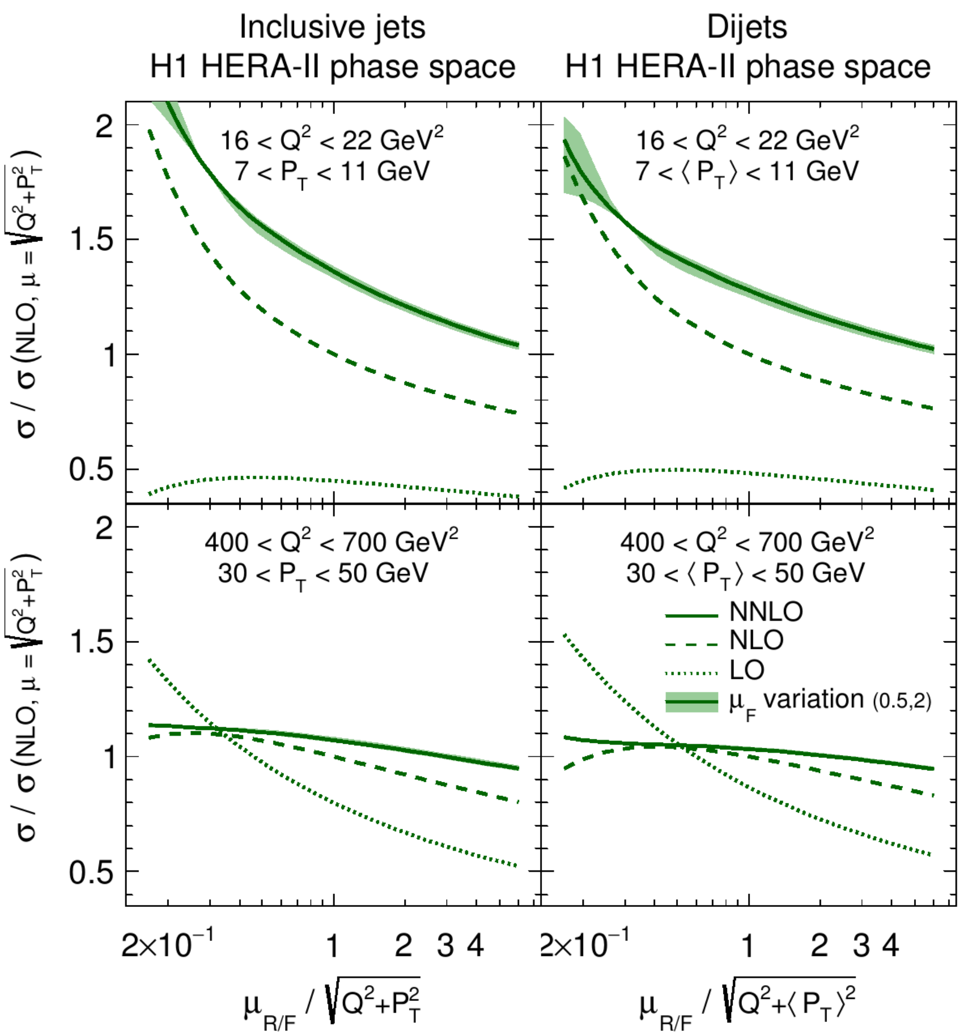
Scale dependence of NNLO cross sections

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



Why α_s?

Strong coupling $\boldsymbol{\alpha_s}$ *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

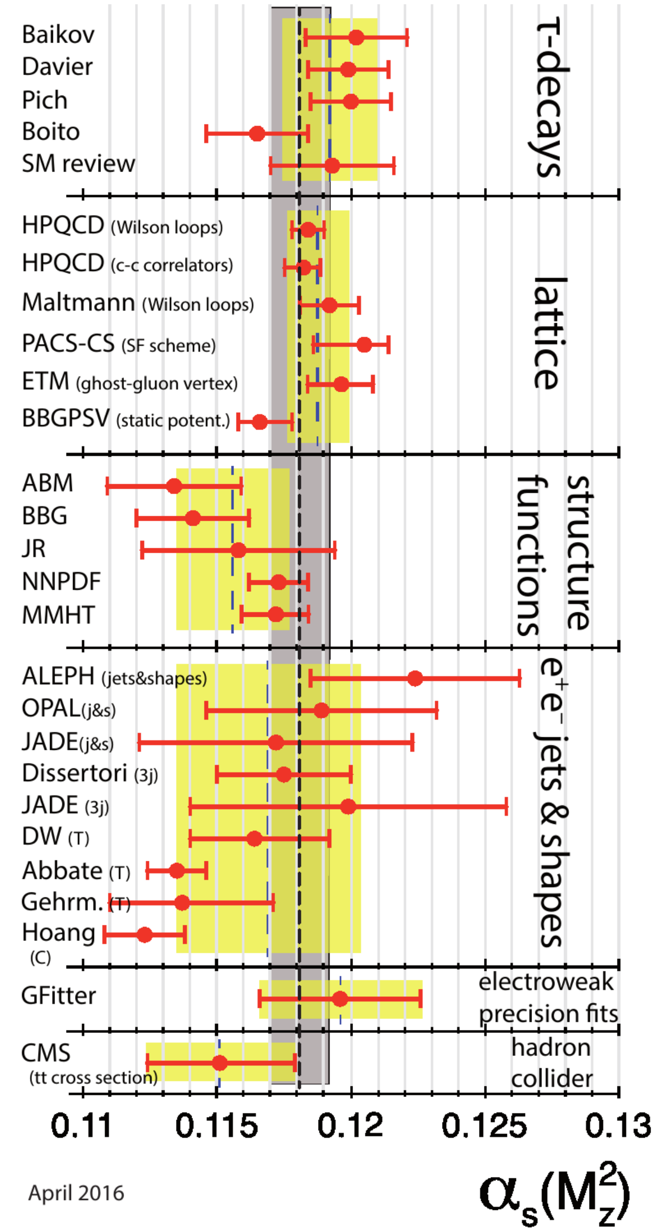
- Relative uncertainty of the fine structure constant: ~$2.3 \cdot 10^{-8}$ % [CODATA]

Uncertainty on $\boldsymbol{\alpha_s}$

- leads to non-negligible uncertainties on many observables
- Notable examples: Higgs production cross sections, branching ratios

Jet measurements

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



Slide after T.Klijnsma

$\alpha_s(m_Z)$ dependence of cross sections

Jet cross sections directly sensitive to α_s

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

- *Two α_s-dependencies*

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

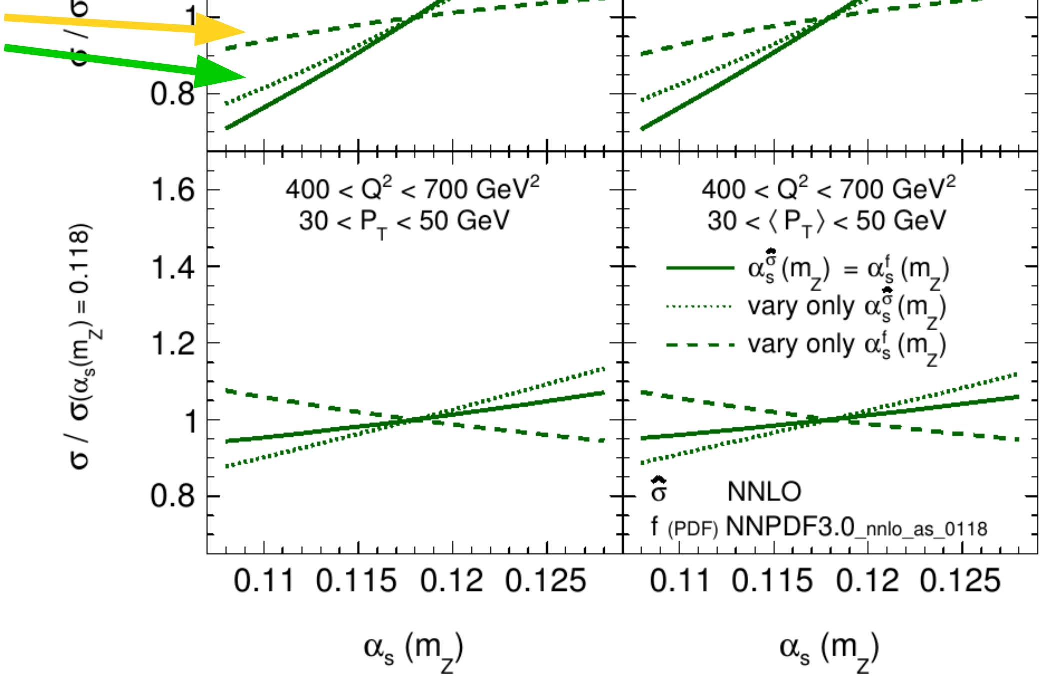
Hard ME's
$\hat{\sigma}^{(n)}_{i,k} = \alpha_s^n(\mu_R)\tilde{\sigma}^{(n)}_{i,k}(x,\mu_R,\mu_F)$

At lower scales

- *Predominant α_s-sensitivity from hard coefficients*
- *PDF's show positive dependence -> Increased sensitivity*

At higher scales

- *negative sensitivity from PDF's -> Reduced sensitivity*



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)

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

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

α_s dependencies separately fitted

Fits to

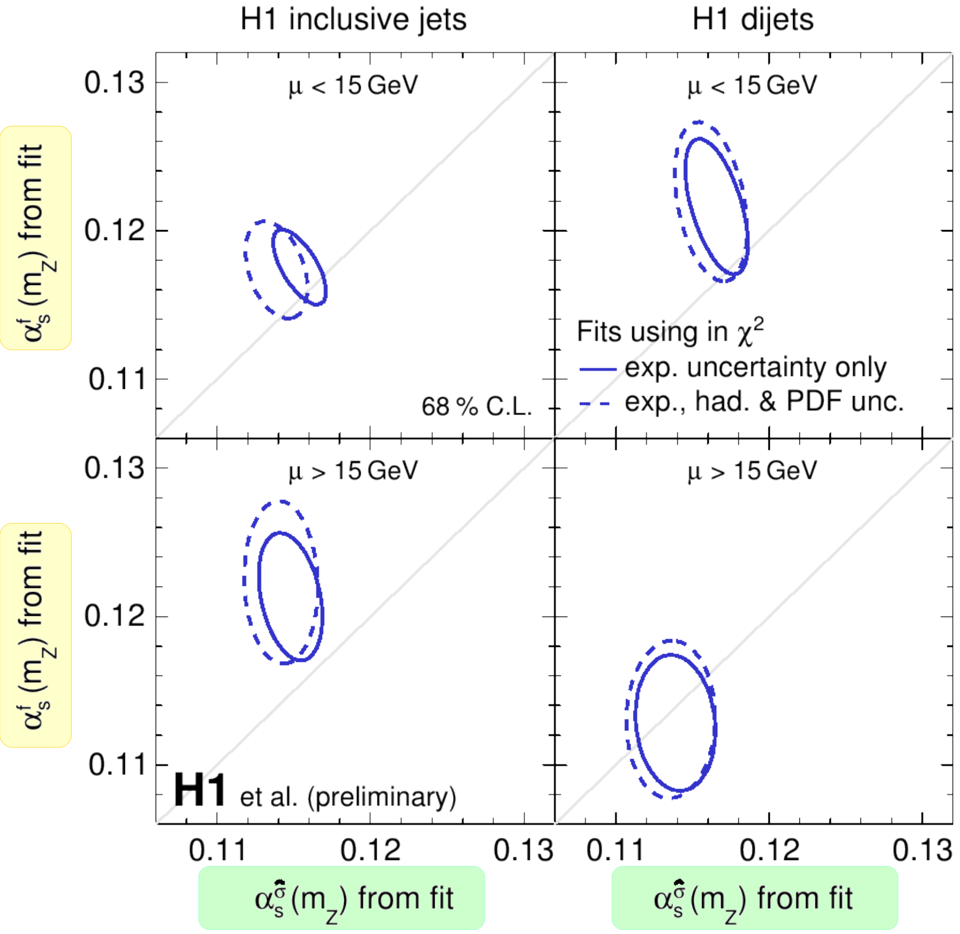
- Inclusive jet or dijet data
- Separate fits to low-μ and high-μ data points
- Fits including PDF uncertainties in χ^2 or not

Fits with two free α_s parameters

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

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
- PDF uncertainties do not yield significant shift
  -> PDF uncertainties with small correlation to α_s^{PDF}



Scale choice for α_s fit

Functional form for scales (μ_r, μ_f)

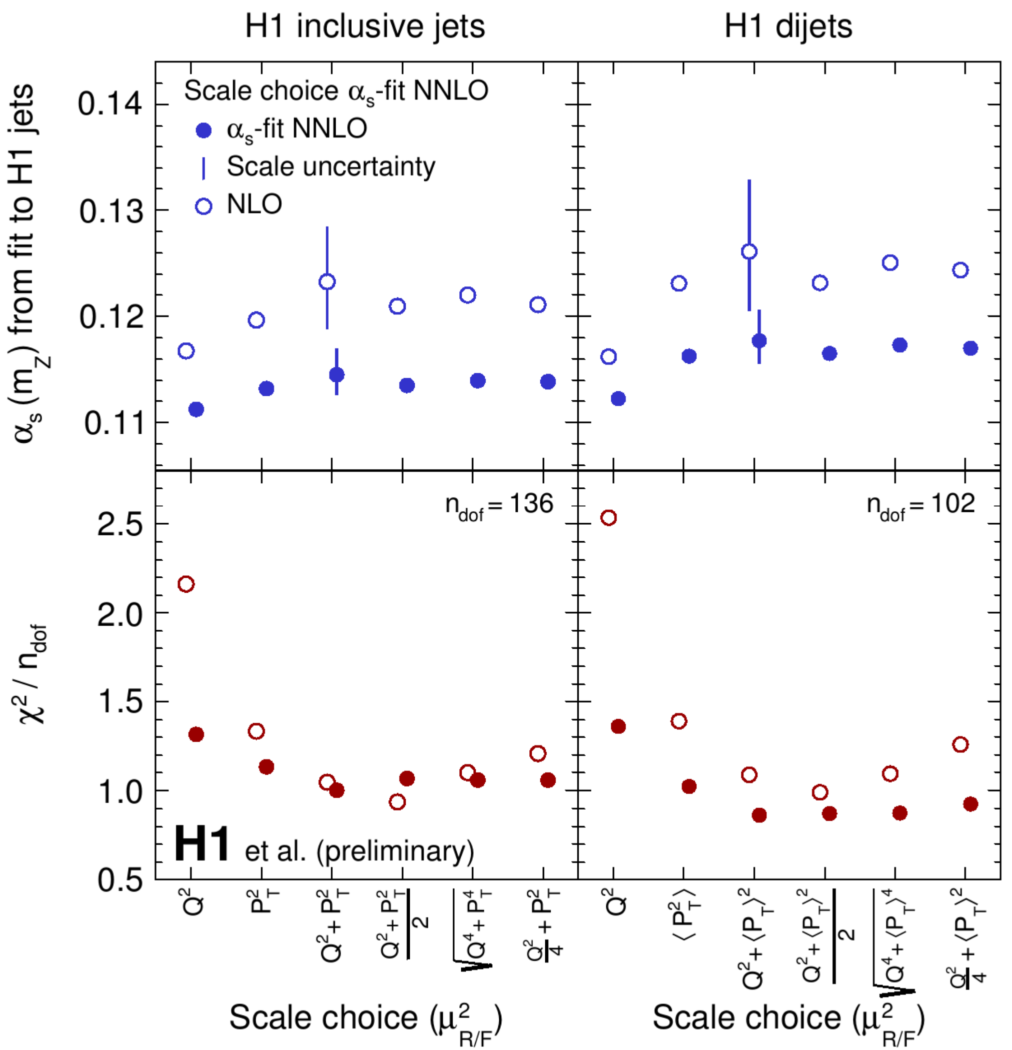
- Study various scales built from Q^2 and p_T
- p_T: p_T^{jet} or $<p_T>$

α_s results and χ^2 values

- Q^2 disvafored (as expected)
- Spread of results covered by scale uncertainty (variation by 0.5 & 2)
- χ^2 values are consistent for different choices

Use of only NLO matrix elements

- Large scale uncertainty
- increased dependence of result on scale choice
- Mainly larger χ^2 values than NNLO
- Larger fluctuation of χ^2 values than NNLO



NNLO with reduced scale dependence

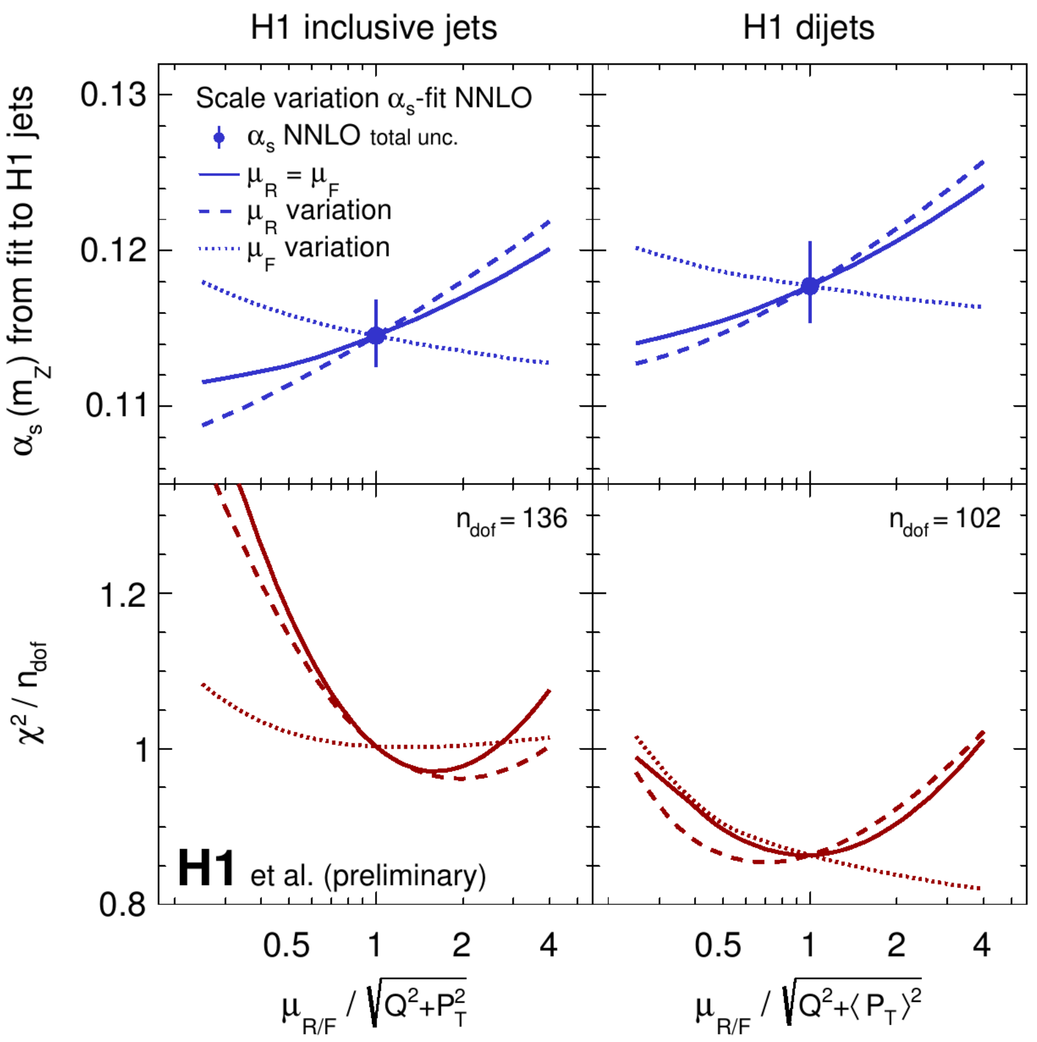
Scale dependence of α_s fit

Scale dependence of α_s fit

- α_s results as a function of scale factors
- Smooth results for all studied scale variations
- μ_r variation with more impact than μ_f

χ^2 values

- just 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



Dependence on the PDF

PDF is external input to cross section calculation

Choice of PDF set

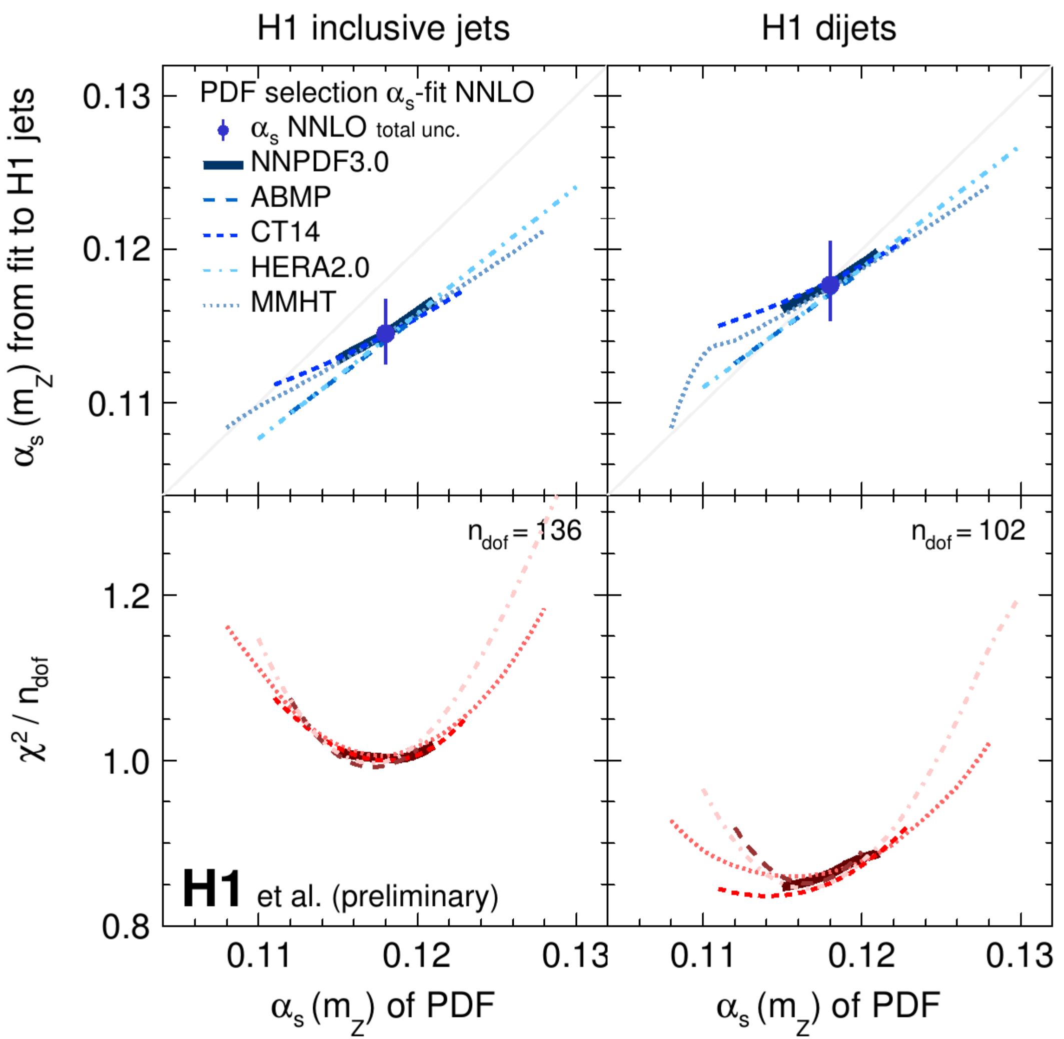
- Different fitting groups:
  different input data sets, PDF parameterisations, model parameters, fit methodology, etc...
- PDF appear to be quite consistent

Choice of α_s as input to PDF

- $\alpha_s(m_Z)$ important input parameter to PDF fit
- Relevant correlation with fitted results
  -> much larger than previous reported
- Differences of PDF sets due to choice of input data to PDF fit

Additional PDF uncertainties considered

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



Strong coupling in NNLO from jets

Full error breakdown

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

α_s results from individual data sets

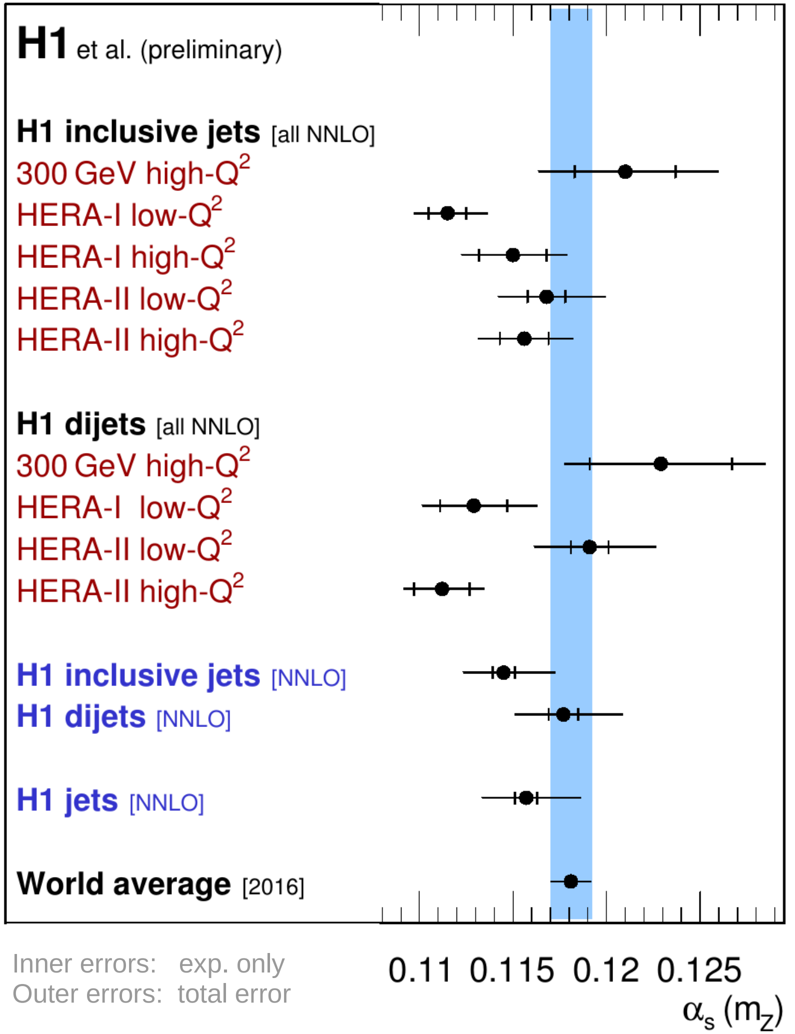
- High experimental precision
- Scale uncertainty is largest (theory) error
- All fits with good χ^2
  -> consistency of data

H1 jets (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

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



Running from inclusive jets and dijets

Test running of strong coupling

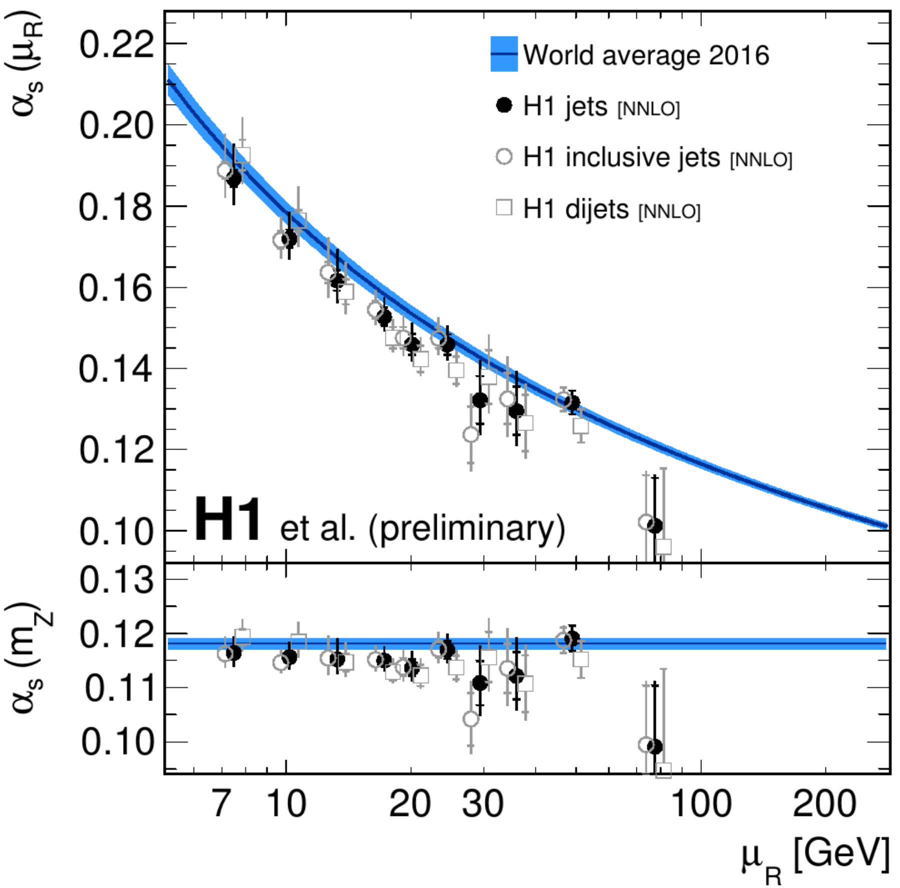
- Repeat fits to groups of data points at similar scales
- All fits with good χ^2
- Study assumes running to be valid only within limited range covered by an interval

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



Strong coupling in NNLO from jets

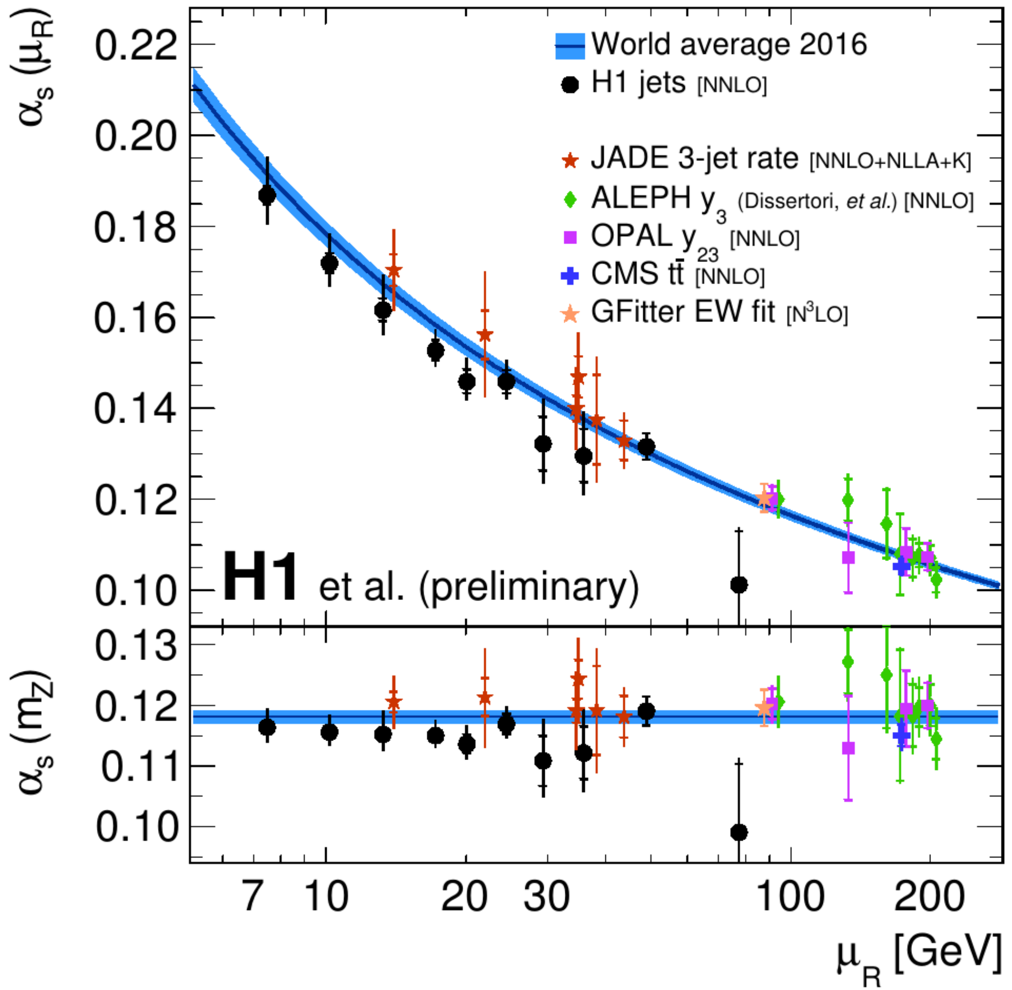
H1 in collaboration with
V. Bertone, J. Currie, T. Gehrmann,
C. Gwenlan, A. Huss, J. Niehues, M. Sutton

Comparison to other measurements

- Restrict selection to NNLO precision or higher

H1 jets

- Consistency with other extractions and with other processes
- Relevant results at lower scales
- Only NNLO study of running from hadron-collider to date



Result in agreement with world average and other measurements with tendency to be a bit lower

Related contributions at (this) conference

K. Rabbertz

- α_s studies of inclusive jet data from different experiments using NLO
  -> Study of inclusive jets from H1, ZEUS, STAR, CDF, D0, ATLAS & CMS

C. Gewnlan

- New developments and common interface of fastNLO & APPLgrid to NNLOJET
  -> Details about fastNLO & APPLgrid use for this study

R. Žlebčík

- NNLO predictions for dijets in diffractive DIS
  -> Same final state and kinematic range as non-diff. DIS
  -> but NNLO matrix elements convoluted with DPDFs

J. Niehues @ Moriond

- ep -> 2jet cross sections in NNLO using antenna function formalism

DB

- Measurements of inclusive jet, dijet and trijet cross sections in DIS (H1)
  -> Data used in present α_s extraction

Conclusion

Strong coupling constant determined *from H1 jet cross sections using NNLO predictions*

NNLO phenomenology evolved rather quickly

- *2 weeks ago NNLO calculations subm. to arXiv*
- *Today all H1 ep->2jet measurements studied in a quantitative way*

H1prelim-17-031

- *Available at: https://www-h1.desy.de/publications/H1preliminary.short_list.html*
- *Fruitful collaboration of theoreticians and experimentalists*

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

- *Very high experimental precision*
- *Competitive theory precision*

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

Finally we arrived: precision QCD phenomenology in NNLO accuracy

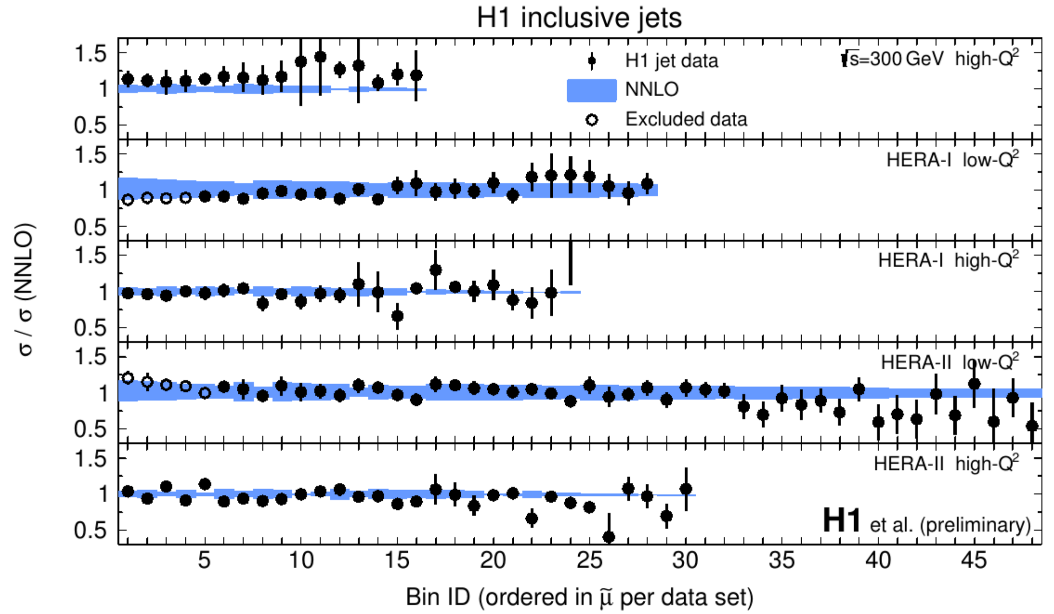
NNLO cross sections

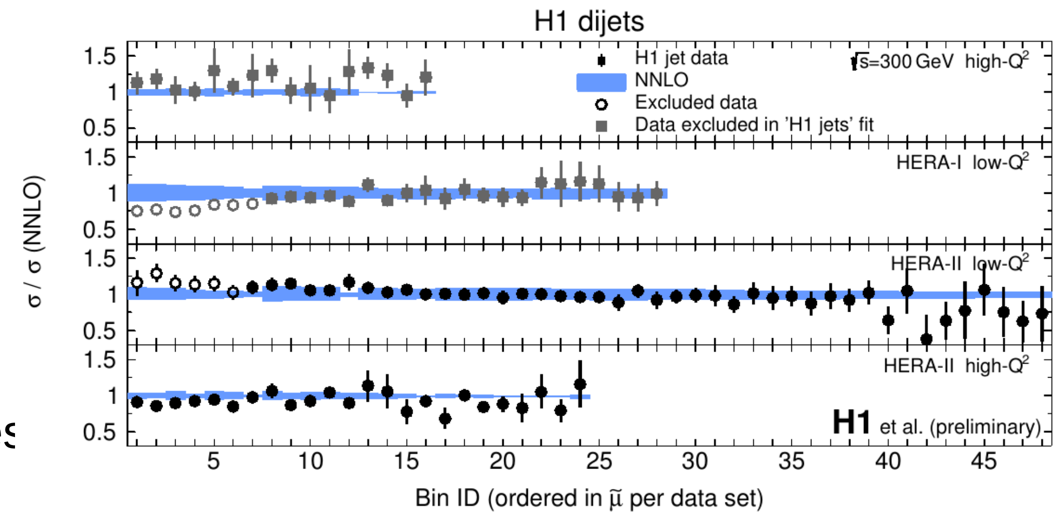
Ratio of data to NNLO predictions

- 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

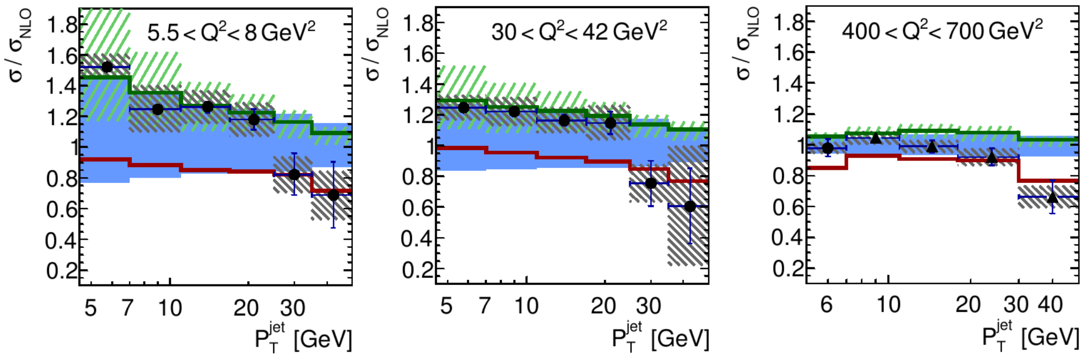




Study of scale uncertainty

Scale uncertainties at various scales μ

- At low-μ: large scale uncertainties...
- ... but also high sensitivity to $\alpha_s(m_Z)$

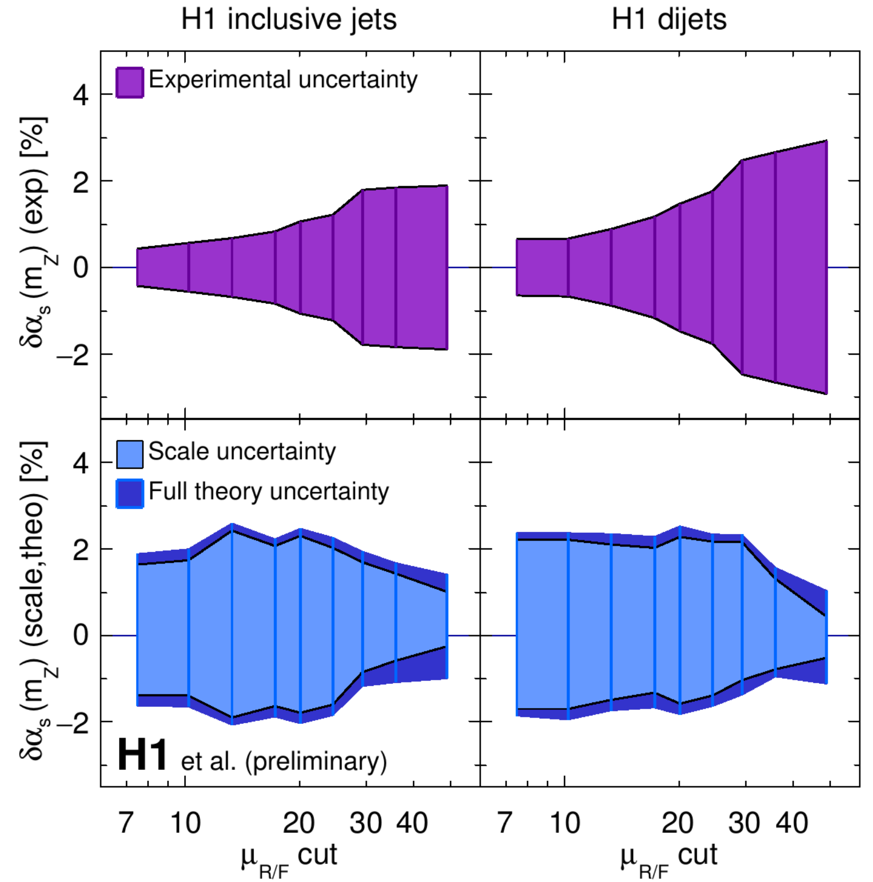


Fits imposing a cut on scale μ_R

- Repeat α_s fits: successively cut awad data below μ_{min}

Results

- Theory (scale) uncertainty almost constant over μ_{min}
- Cross sections suggest large uncertainty at low-μ...
- ... but NNLO at low-μ are equally precise to α_s



Cut on μ can balance between exp. and theoretical uncertainties at constant total precision

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	$150 < Q^2 < 15000\,\text{GeV}^2$ $0.2 < y < 0.7$	$5 < P_T^{\text{jet}} < 50\,\text{GeV}$	$5 < P_T^{\text{jet}} < 50\,\text{GeV}$ $7 < \langle P_T \rangle < 50\,\text{GeV}$ $m_{12} > 16\,\text{GeV}$

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)

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

Cross sections in DIS

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

QCD incorporates two $\alpha_s(m_Z)$ dependencies

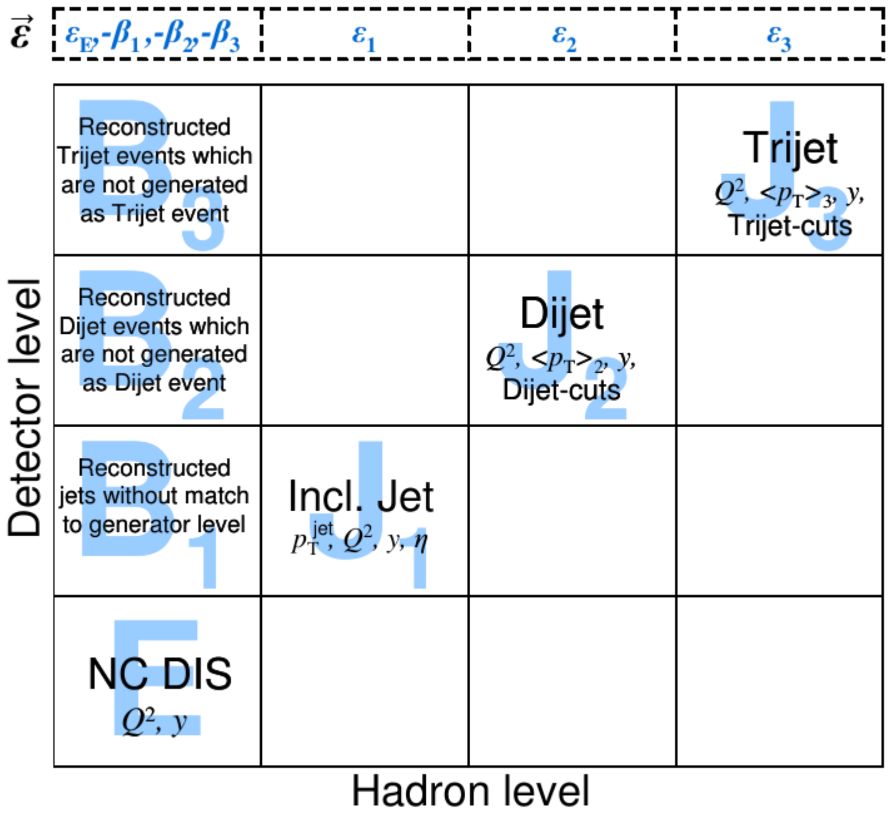
- PDFs & hard coefficients

PDFs $$\frac{\partial f}{\partial \alpha_{\text{s}}} = \frac{\mathcal{P} \otimes f}{\beta}$$

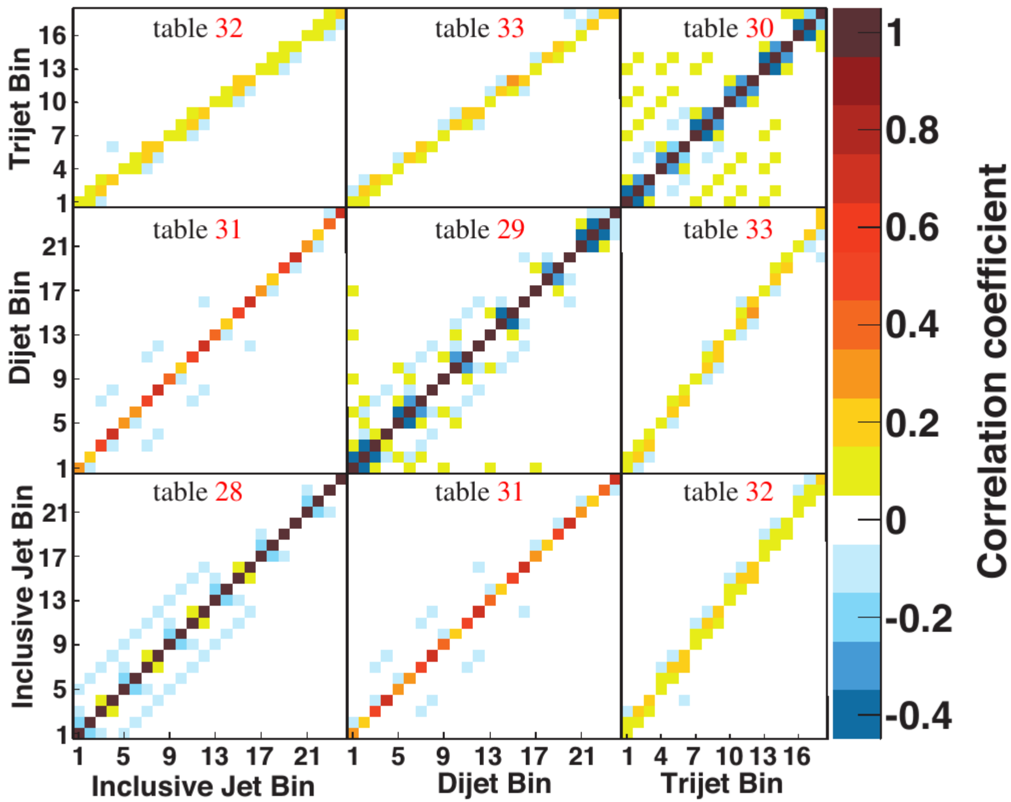
Hard ME's

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

Migration Matrix



Correlation Matrix



α_s input to PDF extraction

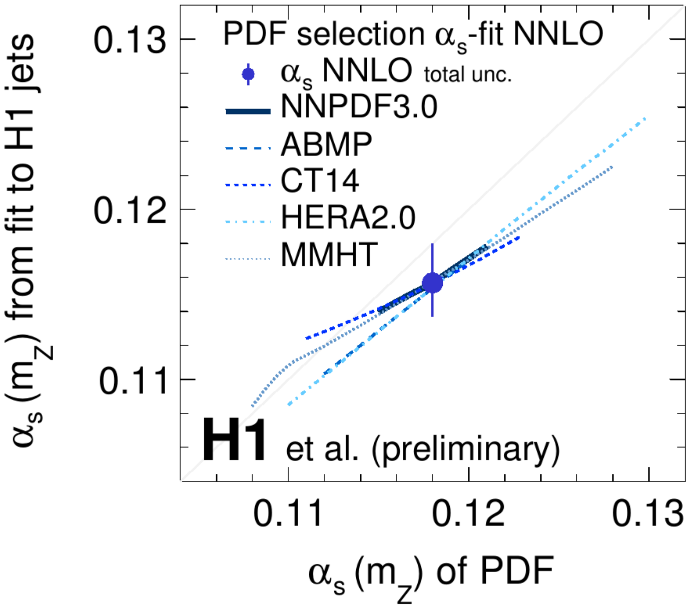
$$\sigma_i = \sum_{n=1}^{\infty} \sum_{k=g,q,\bar{q}} \int dx\, f_k(x, \mu_F) \hat{\sigma}_{i,k}^{(n)}(x, \mu_R, \mu_F) \cdot c_{\text{had}}$$

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

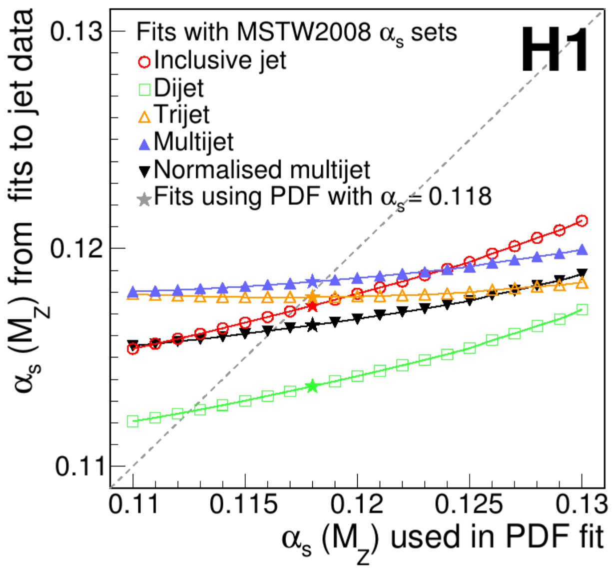
Hard ME's

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

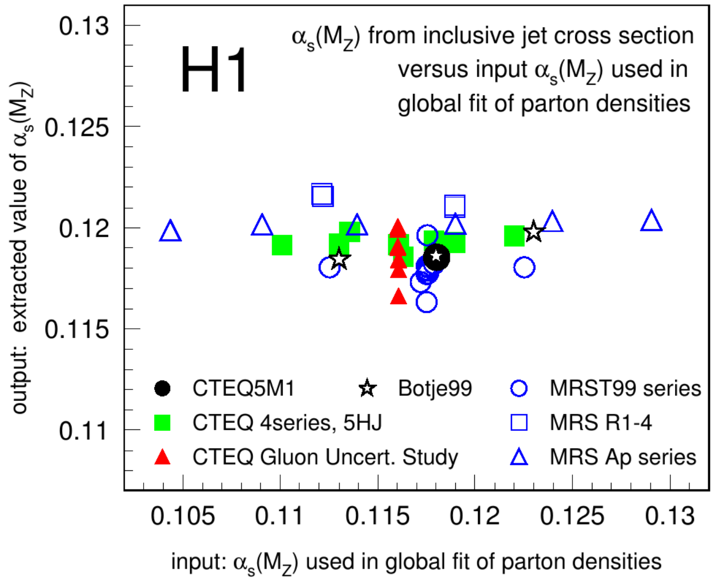
low-Q² & high-Q², H1 jets



HERA-II, high-Q²



300 GeV, high-Q²

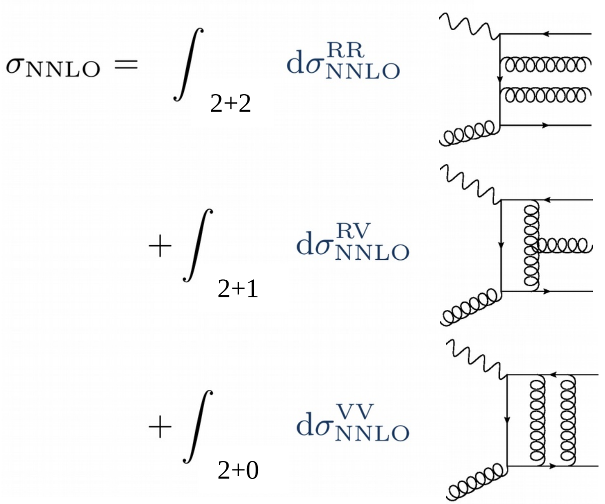


NNLO for DIS jet production

J. Currie, T. Gehrmann, J. Niehues [RPL 117 (2016) 042001]
J. Currie et al. [in preparation]

Recent theoretical advancement: NNLO for DIS jet cross sections

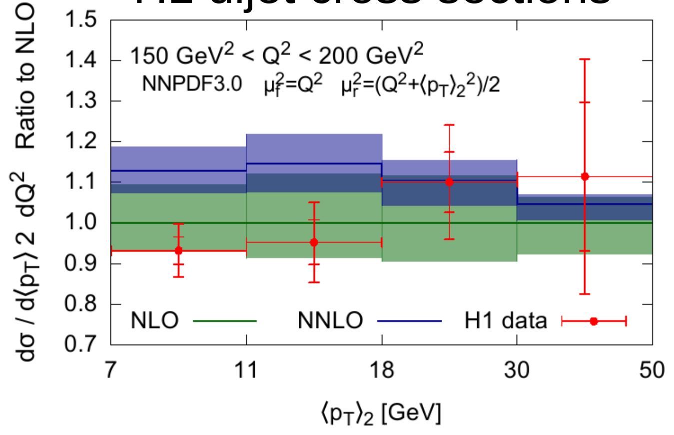
- A bit of history:
  - 1973: asymptotic freedom of QCD
    [PRL 30(1973) 1343 & 1346]
  - 1993: NLO studies of DIS jet cross sections
    [Phys. Rev. D49 (1994) 3291]
  - 2016: NNLO corrections for DIS jet
    [Phys. Rev. Lett. 117 (2016) 042001]



NNLO predictions for jets in DIS are challenging

- Single-particle inclusive observables
- Two colored particles in final state
- Individual contributions are divergent themselves
  -> Divergent parts of calculations have been revealed
  -> Analytic cancellation of soft/collinear divergences (real corrections) with ε-poles (virtual correction)
- Antennae function formalism

H1 dijet cross sections



Results of NNLO calculations

- Reduction of theoretical uncertainty at higher scales
- Theoretical uncertainty becomes similar to data uncertainty