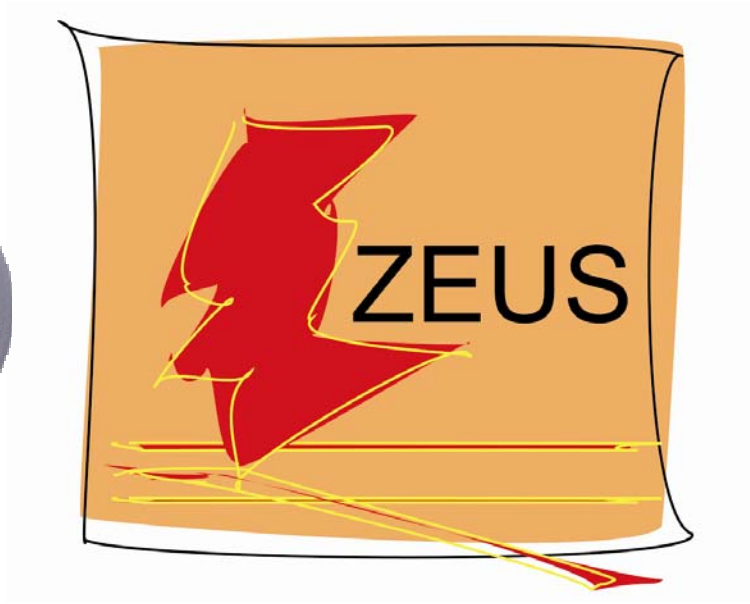
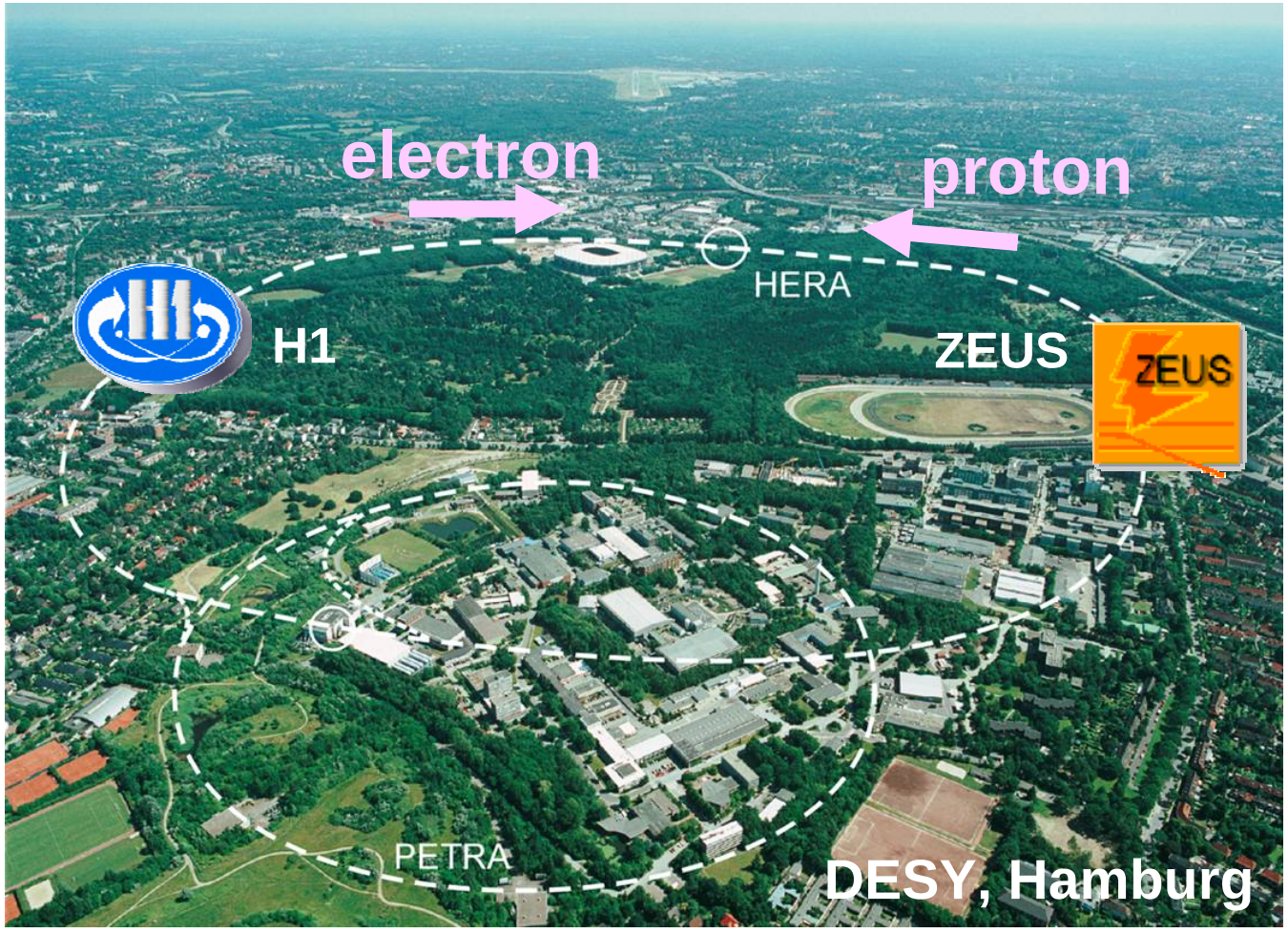
Results on the proton structure from HERA

Shima Shimizu (CERN)



7/Jan/2011 @ KEK

The world only e-p collider: HERA



A unique collider at
DESY, Hamburg

Circumference:
6.3 km

Operated
since 1992 to 2007

2 collider experiments:
H1 & ZEUS

Beam energy

- proton : (460, 575, 820,) 920 GeV
- electron/positron: 27.5 GeV

→ center of mass energy

$\sqrt{s} = (225 \sim) 318\text{GeV}$

History of HERA

- 1992-2000: HERA-I

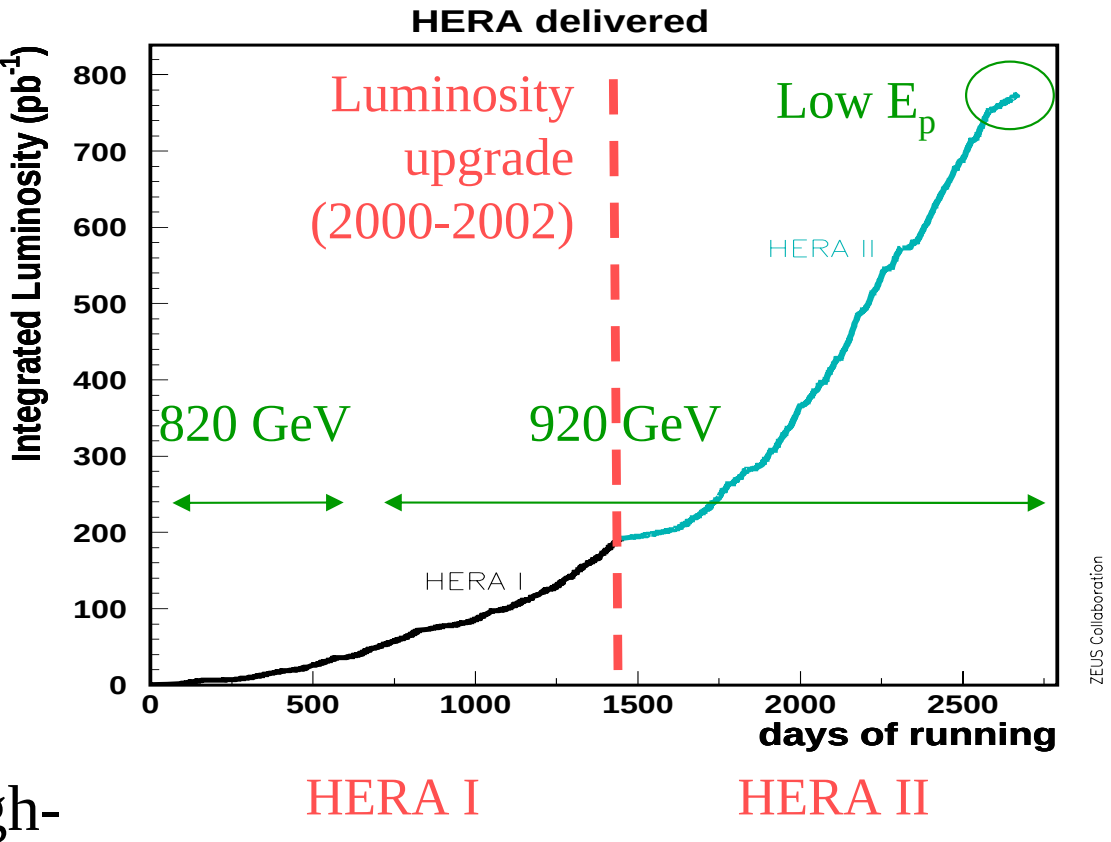
  (started with E_p=820GeV, until 1997)

  → Make full use of large kinematic region.

  $1.5GeV^2<Q^2<30000GeV^2$

- 2002-2007: HERA-II
  - High luminosity to collect high-Q^2 data.

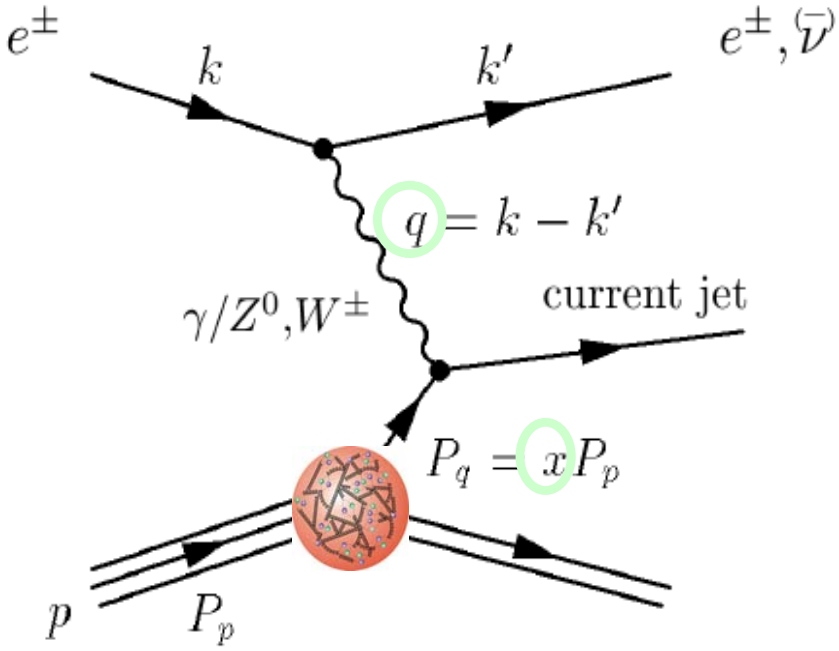
    (high-Q^2 ↔ Weak boson exchange)
  - lepton beams are polarized.
  - Reduced E_p runs at the end.



HERA I HERA II

In total, each H1 and ZEUS gains ~0.5 fb^{-1}.

Deep Inelastic Scattering (DIS)



$e^{\pm}, \overset{(-)}{\nu}$

- Kinematic variables to describe DIS

  Q^2: Virtuality
  → probing power

  x : Bjorken scaling variable
  → momentum fraction of struck quark

  y : Inelasticity

  $\sqrt{s}$: center of mass energy

$$Q^2 = sxy \qquad Q^2 = -q^2 = -(k - k')^2 \qquad x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

- Inclusive DIS cross sections can be written with structure functions.

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ \left[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} xF_3(x,Q^2) \right] \qquad Y_{\pm} = 1 \pm (1-y^2)$$

cross section with point-like particle

Structure functions reflect momentum distribution of partons in the proton.

Structure functions and PDFs

Measured quantity: reduced cross section $Y_{\pm} = 1 \pm (1-y^2)$

$$\sigma_r(e^{\pm}p) = \frac{Q^4 Y_+}{2\pi\alpha^2}\frac{d^2\sigma}{dxdQ^2} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)$$

Structure functions are used for determination of the parton distribution functions (**PDFs**), $q(x,Q^2)$ and $g(x,Q^2)$

- F_2 : [Sea + valence] quarks, (gluon)

$$F_2 = \sum A_q x(q+\bar{q}) \qquad \frac{\partial F_2}{\partial \ln Q^2} \propto xg$$

- F_L : longitudinal structure function

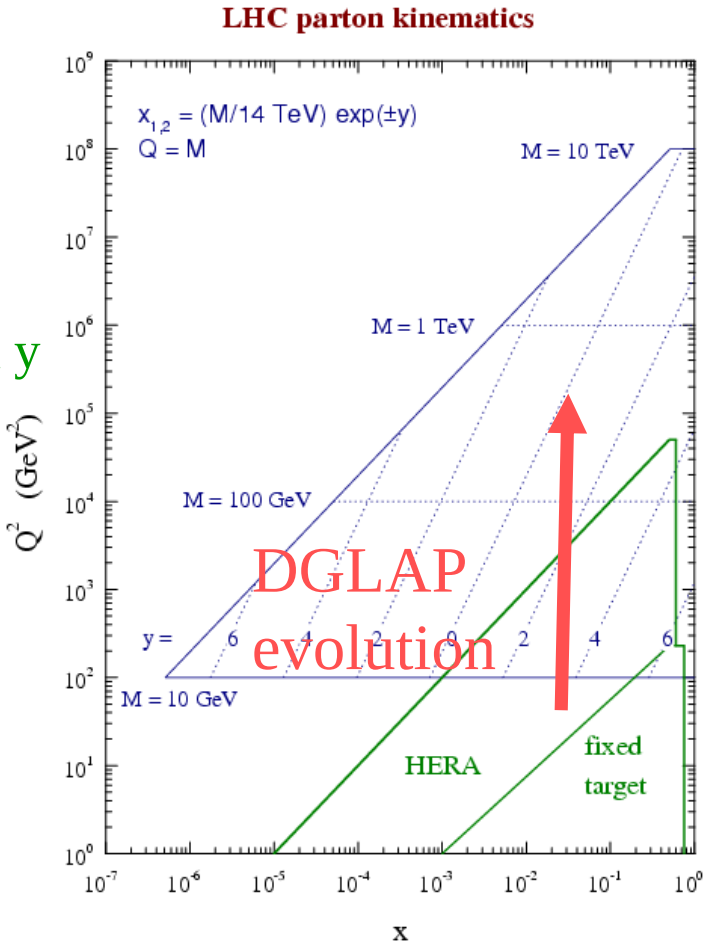
  ⟶ gluon (see later) sizable only at high y

- xF_3 : parity violation term (Electroweak)

$$xF_3 = \sum B_q x(q-\bar{q})$$ high Q^2 only

  ⟶ Valence quarks

The Q^2 evolution can be described by perturbative QCD, using DGLAP equation.

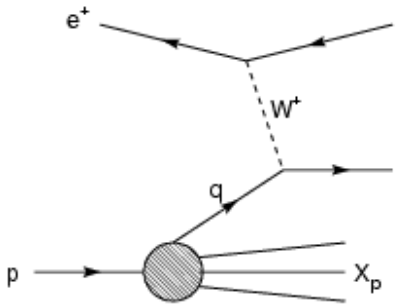


DIS at HERA

Pure proton target

→ Free from target correction, nuclear effect.

◆ Charged current DIS (CC)

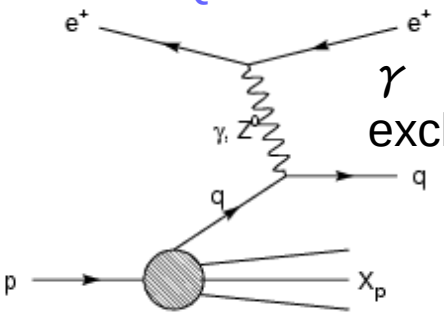


$W^{\pm}$ exchange

Charge selective interaction

e^- : u quark e^+: d quark

◆ Neutral current DIS (NC) at low Q^2

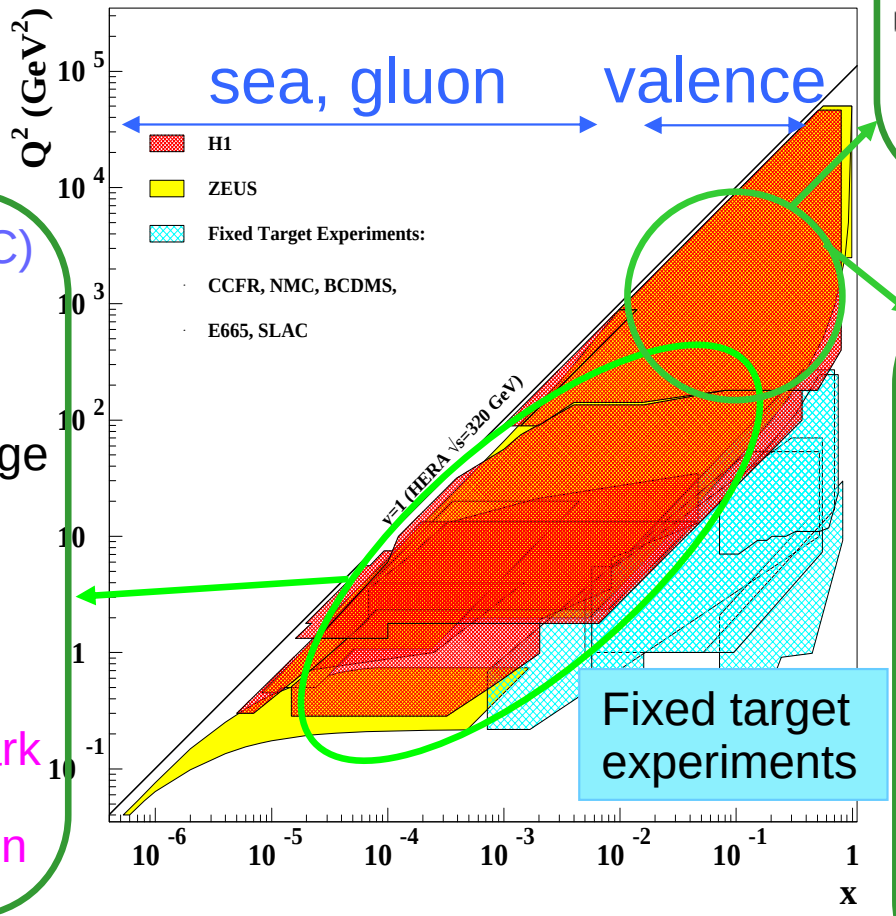


γ exchange

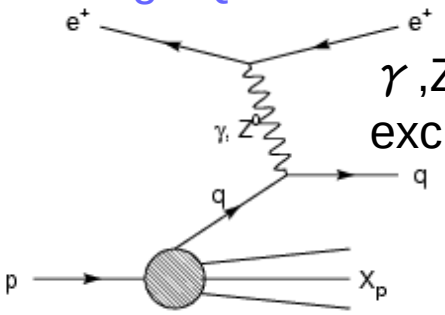
$\gamma \rightarrow \quad F_2 \propto \sum x(q+\bar{q})$

Sea + valence quark

$\frac{\partial F_2}{\partial \ln Q^2} \propto xg$ gluon



◆ Neutral current DIS (NC) at high Q^2



γ, Z^0 exchange

Sea + valence quark

Z^0 introduces parity violation.

$\rightarrow \quad xF_3 \propto \sum x(q-\bar{q})$

valence quark

DIS in the detectors

Neutral current (NC) process

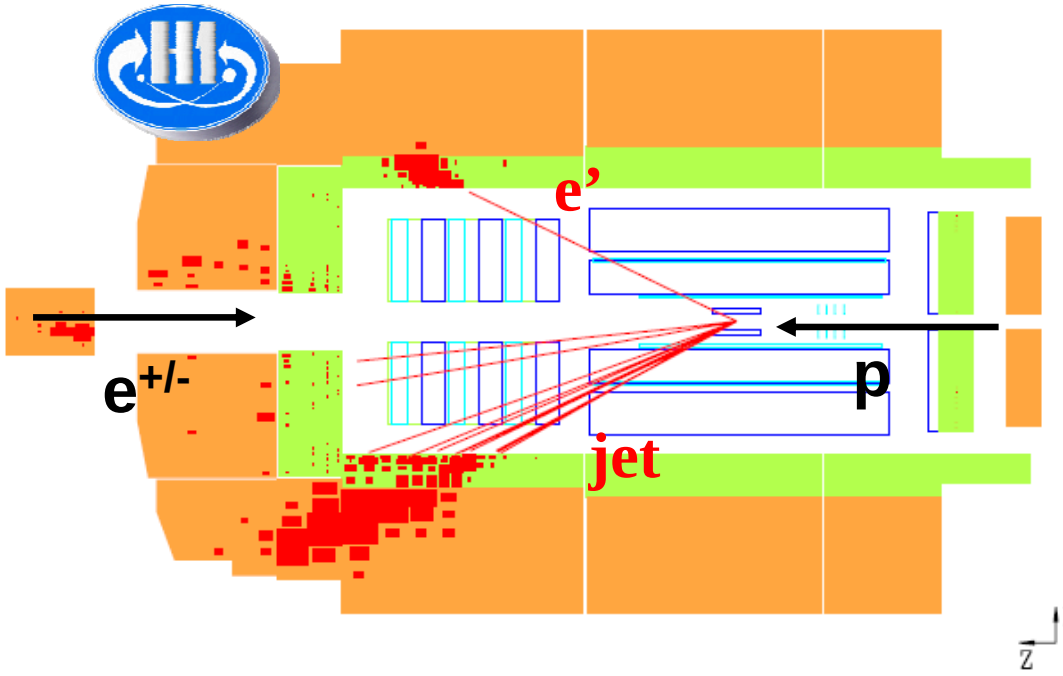
γ /Z^0 exchange

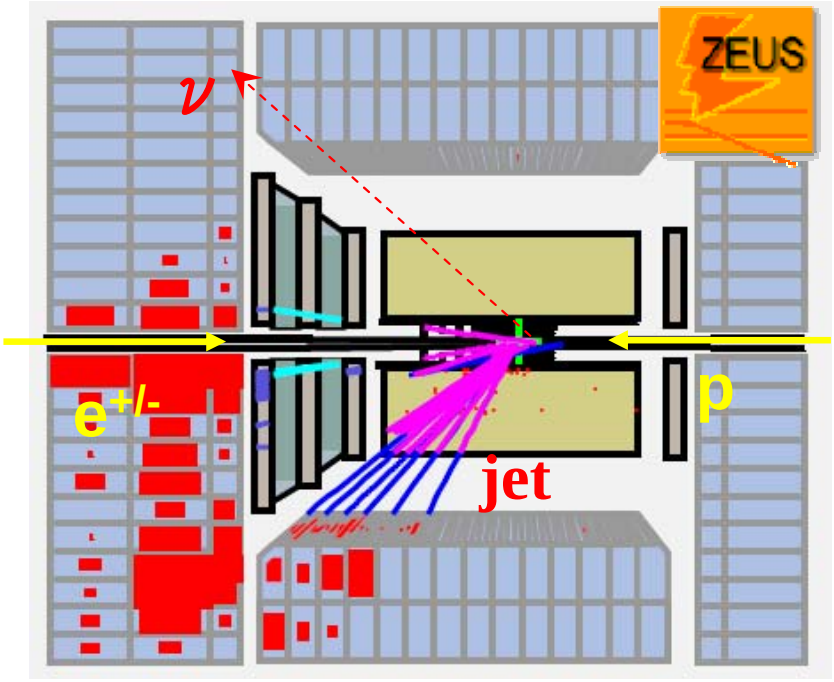
ep→e'X

Charged current (CC) process

W^{+-} exchange

ep→ ν X





- Kinematic variables are reconstructed by two of measured variables;

[energy / angle] of [scattered electron / jet (~ struck quark)]

HERA I inclusive DIS cross sections and HERA PDF1.0

published: JHEP01 (2010) 109

Combining H1 and ZEUS cross sections

Combining all the HERA-I inclusive DIS cross sections from H1 and ZEUS:

- HERA I: e^+p ~$100pb^{-1}$, e^-p ~$16pb^{-1}$
- NC: $0.045 < Q^2 < 30000\ GeV^2$, CC: $280 < Q^2 < 30000\ GeV^2$
- 1402 points (14 papers)

→ After combination: 741 points

Combination is done by averaging each data point by simultaneous χ^2 fit.

- Assumption:

  H1 and ZEUS measure the same cross sections.

- Taking account of correlated systematics within/between experiments.

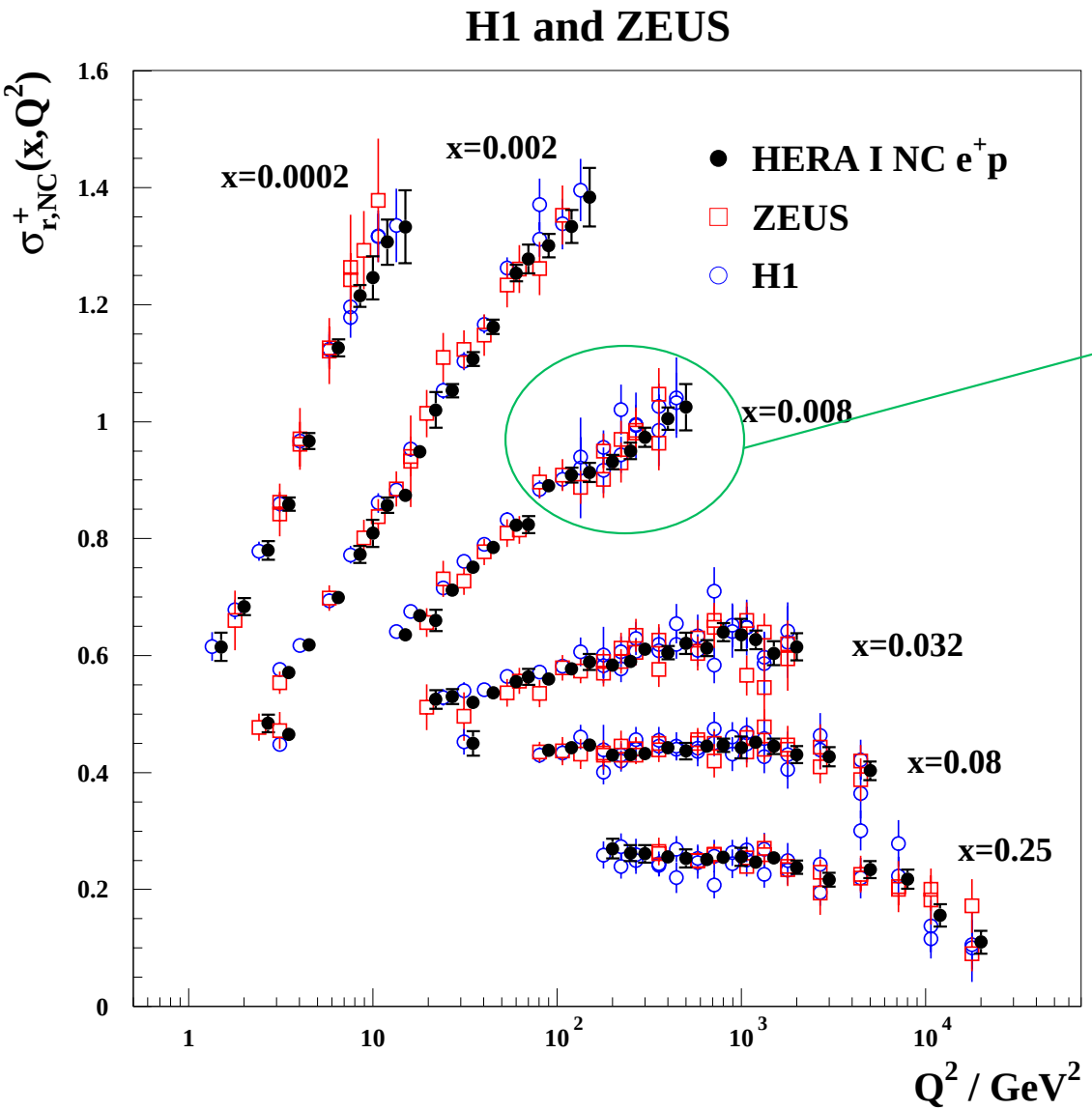
  Different detectors and analysis techniques bring different sensitivities to similar sorce of correlated systematic uncertainties.

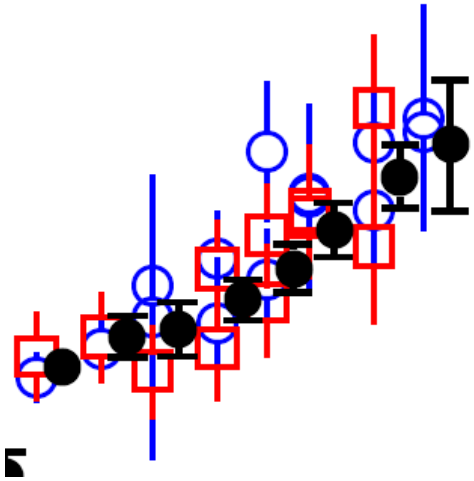
  ➔ Cross calibration of experiments

  Reduction of systematic uncertainties.

JHEP01 (2010) 109

Combining H1 and ZEUS cross sections



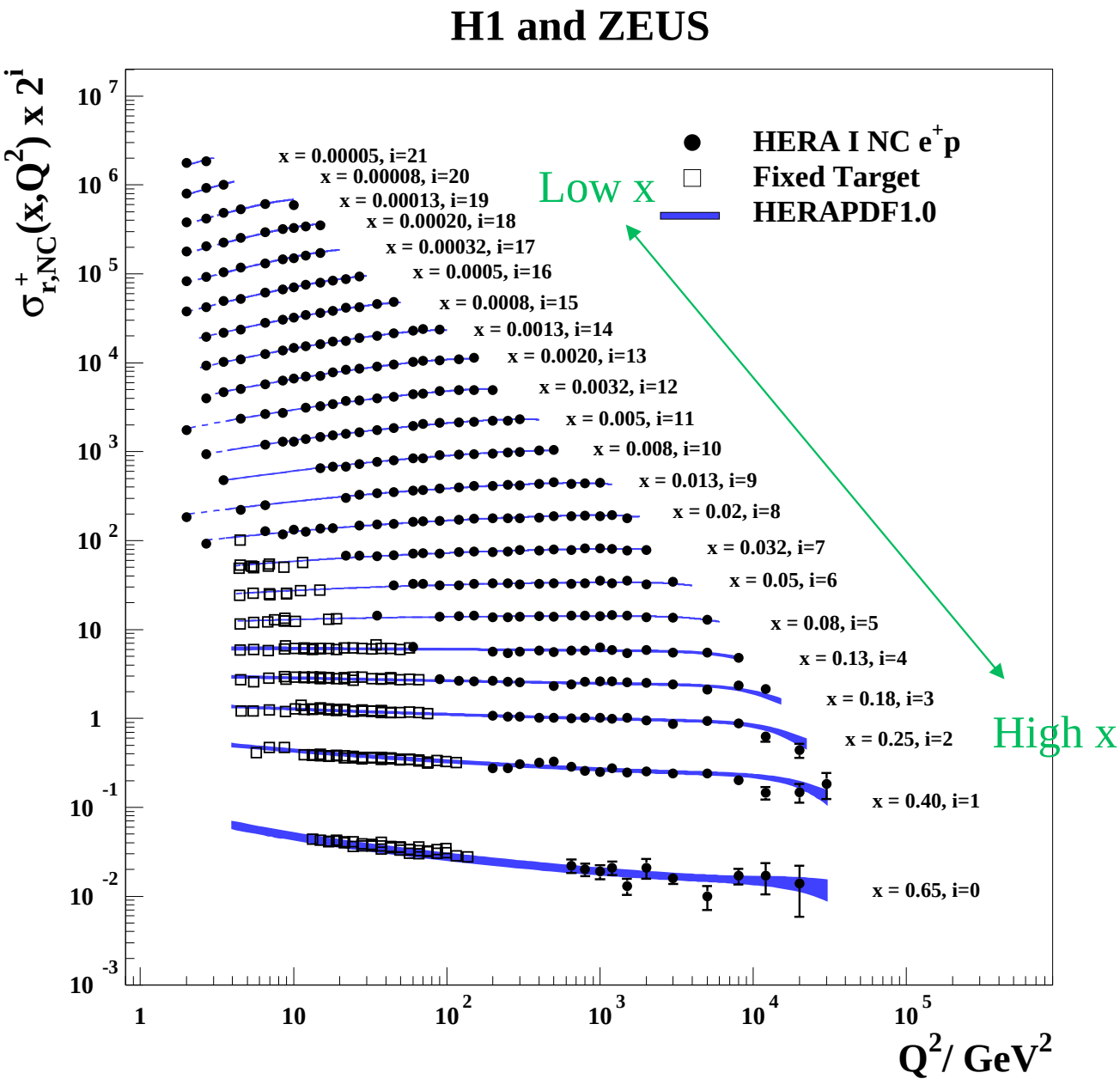


Uncertainty gets improved by more than sqrt(2).

← Main reduction in systematic uncertainties.

JHEP01 (2010) 109

Combined inclusive DIS cross sections



- Precision of 1-2% for $3 < Q^2 < 500$ GeV^2.
- Scaling violation is clearly seen.

$$\frac{\partial F_2}{\partial \ln Q^2} \propto xg$$

JHEP01 (2010) 109

HERA PDF 1.0

Data sets

- Combined HERA I inclusive DIS cross sections
  e^-p CC, e+p CC, e^-p NC ($Q^2>100GeV^2$), e^+p NC ($Q^2> Q^2_{min}$)

Settings

- PDF parameterized at the starting scale Q_0^2

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \quad \bar{U} = \bar{u} + \bar{c} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}. \quad \bar{D} = \bar{d} + \bar{s} + \bar{b}
\end{aligned}
$$

  Central fit has 10 free parameters:

  ← chosen by saturation of χ^2

- RT-VFN scheme
- NLO DGLAP evolution using QCDNUM17.02
- Scales: $\mu_R = \mu_F = Q^2$

$\alpha_S(M_Z)$	0.1176
$fs=s/D$	0.31
m_c (GeV)	1.4
m_b (GeV)	4.75
Q^2_{min} (GeV^2)	3.5
Q_0^2 (GeV^2)	1.9

HERA PDF 1.0

Uncertainties

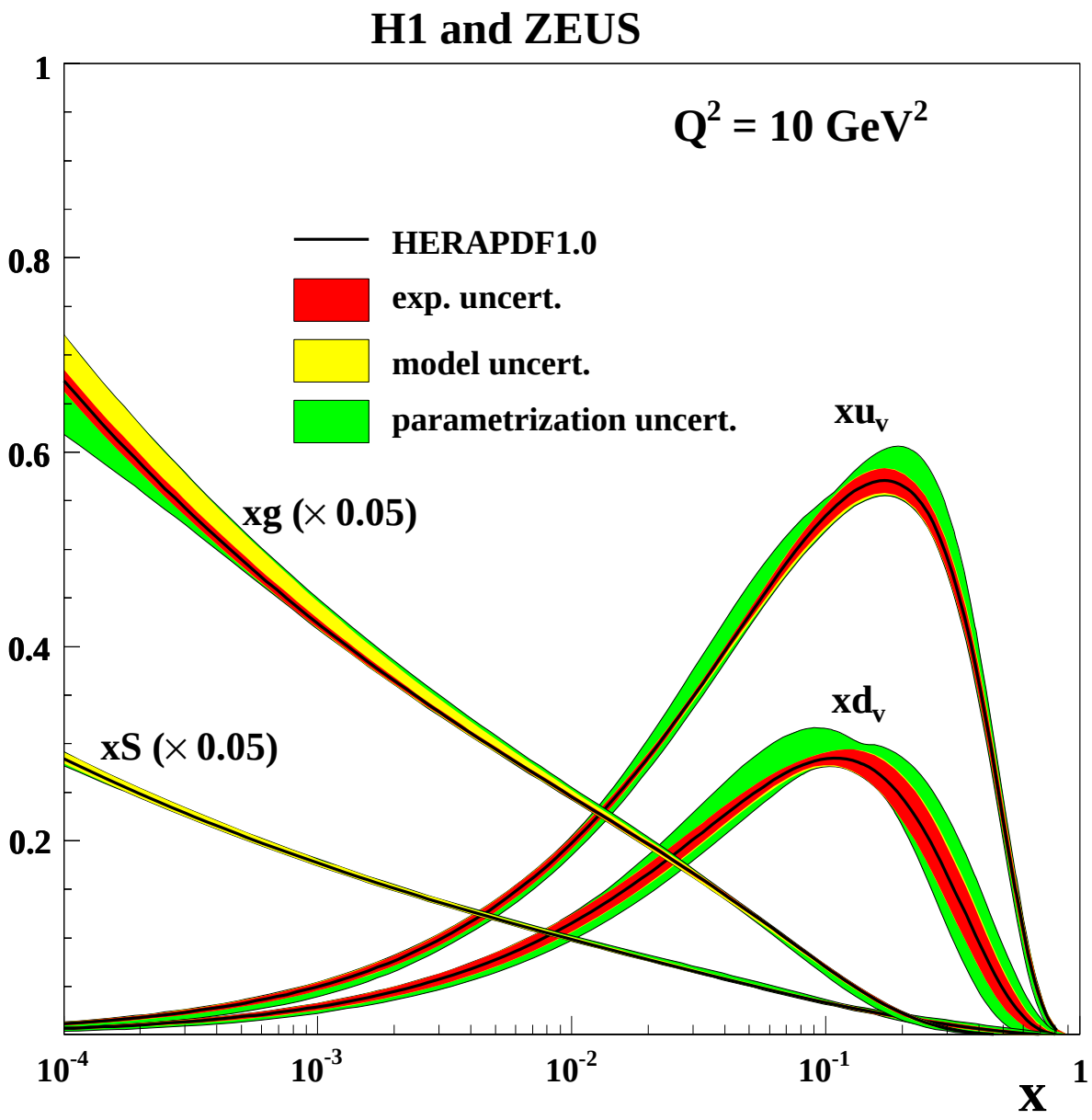
- experimental: $\Delta\chi^2=1$
- model:

  Different set of values of

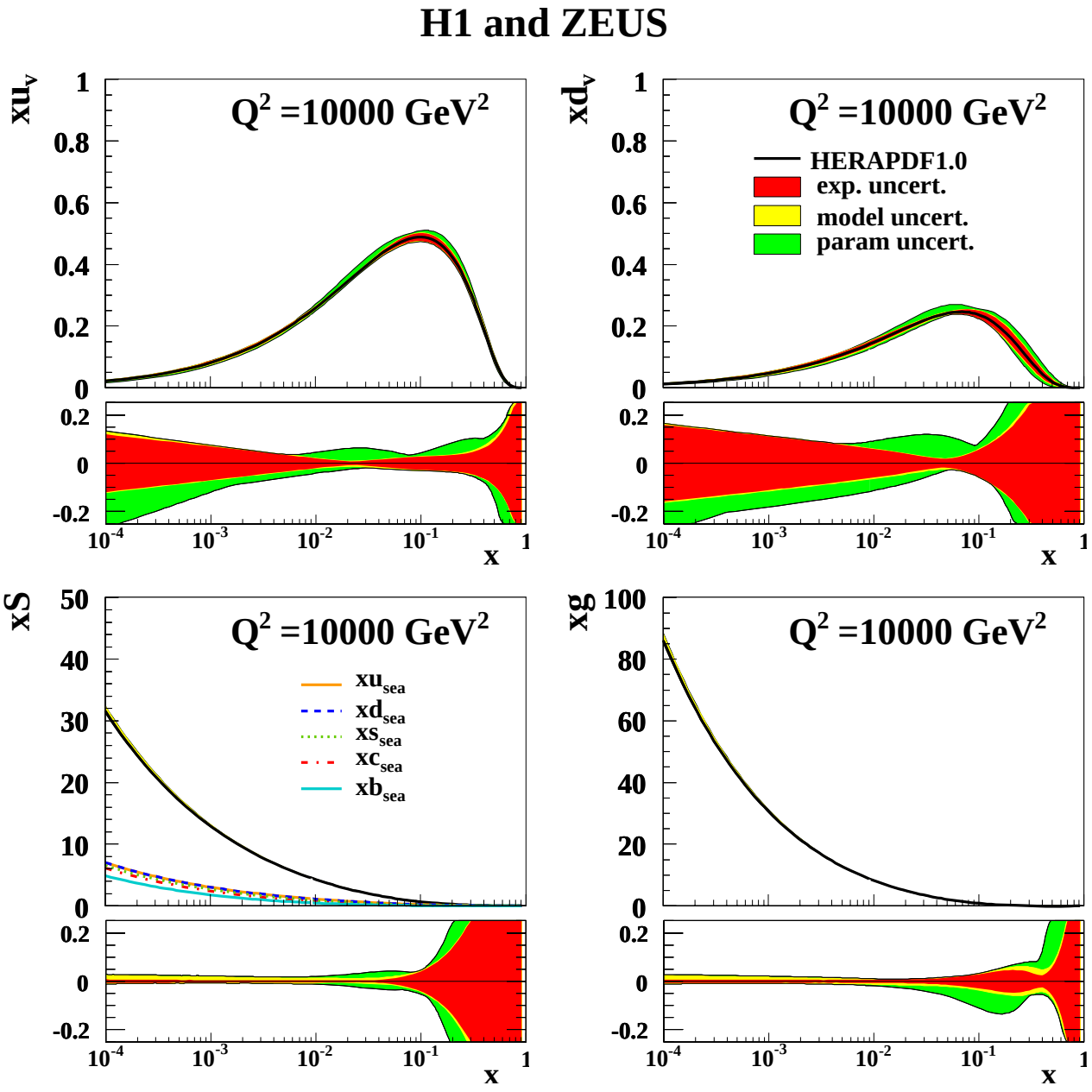
  f_s, m_c, m_b, Q^2_{min}, Q_0^2
- parameterization:

  envelope of parameter variation

  e.g. Q_0^2, negative gluon, relax $B_u=B_d$, additional parameter.

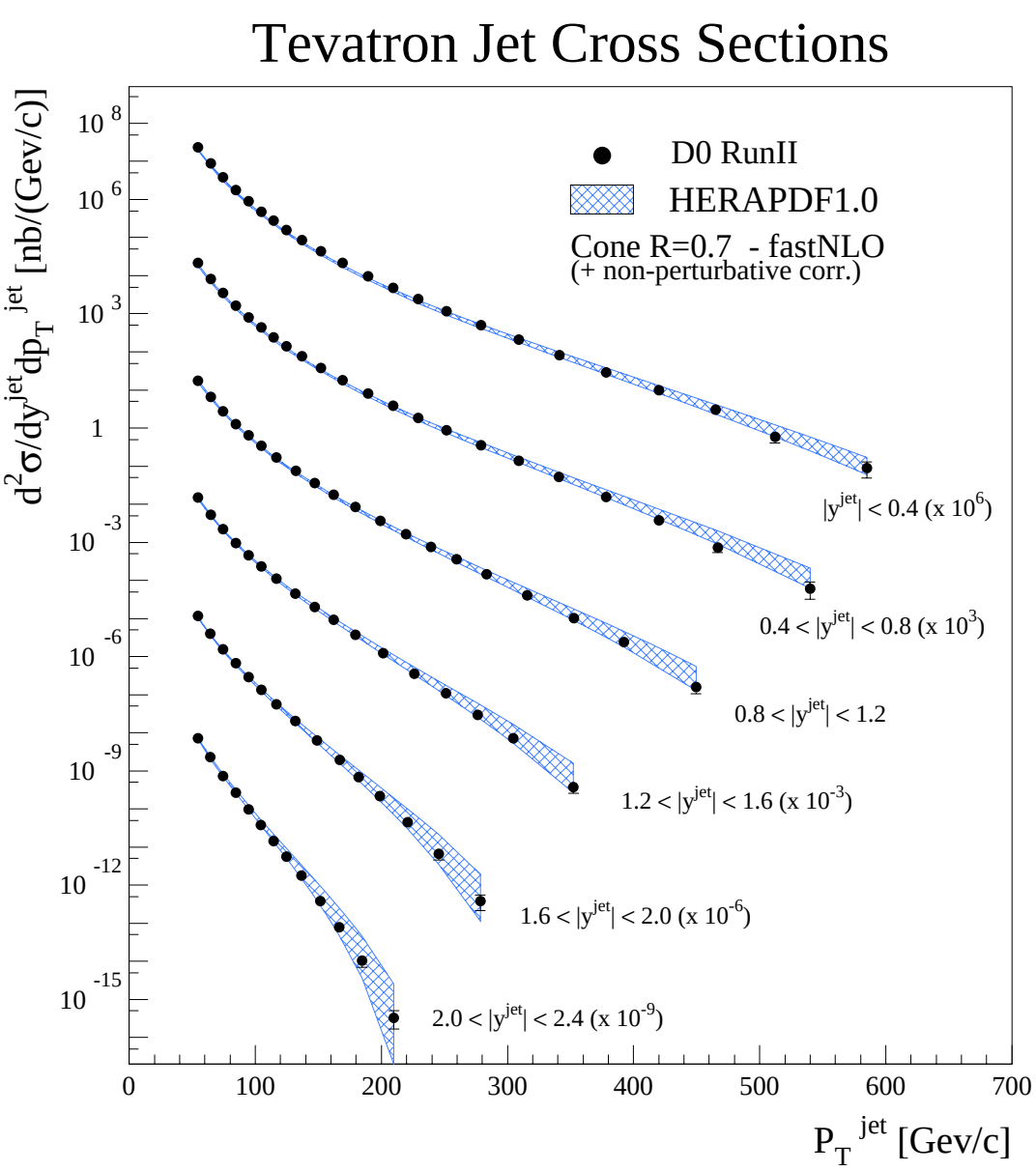


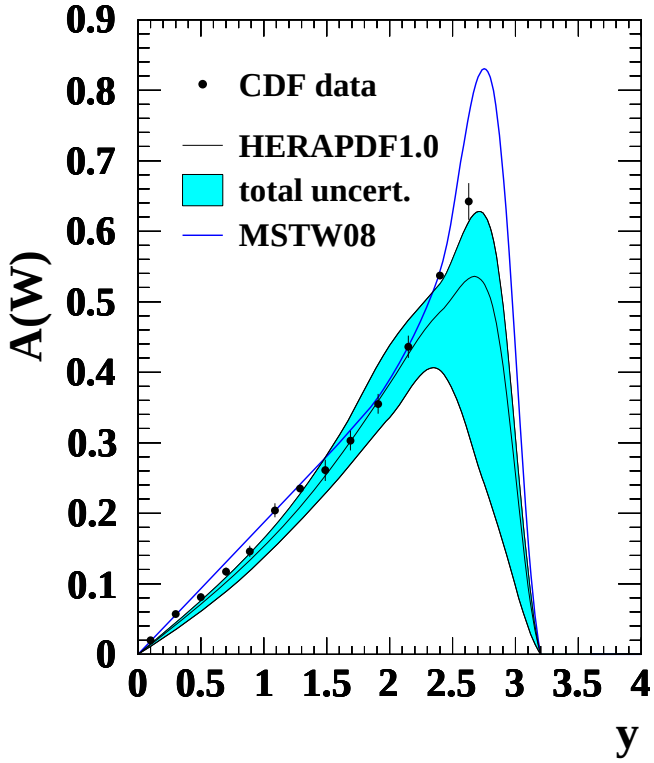
Relative Uncertainties at High Q^2



At $Q^2 = 10000\text{GeV}^2$, 2% uncertainty on gluon for $x<0.01$.

HERA PDF and Tevatron Data

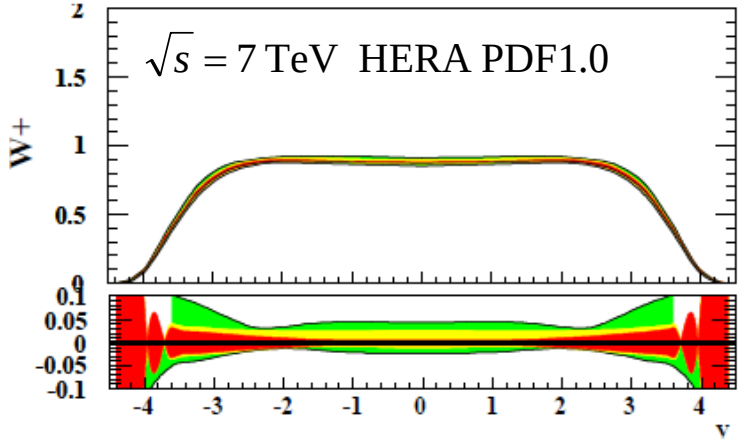


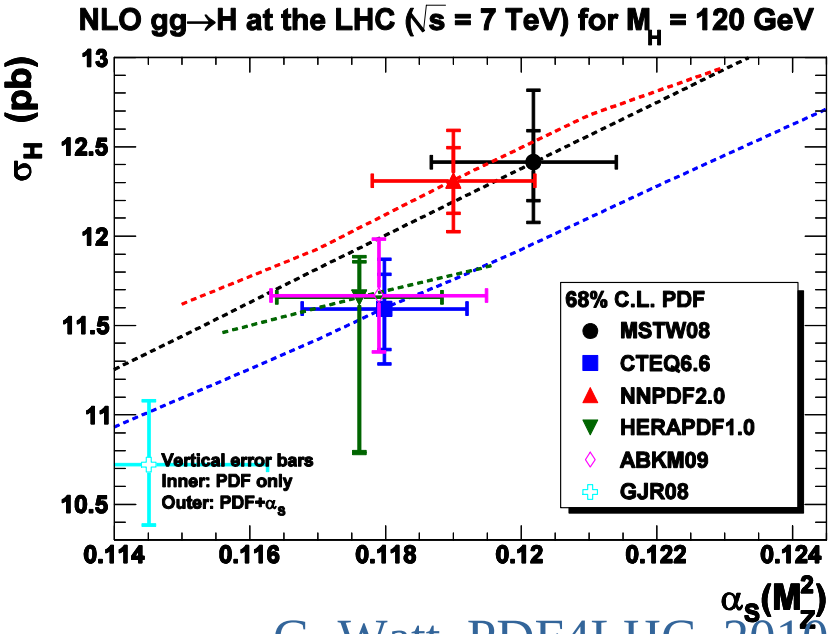


Good description of Tevatron data by HERA PDF.

HERA PDFs for LHC

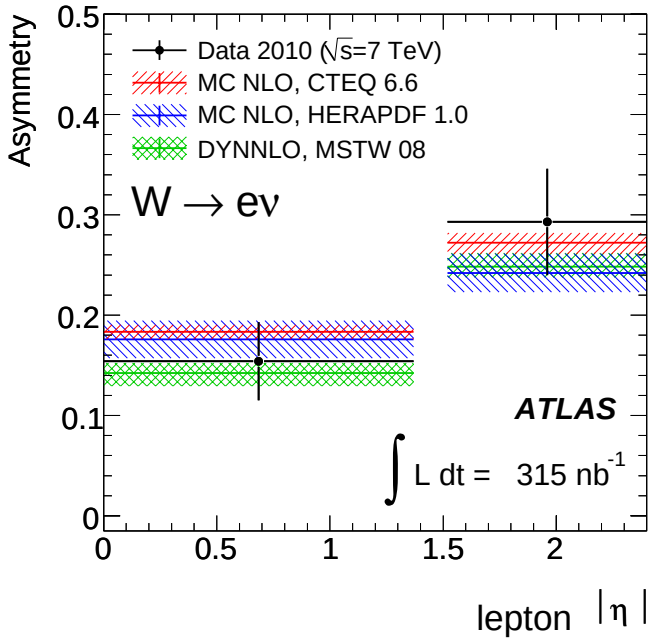
Several predictions are calculated with reasonable uncertainties.

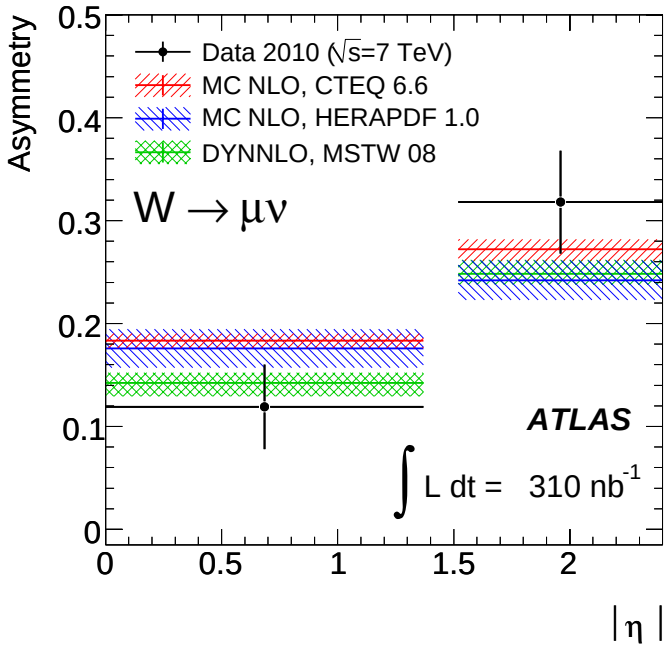




G. Watt, PDF4LHC, 2010

Comparison with data has started.





CERN-PH-EP-2010-037
arXiv:hep-ex 1010.2130

Further measurements at HERA

Further input from HERA

HERA PDF1.0 uses inclusive DIS cross section in HERA I only.

- HERA II High Q^2 NC/CC cross sections
  - Increase of electron data
    → NC: More sensitivity to xF_3
    i.e. valence quarks (u+d)
  - Increase of positron data
    → CC: More sensitivity to d quark

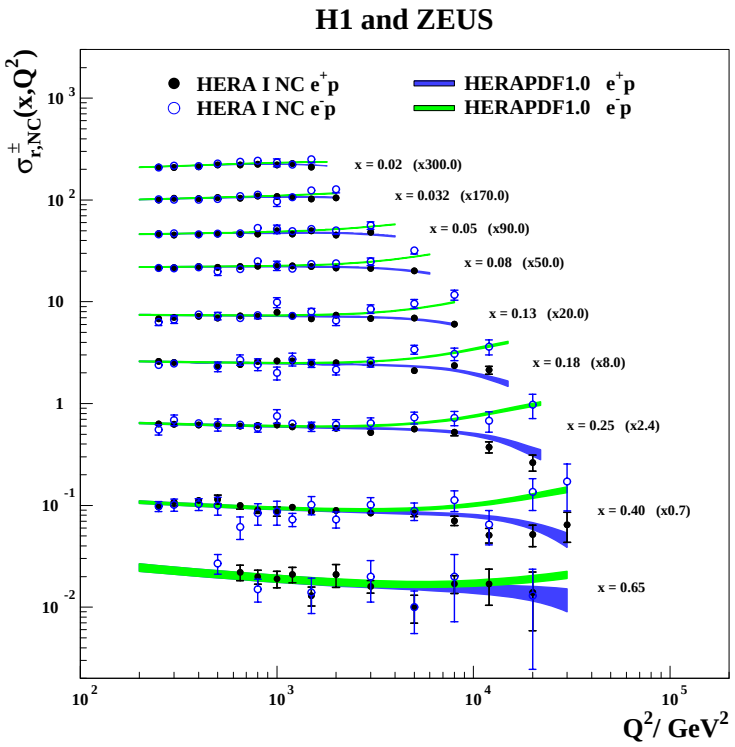
	HERA-I	HERA-II
e^-p	$20pb^{-1}$	$180pb^{-1}$
e^+p	$100pb^{-1}$	$170pb^{-1}$

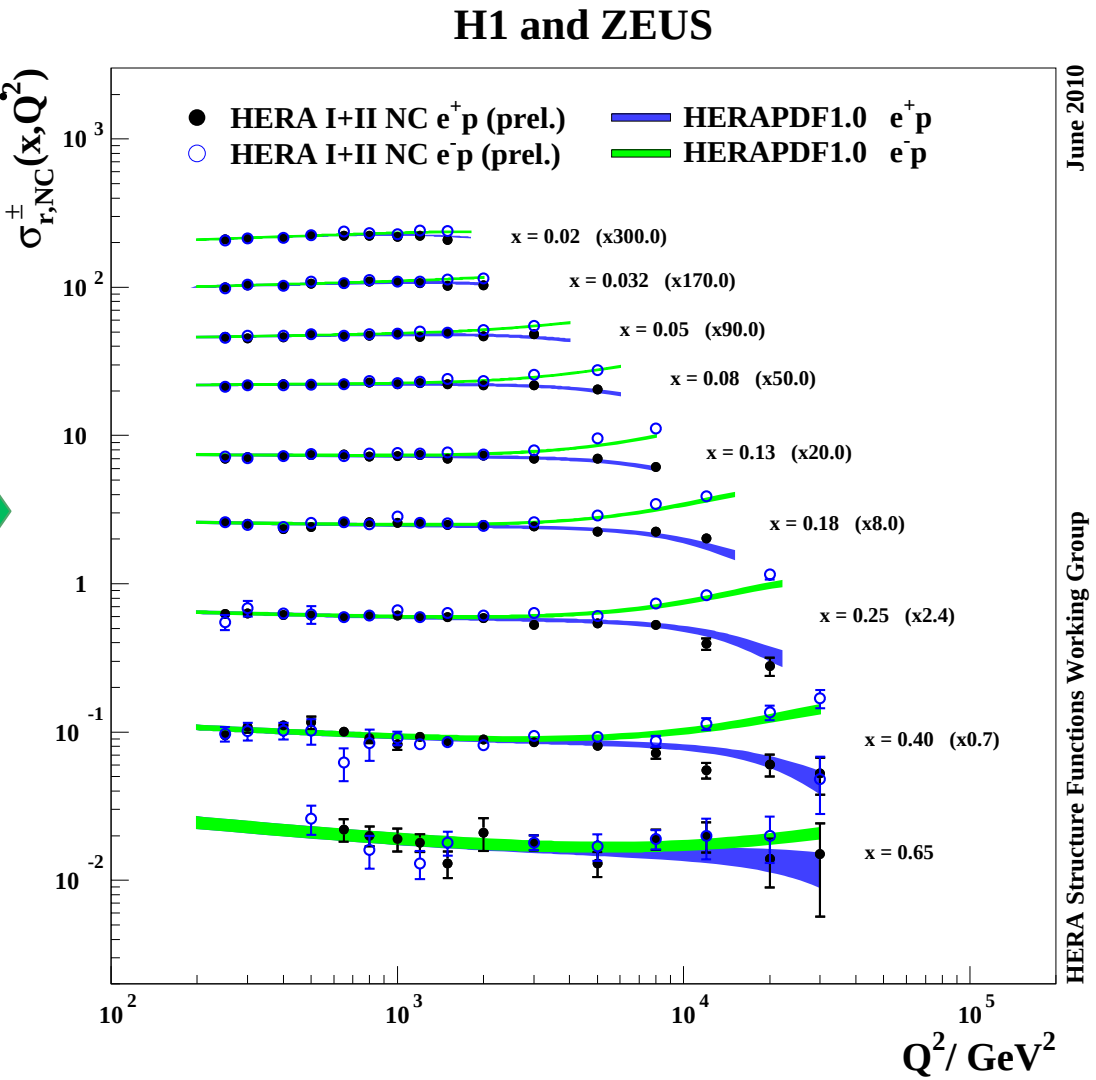
- Inclusive Jet cross sections
- Longitudinal structure functions
- Heavy flavour structure functions

HERA I+II NC cross sections

HERA II NC are also combined.

- H1 e^+p, e^-p
- ZEUS e^-p





- Improved precision.
- Clear separation of e^+p and e^-p at high Q^2

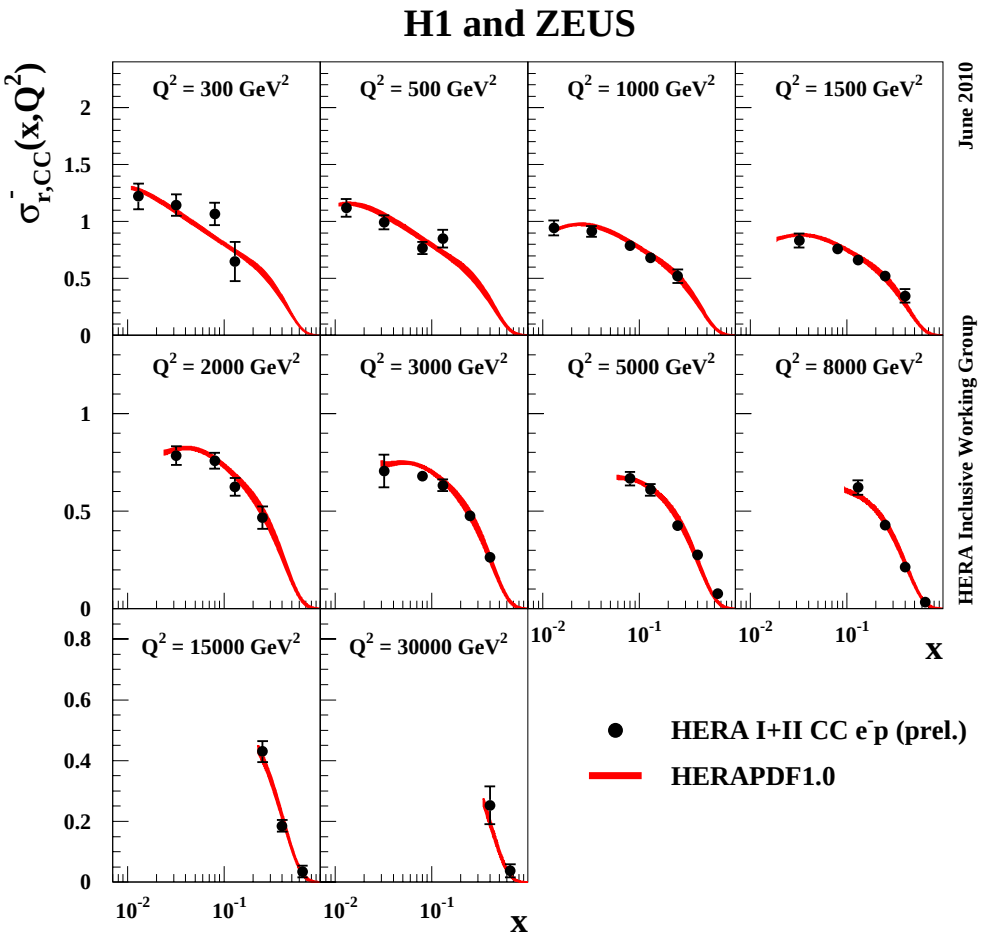
→ $xF_3 = \sum B_q x(q - \bar{q})$ valence quark

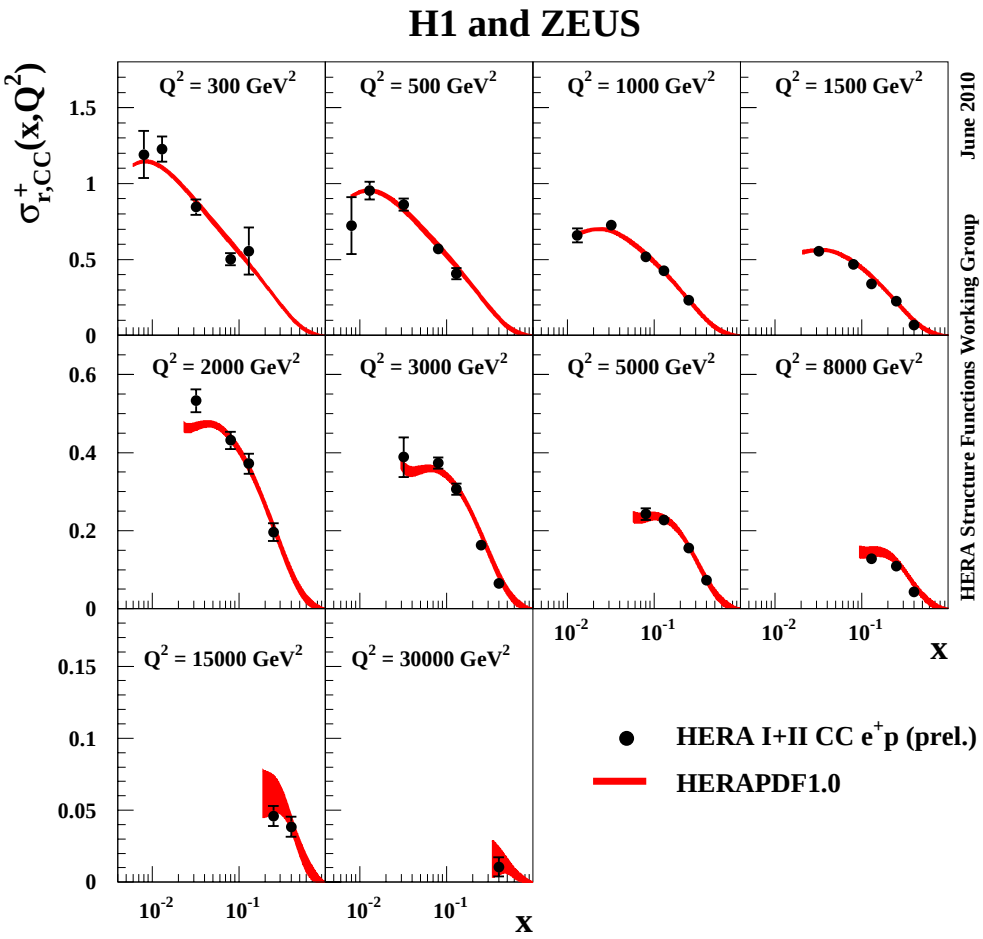
to be included:
ZEUS 06-07 e^+p NC

HERA I+II combined CC cross sections

$$\sigma_r^{CC}(e^- p) \propto \left[u + c + (1-y)^2(\bar{d} + \bar{s})\right]$$

$$\sigma_r^{CC}(e^+ p) \propto \left[\bar{u} + \bar{c} + (1-y)^2(d + s)\right]$$



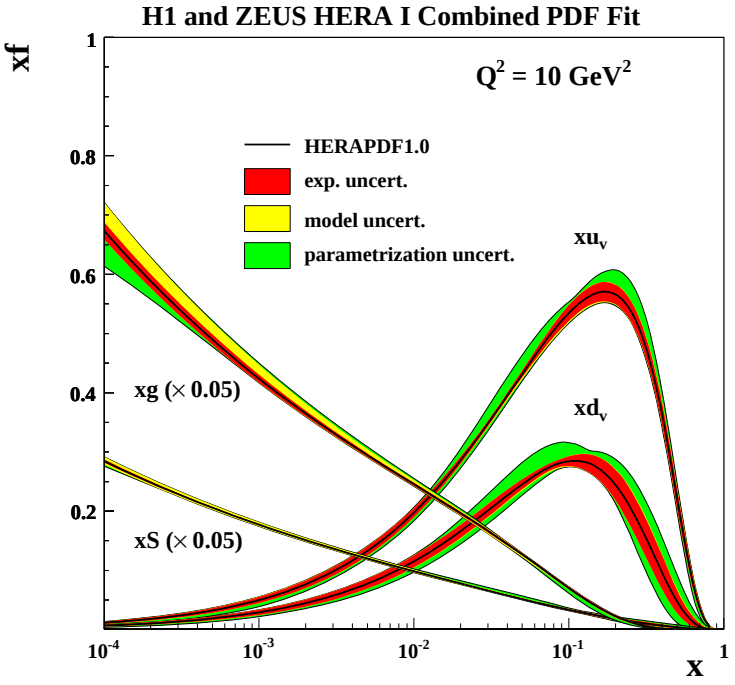


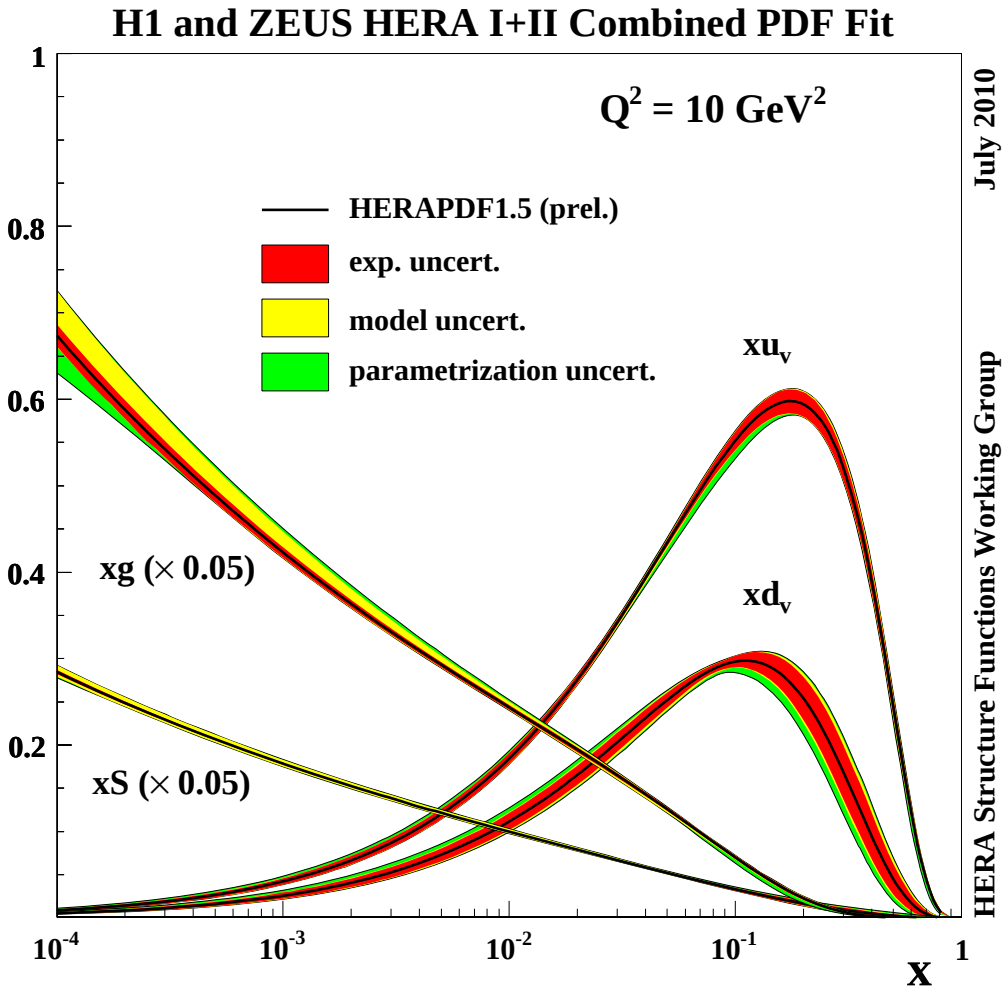
Sensitive to valence quarks.

HERA PDF 1.5 (prel.)

Using HERA I+II combined data.

Same setting as HERA PDF 1.0.

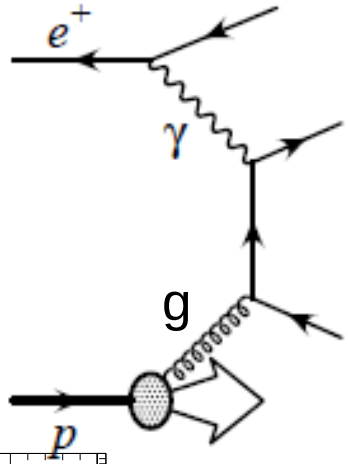


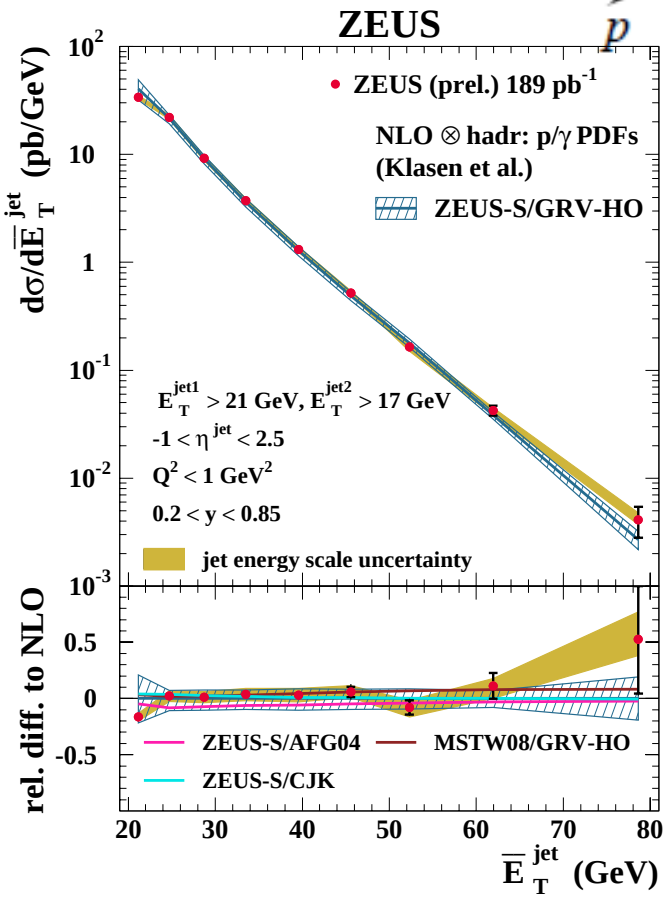


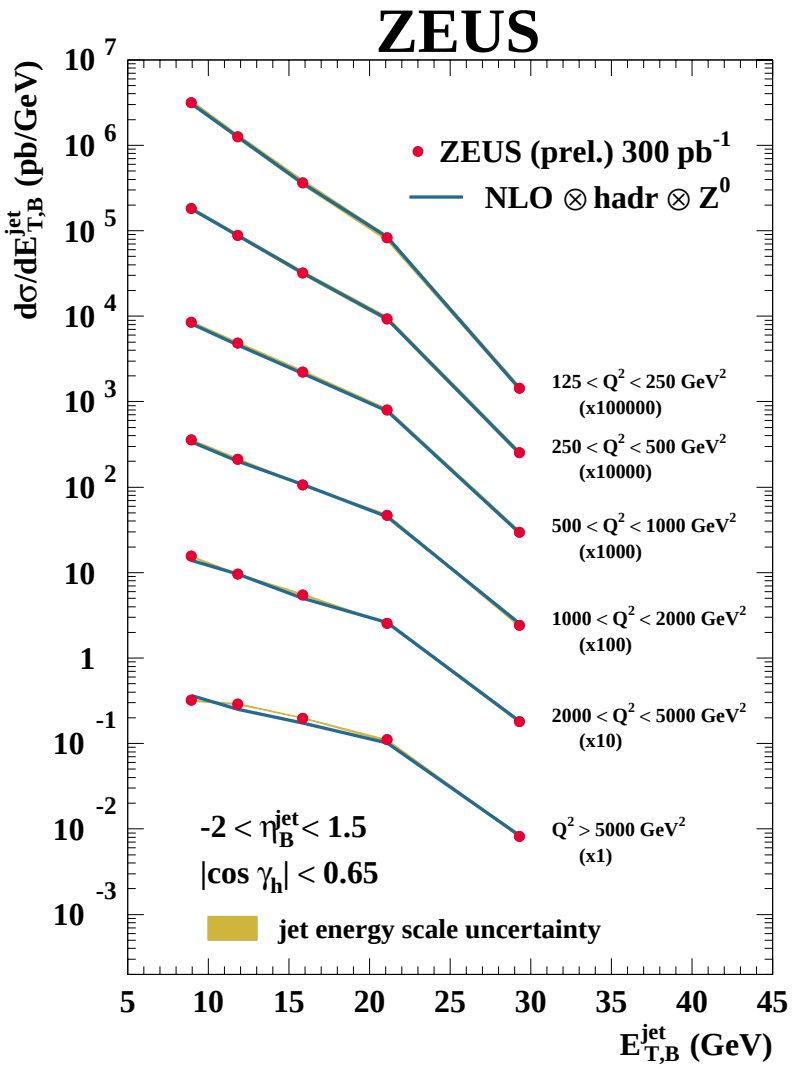
Uncertainties at the high x region reduced.

Inclusive Jet measurements in HERA II

Directly sensitive to gluon density at medium x.







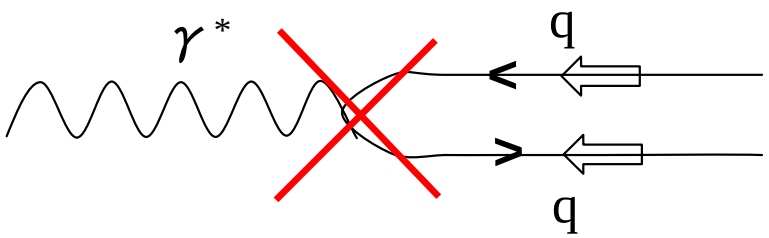
Also allows simultaneous constraints of PDFs and α_s.

Longitudinal structure function: F_L

- F_L is proportional to the cross section of longitudinal photon interacting with proton.

$$F_L \propto \sigma_L$$

- In naïve QPM, proton has co-linear spin ½ quarks only.



Longitudinal photon cannot interact with a quark → $F_L=0$

- gluon emission in the proton → $F_L \neq 0$

  i.e. F_L directly reflects gluon dynamics in the proton.

gluon PDF

$$\text{In pQCD: } F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum_q e_q^2\left(1-\frac{x}{z}\right) z g(z)\right]$$

Measurement of F_L is good test for the current understanding of proton structure and QCD.

Measurement of F_L

- Measured cross section is a combination of F_2 and F_L.

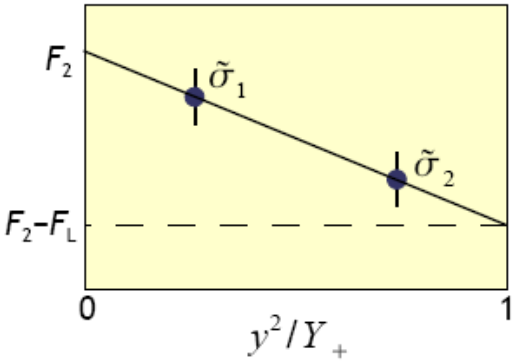
At low Q^2 $$\tilde{\sigma}(e^{\pm}p) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

$$Y_+ = 1 + (1-y^2)$$
$$\rightarrow 1 < Y_+ < 2$$

- Separation of F_L from F_2.

  Cross sections at the same (x, Q^2) but the different y

$$y = \frac{Q^2}{sx}$$ → multiple beam energies



HERA was successfully operated with low E_p for its last months.

Data sets with three different energy are available.

$$\sqrt{s} = 318, 252, 225\,\text{GeV} \qquad (E_p = 920, 575, 460\ \text{GeV})$$

➔ Direct F_L measurements at low x (x: 10^{-4} ~10^{-3}) = gluon dominance.

- Extraction of structure functions without QCD assumption
- Consistency check of pQCD framework for the proton structure.

Reduced cross sec. at E_p = 460,575,920GeV

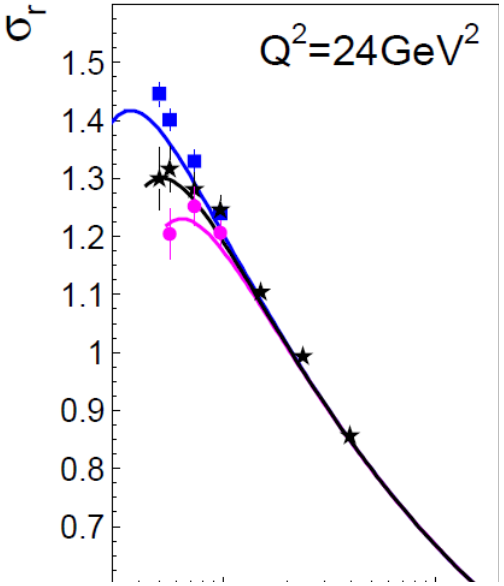
The data covers

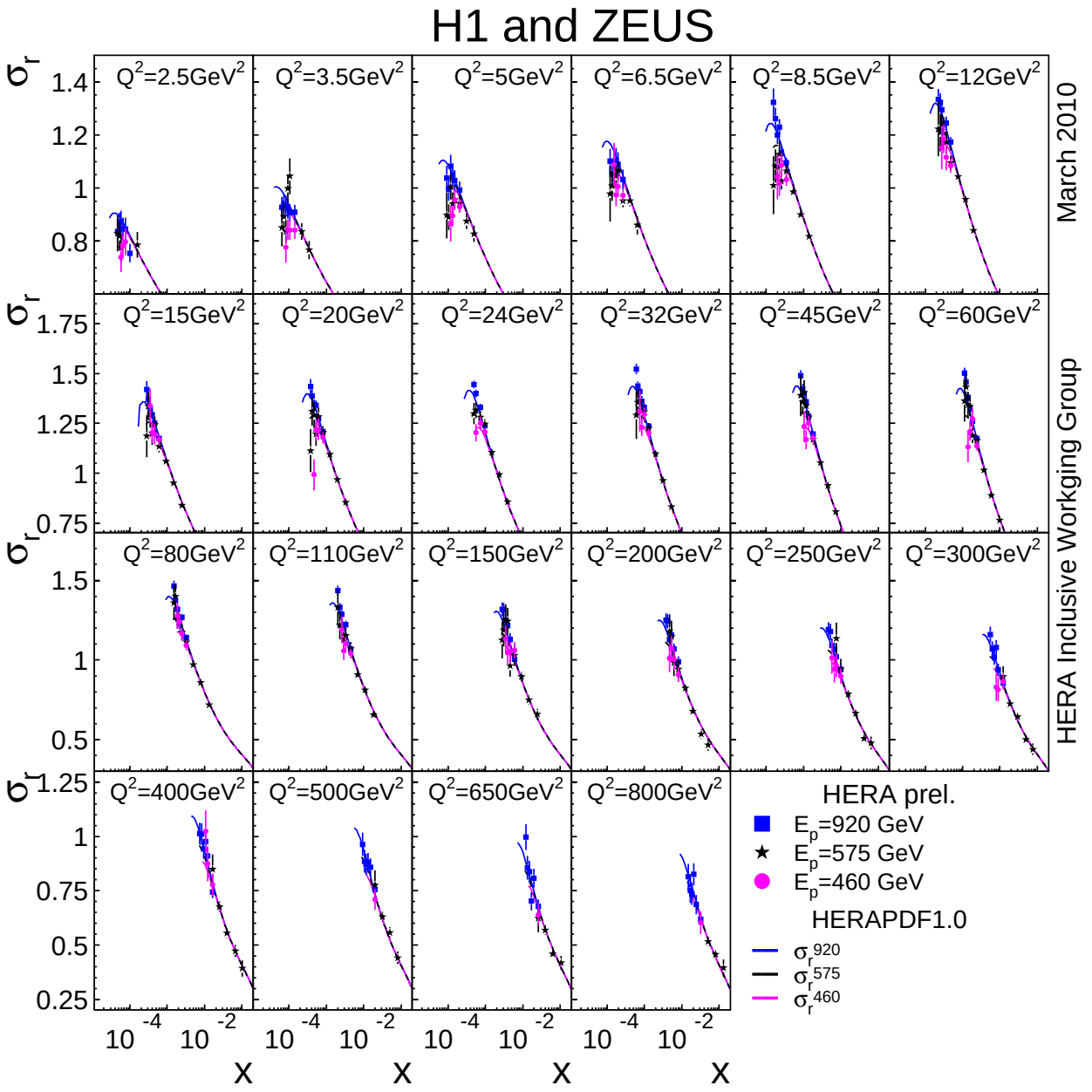
$0.85 > y > 0.1$

Difference at low-x

(i.e. high-y)

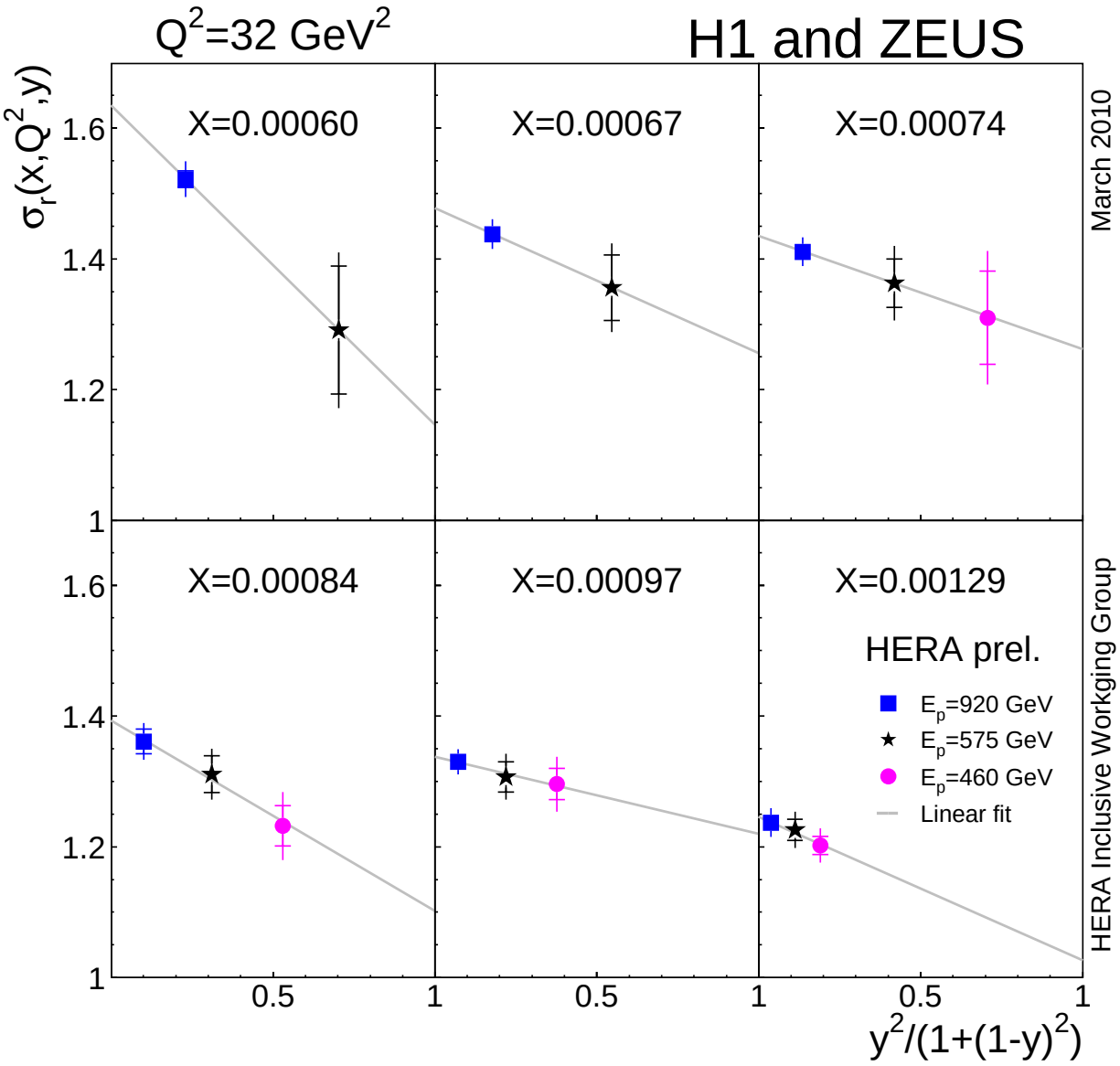
→ F_L





Note: ZEUS covers $24<Q^2<110$ GeV^2. Still trying to go lower Q^2

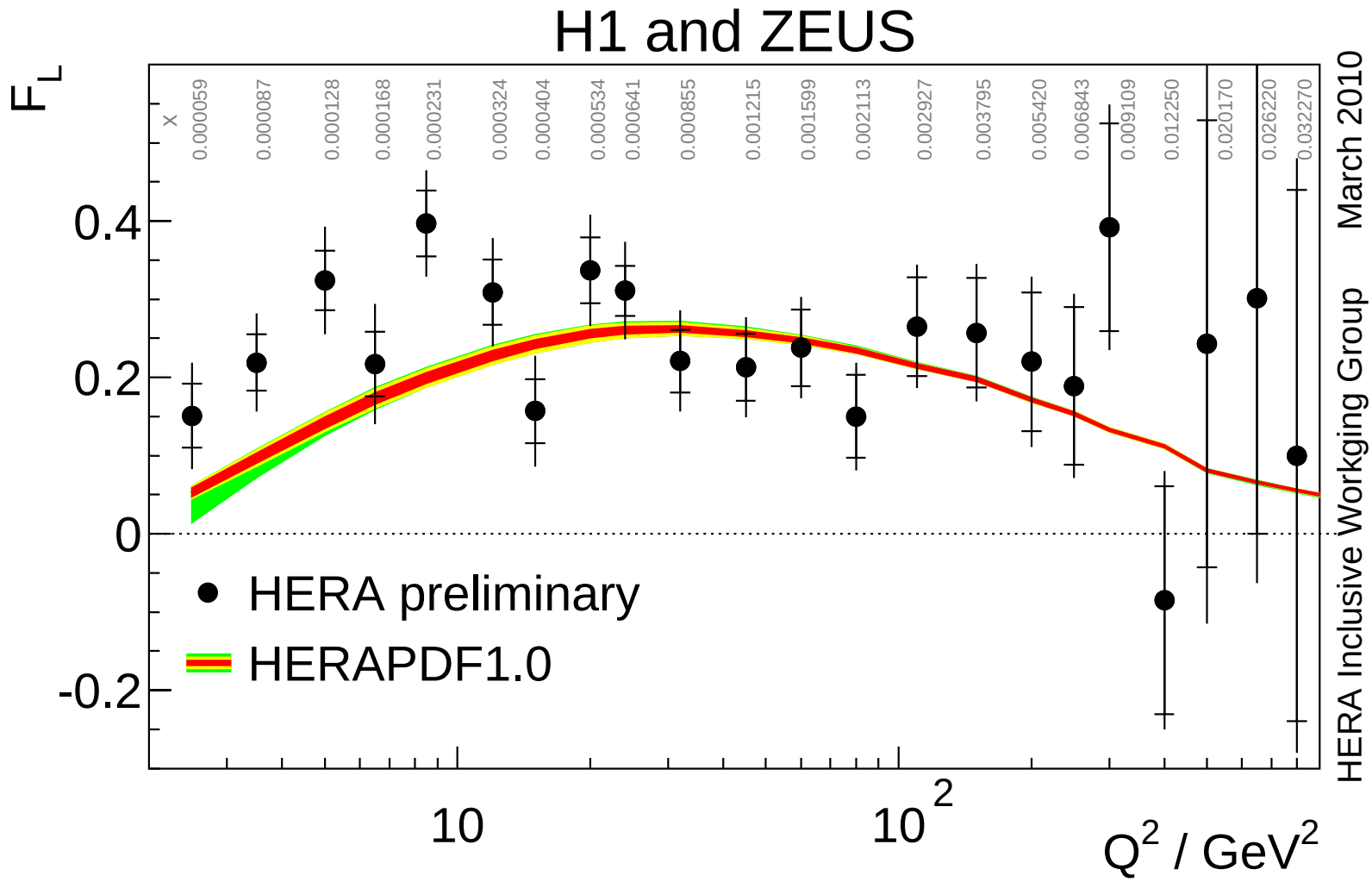
F_L extraction



$$\tilde{\sigma}(e^{\pm}p) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

→ At given (x, Q^2) bin, F_L should be seen as a negative slope.

HERA F_L



F_L, averaged over x, for each Q^2 bin

Good agreement between data and prediction for Q^2>10 GeV^2.

Heavy Flavour production

- Dominant process of heavy quark production: **Boson-Gluon-Fusion (BGF)**
- Two schemes to treat heavy quarks in pQCD;
  - massive scheme (FFN)

    appropriate for $Q^2 \sim M_q^2$

    Heavy quarks are produced via BGF.

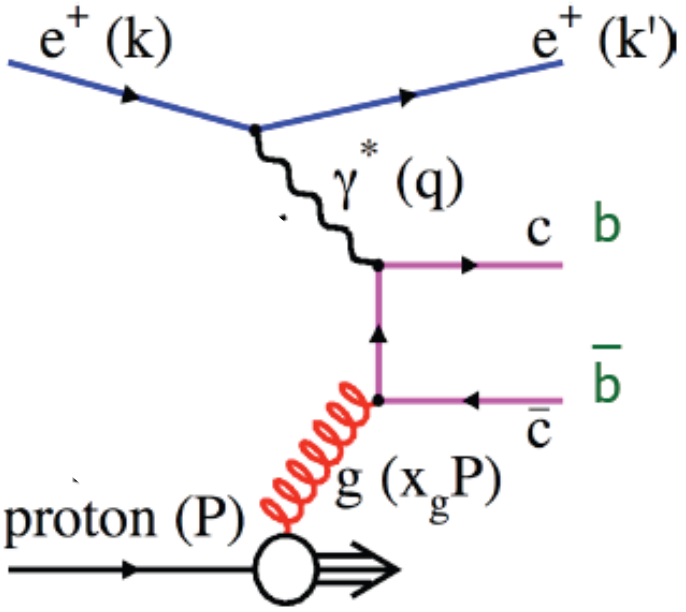
    → Sensitive to gluon PDFs
  - massless scheme (ZMVFN)

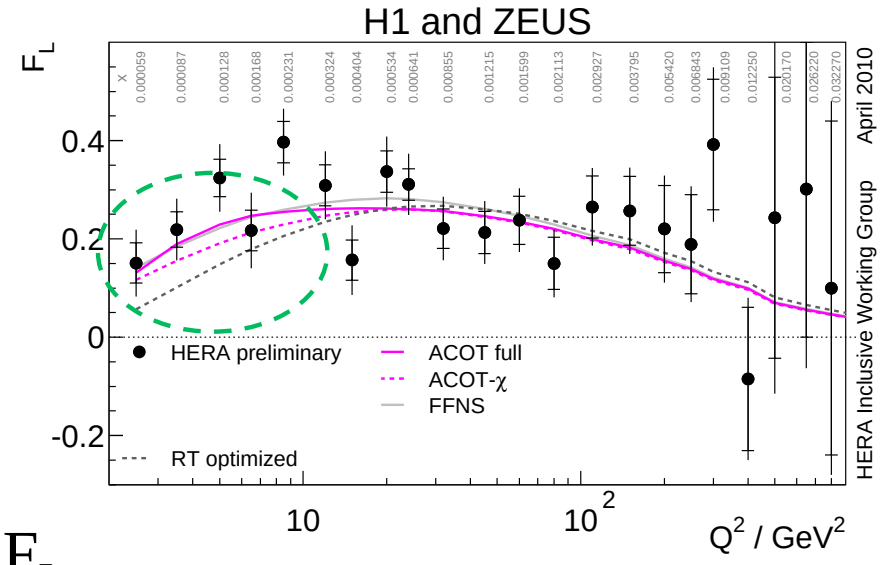
    appropriate for $Q^2 >> M_q^2$

    Heavy quarks are massless and exist in the proton if Q^2 is above the mass threshold.

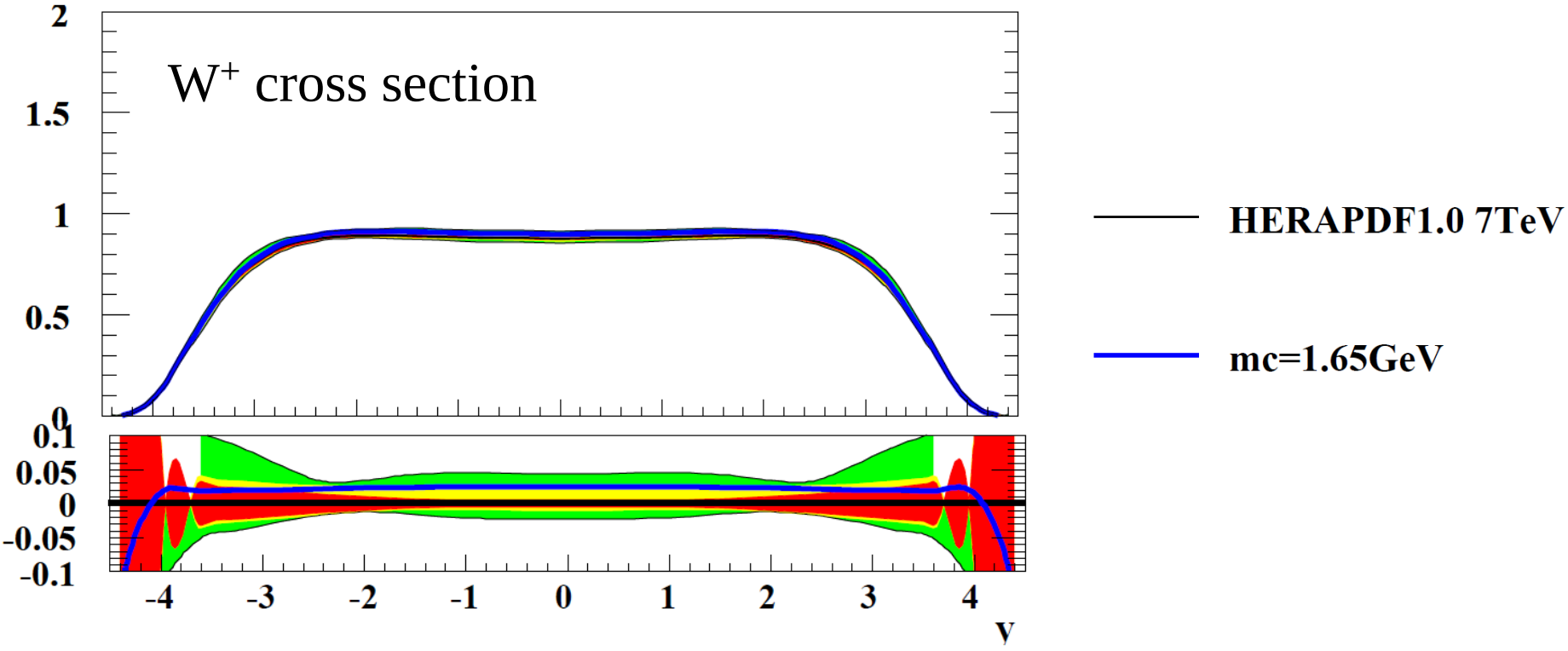
    → Intrinsic heavy quarks' PDFs

May affect on description of low Q^2 F_L.





Charm mass impact on LHC W cross sec.



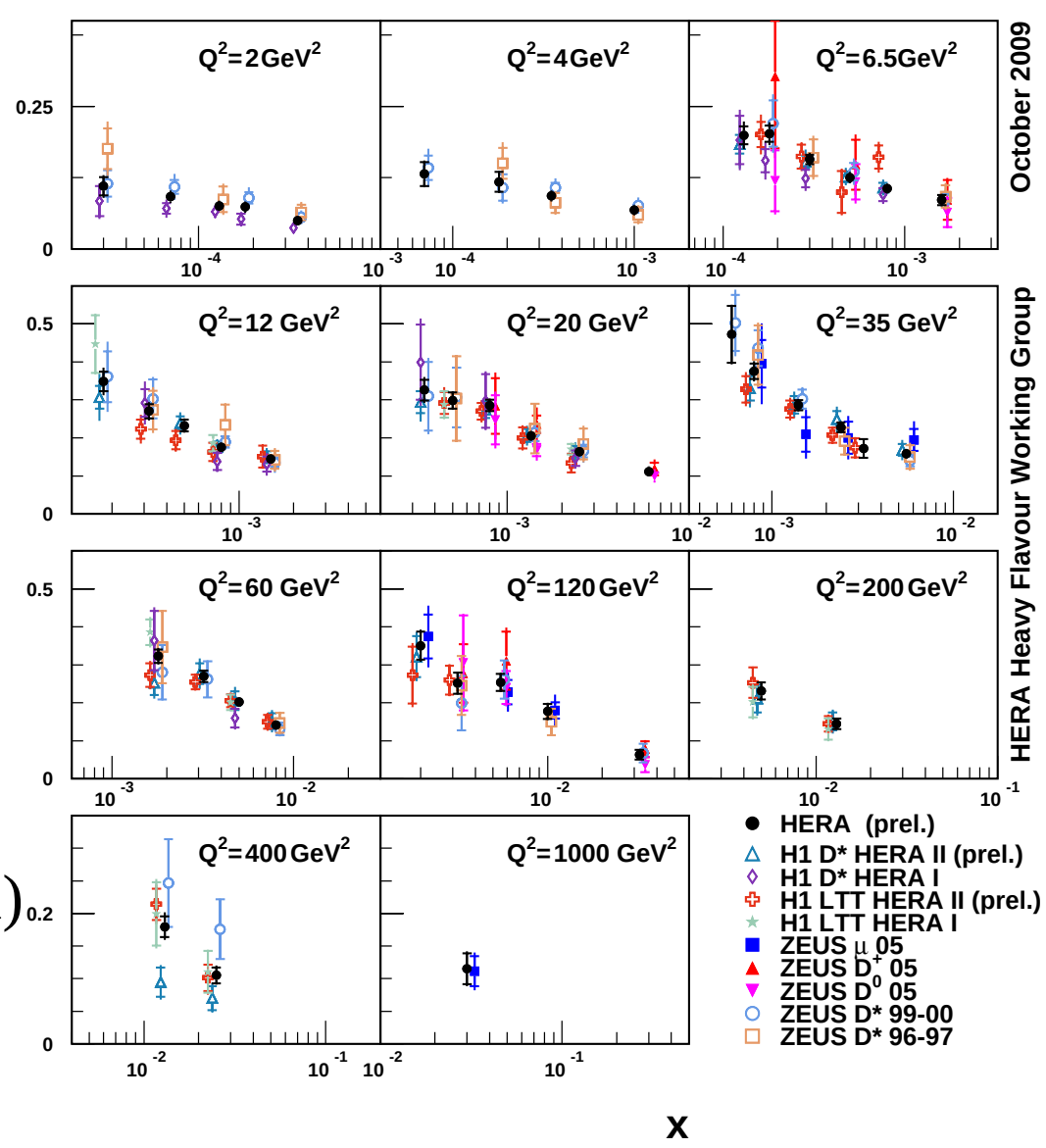
m_c: 1.4 GeV → 1.65 GeV.

m_c value in HERA PDF 1.0 does affect on LHC W cross section by ~ 3%.

HERA combined F_2^{cc}

- F_2^{cc} is extracted for large kinematic region.
  - different methods
    - D mesons by slow pions
    - Impact parameter tagging
    - Muons from semi-leptonic decay
  - different data sets
    - HERA I and II (partial)

→ Combination gives very precise data.

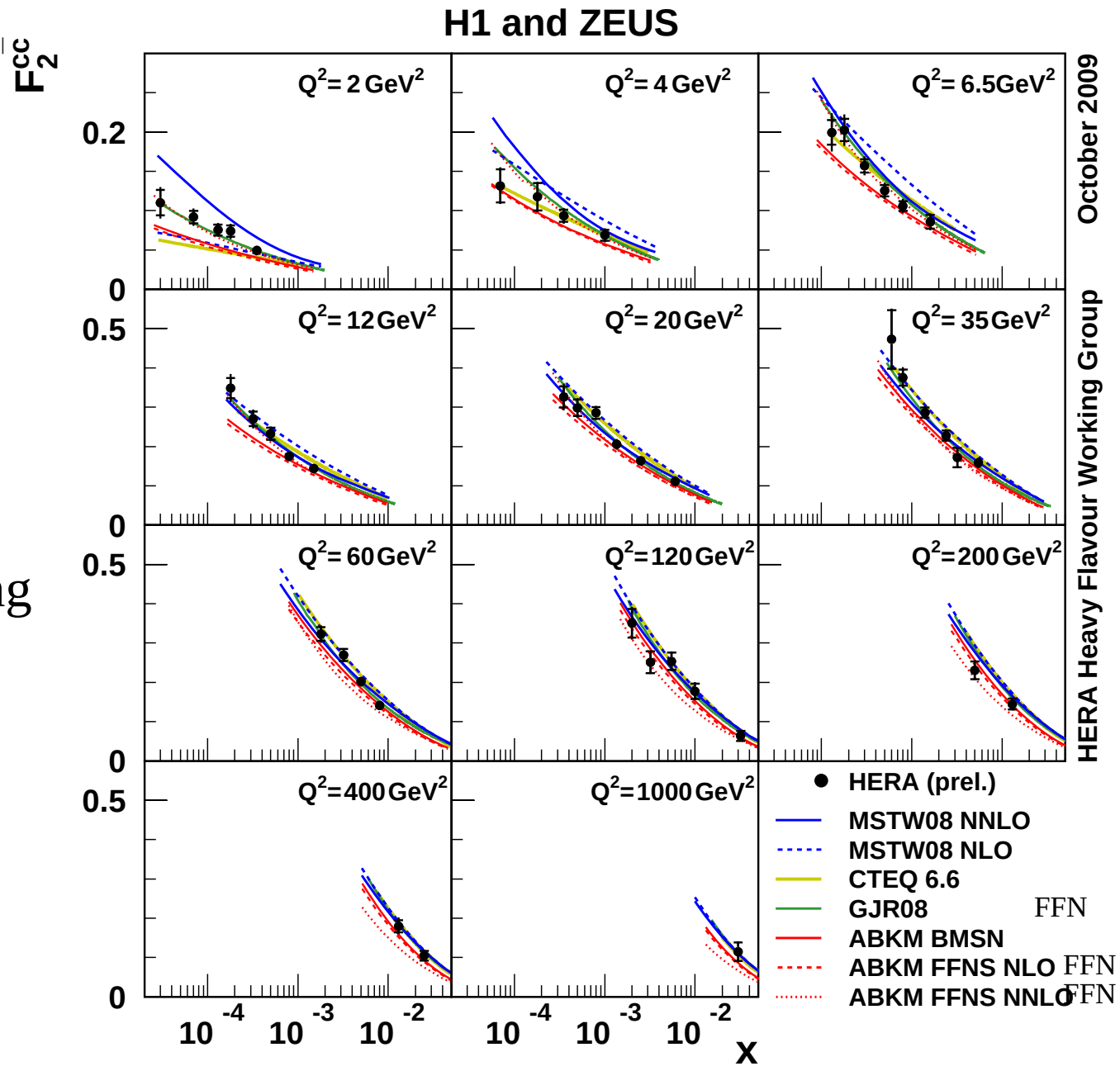


HERA F_2^{cc}

Precision is 5-10%.

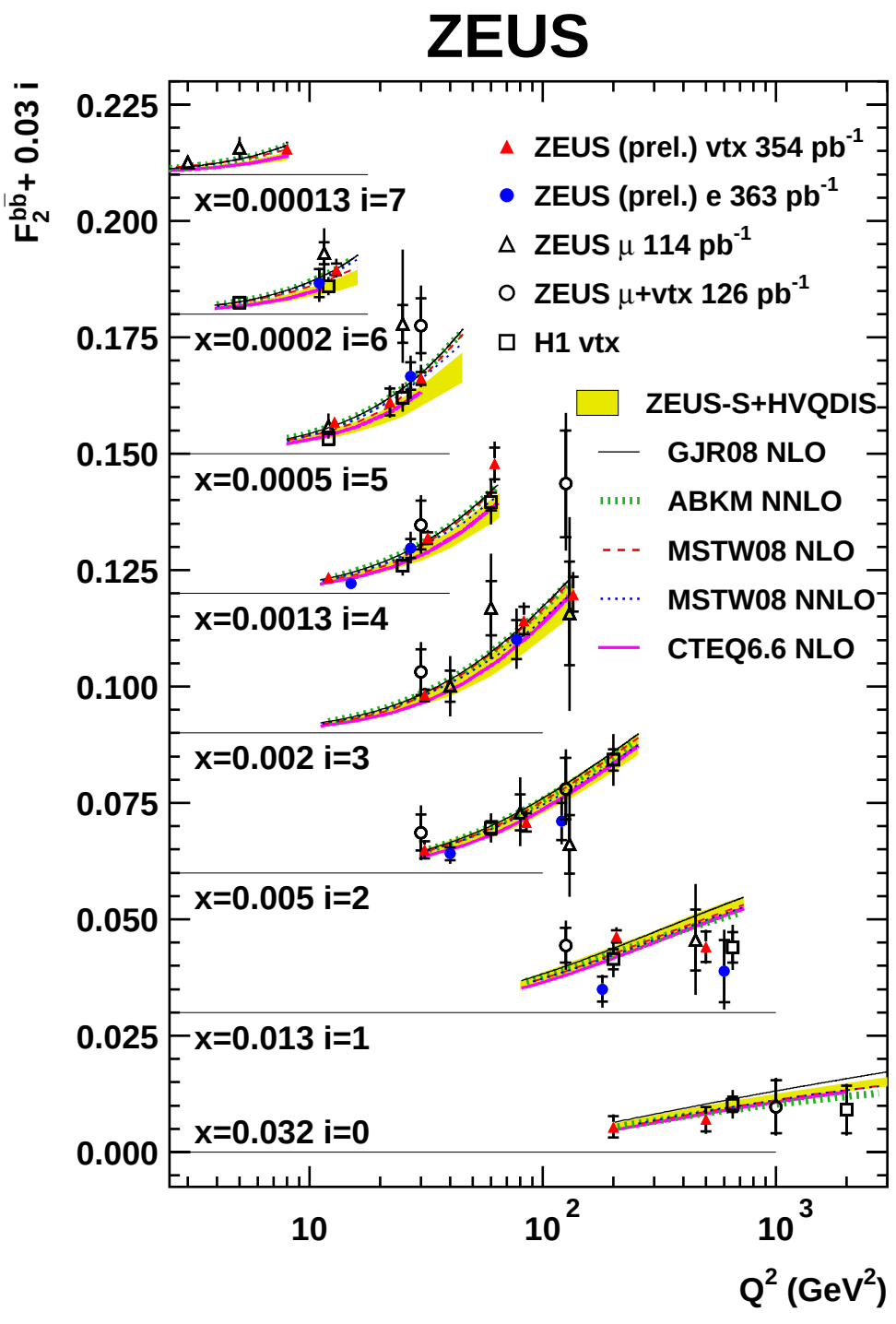
Possible to constrain theory calculation.

→ Better understanding of charm treatment and m_c in QCD fits can be expected.



F_2^{bb}

- Methods:
  - Impact parameter
  - tagging, μ +jet
- Measurements are consistent with each other.
- Combination of H1+ZEUS will provides improved precision



Summary

HERA results are valuable input for to understand the proton structure.

- Combination of H1 and ZEUS measurements provides very precise data.

  → A very good PDF determination in HERA PDF1.0.

- Using the full HERA II statistics, the analyses of high-Q^2 NC/CC, jets and heavy flavour processes will improve the precision of the results.

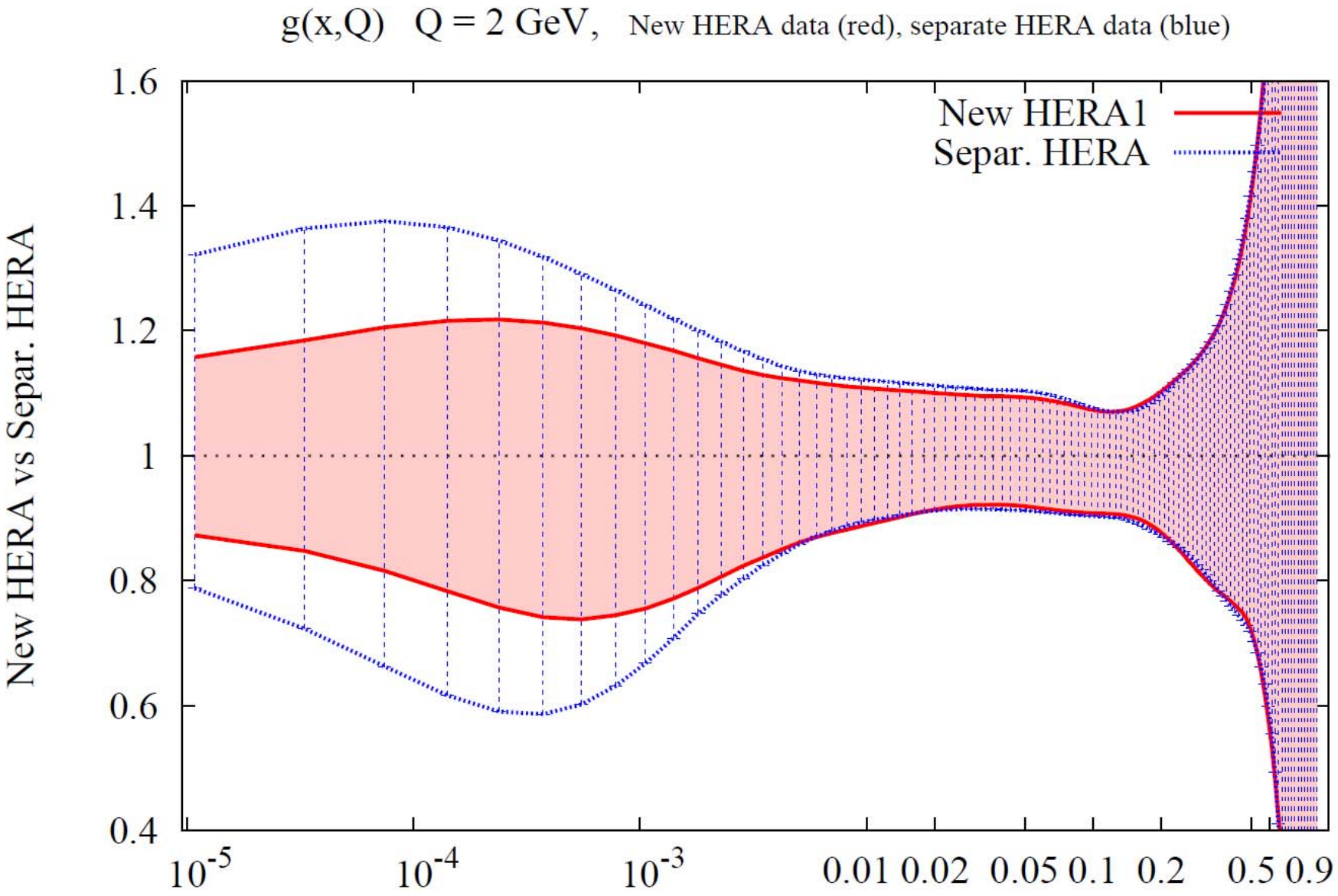
  → Further understanding of the proton structure may come.

Backup

Input for HERA I combined data

Data Set		x Range		Q^2 Range GeV^2		$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	e^+p	301-319
H1 low Q^2	96-00	2×10^{-4}	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	2×10^{-6}	6×10^{-5}	0.11	0.65	1.65	e^+p	301
ZEUS BPT	97	6×10^{-7}	0.001	0.045	0.65	3.9	e^+p	301
ZEUS SVX	95	1.2×10^{-5}	0.0019	0.6	17	0.2	e^+p	301
ZEUS NC	96-97	6×10^{-5}	0.65	2.7	30000	30.0	e^+p	301
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	301
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	319
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	319
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	319
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	319

Impact of combined data on CTEQ PDFs



from M. Guzzi, DIS2010, Floarence