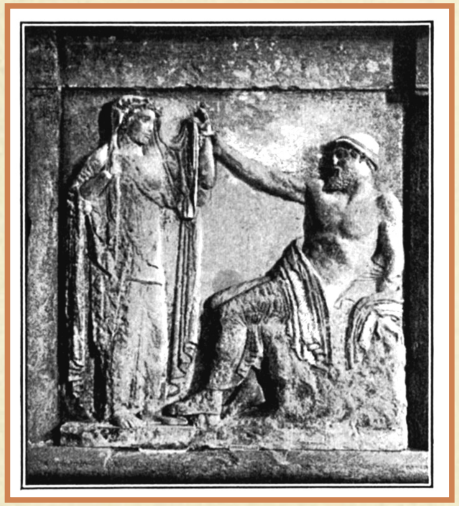
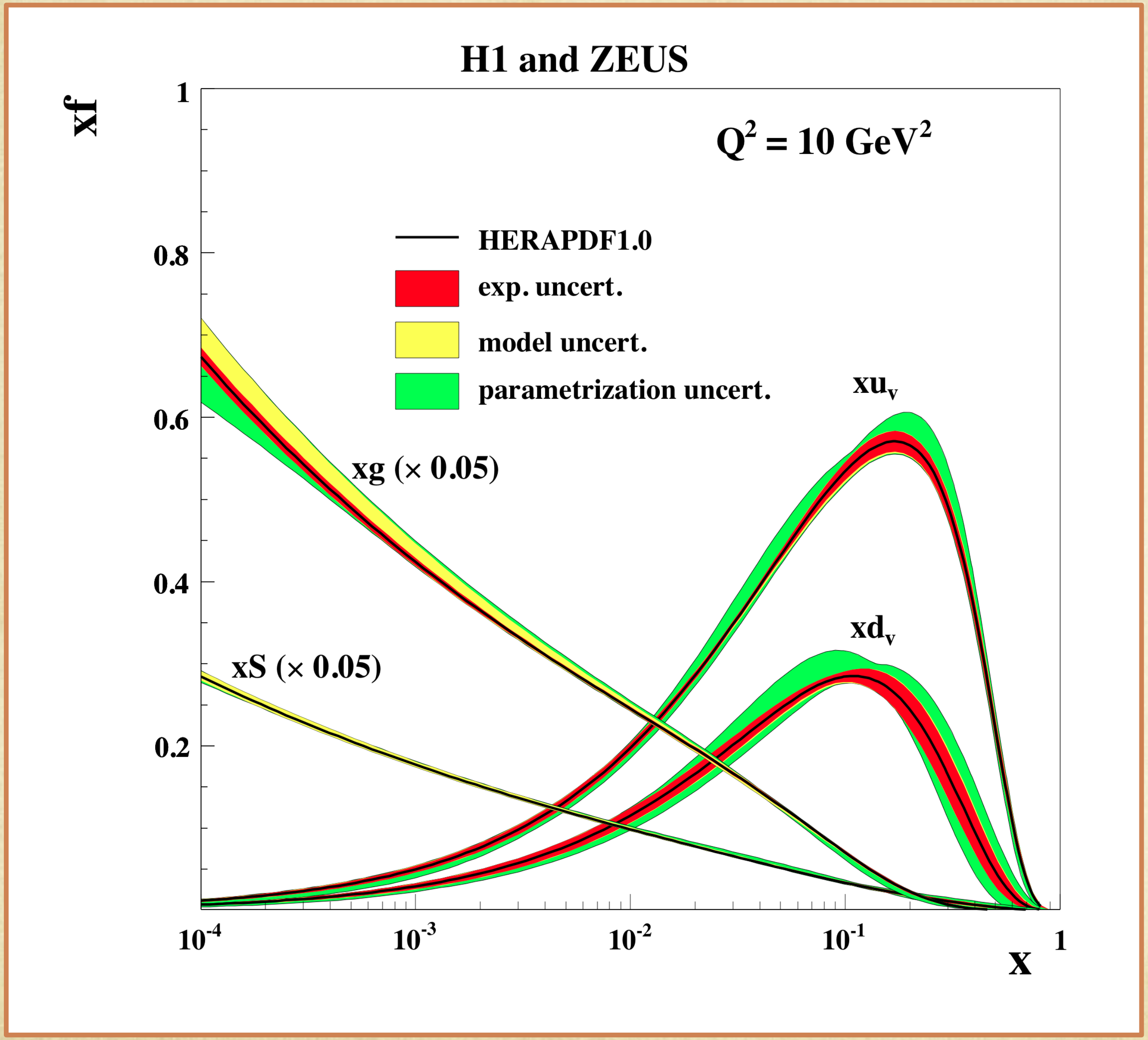
Proton structure : results from HERA

Amita Raval, DESY



Structure of the proton



xu_v xd_v

valence quark distributions

xg

gluon momentum distribution

xS

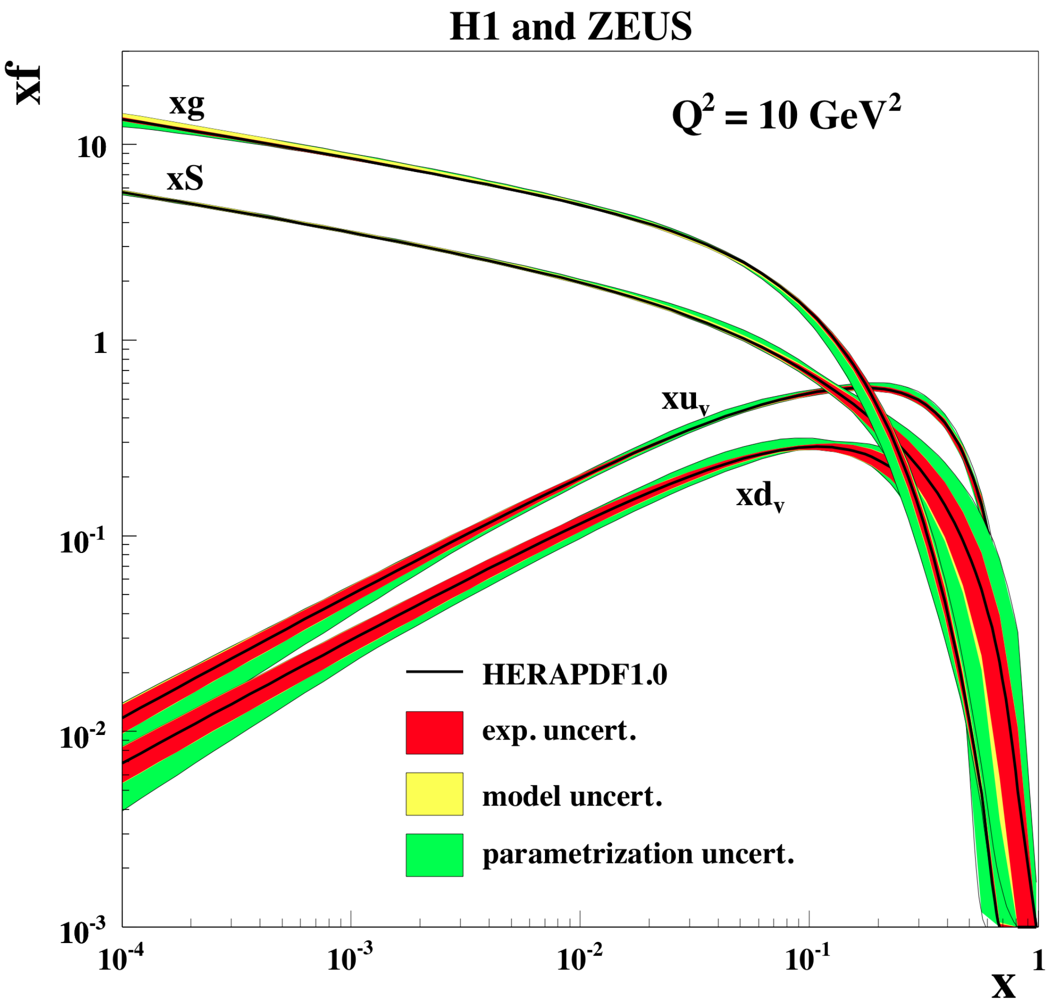
combined sea quark distribution

Q^2 is resolving power of probe

x is momentum fraction carried by struck quark

NB: gluon and sea quark are scaled down by 20%!

Structure of the proton



Gluon momentum & combined sea quark (xg, xS) distributions dominate the structure of the proton, starting at $x \sim 0.2$!

Shown are Parton Distribution Functions (PDFs) from HERA, **HERAPDF1.0** with

- experimental
- model
- parametrization

uncertainties

Parton Distribution Functions

What are Parton Distribution Functions?

- They reflect partonic content of proton → provide probability density of finding a parton in a proton carrying its momentum fraction x at scale Q^2

- Partonic content is universal → PDFs can be used to make predictions for other processes involving protons, eg. cross sections in proton-proton collisions at LHC

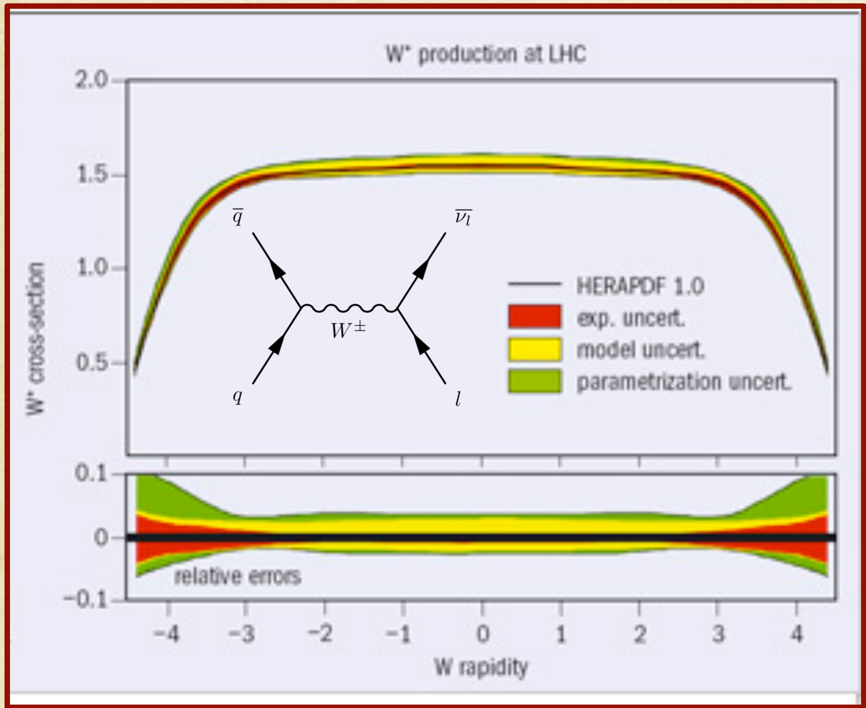
- Are determined experimentally (non-perturbative)

- IF PDFs are precisely determined
  → provide a stringent test of SM
  → can provide a standard candle against new phenomena
  -- controlling QCD background
  -- allowing exploration of properties of new particles

… BUT this requires a precise knowledge of the proton-parton distributions which come from the measurements at HERA

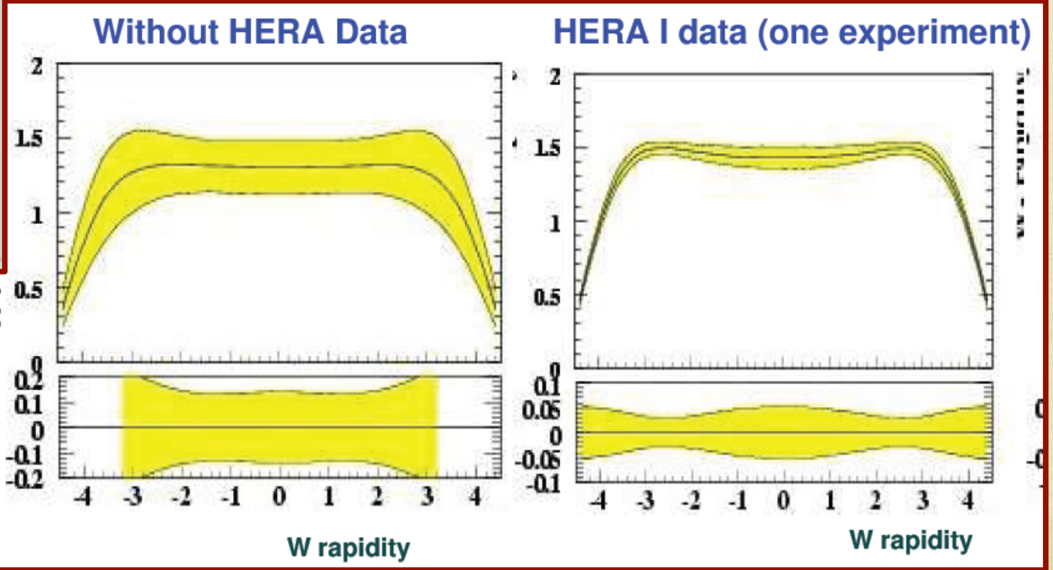
HERAPDFs: impact on LHC

W production can be used to determine luminosity of LHC because this measurement can be done with great accuracy



Incredibly precise σ prediction with HERAPDF:

- uncertainty few % in central region
- experimental uncertainty < 1%



HERAPDF1.0 set available
in LHAPDF since version 5.8.1

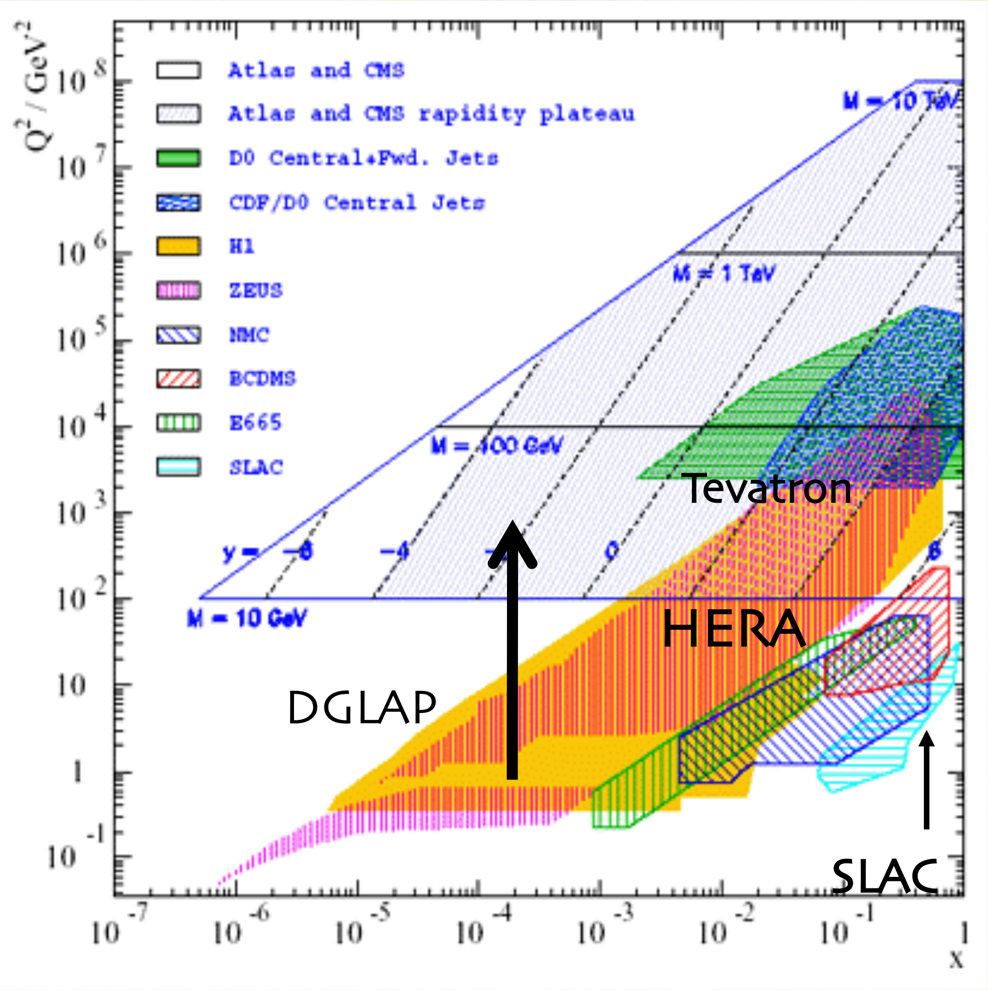
Large extension of knowledge due to HERA

Persistent experimental effort over the last four decades supported by theoretical developments (LO-NLO-NNLO) has extended the explored space in x, Q^2 compared to the original SLAC results.

HERA data, the main source of knowledge on proton structure, cover most of the x,Q^2 plane

HERAPDF1.0:

- utilize $\mathcal{L} = 230\ \text{pb}^{-1}$
- contain combination of 1402 data points (measurements from 14 publications) to obtain 741 cross-section measurements covering
  - $0.045 < Q^2 < 30000\ \text{GeV}^2$
  - $6\times10^{-7} < x < 0.65$



HERA to LHC kinematics → assume validity of (N)NLO DGLAP equations and extrapolate HERA results into the LHC region

HERA operation

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

HERA I: 1992 – 2000

HERA II: 2003 - 2007

End of an (H)ERA

ZEUS HALL on midnight June 30, 07

HERA operation

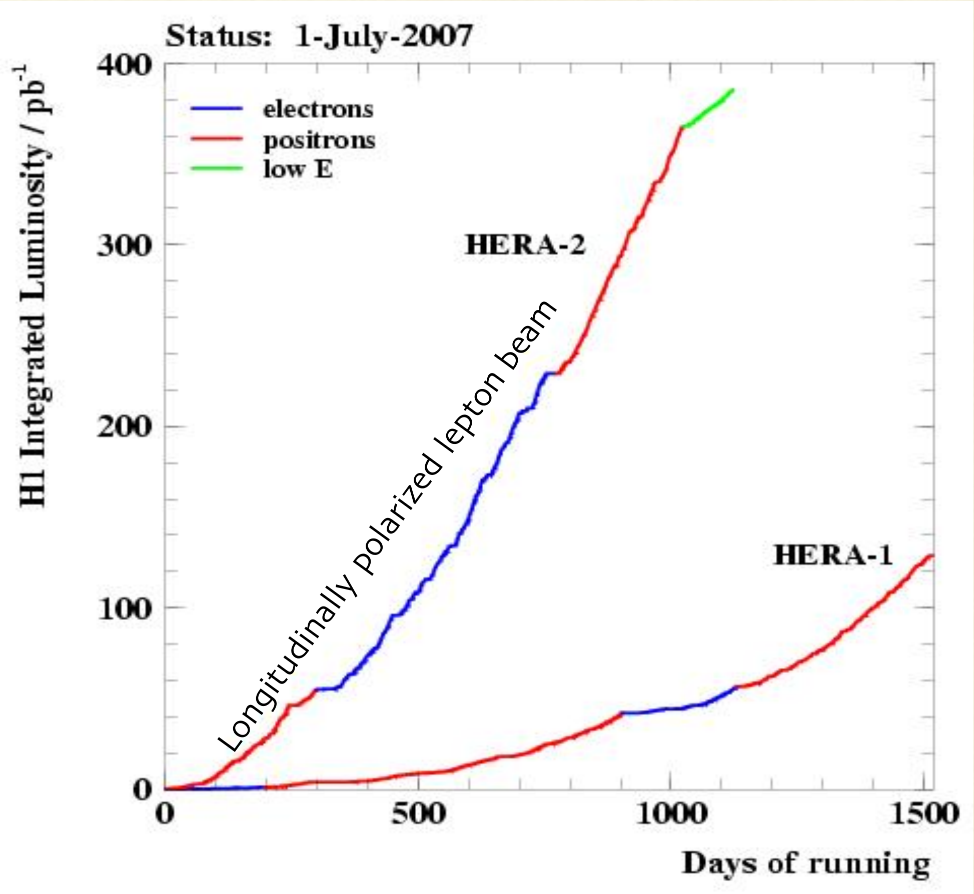
$e^{\pm}$

27.5 GeV

p

820 GeV/
920 GeV

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

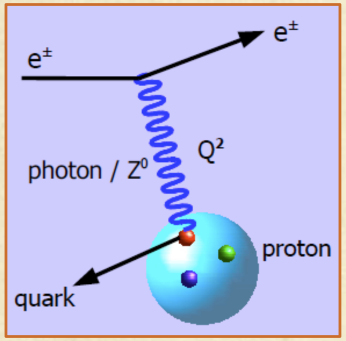


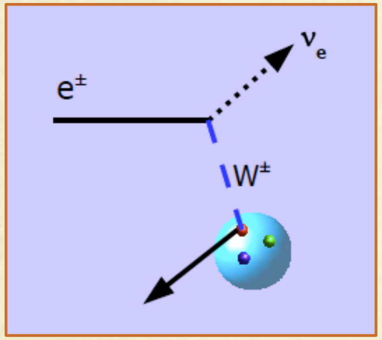
- average (lumi weighted) polarization achieved: 30 - 40%
- e^+p, e^-p samples balanced
- ~ 20 pb^{-1} from low (E_p 460) & medium (E_p 575) energy running (F_L)
- ~ 0.5 fb^{-1} collected per experiment

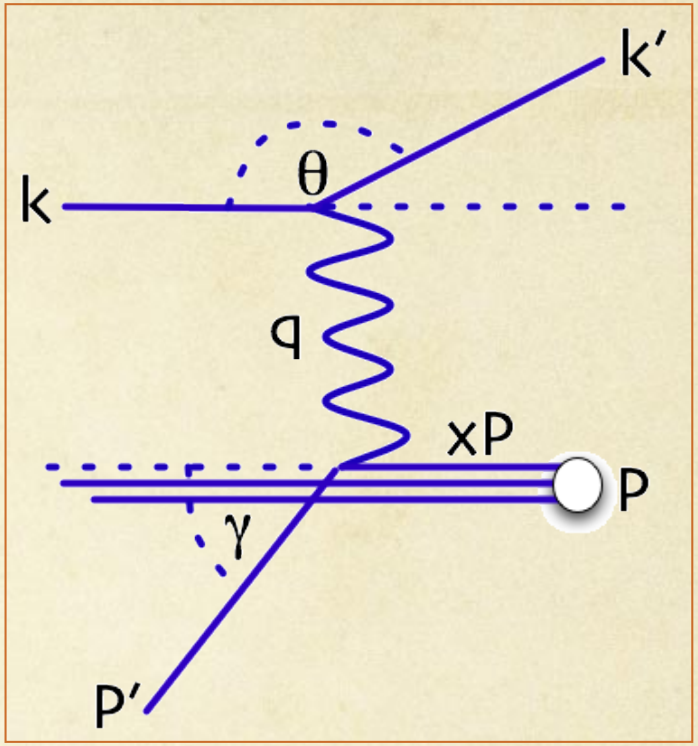
Deep inelastic e±p scattering: probing the proton

At HERA, two deep inelastic scattering processes available to probe the proton:

- Neutral current: exchange of γ or Z^0
- Charged current: exchange of $W^\pm$







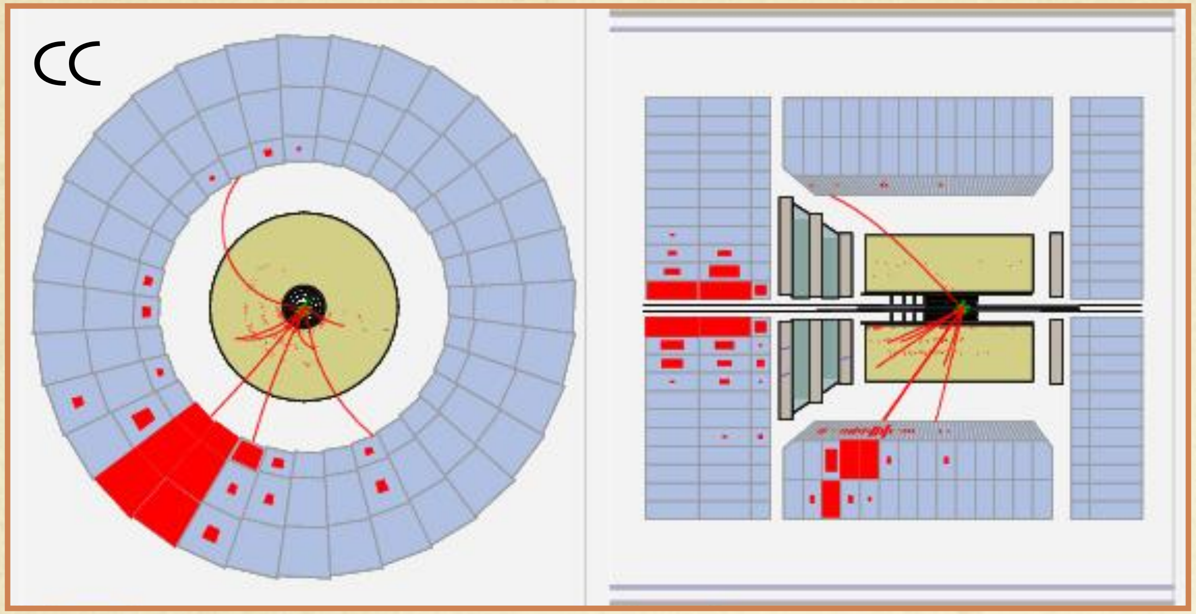
$$Q^2 = -q^2 = -(k-k')^2$$

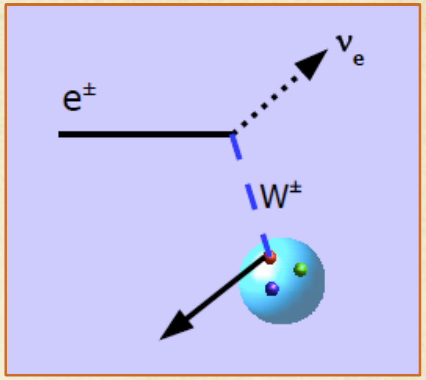
$$x = \frac{Q^2}{2p\cdot q} \qquad y = \frac{p\cdot q}{p\cdot k}$$

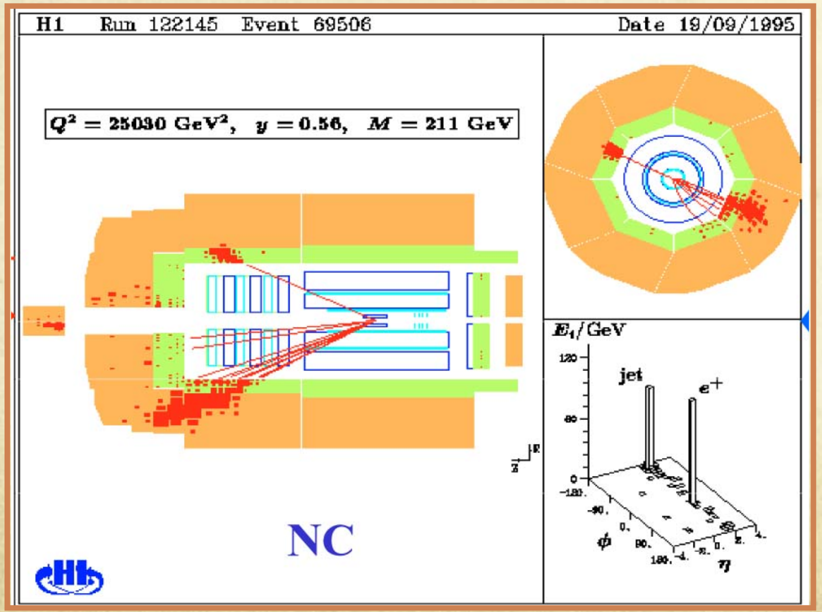
$$s = (p+k)^2 \qquad Q^2 = x\cdot y\cdot s$$

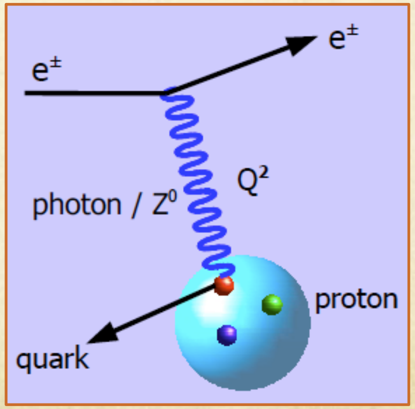
- Q^2 is resolving power of probe
- x is momentum fraction carried by the quark ($10^{-6} \sim 1$)
- y is inelasticity of e
- s is CME

Deep inelastic e±p scattering: probing the proton



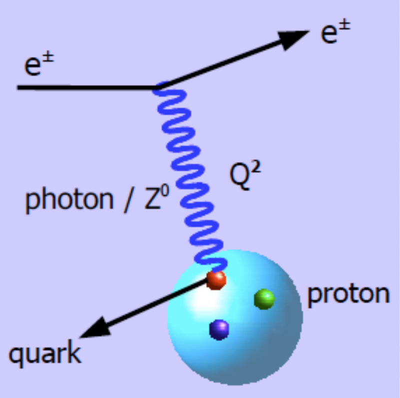






Deep inelastic e±p scattering: NC cross section

NC DIS: ep → eX ---> gluons, sea quarks and valence quarks



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

Define polarization of exchanged boson

valence + sea quarks | gluon | valence quarks

Structure functions F_2, F_L and xF_3 encapsulate parton content of p

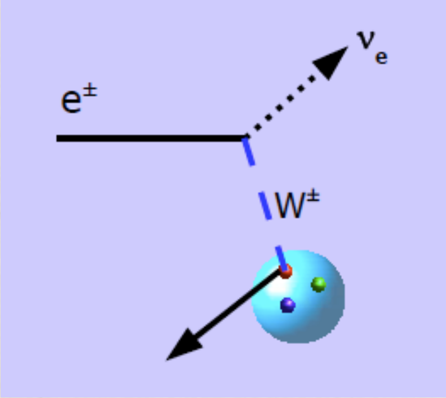
F_2: dominates over most of phase space, except high Q^2 & large y

xF_3: non-zero at high Q^2 → parity violating weak effects from γZ interference at $Q^2 \sim M_Z^2$ (NB: notice the ‘sign of xF_3)

F_L: sizable at large y → gluon radiation in the proton

Deep inelastic e±p scattering: CC cross section

CC DIS: ep → νX ---> valence quarks: flavor separation + more …



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

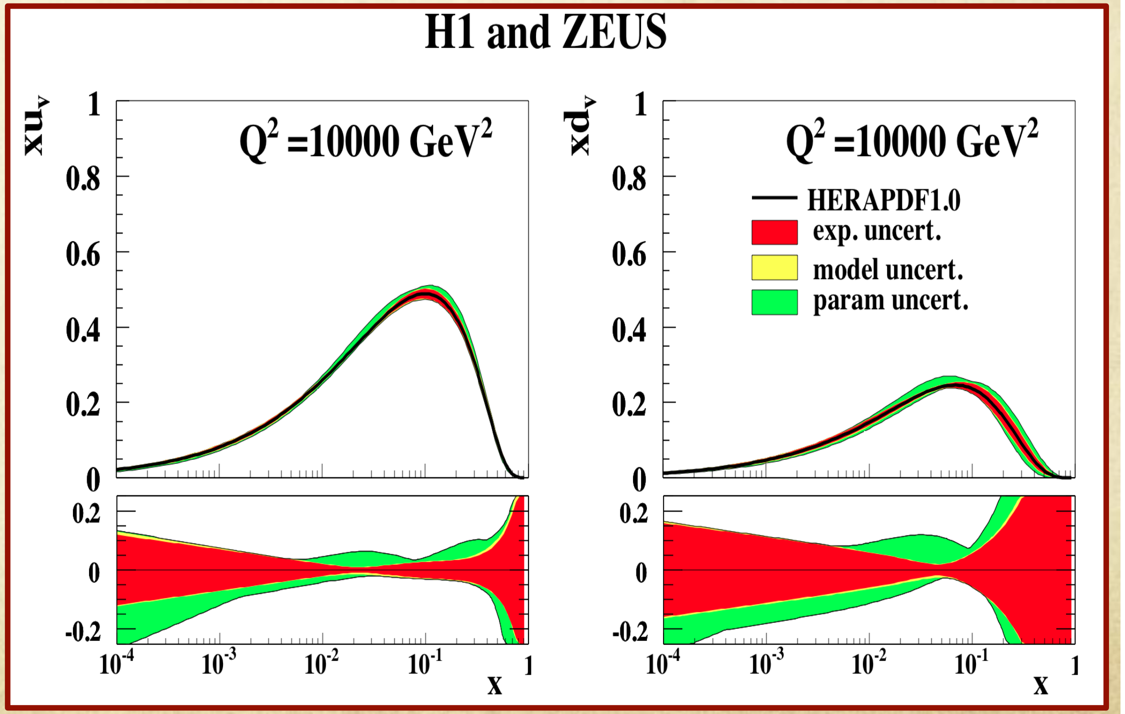
$$\frac{d^2\sigma^{CC}(e^-p)}{dQ^2dx} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[\boxed{u+c}+(1-y)^2(\bar{d}+\bar{s})\right] \quad \times (1 - P_e)$$

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

e^-p: sensitive to u valence q

e^+p: sensitive to d valence q

→ poorly constrained



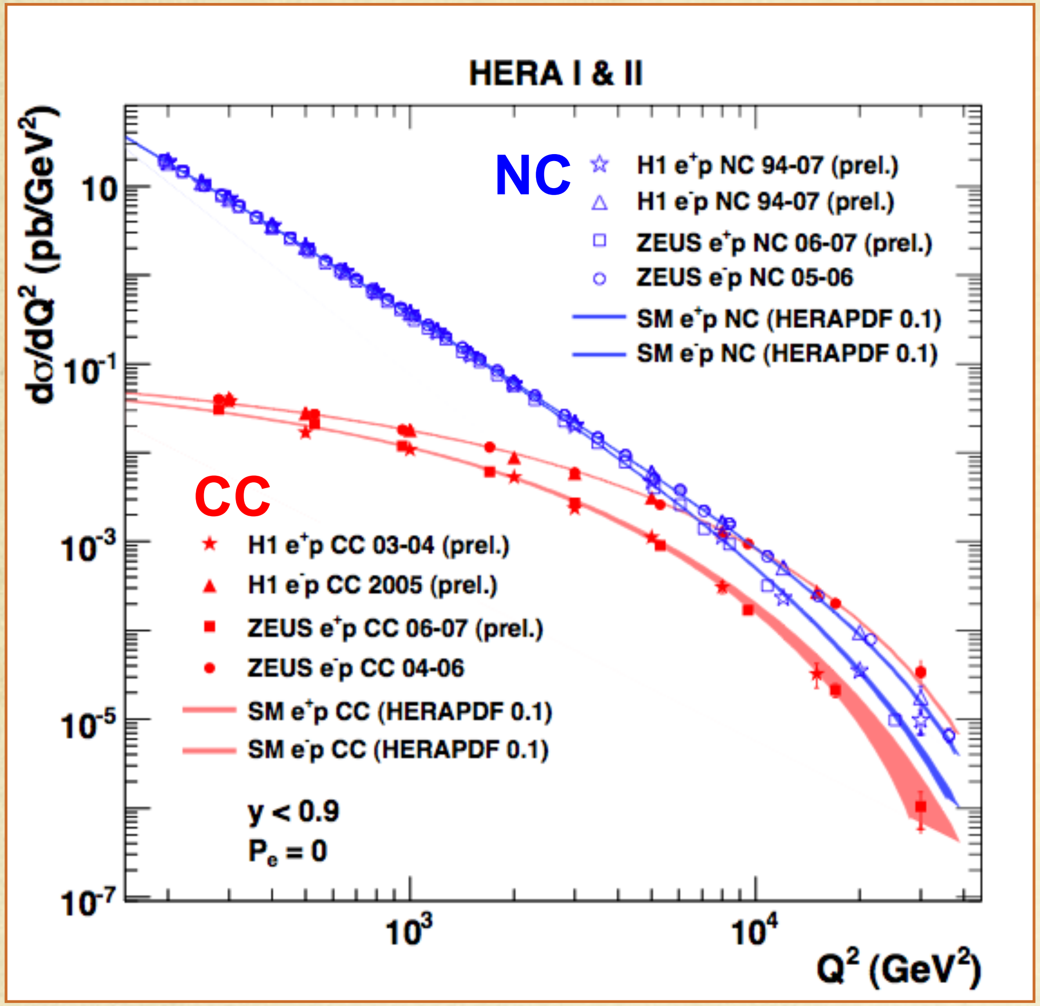
NC and CC cross sections

Message:

NC and CC measurements may be used to determine the combined sea quark distribution functions, xS, and the valence distributions, $xu_v \;\; xd_v$

QCD analysis in DGLAP formalism also allows the gluon momentum distribution, xg, in the proton to be determined (from scaling violations)

DIS: testing ground for SM



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

Neutral Current DIS:

- low Q^2: ϒ exchange dominates (described by F_2)
- high Q^2: Z^0 contribution significant (described by xF3); Z/γ interference:
  - constructive in e-
  - destructive in e+

Charged Current DIS:

- Sensitive to flavor separation and increase/decrease σ
  - e-p (u) enhanced
  - e+p (d) suppressed

CC σ similar to NC σ at high Q^2 ($\sim M^2_W$) → EW unification

The electron probe behaves as expected!

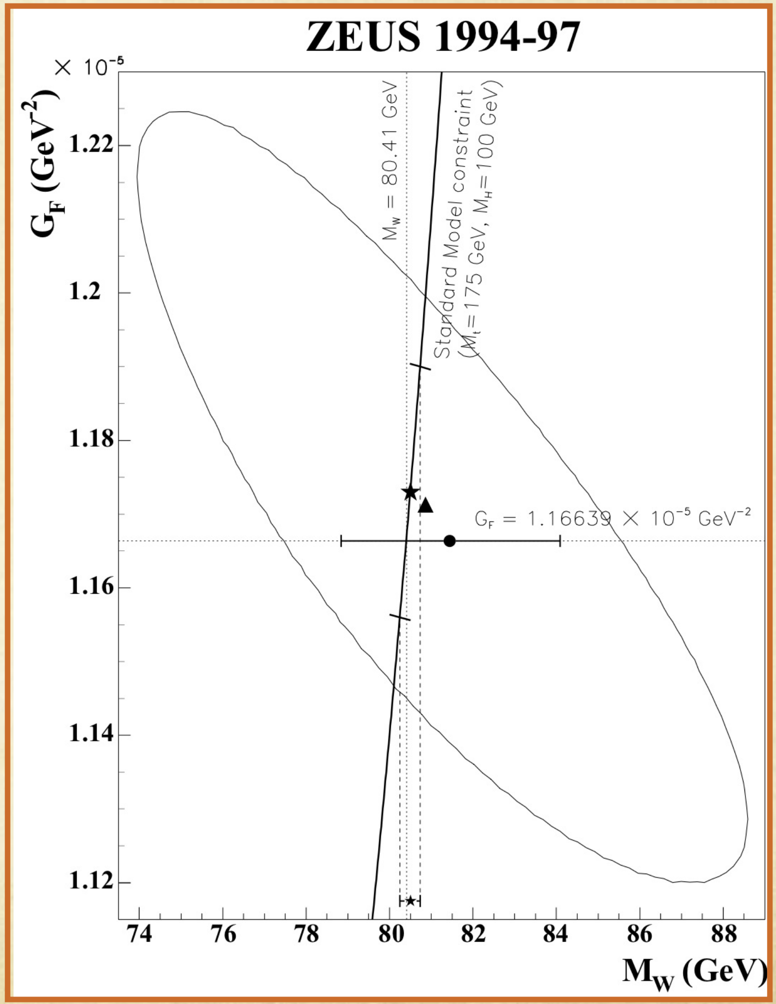
Deep inelastic e+p scattering: CC cross section

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

An aside…

Sensitivity to electro-weak parameters M_W and G_F

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

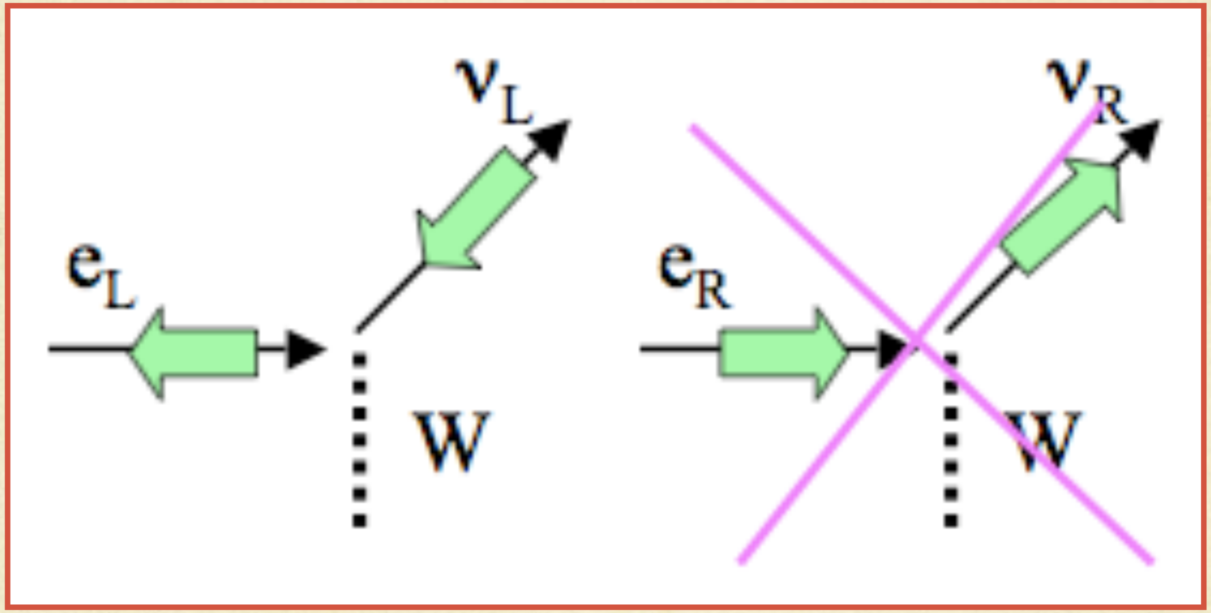


Eur. Phys. J. C 12, 411 (2000) ➔

Deep inelastic e+p scattering: CC cross section

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

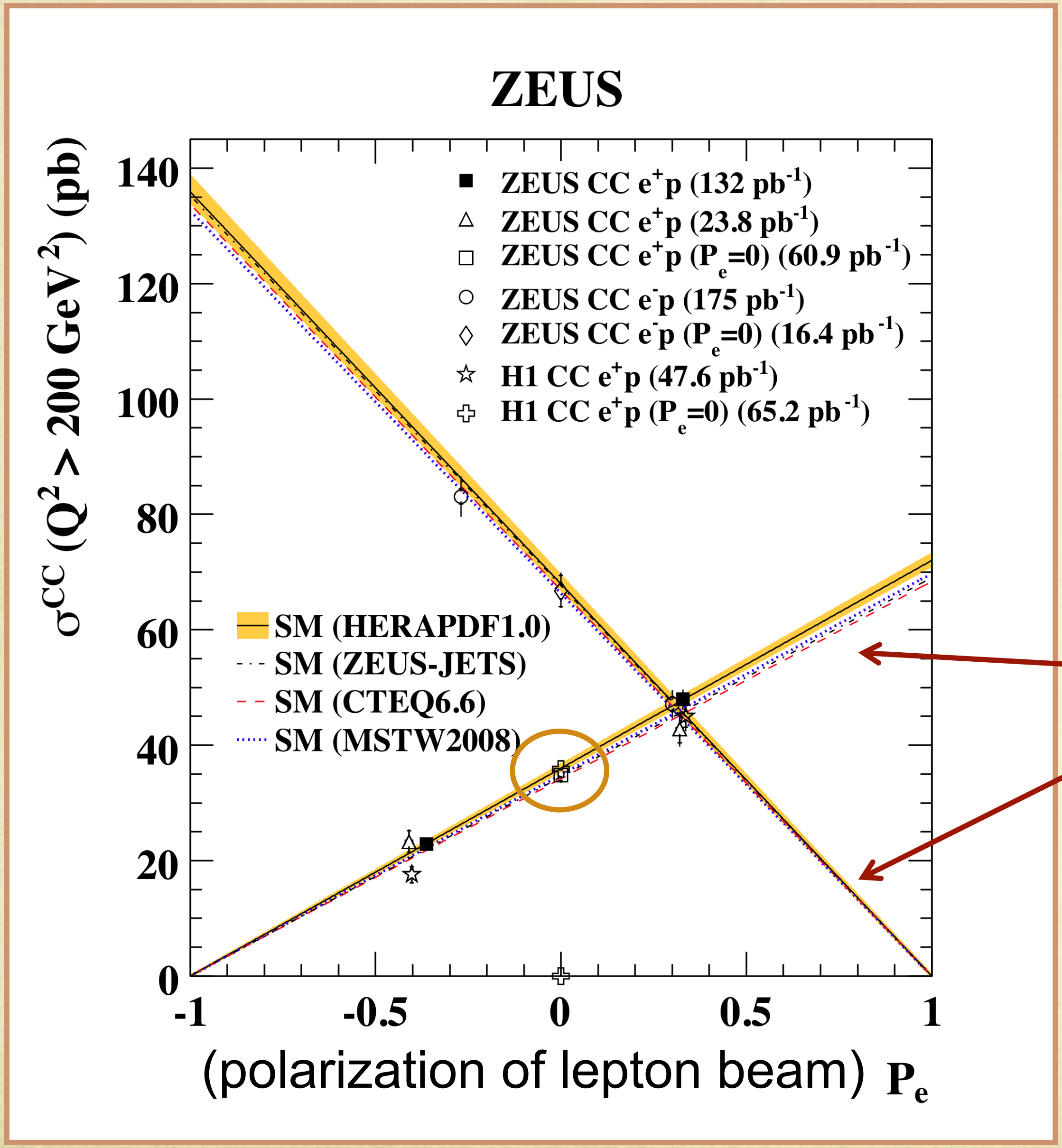
Provides a test of chiral structure of SM ➔ parity non-conservation



CC e^+p DIS cross section becomes zero for fully left-handed (P_e= -1) positron beams ….

A NON-zero cross section at P_e =-1 might point to a right-handed W!

Test of chiral structure of SM



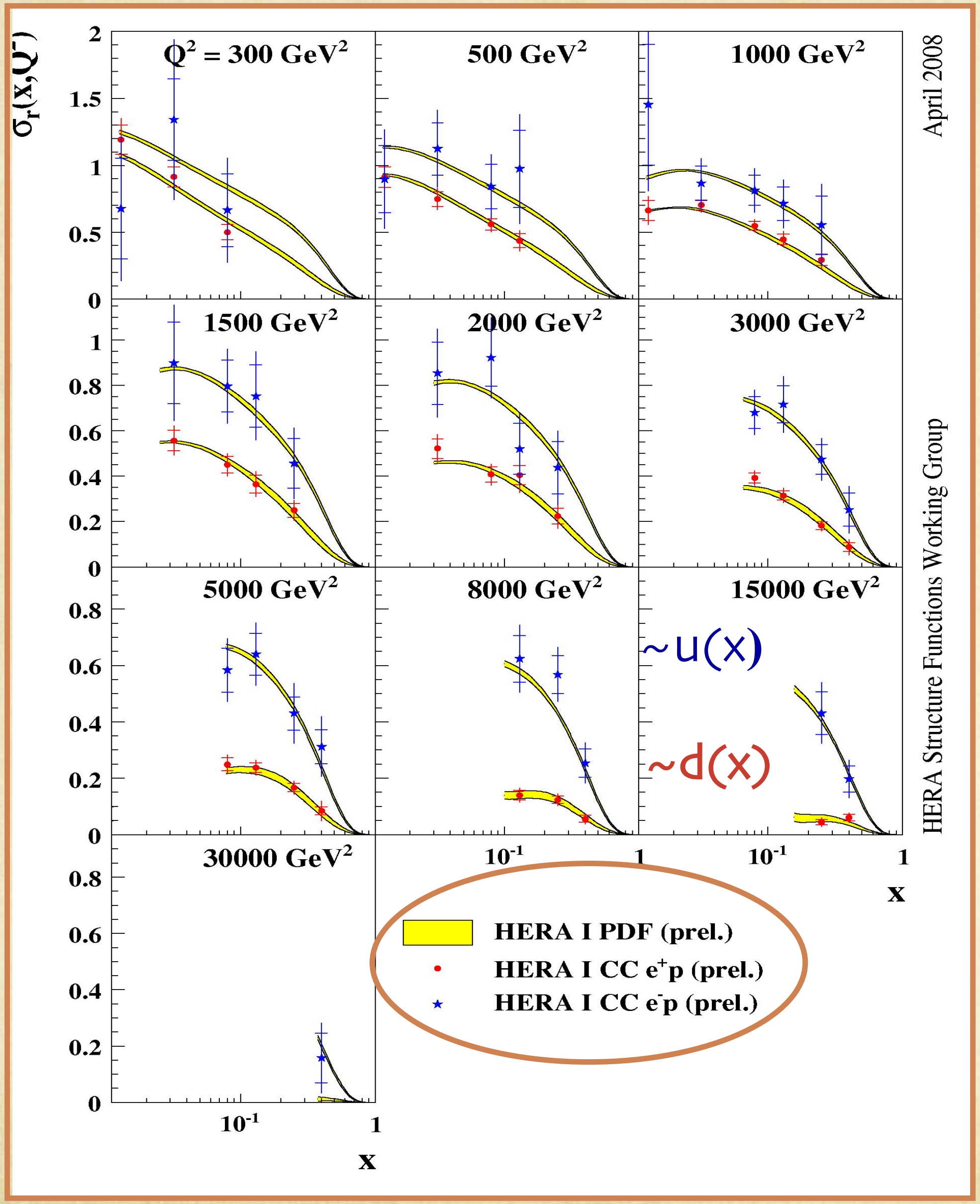
HERA CC: ep → νX

Total cross section at high Q^2

- linearly proportional to the degree of the longitudinal lepton beam polarization
  - ~ (1+P) for e+p
  - ~ (1 - P) for e-p

Results consistent with no right-handed weak currents

Proton structure: valence quarks



HERA I CC: ep → νX

H1 and ZEUS combined data

Comparison between

- σ (CC e+p) and σ (CC e-p)
- and to HERA1 PDF

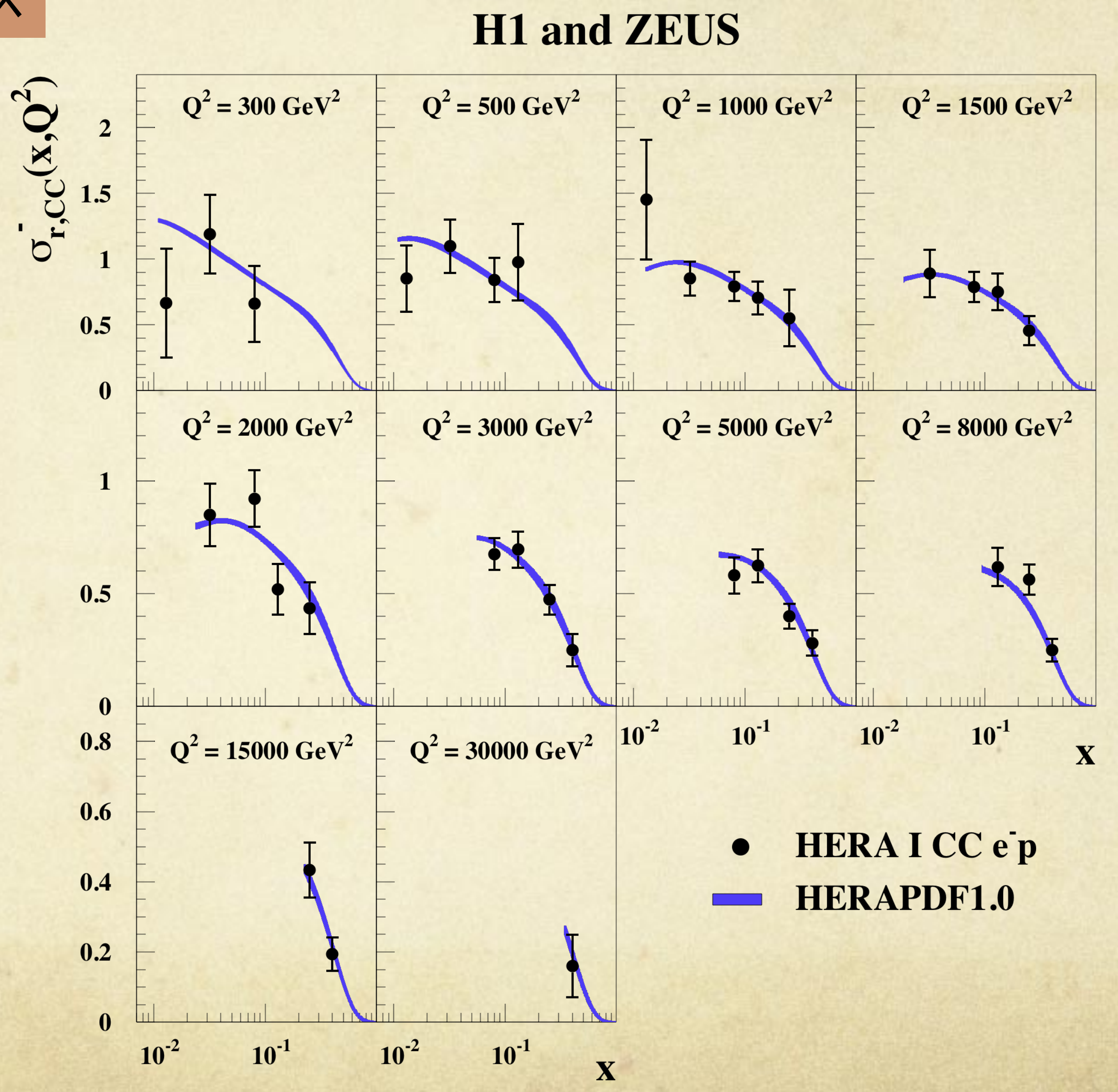
SM describe the data well

Data show flavor sensitivity to charge of electron probe

Final HERA I results → …

Proton structure: valence quarks

HERA I CC: e-p → νX



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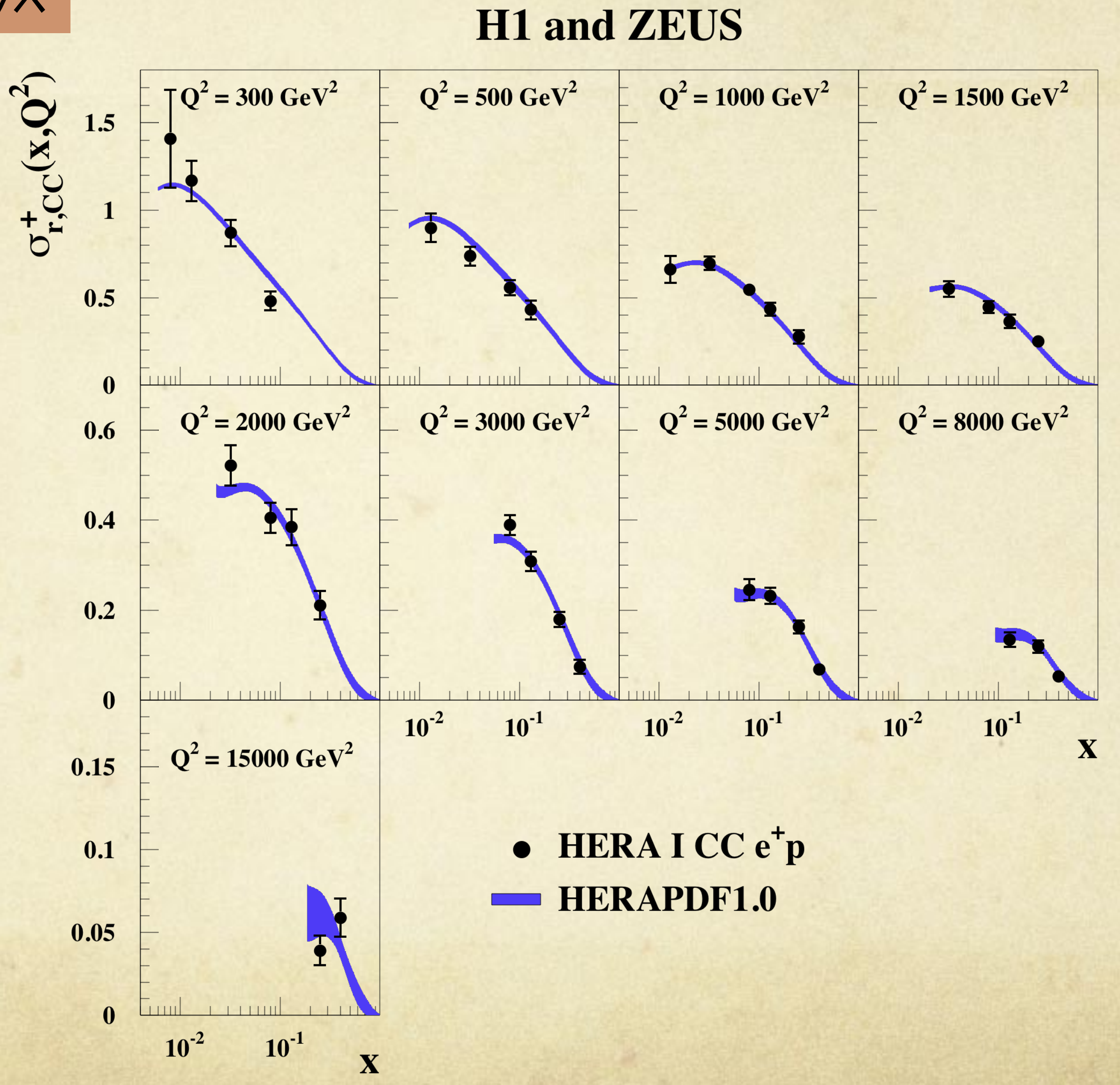
Proton structure: valence quarks

HERA I CC: e+p → νX



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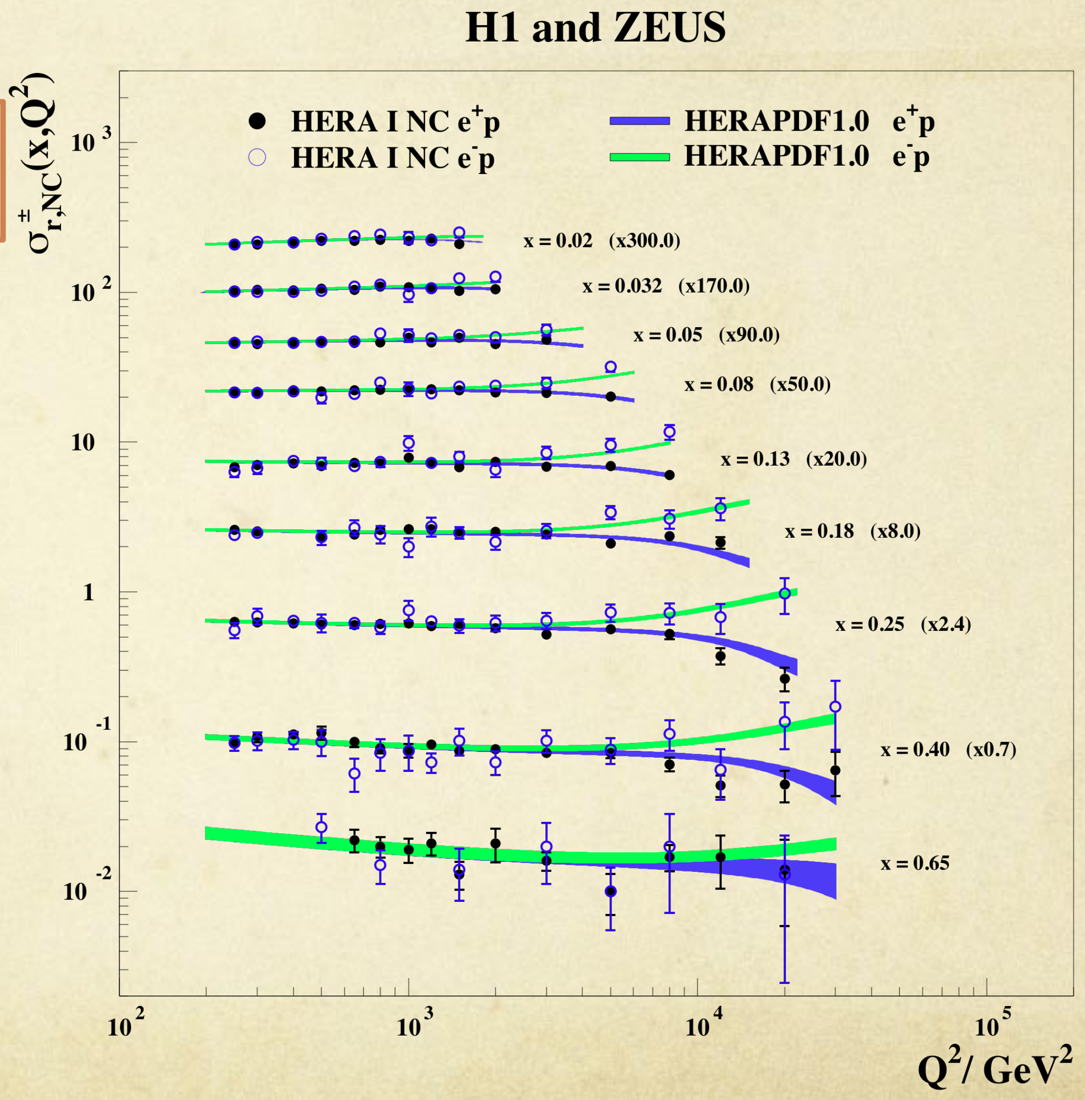
Proton structure: valence quarks

HERA I NC: ep → eX

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

Dominates at high Q²

At high Q^2: contribution from interference term



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Proton structure: valence quarks + ?

HERA I NC: $e^+p \rightarrow e^+X$

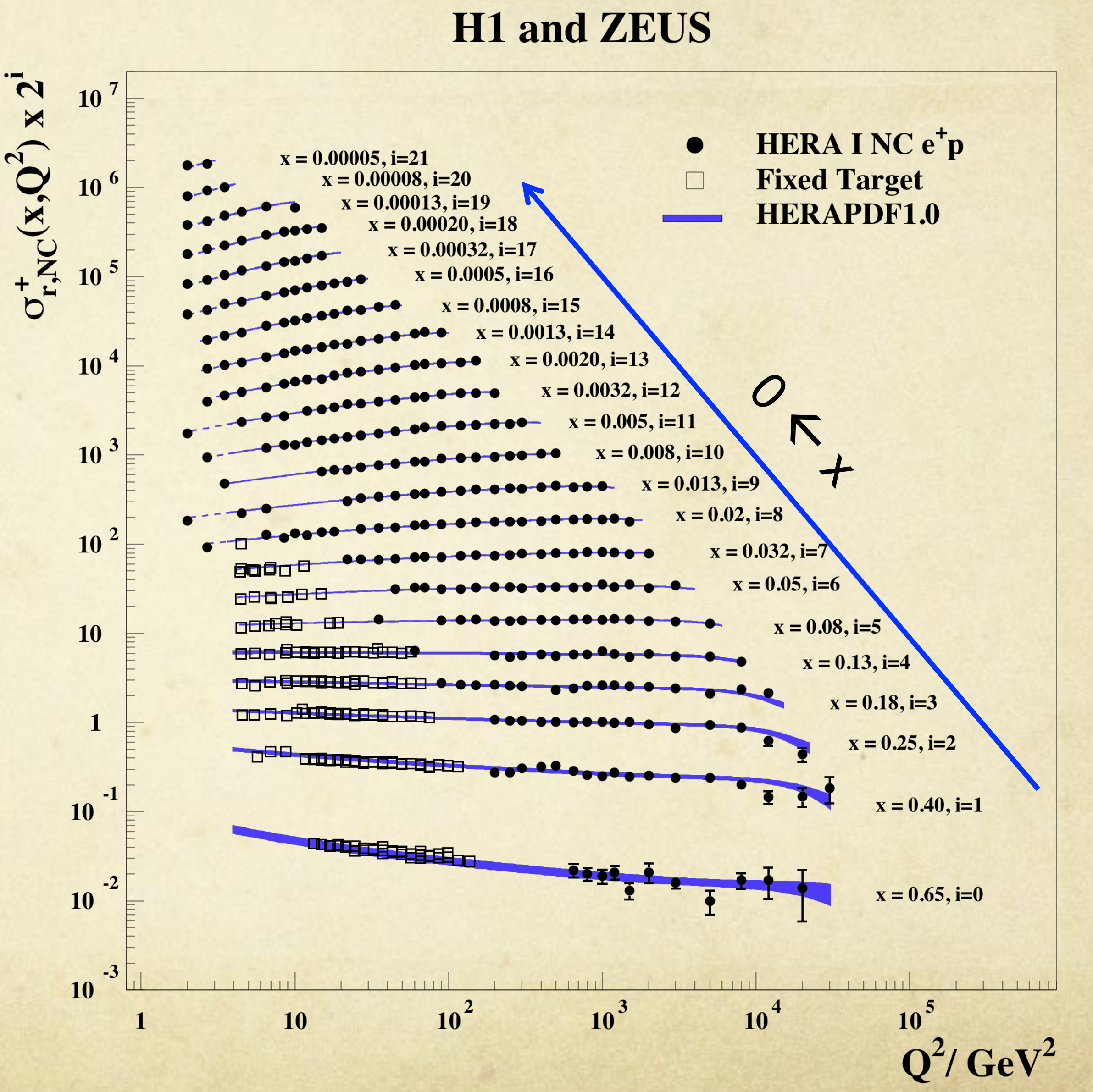
Low Q^2

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

Good agreement between data and NLO QCD over several orders of magnitude in both x and Q^2
Precision approaching 1% !

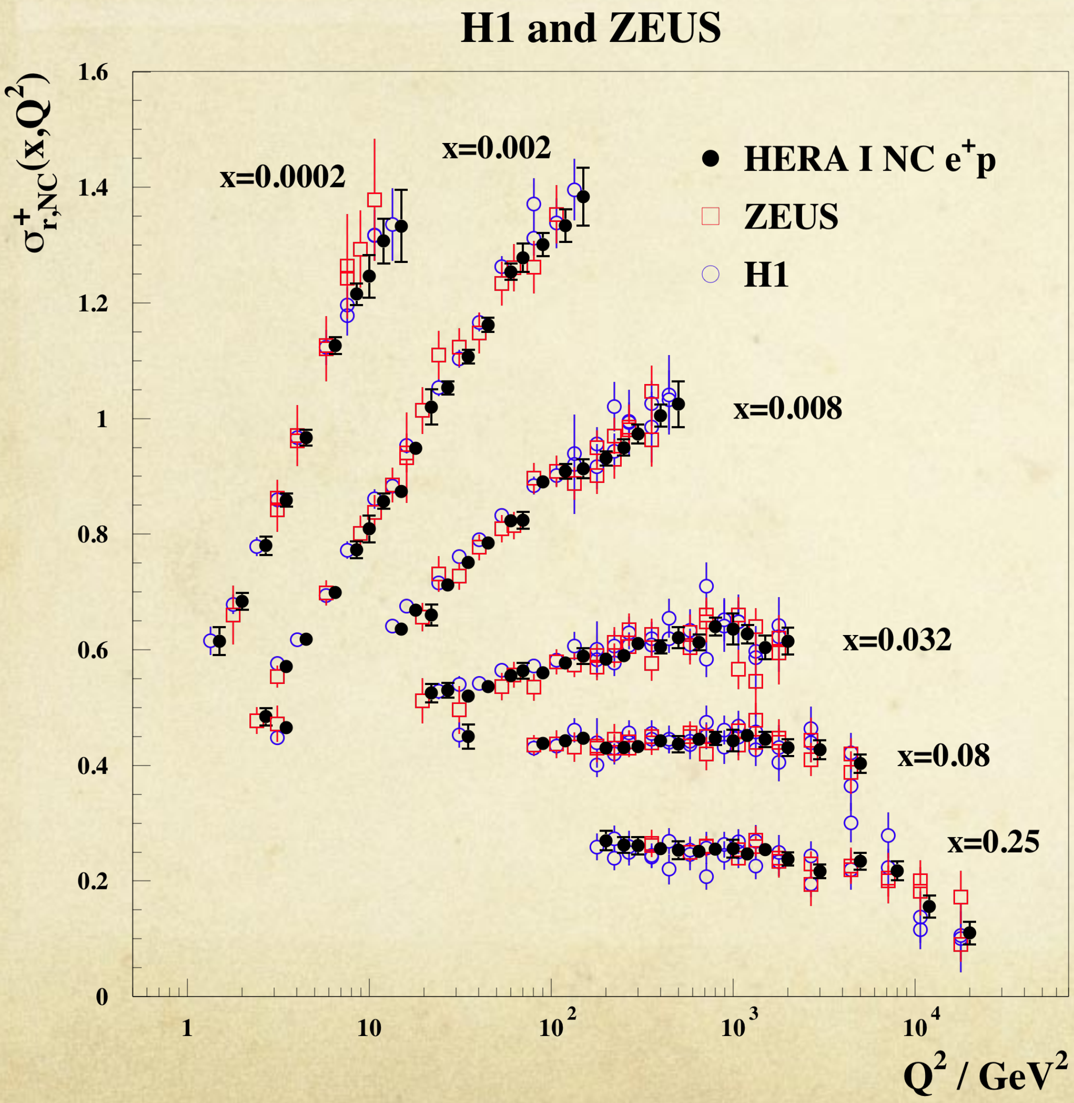
As Q^2 grows, $F_2\ (x,Q^2)$ shows a rise as $x \rightarrow 0$

Scaling violation is an indirect hint of something other than valence quarks…



Proton structure: valence + sea quarks

Scaling violation dramatic on a linear scale…



Large scaling violation at low x:

Indirect hint of large gluon density: contributions to quark component from gluon fluctuations

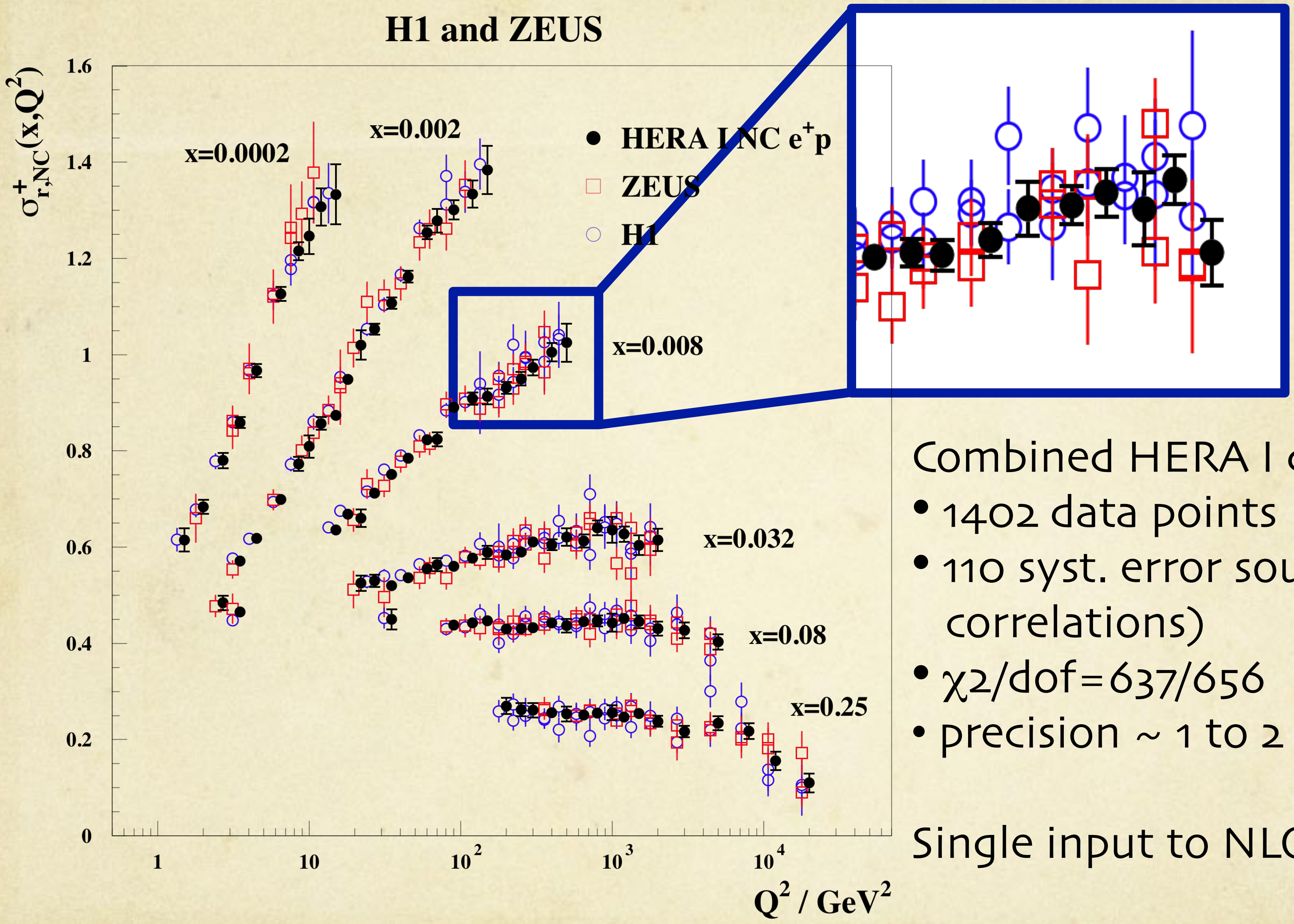
→ gluon splits into quark pair

→ γ resolves the quark-pair

Combination of full published HERA-I NC/CC inclusive data

$\mathscr{L}$ = 240pb^{-1}

Power of combining



Combined HERA I data:

- 1402 data points
- 110 syst. error sources (and correlations)
- $\chi2$/dof=637/656
- precision ~ 1 to 2 %

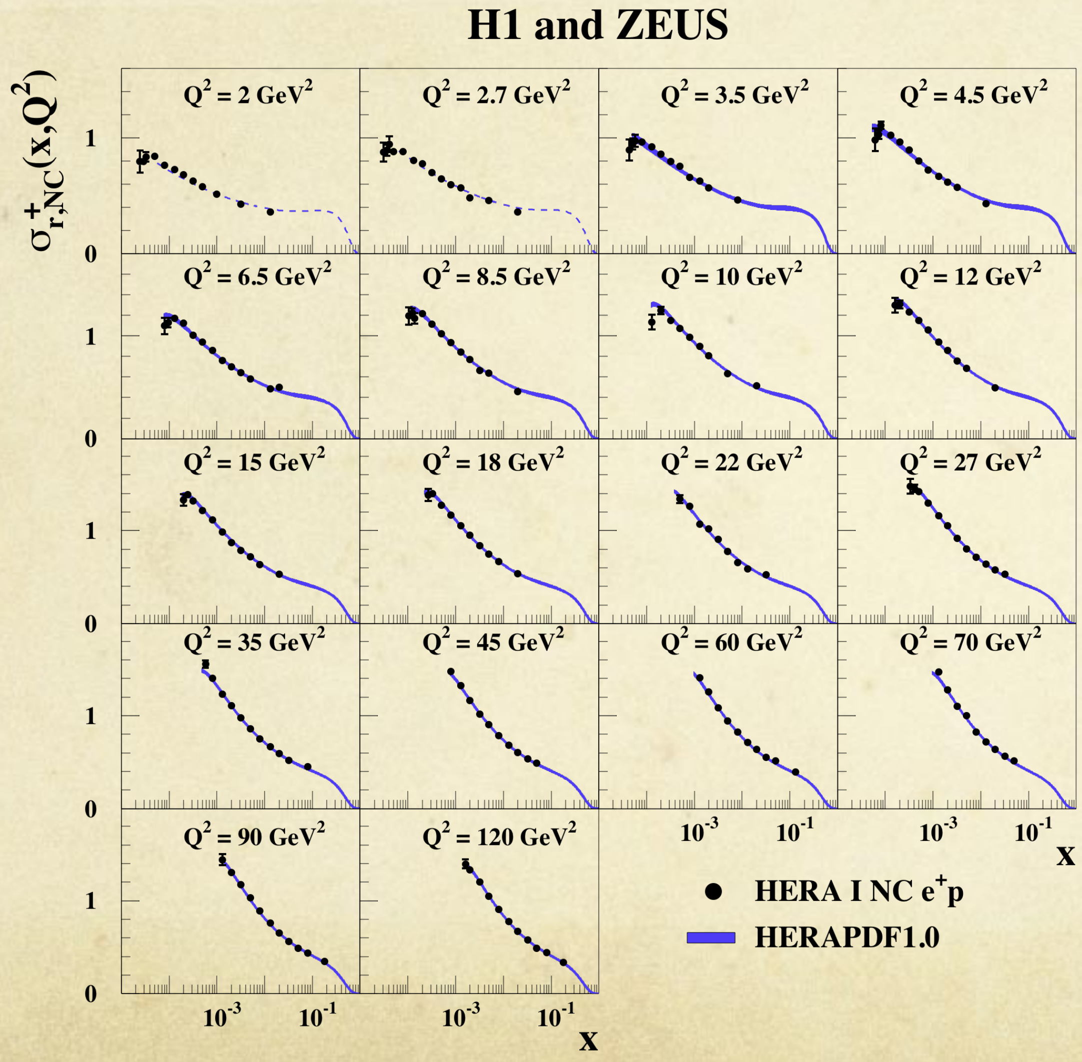
Single input to NLO QCD analysis

Systematic uncertainties reduced as well as statistical errors

Unprecedented precision due to cross calibration of detectors

Proton structure: more hints of gluon

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



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

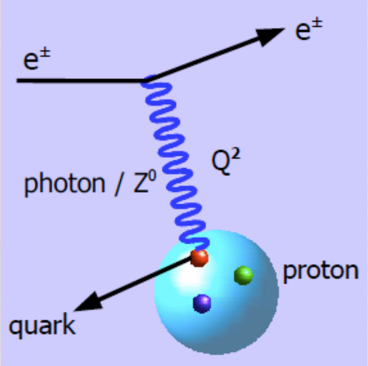
$F_2(x,Q^2)$ shows a strong rise as x → 0

The rise increases with increasing Q^2

… at low Q^2 we start seeing a turn over → hints of gluon (F_L)

Deep inelastic e±p scattering: gluon

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



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

Define polarization of exchanged boson

valence + sea quarks

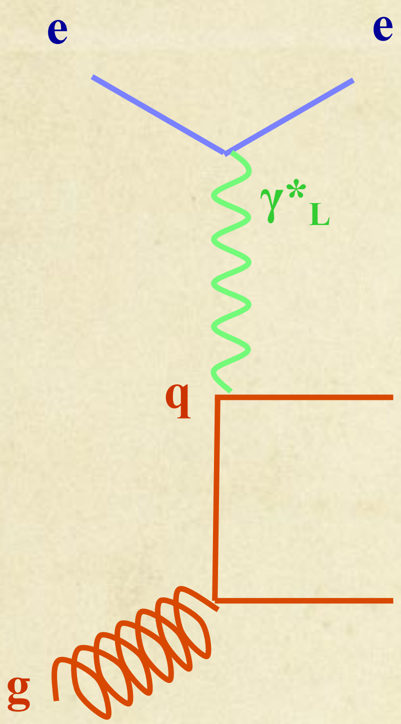
gluon

valence quarks

- In quark-parton model, *F*F_L = 0 for spin 1/2 quarks

  (spin ½ quark absorbs spin -1 photon)
- In QCD, F_L > 0 due to gluon emission
- Large gluon density 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

QCD dynamics: directly probing gluon with F_L



F_L is an independent structure function BUT

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

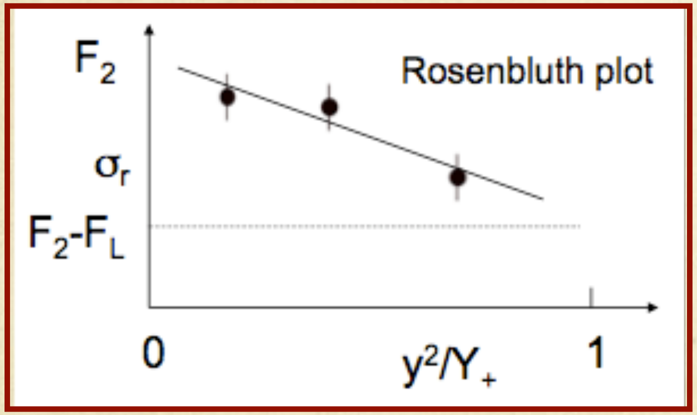
Probing the gluon with F_L: H1

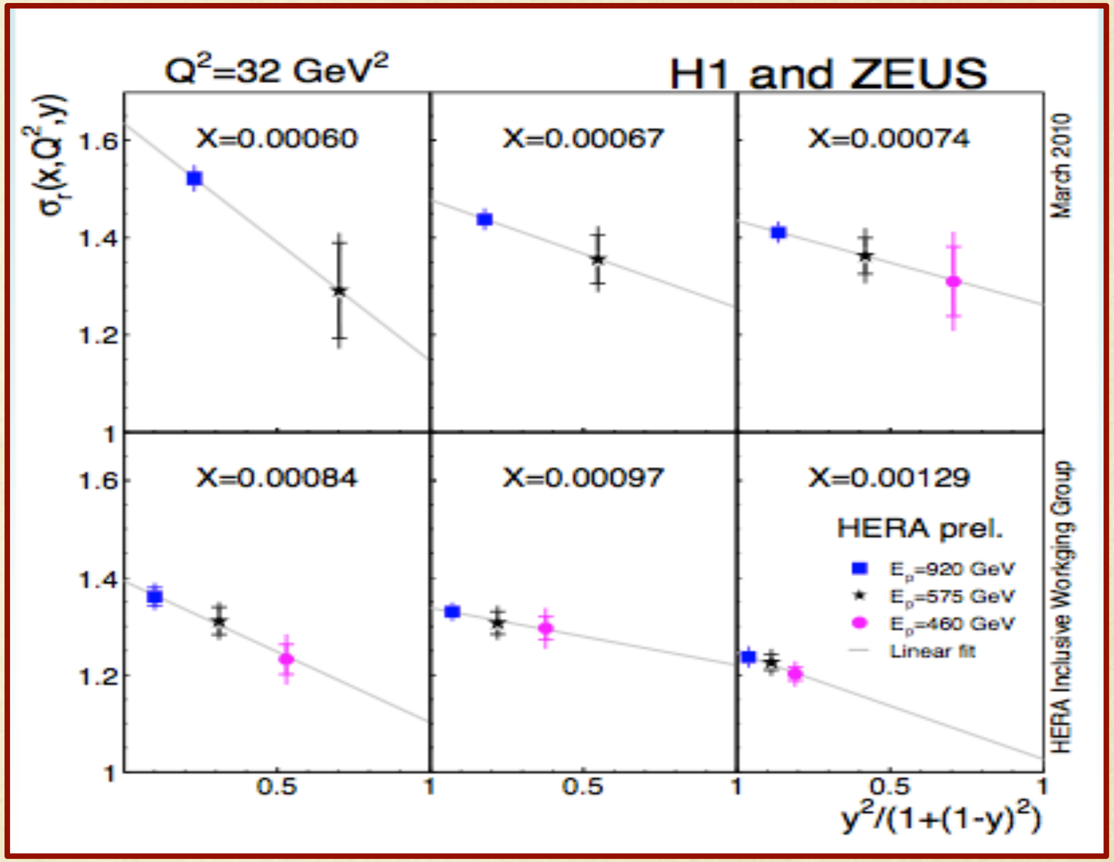
DIS reduced cross section (low x): $$\tilde{\sigma} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

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

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

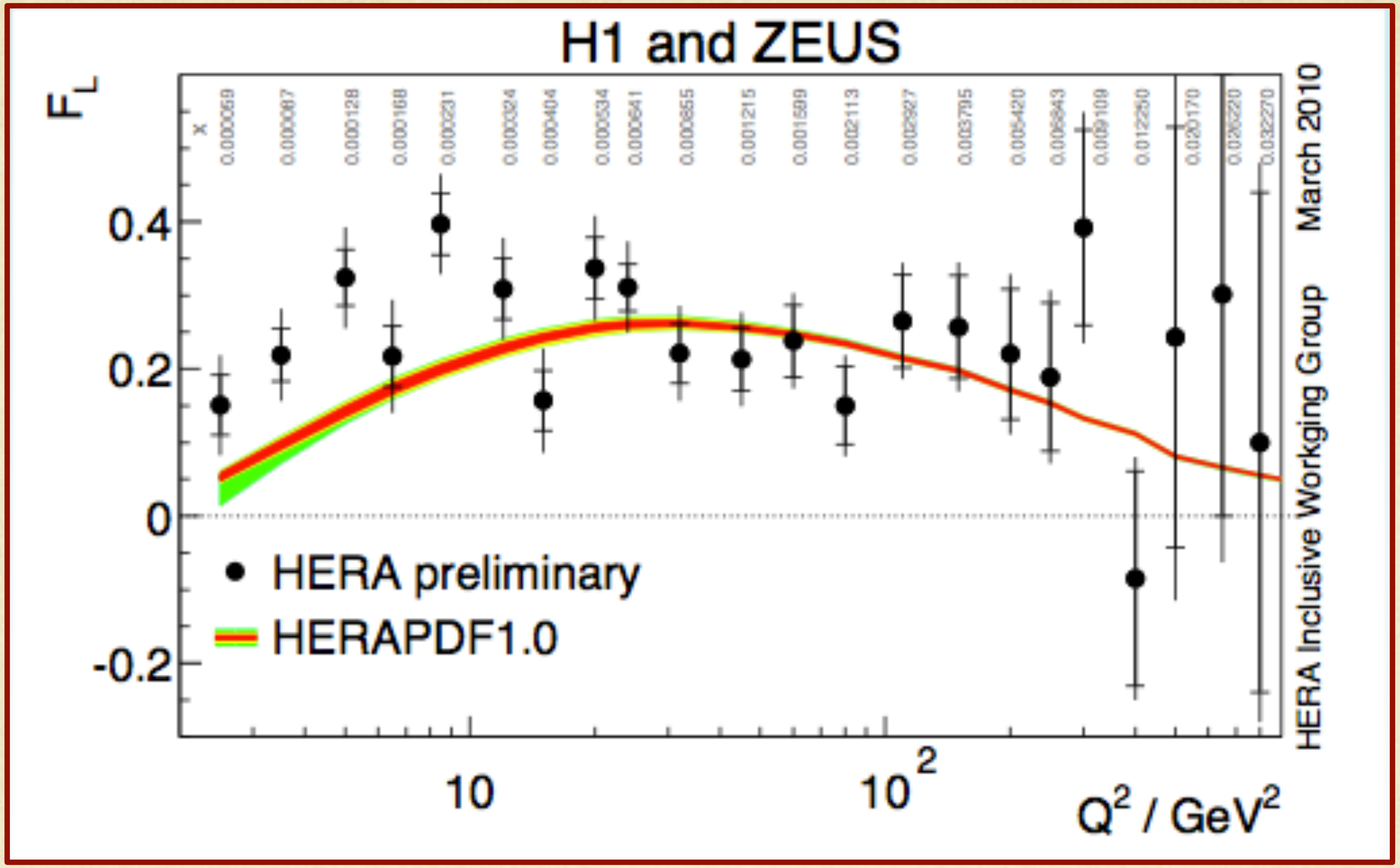
At same (x, Q^2)
Intercept: F_2
Slope: F_L





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

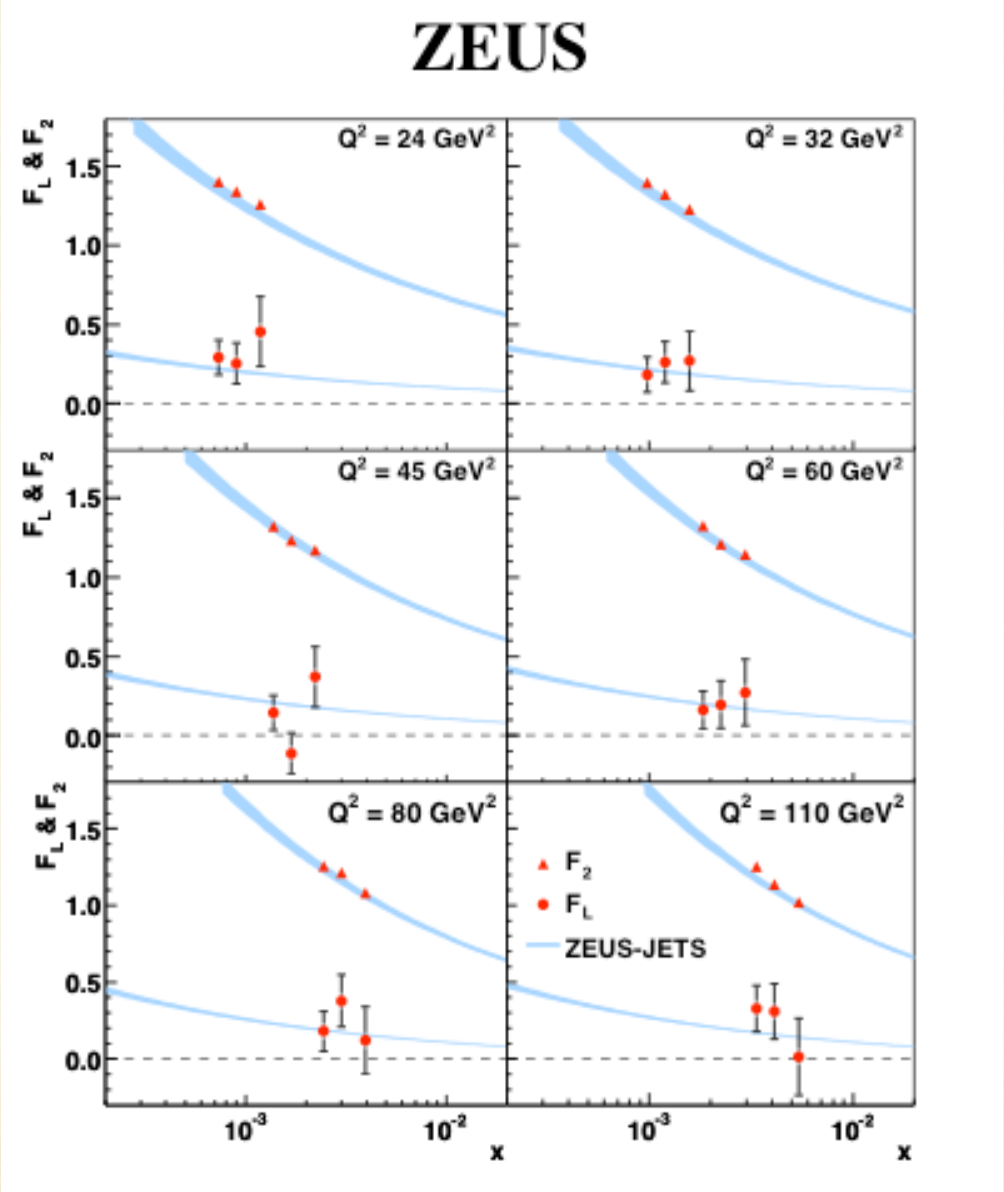
F_L vs QCD (HERAPDF1.0)



F_L is where QCD expects it to be → gives us confidence we understand DGLAP (→ QCD radiation) … except at low Q^2, QCD predictions tend to underestimate data

Using NNLO or different heavy flavor schemes may help…

Probing the gluon with F_L :ZEUS

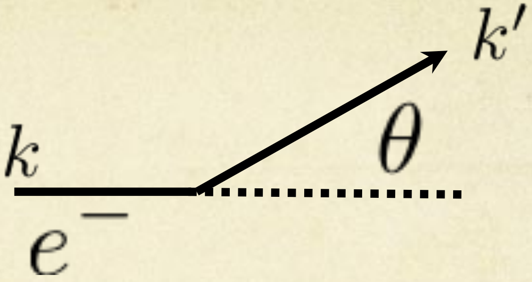


Aside…

- Extraction of F_2 without any assumption on F_L
- Most precise F_2 so far in this kinematic regime (medium Q^2)

A perspective: what about quarks?

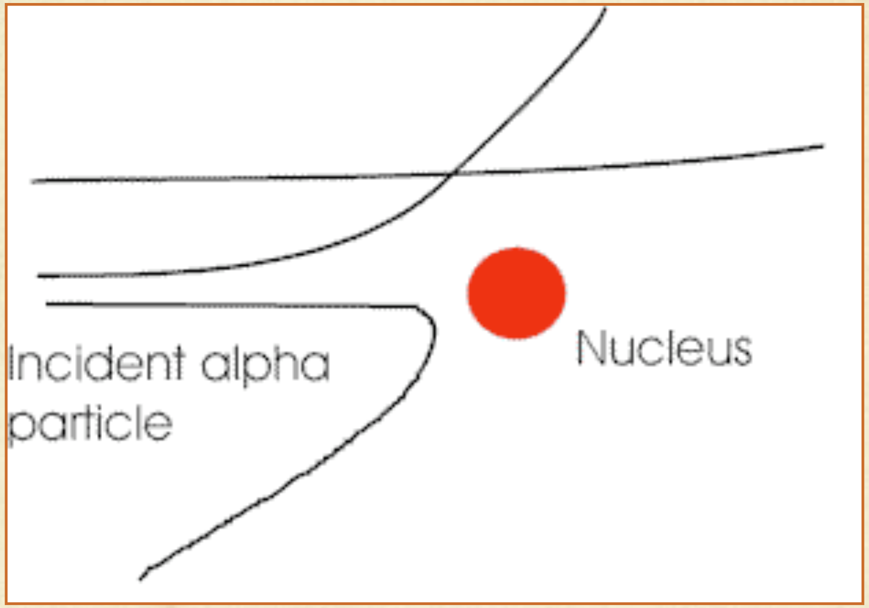
Rutherford scattering (1910)



$$q = k - k'$$

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

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



'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

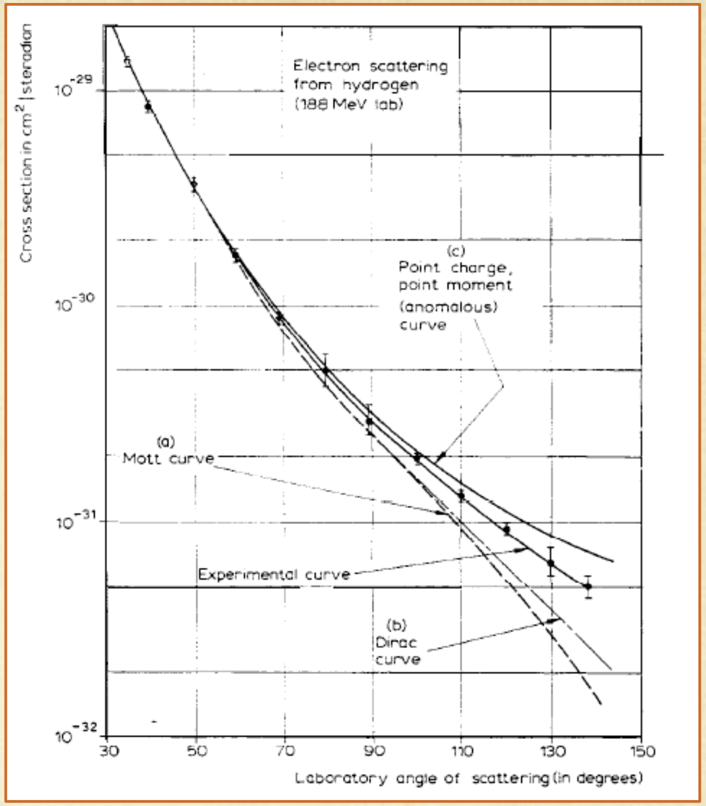
Hofstadter: Radius of nucleus (1955)

electron

nucleon

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

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

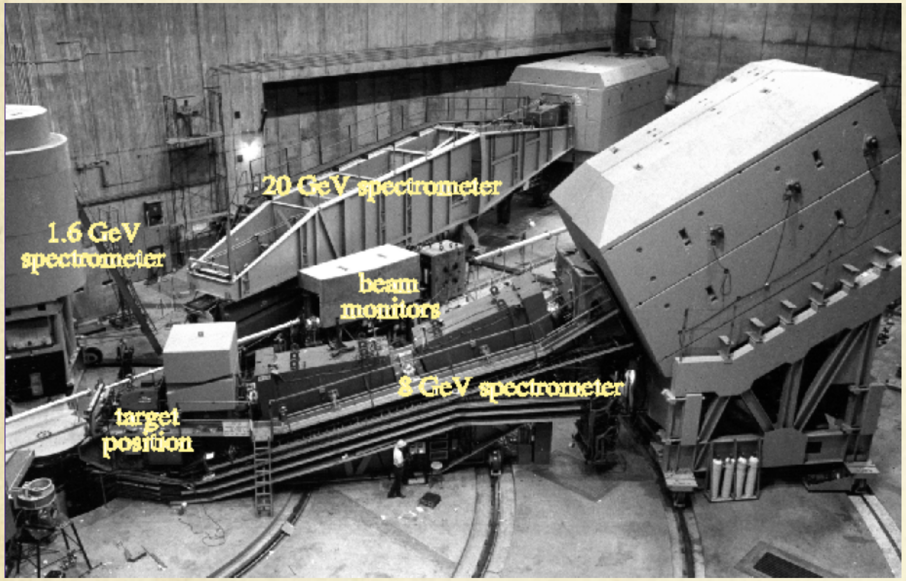


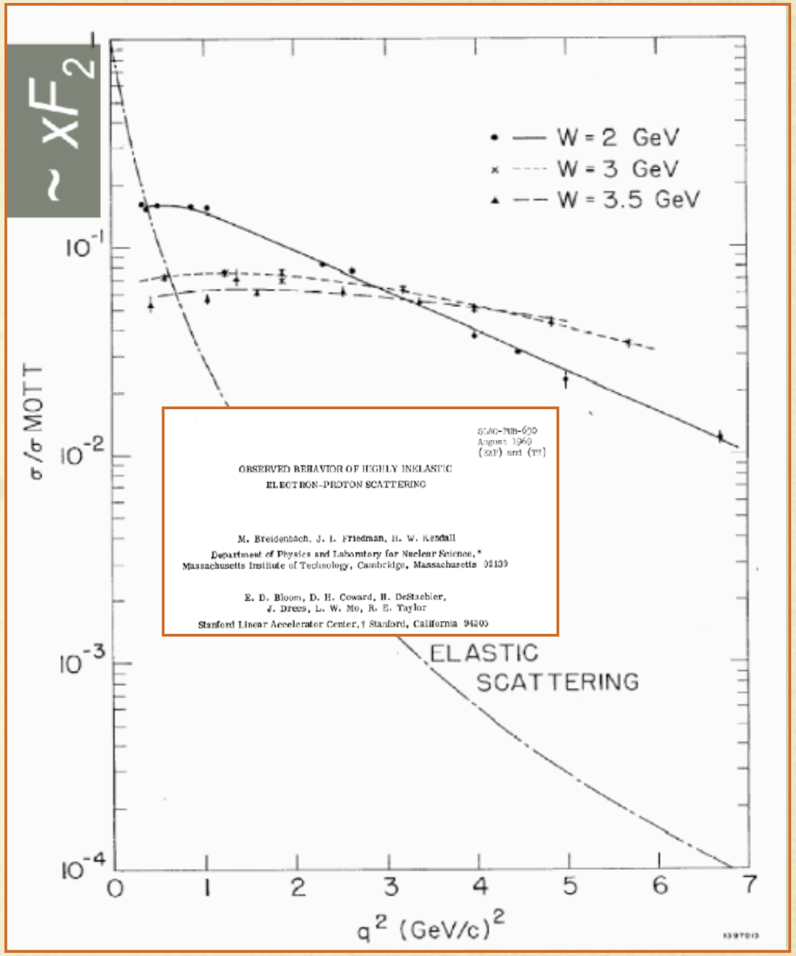
$$q^2 \propto \sin^2(\theta/2)$$

"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)

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





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

OBSERVED BEHAVIOR OF HIGHLY INELASTIC
ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, H. W. Kendall
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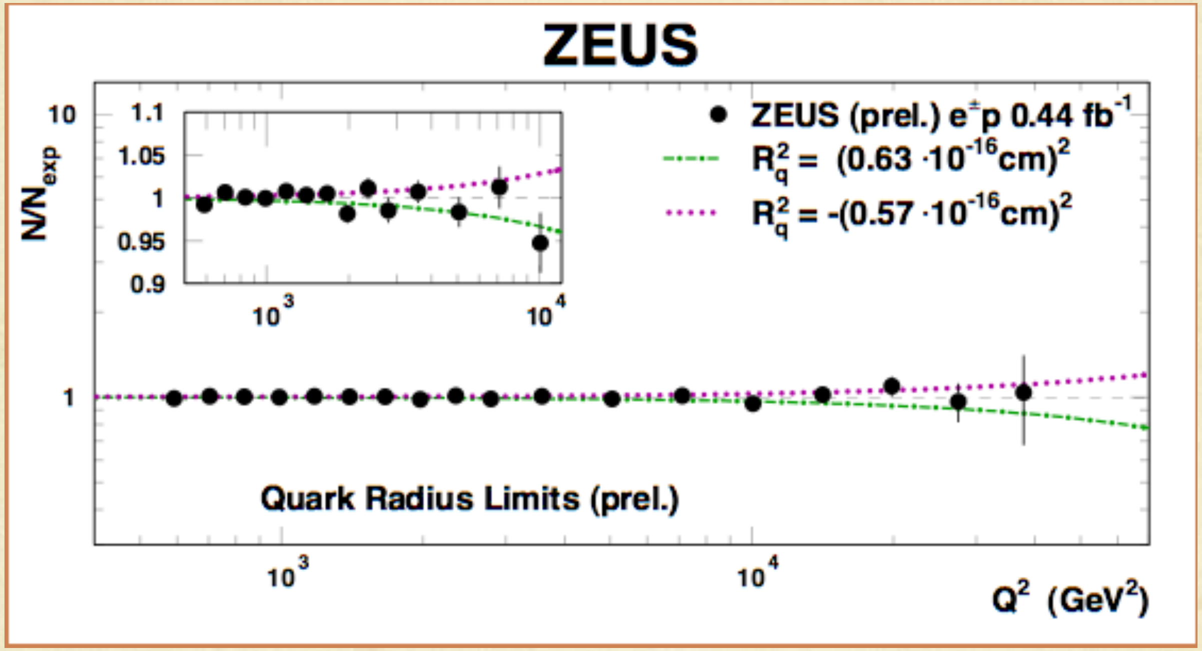
Stanford Linear Accelerator Center,† Stanford, California 94305

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

Quark radius today

Is the quark point like?

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

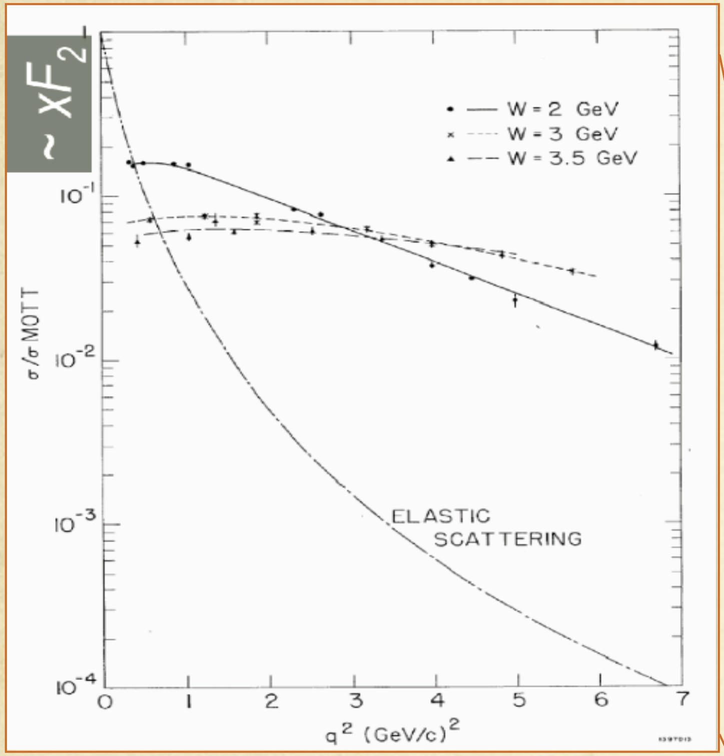


Any deviations? Not so far…

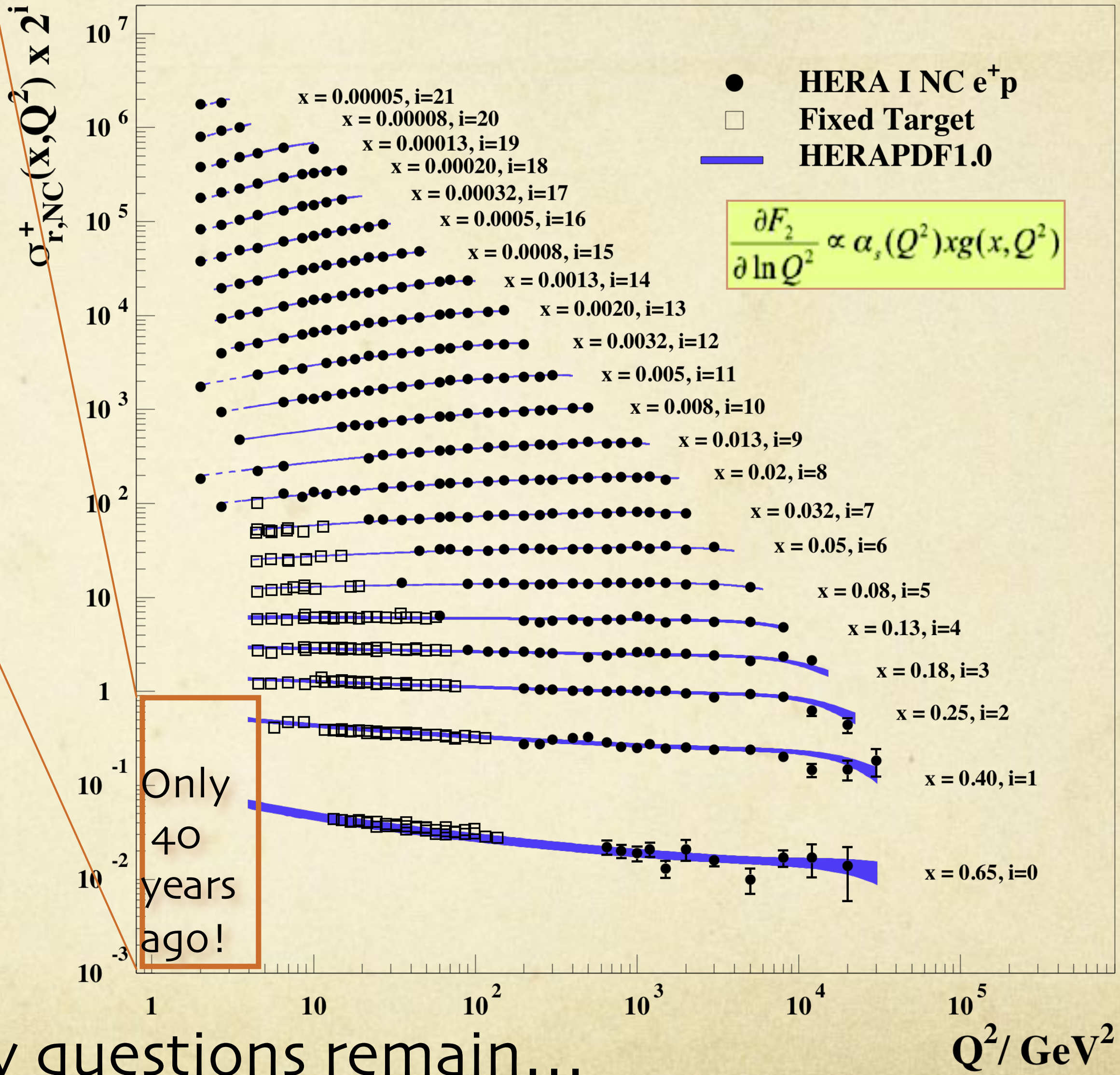
The limit is: $R_Q < 0.6 \times 10^{-18}$ m

We are probing down to 1/1000 proton radius!

Probing matter: a perspective



$\sigma_r(x,Q^2)$



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

Only 40 years ago!

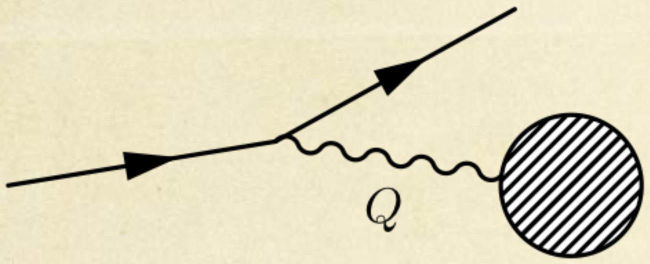
Lessons learned

Scaling → quarks

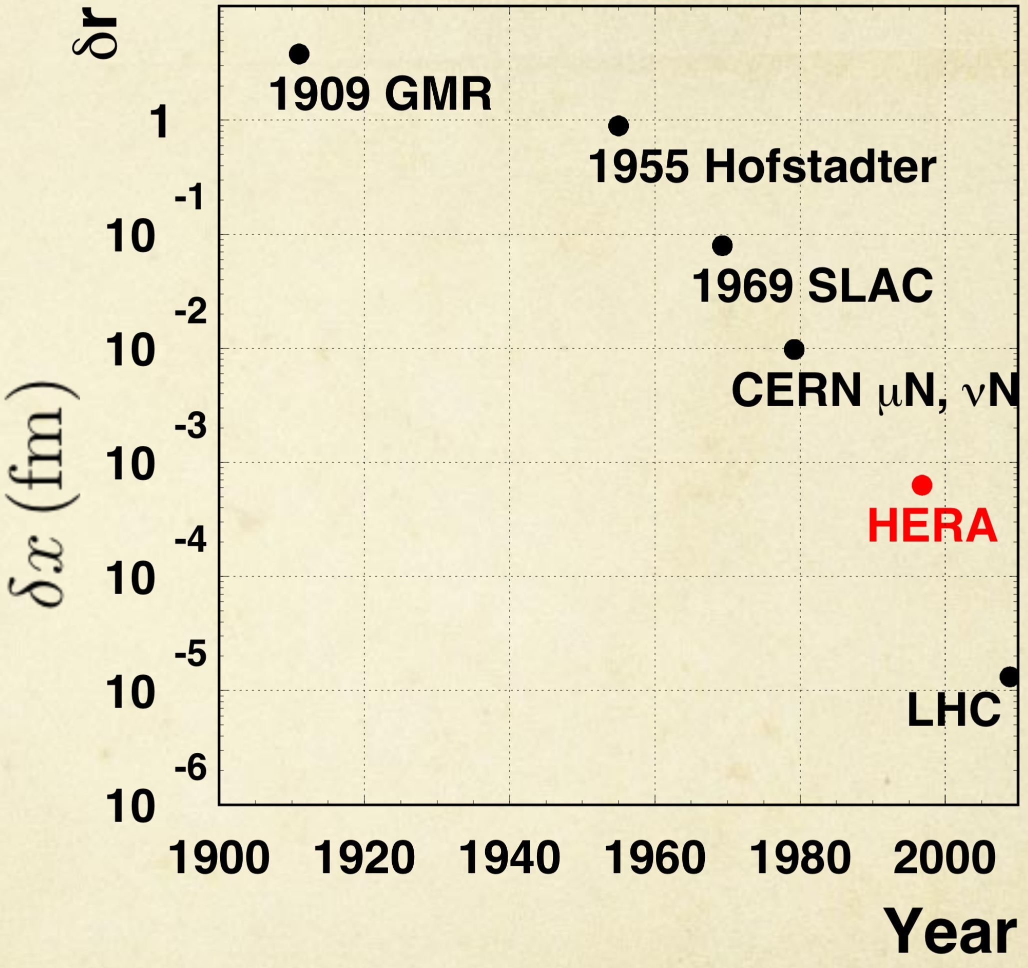
Scaling violation →
gluons and QCD radiation

Many questions remain…

Probing matter: the future



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



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

Summary: which answers has HERA provided?

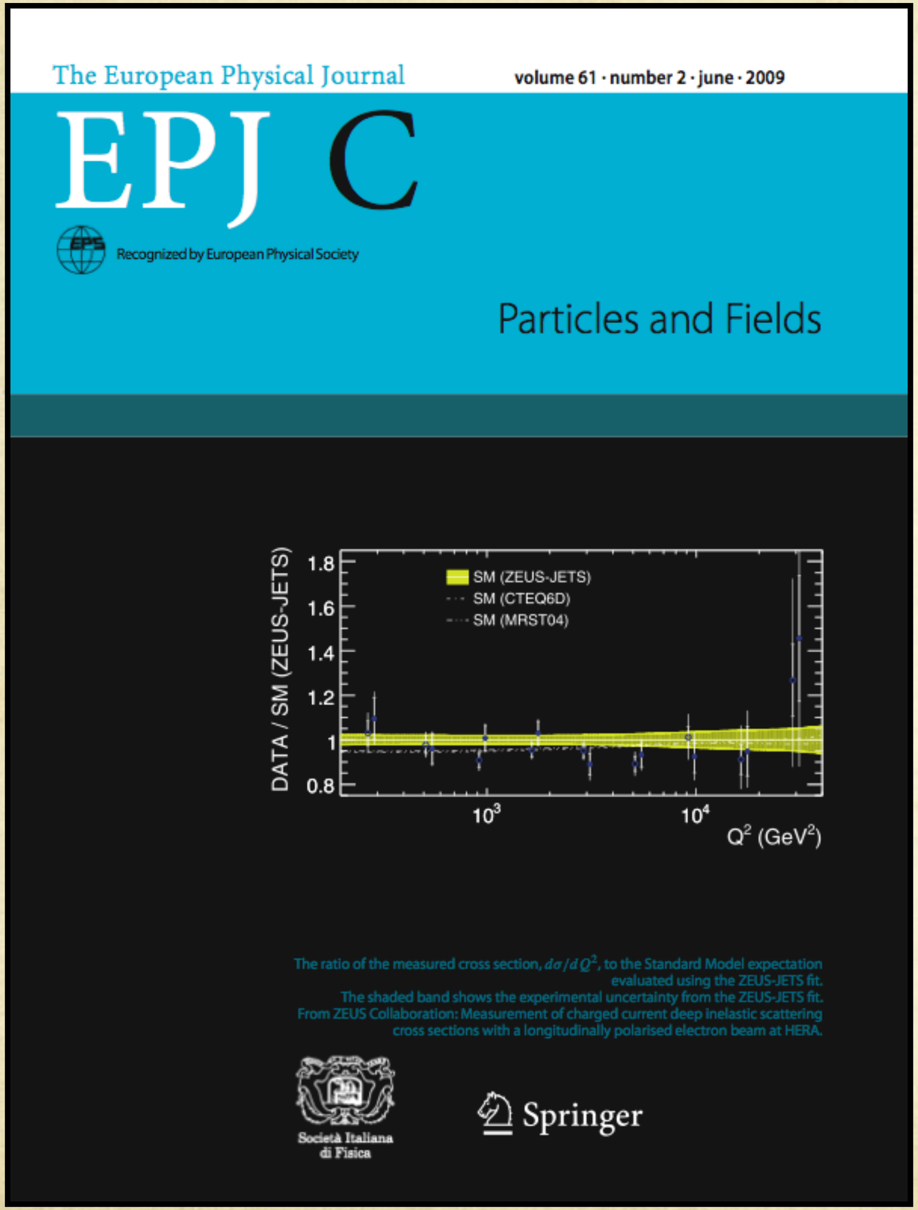
- HERA remains our source of information on proton structure
  - covering $0.045 < Q^2 < 30000$ GeV^2 $6 \times 10^{-7} < x < 0.65$
  - probed down to 1/1000 of the proton radius

- Recent combined results of the H1 and ZEUS collaborations have allowed to determine proton's PDFs with unprecedented precision

- The improvements in the understanding of the PDFs are relevant for the physics program of the LHC

- Results still to come (NNLO PDFs, new DGLAP analysis based on the full HERA-II data samples) …

HERA's reward…



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

EPJ C

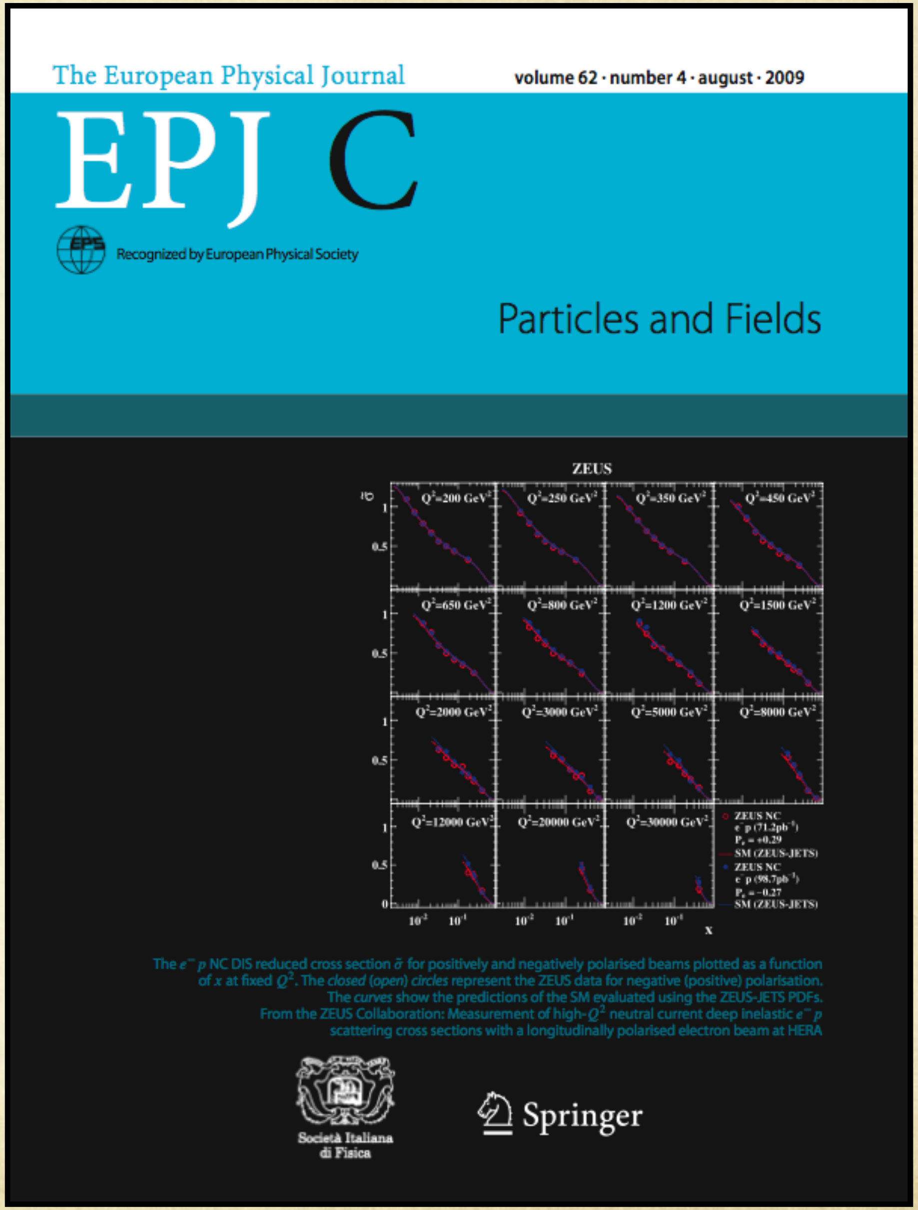
Recognized by European Physical Society

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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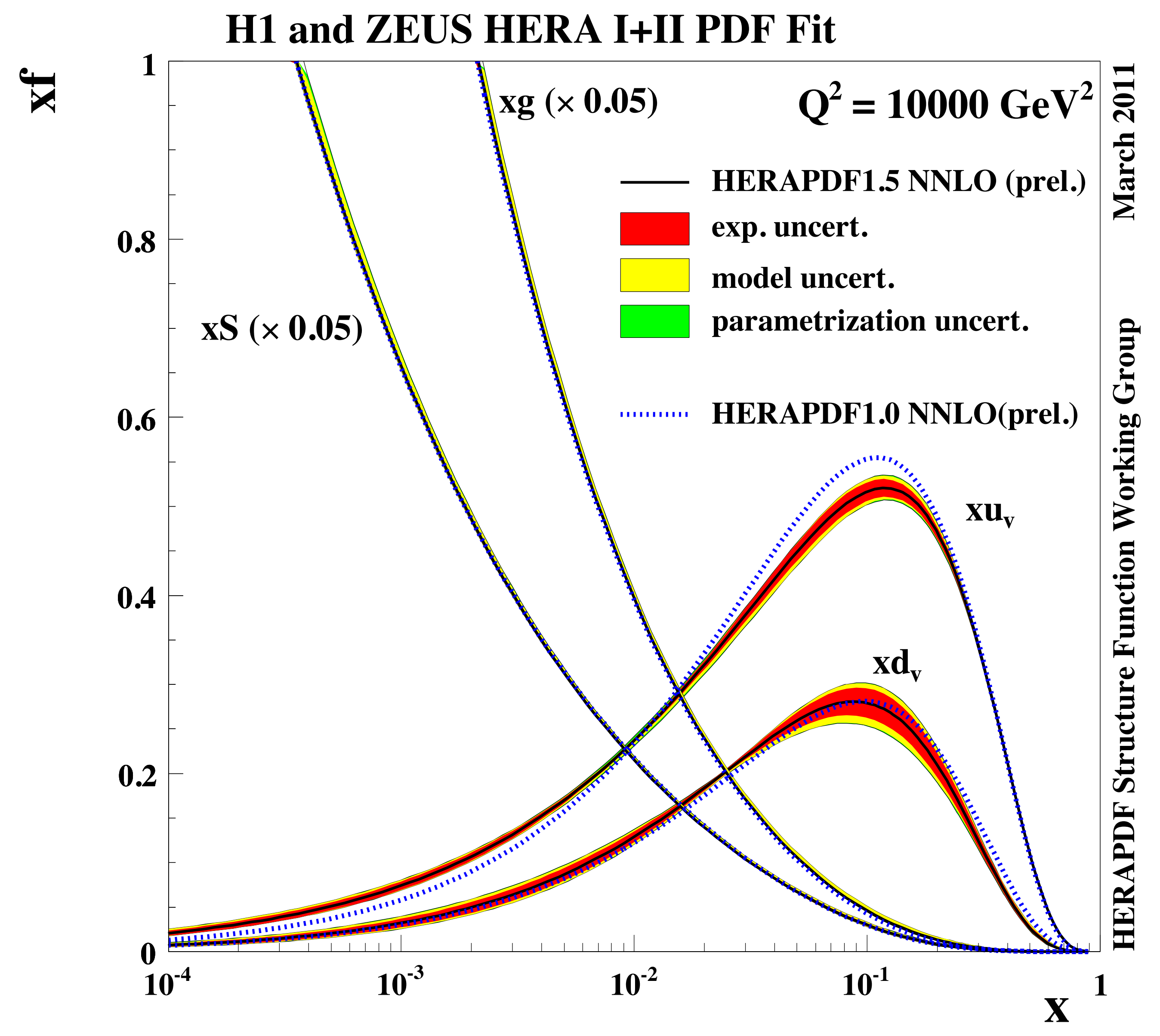
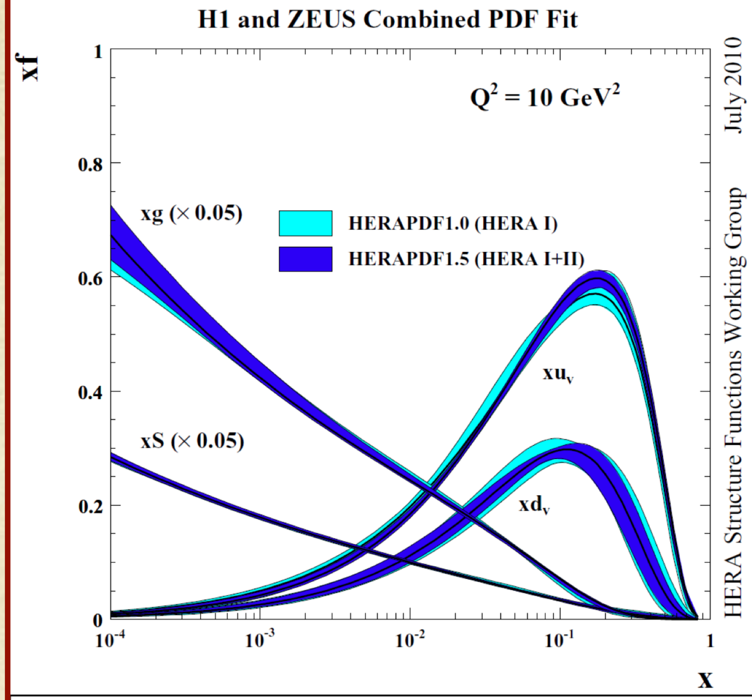
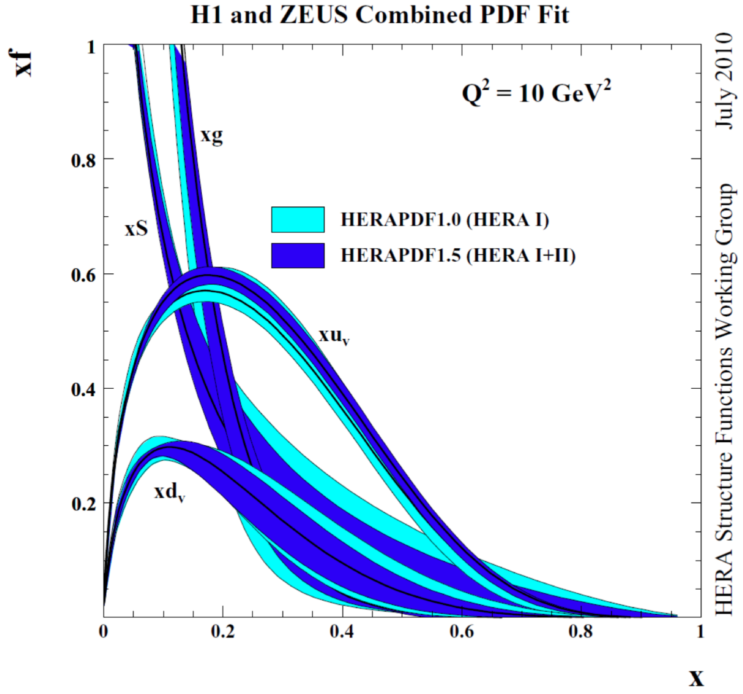
Backup slides

HERAPDF1.0 vs HERAPDF1.5 (NNLO)



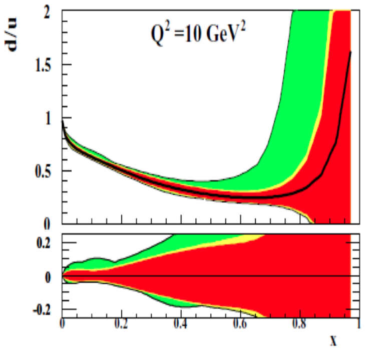
HERAPDF1.0 vs HERAPDF1.5





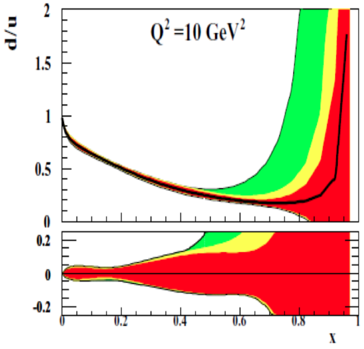
The PDF uncertainties have been reduced at high-x

These plots show total uncertainties (model and parametrization included)



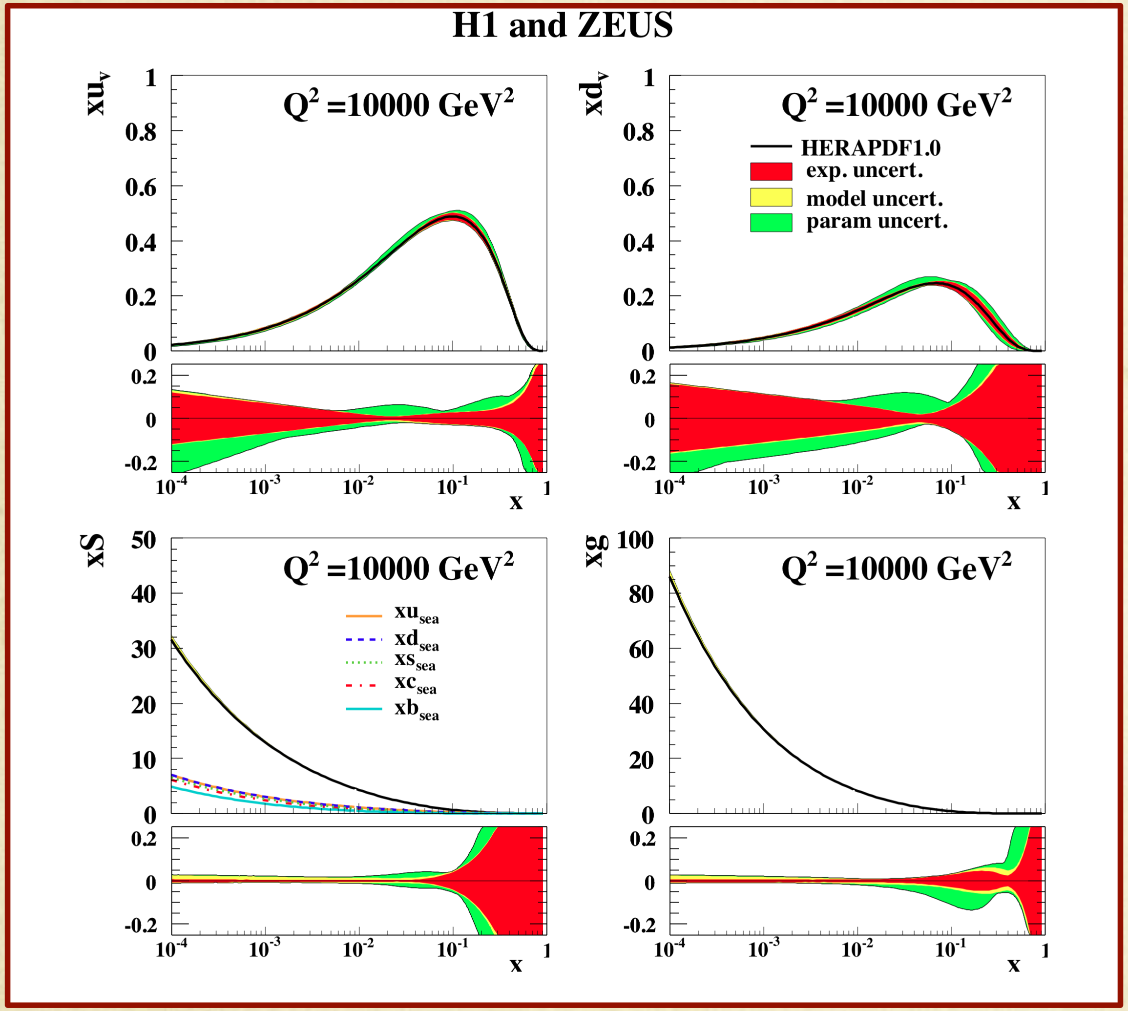
Improved determination of the d/u ratio at high-x.

The only PDF which measures d in a proton rather than an isoscalar target



Courtesy of Amanda Cooper-Sarkar

Extracting the essence of structure functions



HERAPDF1.0 - NLO QCD analysis of the combined HERA data

Separation of:
- experimental
- model
- parametrization

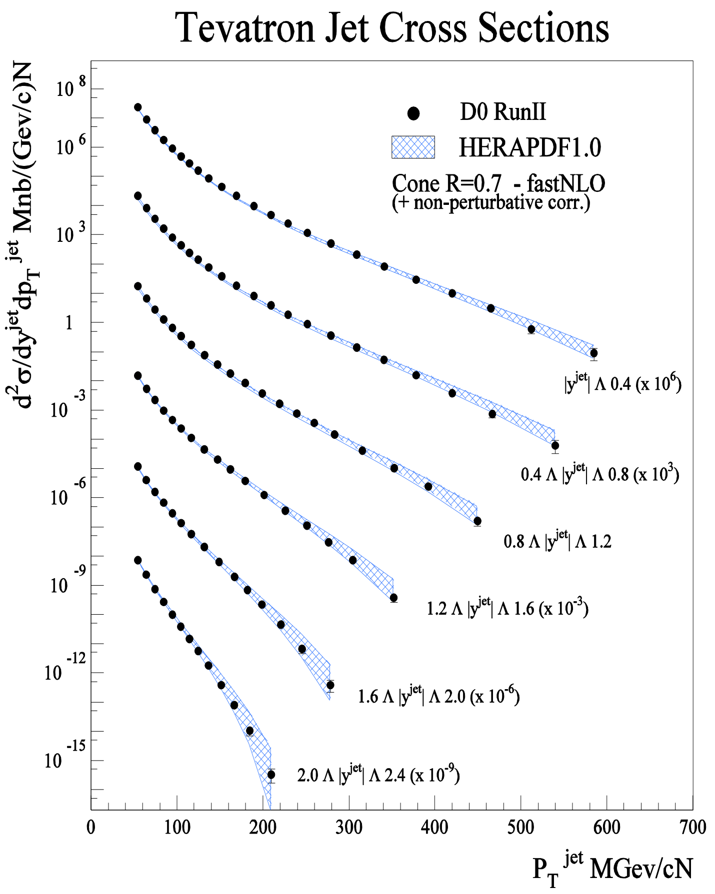
uncertainties

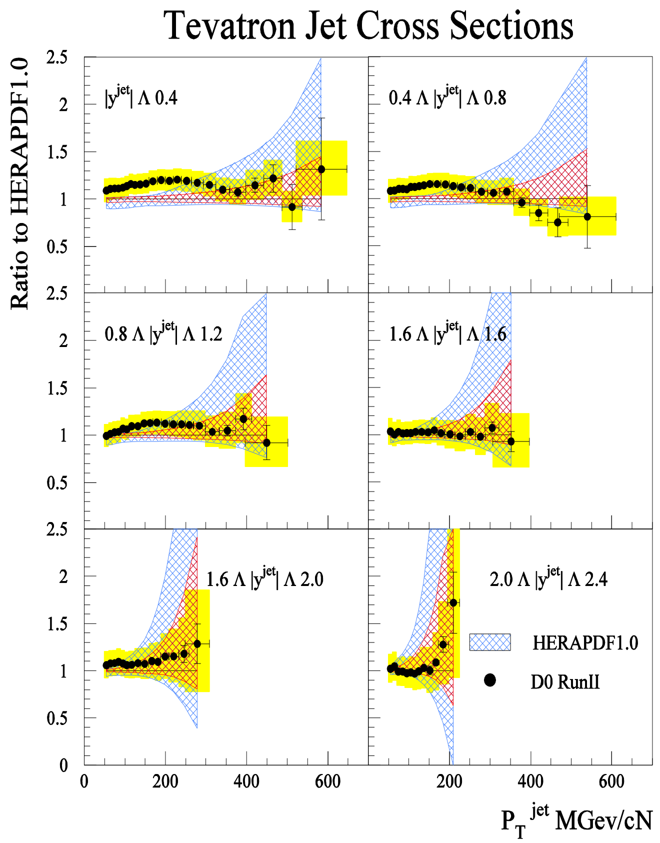
Accurate xS and xg at low x due to precise measurement of F_2!

HERAPDF1.0: crosscheck with Tevatron

Is HERA-only PDF compatible with Tevatron data?

The description of the D0 jet data LOOKS OK but what is the χ2 for such jet data to HERAPDF1.5 central values?





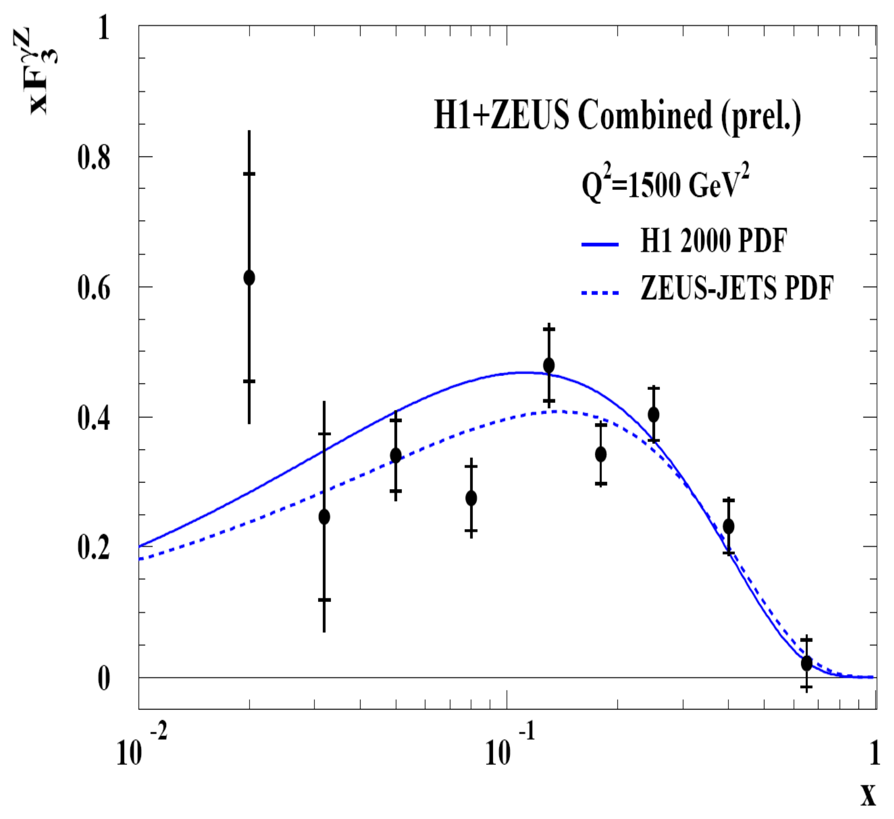
Proton structure: valence quarks

HERA I NC: ep → eX

xF_3 determined by valence quark distributions and predicted to be only weakly depending on Q^2

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

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

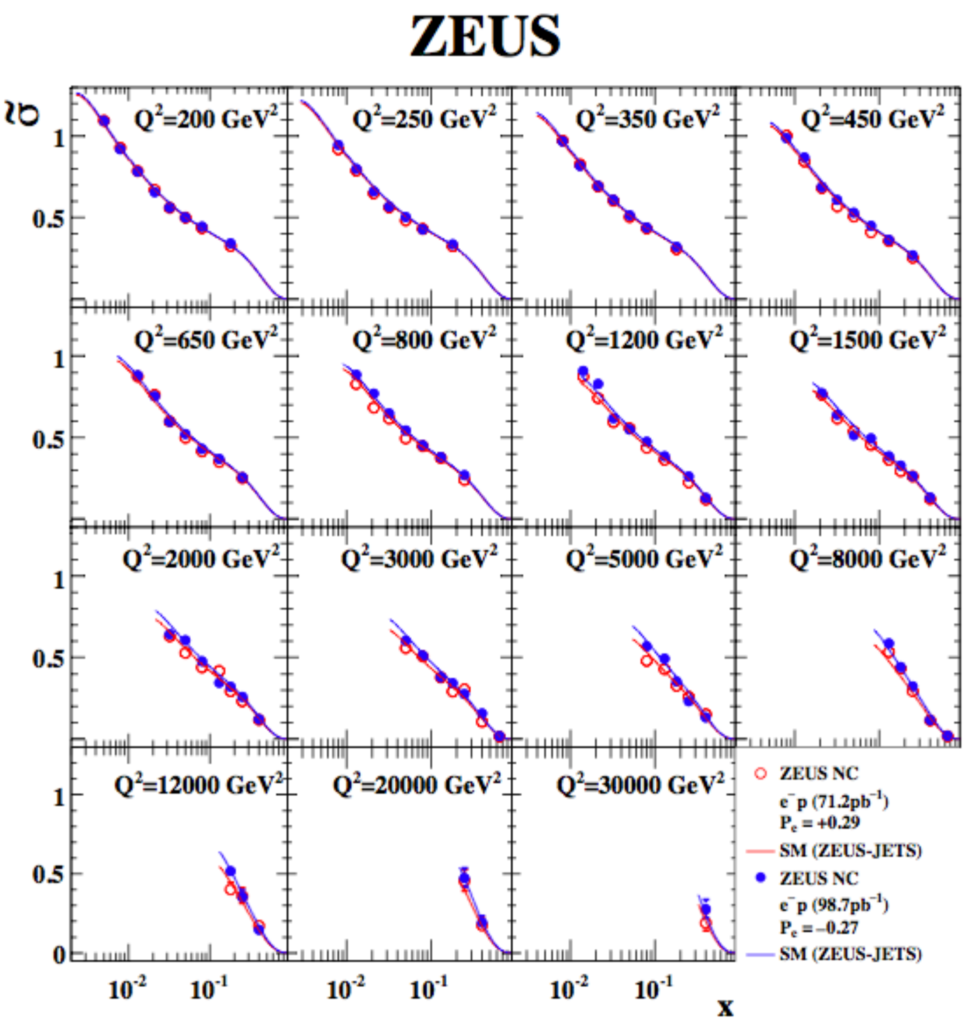


$$\int_0^1 xF_3^{\gamma Z}\frac{dx}{x} = \frac{1}{3}\int_0^1 (2u_v + d_v)dx = \frac{5}{3}$$

$$\int_{0.02}^{0.65} xF_3^{\gamma Z}\frac{dx}{x} = 1.21 \pm 0.09(stat) \pm 0.08(syst)$$

Proton structure: valence quarks

NC cross section at high Q^2



HERA II: ep → eX

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

At leading order

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

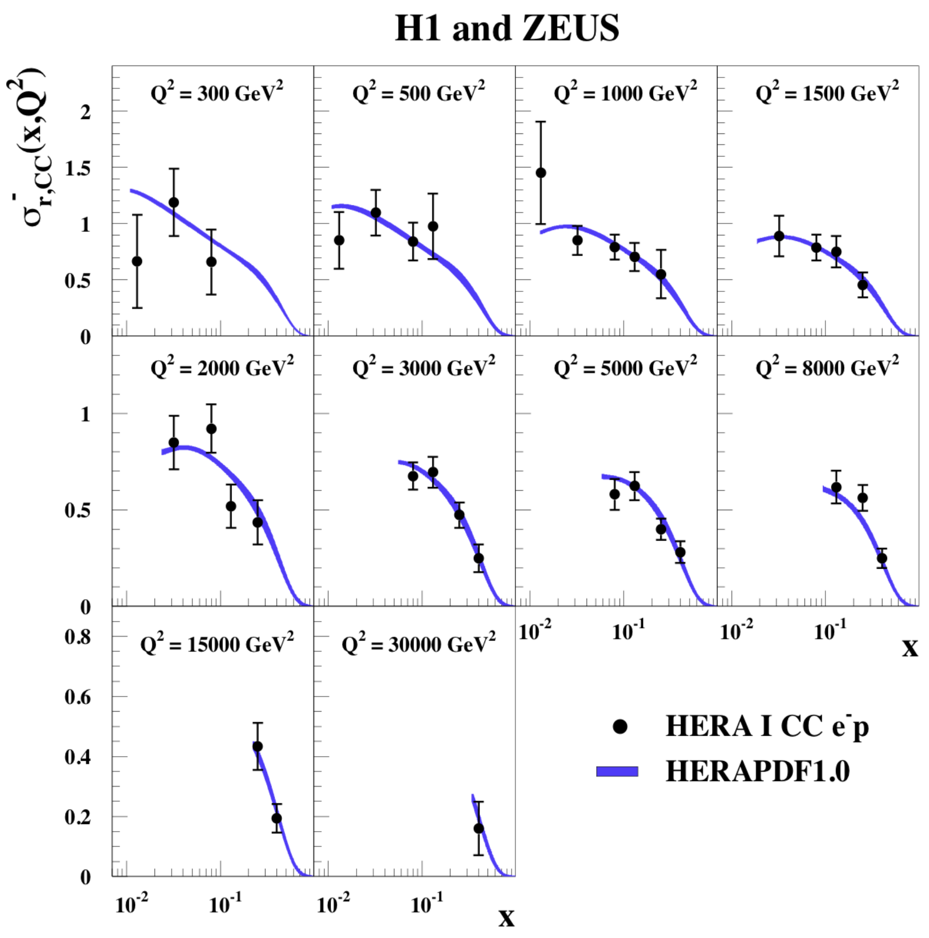
To a good approximation, asymmetry A- is a ratio of two structure functions…

Parity violation is observed via polarization asymmetry

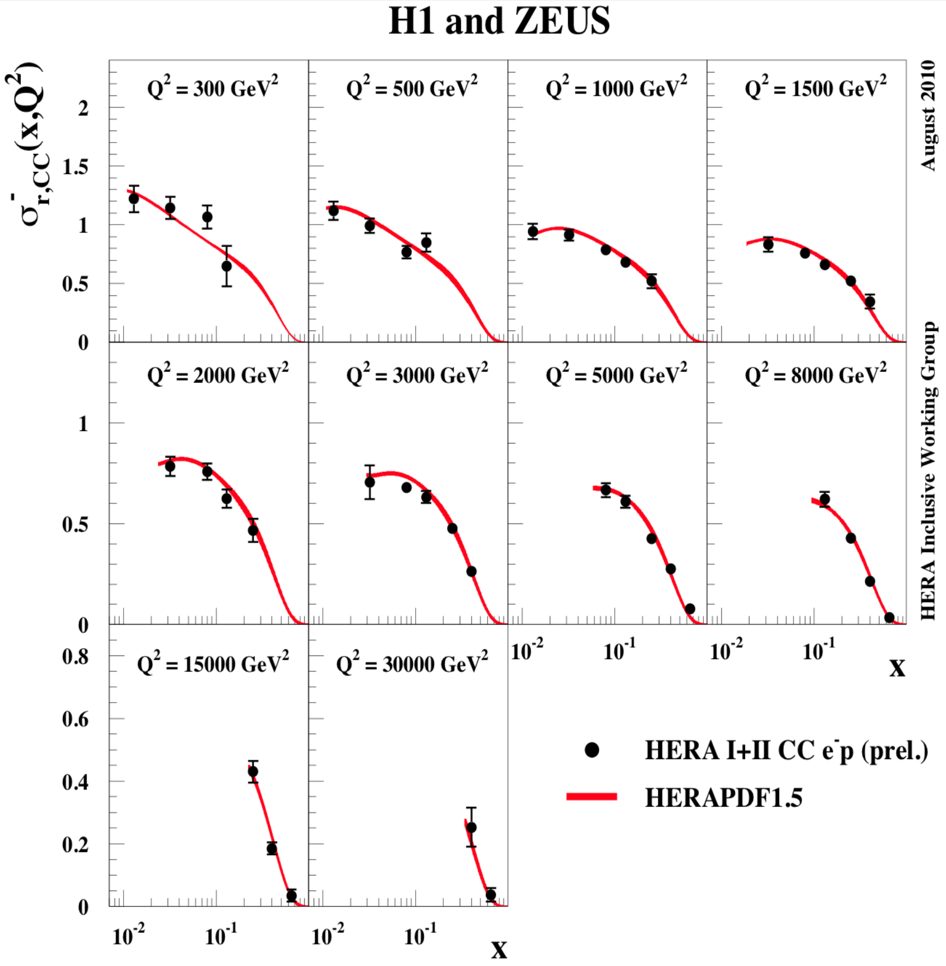
HERA I CC: ep → νX

Inclusion of HERA II data

HERA I combined results



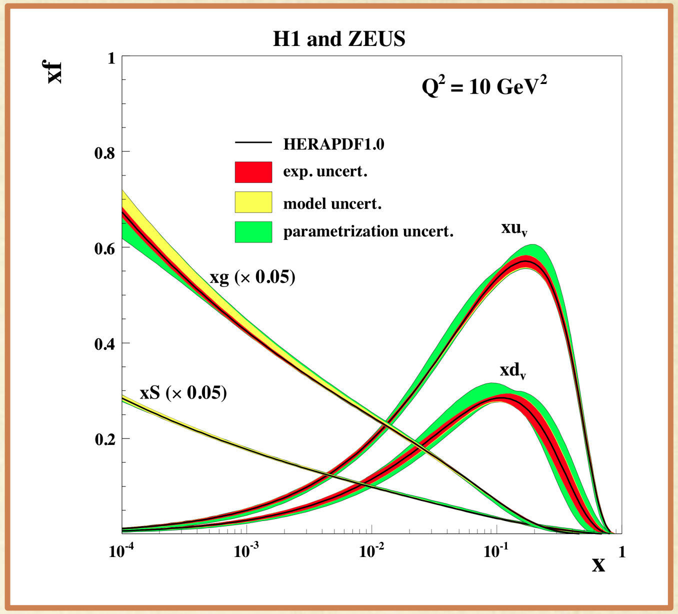
HERA I + II combined results



New HERA II measurements: increased precision at high Q^2

Power of combining

Input: HERA I (1992 – 2000) dataset, ZEUS + H1 combined



Why combine?
- reduction in statistical error
- reduction in systematic error
  - -- fully uncorrelated
  - -- due to energy scale
- no gain in correlated errors
  - -- eg. theoretical calculations needed to extract experimental results…

→ effective cross-calibration of detectors wrt one another using a large sample of independent measurements

Power of combining

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

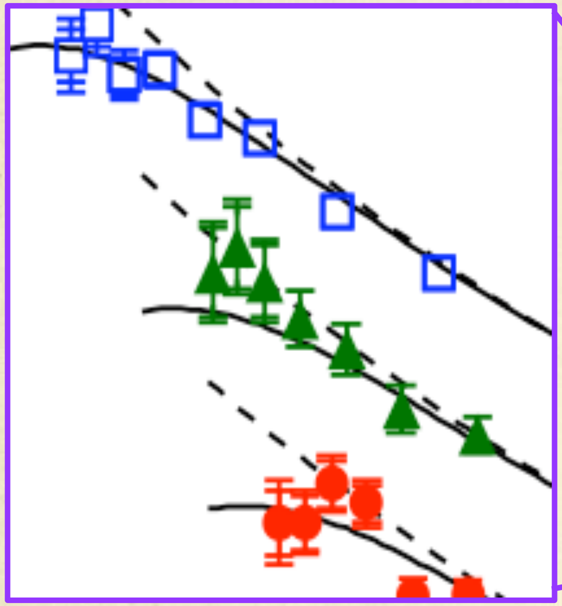
2) Correlated uncertainties:
Point-to-point correlated uncertainties
  e.g. electromagnetic and hadronic energy scale calibration
  Often common for CC and NC for a given experiment and run period

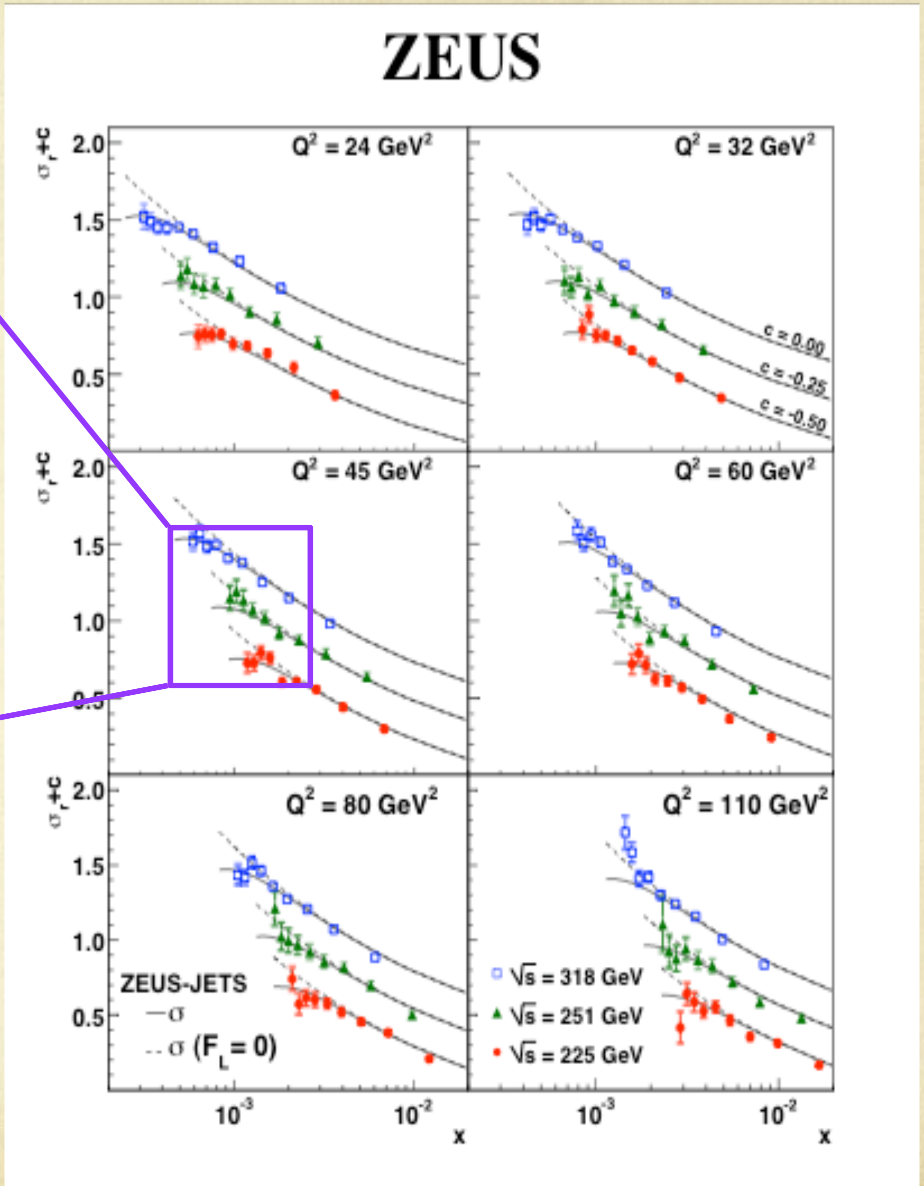
3) Overall normalisation uncertainty:
- Correlated for all data points for a given experiment and run period

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: ZEUS reduced cross sections





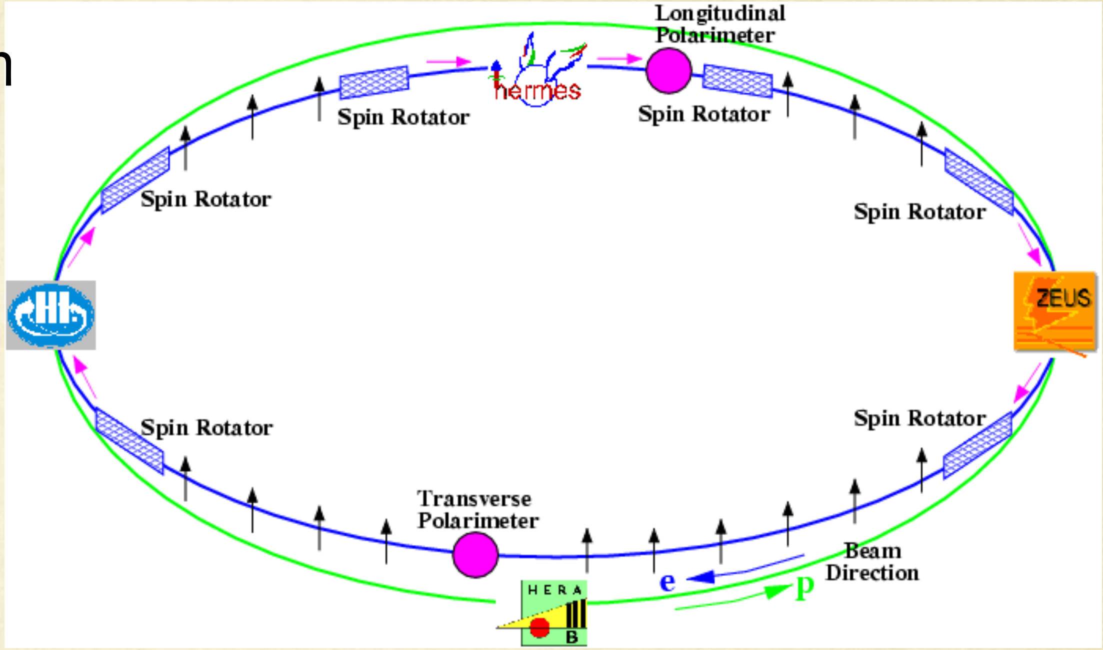
- F_L obtained from differences of cross sections at different CME's
- F_L damps the rise of F_2 at low x
- need to subtract 2 large numbers …
- … hence limited statistical power

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%

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

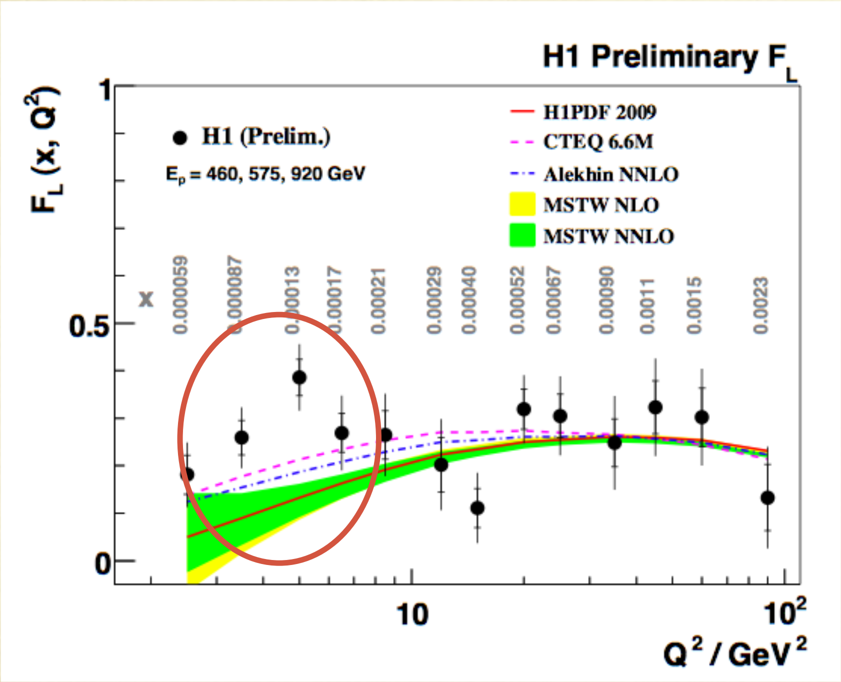
The white elephant in the room: the nucleus

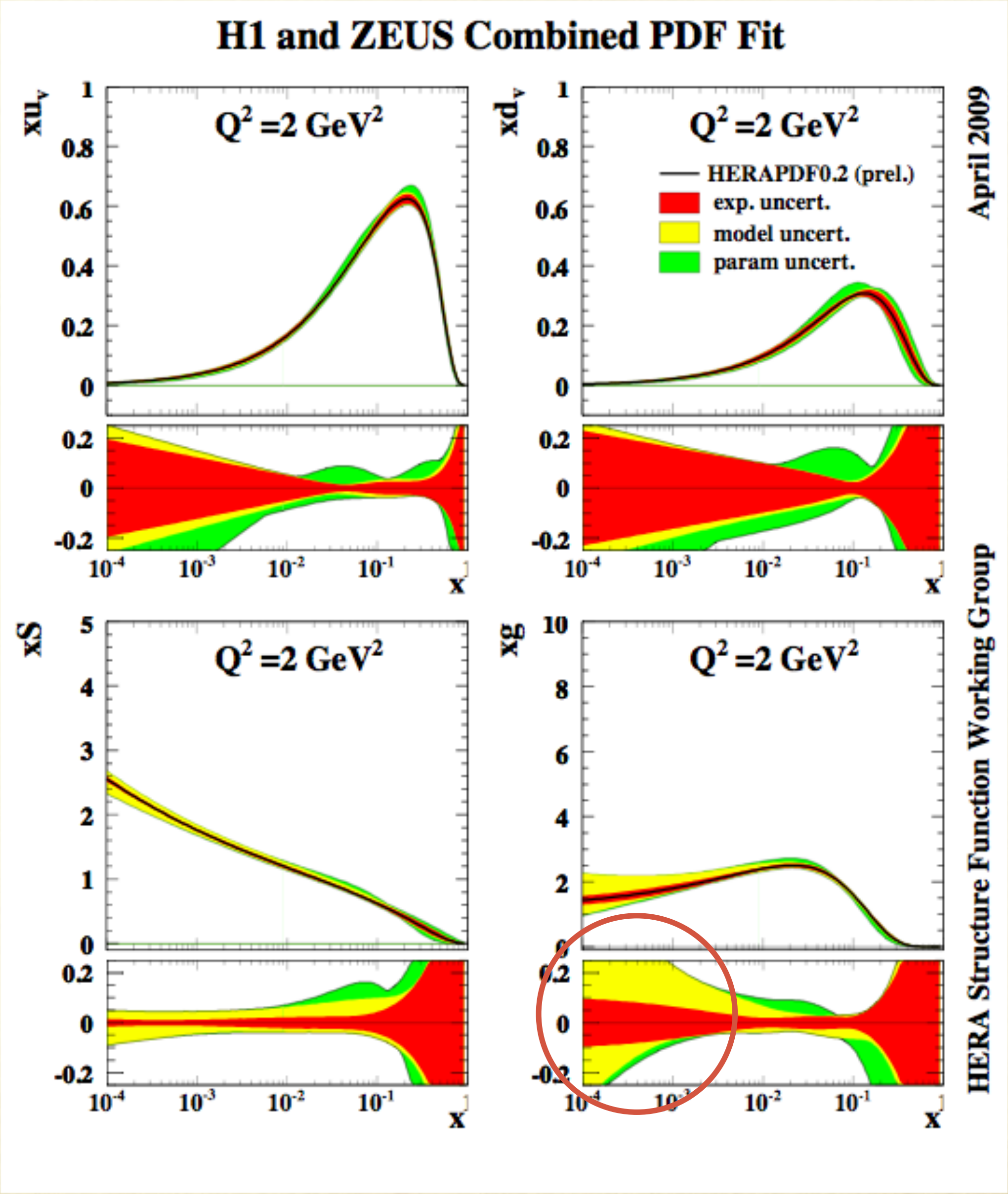
Many questions remain… there is a need (and a hope) for new opportunities (detectors/colliders) to answer them!

Open questions: gluon

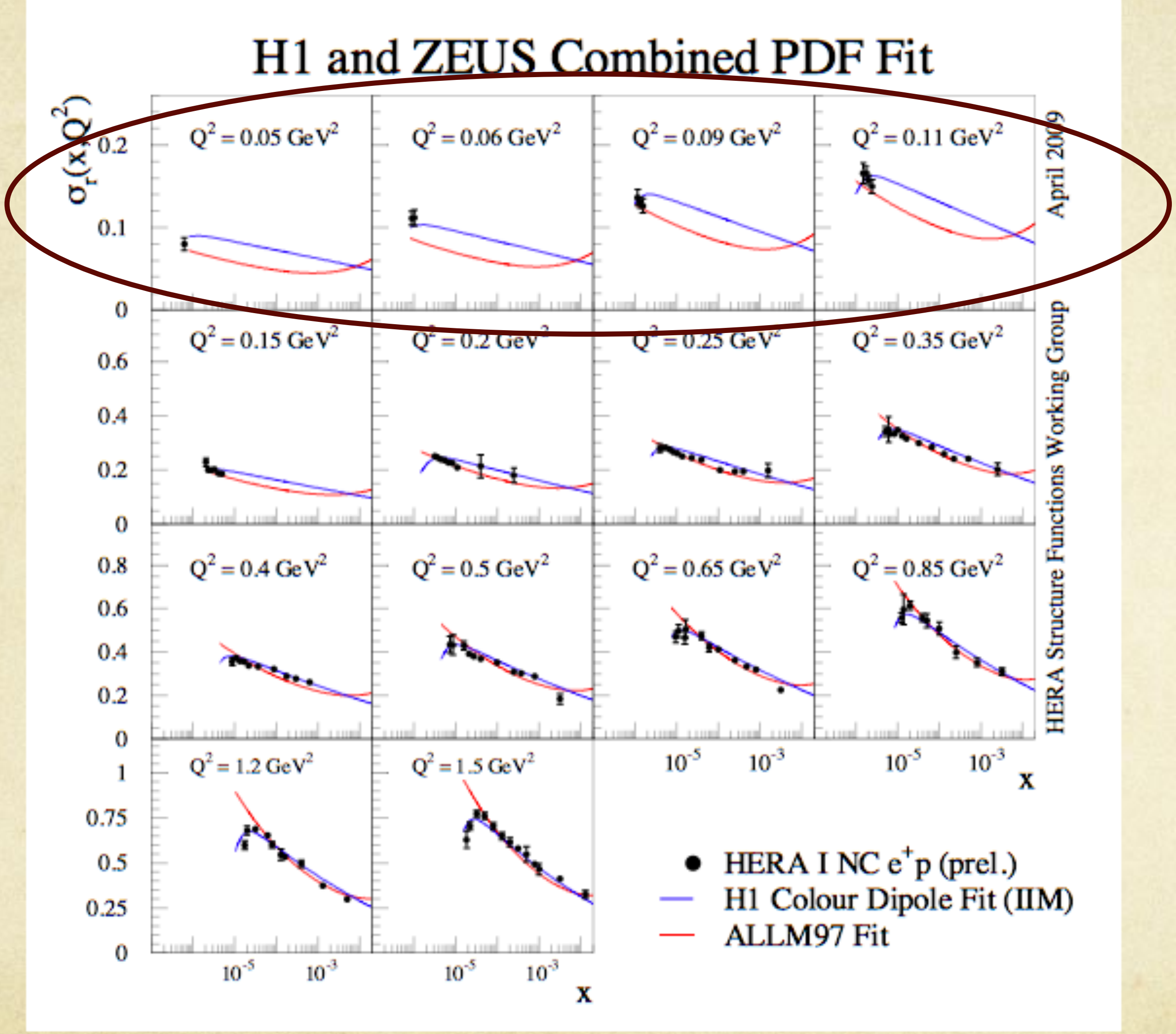
What happens at very low x?
- does gluon keep rising?
- does saturation set in?
- does DGLAP work here?

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