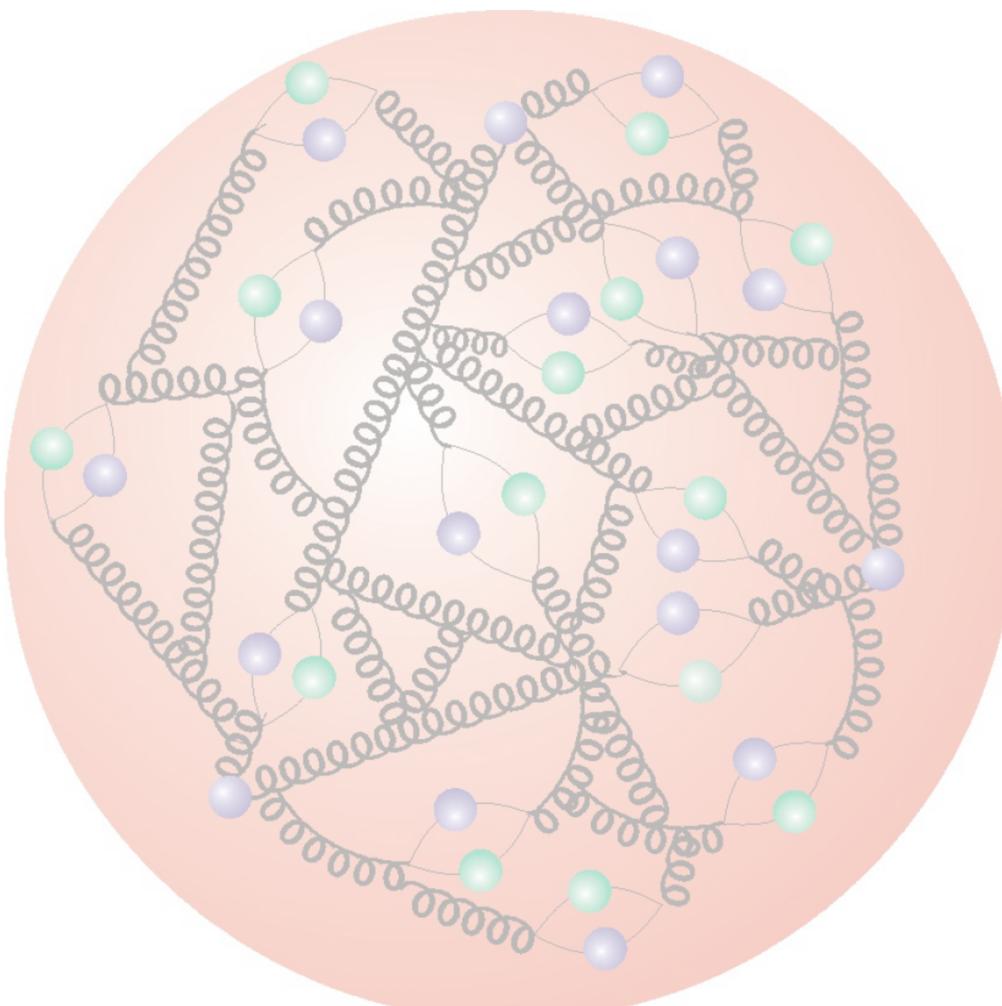
Precision QCD in DIS at HERA



- Introduction
- High y and F_L
- F_2 at medium Q^2
- High Q^2 NC and CC
- Jets and F_2^{cc}

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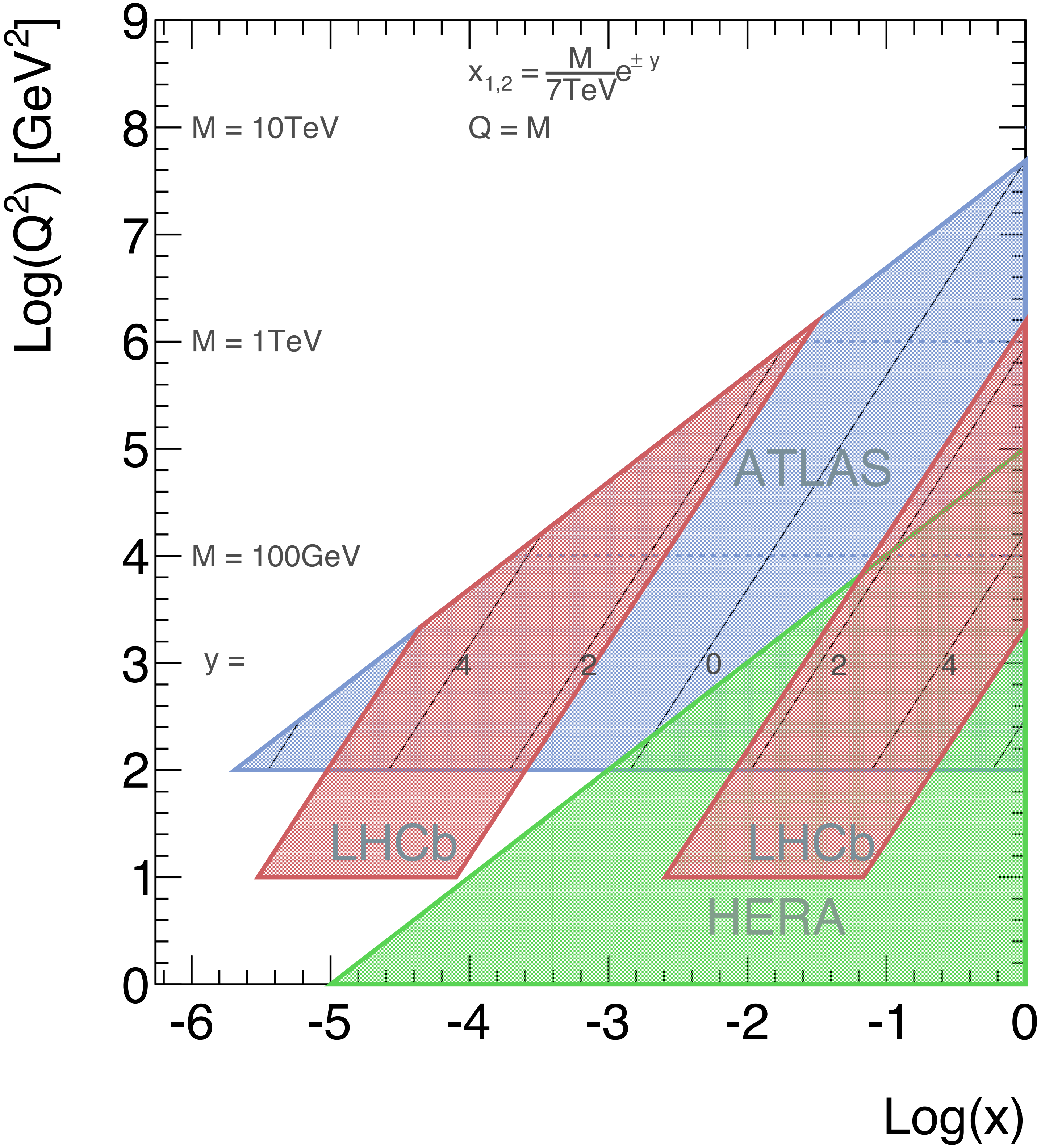
PDF4LHC

DESY, Hamburg – 4th July 2011



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 $x \to 1$

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

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

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

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

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

similarly for pure weak CC analogues:

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

The NC reduced cross section defined as:

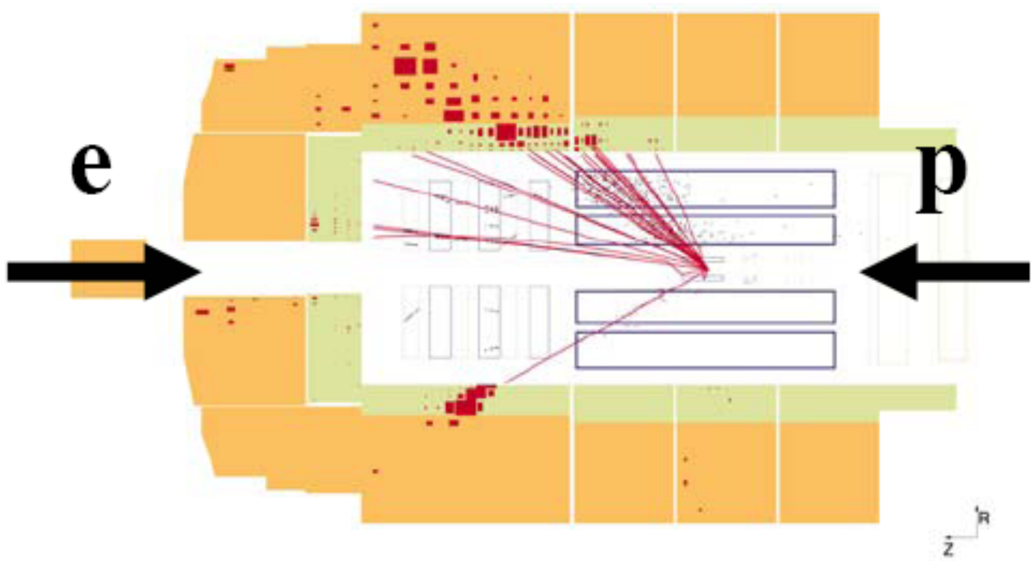
$$\tilde{\sigma}^{\pm}_{NC} = \frac{Q^2 x}{2\alpha\pi^2}\frac{1}{Y_+}\frac{d^2\sigma^{\pm}}{dxdQ^2}$$

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

The CC reduced cross section defined as:

$$\sigma^{\pm}_{CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{d\sigma^{\pm}_{CC}}{dxdQ^2}$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{1}{2}\left[Y_+ W_2^{\pm} \mp Y_- xW_3^{\pm} - y^2 W_L^{\pm}\right]$$



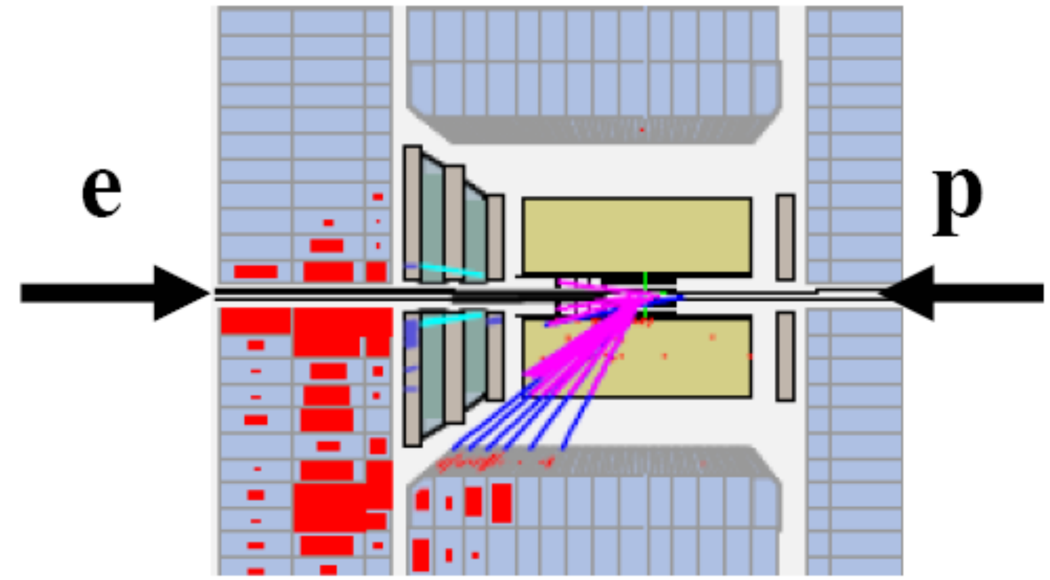
Neutral current event selection:

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

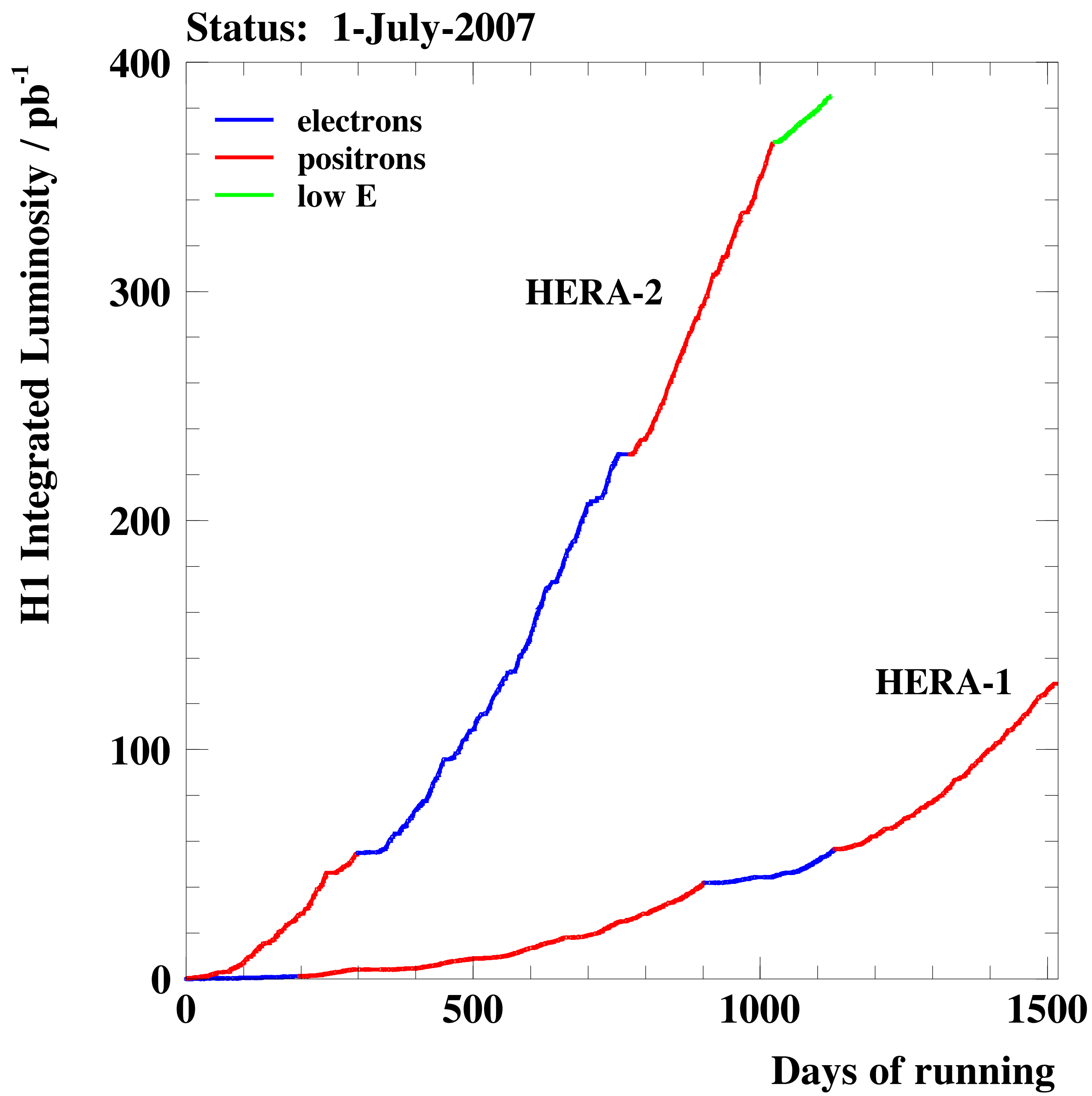
Final selection: ~10^3 events per sample

HERA Operation

<u>HERA-I 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)

For details of fits see Mandy's talk...

Direct Measurement of F_L

Eur. Phys. J. C71, 2011 1579

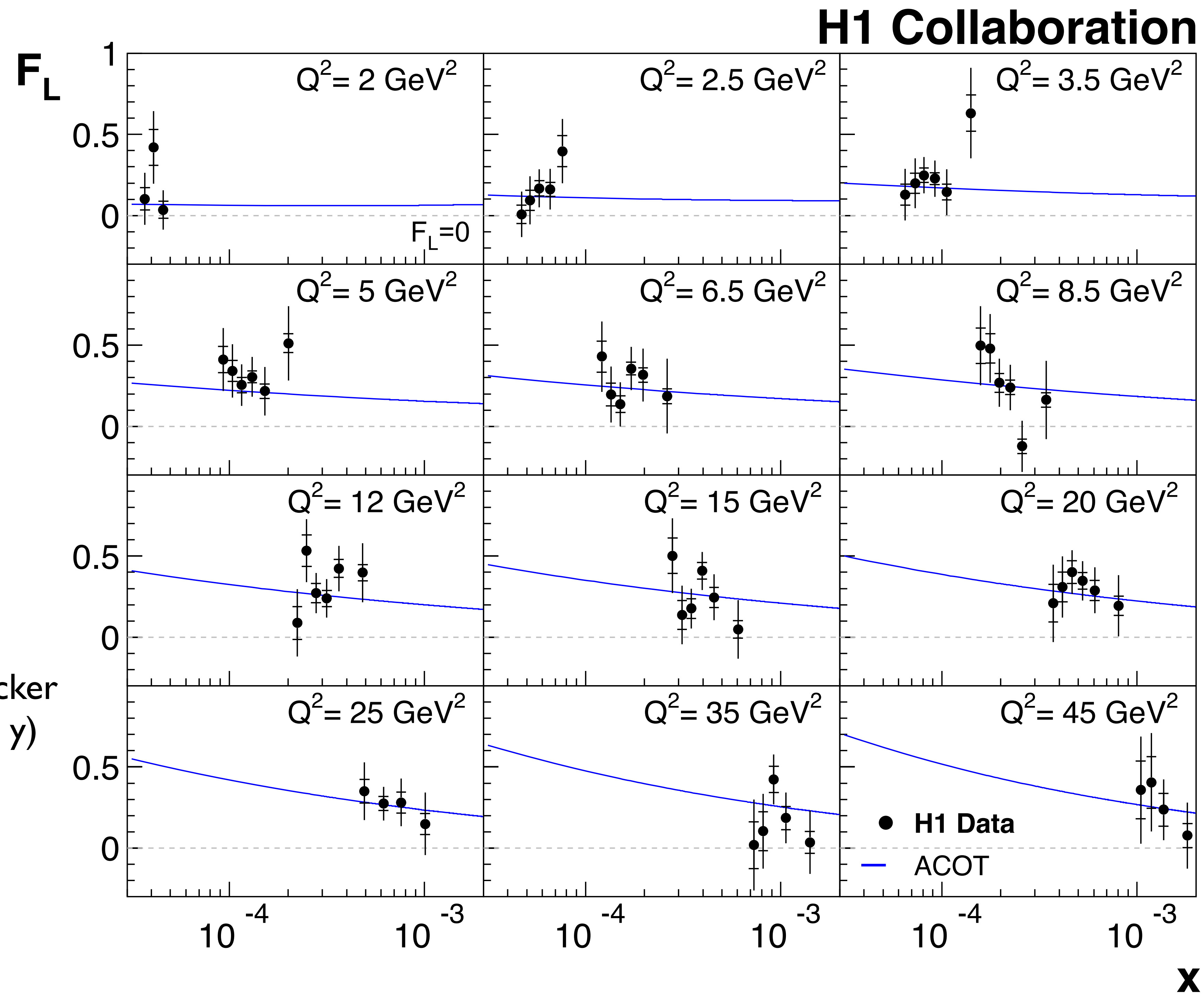
$$\sigma_{NC} = F_2 - \frac{y^2}{Y_+} F_L \qquad Y_+ = 1 + (1-y)^2$$

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 $\sqrt{s}$ = 319 , 252 and 225 GeV

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



Use cross section using low silicon tracker

Allows b/g suppression at low $E_{e'}$ (high y)

Extend Q^2 range to 1.5 GeV^2 (previously 12 GeV^2)

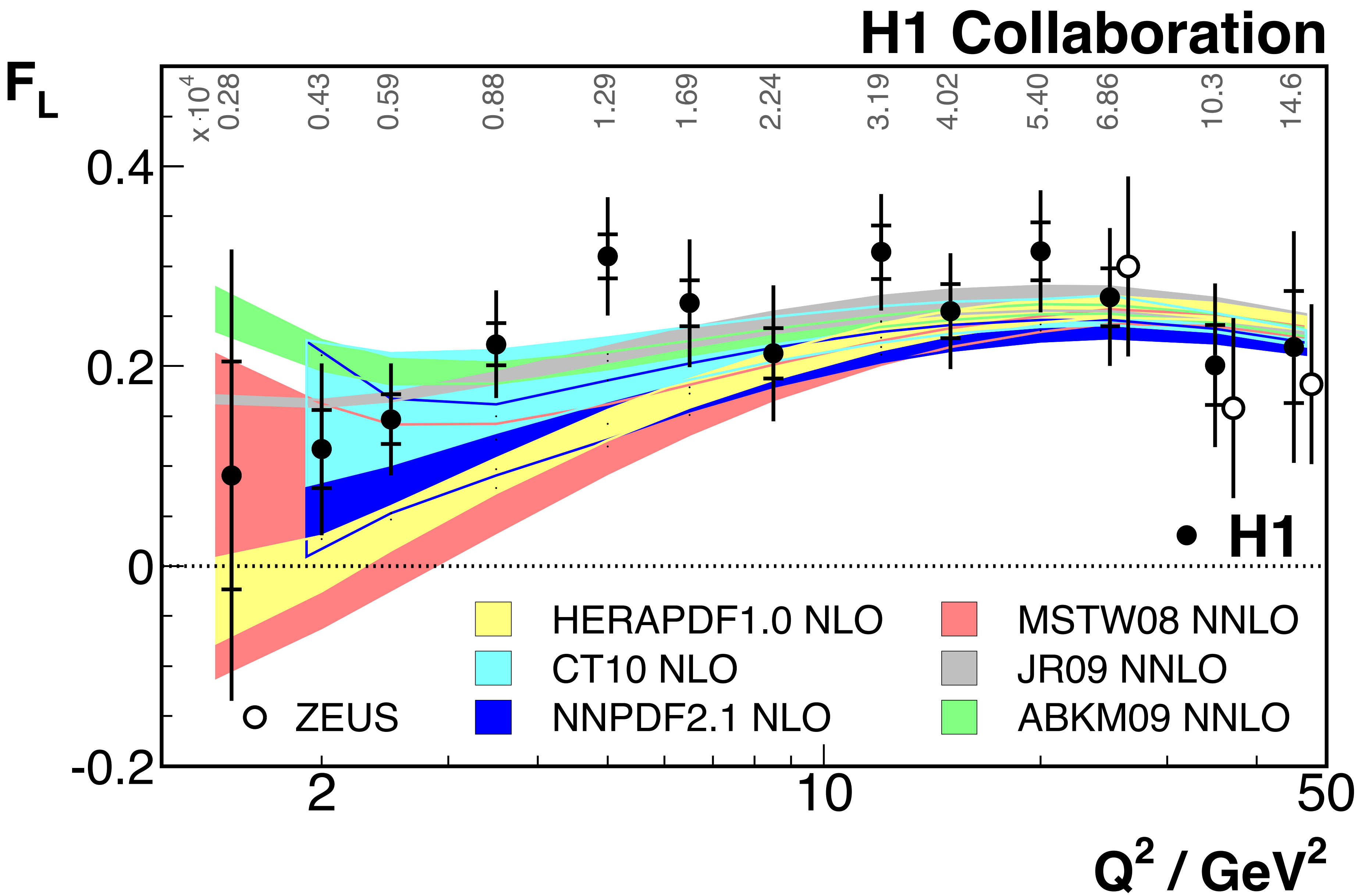
$\int\mathcal{L}$ E_p 920 GeV = 103.5 pb^{-1}

$\int\mathcal{L}$ E_p 575 GeV = 5.9 pb^{-1}

$\int\mathcal{L}$ E_p 460 GeV = 12.2 pb^{-1}

Similar stat and uncorrelated sys sources efficiencies: trigger, track , charge, ID

Direct Measurement of F_L



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

FL measured down to x ~ 3x10^{-5}

Good agreement with ZEUS measurement at higher Q^2

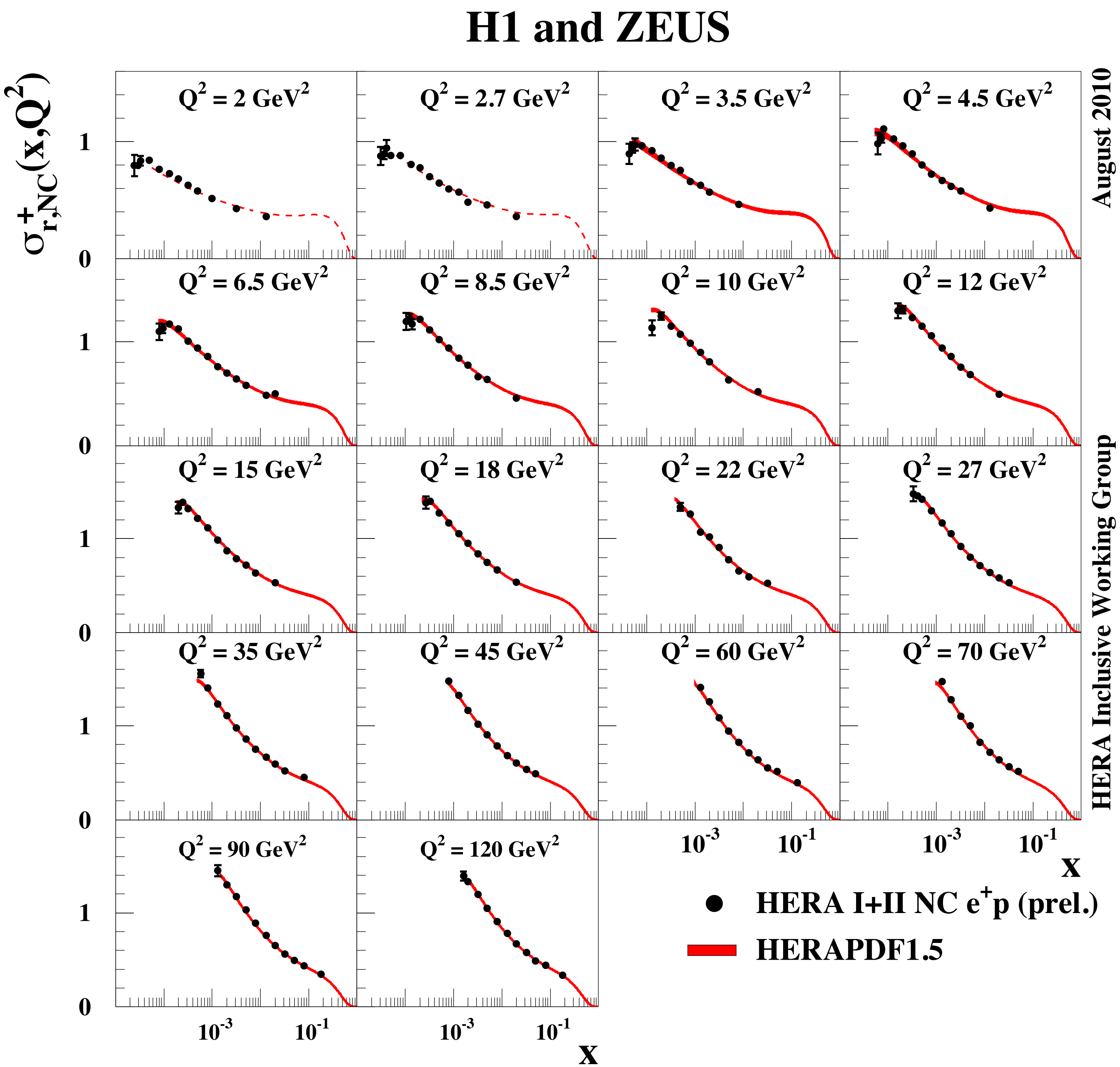
All model predictions describe data reasonably well

Data can provide new constraints to NNLO models

F_2 at Medium Q^2

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

desy-09-158



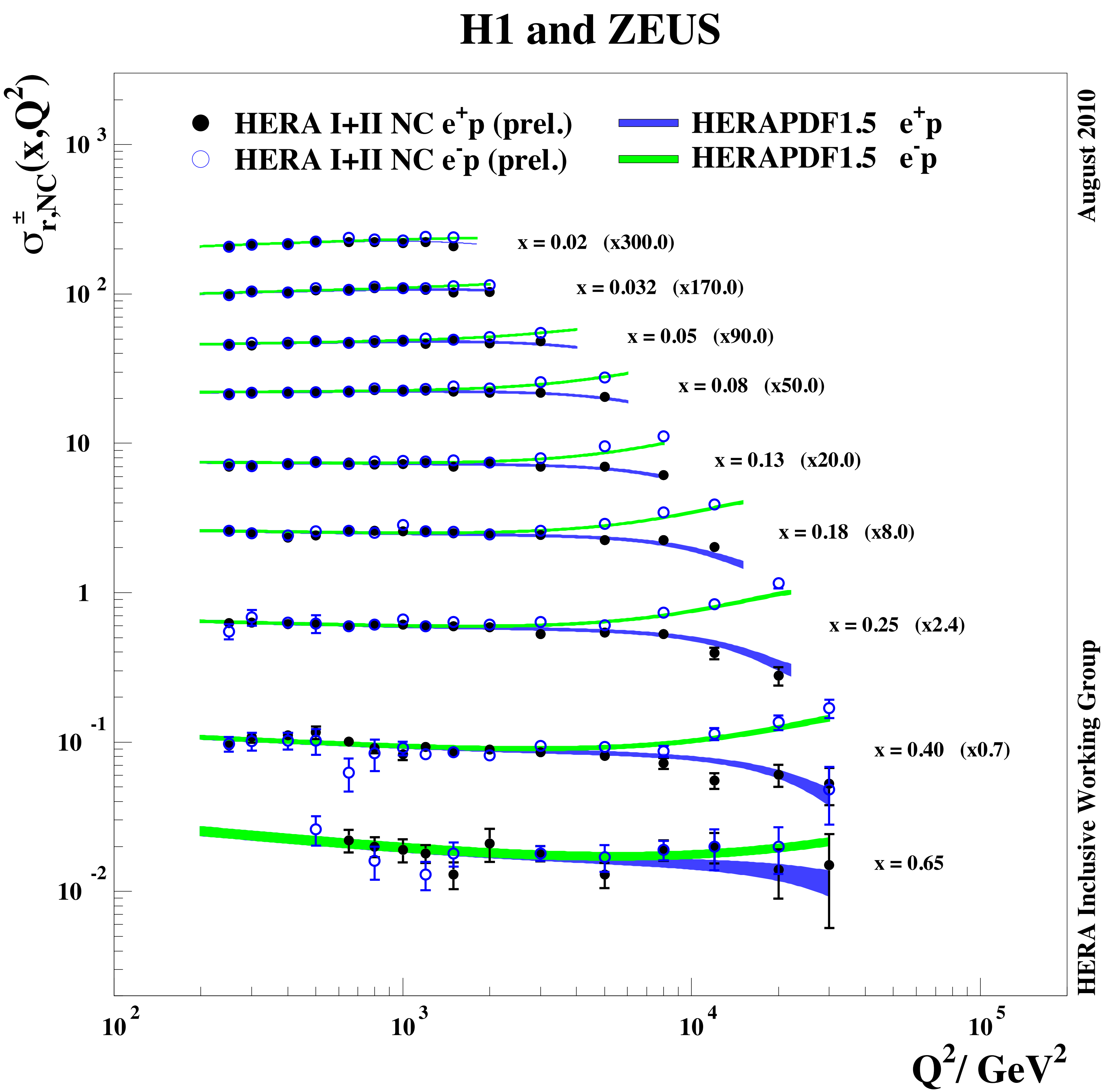
Joint publication from H1 & ZEUS
High precision achieved
Total uncertainty ~1% for 20< Q^2 <100 GeV^2

Data give most stringent constraints on PDFs

Well described by NLO QCD

High Q^2 NC Cross Sections

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



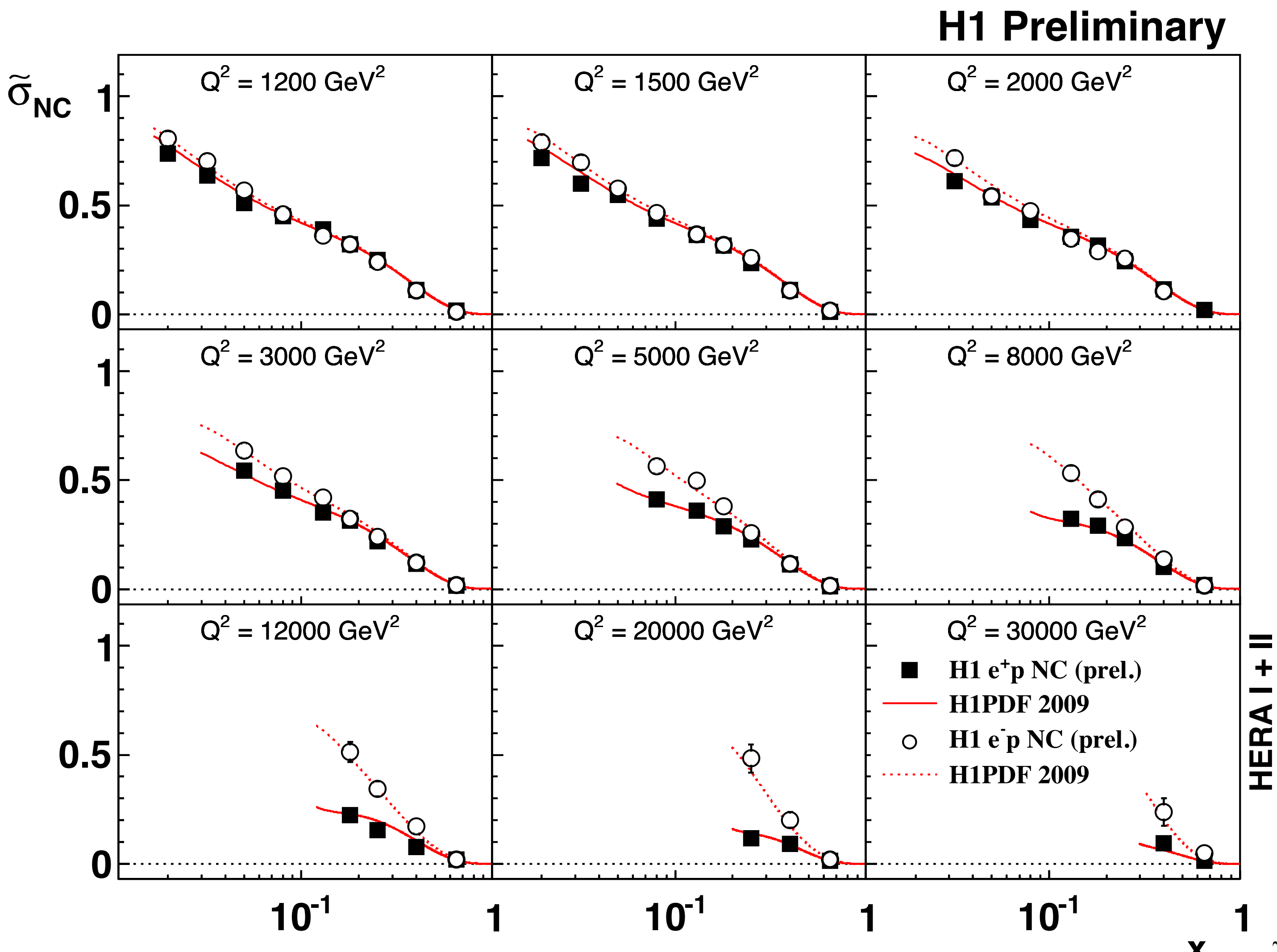
High Q^2 is the EW physics regime

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

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

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

xF_3



At high Q^2 xF_3 arises due to Z^0 effects

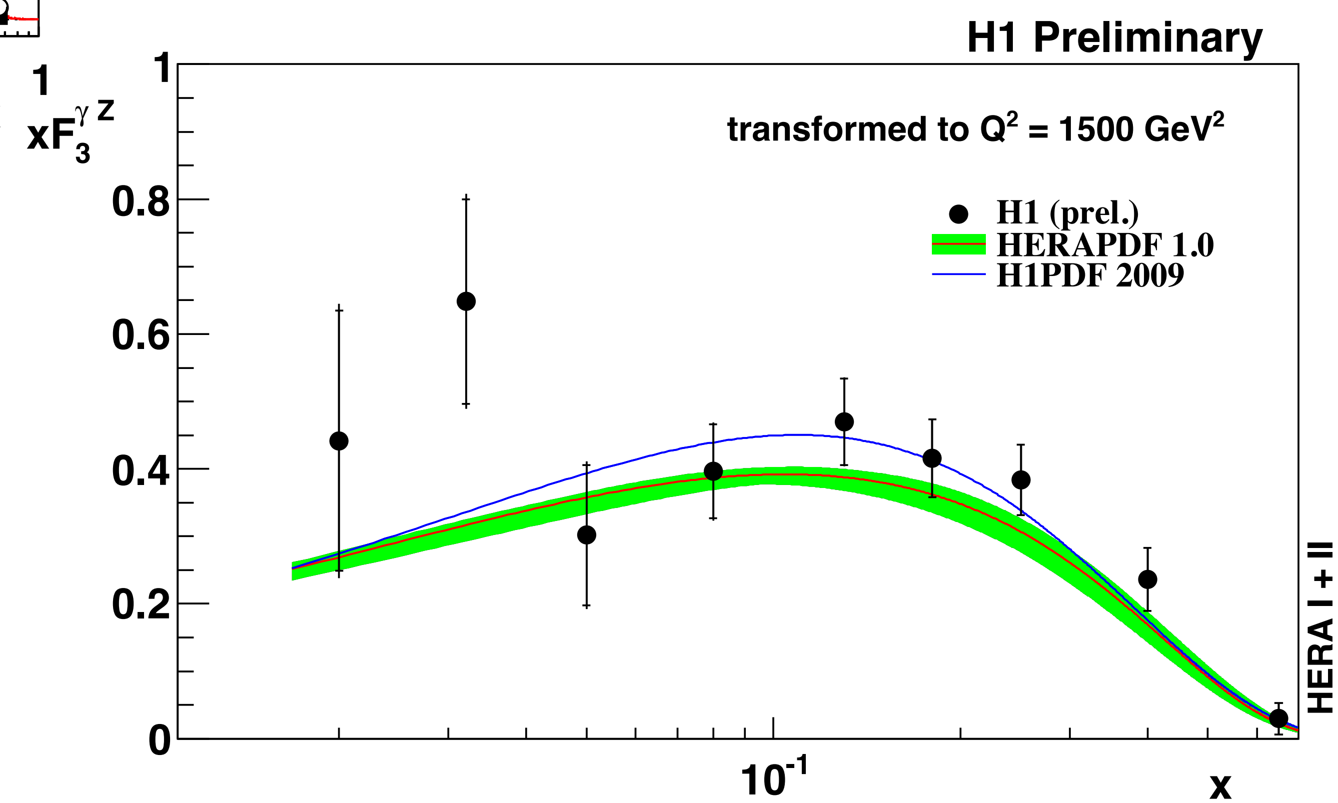
enhanced e^- cross section wrt e^+

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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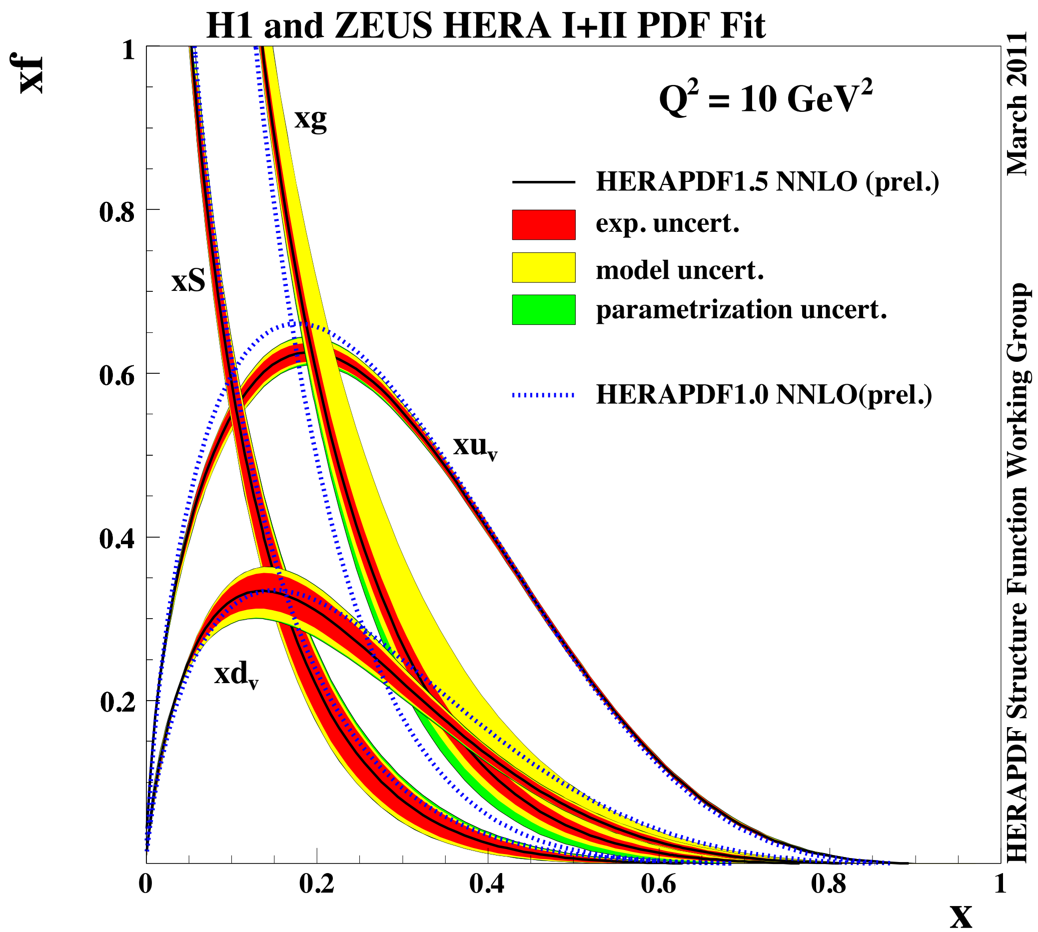
High x NC Cross Sections



High x is a very interesting region

PDFs fall rapidly at high x

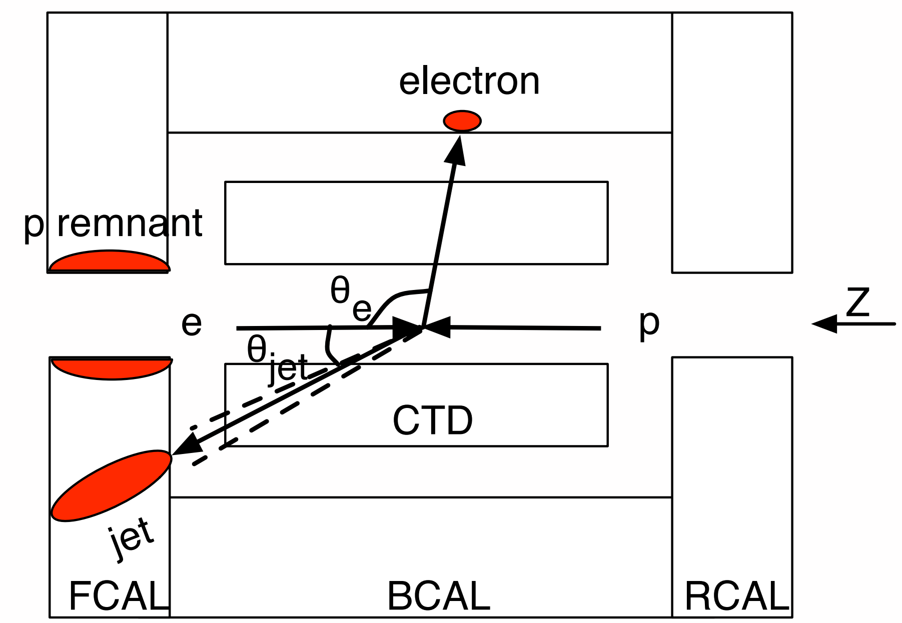
Experimentally very challenging region

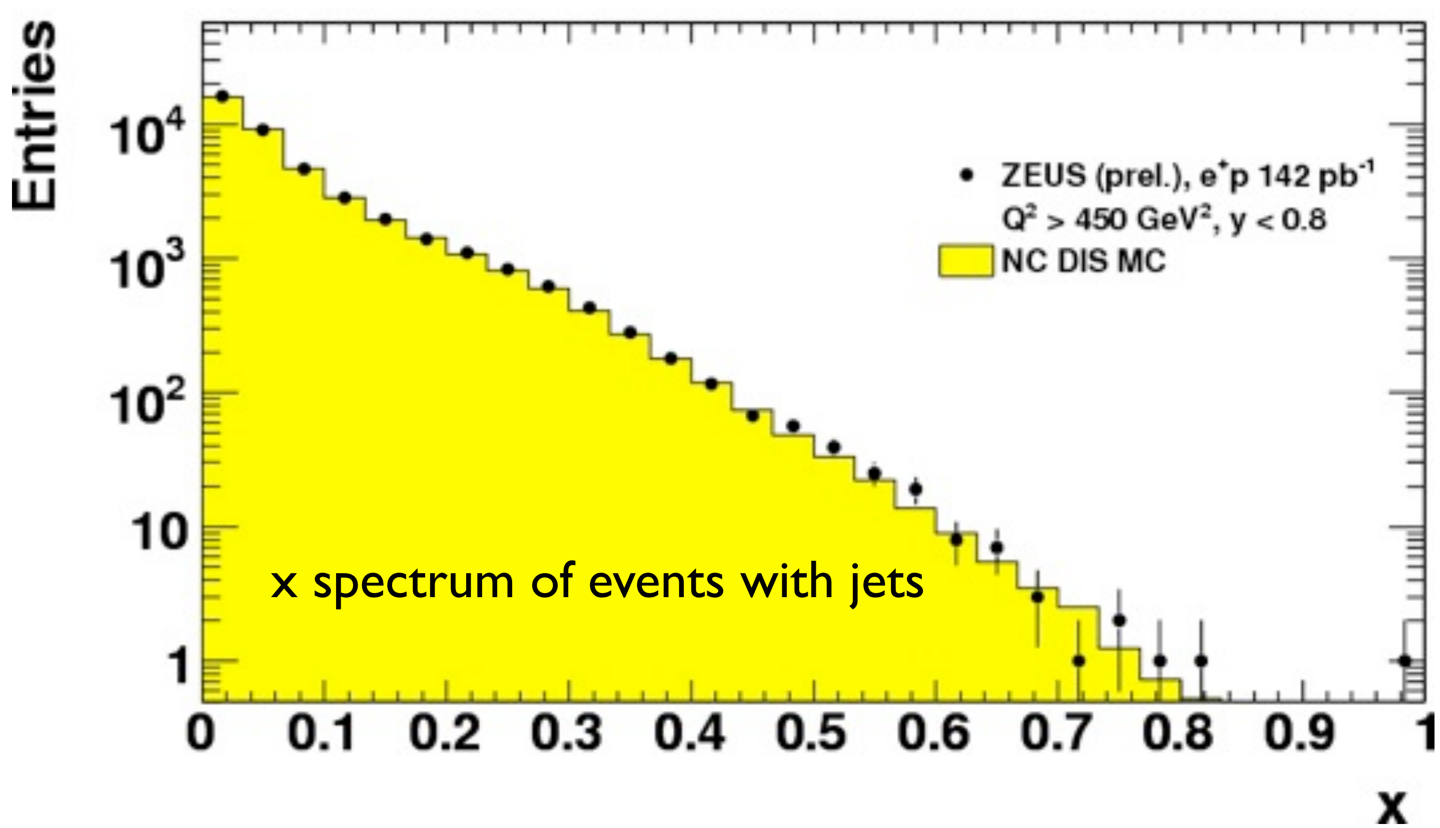
- scattered electron has very poor x resolution
- hadronic final state enters forward beam pipe

Use jets for x reconstruction (not complete hadronic final state)

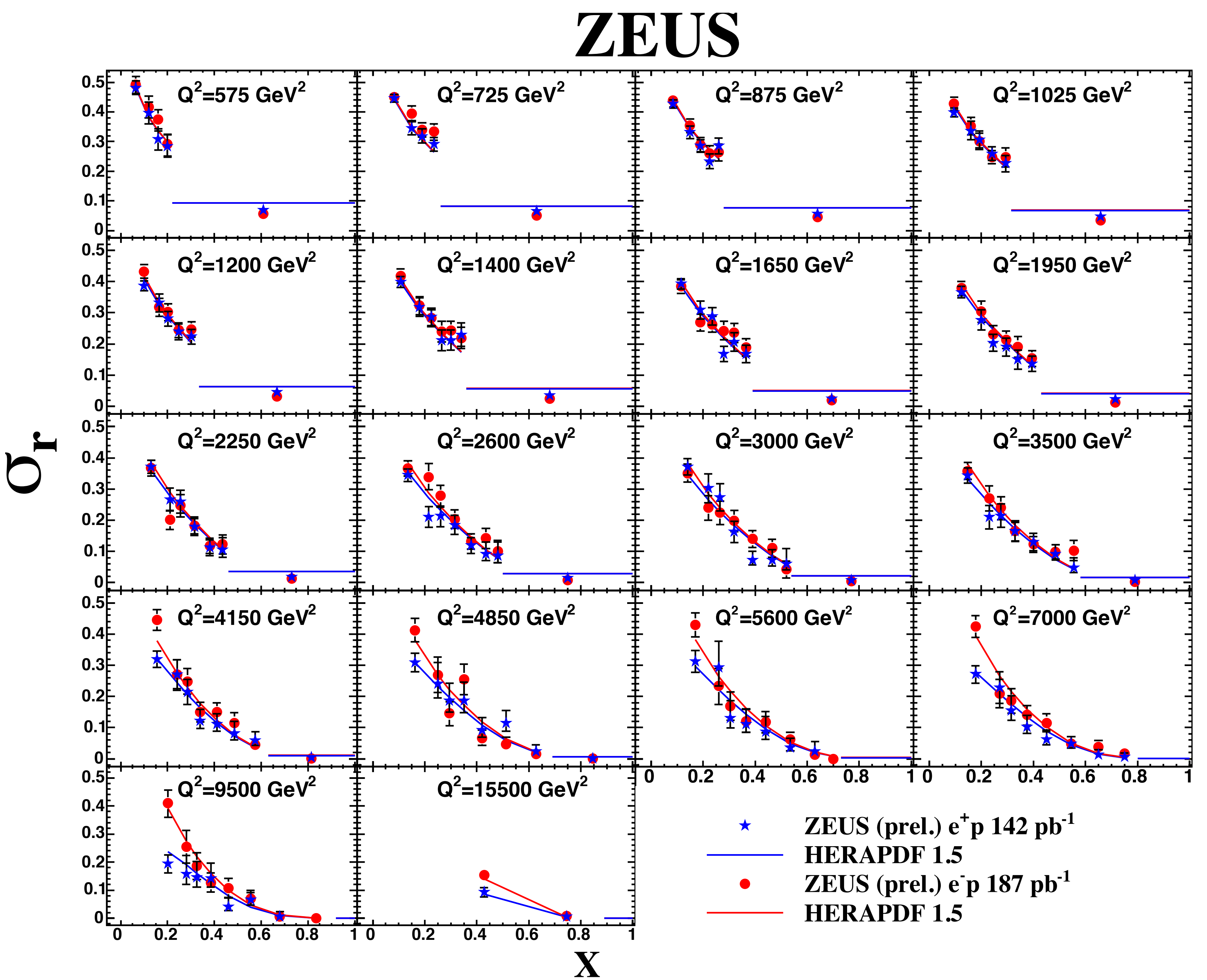
Use jet angle and pT of electron

Improves x resolution





ZEUS-prel-11-004



New for this meeting

e^+p HERA-II NC measurement at high x

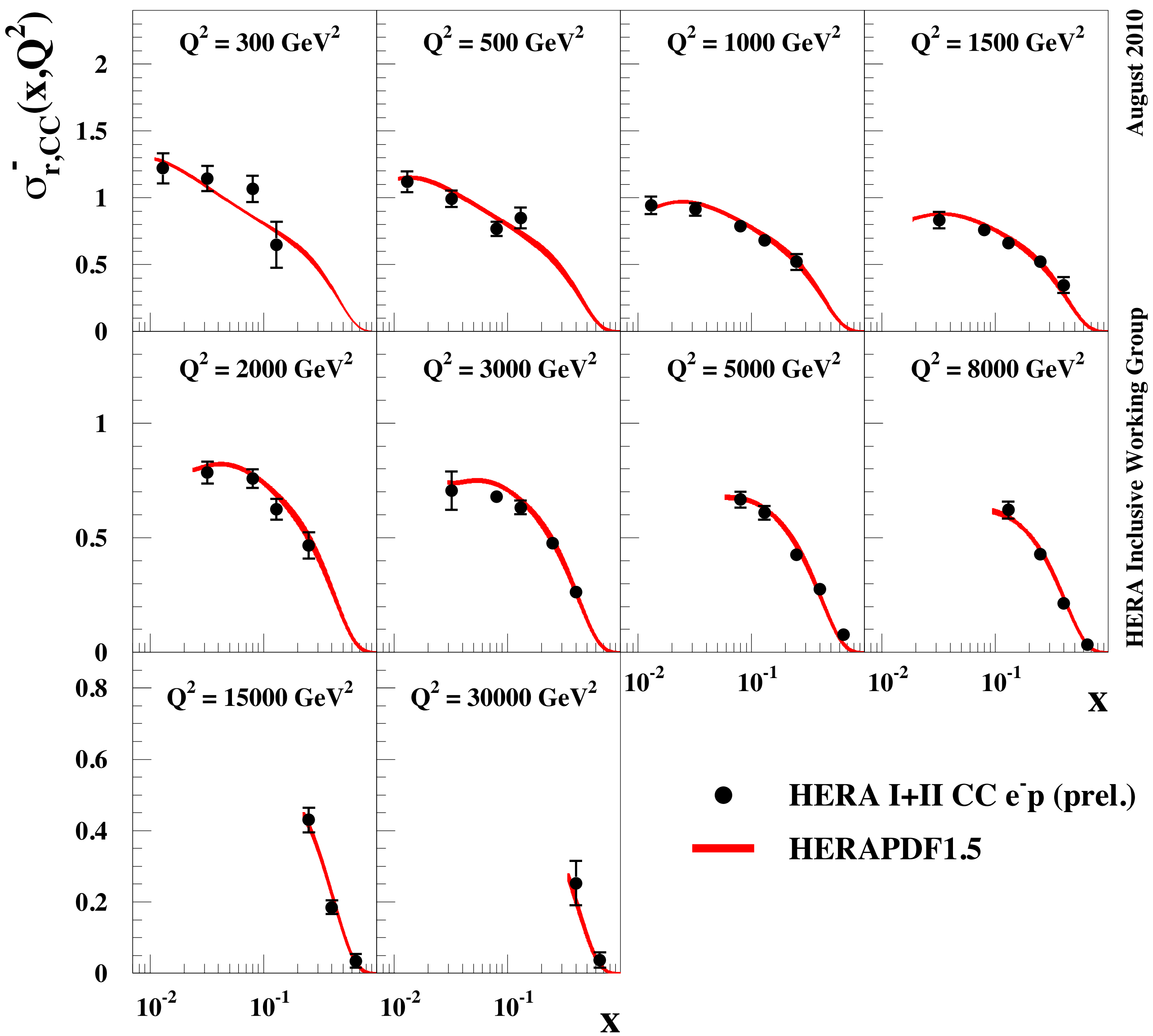
single integrated bin for highest x

e^-p scattering data already released

High Q^2 CC Cross Sections

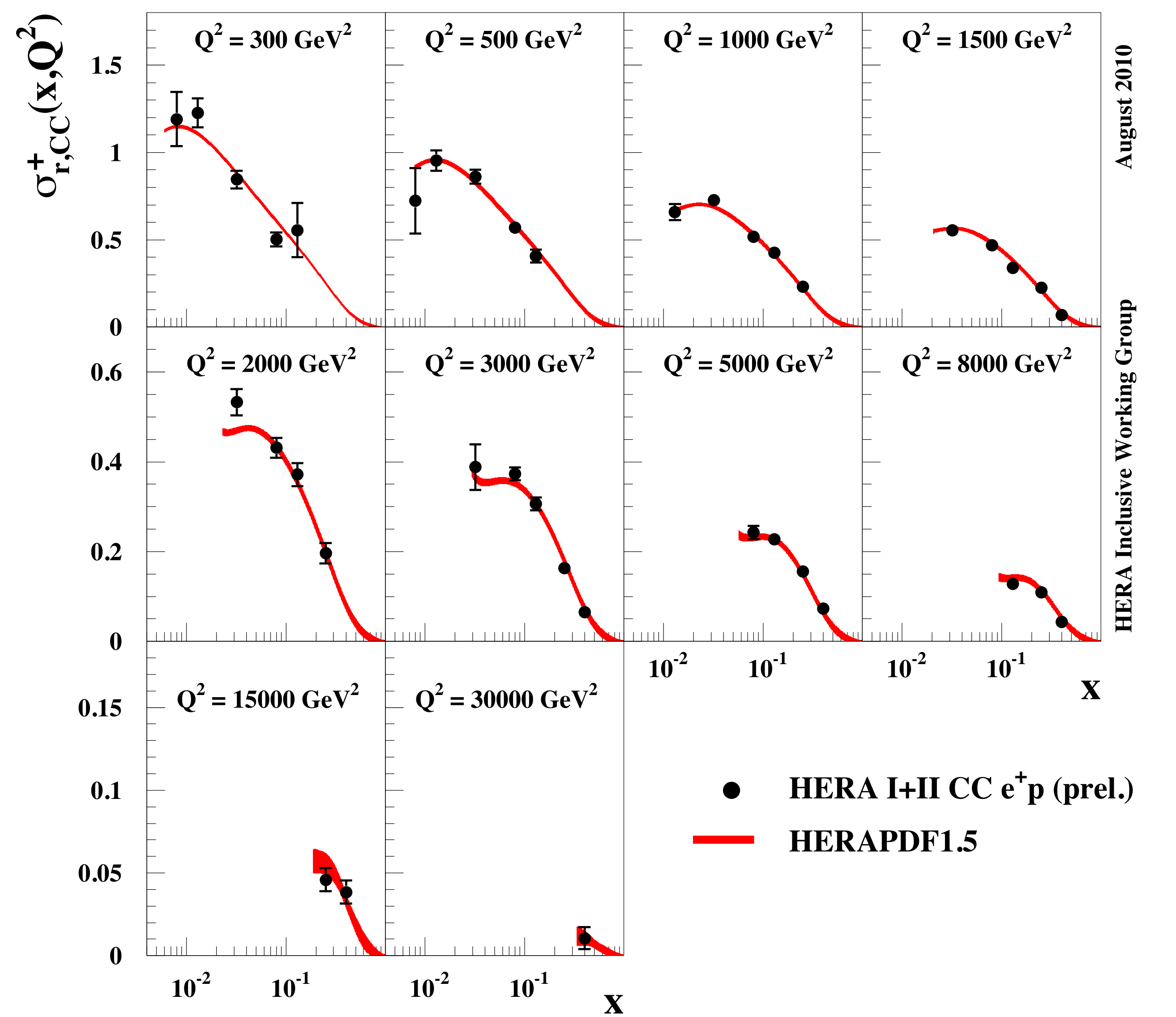
Electron scattering

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



Positron scattering

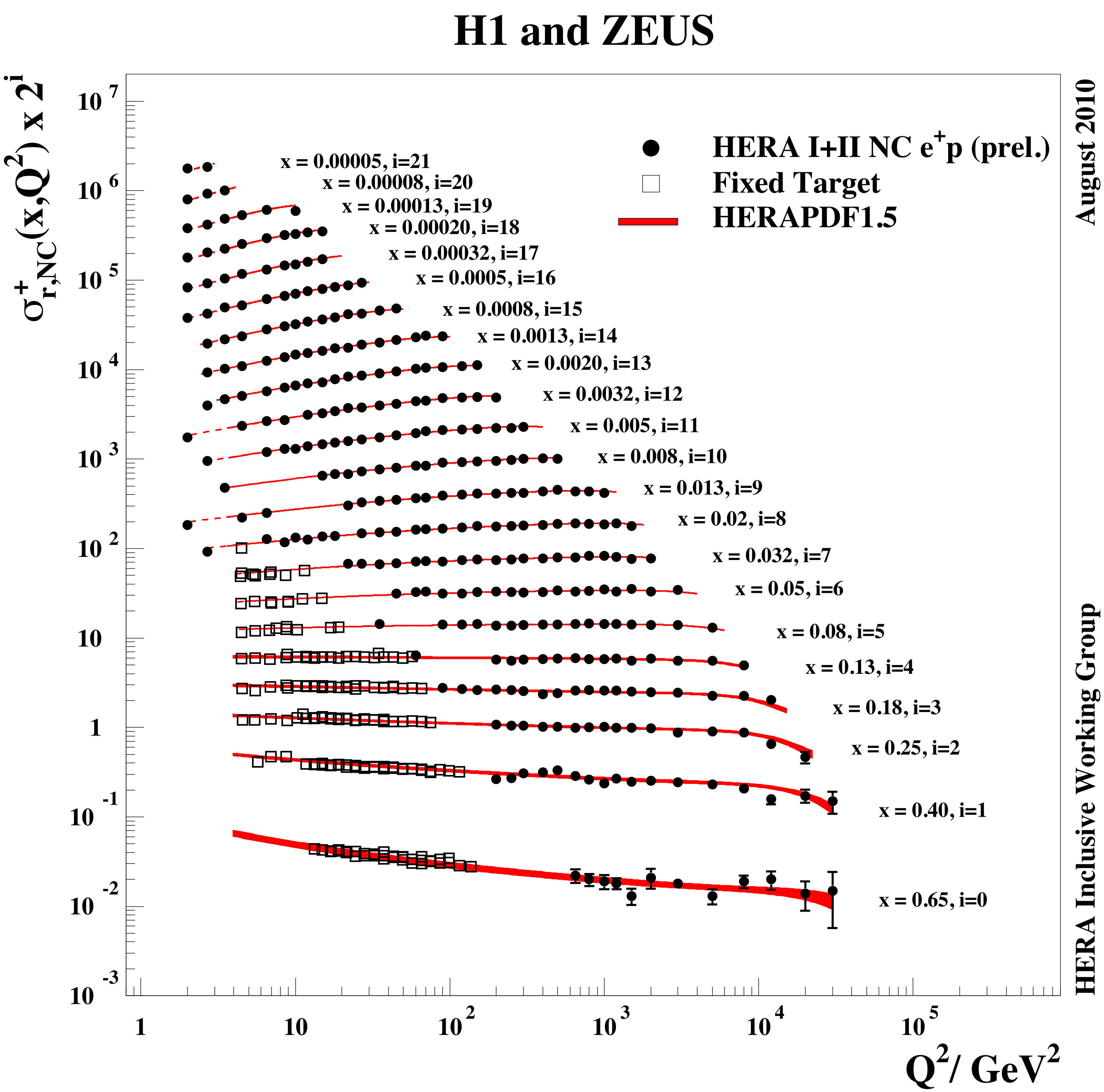
$$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[(\bar{u}+\bar{c})+(1-y)^2(d+s)\right]$$



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



Latest H1/ZEUS combination

Uses complete NC/CC data

(not incl. ZEUS NC e+p)

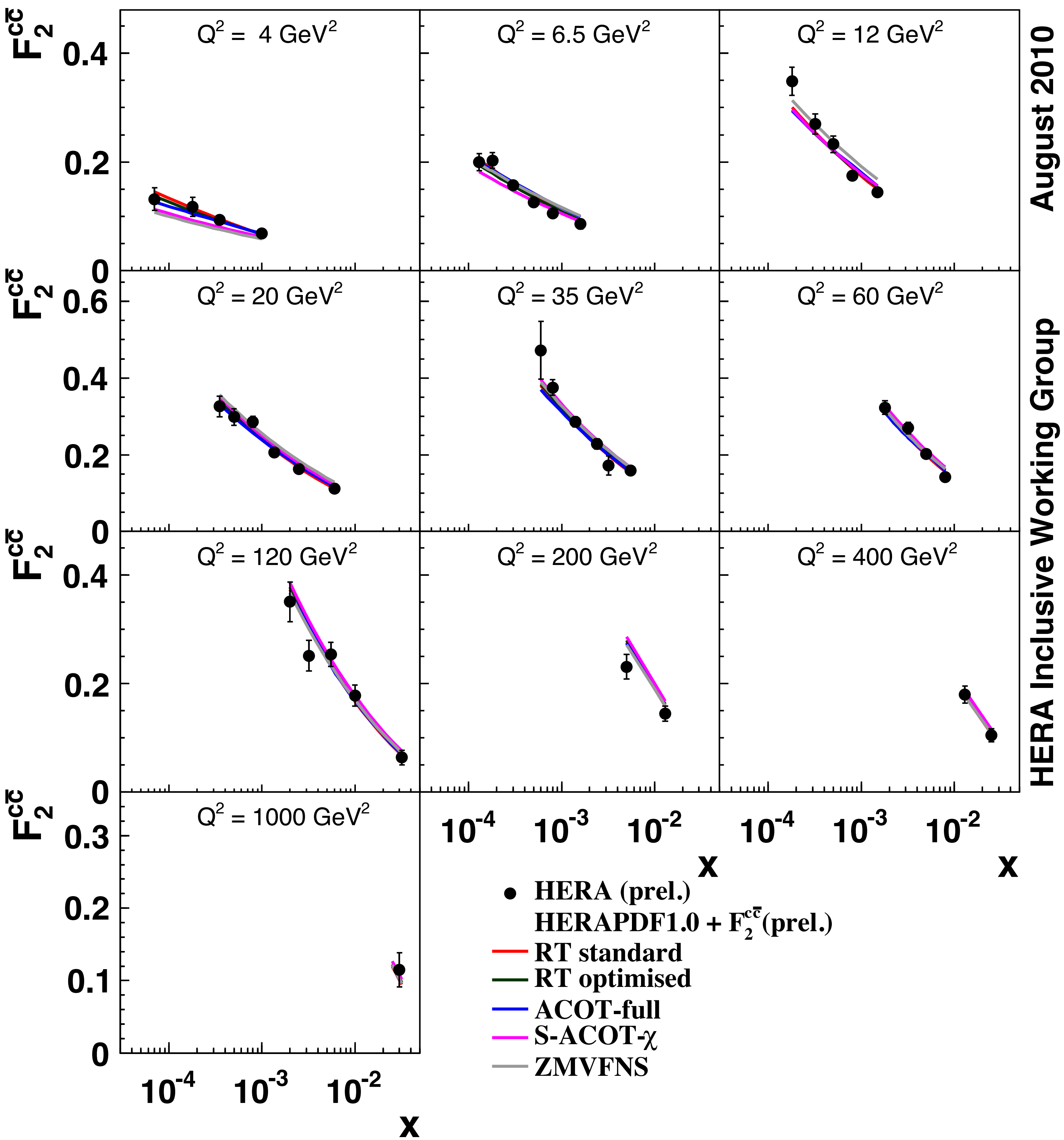
Excellent agreement over full phase space

Consistent description of fixed target data

Strong scaling violations at fixed x

⇒ large gluon density

Charm Content of the Proton



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

Theory predictions have small spread
⇒ use optimised m_c parameter

Spread of LHC Z/W production predictions is reduced ~4.5% → ~0.7% when using optimal value of m_c

DIS Jet Cross Sections

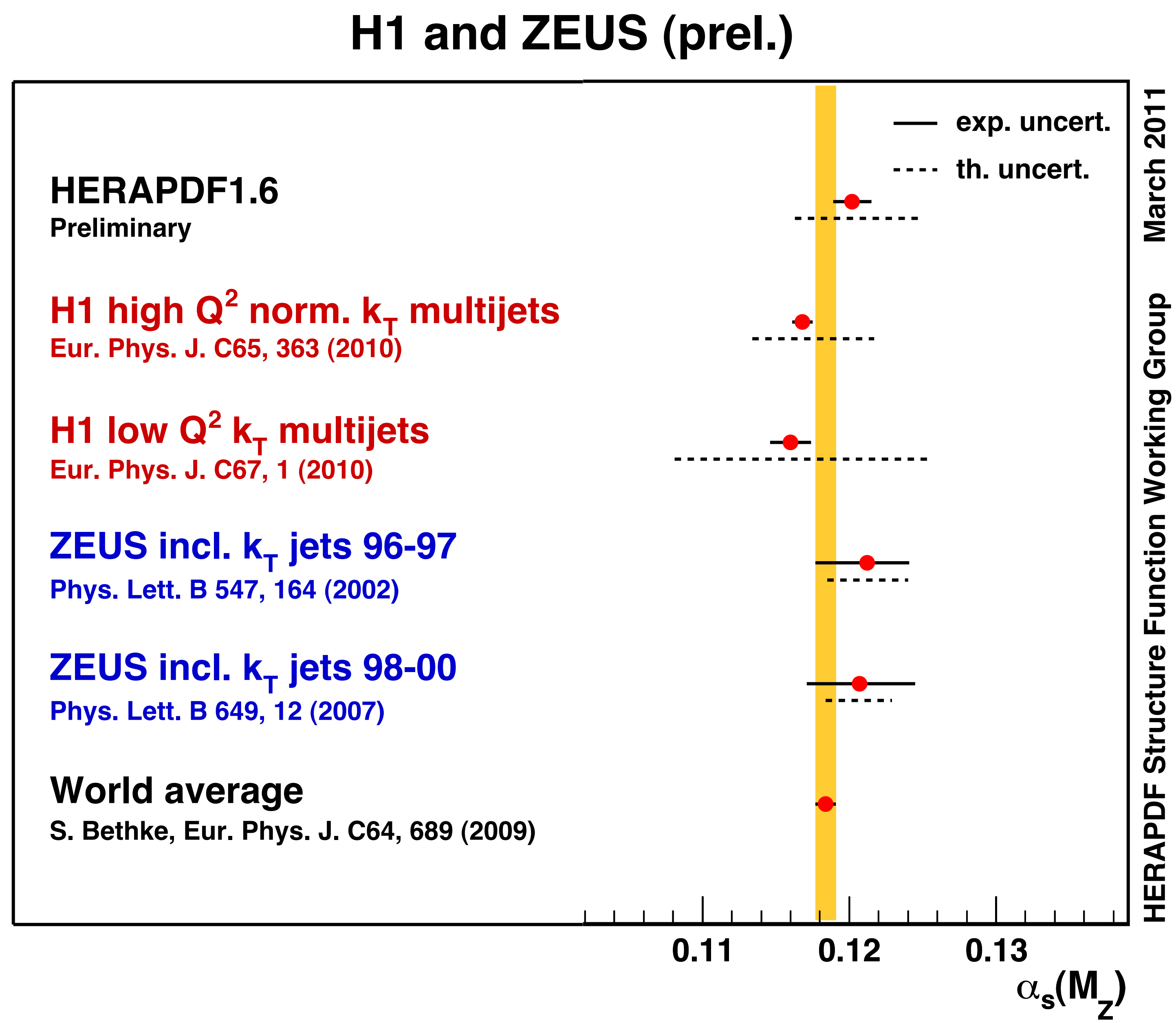
ZEUS inclusive jets	39 pb^{-1}	$Q^2 > 125$	Nucl. Phys. B765 (2007) 1-30
ZEUS inclusive jets	82 pb^{-1}	$Q^2 > 125$	Phys. Lett. B649 (2007) 12
H1 inclusive jets	395 pb^{-1}	$150 < Q^2 < 15000$	EPJ C65 (2010) 363-383
H1 inclusive jets	44 pb^{-1}	$5 < Q^2 < 100$	EPJ C67 (2010) 1-24

Jet data bring significant sensitivity to α_S
Disentangles correlation between $xg(x,Q^2)$ and α_S

HERAPDF1.6 : Simultaneous NLO QCD fit to
- combined NC inclusive cross section data
- combined CC inclusive cross sections data
- normalised H1/ZEUS inclusive jet data

$$\alpha_S(M_Z) = 0.1202 \pm 0.0013\ (\text{exp}) \\ \pm 0.0007\ (\text{model}) \\ \pm 0.0012\ (\text{hadronisation}) \\ {}^{+0.0045}_{-0.0036}\ (\text{scales})$$

Only combined PDF / α_S fit on the market



High Q^2 NC Multi-jets

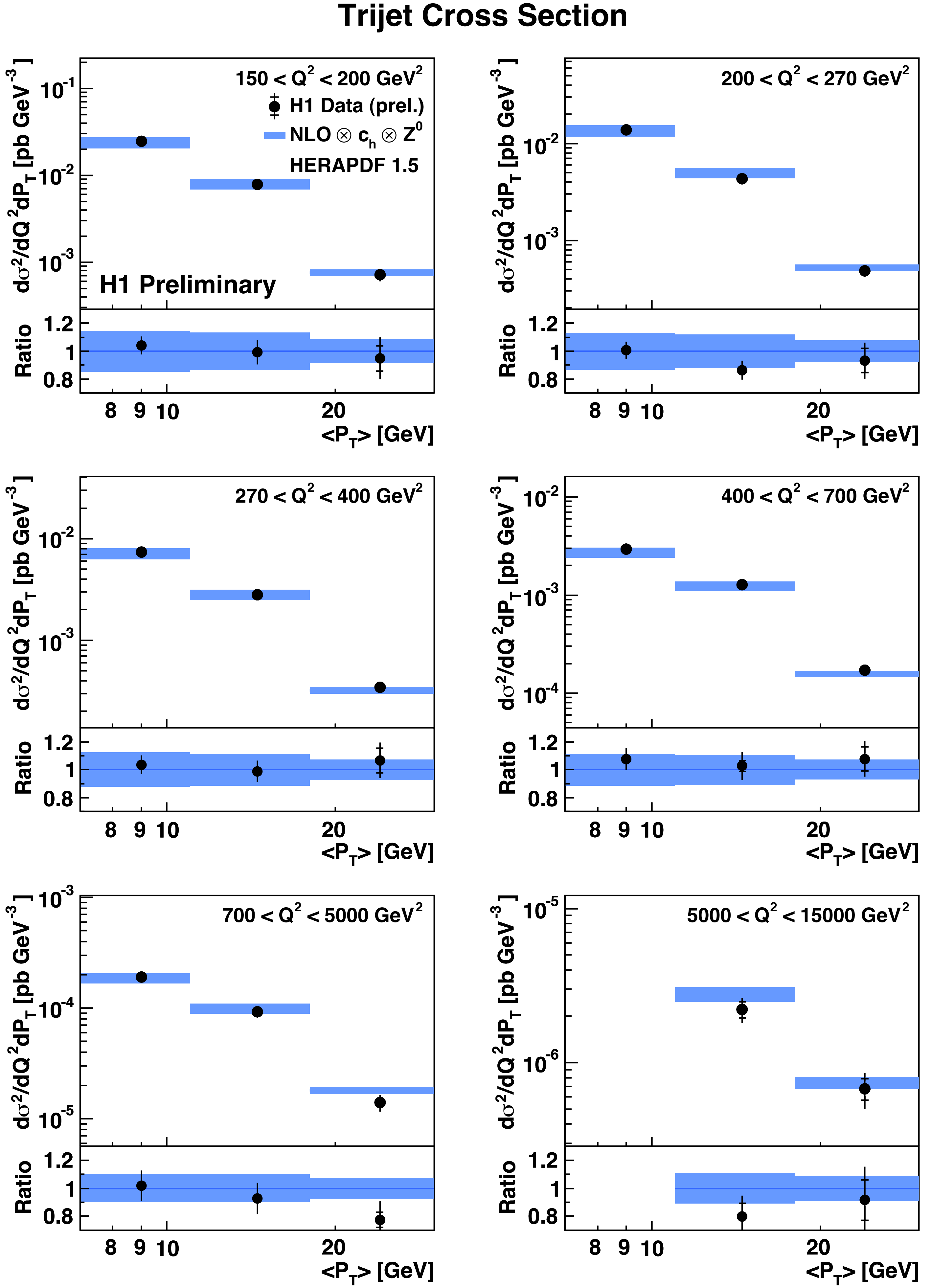
H1prelim-11-032

- New H1 measurement of inclusive, dijet and trijet rates
- First measurement of double diff'l trijet cross section
- Significantly reduced systematic errors
- 1% hadronic scale uncertainty
- For now - unnormalised cross sections...

Jets in Breit frame: $5 < P_T < 50$ GeV
$M_{12} > 16$ GeV

- Greater sensitivity to α_s with more jets
- High Q^2 and large jet $P_T \Rightarrow$ multi-scale QCD problem
- Good description in NLO
- (worse for di-jets at low $\langle P_T \rangle$ ...)

NLO calculation $\mu_R = \mu_F = \sqrt{\frac{1}{2}(Q^2 + P_T^2)}$
scales varied by factors of 2 for uncertainty



High Q^2 NC Multi-jets

H1prelim-11-032

Di-jet rates in reasonable agreement
~10% discrepancy at low $\langle P_T \rangle$
Data want smaller α_s or smaller xg ?

Extract α_s independently for each jet data set in NLO
PDF uncertainty from CT10 error propagation

Inclusive jets:

$$\alpha_s(M_Z) = 0.1190 \pm 0.0021(exp.) \pm 0.0020(pdf)^{+0.0050}_{-0.0056}(th.)$$

Dijets:

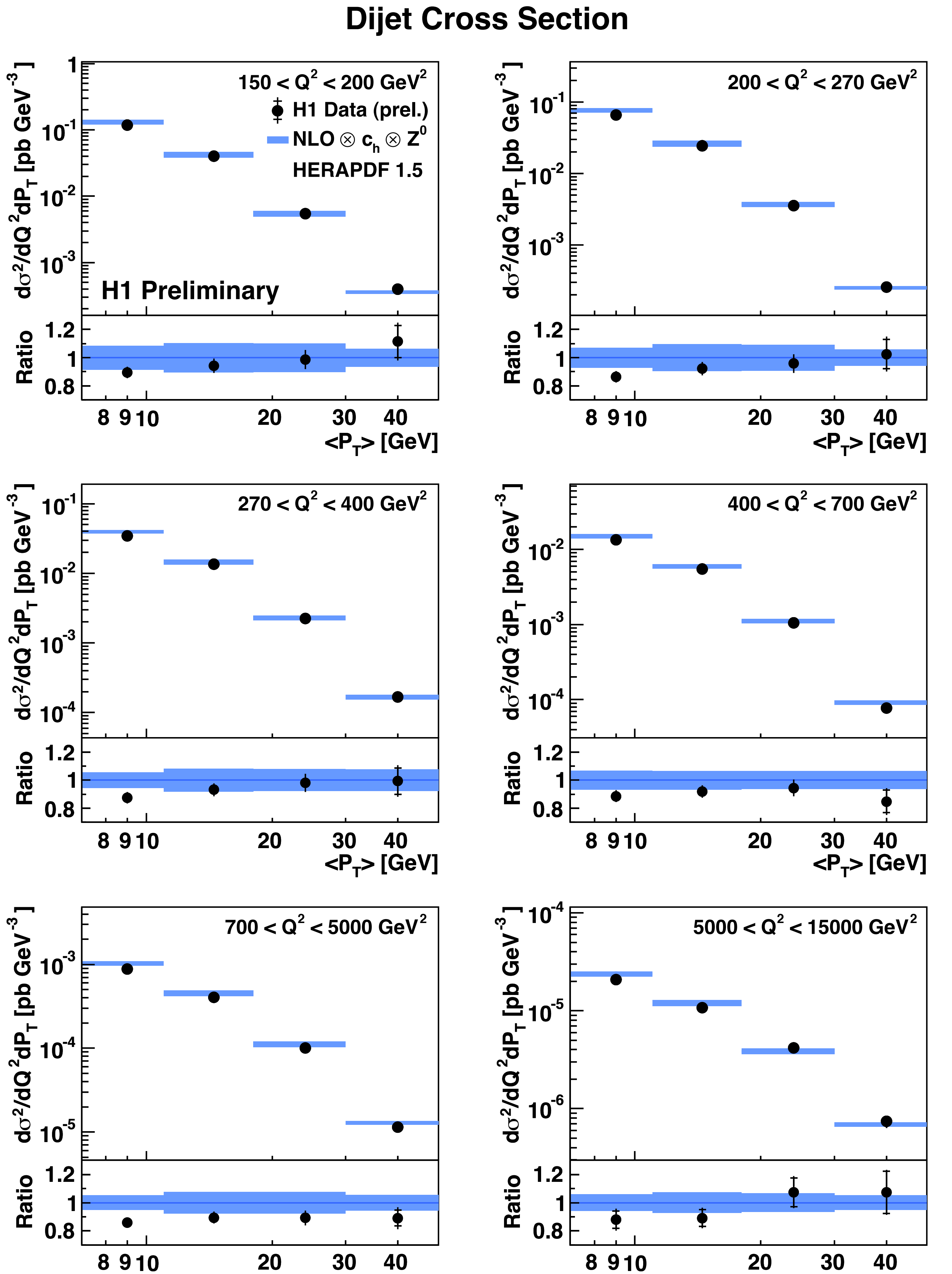
$$\alpha_s(M_Z) = 0.1146 \pm 0.0022(exp.) \pm 0.0021(pdf)^{+0.0044}_{-0.0045}(th.)$$

Trijets:

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016(exp.) \pm 0.0010(pdf)^{+0.0055}_{-0.0039}(th.)$$

Achieved ~1% experimental precision on α_s
Theoretical uncertainty (scales) dominate ~4%
PDF uncertainty ~1%

To come:
Use of normalised cross sections
cancellation of systematic uncertainties
→ reduced error for α_s



Compendium for HERAPDF

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

HERAPDF2.0
Include final:
HERA-II high Q^2 polarised NC/CC data
HERA-I+II F_2^{cc} data
HERA-I+II multijet data

HERAPDF1.5
Include additional NC and CC HERA-II data
Complete MSbar NLO and NNLO fit
NLO: standard parameterisation with 10 parameters

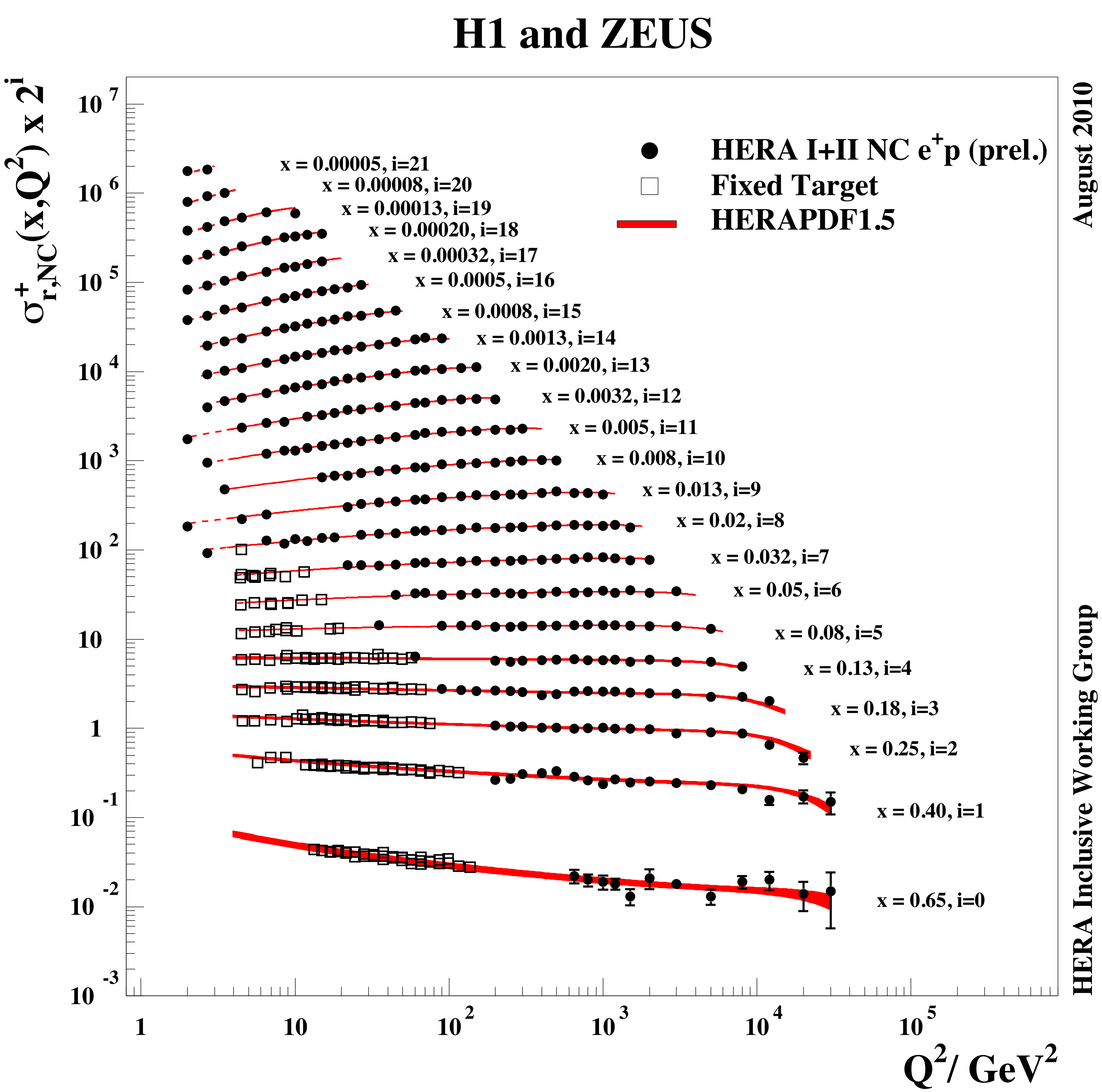
HERAPDF1.5f
NNLO: extended fit with 14 parameters

Details in Mandy's talk...

HERAPDF1.6
Include additional NC inclusive jet data $5 < Q^2 < 15000$
Complete MSbar NLO fit
NLO: standard parameterisation with 14 parameters
$\alpha_s = 0.1202 \pm 0.0013$ (exp) $\pm$ 0.004 (scales) free in fit

HERAPDF1.7
Include 41 additional F_2^{cc} data $4 < Q^2 < 1000$
Include 224 combined cross section points E_p=575/460 GeV
Complete MSbar NLO fit
NLO: standard parameterisation with 14 parameters

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
- HERA jet data allow α_S extraction
- Precision limited by missing jet NNLO theory
- 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

Backup Slides

QCD Analysis

HERAPDF1.0

Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with10 parameters
$\alpha_s = 0.1176$ (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

HERAPDF1.5f

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

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

$x\bar{s} = f_s x\bar{D}$ 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
$2 \times 10^{-4} < x < 0.65$
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:
$\Delta\chi^2 = 1$

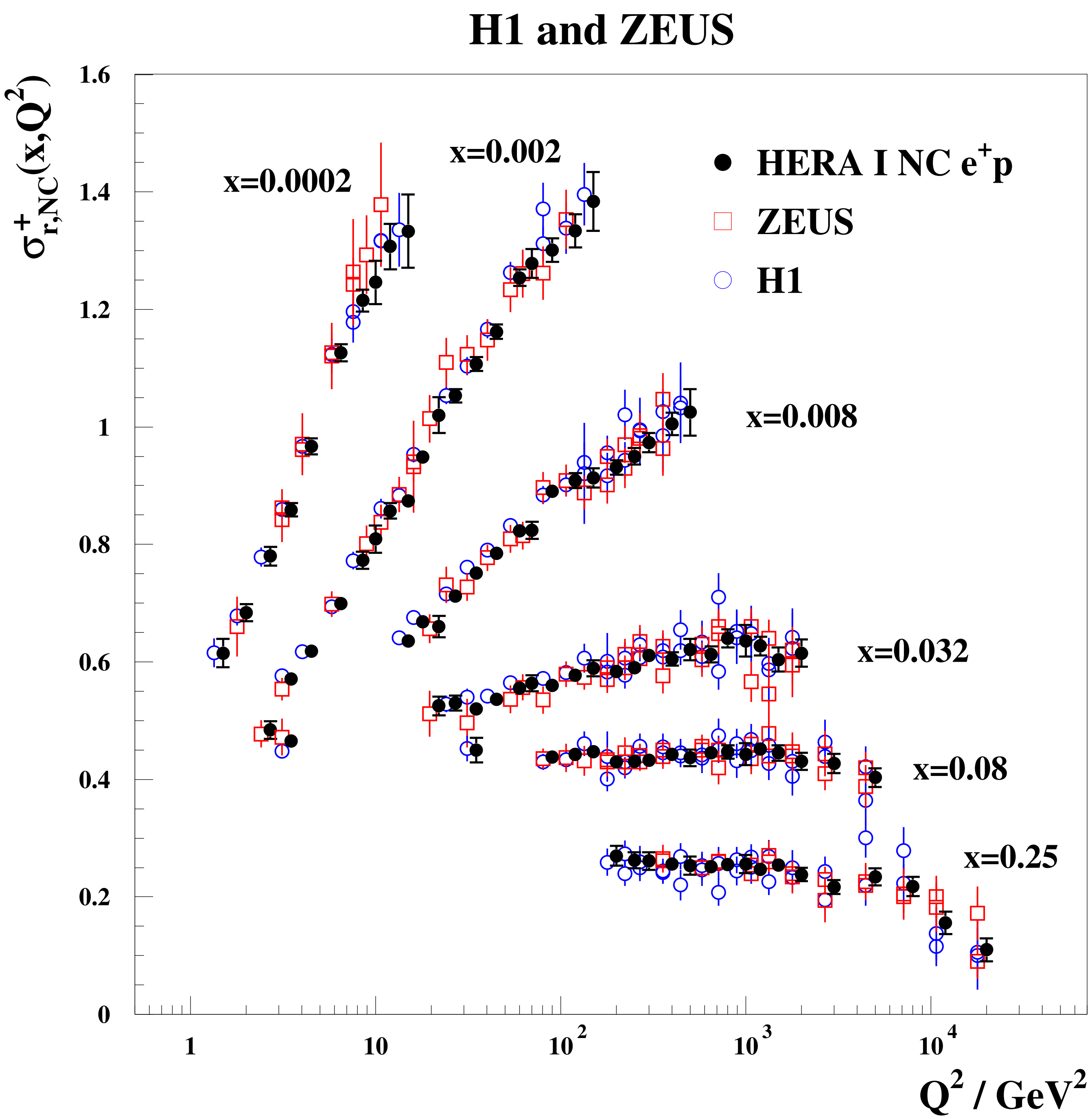
Exclusive jet data required for free α_s fit
See talk of Krzysztof Nowak

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

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

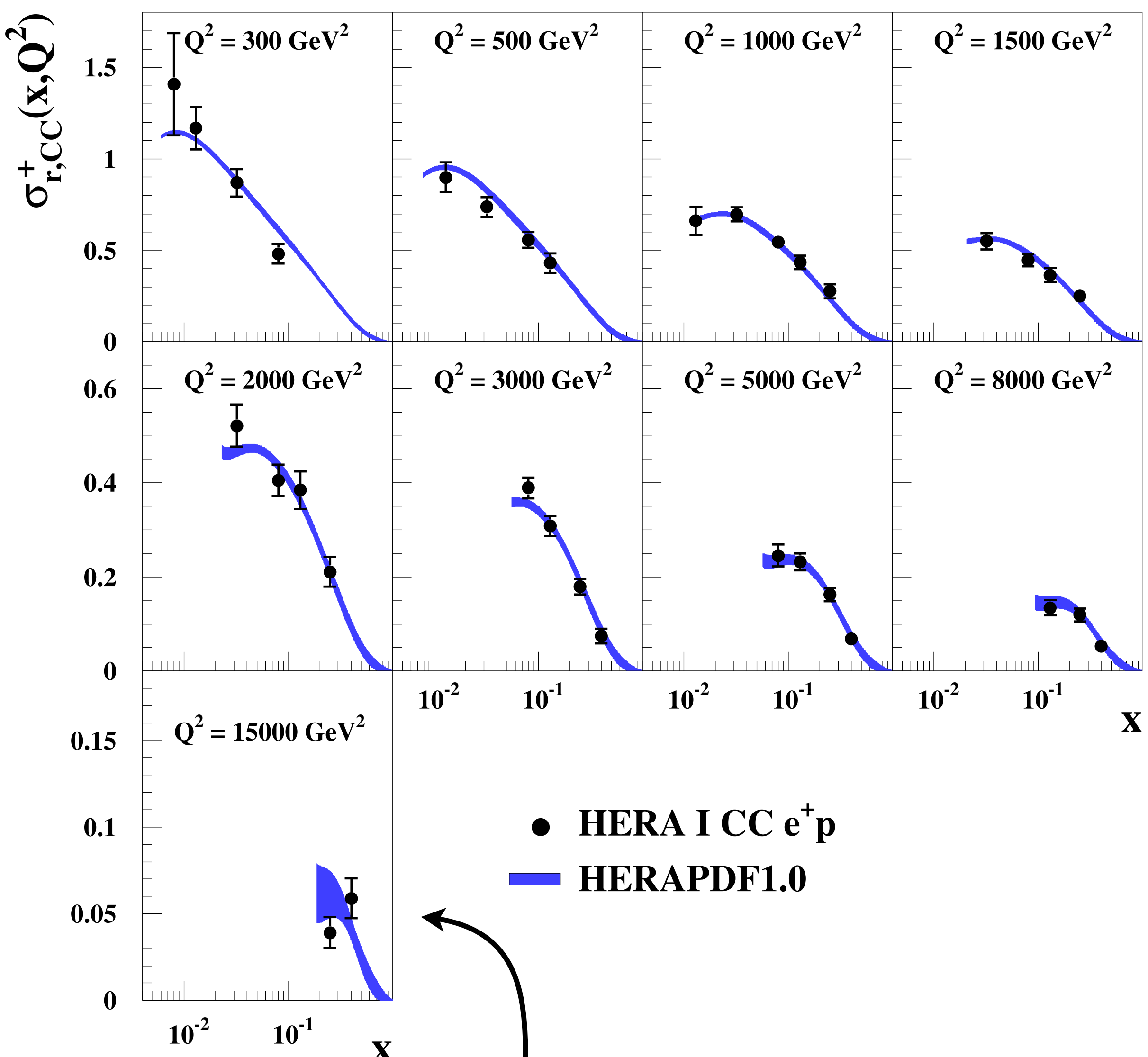
High Q² CC Cross Sections

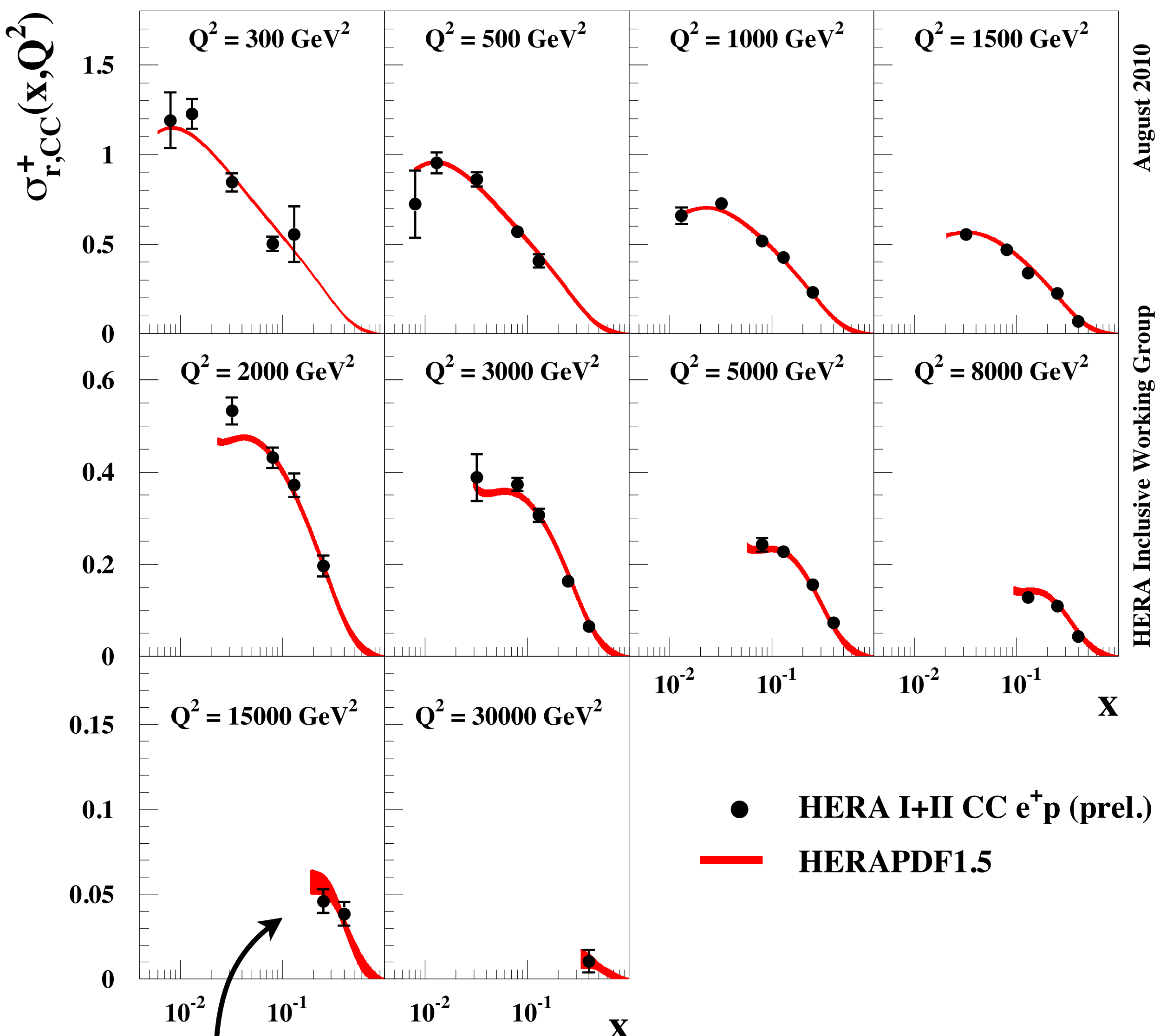
Positron scattering

HERA-I → HERA-I+II

Positron scattering

Significant improvement in measurement precision





Reduced QCD uncertainty at high x