Measurement of the proton structure at HERA: Impact on LHC physics

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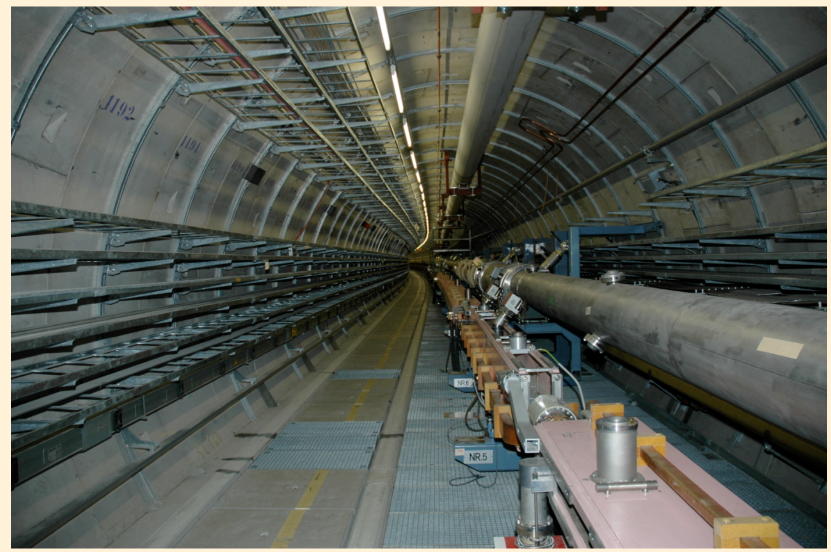
for the H1 and ZEUS collaborations

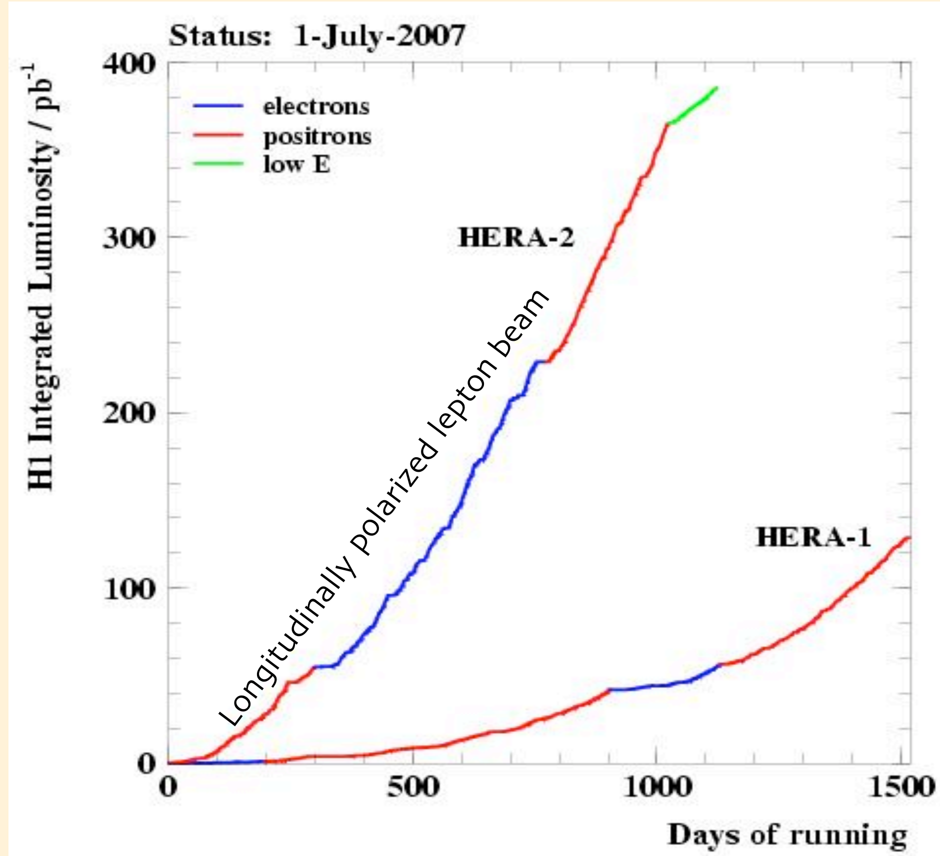
HERA operation



HERA: electron(positron)-proton collider at DESY, Hamburg
delivered luminosity between 1992 and 2007

HERA operation

$\sqrt{s}$ = 300/318 GeV

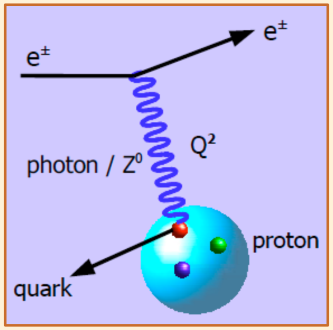


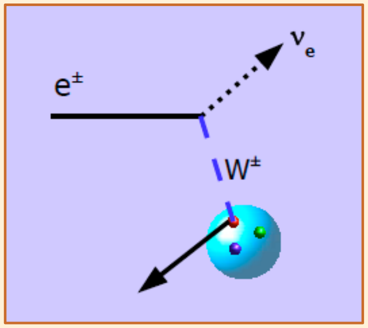
- average (lumi weighted) polarization achieved: 30 - 40%
- e^+p, e^-p samples balanced
- ~ 20 pb^{-1} from low & medium energy running (F_L)
- ~ 0.5 fb^{-1} collected per experiment

Deep inelastic e±p scattering: basics

Two deep inelastic scattering processes:

— Neutral current: exchange of γ or Z°
— Charged current: exchange of W±

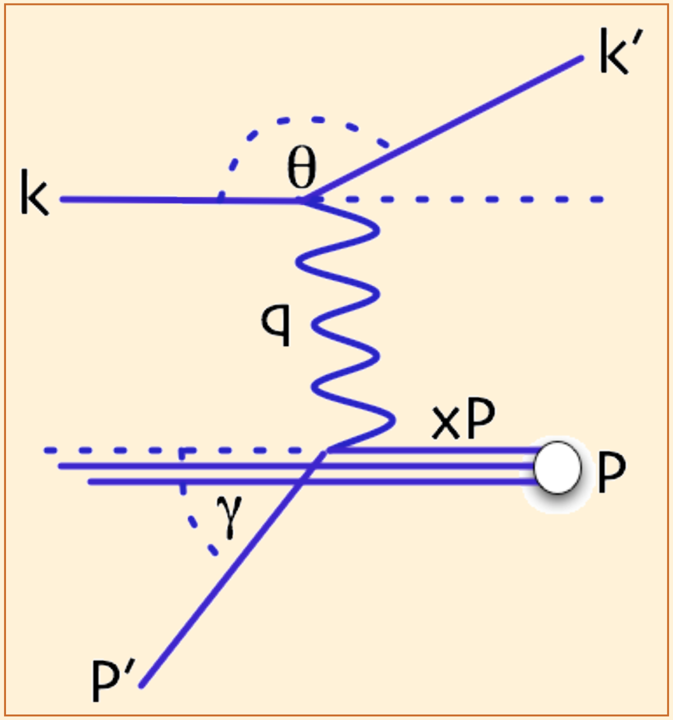




$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

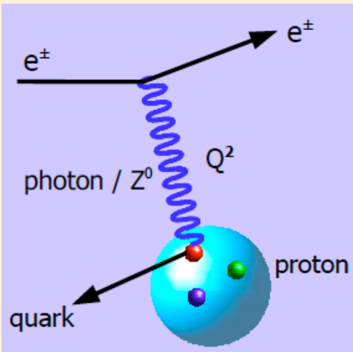
$$s = (p+k)^2 \qquad Q^2 = x\cdot y\cdot s$$



- Q^2 is probing power
- x is Bjorken scaling var.
- y is inelasticity of e
- s is CME

Deep inelastic e±p scattering: probing the proton

NC DIS

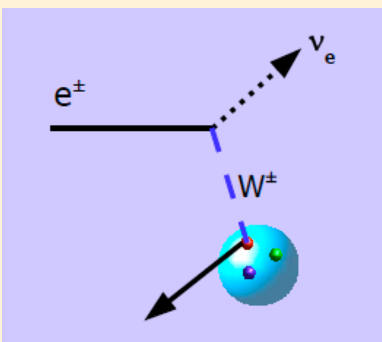


$$\frac{d^2\sigma(e^{\pm}p)}{dQ^2dx} = \frac{2\pi\alpha^2}{Q^4x}Y_+\left(F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3\right); \quad Y_{\pm} = 1 \pm (1-y)^2$$

F_2 → valence + sea quarks; F_L → gluon; xF_3 → valence quarks

-> gluons, sea quarks and valence quarks

CC DIS



$$\frac{d^2\sigma^{CC}(e^+p)}{dQ^2dx} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)[\bar{u}+\bar{c}+(1-y)^2(d+s)] \quad \times (1 + P_e)$$

$$\frac{d^2\sigma^{CC}(e^-p)}{dQ^2dx} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)[u+c+(1-y)^2(\bar{d}+\bar{s})] \quad \times (1 - P_e)$$

-> flavour separation

Outline: questions HERA has to answer

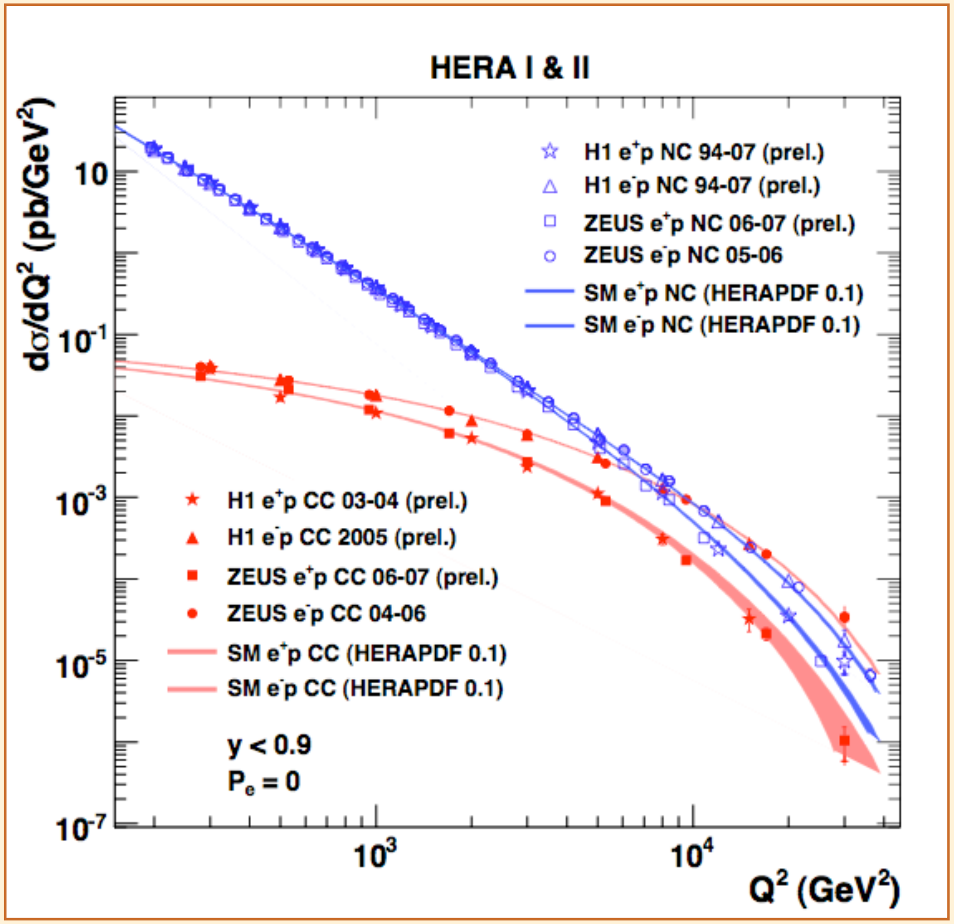
1) Does the electron probe behave as expected?

2) Is the quark point like?

3) What are the quark and gluon distributions in the proton?

4) Are QCD dynamics well understood to evolve to the LHC scale?

The electron probe



Observe EW unification in the t-channel at the $M_{W,Z}$ scale!

NC DIS:

γ exchange dominates at low Q^2 (described by F_2)

Z^0 contribution significant at high Q^2 (described by F_3)

Effect of probe charge:

- EW effects increase/decrease σ (larger for CC DIS)
- Sensitive to valence quarks (NC DIS) & their flavour (CC DIS)

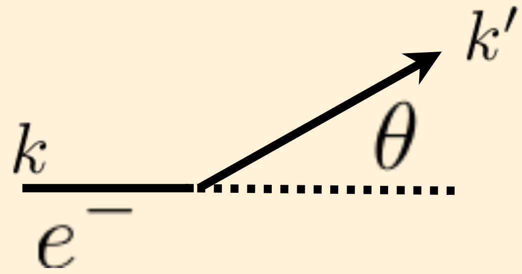
SM provides excellent description of data over many orders of magnitude ⟶ testing ground for SM and QCD

The electron probe indeed behaves as expected!

Intermezzo

…. Is the quark point like?

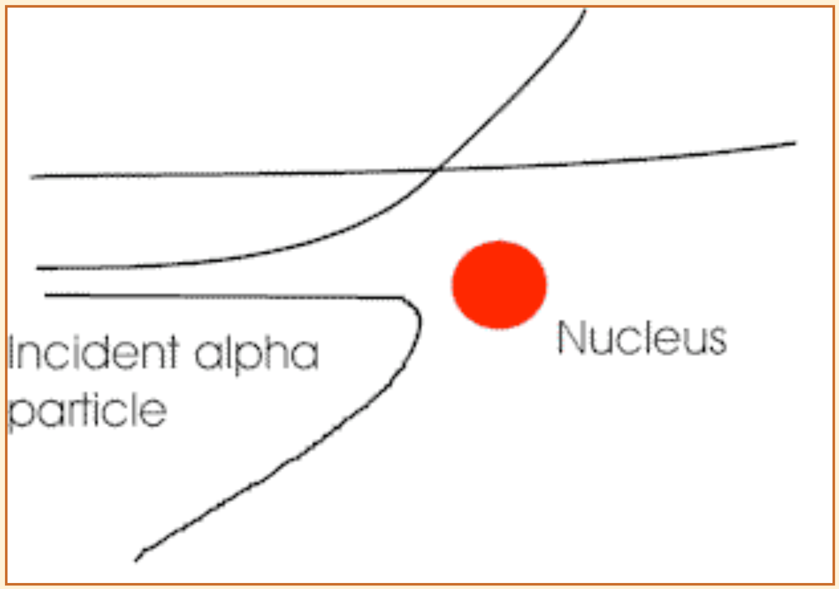
Rutherford scattering (1910)



$$q = k - k'$$

$$q^2 \propto \sin^2(\theta/2)$$

$$\frac{d\sigma}{dq^2} = 4\pi\alpha^2 \frac{Z^2}{q^4}$$



'plum pudding'

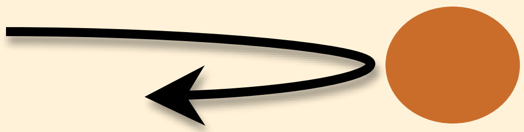
↓

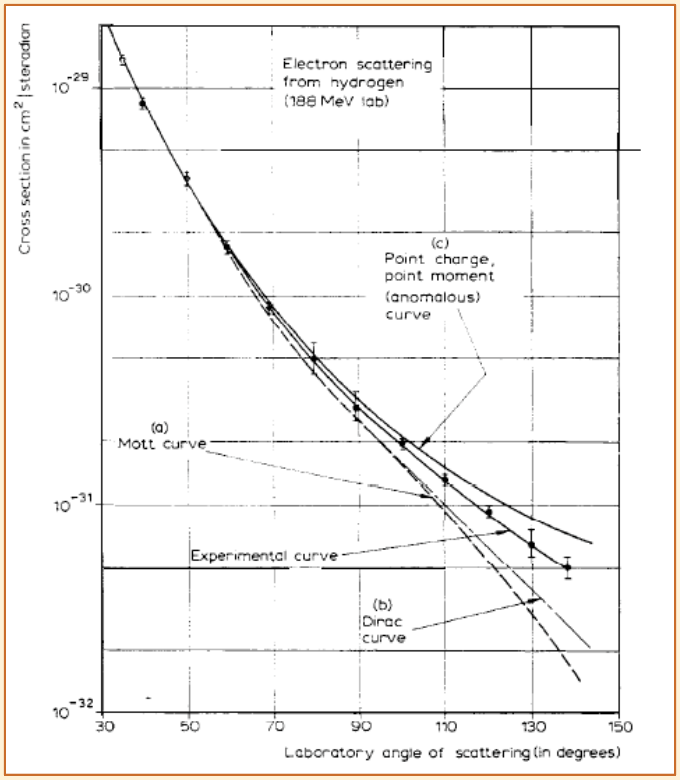
point like

but mostly empty with positive charge in the center

"It's as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." Ernest Rutherford

Hofstadter: Radius of nucleus (1955)





$$\frac{d\sigma}{dQ^2} = 4\pi\alpha^2 \frac{Z^2}{q^4} \boxed{F(q^2)}$$

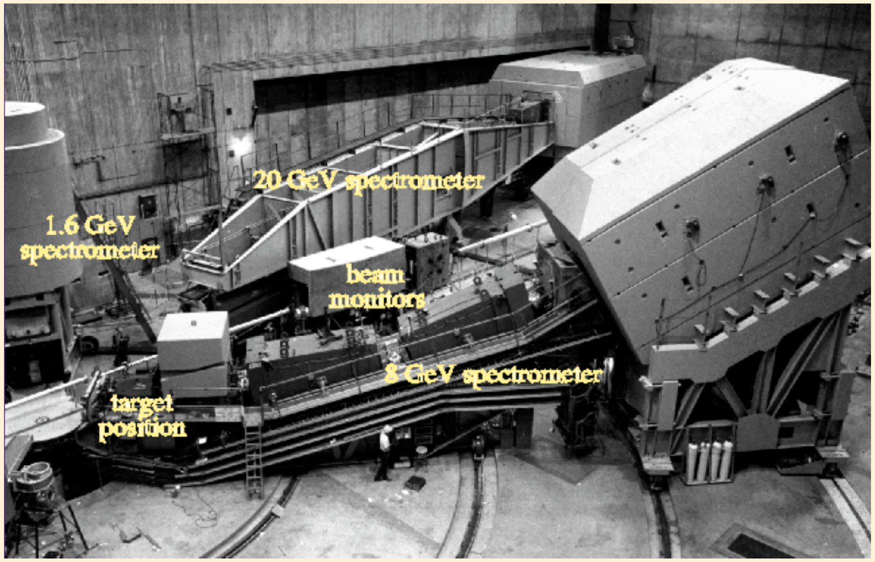
$$q^2 \propto \sin^2(\theta/2)$$

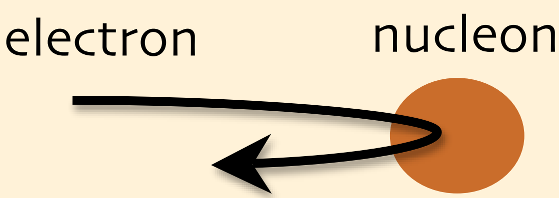
The proton was not a point object, but had a size that was "surprisingly large", about 0.75×10^{-13} cm.

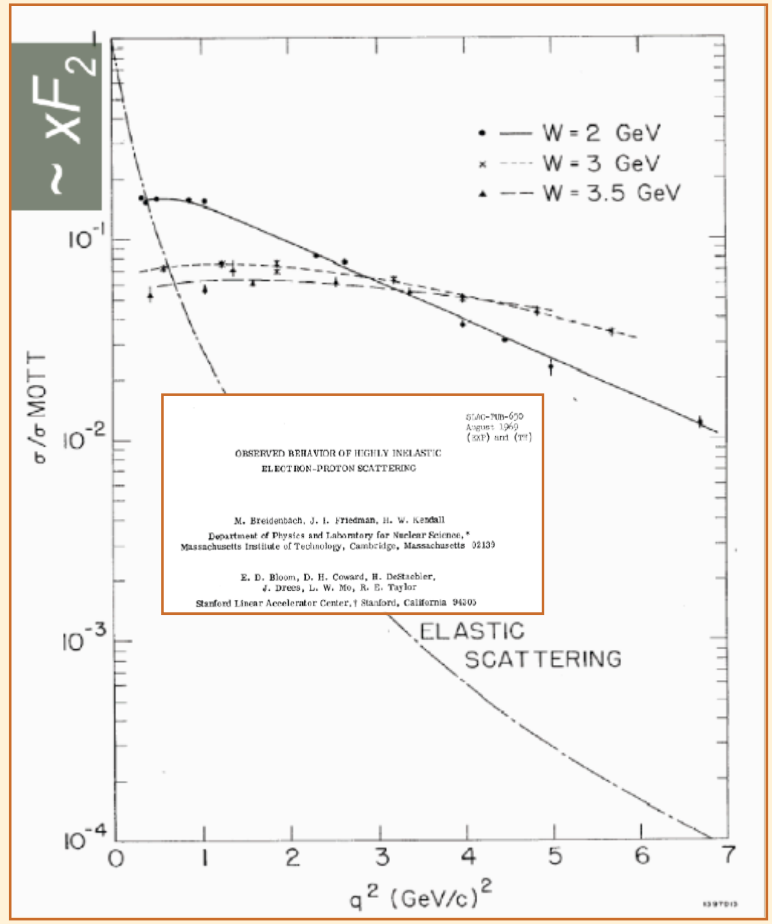
"One can only guess at future problems and future progress, but my personal conviction is that the search for ever-smaller and ever-more-fundamental particles will go on as long as Man retains the curiosity he has always demonstrated." Robert Hofstadter (Nobel lecture)

Deep inelastic scattering (1969)

$$\frac{d^2\sigma}{dq^2dx} = \frac{4\pi\alpha^2}{q^4x}[(1-y)F_2(x,Q^2) + xy^2F_1(x,Q^2)]$$







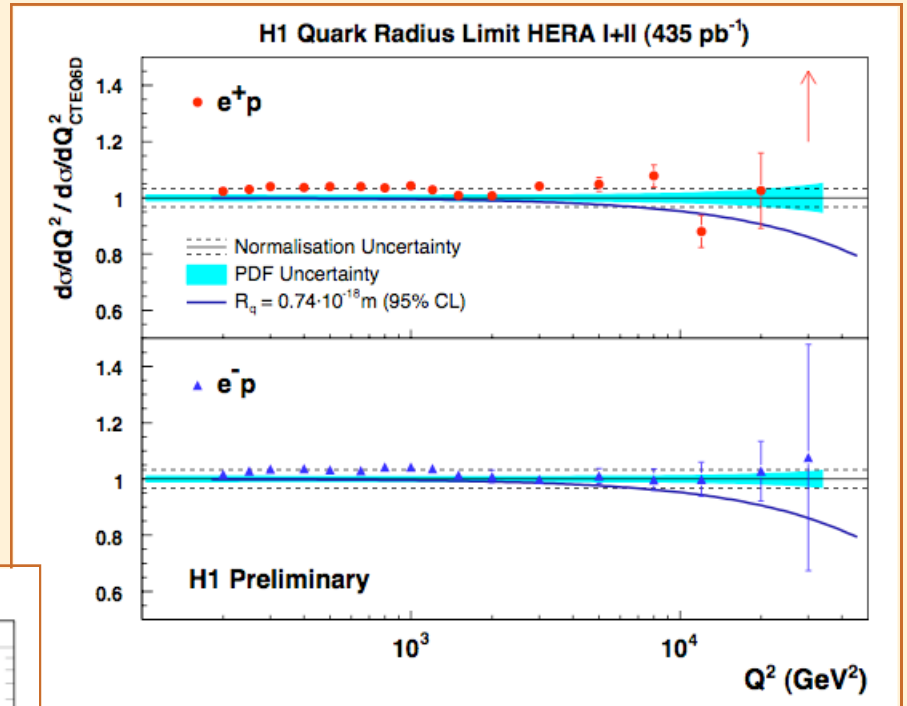
The proton was not an elementary particle, instead it contained much smaller, point-like objects called partons.

Quark radius (2009)

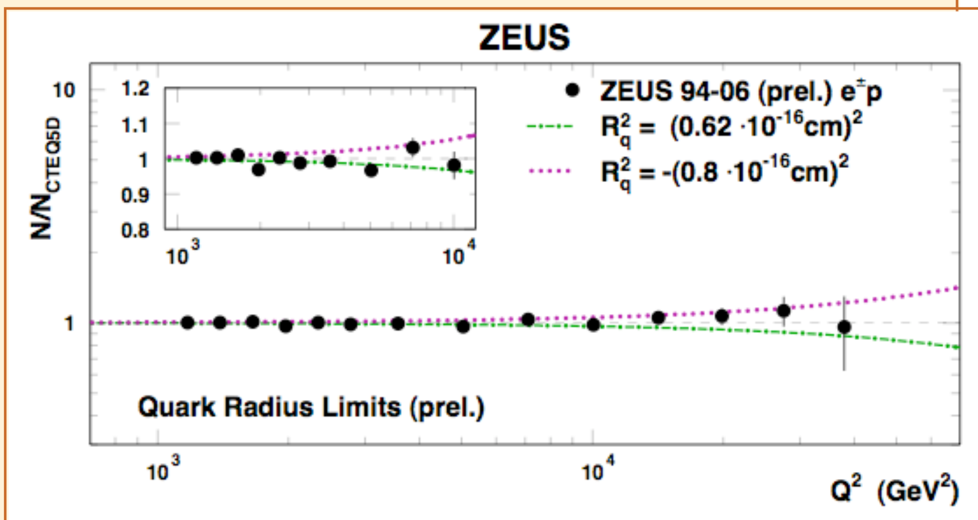
2) Is the quark point like?

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left(1 - \frac{R_q^2}{6} Q^2\right)$$

H1 94-07 data



ZEUS 94-06 data

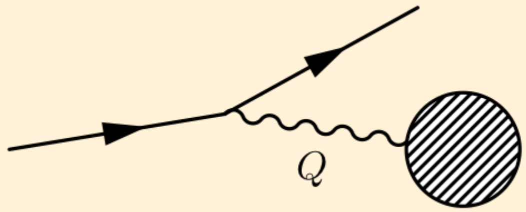


Any deviations? Not so far…
The limit is: $R_Q < 0.6 \times 10^{-18}$ m

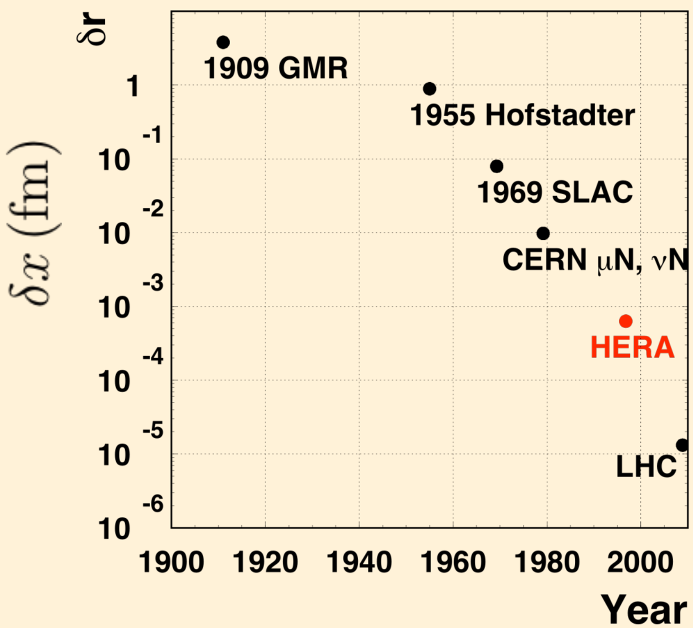
We are probing down to

1/1000 proton radius!!!

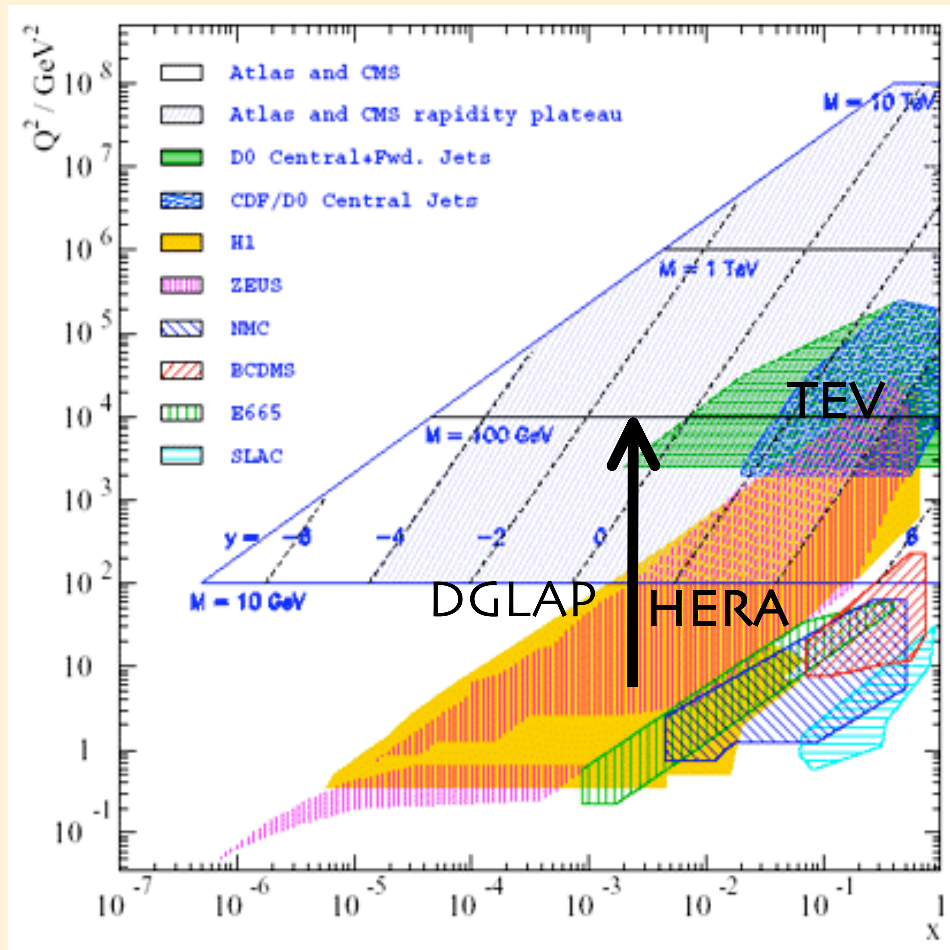
From HERA to LHC: the future



$$\delta x \approx \frac{200\mathrm{MeV}}{Q}$$



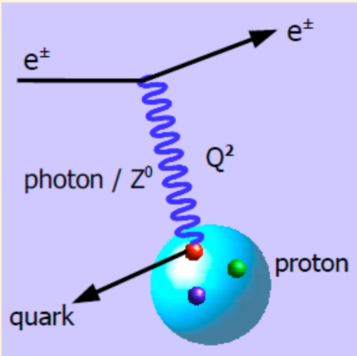
HERA ⟷ LHC Kinematic plane



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

Deep inelastic e±p scattering: probing the proton

NC DIS



$$\frac{d^2\sigma(e^\pm p)}{dQ^2dx} = \frac{2\pi\alpha^2}{Q^4 x} Y_+ \left(F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right); \quad Y_\pm = 1 \pm (1-y)^2$$

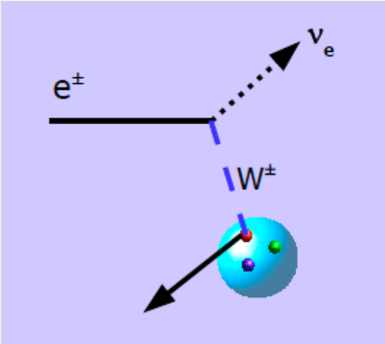
F_2 → valence + sea quarks

F_L → gluon

xF_3 → valence quarks

-> gluons, sea quarks and valence quarks

CC DIS



$$\frac{d^2\sigma^{CC}(e^+p)}{dQ^2dx} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[\overline{u}+\overline{c}+(1-y)^2(d+s)\right] \quad \times (1 + P_e)$$

$$\frac{d^2\sigma^{CC}(e^-p)}{dQ^2dx} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[u+c+(1-y)^2(\overline{d}+\overline{s})\right] \quad \times (1 - P_e)$$

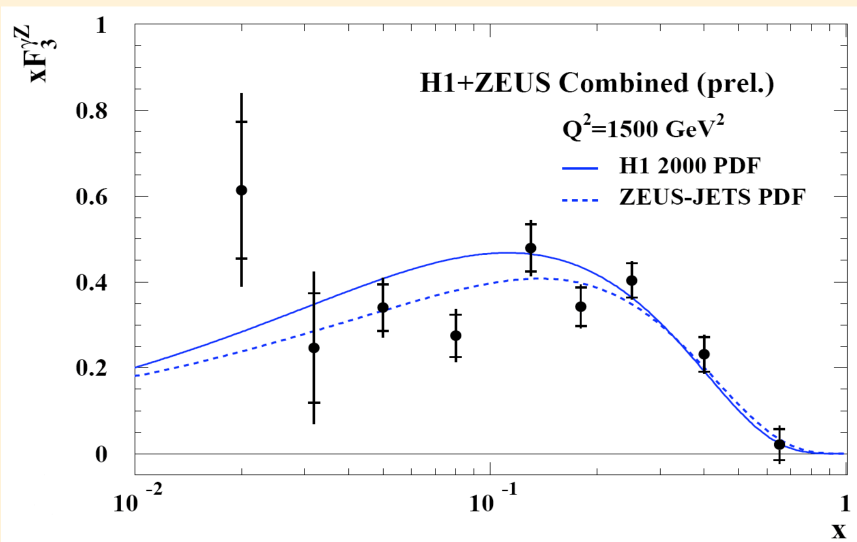
-> flavour separation

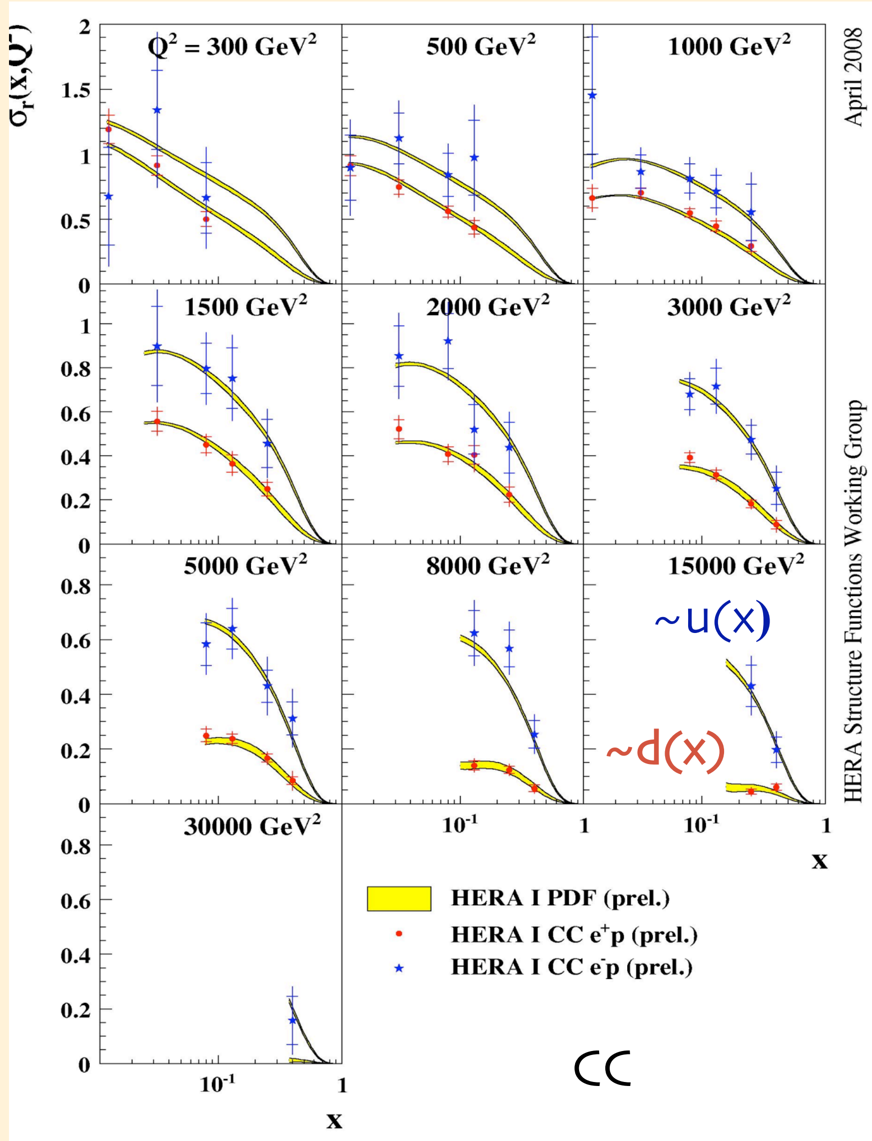
Proton structure: valence quarks

$$xF_3 \propto \sum_{i=u,d,\ldots} (q_i - \overline{q_i})$$

$xF_3 \sim \sigma(e^-) - \sigma(e^+)$
$\sim (2u_v + d_v)$

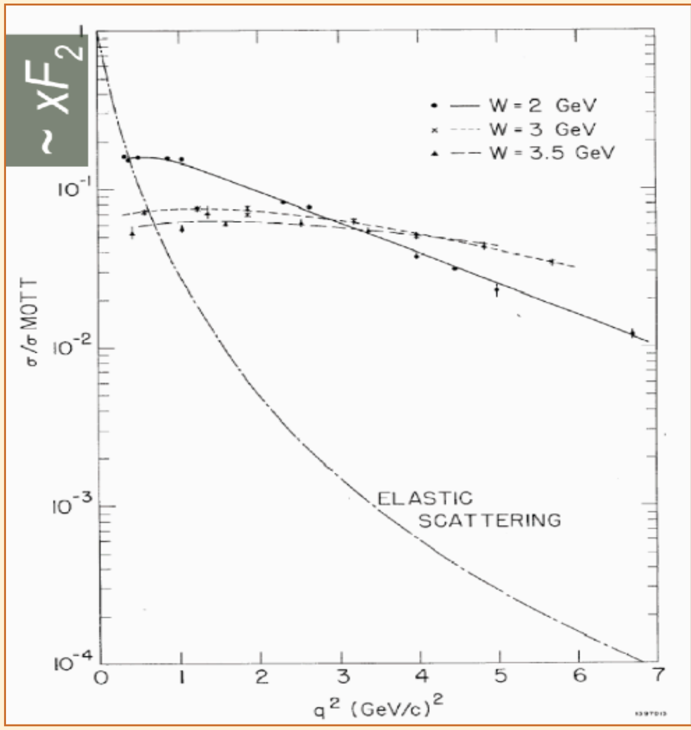
NC



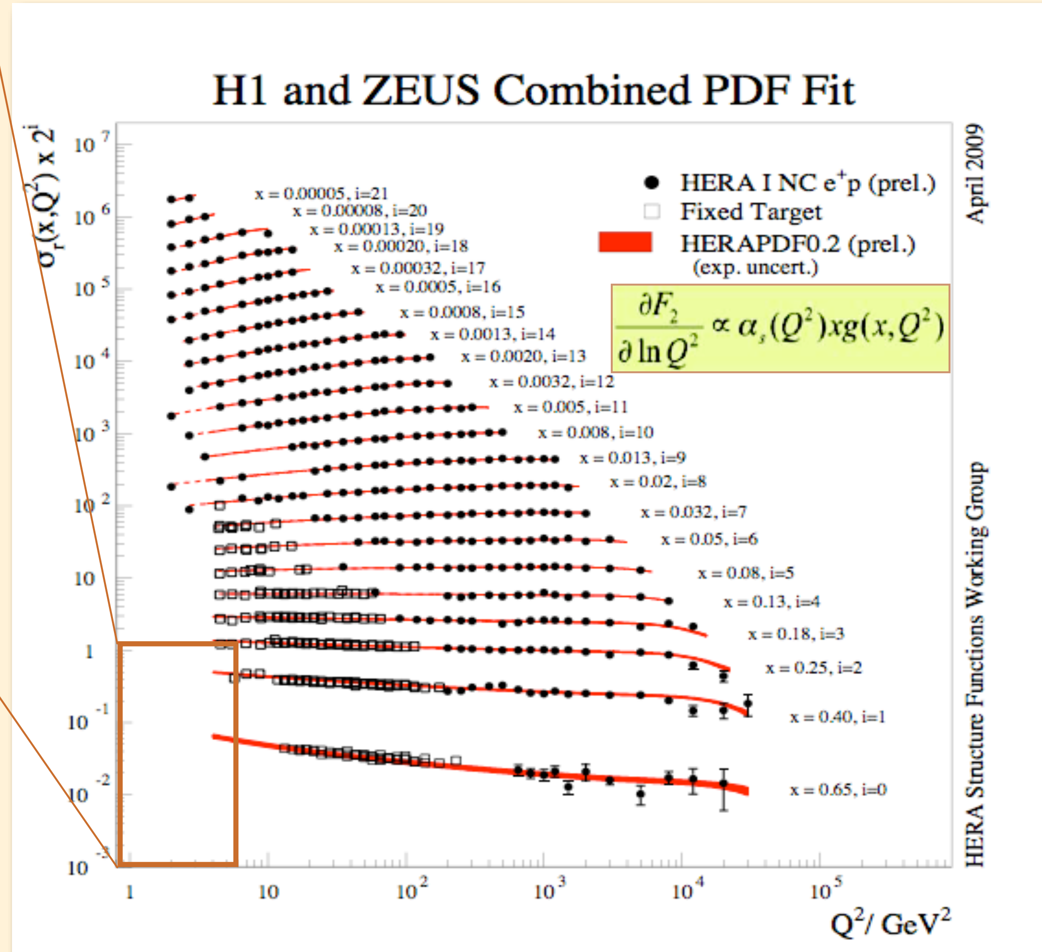


CC

Proton structure: valence + sea quarks



$F_2(x,Q^2)$

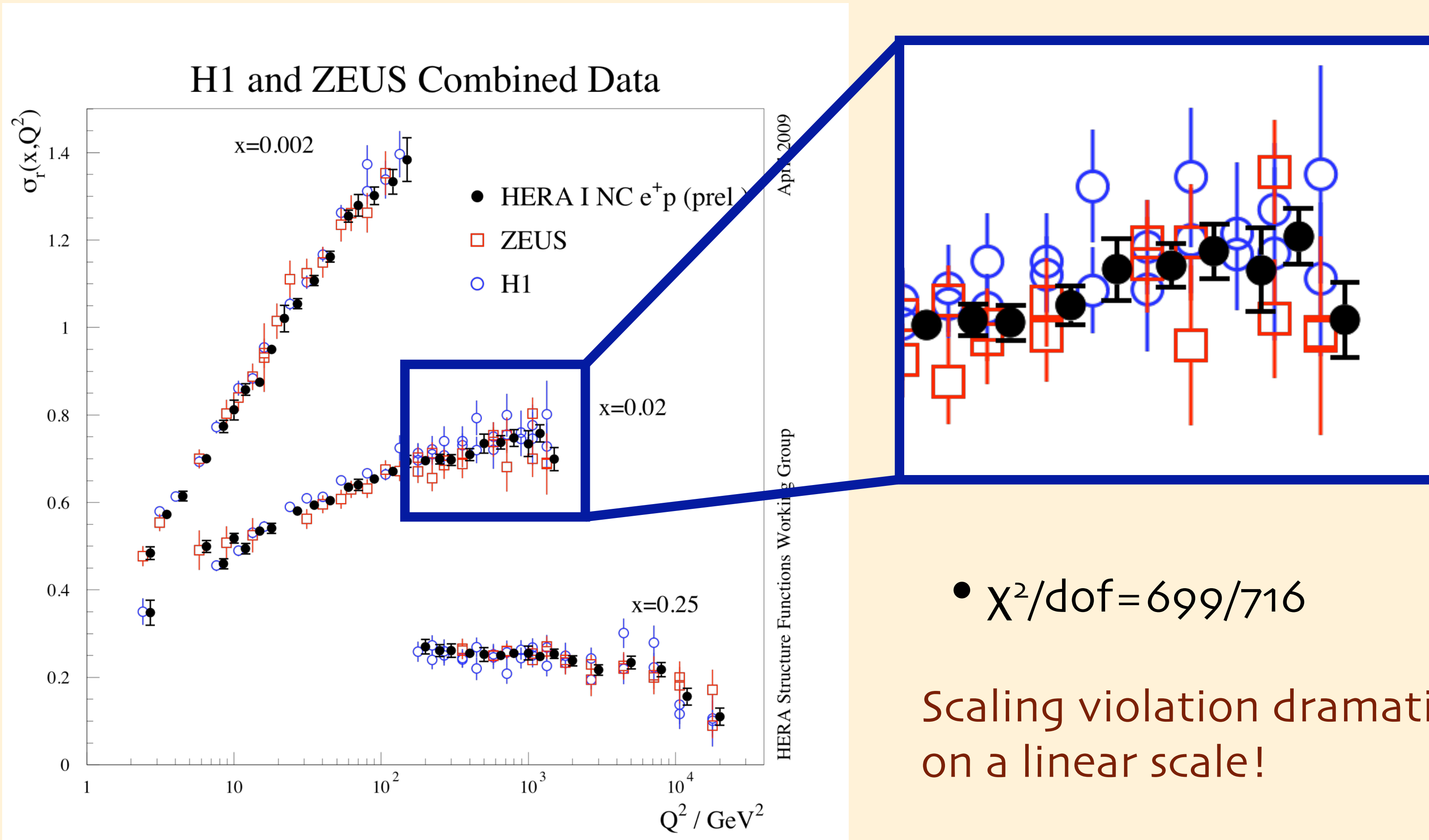


New combination based on full HERA-I inclusive data L=240pb^{-1}

Used as single input to a new QCD analysis:
⇒ HERAPDF0.2

Scaling -> quarks
Scaling violation -> gluons and QCD radiation

Proton structure: power of combining



- χ^2/dof=699/716

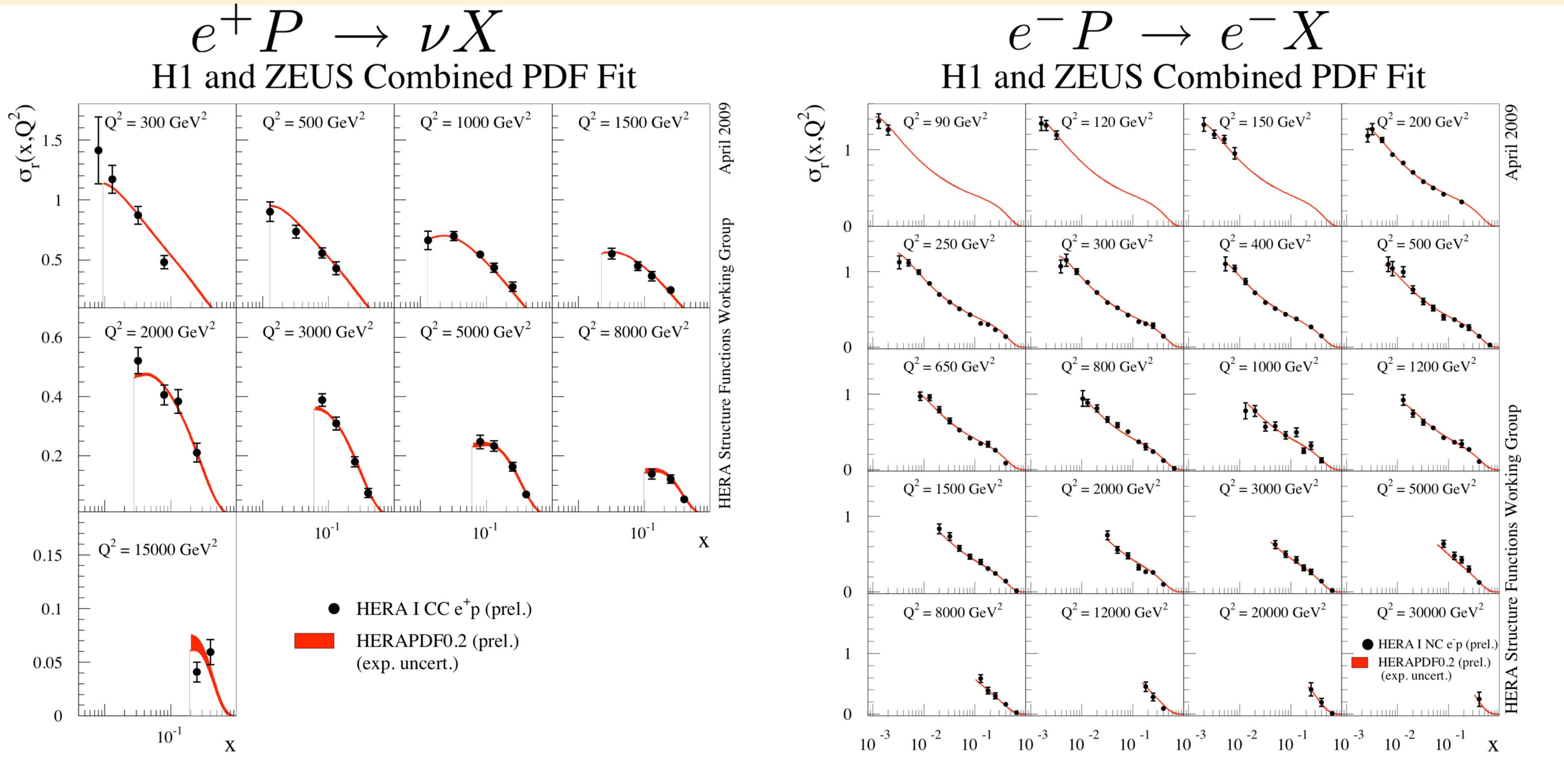
Scaling violation dramatic on a linear scale!

Systematic uncertainties reduced as well as statistical errors

Unprecedented precision due to cross calibration of detectors

Extracting the essence of structure functions

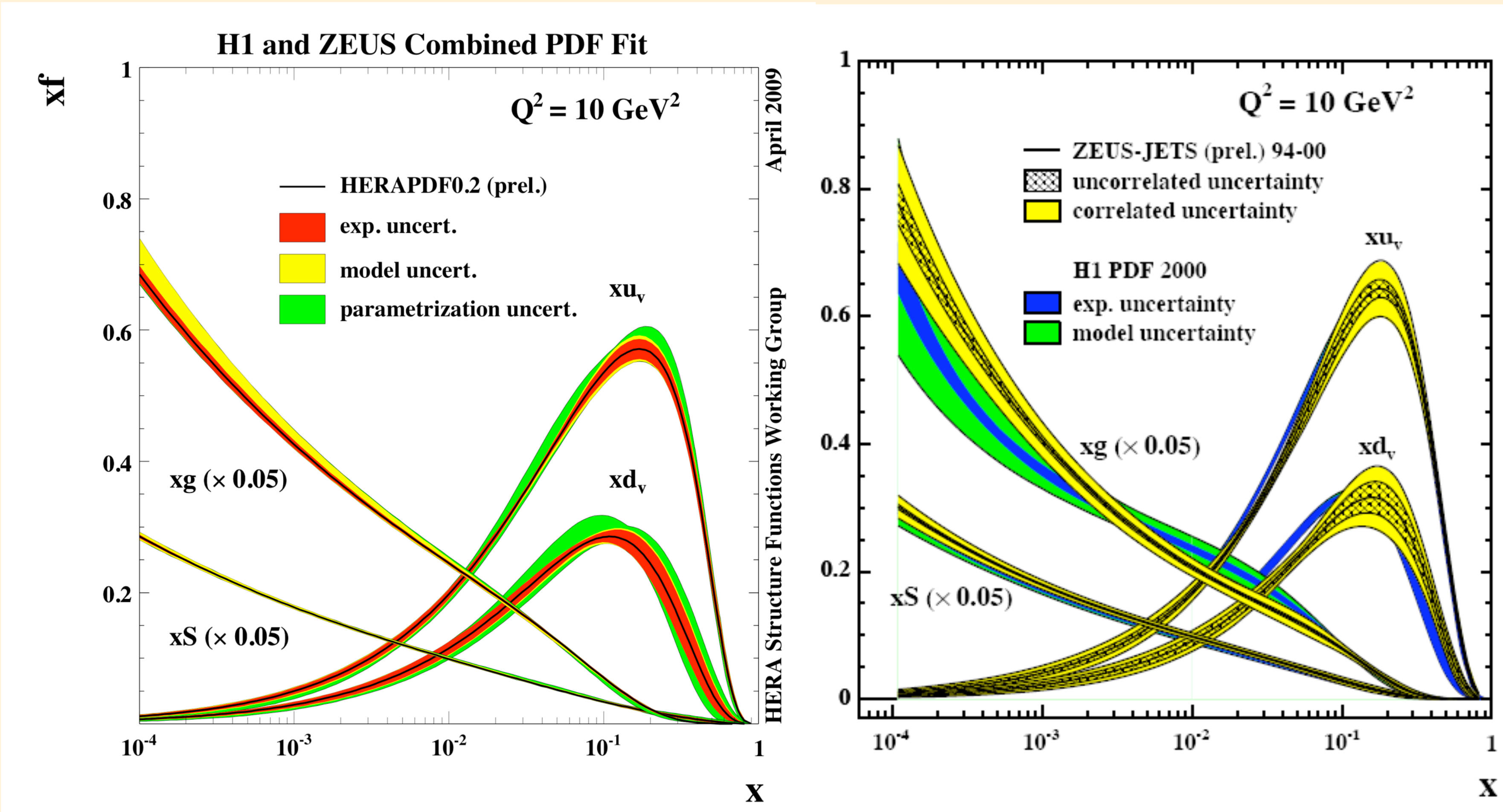
Common PDF Fit on HERA I combined data



Beautiful description for CC/NC and e^+/e^- !!!
(experimental uncertainties included)

Extracting the essence of structure functions

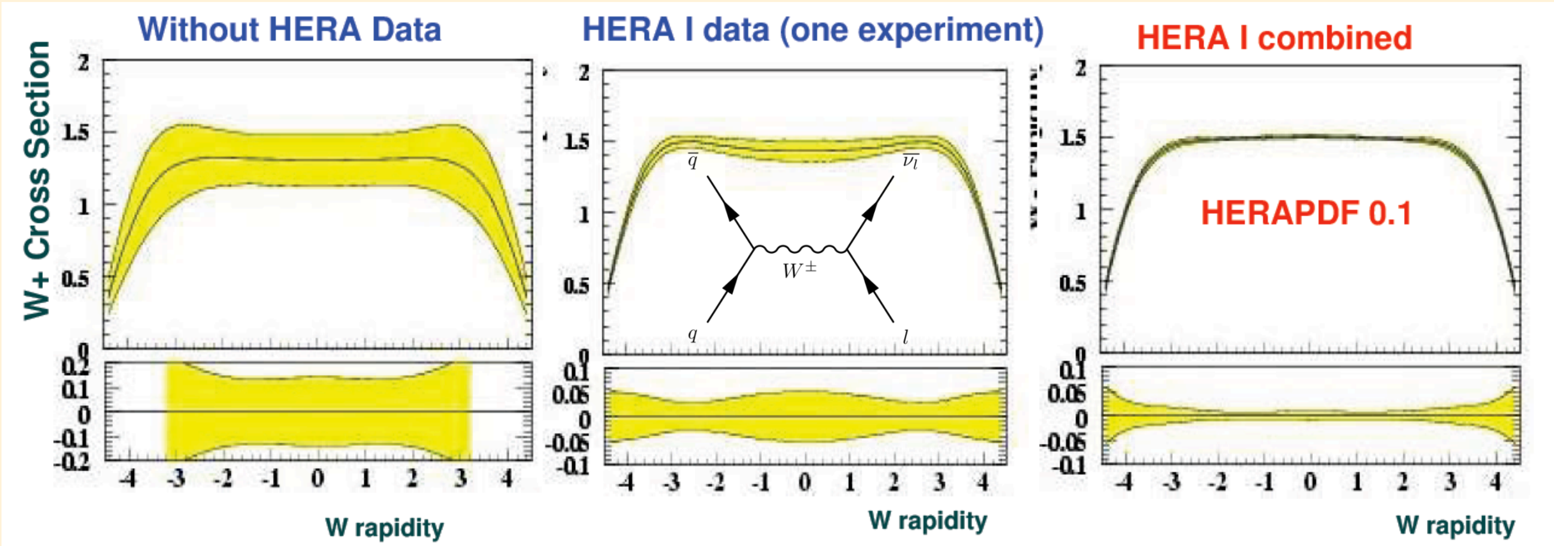
Comparison between HERAPDF0.2 & H1, ZEUS individual fits

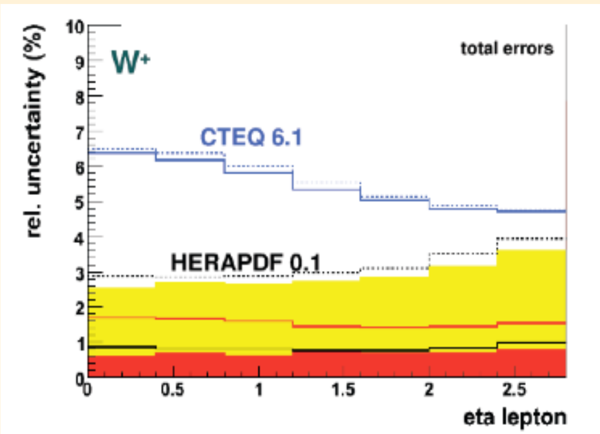


Uncertainty on low-x gluon and sea strongly reduced!

HERAPDF0.1: impact on LHC

An example: W production





Uncertainties ~ 3%

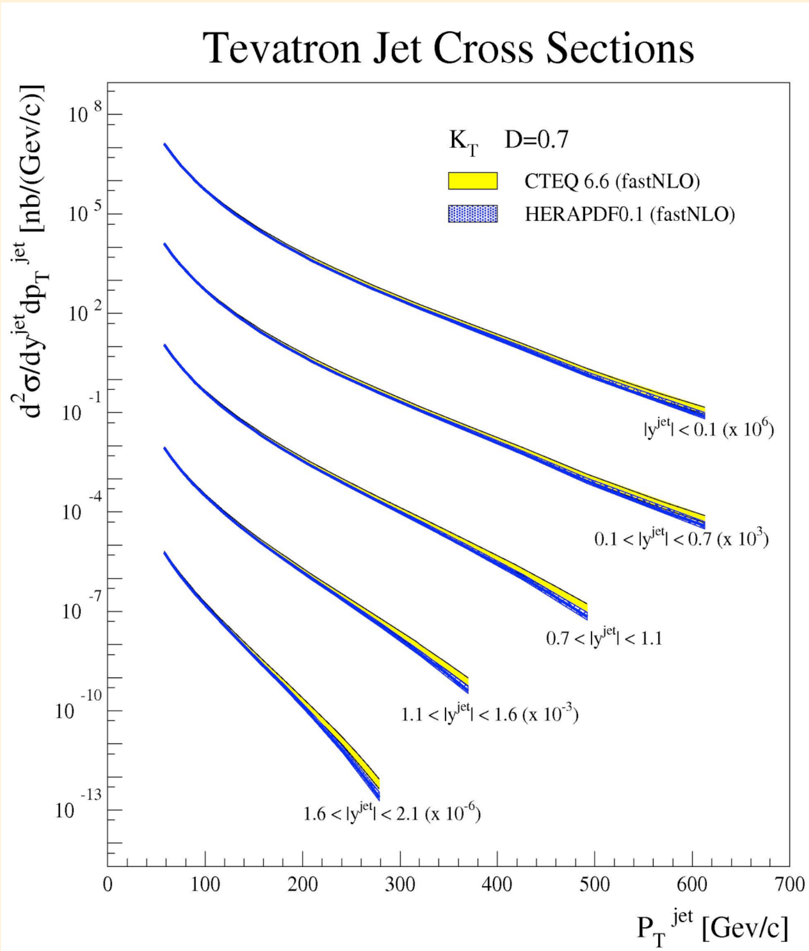
Incredibly precise σ w/ HERAPDF

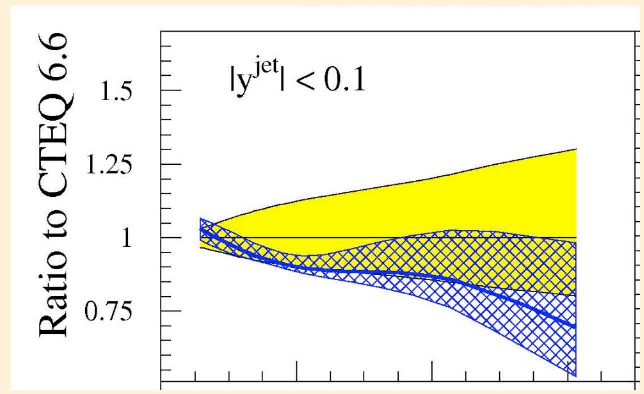
…standard candle for the LHC!

- HERAPDF0.1 is public
- HERAPDF0.2 will be released soon in LHAPDF (version 5.5.x)

HERAPDF0.1: crosscheck with Tevatron

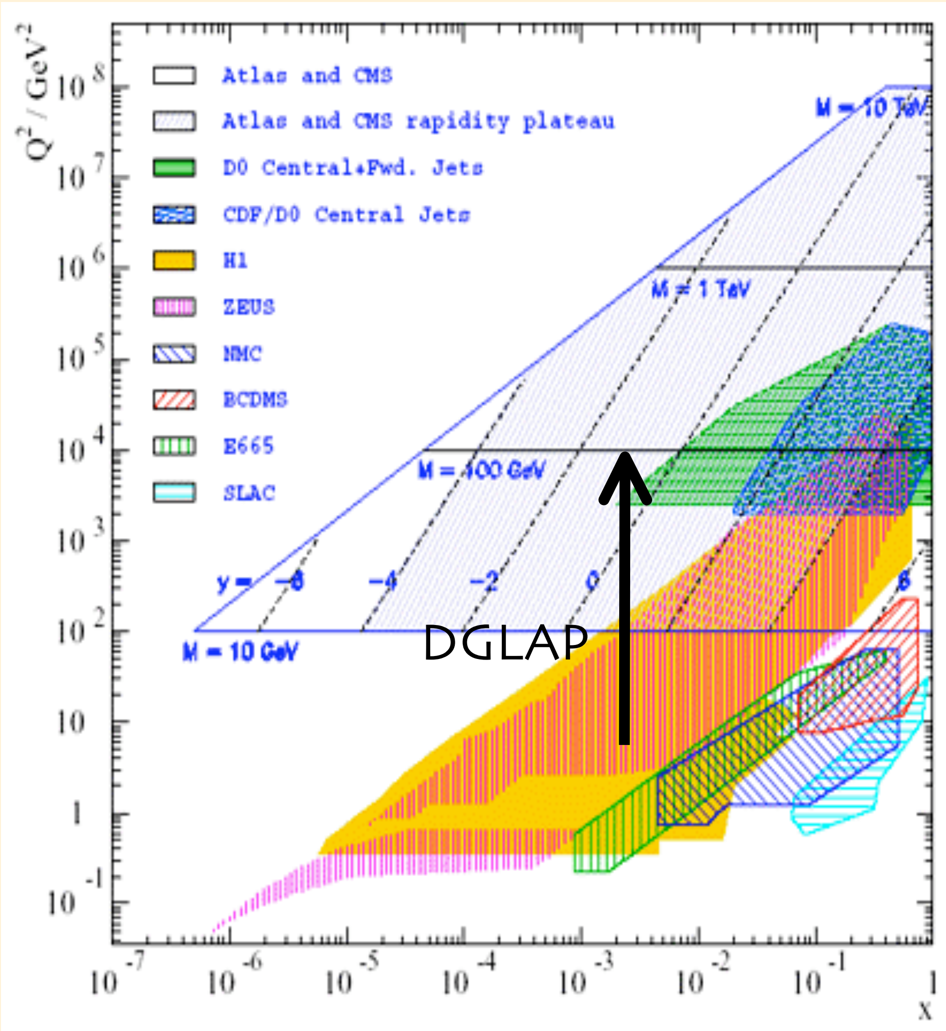
Is HERA-only PDF compatible with Tevatron data?





- HERA not very sensitive to gluon at high x
- CTEQ 6.6 contains Tevatron high E_T jets
- Compatible with HERAPDF

Evolving from HERA to LHC scale…



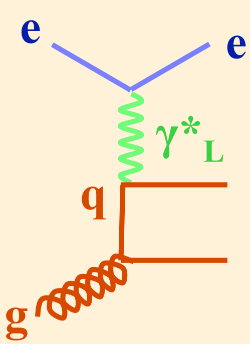
- Beautiful PDFs …

  … but applicable to LHC?
- To move from HERA to LHC, need QCD evolution (DGLAP)
- Question: is DGLAP ok?

  Answer requires an essential piece:
  - SF F_L arises directly from radiation

Powerful way to check DGLAP

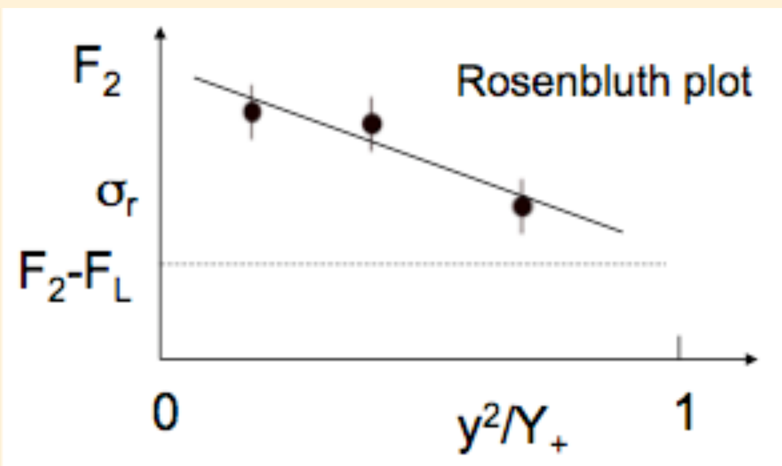
QCD dynamics: directly probing gluon with F_L



- F_L arises from same mechanism which drives DGLAP
- F_L is directly related to the gluon density
- F_L is an independent structure function

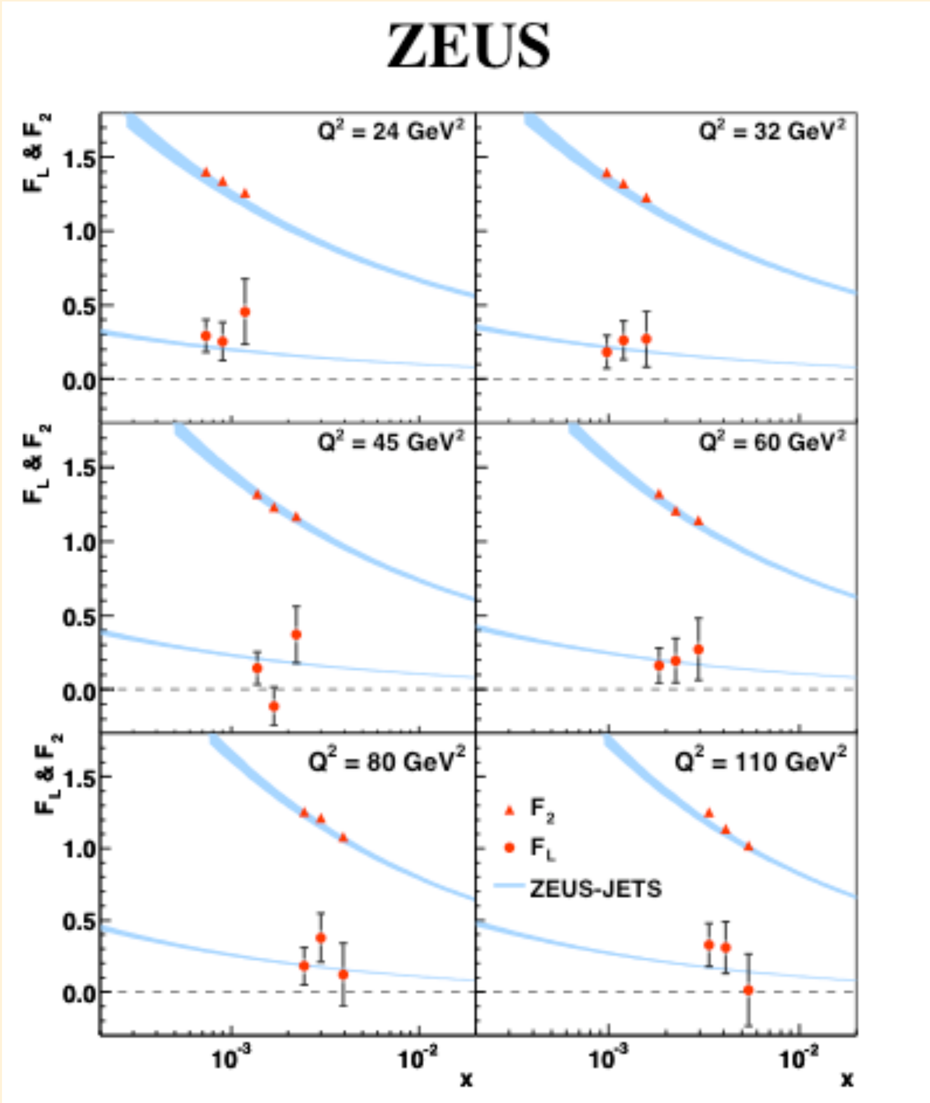
DIS reduced cross section (low x): $\tilde{\sigma} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$

$$Q^2 = sxy$$



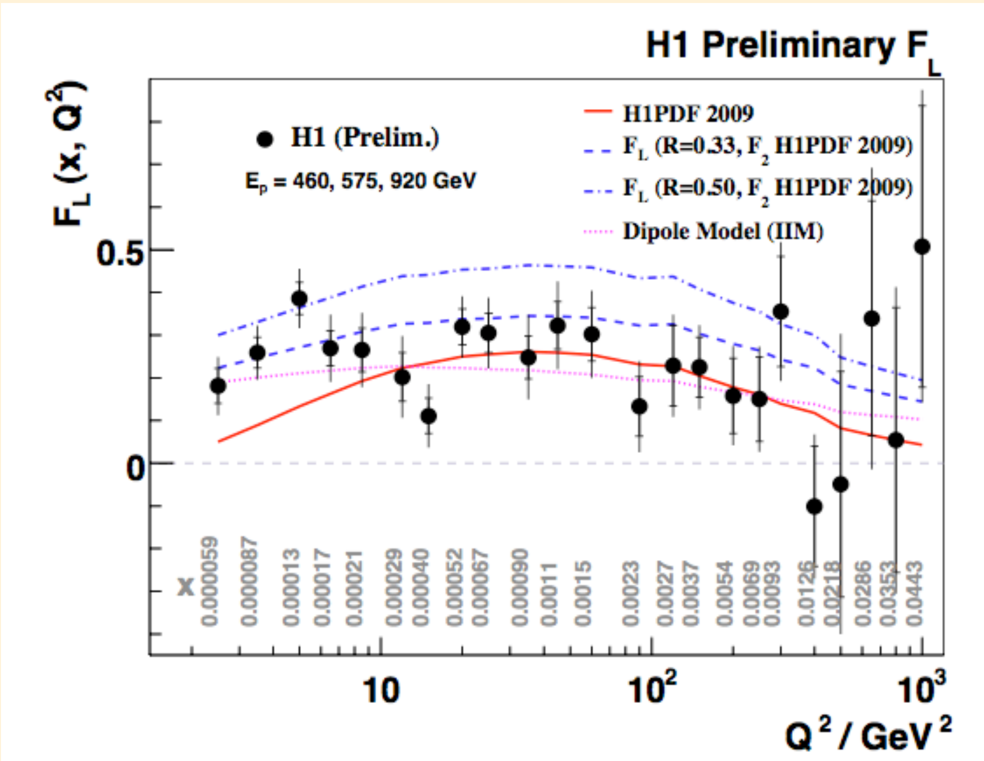
A challenging measurement:
- Identify electrons at small energies
- measure at the edge of acceptance
- control systematics
- need absolute normalization

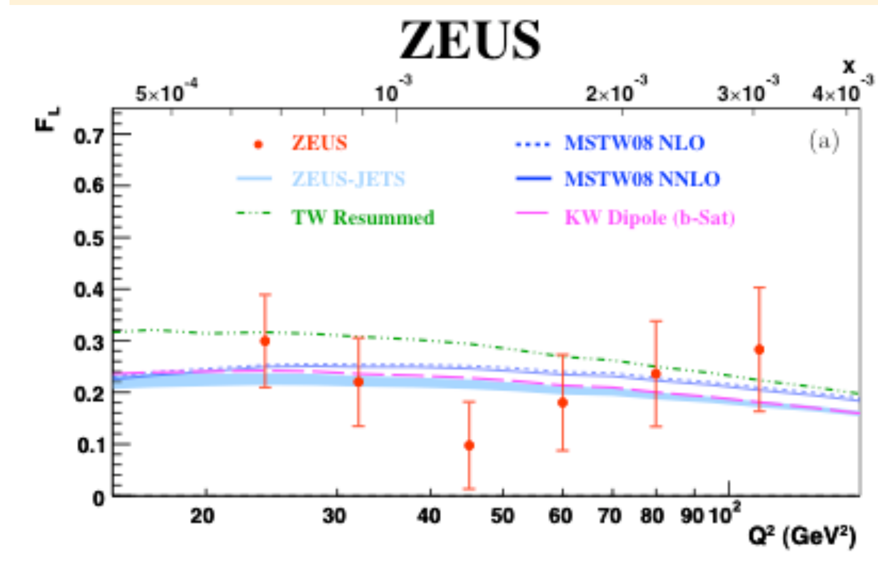
F_L: ZEUS final result



- F_L results …
- … and most precise F_2 so far in this kinematic regime

F_L vs Q^2





F_L is exactly where QCD expects it to be!

This gives us confidence we understand QCD radiation -> DGLAP

Summary: has HERA provided the answers?

- Does the electron probe behave as expected?
  - new effects excluded up to masses of O(300 GeV)
- Is the quark point-like?
  - probed 1/1000 of the proton radius (0.6×10^{-18} m)
- What are the quark and gluon distributions in the proton
  - have precision of 1-3% at $x \sim 10^{-3}$
- Are QCD dynamics well understood to evolve to the LHC scale?
  - new results on F_L inspire confidence

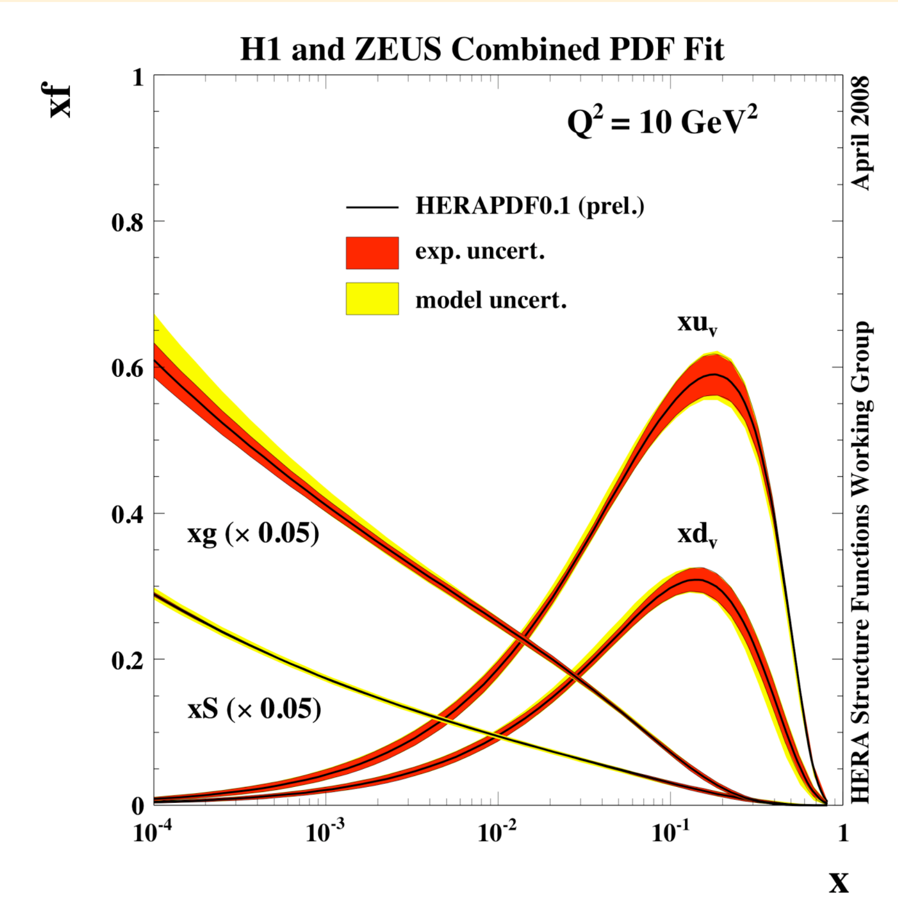
HERA running has finished, but the large data samples collected w/ polarized lepton beams are still being analyzed.

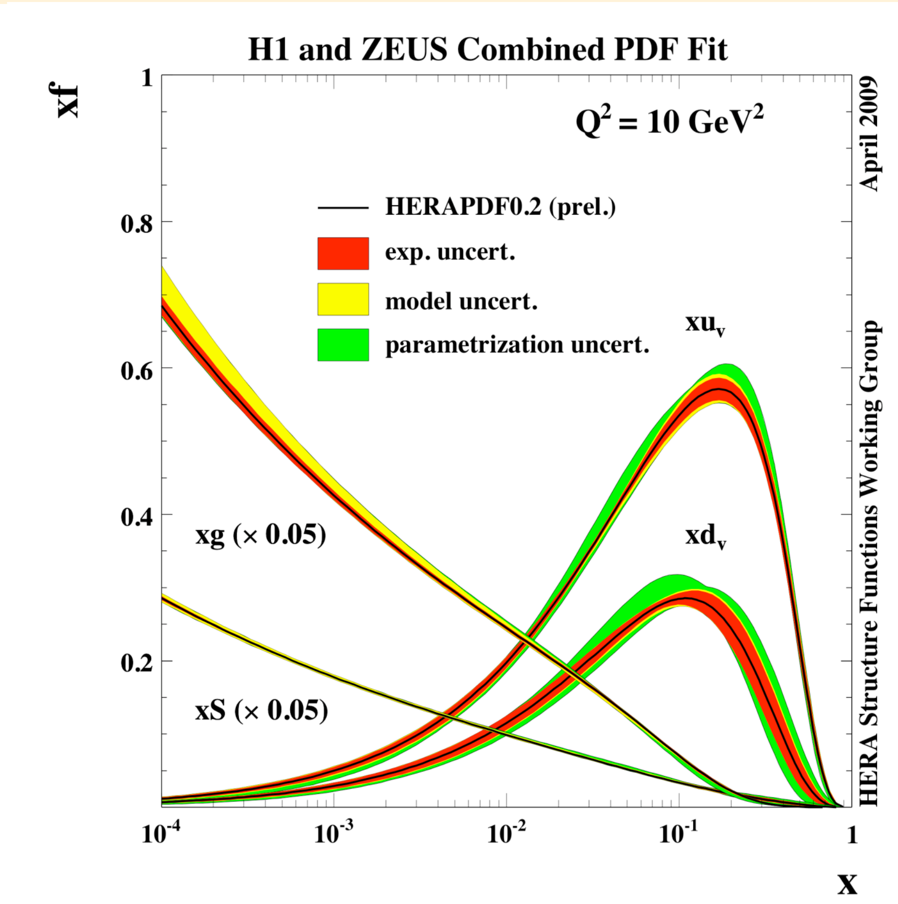
End of an (H)ERA

ZEUS HALL on midnight June 30, 07

Backup slides

HERA PDF 01 vs 02



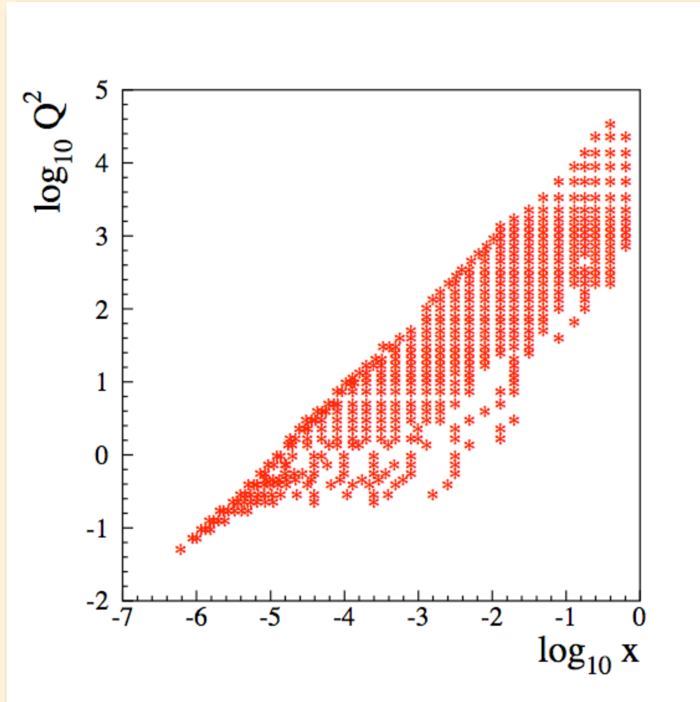


- Errors on gluon even smaller now
- Error on low-x gluon a bit lower…
- But beware: DIFFERENT SCHEMES (ZM-VFNS vs. TR-VFNS)

H1/ZEUS combination

- Combination based on the complete HERA-I inclusive NC and CC DIS data ($L=240\ pb^{-1}$)

  - CC e- p data: H1 98, ZEUS 98
  - CC e+p data: H1 94-97, H1 99-00, ZEUS 94-97, ZEUS 99-00
  - NC e- p data: H1 98, ZEUS 98
  - NC e+p data: ZEUS 96-97, ZEUS 99-00, H1 99-00 "high Q2"
  - H1 95-00 "low Q2" $0.2 \le Q^2 \le 12\ GeV^2$
  - H1 96-00 "bulk" $12 \le Q^2 \le 150\ GeV^2$
  - ZEUS BPC/BPT, SVX95 $0.045 \le Q^2 \le 17\ GeV^2$



- all data swum to common grid
- averaged using least squares fitting with uncorr. systematics as errors
- 110 correlated systematic error sources
- 3 "procedural uncertainties" related to the averaging procedure

H1/ZEUS combination

1) Uncorrelated uncertainties:
Statistical errors
- Point-to-point uncorrelated uncertainties:
  e.g statistical errors due to MC simulations
  are added in quadrature to the statistical errors

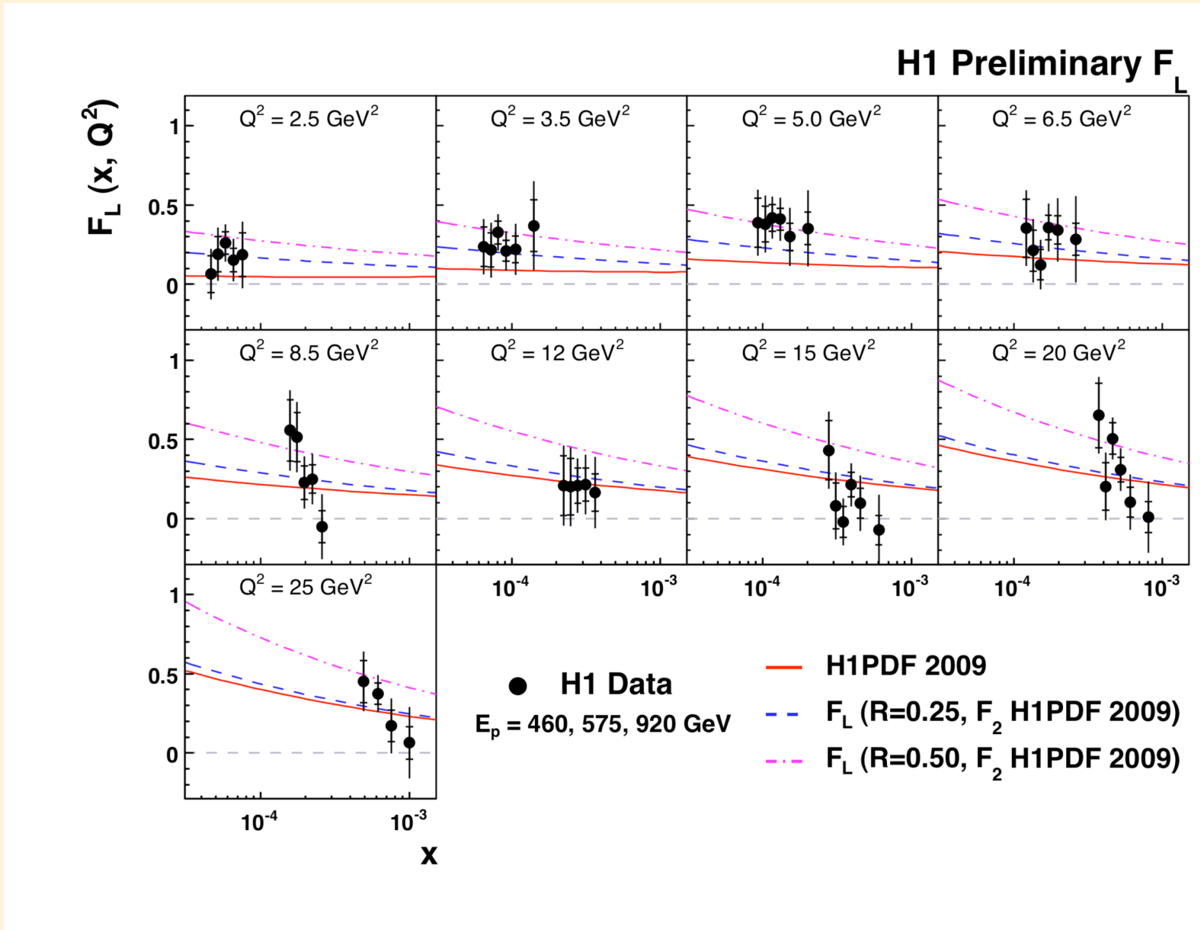
2) Correlated uncertainties:
Point-to-point correlated uncertainties
  e.g. electromagnetic and hadronic energy scale calibration
  Often common for CC and NC for a given experiment and run period

3) Overall normalisation uncertainty:
- Correlated for all data points for a given experiment and run period

4) Correlations between H1 and ZEUS:
- H1 and ZEUS use similar analyses methods
- largest from photo-production MC and hadronic energy scales

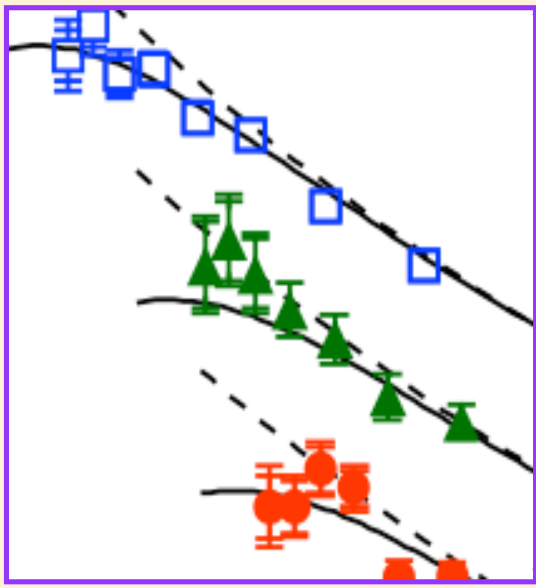
There are 110 systematic errors which are combined in quadrature with the statistical errors and 3 sources of errors from the averaging procedure are offset.
- Small effects observed when errors are treated as correlated

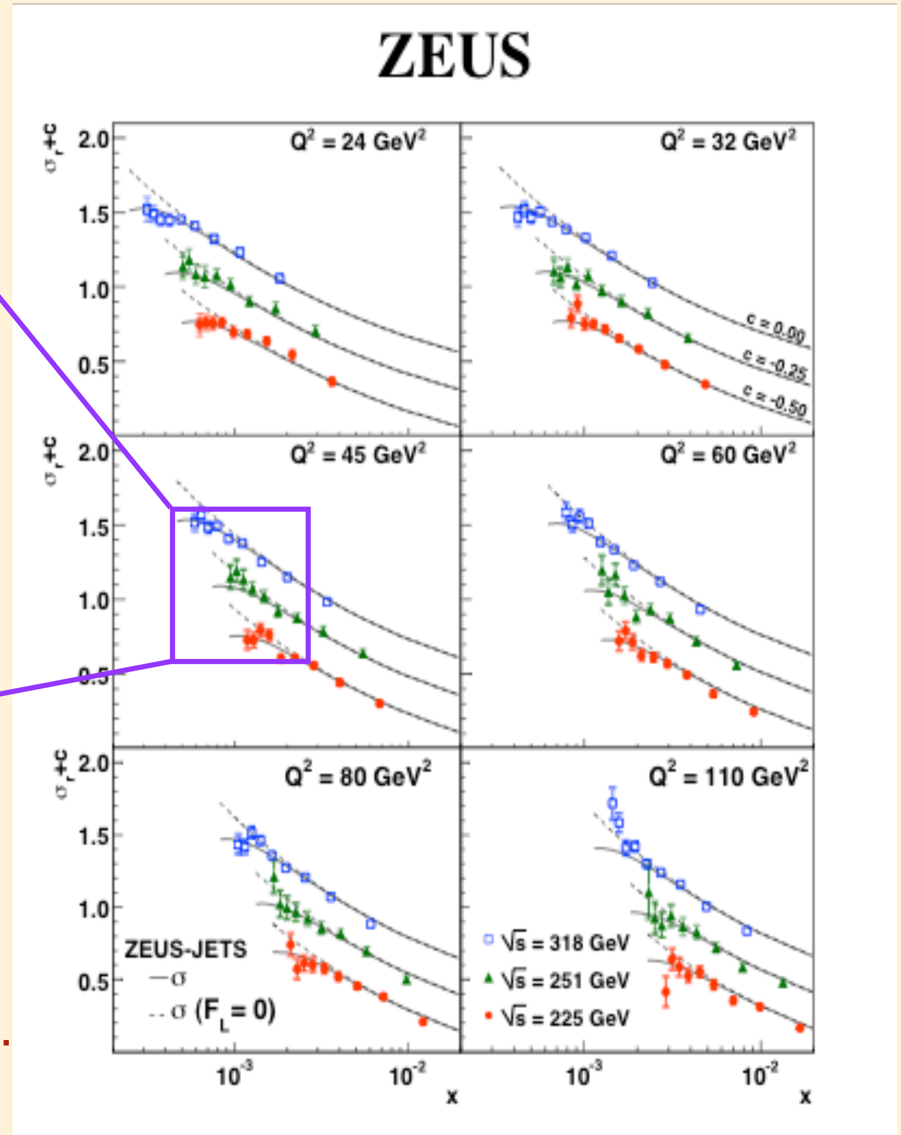
F_L: Most recent H1 result at low Q^2



- Coverage down to low Q^2
- Statistical precision is limited

F_L: ZEUS reduced cross sections





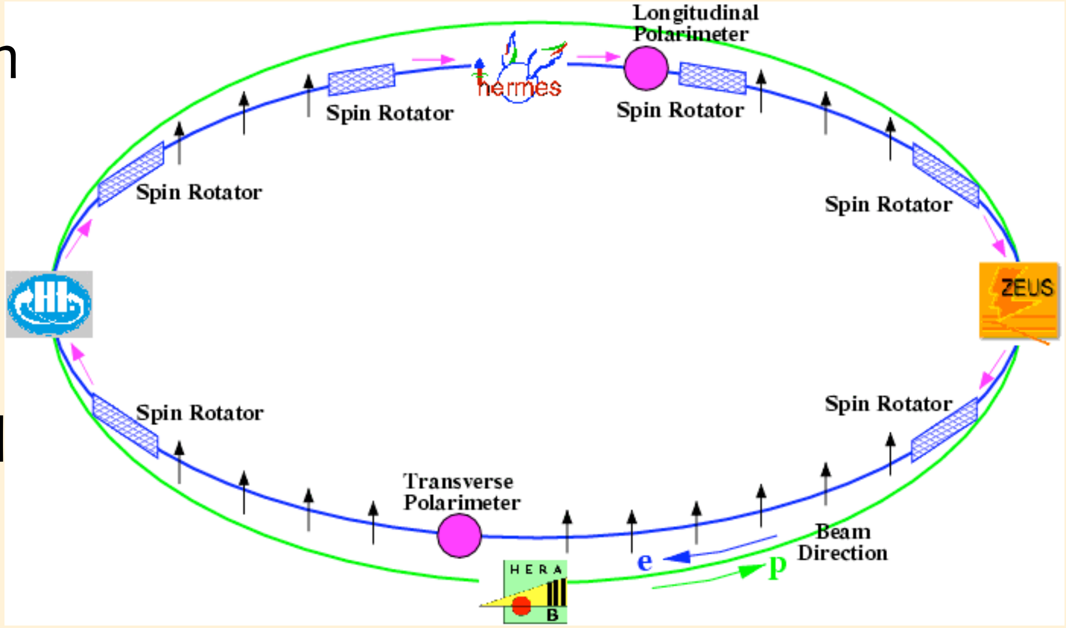
- F_L obtained from differences of cross sections at different CME's
- F_L damps the rise of F_2 at low x
- need to subtract 2 large numbers …
- … hence limited statistical power

HERA operation: polarization

HERA II: 2002 - 2007

Via emission of synchrotron radiation, e beam at HERA becomes transversely polarized

Spin rotators were installed to obtain longitudinal polarization at both IPs



- polarization was measured in dedicated polarimeters
- average (lumi weighted) polarization achieved: 30 - 40%

High Q² CC: total cross sections