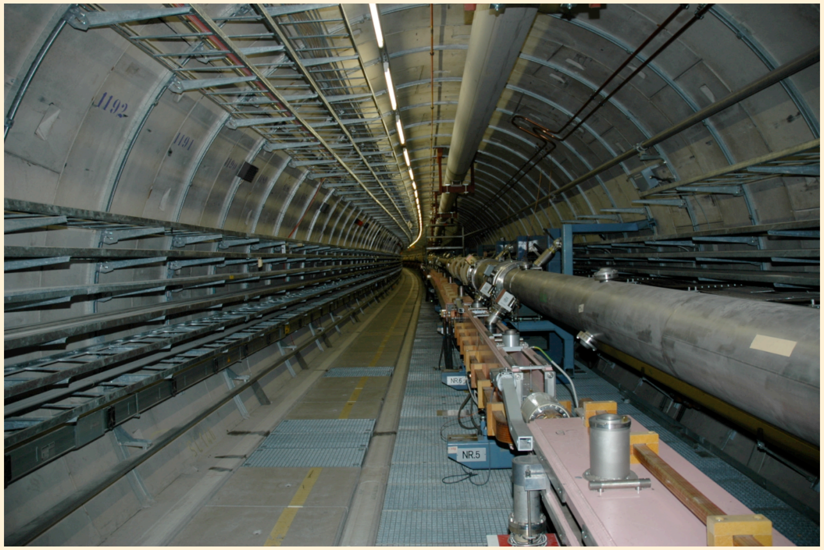
Proton structure :
HERA results and open questions

Amita Raval
DESY

HERA operation



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

HERA operation

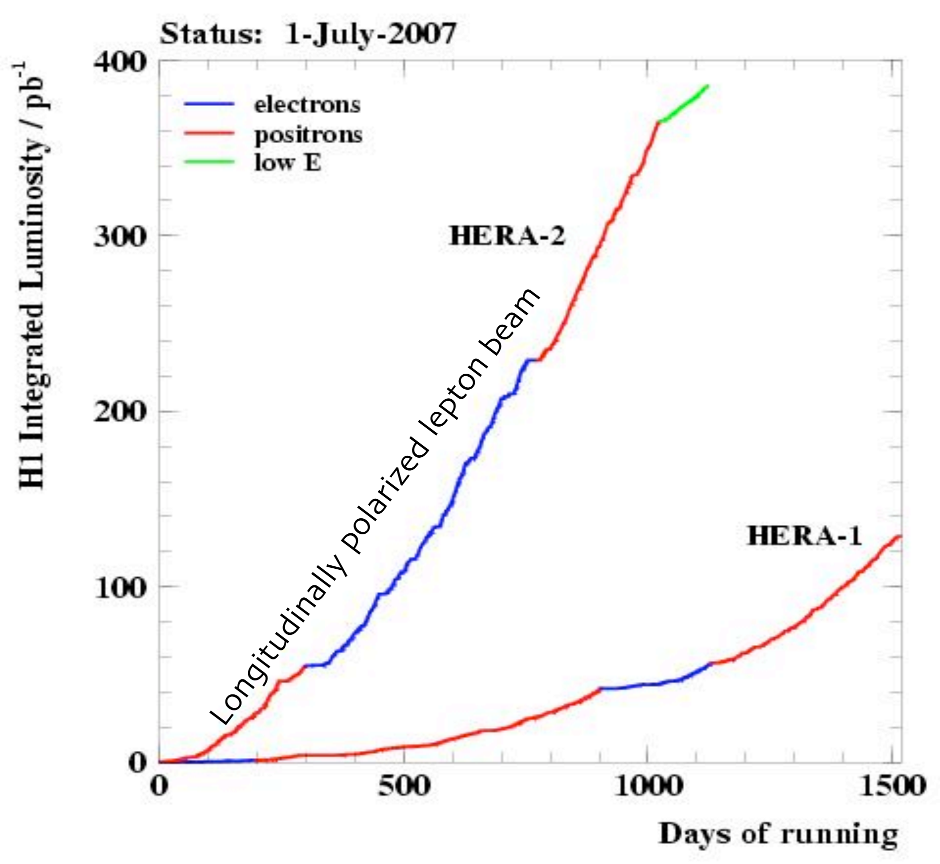

$e^{\pm}$

27.5 GeV

p

820 GeV/
920 GeV

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



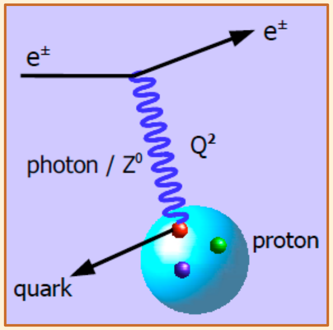
Longitudinally polarized lepton beam

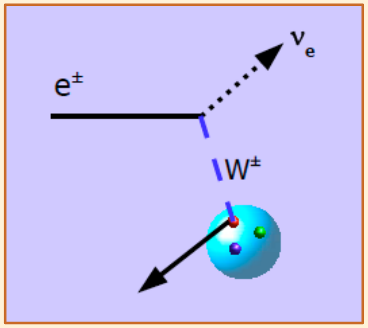
- average (lumi weighted) polarization achieved: 30 - 40%
- e^+p, e^-p samples balanced
- ~ 20 pb^{-1} from low & medium energy running (F_L)
- ~ 0.5 fb^{-1} collected per experiment

Deep inelastic e±p scattering: basics

Two deep inelastic scattering processes:

- Neutral current: exchange of γ or Z⁰
- Charged current: exchange of W±





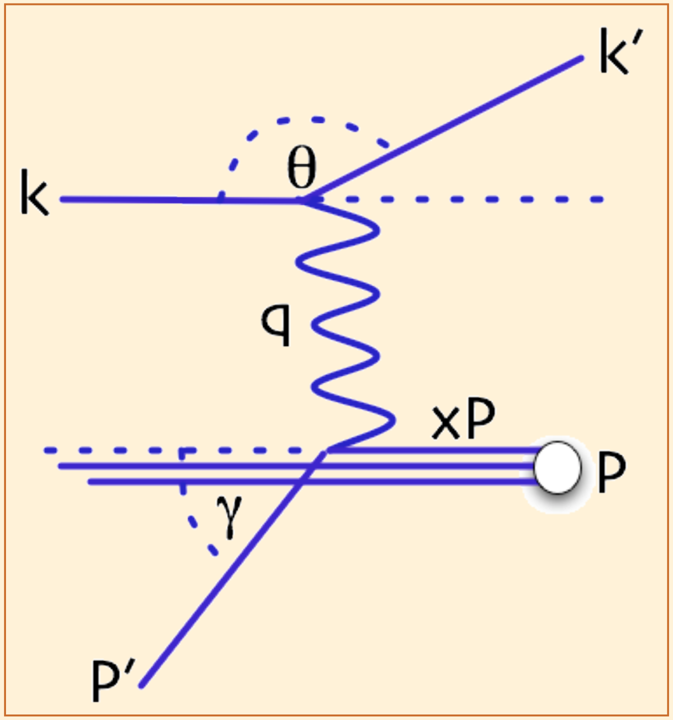
$$Q^2 = -q^2 = -(k - k')^2$$

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

$$y = \frac{p \cdot q}{p \cdot k}$$

$$s = (p + k)^2$$

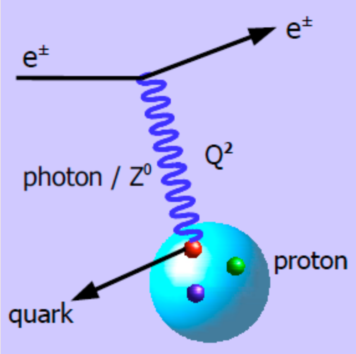
$$Q^2 = x \cdot y \cdot s$$



- Q² 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: $e^- P \rightarrow e^- X$



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

Define polarization of exchanged boson

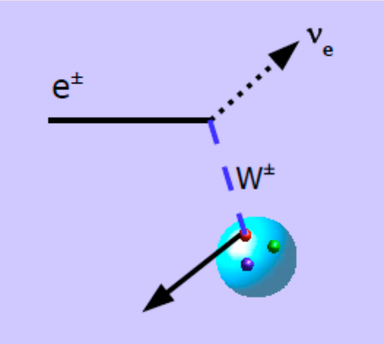
valence + sea quarks

gluon

valence quarks

---> gluons, sea quarks and valence quarks

CC DIS: $e^+ P \rightarrow \nu X$



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

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

---> flavor separation + more …

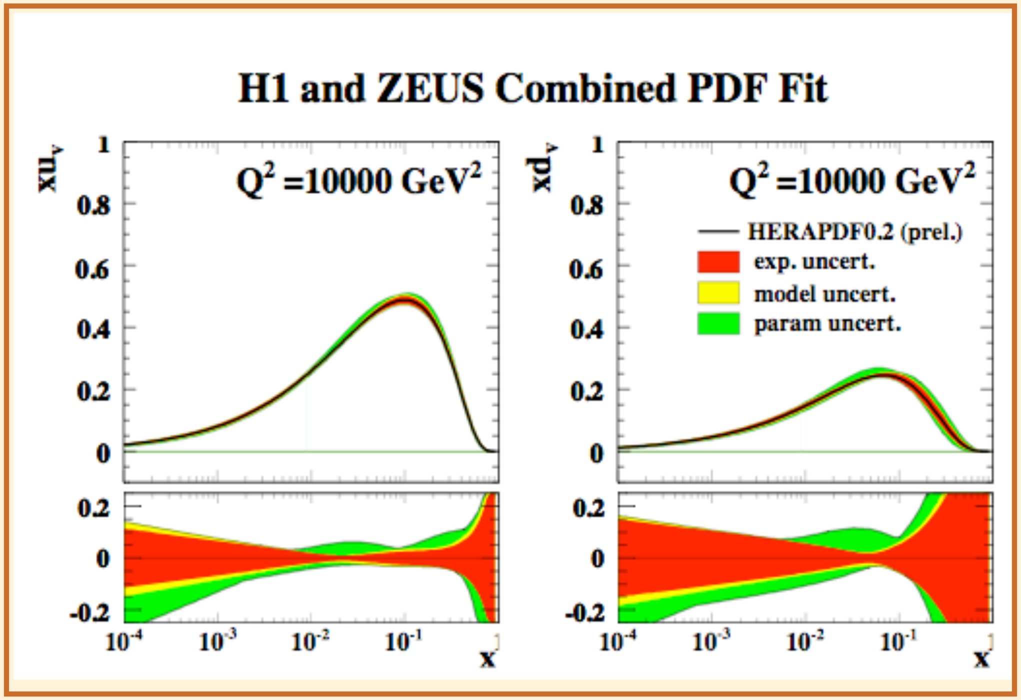
Deep inelastic e+p scattering: CC cross section

$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = (1+P)\frac{G_F^2}{2\pi}\frac{M_W^4}{(Q^2+M_W^2)^2}\boxed{[(\bar{u}+\bar{c})+(1-y)^2(d+s)]}$$

Combination of charge and helicity conservation provides a flavour specific probe of the proton PDFs

➔ charged current provides sensitivity to d-quark, which is poorly constrained.

➔ important for luminosity measurement at the LHC



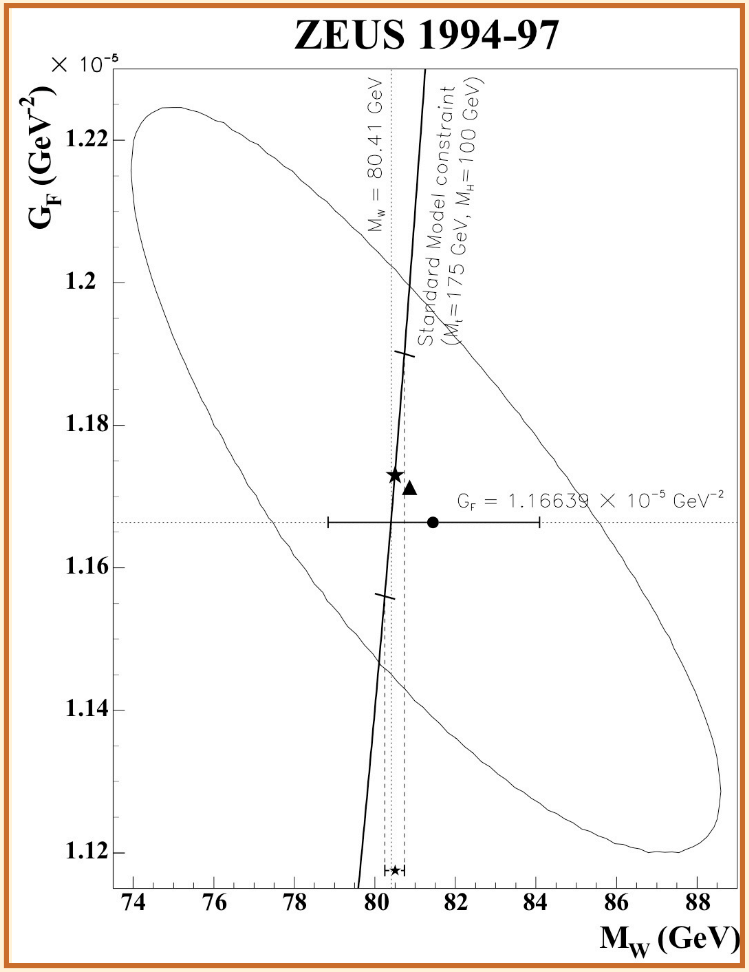
Deep inelastic e+p scattering: CC cross section

$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = (1+P)\boxed{\frac{G_F^2}{2\pi}\frac{M_W^4}{(Q^2+M_W^2)^2}}[(\bar{u}+\bar{c})+(1-y)^2(d+s)]$$

Sensitivity to electro-weak parameters M_W and G_F

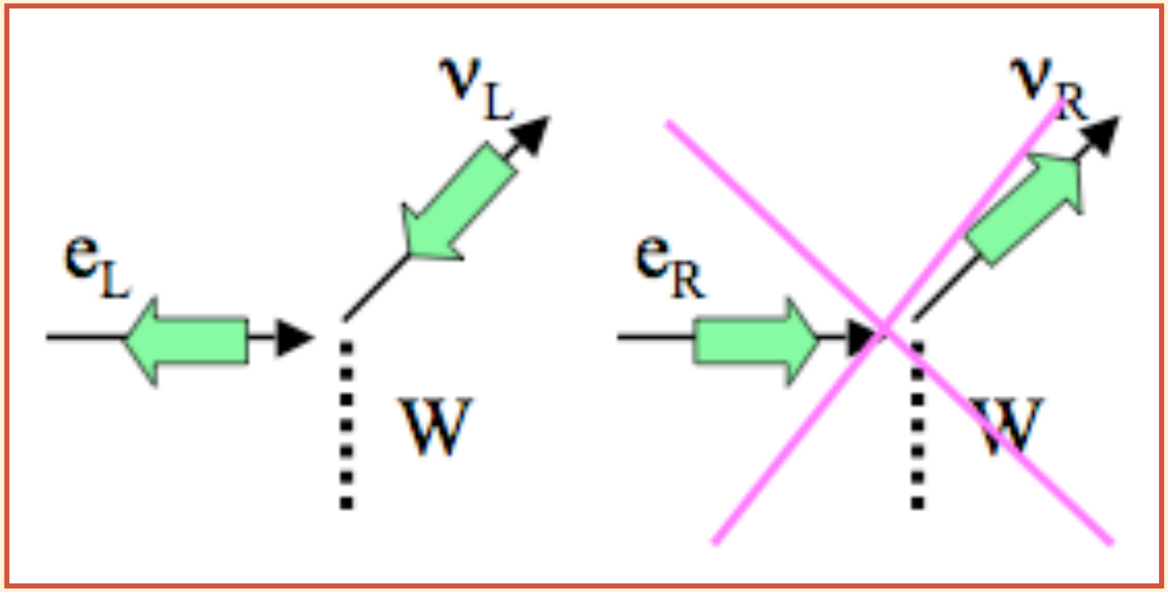
Results of fits for M_W and G_F made under different assumptions ➔ ➔ ➔

Eur. Phys. J. C 12, 411 (2000) ➔



Deep inelastic e+p scattering: CC cross section

$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = \boxed{(1+P)} \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2+M_W^2)^2} [(\overline{u}+\overline{c}) + (1-y)^2(d+s)]$$



Test of chiral structure of SM ➔ parity non-conservation

Outline: questions HERA has addressed

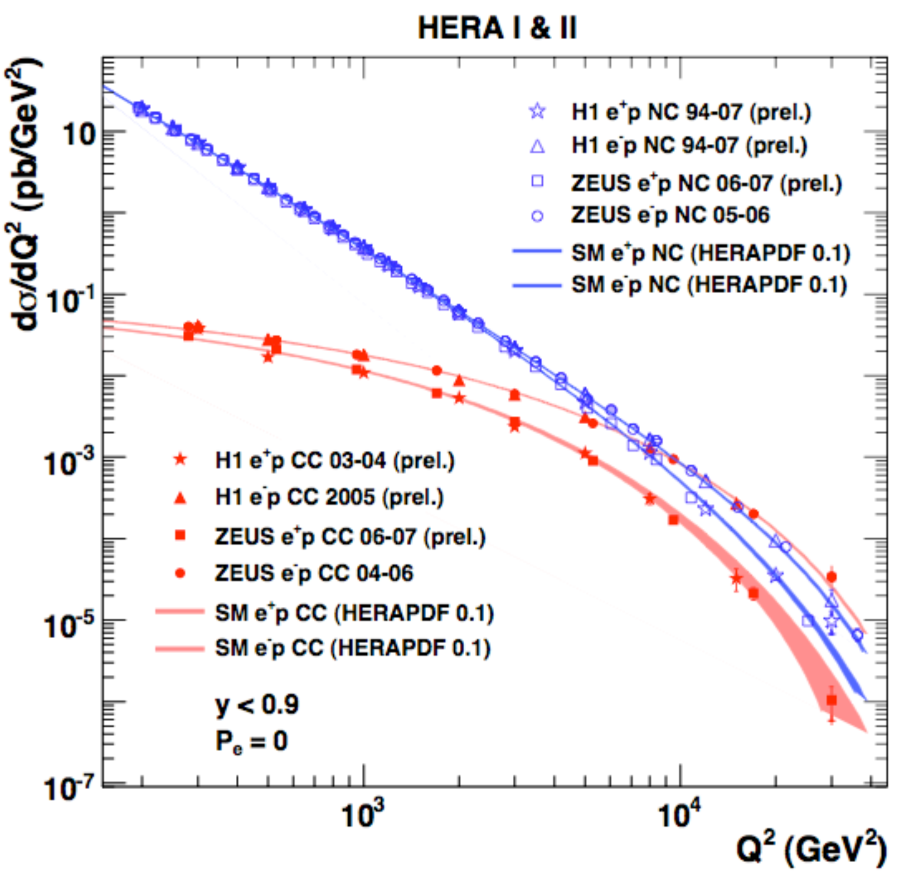
1) Does the electron probe behave as expected?

2) Is the quark point like?

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

4) Are QCD dynamics well understood?

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 F3)

Effect of probe charge:

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

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

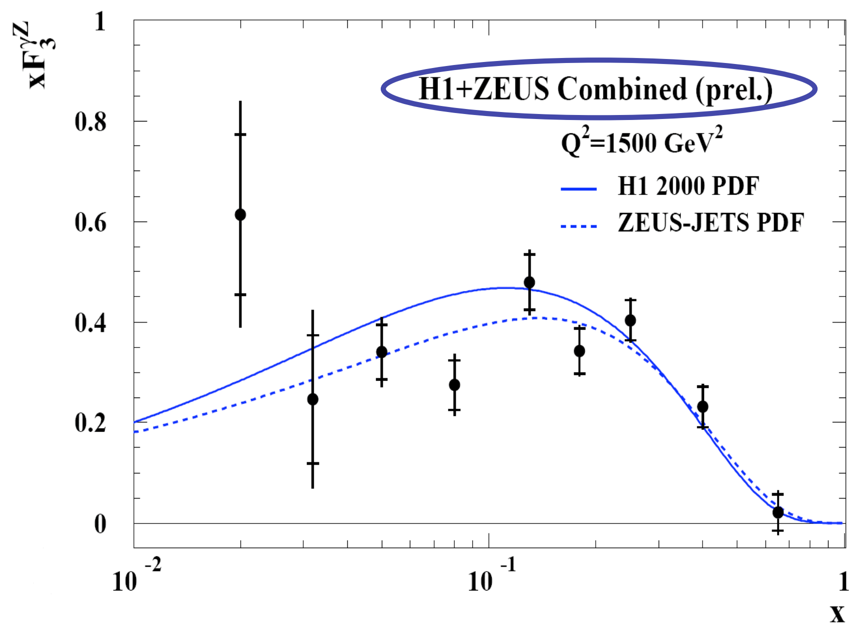
The electron probe indeed behaves as expected!

Proton structure: valence quarks

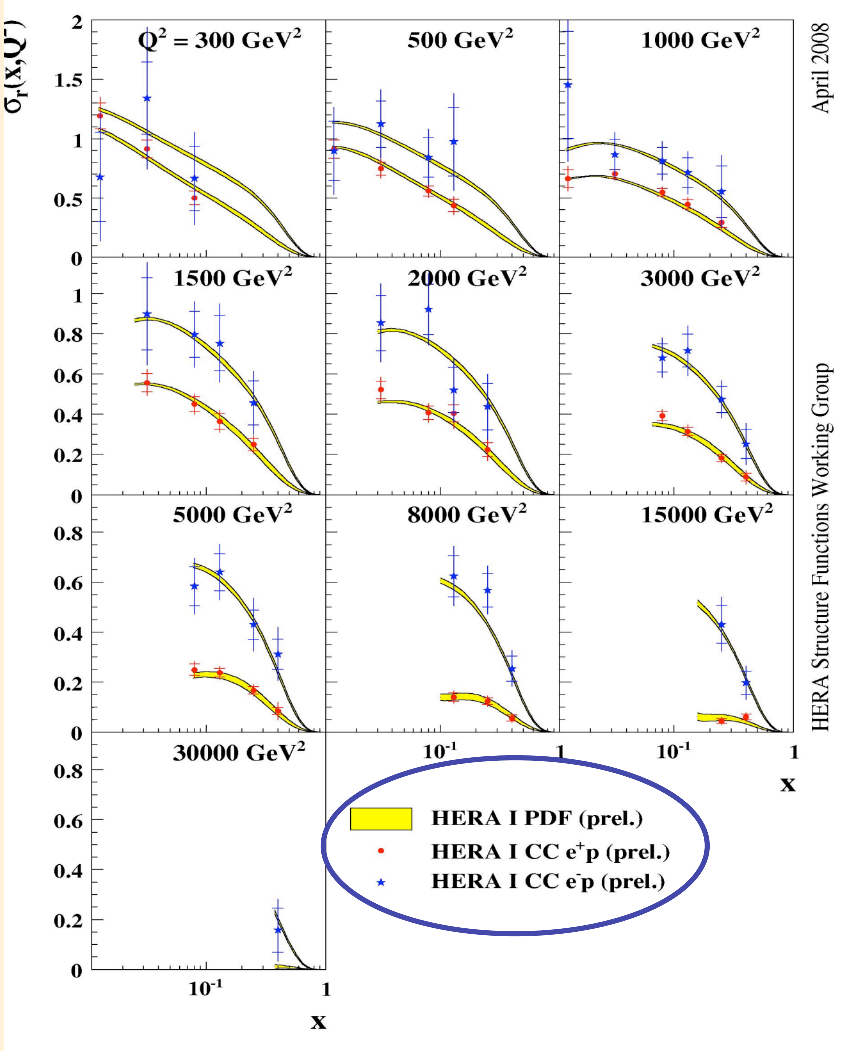
$$xF_3 \propto \sum_{i=u,d,...} (q_i - \overline{q_i})$$

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

HERA I: NC $e^- P \to e^- X$



HERA I: CC $e^+ P \to \nu X$

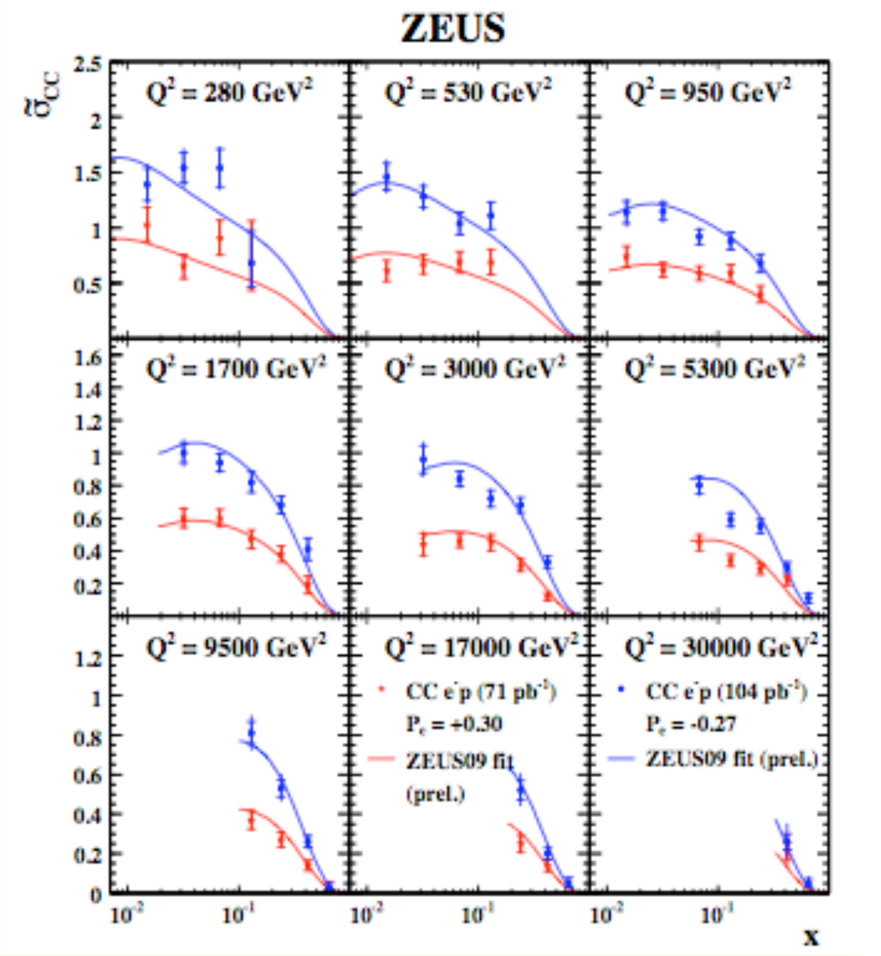


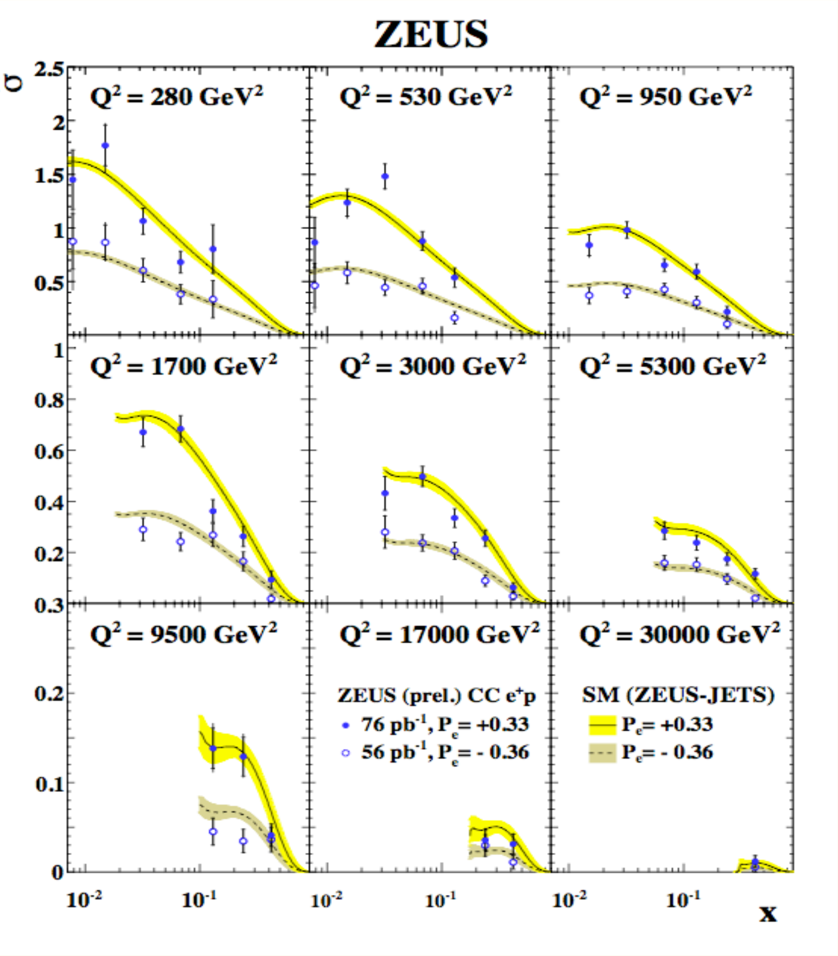
Proton structure: valence quarks II

CC double differential cross section at high Q^2

HERA II: $e^-P \to e^-X$

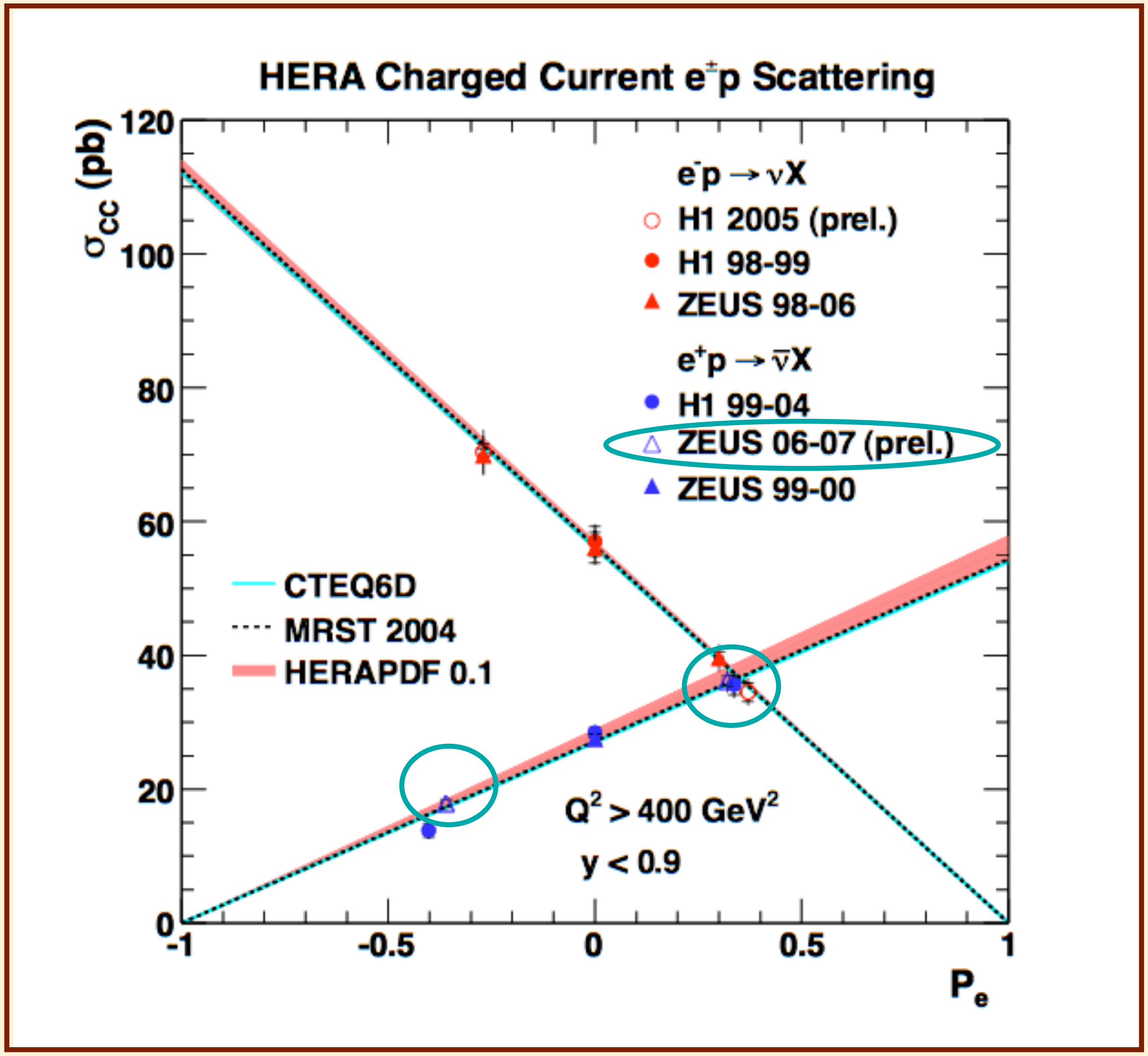
HERA II: $e^+P \longrightarrow e^+X$





Proton structure: test of chiral structure of SM

CC total cross section at high Q^2

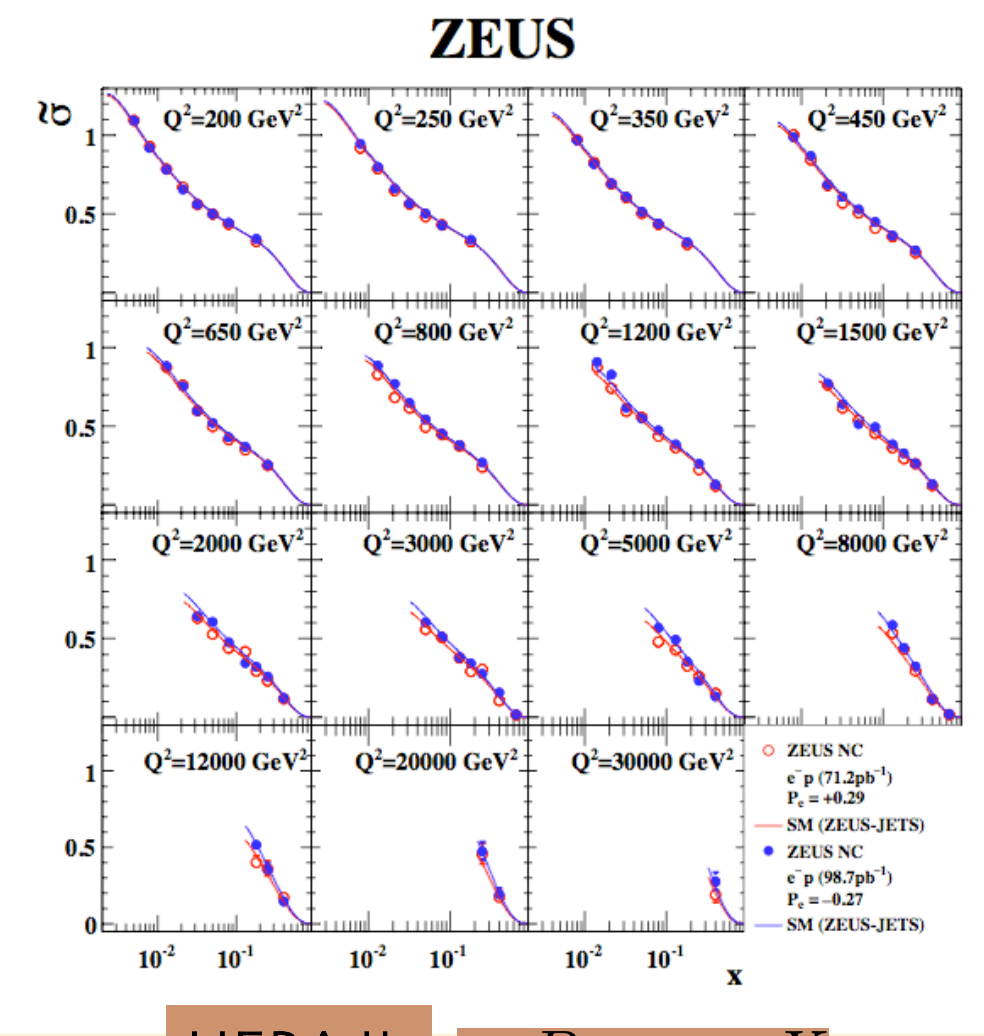


- linearly proportional to the degree of the longitudinal lepton beam polarization

- consistent with no right-handed weak currents

Proton structure: valence quarks IV

NC cross section at high Q^2



HERA II: $e^- P \rightarrow e^- X$

Neglecting pure Z exchange term, generalized F_2:

$$F_2^{\pm} \approx F_2^{\gamma} + k(-\upsilon_e \mp P a_e) F_2^{\gamma Z}$$

Where: $k = \dfrac{1}{4\sin^2\theta_W \cos^2\theta_W} \dfrac{Q^2}{Q^2 + M_Z^2}$

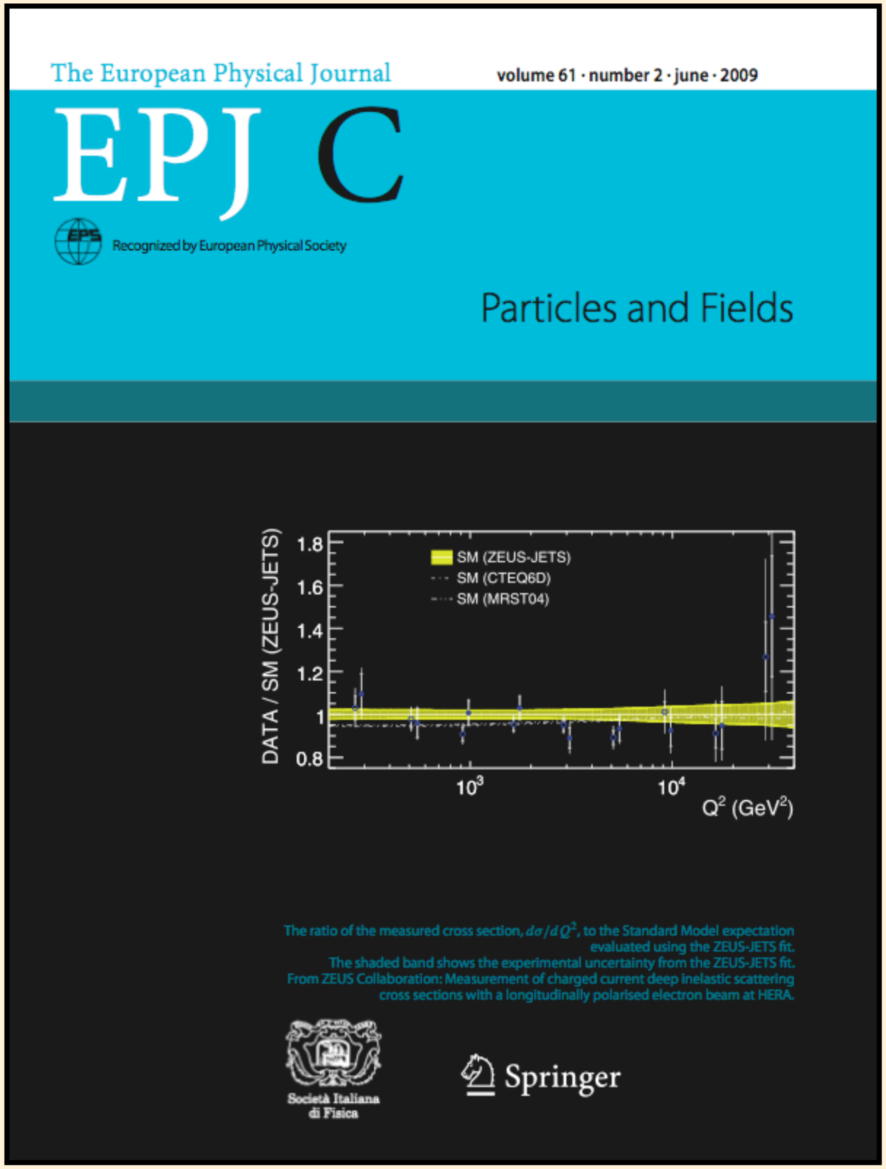
At leading order

$$F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \bar{q})$$

To a good approximation, asymmetry A- is a ratio of two structure functions…

Parity violation is observed via polarization asymmetry

ZEUS's reward…



The European Physical Journal
volume 61 · number 2 · june · 2009

EPJ C

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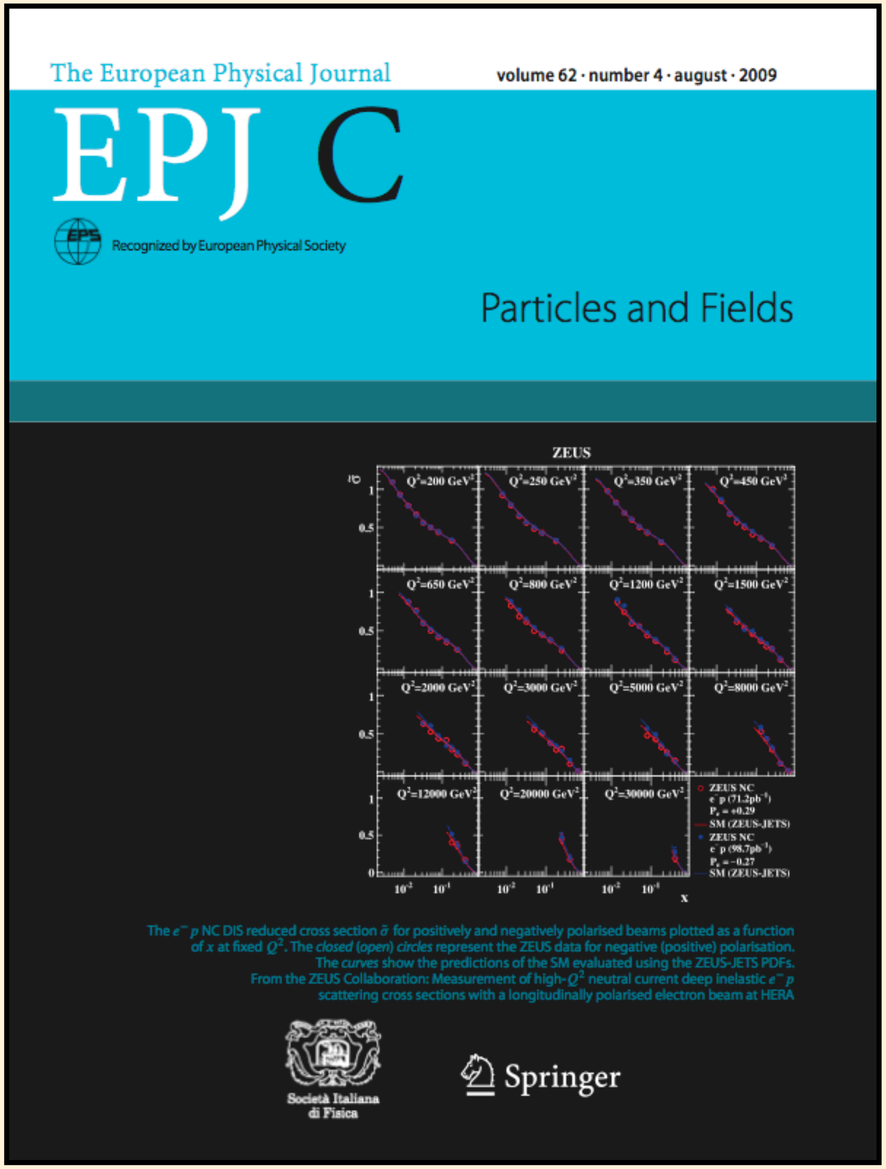
Particles and Fields

The ratio of the measured cross section, $d\sigma/dQ^2$, to the Standard Model expectation evaluated using the ZEUS-JETS fit.
The shaded band shows the experimental uncertainty from the ZEUS-JETS fit.
From ZEUS Collaboration: Measurement of charged current deep inelastic scattering cross sections with a longitudinally polarised electron beam at HERA.

Società Italiana di Fisica

Springer



The European Physical Journal
volume 62 · number 4 · august · 2009

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Particles and Fields

The $e^- p$ NC DIS reduced cross section $\tilde{\sigma}$ for positively and negatively polarised beams plotted as a function of x at fixed Q^2. The *closed* (*open*) *circles* represent the ZEUS data for negative (positive) polarisation.
The *curves* show the predictions of the SM evaluated using the ZEUS-JETS PDFs.
From the ZEUS Collaboration: Measurement of high-Q^2 neutral current deep inelastic $e^- p$ scattering cross sections with a longitudinally polarised electron beam at HERA

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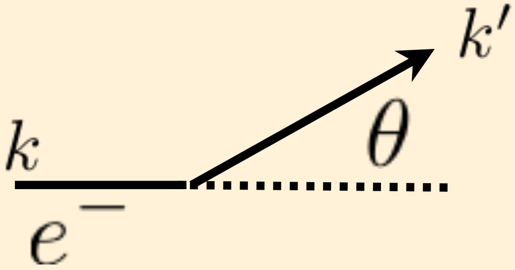
Is the quark point like?

Intermezzo

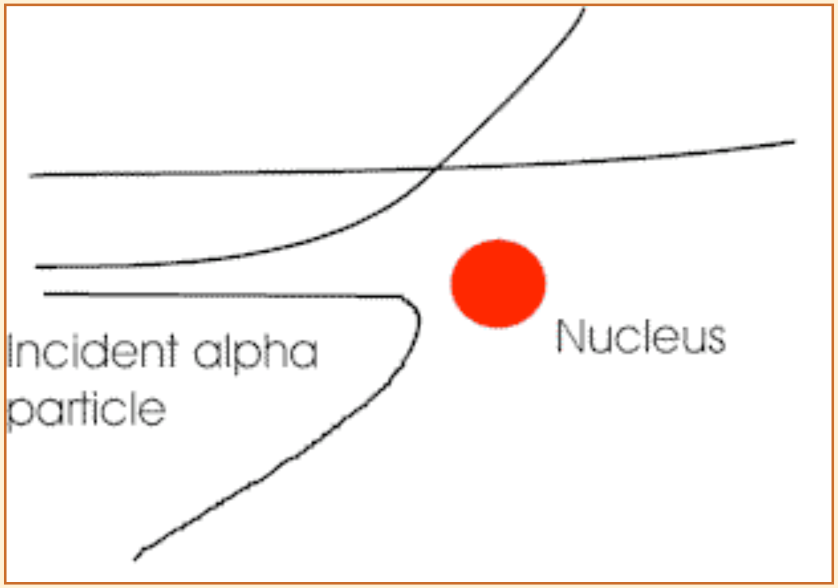
Rutherford scattering (1910)



$$q = k - k'$$

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

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



'plum pudding'

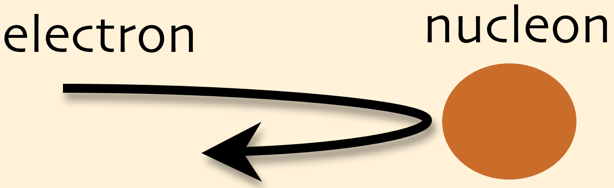
↓

point like

but mostly empty with positive charge in the center

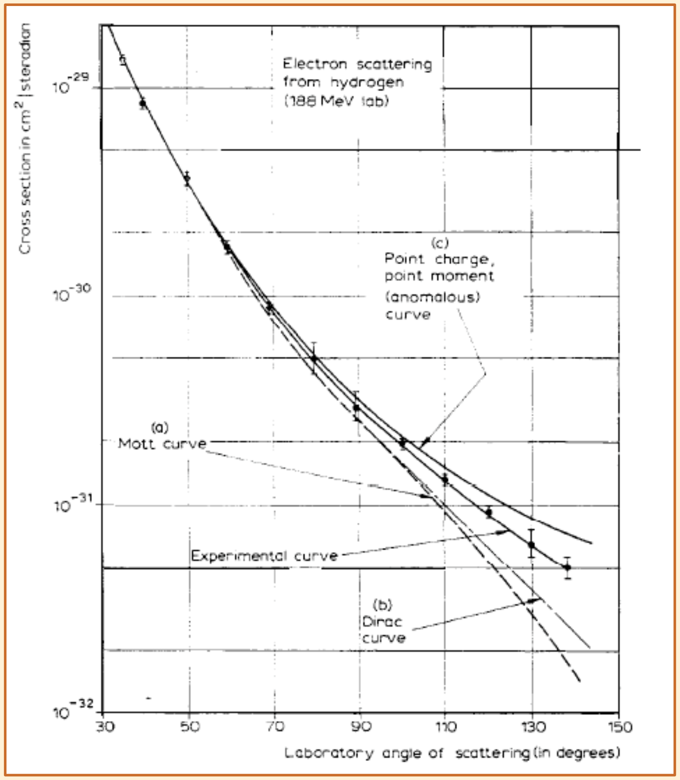
"It's as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." Ernest Rutherford

Hofstadter: Radius of nucleus (1955)



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

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

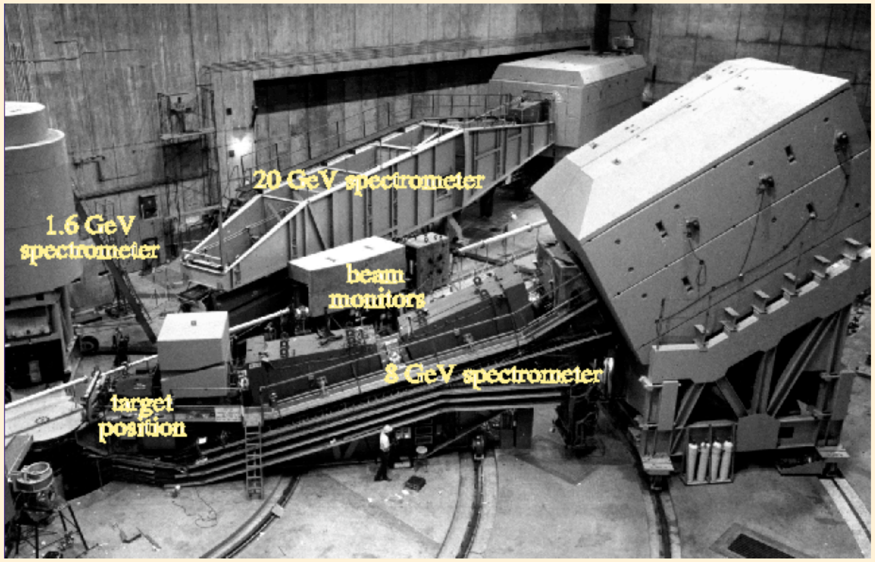


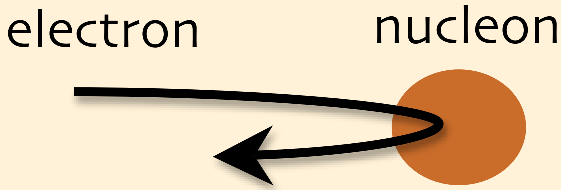
$$q^2 \propto \sin^2(\theta/2)$$

"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)

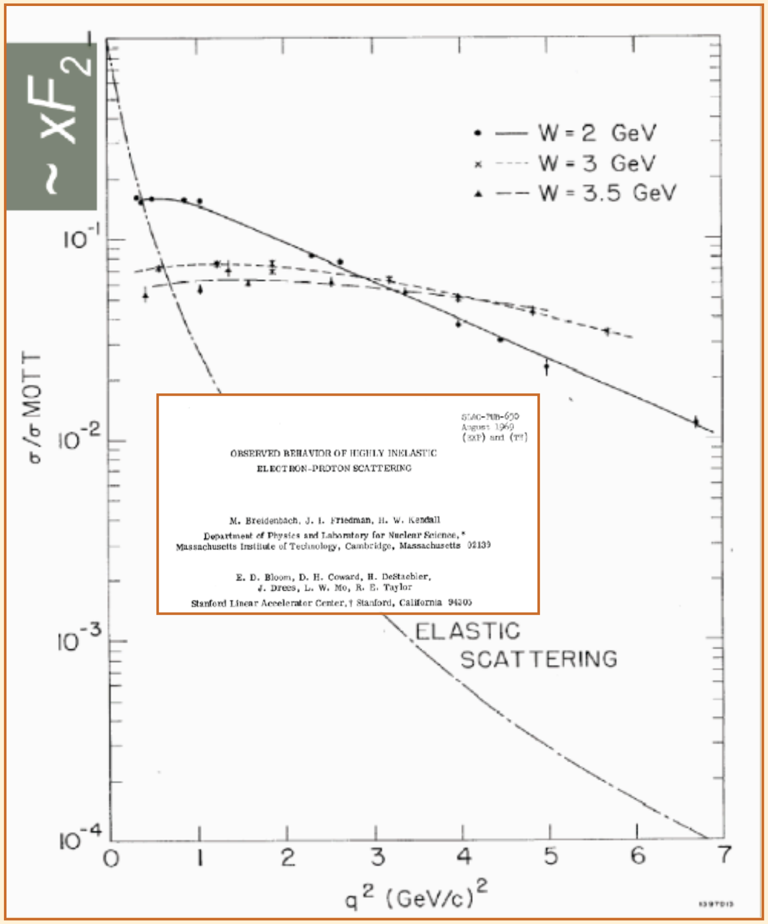
Deep inelastic scattering (1969)

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




electron

nucleon



SLAC-PUB-650
August 1969
(EXP) and (TH)

OBSERVED BEHAVIOR OF HIGHLY INELASTIC
ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

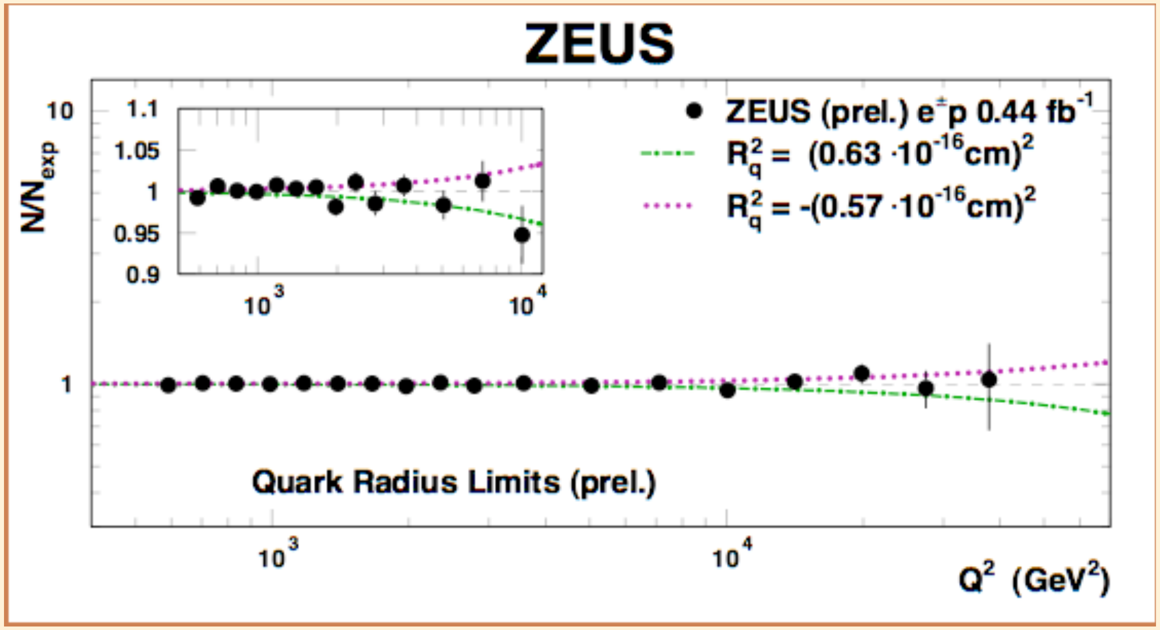
E. D. Bloom, D. H. Coward, H. DeStaebler,
J. Drees, L. W. Mo, R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305

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

Quark radius (2009)

Is the quark point like?

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

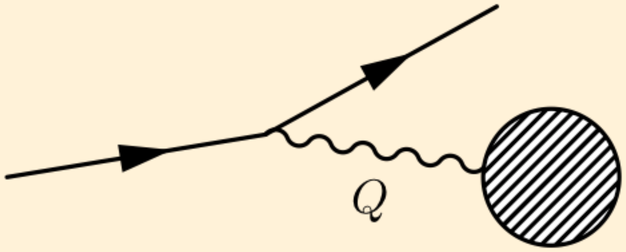


Any deviations? Not so far…

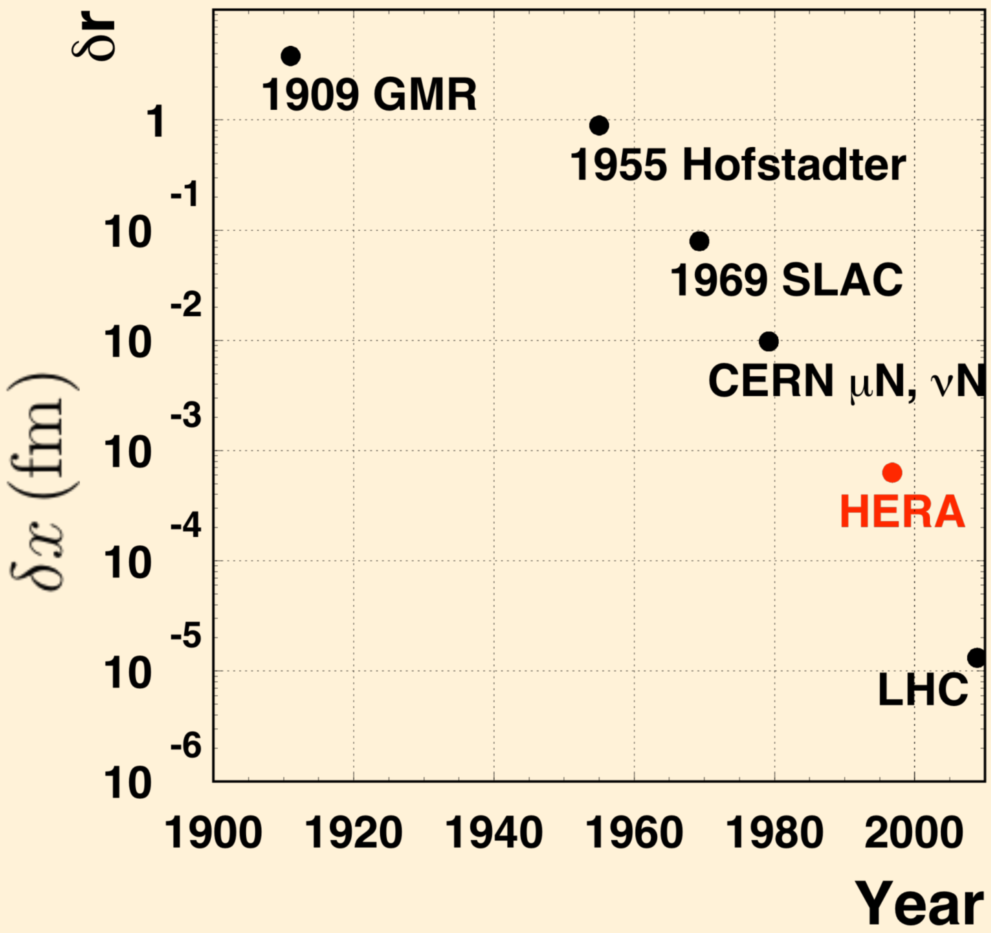
The limit is: $R_Q < 0.6 \times 10^{-18}$ m

We are probing down to 1/1000 proton radius!!!

Probing matter: timeline



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



We've come a long way
in the last 100 years!
Now we pass the torch to
the LHC.

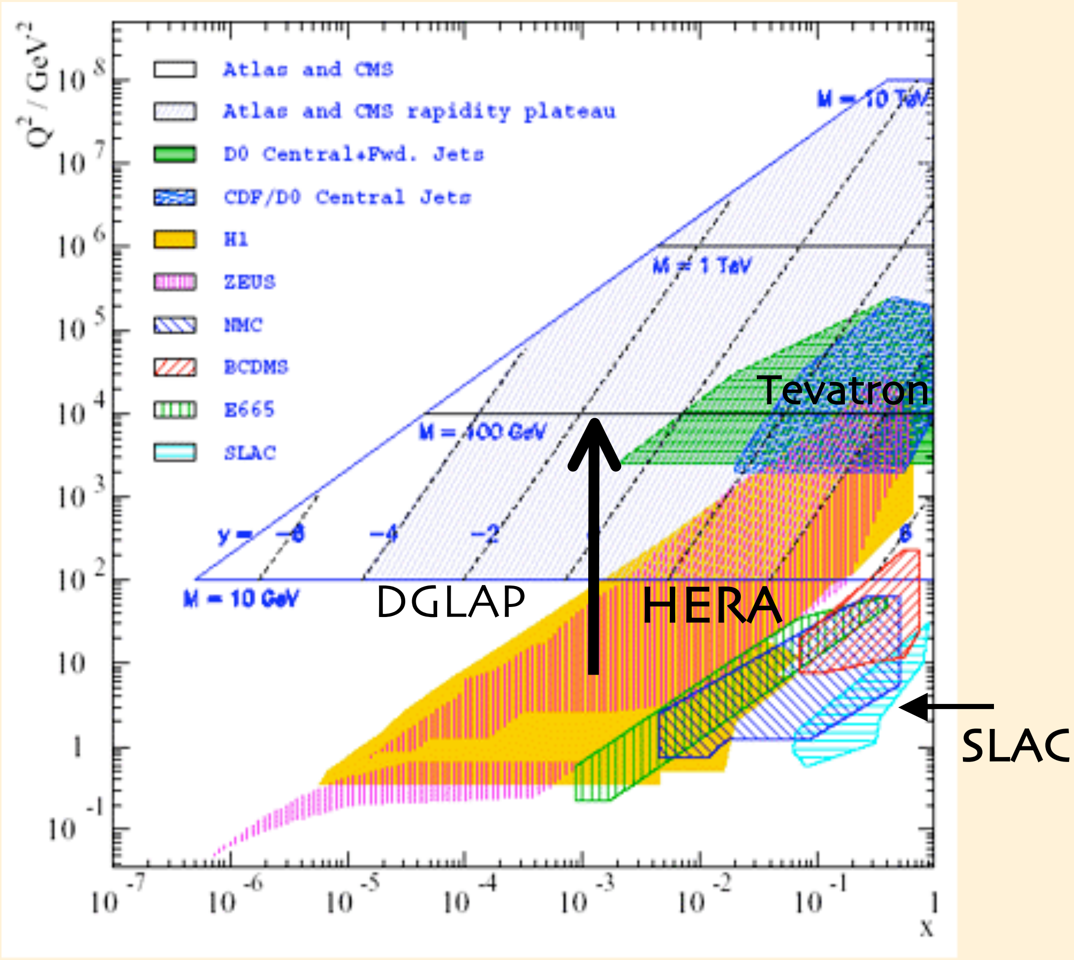
Proton structure: present experimental data

Large extension of knowledge due to the HERA collider!

Persistent experimental effort over the last four decades supported by theoretical developments (LO-NLO-NNLO) →

Large extension of the explored space in x,Q^2 compared to the original SLAC results.

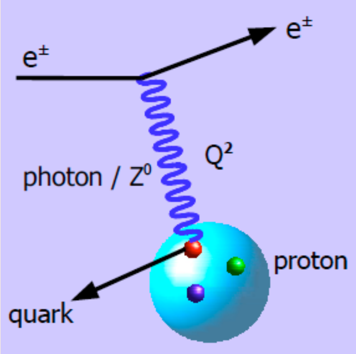
PDFs obtained in low x regime at HERA + (N)LO DGLAP evolution equations are used for precise predictions for the LHC.



Open questions at very low x, Q^2...

Deep inelastic e±p scattering: probing the proton

NC DIS: $e^- P \rightarrow e^- X$

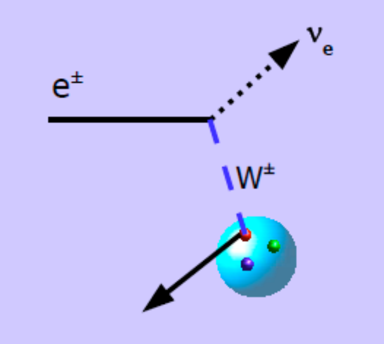


$$\frac{d^2\sigma(e^\pm p)}{dQ^2dx} = \frac{2\pi\alpha^2}{Q^4x}Y_+ \overbrace{\left(\underbrace{\boxed{F_2}}_{\text{valence + sea quarks}} - \frac{y^2}{Y_+}\underbrace{\boxed{F_L}}_{\text{gluon}} \mp \frac{Y_-}{Y_+}\underbrace{\boxed{xF_3}}_{\text{valence quarks}}\right)}^{\sigma_r} \; ; \quad Y_\pm = 1 \pm (1-y)^2$$

Define polarization of exchanged boson

---> gluons, sea quarks and valence quarks

CC DIS: $e^+ P \rightarrow \nu X$



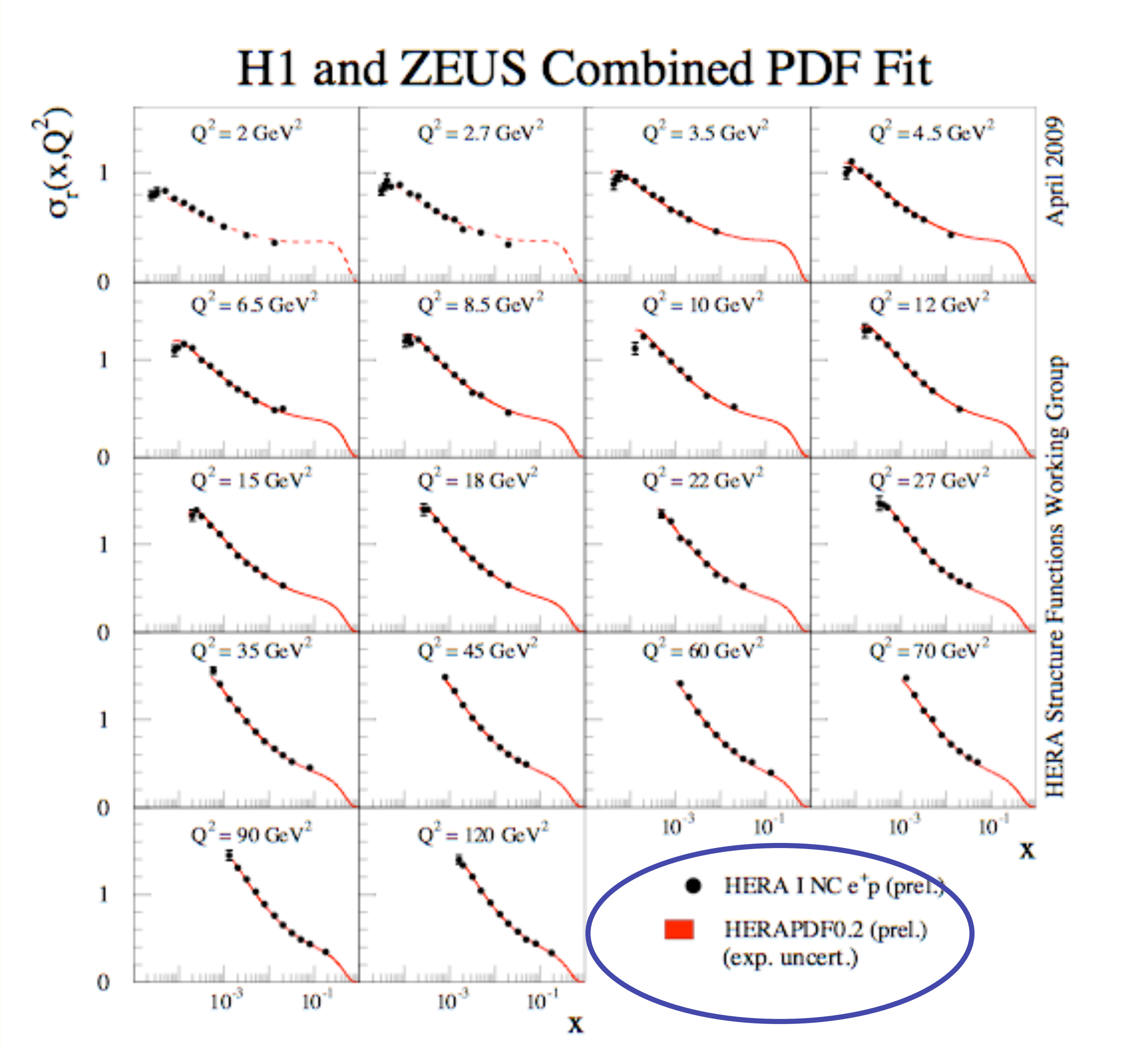
$$\frac{d^2\sigma^{CC}(e^+p)}{dQ^2dx} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[\overline{u}+\overline{c}+(1-y)^2\boxed{(d+s)}\right] \quad \text{x } (1 + P_e)$$

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

---> flavor separation + more …

Proton structure: valence + sea quarks

$\tilde{\sigma} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$ at lower Q^2



At medium Q^2, the measurement of F_2 is in the perturbative region

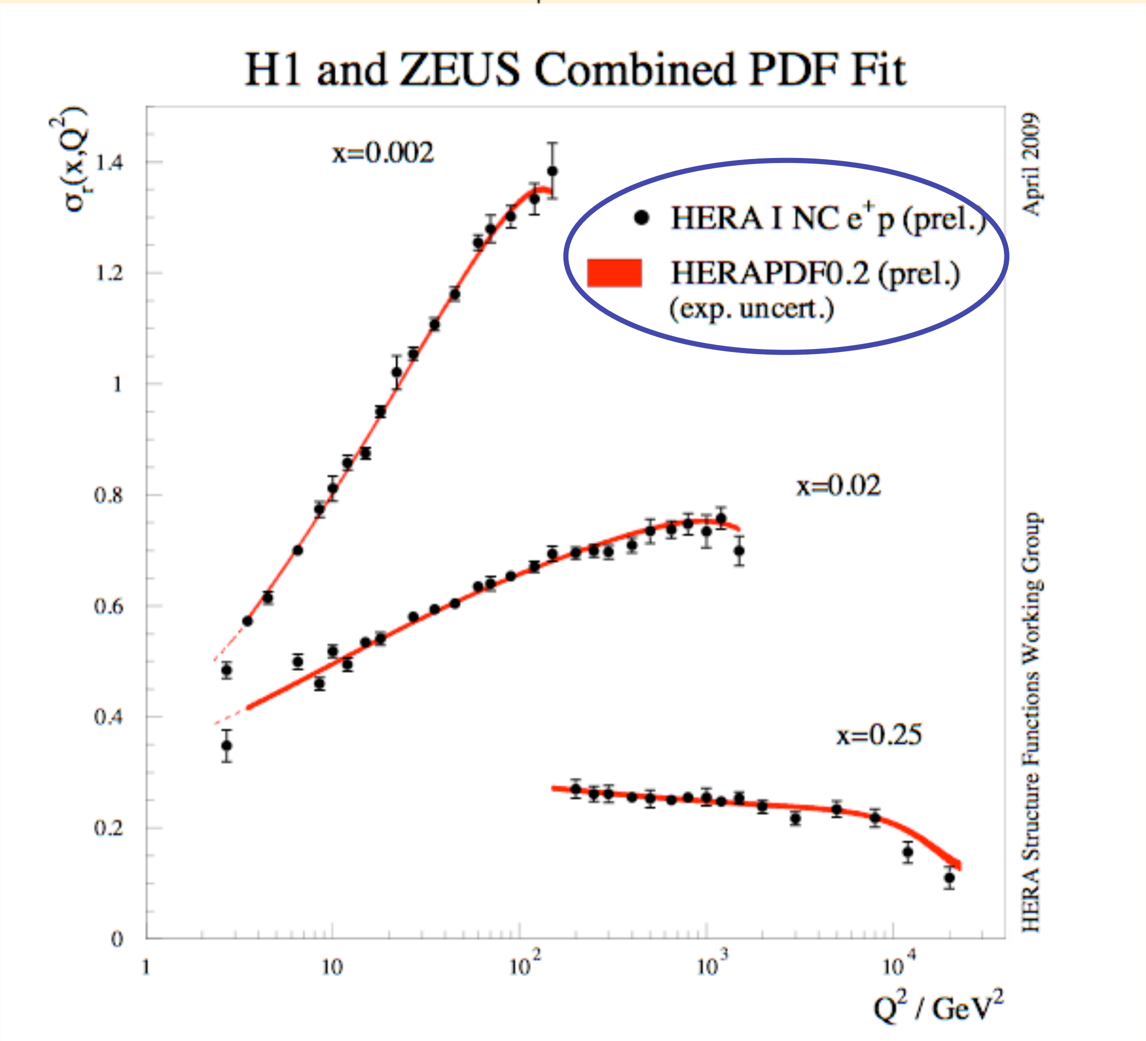
F_2 (x,Q^2) shows a strong rise as x -> 0

The rise increases with increasing Q^2

… at low Q^2 we start seeing hints of gluon, F_L (turnover)

Proton structure: valence + sea quarks

$$\tilde{\sigma} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$ at low Q^2



Scaling violation dramatic on a linear scale…

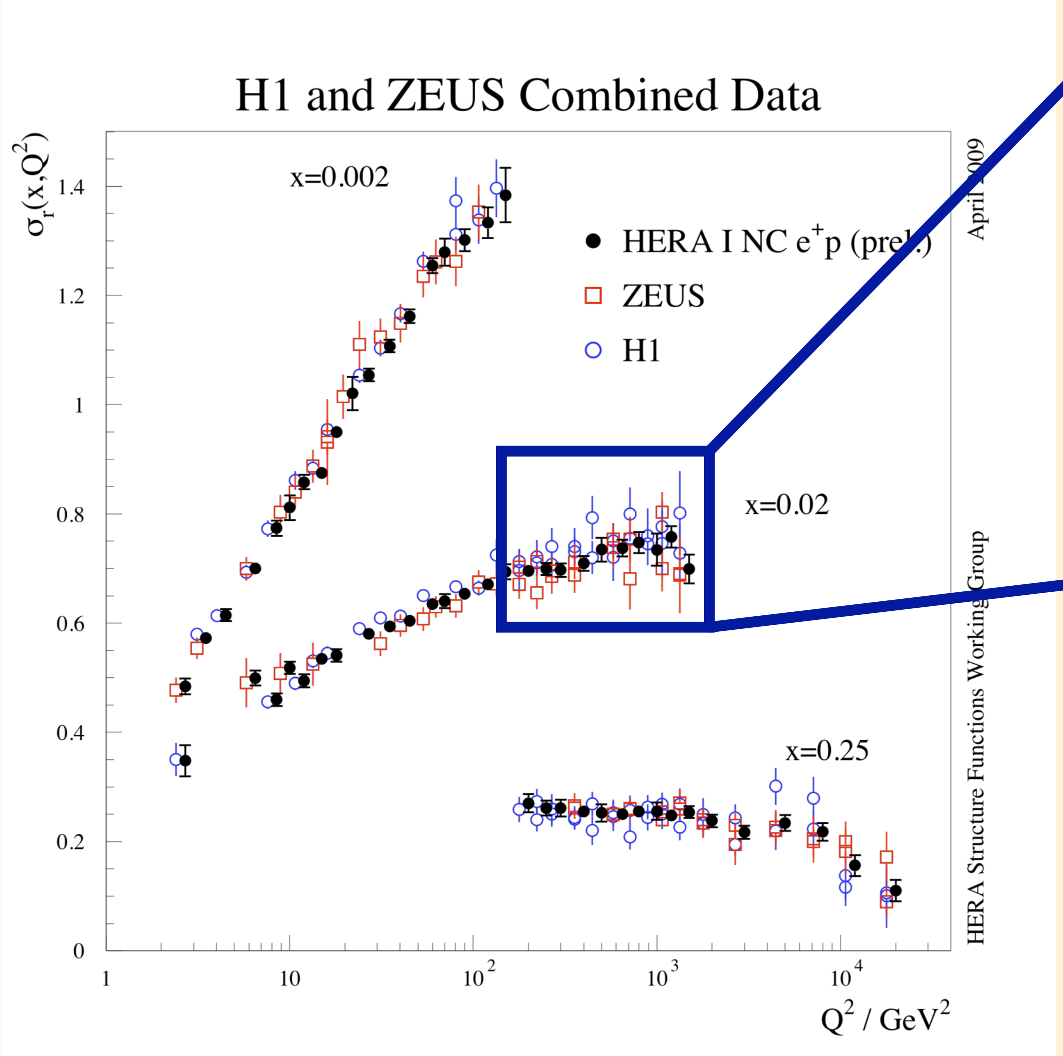
F_2 (x,Q^2) shows a strong rise as x -> 0

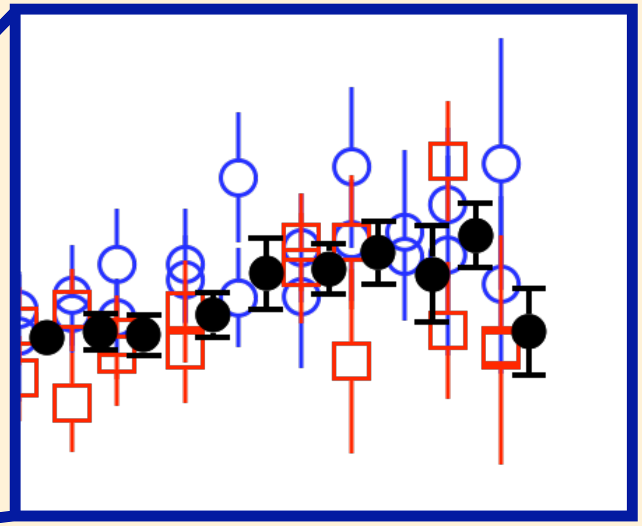
Large scaling violation at low x -> large gluon density. Another hint of gluon… but indirect.

Combined HERA I data: precision ~ 1 %
Single input to new QCD analysis.

Good agreement between data and NLO QCD.

Power of combining





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

χ^2/dof=637/656

Systematic uncertainties reduced as well as statistical errors

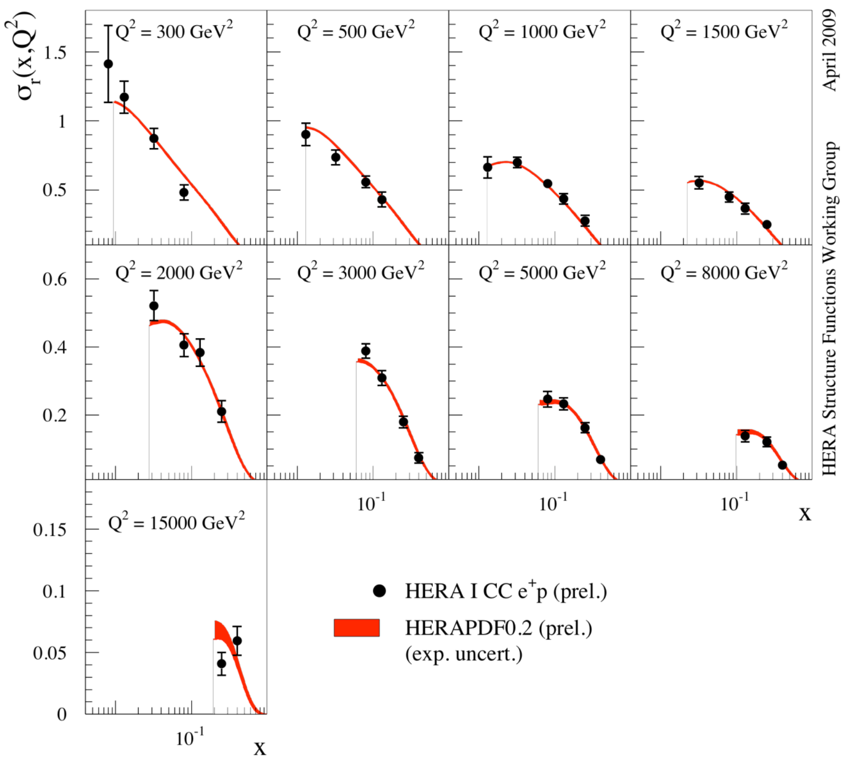
Unprecedented precision due to cross calibration of detectors

Extracting the essence of structure functions

Common PDF Fit on HERA I combined data

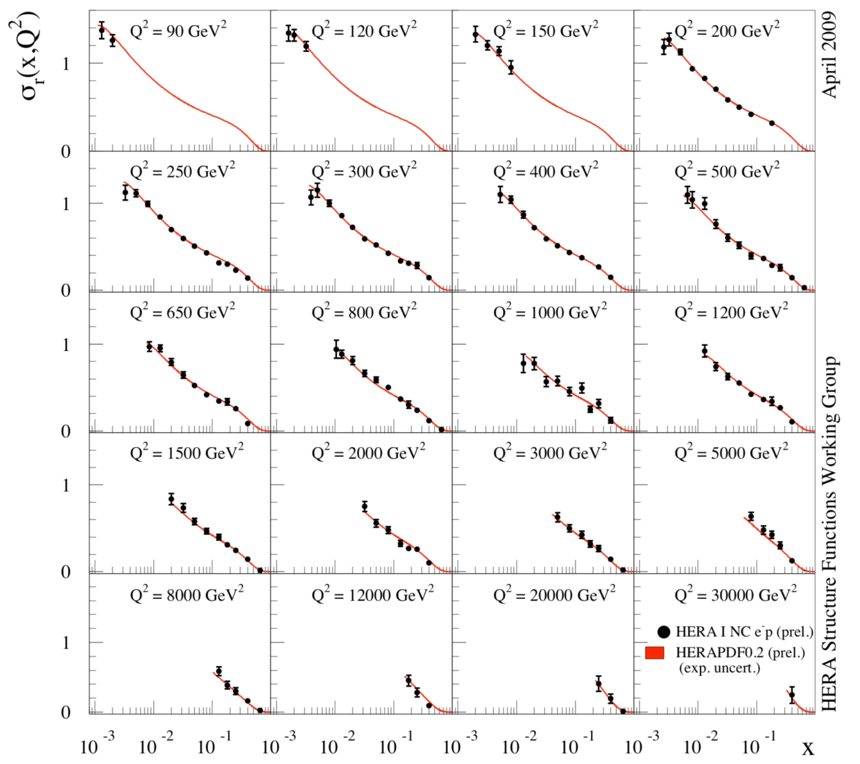
$e^+P \rightarrow \nu X$

H1 and ZEUS Combined PDF Fit



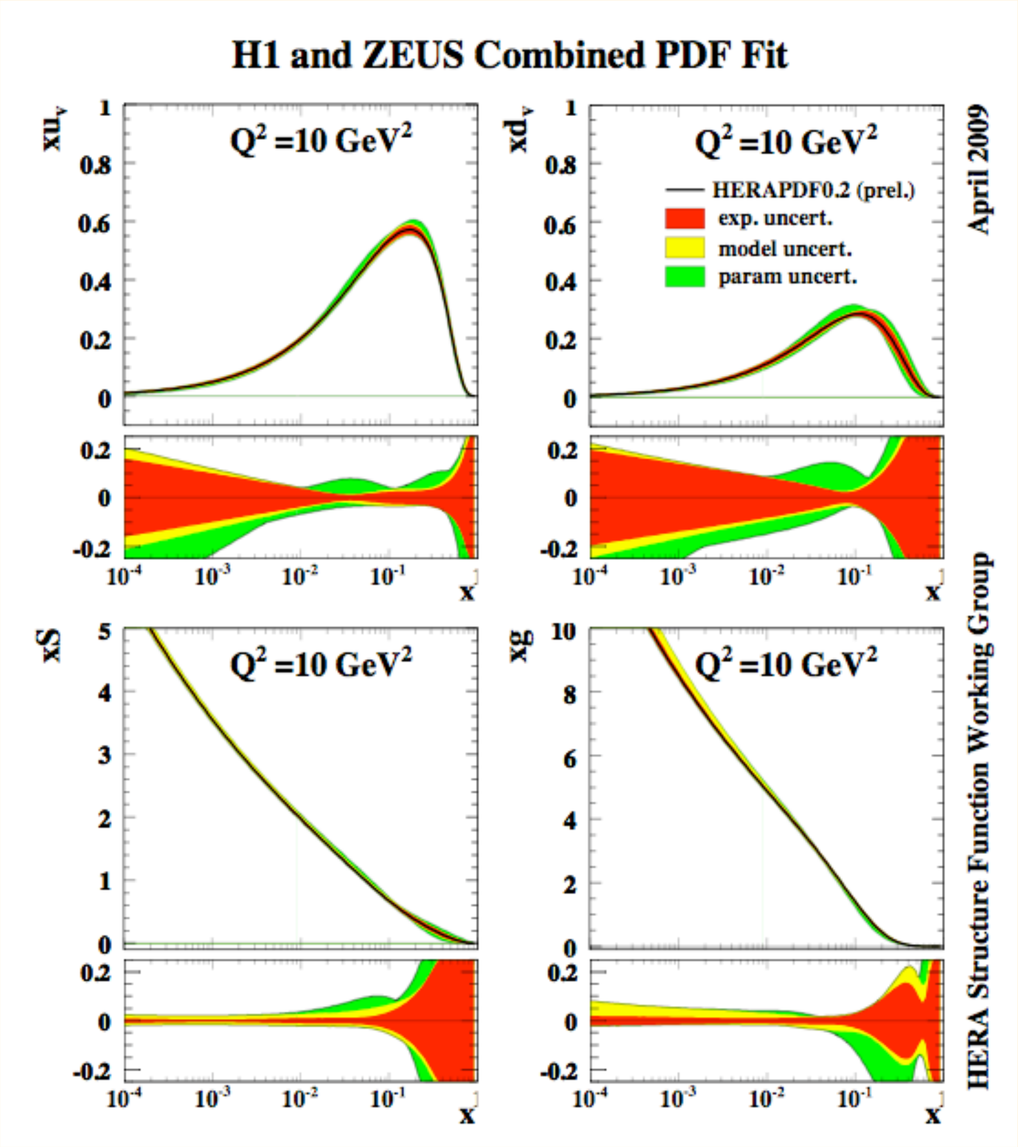
$e^-P \rightarrow e^-X$

H1 and ZEUS Combined PDF Fit



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

Extracting the essence of structure functions



HERAPDF0.2 - NLO QCD analysis of the combined HERA data

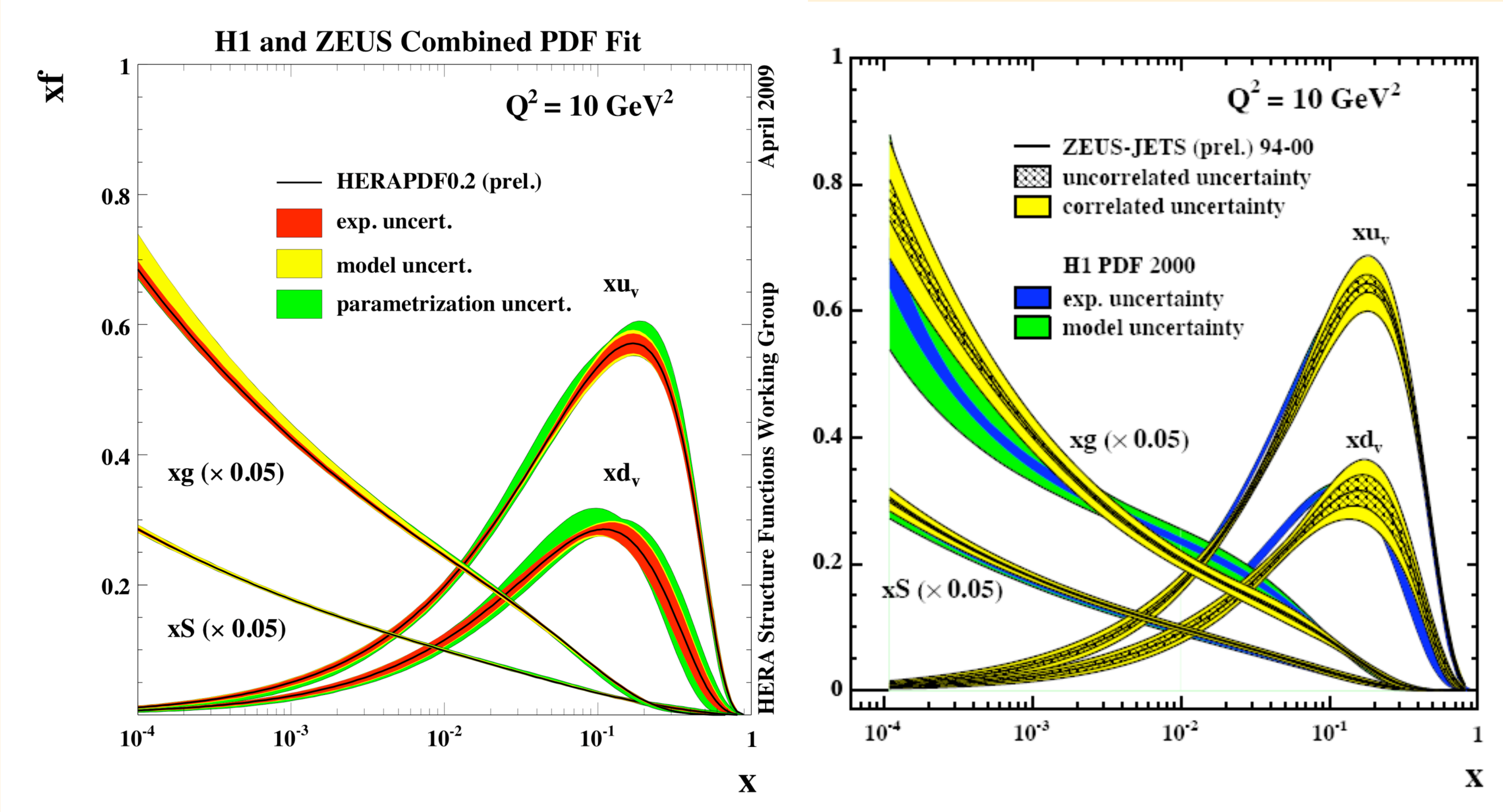
Separation of:
- experimental
- model
- parametrization

uncertainties

Accurate xS and xg at low x due to precise measurement of F2!

Extracting the essence of structure functions

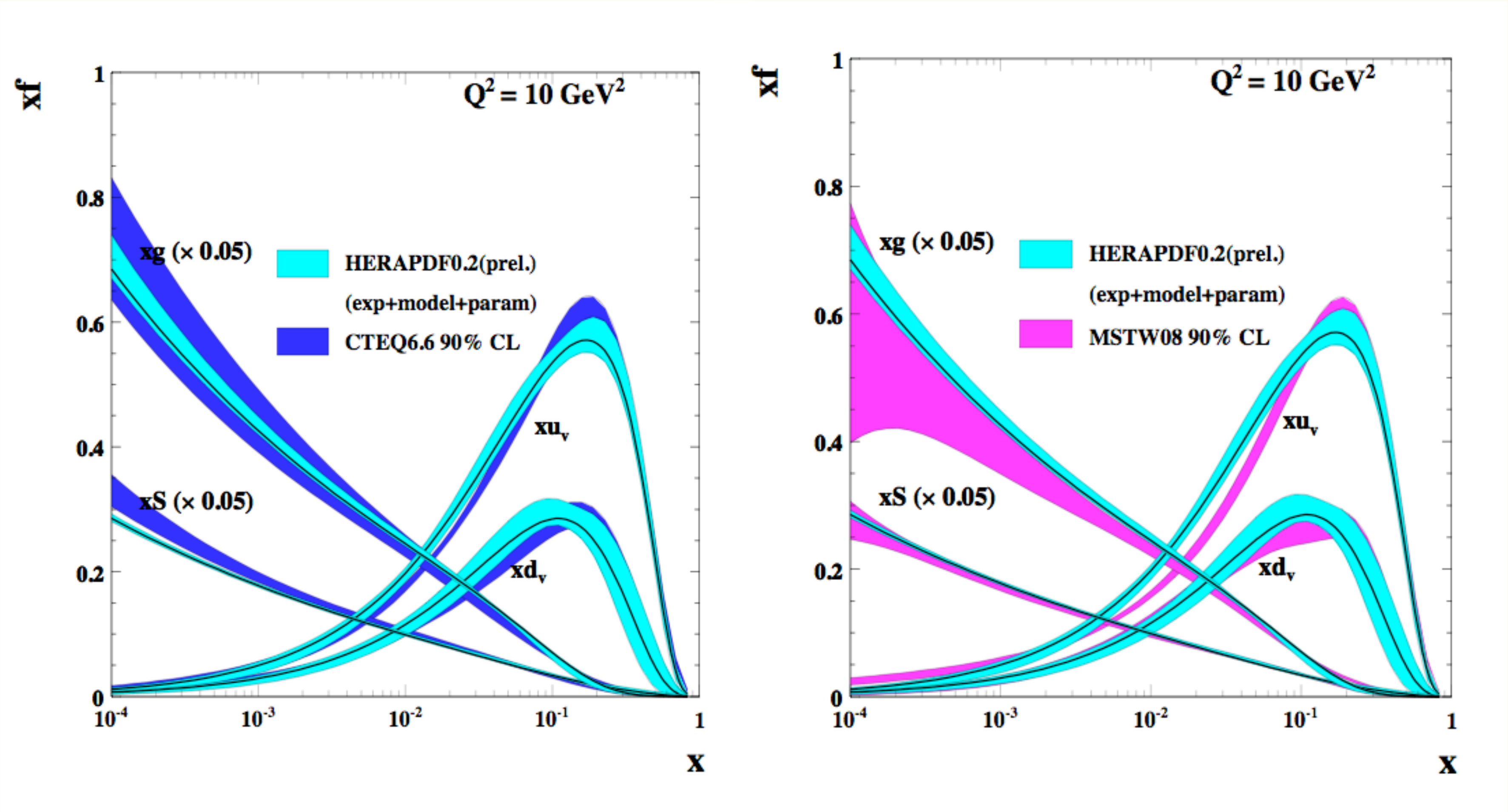
Comparison between HERAPDF0.2 & H1, ZEUS individual fits



Uncertainty on low-x gluon and sea strongly reduced!

Extracting the essence of structure functions

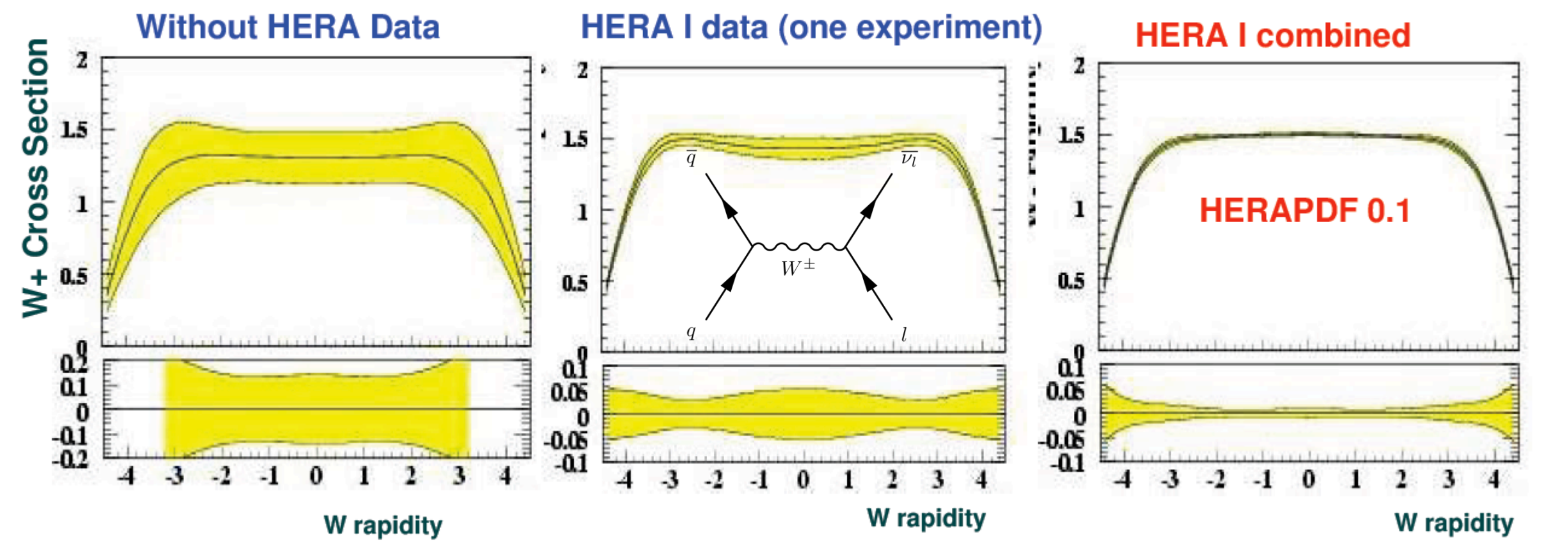
Comparison between HERAPDF0.2 & and global fits

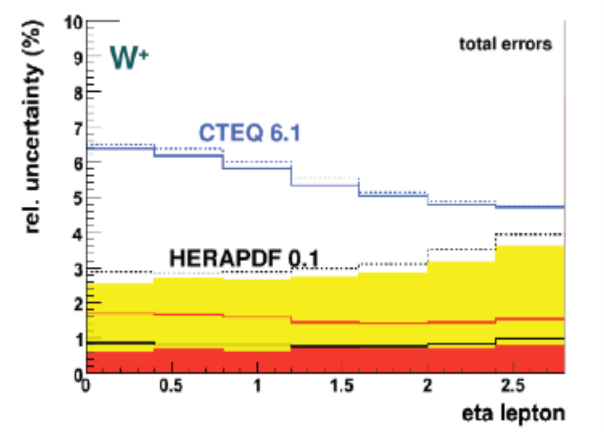


At low-x gluon and sea more precise than CTEQ or MRST!

HERAPDF0.1: impact on LHC

An example: W production





Uncertainties ~ 3%

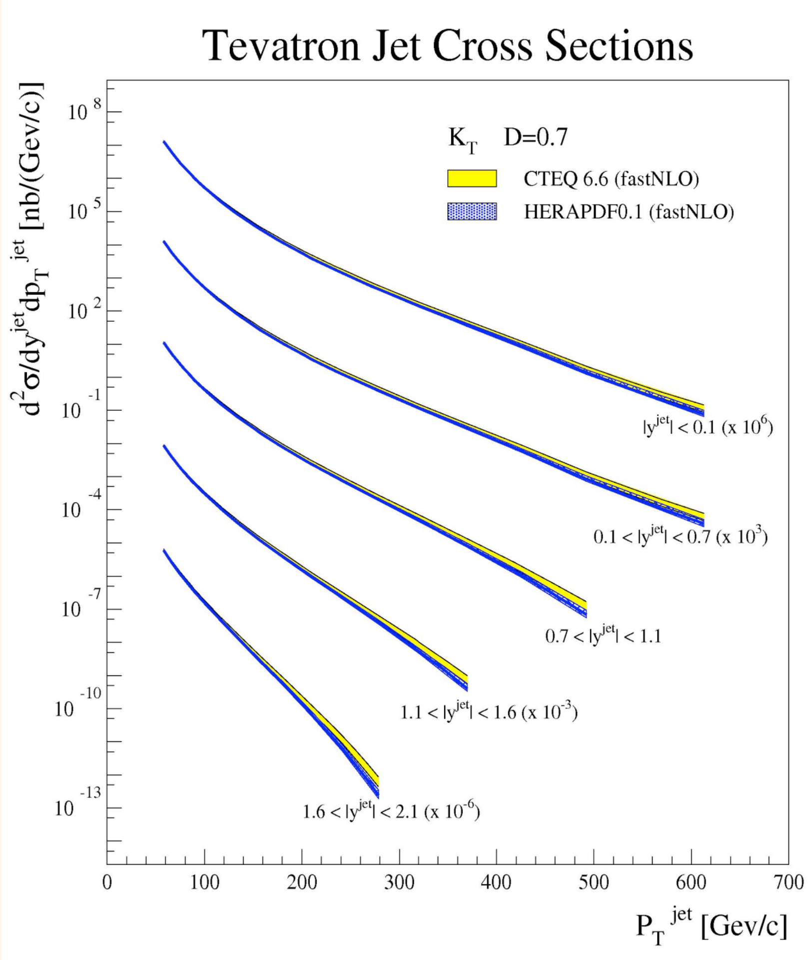
Incredibly precise σ with HERAPDF

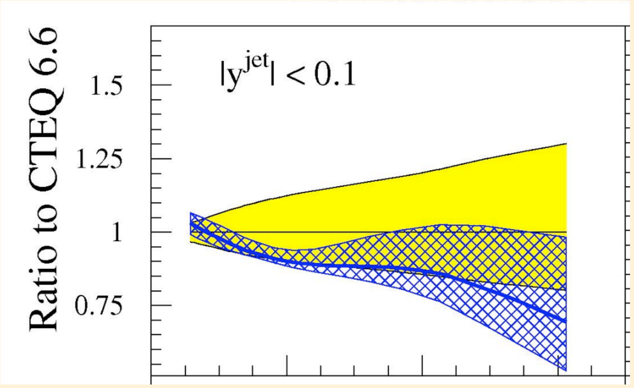
…standard candle for the LHC!

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

HERAPDF0.1: crosscheck with Tevatron

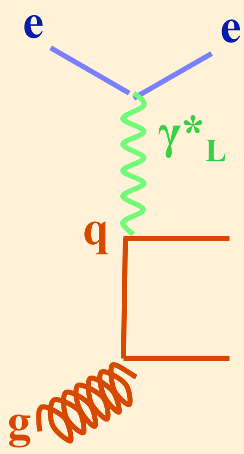
Is HERA-only PDF compatible with Tevatron data?





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

QCD dynamics: directly probing gluon with F_L



- In quark-parton model, $F_L = 0$ for spin 1/2 quarks
- In QCD, $F_L > 0$ due to gluon emission
- Large xg(x) at low x implies sizable F_L
- F_L is a crucial test of QCD
- F_L arises from same mechanism which drives DGLAP -> powerful way to check DGLAP

F_L is an independent structure function BUT

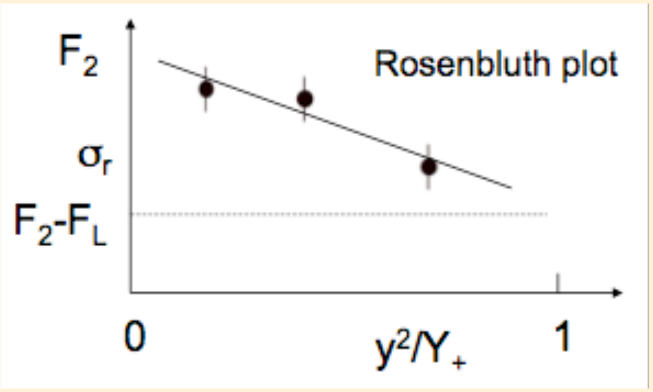
A challenging measurement:
- identify electrons at small energies
- measure at the edge of acceptance
- need different vlaues of y for the same x and Q^2 (proton-beam energies)

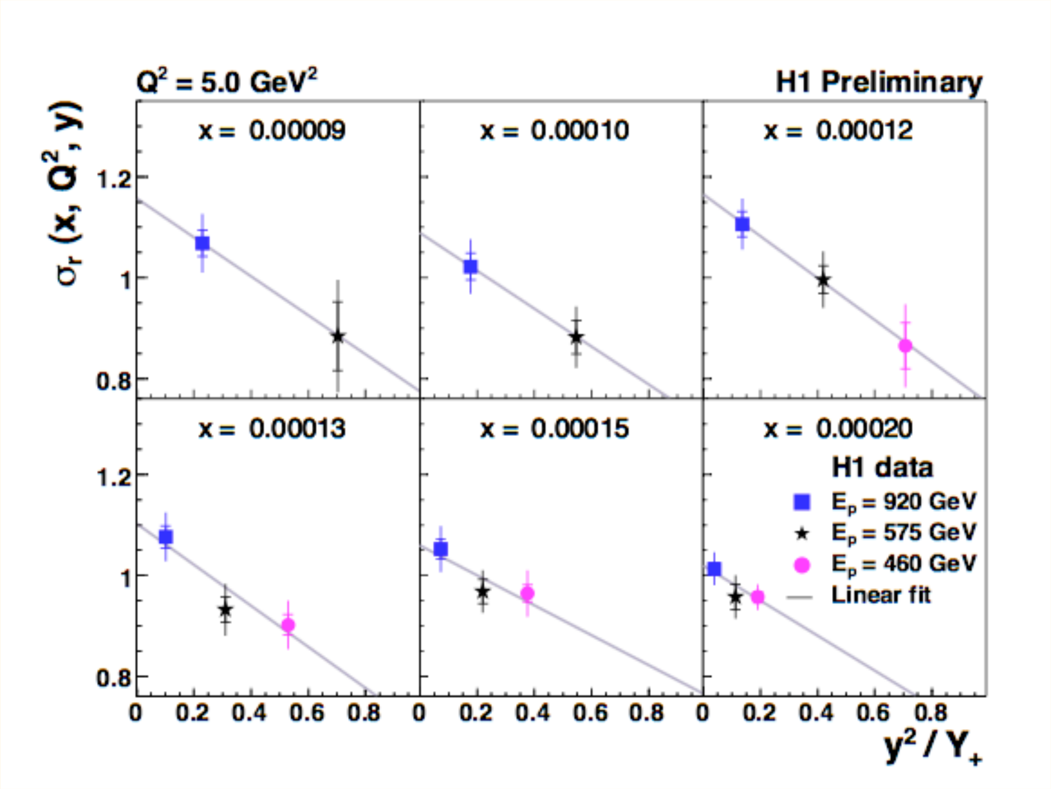
Probing the gluon with F_L: H1

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

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

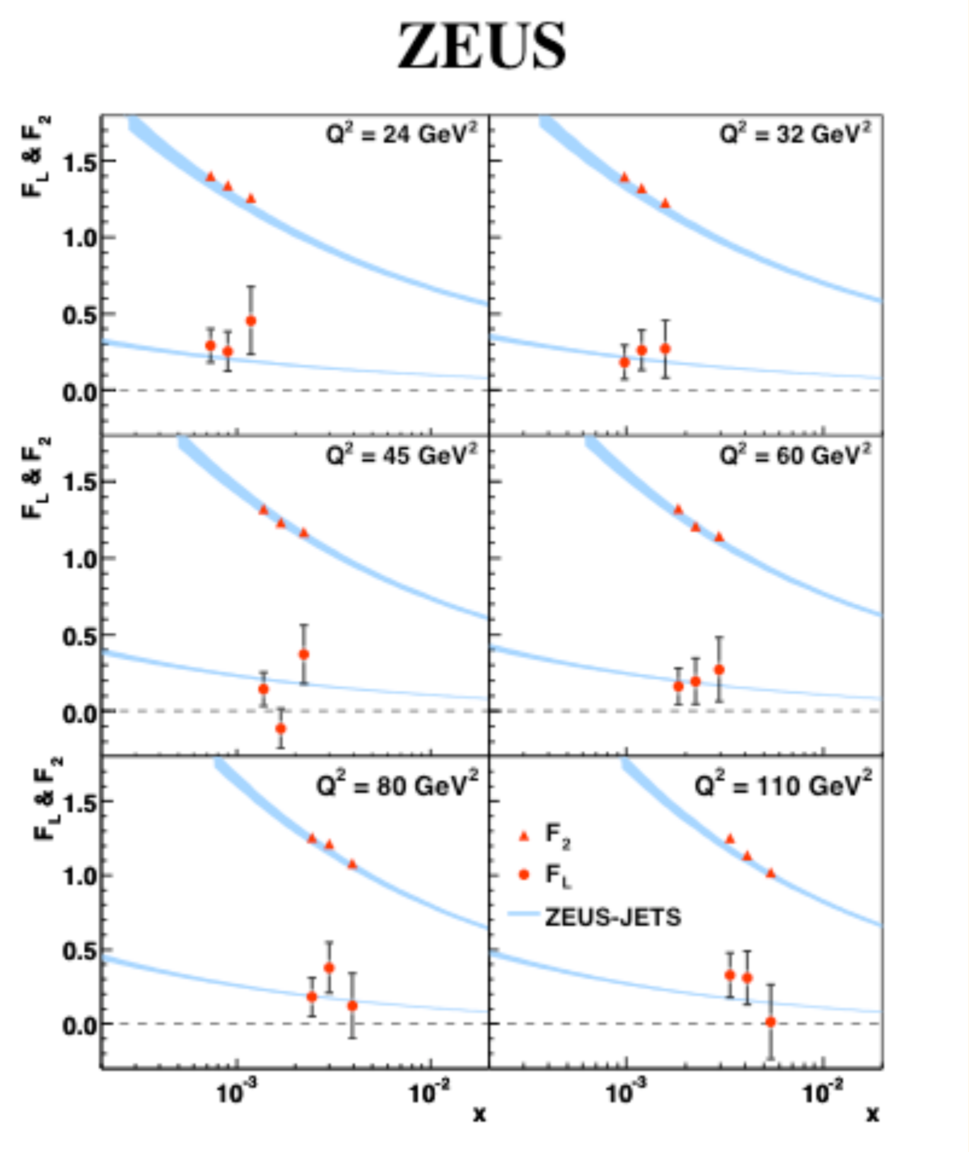
For small y:
- F_L contribution ~ 0
- cross section ~ F_2





Linear fit to data at different com energies to obtain F_2 and F_L
Relative normalization from low y data

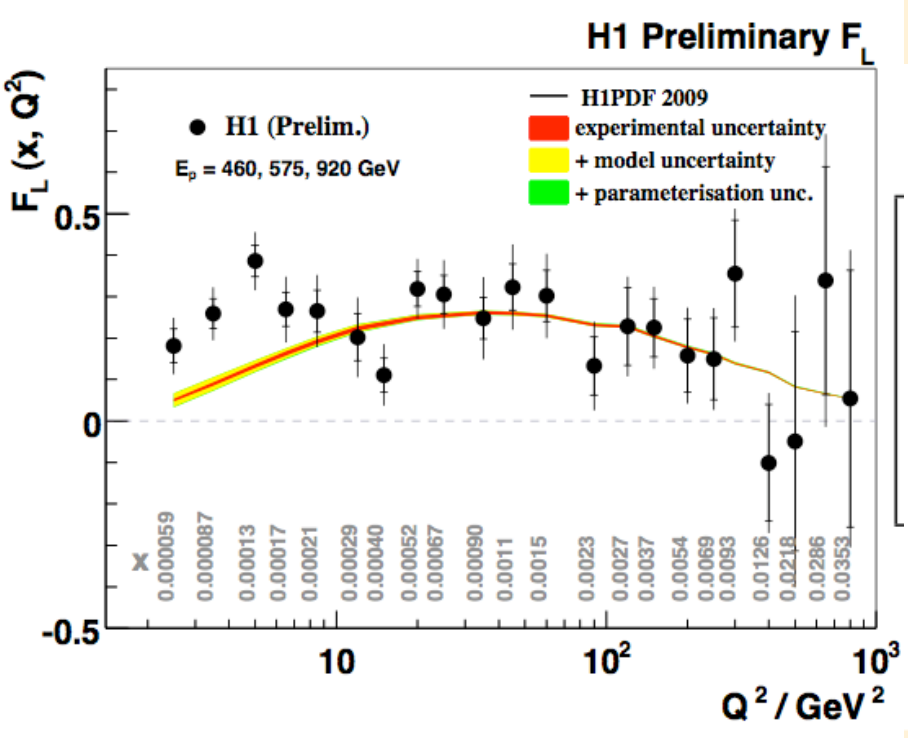
Probing the gluon with F_L :ZEUS

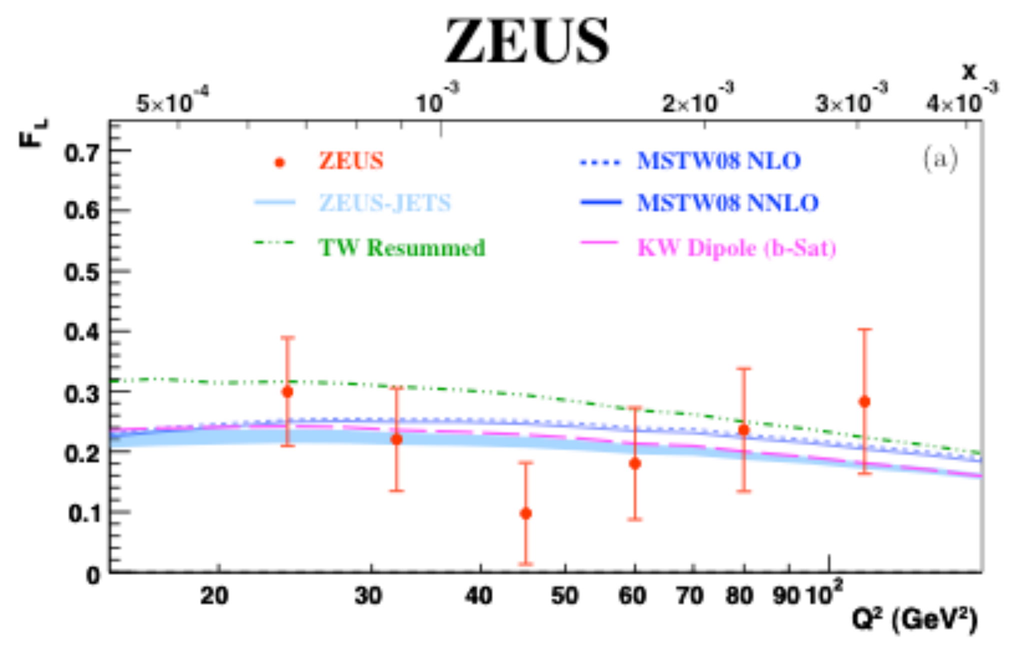


- Extraction of F_2 without any assumption on F_L

- Most precise F_2 so far in this kinematic regime (medium Q^2)

F_L vs Q^2





F_L is exactly where QCD expects it to be!

This gives us confidence we understand DGLAP -->QCD radiation

Has HERA provided the answers?

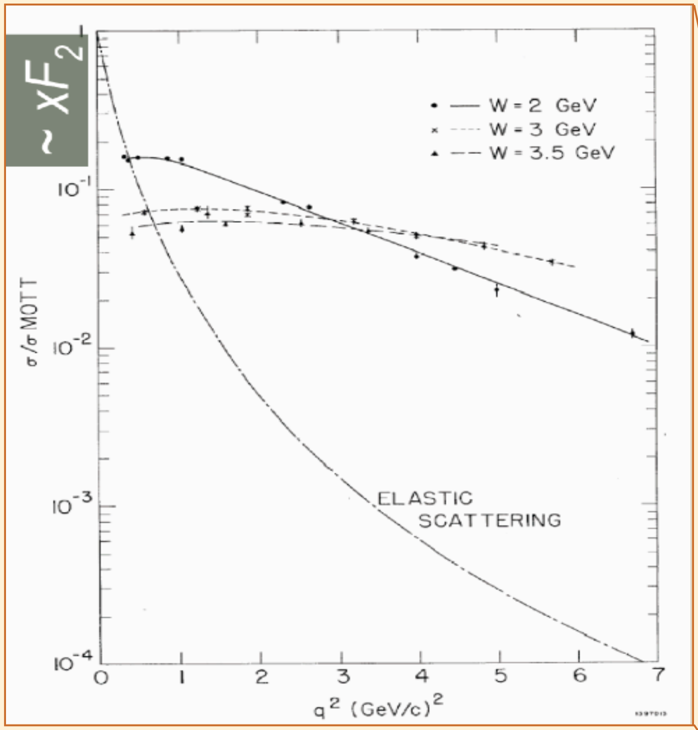
- Does the electron probe behave as expected?
  - new effects excluded up to masses of O(300 GeV)

- Is the quark point-like?
  - probed 1/1000 of the proton radius (0.6 x 10^{-18} m)

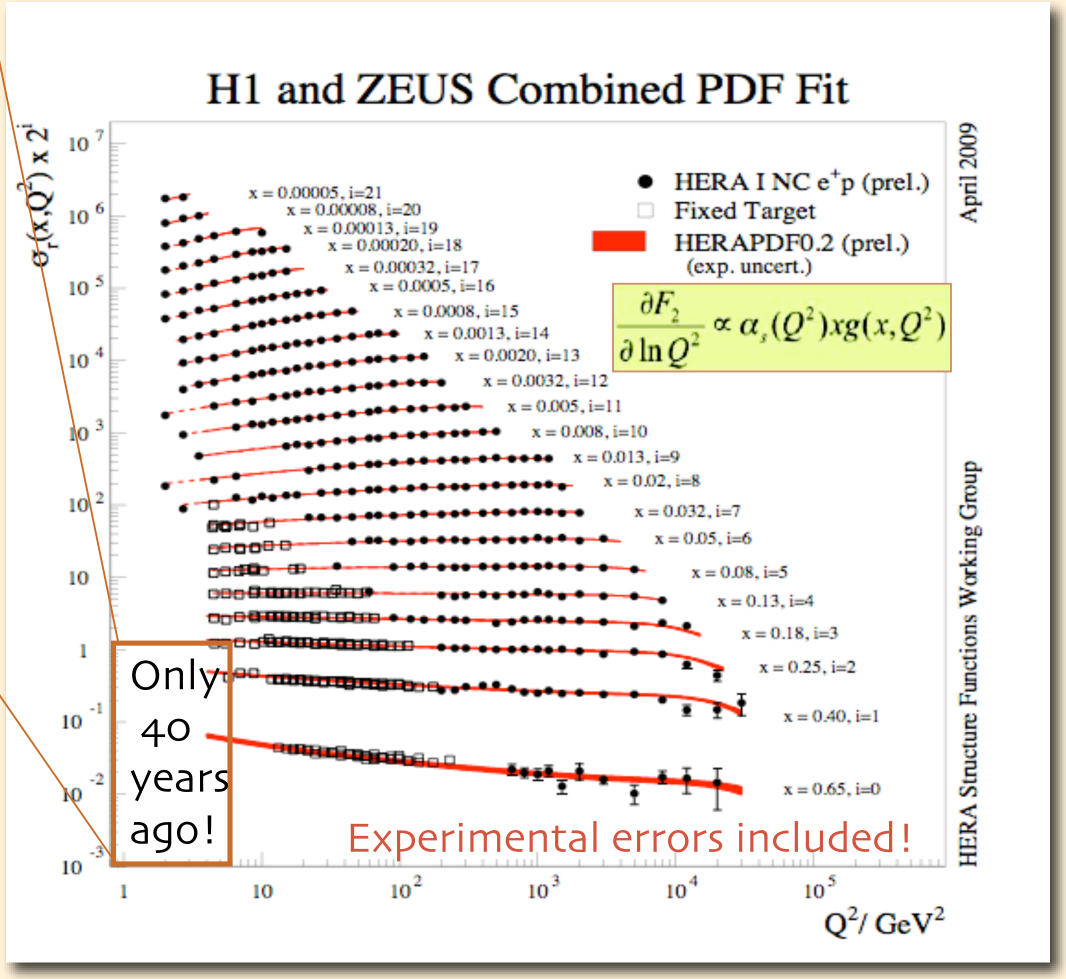
- What are the quark and gluon distributions in the proton
  - have precision of 1-3% at x ~ 10^{-3}

- Are QCD dynamics well understood?
  - new results on F_L inspire confidence

Lessons learned, but…



$F_2(x,Q^2)$



$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2) x g(x,Q^2)$$

Only 40 years ago!

Experimental errors included!

Lessons learned

Scaling ---> quarks

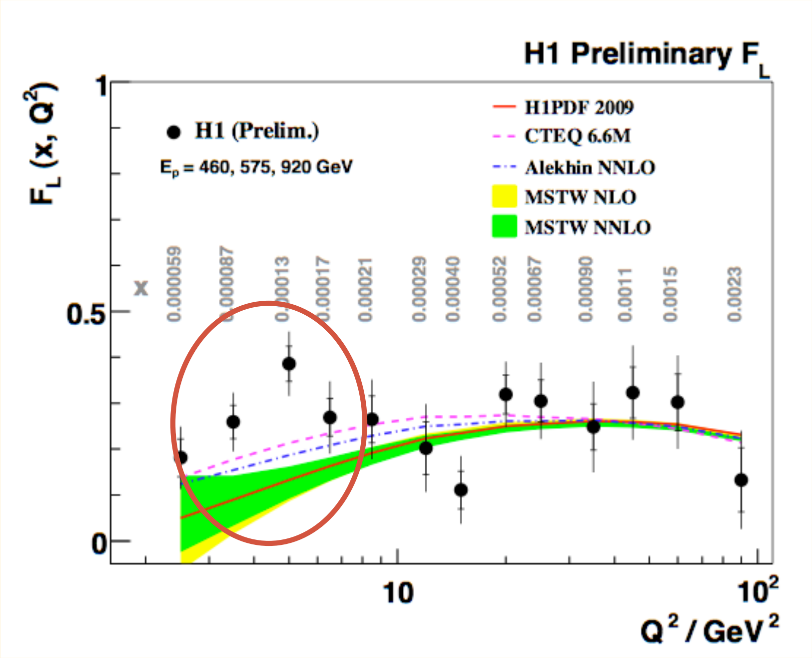
Scaling violation --->
gluons and QCD radiation

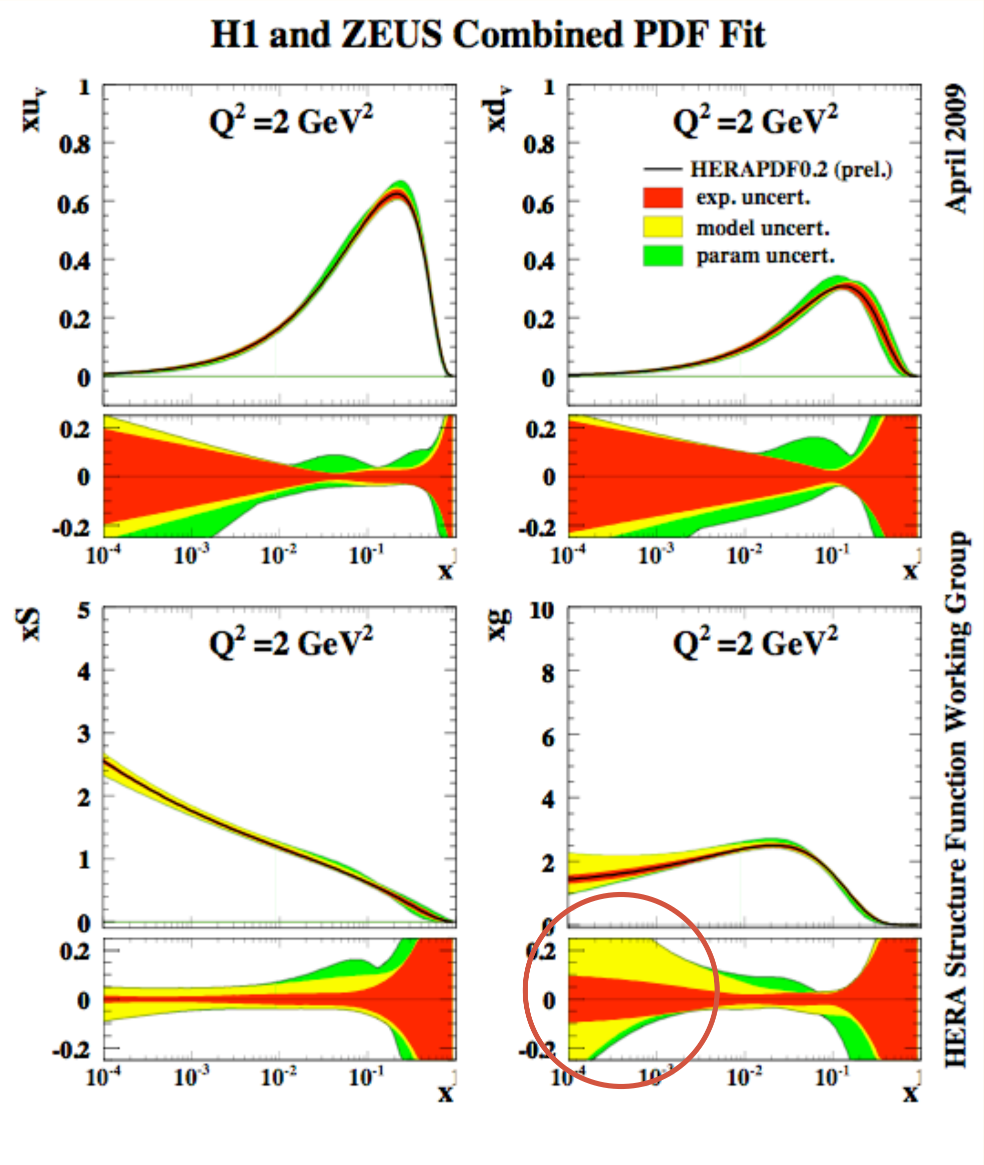
However some questions remain…

Open questions: gluon

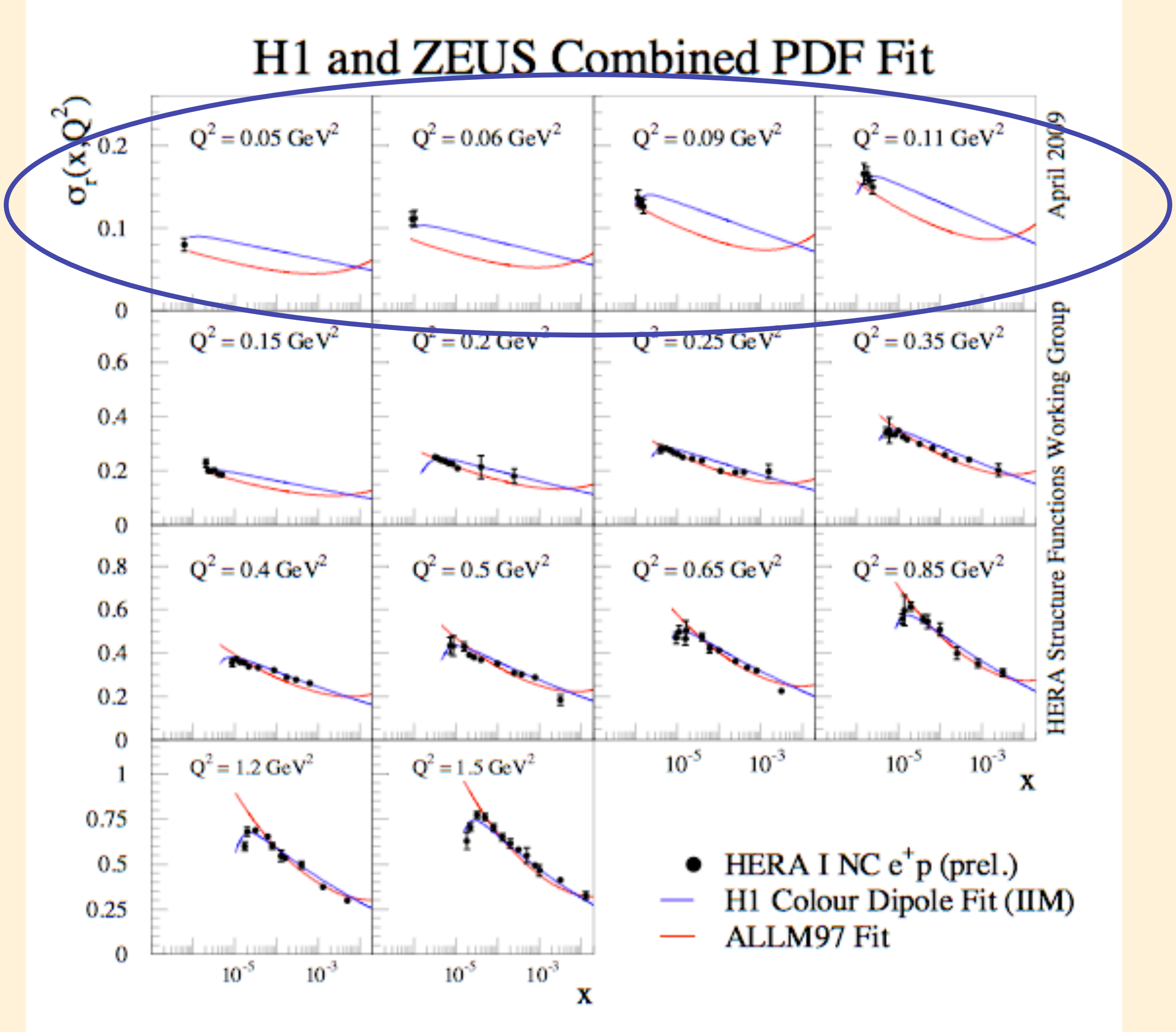
What happens at very low x?
- does gluon keep rising?
- does saturation set in?
- does DGLAP work here?

Are there possible hints in HERA data?





Open questions: gluon



We could do better in this phase space….

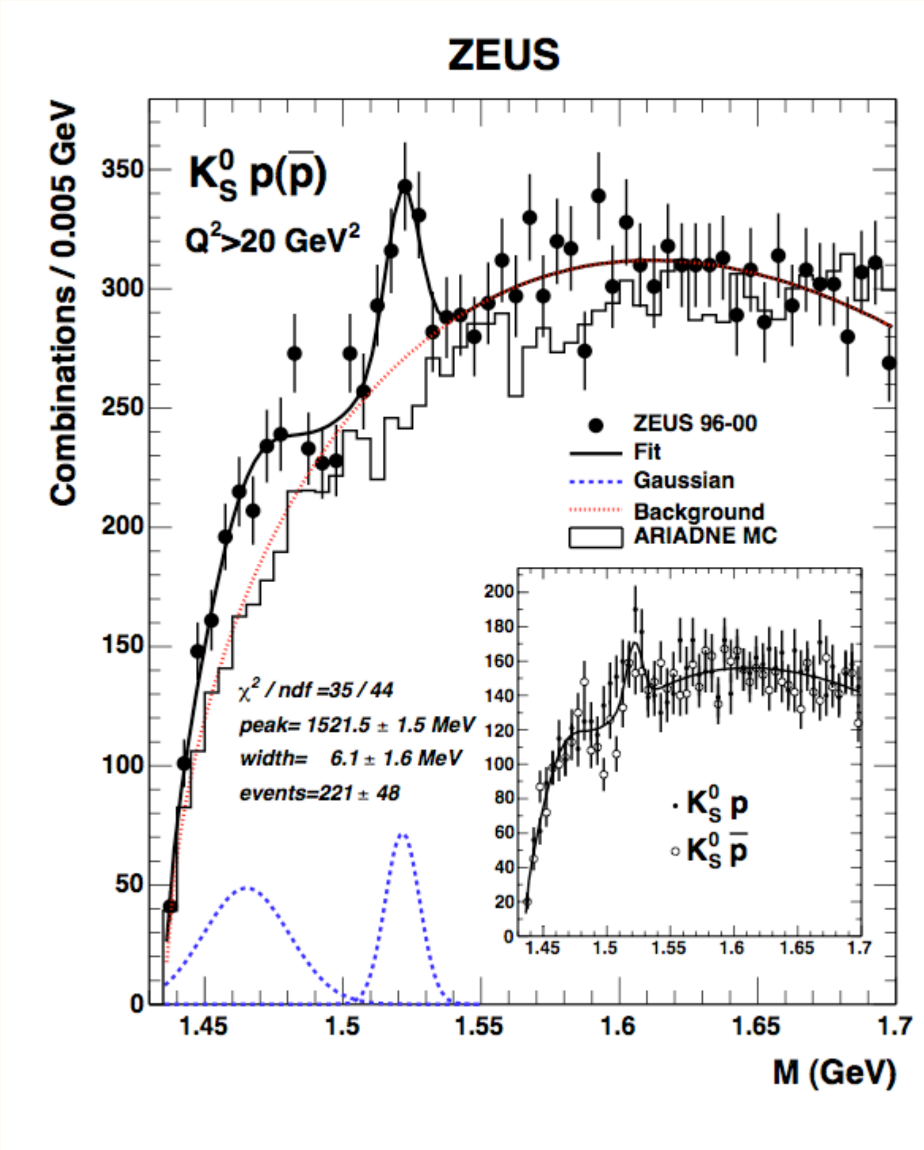
Need more statistics --> access to this kinematic range

Open questions: hadronization

Long distance phenomena…

Have a beautiful description of pQCD but only hints at what it says quantitavely about hadronization!

ZEUS's search for Θ^+ (my Ph.D. thesis…)



Other open questions

How do gluons contribute to nucleon spin?

What is the impact of quarks & gluons on the transverse dynamics?

Spatial resolution of quarks: HERA provides first hints via measurements of DVCS but only rudimentary information so far

Diffraction - still a puzzle

The nucleus: the white elephant in the room

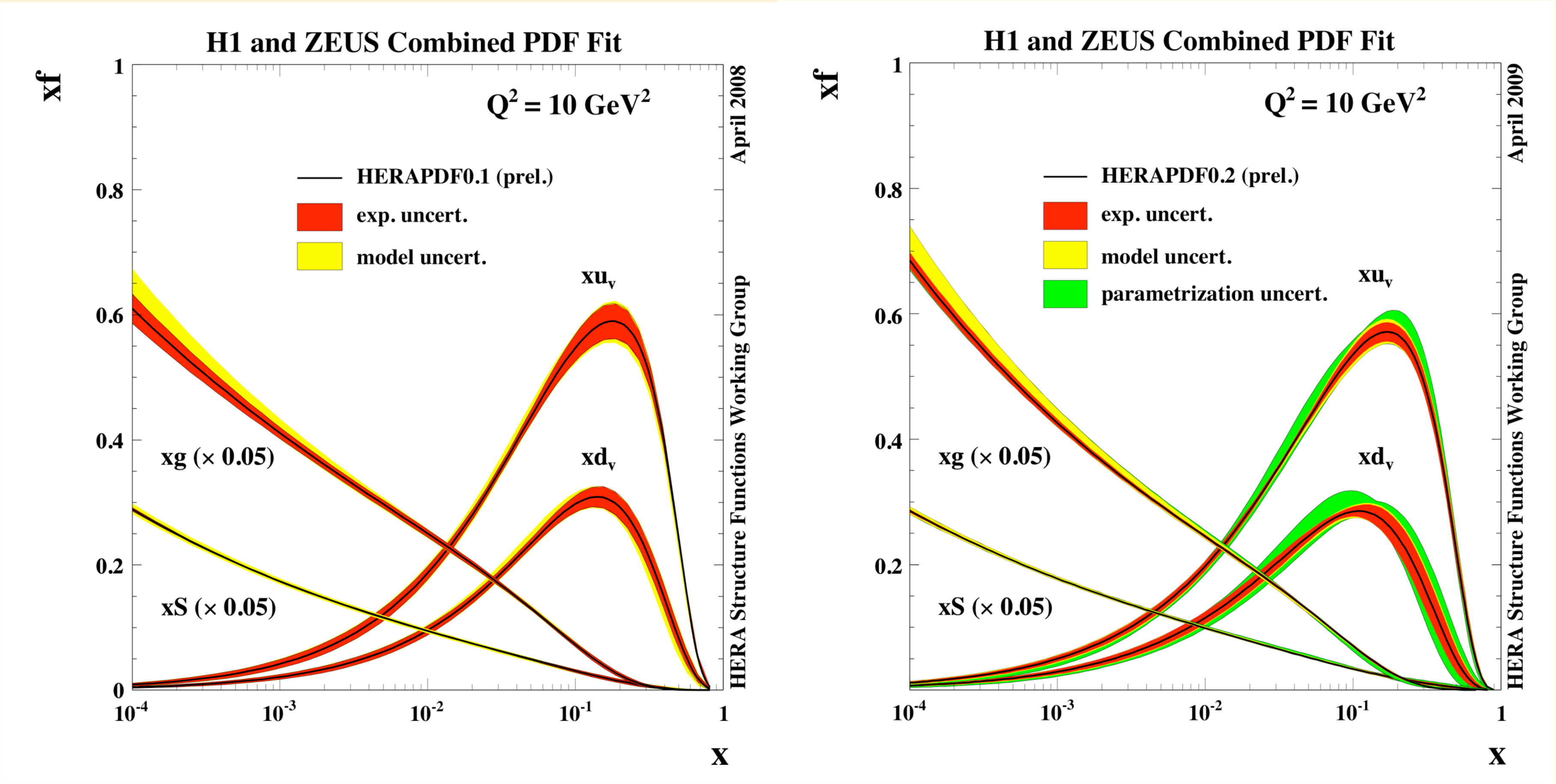
Many questions remain… there is a need (and a hope) for new opportunities (detectors/colliders) to answer them!

End of an (H)ERA

ZEUS HALL on midnight June 30, 07

Backup slides

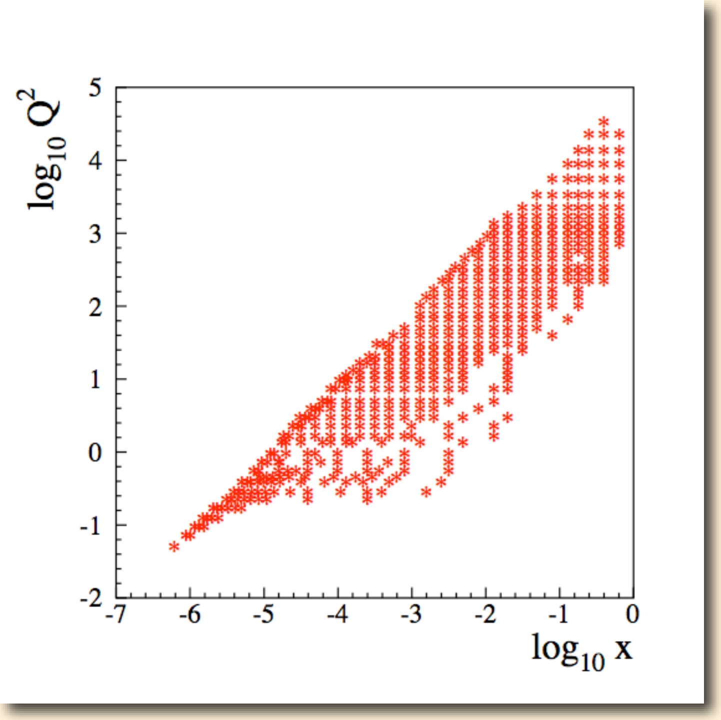
HERAPDF: 01 vs 02



- 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" $0.2 \leq Q^2 \leq 12$ GeV^2
  - H1 96-00 "bulk" $12 \leq Q^2 \leq 150$ GeV^2
  - ZEUS BPC/BPT, SVX95 $0.045 \leq Q^2 \leq 17$ 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

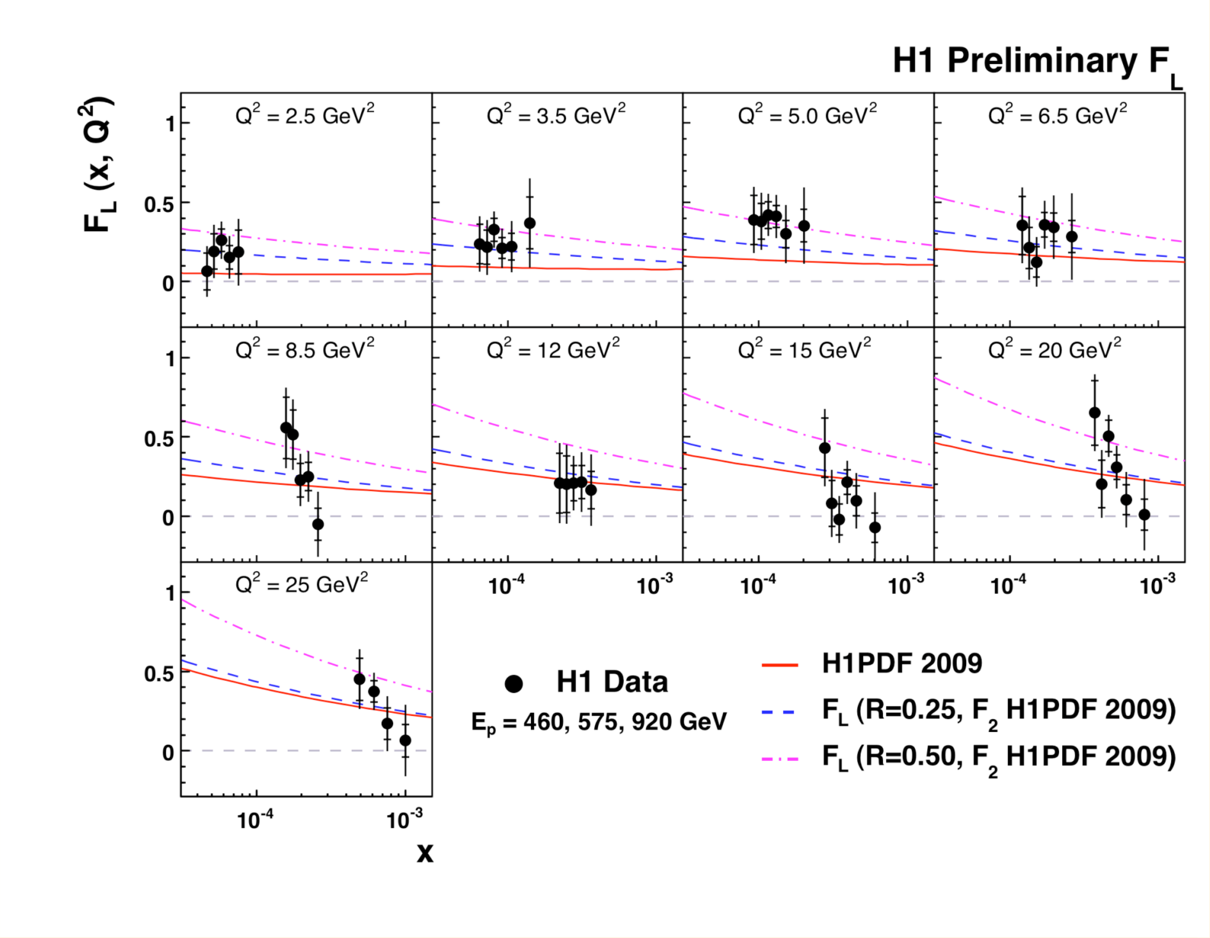
2) Correlated uncertainties:
Point-to-point correlated uncertainties
  - e.g. electromagnetic and hadronic energy scale calibration
  - Often common for CC and NC for a given experiment and run period

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

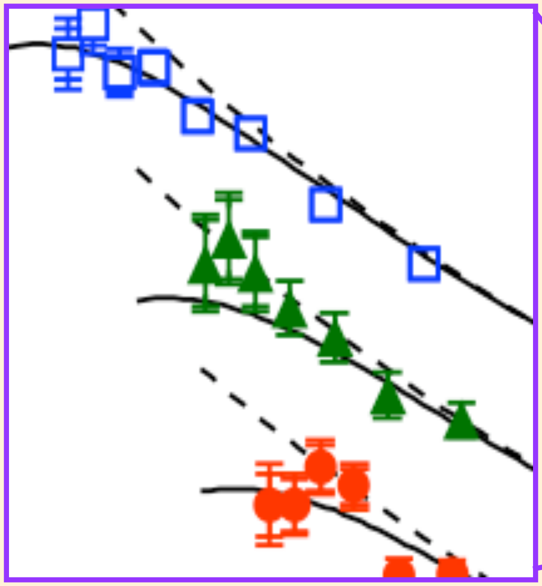
There are 110 systematic errors which are combined in quadrature with the statistical errors and 3 sources of errors from the averaging procedure are offset.
- Small effects observed when errors are treated as correlated

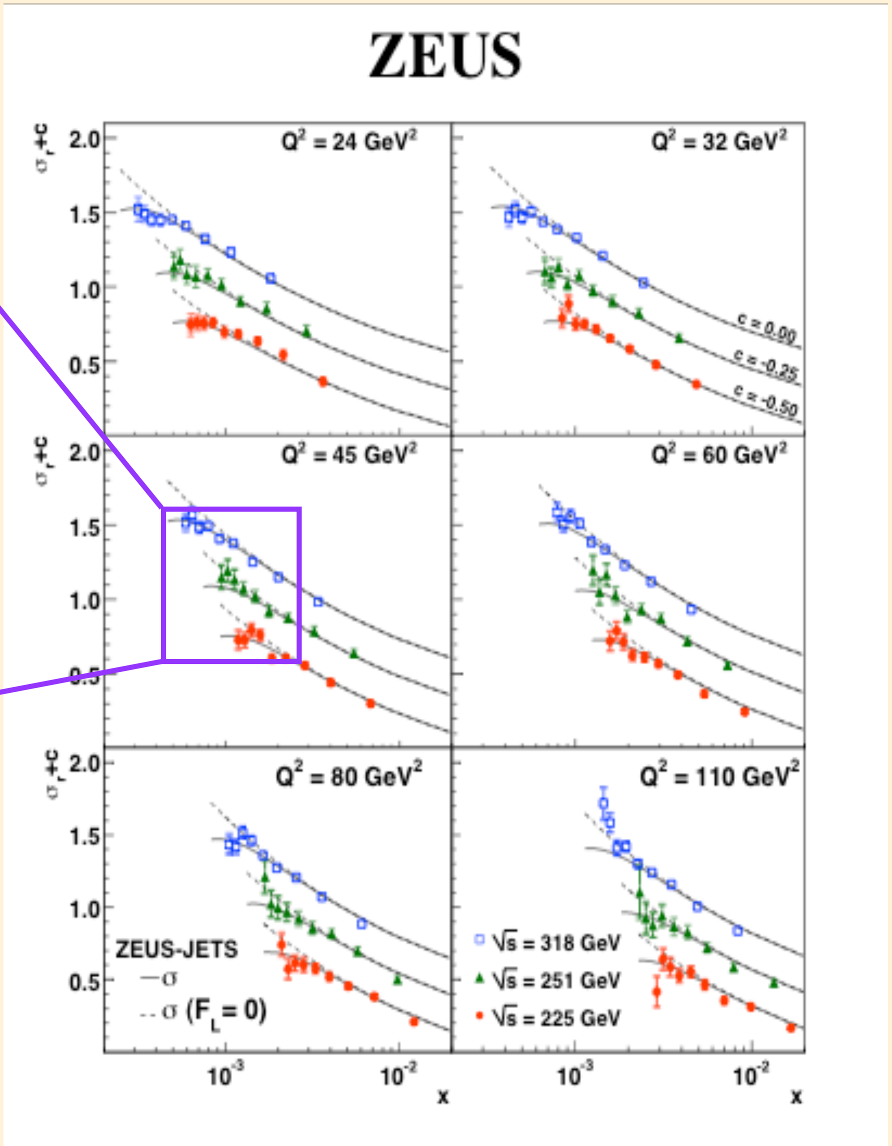
F_L: Most recent H1 result at low Q^2



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

F_L: ZEUS reduced cross sections





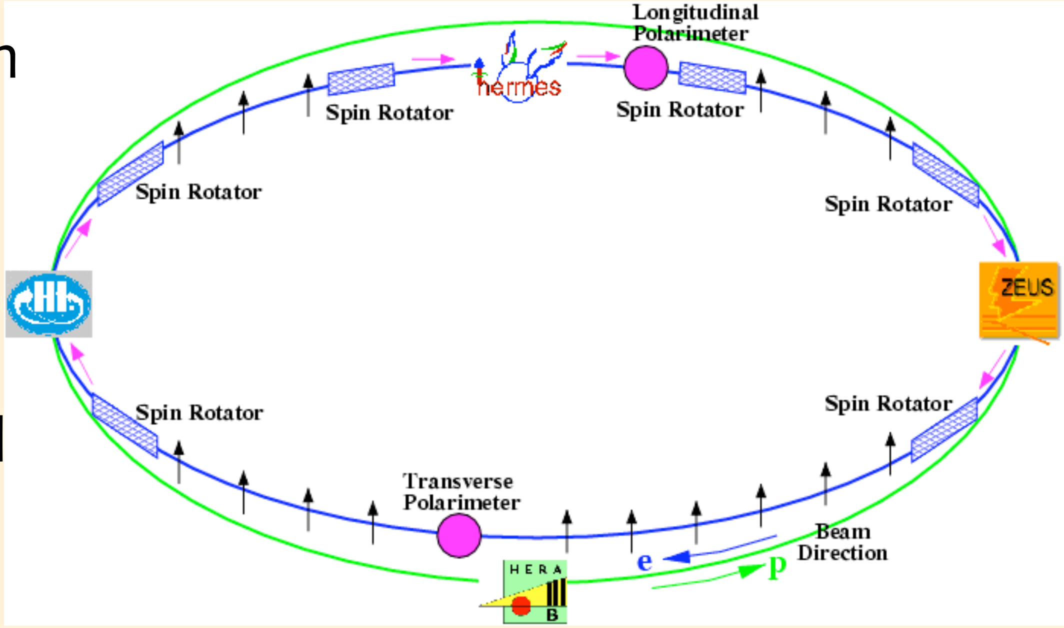
- F_L obtained from differences of cross sections at different CME's
- F_L damps the rise of F_2 at low x
- need to subtract 2 large numbers …
- … hence limited statistical power

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%