Recent experimental constraints on proton structure

Focusing on:

- Neutral and Charged Current Deep Inelastic Scattering
- Open Charm Production

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on behalf of H1 and ZEUS collaborations

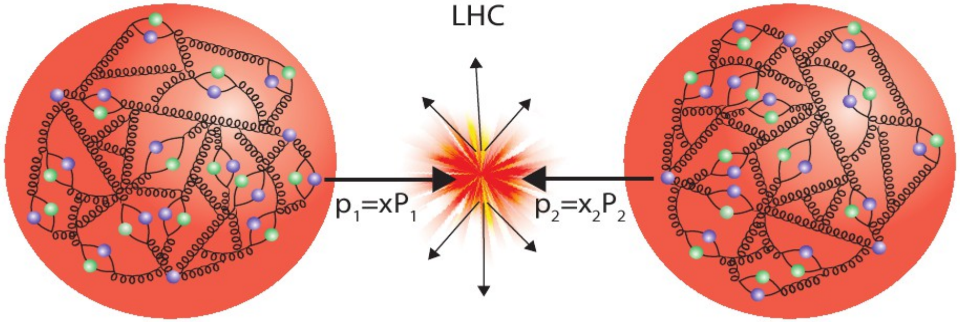
Lake Louise Winter Institute
Canada, 17 – 23 February 2013

Why study proton structure?

- *Fundamental interest*: QCD confinement
- *Practical interest*: needed for

  theory calculations at $p/\bar{p}$ colliders

  → Both for SM measurements and BSM searches



- **P**arton **D**ensity **F**unctions: probability to carry a fraction of proton momentum

  → pQCD predicts evolution of PDFs with scale (DGLAP equations)

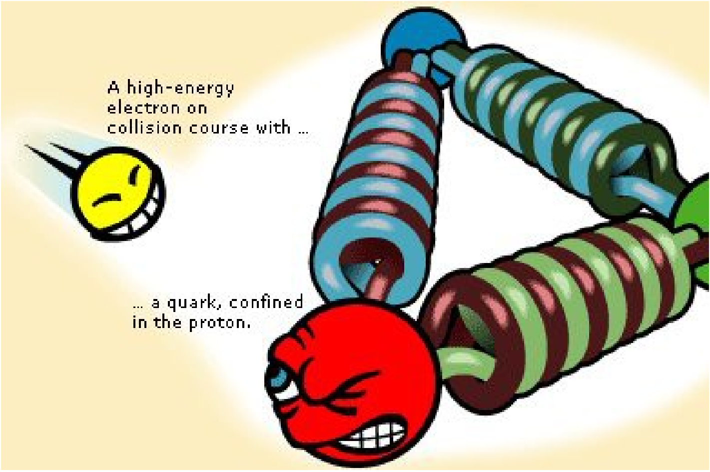
  → But PDF themselves have to be measured
- HERA *ep*-collider – a unique place to study

  proton structure:

  → Clean electroweak probe ($e^{\pm}$ in the initial state)

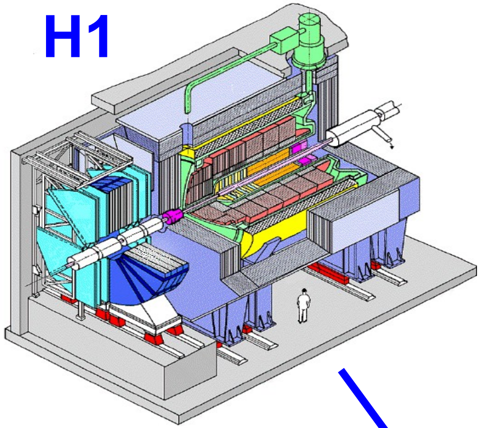
  → Possible to probe partons at very low momenta

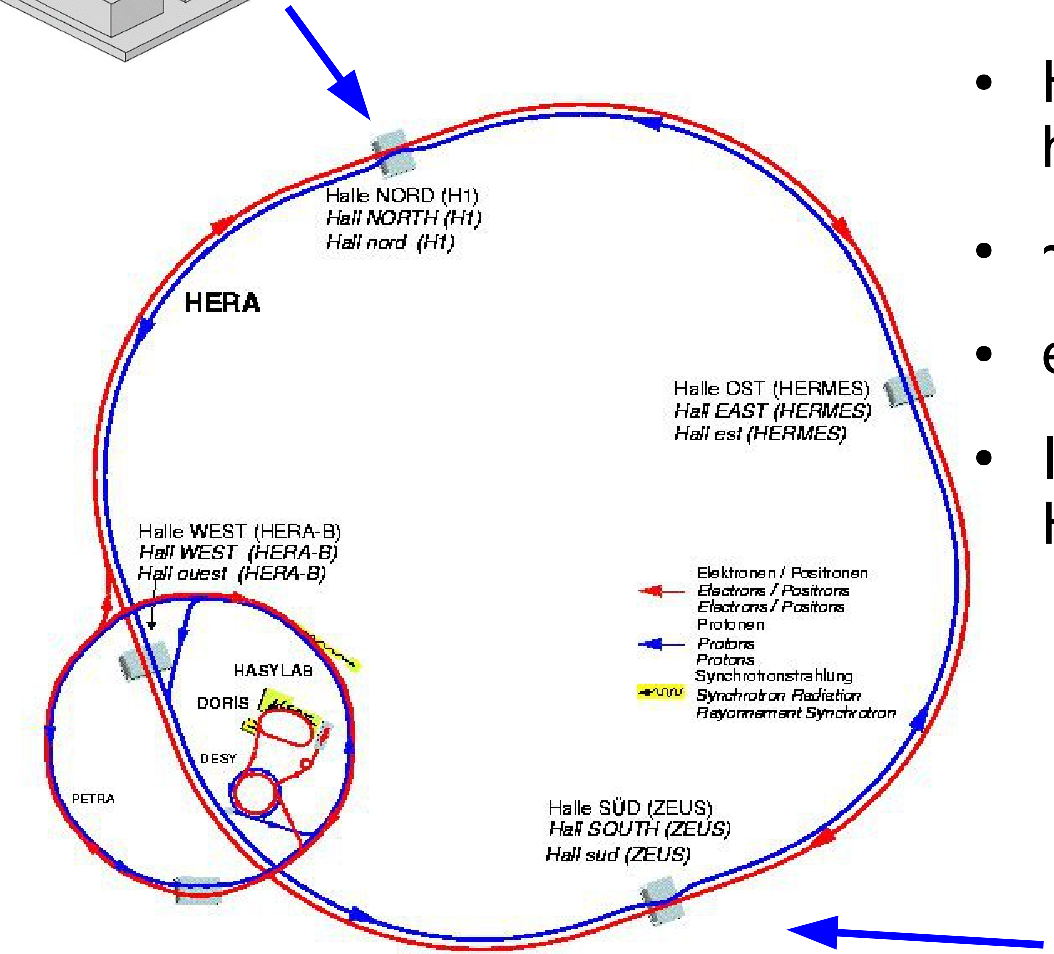
  (thanks to high $\sqrt{s}$)



HERA collider

H1



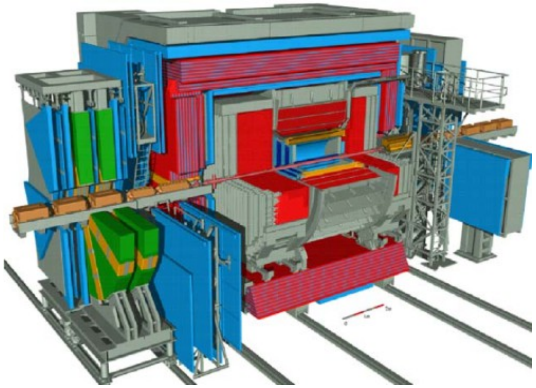


- Protons 920 GeV
- Electrons 27.6 GeV

$$\sqrt{s} = 318\ \text{GeV}$$

- Operational: 1992-2000 (HERA I)

  2003-2007 (HERA II)
- H1 and ZEUS – general purpose hermetic detectors
- ~0.5 fb^{-1} per experiment
- e^{+}/e^{-} polarization for HERA II
- In the **precision era** now: finalizing HERA II, combining ZEUS and H1



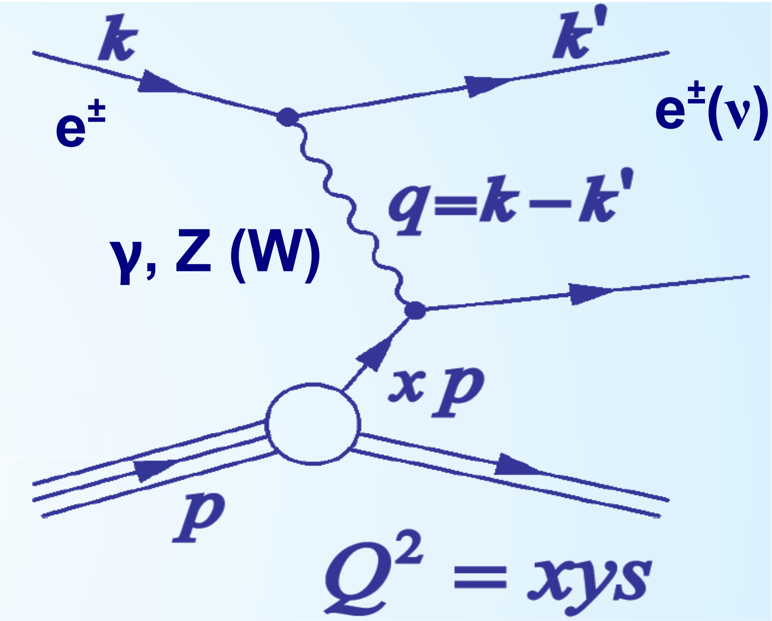
ZEUS

What do we actually do?

Measure cross sections → Extract structure functions → Perform QCD analysis → Determine **P**arton **D**ensity **F**unctions (HERAPDF)

(using HERAFITTER, p. 16) → Determine theory parameters (e.g. m_c, α_s)

Deep Inelastic Scattering:



Kinematics:

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

$x = \frac{Q^2}{2p\cdot q}$ Bjorken variable

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

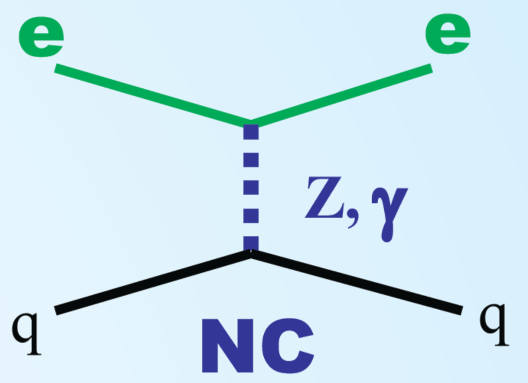
Factorization:

$$\text{HERA: Cross Section} = \text{PDF} \otimes \text{Matrix Element}$$

$$\text{LHC: Cross Section} = \text{PDF}_1 \otimes \text{Matrix Element} \otimes \text{PDF}_2$$

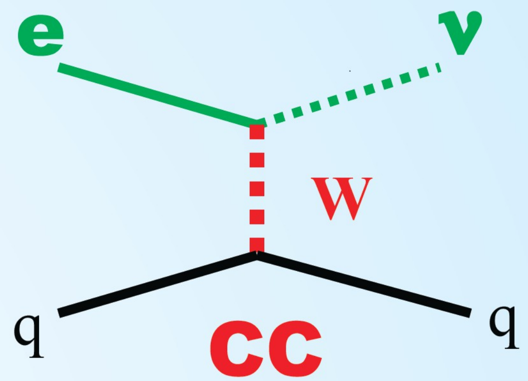
Inclusive DIS and proton structure functions

- Main source of information on PDFs (valence/sea and gluon)



$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{[Y_+\tilde{F_2}^{\pm} \mp Y_-x\tilde{F_3}^{\pm} - y^2\tilde{F_L}^{\pm}]}$$

Proton structure functions (related to PDFs)



$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \overbrace{[Y_+W_2^{\pm} \mp Y_-xW_3^{\pm} - y^2W_L^{\pm}]}$$

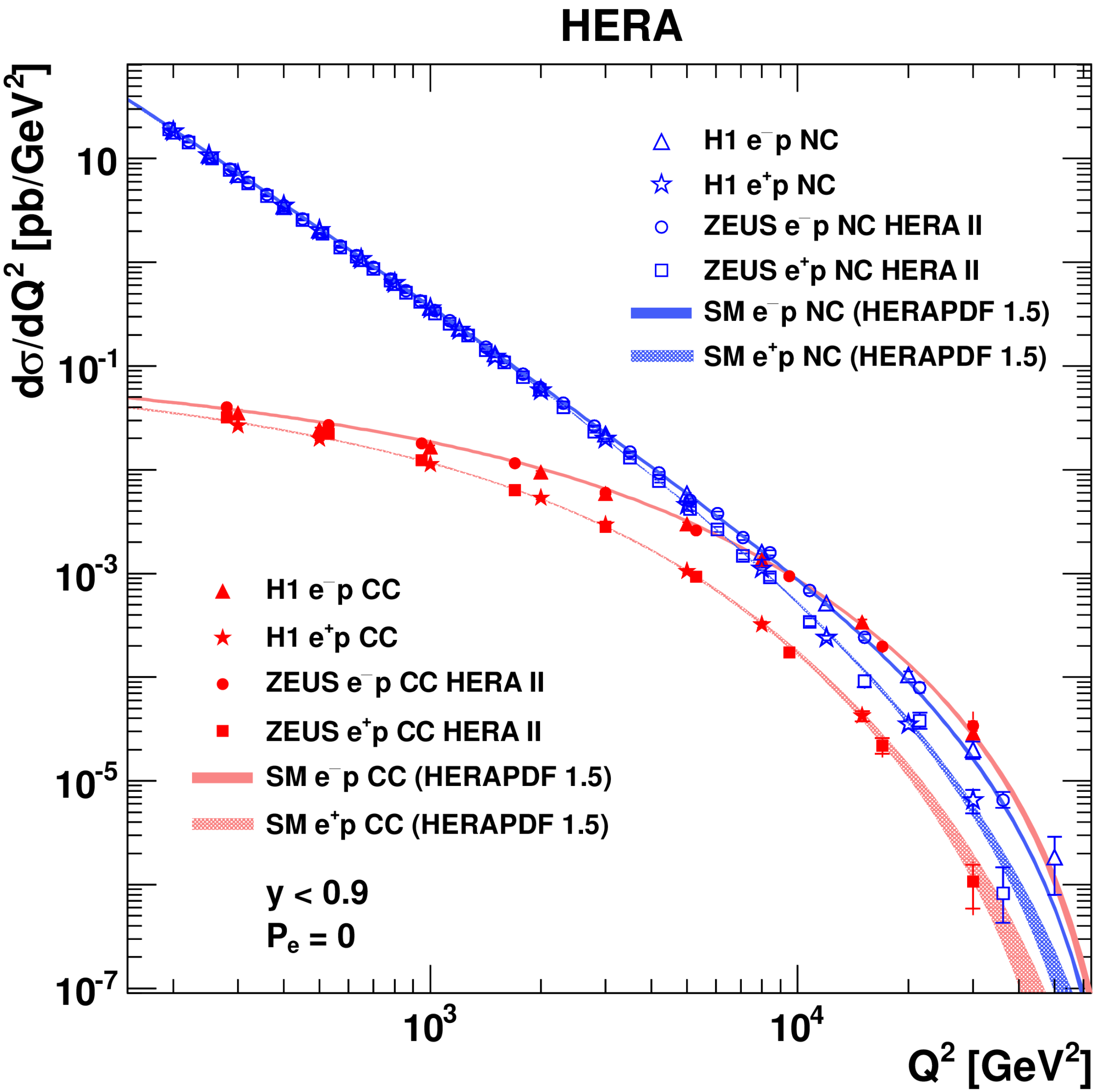
(unpolarized)

here $Y_{\pm} = 1 \pm (1-y)^2$

- **HERA I** data are published (H1/ZEUS combination: **JHEP01 (2010) 109**)
- Inclusive DIS **HERA II** analyses were finalized recently → next slides

Inclusive NC and CC DIS

JHEP09 (2012) 061
DESY-12-145

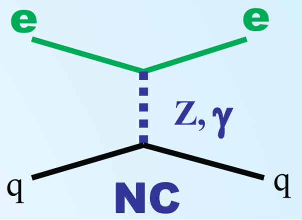


$$\frac{d\sigma^{NC}}{dQ^2} \sim \frac{1}{Q^4}$$

$$\frac{d\sigma^{CC}}{dQ^2} \sim \frac{1}{(M_W^2 + Q^2)^2}$$

CC << NC at low Q^2
CC ~ NC at high Q^2
→ EW unification

- Impressive kinematic reach
- Good agreement to SM prediction



Reduced NC DIS cross sections

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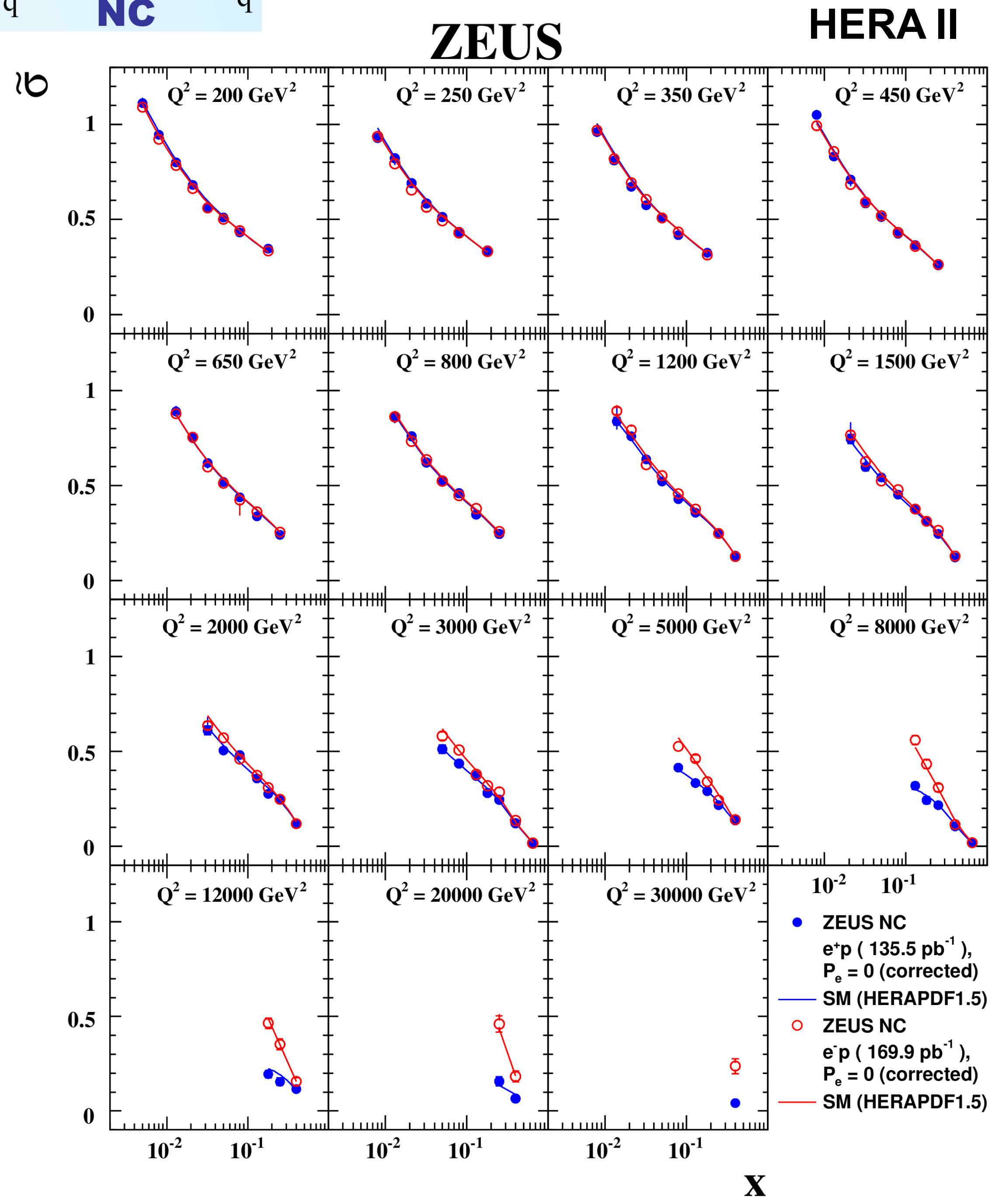


$$\tilde{\sigma}^{NC}_{red}(e^{\pm}p) = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = $$

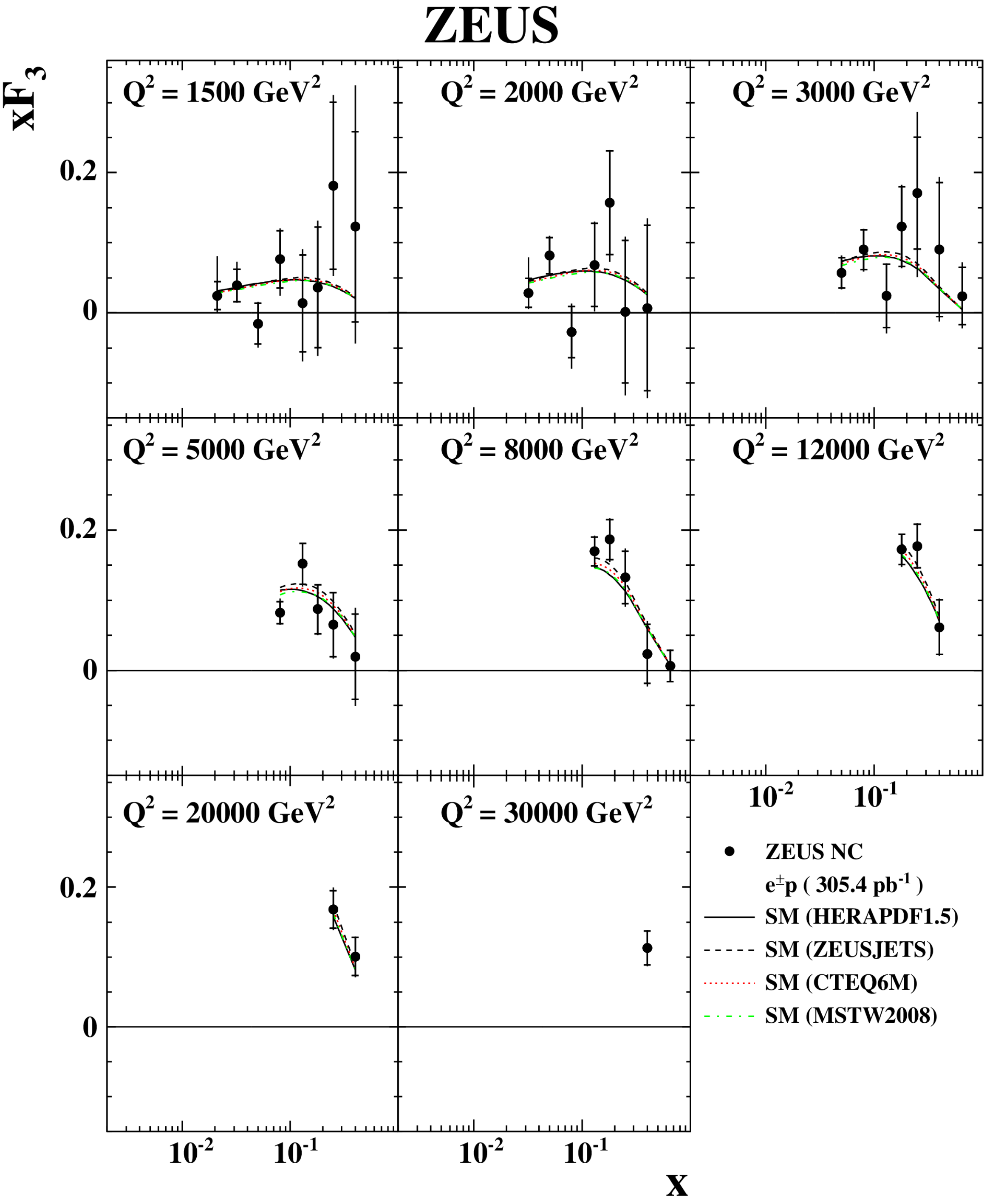
$$= \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{1}{Y_+}y^2\tilde{F}_L$$

- $\tilde{F}_2$ dominates at low Q^2
- Difference between e^+ and e^- is visible at high Q^2

  → sensitivity to $x\tilde{F}_3$!

$x\tilde{F}_3$ extraction

DESY-12-145



- Determination:

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left[\tilde{\sigma}^{NC}_{red}(e^-p) - \tilde{\sigma}^{NC}_{red}(e^+p)\right]$$

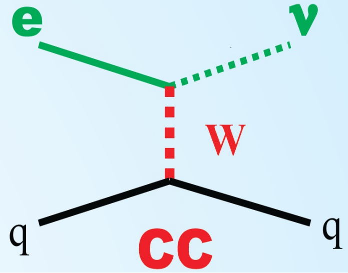
- Interpretation in LO QCD:

$$x\tilde{F}_3 \sim x(2u_v + d_v)$$

→ Sensitive to valence quarks!

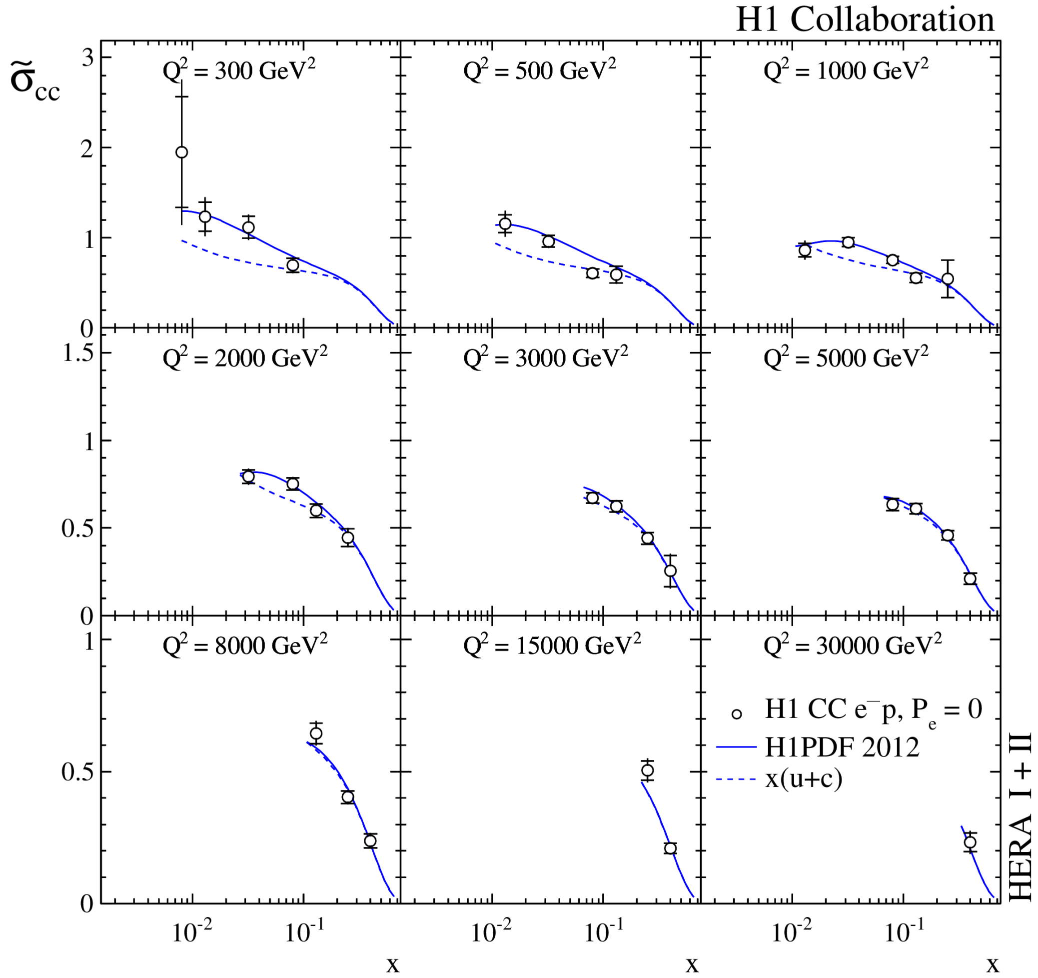
Inclusive CC DIS

JHEP09 (2012) 061

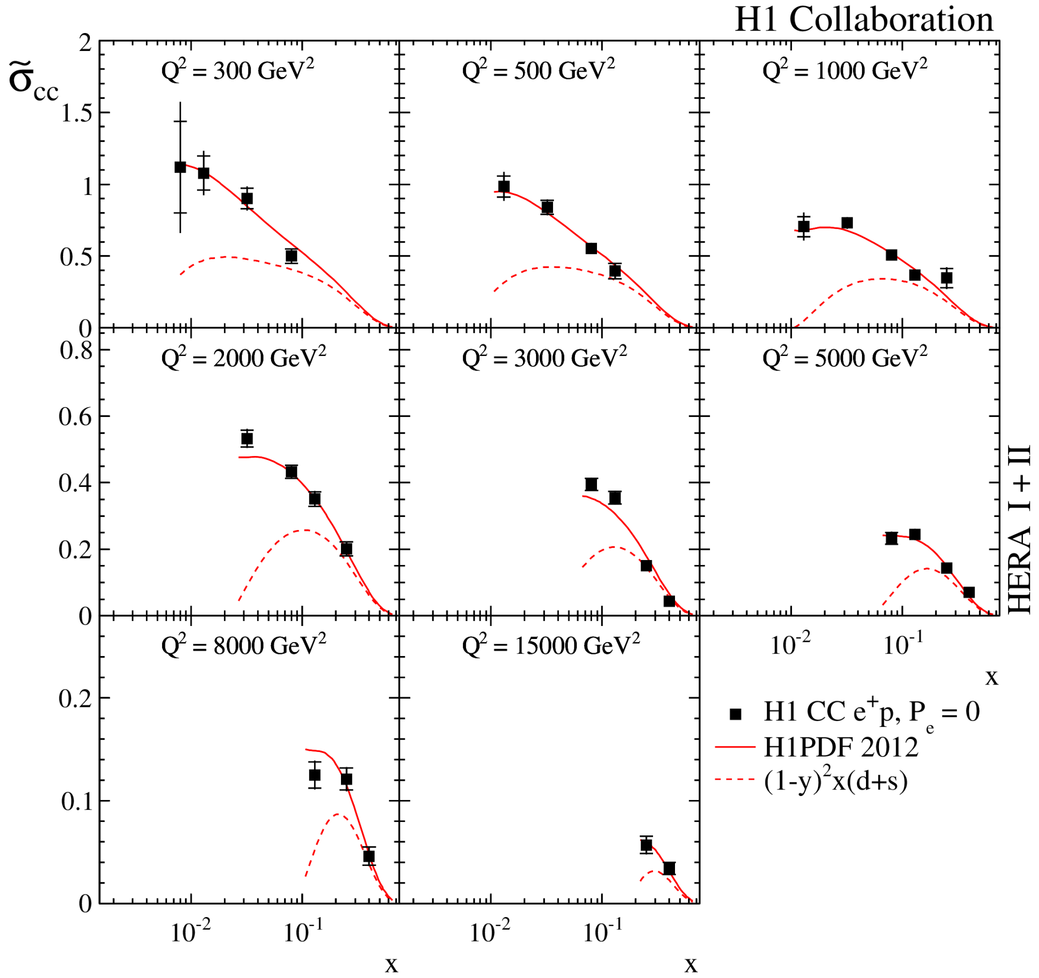


$$\tilde{\sigma}^{CC}_{red}(e^{\pm}p) = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{d^2\sigma^{CC}(e^{\pm}p)}{dx\,dQ^2}$$

$e^- p$



$e^+ p$



$$\tilde{\sigma}^{CC}_{red}(e^-p) = x(u+c) + (1-y)^2 x(\overline{d}+\overline{s})$$

$$\tilde{\sigma}^{CC}_{red}(e^+p) = (1-y)^2 x(d+s) + x(\overline{u}+\overline{c})$$

u_v at high x

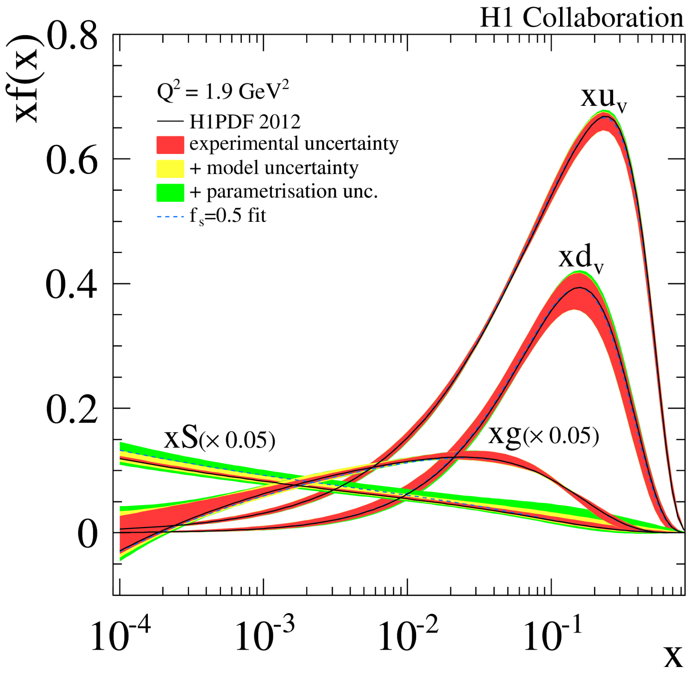
d_v at high x

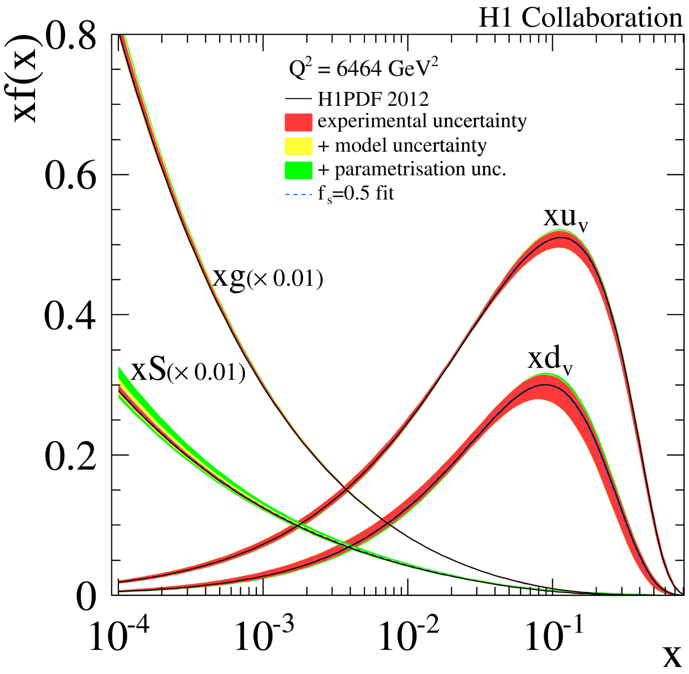
CC data give flavour decomposition

Impact of H1 HERA II DIS data on PDFs

New PDF fit including HERAI and HERAII inclusive DIS

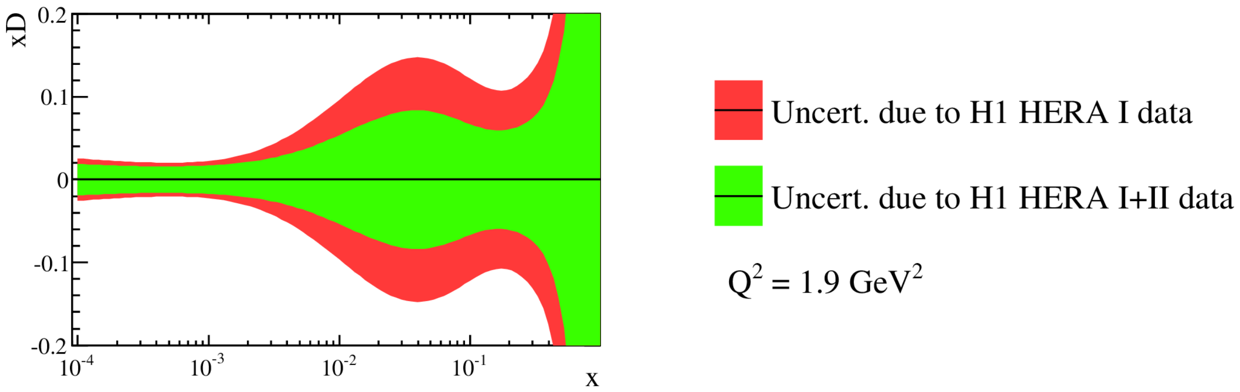
(HERAFITTER – see p. 16)





- Fitting xg, xu_v, xd_v, $x\overline{U}$, $x\overline{D}$ (parametrization see backup p. 20)
- Starting scale $Q^2_0 = 1.9$ GeV^2

Comparison of uncertaintites to HERA I only



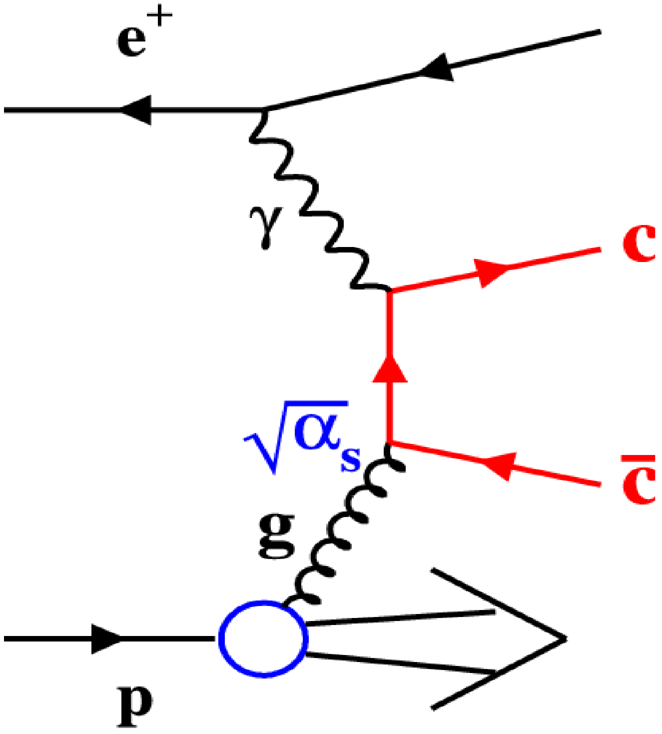
→ Precision improves!

- Ultimate accuracy will be achieved after ZEUS+H1combination of HERA II data and performing a fit together with HERA I data

Open charm production

- Contributes up to 30% to inclusive DIS at high Q^2

→ needs to be understood!



- Stringent pQCD test (talk M. Sauter)
- Sensitive to the gluon density
- Sensitive to charm mass

Tagging:

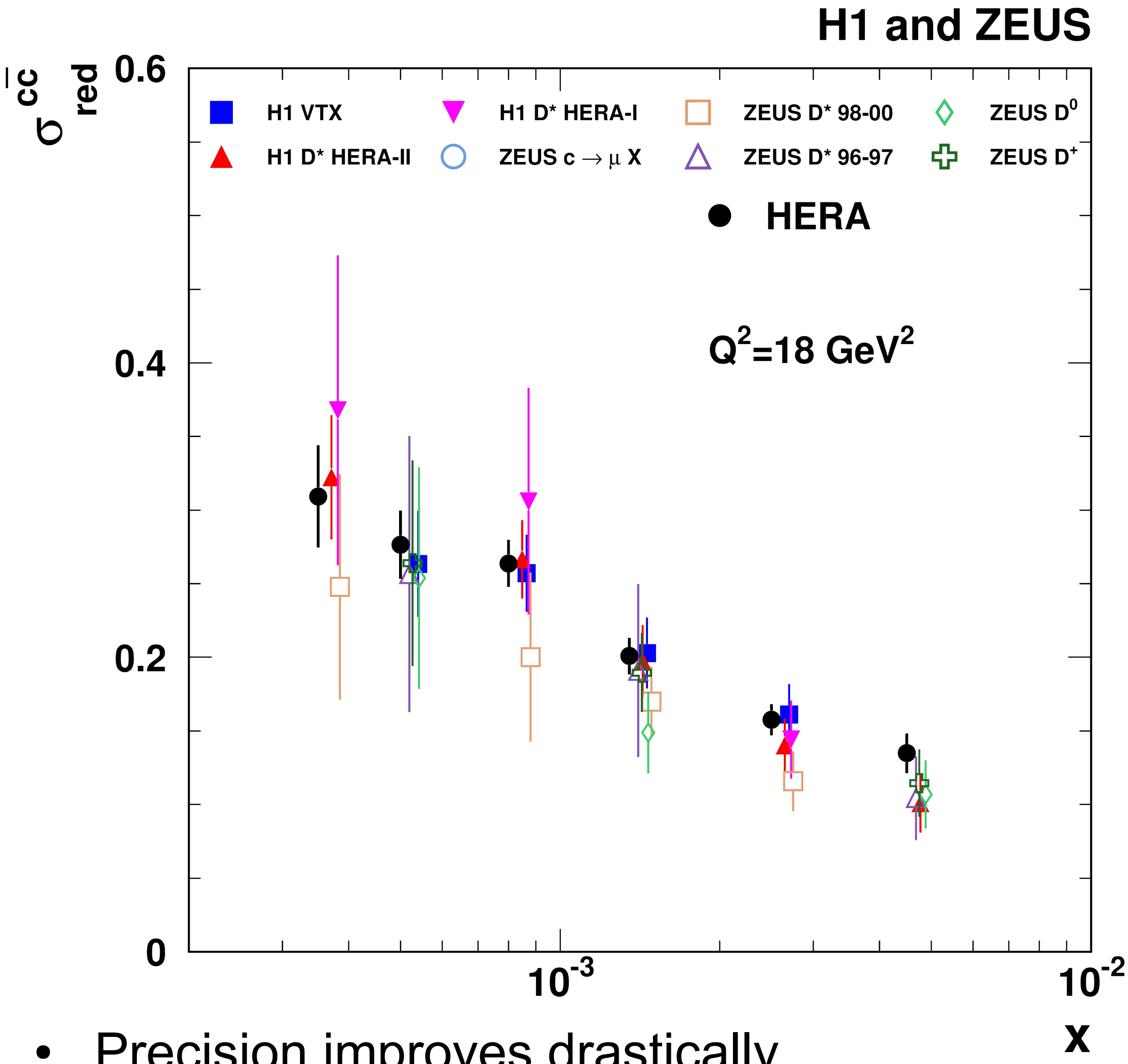
→ reconstruct charm mesons (D^*, D^+)
→ detect muons from semileptonic decays
→ employ long lifetime

Many measurements available by H1 and ZEUS
→ need to be combined (next slide)

Open charm in DIS: combination

DESY-12-172

- All published charm measurements by ZEUS and H1 were combined



$$\sigma_{red}^{c\bar{c}} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma^{c\bar{c}}}{dxdQ^2}$$

- Reduced charm cross sections were extracted in a coherent manner for every measurement before the combination

Example:
Q^2=18 GeV ^{2}

- Precision improves drastically

→ a factor of two compared to the most precise individual measurement!

Combined charm cross sections

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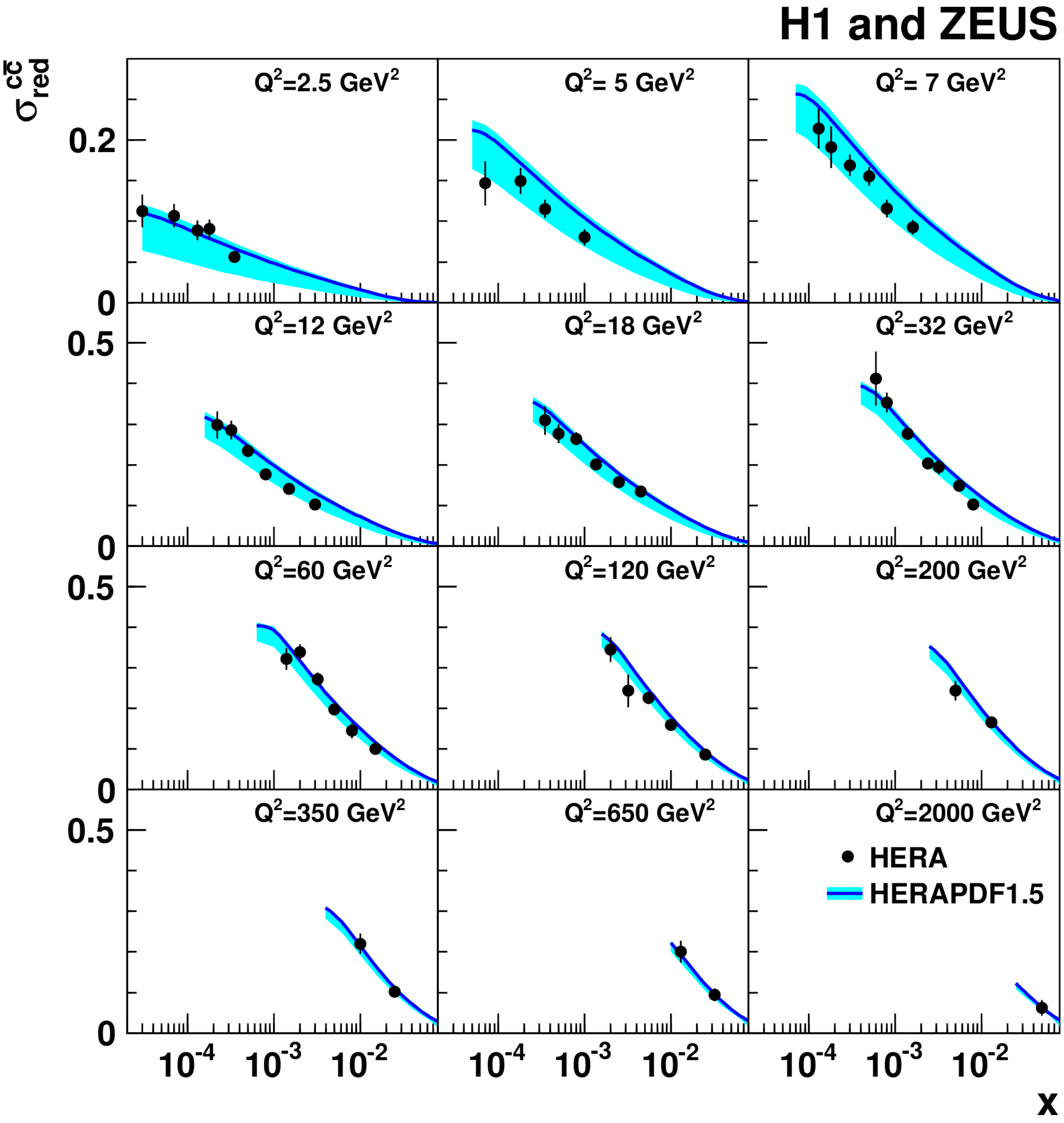


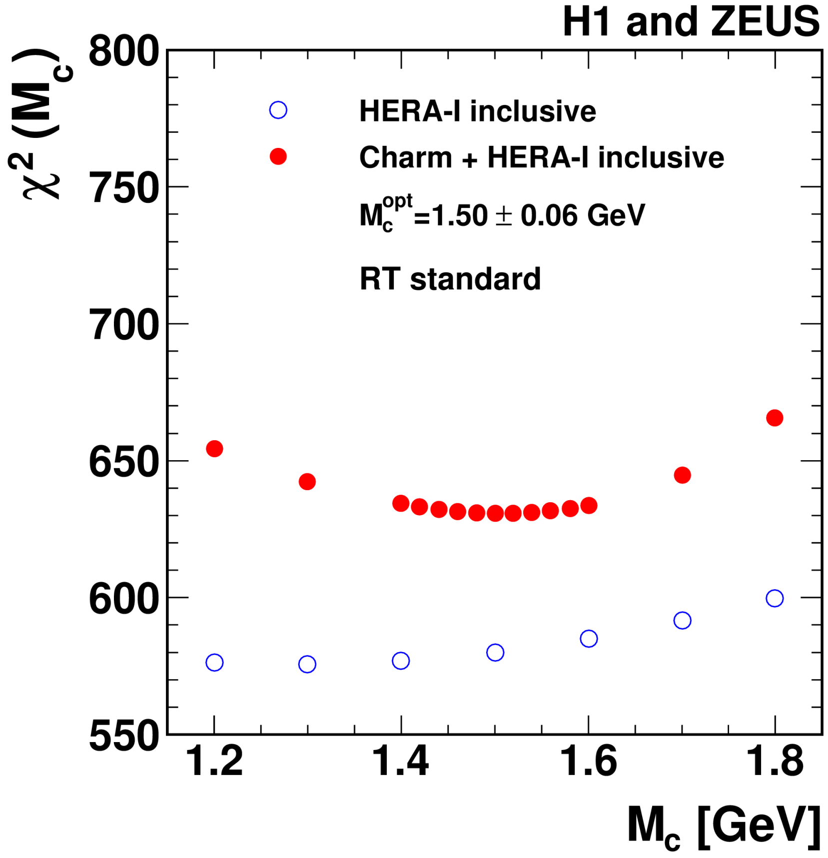
- Theory describes data well
- Theory uncertainty is dominated by charm mass (parameter) M_c variation
- Data are more precise than theory

  → have constraining power on M_c!

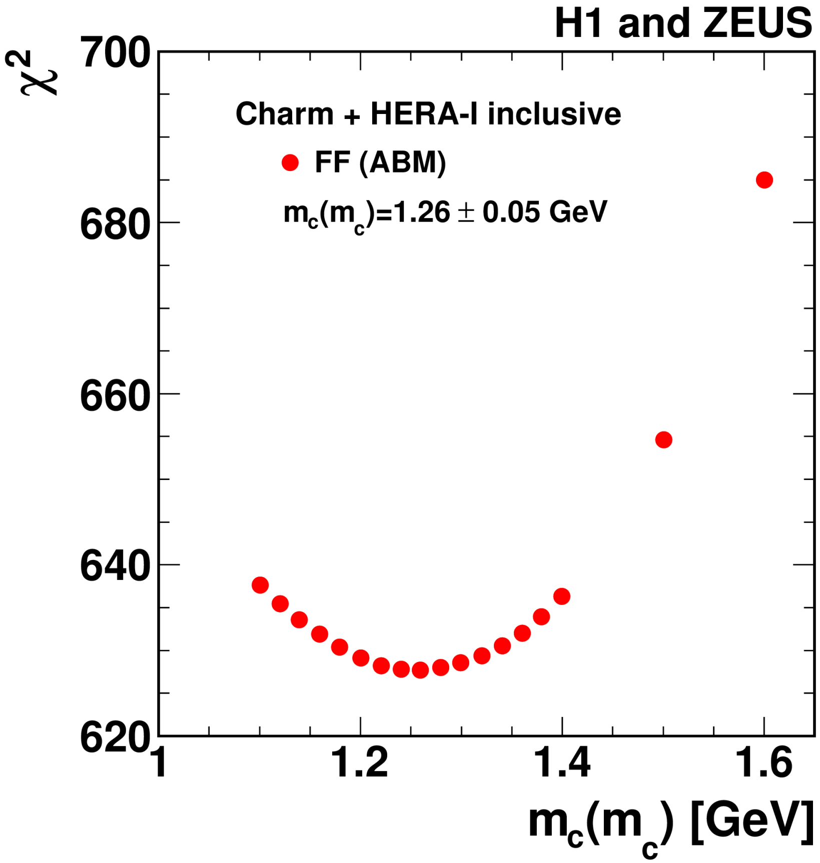
Charm mass determination

DESY-12-172

Charm data provides sensitivity to charm mass (parameter) M_c



Charm (running) mass m_c scan



$$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{param} \pm 0.02_{\alpha_s}\,\mathrm{GeV}$$

Consistent with the world average of $m_c(m_c)$=1.275±0.025 GeV

What about impact on PDFs?

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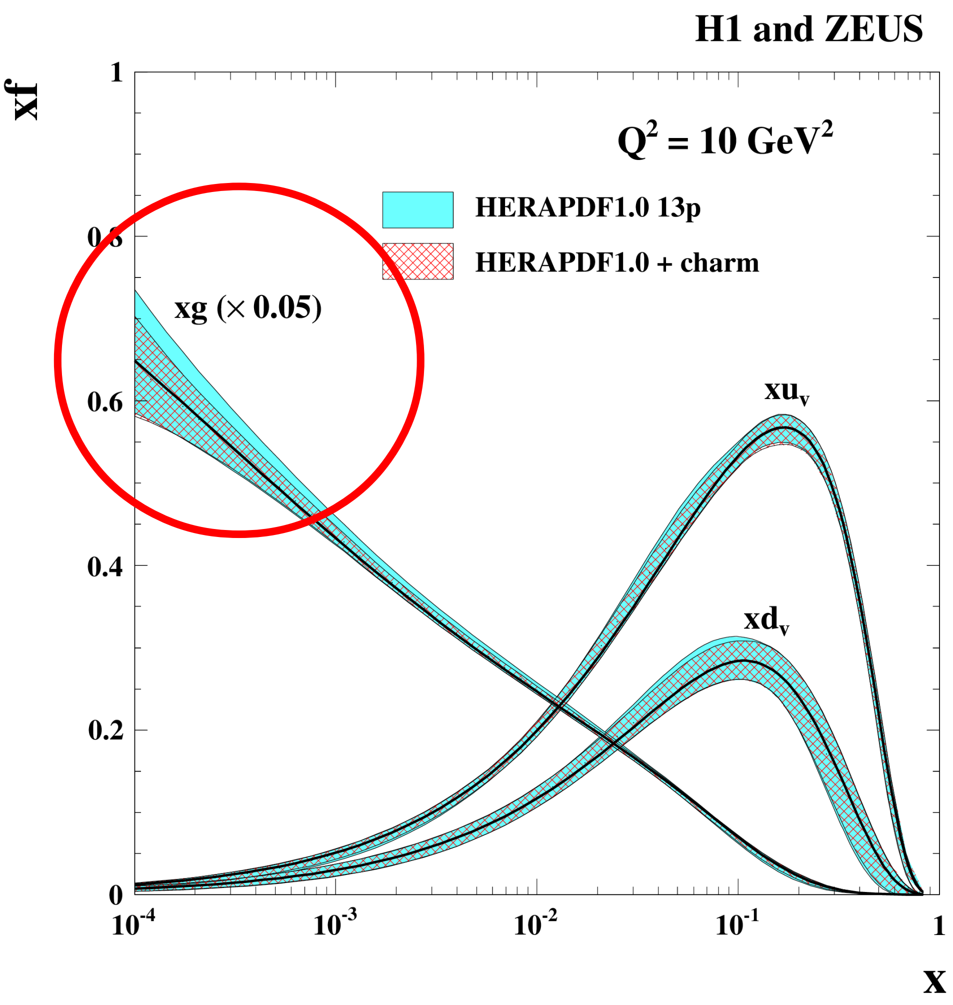
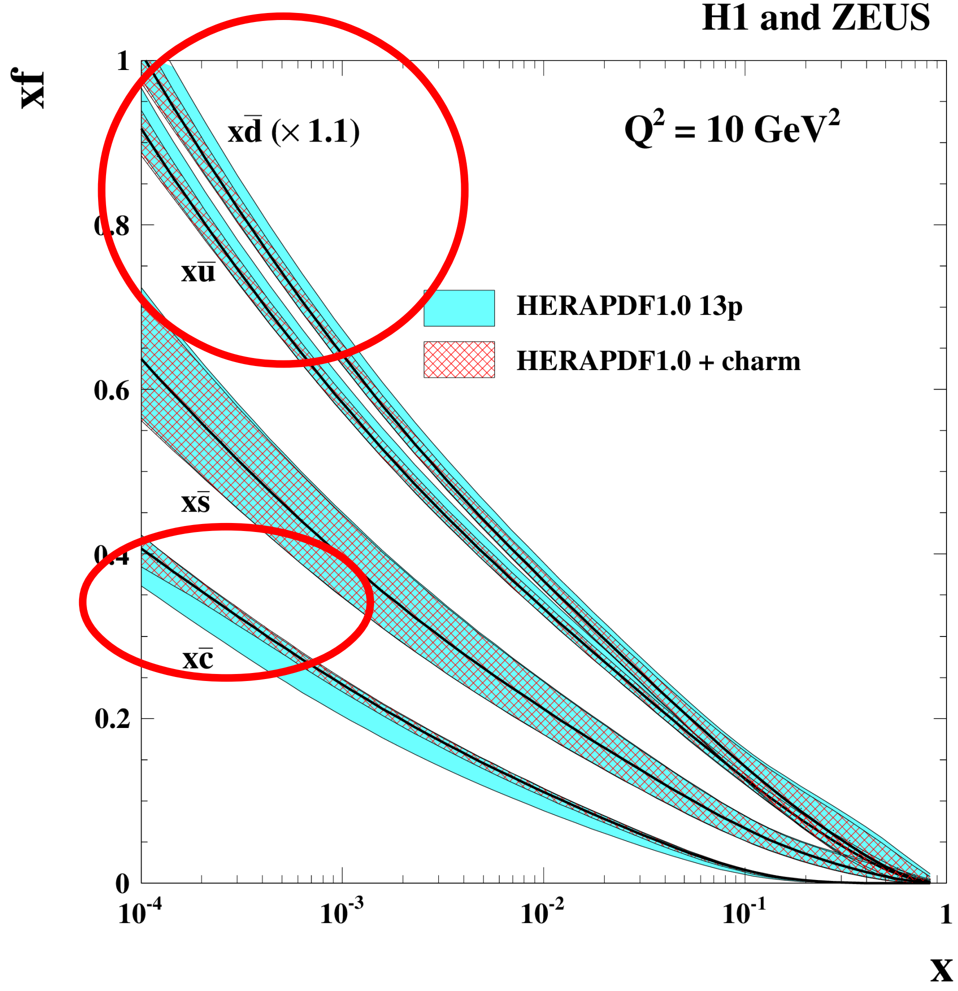


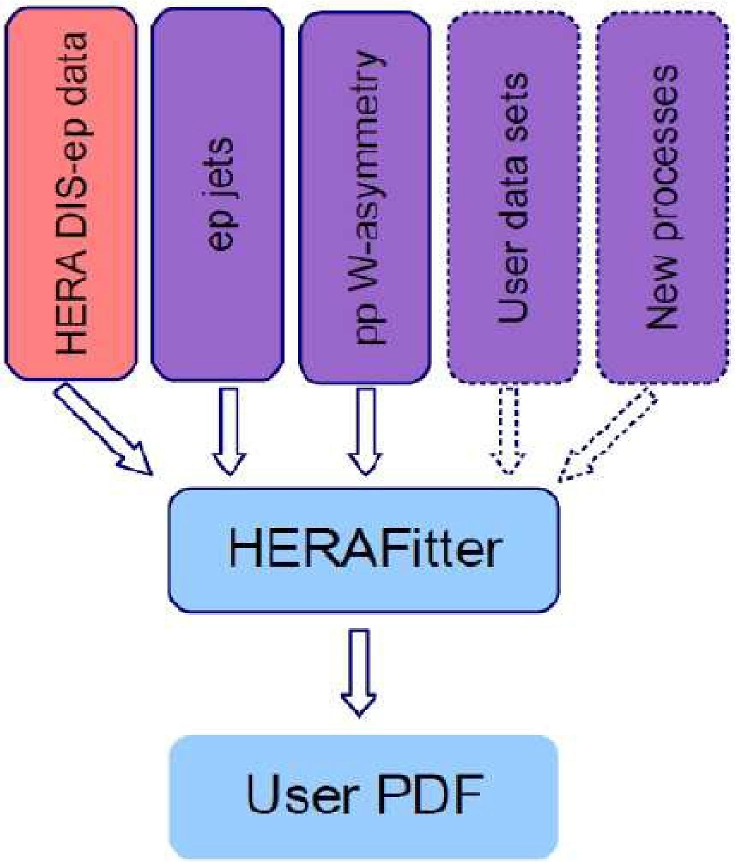


- Central values don't change significantly
- Uncertainties on PDFs reduce (xg, $x\bar{c}$, $x\bar{d}$, $x\bar{u}$)!

HERAPDF and HERAFITTER

- HERAFITTER – an open source tool for PDF analyses

http://herafitter.hepforge.org/



HERA DIS-ep data

ep jets

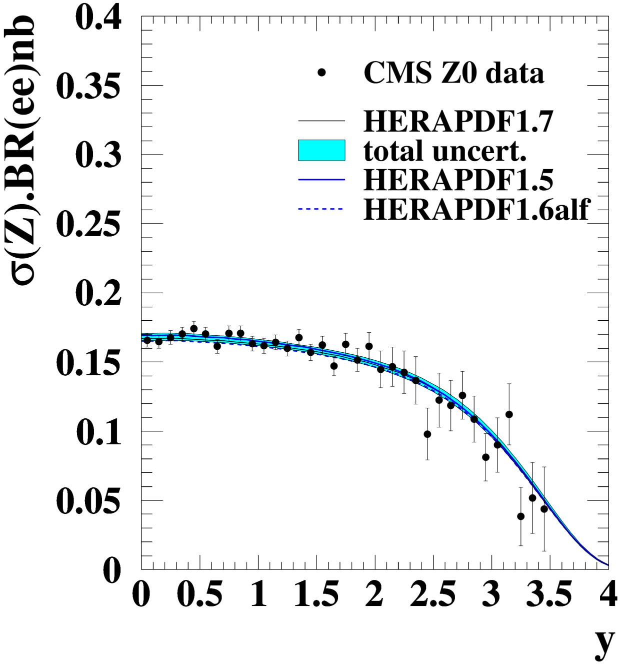
pp W-asymmetry

User data sets

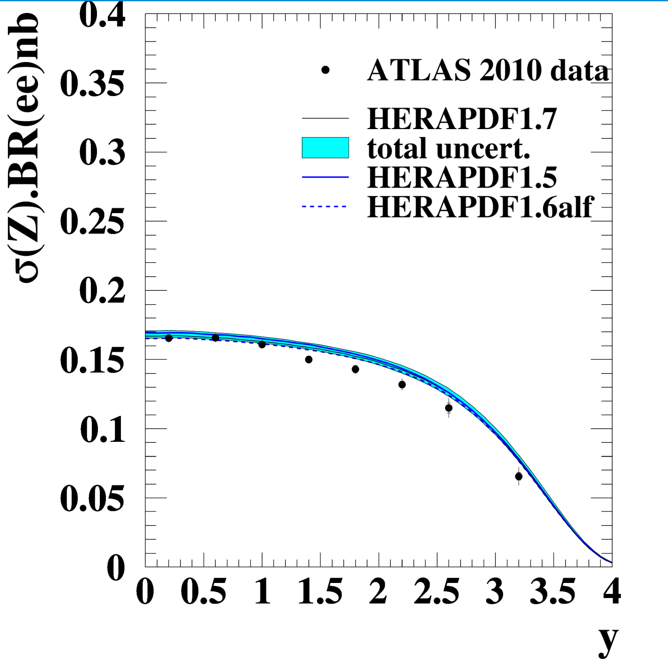
New processes

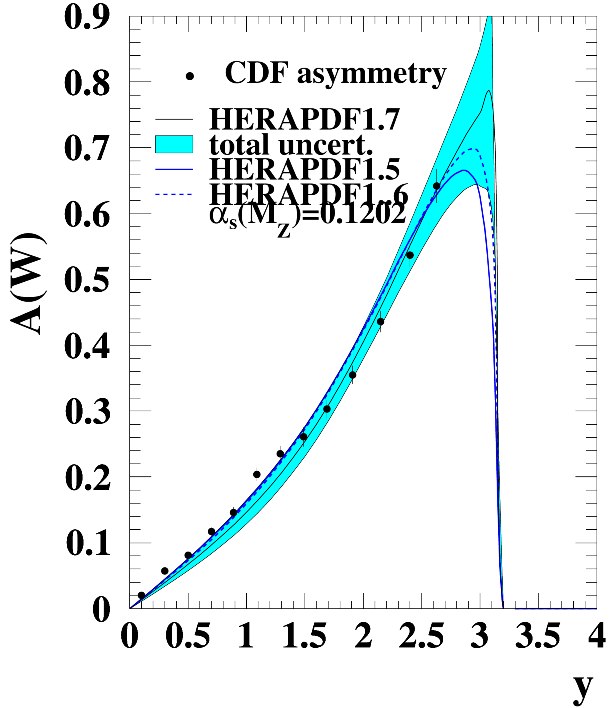
HERAFitter

User PDF



Good description of LHC/Tevatron data





Summary

- HERA community finalizes data analyses – still very active after five years after HERA shutdown!

- Inclusive DIS measurements program is completed now

  → Next step: combine between H1 and ZEUS + QCD analysis

- Open charm data combination was performed – dramatic improvement of precision compared to individual measurements

  → Charm running mass was determined with good precision

  → PDF uncertainties reduce

- HERAFITTER - an open source tool for QCD analyses, also of non-*ep* data

- HERAPDF sets do good job for LHC and TEVATRON predictions

Thanks a lot for your attention!

BACKUP
slides

Proton structure functions and QPM

$$\tilde{F_2}^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z,$$

$$x\tilde{F_3}^{\pm} = -(a_e \pm P_e v_e)\chi_Z x F_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 x F_3^Z.$$

$$x\tilde{F}_3 \simeq -a_e \chi_Z x F_3^{\gamma Z}$$

$$\chi_Z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2}.$$

$$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q}),$$

$$[xF_3^{\gamma Z}, xF_3^Z] = \sum [e_q a_q, v_q a_q] 2x(q - \bar{q}),$$

$$xF_3^{\gamma Z} = 2x[e_u a_u u_v + e_d a_d d_v] = \frac{x}{3}(2u_v + d_v)$$

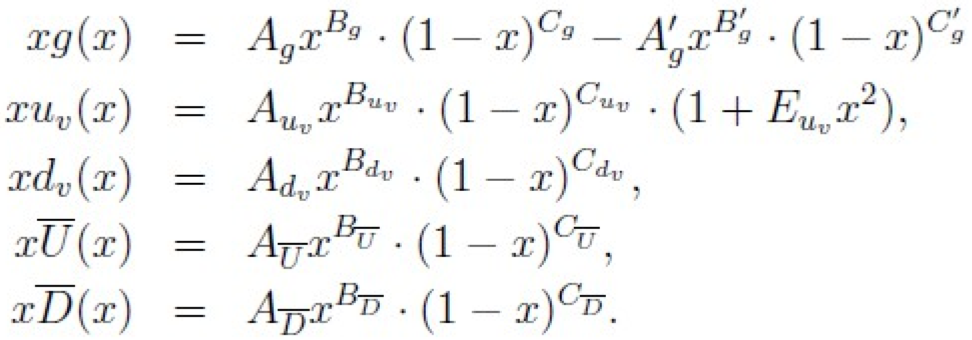
$$\begin{aligned} W_2^- &= x(U + \overline{D}), \quad W_2^+ = x(\overline{U} + D) \\ xW_3^- &= x(U - \overline{D}), \quad xW_3^+ = x(D - \overline{U}) \end{aligned}$$

$$U = u + c, \quad \overline{U} = \bar{u} + \bar{c}, \quad D = d + s, \quad \overline{D} = \bar{d} + \bar{s}.$$

PDF parametrization

The following parametrizations were used for PDF fits described in this talk

13 parameter fit,
a more flexible gluon
compared to HERAPDF 1.0



$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g} \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}, \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.
\end{aligned}
$$

Charm mass scan

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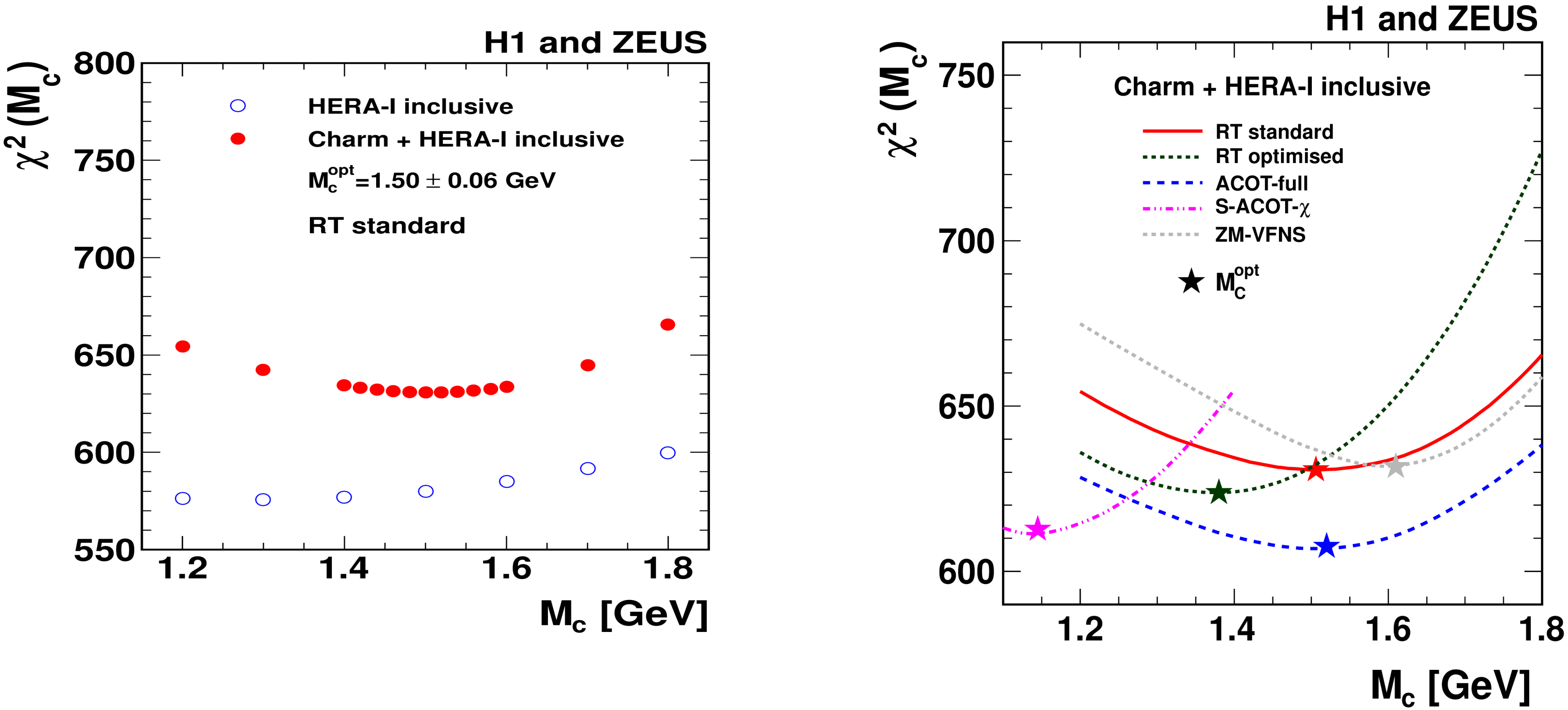

Charm data provides sensitivity to M_c ⇨ Optimal M_c depends on the heavy flavour scheme!

Implications for LHC

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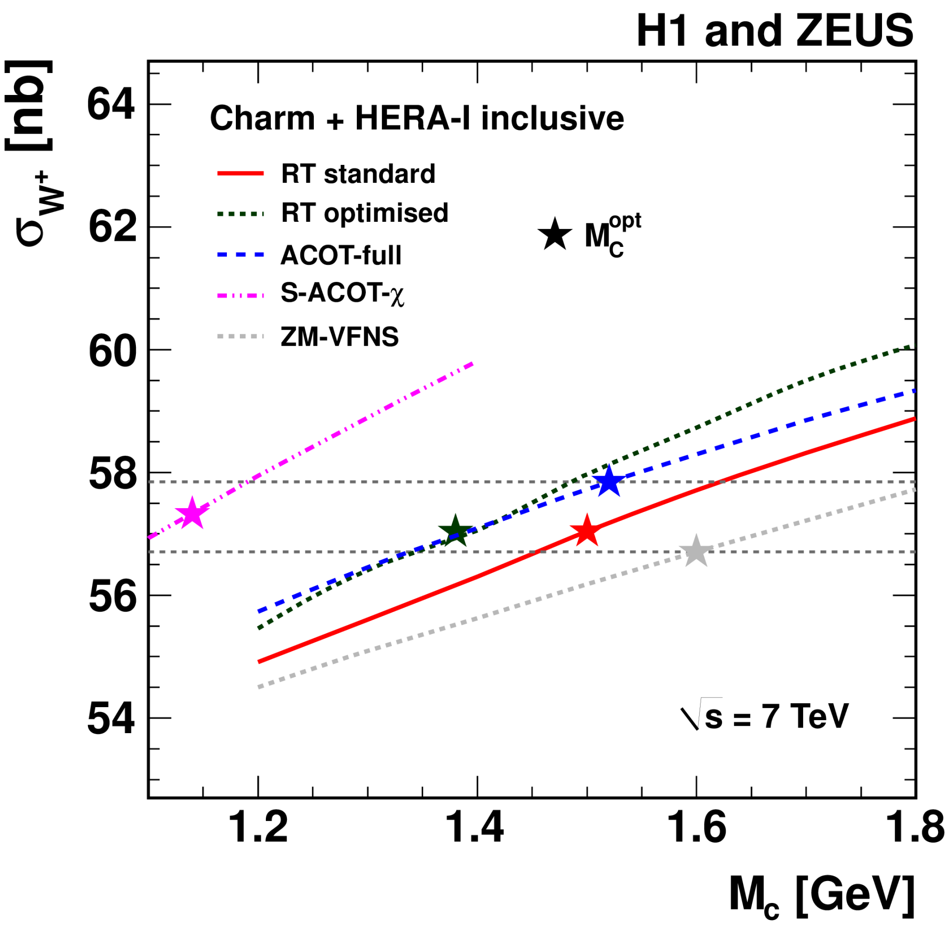
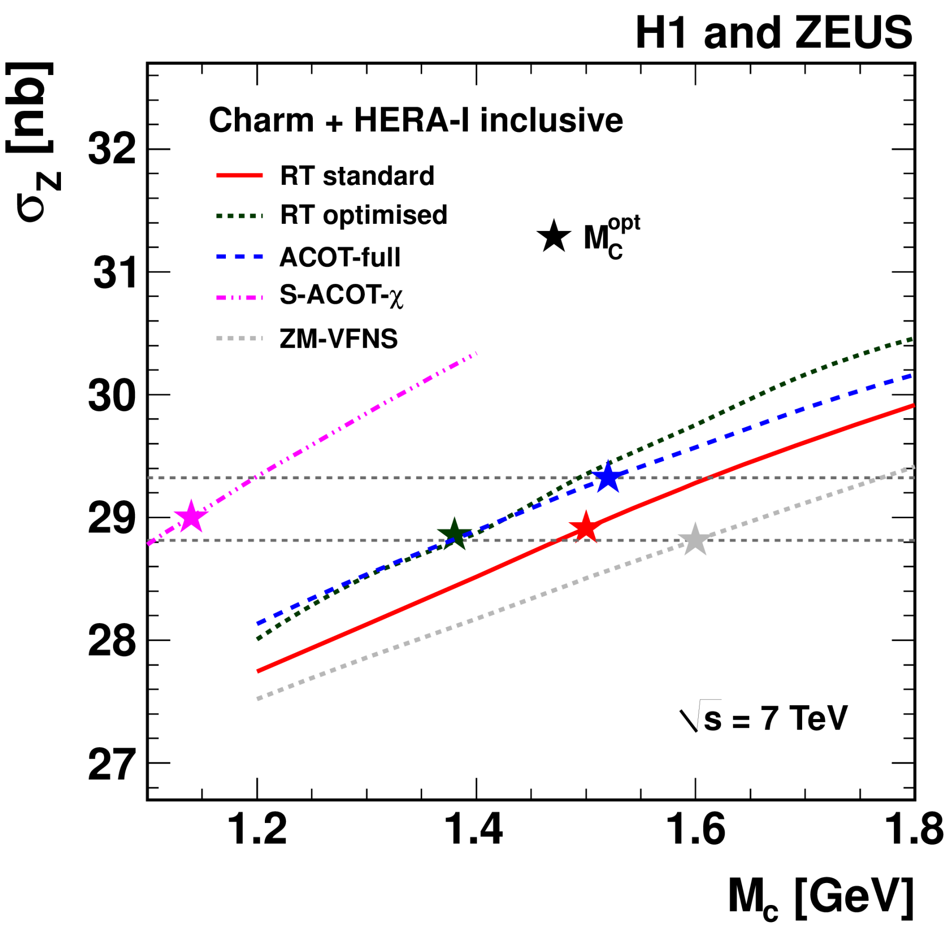
W production @ 7 TeV



Z production @ 7 TeV



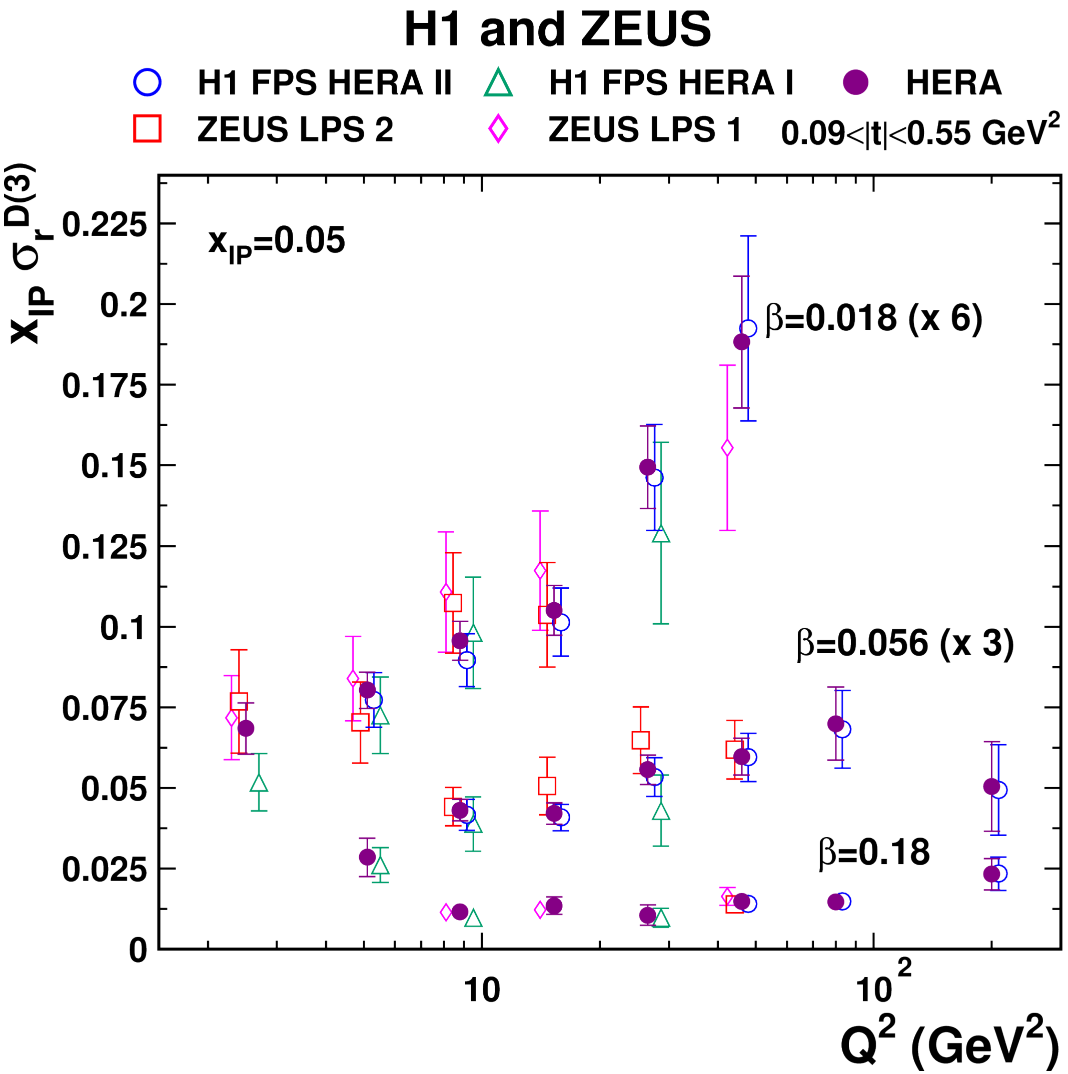
Using M_c optimal for each scheme stabilizes predictions!

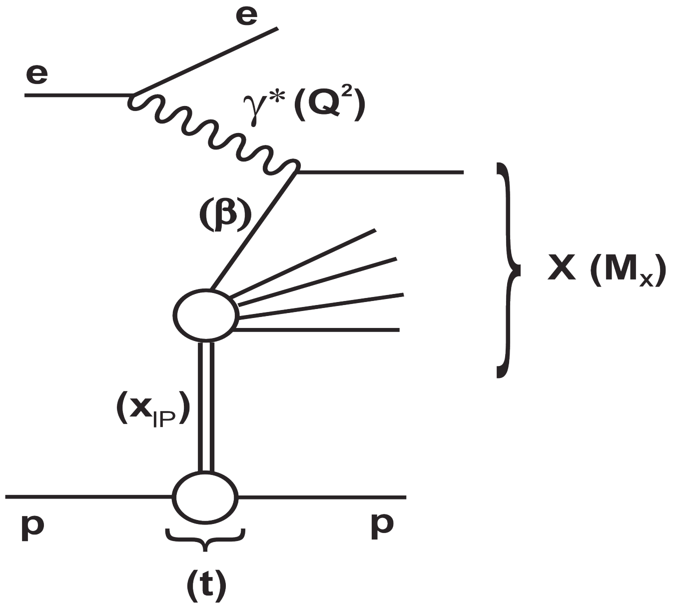
A word on diffraction

EPJC (2012) 72-2175

$$\frac{\mathrm{d}\sigma^{ep\rightarrow eXp}}{\mathrm{d}\beta\mathrm{d}Q^2\mathrm{d}x_{I\!P}\mathrm{d}t} = \frac{4\pi\alpha^2}{\beta Q^4}\left[1 - y + \frac{y^2}{2}\right]\ \sigma_r^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

$\sigma_r^{D(3)}$ is obtained by integrating over t

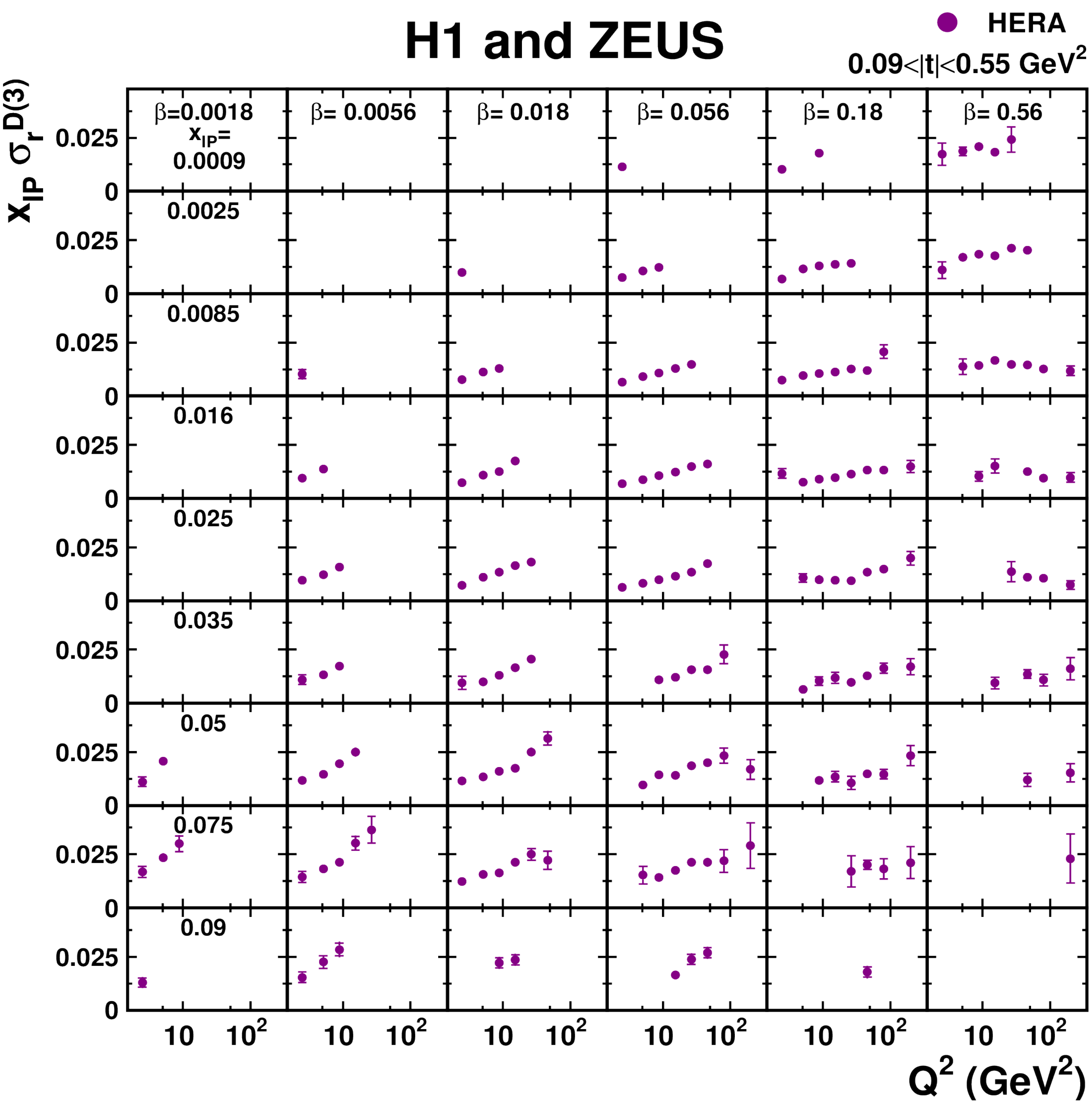


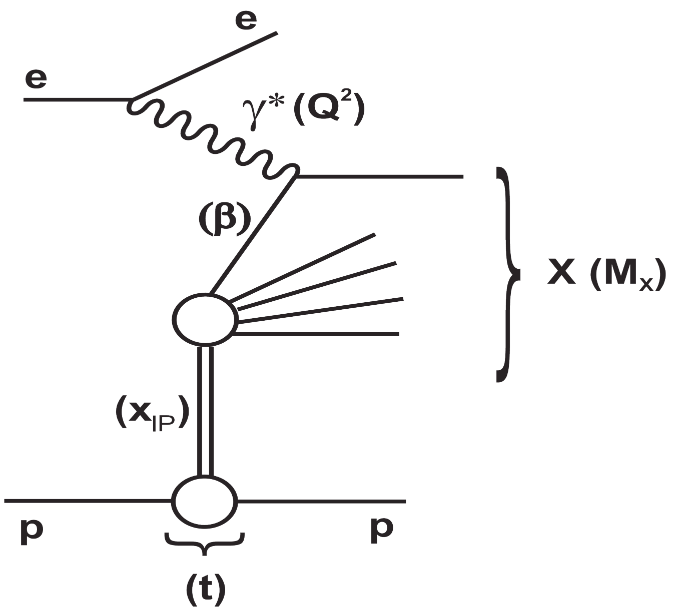


- ~10% of inclusive cross section are diffractive events → need to be understood
- First ever combination of diffractive structure functions
- Significant precision improvement!

A word on diffraction

EPJC (2012) 72-2175





- Great kinematic reach
- Input to future QCD fits