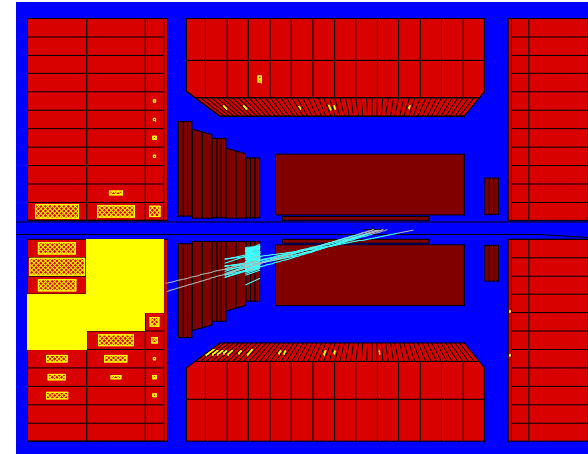
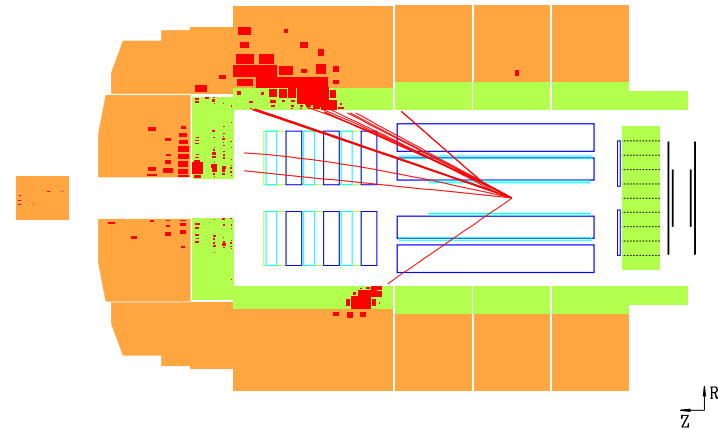


Deep Inelastic Lepton-Nucleon Scattering at HERA

Paul Newman Birmingham University



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

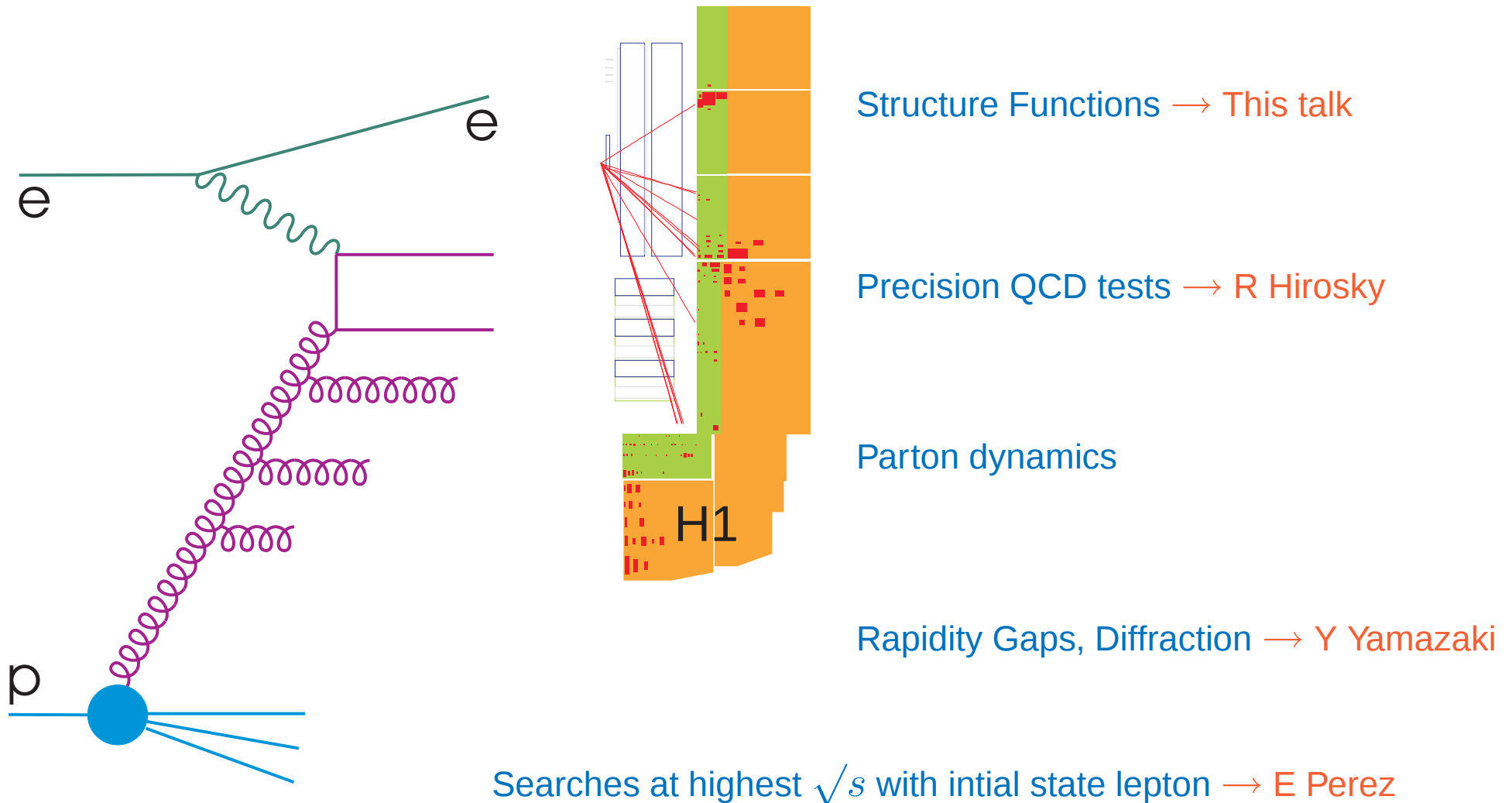


Lepton Photon 2003

FNAL

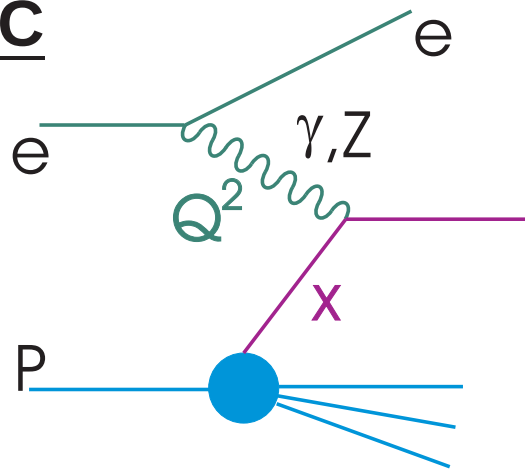
HERA: QCD from the established to the “speculative”

Precise electron and hadron reconstruction over wide rapidity range

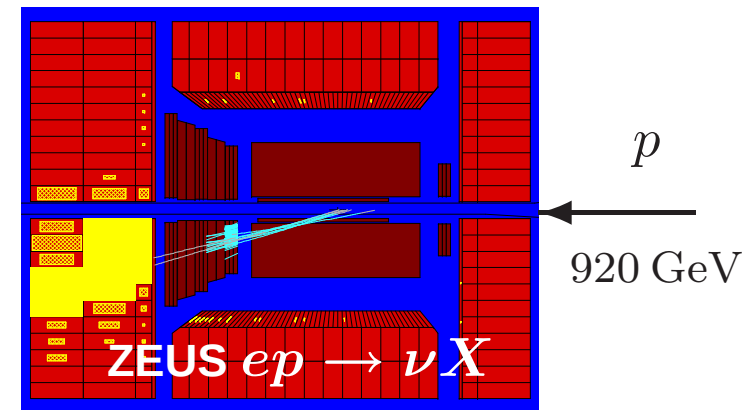
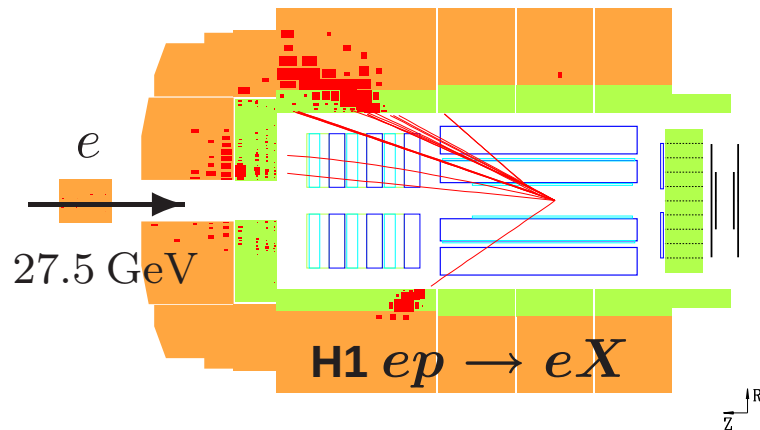
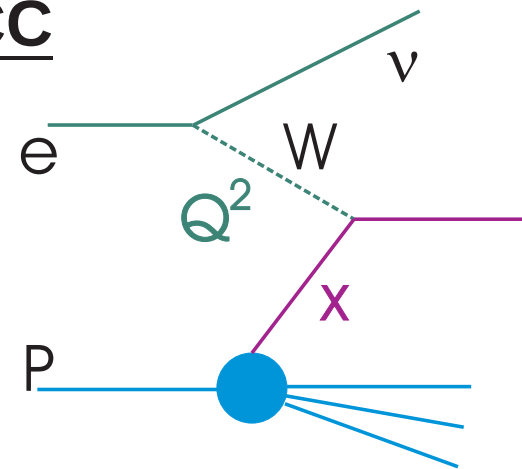


HERA Kinematics

NC



CC



$$Q^2 = -\gamma^2 = -(e - e')^2$$

$$x = Q^2 / (2p \cdot e)$$

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

$$W_{\gamma^* p}^2 \sim Q^2 / x$$

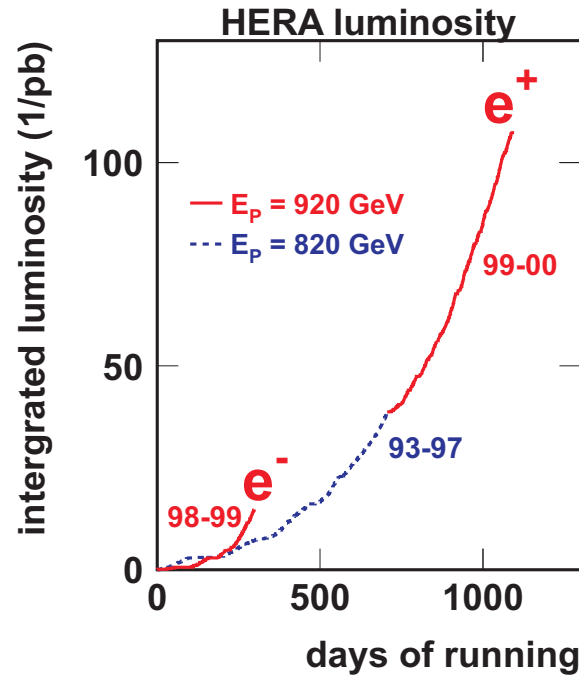
$$(0 < Q^2 < 10^5 \text{ GeV}^2)$$

$$(10^{-6} < x < 1)$$

$$(\text{Low } x \rightarrow W_{\gamma^* p} \lesssim 300 \text{ GeV})$$

Sensitive to structures
on scales $\gtrsim 10^{-18} \text{ m}$

HERA-I Run: 1992-2000



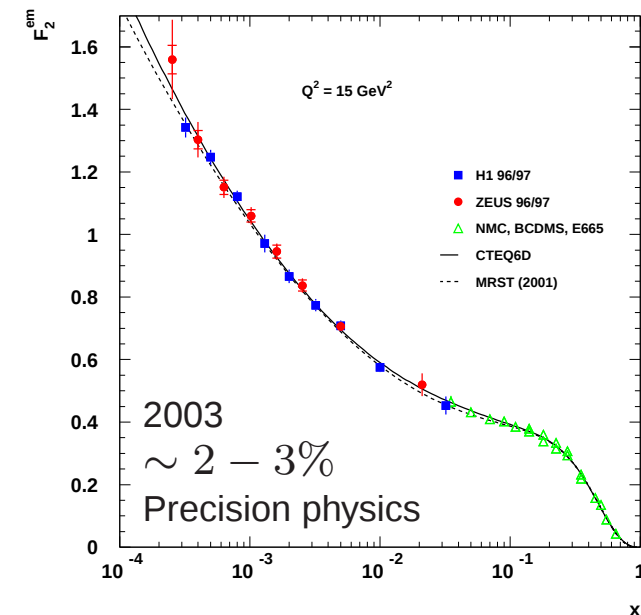
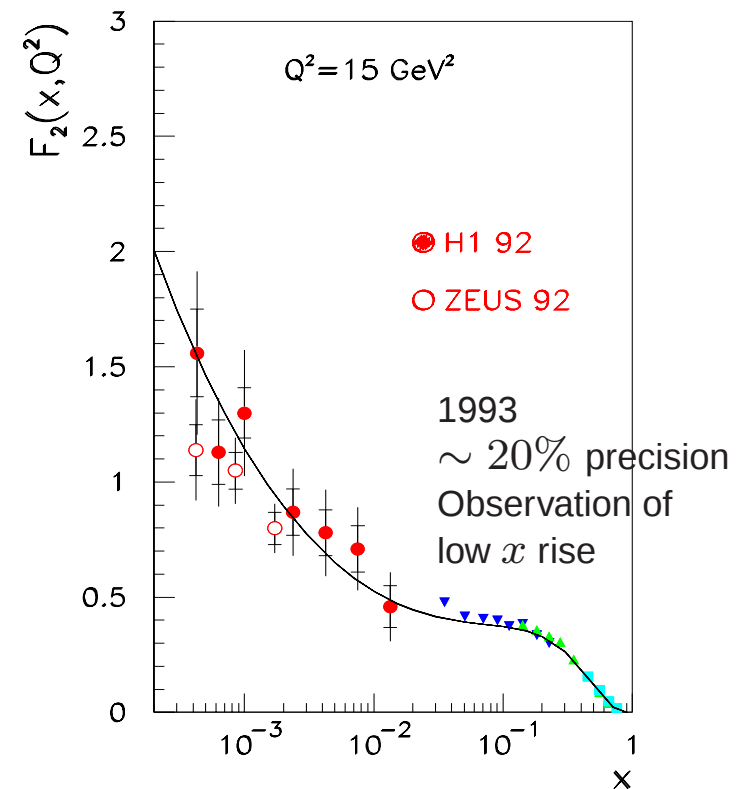
$\sim 100 \text{ pb}^{-1}$ per experiment e^+p

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

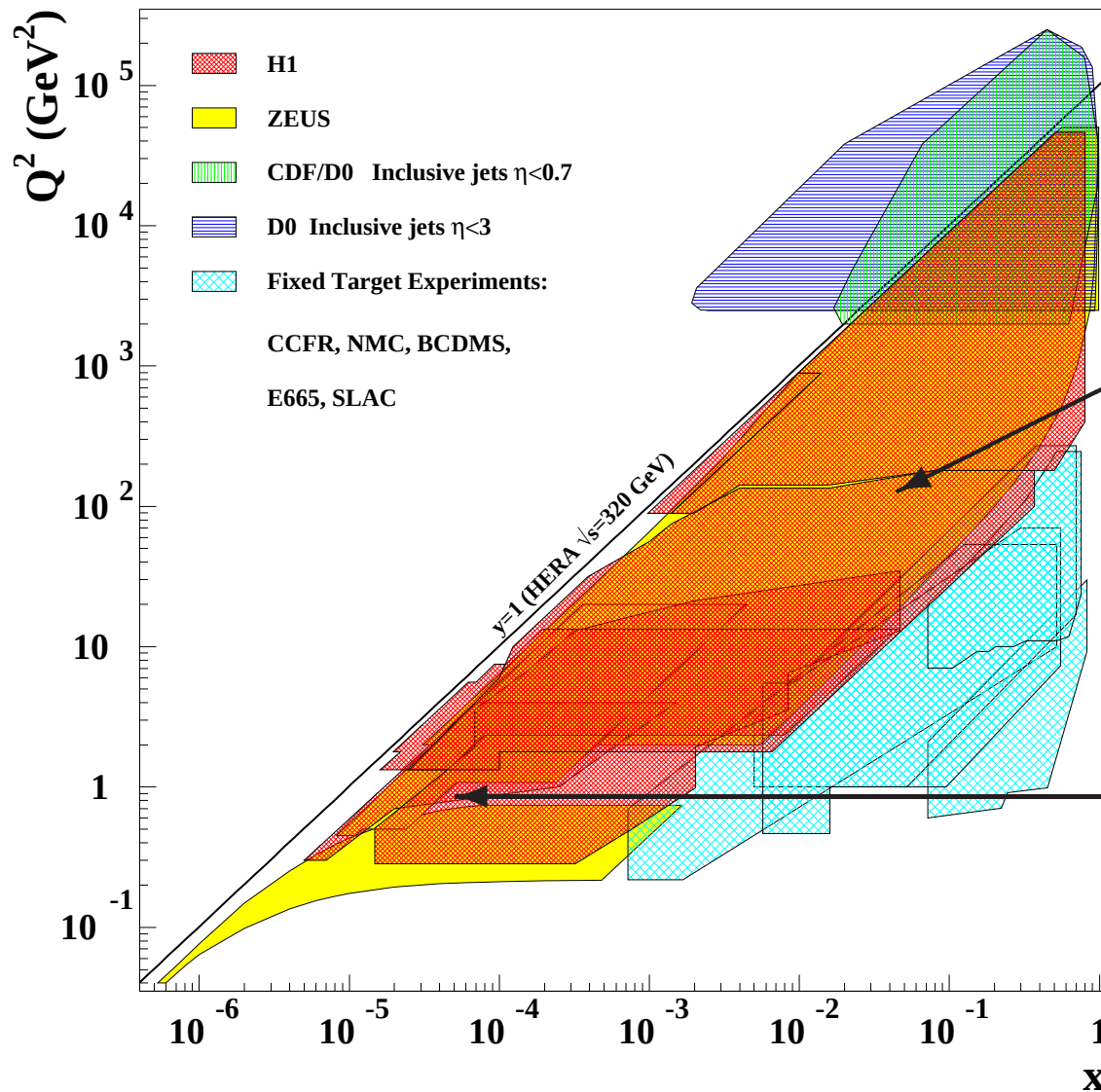
Sufficient for precision measurements at low/medium Q^2, x

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 $\rightarrow$ PDFs

Part 2

Low $Q^2 \sim 1$ GeV² ...

Transition to hadronic physics

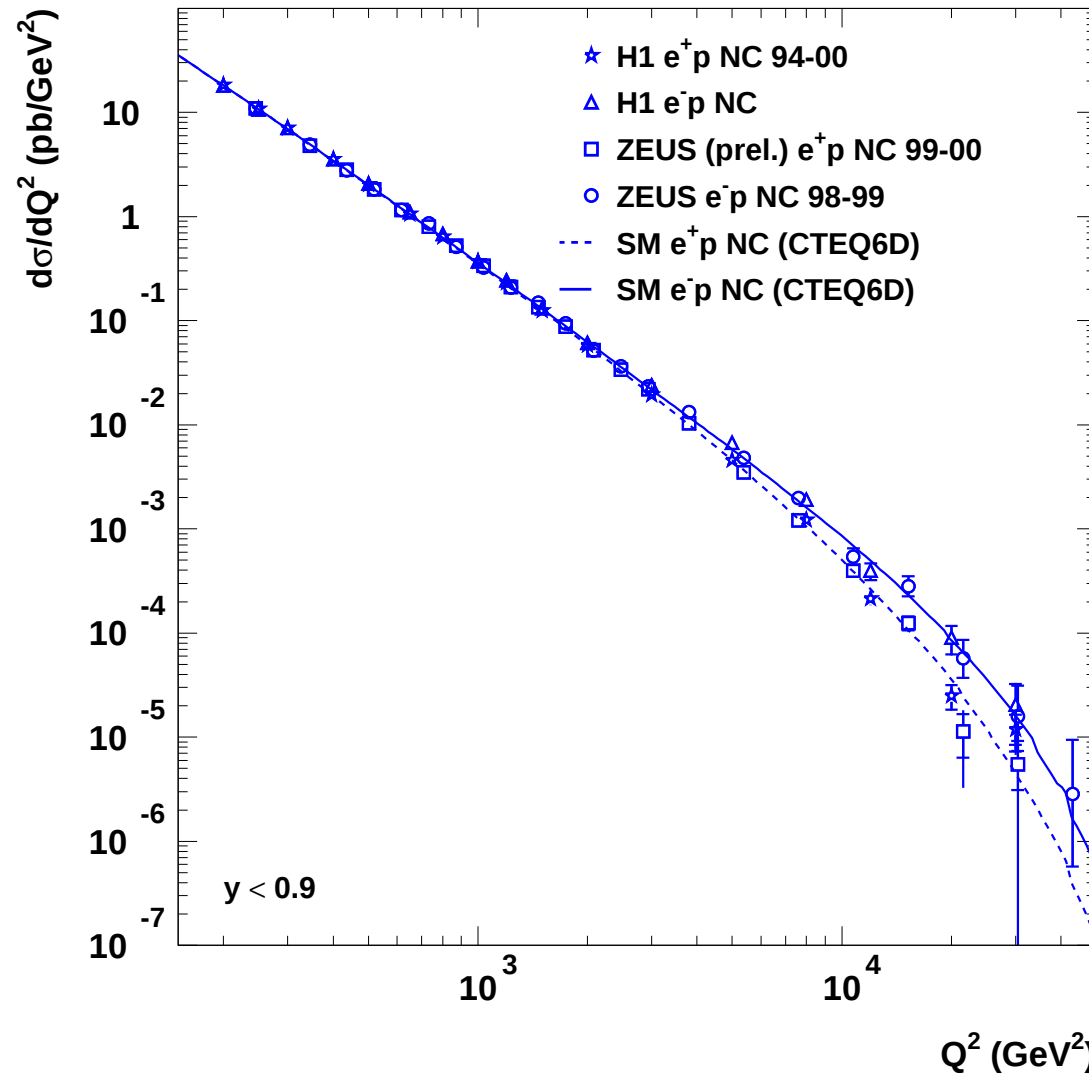
... QCD and confinement

Low x ... High parton

densities, novel QCD dynamics?

High Q^2 Neutral Current Cross Section

HERA



Neutral current cross sections

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

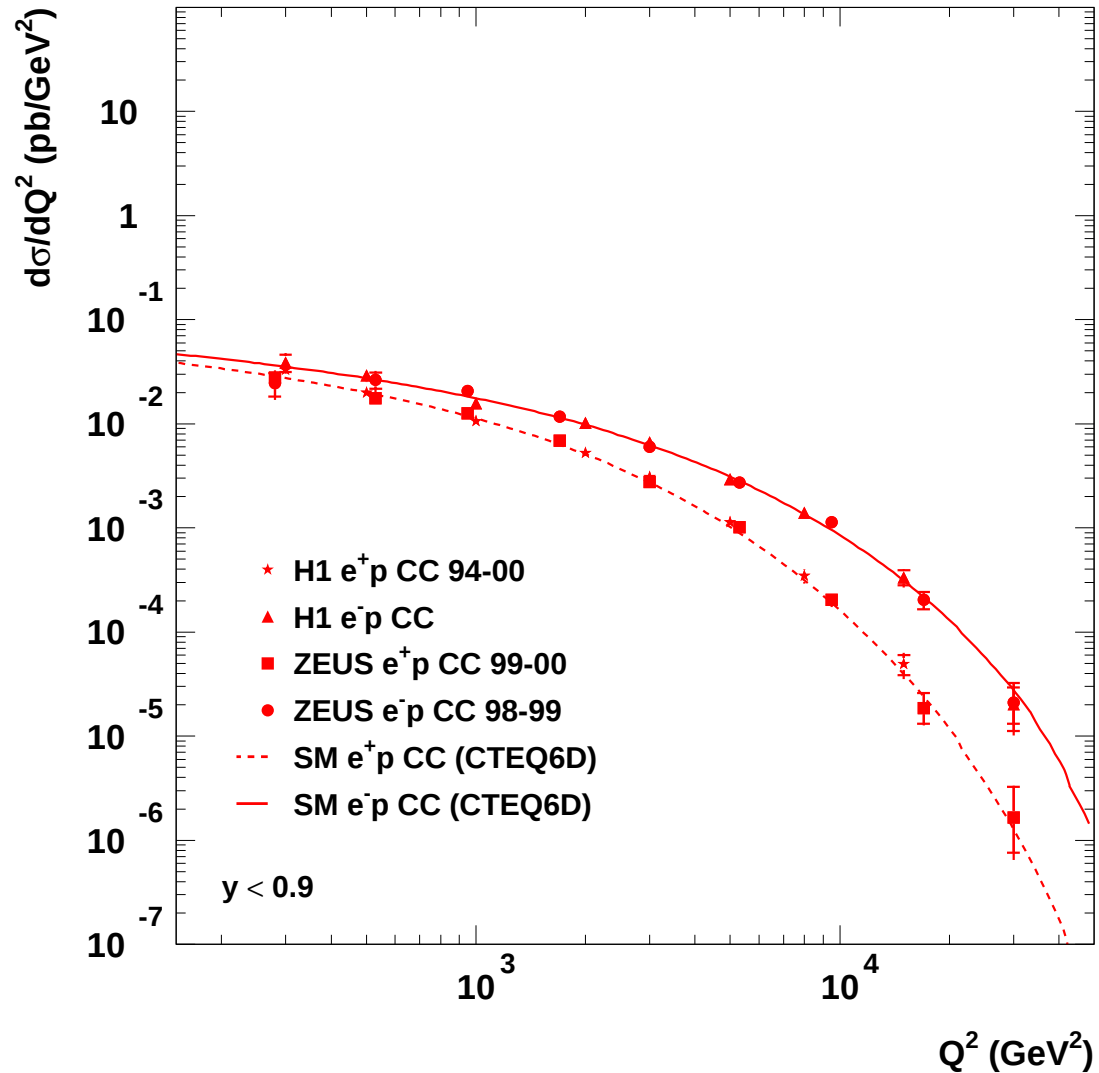
Photon dominated

Propagator

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

High Q^2 Charged Current Cross Section

HERA



Charged current cross sections

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

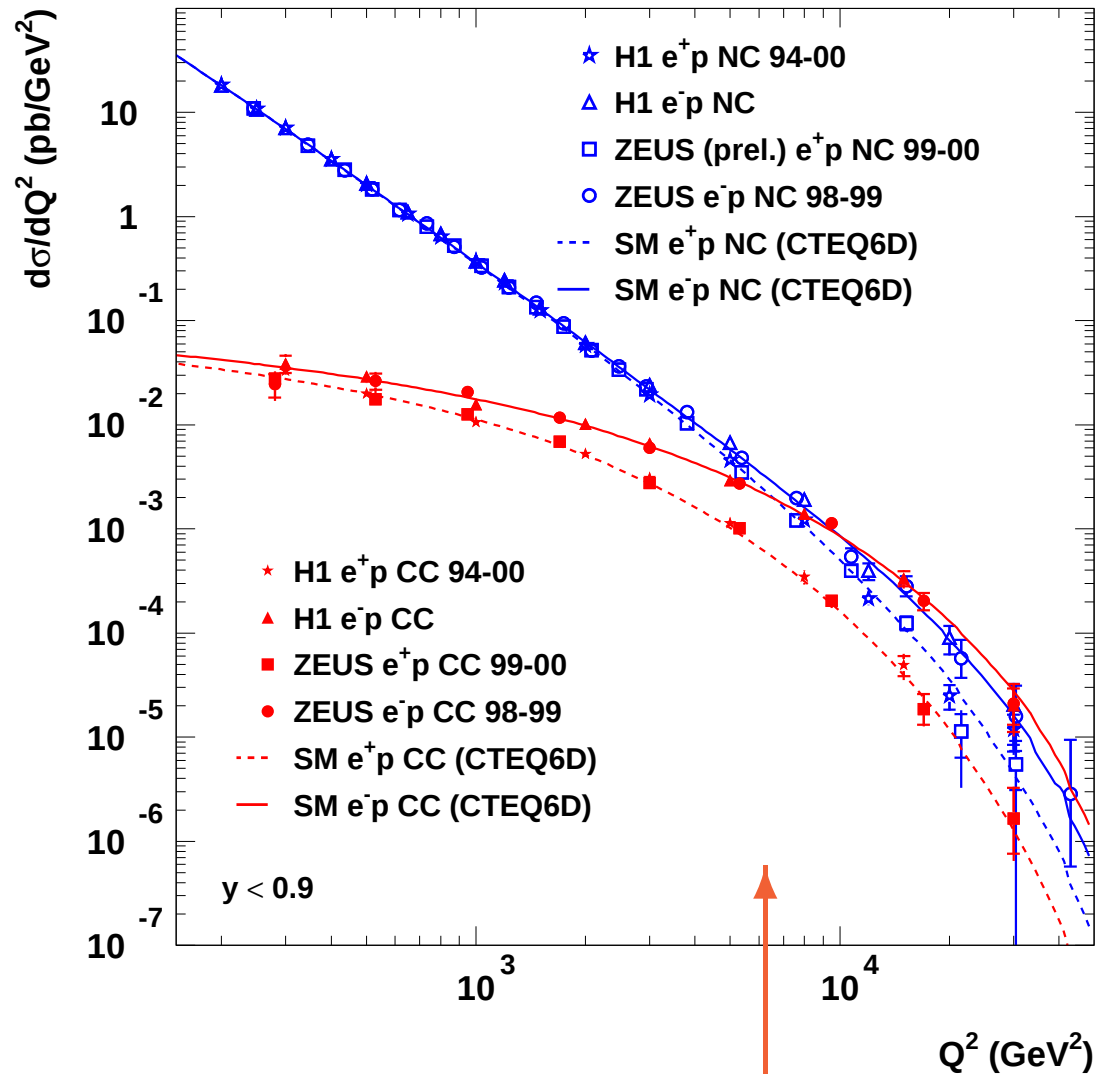
Pure weak

Propagator

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

High Q^2 and Electroweak Unification

HERA



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

Neutral current cross sections

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

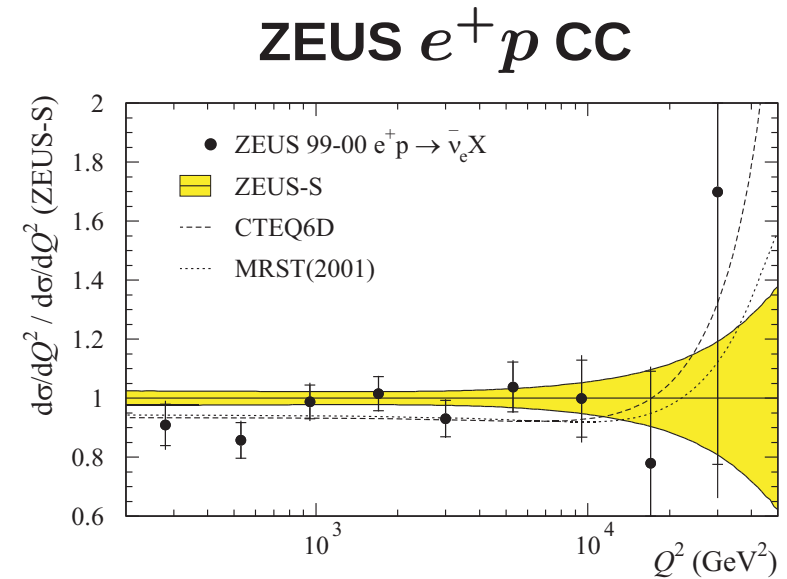
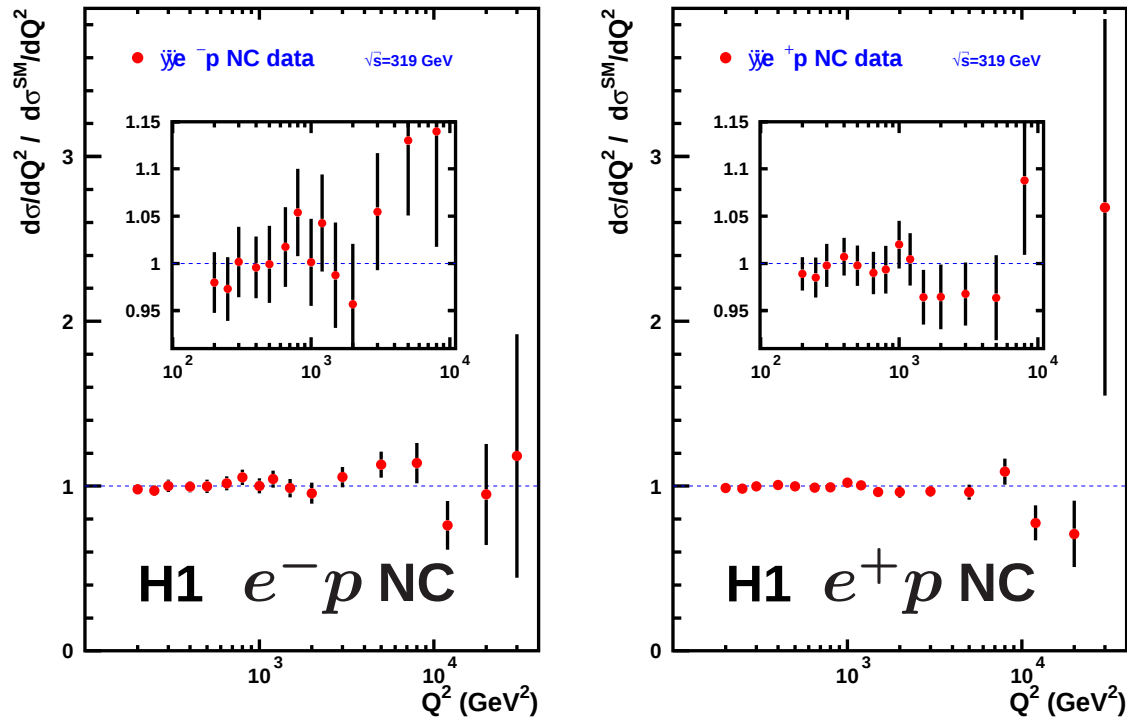
Charged current cross sections

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

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



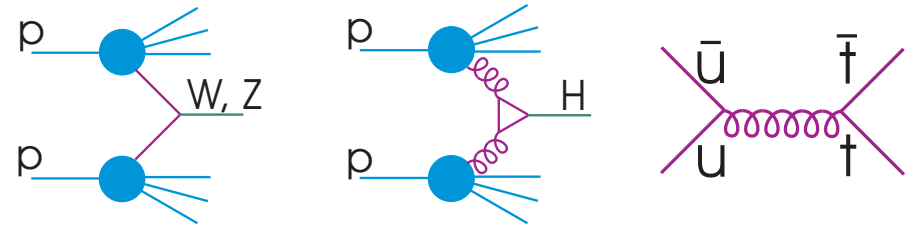
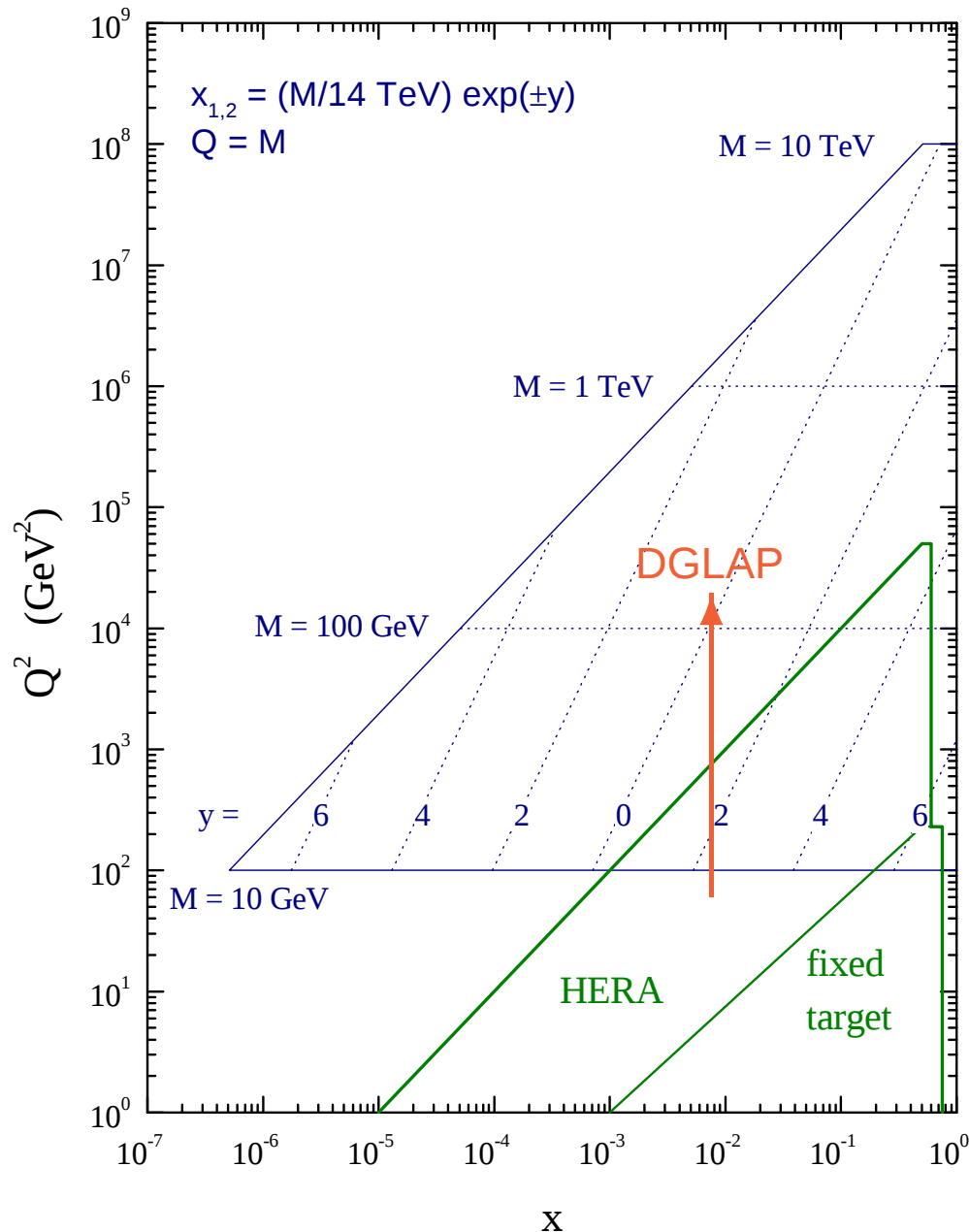
Ratios to SM $\otimes$ PDF predictions independent of HERA high Q^2 data

Good agreement with SM $\otimes$ PDF for NC and CC up to $Q^2 \sim 30\,000$ GeV²

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

LHC parton kinematics



e.g. Production at central rapidity ...

$M \text{ (GeV)}$	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

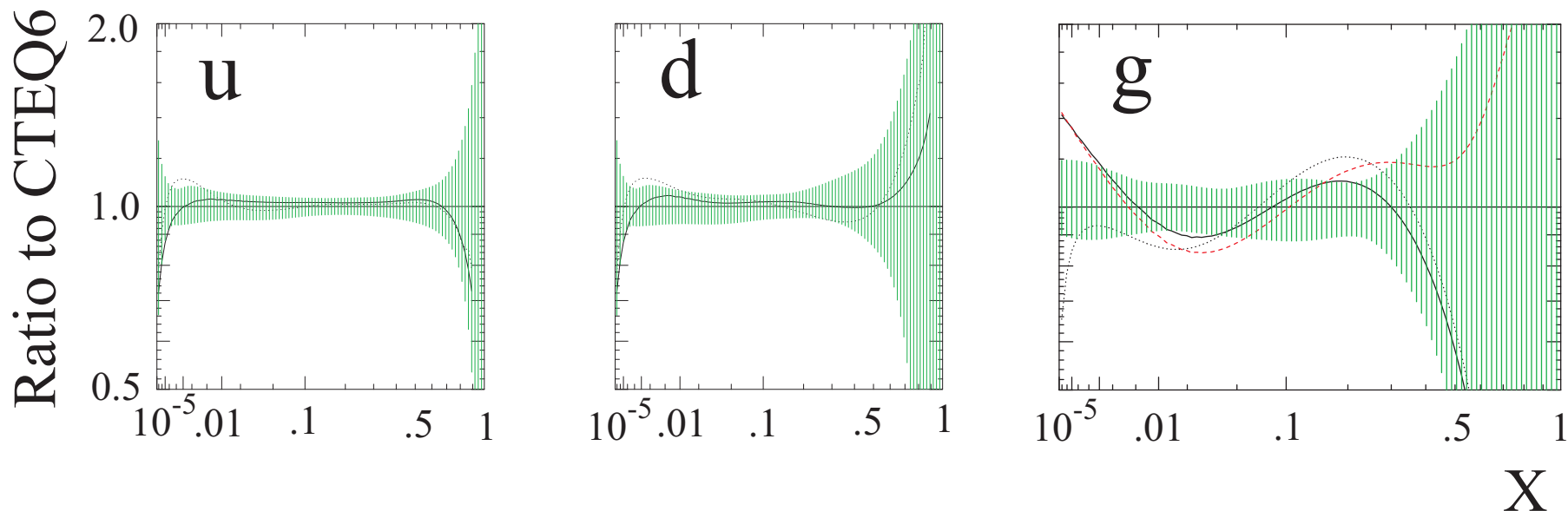
Present Knowledge of Parton Densities

Uncertainty estimates at $Q^2 = 10 \text{ GeV}^2$ 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



$$F_2(x, Q^2)$$

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

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

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

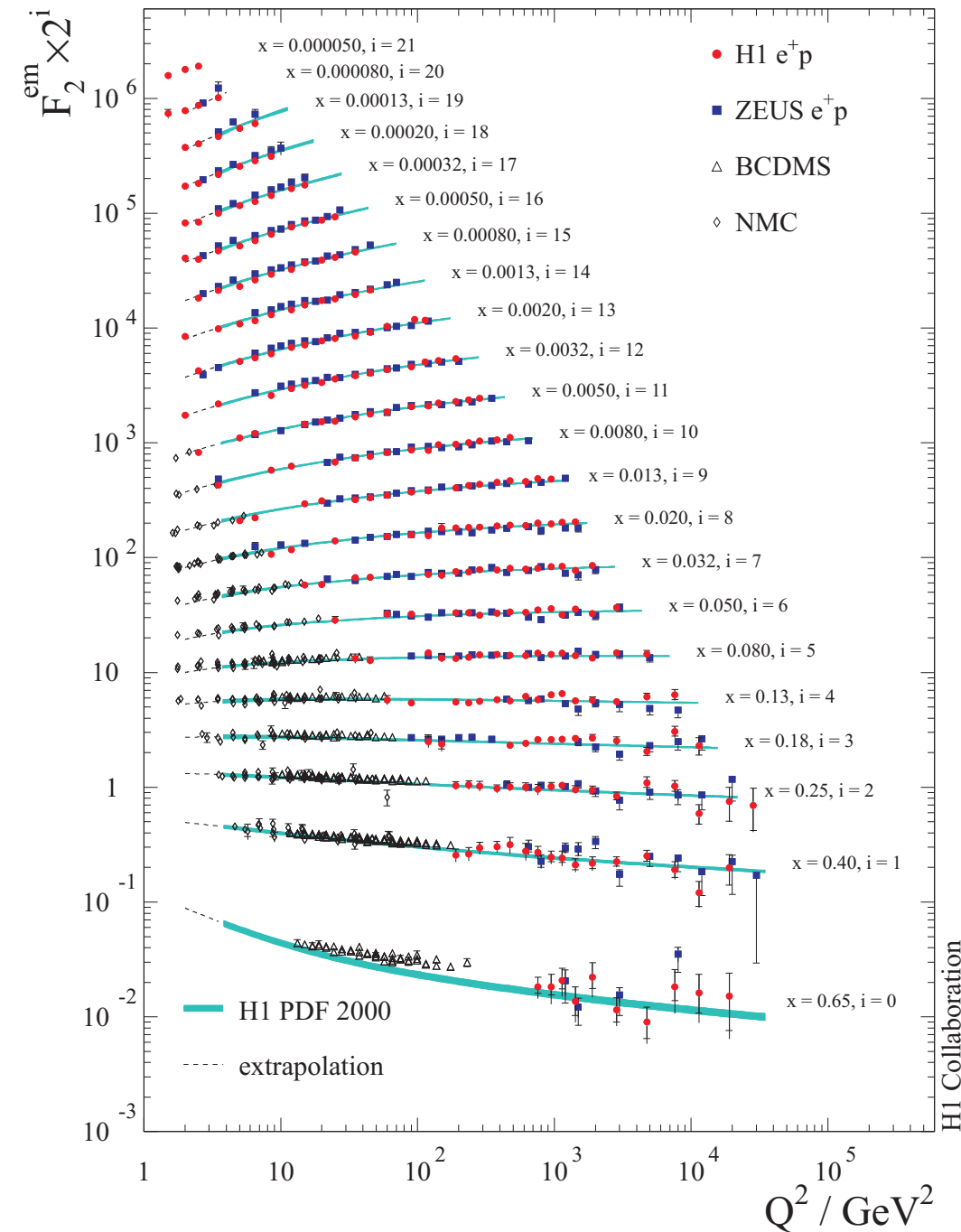
$$F_2^{\text{em}}(x, Q^2) \sim x \sum_q e_q^2 (q + \bar{q})$$

... 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



$$F_2(x, Q^2)$$

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

Measured over huge kinematic range

Beautifully described by QCD fits

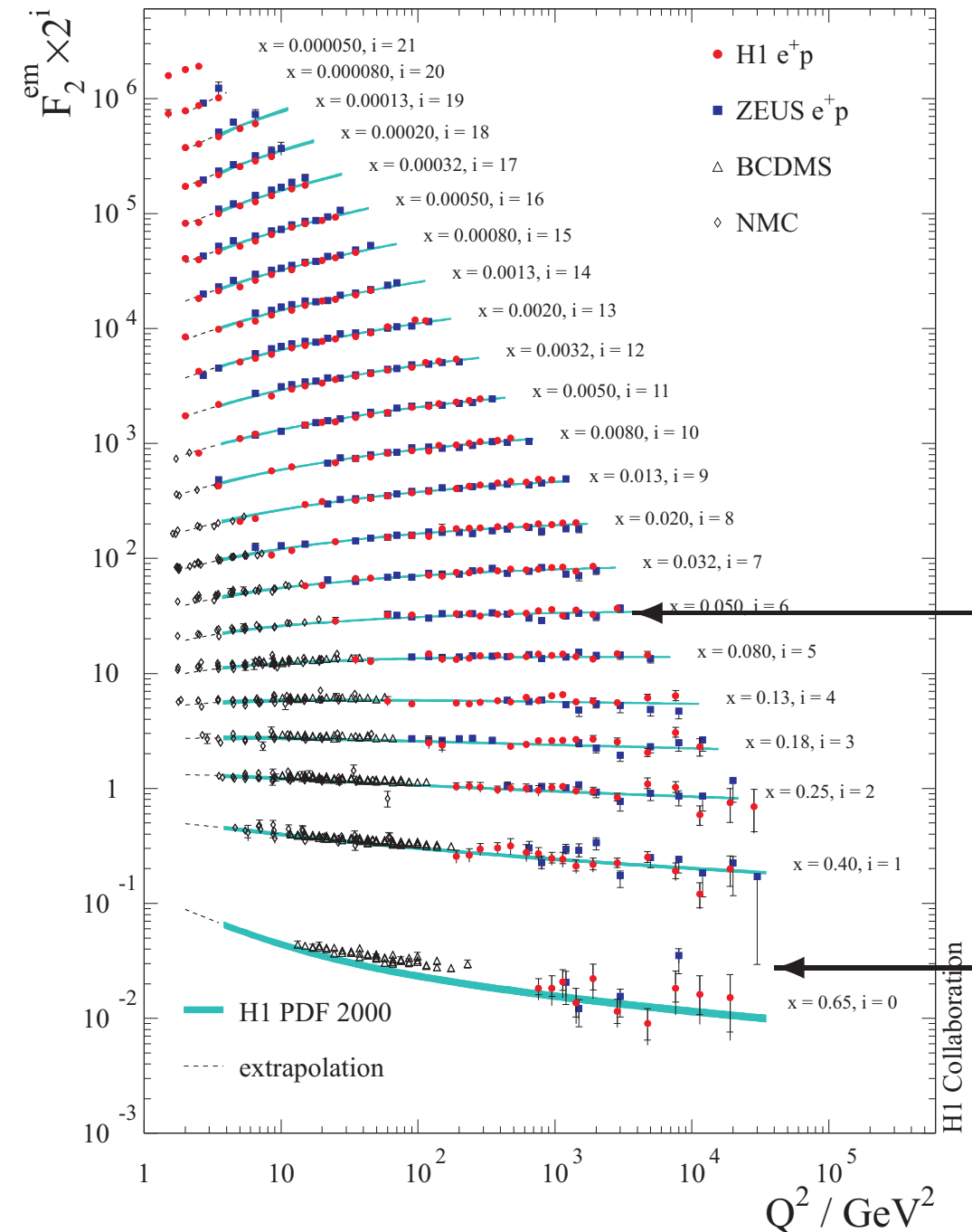
2-3% precision in bulk of phase space

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



$$xF_3(x, Q^2)$$

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

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

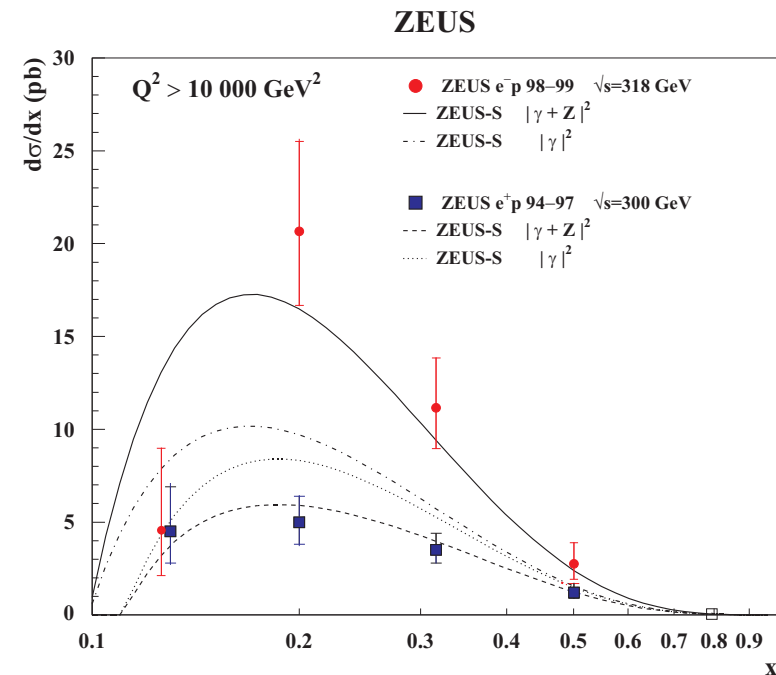
$$xF_3 = -a_e \frac{\kappa Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + \Delta(Z^2)$$

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 ($\tilde{\sigma}_{\text{NC}}^- \gg \tilde{\sigma}_{\text{NC}}^+$)



$$xF_3(x, Q^2)$$

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

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

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

Destructive / constructive $\gamma - Z$ interference

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

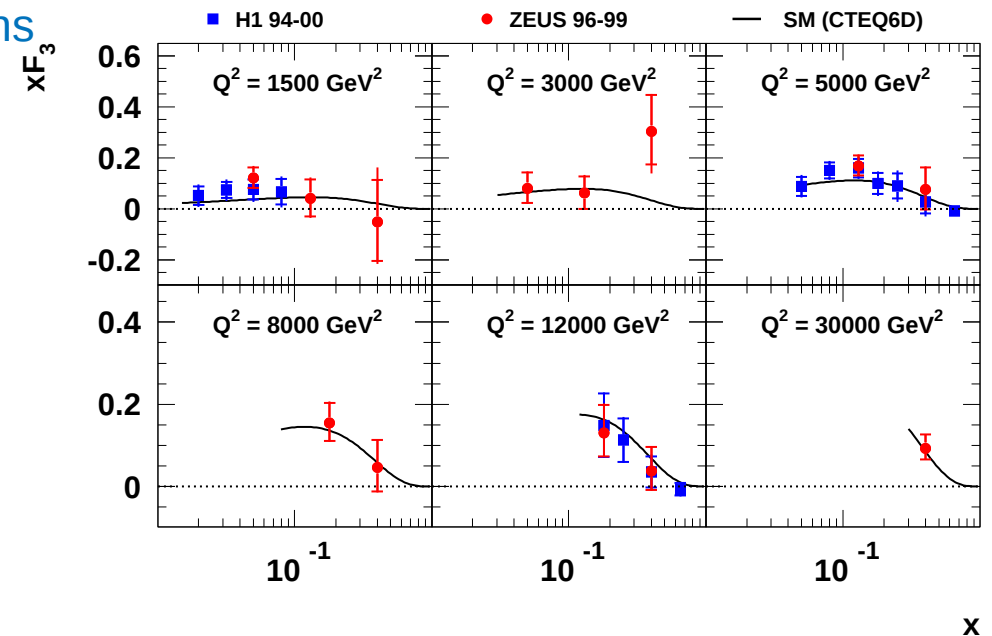
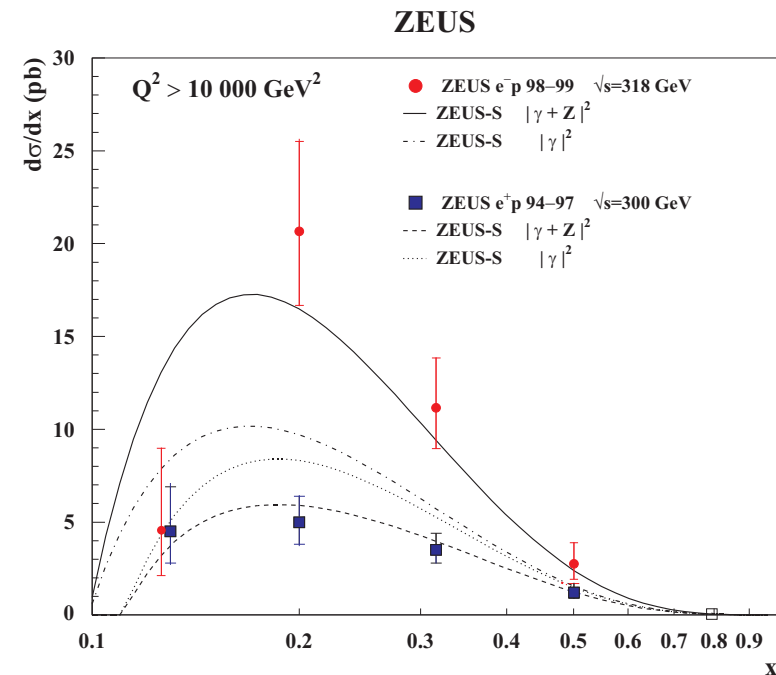
Assumption-free access to valence distributions

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

First “exploratory” extractions agree

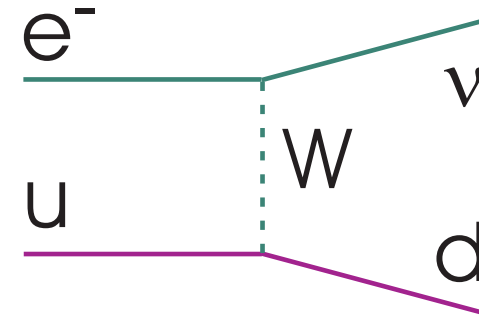
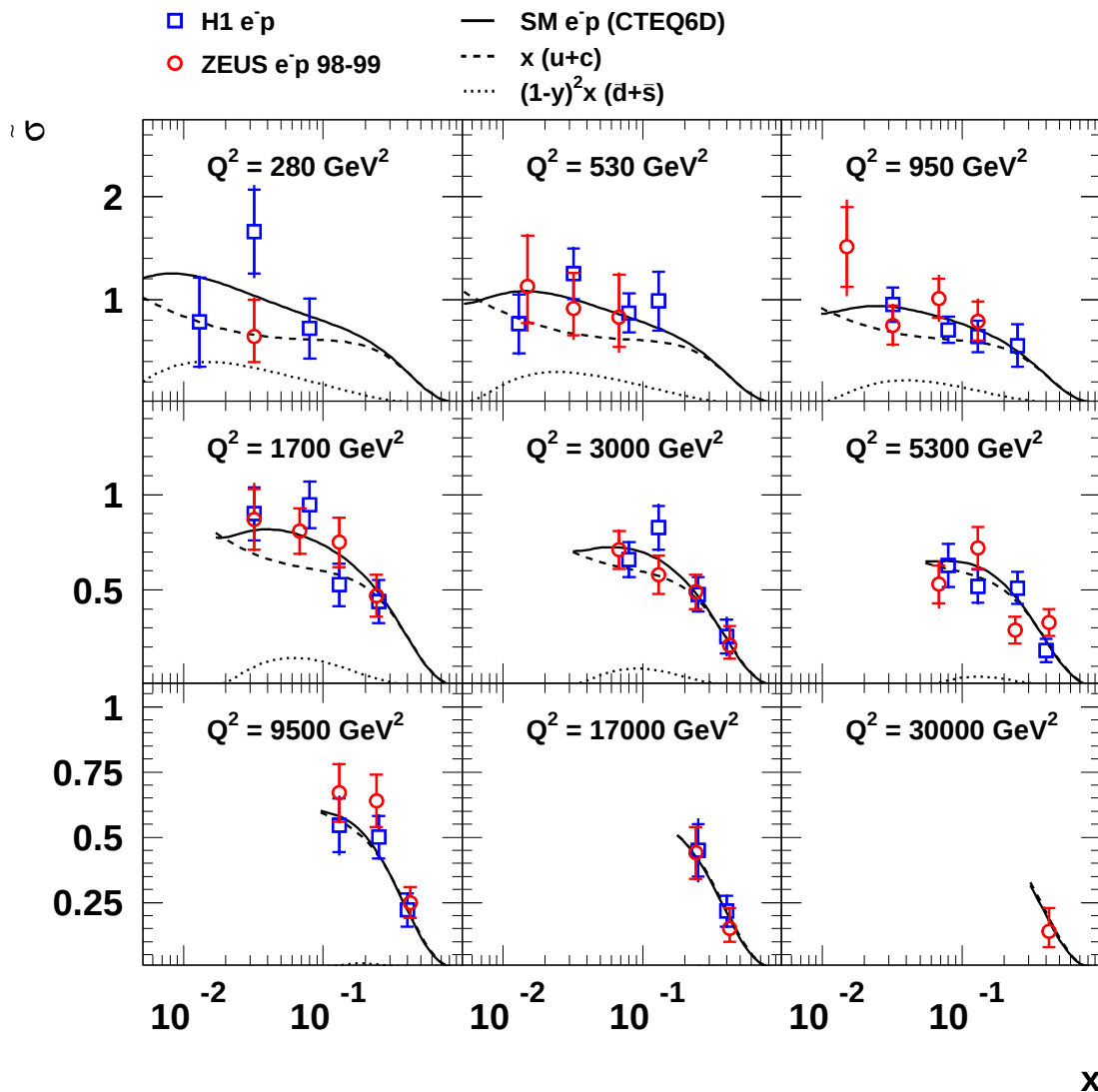
well with SM $\otimes$ PDF predictions

Much more data required for full exploitation



$e^- p$ Charged Current Cross Sections

HERA $e^- p$ Charged Current



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

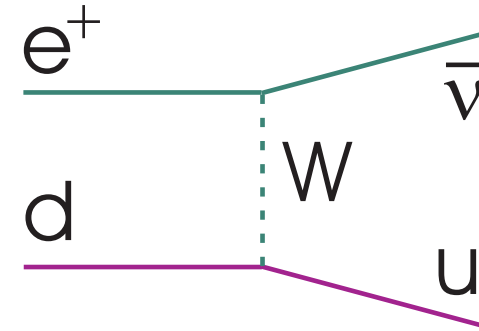
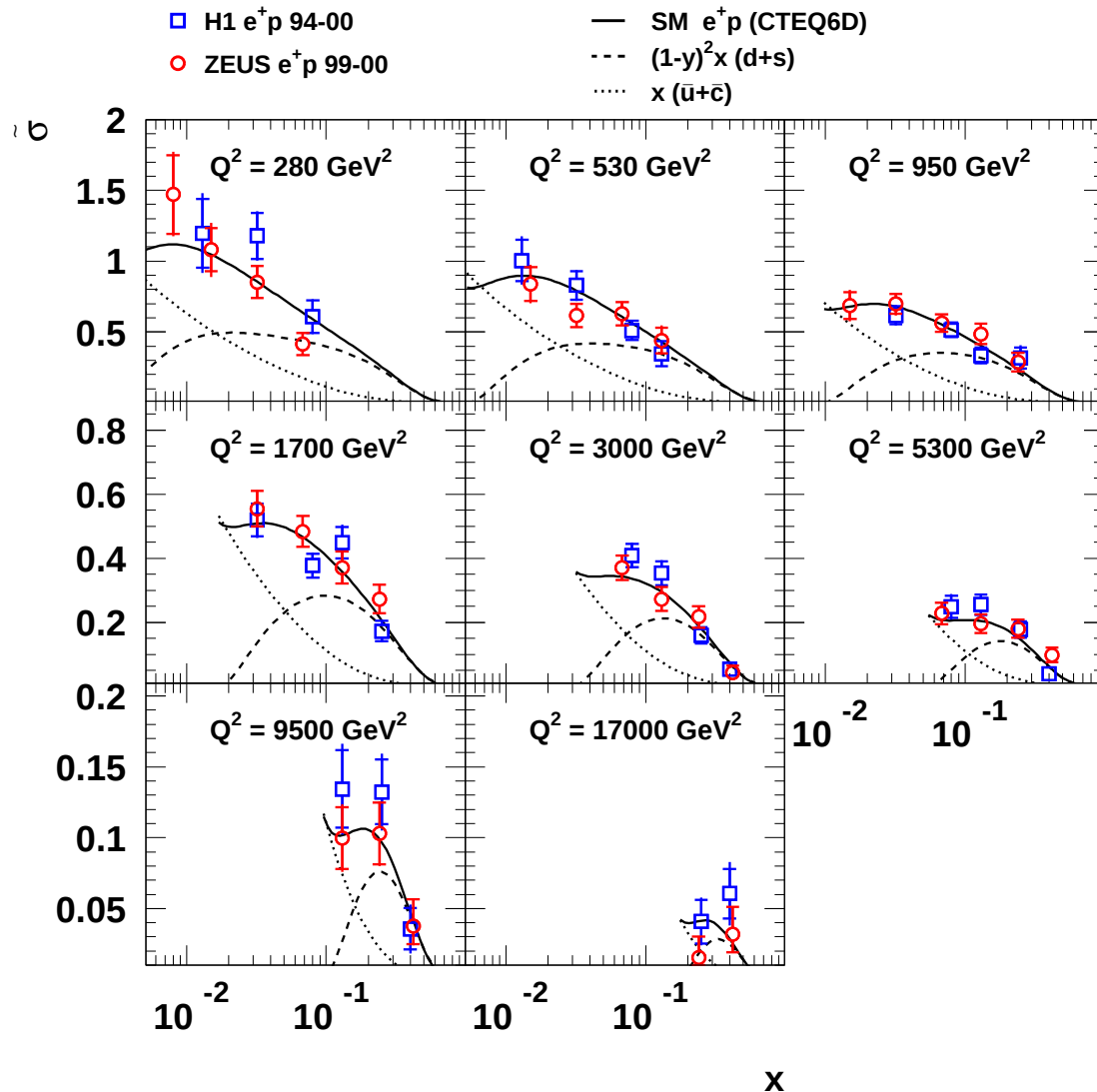
Sensitive to flavour decomposition

Clean constraint on u density at high x

Complementary to F_2

e^+p Charged Current Cross Sections

HERA e^+p Charged Current



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

Promising for d density at high x

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

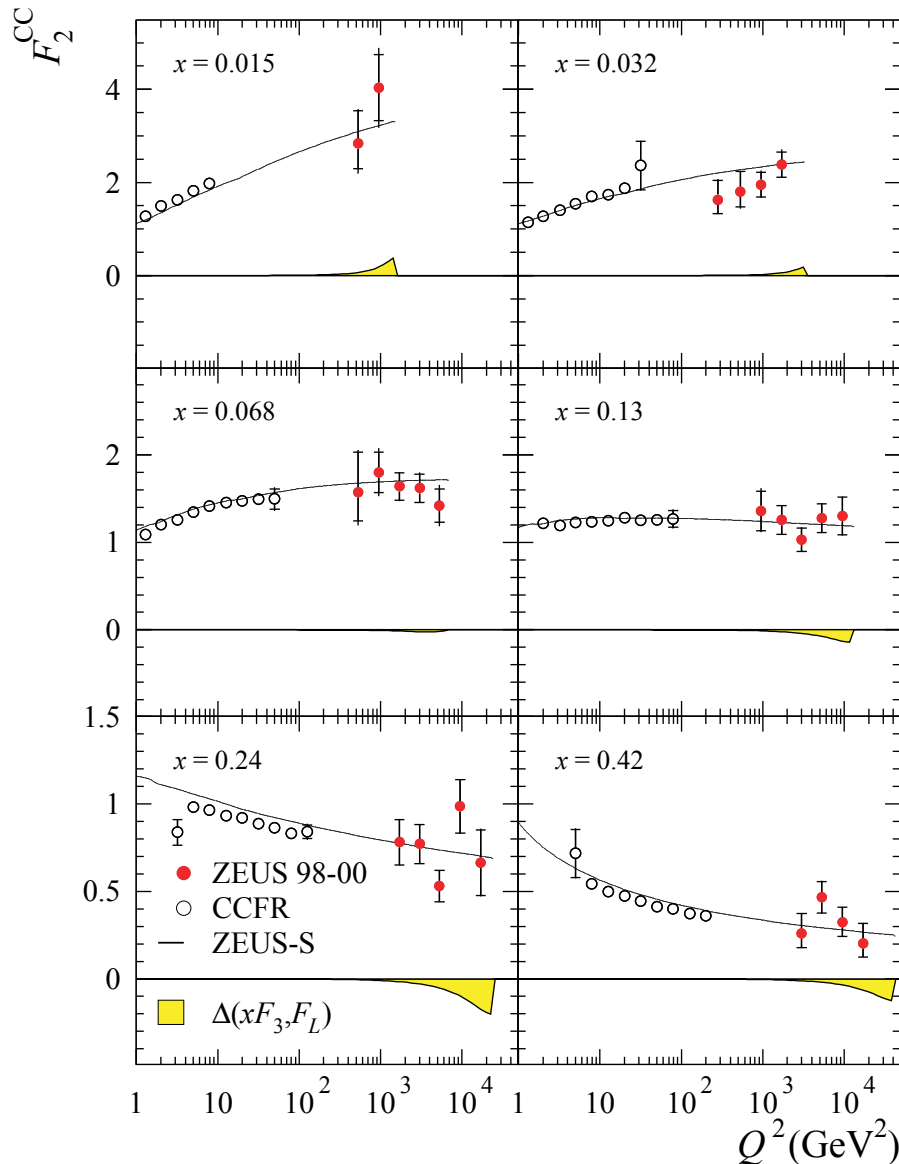
More data will help a lot

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

eD data would constrain d/u at large x

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

ZEUS



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

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

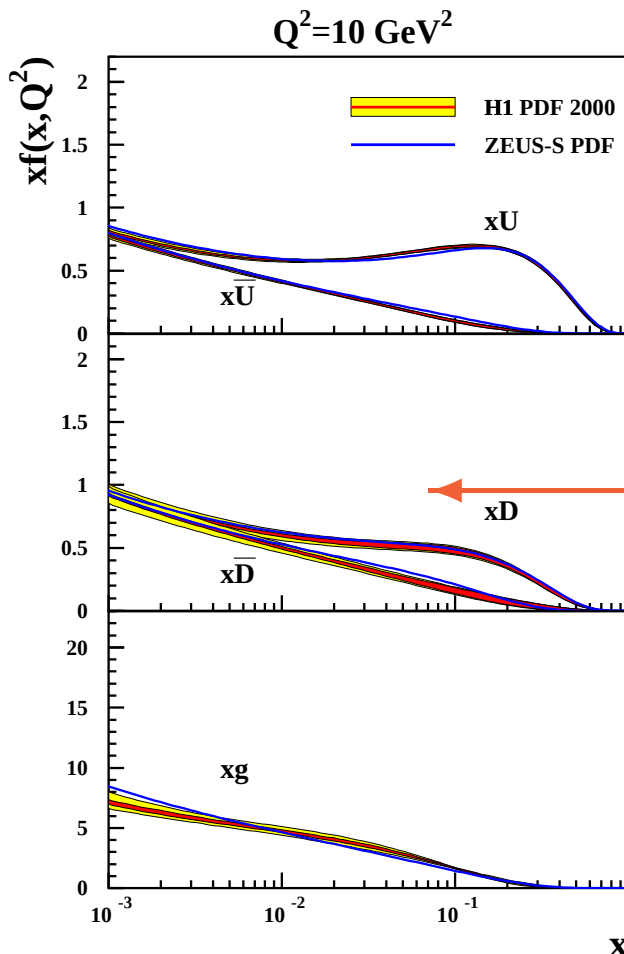
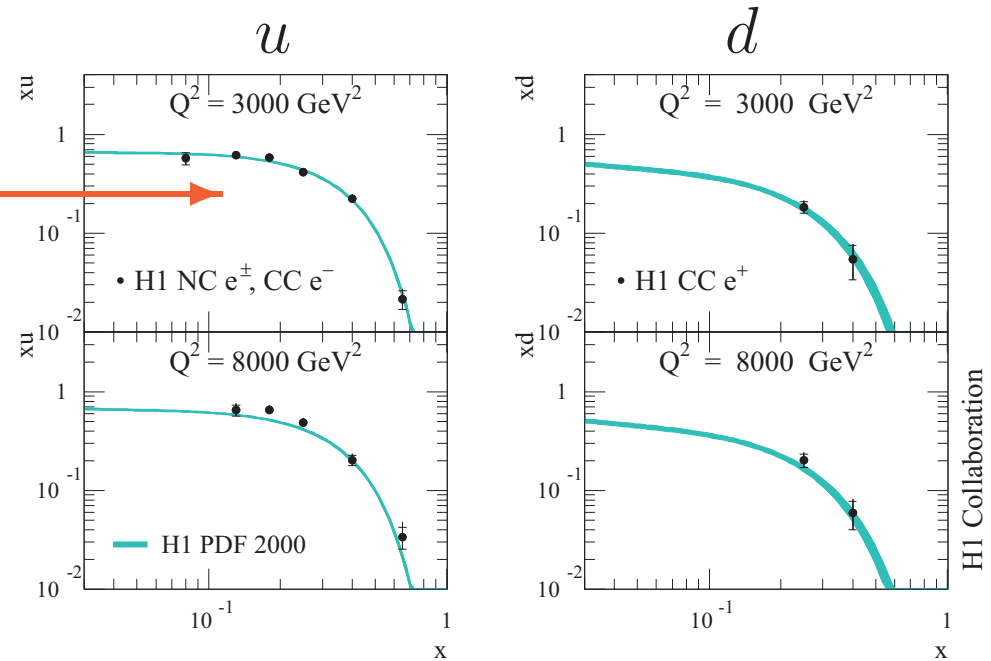
Data span more than 4 orders of magnitude in Q^2

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 ...

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

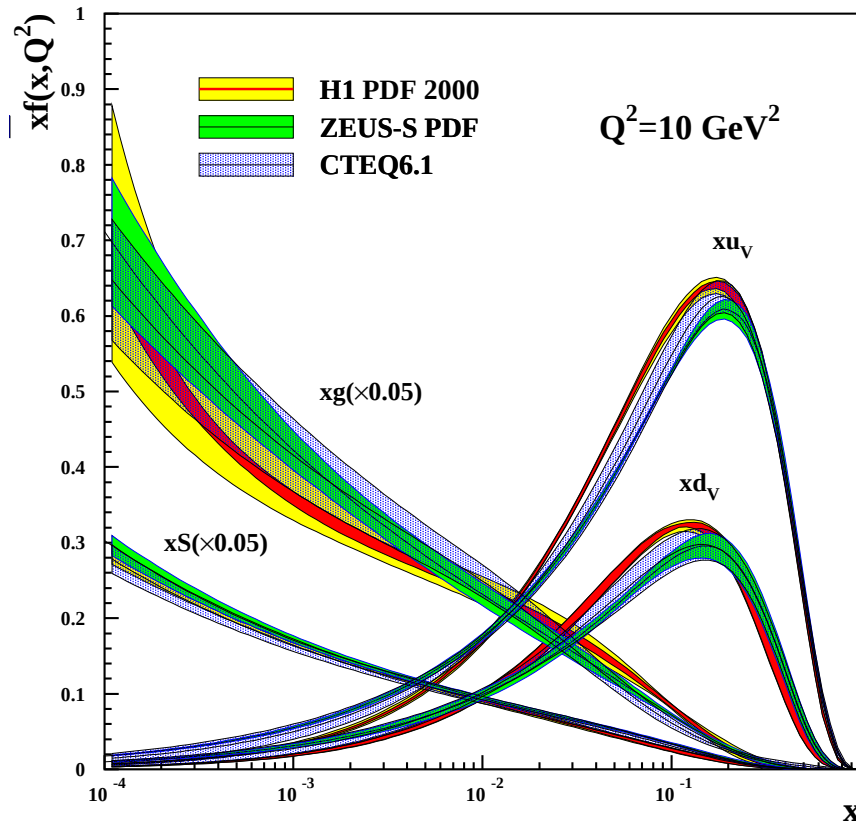
$$u_v = U - \bar{U} \text{ etc}$$

Fixed target still needed for high x precision

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

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 $Q^2 = 10 \text{ GeV}^2$, $10^{-4} < x < 10^{-1}$

High $x \rightarrow$ poorly constrained

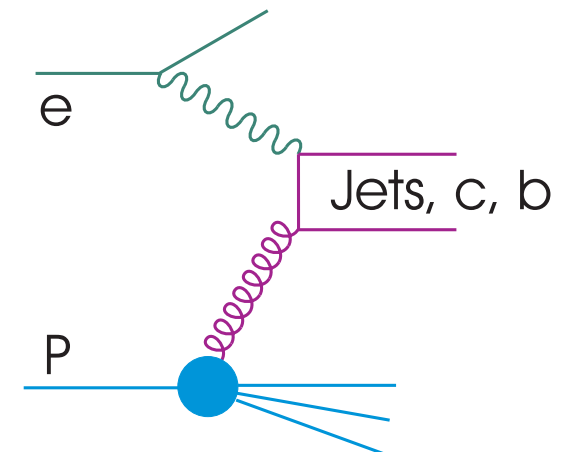
Low $x \rightarrow$ gluon very large ... DGLAP sufficient?

Direct constraints from final state data ...

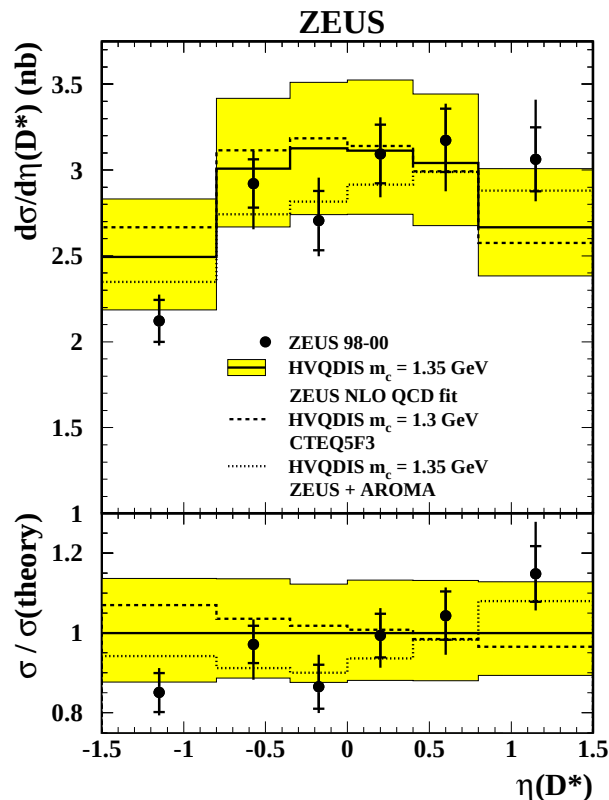
$$\sigma(\text{jets}), \sigma(\text{charm}), \sigma(\text{beauty}) \sim \alpha_s xg(x) \quad (\text{LO QCD})$$

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

Fast improving charm and beauty data ...



Charm and the Gluon

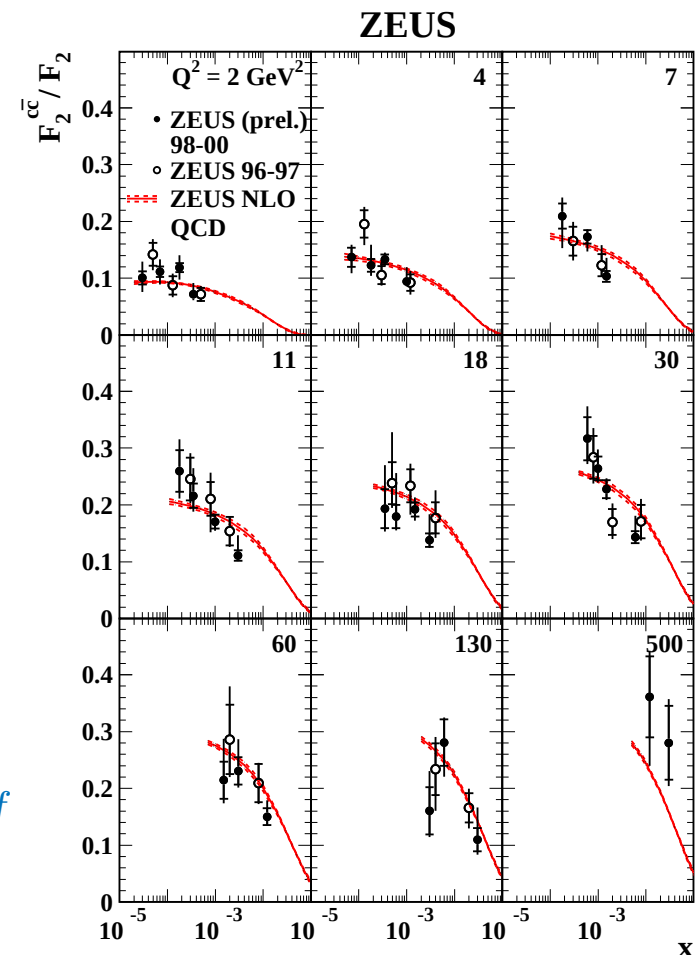


Charm from $\sigma(D^*)$
 ν NLO QCD $\otimes xg(x)$

Beautiful confirmation
of gluon from scaling
violations at 10% level

Sensitive to differences
between fitted gluons

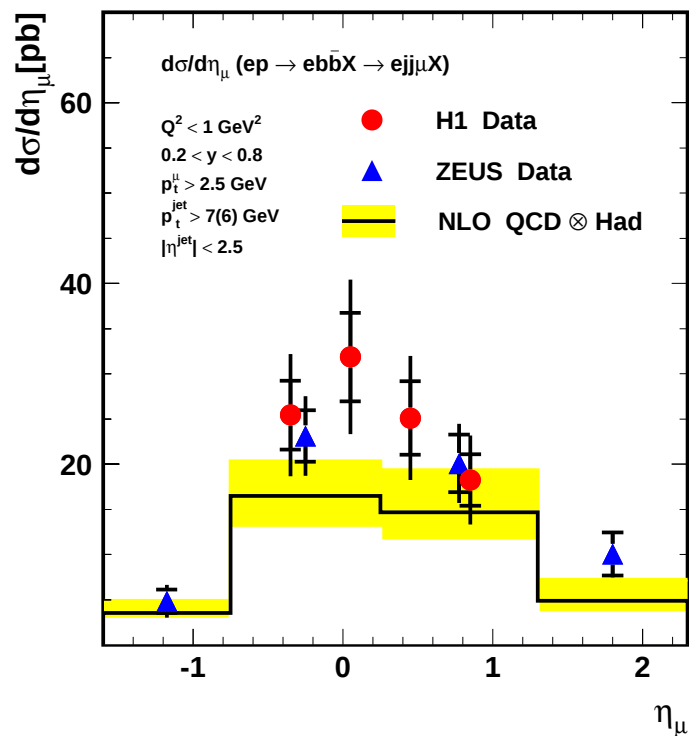
Theoretical uncertainties
dominate $\rightarrow m_c, \mu_r, \mu_f$
 ϵ_c , HF scheme



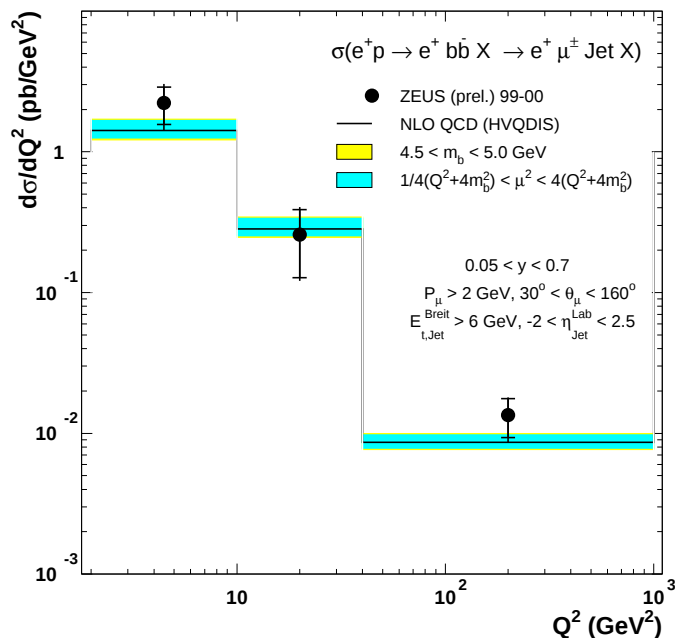
$F_2^{c\bar{c}}$ obtained with extrapolation in η, p_t (NLO HVQDIS)

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

Upgraded Silicon detectors, triggers $\rightarrow$ big charm future at HERA-II



ZEUS



Beauty Production

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

- Understanding parton dynamics and multi-scale QCD
- Previously reported HERA, Tevatron beauty “anomalies” ...

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

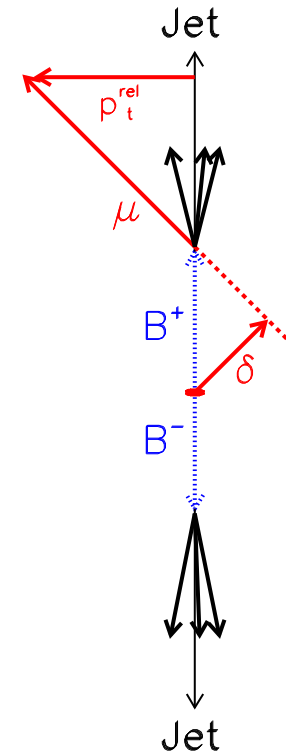
Unfold from charm, uds using δ (Si) and $p_T^{\text{rel}}(\mu - \text{jet})$

Compare with NLO QCD directly in measured range

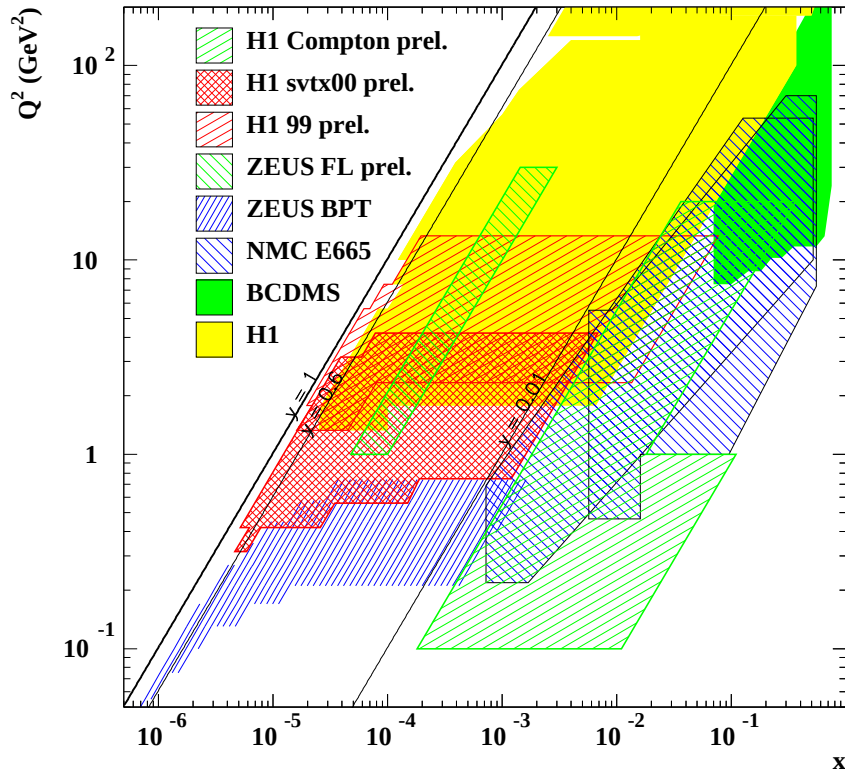
Good agreement at large Q^2, p_T

Data > theory at $Q^2 = 0$ (1.5σ)

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



Low x and Q^2 Physics



Low x , low Q^2 kinematically correlated

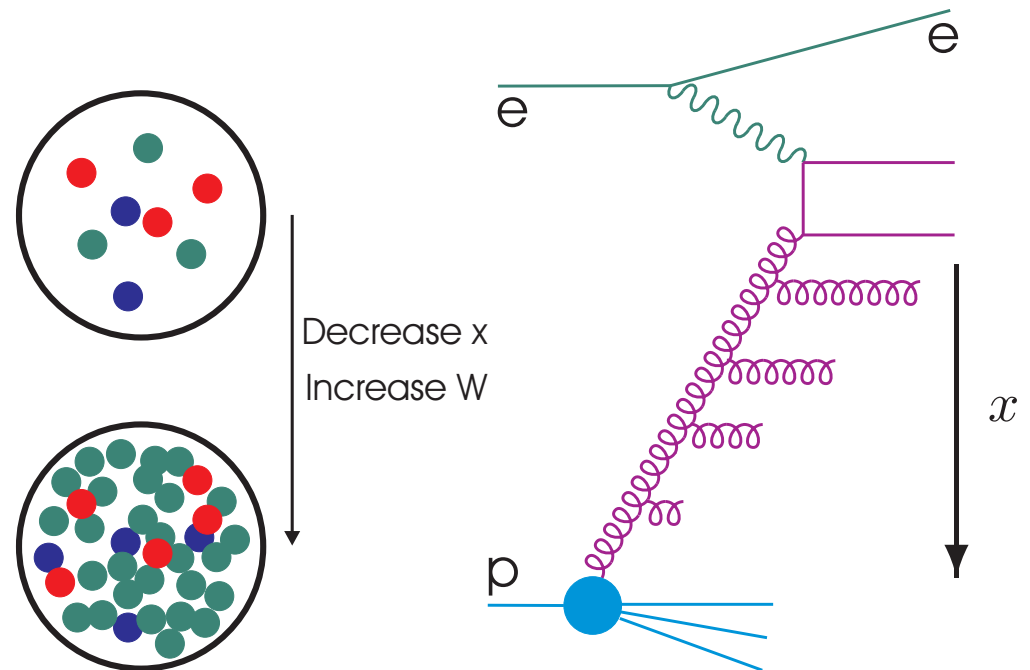
Recent progress in inclusive and final state data

• $Q^2 \rightarrow \Lambda_{\text{QCD}}^2 \rightarrow$ transition to long distance non-perturbative physics, confinement?

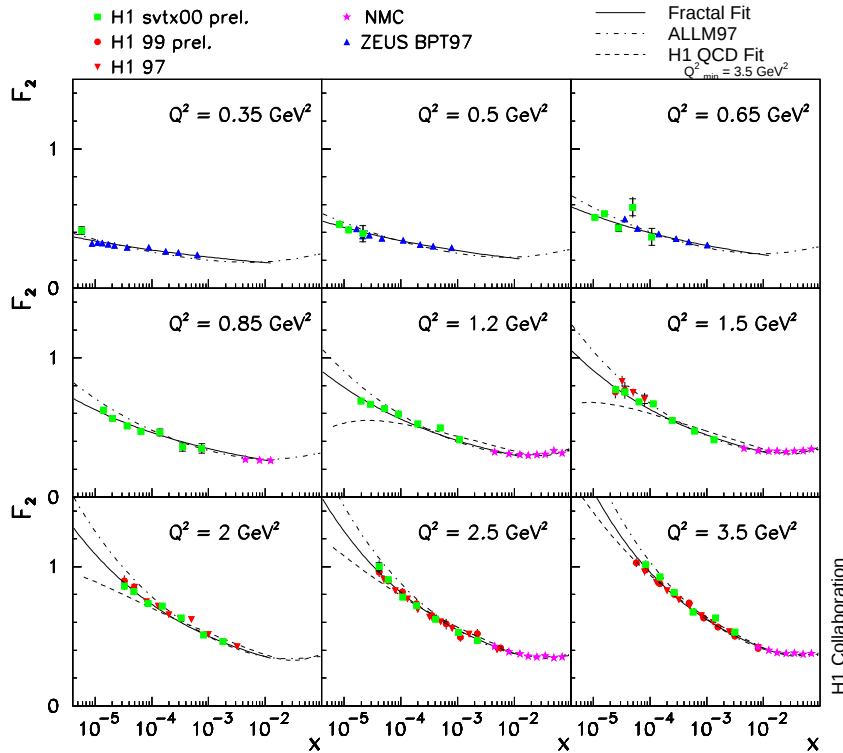
• Low x ...

High parton densities $\rightarrow$ unitarity limit, gluon recombination?

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



F_2 at low Q^2



F_2 measurements at low $Q^2 \sim 1 \text{ GeV}^2$
($y < 0.6$ to avoid F_L effects)

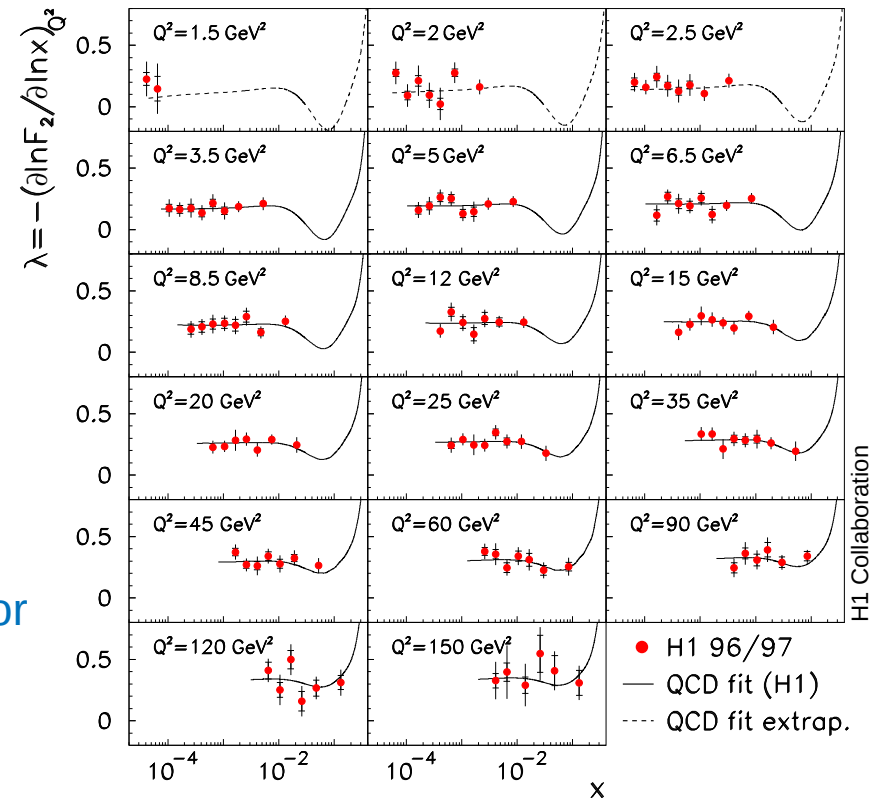
$Q^2 = 3.5 \text{ GeV}^2 \rightarrow$ fast rise with decreasing $x \dots$

$Q^2 = 0.35 \text{ GeV}^2 \rightarrow$ 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

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

$Q^2 \gtrsim 3 \text{ GeV}^2$:

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

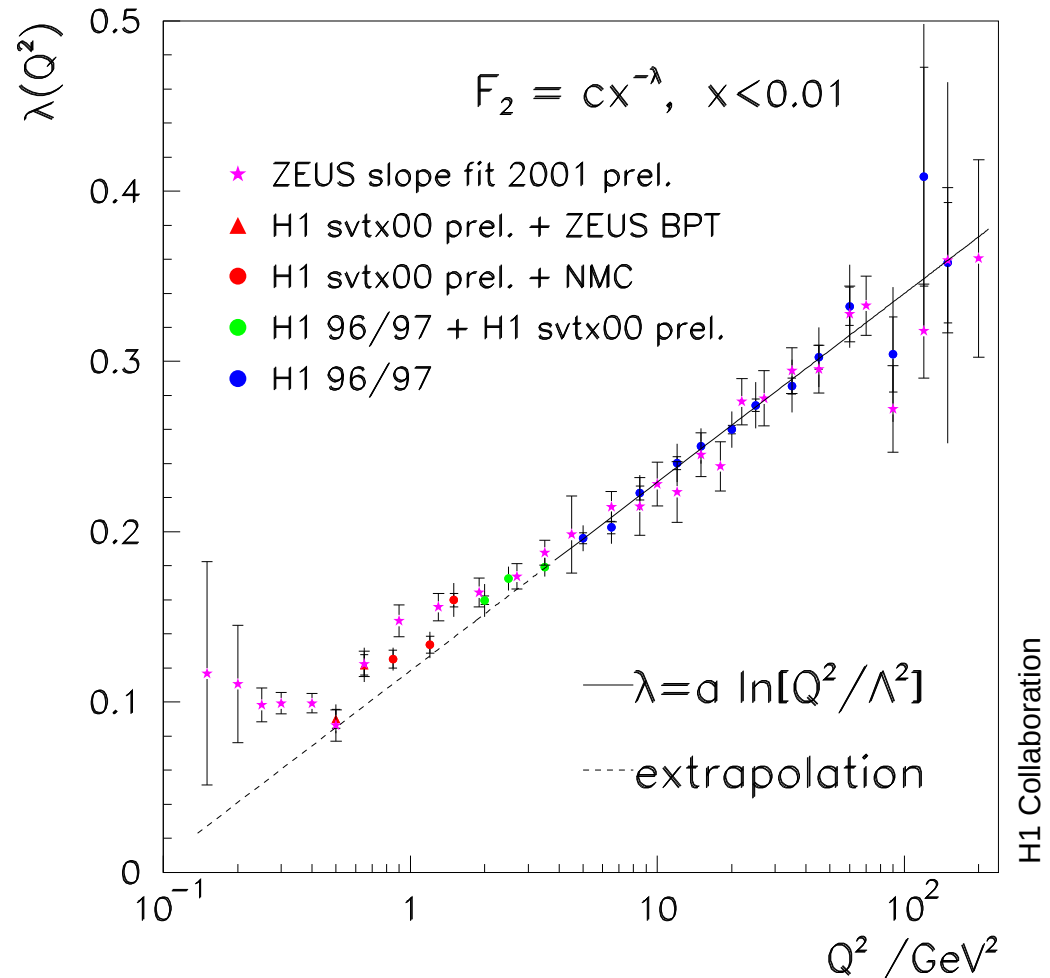
Partons as degrees of freedom

$Q^2 \lesssim 1 \text{ GeV}^2$:

$$\lambda(Q^2) \rightarrow \alpha_{\text{IP}}(0) - 1 \sim 0.08$$

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

(scale $\sim 0.3 \text{ fm}$)



F_L at Low Q^2

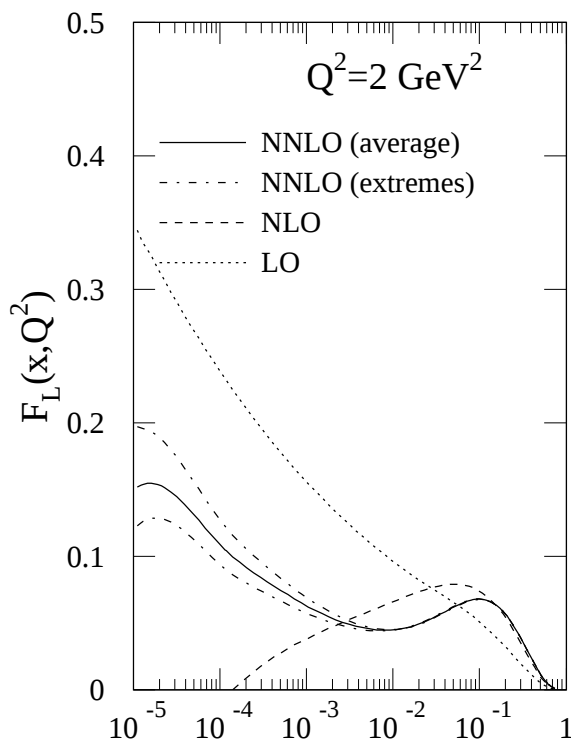
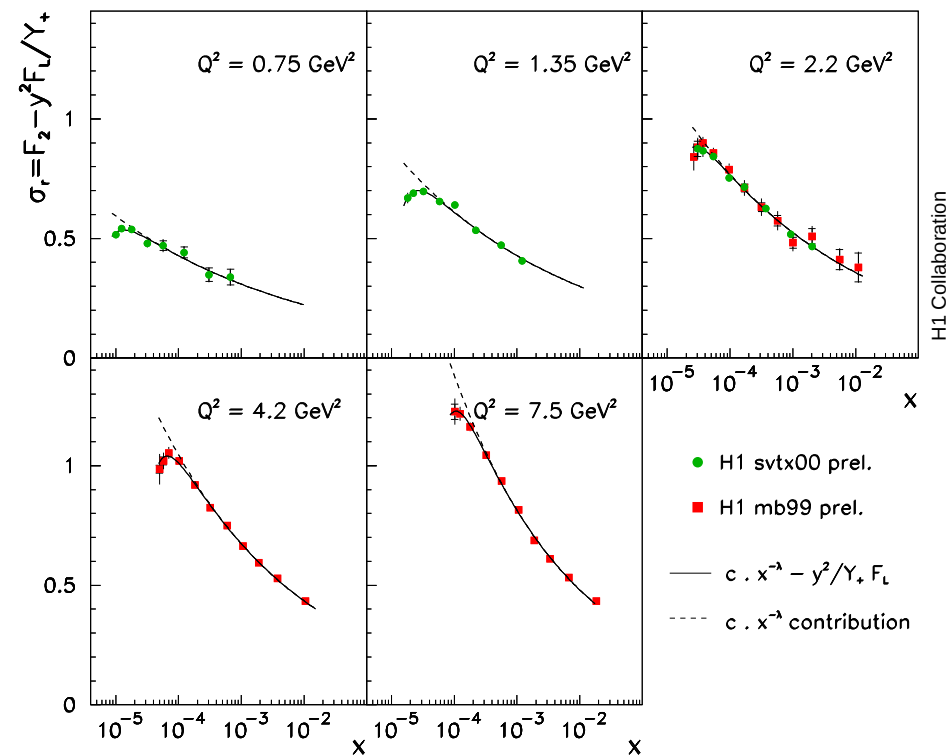
$xg(x)$ poorly known in low Q^2 region where DGLAP questionable

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 $y \rightarrow 0.9$ ($E'_e > 3$ GeV)

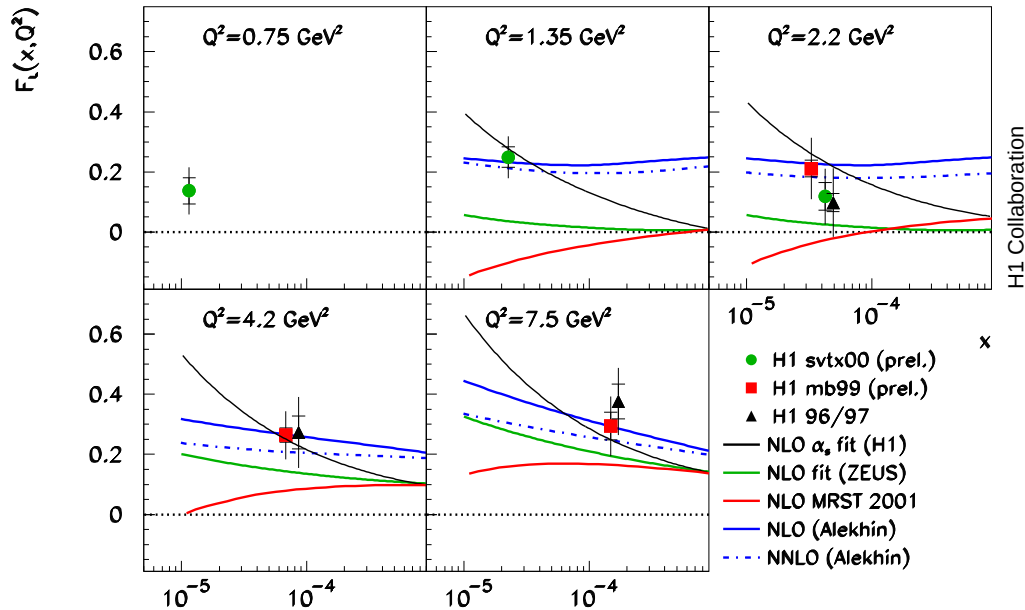
$$\sigma_r = F_2 - (y^2/Y_+) F_L$$

Requires model for F_2 at high y ...

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

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

F_L at Low Q^2



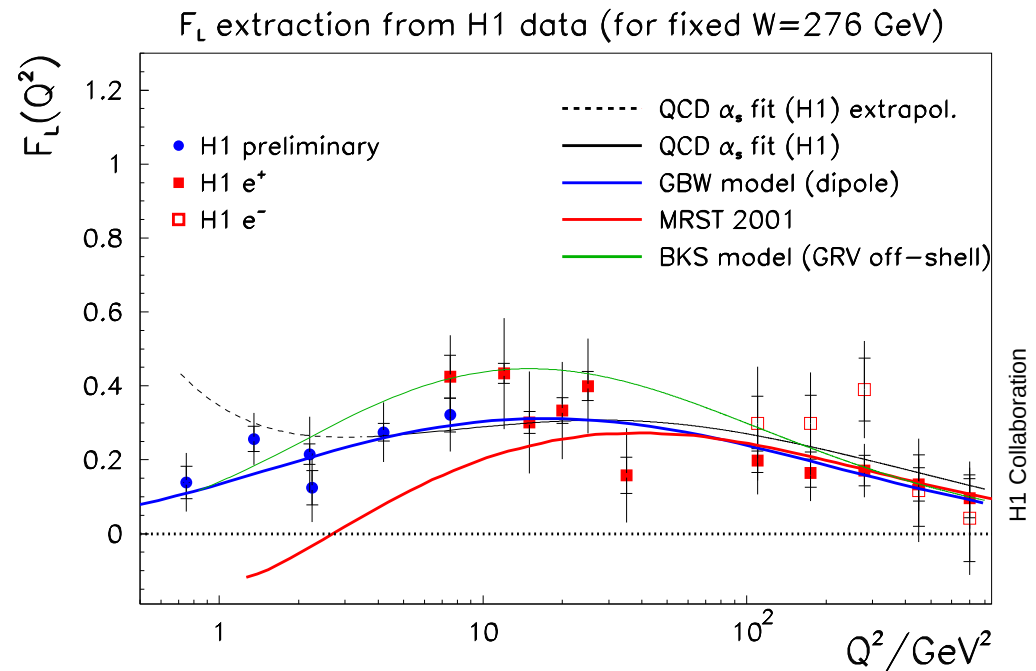
First data at $Q^2 \sim 1 \text{ GeV}^2$

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 ...
 - Si tracking
 - Triggering
- Longitudinally polarised leptons
 - Forward tracking
 - Proton tagging

2001-2002

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

HERA-II restart Sept '03

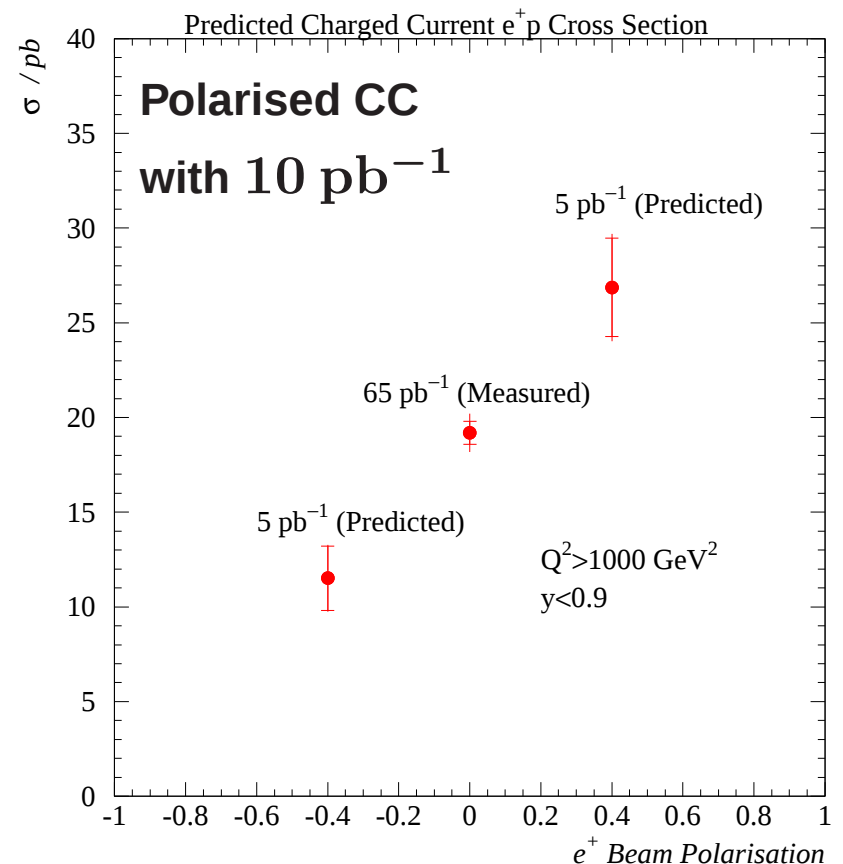
- few $\times 10 \text{ pb}^{-1}$ expected in 2003
- sufficient to establish polarisation dependence

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

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

→ 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

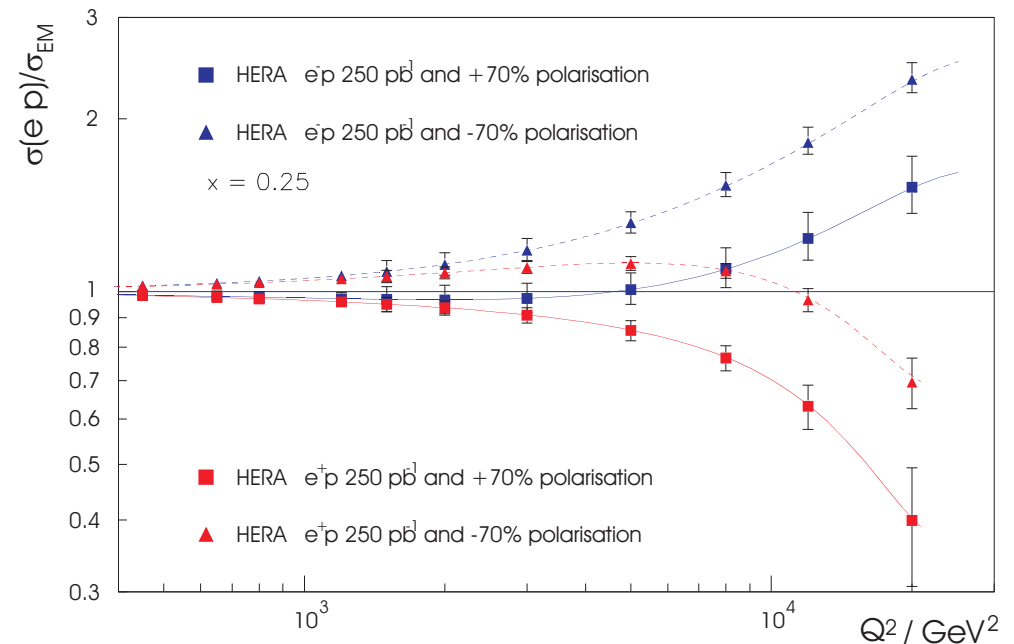
High luminosity $\rightarrow$ improved high x , Q^2

Polarised leptons $\rightarrow$ chiral structure

Detector upgrades $\rightarrow$ precision HF era

Reduced $E_p \rightarrow$ 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!

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