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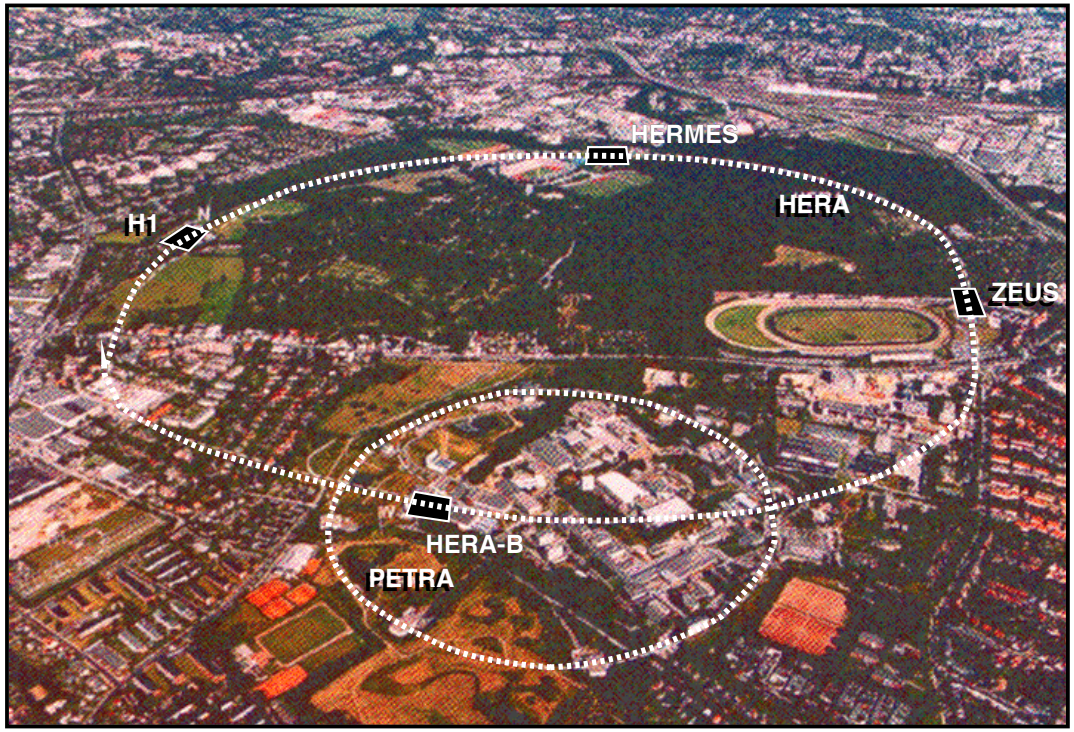
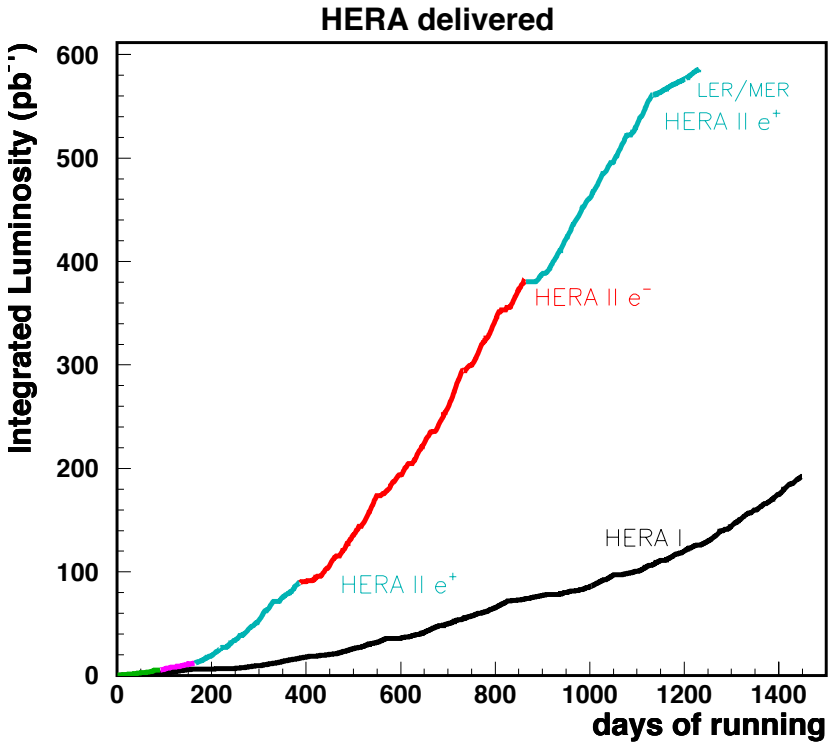
Latest results from HERA

Matthew Wing (UCL / DESY)

- Introduction: HERA, H1 and ZEUS and DIS
- Latest results
  - Hard QCD: prompt photon and jet production, α_s extraction
  - Heavy quarks: data combination, extraction of masses
  - Diffraction: factorisation in DIS and photoproduction
  - Low Q^2 and low x: transition DIS to photoproduction
- Summary

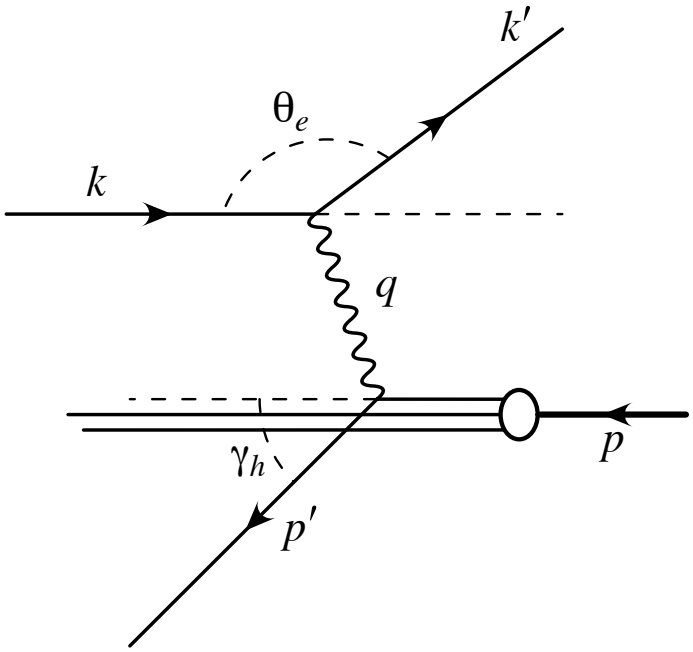
The HERA collider

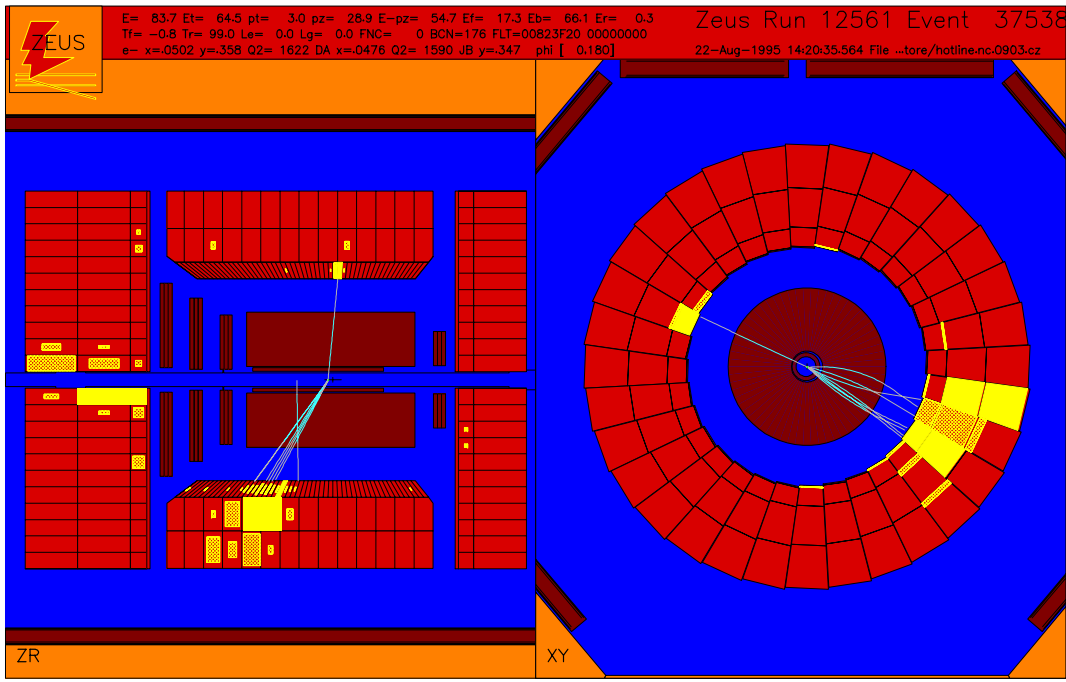




- During 1992–2007, mainly E_e = *27.5 GeV*, E_p = *920 GeV* giving $\sqrt{s}$ ~ *320 GeV;* and dedicated data at different proton energies.
- Colliding-beam experiments collected combined sample ~ *1 fb*$^{-1}$.
- About 75% data taken with polarised (~ 30%) lepton beams, with equal amounts of e^- and e^+ and positive and negative polarisation.

Deep inelastic scattering (DIS)





Momentum transfer :

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

Momentum fraction carried by struck parton :

$$x = Q^2/(2p\cdot q)$$

Inelasticity :

$$y = (q\cdot p)/(k\cdot p)$$

And : $Q^2 = s\cdot x\cdot y$

$Q^2 > 1\ GeV^2$ — deep inelastic scattering

$Q^2 < 1\ GeV^2$ — photoproduction

Motivation: HERA physics

- As will all general-purpose high energy colliders, investigate a wide range of physics.
- Measurement of proton structure has been and continues to be central to the programme.
- Investigation of QCD at HERA still going strong.
  - Although HERA stopped taking data in 2007, H1 and ZEUS have published >130 papers in almost 10 years since.
  - New processes are being measured; final measurements are being performed; fundamental parameters are being extracted; deeper understanding of QCD pursued.
  - Unique environment of a point-like probe of a hadron.
  - Mature data sets with fully calibrated data and relatively easy to use analysis frameworks.
- **Will here review recent results at HERA from H1 and ZEUS on QCD.**

See also talk on contact interactions by O. Turkot, WG3

Prompt photon production

Prompt photon production has a clear signal.

Photon produced in hard scatter and not subject to hadronisation.

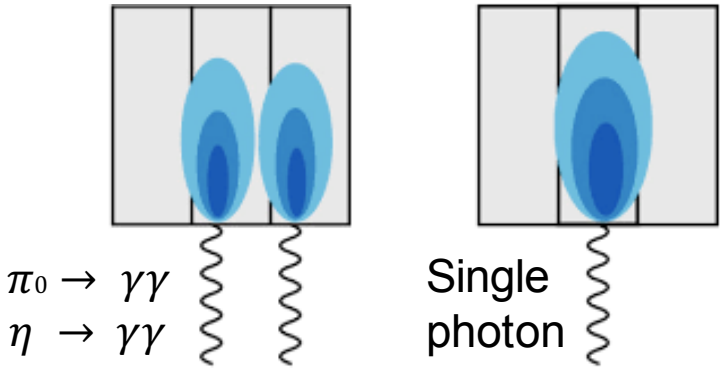
Fewer possible diagrams compared to parton−parton scattering.

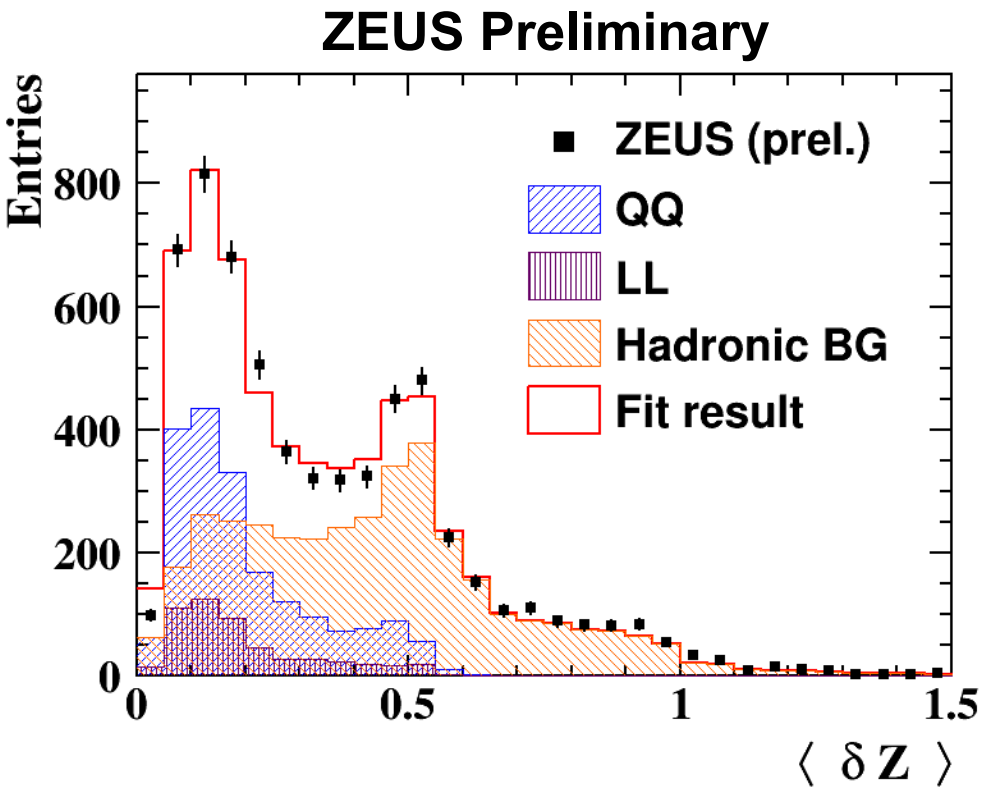
Sensitivity to parton densities in proton, photon and Pomeron.

Prompt photon can be background to new physics.

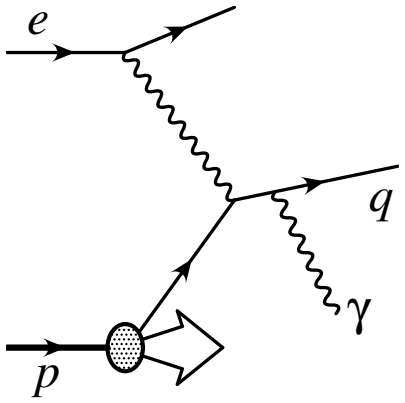
Here measure:

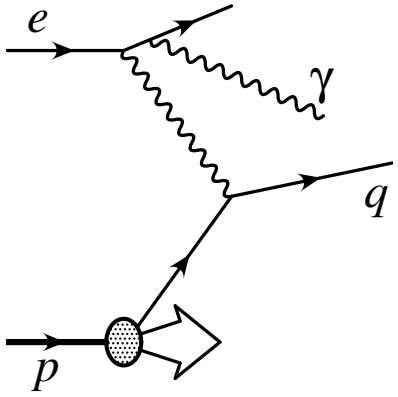
- in DIS and compare to theories
- in diffraction for the first time and compare to MC models.



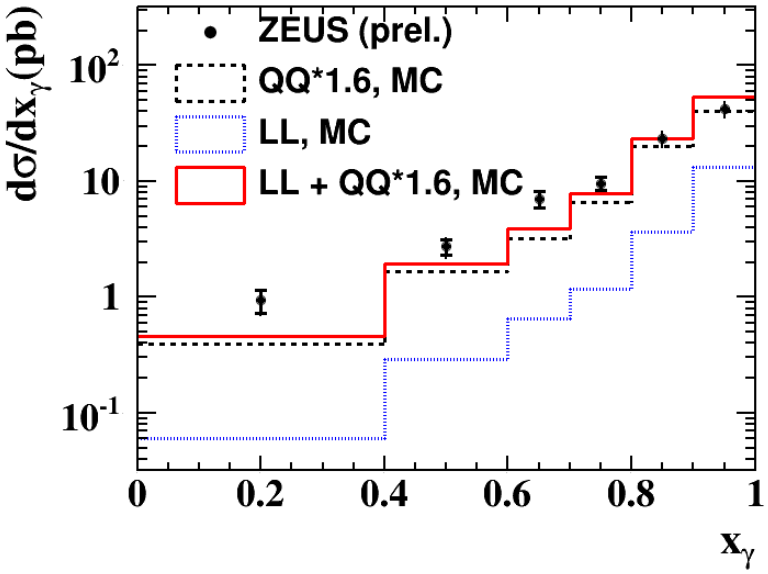


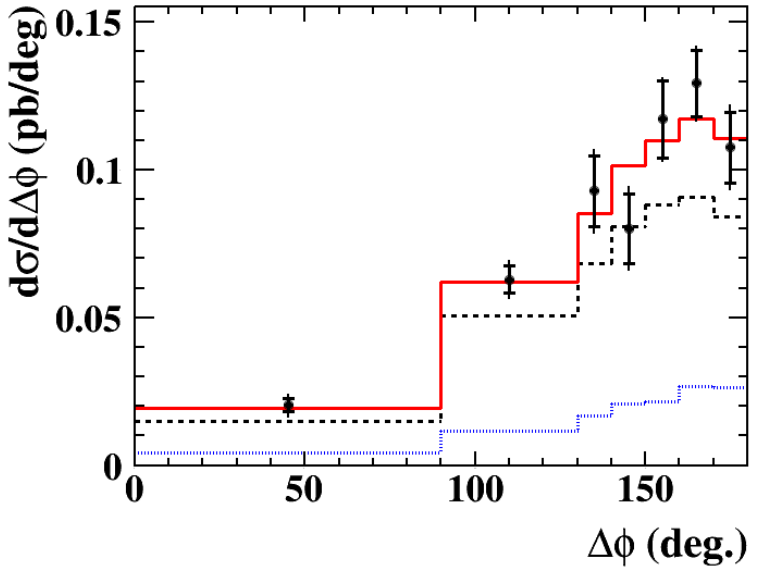
Prompt photons in DIS





ZEUS Preliminary



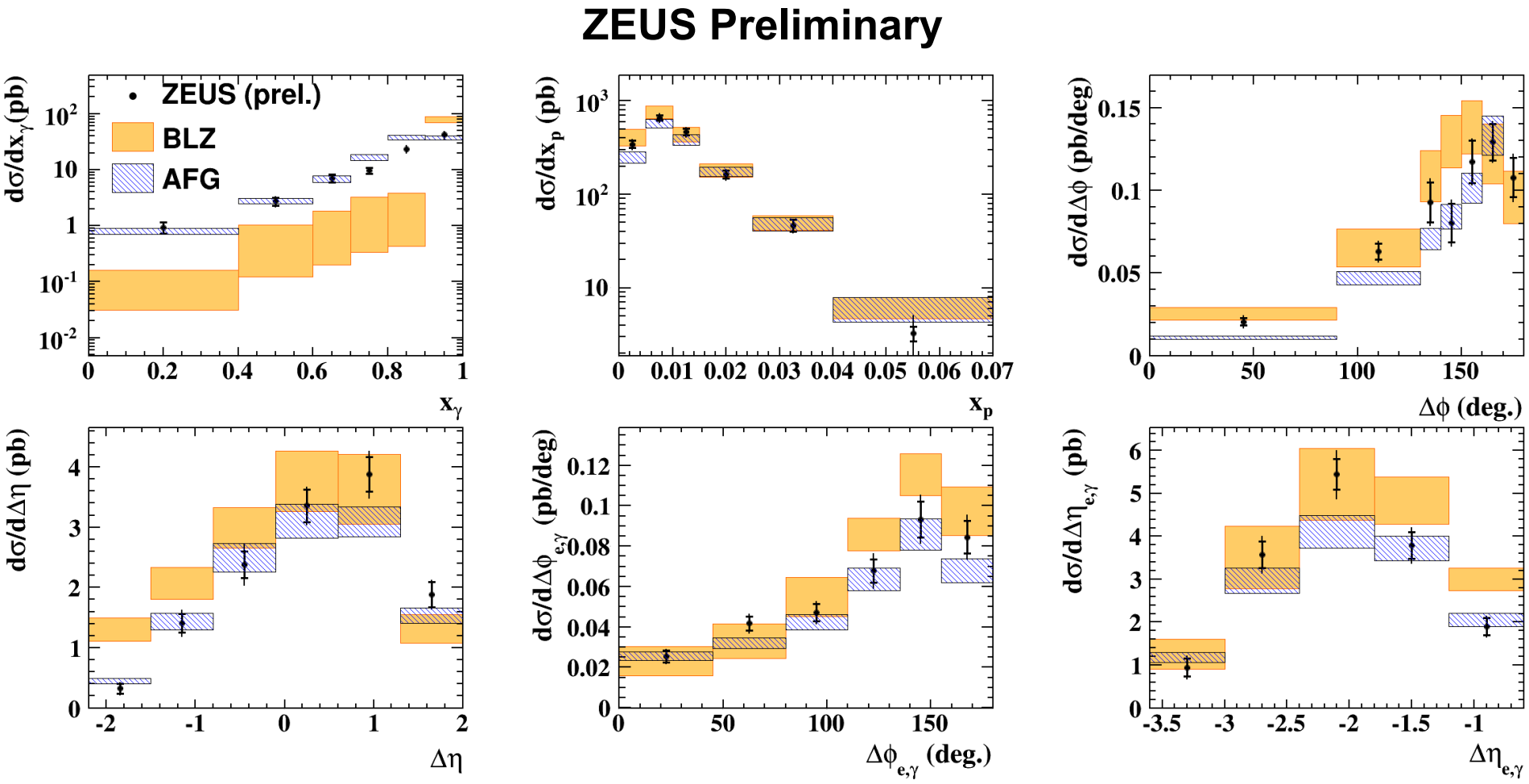


$$x_\gamma = \frac{E^\gamma - p_Z^\gamma + E^{jet} - p_Z^{jet}}{2E_e y_{JB}}$$

Monte Carlo simulations of QQ and LL give a good description of the data

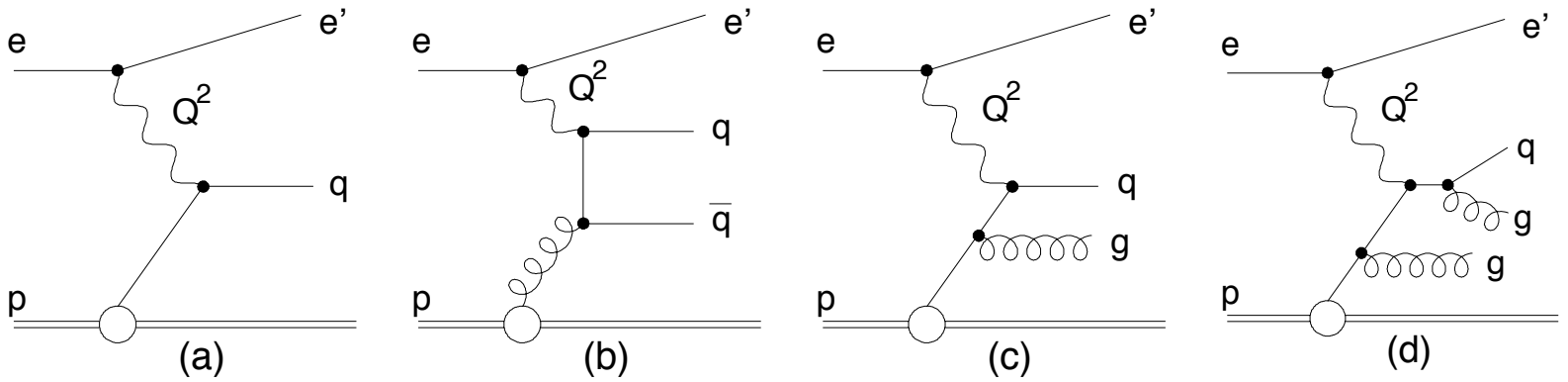
Prompt photons in DIS

See talk by
O. Hlushchenko, WG4



- Description by k_T factorisation (BLZ) not great, particularly x_γ and $\Delta\eta$.
- Description by collinear factorisation (AFG) is better and reasonable.

Jet production in DIS



- Stringent test of pQCD calculations.
- Direct sensitivity to PDFs.
- Can extract strong coupling α_s.

H1 analysis of

- Jet data in DIS using ~ *290* pb^{-1}, simultaneously measuring inclusive jet, dijet and trijet cross sections.
- Comparison with NLO QCD calculations and **also NNLO QCD** calculations.
- Extraction of α_s at both orders and also its running.

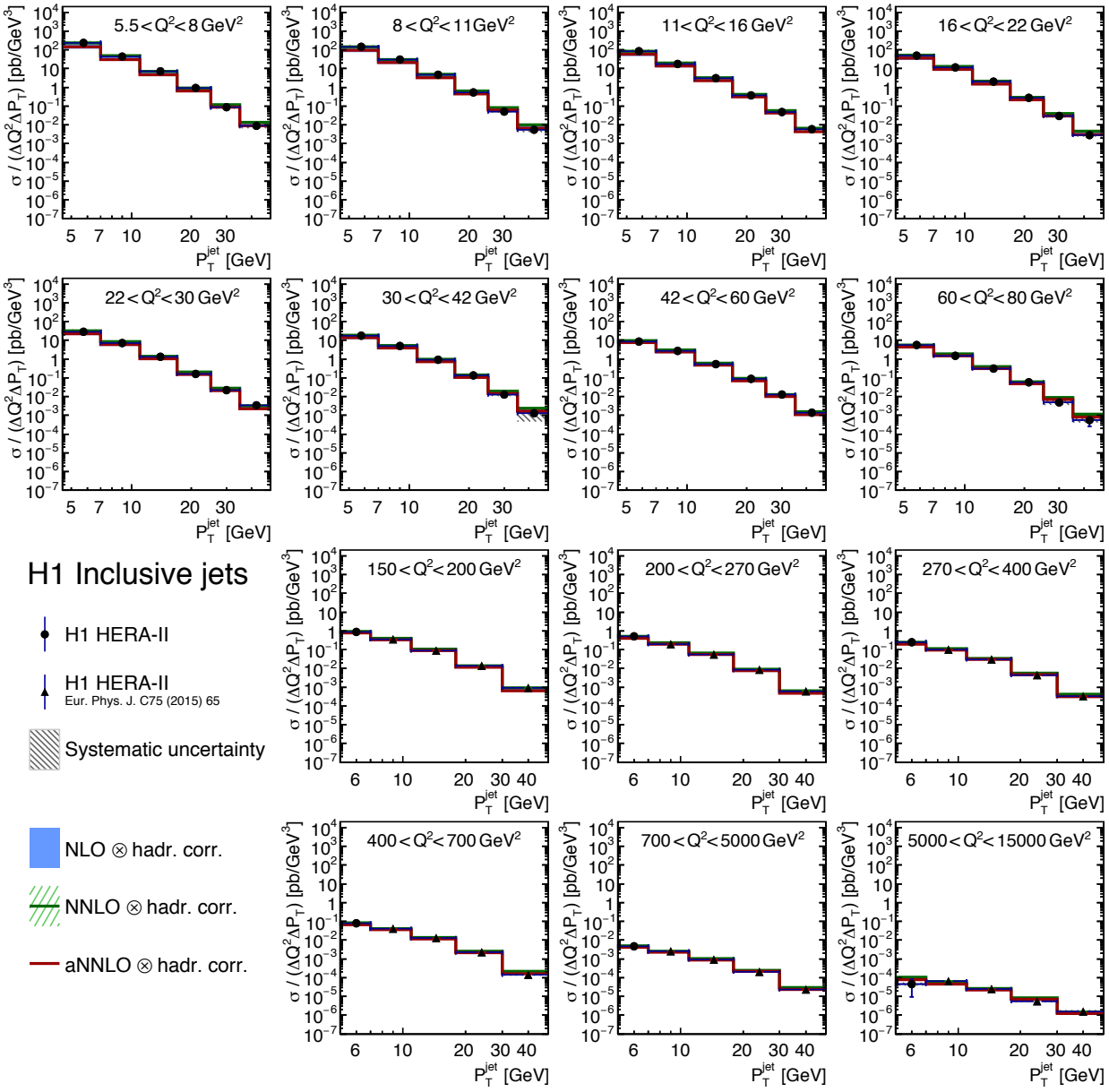
H1 Coll., DESY-16-200, H1prelim-17-031 (also V. Bertone, J. Currie, T. Gehrmann, A. Huss, J. Niehues.)

Jet production in DIS

Jet cross sections normalised to inclusive DIS cross section.

Significant cancellation of uncertainties.

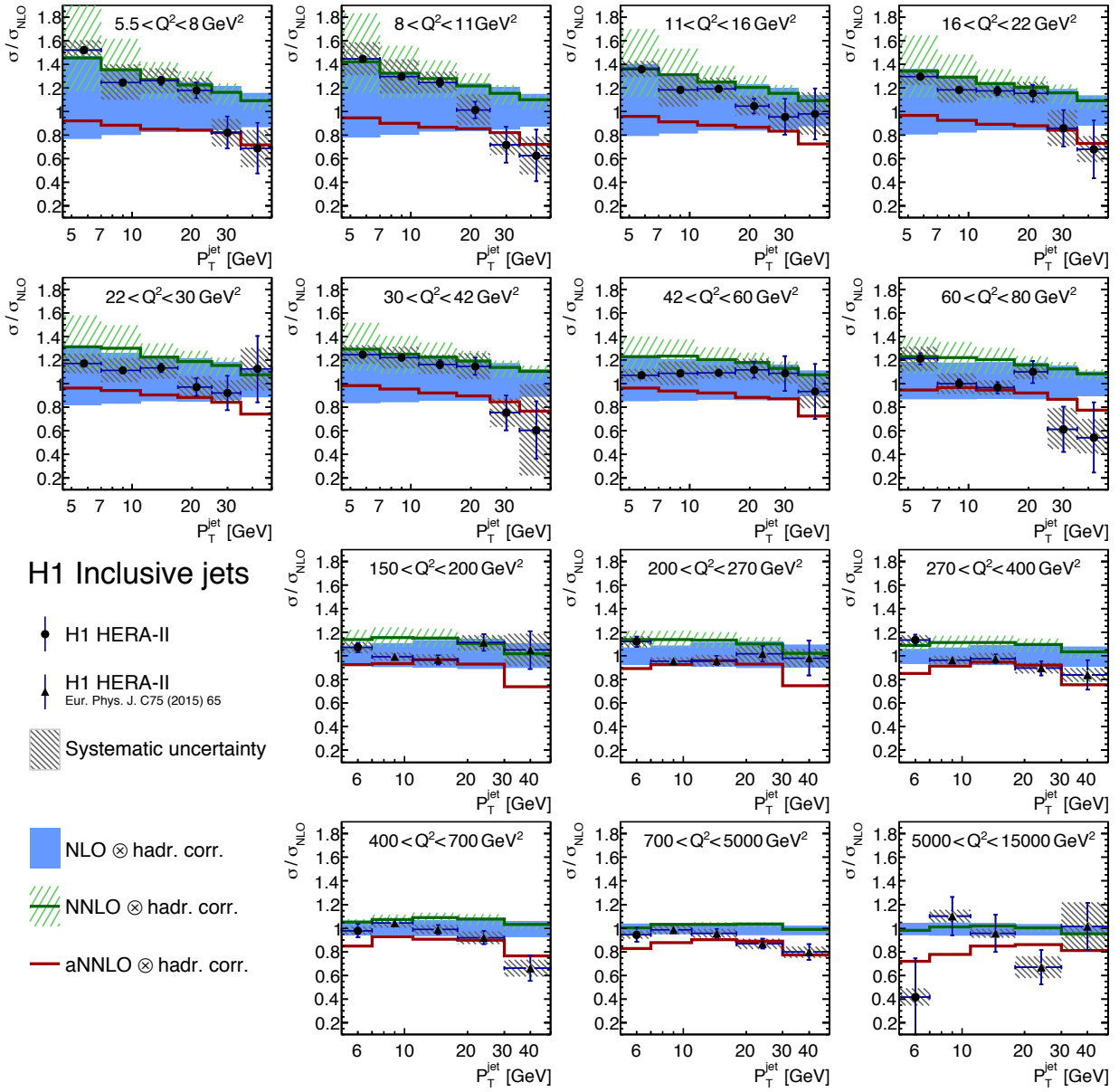
High-precision data over wide kinematic range.



See talks by D. Britzger, WG4 and WG1+WG4.

Jet production in DIS: comparison with pQCD

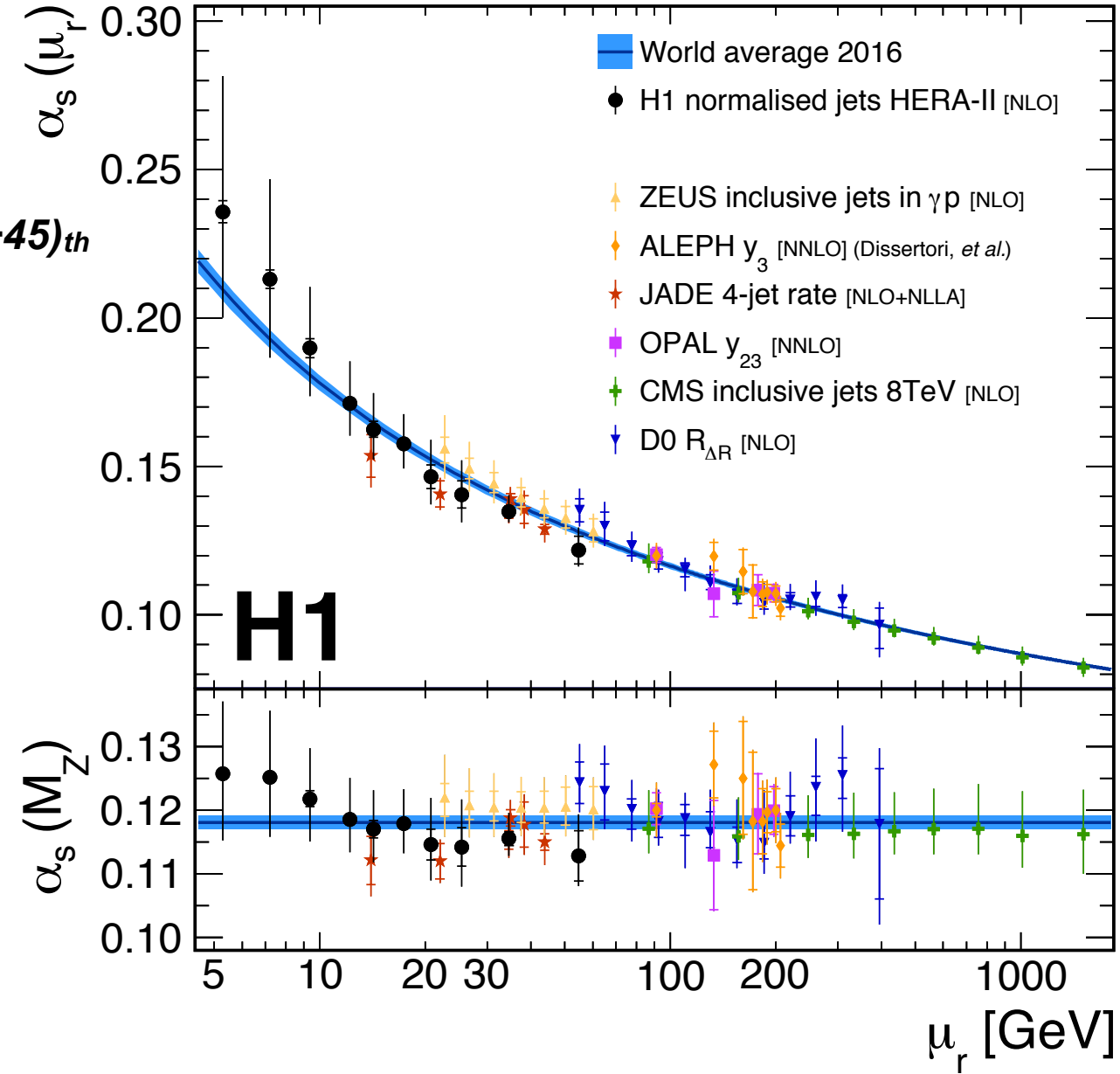
- NLO QCD
  - Reasonable description of data.
  - Large scale uncertainties.
- Approx. NNLO
  - Improved shape
- NNLO
  - Improved description
  - Smaller scale uncertainties.



Jet production in DIS: extraction of α_s at NLO

$\alpha_s(M_Z) = 0.1172\ (4)_{exp}\ (+53/-45)_{th}$

- Extraction has a high experimental precision.
- Consistent with other extractions.
- Clearly shows running of α_s.
- Running consistent with other experiments and QCD.



Jet production in DIS: extraction of α_s at NNLO

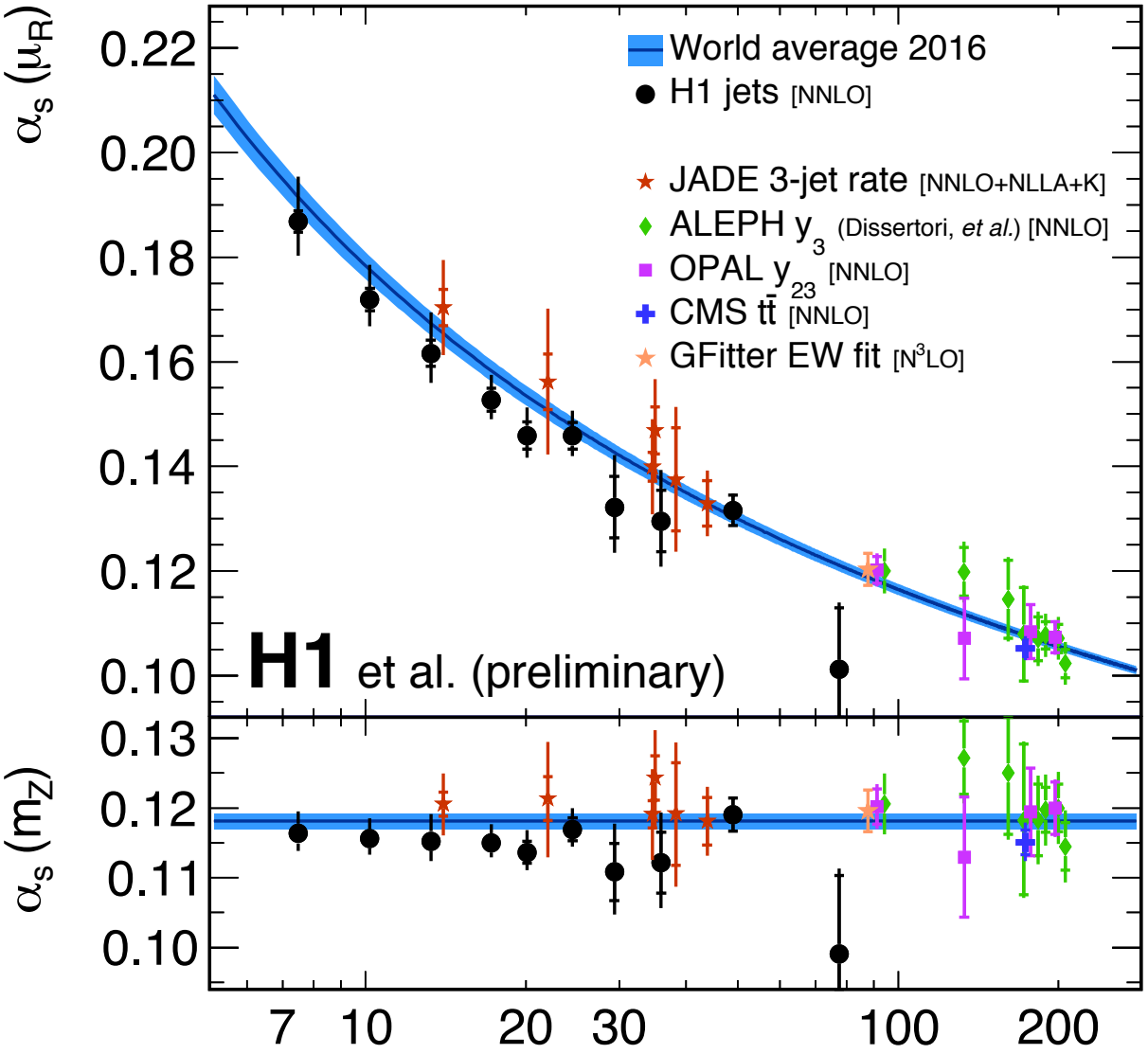
New NNLO fits of H1 jet measurements.

Good consistency of different data sets.

Theory scale uncertainty reduced compared to NLO.

Confirm running.

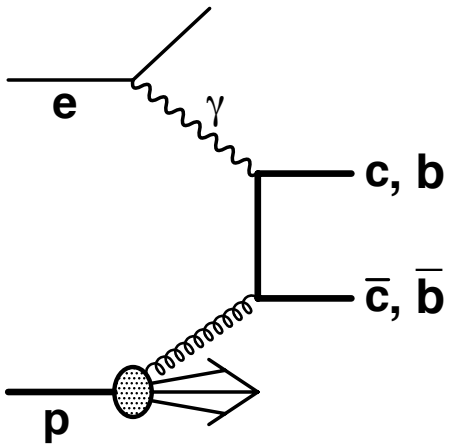
In agreement with world average, although a bit lower.



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

Measurement of heavy-quark production

- Charm production is a rich testing ground for perturbative QCD.
  - Expect reliable predictions as charm mass provides hard scale.
  - There are in fact multiple hard scales.
  - Production at HERA dominated by boson–gluon fusion.
  - Hence sensitivity to gluon density in proton.
  - Also sensitive to the masses and can extract them.



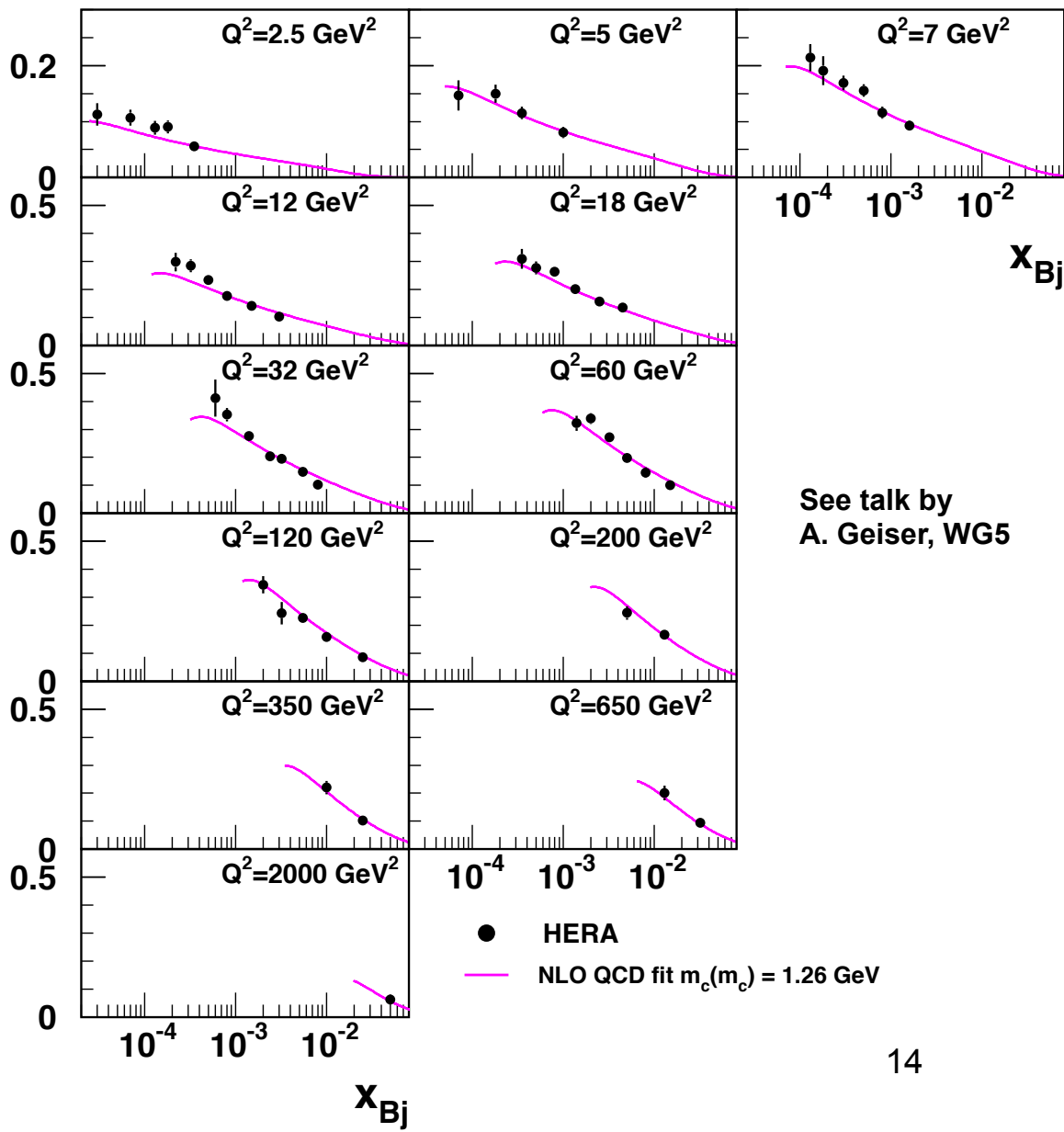
- **Extraction of running of charm-quark mass.**
- **Combination of all *c* and *b* DIS data and extraction of heavy-quark masses.**

Running of the charm-quark mass

- As with e.g. α_s, consider running of m_c.
- Fit NLO QCD to HERA charm (2012) DIS data.

$$\sigma_{\mathrm{red}}^{Q\bar{Q}} = \frac{\mathrm{d}^2\sigma^{Q\bar{Q}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2} \cdot \frac{xQ^4}{2\pi\alpha^2\left(1+(1-y)^2\right)}$$

- Use ABM PDF in 3 flavours.
- Extraction done in Q^2 rows shown.
- **Simultaneous fit of charm and inclusive data.**
- NLO QCD (using global fit m_c) gives a good description of the data.

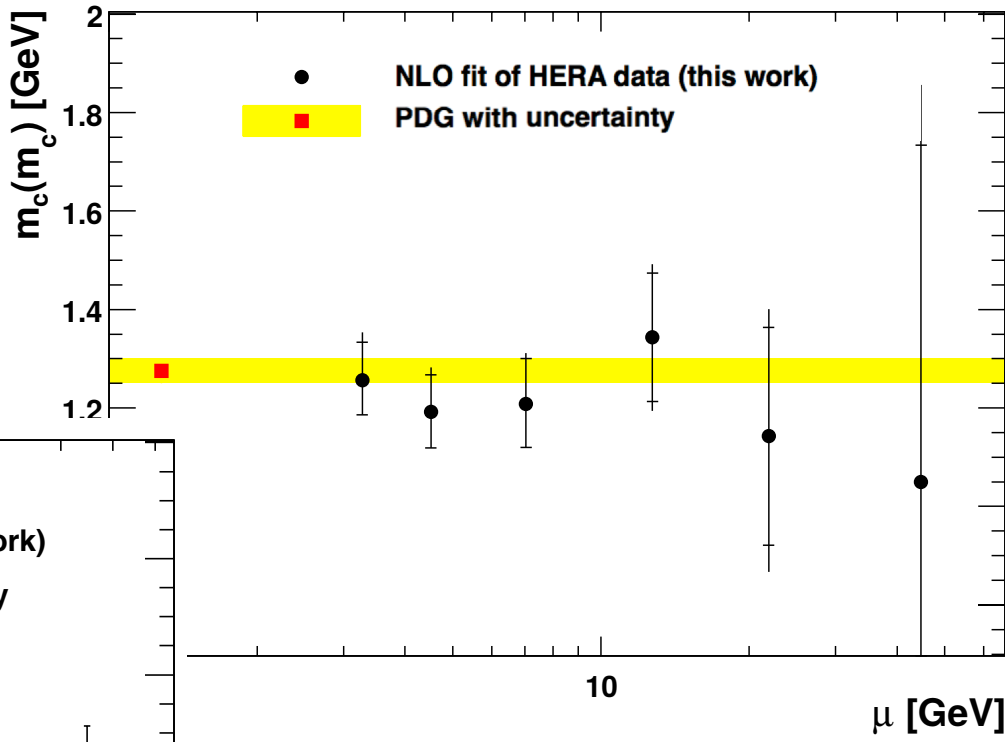


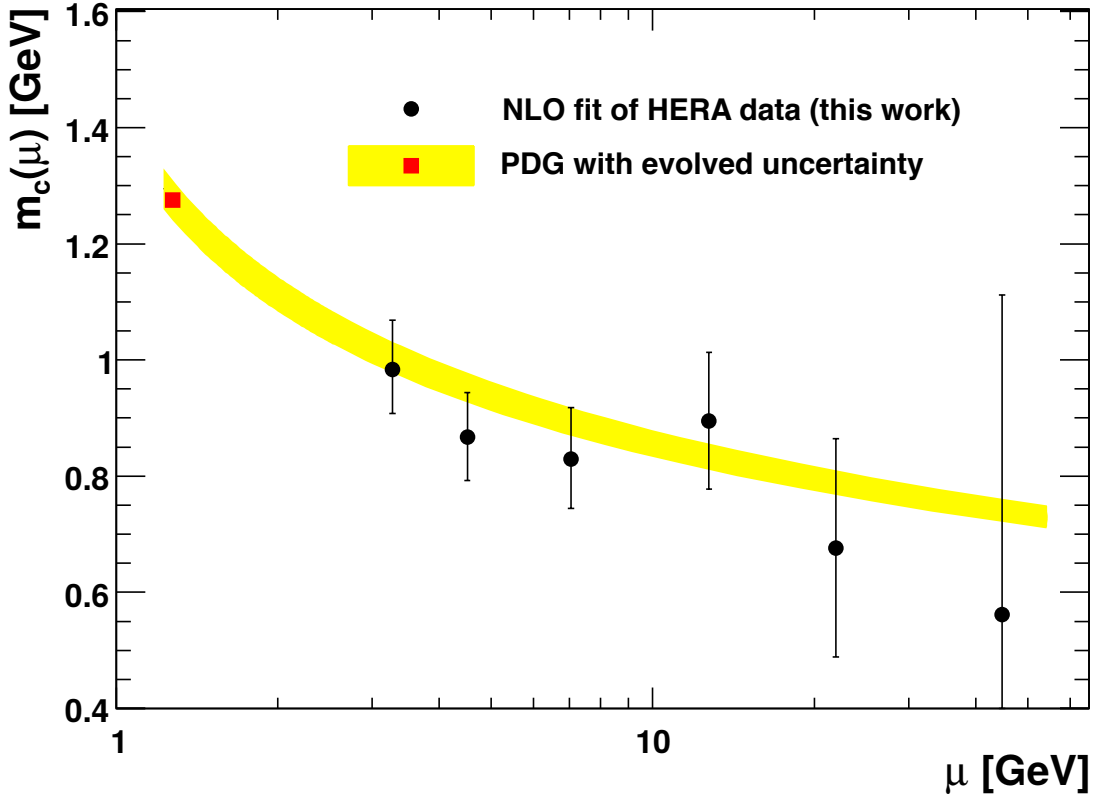
See talk by A. Geiser, WG5

A. Gizhko, A. Geiser, S. Moch et al., DESY-17-048

Running of the charm-quark mass

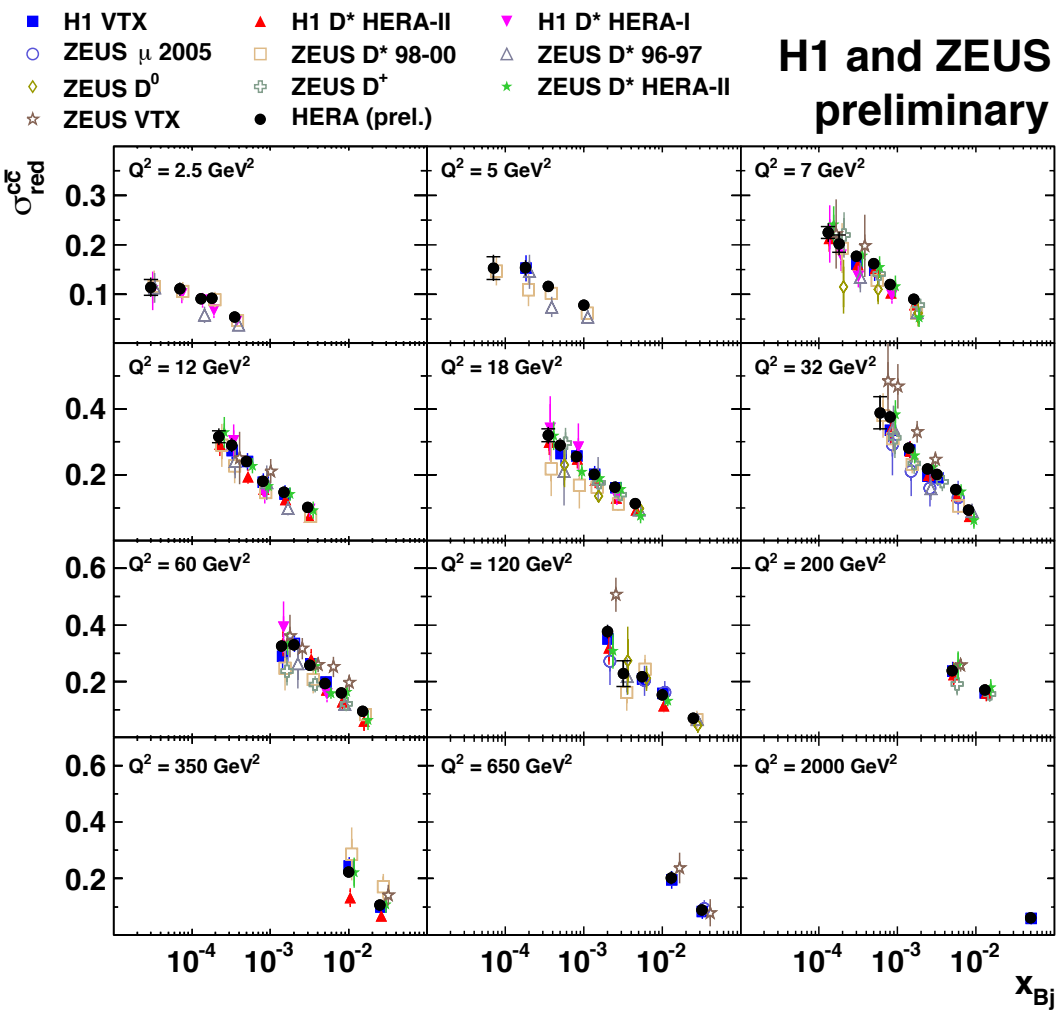
- The χ^2 distribution is used to extract m_c.
- The values of m_c extracted at different scales agree very well with each other.





- Assuming running, $m_c(m_c)$ translated to $m_c(\mu)$.
- Extracted values well described by QCD.
- **Running of charm-quark mass versus scale clearly observed.**

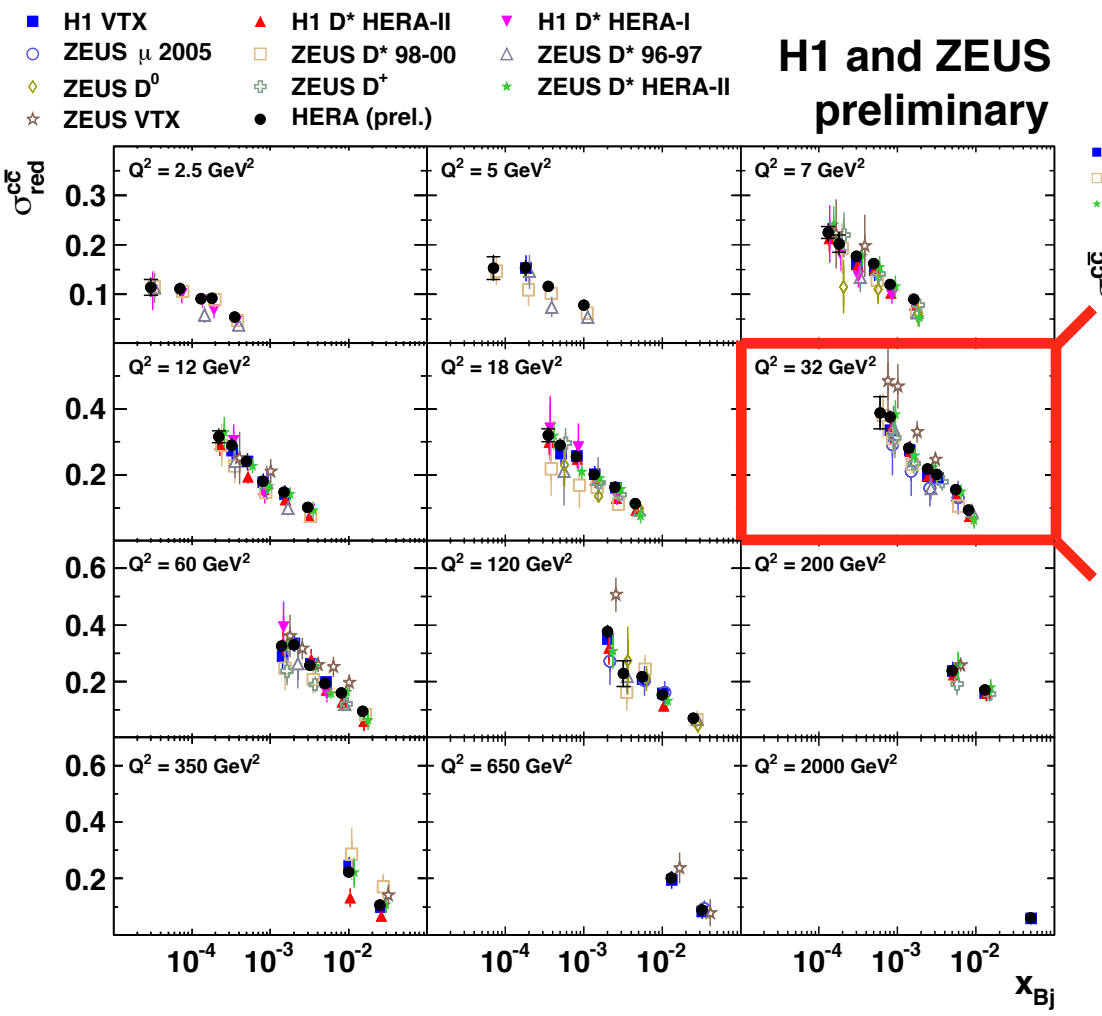
Combination of *c* DIS cross sections

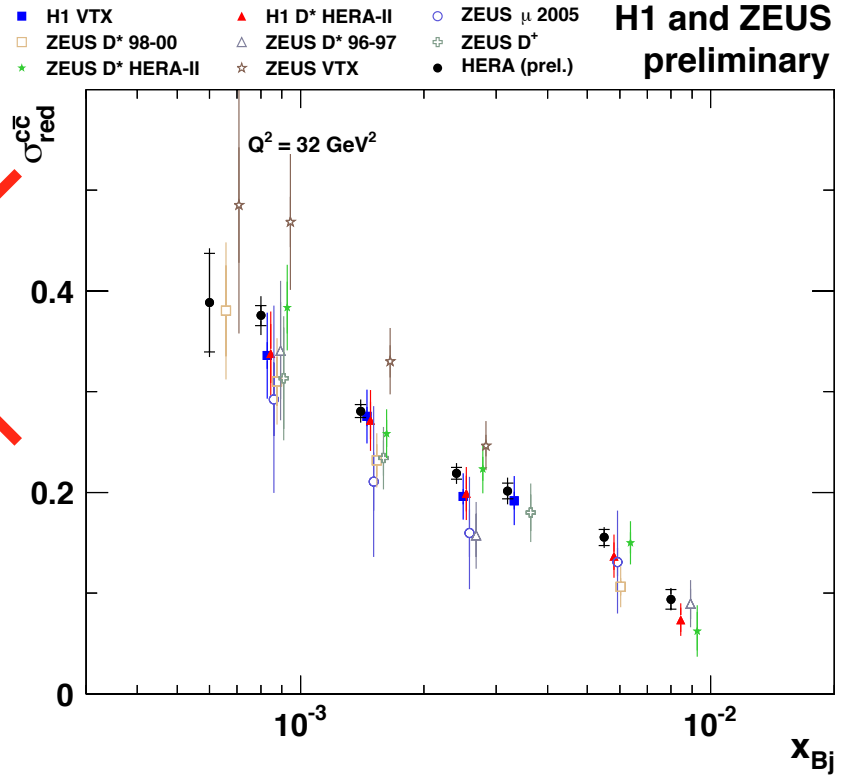


- New combination of heavy-quark data
  - Account for correlations in data sets as well as in *b* and *c* measurements.
  - Including new *c* data.
  - *209 c*, *52 b* data points → *52 c*, *27 b* data points,
  - Good consistency: χ^2/ndf = 149/187
- **Significant improvement in precision**

See talk by
O. Zenaiev, WG1,5

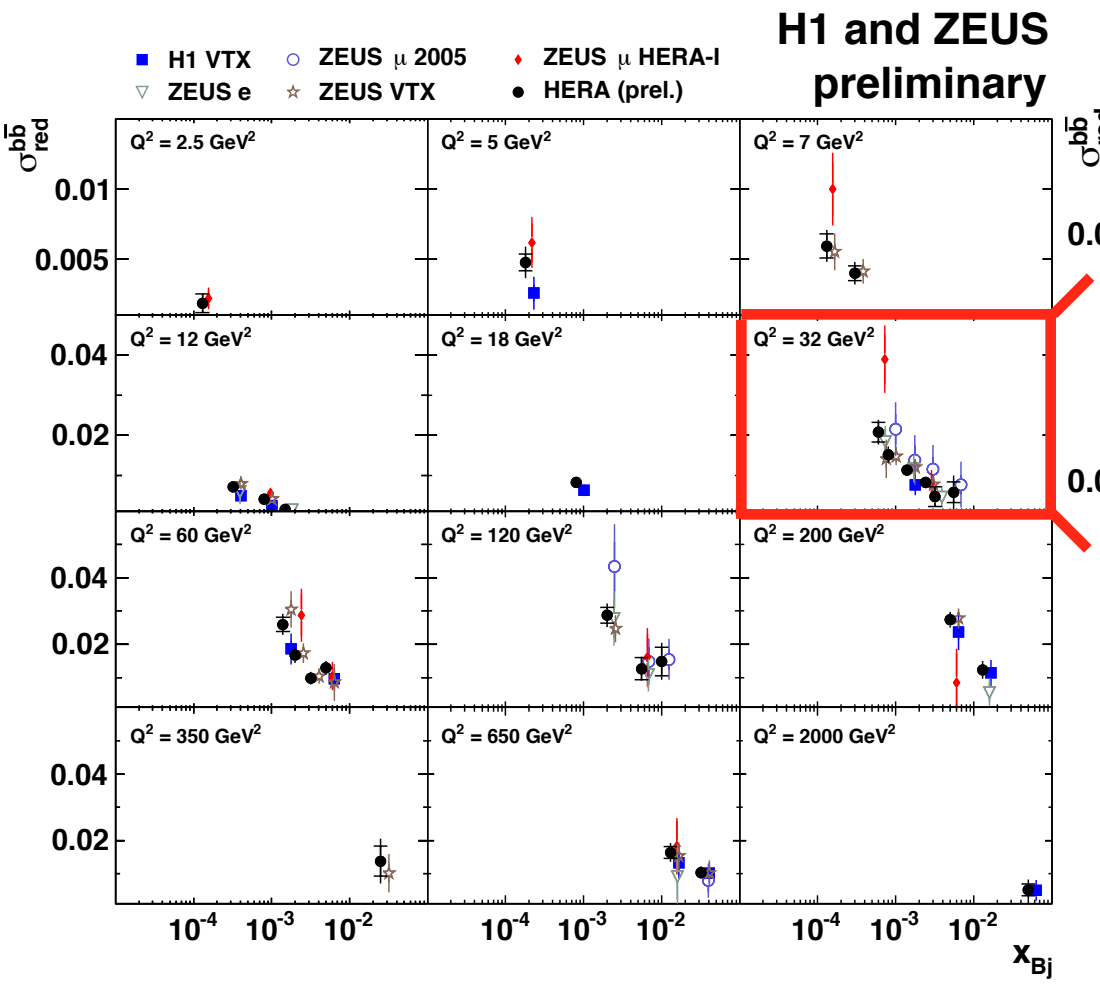
Combination of *c* DIS cross sections

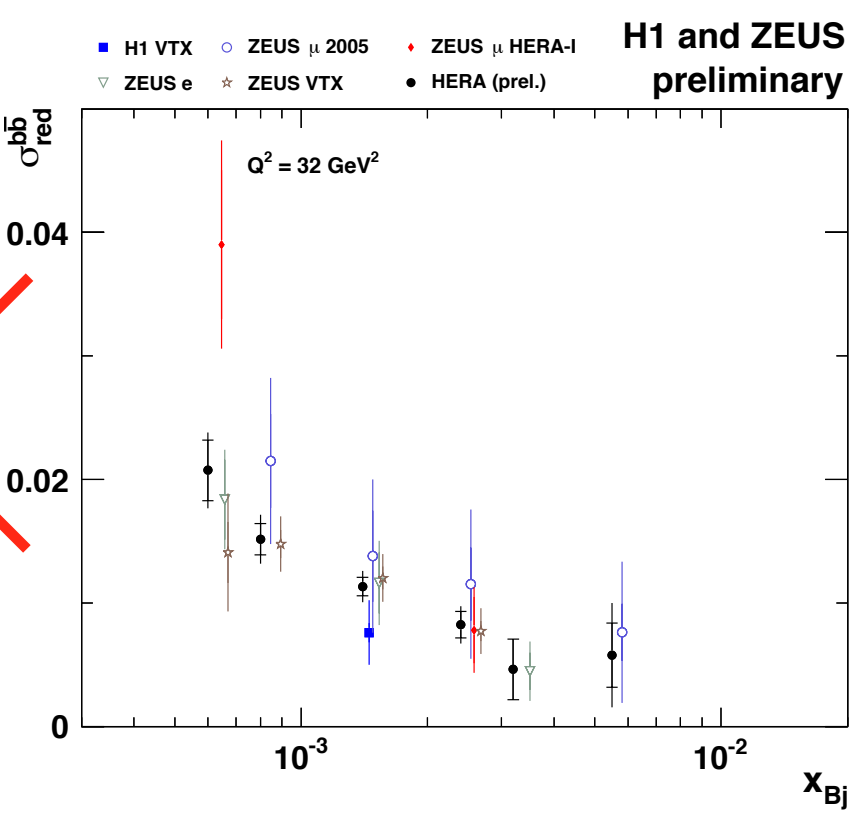




- **Significant improvement in precision compared to input measurements.**

Combination of *b* DIS cross sections



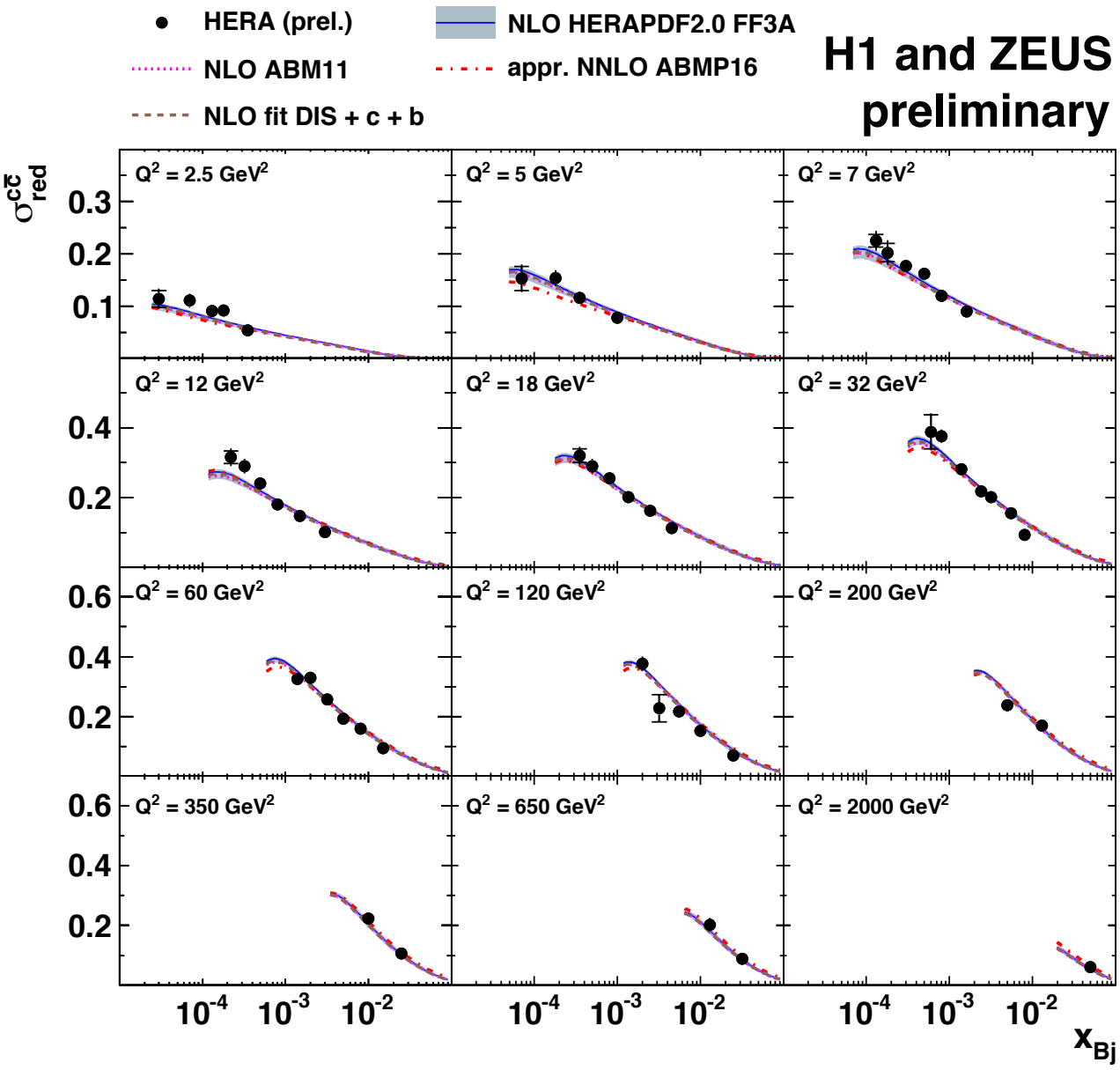


- **First combination of *b* cross sections.**
- **Significant improvement in precision compared to input measurements.**

Charm DIS cross sections compared with QCD

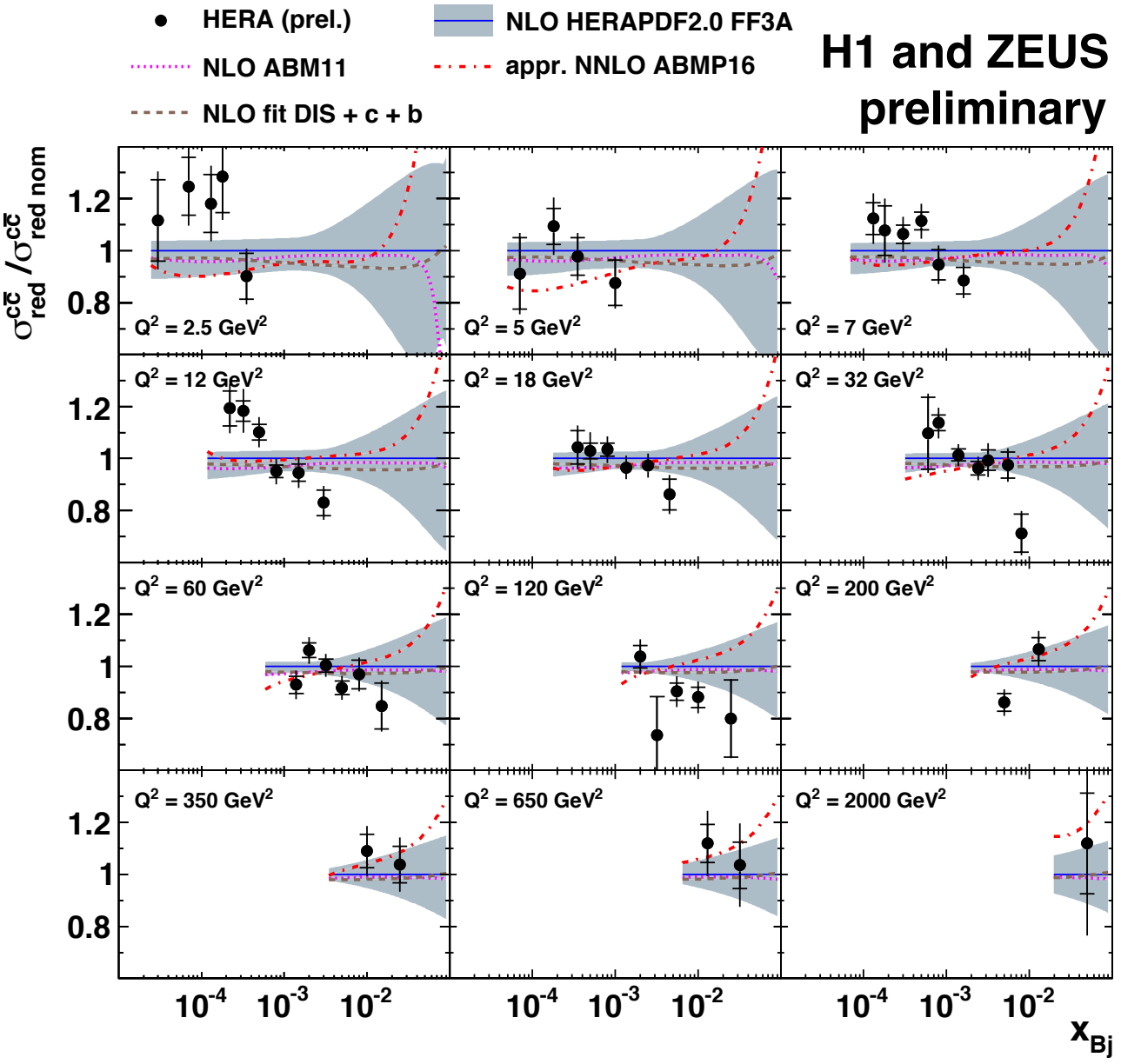
- Comparison to different NLO and approximate NNLO calculation.
- Dominant uncertainty comes from scale change.
- PDFs are all similar.

- **Overall reasonable description of data.**
- **But some difference in slope at low and medium Q^2.**



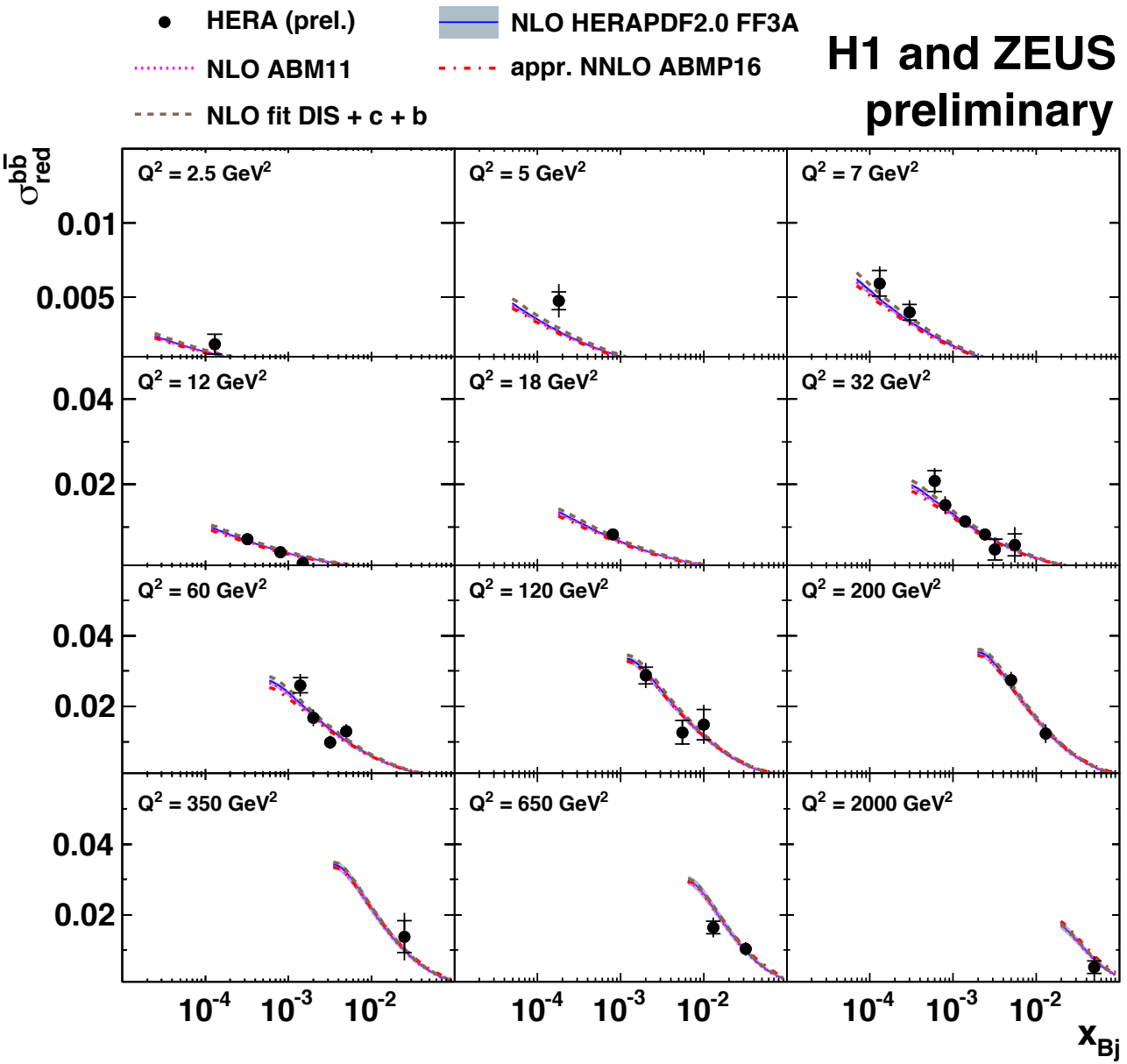
Charm DIS cross sections compared with QCD

- Comparison between data and QCD more clearly seen.
- In region $10^{-4} < x < 10^{-2}$, PDFs similar.
- **Can some change in the gluon PDF describe the data ?**



Beauty DIS cross sections compared with QCD

- **Description of beauty data is good.**
- **Similar by all PDFs.**
- Use data to extract quark masses →



Extraction of quark masses

- QCD analysis of heavy-quark and inclusive data with simultaneous fit of PDFs.
- Heavy-quark data needed as inclusive data alone cannot constrain masses.

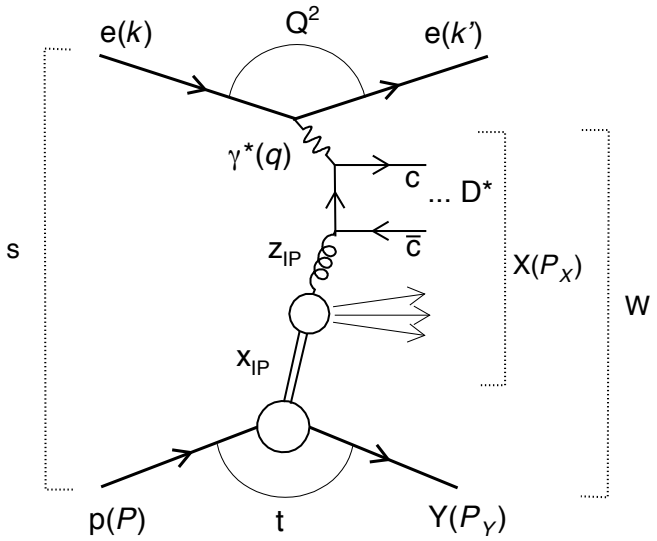
$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+7}_{-31}(\text{par})\ \text{MeV},$$
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{mod})^{+1}_{-31}(\text{par})\ \text{MeV}.$$

PDG2016: $m_c(m_c) = 1270 \pm 30$ MeV, $m_b(m_b) = 4180^{+40}_{-30}$ MeV

Precise value of heavy-quark masses, particularly charm, extracted and consistent with PDG value.

Diffractive charm production in DIS

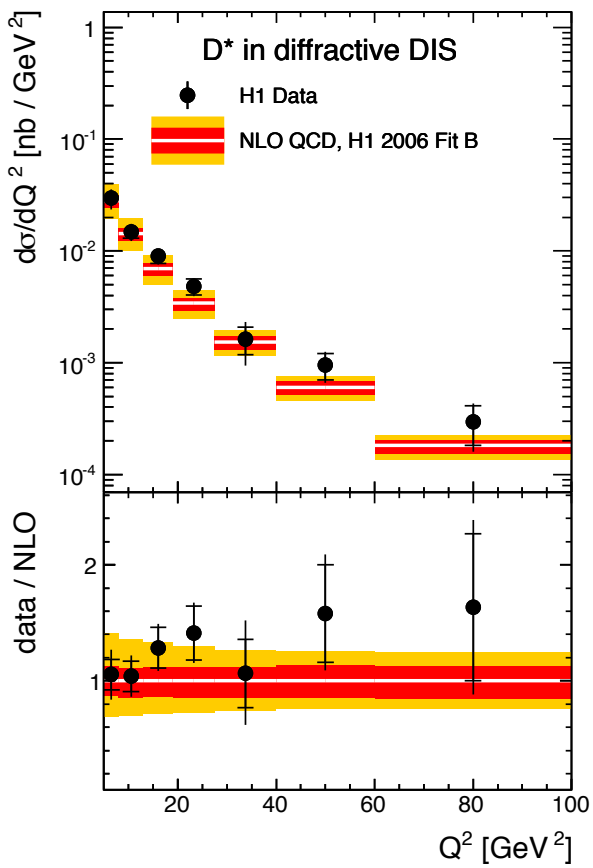
- Can extract diffractive PDFs from inclusive diffractive data.
- Can these then be used to predict other processes:
  - Factorisation (Collins) says yes.
  - Supported in various DIS reactions, e.g. jets
  - Not supported in *pp* collisions.
  - Not clear in photoproduction.

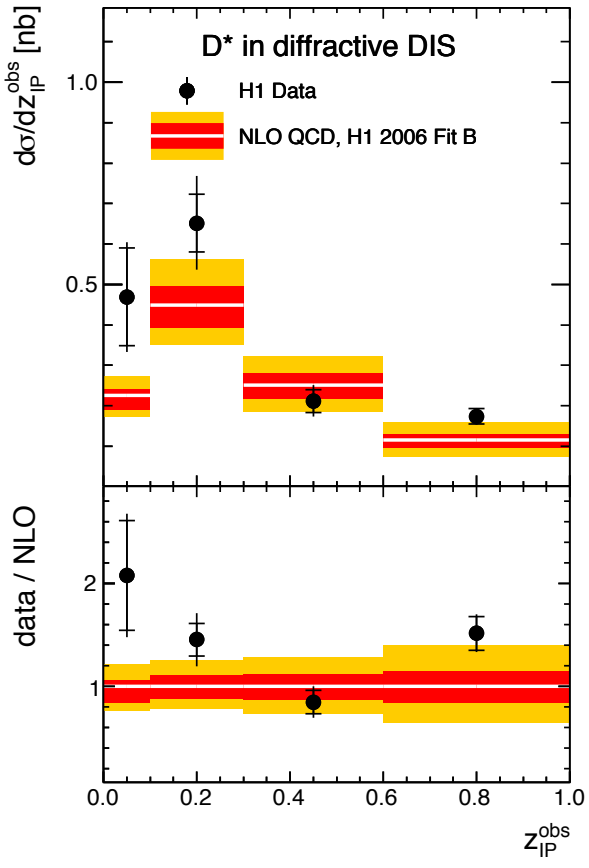


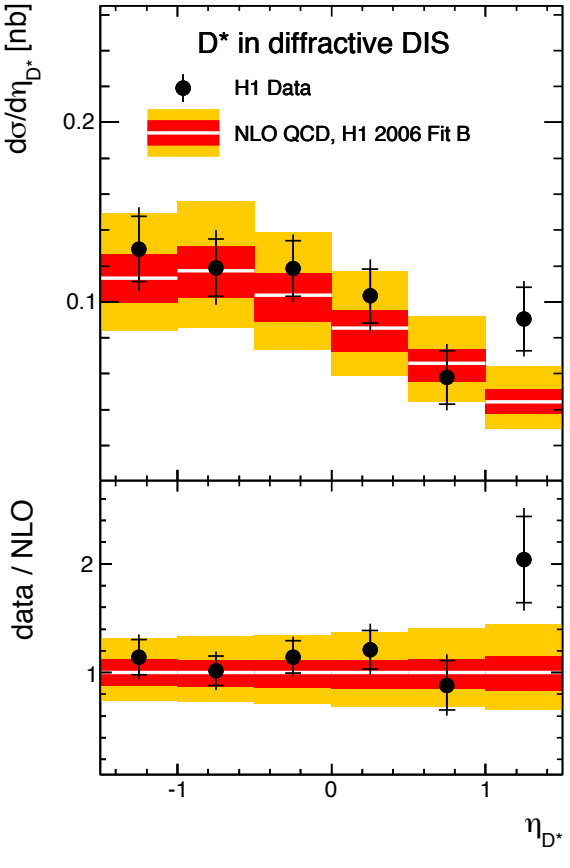
- New analysis tests factorisation in diffractive charm production in DIS
  - by tagging D* mesons
  - using a high luminosity, *287* pb^{-1}
- Theory at NLO QCD and using H1 2006 DPDF Fit B.

Diffractive charm data versus NLO QCD

H1 Coll.,
DESY-17-043







- Data are well described by NLO QCD predictions, for DIS, diffractive and *D** variables.
- **Supports the theory that factorisation holds in diffractive DIS.**
- Fraction of *D** diffraction to *D** inclusive about ~6%, also observed in photoproduction and predicted by QCD.

See talk by K. Cerny, WG2

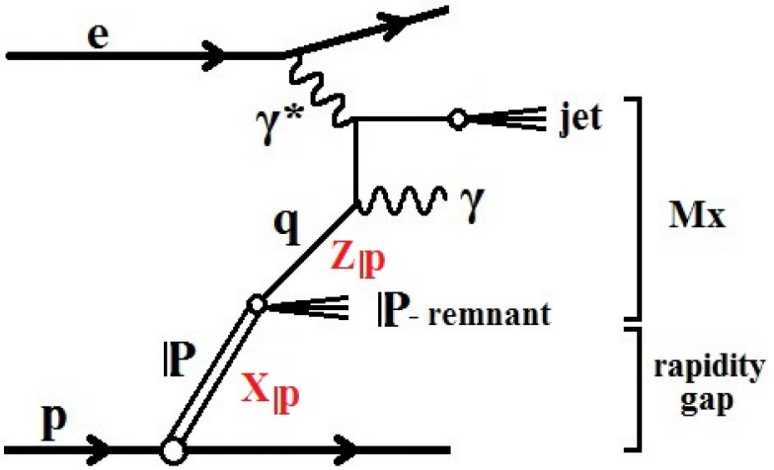
Prompt photons in diffractive photoproduction

First measurement of prompt photons in diffraction

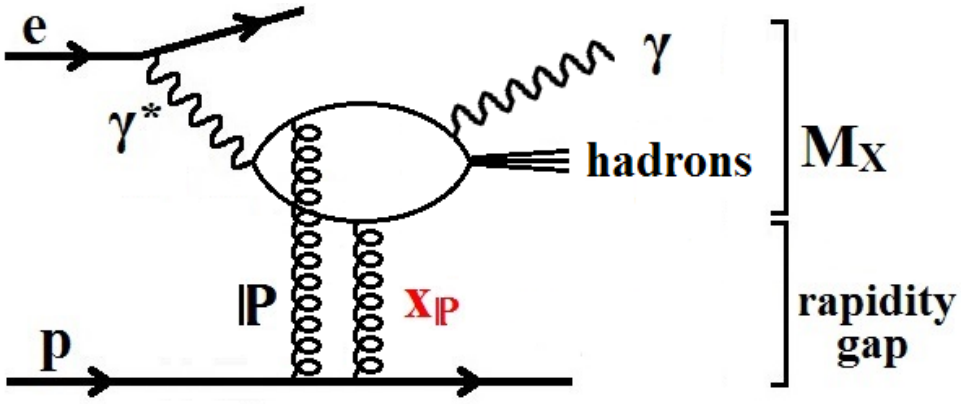
Several possible processes at LO (also resolved γ, direct Pomeron

Another hard probe to investigate diffraction

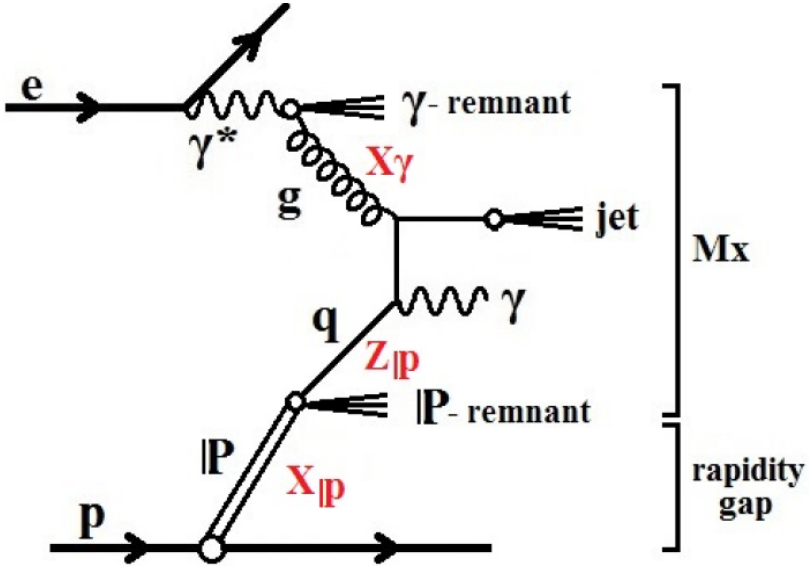
Direct sensitivity to the quark structure of the Pomeron



Direct γ, resolved Pomeron



Direct γ, direct Pomeron



Resolved γ, resolved Pomeron

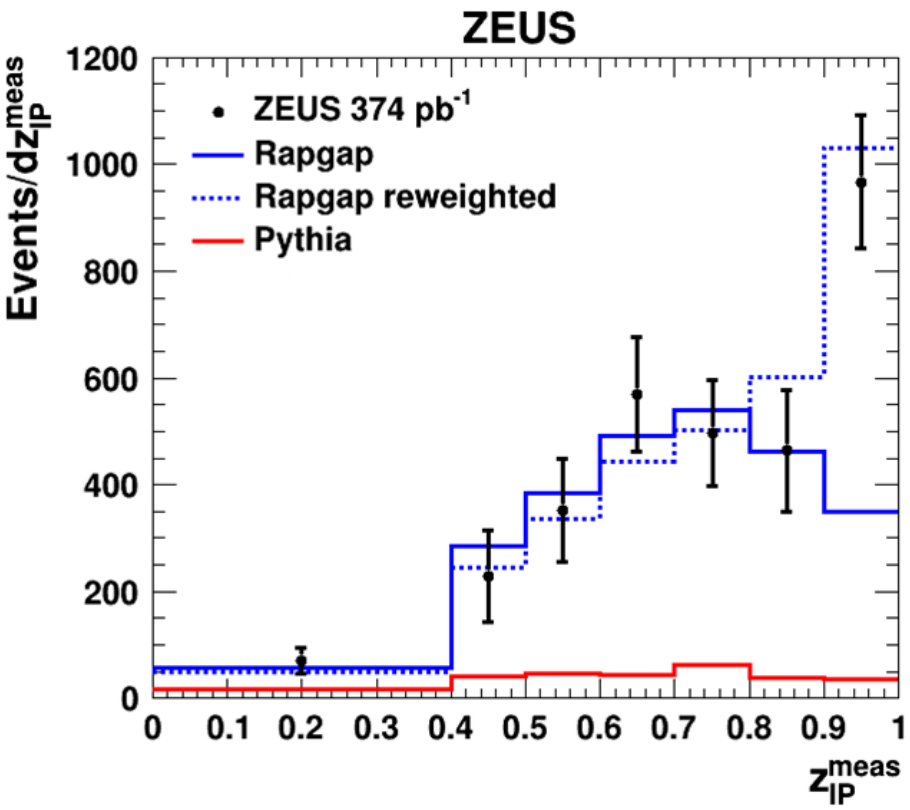
Prompt photons in diffraction

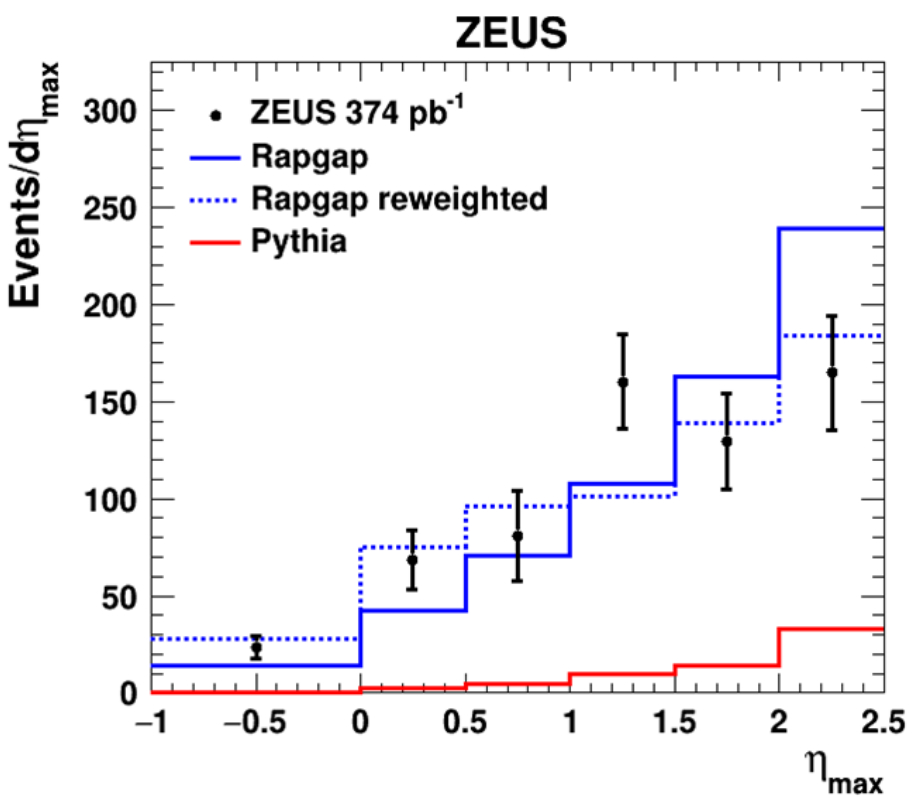
Use RAPGAP MC with H1 2006 DPDF Fit B for correction and comparisons

Data is not well described by RAPGAP at high z_{IP}

Simulation missing some processes at high z_{IP} → evidence for direct Pomeron interactions (dominantly for direct photons) as also seen in exclusive dijets.

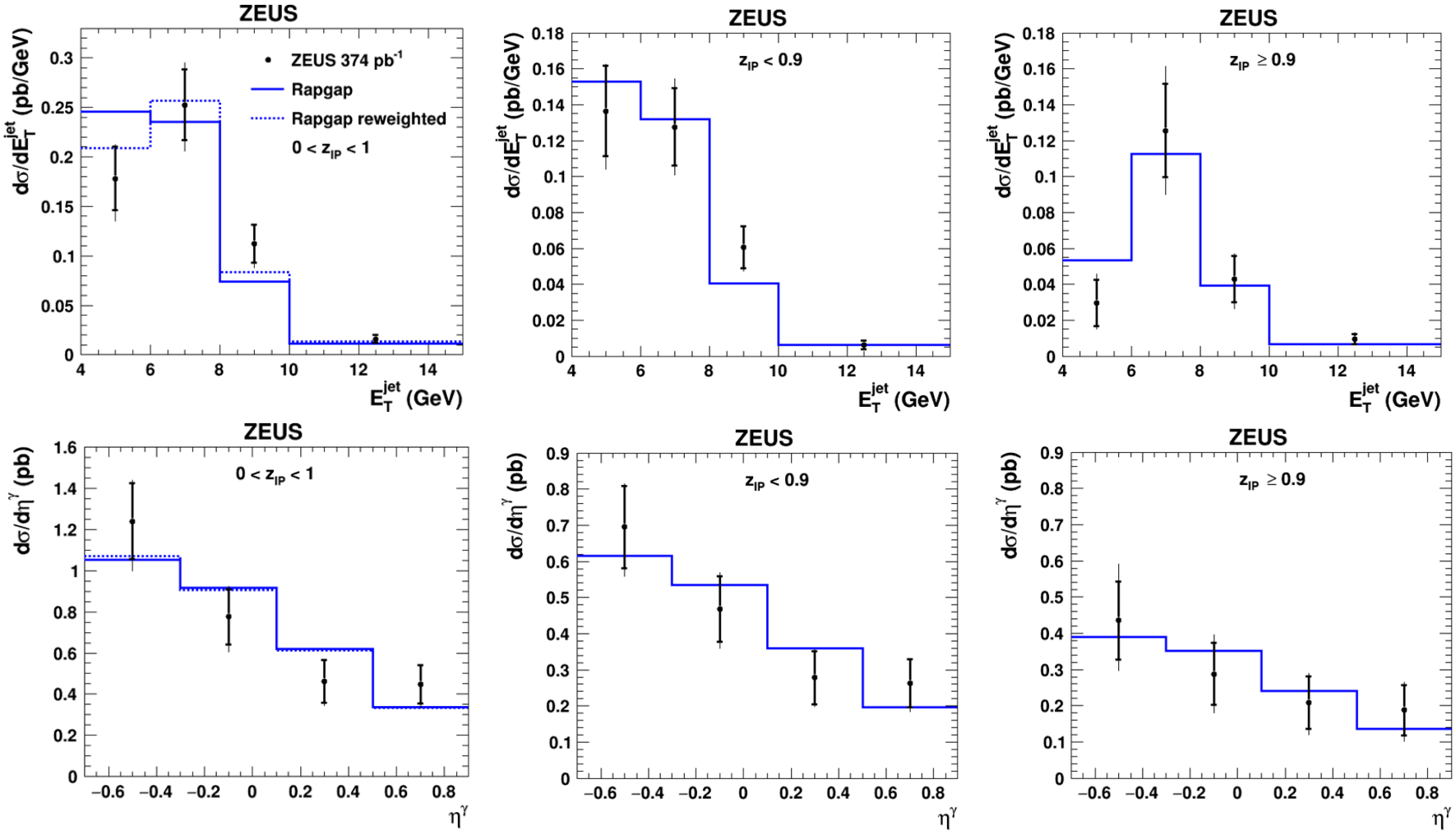
Reweighted RAPGAP MC gives a better description of the data also in η_{max}





Prompt photons in diffraction

See talk by P. Bussey, WG2



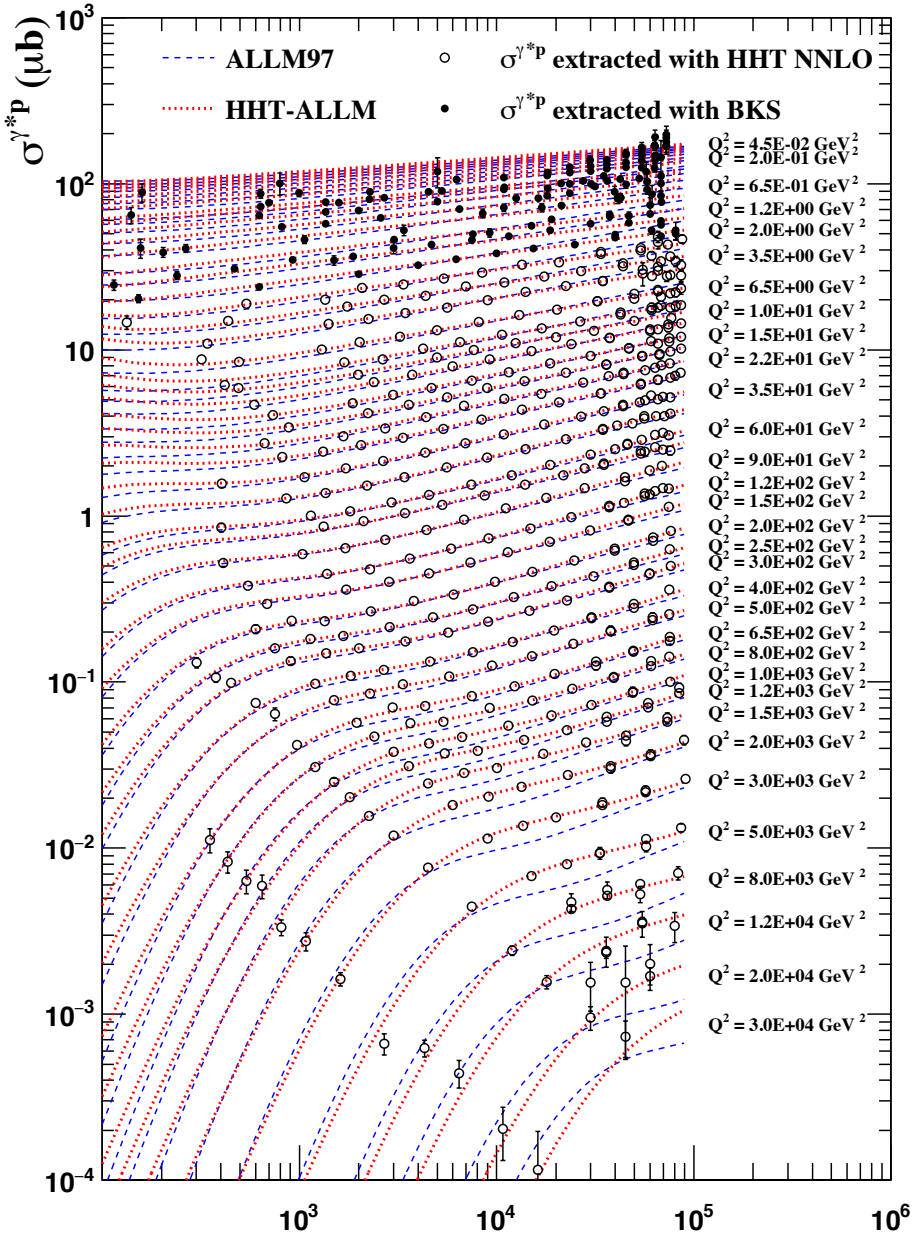
Otherwise good agreement in shape with all variables, also for $z_{IP} < 0.9$ and $z_{IP} > 0.9$.

Would be good to test factorisation by comparing with an NLO QCD calculation.

Investigation of low-Q^2 data

- HERA combined data used to investigate low x, low Q^2 data.
- Perturbative QCD successful down to Q^2 of few GeV^2.
- Transition region to photoproduction at lower Q^2 ?
- Phenomenological models at low Q^2 ?
- Look at data in different ways, recasting as $\sigma^{\gamma^* p}$ and F_2.
- **Cross sections rise rapidly for increasing W^2.**
- **Smooth behaviour around $Q^2 \sim 1\ GeV^2$**
- Compare to ALLM parametrisations

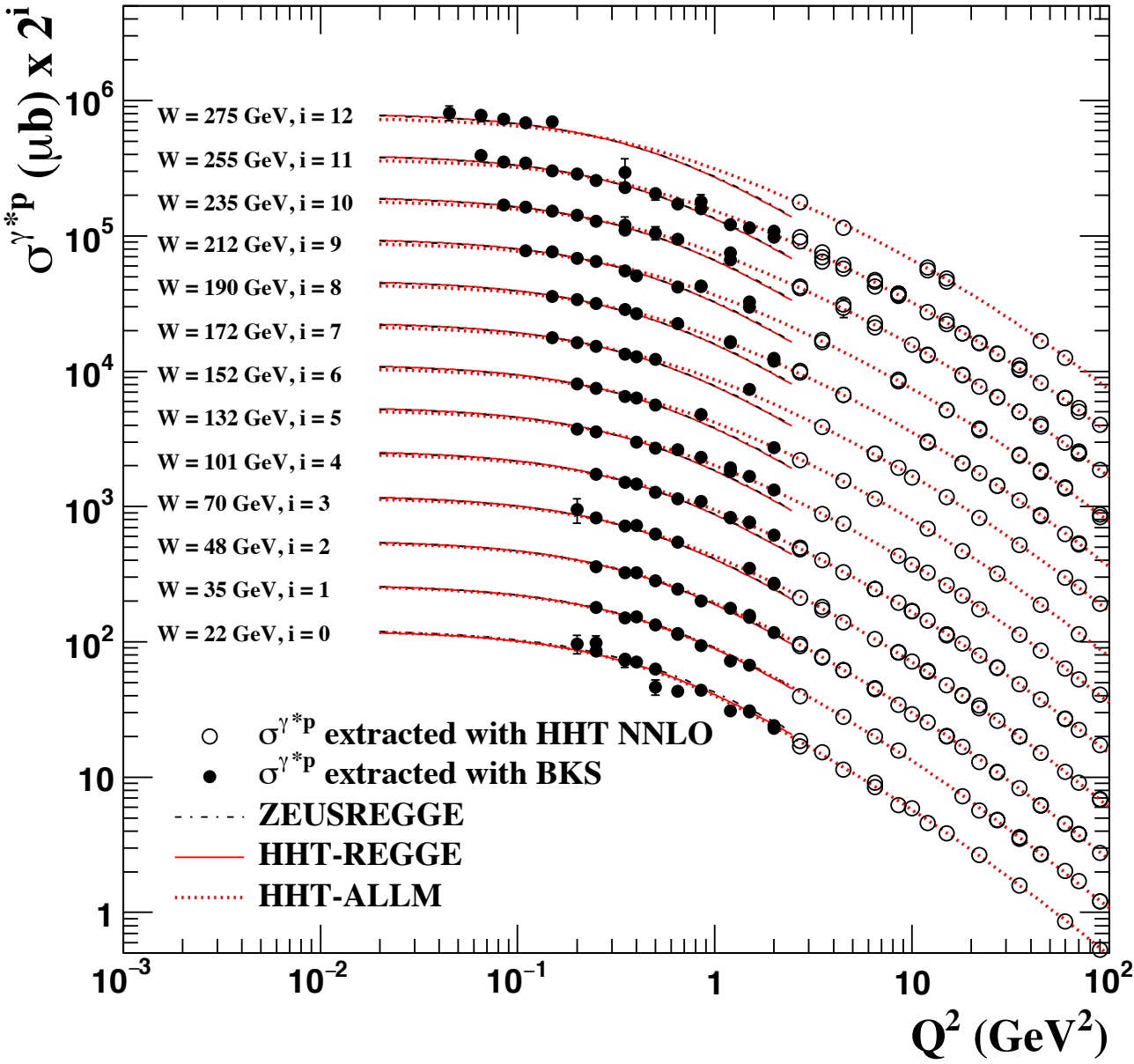
$$F_2 = \frac{Q^2}{Q^2 + m_0^2} \cdot (F_2^{I\!P} + F_2^{I\!R})$$



I. Abt, A. Cooper-Sarkar, B. Foster, V. Myronenko, K. Wichmann and M. Wing, DESY-17-051, to submit to arXiv and PRD.

Investigation of low-Q^2 data

- **Strikingly smooth trend at low Q^2.**
- Generally well described by ALLM model.
- Regge theory describes the cross section as a hadron−hadron process
- Regge describes the data up to $Q^2 \sim 0.65\ GeV^2$.



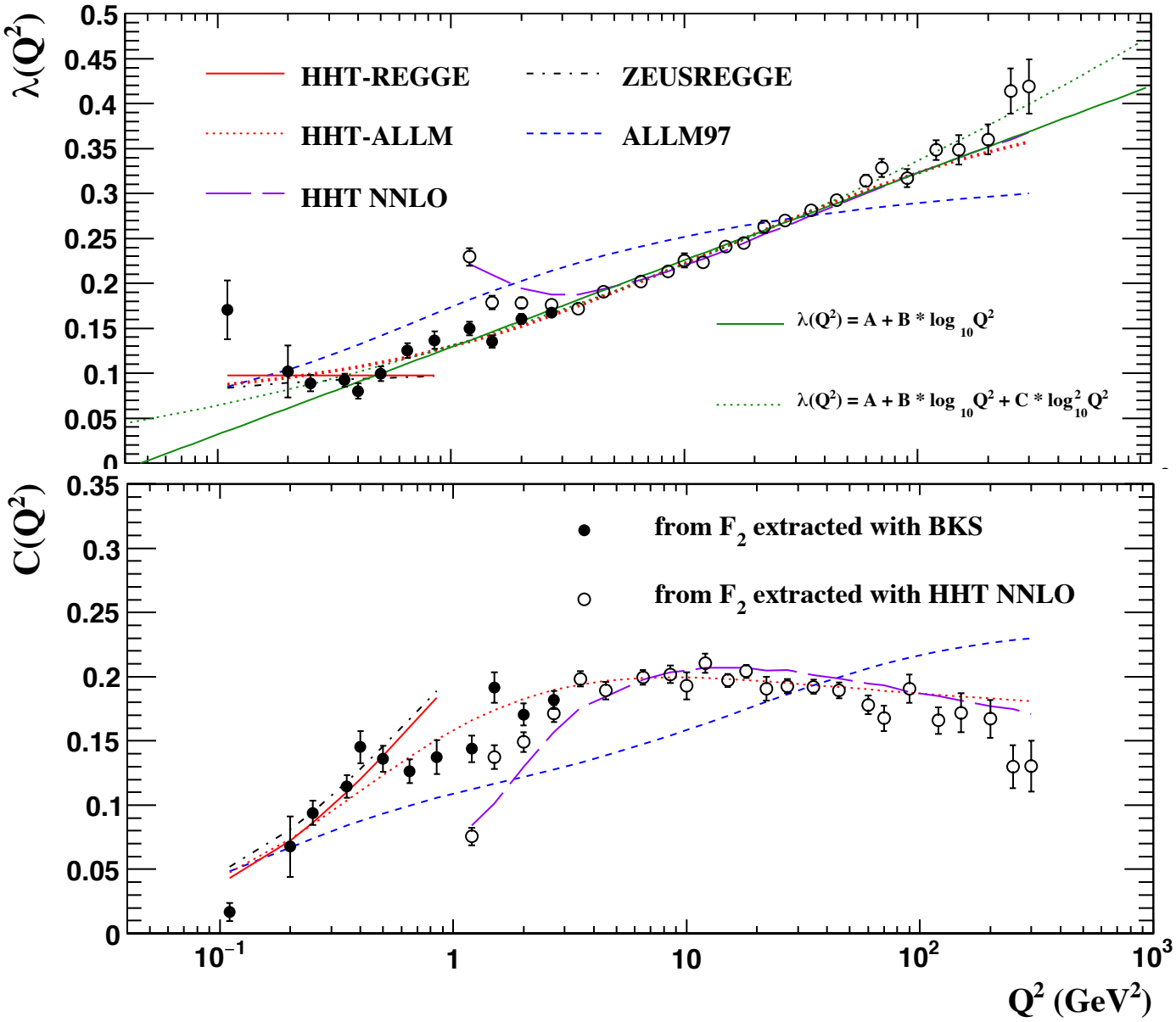
Investigation of low-Q^2 data

Can parametrise F_2 as:

$$F_2 = C(Q^2)x_{\mathrm{Bj}}^{-\lambda(Q^2)}$$

- Regge theory says λ flat for low Q^2.
- Higher Q^2, λ can rise.
- **Expectations confirmed.**
- **Can also fit data with a quadratic function.**

Future *ep/eA* colliders probing low *x* will deepen our understanding



See talk by K. Wichmann, WG1

Summary

- High transverse energy objects are valuables probes of QCD and the recent NNLO jet calculations and their use in extracting α_s is a real highlight.
- Combined charm and beauty DIS cross sections lead to precise extractions of the quark masses.
- More information on validity of factorisation in diffraction; in DIS holds, but picture still not completely clear.
- The transition region from DIS to photoproduction is smooth and HERA data can constrain QCD models at low x.

Back-up