Structure Function Measurements From HERA

IOP Celebration of HERA Physics

Rutherford Appleton Laboratory
25th June 2008

- Introduction
- Neutral and Charged Current SFs
- H1 & Zeus Combined Data
- Extraction of Parton Densities
- The Remaining Work...

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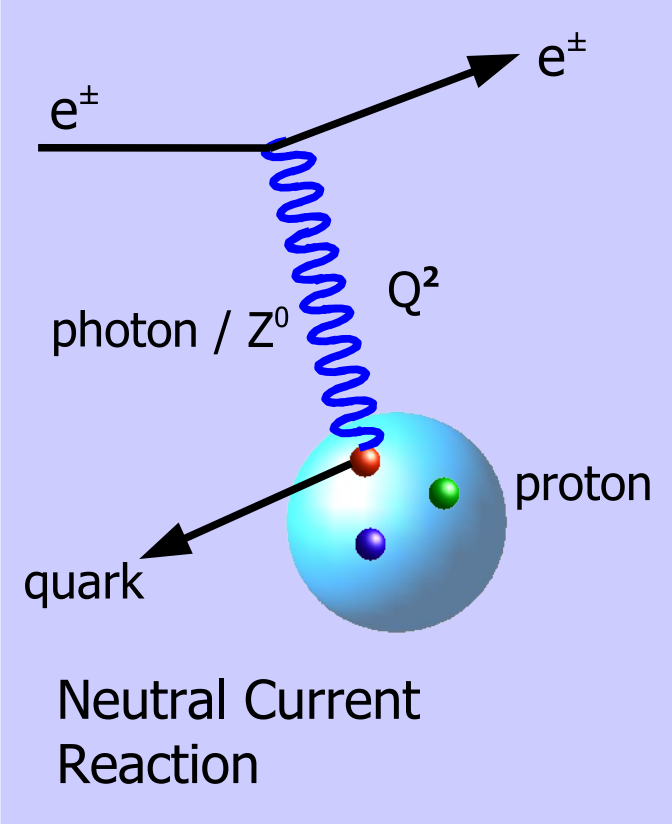
HERA performs measurements at Q^2 ~ EW scale
Tests Standard Model in region of large spacelike momentum transfer

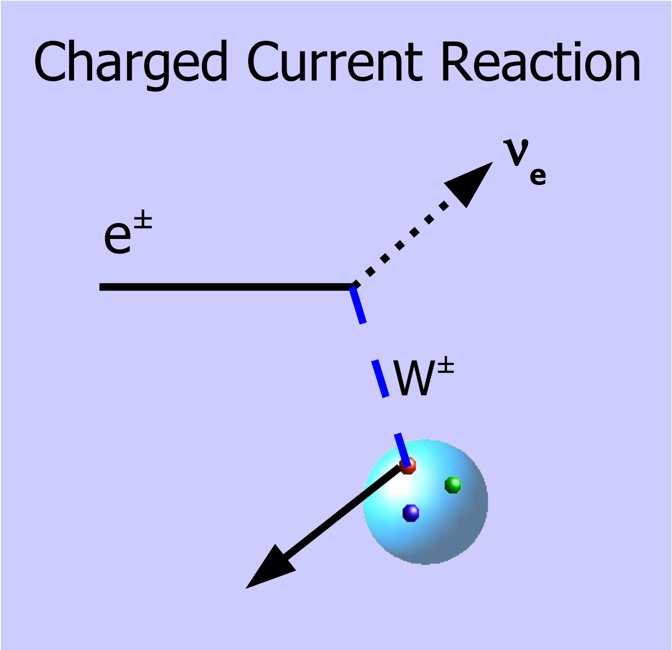
HERA collides e and p
study strong, electromagnetic & weak forces through Deep Inelastic Scattering

At fixed √s: two kinematic variables: x & Q^2
$Q^2 = s\ x\ y$

Q^2 = "resolving power" of probe
High Q^2 : resolve 1/1000th size of proton

x = momentum fraction of proton carried by quark
HERA: ~10^{-6} - 1





$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

Modified at high Q^2 by Z propagator

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{1\pm P_e}{2}\frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2 \left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

Structure functions parameterise partonic structure of proton: how far from point like

For pointlike proton: $\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{e^4}{8\pi x}\frac{1}{Q^4}Y_+$

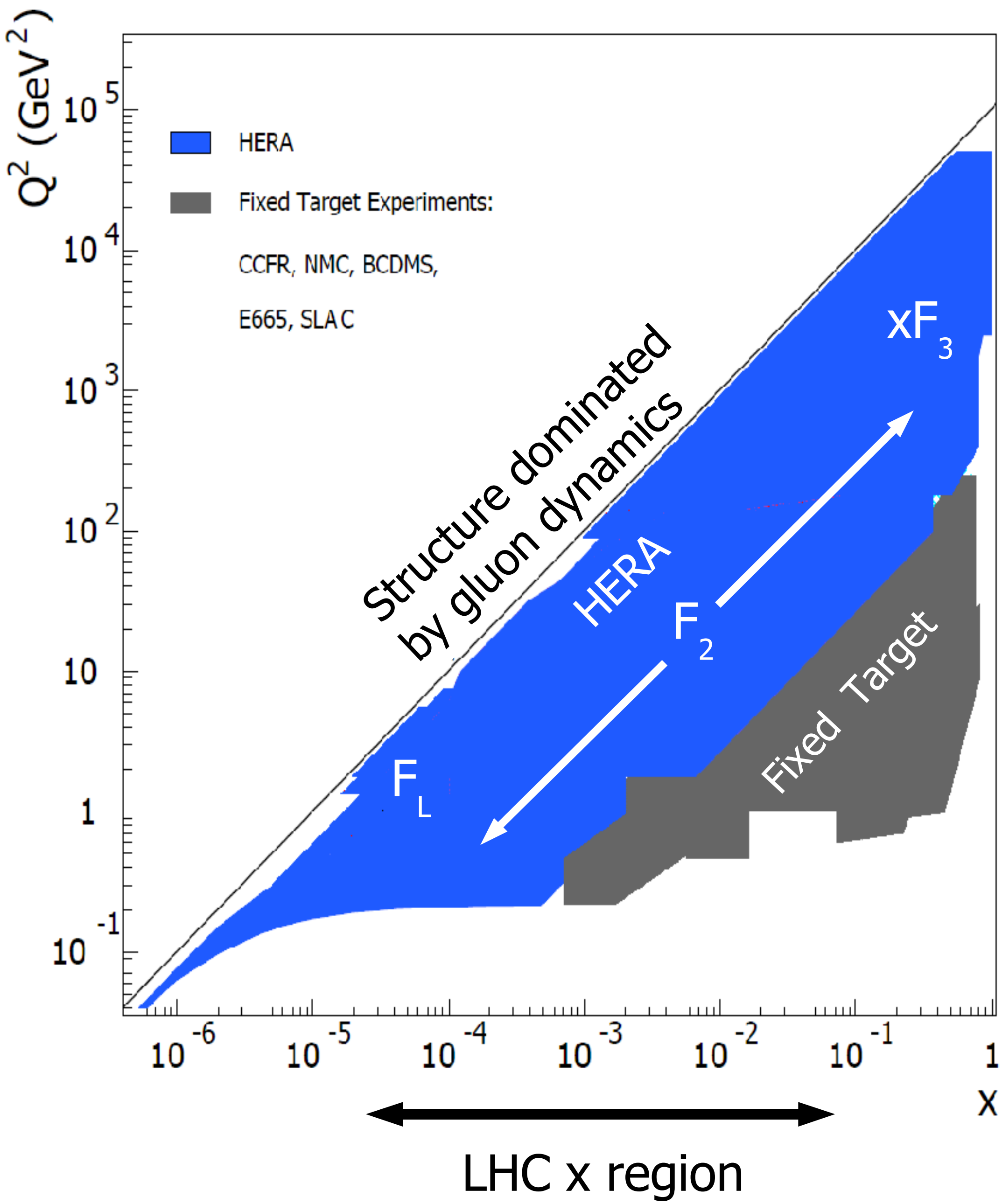
$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$	dominant contribution
$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$	only sensitive at high Q^2
$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$	only sensitive at low Q^2 and high y

similarly for $W_2^{\pm}$, $xW_3^{\pm}$ and $W_L^{\pm}$

SM predicts CC cross section $\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} \propto \frac{1\pm P_e}{2}$

linear scaling of cross section
zero for LH e^+ or RH e^-

$P_e=-1$ $P_e=+1$



HERA has large kinematic reach

QCD understanding needed across full x, Q^2 range

NC process: EW physics lies at high Q^2

CC process: purely weak - flavour info for PDFs

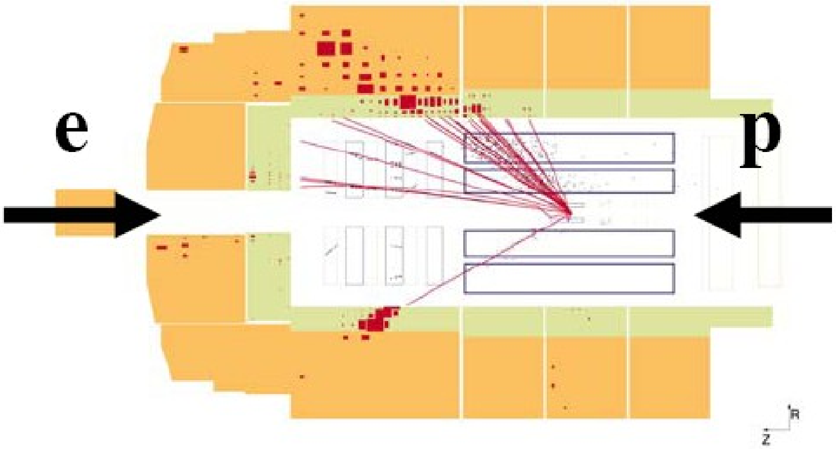
Measure cross sections

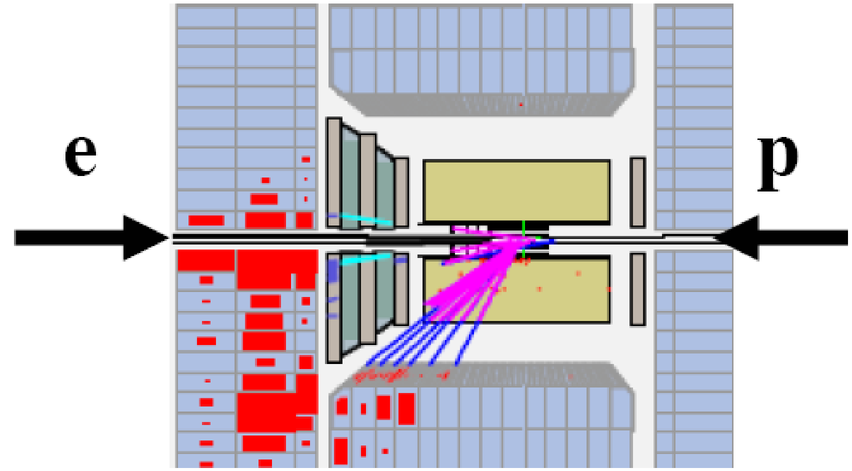
Fit data – extract PDFs & EW physics

HERA PDFs extrapolate into LHC region

LHC probes proton structure where gluon dominates (gluon collider)

HERA data crucial in calculations of new physics & measurements at LHC





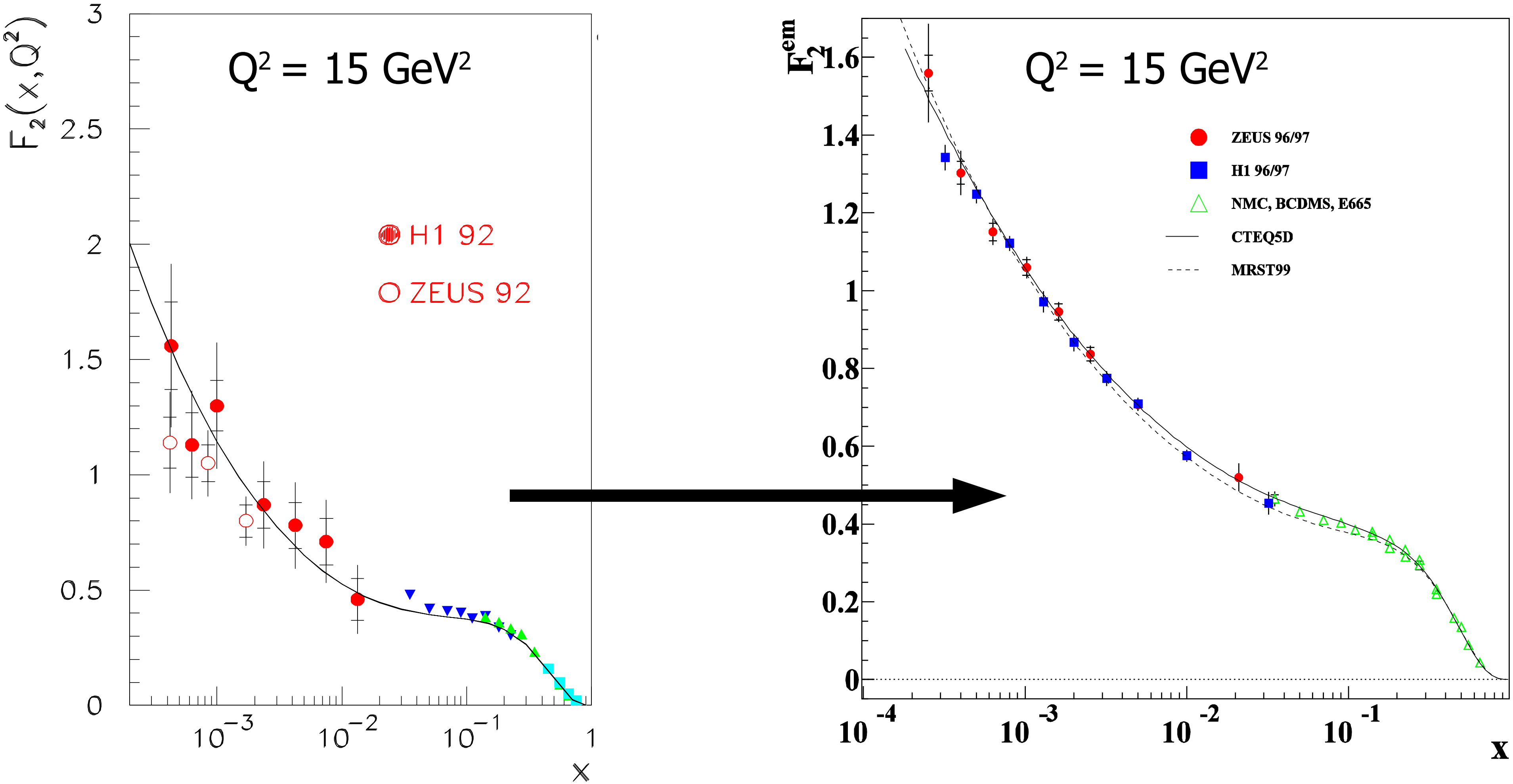
Neutral current event selection:

- High P_T isolated scattered electron/positron
- Suppress huge photoproduction background by imposing longitudinal energy-momentum conservation
- Kinematics may be reconstructed in many ways: energy/angle of hadrons & scattered lepton provides excellent tools for sys cross checks
- Removal of scattered lepton provides a high stats "pseudo-charged current sample" Excellent tool to cross check CC analysis
- Final selection: ~10^7 events per experiment

Charged current event selection:

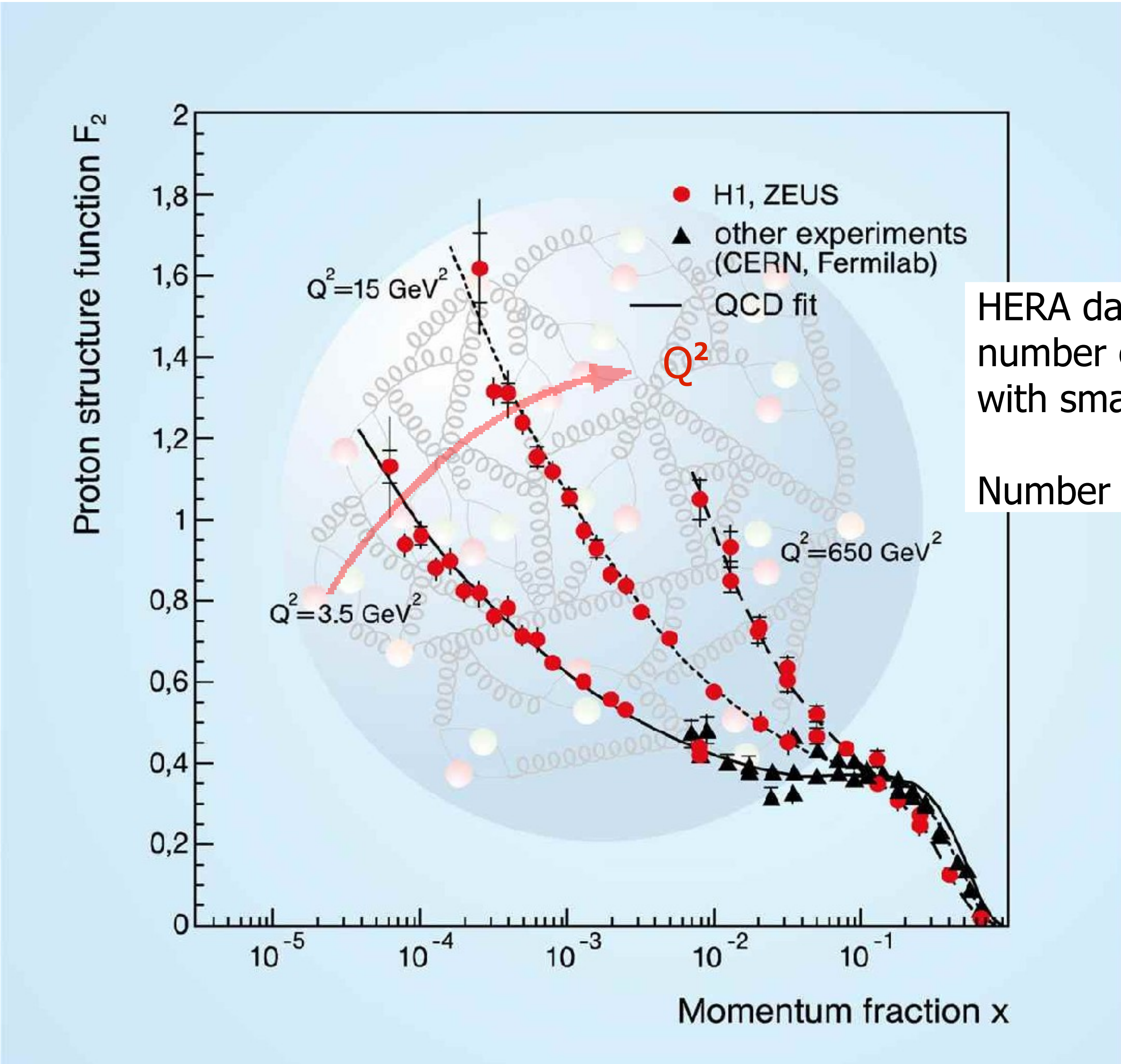
- Large missing transverse momentum (neutrino)
- Suppress huge photoproduction background
- Topological finders to remove cosmic muons
- Kinematics reconstructed from hadrons
- Final selection: ~10^4 events per experiment

$$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$$



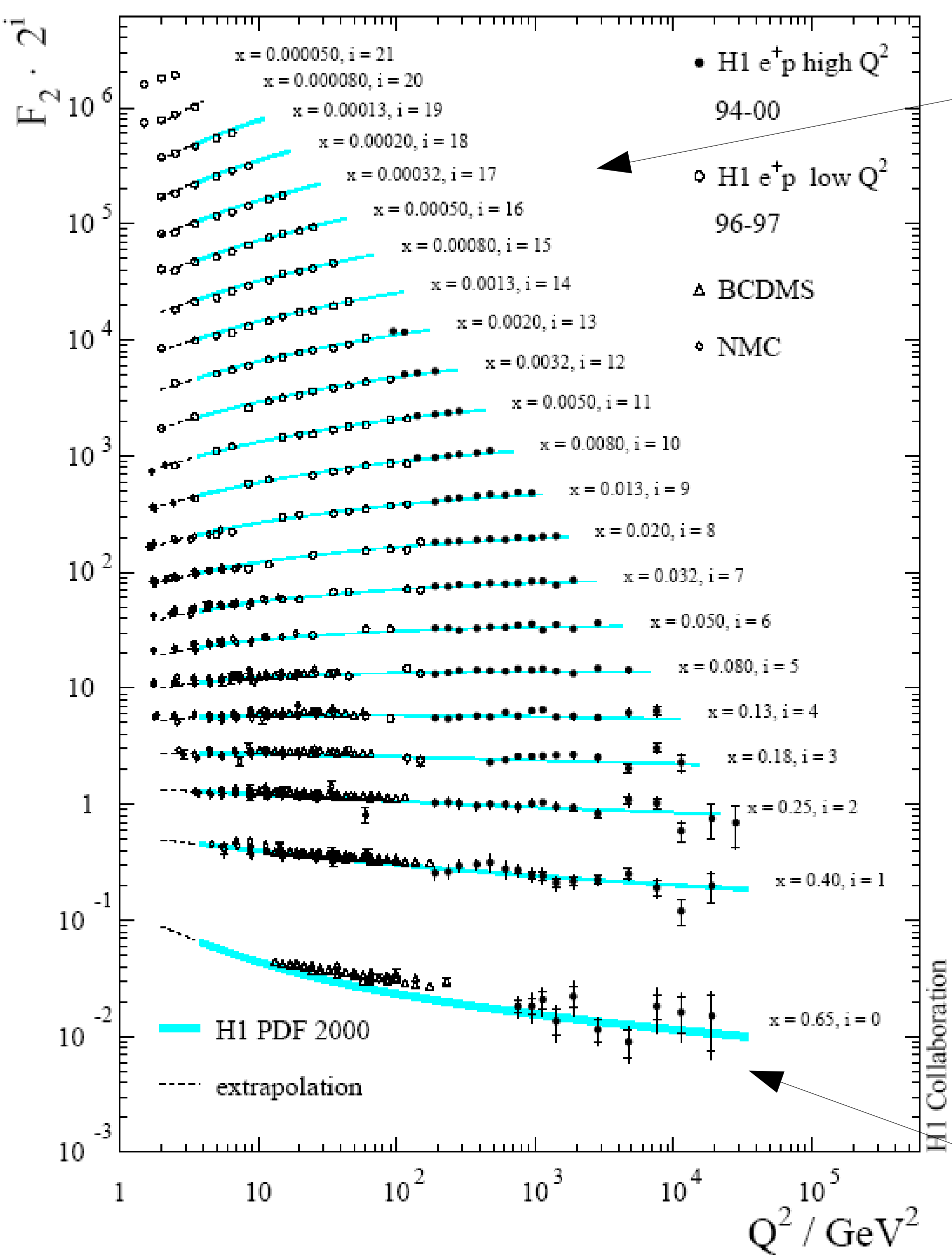
8 years to shrink uncertainties from ~20% to ~2%
Another 8 years to go from 2% to ~1% !

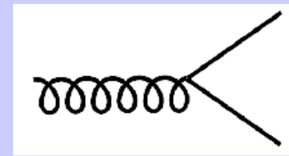
Proton Structure



HERA data show a rising number of quarks & gluons with small momentum fractions x

Number increases as Q^2 increases



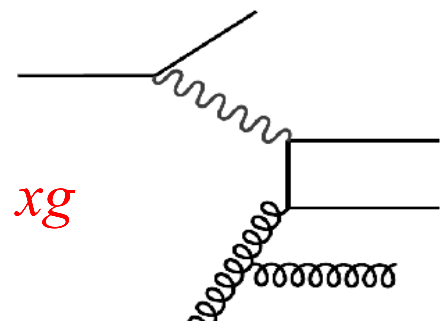


Low x: gluon splitting

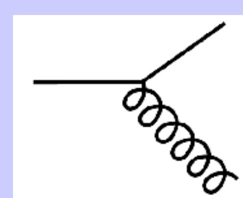
At low x proton content dominated by dynamic sea of partons

Measurements well described by pQCD

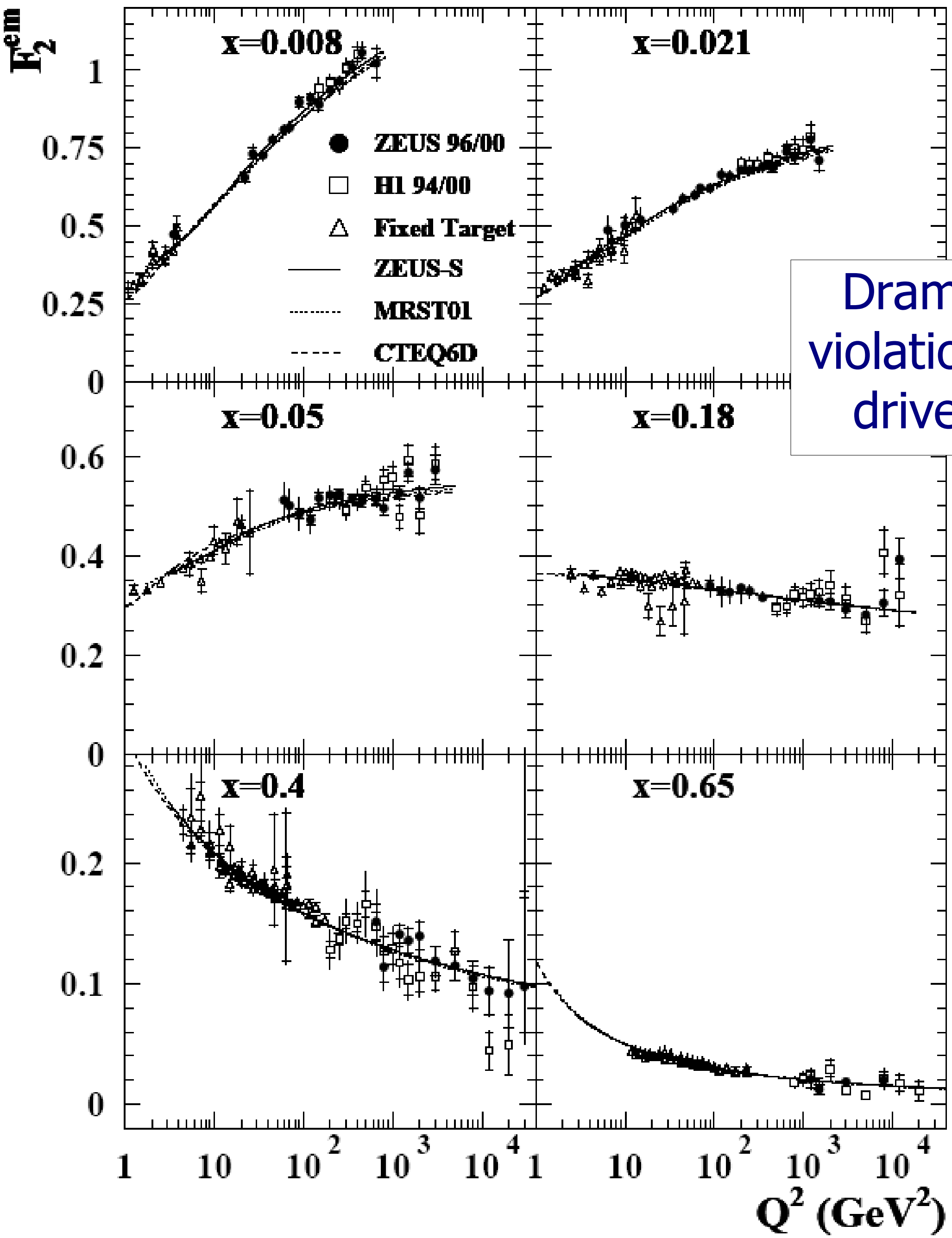
HERA has given us a precise map of the proton - a good understanding of QCD



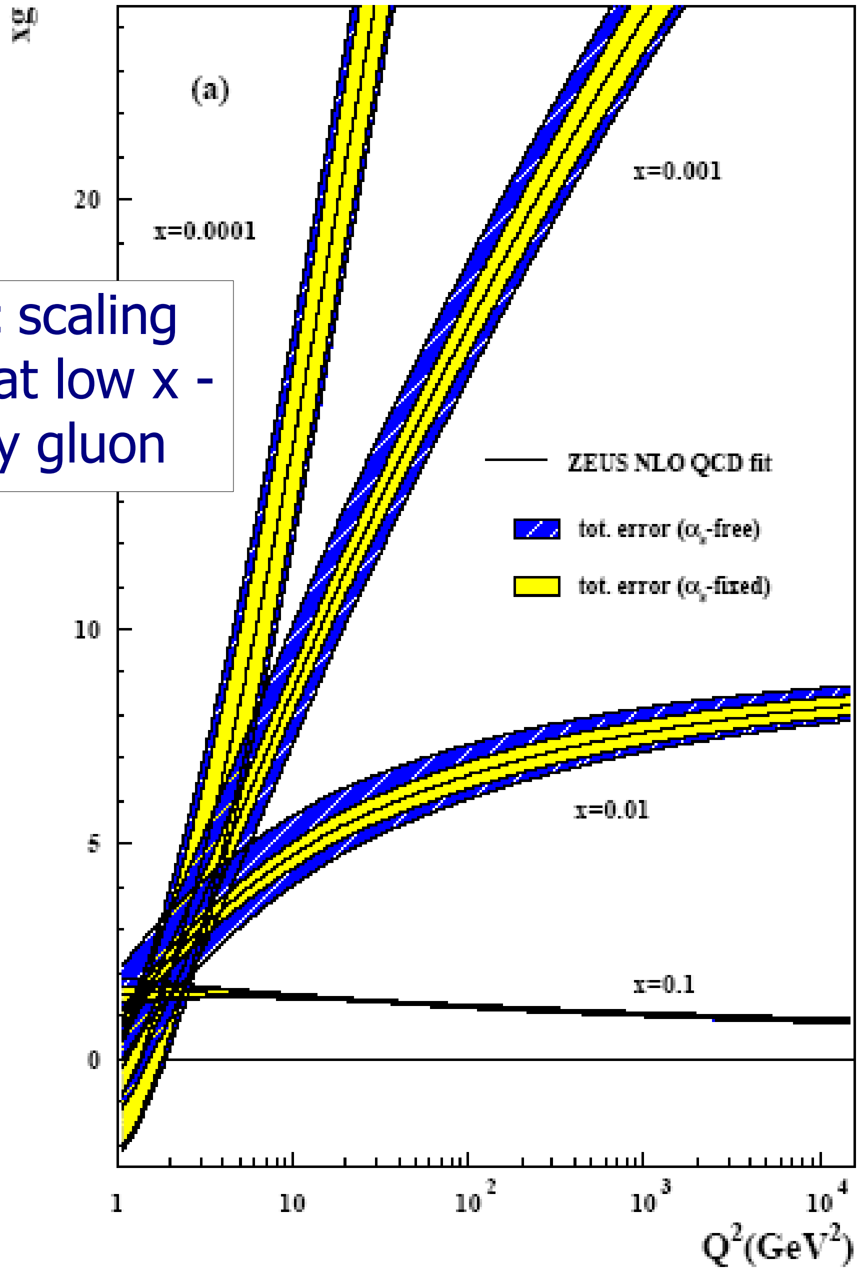
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s \cdot xg$$



High x: gluon emission



Dramatic scaling violations at low x - driven by gluon



Measure gluon density directly - F_L

$$F_2 \sim \sigma_T + \sigma_L$$
$$F_L \sim \sigma_L$$

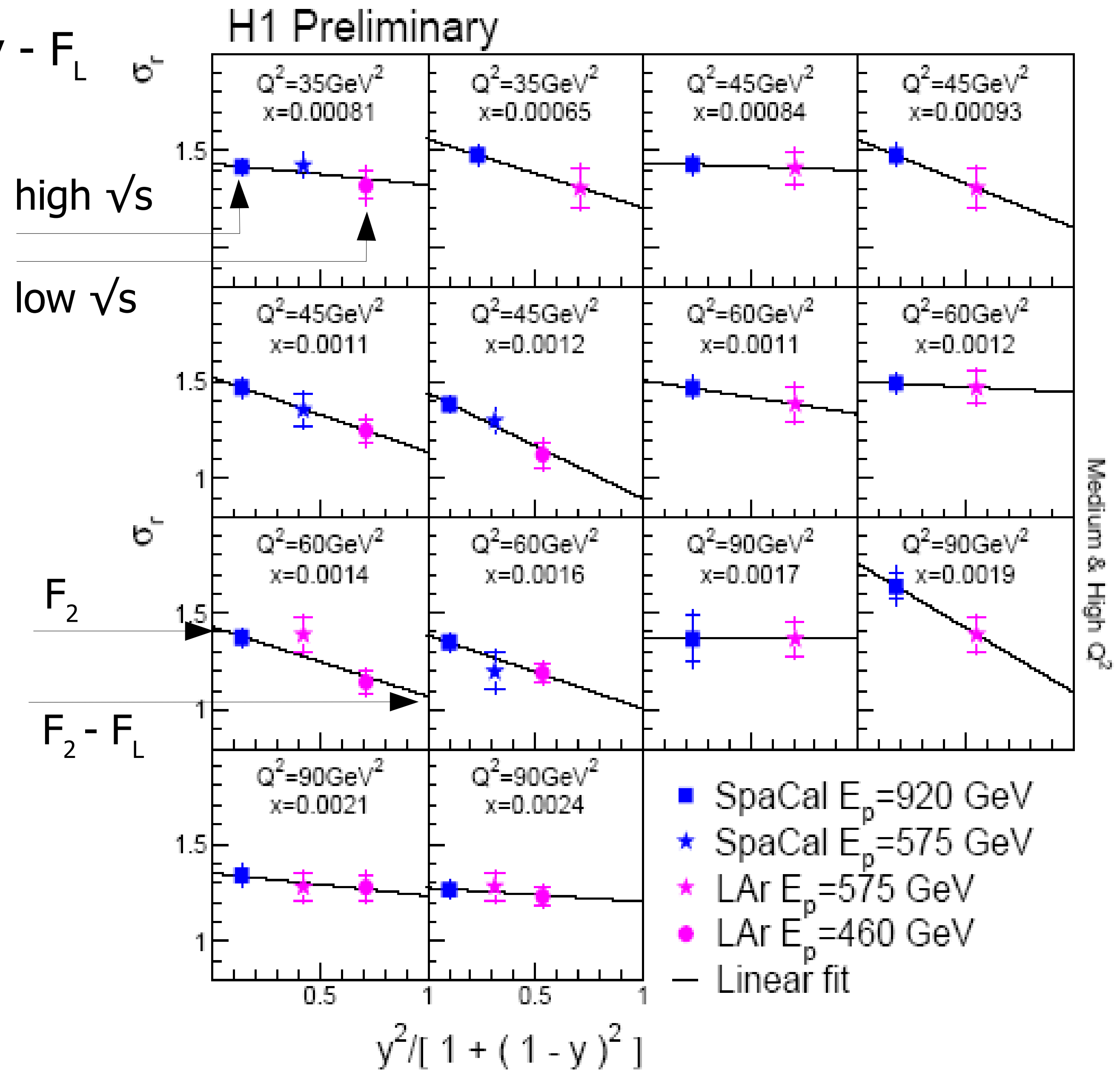
- $F_L \equiv 0$ in quark-parton model
- Acquires non-zero value from gluon emission

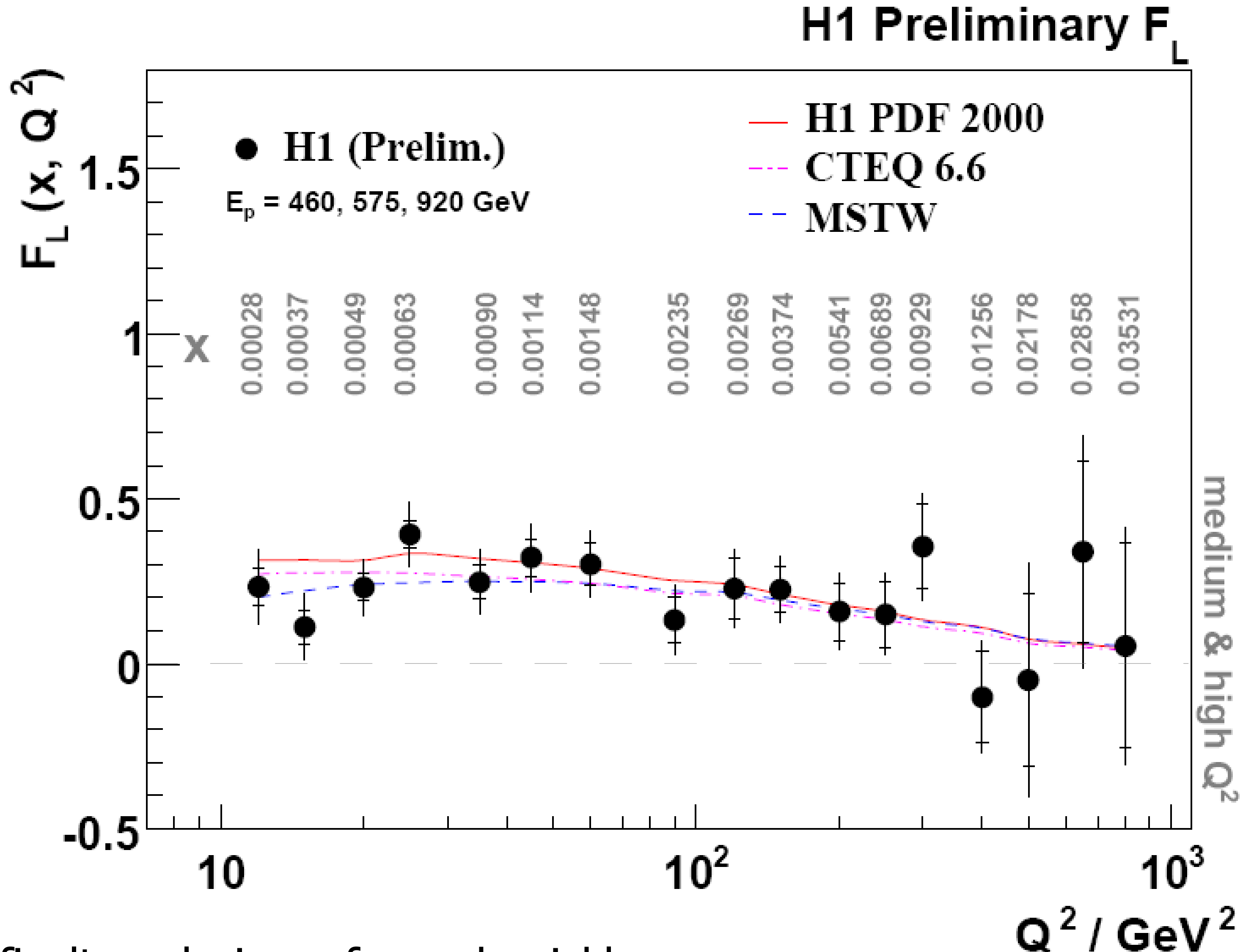
$$F_L \propto \alpha_S \cdot xg$$

- Affects NC cross section at high y
- Measure cross section at same x,Q^2 but different $\sqrt{s}$

$$\tilde{\sigma}^{\pm}_{NC} \approx \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L$$

- Low proton beam energy data taken March-June 2007





Difficult analysis performed quickly

Preliminary measurements released at DIS April 2008

First publication of part of this data now accepted by Phys.Lett. B

At low x gluon dominates proton structure
At high x valence quarks dominate

NC cross section ~ $\left[\frac{1}{Q^4}\right](1-x)^4$

HERA able to constrain valence PDFs
free of messy nuclear effects
and other non-pQCD effects

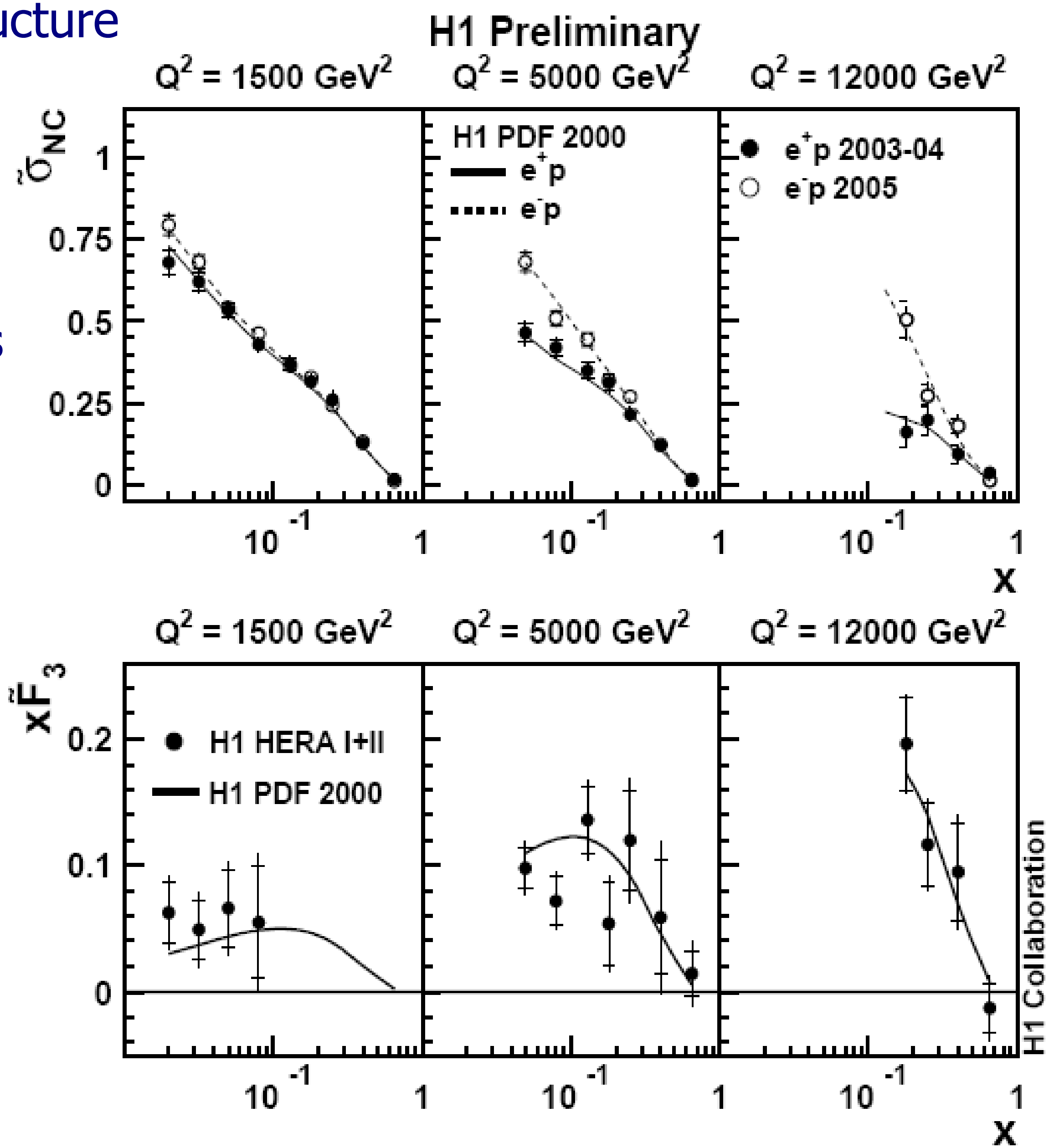
Direct sensitivity from F_2 as well as
non-singlet structure function xF_3

In unpolarised case

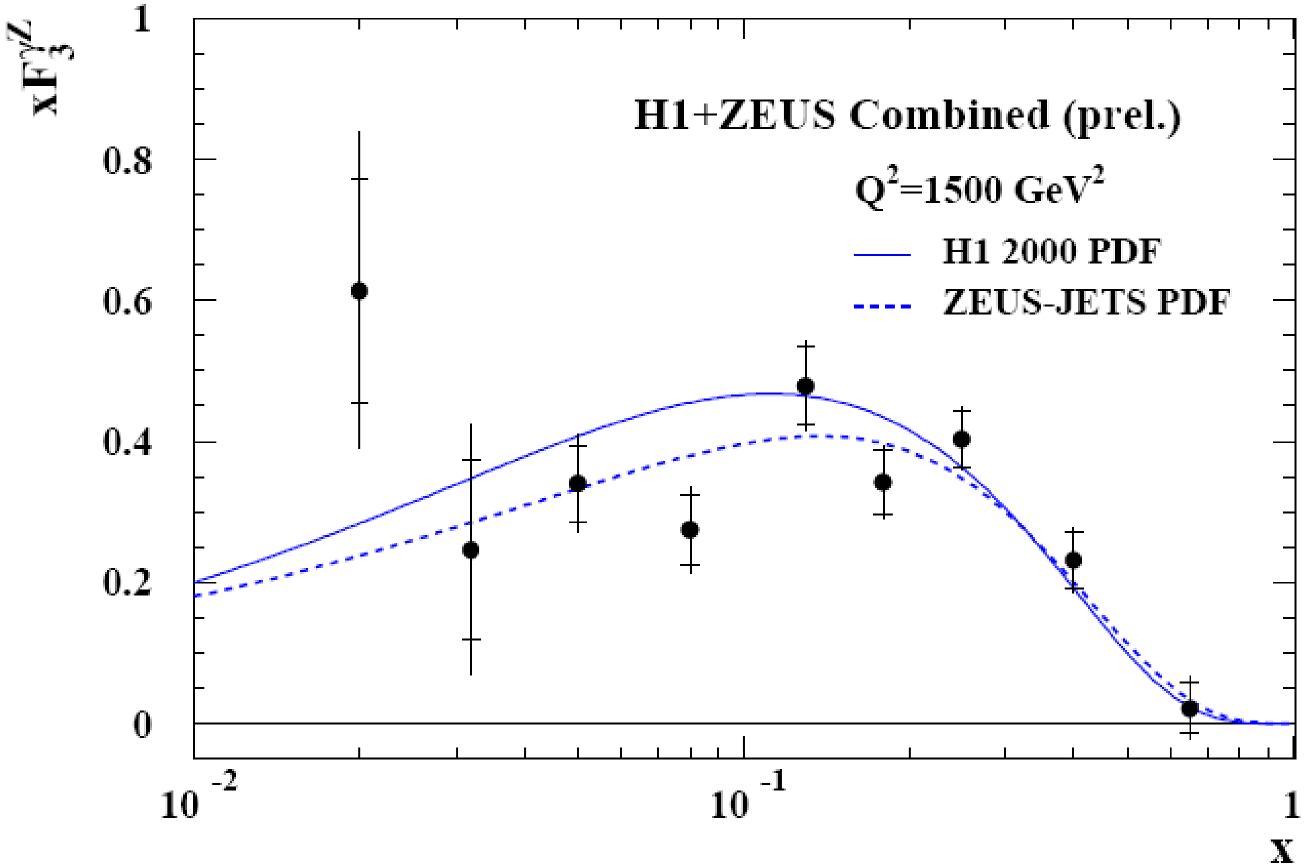
$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

$$\tilde{\sigma}^{\pm}_{NC} \approx \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC})$$



Neutral Current Channel (Unpolarised)



Large luminosity of HERA-II sample allows improved xF_3 measurement

Precision further improved by combining H1 & ZEUS data

Measurement statistically limited

Dominant NC cross section allows precision measurements of partonic content
- sensitivity to singlet quark distribution
- limited direct sensitivity to gluon density
- separation of valence from sea content

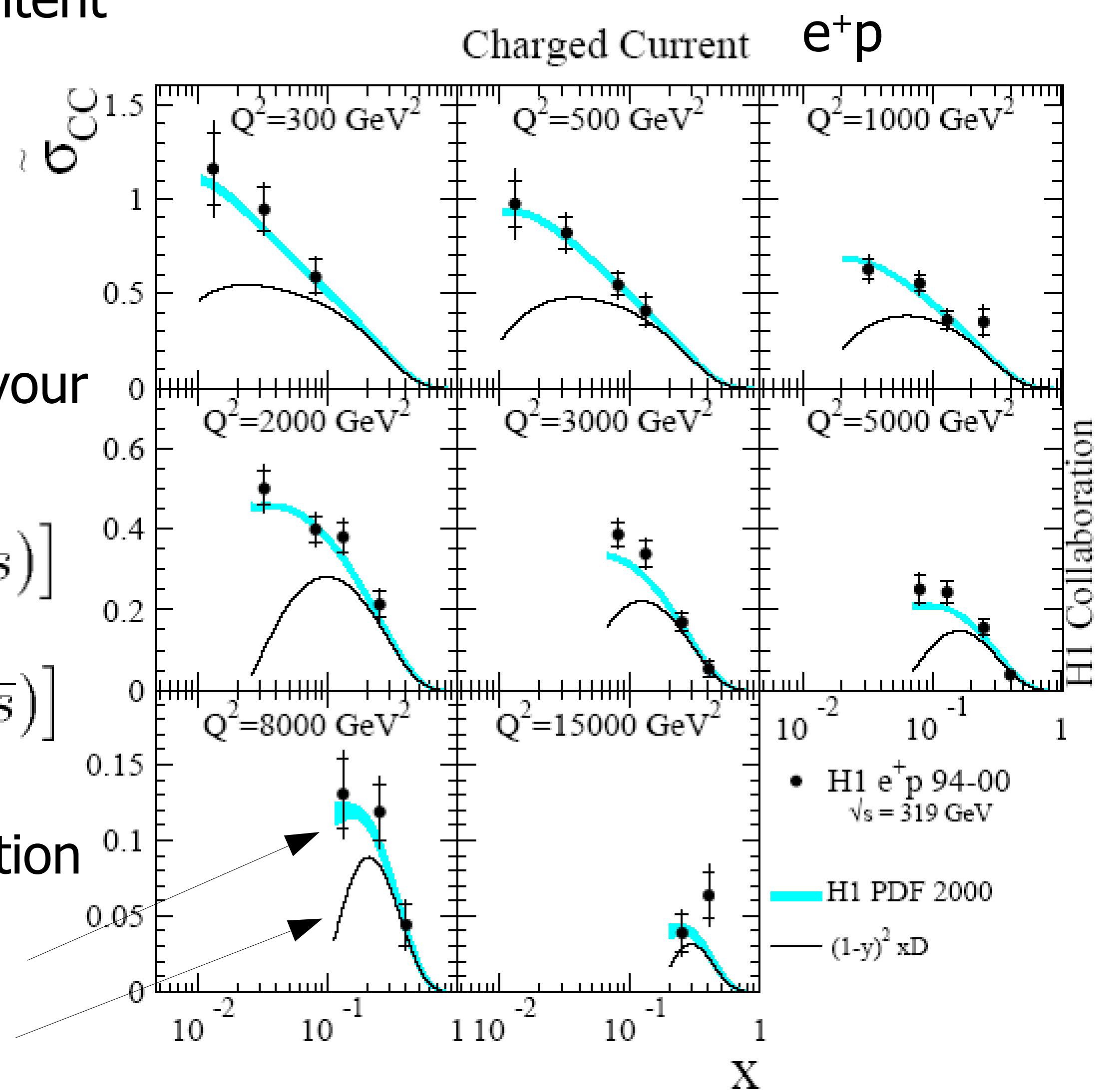
NC process weakly flavour dependent
- 4/9 charge coupling to u
- 1/9 charge coupling to d

Purely weak CC process is strongly flavour dependent:

$$\sigma^{+}_{CC} = x\left[(\bar{u}+\bar{c}) + (1-y)^2(d+s)\right]$$

$$\sigma^{-}_{CC} = x\left[(u+c) + (1-y)^2(\bar{d}+\bar{s})\right]$$

Provides handle on flavour decomposition



Precision of cross section data can be improved by combining H1 & Zeus

Can be done in model independent way:

- Assume that both experiments measure same cross section
- Minimise a χ^2 function - free parameters are combined cross sections
- Fast solution of $N_{meas} + N_{syst}$ system of linear equations

Trivial reduction of statistical uncertainties

Impressive reduction of systematic uncertainties occurs - cross calibration!

$$\chi^2_{\rm exp}\left(M^{i,\rm true},\alpha_j\right)=\sum_i \frac{\left[M^{i,\rm true}-\left(M^i+\sum_j \frac{\partial M^i}{\partial \alpha_j}\alpha_j\right)\right]^2}{\delta_i^2}+\sum_j \frac{\alpha_j^2}{\delta_{\alpha_j}^2}\ .$$

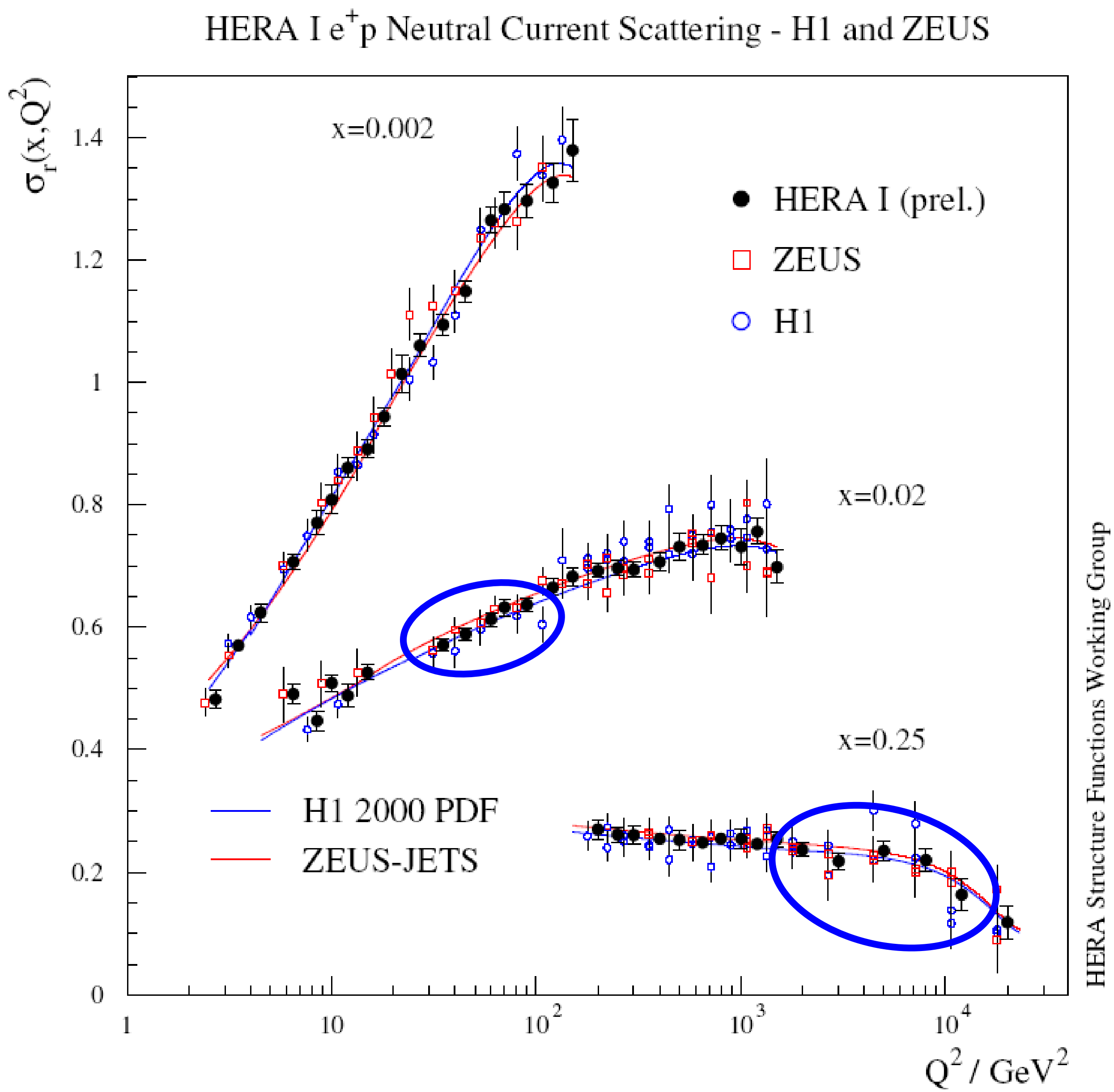
This is the usual χ^2 definition - CTEQ-like

M^i are measurements

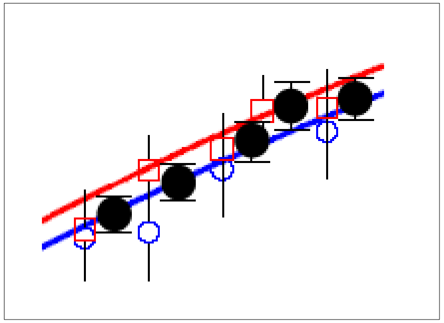
$M^{i,true}$ are averaged values

α_j are the j sys errror sources

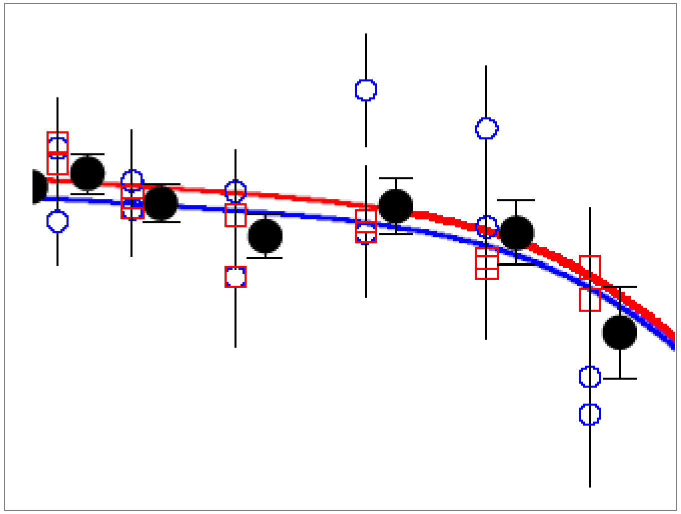
δ_i are the uncorrelated errors



Combined data have uncertainties:
better than 2% for $Q^2 < 12$
~1.5% for $Q^2 < 60$

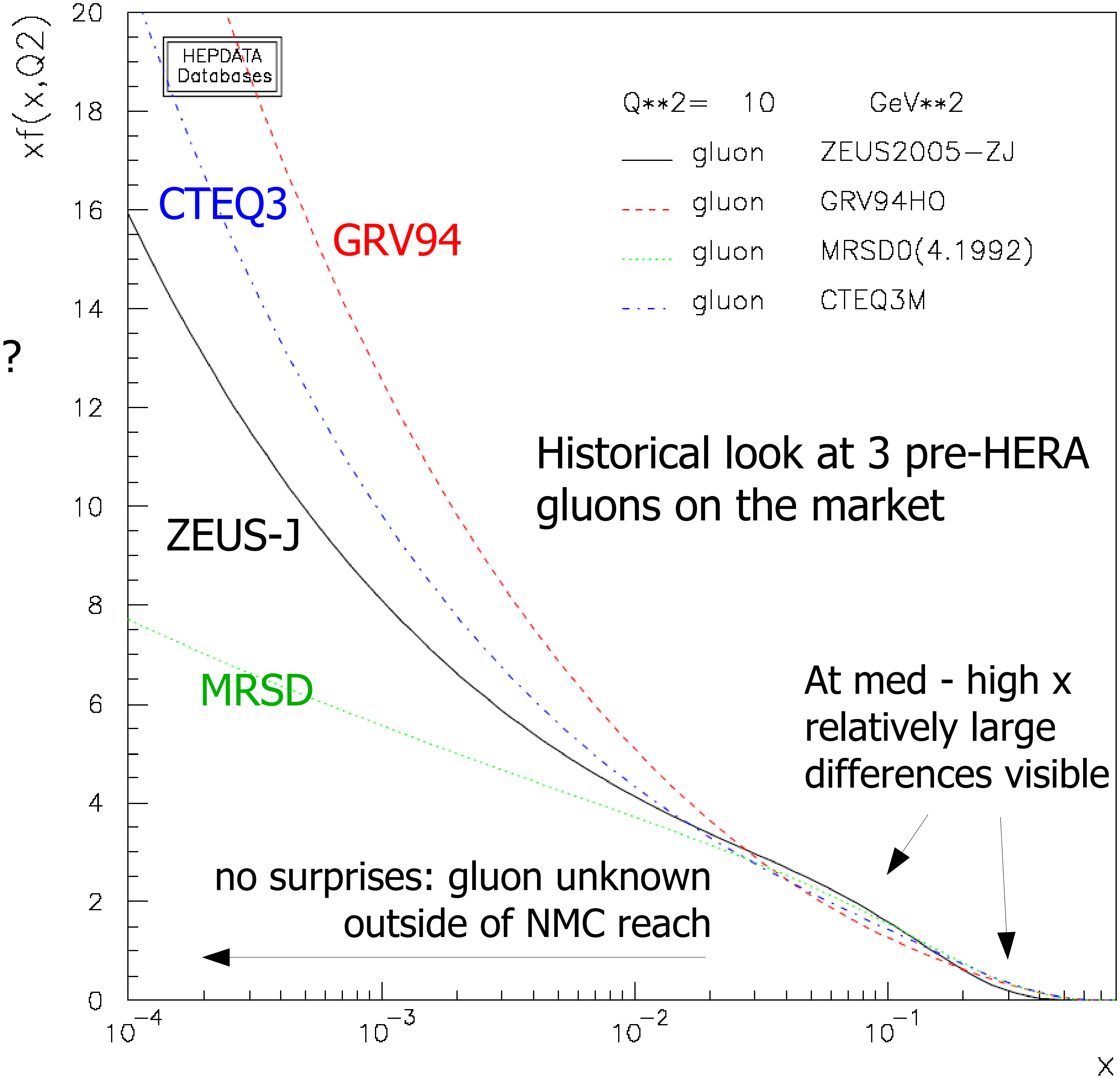


At high Q^2 data have errors ~10% from improved statistical precision



We now have enough ingredients to extract proton parton densities

Where were we in ~1993?



Parton densities extracted by parameterising densities at starting scale Q_0^2

Use pQCD to evolve PDFs in Q^2 and predict cross sections

Use χ^2 minimisation

HERA data have enough constraints for a std proton flavour decomposition

- can be done in a single experiment! (or two...)
- coherent treatment of systematic uncertainties
- avoid non-perturbative region
- no meddlesome nuclear effects

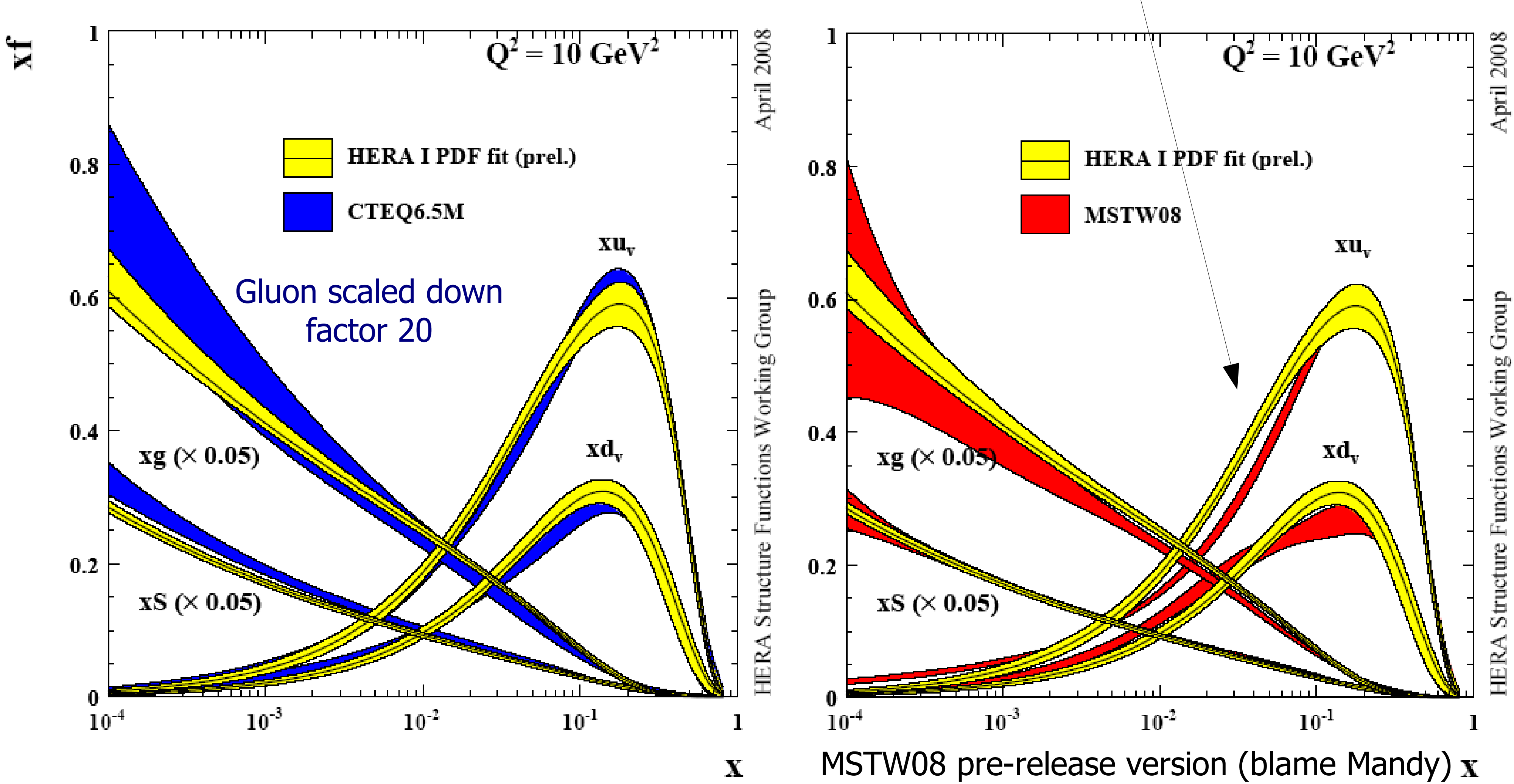
QCD analyses require many choices to be made - reflected in PDF uncertainty:

- Q_0^2 starting scale
- Choice of data sets used
- Cuts to limit analysis to perturbative phase space (Q^2_{min})
- Choice of densities to parameterise (e.g. u_v, d_v, xg, xS)
- Treatment of heavy quarks
- Allowed functional form of PDF parameterisation
- Treatment of experimental systematic uncertainties
- Renormalisation / factorisation scales
- Choice of α_s
- etc...

First joint HERA PDFs based on combined data released in April

Reduced uncertainties - largely due to combined data

In broad agreement - though differences visible



Mandy Cooper-Sarkar

PDF set	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_{Z} B_{Z\to ll}$ (nb)
ZEUS-2005	11.87±0.45	8.74±0.31	1.97±0.06
MRST01	11.61±0.23	8.62±0.16	1.95±0.04
HERA-I	**12.13±0.13**	**9.13±0.15**	**2.01±0.025**
CTEQ65	12.47±0.47	9.14±0.36	2.03±0.07

HERAPDFs make most precise predictions for W/Z production at LHC ~1%

PDFs broadly agree at low x (HERA data)

Discrepancies in med-high x region

Some uncertainties unaccounted?

- data sets inconsistent?
- missing theory
- PDF parametric forms?
- different assumptions

This is the end game:

- final measurement of F_2 med & low Q^2 (H1) precision ~1%
- F_L measurements at lowest Q^2 ~1 GeV^2
- final publication of high Q^2 NC and CC cross sections (H1 & Zeus)
- final combination of H1 & Zeus data
- final HERAPDF fit to combined data

This legacy data will not be superceded for many years

Important for the understanding of QCD and predictions for LHC

Requires the continued financial support of STFC to UK HERA community

$$F_2 = c(Q^2) \cdot x^{-\lambda(Q^2)}$$

- At $Q^2 \gtrsim 2\,\mathrm{GeV}^2$:

  $\lambda \sim \ln Q^2$

  Partonic degrees of freedom

- At $Q^2 \lesssim 2\,\mathrm{GeV}^2$:

  Transition to hadronic d.o.f.

  $Q^2 \to 0$: $\lambda \to 0.08$ (Regge model)