XIX International Workshop on Deep-Inelastic Scattering and Related Subjects

Universität Hamburg

Combined measurement of NC & CC DIS cross-sections at HERA

(JHEP01 (2010) 109, H1-prel-10-141/ZEUS-prel-10-017 & H1-prel-10-142/ZEUS-prel-10-018)

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on behalf of

H1 and ZEUS

Outline:

- H1 and ZEUS at HERA
- Deep Inelastic ep Scattering
- Data combinations procedure
- Results

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

DIS 2011, Newport News, April 12, 2011

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

Motivation

HERA analyses of NC and CC inclusive cross sections almost completed → important to combine, in a model independent way, the H1 and ZEUS measurements:

⇒ Strong consistency check of the measurements

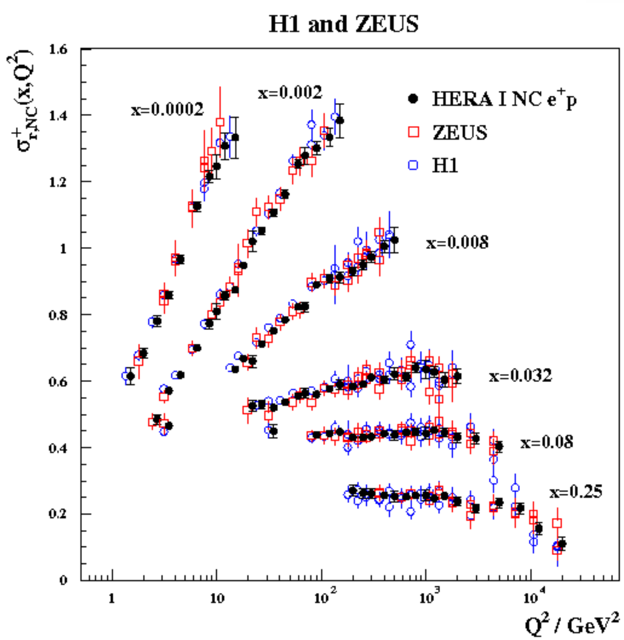
⇒ Experiments "cross-calibrate" each other: reduction of the syst. uncert.

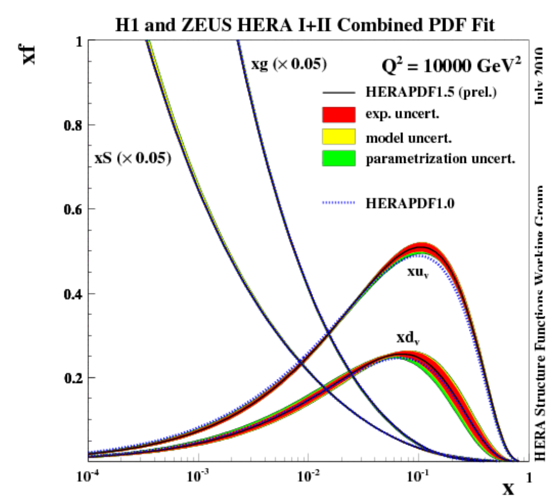
⇒ Combined data set ideal input for a DGLAP QCD analysis to extract proton's PDFs :

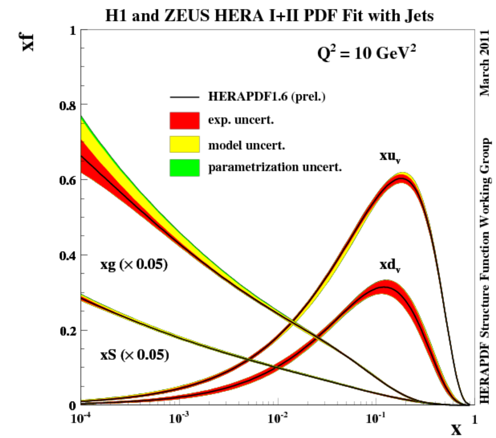
HERA-I → HERAPDF1.0

HERA-I + HERA-II high-Q^2 → HERAPDF1.5, HERAPDF1.6(+jets)

=> most precise HERA PDFs for LHC

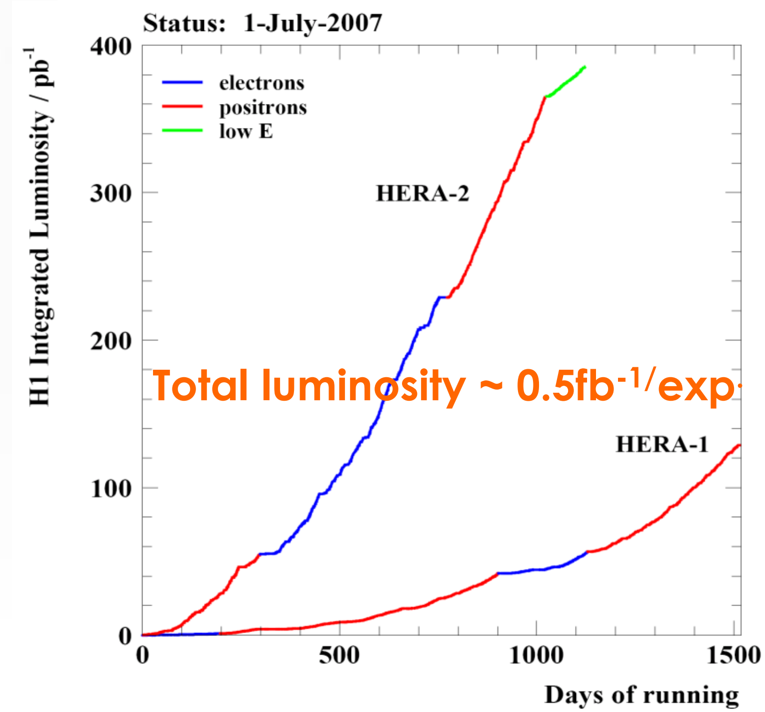






HERA: World's Only ep Collider

HERA: world's largest "electron-microscope"!
(with "resolving power": $Q^2 \sim 1/\lambda^2$ (10^{-18}m))



Presented results:

HERA-I: 1992-2000 L~120 pb^{-1}/exp.

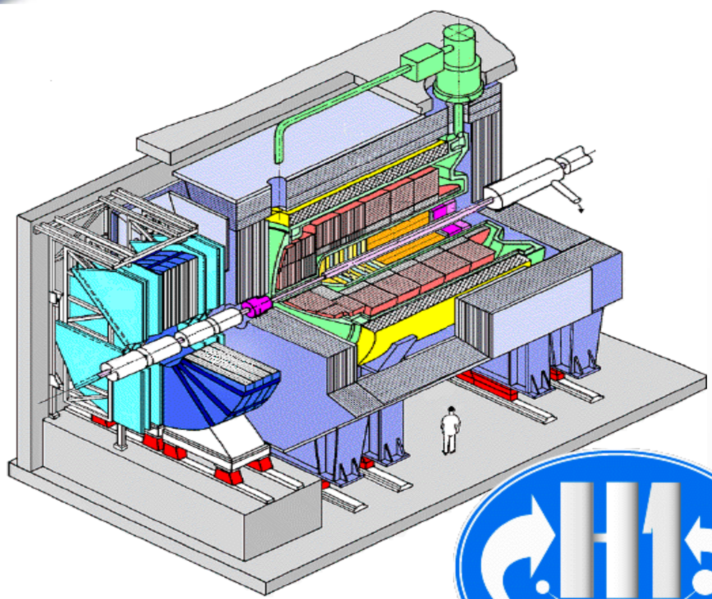
- precision measurements at low/medium-Q^2

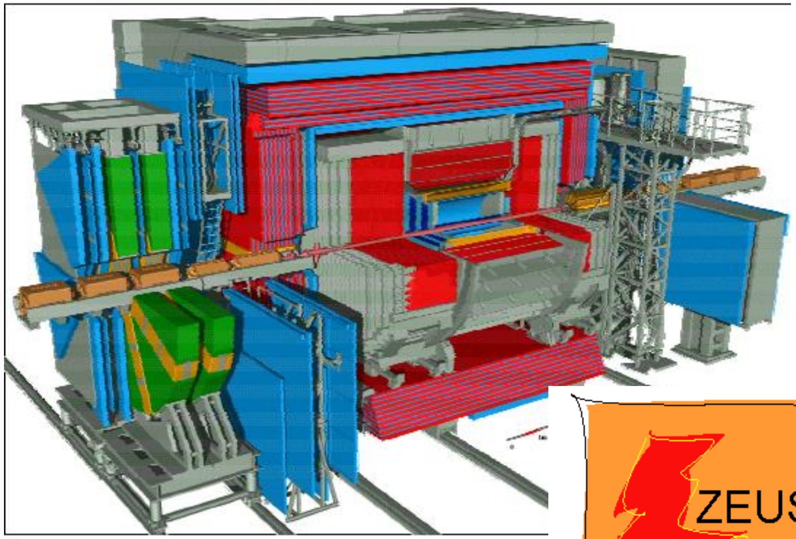
…and a glimpse of high-Q^2 potential

HERA-II 2002-2007 L~350 pb^{-1}/exp.

- luminosity upgrade → larger statistics for high-Q^2
- Polarized e+/e- beam → direct EW sensitivity
- Low energy data (Ep=450, 575 GeV) → FL

H1 & ZEUS: Hermetic multi-purpose detectors





Liquid Argon Calorimeter

optimized for precision measurement of the scattered lepton

$\sigma_E/E = 11\%/\sqrt{E}$ (electrons)

$\sigma_E/E = 50\%/\sqrt{E}$ (hadrons)

Uranium-scintillator Calorimeter

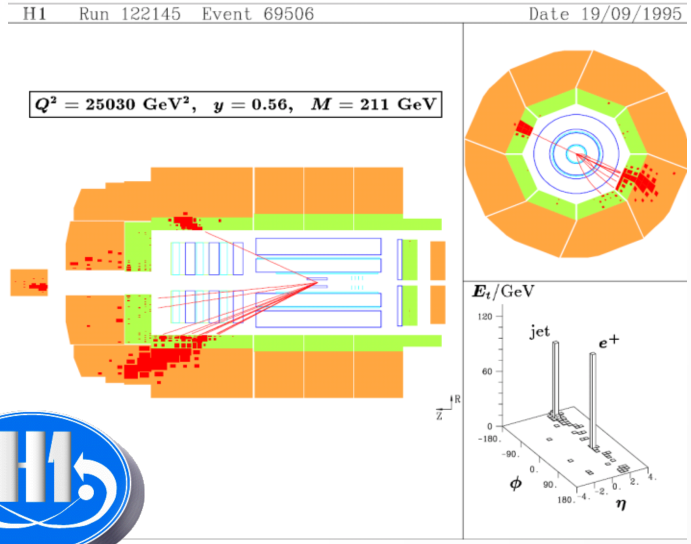
optimized for precision measurement of the hadronic final state

$\sigma_E/E = 18\%/\sqrt{E}$ (electrons)

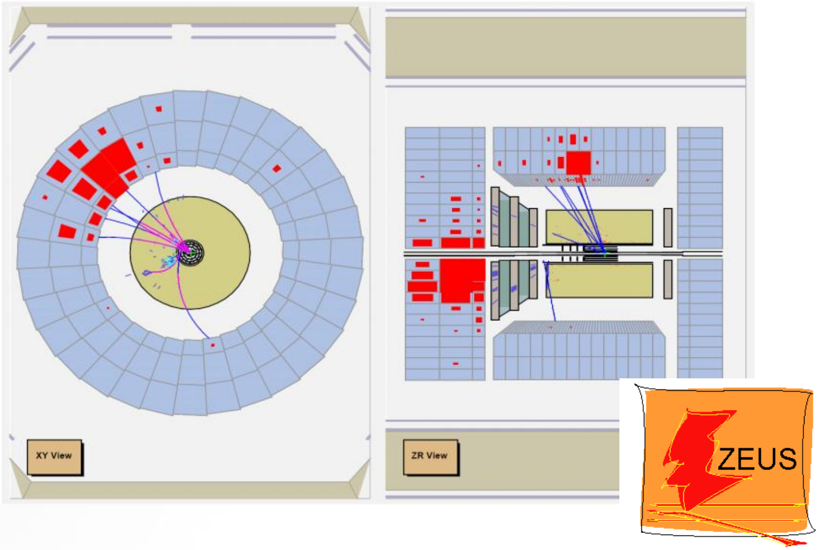
$\sigma_E/E = 35\%/\sqrt{E}$ (hadrons)

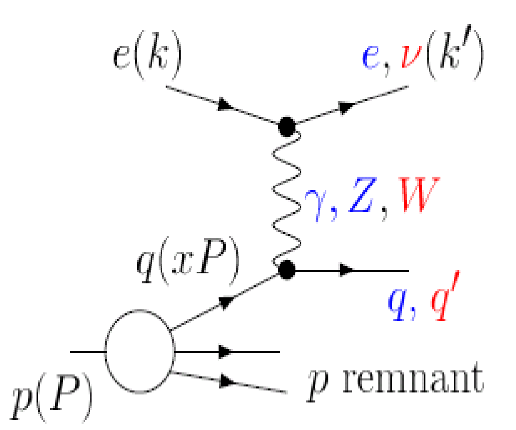
Deep Inelastic Scattering Processes

Neutral Current



Charged Current





$$Q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

Q^2 = -(4-momentum of propagator)^2 – the virtuality of the exchanged boson.

x – fractional momentum of proton carried by struck quark q

y – fractional energy of the incoming lepton transferred to the proton in the proton's rest frame (inelasticity)

Deep Inelastic Scattering

NC: Sensitive to gluons, valence quarks and see quarks

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{2\alpha\pi^2}{xQ^4}\left[Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right] \qquad Y_\pm = \tfrac{1}{2}(1 \pm (1-y^2))$$

$$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$$

Directly sensitive to quark distribution
Gluon from scaling violations.

$$xF_3 \propto \sum_i xq_i - x\bar{q}_i$$

Valence quarks

$$F_L \propto \alpha_s xg$$

Gluon at NLO

Use 'reduced cross section'
to remove kinematic dependence:

$$\sigma_r = \frac{xQ^2}{2\alpha\pi^2 Y_+}\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} \approx F_2$$

CC: Flavour decomposition

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

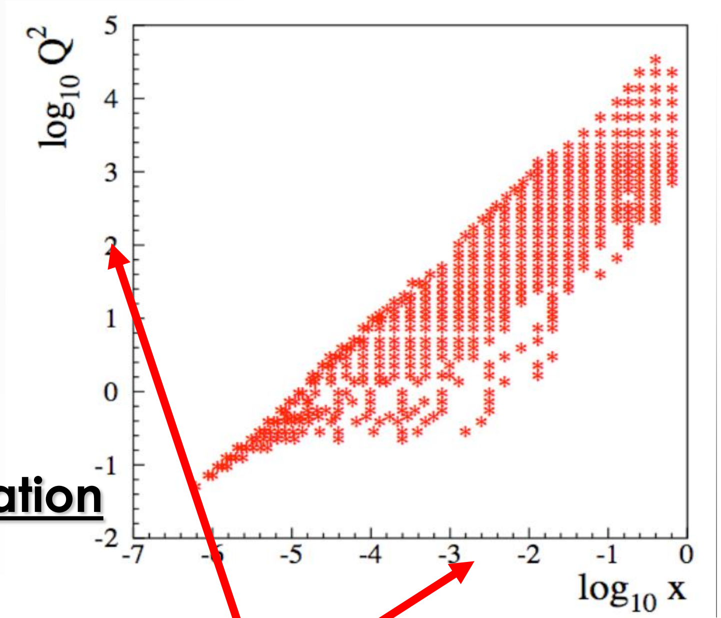
e+p:
$$\frac{d^2\sigma^{+}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[\bar{u} + \bar{c} + (1-y)^2(d+s)\right]$$

Inclusive cross section combination HERA-I

- H1 & ZEUS have combined inclusive DIS cross sections from HERA I data => New average with L=240 pb^{-1}

- <u>Combination procedure:</u>

1) Swim all point to a common Q^2-x grid
2) Move 820 GeV data to 920 GeV p-beam energy (not for NC at y>0.35)
3) Calculate average values and uncertainties
4) Evaluate "procedural uncertainties"



- <u>$\chi 2$ minimalisation method for data combination</u>

1402 data points combined to 741 cross section measurements:

- 110 correlated syst. error sources (H1 & ZEUS)

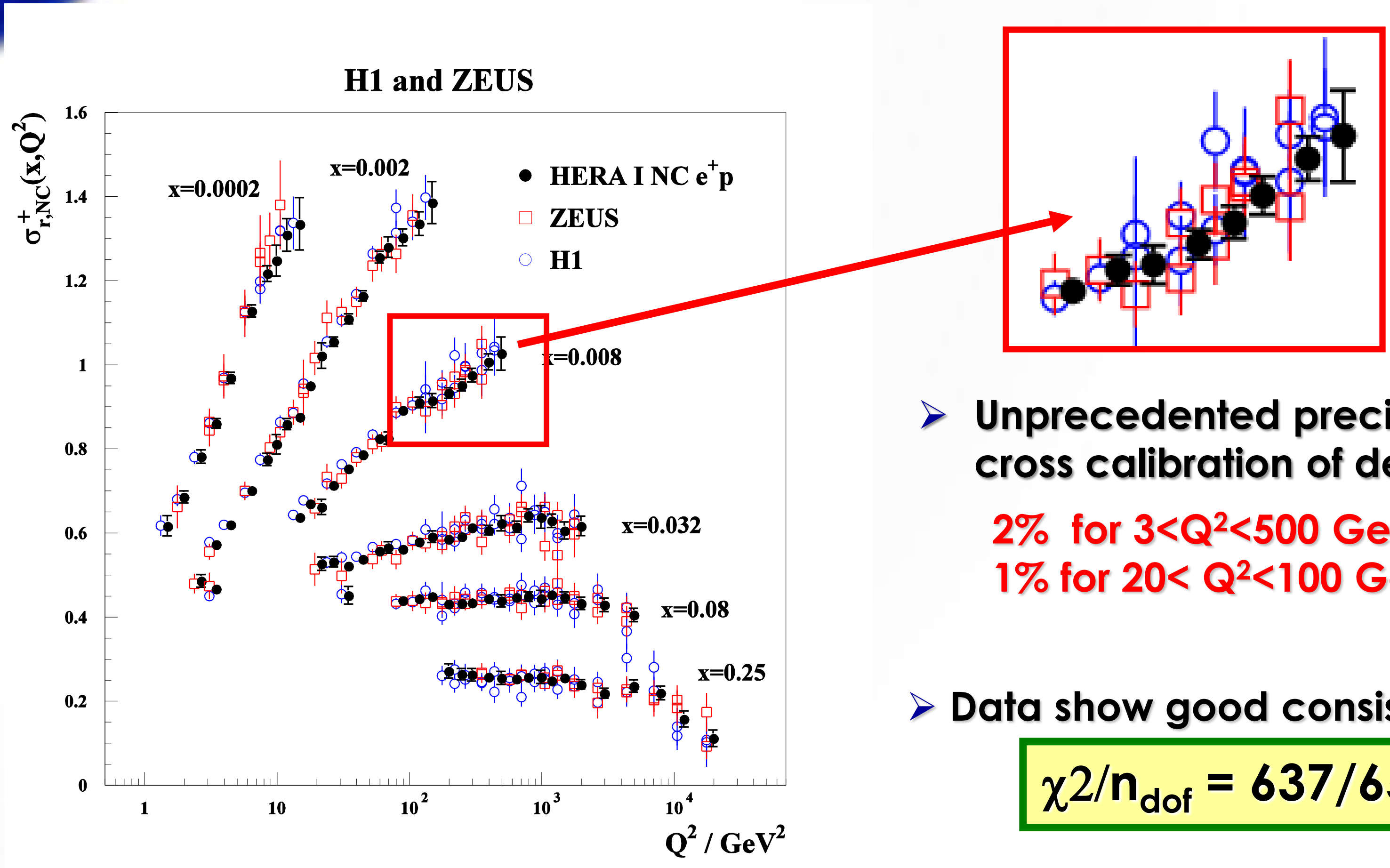
- 3 procedural uncertainties

-H1 & ZEUS syst. assumed independent (except 0.5% lumi normalisation)

Span 6 orders of magnitude in x and Q^2

The Power of Combination (JHEP01 (2010) 109)

- Combined are full published HERA-I NC, CC $e^{\pm}p$ cross sections



- Unprecedented precision due to cross calibration of detectors

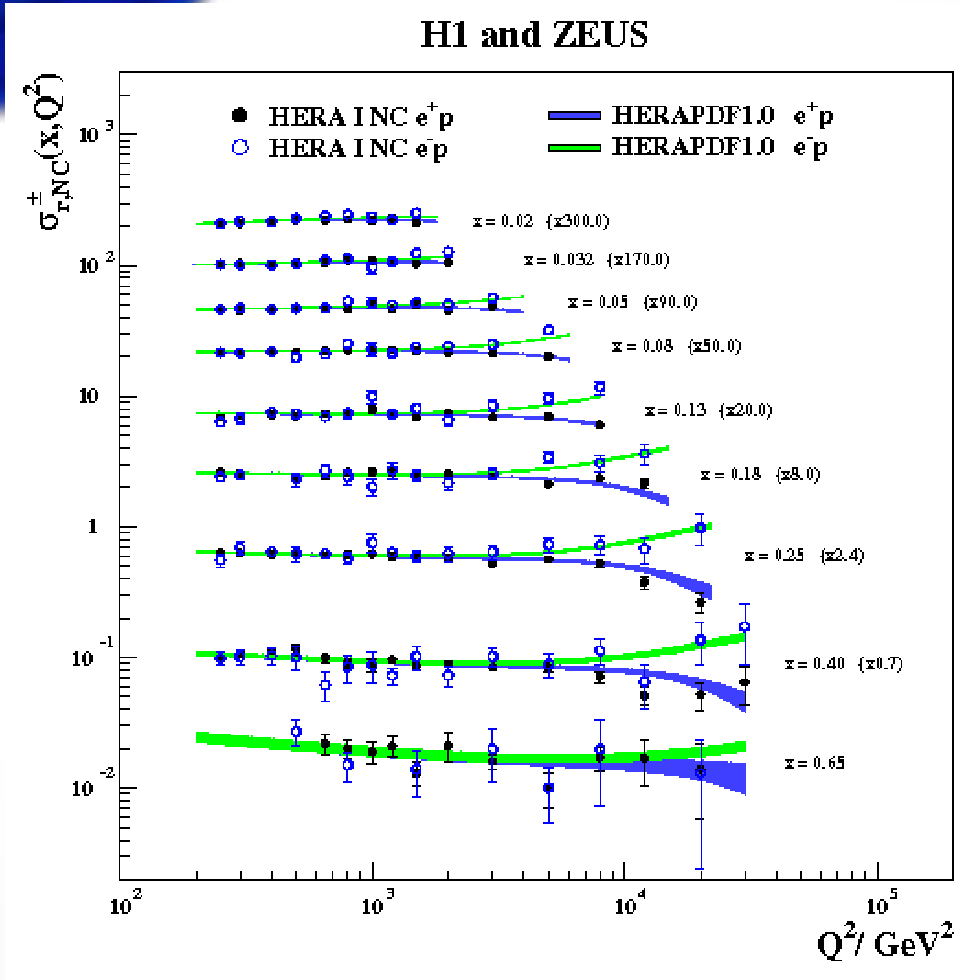
  2% for $3<Q^2<500$ GeV^2
  1% for $20< Q^2<100$ GeV^2

- Data show good consistency

  $\chi 2/n_{dof}$ = 637/656

QCD analysis based on HERA-I data → HERAPDF1.0

HERA-I combined NC data



NC data at high-Q^2 → $Z\gamma$ interference **destructive (e+p)** and **constructive (e-p)**

- Good agreement between data and **NLO QCD fit (HERAPDF1.0)**

Including **HERA-II high-Q^2 data** → improvement **at high-Q^2 and high-x** is expected

Combination of the high-Q^2 data

Extension of the published combination of the HERA I data:

Used data:

✓ HERA-I as in JHEP01(2010)109

✓ HERAII:

H1, HERA II (high Q^2, P=0)
CC e-p
CC e+p
NC e-p
NC e+p

ZEUS, HERA II (high Q^2, P=0)
NC e-p
CC e-p
CC e+p

Method of combination:

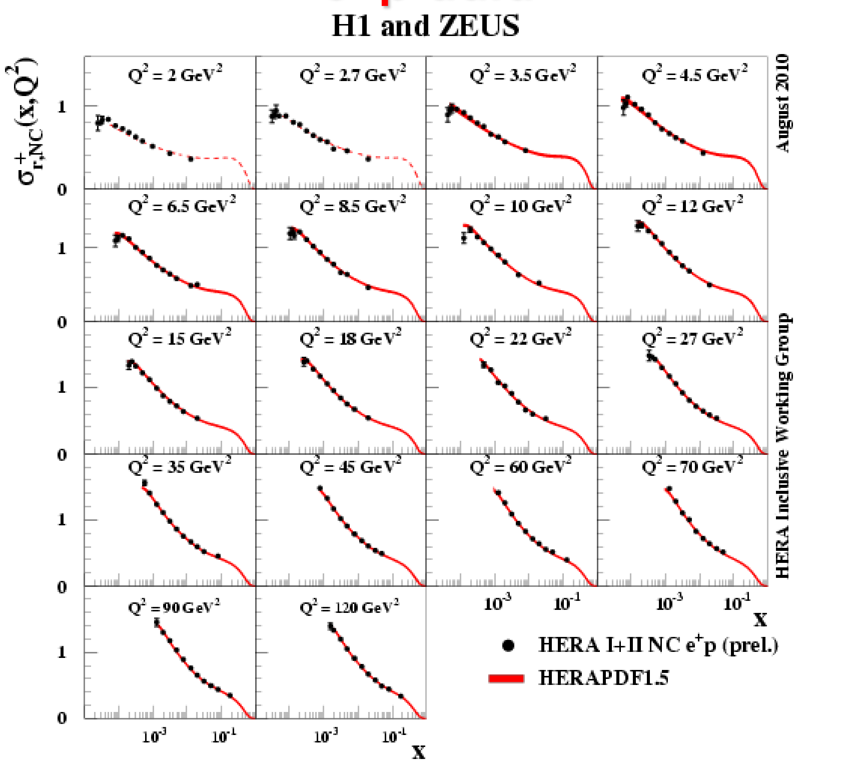
- HERA-I : same as in JHEP01(2010)109
- HERA-II : three additional procedural errors

$\chi 2/n_{dof} = 967/1032$

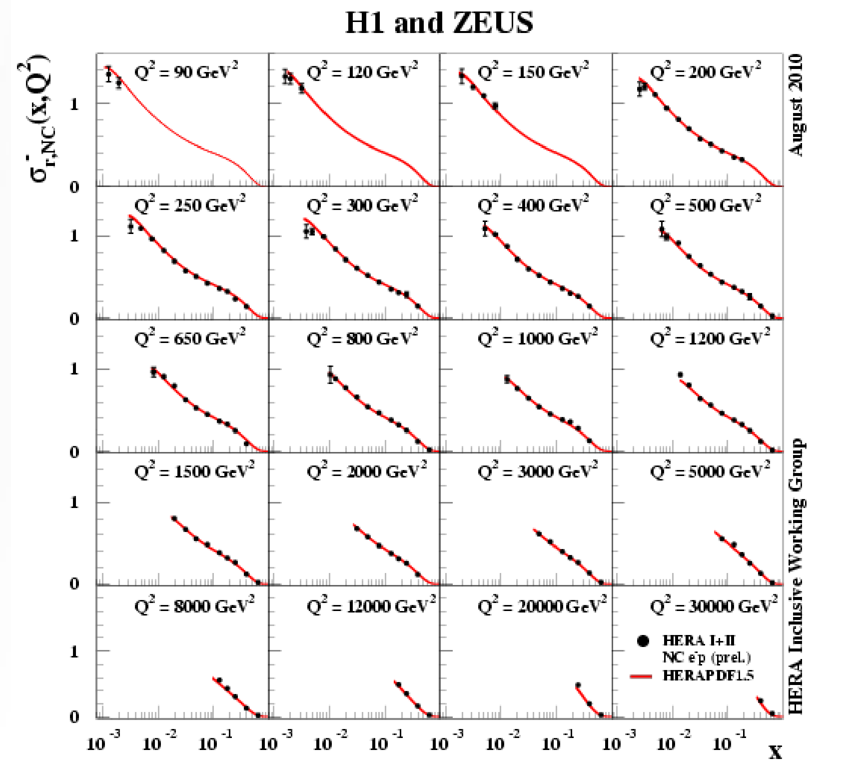
QCD analysis based on HERA-I + HERA-II high-Q^2 data
HERAPDF1.5

F_2 with combined HERA-I+II NC

Low/medium Q^2 bins (2-120 GeV^2)
e+p data



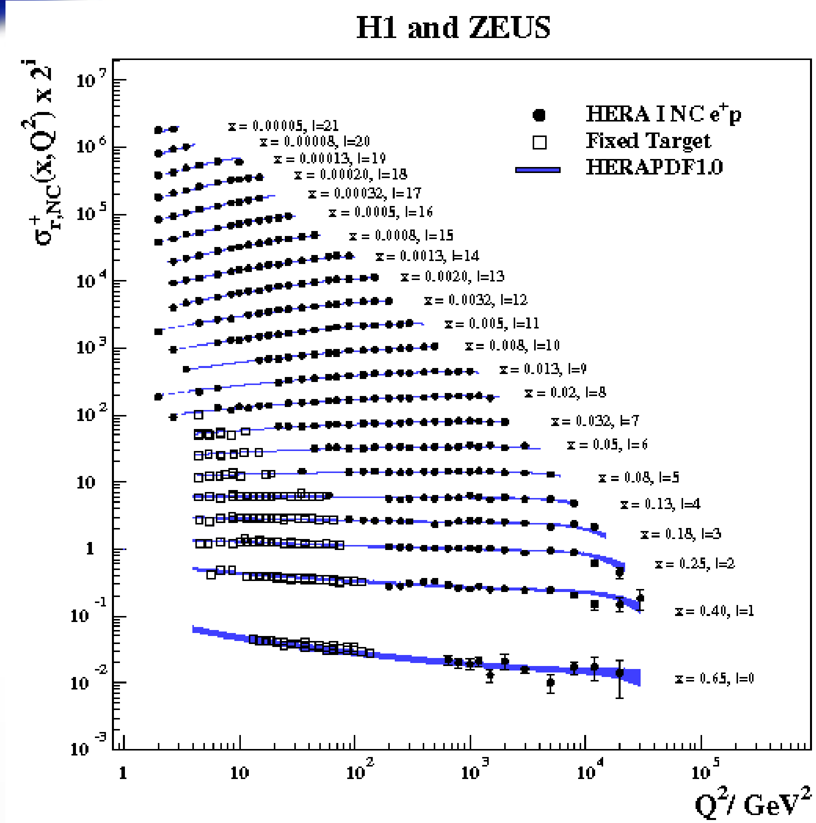
High Q^2 bins (90-30000 GeV^2)
e-p data



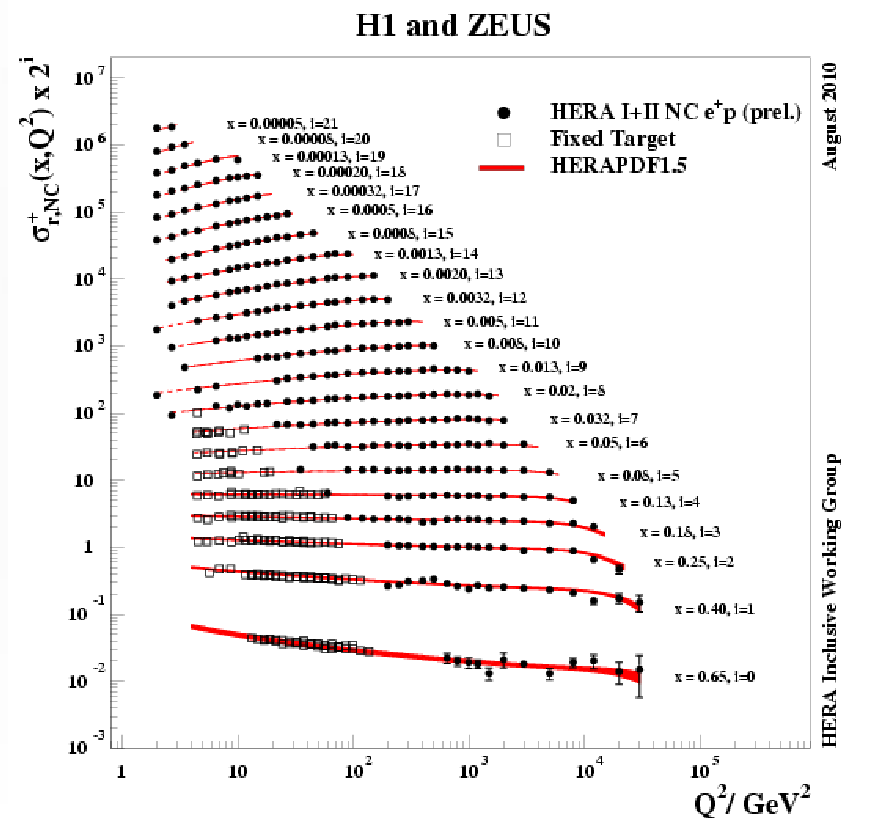
- **$F_2(x,Q^2)$** shows strong rise as **x->0**, the rise increases with increasing Q^2
- Data well described by QCD fit from Q^2=2 to 30000 GeV^2

Combination of NC data

HERA-I combined results:



HERA-I+II combined results:



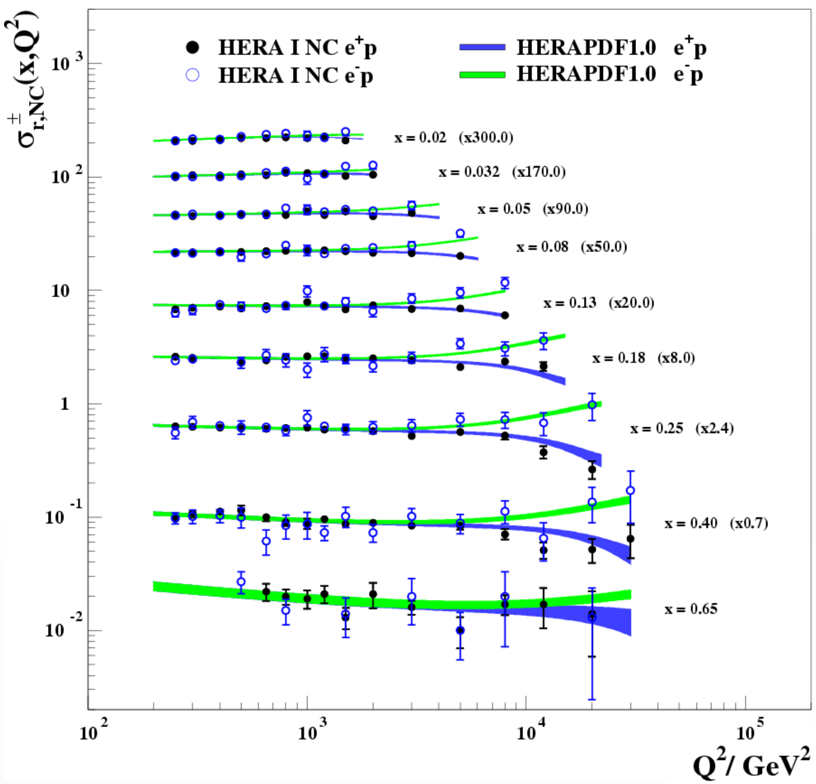
- Data show strong scaling violations at low x → large gluon density

New HERA-II measurements → increased precision at high-Q^2

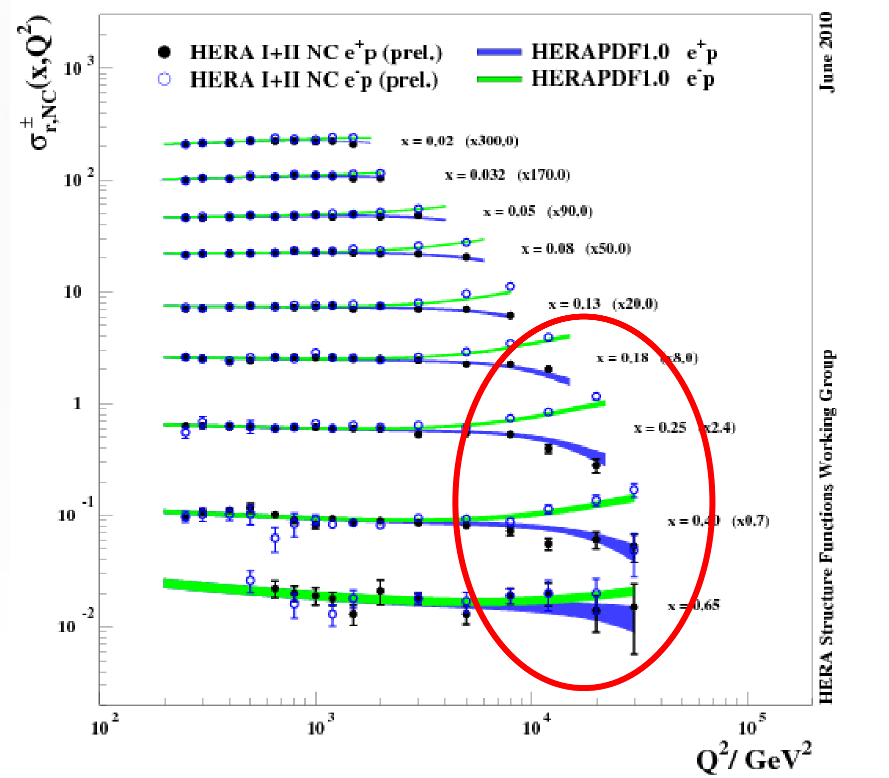
Combination of NC high-Q^2 data

NC data at high-Q^2 → $Z\gamma$ interference destructive (e+p) & constructive (e-p)

HERA-I combined results vs. HERAPDF1.0



HERA-I+II combined results vs HERAPDF1.0



Including HERA-II high-Q^2 data →
improved data precision at high-Q^2 and high-x

Combination of NC high-Q^2 data

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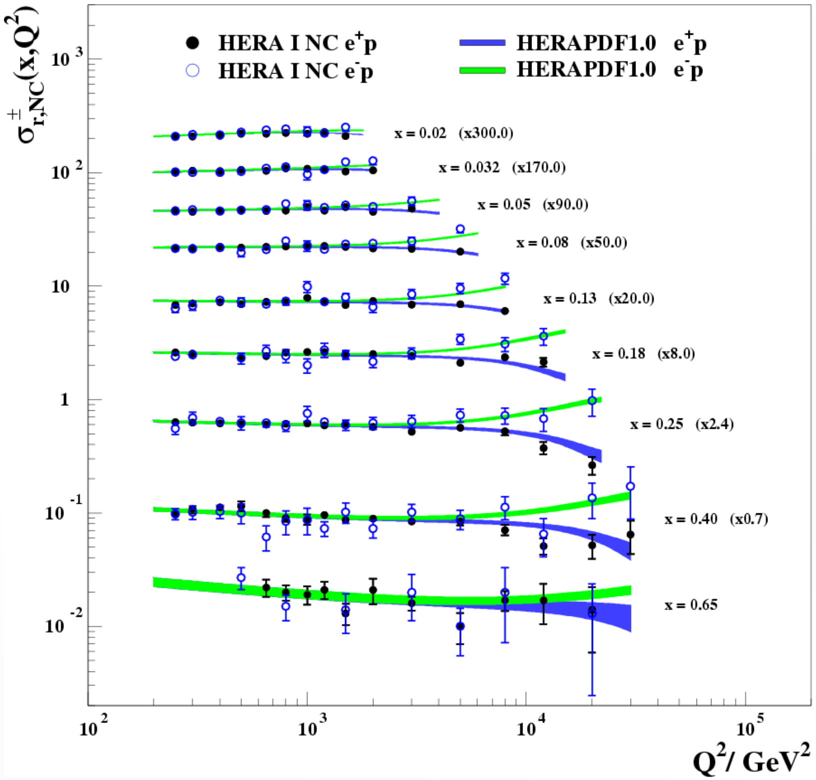
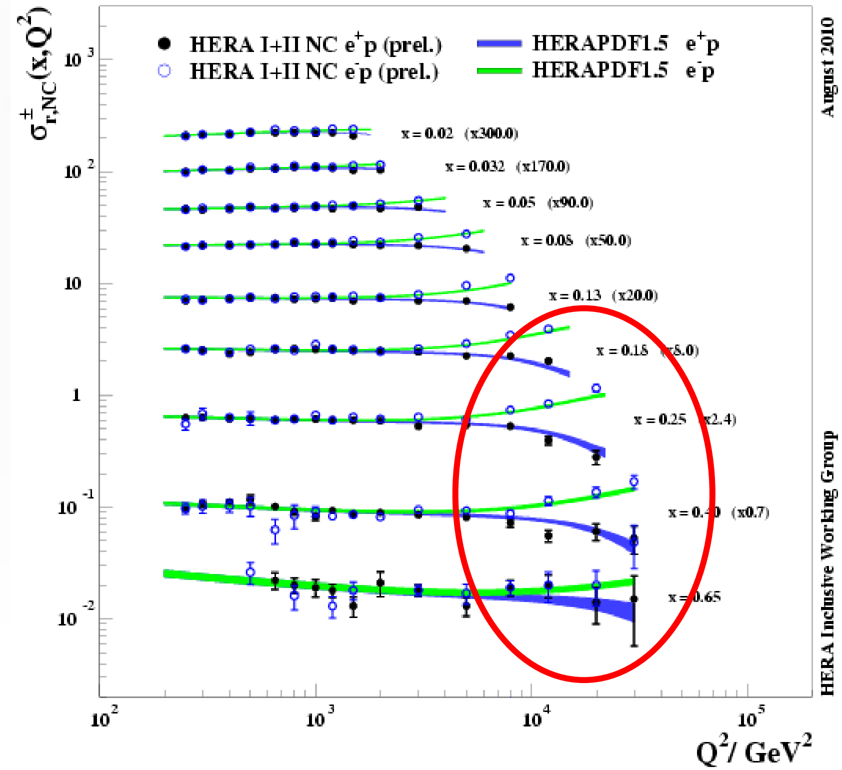


HERA-I+II combined results vs. HERAPDF1.5



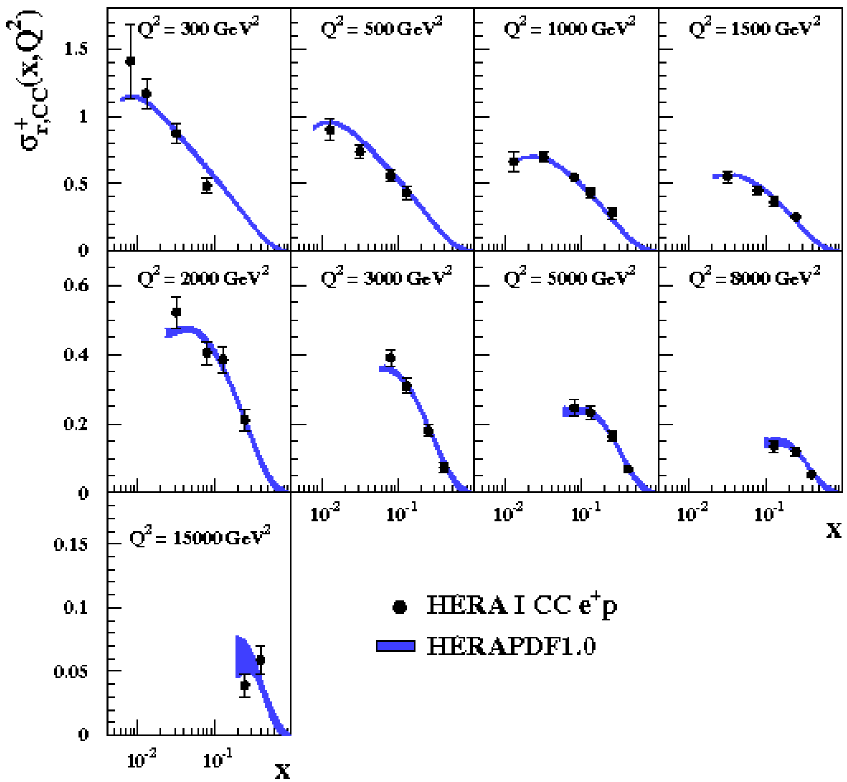
Including HERA-II high-Q^2 data →
improved PDF precision at high-Q^2 and high-x

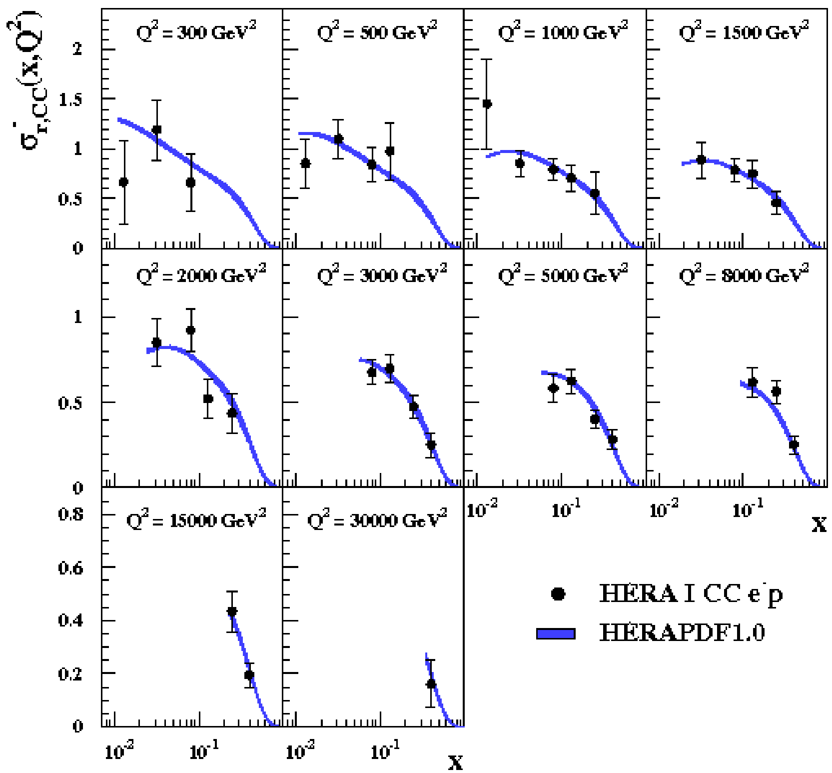
Combined HERA-I CC data vs. HERAPDF1.0

- CC e^+p/e^-p allows to disentangle contributions of d and u quarks
- Probes flavor structure of the proton

$$\tilde{\sigma}_{cc}^{e+p} \sim \bar{u} + \bar{c} + (1-y)^2 (d+s)$$

$$\tilde{\sigma}_{cc}^{e-p} \sim u + c + (1-y)^2 (\bar{d} + \bar{s})$$





e^+p most sensitive to $d(x,Q^2)$
e^+p valence quarks suppressed by factor $(1-y)^2$

e^-p most sensitive to $u(x,Q^2)$

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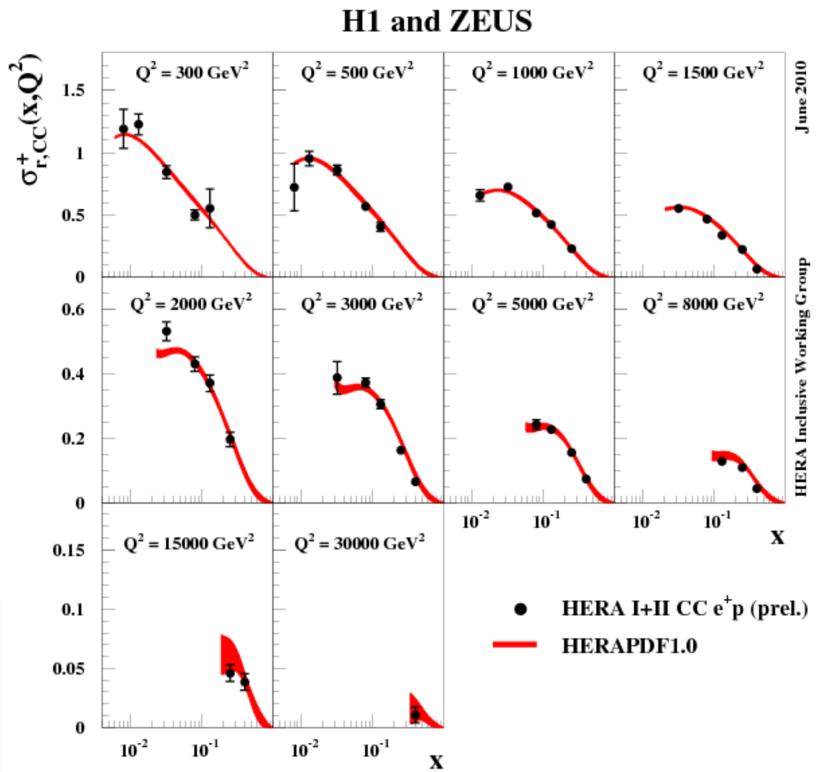

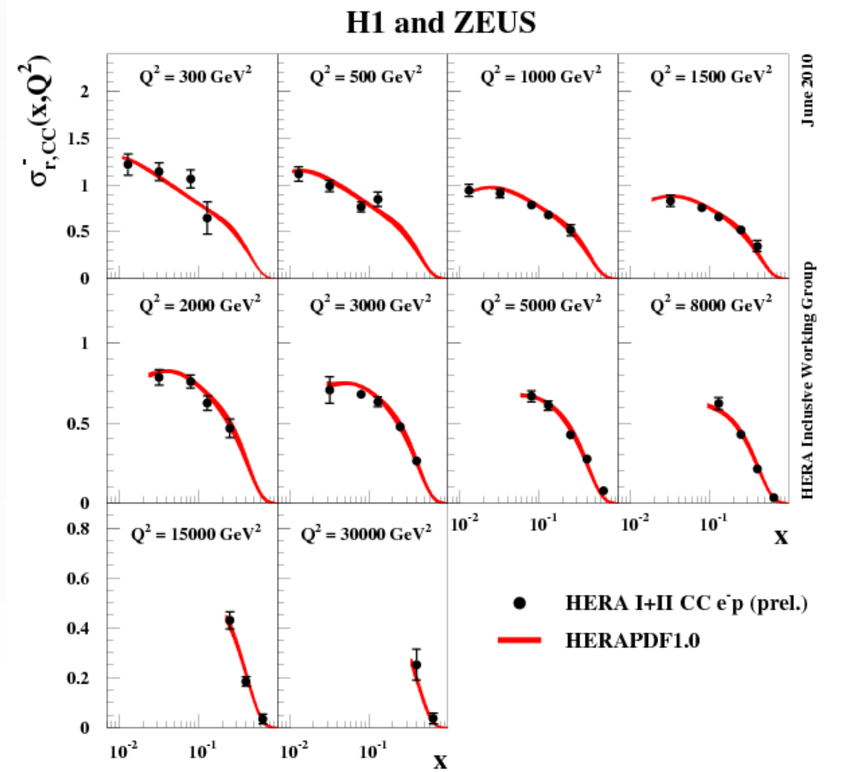

e^+p most sensitive to $d(x,Q^2)$
e^+p valence quarks suppressed by factor $(1-y)^2$

e^-p most sensitive to $u(x,Q^2)$
10 x higher statistic than in JHEP01(2010)109

Including HERA-II high-Q^2 data → increased data precision

Combined HERAI+II CC data vs. HERAPDF1.5

- CC e^+p/e^-p allows to disentangle contributions of **d** and **u** quarks
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$$\tilde{\sigma}_{cc}^{e+p} \sim \bar{u} + \bar{c} + (1-y)^2 (d+s)$$

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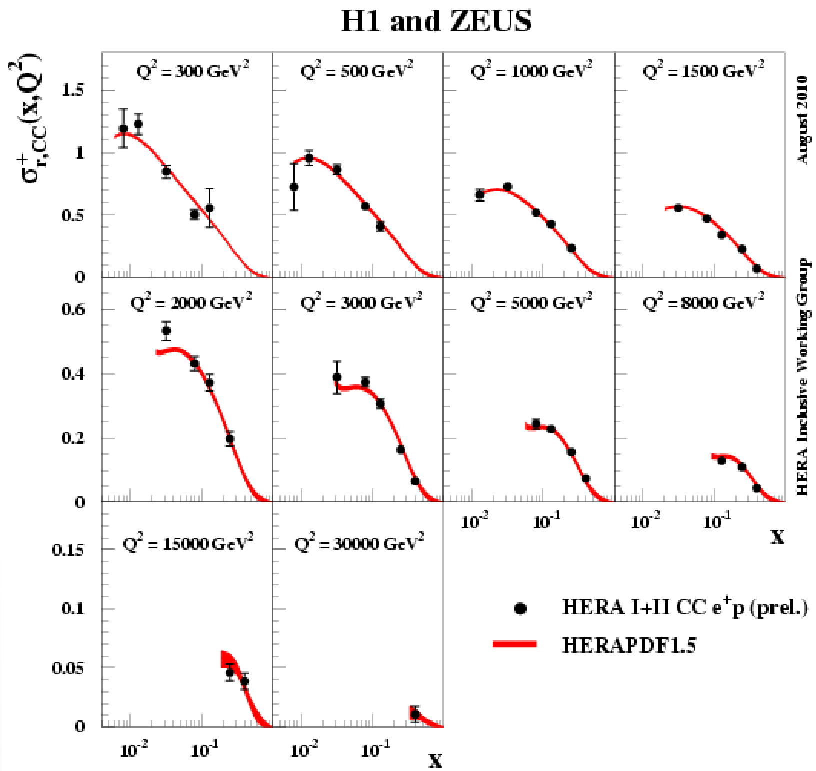

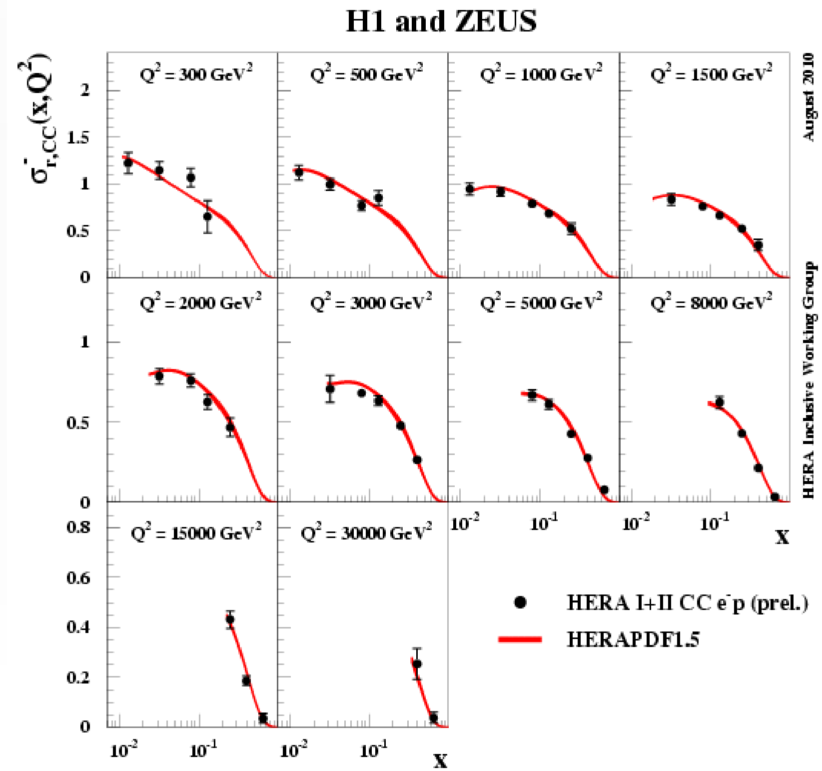

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10 x higher statistic than in JHEP01(2010)109

Including HERA-II high-Q² data → increased PDF precision

Summary

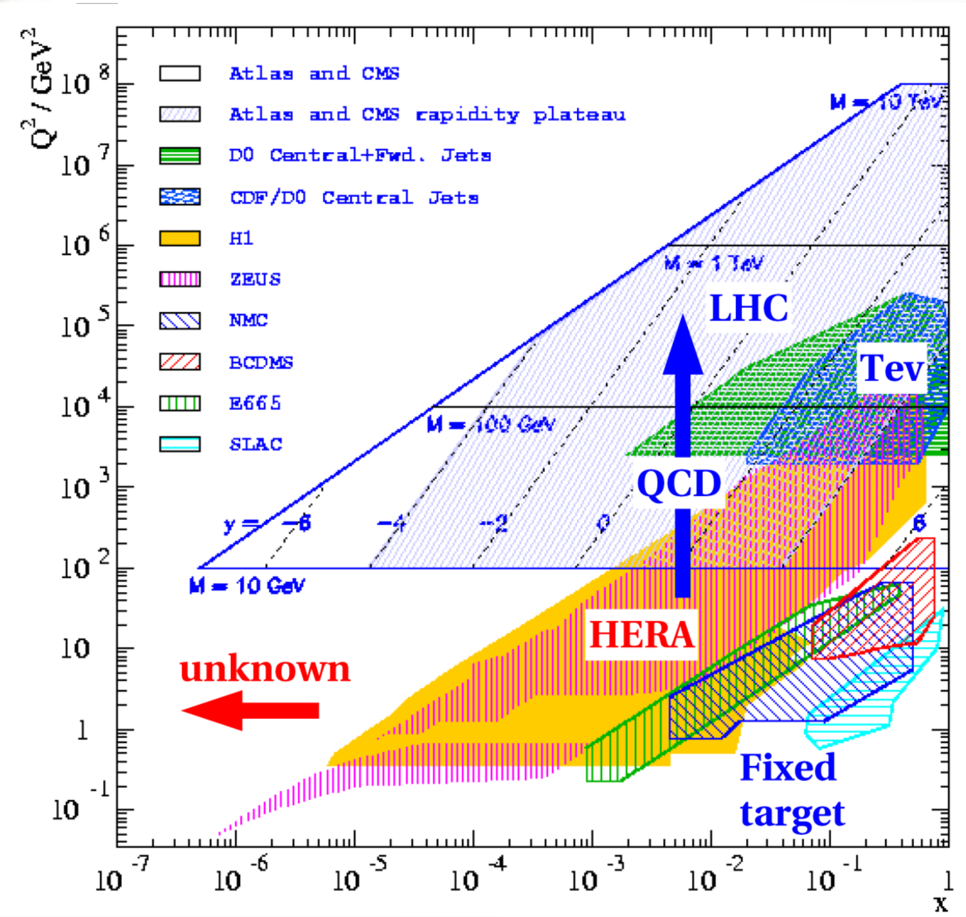
- The H1 and ZEUS HERA-I + II cross sections have been combined using a model-independent approach that leads to a cross-calibration of the H1 and ZEUS measurments:
  - Combined data span six orders of magnitude in x and Q2
  - Large reduction of the systematic uncertainties
  - 1%-level precision for $20 < Q^2 < 100$ GeV
  - Including HERA-II data improved precision at high-Q^2 and high-x

- Recent combined results of the H1 & ZEUS Collaboration have allowed to determine proton's PDFs with an unprecedented precision:
  - HERA-I data:
    HERAPDF1.0 (published)
  - HERA-I+HERA-II data:
    HERAPDF1.5 (NLO, NNLO, unconstrained fit) → see Allen Caldwell's talk
    + jets data:
    HERAPDF1.6 → see Krzysztof Nowak's talk

Inclusive measurements at HERA still a very active field

Extra-slides

Kinematic plane



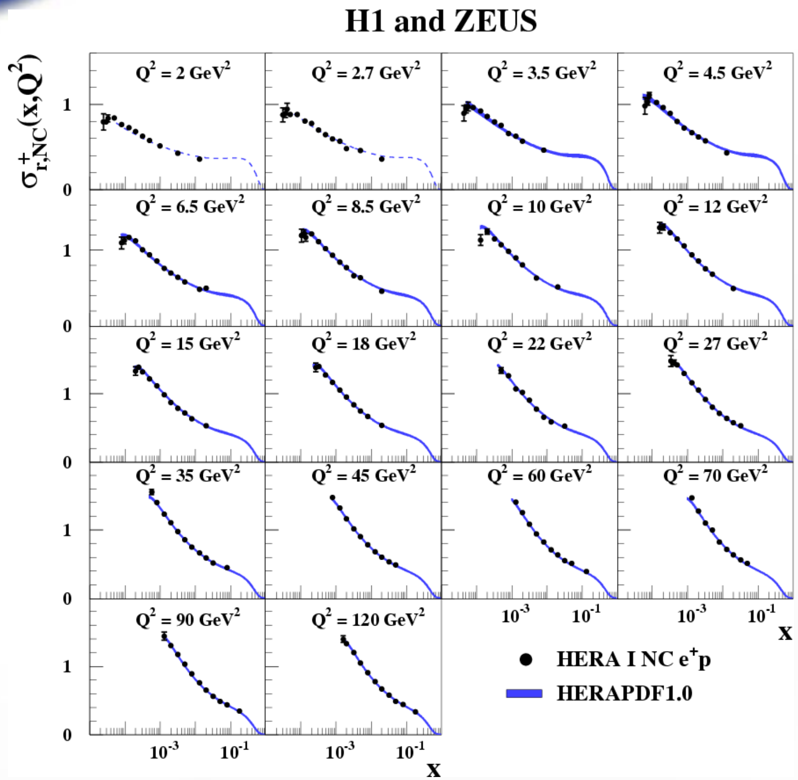
QCD evolution extrapolates HERA measured PDFs to LHC

PDF's obtained in low x regime at HERA are applicable to LHC

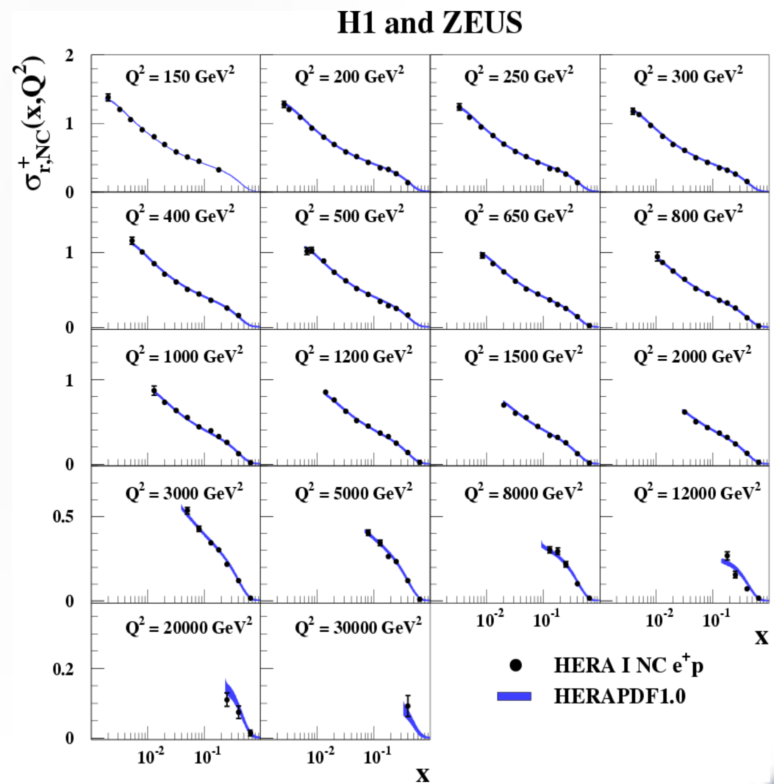
HERA data cover LHC central rapidity range for M > 100 GeV

F_2 with combined e+p HERA-I NC

Low/medium Q^2 bins (2-150 GeV^2)



High Q^2 bins(150-30000 GeV^2)

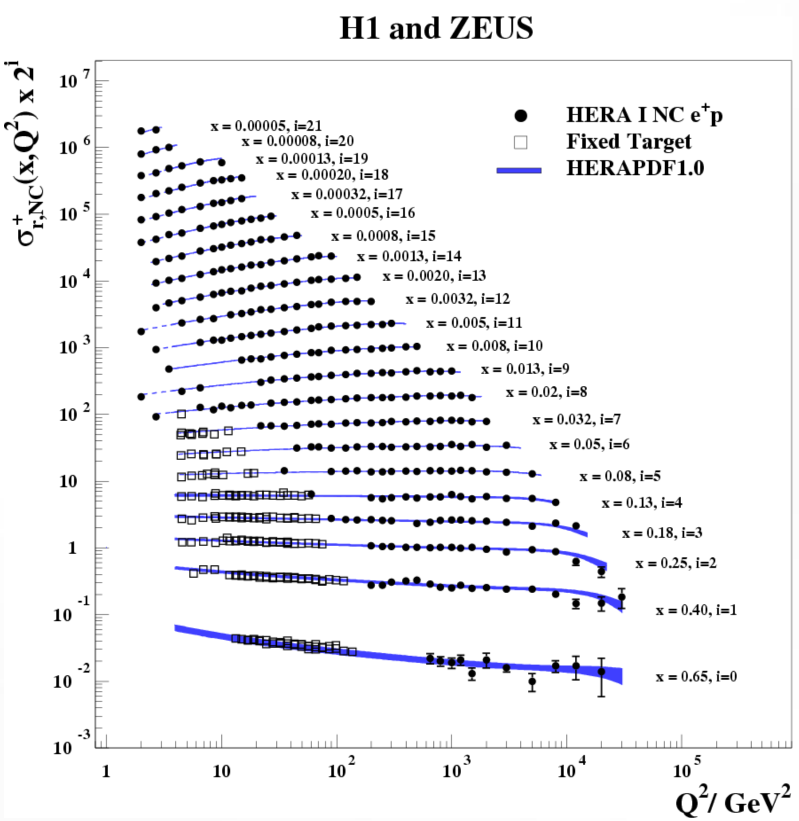


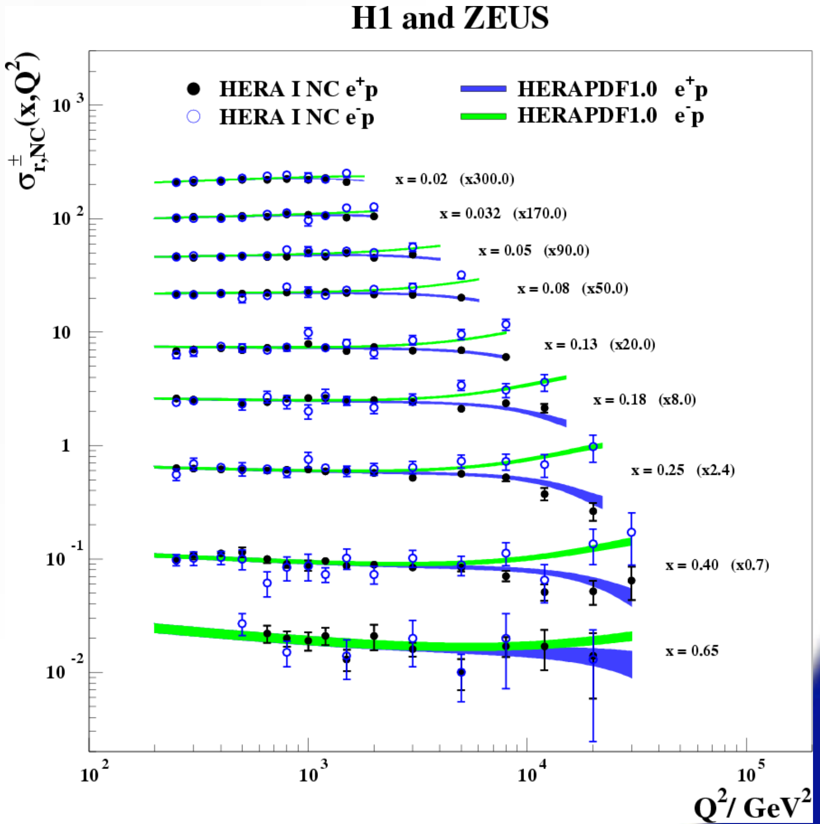
- $F_2(x,Q^2)$ shows strong rise as $x \to 0$, the rise increases with increasing Q^2
- Data well described by QCD fit from Q^2=2 to 30000 GeV^2

HERA-I combined NC

➢ Data show strong **scaling violations at low x** → large gluon density

➢ NC data at high-Q2: Zγ interference **destructive (e+p)** and **constructive (e-p)**





Good agreement between data and NLO QCD fit!

HERA-I combined CC data

- CC e^+p/e^-p allows to disentangle contributions of d and u quarks
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$$\tilde{\sigma}_{cc}^{e+p} \sim \bar{u} + \bar{c} + (1-y)^2 (d+s)$$

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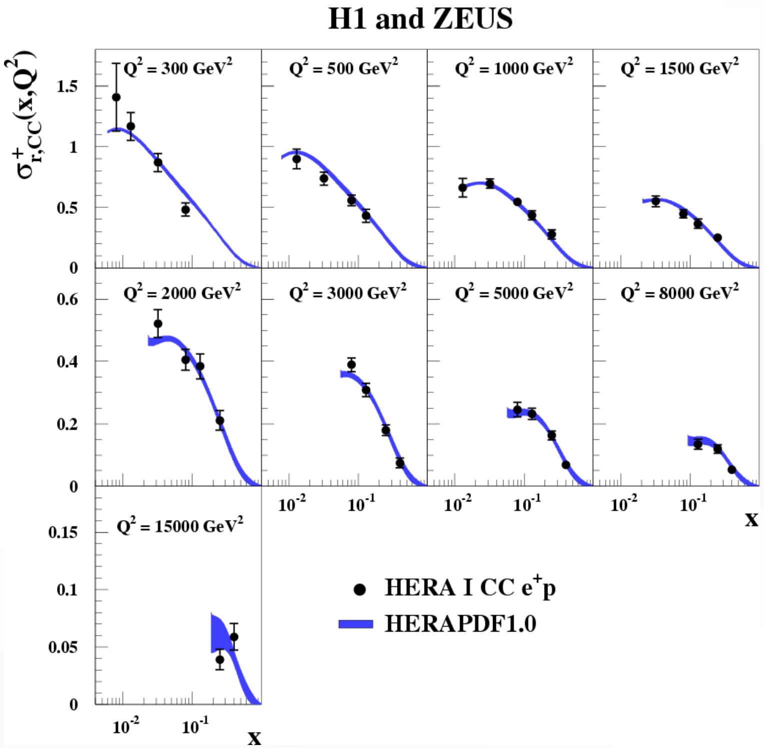
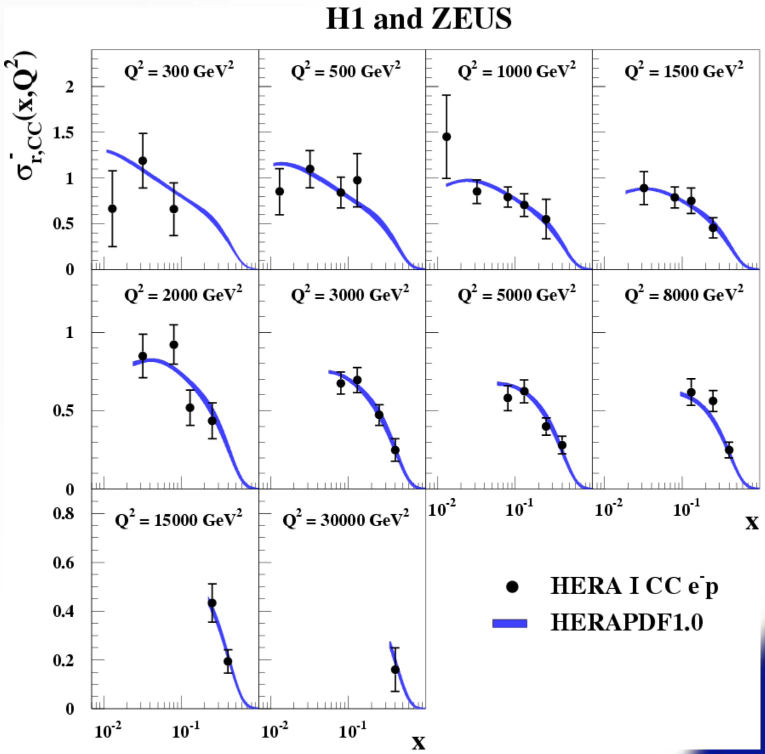




- e^+p most sensitive to $d(x,Q^2)$
- e+p valence quarks suppressed by factor $(1-y)^2$

- e^-p most sensitive to $u(x,Q^2)$
- Low luminosity (16pb-1/exp.) → Big statistical errors

HERA-I QCD fit - HERAPDF1.0

- Fit uses **combined H1&ZEUS NC, CC data only**
- DGLAP equations at **NLO in MSbar scheme**
- Parameterize parton distribution functions at starting scale and evolve with Q^2.
- **Thorne-Roberts Variable Flavour Number Scheme** (as for MSTW08):
  →takes the quark masses into account

Scheme	TRVFNS
Evolution	QCDNUM17.02
Order	NLO
Q_0^2	1.9 GeV^2
$f_s = s/D$	0.31
Renorm. scale	Q^2
Factor. scale	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

PDFs at the starting scale parameterised as:

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

where xf = xu_{val}, xd_{val}, xg, xUbar, xDbar

PDF	A	B	C	D	E
xg	sum rule	FIT	FIT	-	-
xu_{val}	sum rule	FIT	FIT	-	FIT
xd_{val}	sum rule	$=B_{u_{val}}$	FIT	-	-
$x\bar{U}$	$\lim_{x\to 0}\bar{u}/\bar{d} \to 1$	FIT	FIT	-	-
$x\bar{D}$	FIT	$=B_{\bar{U}}$	FIT	-	-

Results:
10 parameters for central fit
$\chi 2/n_{dof}$ = 574/582

HERA-I QCD fit - uncertainties

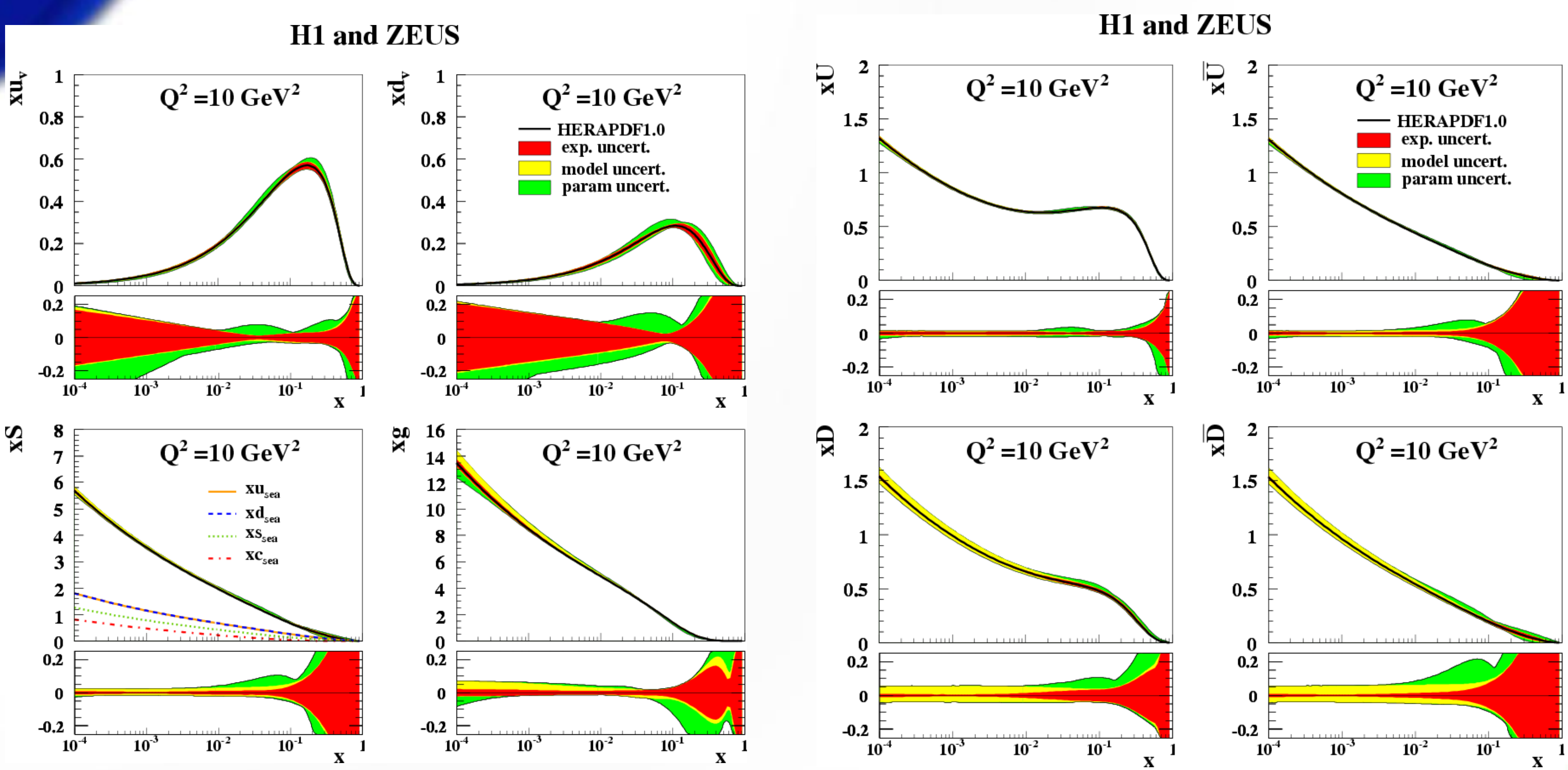
- **Experimental uncertainty:**
  Take into account experimental errors including, correlations bin to bin and between experiments/datasets => $\Delta\chi^2=1$

- **Model uncertainty includes theoretical errors:**

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	$1.5^{(b)}$	$2.5^{(c,d)}$

- **Parameterisation uncertainty:**
  Vary parameterisation of PDFs at starting scale by adding in extra parameters in the fit

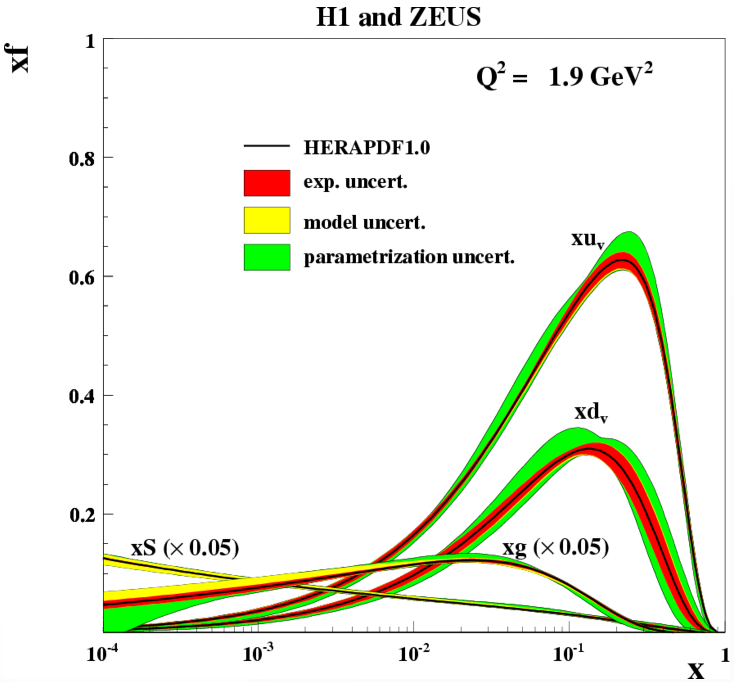
HERAPDF1.0 at Q^2=10GeV^2

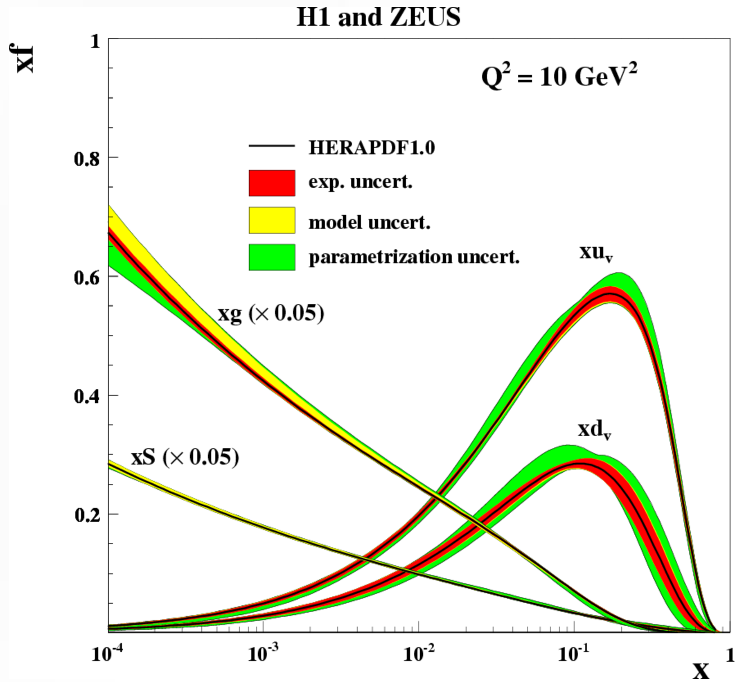


- High precision for sea and gluon at low x
- Reasonable precision for valence at high x
- Gluon error relatively large at high x

HERAPDF1.0

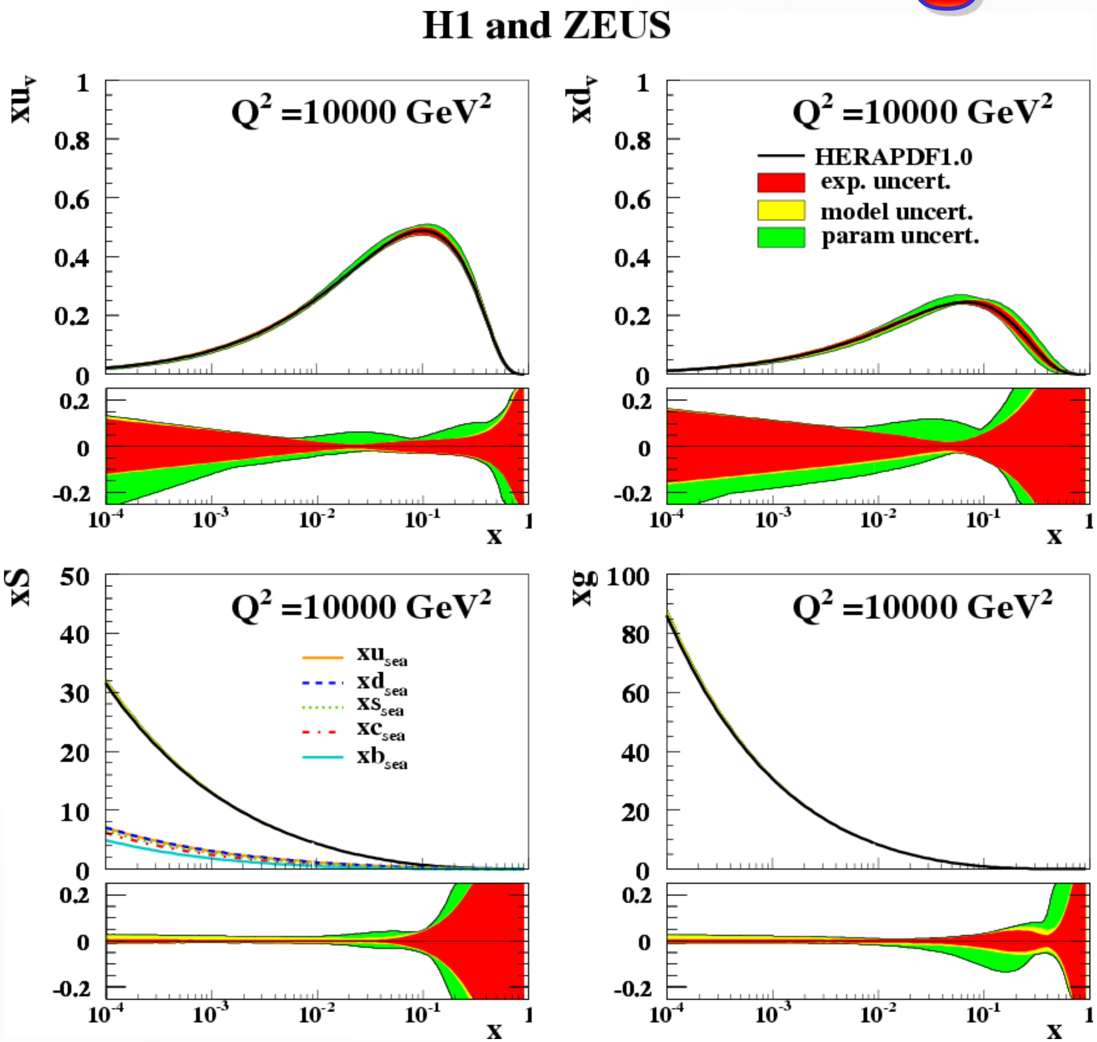
Distributions for valence quarks, see and gluons





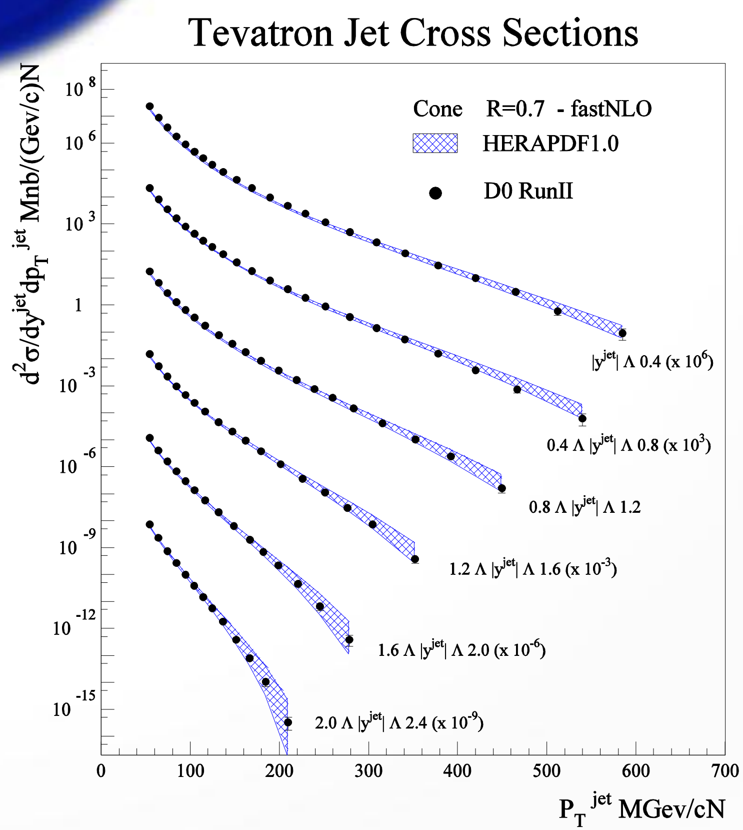
Gluon and see distributions are scaled by factor 20

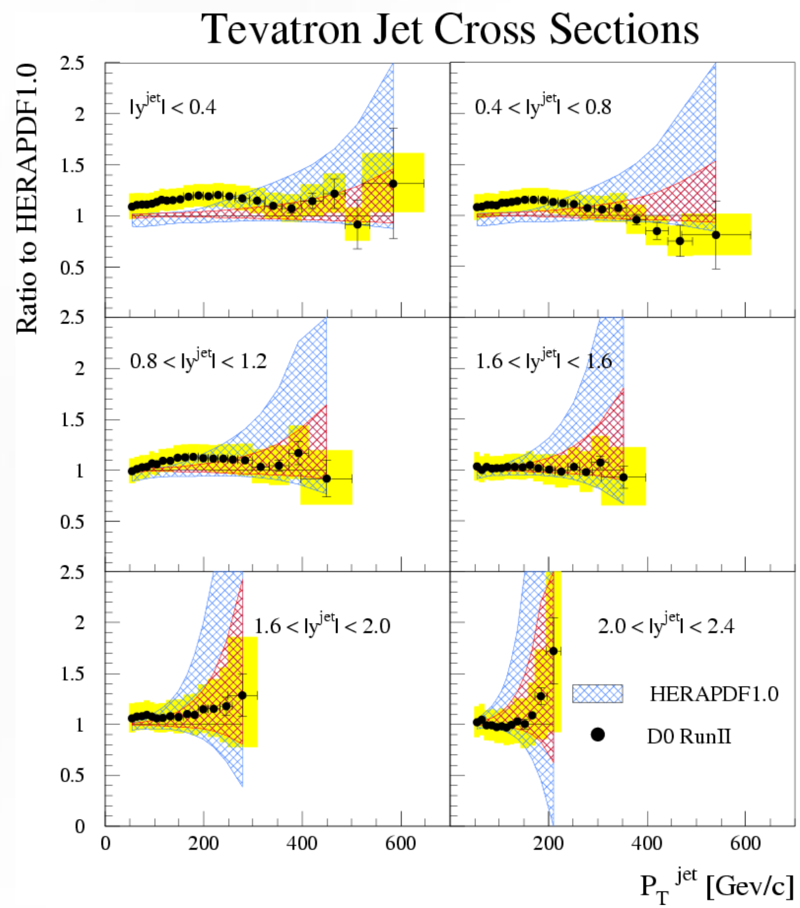
HERAPDF1.0 at high Q^2



Small errors on gluon & see distributions at LHC energies
→ enables precise predictions for LHC cross sections

HERAPDF1.0: Crosscheck with TeVatron data





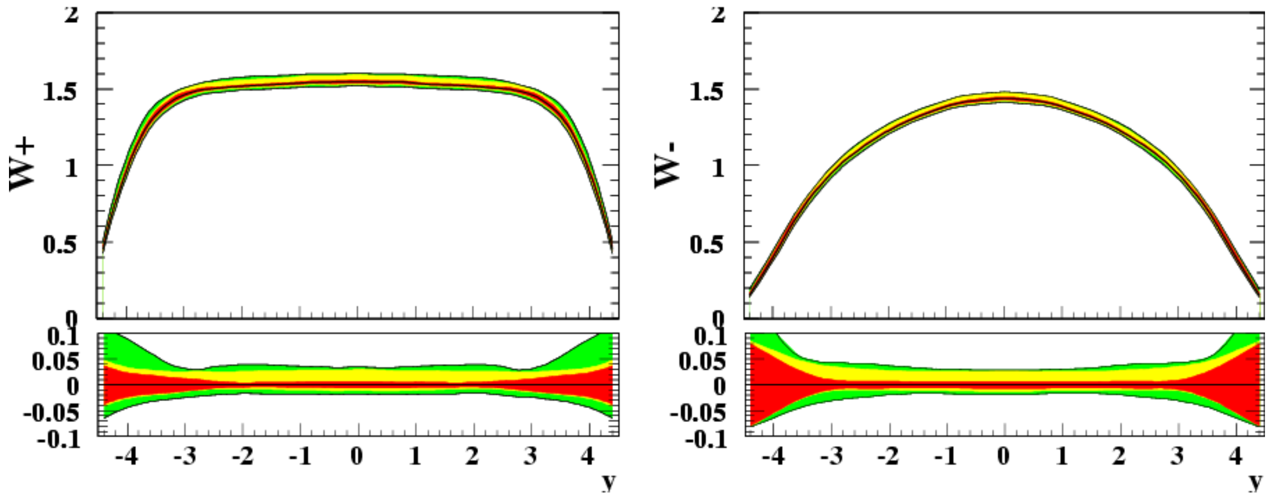
HERAPDF1.0 describes TeVatron data up to the high-Et jet production!

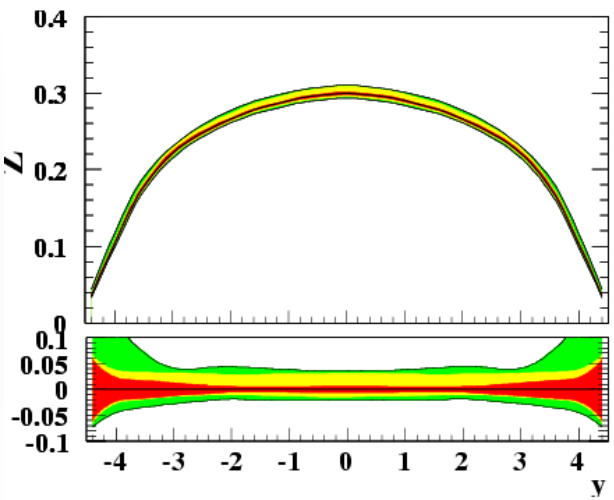
Ratio of D0 high Et jet cross-section to HERAPDF1.0 prediction:
- **Total PDF uncertainty blue**
- **PDF experimental red**
- **Systematic experimental error yellow**

HERAPDF1.0: Impact on LHC

Predictions for the W/Z production cross sections using HERAPDF1.0 (including experimental, model and parameterisation uncertainties)

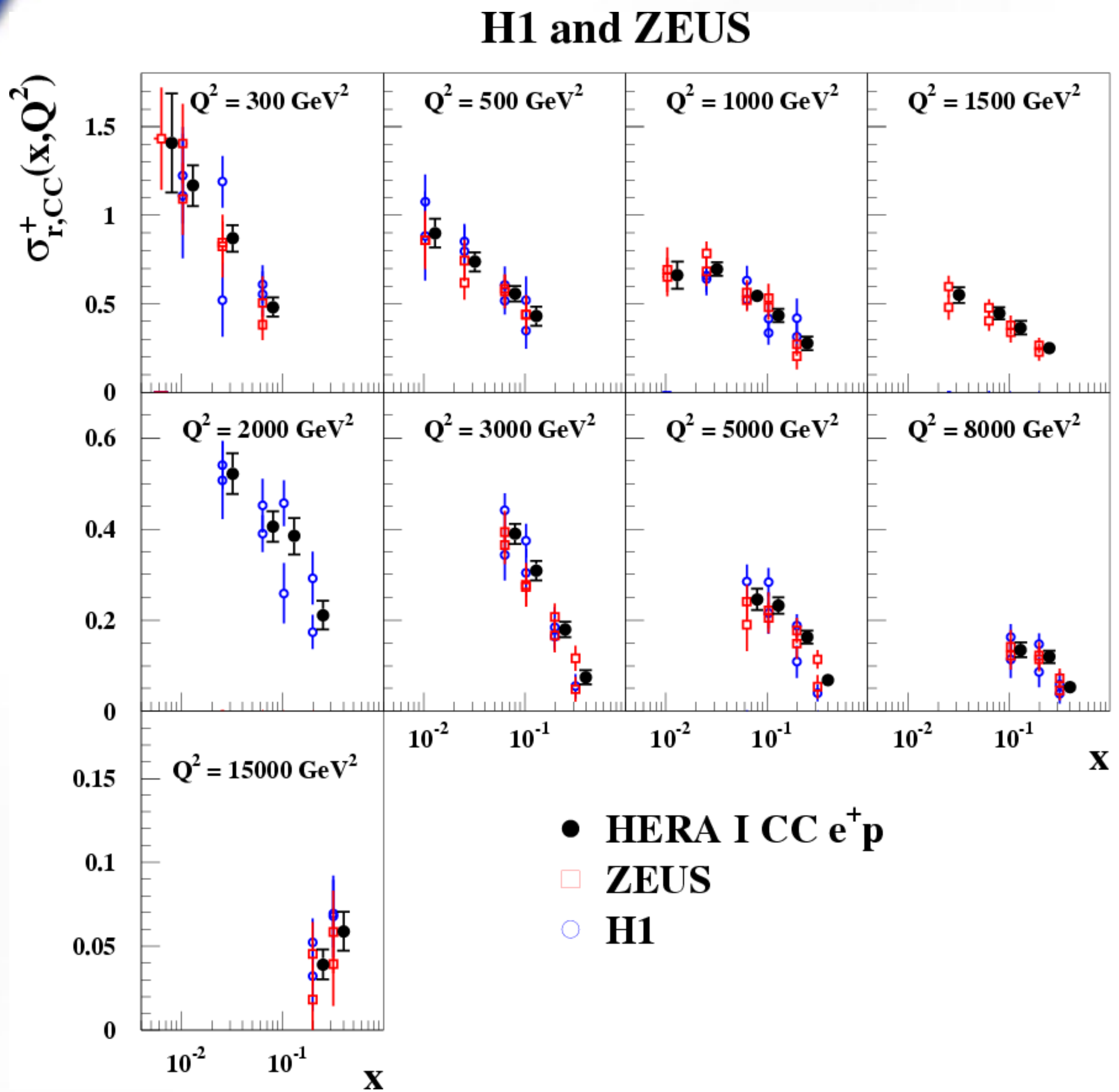
W and Z rapidity distributions



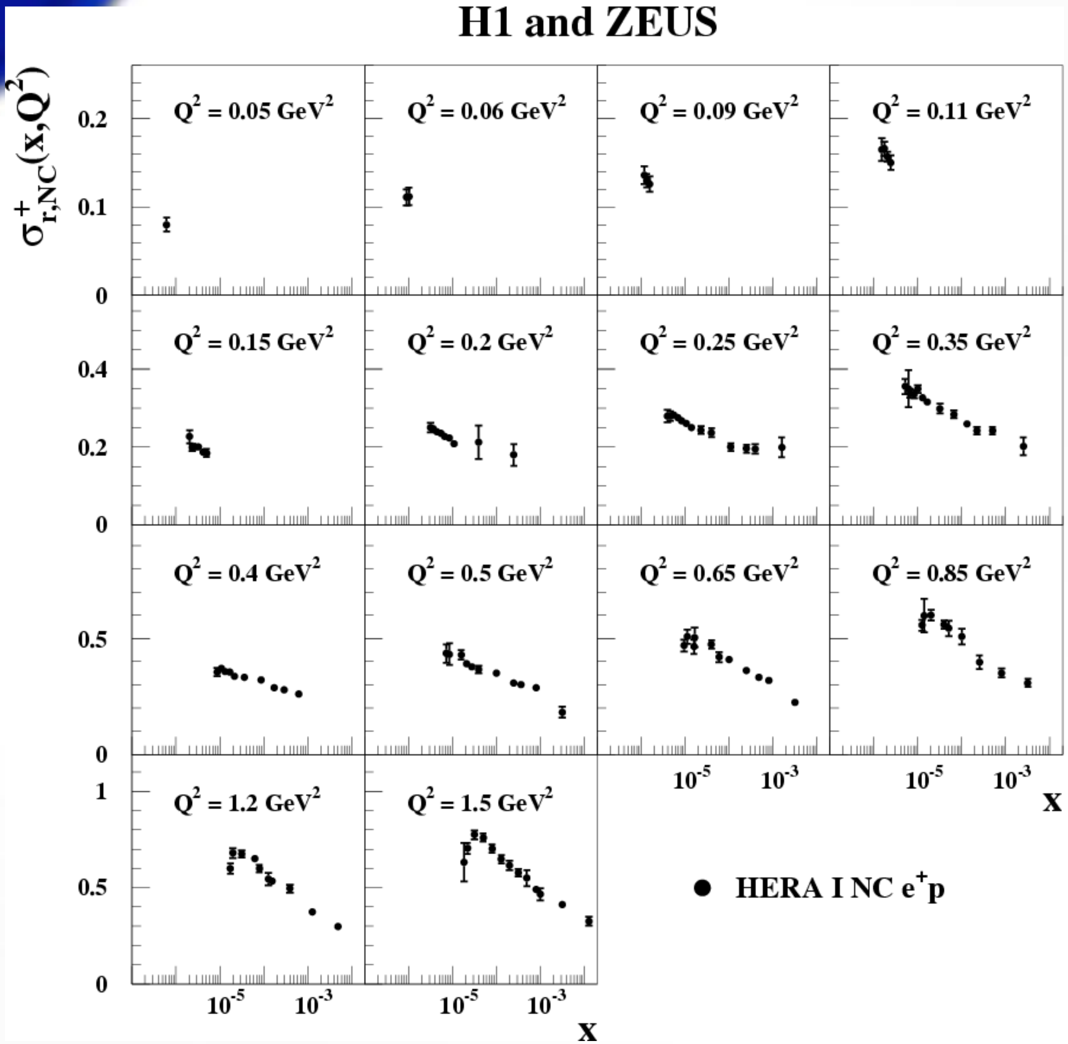


- **Precision:**
4% uncertainties in the central rapidity range
- **Improvement is expected with HERAII data at large y (high-x)**

HERA combined CC e+p

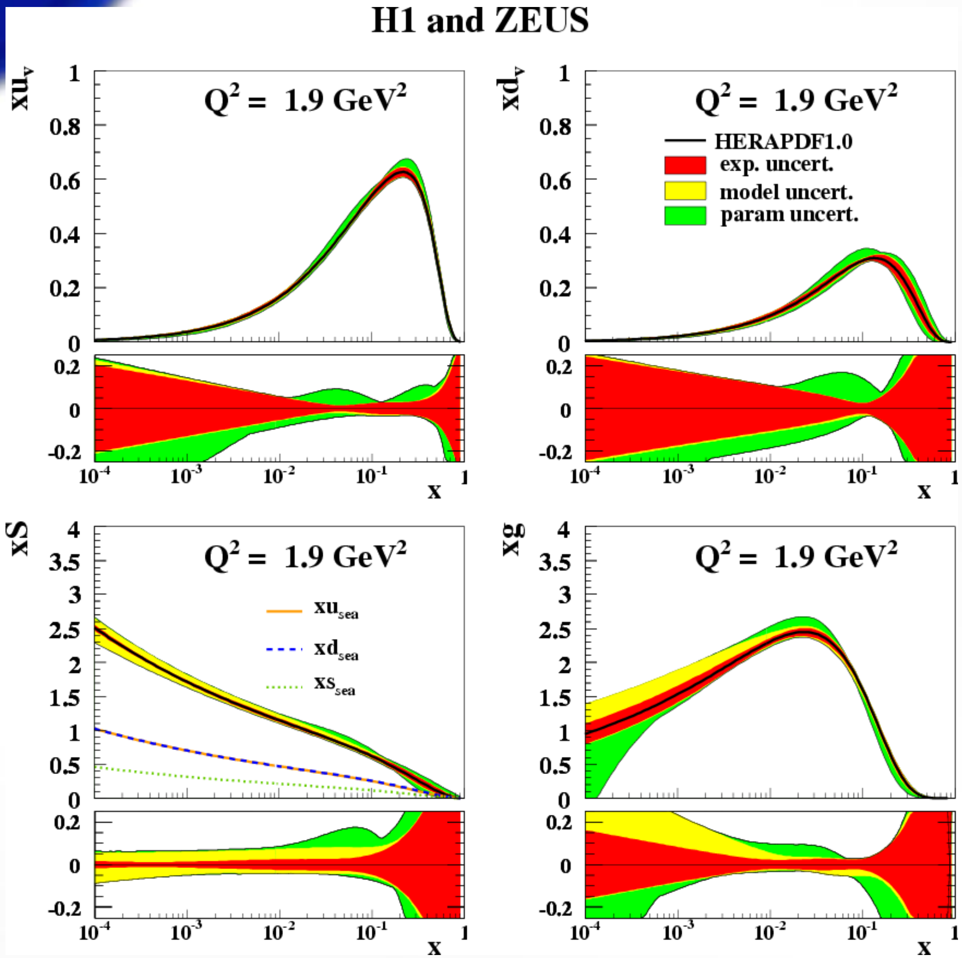


HERA combined NC e+p at very low Q2

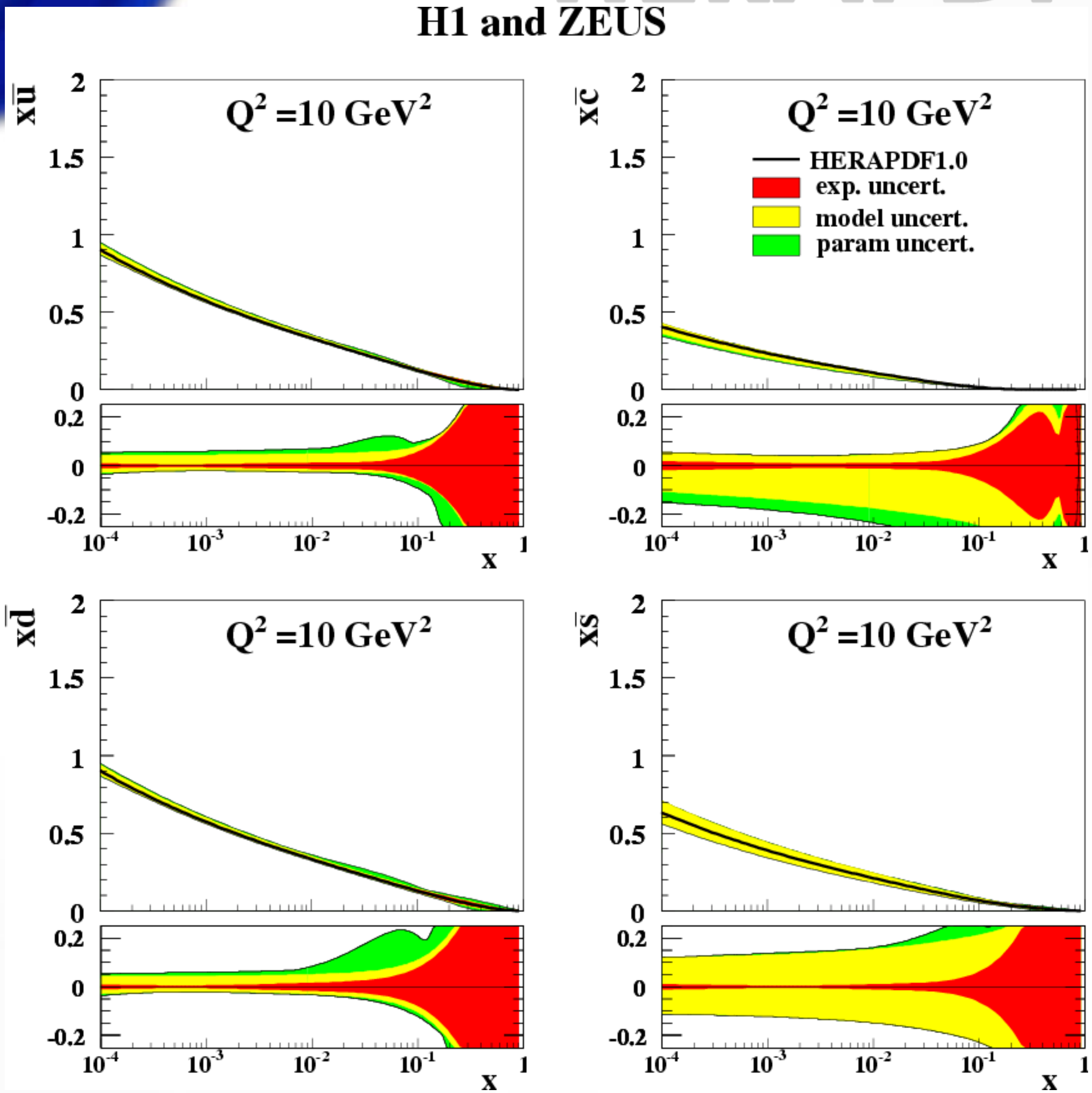


- Data shown in very low Q^2 region (0.05-1.5 GeV2)
- pQCD not expected to work in the very low Q^2 region.

PDF from HERAPDF1.0 at low Q2

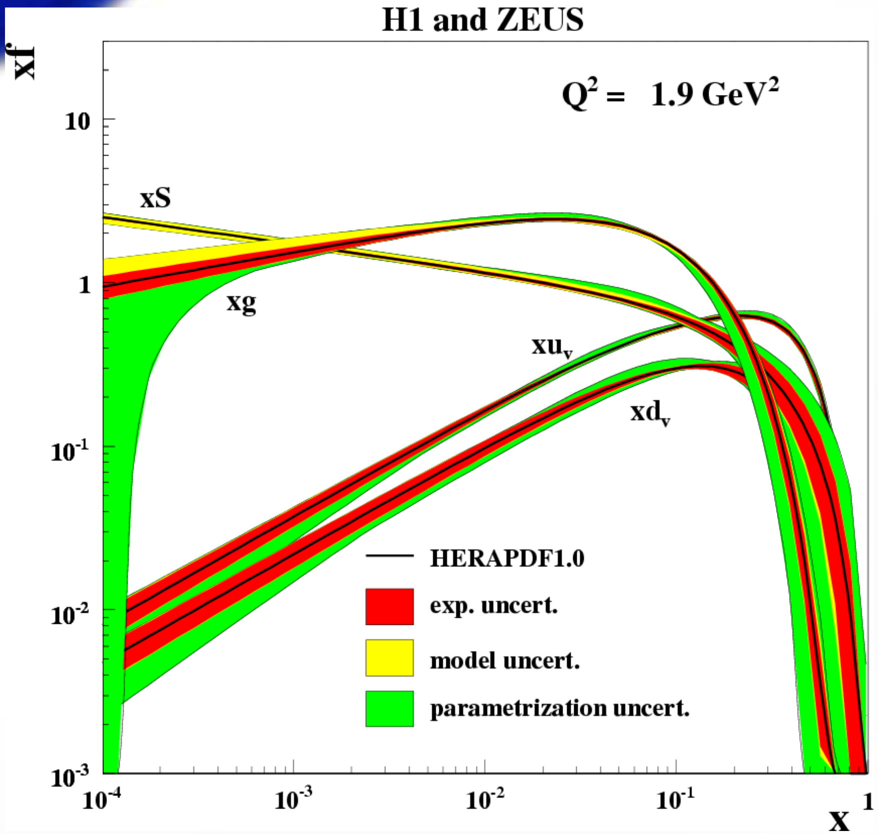


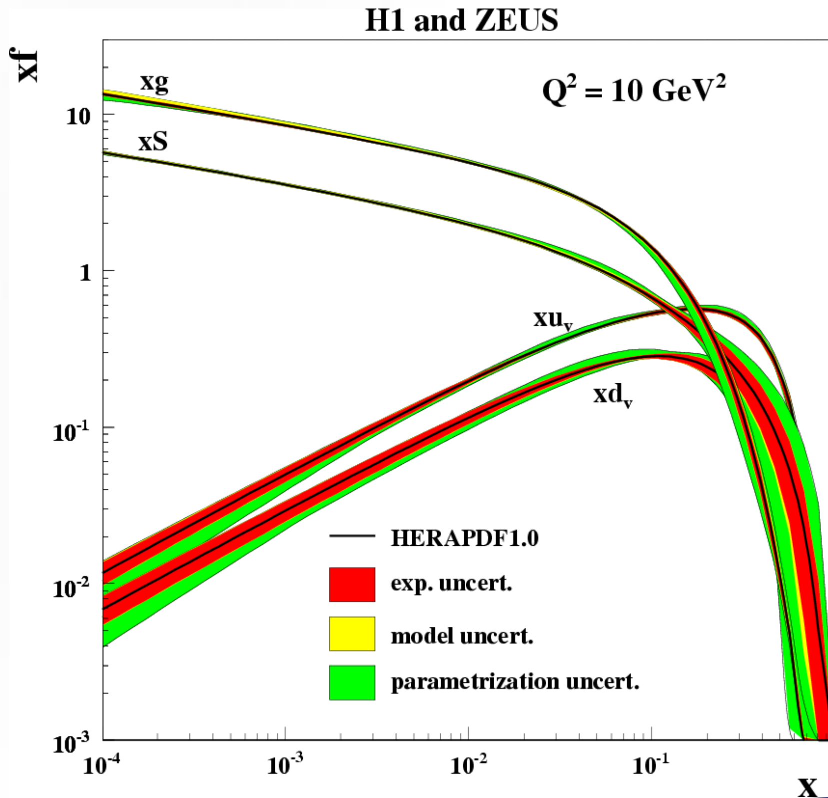
HERAPDF1.0



Parton Distribution Function xu, xd, xs and xc at Q^2 = 10 GeV^2

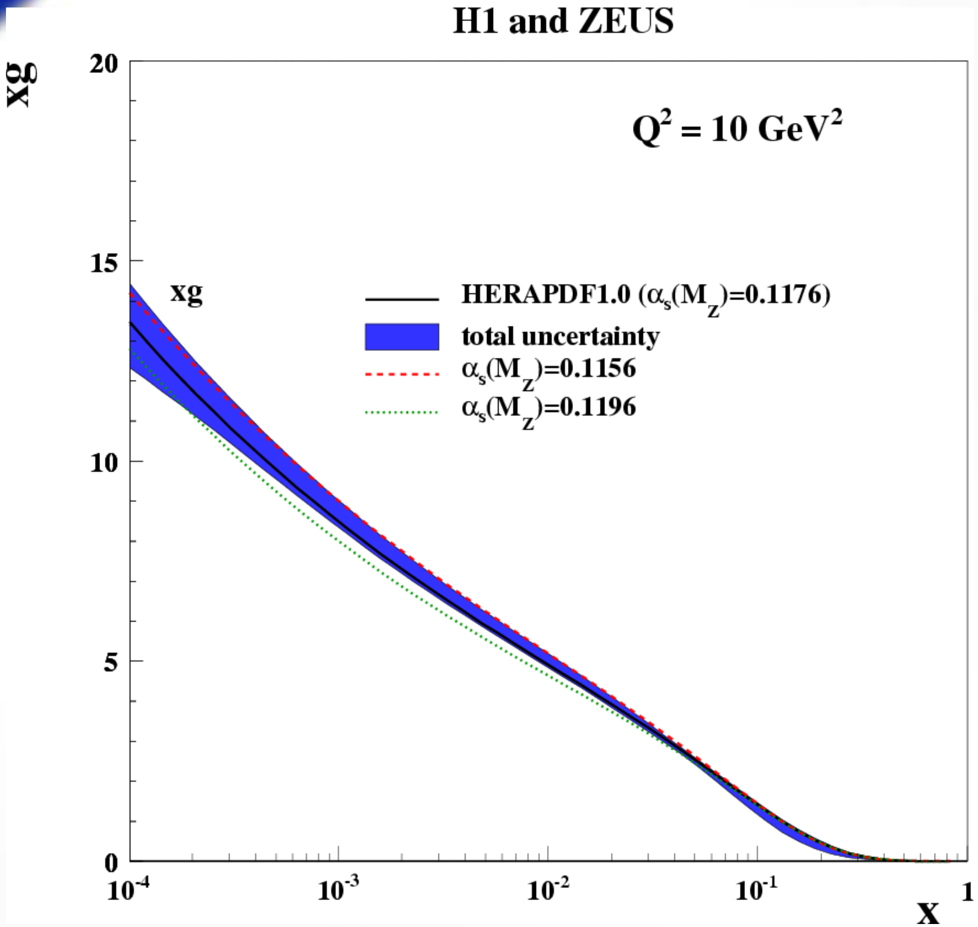
PDF from HERAPDF1.0



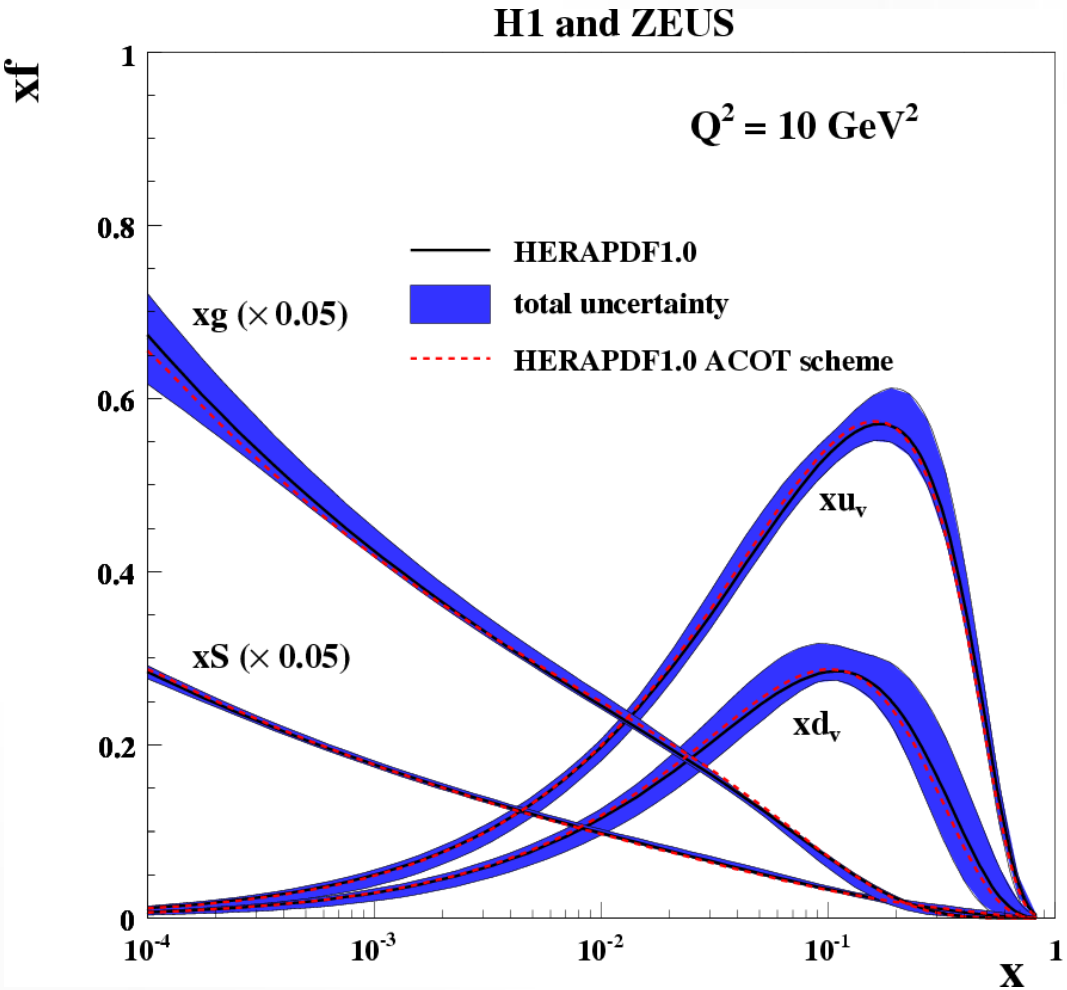


Distributions for valence quarks, see and gluons (logarithmic scale)

Gluon density vs different α_s values

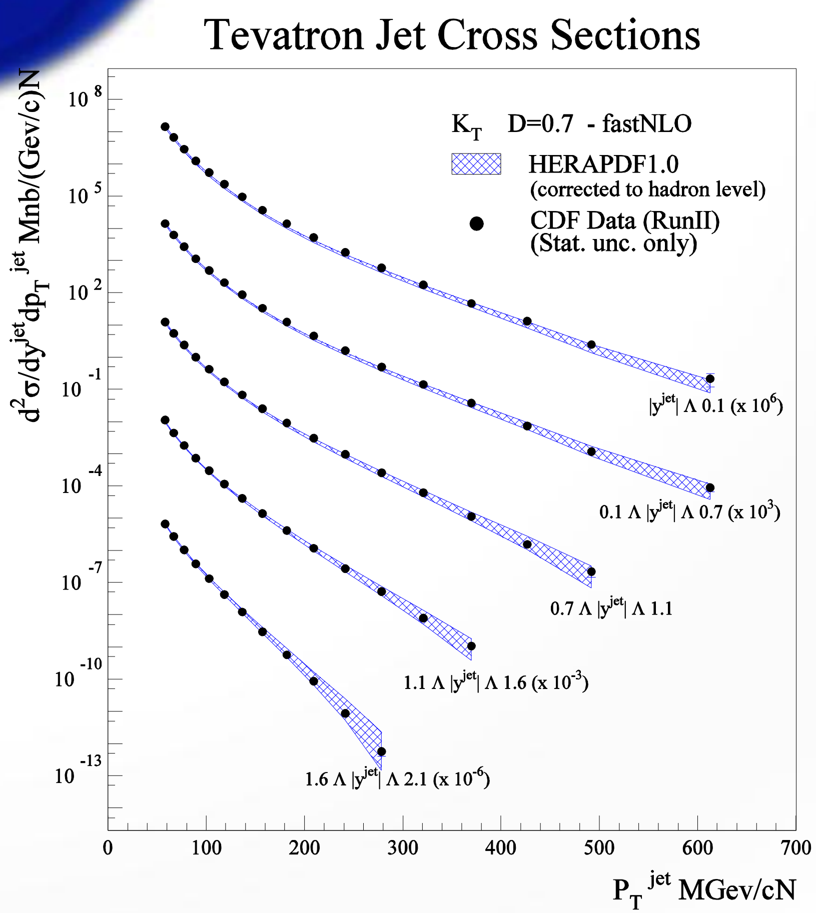


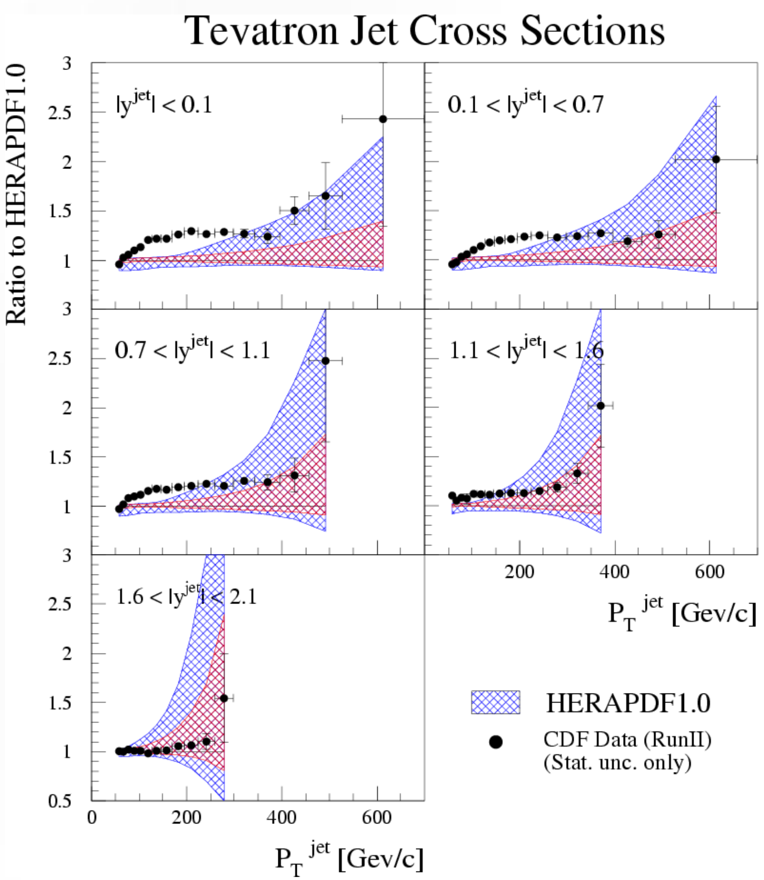
HERAPDF1.0 vs. HERAPDF1.0 ACOT scheme

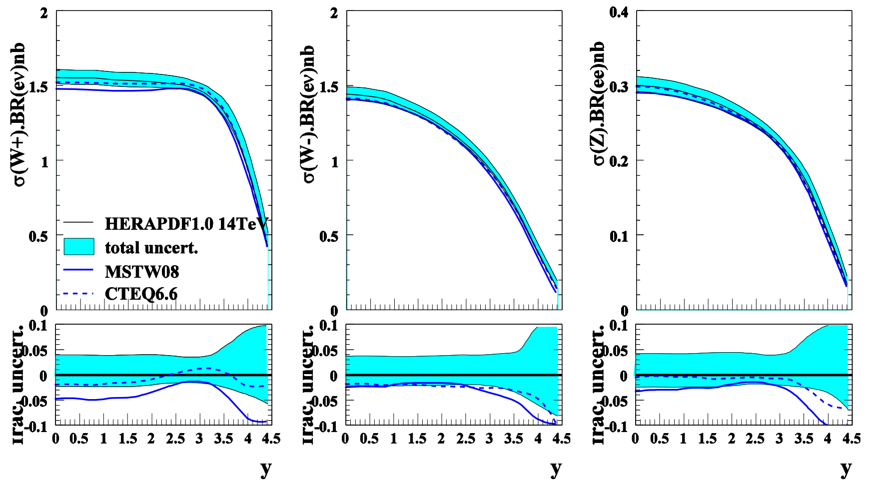


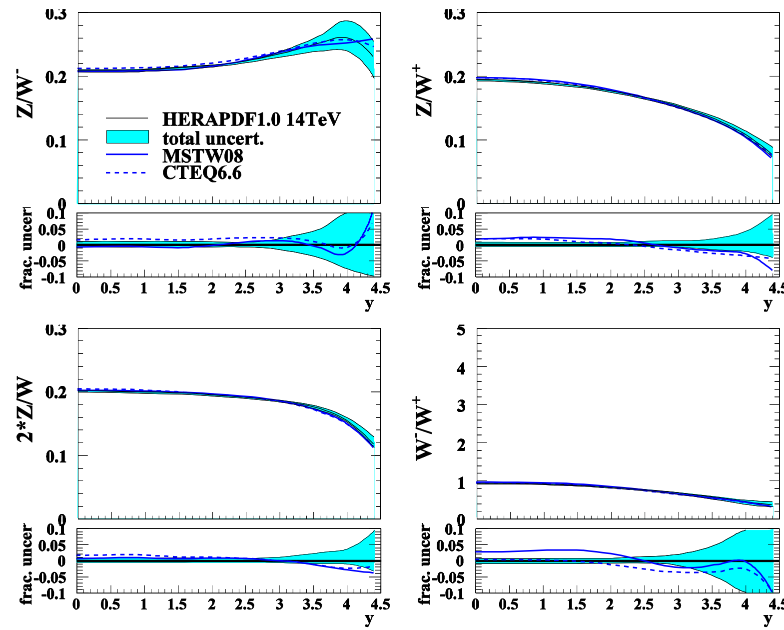
Distributions for valence quarks, see and gluons

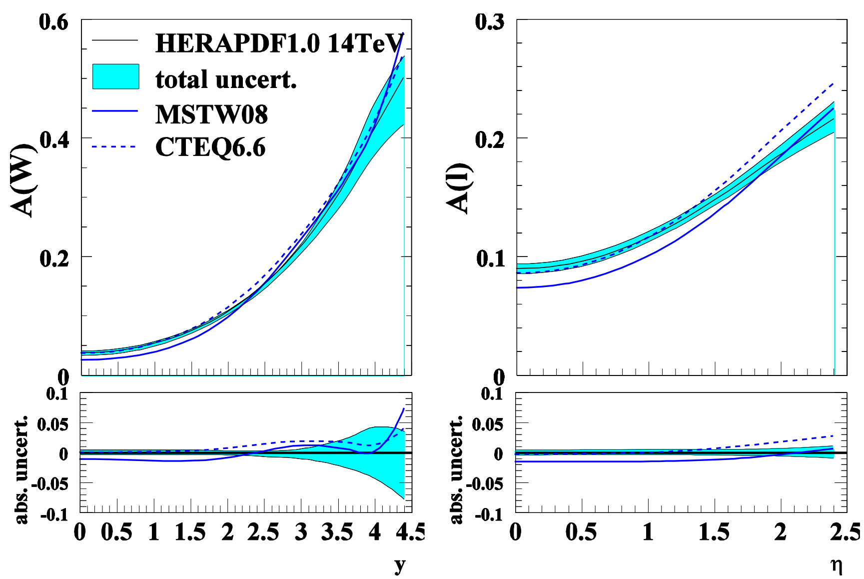
CDF jet data with HERAPDF1.0











HERAPDF1.0 predictions for W/Z production at LHC

These are at 14TeV but 10TeV and 7TeV exist

These show the full uncertainty bands of HERAPDf1.0 and compare to CTEQ66 and MSTW08 central values

Procedural Uncertainties

1. Additive vs Multiplicative nature of the error sources

Only normalizations uncertainties are taken as multiplicative
(=> Typically below 0.5%, a few % at high-Q2)
A general study of the possible correlated systematic uncertainties between H1 and ZEUS has been performed:
- Identified 12 possible uncertainties of common origin
- compared 212 averages taking all pairs as corr/uncor in turn

Mostly negligible except for:

2. Correlated syst. uncert. for the photoproduction background

(Typically below 0.5%, but larger at high-y)

3. Correlated syst. uncert. for the hadronic energy scale

(Typically below 0.5%, significant only at low-y)

Procedural Uncertainties for HERA-II high-Q^2

Three additional procedural errors

- **Correlate across all data files**
  $\delta_{ave,had}$ hadronic energy scale
  $\delta_{ave,gp}$ background due to photoproduction
- **$\delta_{ave,rel}$ change <u>relative to absolute errors</u>**
  (Only lumistays relative)