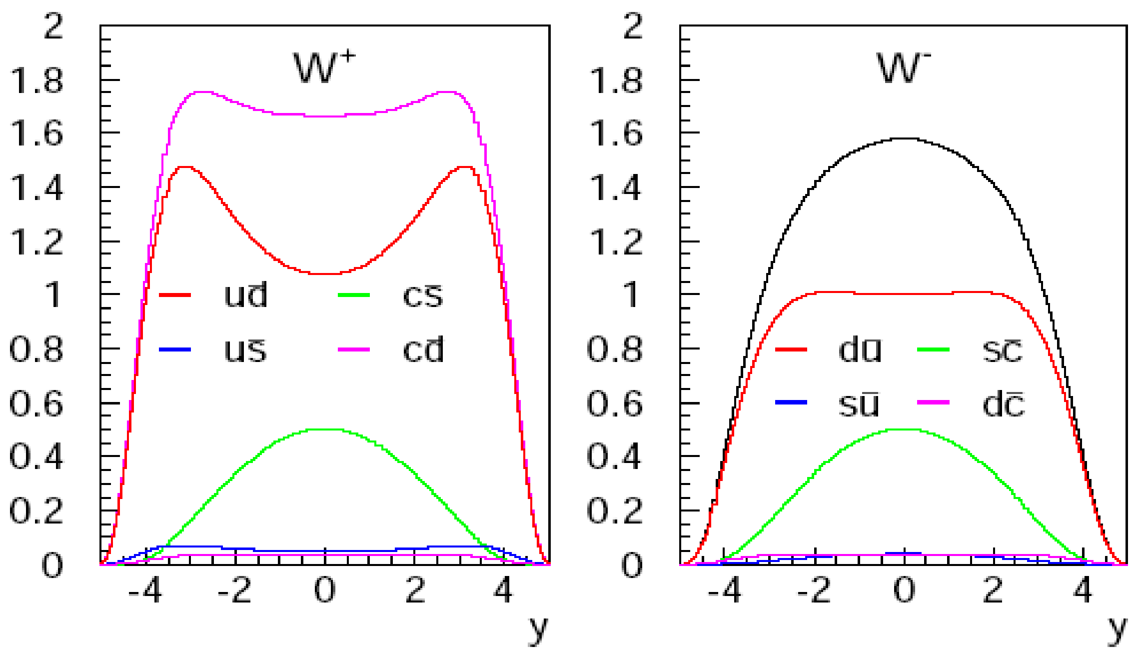
Proton structure from HERA

Daniel Pitzl
DESY
Physics at the LHC 2010

- From LHC to HERA
- DIS measurements
- HERAPDF1.0
- F_L, heavy flavours
- Tevatron, LHC
- Summary

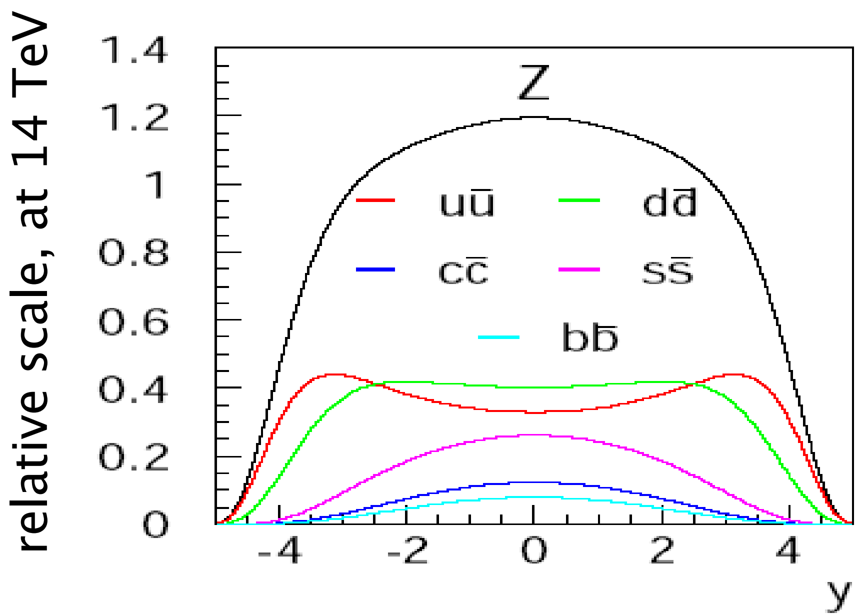
partons for LHC W and Z production



ud dominates for W.

valence u peaks at large y.

sc important at mid y.



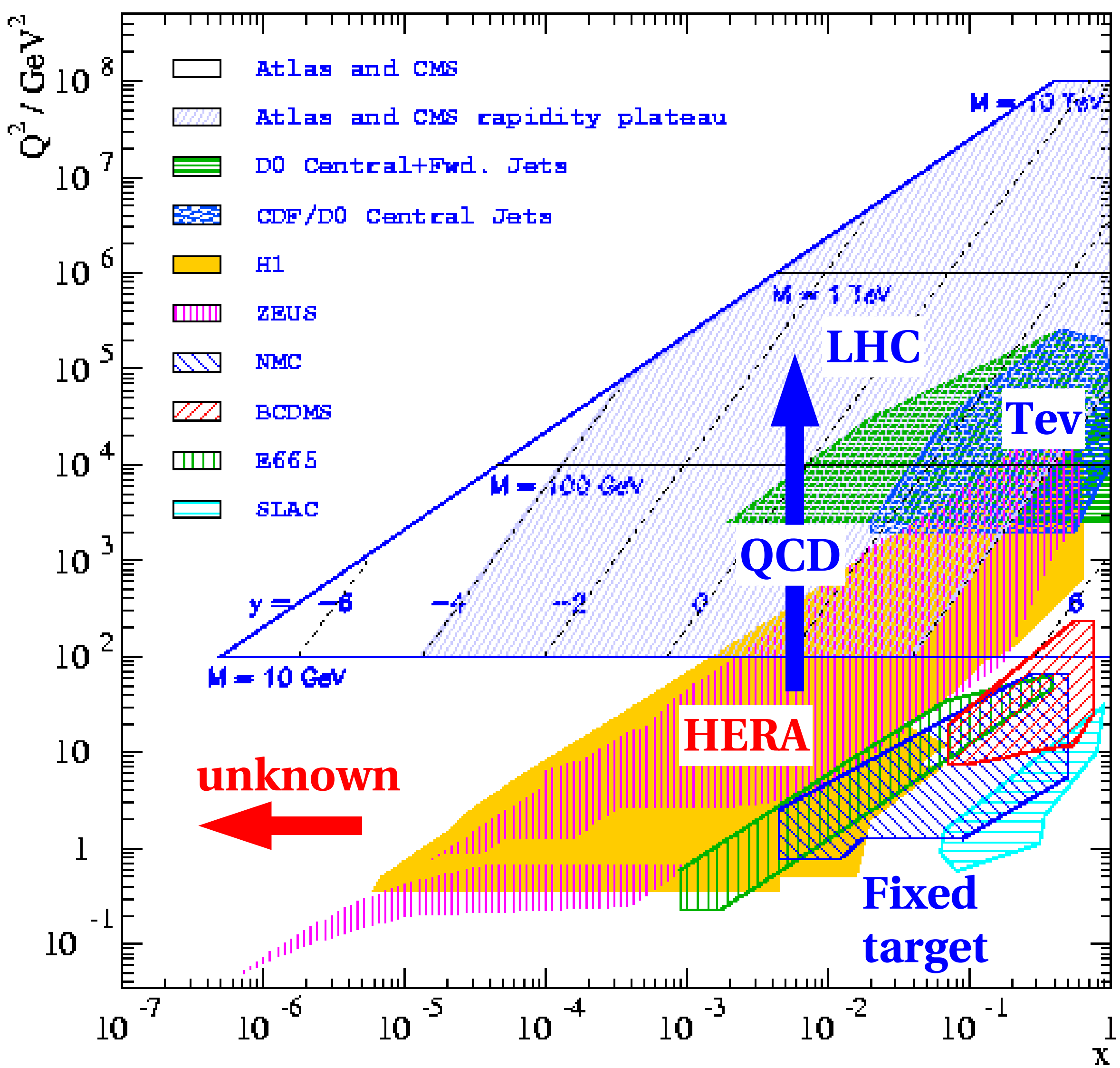
all flavours contribute for Z, even b is significant.

Z-q couplings are needed.

no f-b asymmetry in pp.

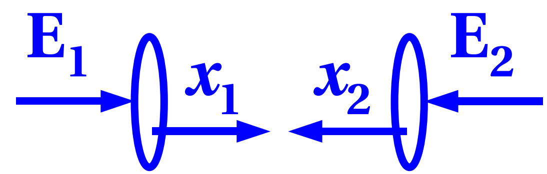
Precise parton distributions are needed for LHC analyses.

LHC and HERA kinematics



QCD evolution
(DGLAP equation).

Proton-proton collisions:



$s = 4\, E_1\, E_2$.

$\hat{s} = x_1\, x_2\, s \geq M^2$.

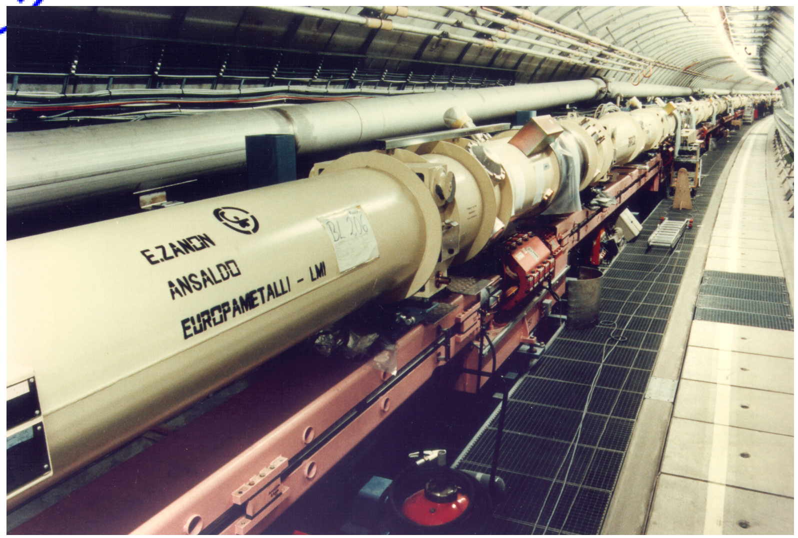
scale $M^2 \triangleq Q^2$.

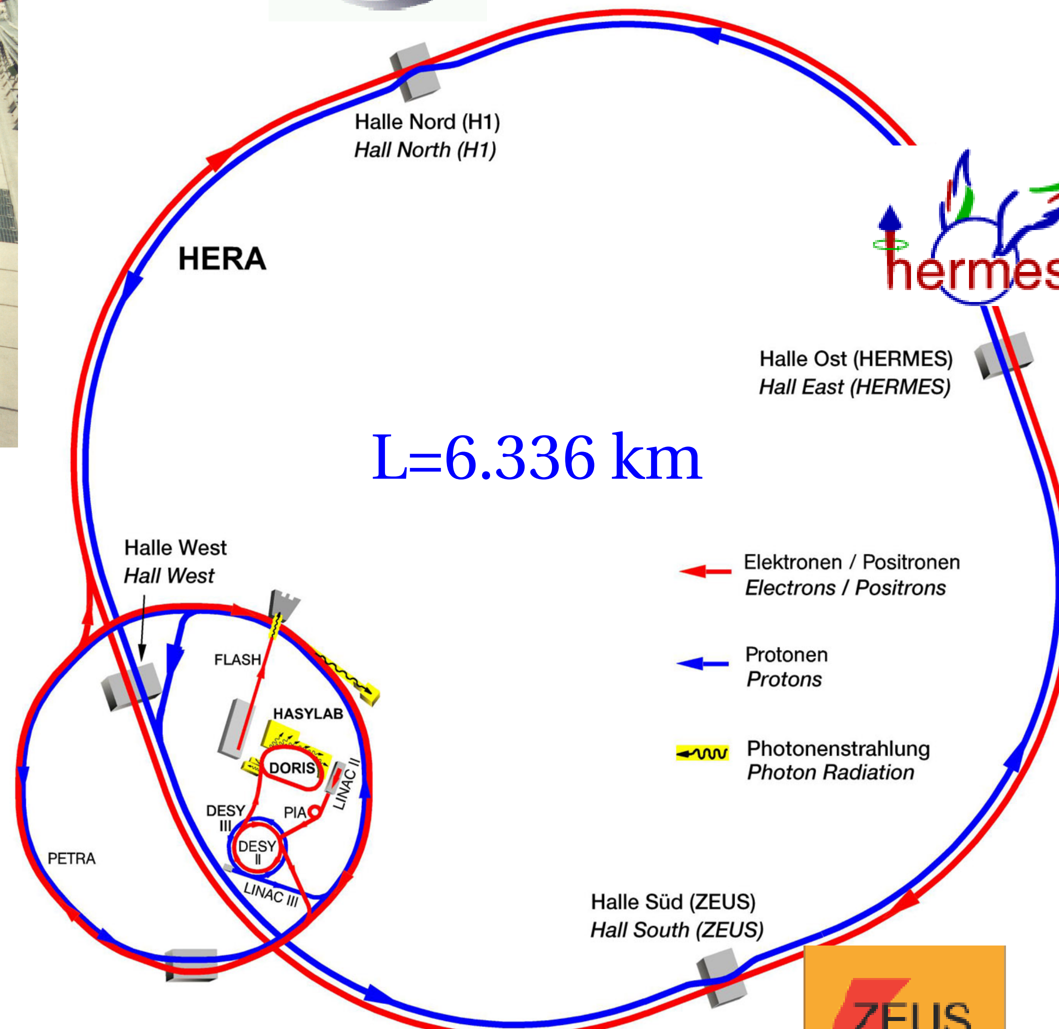
$x_{1,\,2} = M / \sqrt{s} \cdot \exp(\pm y)$

Rapidity y.

x-distributions of partons cannot be calculated, yet.
Lattice QCD provides lowest moments $\int x^n f\, dx$.

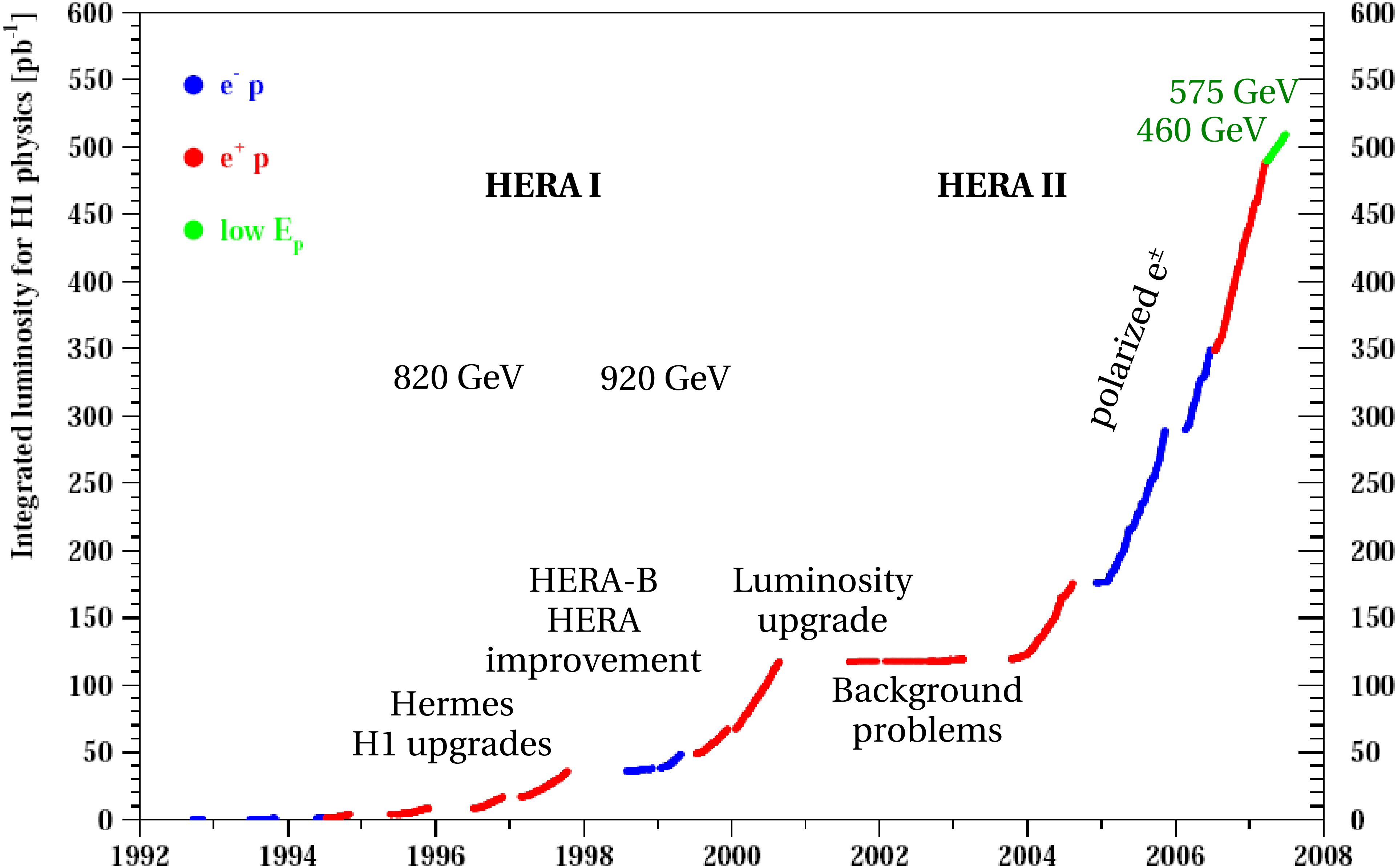
Hadron Elektron Ring Anlage HERA





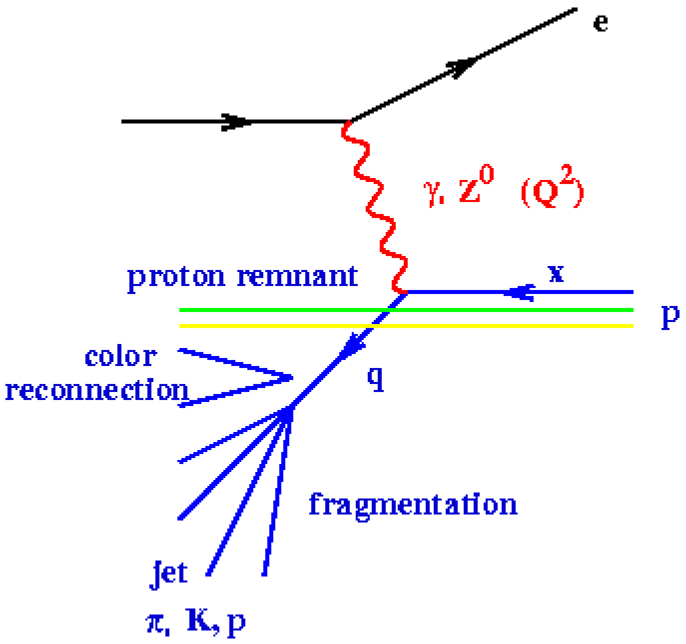
- World's only ep accelerator and collider
- Operated 1992 - 2007
- p: 460-920 GeV, 110 mA
- e: 27.6 GeV, 45 mA
- 2 ep collider experiments: H1 and ZEUS.

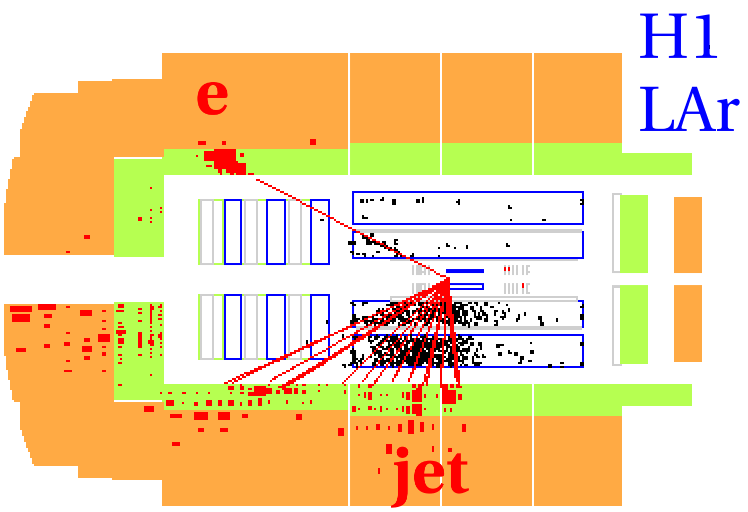
Luminosity collection



Deep inelastic scattering

Neutral current: γ or Z exchange



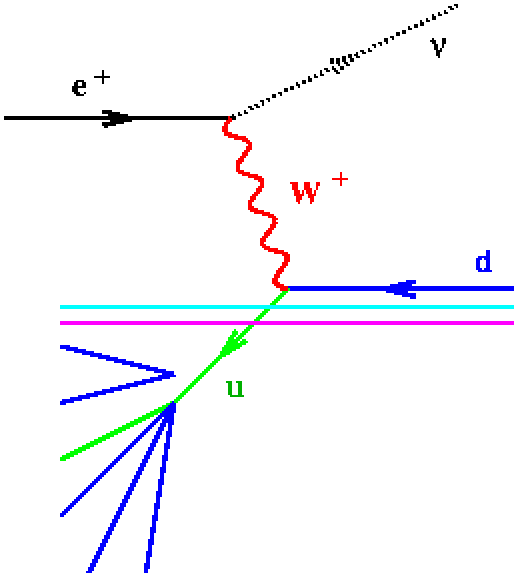


jet balanced by the electron: good calibration.

1% jet energy scale uncertainty.

- $y = (1 - E'_e(1 - \cos\theta_e)) / 2E_e$ = inelasticity (notation clash with rapidity)
- $Q^2 = E_{t,e}^2 / (1-y)$ = 4-momentum transfer.
- $x = Q^2/ys$ = momentum fraction of the quark in the proton.
- HERA maximum $\sqrt{s}$ = 318 GeV.

Charged current: W± exchange

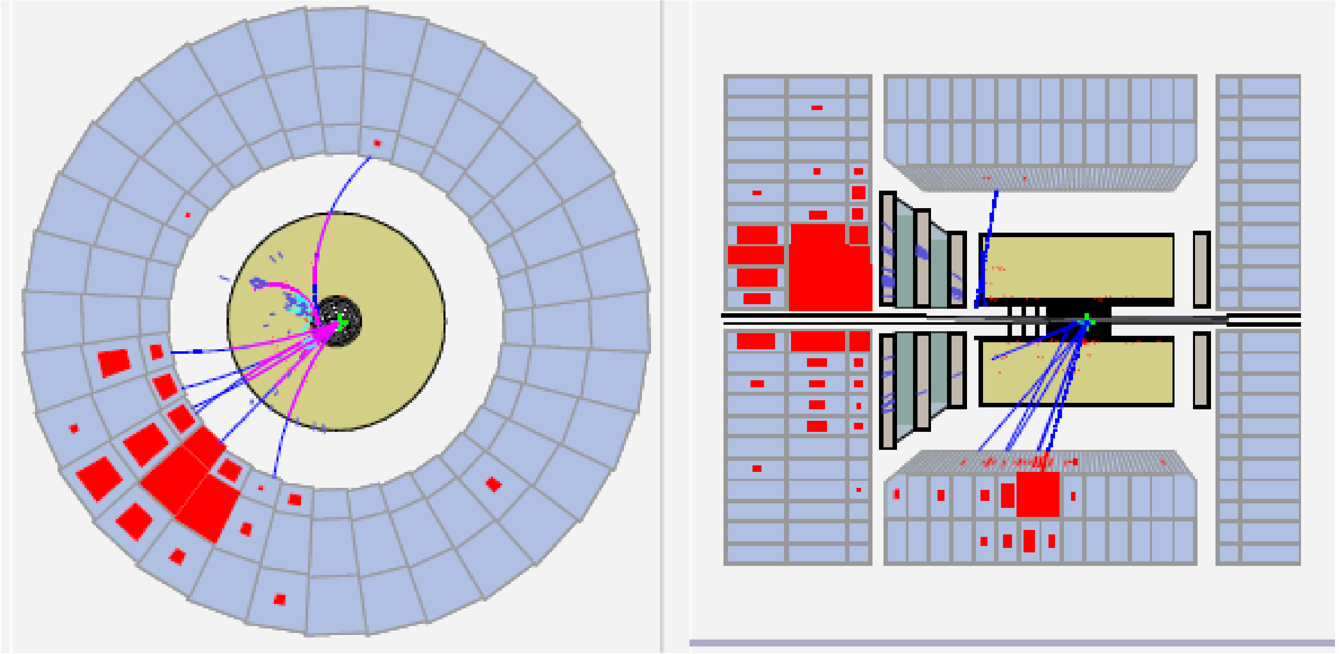


Neutrino signature: missing transverse momentum.

Q^2 and *x* can be reconstructed from the hadronic final state:

$y = \sum(E-p_z) / 2E_e$

$Q^2 = p_t^2 / (1-y)$



ZEUS compensating U-scintillator calorimeter

DIS cross sections and structure functions

NC $e^{\pm}p \longrightarrow e^{\pm}X$

$$\frac{\mathrm{d}^2\sigma^{\pm}_{NC}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right] \equiv \frac{2\pi\alpha^2}{xQ^4}Y_+\tilde{\sigma}^{\pm}_{NC}$$

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

$\tilde{F}_2$	dominant contribution in LO QCD	$\{F_2, F_2^{\gamma Z}, f_2^Z\} = x\sum_q\{e_q^2, 2e_qv_q, v_q^2 + a_q^2\}(q+\bar{q})$
$x\tilde{F}_3$	γZ interference at $Q^2 \sim m_Z^2$	$\{xF_3^{\gamma Z}, xF_3^Z\} = 2x\sum_q\{e_qa_q, v_qa_q\}(q-\bar{q})$
$\tilde{F}_L$	sensitivity at low Q^2, high y	$\sim \alpha_s xg(x,Q^2)$

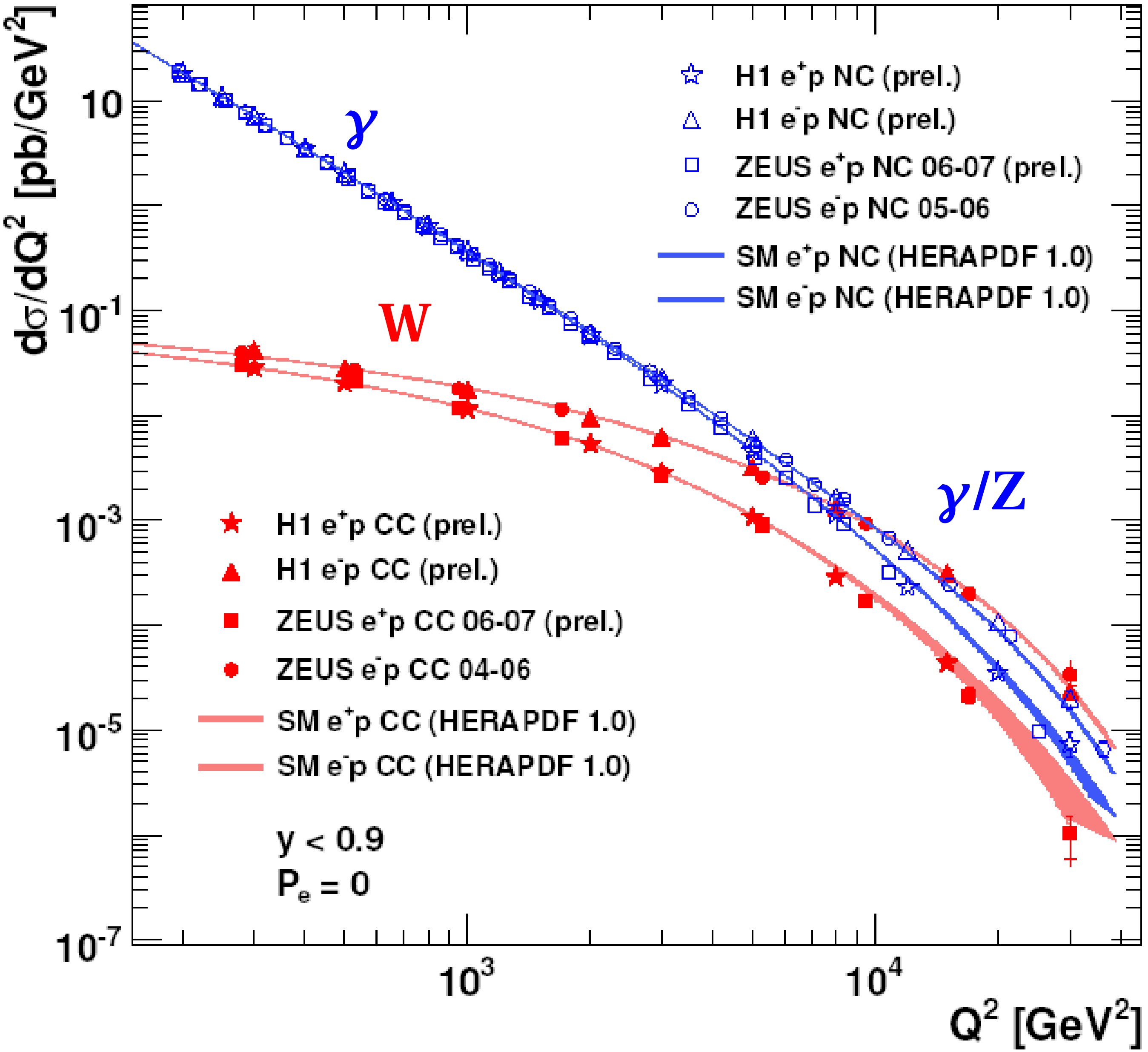
CC $e^{\pm}p \longrightarrow \nu X$

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

$\tilde{\sigma}^{+}_{CC} = x[(\bar{u}+\bar{c}) + (1-y)^2(d+s)]$ sensitive to d quark at high x

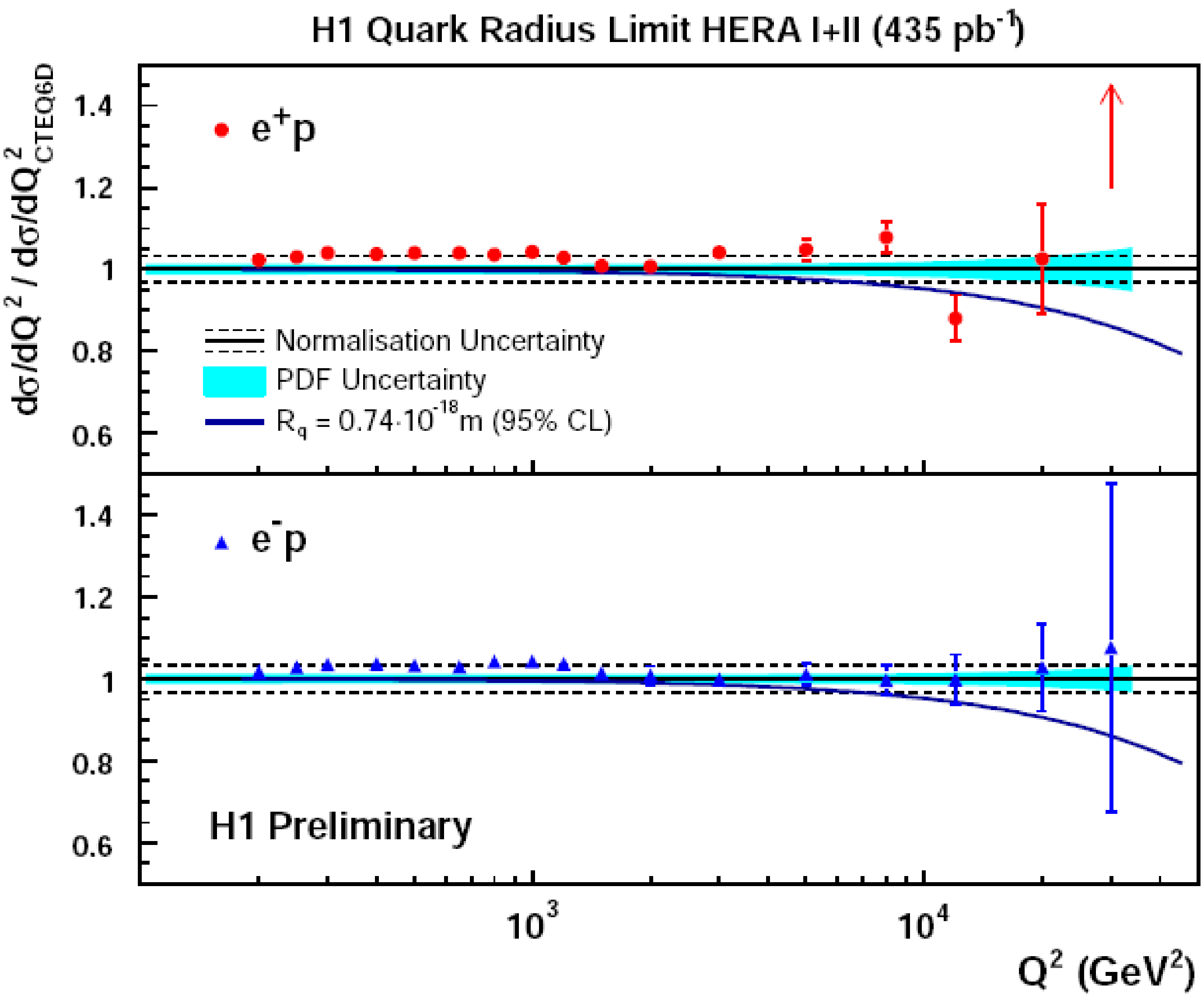
$\tilde{\sigma}^{-}_{CC} = x[(u+c) + (1-y)^2(\bar{d}+\bar{s})]$ sensitive to u quark at high x

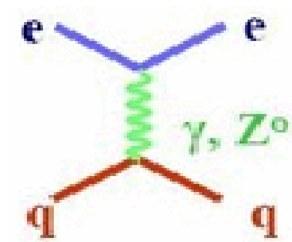
e⁺ p and e⁻ p cross sections vs Q^2



- Well described over 6 orders of magnitude.
- Destructive (e^+) and constructive (e^-) γZ interference in Neutral Current.
- Charged Current:
  - e^- u dominates,
  - e^+ d is suppressed.
- Electroweak unification at $Q^2 \sim m_W^2$.

Quark radius limit



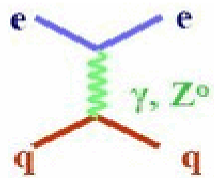


Quark radius form factor:
$(1 - R_q^2\, Q^2/6)^2$

H1 limit:
$R_q < 0.74 \cdot 10^{-18}$ m

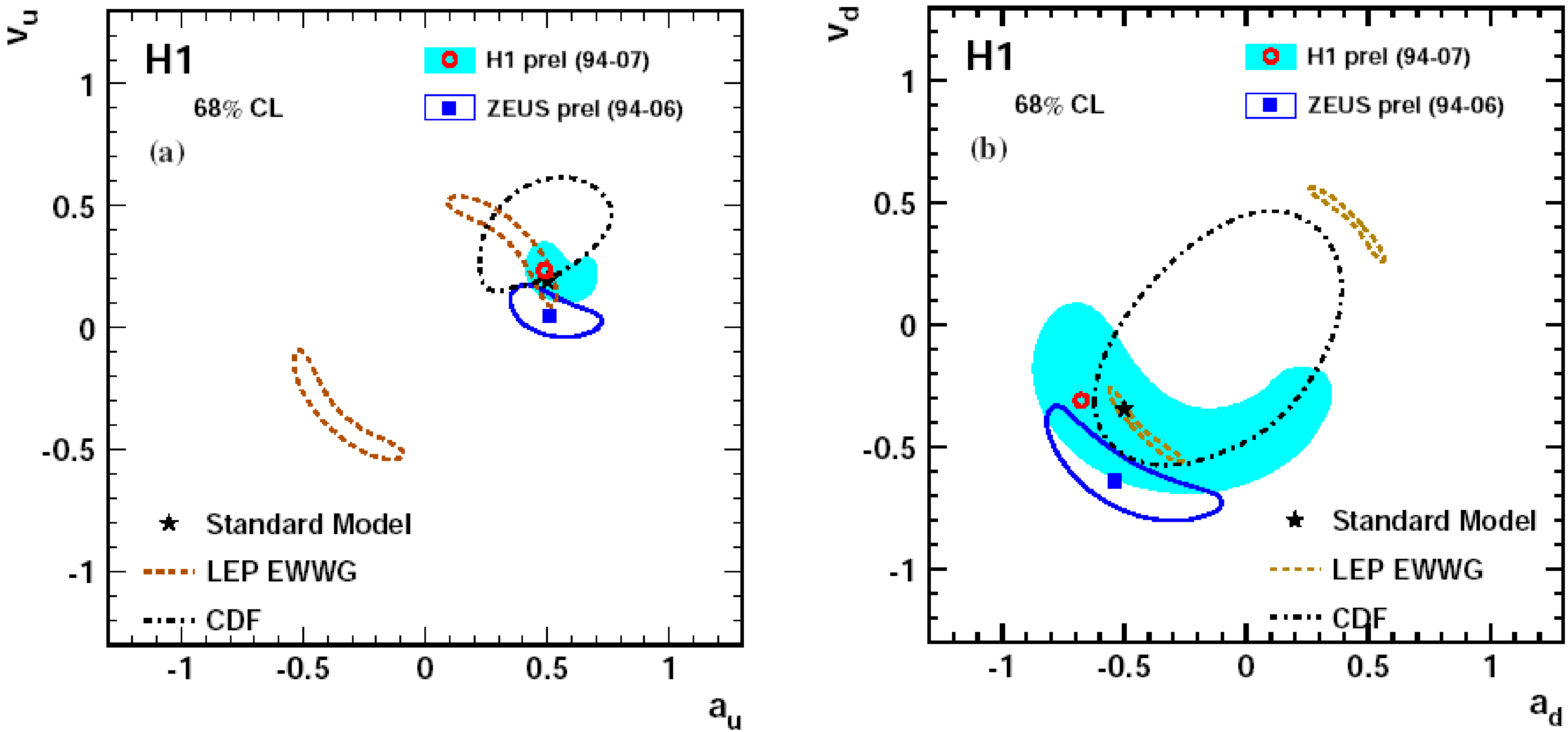
ZEUS limit:
$R_q < 0.62 \cdot 10^{-18}$ m

Z couplings to u and d



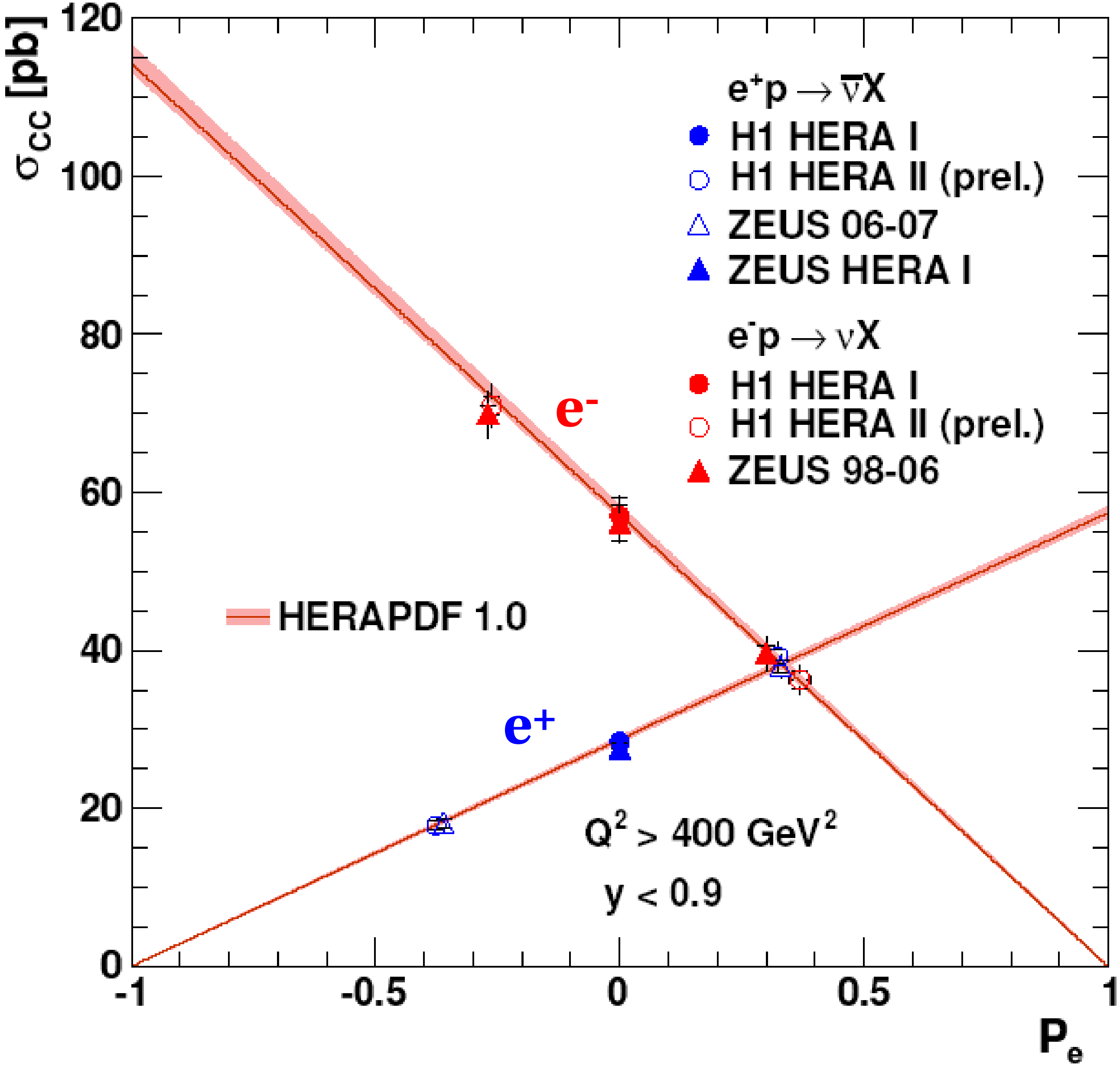
simultaneous EW+PDF analysis of NC and CC data

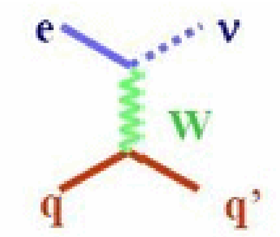
$$v_q = I_q^3 - 2e_q \sin^2\Theta_W \qquad a_q = I_q^3$$



H1+ZEUS combination still to come...

Charged current vs polarisation





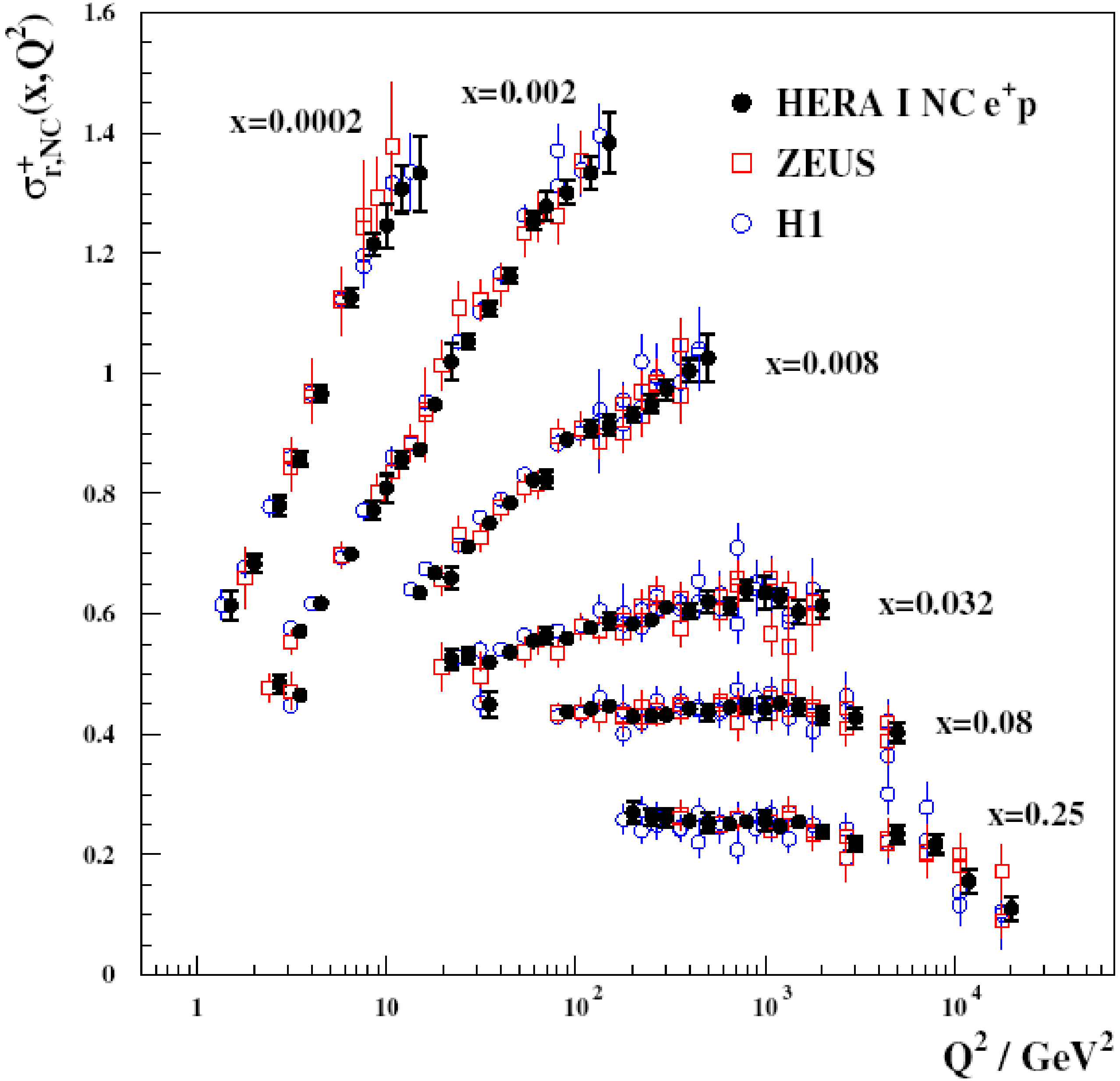
Standard Model:

$$\sigma^{CC}(e^{\pm}p) = (1 \pm P_e)\sigma^{CC}_{P_e=0}$$

Absence of right-handed weak currents confirmed

HERA I averaged data

$$\sigma_r = \frac{xQ^4}{2\pi\alpha^2 Y_{+.}} \frac{d^2\sigma}{dx\, dQ^2}$$



H1 ⊕ ZEUS

6 *x* bins shown.

total uncertainty:

1% for

$20 < Q^2 < 90$ GeV^2.

<2% for

$3 < Q^2 < 500$ GeV^2.

Published

10-16 years after

data taking:

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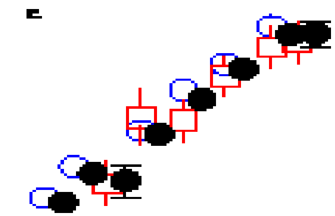
Averaging H1 and ZEUS data

- Average not done point-by-point but in a global fit (correlated systematics):



$$\chi^2_{\rm exp}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\rm stat}\,\mu^i\left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\rm uncor}\, m^i\right)^2} + \sum_j b_j^2\,.$$

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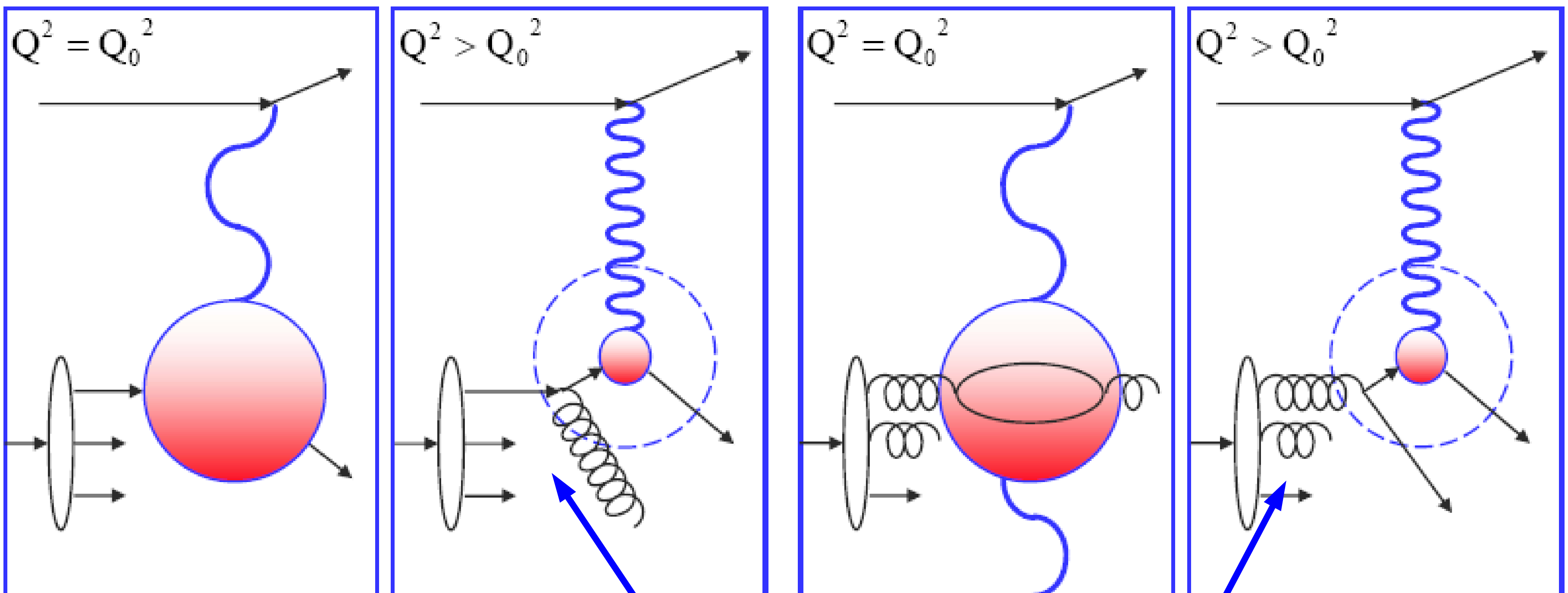
- 1402 H1 and ZEUS measurements $\boldsymbol{\mu}$ combined into 741 points $\boldsymbol{m}$.
- Data allowed to shift by $\boldsymbol{b}$ within correlated systematics $\gamma\, m$.
- 110 sources of experimental systematics $\boldsymbol{\gamma}$. Final result has reduced systematics, some by factor 2 or 3.
- Statistical δ_s and uncorrelated systematics δ_u are multiplicative.
- final χ^2 / DOF = 637 / 656: H1 and ZEUS are consistent.

Scaling violations in QCD

Large x:
quarks radiate gluons,
photon probes smaller x,
⇒ F_2 falls with Q^2.

Small x:
gluons split into quark pair,
photon resolves quark pair,
⇒ F_2 rises with Q^2.



$$\frac{d\Sigma(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{qq}\left(\frac{x}{z}\right)\Sigma(z,Q^2) + P_{qg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

DGLAP equation of QCD. Now calculated in NNLO (α_S^3).

HERAPDF1.0

PDF evolution	:	$Q_0^2 = 1.9$ GeV^2 use DGLAP @ NLO
Renormalization & Factorization scale	:	Q^2
m_c	:	1.4 GeV
m_b	:	4.75 GeV
$\alpha_s(M_z)$	:	0.1176
Q^2_{min} of Data	:	3.5 GeV^2
$f_s = \bar{s} / (\bar{s}+\bar{d})$ @ Q_0^2	:	0.31
Heavy Quark Coefficient Functions	:	GMVFNS Robert Thorne VFNS 2008

variations → model systematics

10 parameter fit, at starting scale Q_0:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}},$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$$

Additional Contraints:

- Quark Number Sum Rules
- Momentum Sum Rule
- $B_{\bar{U}} = B_{\bar{D}}$ & $A_{\bar{U}} = A_{\bar{D}}(1\text{-}f_s)$
  $\bar{u} \to \bar{d}$ as $x \to 0$
- $B_{u_v} = B_{d_v}$

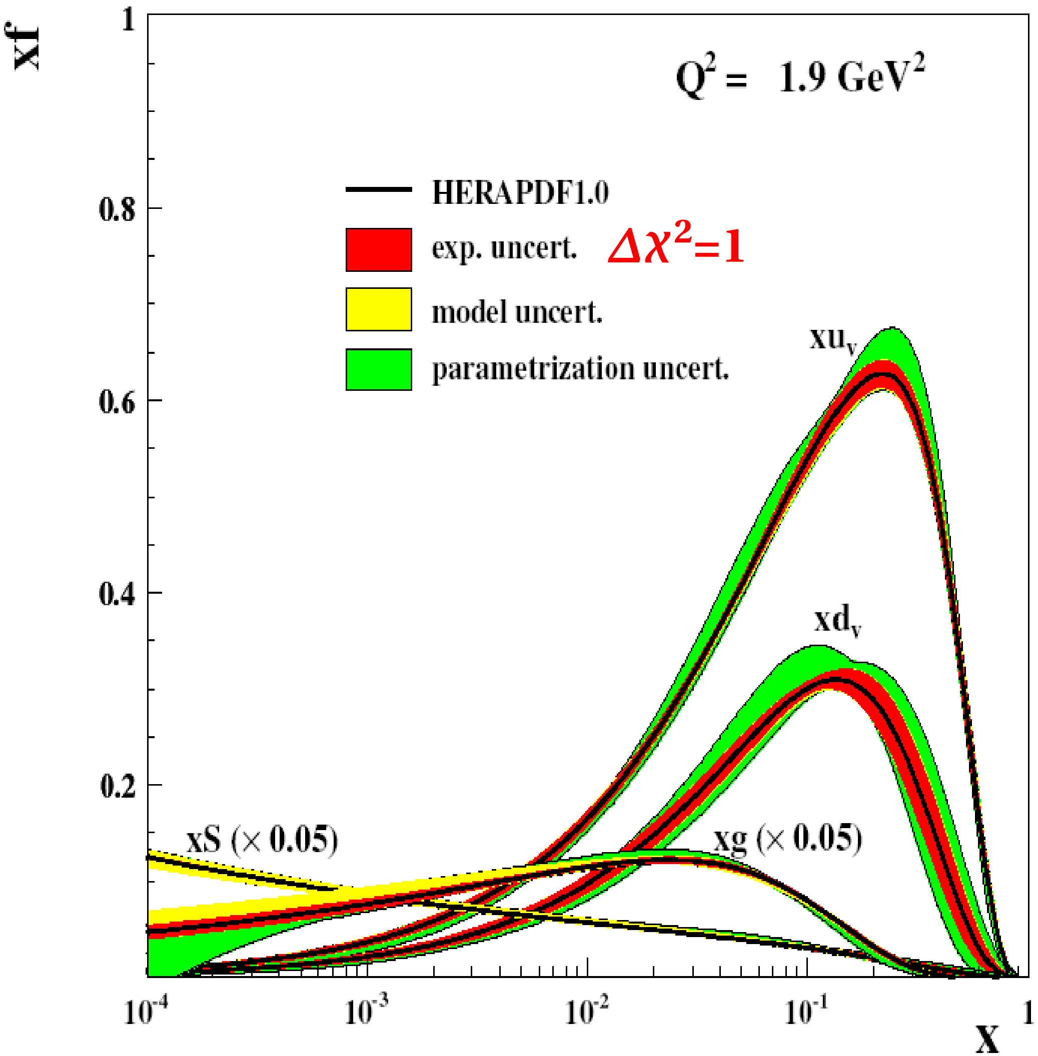
variations → parametrization systematics

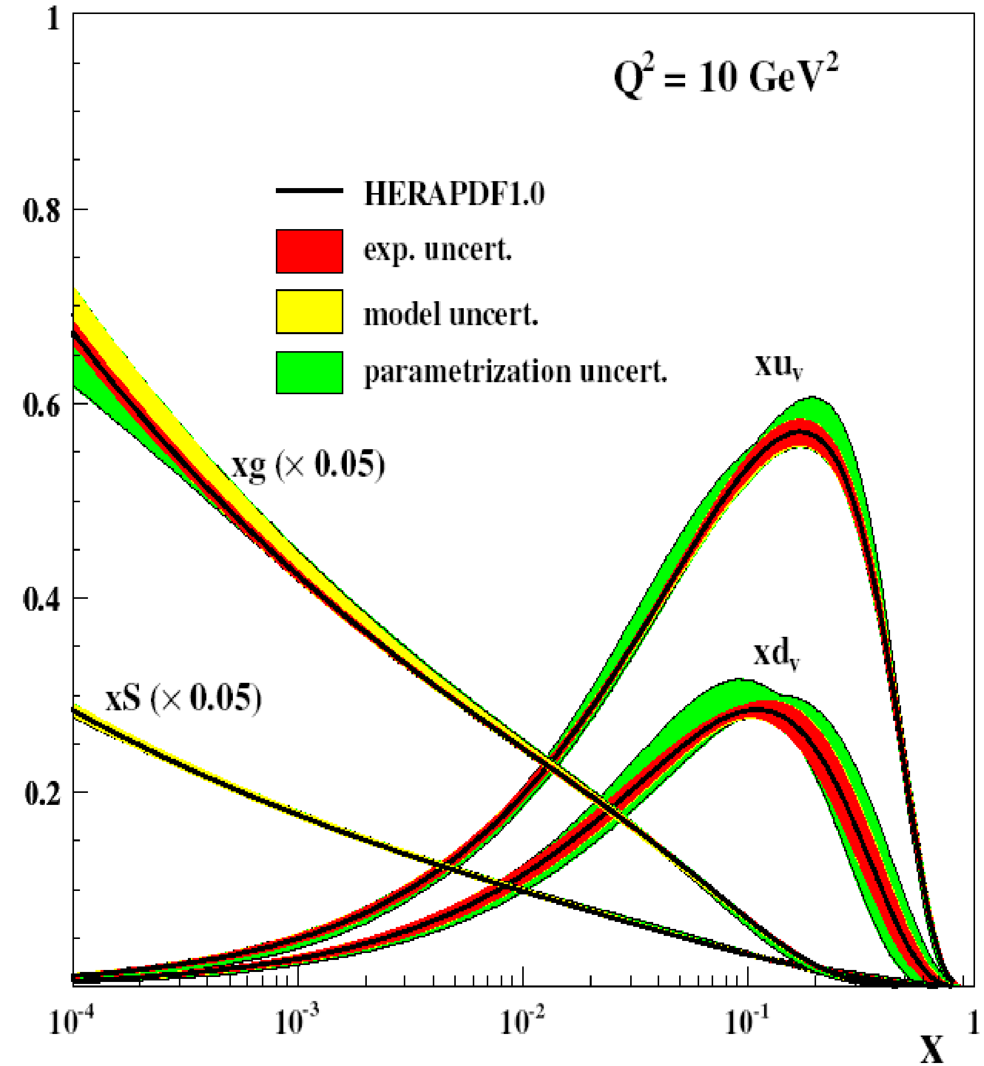
HERAPDF1.0

Available in LHAPDF since 5.8.1 (Dec 2009)

Starting scale:

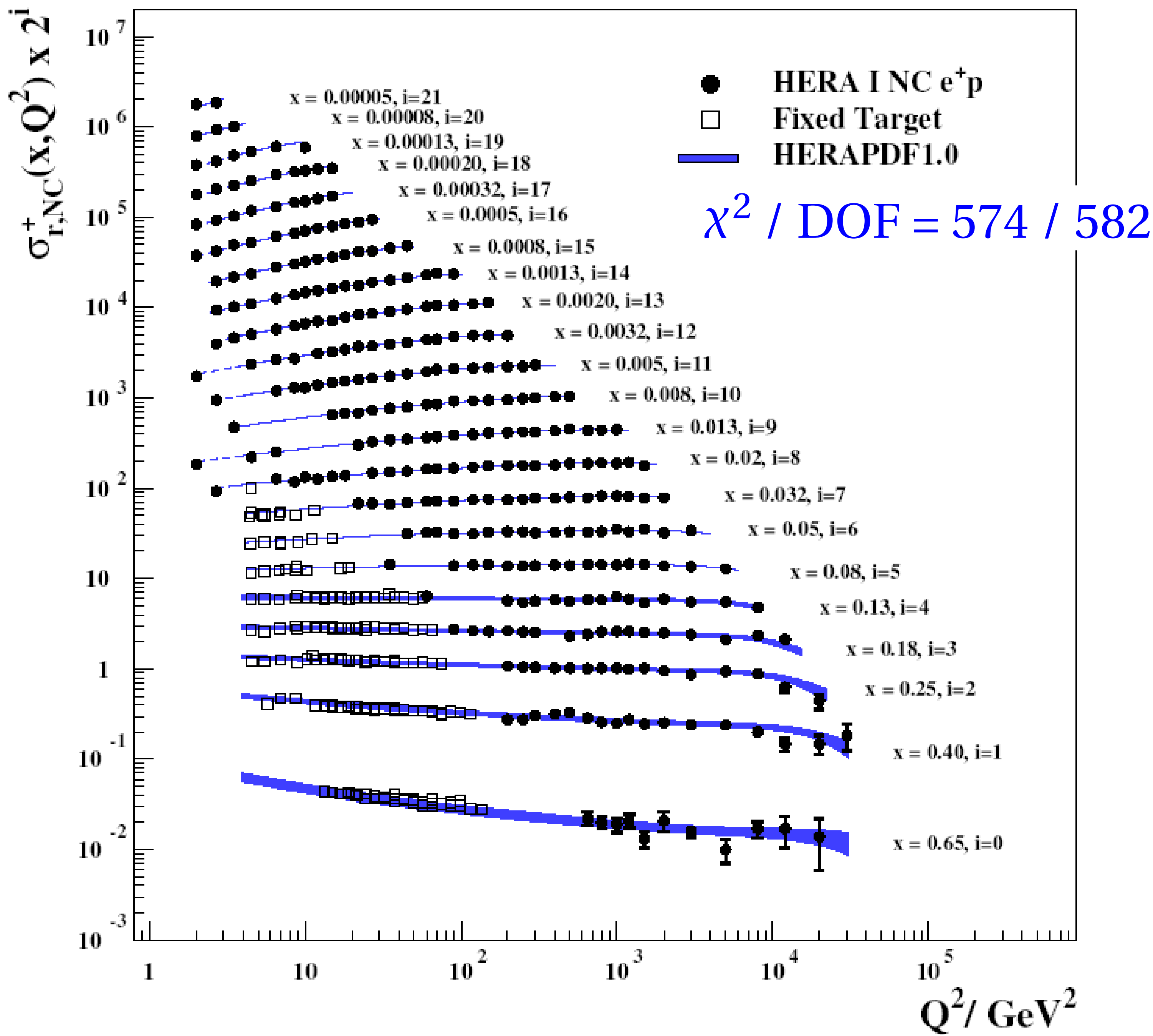
10 GeV^2:



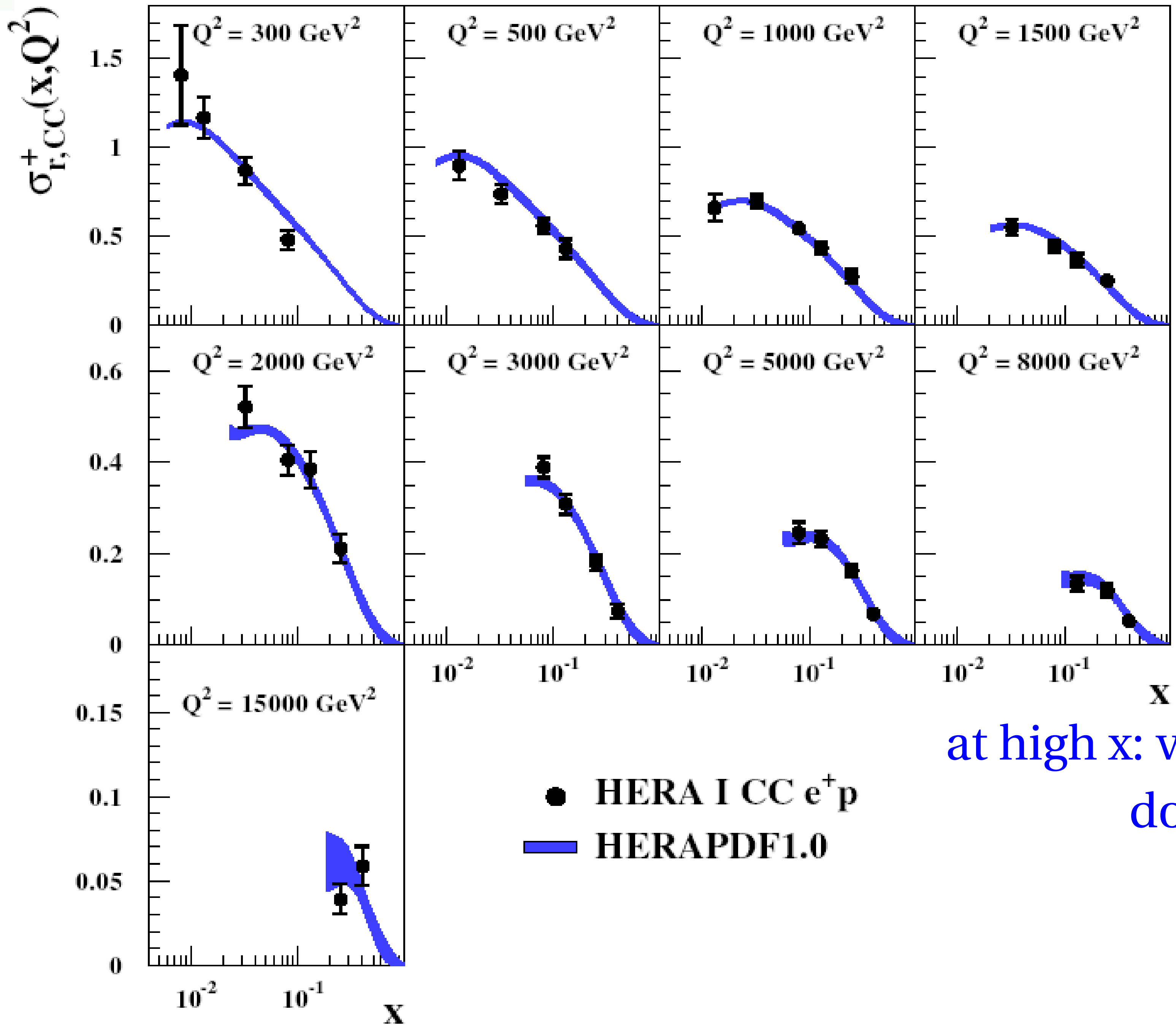


Valence-like gluon density.

HERAPDF1.0 and HERA I NC data



Combined Charged Current data



at high x: valence d dominates

Longitudinal structure function F_L

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right]$$

Angular momentum conservation in DIS:
spin ½ quark has to absorb a spin 1 virtual photon.

QPM: quark helicity always ±1, $F_L = 0$.

QCD: off-shell quarks may absorb longitudinal photons.

Altarelli-Martinelli (1978):

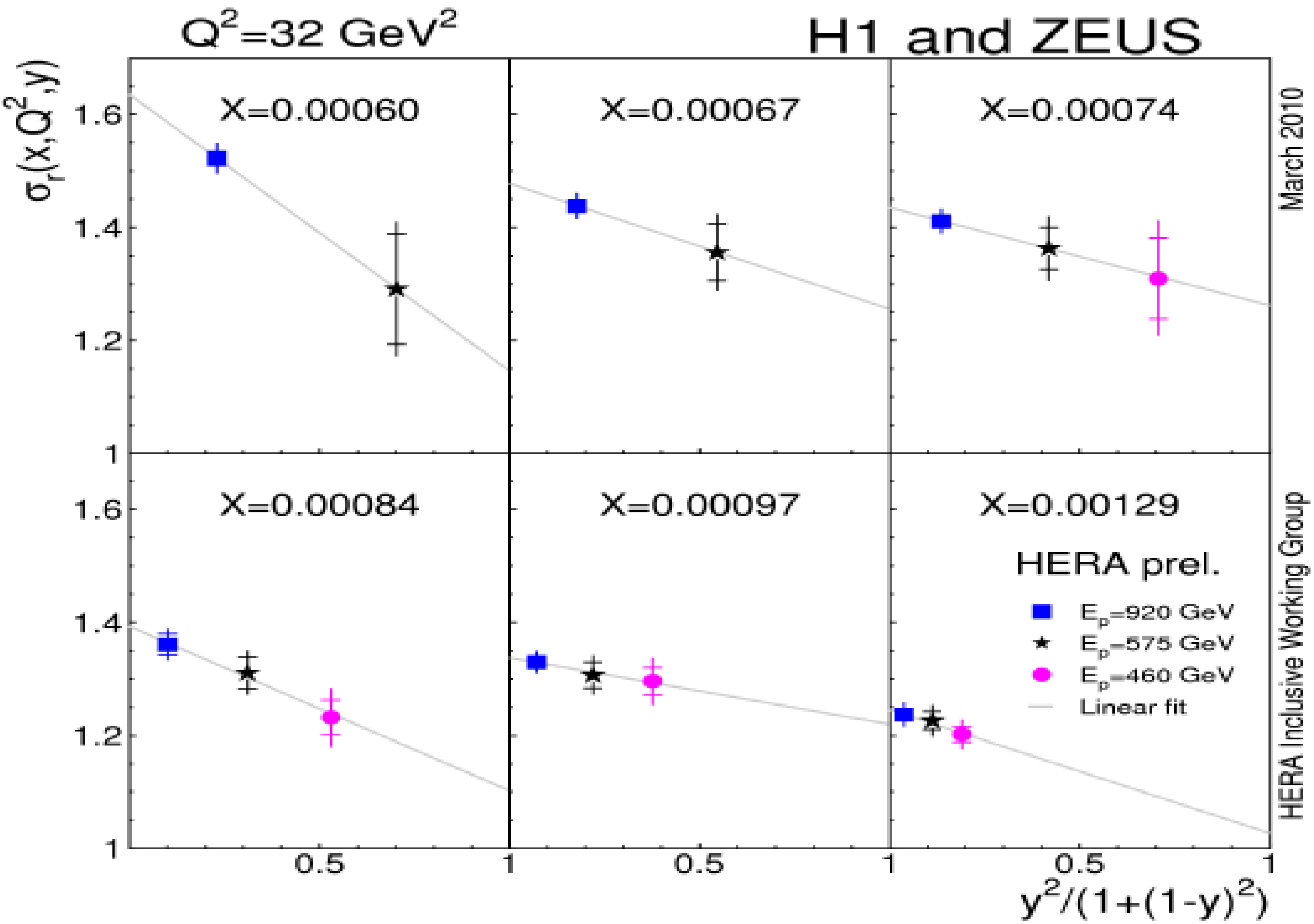
$$F_L(x,Q^2) = \frac{\alpha_s}{4\pi}x^2\int_x^1\frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum_q e_q^2\left(1-\frac{x}{z}\right)\cdot xg\right]$$

quarks radiating a gluon	gluons splitting into quarks

Direct measurement of F_L

$$\frac{d^2\sigma^{ep}_{NC}}{dx\,dQ^2} \Big/ \left(\frac{2\pi\alpha^2}{xQ^4}Y_+\right) = F_2 - \frac{y^2}{1+(1-y)^2}F_L$$

$y = Q^2 / sx.$

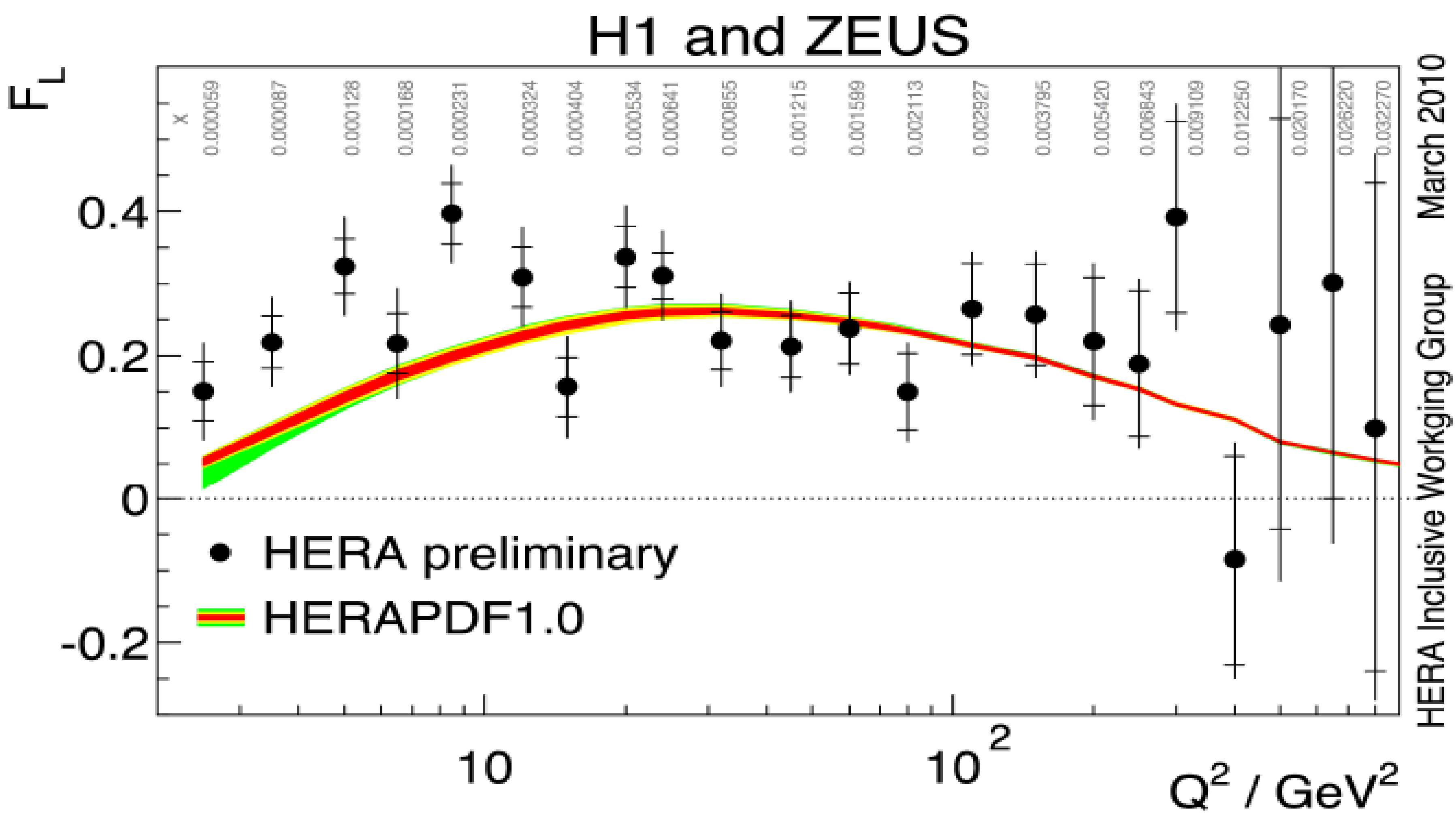


Need to vary s to extract F_L in x, Q^2 bins.

$\Rightarrow$ low E_p runs.

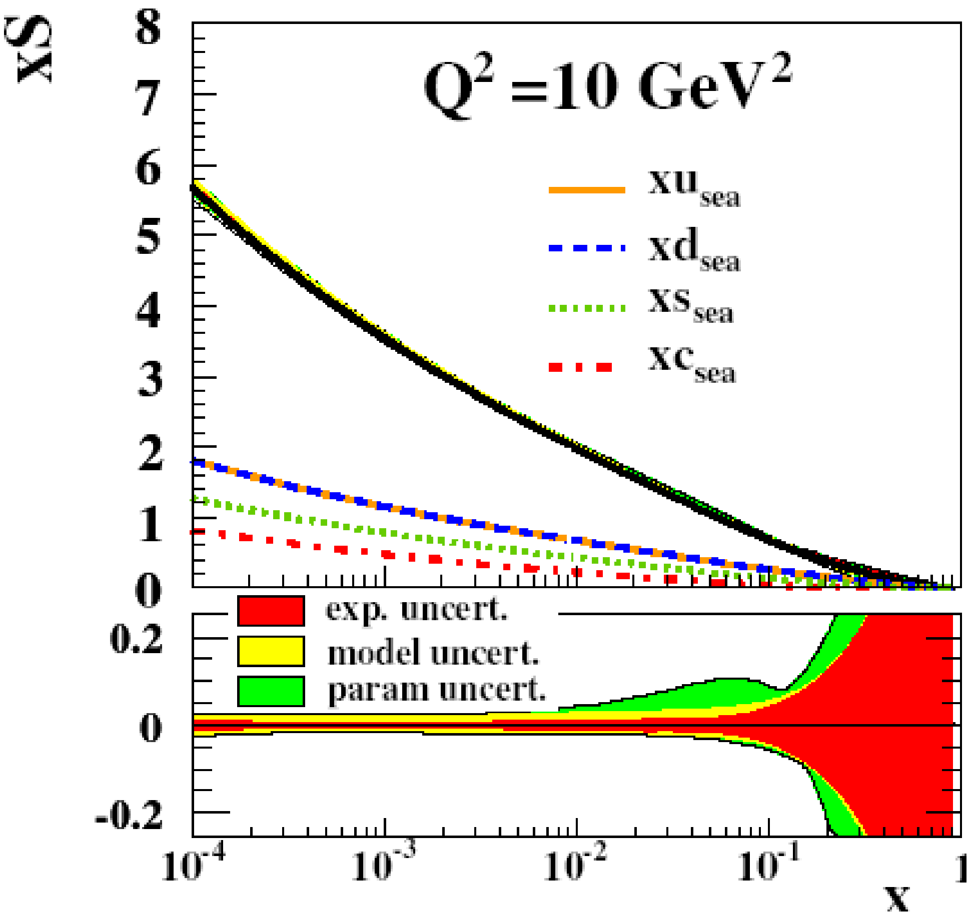
Combined F_L

H1 and ZEUS published F_L data, preliminary combination:

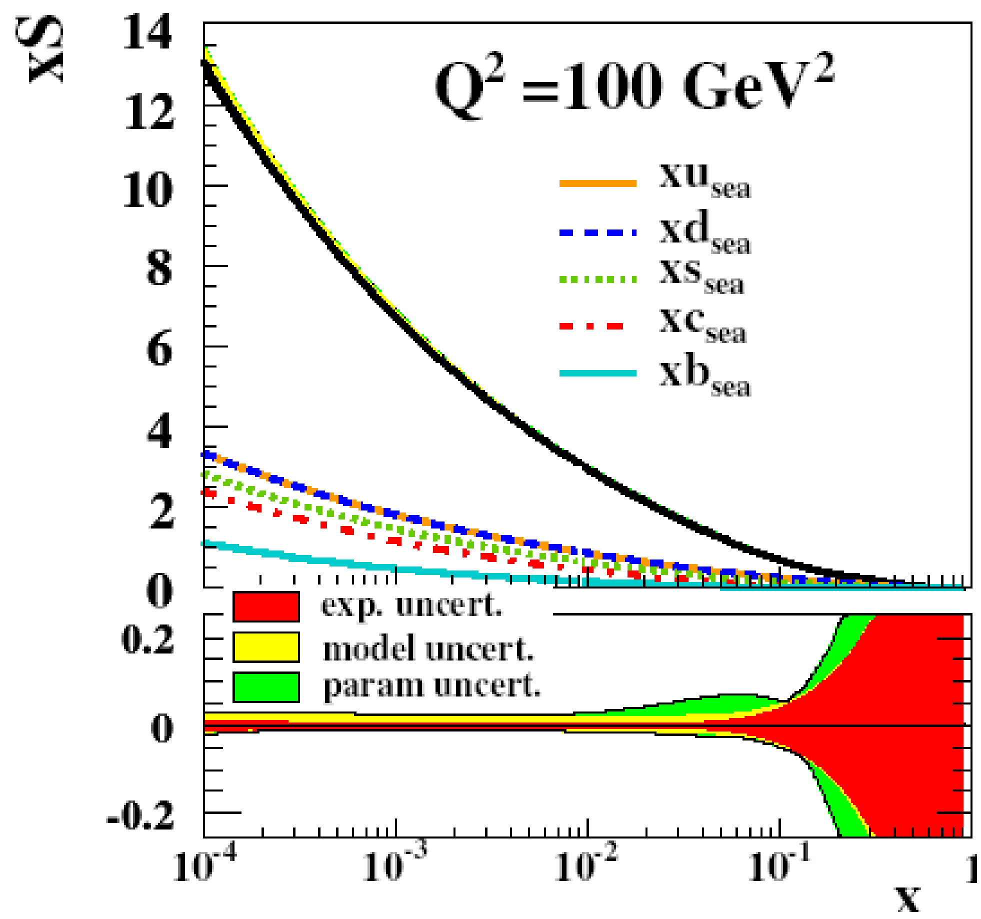


Some tension at low Q2 with QCD prediction – under study.

HERAPDF1.0 sea quarks

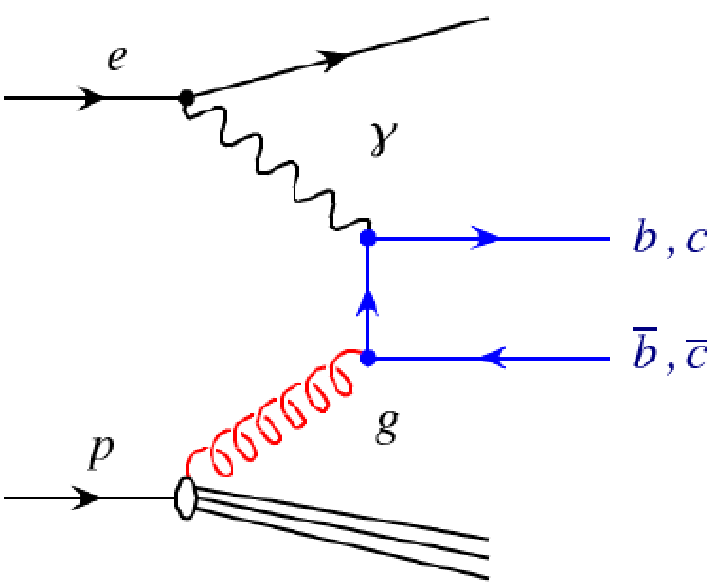


Above charm threshold

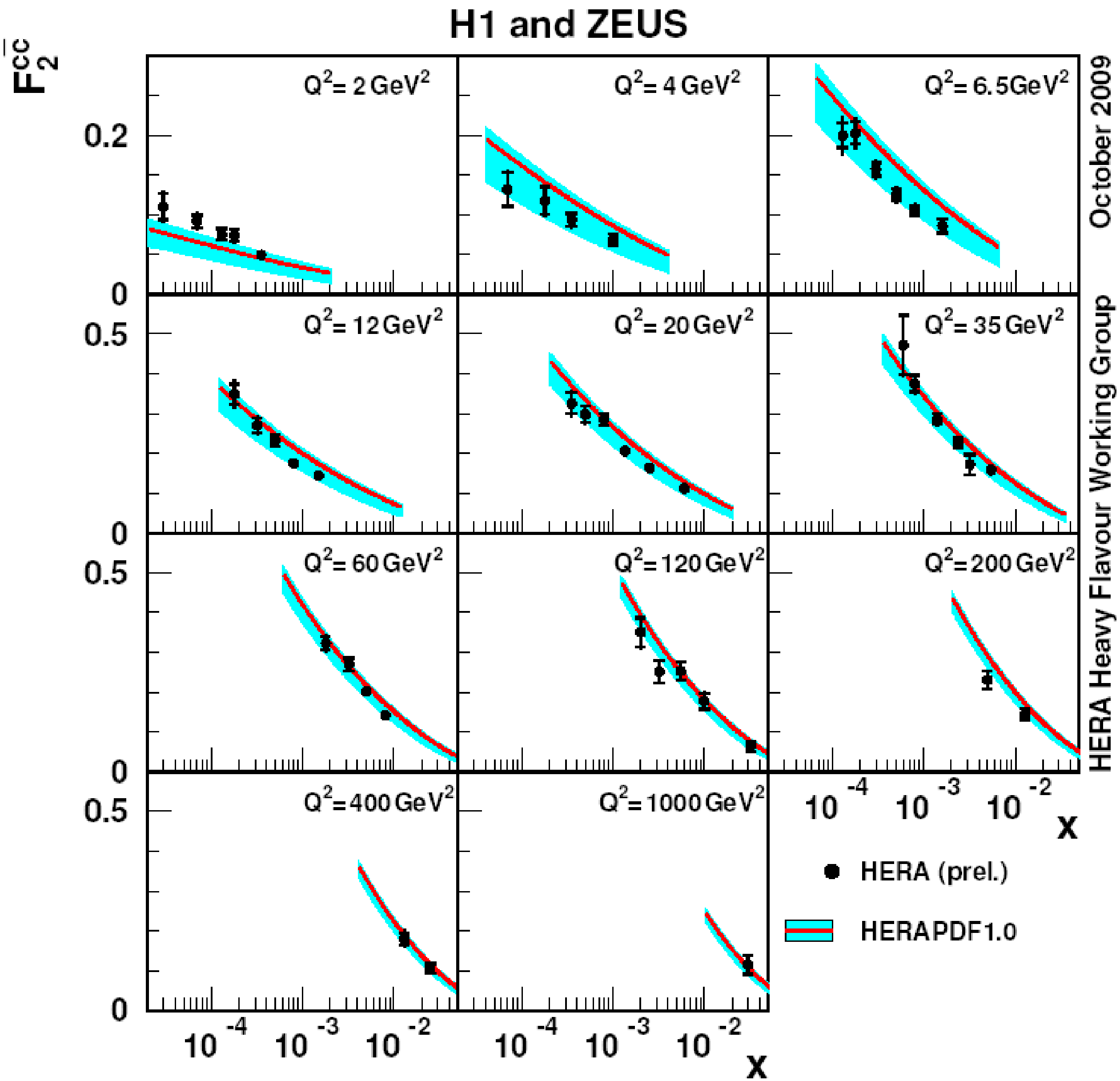


Above beauty threshold

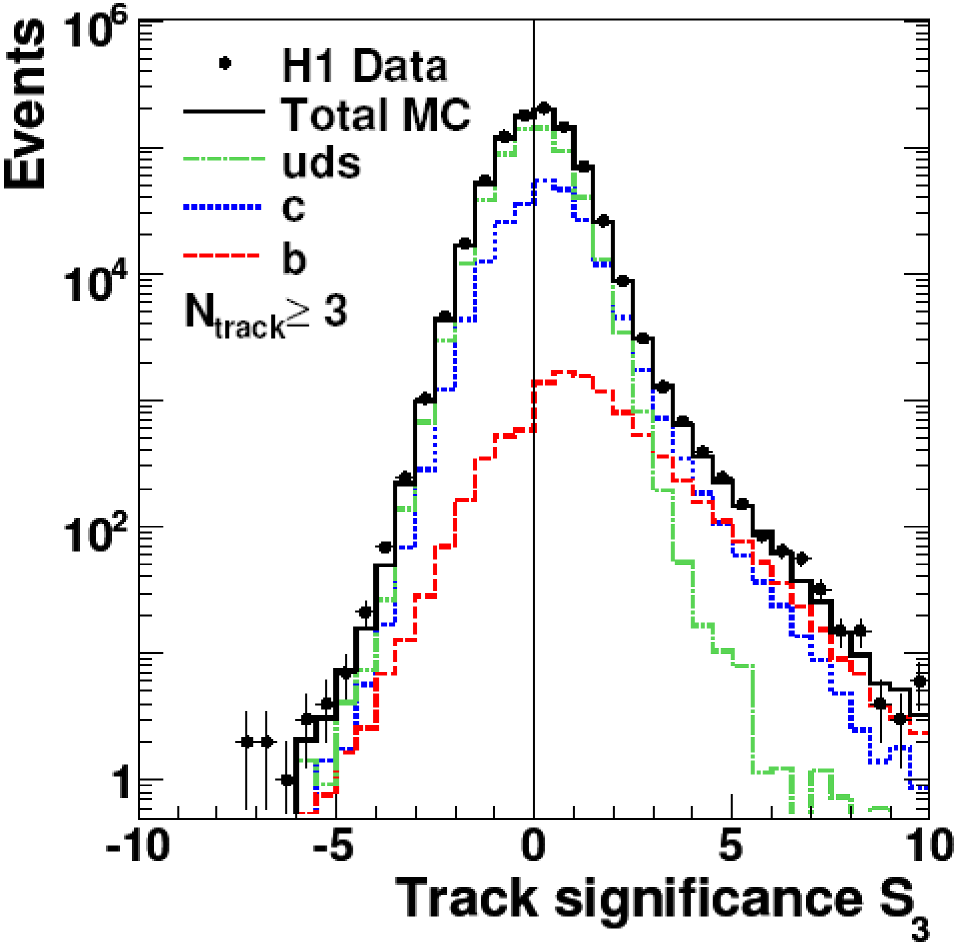
Charm production and HERAPDF1.0

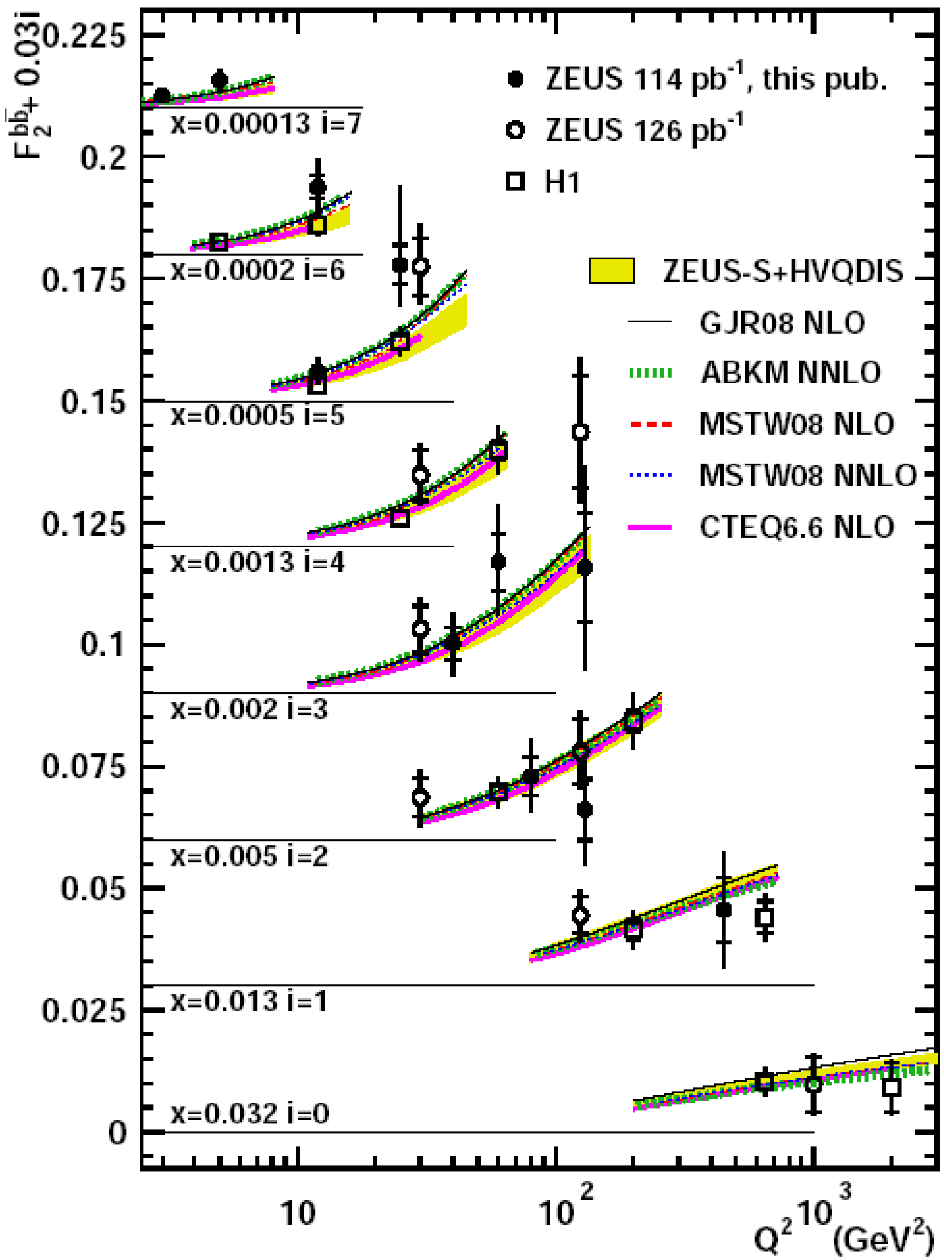


Charm tagging with D*, D+, muons, impact parameter



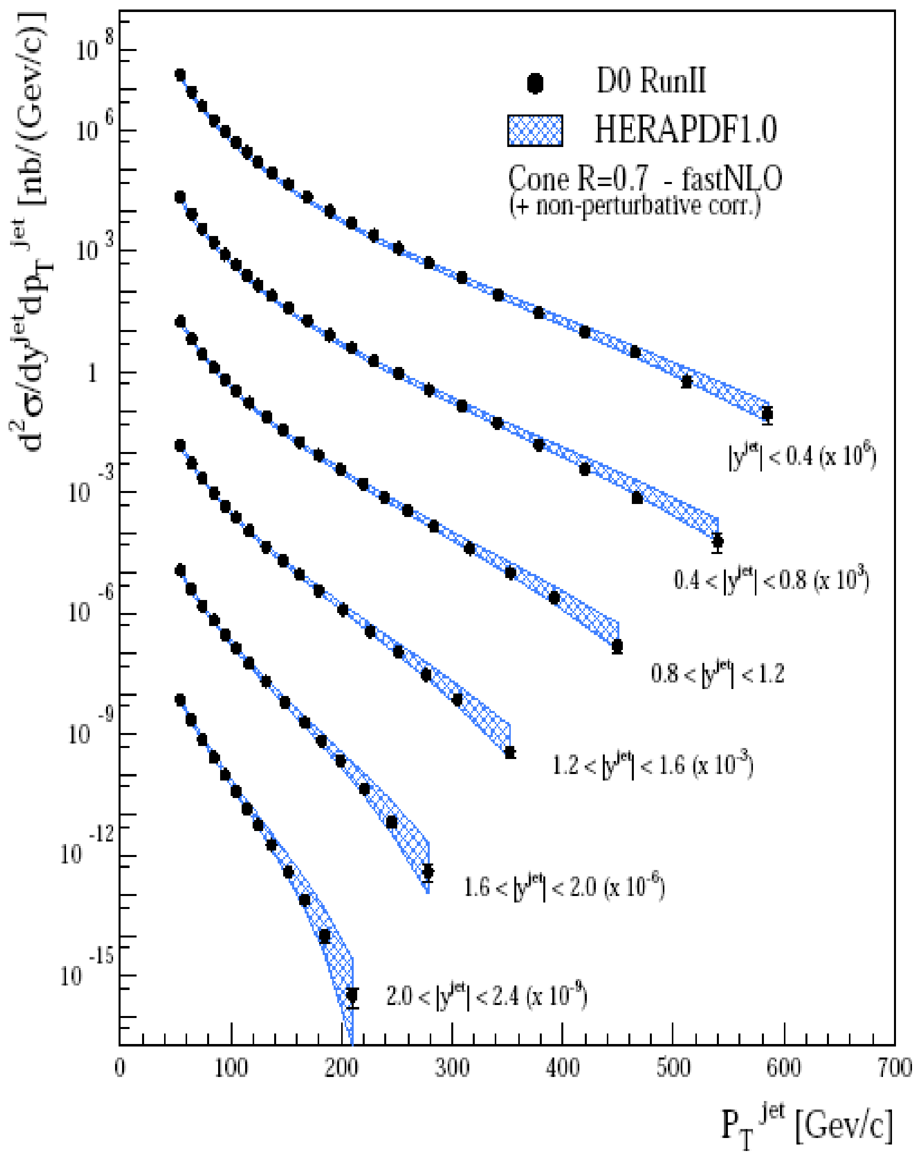
Beauty production at HERA

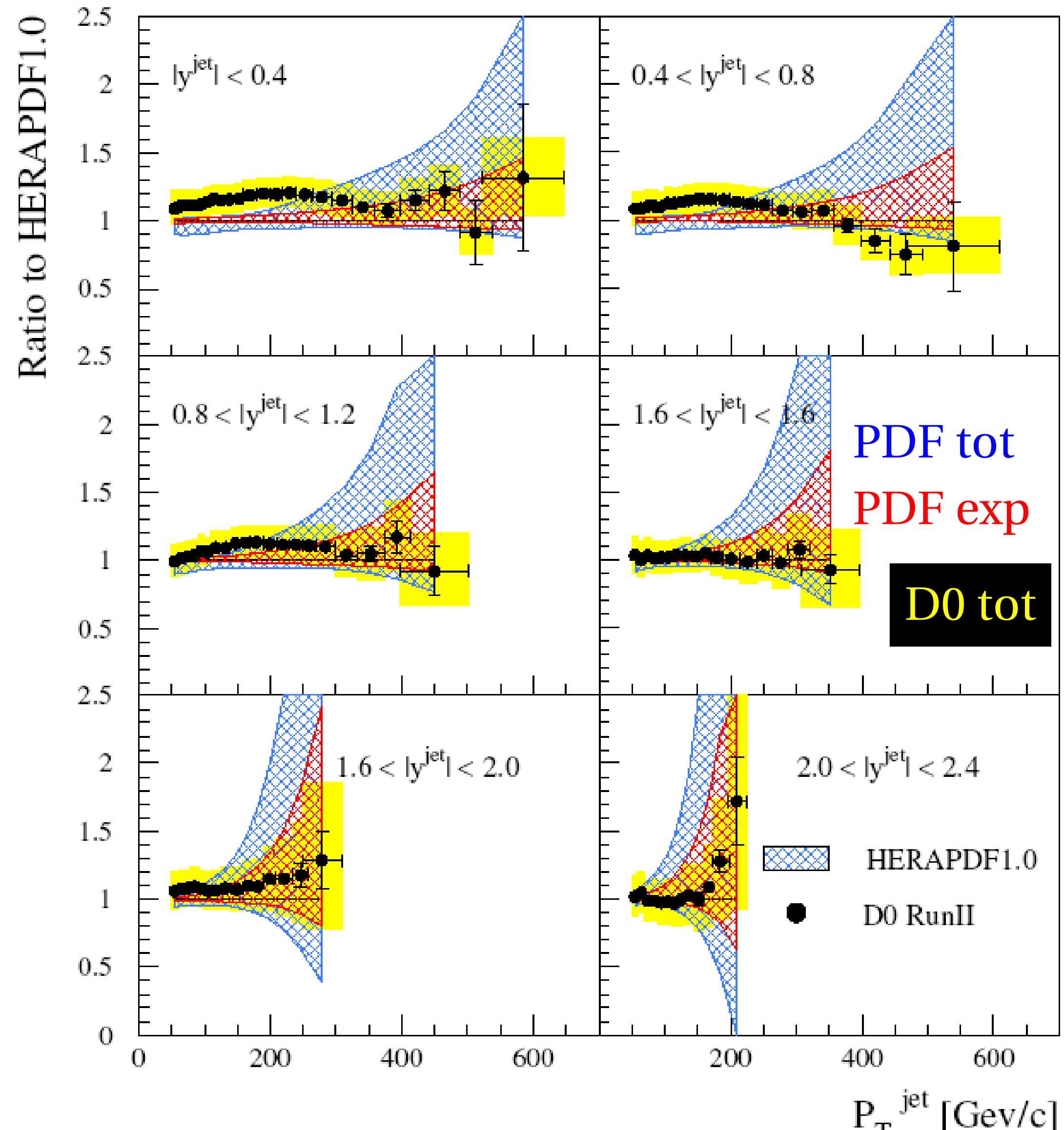




b tagging with track impact parameter using a silicon strip vertex detector

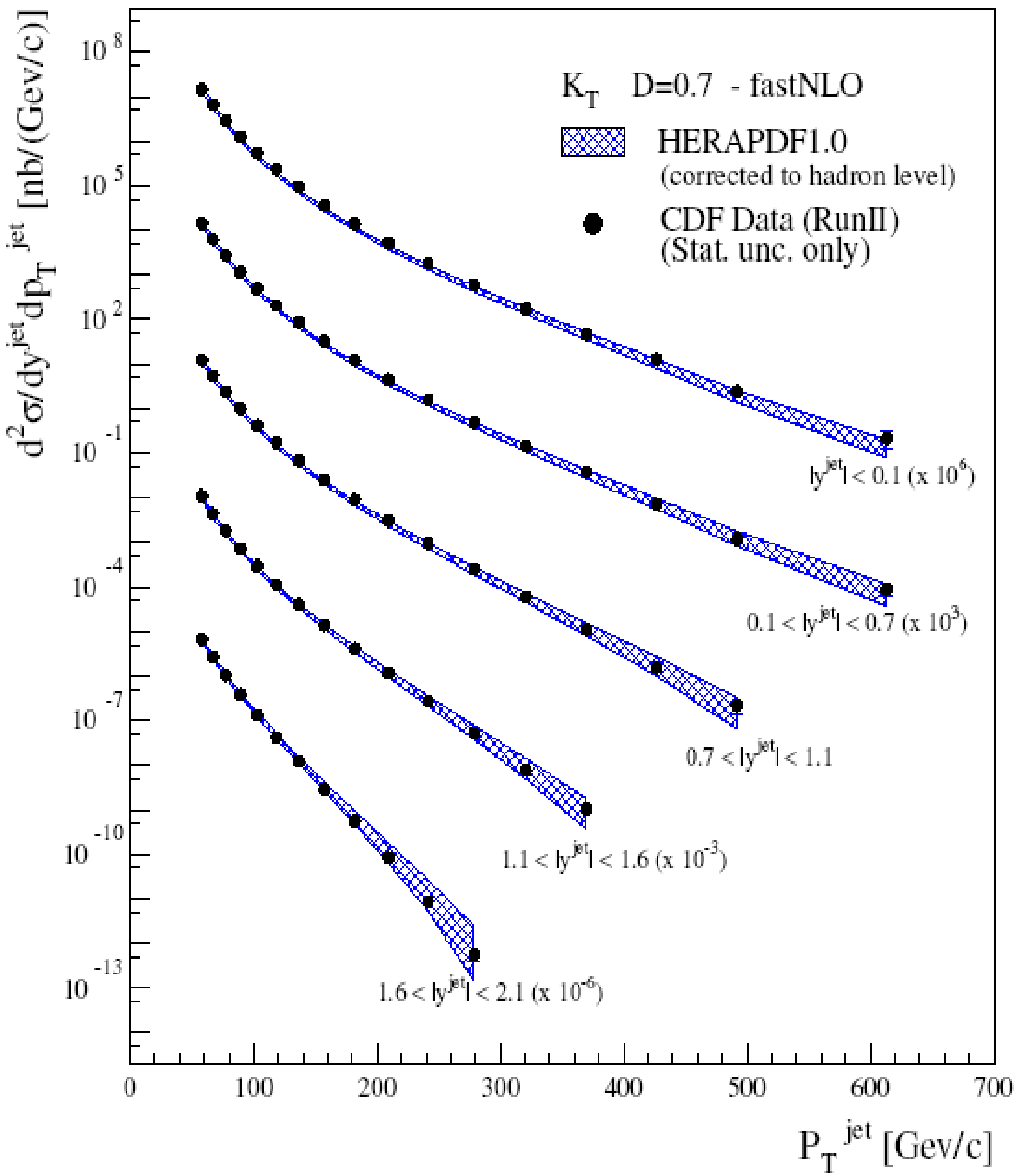
HERAPDF1.0 and D0 jets

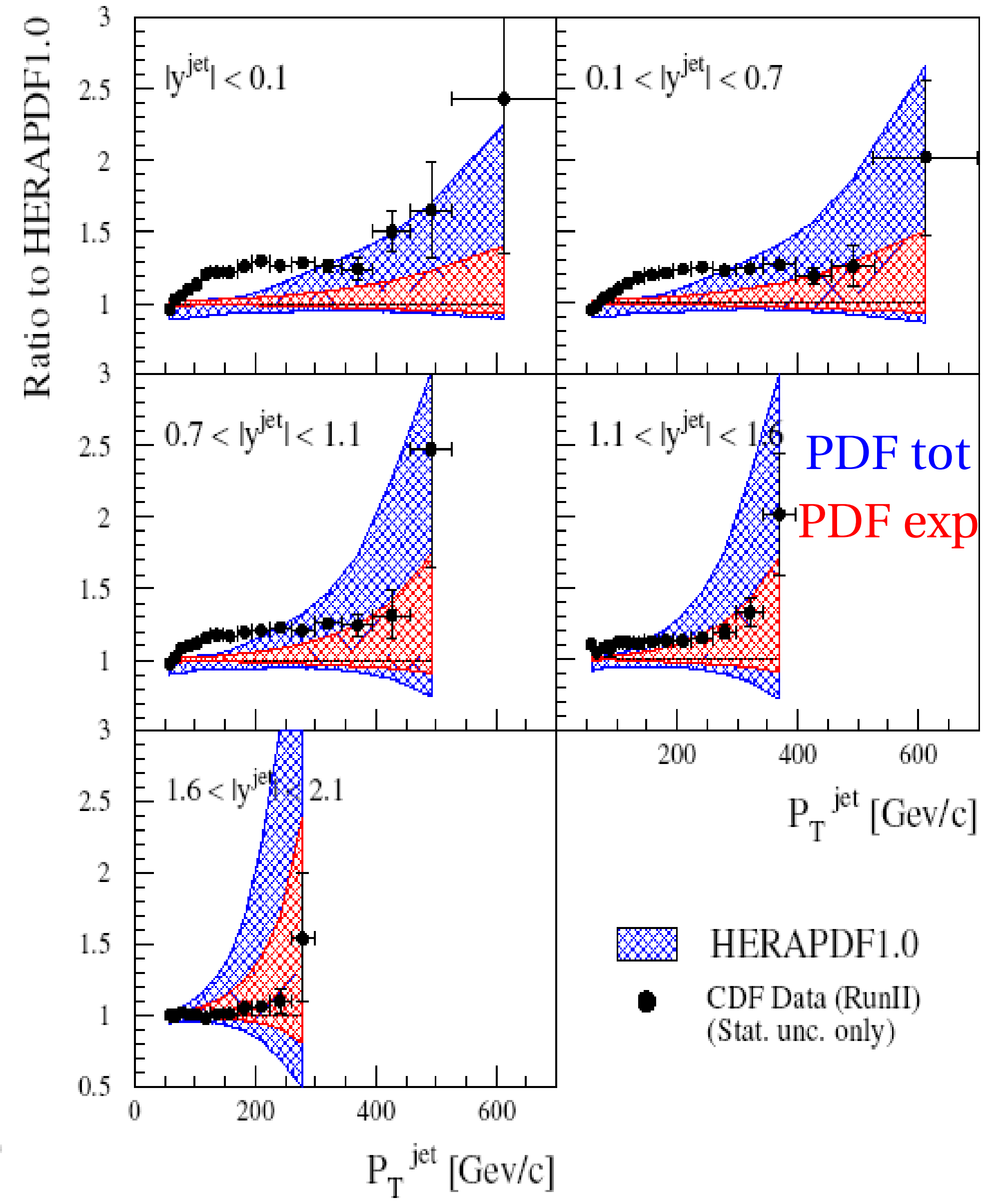




fastNLO scale uncertainty not included.
HERA II data will reduce uncertainty at high x.

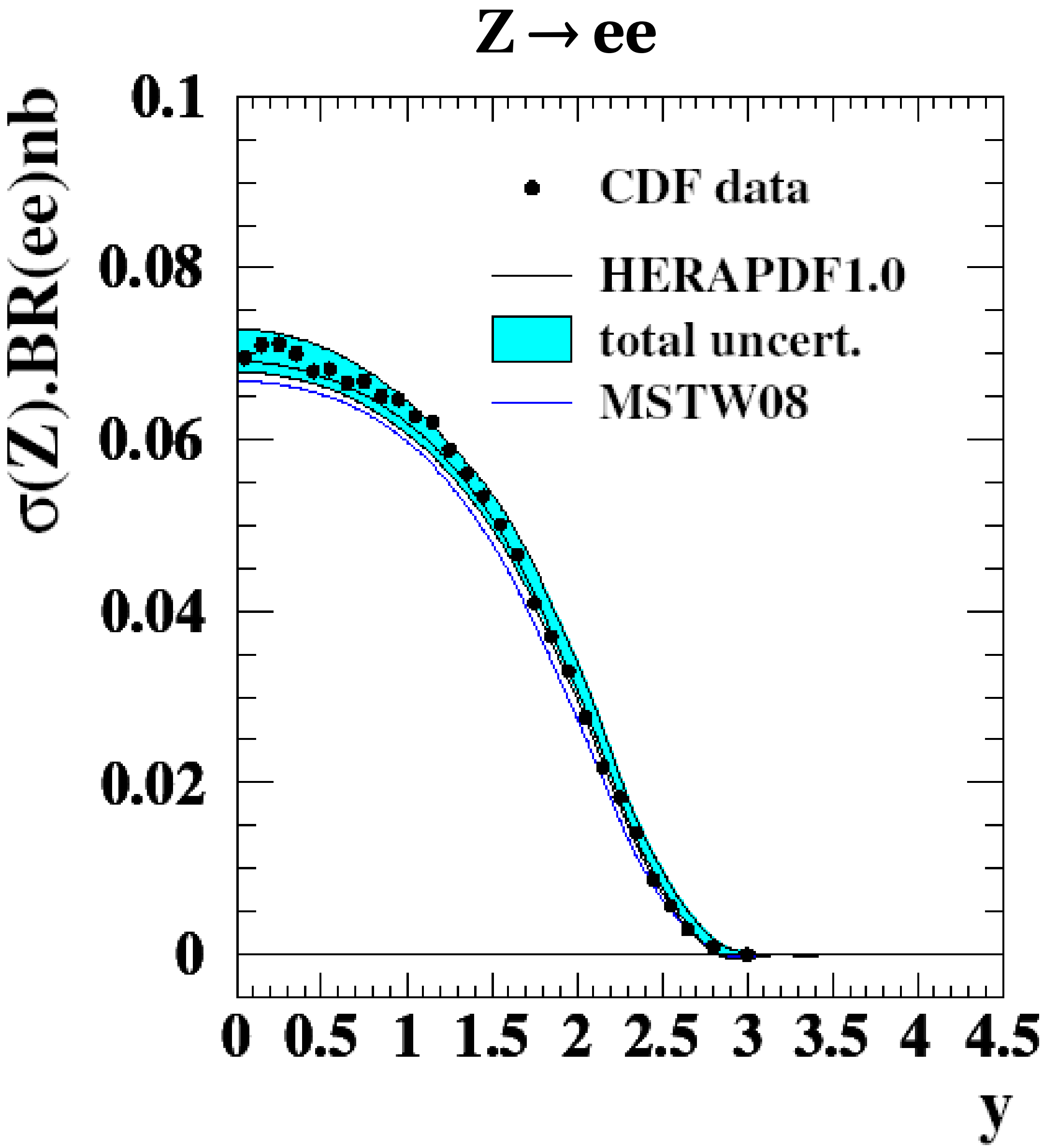
HERAPDF1.0 and CDF jets

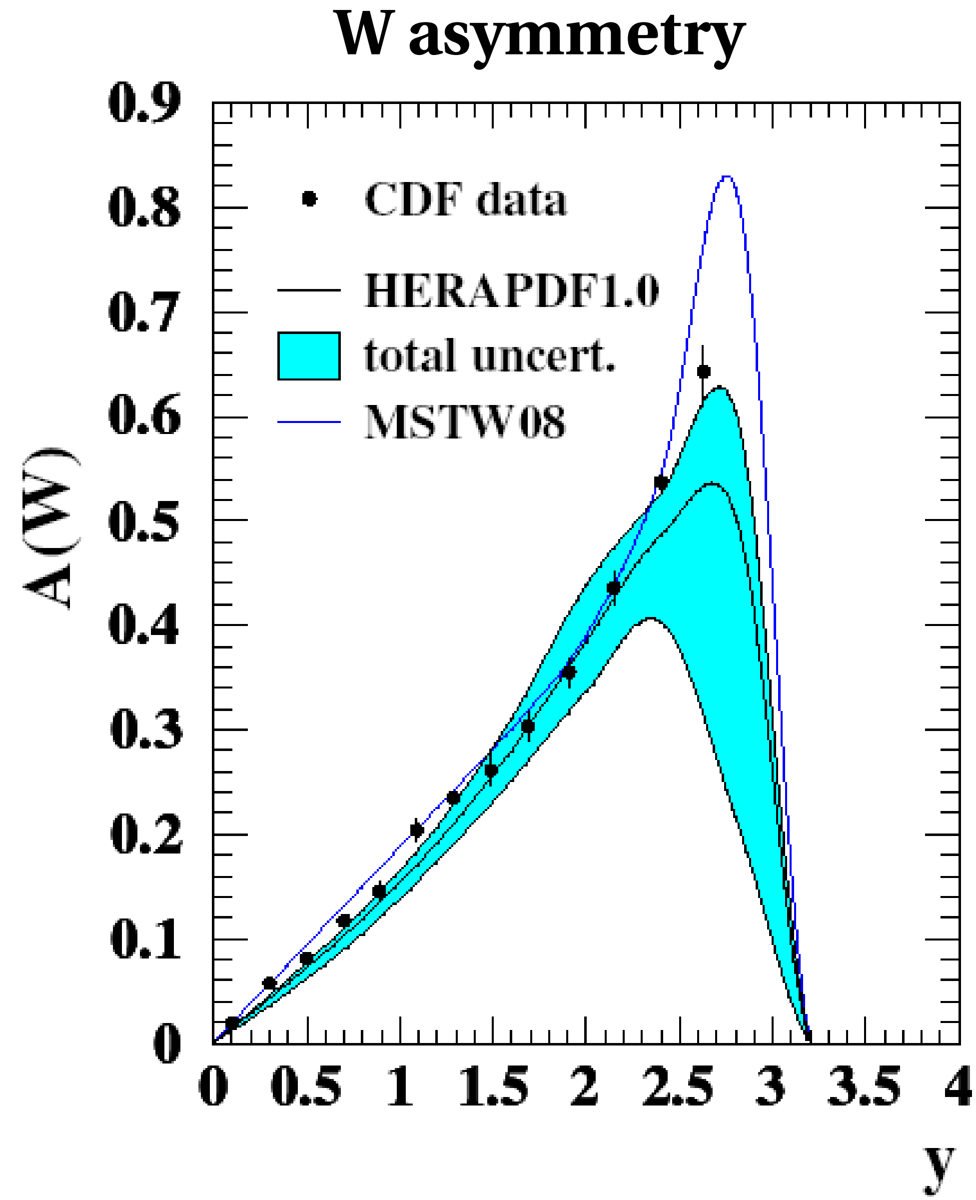




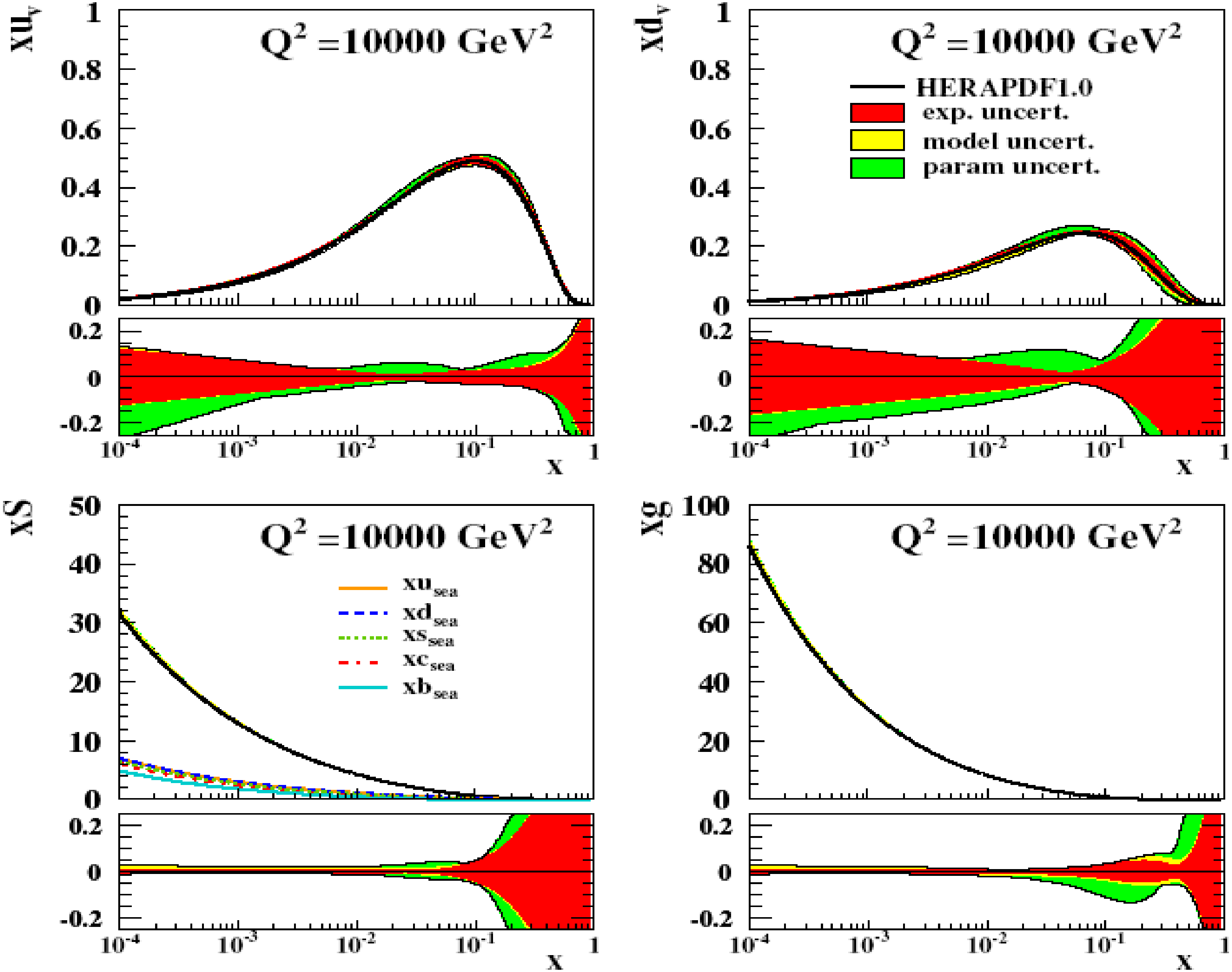
fastNLO and CDF scale uncertainty not included.

HERAPDF1.0 and Tevatron Z, W



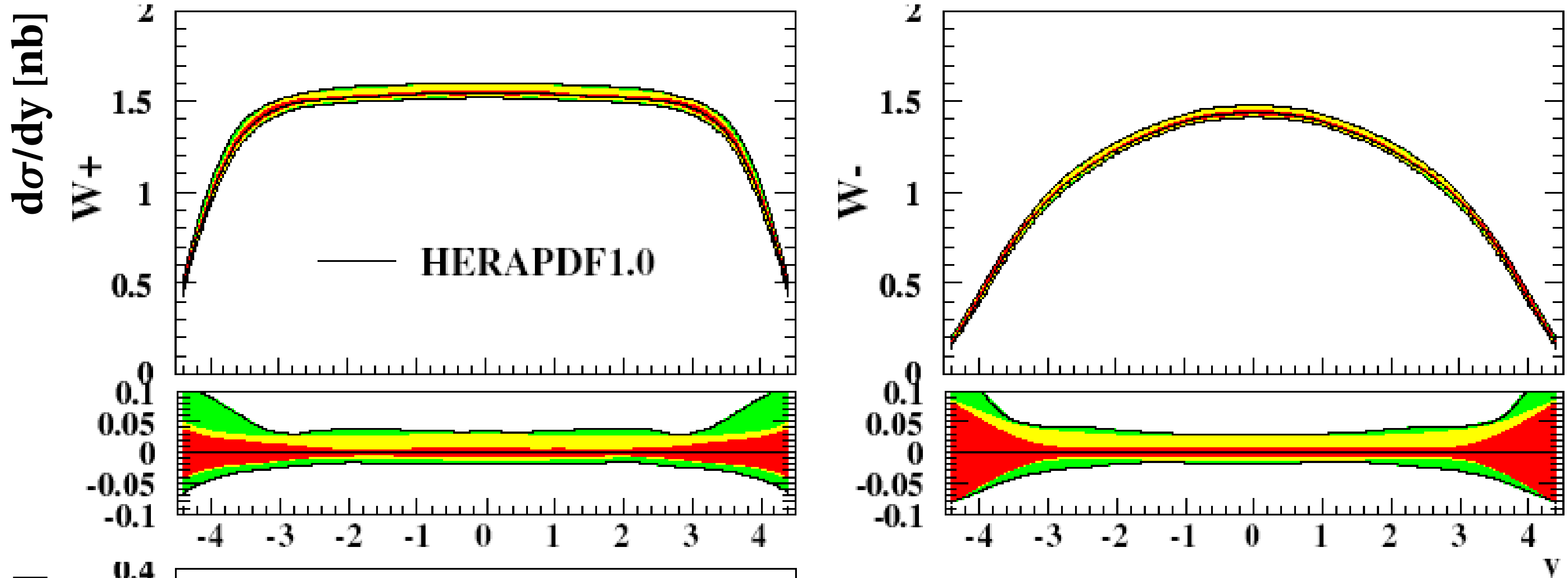


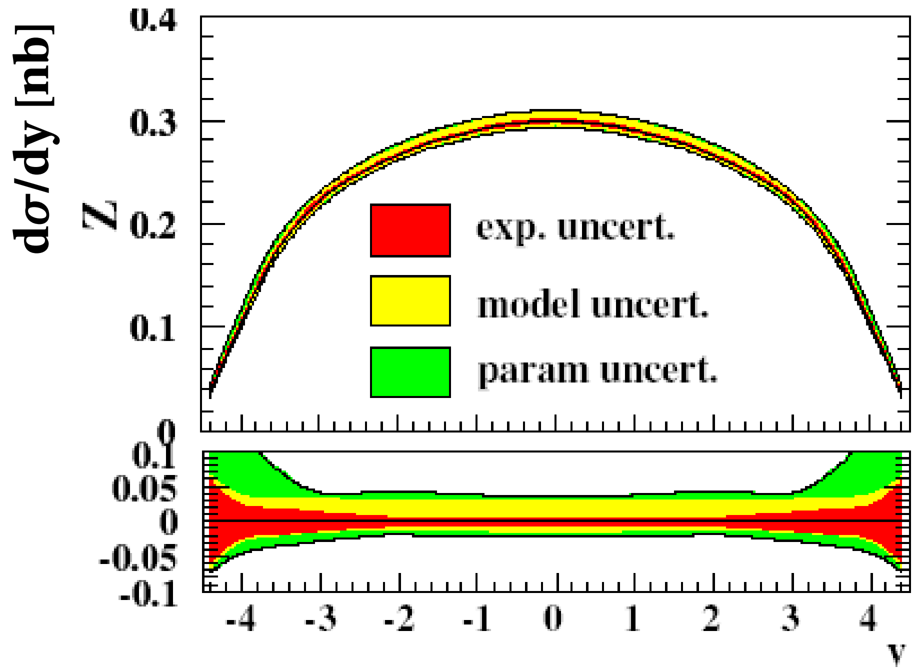
HERAPDF1.0 at Q^2 = 10'000 GeV^2



W and Z with HERAPDF1.0

LHC at 14 TeV





4% precision in the mid rapidity range.
Expect improvements at large y (high x) from HERA II.

HERAPDF future developments

- Combine all H1 and ZEUS DIS measurements from HERA I and II.
- Include combined charm and beauty data.
- Perform QCD fit in NNLO.
- Use latest theory developments in heavy quark treatment.
- Include jet data to disentangle α_S and the gluon density.
- Further study the parametrization uncertainty.
- In time for the 14 TeV LHC run...

Summary

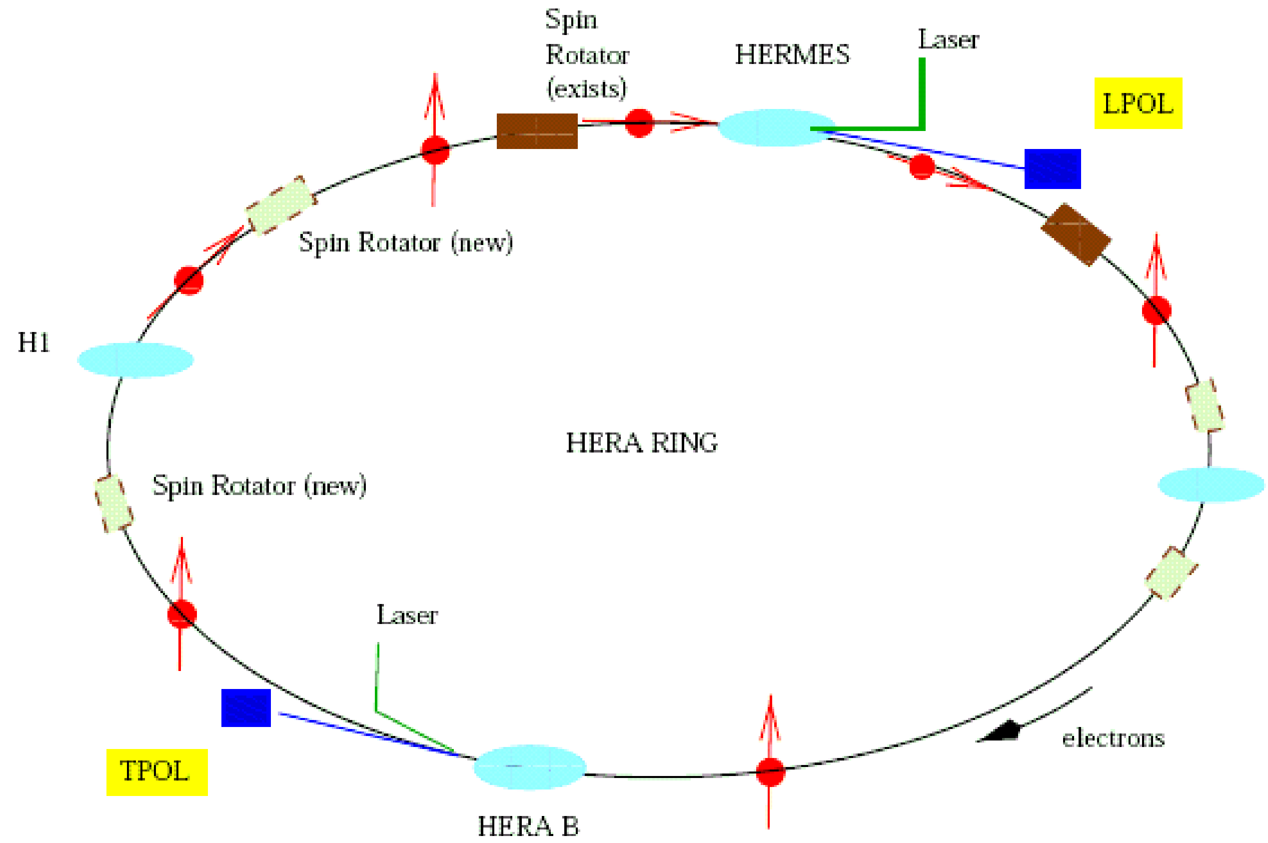
- H1 and ZEUS each collected 0.5 fb^{-1} of high quality data with precision detectors in 15 years of HERA operation.
- Combined cross section measurements reach 1% precision.
- QCD evolution equations describe the Q^2 dependence well.
- Gluon-induced processes like F_L, heavy flavors, and jets are also well described by QCD.
- HERAPDF1.0 has been published, with error bands. It can be used for a precise understanding of physics at the LHC.
- Further analyses of the full HERA data are underway, with the aim of extending the range of precision QCD tests and parton determinations.

Backup

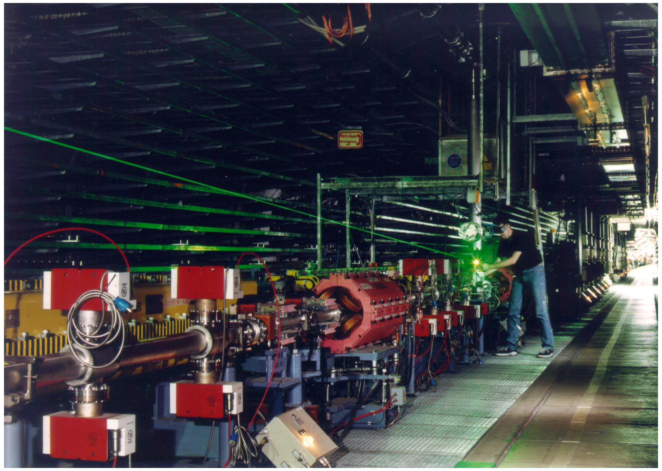
Polarized e$^{\pm}$

e beam acquires transverse polarization by the Sokolov-Ternov effect (magnetic moment couples to the dipole B field, spin flip by synchrotron radiation emission).

Spin rotators provide longitudinal polarization at the experiments (Hermes since 1995, H1 and ZEUS since 2003).

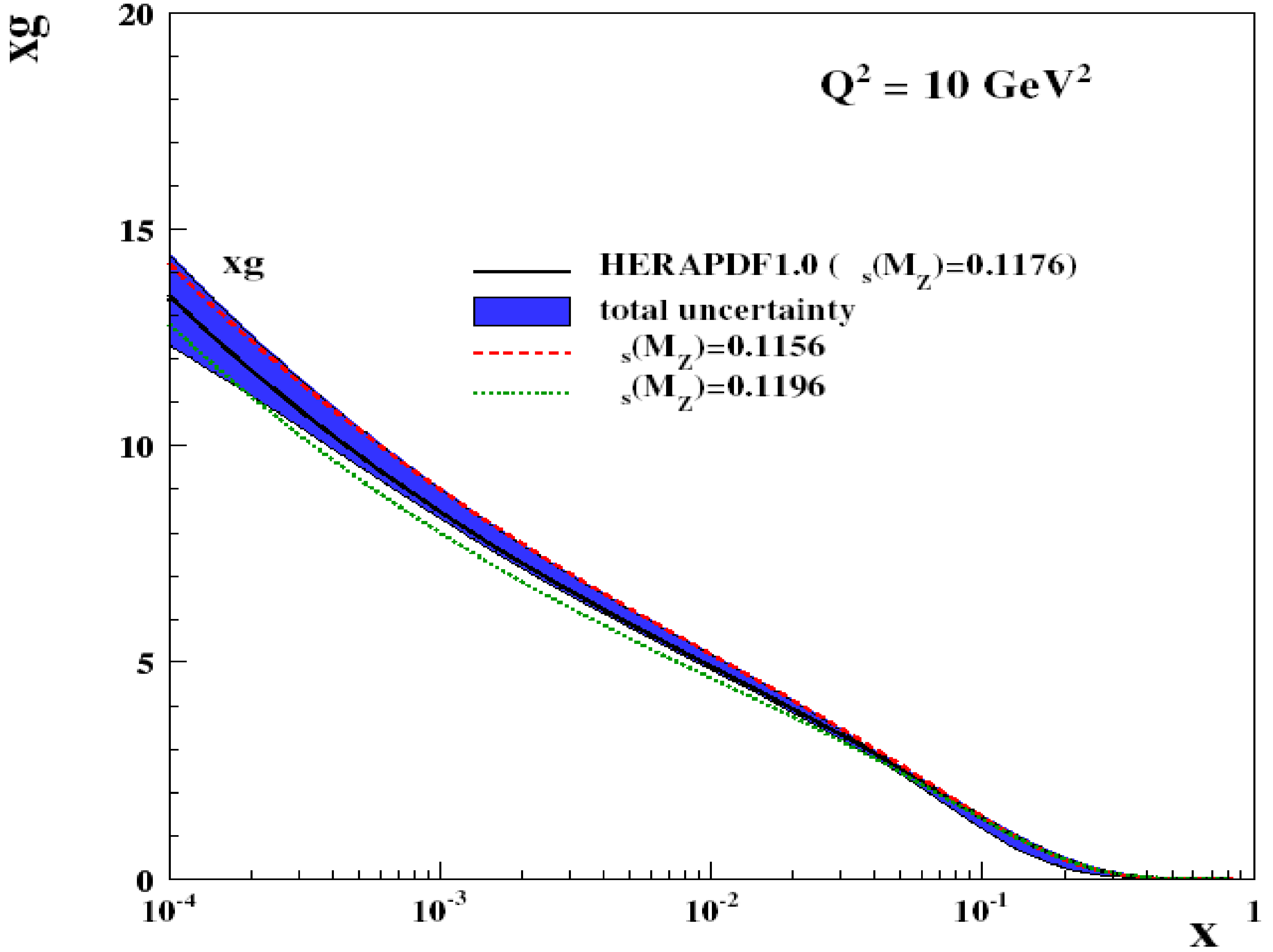


- Polarization typically 30-40%.
- Polarization monitored by Compton backscattering of laser beams.

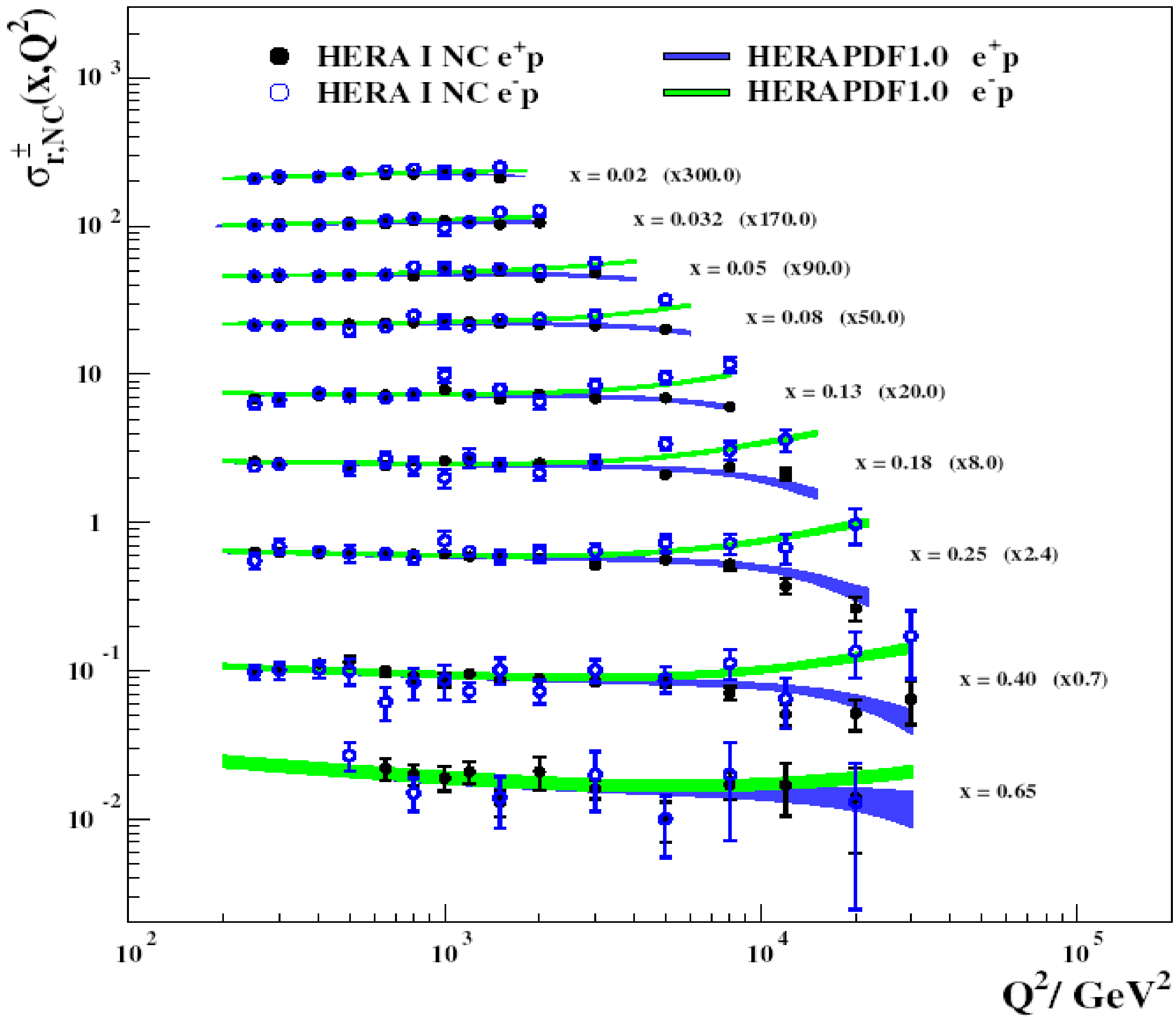


HERAPDF1.0

$\alpha_S(M_Z)$ variation and gluon density



HERA I combined high Q^2 NC



Constructive
and
destructive
γ-Z interference
at high Q^2.