Recent HERA results on proton structure

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On behalf of the H1 and ZEUS collaborations

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North-Holland

PHYSICS LETTERS B

A measurement of $\sigma_{tot}(\gamma p)$ at $\sqrt{s} = 210$ GeV

ZEUS Collaboration

Volume 293, number 3,4 PHYSICS LETTERS B 29 October 1992

K. Charchuła, J. Ciborowski, J. Gajewski, G. Grzelak, M. Kasprzak, M. Krzyżanowski, K. Muchorowski, R.J. Nowak, J.M. Pawlak, K. Stojda, A. Stopczyński, R. Szwed, T. Tymieniecka [30], R. Walczak, A.K. Wróblewski, J.A. Zakrzewski, A.F. Żarnecki

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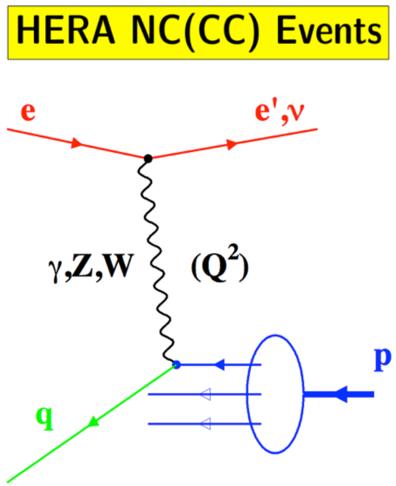
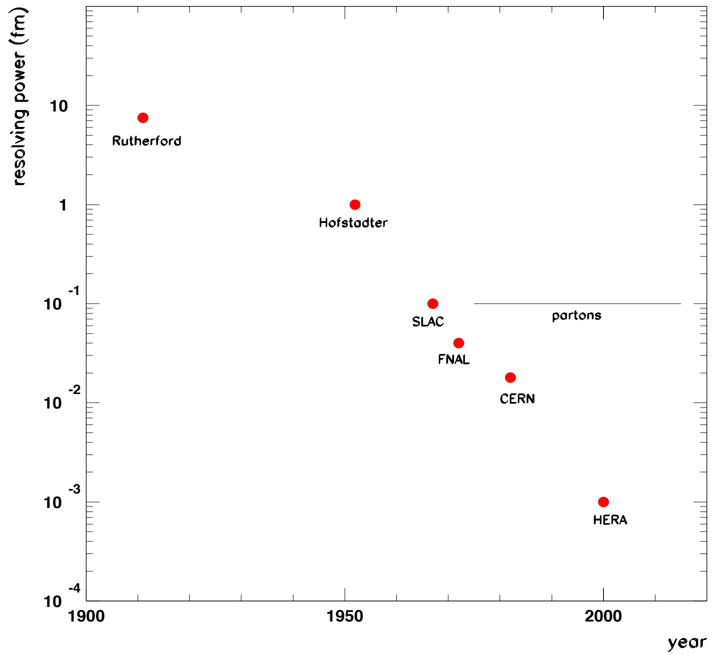
Received 23 September 1992

The total photoproduction cross section is determined from a measurement of electroproduction with the ZEUS detector at HERA. The Q^2 values of the virtual photons are in the range $10^{-7} < Q^2 < 2 \times 10^{-2}$ GeV^2. The γp total cross section in the γp centre of mass energy range 186–233 GeV is 154 ± 16 (stat.) ± 32 (syst.) μb.

Resolving Structure of Matter

HERA, e (27.5 GeV) p (920 GeV) collider to study the proton structure with a high resolving power. (~ 10^{-3} fm)



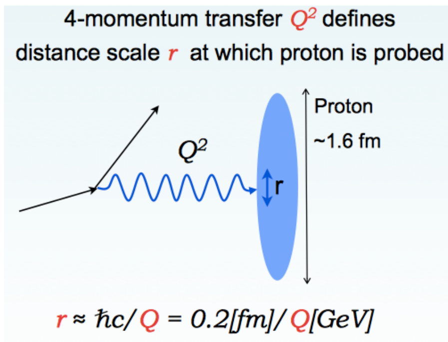


Kinematics:

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

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

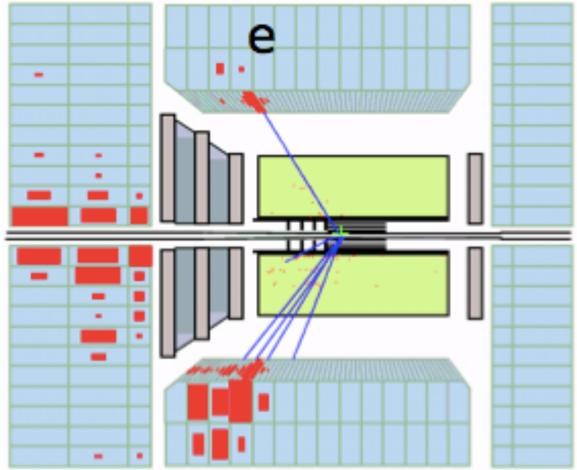
$$y = \frac{p \cdot q}{p \cdot k}$$ Inelasticity



ep Scattering at HERA

DIS cross sections provide an access to parton distribution functions in proton:

Neutral Currents



$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm \mp Y_- x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm\right]$$

$\tilde{F}_2^\pm$: dominant contribution

$x\tilde{F}_3^\pm$: important at high Q^2

$\tilde{F}_L^\pm$: sizable at high y

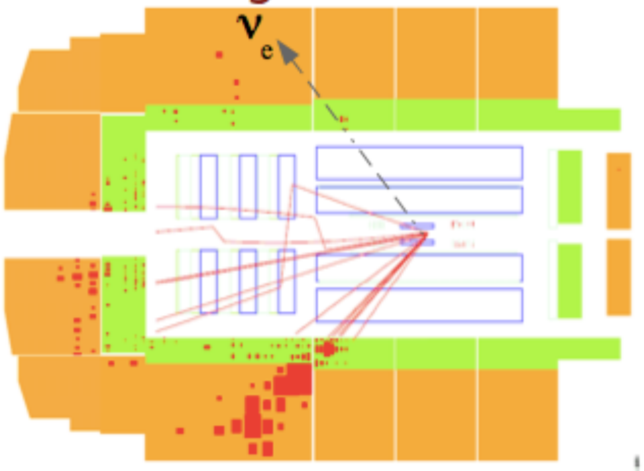
$$Y_\pm = 1 \pm (1-y)^2$$

PDFs

LO: $F_2 \approx x\sum e_q^2(q+\bar{q})$ (in NLO $(\alpha_s g)$ appears)

$xF_3 \approx x\sum 2e_q a_q(q-\bar{q})$

Charged Currents



In LO e^+/e^- charged current cross sections are sensitive to different quark densities:

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

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

Structure of talk

Present new results since last Symposium

- **Data combination**
- **HERAPDF2.0**
- **F_2^{cc} + charm mass, F_2^{bb} + b mass**
- **Energy dependence of D***
- **Inclusive cross section at high x (ZEUS)**
- **F_L**
- **Outlook**

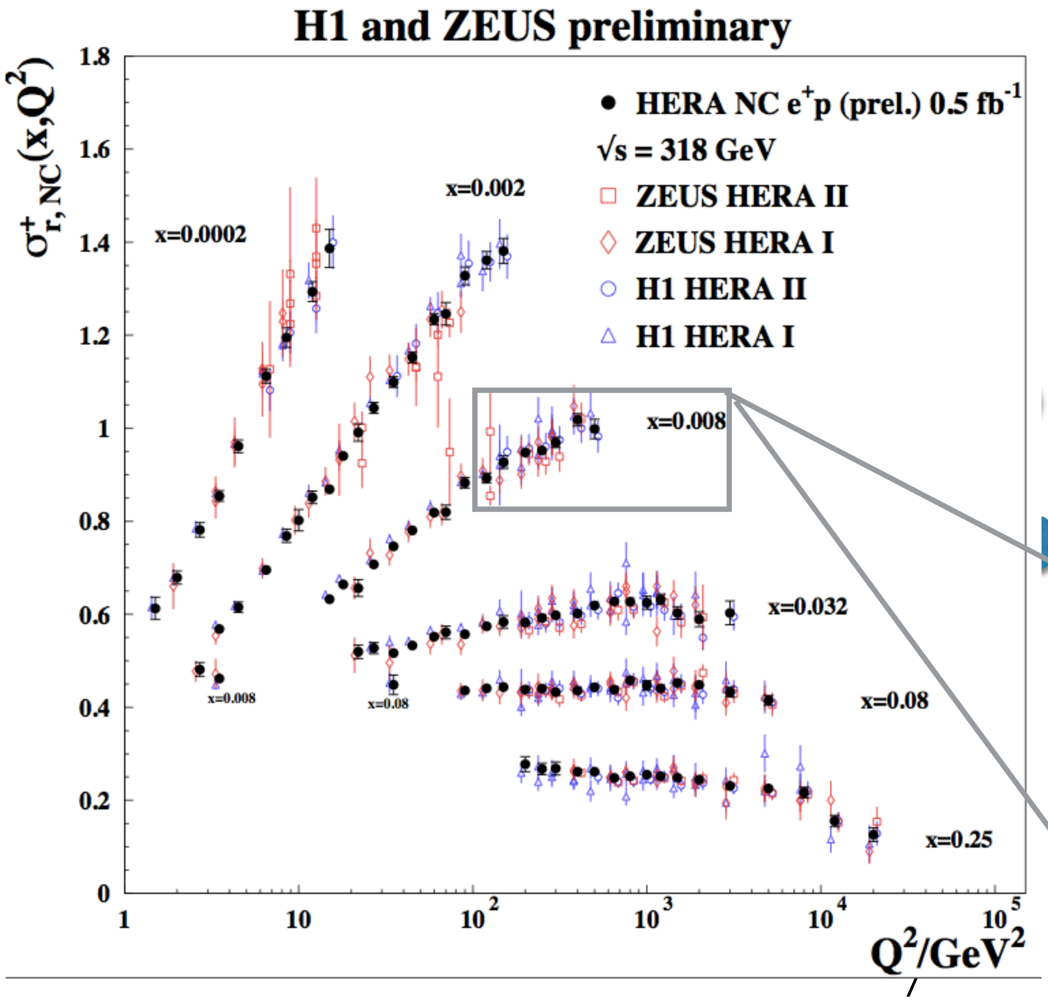
Data Combination

- **Is the "climax" of an experiment; produces text-book results**
- **Should be done right after each collaboration published**
- **Make sure that the knowledgeable people are still available**

Towards final HERA data combination

H1prelim-14-041,042 and ZEUS-prel-14-005,007

- **All individual measurements from H1 and ZEUS are published.**
  - 41 data sets: 2927 data points are combined into 1307 averaged measurements with 165 sources of correlated systematic uncertainties.
  - Consistent data sets: total χ^2/ndf = 1685/1620=1.04.

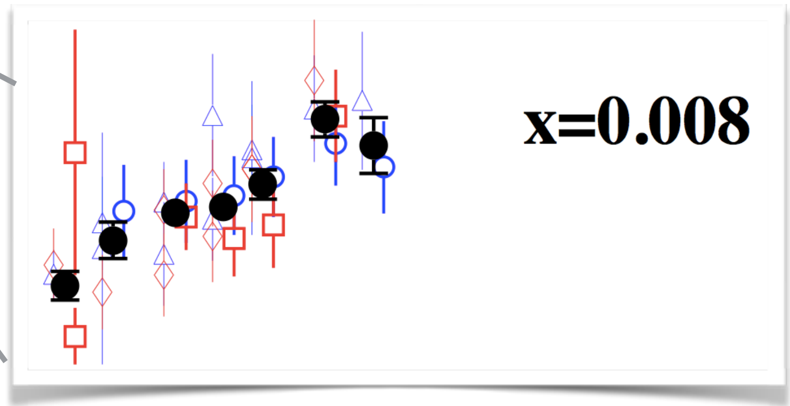


Up to 6-8 data points combined into one.
Significant reduction of the uncertainties.

- **increased statistics**

  < 0.9% stat. unc. for Q^2 up to 400 GeV^2
- **improved systematic**

  total unc. < 1.3% for Q^2 up to 400 GeV^2



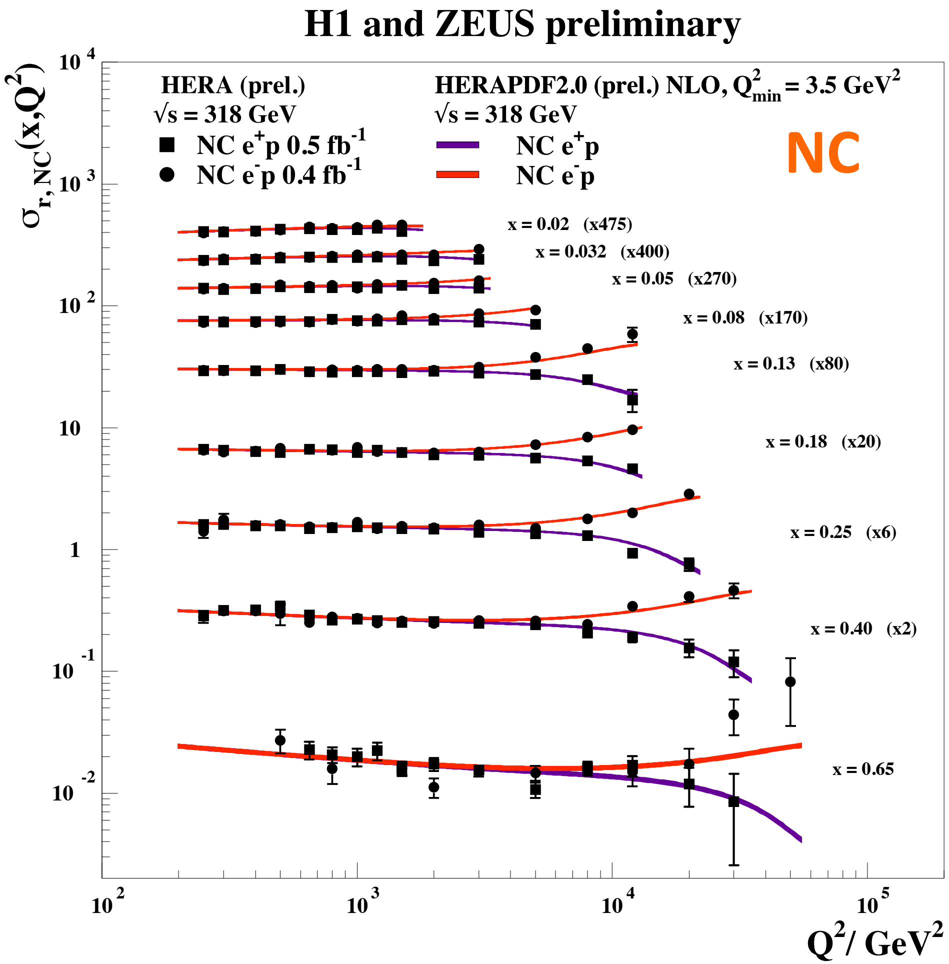
HERAPDF History

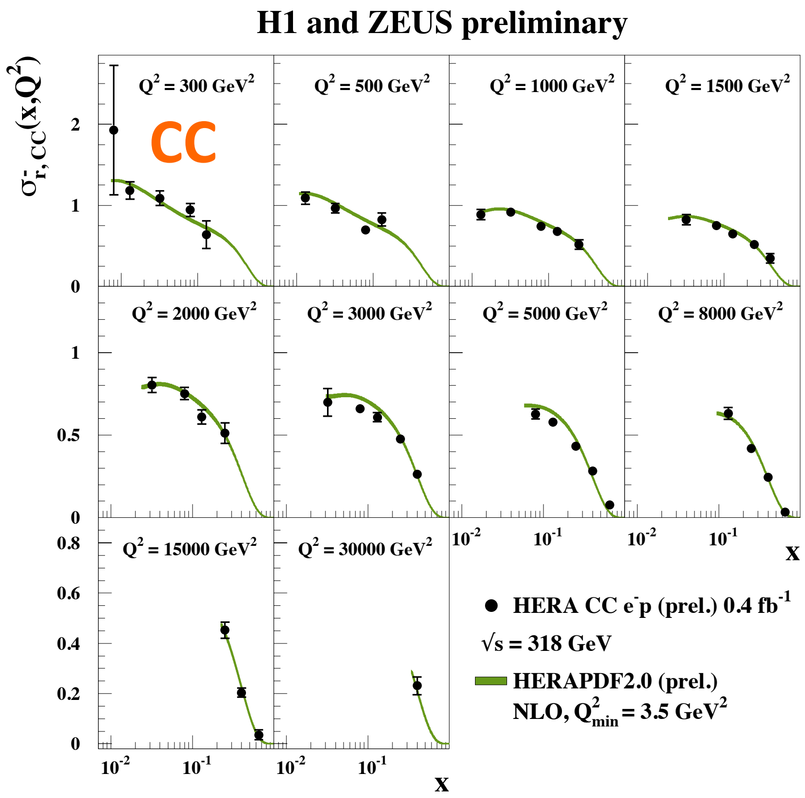
HERAPDFs:
DGLAP analyses based only on the final combination of the HERA incl. cross sections
- no need for heavy target/deuterium correction or strong isospin assumptions

Data	PDF Set
H1+ZEUS NC,CC - HERA I α_S = 0.1176 (fixed in fit)	HERAPDF1.0 (NLO, 10 pars)
H1+ZEUS NC,CC - HERA I +II (part)	HERAPDF1.5 (NLO,NNLO, 10 pars) 1.5f (NNLO, 14 pars)
NC,CC HERA I + II (part) + jets α_S = 0.1202 ±0.0013(exp)±0.004(scales)	HERAPDF1.6 (NLO, 14 pars)
NC,CC HERA I + II (part) + jets + charm + low-energy runs (√s = 251, 225 GeV)	HERAPDF1.7 (NLO, 14 pars)
Complete HERA inclusive data **α_S = 0.118 (fixed in fit) NLO, NNLO**	**HERAPDF2.0 (NLO, NNLO, 15 pars)** ←

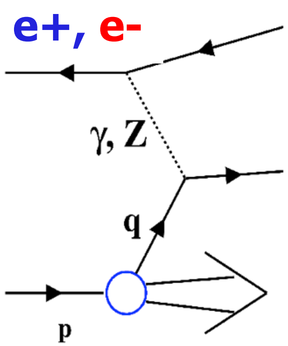
HERAI+II data sets → HERAPDF2.0

$e^{\pm}p$ NC&CC (E_p = 920 GeV), $e^{+}p$ NC (E_p = 820, 575, 460 GeV), corresponding to 1 fb^{-1};
165 correlated syst unc.; 0.045 ≤ Q^2 ≤50000 GeV^2, 6*10^{-7}≤ x ≤ 0.65





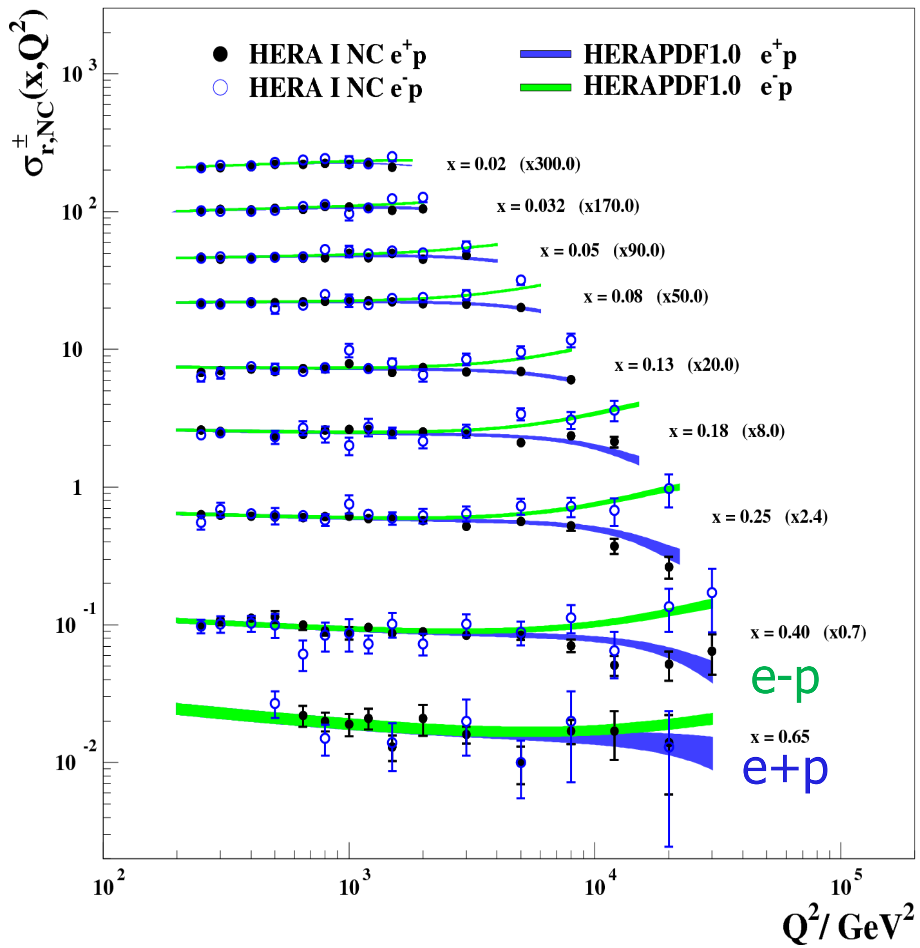
NC HERAI vs All

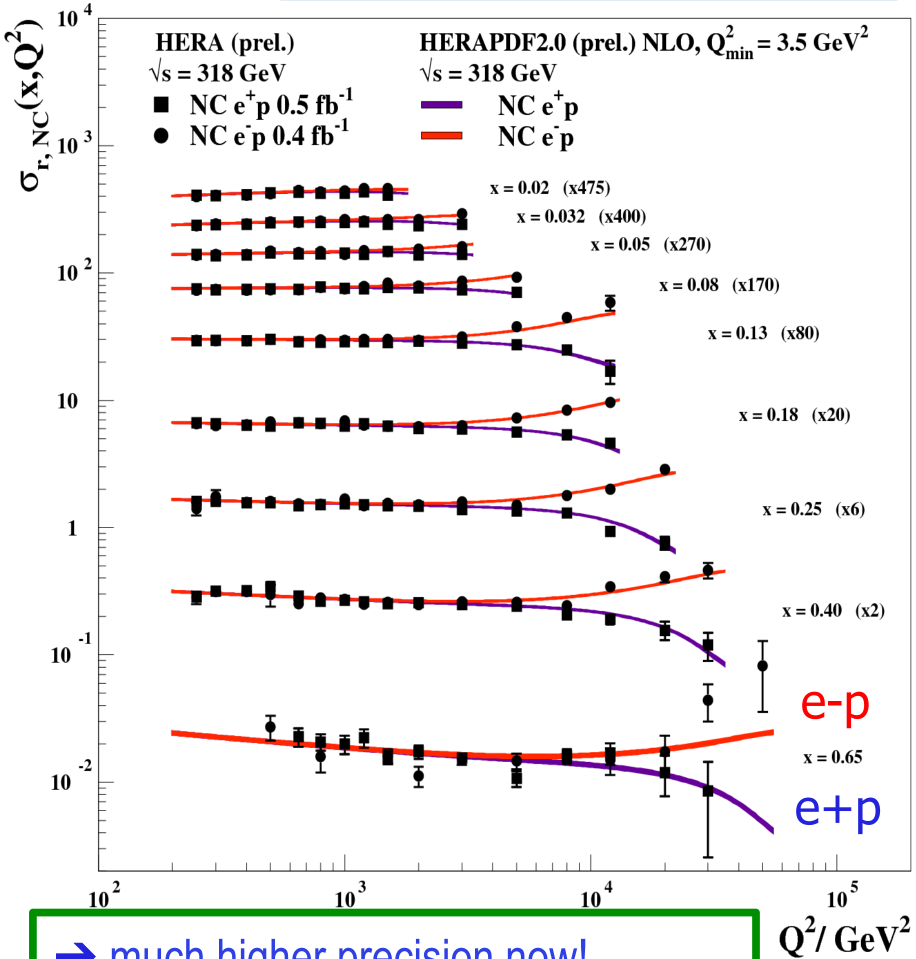


➔ See clear γZ interference effects

HERAPDF1.0 = HERA I

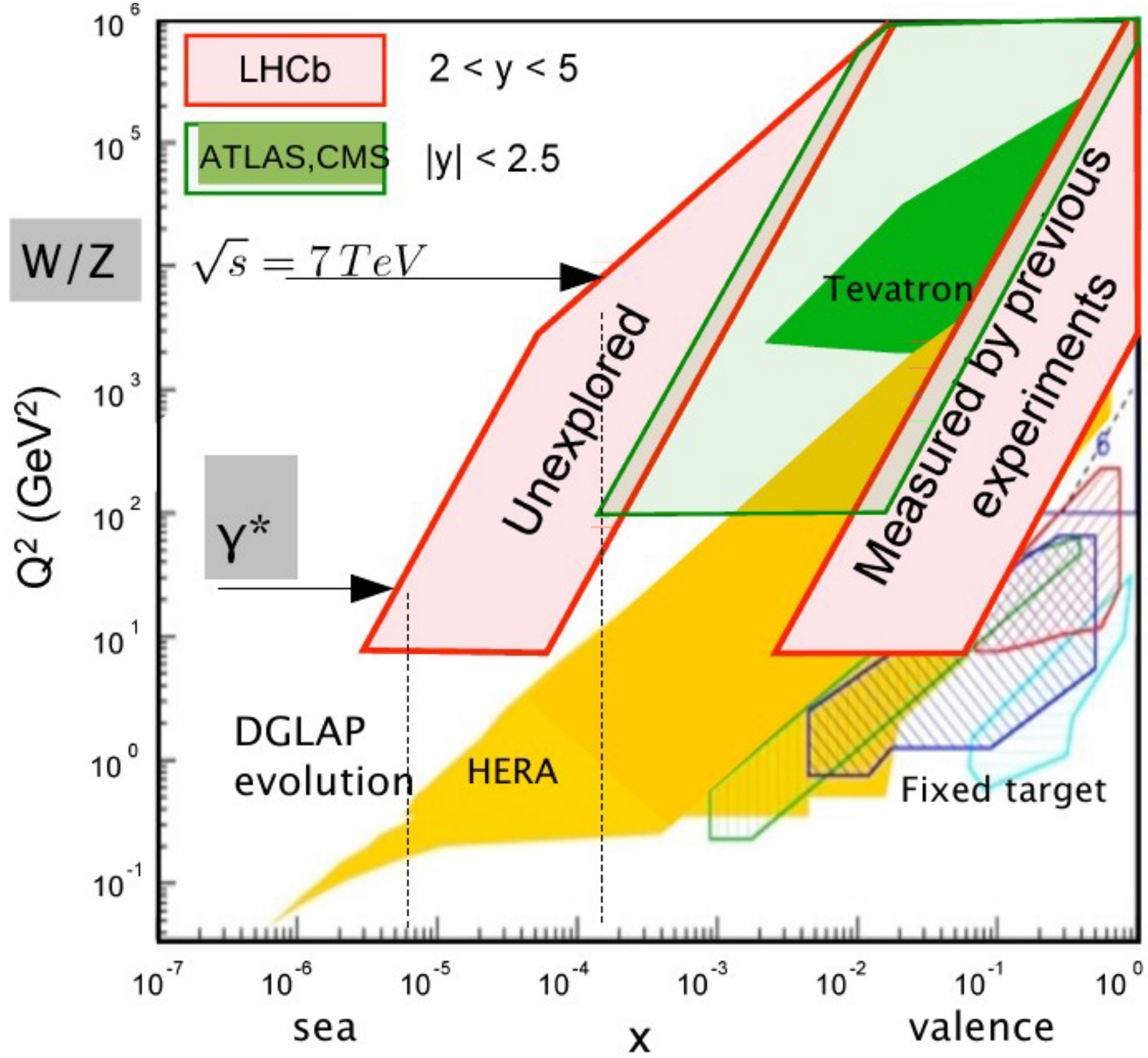
HERAPDF2.0 = ALL



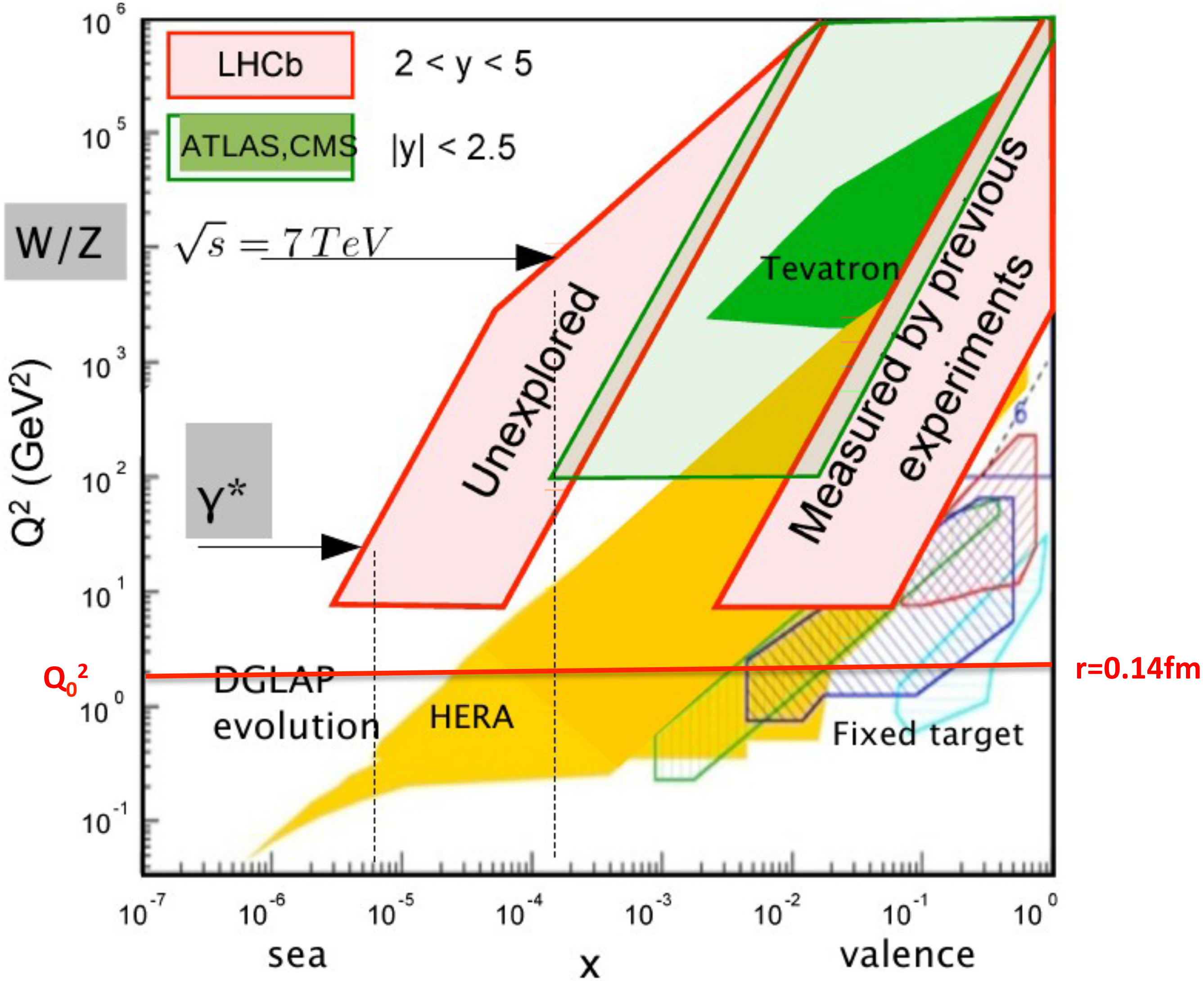


➔ much higher precision now!

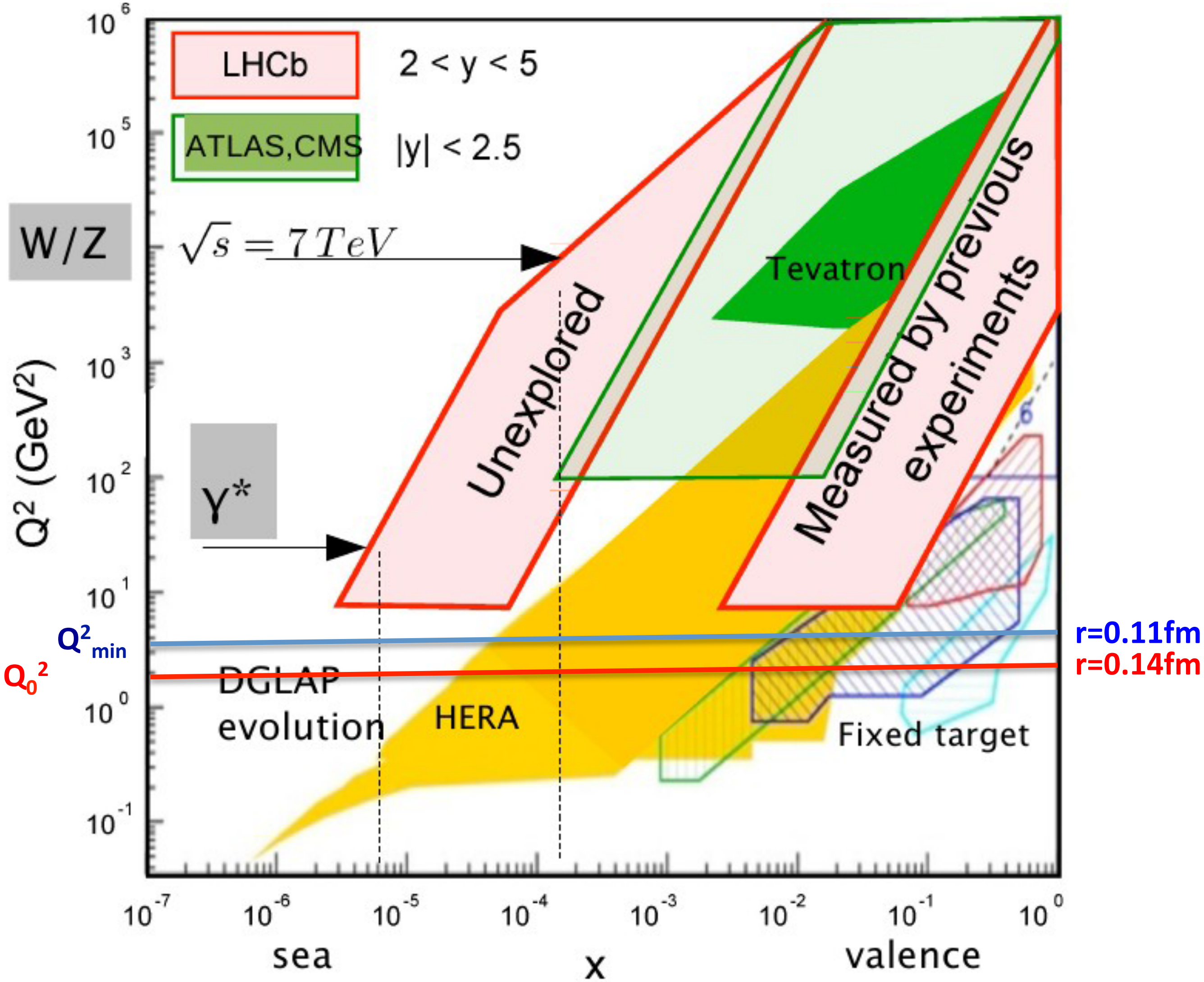
Phase space of measurements (partons) in x and Q^2



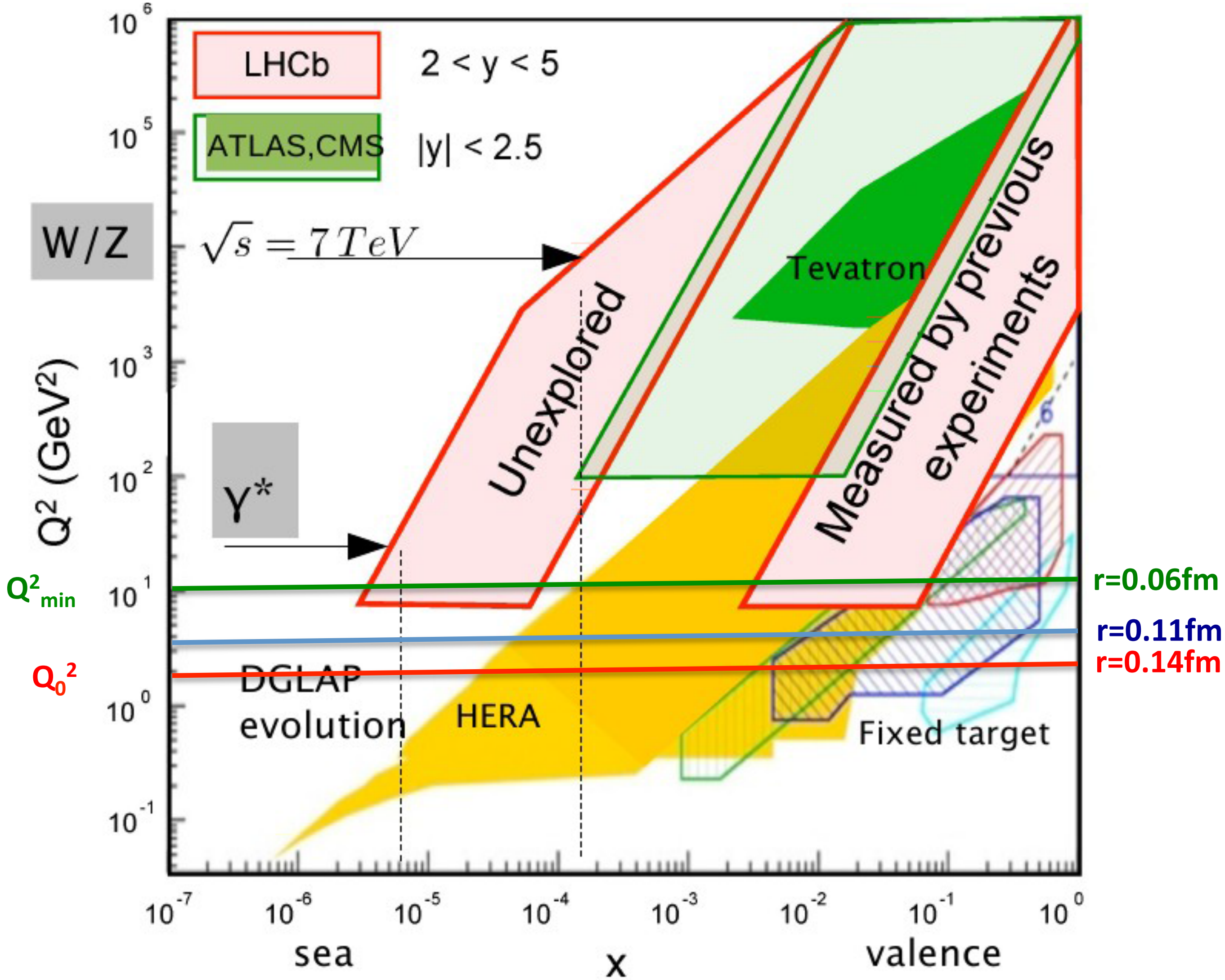
Phase space of measurements (partons) in x and Q^2



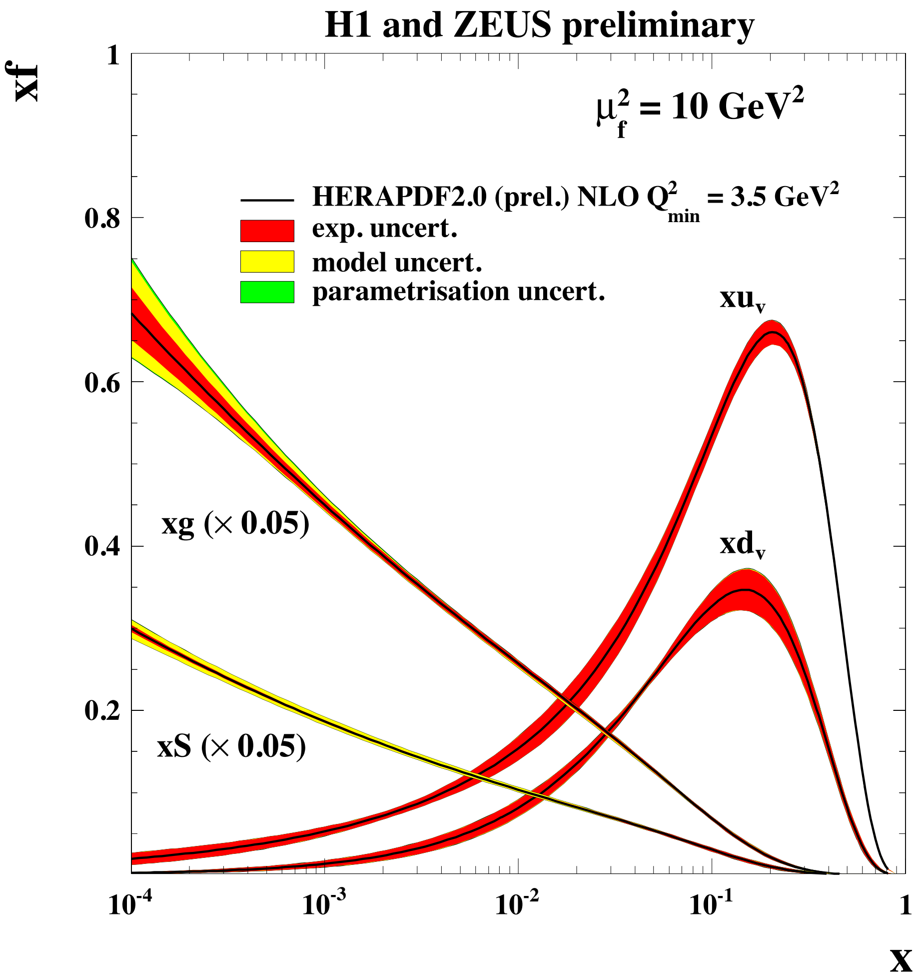
Phase space of measurements (partons) in x and Q^2



Phase space of measurements (partons) in x and Q^2



HERAPDF2.0: Uncertainties



Experimental uncertainty:

Consistent data set → use $\Delta\chi^2 = 1$

Model Uncertainty:

Variation of the input parameter values

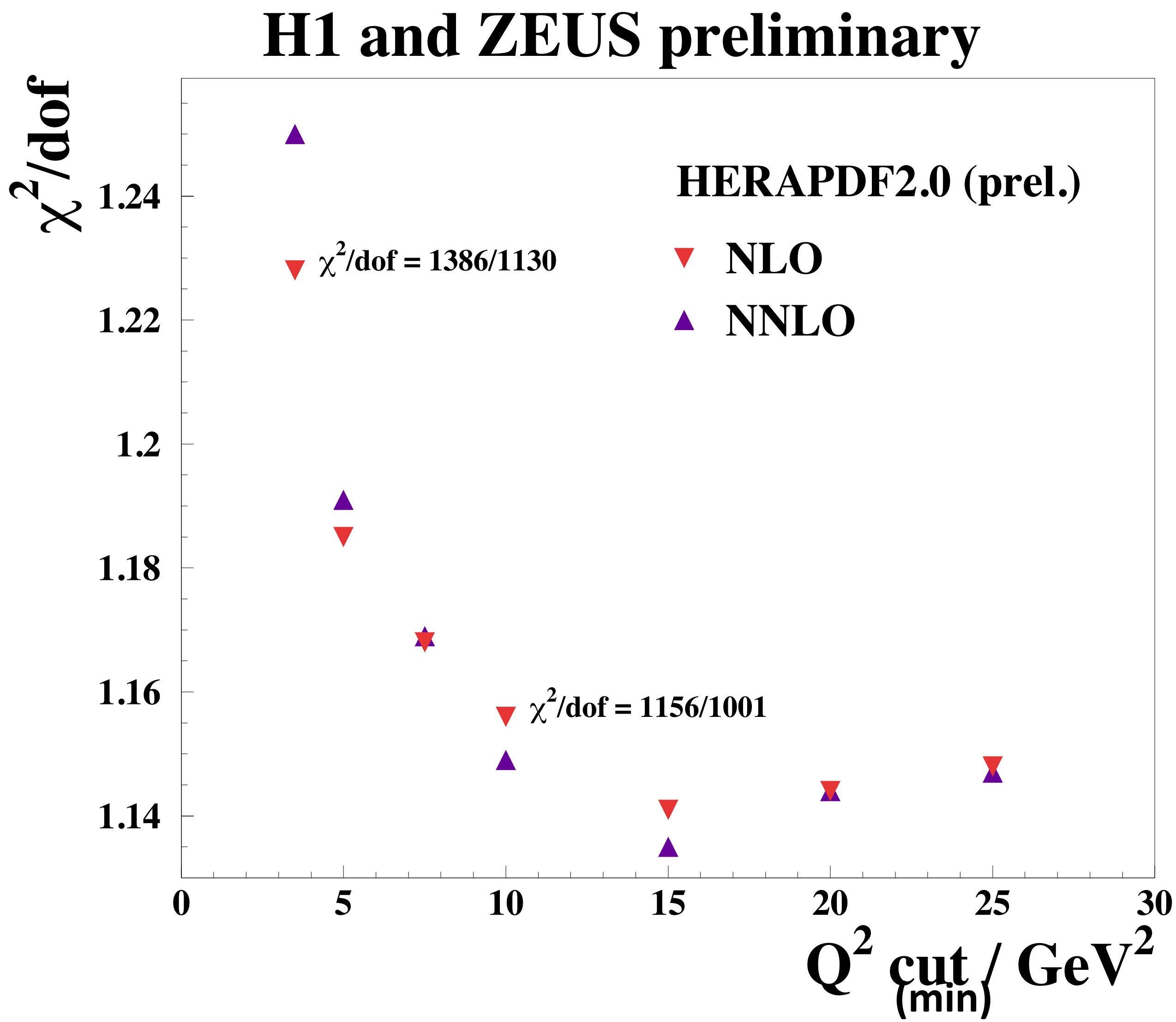
Parametrization uncertainty:

1. Envelope from DGLAP fits using variants of the parametrization form at Q_0^2

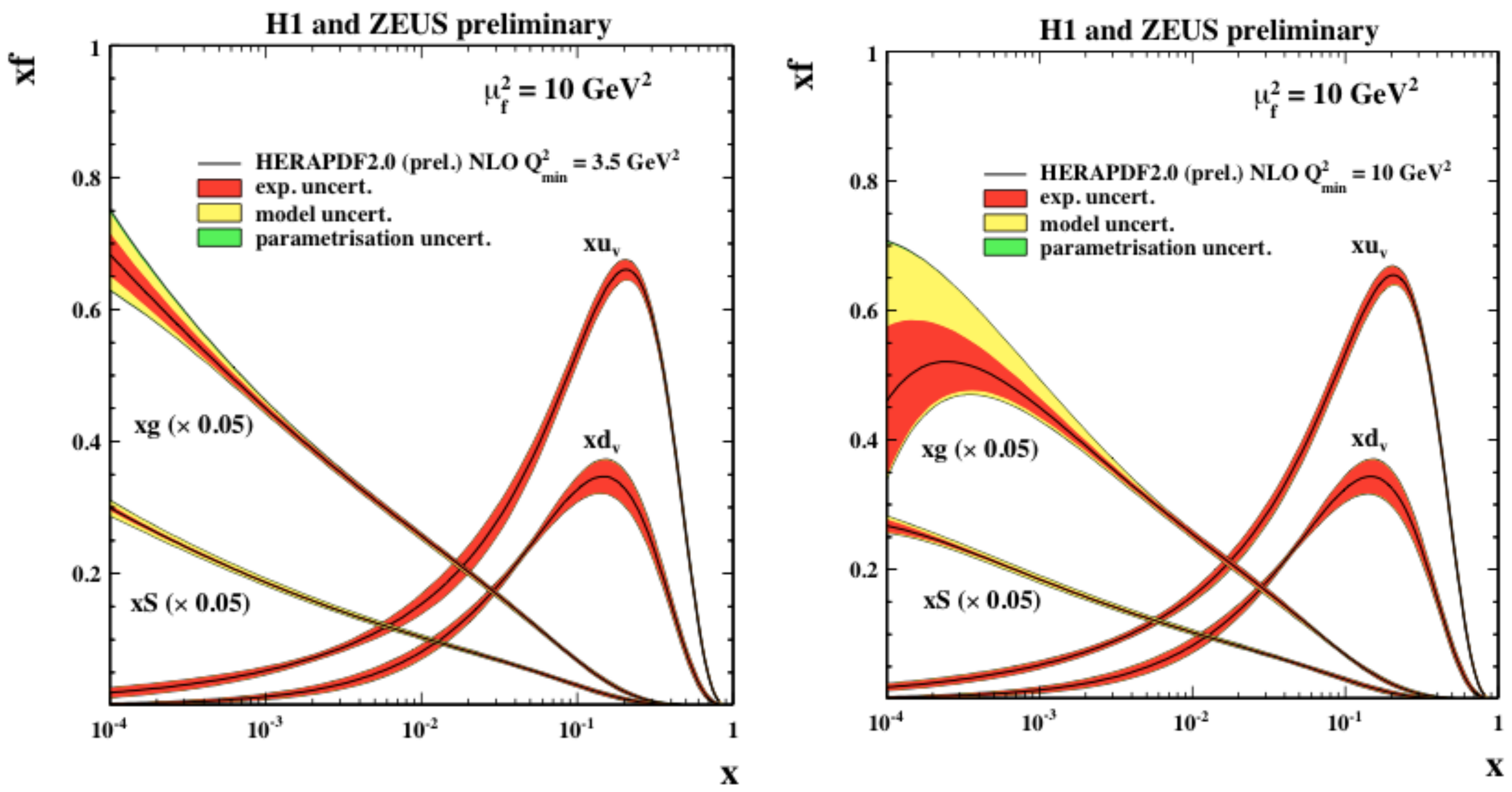
$$xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2)$$

2. Variation of the starting scale Q_0^2

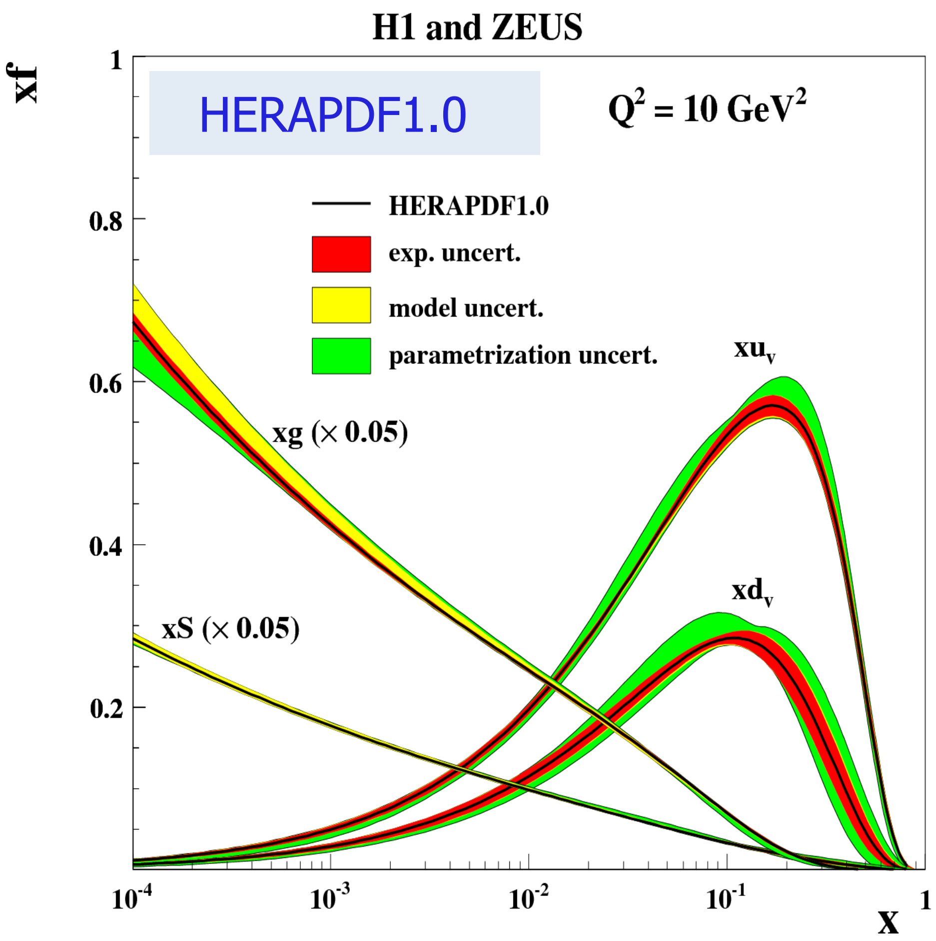
First signs that DGLAP cannot be abused

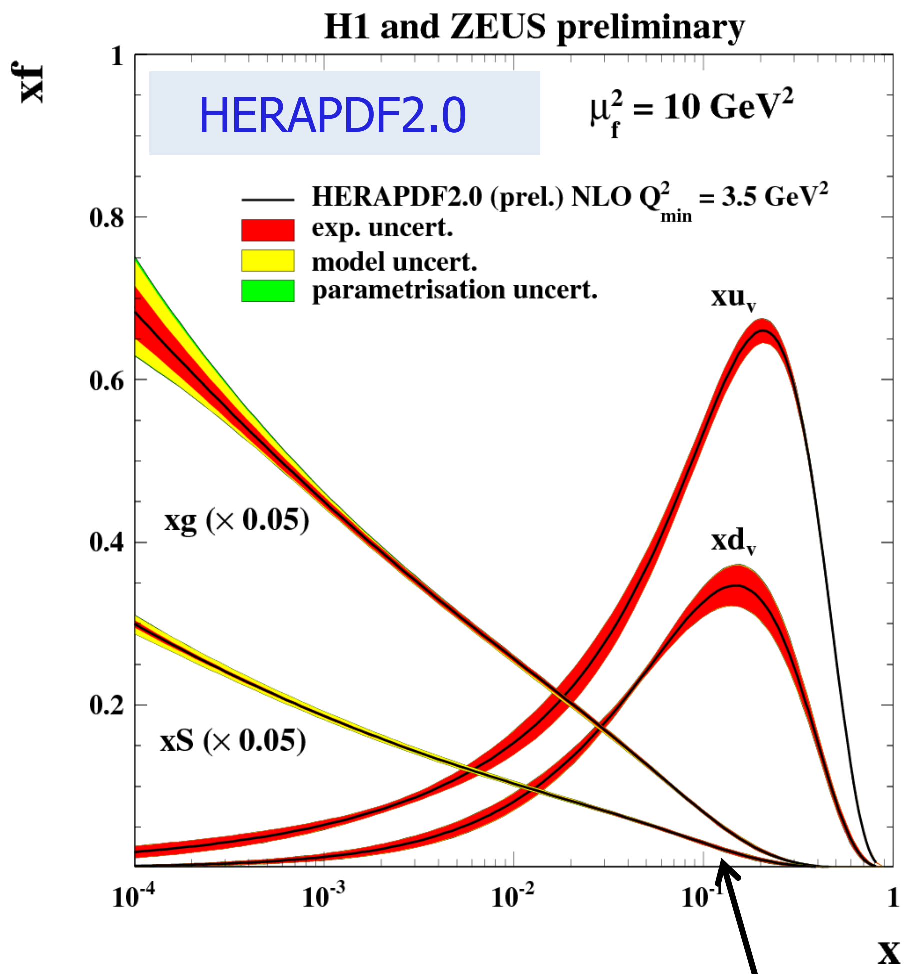


Price to pay for constraining partons only above 10 GeV^2



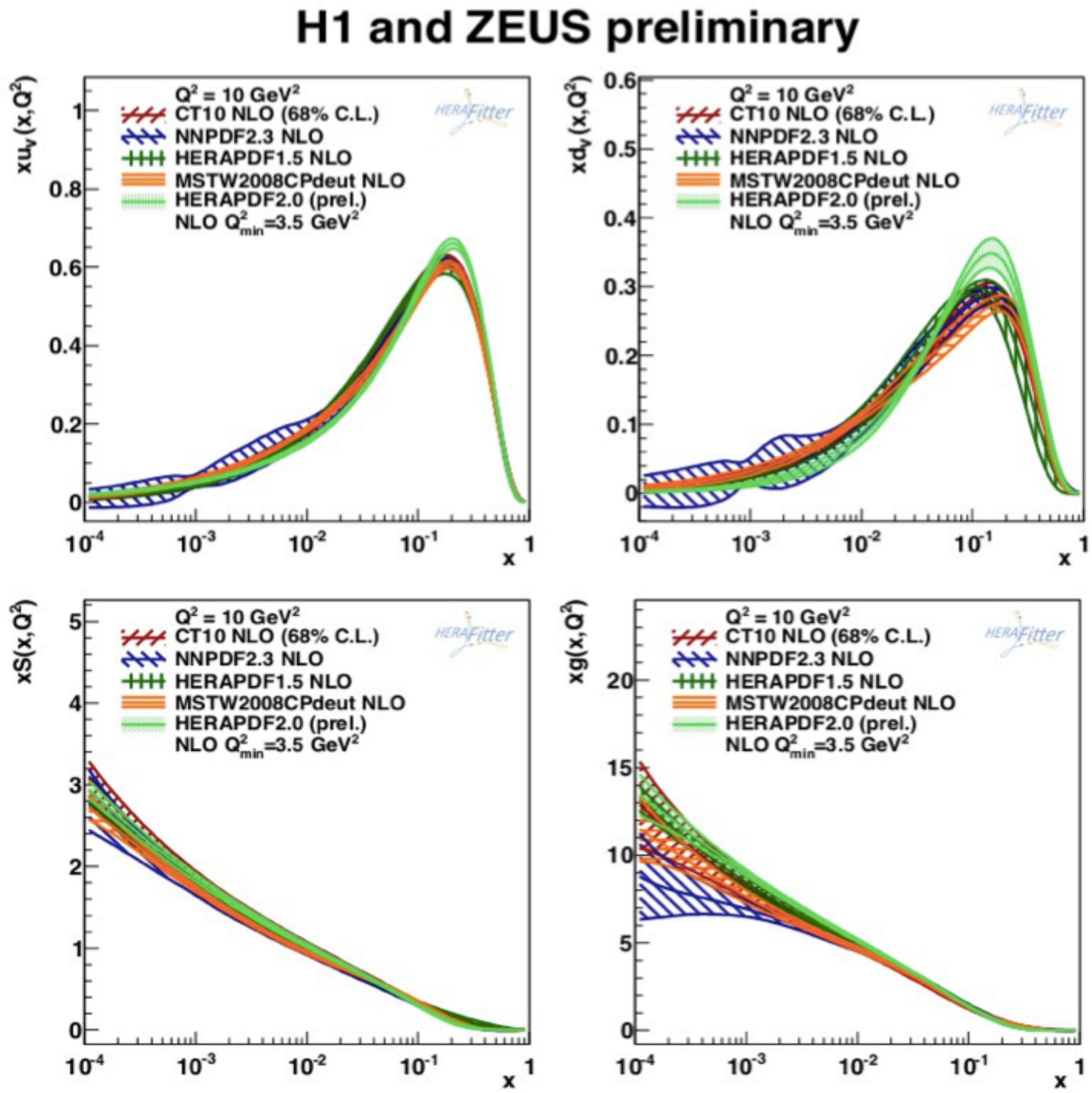
HERAPDF1.0 and 2.0 with Q^2_{min}=3.5 GeV^2





➔ HERAPDF2.0: softer sea & overall reduced uncertainties

Comparison to other popular PDFs

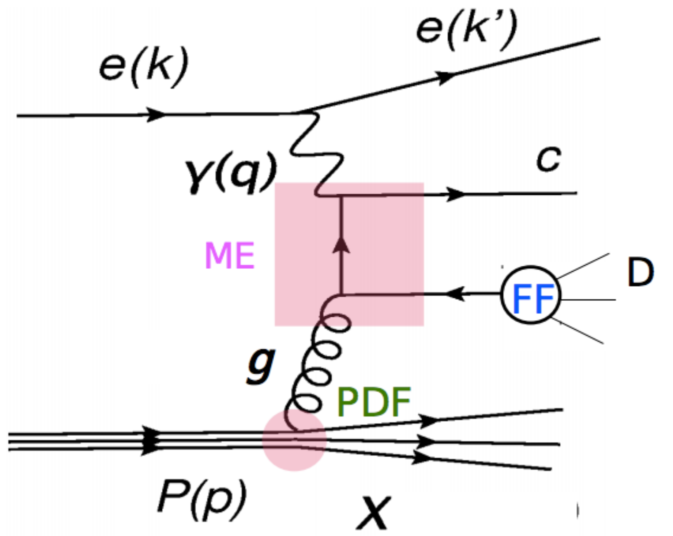


Heavy Flavour Production at HERA

- Heavy Flavour (HF) production: multi-hard scales pose a challenge for pQCD
  - m_c, m_b, p_T, Q^2 —> several calculations (schemes) exist
    - Zero-Mass Variable Flavour Number Scheme (ZMVFNS) — massless scheme
    - Fixed Flavour Number Scheme (FFNS) — massive scheme
    - General-Mass Variable Flavour Number Scheme (GM-VFNS) — matched scheme

- Main process of heavy quark production at HERA is Boson Gluon Fusion

- Measurements of heavy quarks:
  - are sensitive to the gluon PDF
  - are sensitive to the masses of the heavy quarks
  - are sensitive to the fragmentation process of heavy flavour hardons

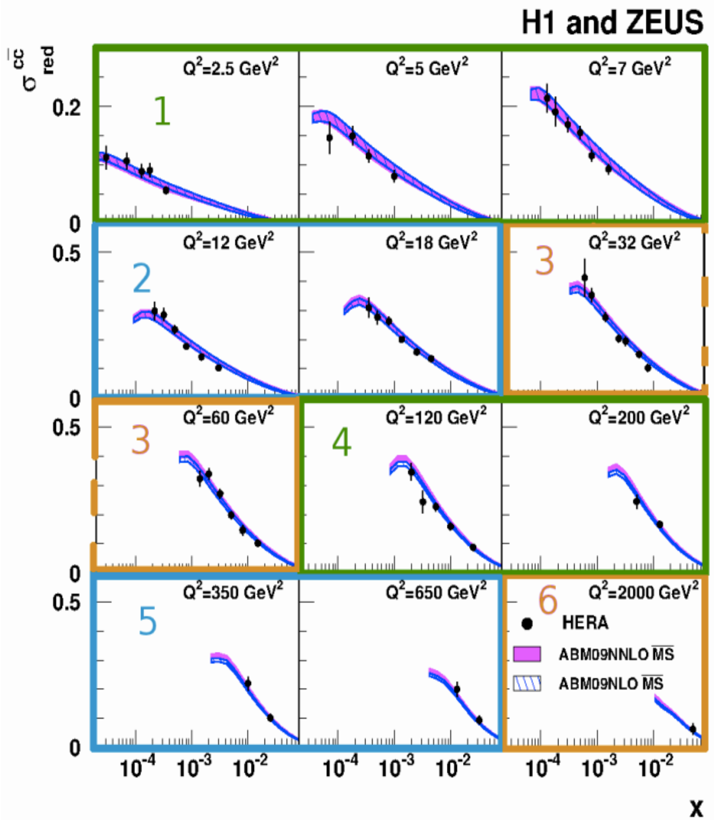


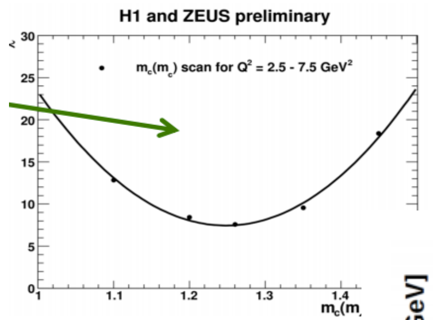
Charm Mass Running

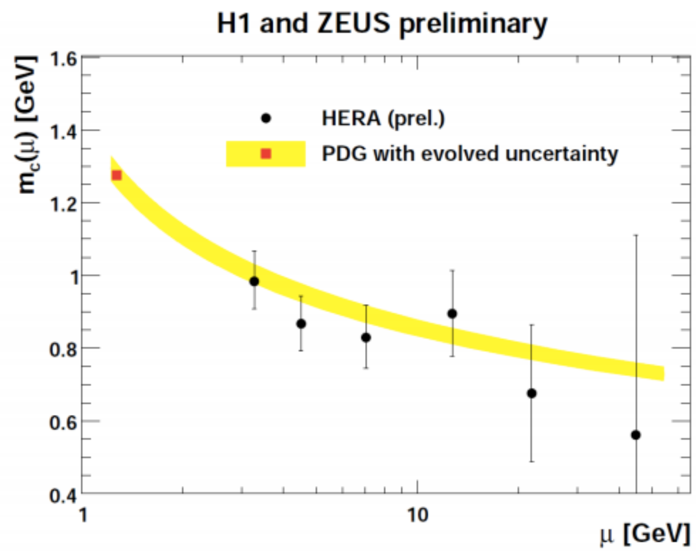
H1-prelim-14-071 ZEUS-prel-14-006 and S. Moch

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]**

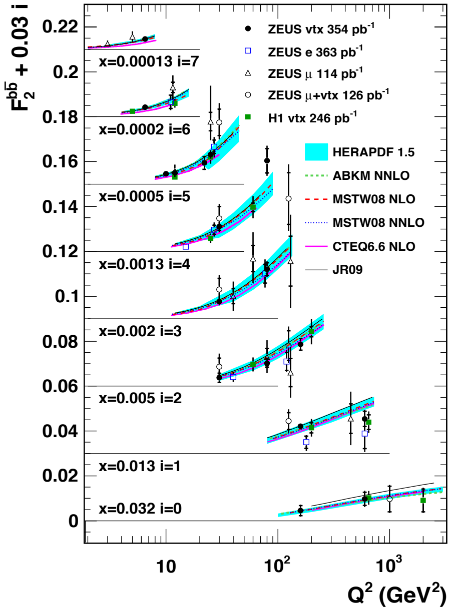


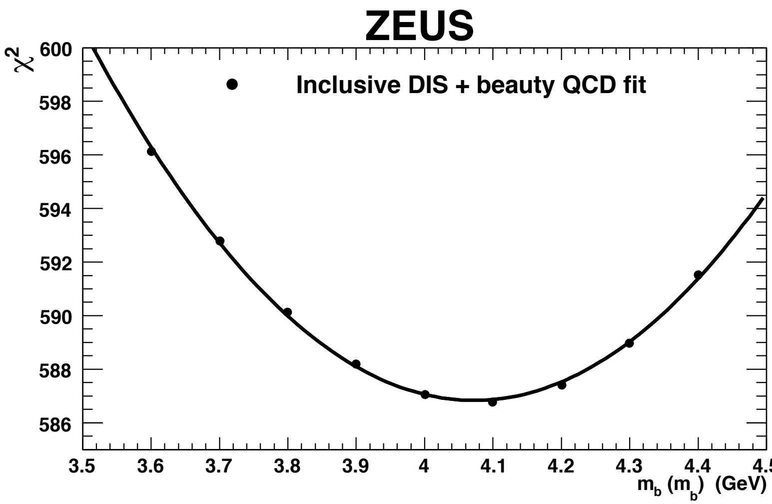




Extraction of MS beauty mass

JHEP09(2014)127

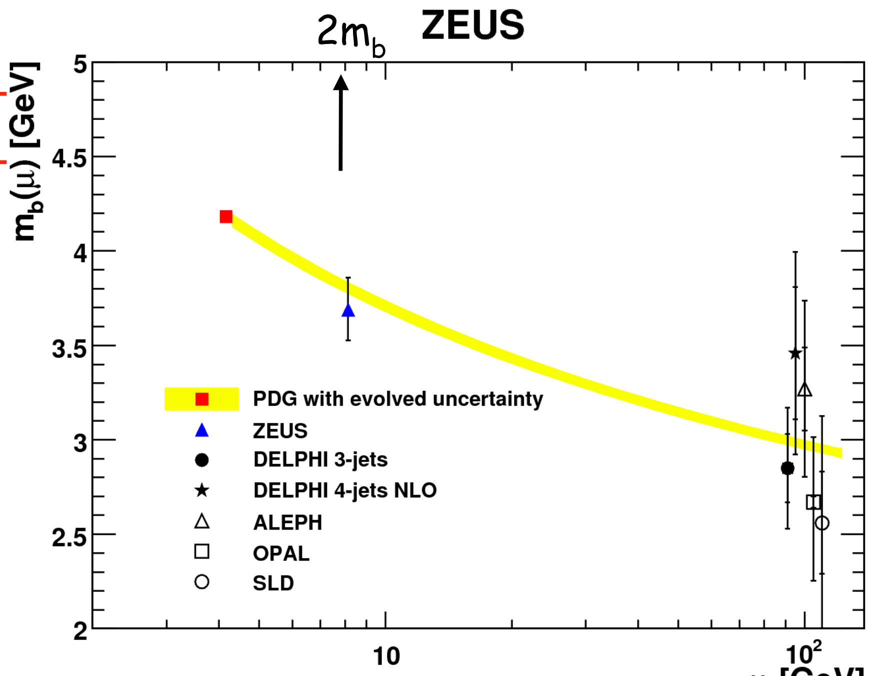




$$m_b(m_b) = 4.07 \pm 0.14\,(\text{fit})^{+0.01}_{-0.07}\,(\text{mod.})^{+0.05}_{-0.00}\,(\text{param.})^{+0.08}_{-0.05}\,(\text{theo.})\ \text{GeV}$$

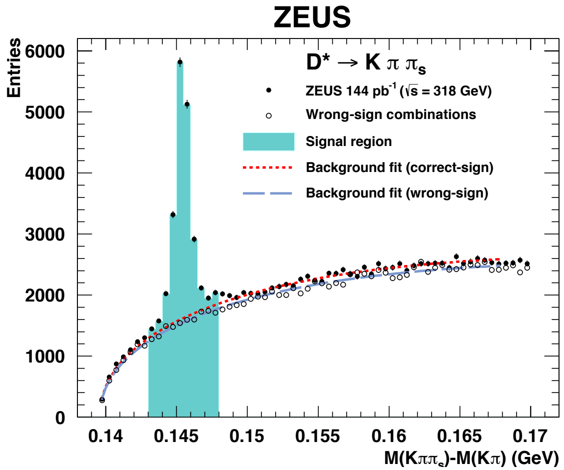
PDG 2012 : $m_c(m_c)$ = 4.18 ± 0.03 GeV

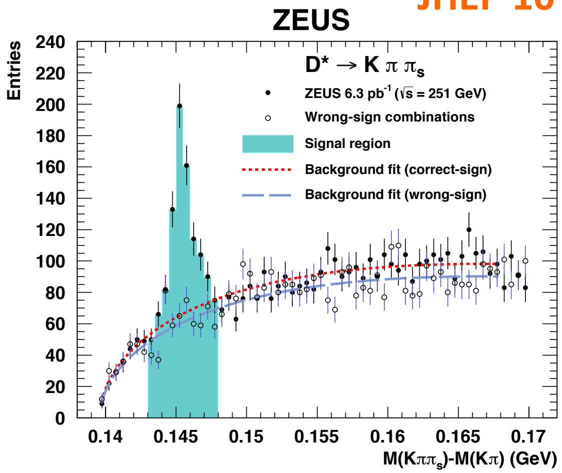
- The largest sensitivity to m_b at low Q^2.
- The extracted MS beauty-quark mass is in agreement with PDG average and LEP results.
- Important QCD consistency check.

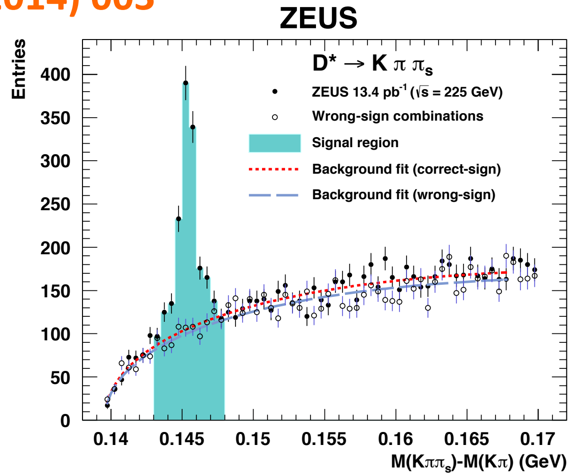


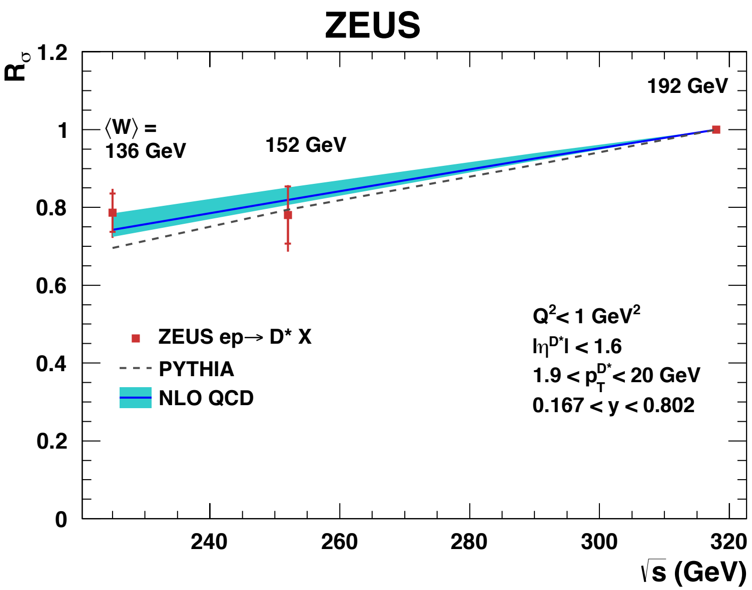
Energy dependence of D*

JHEP 10 (2014) 003







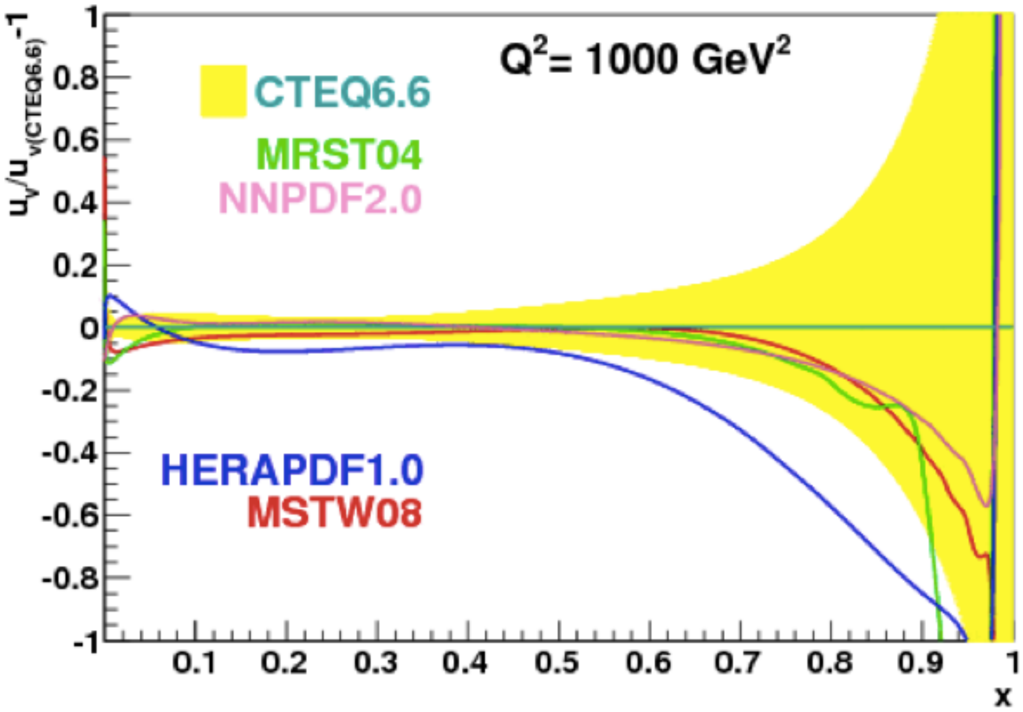


- Variation of cross section with √s sensitive to gluon PDF
- NLO QCD (Frixione, using proton and photon PDFs from DIS (ZEUS-S 3-flavor FFNS, GRV-HO), α_S = 0.118, ε (Peterson) = 0.079) describe energy dependence

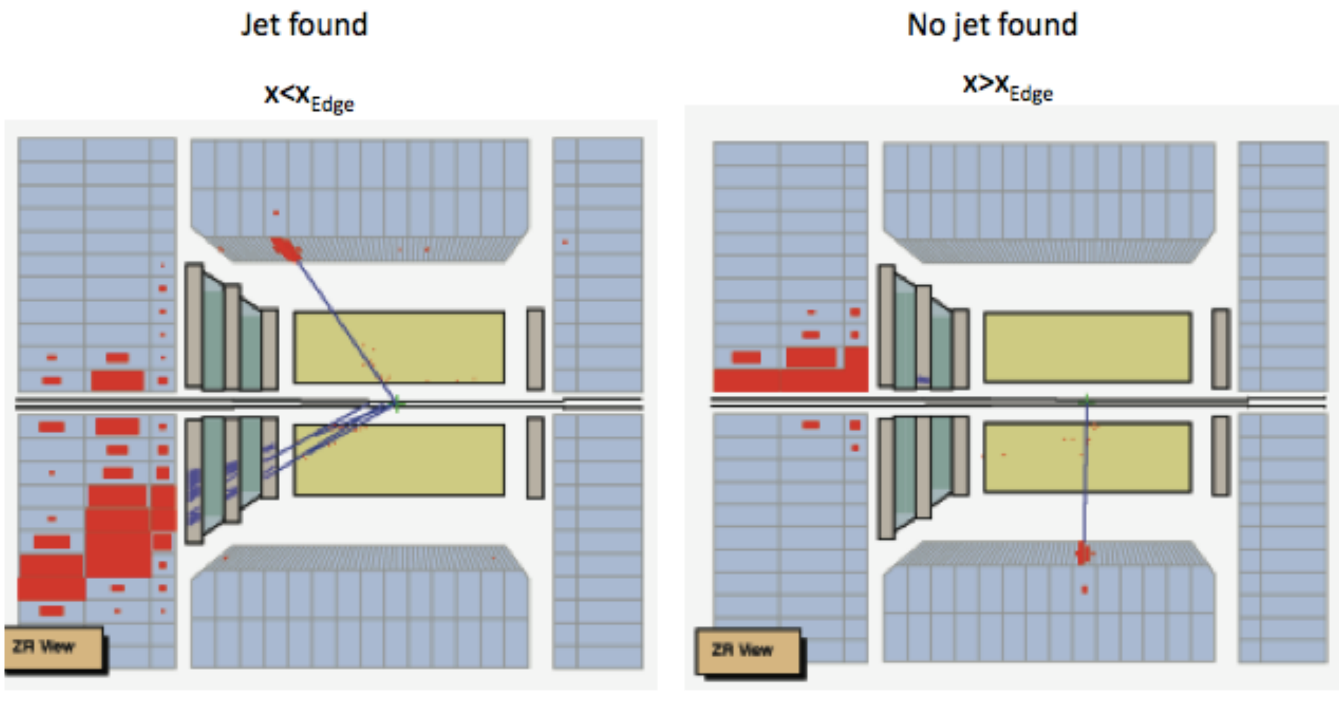
High x - Motivation

See Allen's talk tomorrow

The PDF's are poorly determined at high-x. Sizeable differences despite the fact that all fitters use the same parametrization $xq \propto (1-x)^{\eta}$. Is it possible to check this ?



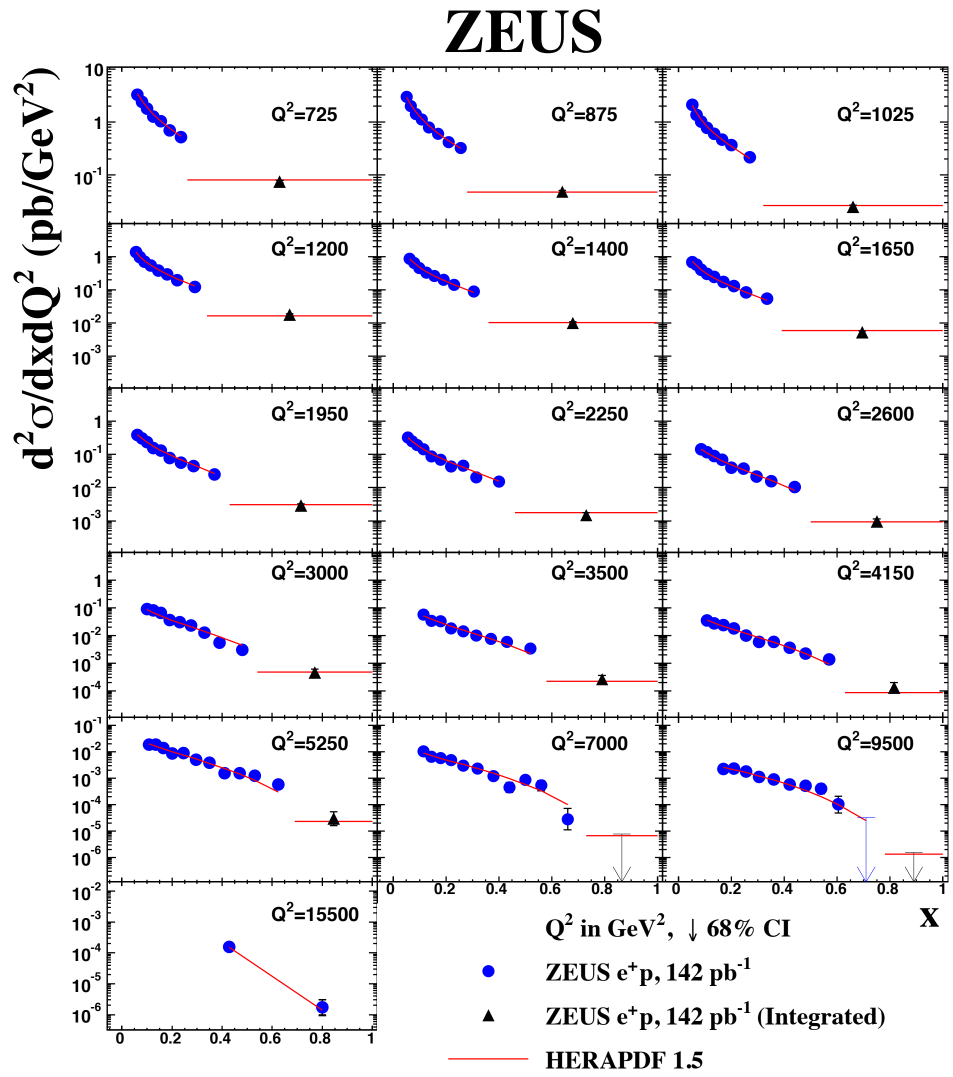
1-jet, 0-jet

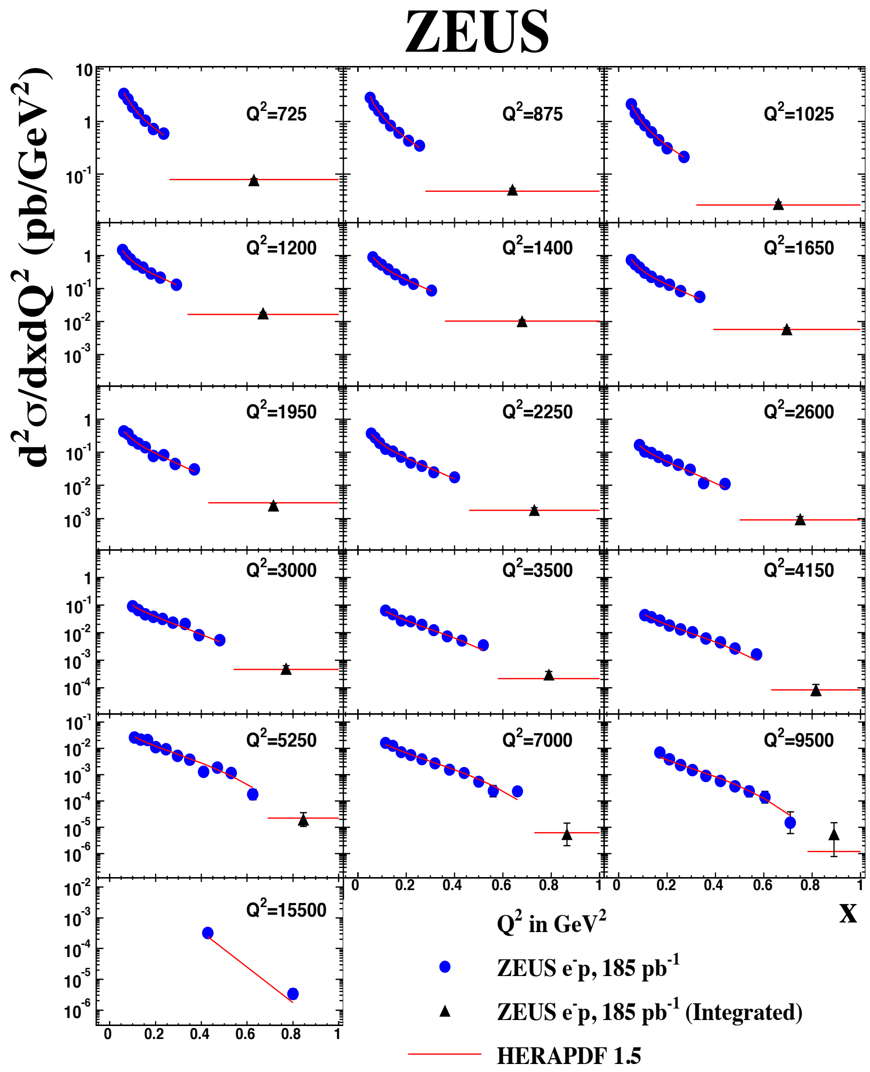


- At high Q^2, scattered electron seen ≈ 100% acceptance
- For not too high x, Q^2 from electron, x from jet
- For $x>x_{edge}$, Q^2 from electron, integrated cross section from x_{edge} to 1

NC cross section $e^{\pm}p$

DESY-13-245, Phys. Rev. D 89 (2014) 072007



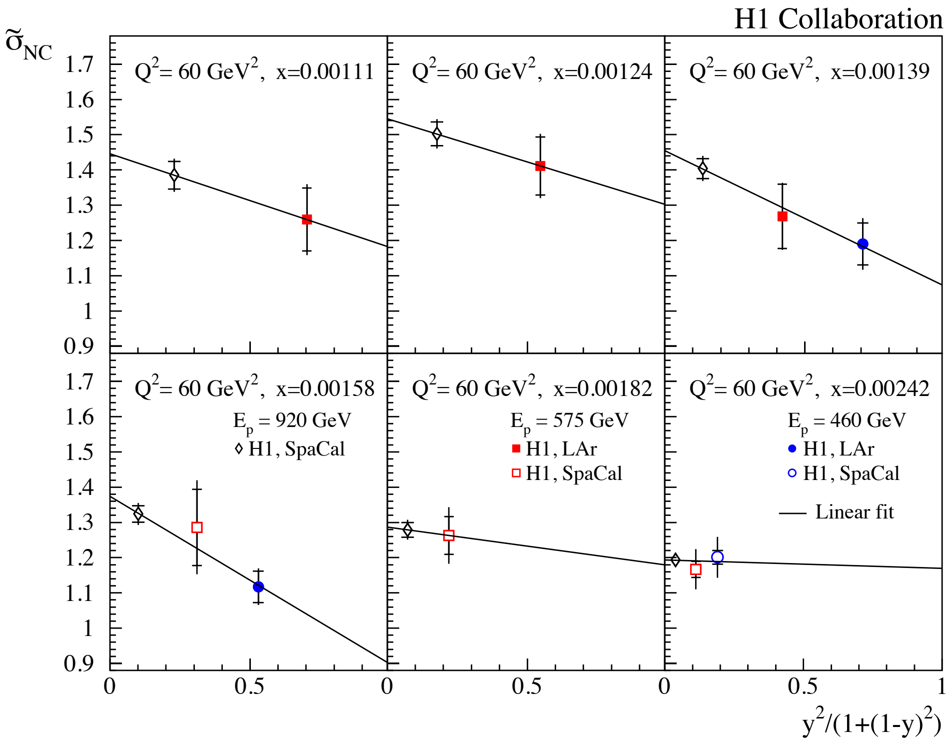


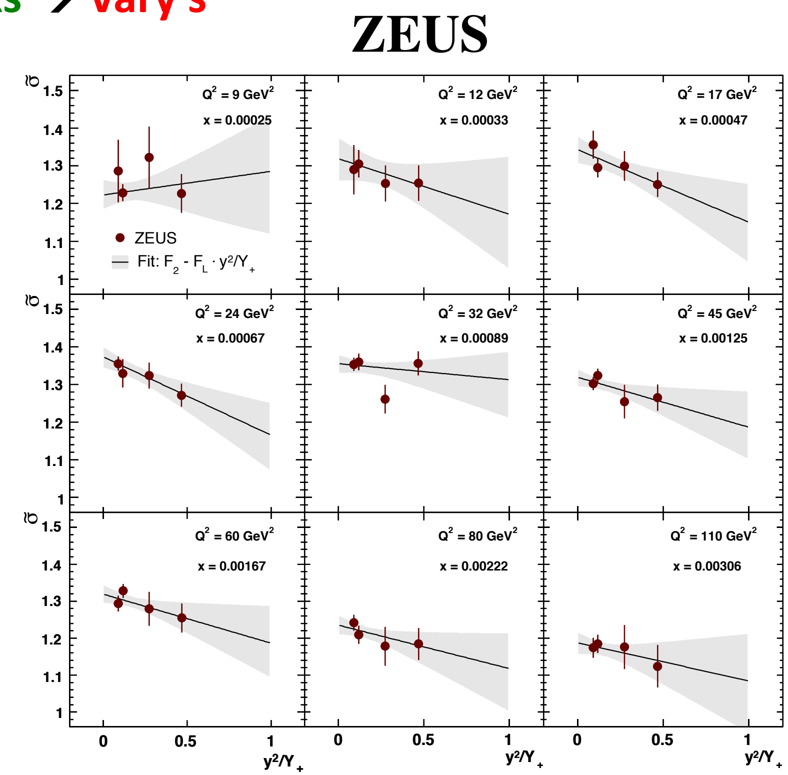
F_L, linear fits

Measure reduced cross sections

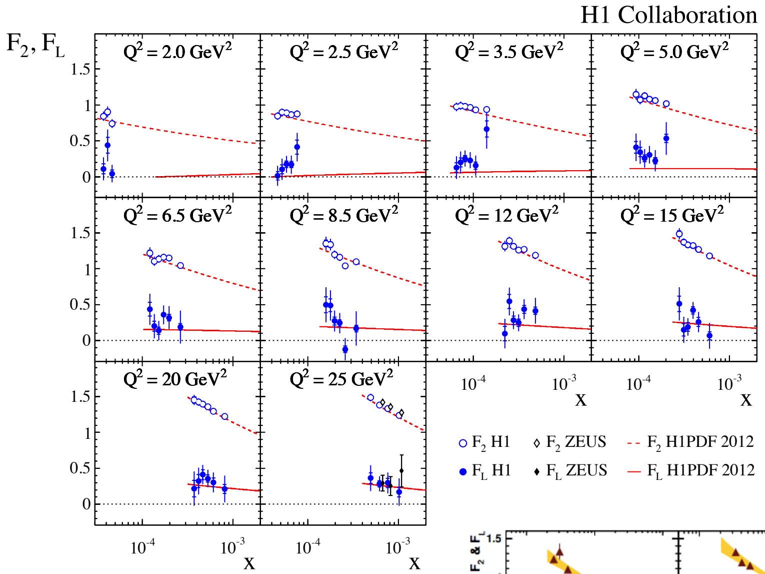
$\sigma_r = F_2(x,Q^2) - (y^2/Y_+)F_L(x,Q^2)$

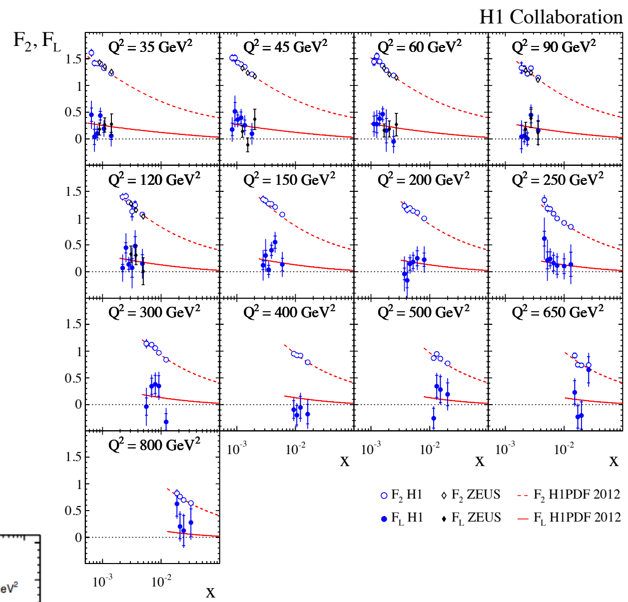
at same x, Q^2 but different $y=Q^2/xs$ → vary s

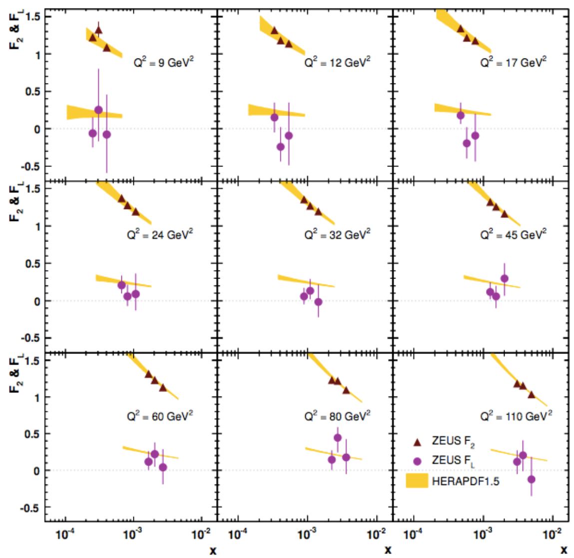




F_2 and F_L theory independent extraction







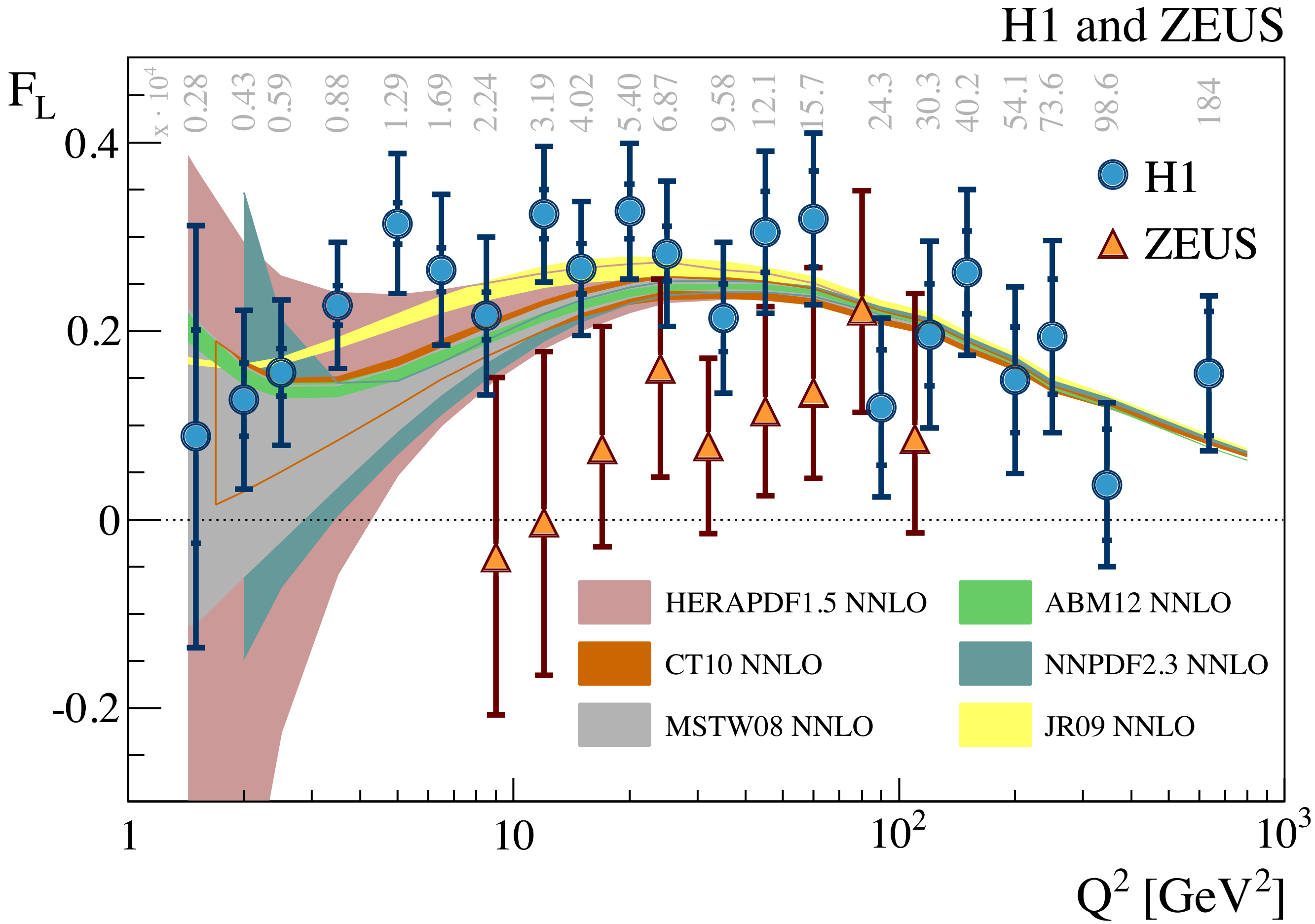
H1 – ZEUS, FL

H1: DESY 13-211
Eur. Phys. J. C 74 (2014) 2814
ZEUS: DESY-14-053
Phys. Rev D 90 (2014) 072007

Final measurements of F_L published by HERA.

H1 covers large kinematic range in Q^2, (1.5 – 800 GeV^2); good tracking & EM calorimetry in the rear direction, go to smaller electron energies.

At low Q^2, very large uncertainties in the theoretical predictions.



Outlook of Combinations

Papers in editorial process and to publish soonish

- **Combined inclusive HERA I+II data and HERAPDF2.0**
- **Combined D* cross sections**

These are results we are planning ('wish list', 'dreams'.....)

- **Running mass(charm)**
- **Polarised data and electroweak fits**
- **Contact interaction fits**
- **New combined F_2^{cc} and combined F_2^{bb}**
- **Combined jets and α_S from jets**

BACKUPS

Global QCD fits

Input parameters of the fit (Q^2_0=1.9 GeV^2)

$$xg,\ xu_v,\ xd_v,\ x\bar{U} = x\bar{u},\ x\bar{D} = x\bar{d} + x\bar{s}$$
$$xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2)$$

In addition

- M_c^{opt} – mass of the charm quark (best χ^2 to F_2^c)
- M_b - mass of the bottom quark
- f_s – suppression of strange quarks (neutrino and ATLAS)
- **Q^2_{min} – for determination of χ^2 (3.5 GeV^2, 10 GeV^2)**
- $\alpha_s(M_Z^2)$ = 0.118
- Momentum sum rule
- Flavour conservation

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.6	2.2