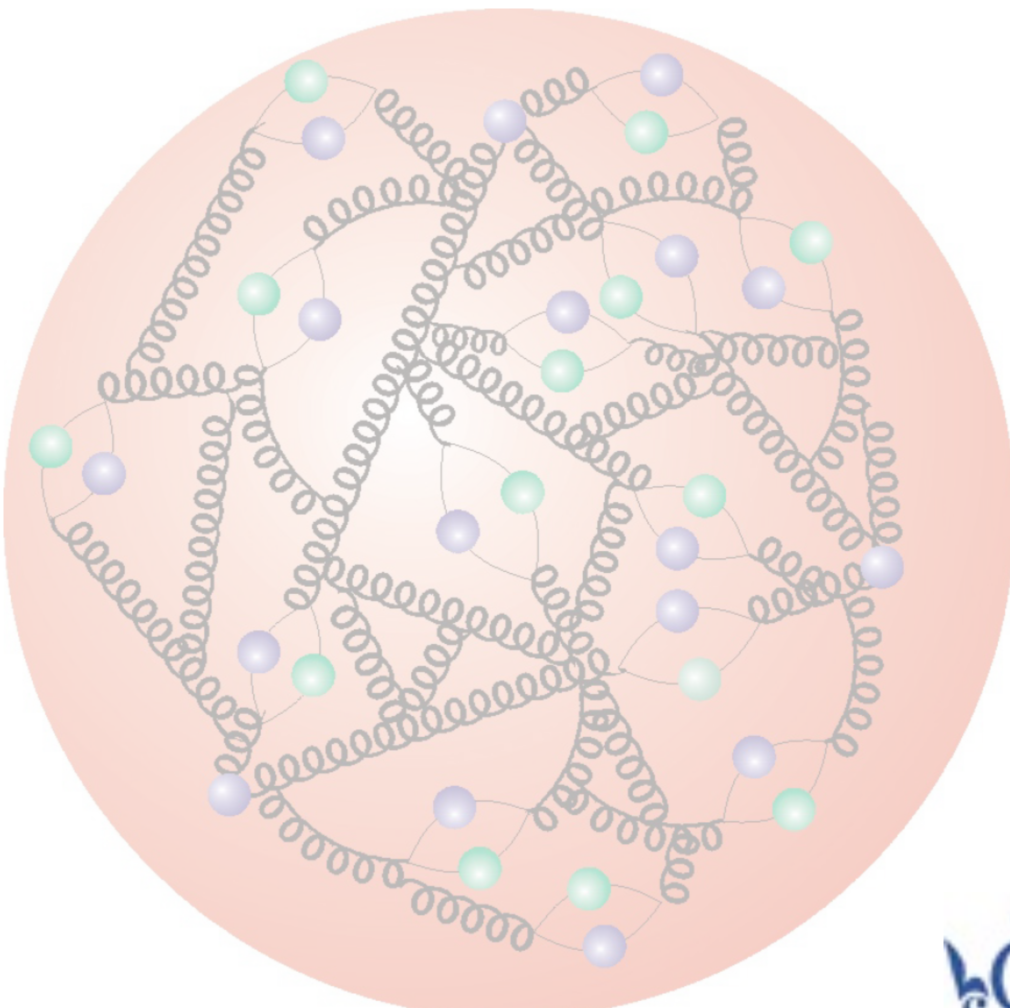
Structure Functions and PDFs From HERA to LHC



- Introduction
- High y and F_L
- F_2 at medium Q^2
- High Q^2
- QCD Fits
- Charm Mass Constraints

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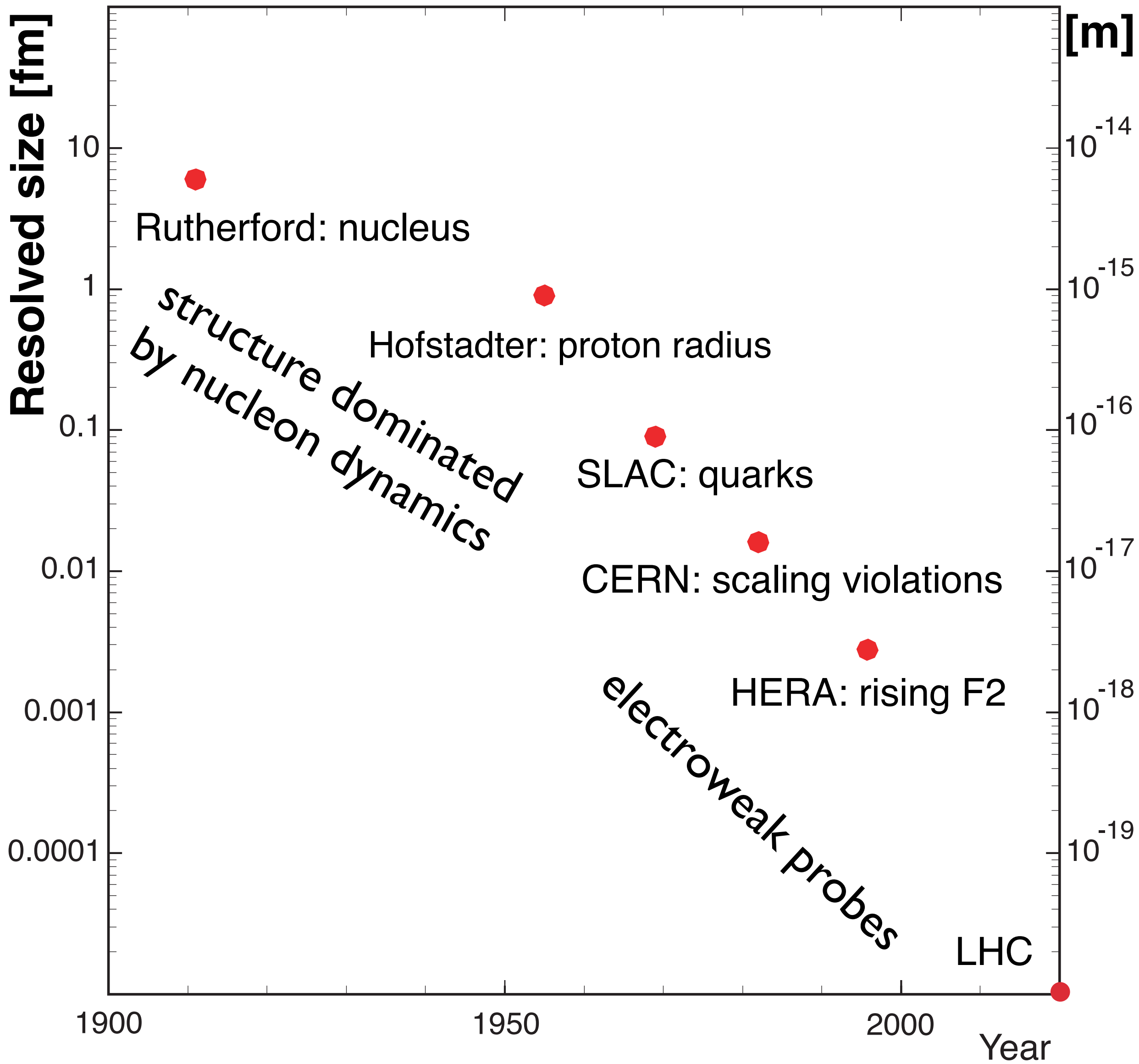
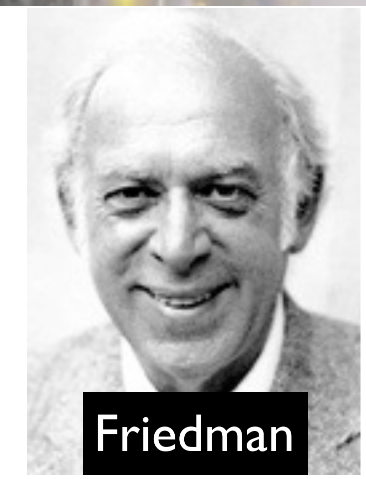
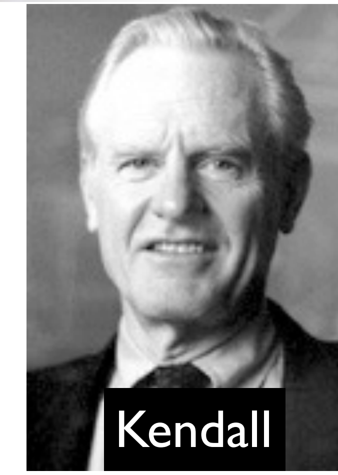
International Conference on Structure and Interactions of the Photon
Spa, Belgium
22nd - 27th May 2011

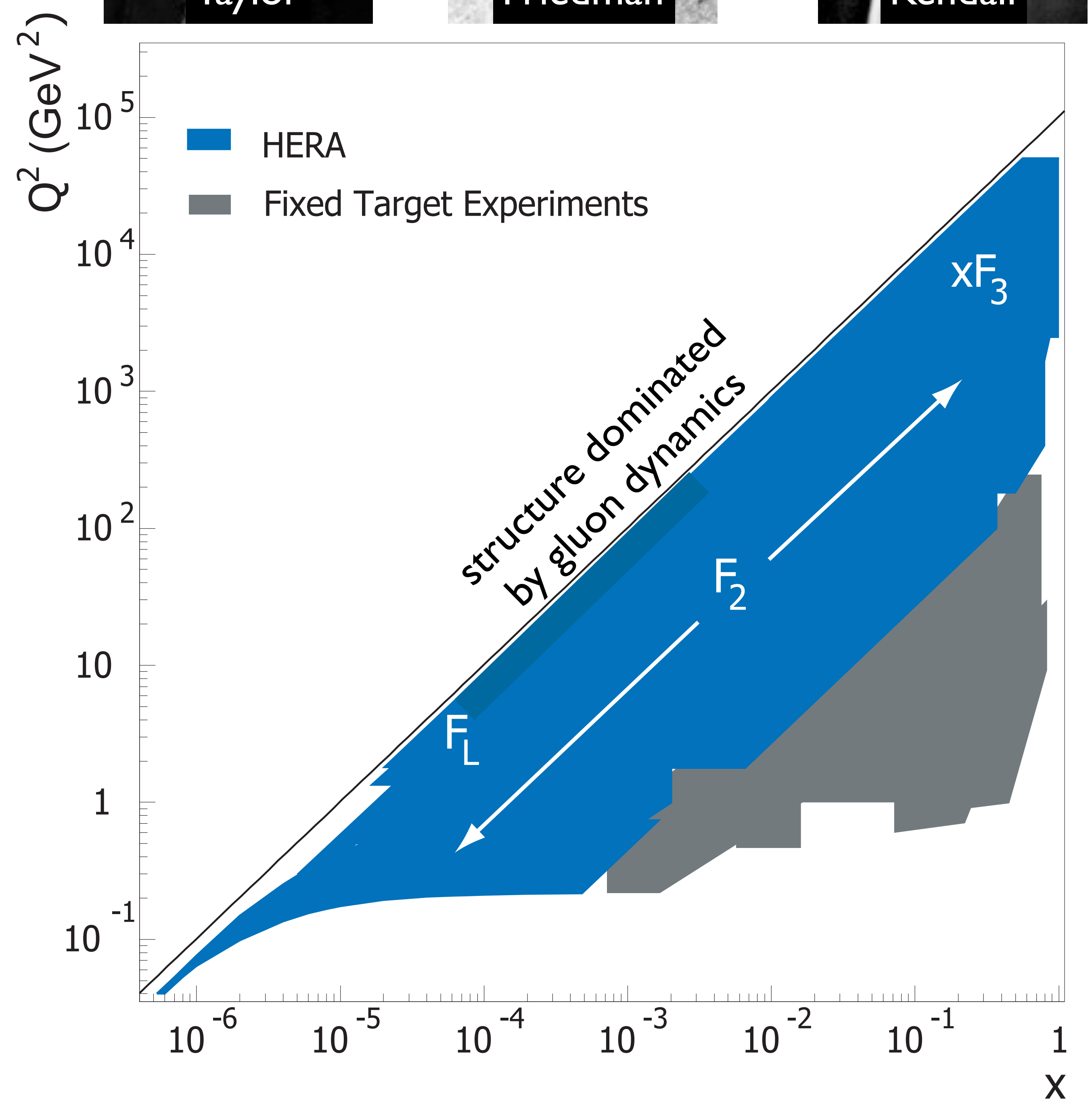
A Century of Virtual Photon Probes

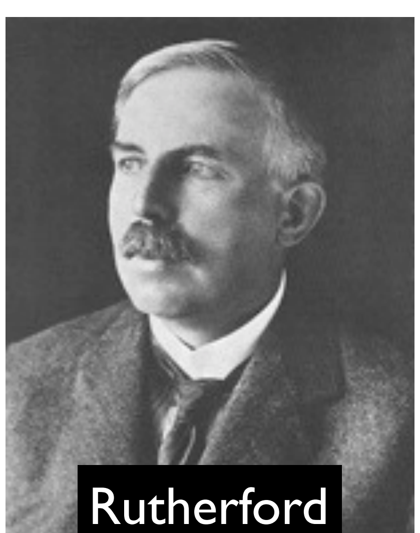


Nobel Prize 1990



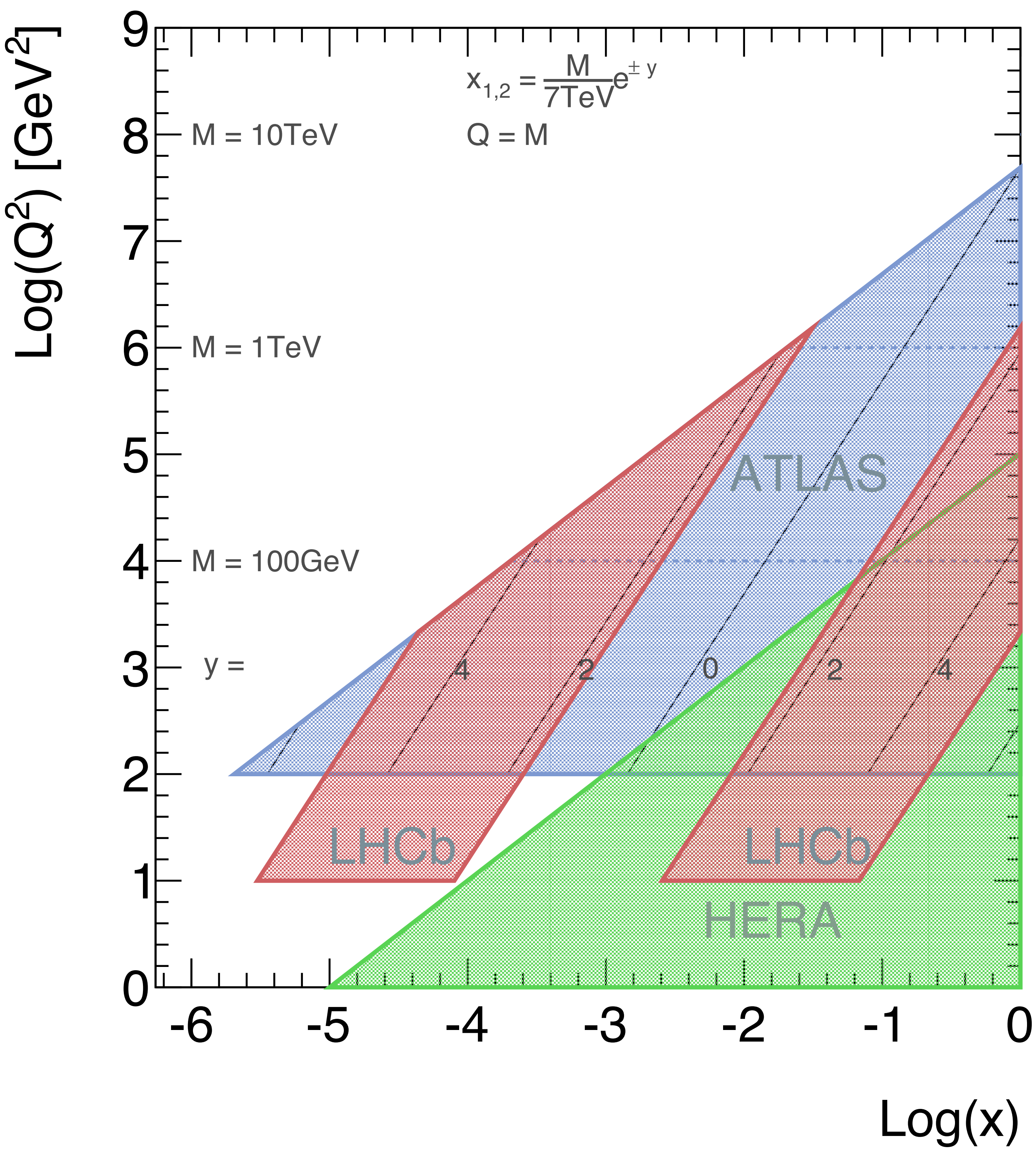






Nobel Prize 1961

Where Are We Going?



LHC: largest mass states at large x

For central production $x=x_1=x_2$

$$M=x\sqrt{s}$$

i.e. M > 1 TeV probes x>0.1

Searches for high mass states require precision knowledge at high x

Z′ / quantum gravity / susy searches...

DGLAP evolution allows predictions to be made

High x predictions rely on

- data (DIS / fixed target)
- sum rules
- behaviour of PDFs as $x \to 1$

$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

modified at high Q^2 by Z exchange

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2\left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

Structure functions parameterise proton structure: how far from point-like

For point-like proton: $$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{e^4}{8\pi x}\frac{1}{Q^4}Y_+$$

Like Rutherford scattering

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

Dominant contribution

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

Only sensitive at high $Q^2 \sim M_Z^2$

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

Only sensitive at low Q^2 and high y

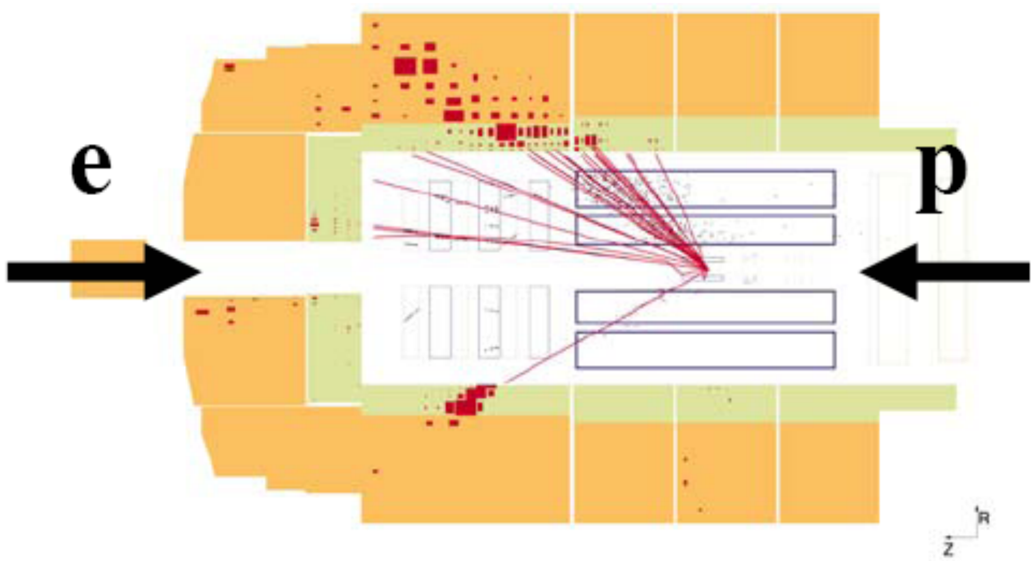
$$\tilde{\sigma}^{\pm}_{NC} = \frac{Q^2 x}{2\alpha\pi^2}\frac{1}{Y_+}\frac{d^2\sigma^{\pm}}{dxdQ^2}$$

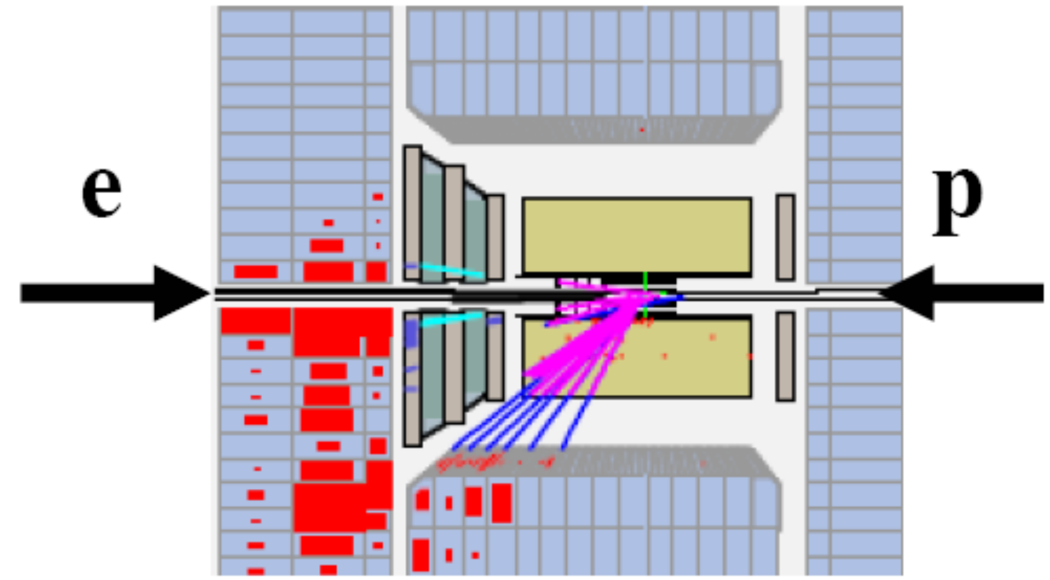
$$\tilde{\sigma}^{\pm}_{NC} \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

similarly for CC analogues:

$W_2^{\pm}$, $xW_3^{\pm}$ and $W_L^{\pm}$

H1 and ZEUS





Neutral current event selection:

High P_T isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways:
energy/angle of hadrons & scattered lepton
provides excellent tools for sys cross checks

Removal of scattered lepton provides a
high stats "pseudo-charged current sample"
Excellent tool to cross check CC analysis

Final selection: ~10^5 events per sample at high Q^2
~10^7 events for $10 < Q^2 < 100$ GeV^2

Charged current event selection:

Large missing transverse momentum (neutrino)

Suppress huge photo-production background

Topological finders to remove cosmic muons

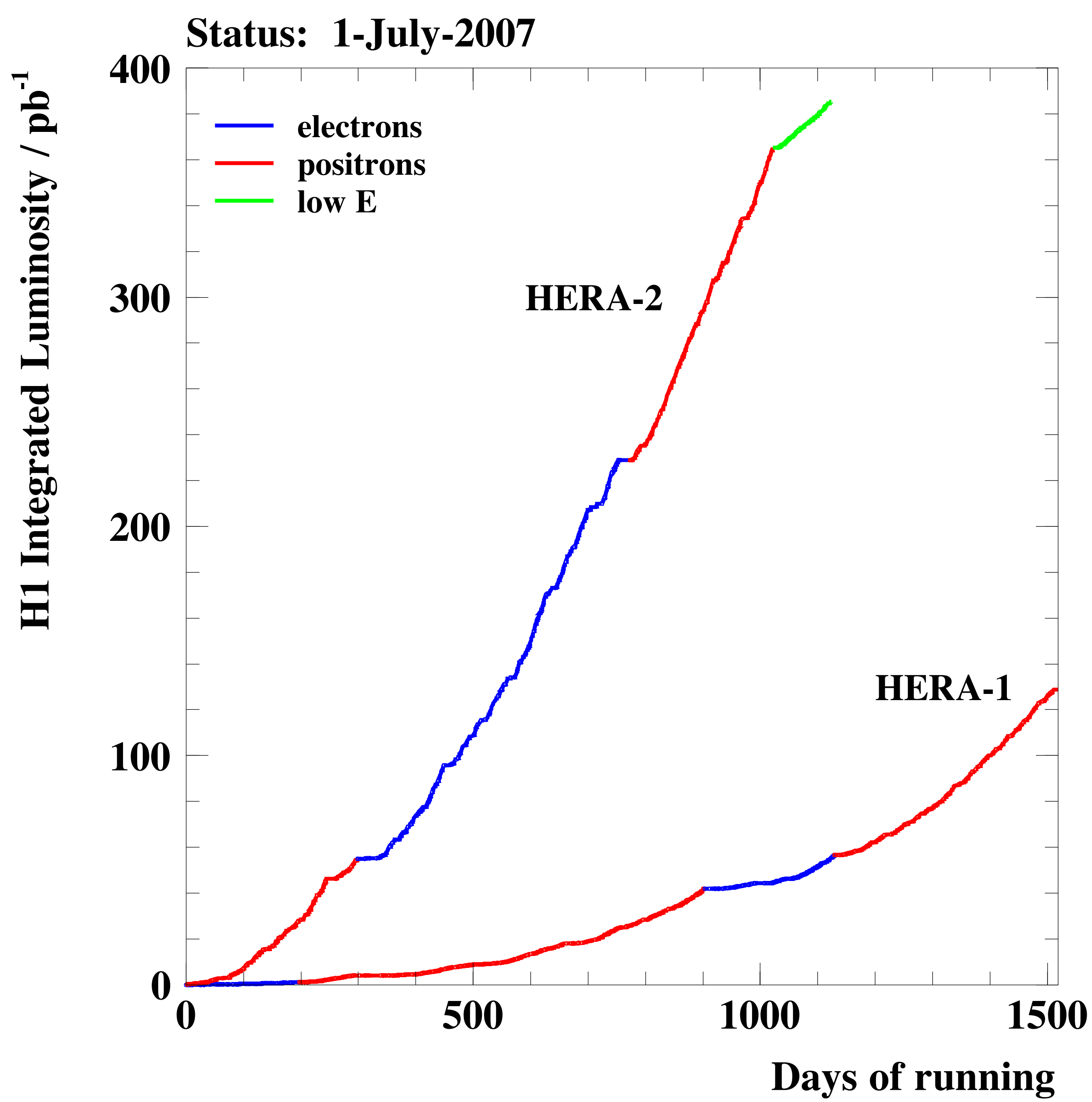
Kinematics reconstructed from hadrons

Final selection: ~10^3 events per sample

<u>HERA-1 operation 1993-2000</u>
Ee = 27.6 GeV
Ep = 820 / 920 GeV
$\int\mathcal{L}$ ~ 110 pb^{-1} per experiment

<u>HERA-II operation 2003-2007</u>
Ee = 27.6 GeV
Ep = 920 GeV
$\int\mathcal{L}$ ~ 330 pb^{-1} per experiment
Longitudinally polarised leptons

<u>Low Energy Run 2007</u>
Ee = 27.6 GeV
Ep = 575 & 460 GeV
Dedicated F_L measurement



HERA Structure Function 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

Summary of HERA-I datasets Combined in HERAPDF1.0

ZEUS CC e^-p	175 pb^{-1}	EPJ C 61 (2009) 223-235
ZEUS CC e^+p	132 pb^{-1}	EPJ C 70 (2010) 945-963
ZEUS NC e^-p	170 pb^{-1}	EPJ C 62 (2009) 625-658
ZEUS NC e^+p	135 pb^{-1}	ZEUS-prel-11-003
H1 CC e^-p	149 pb^{-1}	H1prelim-09-043
H1 CC e^+p	180 pb^{-1}	H1prelim-09-043
H1 NC e^-p	149 pb^{-1}	H1prelim-09-042
H1 NC e^+p	180 pb^{-1}	H1prelim-09-042

HERA-II datasets
Combined in HERAPDF1.5
(except ZEUS NC e^+p)

Direct Measurement of F_L

Eur. Phys. J. C71, 2011 1579

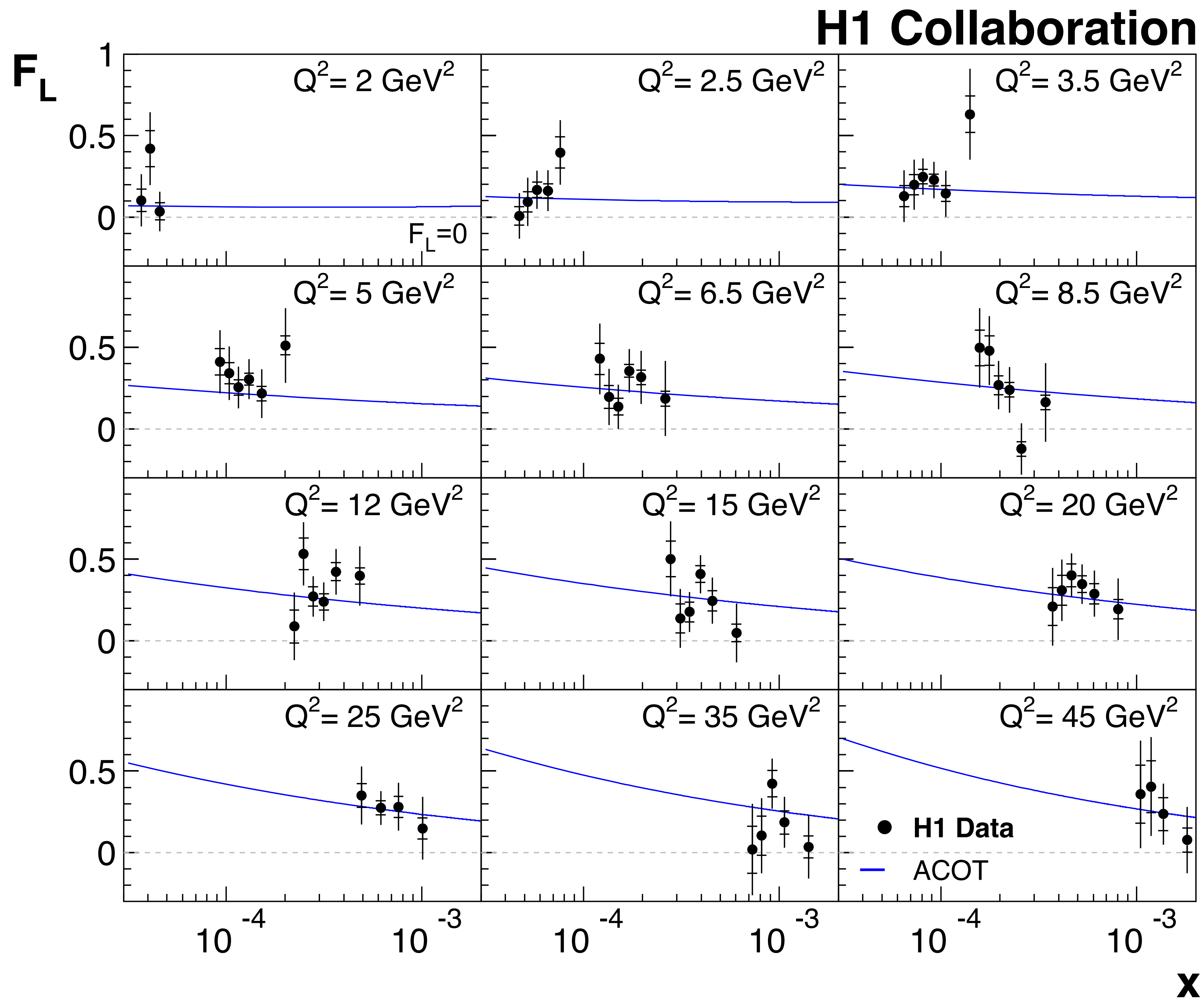
$$\sigma_{NC} = F_2 - \frac{y^2}{Y_+} F_L \qquad Y_+ = 1 + (1-y)^2$$

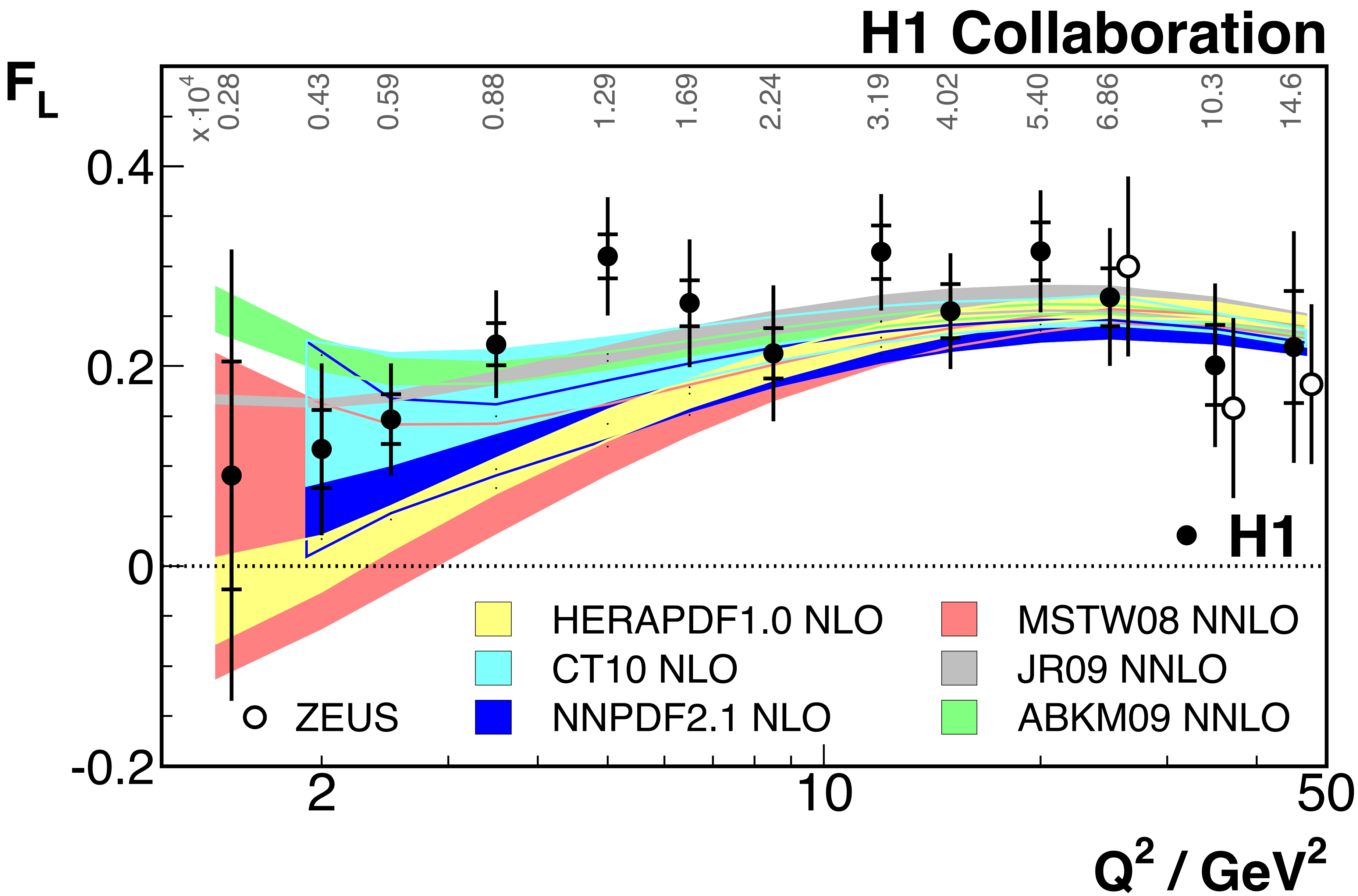
Since $y = \frac{Q^2}{sx}$

then measuring cross section at fixed x, Q^2 but different $y \Rightarrow F_L$

Use three values of $\sqrt{s}$ = 318 , 252 and 225 GeV

Important and direct method to access $xg(x,Q^2)$





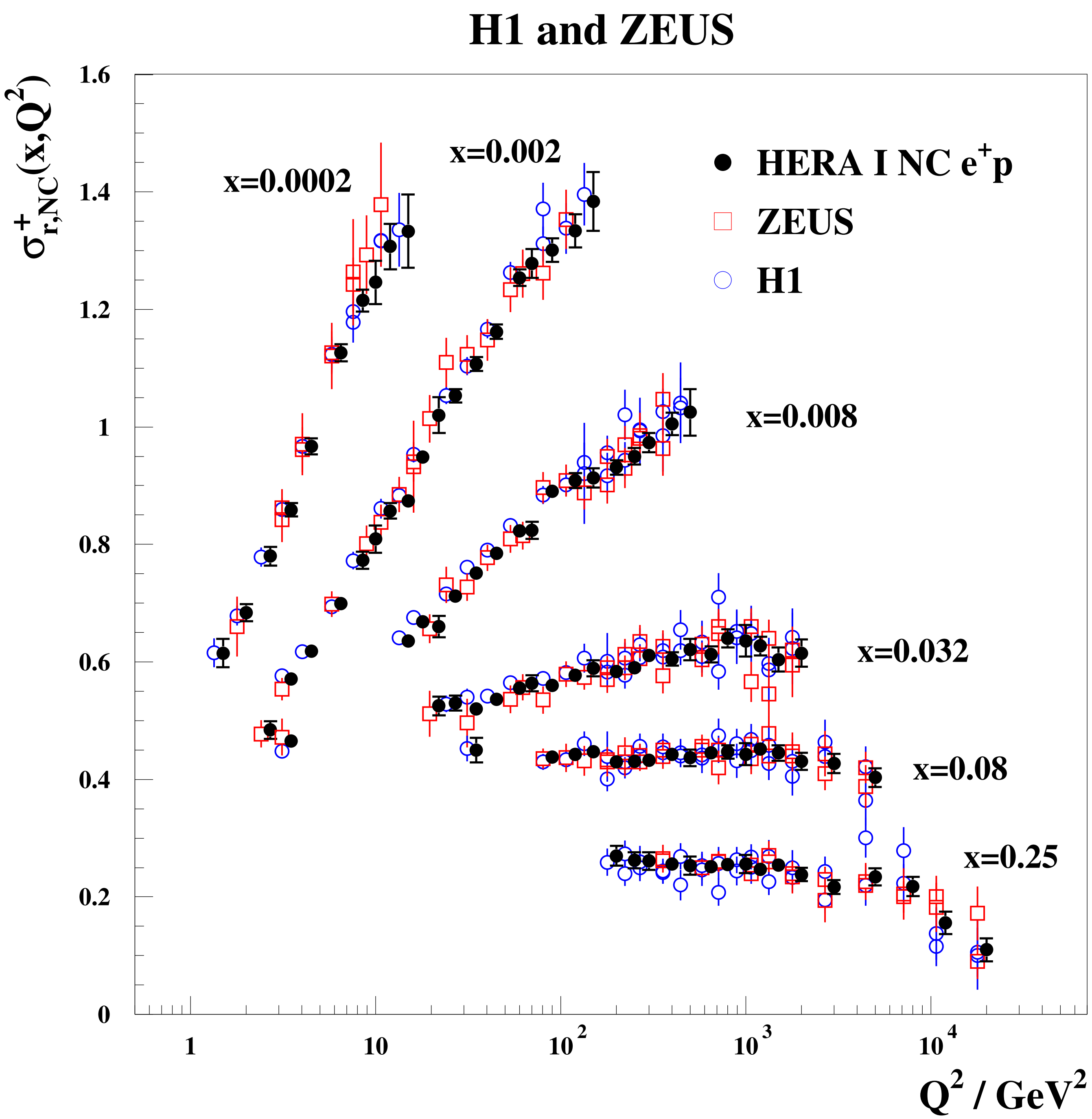
New H1 measurement extends to F_L down to Q^2 ~1.5 GeV^2

Good agreement with ZEUS measurement at higher Q^2

Model predictions describe data reasonably well

Data can provide new constraints to NNLO models

Combined HERA Data



Systematic uncertainties are point-to-point correlated
Average H1 / ZEUS data using χ^2 minimisation
Allow sys error sources free in fit
Constraint of equal cross sections cross calibrates expts.
Different exptl. methods yield different sys errors
Reduce sys uncertainties of both experiments

Data moved to common x,Q^2 grid for averaging
1402 data points → 741 averaged measurements
110 correlated systematic error sources taken into account
All H1/ ZEUS sys treated independently*
3 additional procedural uncertainties are included

χ^2/ndf = 637/656

* except 0.5% normalisation uncertainty

F_2 at Medium Q^2

HERA-I Q^2 from 2 to 120 GeV^2

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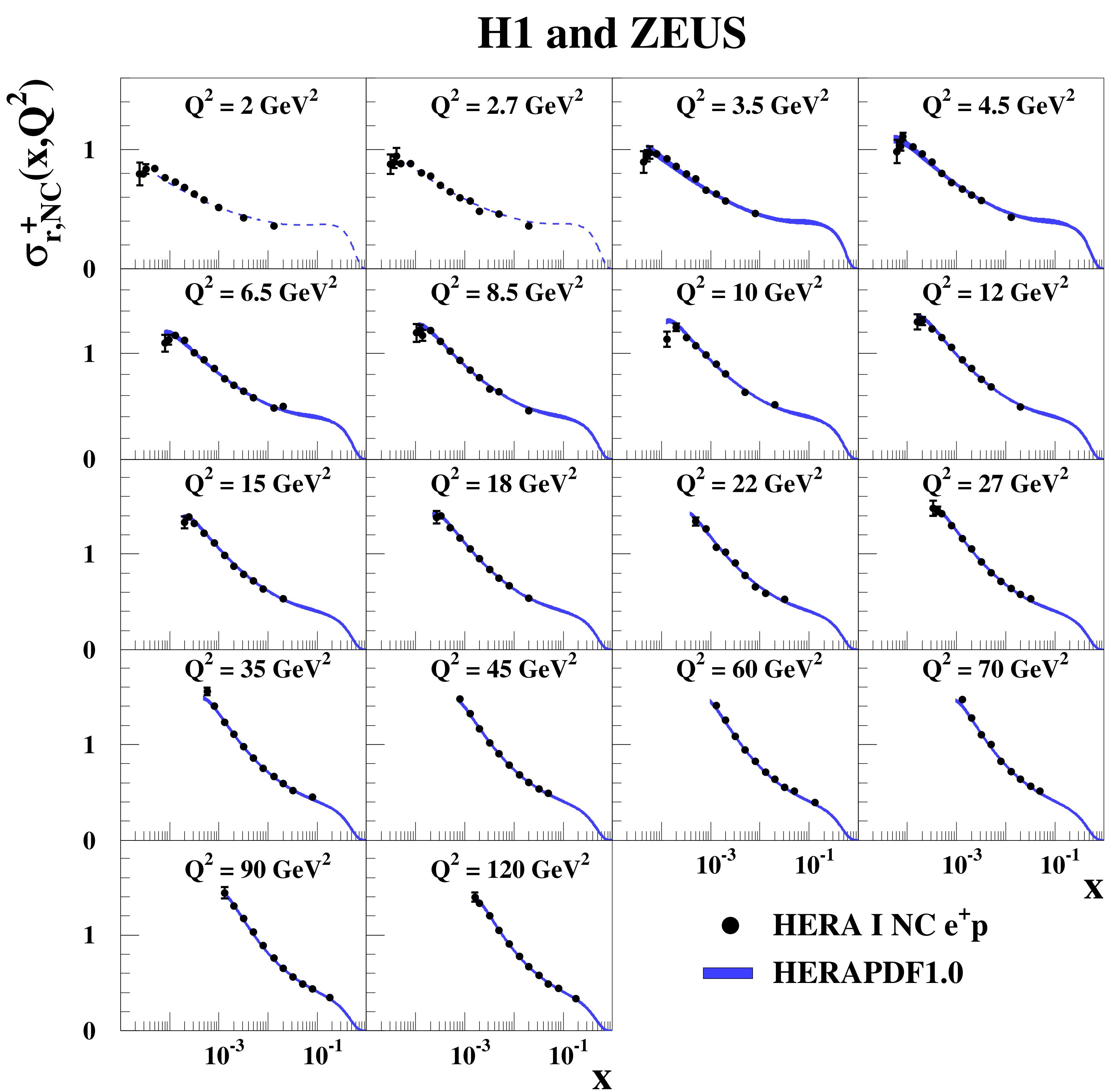

Joint publication from H1 & ZEUS
High precision achieved
Total uncertainty ~1% for 20< Q^2 <100 GeV^2

Data give most stringent constraints on PDFs

Well described by NLO QCD
Fits will be discussed later...

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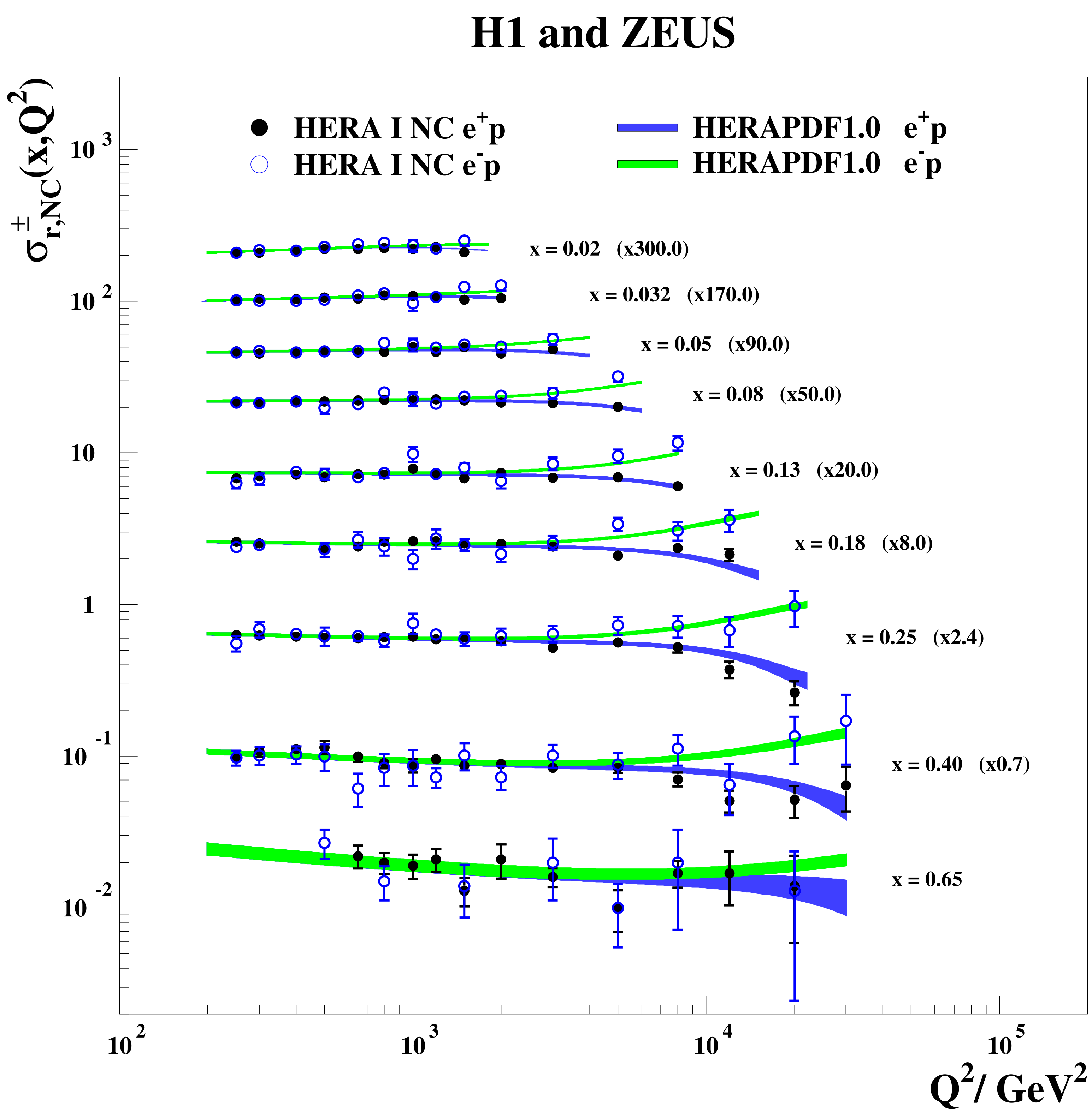
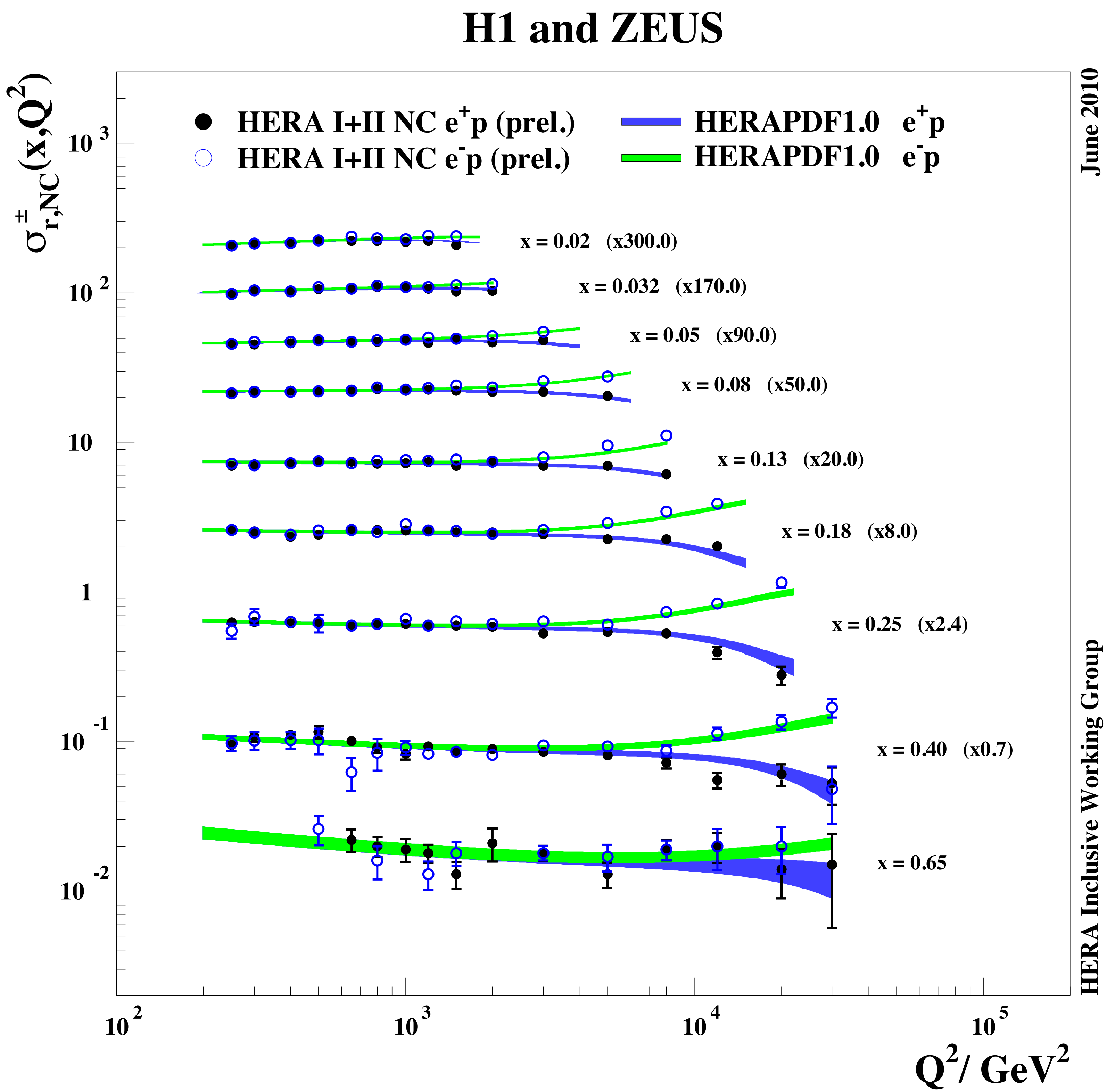


High Q^2 is the EW physics regime
See talk of Friederike Januschek

Precision ~ 2% precision for $Q^2 < 500$ GeV^2
Statistics limited at higher Q^2 and high x

High Q^2 NC Cross Sections

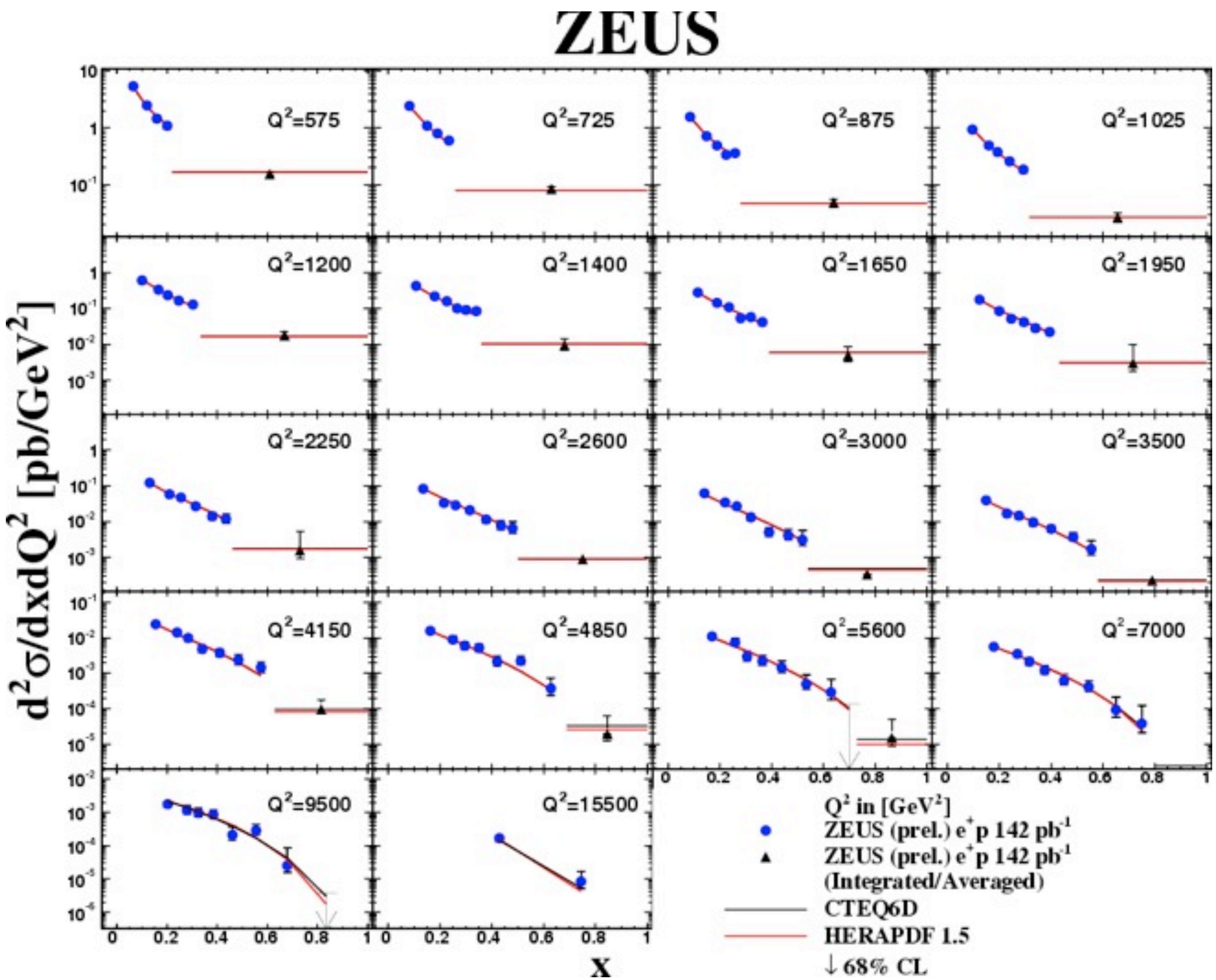
H1-10-141 / ZEUS-prel-10-017



Combination of preliminary high Q^2 data HERA-I and HERA-II

Larger HERA-II luminosity
→ improved precision at high x / Q^2

ZEUS-prel-11-004



New for this conference

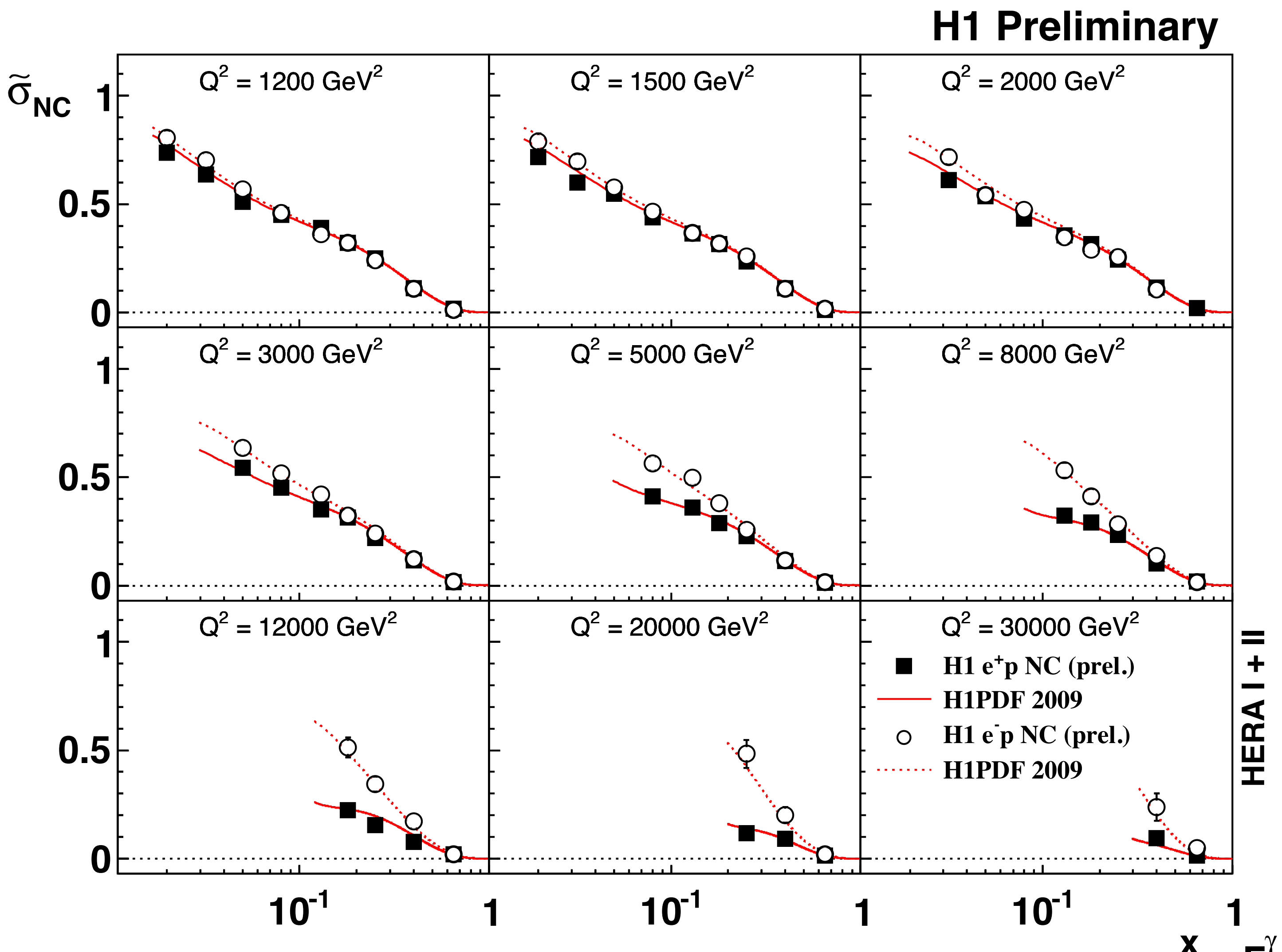
NC measurement at high x

x reconstruction relies on jets

Force jets to balance pT of electron

Gives better x resolution

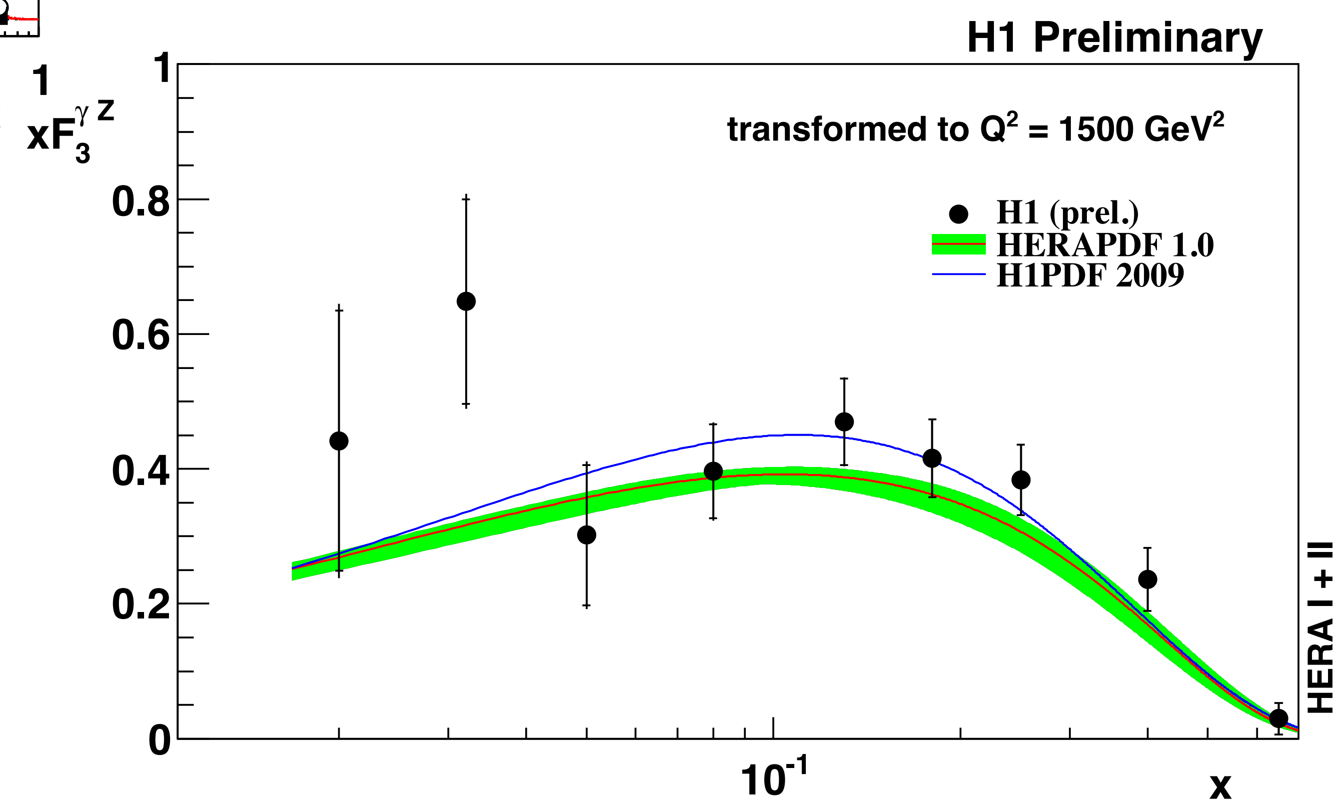
xF_3



At high Q^2 xF_3 arises due to Z^0 effects
enhanced e^- cross section wrt e^+
Difference is xF_3
Sensitive to valence PDFs

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}) \approx a_e \chi_Z x F_3^{\gamma Z}$$

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



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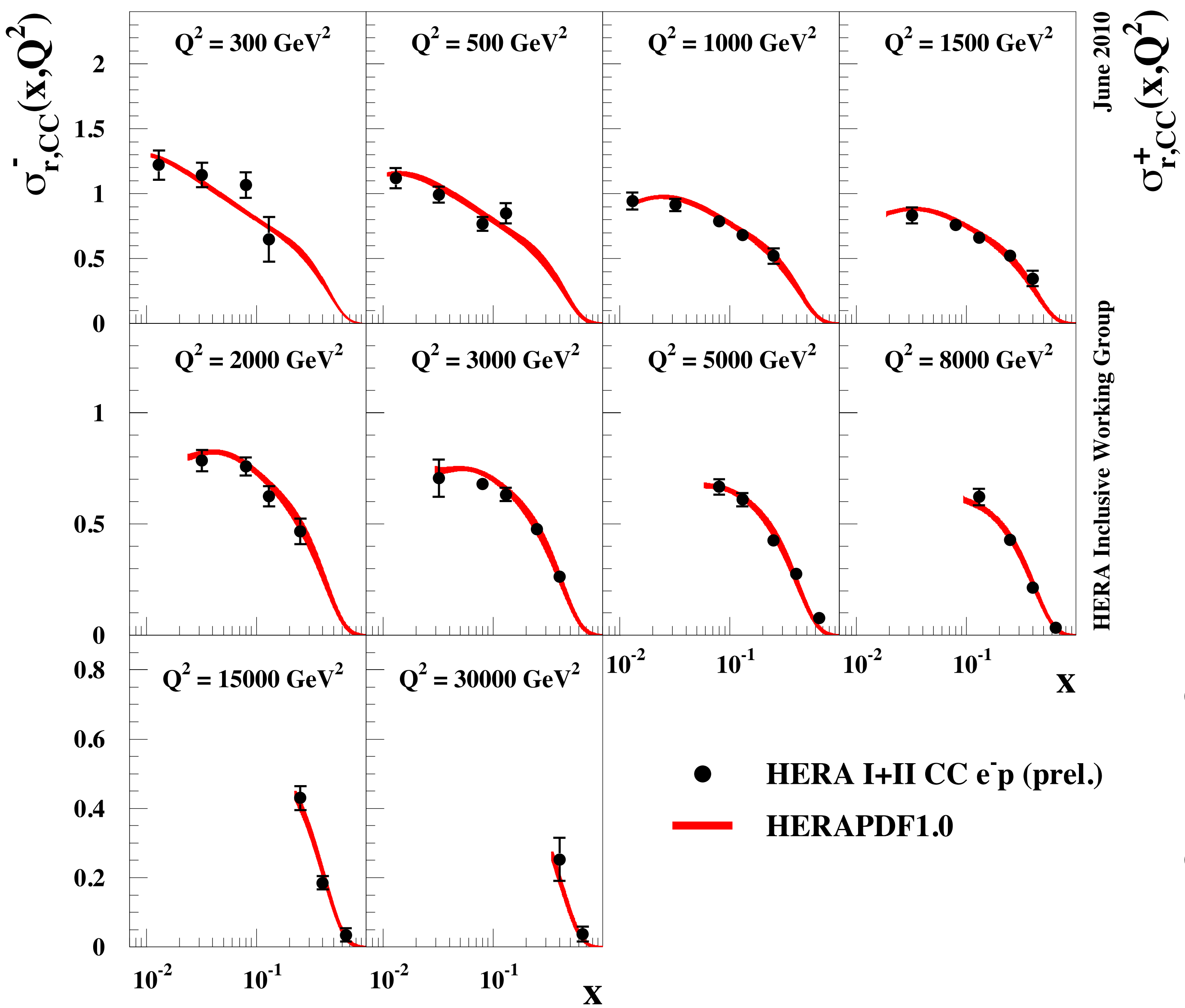
High Q^2 CC Cross Sections

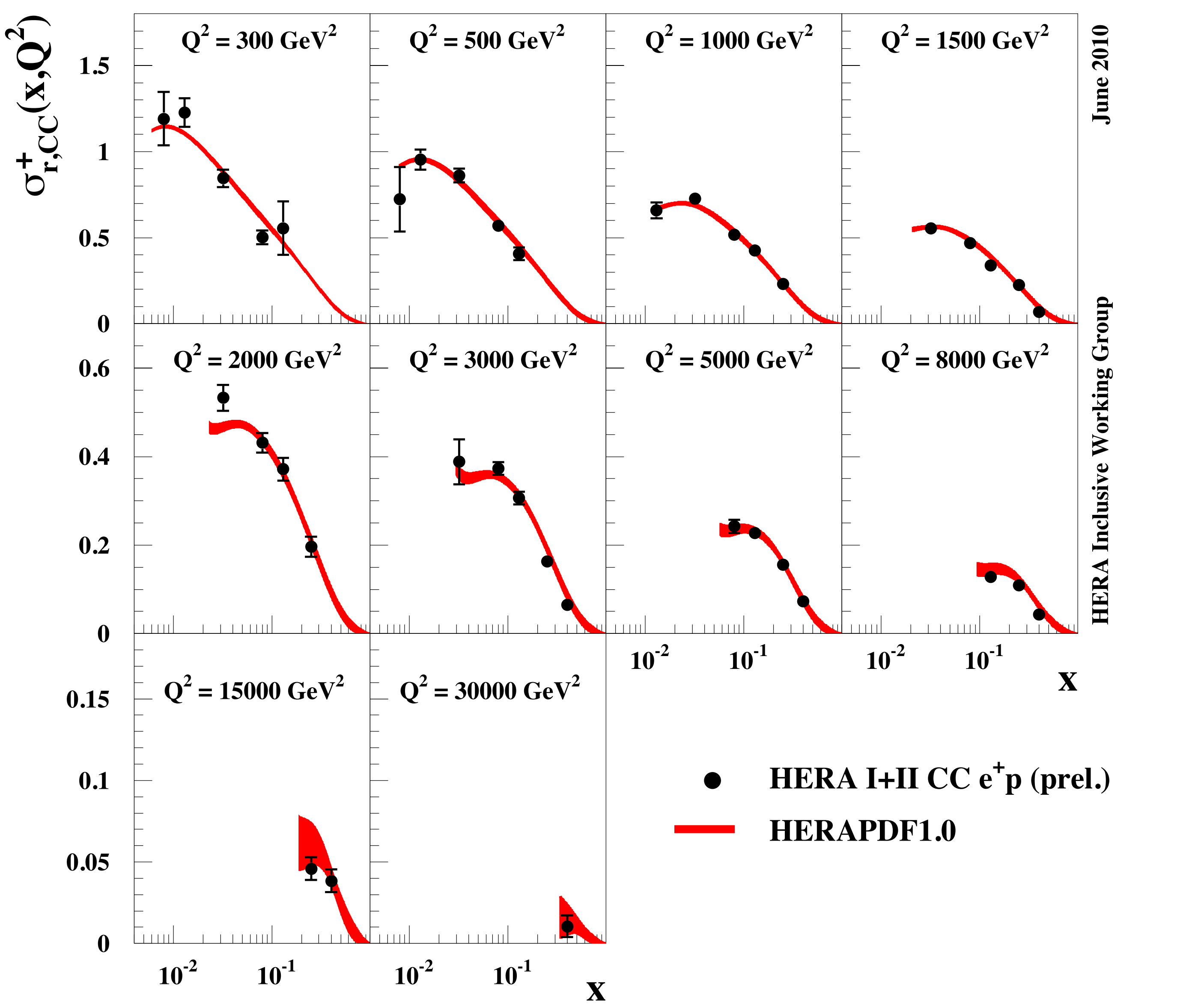
Electron scattering

Positron scattering

$$\frac{d^2\sigma^-_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[(u+c)+(1-y)^2(\bar{d}+\bar{s})\right]$$

$$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[(\bar{u}+\bar{c})+(1-y)^2(d+s)\right]$$





Preliminary combination of High Q^2 CC data
Improvement of total uncertainty
Dominated by statistical errors
Provide important flavour decomposition information

CC e+ data provide strong d_v constraint at high x

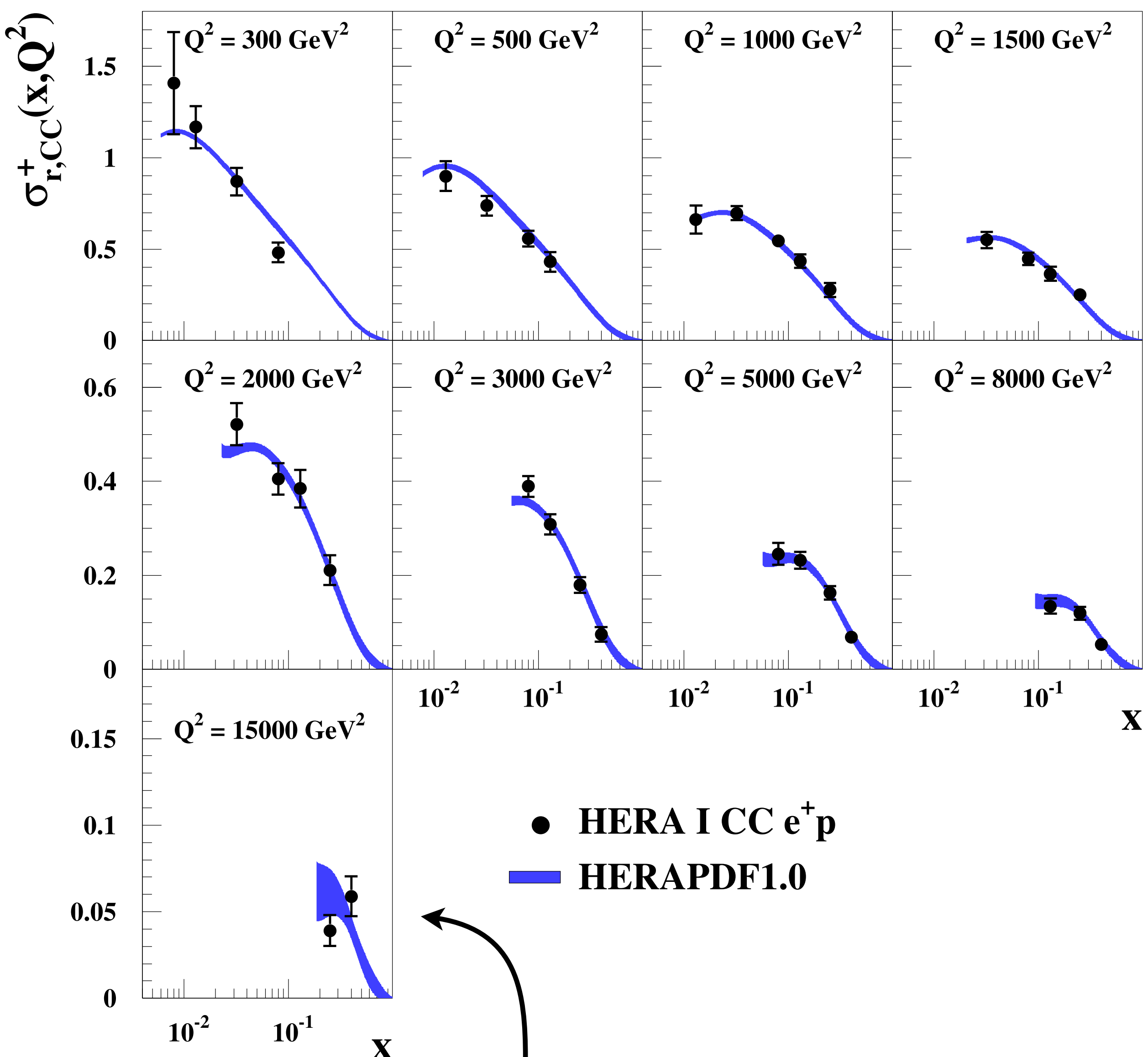
H1-10-141 / ZEUS-prel-10-017

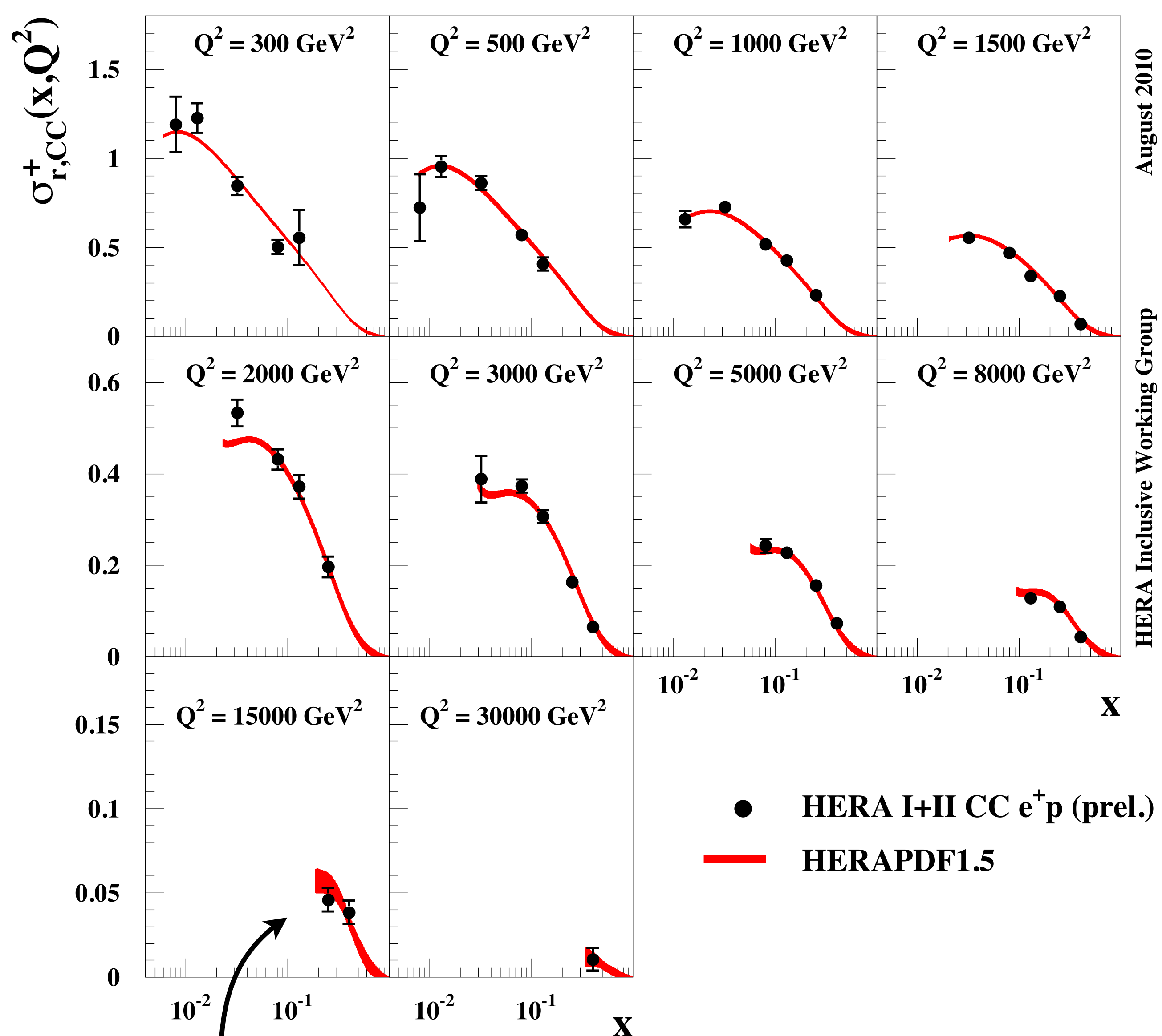
High Q^2 CC Cross Sections

Positron scattering | Positron scattering

HERA-I → HERA-I+II

Significant improvement in measurement precision





Reduced QCD uncertainty at high x

QCD Analysis

HERAPDF1.0
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with10 parameters
α_s = 0.1176 (fixed in fit)

desy-09-158

HERAPDF1.5
Include additional NC and CC HERA-II data
Complete MSbar NLO and NNLO fit
NLO: standard parameterisation with10 parameters
NNLO: extended fit with 14 parameters

H1-10-142 / ZEUS-prel-10-018

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C \cdot (1 + Dx + Ex^2)$$

$$xg,\quad xu_v,\quad xd_v,\quad x\bar{U},\quad x\bar{D} \;\longrightarrow\; xg,\quad xU = xu + xc,\quad xD = xd + xs,\quad x\bar{U} = x\bar{u} + x\bar{c},\quad x\bar{D} = x\bar{d} + x\bar{s} \;\longrightarrow$$

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

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

Apply momentum/counting sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

Parameter constraints:
$B_{uv} = B_{dv}$
$B_{Ubar} = B_{Dbar}$
sea = 2 x (Ubar +Dbar)
Ubar = Dbar at x=0

Q_0^2 = 1.9 GeV^2 (below m_c)
Q^2 > 3.5 GeV^2
2 x $10^{-4} < x <$ 0.65
Fits performed using RT-VFNS

HERAPDF1.0 central values:

	A	B	C	E
xg	6.8	0.22	9.0	
xu_v	3.7	0.67	4.7	9.7
xd_v	2.2	0.67	4.3	
$x\bar{U}$	0.113	−0.165	2.6	
$x\bar{D}$	0.163	−0.165	2.4	

χ^2/ndf = 574/582

Experimental systematic sources of uncertainty allowed to float in fit
Include model assumptions into uncertainty:
f_s , m_c , m_b , $Q^2{}_0$, $Q^2{}_{min}$

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	$1.35^{(a)}$	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	$1.5^{(b)}$	$2.5^{(c,d)}$

$^{(a)}Q^2_0 = 1.8$ $^{(c)}m_c = 1.6$
$^{(b)}f_s = 0.29$ $^{(d)}f_s = 0.34$

Excellent consistency of input data allow standard statistical error definition:
$\Delta\chi^2 = 1$

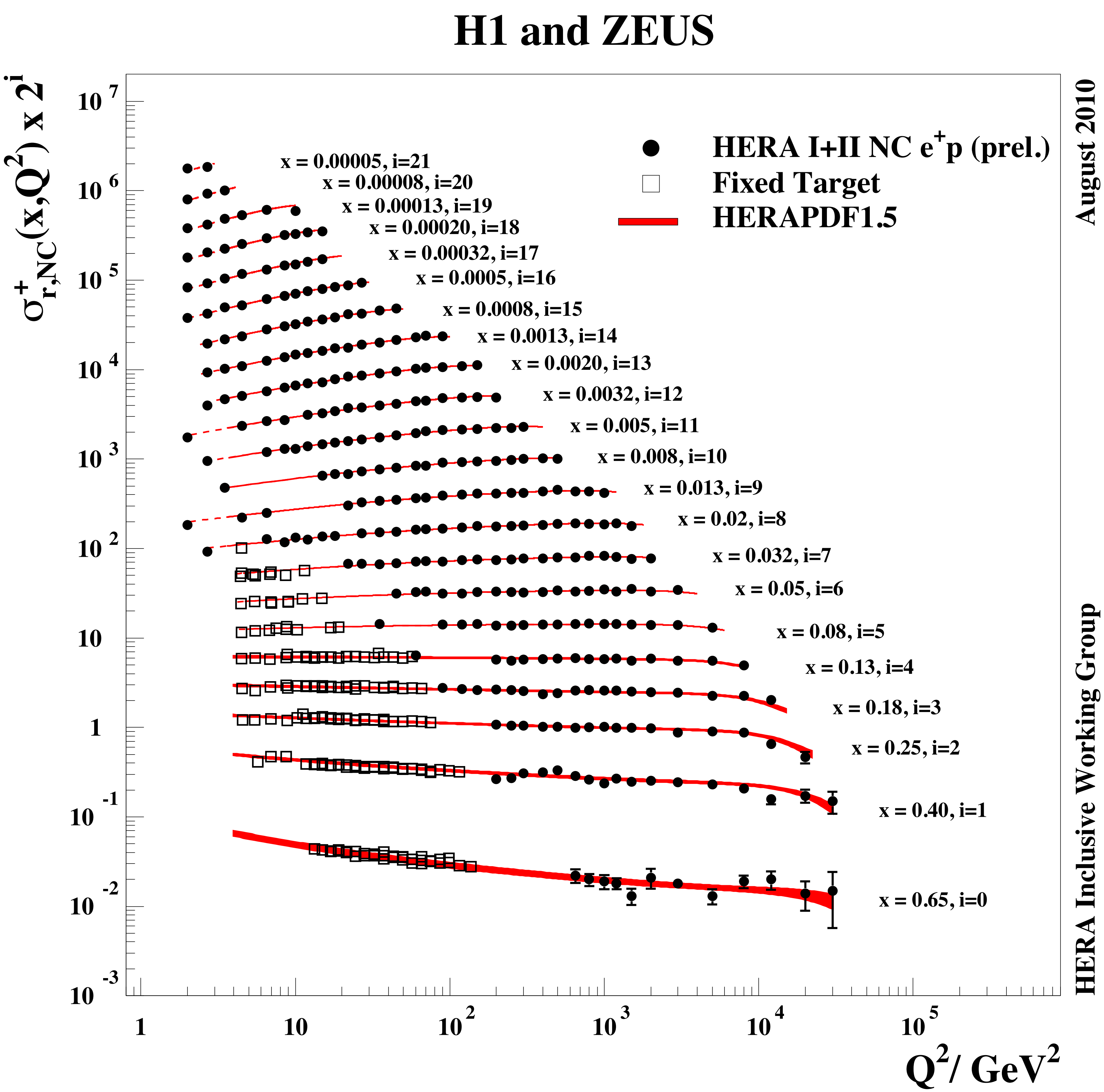
Exclusive jet data required for free α_s fit
See talk of Krzysztof Nowak

In 14 parameter fit:
release $B_{uv} = B_{dv}$ constraint
allow more flexible gluon

$$xg(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C - A' \cdot x^{B'} \cdot (1-x)^{25}$$

allows for valence-like or negative gluon at Q_0^2

High Q^2 NC Cross Sections



Latest H1/ZEUS combination

Uses complete NC/CC data

(not incl. ZEUS NC e+p)

Excellent agreement over full phase space

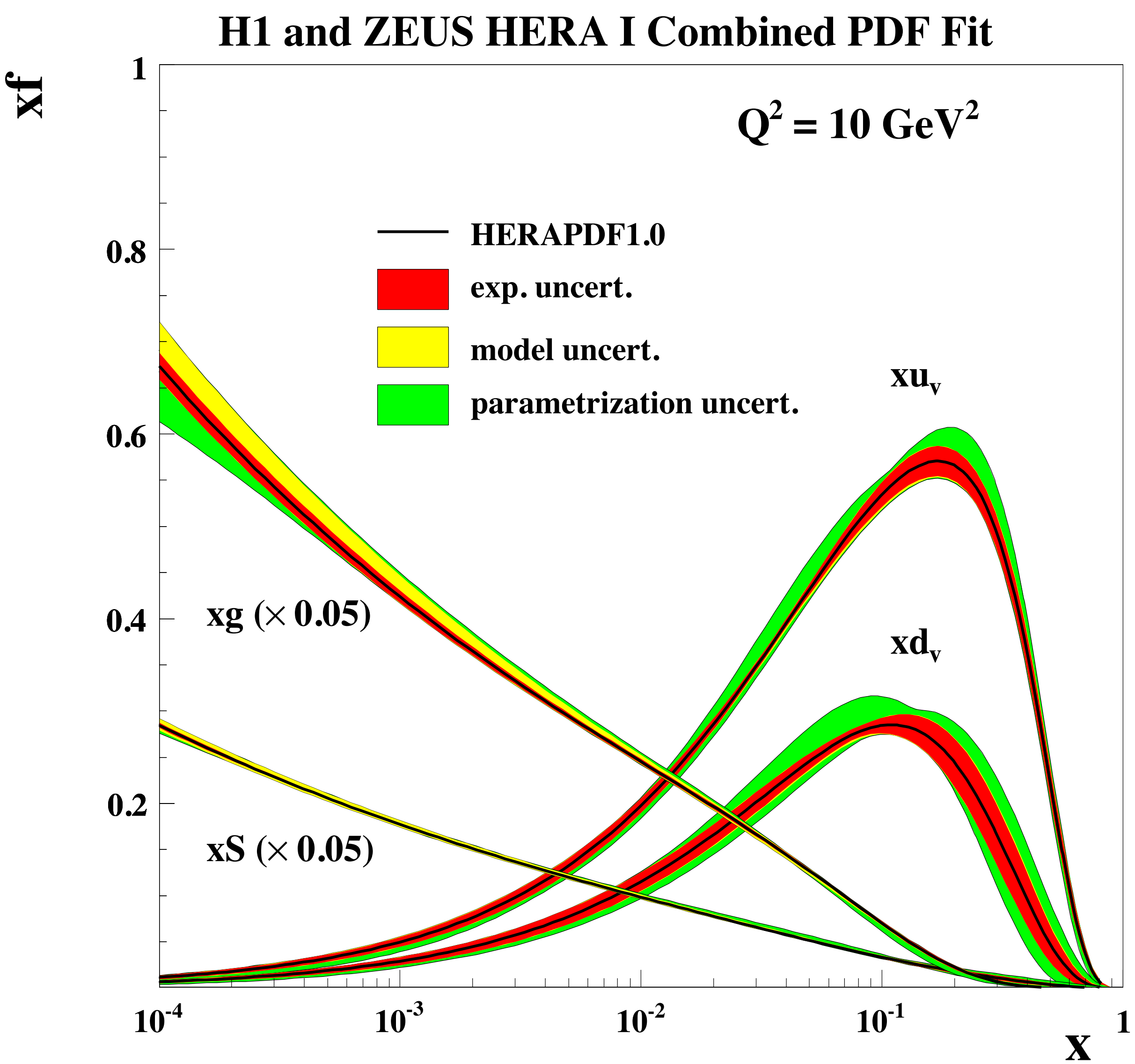
Consistent description of fixed target data

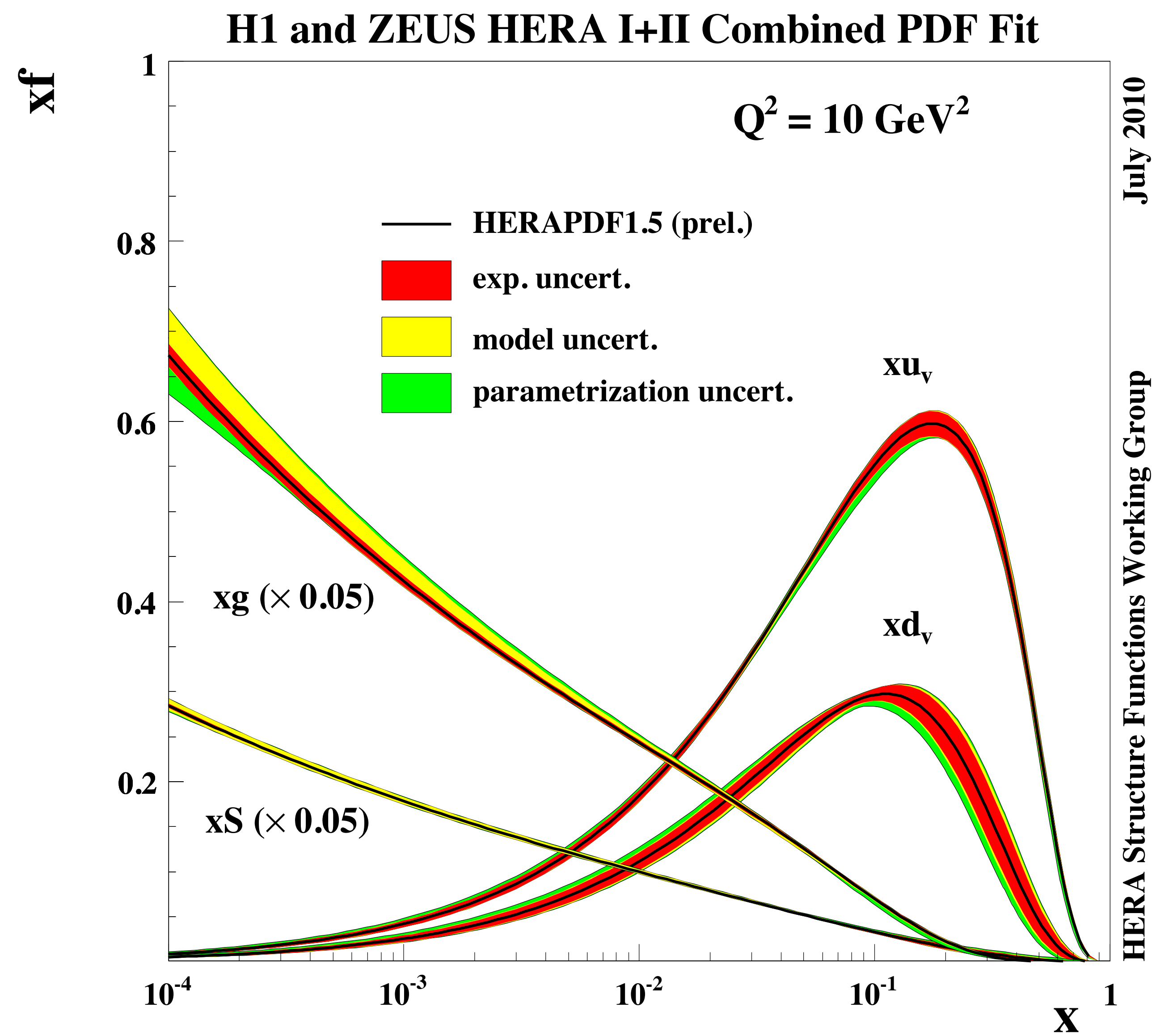
Strong scaling violations at fixed x

⇒ large gluon density

HERA-I ⟶ HERA-I+II

Improved precision on PDFs when including HERA-II data





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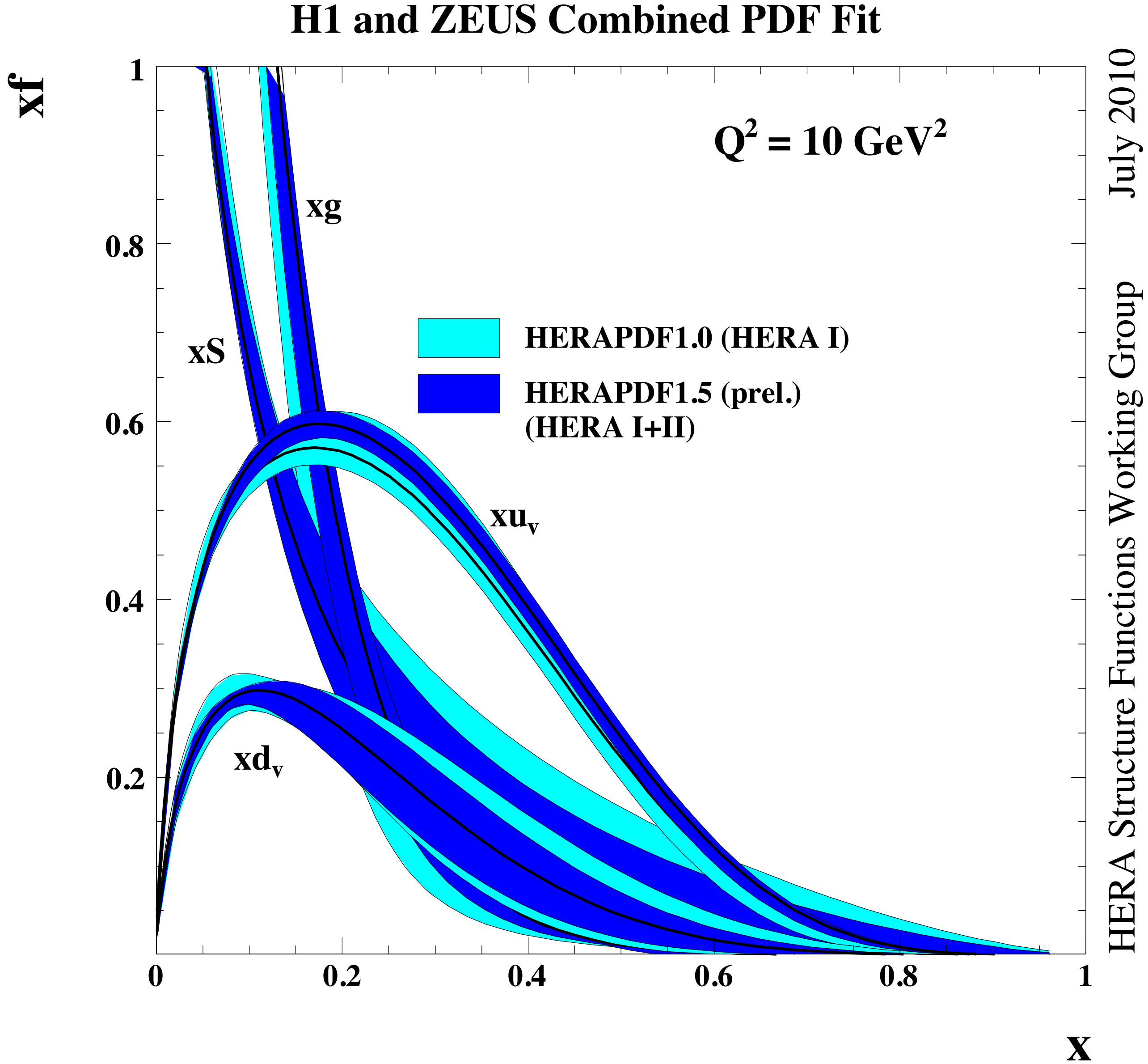
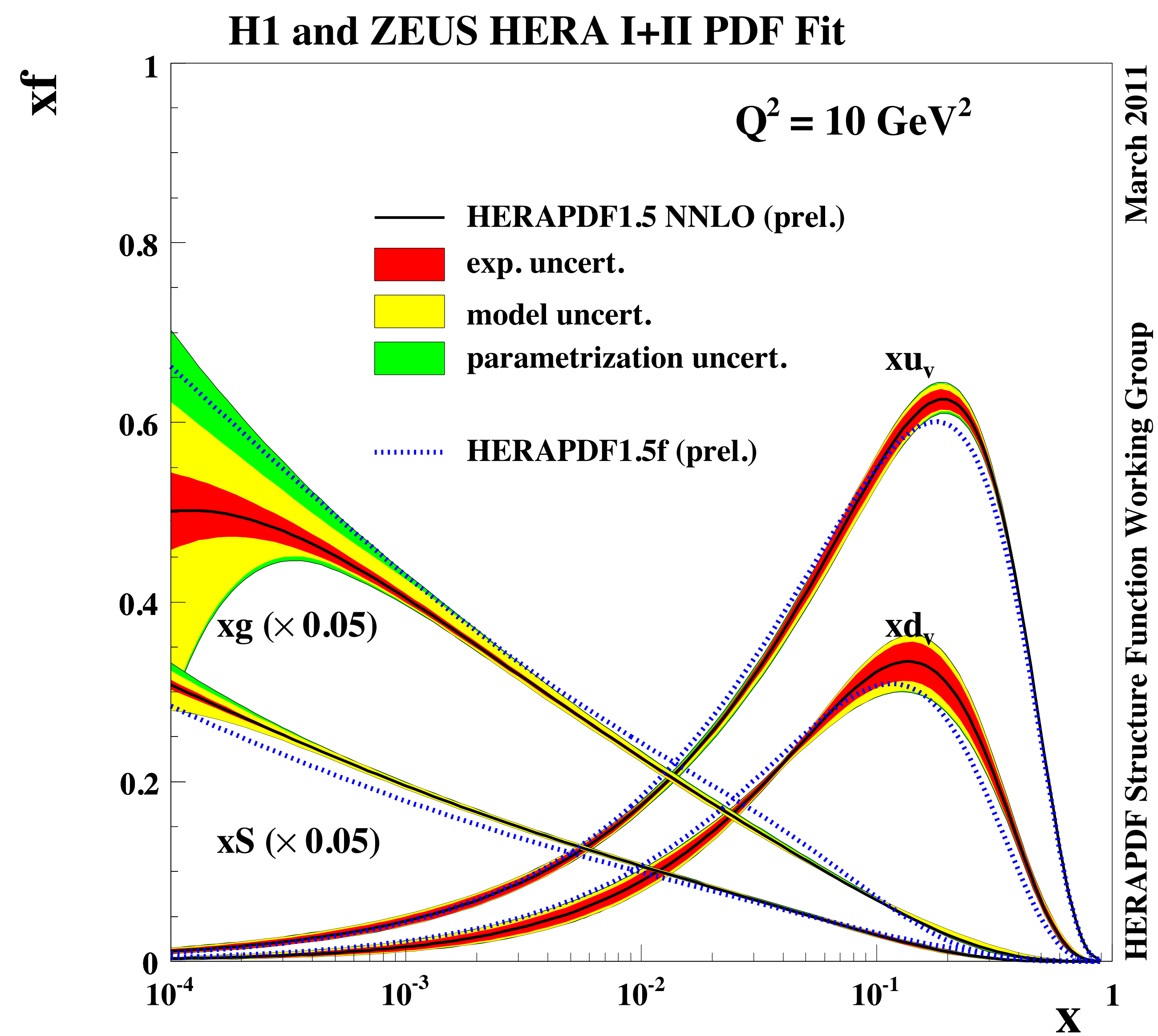
H1-10-142 / ZEUS-prel-10-018

QCD Analaysis

Comparison of HERA-I vs HERA-I+II fits at high x
Strong constraints on xu_v from NC data $Q^2 > \sim 200\ GeV^2$
Moderate constraints on xd_v from $CC(e^+p)$ data
Final high Q^2 data for H1 & ZEUS will constrain this further

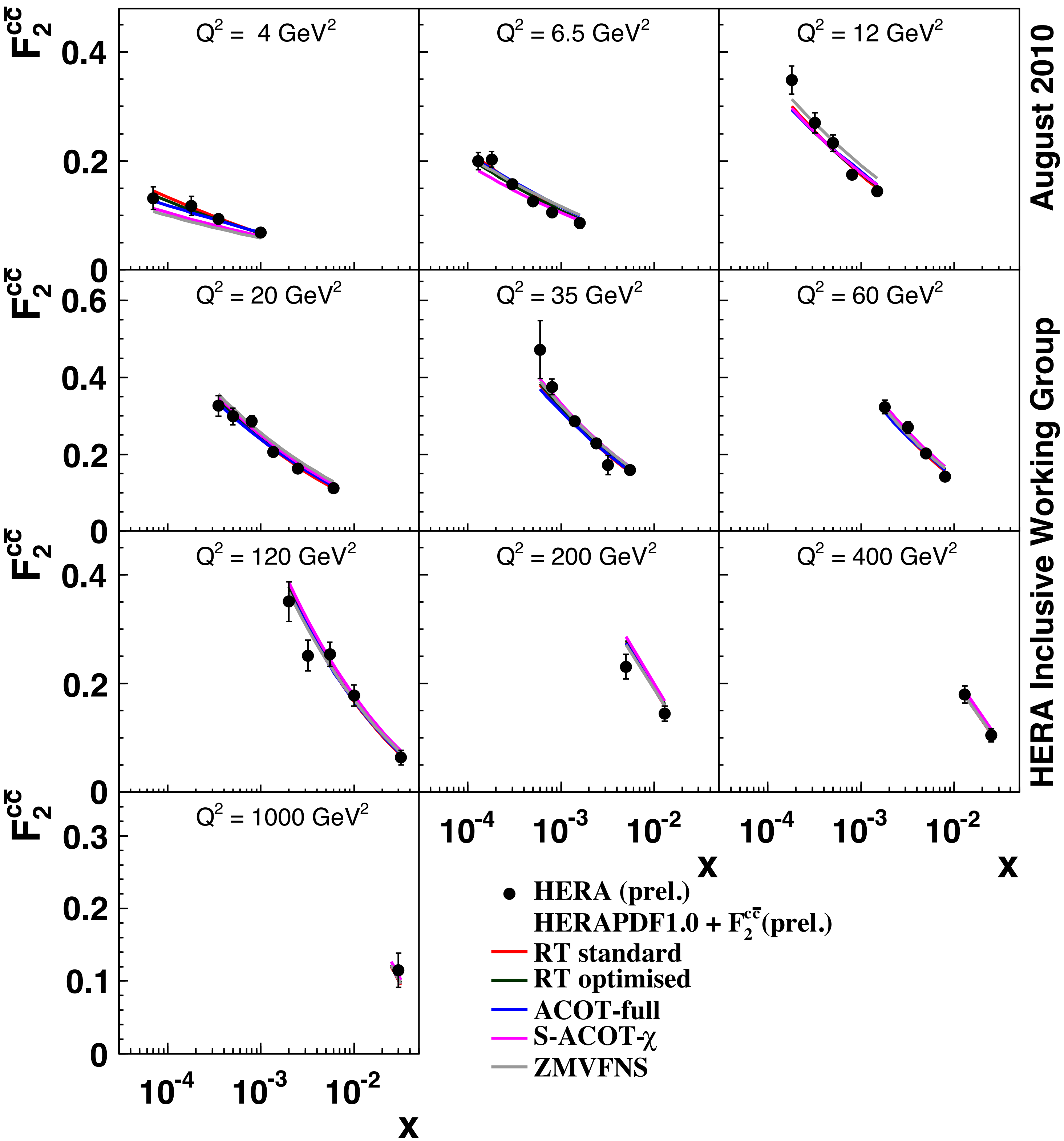
Comparison of NNLO vs NLO
For HERAPDF1.0 NLO/NNLO comparison $\Delta\chi^2 = 60$
For HERAPDF1.5 NNLO & NLO fit use 14 params
Significant shifts observed in all PDFs $\Delta\chi^2 = 9$
Better consistency achieved with 14 parameters
⇒ data are very precise!





PDFs well constrained with α_s fixed
$\alpha_s = 0.1176$

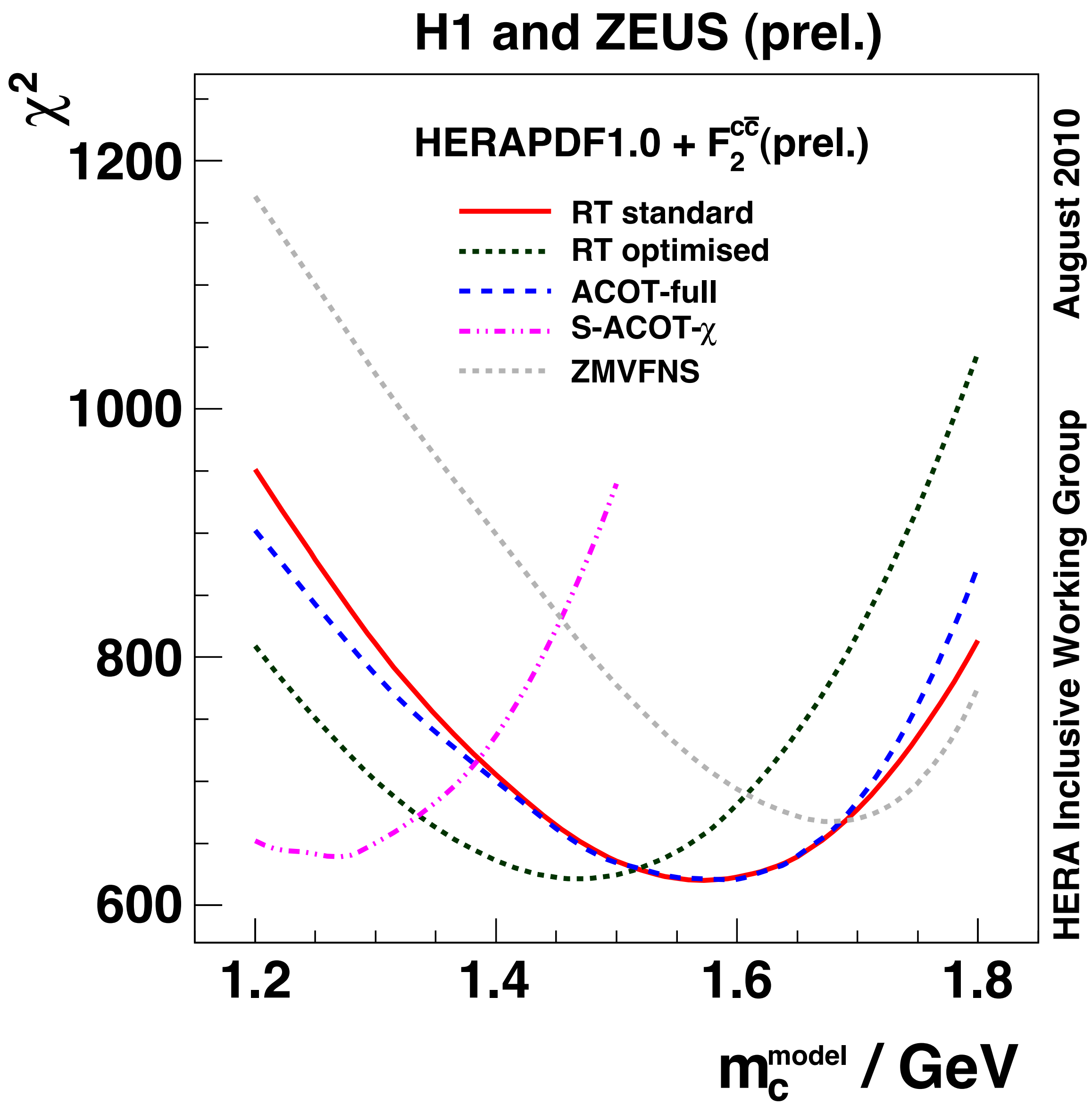
H1-10-142 / ZEUS-prel-10-018



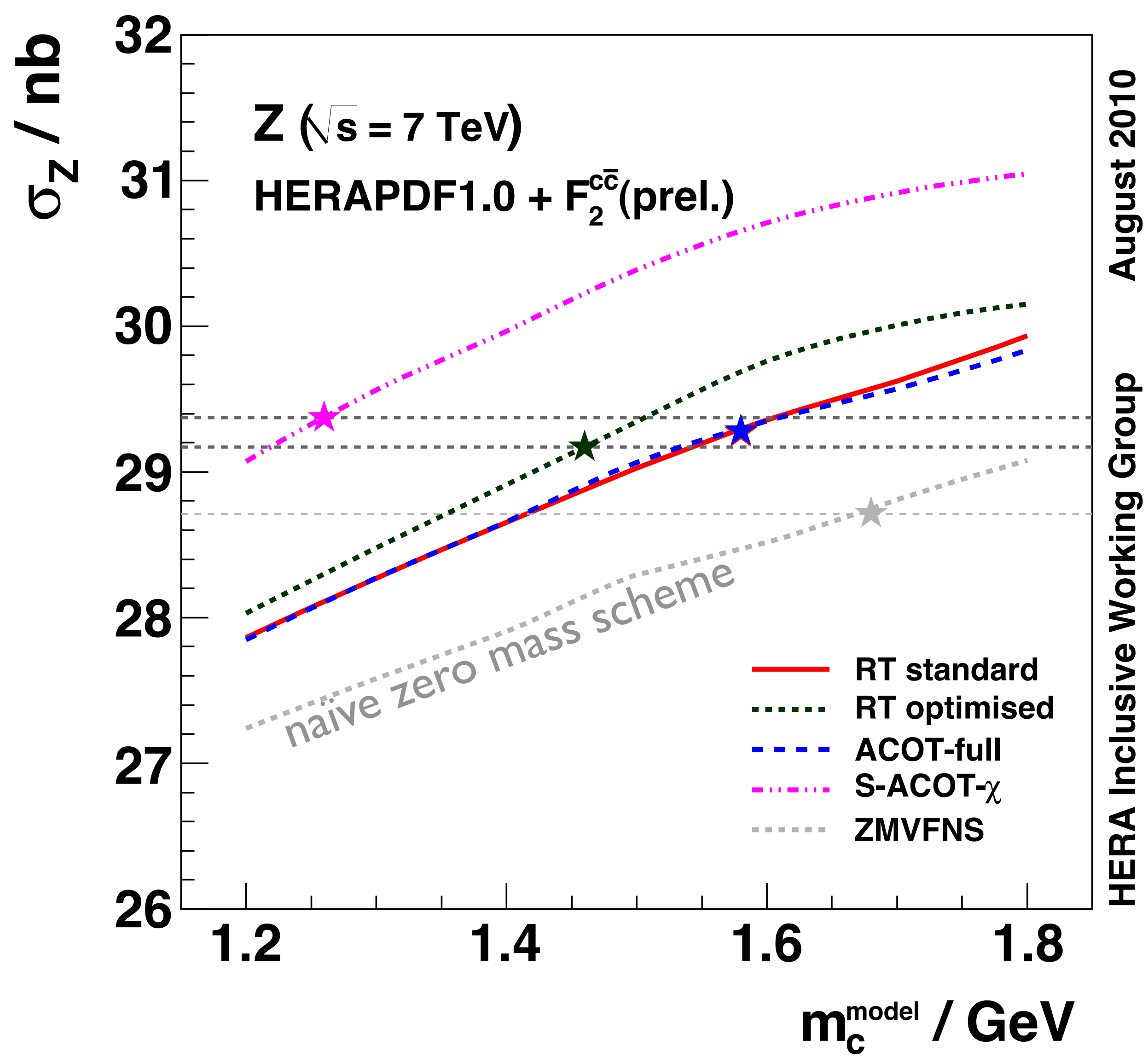
The inclusive charm content of proton can be measured in several methods: D* decays , impact parameter significance... Combination yields ~5-10% precision

Data cover wide phase space region including charm threshold region

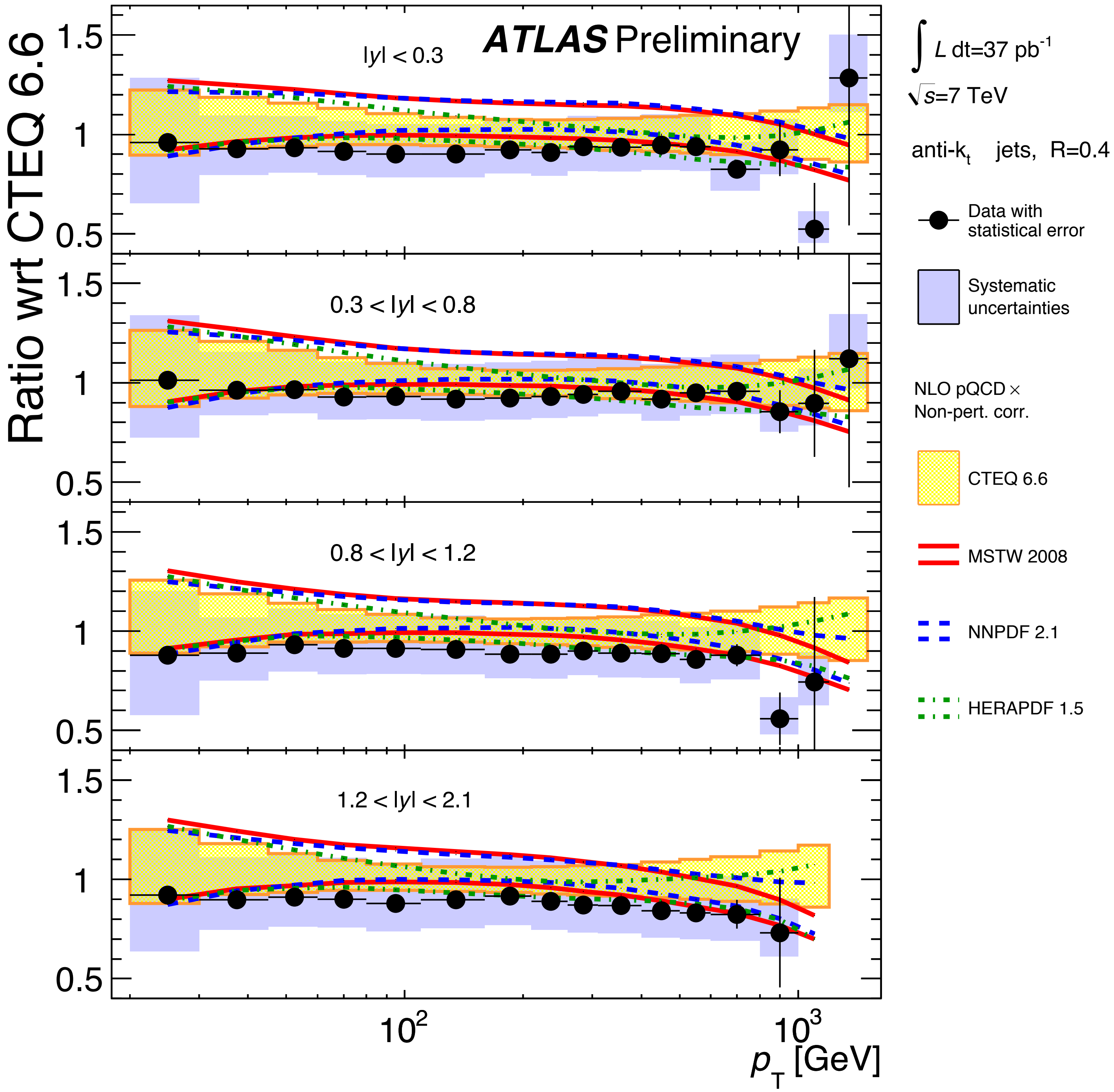
Fixing Charm Model Parameter

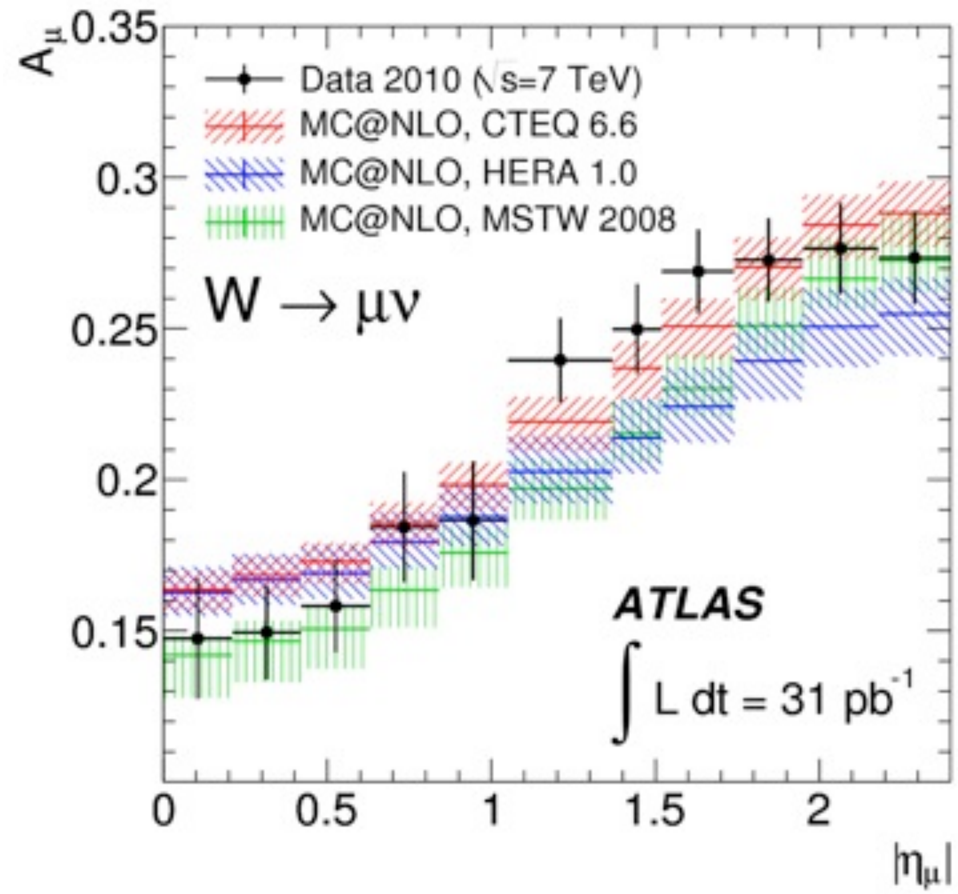


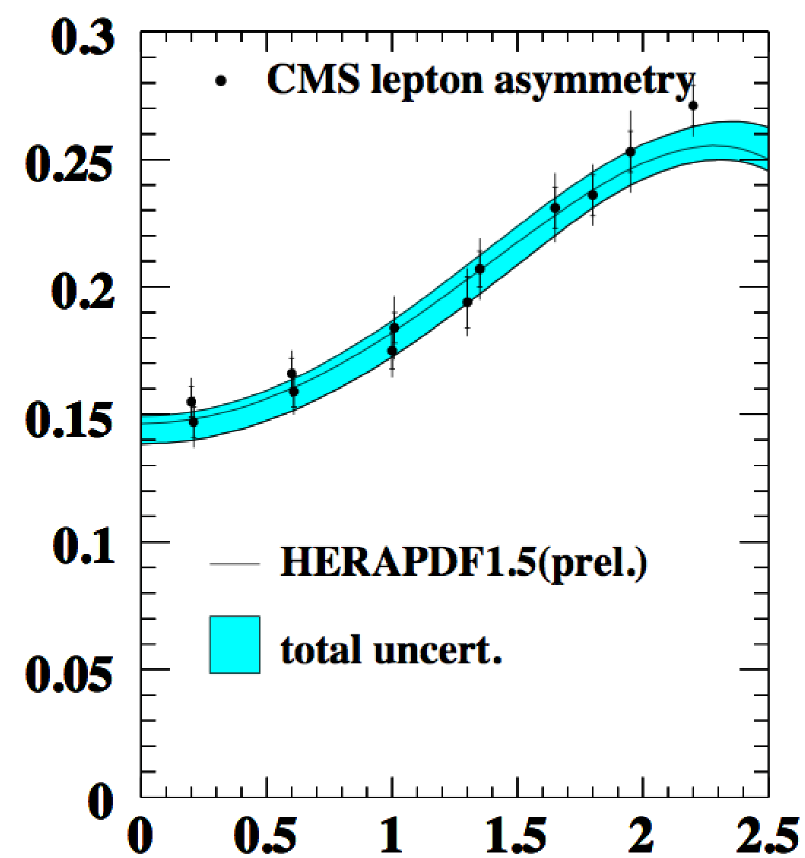
- Different heavy-quark schemes have different dependence on model parameter m_c related to charm pole mass
- Perform χ^2 scan for each heavy-quark scheme
- Using optimal value of m_c spread of LHC predictions dramatically reduced ~4.5% → ~0.7%



LHC Predictions using HERAPDF1.0

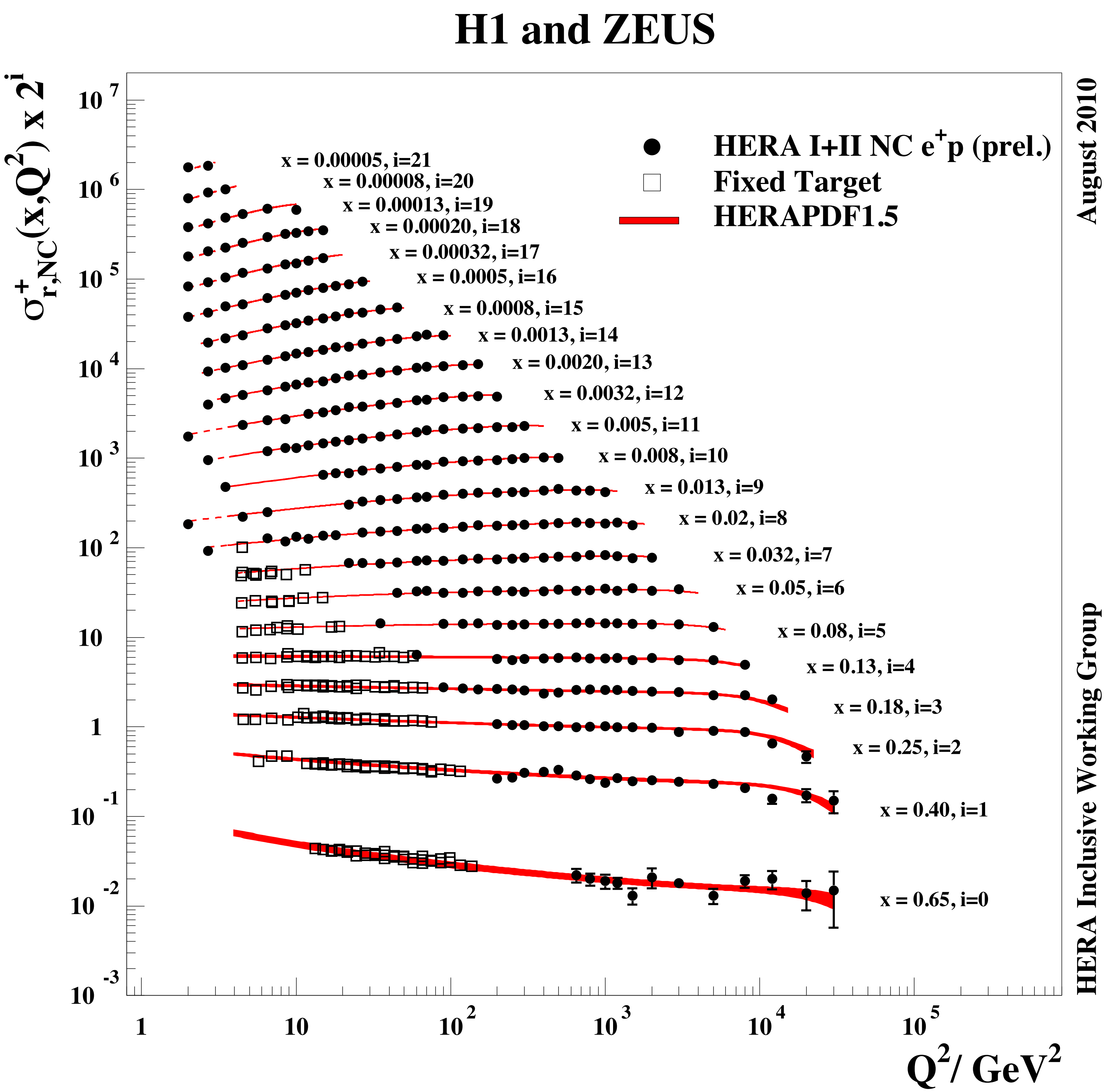






HERAPDF predictions for 2010 LHC data:
ATLAS high p_T jet data best described by HERAPDF
ATLAS lepton (μ) charge asymmetry measurement
CMS lepton (e,μ) charge asymmetry measurement

Conclusions



- H1 / ZEUS combined data reach ~1% precision
- These data provide some of the most stringent constraints on PDFs
- Stress-test of QCD over 4 orders of mag. in Q^2
- DGLAP evolution works very well
- HERA data provide a self-consistent data set for complete flavour decomposition of the proton
- QCD analysis performed in NLO and NNLO
- NNLO/NLO in better agreement with more flexible parameterisations
- New combination with HERA-II data provide tighter constraints at high x / Q^2

Soon to publish final HERA-II data

Produce last HERA combined data set

Legacy DIS NC and CC data