Deep Inelastic Scattering at High Q^2

Physics At The Terascale
School on PDFs
DESY Zeuthen, Berlin
12th-14th Nov 2008

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HERA the 800 ~~Pound~~ Kilo Gorilla

Outline

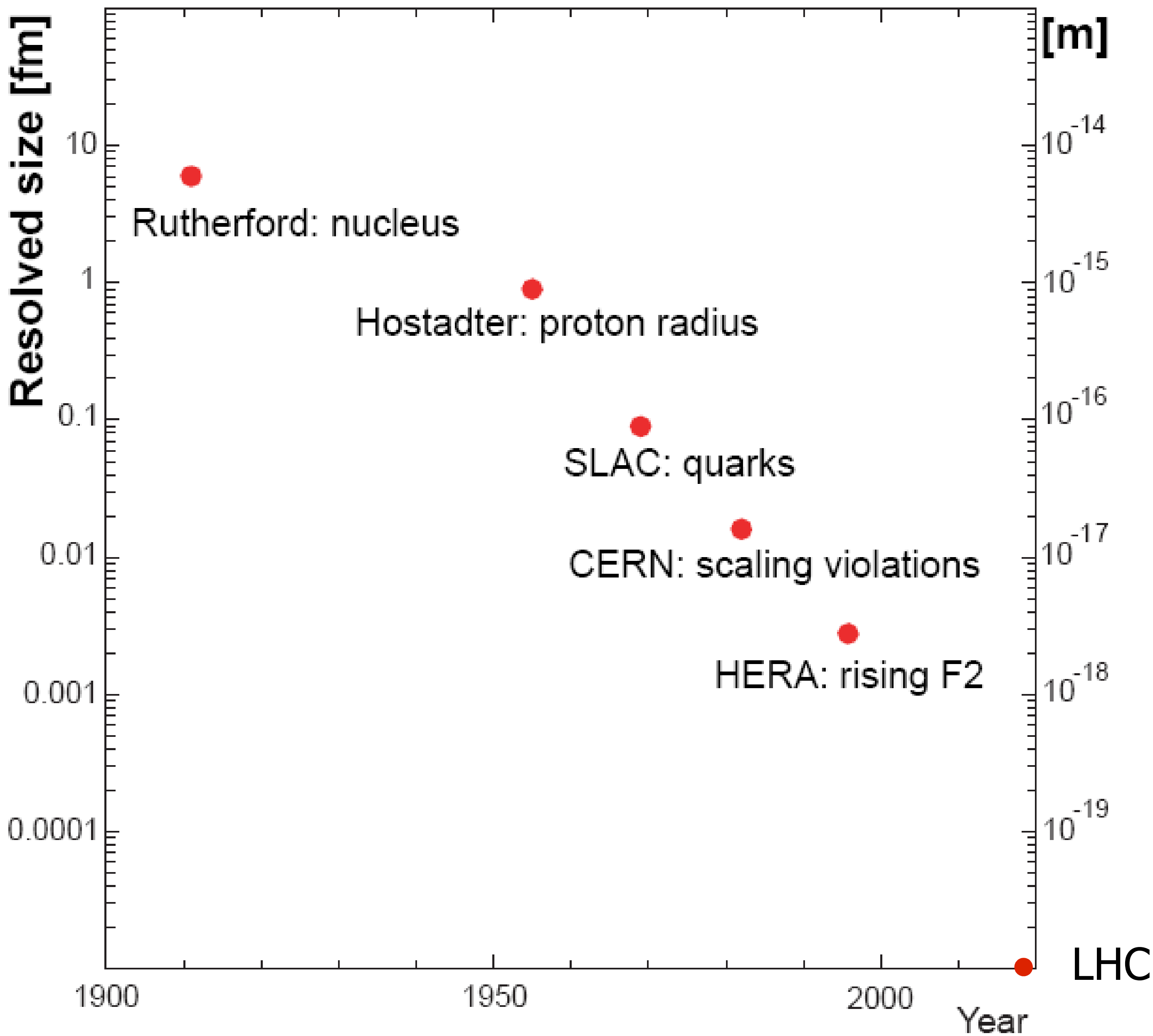
- Reminder of DIS & Structure Functions
- Measurements & DIS data from HERA
- HERA with Polarised Leptons
- QCD Fits
- PDFs at the LHC

Not all HERA data have been analysed

Plots may not be most up-to-date

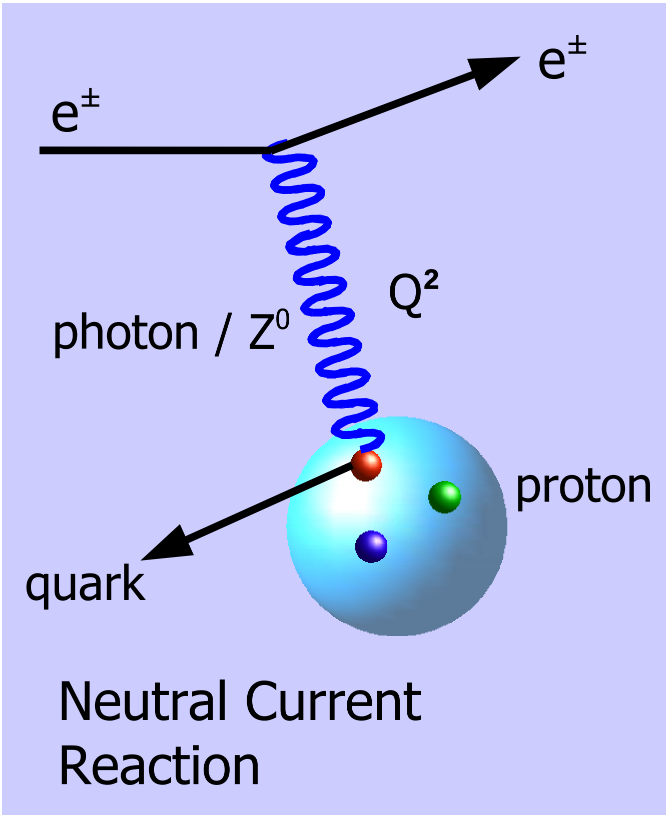
Chosen to illustrate a particular point

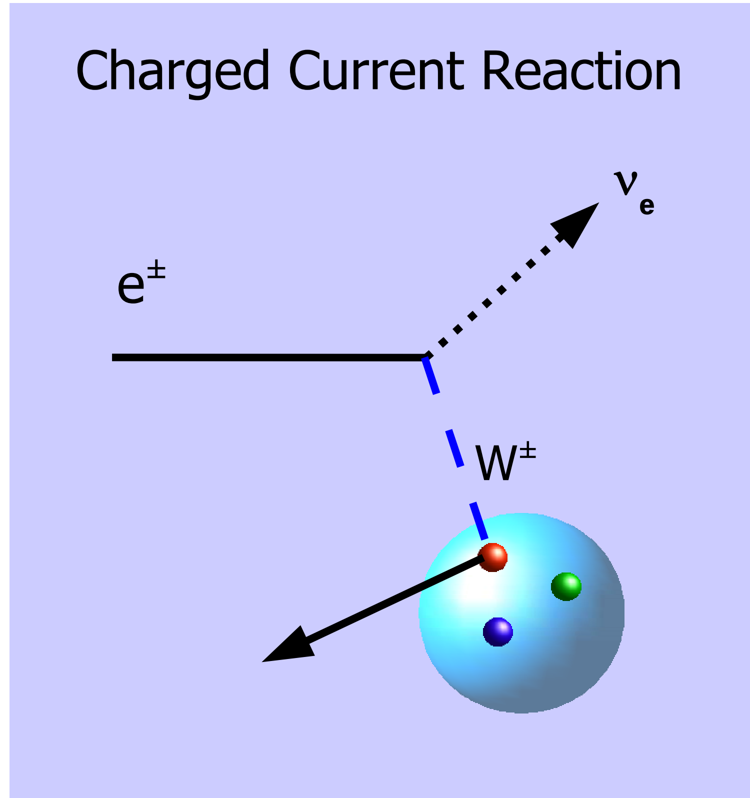
Tried to indicate where additional data will be added



won't reach Planck length anytime soon...

Deep inelastic scattering allows us to probe the proton - and quark dynamics
Tells us about QCD





Use a "clean" EW probe to delve into the messy proton

HERA = EW ⊗ QCD

x = fractional proton momentum Q^2 = probing scale

y = inelasticity

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

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

Modified at high Q^2 by Z propagator

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

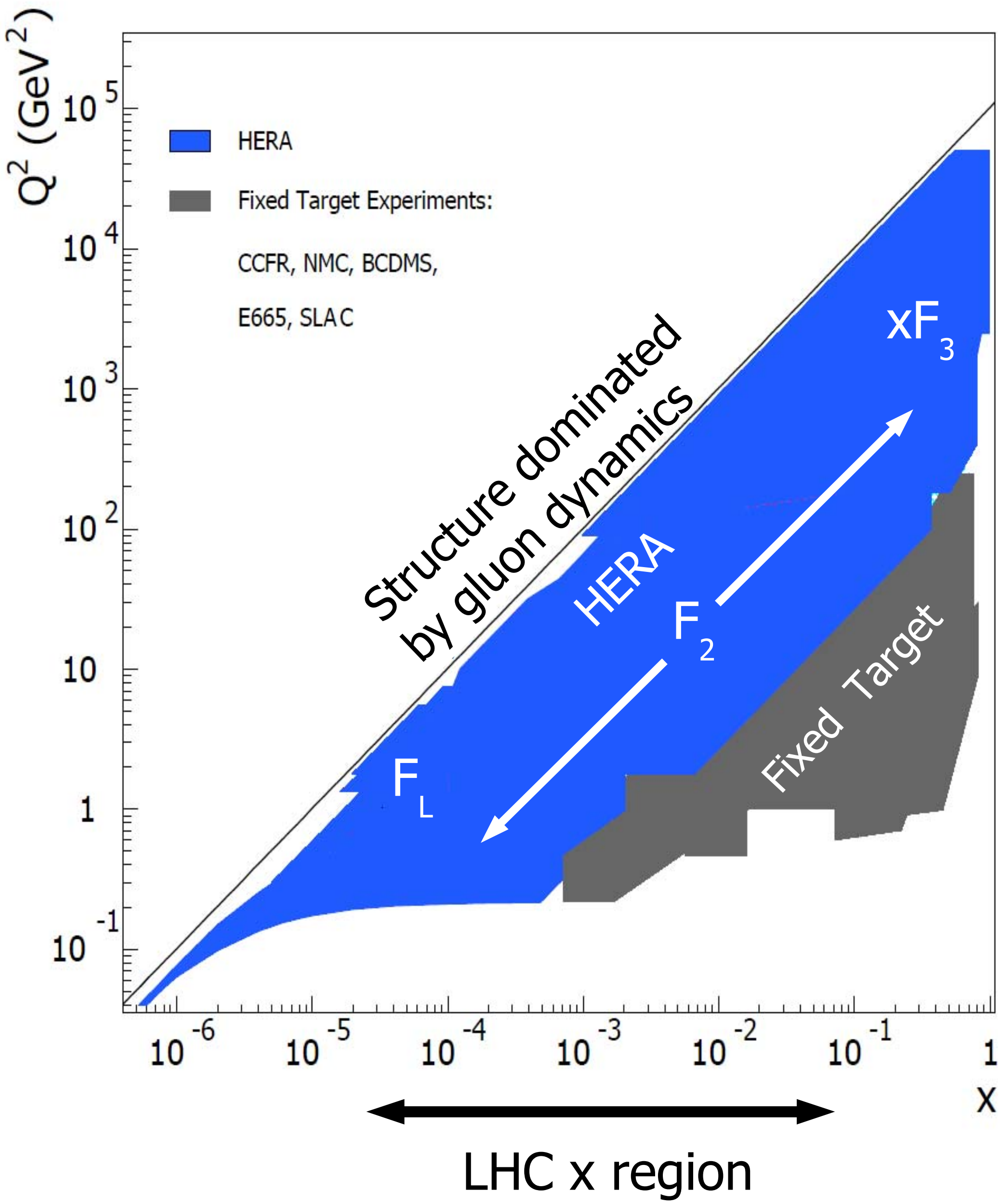
Structure functions parameterise proton structure: how far from point like

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

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

Below EW scale:
NC process sees only photon propagator
CC process ~ constant with Q^2

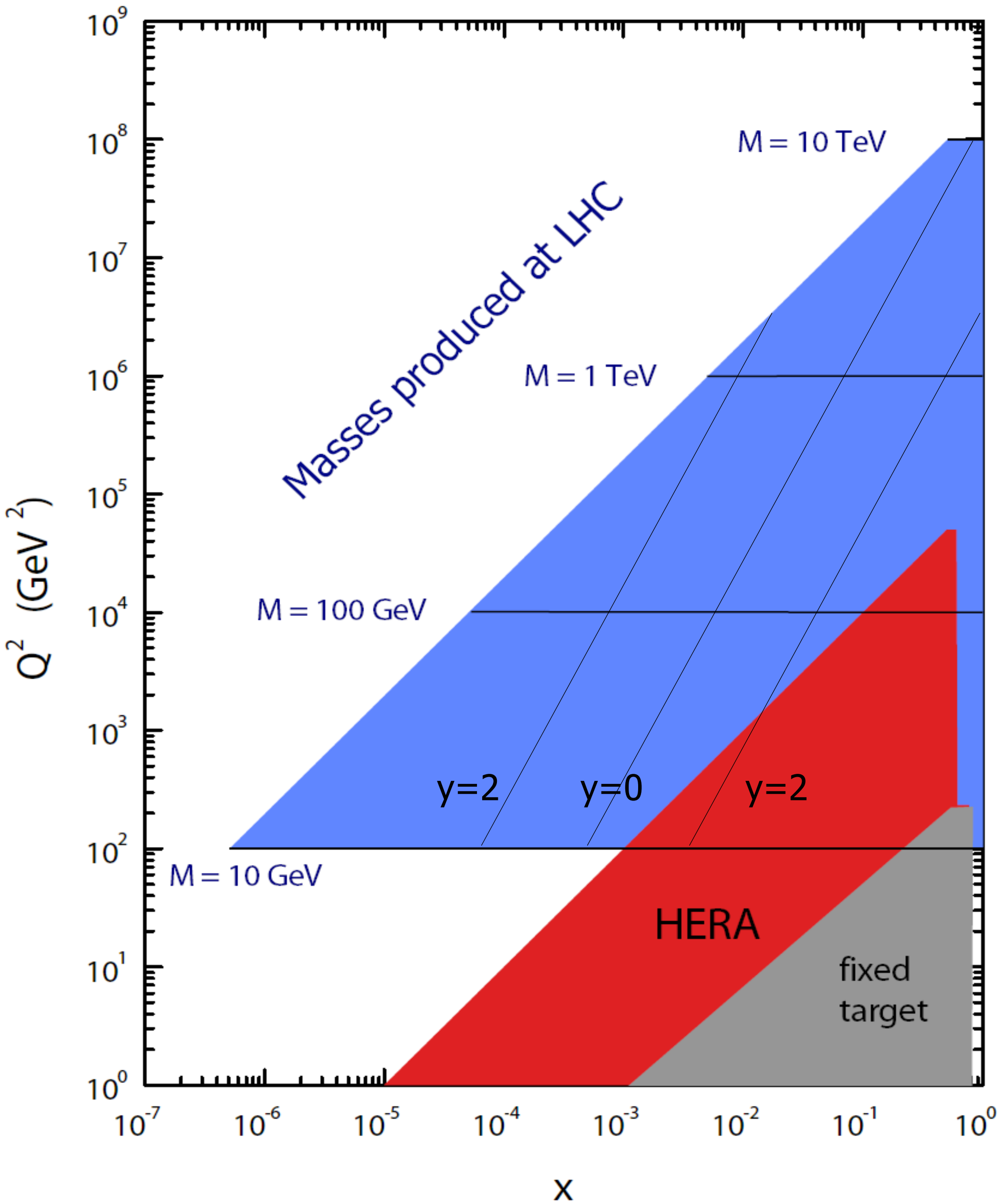


In charged lepton DIS F_2 is dominant piece of total scattering cross section

Contributes across all phase space

F_L only at high y
lepton loses substantial fraction of beam energy - see previous HERA talk (Sasha)

At the EW scale xF_3 plays increasing role
Influence of Z^0 exchange



LHC: largest mass states at large x

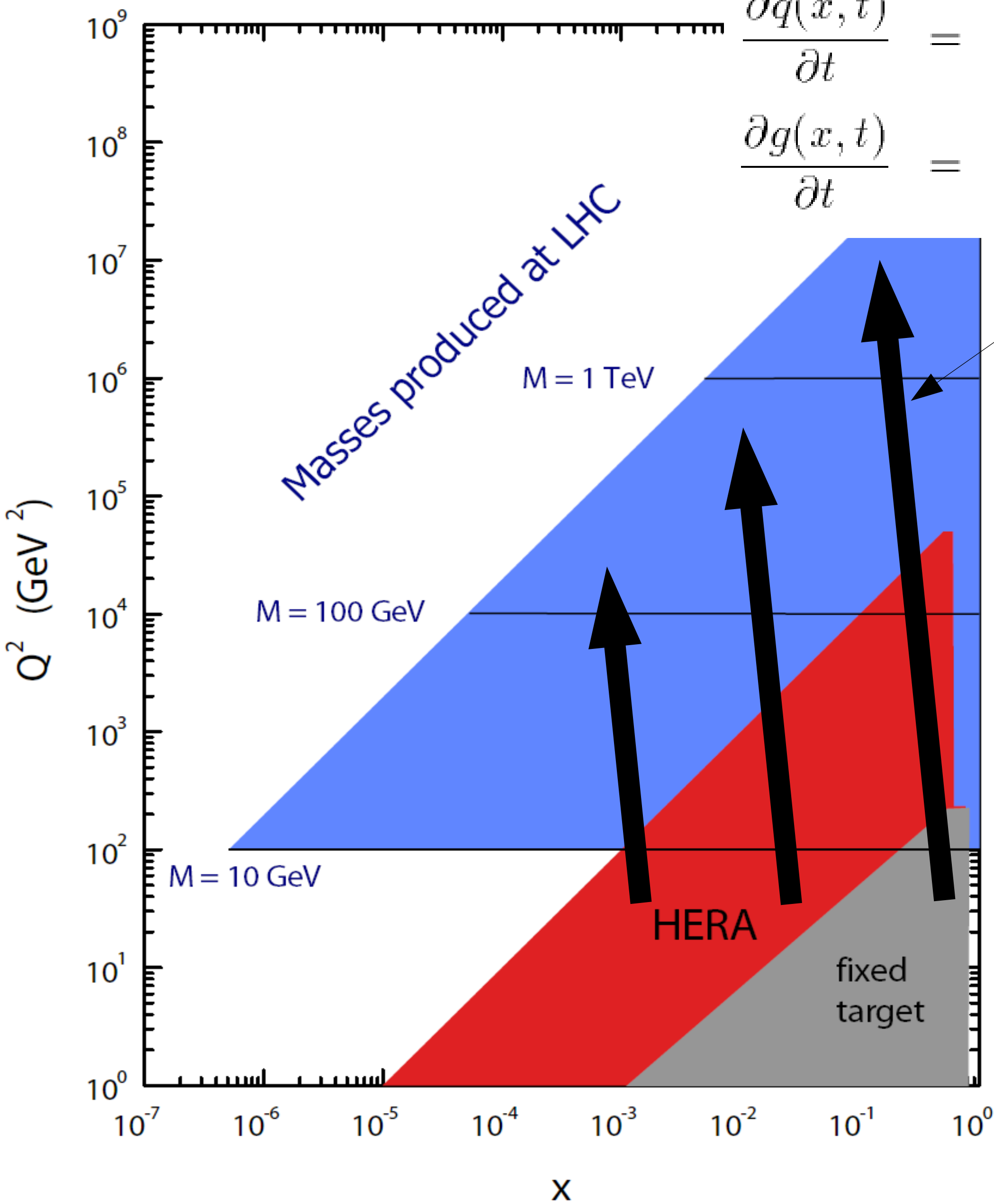
For central production $M=x\sqrt{s}$
$x=x_1=x_2$ i.e. M > 2 TeV probes x>0.1

Searches for high mass states require precision knowledge at high x

Black holes/susy searches...

DGLAP evolution allows predictions to be made

High x predictions rely on
- data (DIS fixed target)
- sum rules
- behaviour of PDFs as $x \to 1$



$$\frac{\partial q(x,t)}{\partial t} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y}\left[q(y,t)P_{qq}(\frac{x}{y}) + g(y,t)P_{qg}(\frac{x}{y})\right]$$

$$\frac{\partial g(x,t)}{\partial t} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y}\left[q(y,t)P_{gq}(\frac{x}{y}) + g(y,t)P_{gg}(\frac{x}{y})\right]$$

$$t = \ln(Q^2)/\Lambda_{\mathrm{QCD}}$$

DGLAP evolution allows predictions to be made

Splitting functions P_{qq}, P_{gg}, P_{gq}

Describe probability of QCD emission
i.e. high x $\rightarrow$ lower x

x dependance is unknown
Q^2 behaviour is predicted!

Thus: measure x dependance

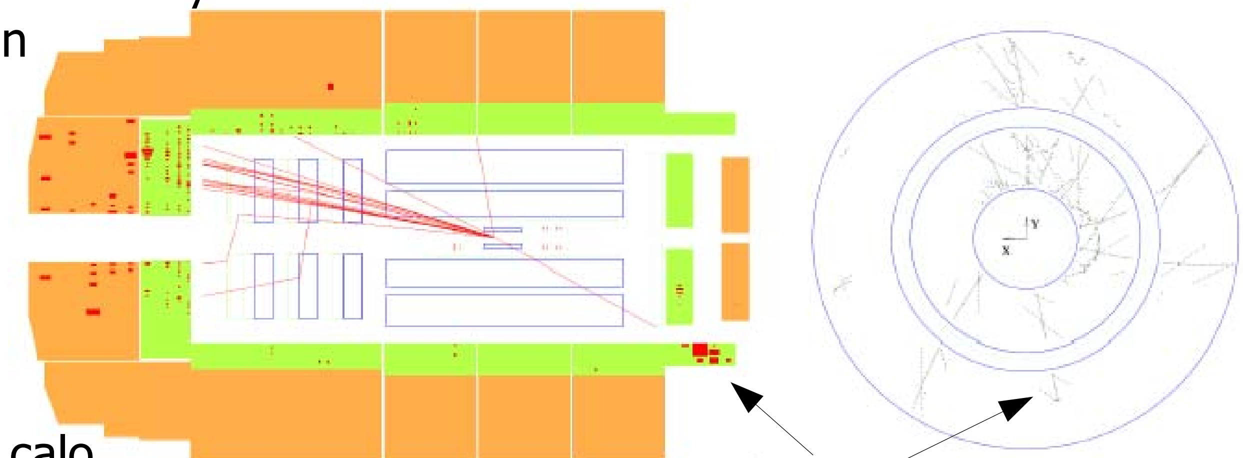
Measurement of NC and CC processes have different requirements

- CC process only provides a handle via HFS / missing P_T
- NC process is balanced in P_T between lepton & HFS - overconstrained

At HERA - scattered electron/positron easily identified

- compact EM energy deposition

typical NC event at H1



electron

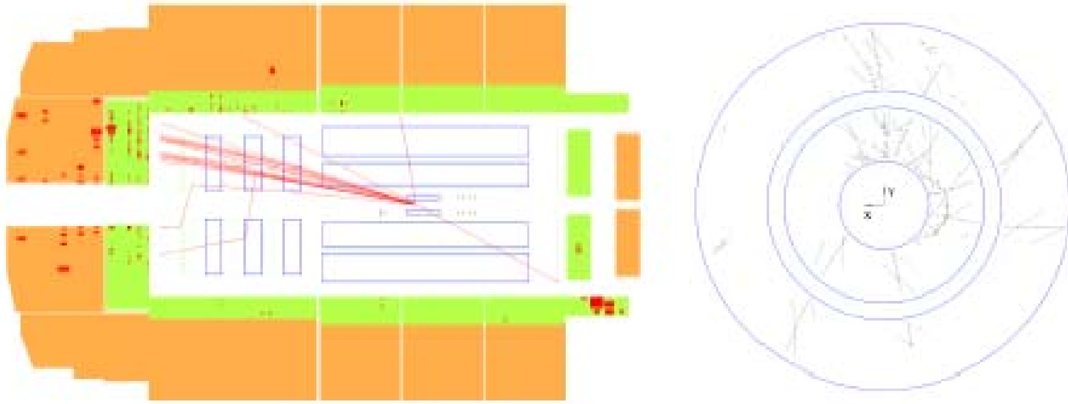
Hadronic environments are difficult:

- specially missing E_T - sum E whole calo
- discriminate many smaller energy depositions across wide region
- noise & b/g might be causes for concern

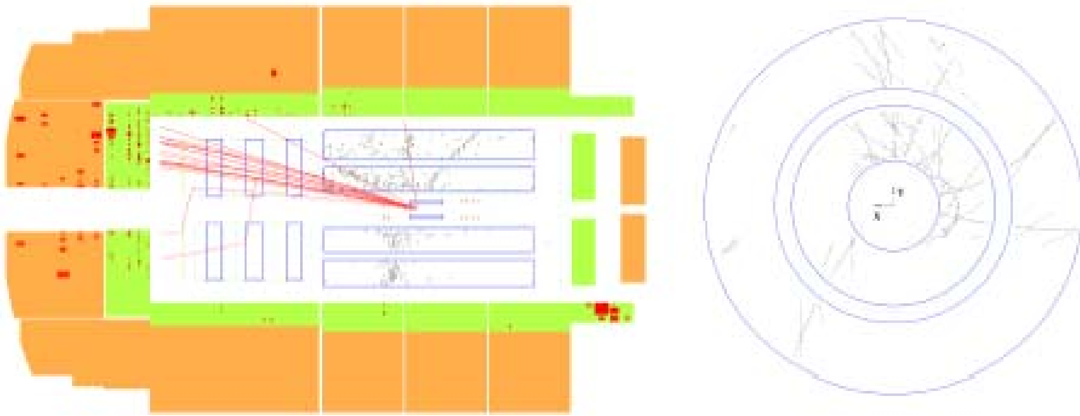
Technique to understand these better: Pseudo-data (i.e. <u>not</u> monte carlo!)

manipulate NC data to mimic CC - i.e. remove all electron information from event

- remove EM energy in cluster
- remove associated track
- remove associated hits in tracker

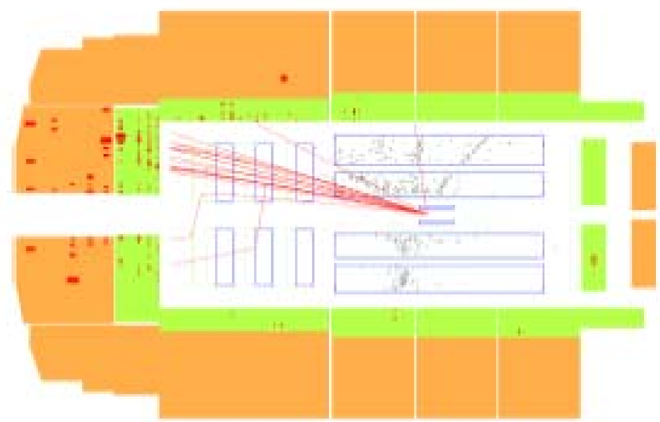


← original NC event
(357160 2469)

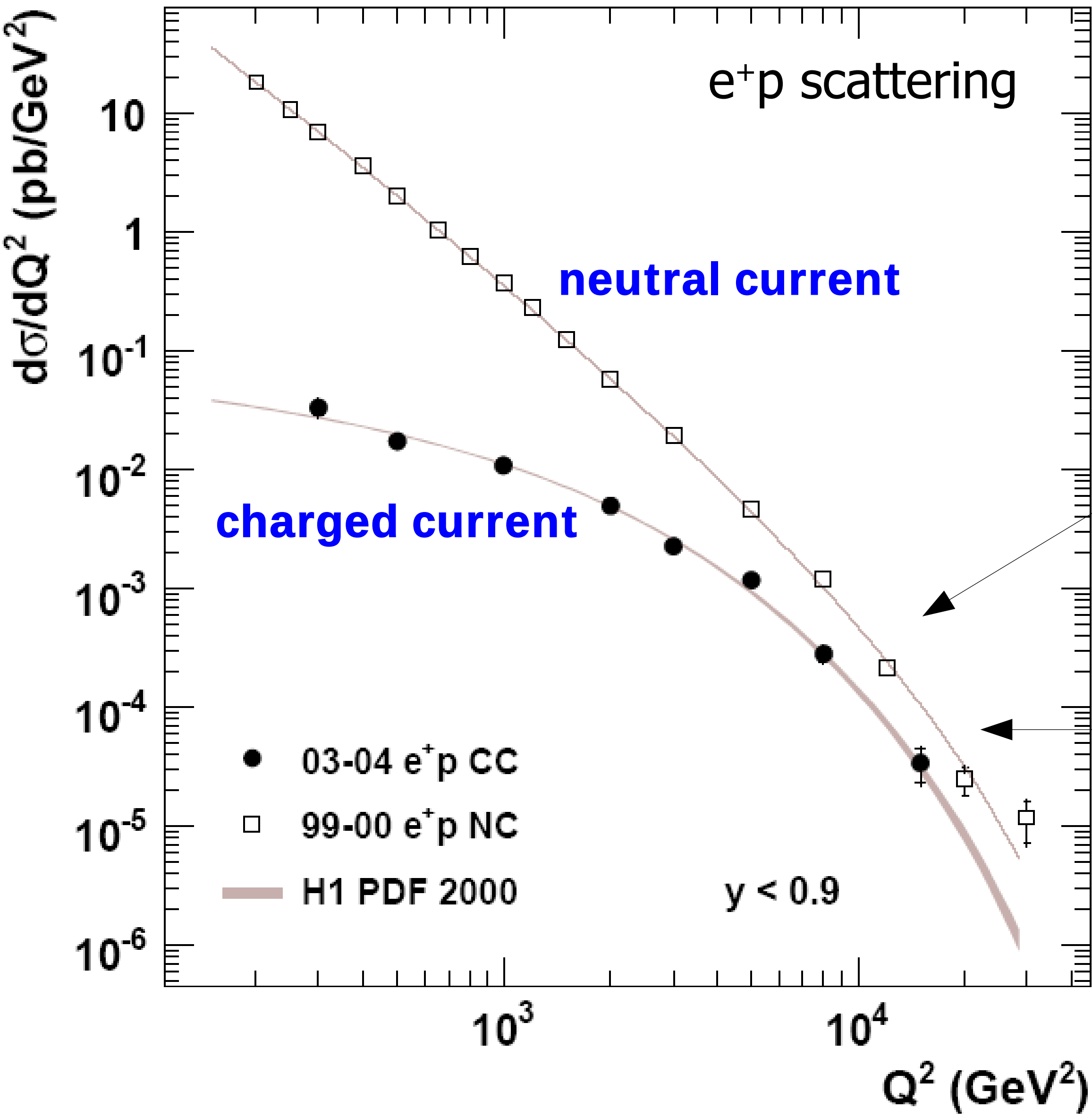


← after e hit removal
and reprocessing

after pscc simulation →



Same technique can be used at LHC
for W→ lν and Z → $l^+ l^-$
Powerful cross check of analyses - independent of MC!



NC process dominates at low Q^2
single photon exchange

The EW regime
$Q^2 \sim M^2_{Z,W}$
Weak propagators visible

difference in precision of predictions at high Q^2 / x

similar (not identical) picture for electron scattering

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

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

$$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$$

F_2 couples to charge^2 weighted singlet quark distribution

Thus provides info on sea quarks for x below ~ 0.01

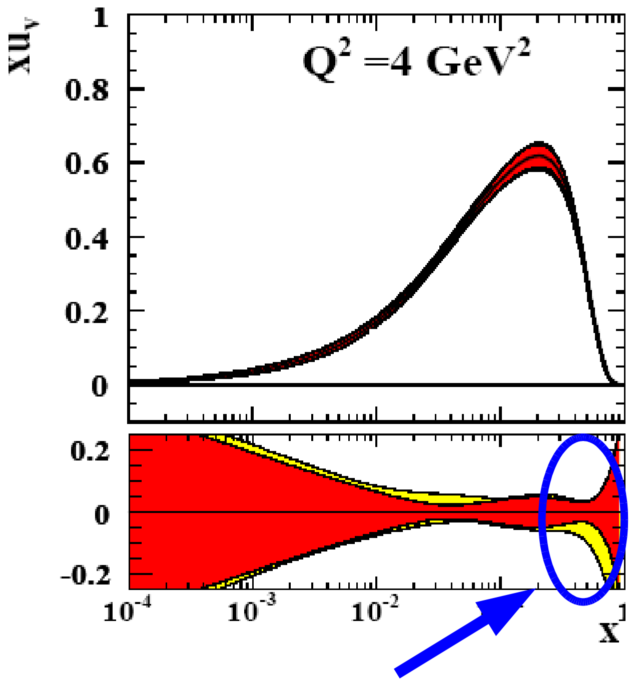
And u density for x > 0.1

$q_u^2 = 4/9$

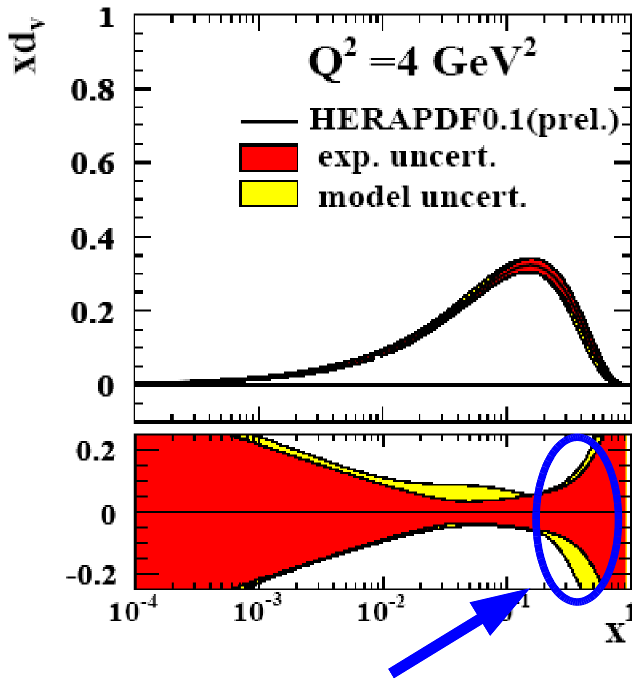
$q_d^2 = 1/9$

F_2 provides limited flavour separation

⇒ d valence is weakly constrained



δ ~ 7% at x=0.3



δ ~ 15% at x=0.3

xF_3 provides additional info

Limited to high x!

Problem: only measured for $Q^2 > 1000\ GeV^2$ (at HERA)

NC cross section ~ 10^4 smaller than at $Q^2 \sim 10\ GeV^2$

⇒ xF_3 is statistically limited

At high Q^2 we use CC process to provide flavour separation info

$$W_2^+ \propto \sum (xD + x\bar{U}) \qquad W_2^- \propto \sum (xU + x\bar{D})$$

$$xW_3^+ \propto \sum (xD - x\bar{U}) \qquad xW_3^- \propto \sum (xU - x\bar{D})$$

$$W_L \propto \alpha_s \cdot xg(x, Q^2)$$

only sensitive at high y

$$\begin{aligned} xU &= x(u+c) \\ x\bar{U} &= x(\bar{u}+\bar{c}) \\ xD &= x(d+s) \\ x\bar{D} &= x(\bar{d}+\bar{s}) \end{aligned}$$

For purely weak CC interaction
xW_3 contributes over full phase space

At HERA CC data limited to ~ $Q^2 > 200$ GeV^2
Limit arises from trigger constraint: $Q^2 \approx P_T^2$ for inclusive hadronic final state (HFS)

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

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

$P_e = -1$ $\qquad$ $P_e = +1$

At high Q^2 we use CC process to provide flavour separation info

fixed target experiments provide data at lower CMS energies
Flavour separation achieved using:

- neutrino beams
- deuteron target (n+p) & using strong isospin symmetry
- i.e. neutron PDFs $u_v = d_v$ for proton & vice versa

Problems:

- Low CMS energy $\Rightarrow$ lower Q^2 in non-perturbative region
- Need to account for models of deuteron binding
- Different models have ~7% difference at high x
- Target mass effects at high x when $Q^2 \sim M^2$
- Nuclear correction for Iron targets in neutrino scattering

Advantage:

- High luminosity possible (higher target denisties)

HERA data are largely free of these issues

The über DIS dataset

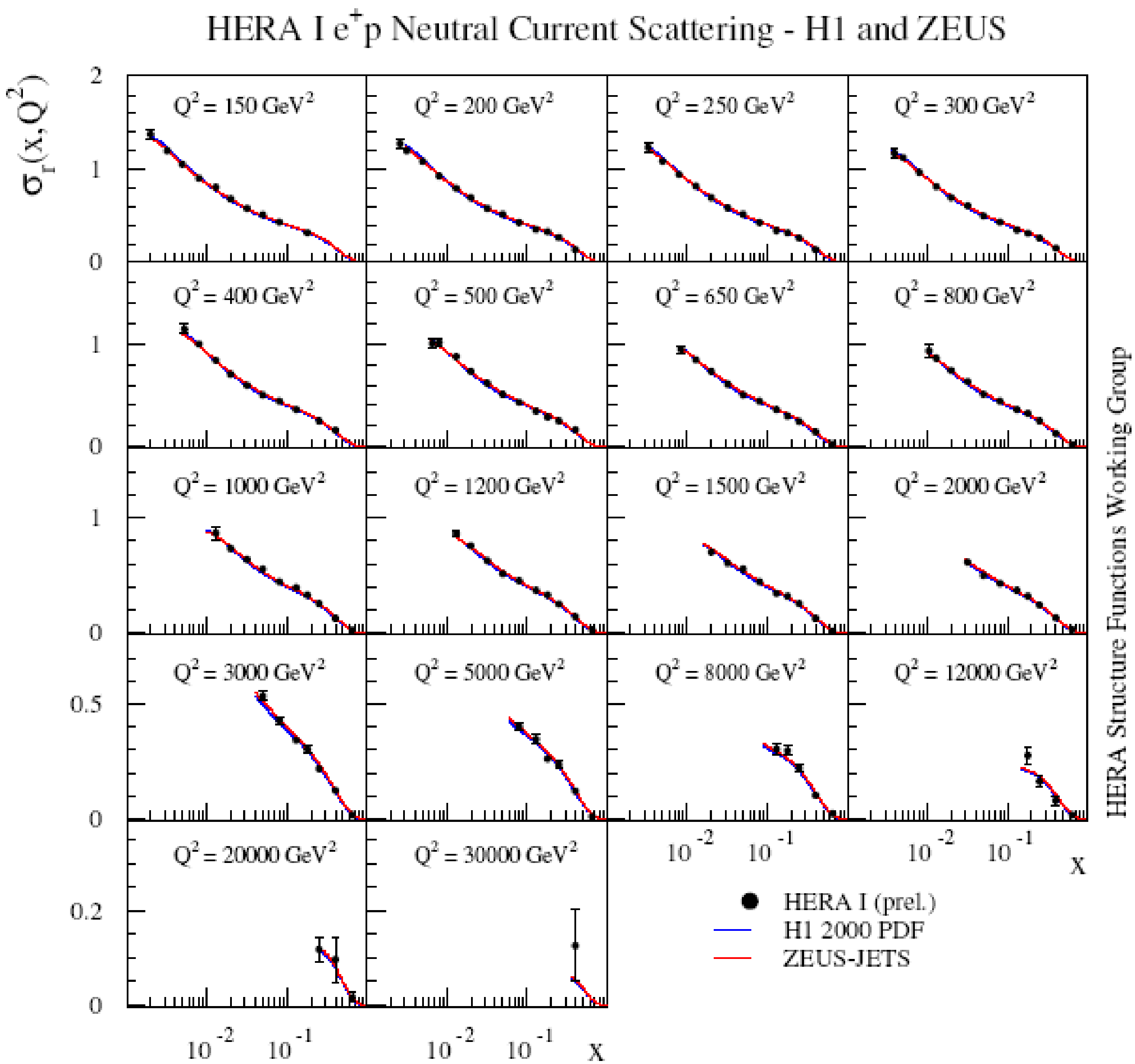
For low Q^2 H1 / Zeus data systematically dominated
For high Q^2 H1 / Zeus data statistically limited

Combination of the measurements yields improvements across all Q^2 !

Assume only that H1 & Zeus measure the same cross section
Average data taking care with systematic errors
Allows H1 $\Leftrightarrow$ Zeus cross calibration
Achieve dramatic improvements in some sys errors

At high Q^2 trivial gain in $\sqrt{2}$ statistical precision

Can simultaneously combine NC & CC measurements for
all datasets / lepton charges / polarisations

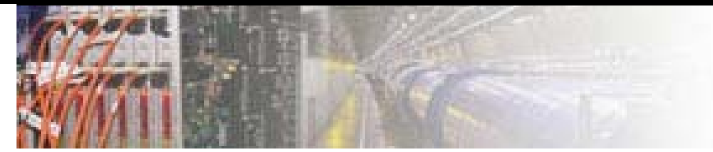


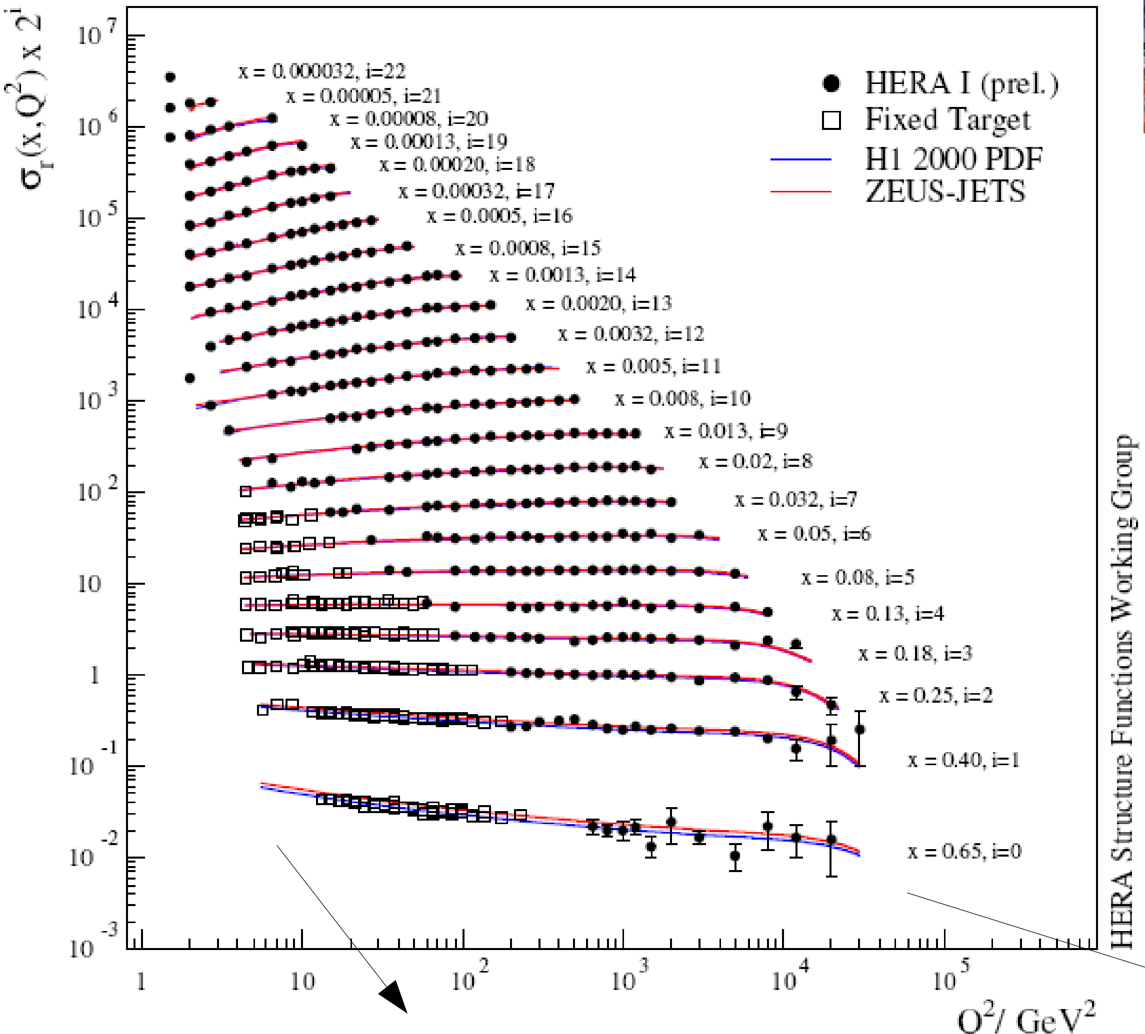
combined H1 / Zeus data achieve a precision ~2% at $Q^2 \sim 100\text{-}500\ GeV^2$

Even better for $Q^2 < 60\ GeV^2$

At high $Q^2 > 5000\ GeV^2$ data are statistically limited

Hera-I data only

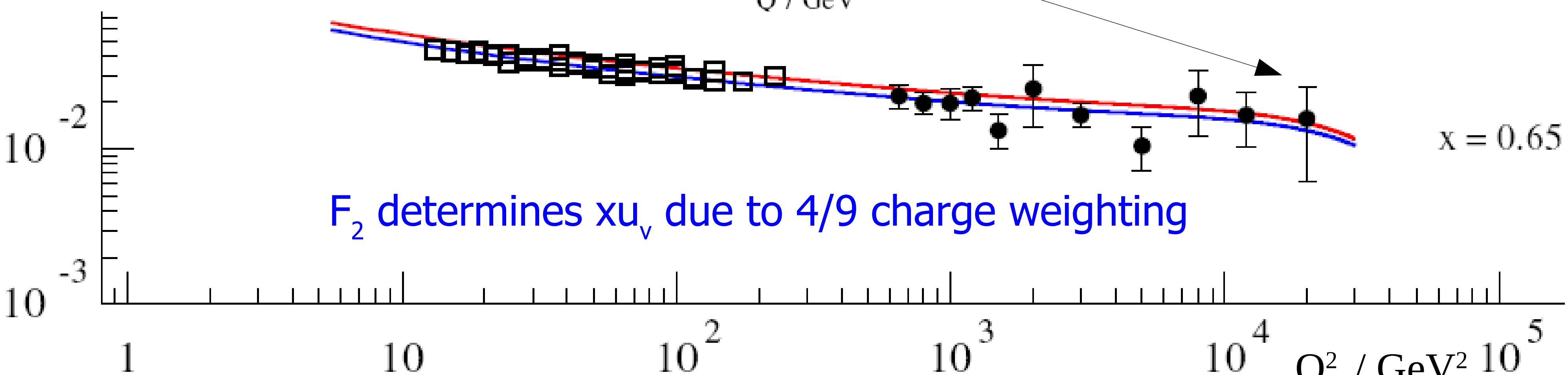




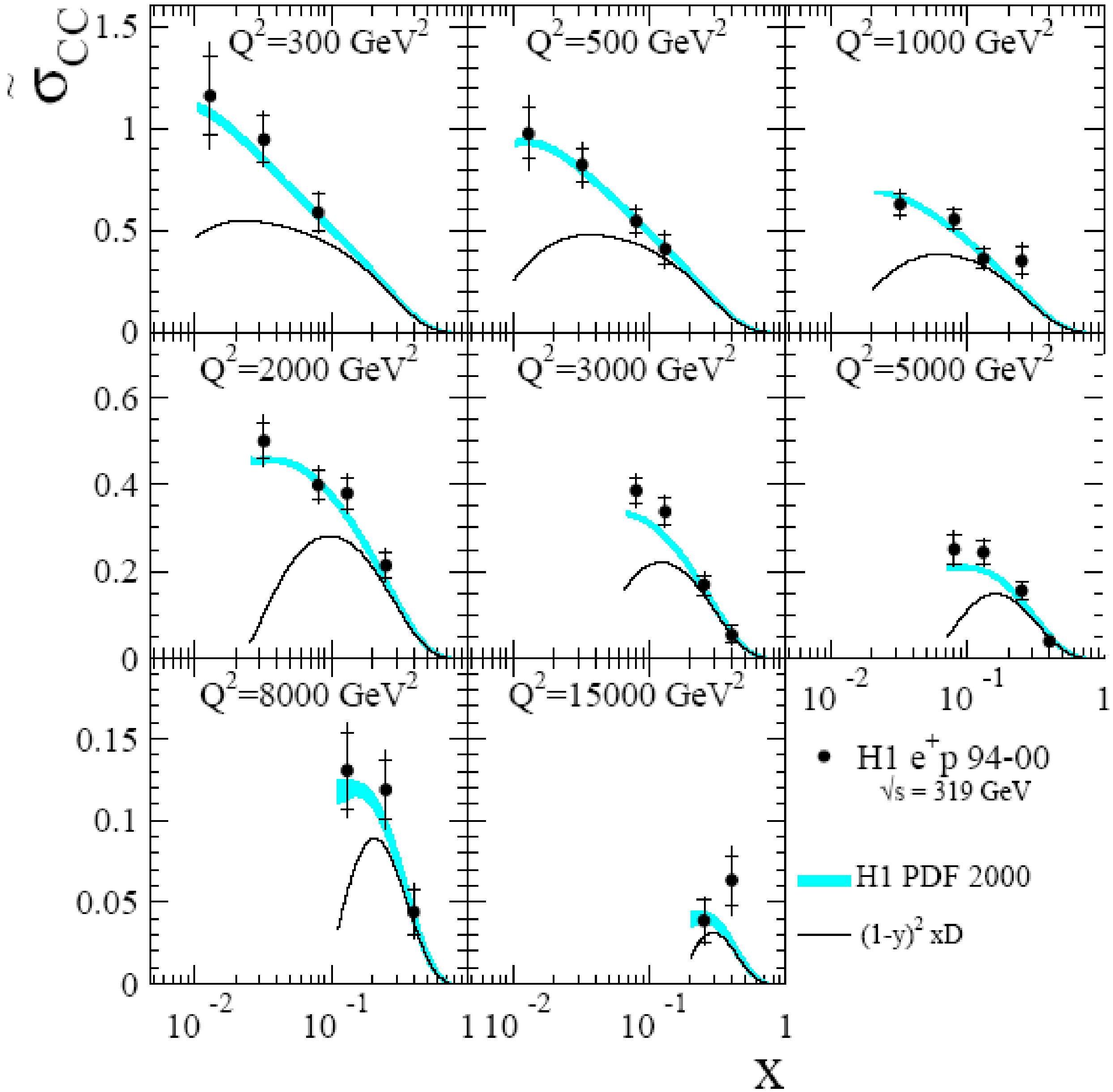
~230 pb^{-1}
Another 600 pb^{-1} to be added split for

- 2 experiments
- 2 lepton charges
- 2 polarisation

At highest x=0.65 we compare to precision fixed target μp DIS data from BCDMS



F_2 determines xu_v due to 4/9 charge weighting

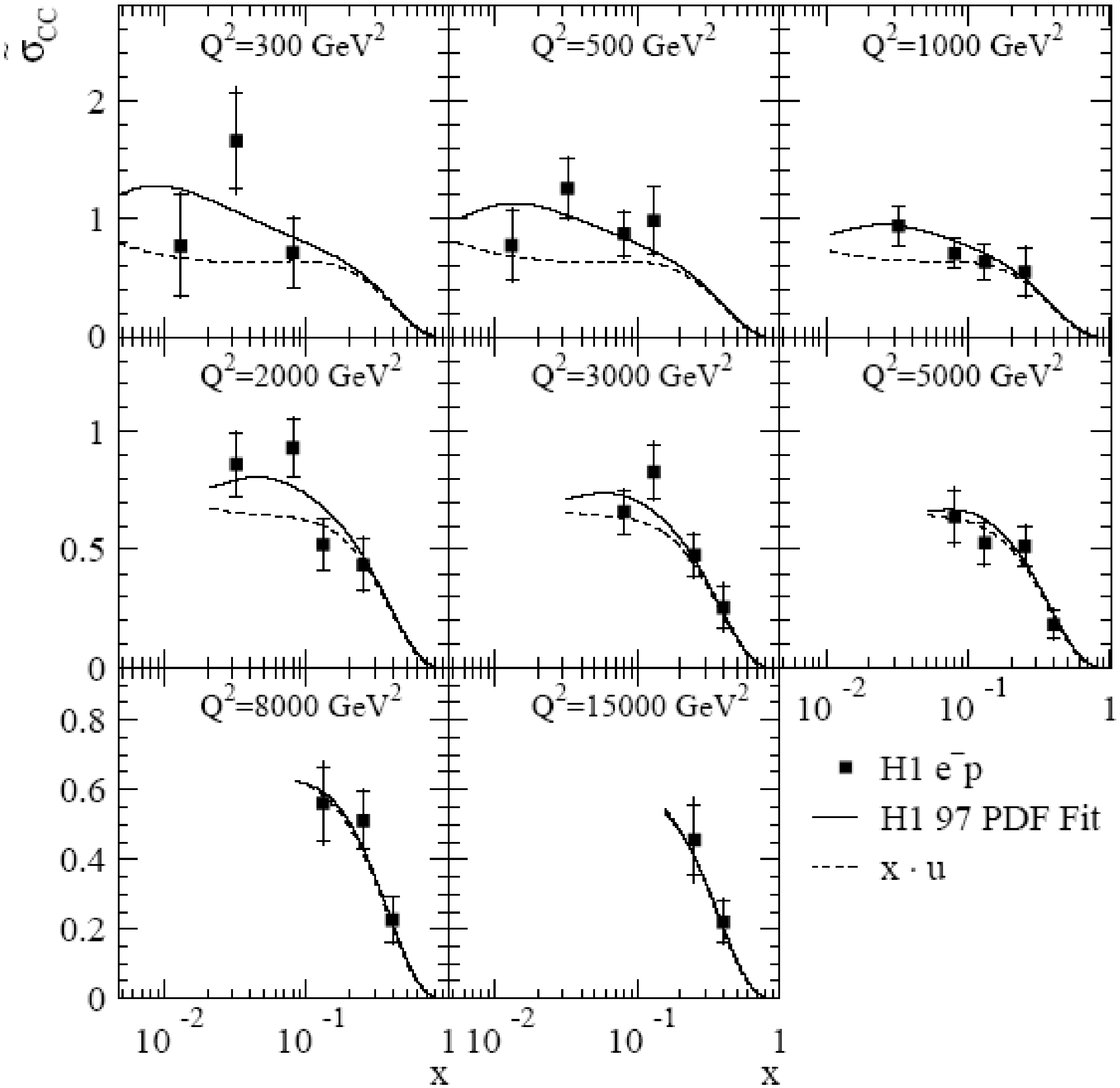


e^+p CC data from H1 ~ 100 pb^{-1}

Solid line = xd + xs + xb quarks coupling to W^+

At x ~ 0.1 xd_v dominates

Thus CC e^+p data delivers access to the valence d



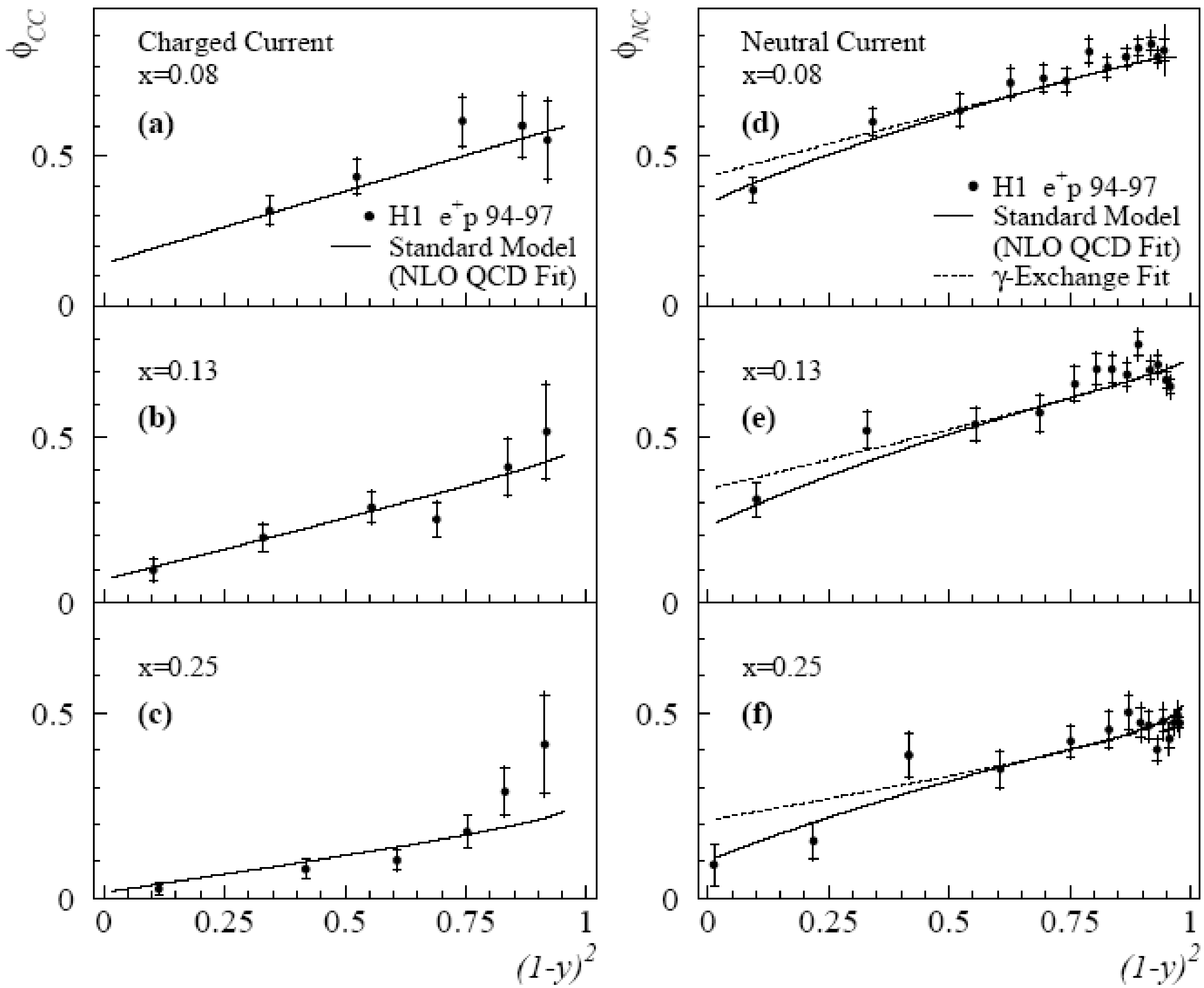
H1 e^-p CC data ~ 16 pb^{-1}

Solid line = xu

At x ~ 0.1 xu_v dominates

Thus CC e^+p accesses xu

Complementary to NC process



Can check helicity structure

For e^+p

$$\sigma_{CC} \approx x(\bar{u}+\bar{c}) + (1-y)^2(d+s)$$

$$y = 1 - \cos^2\left(\frac{\theta^*}{2}\right)$$

Isotropic anti-quarks comp.

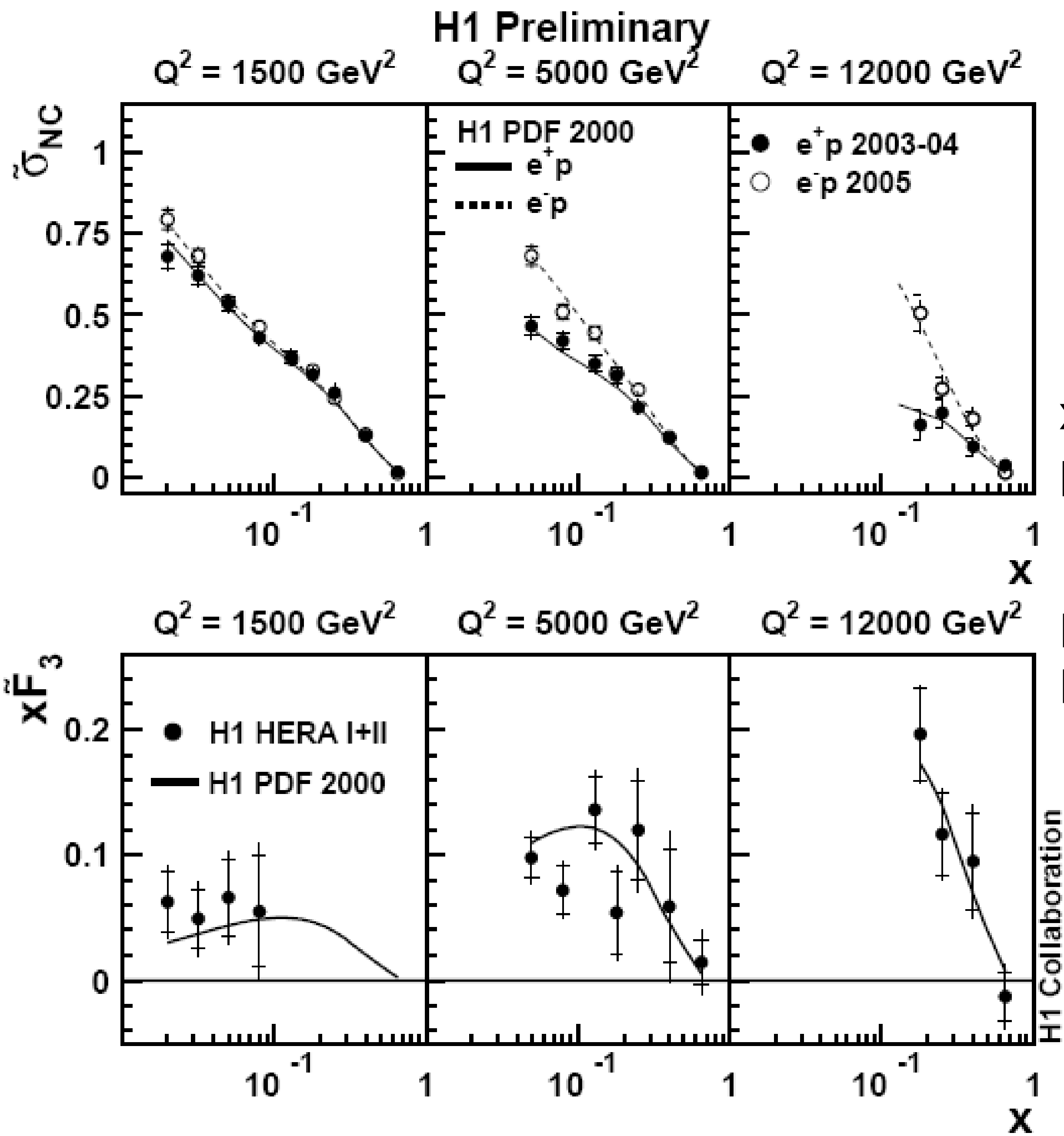
Linear quark component

Less anti-quarks at high x

Similar effect in NC

smaller in magnitude

F_2 insensitive to difference between quarks & anti-quarks

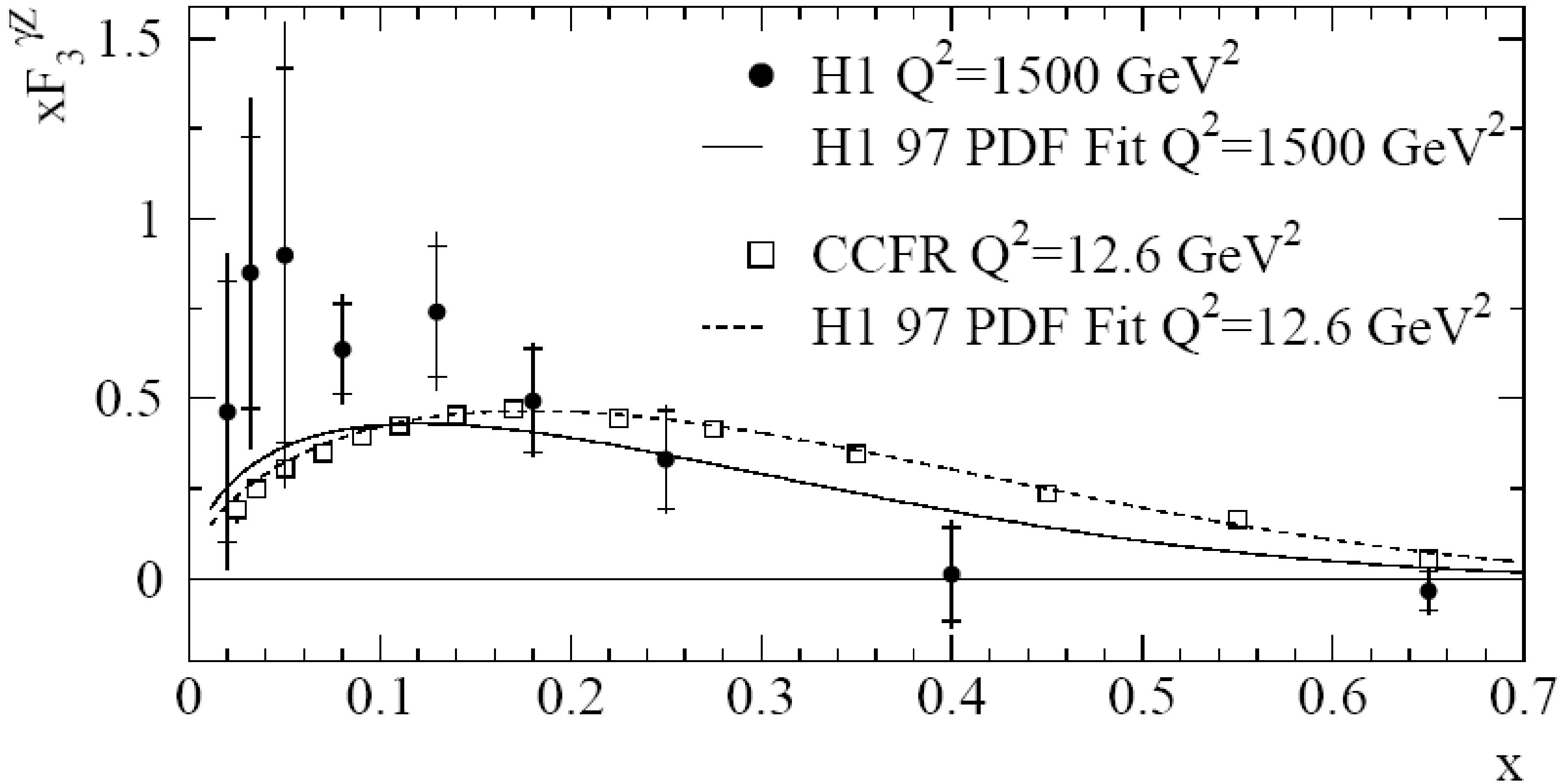


$$x\tilde{F}_3 \propto \sum (xq_i - x\overline{q}_i)$$

$$= ux_v + xd_v$$

xF_3 is measured as the difference between e^+p and e^-p NC scattering

Difference increases with Q^2
But cross sections fall rapidly too...



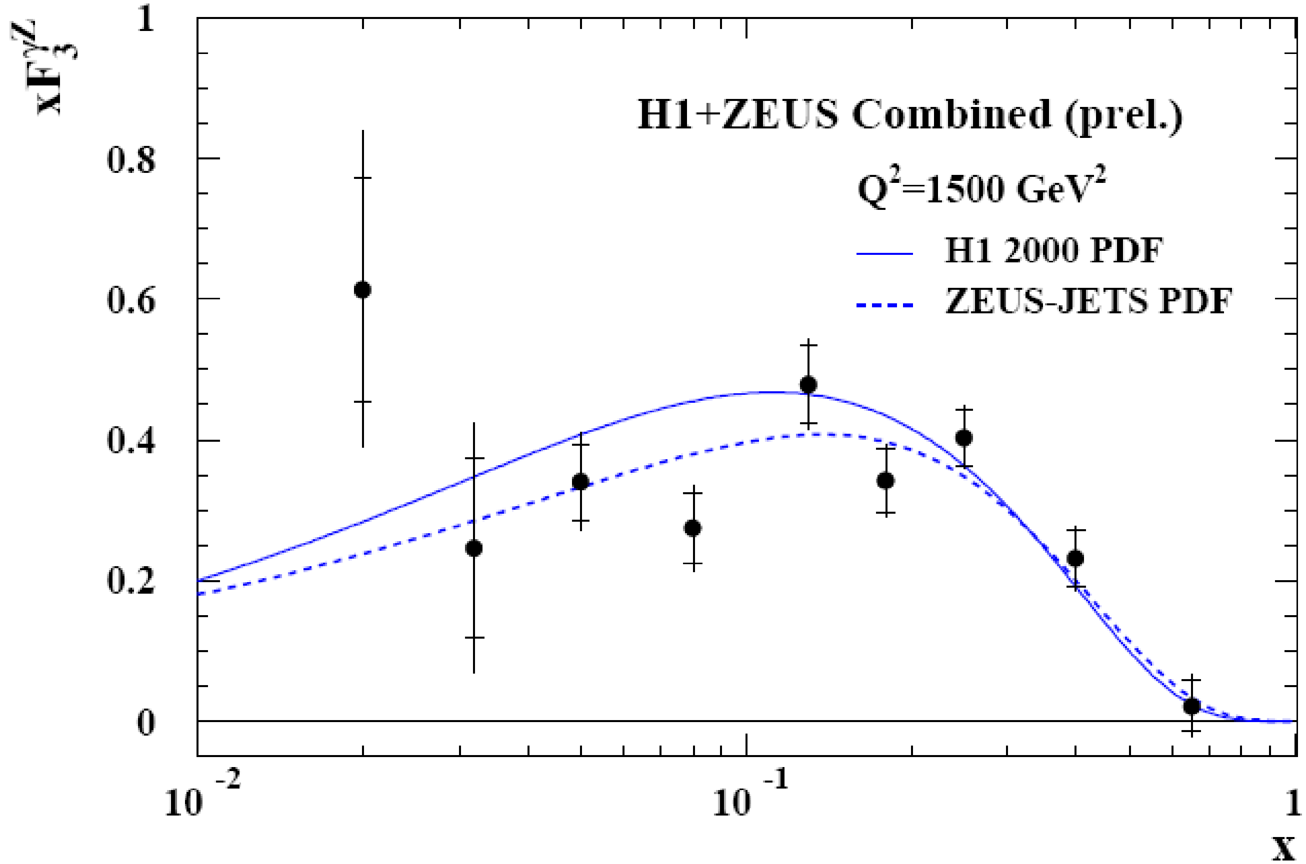
Comparison of older H1 measurement with neutrino fixed target data

H1 measurement uses ~ 50 pb^{-1} luminosity

Combined HERA data will have ~600 pb^{-1} luminosity

Reduction in errors by factor ~ 3

HERA data free of issues regarding Iron target etc...



- Large luminosity of HERA-II sample allows improved xF_3 measurement
- Combine L & R handed datasets
- Precision further improved by combining H1 & ZEUS data
- Measurement statistically limited

An alternative approach to extracting PDFs - simple cross check

take data in region where one flavour dominates (>70% of cross section)

use theory to correct measured cross section to underlying PDFs

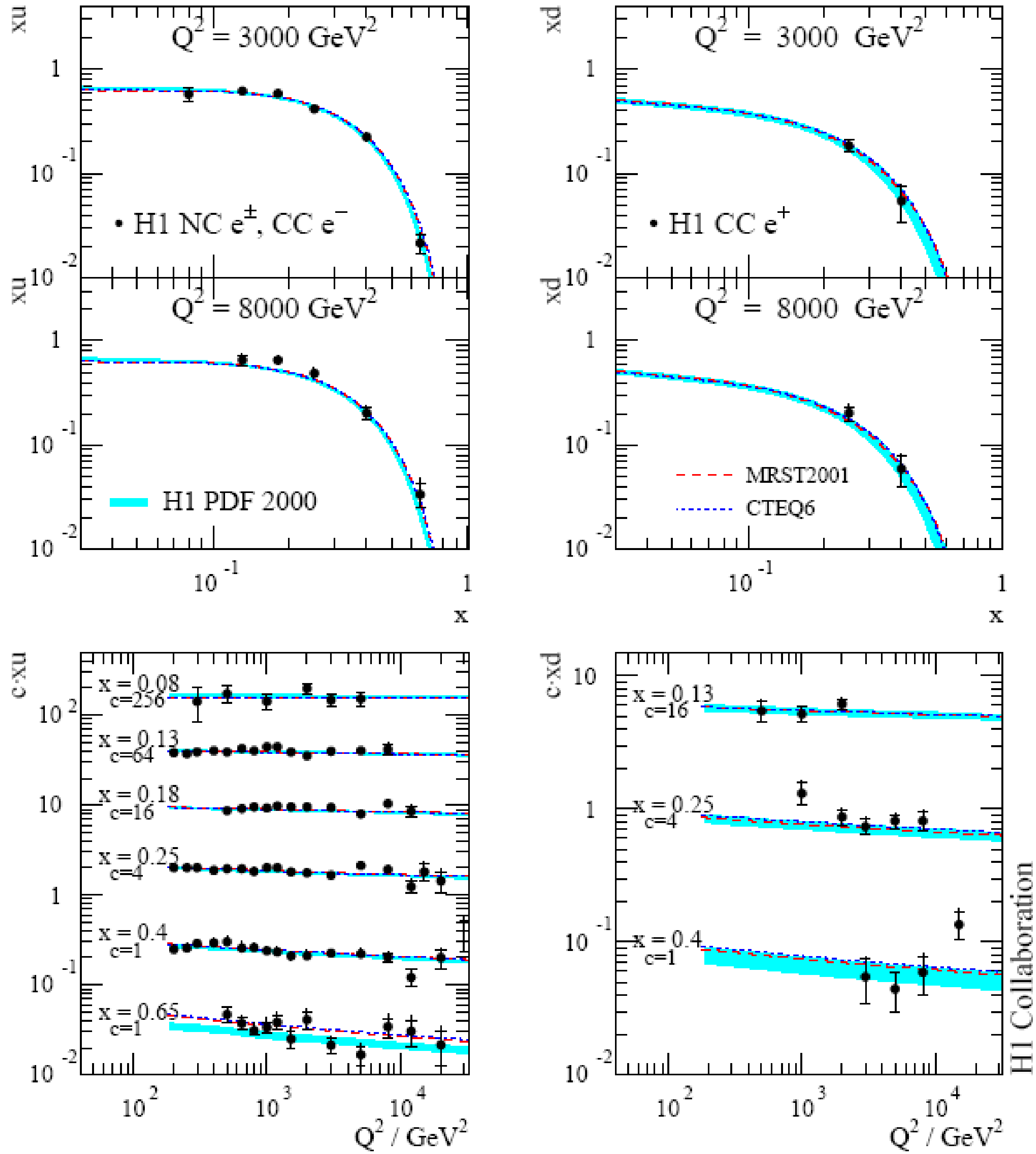
$$xu(x,Q^2) = \sigma_{NC}^{Data}(x,Q^2) \cdot \left[\frac{xu}{\sigma_{NC}}\right]_{Theory} \qquad xd(x,Q^2) = \sigma_{CC}^{Data}(x,Q^2) \cdot \left[\frac{xd}{\sigma_{CC}}\right]_{Theory}$$

Local extraction of PDFs - unlike QCD fit (global extraction)

Assumptions in theory largely cancel in ratio

Robust against large (±50%) variations in theory PDF

Insensitive to data in other regions of phase space



Extraction at high x
$0.08 < x < 0.65$

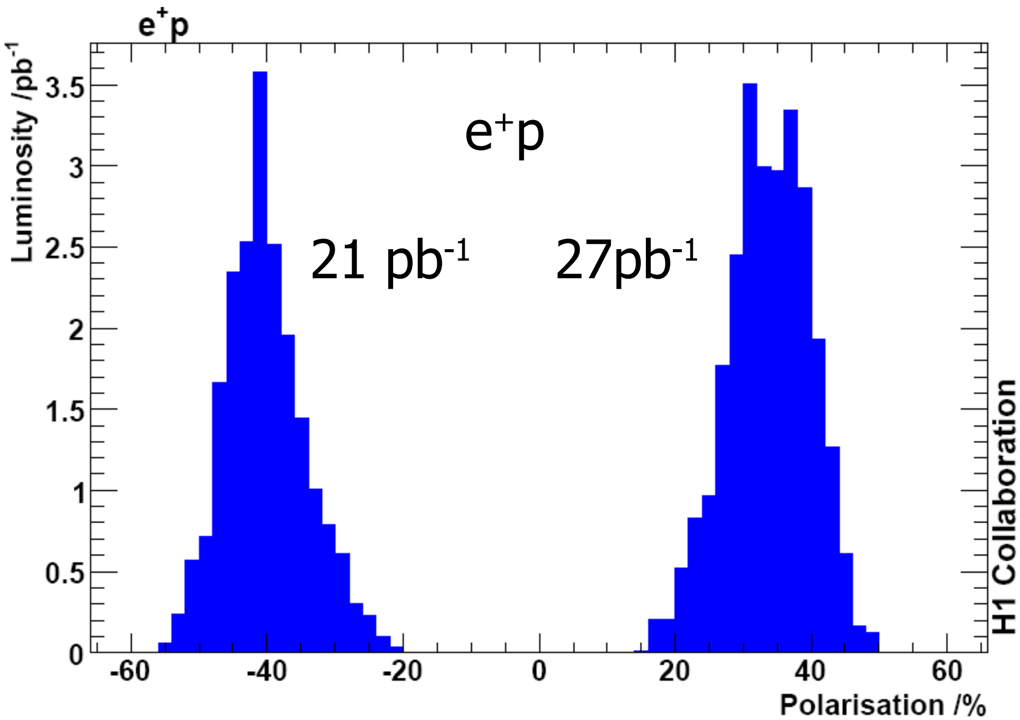
Compares well with
- H1 QCD Fit
- MRST2001
- CTEQ6.1

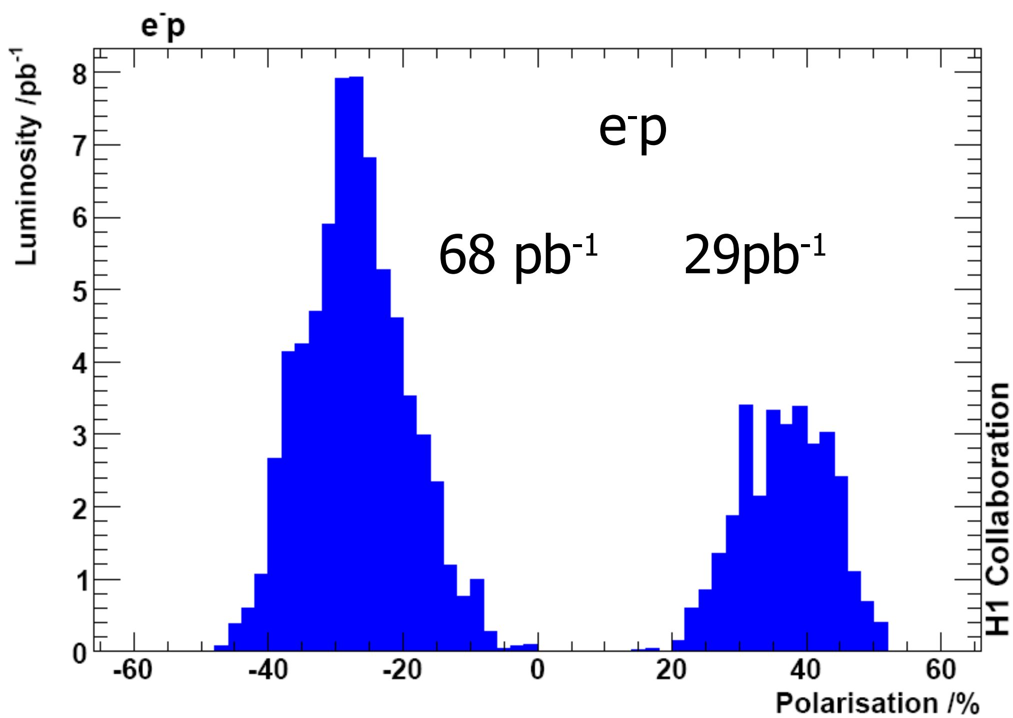
At high Q^2 EW parts of SM play a role in DIS

Z exchange effects become important in NC channel

HERA-II program ran with polarised lepton beams

Luminosity collected for part of HERA-II running period by H1





H1 collected another 125 pb^{-1} in e^+p and 50 pb^{-1} in e^-p

Neutral Current Channel

Effect of polarisation is subtle in neutral current channel

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

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} + (2 v_e a_e \pm P_e (v_e^2 + a_e^2))\chi_z^2 xF_3^Z$$

pure photon — photon/Z^0 interference — pure Z^0

χ_Z ~ Z^0 propagator

To first order: polarisation effects dominated by photon / Z^0 interference terms
pure Z exchange suppressed by additional propagator factor
i.e. $\chi_Z \gg \chi_Z^2$ and $v_e \approx 0.05$ we can neglect pure Z^0 terms

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

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}_{NC}^- - \tilde{\sigma}_{NC}^+) \approx a_e \chi_Z xF_3^{\gamma Z}$$

Neutral Current Channel

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

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} + (2 v_e a_e \pm P_e (v_e^2 + a_e^2))\chi_Z^2 xF_3^Z$$

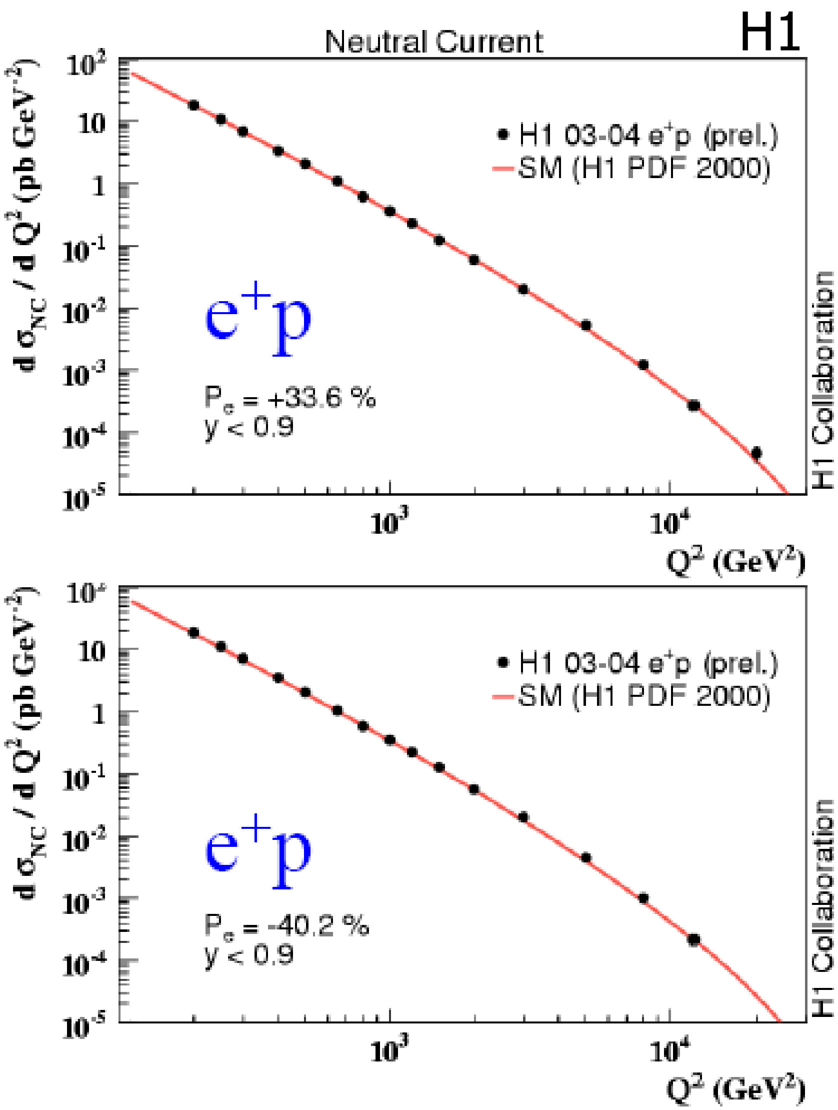
Since $\chi_Z \gg \chi_Z^2$ and $v_e \approx 0.05$ we can neglect pure Z^0 terms

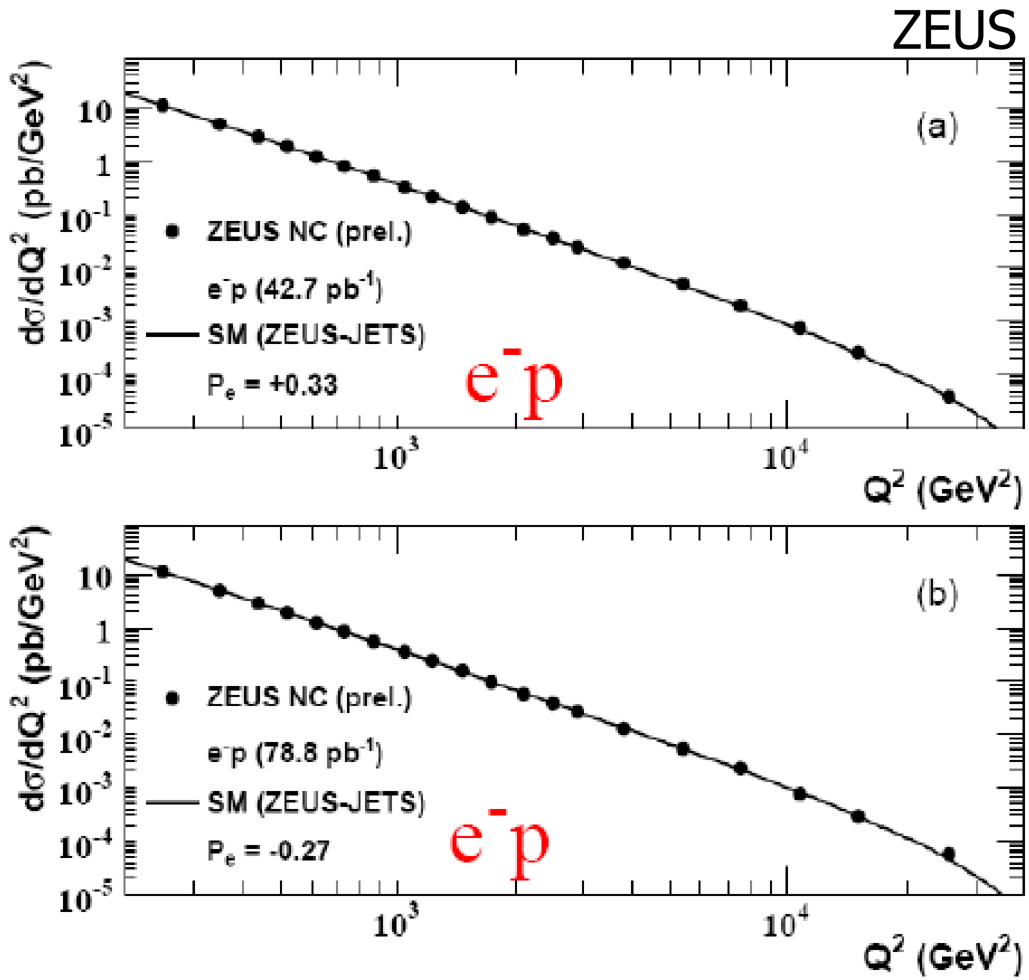
$$\tilde{F}_2^{\gamma Z} = \sum 2 e_i v_i (xq_i + x\overline{q}_i)$$

$$x\tilde{F}_3^{\gamma Z} = \sum 2 e_i a_i (xq_i - x\overline{q}_i)$$

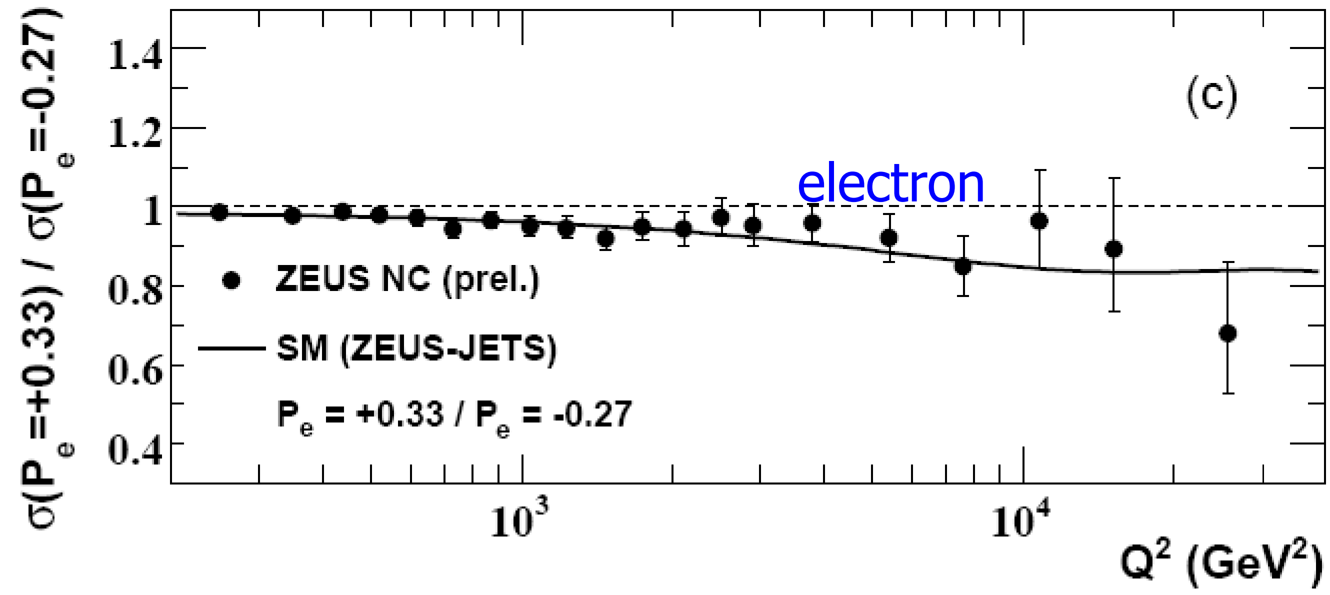
Sensitivity to axial and vector couplings of quarks to Z^0

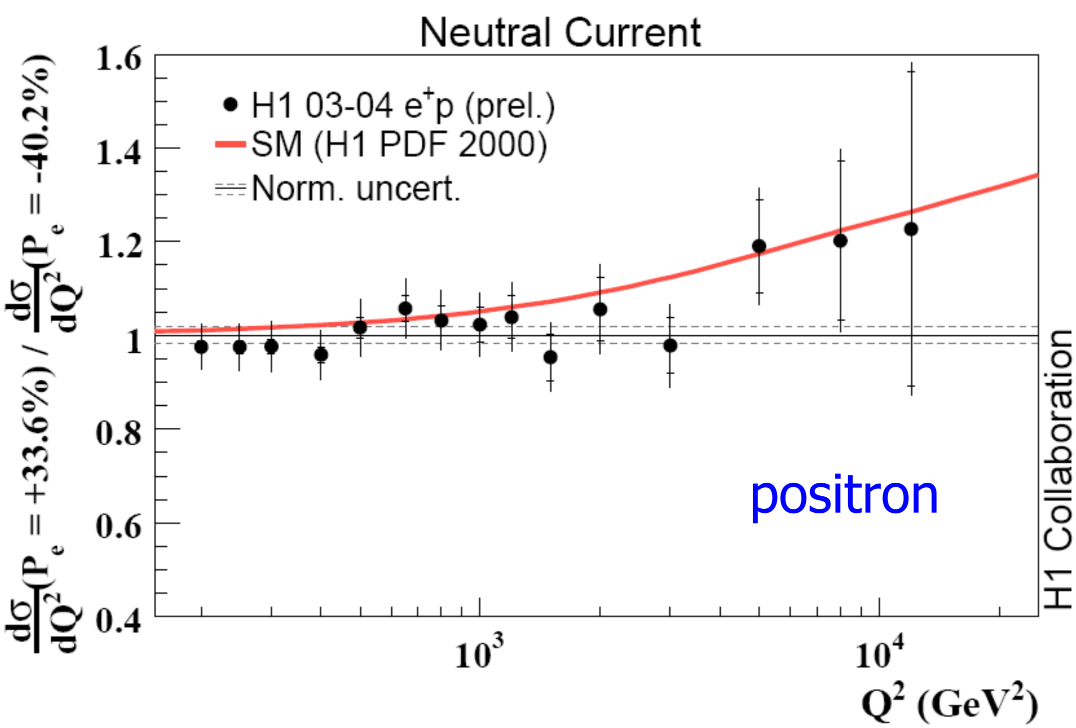
These can be extracted by fits to HERA-I and HERA-II data
Fitting NC and CC data allow simultaneous extraction of PDFs





Both experiments measured positron/electron, left/right cross sections





Measure ratio of NC cross section

$$\frac{d\sigma}{dQ^2} \quad \text{R/L}$$

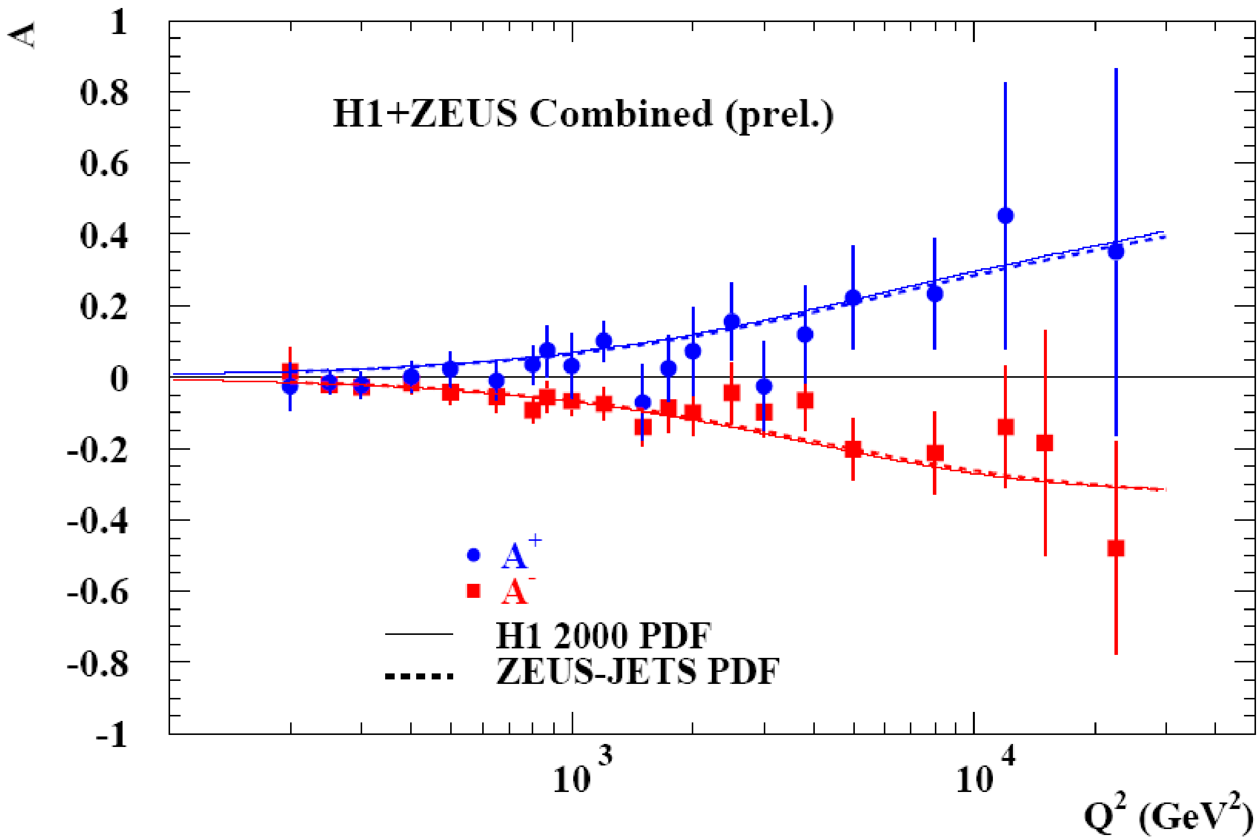
Effect increases with Q^2
As do the statistical uncertainties!

Data consistent with SM

suppression of electron R
enhancement of positron R

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)} \approx \chi_Z a_e \frac{F_2^{\gamma Z}}{F_2} \approx \chi_Z a_e \frac{1 + d/u}{4 + d/u}$$

sensitive to d/u ratio at high x



Subtle effect

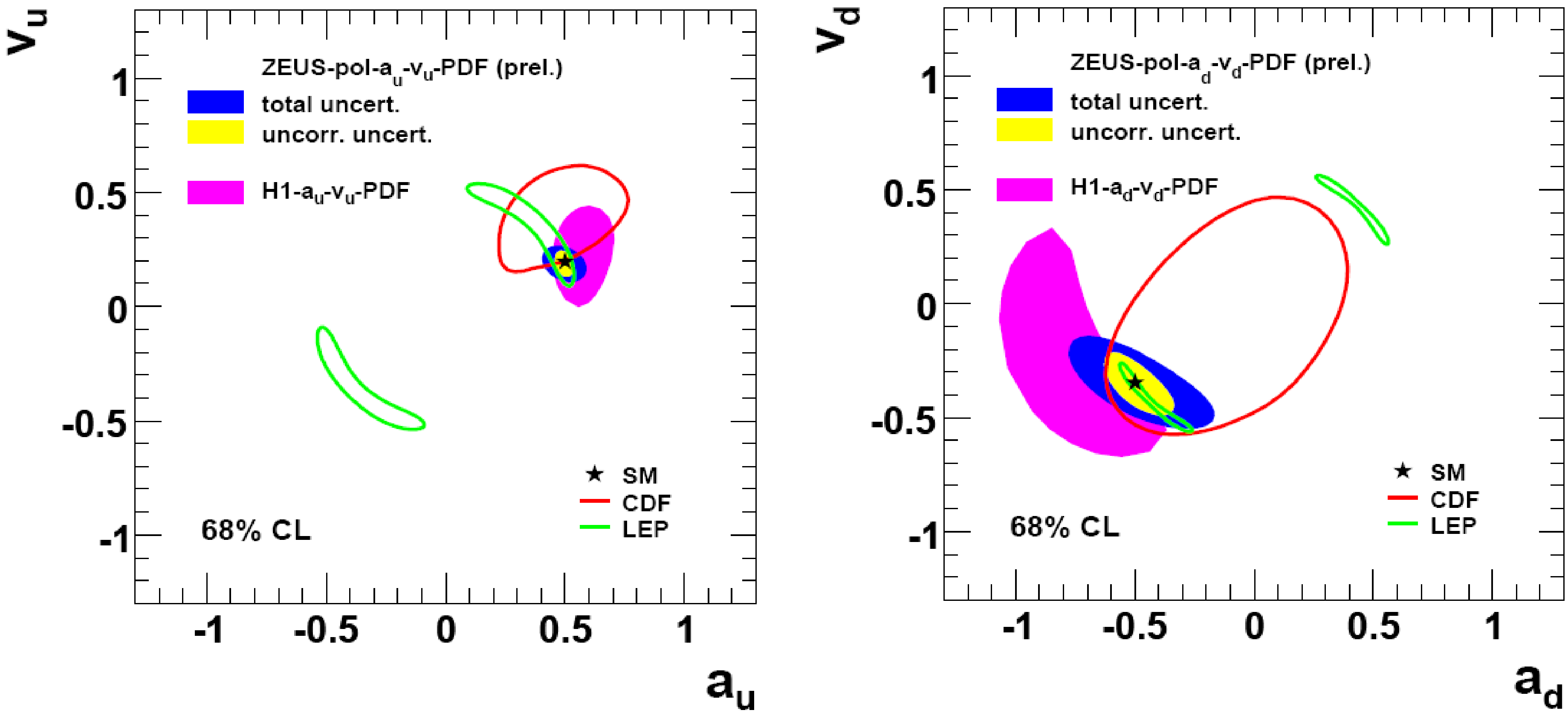
Plot uses ~300 pb^{-1} from H1+Zeus combined

Another 350 pb^{-1} to be analysed

define the difference of positron and electron polarisation asymmetries

$$\delta A = A^{+} - A^{-}$$

χ^2 of δA being different from zero = 4.0 (3.1 x 10^{-3} probability)



Precise PDFs allows precision SM tests: HERA data constrain QCD + EW

Fit to PDFs & up-type axial + vector couplings or

PDFs & down-type axial + vector couplings

Improved on Tevatron precision & removed LEP ambiguity

Charged Current Channel

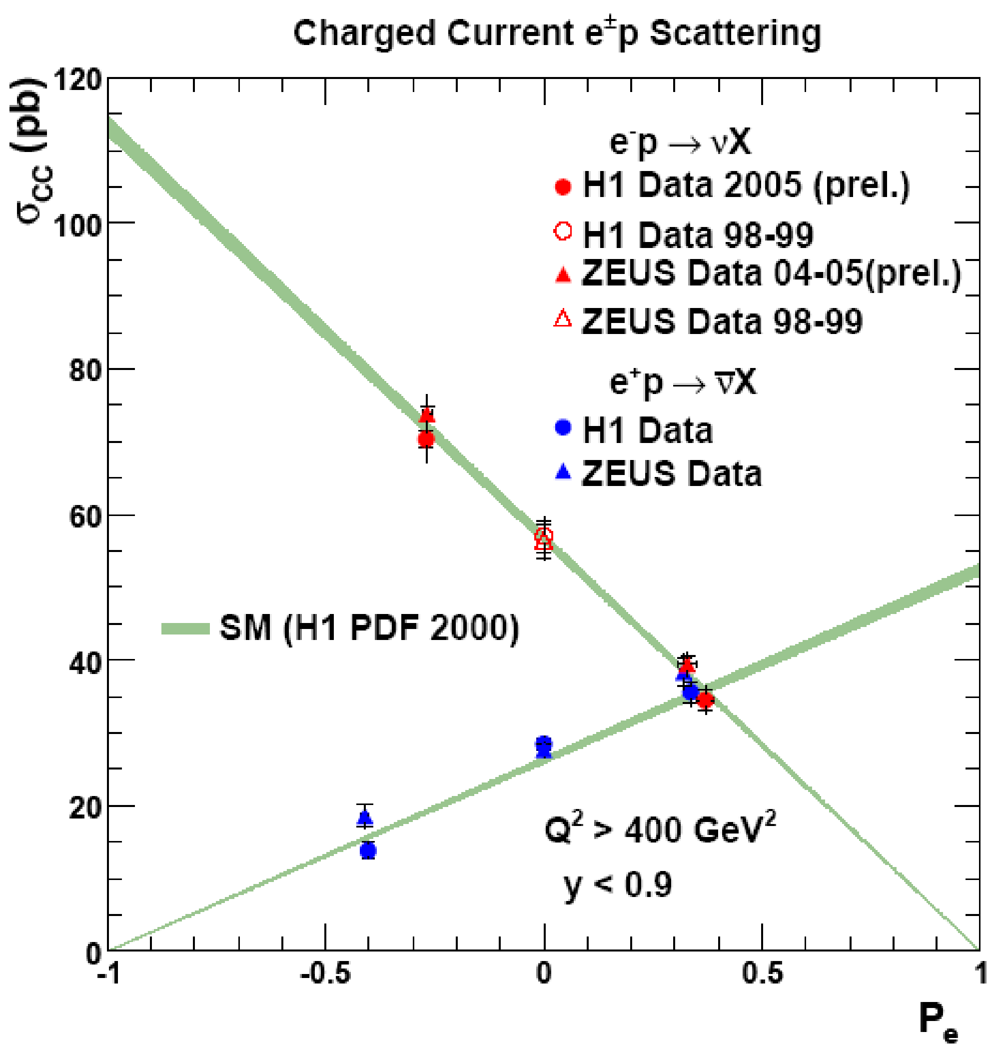
$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} \approx \frac{1 \pm P_e}{2} \frac{g^4}{64\pi x} \left[\frac{1}{M_W^2 + Q^2} \right]^2 \left[Y_+ \tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2 \tilde{W}_L^{\pm} \right]$$

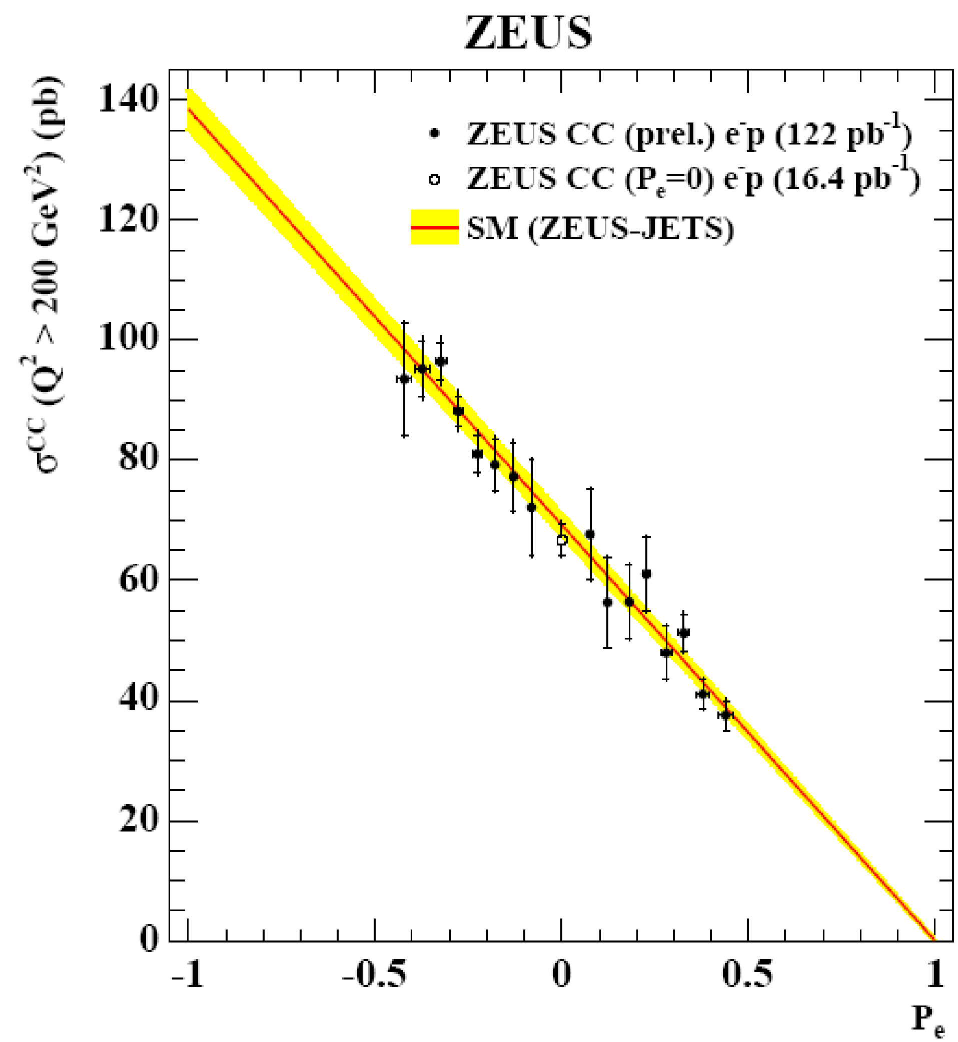
SM predicts CC cross section $\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} \propto \frac{1 \pm P_e}{2}$ linear scaling of cross section zero for LH e^+ or RH e^-

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

Can perform precision SM tests of EW sector of SM

Search for right handed weak currents

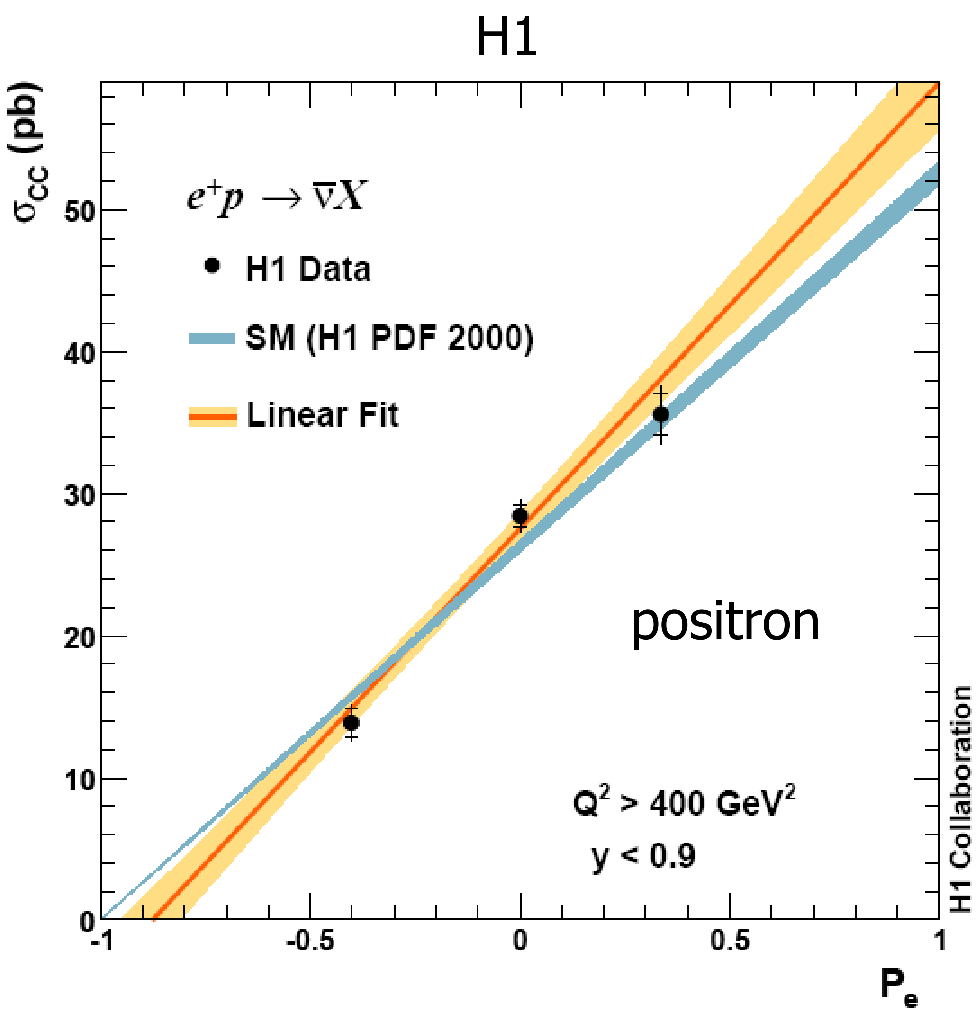


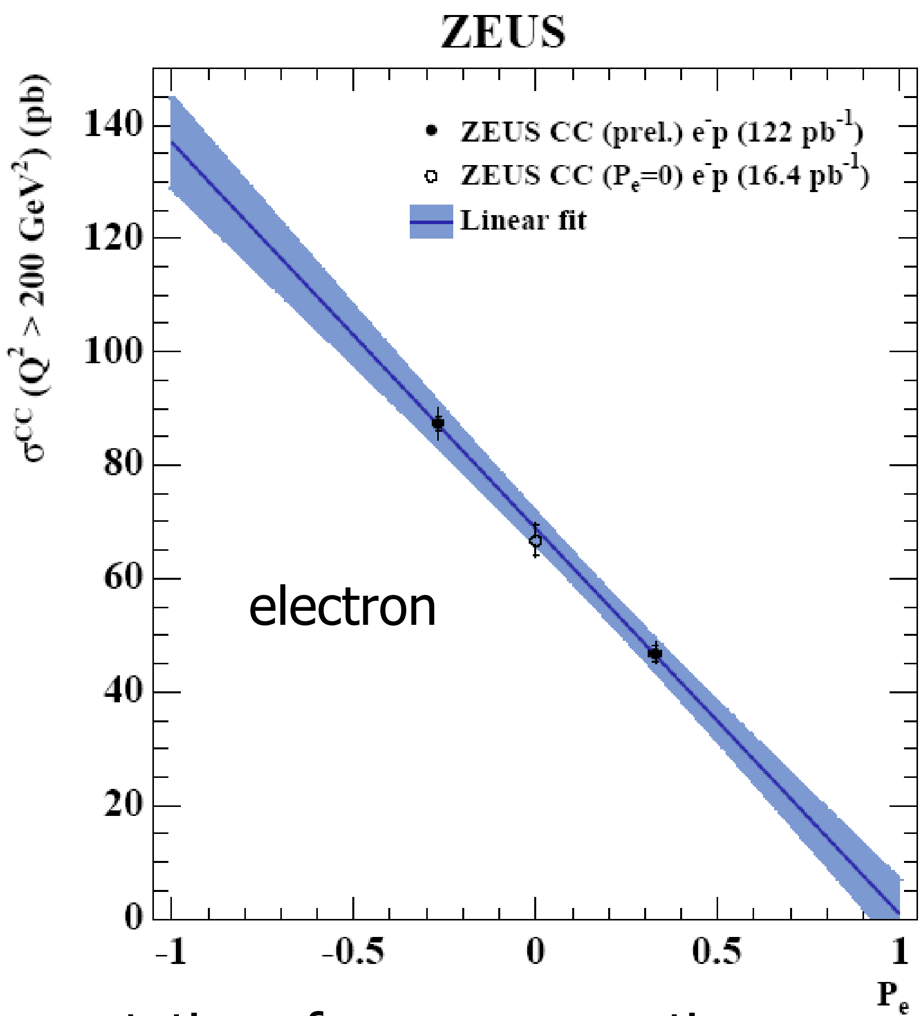


Polarisation dependence of CC cross section clearly seen $\propto$ ½(1-P)

Data consistent with SM prediction of no e^-_R or no e^+_L

Direct sensitivity of right handed W





Do not constrain linear fit to SM expectation of zero cross section

Derive mass limit on W_R assuming $g_L=g_R$ and massless ν_R

positron data: 208 GeV (H1)   electron data: 186 GeV (H1)
180 GeV (Zeus)

Lets return to QCD and PDFs

How do we extract the PDFs from all this data ?

Perform QCD fits in NLO / NNLO

Choose which PDFs to fit

Parameterise the shapes of the PDFs with some function

evolve using DGLAP and calculate cross sections

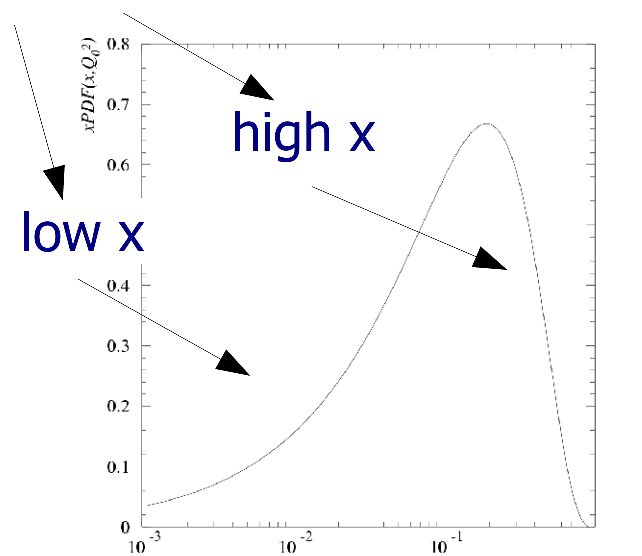
compare calculation with data in a χ^2 function

$$\int u_v \, dx = 2$$

Seems simple, but there are many choices to be made

- 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...

All should be reflected in PDF uncertainties



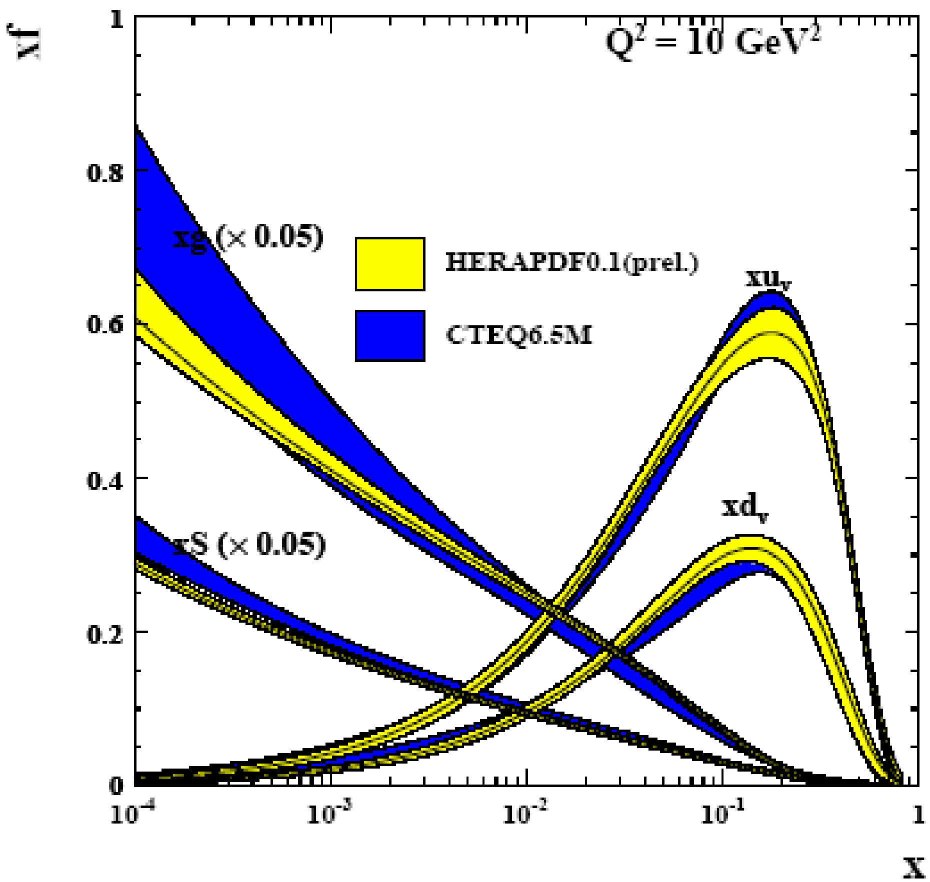
$\int u_v dx=2$

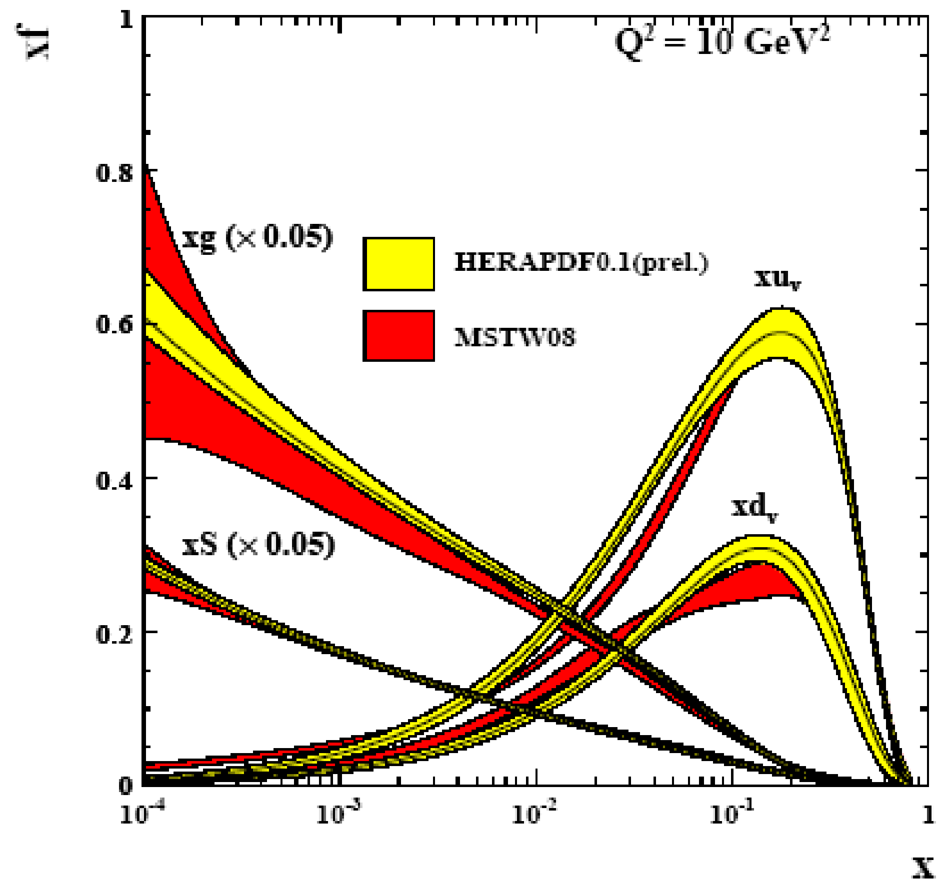
$$\int d_v \, dx = 1$$

An example of contrast is between CTEQ / MSTW approaches & HERA approach

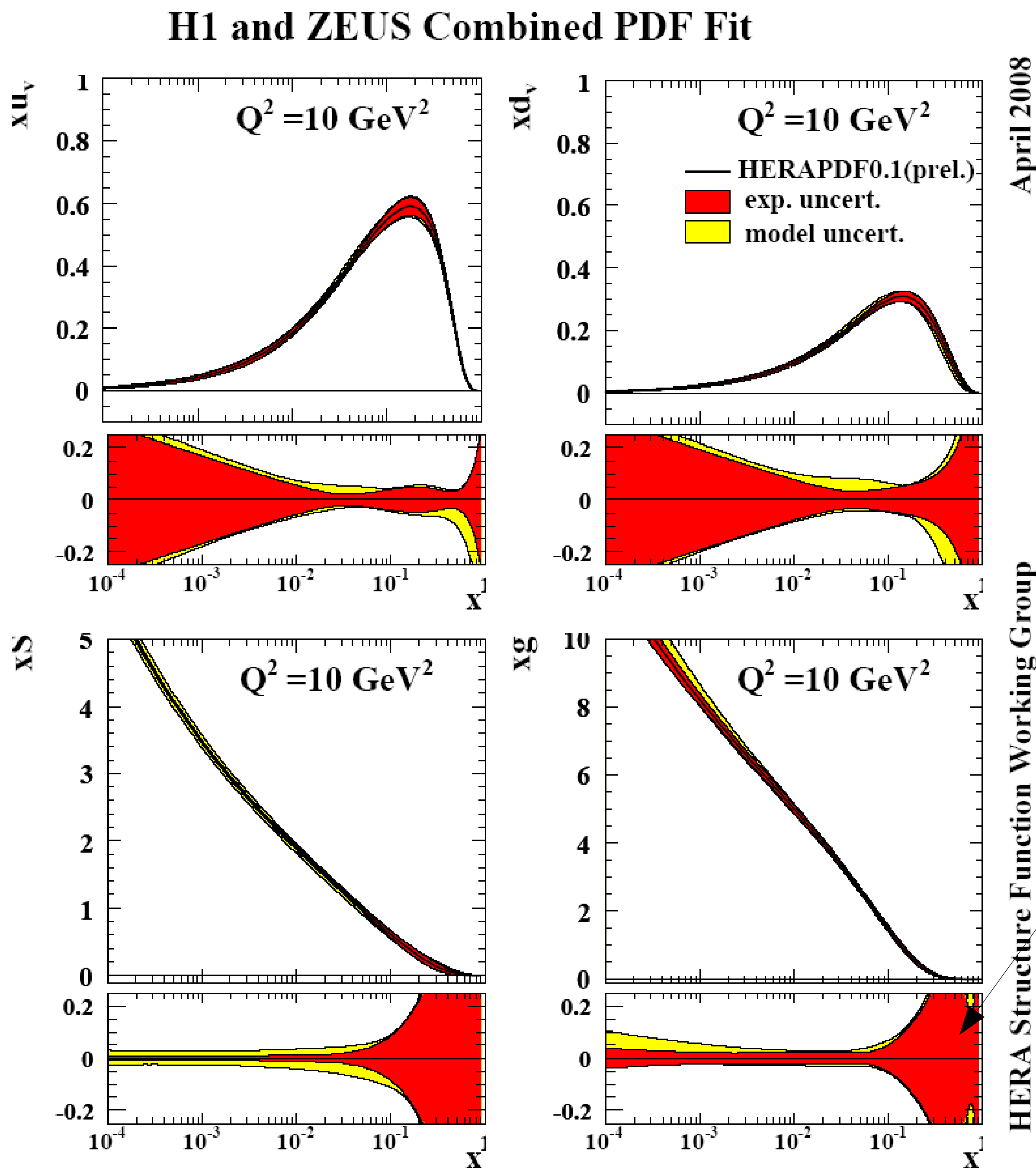
CTEQ / MSTW = global fitters - use all data available
many experiments
many cross sections - F_2, exclusive states, Drell-Yan
many targets - proton, deuteron, iron, copper...
This approach has much more power to distinguish each PDF e.g. $s \neq \bar{s}$
Development of better theoretical treatment - e.g. heavy flavours
Have to deal with nuclear corrections, higher twist etc...
Problem with inconsistent data ...

HERA use only H1 / Zeus data sets which can be controlled
check for consistency of data from two experiments
treat systematics in detailed way
NC & CC and e^+p and e^-p scattering allow PDF extraction





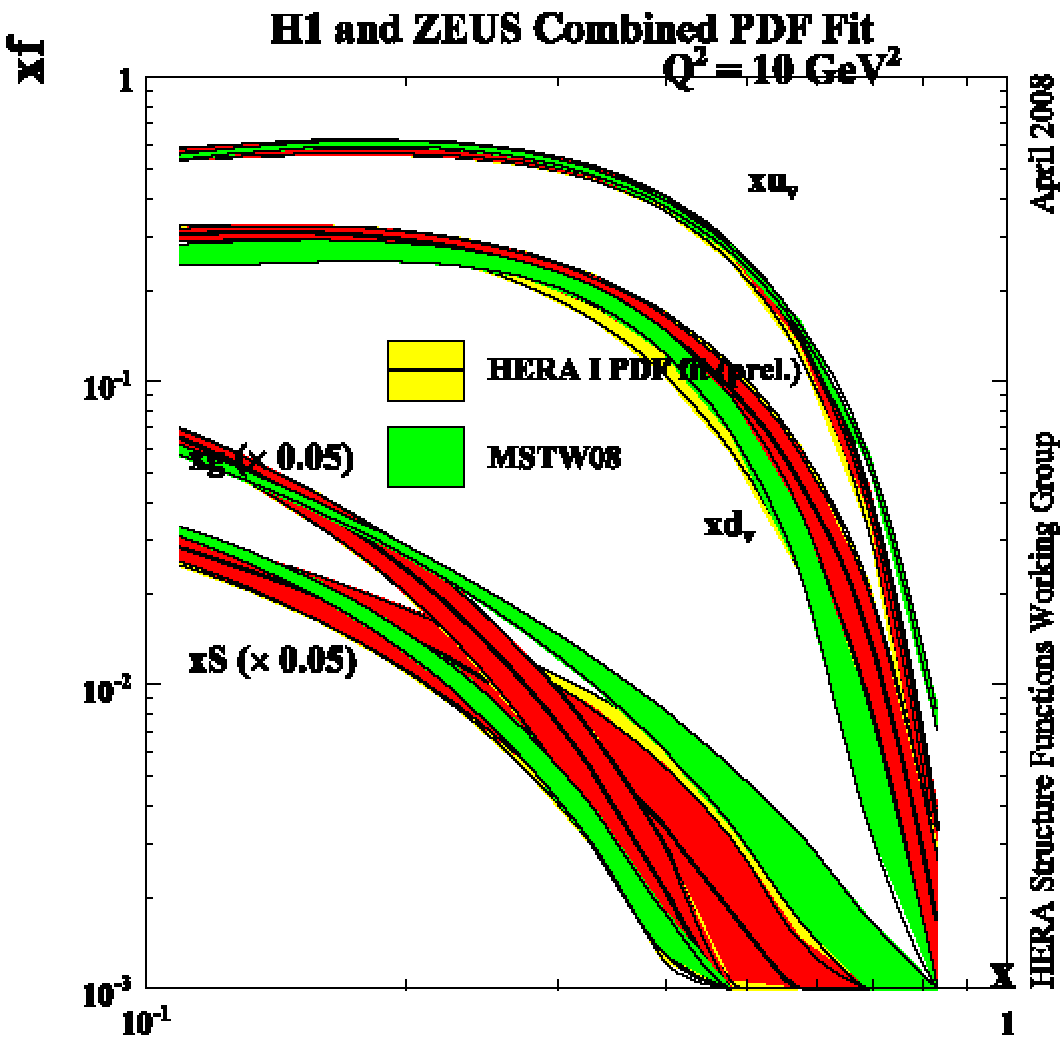
Can compare these approaches: HERA, MSTW, CTEQ
Broad consistency
Small uncertainty for HERAPDF (due to latest combined HERA data)
Valence distributions markedly different for MSTW
Are we estimating uncertainties correctly? Parameterisation error...



At high x
large uncertainty on xg & sea

weak constraints from
- momentum sum rule
- scaling violations
- subtle at high x

The fractional error explodes...



One example:
compare HERAPDF0.1 with MSTW for x>0.1

xu_v and xd_v in good agreement

xS is in good agreement too, but...

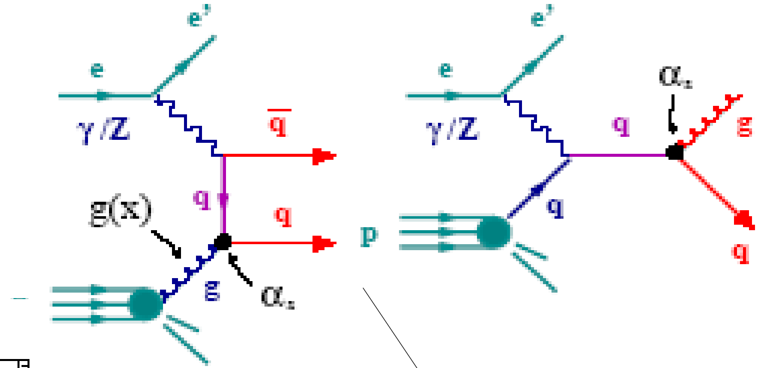
MSTW gluon very different

Outside both error bands

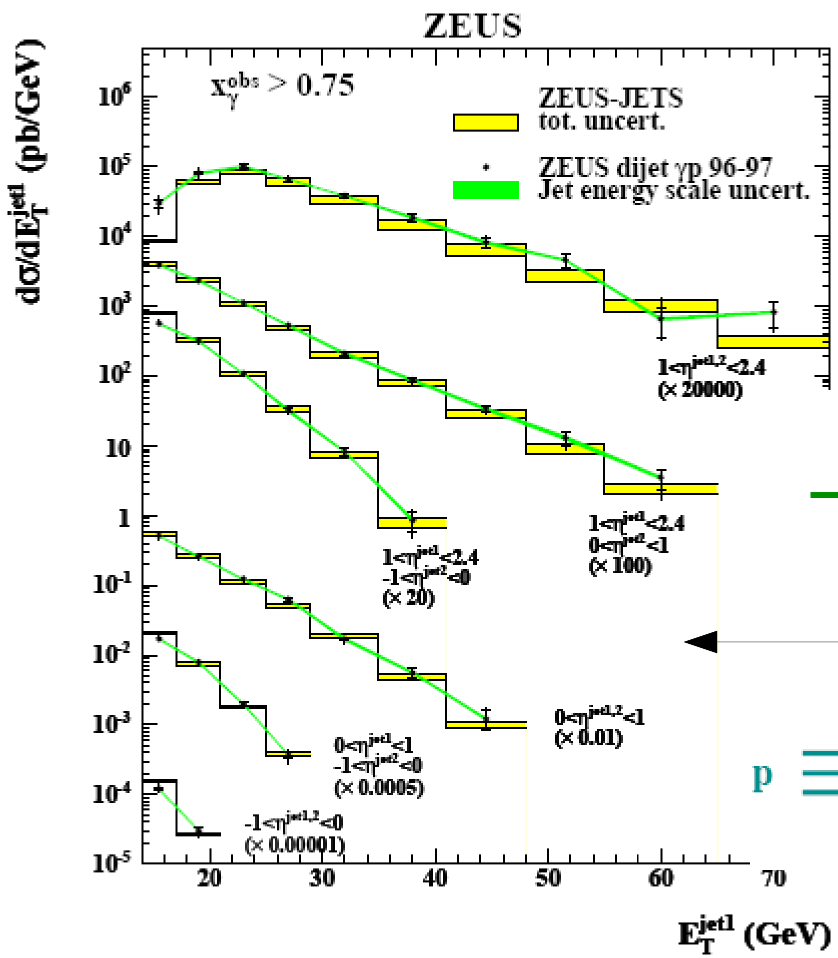
Are functions flexible enough?

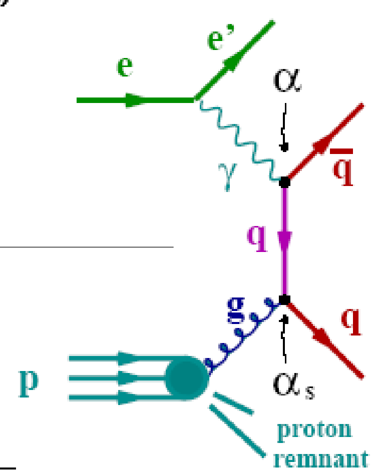
What data can constrain high x glue ?

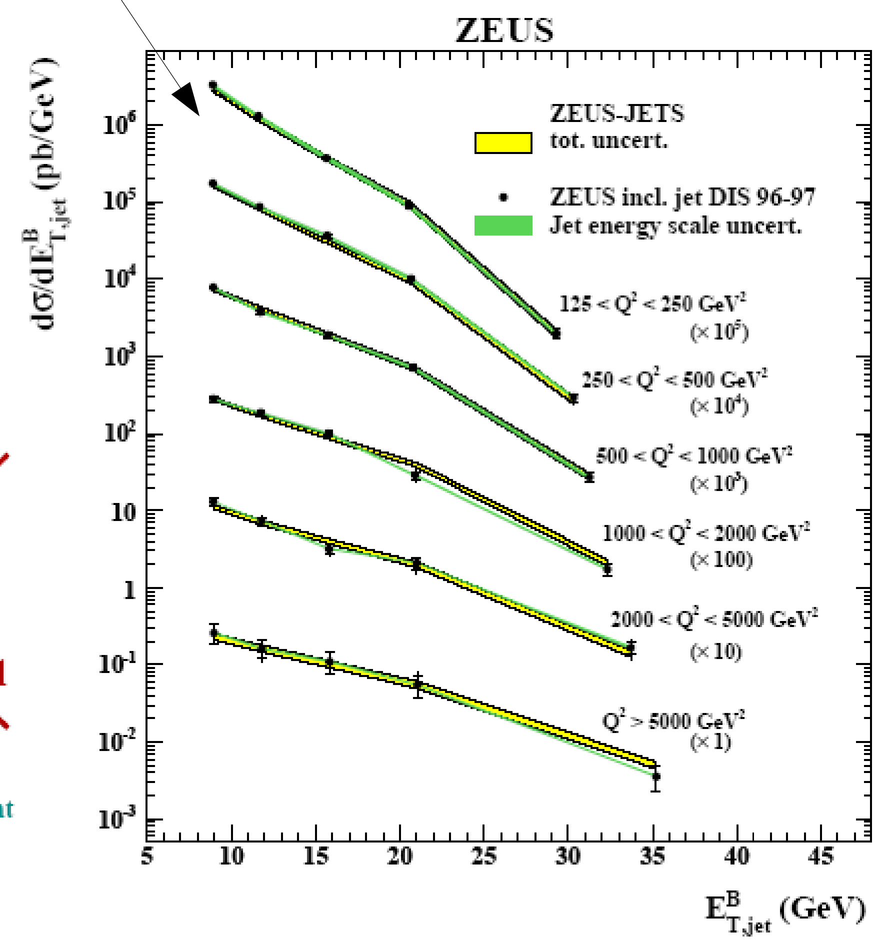
di-jet cross sections in photoproduction $Q^2 \sim 0$

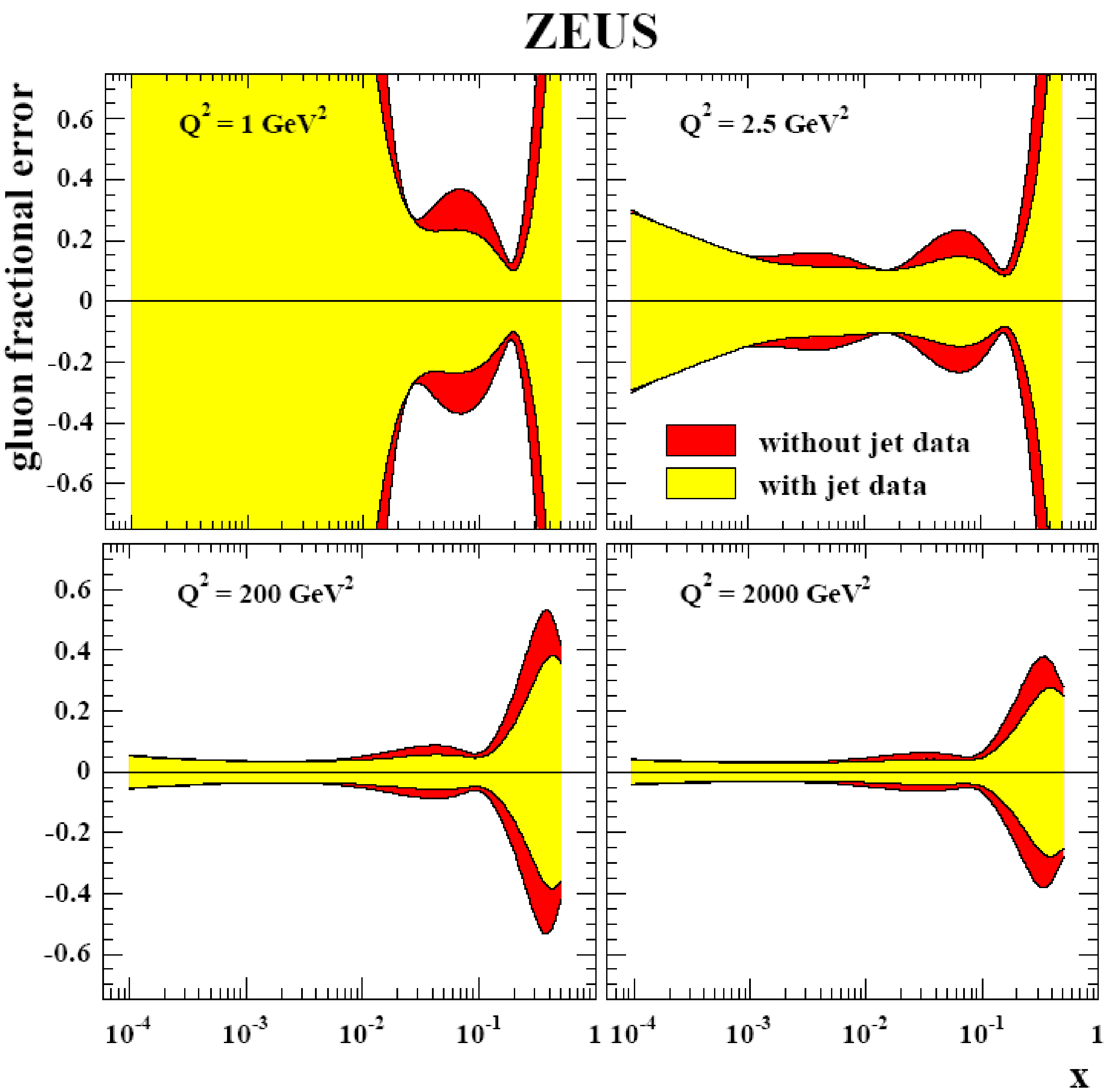


di-jet data in DIS $Q^2 > 200$ GeV^2









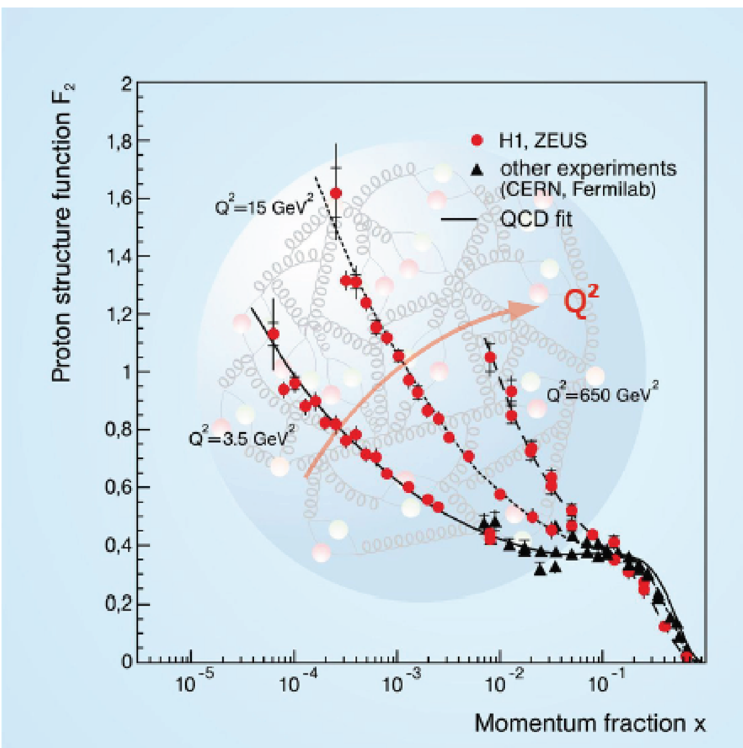
Addition of jet data improves precision on xg

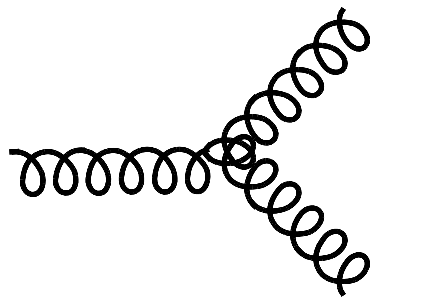
specially in region of x~0.05

mostly driven by γp di-jets

Work in progress to tie this up for “final” HERA data / PDFs

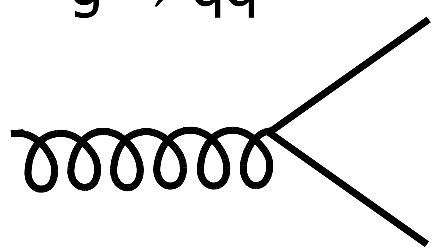
- Perturbative QCD is known in approximate form: DGLAP evolution
- Describes HERA data very well across whole perturbative regime
  4 decades in x and Q^2
- DGLAP: Given f(x) at Q_0^2 PDF Q^2 evolution is determined
- DGLAP sums pQCD expansion terms like $\alpha_s^n.\ln^m(Q^2)$
- Corresponds to gluon (and quark) splittings e.g.:

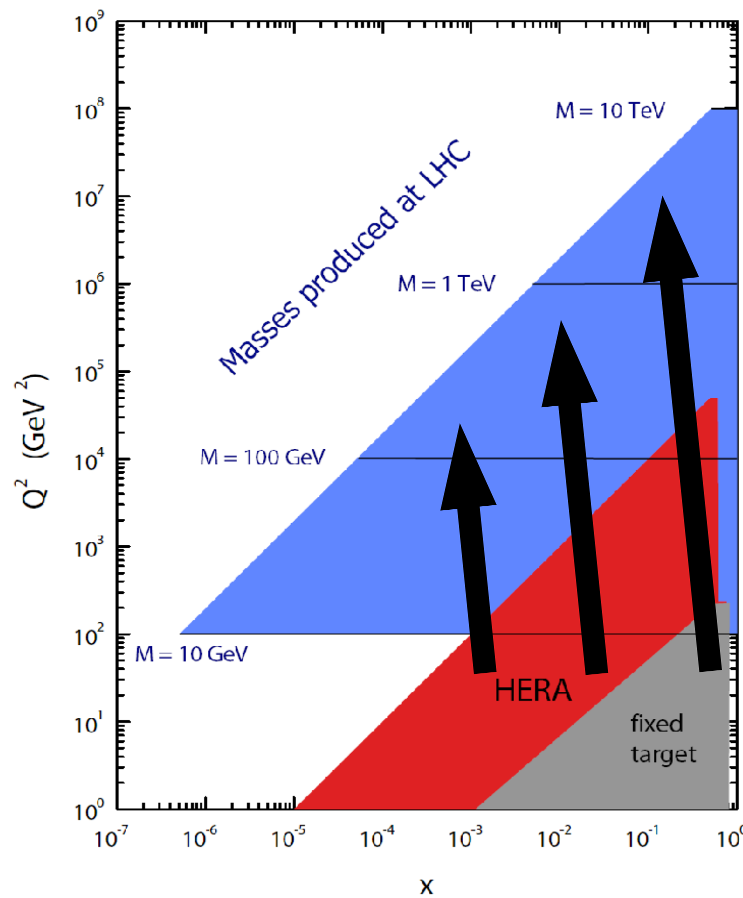


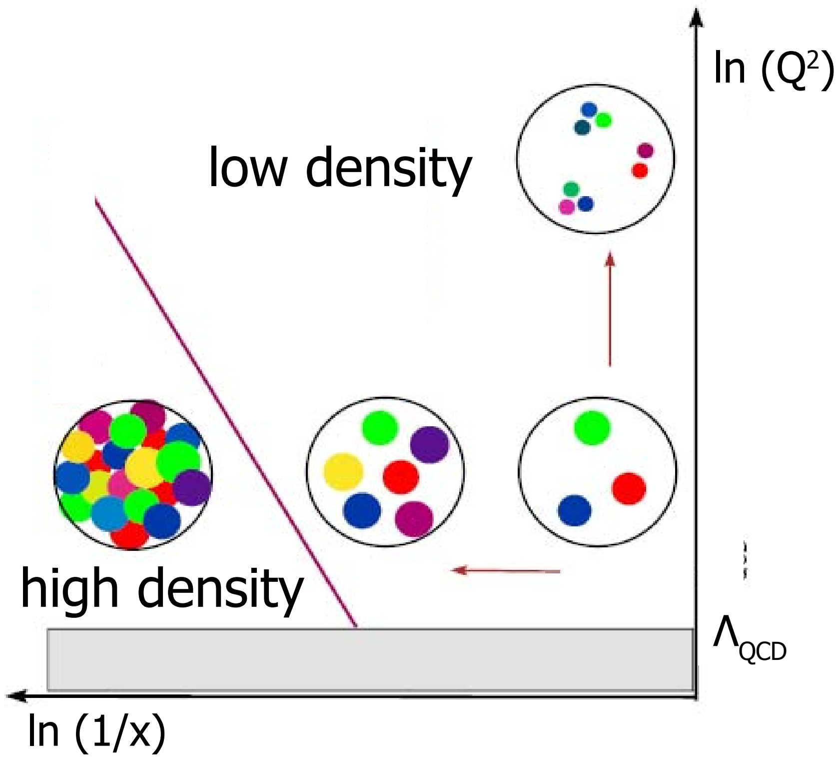


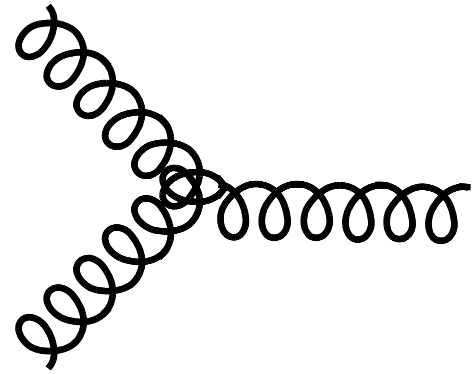
$g \rightarrow gg$

$g \rightarrow q\bar{q}$









In low x region evolution dominated by xg

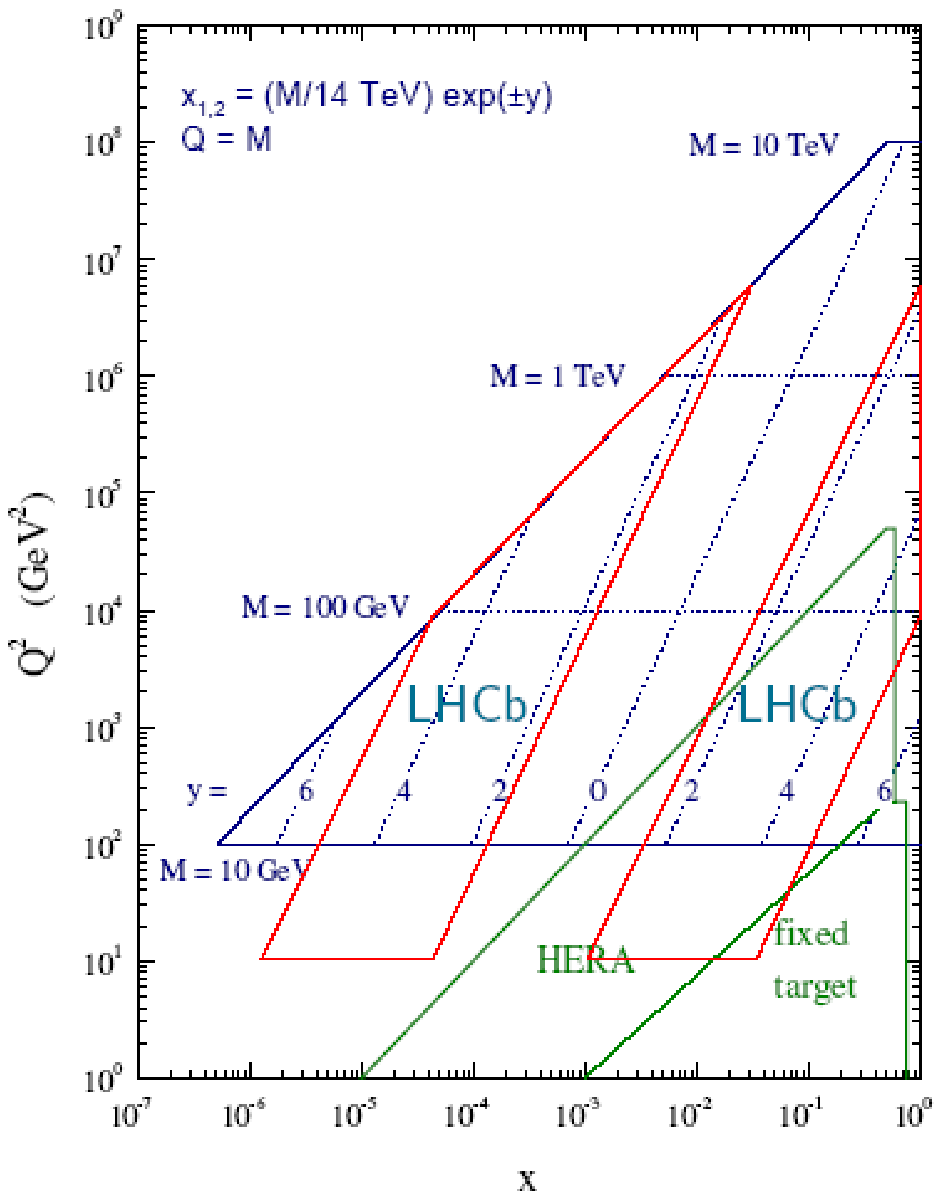
Very high $xg(x,Q^2)$ will lead to saturation

- rise of F_2 is tamed
- corresponds to gluon recombination

- At very small x (and high enough Q^2) other logs become large e.g. $\alpha_s^n . \ln^m(1/x)$
- At high x may need additional resummation of $\alpha_s^n . \ln^m(1-x)$

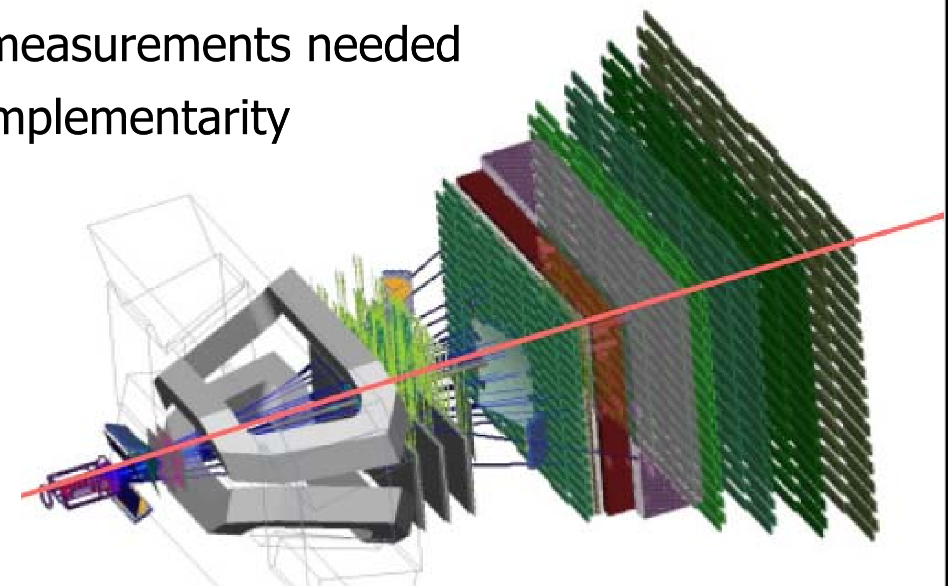
Domain of new QCD dynamics
Was expected to be found in HERA phase space
No firm evidence...

New evolution dynamics visible at LHC?



For M ~ 1 TeV probe PDFs at x~1

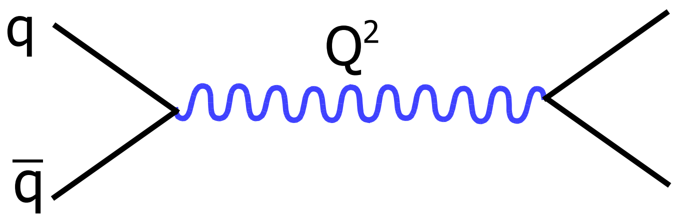
- Low x important for ultra-high energy neutrino scattering
- For $Q^2 \sim 100\ GeV^2$ (M ~ 10 GeV):
  - Atlas / CMS could probe $x \sim 10^{-5}$
  - LHC b could probe $x \sim 10^{-6}$!
- LHCb greater acceptance for high rapidity
- Diagram shows rapidity of M, not decay products!
- Both measurements needed
  - Complementarity



How do we see this at LHC ?

Measure Drell-Yan process: quark - antiquark annihilation

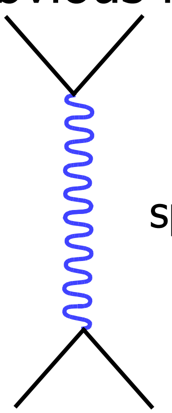
Cross section has a pole at $Q^2 = M_Z^2$



off-resonance (away from Z pole) measurements probe quark and anti-quark distributions

sensitive to new evolution for large and small M

Process has obvious relationship to DIS



space-like scattering

Atlas / CMS restricted to central rapidity $y = \pm 2$ (for produced particle)

Can extend by requiring
1 central & 1 forward lepton
difficult...

- trigger
- idenitification
- resolution

Conclusions / Summary

HERA data will have large impact on LHC predictions

NC / CC data in $e^{\pm}p$ scattering allows flavour separation of PDFs

We're in HERA endgame - final precision DIS data are on horizon

Combined H1 / Zeus data will bring improved precision

Precise PDFs allow tests of EW part of Standard Model

Different fitting philosophies $\rightarrow$ not so different PDFs

One issue with PDF fits is parameterisation uncertainty

Plan to release new HERA PDFs in time for LHC turn on

Plenty of scope for precision PDF studies at LHC