Hard and Precision QCD @ HERA

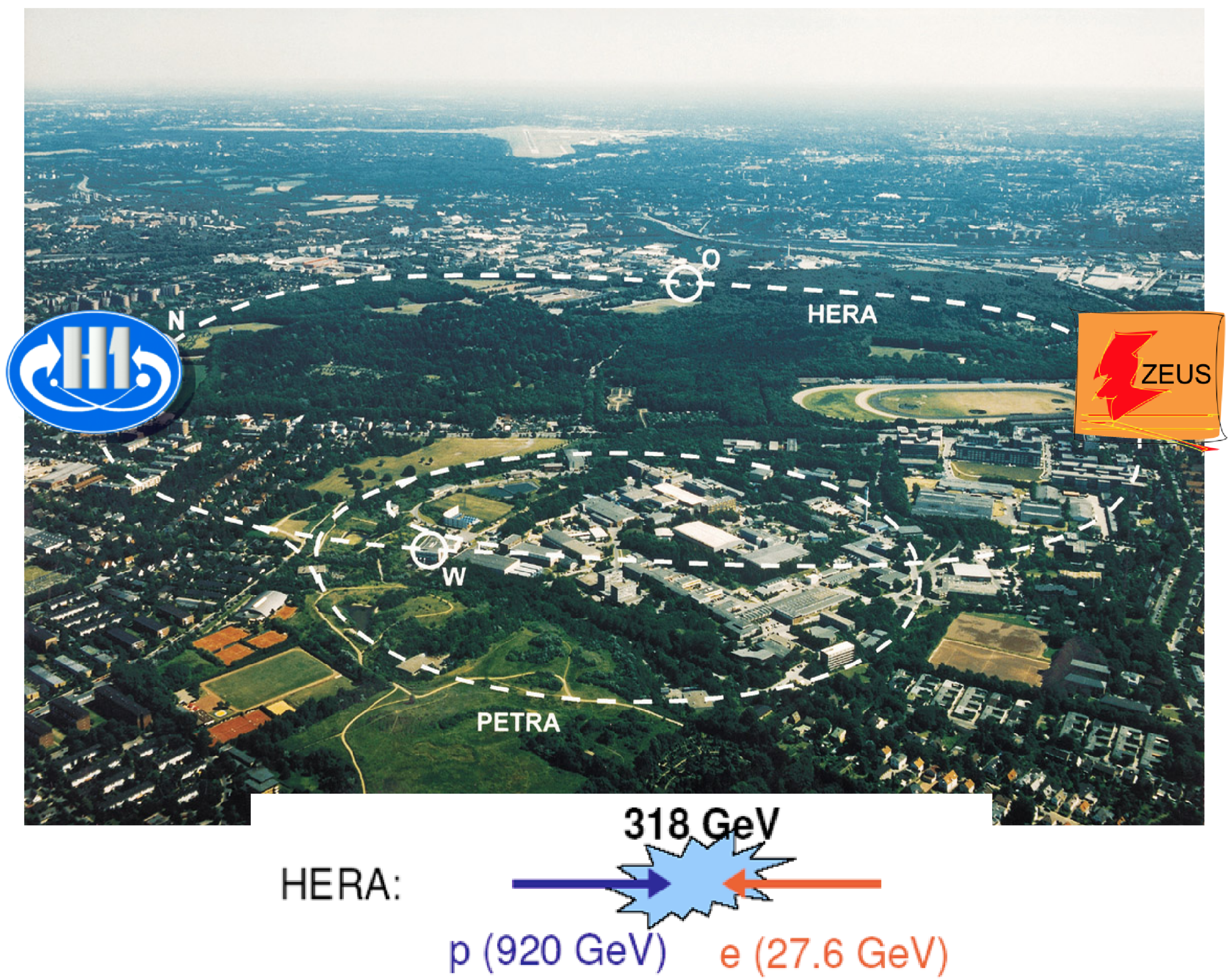
Günter Grindhammer, Max-Planck-Institute for Physics, Munich
on behalf of the H1 and ZEUS collaborations

20th High-Energy Physics Int. Conf. in QCD, Montpellier, July 3-7, 2017

Combination of open c & b prod. data in DIS

Comparison to NLO & aNNLO

Extraction of m_c & m_b in NLO



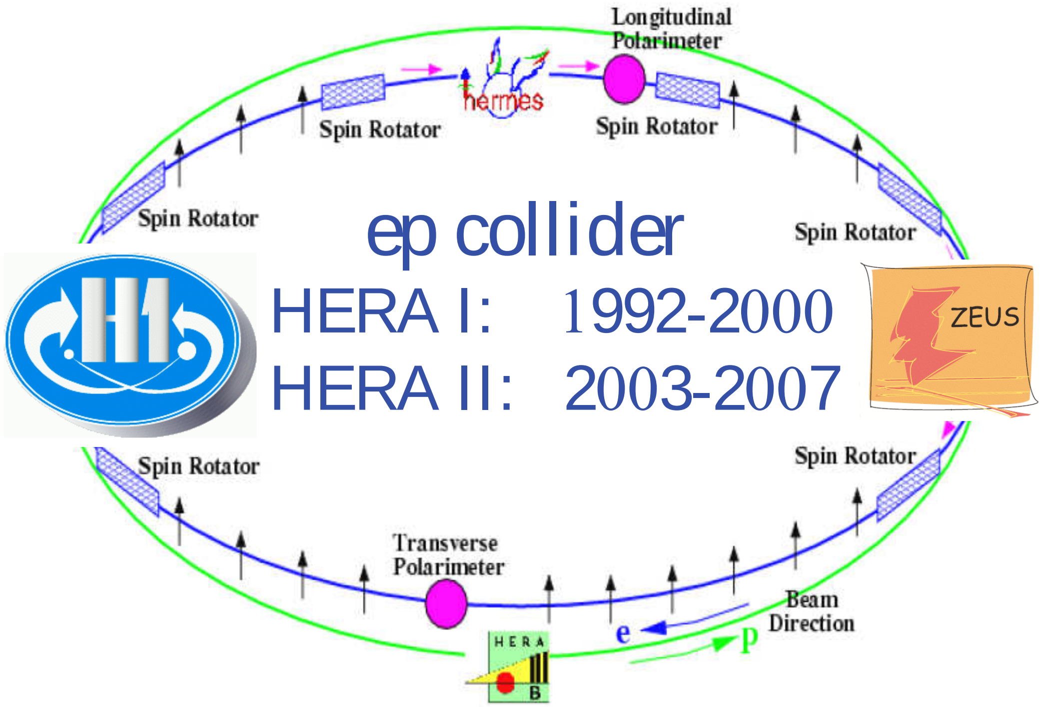
New multijet cross sections in DIS

Extraction of $\alpha_S(M_Z)$ in NNLO

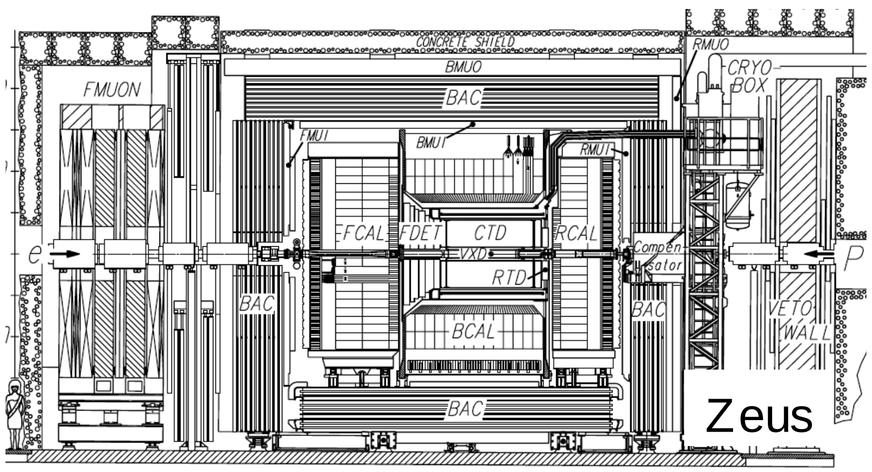
Prompt photons plus jets in DIS

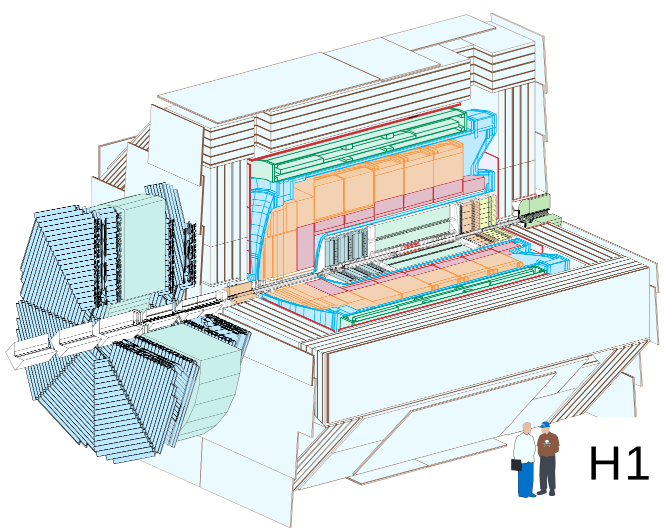
HERA ep Collider, H1 & ZEUS

- **H1 & ZEUS** experiments collected a combined data sample of ~**1** fb^{-1}
- ~**75%** of data taken with polarized **(~30%)** lepton beams, with about equal numbers of e^- and e^+ and positive and negative polarization.
- **HERA** was the only ep-collider and allowed to investigate a wide range of physics **(DIS, DIFF, PHP)** and processes.
- **M**easurement of the proton structure has been a central part of the program.
- **H1 & ZEUS** provide well calibrated datasets, e.g. hadronic energy scale uncertainty ~**1%**.
- **H1 & ZEUS** have published **> 130** papers since the end of data talking in **2007**.



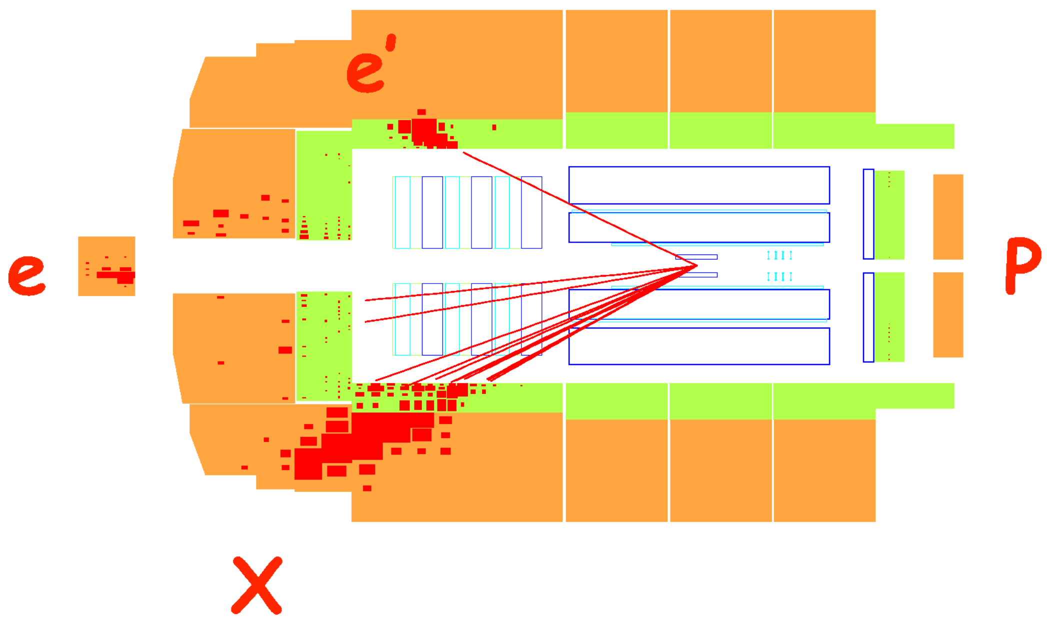
E

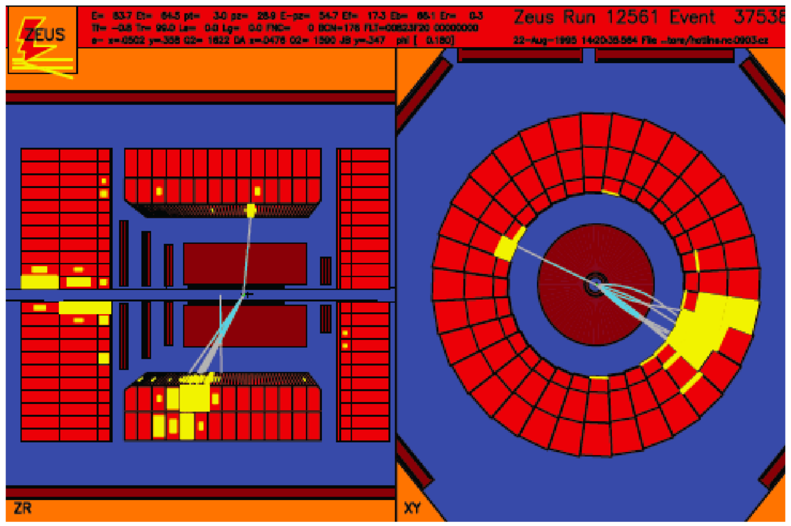




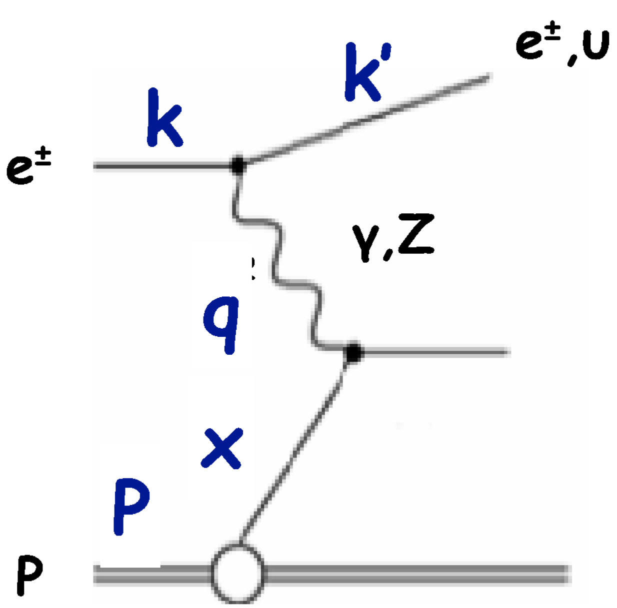
Inclusive DIS kinematics

e p → e (ν) X





Measurement



virtuality $\quad Q^2 = -(k - k')^2 \qquad Q^2_e = \frac{E'^2_e \sin^2\theta_e}{1 - y_e}$

inelasticity $\quad y = (P \cdot q)/(P \cdot k) \qquad y_e = 1 - (E'_e/2E_e)(1 - \cos\theta'_e)$

Bjorken x $\quad x_{Bj} = Q^2/(2P \cdot q) \qquad x_e = \frac{Q^2_e}{4E_p E_e y_e}$

$$Q^2 = xys \qquad s = (k + P)^2$$

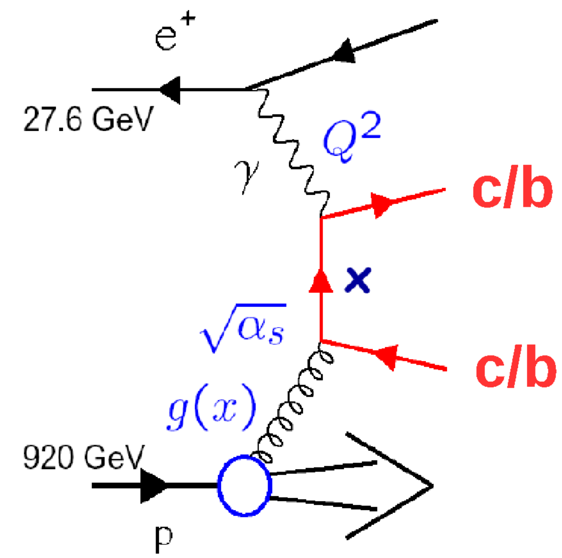
Heavy quark production in DIS

- Main prod. process is photon-gluon fusion
- Combine H1 & ZEUS measurements based on different tagging techniques
  - reconstructed D^{*+}, D^{+} and D^{0} meson decays
  - μ and e from semi-leptonic decays
  - analysis of tracks (VTX) exploiting lifetime info
- Extension of previous combination for charm [EPJ C 73 (2013) 2311]
  - 3 new charm data sets
  - 5 beauty data sets
  - 13 analyses in total
  - Reduced cross sections

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

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

- H1prelim-17-071, ZEUS-prel-17-01]

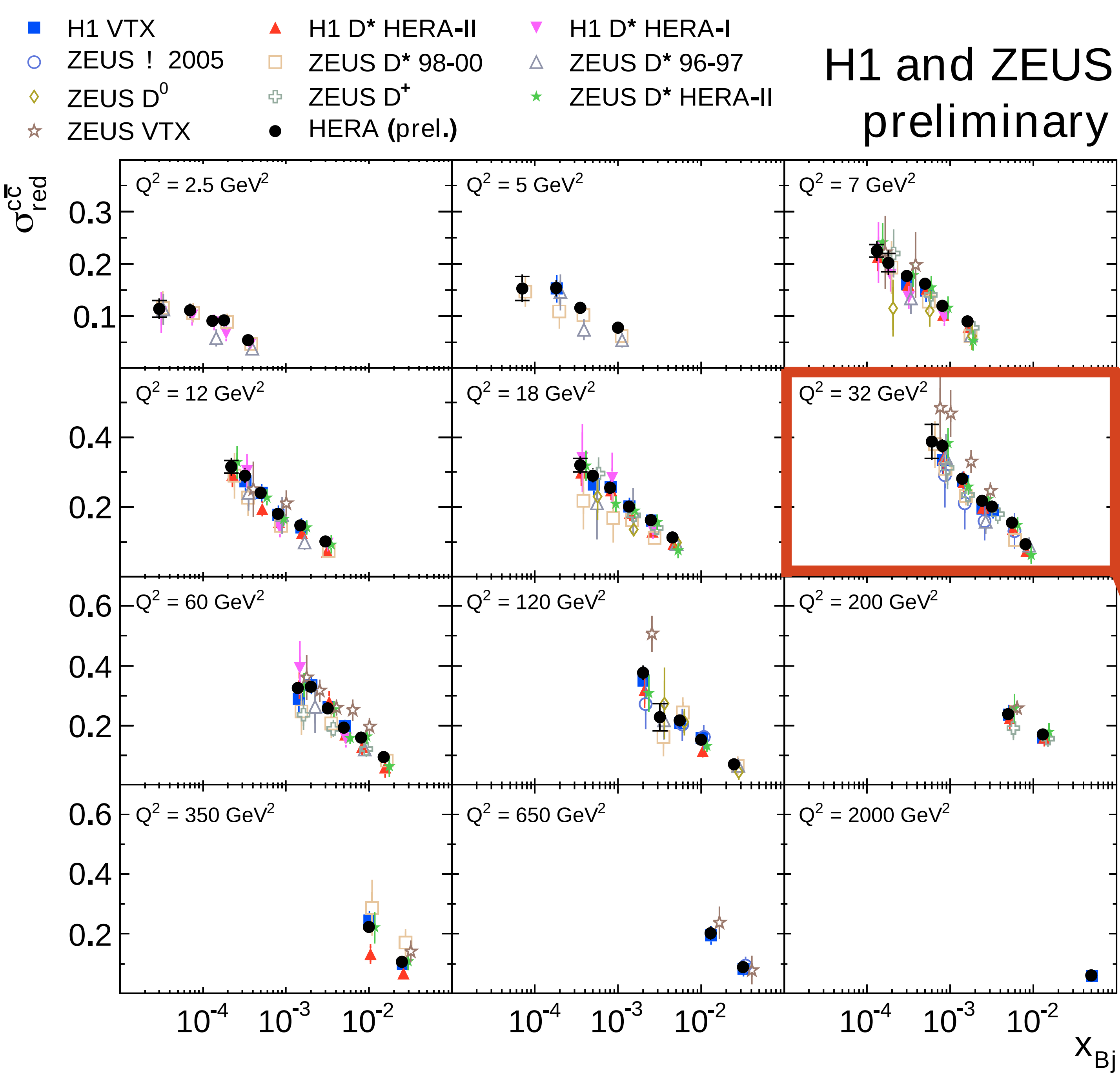


up to 30% of the inclusive prod. is due to charm, up to 1% due to beauty

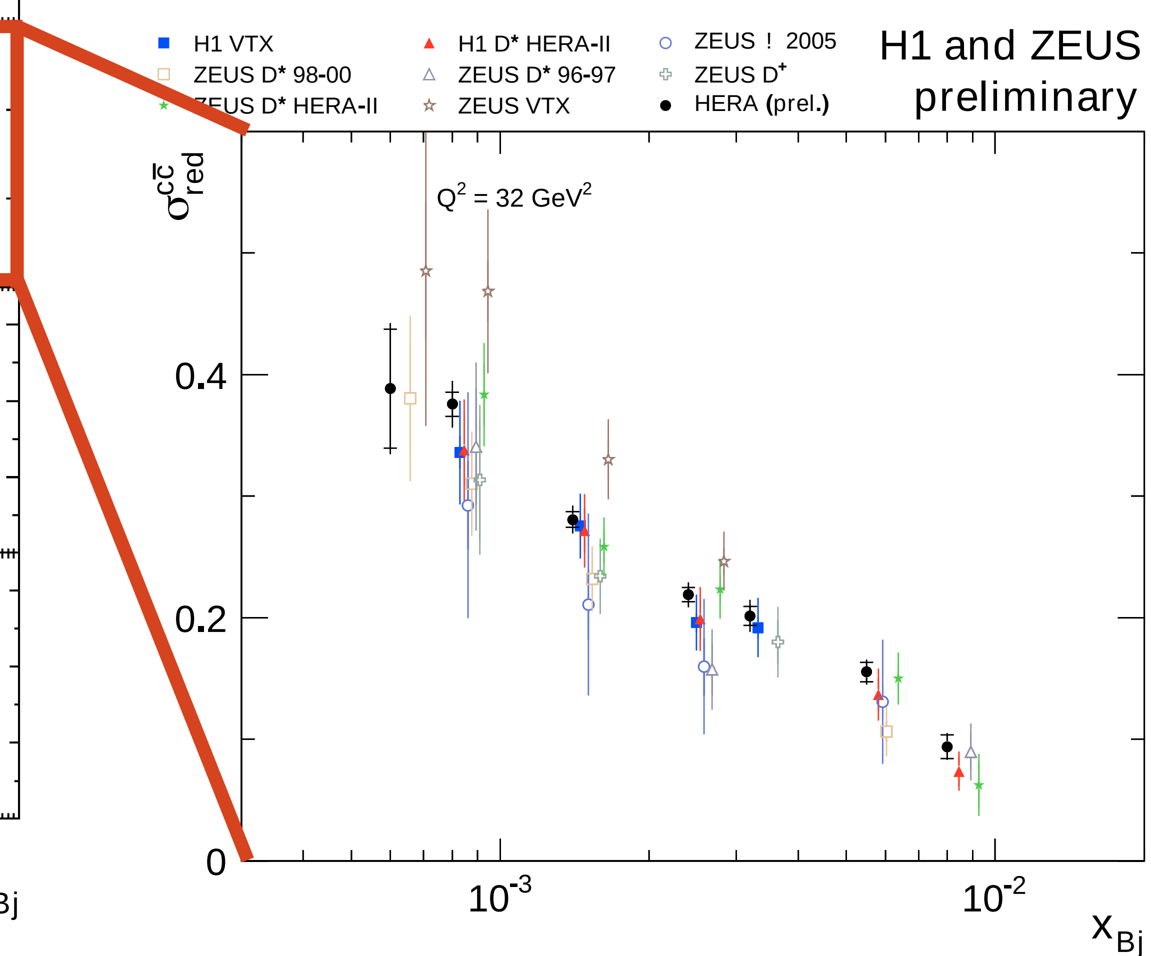
NLO calculations:

- FFNS: PDFs contain only u,d,s,g. Heavy quarks are generated in ME (multiple scales)
- VFNS: massless quarks in ME.

Combination of c cross sections in DIS

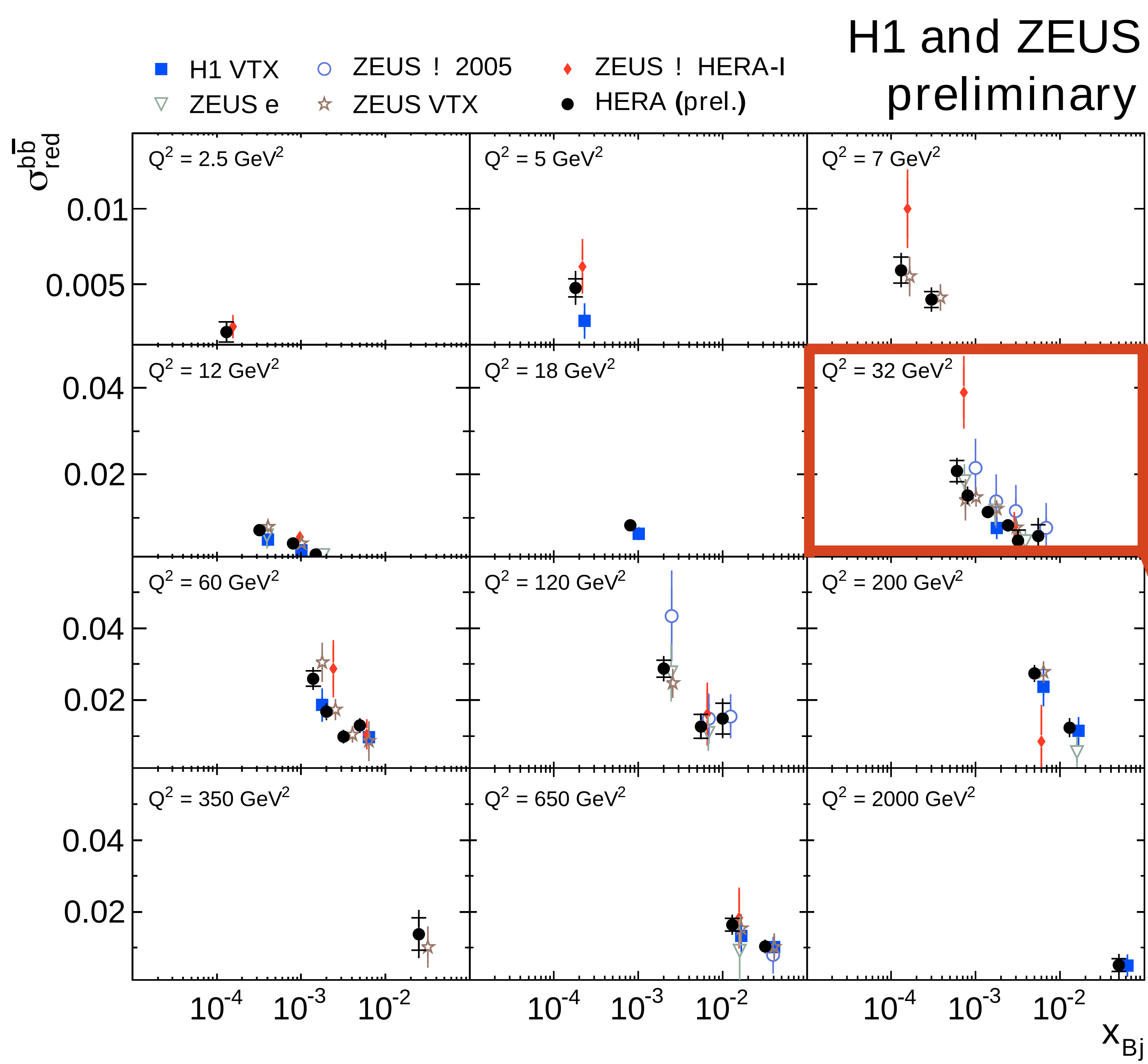


- **209** c + **52** b data points combined simultaneously ! **52** c + **27** b data points
- accounting for correlations in c & b data sets as well as between them
- good consistency: χ^2/ndf = **149/187**

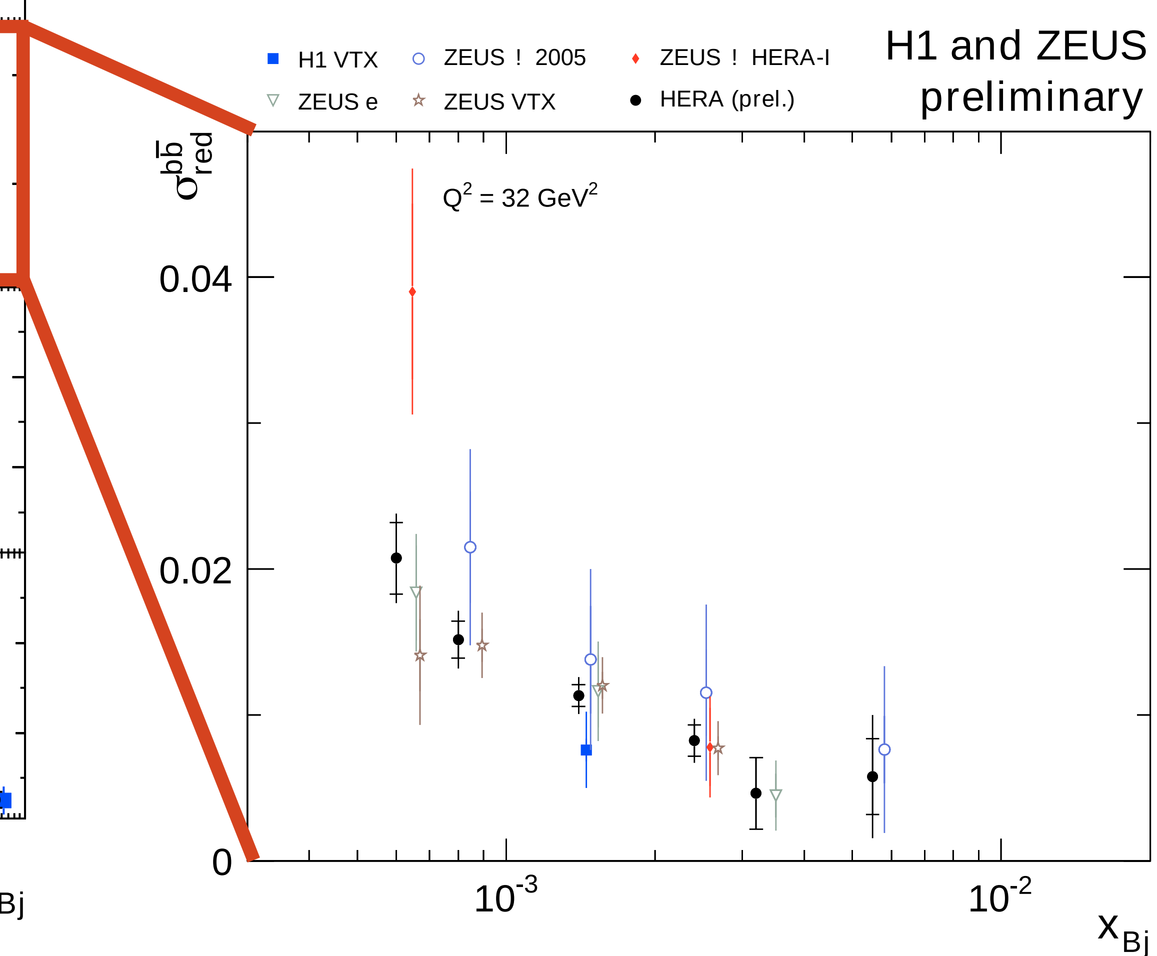


⇒ **S**ignificant improvement in precision compared to input data

Combination of b cross sections in DIS



- inner error bars = uncorrelated part of uncertainties
- outer error bars = total uncert.
- for the presentation: each data point is shifted in x_{Bj}



- 1st combination of b cross sections

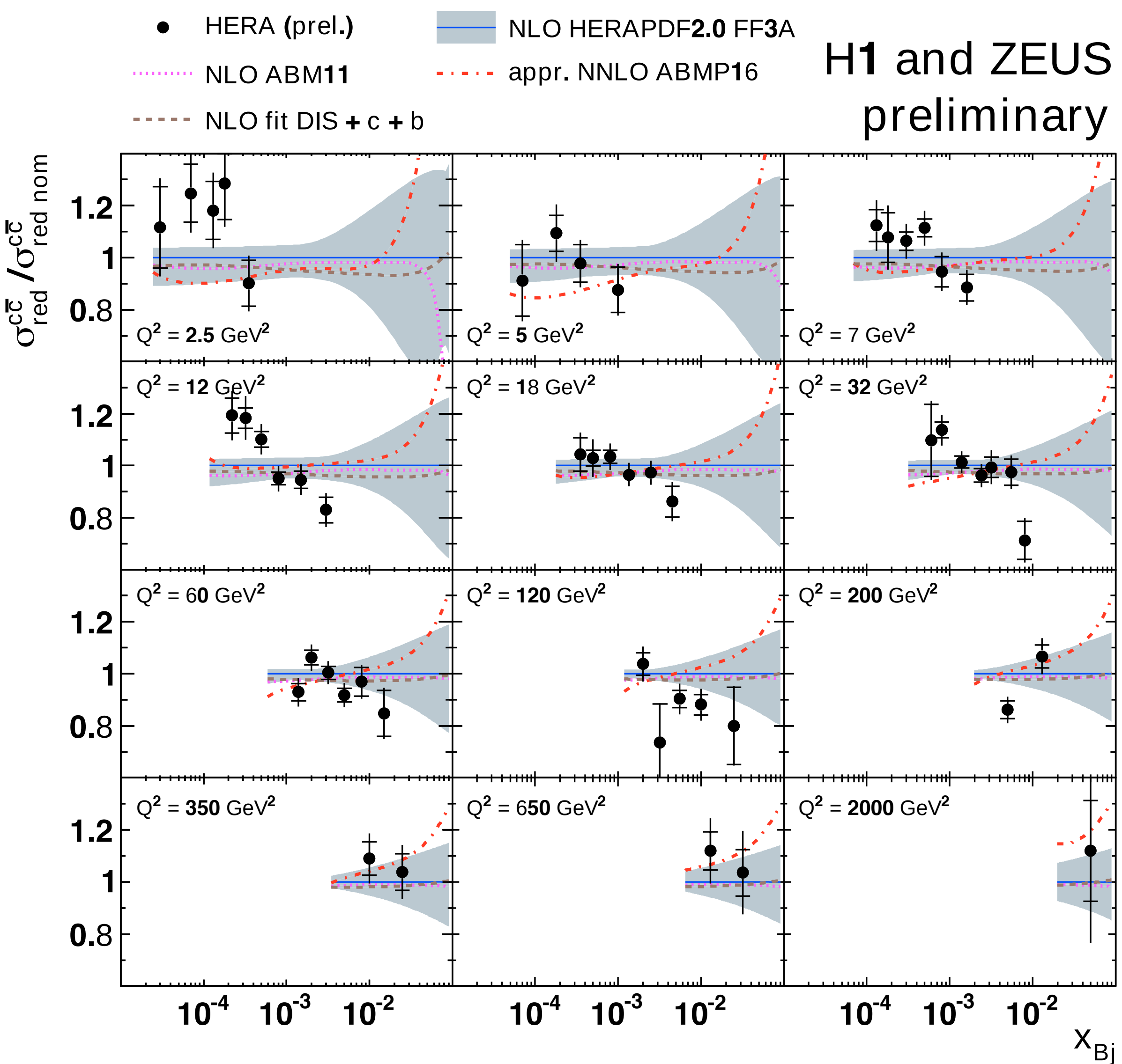
Ratios to NLO QCD

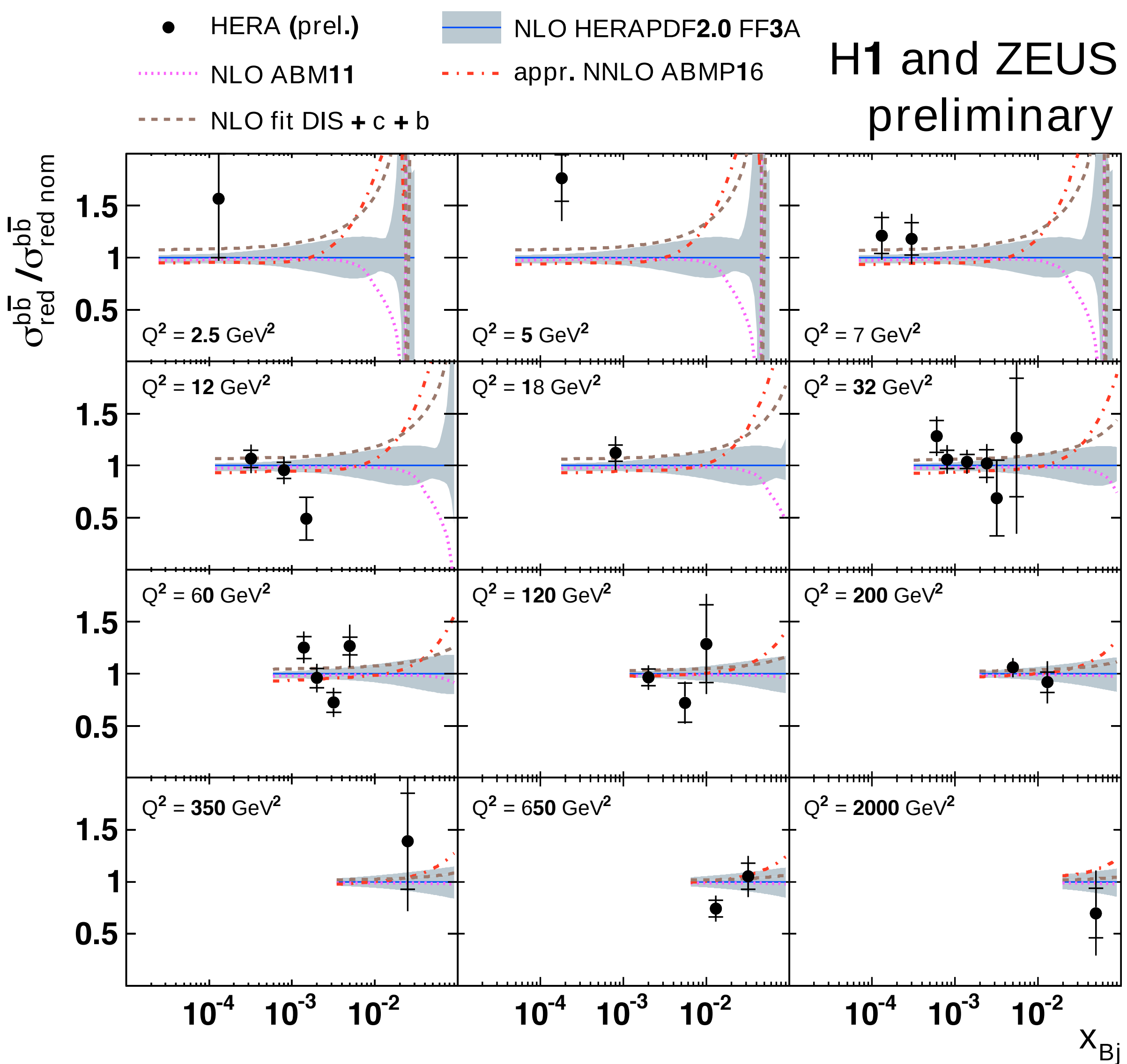
Predictions from **OPENQCDRAD**

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

' R = ' F = $(Q^2+4m^2_{c,b})^{1/2}$

cross sections are normalized to **NLO** predictions using **HERAPDF2.0 FF3A**





QCD provides reasonable overall description of the data; no improvement by approx. **NNLO**; slope diff. at Q^2 & **12** GeV^2
dominant theory uncertainty from variation of scale (factor of **0.5** to **2**)

Extraction of c & b masses

- **P**erform **QCD** fit in **NLO** in **FFNS** **(**n_f **= 3):**
  - besides c **&** b data**,** inclusive **HERA NC & CC** data are used
  - m_c **&** m_b are free parameters in the fit
  - the light flavor **PDF**s are parameterized as in the **HERAPDF2.0** fit

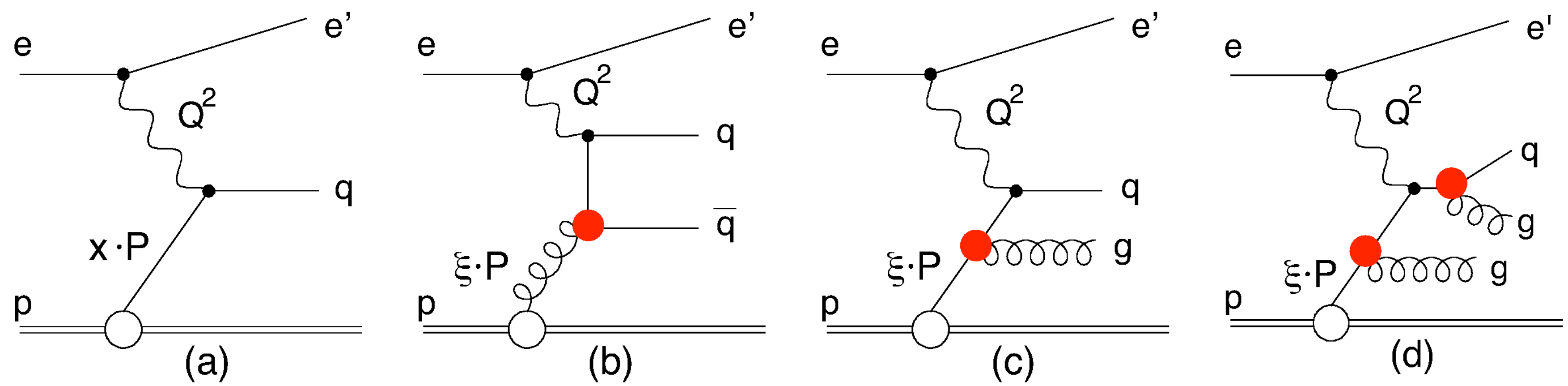
$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})\,^{+62}_{-14}(\text{mod})\,^{+\ 7}_{-31}(\text{par})\ \text{MeV}$$

$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})\,^{+90}_{-32}(\text{mod})\,^{+\ 1}_{-31}(\text{par})\ \text{MeV}$$

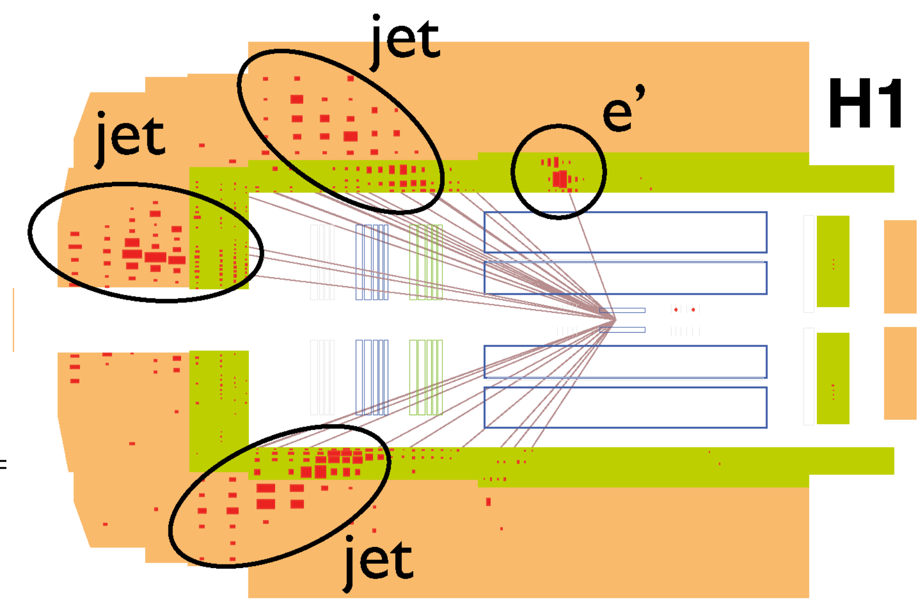
- the **QCD** fit gives χ^2**/**ndf **= 1435/1208**
- the model uncertainties are significant and are dominated by the variation of the scale **(**factor **0.5** to **2)**
- the c **&** b masses given are the running masses in the **MS**bar scheme**;** consistent with the **PDG** values**:** $m_c(m_c)$ **= 1270** ± **30 M**eV and $m_b(m_b)$ **= 4180** ± **30 M**eV

Multijetproduction in NC DIS

BGF QCDC



elweak coupling $\propto \alpha_S$ $\propto \alpha_S$ $\propto \alpha_S^2$

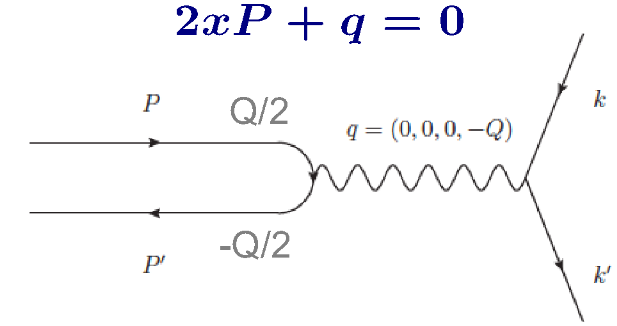


Jets in DIS are measured in the Breit frame:

- virtual boson collides head-on with parton from proton
- jets reconstructed using the k_T algorithm
- each jet must have a minimum P_T in the Breit frame
  - jets depend already in LO on $\alpha_S \otimes g$ (or q or qbar) in IS and on α_S in FS, allowing for a determination of α_S
  - BGF dominant in largest phase space region (lower Q^2, lower x)
  - QCDC important for high-p_T jets (high x)

boost events into Breit frame:

$$2xP + q = 0$$



Jets in DIS at low Q^2

- **Simultaneous measurement and unfolding of**
  - inclusive jets, dijet and trijet as well as incl. NC DIS cross sections
  - accounting for correlations & detector effects

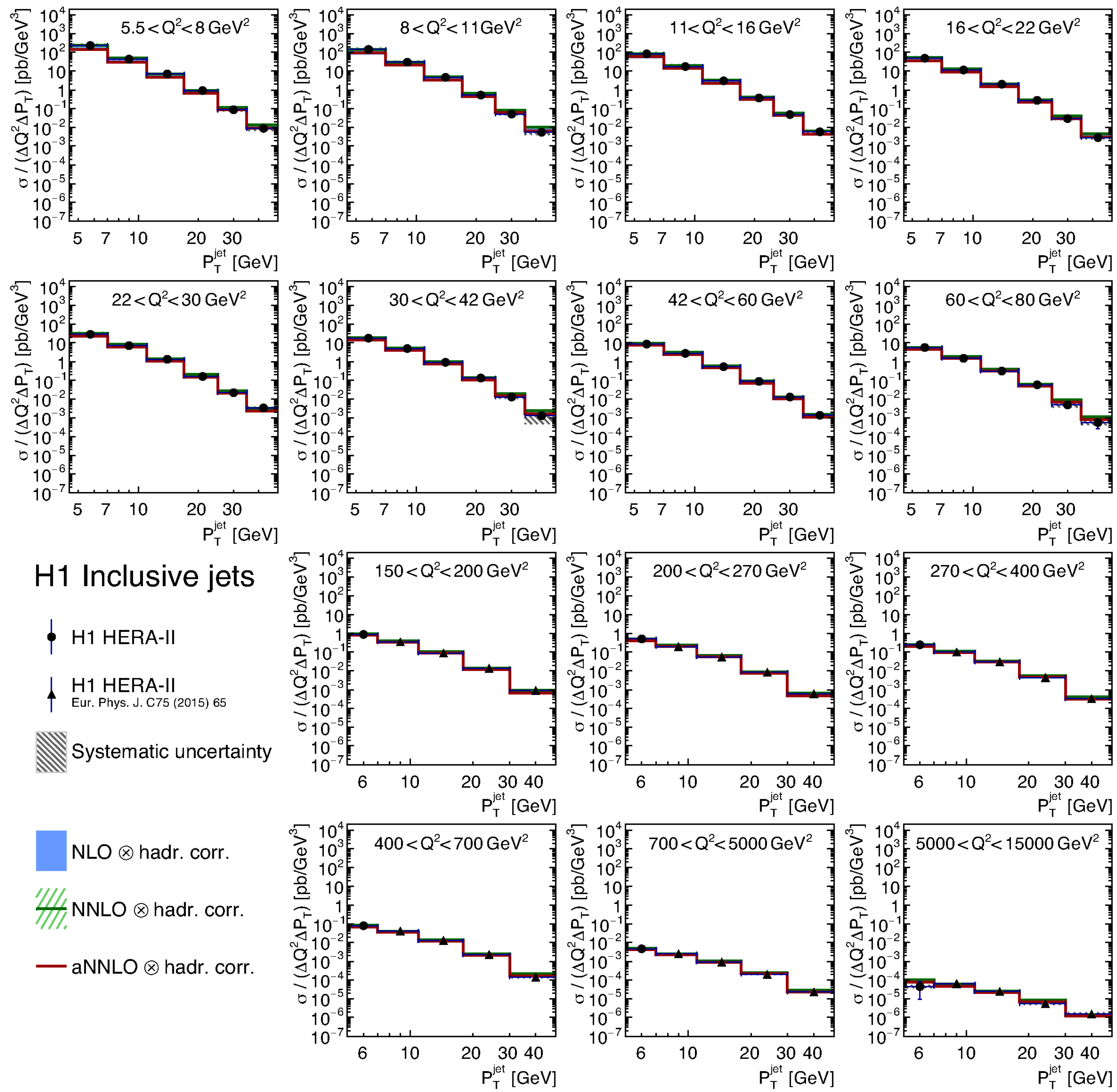
- **Phase space of cross sections:**

NC DIS	$5.5 < Q^2 < 80$ 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

- EPJ C 77 (2017) 4, 215

- **Include extension of previous high-Q^2 result**

- EPJ C 75 (2015) 2, 65

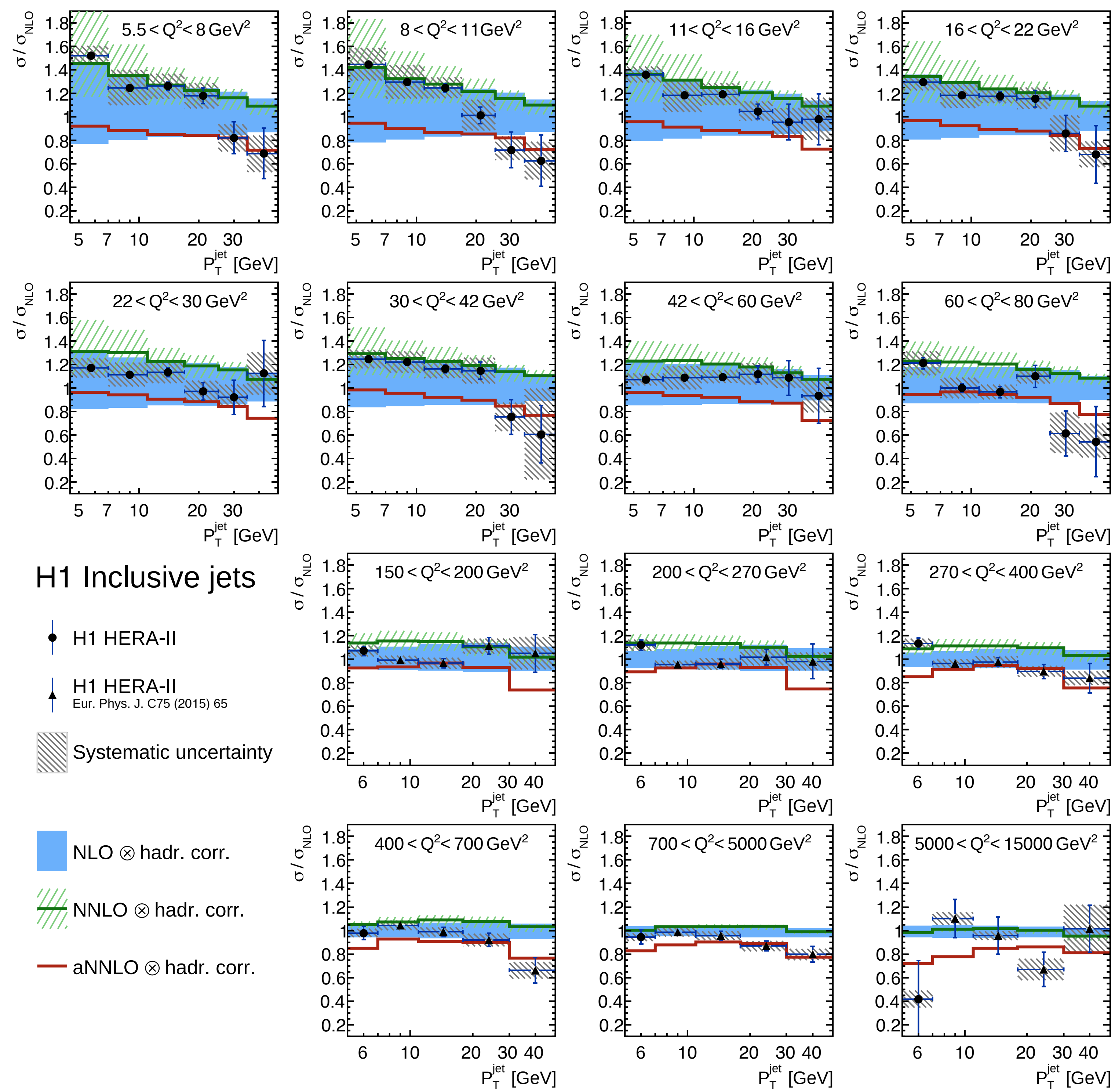


High precision data over wide kinematic range

Comparison to NLO & aNNLO & NNLO

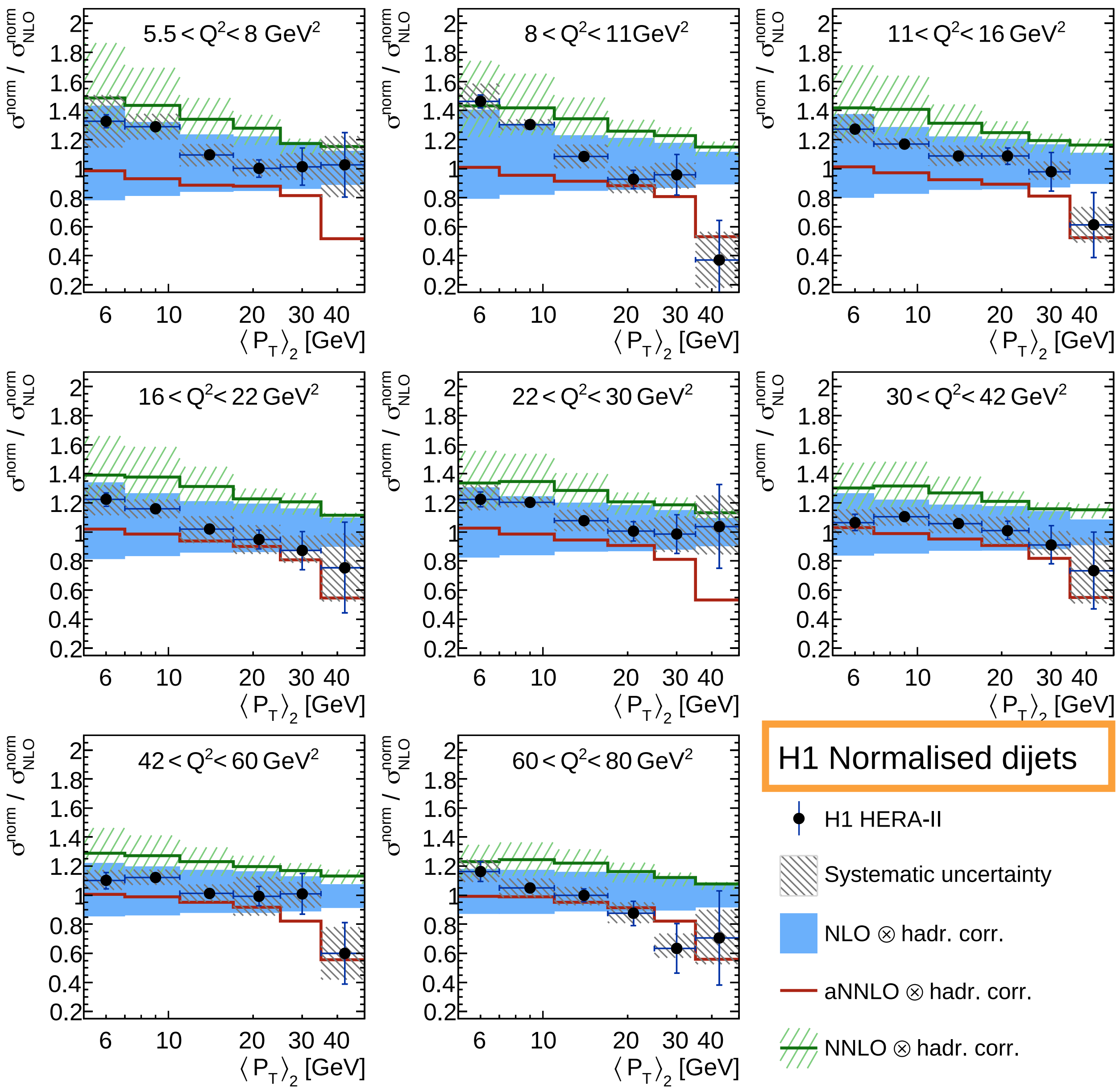
$\frac{\sigma_{\text{jet}}}{\sigma_{\text{NLO}}}$ & $\frac{\sigma_{\text{aNNLO}}}{\sigma_{\text{NLO}}}$ & $\frac{\sigma_{\text{NNLO}}}{\sigma_{\text{NLO}}}$

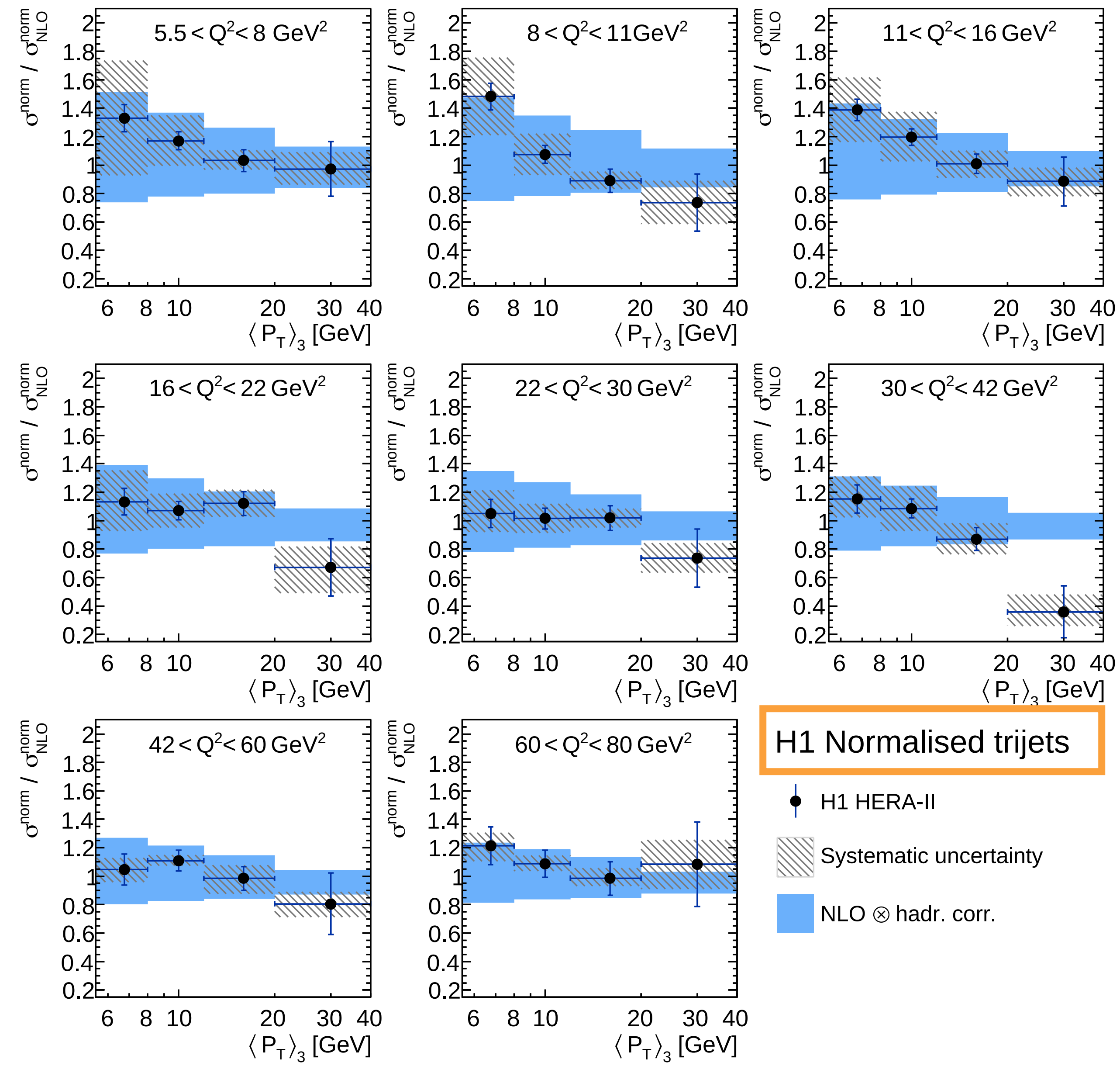
- **NLO QCD (NLOjet++)**
  - PRL 87 (2001) 082001
  - reasonable description of data
  - large scale uncertainty
- **Approximate NNLO (JETVIP)**
  - threshold resummation
  - PRD 92 (2015) 074037
  - somewhat improved shape
- **NNLO QCD (NNLOJET)**
  - PRL 117 (2016) 042001
  - improved description
  - significantly reduced scale uncertainty, particularly for higher scales



Dijet & Trijet production in DIS

$\frac{\sigma_{\mathrm{jet}}}{\sigma_{\mathrm{NLO}}}$ & $\frac{\sigma_{\mathrm{aNNLO}}}{\sigma_{\mathrm{NLO}}}$ & $\frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{NLO}}}$ but for jet cross sections normalized to (**NC DIS**) in the respective **Q^2** and **P_T** bin





- **Dijet:** in **NNLO** improved description of shape
- **Trijet:** in **NLO** good description at moderate precision

Extraction and running of ! s at NLO

From comb. fit to normalized incl. jet, dijet and trijet cross sections at low and high Q^2:

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

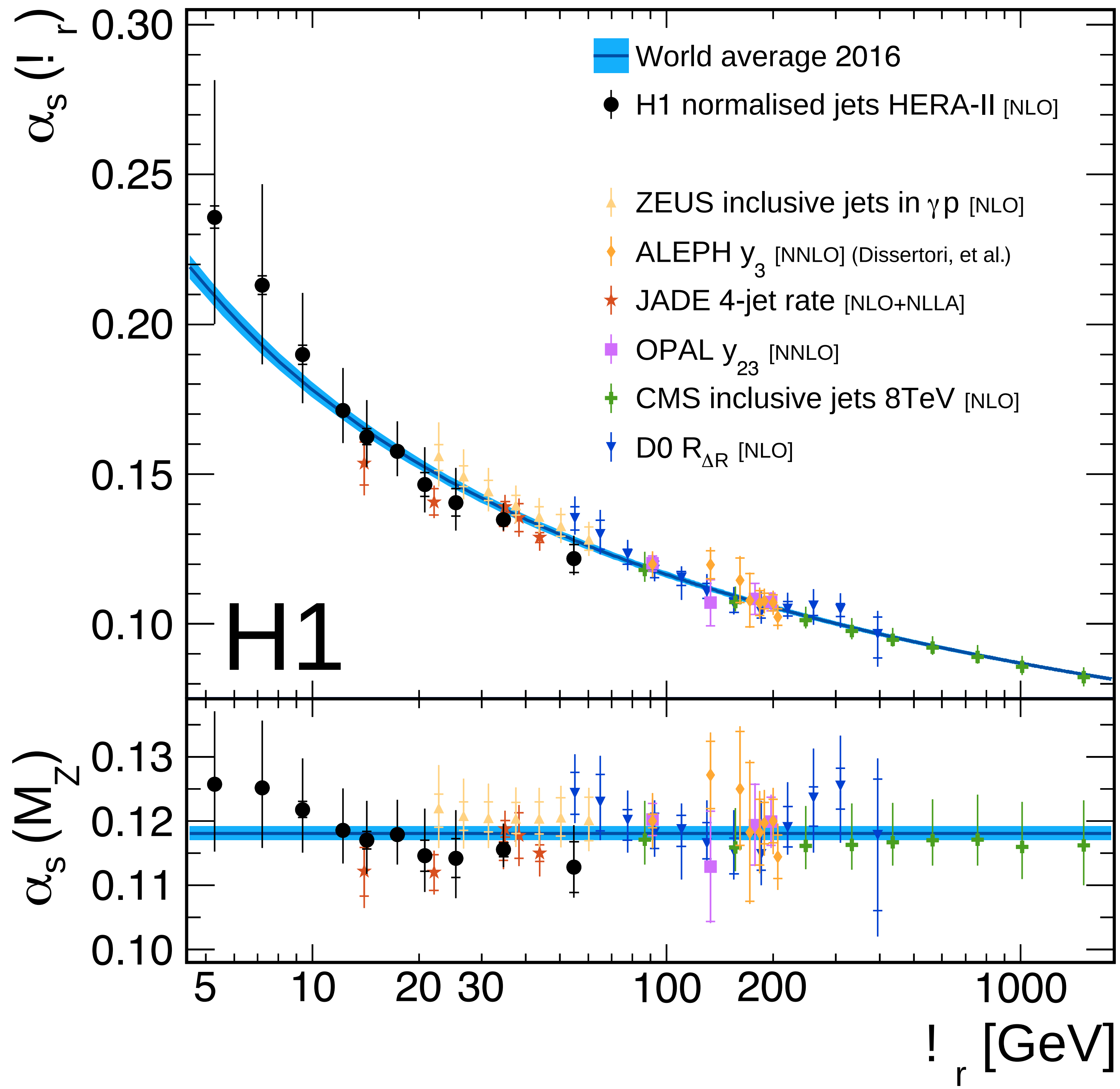
- EPJ C77 (2017) 4, 215

- high exp. precision
- large scale uncertainty

Running of as(' R):

- data points are grouped into **10** groups with comparable values of μR
- as(MZ) is fitted for each group
- as(' R) is obtained from as(MZ) using **RGE**

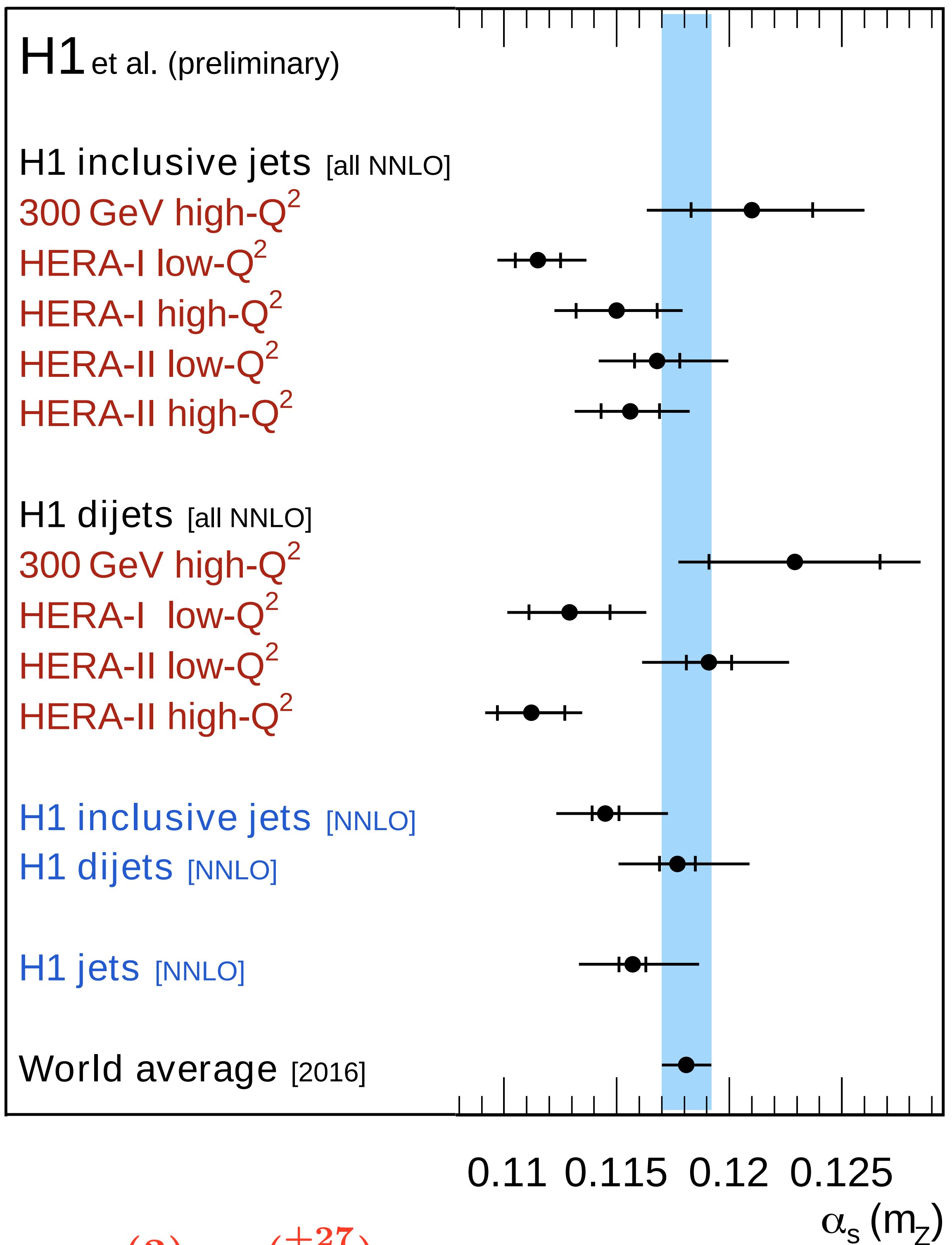
- consistent with other results from **HERA, PETRA, LEP, Tevatron** and **LHC & QCD**



Extraction of $!_s$ at NNLO

H1-prelim-17-031: H1 in collaboration with **V.**Bertone, **T.**Gehrmann, **C.**Gwenlan, **A.**Huss, **J.**Niehues and **M.**Sutton

- New **NNLO** fits to all suitable **H1** inclusive jet and dijet measurements **(203** data points**)**
- **F**ull error breakdown
  - corr. & uncorr. exp. uncertainties
  - theory uncertainty: scale variation (factors **0.5** and **2)**
  - various **PDF** uncertainties
  - hadronisation uncertainties
- a_s **(**M_Z**)** results from distinct data sets and from all of them (`**H1** jets´)
  - all fits yield good $\%^2$, indicating consistency of data
  - high exp. precision
  - uncertainties due to **PDF**s are sizeable
  - scale uncertainty is dominant, but considerably reduced w.r.t. **NLO**

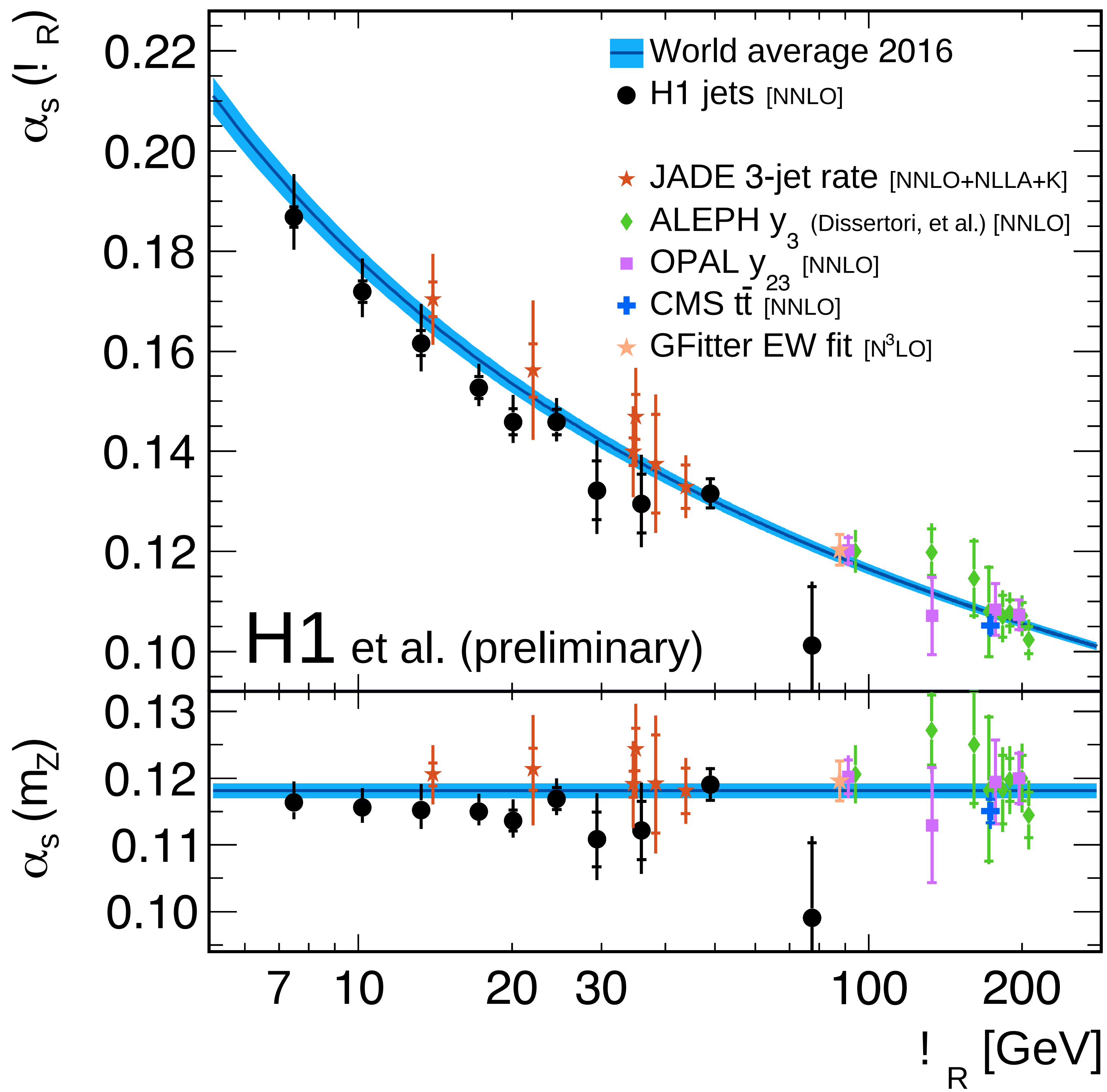


$$\alpha_s(M_Z) = \mathbf{0.1157}\ \mathbf{(6)_{exp}}\ \mathbf{(6)_{PDF}}\ \mathbf{(12)_{PDF(\alpha_s)}}\ \mathbf{(2)_{PDFset}}\ \mathbf{(3)_{had}}\ \mathbf{(^{+27}_{-21})_{scale}}$$

Running of a_s at NNLO

- Repeat fits to **10** groups of data points at similar scales
- Values of a_s are consistent with other extractions at **NNLO**
- Running is consistent with other experiments and with **QCD**
- Value of a_s consistent with the world average, however a bit lower

$$\alpha_{s(M_Z)} = \mathbf{0.1157\ (6)_{exp}\ (^{+38}_{-25})_{pdf,theo}}$$

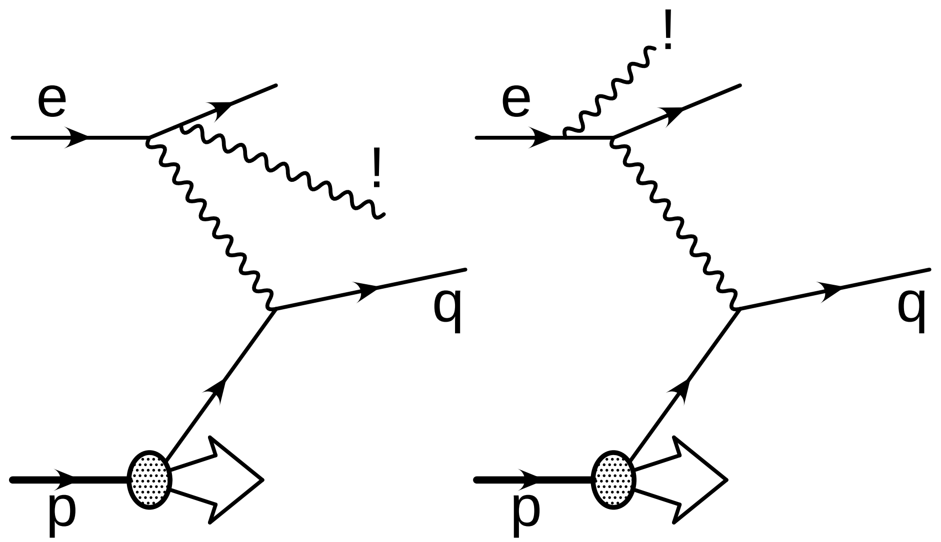


World average: ! $_s(M_Z)$ = 0.1181 ± 0.0011
S.Bethke, Montpellier 2016

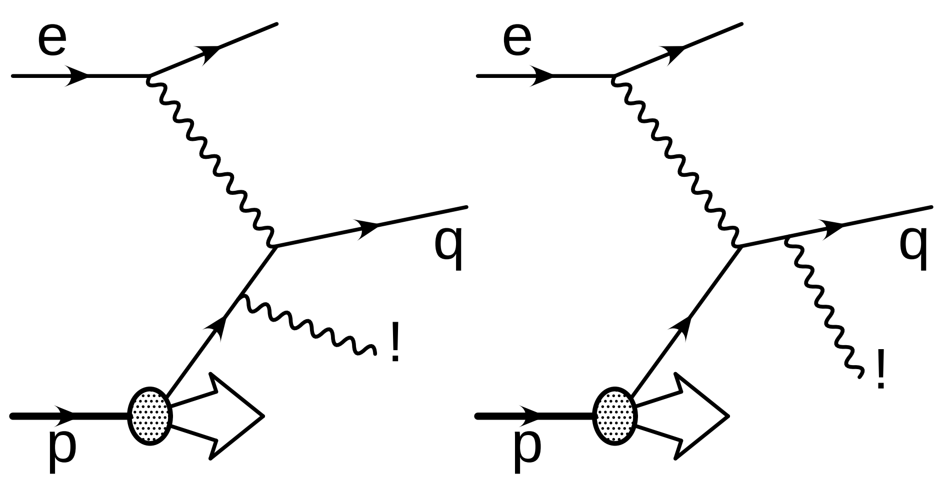
Prompt photons + jets in DIS

- Photons with high P_T may be:
  - radiated from the incoming or outgoing lepton (LL)
  - produced in a hard QCD interaction (QQ)
  - radiated from a quark within a jet ($f_{q\rightarrow\$}(z)$)
  - a decay product of) o or * mesons within a jet
- LL and QQ photons are relatively isolated from other particles (use isolation criteria).
- Prompt QQ photons emerge directly from the hard interaction and (with jets) allow a more direct test of the ME.
- New preliminary results, using combined photon-jet-electron variables, allow more detailed ways to test theory. ZEUS-prel-16-001, previous ZEUS results in PL B 715 (2012) 88

LL



QQ



Prompt photons + jets in DIS

- Use segmentation of the barrel calorimeter in Z-direction to suppress photons from meson decays
- Main requirements:
  - $4 < E_T^{\gamma} < 15$ GeV
  - $E_T^{jet} > 2.5$ GeV
  - $10 < Q^2 < 350$ GeV^2
- Measure diff. cross sections as a function of:

$$x_\gamma = \sum_{\gamma,\mathrm{jet}} (E^i - p_Z^i) \ / \ (2E_e y_{JB})$$

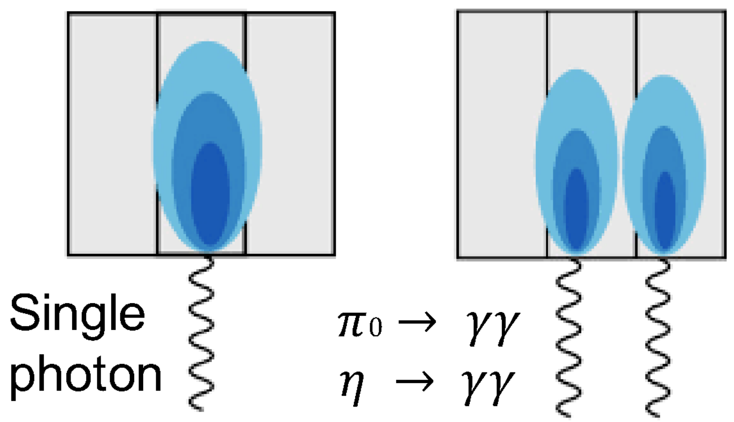
$$x_p = \sum_{\gamma,\mathrm{jet}} (E^i + p_Z^i) \ / \ 2E_p$$

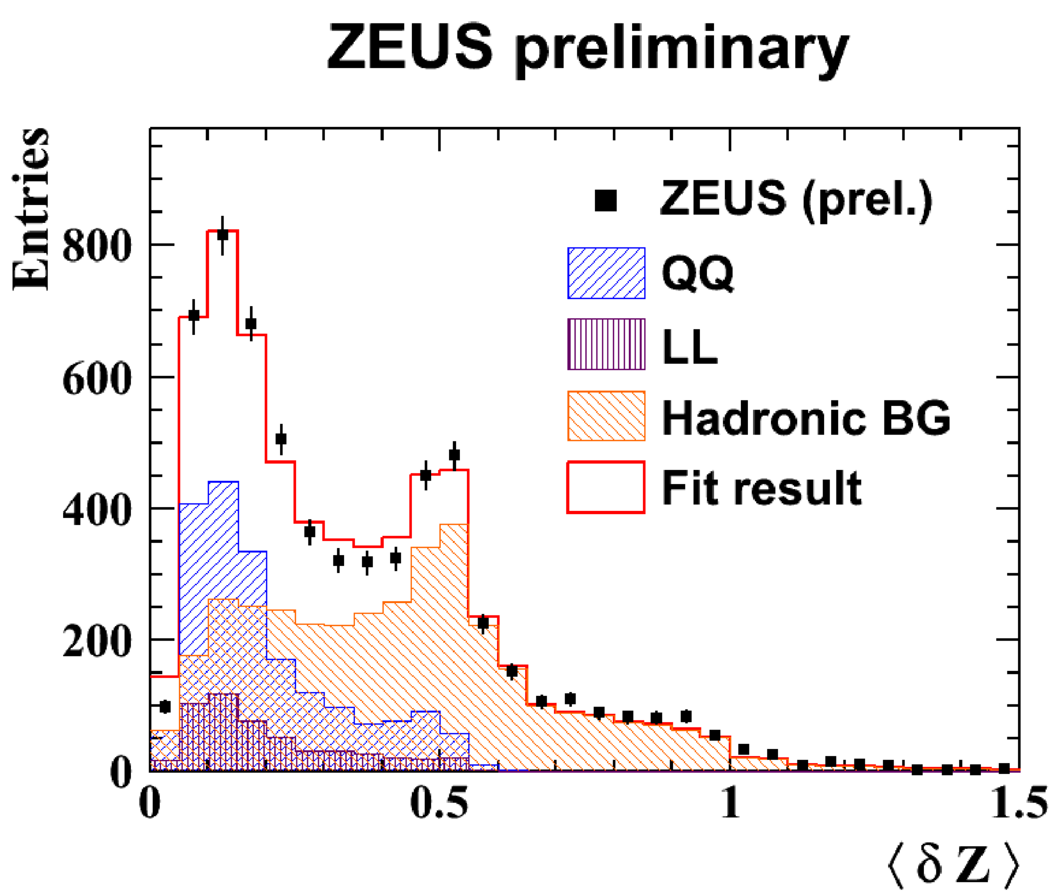
$$\Delta\eta = \eta_{\mathrm{jet}} - \eta_\gamma$$

$$\Delta\phi = \phi_{\mathrm{jet}} - \phi_\gamma$$

$$\Delta\phi_{e,\gamma} = \phi_e - \phi_\gamma$$

$$\Delta\eta_{e,\gamma} = \eta_e - \eta_\gamma$$

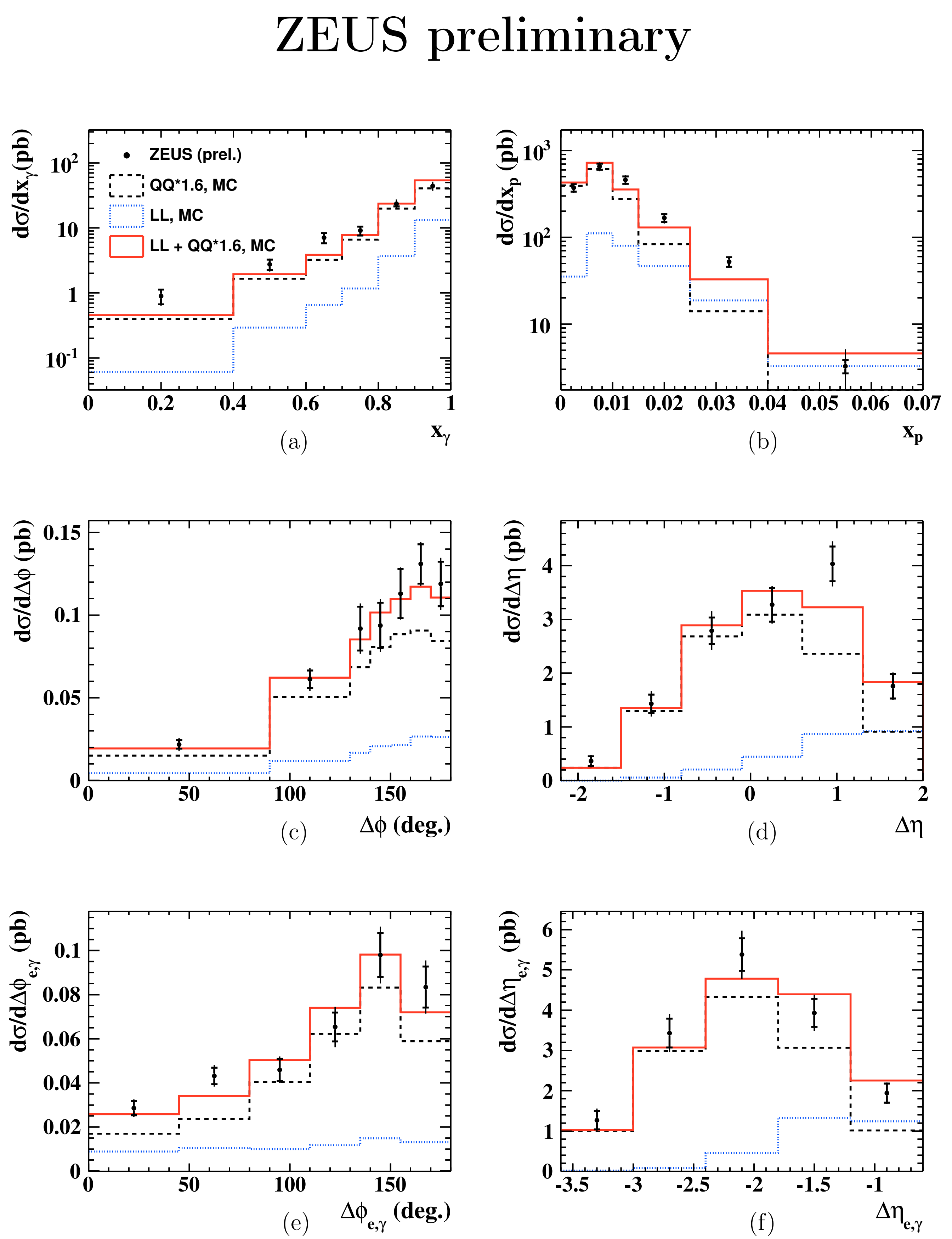




$$< \delta Z >= \sum_i E_i |Z_i - Z_{\mathrm{cluster}}| \ / \ (w_{\mathrm{cell}} \sum_i E_i)$$

Prompt photons + jets in DIS

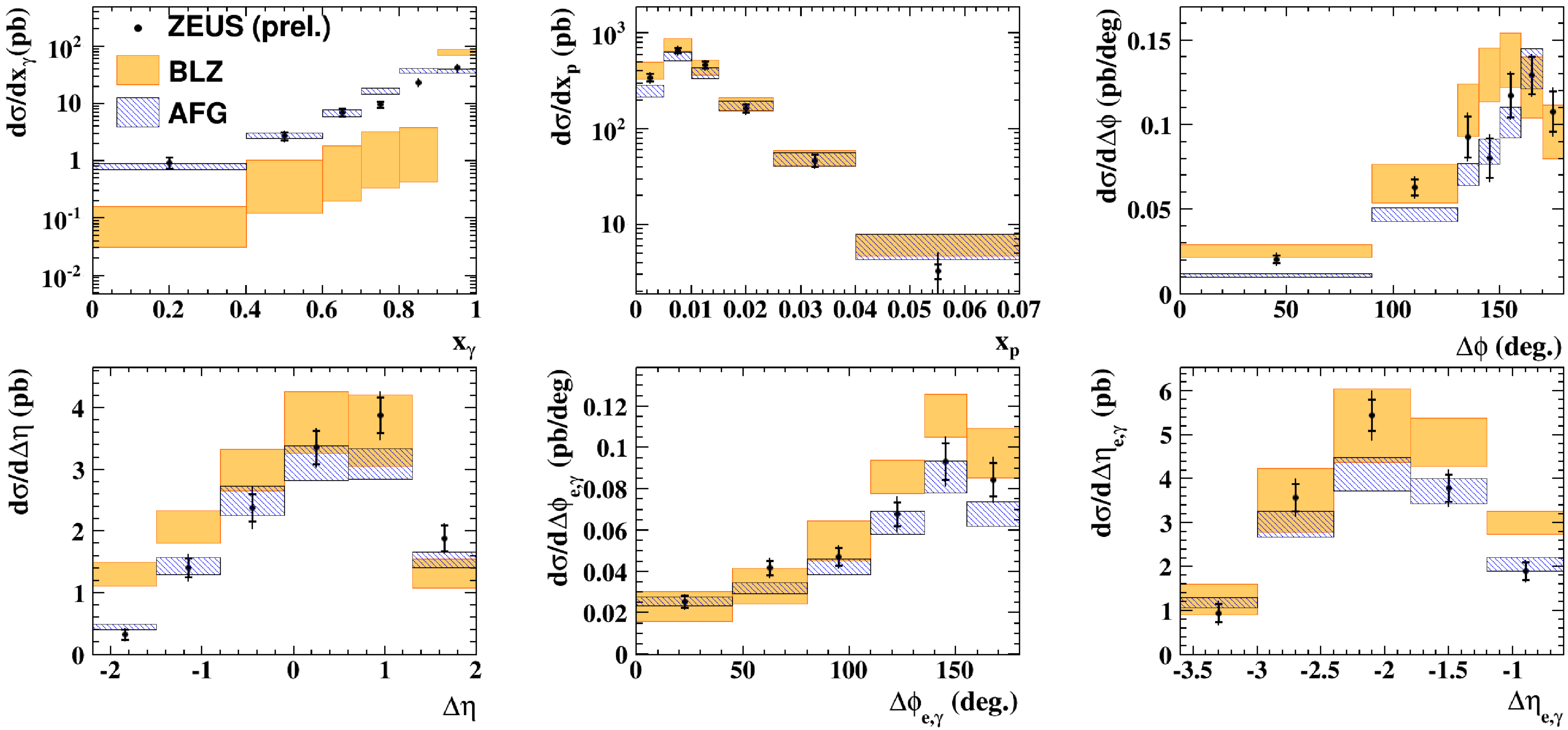
- LO + LLog MC (Djangoh for LL + Pythia for QQ) provides a good description of the data
  - if the LO QQ contribution is weighted by a factor of 1.6
  - and the LL contribution is taken as is in the MC



Prompt photons + jets in DIS

Collinear factorisation in NLO (AFG), *Aurenche, Fontannaz and Guillet : EPJ C 75 (2015) 64, arXiv:1704.08074v1*

k_T-factorisation (BLZ), *Baranov, Lipatov and Zotov: PR D 81 (2010) 094034*



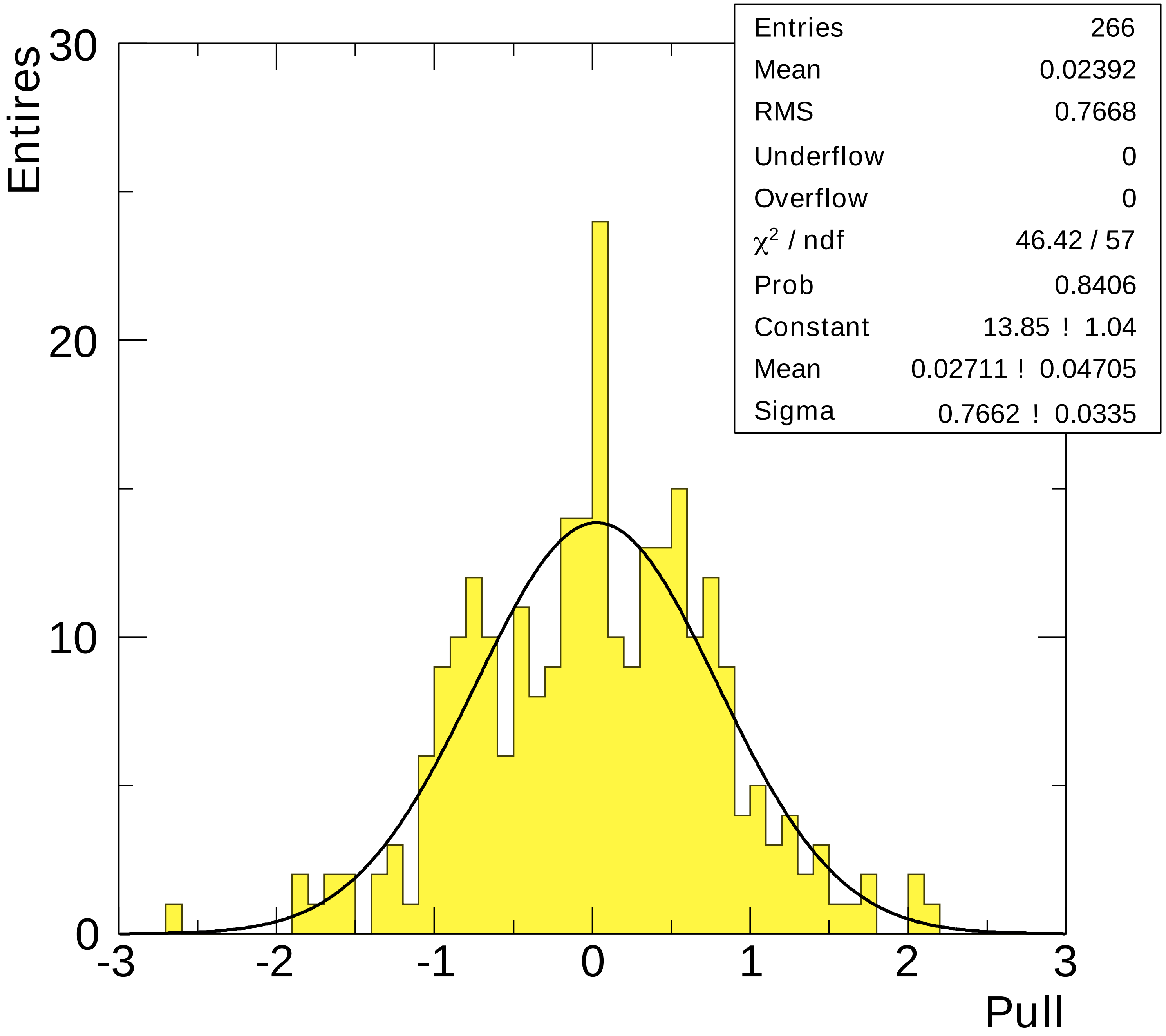
- AFG provides a reasonably good description of data
- BLZ fails to describe data particularly for x_γ and $\Delta\eta$

Summary

- New combination of charm & beauty cross sections in DIS by H1 & ZEUS
  - improved precision
  - FFNS in NLO & aNNLO provide overall satisfactory description of data
  - PDF fit to inclusive & c & b data in DIS at HERA alone yields values for running quark masses consistent with PDG
- New results on multijet prod. at low Q^2 & previous results at high Q^2 by H1
  - satisfactory description by NLO, improved shape in P_T by NNLO with significantly reduced scale uncertainty compared to NLO, particularly at higher scales
  - extraction of α_s and running of α_s in NNLO using all suitable H1 HERA inclusive jet and dijet data: $\alpha_s(M_Z) = 0.1157\ (6)_{exp}\ (^{+38}_{-25})_{pdf,theo}$
- New results on prompt photons & jets in DIS by ZEUS
  - agree better with AFG (coll. fact. NLO) than with BLZ (k_T fact.)
  - agree also, after QQ rescaling, with Djangoh & Pythia

back-up slides

Pull dist. for the c & b combination



Jet cross sections

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

- α_s dependence calculated in orders of α_s:
  - in hard coefficients

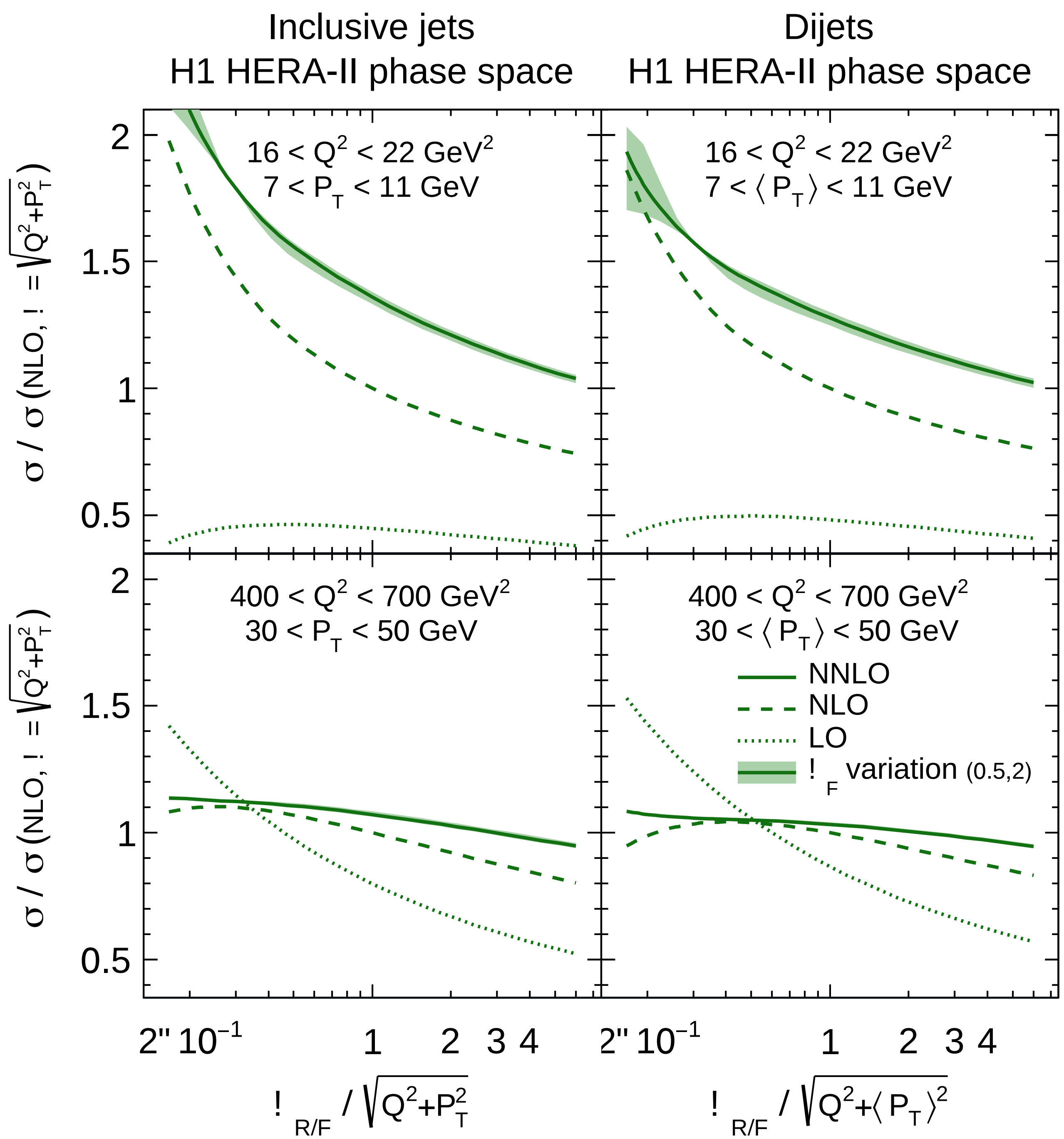
$$\hat{\sigma}_{i,k} = \sum_{n=1} \alpha_s^n(\mu_R)\hat{\sigma}_{i,k}^{(n)}(x,\mu_R,\mu_F)$$

$$\mu_R^2 \frac{d\alpha_\mathrm{s}}{d\mu_R^2} = \beta(\alpha_\mathrm{s})$$

  - in **PDF (**splitting functions**)**

$$\mu_F^2 \frac{df}{d\mu_F^2} = \mathcal{P}(\alpha_\mathrm{s}) \otimes f$$

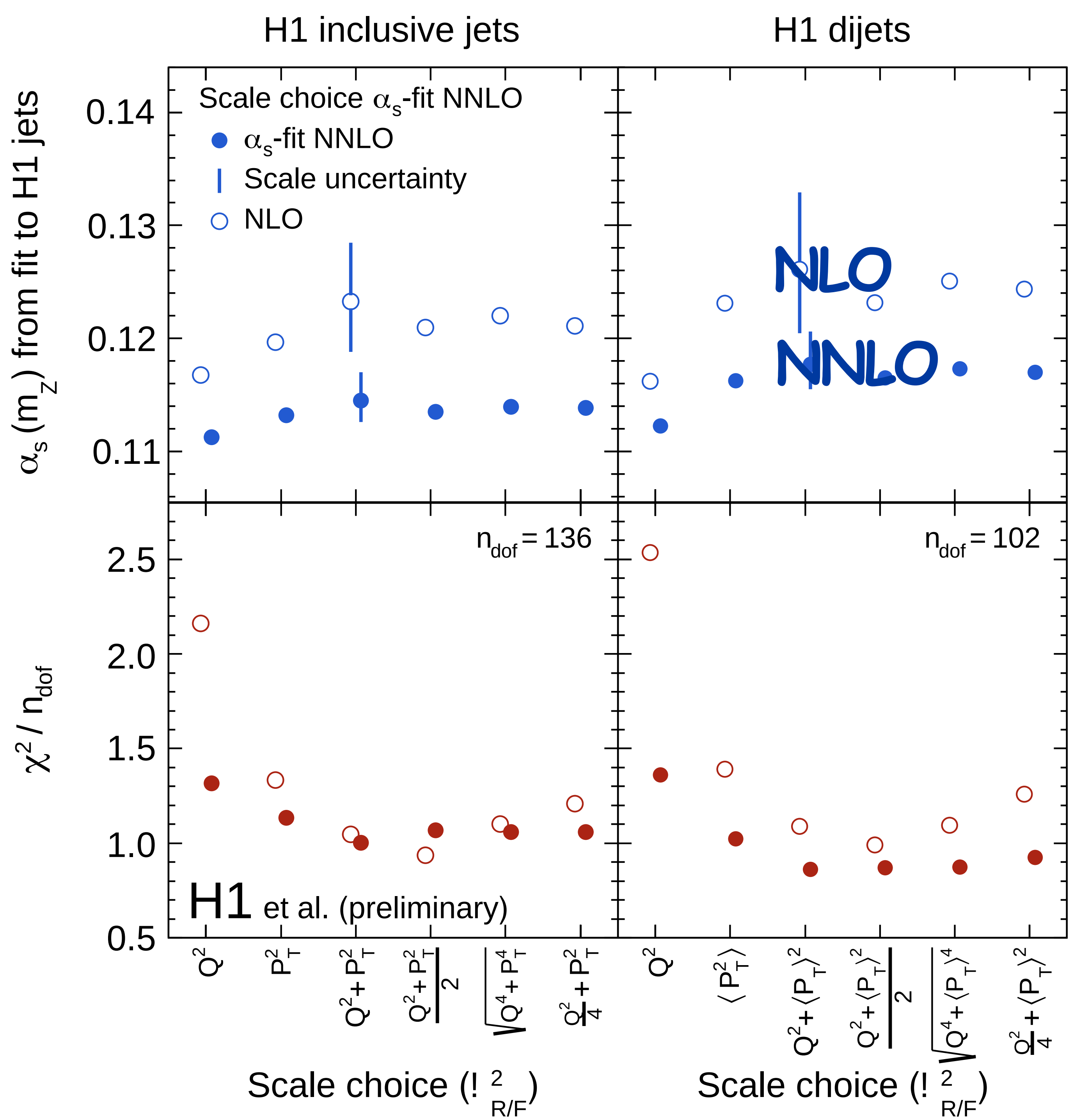
Scale dependence



all calculat ions ar e done using
NNPDF3.0 NNLO

Dependence of α_s on scale choice

Study various scales consisting of Q^2 and P_T or $\langle P_T \rangle$



Reduced scale dependence in NNLO

Extraction of α_s

Fit theory to jet data, using:

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

taking experimental, PDF and hadronization uncertainties into account

- define theory inputs (order in α_s, PDFs, scales, ...
- minimise χ^2 using Minuit and obtain α_s
- propagate exp., PDF, had. uncertainties