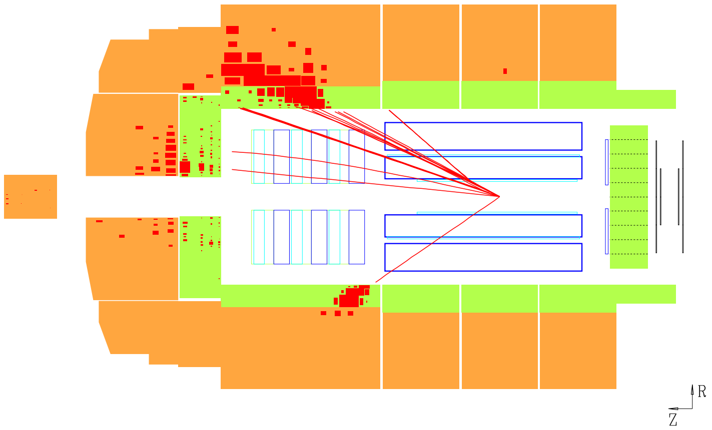
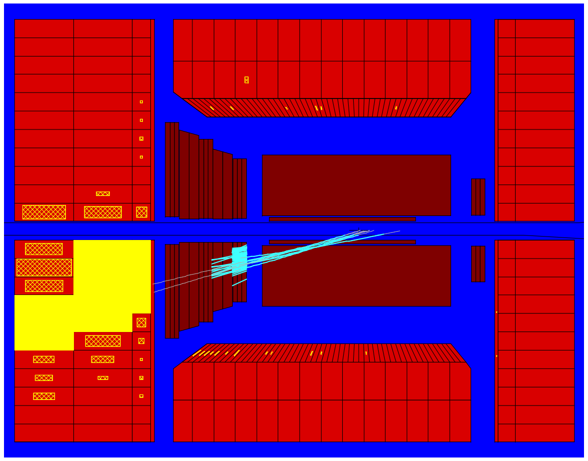
Deep Inelastic Lepton-Nucleon Scattering at HERA



Paul Newman   Birmingham University

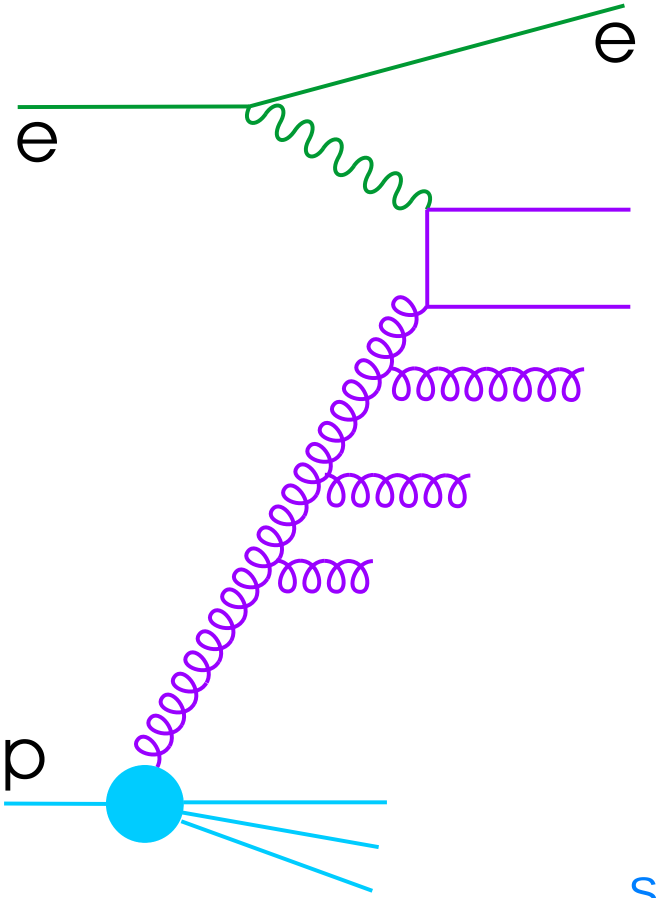


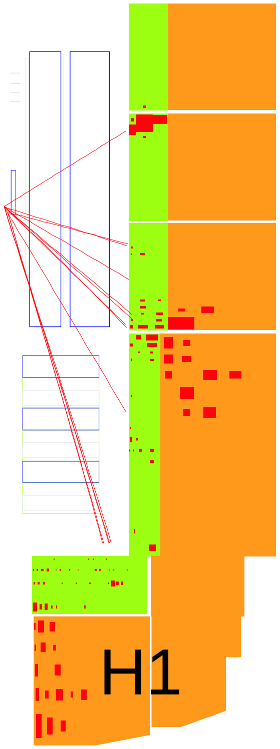
- **DIS and Proton Structure**
- **DIS pushing the boundaries of pQCD**

Lepton Photon 2003   FNAL

HERA: QCD from the established to the “speculative”

Precise electron and hadron reconstruction over wide rapidity range





Structure Functions → This talk

Precision QCD tests → R Hirosky

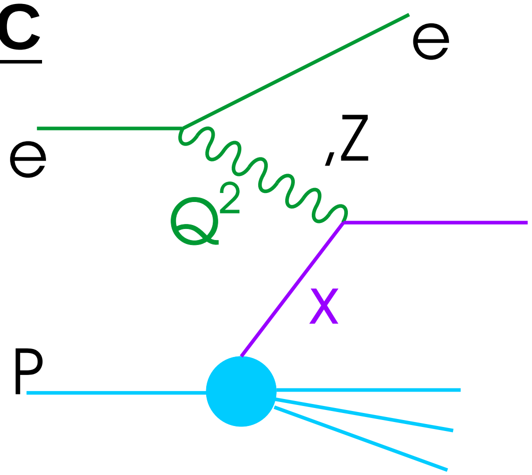
Parton dynamics

Rapidity Gaps, Diffraction → Y Yamazaki

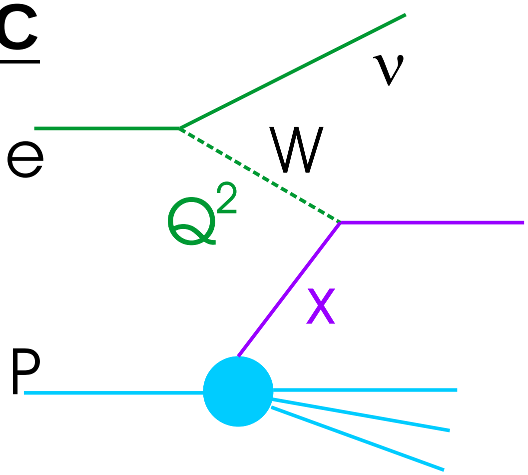
Searches at highest $\sqrt{s}$ with intial state lepton → E Perez

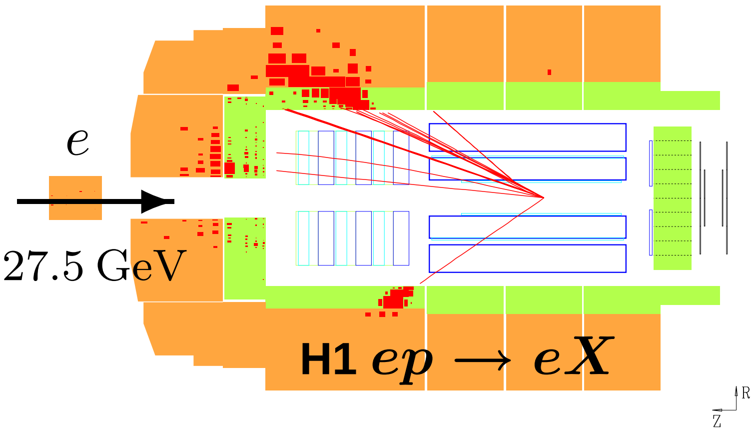
HERA Kinematics

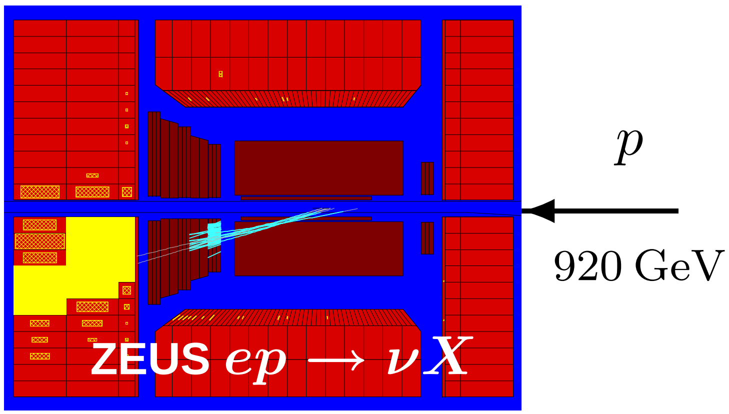
NC



CC







$Q^2 = -\gamma^2 = -(e - e')^2$ $(0 < Q^2 < 10^5 \text{ GeV}^2)$

$x = Q^2/(2p \cdot e)$ $(10^{-6} < x < 1)$

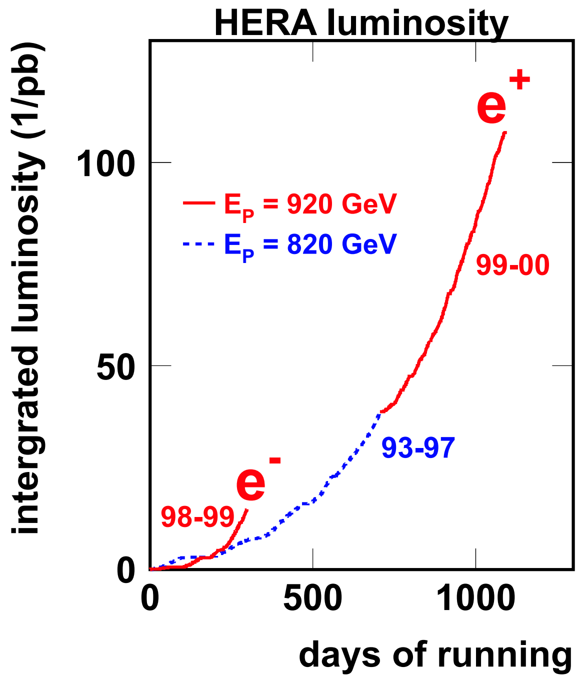
$y = (p \cdot \gamma)/(p \cdot e)$

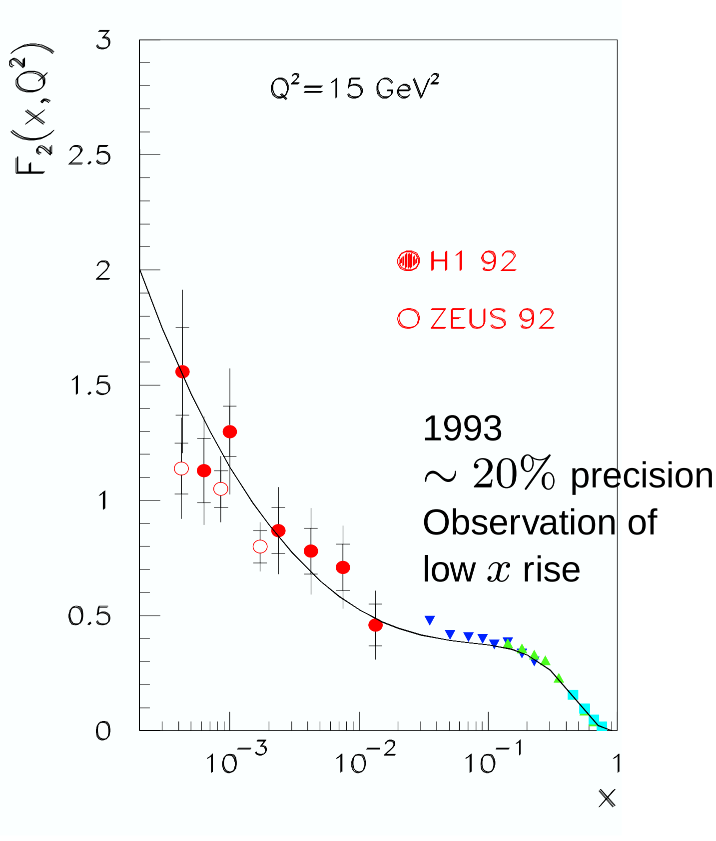
$W^2_{\gamma^* p} \sim Q^2/x$ (Low x $\longrightarrow$ $W_{\gamma^* p} \lesssim 300 \text{ GeV}$)

Sensitive to structures

on scales $\gtrsim 10^{-18}$ m

HERA-I Run: 1992-2000

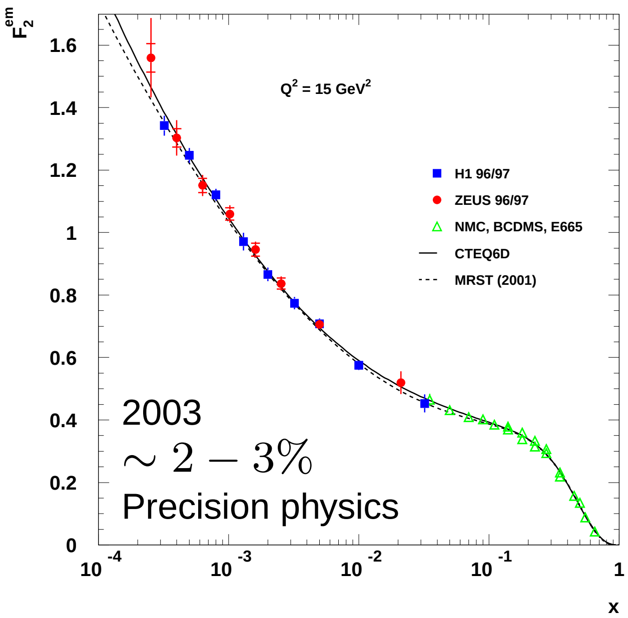




1993

$\sim 20\%$ precision

Observation of low x rise



2003

$\sim 2-3\%$

Precision physics

$\sim 100\ \mathrm{pb}^{-1}$ per experiment e^+p

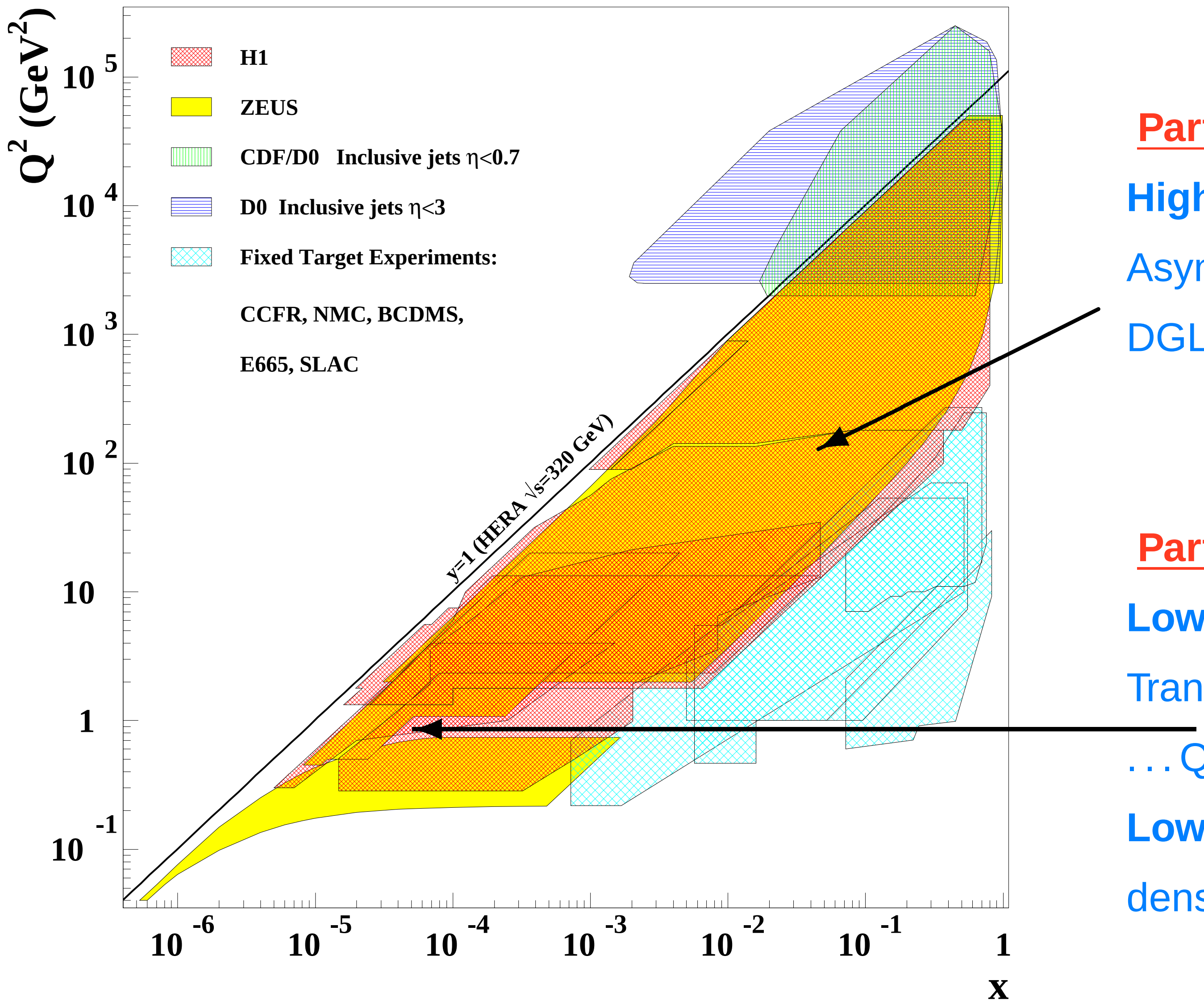
$\sim 15\ \mathrm{pb}^{-1}$ per experiment e^-p

Sufficient for precision measurements at low/medium Q^2, x

Glimpse at potential of highest Q^2, x region

to be studied at HERA-II from Sept ’03

Kinematic Plane



Part 1

High Q^2, high x

Asymptotic freedom

DGLAP evolution $\longrightarrow$ PDFs

Part 2

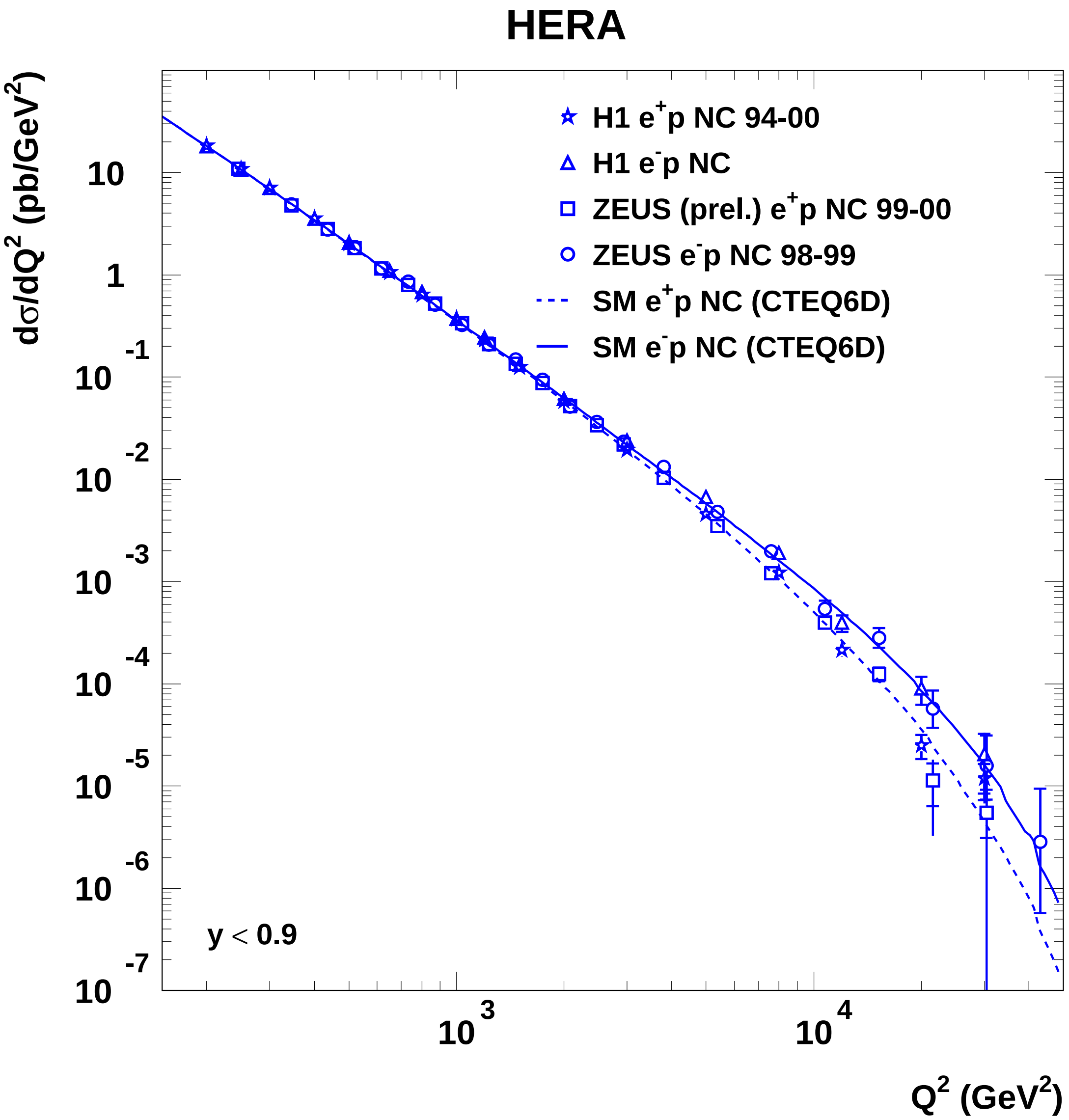
Low $Q^2 \sim 1\,\mathrm{GeV}^2 \ldots$

Transition to hadronic physics

. . . QCD and confinement

Low x . . . High parton densities, novel QCD dynamics?

High Q^2 Neutral Current Cross Section



Neutral current cross sections

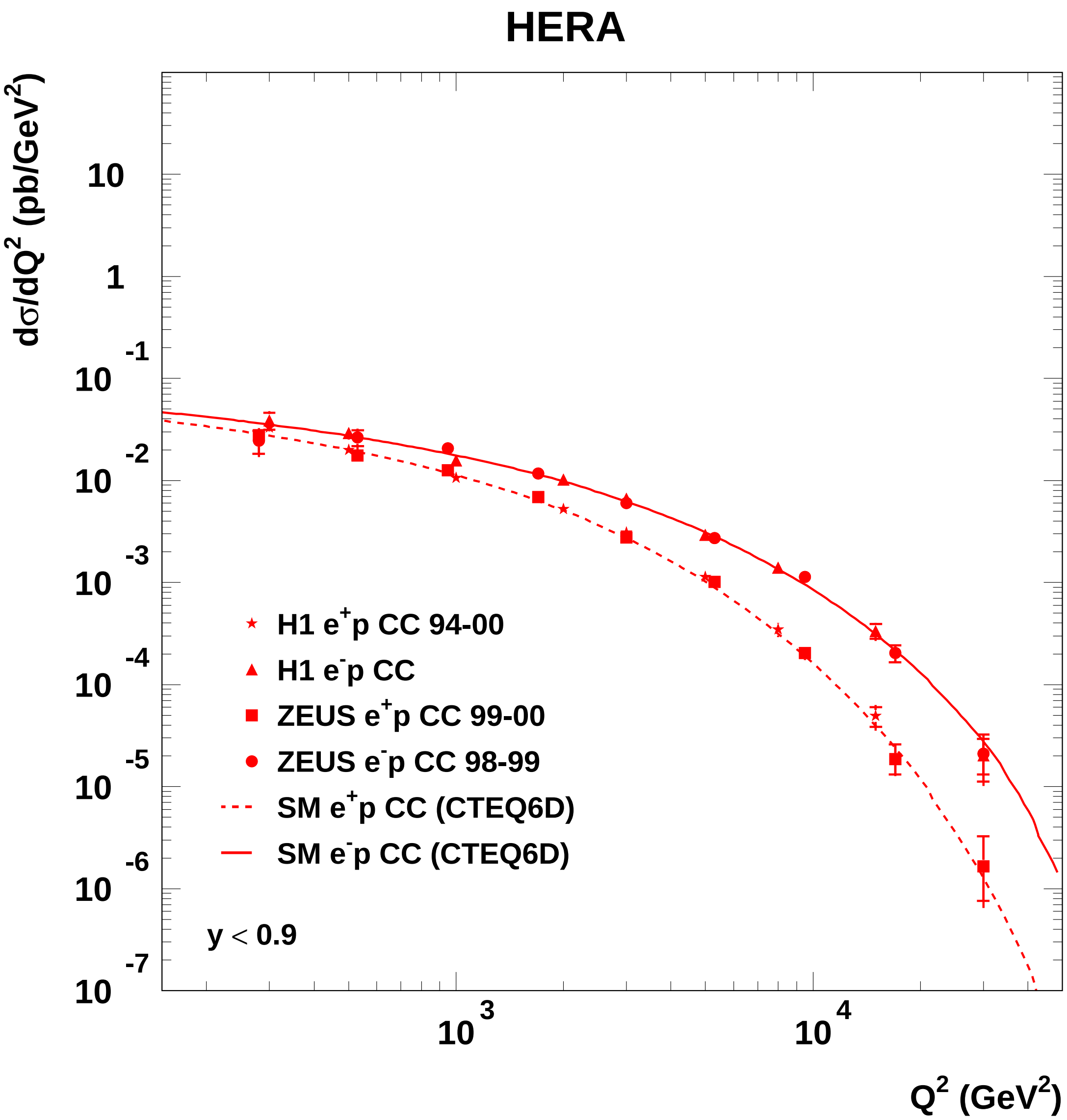
$$\frac{\mathrm{d}\sigma^{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} \sim \alpha_{\mathrm{em}}^2 \cdot \left(\frac{1}{Q^2}\right)^2 \cdot \frac{1}{x} \cdot \tilde{\sigma}_{\mathrm{NC}}$$

Photon dominated

Propagator

$\tilde{\sigma}_{\mathrm{NC}}$ contains helicity factors, weak terms and structure functions

High Q^2 Charged Current Cross Section

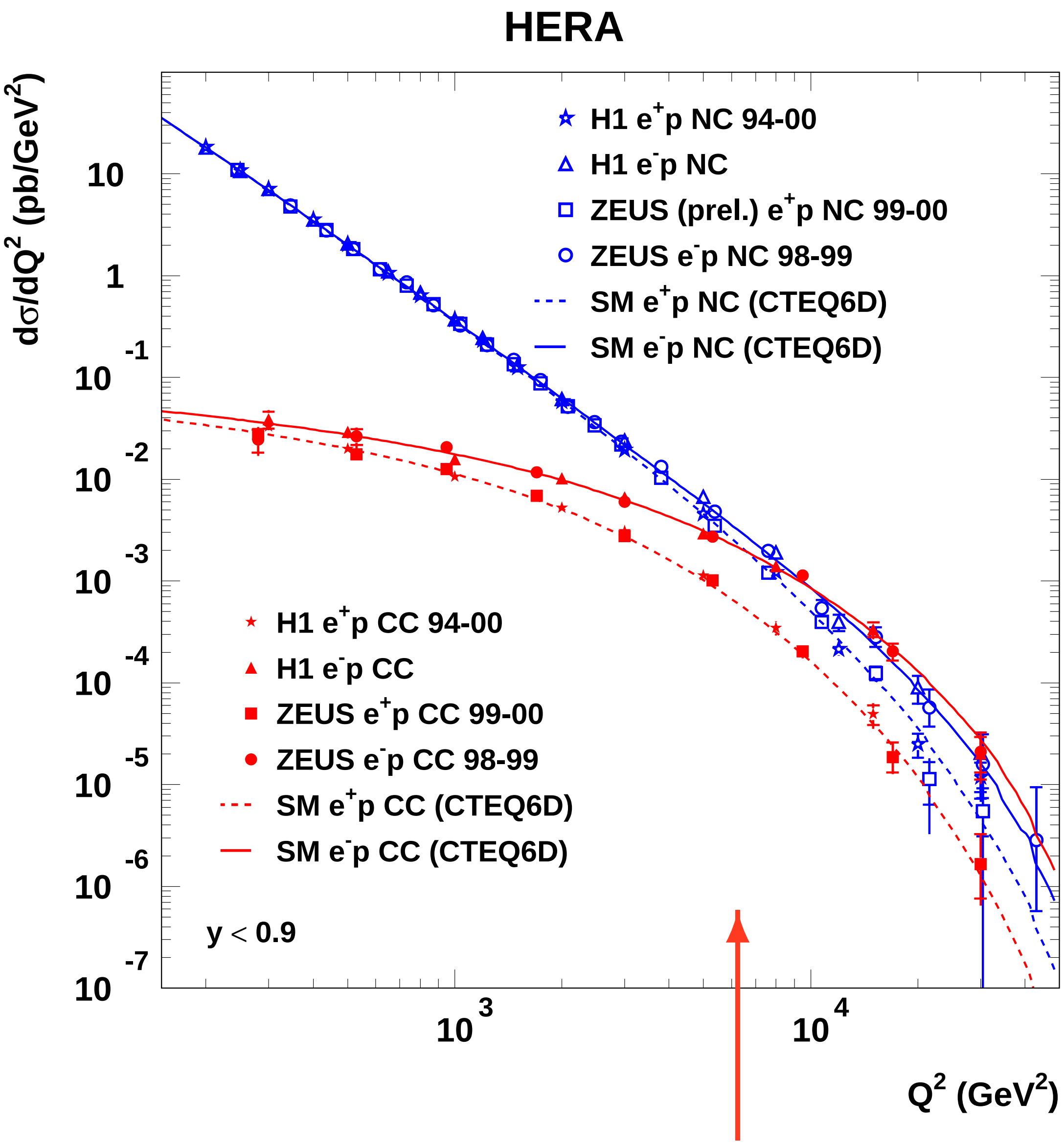


Charged current cross sections

$$\frac{d\sigma^{CC}}{dx dQ^2} \sim \underbrace{G_F^2 M_W^4}_{\text{Pure weak}} \cdot \underbrace{\left(\frac{1}{Q^2+M_W^2}\right)^2}_{\text{Propagator}} \cdot \frac{1}{x} \cdot \tilde{\sigma}_{CC}$$

$\tilde{\sigma}_{CC}$ contains helicity factors and structure functions

High Q^2 and Electroweak Unification



$Q^2 \sim M_W^2, M_Z^2$

Neutral current cross sections

$$\frac{d\sigma^{NC}}{dx dQ^2} \sim \alpha_{em}^2 \cdot \left(\frac{1}{Q^2}\right)^2 \cdot \frac{1}{x} \cdot \tilde{\sigma}_{NC}$$

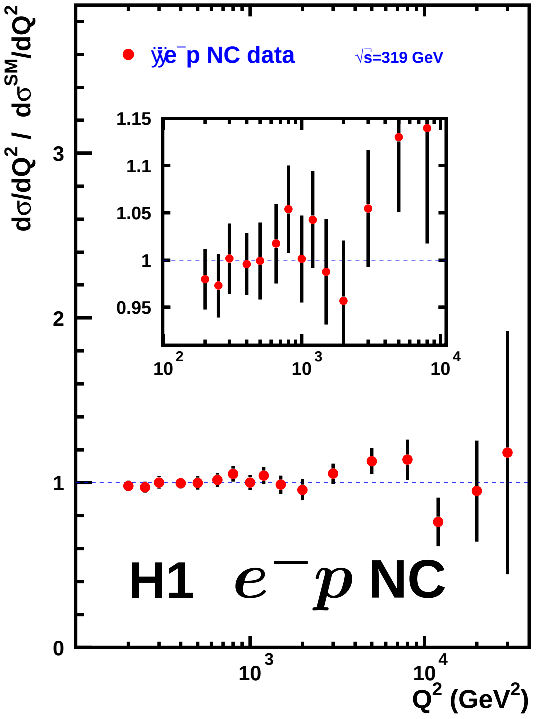
Charged current cross sections

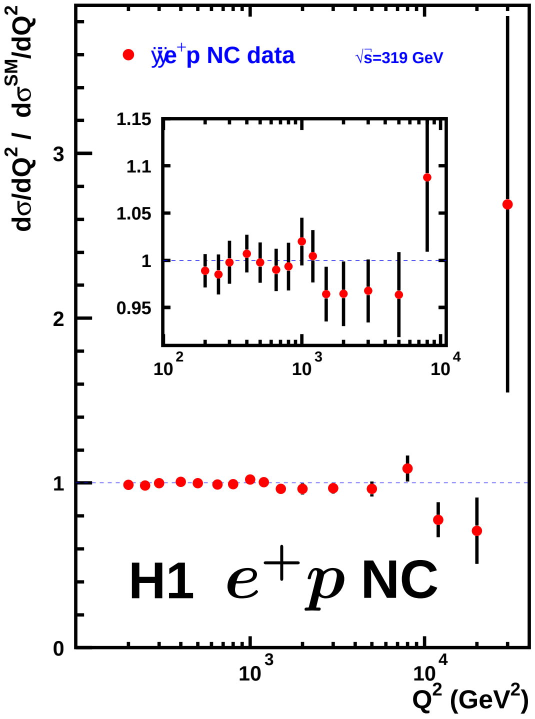
$$\frac{d\sigma^{CC}}{dx dQ^2} \sim G_F^2 M_W^4 \cdot \left(\frac{1}{Q^2+M_W^2}\right)^2 \cdot \frac{1}{x} \cdot \tilde{\sigma}_{CC}$$

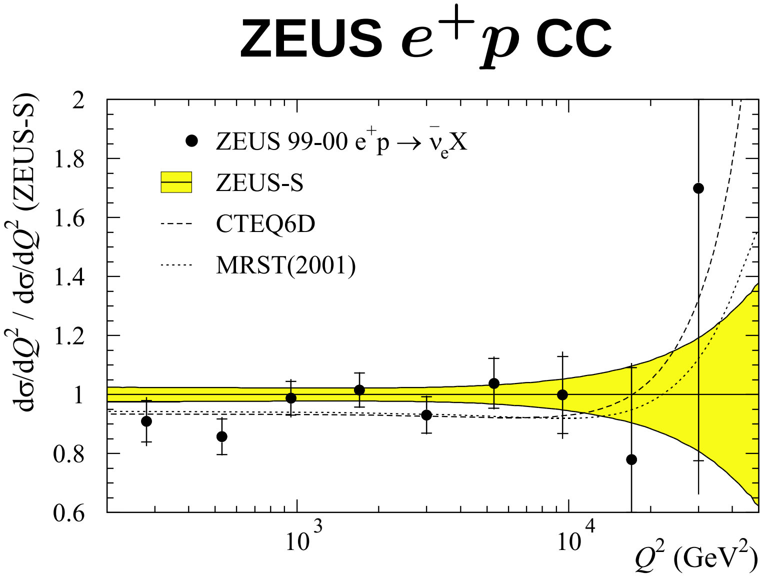
NC and CC cross sections become comparable at EW unification scale

Illustration of electroweak unification with space-like gauge bosons

Ratio of Data to Theory







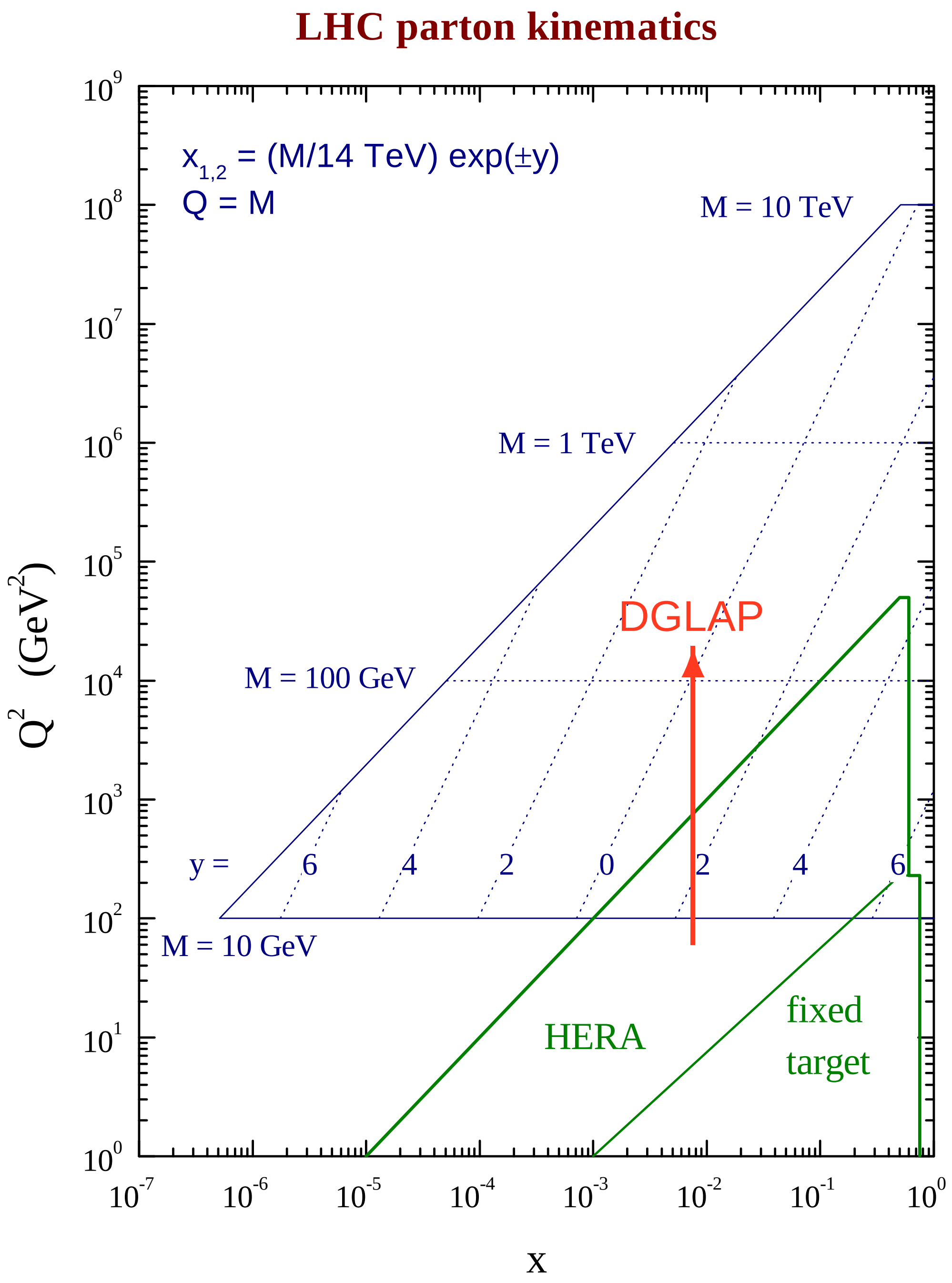
Ratios to SM $\otimes$ PDF predictions independent of HERA high Q^2 data

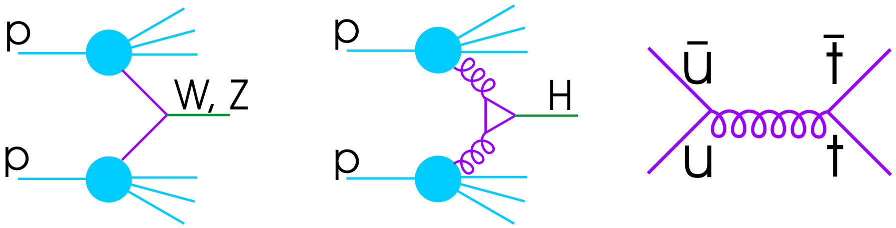
Good agreement with SM $\otimes$ PDF for NC and CC up to $Q^2 \sim 30\,000\ \mathrm{GeV}^2$

Quark or electron sub-structure ruled out down to scales of $\sim 10^{-18}$ m

More data needed to improve statistical uncertainties and range at highest Q^2

PDFs and Tevatron/LHC





e.g. Production at central rapidity . . .

M (GeV)	x_{Tevatron}	x_{LHC}
100	0.05	0.007
350	0.2	0.025
1000	0.5	0.07

To understand signal and background at Tevatron and LHC, need precise quark and gluon at all x

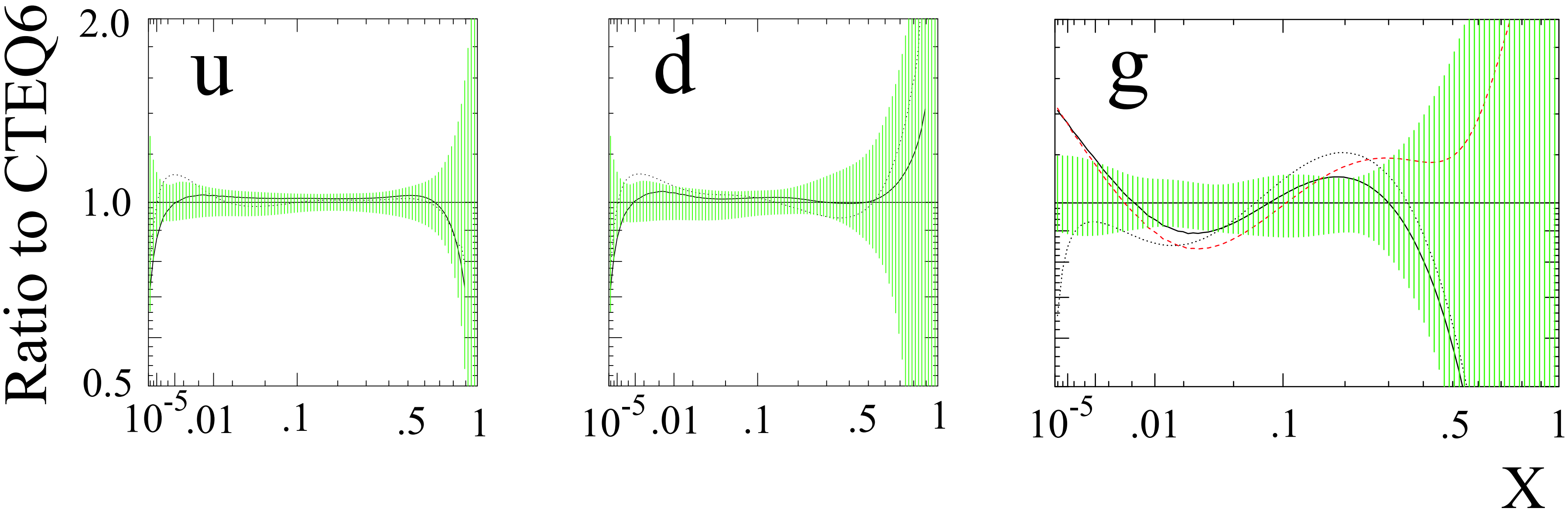
Present Knowledge of Parton Densities

Uncertainty estimates at $Q^2 = 10\ \mathrm{GeV}^2$ according to CTEQ . . .

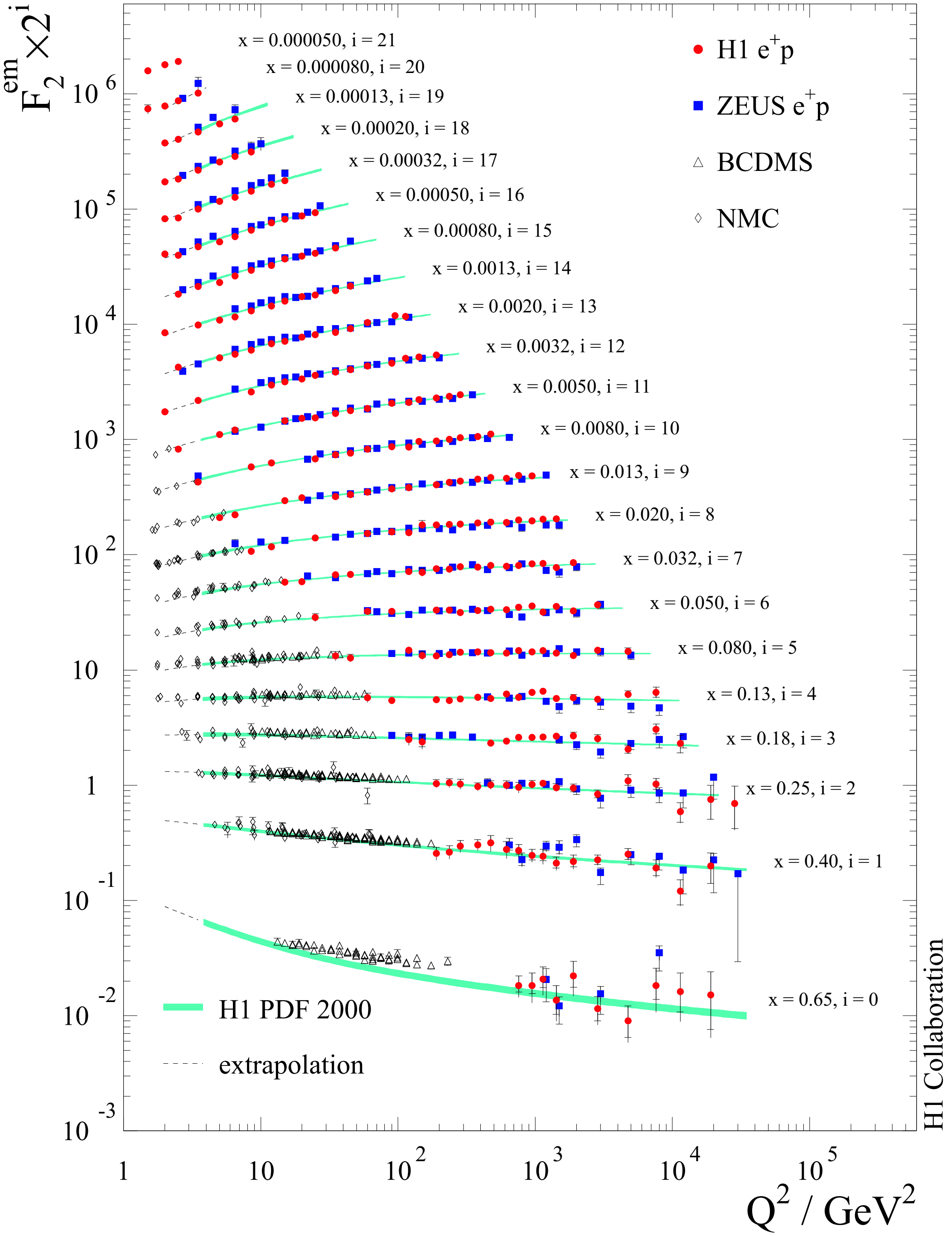
- u density best known - still poorly constrained at largest and smallest x
- d density less well known
- gluon density has very large uncertainty at high x

Includes some, but not all HERA data

Uncertainty bands relative to central CTEQ Fit



$F_2(x, Q^2)$



$$\tilde{\sigma}^{\pm}_{\rm NC} = Y_+ F_2 \mp Y_- x F_3 - y^2 F_L$$

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

$$F_2^{\rm em} = F_2 - \Delta(\gamma Z, Z^2)$$

$$F_2^{\rm em}(x, Q^2) \sim x \sum_q e_q^2 \, (q + \bar{q})$$

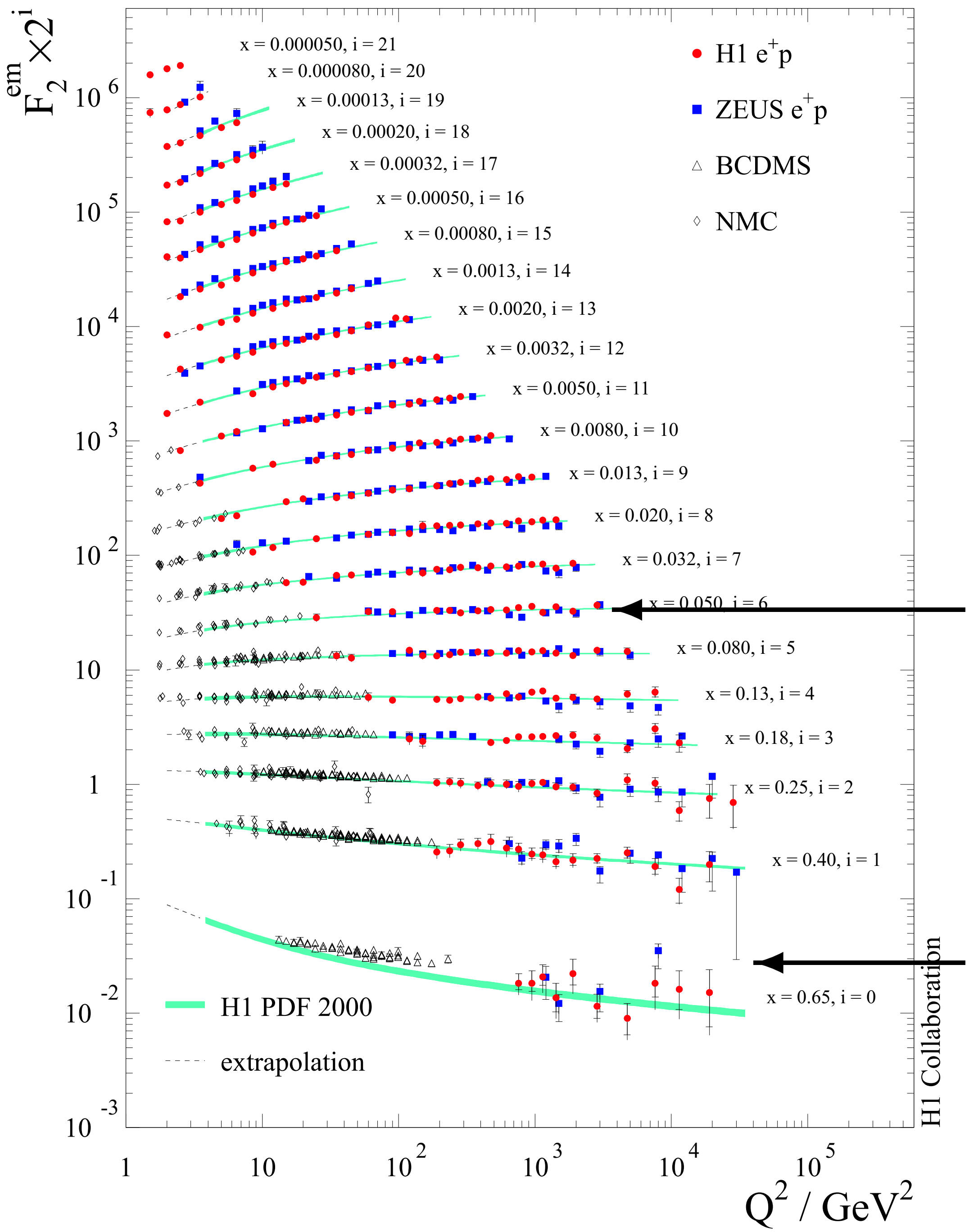
…dominates in most of phase space

→ strong constraint on u, $\bar{u}$

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

→ good constraint on g and α_s

$F_2(x,Q^2)$



$F_2^{\rm em}(x,Q^2) \sim x \, \sum_q \, e_q^2 \, (q+\bar{q})$

Measured over huge kinematic range

Beautifully described by QCD fits

2-3% precision in bulk of phase space

Highest x, Q^2 region remains problematic

HERA still far from fixed target precision

High x, medium Q^2 with reduced E_p HERA data … larger cross section, free of higher twist and nuclear corrections

$xF_3(x, Q^2)$

$$\tilde{\sigma}^{\pm}_{\rm NC} = Y_+ F_2 \mp Y_- xF_3 - y^2 F_L$$

$$xF_3 = \frac{1}{2Y_-}\left(\tilde{\sigma}^{-}_{\rm NC} - \tilde{\sigma}^{+}_{\rm NC}\right)$$

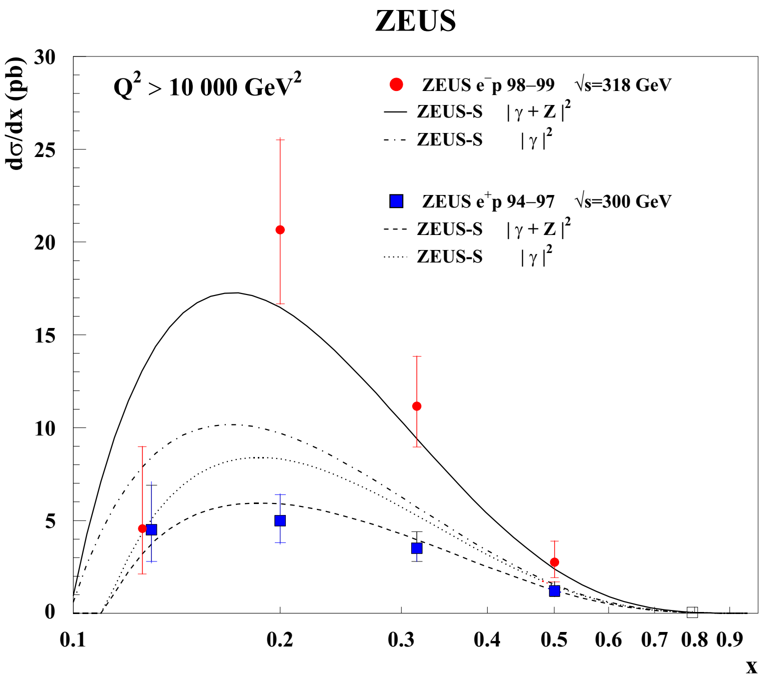
$$xF_3 = -a_e \frac{\kappa Q^2}{Q^2+M_Z^2}\, xF_3^{\gamma Z} + \Delta(Z^2)$$

Destructive / constructive $\gamma - Z$ interference

$$xF_3^{\gamma Z} \sim 2x \sum_q e_q a_q (q - \bar{q}) \sim q_v$$

Assumption-free access to valence distributions

Sensitivity at largest Q^2 ($\tilde{\sigma}^{-}_{\rm NC} \gg \tilde{\sigma}^{+}_{\rm NC}$)



$xF_3(x, Q^2)$

$$\tilde{\sigma}^{\pm}_{\mathrm{NC}} = Y_+ F_2 \mp Y_- xF_3 - y^2 F_L$$

$$xF_3 = \frac{1}{2Y_-}\left(\tilde{\sigma}^{-}_{\mathrm{NC}} - \tilde{\sigma}^{+}_{\mathrm{NC}}\right)$$

$$xF_3 = -a_e \frac{\kappa Q^2}{Q^2+M_Z^2}\, xF_3^{\gamma Z} + \Delta(Z^2)$$

Destructive / constructive $\gamma - Z$ interference

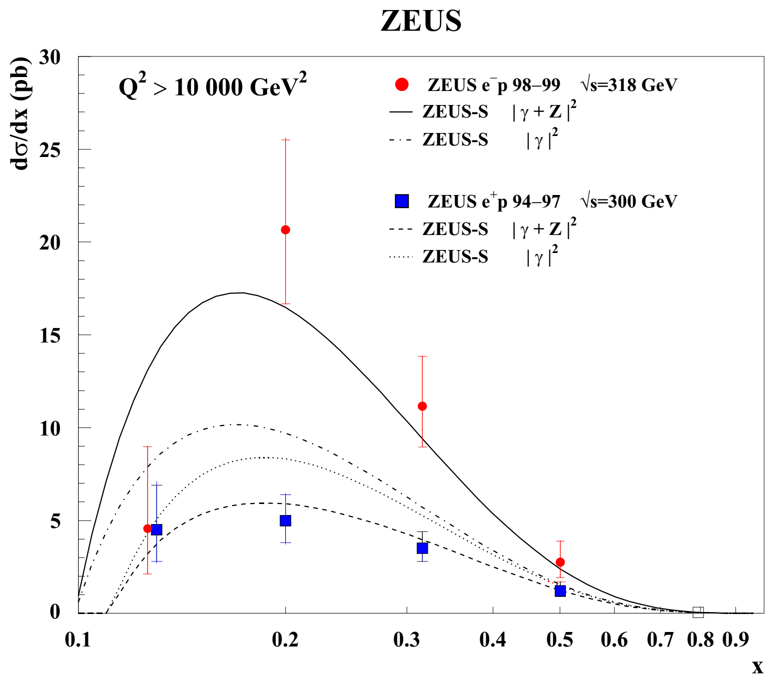
$$xF_3^{\gamma Z} \sim 2x \sum_q e_q a_q (q - \bar{q}) \sim q_v$$

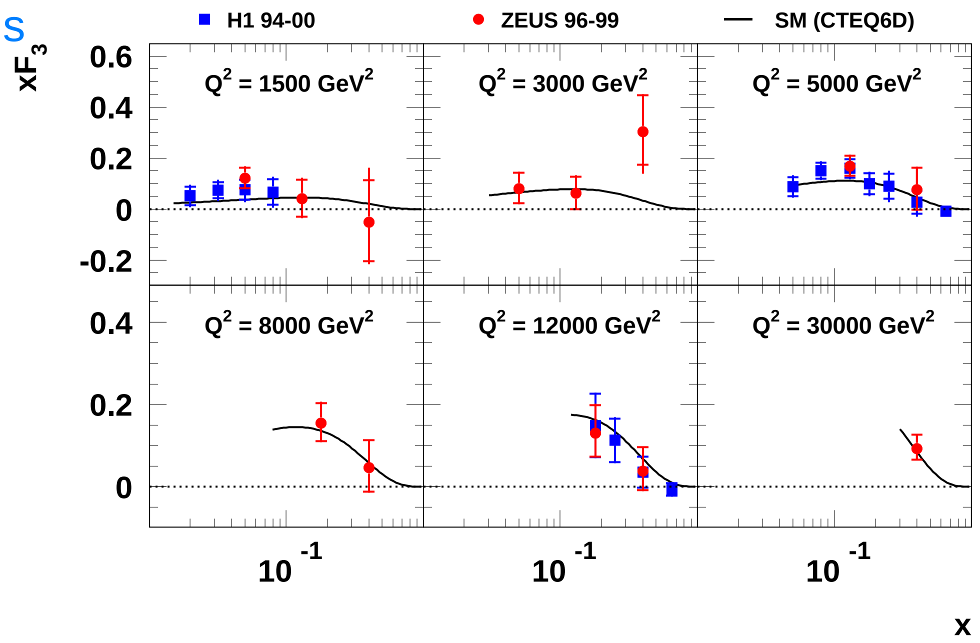
Assumption-free access to valence distributions

Sensitivity at largest Q^2 ($\tilde{\sigma}^{-}_{\mathrm{NC}} \gg \tilde{\sigma}^{+}_{\mathrm{NC}}$)

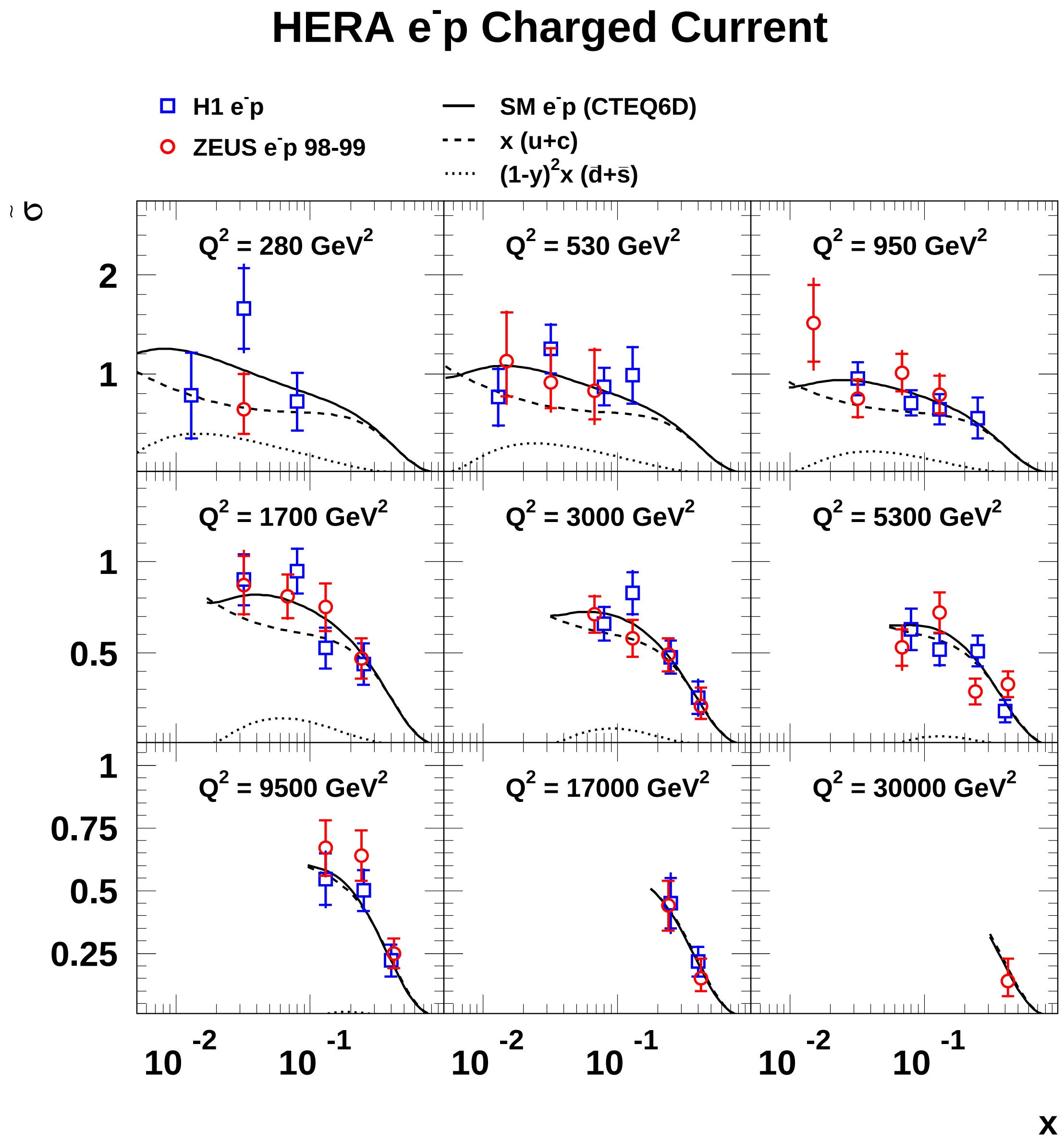
First “exploratory” extractions agree well with SM $\otimes$ PDF predictions

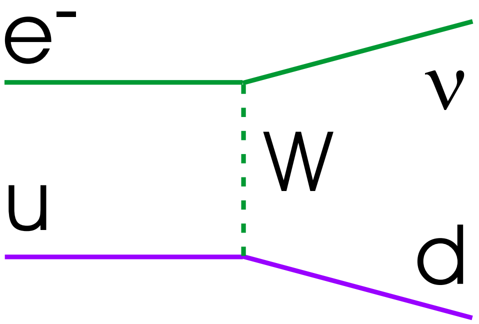
Much more data required for full exploitation





$e^{-}p$ Charged Current Cross Sections





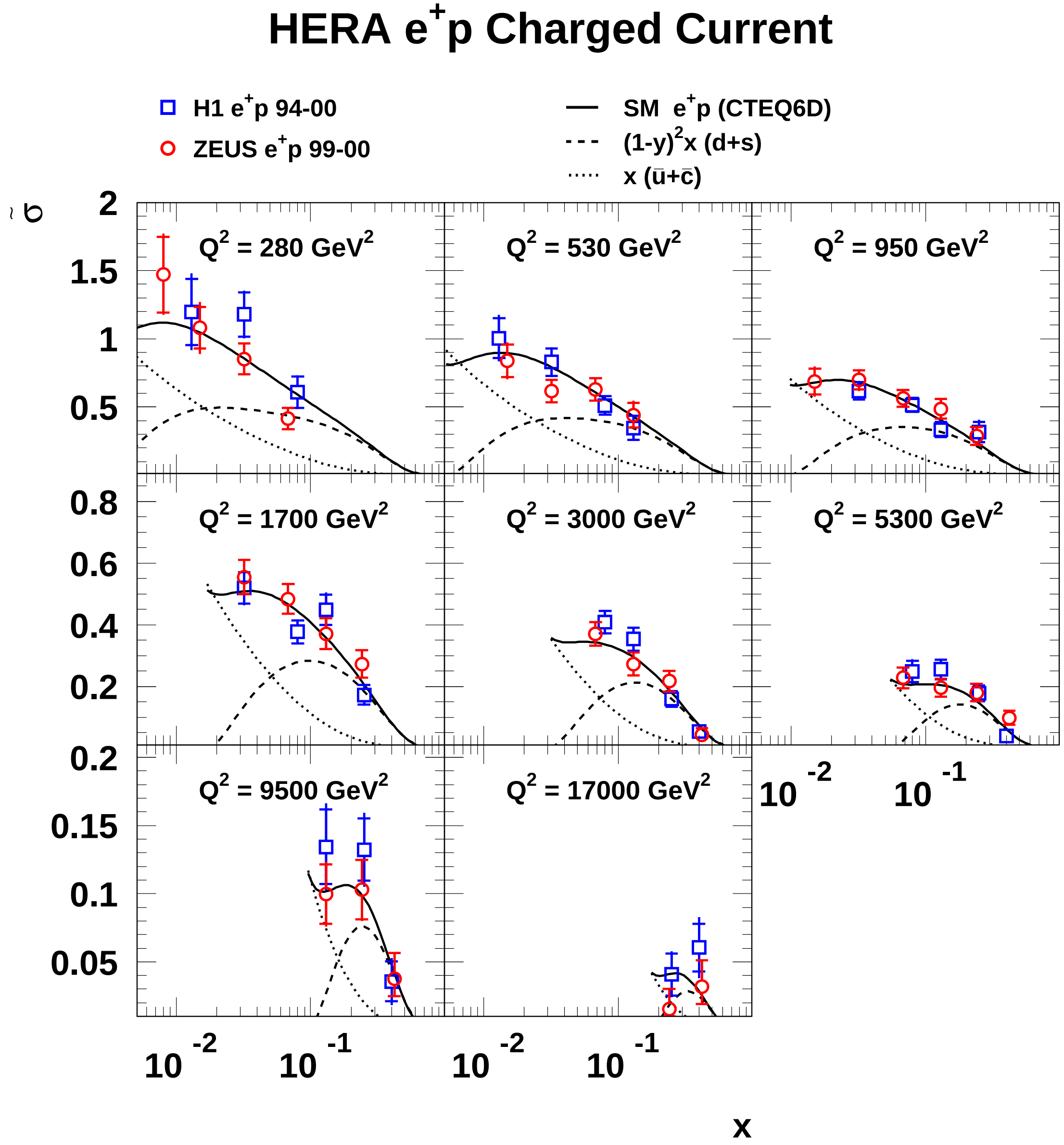
$$\tilde{\sigma}^{-}_{\mathrm{CC}} \sim x(u+c) \; + \; (1-y)^2 \, x(\bar{d}+\bar{s})$$

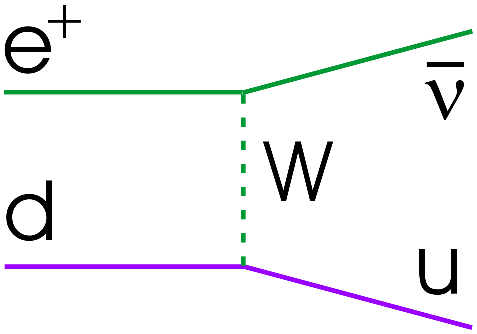
Sensitive to flavour decomposition

Clean constraint on u density at high x

Complementary to F_2

e^+p Charged Current Cross Sections





$$\tilde{\sigma}^+_{\rm CC} \sim x(\bar{u}+\bar{c}) \; + \; (1-y)^2\, x(d+s)$$

Promising for d density at high x

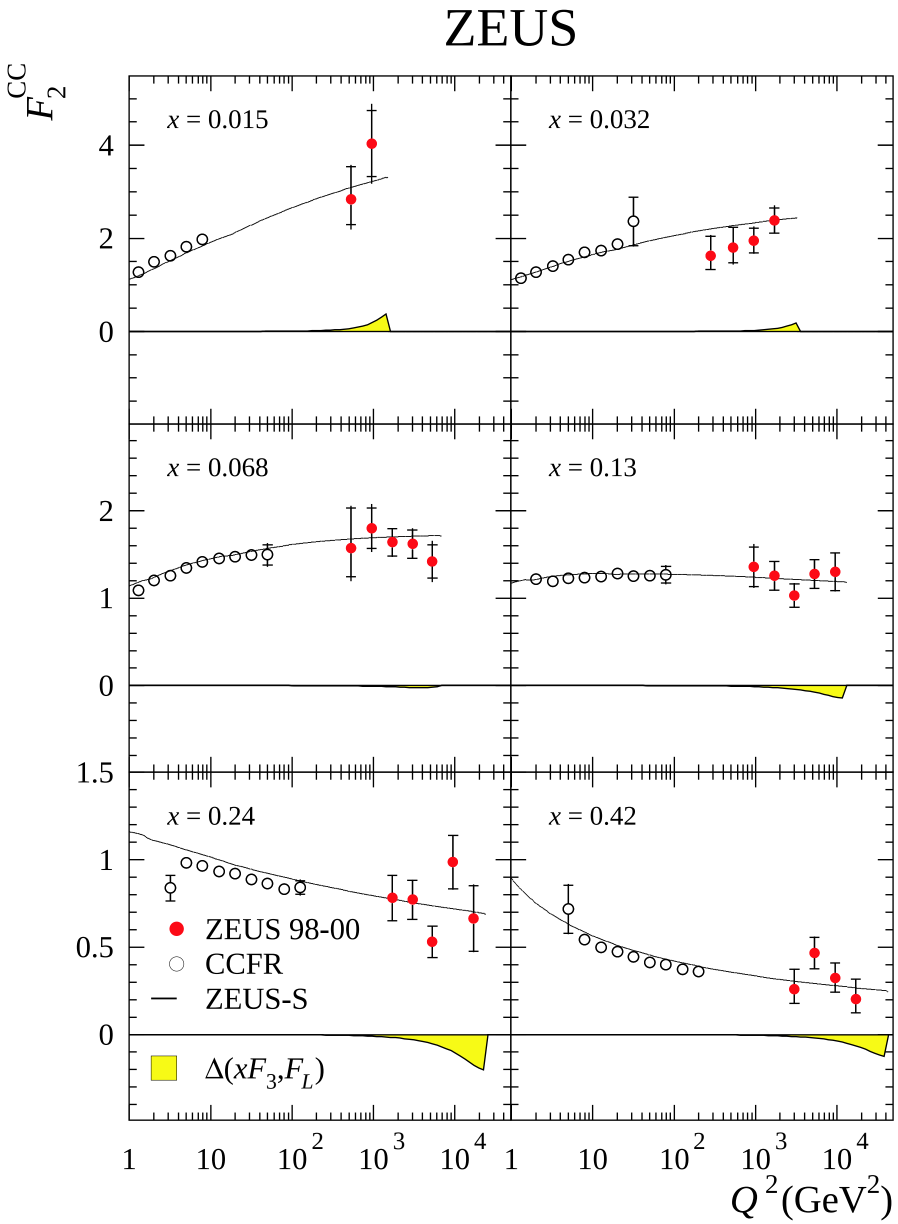
Suppressed by helicity factor $(1-y)^2$

More data will help a lot

Still large errors at $x \gtrsim 0.5$ with $1\ {\rm fb}^{-1}$

eD data would constrain d/u at large x

Charged Current Structure Function $F_2^{CC}(x, Q^2)$



$$F_2^{CC} = \frac{2}{Y_+}\left(\tilde{\sigma}_{CC}^{+} + \tilde{\sigma}_{CC}^{-}\right) + \Delta(xF_3^{CC}, F_L^{CC})$$

Flavour singlet distribution

Can compare with precise fixed target ν data (CCFR)

(CCFR not included in fit)

Well described by SM $\otimes$ PDF prediction

Clear scaling violations in CC data

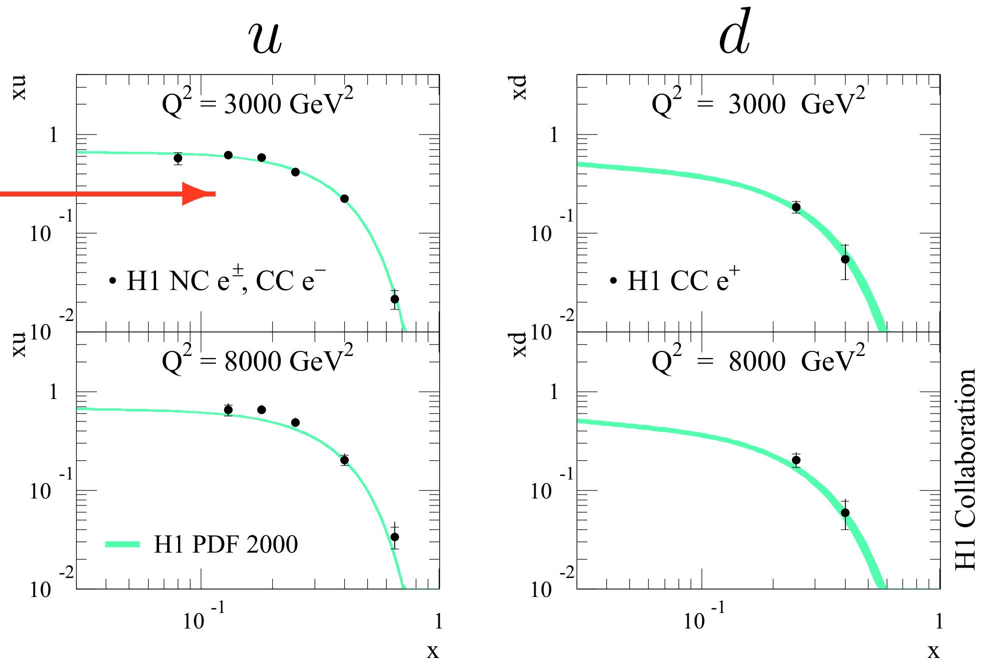
Data span more than 4 orders of magnitude in Q^2

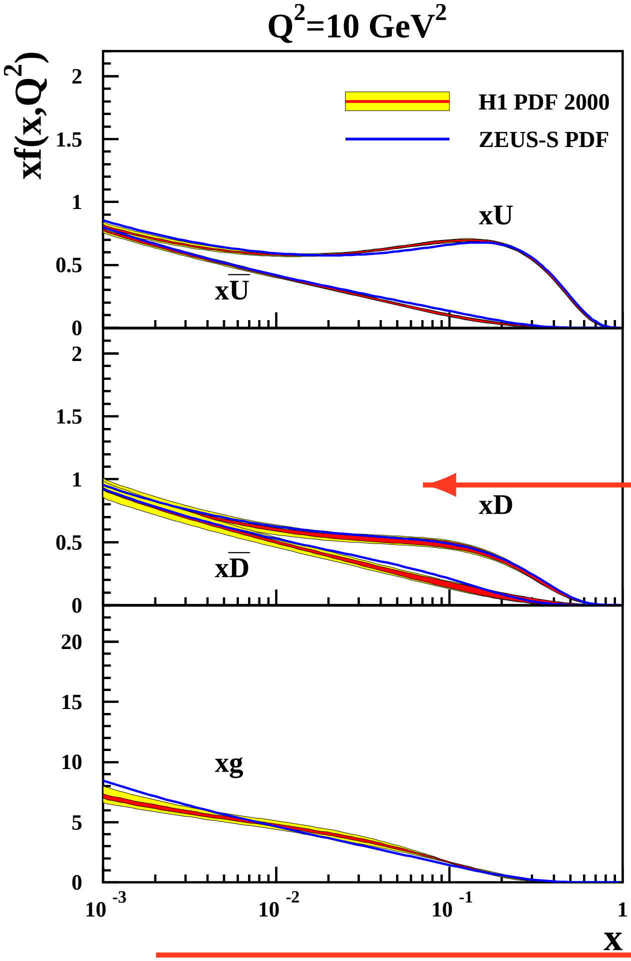
Parton Density Extractions from HERA data alone

Extract PDFs locally from data using bins where d or u dominates cross section.

Relatively insensitive to fit assumptions

“Direct” extraction at large x





NLO DGLAP fits for PDFs from HERA NC, CC data alone

Presented in terms of directly accessible distributions . . .

$U = u + c$ $\quad D = d + s$ $\quad \bar{U} = \bar{u} + \bar{c}$ $\quad \bar{D} = \bar{d} + \bar{s}$

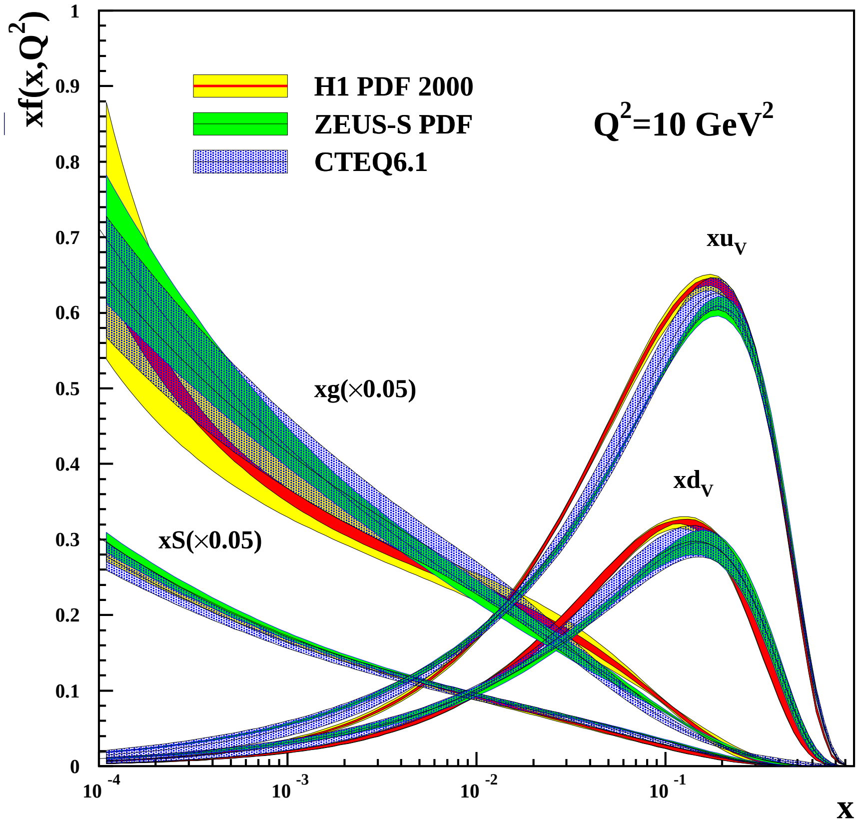
$u_v = U - \bar{U}$ etc

Fixed target still needed for high x precision

eD data needed to relax assumptions ($\bar{d} - \bar{u} \longrightarrow 0$ as $x \longrightarrow 0$)

More details ⟶ talk of R Thorne

Final States and the Gluon



Inclusive data indirectly sensitive to $xg(x)$ …

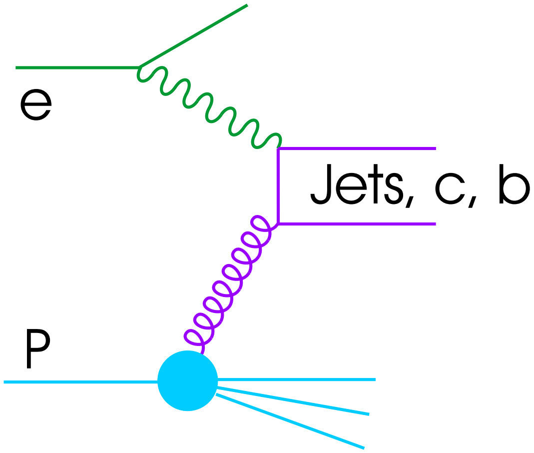
$$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s xg(x)$$

From DGLAP fits, experimental uncertainty $\sim 3\%$ at $Q^2 = 10\ \mathrm{GeV}^2$, $10^{-4} < x < 10^{-1}$

High x $\longrightarrow$ poorly constrained

Low x $\longrightarrow$ gluon very large … DGLAP sufficient?

Direct constraints from final state data …

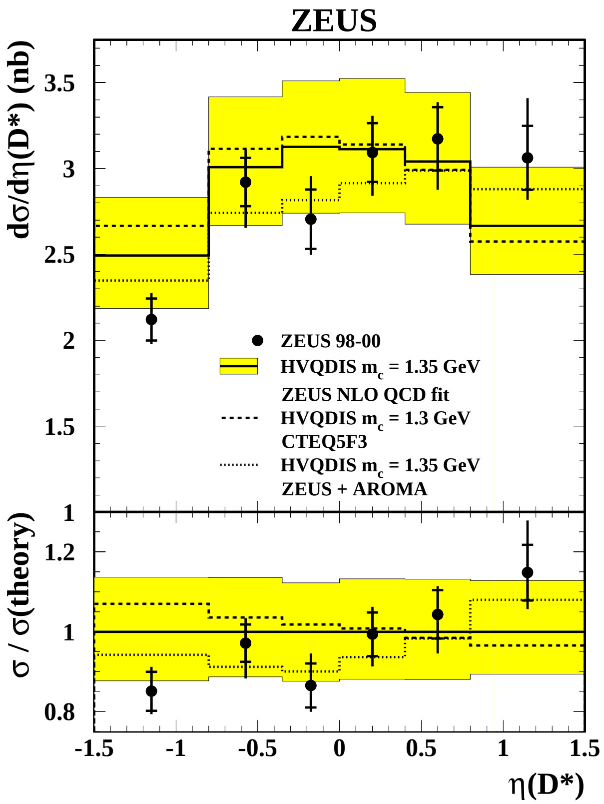


$\sigma(\text{jets}), \sigma(\text{charm}), \sigma(\text{beauty}) \sim \alpha_s\, xg(x)$ (LO QCD)

HERA jet data sensitive up to $x \sim 0.6$ $\longrightarrow$ talk of R. Hirosky

Fast improving charm and beauty data …

Charm and the Gluon



Charm from $\sigma(D^*)$

v NLO QCD $\otimes\ xg(x)$

Beautiful confirmation

of gluon from scaling

violations at 10% level

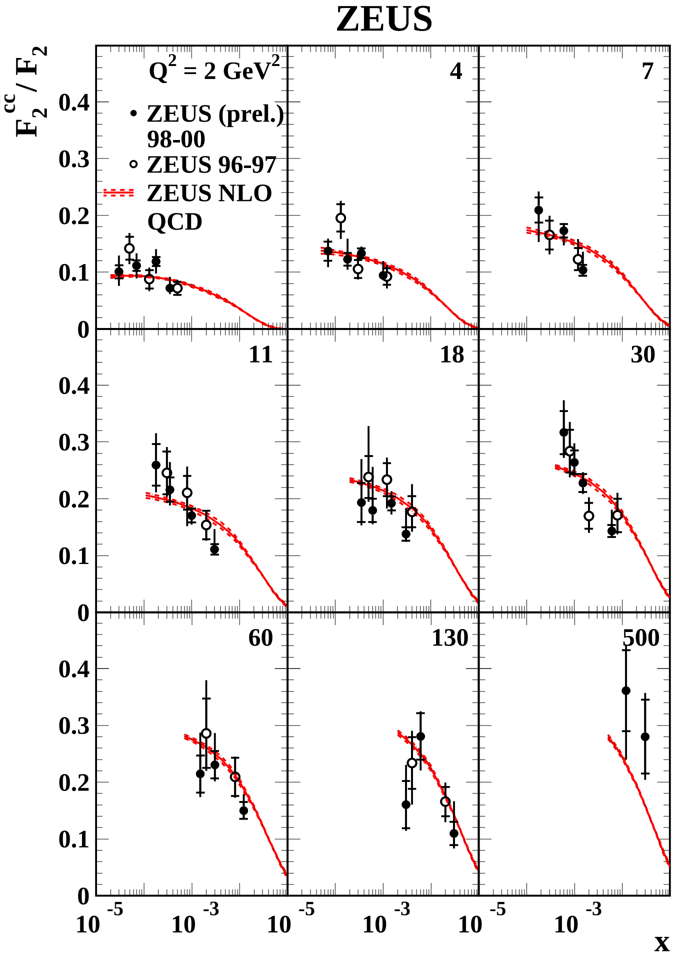
Sensitive to differences

between fitted gluons

Theoretical uncertainties

dominate $\longrightarrow\ m_c, \mu_r, \mu_f$

ϵ_c, HF scheme

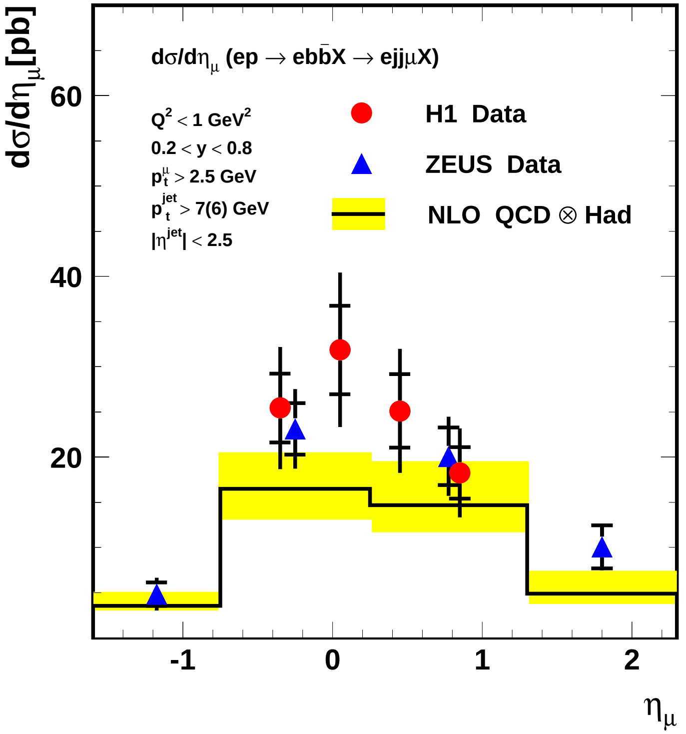


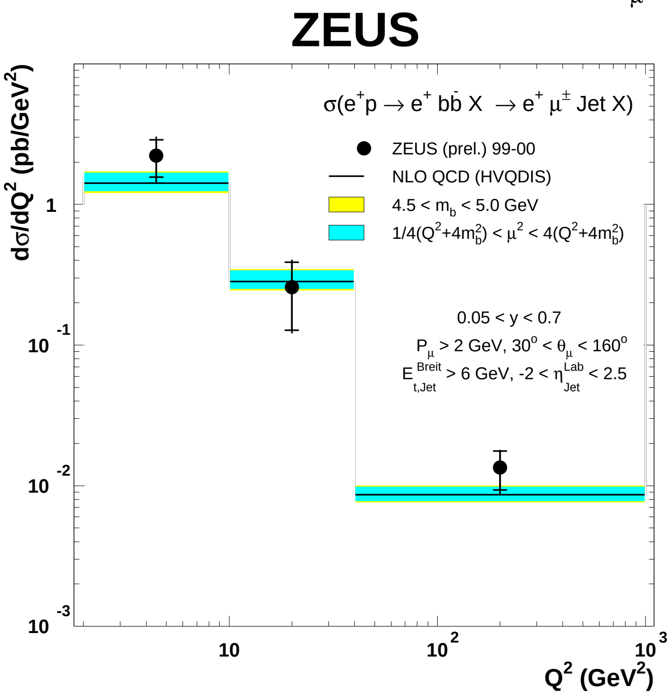
$F_2^{c\bar{c}}$ obtained with extrapolation in η, p_t (NLO HVQDIS)

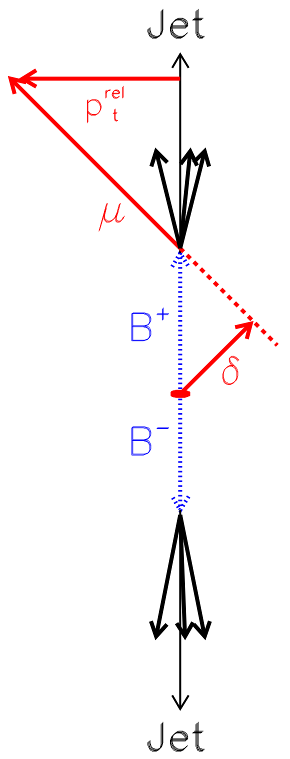
Well above threshold, for massless charm, $\frac{F_2^{c\bar{c}}}{F_2} \longrightarrow \frac{e_c^2}{e_u^2+e_d^2+e_s^2+e_c^2} = \frac{4}{10}$

Upgraded Silicon detectors, triggers → big charm future at HERA-II

Beauty Production







$\sigma(b)\ :\ \sigma(c)\ \sim\ 1\ :\ 200$

- Understanding parton dynamics and multi-scale QCD

- Previously reported HERA, Tevatron beauty "anomalies" . . .

Measure using $b \longrightarrow c\nu\mu$

Unfold from charm, uds using δ (Si) and $p_T^{\rm rel}(\mu - jet)$

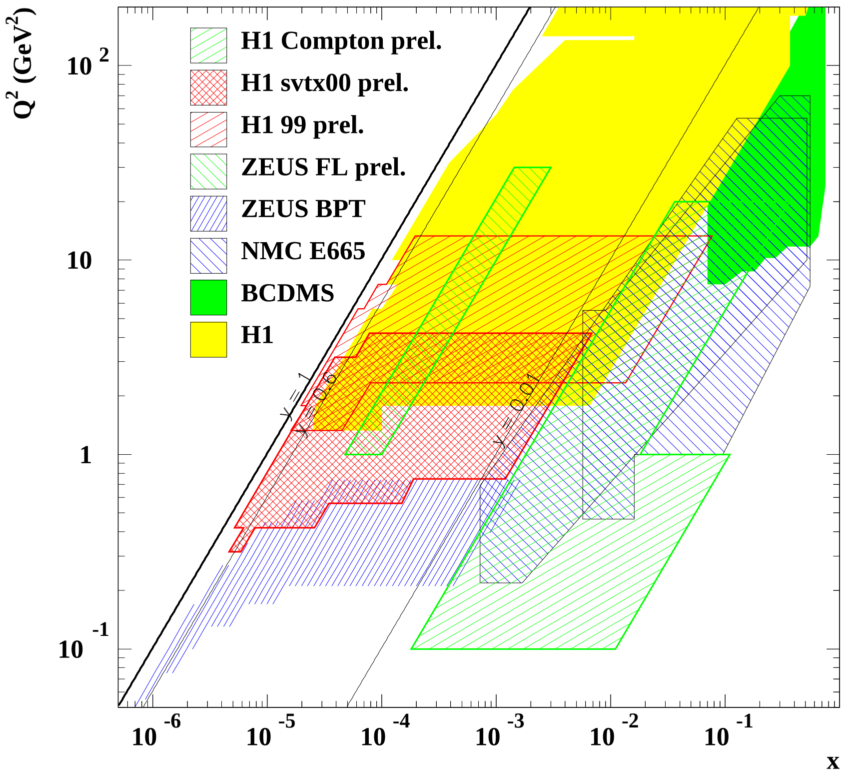
Compare with NLO QCD directly in measured range

Good agreement at large Q^2, p_T

Data $>$ theory at $Q^2 = 0\ \ (1.5\sigma)$

Larger statistics and more Si in future $\longrightarrow F_2^{b\bar{b}}$

Low x and Q^2 Physics



Low x, low Q^2 kinematically correlated

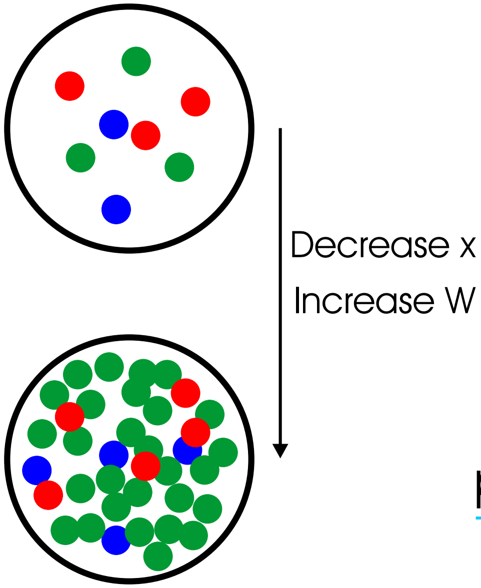
Recent progress in inclusive and final state data

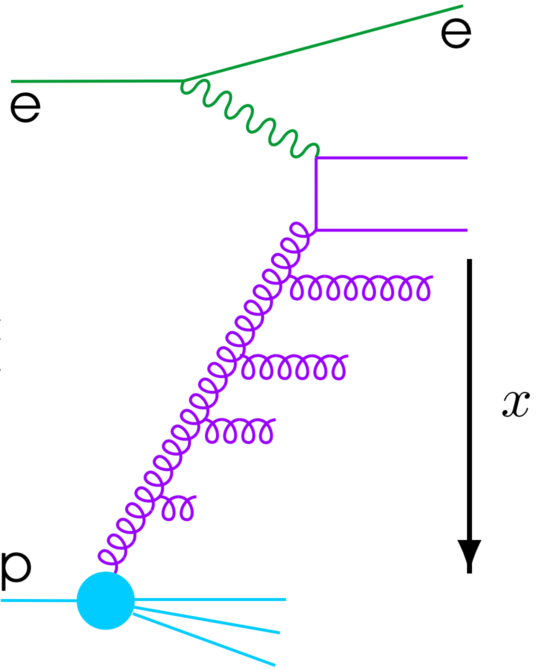
- $Q^2 \rightarrow \Lambda^2_{\rm QCD}$ → transition to long distance non-perturbative physics, confinement?

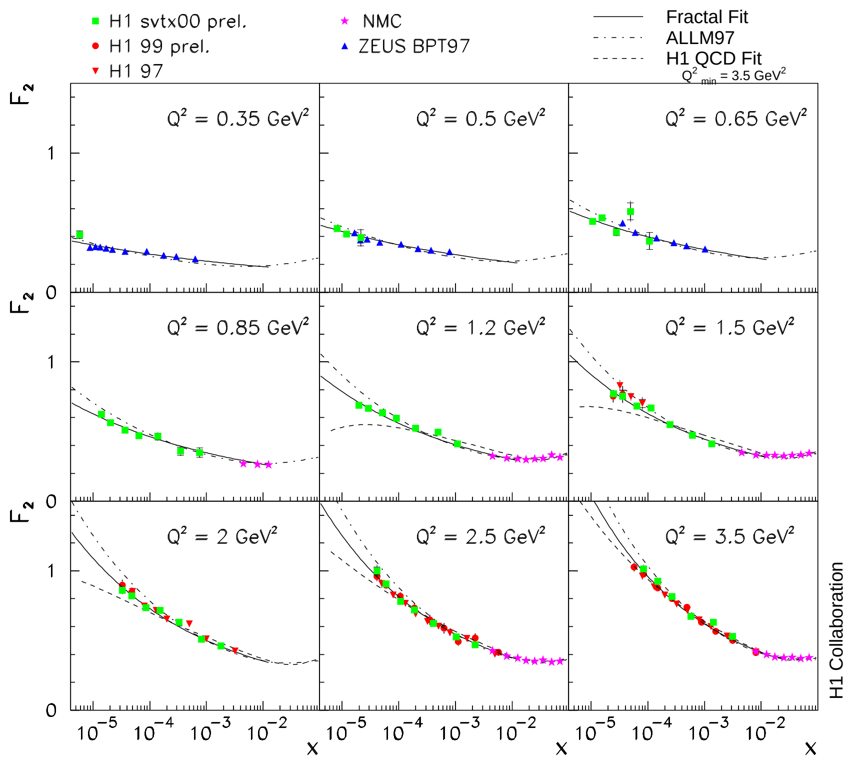
- **Low x . . .**

High parton densities → unitarity limit, gluon recombination?

Long parton cascades → Breakdown of DGLAP approximation? ($\log 1/x$ evolution?)







F_2 at low Q^2

F_2 measurements at low $Q^2 \sim 1\,\mathrm{GeV}^2$

($y < 0.6$ to avoid F_L effects)

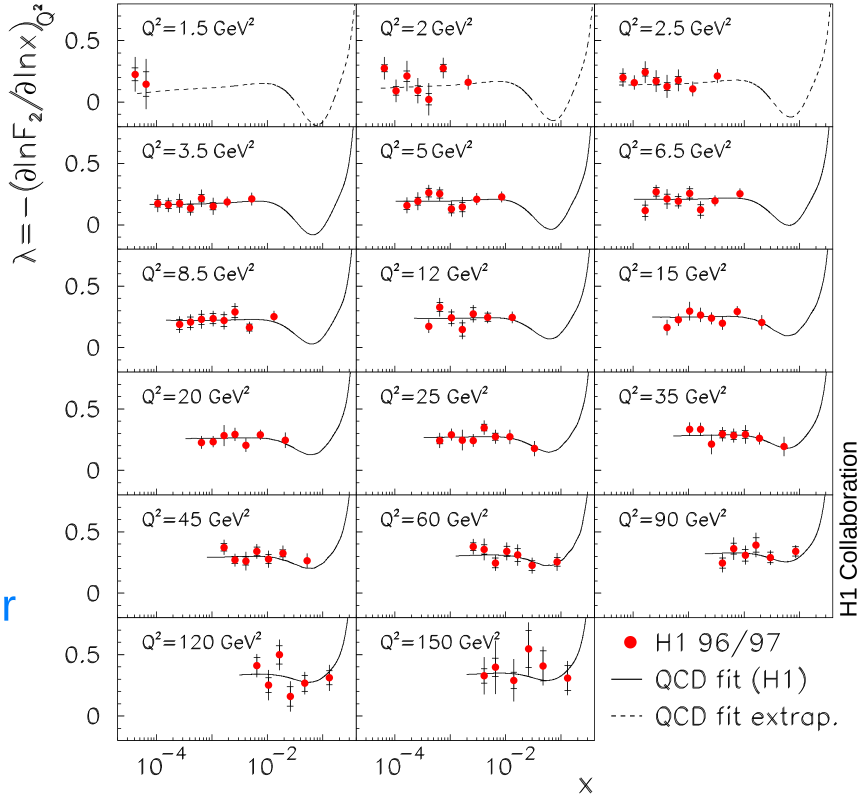
$Q^2 = 3.5\,\mathrm{GeV}^2 \rightarrow$ fast rise with decreasing $x \ldots$

$Q^2 = 0.35\,\mathrm{GeV}^2 \rightarrow$ soft rise with decreasing x

If unitarisation effects present, expect taming of rise of $xg(x)$ and hence F_2 at low x

Extract $\lambda = \frac{\partial F_2}{\partial \ln x}$ at fixed Q^2 locally from precise data

Derivative independent of x for $x < 10^{-2}$: no evidence for saturation in perturbative part of HERA kinematic range



x Dependence of F_2 at low Q^2

Rise of F_2 well parameterised as

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

$\boldsymbol{Q^2 \gtrsim 3\ \mathrm{GeV}^2}$:

$$\lambda \sim \ln Q^2 \ \ , \ \ c(Q^2) \sim \mathrm{const.}$$

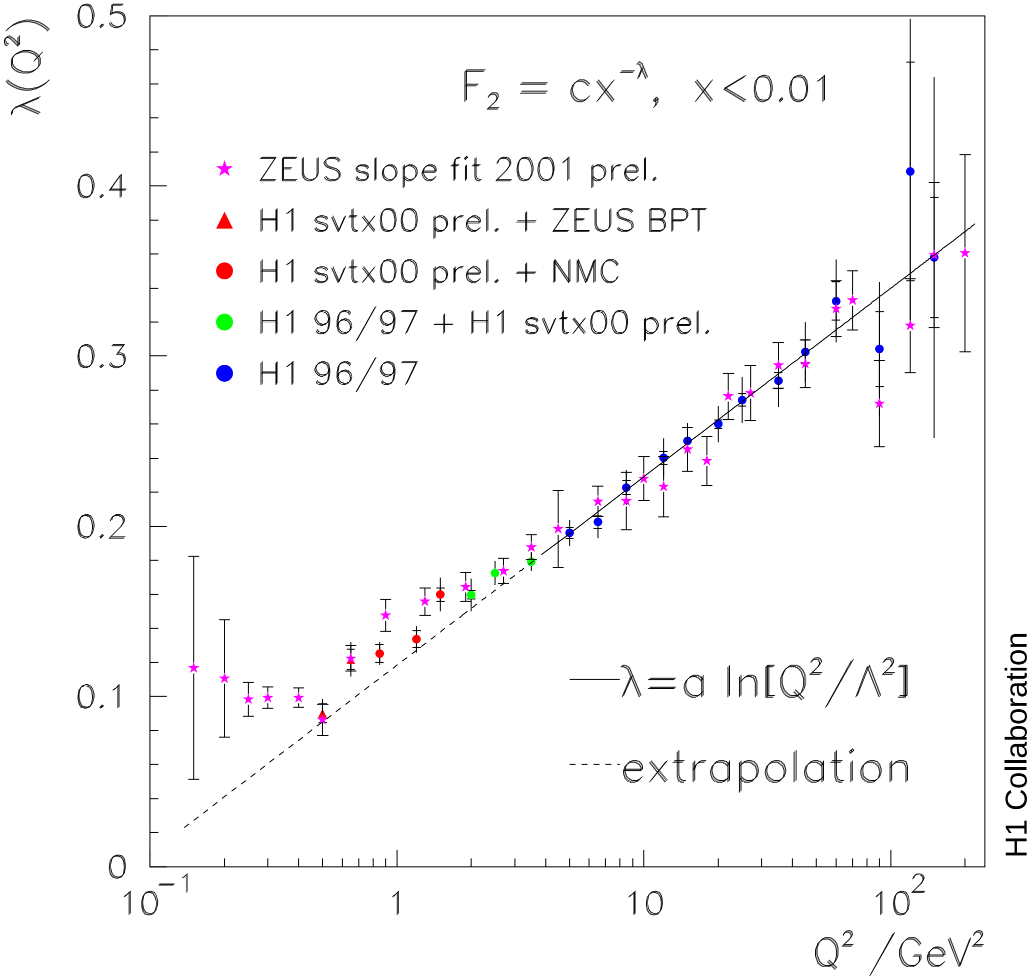
Partons as degrees of freedom

$\boldsymbol{Q^2 \lesssim 1\ \mathrm{GeV}^2}$:

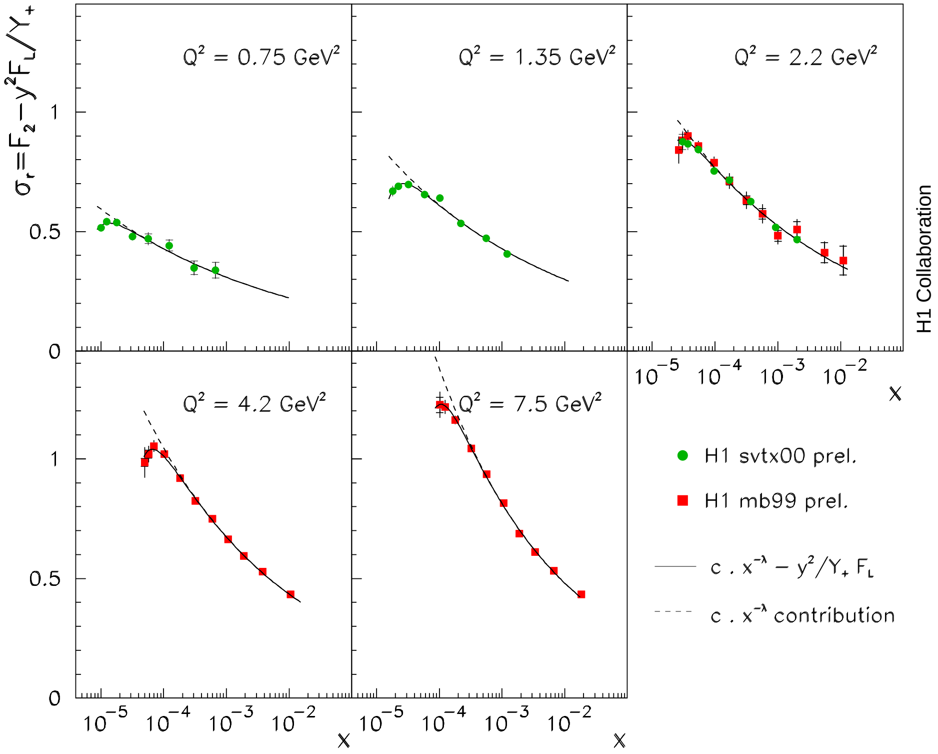
$$\lambda(Q^2) \rightarrow \alpha_{I\!P}(0) - 1 \sim 0.08$$

Observation of transition to hadronic degrees of freedom (confinement?)

(scale ~ 0.3 fm)



F_L at Low Q^2



$xg(x)$ poorly known in low Q^2 region where

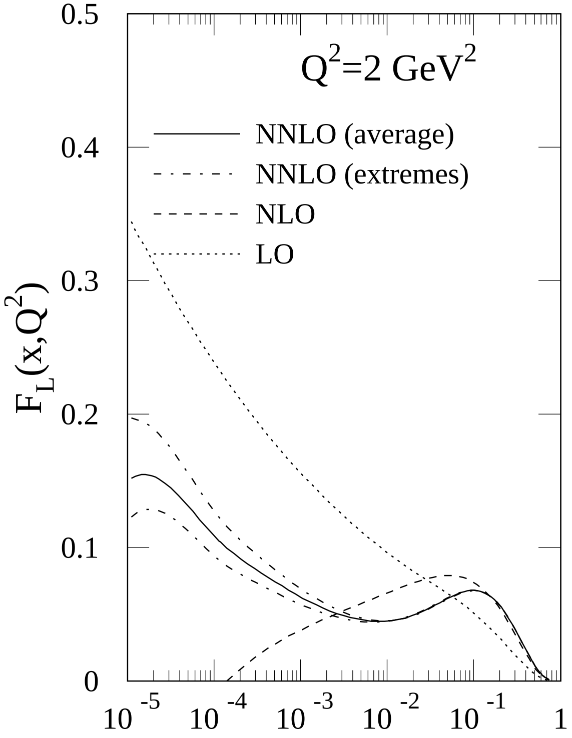
DGLAP questionable

Beyond x reach of jet, charm data.

F_L is ideal observable for the gluon in this region

$\neq 0$ at $\mathcal{O}(\alpha_s^1)$ due to gluon radiation

Experimental data needed to constrain theory



Sensitivity at highest $y \rightarrow 0.9 \quad (E'_e > 3 \text{ GeV})$

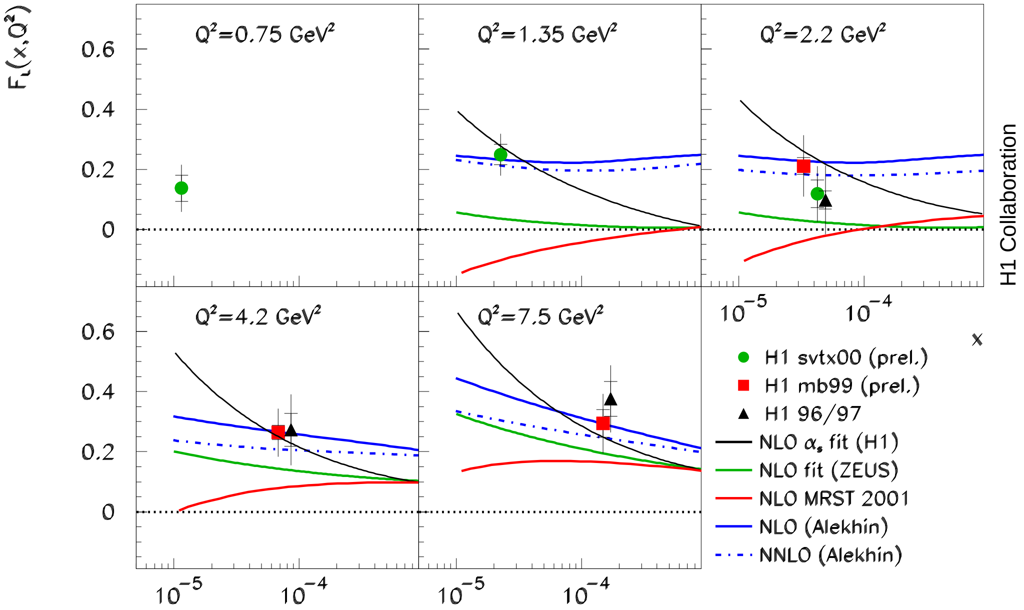
$$\boldsymbol{\sigma_r = F_2 - (y^2/Y_+)\, F_L}$$

Requires model for F_2 at high $y \ldots$

New method: fit at fixed Q^2: $\quad \sigma_r = c \cdot x^{-\lambda} \; - \; (y^2/Y_+)\, F_L$

F_L determination in crucial region $Q^2 \sim 1$

F_L at Low Q^2



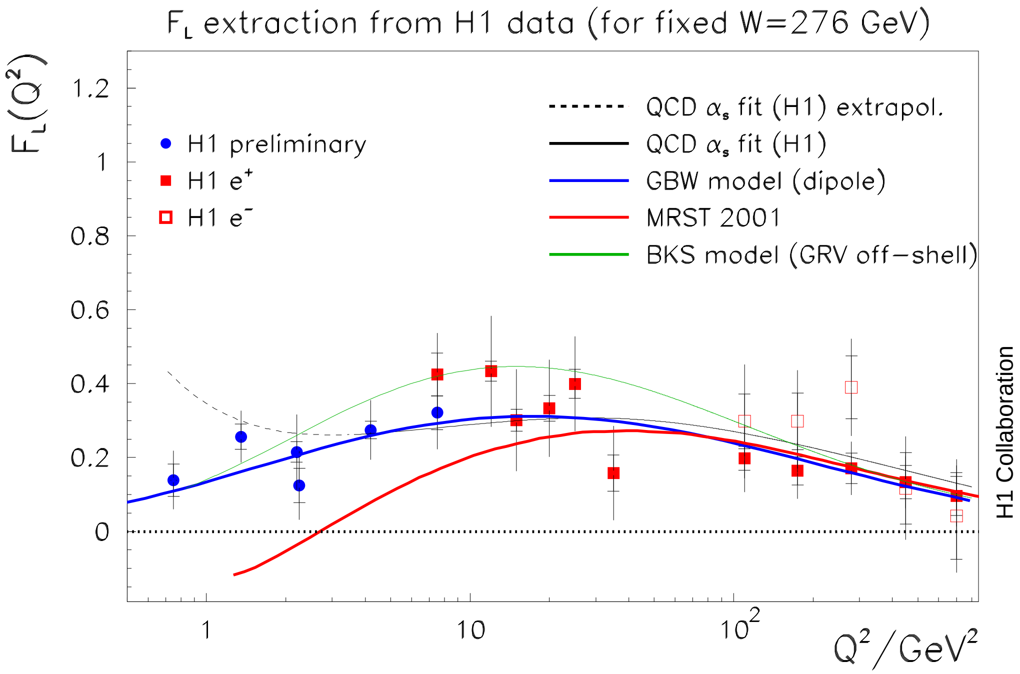
First data at $Q^2 \sim 1\ \mathrm{GeV}^2$

Distinguishes between DGLAP fits & other approaches at low Q^2

F_L determination now spans 3 orders of magnitude in Q^2

. . . but measurements of x dependence still required to see the full picture

Reduced E_p running required for x dependence and to avoid assumptions on F_2



HERA Status and Future Prospects

Shutdown for Upgrade 2000

- Factor of 5 increase in lumi
- Upgraded experiments . . .
- Longitudinally polarised leptons

- Si tracking
- Triggering
- Forward tracking
- Proton tagging

2001-2002

- Understanding and improving beam backgrounds
- 60% polarisation achieved with ep collisions

HERA-II restart Sept ’03

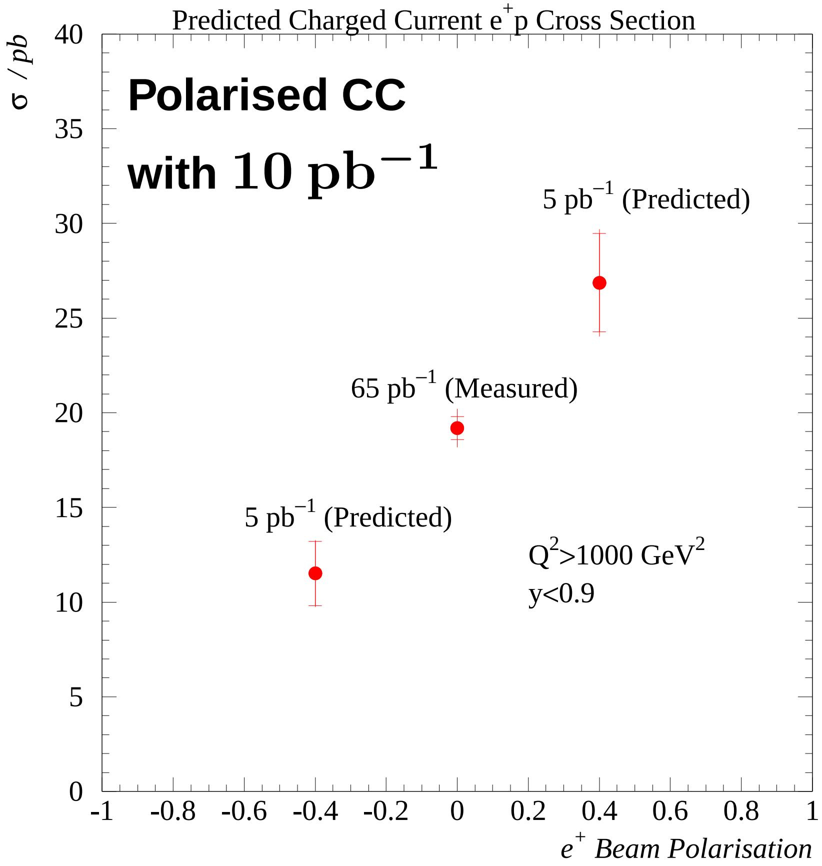
- few $\times 10\ \mathrm{pb}^{-1}$ expected in 2003
- sufficient to establish polarisation dependence

$\longrightarrow 1\ \mathrm{fb}^{-1}$, split between $e^{\pm}$, L, R polarisation

- Precision at high x, Q^2, chiral structure
- Precision heavy flavour physics

$\longrightarrow$ Reduced E_p Data

- High x, moderate Q^2, F_L



Summary

- **Ongoing analysis of HERA-I data**

  Ever stronger constraints on PDFs ($10^{-4} \lesssim x \lesssim 10^{-1}$)

  Final states test QCD and give competitive information on gluon

  Progress in testing range of validity of DGLAP at low x, Q^2

- **HERA-II imminent**

  High luminosity → improved high x, Q^2

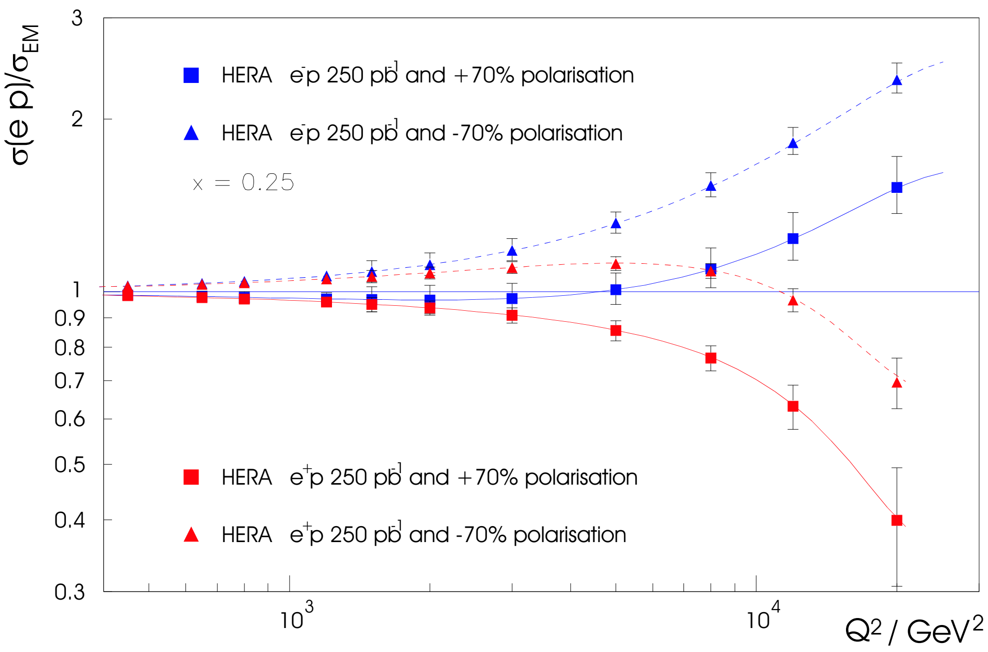
  Polarised leptons → chiral structure

  Detector upgrades → precision HF era

  Reduced E_p → high x, medium Q^2, F_L

  Further running (“HERA-III”) would allow

  study of eD, eA, nucleon spin, low x



Looking forward to resuming data taking!

Thanks! J Butterworth, E Elsen, T Greenshaw, B Heinemann, V Hudgson, M Klein, T Lastovicka, K McFarland, D Naples, E Rizvi, R Thorne, R Wallny . . .