

Structure Function Working Group

Experimental Summary

Convenors:

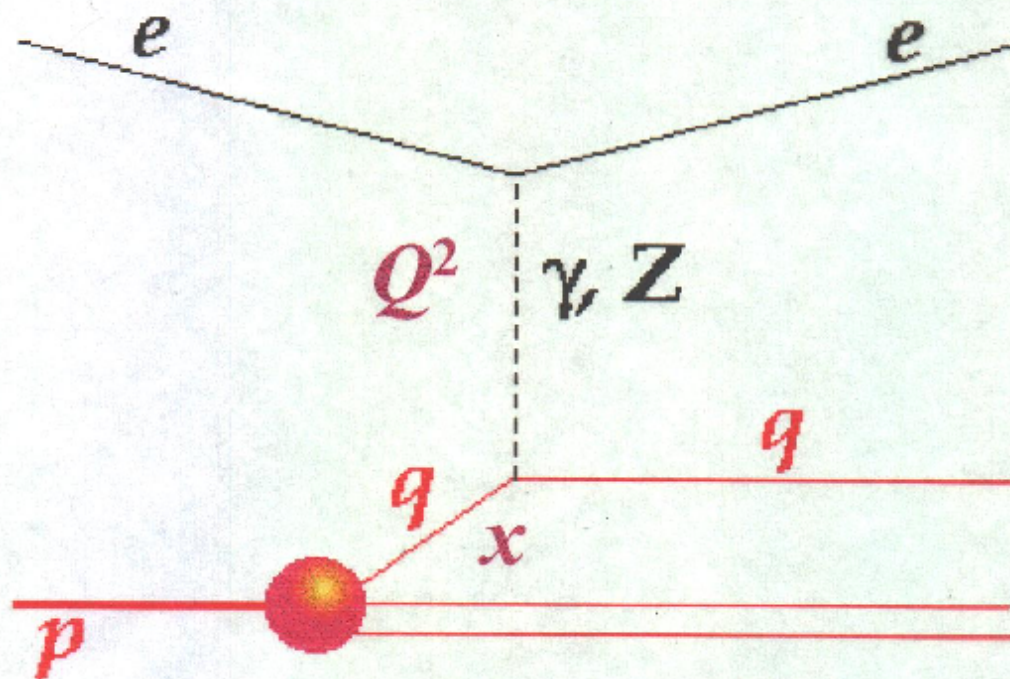
K. Long (Imperial College London)

R. Nisius (CERN)

J. Stirling (Durham)

- **High Q^2 NC and CC Cross Sections**
- **NLO fits: extraction of xG and α_s**
- **Structure functions at low Q^2**
- **The longitudinal structure function**
- **Flavour specific PDFs**
- Future - ep [Klein] - taken up by next speaker
up [Morfin]

Neutral Current DIS

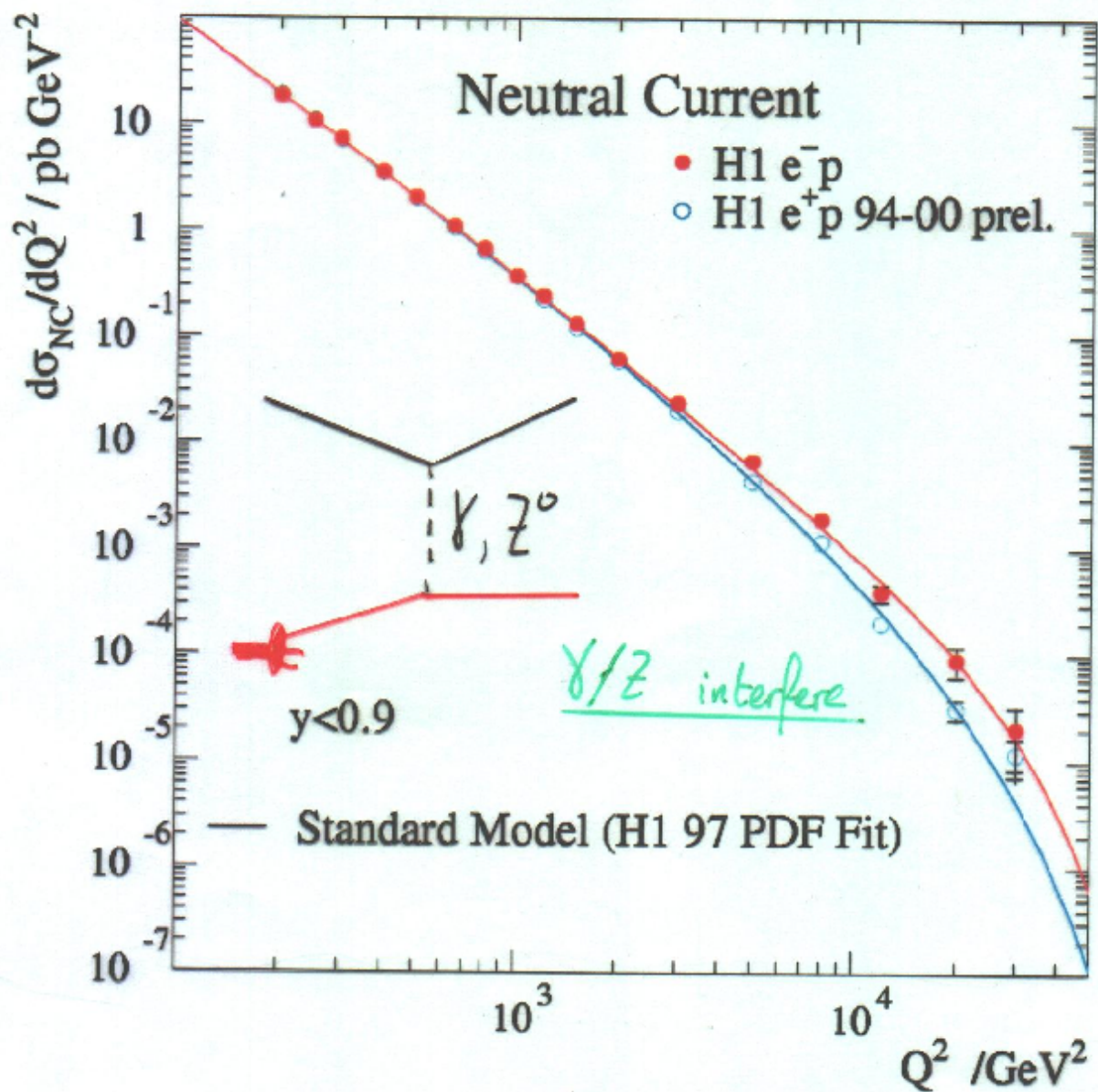


$$\frac{d^2 \sigma_{\text{NC}}^{e^\pm P}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \left[Y_+ F_2^{\text{NC}} \mp Y_- x F_3^{\text{NC}} - y^2 F_L^{\text{NC}} \right]$$

$$Y_\pm = \left(1 \pm (1-y)^2 \right) \quad y = \frac{Q^2}{xs} = \sin^2 \frac{\theta^*}{2}$$

$$F_2^{\text{NC}} = x \sum_q A_q (q + \bar{q}) \quad F_3^{\text{NC}} = x \sum_q B_q (q - \bar{q})$$

NC Single Differential Cross Section

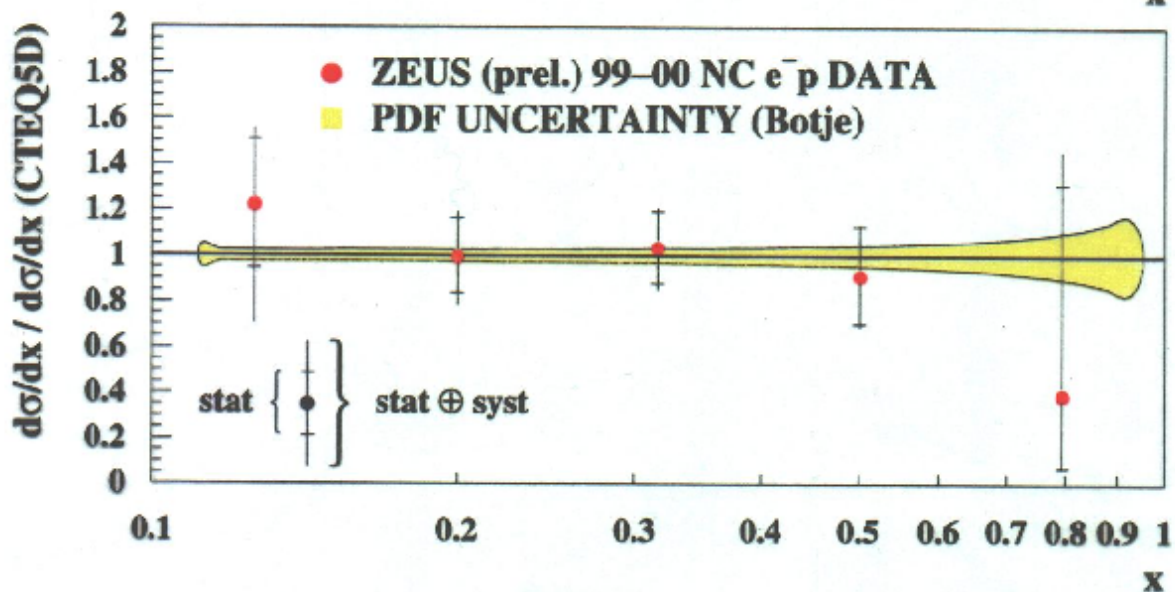
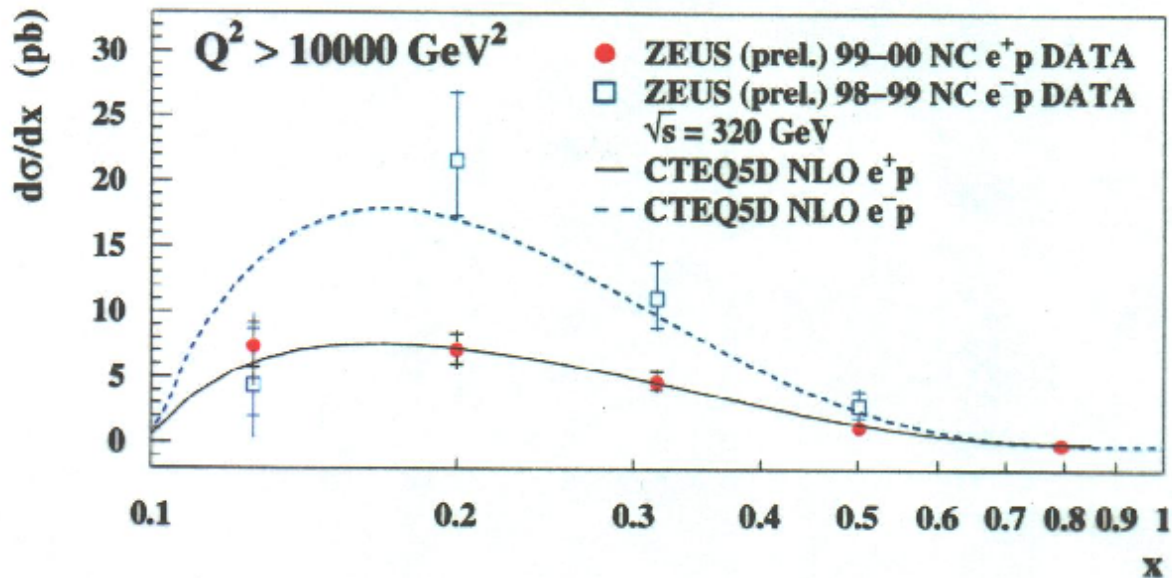


- $d\sigma/dQ^2$ falls by 7 orders of magnitude
- well described by SM
- $d\sigma/dQ^2$ for e^+p and e^-p the same at low Q^2 , differ at high Q^2

$\frac{d\sigma}{dx}$ for NC events for $Q^2 \geq 10000 \text{ GeV}^2$.

Data sample $(e^+p)^{920}$ and $(e^-p)^{920}$

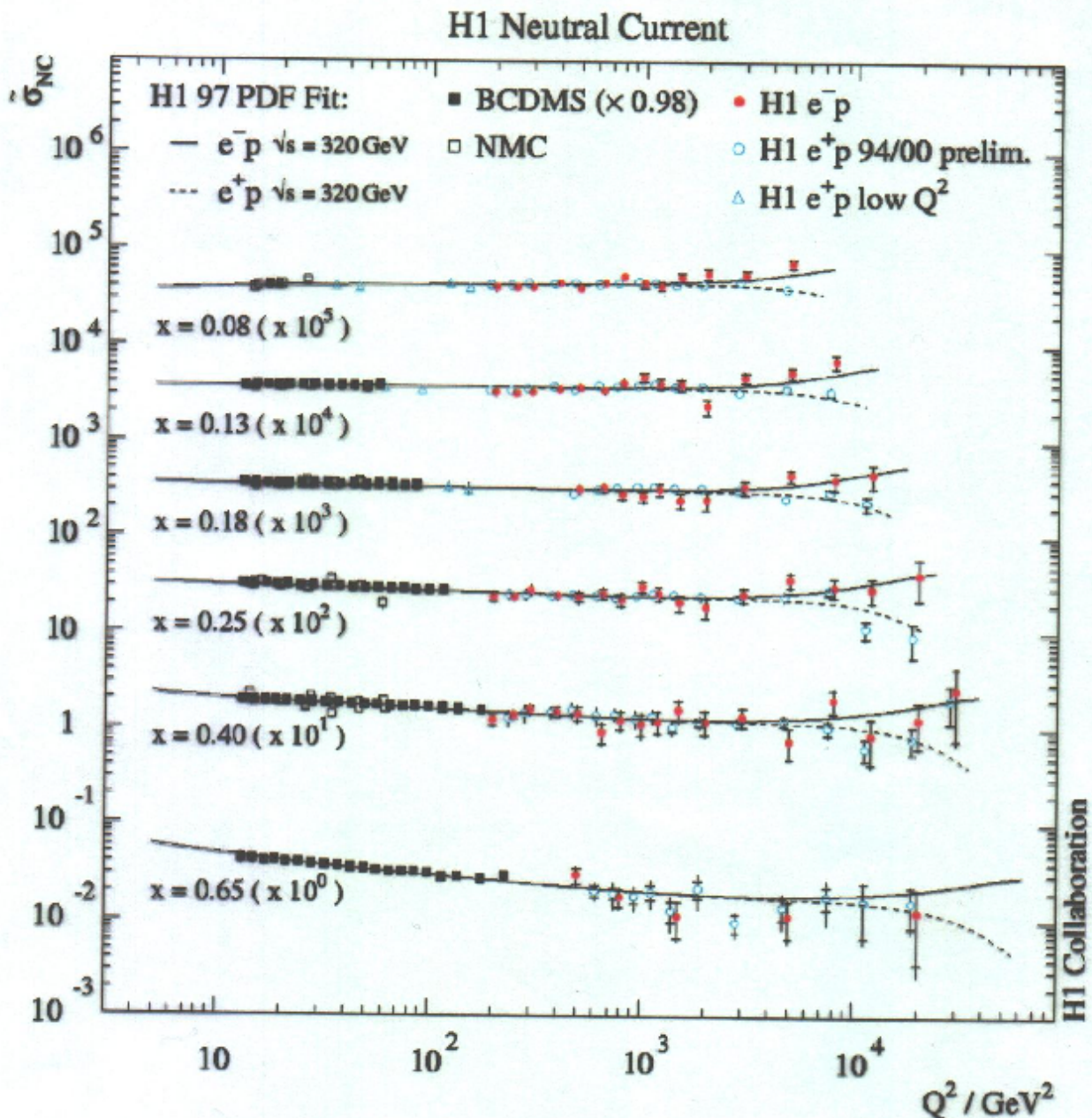
ZEUS



$\gamma - Z^0$ interference at high Q^2 **constructive** for e^-p data, **destructive** for e^+p data

Double Differential Cross Section at high x

$$\bar{\sigma}_{\text{NC}}(e^{\pm}p) = \tilde{F}_2 \mp \frac{Y_{\pm}}{Y_{+}} x\tilde{F}_3, \quad Y_{\pm} = 1 \pm (1-y)^2$$



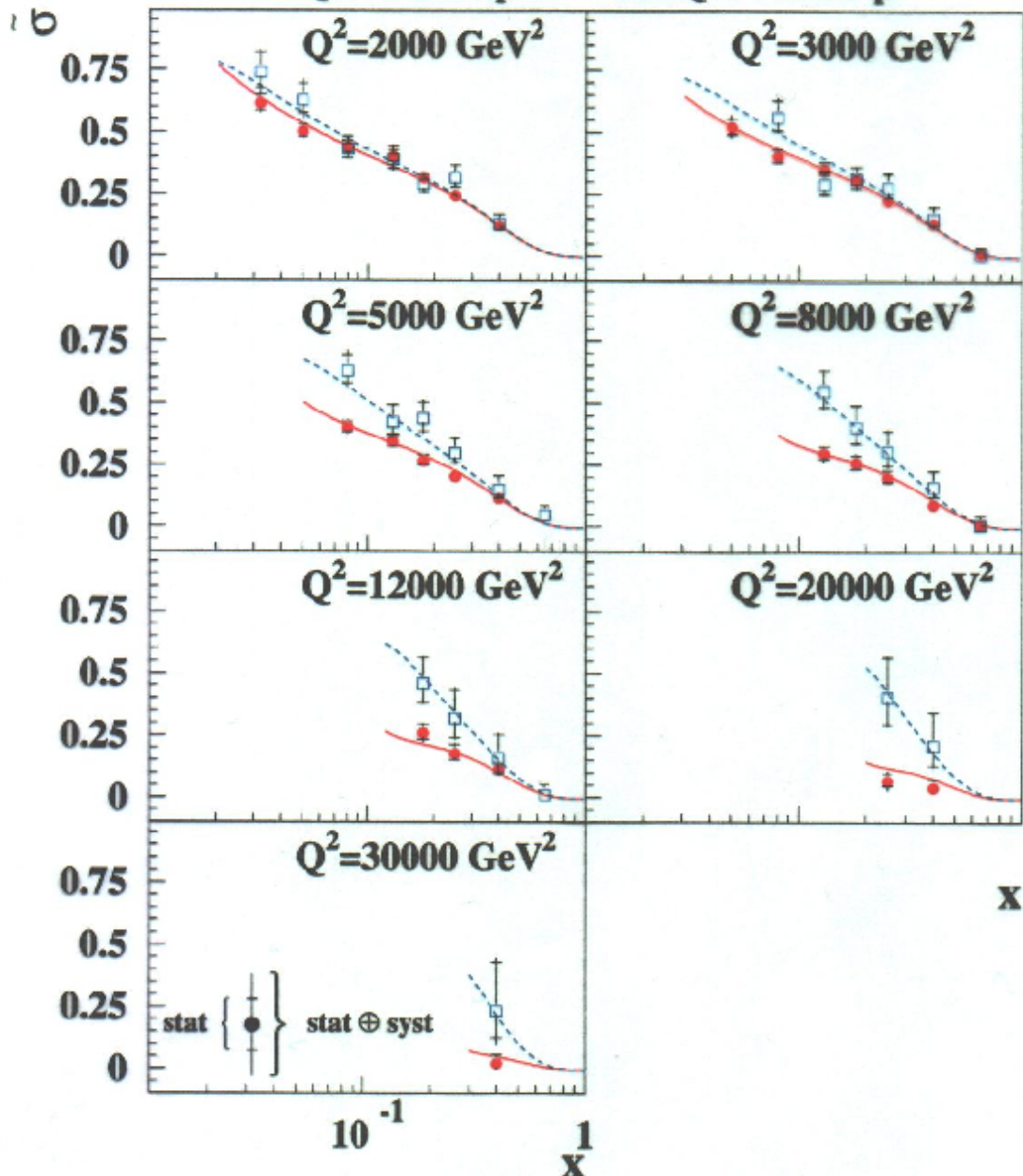
- negative (positive) contribution from $x\tilde{F}_3$ in e^+p (e^-p)

$\frac{d^2\sigma}{dx dQ^2}$ in Q^2 bins for NC events.

Data sample $(e^+p)^{920}$ and $(e^-p)^{920}$. Cont.

ZEUS

- ZEUS (prel.) 99–00 NC e^+p DATA $\sqrt{s} = 320$ GeV
- ZEUS (prel.) 98–99 NC e^-p DATA $\sqrt{s} = 320$ GeV
- CTEQ5D NLO e^+p - - CTEQ5D NLO e^-p



$x F_3(x, Q^2)$ extraction. Data sample $(e^+p)^{820}$ and $(e^-p)^{920}$

Want to extract $x F_3(x, Q^2)$

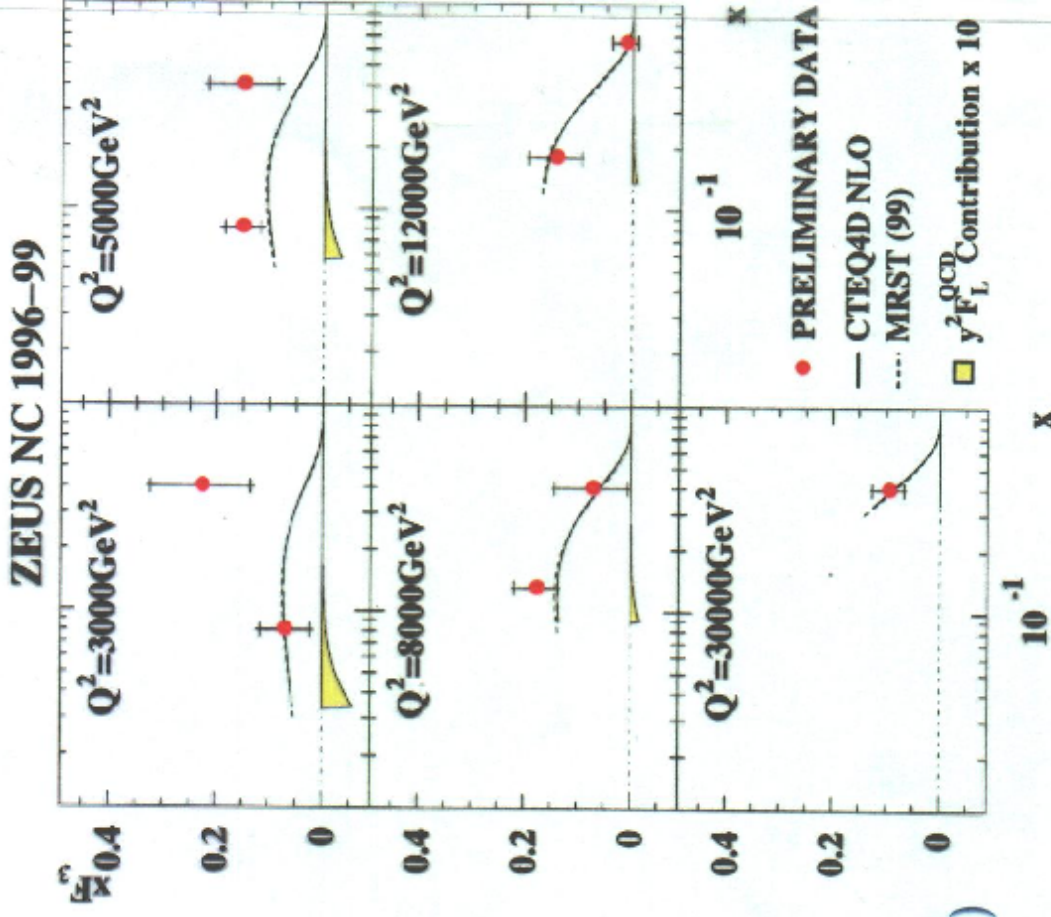
$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2(Q^2)}{xQ^4} [Y_+ F_2 \mp Y_- x F_3 - y^2 F_L]$$

Taking care of the different center-of-mass energy

$$x F_3(x, Q^2) = \left(\frac{xQ^4}{2\pi\alpha^2} \right) \left(\frac{Y_-^{920}}{Y_+^{920}} + \frac{Y_-^{820}}{Y_+^{820}} \right)^{-1} \left(\frac{1}{Y_+^{920}} \frac{d^2\sigma^-}{dx dQ^2} - \frac{1}{Y_+^{820}} \frac{d^2\sigma^+}{dx dQ^2} \right) - \Delta F_L(x, Q^2)$$

Where

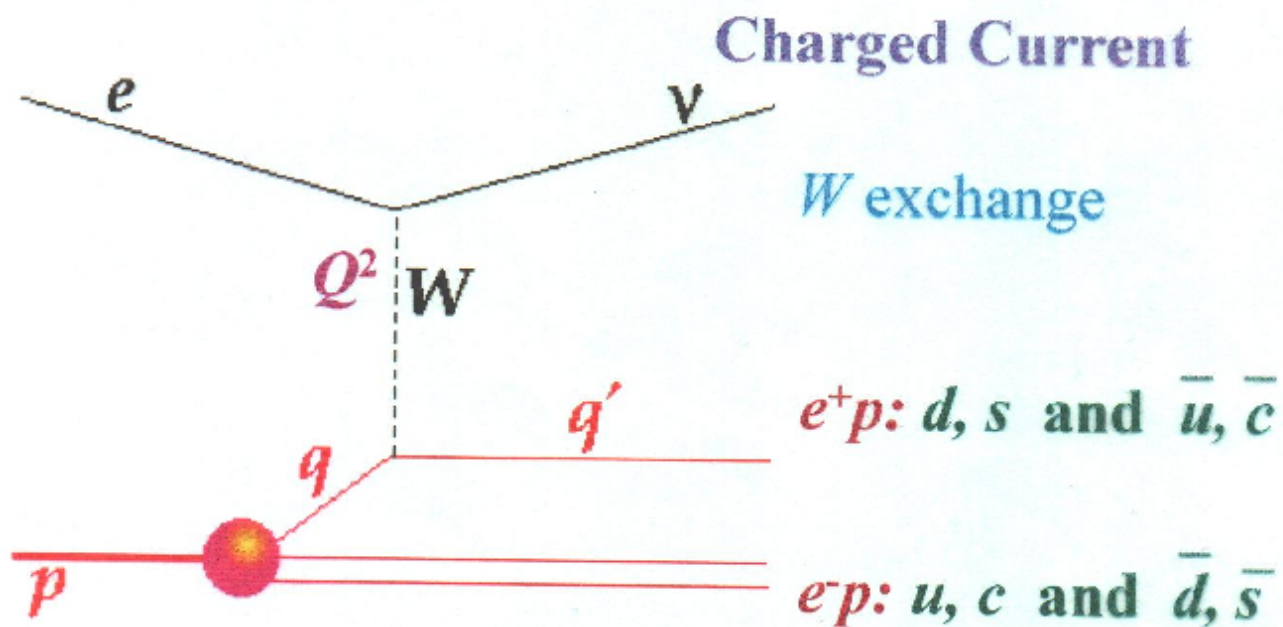
$$\Delta F_L(x, Q^2) = \frac{Y_+^{820} \cdot (y^{920})^2 - Y_+^{920} \cdot (y^{820})^2}{Y_-^{920} \cdot Y_+^{820} + Y_-^{820} \cdot Y_+^{920}} \cdot F_L(x, Q^2)$$



Charged Current DIS

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

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

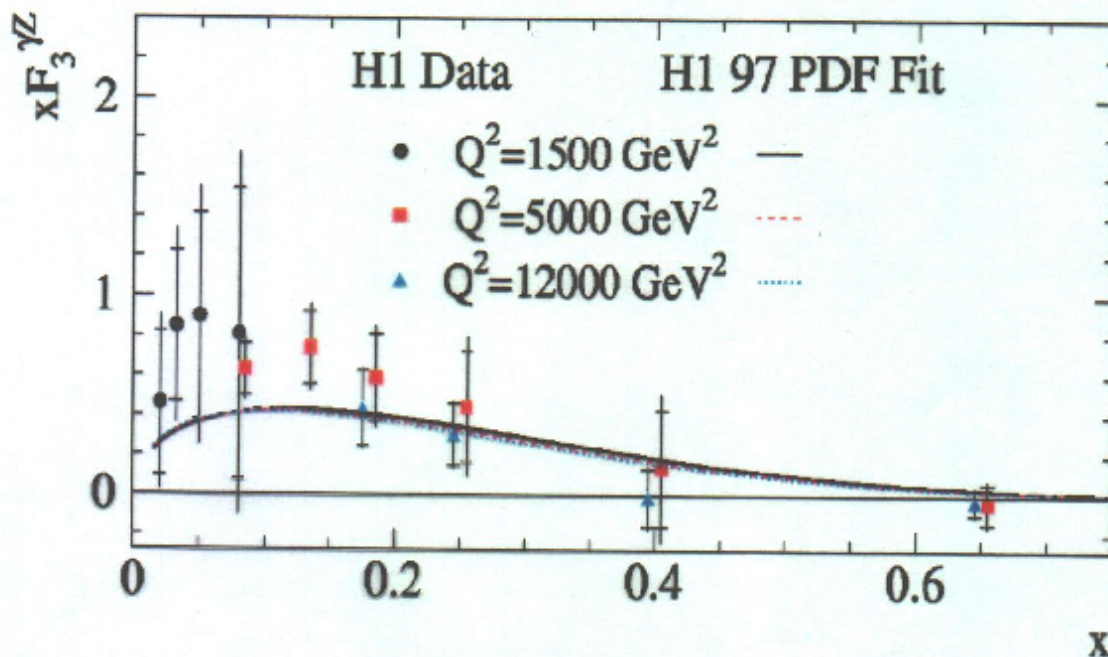


$$\tilde{\sigma}_{\text{CC}}^{e^-P} = \left\{ \frac{G_\mu^2}{2\pi x} \left[\frac{M_W^2}{Q^2 + M_W^2} \right]^2 \right\}^{-1} \frac{d^2 \sigma_{\text{CC}}^{e^-P}}{dx dQ^2}$$

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

Sum Rule for $F_3^{\gamma Z}$

in LO : $x F_3^{\gamma Z} = x \sum_i 2e_i a_i (q_i - \bar{q}_i)$



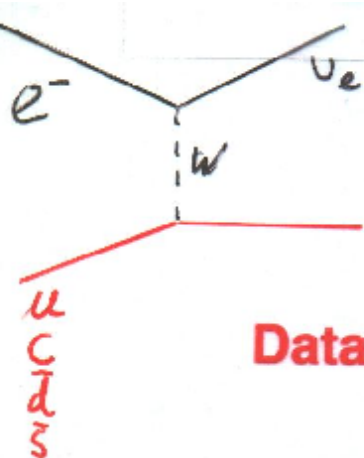
Sum rule for $F_3^{\gamma Z}$:

(by analogy with *Gross Lewellyn-Smith* sum rule for νN scattering)

$$\int_0^1 F_3^{\gamma Z} dx \approx 2e_u a_u N_u + 2e_d a_d N_d = \frac{5}{3}$$

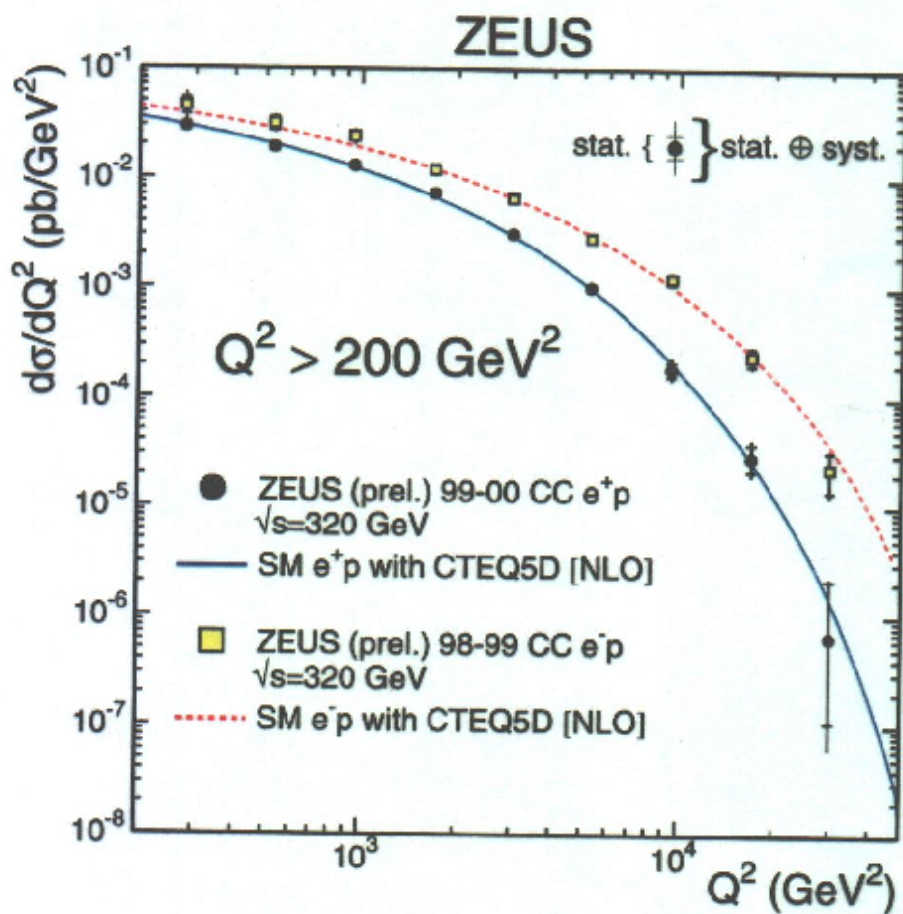
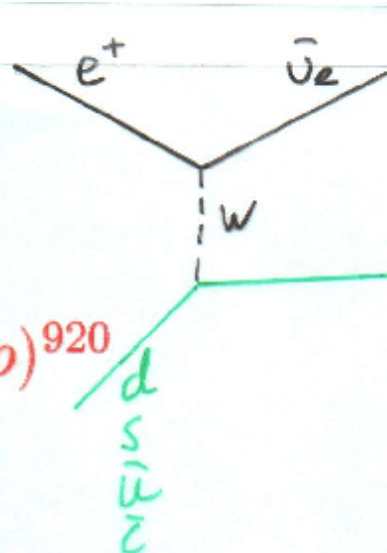
H1: $\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.88 \pm 0.35(\text{stat.}) \pm 0.27(\text{syst.})$

(H1 97 PDF fit: $\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.11$)



$\frac{d\sigma}{dQ^2}$ for CC events.

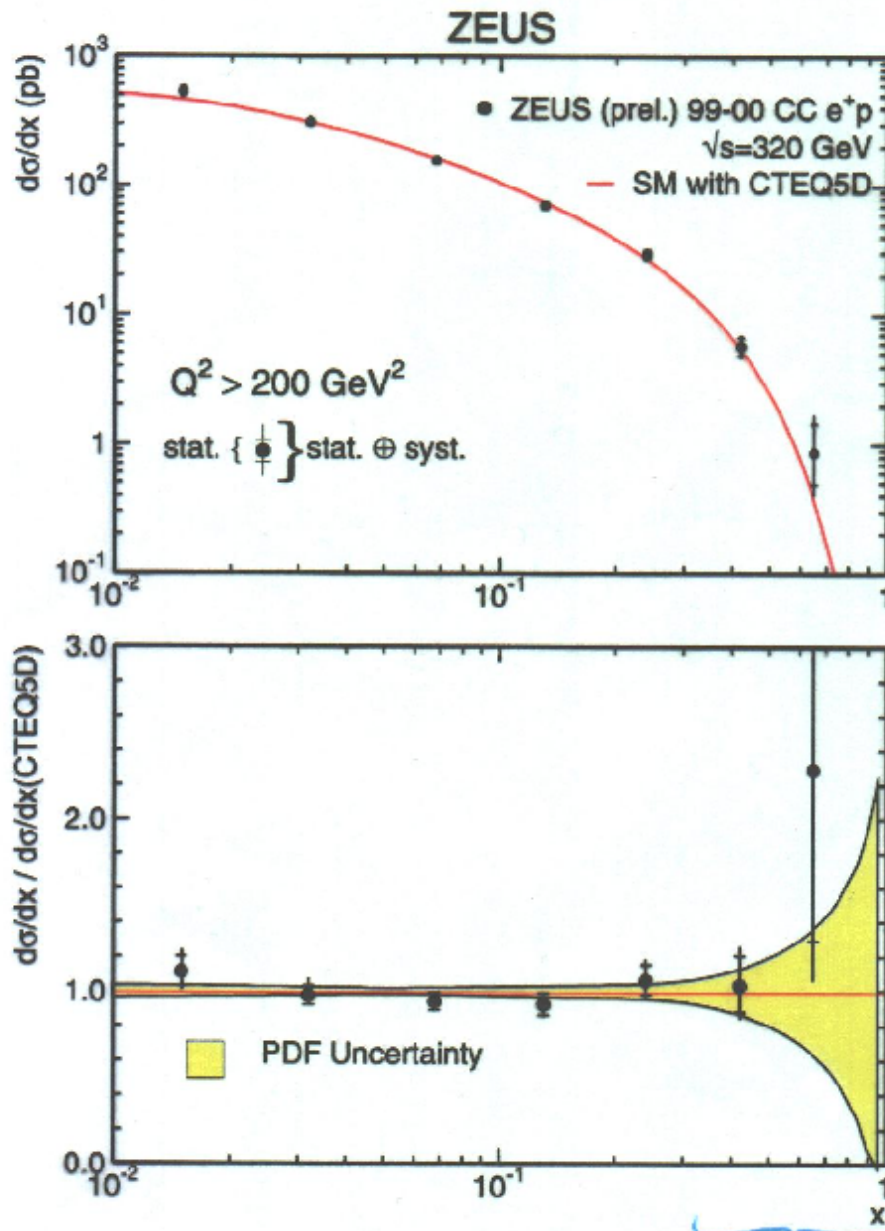
Data sample $(e^+p)^{920}$ and $(e^-p)^{920}$



Low $Q^2 \rightarrow e^-p$ cross-section $\approx$ twice e^+p

High $Q^2 \rightarrow (1 - y)^2$ term dumps e^+p cross-section

$\frac{d\sigma}{dx}$ for CC events.
Data sample $(e^+p)^{920}$



Sensitive to d_v

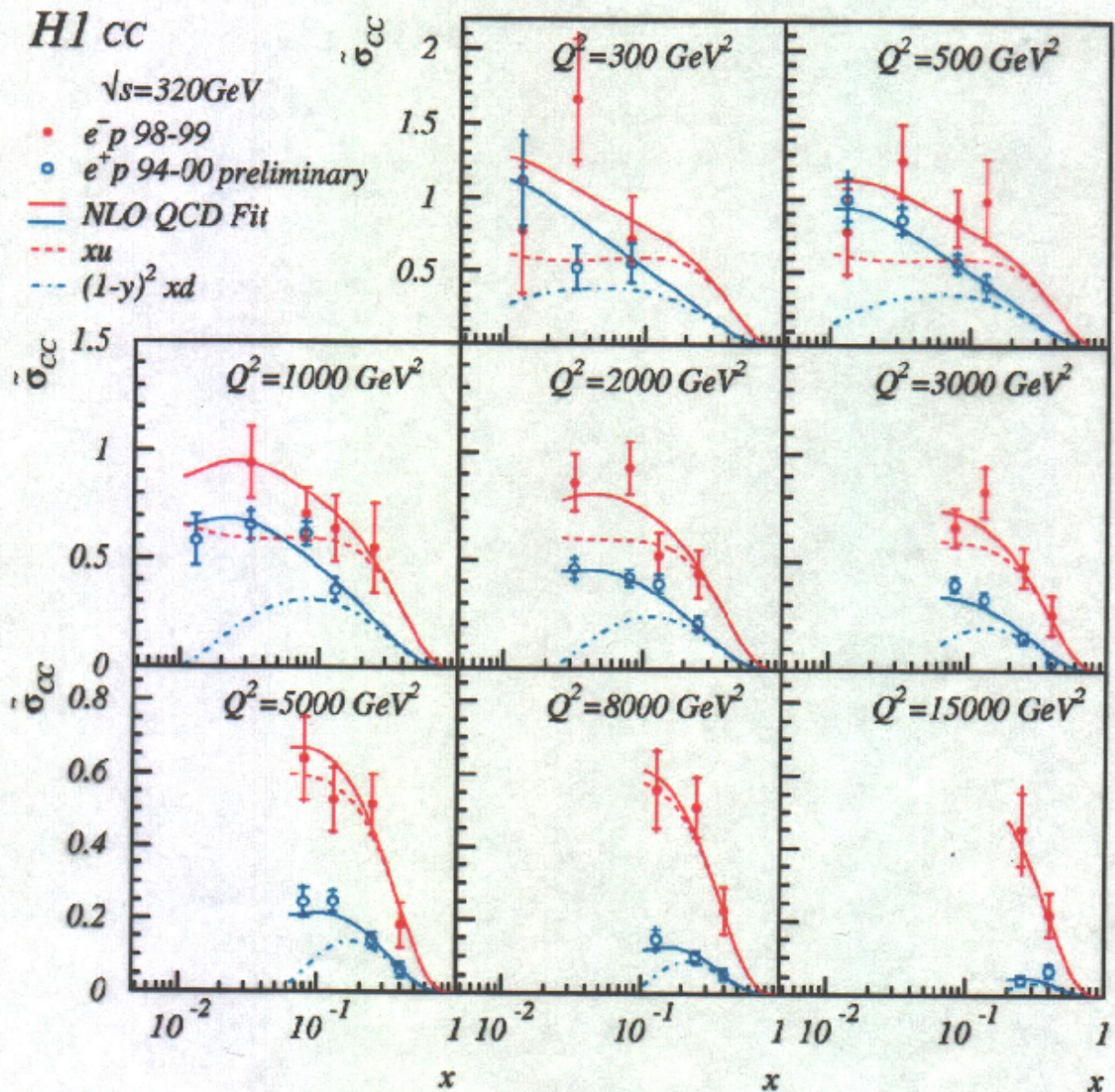
Agreement with CTQ5D prediction at **high x**

Double Differential CC Cross Section

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

$$\tilde{\sigma}_{CC}^+ = x[(\bar{u} + \bar{c}) + (1-y)^2(d+s)] \simeq (1-y)^2 x d_v$$

$$\tilde{\sigma}_{CC}^- = x[(u+c) + (1-y)^2(\bar{d} + \bar{s})] \simeq x u_v \quad x \rightarrow 1$$

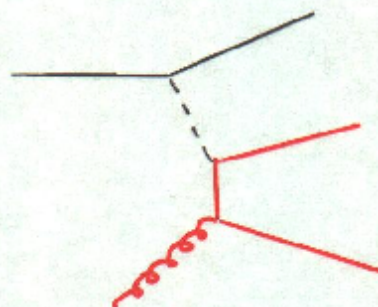
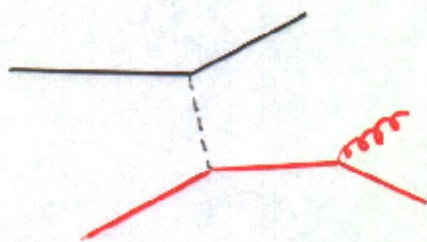


NLO Fits: extraction of gluon and α_S

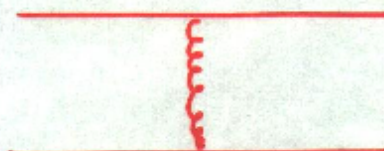
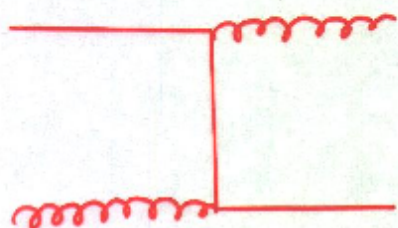
Inclusive DIS:

$$\frac{dF_2}{d \ln Q^2} \propto \alpha_S P_{qG} \otimes xG$$

Jet production in DIS:

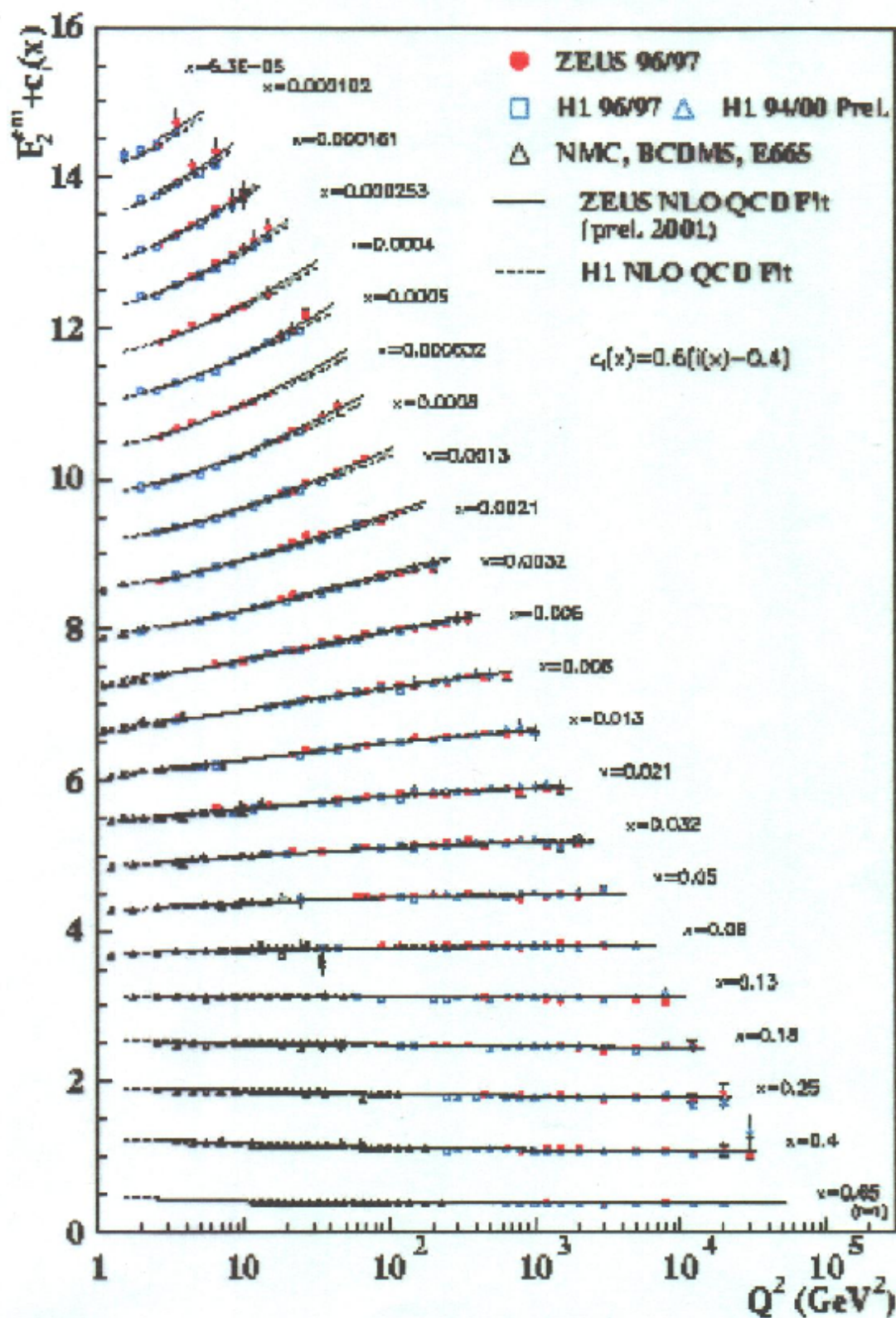


Jet production at Tevatron:



High precision Structure Function data ...

ZEUS+H1



... allows extraction of gluon and α_s

ZEUS NLO QCD fit

K. Nagano

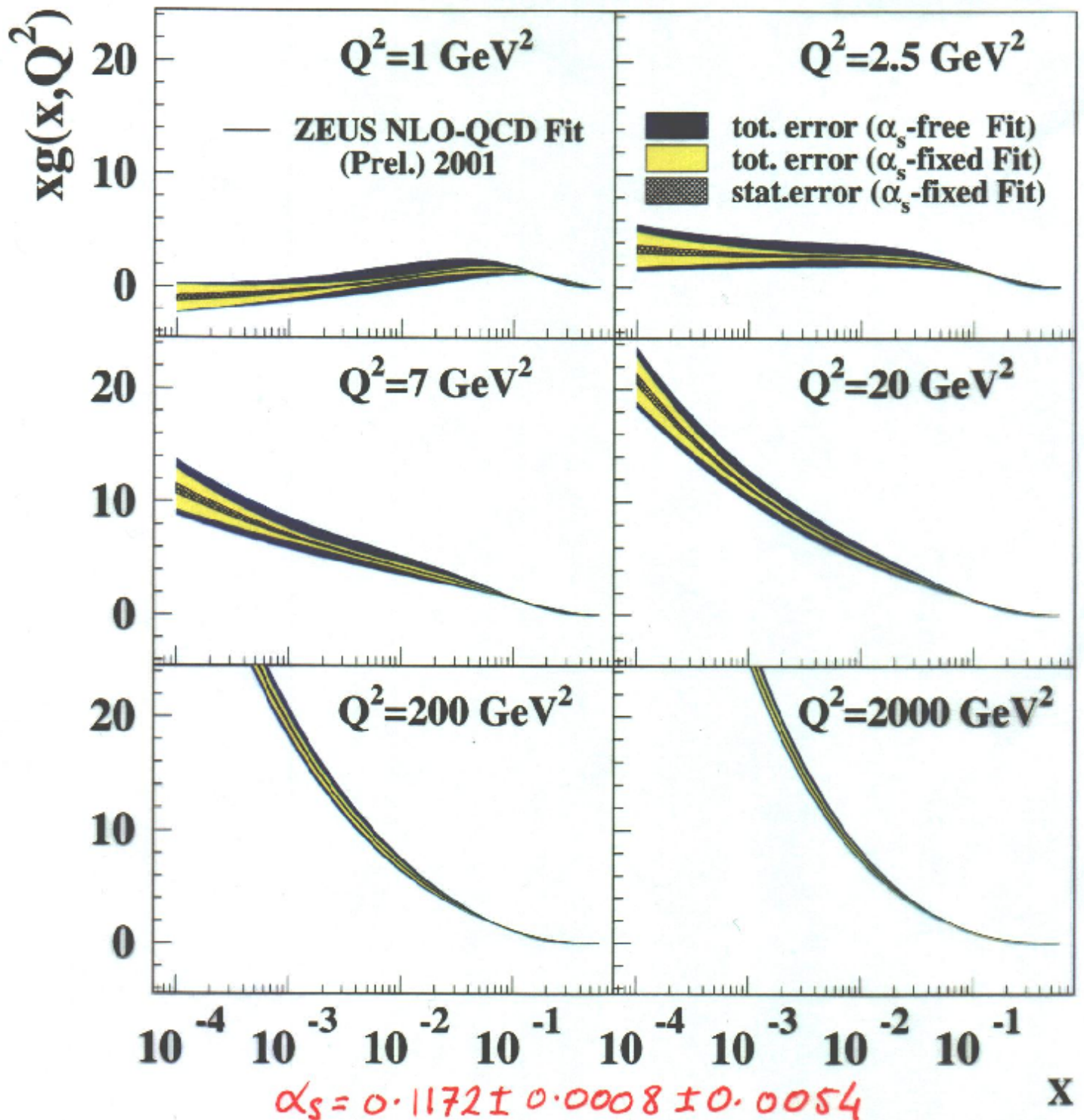
- Fit ZEUS, BCDMS, E665, NMC_(p,d), CCFR_(xF₃)
- Parameterise $u_v, d_v, xg, xS, x(d - u)$ at $Q_0^2 = 7 \text{ GeV}^2$
- RT-VFN heavy quark scheme
- Careful (Pascaud-Zomer) treatment of point-to-point correlated systematic errors
- Systematic offsets NOT modified by the fit

H1 NLO QCD fit

R. Wallny

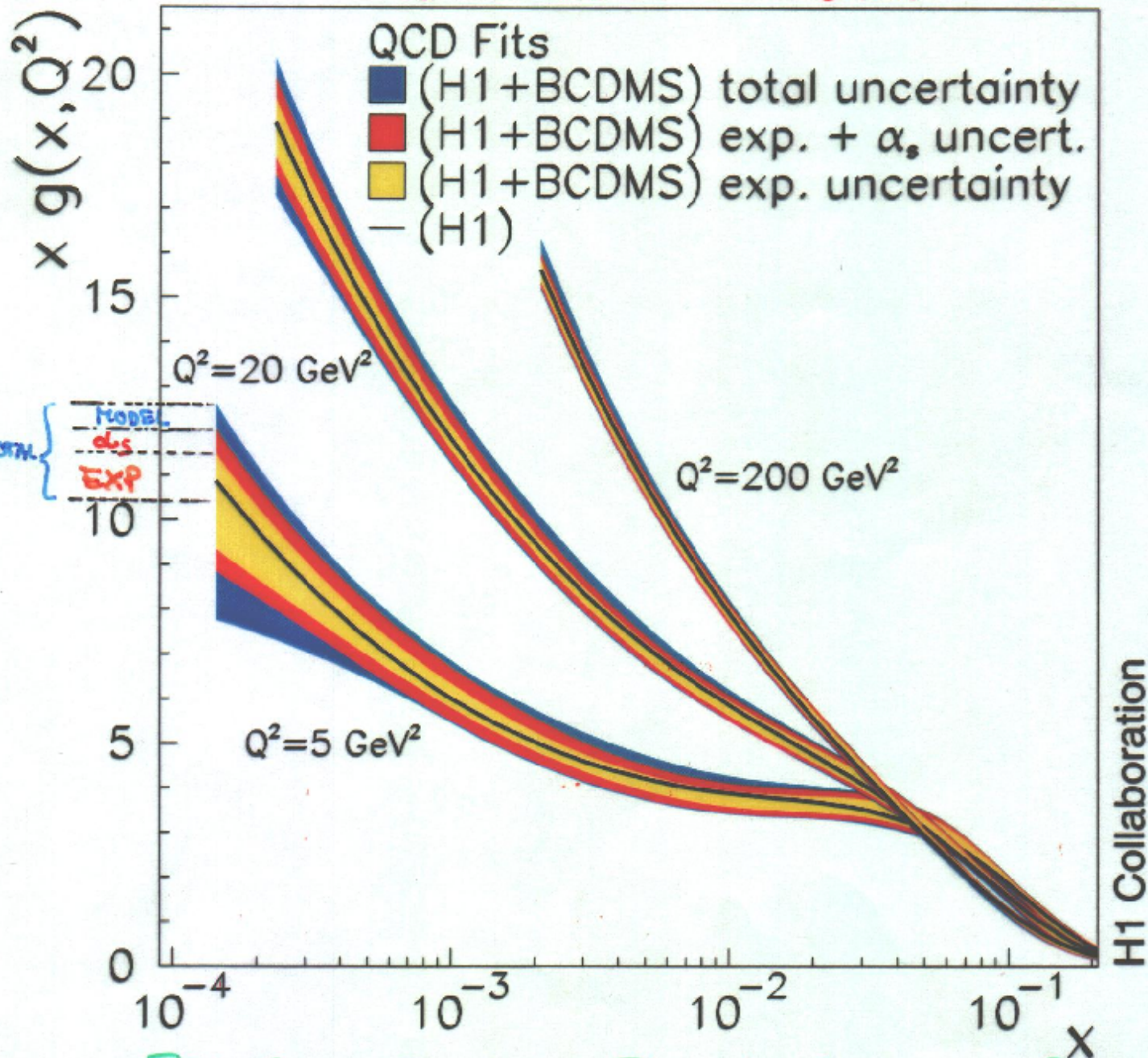
- **Lepton-proton data (H1+BCDMS) only**
- **Parameterise effective valence and effective sea at $Q_0^2=4 \text{ GeV}^2$**
- **Number of parameters in gluon and sea chosen so that χ^2 saturates**
- **FFN massive heavy quark scheme**
- **Careful (Pascaud-Zomer) treatment of point-to-point correlated systematic errors**
- **Systematic offsets determined by the fit**

ZEUS



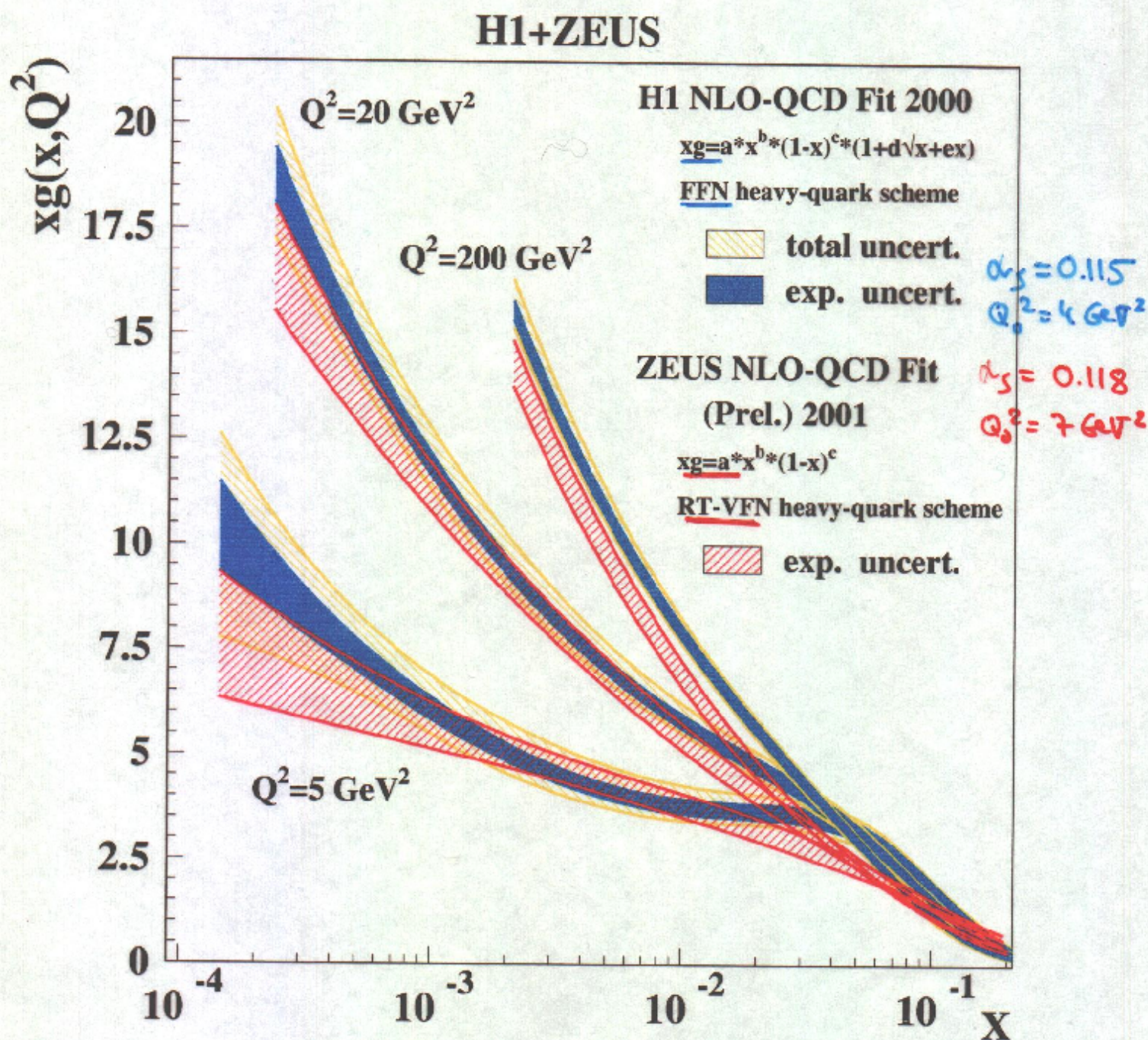
- Total uncertainty (due to exp.errors) of the “ α_s -FREE fit” is also displayed.
- At $Q^2 = 1 \text{ GeV}^2$: valence like, consistent with 0 at low x .
- Consistent with ZEUS '95 gluon and H1 '00 gluon.
(See R. Walley's talk)

$$\alpha_s = 0.1150 \pm 0.0017 \text{ (stat)} \pm 0.0009 \text{ (Model)} \pm 0.0005 \text{ (Scale)}$$



- FIRST GLUON EXTRACTION FROM H1 DATA ALONE!
- GLUON DERIVED FROM H1 AND H1+BCDMS(p) DATA AGREE

COMPARISON H1 + ZEUS QCD ANALYSES:

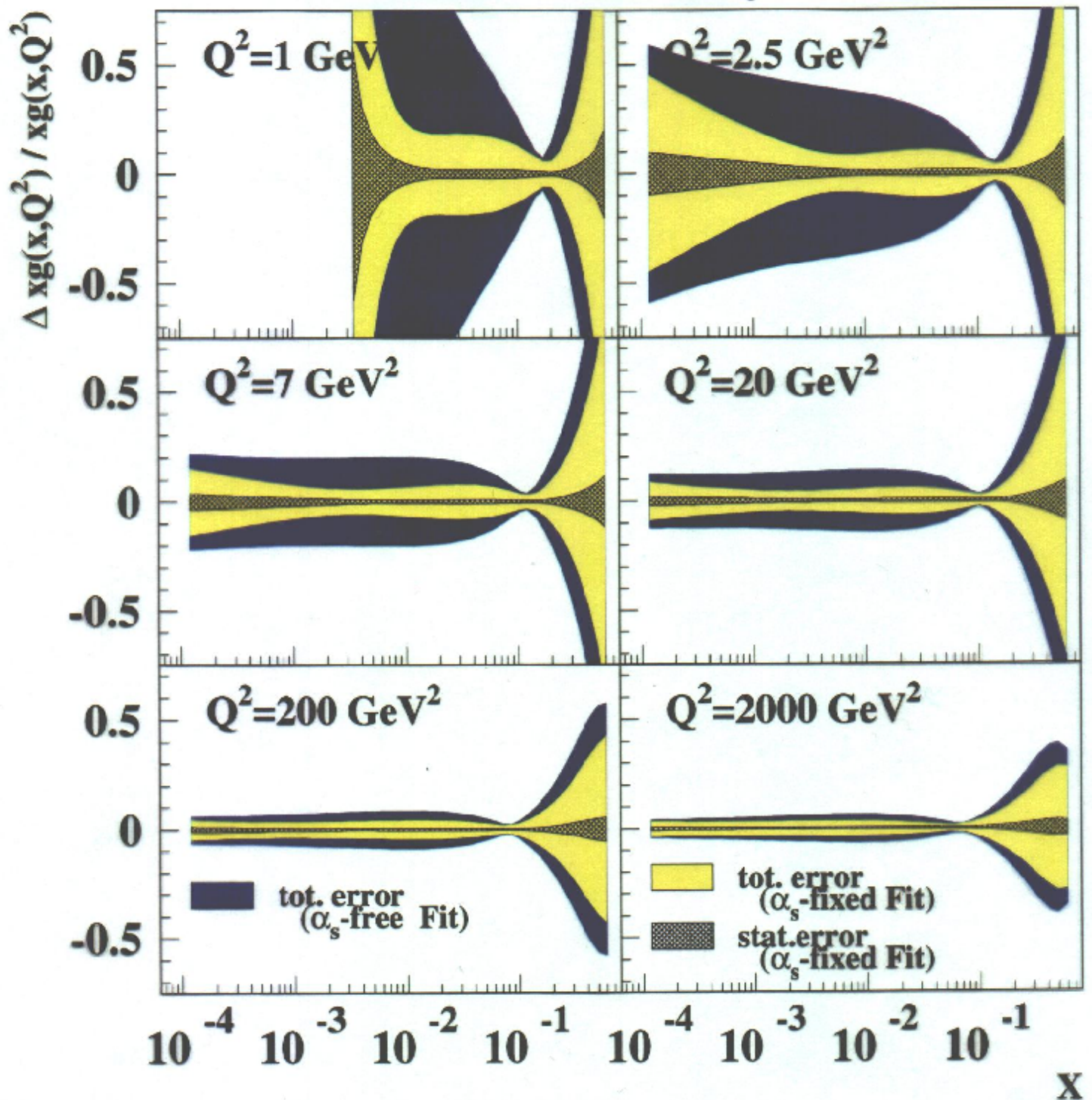


DIFFERING MODEL ASSUMPTIONS

- i, Parametrisation of xg
- ii, α_s different H1 $\leftrightarrow$ ZE
- iii, Treatment of heavy quarks
- [Treatment of systematic error]

uncertainty of x Gluon distribution

ZEUS Preliminary



- Uncertainty is reduced as Q^2 evolves.
- $10^{-3} < x < 10^{-1}$: well determined within $\lesssim 10\%$.
- $x \gtrsim 10^{-1}$: large uncertainty.

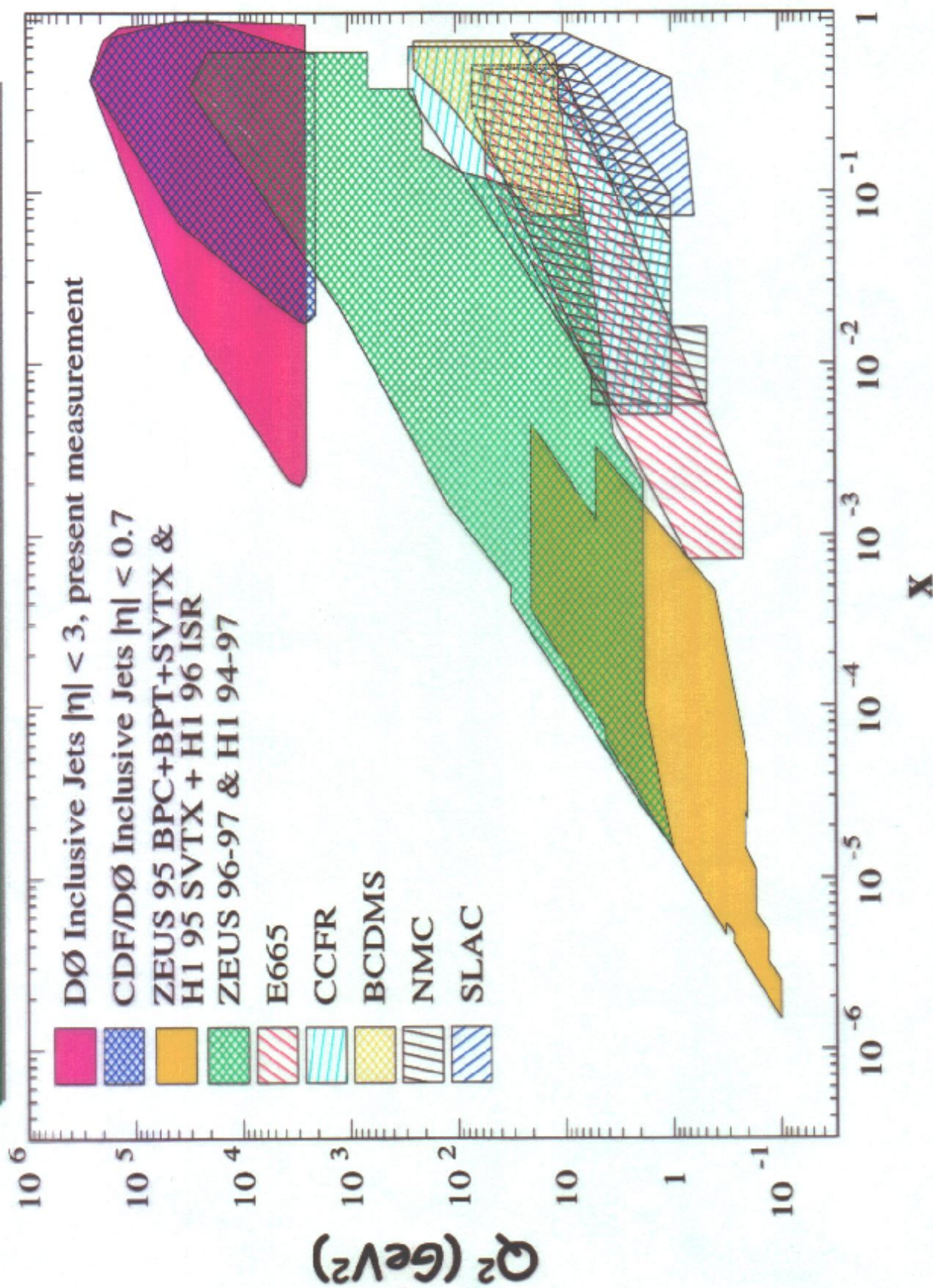
Gluon from Jet production at the Tevatron

L. Babukhadia

- NLO QCD fits to Inclusive DIS do not constrain high x gluon
- At the Tevatron it is possible to use the inclusive jet cross section to gain information on xg at high x

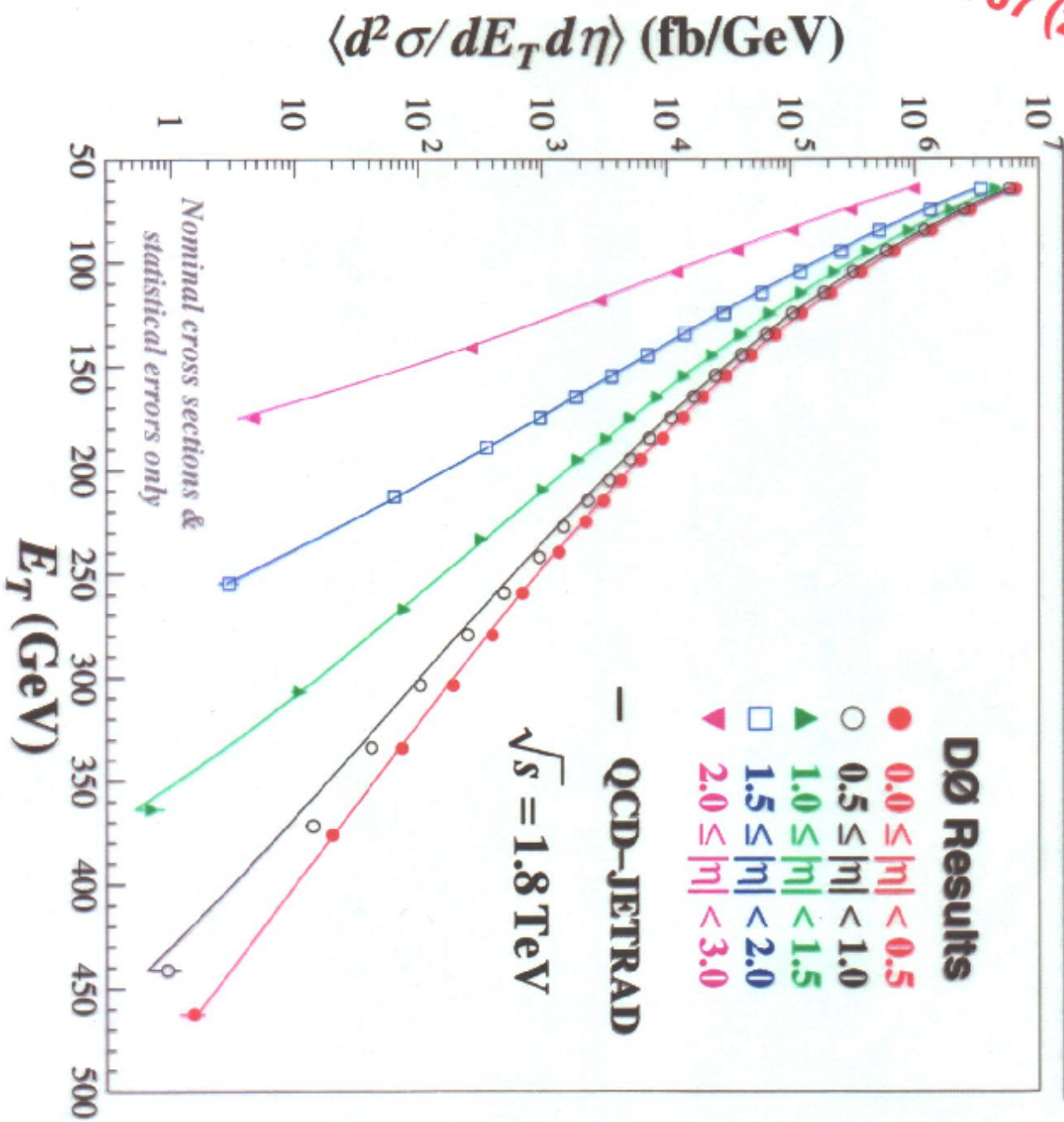
→ Measure jet cross section
at high E_T as fn of E_T
and η

Significantly Extended x - Q^2 Reach



PRL in print
Phys. Rev. Lett. 86, 1707 (2001)

Inclusive Jet Cross Section



PDF Discrimination / Derivation

World's best constraint on gluon PDF at high x

$$\chi^2 = \sum_{i,j} (D_i - T_i) \times [\text{Cov}_{i,j}^{\text{Full}}]^{-1} \times (D_j - T_j)$$

$$\text{Cov}_{i,j}^{\text{Full}} = \sum_{\beta} \text{errors} p_{i,j}^{\beta} \times \sigma_i^{\beta} \times \sigma_j^{\beta}$$

Variations of correlation coefficients within their uncertainties give a similar ordering of the χ^2 , hence a similar relative preference of PDFs

PDF	χ^2	χ^2/dof	Prob
CTEQ3M	121.56	1.35	0.01
CTEQ4M	92.46	1.03	0.41
CTEQ4HJ	59.38	0.66	0.99
MRST	113.78	1.26	0.05
MRSTgD	155.52	1.73	<0.01
MRSTgU	85.09	0.95	0.63

Currently being incorporated in new global PDF fits
by MRST group, CTEQ group next ...

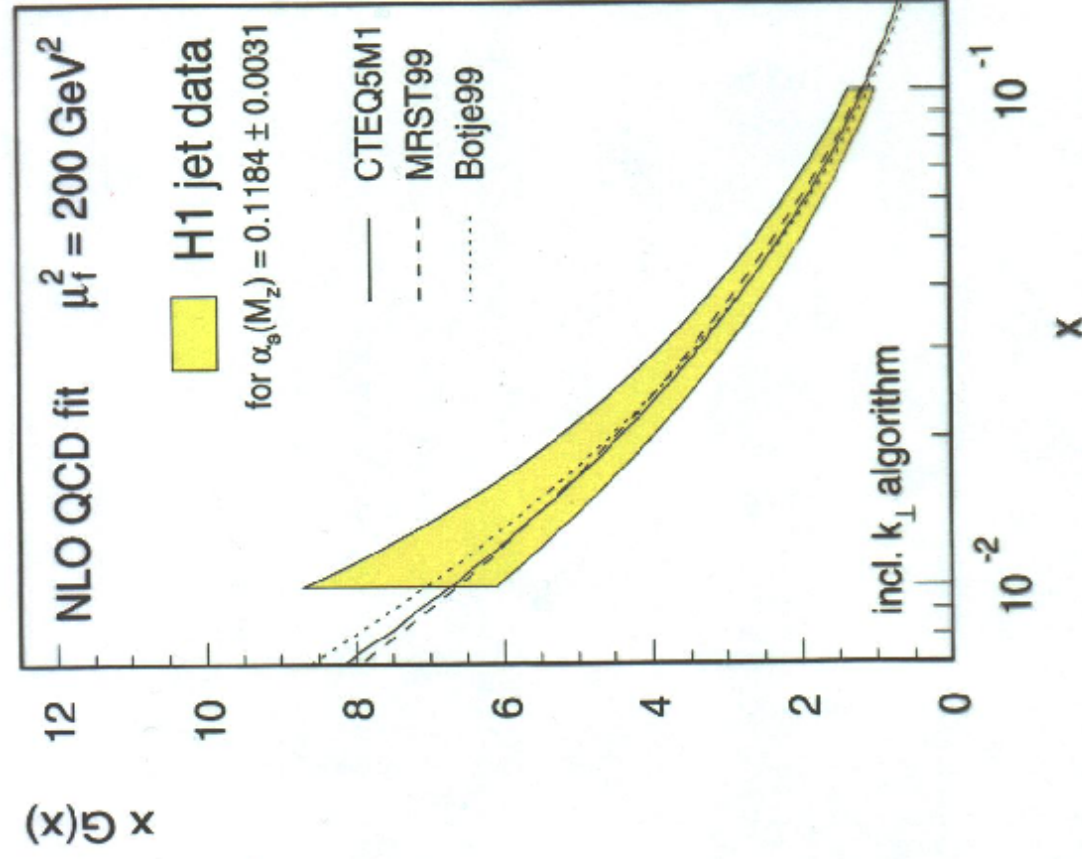
Gluon and α_s from Jet Cross Sections

G. Grindhammer

E. Tassi

- Jet production at high Q^2 sensitive to xq , xg and α_s
- Using JET Cross sections (G. Grindhammer)
Several possibilities:
 - $\Rightarrow$ Fit for PDFs and α_s ; large correlations, not too large sensitivity
 - $\Rightarrow$ Fix α_s and fit for xg (use inclusive DIS to constrain xq); 
 - $\Rightarrow$ Use 'off the shelf' PDFs and fit for α_s 
- Using ratio of rate of events with 2 (+1) jets to all events (E. Tassi)
 - $\Rightarrow$ Use 'off the shelf' PDFs and fit for α_s 

Determination of $xg(x)$

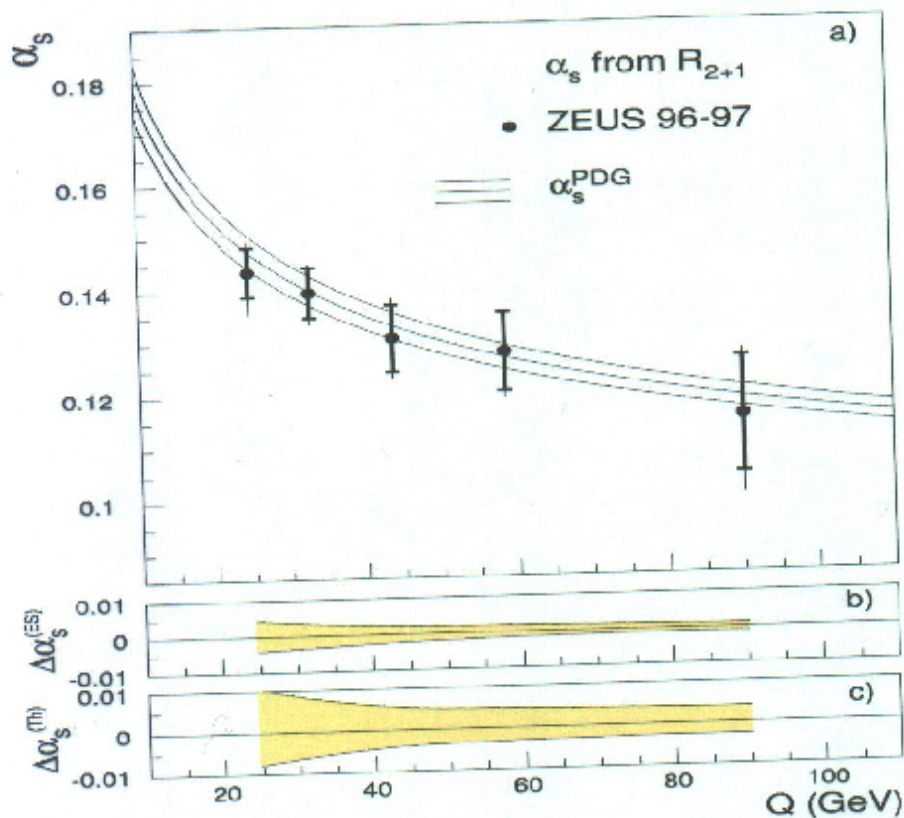


- Jet cross sections directly sensitive to $xg(x)$ and $xq(x)$
- Inclusive DIS (F_2) directly sensitive to $xq(x)$ only
- $\alpha_s(M_Z) = 0.1184 \pm 0.0031$

Direct determination from jets at $0.01 < x < 0.1$ is consistent with results from global fits

α_s from dijet production

ZEUS



$$\alpha_s(M_Z) = 0.1166 \pm 0.0019(\text{stat.}) \begin{matrix} +0.0024 \\ -0.0033 \end{matrix} (\text{exp.}) \begin{matrix} +0.0057 \\ -0.0044 \end{matrix} (\text{th.})$$

- Value in excellent agreement with the world average
- Competitive uncertainty (5-6%)
- Running checked over a large range in Q
- Limited by theory ($\Rightarrow$ NNLO)

Determination of $\alpha_s(M_Z)$

- Central pdf: CTEQ5M1

- Data: $d^2\sigma_{\text{jet}}/dE_T dQ^2$

$$\alpha_s(M_Z) = 0.1186 \pm 0.0030 \text{ (exp.) } {}^{+0.0039}_{-0.0045} \text{ (th.)}$$

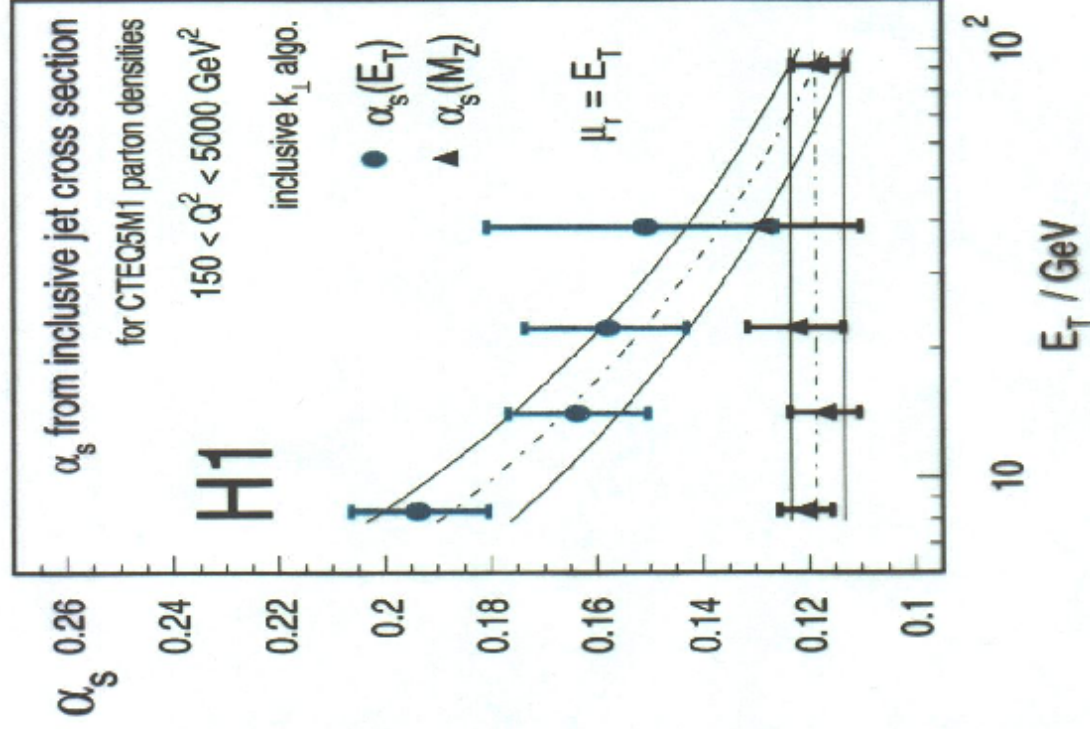
- Experimental error:

- stat. error = 0.0007
- largest syst. error due to hadronic energy scale uncertainty

- Theory error:

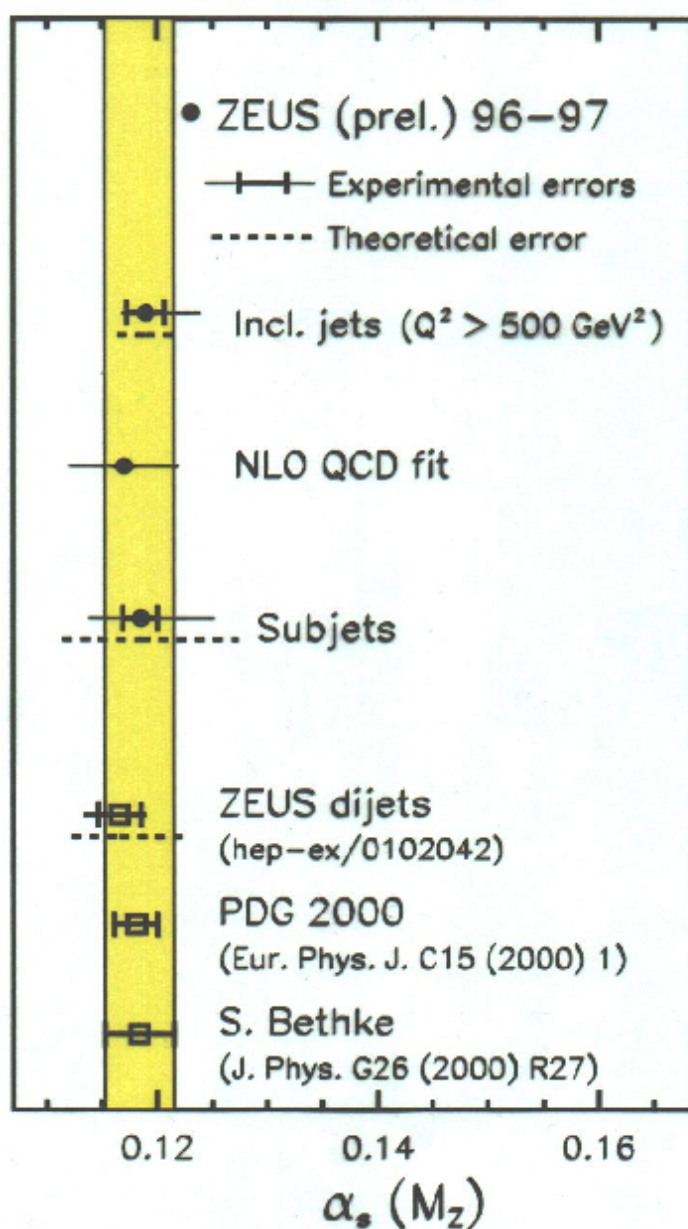
- hadronization uncertainty ≈ 0.0030
- μ_R scale uncertainty ≈ 0.0030

Running of $\alpha_s(E_T)$ consistent with RGE

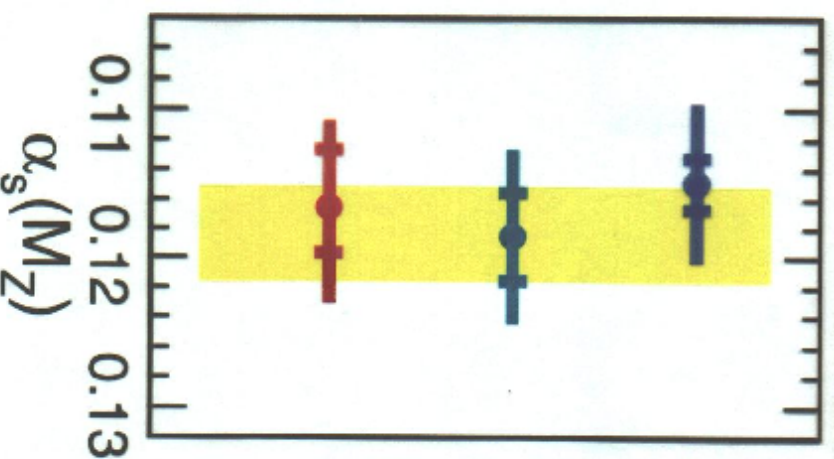


α_s Summary

ZEUS



$\alpha_s(M_Z)$ from Jets and F_2 in DIS at HERA



(H1+BCDMS) Structure Functions

$$3.5 < Q^2 < 3000 \text{ GeV}^2 \quad / \quad \mu_r = Q$$

H1 – Inclusive Jet Cross Section

$$150 < Q^2 < 5000 \text{ GeV}^2 \quad / \quad \mu_r = E_T$$

ZEUS – Dijet Rate

$$470 < Q^2 < 20000 \text{ GeV}^2 \quad / \quad \mu_r = Q$$

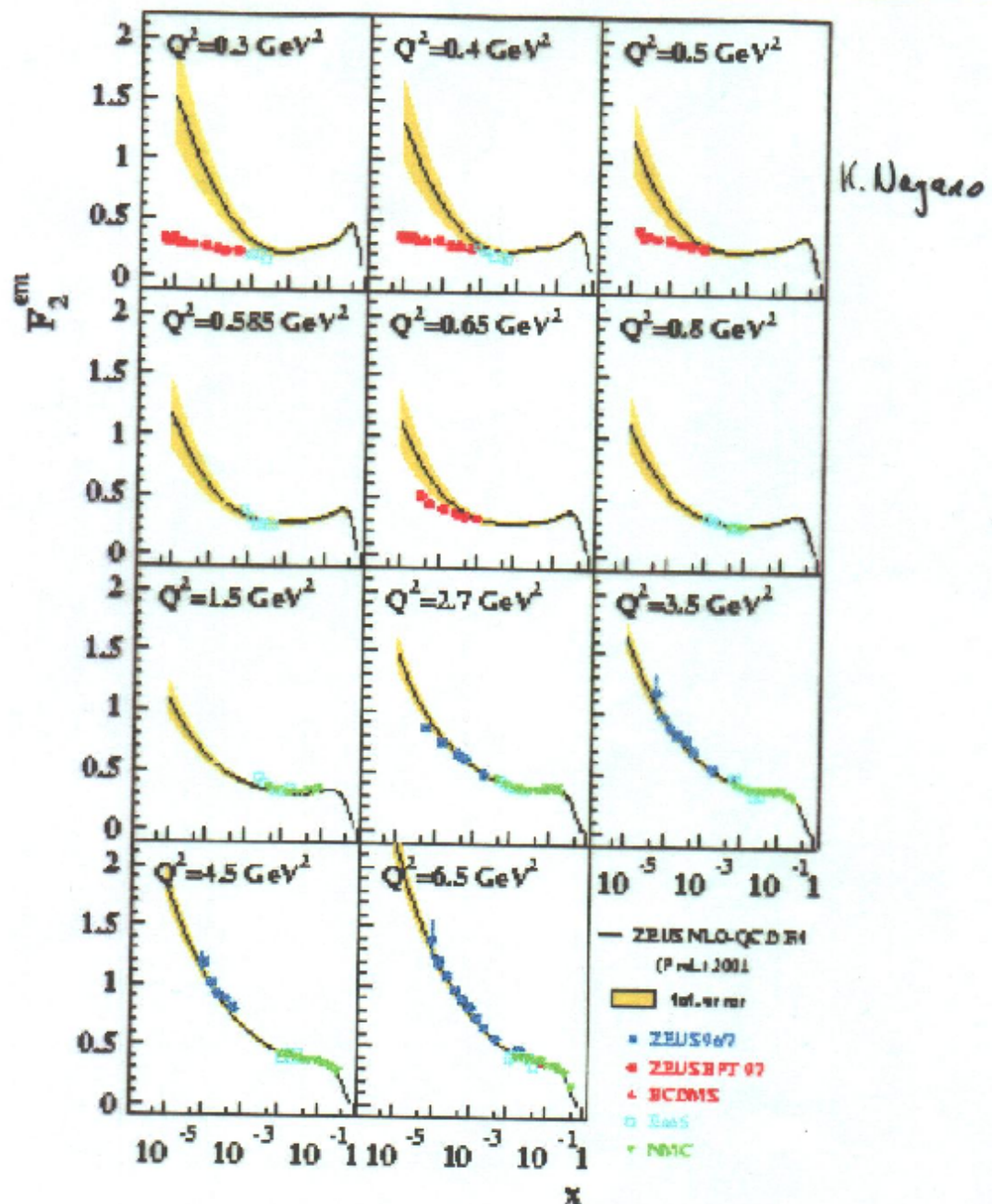
World average

(S. Bethke, J.Phys. G26 (2000) R27)

⇒ Consistent new determinations of $\alpha_s(M_Z)$ from jets and from inclusive DIS at HERA

⇒ Small errors allow impact on world average value

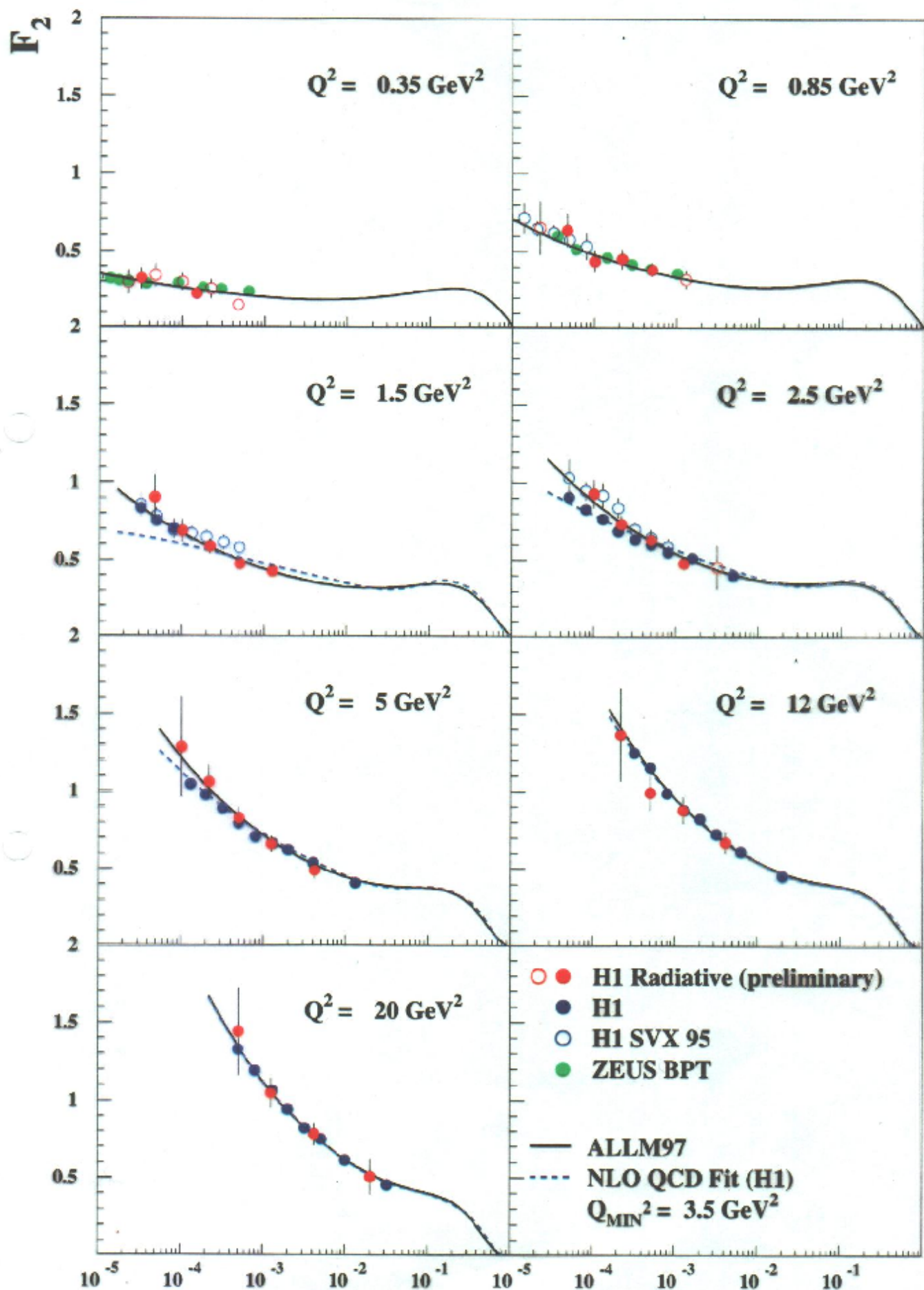
Structure Functions at low Q^2

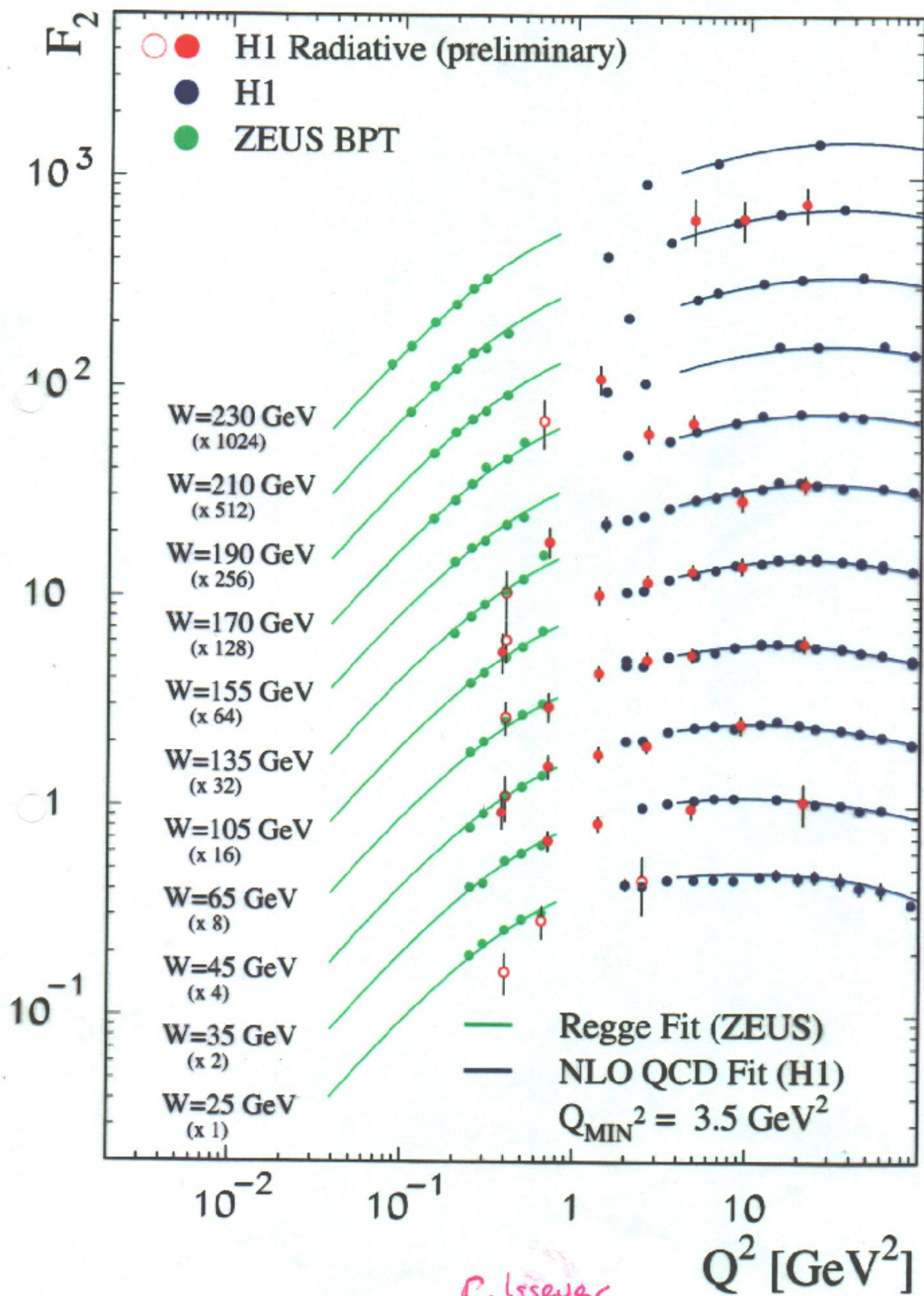


- Behavior of F_2 at low Q^2 appears to undergo a transition in the region of $Q^2 \sim 1-2 \text{ GeV}^2$
- New measurements of F_2 from H1 for $Q^2 < 2.5 \text{ GeV}^2$ using events with initial state radiation

C. Issever

Radiative - Non Radiative



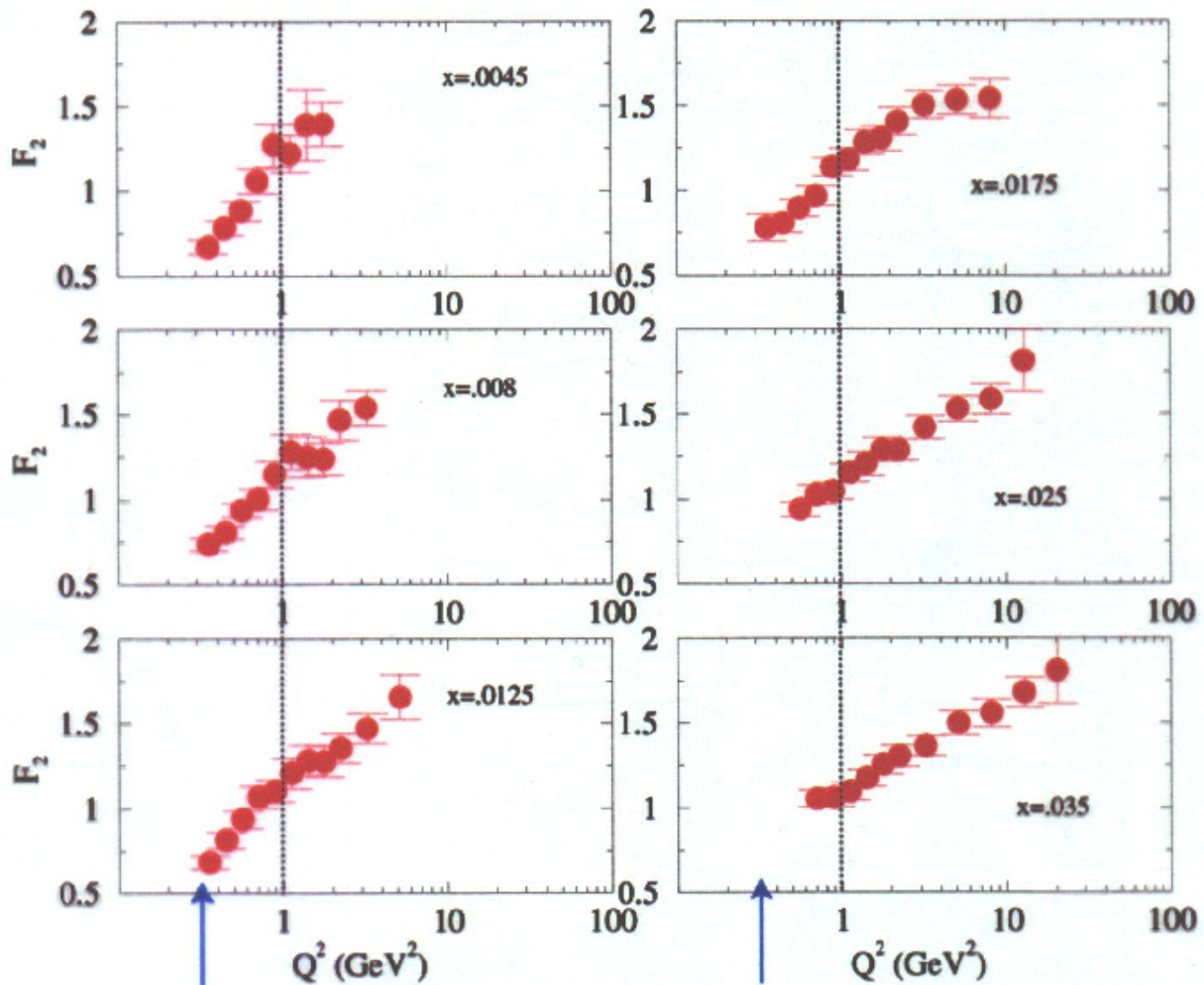


First measurement of F_2^ν

at low x , low Q^2 in νN DIS

CCFR $F_2(x, Q^2)$

hep-ex/0011094 accepted in PRL



New
Analysis

New
Analysis

R. Bernstein

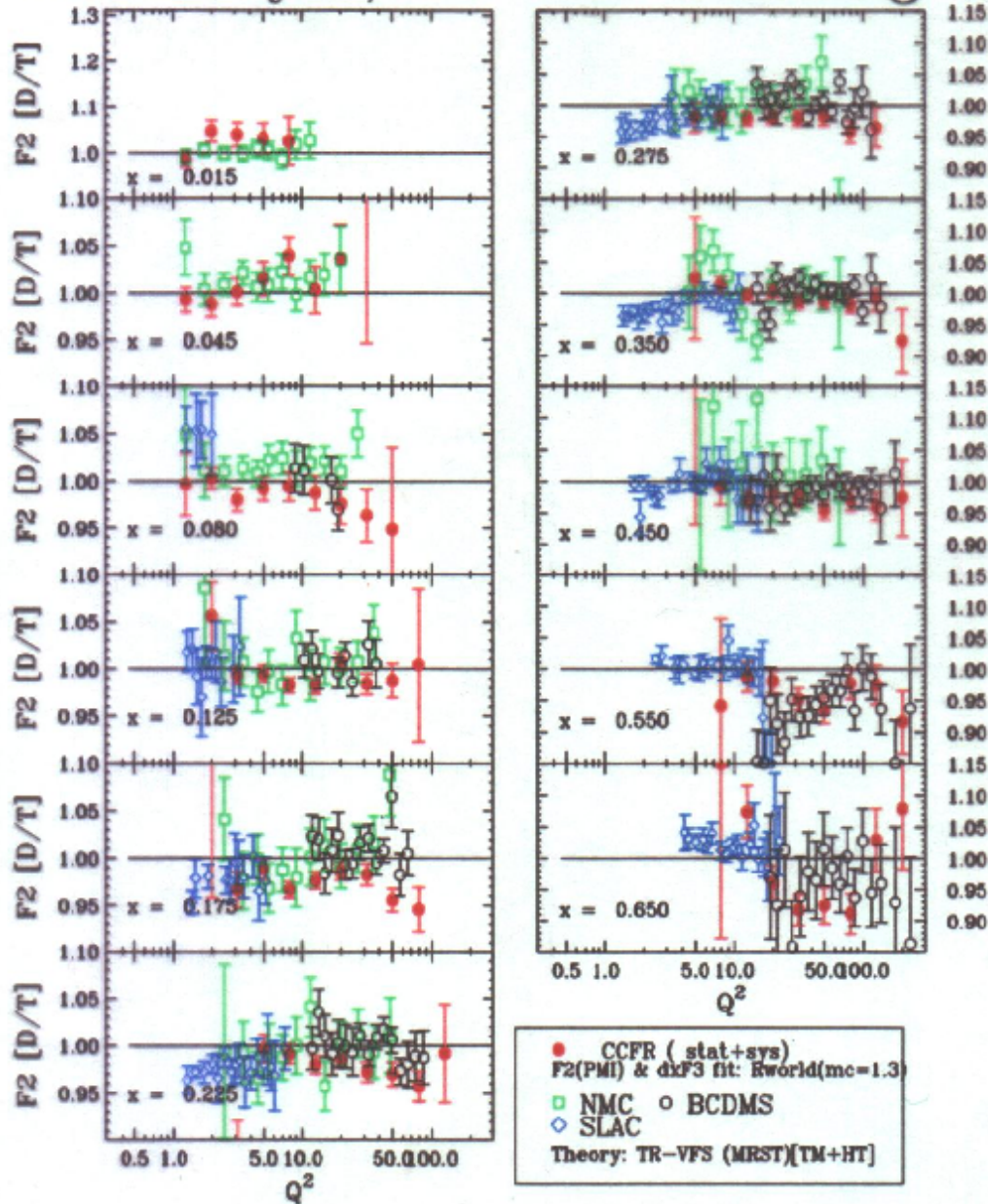
Resolved Long-Standing
Discrepancy By

(1) m_c NLO corrections

(2) $\Delta x F_{3,R}$ (see Bodek)

Comparison of F_2^ν and F_2^μ

- This analysis, **NO** Slow-Rescaling Applied



- Discrepancy Gone

R. Bernstein

The Longitudinal Structure Function

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

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

$$F_L^{\text{NC}} \propto \frac{\alpha_S}{\pi} \beta_2 \otimes xG$$

- Several determinations of F_L and R presented:

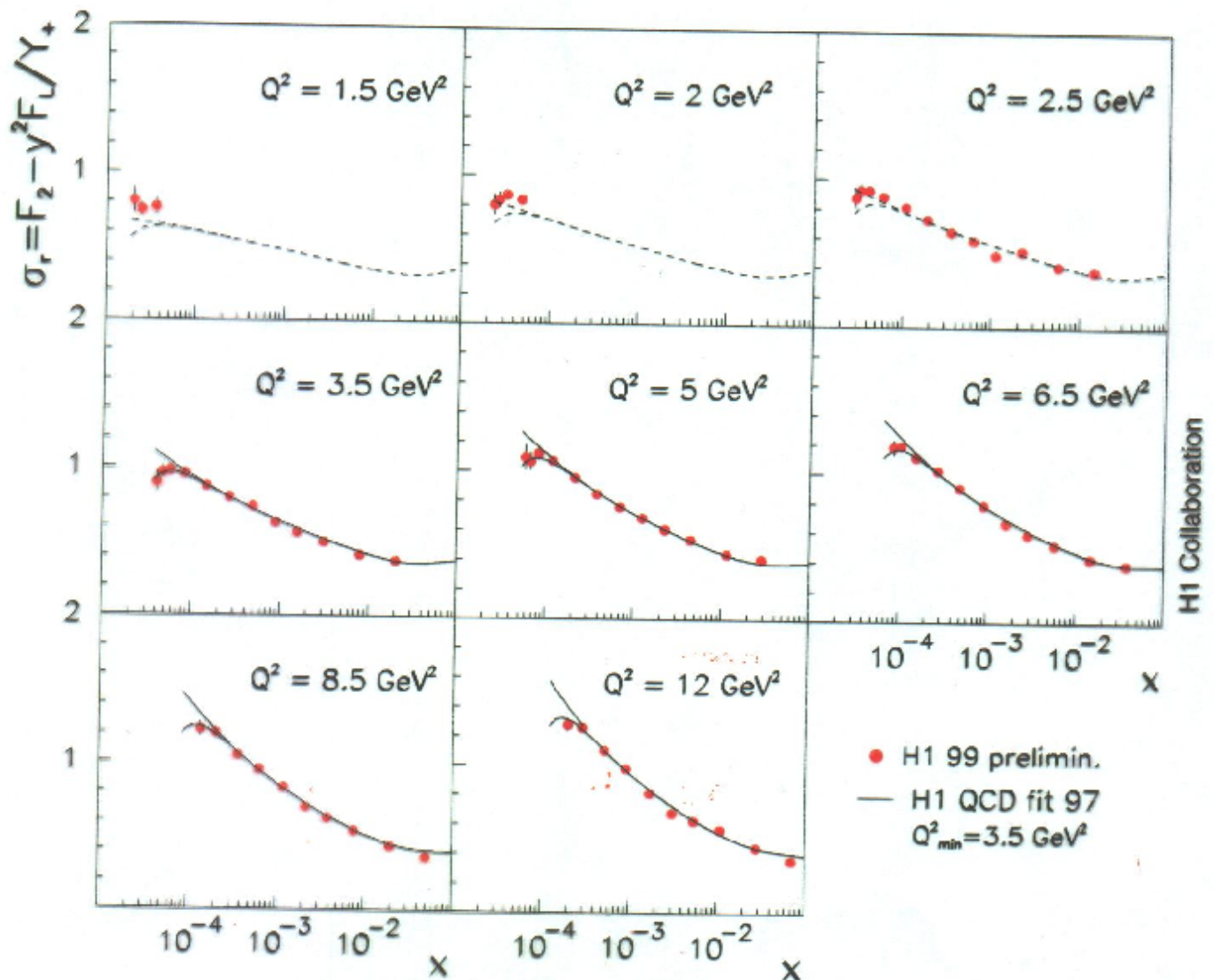
⇒ From measurement of reduced cross section at high y in ep

D. Eckstein, A. Dubak

⇒ From sum of neutrino and anti-neutrino nucleon DIS cross section (see later)

A. Bodek

+ new cross section data @ $1.5 \leq Q^2 \leq 12 \text{ GeV}^2$

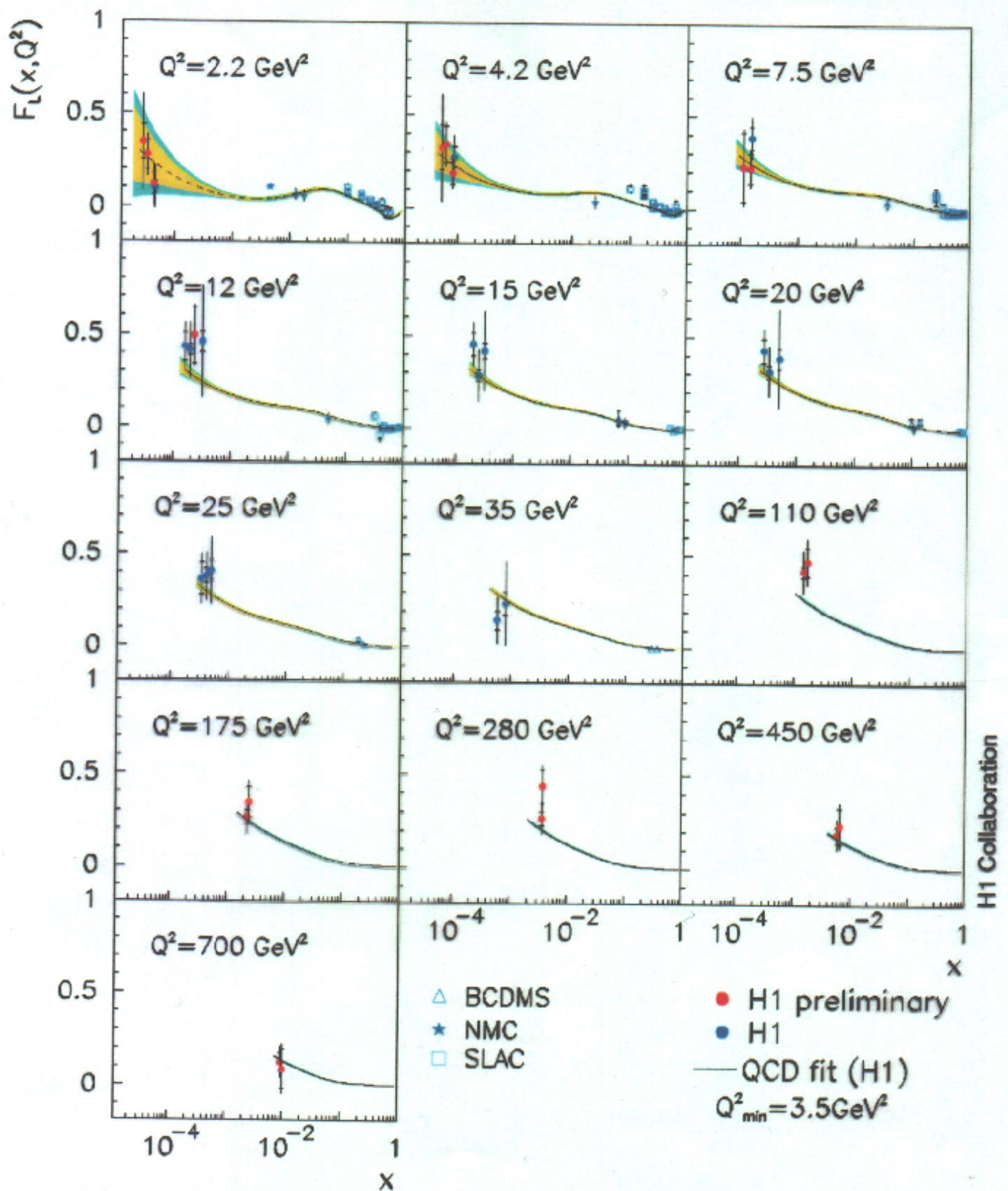


+ agrees with H1 NLO QCD fit to 96/97 data

$$Q^2 = xgs$$

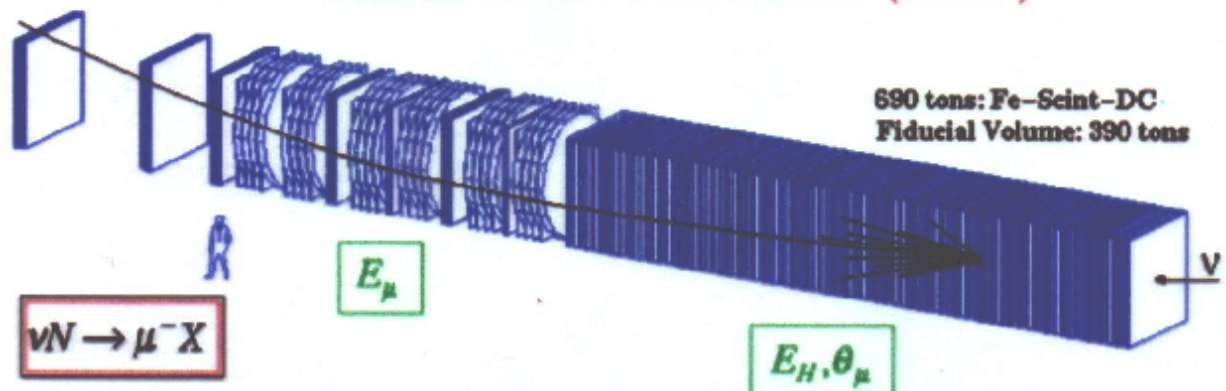
D. Eckstein

H1 Results for F_L

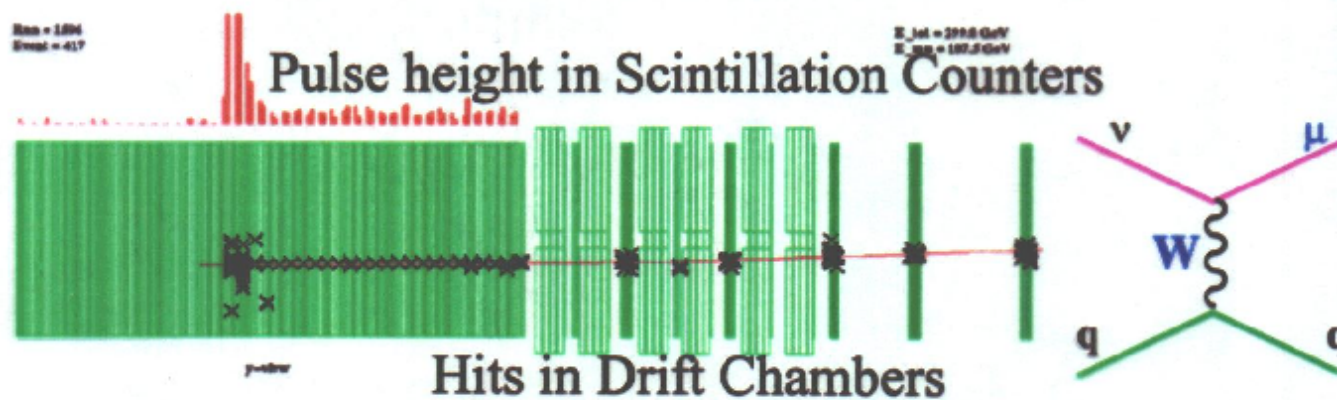


CCFR = WideBand
NuTeV = Sign-Selected

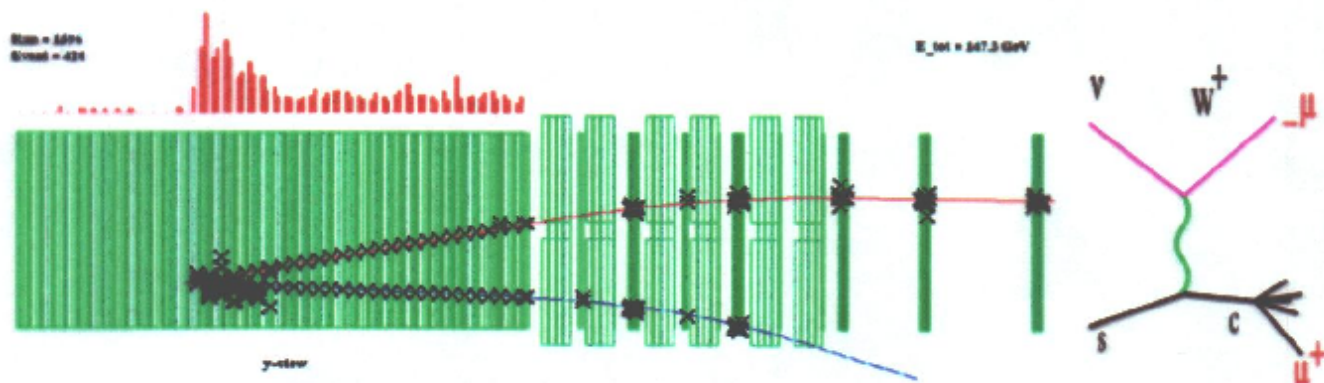
LAB-E Detector - Fermilab E815 (NuTeV)



Charged Current



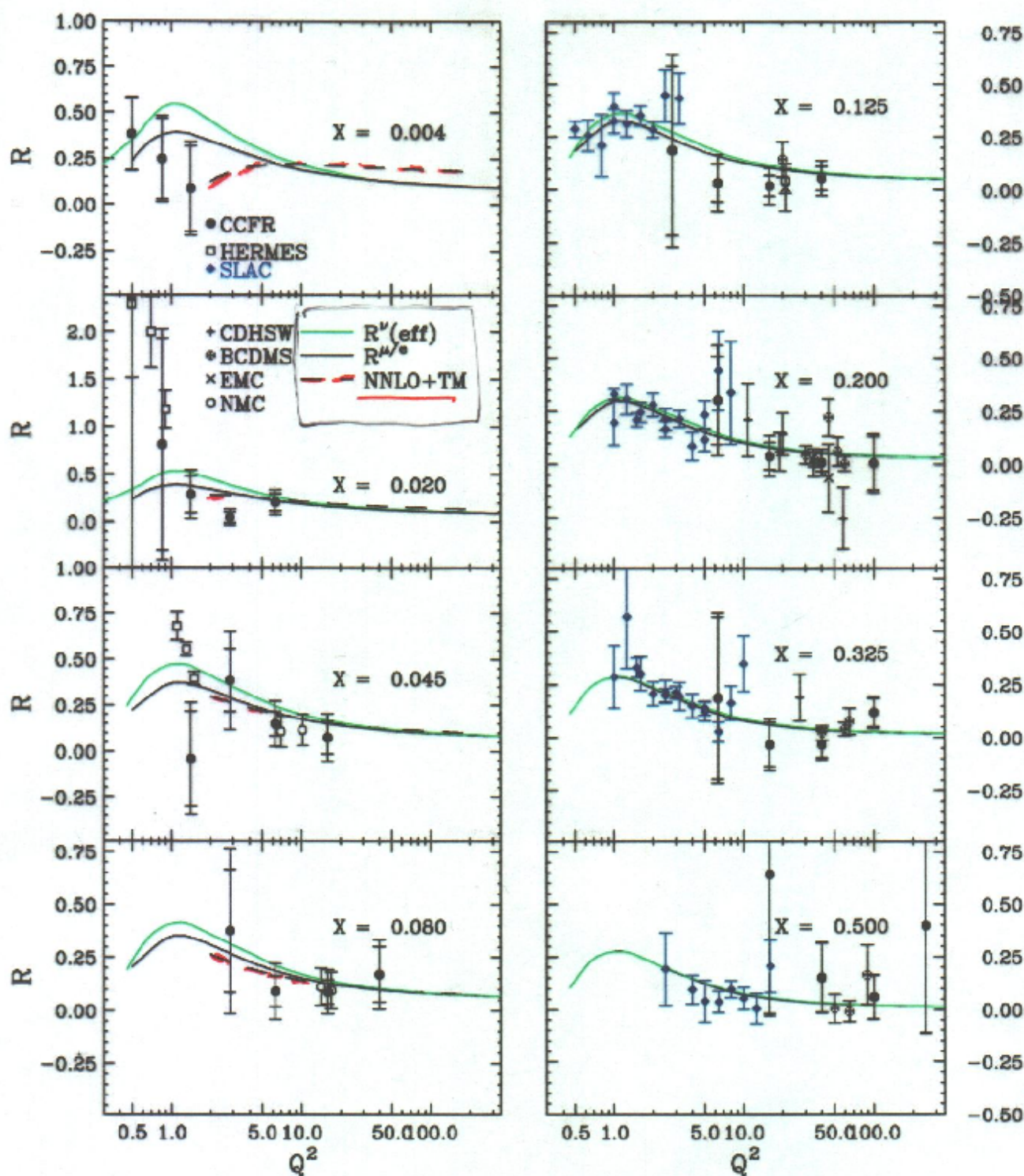
Opposite Sign Dimuon



R. Bernstein

R^{ν} - from $\sigma^{\nu} + \sigma^{\bar{\nu}}$ CCFR (wide-band)

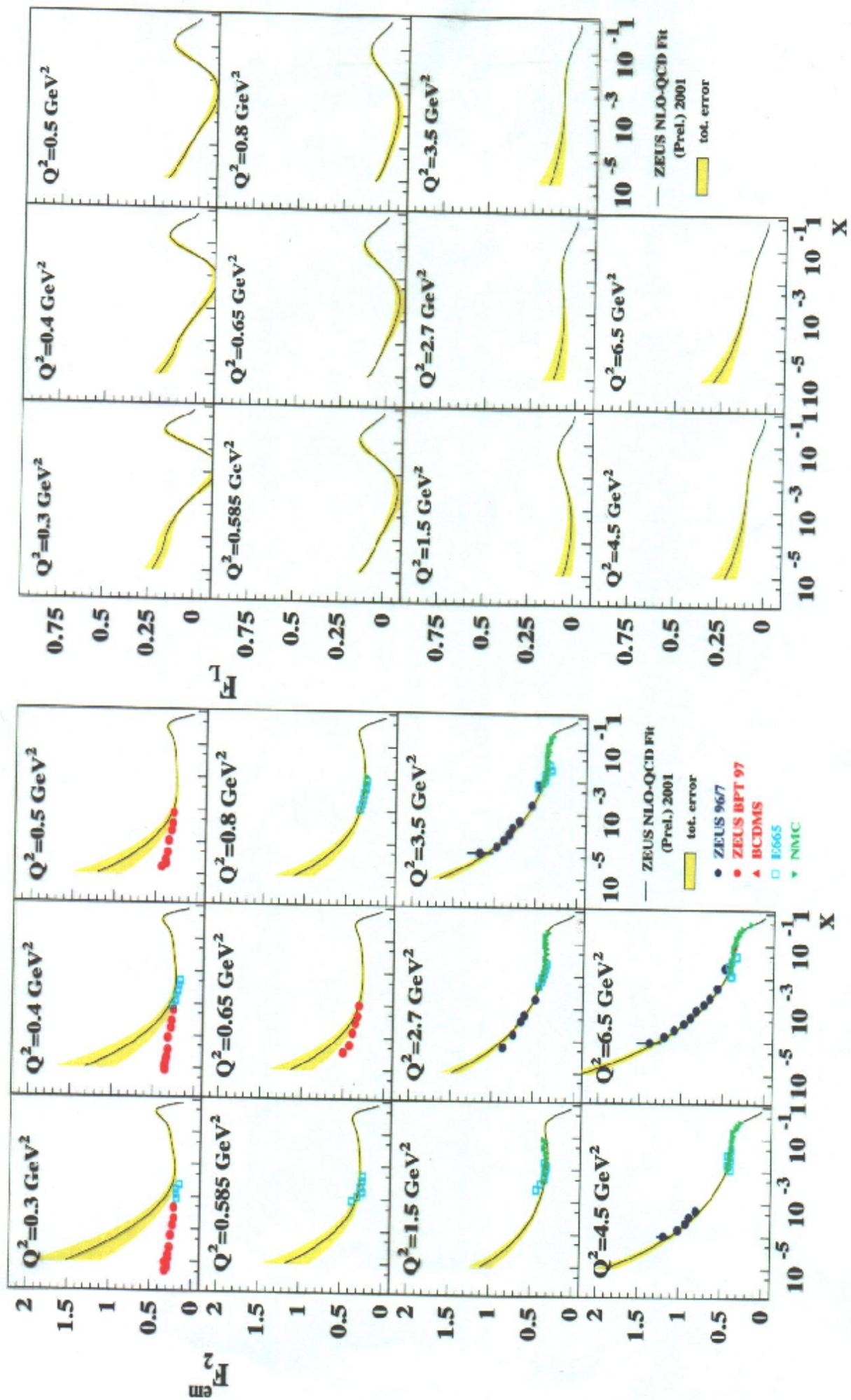
A. Bodek



--- NNLO+TM (including MRST NNLO PDFs) + NNLO $g/4\pi W$

[systematic errors include uncertainty in PDFs due to theory + due to strange sea]

Transition region: extrapolation down to very low $Q^2 \sim 0.3 \text{ GeV}^2$

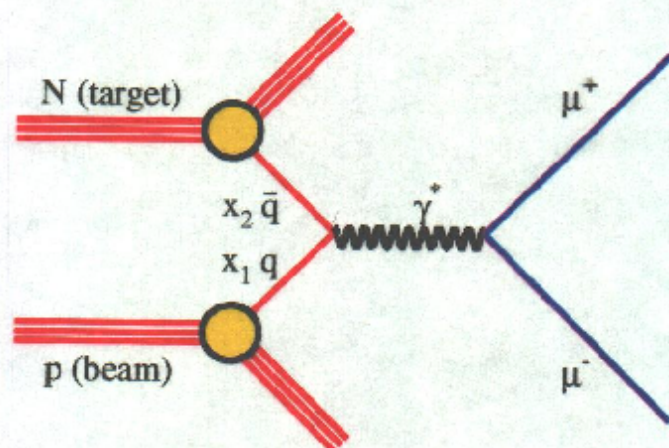


- QCD-fit tends to overshoot ZEUS BPT data points.
- Limit of pQCD: seems to be $Q^2 \sim 1 \text{ GeV}^2$; F_L goes negative.

Flavour specific PDFs

- At Tevatron: $\bar{d}/\bar{u}$ by Drell-Yan ($pN \rightarrow \mu\mu X$) 
- At HERA: $c/\bar{c}$ by identification of charm in final state: D^* tag (ZEUS and H1) or semi-leptonic tag (ZEUS) 
- At NuTeV/CCFR: $s/\bar{s}$ by semi-leptonic tag 
- Also at NuTeV/CCFR measurement of sum of neutrino and anti-neutrino cross sections gives measure of $s-c$ 

The Drell-Yan Process: $pN \rightarrow \mu^+ \mu^- X$



- Directly sensitive to **antiquark** distributions.

$$\frac{d^2\sigma^{pN}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1x_2} \sum_i e_i^2 [q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)]$$

- Relevant kinematic quantities:

$$x_F \approx 2p_L/\sqrt{s} = x_1 - x_2 \text{ and } M_{\mu^+\mu^-}^2 = sx_1x_2$$

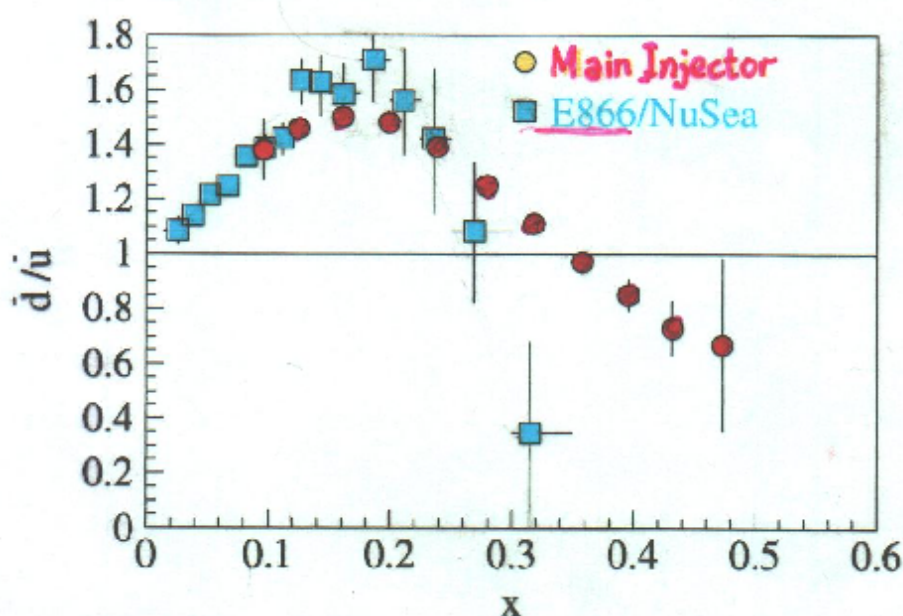
- Compare **Drell-Yan** yields from nuclear targets (Liquid H_2 and D_2) and extract $\bar{d}/\bar{u}$.
if charge symmetry is assumed.

$$\left. \frac{\sigma^{pd}}{2\sigma^{pp}} \right|_{x_1 \gg x_2} \approx \frac{1}{2} \left[1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right]$$

D. Isehower

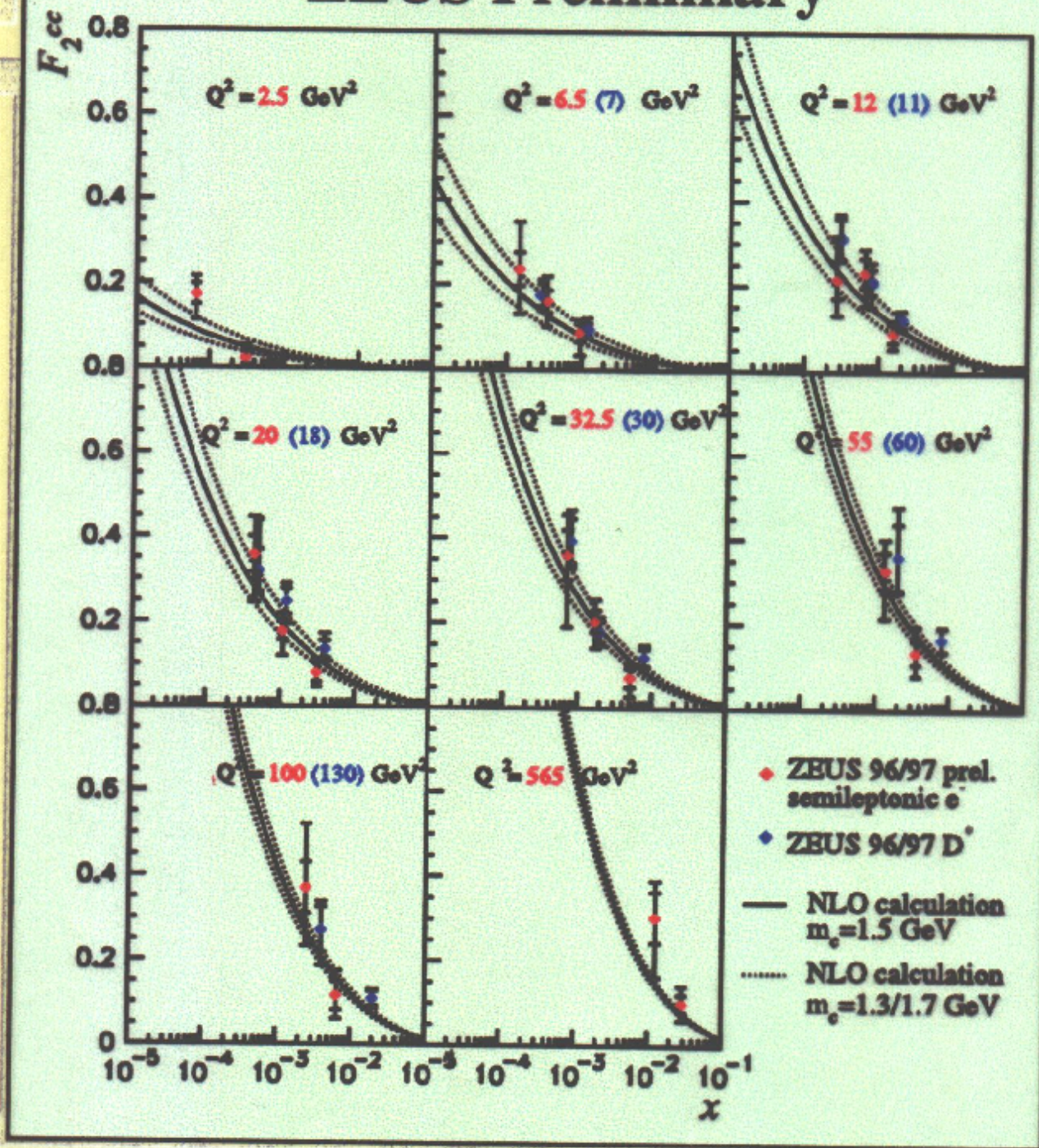
Summary

- Strong Motivation in Fundamental QCD Physics:
 - Measure **antiquark distributions at high x** .
 - Understand **origins of the proton's partonic sea**.
 - Study parton level **differences between the nucleon and nuclei**.
- Well Understood Measurements:
 - NLO QCD nicely describes Drell-Yan process—provided antiquark and quark distributions are known.
- Easily Achievable Detector/Experiment:
 - **Most equipment already exists**.
 - **No technological show-stoppers**.
 - **Low proton intensity requirements** (10^{12} protons/pulse).



F_2^{charm}

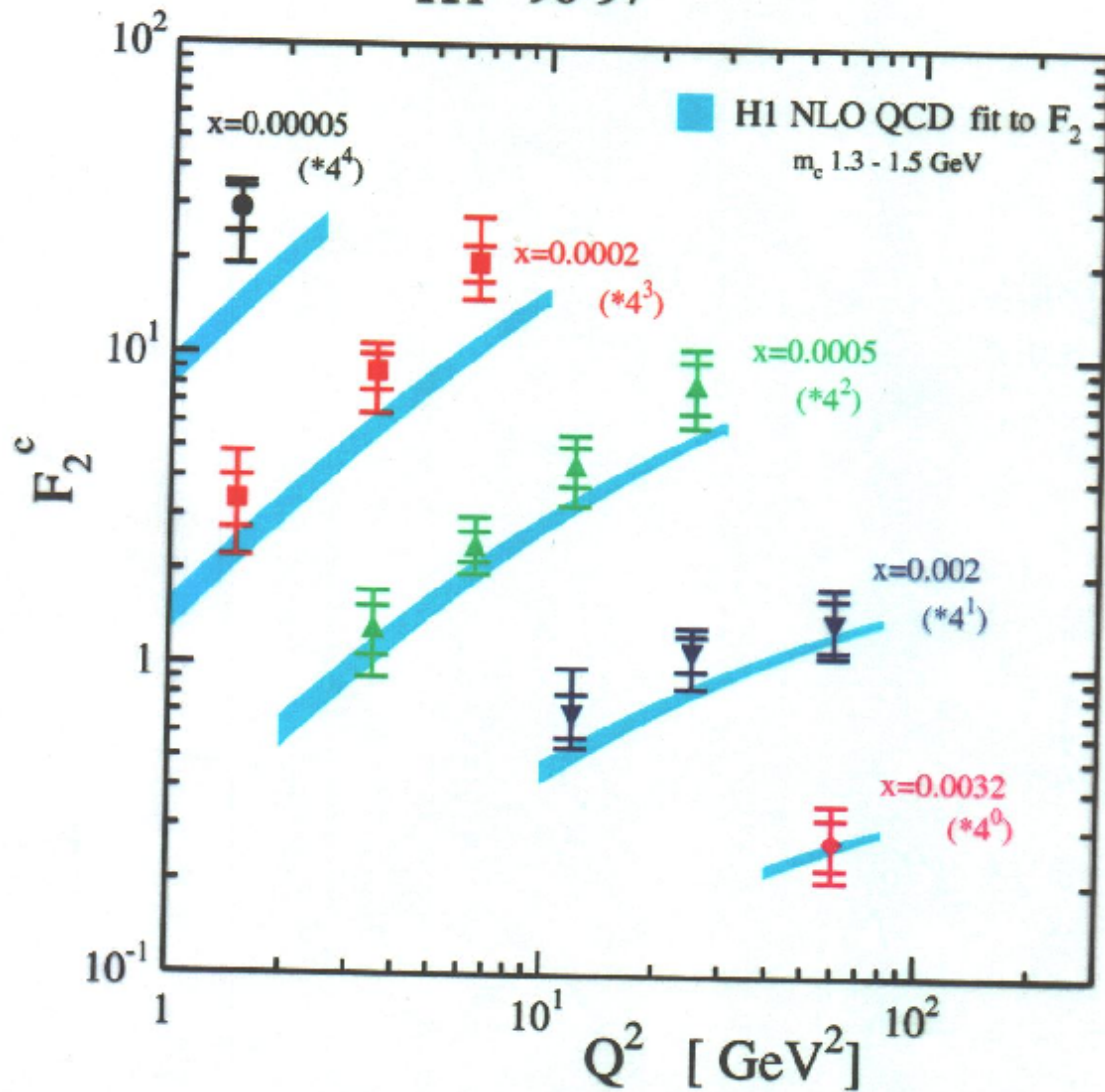
ZEUS Preliminary



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

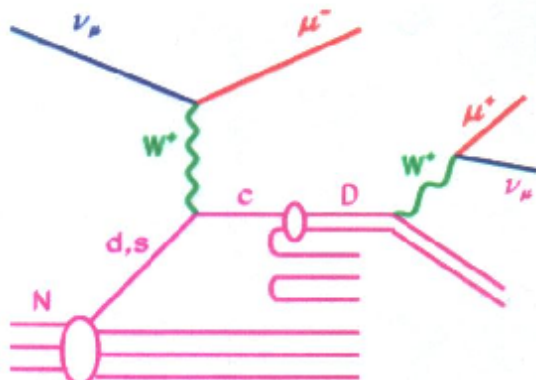
S. Mohr diech

F_2^c in the NLO DGLAP scheme
H1 96-97



- strong scaling violations
- Q^2 slope tends to be stronger in data

Charm Production $\Rightarrow$ Dimuons



$$\nu_\mu + N \rightarrow \mu^- + c + X$$

$$c \rightarrow q + \mu^+ + \nu_\mu$$

- $\sim 0.5\%$ of NuTeV CC events
- $\sigma \sim 10\%$ of total CC at high E_ν
- charmed hadron decay probability $\sim 10\%$

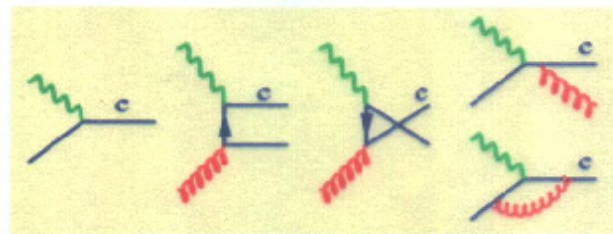
Production from $d(\bar{d})$ quarks **Cabibbo suppressed** $\Rightarrow$ **large s contribution**: $\sim 50\%$ in ν and $\sim 90\%$ in $\bar{\nu}$

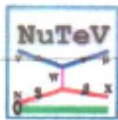
★ Measure s-PDF

- potential non-pQCD effects ($s/\bar{s}$ asymmetry)
- charged lepton/neutrino SF comparison
- important x-section calculations (e.g. stop search in hadron colliders, where BGND is $g + s \Rightarrow W + c$)

★ Study heavy quark production (2scale QCD problem)

★ Measure c-mass, V_{cd}





Dimuon Cross-Section Tables

Model independent result: x-section

✓ measurement for $E_{\mu 2} > 5\text{GeV}$ (acceptance $> 55\%$)

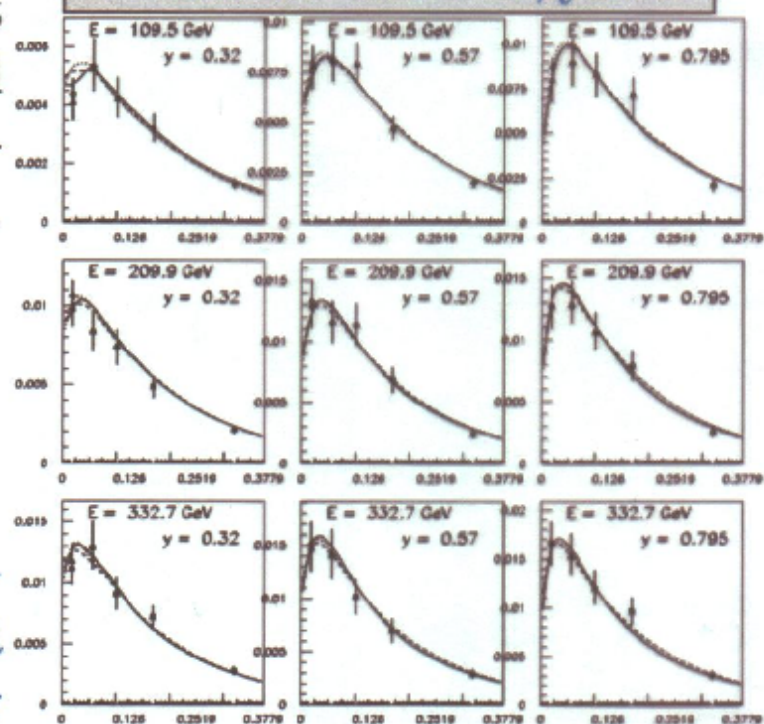
✓ MC described data well with all LO PDF sets

- use MC to unfold flux, correct for acceptance, smearing

✓ x-section extracted with all 3 PDFs: no model dependence

→ as a check, fit to x-section tables, and compare model parameters to direct data fits. No bias found!

ν x-section vs x in E, y bins



→ clean way to combine NuTeV with CCFR
⇒ just produce tables for each experiment

X →

Select your favorite DIS charm production, fragmentation and decay models and fit table entries

- NLO QCD fit to ν and $\bar{\nu}$

Dimuon xsections performed

$$\Rightarrow \text{Strange sea} \approx 0.4 \times [u, \bar{u} \text{ sea}]$$

$$\Rightarrow S \approx \bar{S}$$

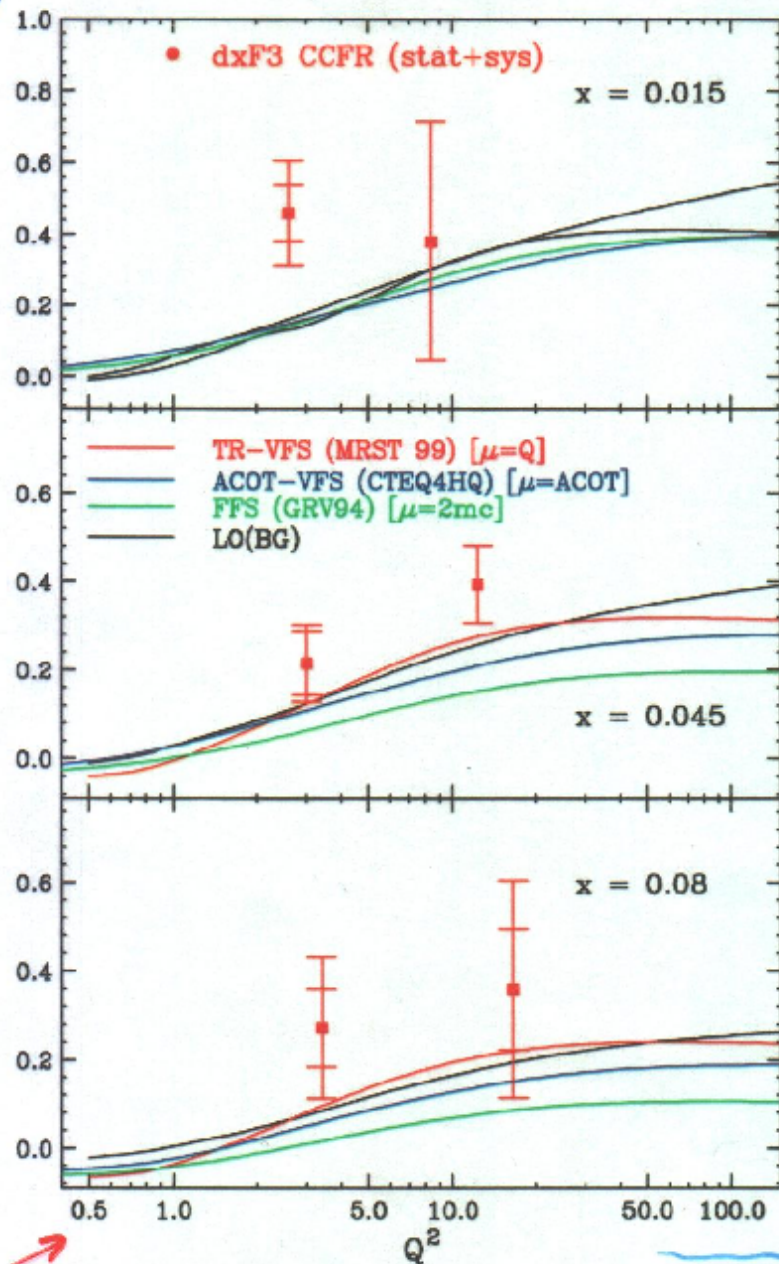
- Neutral current (single muon) cross sections do not require introduction of intrinsic charm.

M. Goncharov

At

L.O.

$$\Delta x \bar{F}_3^v = x \bar{F}_3^{\text{LO}} - x \bar{F}_3^{\text{LO}} = 4x(s-c)$$

 $\Delta x \bar{F}_3^v$ A. Bodek

low Q^2
 s quark is
 very small

Fitting for $\Delta x F_3, F_2$
 assuming $R = R_{\text{eff}}(\text{world})$

$(\Delta x F_3)_{\text{LO}} = 4x(s-c)$
 get s quark from deinson data.

April 23, 2009

Outlook:

- At DIS01 we have seen:
 - ⇒ High Q^2 NC and CC Cross Sections
 - ⇒ NLO fits: extraction of xG and α_s
 - ⇒ Structure functions at low Q^2
 - ⇒ The longitudinal structure function
 - ⇒ Flavour specific PDFs
- Eagerly awaiting new data from HERA, Tevatron (collider and neutrino experiments) ...