

*EPS - July 2015*

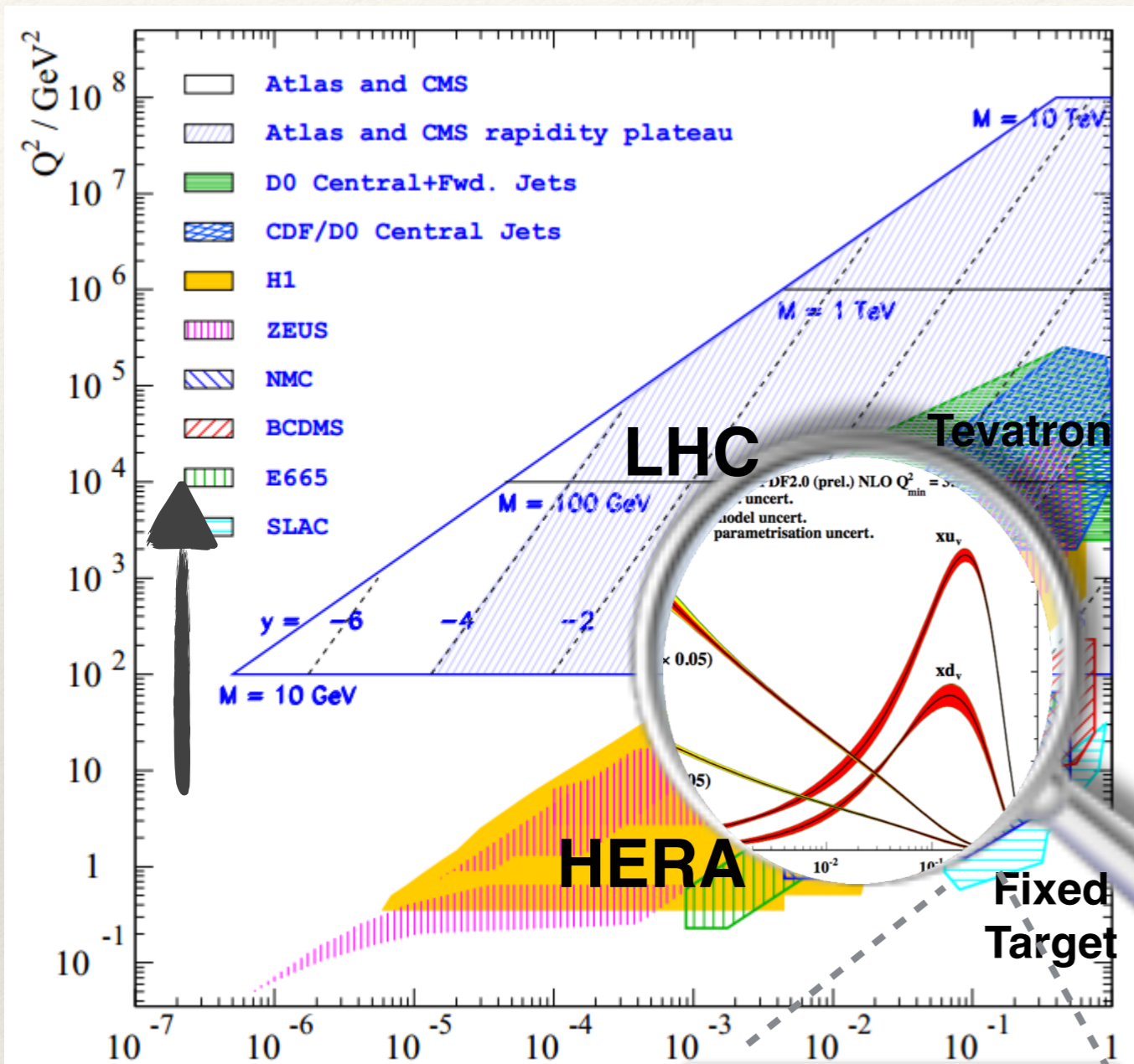
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# QCD Analysis of the combined HERA structure function data - HERAPDF2.0

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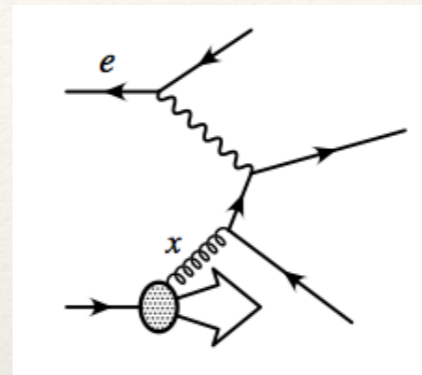
Voica Radescu   
Physikalisches Institut Heidelberg  
on behalf of H1 and ZEUS

# Today's data on proton structure



The cleanest way to probe Proton Structure is via Deep Inelastic Scattering [DIS]:

- Neutrinos, muons, electrons

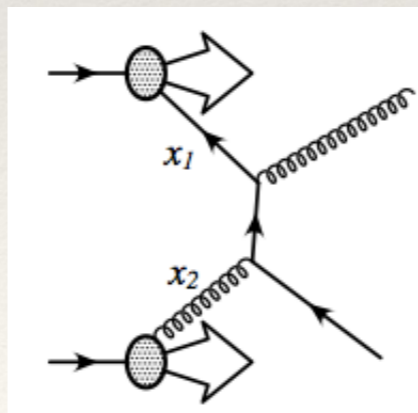


—> probes linear combination of quarks: sea quarks, gluon

**HERA provides the basis of any PDFs**

Precision of PDFs can be complemented by the Drell Yan [DY] processes at the collider experiments

$$\sigma_{hh \rightarrow X} = f_{h \rightarrow a} \otimes \hat{\sigma}_{ab \rightarrow X} \otimes f_{h \rightarrow b}$$

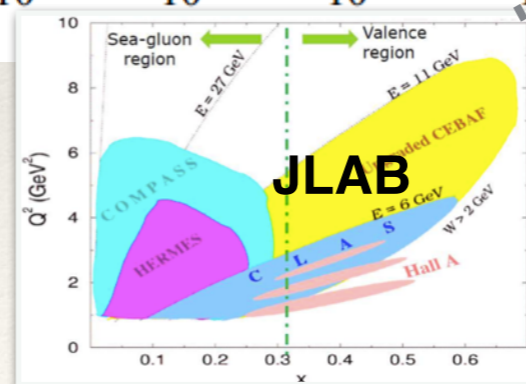


—> can provide flavour separation and more insight into gluons  
 —> probes bilinear combination of quarks

$$Q^2 = -q^2 = -(k - k')^2 \quad \text{Photon virtuality}$$

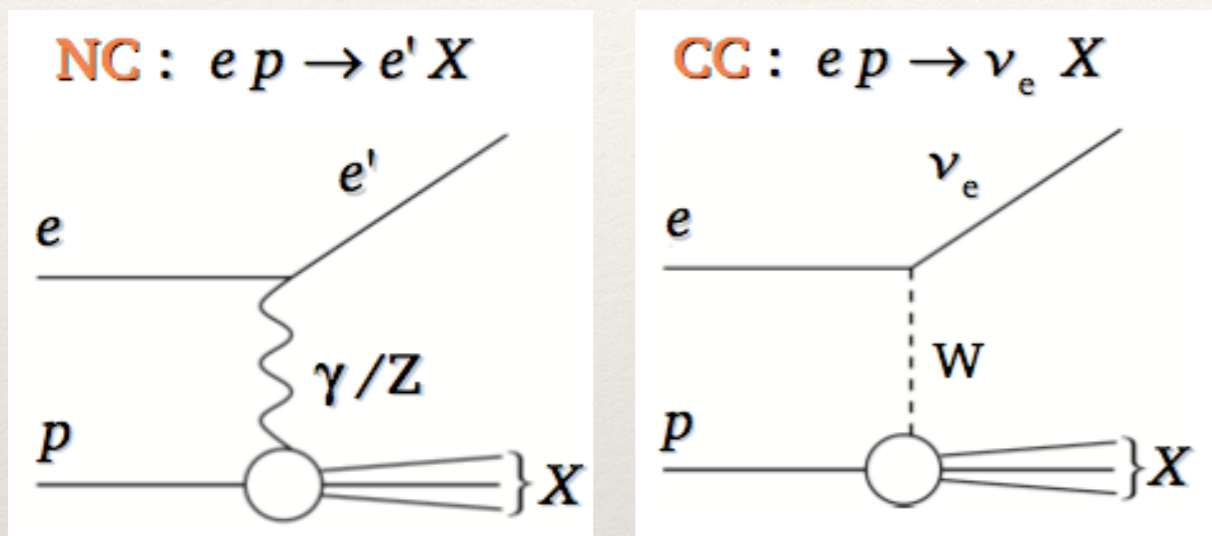
$$x = \frac{Q^2}{2p \cdot q} \quad \text{Bjorken variable}$$

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



# HERA ep collider (1992-2007) @ DESY

- ❖ H1 and ZEUS experiments at HERA collected  $\sim 1$  / fb of data
  - ❖  $E_p=460/575/820/920$  GeV and  $E_e=27.5$  GeV
- ❖ 4 type of processes accessed at HERA: **Neutral Current** and **Charged Current ep**



$$\frac{d\sigma_{NC}^{\pm}}{dx dQ^2} = \frac{2\pi\alpha^2}{x} \left[ \frac{1}{Q^2} \right]^2 [Y_+ \tilde{F}_2 \mp Y_- x \tilde{F}_3 - y^2 \tilde{F}_L]$$

$$\frac{d\sigma_{CC}^{\pm}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 [Y_+ \tilde{W}_2^{\pm} \mp Y_- x \tilde{W}_3^{\pm} - y^2 \tilde{W}_L^{\pm}]$$

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

$$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$$

$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

$$\tilde{F}_L \propto \alpha_s \cdot xg(x, Q^2)$$

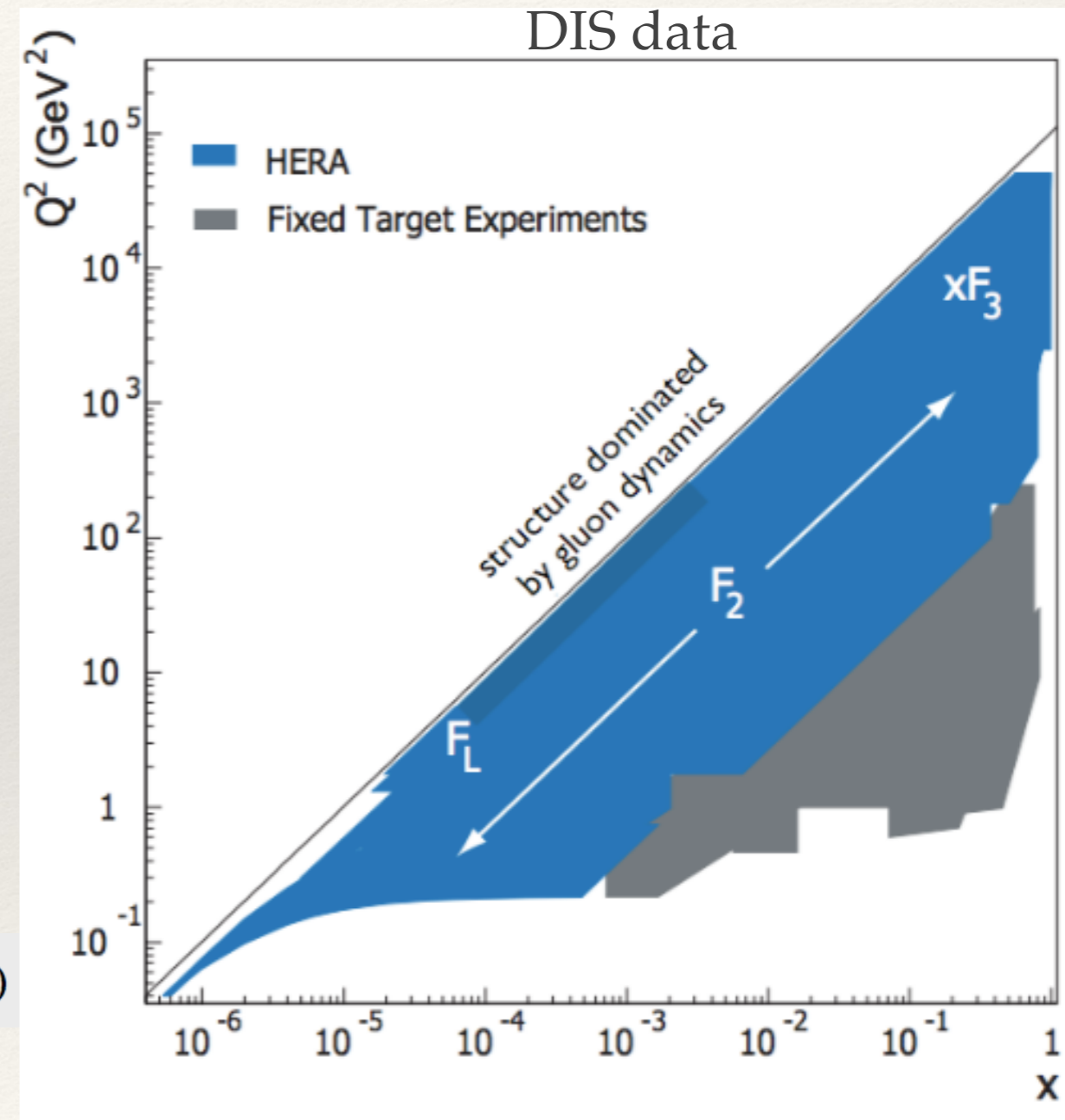
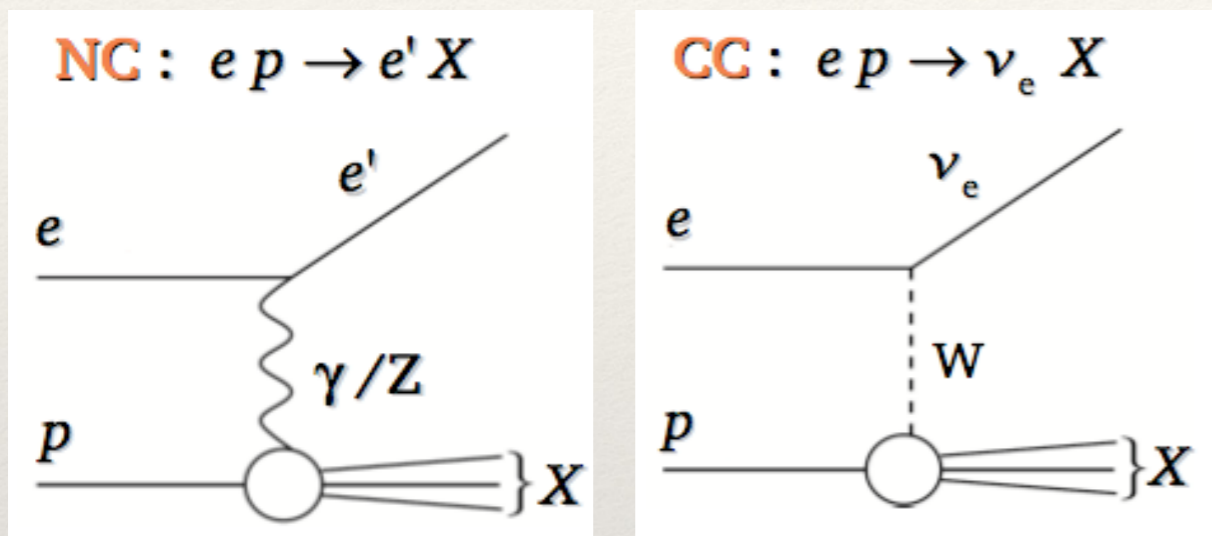
dominant contribution  
(all  $Q^2$  plane)

significant  
contributions at high  $Q^2$

high  $y$

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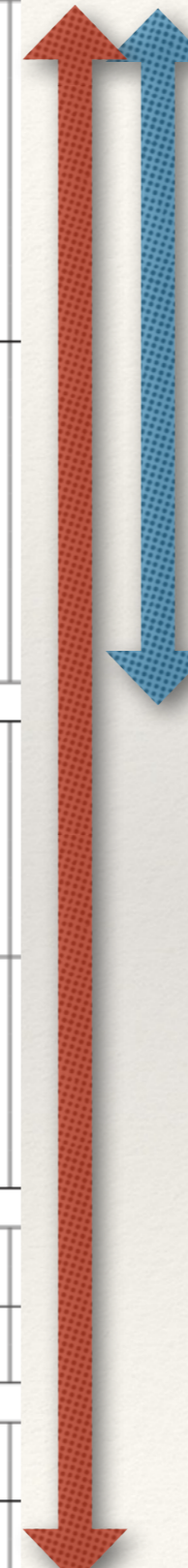
significant  
contributions at high  $Q^2$

high  $y$

# HERA ep collider (1992-2007) @ DESY

Data Set		$x_{Bj}$ Grid	$Q^2$ [GeV <sup>2</sup> ] Grid	$\mathcal{L}$	$e^+/e^-$	$\sqrt{s}$
		from to	from to	pb <sup>-1</sup>		GeV
HERA I $E_p = 820$ GeV and $E_p = 920$ GeV data sets						
H1 svx-mb [2]	95-00	0.000005 0.02	0.2 12	2.1	$e^+p$	301, 319
H1 low $Q^2$ [2]	96-00	0.0002 0.1	12 150	22	$e^+p$	301, 319
H1 NC	94-97	0.0032 0.65	150 30000	35.6	$e^+p$	301
H1 CC	94-97	0.013 0.40	300 15000	35.6	$e^+p$	301
H1 NC	98-99	0.0032 0.65	150 30000	16.4	$e^-p$	319
H1 CC	98-99	0.013 0.40	300 15000	16.4	$e^-p$	319
H1 NC HY	98-99	0.0013 0.01	100 800	16.4	$e^-p$	319
H1 NC	99-00	0.0013 0.65	100 30000	65.2	$e^+p$	319
H1 CC	99-00	0.013 0.40	300 15000	65.2	$e^+p$	319
ZEUS BPC	95	0.000002 0.00006	0.11 0.65	1.65	$e^+p$	300
ZEUS BPT	97	0.0000006 0.001	0.045 0.65	3.9	$e^+p$	300
ZEUS SVX	95	0.000012 0.0019	0.6 17	0.2	$e^+p$	300
ZEUS NC [2] high/low $Q^2$	96-97	0.00006 0.65	2.7 30000	30.0	$e^+p$	300
ZEUS CC	94-97	0.015 0.42	280 17000	47.7	$e^+p$	300
ZEUS NC	98-99	0.005 0.65	200 30000	15.9	$e^-p$	318
ZEUS CC	98-99	0.015 0.42	280 30000	16.4	$e^-p$	318
ZEUS NC	99-00	0.005 0.65	200 30000	63.2	$e^+p$	318
ZEUS CC	99-00	0.008 0.42	280 17000	60.9	$e^+p$	318
HERA II $E_p = 920$ GeV data sets						
H1 NC <sup>1.5p</sup>	03-07	0.0008 0.65	60 30000	182	$e^+p$	319
H1 CC <sup>1.5p</sup>	03-07	0.008 0.40	300 15000	182	$e^+p$	319
H1 NC <sup>1.5p</sup>	03-07	0.0008 0.65	60 50000	151.7	$e^-p$	319
H1 CC <sup>1.5p</sup>	03-07	0.008 0.40	300 30000	151.7	$e^-p$	319
H1 NC med $Q^2$ <sup>*y.5</sup>	03-07	0.0000986 0.005	8.5 90	97.6	$e^+p$	319
H1 NC low $Q^2$ <sup>*y.5</sup>	03-07	0.000029 0.00032	2.5 12	5.9	$e^+p$	319
ZEUS NC	06-07	0.005 0.65	200 30000	135.5	$e^+p$	318
ZEUS CC <sup>1.5p</sup>	06-07	0.0078 0.42	280 30000	132	$e^+p$	318
ZEUS NC <sup>1.5</sup>	05-06	0.005 0.65	200 30000	169.9	$e^-p$	318
ZEUS CC <sup>1.5</sup>	04-06	0.015 0.65	280 30000	175	$e^-p$	318
ZEUS NC nominal <sup>*y</sup>	06-07	0.000092 0.008343	7 110	44.5	$e^+p$	318
ZEUS NC satellite <sup>*y</sup>	06-07	0.000071 0.008343	5 110	44.5	$e^+p$	318
HERA II $E_p = 575$ GeV data sets						
H1 NC high $Q^2$	07	0.00065 0.65	35 800	5.4	$e^+p$	252
H1 NC low $Q^2$	07	0.0000279 0.0148	1.5 90	5.9	$e^+p$	252
ZEUS NC nominal	07	0.000147 0.013349	7 110	7.1	$e^+p$	251
ZEUS NC satellite	07	0.000125 0.013349	5 110	7.1	$e^+p$	251
HERA II $E_p = 460$ GeV data sets						
H1 NC high $Q^2$	07	0.00081 0.65	35 800	11.8	$e^+p$	225
H1 NC low $Q^2$	07	0.0000348 0.0148	1.5 90	12.2	$e^+p$	225
ZEUS NC nominal	07	0.000184 0.016686	7 110	13.9	$e^+p$	225
ZEUS NC satellite	07	0.000143 0.016686	5 110	13.9	$e^+p$	225

- 41 data sets: 2927 data points are combined to 1307 averaged measurements with 169 sources of correlated systematic uncertainties.



**HERAPDF1.0**

JHEP01 (2010) 109

**HERAPDF1.5**

**HERAPDF2.0**

[arxiv:1506.06042]

# Combination of the H1 and ZEUS Measurements

FINAL HERA I+II inclusive data combination [arxiv:1506.06042]

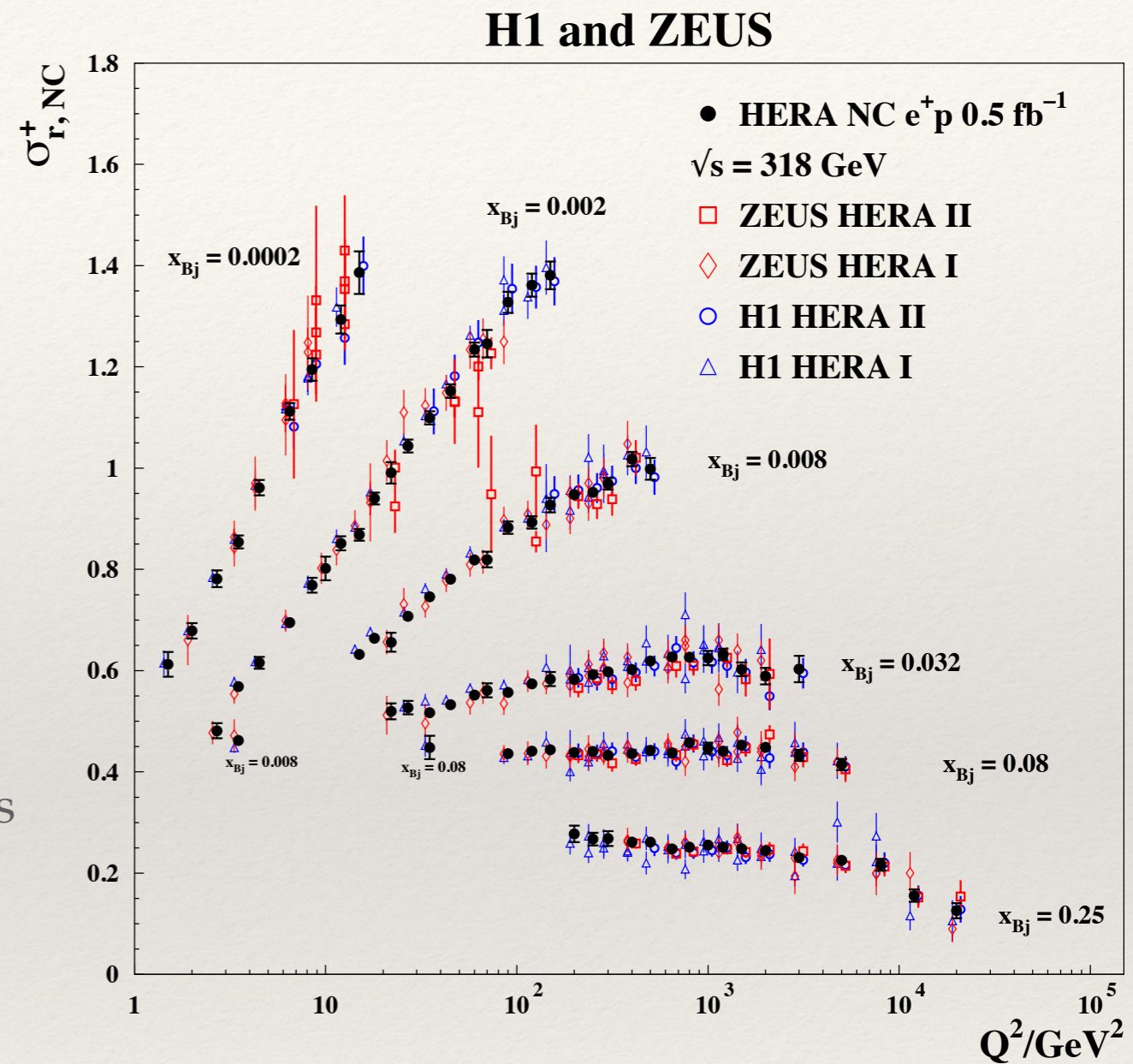
- Ultimate precision is obtained by combining the H1 and ZEUS measurements

- The combination procedure is performed before QCD analysis using  $\chi^2$  minimisation

- $\chi^2 / \text{dof} = 1687 / 1620$

- Improvement on Statistical precision:
- Improvement of Systematic precision:
  - ❖ H1 and ZEUS are different detectors and use different analysis techniques;
  - ❖ The H1 and ZEUS cross sections have different sensitivities to similar sources of correlated systematic uncertainty.

→ total uncertainty < 1.3% for Q2 up to 400 GeV2



$$0.045 < Q^2 < 50000 \text{ GeV}^2 \quad 6 \cdot 10^{-7} < x_{Bj} < 0.65$$

$$\sigma_{r,NC}^{\pm} = \frac{d^2 \sigma_{NC}^{e^{\pm}p}}{dx_{Bj} dQ^2} \cdot \frac{Q^4 x_{Bj}}{2\pi\alpha^2 Y_{\pm}} = \tilde{F}_2 \mp \frac{Y_{-}}{Y_{+}} x \tilde{F}_3 - \frac{y^2}{Y_{+}} \tilde{F}_L$$

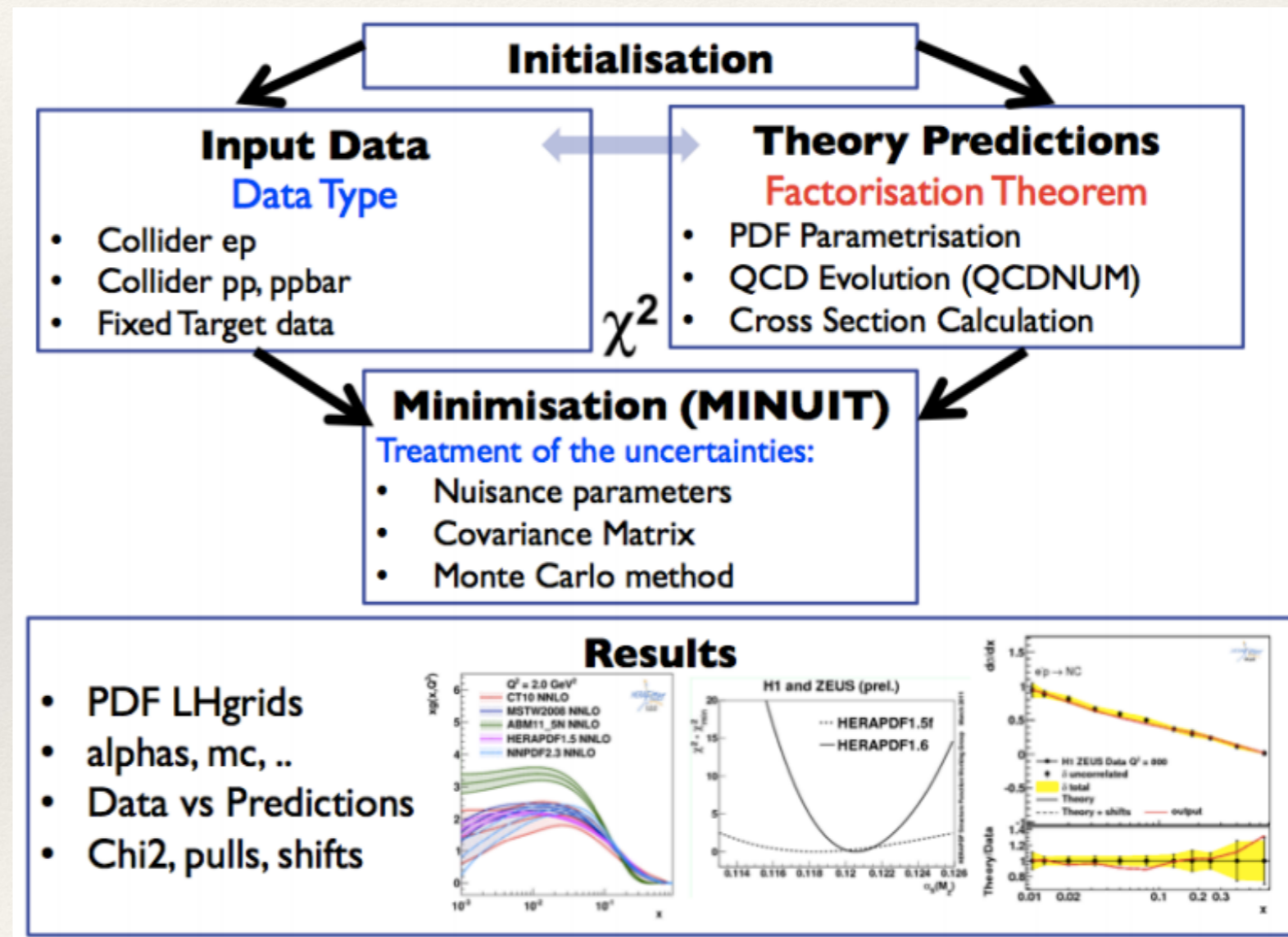
Combination of data is now actively used at LHC for ex W, Z for muon and electron channels

# Extraction of PDFs through QCD fits

- ❖ Extraction of PDFs relies on the factorisation:  $\sigma = \hat{\sigma} \otimes \text{PDF}$
- ❖ Typical measurements sensitive to PDFs are precise, with statistical uncertainties  $< 10\%$ , so they follow normal distribution  $\rightarrow$  use of  $\chi^2$  minimisation for PDF extraction.

## Main Steps:

- Parametrise PDFs at a starting scale
- Evolve PDFs to the scale corresponding to data point
- Calculate the cross section
- Compare with data via  $\chi^2$
- Minimise  $\chi^2$  with respect to PDF parameters which takes about  $\sim 2000$  iterations:



[herafitter.org](http://herafitter.org): open source QCD platform arXiv:1503.05221

# QCD Settings for HERAPDF2.0

The QCD settings are optimised for HERA measurements of proton structure functions:  
PDFs are parametrised at the starting scale  $Q_0^2=1.9 \text{ GeV}^2$  as follows:

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

fixed or constrained by sum-rules

parameters set equal but free

NC structure functions

$$F_2 = \frac{4}{9} (xU + x\bar{U}) + \frac{1}{9} (xD + x\bar{D})$$

$$xF_3 \sim xu_v + xd_v$$

CC structure functions

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

Due to increased precision of data, more flexibility in functional form is allowed → 14 free parameters

- ❖ PDFs are evolved via evolution equations (DGLAP) to NLO and NNLO (as(MZ)=0.118)
- ❖ Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MMHT
- ❖ Chi2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

$$\chi_{tot}^2(\mathbf{m}, \mathbf{b}) = \sum_i \frac{[\mu^i - m^i(1 - \sum_j \gamma_j^i b_j)]^2}{\delta_{i,stat}^2 \mu^i m^i (1 - \sum_j \gamma_j^i b_j) + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2 + \sum_i \ln \frac{\delta_{i,unc}^2 m_i^2 + \delta_{i,stat}^2 \mu^i m^i}{\delta_{i,unc}^2 \mu_i^2 + \delta_{i,stat}^2 \mu_i^2}$$

# Modern understanding of PDFs

Different types of PDF uncertainties are considered:

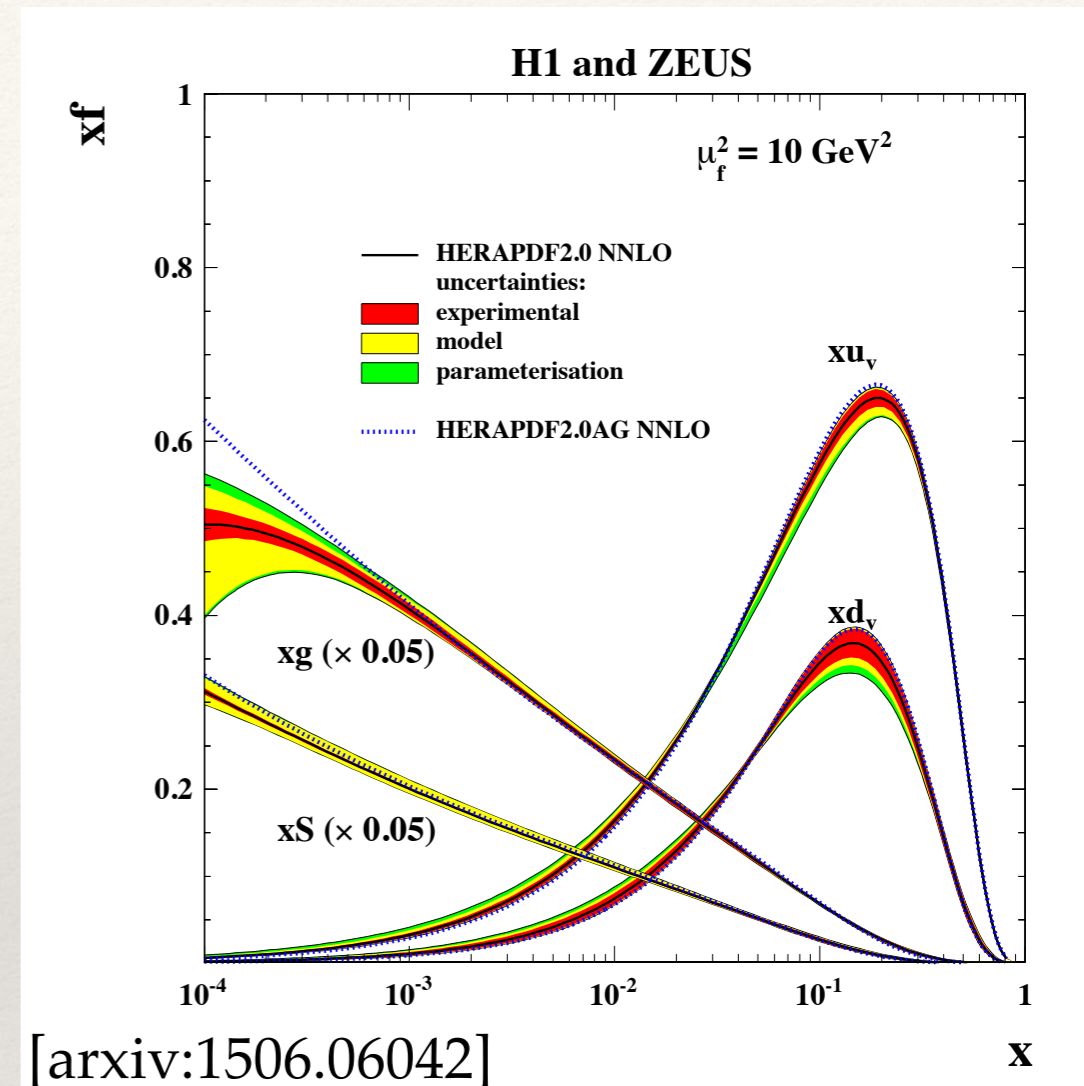
## ❖ Experimental:

- ❖ Hessian method used: MMHT, CT, ...
- ❖ Consistent data sets  $\rightarrow$  use  $\Delta\chi^2=1$
- ❖ Monte Carlo Method: replicas of data (NNPDF)

## ❖ Model:

- ❖ variations of all assumed input parameters in the fit

Variation	Standard Value	Lower Limit	Upper Limit
$Q_{\min}^2$ [GeV <sup>2</sup> ]	3.5	2.5	5.0
$Q_{\min}^2$ [GeV <sup>2</sup> ] HiQ2	10.0	7.5	12.5
$M_c$ (NLO) [GeV]	1.47	1.41	1.53
$M_c$ (NNLO) [GeV]	1.43	1.37	1.49
$M_b$ [GeV]	4.5	4.25	4.75
$f_s$	0.4	0.3	0.5
$\alpha_s(M_Z^2)$	0.118	–	–
$\mu_{f_0}$ [GeV]	1.9	1.6	2.2



## ❖ Parametrisation: only HERAPDF includes this as an additional uncertainty

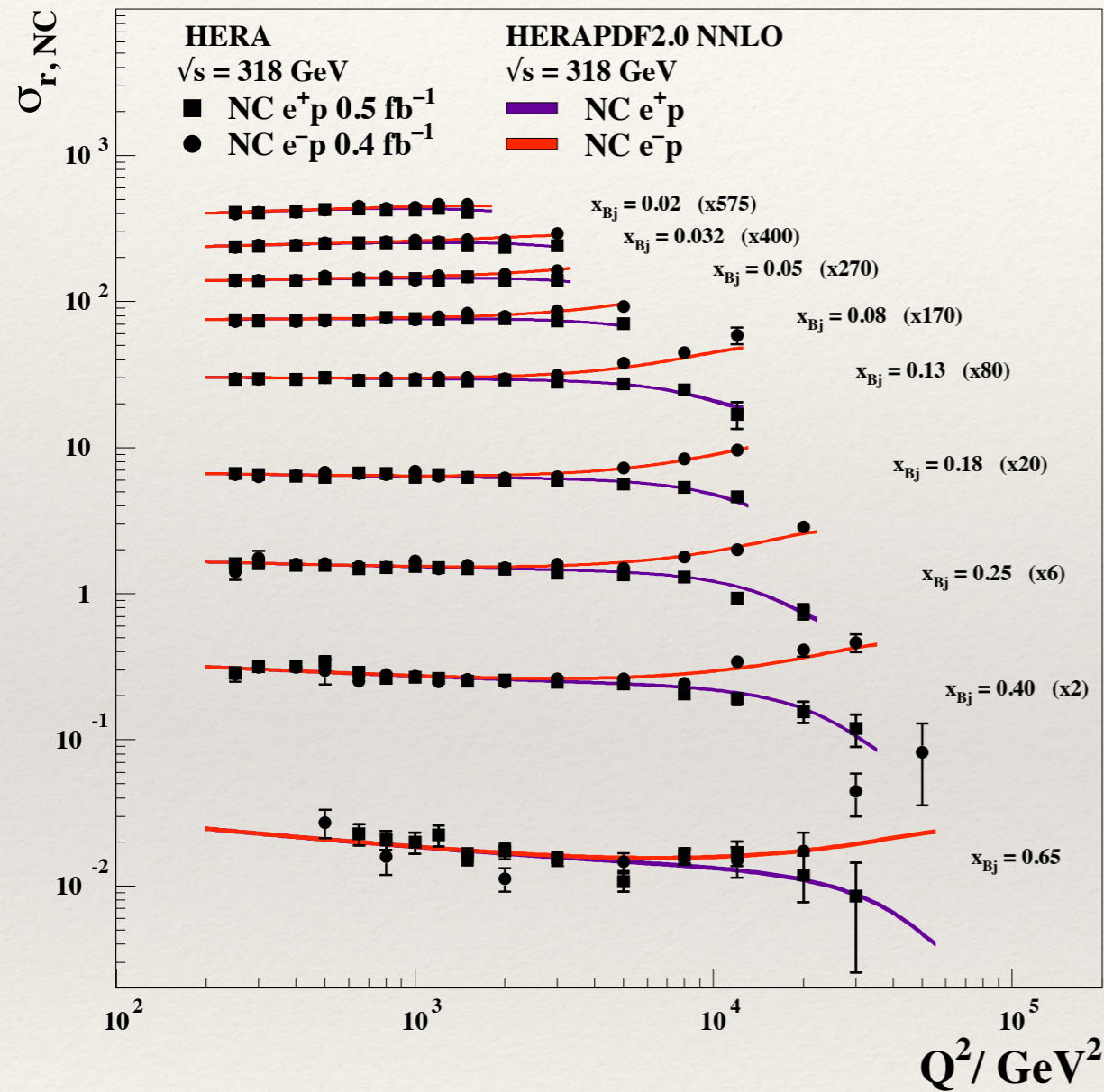
- ❖ NNPDFs use neural network approach based on data driven regularisation

# QCD scaling and EW effects

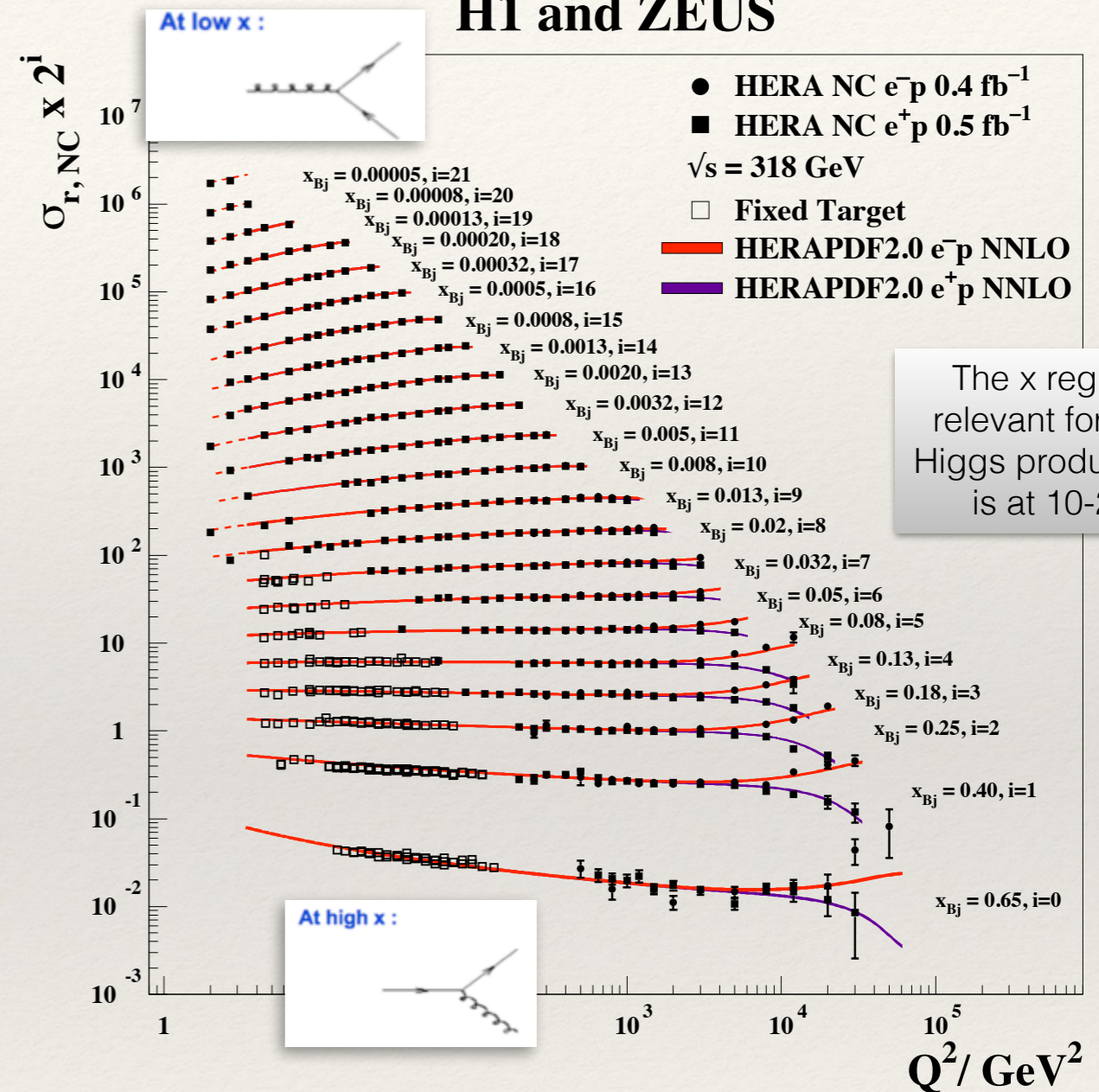
EW effects clearly seen at high  $Q^2$ :

QCD scaling violations nicely seen:

H1 and ZEUS



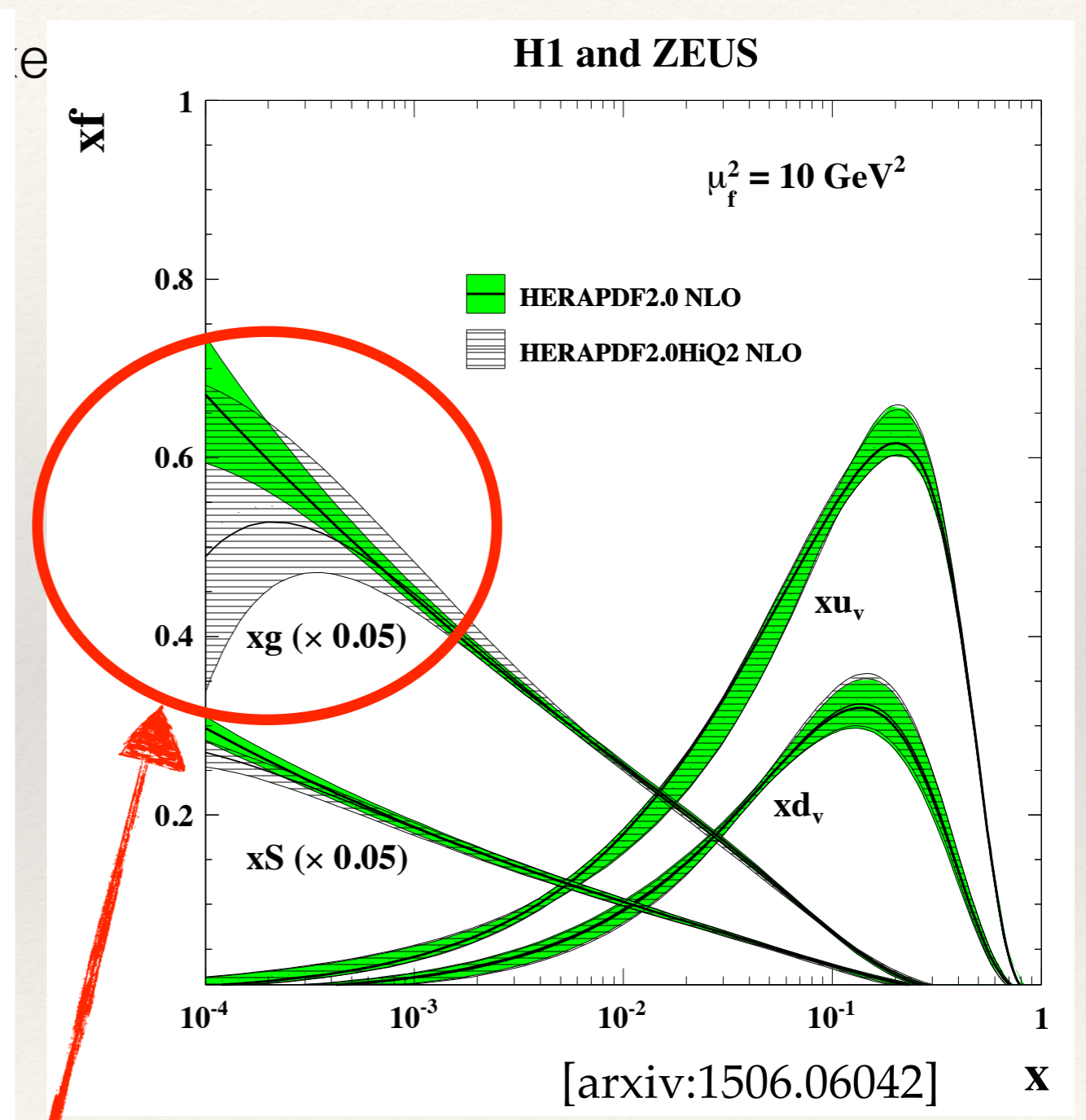
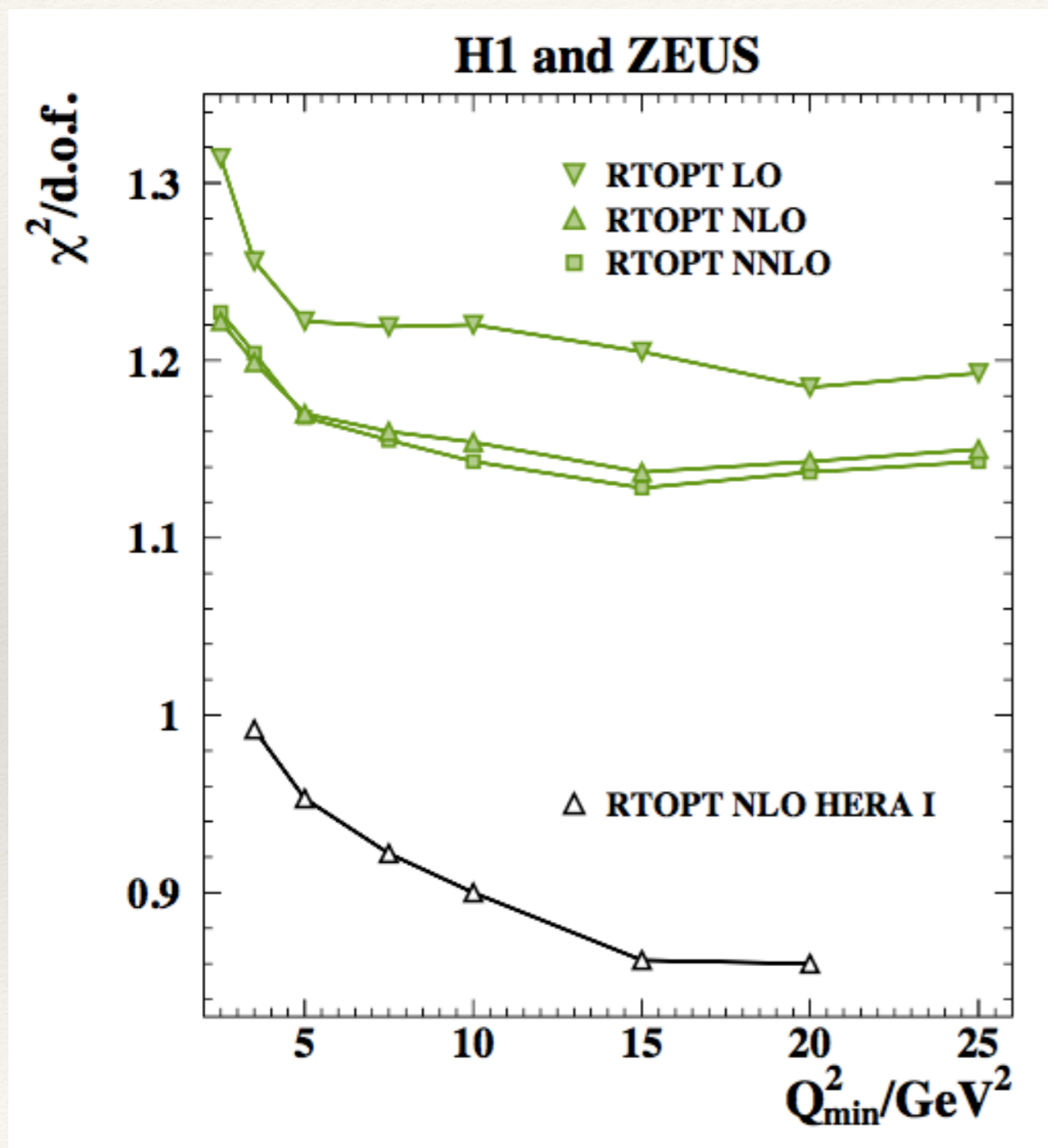
H1 and ZEUS



The  $x$  region relevant for the Higgs production is at  $10^{-2}$ .

# Q<sup>2</sup> cut dependence on PDFs

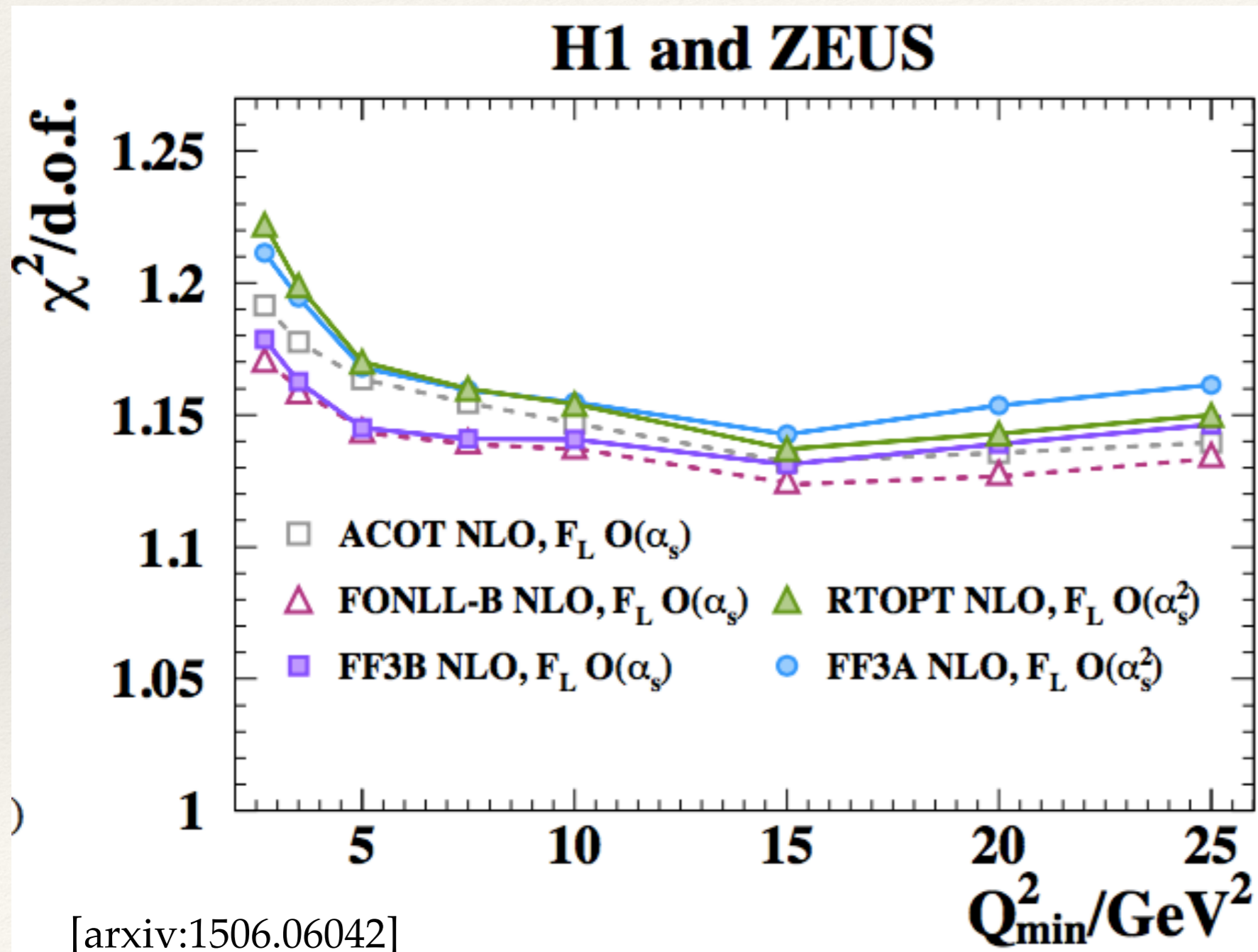
- HERA data provides a unique access to the low x, low Q<sup>2</sup> region to investigate:
  - the validity of the DGLAP mechanism



low Q<sup>2</sup> data very important to constrain low x PDFs!

# Q<sup>2</sup> cut dependence

- HERA data provides a unique access to the low x, low Q<sup>2</sup> region to investigate:
  - the validity of the DGLAP mechanism
  - the various scheme dependence (fixed vs variable flavours)



ACOT -> as used by CT  
 RT -> as used by MMHT  
 FONLL -> as used by NNPDF  
 FF3A -> as used by ABM

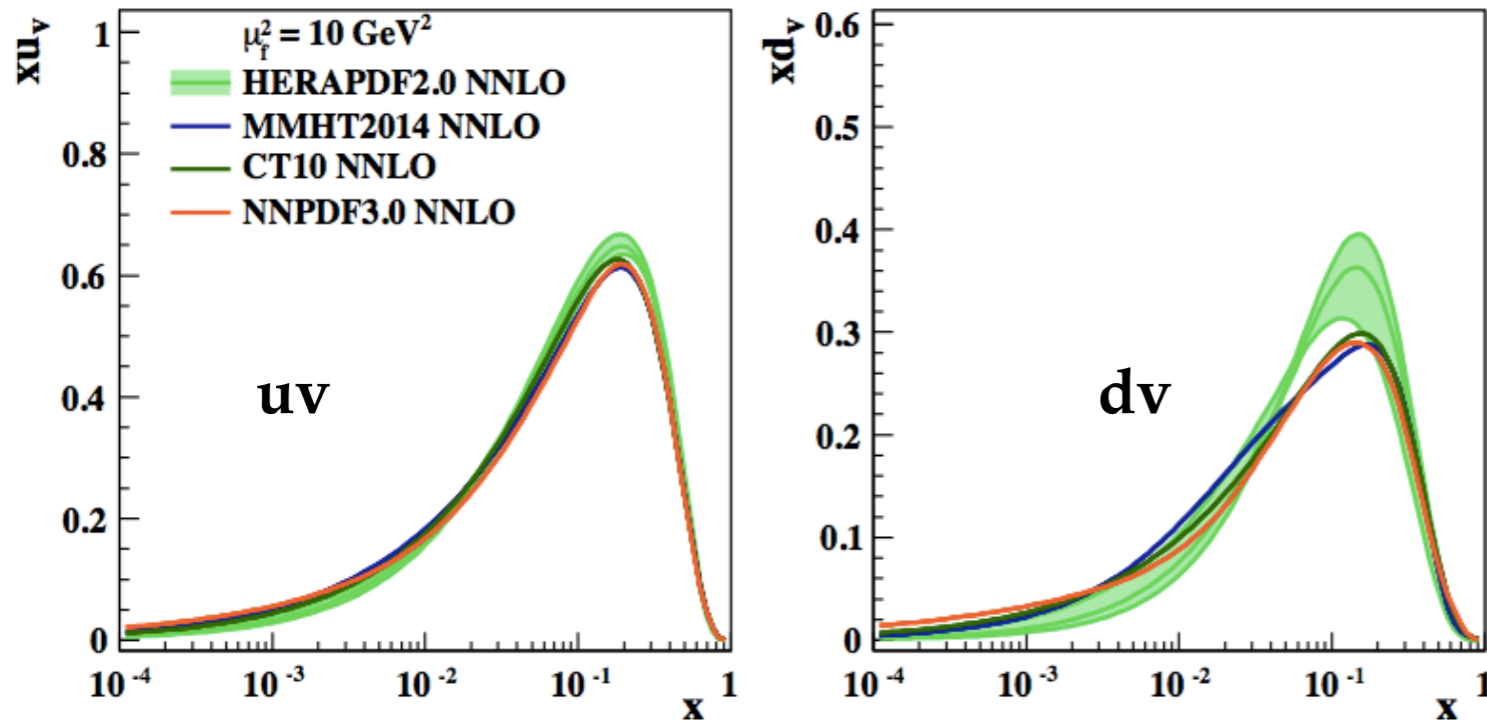
Low Q<sup>2</sup> remains  
 an interesting region  
 to investigate  
 (low x phenomenology)

[arxiv:1506.06042]

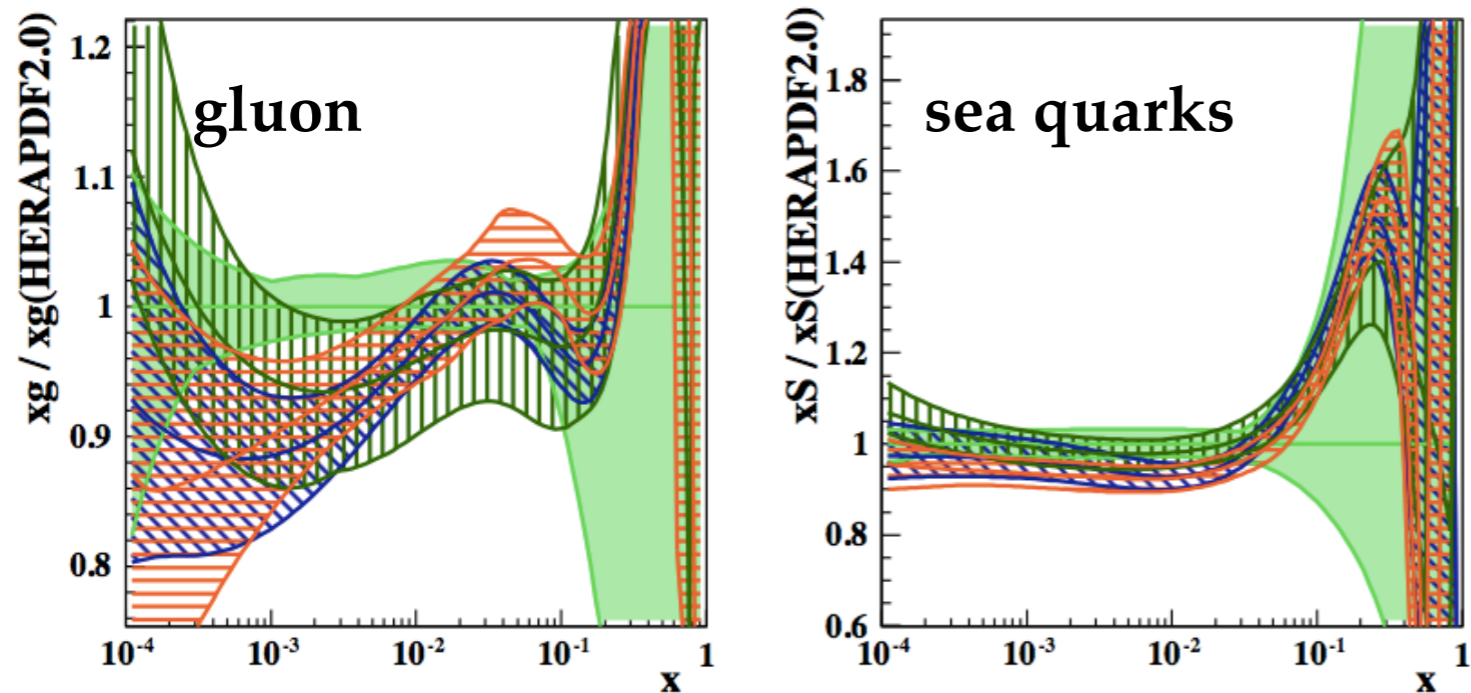
# HERAPDF2.0 vs other PDF sets

- HERAPDF sets are extracted solely from ep data and require no assumptions or corrections, hence provide an important cross check of PDF universality (process independence):

H1 and ZEUS



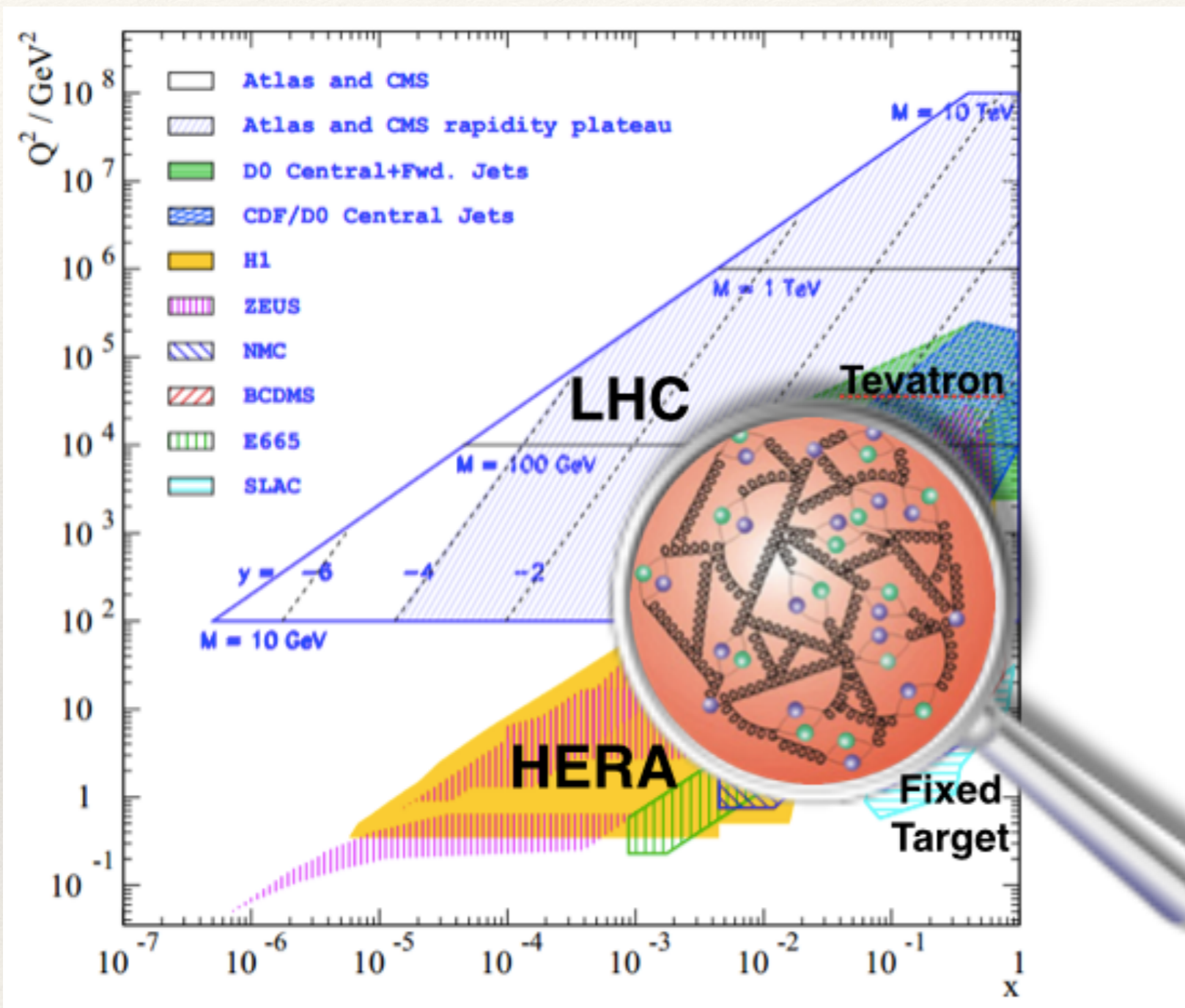
high x valence different:  
new high- x data and use of  
proton target only



At NNLO gluon and Sea are both  
compatible with other PDFs

[arxiv:1506.06042]

# Summary



PDFs are very important as they still limit our knowledge of cross sections whether SM or BSM.

- ◆ HERA has finalised its separate measurements relevant to PDFs and has combined them into final measurements to reach its ultimate precision:
  - ◆ PDFs, mc, mb, alphas
  - ...

back-up slides  
not necessarily useful ...

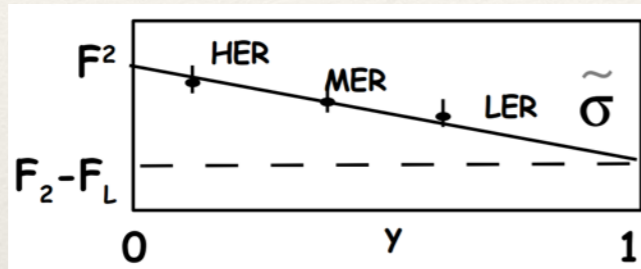
# Longitudinal Structure Function

Longitudinal structure function  $F_L$  is a pure QCD effect:

—> an independent way to probe sensitivity to gluon

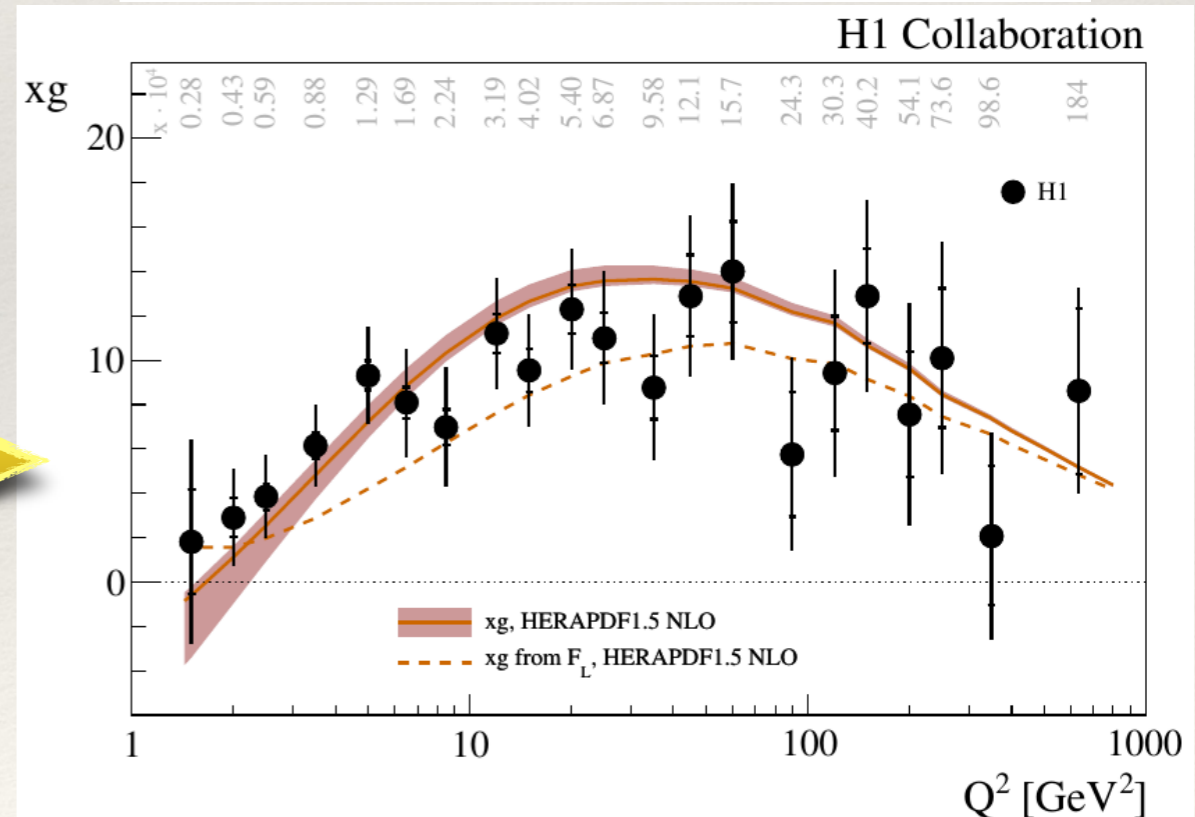
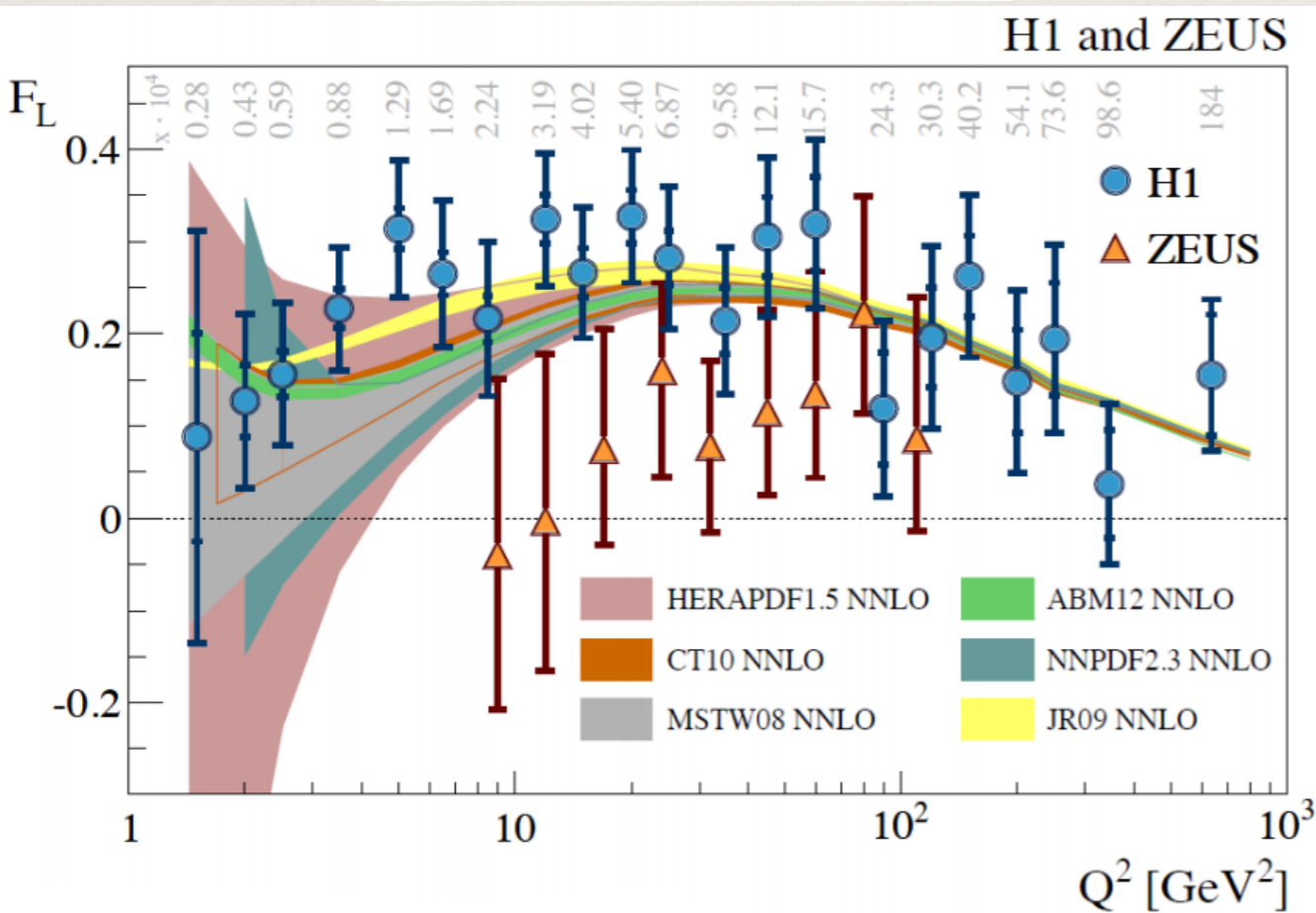
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \underbrace{\frac{16}{3} F_2}_{\text{quarks radiating a gluon}} + 8 \sum_q \underbrace{e_q^2 \left(1 - \frac{x}{z}\right) z g(z)}_{\text{gluons splitting into quarks}} \right]$$

Direct measurement of  $F_L$  at HERA required differential cross sections at same  $x$  and  $Q^2$  but different  $y$  —> different beam energies:  $E_p = 460, 575, 920$  GeV



$$\sigma_{NC}(x, Q^2, y) \propto F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)$$

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_s(Q^2)} F_L(ax, Q^2)$$



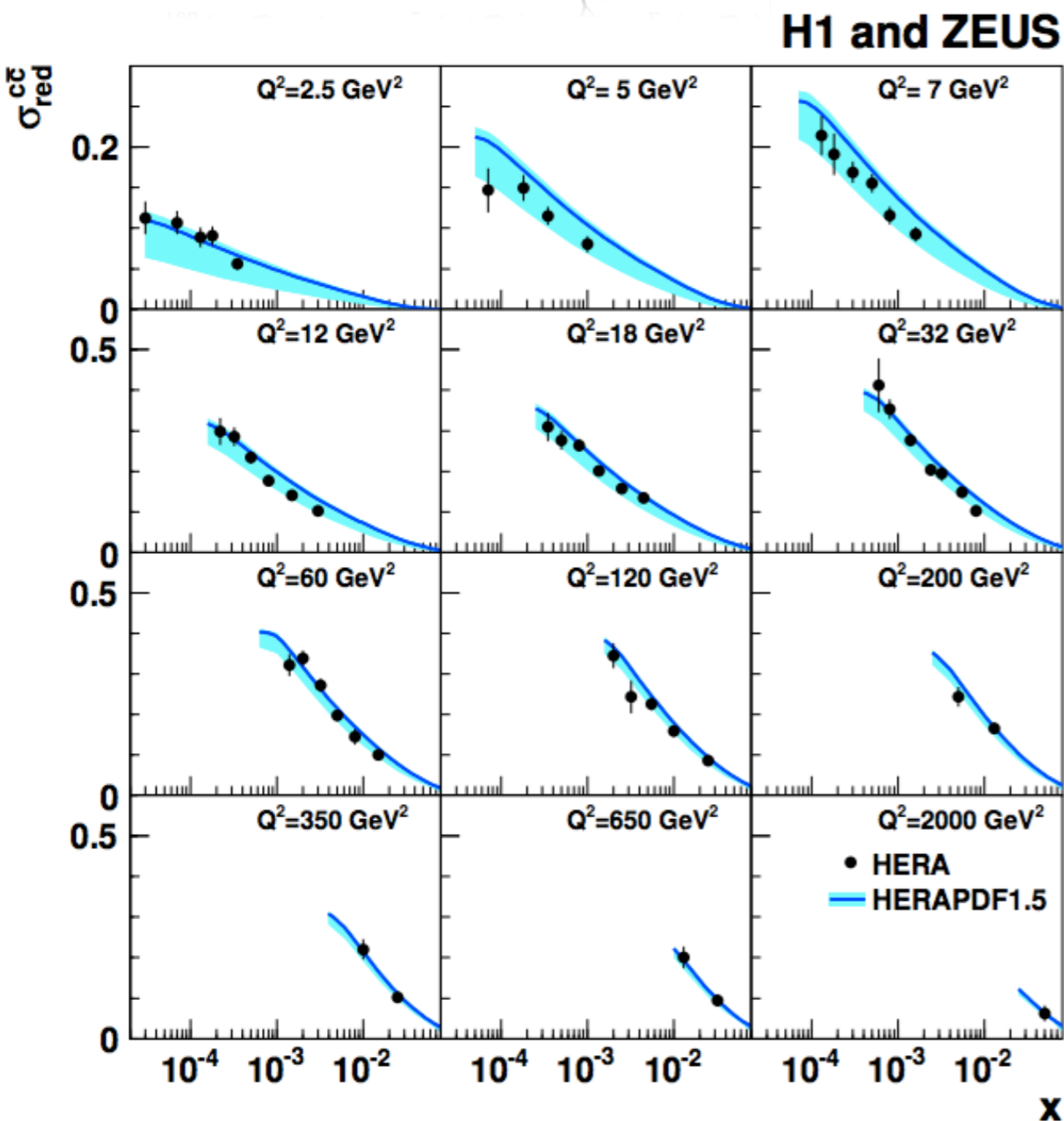
*Eur. Phys. J. C* 74 (2014) 2814 [arXiv:1312.4821]

# F2 charm Structure Function

EPJC 73 (2013) 2311

- Rates at HERA in DIS regime  $\sigma(b) : \sigma(c) \approx O(1\%) : O(20\%)$  of  $\sigma_{TOT}$
- Charm data combination is performed at charm cross sections level:
  - they are obtained from xsec in visible phase space and extrapolated to full space

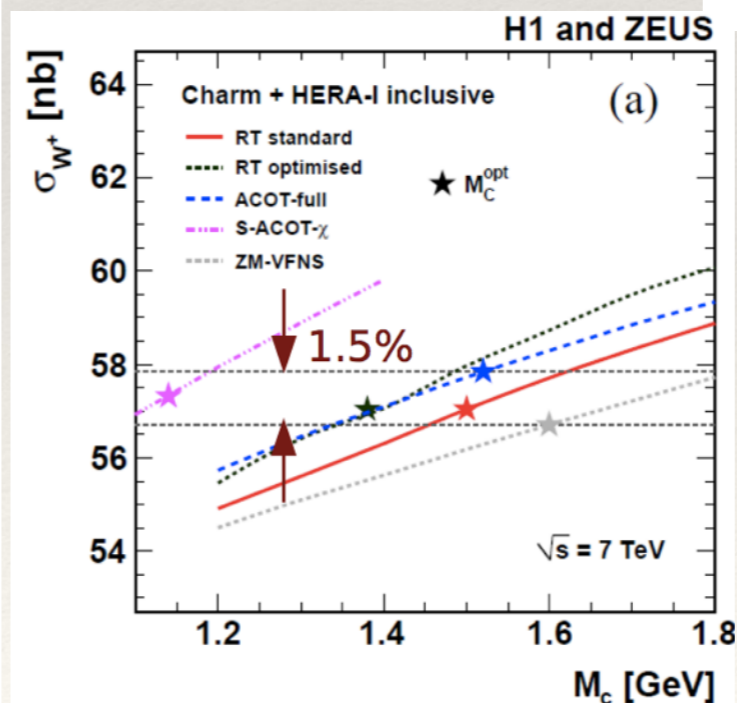
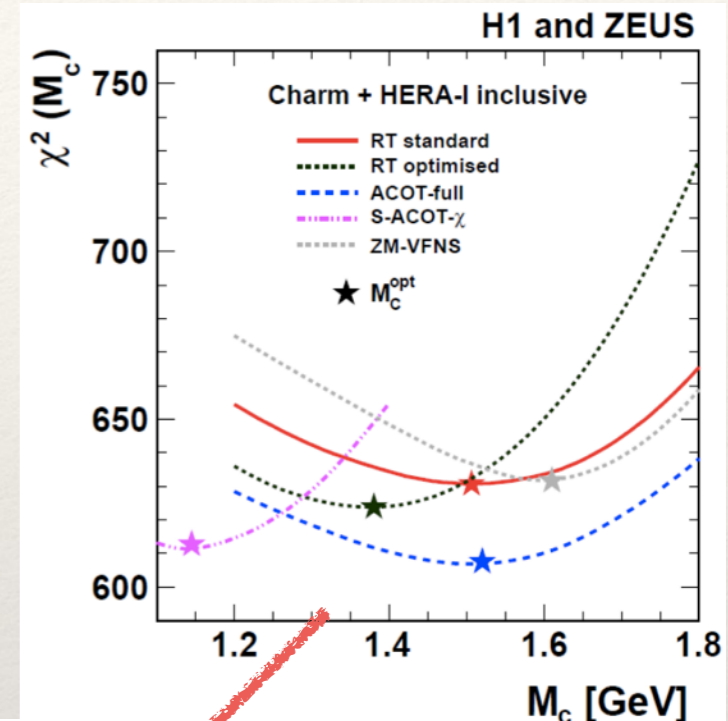
$$\sigma_{red}^{c\bar{c}}(x, Q^2, s) = F_2^{c\bar{c}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x, Q^2)$$



QCD Fits  
HERA I+charm



Different calculation schemes prefer different  $M_c$



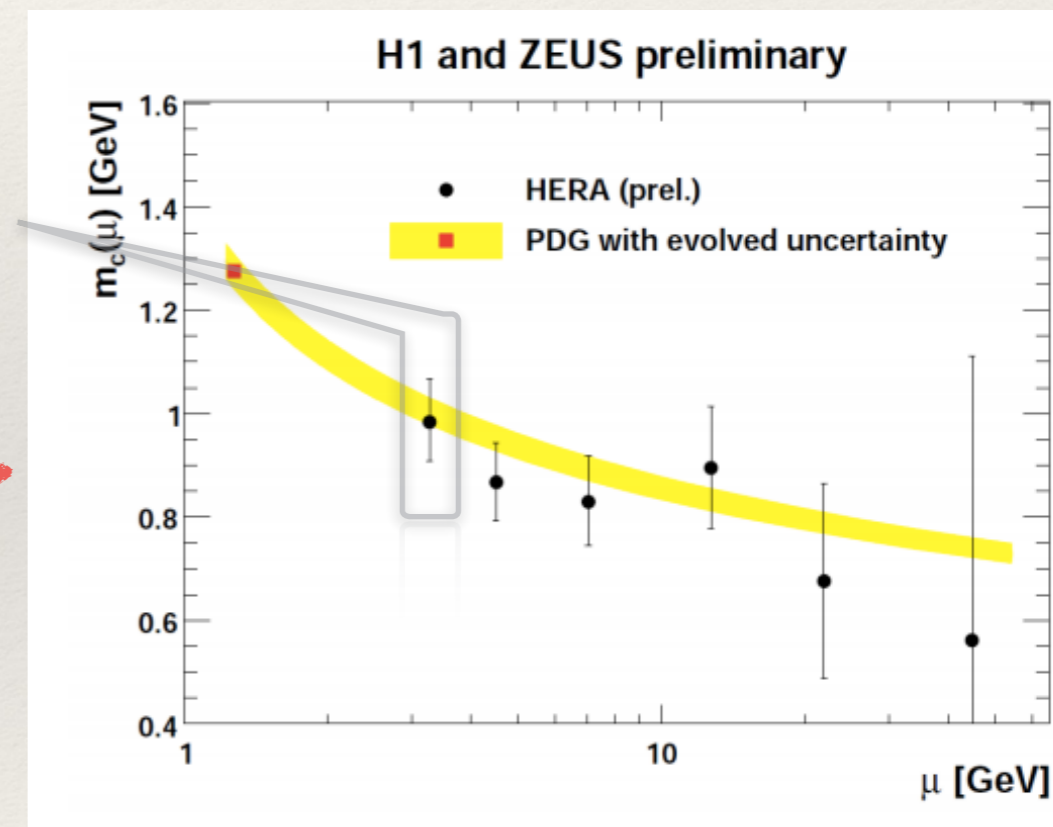
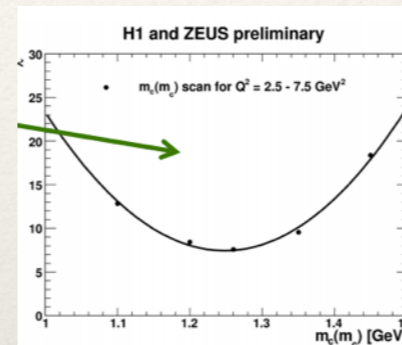
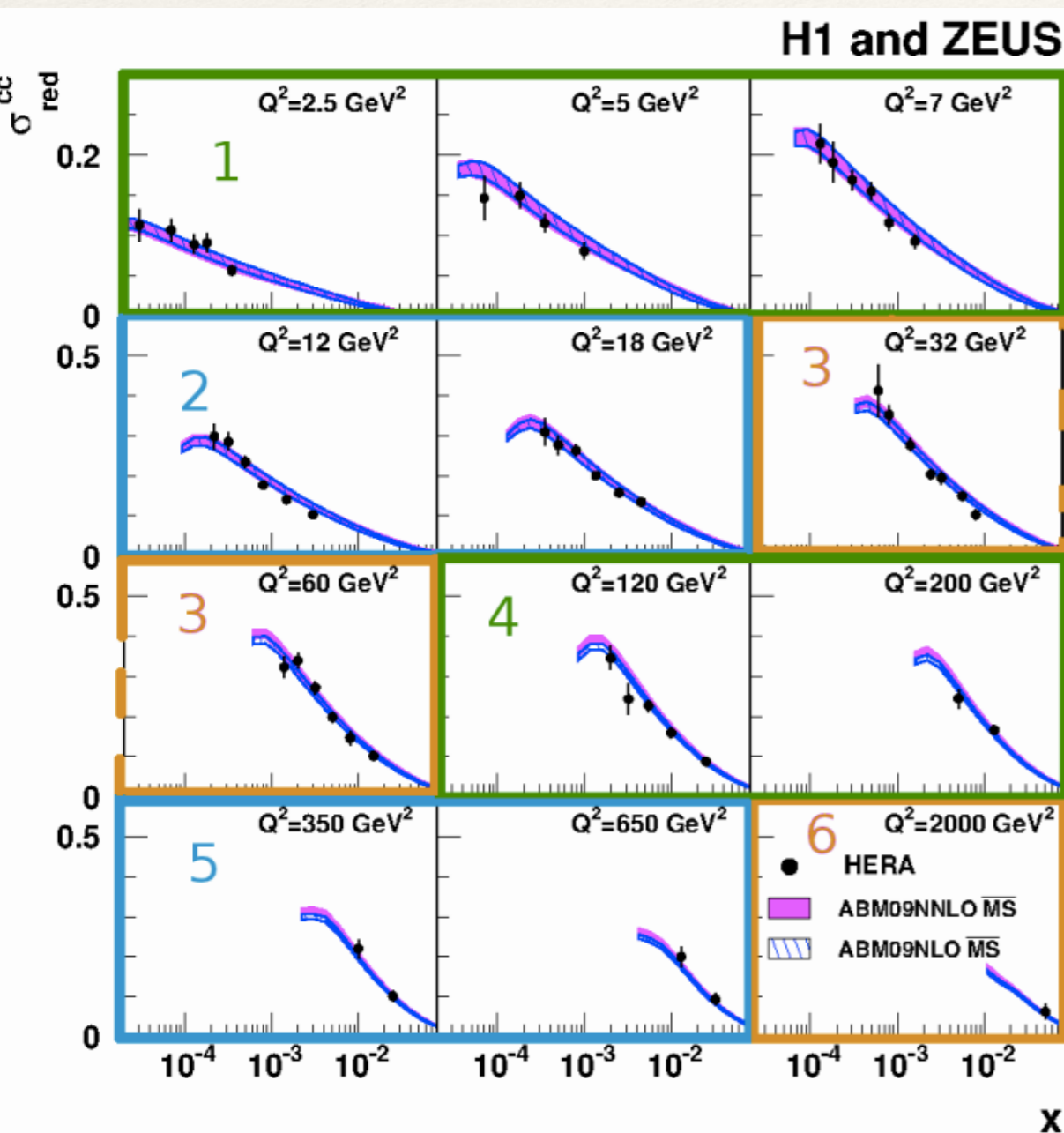
measurements help reduce uncertainties of predictions for the LHC

# New Measurement of Charm Mass Running

H1-prelim-14-071 ZEUS-prel-14-006 and S. Moch

The running of the charm mass in the  $\overline{\text{MS}}$  scheme is measured for the first time from the same HERA combined charm data:

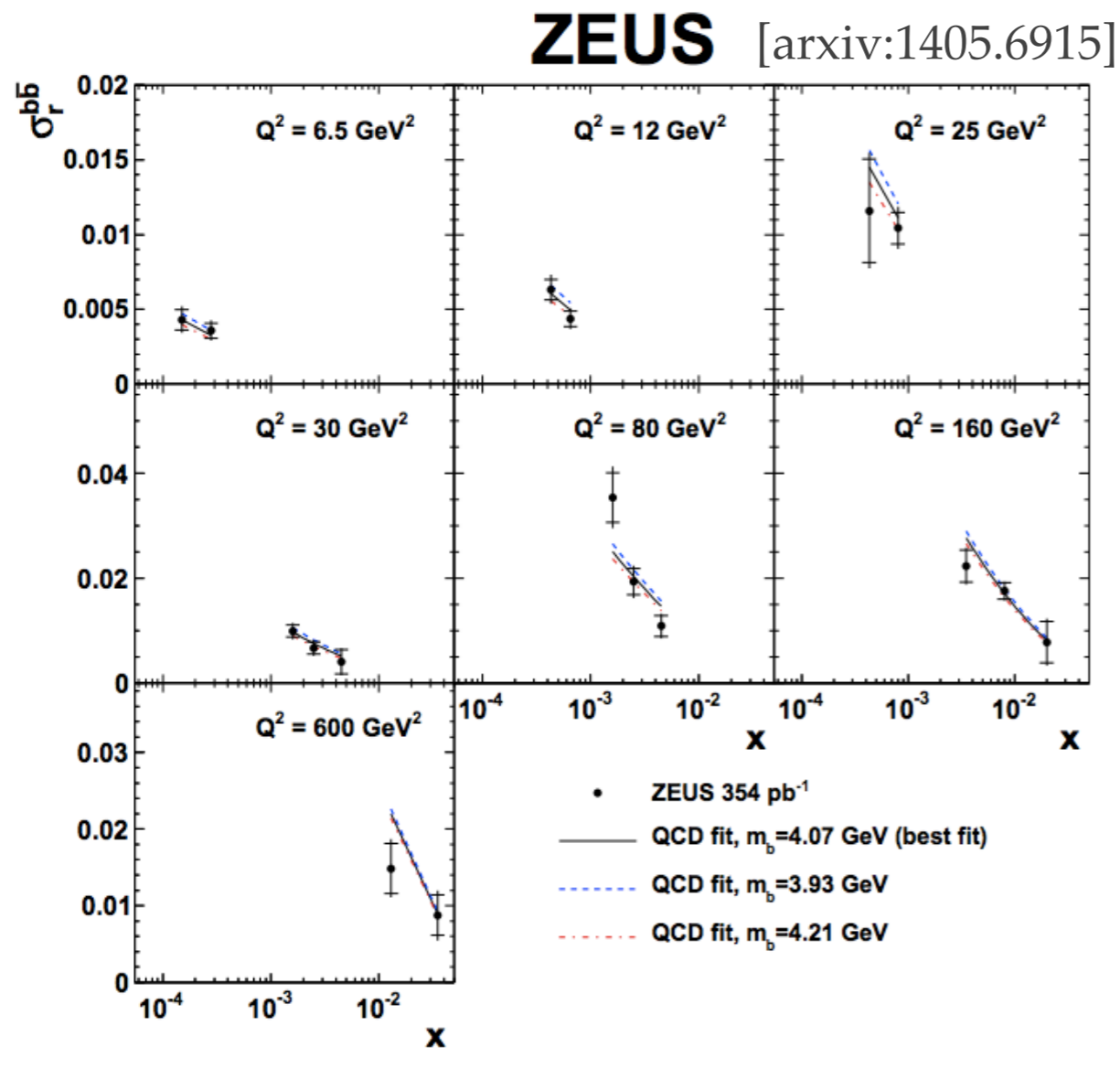
- Extract  $m_c(m_c)$  in 6 separate kinematic regions
- Translate back to  $m_c(\mu)$  [with  $\mu = \sqrt{Q^2 + 4m_c^2}$ ] using OpenQCDrad [S.Alekhin's code].



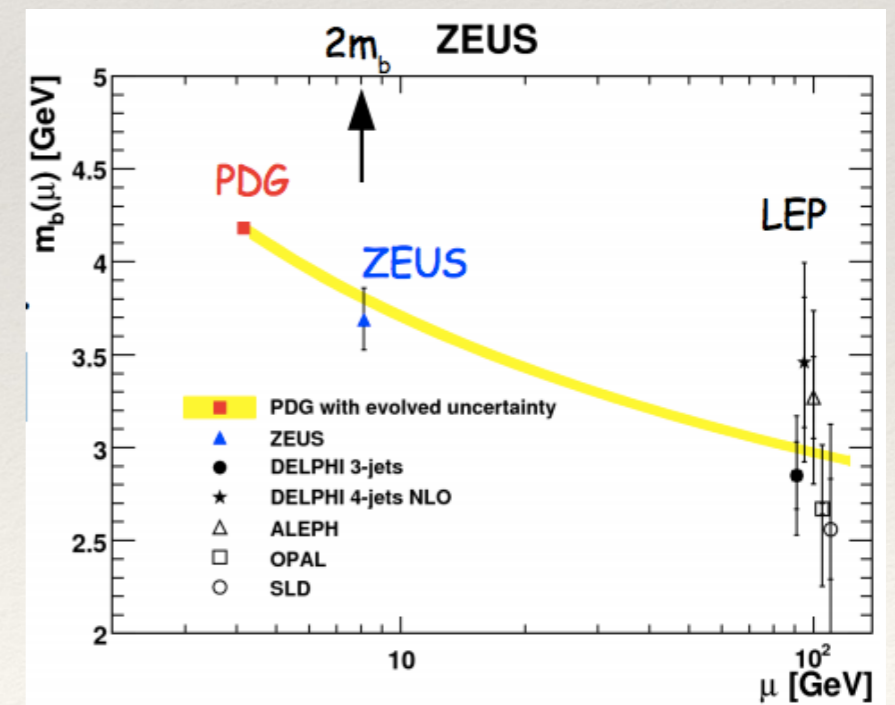
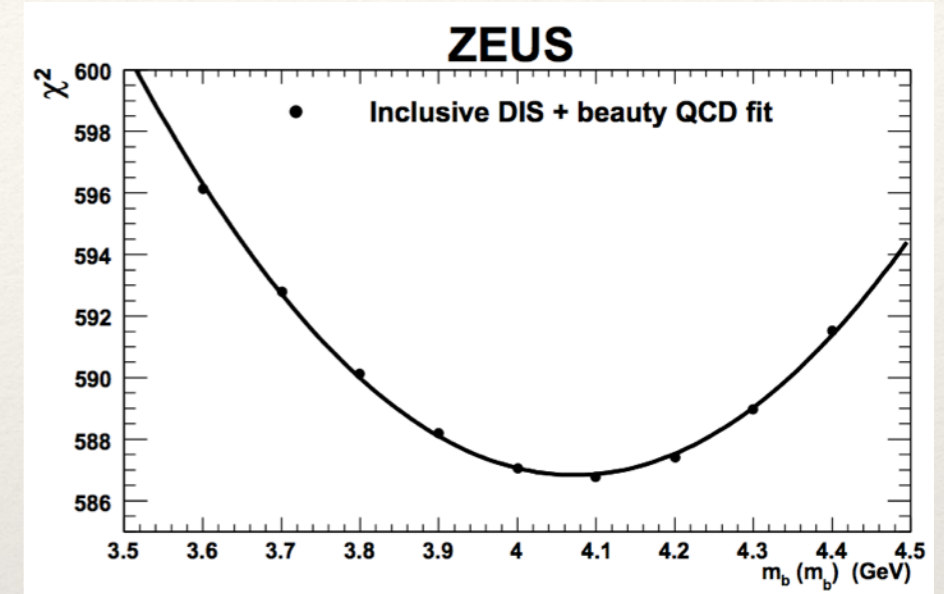
The scale dependence of the mass is consistent with QCD expectations

# Running beauty mass from F2b

- ❖ The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):
  - ❖ chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the  $\overline{\text{MS}}$  scheme.



QCD Fits  
HERA I+beauty



The extracted  $\overline{\text{MS}}$  beauty-quark mass is in agreement with PDG average and LEP results.

# DIS Cross Sections

- ❖ Differential cross section is experimentally measured: **theory meets the experiment**
- ❖ Factorisable nature of interaction: Inclusive scattering cross section is a product of leptonic and hadronic tensors times propagator characteristic of the exchanged particle:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \sum_j \eta_j L_j^{\mu\nu} W_j^{\mu\nu}$$

For NC:  $j = \gamma, Z, \gamma Z$   
For CC:  $j = W^+, W^-$

$$\eta_\gamma = 1; \quad \eta_{\gamma Z} = \left( \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha} \right) \left( \frac{Q^2}{Q^2 + M_Z^2} \right); \quad \eta_Z = \eta_{\gamma Z}^2;$$

$$\eta_W = \frac{1}{2} \left( \frac{G_F M_W^2}{4\pi\alpha} \frac{Q^2}{Q^2 + M_W^2} \right)^2,$$

**Leptonic tensor:** related to the coupling of the lepton with the exchanged boson

- contains the electromagnetic or the weak couplings
- can be calculated exactly in the standard electroweak  $U(1) \times SU(2)$  theory.

**Hadronic tensor:** related to the interaction of the exchanged boson with proton

- can't be calculated, but only be reduced to a sum of structure functions:

$$W^{\alpha\beta} = -g^{\alpha\beta} W_1 + \frac{p^\alpha p^\beta}{M^2} W_2 - \frac{i\epsilon^{\alpha\beta\gamma\delta} p_\gamma q_\delta}{2M^2} W_3 + \frac{q^\alpha q^\beta}{M^2} W_4 + \frac{p^\alpha q^\beta + p^\beta q^\alpha}{M^2} W_5 + \frac{i(p^\alpha q^\beta - p^\beta q^\alpha)}{2M^2} W_6 \quad \sim m_{\text{lepton}}$$

$$\frac{d^2\sigma}{dx dQ^2} = A^i \left\{ \left(1 - y - \frac{x^2 y^2 M^2}{Q^2}\right) F_2^i + y^2 x F_1^i \mp \left(y - \frac{y^2}{2}\right) x F_3^i \right\}$$

$A^i$ : process dependent