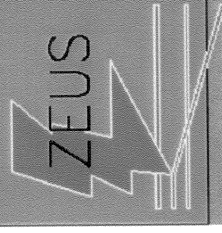


Deep Inelastic Scattering



DIS

Introduction

- Experiments

Data

- HERA
- Fermilab

Interpretation

QCD $\rightarrow$ E/W $\rightarrow$

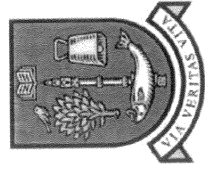
BSM $\rightarrow$ Future

Outline

Tony Doyle

CTEQ-IPPP Summer School

St Andrews, June 17-18th



UNIVERSITY
of
GLASGOW

Deep Inelastic Scattering
and Structure Functions

Outline

Experiment

H1 and ZEUS Detectors
Calibration
Formalism
Motivation

Introduction

HERA PROGRESSES

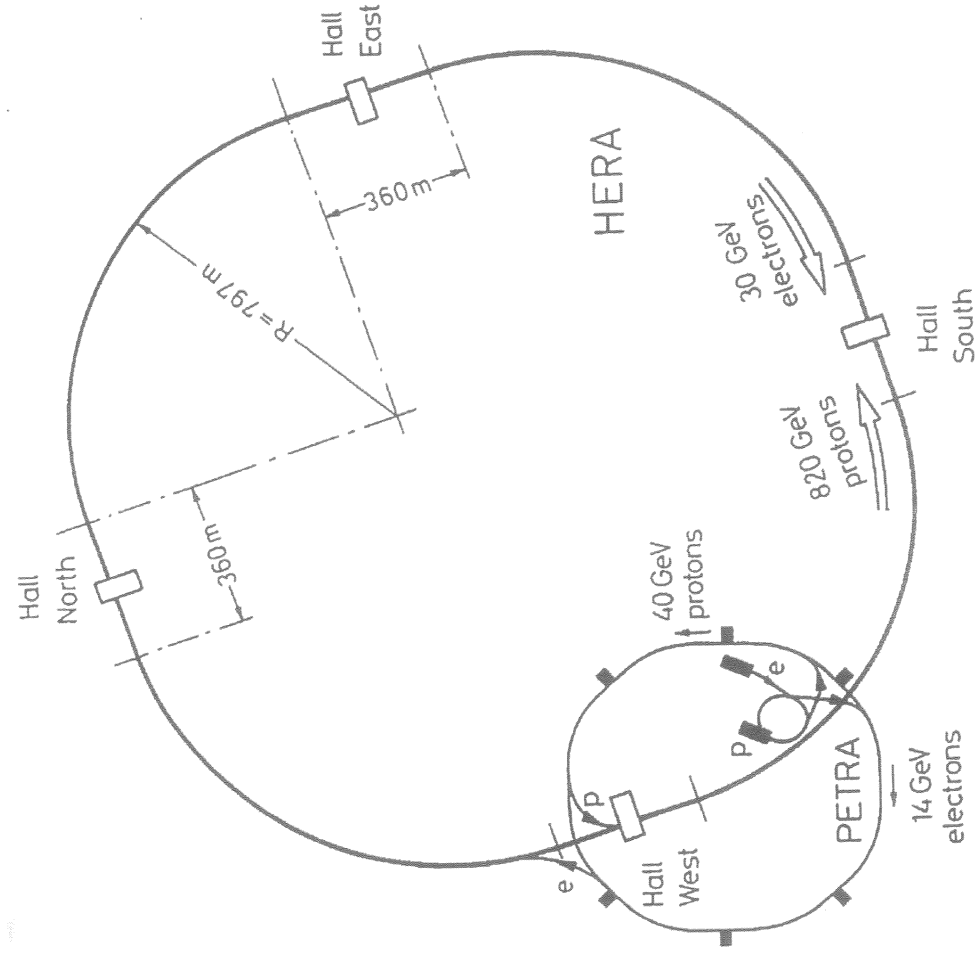
Proton
Structure
Function
 F_2

F_2 Progress
Low y
Low (x, Q^2)
Transition Region
Gluon Density
 F_2^c
 F_L

FIXED
TARGET
RESULTS

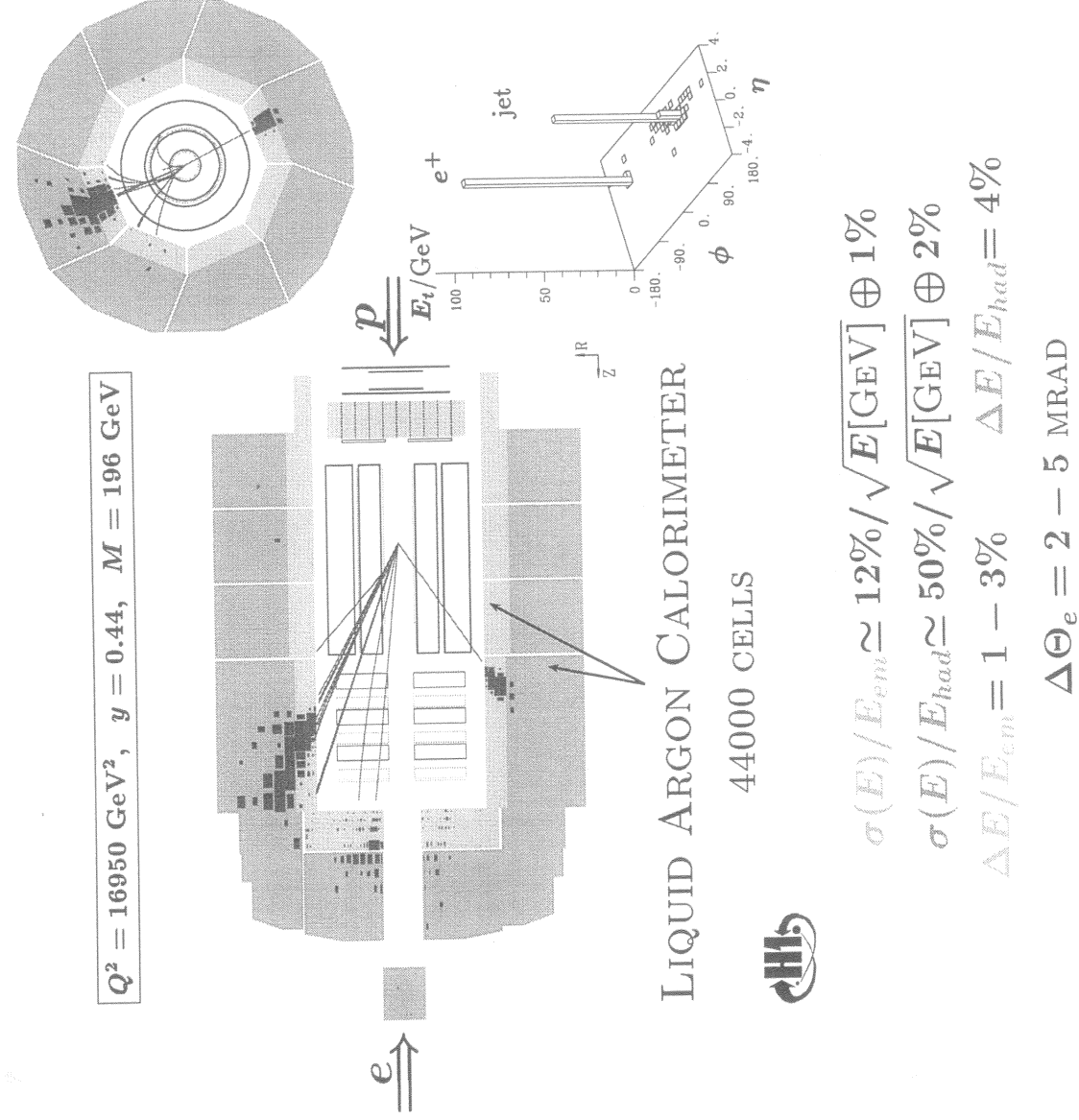
NMC d/u
► High Energy Predictions
E866 ► $\bar{d}/\bar{u}$
► Parton Uncertainties
NuTeV α_S and $\sin^2 \theta_W$

HERA Accelerator



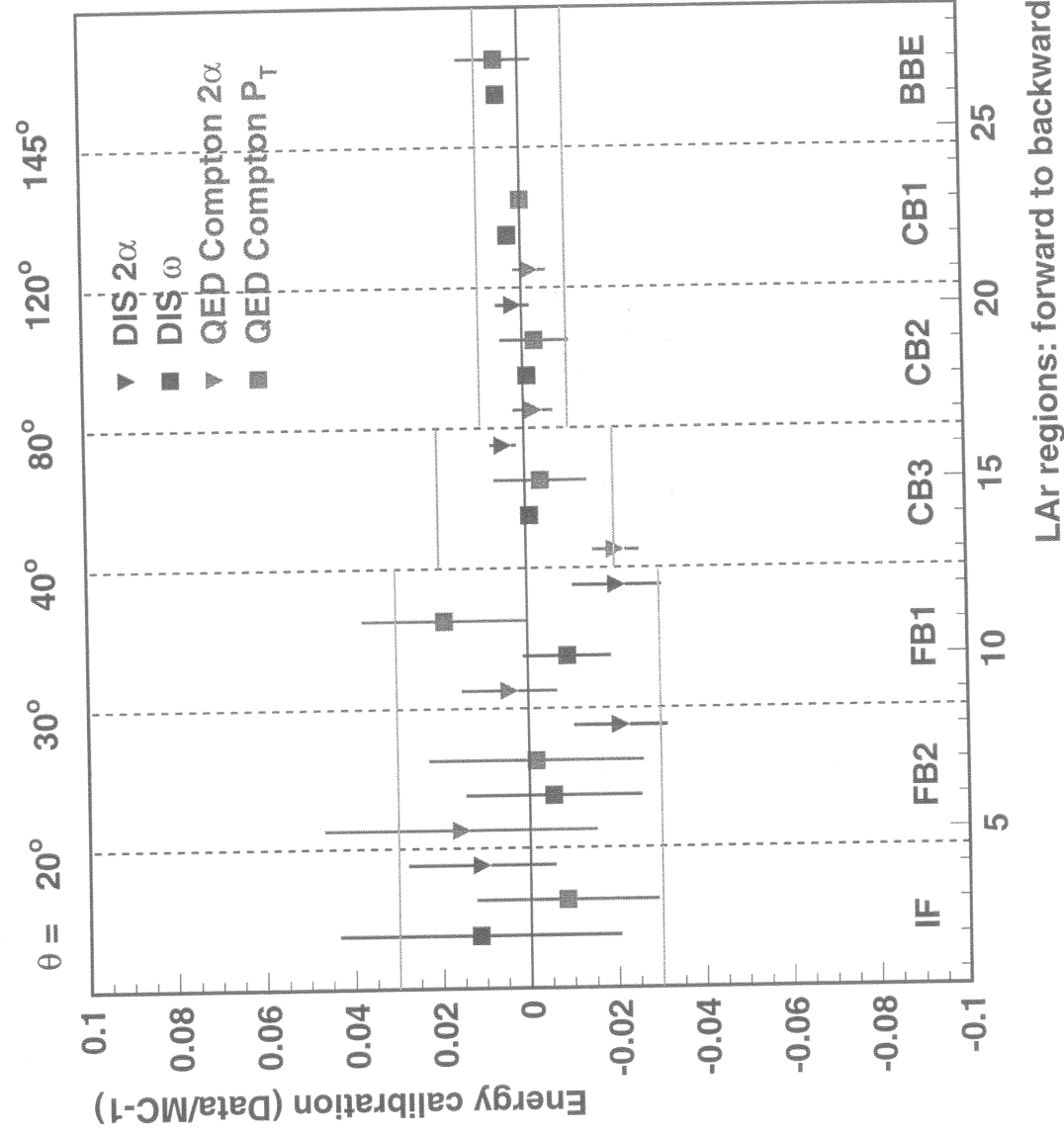
- Based in Hamburg, Germany
- Collides $e^\pm$ with protons
- Study Proton Structure
- First data taken in 1992
- e^+p ($27.5 \otimes 820\text{ GeV}$) 1994-97
- e^-p ($27.5 \otimes 920\text{ GeV}$) 1998-99

H1 Detector



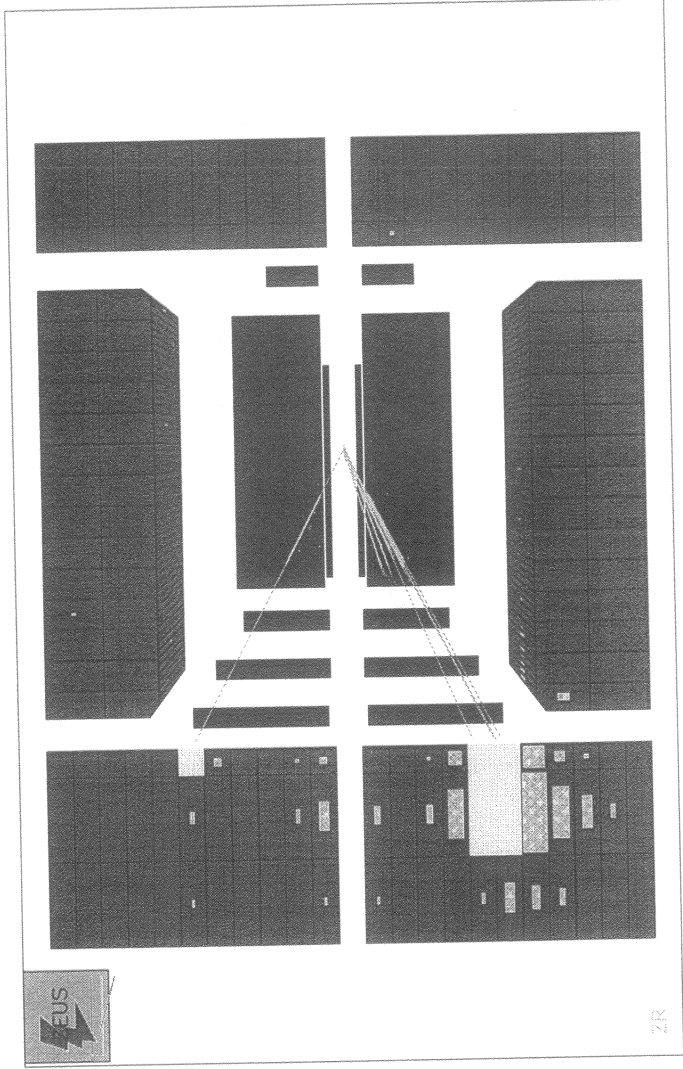
- Optimised for precision electron reconstruction

H1 Calibration



- Basic method: Use redundancy of NC DIS kinematics to calibrate E'
- Double-angle method yields E' independent of calorimeter energy scale
- Accuracy still statistics-limited
- E' energy scale reliable to 1 – 3%

ZEUS Detector



Uranium-Scintillator Calorimeter

6000 Cells, each read out by 2 PMTs

$$\sigma_{\theta_e} = 3 \text{ mrad}$$

$$\sigma(E) \text{ (em)} = 18\% \sqrt{E} \oplus 1\% E$$

$$\sigma(E) \text{ (had)} = 35\% \sqrt{E} \oplus 2\% E$$

Energy Scale Uncertainty =		FCAL	BCAL	RCAL
	em	3%	1%	2%
	had	3%	3%	3%

Central Tracking Detector

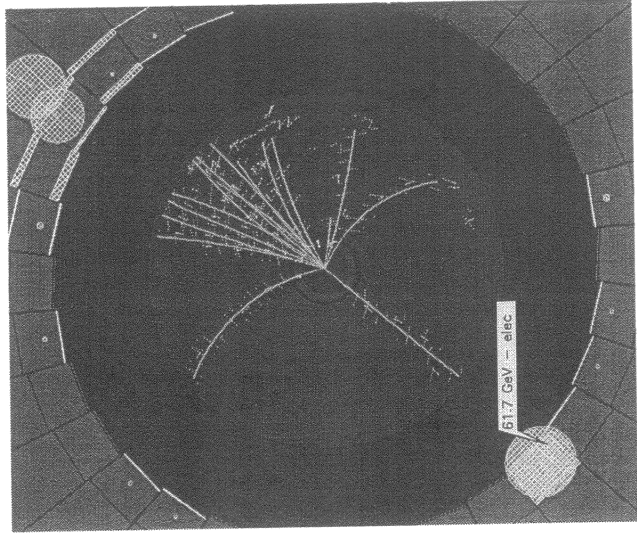
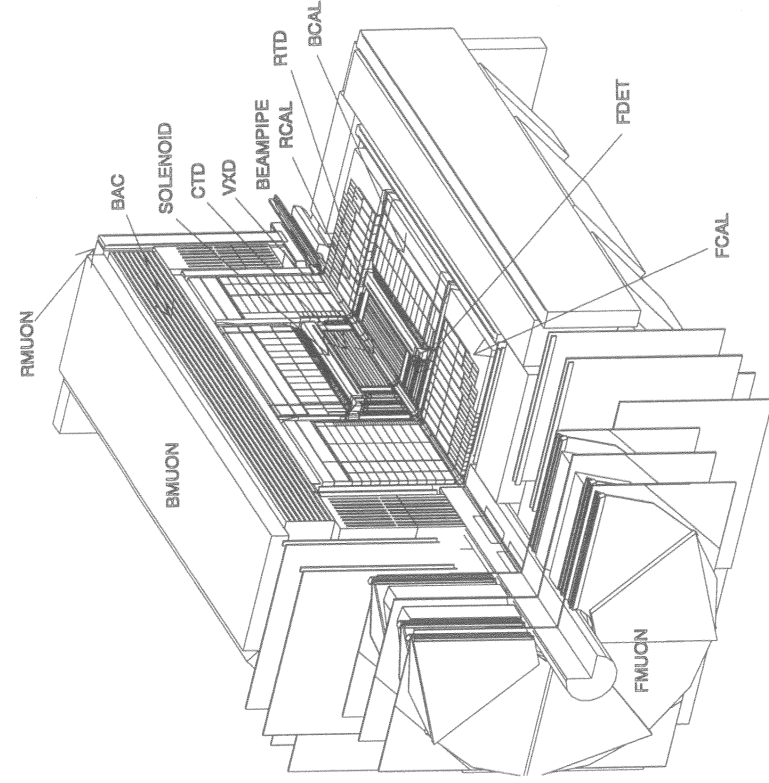
Angular acceptance: $15^\circ < \theta < 164^\circ$

Momentum resolution: $\sigma(p_t)/p_t = (0.005 \text{ GeV}^{-1} P_t) \oplus 0.016$

- Optimised for precision hadronic and track reconstruction

ZEUS Calibration 1.

Using large data samples to calibrate in situ...



CTD:

Spatial resolution $\simeq 190 \mu\text{m}$

Momentum resolution $[\text{GeV}]$:

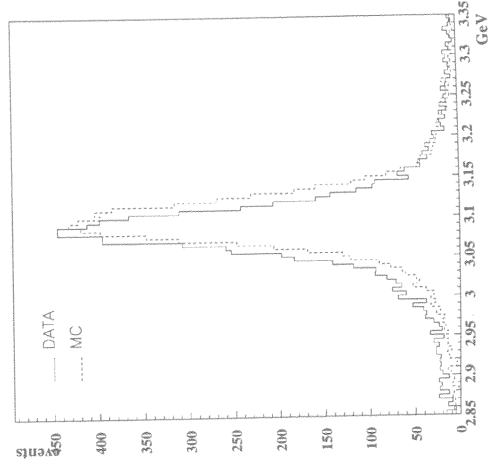
$$\sigma_{p_T}/p_T = 0.005 p_T \oplus 0.016$$

Elastic J/ψ (95-97) data:

Mass resolution well reproduced in Monte Carlo

► calibration offset -0.3%

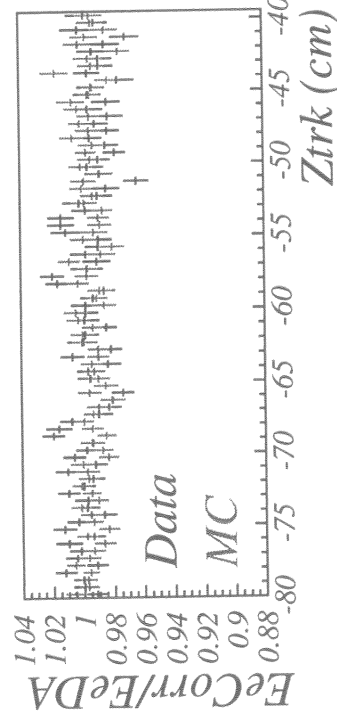
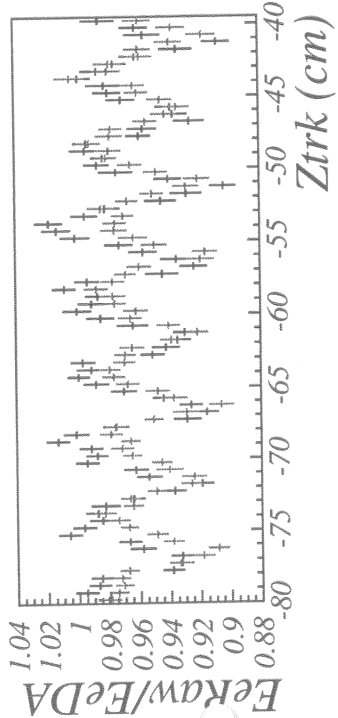
cross-checked with e.g. D^*



ZEUS Calibration 2.

Electron energy resolution: $\sigma_e/\sqrt{E_e} = 18\%$

BCAL



after non-uniformity

correction

► Electron energy scale uncertainty:

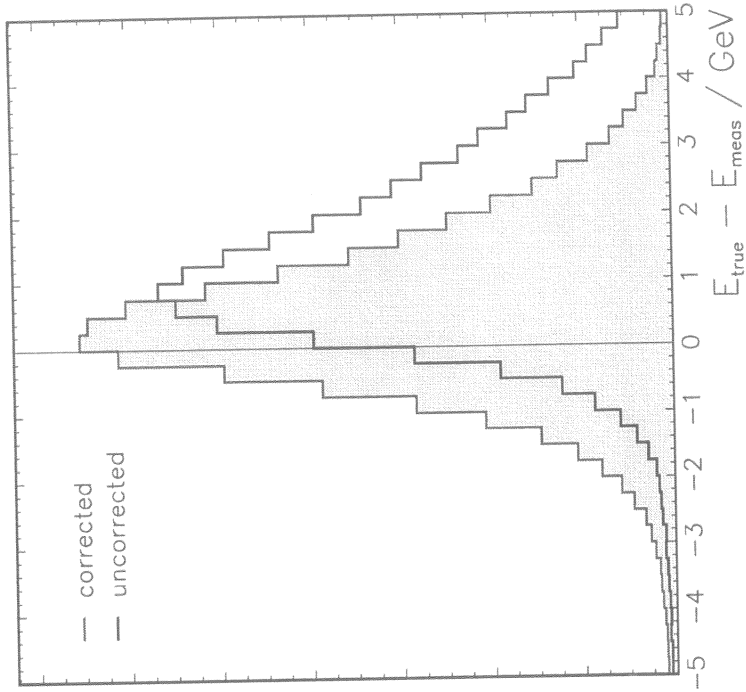
BCAL

±1%

FCAL

±3%

RCAL



after presampler

correction

RCAL

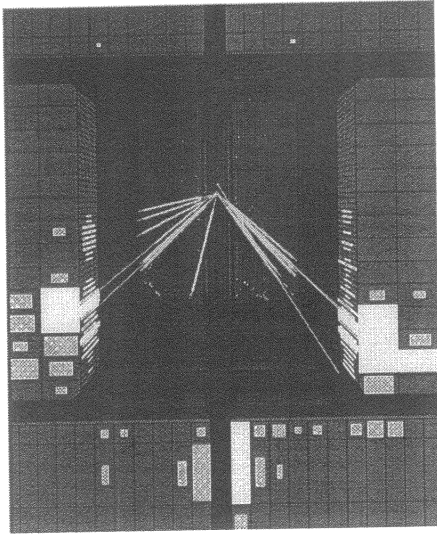
±2%

► NC High Q²
Systematics
(see later)

ZEUS Calibration 3.

Hadronic energy resolution: $\sigma_{had}/\sqrt{E_{had}} = 35\%$

Jet energy scale:
determined using
e-jet p_T -balance
in DIS events...
and established
using dijet events.

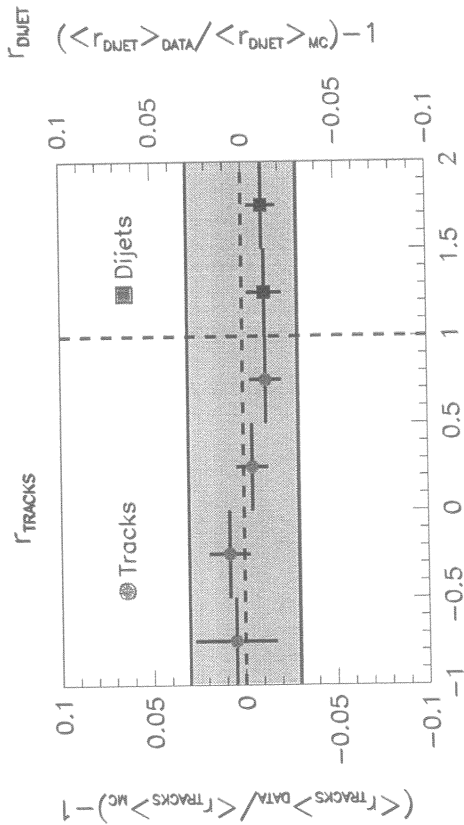
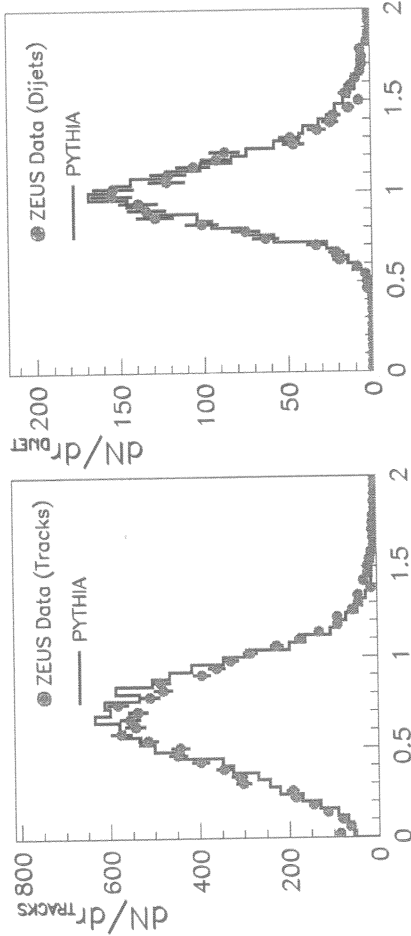


Tracks: $\Sigma p_T^{tracks} / \Sigma E_T^{CAL}$

Dijets: $\Sigma E_T^{bkwd} / \Sigma E_T^{forw}$

$$-1 < \eta^{jet} < 1$$

$$1 < \eta^{jet} < 2$$



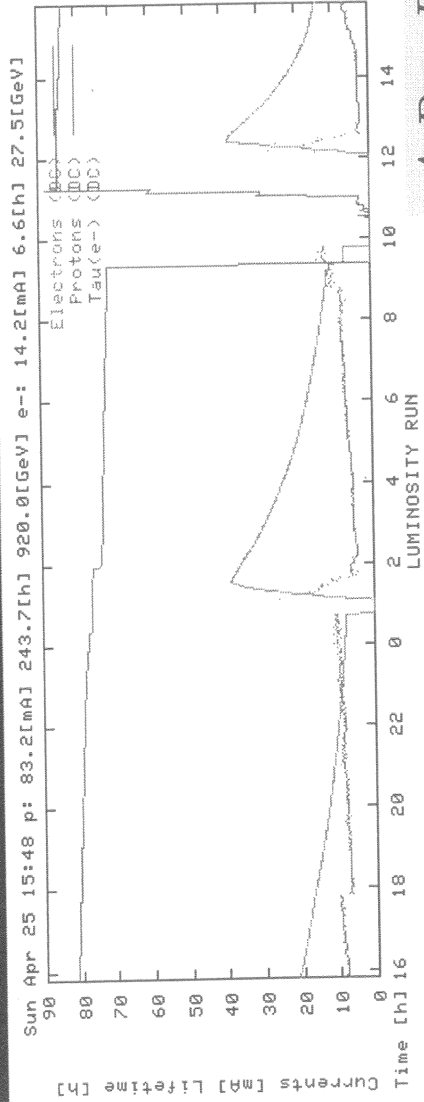
Additional uncertainties due to:

- MC model dependence
- cone radius variation

► Jet Systematics

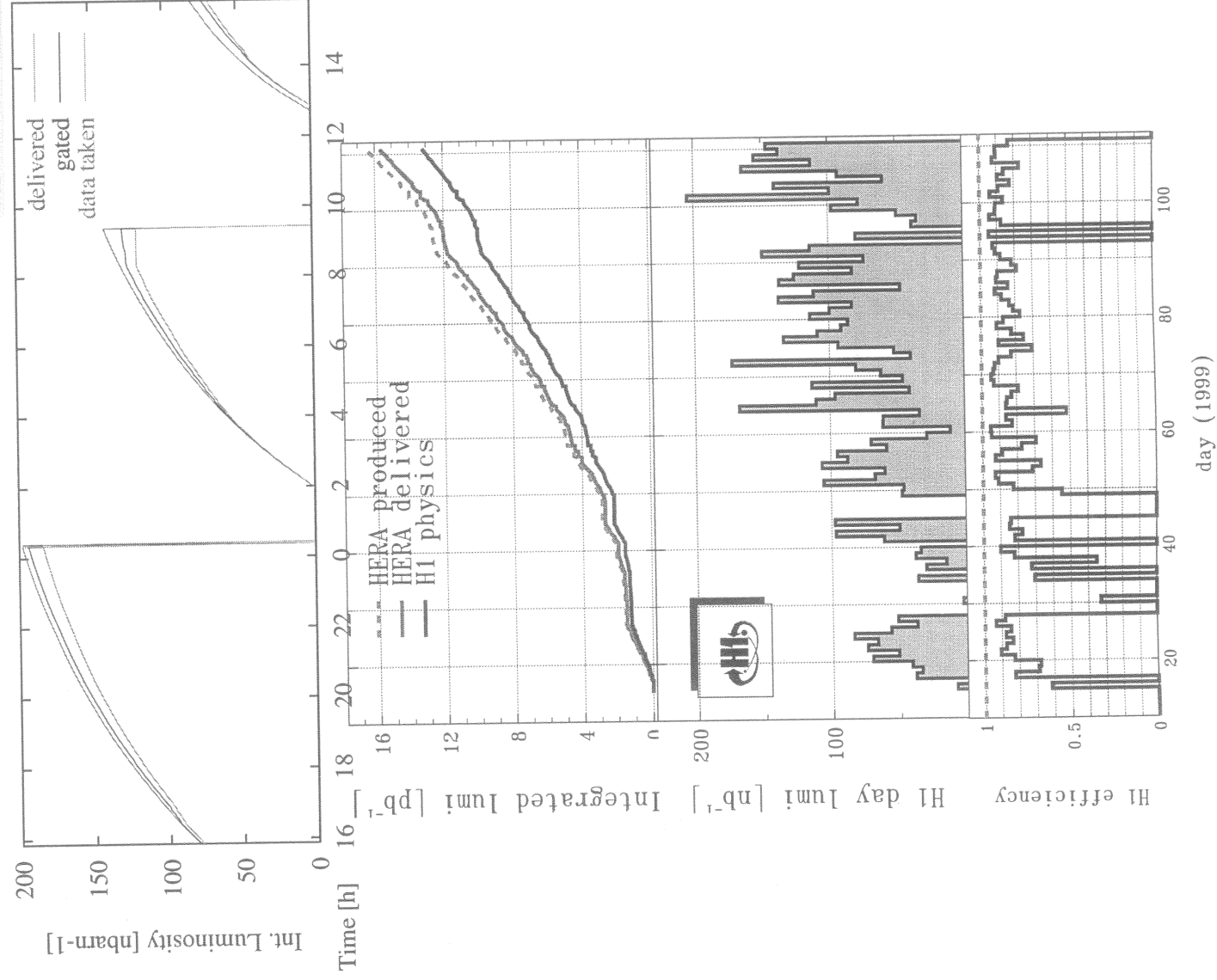
► Jet energy scale uncertainty: $\pm 3\%$

HERA e^-p Running



A Day In The Life

H1 on Sun Apr 25 15:51 1999



LUMINOSITY

HERA

98-99

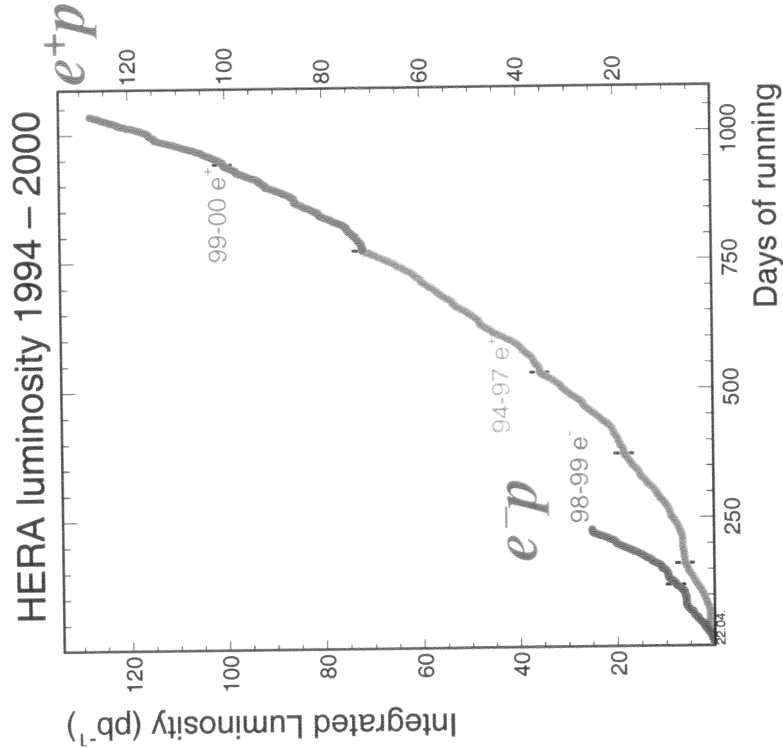
Electron Proton
27.5 GeV 920 GeV



94-97

Positron Proton
27.5 GeV 820 GeV

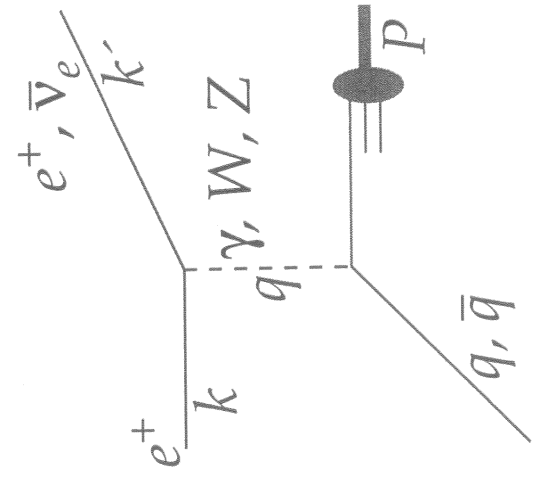
Luminosity Delivered...



... Luminosity
Recorded

Luminosity (pb^{-1})	
H1	ZEUS
e^+P (820)	37
e^-P (920)	16
e^+P (920)	> 40

Formalism



$$Q^2 = -q^2 \qquad x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k} \qquad W^2 = (P + q)^2$$

$$Q^2 = sxy$$

$$\frac{d^2 \sigma(l^{\pm}N)}{dx \, dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot [Y_+ F_2^{lN}(x, Q^2) \mp Y_- xF_3^{lN}(x, Q^2) - y^2 F_L^{lN}(x, Q^2)]$$

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

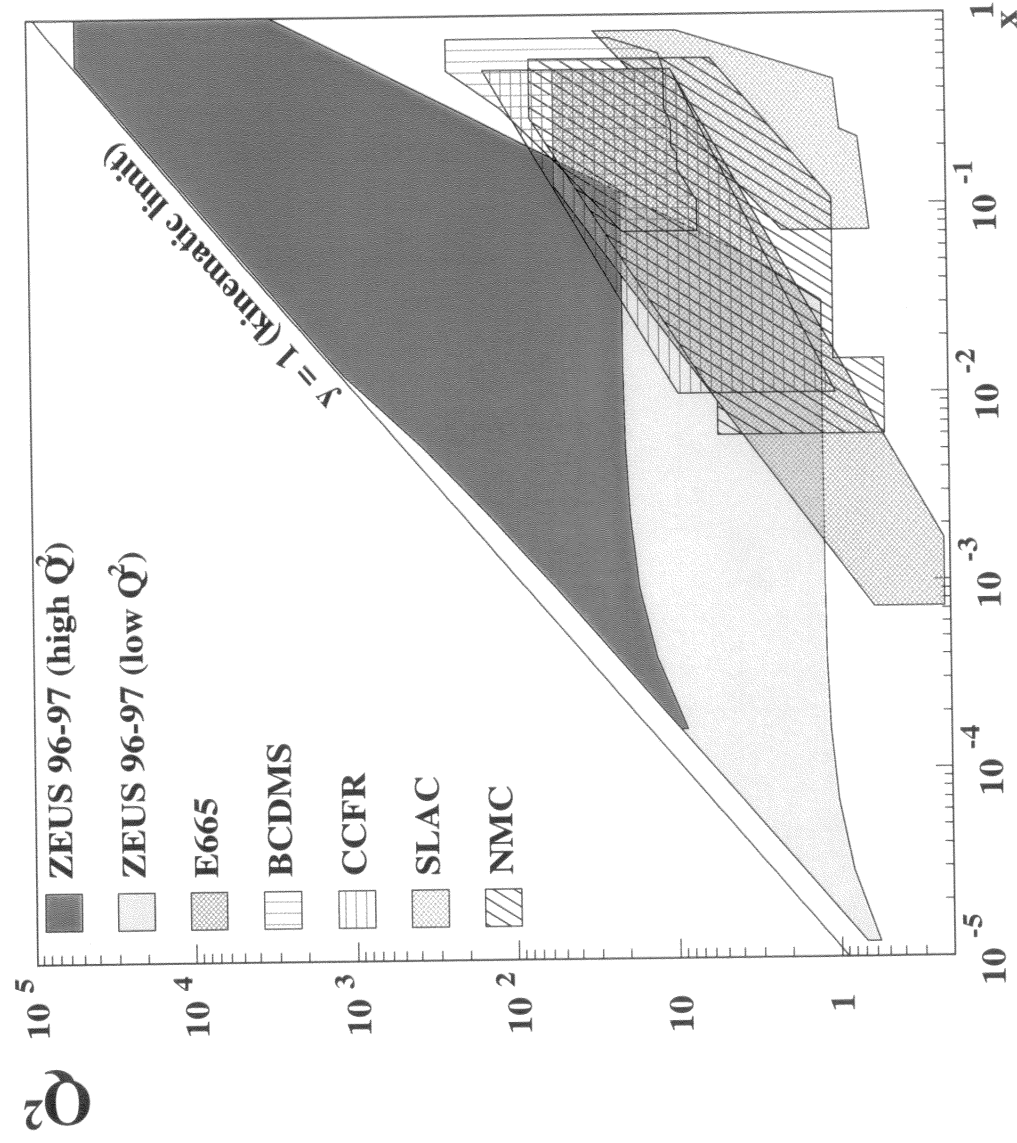
- Contribution from F_L^{lN} important only at large y
- Contribution from $x F_3^{lN}$ is negligible for $Q^2 \ll M_Z^2$
- Either F_L^{lN} and $x F_3^{lN}$ treated as QCD corrections
- Or reduced cross section:

$$\sigma(e^+p) \equiv \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_+} \frac{d^2\sigma(e^+p)}{dx dQ^2}$$

In QPM (QCD DIS scheme),

$$F_2^{lN}(x, Q^2) = \sum_i e_i^2 x [q_i(Q^2) + \bar{q}_i(Q^2)]$$

Kinematic Plane



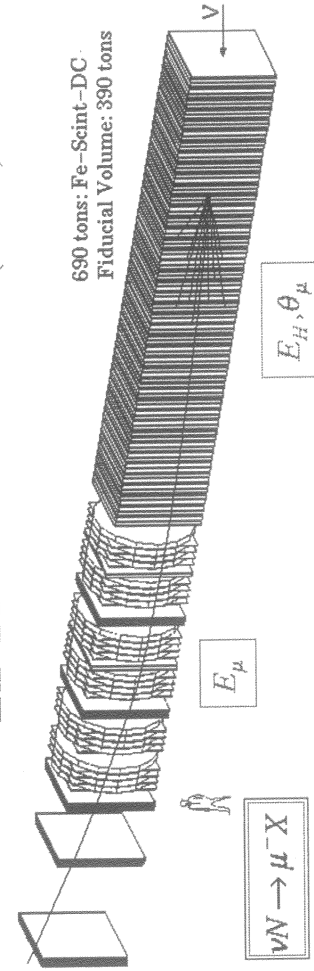
- Accessible kinematic plane $\sim$ covered $\Rightarrow F_2$
 - Low $Q^2 \Rightarrow$ Transition Region
 - High $y \Rightarrow F_L$
 - Low $y \Rightarrow$ Overlap with e.g. CCFR/NMC
 - High $Q^2 \Rightarrow$ Overlap with Tevatron
- $\Rightarrow$ High- x partons and electroweak

D.I.S. Experiments

- Worldwide Programme

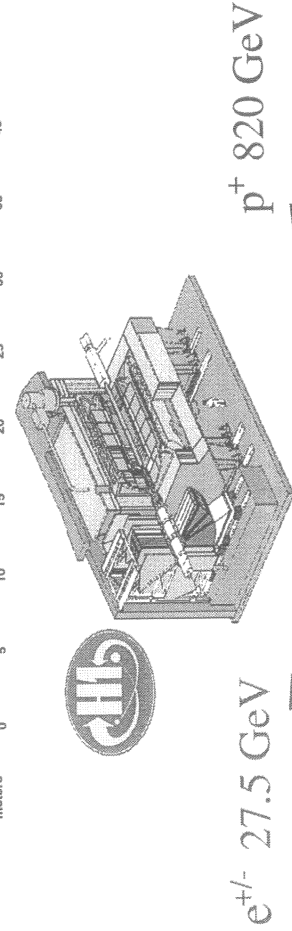
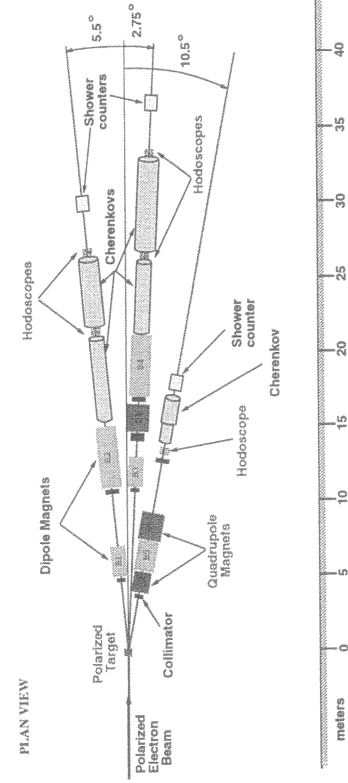
Fixed Target Precision :

LAB-E Detector – Fermilab E815 (NuTeV)

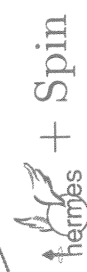


Spin Structure :

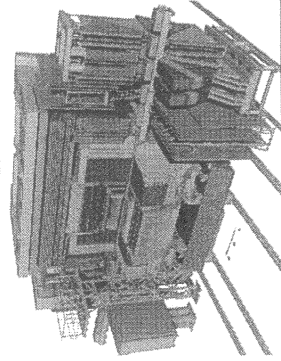
E155 Spectrometers



High Energy Frontier



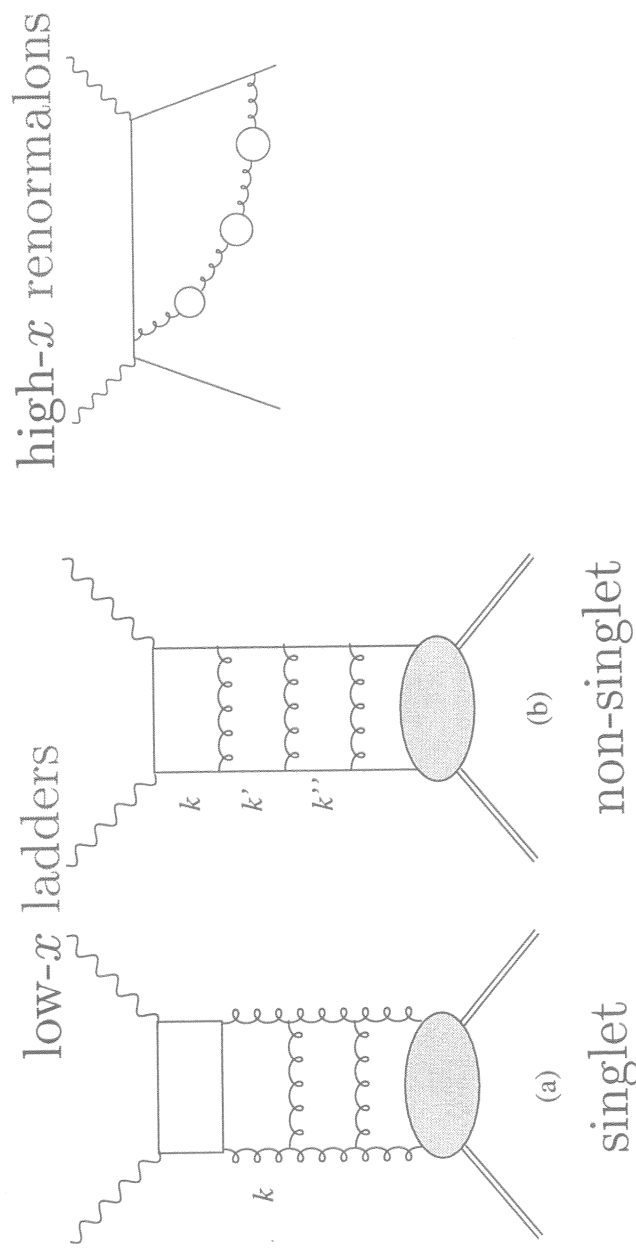
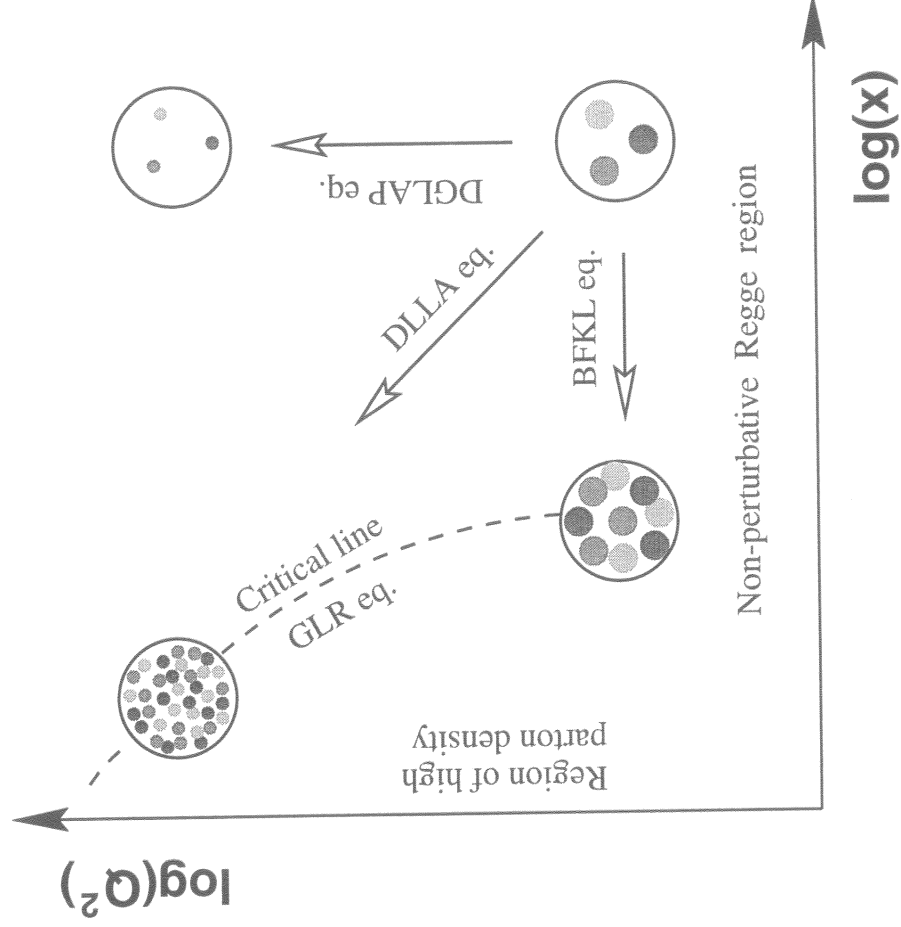
+ Spin Structure



Low- x Road Map

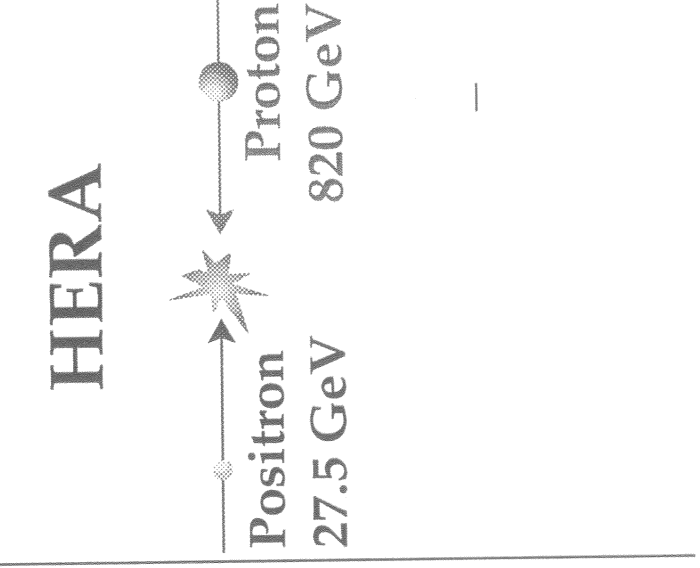
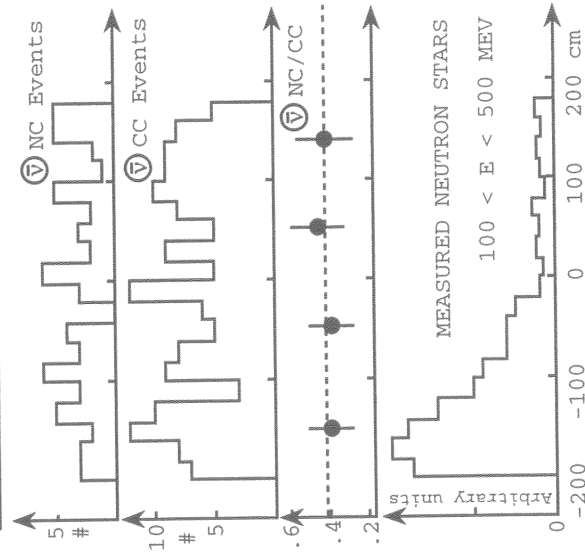
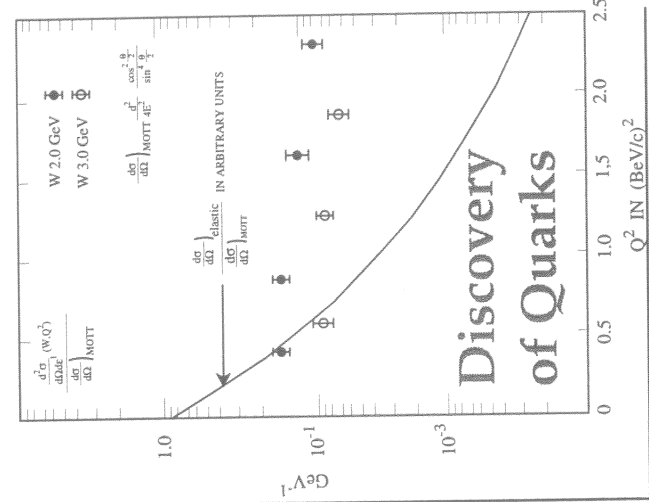
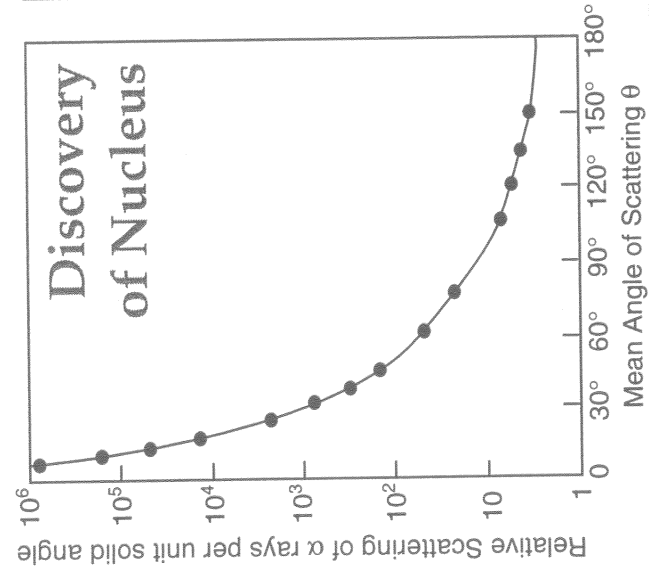
- *Theoretical Expectations*

- High Gluon Density Regime
- Importance of NLO BFKL ?



D.I.S.covery Potential

- *Historical Perspective*



Geiger and Marsden; Proc. Roy. Soc. lxxxii P. 495 (1909)
Friedman, Kendall, Taylor; Rev. Mod. Phys. 63(3) (1991)
Hasert et al.; Phys. Lett. 45B(1) 138 (1973)

QCD Fits

- DGLAP evolution equations ($\alpha_S \ln Q^2$ terms large)

$$P_{qg}^{(0)} = \begin{array}{c} \bar{q} \\ \diagup \\ \text{---} g \text{---} \\ \diagdown \\ q \end{array} \qquad P_{gg}^{(0)} = \begin{array}{c} g \\ \diagup \\ \text{---} g \text{---} \\ \diagdown \\ g \end{array}$$

$$P_{qq}^{(0)} = \begin{array}{c} g \\ \diagup \\ \text{---} q \text{---} \\ \diagdown \\ q \end{array} \qquad P_{gq}^{(0)} = \begin{array}{c} q \\ \diagup \\ \text{---} q \text{---} \\ \diagdown \\ g \end{array}$$

$$\frac{\partial q_{NS}}{\partial \ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} P_{qq}^{NS} \otimes q_{NS}$$

$$\frac{\partial}{\partial \ln Q^2} \begin{pmatrix} \Phi_\Sigma \\ \Phi_g \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi} \begin{bmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{bmatrix} \otimes \begin{pmatrix} \Phi_\Sigma \\ \Phi_g \end{pmatrix}$$

- singlet (Φ_Σ) contribution mixed with gluon (Φ_g):
- $\alpha_S(Q^2)$ ↑'s - $g(x, Q^2)$ ↓'s

$$\text{e.g. } F_2 = P \otimes f = \int_x^1 \frac{dy}{y} P\left(\frac{x}{y}, Q^2\right) \Phi(y, Q^2)$$

Assumed form for light quarks and gluon (e.g. MRST):

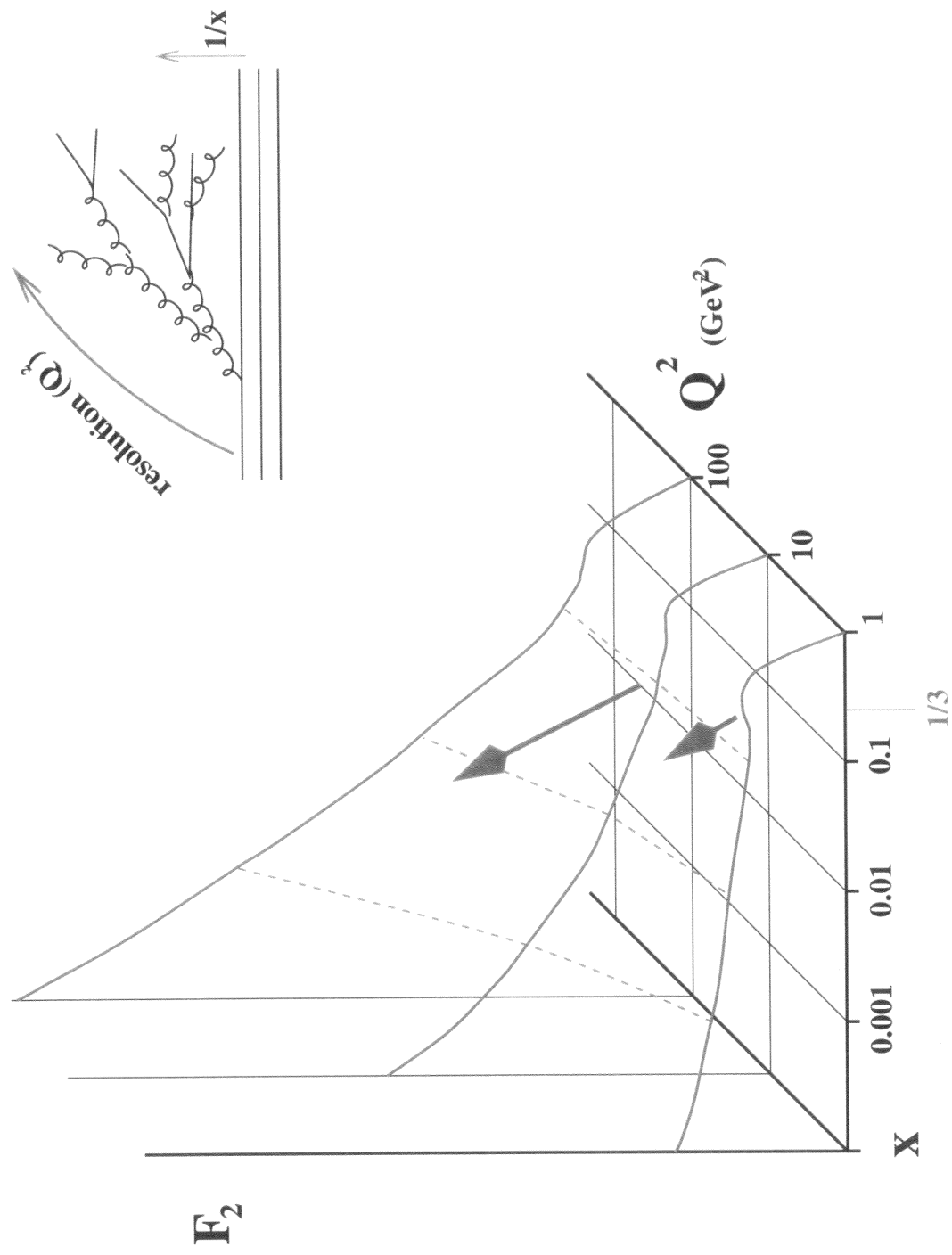
$$f_i = A_i x^{\delta_i} (1-x)^{\eta_i} (1 + \epsilon_i \sqrt{x} + \gamma_i x)$$

- some parameters set to 0 or fixed by sum rules

global fits ► optimum parameters at fixed Q_0^2 .

Latest fits MRST', GRV98 and CTEQ4.5

DGLAP Evolution



- At smaller distances (large Q^2) more partons are resolved: *
- Gluons drive rise of $F_2^{\text{em}} = x \sum e_q^2 (q(x) + \bar{q}(x))$ *

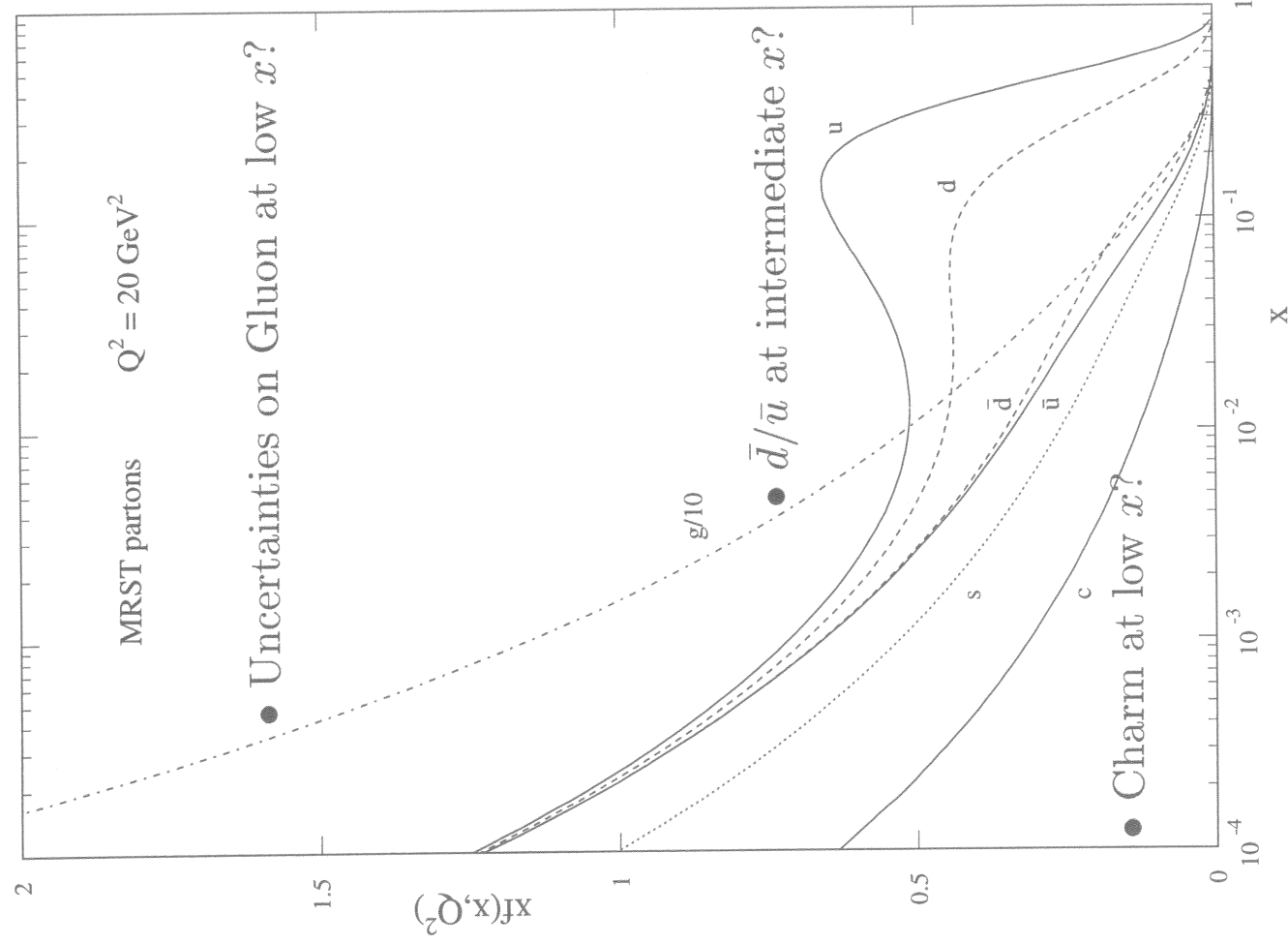
⇒ Scaling violations (dotted lines) reflect gluon

LO in DGLAP at low x: *

$$\frac{dF_2^{\text{em}}}{d \ln Q^2} \propto \alpha_s P_{qg} \otimes xg$$

Proton Structure MRST

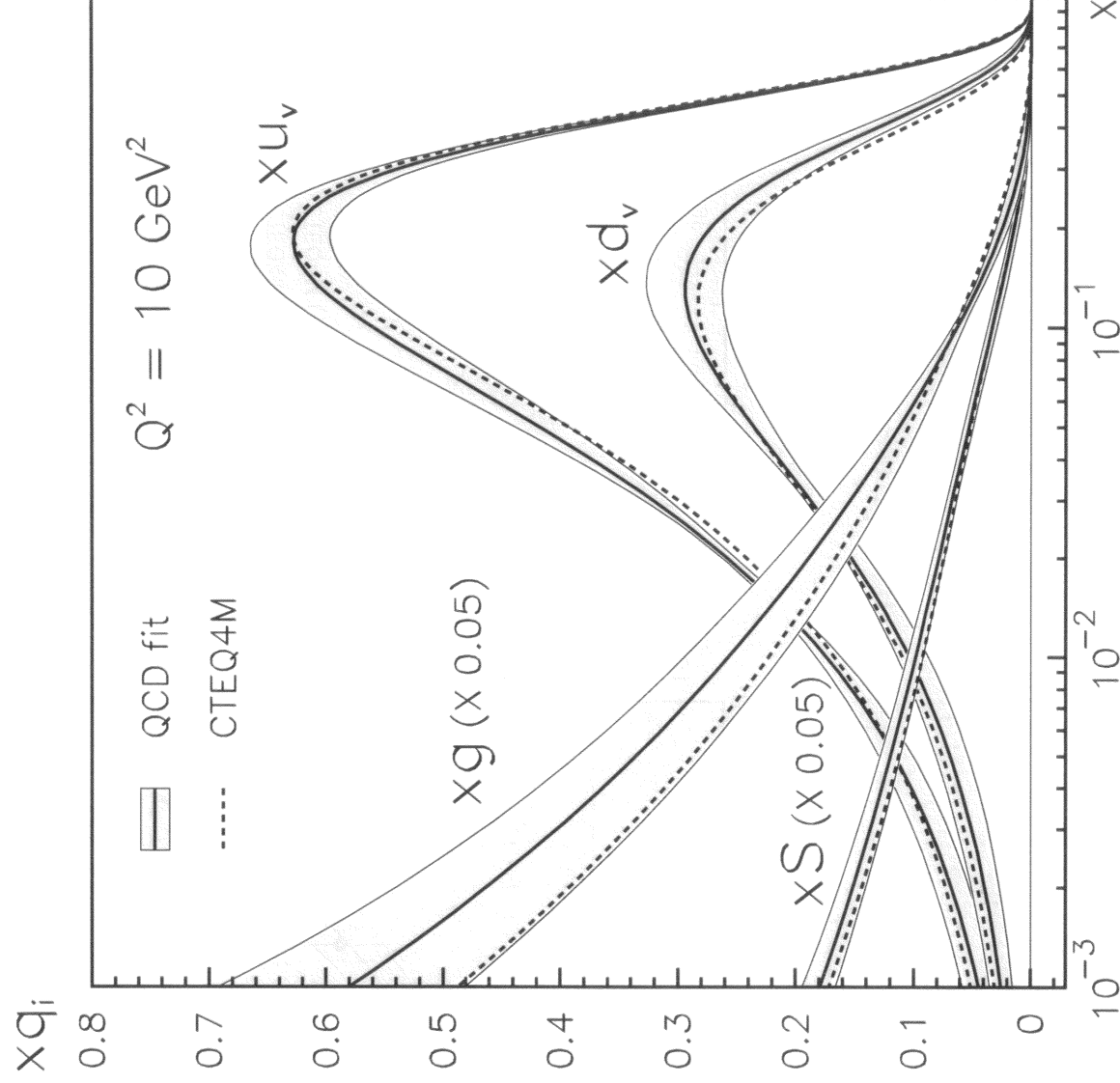
- *Output Parton Distributions*



- Uncertainties at Large x - HT? d/u ?
- New Cross Section Data at Highest Q^2

Proton Structure

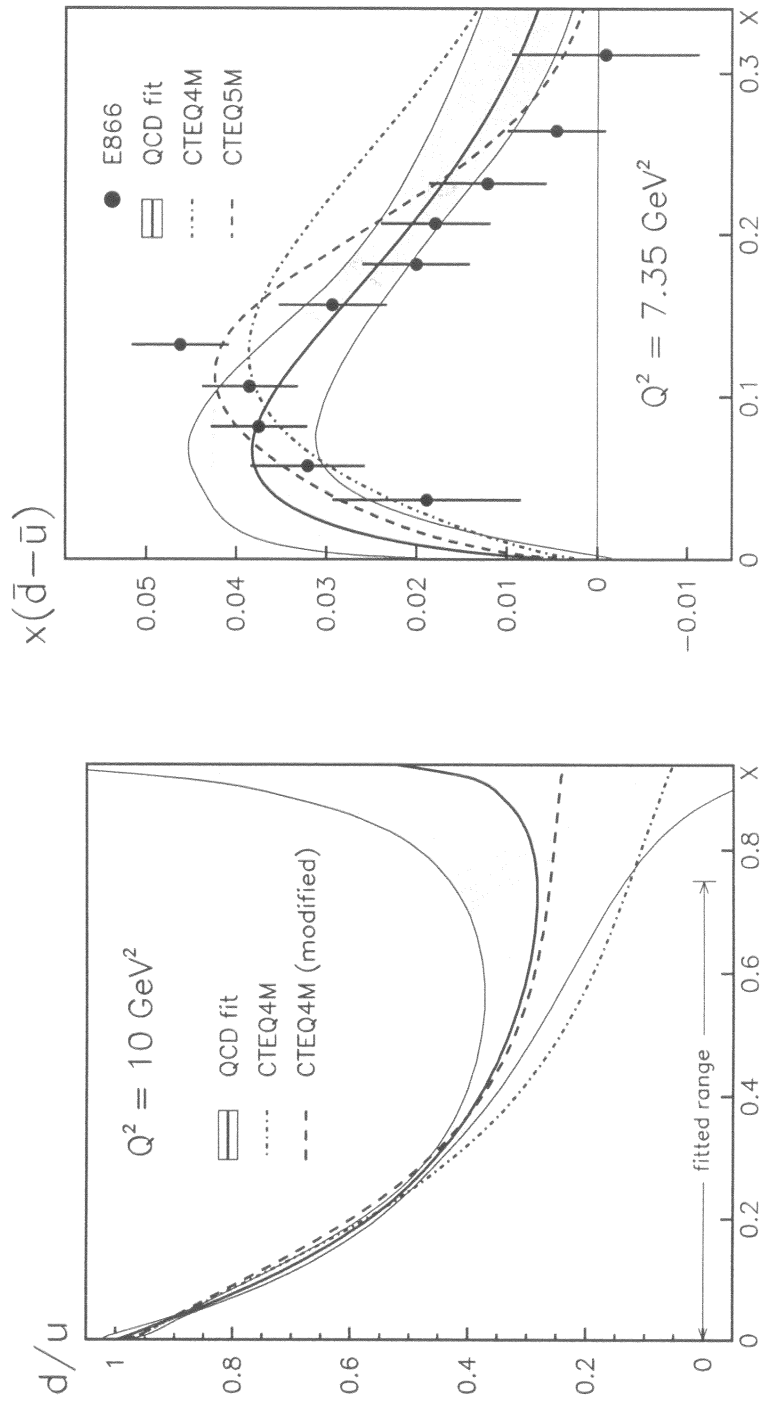
- Parton Distributions and Uncertainties



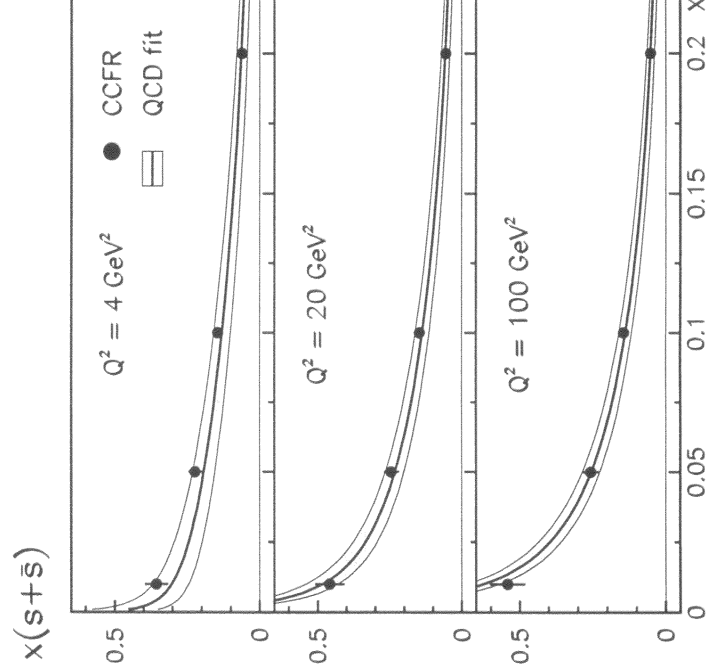
- Not only error bands but correlations
- NLO charm determined from gluon at low x
- Future for MRST, CTEQ and others
- Predictions for HERA, Tevatron and LHC

Proton Structure

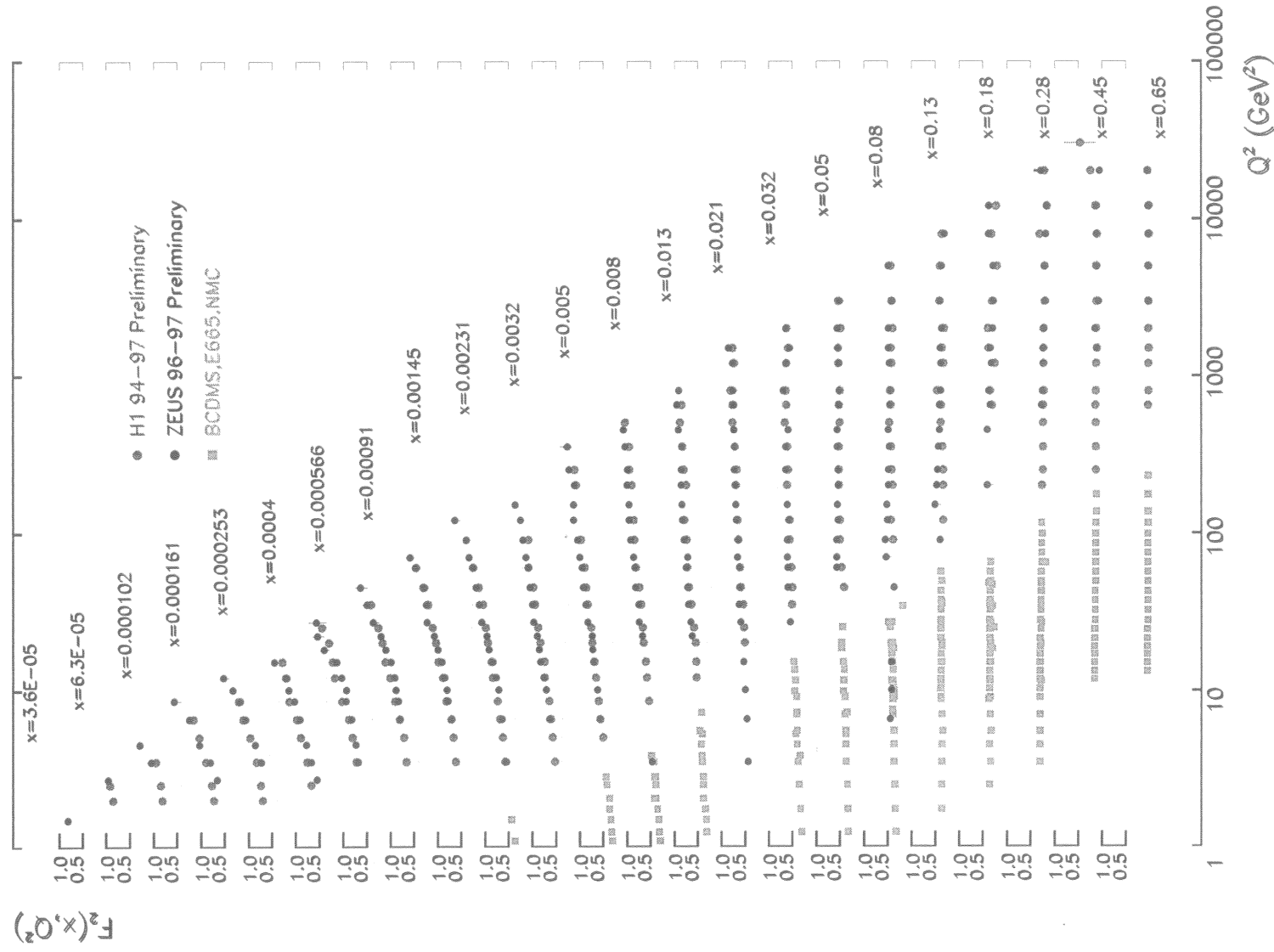
- d/u , $\bar{d} - \bar{u}$ and $s + \bar{s}$



- Large d/u uncertainties at high x
- Reasonable fit to E866 data
- Strange sea from CCFR dimuon data



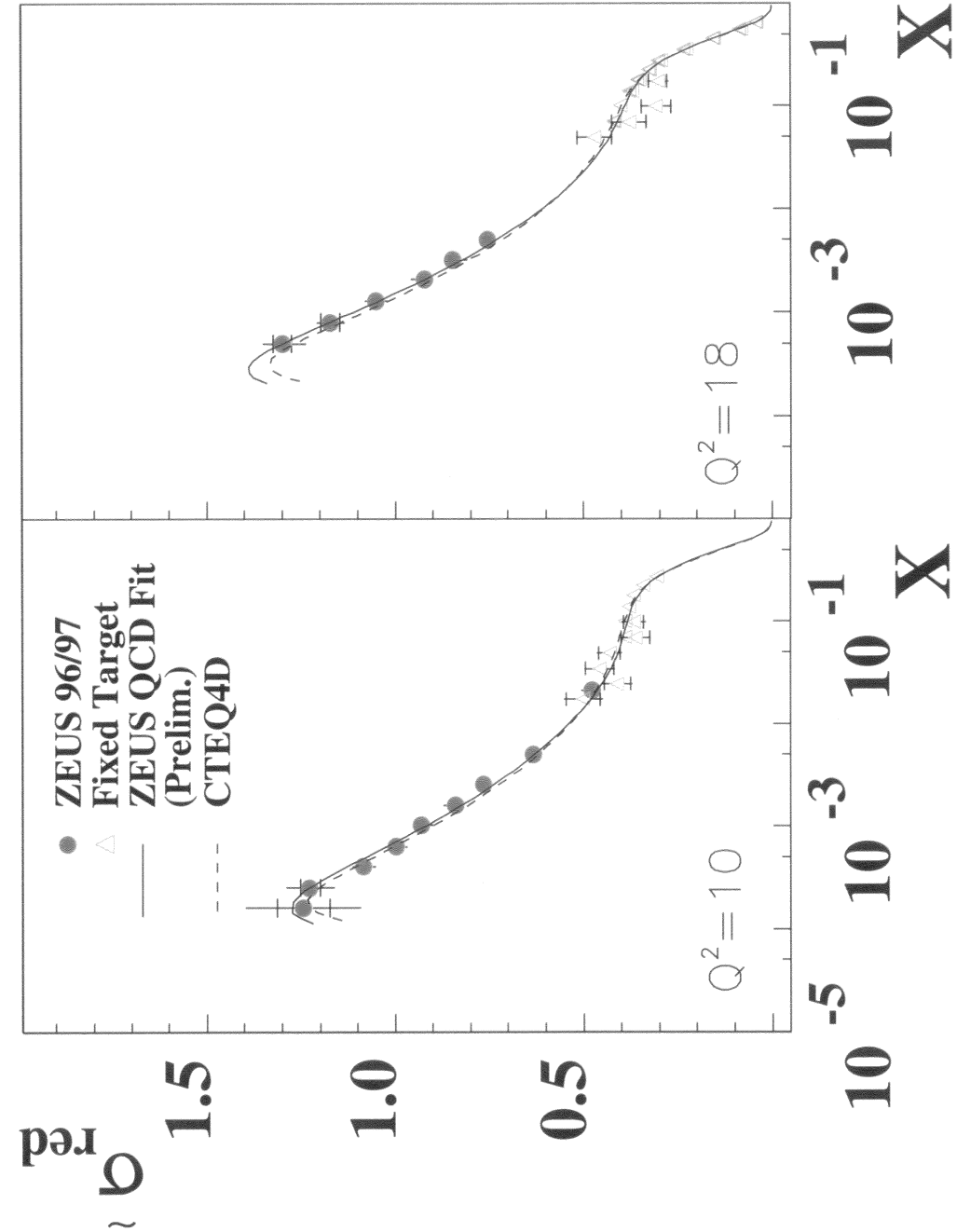
F_2 vs Q^2



Proton Structure

Concentrate on medium to low Q^2 for extraction of F_2 :

$$Y_+\sigma_r = Y_+\tilde{\sigma}_{e^+p}^{\rm NC} = Y_+F_2^{\rm NC} - Y_xF_3^{\rm NC} - y^2F_L^{\rm NC}$$



Determine cross section, σ_r , make small corrections for $x F_3$, F_L , e/w contribution to F_2 (and radiative corrections)

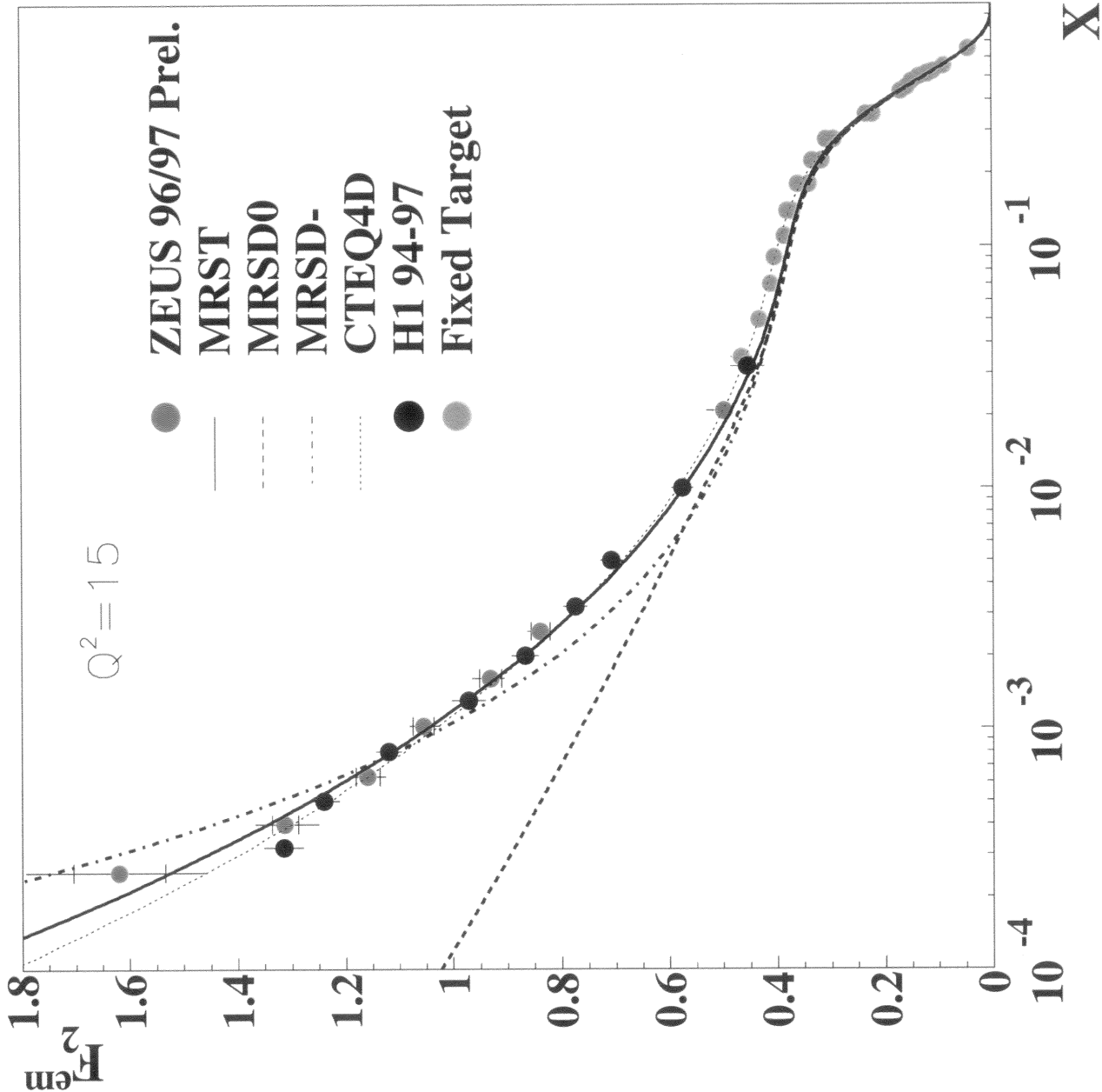
$$F_2^{\rm em} = \sigma_r(x,Q^2) \Big(1 + \delta_{F_2}^{\rm ew} + \delta_{xF_3} + \delta_{F_L} \Big) (1 + \delta_{\rm rad})$$

Proton Structure

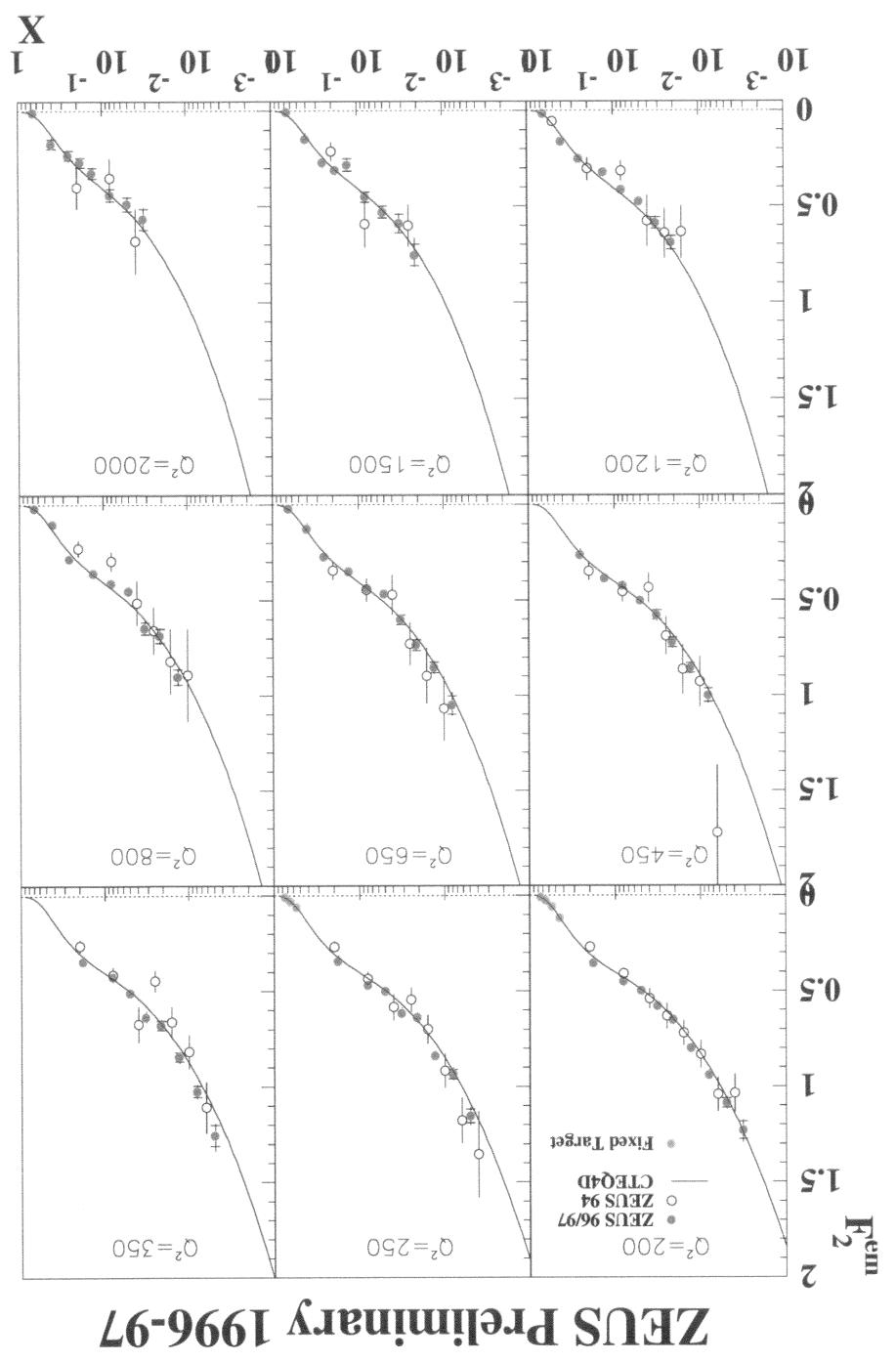
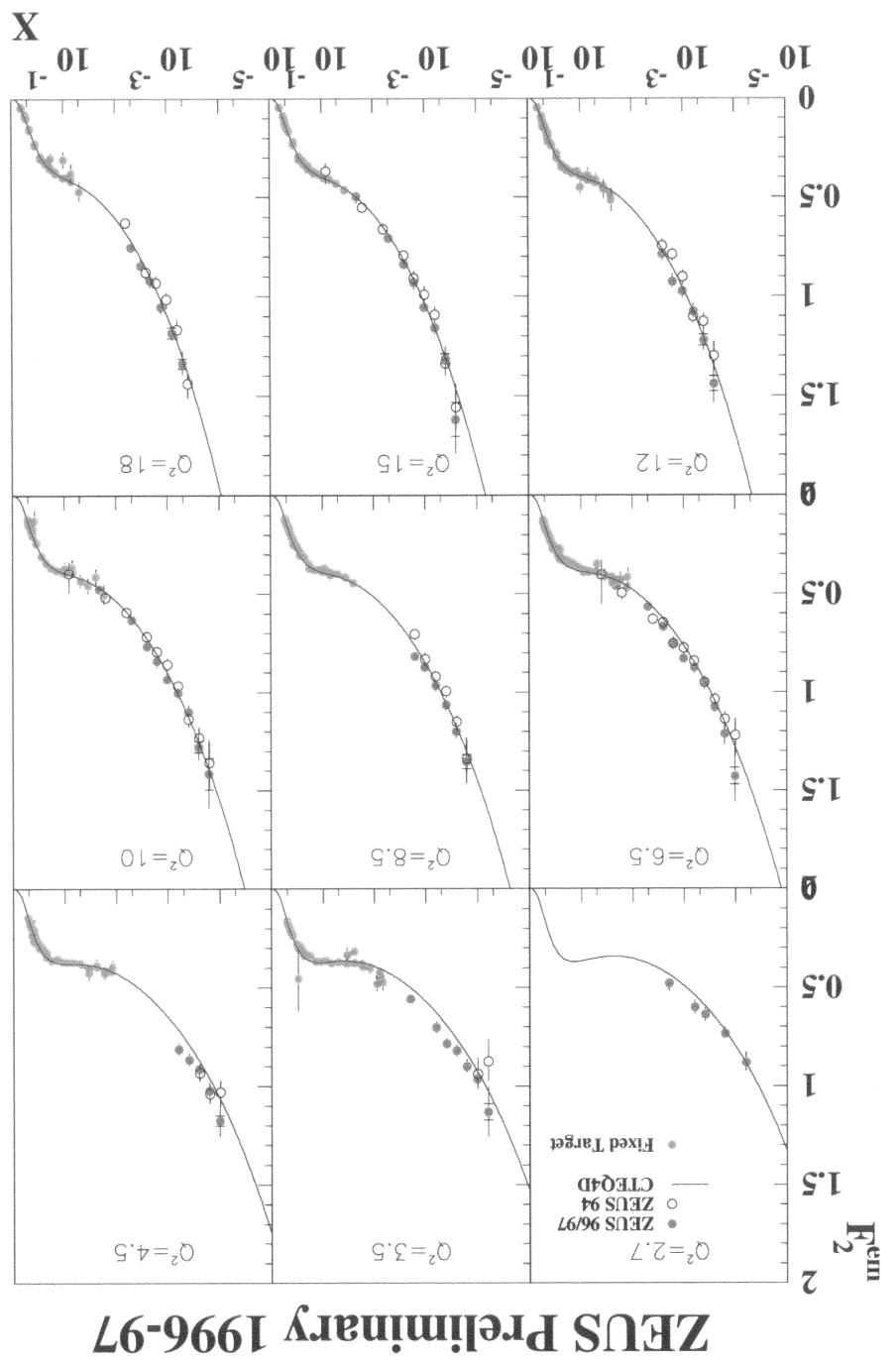
- The proton structure function F_2 :

$$F_2^{\text{NC}} = x \sum A_q (q(x) + \bar{q}(x))$$

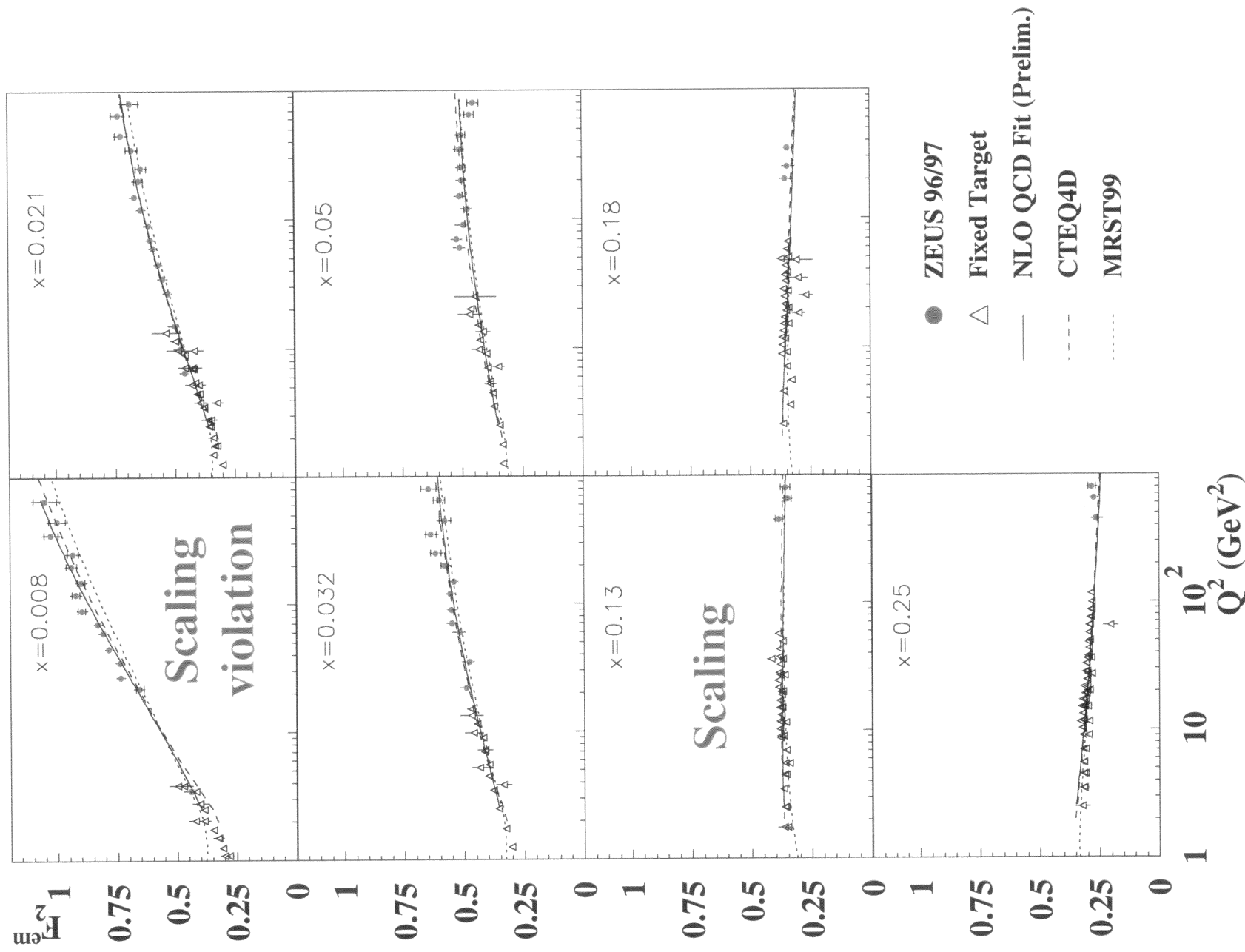
$$F_2^{\text{em}} = x \sum e_q^2 (q(x) + \bar{q}(x))$$



• HERA: Low x: Rapid rise of $F_2 - F_2 \sim x^{-\lambda}$



ZEUS Preliminary 1996-97

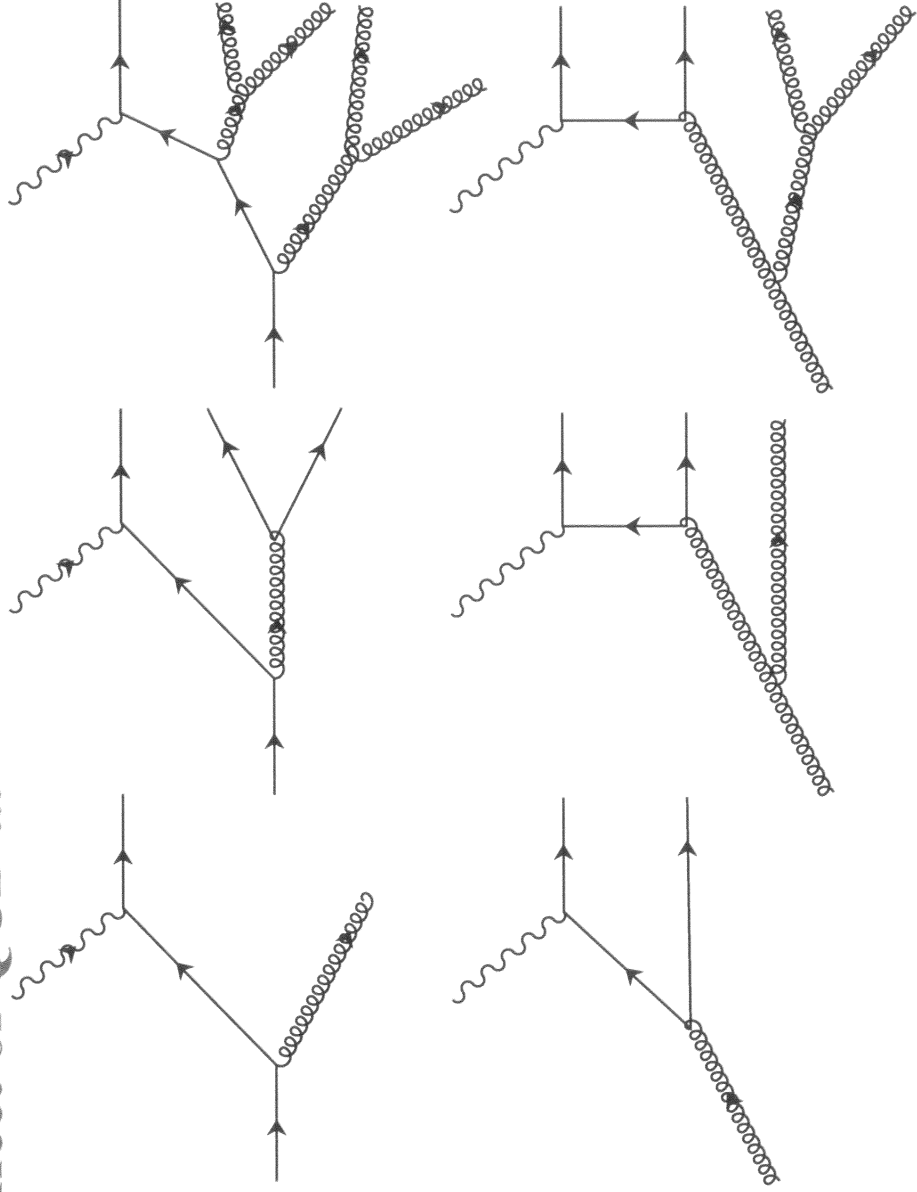


Scaling Violations and F_L

$$F_2^{\text{em}} = x \sum A_q(q + \bar{q})$$

Massless quarks with no transverse momentum
would leave q and $\bar{q}$ functions of x only

Effect of QCD ...



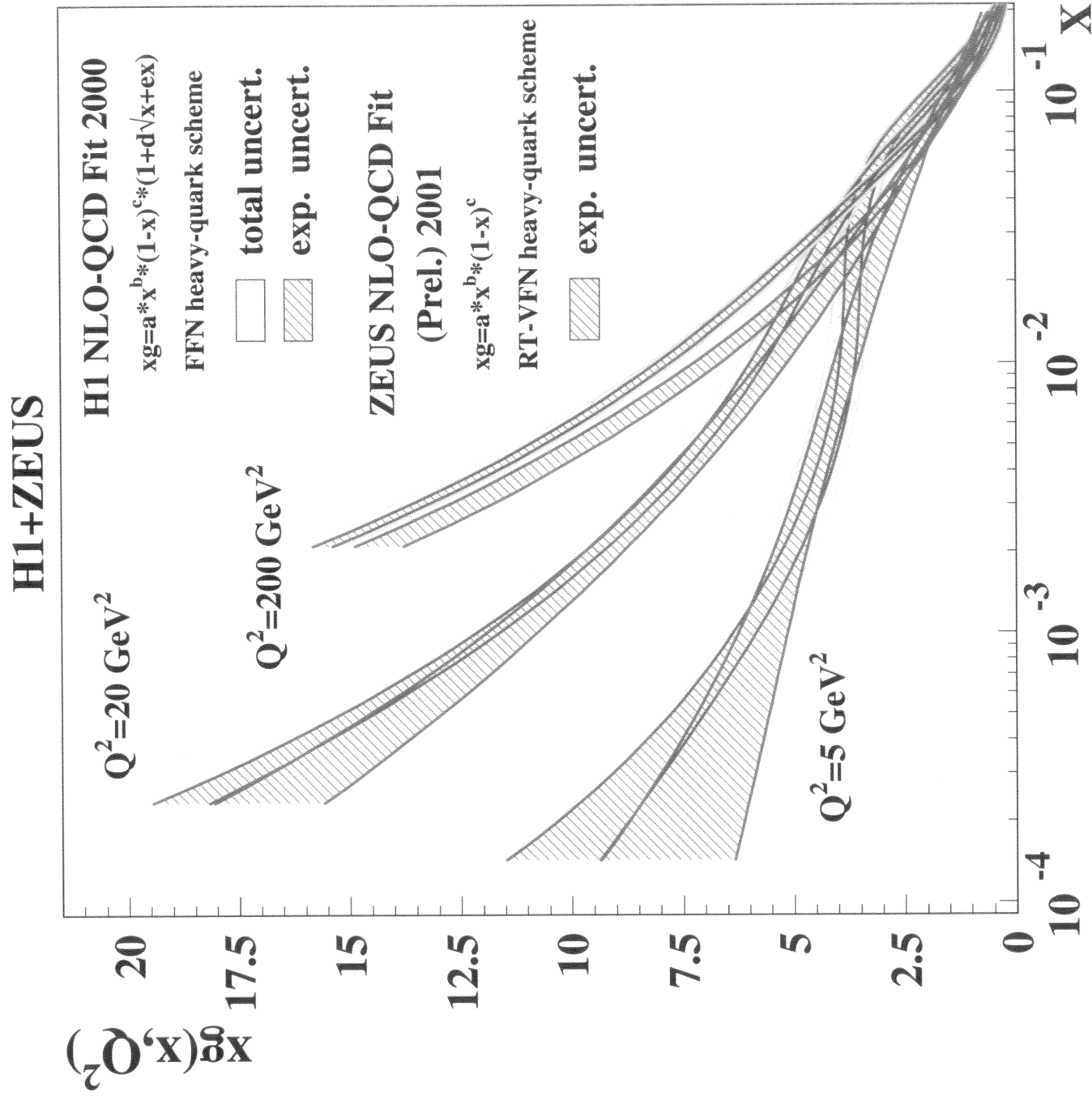
... gives q and $\bar{q}$ effective mass and
transverse momentum

$$F_L^{\text{em}} = \frac{\alpha_s}{\pi} \{ \beta_1 \otimes F_2^{\text{em}} \} + [\beta_2 \otimes xg] \}$$

$$\frac{dF_2^{\text{em}}}{d \ln Q^2} = \frac{\alpha_s}{2\pi} \{ P_{\text{qq}} \otimes F_2^{\text{em}} \} + [P_{\text{qG}} \otimes xg] \}$$

gluon distribution

$$\frac{dF_2^{\text{em}}}{d\ln Q^2} \propto \alpha_S P_{qg} \otimes xg$$



Latest Status

Extraction of F_L

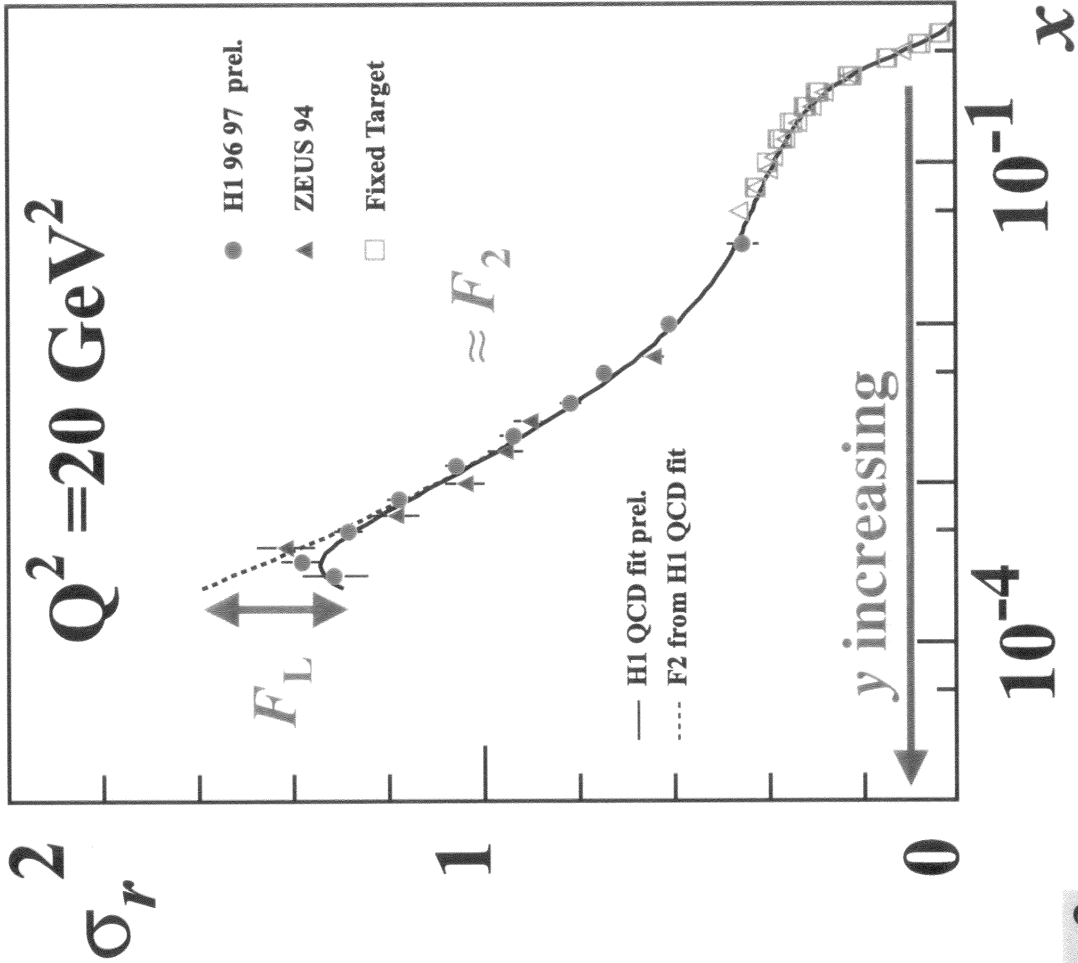
$$F_L^{\text{NC}} \propto \frac{\alpha_s}{\pi} \beta_2 \otimes xg$$

- extraction of F_L

F_L directly related to gluon density

Measured

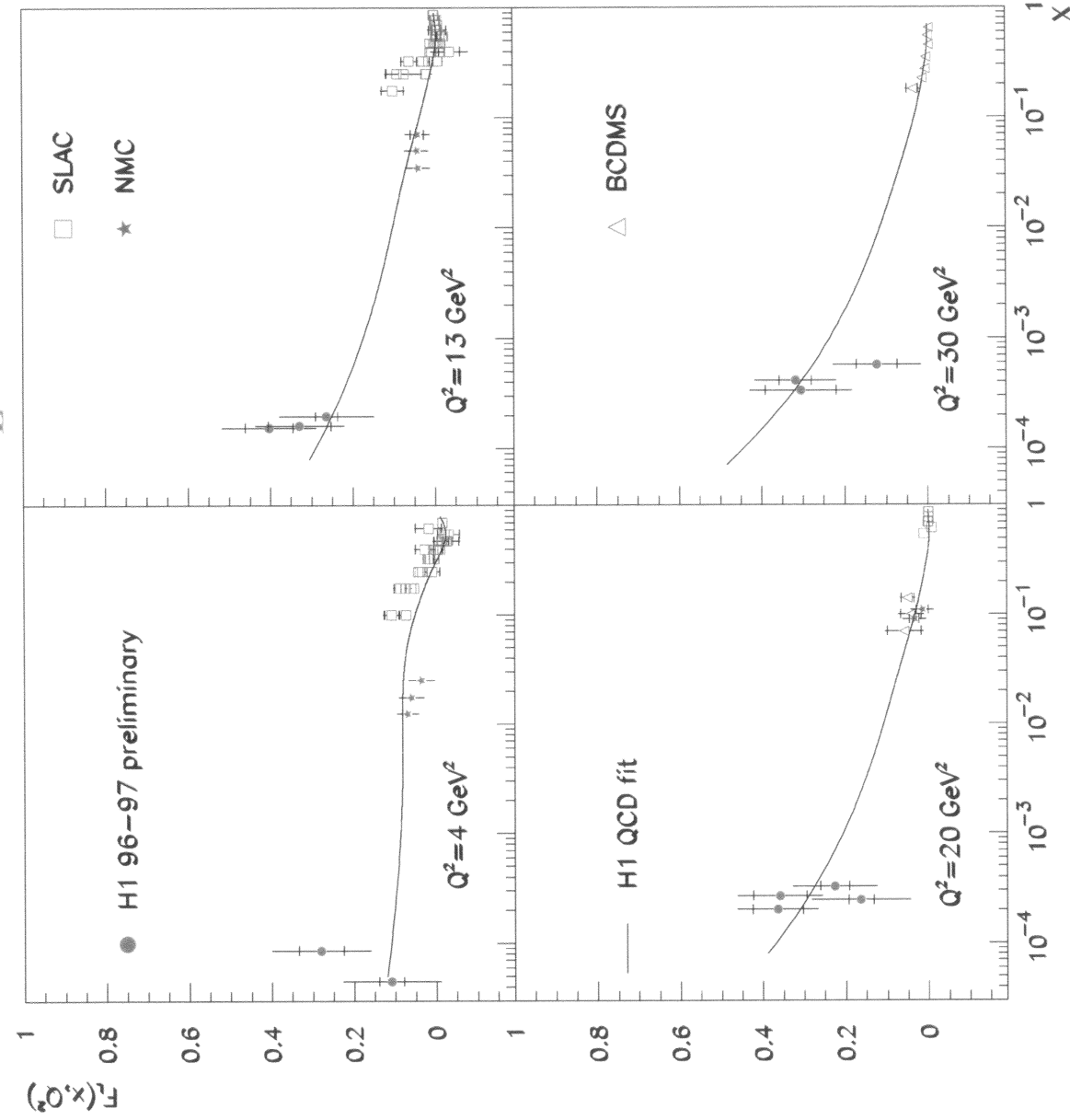
$$\sigma_r = \left[\frac{2\pi\alpha^2}{Q^4 x} Y_+ \right]^{-1} \overbrace{\frac{d^2\sigma_{\text{NC}}^{e^+P}}{dx dQ^2}}^{\text{Measured}} \approx F_2^{\text{NC}} - \frac{y^2}{Y_+} F_L^{\text{NC}}$$



$$Q^2 \ll M_Z^2$$

Extraction of F_L

Indirect measurement of F_L :

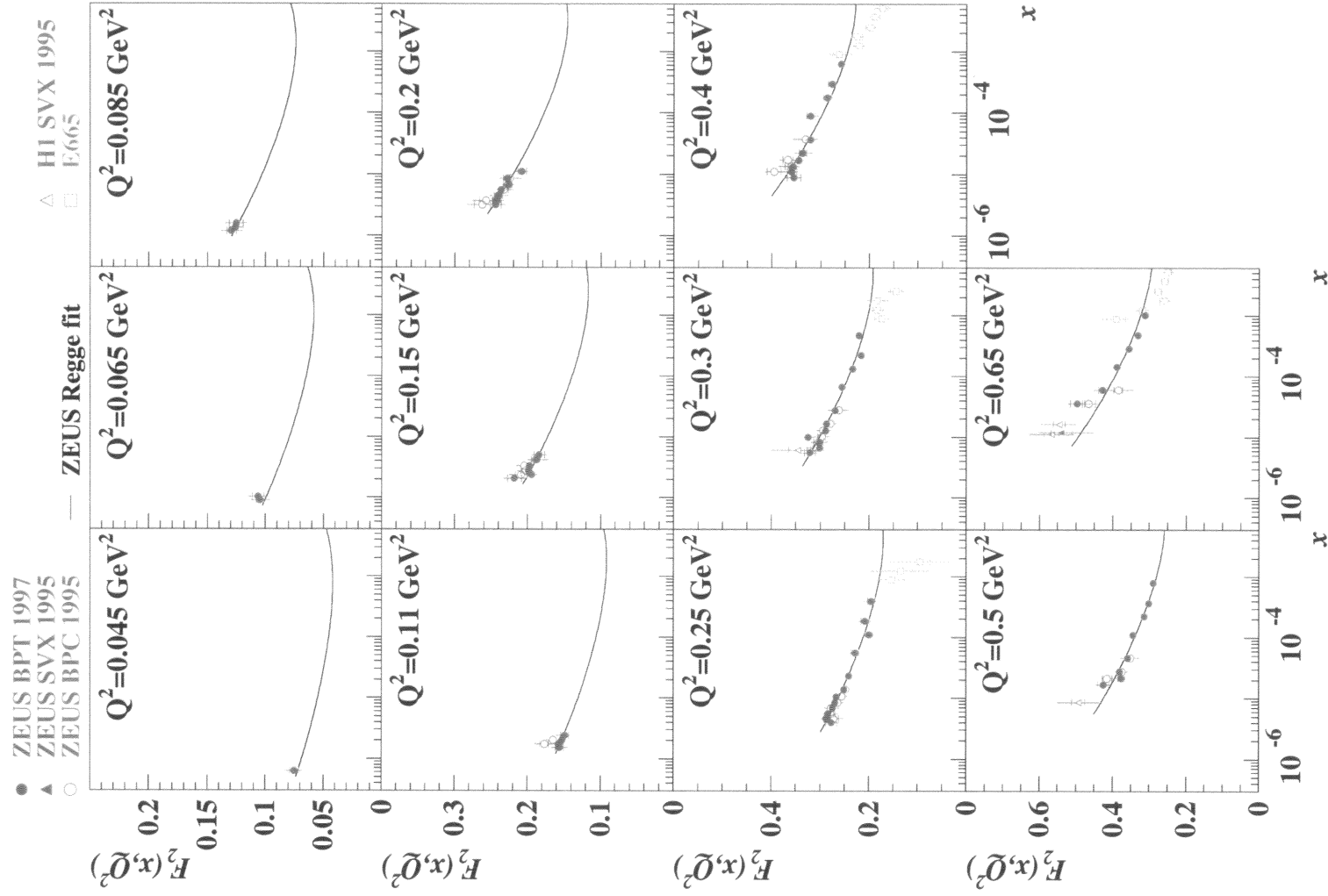


- QCD fit gives consistent description of data
- Estimate of F_L to very low values of x
- Need to lower E_p ($Q^2 = xys$) to make direct measurement

Proton Structure

$-F_2$ at very low Q^2 , low x :

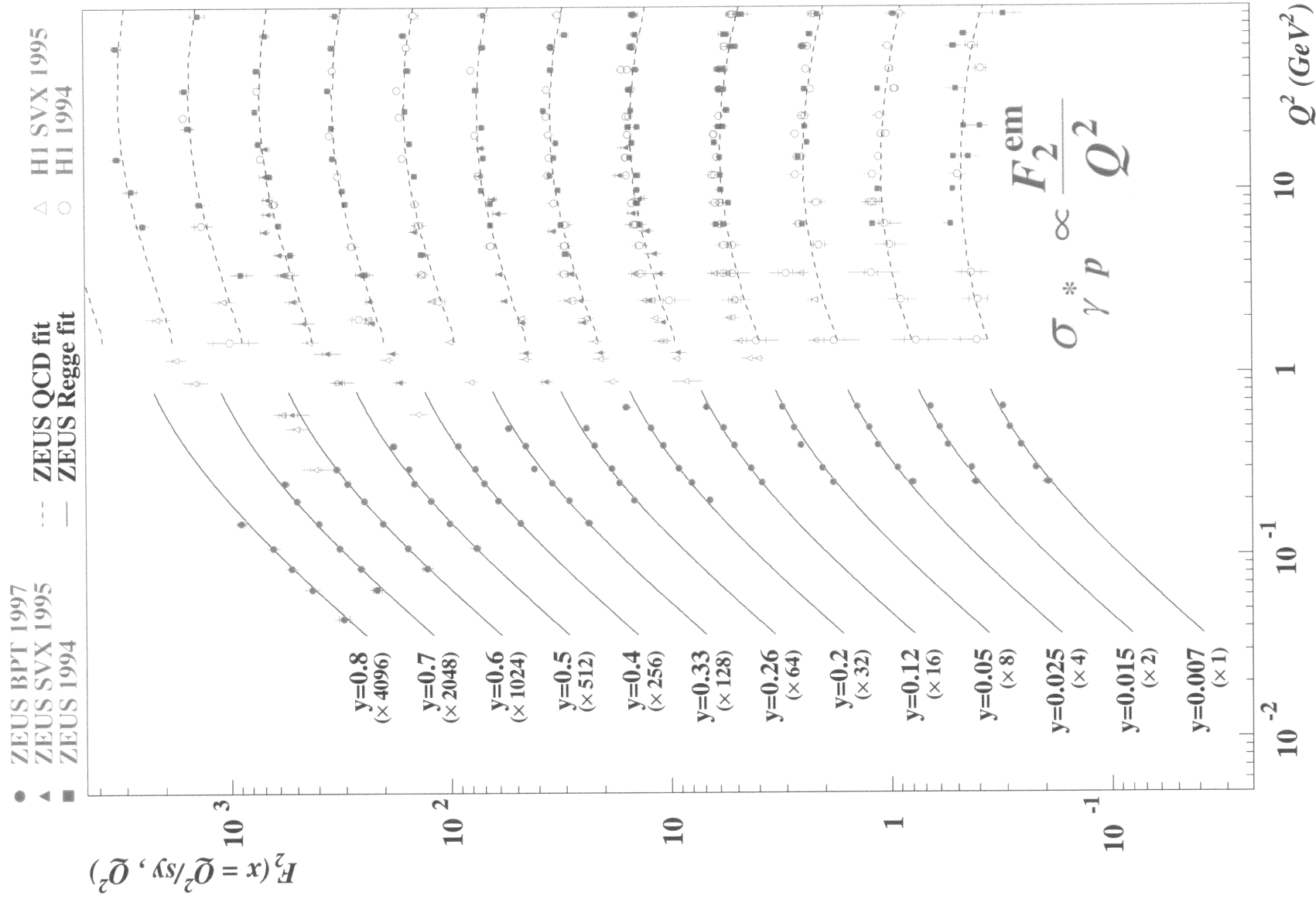
ZEUS 1997



- F_2 rises even at very low Q^2 ; but rate of rise appears to change

Proton Structure

ZEUS 1997



Low (x, Q^2) Formalism

Differential $e^\pm p \rightarrow e^\pm X$ cross section:

$$\frac{d^2\sigma^{\text{NC}}}{dy\,dQ^2} = \frac{2\pi\alpha^2}{yQ^4} (Y_+F_2 - y^2F_L \mp Y_-xF_3)$$

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

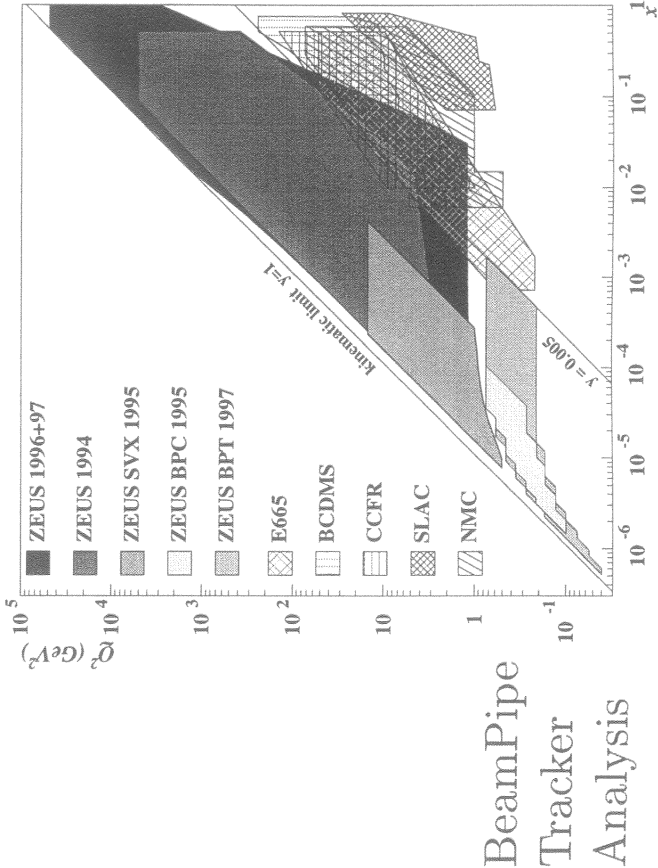
factorization in γ^* flux and γ^*p cross section:

$$\frac{d^2\sigma^{\text{NC}}}{dy\,dQ^2} = \Gamma \cdot \left(\sigma_T^{\gamma^*p} + \epsilon \sigma_L^{\gamma^*p} \right)$$

- $\Gamma = \alpha Y_+ / 2\pi y Q^2$ virtual photon flux
- $\epsilon = 2(1 - y) / Y_+$ photon polarization

often used (approximation for low x):

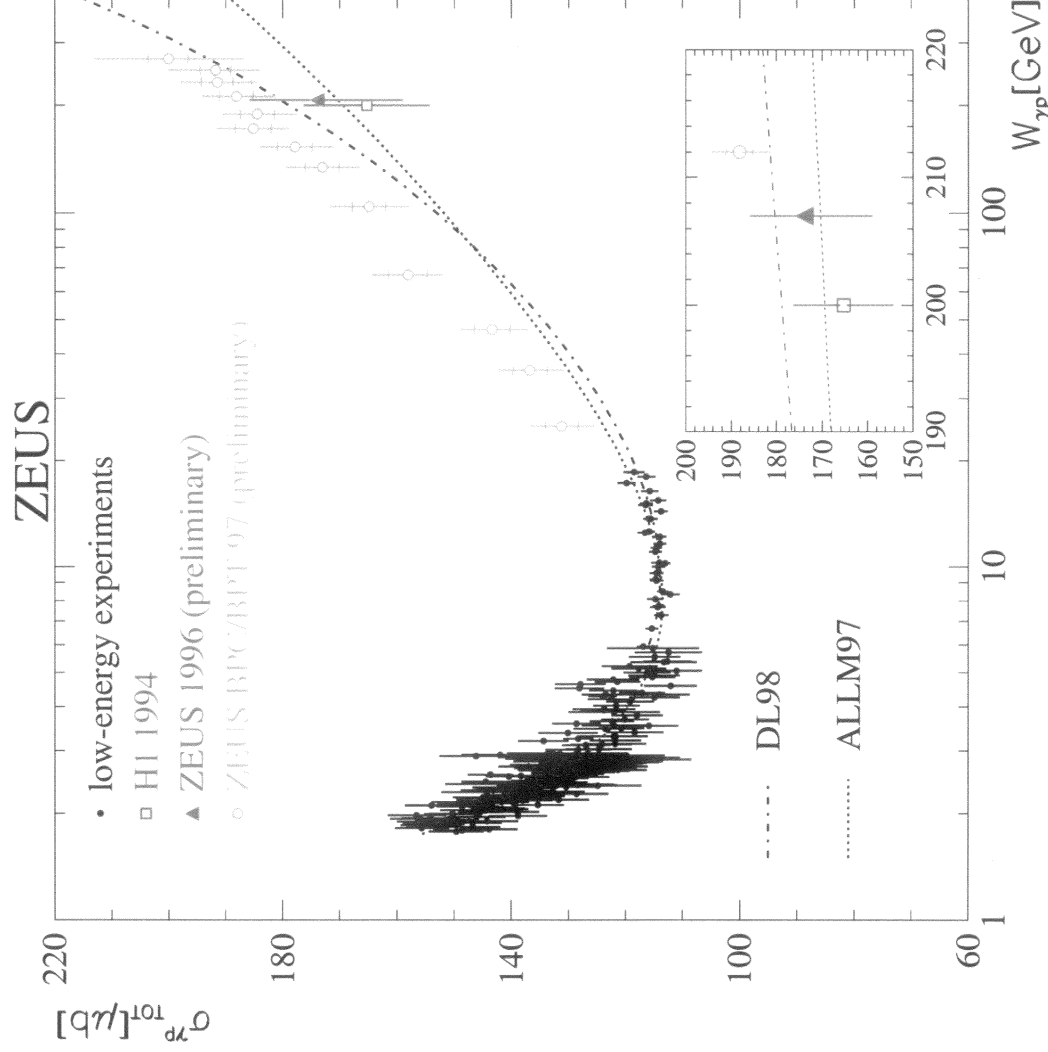
$$\sigma_{\text{tot}}^{\gamma^*p} = \sigma_T^{\gamma^*p} + \sigma_L^{\gamma^*p} \approx \frac{4\pi^2\alpha}{Q^2} F_2$$



Photon Structure

- real and virtual photons:

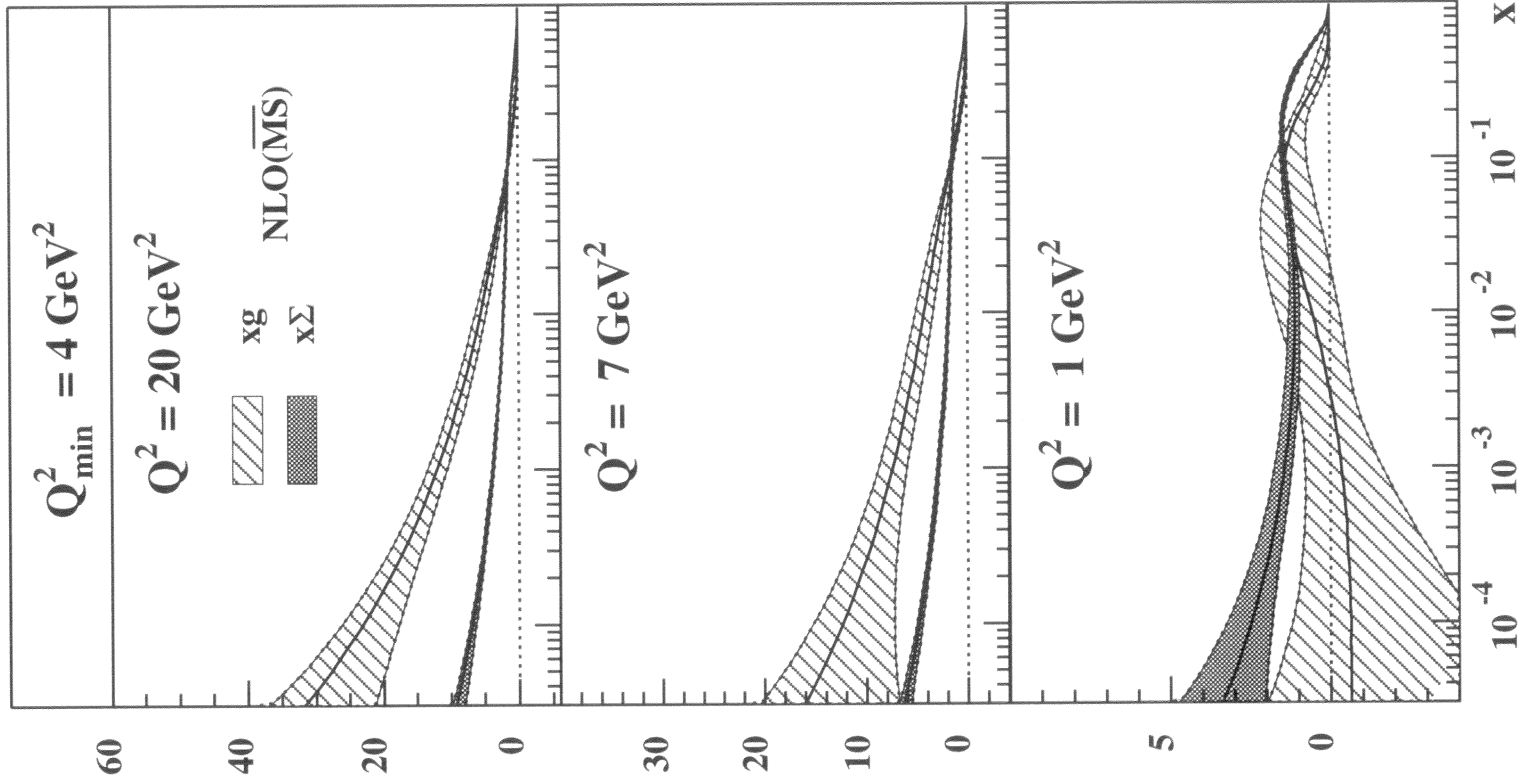
- Real photon behaves hadronically - i.e. dependence of total γ - p cross section increases slowly with s as in the case of hadron- p scattering
- As Q^2 decreases photon becomes 'more real' and tendency to behave hadronically increases



gluon distribution

ZEUS 1995

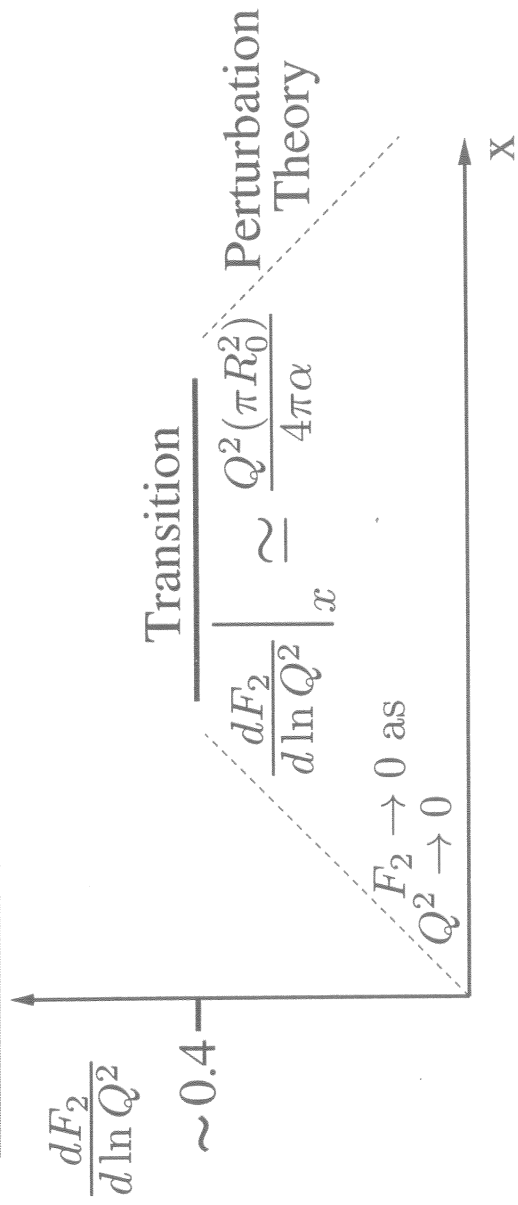
Parton
distributions
from NLO QCD
fit



$$\frac{dF_2^{\text{em}}}{d \ln Q^2} \propto \alpha_S P_{qg} \otimes xg$$

Gluon from scaling violation

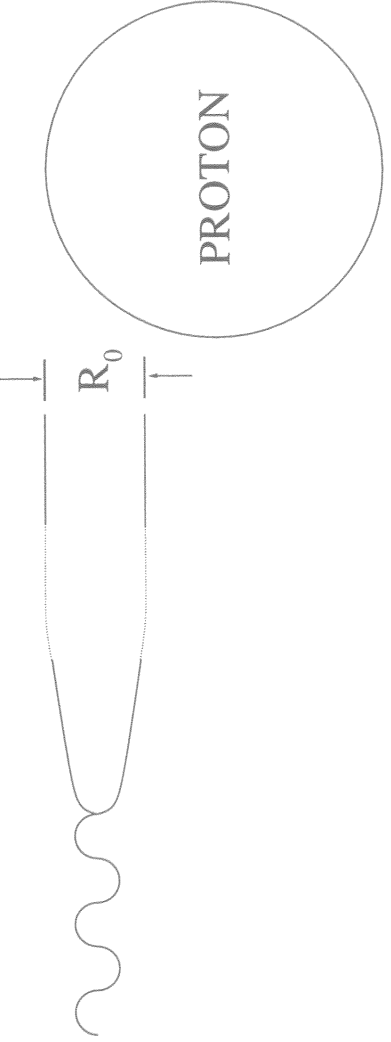
Transition Physics



- $\frac{dF_2}{d \ln Q^2} \Big|_x \sim \alpha_s(Q^2) x g(x)$ increases with decreasing x .
- $\frac{dF_2}{d \ln Q^2} \Big|_x \simeq \frac{Q^2 (\pi R_0^2)}{4\pi\alpha}$ - Mueller geometry

$$Q_0^2 \sim 4 \text{ GeV}^2$$

$$R_0 \sim 0.3 \text{ fm}$$



Charm in DIS

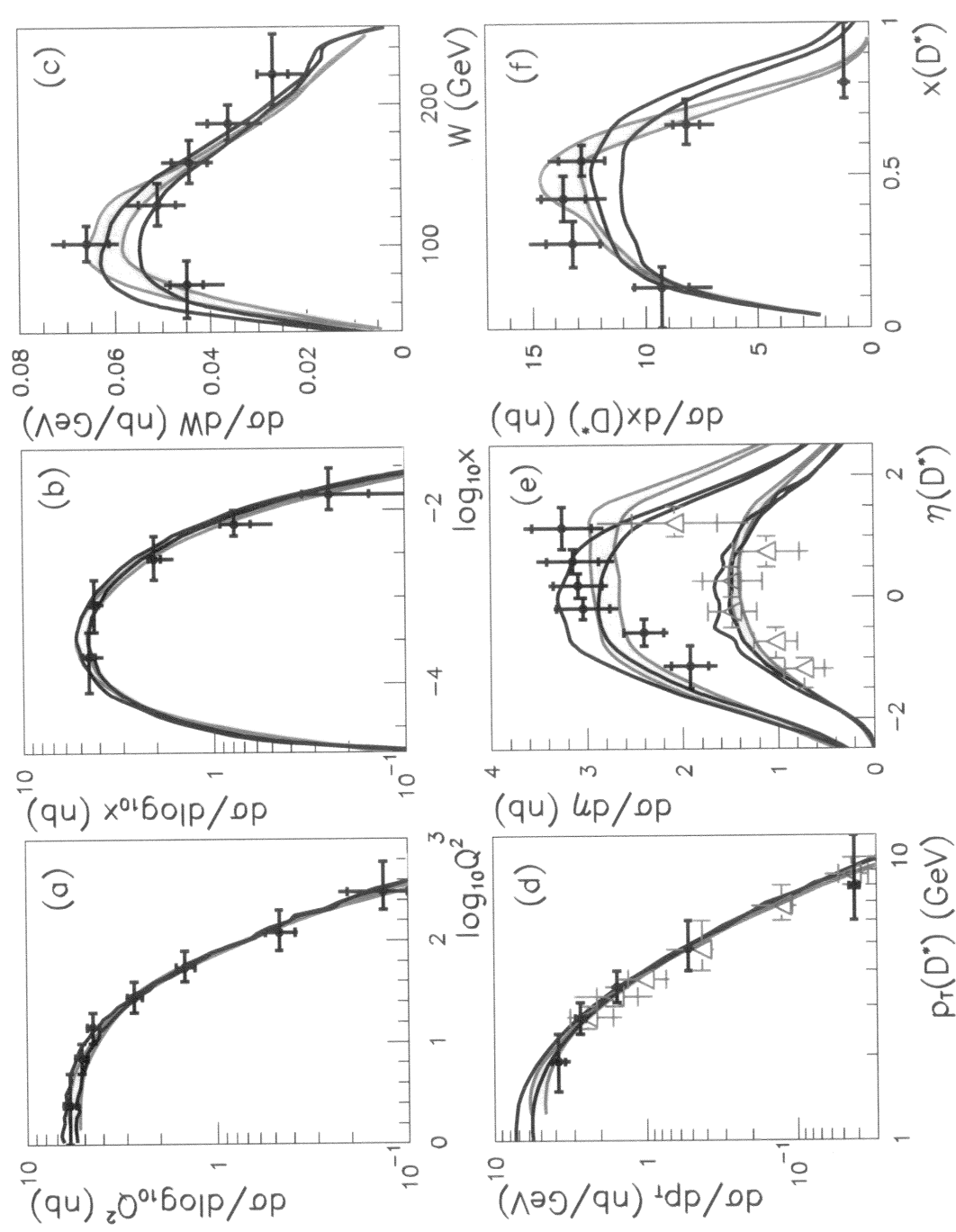
- Precision results from HERA

For $1 < Q^2 < 600 \text{ GeV}^2$, $0.02 < y < 0.7$,

$$1.5 < p_T(D^*) < 15 \text{ GeV}, \quad |\eta(D^*)| < 1.5$$

$$\Rightarrow \sigma(ep \rightarrow eD^*X) = 8.31 \pm 0.31^{+0.30}_{-0.50} \text{ nb}$$

ZEUS 1996–97



$K2\pi$ and $K4\pi$ data

$\Rightarrow$ agreement with “massive” NLO pQCD HVQDIS[†]

band: m_c uncertainty (1.3–1.5 GeV)

$$f(c \rightarrow D^{*+}) = 0.222 \pm 0.014 \pm 0.014^{\dagger}$$

[†]B. W. Harris and J. Smith, hep-ph/9706334

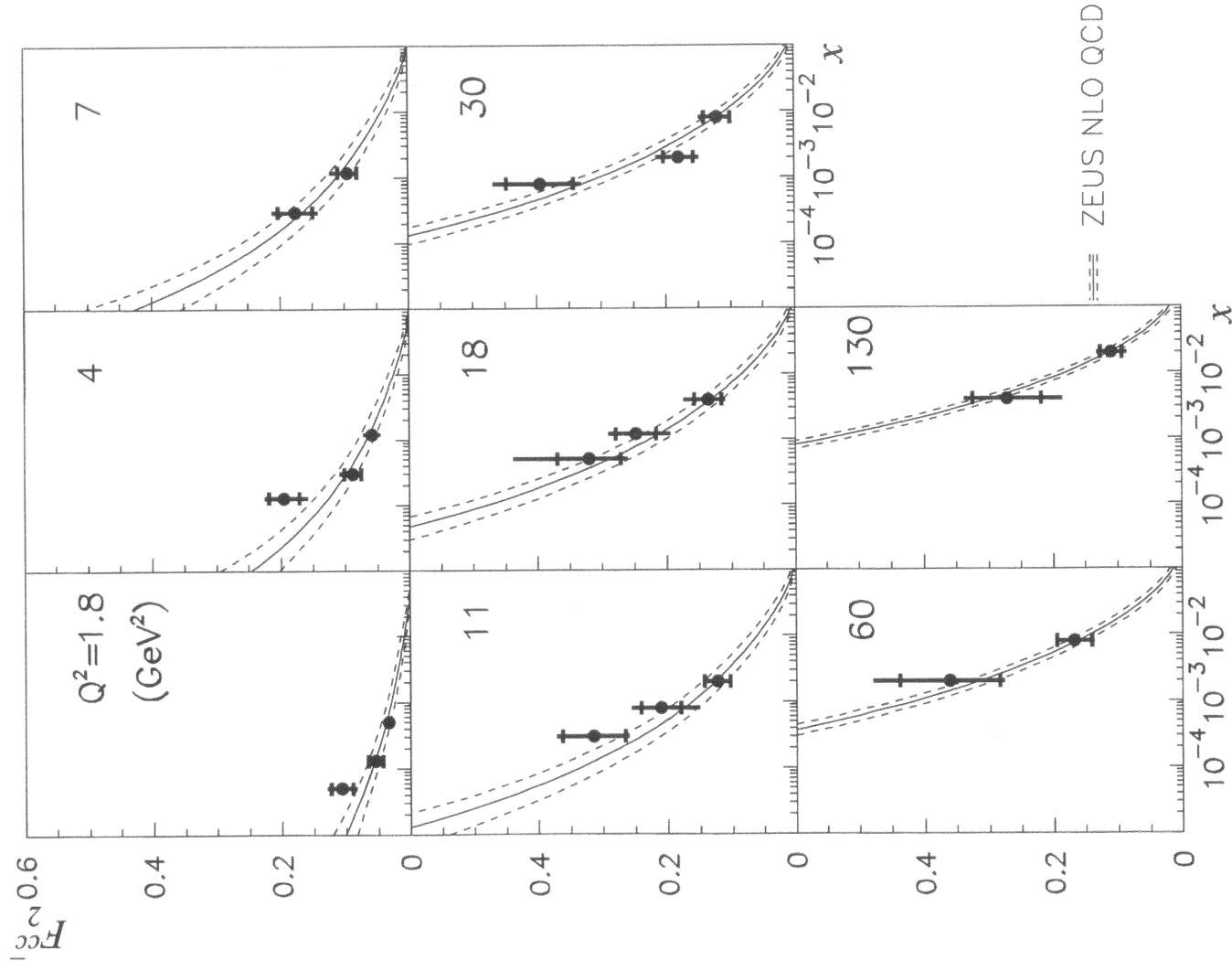
[†]OPAL Collab., Eur. Phys. J C1(1998)439

F_2^{charm}

$$\frac{d^2\sigma_{c\bar{c}X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [1 + (1-y)^2 F_2^c(x, Q^2) - y^2 F_L^c(x, Q^2)]$$

Extraction of F_2^c requires extrapolation to full $\{\eta, p_T\}$ range.

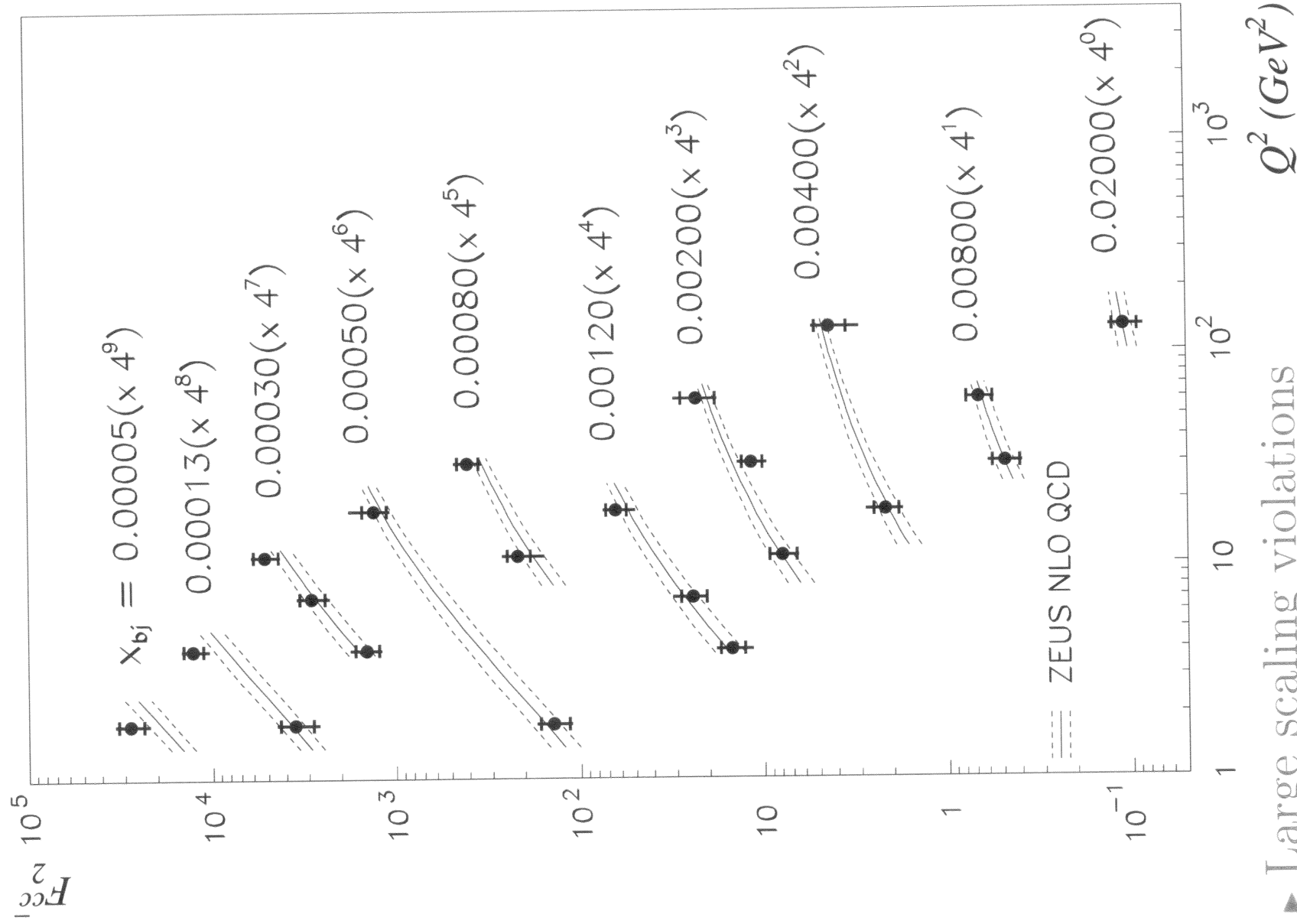
ZEUS 1996–97



- Precision $\simeq 15 - 20\%$
- Significantly more precise than earlier measurements
- Steep rise towards small $x \rightarrow$ gluons

F_2^c Scaling Violations

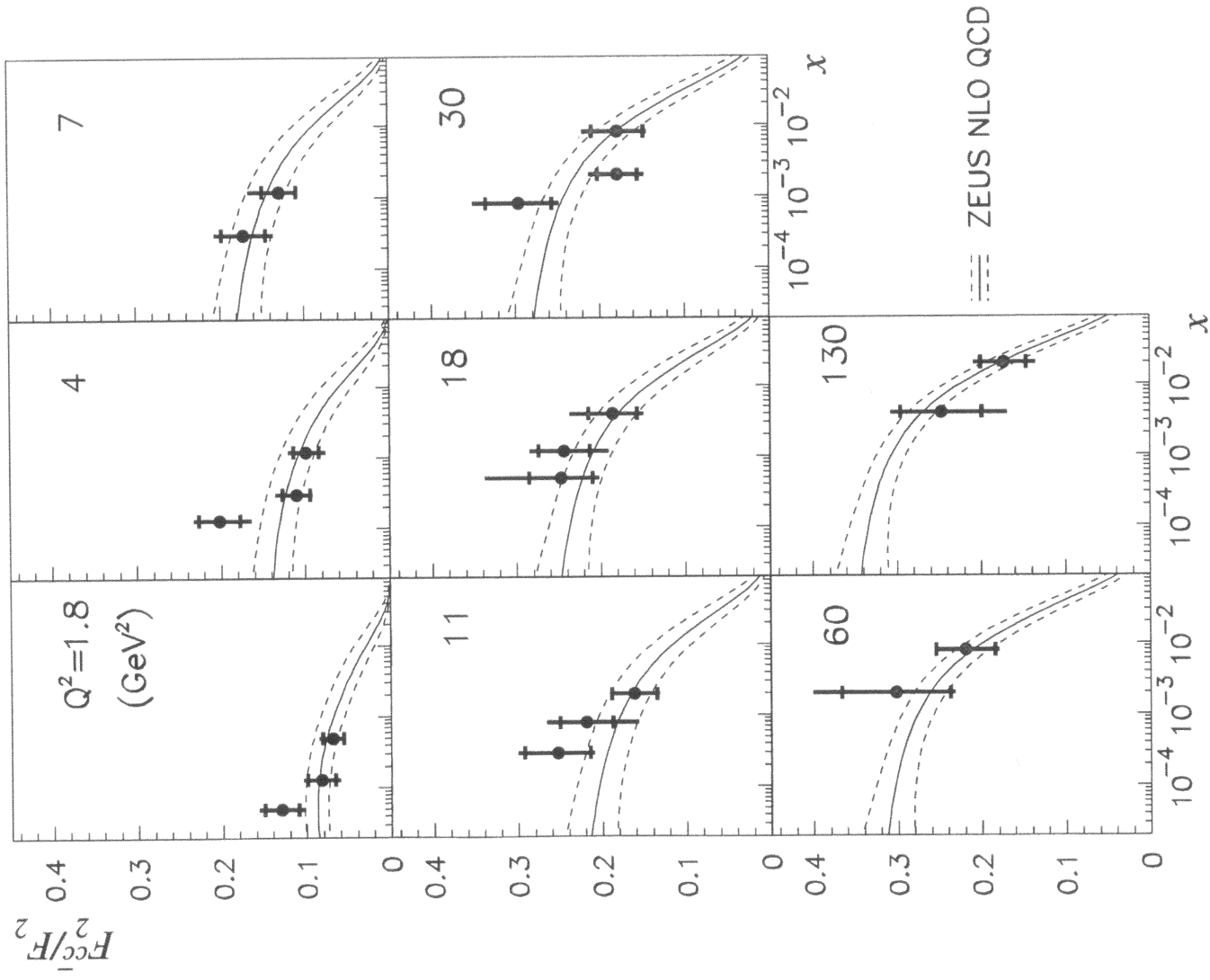
ZEUS 1996–97



$$F_2^c/F_2$$

Significant fraction of inclusive F_2
Comparison with prediction of ZEUS F_2 fit

ZEUS 1996–97



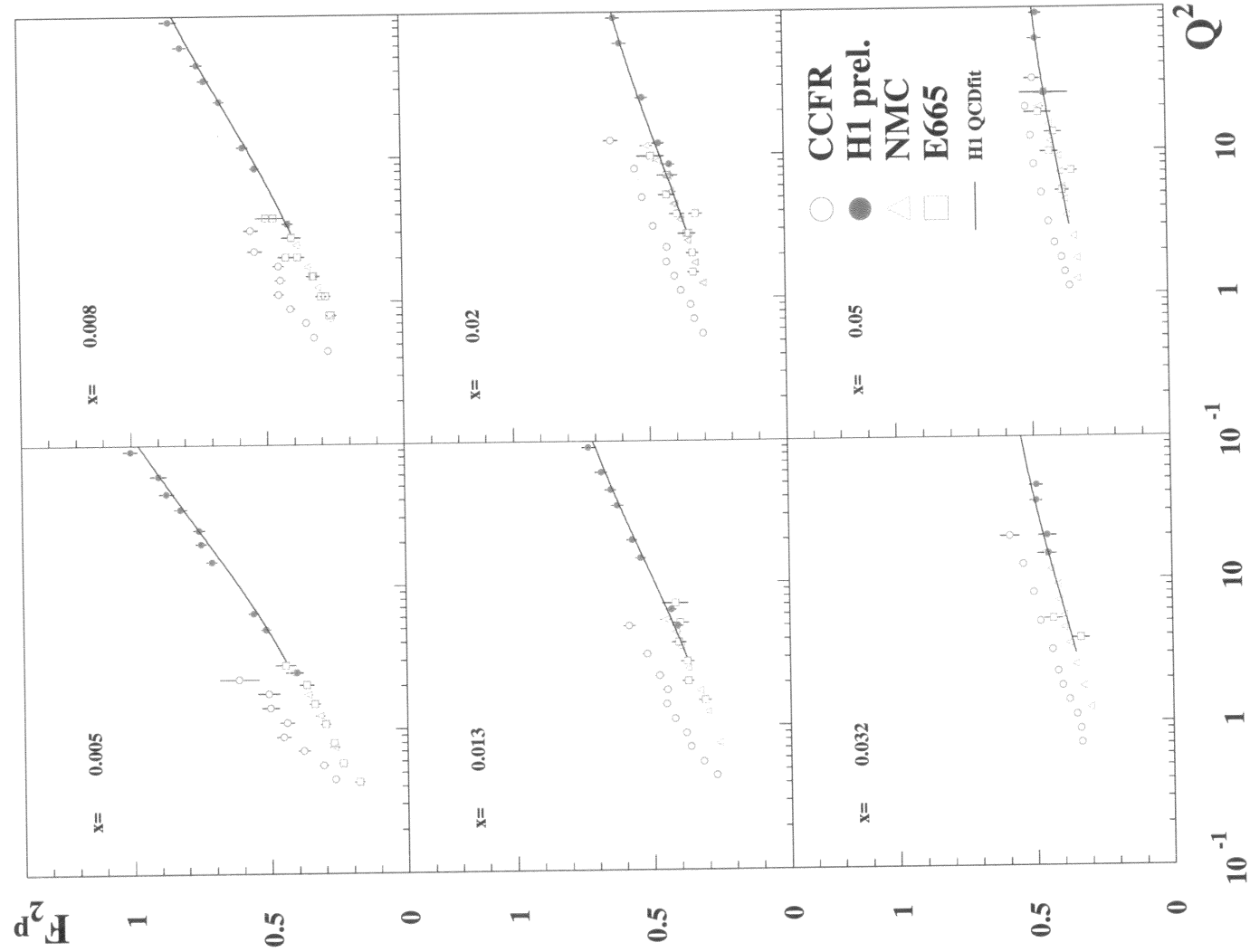
- F_2^c/F_2 threshold behaviour
- c.f. CCFR massive charm

CCFR - NMC Discrepancy

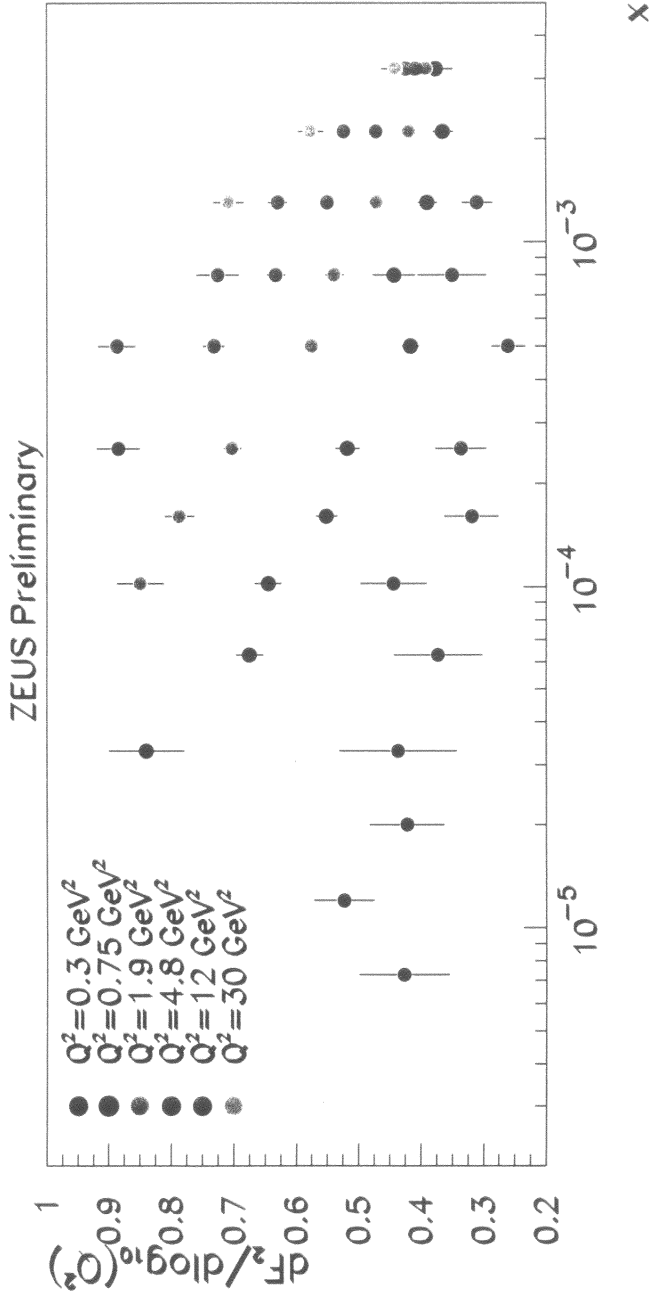
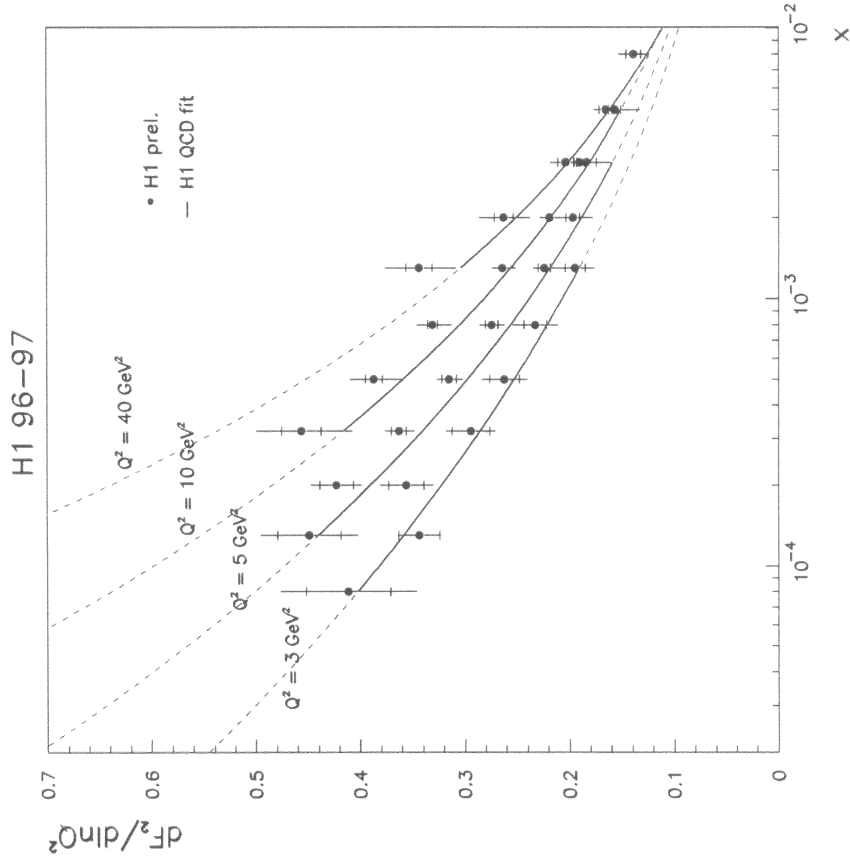
$$F_2^{\mu N} = \frac{5}{18} [1 - \frac{3}{5} \frac{xs(x) + x\bar{s}(x)}{xq(x) + x\bar{q}(x)}] F_2^{\nu N}$$

5/18 rule OK except at low- x

- CCFR heavy target? (5% effect)
- CCFR strange sea $\rightarrow$ charm production?
- HERA data $\blacktriangleright$ CCFR re-analysis required?...



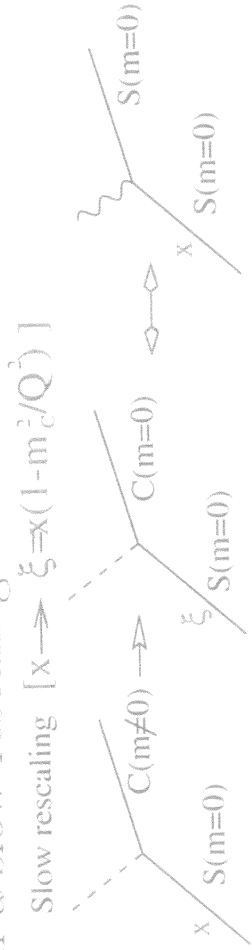
$dF_2/d\log(Q^2)$



Monotonic rise with increasing Q^2
Flattening at lowest accessible Q^2
Saturation?? See e.g. Bartels, Ryskin

CCFR - Massive Charm

- Previous CCFR F_2 extraction was done with a slow rescaling correction

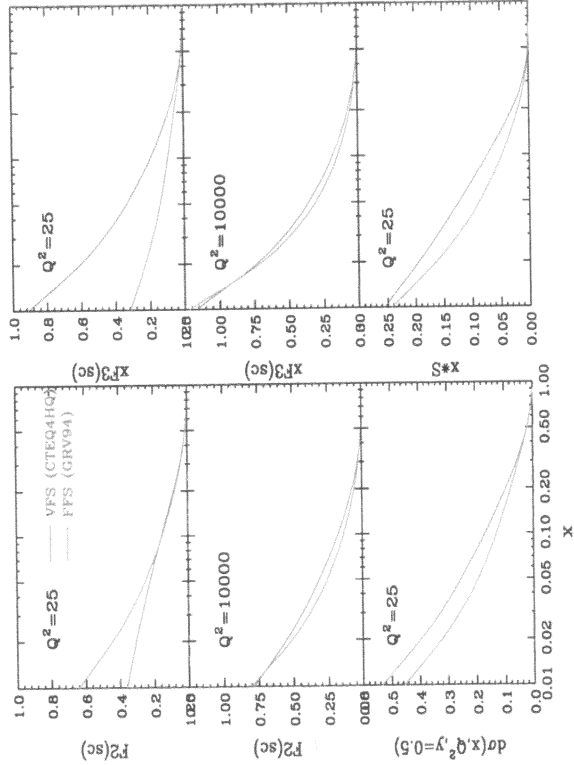


◁ Such that F_2^ν can be directly compared with F_2^μ

Various NLO heavy quark treatments now available:



- ▷ Variable Flavor Scheme [VFS]: heavy quark inside proton
LO + NLO - SUB (good for $Q \gg m_h$ region) [$\mu = 2P_t^{max}$]
- ▷ Fixed Flavor Scheme [FFS]: No heavy quark inside proton
only NLO (good for $Q \approx m_h$) [$\mu = 2m_c$]
- ▷ Mixed Flavor Scheme [MFS]
 $FFS(Q \approx m_h) + VFS(Q > m_h)$ [$\mu = Q$]

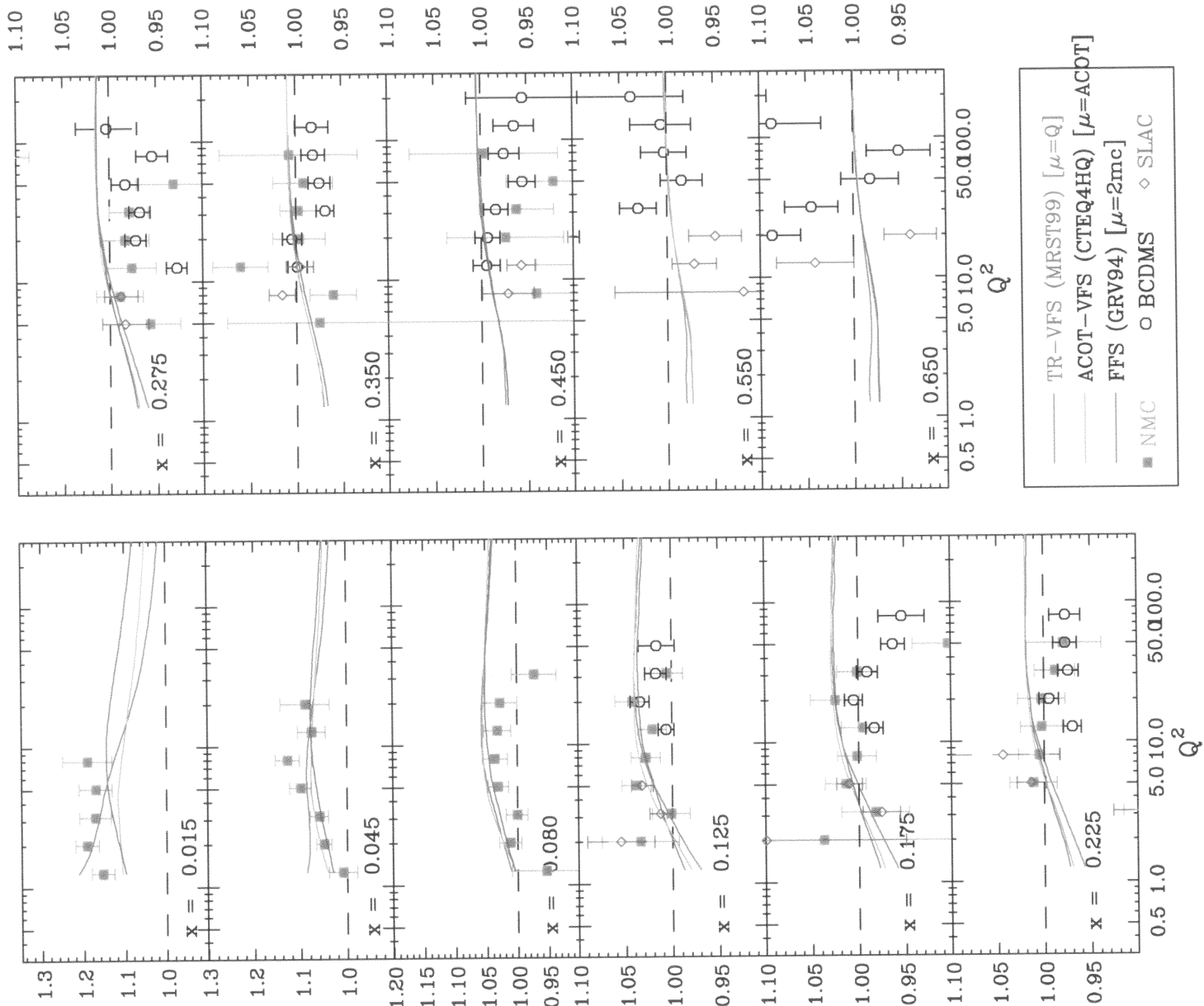


CCFR - NMC Agreement

$$\text{ratio} = \frac{5}{18} F_2^{\nu N} / F_2^{\mu N}$$

- No massive charm correction made to F_2 (and $\Delta x F_3^{\nu-\bar{\nu}}$)

► Physics Model Independent approach

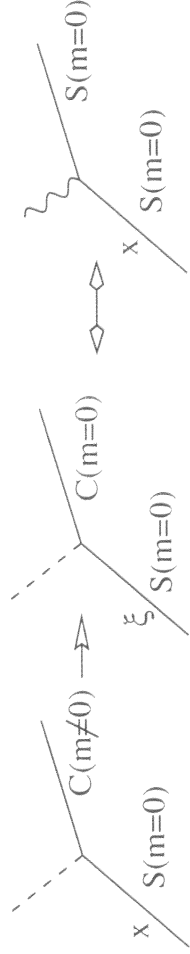


- Departure from 5/18 rule due to massive charm
- Described by latest NLO approaches (MRST, CTEQ, GRV)

CCFR - Massive Charm

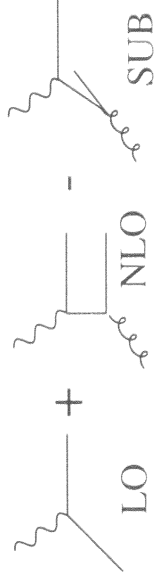
- Previous CCFR F_2 extraction was done with a slow rescaling correction

$$\text{Slow rescaling } [x \rightarrow \xi = x(1 - m_c^2/Q^2)]$$

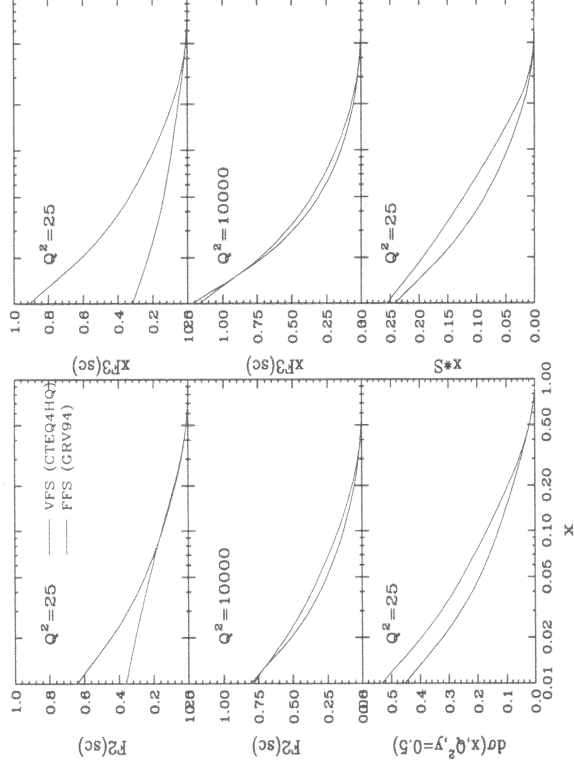


◁ Such that F_2^ν can be directly compared with F_2^μ

Various NLO heavy quark treatments now available:

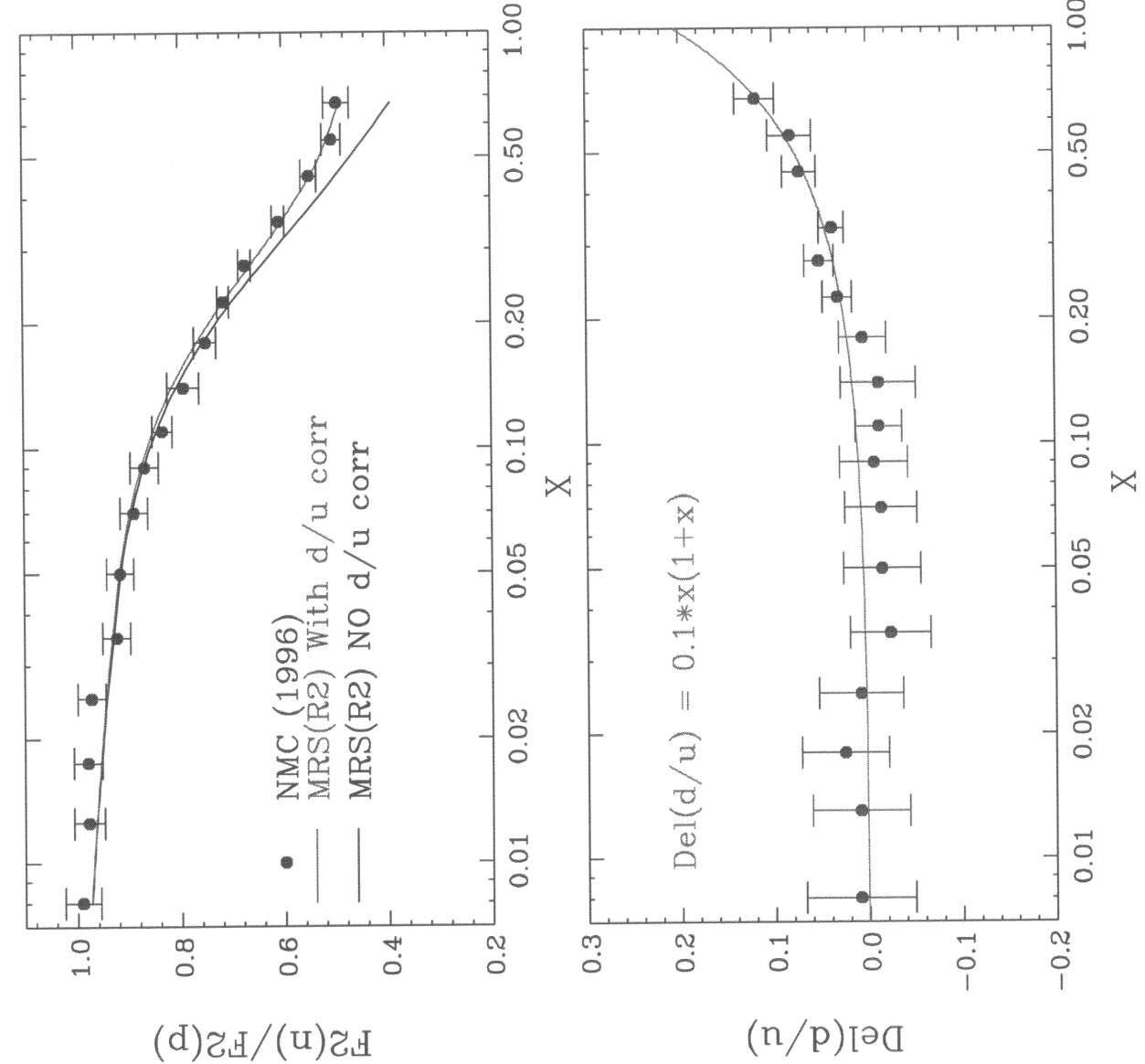


- ▷ Variable Flavor Scheme [VFS]: heavy quark inside proton
LO + NLO - SUB (good for $Q \gg m_h$ region) [$\mu = 2P_{f_i}^{max}$]
- ▷ Fixed Flavor Scheme [FFS]: No heavy quark inside proton
only NLO (good for $Q \approx m_h$) [$\mu = 2m_c$]
- ▷ Mixed Flavor Scheme [MFS]
FFS($Q \approx m_h$) + VFS($Q > m_h$) [$\mu = Q$]



d/u at Low Q^2

- Analysis of NMC Proton and Deuteron data,
- d/u increased significantly at high x .

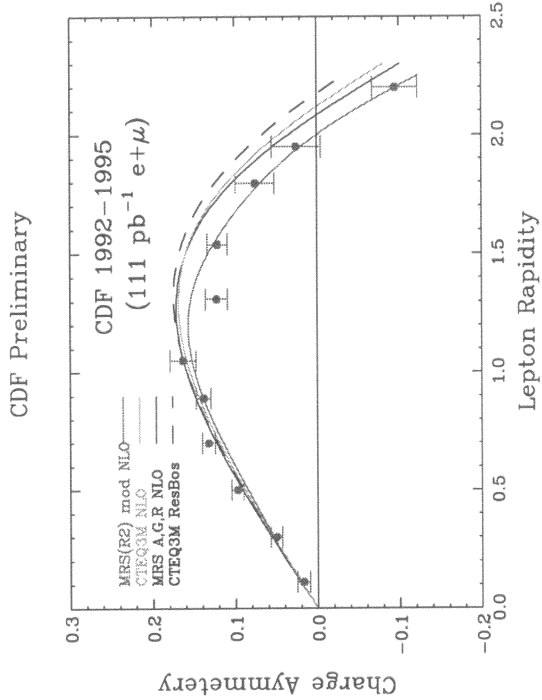


- Fit NMC data (including nuclear correction to deuteron data)

High Energy Predictions

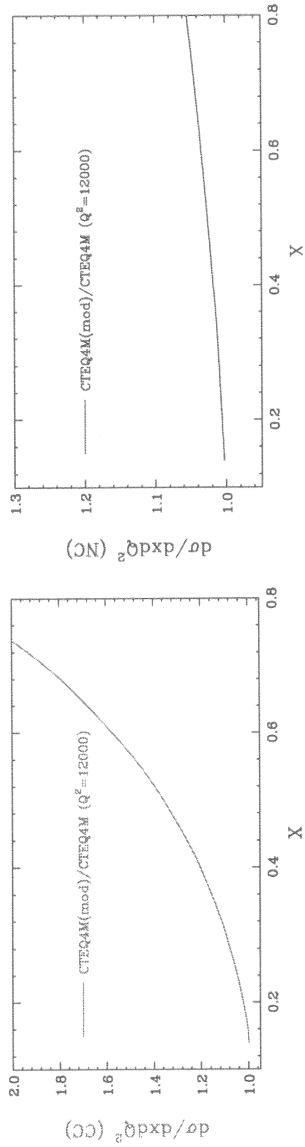
A. W Production at Tevatron

- Increasing $d/u \Rightarrow$ smaller exchange asymmetry at large η ,
- $u(x)$ peaked at higher $x \rightarrow W^+$ enhanced in proton direction.



- Agrees with Tevatron data
(c.f MRST, CTEQ4 give good description).

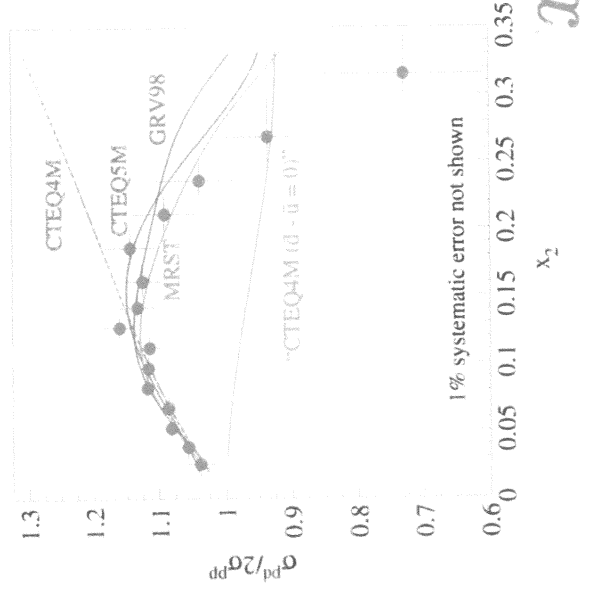
B. High Q^2 Cross Sections at HERA



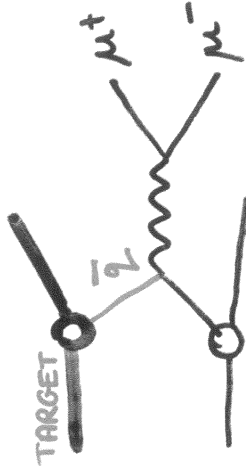
- Increase in CC cross sections

Sea Quark Distribution

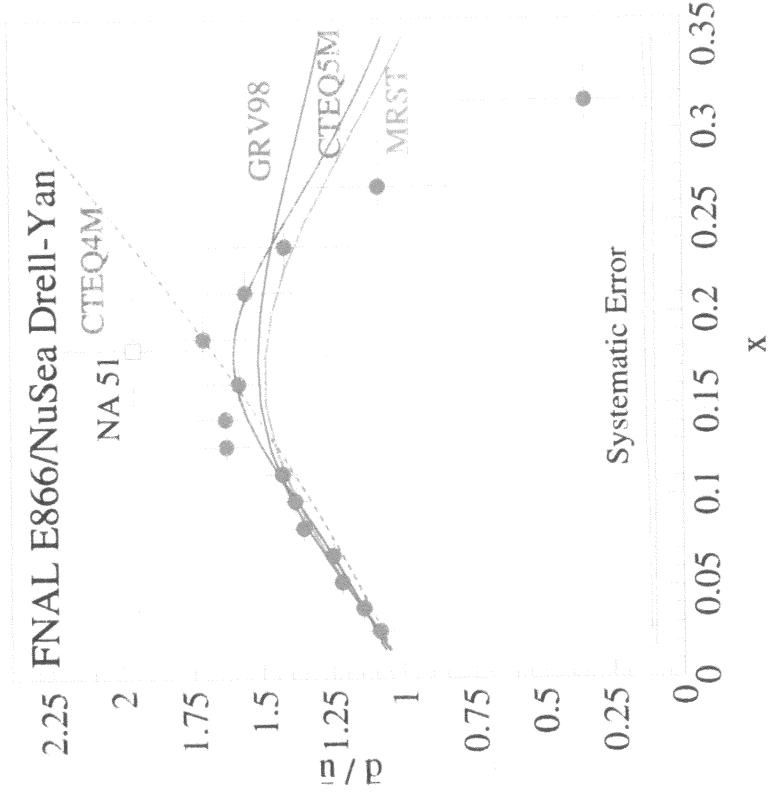
$$\frac{\sigma^{pd}}{2\sigma^{pp}}$$



E866 Drell-Yan on proton and deuteron
 ► strong constraint on sea quarks



► $\bar{d}/\bar{u}$



FNAL E866/NuSea Drell-Yan

CTEQ4M

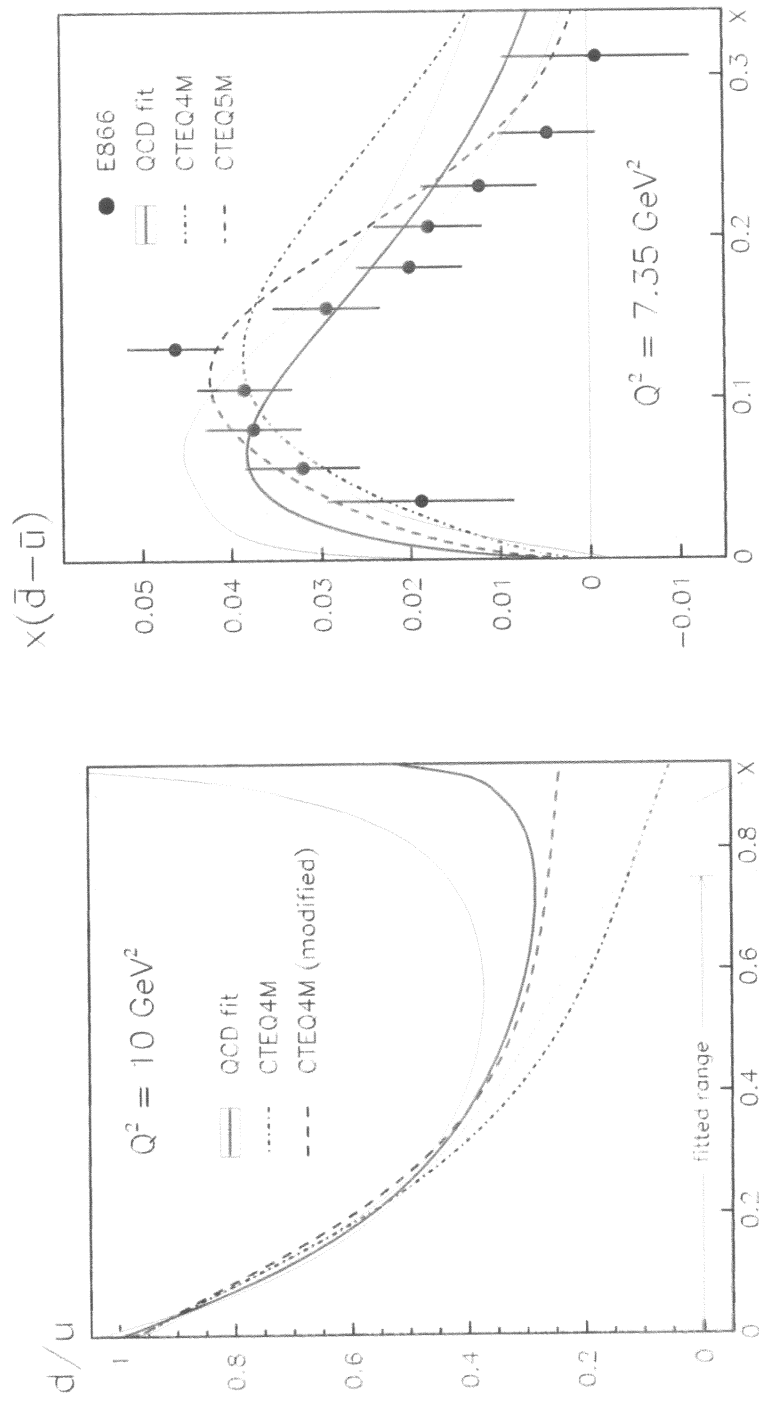
NA 51

$\sigma^{pd}/2\sigma^{pp}$

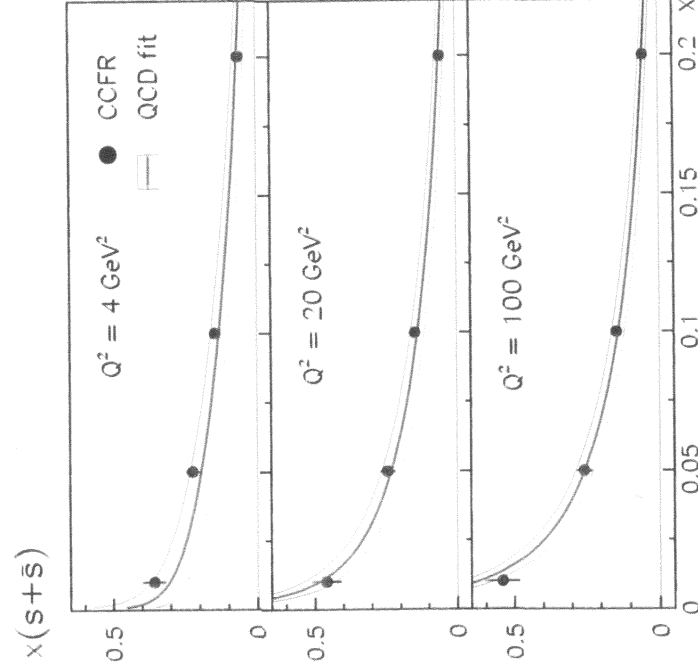
Systematic Error

Proton Structure

- d/u , $\bar{d} - \bar{u}$ and $s + \bar{s}$



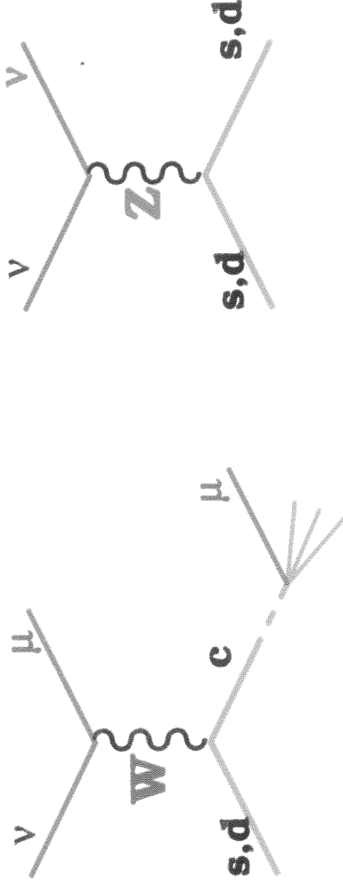
- Large d/u uncertainties at high x
- Reasonable fit to E866 data
- Strange sea from CCFR dimuon data



NuTeV $\sin^2\theta_W$

Tagged ν and $\bar{\nu}$ ► reduced charm quark uncertainty

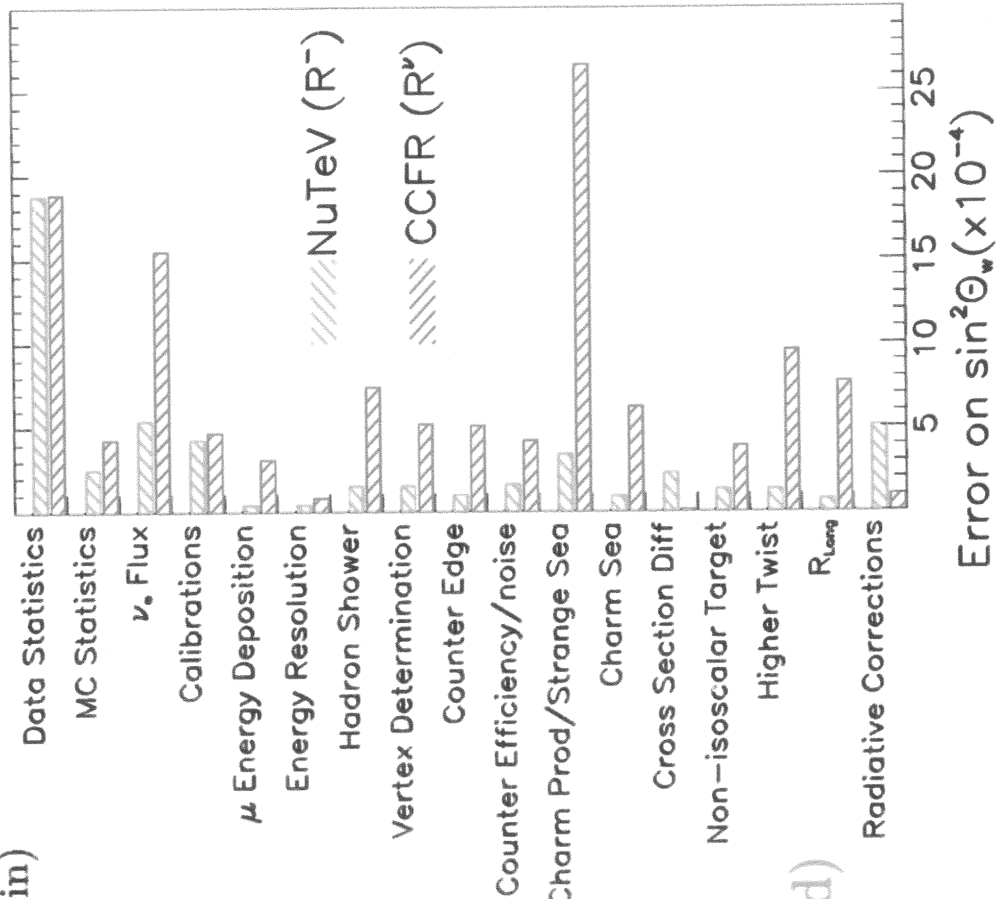
- Dominant CCFR systematic (measured $R = \frac{\sigma_{NC}}{\sigma_{CC}}$)



constraint from di-muon events ($m_c = 1.31 \pm 0.24$ GeV) - insufficient

NuTeV ► $R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{R^{\nu} - rR^{\bar{\nu}}}{1-r} = \rho(\frac{1}{2} - \sin^2\theta_W)$

where $R^{\nu/\bar{\nu}} = \sigma_{NC}^{\nu/\bar{\nu}}/\sigma_{NC}^{\nu/\bar{\nu}}$ and $r = \sigma_{CC}^{\bar{\nu}}/\sigma_{CC}^{\nu}$
(Paschos-Wolfenstein)



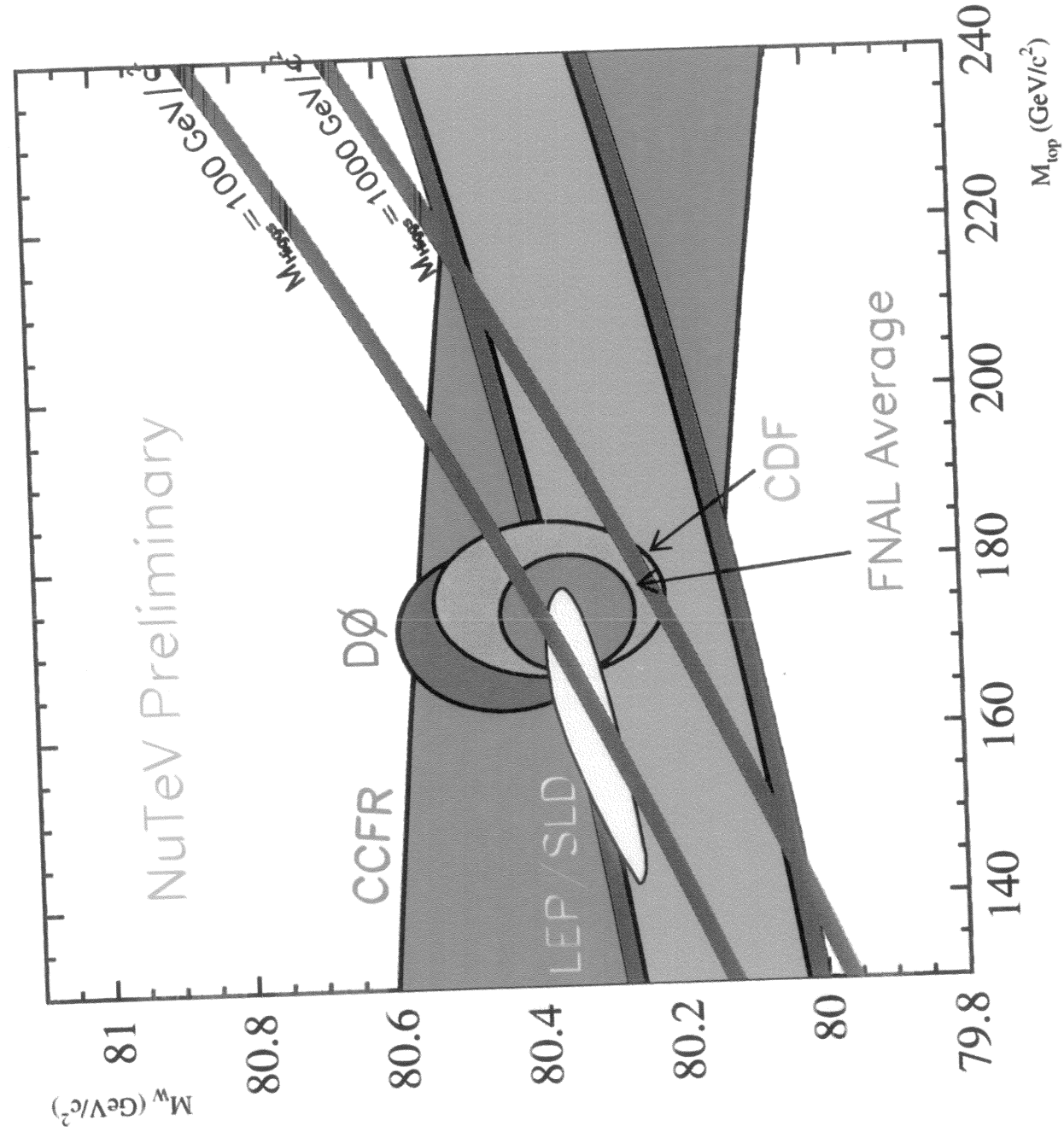
Charm production: Charm Prod/Strange Sea
~ cancels for $\nu - \bar{\nu}$

(also HT, R reduced)

► improved uncertainty on $\sin^2\theta_W$

NuTeV $\sin^2 \theta_W$

$$\sin^2 \theta_W^{(\text{on-shell})} = 0.2253 \pm 0.0019 \pm 0.0010$$



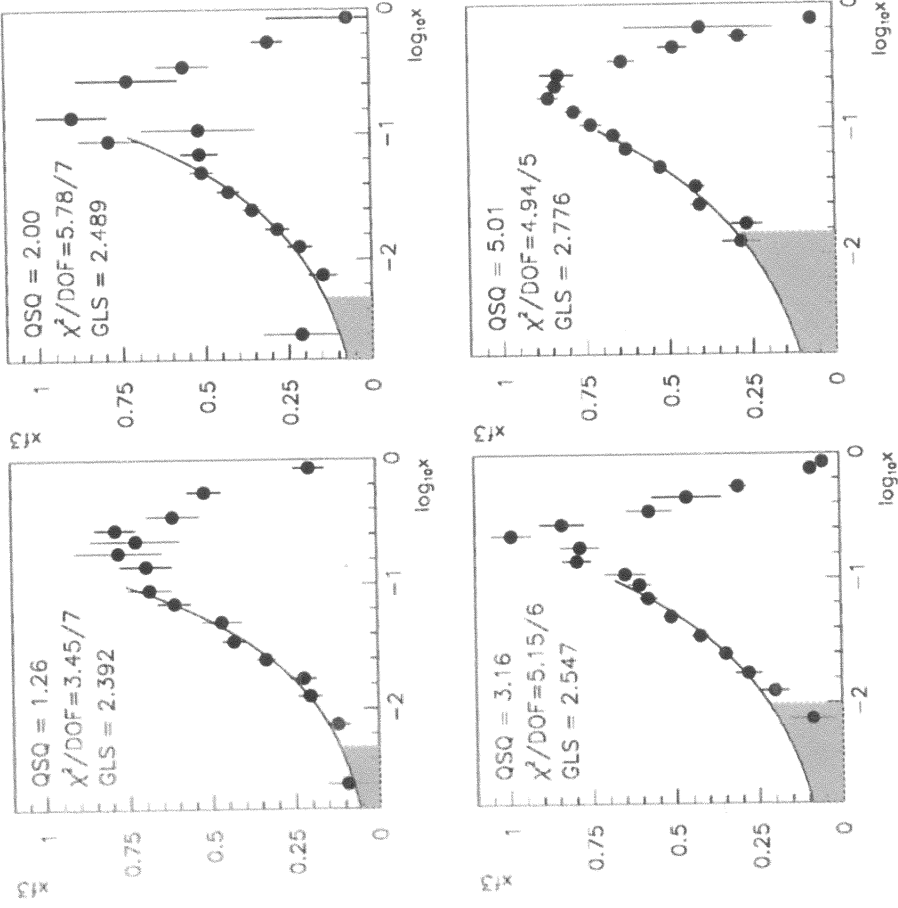
- different sensitivity to E/W corrections compared to LEP/SLD

$$\begin{aligned} \sin^2 \theta_W^{(\text{on-shell})} &\equiv 1 - \frac{M_W^2}{M_Z^2} \\ &\Rightarrow M_W = 80.26 \pm 0.11 \text{ GeV (prel.)} \end{aligned}$$

- 3 Valence Quarks in the Nucleon

$$\int_0^1 x F_3(x, Q^2) \frac{dx}{x} = 3 \left(1 - \frac{\alpha_s}{\pi} - a_2(n_f) \left(\frac{\alpha_s}{\pi} \right)^2 - a_3(n_f) \left(\frac{\alpha_s}{\pi} \right)^3 \right) - \frac{\Delta HT_{GLS}}{Q^2}$$

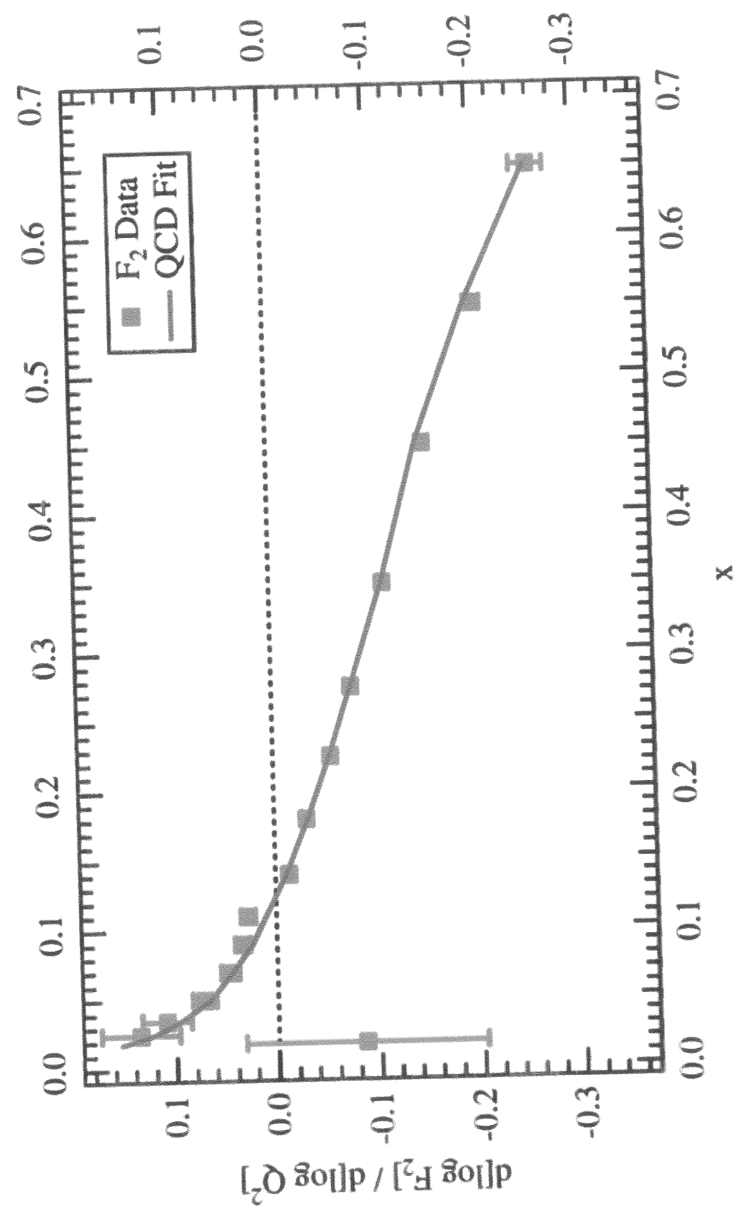
- Fundamental Prediction of QCD
- Theoretically Robust low Q^2 Prediction
- Independent of Gluon Distribution
- Calculated to $\mathcal{O}(\alpha_s^3)$, estimated to $\mathcal{O}(\alpha_s^4)$
- $\Delta HT_{GLS} = 0.15 \pm 0.15$ - large theory uncertainty



- GLS Approaching 3 as Q^2 increases

$$\alpha_s(M_Z^2) = 0.114^{+0.005}_{-0.006}(stat)^{+0.007}_{-0.009}(syst)^{+0.004}_{-0.005}(theory)$$

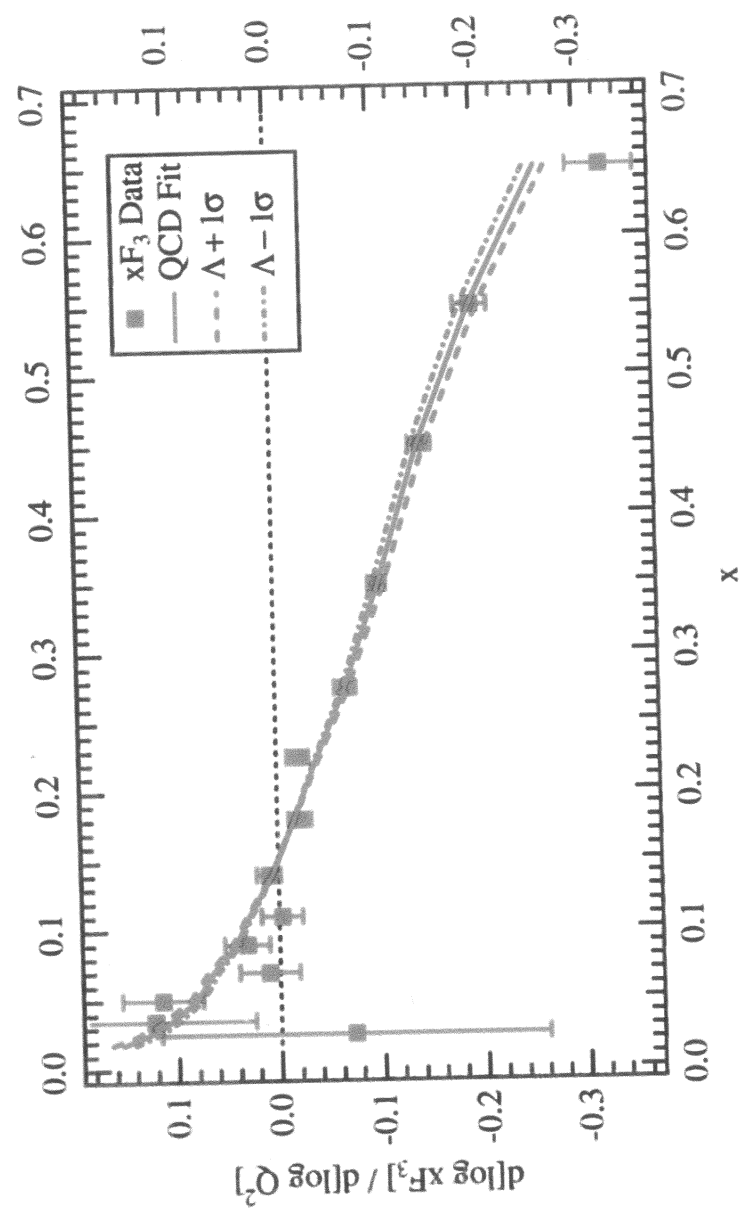
CCFR: High- x Scaling Violations



$$\alpha_s(M_Z^2) = 0.119 \pm .002(exp) \pm .004(theory)$$

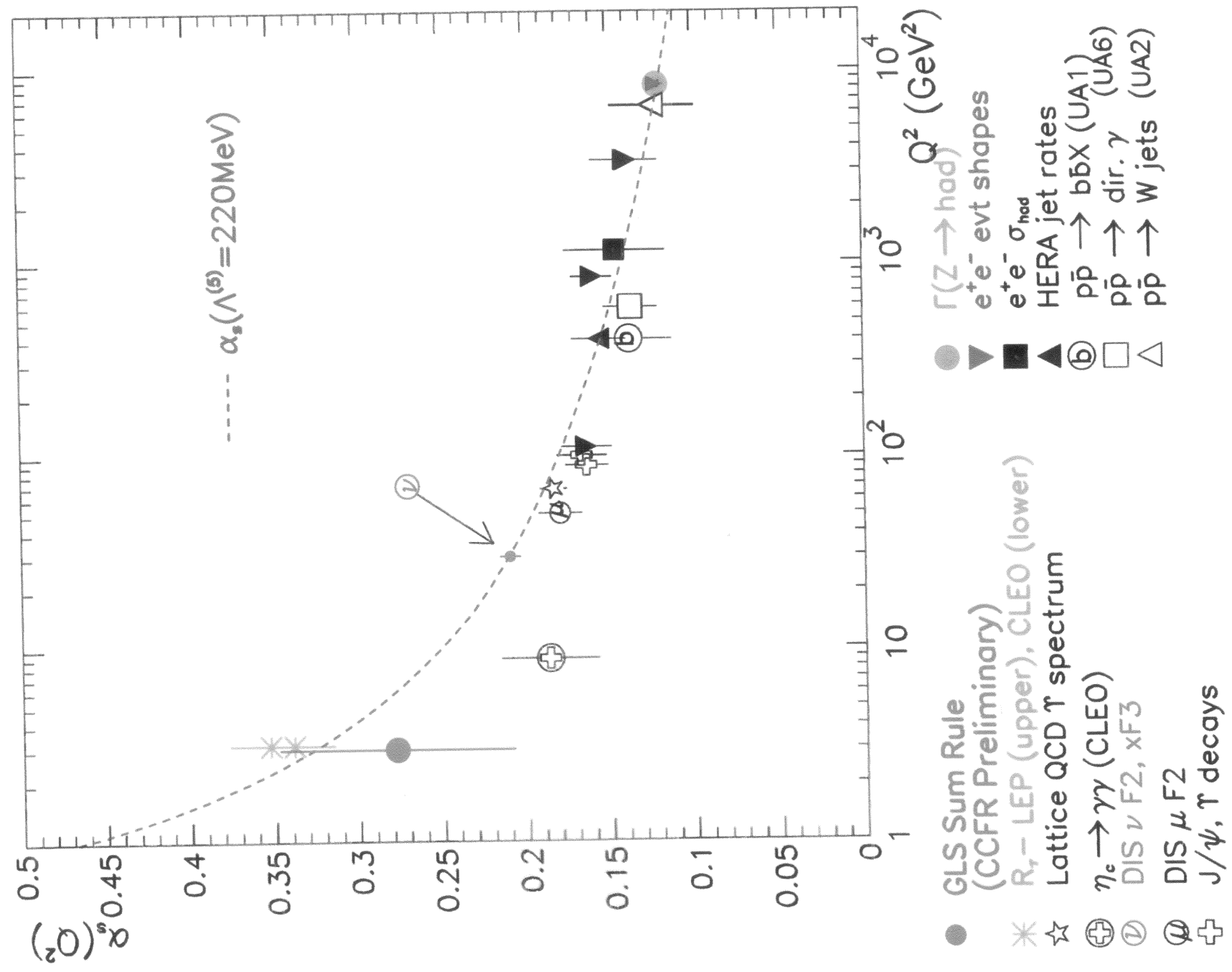
(combined fit to F_2 and xF_3)

- Higher than BCDMS analysis



- xF_3 independent of gluon

Comparison of DIS Results with World Data



- NuTeV Aim to reduce total error on scaling violations to 0.003 (assuming NNPDF)

High (x, Q^2) and Beyond the Standard Model

Outline

Introduction

DIS Standard Model
PDF Uncertainties

High
 (x, Q^2)
Cross-Sections

Charged Current
 W Mass Sensitivity
Neutral Current
Sensitivity to Z
 $e^\pm p$ Data
 $x\bar{F}_3$ extraction
Input on d/u

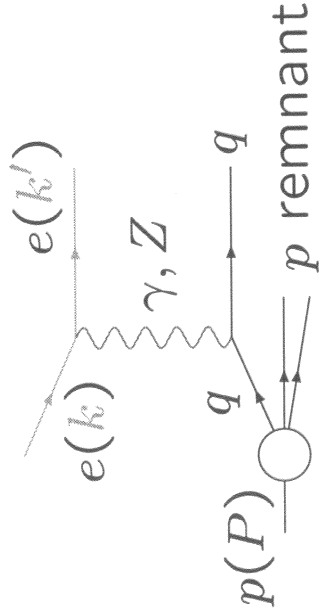
Beyond
The
Standard
Model

Leptoquark
Search
Limits
Contact Interactions
Search
Limits

Future Physics
at HERA

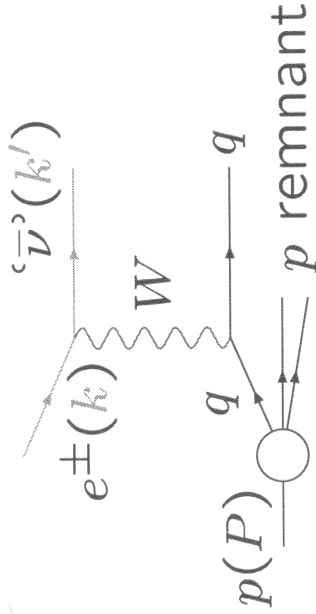
Outlook

DIS Kinematics



Neutral Current (NC)

Scattered e in main detector
 e balances hadronic p_t



Charged Current (CC)

Scattered ν invisible
 Only hadronic system
 available for measurements

Kinematic Variables:

Four-momentum transfer:

$$q = k - k'; \quad Q^2 = -q^2 = 2E_e E'(1 + \cos \theta_e)$$

Bjorken scaling variable:

$$x = Q^2 / (2 q \cdot P) = \text{momentum fraction of quark}$$

Inelasticity:

$$y = (q \cdot P) / (k \cdot P)$$

$$y = (1 - \cos \theta_e^*) / 2; \quad \theta_e^* = e q \text{ c.m.s. scattering angle}$$

ep centre-of-mass energy:

eq invariant mass:

$$s = (k + P)^2 = 4E_e E_p$$

$$M = \sqrt{xs}$$

DIS Standard Model

Deep-inelastic ep scattering =
incoherent sum of elastic eq scatterings

$$\sigma(ep) = \sum_{q,\bar{q}} f_{q|p} \cdot \sigma(eq)$$

$f_{q|p} \equiv q$ = Parton distribution function (PDF)

Probability density to find quark q in the proton
carrying a fraction x of the proton momentum
Not predicted by theory

$\sigma(eq)$ = electron-quark cross-section

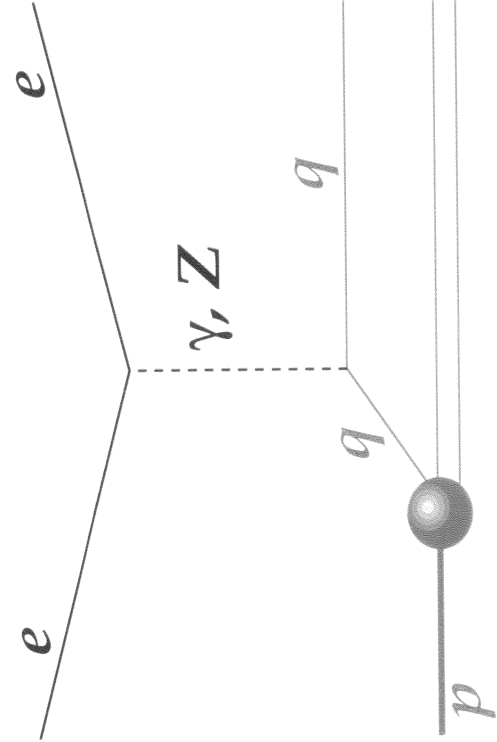
Leading Order:

$$\sigma(eq \rightarrow eq) \propto \left| \begin{array}{c} \text{Diagram 1: } e \text{ and } q \text{ exchange a photon } \gamma \text{ with vertices } Q_e \text{ and } Q_q. \\ \text{Diagram 2: } e \text{ and } q \text{ exchange a Z boson with vertices } (v_e, a_e) \text{ and } (v_q, a_q). \end{array} \right|^2 + \left| \begin{array}{c} \text{Diagram 3: } e \text{ and } q \text{ exchange a W boson with vertices } (v_e^{cc}, a_e^{cc}) \text{ and } (v_q^{cc}, a_q^{cc}). \\ \text{Diagram 4: } e \text{ and } q \text{ exchange a W boson with vertices } (v_e^{cc}, a_e^{cc}) \text{ and } (\bar{\nu}_e, q'). \end{array} \right|^2$$

$$\sigma(eq \rightarrow \nu q') \propto \left| \begin{array}{c} \text{Diagram 5: } e \text{ and } q \text{ exchange a W boson with vertices } (v_e^{cc}, a_e^{cc}) \text{ and } (\bar{\nu}_e, q'). \end{array} \right|^2$$

Given by electroweak sector of Standard Model
as functions of α , G_F , $\sin^2 \theta_W$, (m_t, m_H)

Neutral Current DIS



$$\frac{d^2\sigma_{\text{NC}}^{\text{e}^\pm\text{P}}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \left[Y_+ F_2^{\text{NC}} \mp Y_- x F_3^{\text{NC}} - y^2 F_L^{\text{NC}} \right]$$

$\bar{Q}PM$:

$$F_2^{\text{NC}} = x \sum_{\text{Quarks}} A_f(Q^2) [q(x, Q^2) + \overline{q}(x, Q^2)]$$

$$A_f = Q_q^2 - 2Q_q v_e v_q . P_Z + (v_e^2 + a_e^2) (v_q^2 + a_q^2) . P_Z^2 \text{ where } P_Z = Q^2/(Q^2 + M_Z^2)$$

$$xF_3^{\text{NC}} = x \sum_{\text{Quarks}} B_f(Q^2) [q(x, Q^2) - \overline{q}(x, Q^2)]$$

$$B_f = -2Q_q a_e a_q . P_Z + 4v_e a_e v_q a_q . P_Z^2$$

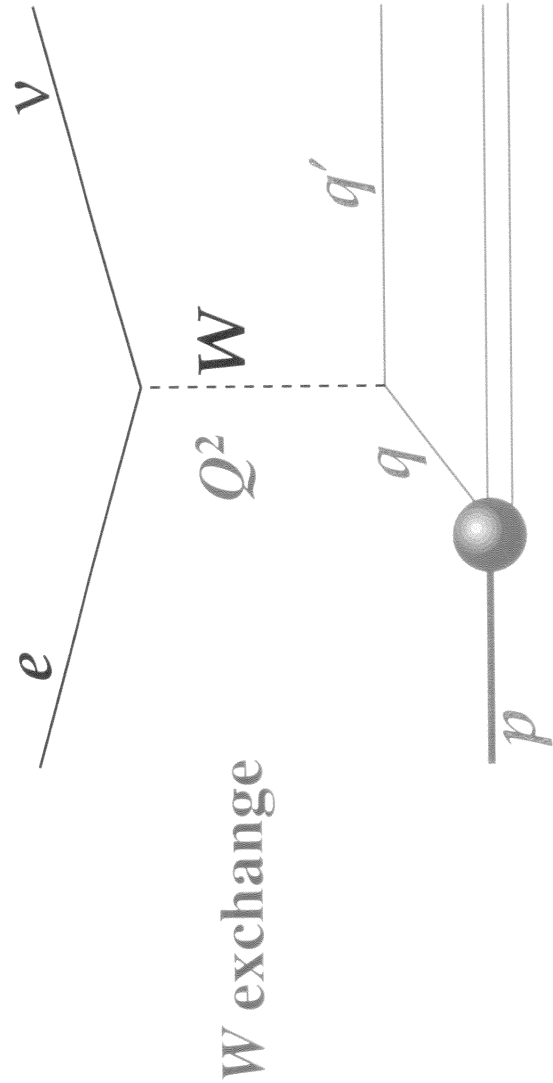
$$F_L^{\text{NC}}(x, Q^2)$$

LO QCD contribution

Reduced cross section

$$\tilde{\sigma}_{\text{NC}}^\pm = \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_+} \frac{d^2\sigma^{\text{NC}}}{dx dQ^2} = F_2^{\text{NC}} \mp \frac{Y_-}{Y_+} x F_3^{\text{NC}} - \frac{y^2}{Y_+} F_L^{\text{NC}}$$

Charged Current DIS



QPM Cross-Sections

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

Probe d valence

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

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

Probe u valence

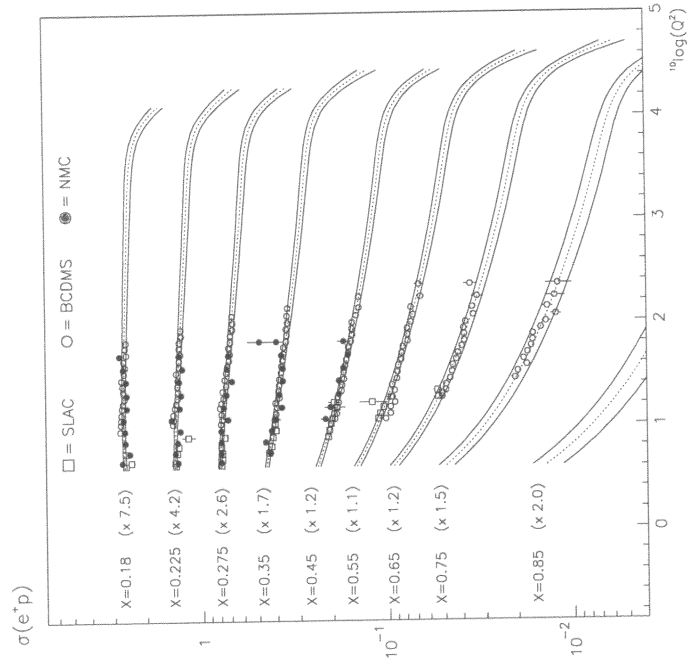
$$\frac{d^2 \sigma^{\text{CC}}}{dx dQ^2} = \frac{G_F^2}{2\pi} \left[\frac{Q^2}{Q^2 + M_W^2} \right]^2 \left[u + c + (1 - y^2)(\bar{d} + \bar{s}) \right]$$

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

Reduced Cross Section

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

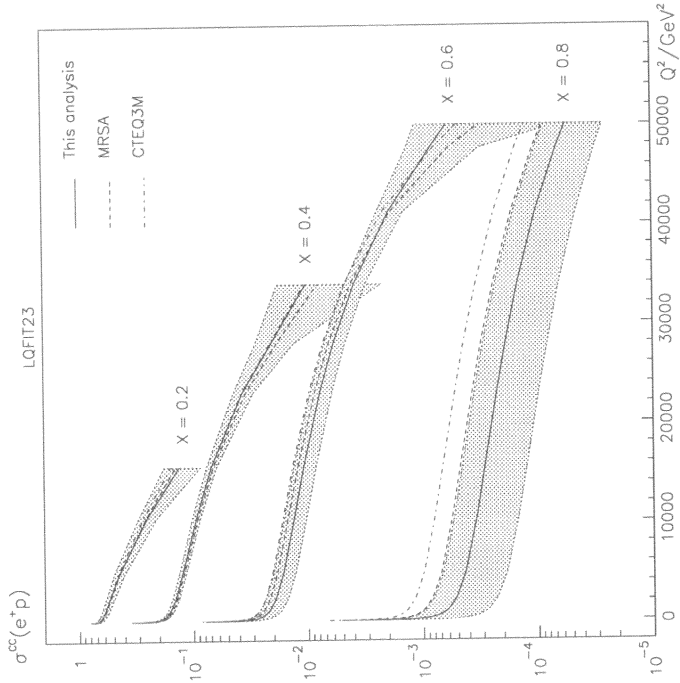
PDF Uncertainties



NC:

$$\tilde{\sigma} = \frac{xQ^4}{2\pi\alpha^2 Y_+ dx} \frac{d^2\sigma}{dQ^2}$$

$$\Delta\tilde{\sigma}/\tilde{\sigma} \lesssim 6.5\%$$



CC:

$$\tilde{\sigma} = x \frac{2\pi}{G_F^2 P_W^2} \frac{d^2\sigma}{dx dQ^2}$$

$$\Delta\tilde{\sigma}/\tilde{\sigma} \gtrsim 20\%$$

for $x \gtrsim 0.5$ or $Q^2 \gtrsim 2 \cdot 10^4 \text{ GeV}^2$

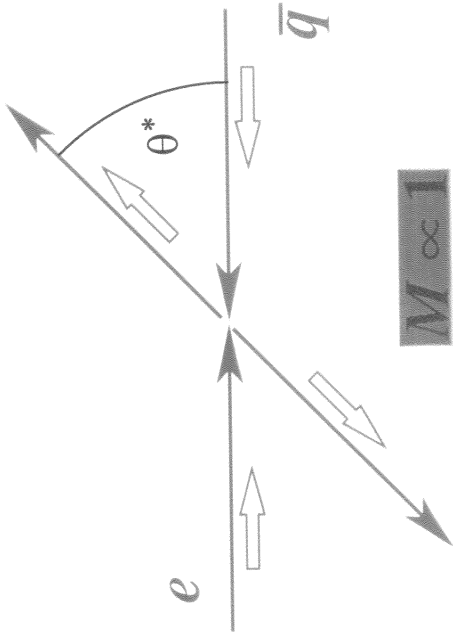
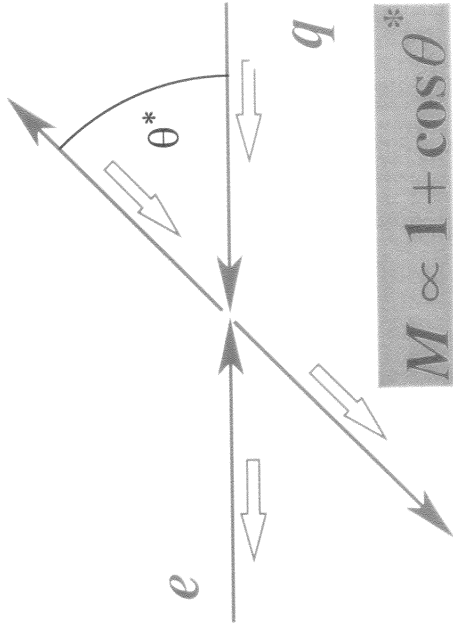
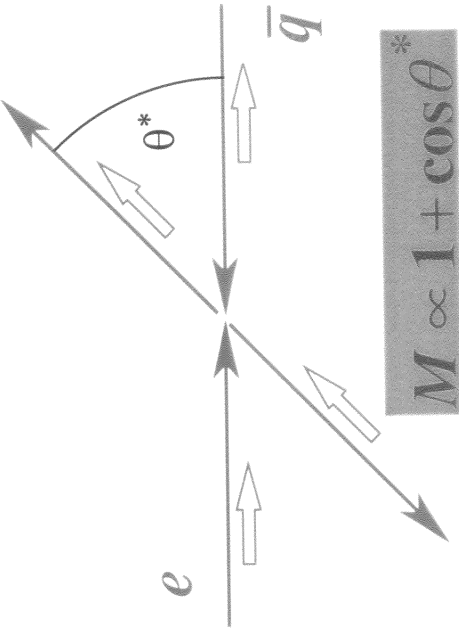
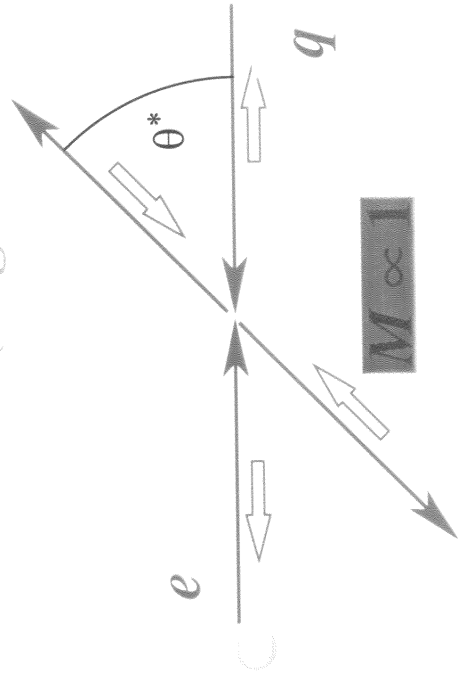
- $\tilde{\sigma}$ = reduced cross-section ($\sim$ PDF's)
- Experimental errors on input data and on α_s were propagated in QCD fit (M. Botje, ZEUS)

Lepton-quark scattering

γ, Z and W are *vector* bosons

$\Rightarrow$ helicity conserved (since $m_q, m_e \ll E$)

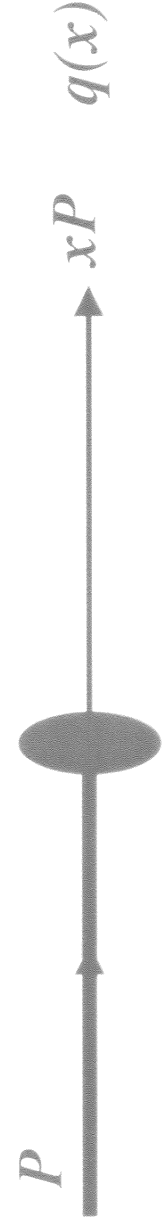
(angular momentum conserved)



$$\begin{aligned}
 |M(e_L + q_L)|^2 &= |M(e_R + q_R)|^2 && \propto && 1 \\
 |M(e_L + q_R)|^2 &= |M(e_R + q_L)|^2 && \propto && (1 + \cos \theta^*)^2 \\
 &&& \propto && \left(1 - \sin^2 \frac{\theta^*}{2}\right)^2
 \end{aligned}$$

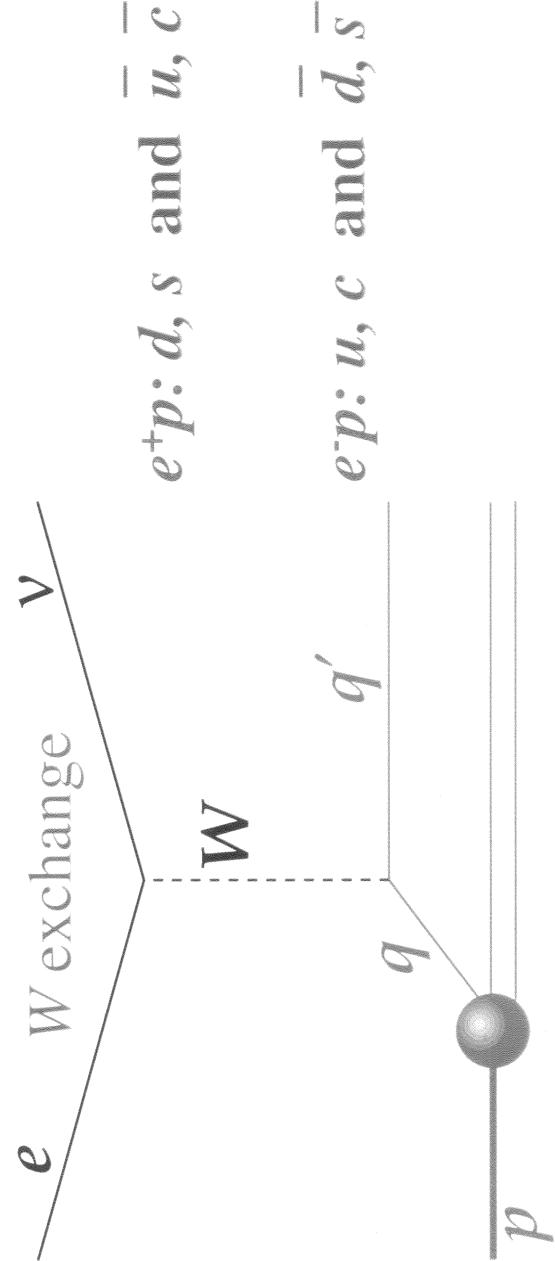
Lepton-quark scattering

- the proton - a beam of quarks:



Define: $y = \sin^2 \frac{\theta^*}{2}$ - kinematics:

- first example: charged current



$$\frac{d^2\sigma^{\text{CC}}}{dxdy} = \{\text{Coupling}\}\{\text{Propagator}\}\{\text{Angular factor} \otimes \text{PDF}\}$$

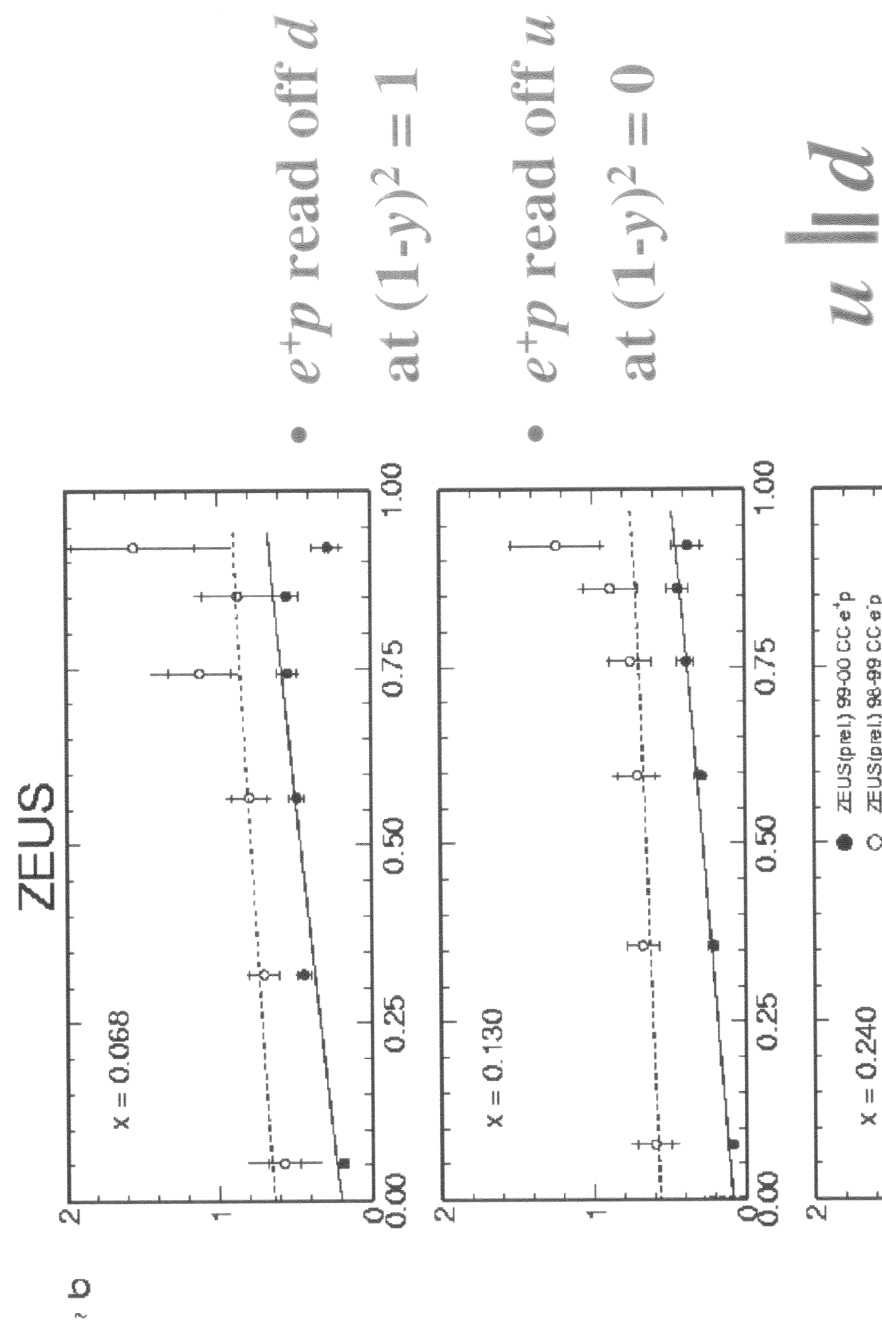
$$= \{\text{Coupling}\}\{\text{Propagator}\}\{\tilde{\sigma}^{\text{CC}}(x)\}$$

Check: fix x and plot $\tilde{\sigma}^{\text{CC}}$ versus $(1 - y)^2$

Lepton-quark scattering

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

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



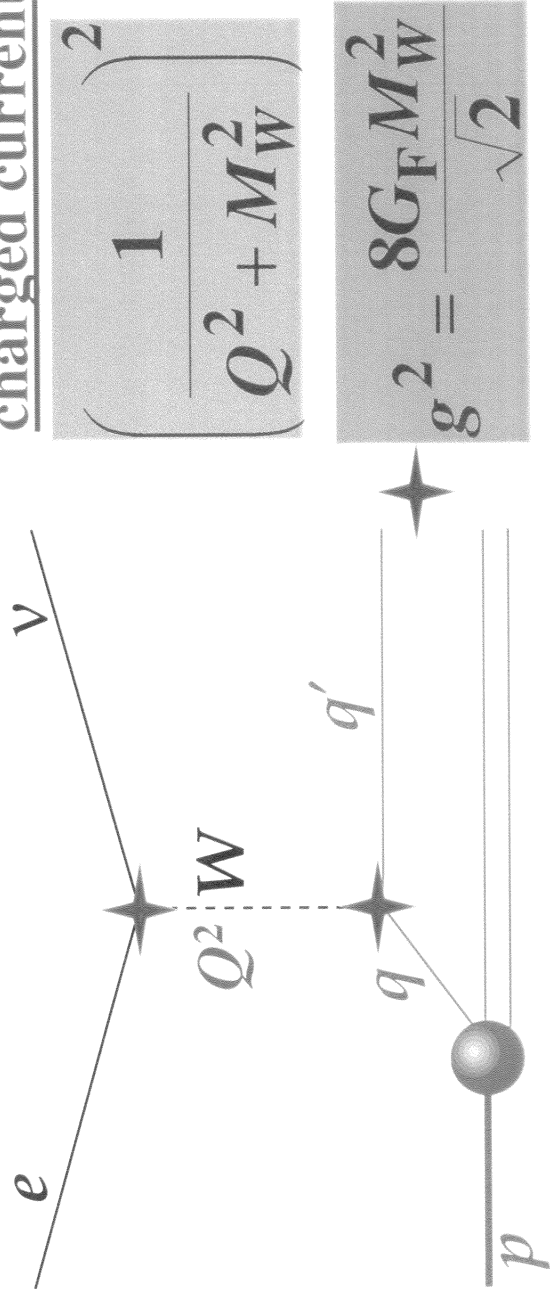
- e^+p read off d at $(1-y)^2 = 1$
- e^+p read off u at $(1-y)^2 = 0$

⇒ CC can be used to determine u, d PDFs

Lepton-proton scattering

- continue with first example:

charged current

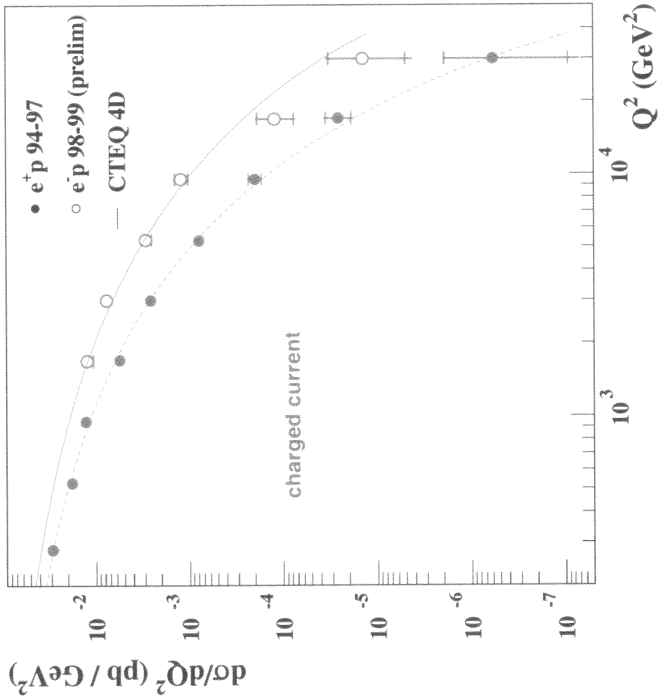


$$\left(\frac{1}{Q^2 + M_W^2} \right)^2$$

$$g^2 = \frac{8G_F M_W^2}{\sqrt{2}}$$

$$\frac{d\sigma_{e^\pm p}^{\text{CC}}}{dQ^2} = \frac{G_F^2}{2\pi} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \int \tilde{\sigma}_{e^\pm p}^{\text{CC}} dx$$

ZEUS DIS Cross Sections



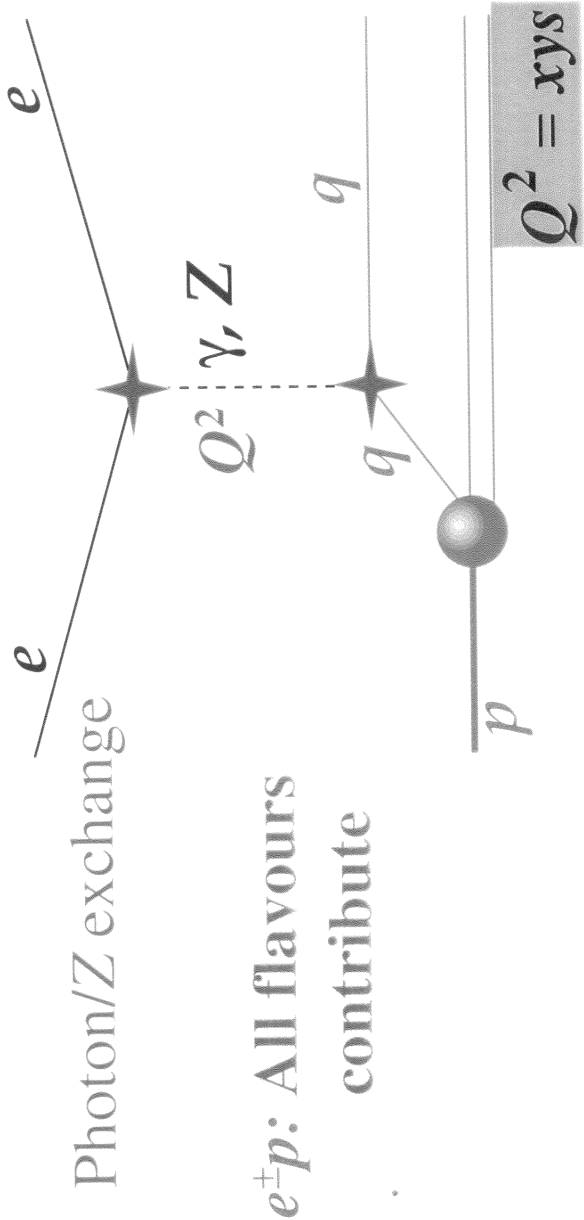
Fit shape of $\frac{d\sigma_{e^\pm p}^{\text{CC}}}{dQ^2}$ for M_W

$$M_W = 81.4 \pm 2.7 \pm 2.0 \pm 3.3 \text{ GeV}$$

Errors : Stat.; Sys.; PDF

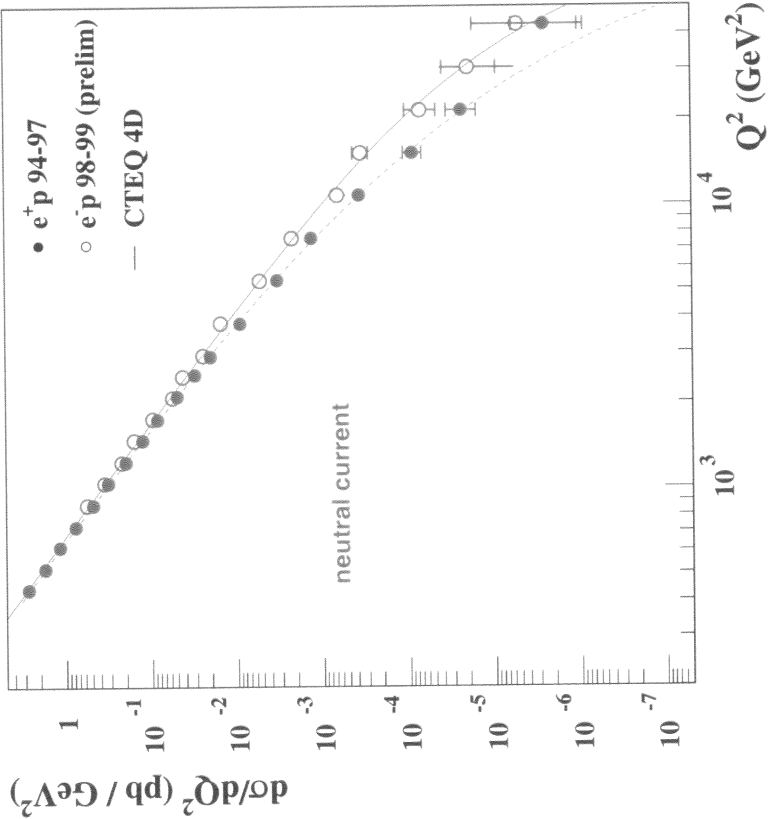
Lepton-proton scattering

Neutral Current



$$\frac{d\sigma_{\text{NC}}^{\pm}}{dQ^2} \propto \left[\eta_{\gamma}^{\pm} \frac{1}{Q^2} + \eta_Z^{\pm} \frac{1}{Q^2 + M_Z^2} \right]^2 \int \tilde{\sigma}_{\text{NC}}^{\pm} dx$$

ZEUS DIS Cross Sections



Lepton-proton scattering

- Photon exchange - parity conserving
- Z exchange: Two pieces; one is parity conserving, the other violates parity

⇒ Parameterise cross section:

parity conserving piece: F_2

piece which violates parity: xF_3

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

$$\frac{d^2 \sigma_{\text{NC}}^{e^{\pm}P}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \left[Y_+ F_2^{\text{NC}} \mp Y_- x F_3^{\text{NC}} - y^2 F_L^{\text{NC}} \right]$$

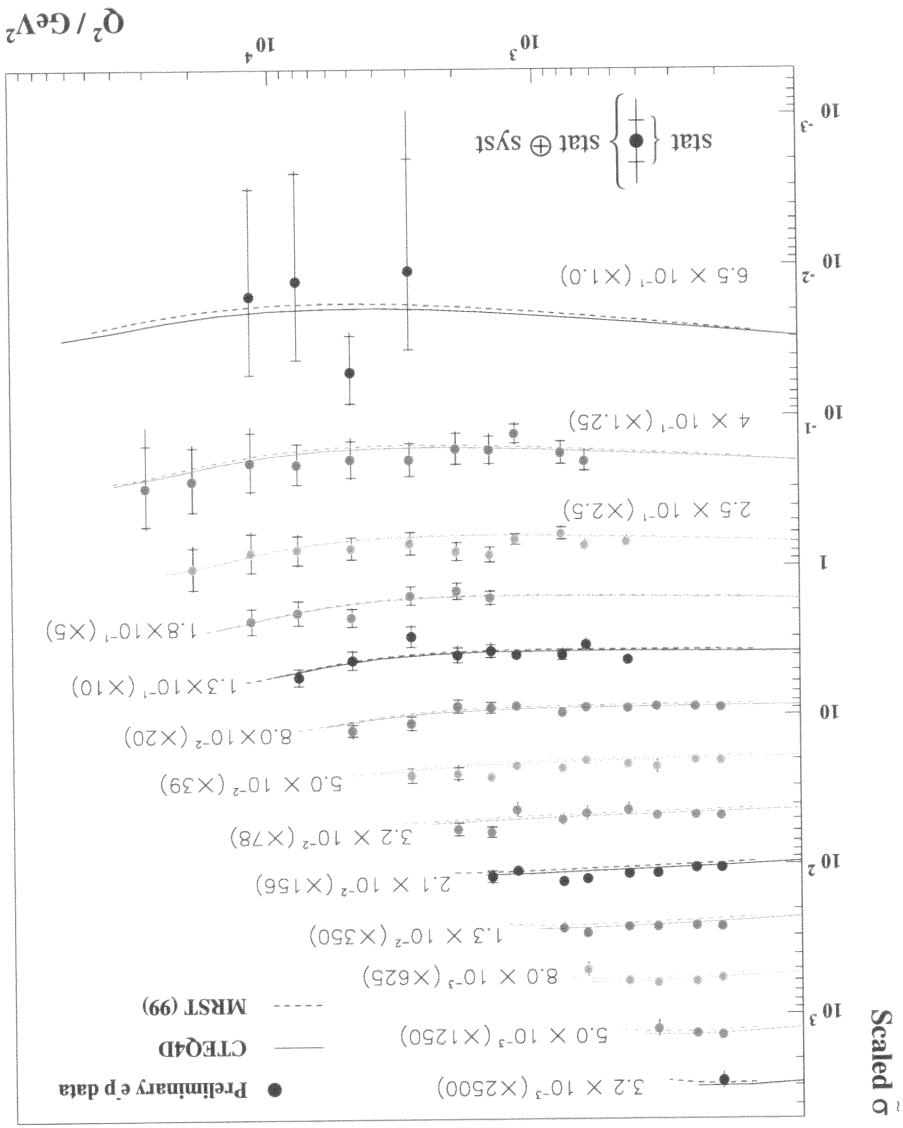
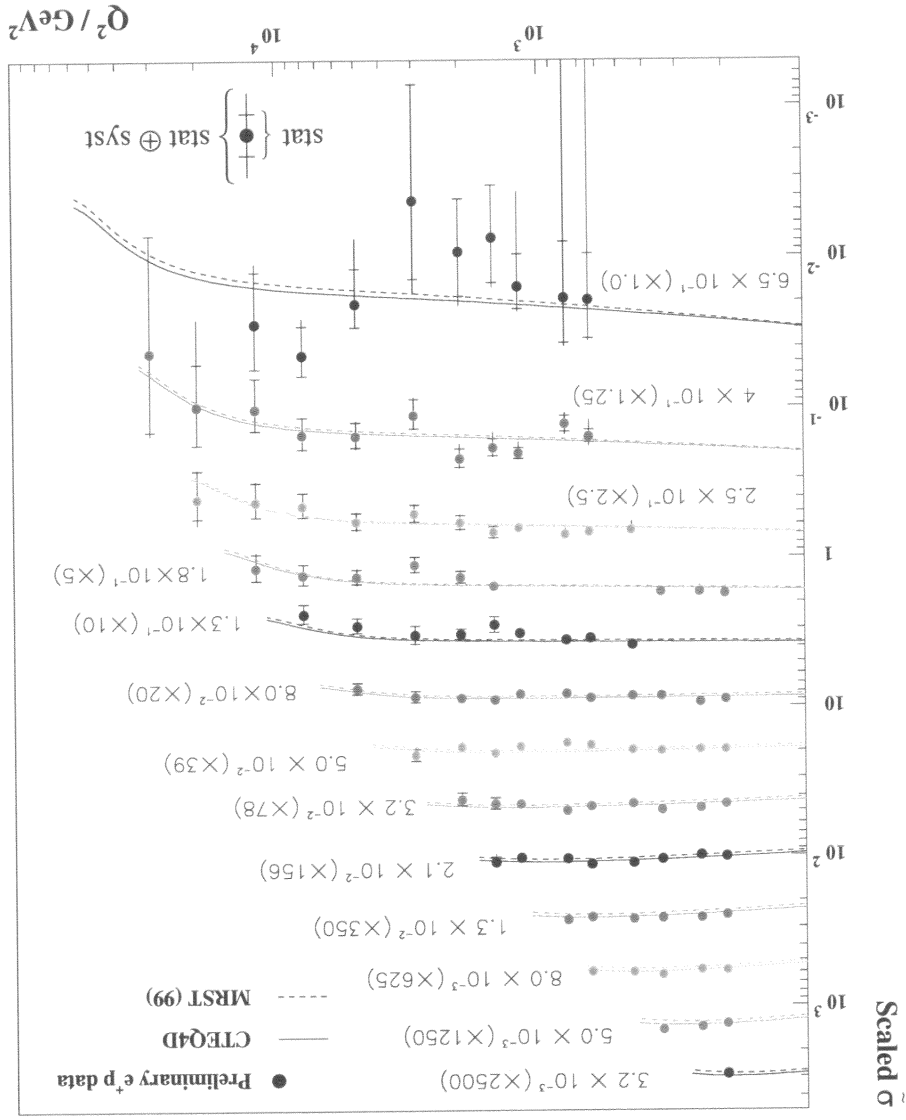
$$\tilde{\sigma}_{e^{\pm}p}^{\text{NC}} = \left[\frac{2\pi\alpha^2}{Q^4 x} \right]^{-1} \frac{1}{Y_+} \frac{d^2 \sigma_{\text{NC}}^{e^{\pm}P}}{dx dQ^2}$$

$$F_2^{\text{NC}} = x \sum A_q(q(x) + \bar{q}(x)) \quad \text{Singlet}$$

$$xF_3^{\text{NC}} = x \sum B_q(q(x) - \bar{q}(x)) \quad \text{Non-singlet}$$

Focus on highest possible Q^2 to look for Z exchange

ZEUS NC 1996-97



Lepton-proton scattering

For electrons: $\tilde{\sigma}_{e^- p}^{\text{NC}} = Y_+ F_2 + Y_- xF_3$

For positrons: $\tilde{\sigma}_{e^+ p}^{\text{NC}} = Y_+ F_2 - Y_- xF_3$

... origin of relative 'minus' sign?

Effect of parity:

$$P(e_L^-) = e_R^- \quad \Rightarrow xF_3 \rightarrow -xF_3$$

- because that's the parity violating term!

However, HERA only measures e^- and e^+ at the moment ...

... have to be more careful

Effect of CP : (assume quark PDF in proton

= anti-quark distribution in anti-proton)

$$CP(e_L^-) = e_R^+ \quad \Rightarrow xF_3 \rightarrow xF_3$$

- because CP is a good symmetry for NC

$$P(CP(e_L^-)) = e_L^+ \quad \Rightarrow xF_3 \rightarrow -xF_3$$

So, difference between ep and e^+p cross section can be used to determine xF_3

NC - $x F_3$ Extraction

$$\frac{d^2 \sigma_{\text{Born}}^{\text{NC}}(e^\pm p)}{dx dQ} = \frac{2\pi\alpha^2}{xQ^4} \left[Y_+ F_2^{\text{NC}}(x, Q^2) \mp Y_- x F_3^{\text{NC}}(x, Q^2) - y^2 F_L^{\text{NC}}(x, Q^2) \right]$$



Sign of $x F_3$ term depends on lepton charge



$y^2 F_L$ small at high Q^2

Extraction Method

(subtraction method modified due to changing beam energies)

$$\sigma^- = \frac{d^2 \sigma^-}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[Y_+^{820} F_2 + Y_-^{920} x F_3 \right]$$

—

$$\sigma^+ = \frac{d^2 \sigma^+}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[Y_+^{820} F_2 - Y_-^{820} x F_3 \right]$$

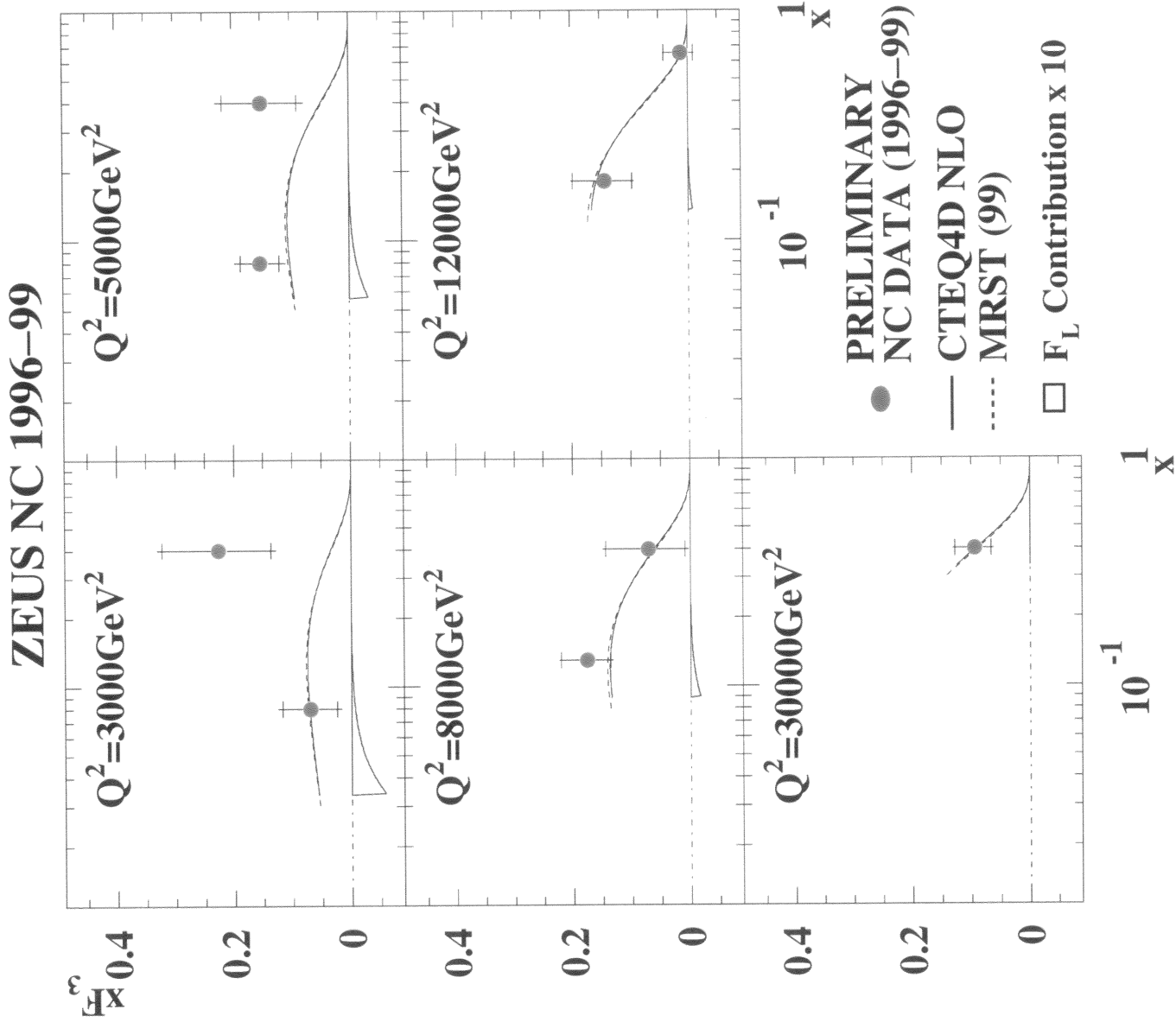
$$x F_3 = \frac{xQ^4}{2\pi\alpha^2} \cdot \left(\frac{Y_-^{820}}{Y_+^{820}} + \frac{Y_-^{920}}{Y_+^{920}} \right)^{-1} \cdot \left(\frac{1}{Y_+^{920}} \cdot \sigma^- - \frac{1}{Y_+^{820}} \cdot \sigma^+ \right)$$

- Error limited by electron sample (16 pb⁻¹)
- Positron data sample (30 pb⁻¹)

Lepton-proton scattering

First direct look at the valence quarks in ep

$$xF_3^{\text{NC}} = x \sum B_q(q(x) - \bar{q}(x))$$



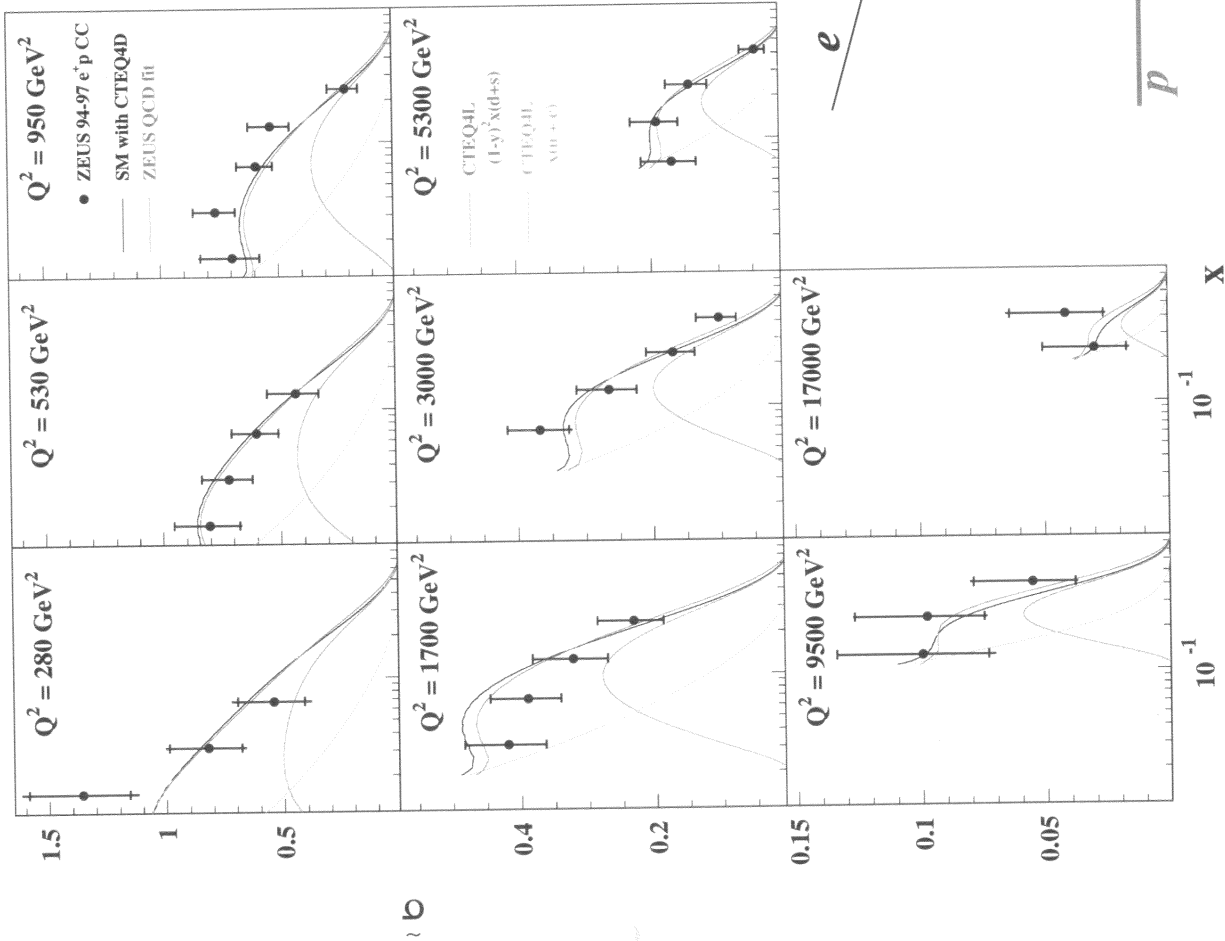
Proton Decomposition

- Charged current DIS:

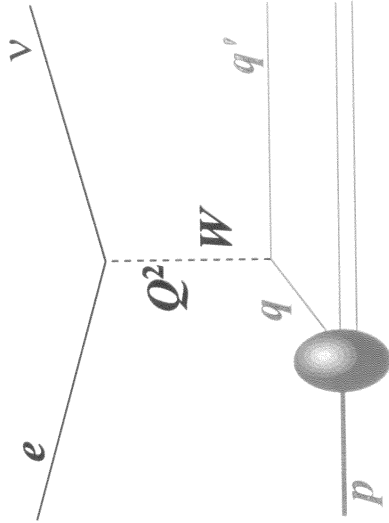
$$\tilde{\sigma}_{\text{CC}}^{e^+p} = \left\{ \frac{G_\mu^2}{2\pi x} \left[\frac{M_W^2}{Q^2 + M_W^2} \right]^2 \right\}^{-1} \frac{d^2 \sigma_{\text{CC}}^{e^+p}}{dx dQ^2}$$

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

ZEUS CC 1994-97

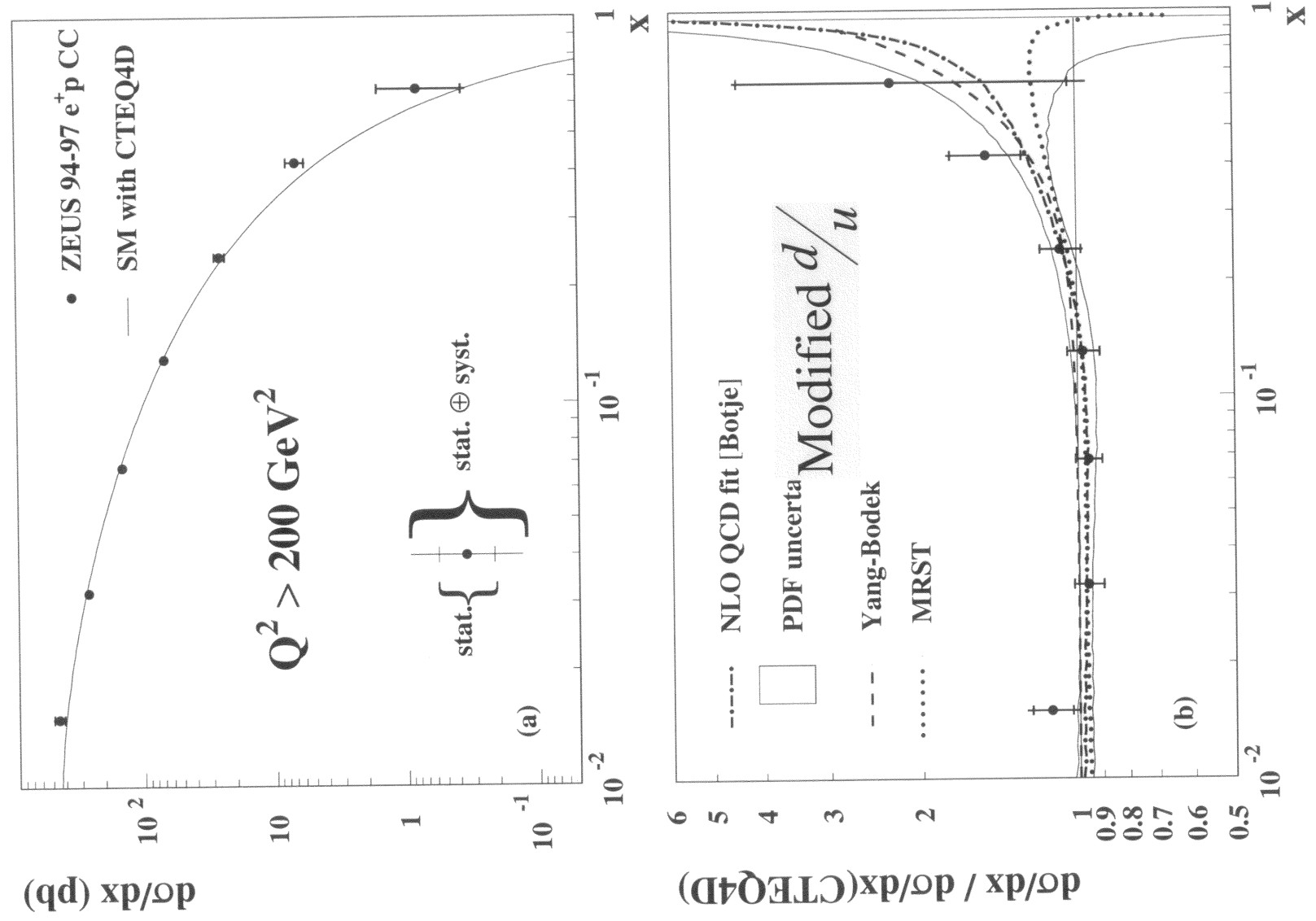


Sensitive to
specific
PDFs:
High x : d
Low x : $\bar{u}$



Proton Decomposition

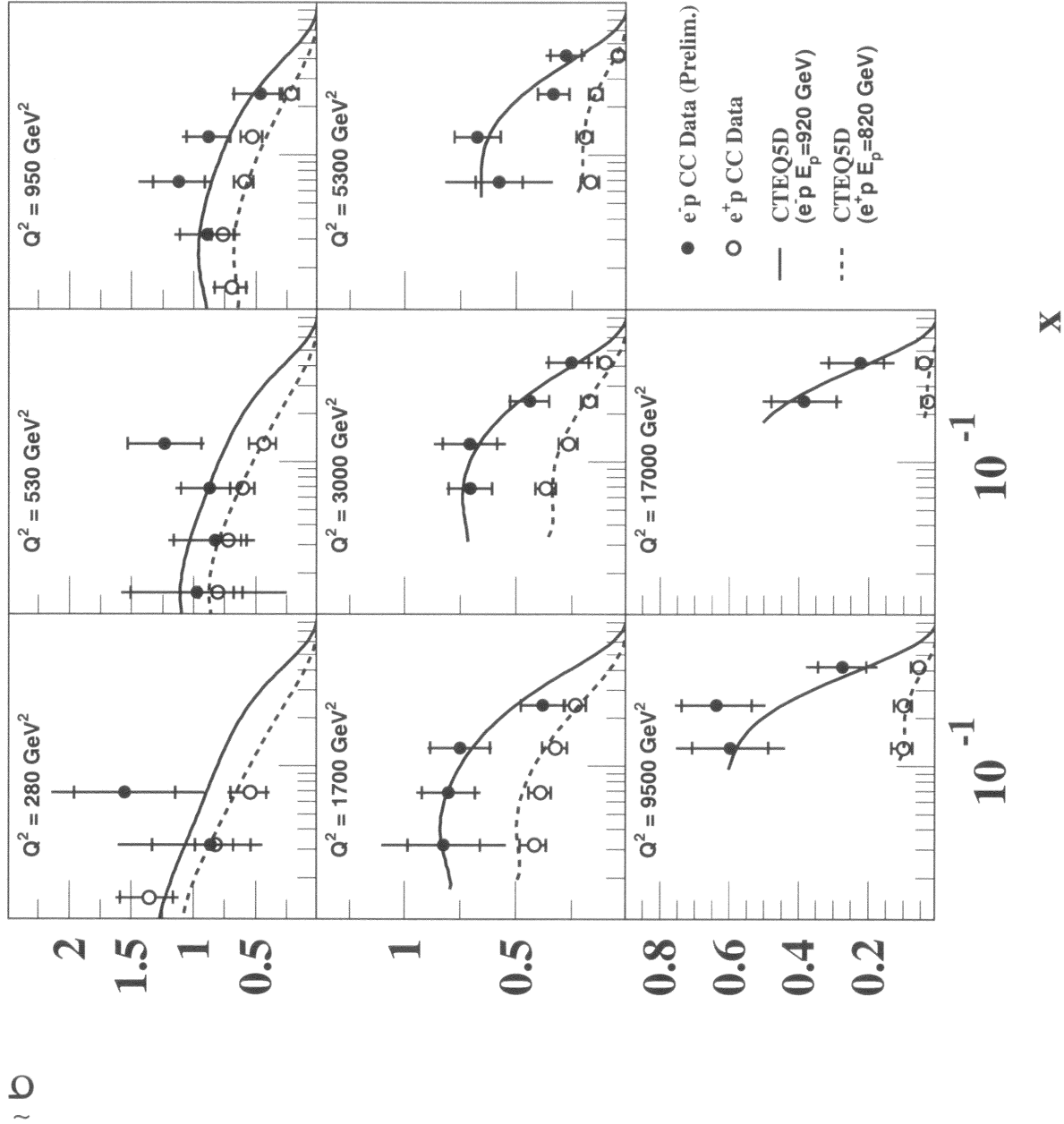
ZEUS CC 1994-97



Proton Decomposition

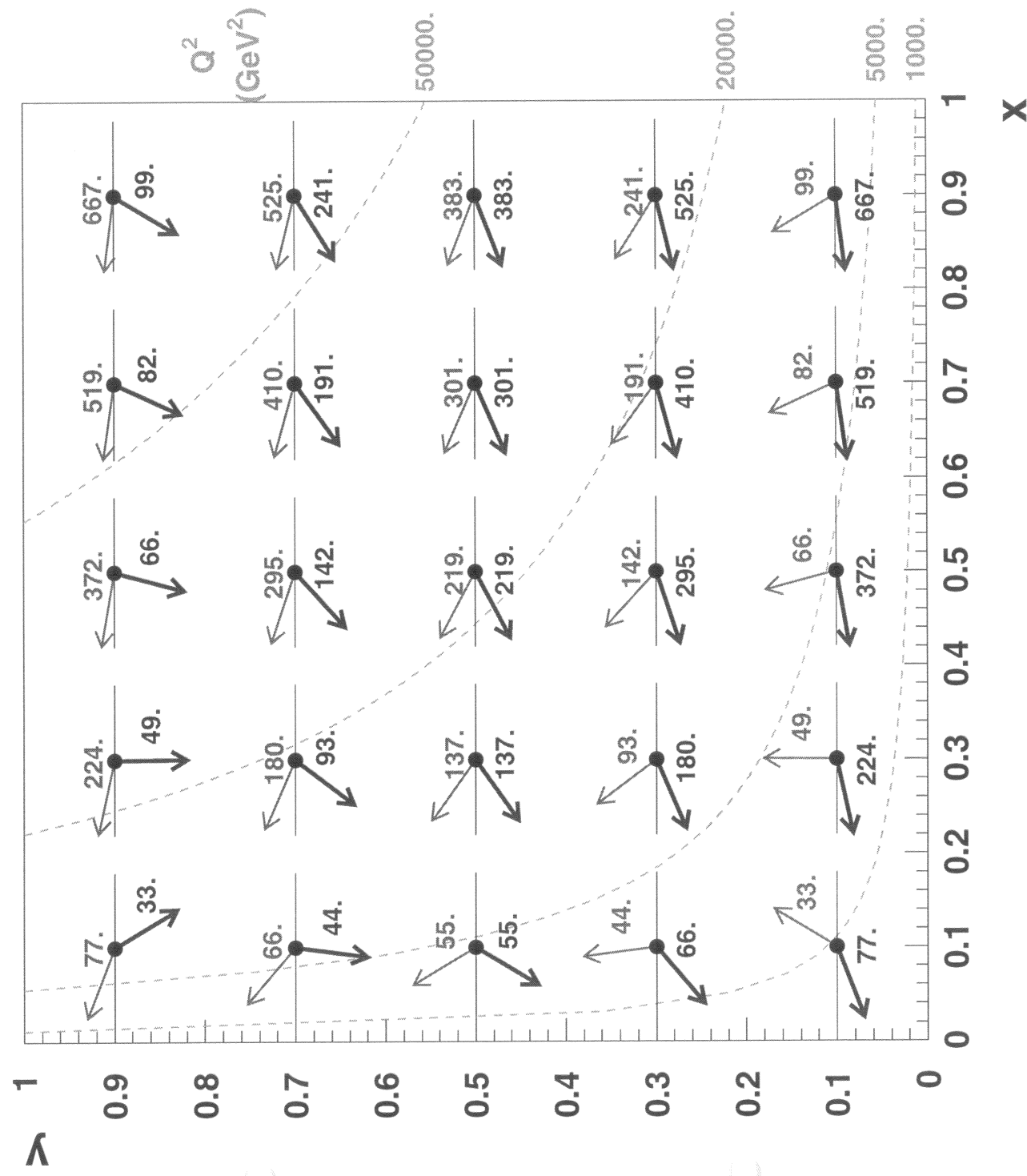
$$\begin{aligned}\sigma_{\text{CC}}^{e^-P} &= x(u+c+(1-y)^2(\bar{d}+\bar{s})) \\ \sigma_{\text{CC}}^{e^+P} &= x(\bar{u}+\bar{c}+(1-y)^2(d+s))\end{aligned}$$

ZEUS CC DATA



- $\sigma_{\text{CC}}^{e^-P} > \sigma_{\text{CC}}^{e^+P} : xu \text{ versus } (1-y)^2 xd$
- Towards a measurement of d/u

High- Q^2 Event Topologies

Final state topologies for elastic $eq \rightarrow eq$ scattering

Positrons enter from left, protons from right

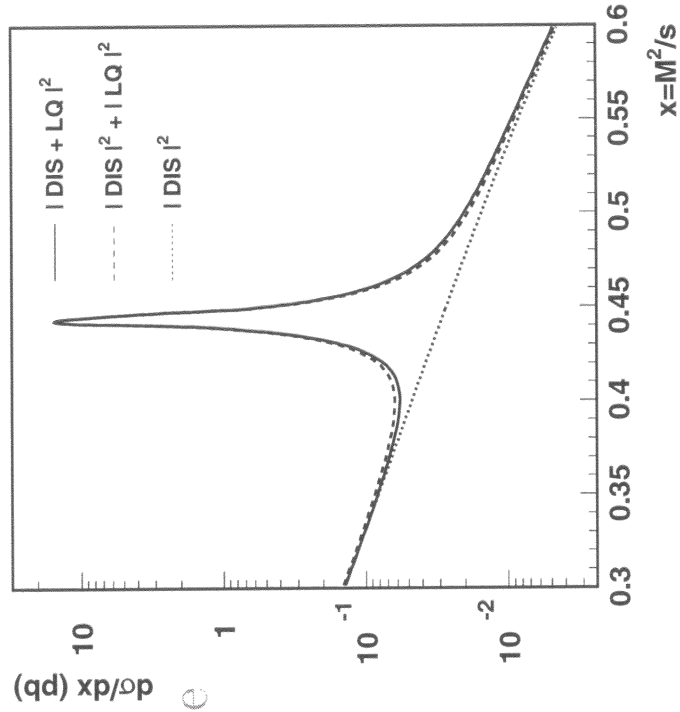
Arrows = scattering angles of e and q
Numbers = energies of scattered e and q (in GeV)

Leptoquark Search

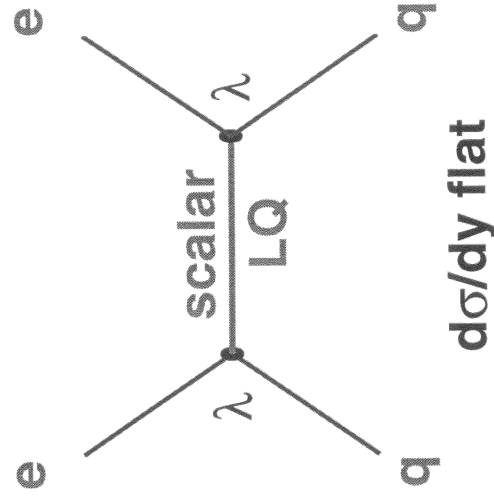
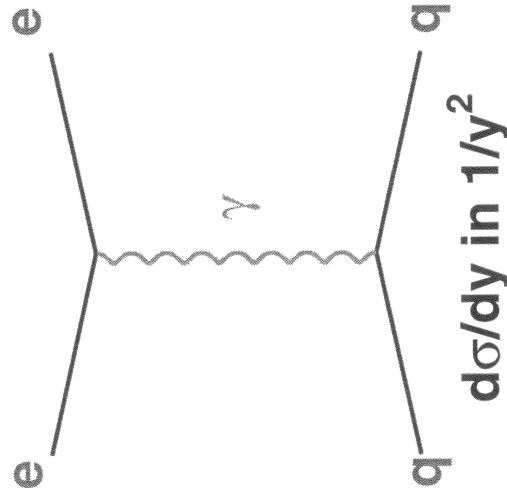
Scalar and Vector Bosons

- ◀ GUTs, SUSY E_6 , Composite Models
1st generation LQ
- ▶ similar event topologies to NC or CC

Signature:
Narrow Resonance
in $d\sigma/dx$
at $M = \sqrt{xs}$

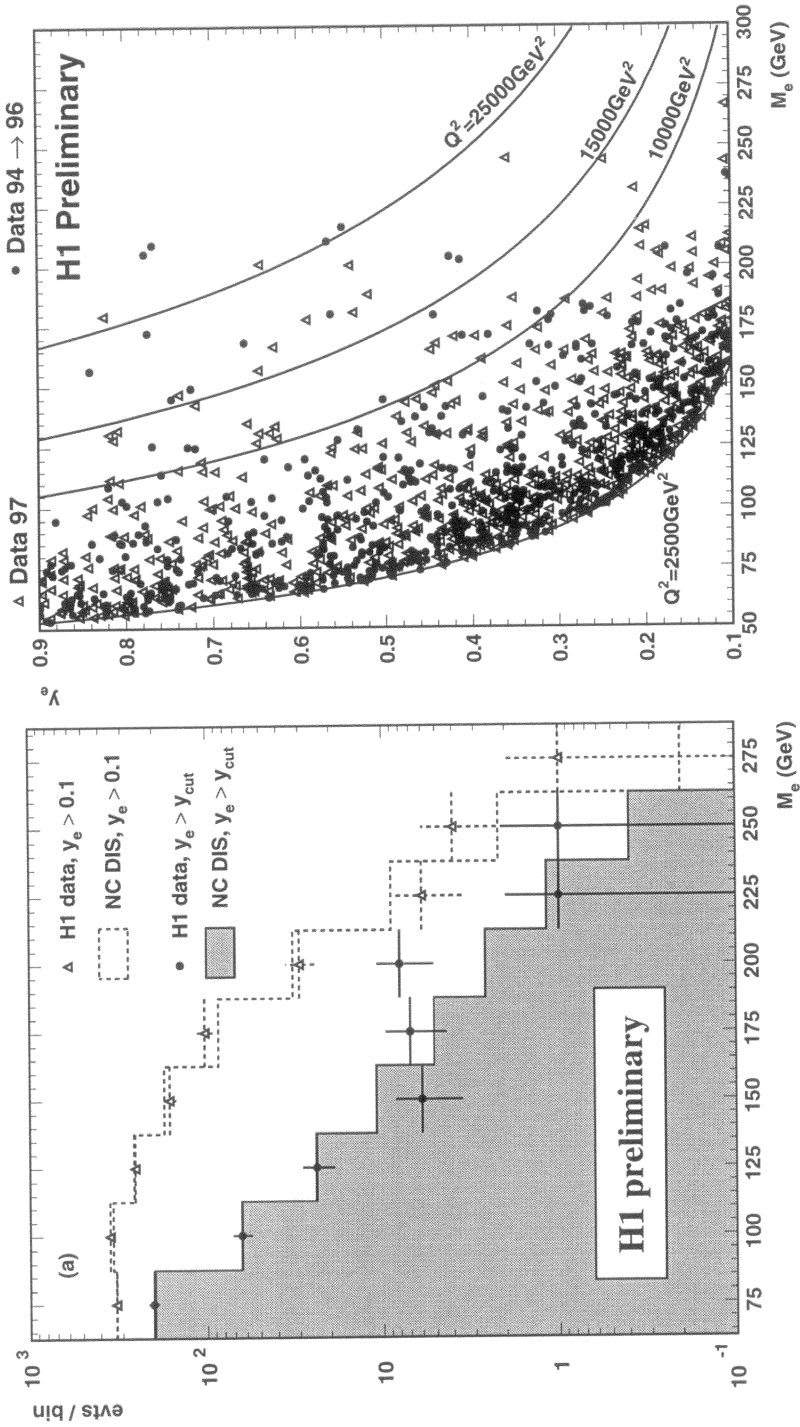


Characteristic Angular Distribution



Leptoquark Mass Spectrum

Optimise $y > y_{cut}(M)$



$$\sigma(eq \rightarrow LQ \rightarrow eq) \propto \lambda^2 \beta q(x)$$

$\lambda =$ Yukawa coupling

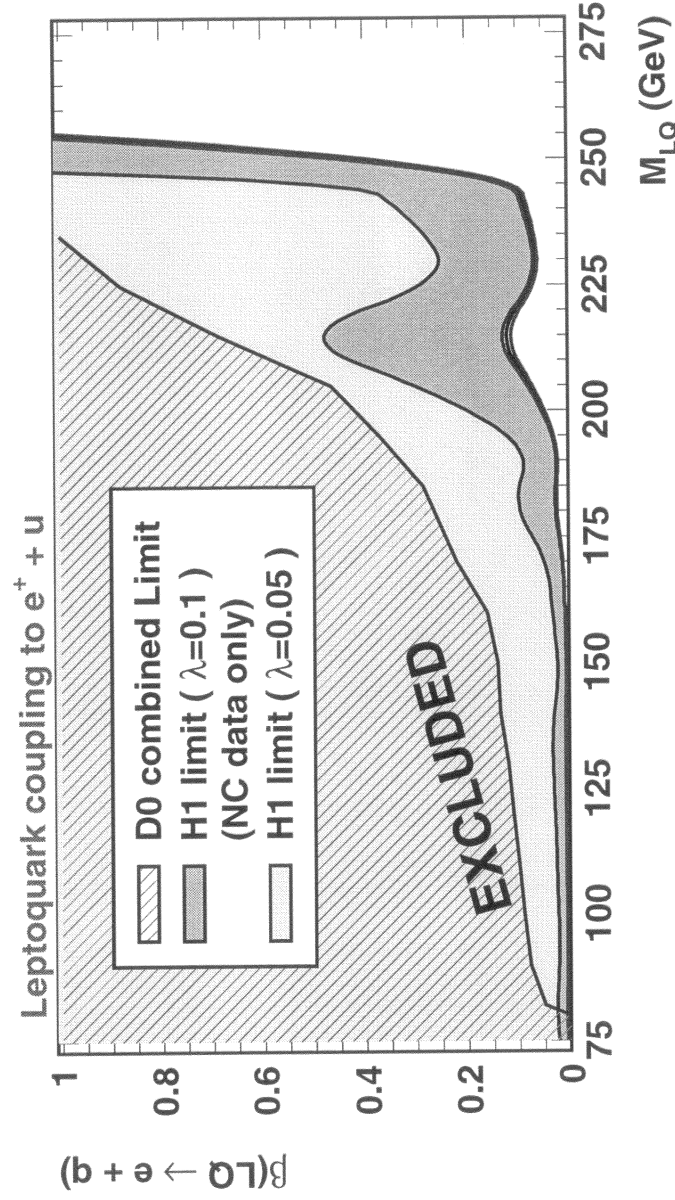
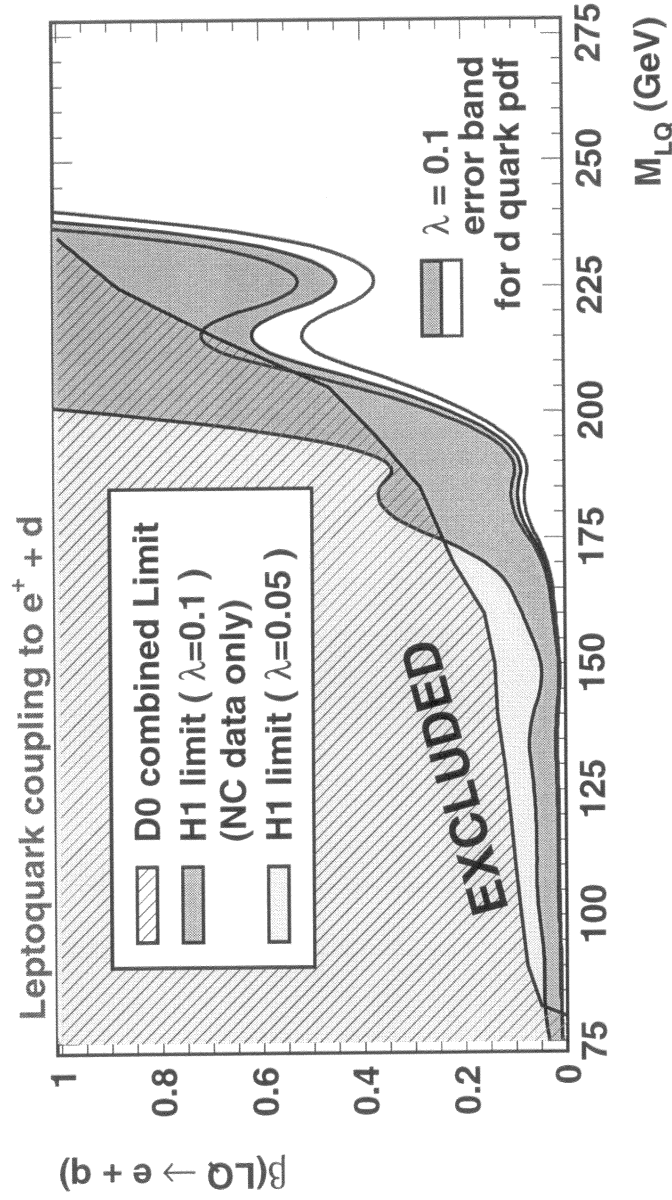
$\beta = BR(LQ \rightarrow eq)$

Leptoquark mass $M = \sqrt{x}s$

Leptoquark Limits

- Use Poissonian statistics in “sliding mass window”
- Fix λ ; derive M limit as function of $BR(LQ \rightarrow eq)$
- $\lambda = 0.1$ corresponds to $\sim 0.1\alpha_{em}$

H1 Preliminary

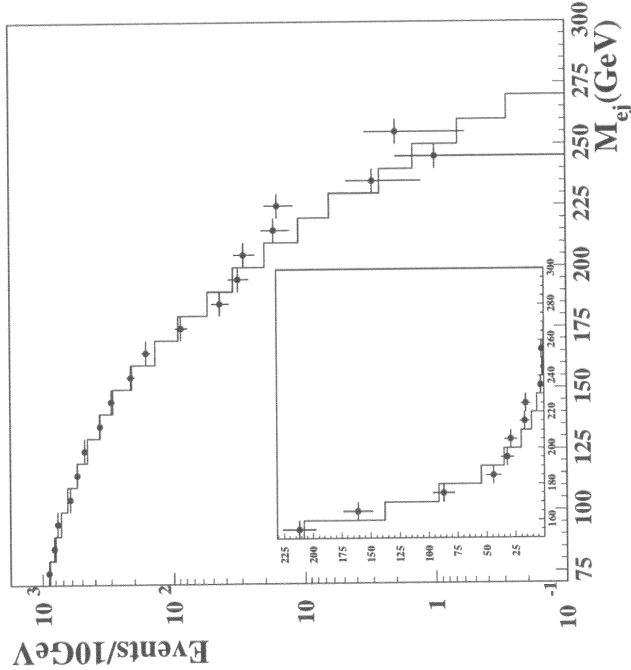


- $M > \sqrt{xs}$ by $\sim 4\text{GeV}$ due to QCD effects
- Open window at small $BR(LQ \rightarrow eq)$

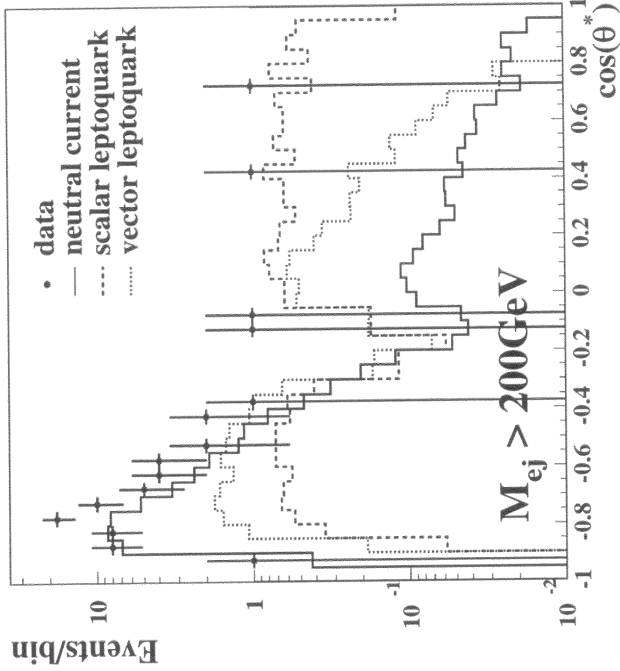
Leptoquark Limits

Study M_{ej} and $\cos\theta^*$ of $e^+ + \text{jet}$ in NC events:

ZEUS 1994-97 Preliminary



ZEUS 1994-97 Preliminary



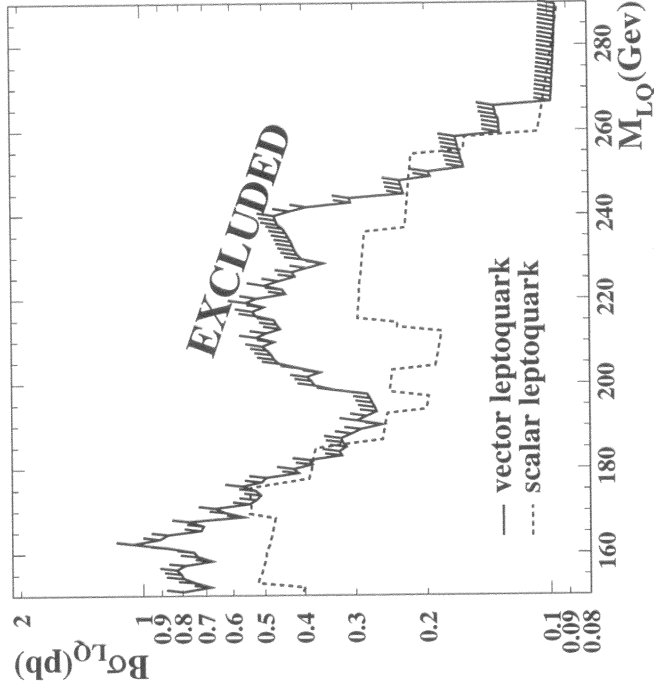
LQ limits:

- Use MC to define $\theta_{\text{cut}}^*(M_{ej})$
- Compare observed and expected event numbers with $\cos\theta^* > \cos\theta_{\text{cut}}^*$ in mass bin around M_{ej}

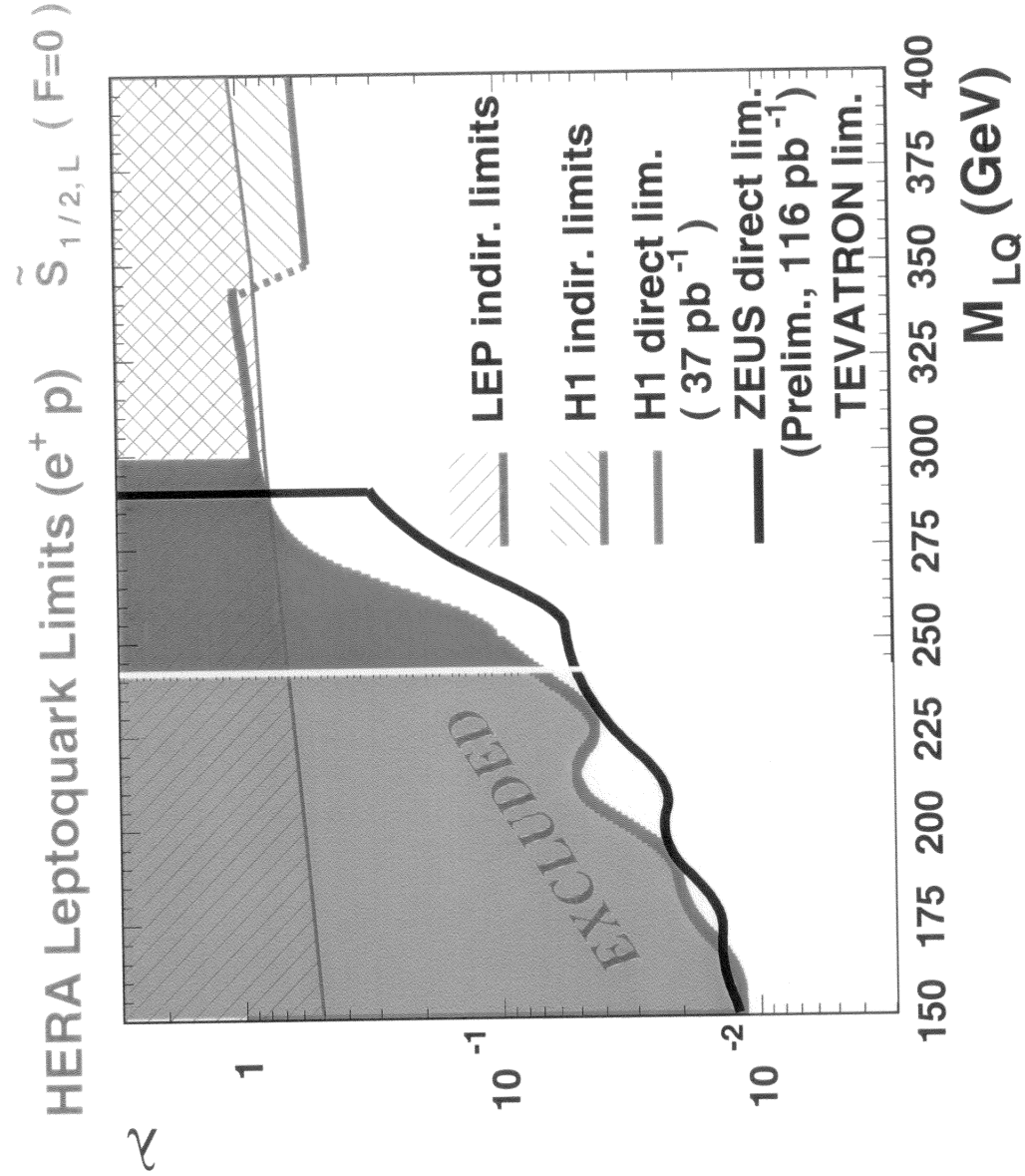
→ Upper limit on

$$\sigma(\text{LQ}) \cdot \text{BR}(\text{LQ} \rightarrow e^+ q)$$

ZEUS 1994-97 Preliminary

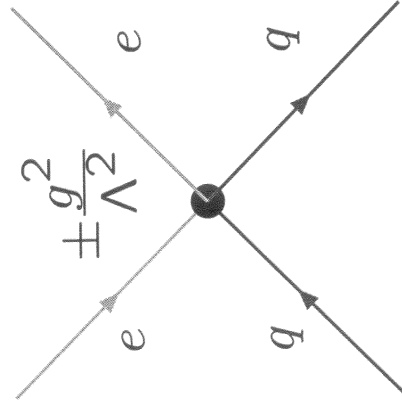


Leptoquark Limits



Latest Status

Contact Interactions



Can represent:

- Heavy boson exchange
- Leptoquark (s or t channel)
- Interaction of composite electron and quark
- ...

Historical equivalent:
4-fermion interaction

Effective Lagrangian:

$$\mathcal{L} = \frac{g^2}{\Lambda^2} \cdot \sum_{\substack{a,b=L,R \\ q=u,d}} \eta_{ab}^q (\bar{e}_a \gamma^\mu e_a) (\bar{q}_b \gamma_\mu q_b)$$

- $\eta_{ab}^q = \pm 1, 0$ and $g^2 = 4\pi$ by convention
- Only chiral vector couplings considered
(avoids e.g. severe constraints from π decays)
- Interference with SM constructive or destructive

All CI's also modify $\sigma(e^+e^-)$ and $\sigma(p\bar{p})$

- Interference sign is different
- LEP/Tevatron and HERA have different sensitivity

Contact Interaction Scenarios

CI scenarios = linear combinations of η_{ab}^q

CI	η_{LL}^u	η_{LR}^u	η_{RL}^u	η_{RR}^u	η_{LL}^d	η_{LR}^d	η_{RL}^d	η_{RR}^d	studied by
VV	+	+	+	+	+	+	+	+	ZEUS,H1
AA	+	-	-	+	+	-	-	+	
VA	+	-	+	-	+	-	+	-	
X1	+	+	+	0	+	-	0	0	ZEUS
X2	+	+	0	0	+	0	+	0	
X3	+	+	0	+	+	0	0	+	
X4	0	+	+	0	0	+	+	0	
X5	0	+	0	+	0	+	0	+	
X6	0	0	+	-	0	0	+	-	
U1	+	+	+	0	0	0	0	0	ZEUS
U2	+	+	+	0	0	0	0	0	
U3	+	+	0	+	0	0	0	0	
U4	0	+	+	0	0	0	0	0	
U5	0	+	0	+	0	0	0	0	
U6	0	0	+	-	0	0	0	0	

→ Marginal effect if including s, c, b, t

Restrictions:

- Severe limits from Atomic Parity Violation for all scenarios having

$$\eta_{LL} + \eta_{LR} - \eta_{RL} - \eta_{RR} \neq 0$$

... refers in particular to pure LL,LR,RL,LL scenarios
- $SU(2)_L \times U(1)_R \Rightarrow \eta_{ab}^u = \eta_{ab}^d$ (not U1–U6)

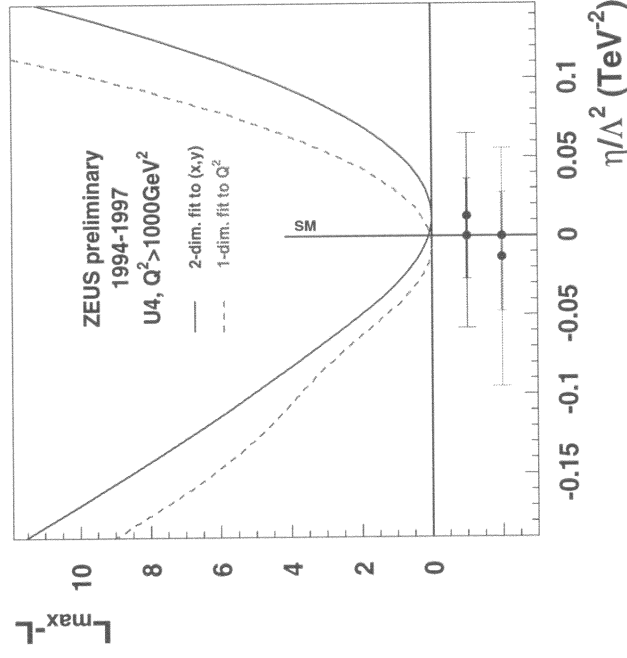
Contact Interaction Analyses

ZEUS analysis:

- Input: raw distributions without acceptance or migration corrections
- Simulate CI's by reweighting MC events
- Determine log-likelihood: $LL(\pm 1/\Lambda^2)$

Two approaches:

- Binned LL in Q^2
- Unbinned LL in (x, y)
- Very similar results



- Limit setting:

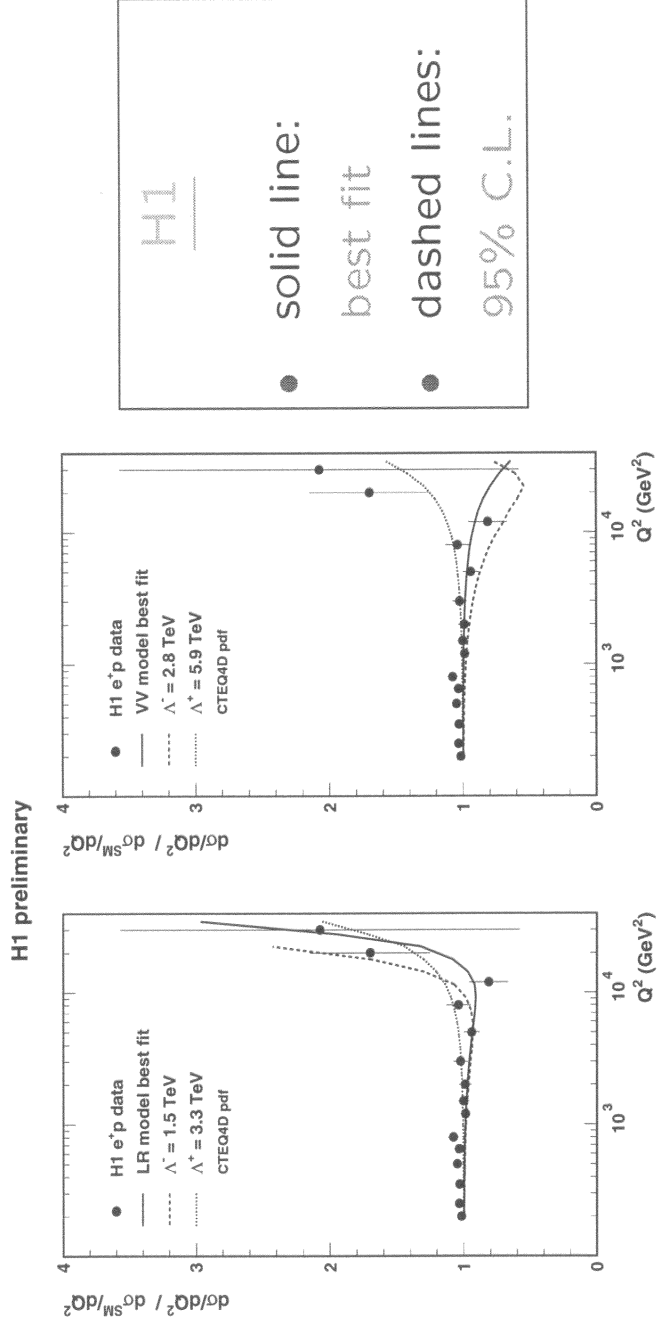
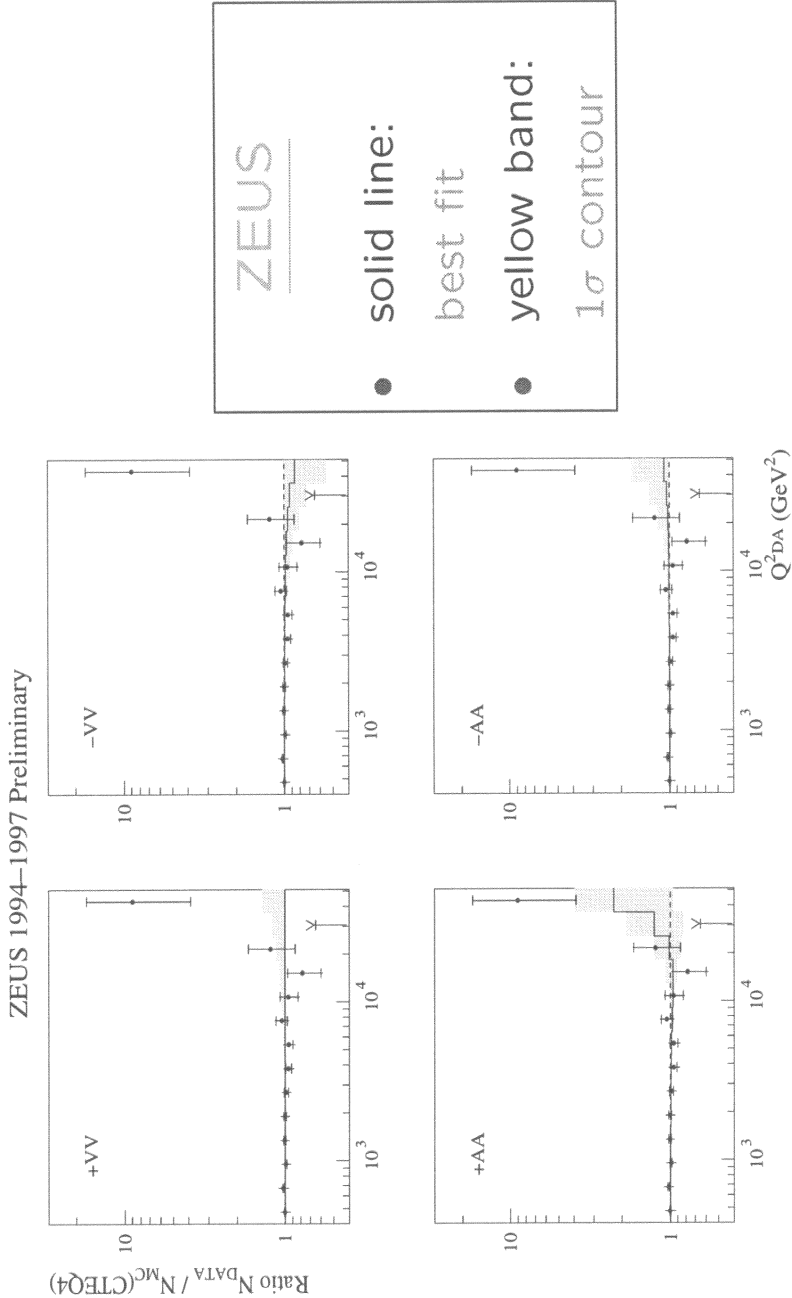
Log-likelihood $\Rightarrow$ best fit, 1σ -intervals
One-sided 95% C.L. limits from MC experiments

H1 analysis:

- χ^2 -fit to $d\sigma/dQ^2$
- Two-sided 68% and 95% C.L. intervals from χ^2 -contour

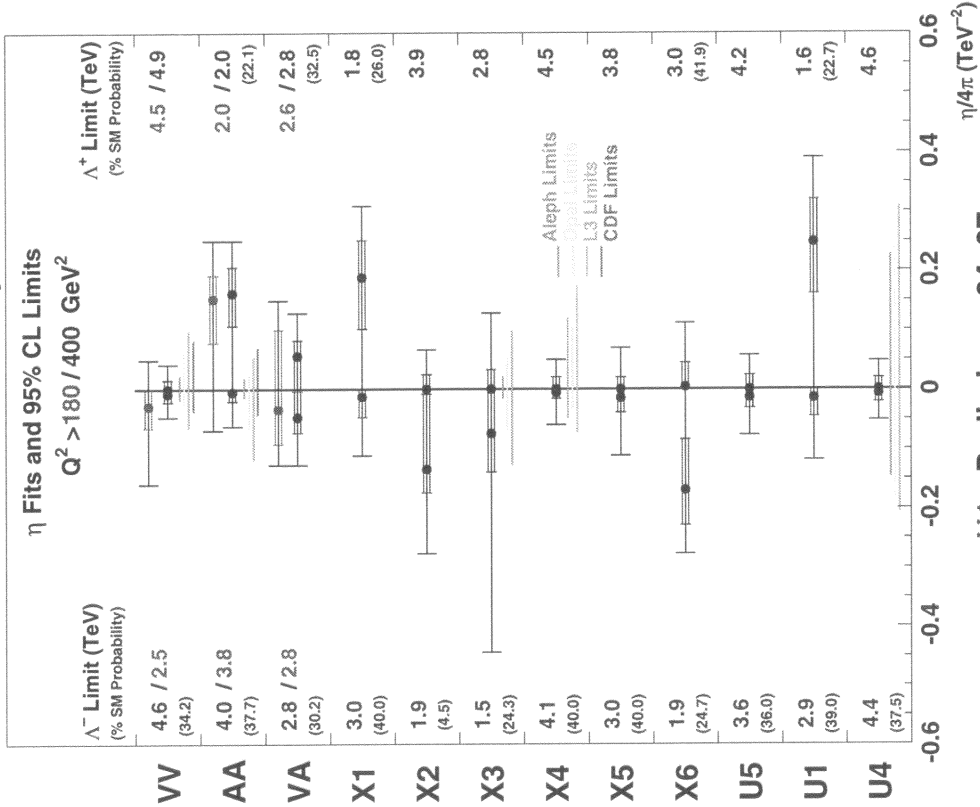
CI Example Fits

$$\frac{d\sigma/dQ^2(SM+CI)}{d\sigma/dQ^2(SM)}$$

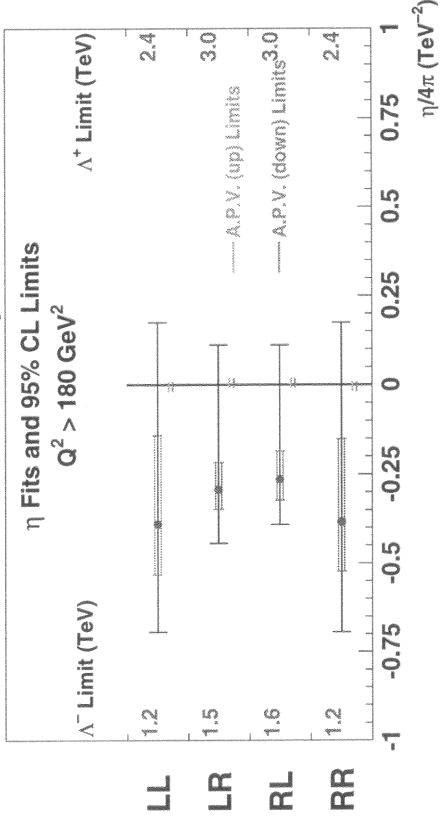


CI Limits from HERA

H1/ZEUS Preliminary 94–97



H1 Preliminary 94–97



All CI fits compatible with SM within 2σ

Comparison to Other CI Limits

Type	95% C.L. Limits on Λ [TeV]						
	ZEUS,H1		CDF	OPAL,ALEPH,L3	APV (u/d)		
VV+	4.9	4.5	3.5	4.1	6.7	3.2	-
VV-	4.6	2.5	5.2	5.7	7.4	3.9	-
AA+	2.0	2.0	3.8	6.3	7.4	4.3	-
AA-	4.0	3.8	4.8	3.8	8.2	2.9	-
VA+	2.8	2.6	-	-	-	-	-
VA-	2.8	2.8	-	-	-	-	-
X3+	2.8	-	-	4.4	6.9	3.2	-
X3-	1.5	-	-	3.8	7.7	2.8	-
X4+	4.5	-	-	3.1	2.9	2.4	-
X4-	4.1	-	-	5.5	4.5	3.7	-
LL+	-	2.4	2.5	4.4	5.6	3.0	7.4/7.9
LL-	-	1.2	3.7	2.8	6.4	2.1	11.7/12.3
LR+	-	3.0	2.8	3.3	3.0	2.4	7.4/7.9
LR-	-	1.5	3.3	3.6	3.2	2.6	11.7/12.3
RL+	-	3.0	2.9	2.5	2.3	2.0	11.7/12.3
RL-	-	1.6	3.2	4.9	4.0	3.2	7.4/7.9
RR+	-	2.4	2.6	3.0	4.1	2.3	11.7/12.3
RR-	-	1.2	3.6	3.9	4.5	2.7	7.9/7.4

CDF Coll., F.Abe et al., Phys.Rev.Lett 79(1997)2198
 OPAL Coll., G.Abbiendi et al., CERN-EP/98-108 (ICHEP98, Abs. 264)
 ALEPH Coll., ALEPH 98-060(1998) (ICHEP98, Abs. 906)
 L3 Coll., M.Acciarri et al., CERN-EP/98-31(1998)
 APV: A.Deandrea, Phys.Lett. B409(1997)277 and references therein

- Similar sensitivity at HERA, LEP, Tevatron
- No obvious indication for existence of a CI
- Unique limits from ZEUS for several scenarios

HERA Upgrade

Luminosity Upgrade:

- Factor 5 larger than present luminosity
⇒ 150 pb⁻¹ / year

Polarisation for Collider Experiments:

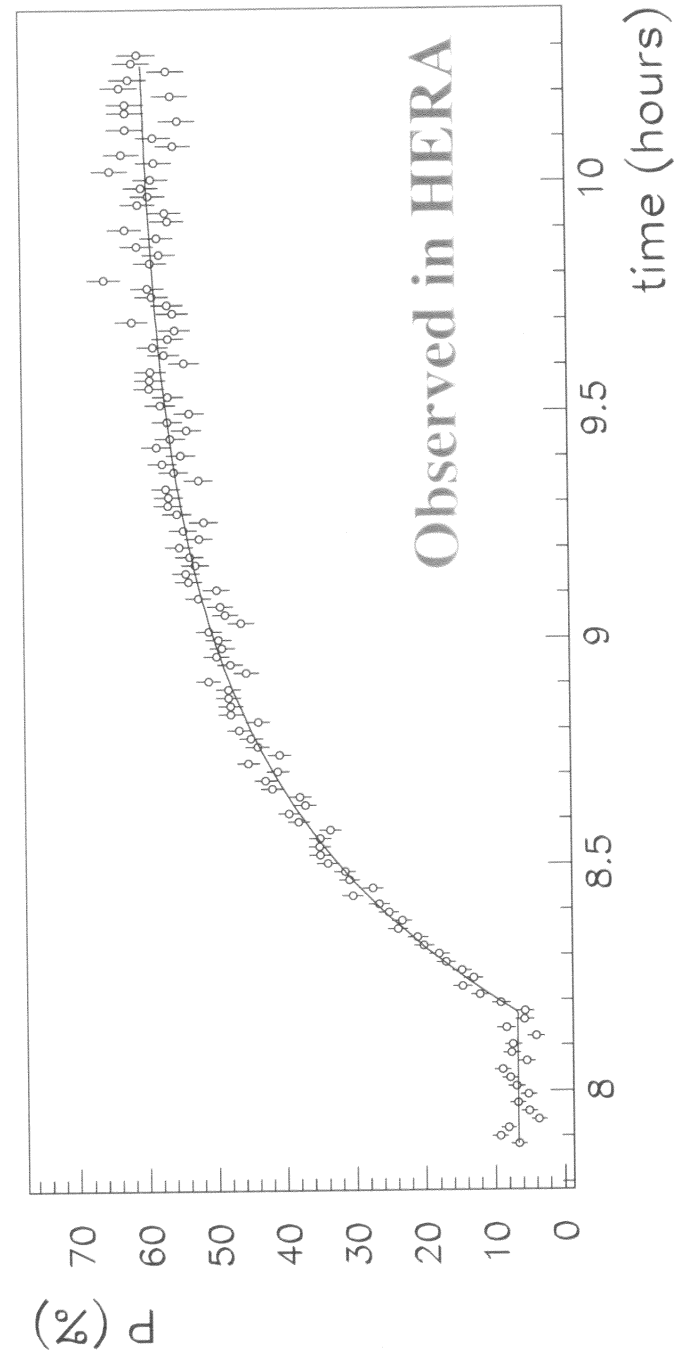
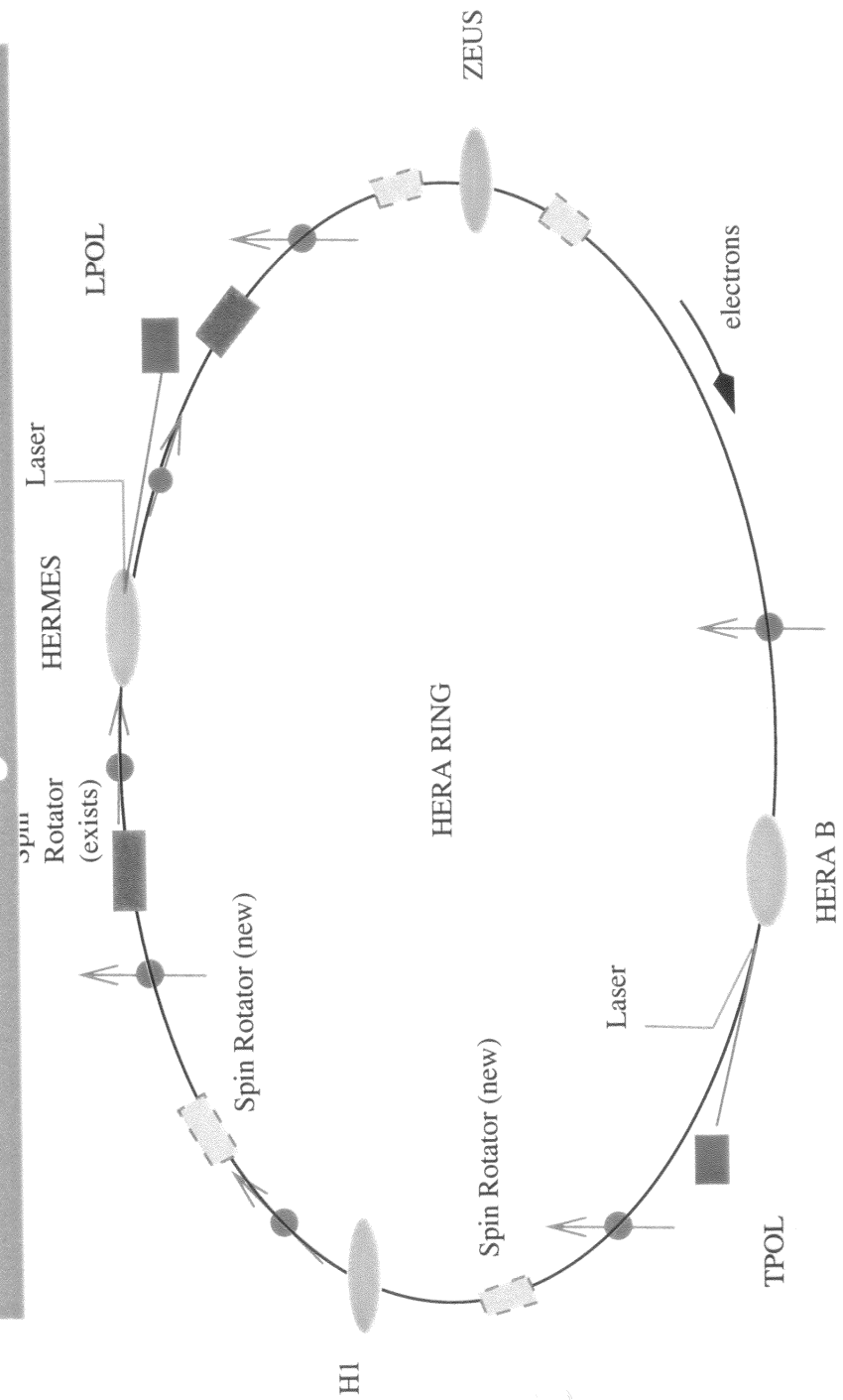
- Polarised electron/positron beams
⇒ > 50% (70% design goal)

Running Programme:

- Six years of running at 150 pb⁻¹/year
starting after 2000/2001 shutdown
⇒ ~ 1000 pb⁻¹ for H1 and ZEUS

1000 pb ⁻¹	$\sigma(e^-P)$ pb $Q^2 > 10,000 \text{ GeV}^2$		$\sigma(e^+P)$ pb $Q^2 > 10,000 \text{ GeV}^2$	
	NC	CC	NC	CC
	E_P GeV			
820	4.1	4.8	2.0	0.5
920	4.9	5.7	2.5	0.7

Future Physics at HERA

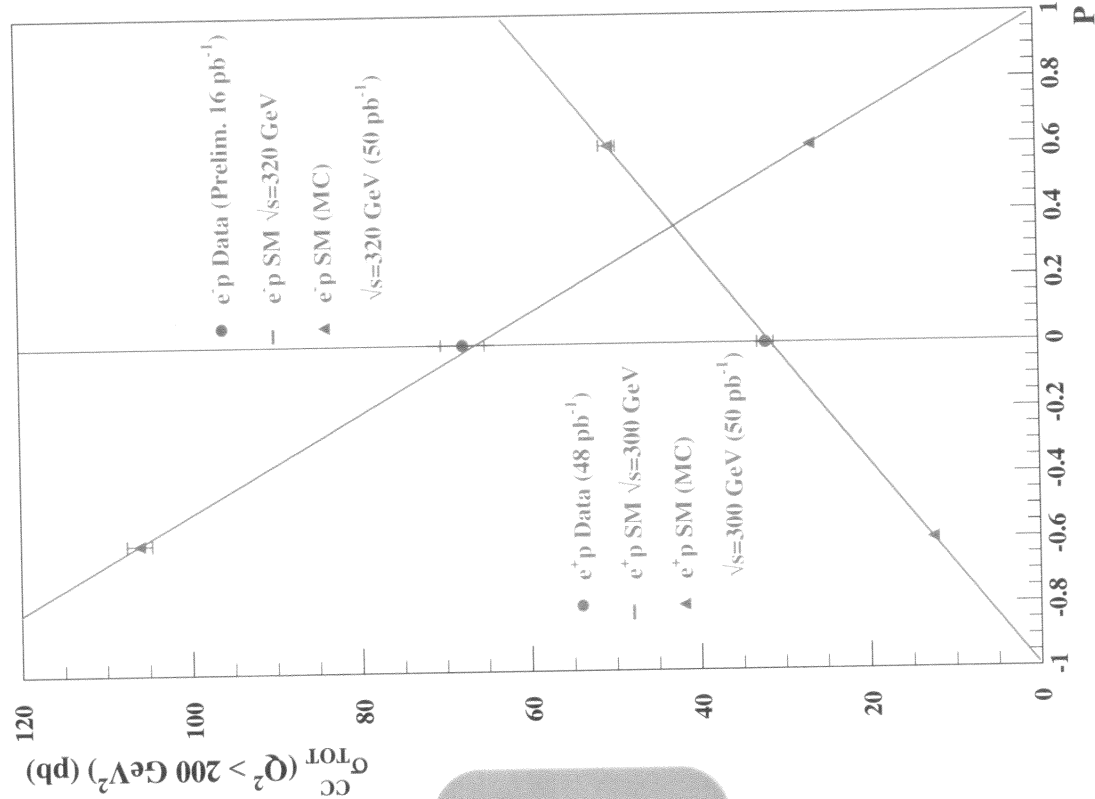


- Polarisation of 50-60% routinely achieved

Future Physics at HERA

Charged Current:

ZEUS CC Cross Sections



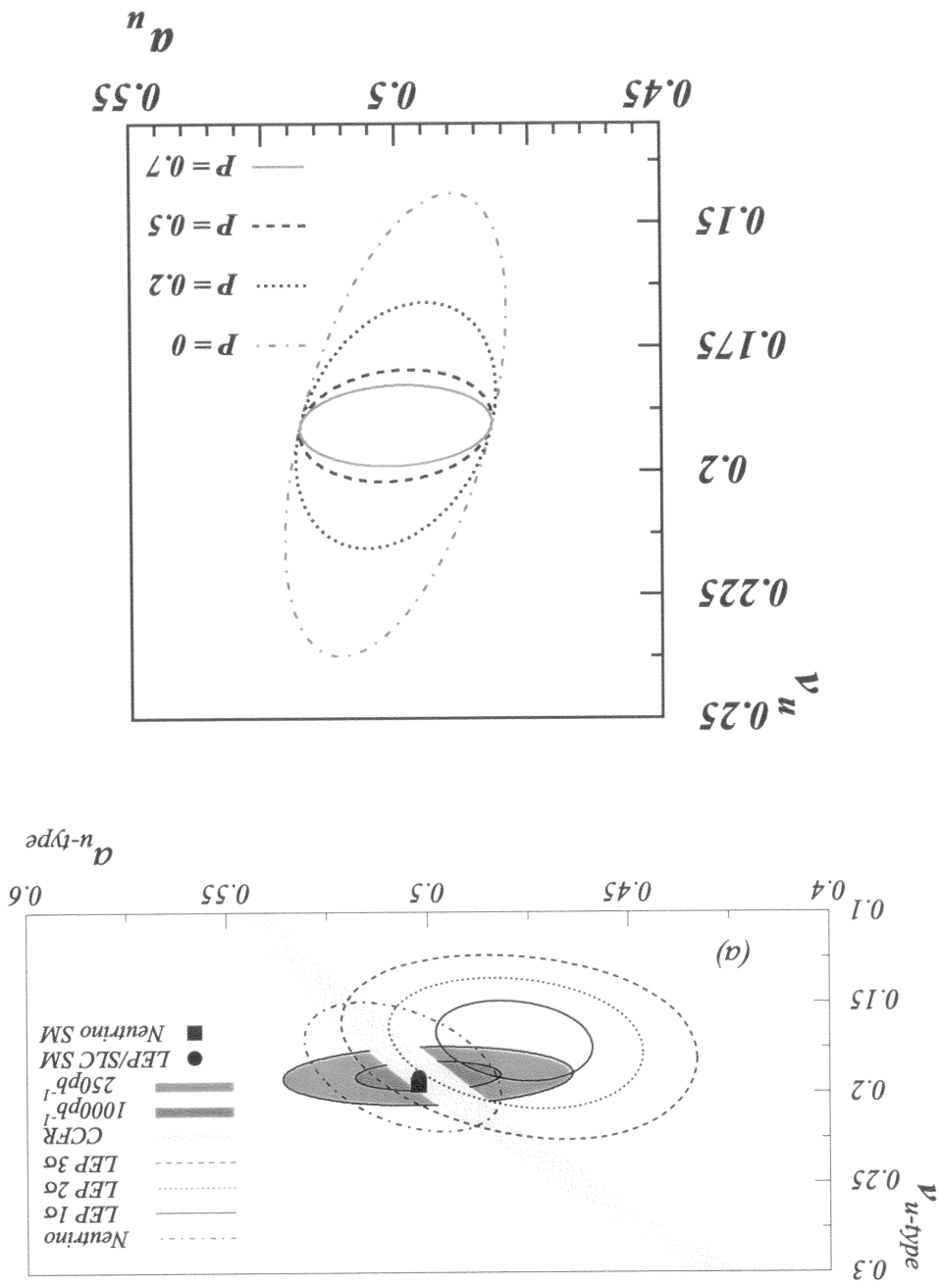
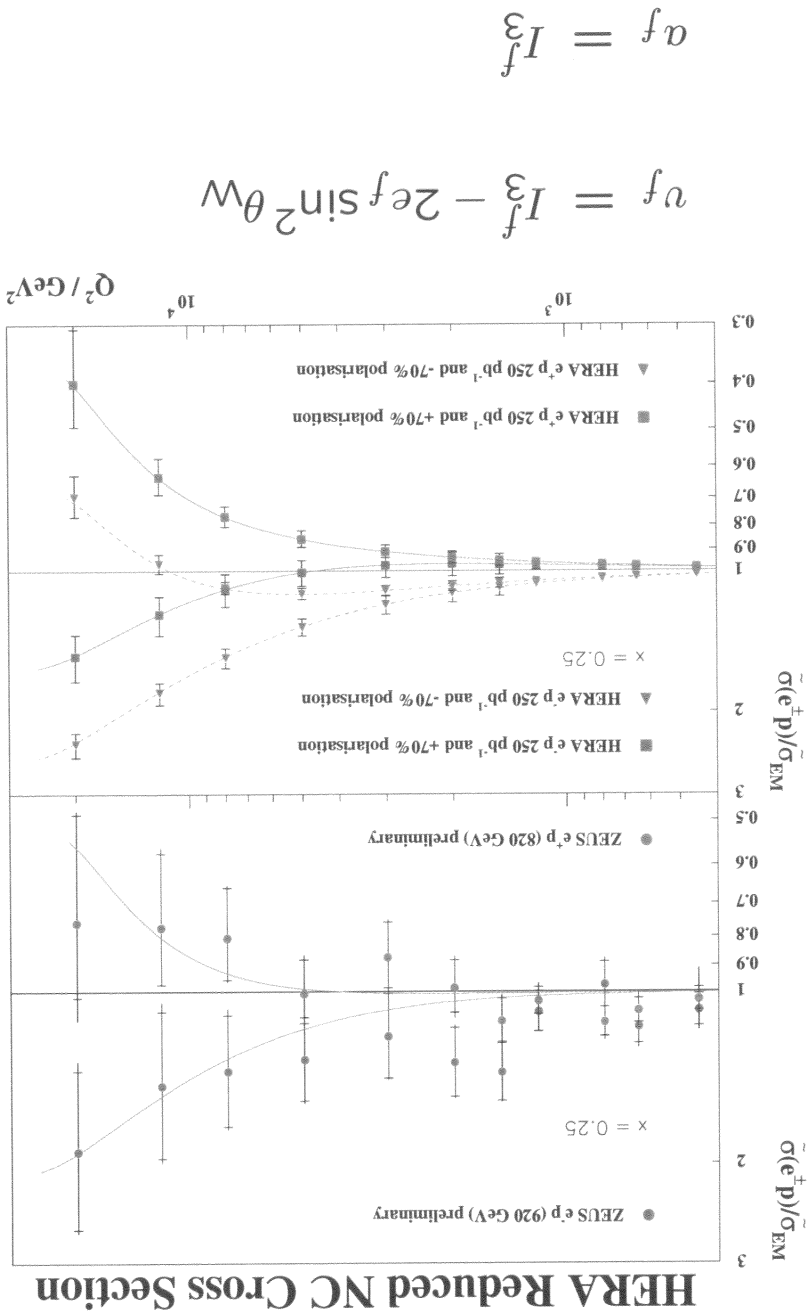
$$\sigma_{e^\pm p}^{\text{CC}} \propto (1 \pm P)$$

 $P = \text{polarisation}$

Exclusion limit
 $M_W(R) > 400 \text{ GeV}$

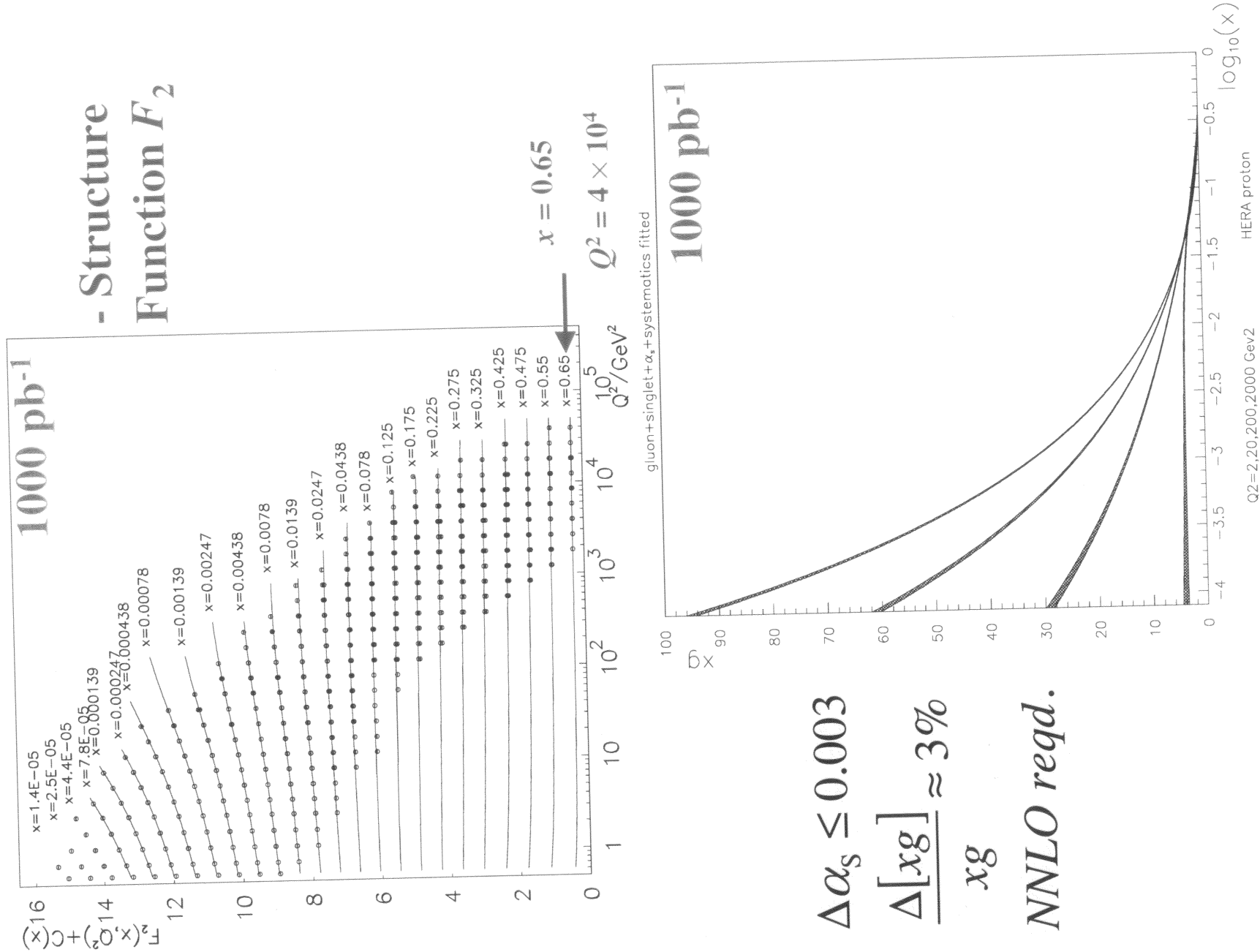
First measurement:

Possible with *one* year's data



Future Physics at HERA

Future HERA Physics



Outlook

HERA data enables us to look at...

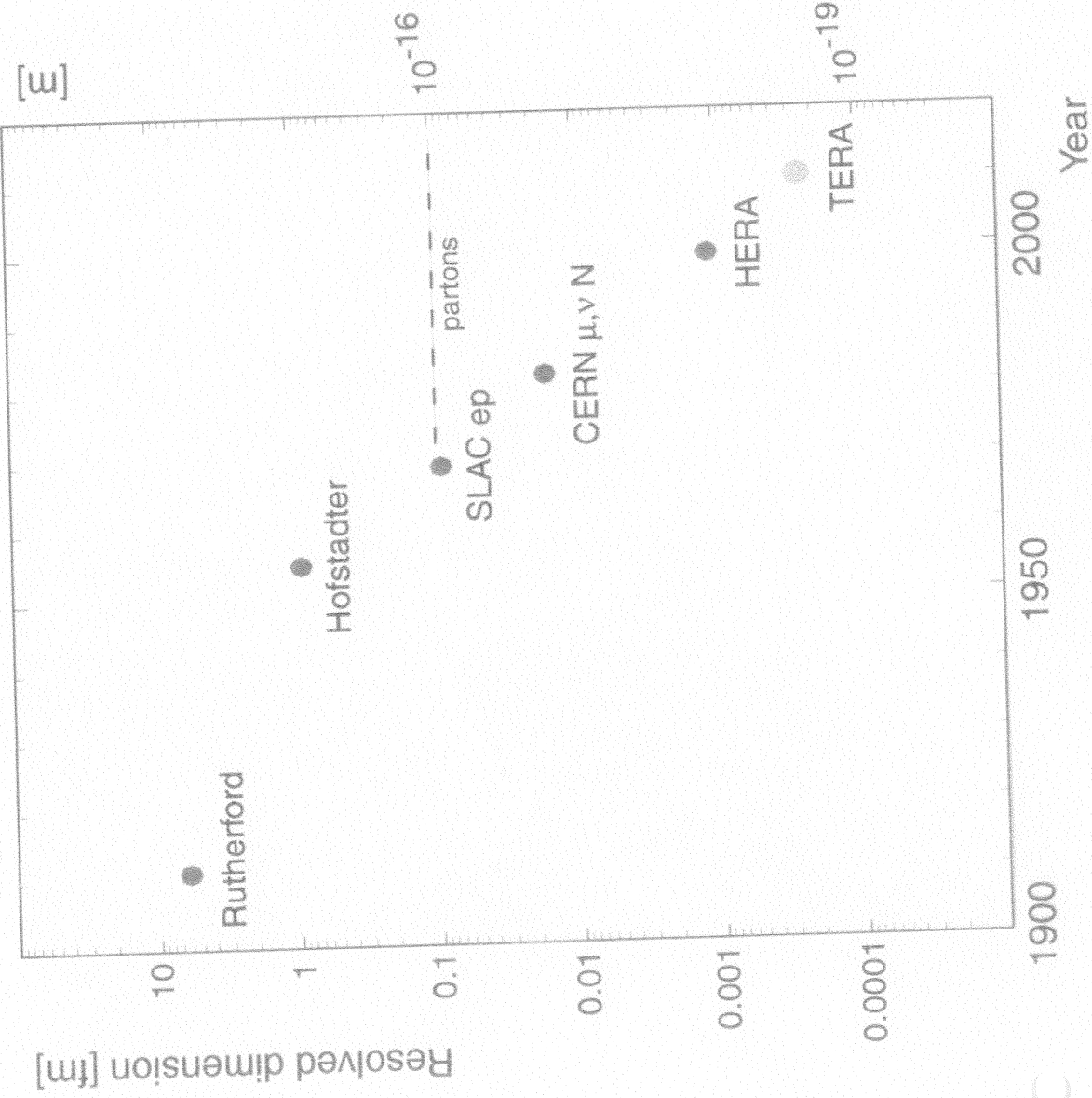
- Gluons: QCD fits
- High density limit of QCD: detailed study of transition region
- Partons at high x : NC and CC cross sections
- Valence partons: xF_3
- Ratio d/u : CC cross sections
- Beyond the Standard Model: e.g. leptoquarks and contact interactions

Opportunities with high lumi + polarisation ...

- Partons: High precision studies
- Electroweak: Directly address chiral structure of SM through polarisation dependence of CC and NC

Historical Perspective

- Future of D.I.S.



- Resolved dimension = $0.2[\text{GeV}\cdot\text{fm}]/Q_{\text{max}}$
- TESLA(500 GeV)+HERA(1 TeV)=TERA
- (Proof that Rutherford was 30 years ahead of his time...)