HERA Experience
Physics Aspects

- **DIS in collider mode:**
  Accelerator and Experiments
- **HERA success story:**
  Precision cross sections, structure functions and parton densities
- **HERA outlook:**
  What's still in the queue?
- **Open Issues**

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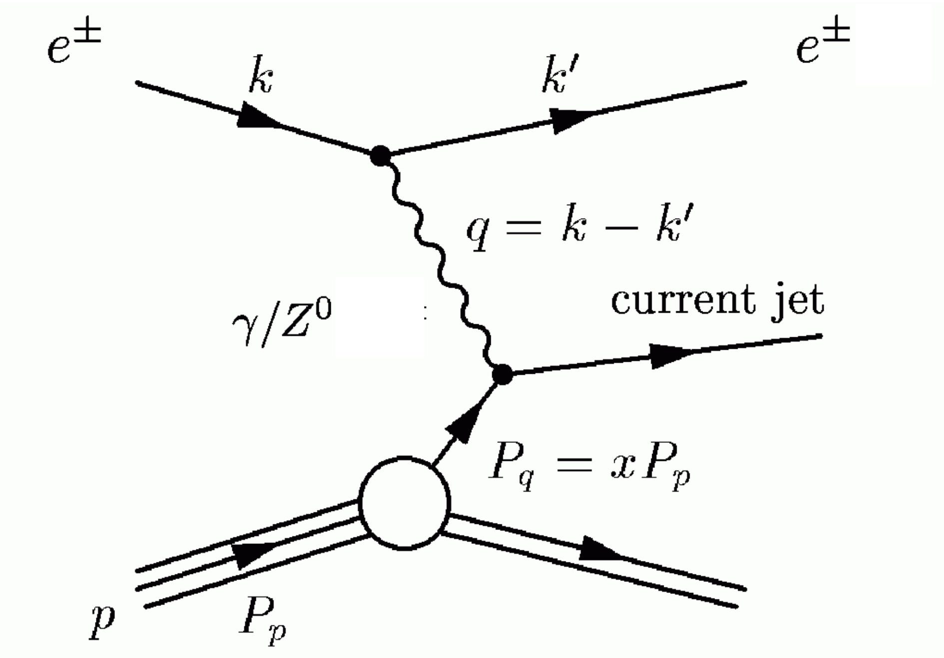
Deep Inelastic Scattering



Kinematic Variables

- 4-momentum transfer resolving power
  $$Q^2 = -q^2 = -(k - k')^2$$
- Bjørken scaling variable momentum fraction of struck parton
  $$x = \frac{Q^2}{2p \cdot q}$$
- Inelasticity: $y = \dfrac{p \cdot q}{p \cdot k}$

Center of mass energy $\sqrt{s}$: $s = (k + p)^2$ relation for fixed s: $Q^2 = sxy$

- **Neutral current DIS cross section expressed by structure functions:**

$$\frac{d^2\sigma^{e^\pm p \to e^\pm X}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1 + (1-y)^2\right)}_{Y_\pm = 1 \pm (1-y)^2} \cdot \left(F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} xF_3(x,Q^2) \right)$$

valence & sea quarks (F_2) — gluons (F_L) — valence quarks (xF_3)

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Mapping the Kinematic Plane

- large reach in x
- large reach in Q^2

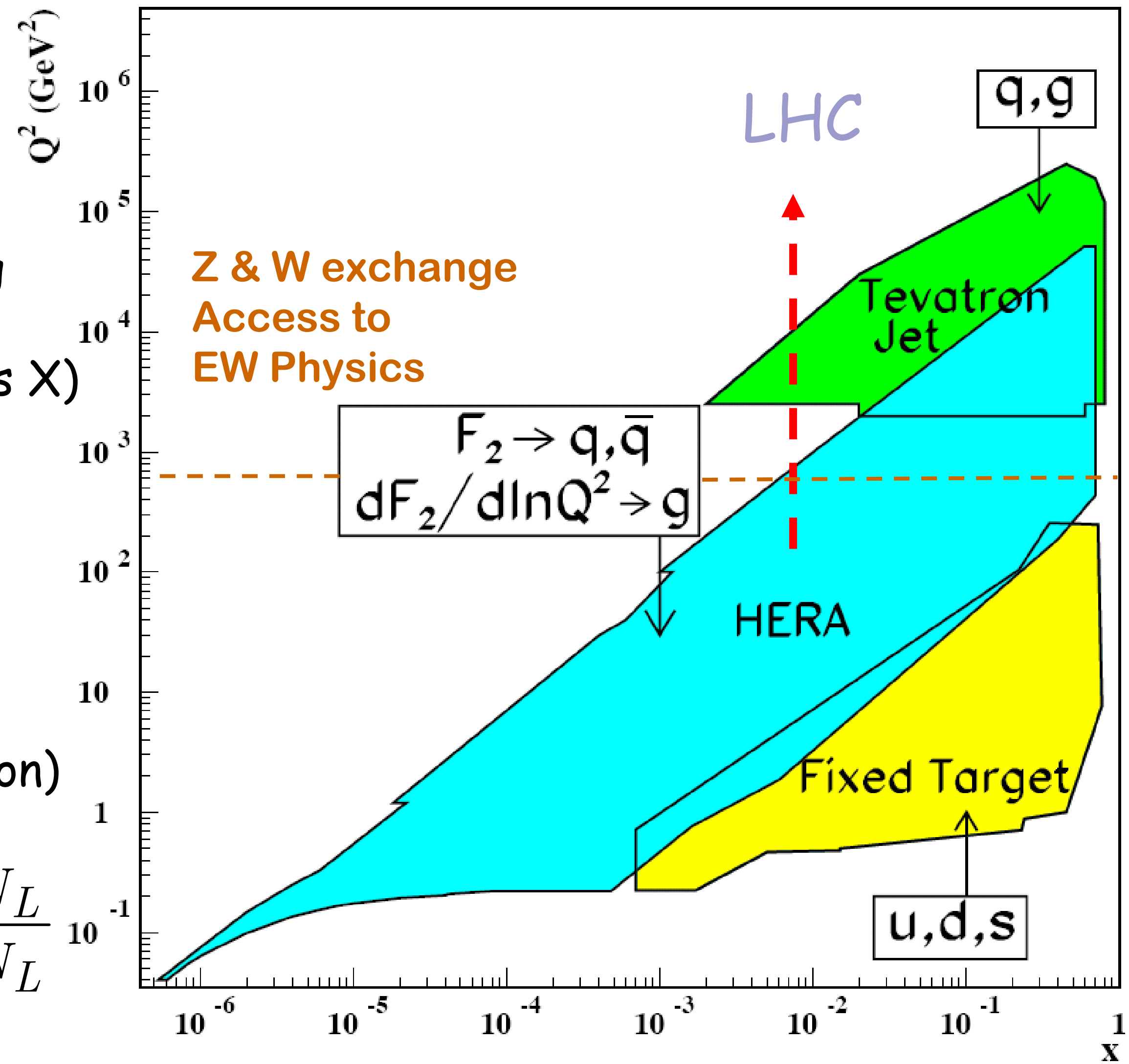
"Inclusive" scattering (integrate over all hadronic final states X)

→ pdf's of quarks from F_2

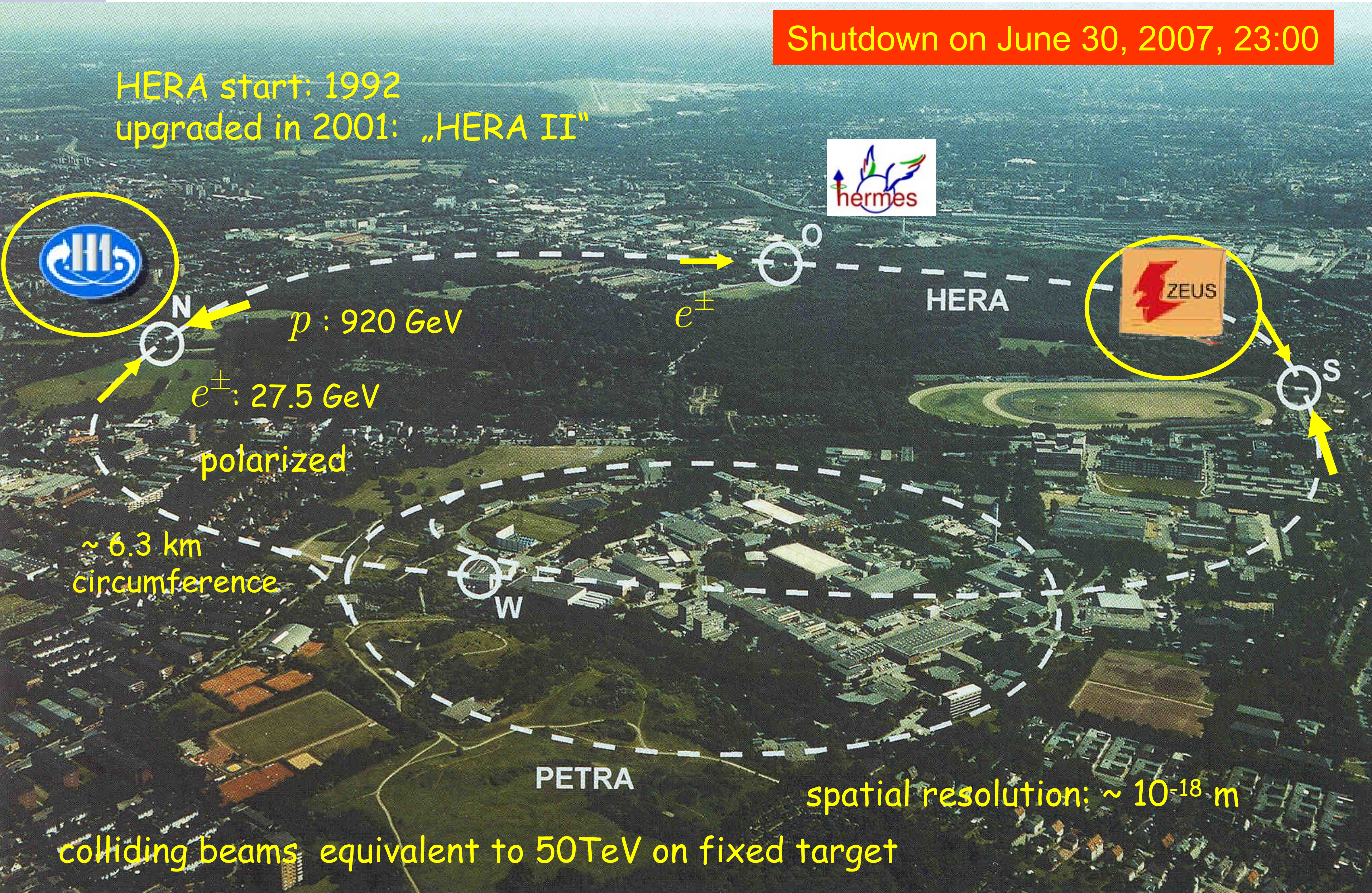
→ pdf of gluon from Q^2 variation of F_2 (e.g. DGLAP evolution)

HERA II: $P_e = \frac{N_R - N_L}{N_R + N_L}$

longitudinal polarization



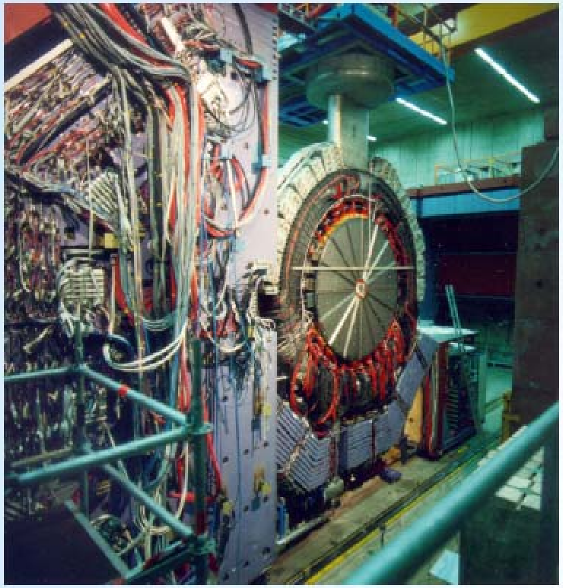
HERA – the world's largest electron microscope
(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)

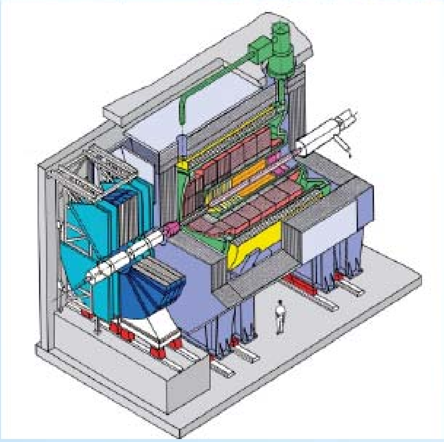


Collider Experiments at HERA

H1

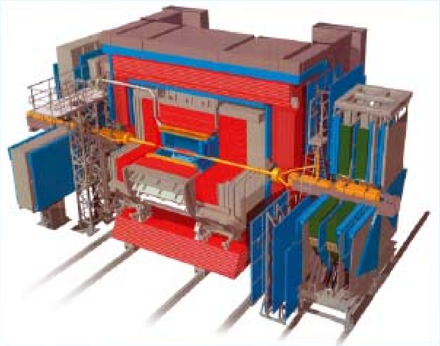
went for LAr





ZEUS

went for compen-sation



A final salute to our experiments

How we like to remember H1 and ZEUS

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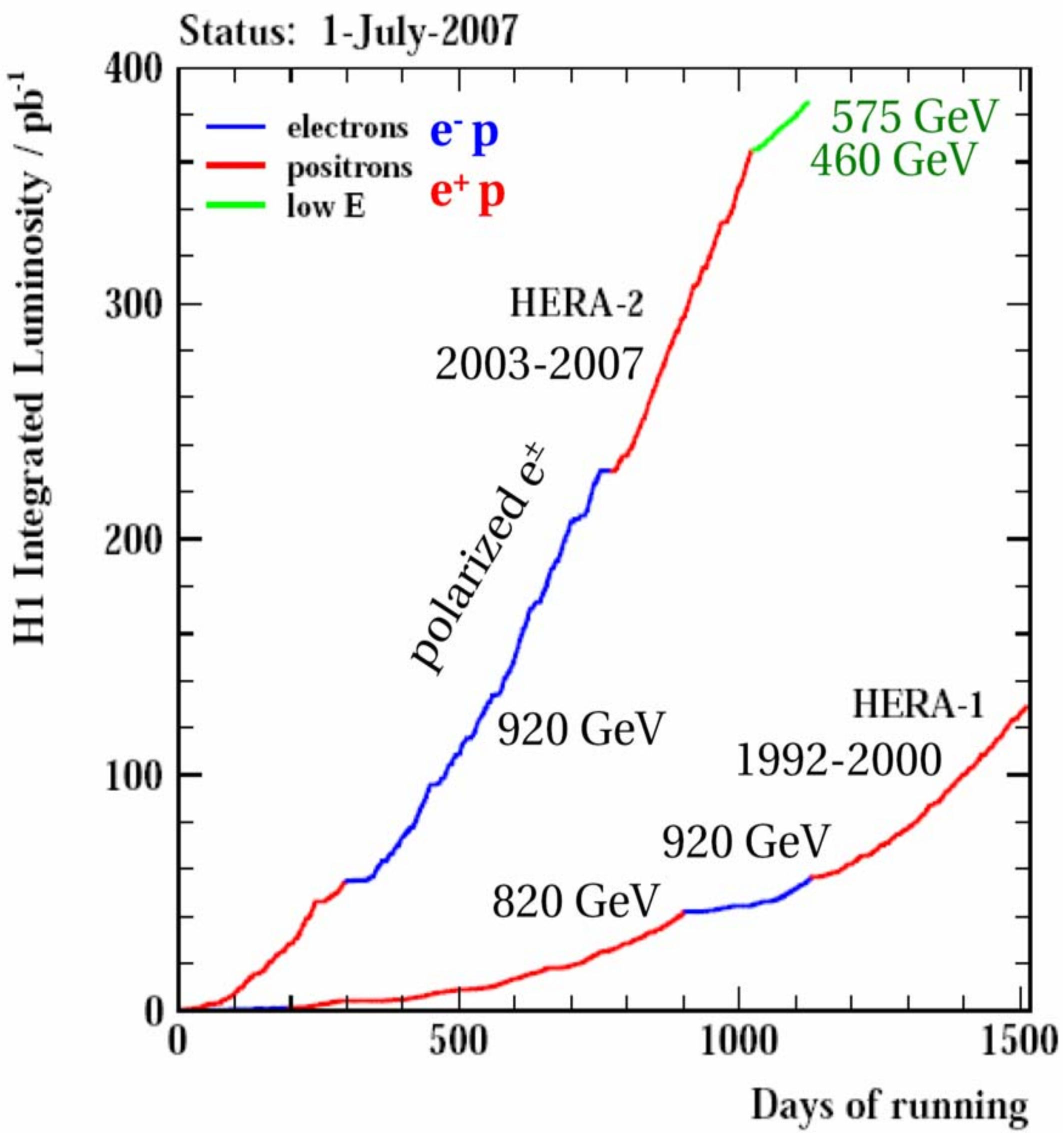
Hera Luminosity



HERA I: 1992-2000

HERA II upgrade:

- luminosity
- longitudinal polarization of the lepton beams (spin rotator pairs around the interaction regions)
- massive upgardes also for the detectors
- running efficiently from 2003 onwards
- Luminosity
  L = 500 pb^{-1} per exp.

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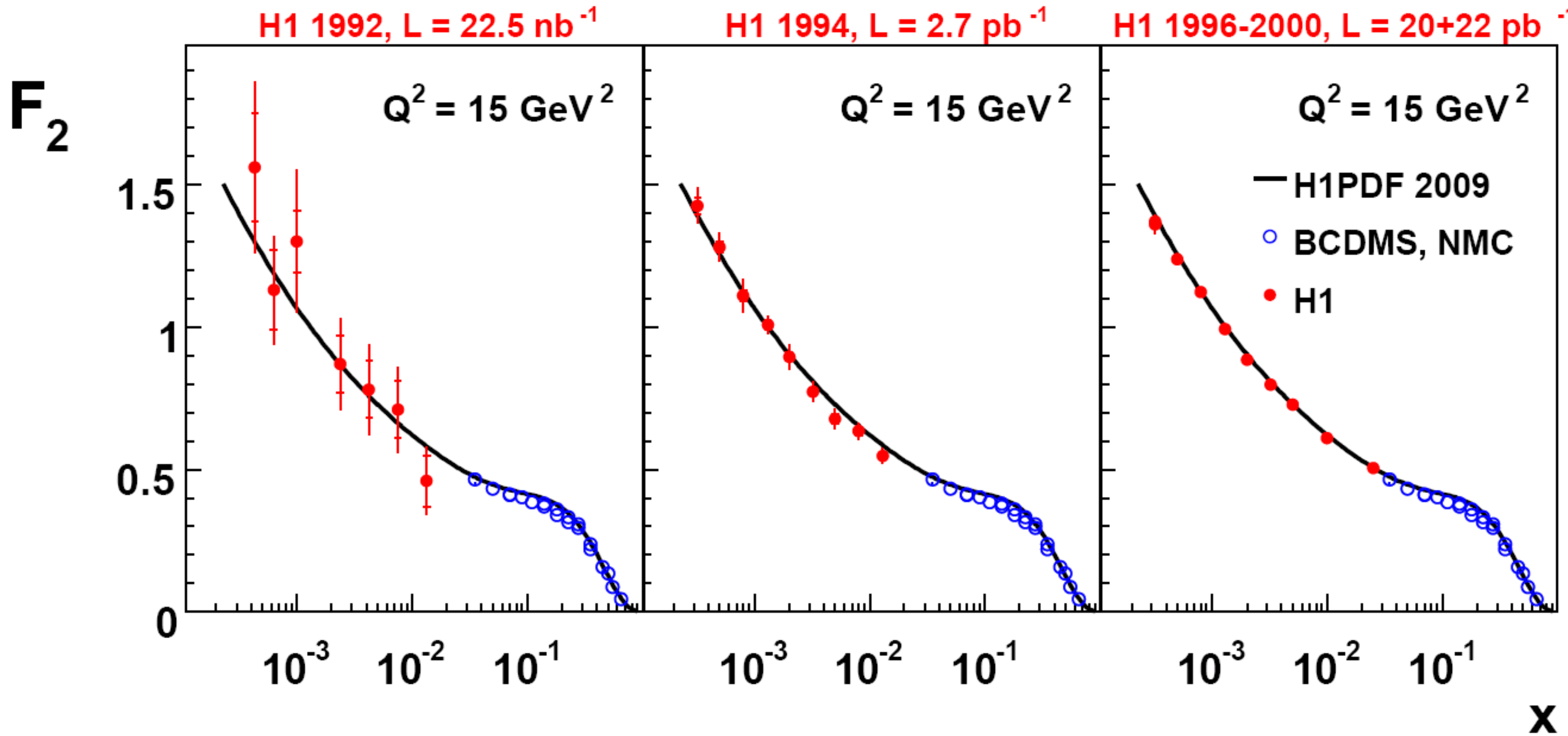
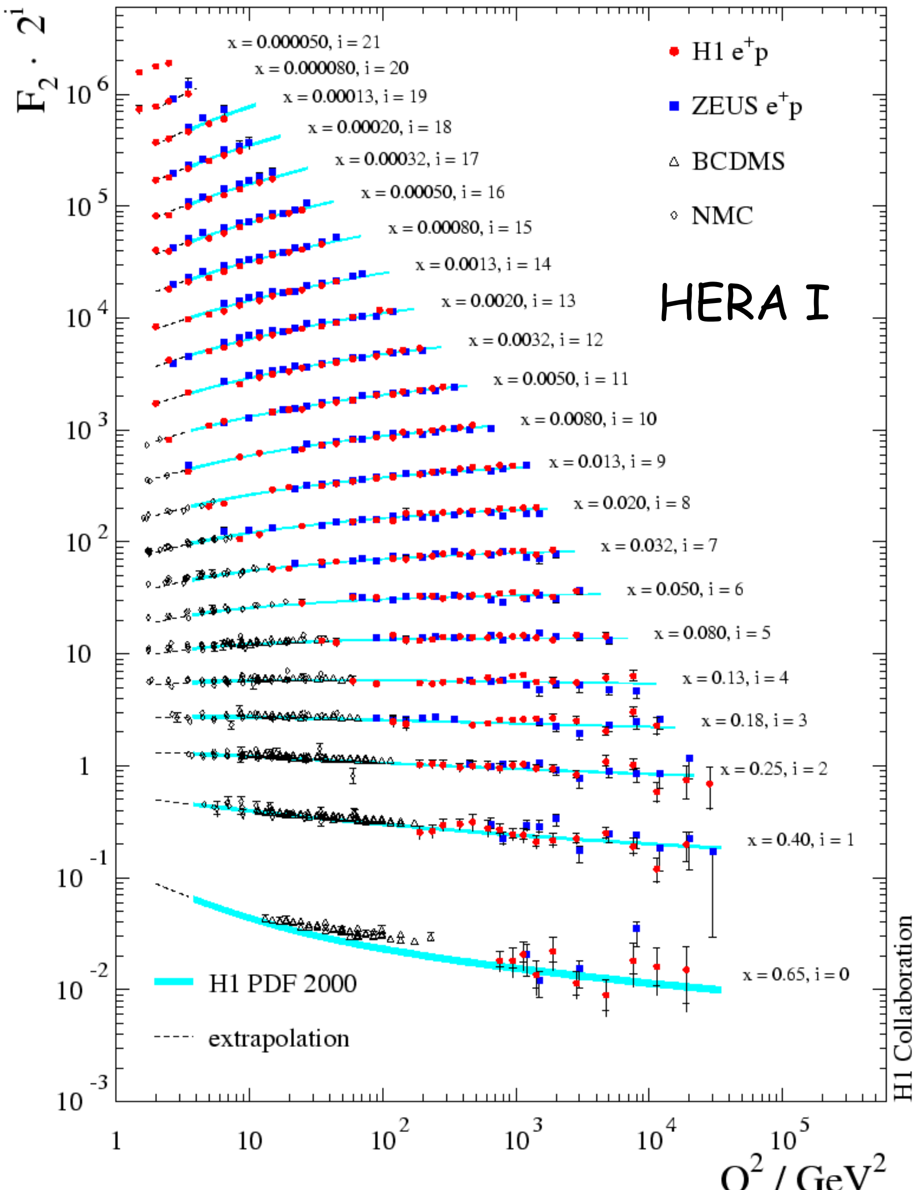
History of H1 F_2 Measurements

DIS 2009, Jan Kretzschmar, University of Liverpool – p.10

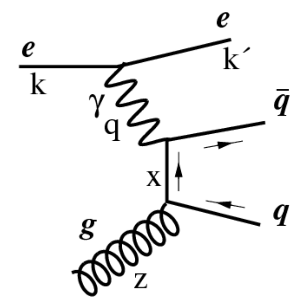


- Accuracies starting from 20 − 30%, reaching 4 − 6%, last publication using 1996/97 data 2 − 3%, and finally 1.3 − 2%

Structure Function F_2

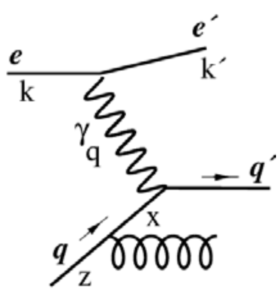


- H1 & ZEUS extended fixed target kinematic regime in x and Q^2 by 2 Orders
- Described by DGLAP
- Scaling violations



rise at low x

drop at high x



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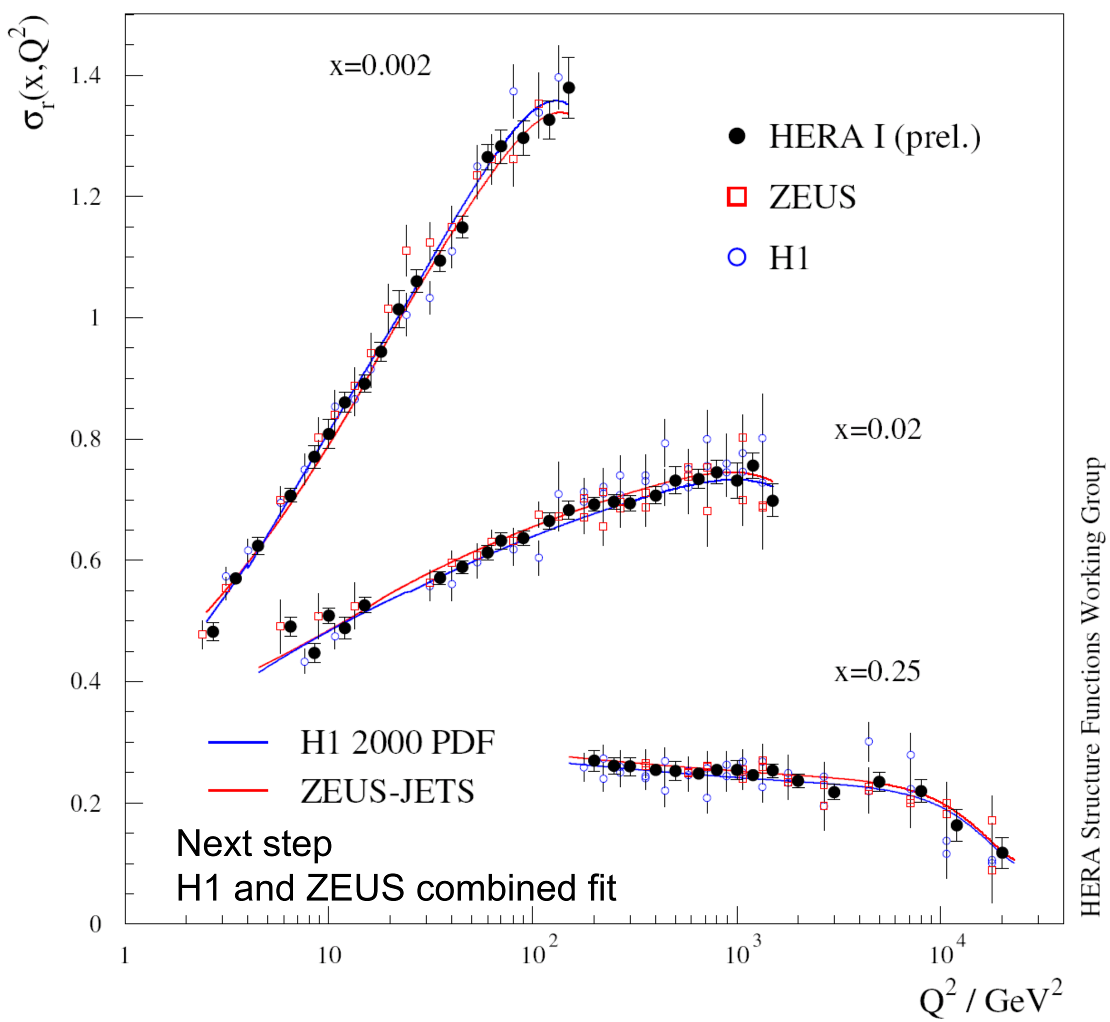
HERA Averaged NC cross sections

$$\sigma_r^{e^\pm p \to e^\pm X} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3$$

HERA I e⁺p Neutral Current Scattering - H1 and ZEUS



- Precise measurements from two experiments
- For $Q^2 \leq 100$ GeV²

  $\delta_{stat} \leq 1\%, \delta_{sys} \leq 3\%$

  for $Q^2 \geq 1000$ GeV²

  $\delta_{stat} > \delta_{sys}$

- Combine datasets from both experiments:

  Key assumption

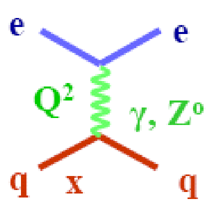
  H1 and ZEUS measure the same cross section at the same x, Q^2, y

- Improved precision of combined H1 and ZEUS datasets (stat and sys)

Input to HERA PDF Fits

- NC

$$\frac{d^2\sigma^{e^\pm p \to e^\pm X}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm = 1\pm(1-y)^2}\cdot\left(\tilde{F}_2(x,Q^2) - \frac{y^2}{Y_+}\tilde{F}_L(x,Q^2) \mp \frac{Y_-}{Y_+}x\tilde{F}_3(x,Q^2)\right)$$

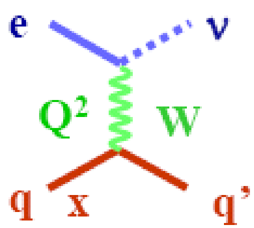


$$\tilde{F}_2 = \sum_i A_i(Q^2)\left[xq_i + x\bar{q}_i\right] \Rightarrow F_2^{em} = \frac{4}{9}x\left(u+\bar{u}+c+\bar{c}\right) + \frac{1}{9}x\left(d+\bar{d}+s+\bar{s}\right)$$

$$x\tilde{F}_3 = \sum_i B_i(Q^2)\left[xq_i - x\bar{q}_i\right] \Rightarrow xF_3 = B_U x\left(u-\bar{u}+c-\bar{c}\right) + B_D x\left(d-\bar{d}+s-\bar{s}\right)$$

Electroweak Coefficient Functions $A_i(Q^2)$, $B_i(Q^2)$ (QED: $A_i = e_i^2$)

- CC



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

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

PDF general form: $xPDF = Ax^B(1-x)^C \cdot (1+Dx+\ldots)$

Parameterize: g, u_v, d_v, $\bar{U}(=\bar{u}+\bar{c})$, $\bar{D}(=\bar{d}+\bar{s})$

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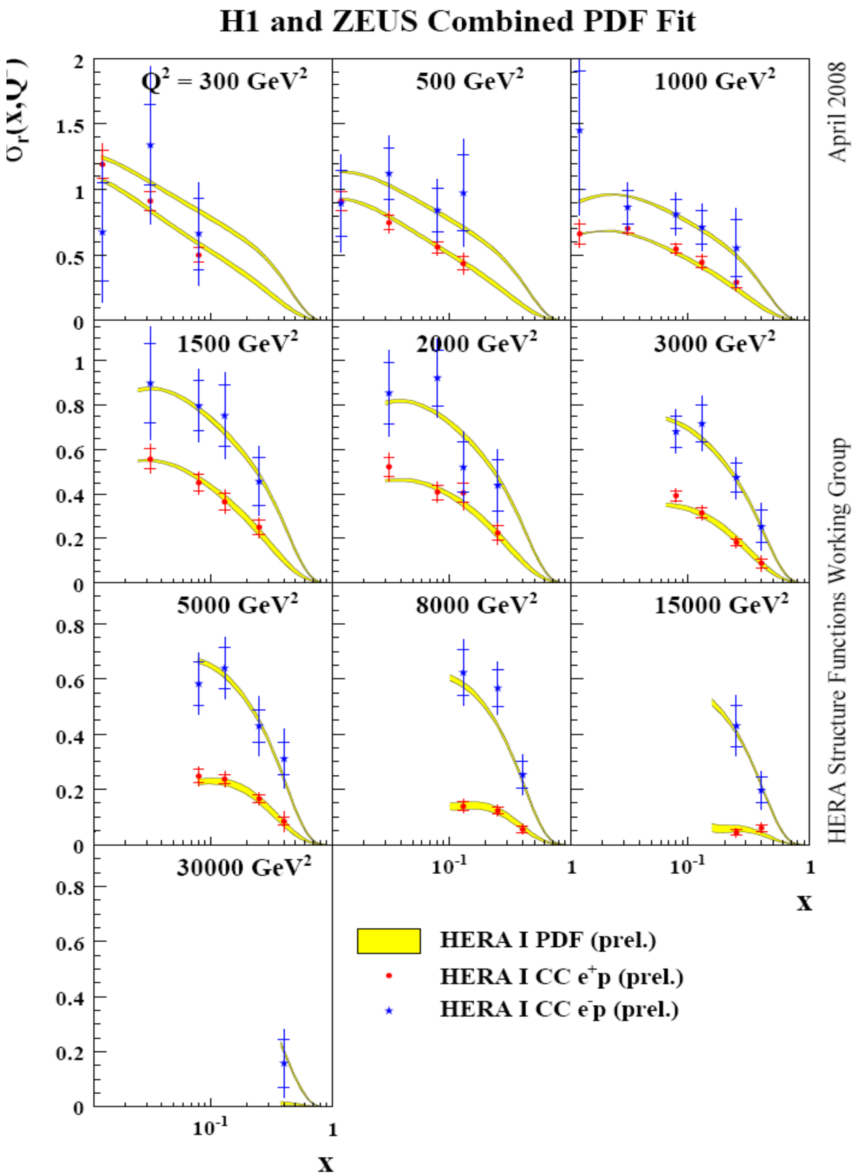
Charged Current Cross Section



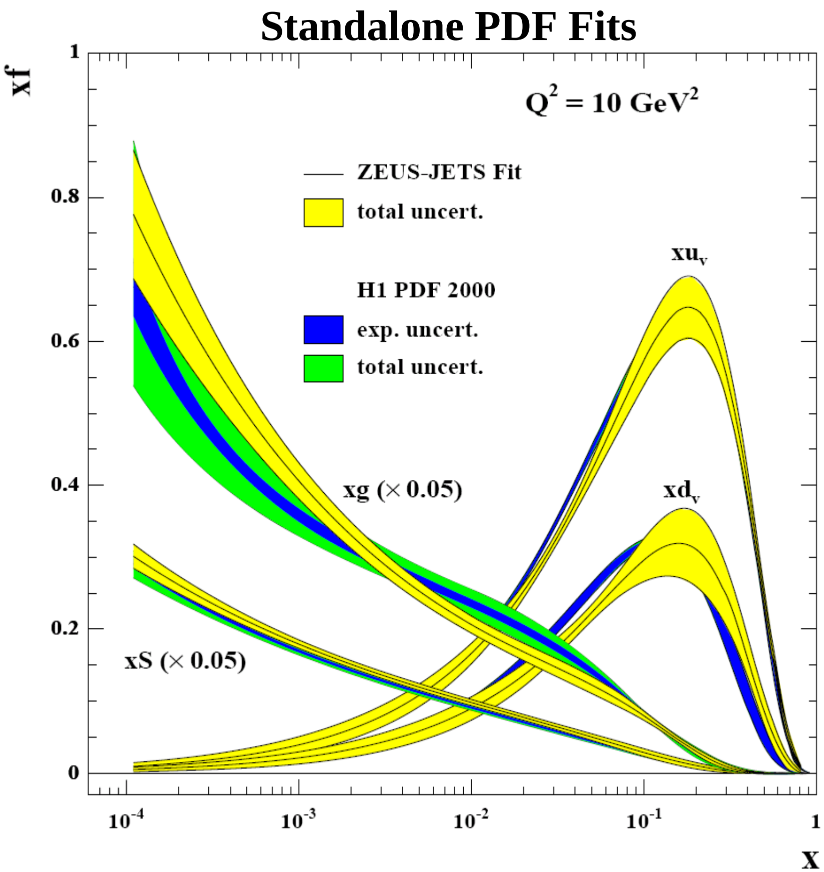
CC Cross section provide flavor sensible constrains at high x

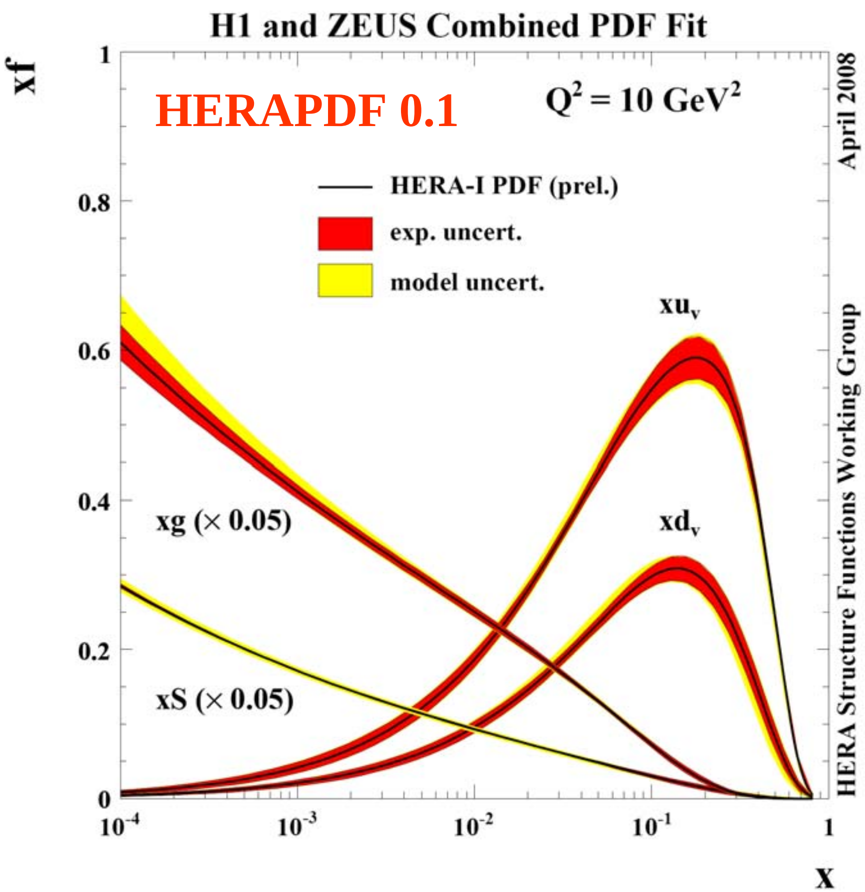
$$\sigma_{CC}(e^+ p) \propto x\left[(1-y^2)D+\bar{U}\right]$$

$$\sigma_{CC}(e^- p) \propto x\left[U+(1-y^2)\bar{D}\right]$$

Improved precision of σ_{CC} By combining H1 and ZEUS

PDF Fits on HERA I Data





Impressive reduction of uncertainties of combined PDFs

Model uncertainty: variation of charm and bottom mass, starting scale Q_0^2, Q^2_{min} of included data, strange and charm fraction at starting scale

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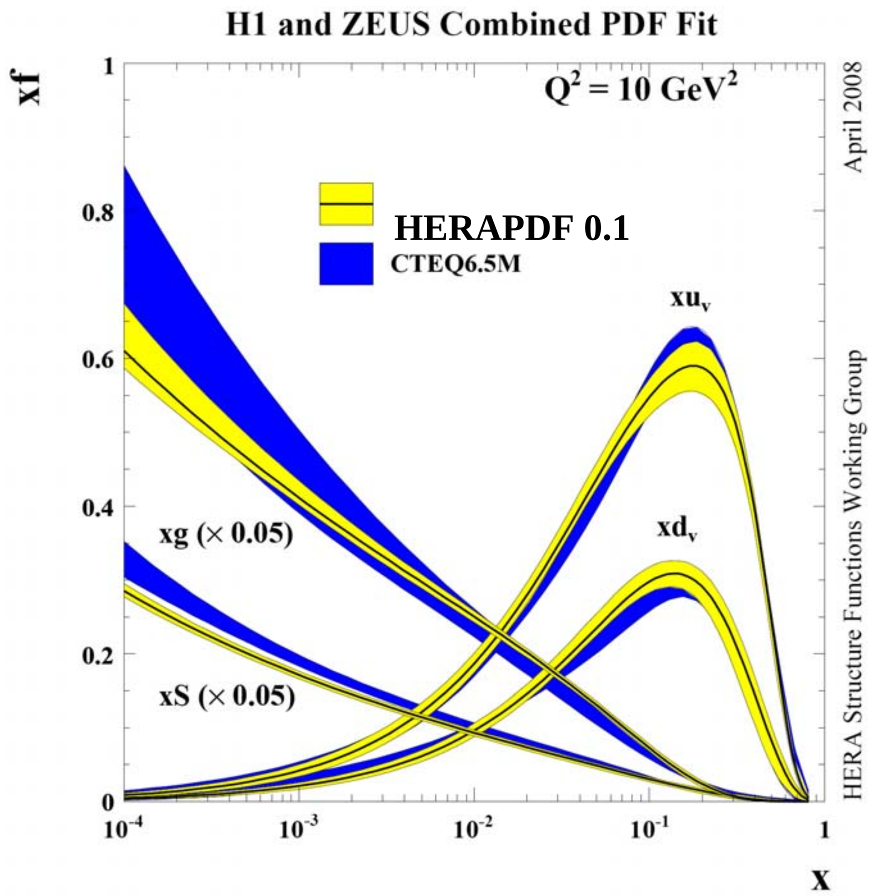
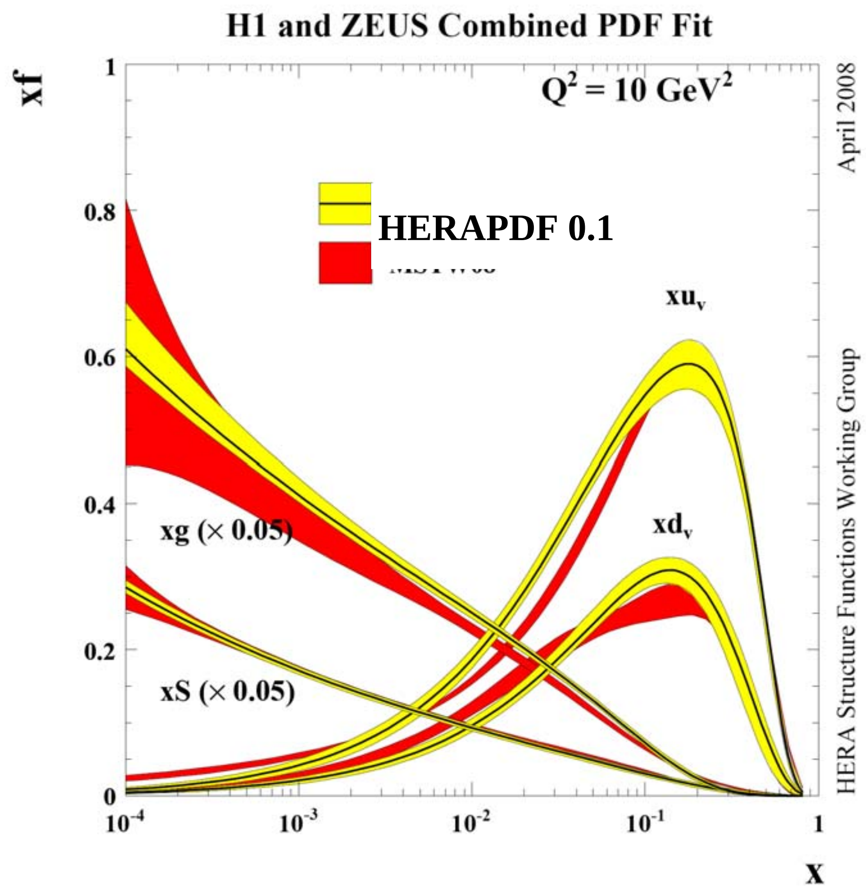
Comparison to Global Fits





not a completely fair comparison:
HERA combined data were not available to global fitters

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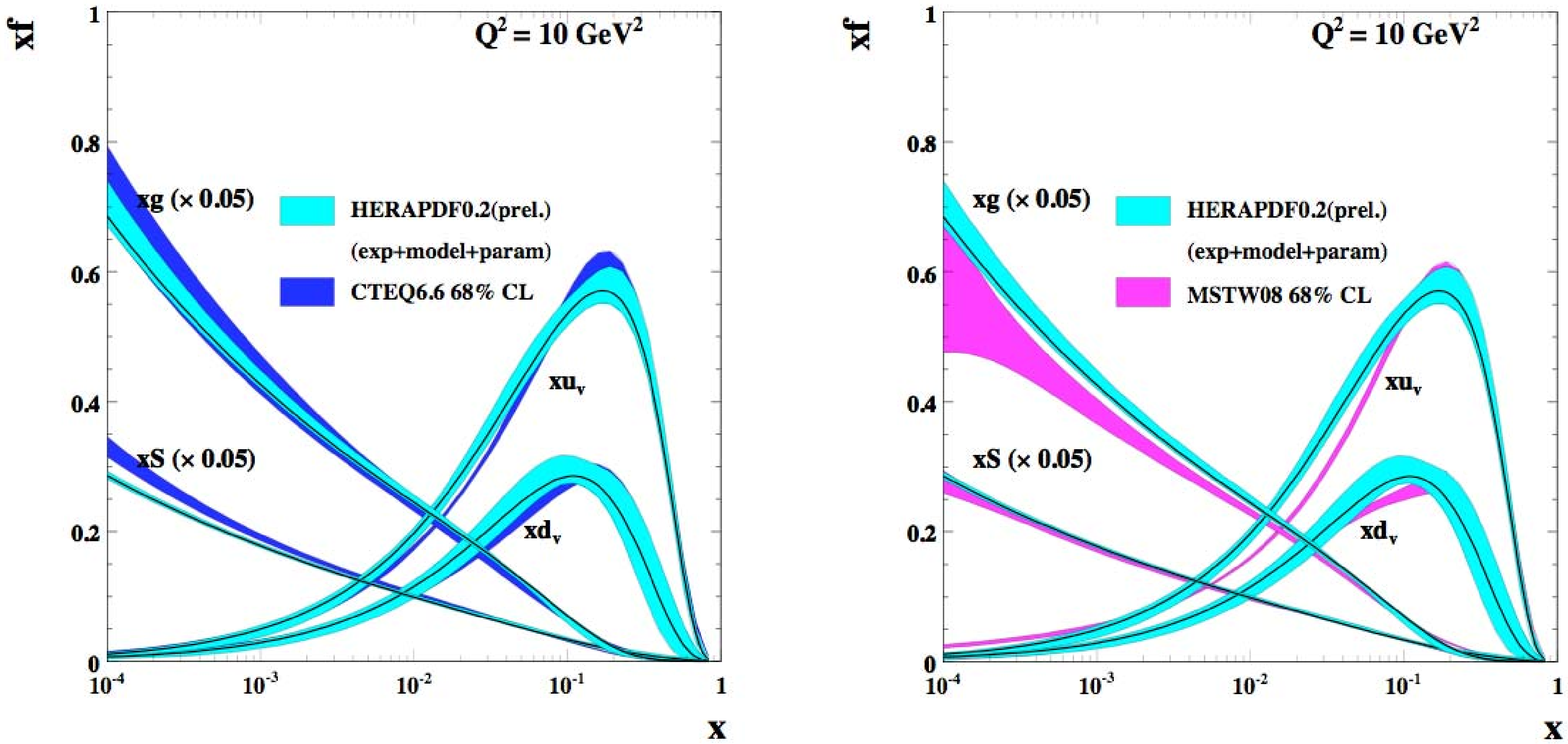
Comparison to Global Fits



not a completely fair comparison:
HERA combined data were not available to global fitters

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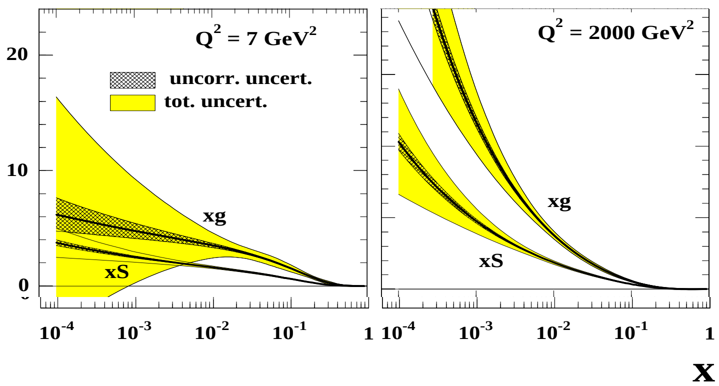
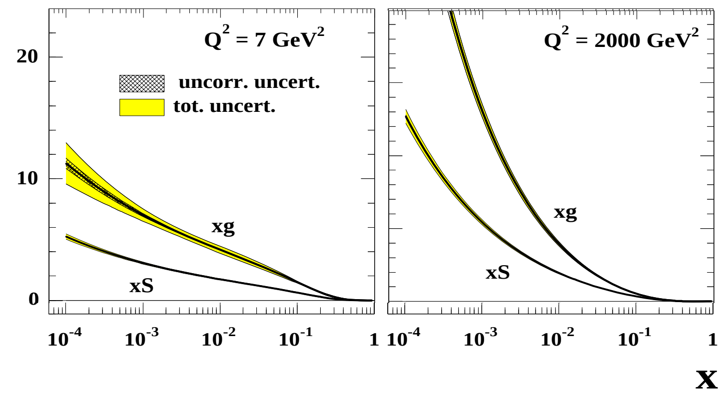
Impact of HERA data

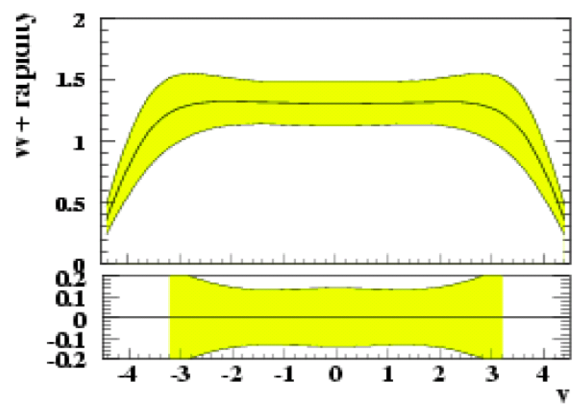
Pre-HERA uncert. in gluon/sea PDFs

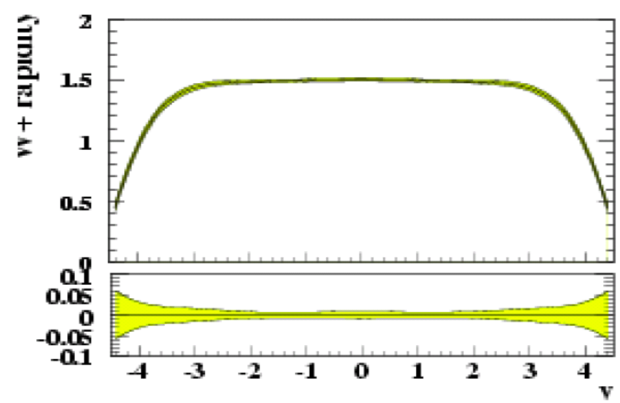


HERA PDFs combining H1 and ZEUS



Example: W^+ production at the LHC (Study by A. Cooper-Sakar)





Note: Error bands are experimental uncertainties only
model uncertainty will become increasingly important

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Future HERA PDF Fits

- So far only part (all) of the inclusive HERA I were used → HERAPDF0.1 (0.2)

→Incorporate all NC and CC from HERA I&II

→Include jet cross sections
→constrain high x gluon

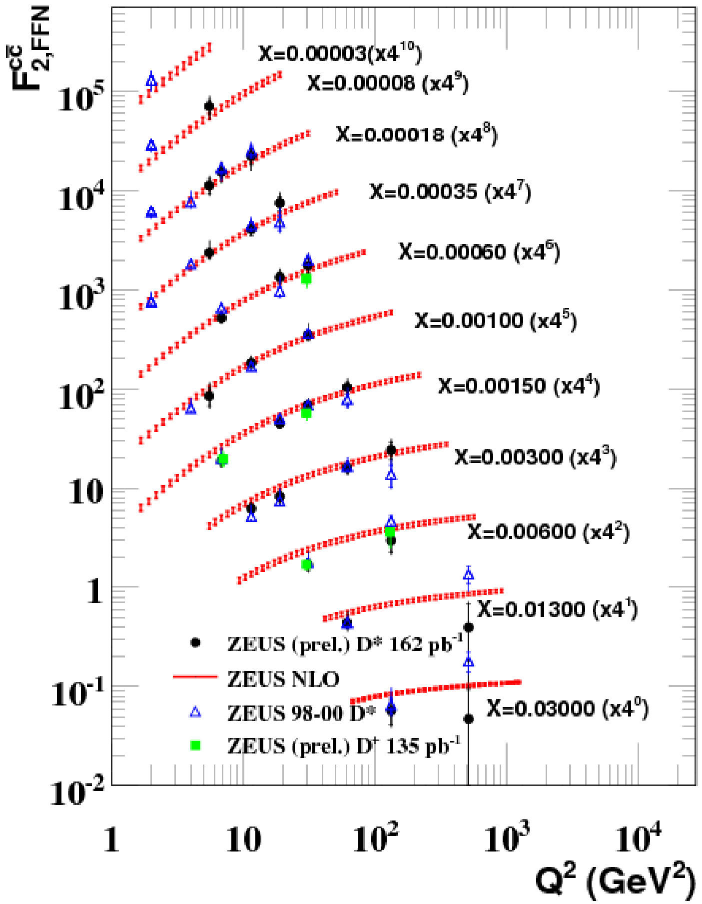
→Include charm and beauty
→ flavor decomposition of the sea

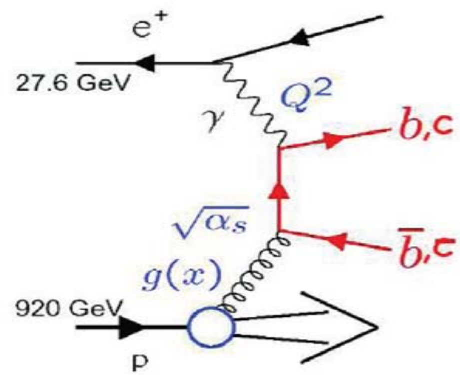
→Charged & Neutral current cross sections with polarized $e^{\pm}$ beams
→ constrain valence quark region

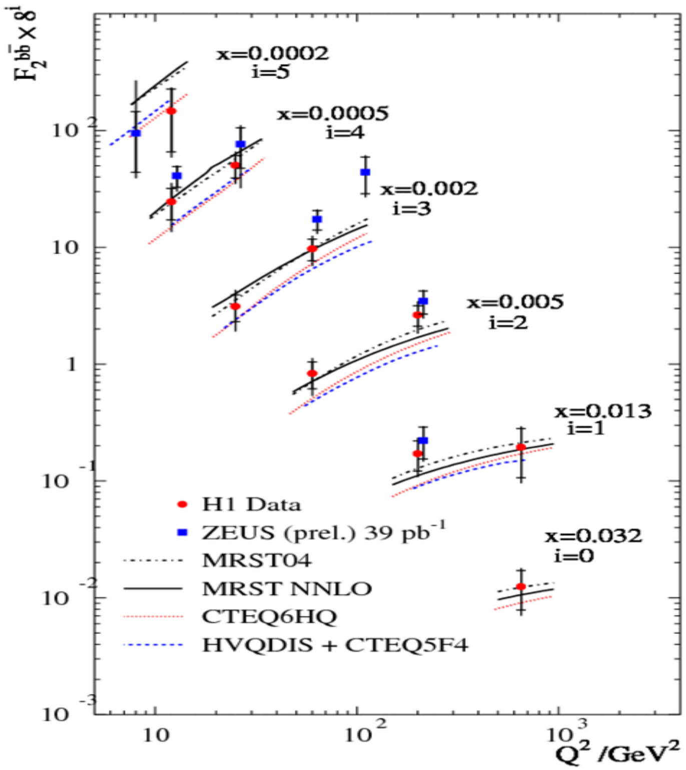
Charm & Beauty Structure

Charm and Beauty production in DIS is driven by gluons in the proton

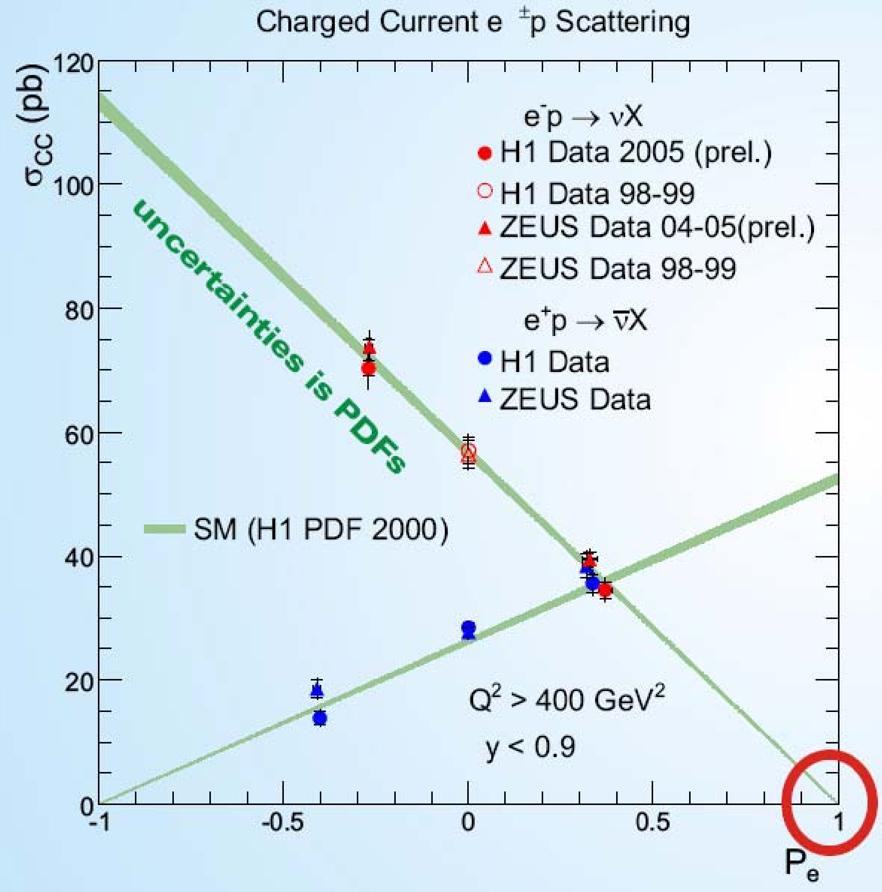
Charm tag: reconstruct D mesons
Beauty tag: displaced vertex, soft μ

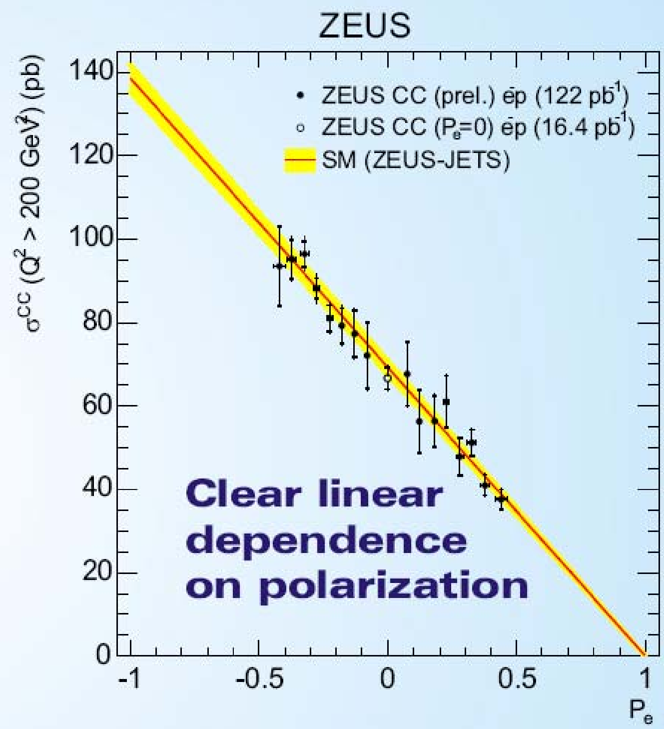






Polarization dependence of CC





Consistent with SM prediction
$\sigma(CC_{RH}) = 0$

Input to PDF fits: Double differential CC e±p cross sections

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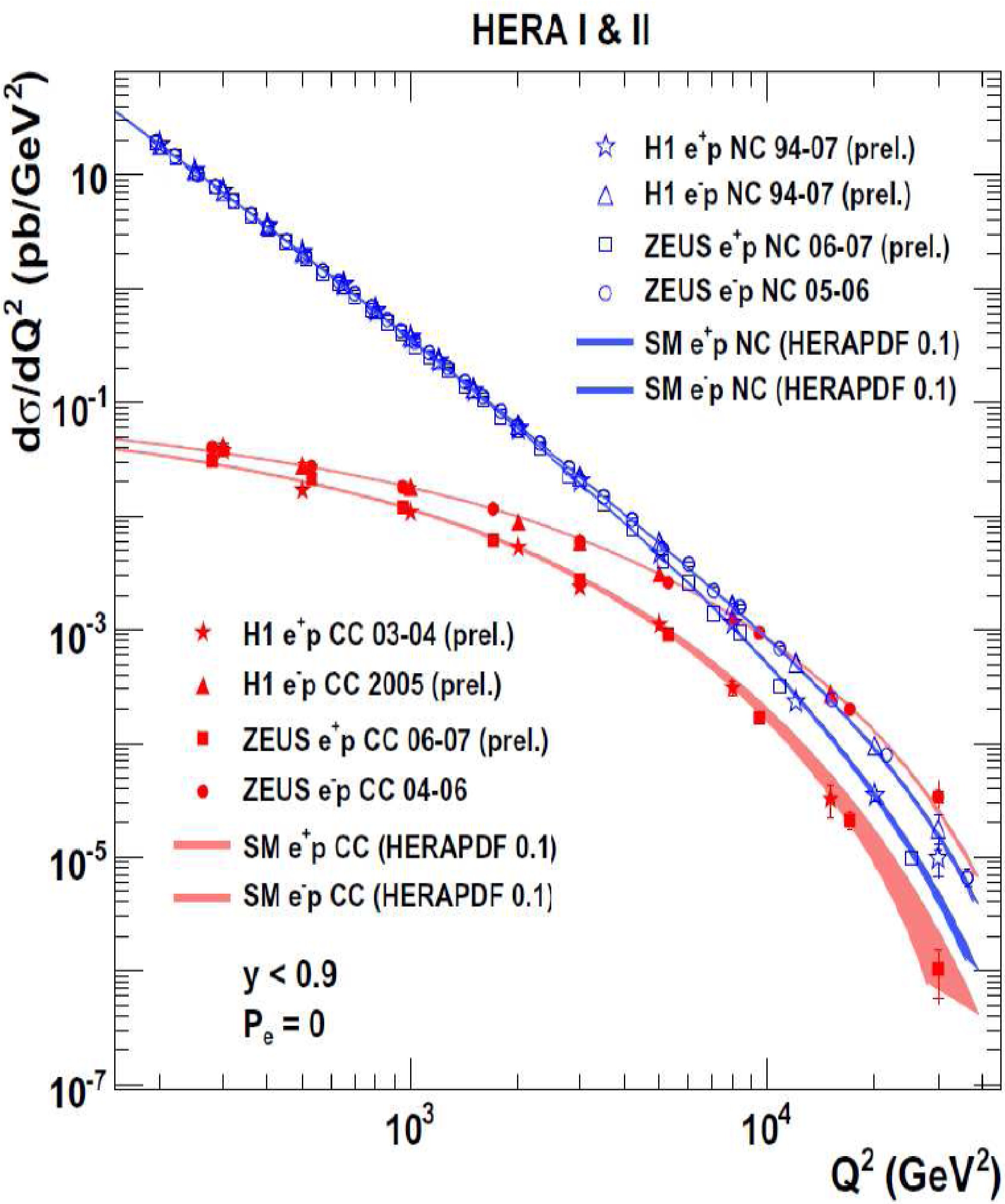
NC&CC

Manifestation of electroweak unification



More details on HERA EW physics → see backup

OPEN ISSUES

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Open Issues (I): high x

Inclusive cross sections at high x:

$$NC \quad e^{\pm}p:\sigma \propto \frac{4}{9}xu$$

$$CC \quad e^{-}p:\sigma \propto xu$$

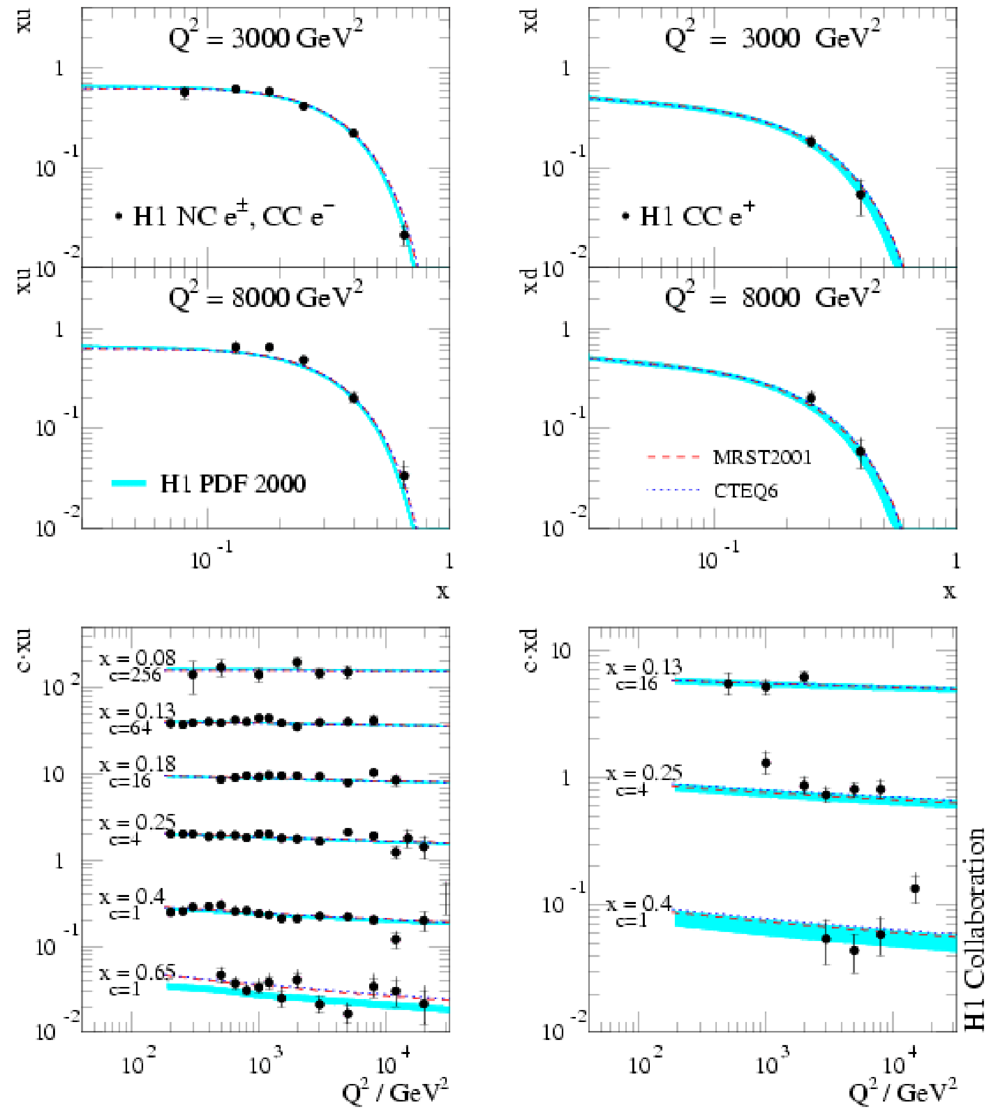
$$e^{+}p:\sigma \propto (1-y^{2})xd$$

Quark distributions can be extracted with minimal corrections from QCD fits

Reach in x limited by detector acceptance, hadronic final state goes down the proton beam line

u: x_{max} = 0.65

d: x_{max} = 0.4



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Open Issues(I): High x continued

Events at high x at acceptance limit

Poor resolution for x
→cannot measure differential σ at x,Q2 point

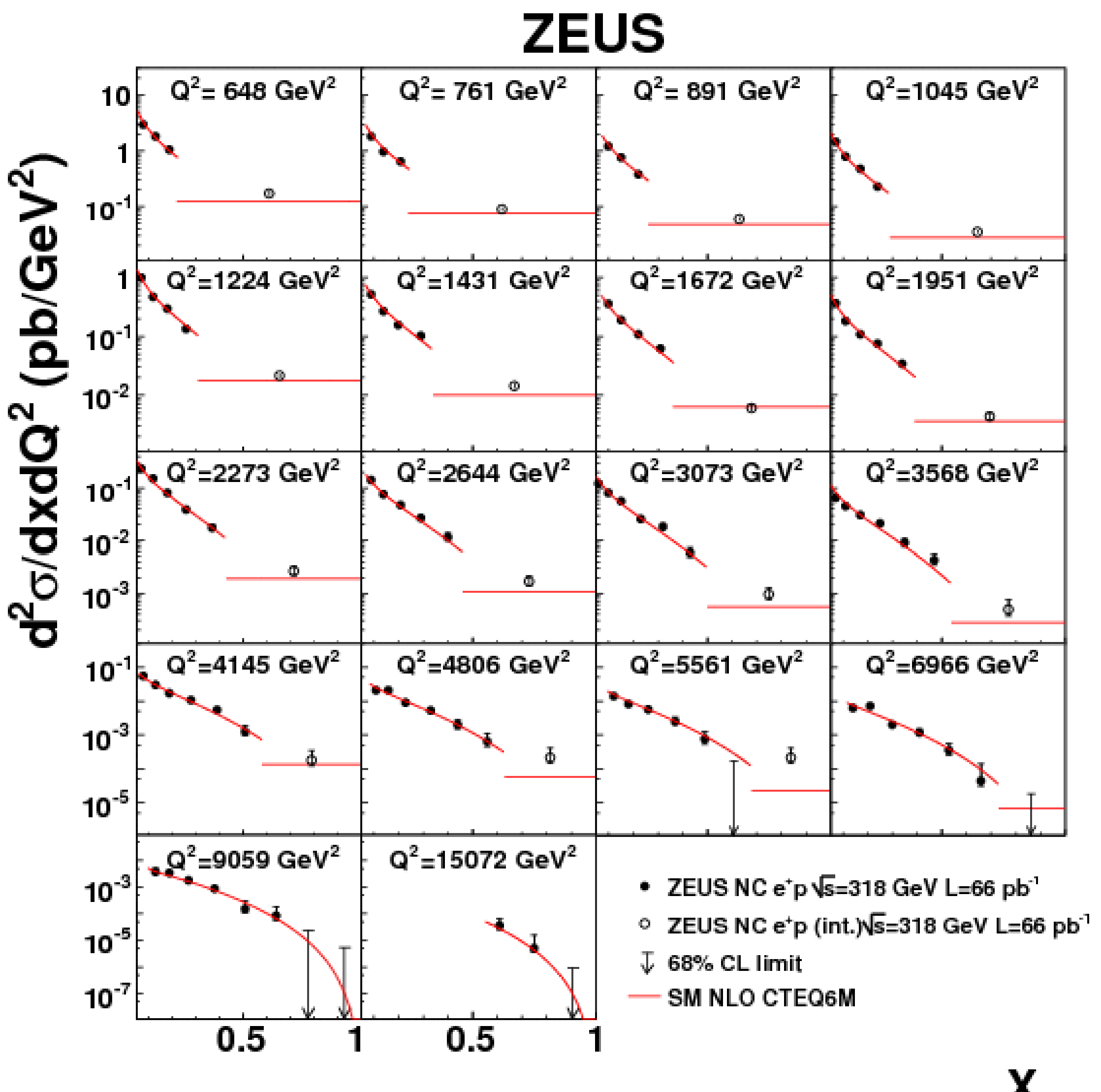
Measure integrated σ for x > x_{limit}

σ larger than expected

PDFs at high x

$$f \propto (1-x)^C \Rightarrow f \xrightarrow{x->1} 0$$

Constraint by shape
→ underestimated uncertainty?



Here HERA I e⁺p, e⁻p see backup

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Open Issues II:
Light flavor decomposition of the $q\bar{q}$ sea

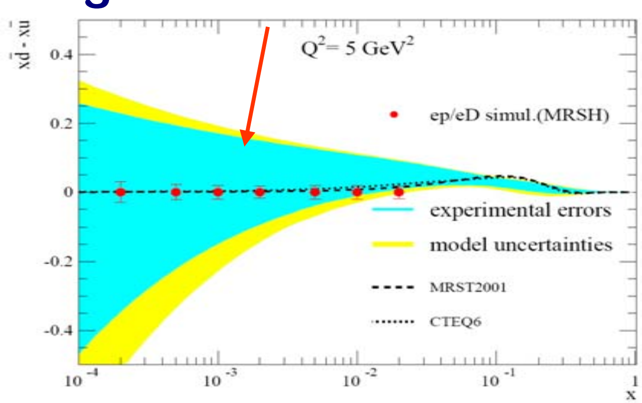
PDF fits conventionally assume

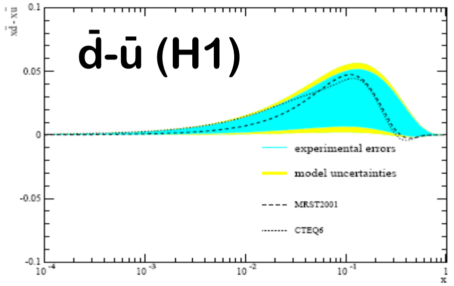
$$x\bar{d} - x\bar{u} \xrightarrow{x \to 0} 0$$

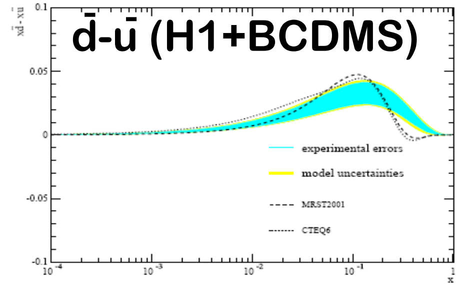
NMC found $\bar{d} \neq \bar{u}$ at medium x

Here is what happens when the $x\bar{d} - x\bar{u}$ constraint at low x is relaxed →

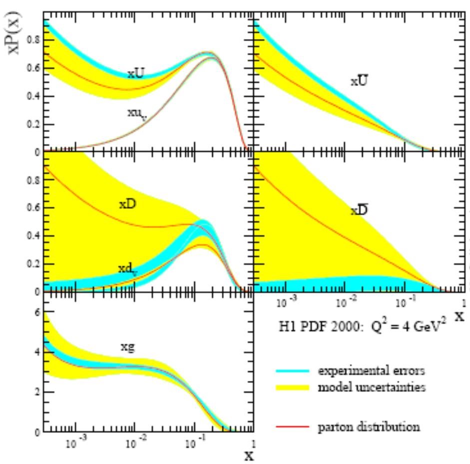
A deuteron run at HERA Could have disentangled the light flavor sea



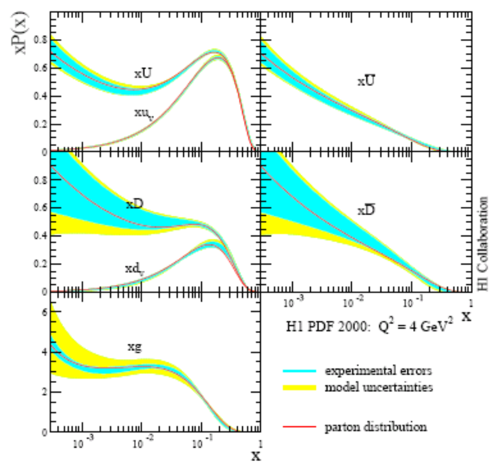




H1 only (HERA I)



H1 +BCDMS



Poorly constrained

Attempt to fit U and D Only one input: F_2 ep

Fit stabilized by fixed target data (sum rules help)

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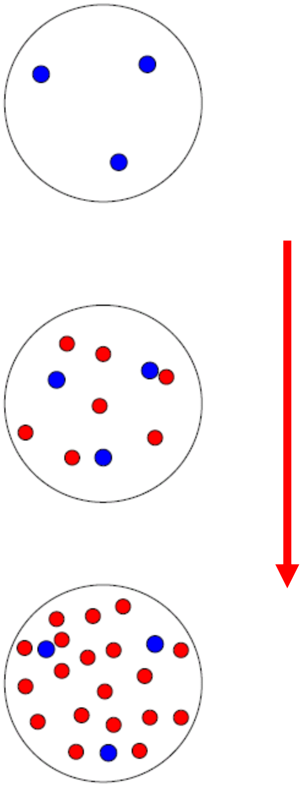
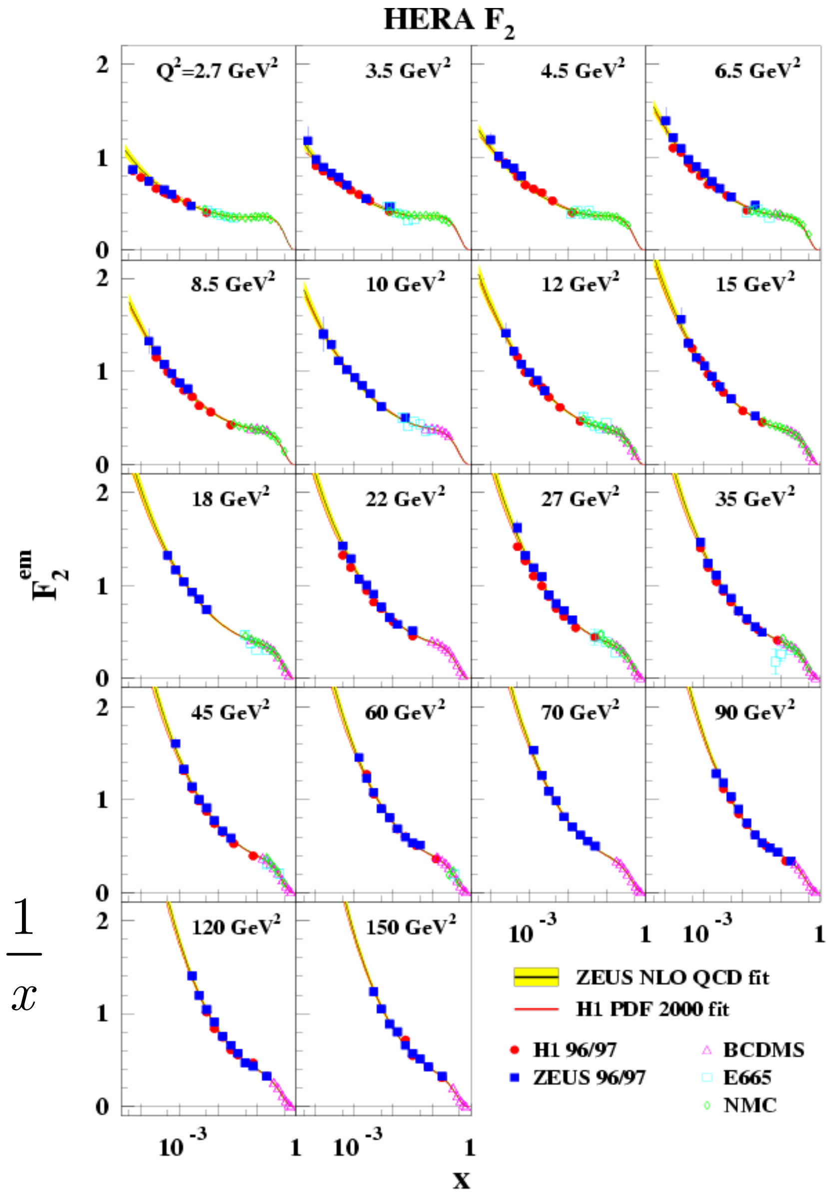
Low x, Large Parton Densities and Saturation



at fixed resolution scale (Q^2) go to very large hadronic center of mass energy

low x $$x = \frac{Q^2}{Q^2 + W^2}$$

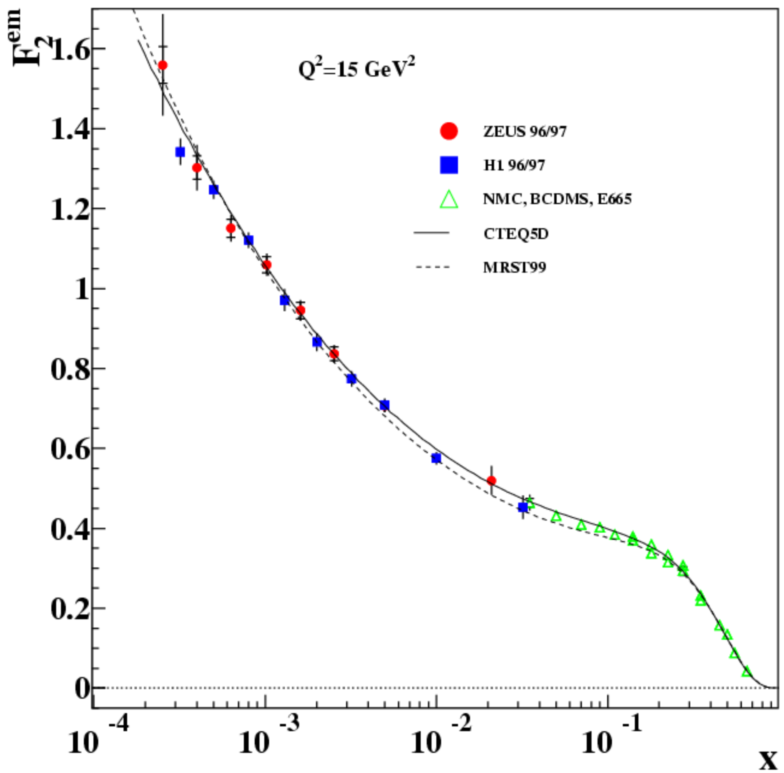
ultimately expect partons to overlap („saturation")

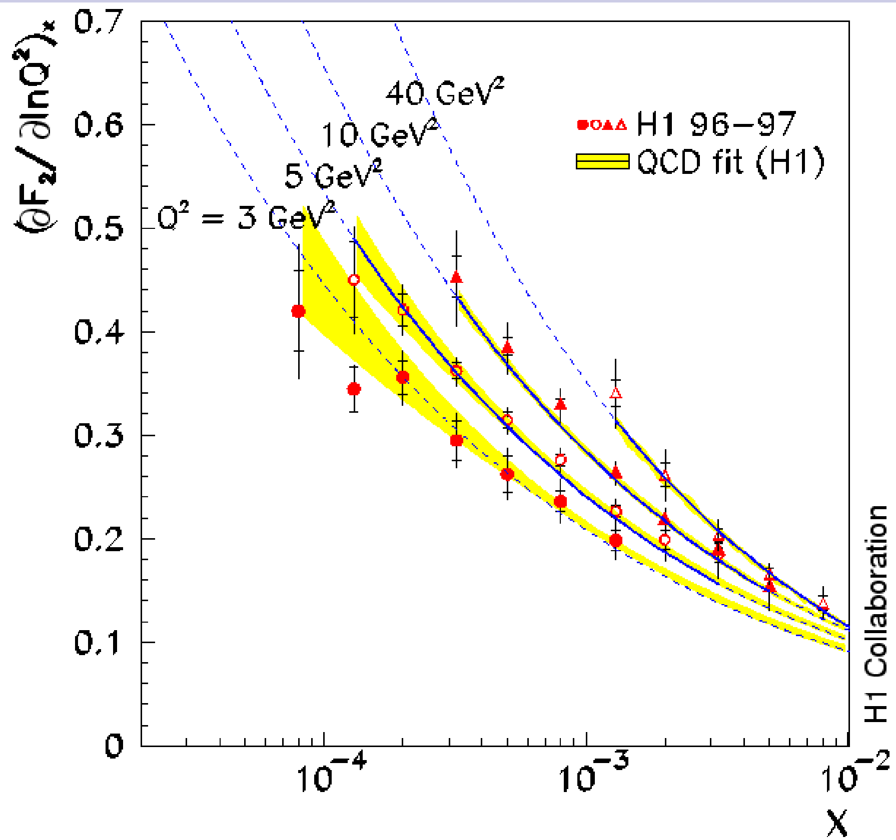


Rise of pdf should flatten with decreasing x $$\left(\frac{1}{x}\right)^{\lambda} \rightarrow \ln\frac{1}{x}$$

No saturation observed at HERA

The Birth of Experimental Low x Physics





- Biggest HERA discovery: strong increase of quark density (F_2) and gluon density ($d F_2 / d \ln Q^2$) with decreasing x in newly explored regime.
- Low x, `large' Q^2 is high density, low coupling limit of QCD …
- No saturation observed yet → probe at even smaller x

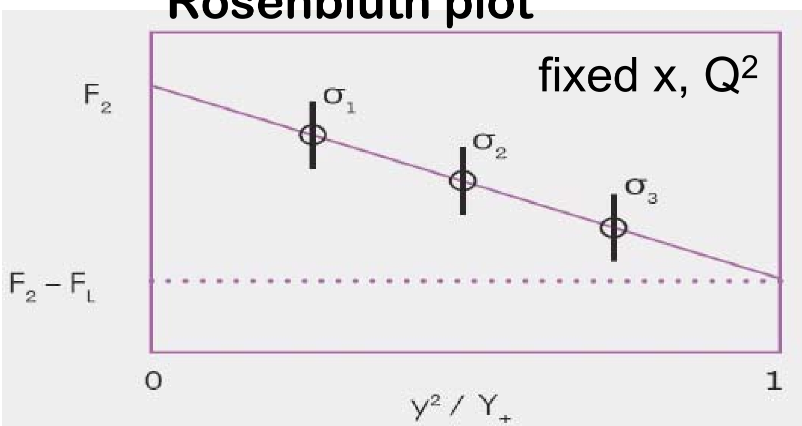
Issues at low x? Low x = High y !

- **Neutral current DIS cross section expressed by structure functions:**

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm = 1\pm(1-y)^2}\cdot\left(F_2\left(x,Q^2\right) - \frac{y^2}{Y_+}F_L\left(x,Q^2\right)\right)$$

$\tilde{\sigma}$: Reduced cross section

Rosenbluth plot



$$F_2\left(x,Q^2\right) = \sigma_r\left(x,Q^2,y=0\right)$$

$$F_L\left(x,Q^2\right) = -\frac{\partial\sigma_r\left(x,Q^2,y\right)}{\partial\left(y^2/Y_+\right)}$$

Measure σ_r at fixed x, Q2 but varying y

$$y = Q^2/sx \qquad \sqrt{s} = ep \text{ center-of-mass energy}$$

Varying y →varying s → dedicated low E_p runs at end of HERA

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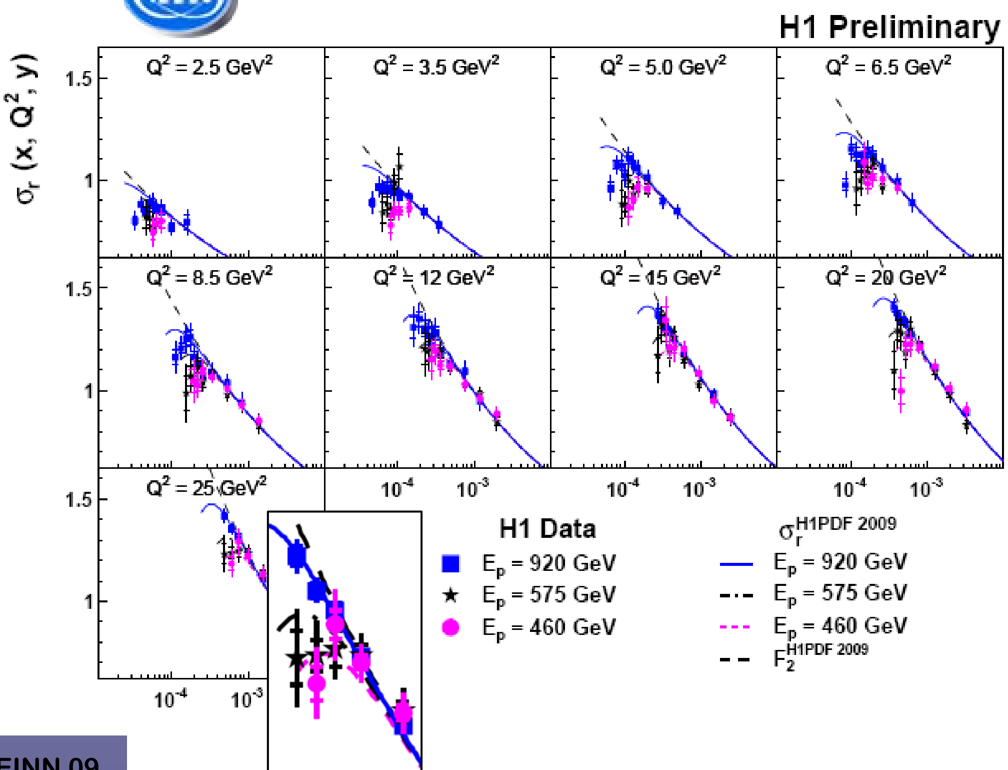
Cross Sections for direct FL extraction

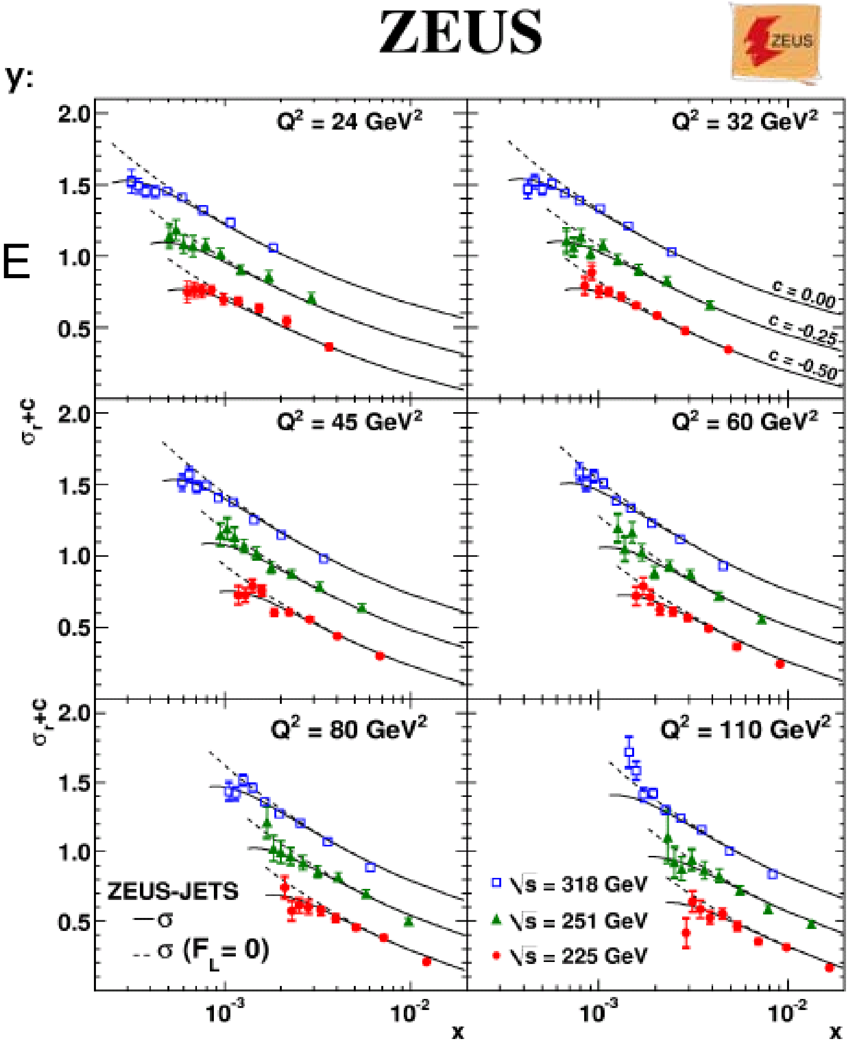
Direct F_L measurement requires measurement of the reduced cross sections at **same x and Q^2 but different y:**

$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)$$

$$y = \frac{Q^2}{x \cdot s}$$

different y → different s → different beam E





most precise σ_r from ZEUS

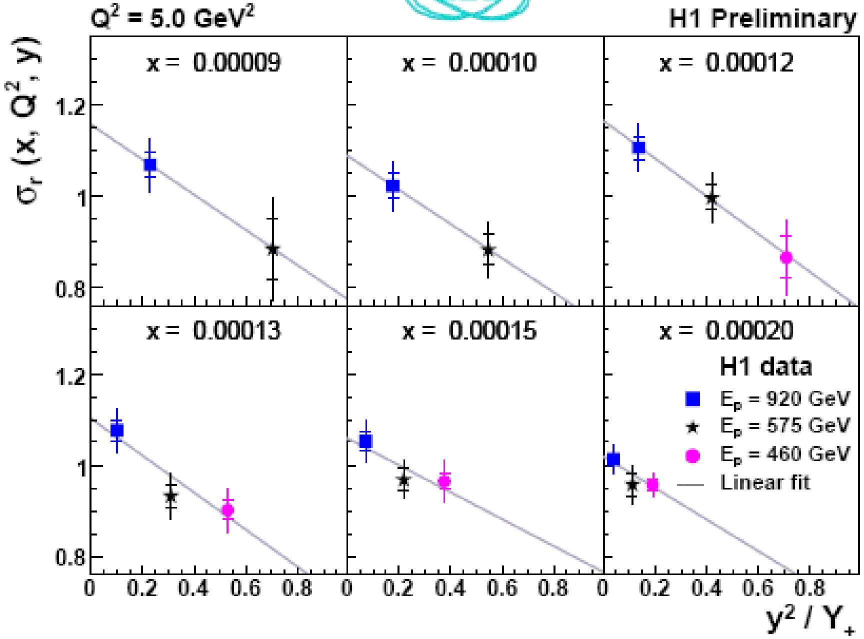
Turnover due to F_L small but visible

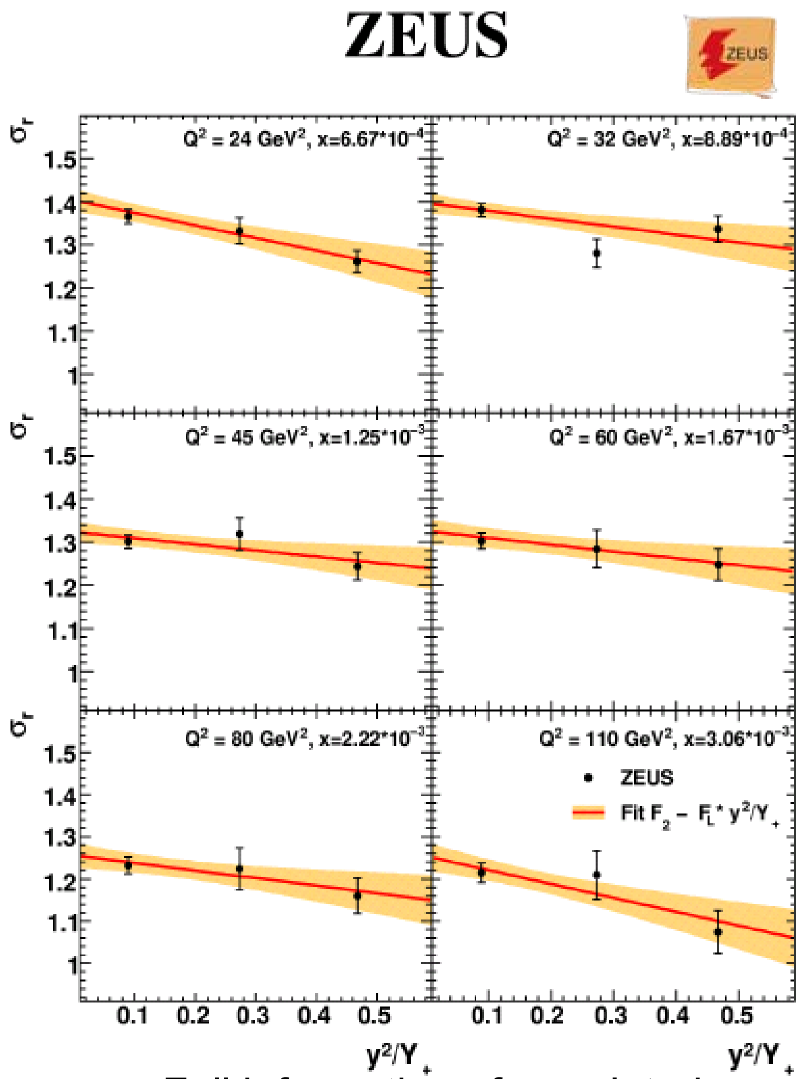
arXiv:0904.1092v1

F_L Extraction: Rosenbluth plots

$$\sigma_r(x,Q^2,y) = F_2(x,Q^2) - \frac{y^2}{Y_+} \cdot F_L(x,Q^2)$$

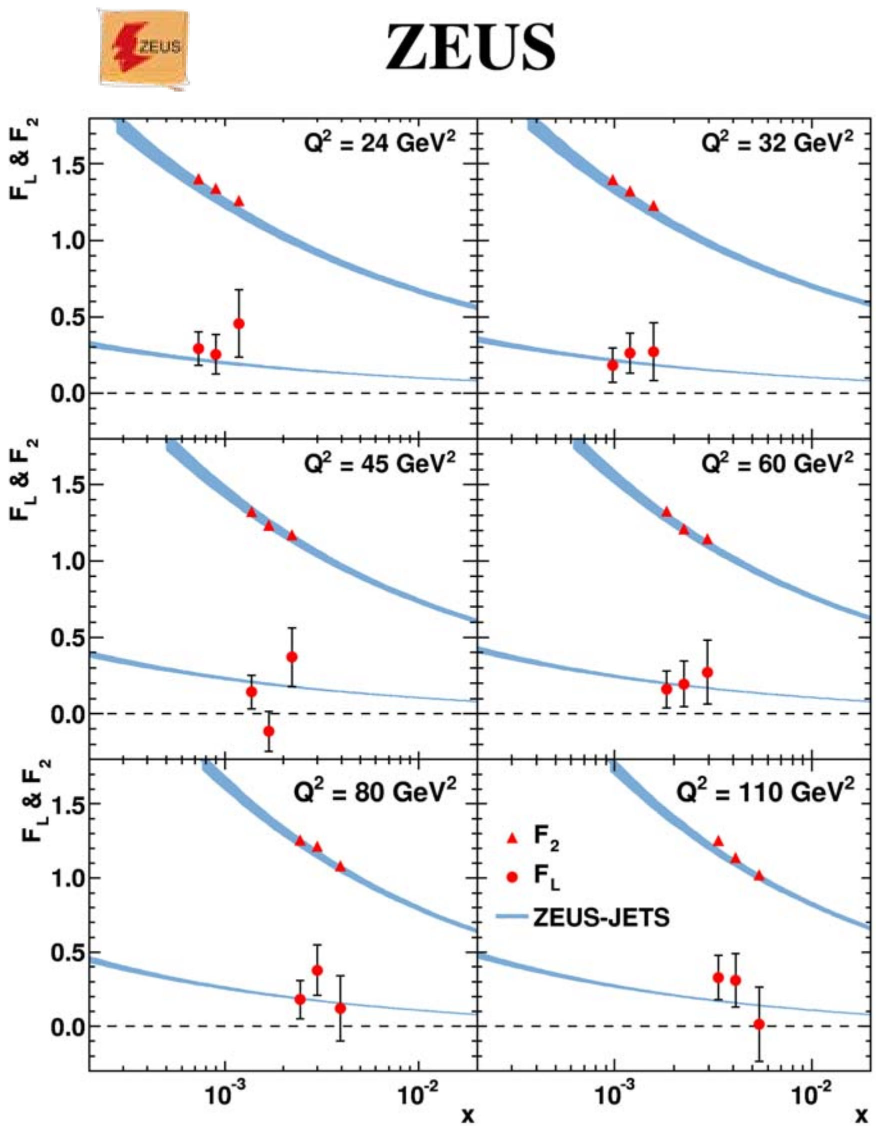
Straight line fit of σ_r vs y^2/Y_+
F_L slope, F_2 intercept





Full information of correlated systematics taken into account

Extracted F_L and F_2 – ZEUS



- Most precise F_2 measurement from ZEUS in kinematic region studied
- First F_2 measurement without assumptions on F_L
- Data support a non-zero F_L
- Predictions for F_2 and F_L are consistent with data

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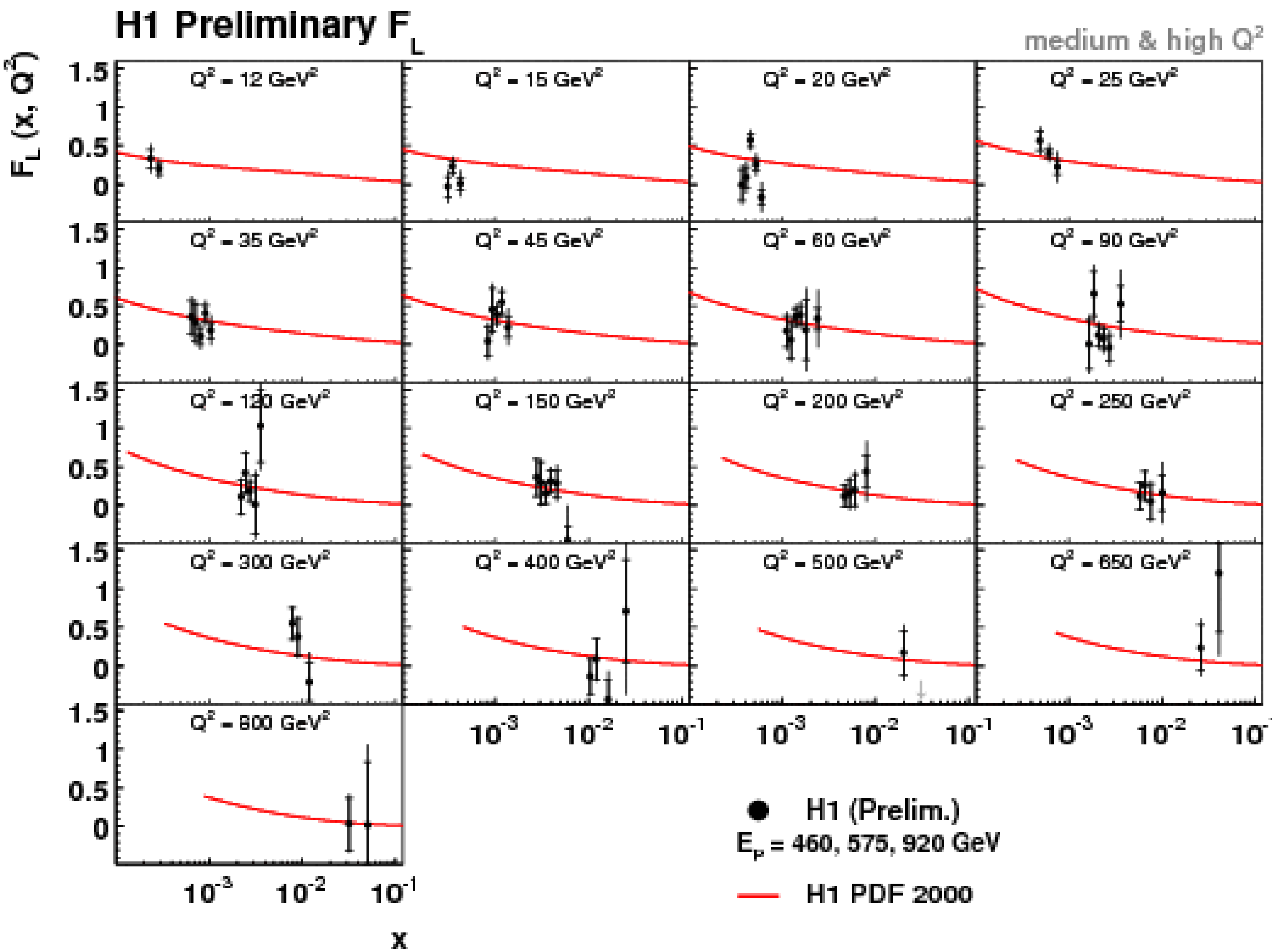
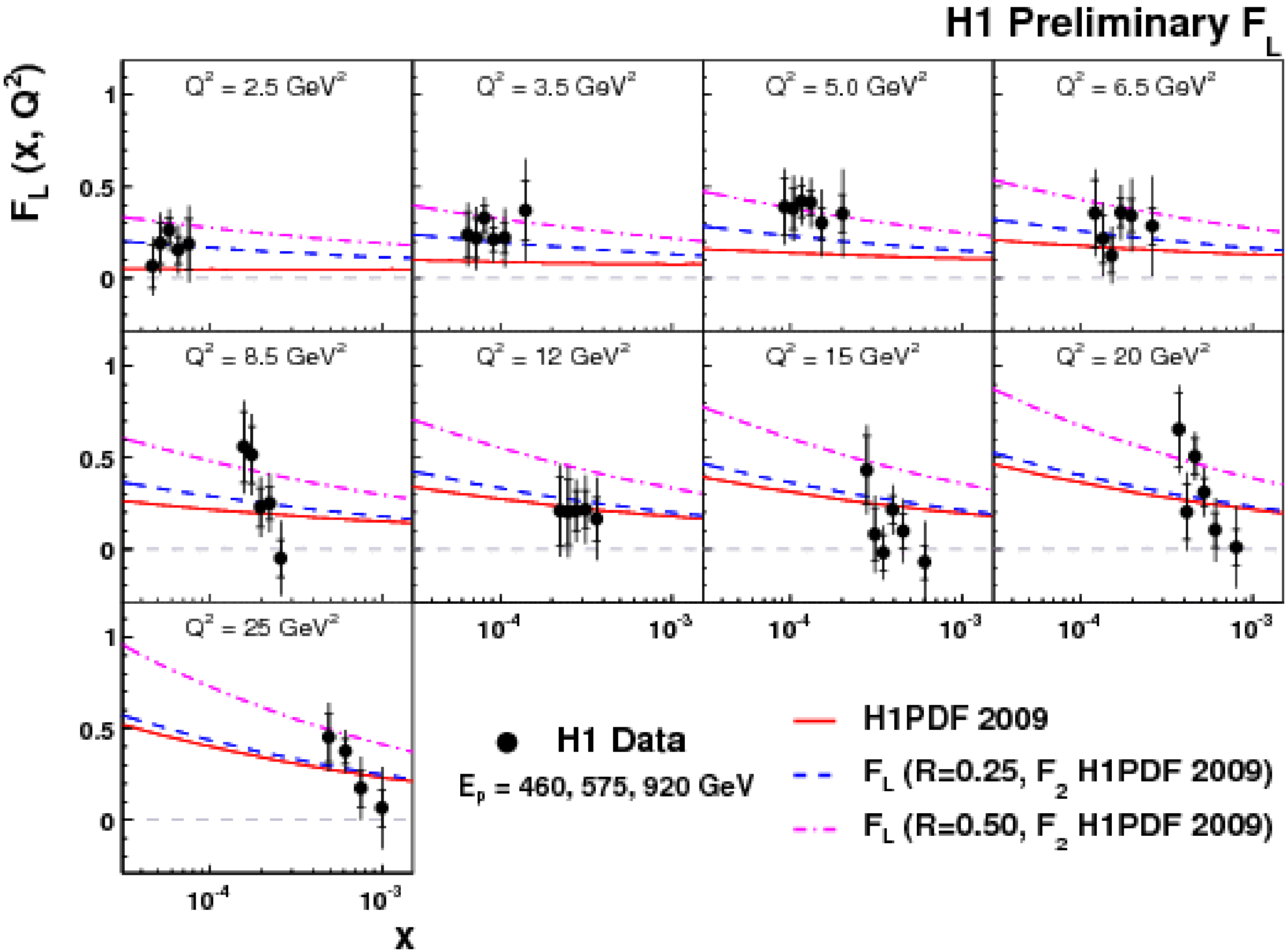
Extracted F_L – medium & high Q^2



Medium Q2 published in Phys. Lett. B665, p. 139

Extracted F_L – Low Q^2



F_L measured down to $Q^2 = 2.5$ GeV^2 !
Data are consistent with R~0.25 ($F_L = 0.2 \cdot F_2$)

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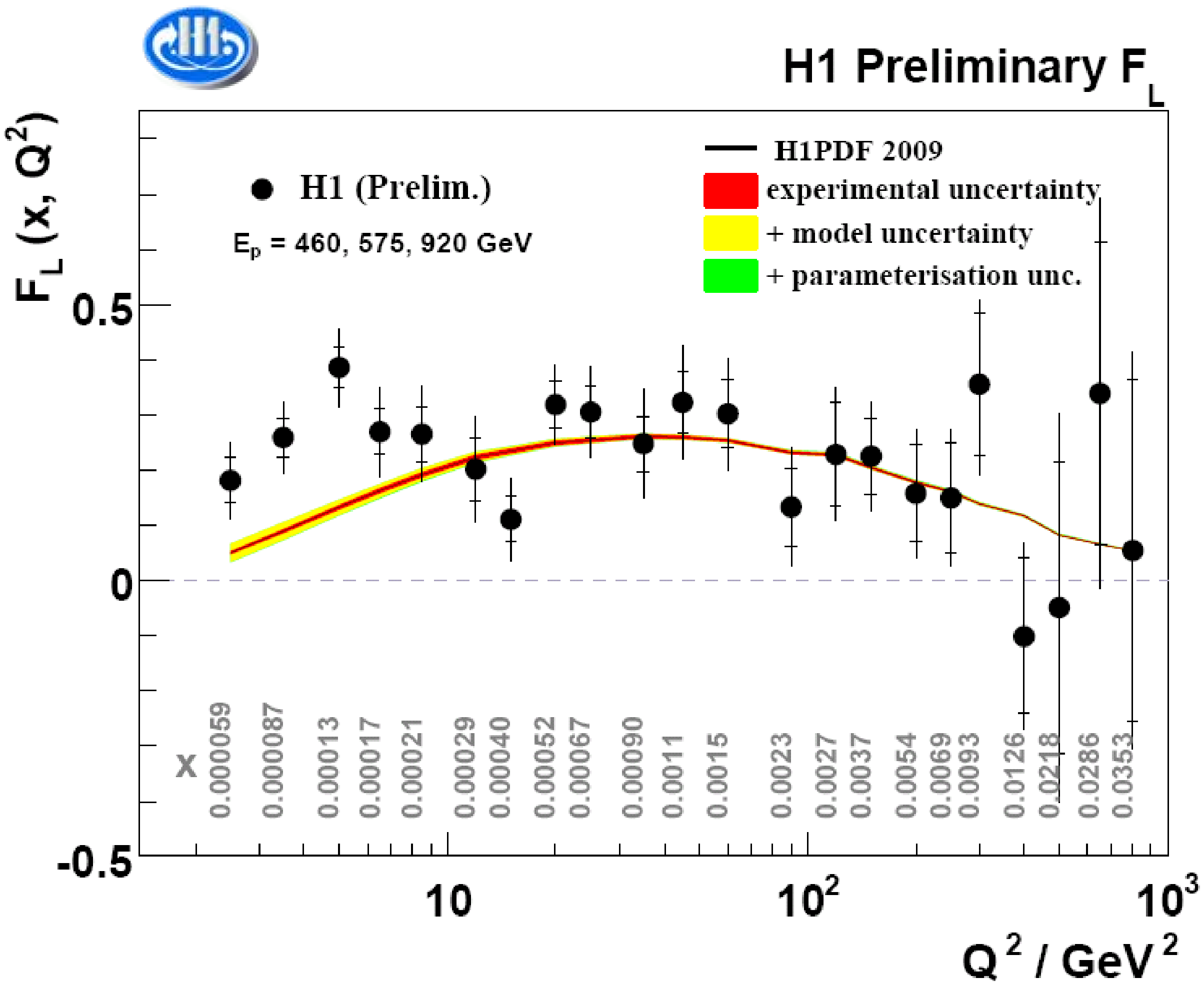
Average F_L – H1



H1 measurements cover $2.5 \leq Q^2 \leq 800$ GeV^2 and $0.00005 \leq x \leq 0.05$
For $Q^2 \geq 10$ GeV^2, agree well with H1PDF 2009 prediction.

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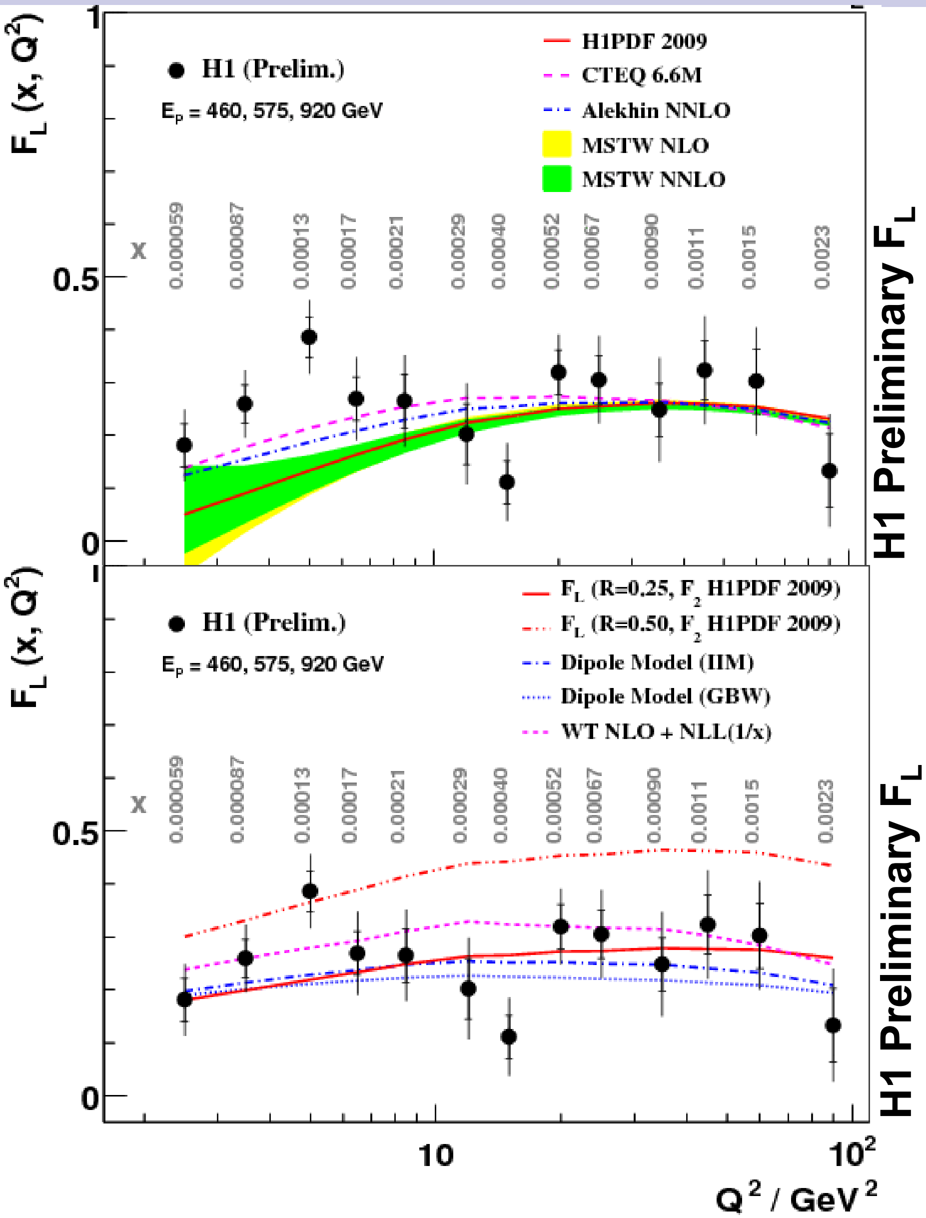
Average F_L < 100 GeV^2



- MSTW and H1PDF 2009 predictions use the same heavy flavour scheme to calculate F_L.
- Data agree better with calculation of CTEQ (and Alekhin)
- Data is consistent with constant $R \sim 0.25$ (H1)
  $R = 0.18^{+0.07}_{-0.05}$ (ZEUS).
  $R = F_L/(F_2-F_L)$
- Good agreement with IIM and GBW dipole models, NLL(1/x) prediction.

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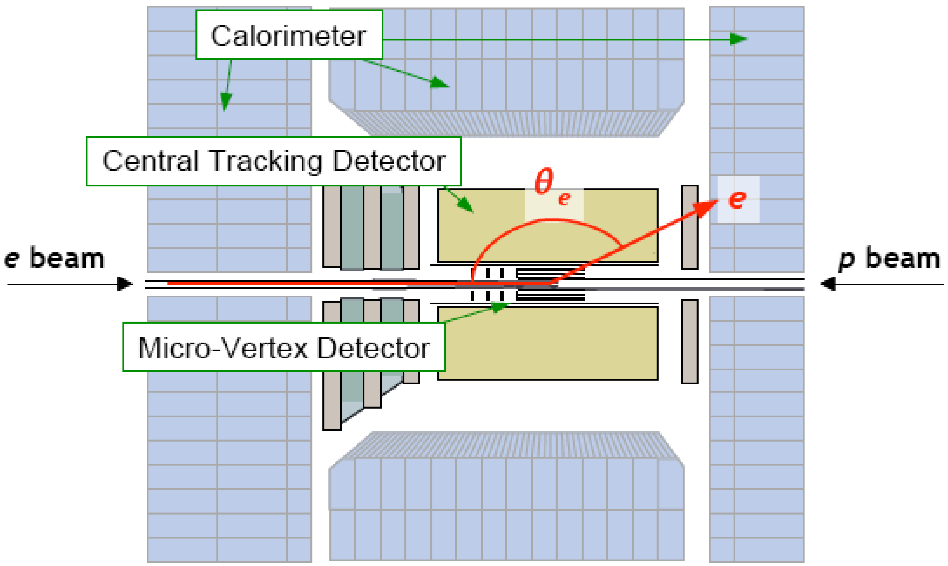
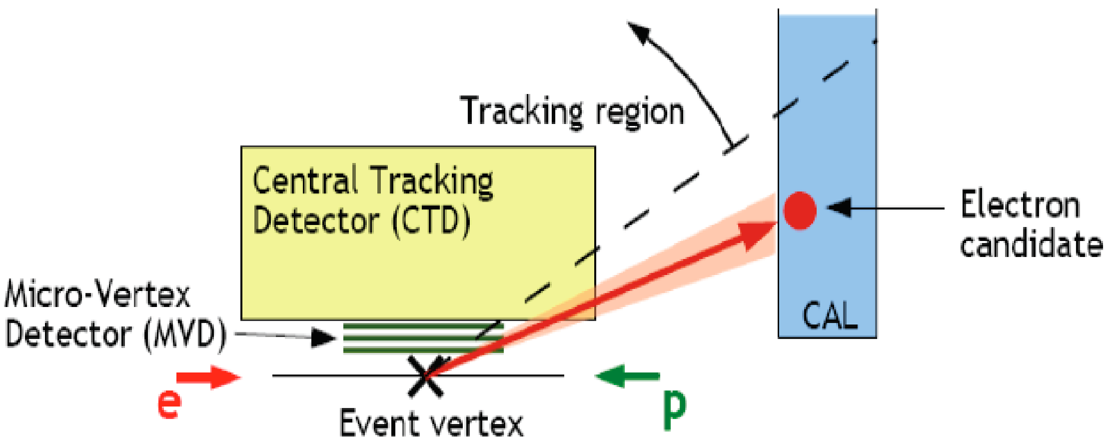
Measuring FL with ZEUS



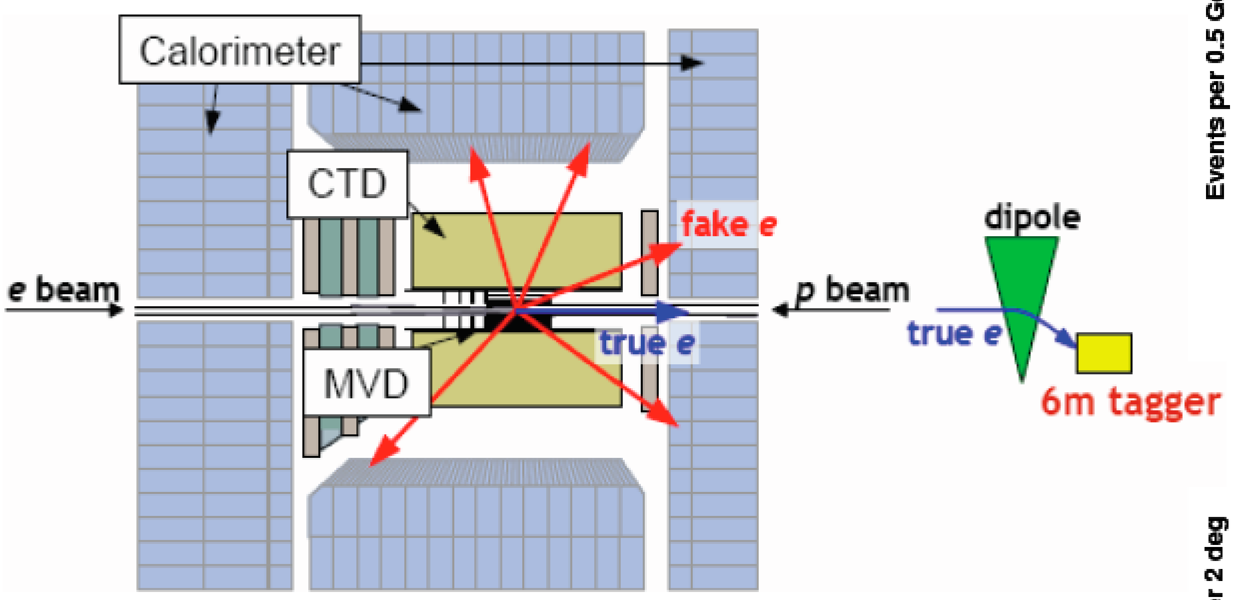
Event Selection:

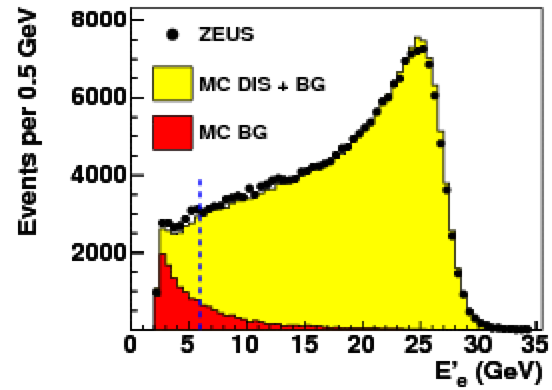
Electron in backward Calo
E'_e >6 GeV (Cluster & Trigger)
Hits in CTD & MVD (reject neutrals)
Event vertex
$42 < E-p_z < 65$ GeV

Q^2 range between 24 and 110 GeV^2

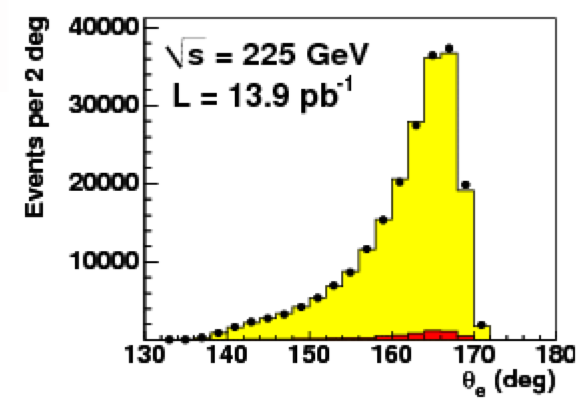


Background Subtraction - ZEUS





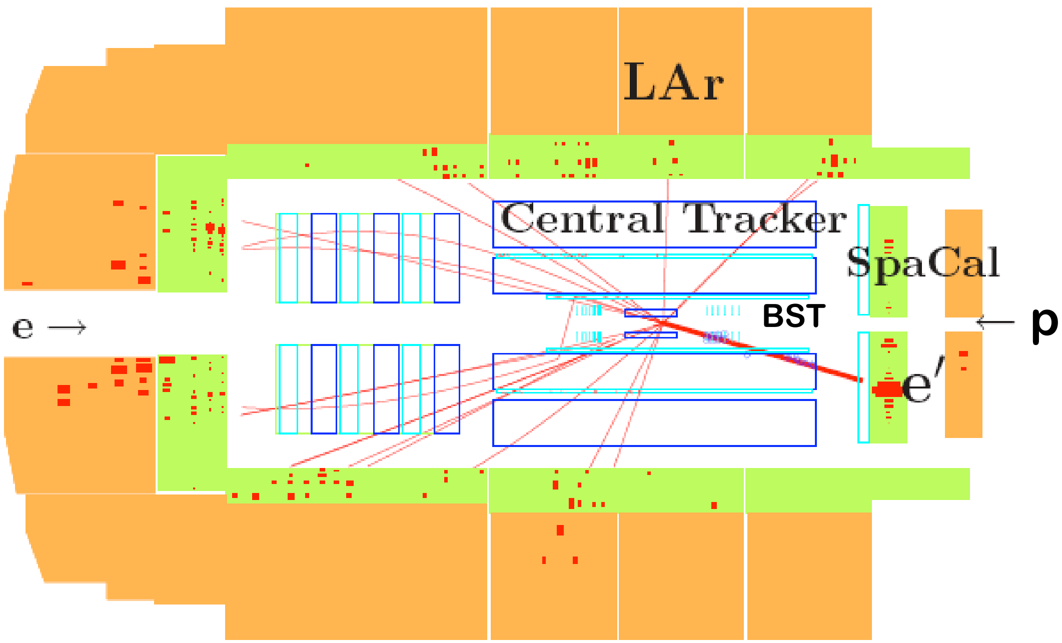
ZEUS



Photoproduction BG removed using PYTHIA MC with subprocesses (direct, resolved, diffractive,…) weights Adjusted to γp cross section measurement.
Control using 6m electron tagger. Complimentary studies with γp enriched data sample.

Measuring F_L with H1

DIS event of Q^2 near 30 GeV^2



Upgrades for FL

SpaCal (94)

BST (95+03)

Triggers (03-07)
- **Inner Chamber (CIP)**
- **SpaCal**
- **Fast Tracking (CJC)**
- **Jet Trigger (LAr)**

Three Q^2 ranges

3 to 12 GeV^2	**SpaCal+BST**	**prelim. 04/09**
12 to 90 GeV^2	**SpaCal+CT:**	**published 08**
35 to 800 GeV^2	**LAr+CT:**	**prelim. 03/08**

Event selection Criteria

El. in SpaCal or LAr (Calo & Trig) E'_e >3 GeV
Track in CT or BST (veto neutrals, e/p)
Interaction vertex
$E-P_z = \Sigma_i E_i(1-\cos\theta_i)$ >35 GeV
Reduces largely radiative corrections

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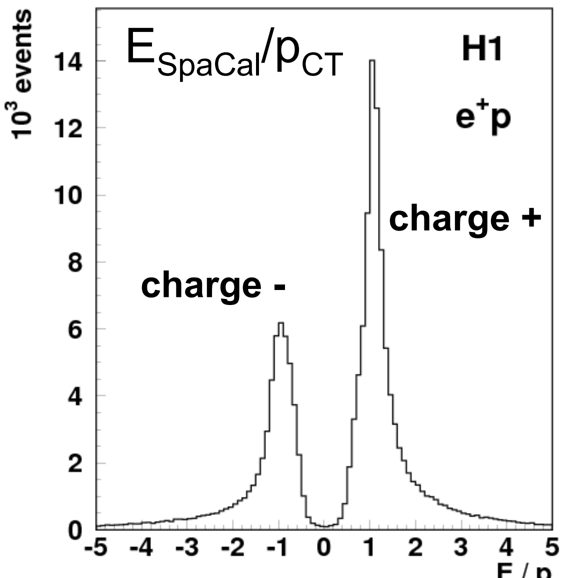
Background Subtraction – H1

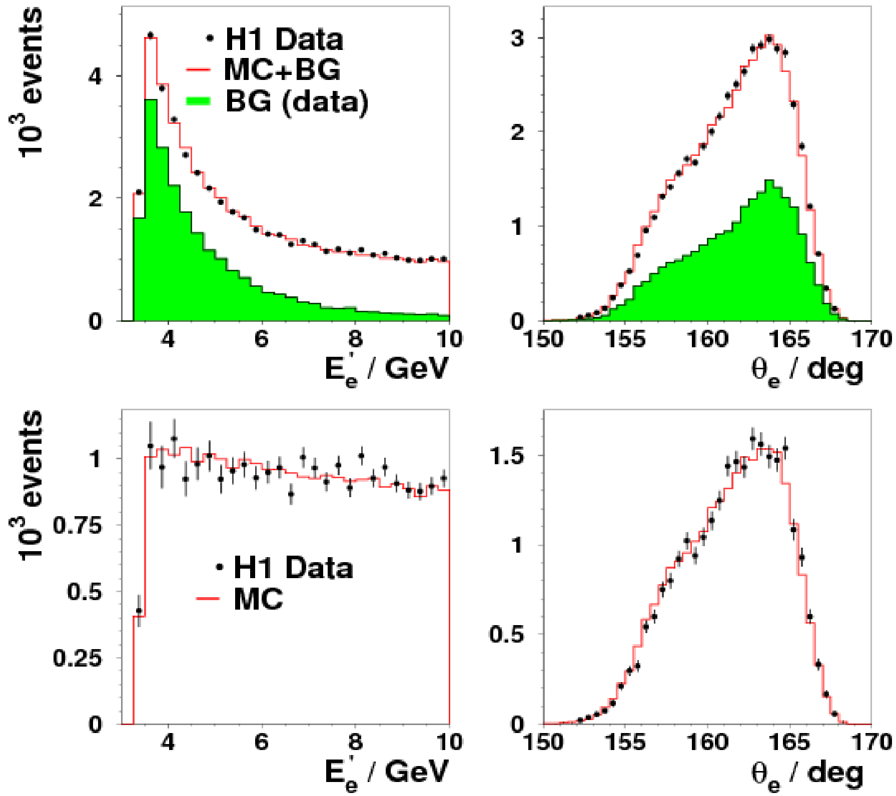
At small energies severe contamination by γp events.

Those are charge symmetric, apart from small effects due to anti-proton vs protons, which is measured using e+p and e-p data, and corrected for



H1 has tracking coverage for the electron candidates for all full Q2 ranges (CT & BST)

Scattered electron distributions (SpaCal + CT)



H1 background subtraction based on data. Trade off between background rejection and stat. unc. of background sample (wrong chrg.)

Summary

Precision measurements from HERA

- inclusive NC & CC cross sections
- structure functions
- parton densities

Many more not shown:
QCD-Jets, Diffraction,
Exclusive vector mesons,
DVCS, searches BSM limits …

Issues:

- valence quarks constrained by NC & CC at high Q^2
  d_v will remain less precise than u_v
- sea quarks obtained from F_2 at low x
  possibility of an asymmetric light flavor sea $\bar{d}-\bar{u}\neq 0$
- gluons from scaling violations, F_L, jets, vector mesons, $c\bar{c}$ $b\bar{b}$
  ultimately precision to be seen, final uncertainty at high x?
- high x: extrapolating towards $x\rightarrow 1$
  How to assess uncertainties?
- low x: When does the strong rise saturate?

Backup Slides

Polarisation Effects in NC

$$\tilde{F}_2 = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + ((v_e^2 + a_e^2) \pm P_e 2 v_e a_e))\chi_Z^2 F_2^Z$$
$$\tilde{F}_3 = - (a_e \pm P_e v_e)\chi_Z F_3^{\gamma Z} + ((2 v_e a_e \pm P_e (v_e^2 + a_e^2))\chi_Z^2 F_3^Z$$

Nb.: xF_3 is written as F_3 for simplicity

- Polarization modifies γZ and Z terms:
  - -- Axial in F_2, vector in F_3
  - -- dependent on size of P_e

$v_e \approx 0$

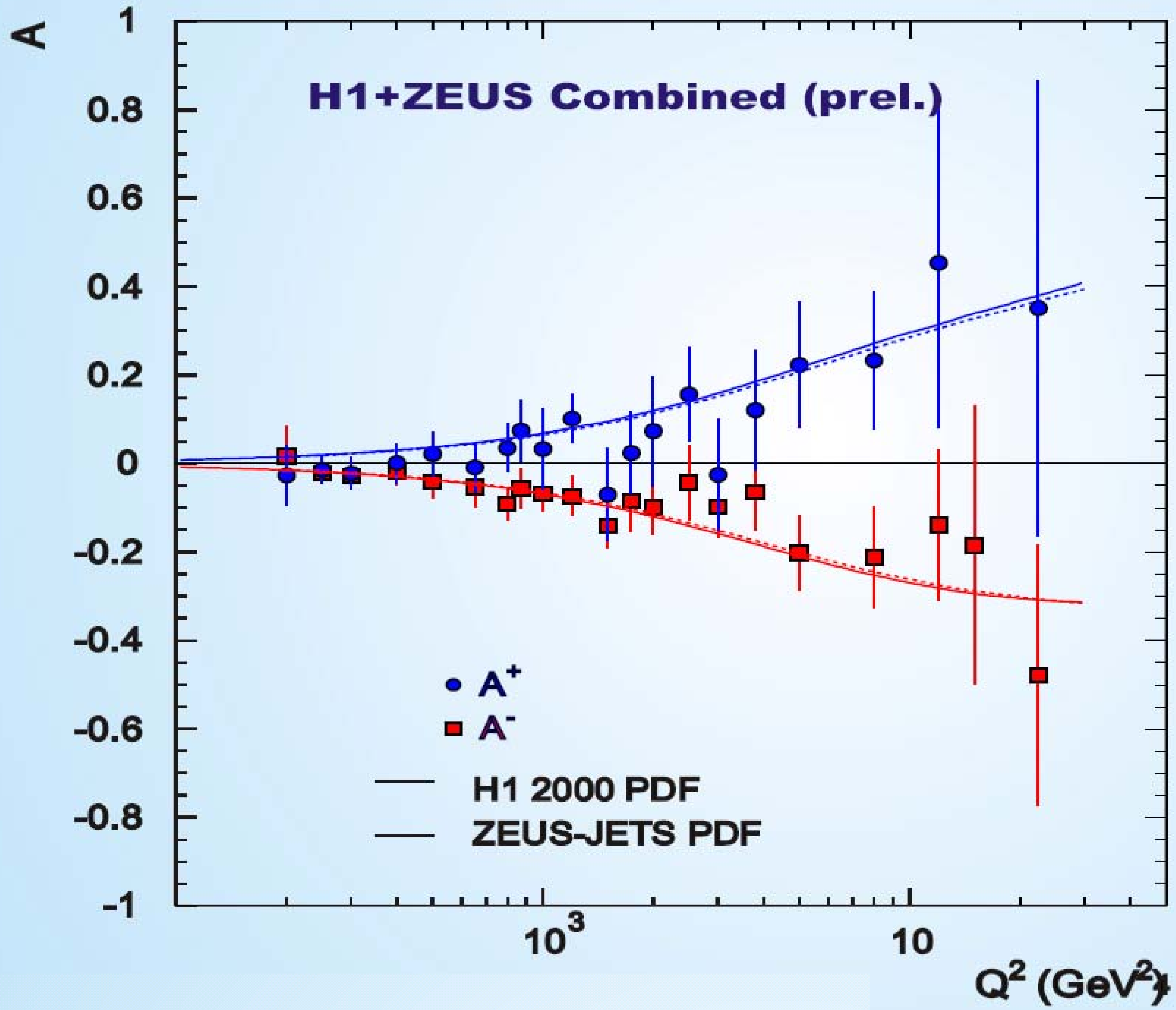
-- F_2 : 1st order, ~ $\pm P_e a_e \chi_Z F_2^{\gamma Z}$

-- F_3 : 2nd order only, ~ $\pm P_e a_e^2 \chi_Z^2 F_3^Z$

Unpol:
$\sigma(e^+) - \sigma(e^-) \rightarrow F_3^{\gamma Z}$
Pol :
$\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow F_2^{\gamma Z}$

- Polarization effects expected only at EW scale, i.e large Q^2

NC Cross Section Asymmetries



Parity Violation due to γZ interference

At high x, assuming SM couplings

$$A_\pm \sim \frac{u_v + d_v}{4u_v + d_v}$$

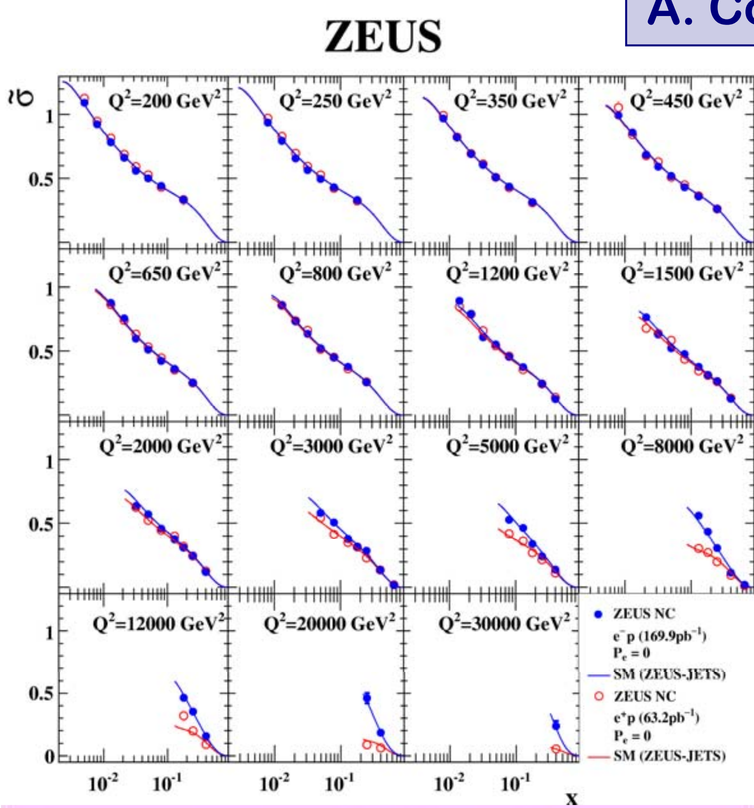
constrain d/u

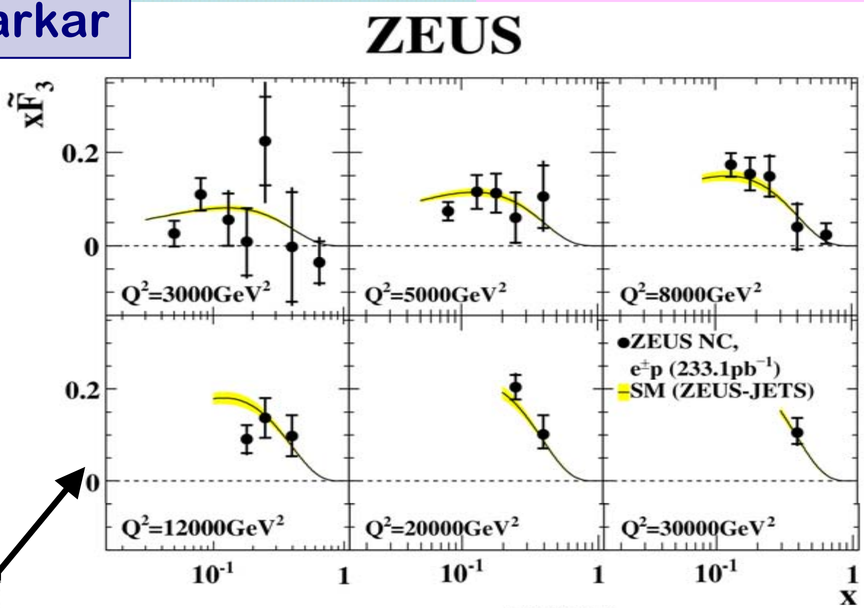
$$A_\pm = \frac{2}{P_R - P_L} \frac{\sigma_\pm(P_R) - \sigma_\pm(P_L)}{\sigma_\pm(P_R) + \sigma_\pm(P_L)}$$

$160\,pb^{-1}$ NEW NC e-p data: first combine the polarisations to look at unpolarised cross-sections

DESY-08-202

A. Cooper-Sarkar

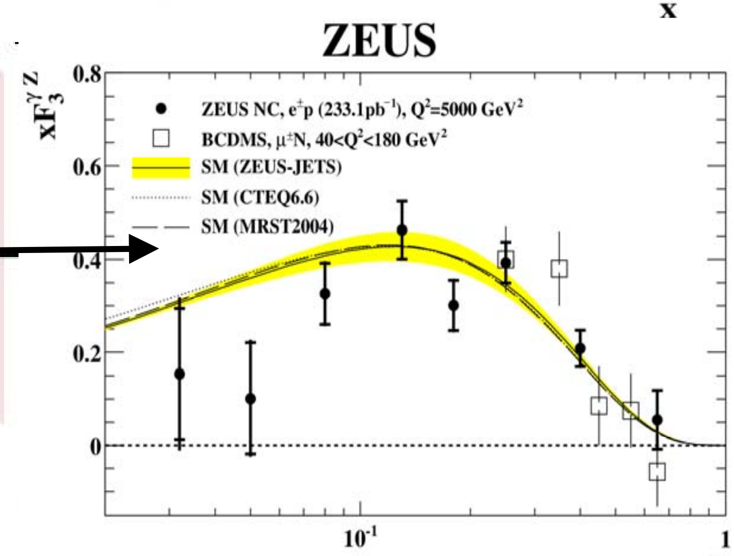




Compare these NEW e- NC data with HERA-I e+ NC data and use these two data sets to extract xF3

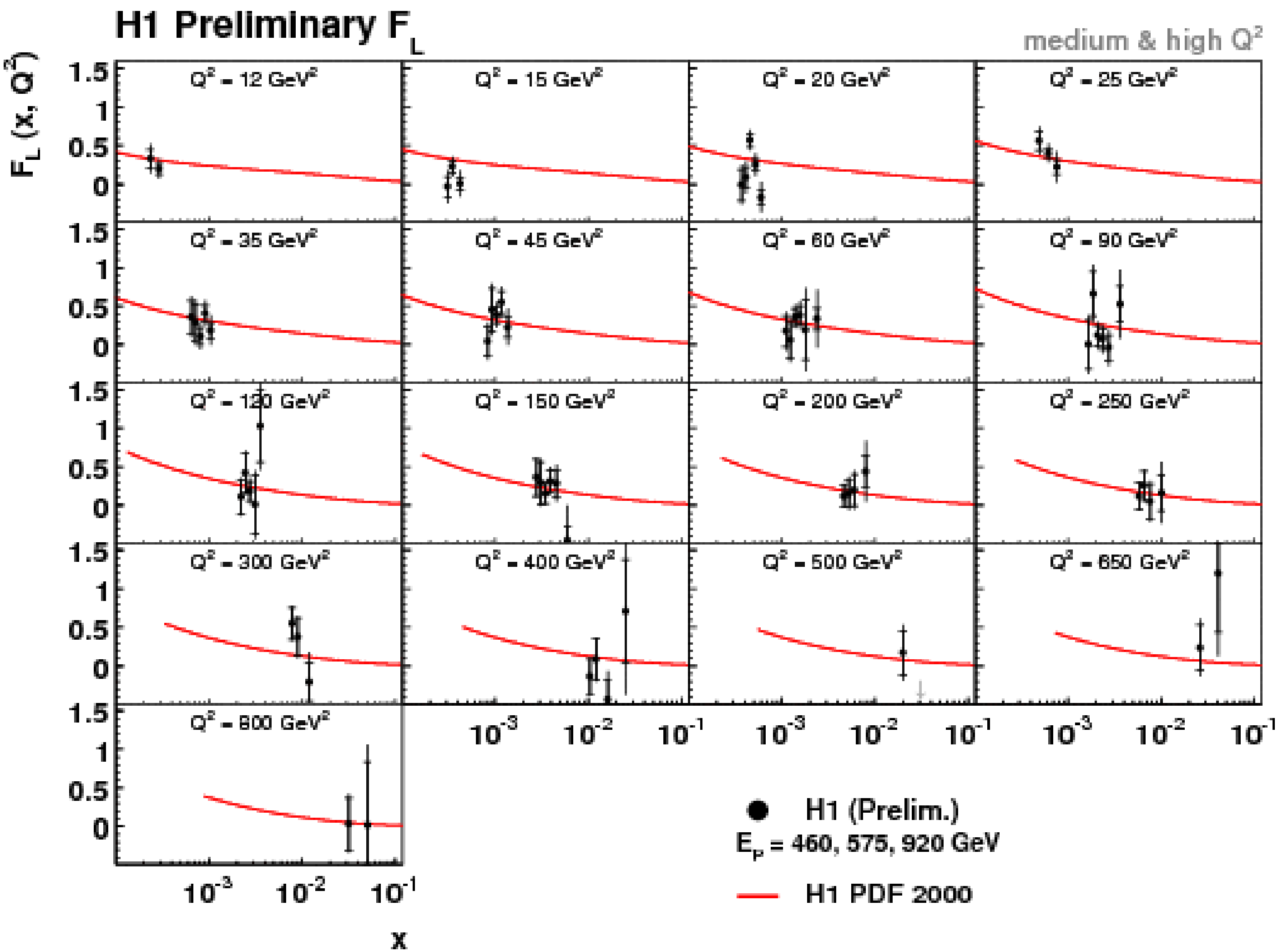
Much improved xF3 compared to previous extraction which used only 16.4 pb^{-1} of e- NC data

Measurements from 1500 to 30000 GeV^2 have been extrapolated to 5000 GeV^2 to measure $xF_3^{\gamma Z}$ and compare to BCDMS at high-x



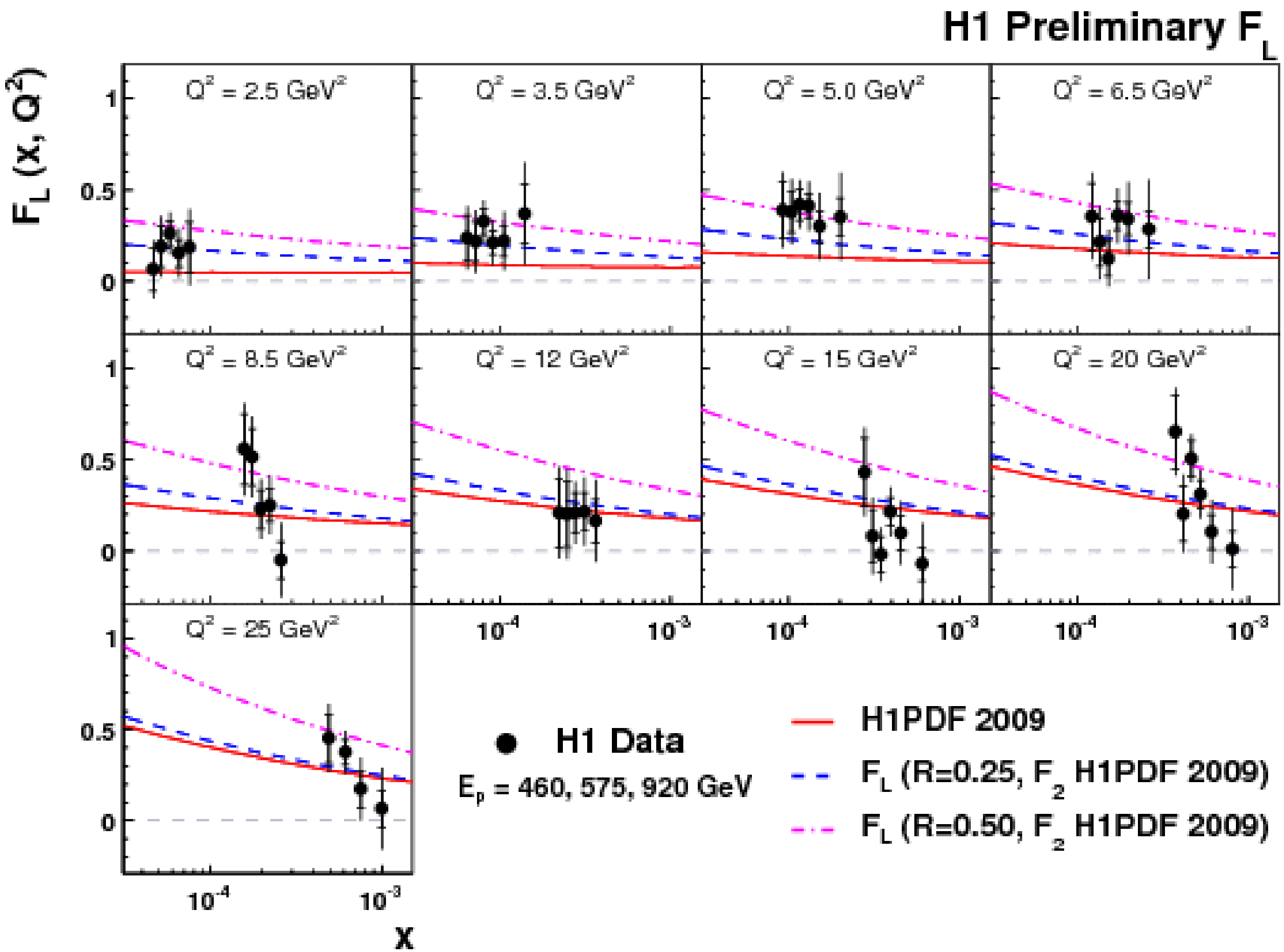
$$\frac{d^2\sigma(e\pm N)}{dxdy} = \frac{2\pi\alpha^2 s}{Q^4} Y_+ \left[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \pm \frac{Y_-}{Y_+} xF_3(x,Q^2) \right],$$

Extracted F_L – medium & high Q^2



Medium Q2 published in Phys. Lett. B665, p. 139

Extracted F_L – Low Q^2



F_L measured down to $Q^2 = 2.5$ GeV^2 !

Data are consistent with R~0.25 ($F_L = 0.2 \cdot F_2$)

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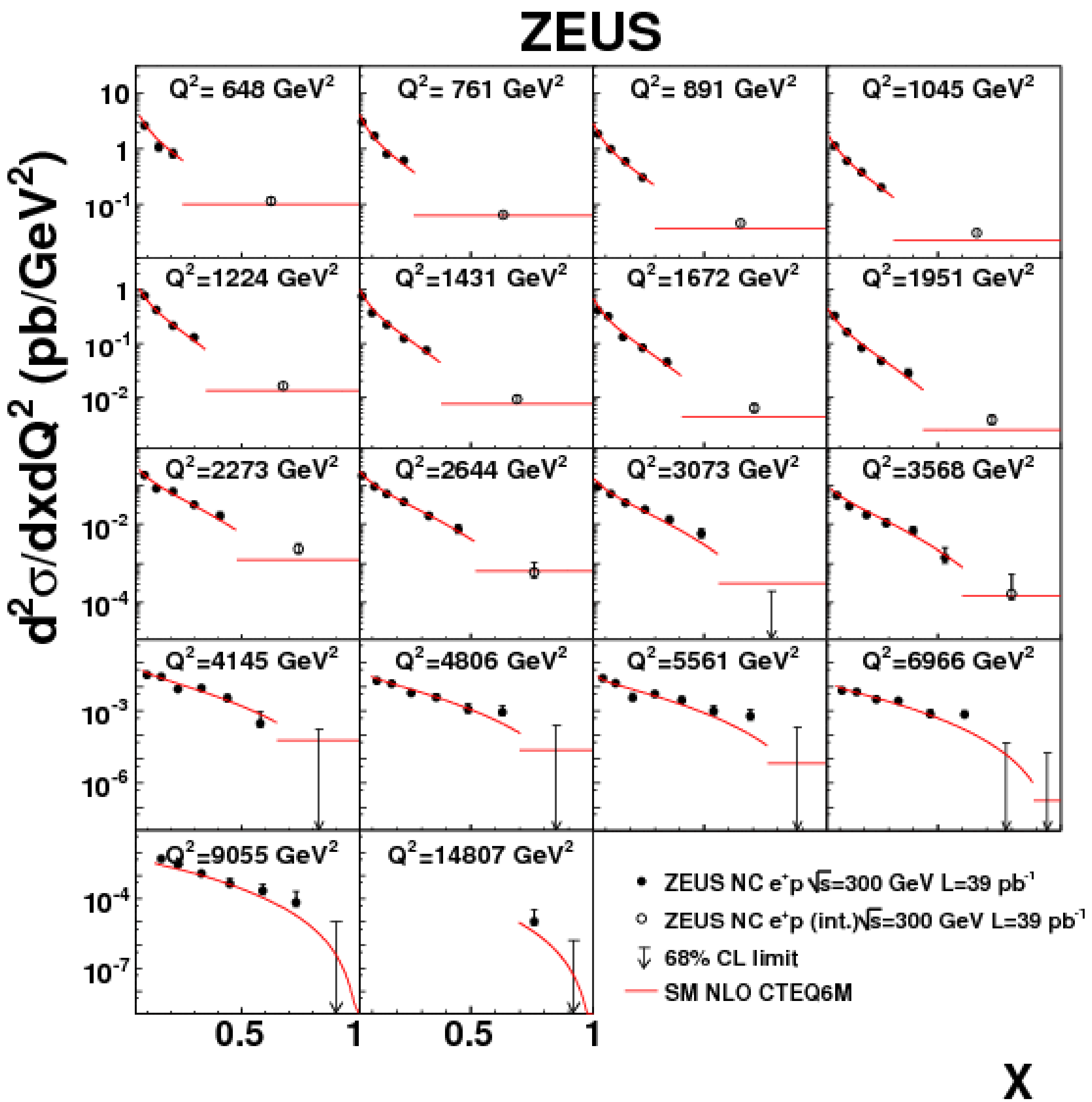
Low x & SF



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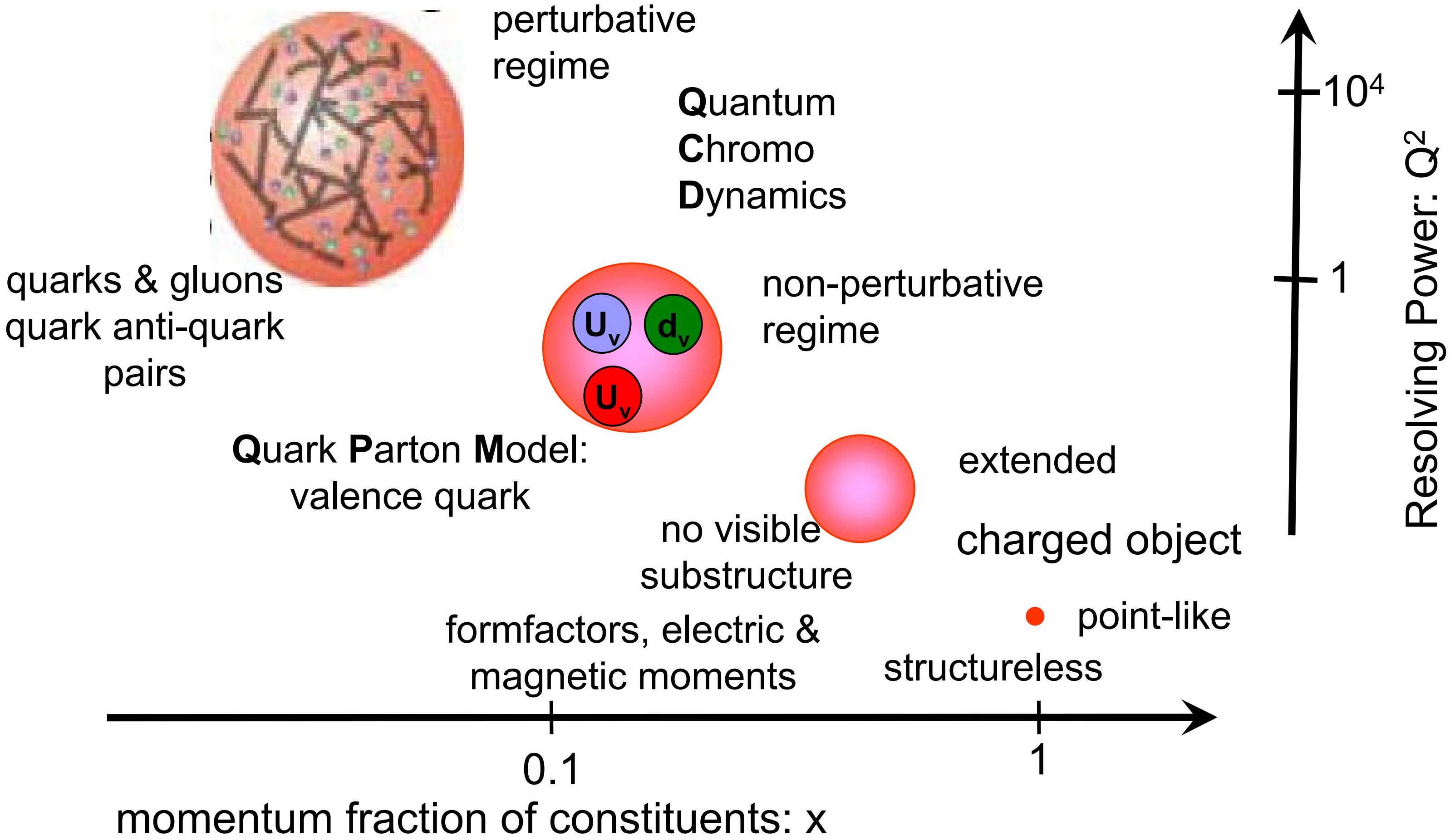
“Imaging” of the Proton



Low Q^2 : probing transition perturbative to non-perturbative QCD
Low x: probing quarks and gluons at high density
$\Delta E \Delta t \sim h \rightarrow$ high Q^2 “high resolution but time averaged picture”