HERA Structure Function Measurements

Advanced Topics in QCD 2002
Beijing

August 5th – 9th

Eram Rizvi

Birmingham University (UK)

HERA Structure Function Measurements

Status of the HERA Upgrade Project

H1 and ZEUS Detectors

Neutral and Current Processes

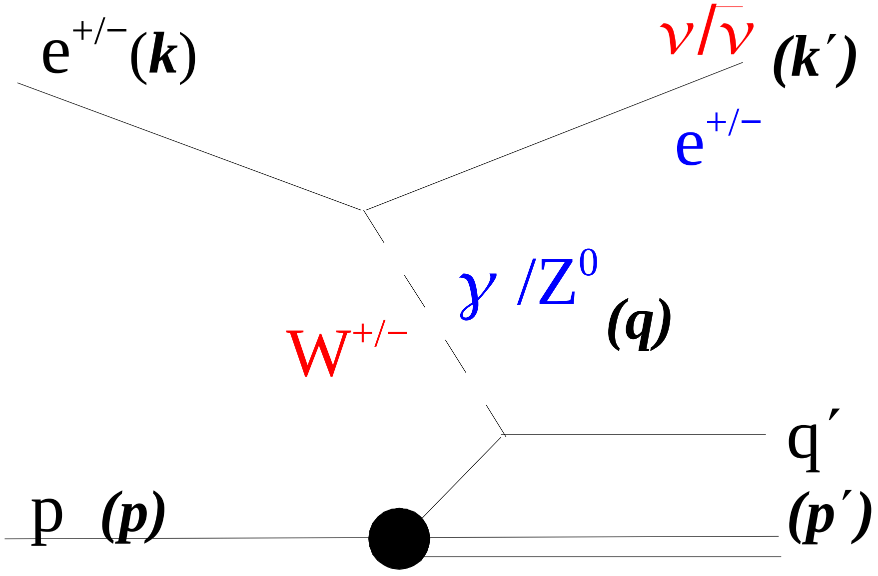
Measurements of Proton Structure Functions

Charged Current Measurements

QCD Phenomenology

Summary

HERA Kinematics



Kinematic Variables

Resolving power

Negative of the four−momentum transfer between lepton and proton

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

"Momentum fraction of proton carried by the struck quark"

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

Inelasticity

Momentum fraction of the lepton carried by the exchange

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

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

$$Q^2 = s.x.y$$

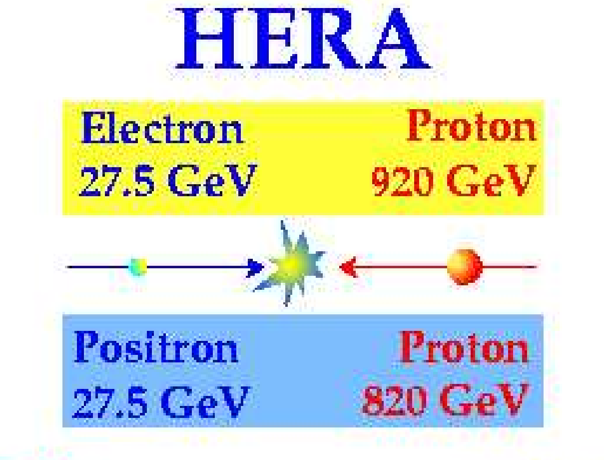
$$W^2 = (p+q)^2$$

HERA Operation 1994 − 2000

e^+p and e^-p

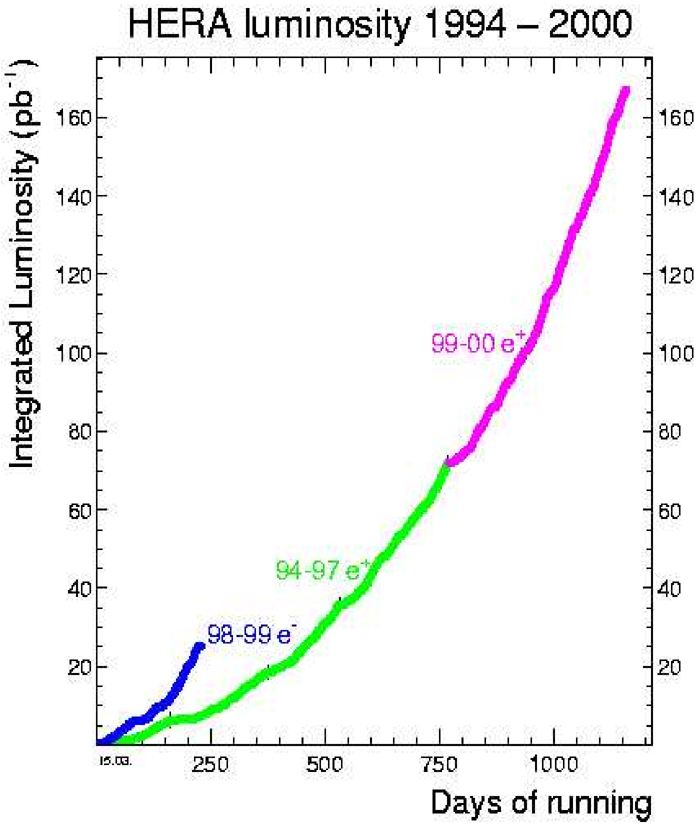
1998−2000

1994−1997

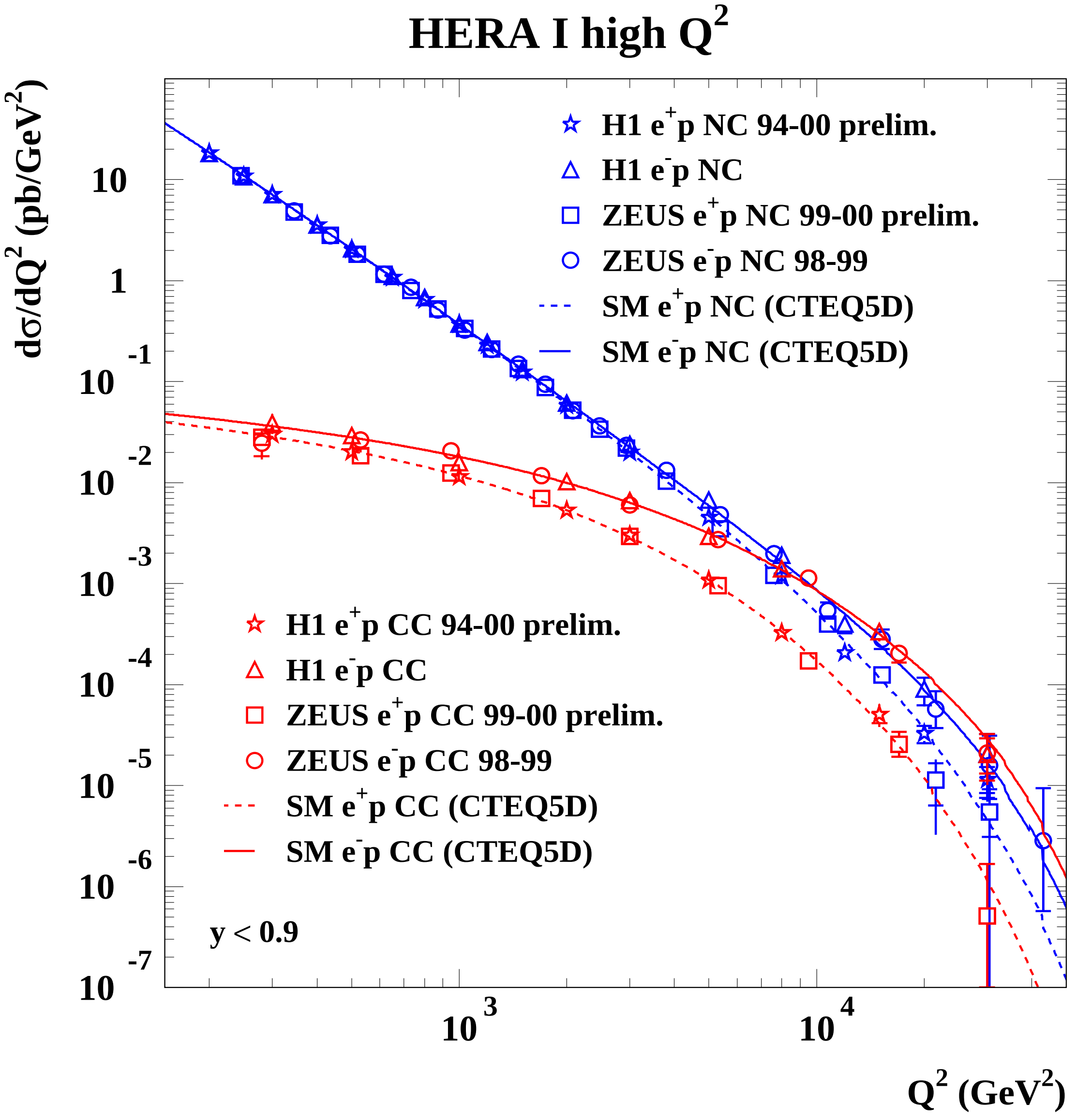


	Luminosity (pb^{-1})	
	H1	ZEUS
e^-p	~16	~16
e^+p	~100	~110

Luminosity Delivered

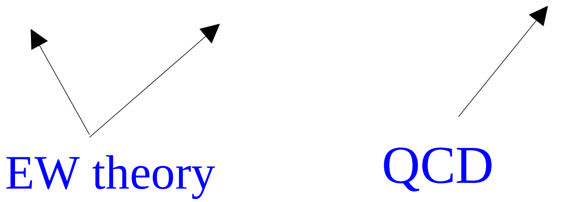


Reasons For HERA Upgrade



- Well described by Standard Model:

σ ~ (coupling) x (propagator) x (PDFs)



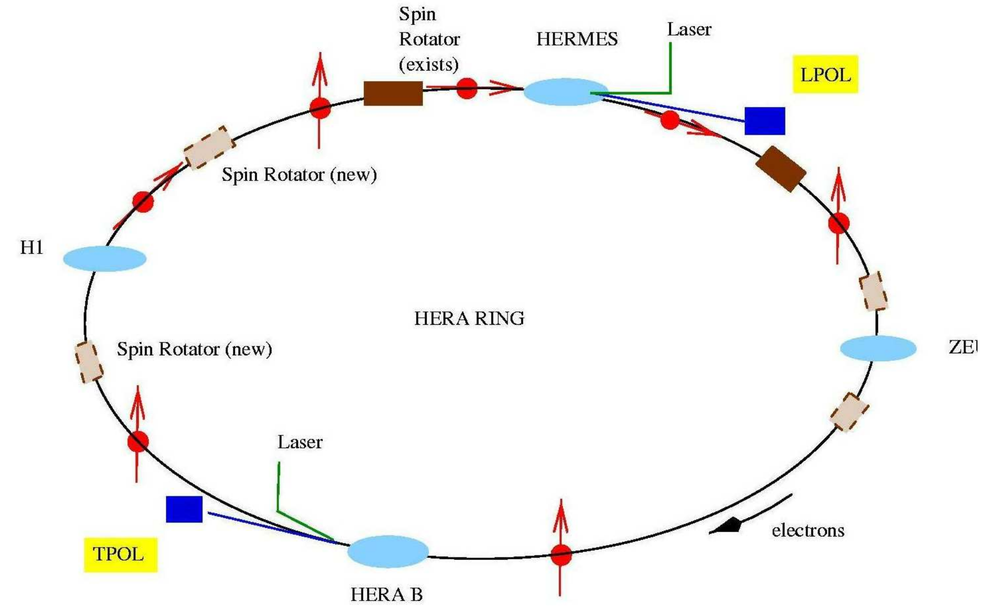
EW theory

QCD

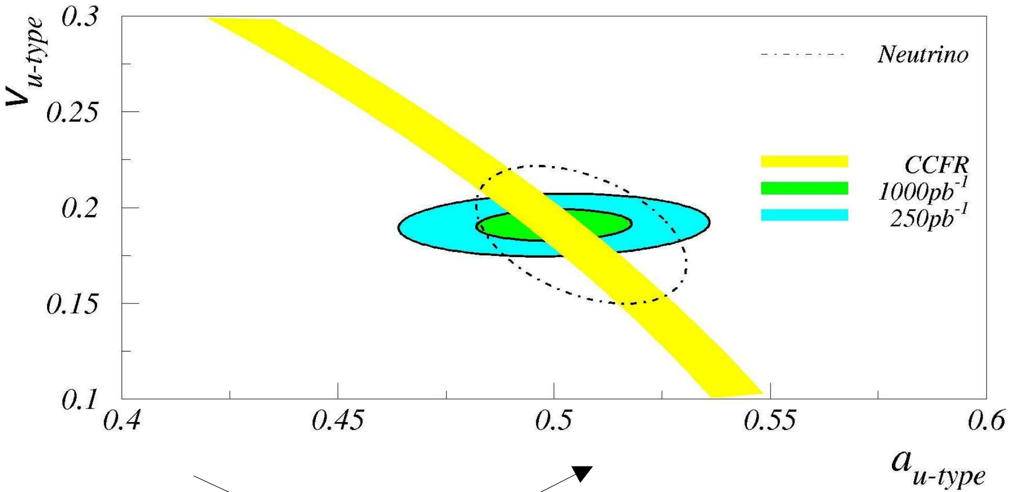
- Q^2 dependence of the NC and CC cross sections − statistically limited at high Q^2
- Need more luminosity: aim for 1 fb^{-1} by 2006

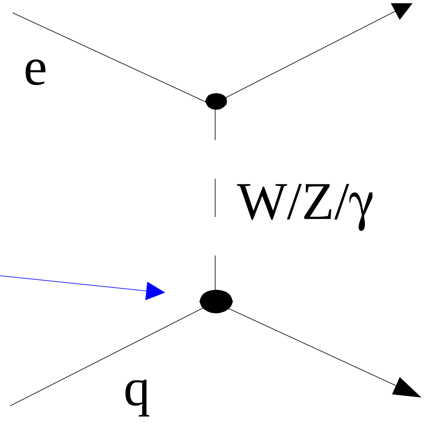
New Possibilities at HERA II

- Addition of spin rotators gives new dimension to HERA physics.



- E.g. measure vector and axial couplings of light quarks to Z^0.





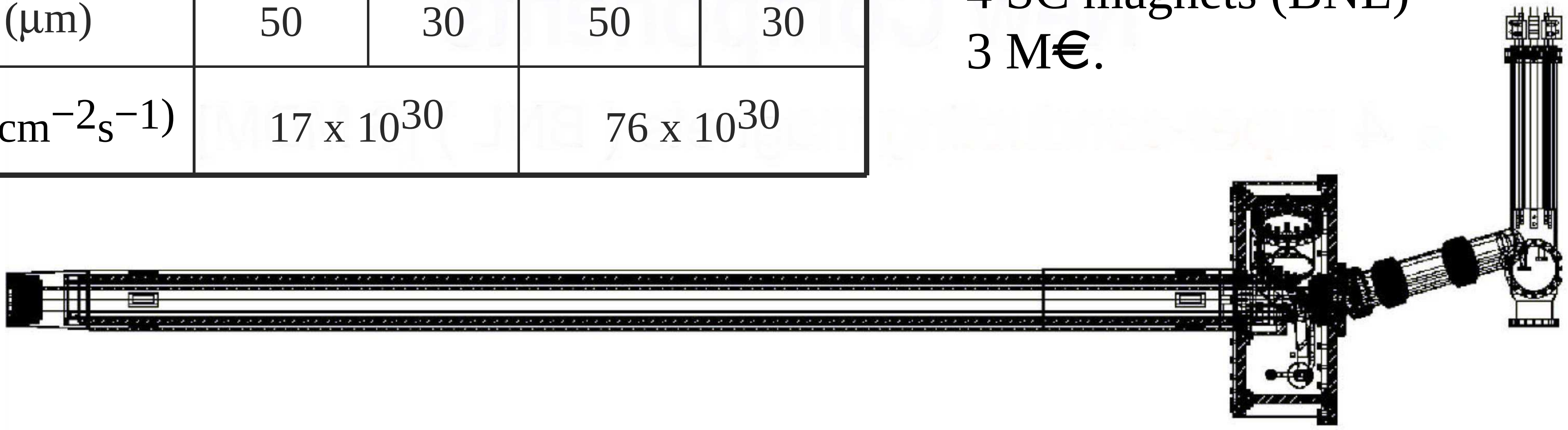
Extract quark couplings

HERA Upgrade

- Increased luminosity through…

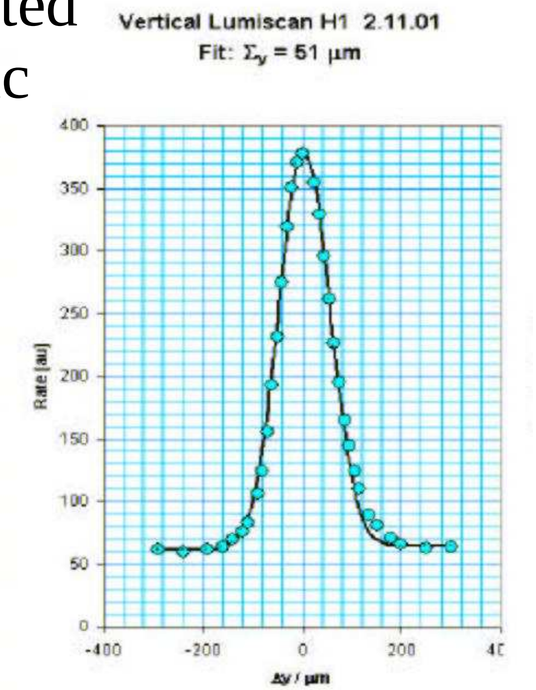
Ring	Electron		Proton	
Date	2000	2002	2000	2002
I (mA)	50	58	100	140
σ_x (μm)	192	112	189	112
σ_y (μm)	50	30	50	30
L ($cm^{-2}s^{-1}$)	17 x 10^{30}		76 x 10^{30}	

- Upgrade required addition of:
  - 448 m UHV system 3 M€.
  - Absorbers, instrumentation, control systems… 3 M€.
  - 56 NC magnets (Eframov Inst.) 3 M€.
  - 4 SC magnets (BNL) 3 M€.



HERA Upgrade

- Shutdown started Sept. 2000.
- HERA upgrade installation completed end July 2001.
- First collisions August 2001.
- Demonstrated that specific luminosity goals met (necessary focussing achieved).



Transverse beam profile

- First luminosity runs planned for November 2001.
- Very (too!) ambitious schedule.
- Initial luminosity low, sporadic and backgrounds large
- Many problems, large and small, compounded to make running very difficult.

HERA Upgrade

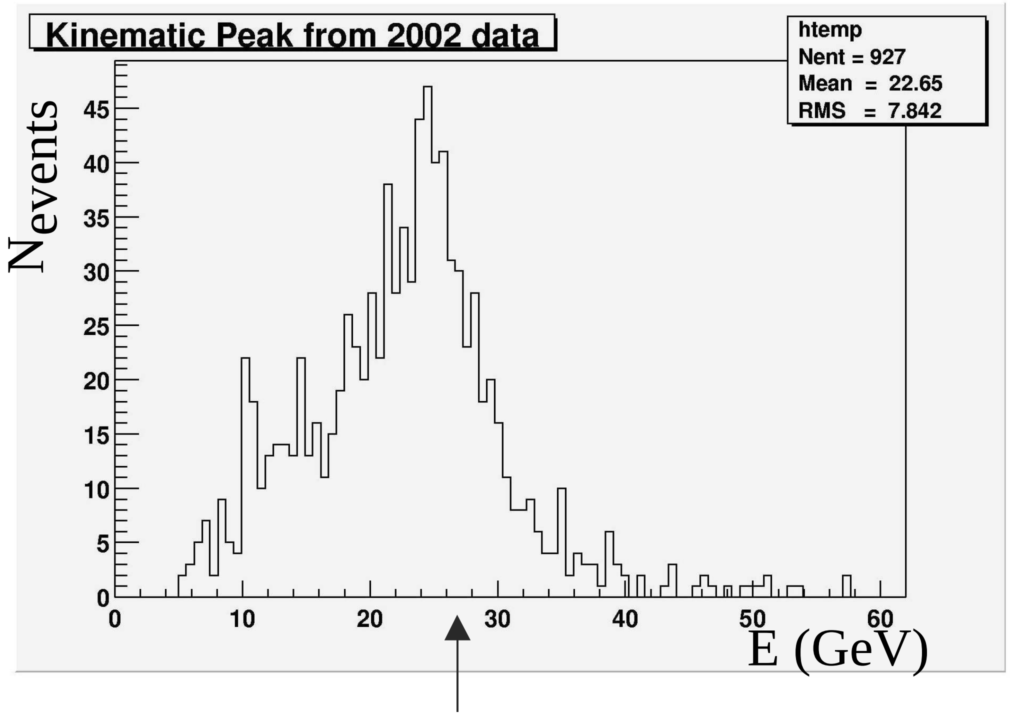
- Example of large problem:
  - Failure of supports in section of p+ ring.
- Many minor failures
  - Example, corrosion of cooling water valve systems.

- Main problem for experiments large backgrounds due to:
  - Poor vacuum.
  - Synchrotron radiation.
- Solve former by “baking out” beam pipe.
- Solve latter by improving machine alignment, collimation systems.
  - Many new BPMs.
  - Improved monitoring and feedback.

HERA Upgrade

- To carry out this programme, DESY moved manpower from TESLA to HERA early in 2002.
- Progress has been slow but steady since then, faster in last weeks.
- Record specific luminosity of ~1.7 x 10^{30} measured for 28.5 mA p and 18 mA e^+
- Integrated luminosity 240 nb^{-1}.

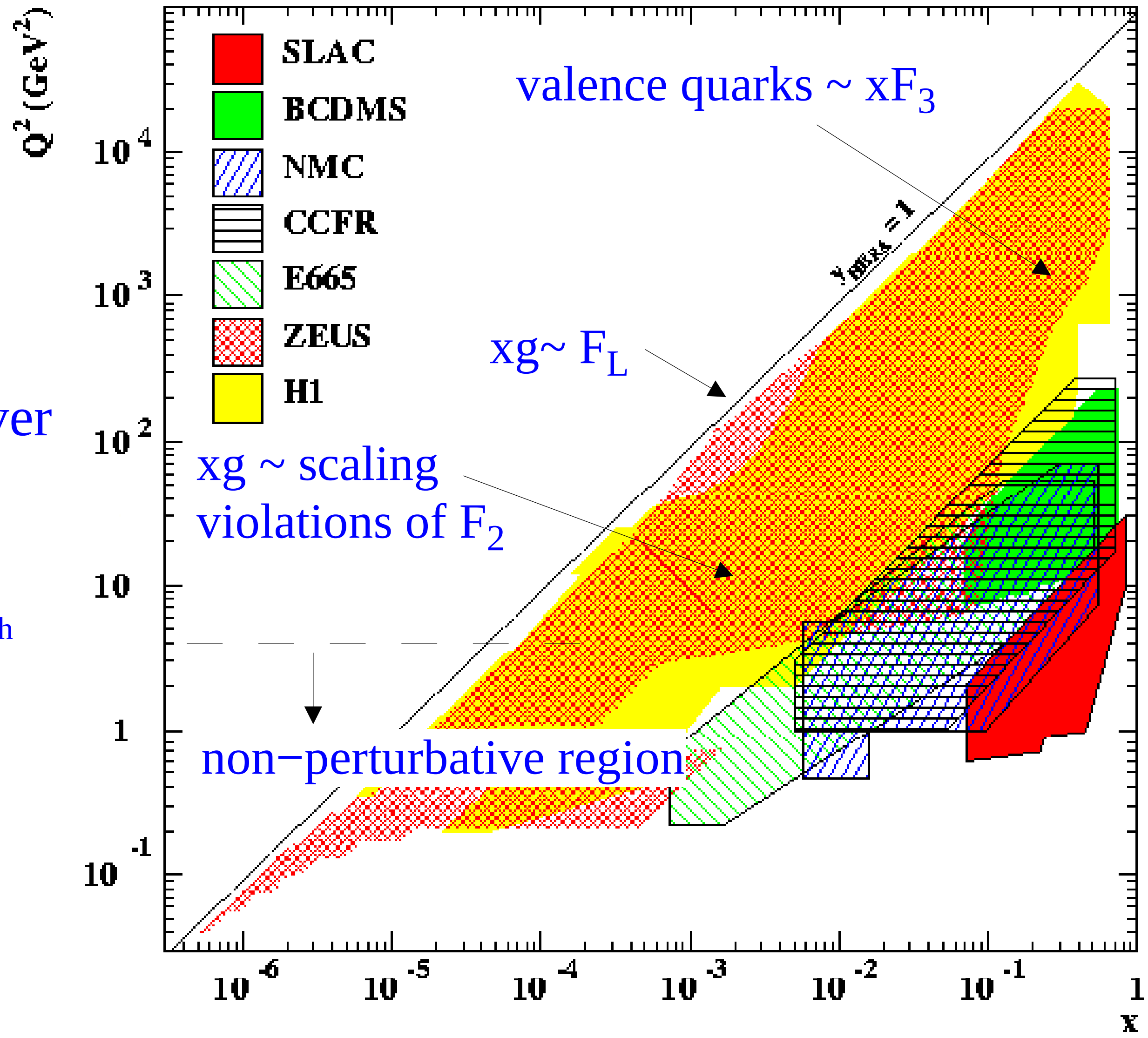
- “Kinematic peak” from recent HERA run…



scattered $e^{+/-}$ energy

Kinematic Range of HERA Data

- Accessible kinematic plane now almost covered
- Measurements extend to cover high y, high x, and high Q^2
- Probe distances to ~1/1000th of proton size



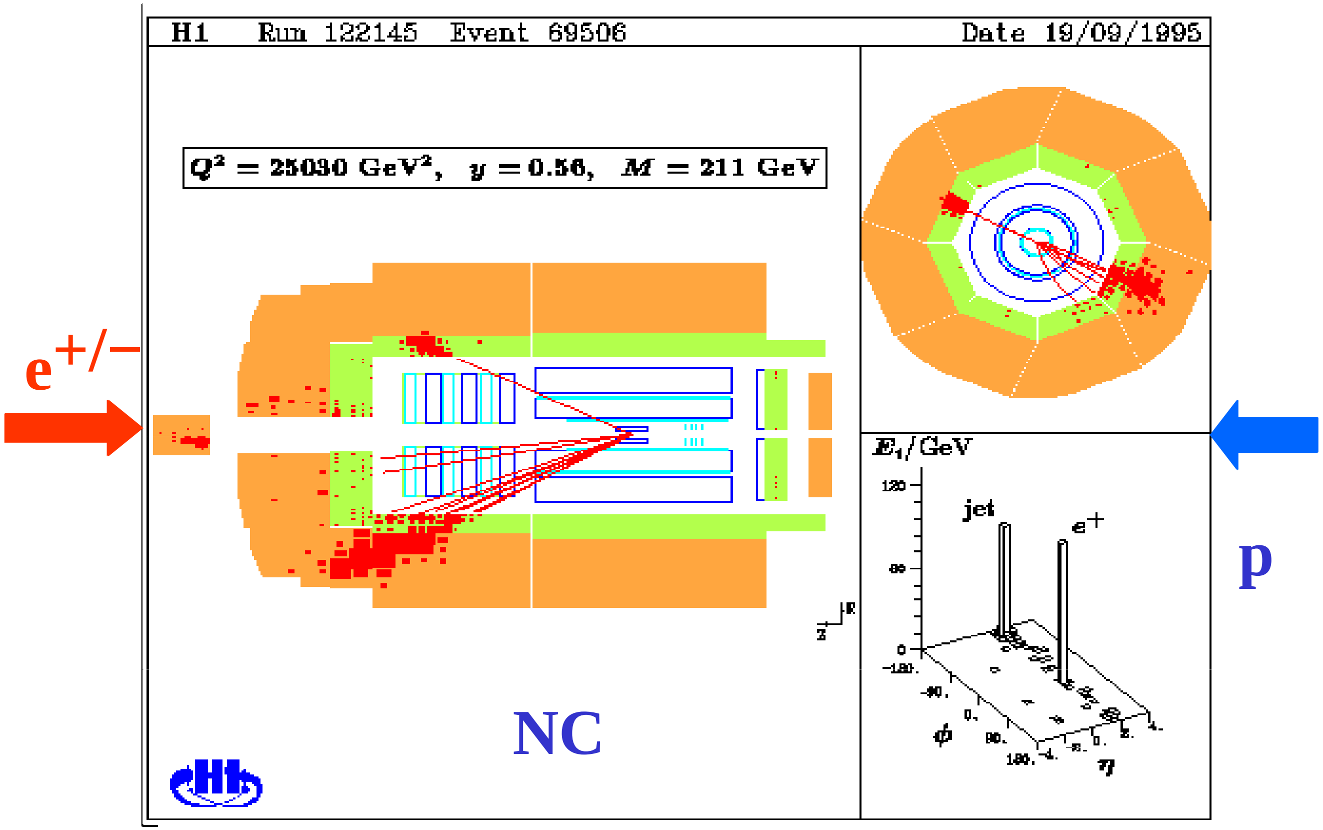
valence quarks ~ xF_3

$xg \sim F_L$

xg ~ scaling violations of F_2

non−perturbative region

The H1 Detector



Fine Grained Liquid Argon Calorimeter (45 000 channels)

EM section

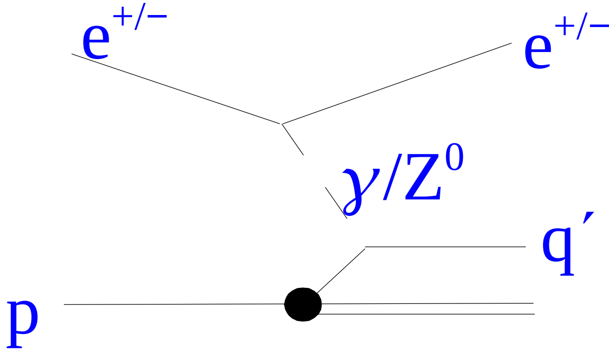
$$\frac{\delta E}{E} = \frac{12\ \%}{\sqrt{E}} \oplus 1\ \%$$

HAD section

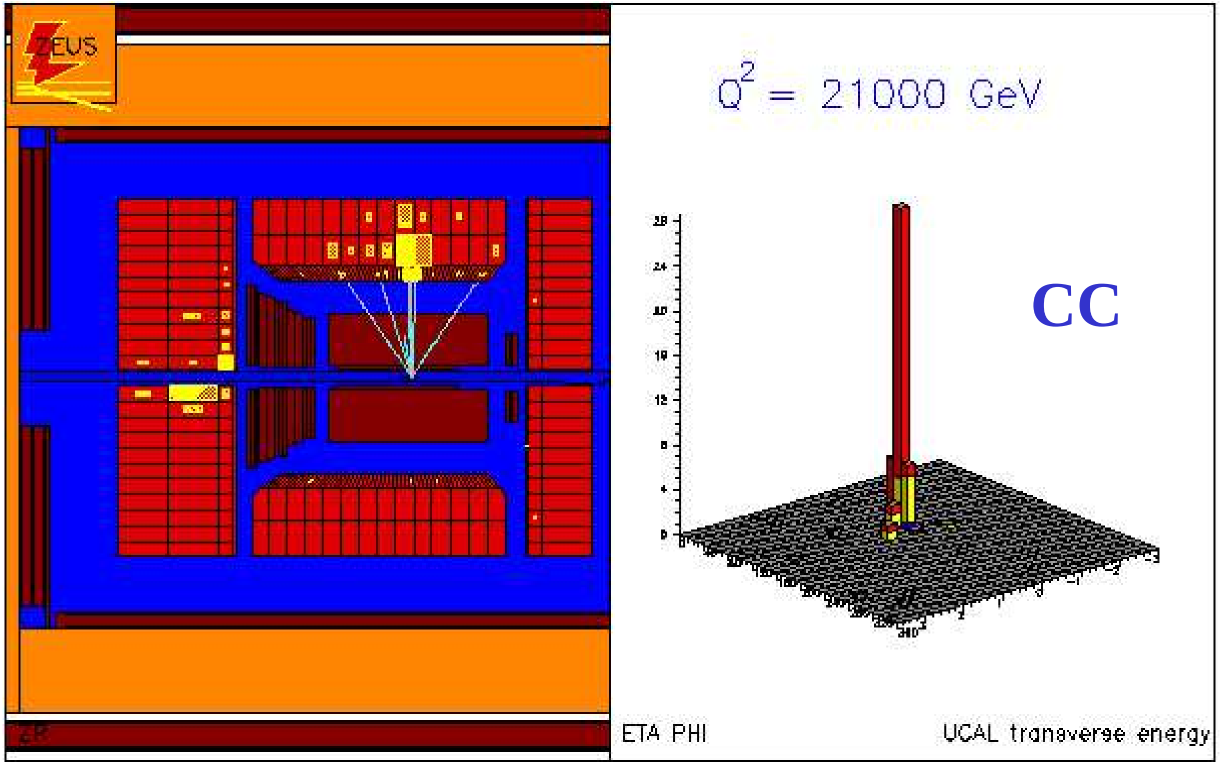
$$\frac{\delta E}{E} = \frac{50\ \%}{\sqrt{E}} \oplus 1\ \%$$

Tracking Chambers

$$\sigma_p / p \approx 0.003\ p$$



The ZEUS Detector



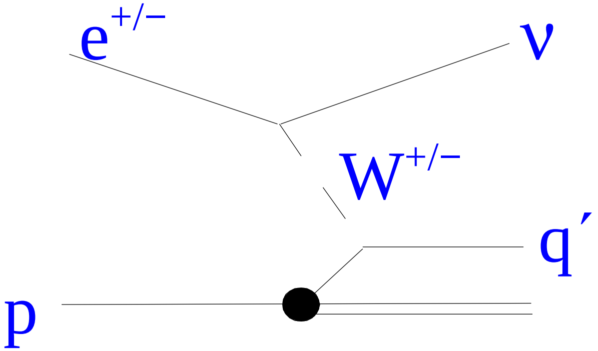
Compensating Uranium−Scintillator Calorimeter

EM section $$\frac{\delta E}{E} = \frac{18\ \%}{\sqrt{E}}$$

HAD section $$\frac{\delta E}{E} = \frac{35\ \%}{\sqrt{E}}$$

Tracking Chambers

$$\delta p_T \,/\, p_T = 0.0058\, p_T \oplus 0.0065 \oplus 0.0014 \,/\, p_T$$



Neutral Current Cross Sections

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\alpha\pi^2}{Q^4 x}\left[Y_+ \tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2 F_L\right]$$

$$\tilde{F}_2 \equiv F_2 - v_e \frac{\kappa_w Q^2}{Q^2+M_Z^2} F_2^{\gamma Z} + (v_e^2 + a_e^2)\left[\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z$$

$$x\tilde{F}_3 \equiv -a_e \frac{\kappa_w Q^2}{Q^2+M_Z^2} xF_3^{\gamma Z} + (2v_e a_e)\left[\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z$$

In Leading Order:

$$\tilde{F}_2 \propto \sum_{quarks} (xq + x\bar{q})$$

$$x\tilde{F}_3 \propto \sum_{quarks} (xq - x\bar{q})$$

$$\kappa_w = \frac{1}{4\sin^2(\vartheta_w)\cos^2(\vartheta_w)}$$

Reduced cross section

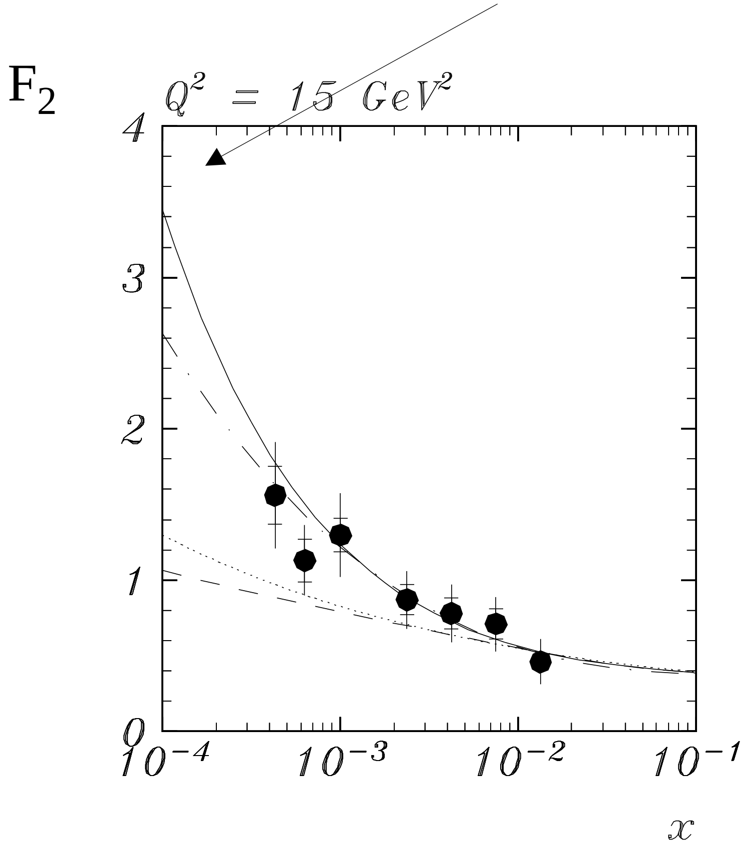
$$\tilde{\sigma}^{\pm}_{NC} \equiv \tilde{F}_2 \quad when \quad F_L \equiv x\tilde{F}_3 \equiv 0$$

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

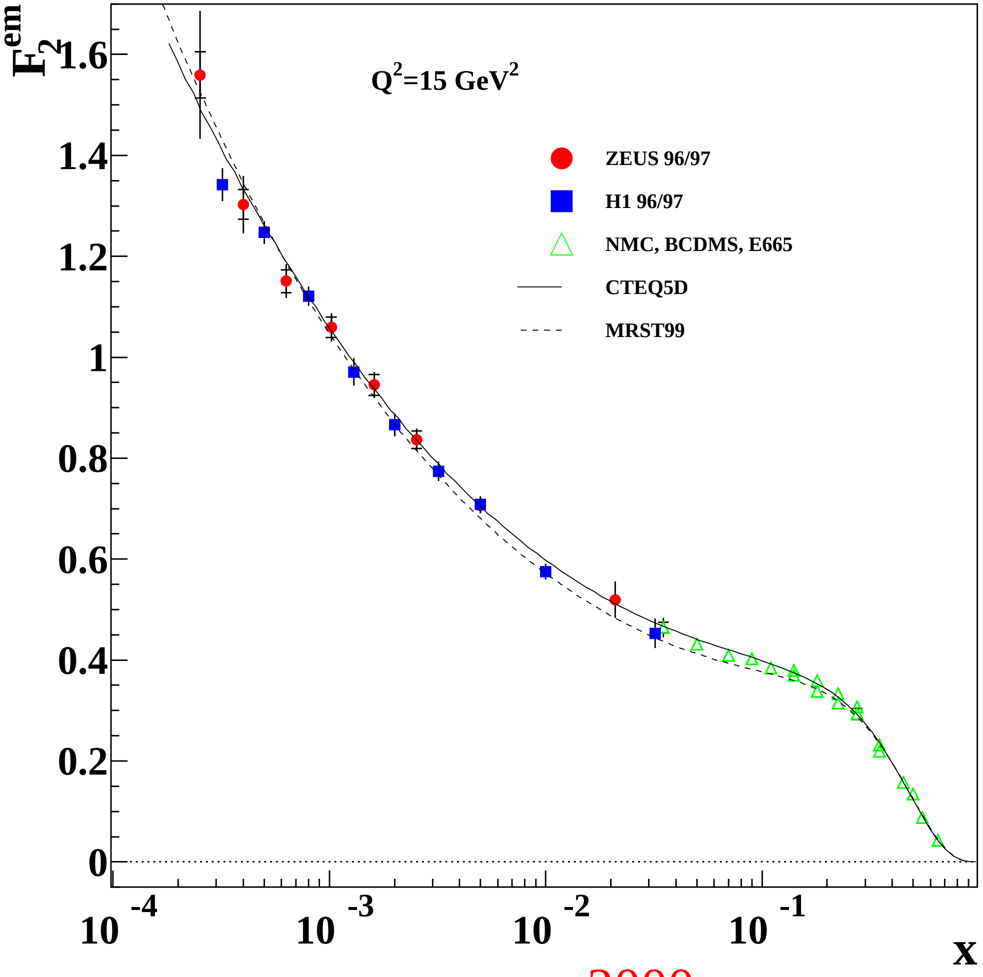
The Structure Function F_2

Impressive progress since startup of HERA

wide range of predictions pre−HERA

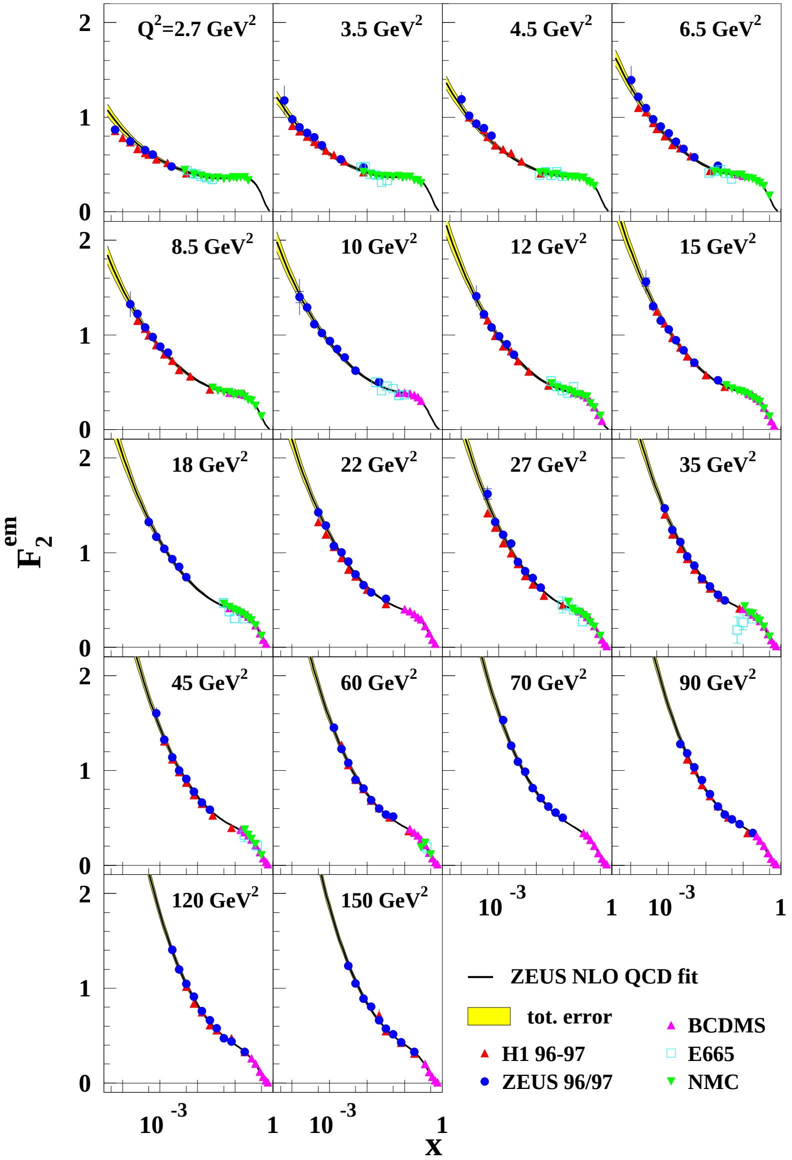


1993



2000

F_2



$$\tilde{F}_2 \propto \sum_{quarks} e_{q,i}^{\;2} \left(x q_i + x \bar{q}_i \right)$$

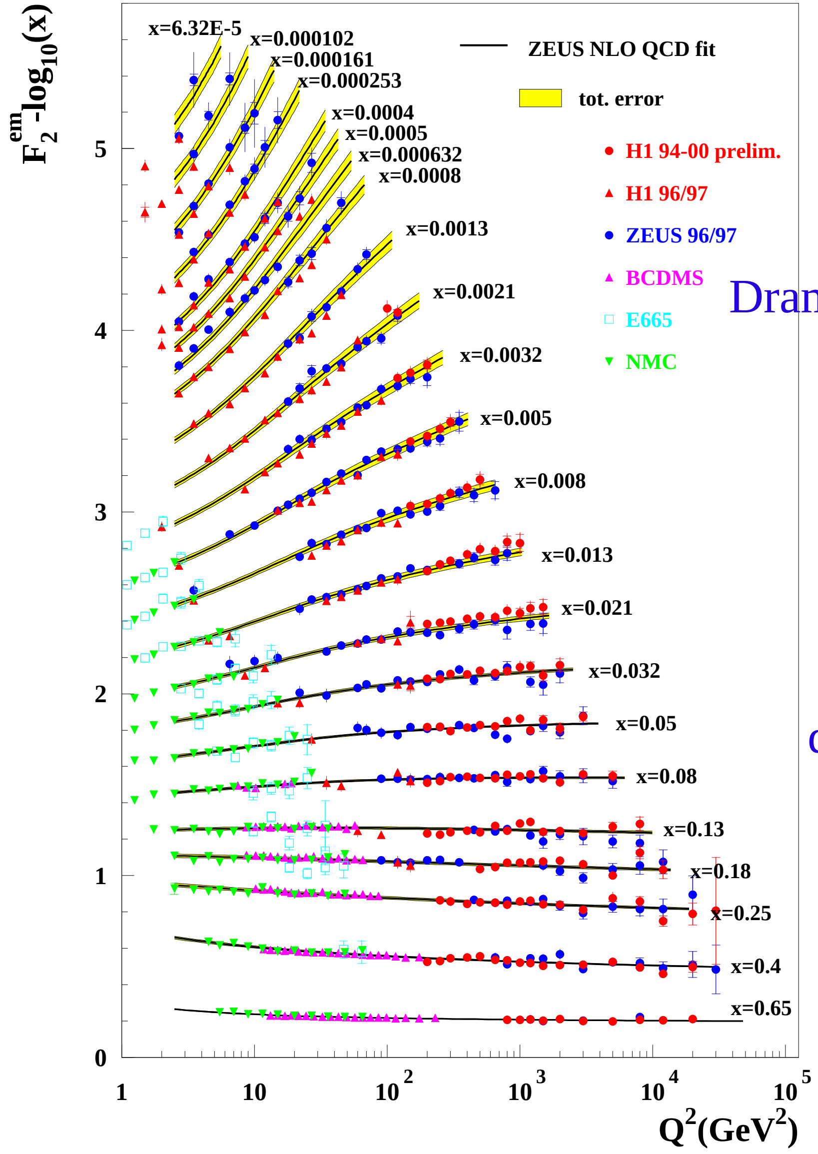
F_2 dominates cross−section

Measured with ~2−3% precision

Directly sensitive to sum of all quarks and anti−quarks

Indirectly sensitive to gluons via QCD radiation − scaling violations

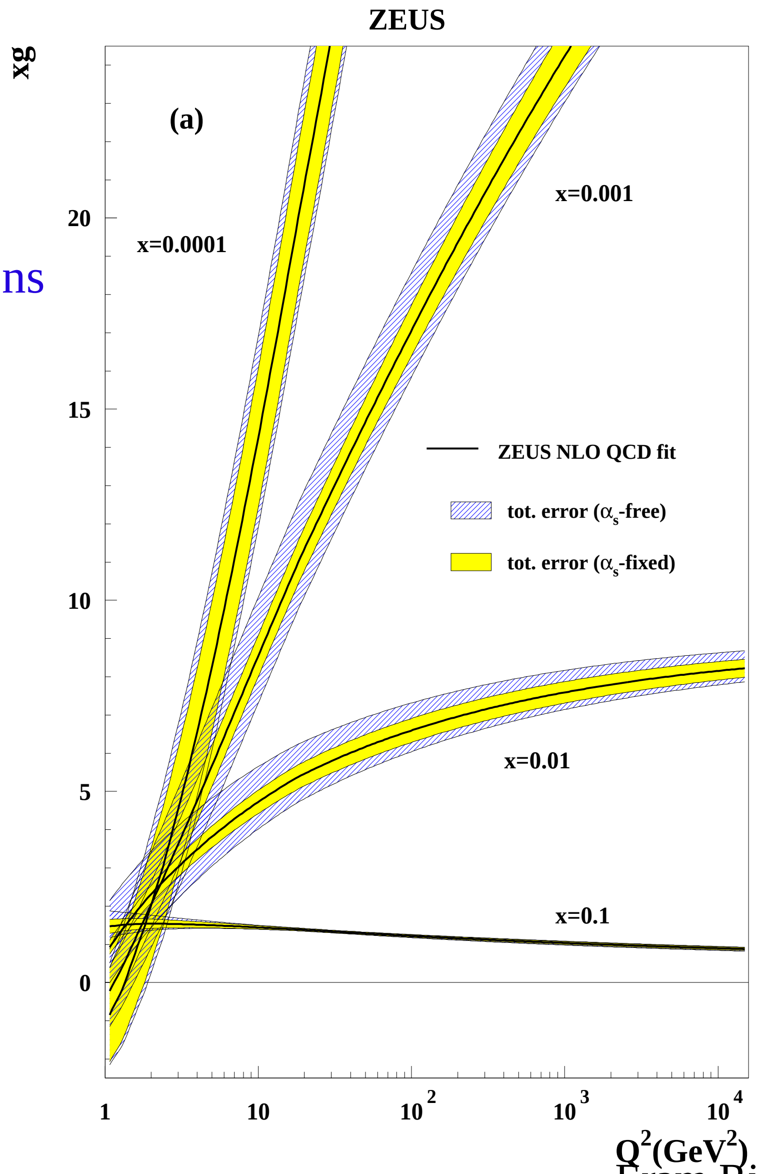
Scaling Violations of F_2



Dramatic scaling violatons at low x

driven by gluon

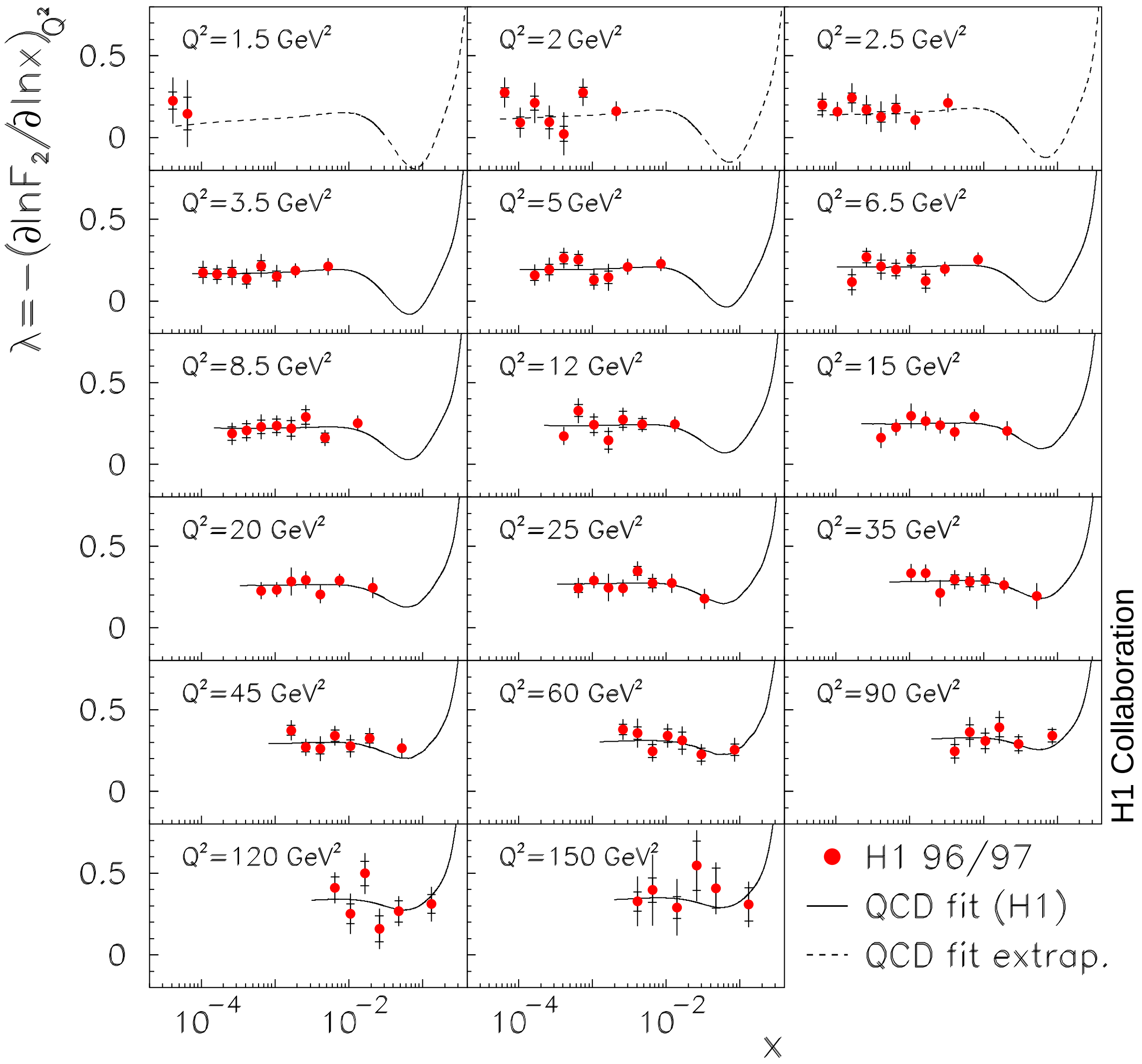
described by QCD



The Rise of F_2 at Low x

- Very rapid increase in F_2 at low x
- Is this tamed?
- Does F_2 saturate ?
- Cross section must obey unitarity
- At some point gluon density is so large that gluon fusion must occur
- This process not part of standard DGLAP QCD → BFKL = QCD in large gluon field

The Rise of F_2 at Low x



- Current F_2 precision allows study of the rise of F_2 at low x
- Use data from Q^2 = 0.5 − 150

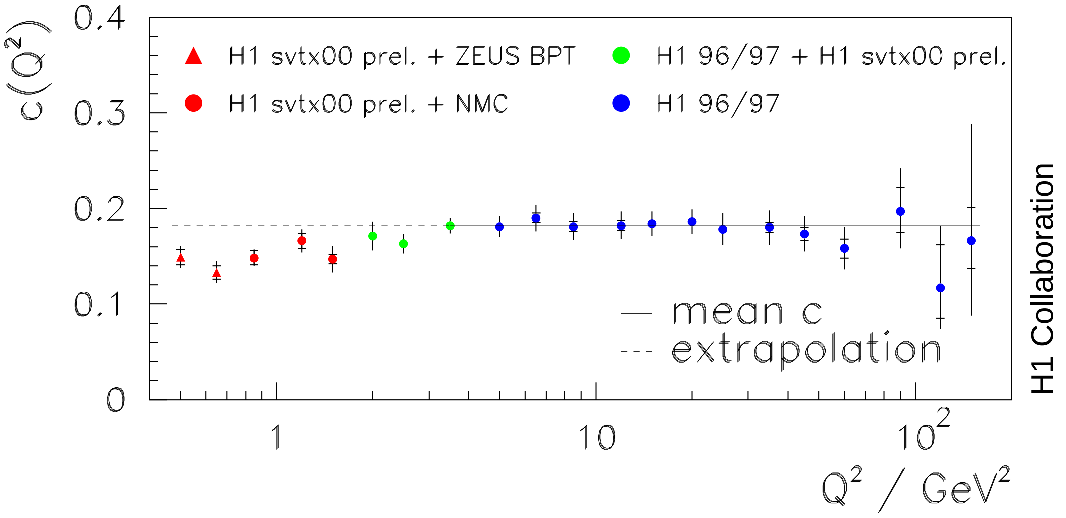
$$\lambda = -\left[\frac{\partial \ln(F_2)}{\partial \ln(x)}\right]_{Q^2}$$

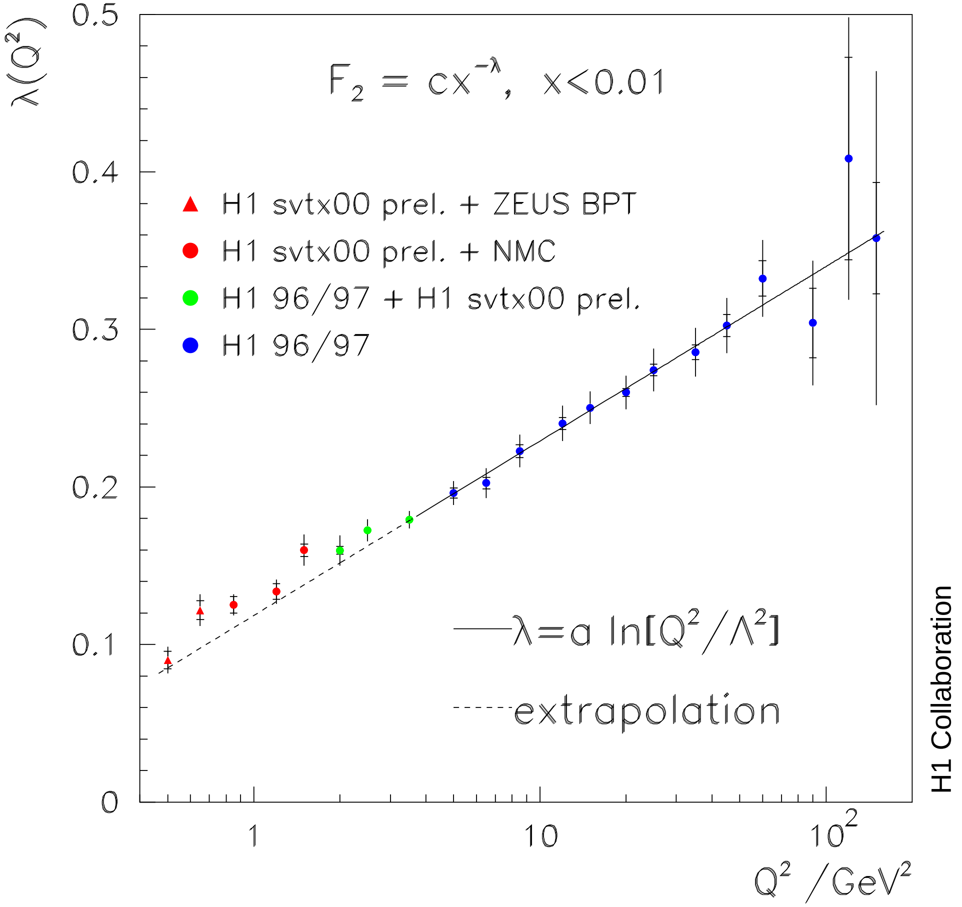
λ constant at fixed Q^2 and x<0.01

$$F_2 \approx x^{-\lambda(Q^2)}$$

Thought to be assymptotic behaviour of F_2 at low x in BFKL

HERA Structure Function Measurements





Use H1 / ZEUS / NMC data to fit Q^2 dependence for $x<0.01$:

$$F_2(x,Q^2)=C(Q^2)\,x^{-\lambda(Q^2)}$$

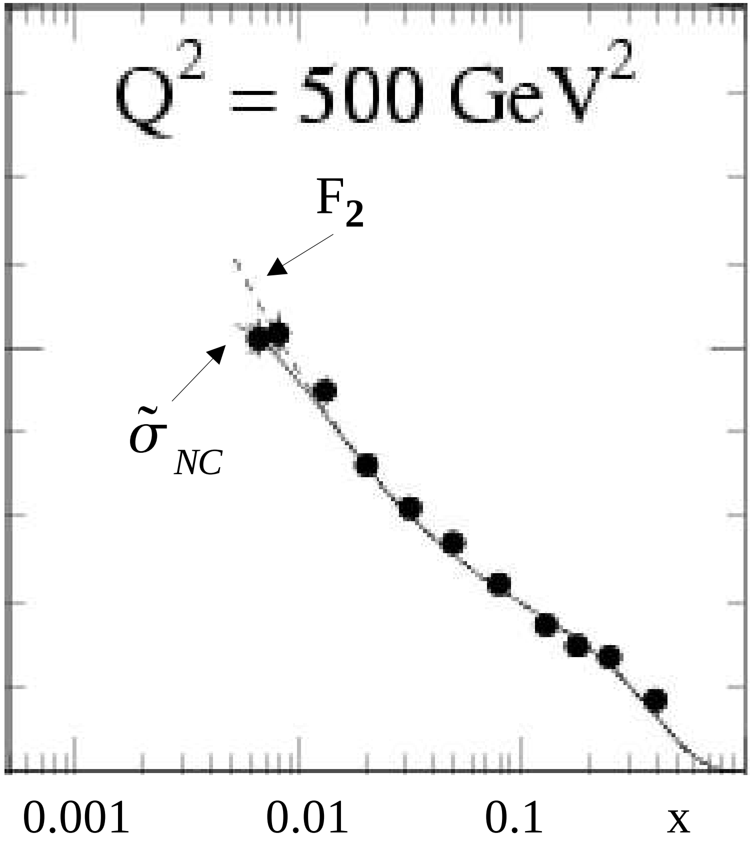
reduction of C at low Q^2 : $F_2 \to 0$ as $Q^2 \to 0$

This works phenomenologically − different behaviour at low Q^2 ?

The Longitudinal Structure Function F_L

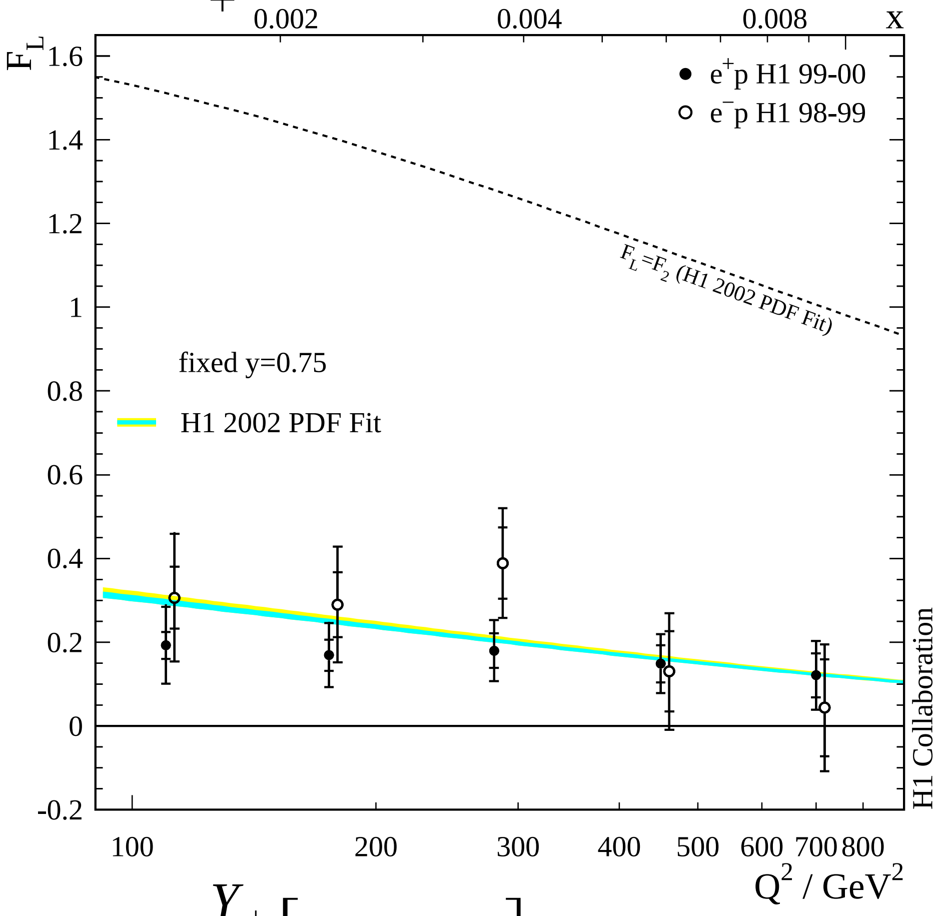
- In leading order QCD F_L is zero
- Only appears in NLO QCD
- Directly proportional to gluon distribution
- Are the scaling violations in F_2 due to the same gluons that give rise to F_L?

Determination of F_L – Extrapolation Method



$$\tilde{\sigma}_{NC} \approx F_2 - \frac{y^2}{Y_+} F_L$$

high y contribution



F_L extracted from cross section by extrapolating F_2 from QCD fit to y<0.35:

$$F_L = \frac{Y_+}{y^2}\left[F_2 - \sigma_{NC}\right]$$

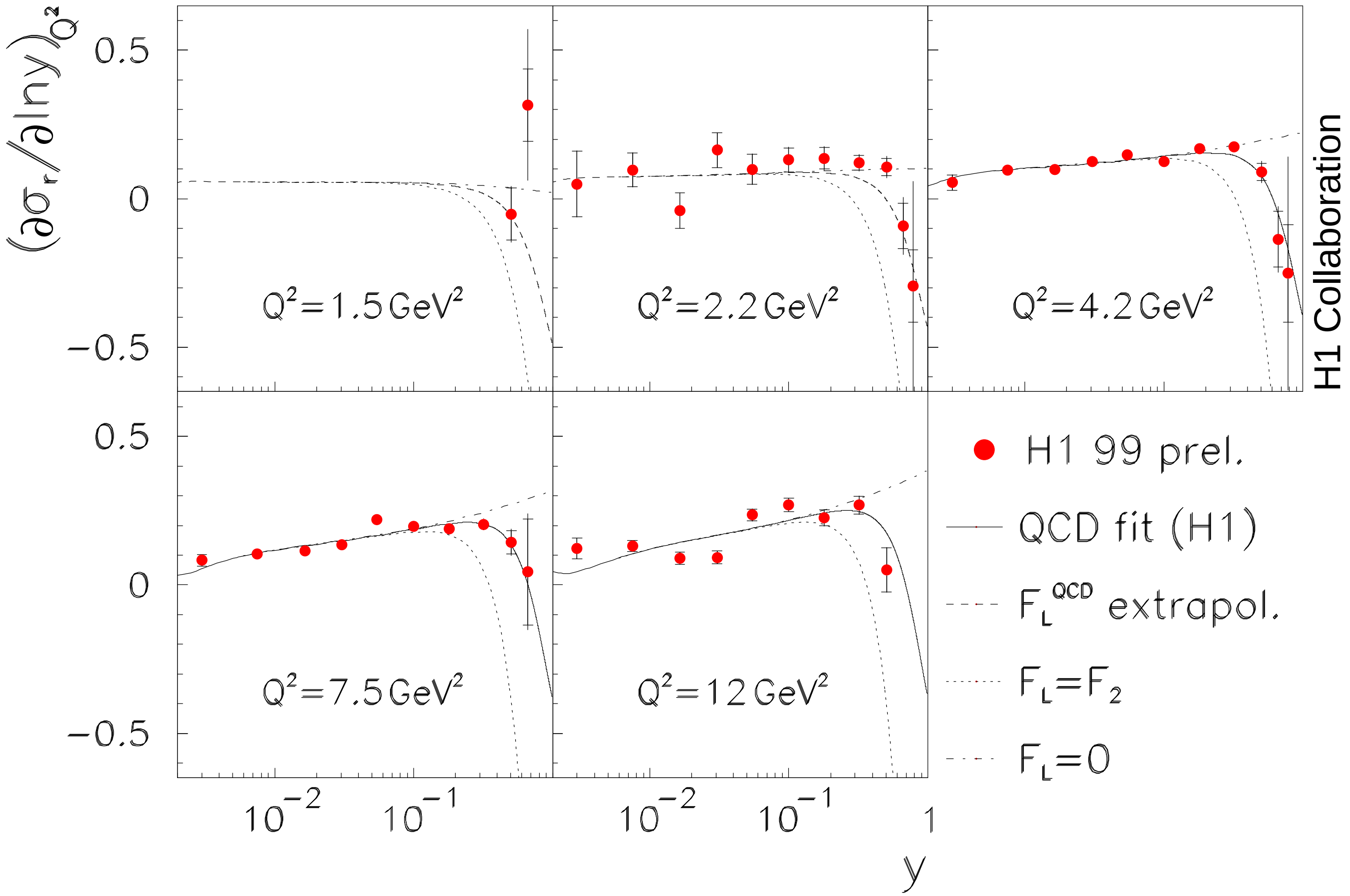
Determination of F_L − Derivative Method

At low Q^2 a QCD description of F_2 is difficult − use new method to extract F_L

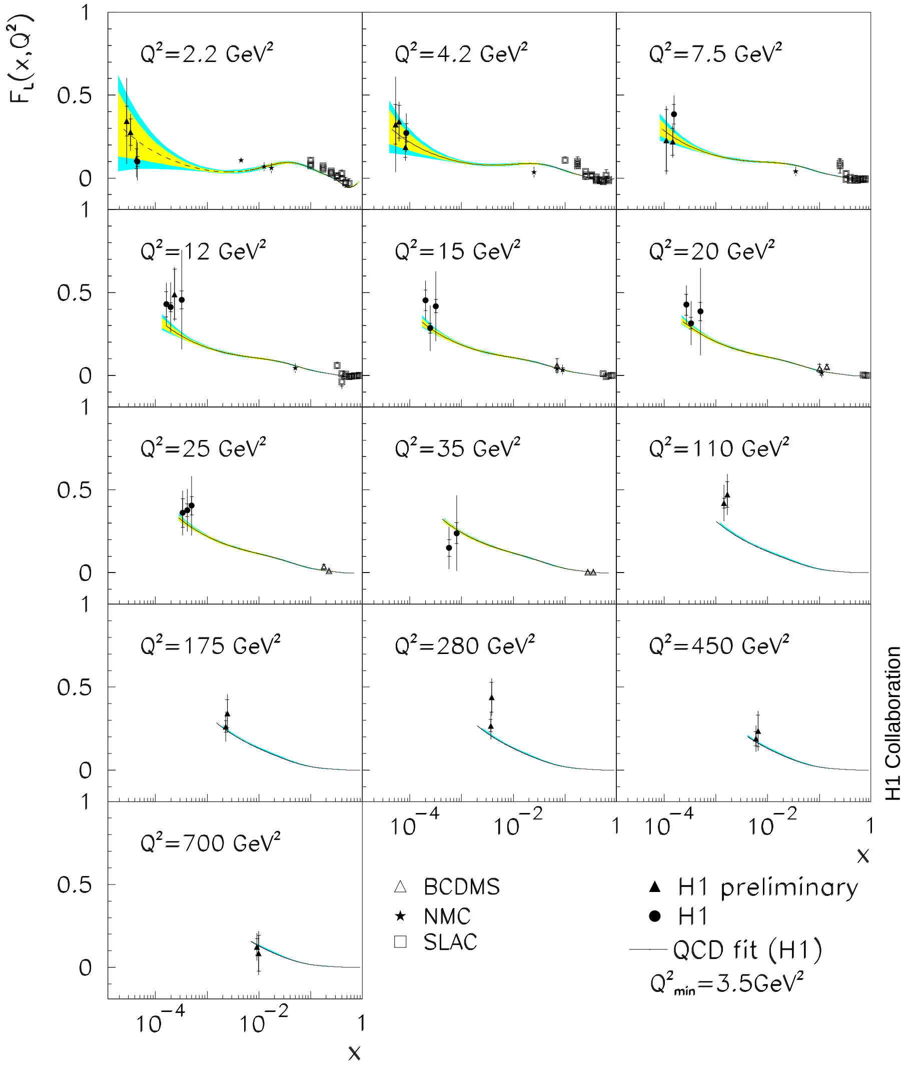
$$\frac{\partial \sigma_r}{\partial \ln y} \approx \frac{\partial F_2}{\partial \ln y} - 2F_L$$

as y → 1 for fixed Q^2

dominated by F_L term



F_L Extraction



F_L extracted over large range in Q^2 from 2.2 to 700 GeV^2 for the first time

QCD able to describe the data – consistency check

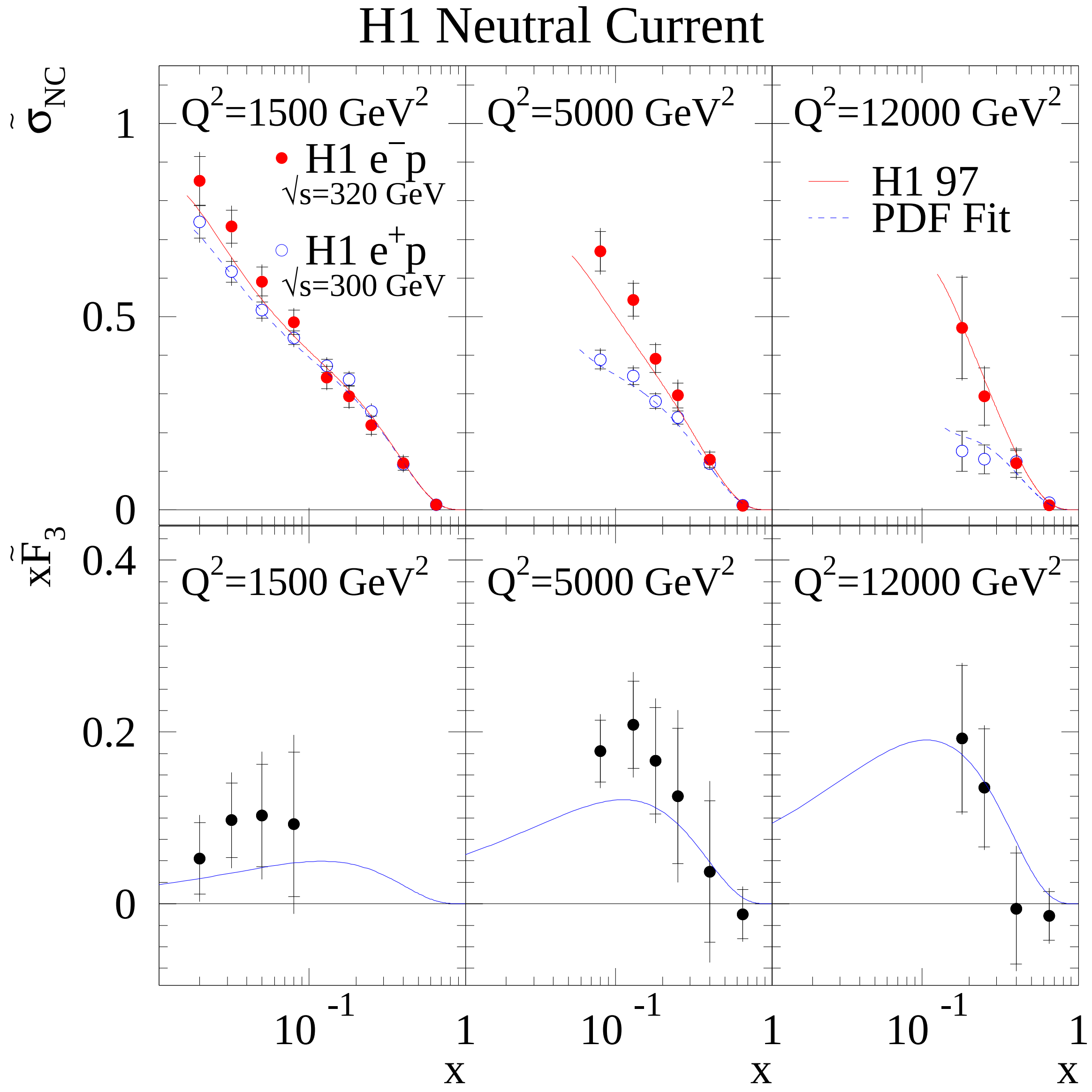
gluons derived from F_2 ARE the same gluons giving rise to F_L

Need change of beam energy for measurement of F_L

Valence Quarks and xF_3

- Measurement of valence quarks at high x is important
- Current knowledge comes from fixed target data
- Problematic: data precise − but subject to theoretical uncertainty
  - deuteron scattering − how to treat nuclear binding effects
  - non−perturbative effects also at low Q^2
  - effects of higher twist at low Q^2
- HERA data are free of these uncertainties
- Data at high Q^2 / large x constrain the valence quarks
- Problem is statistics (low cross section...)
- Also sensitive to EW effects − xF_3 only arises from Z exchange

First Measurment of xF_3 at HERA



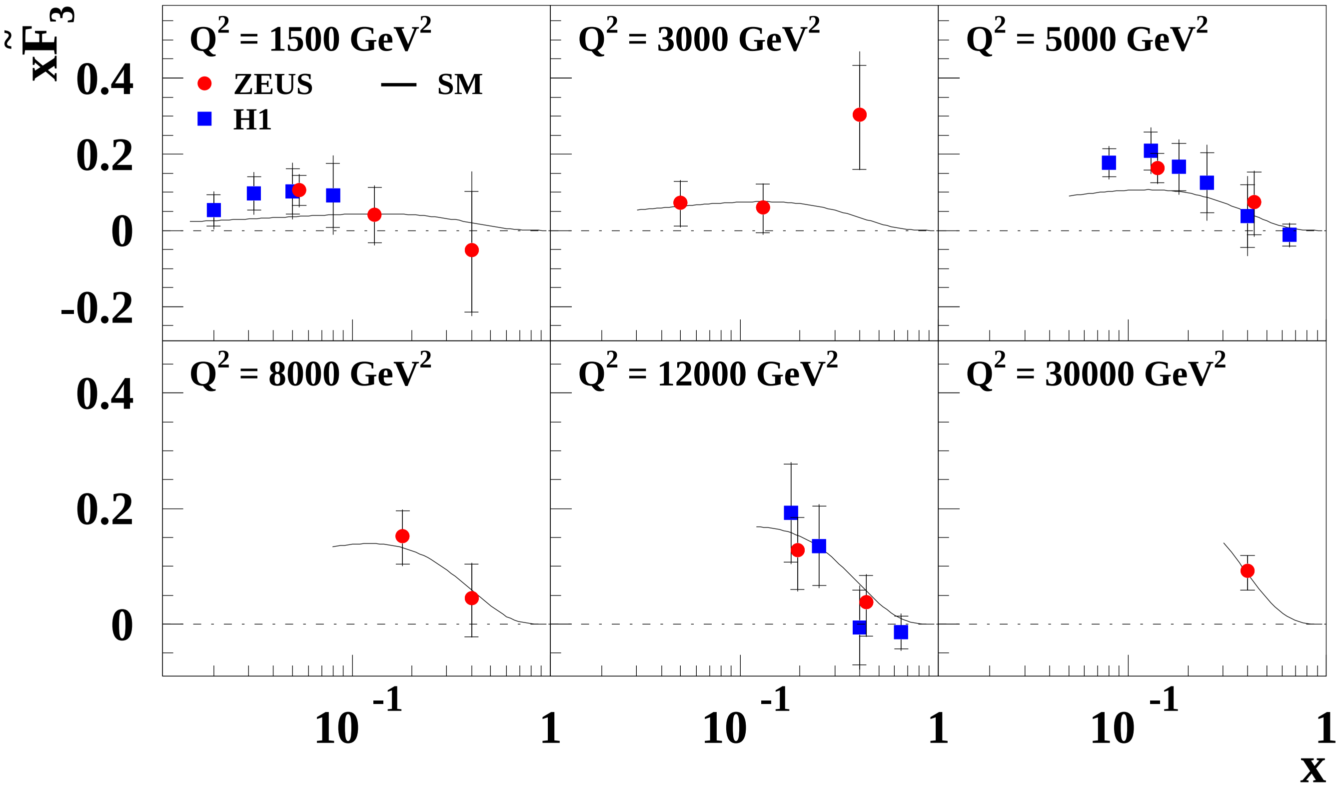
For $Q^2 > 1000$ GeV^2 F_L influence is small

Become sensitive to xF_3 and high x valence quarks

$$x\tilde{F}_3 \propto \sum_{quarks} (xq - x\bar{q})$$

Subtract e^+ from e^- NC cross sections

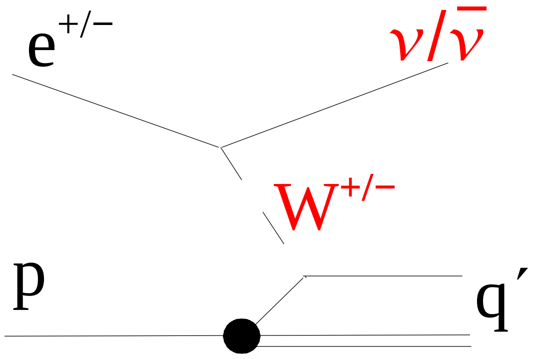
First Measurement of xF_3 at HERA



- HERA confirm valence quark structure
- Errors dominated by stat. error of e− sample

Clear need for high luminosity

Charged Current Cross Sections



L.O. CROSS SECTIONS

- $e^+p \rightarrow \bar{\nu}X$

Probe d valence

$$\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2}{2\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\left[\bar{u}+\bar{c}+(1-y^2)(d+s)\right]$$

- $e^-p \rightarrow \nu X$

Probe u valence

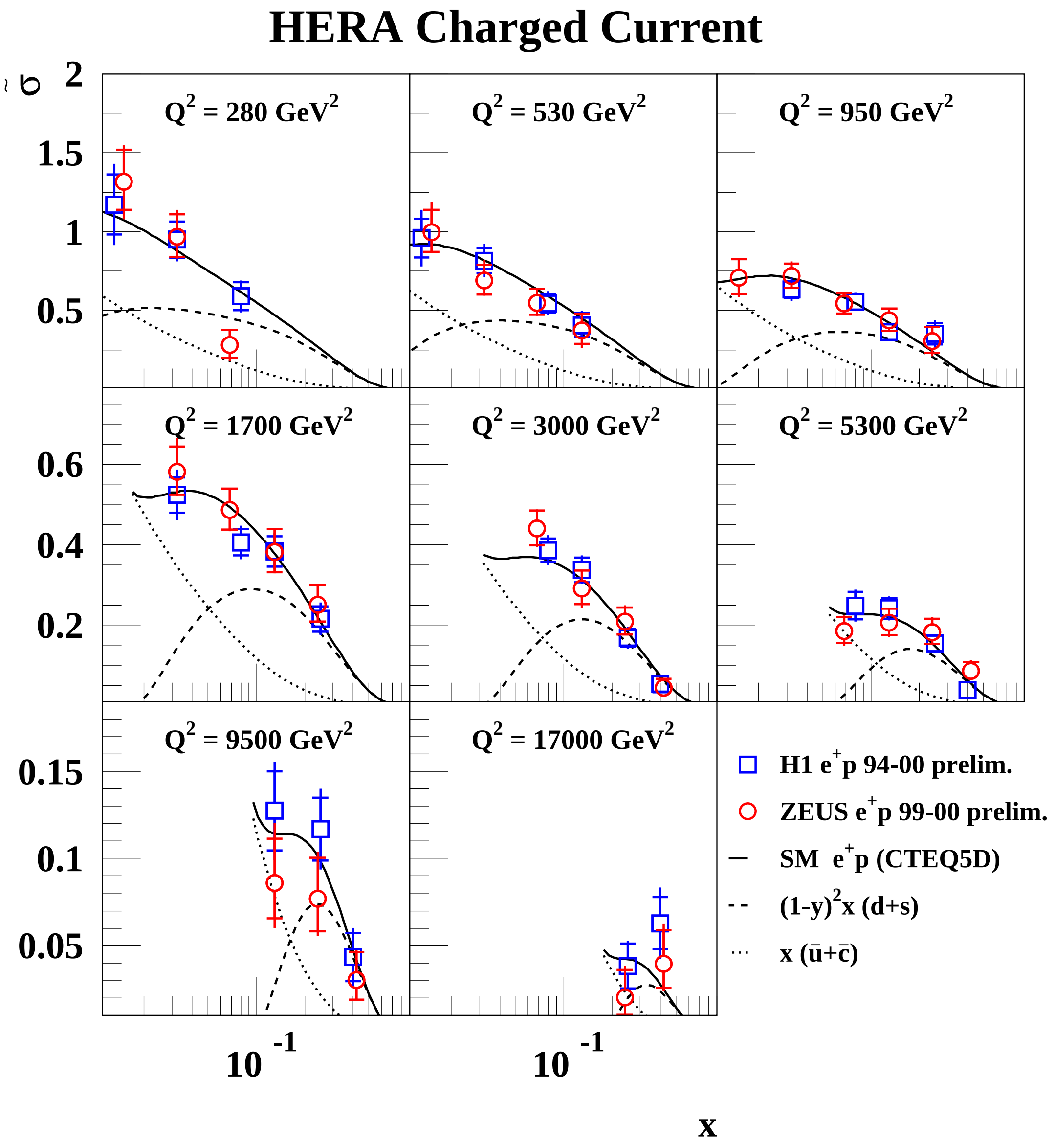
$$\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2}{2\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\left[u+c+(1-y^2)(\bar{d}+\bar{s})\right]$$

- **Sensitivity to separate parton densities**
- **Effect of W mass − from propagator**

Reduced Cross Section

$$\tilde{\sigma}_{CC} = \frac{2\pi x}{G_F^2}\left[\frac{Q^2+M_W^2}{M_W^2}\right]\frac{d^2\sigma}{dxdQ^2}$$

Charged Current Cross Sections

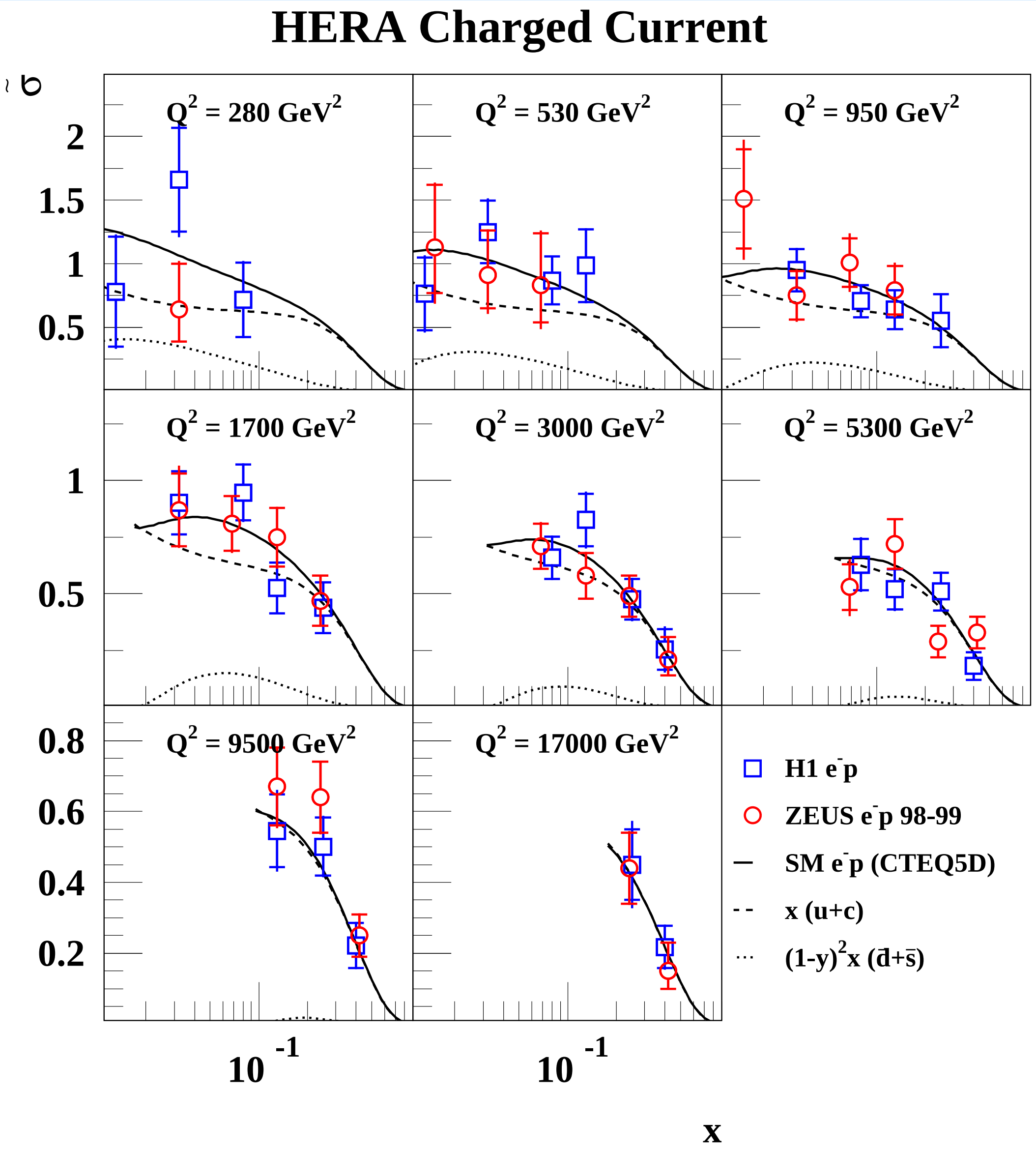


Current measurements limited by statistics

In agreement with global PDFs

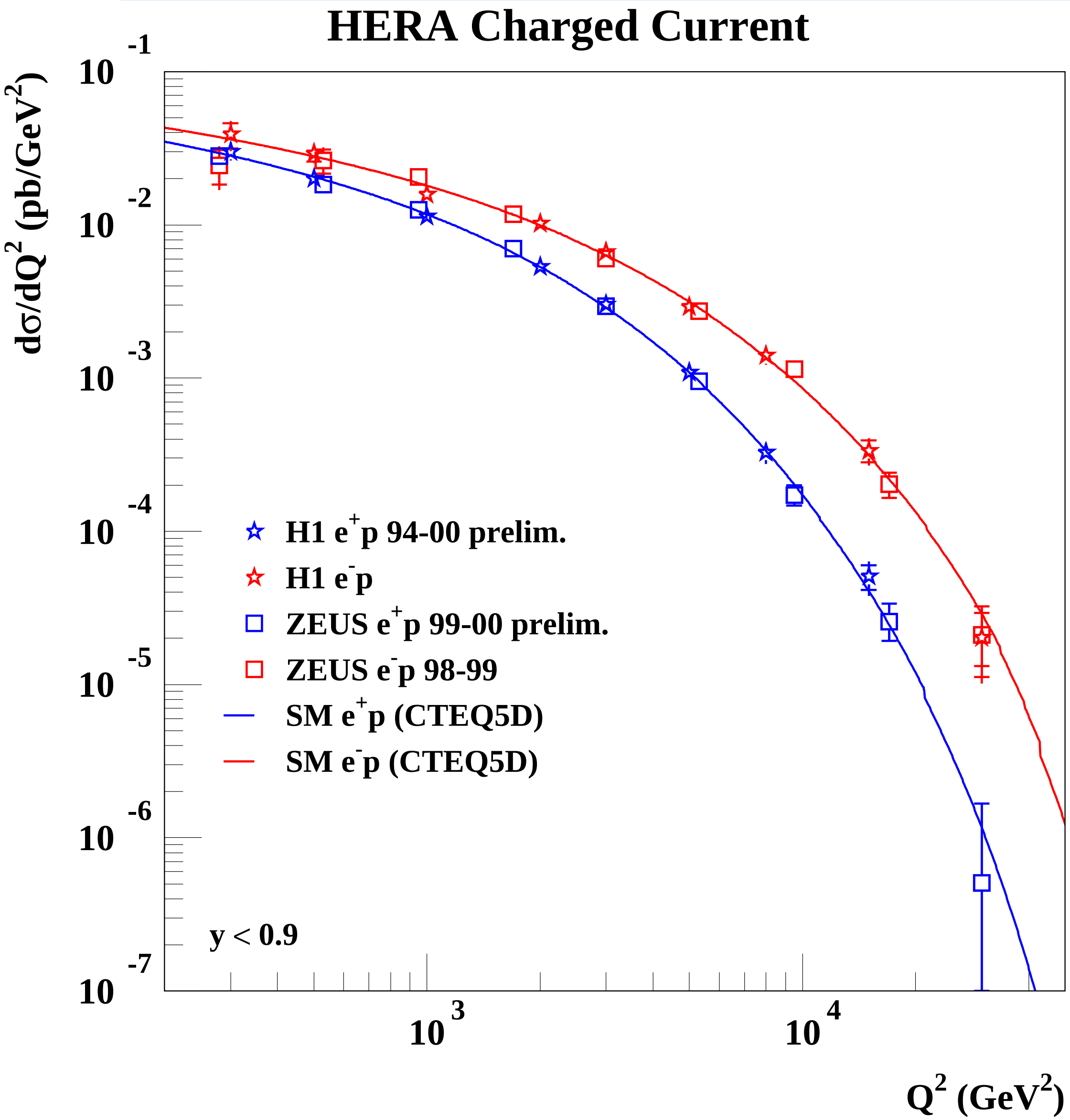
At high x direct sensitivity to xd_v

HERA Structure Function Measurements



At high x direct sensitivity to xu_v

HERA Structure Function Measurements



- CC Q^2 dependence shows sharp drop at highest Q^2

- Different for e^+p and e^-p due to different quark contributions

$$\frac{d\sigma}{dQ^2} \sim \left[\frac{M^2{}_W}{Q^2 + M^2{}_W}\right]^2$$

~ 1 at low Q^2

HERA Structure Function Measurements

- Use the Q^2 dependence to determine Mw in space−like region
- Independent check of SM consistency
- Fit the mass entering the CC propagator

$$\begin{array}{llllllll}
 & & & & \textbf{stat.} & \textbf{syst.} & \textbf{theo.} & \\
ZEUS & e^{+} & M_{W} = 81.4 & \pm & 2.7 \pm & 2.0 \pm & 3.3 & GeV \\
ZEUS & e^{-} & M_{W} = 80.3 & \pm & 2.1 \pm & 1.2 \pm & 1.0 & GeV \\
H1 & e^{+} & M_{W} = 80.9 & \pm & 3.3 \pm & 1.7 \pm & 3.7 & GeV \\
H1 & e^{-} & M_{W} = 79.9 & \pm & 2.2 \pm & 0.9 \pm & 2.1 & GeV
\end{array}$$

Measure total CC cross section:

$$Q^{2} > 1000 \;\; GeV^{2} \qquad y < 0.9$$

H1: $\sigma_{CC}^{tot}(e^{-}) = 43.08 \pm 1.84(stat.) \pm 1.74(syst.) \;\; pb$

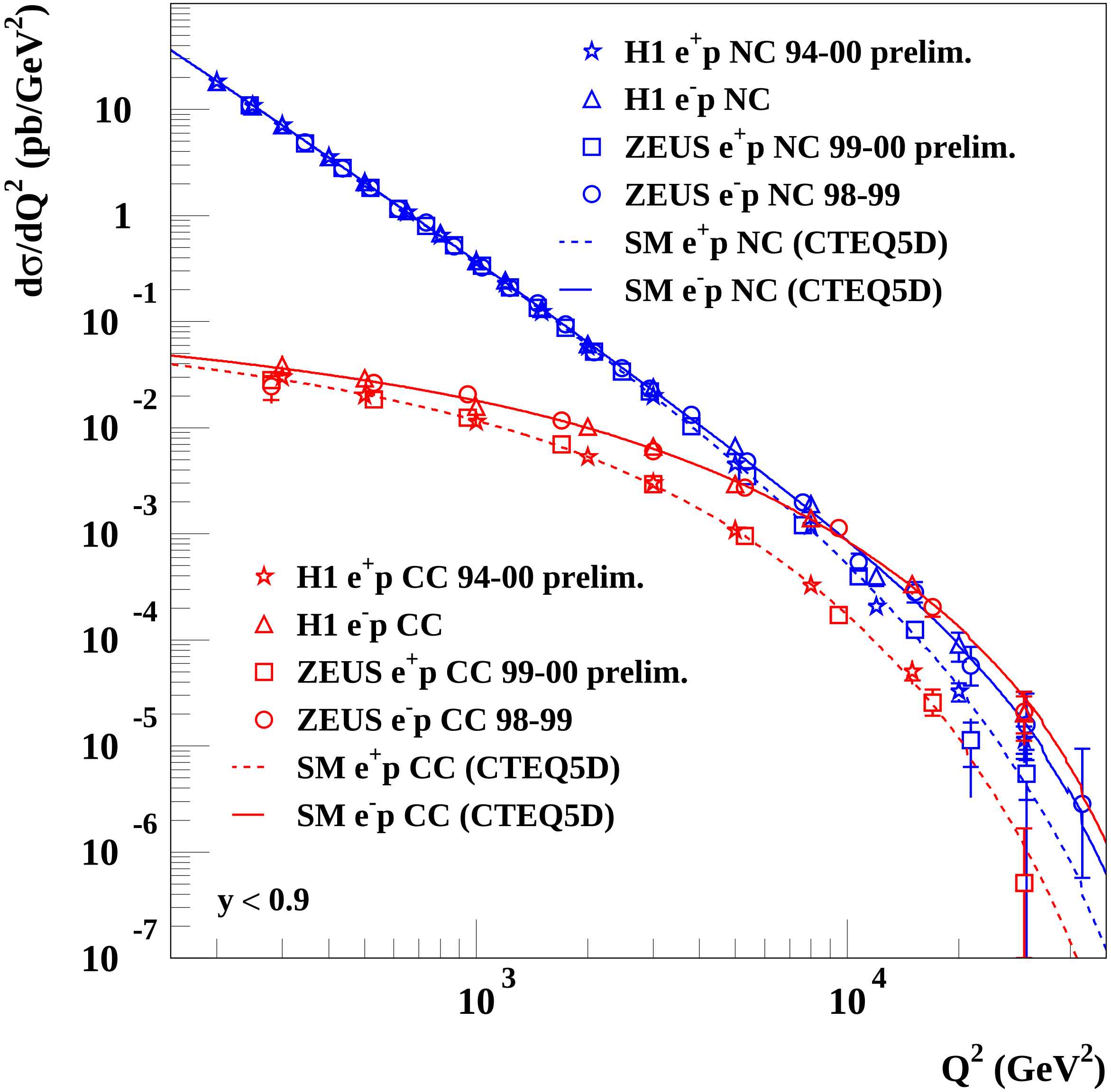
Standard Model: $\sigma_{CC}^{tot}(e^{-}) = 42.70 \pm 1.65 \;\; pb$

$$Q^{2} > 200 \;\; GeV^{2}$$

ZEUS: $\sigma_{CC}^{tot}(e^{+}) = 32.10 \pm 1.97(stat.) \,^{+0.78}_{-0.79}(syst.) \;\; pb$

Standard Model: $\sigma_{CC}^{tot}(e^{+}) = 32.50$

HERA Structure Function Measurements

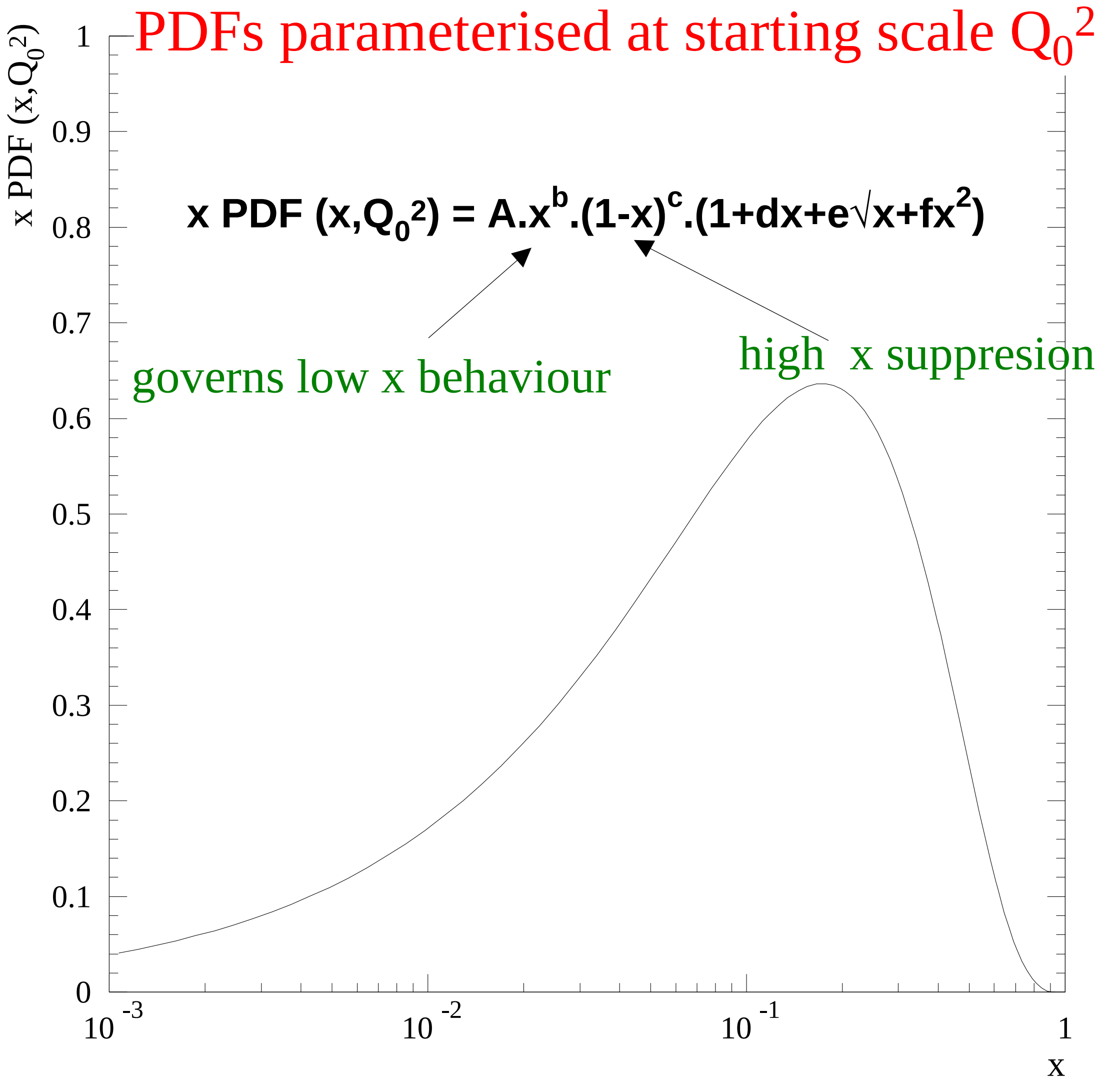


Measurement of Q^2 dependence of NC and CC cross−sections for e^+ and e^- scattering

Described by Standard Model over large Q^2 range

At Electroweak Unification is observed at $Q^2 \sim M_z^2 \sim M_w^2$

Parton Distribution Functions and α_s



PDFs parameterised at starting scale Q_0^2

$$x\,\mathrm{PDF}\,(x,Q_0^2) = A.x^b.(1-x)^c.(1+dx+e\sqrt{x}+fx^2)$$

governs low x behaviour

high x suppresion

- QCD does not predict x dependence of PDFs
- Must be extracted from data
- Accurate determinations of PDFs allow accurate SM predictions (for LHC etc)

parameters A,b,c,d,e,f optimised in fit for each PDF

some are constrained by sum rules (e.g. momentum sum=1)

Parton Distribution Functions and α_s

QCD analyses require many choices to be made

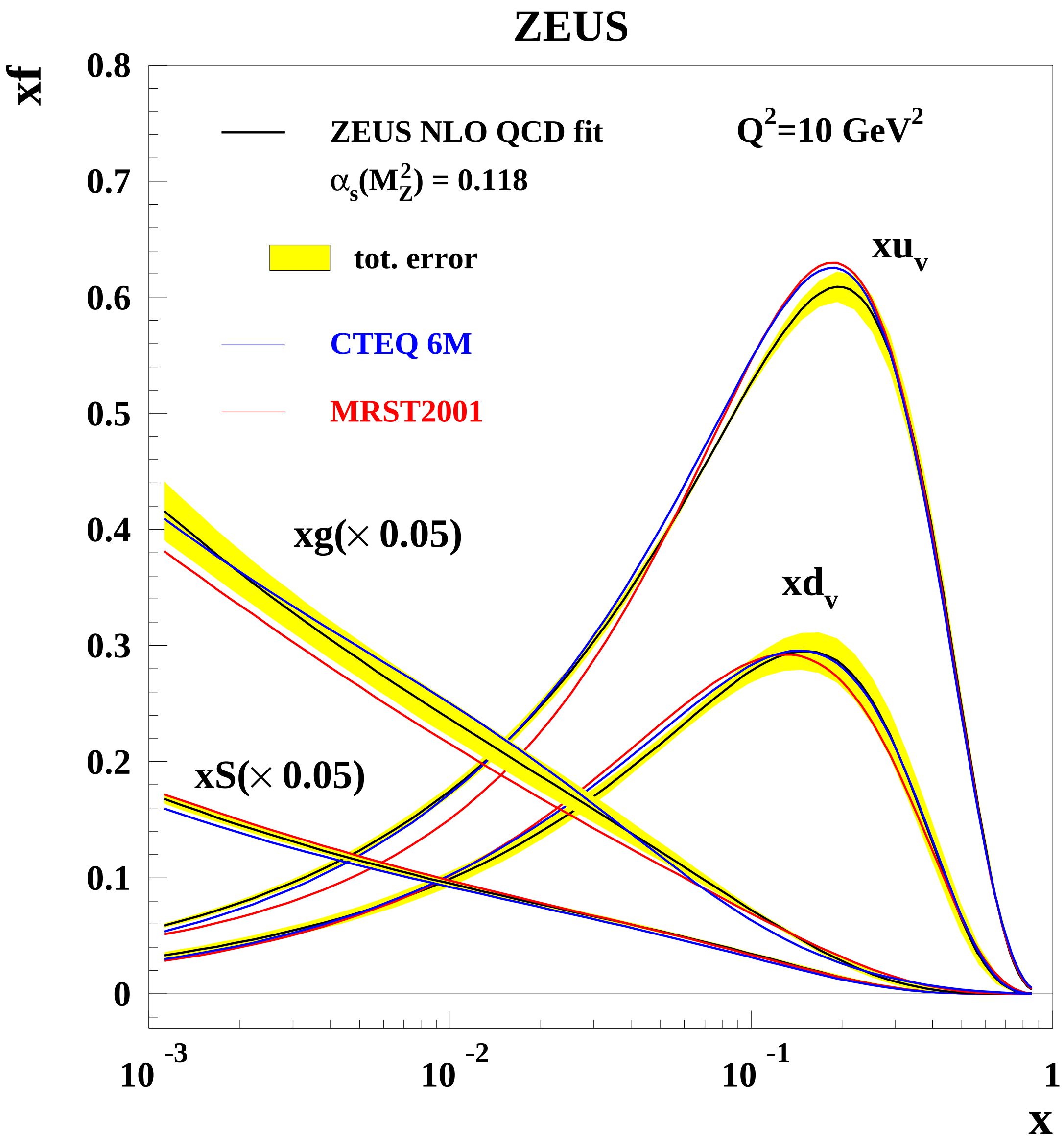
Should be reflected in PDF uncertainty:

- Q_0^2 starting scale
- Q^2_{min} of data included in fit
- Choice of data sets used
- Cuts to limit analysis to perturbative phase space
- Choice of densities to parameterise
- Treatment of heavy quarks
- Allowed functional form of PDF parameterisation
- Treatment of experimental systematic uncertainties
- Renormalisation / factorisation scales
- etc...

ZEUS QCD Analysis

- ZEUS perform a new global analysis − use world structure function data
  - ZEUS 96/97 NC e^+ reduced cross sections → gluon / quarks at low x / Q^2
  - F_2 NMC p &D and ratio F_2 D/p → quarks at medium x
  - F_2 E665 p & D → quarks at medium x
  - F_2 BCDMS p only → u quarks at high x / low Q^2
  - xF_3 CCFR ($0.1 < x < 0.65$) → valence quarks at high x / low Q^2
- Standard xg, xu_v, xd_v, Sea, x(db−ub) decomposition of p^+
- $Q^2_0 = 7\ \mathrm{GeV}^2$ / $Q^2_{min} = 2.5\ \mathrm{GeV}^2$
- Impose conventional sum−rules (momentum & quark counting)
- Additional constraints on valence quark parameters ($b_{uv}=b_{dv}=0.5$)
- Use funtional form = $A\ .\ x^b \cdot (1-x)^c \cdot\ (1 + dx + e\sqrt{x})$
- Experimental systematic uncertainties are propagated onto final PDF uncertainty
- Use Thorne/Roberts variable flavour number scheme.
- x(db−ub) params taken from MRST − only normalisation free in fit.

ZEUS PDFs



ZEUS global analysis in agreement with CTEQ/MRST

$\Delta xg \sim 10\%$ for $Q^2 > 20$ GeV²

xg/F_L negative for $Q^2 \sim 1$ GeV²

Can set α_s free in fit:

$$\alpha_s(M_z) = 0.1166 \pm \overset{\text{stat}}{0.0008} \pm \overset{\text{sys}}{0.0048} \pm \overset{\text{model}}{0.0018}$$

scale uncertainty +/− 0.004

H1 QCD Analysis

Different approach: Minimise theory uncertainty − minimise data sets

- Perform dedicated QCD analysis for simultaneous α_s and xg fit at low x / Q^2.
- Use precise H1 and BCDMS−p F_2 data to constrain valence region.
- Check consistency of data sets.
- Tune fitted PDFs to measured cross sections.

no nuclear corrction required

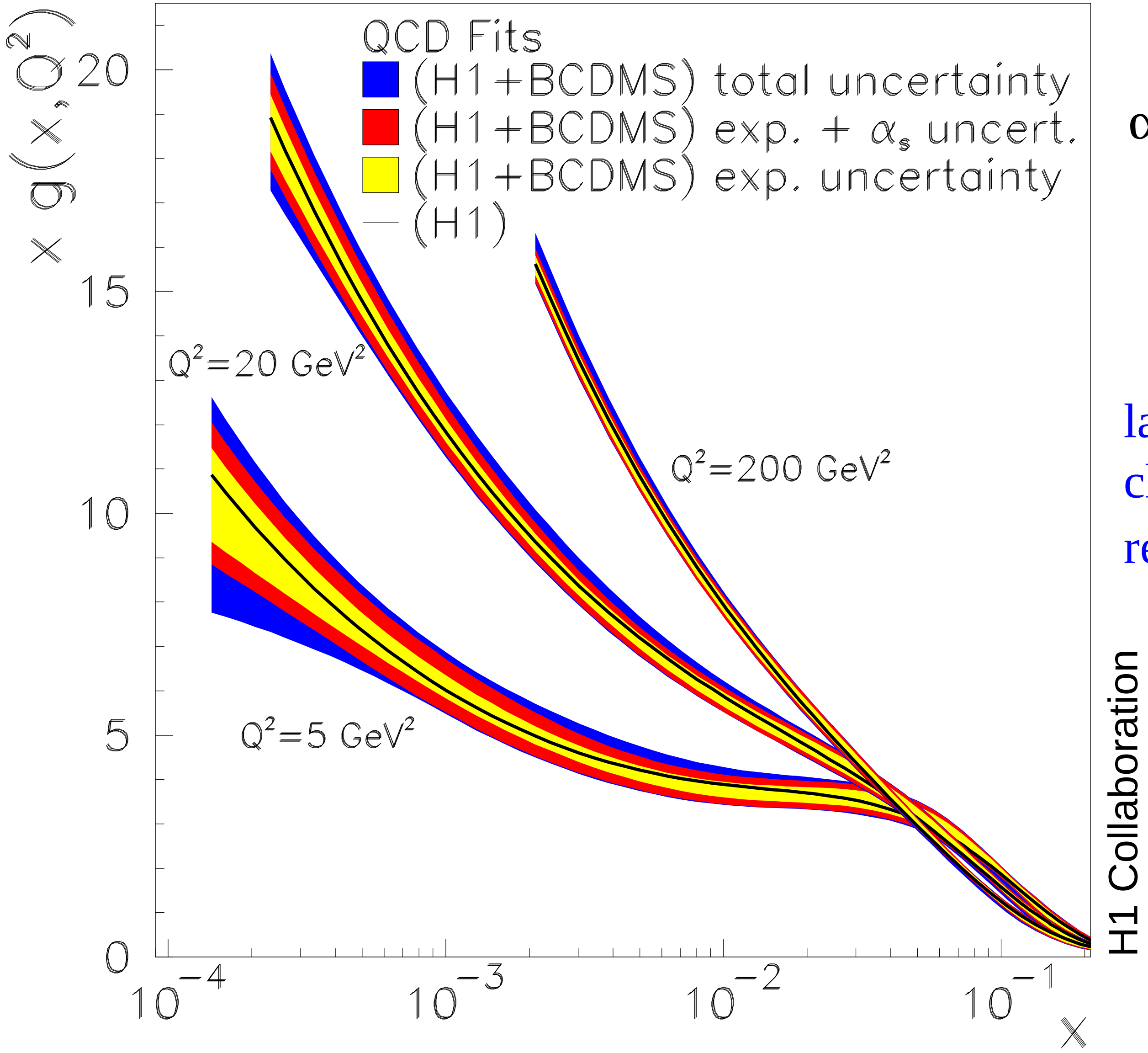
  - xg
  - $xV = \frac{9}{4}u_v + \frac{3}{2}d_v$
  - $xA = \bar{u} + \frac{1}{4}(u_v - 2d_v)$

$$F_2 = \frac{1}{3}xV + \frac{11}{9}xA$$

used for systematic checks

- Use parametric form of: $A.x^{b} \cdot (1-x)^{c} \cdot (1 + dx + e\sqrt{x} + fx^{2})$
- Use 3−flavour number scheme − optimal choice in region of precision H1 data
- Experimental systematics are fitted → PDF error bands
- Apply sum / counting rules

H1 Gluon and $\alpha_s(M_Z)$



α_s fixed get Δxg ~ 3% Q^2 ~ 20 GeV^2

exp. model

$$\alpha_s(M_Z) = 0.1150 \pm 0.0017 ^{+0.0009}_{-0.0005}$$

large additional model unc. due to change in μ_f ⇒N−NLO theory required!

HERA PDFs

H1 and ZEUS have analysed complete HERA data set:

NC & CC e+ data $\sqrt{s}=300$	(94−97)	35 pb^{-1}
NC & CC e− data $\sqrt{s}=320$	(94−97)	16 pb^{-1}
NC & CC e+ data $\sqrt{s}=320$	(94−97)	65 pb^{-1}
NC data at low $Q^2 < 100$	(96−97)	

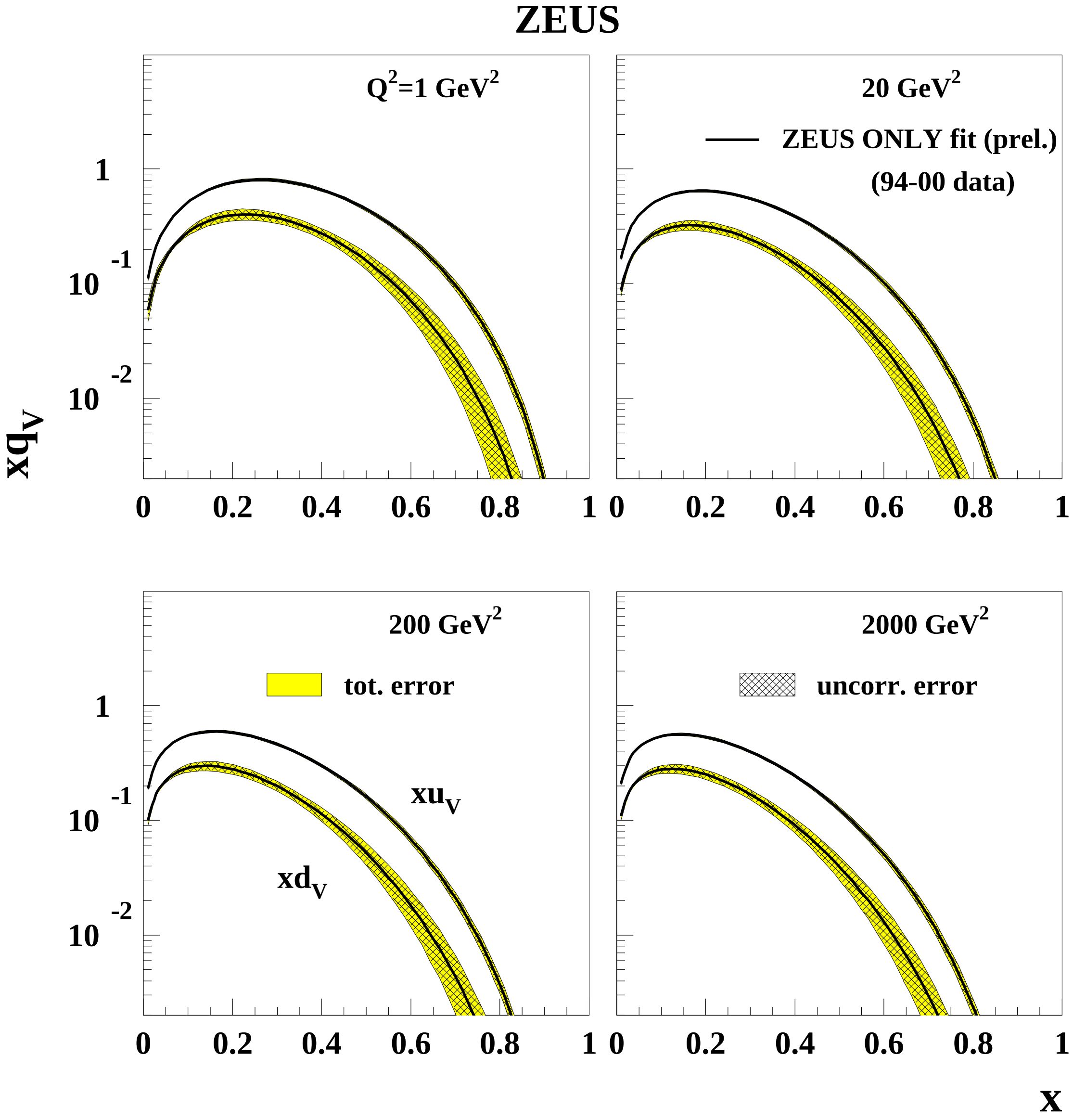
NC & CC data with different lepton charges provides quark flavour sensitivity

xg and Sea distributions determined by low x / Q^2 HERA F_2 data

xu_v determined from high x NC data

xd_v determined from high x CC e+ data

HERA PDFs

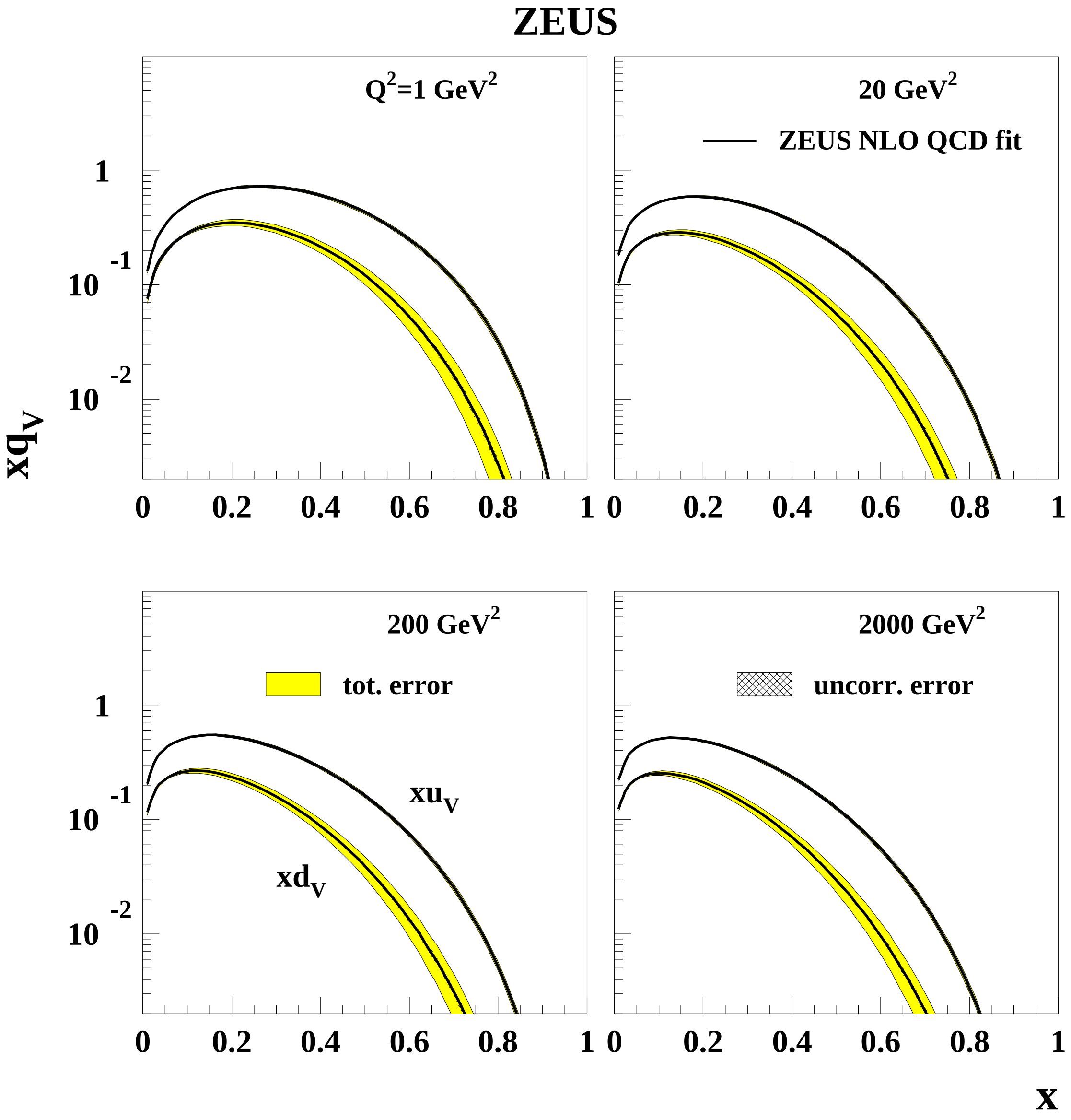


Fit to ZEUS data only: HERA data provide valence constraint

xd_v found to be larger but in agreement

low x parameters fixed in PDF fit

HERA PDFs



Fit to ZEUS data + global DIS data -
smaller uncertainty ~ factor 2

HERA PDFs

H1 perform a dedicated fit: tune fitted PDFs to NC/CC cross section sensitivity:

$$\begin{aligned} xU &= xu + xc \\ xD &= xd + xs \\ x\bar{U} &= x\bar{u} + x\bar{c} \\ x\bar{D} &= x\bar{d} + x\bar{s} \\ &xg \end{aligned}$$

$$u_v = U - \bar{U}$$

$$d_v = D - \bar{D}$$

$$F_2 = \frac{4}{9}(xU + x\bar{U}) + \frac{1}{9}(xD + x\bar{D})$$

$$\tilde{\sigma}^{+'}_{CC} = x\bar{U} + (1-y)^2 xD$$

$$\tilde{\sigma}^{-'}_{CC} = xU + (1-y)^2 x\bar{D}$$

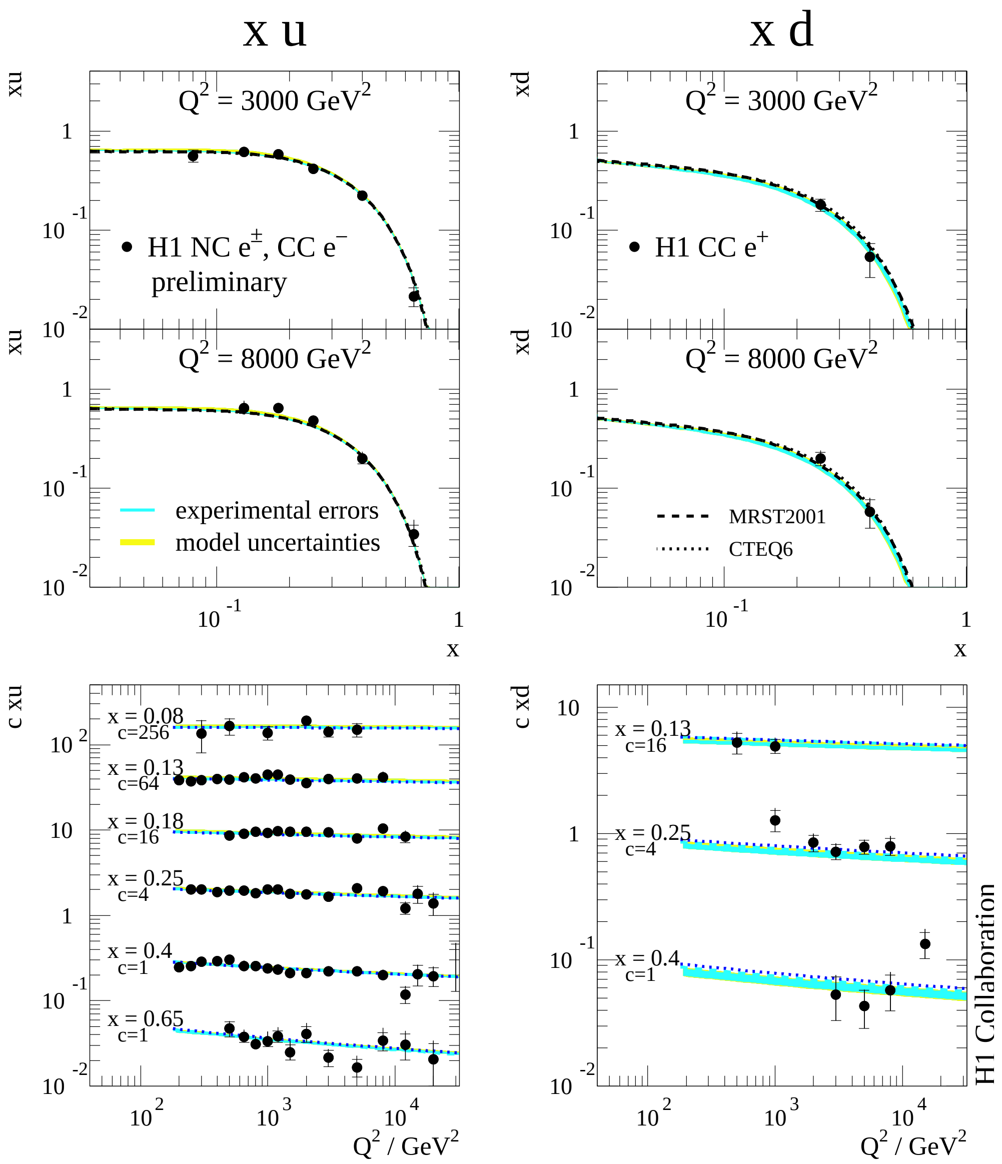
F_2^N requires additional small assumption on fraction of charm and strange

Perform fit in massless scheme − appropriate for high Q^2

Careful choice of parameterisations $(1 + Ex + D\sqrt{x} + Fx^2)$

Include BCDMS p and D data

HERA PDFs



Fit provides tight constraint on xu and xd at high x

xd ~ 9%

xu ~ 1% at x=0.4

Can compare fit result with local extraction method:

Use cross section measurements at high x dominated (>70%) by xu or xd

Insensitive to QCD evolution effects

Complementary to QCD fit

Summary

- First phase of HERA has yielded mass of interesting results
- Analysis of all structure function data is (almost) complete
- Precision of ~2−3 % achieved for F_2
- HERA data provide consistent picture of the proton from NC / CC/ xF_3 / F_L / F_2
- α_s extracted from DIS data − competetive with world average
- Measurements cover 5 orders of magnitude in Q^2 and x − probe structre of matter at scale of 10^{-18} m
- QCD abe to describe data
- Fits allow HERA data to constrain PDFs − require more data
- HERA upgrade now in full swing − awaiting 1 fb^{-1}