QCD Results from HERA

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for the H1 and ZEUS Collaborations

Moriond QCD 2017
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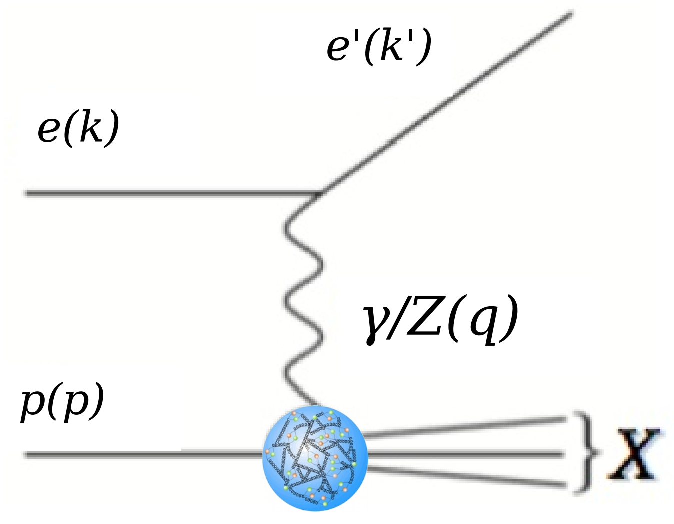
Deep-inelastic *ep* scattering

Neutral current scattering (NC)

$ep \rightarrow e'X$



Covered topics in this talk

Charm and beauty cross sections

Prompt photons in DIS

Jet production in DIS

α_s from jet cross sections in NNLO

Kinematic variables

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

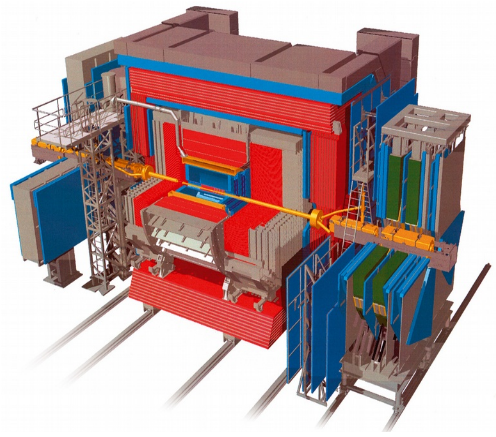
Inelasticity
$$y = \frac{p \cdot q}{p \cdot k}$$

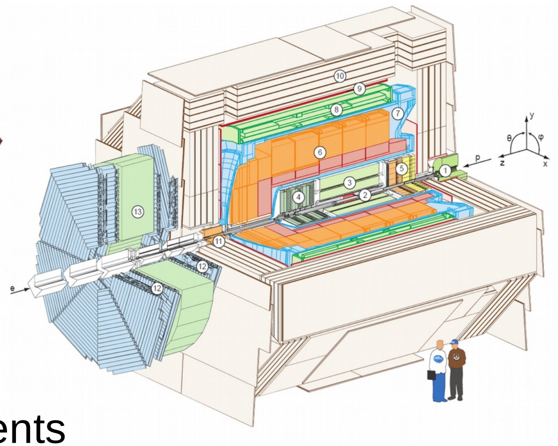
Bjorken-*x*
$$x = \frac{Q^2}{2\, p \cdot q}$$

H1 and ZEUS at HERA

HERA electron-proton collider
- Electrons and positrons: E_e = 27.6 GeV
- Nom. proton energy: E_p = 920 GeV

Data taking
- HERA-I: 1993 – 2000
- HERA-II 2003 – 2007
- int. Lumi. ~0.5 fb^{-1} per experiment





H1 and ZEUS
- Two multi-purpose experiments
- Trackers, calorimeters, magnets, muon System, Lumi system, taggers, forward stations, etc...

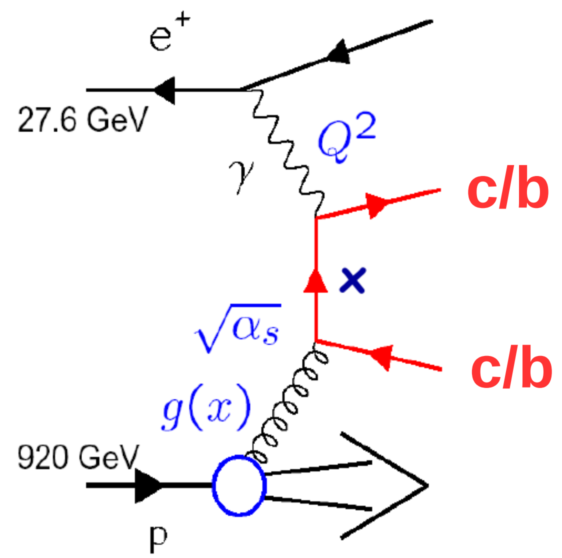
DIS allows for excellent calibration
- Overconstrained system in DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Trigger and normalization uncertainties: 1-2 %
- Luminosity: 1.8 – 2.5%

Heavy quark production in DIS

Heavy quark production
- Produced in photon-gluon fusion in DIS

Combination of charm and beauty cross sections
- H1 & ZEUS measurements
- $2.5 < Q^2 < 2000$ GeV^2

Extension of 2012 combination *[EPJ C73 (2013) 2311]*
- 3 new charm data sets
- 5 beauty data sets
- 13 analyses in total



	Data set	Tagging	Q^2 range [GeV^2]	N_c	$\mathscr{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_b
1	H1 VTX [8]	VTX	5 – 2000	29	245	318	12
2	H1 D^{*+} HERA-I [9]	D^{*+}	2 – 100	17	47	318	
3	H1 D^{*+} HERA-II (medium Q^2) [10]	D^{*+}	5 – 100	25	348	318	
4	H1 D^{*+} HERA-II (high Q^2) [11]	D^{*+}	100 – 1000	6	351	318	
5	ZEUS D^{*+} 96-97 [12]	D^{*+}	1 – 200	21	37	300	
6	ZEUS D^{*+} 98-00 [13]	D^{*+}	1.5 – 1000	31	82	318	
7	ZEUS D^0 2005 [14]	D^0	5 – 1000	9	134	318	
8	ZEUS μ 2005 [7]	μ	20 – 10000	8	126	318	8
9	ZEUS D^+ HERA-II [2]	D^+	5 – 1000	14	354	318	
10	ZEUS D^{*+} HERA-II [3]	D^{*+}	5 – 1000	31	363	318	
11	ZEUS VTX HERA-II [4]	VTX	5 – 1000	18	354	318	17
12	ZEUS e HERA-II [5]	e	10 – 1000		363	318	9
13	ZEUS μ + jet HERA-I [6]	μ	2 – 3000		114	318	11

Reduced cross sections

$$\sigma_{\rm red}^{Q\bar{Q}} = \frac{d^2\sigma^{Q\bar{Q}}}{dx_{\rm Bj}dQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)}$$

- 'Visible cross sections' extrapolated using NLO theory (HVQDIS)

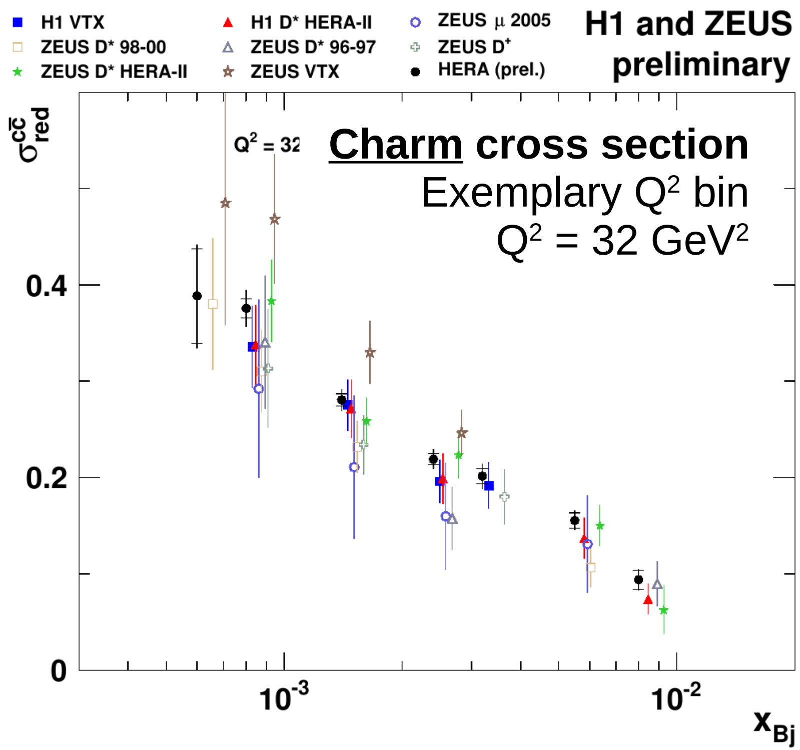
Charm and beauty combination

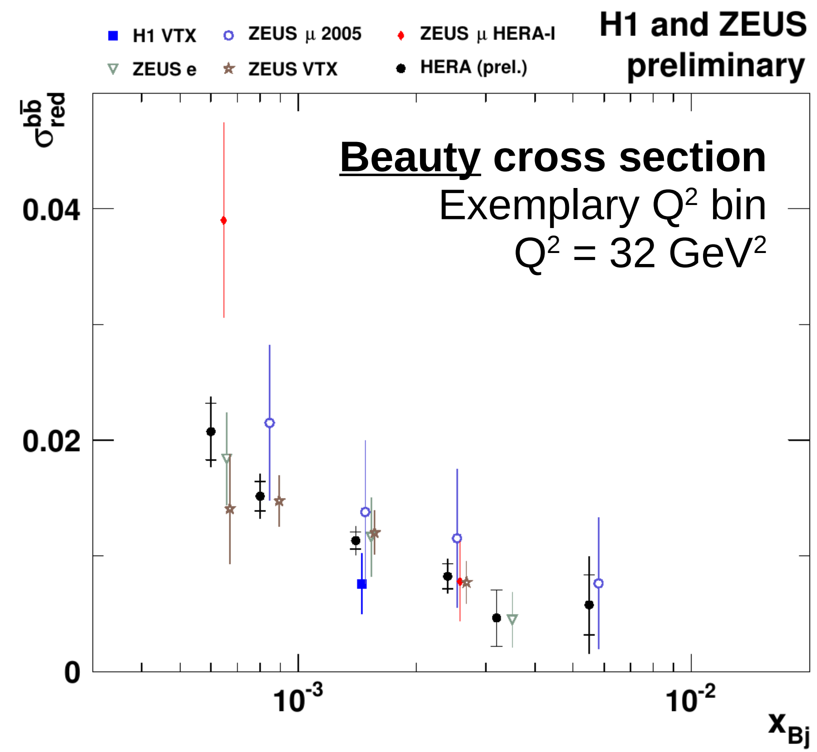
Combination

- 209 charm and 57 beauty data points are combined to...
- 52 charm and 27 beauty reduced CS

Results from combination

- data sets are found to be consistent
  χ^2 / ndf = 149 / 187
- Uncertainties are significantly reduced
- Higher precision than previous combination





Charm and beauty combination

Charm cross sections

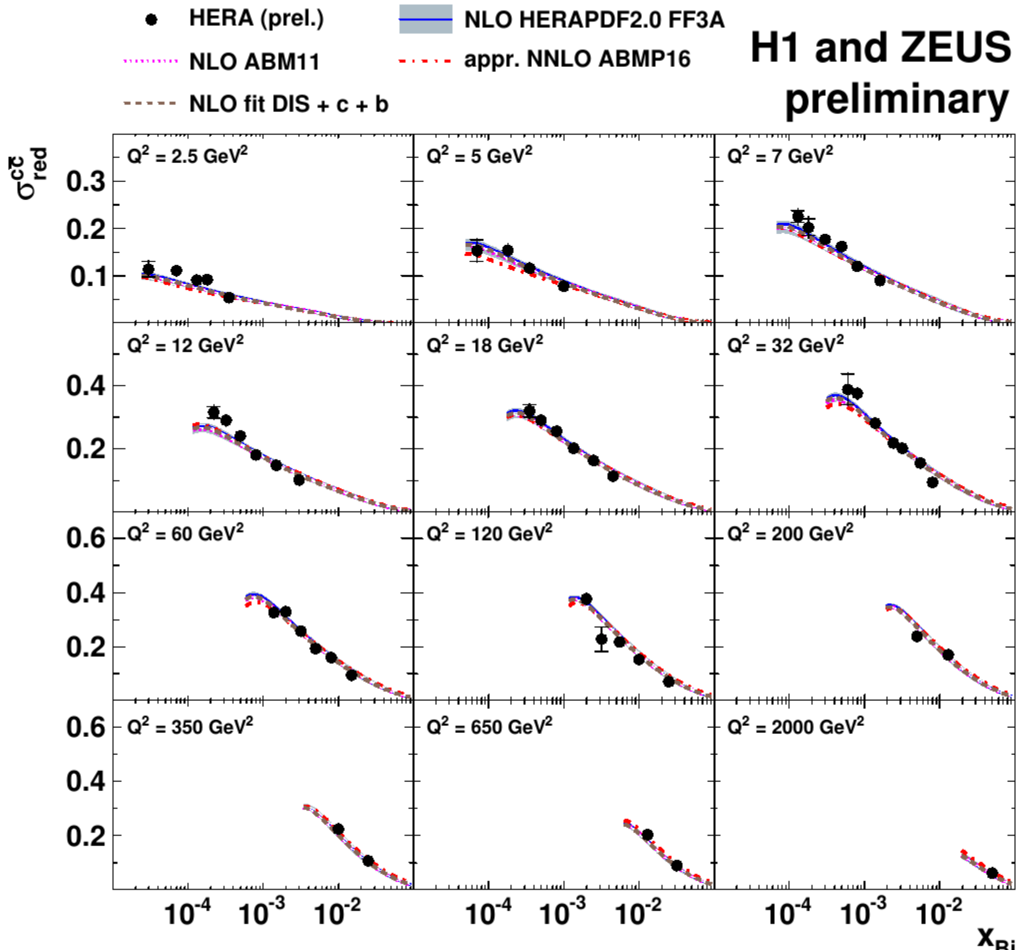
Predictions from OPENQCDRAD

- HERAPDF2.0 FF3A
- ABM11
- ABMP16 + approx. NNLO
- PDF-fit

Scales are...

$$\mu_r = \mu_f = \sqrt{Q^2 + 4m_Q^2},$$

Theory provides in general reasonable agreement



Combination and quark masses

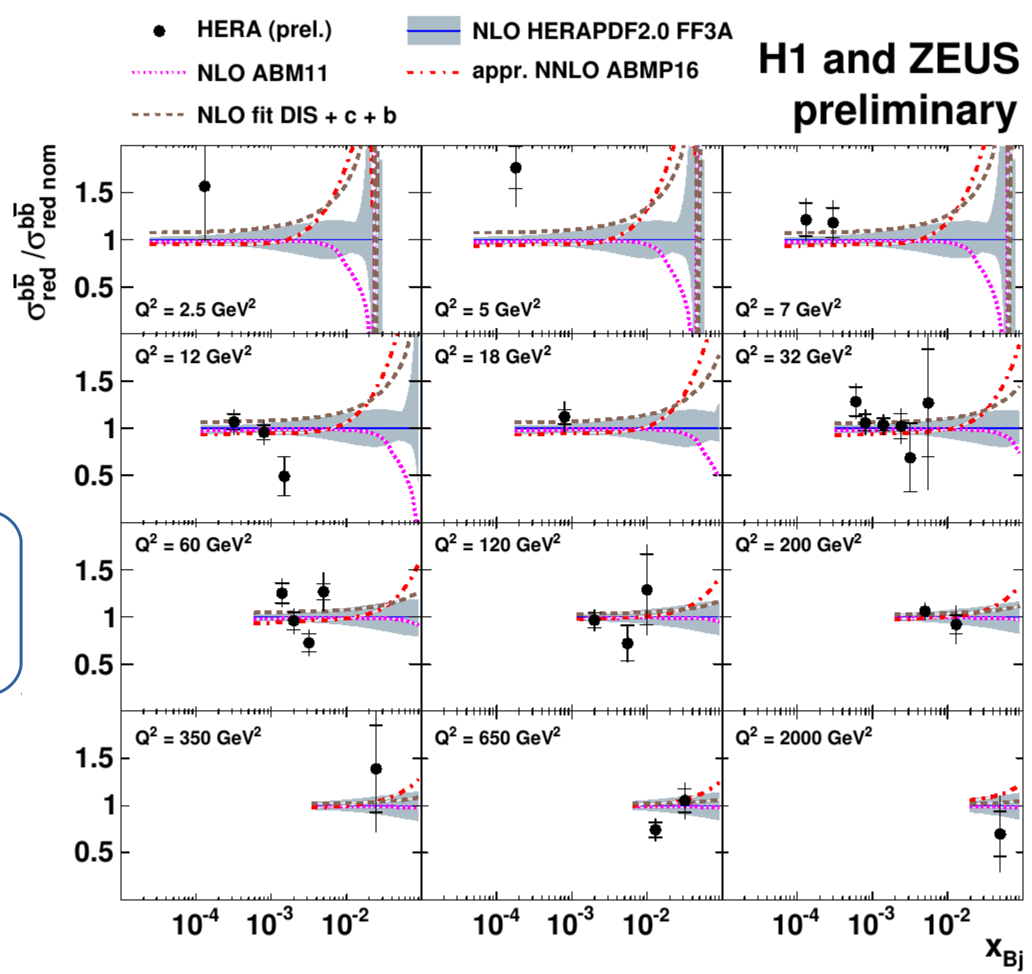
Beauty cross sections
- First combination of beauty cross sections
- In general well described by theory
- Marginal differences between PDFs

HQ mass determinations
- Perform FFNS (n_f=3) PDF fit including HERA inclusive NC&CC data
- m_c and m_b are free parameters in PDF fit

$$m_c(m_c) = 1290^{+46}_{-41}(\mathrm{fit})^{+62}_{-14}(\mathrm{mod})^{+7}_{-31}(\mathrm{par})\ \mathrm{MeV},$$
$$m_b(m_b) = 4049^{+104}_{-109}(\mathrm{fit})^{+90}_{-32}(\mathrm{mod})^{+1}_{-31}(\mathrm{par})\ \mathrm{MeV}.$$

Competitive experimental precision
- Consistent with PDG values
- model and parameterisation uncertainties are significant

Beauty cross sections



Prompt photons in DIS

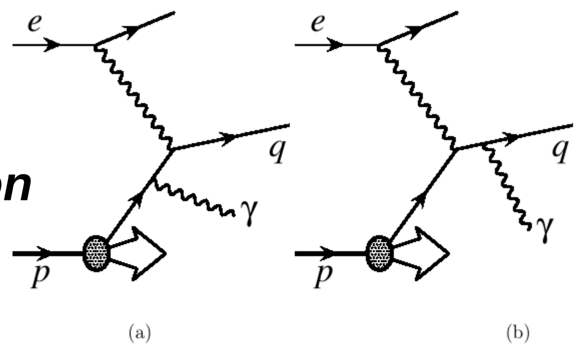
Prompt photons with jets in DIS

- Photons emitted from quark or lepton
- Photons are radiated before hadronisation
- Direct test of ME
- Complements earlier result *[Phys. Lett. B 715 (2012) 88]*

Fine segmentation of calorimeter in z-direction

- Suppression of $\pi^0 \to \gamma\gamma$ background

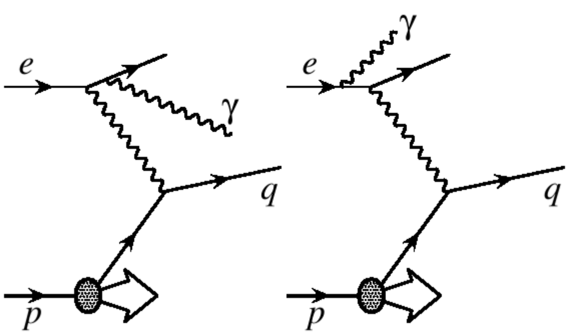
QQ - photons



γ is emitted from quark as part of hard process

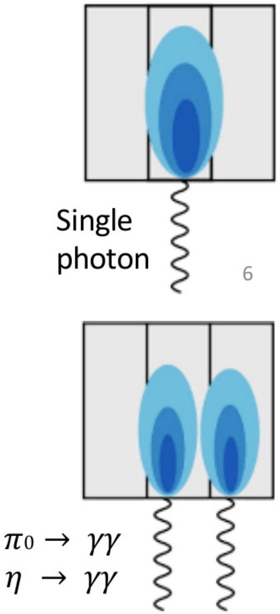
→ hard process, similar to multi-jets

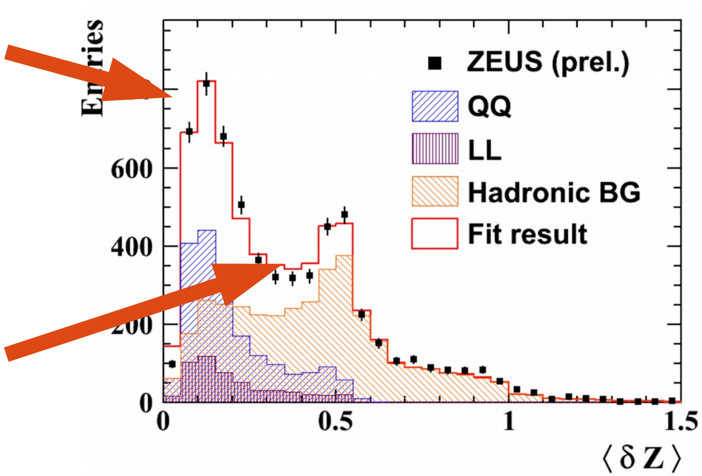
LL - photons



γ is radiated from incoming or outgoing lepton

→ theoretically well determined





<δZ> calculated for each cluster from individual BEMC cell deposits

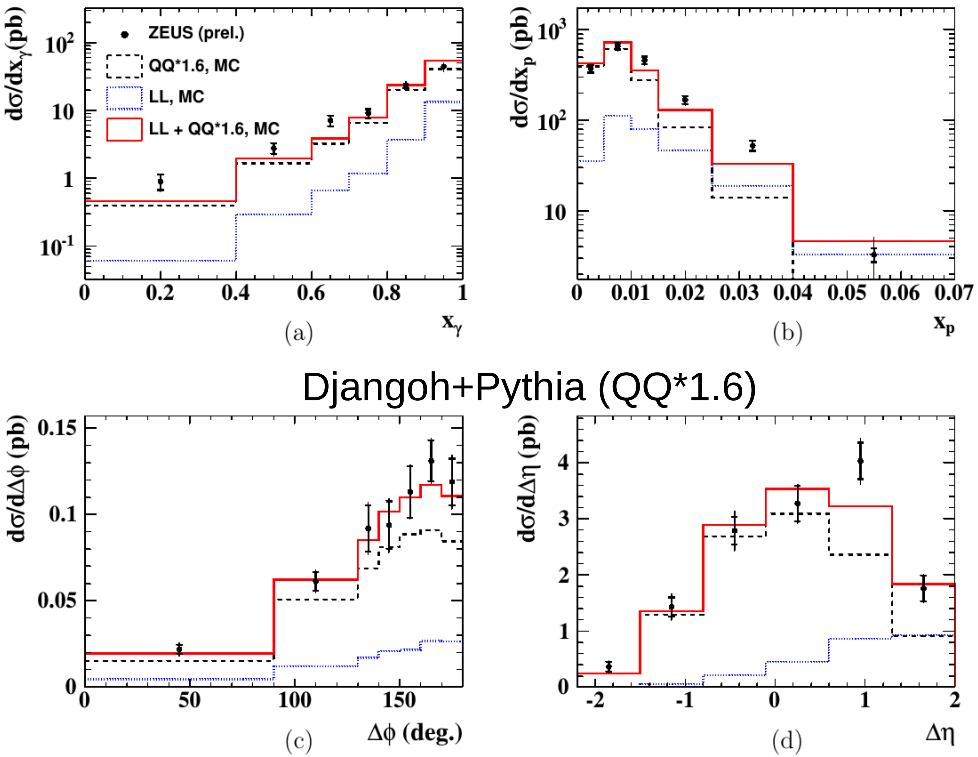
Prompt photons in DIS

Cross section as a function of

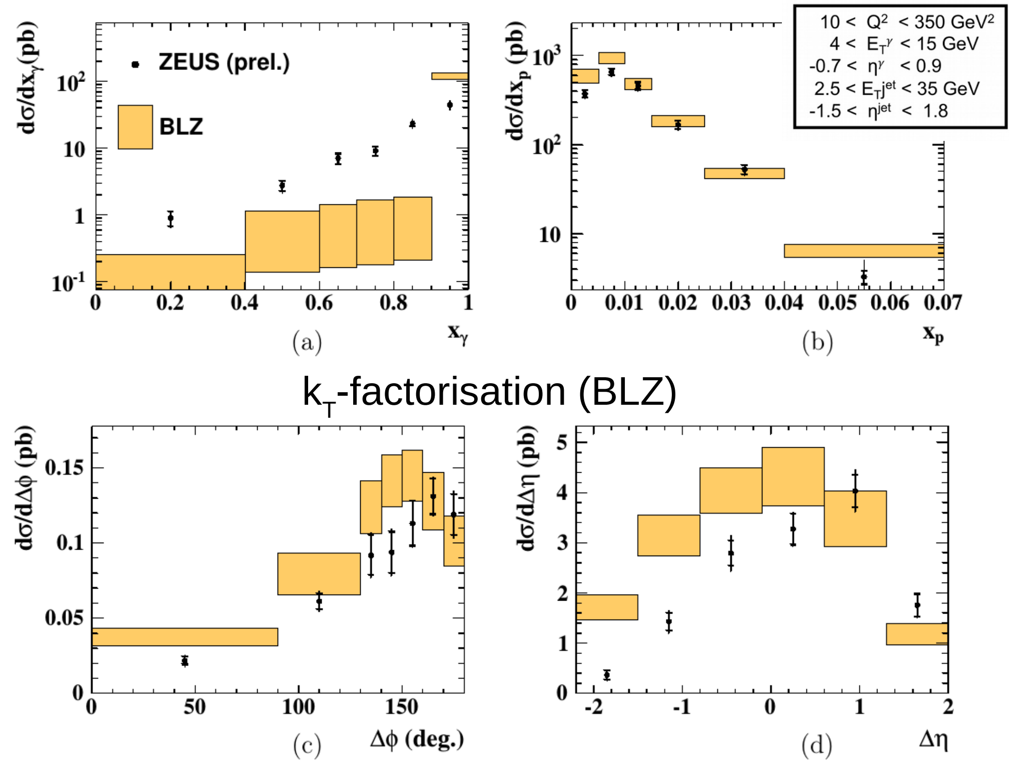
- x_γ,x_p – fraction of incoming photon (proton) energy taken by γ+jet (parton)
- $\Delta\varphi$,$\Delta\eta$ – separations of photon and e or jet

Weighted LO MC – Djangoh/Pythia

- Weighting of QQ by 1.6 provides good description
- k_T-factorisation fails to describe x_γ -> More investiagations needed (-> DIS17)

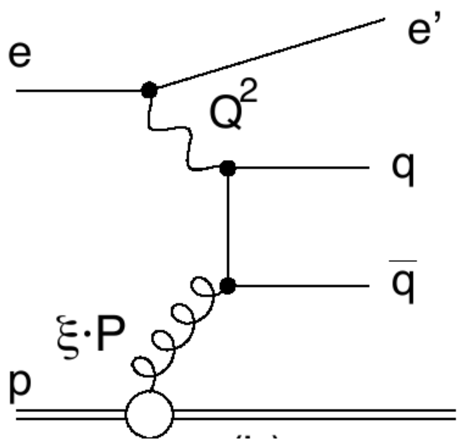


Djangoh+Pythia (QQ*1.6)

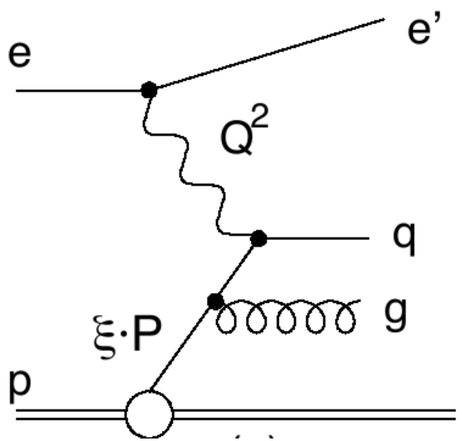


k_T-factorisation (BLZ)

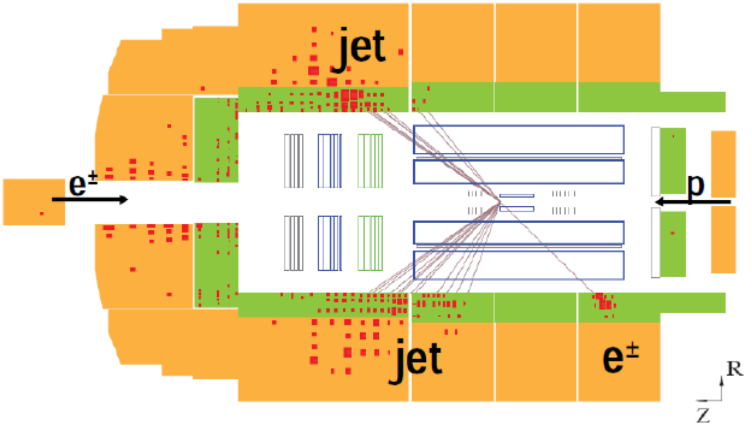
Jet production in DIS



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

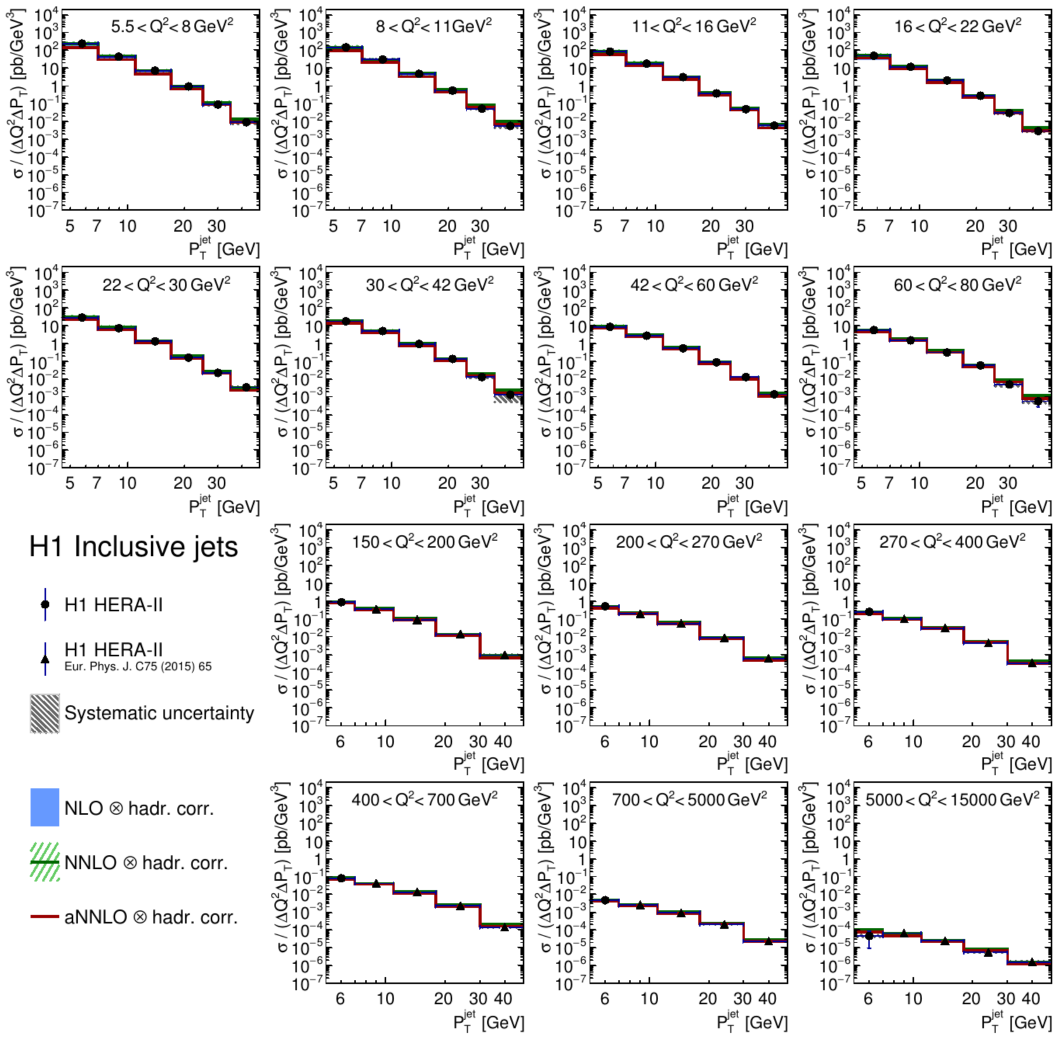
Jet production in DIS at low Q^2

Simultaneous measurement of
- <u>inclusive jets</u>, <u>dijet</u> and <u>trijet</u>
- Statistical correlations preserved

Moreover
<u>normalised</u> jet cross sections
- Normalisation to inclusive NC DIS
- Some cancellation of uncertainties

Phase space of cross sections

NC DIS	$5.5 < Q^2 < 80\ \mathrm{GeV}^2$
	$0.2 < y < 0.6$
(inclusive) Jets	$P_T^{jet} > 4.5$ GeV
	$-1.0 < \eta^{lab} < 2.5$
Dijet and Trijet Measure average p_T	$\langle P_T^{jet}\rangle_2 > 5.0$ GeV
	$\langle P_T^{jet}\rangle_3 > 5.5$ GeV



Jet production in NC DIS

Inclusive jets

- Low-Q^2 new analysis
- High-Q^2 extension of previous results

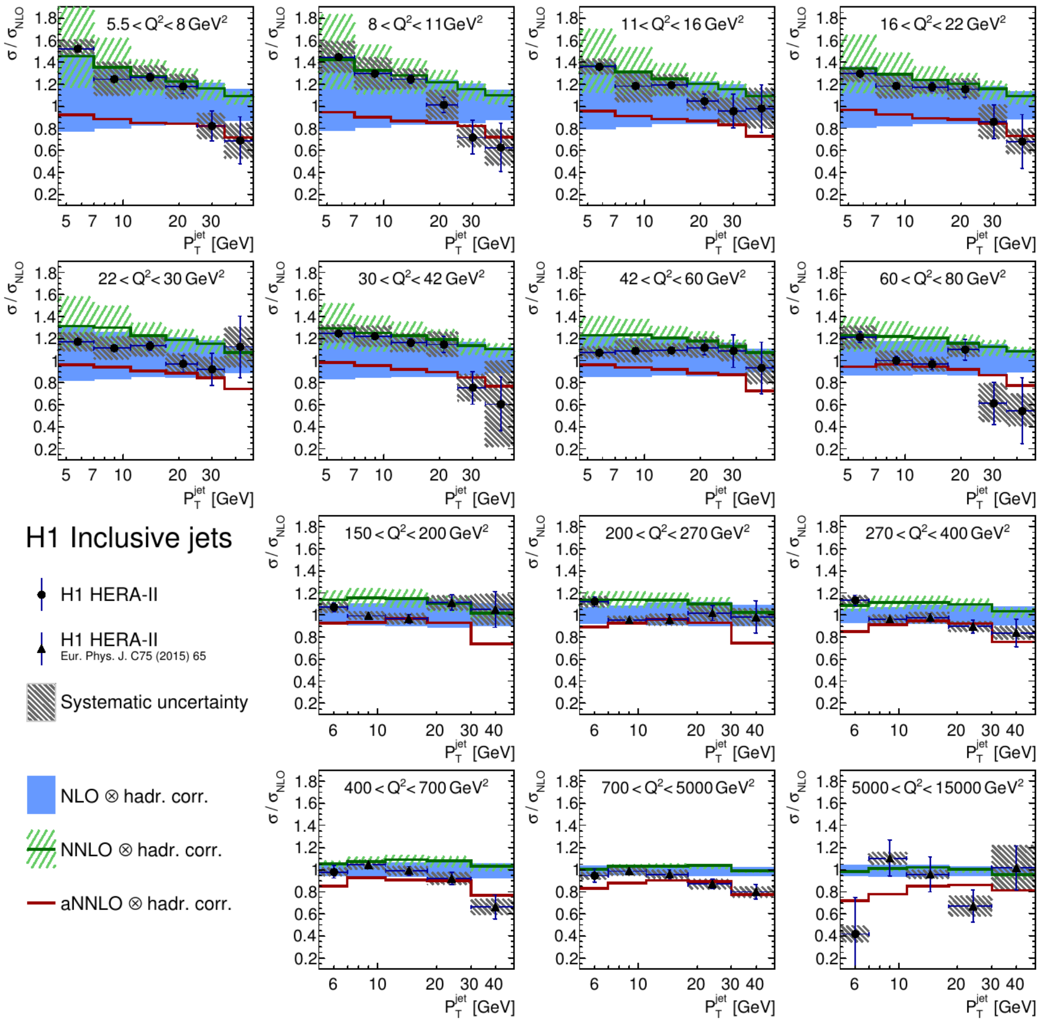
NLO & aNNLO

- Reasonable description by NLO
- approx. NNLO from JetVip
  - threshold resummation
    [PR D 92 (2015) 074037]
  - somewhat improved shape

NNLO from NNLOJET

PRL 117 (2016) 042001
arXiv:1703.05977

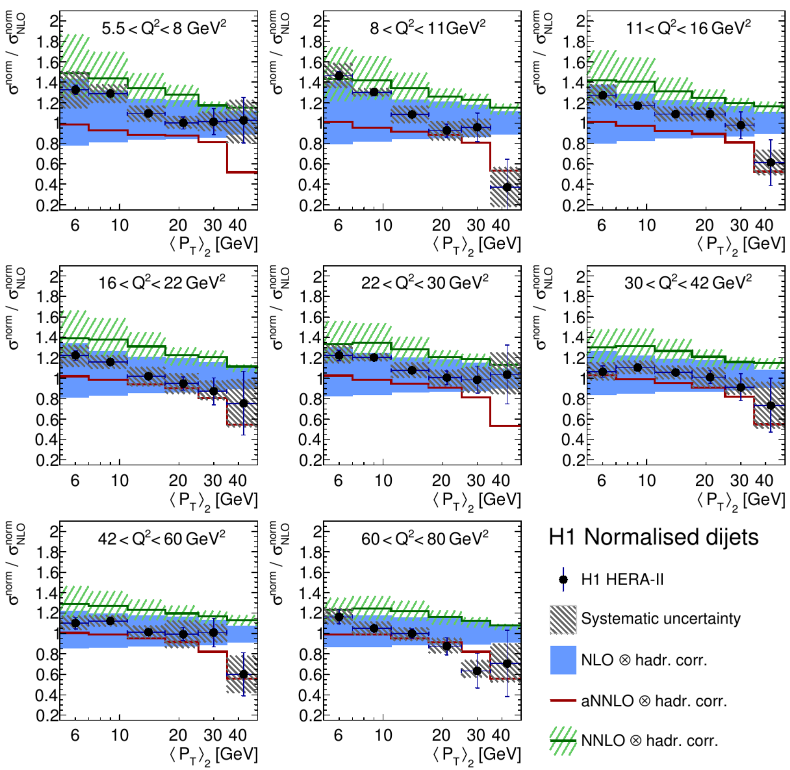
- Improved description
- Significantly reduced scale uncertainty (particularly for higher scales)
- See talk by J. Niehues



Dijet and trijet production

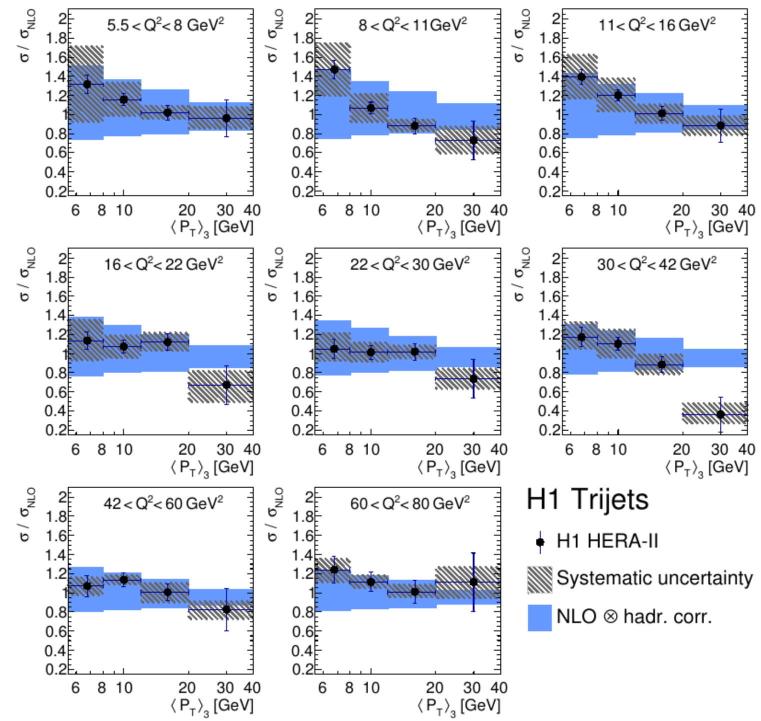
Dijets in comparison to theory

- NLO reasonable description
- NNLO Significantly improved shape
- Norm. jets: NC DIS problematic in NNLO



Trijet

- NLO good description with moderate precision



$\alpha_s(m_Z)$ in NLO ... (now improved with NNLO [next slides])

$$\alpha_s(M_Z) = 0.1172\,(4)_{\mathrm{exp}}\,(3)_{\mathrm{PDF}}\,(7)_{\mathrm{PDF}(\alpha_s)}\,(11)_{\mathrm{PDFset}}\,(6)_{\mathrm{had}}\,(^{+51}_{-43})_{\mathrm{scale}}$$

Strong coupling from jets in NNLO

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

Jet cross sections directly sensitive to α_s

- *Two α_s-dependencies* (we consider both)

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

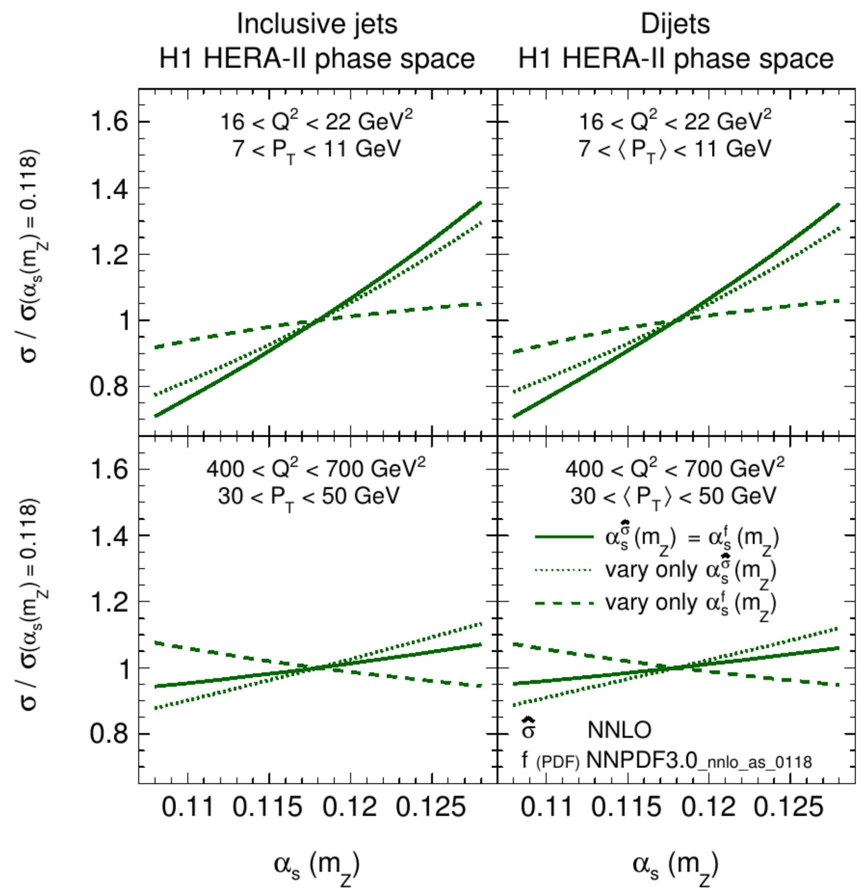
PDFs $\frac{\partial f}{\partial \alpha_s} = \frac{\mathcal{P} \otimes f}{\beta}$

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

Jet measurements by H1

Kinematic range of H1 jet data

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

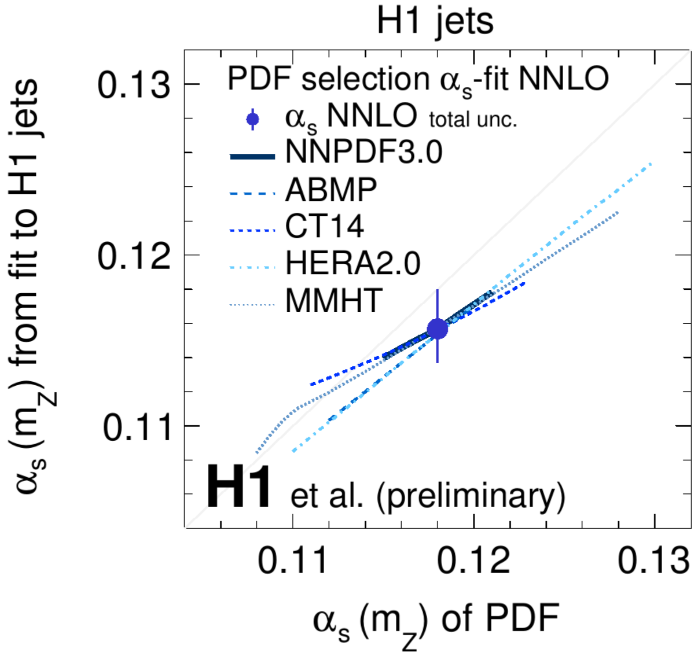


- 5 inclusive jet data sets (137 pts)
- 4 dijet data sets (103 pts)

Strong coupling in NNLO from jets

PDF selection for predictions

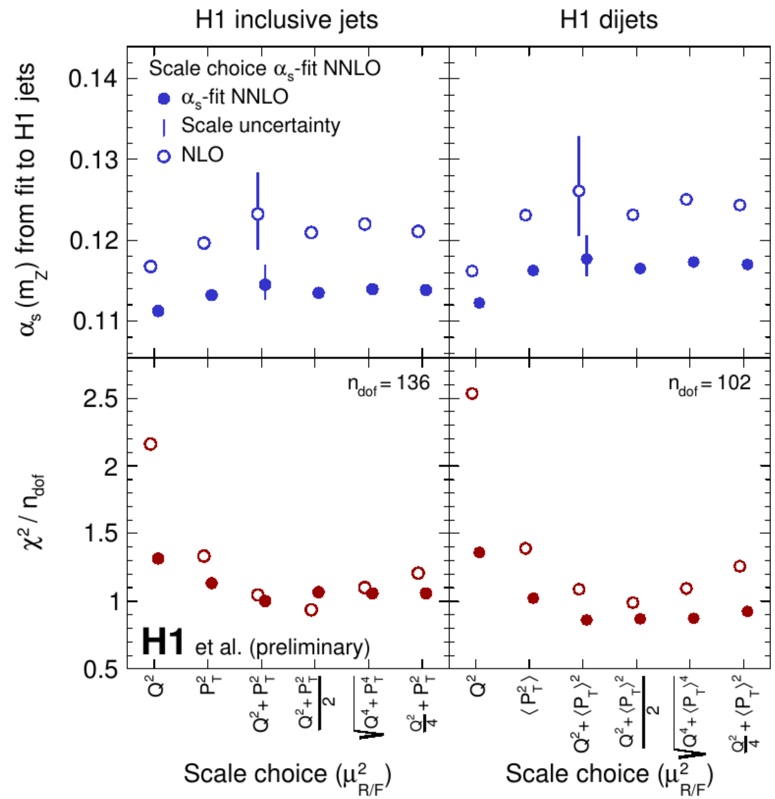
- PDF are external input to NNLO theory
  - PDF set (ABMP,CT,HERA,MMHT,NNPDF)
  - $\alpha_s(m_Z)$ which is input to PDF extraction



- All PDFs with comparable results
- $\alpha_s(m_Z)$ of PDF is important

Scale choice for NNLO predictions

- Study functional form of μ_R and μ_F



Reduced scale-dependence w.r.t NLO
More NNLO studies: talk by J. Niehues

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

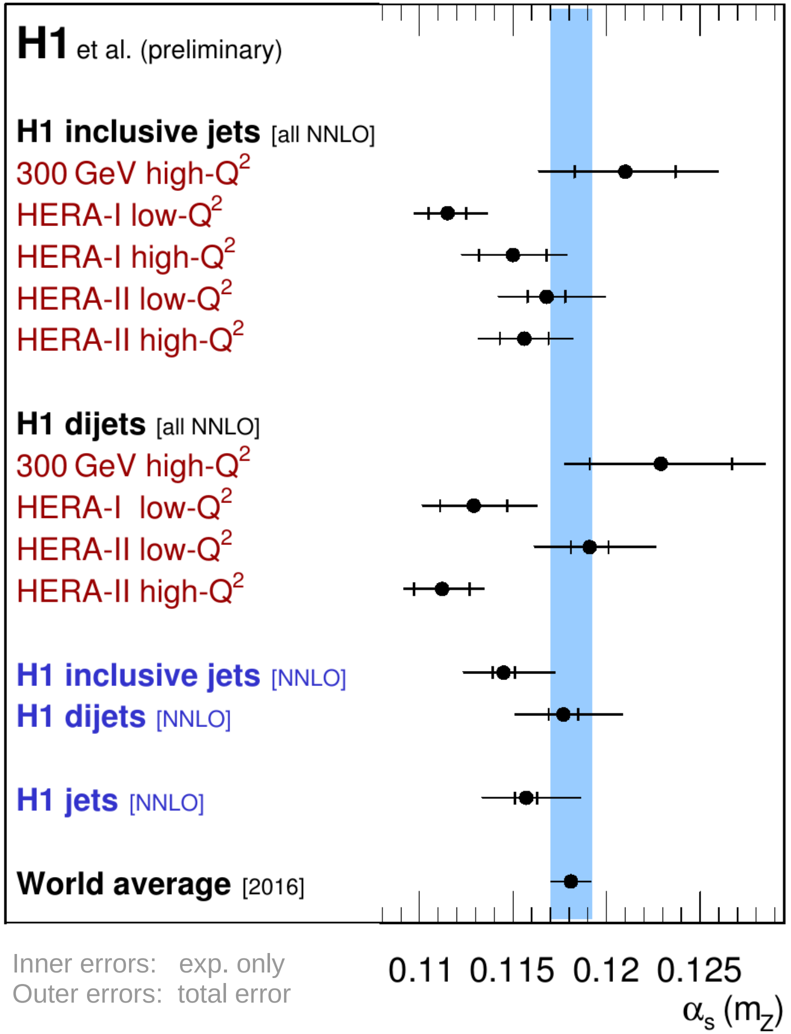
- High experimental precision
- Scale uncertainty is largest (theory) error
- All fits with good χ^2
  -> consistency of data

H1 jets (203 data points)

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

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

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



Strong coupling in NNLO from jets

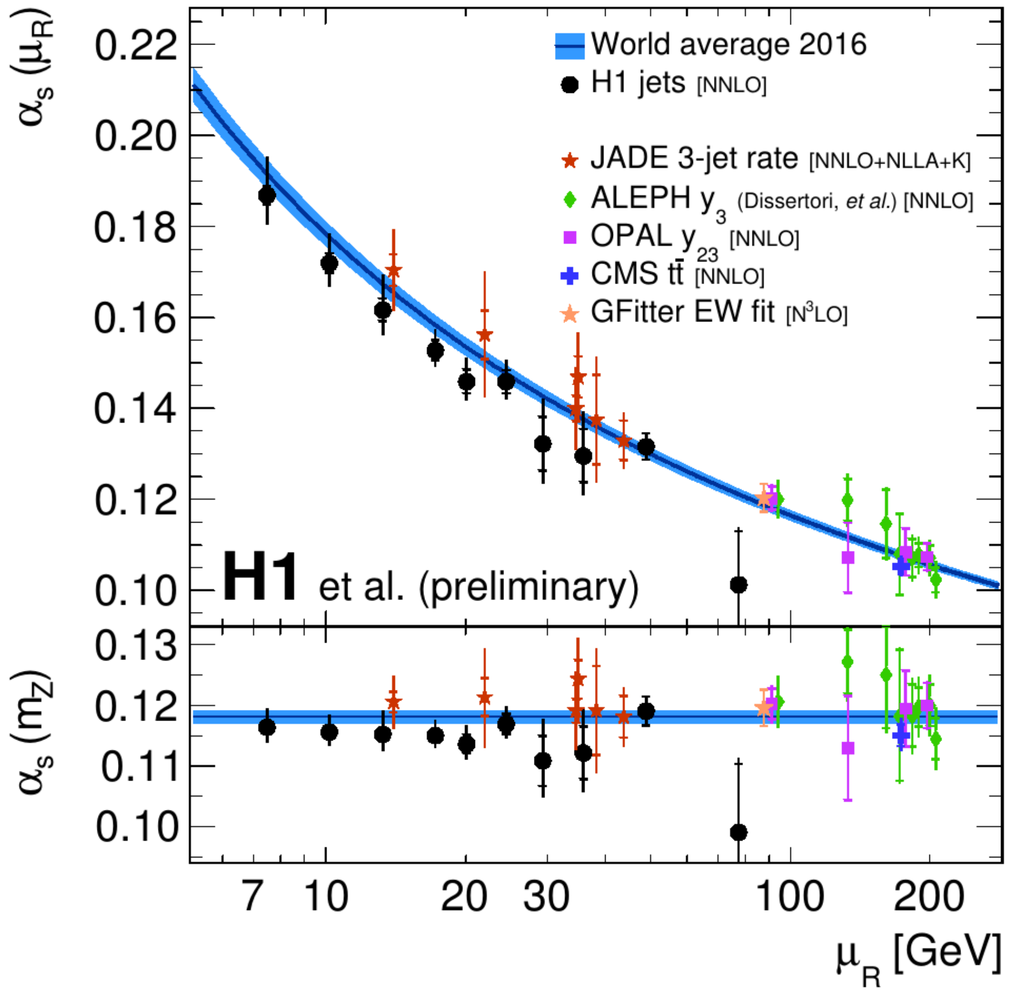
H1 in collaboration with
V. Bertone, J. Currie, T. Gehrmann,
C. Gwenlan, A. Huss, J. Niehues, M. Sutton

Test running of strong coupling

- Repeat fits to groups of data points at similar scales
- All fits with good χ^2

- Theory uncertainty often larger than experimental uncertinaty
- Confirmation of 'running' between 7-90 GeV

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



Summary

Combination of charm and beauty reduced cross sections

- Charm and beauty quark masses

H1prelim-17-071, ZEUS-prel-17-001

Prompt photons in DIS: new observables studied

- Direct tests of hard process

ZEUS-prel-16-001

Jet cross sections in DIS

- New NNLO predictions provide good description
- High sensitivity to gluon PDF and strong coupling

DESY-16-200 (acc. by EPJ C)

Strong coupling in NNLO from jets

- Comprehensive phenomenological study of new NNLO calculations
  -> High experimental precision and good theoretical precision

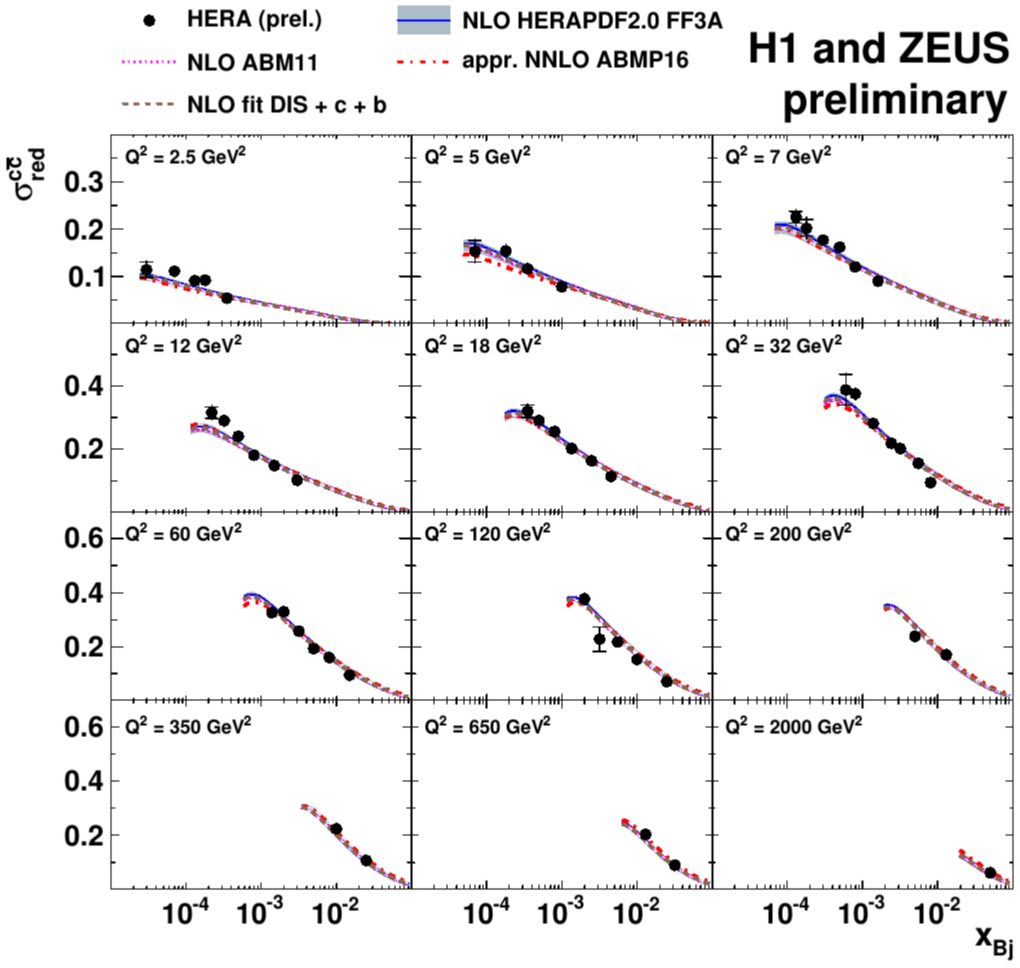
H1prelim-17-031 (H1 et al.)

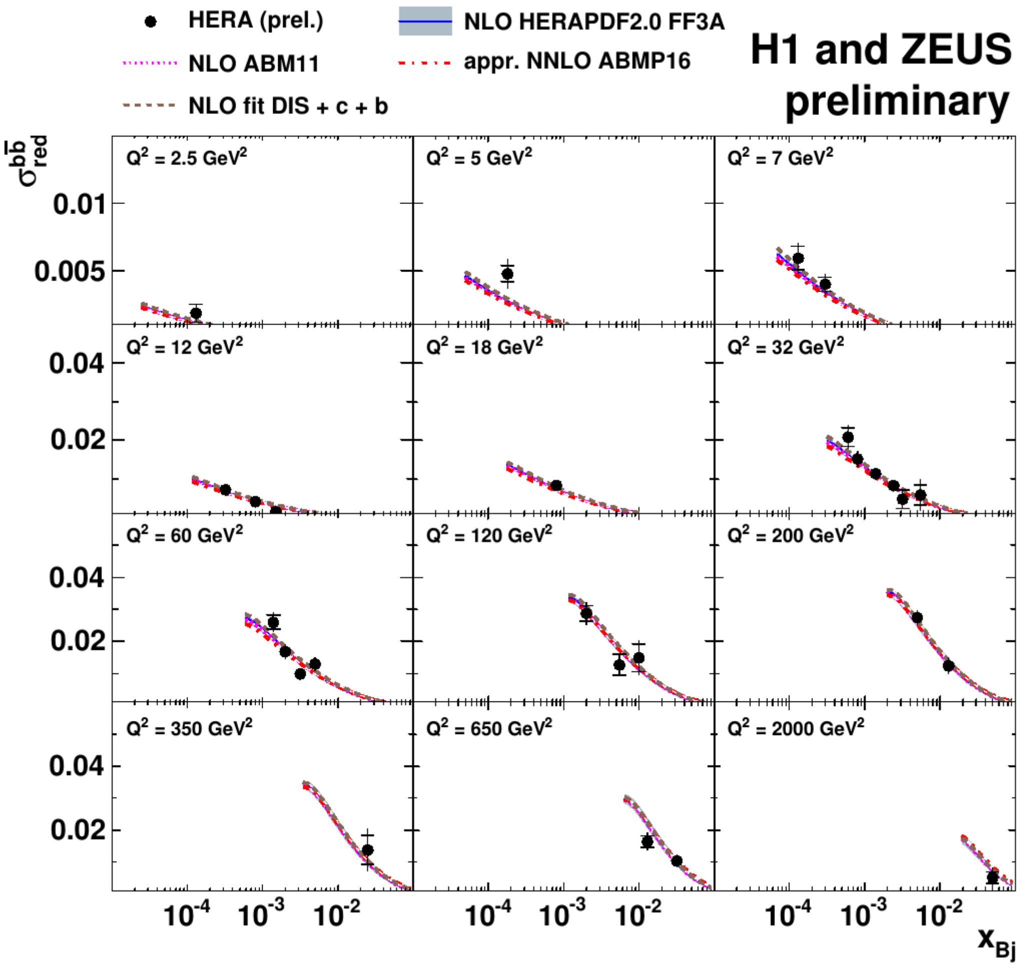
Results not covered in this talk

- Search for QCD instantons
  -> excludes significant part of phase space predicted by Instanton model
  EPJ C76 (2016), 7
- Improved limit on Pentaquark production cross section (pK^0_s)
  Phys. Lett. B 759 (2016) 446
- Diffractive photoproduction of prompt photons
  to be subm. next week
- Running of the charm mass
  to be subm. O(2 weeks)
- Charm production (D*) in diffractive DIS
  -> probes: DPDFs, NLO theory & factorisation properties in diffr. DIS
  to be subm. next week

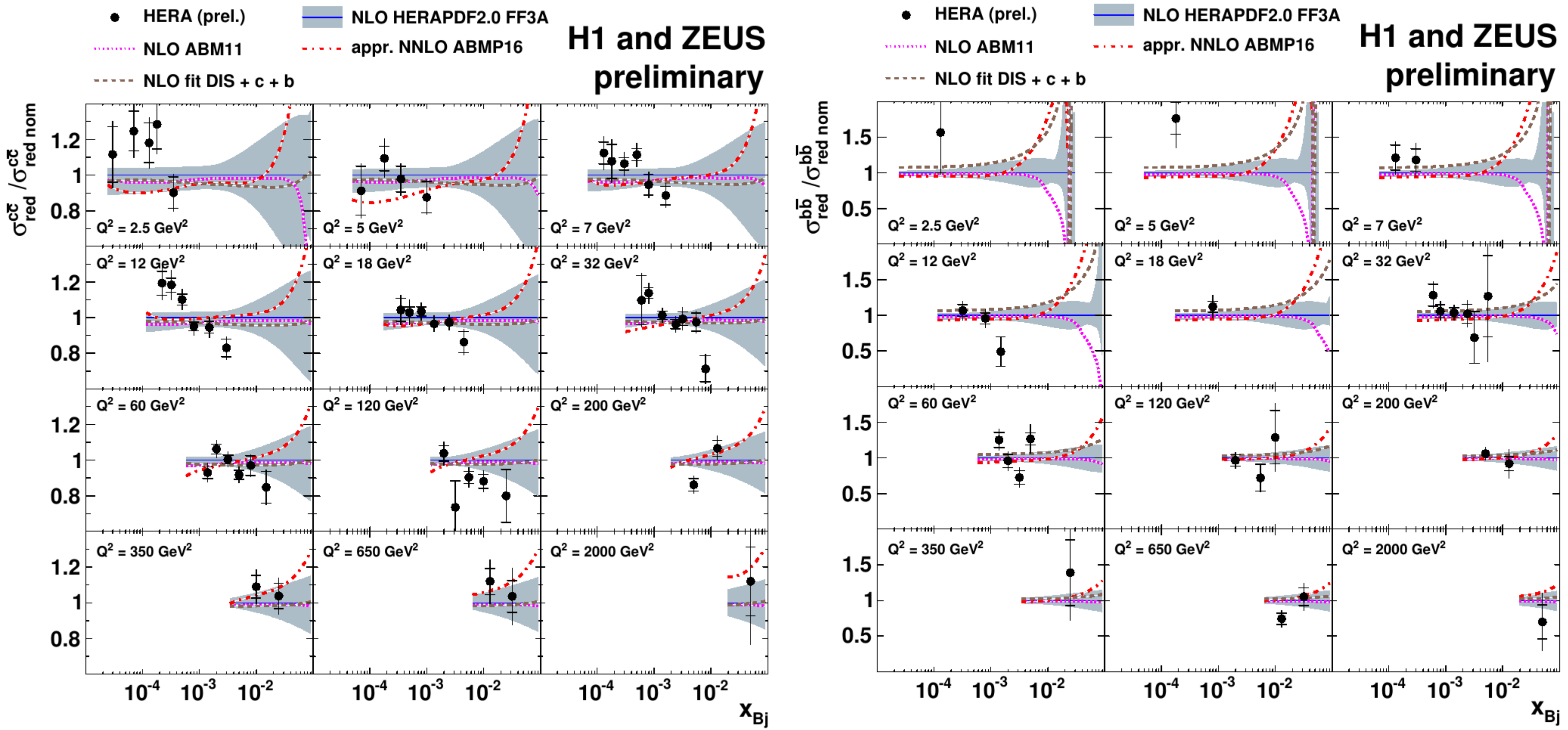
Backup

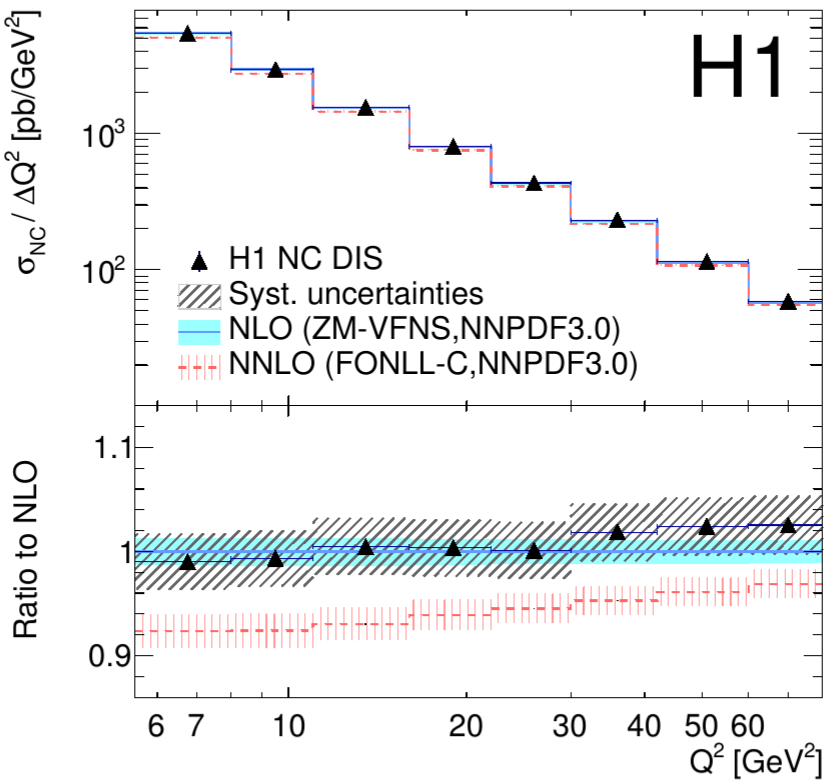
Charm and beauty combination

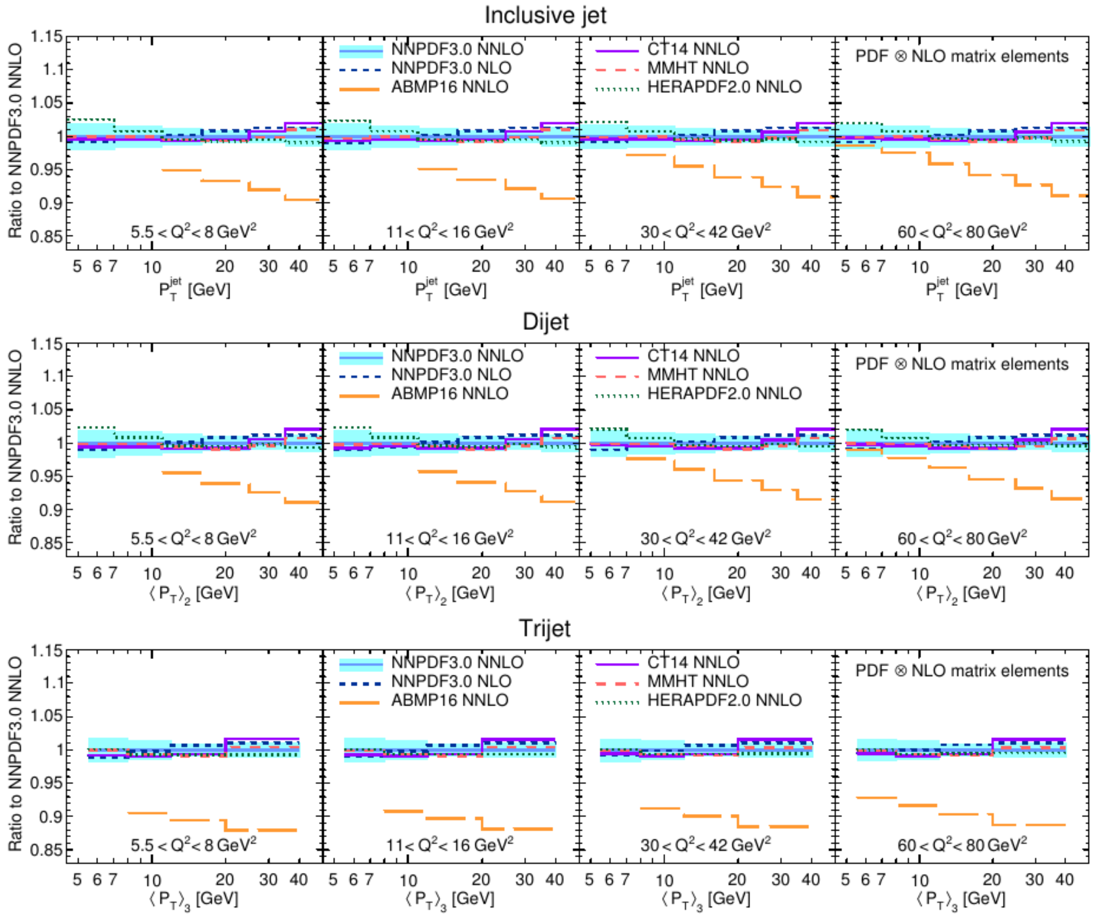




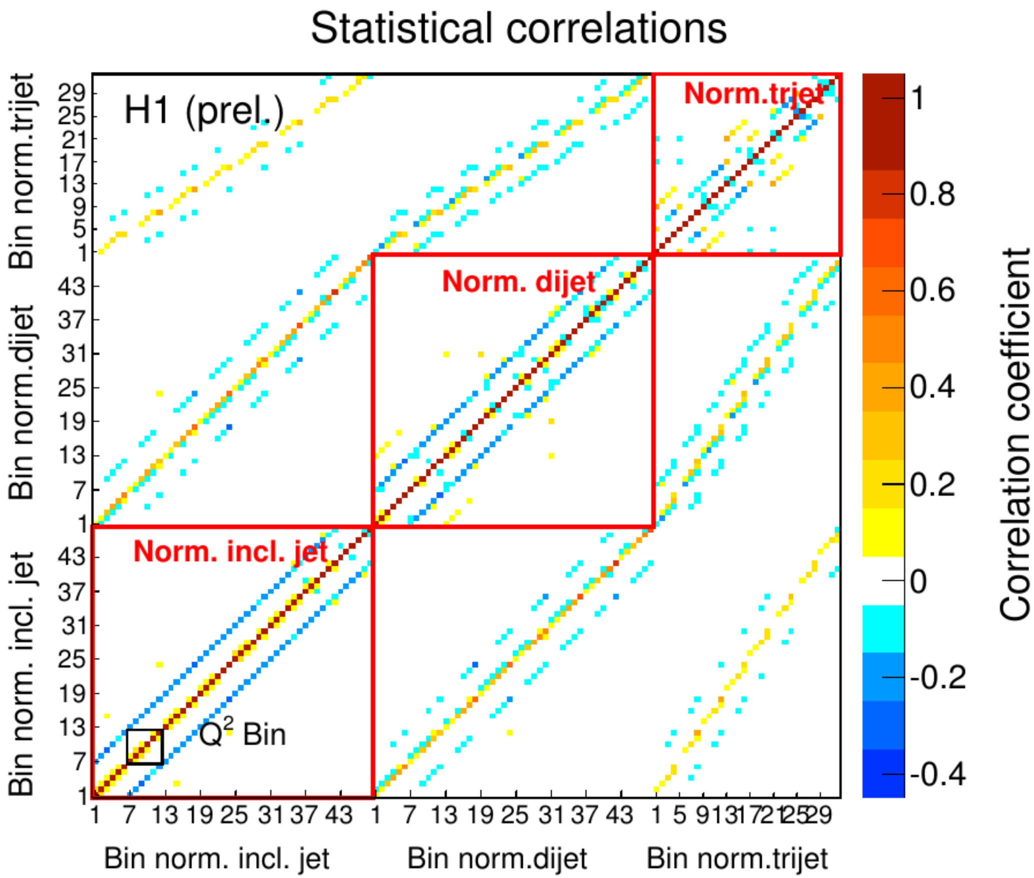
Charm and beauty cross section ratios




H1
H1 NC DIS
Syst. uncertainties
NLO (ZM-VFNS,NNPDF3.0)
NNLO (FONLL-C,NNPDF3.0)
$\sigma_{NC} / \Delta Q^2$ [pb/GeV^2]
Ratio to NLO
Q^2 [GeV^2]


Inclusive jet
Dijet
Trijet
NNPDF3.0 NNLO
NNPDF3.0 NLO
ABMP16 NNLO
CT14 NNLO
MMHT NNLO
HERAPDF2.0 NNLO
PDF ⊗ NLO matrix elements
Ratio to NNPDF3.0 NNLO
$5.5 < Q^2 < 8$ GeV^2
$11 < Q^2 < 16$ GeV^2
$30 < Q^2 < 42$ GeV^2
$60 < Q^2 < 80$ GeV^2
P_T^{jet} [GeV]
$\langle P_T \rangle_2$ [GeV]
$\langle P_T \rangle_3$ [GeV]

Stat. correlations of H1 low-Q^2 multijets



Strong coupling from jets in NNLO

Jet cross sections directly sensitive to α_s

- *Two dependencies* *(we consider both)*

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

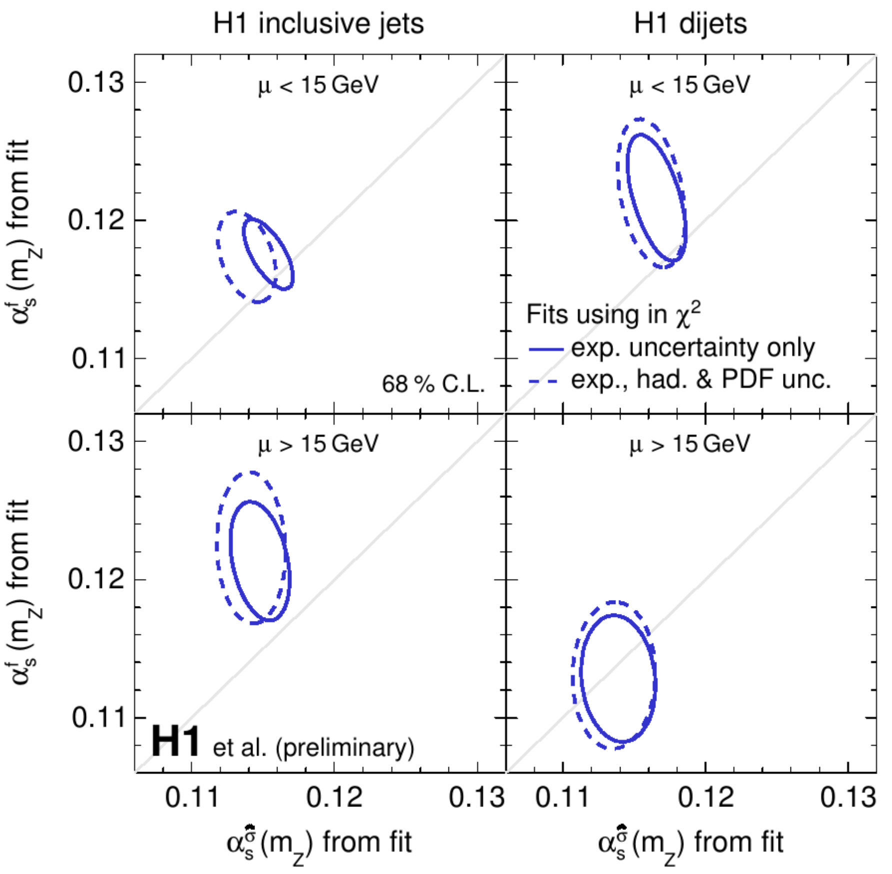
PDFs $\frac{\partial f}{\partial \alpha_s} = \frac{\mathcal{P} \otimes f}{\beta}$

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

Fit with two free parameters

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

- *Most sensitivity arises from matrix elements*
- *PDF and ME values are consistent*



Strong coupling in NNLO from jets

Jet measurements by H1

- 5 inclusive jet data sets
- 4 dijet data sets
- 137 & 103 considered data points

- high & low-Q^2 data
- Different running periods and $\sqrt{s}$

- p_T > 4.5 GeV (often > 7 GeV)
- Data below $2m_b$ excluded from fit

Kinematic range of H1 jet data

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

Perform α_s-determination from...

- Individual data sets
- All inclusive jet cross sections
- All dijet cross sections
- 'H1 jet' cross sections (incl. jet & dijet)
  (exclude HERA-I dijets, because of correlations)
- Data points at similar scale (running)

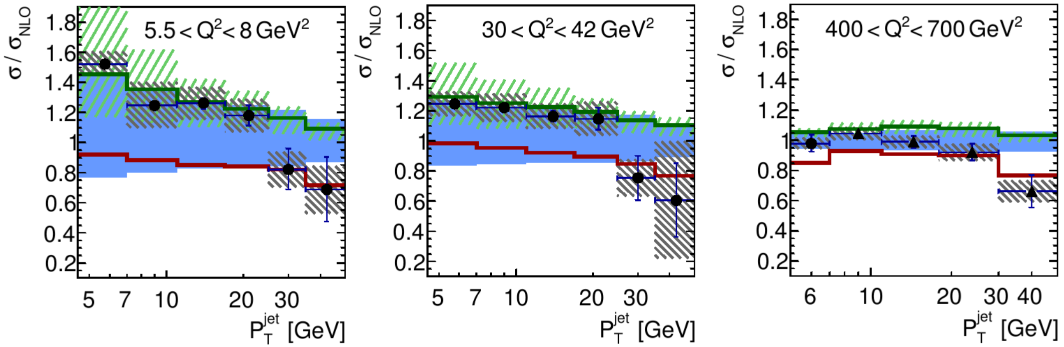
χ^2 minimization

- Account also for PDF and hadronisation uncertainties
- Correlations between data sets

Study of scale uncertainty

Scale uncertainties at various scales μ

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

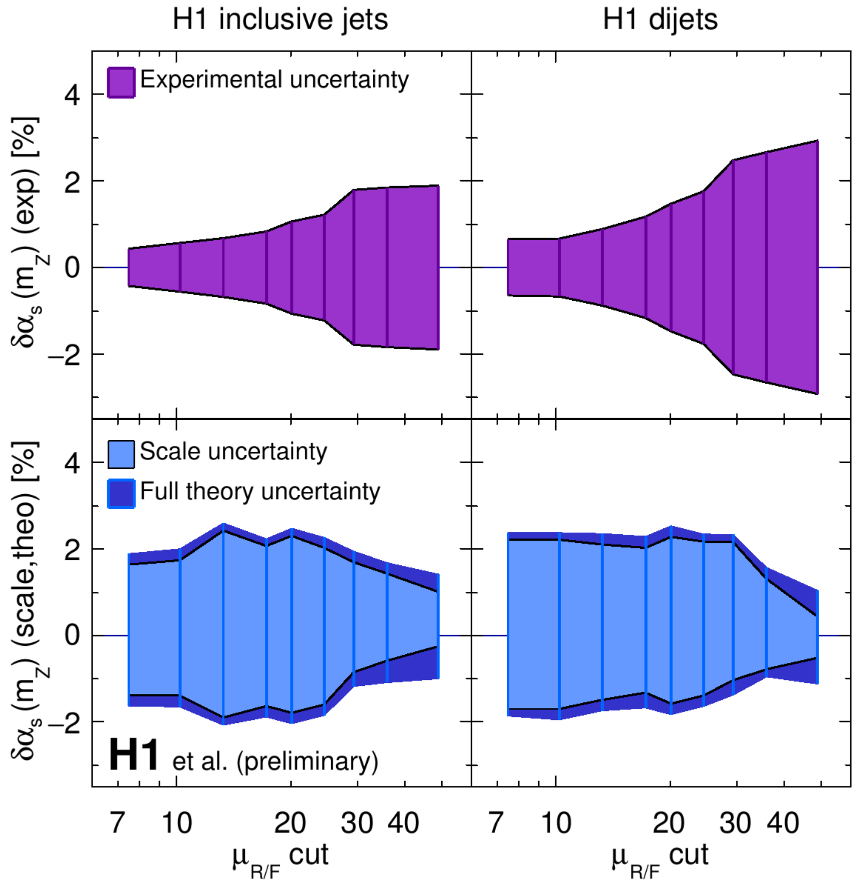


Fits imposing a cut on scale μ_R

- Each data point is assigned a representative scale μ
- Repeat α_s fits: successively cut on μ

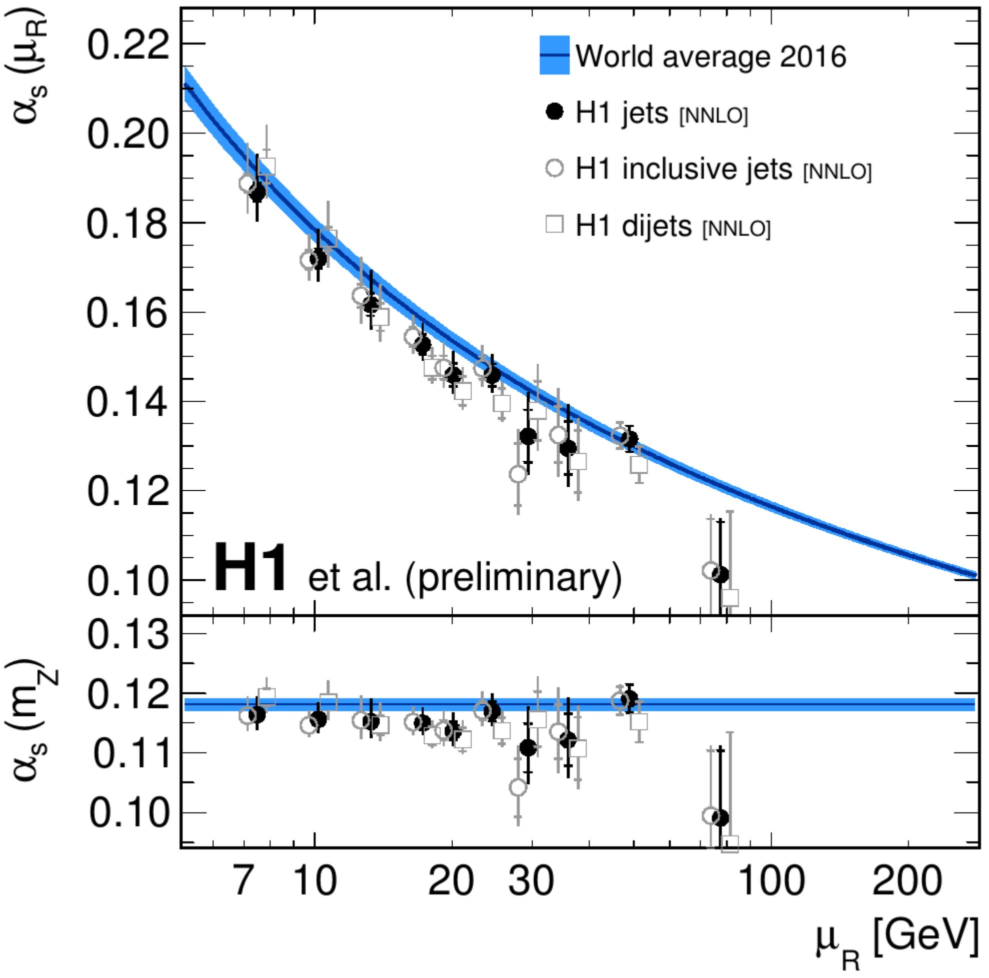
Results

- Experimental uncertainty increases
  (as number of data points decreases)
- Theory (scale) uncertainty remains almost constant
  - NNLO cross sections suggest large scale uncertainty at low-μ...
  - ... but the NNLO predictions at low-μ are finally equally sensitive to α_s

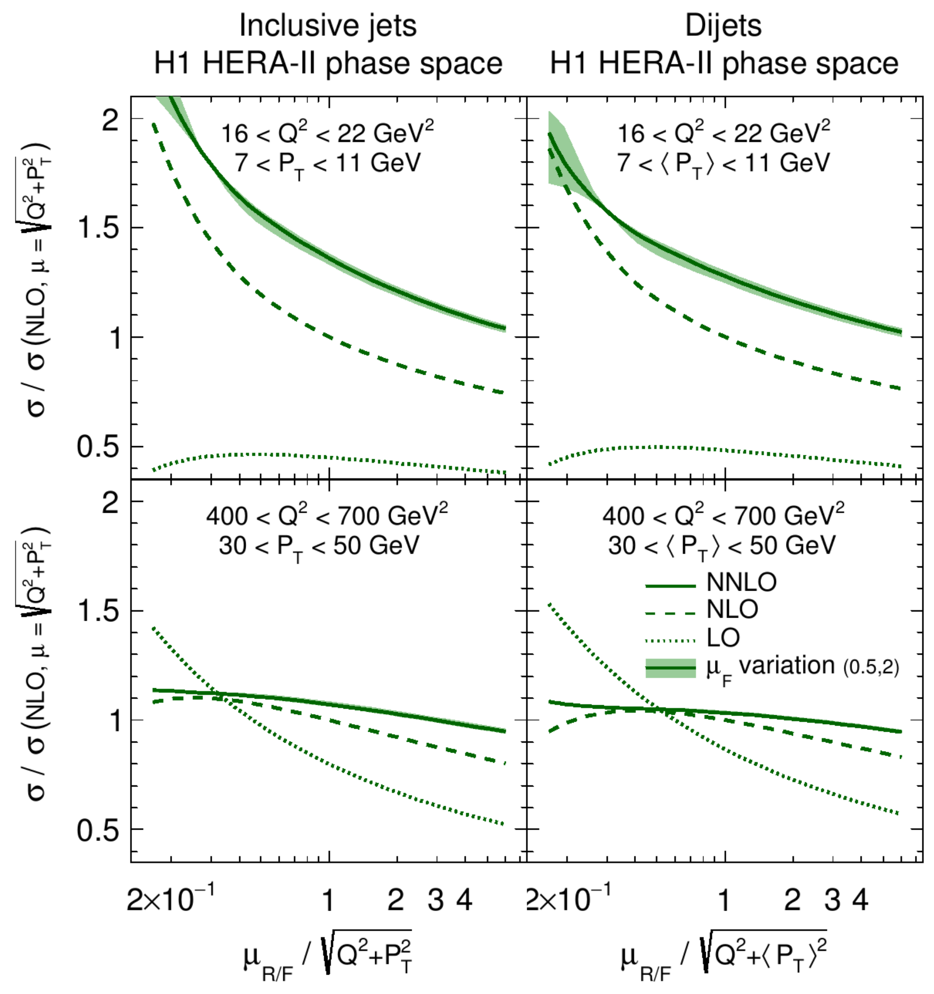


Cut on μ can balance between exp. and theoretical uncertainties at constant total precision

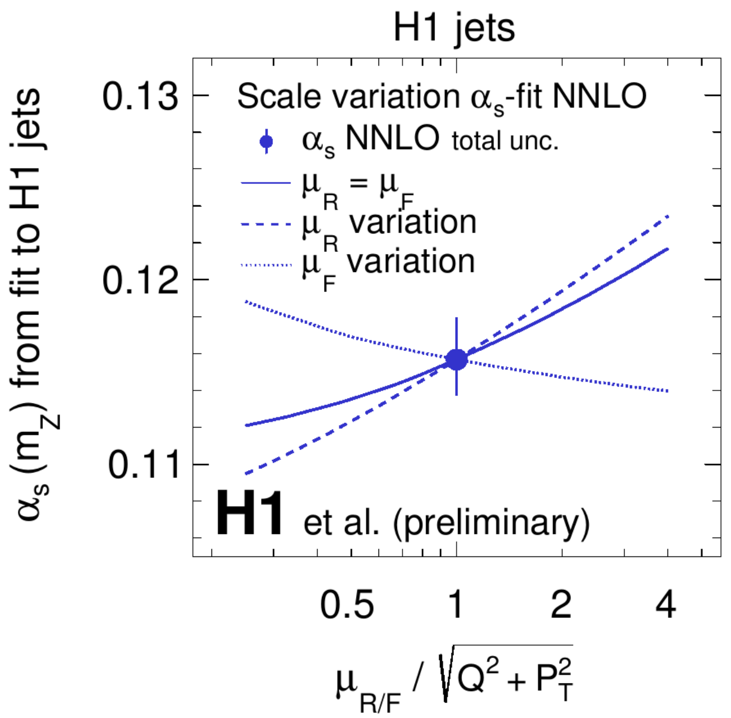
Running from inclusive jets and dijets

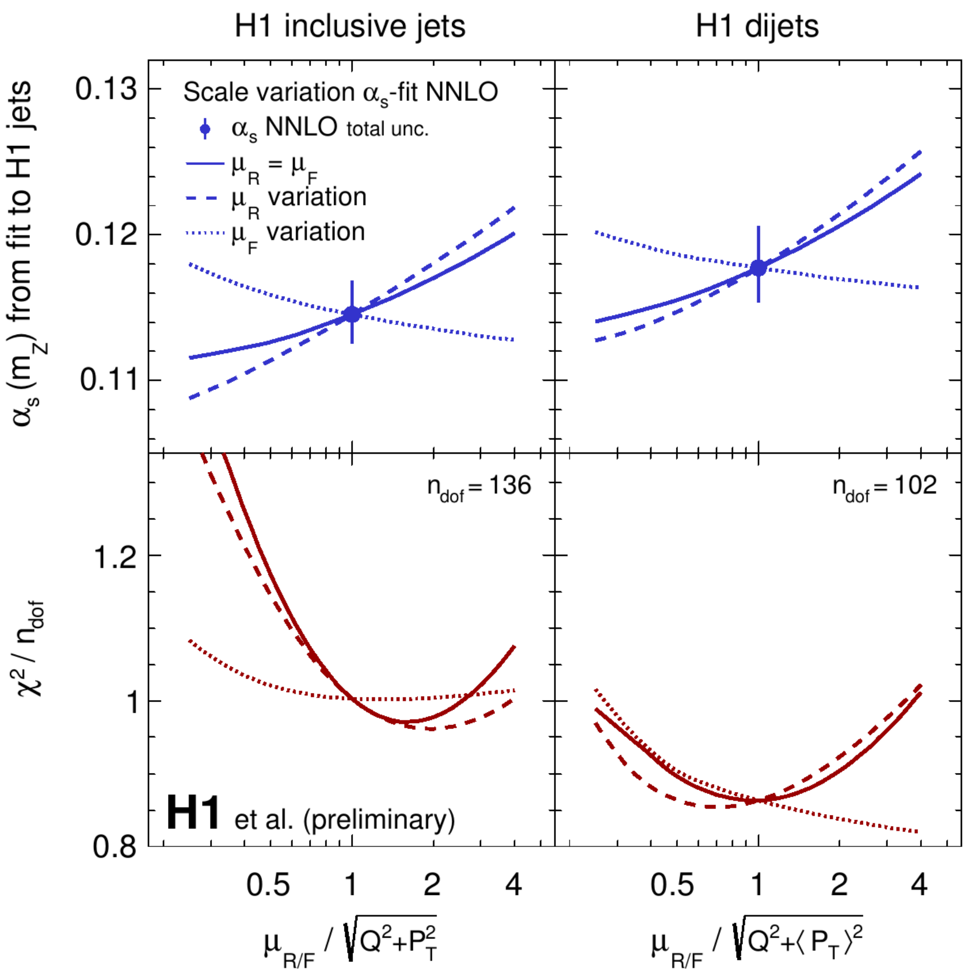


Scale dependence of cross sections

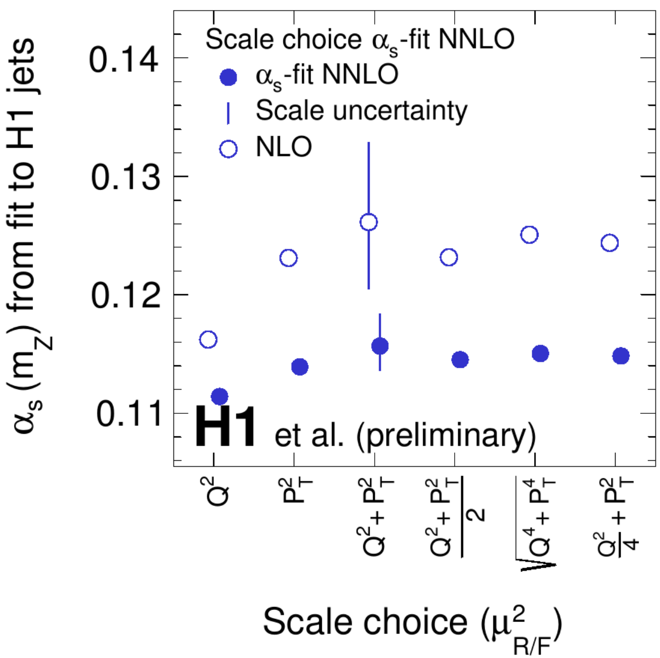


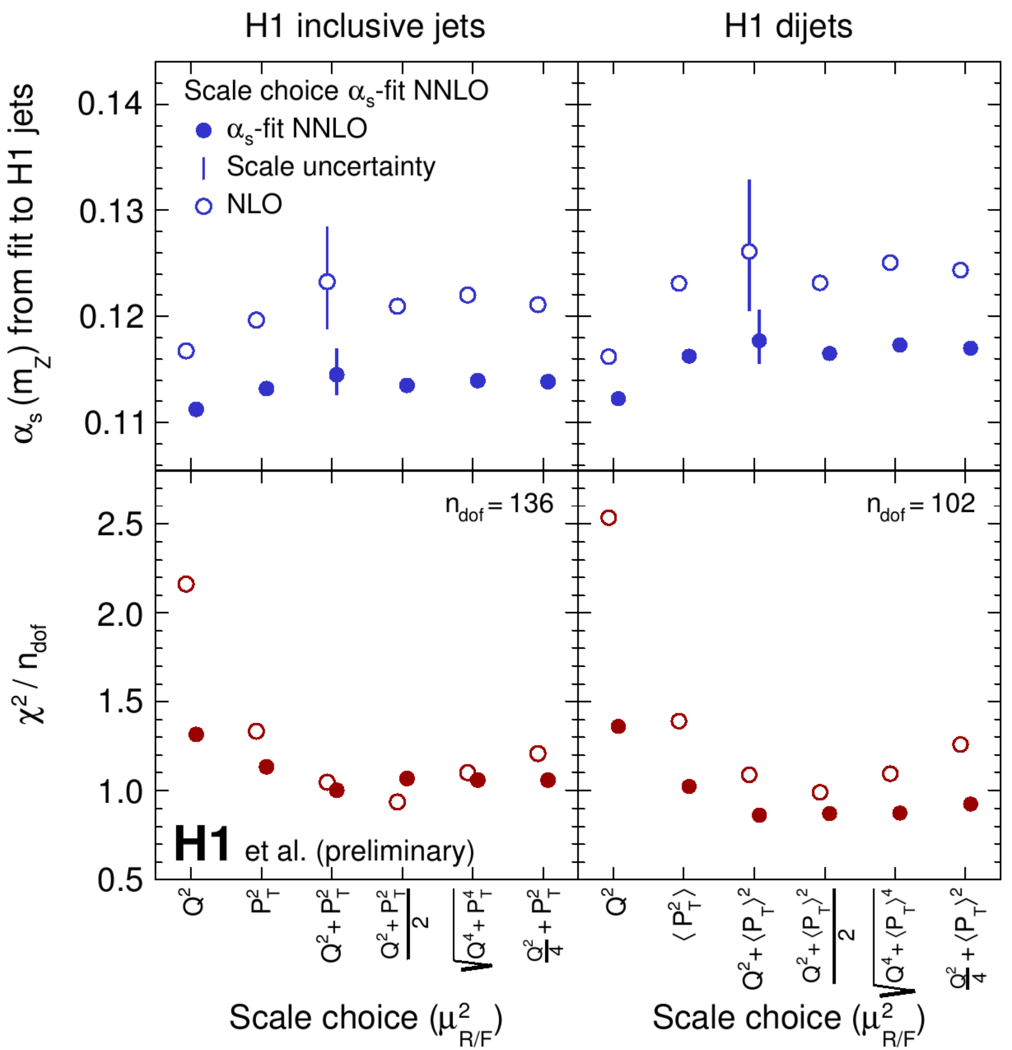
Scale dependence of α_s fit



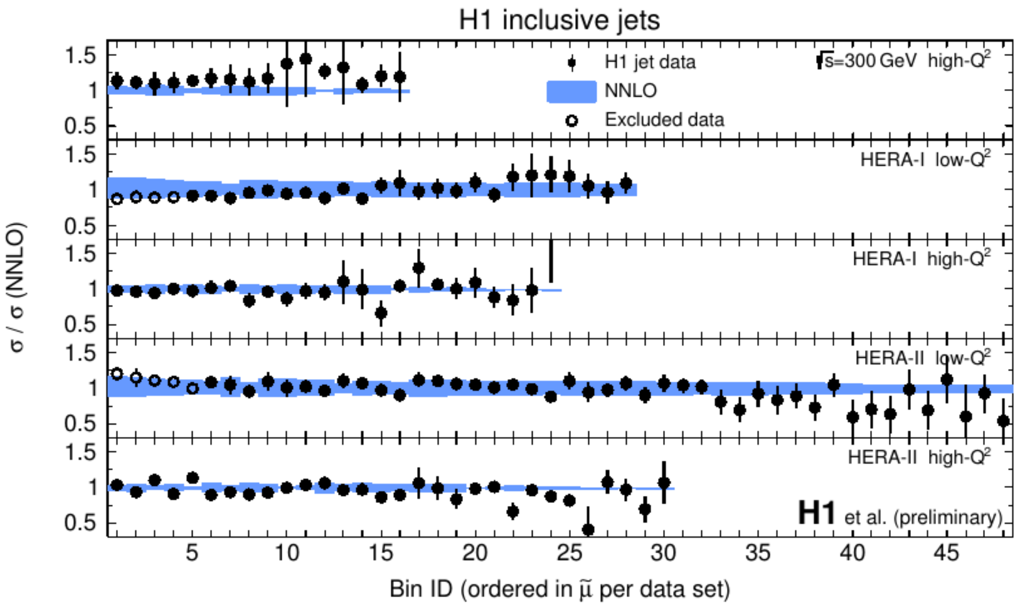


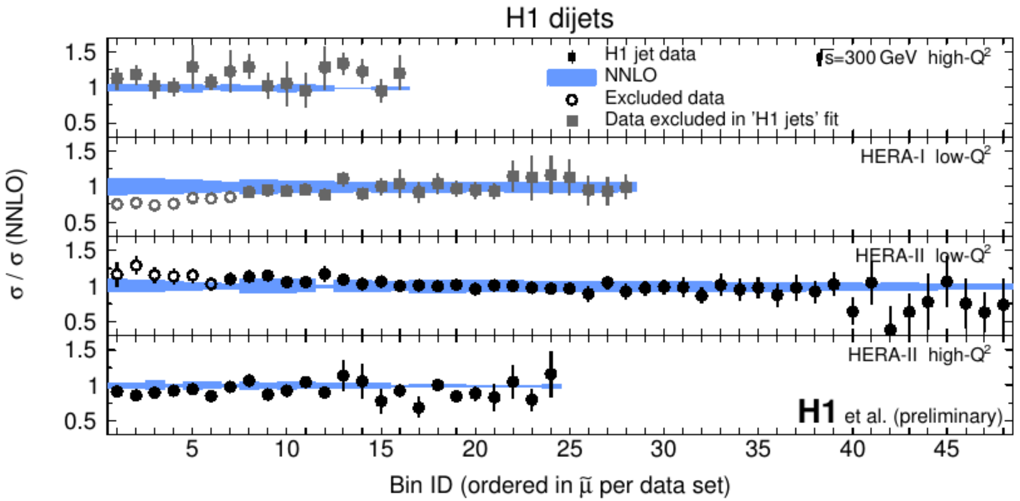
Scale choice for α_s fit



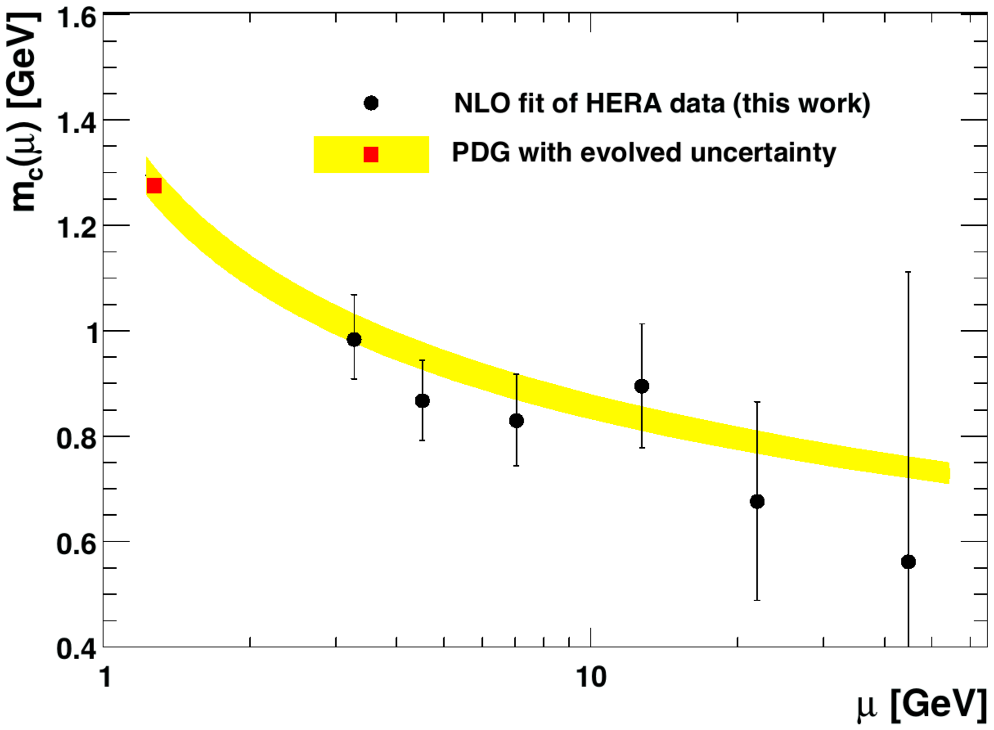


Inclusive jet and dijet cross sections in comparison to NNLO using best-fit α_s





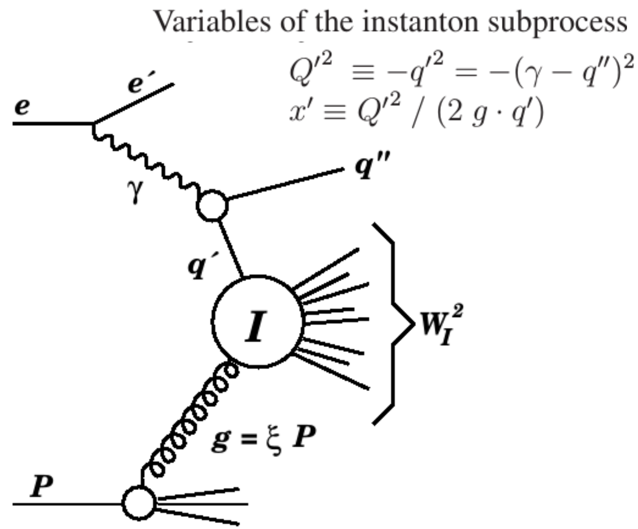
Tests of the charm mass running



QCD Instantons

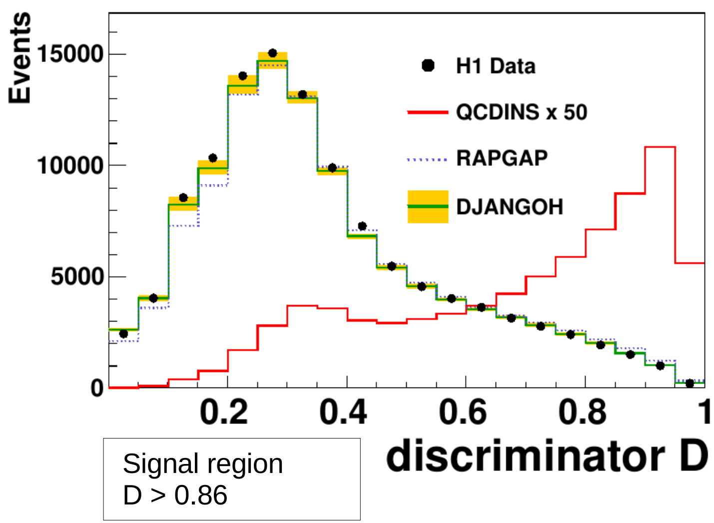
QCD Instantons

- Solution to Yang-Mills equation of motion
  - Non-perturbative fluctations of the gauge field
  - Physical interpretation: Pseudo-particle or tunneling process between topologicaly different vacuum states
- The discovery of instantons would be the first evidence for non-perturbative QCD effect at high energies
- QCDINS MC generator by Ringwald/Schrempp
  - Sizeable cross section using Instanton-perturbation theory
  - Uncertainty coming from Λ_{QCD}(MSbar)



Characteristic signature of Instanton

- One hard jet (not originating from instanton)
- Densily populated narrow band; flat in φ
- Large particle multiplicities



Strategy

- Find jets in hadronic center of mass frame
- Remove hardest jets from HFS
- Define topological input-variables in 'instanton rest-frame' which are input to TMVA
  - Train MVA with QCDINS Monte Carlo