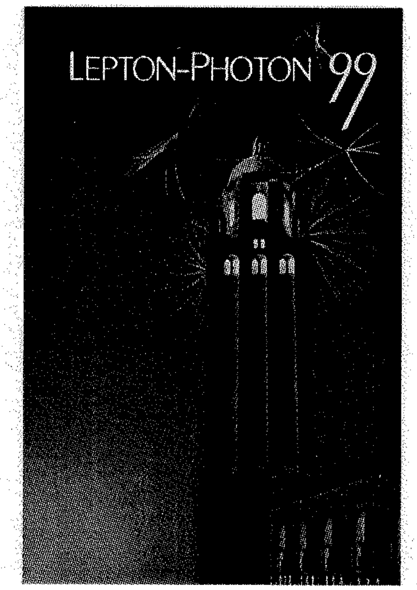
Structure Functions in Deep-Inelastic Lepton-Nucleon Scattering

Max Klein

DESY Zeuthen

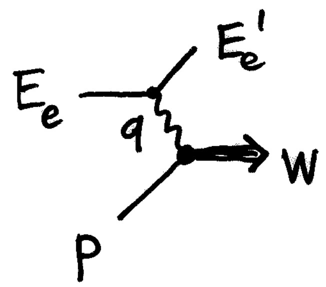


LEPTON-PHOTON '99
XIX International Symposium
on Lepton and Photon Interactions at
High Energies
Stanford University
August 9-14, 1999

1969

" observed behaviour of highly inelastic ep scattering "

SLAC · MIT



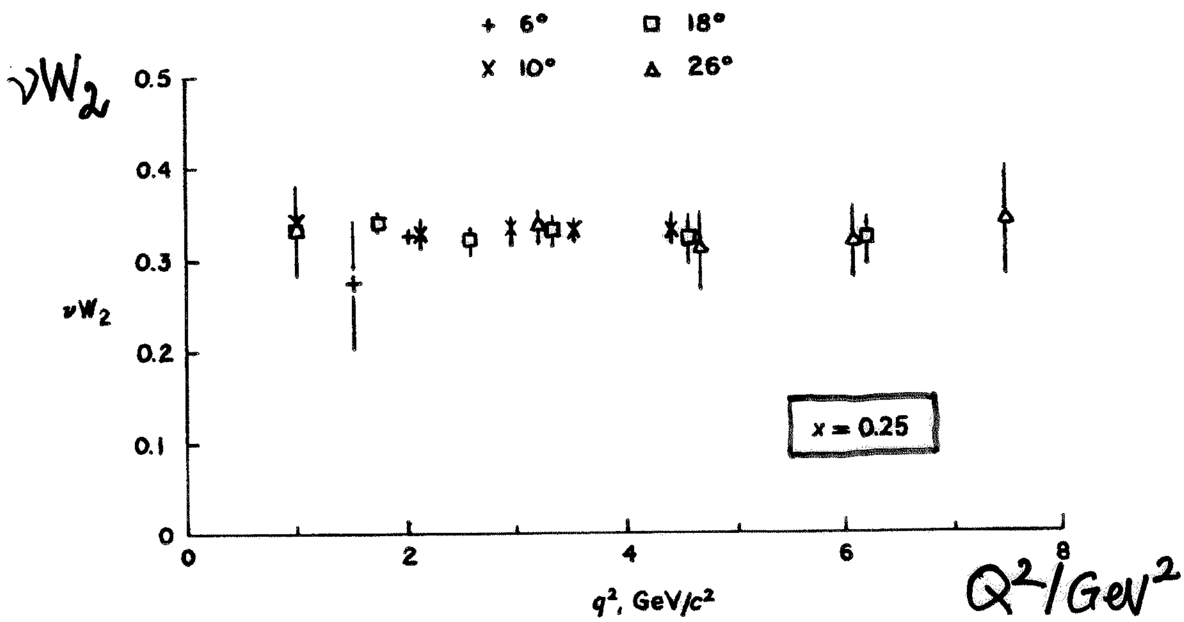
$$W^2 = (q+p)^2 = M^2 - Q^2 + 2M\underbrace{(E_e - E_e')}_{\nu}$$

$$x = \frac{Q^2}{2M\nu} \quad , \quad 2M\nu = s \cdot y \quad , \quad s = 2ME_e$$

proton structure function $\quad \nu W_2(Q^2,\nu) \rightarrow F_2(x)$

$Q^2 \rightarrow \infty, \ \nu \rightarrow \infty$

Bj scaling



- partons at 10^{-16} m. $\qquad F_2 = x \sum Q_q^2 (q + \bar{q})$

1979

polarized $\vec{e}p$ scattering asymmetry measured at SLAC

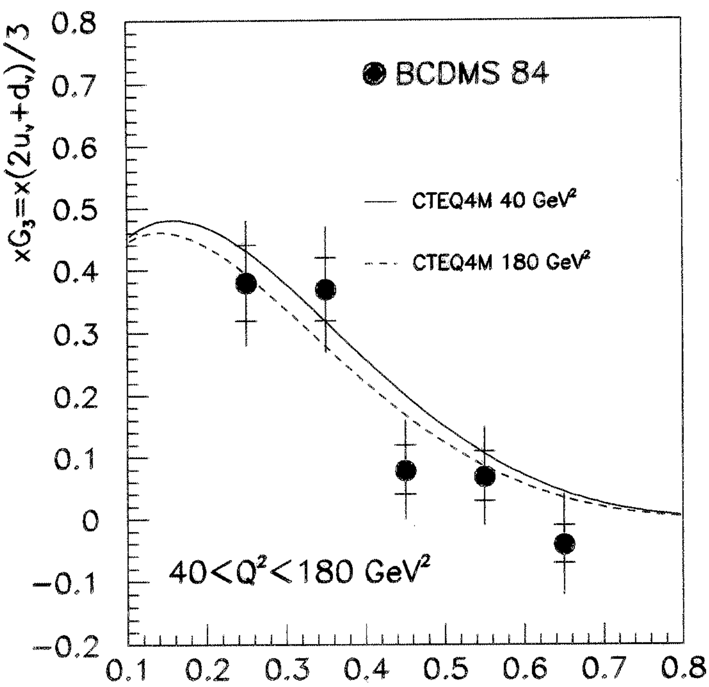
$$A = \frac{\sigma(\lambda)-\sigma(-\lambda)}{\sigma(\lambda)+\sigma(-\lambda)} \sim \lambda \cdot K \cdot a_e \frac{G_2}{F_2} \quad , \; K \sim 10^{-4} \frac{Q^2}{GeV^2}$$

$a_e = I_3^L(e) - I_3^R(e)$. e_R singlet . $A \sim a_e v_q$ PV.

- probe nucleon structure with γ and Z exchanged

$$F_2 \rightarrow x \sum (Q_q^2, 2Q_q v_q, v_q^2 + a_q^2)(q+\bar{q}) = (F_2, G_2, H_2)$$

xG_3



x

γZ interference structure function $xG_3 = x(2u_v + d_v)/3$

$$\mu^\pm(\mp\lambda)C \rightarrow \mu^\pm X$$

$$xF_3 \text{ in NC}: 2x \sum(-, Q_q a_q, v_q a_q)(q-\bar{q}) = (0, xG_3, xH_3)$$

$$\sigma^\pm \sim Y_+ F_2 \mp K Y_- xG_3 \quad . \; Y_\pm = 1 \pm (1-y)^2$$

- ν, μ exps . renorm. group $\alpha_s = \frac{4\pi}{\beta_0 \ln Q^2/\Lambda^2}$

1989

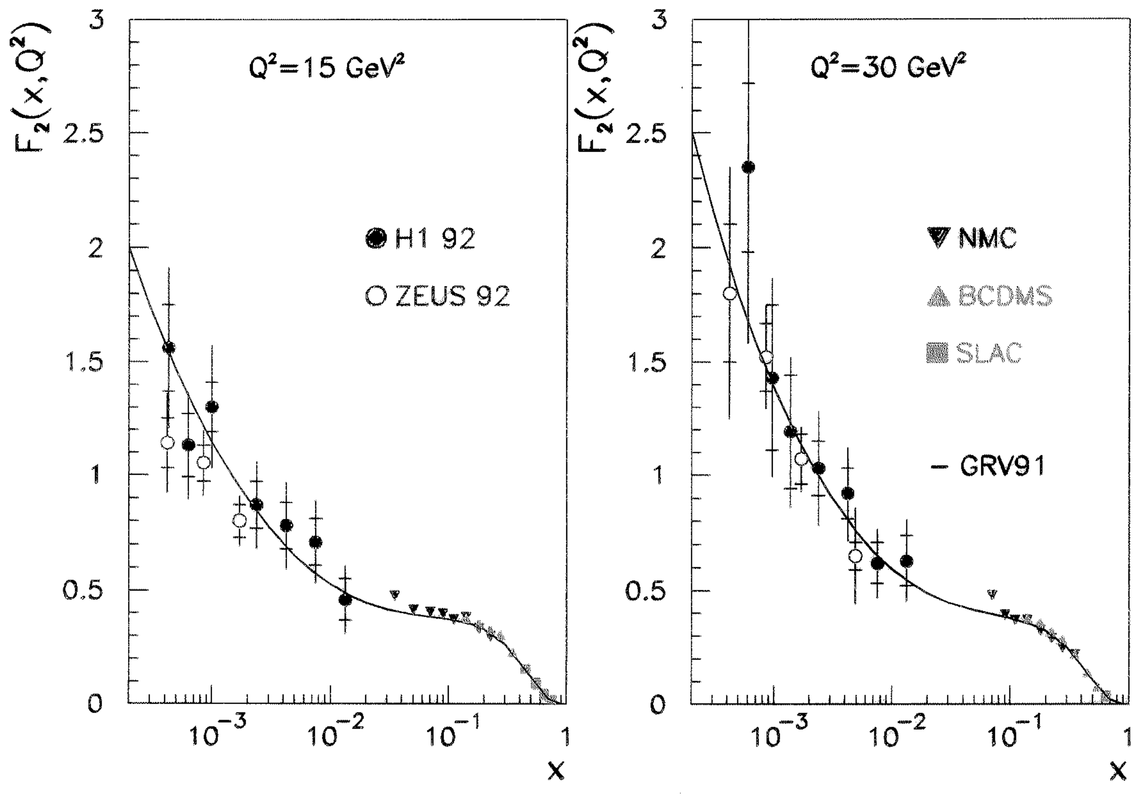
and 3 more years

HERA : electron-proton collider $s = 4E_eE_p \approx 10^5\,GeV^2$

high $Q^2 \sim M_{W,Z}^2$ neutral and charged currents

low $x = \frac{Q^2}{s \cdot y}$

the rise of F_2



and the importance of the gluon distribution

$\partial F_2 / \partial \ln Q^2 \sim \alpha_s \cdot xg$, $xg \sim \exp\sqrt{c \cdot \ln T \cdot \ln 1/x}$

$T = \ln Q^2/\Lambda^2 \,/\, \ln Q_0^2/\Lambda^2$

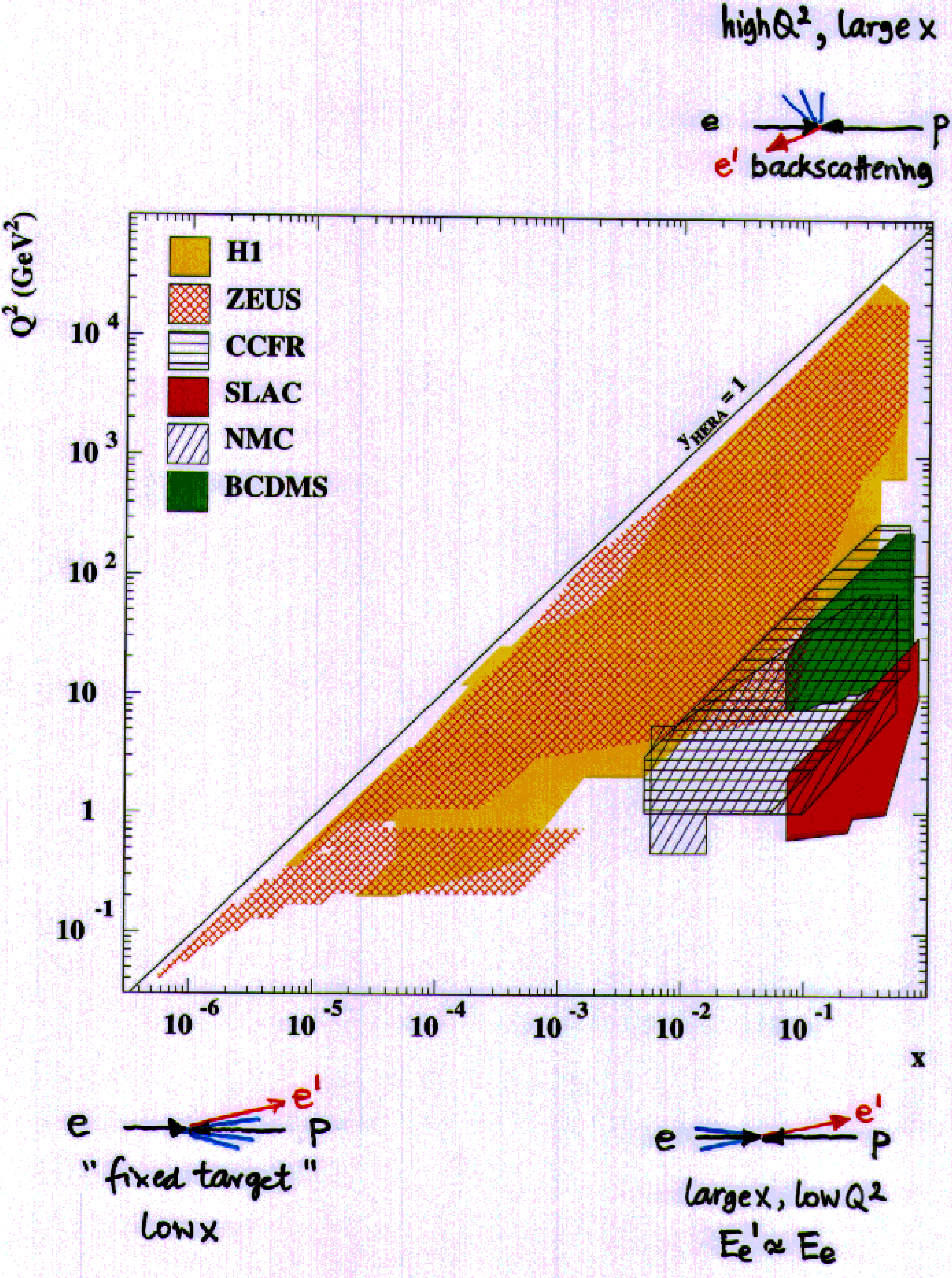
Possible non Regge Behaviour of Electroprod. Structure Fcts.
De Rujula, Glashow, Politzer, Treiman, Wilczek, Zee . 1974

"dynamical partons": Parisi, Petronzio, ITEP, Glück, Reya 1976/77

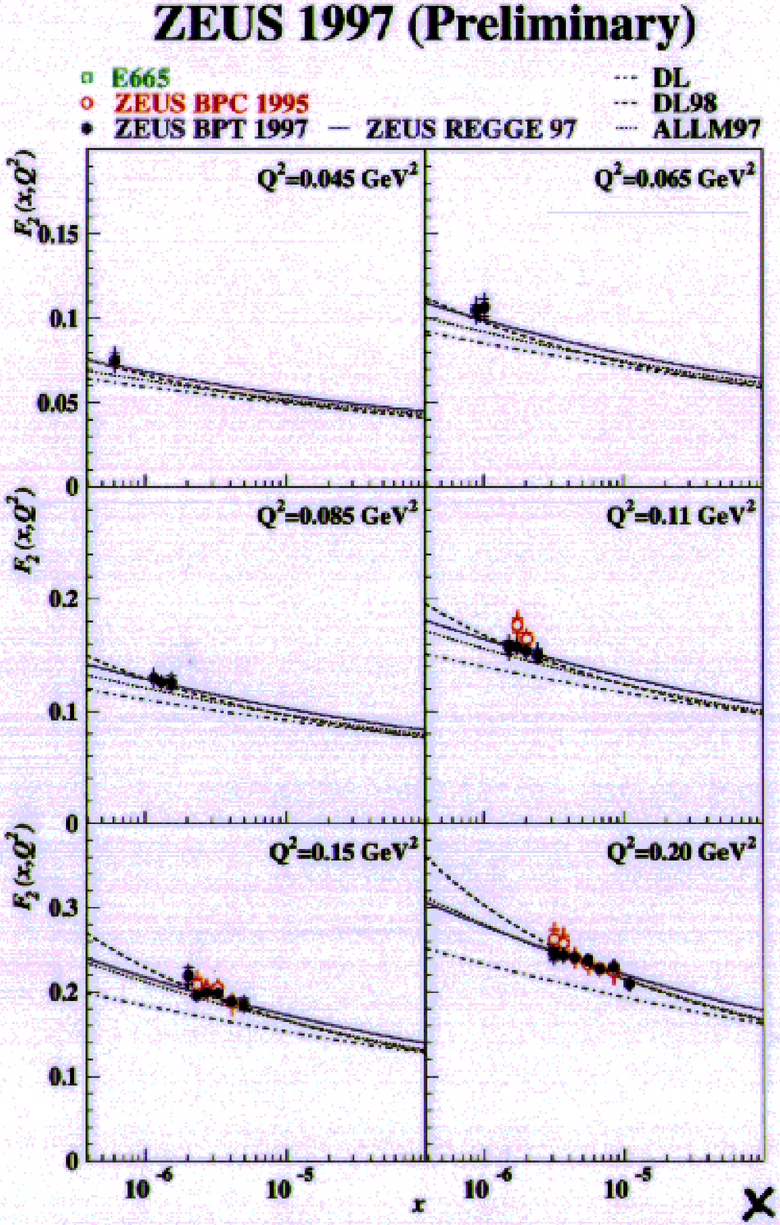
1999

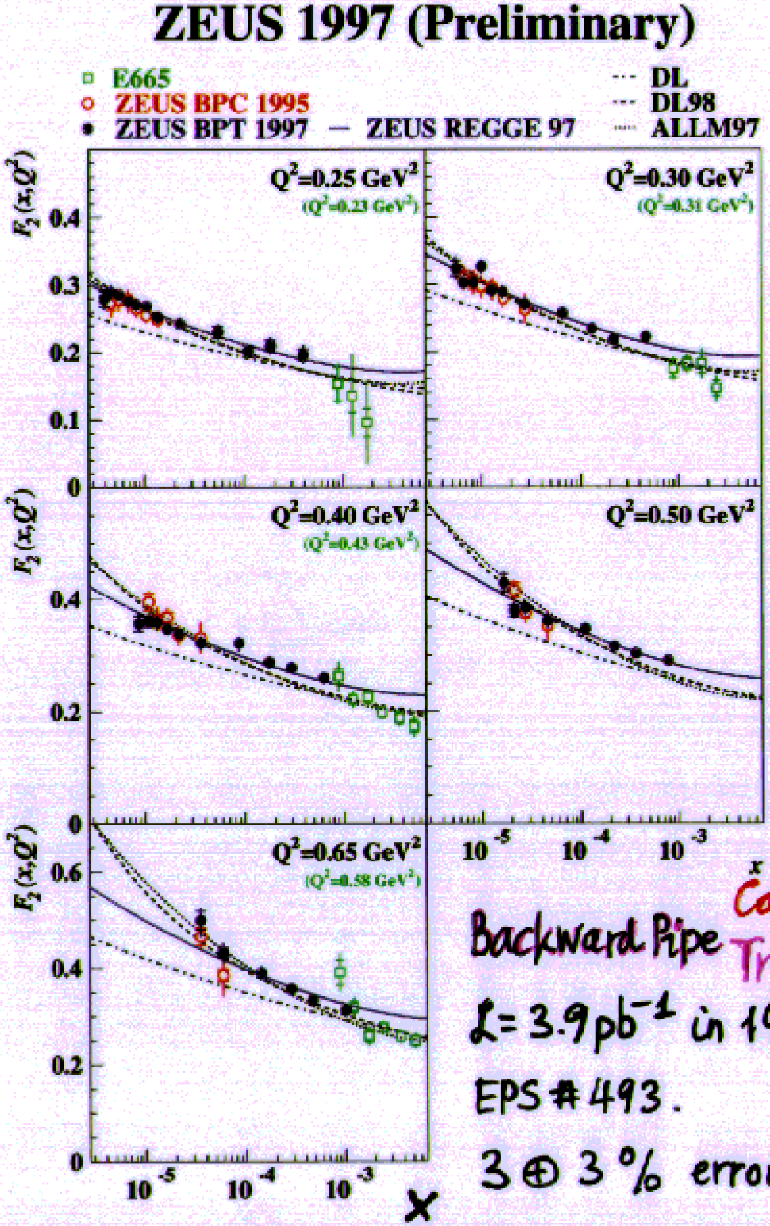
- recent measurements of structure functions
- quark distributions including charm
- gluon distribution and α_s
- towards 2009

HERA kinematics



F_2





Backward Pipe Calorimeter / Tracker

$\mathcal{L} = 3.9\,pb^{-1}$ in 1997

EPS #493.

$3 \oplus 3\%$ errors

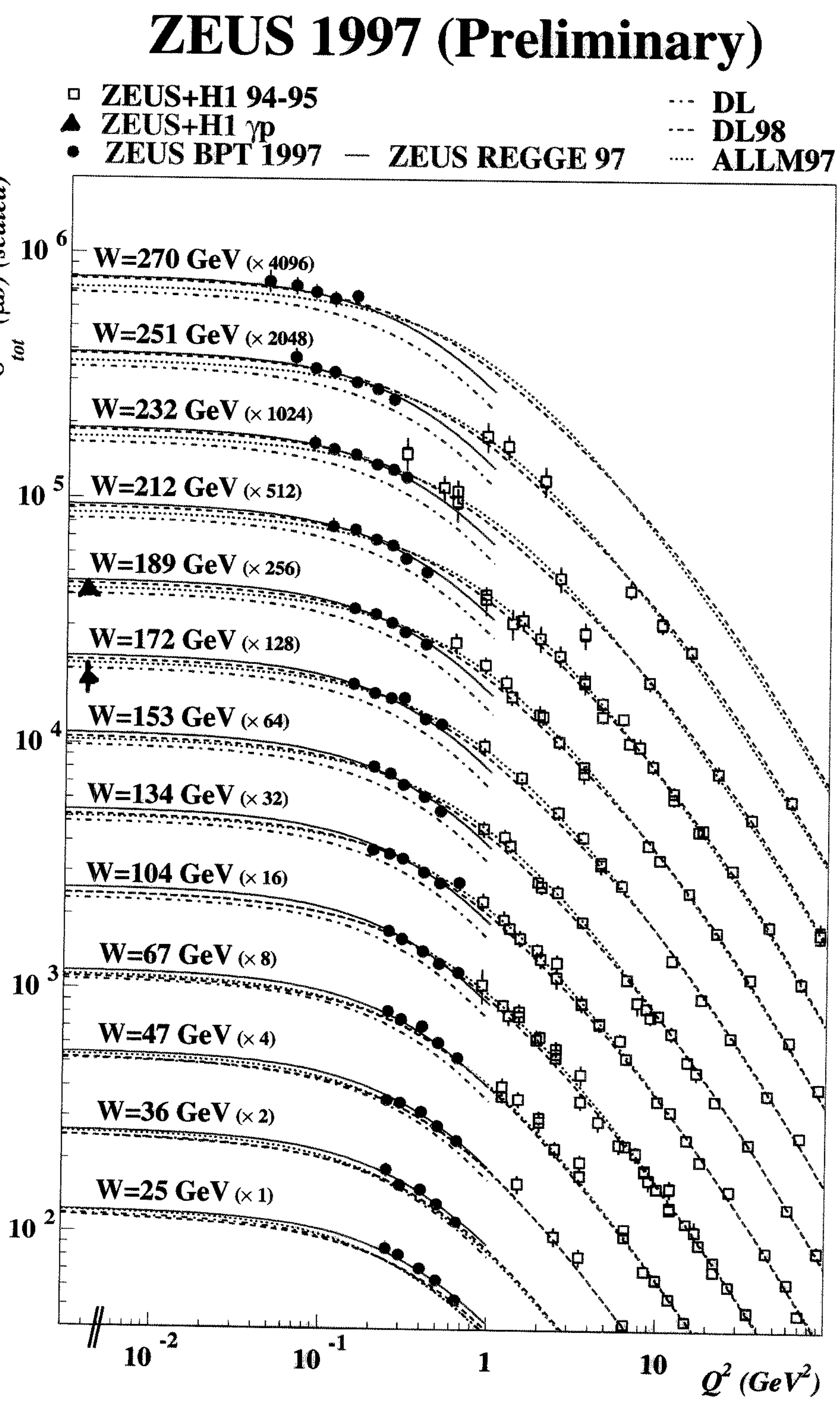
- Soft physics ← deep-inelastic scattering

$\sigma_{tot}^{\gamma^* p}(W^2, Q^2) = \frac{4\pi^2 \alpha}{Q^2} F_2$

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

$\lambda \to 0.1 \approx \alpha_{I\!P} - 1$ for low Q^2

$\sigma^{\gamma^* p}$



$W^2 = s \cdot y$

Regge and GVDM phenomenology.

$F_2 = f(Q^2) \cdot g(W^2)$

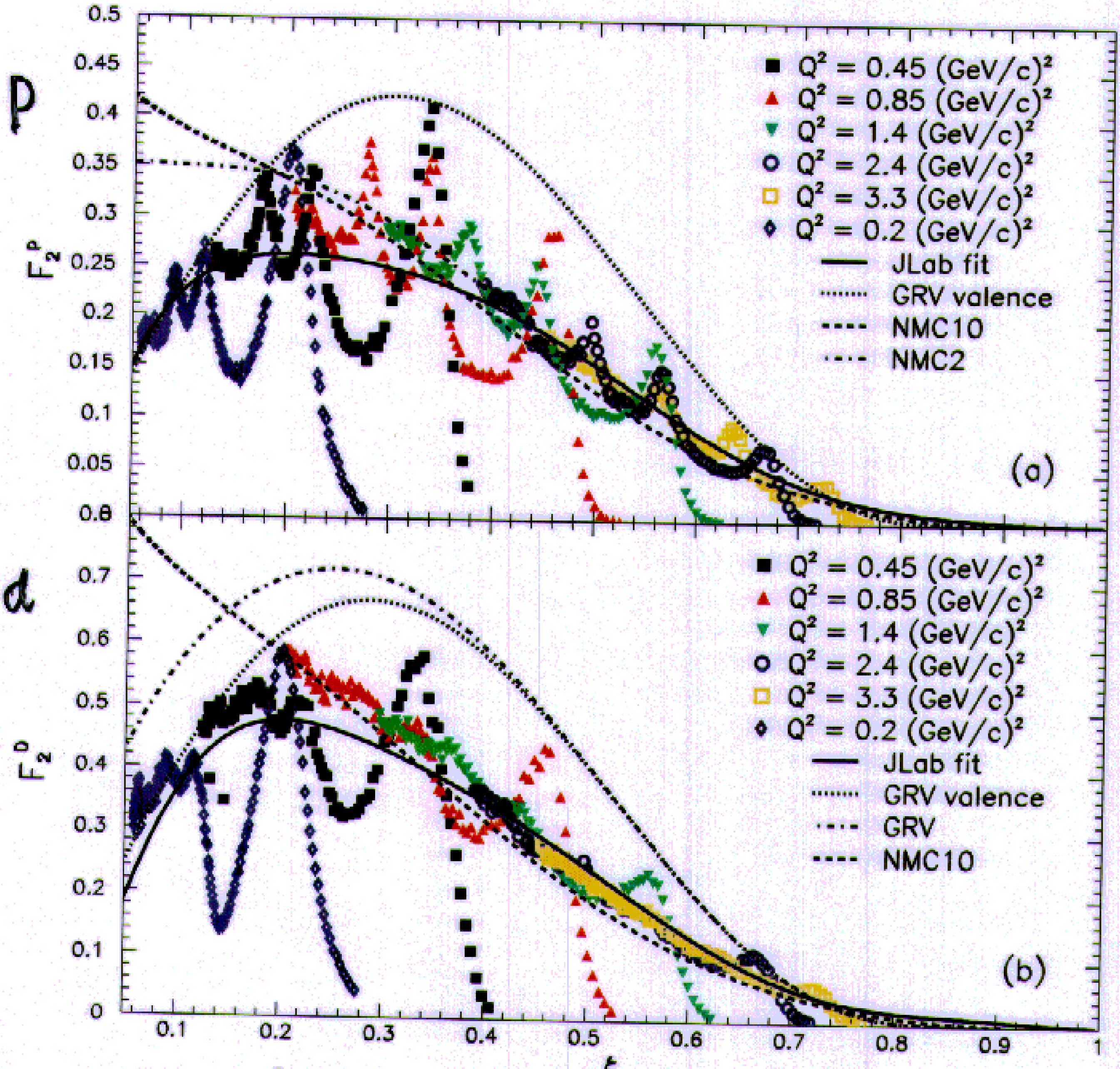
to approach $Q^2 \to 0$ limit:

- HERA $Q^2/4$ with $E_e/2$

parton-hadron duality.*)

Jefferson Lab, ep, eD in resonance region W ~ 1 GeV . 3%

- valence like structure at $Q^2 < 1\,GeV^2$
- small higher twist
- G_M^p elastic form factor from inelastic data . R: E94-110



$$\xi = x \cdot \frac{2}{1+\sqrt{1+4x^2M^2/Q^2}}$$

C. Keppel DIS99, April 99, Zeuthen.

* Bloom. Gilman PRD4 (71) 2901

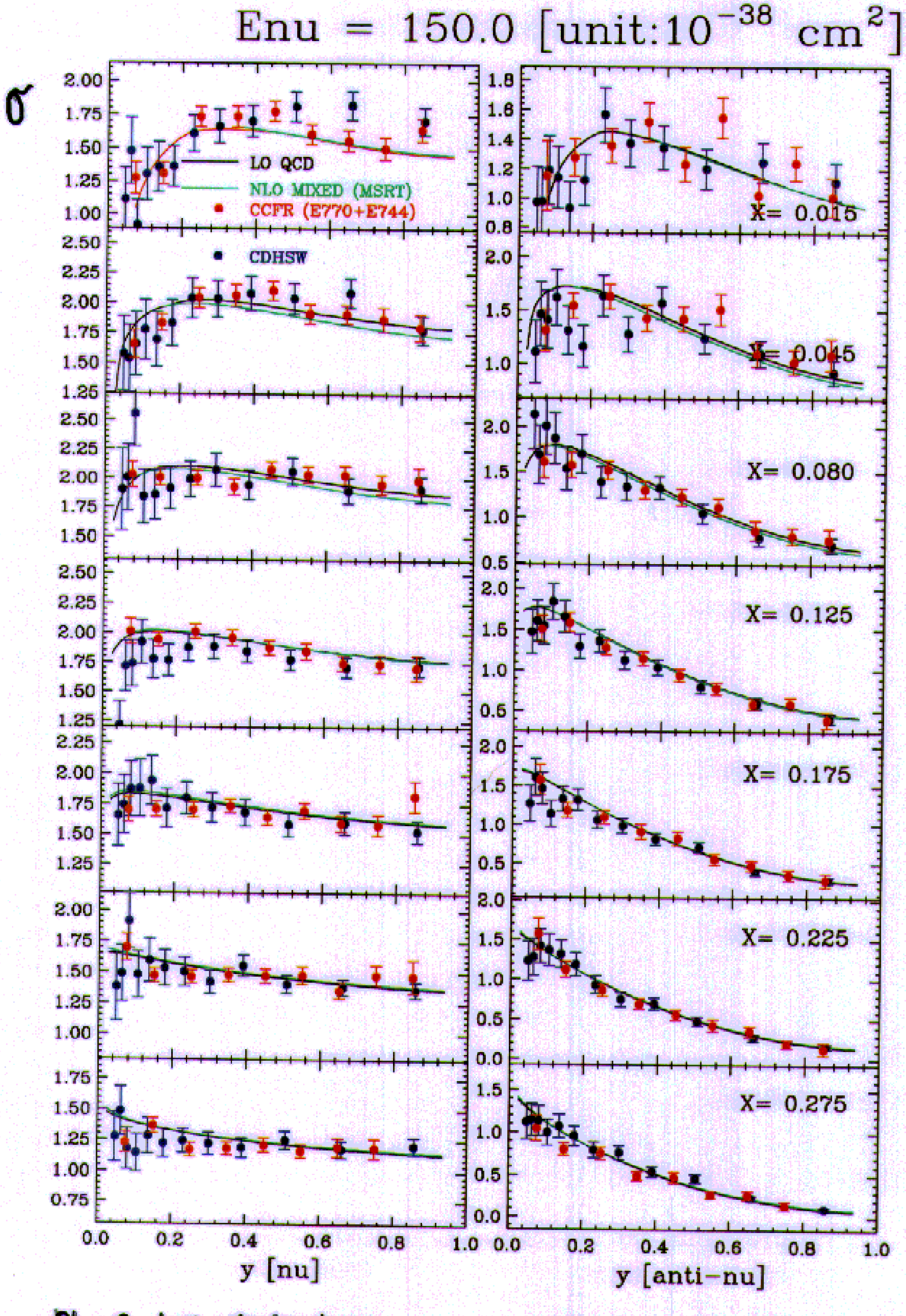
$^{(\bar{\nu})}$Fe CCFR

$\sigma^{\nu} \sim [q + \bar{q}(1-y)^2]$

10^6 events

$\sigma^{\bar{\nu}} \sim [q(1-y)^2 + \bar{q}]$

$1.8 \cdot 10^5$ events



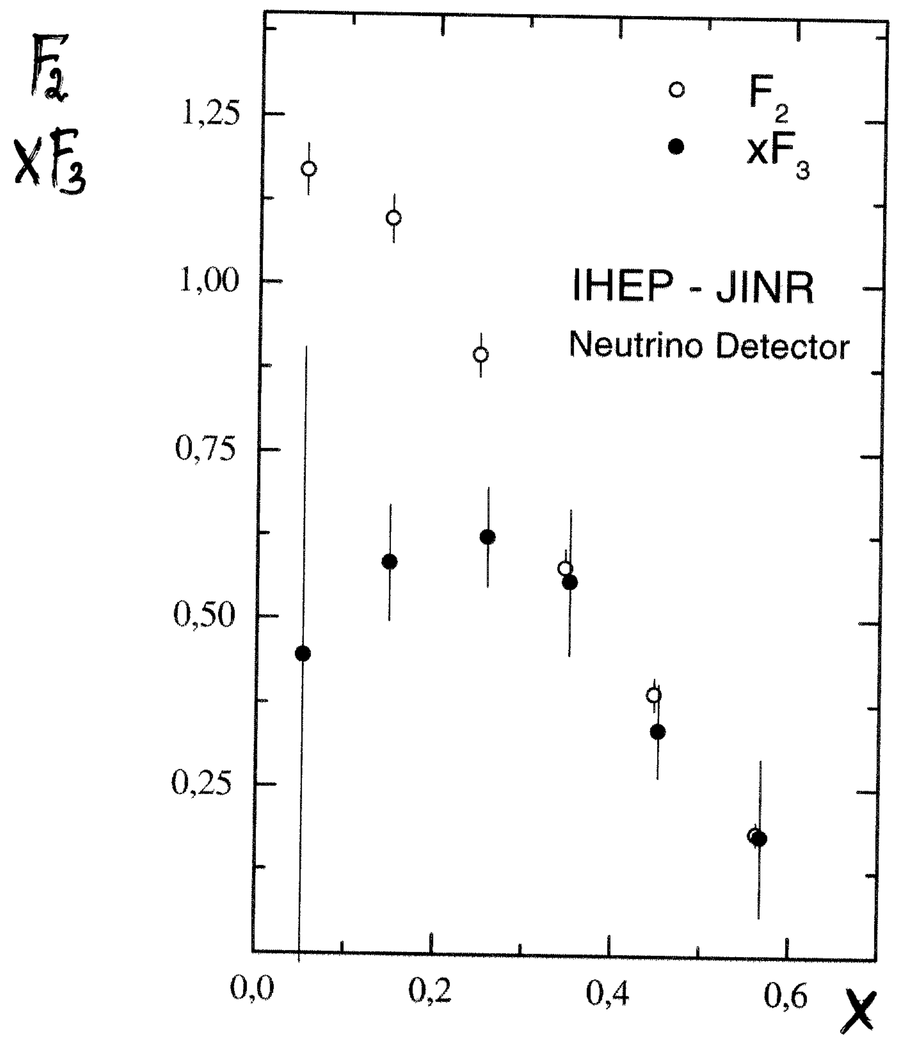
PhysRevLett. 79 (97) 1213 . x>0.75 : hepex/9905052 . more than Fermi motion.

IHEP-JINR ν Detector ИФВЭ-ОИЯИ

- Liquid Sc.-Al calorimeter, μ toroid, drift chambers

  $\nu(\bar{\nu})$ wbbeam at Serpukhov U70. $\bar{E}_\nu \sim 7$ GeV

		ν	$\bar{\nu}$	
o	events	741	5987	, $W^2 > 1.7$ GeV^2
	$\langle Q^2 \rangle$	1.2	2.3	GeV^2



- α_s analysis $\alpha_s(M_Z^2) = 0.123^{+0.010}_{-0.013}$ hep-ex/9905038

H1

low Q^2 (1.5 - 150 GeV^2), low x (0.00003 - 0.2)

- new backward apparatus
  lead-fibre high resolution calorimeter (elm, had)
  drift chamber
  backward silicon tracker

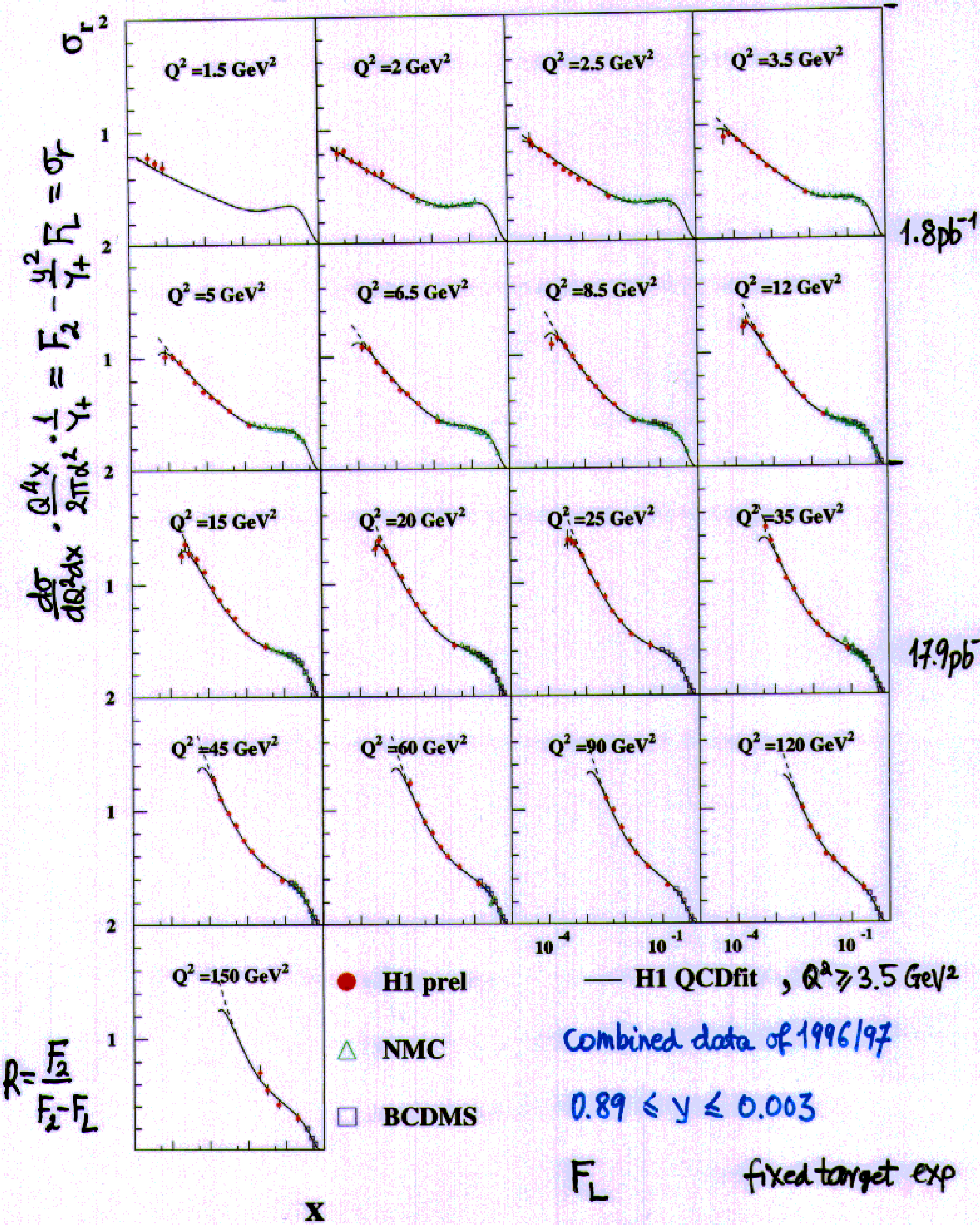
- e ID down to 3 GeV, vertex at large x (low $y = Q^2/sx$)
  $\delta E_e' = 0.3\%$, $\delta \vartheta_e = 0.3$ mrad, $\delta E_h = 2\%$

- HERA $\mathcal{L}$ increased : systematics improved

- most precise structure function data so far @ HERA
  $\lesssim 1\%$ statistical and $\gtrsim 2\%$ systematic errors.

[27.6e x 820p]

$F_2 - \frac{y^2}{Y_+} F_L \longrightarrow F_2 - F_L$ (y → 1) H1 96-97 ← $y = Q^2/sx$



ultra high energy neutrinos $E_\nu \approx 10^{12}$ GeV

AGN, GRB ...

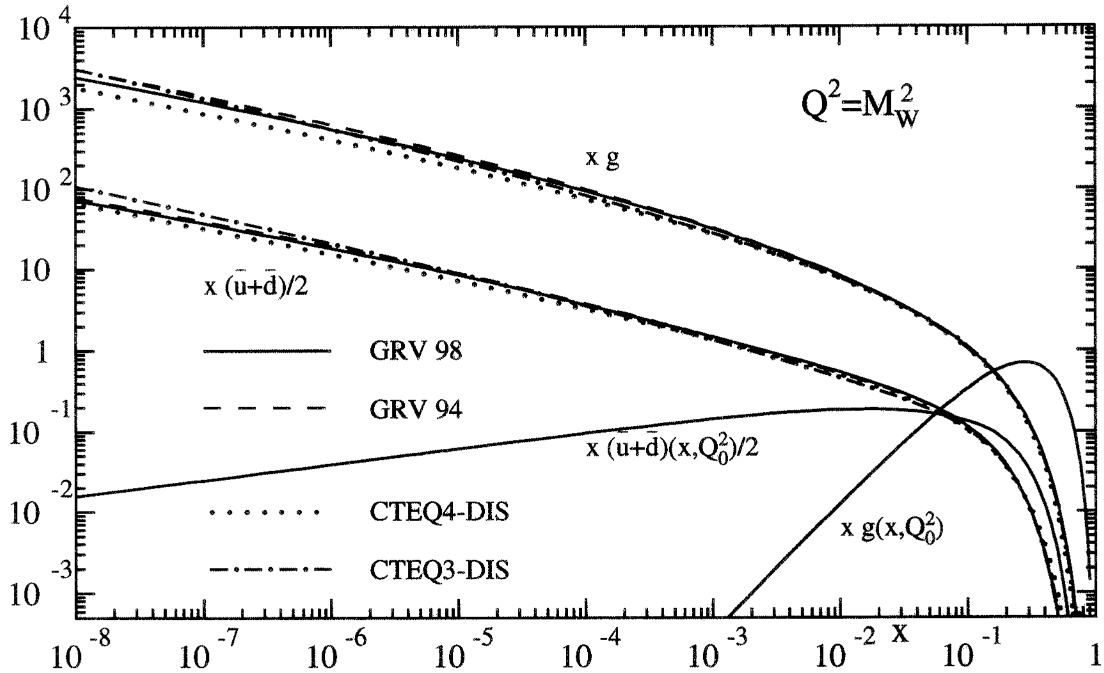
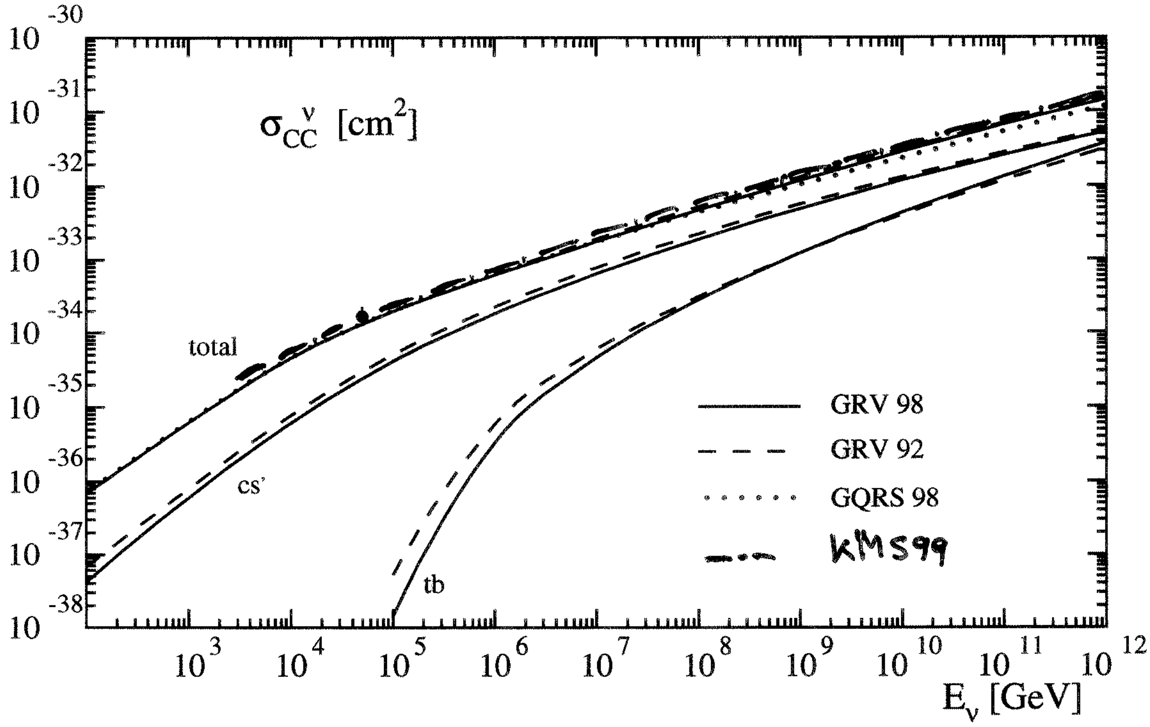


Fig. 1

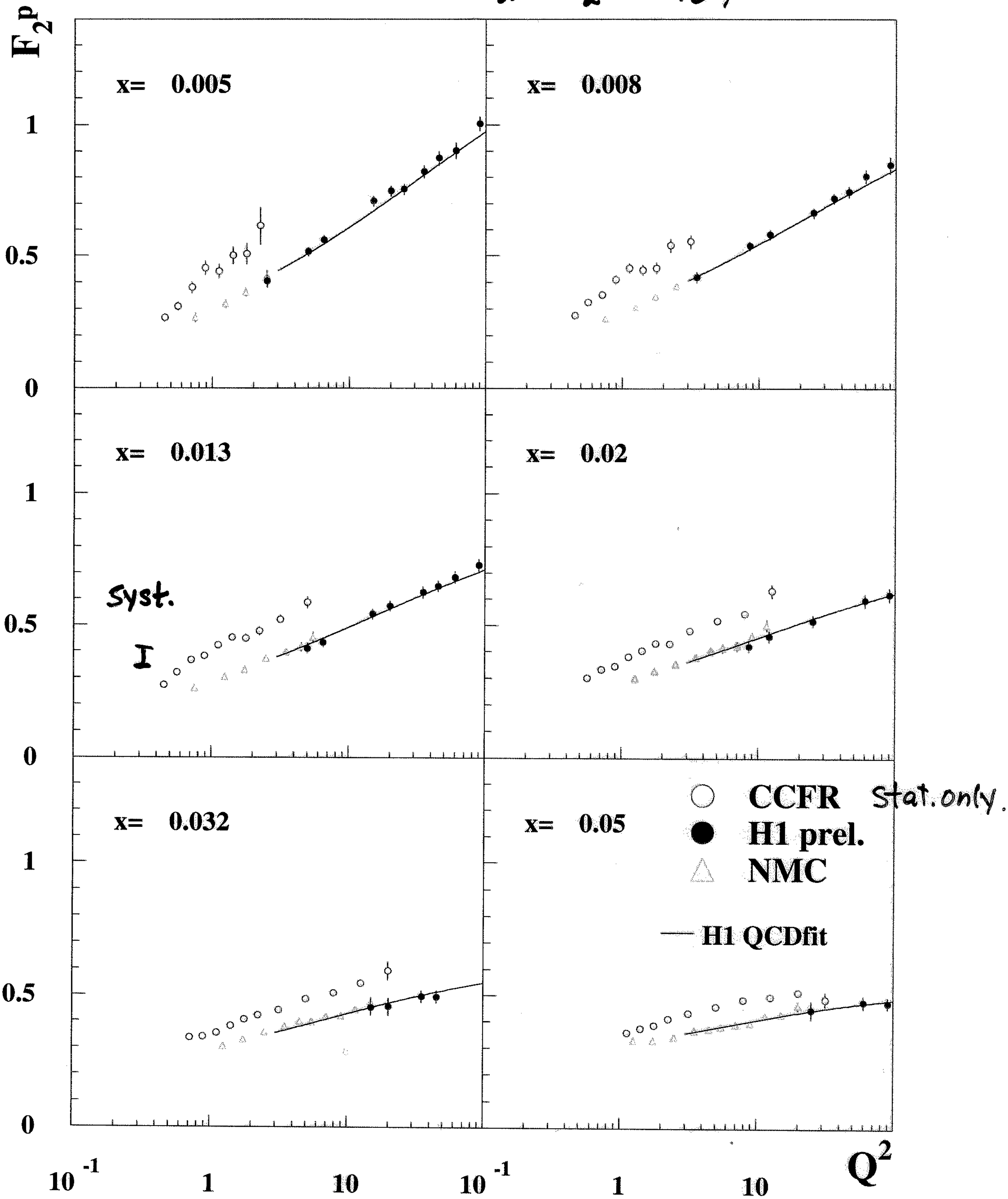


$\delta\sigma = 20\%$

Fig. 2

Glück, Reya, Kretzer, astro-ph/9809273 , Gandhi, Quigg, Reno, Sarcevic, hep-ph/9807264 , Kwiecinski, Martin Stasto, hep-ph/9905307

$F_2^p \leftarrow F_2^{\nu Fe}$ $\frac{d}{Fe}$ $\frac{\Delta+p}{d}$ $\frac{\mu}{\nu}$



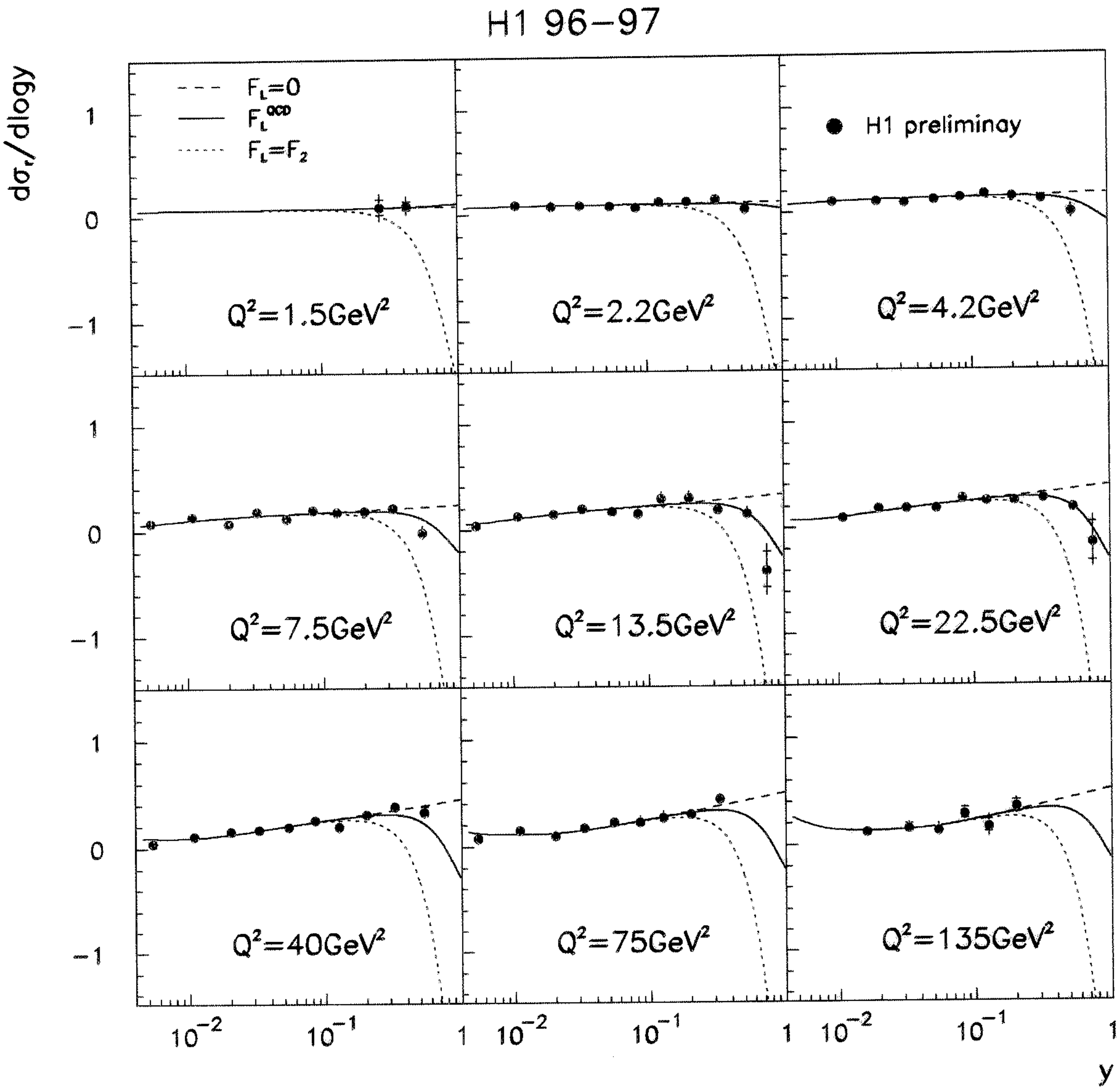
- CCFR : extended low Q^2 data > NMC. reanalysis : RC, ΔxF_3, charm soon out.
- see also: hep-ph/9908280 Boos-

$$F_2 - \frac{y^2}{Y_+} \cdot F_L$$

measurement of F_L is crucial test of QCD in NLO

- HERA has > 2 orders of magnitude of y covered at small x
- large $y = 1 - \frac{E_e'}{E_e} \sin^2\frac{\theta}{2}$ $\leftrightarrow$ low E_e' : eID, γp bgd.

- extraction of F_L at $Q^2 > 10\,GeV^2$ with NLO QCD extrap. of F_2
- low Q^2: $\frac{\partial \sigma_r}{\partial \log y}\Big|_{Q^2} = \frac{\partial F_2}{\partial \log y} + f(y) \cdot F_L + ..$

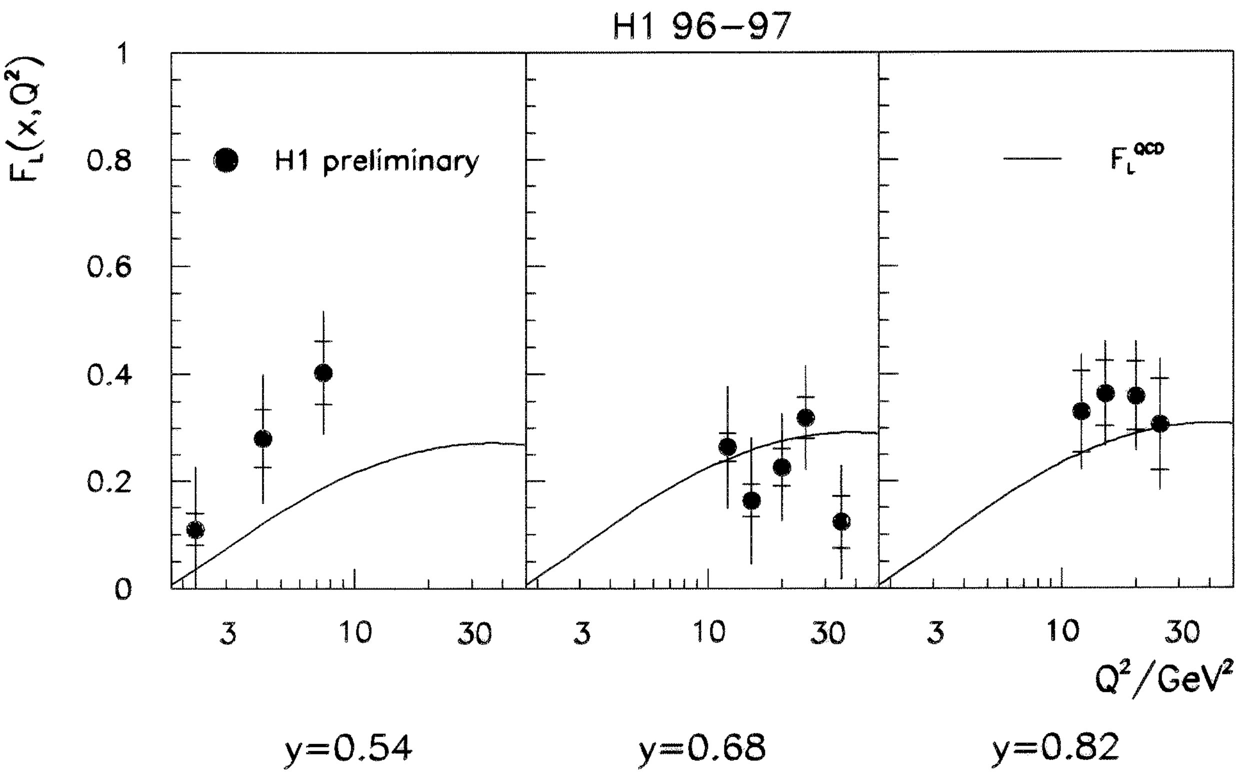


$F_2 \sim y^\lambda$, $F_2' \sim \lambda(1 + \lambda \ln y)$ linear at low λ

- new data, 6.2 pb^{-1} taken in 1996/97

- tracks to suppress / identify hadronic bgd
  BST · jet chamber

- F_L consistent with NLO QCD : fit to F_2 for $y < .35$ constrains xg.

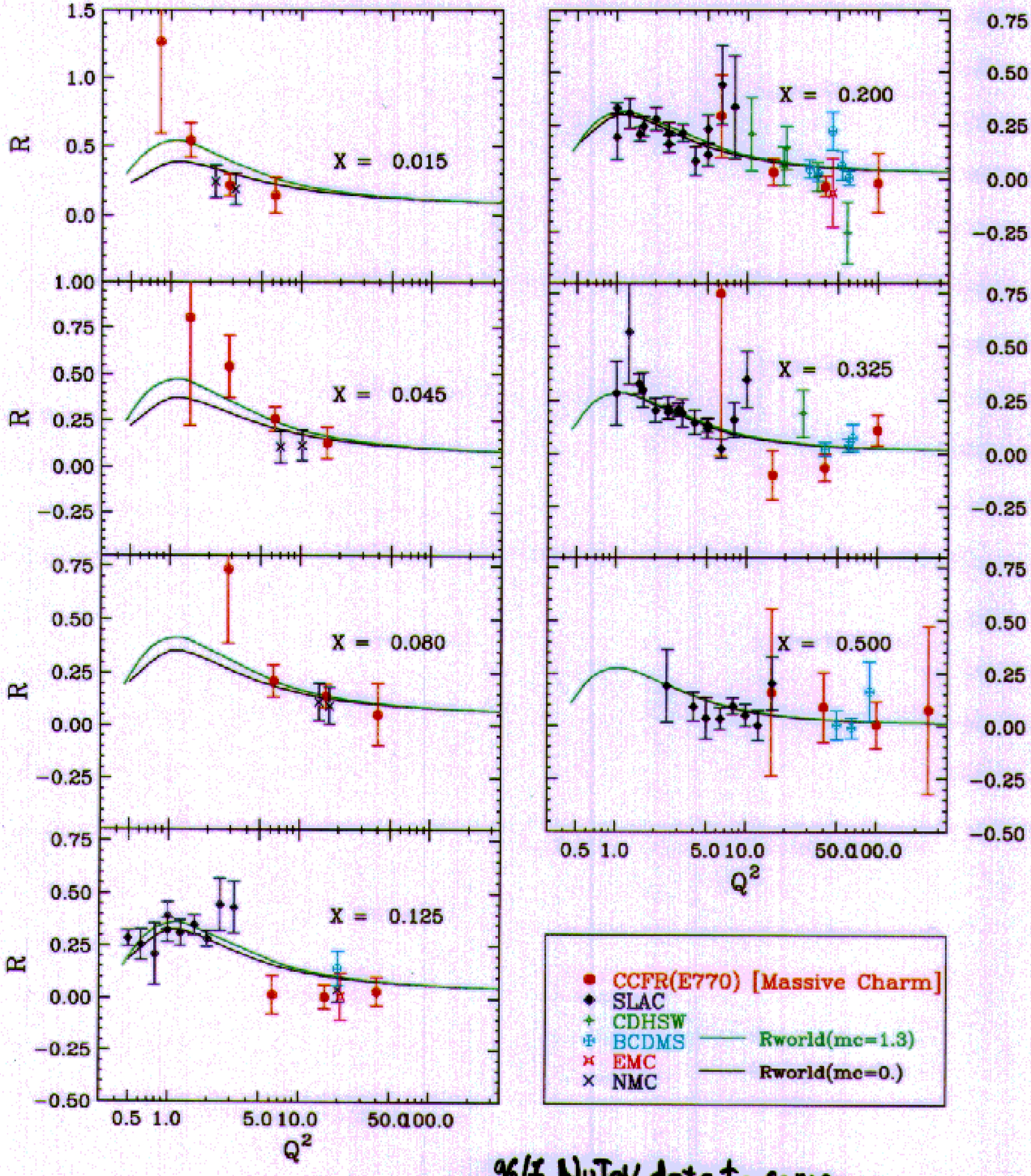


- F_L^{ho} possibly negative at low Q^2

  Zijlstra, v Neerven

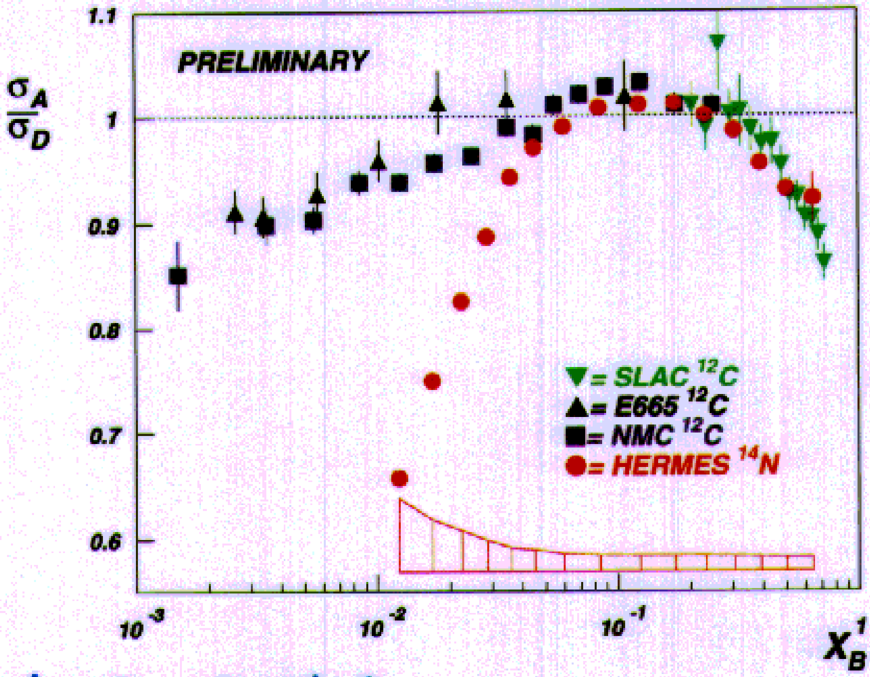
- $(\sigma^{\nu}+\sigma^{\bar{\nu}}) \sim 2xF_1(1+\varepsilon R) - \frac{y(2-y)}{2Y_+}\Delta xF_3$, $\varepsilon = \frac{2(1-y)}{Y_+}$
- $\Delta xF_3 \simeq 4x(s-c)$
- $R(Q^2)$ at low x, low Q^2 ?

also extract ΔxF_3 at $Q^2 \gtrsim 10\,GeV^2$



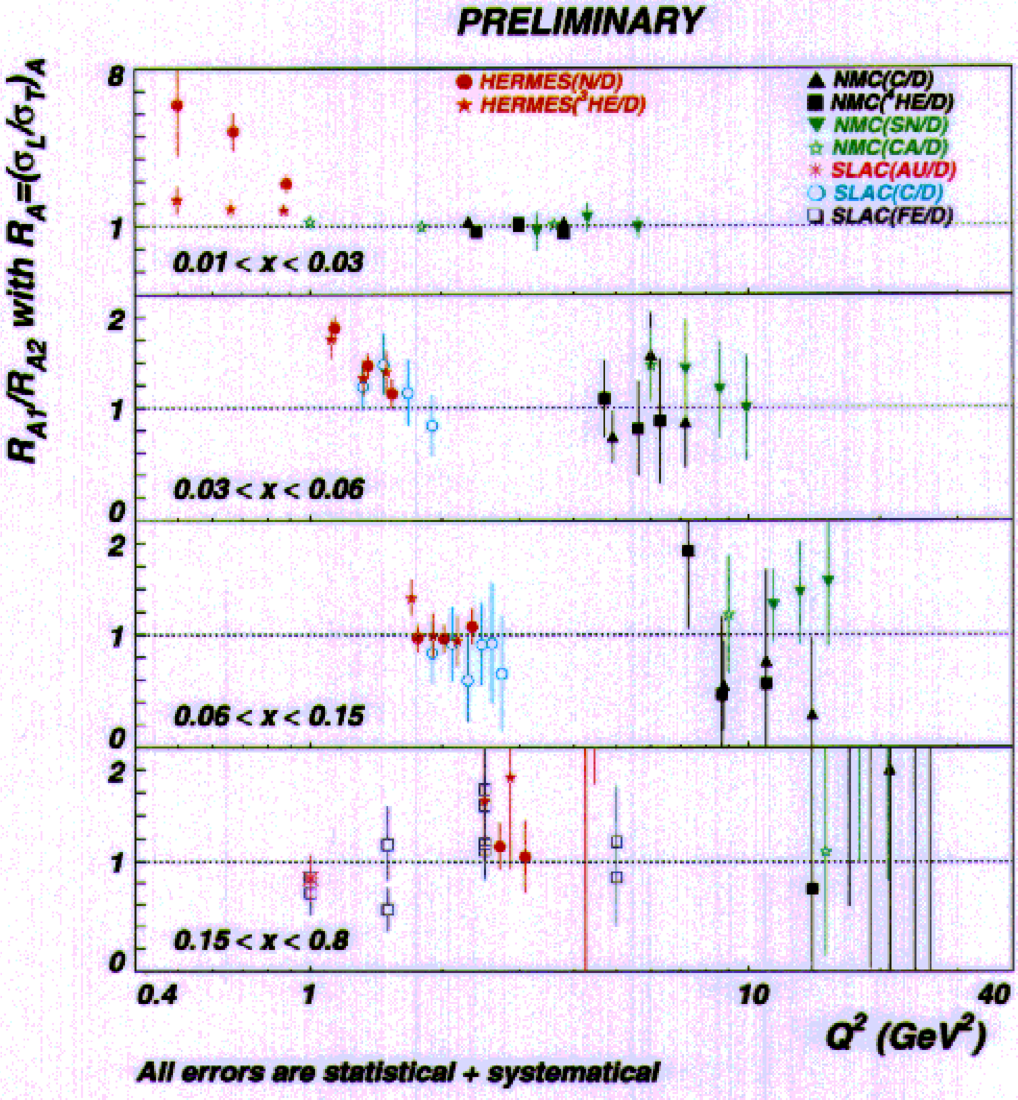
96/7 NuTeV data to come.

- HERMES. unpolarized D, ^{3}He, N data.



$Q^2 < 1 GeV^2$

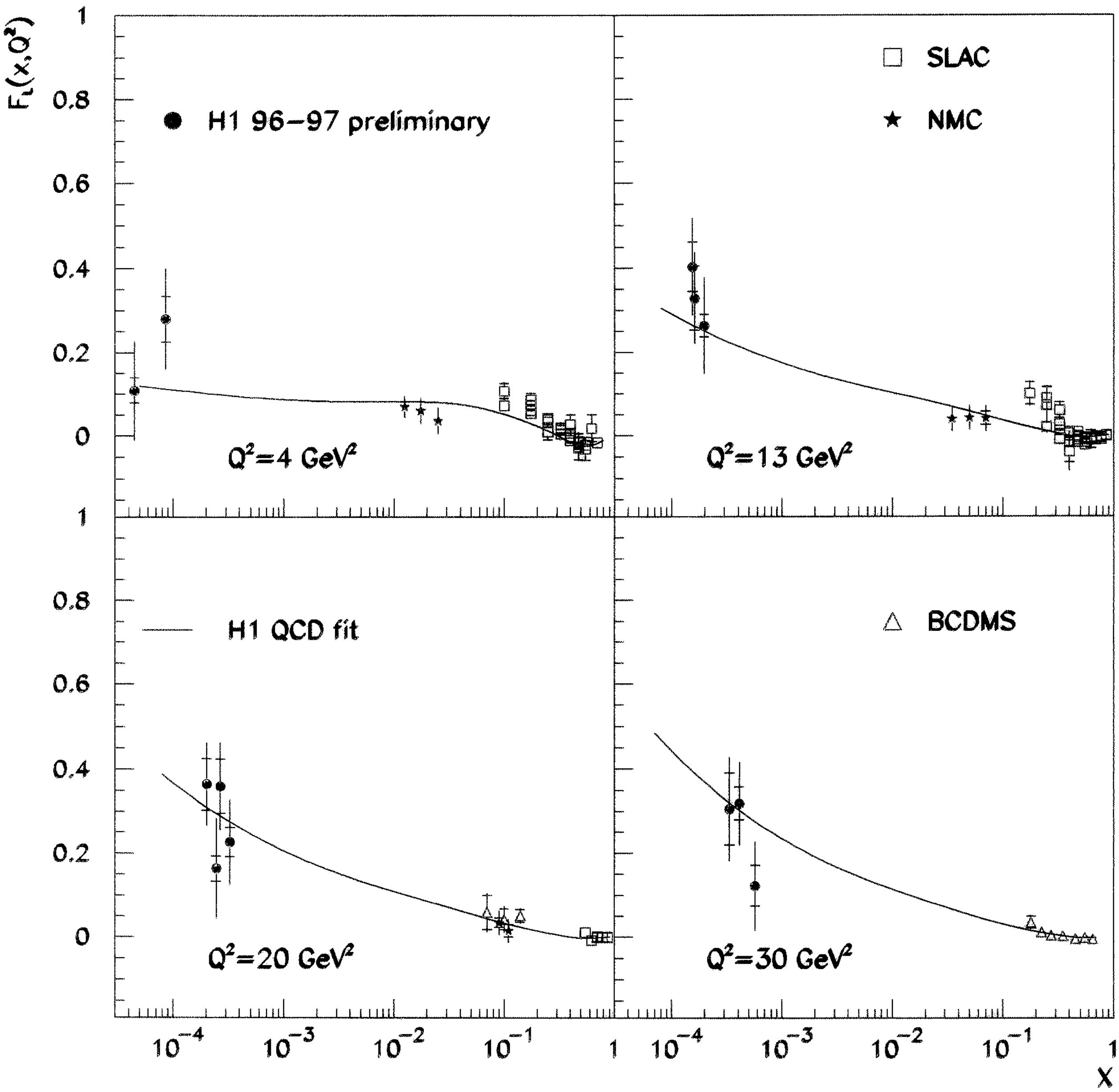
- A dependent R at low Q^2 & x ?



e/μ p data - longitudinal structure function.

rise towards low x consistent with behaviour of $xg(x,Q^2)$

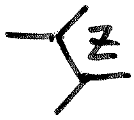
$$(N)LO: \quad F_L = \frac{\alpha_s}{4\pi} x^2 \int \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum Q_q^2 \left(1-\frac{x}{z}\right) g \right]$$



• more precision!

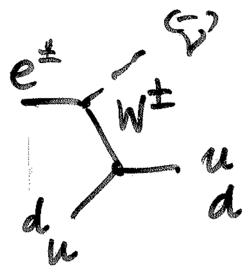
• $F_L \underset{Q^2 \to 0}{\sim} O(Q^4)$?

high $Q^2 \sim M_{W,Z}^{\ 2}$

-  +  neutral currents

$$\frac{d^2\sigma^\pm}{dQ^2 dx} = \frac{2\pi\alpha^2}{Q^4 x} \cdot \left[Y_+ \mathcal{F}_2^{\pm} + Y_- x \mathcal{F}_3^{\pm}\right] \quad \gamma^2, \gamma Z, Z^2$$

five structure functions (and longitudinal ones)

- $\sigma^\pm \simeq Y_+ F_2 \mp \kappa Y_- a_e x G_3$
  - $1-(1-y)^2$ large y
  - $\kappa \sim \frac{G}{\sqrt{2}\, 2\pi\alpha} Q^2$ large Q^2
- charge asymmetry, parity conserving $\sim a_e a_q$
-  charged currents

$$\frac{d^2\sigma^\pm}{dx\,dy} = \frac{G^2}{2\pi} \cdot \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \cdot s\, \frac{1 \pm \lambda}{2} \left[Y_+ W_2^\pm \mp Y_- x W_3^\pm\right]$$

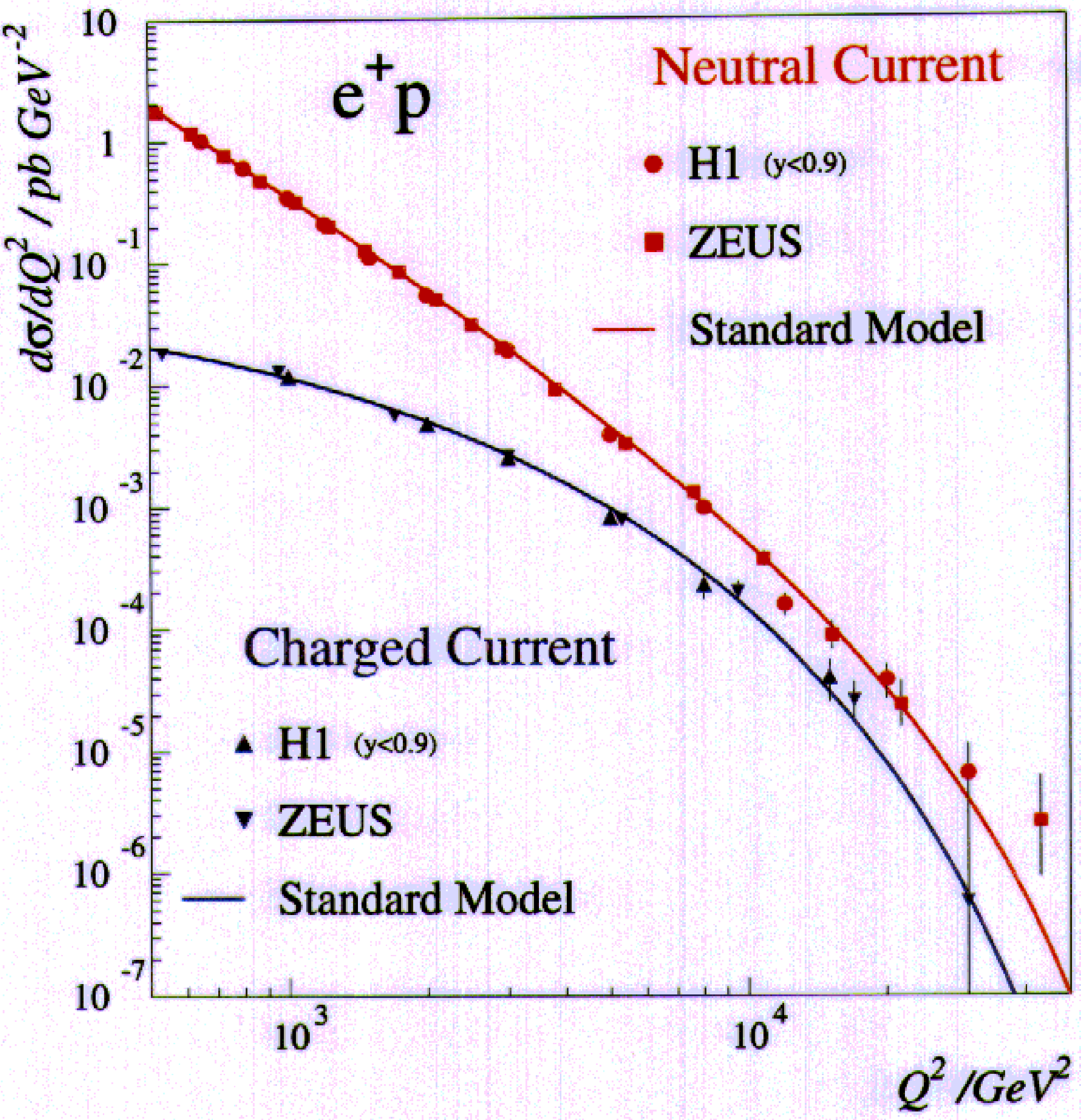
four structure functions

$W_2^+ = D + \bar{U} \quad W_2^- = U + \bar{D} \quad xW_3^+ = D - \bar{U} \quad xW_3^- = U - \bar{D}$

- $\sigma(e^+p \to \bar{\nu}X) \sim \bar{U} + (1-y)^2 D \to (1-y)^2 d_v$
- $\sigma(e^-p \to \nu X) \sim U + (1-y)^2 \bar{D} \to u_v$

large x

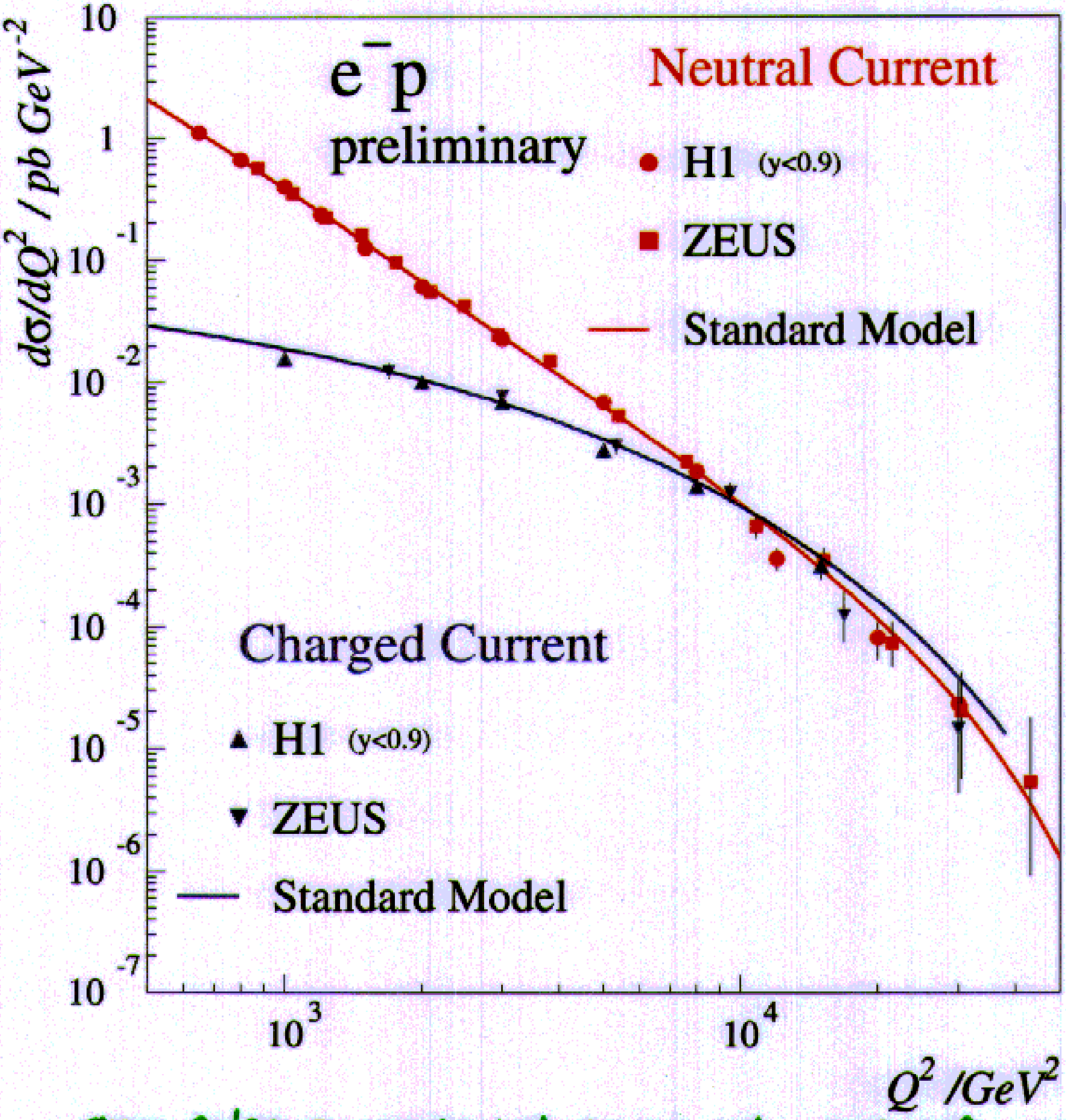
● H1 e^+ 35.6 pb^{-1} NC, CC double diff. cross sections
▲ 94-97 DESY 99-107
$\delta\vartheta \approx 1$-3 mrad, $\delta E_e' \sim 0.7$-3% $\delta E_h = 2\%$



e^+: 820 GeV

■ ZEUS e^+ NC single diff. cross sections 47.7 pb^{-1} 99-056
▼ 94-97 CC double diff. 99-057.
$\delta\vartheta \approx 1$ mrad, $\delta E_e' \sim 1$-3%, $\delta E_h \approx 2\%$

H1 98/99 e^- 15 pb^{-1} double diff. cross sections, prel.

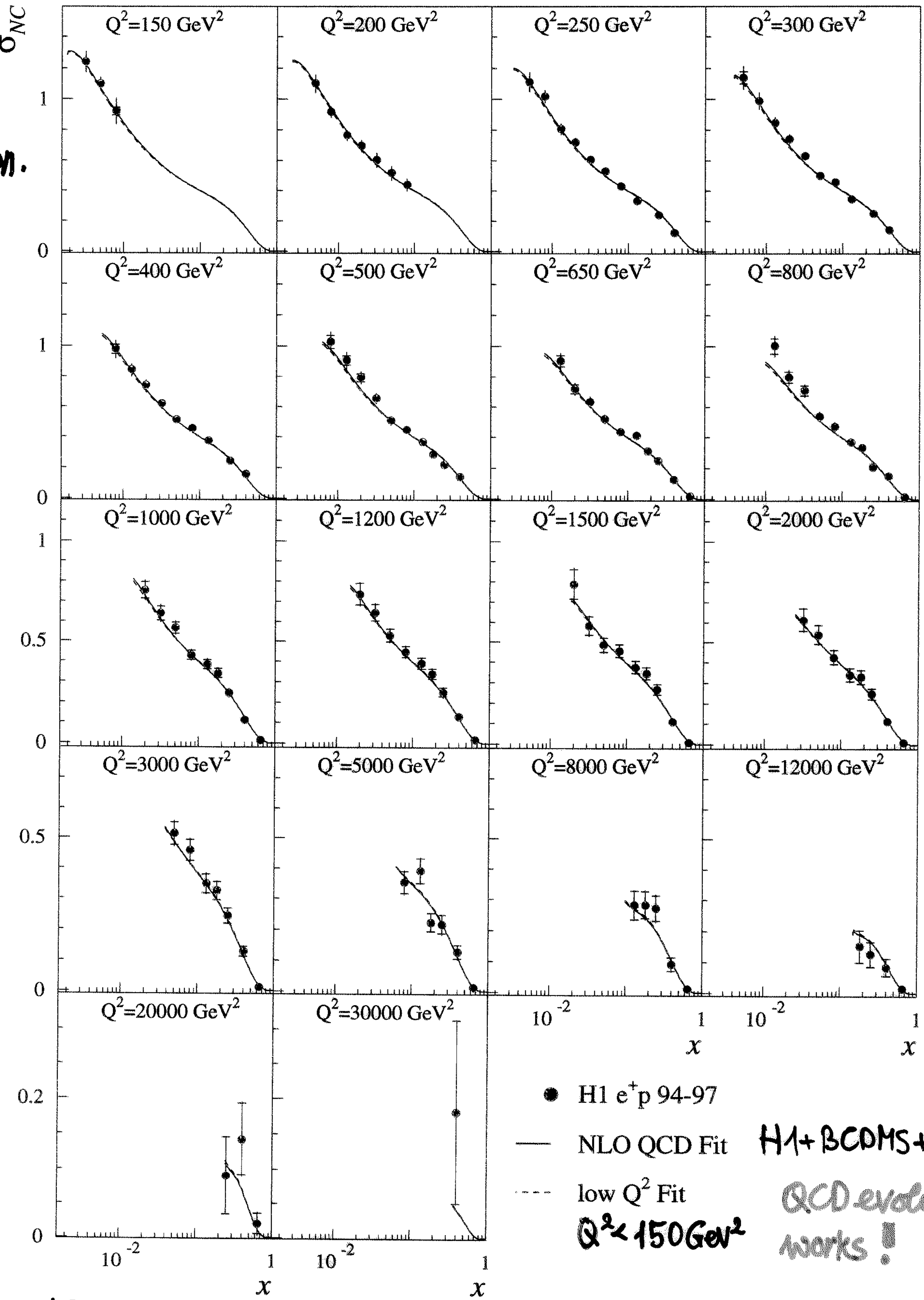


e^-: 920 GeV

ZEUS 98/99 e^- NC 16 pb^{-1} CC 6.3 pb^{-1} single diff., prel.

$$\tilde{\sigma} = \frac{1}{Y_+} \frac{Q^4 x}{2\pi\alpha^2} \frac{d\sigma}{dQ^2 dx} = F_2 (1 + \text{electroweak} + F_L \text{ corr's})$$

tree xsection.



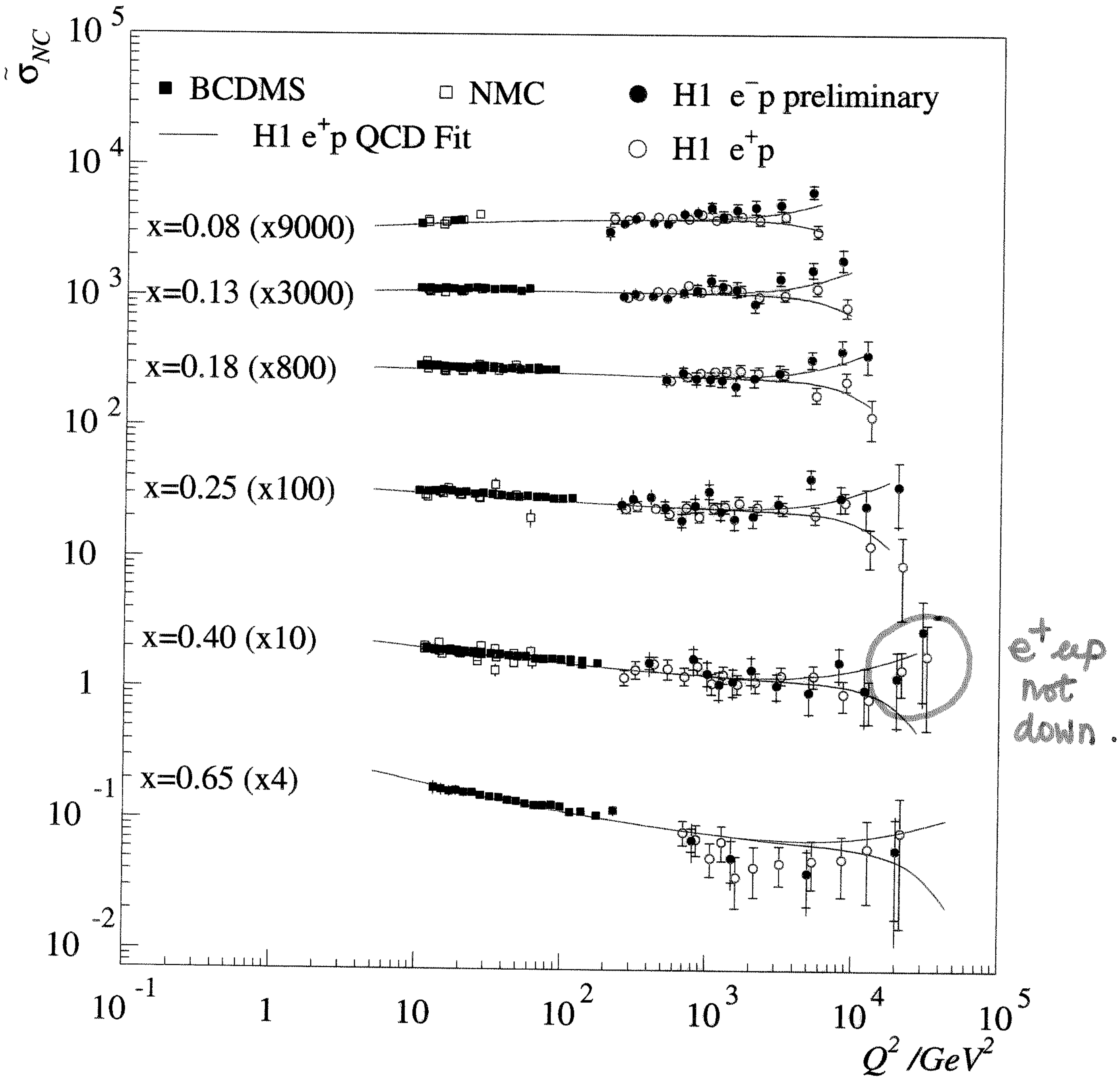
H1+BCDMS+NMC

$Q^2 < 150$ GeV^2

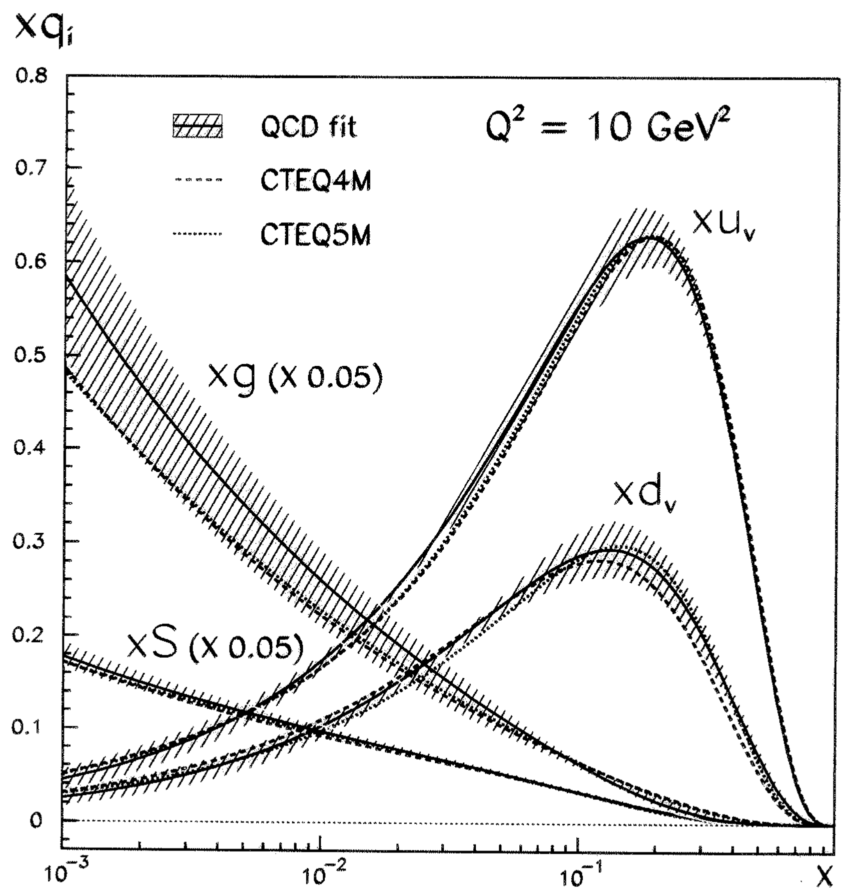
QCD evolution works !

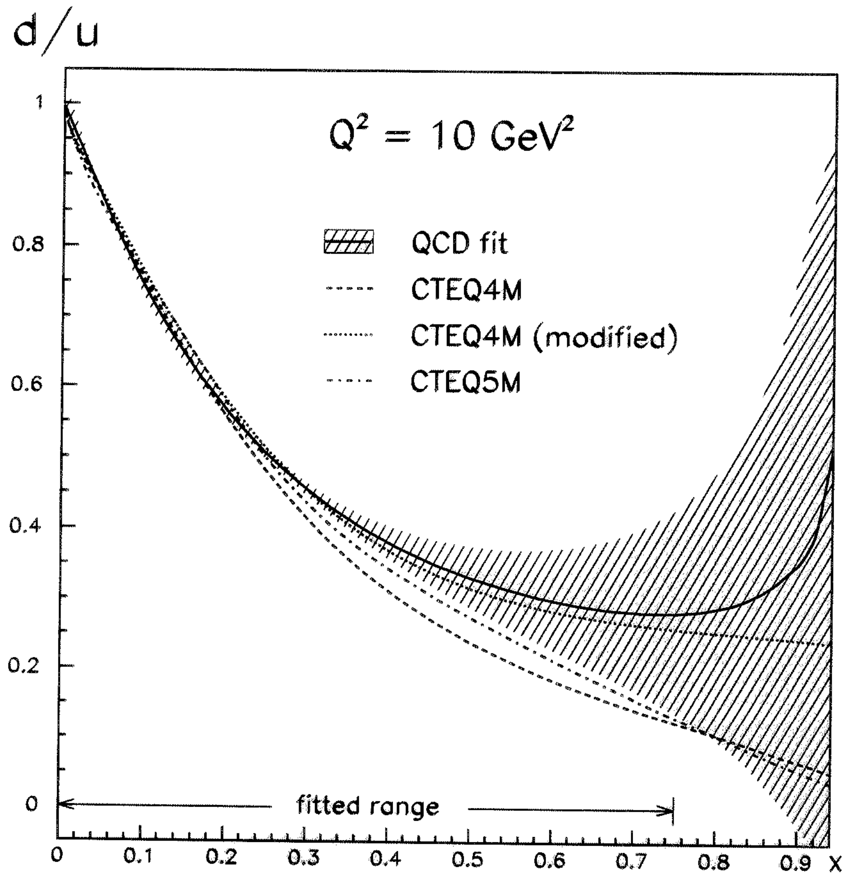
DESY 99-107

observe γZ interference (charge asymmetry) at HERA



Quark Distributions and Heavy Flavour





NLO QCD fit

p, d DIS

$xF_3^{\nu Fe}$

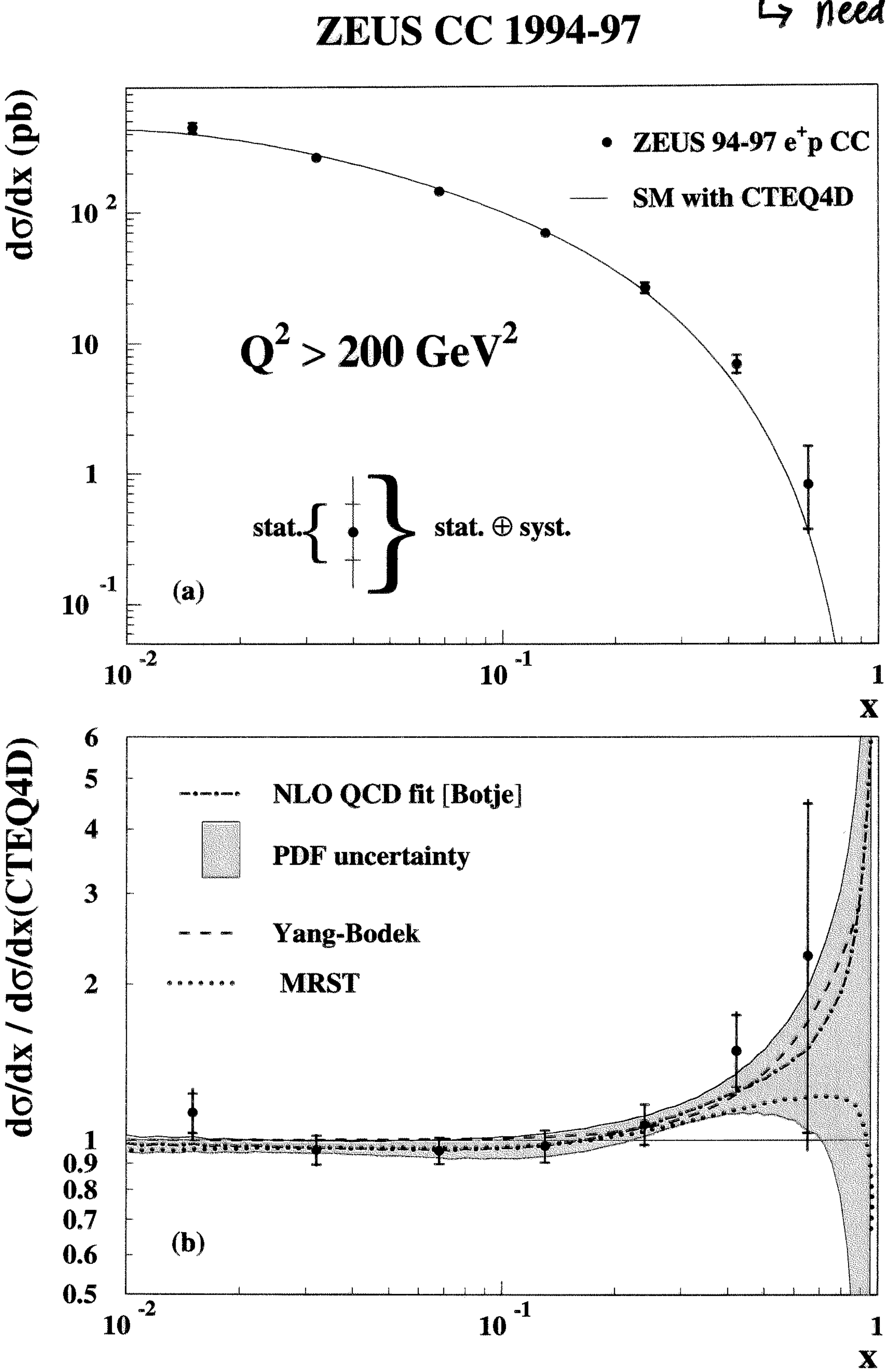
$\bar{d}-\bar{u}$

M. Botje

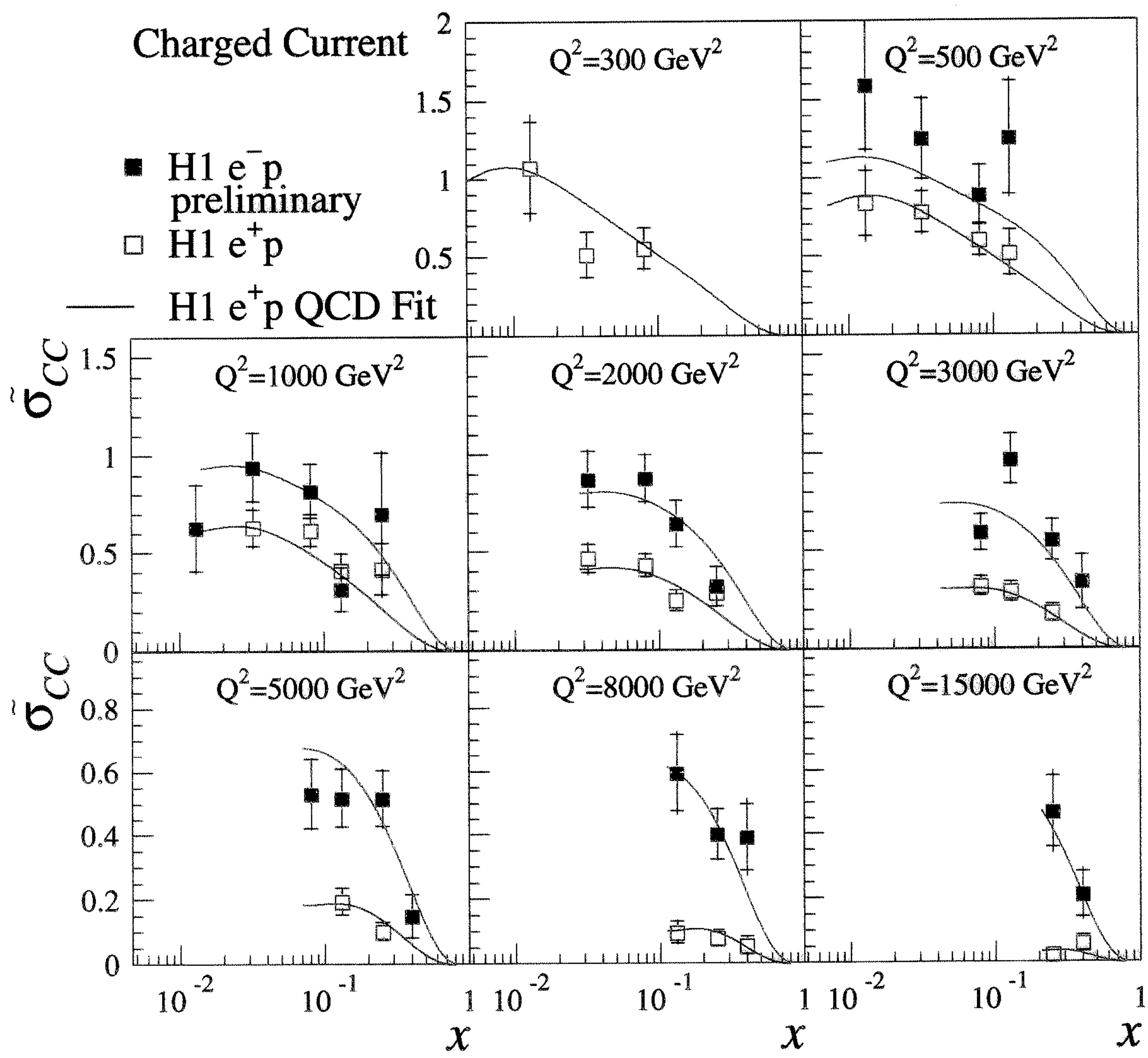
Proc. DIS99

• d/u for x→1

F_2^p/F_2^D : D binding reconsidered. d↗ : $[d/u \underset{x\to 1}{\to} 0.2]^{*)}$
Consistent with CDF W asymmetry and HERA CC.
↳ need ~ 200pb^{-1}



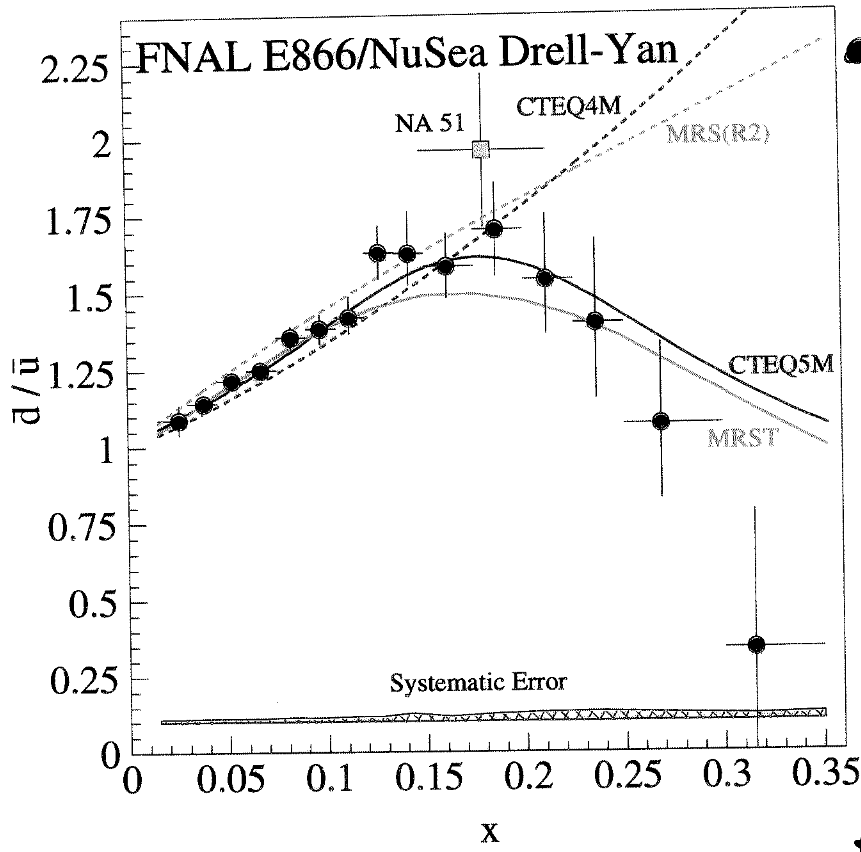
A. Bodek, UK. Yang PRL 82 (99) 2467.



■ $\sigma^- \sim U + (1-y)^2 \bar{D} \rightarrow u_v$ 15pb⁻¹

□ $\sigma^+ \sim \bar{U} + (1-y)^2 D \rightarrow (1-y)^2 d_v$ 36pb⁻¹

flavour asymmetry in the nucleon sea $\bar{u} \neq \bar{d}$

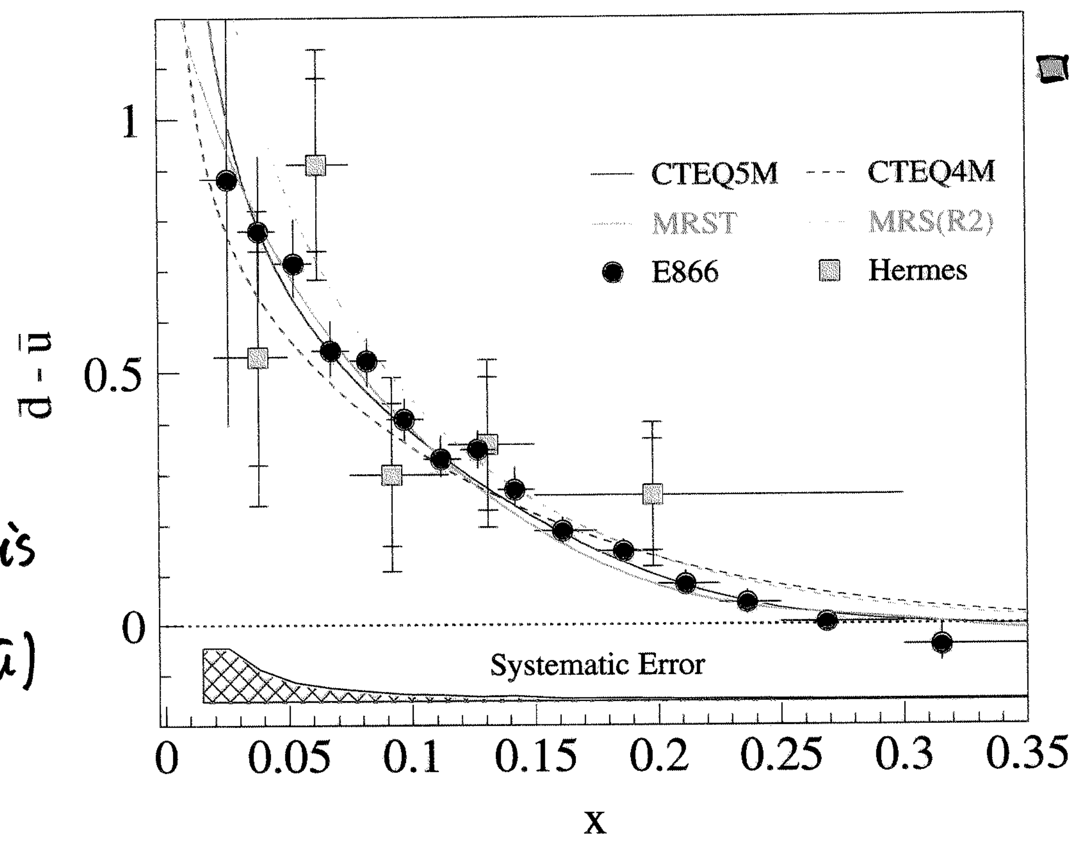


● E866/NuSea
pp, pd DY.
$3.7 \cdot 10^5$ μ pairs
$\langle Q^2 \rangle \simeq 54\,GeV^2$

$\int_0^1 (\bar{u}-\bar{d})\,dx$

Gottfried SR: $\int \frac{1}{x}(F_2^p - F_2^n)\,dx = \frac{1}{3} + \frac{2}{3}\int(\bar{u}-\bar{d})\,dx$

E866 : -0.118 ± 0.011
NMC : -0.15 ± 0.04



■ HERMES
$eN \to e\pi^{\pm}X$
p, d
$\langle Q^2 \rangle = 2.3\,GeV^2$

this is not $x(\bar{d}-\bar{u})$

Strange sea

- NuTeV
  hep-ex/9906038

  dimu data

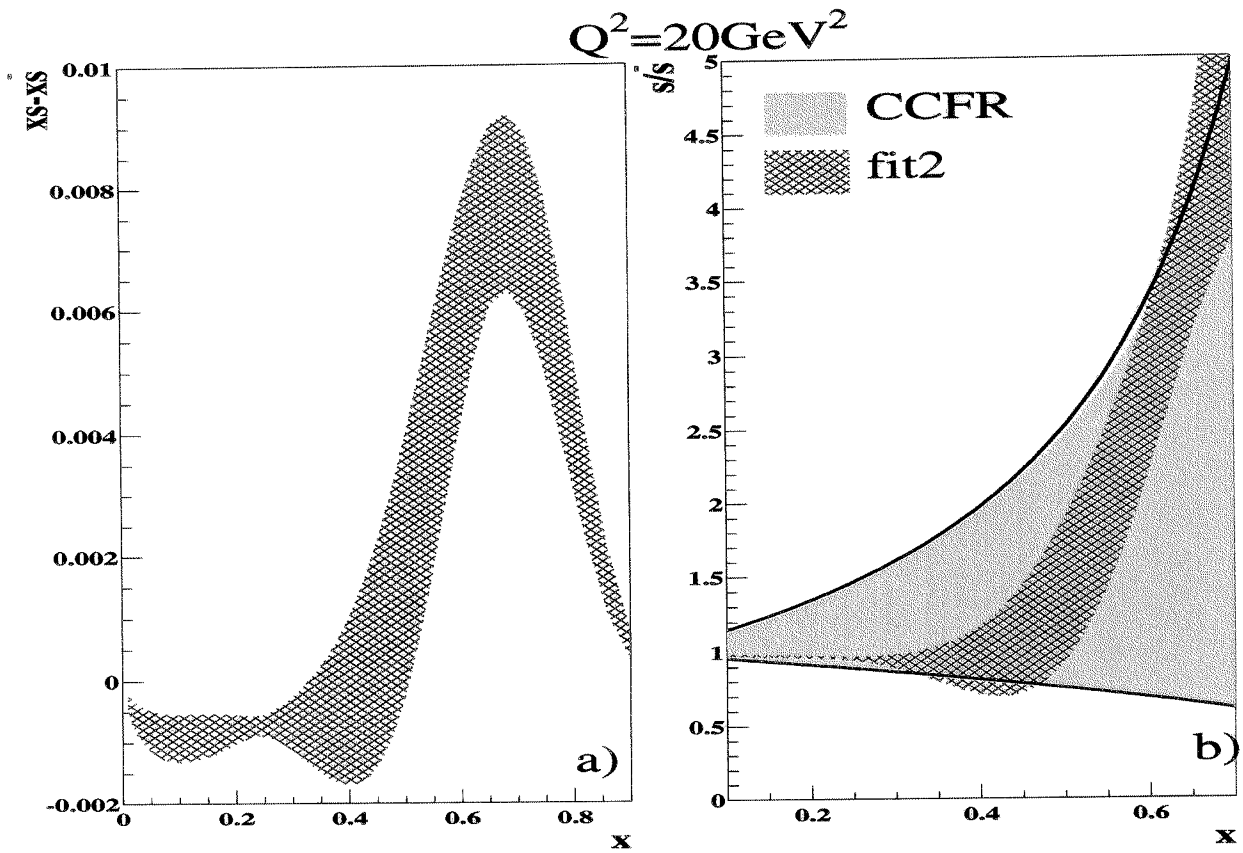
  $$s = (0.42 \pm 0.07 \pm 0.06)\,\frac{\bar{u}+\bar{d}}{2}$$

  consistent with CHARM II, CDHS, CCFR.

- $s \neq \bar{s}$? Brodsky, Ma intrinsic s states $K^+\Lambda$ *)
  $\bar{s} \sim (1-x)$ ← ↳ $s \sim (1-x)^3$

- V. Barone, C. Pascaud, F. Zomer
  reanalysis and global analysis of ℓN, νN, DY data

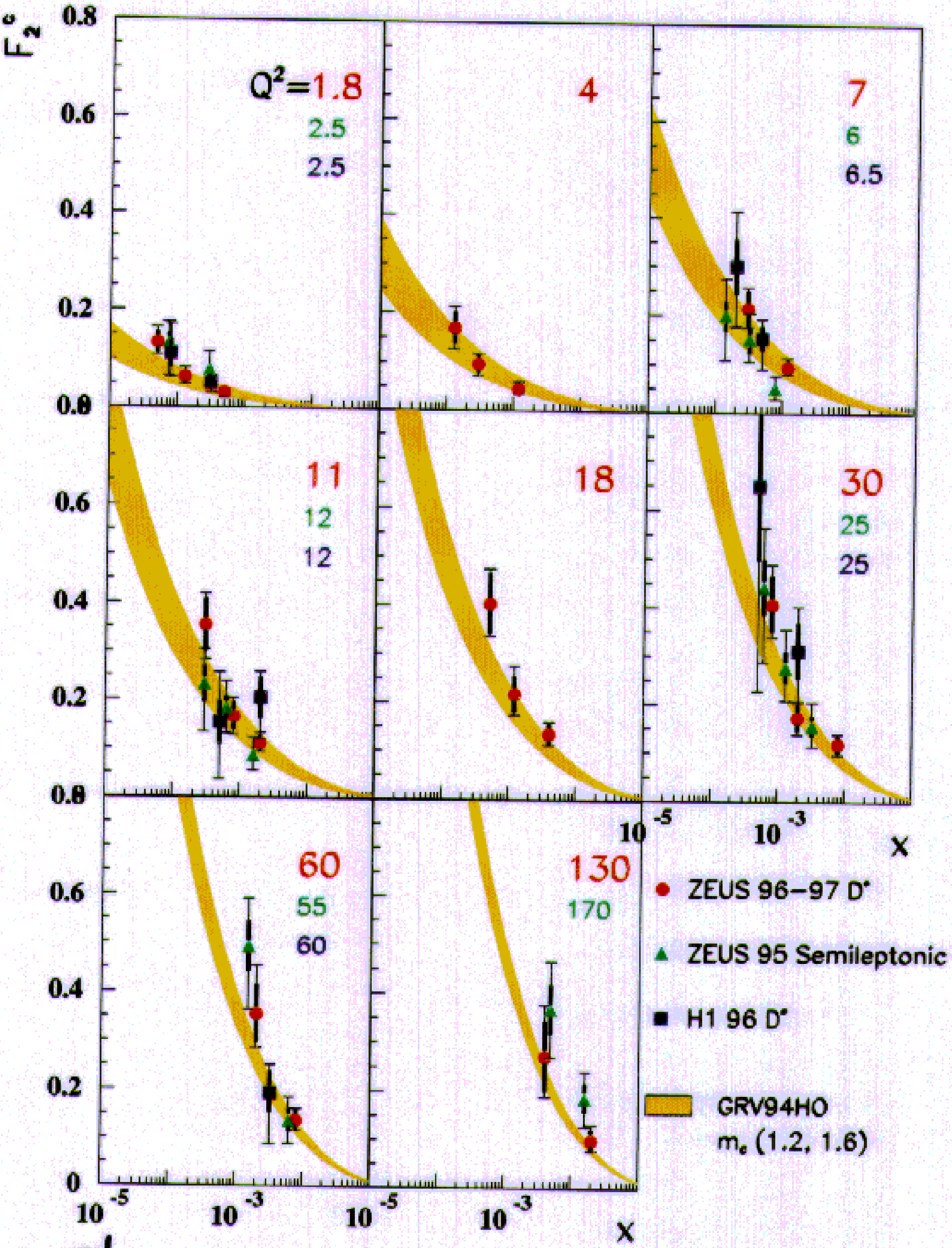
  $$\sigma^{\nu} - \sigma^{\bar{\nu}} \sim x(s-\bar{s}) + Y_{-}\,x(u_v + d_v) \quad \text{, CDHS}$$

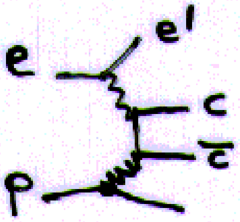


*) see W. Melnitchouk, hep-ph 9906488 for disc. & ref's

extrinsic charm *)

HERA 95-97 PRELIMINARY





$D^* \to D^0 \pi_s$

$\hookrightarrow K^- \pi^+, K3\pi$

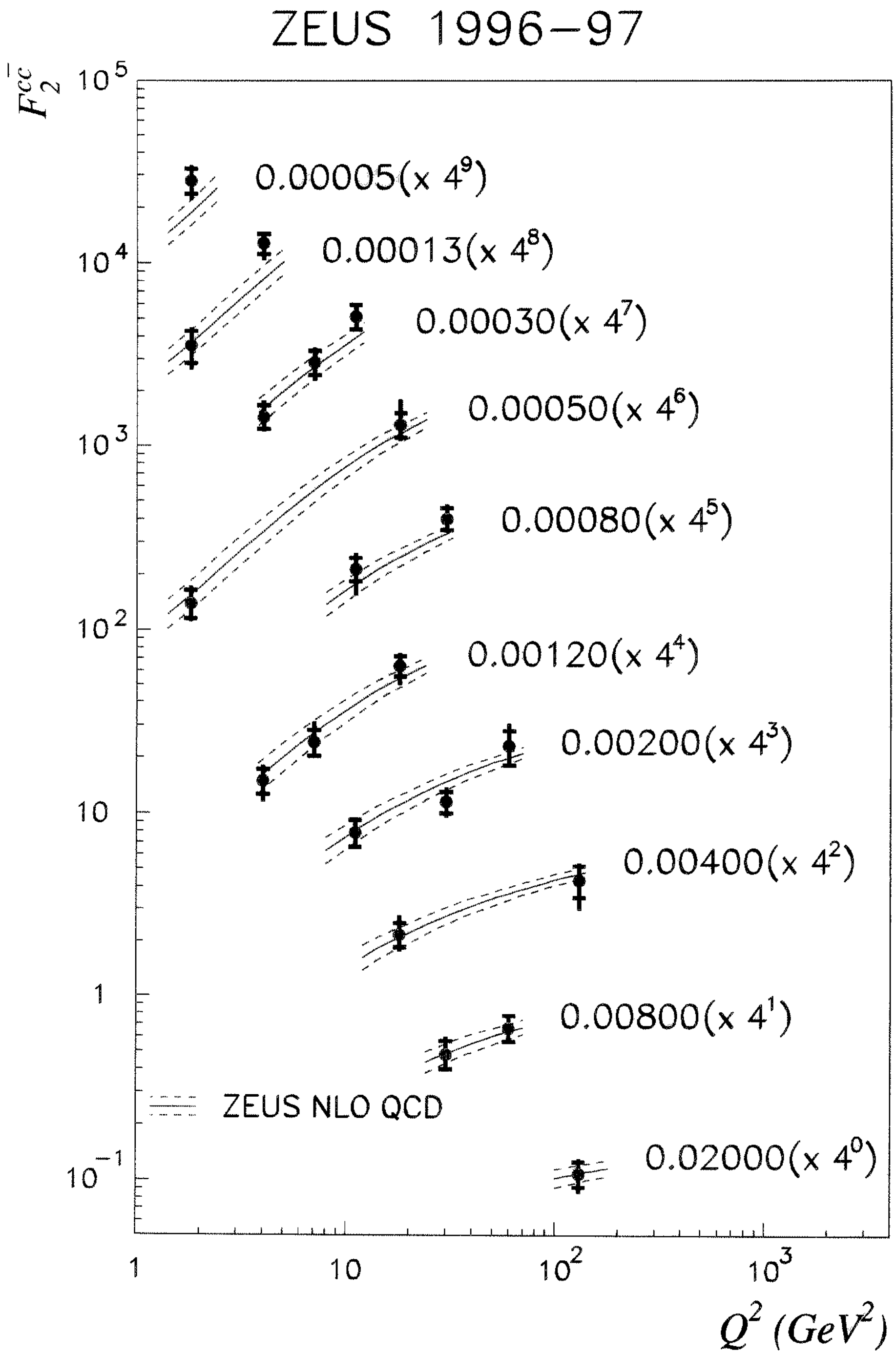
extrapolation F_2^D

fragmentation F_2^c

Witten, Shifman, Glück, Reya 1976-79

charm structure function.

ZEUS $D^* \to K2\pi, K4\pi$. $37 pb^{-1}$. DESY 99-101 hep-ex/9908012



scaling violations

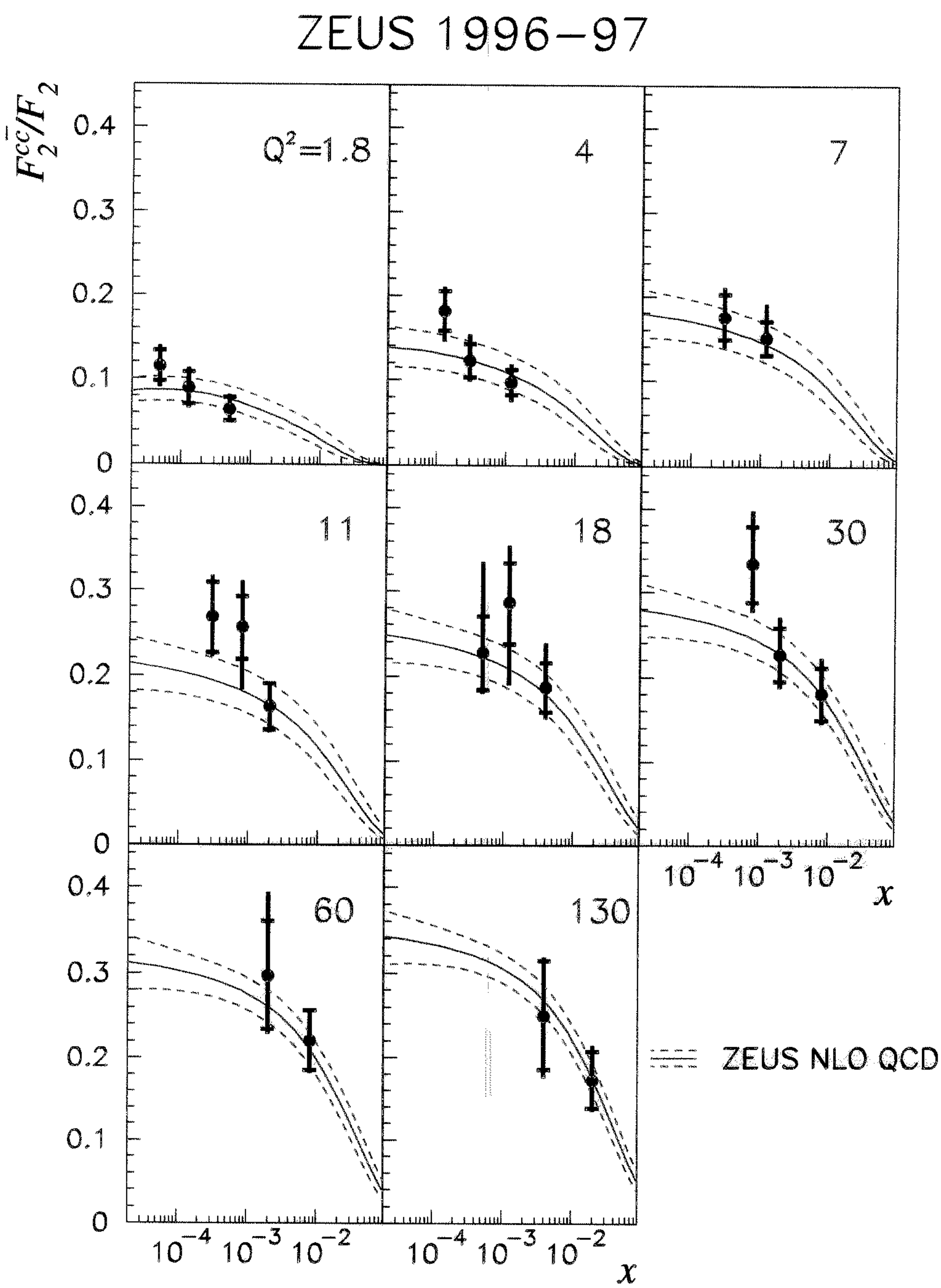
m_c 1.2 .. 1.6 GeV dominantly.

thy: 4 flavours, $Q^2 \gg m_c^2$

3 flavour + bg fusion $Q^2 \gtrsim m_c^2$ Laenen, vNeerven, Smith Riemersma

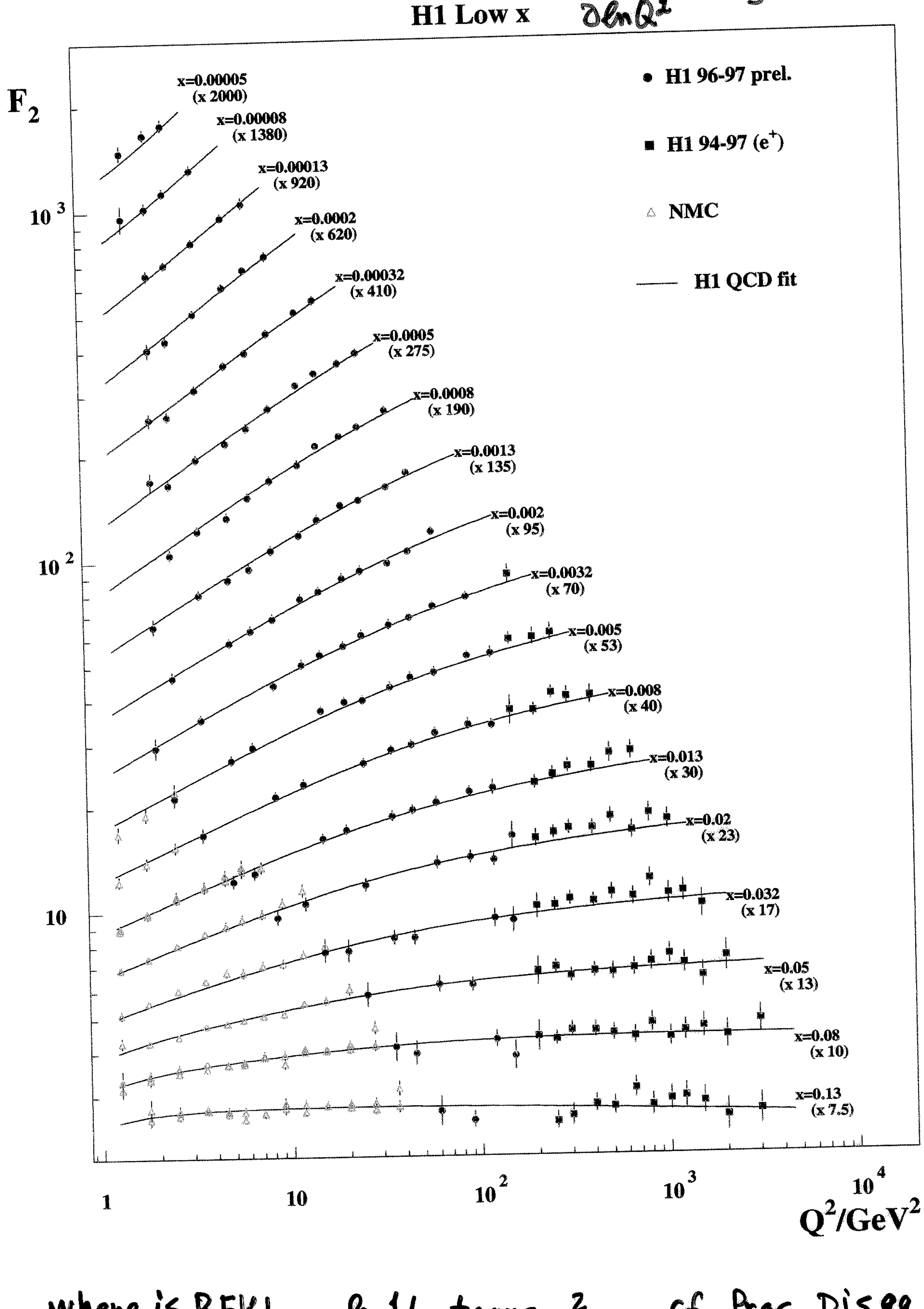
variable flavour schemes cf. J. Smith DIS 99 proc.

charm contribution to F_2. ~ 20%



large scaling violations described by NLO DGLAP

$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s \cdot xg$



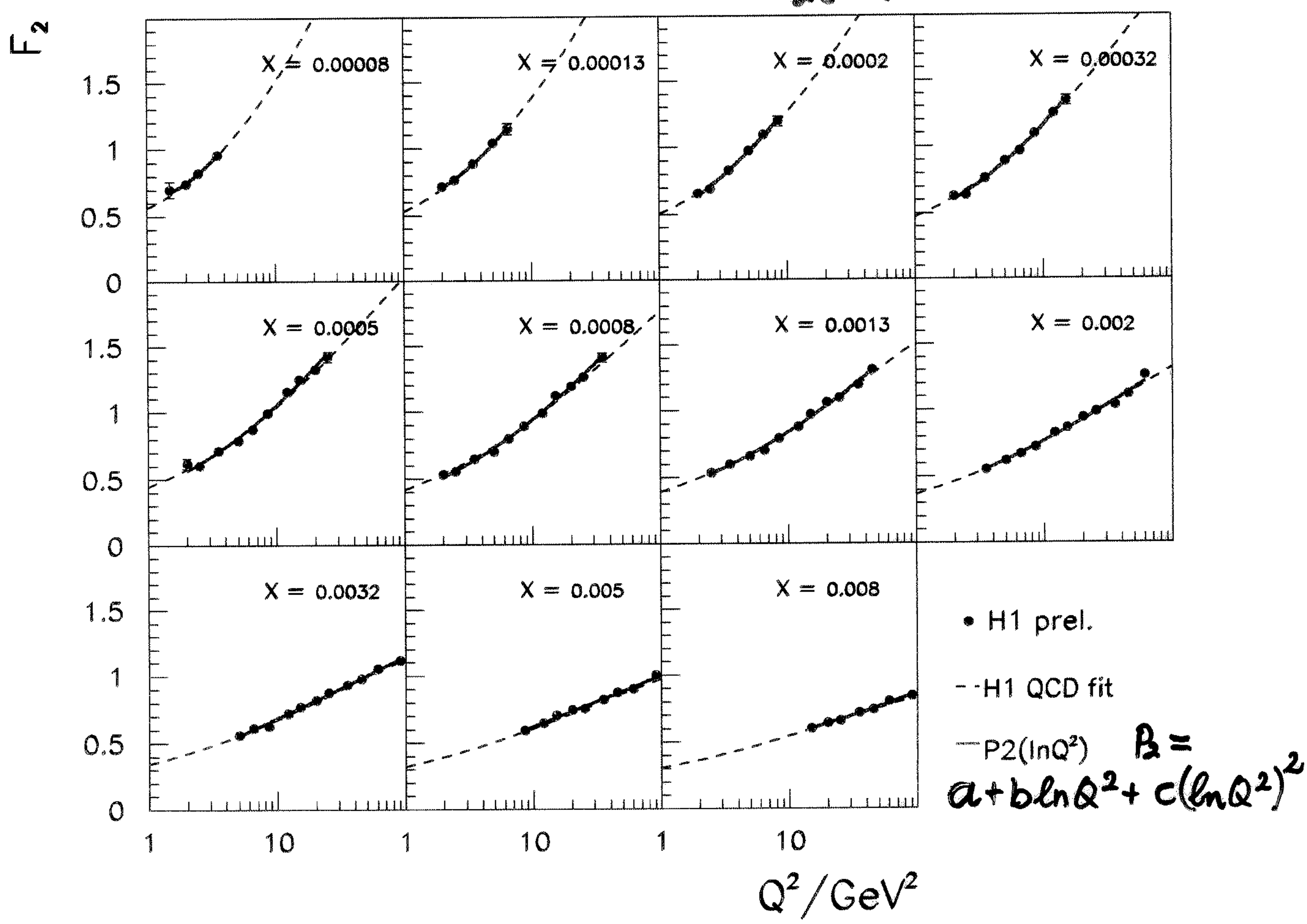
where is BFKL, $\ln 1/x$ terms ?

Balitzkii, Fadin, Kuraev, Lipatov 1975,78

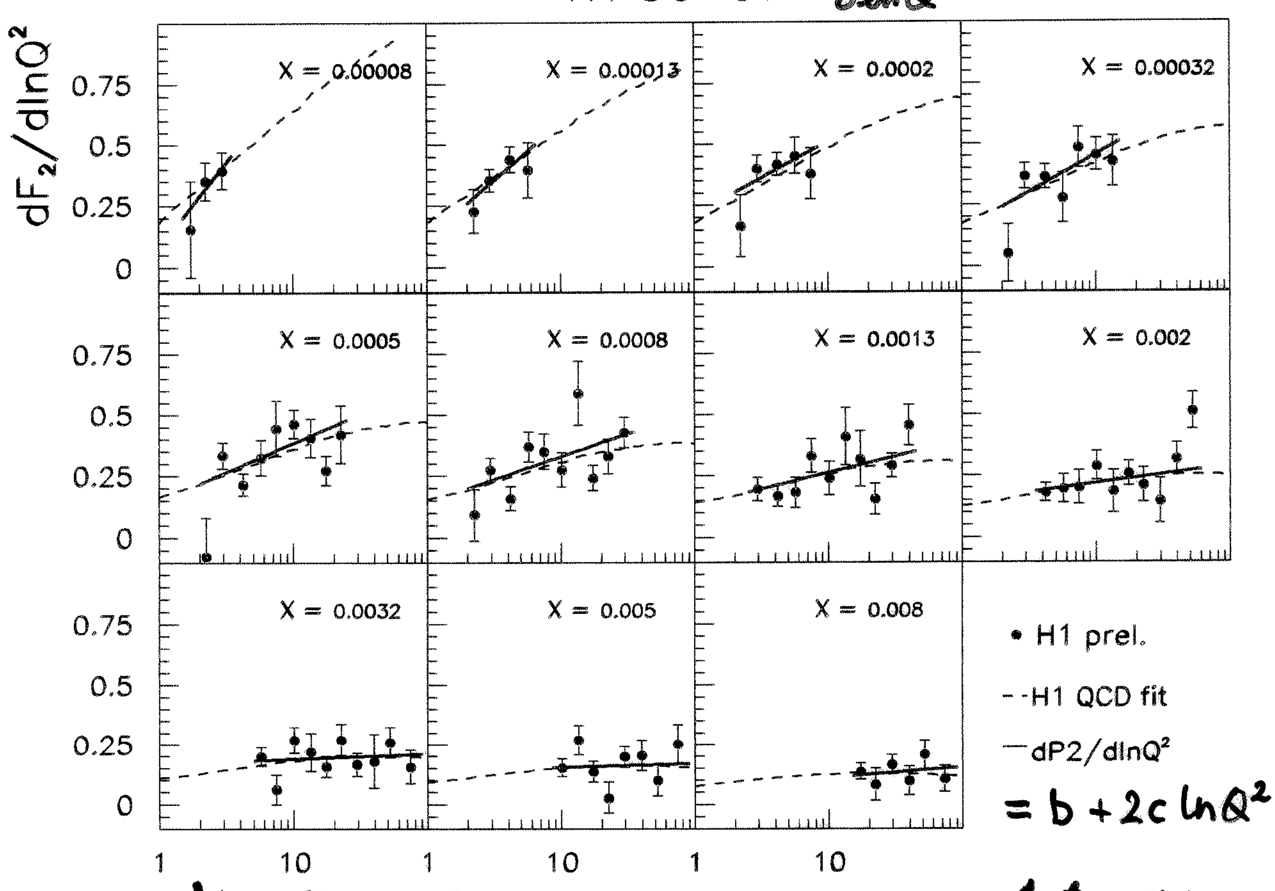
cf. Proc. Dis 99

Ciafaloni, Fadin, delDuca
Thorne ...

H1 96–97 $F_2(\ln Q^2)$ non-linear.

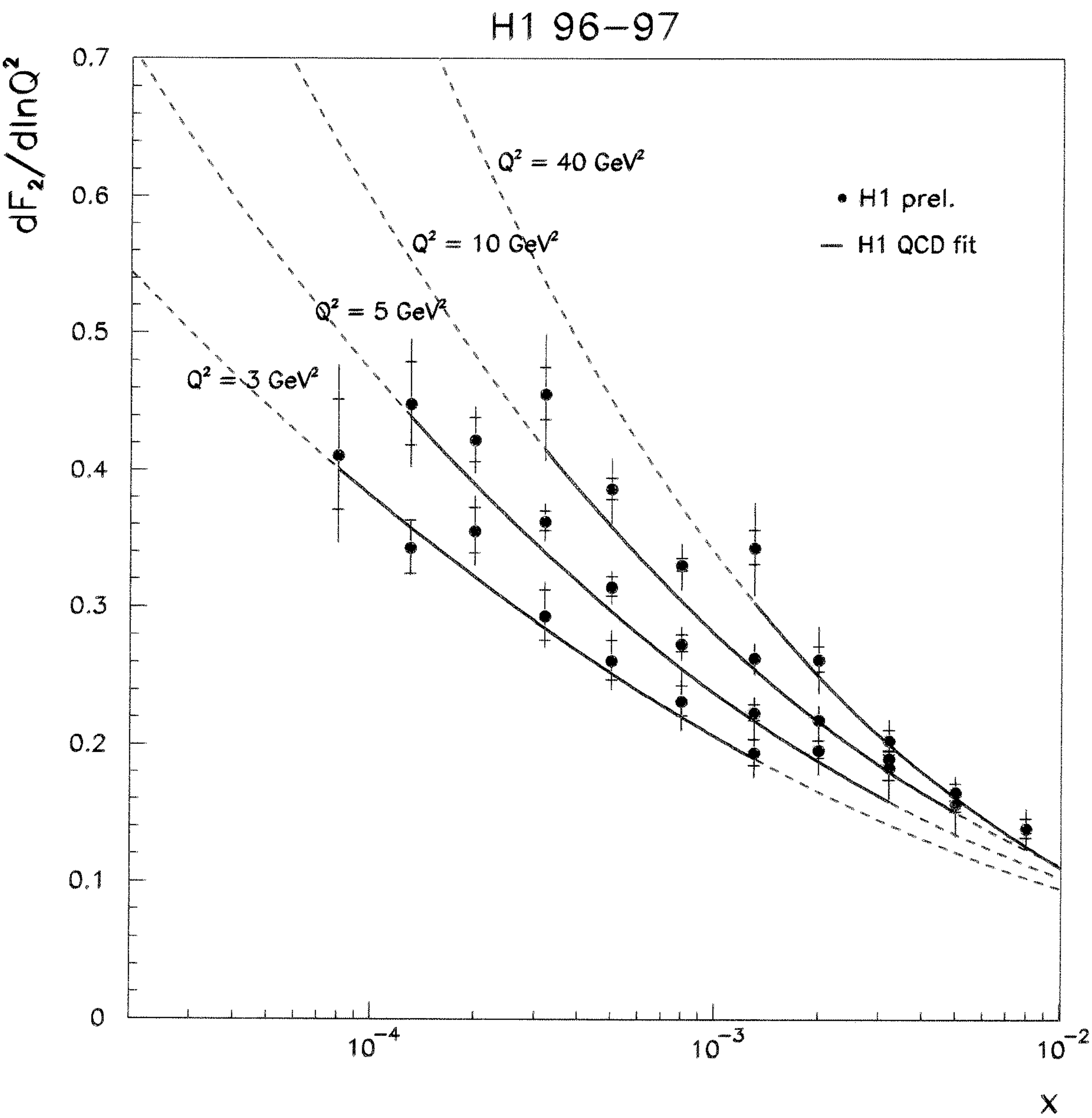


local derivatives H1 96–97 $\frac{\partial F_2}{\partial \ln Q^2}(x, Q^2)$



$F_2'(\ln Q^2)$ non-linear in QCD. NLO

data are well described $\forall Q^2 \geq 2$ GeV²

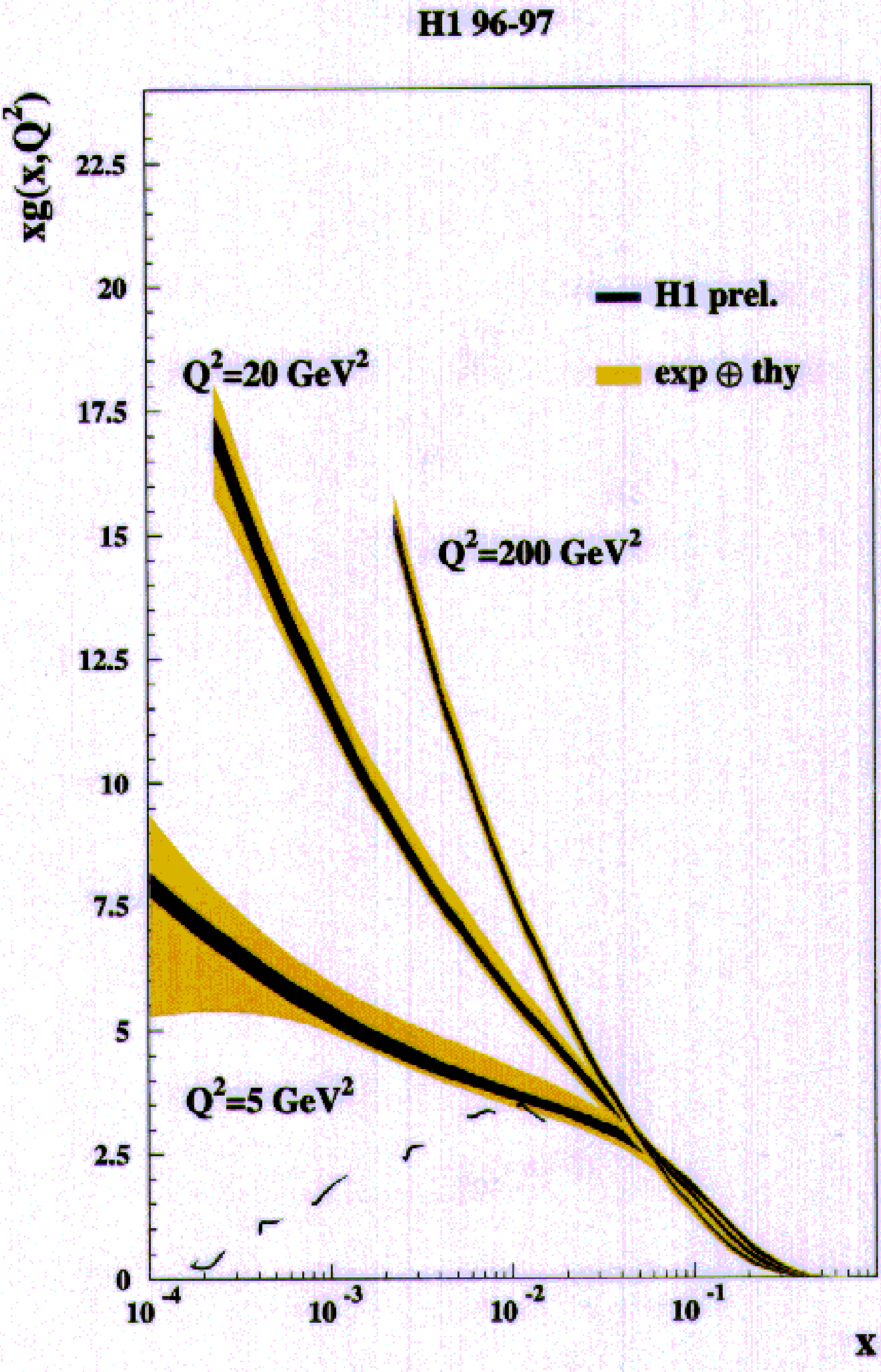


use quadratic approximation to determine $\frac{\partial F_2}{\partial \ln Q^2}(x, Q^2)$

no departure from rising behaviour seen for $Q^2 \geq 3\ GeV^2$.

below $\sim 3\ GeV^2$: NLO QCD fits depend much on starting conditions and h.o calculations become unreliable. } shadowing corr's

gluon distribution

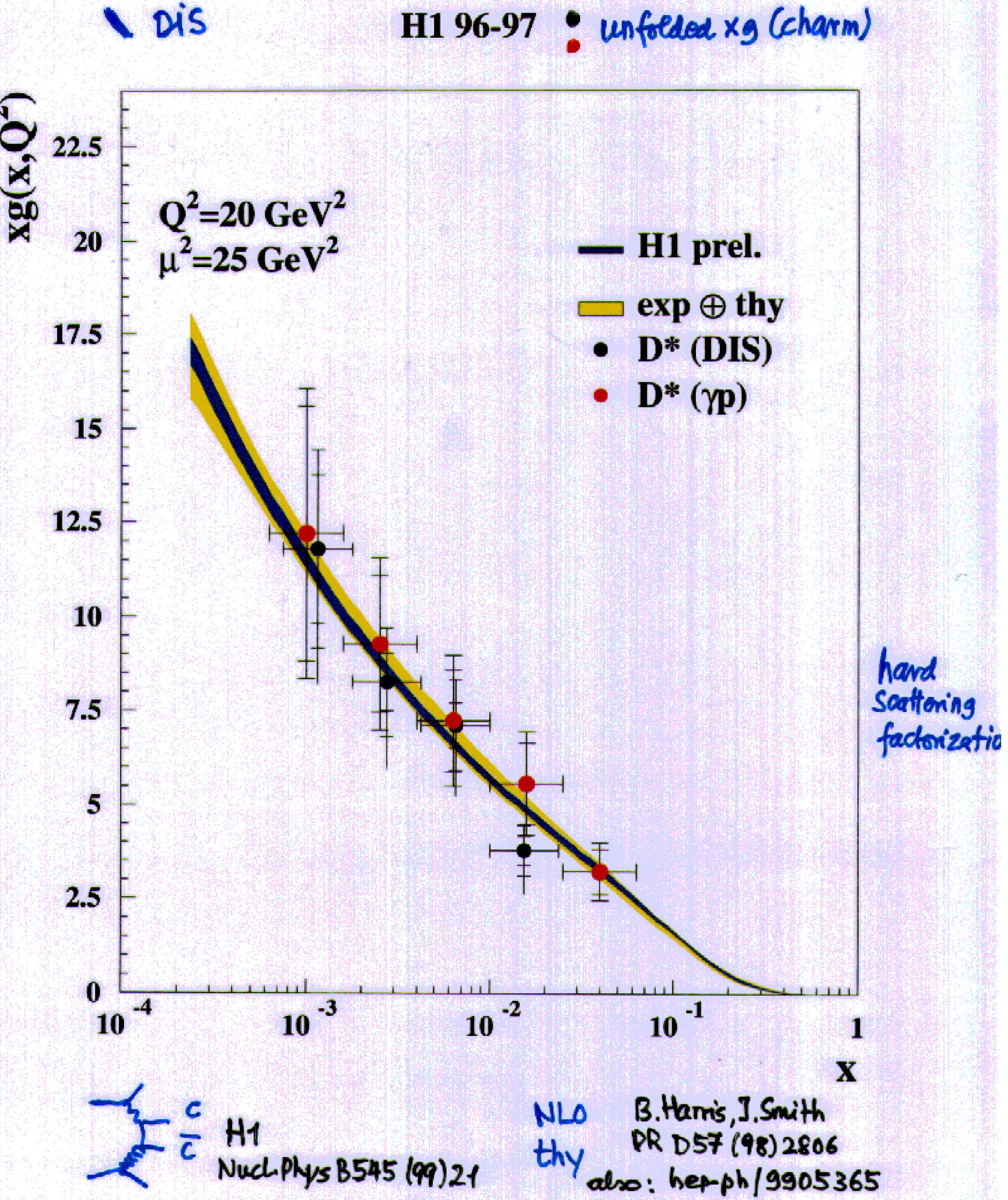


exp. uncertainty

Q_0^2, Q^2_{min}
deuteron
$\delta\alpha_s = 0.002$
m_c
parametriz.
⋮

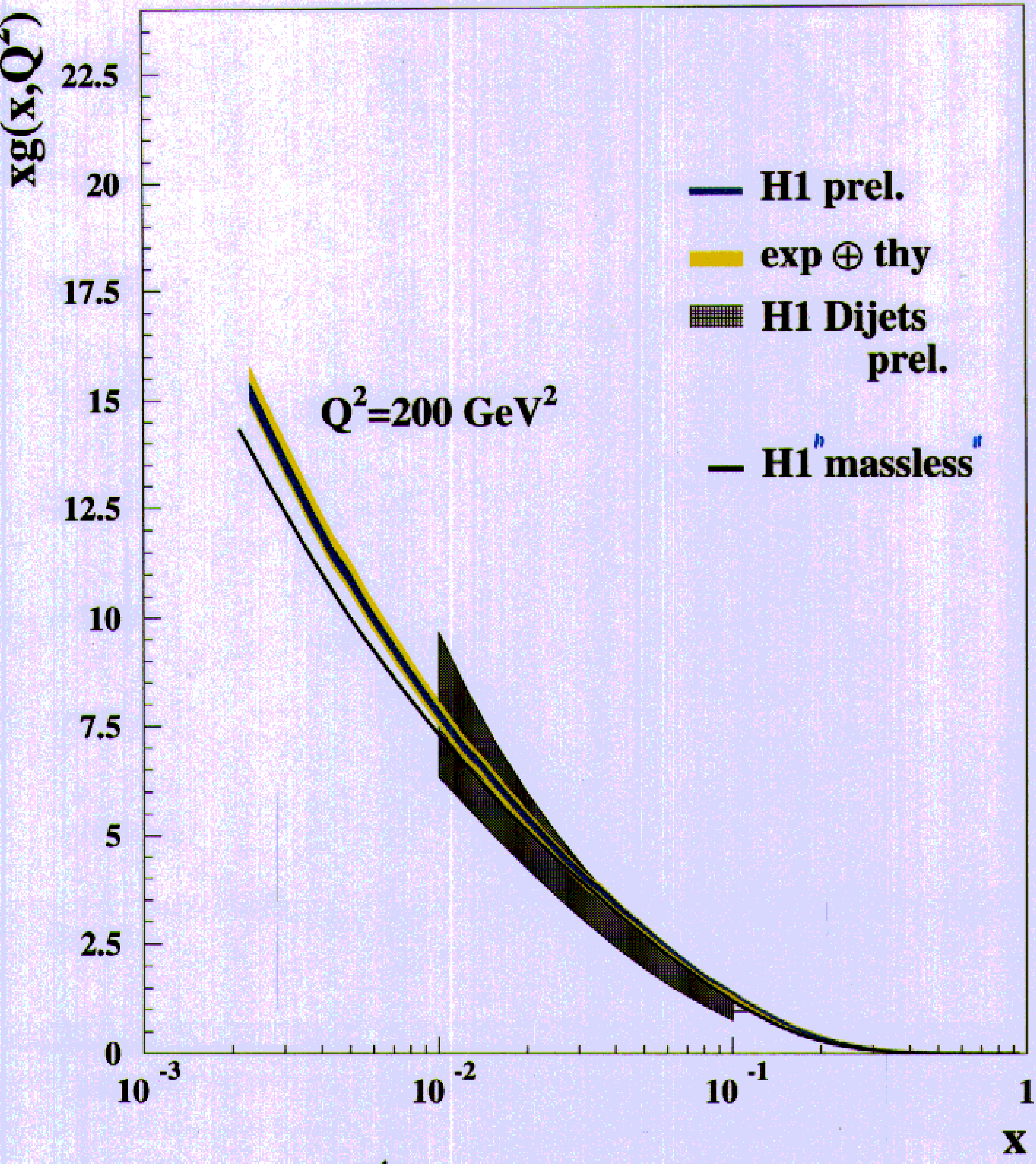
H1 + NMC$_p$

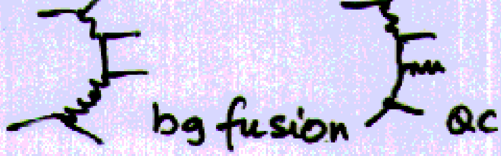
$Q^2 = 3.5 \cdots 3000$ GeV^2 bgf for c,b : massive scheme


DIS
H1 96-97
unfolded xg (charm)
xg(x,Q^2)
Q^2=20 GeV^2
μ^2=25 GeV^2
H1 prel.
exp ⊕ thy
D* (DIS)
D* (γp)
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
10^-4
10^-3
10^-2
10^-1
1
x
hard scattering factorizatio
c
c̄
H1
Nucl. Phys B545 (99) 21
NLO thy
B. Harris, J. Smith
PR D57 (98) 2806
also: hep-ph/9905365

\ DIS

H1 96-97 dijets



- 

$\frac{d\sigma}{dQ^2 d\xi}$, $\xi = \left(1 + \frac{m_{ij}^2}{Q^2}\right) \cdot x$

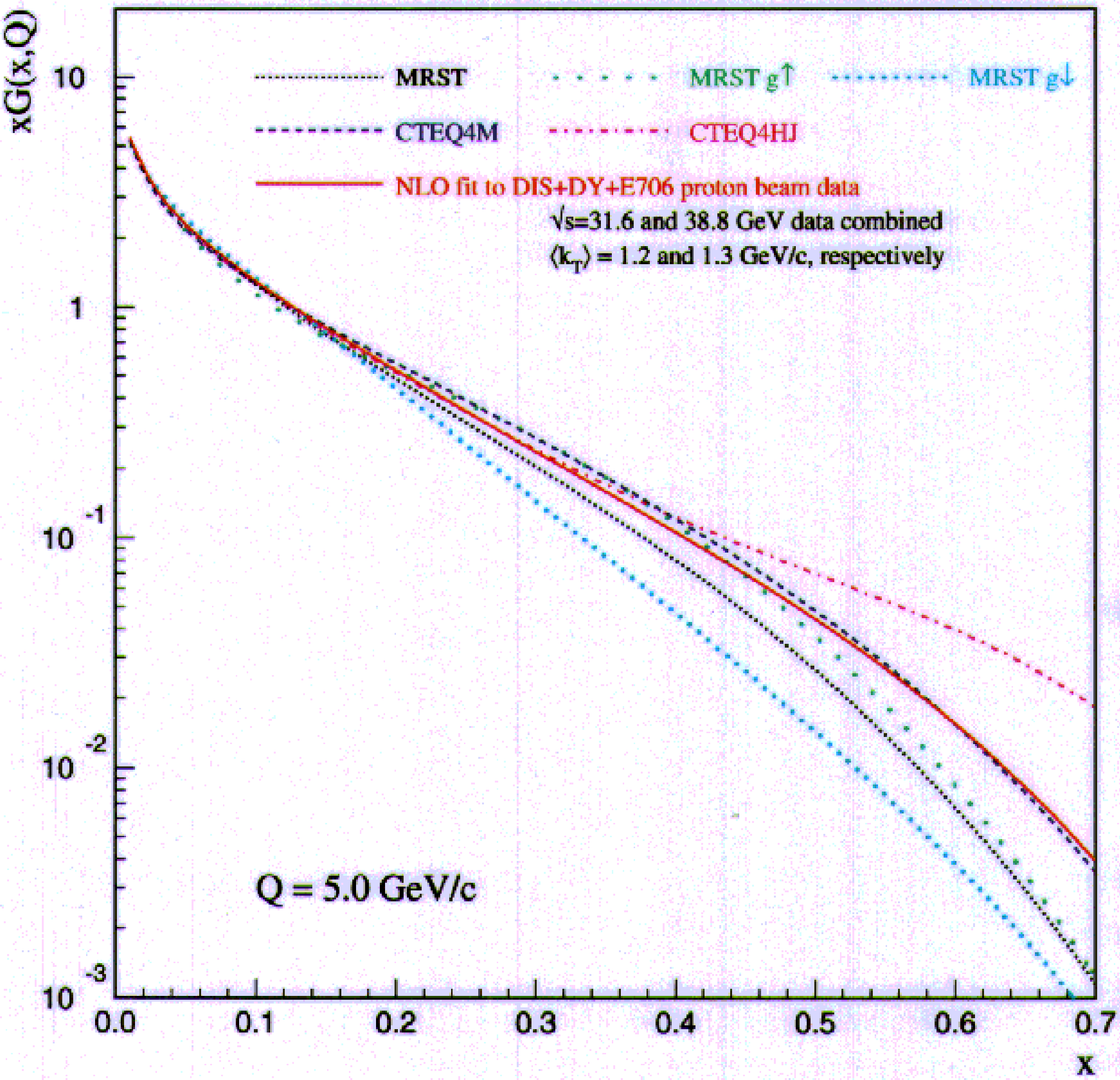
jet definition, hadronization, NLO QCD

& DIS Q^2 200 - 650 GeV^2

xg at high x ?

DIS: bremstrahlung, direct photons, high $p_\perp$ jets

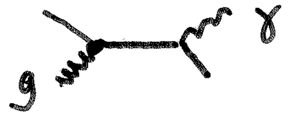
- MRST99 hep-ph/9907231 : WA70, vary $k_\perp$, α_s, m_c, d/u
- CTEQ5 9903282 : jets $M = \overline{MS}$, HJ = high xg, HQ ACOT



differences in xg, c, d/u ⋮ depending on thy formalism and data sets used.

- GRV 98 hep-ph/9806404 DIS, n/p, DY $\alpha_s = 0.114$.

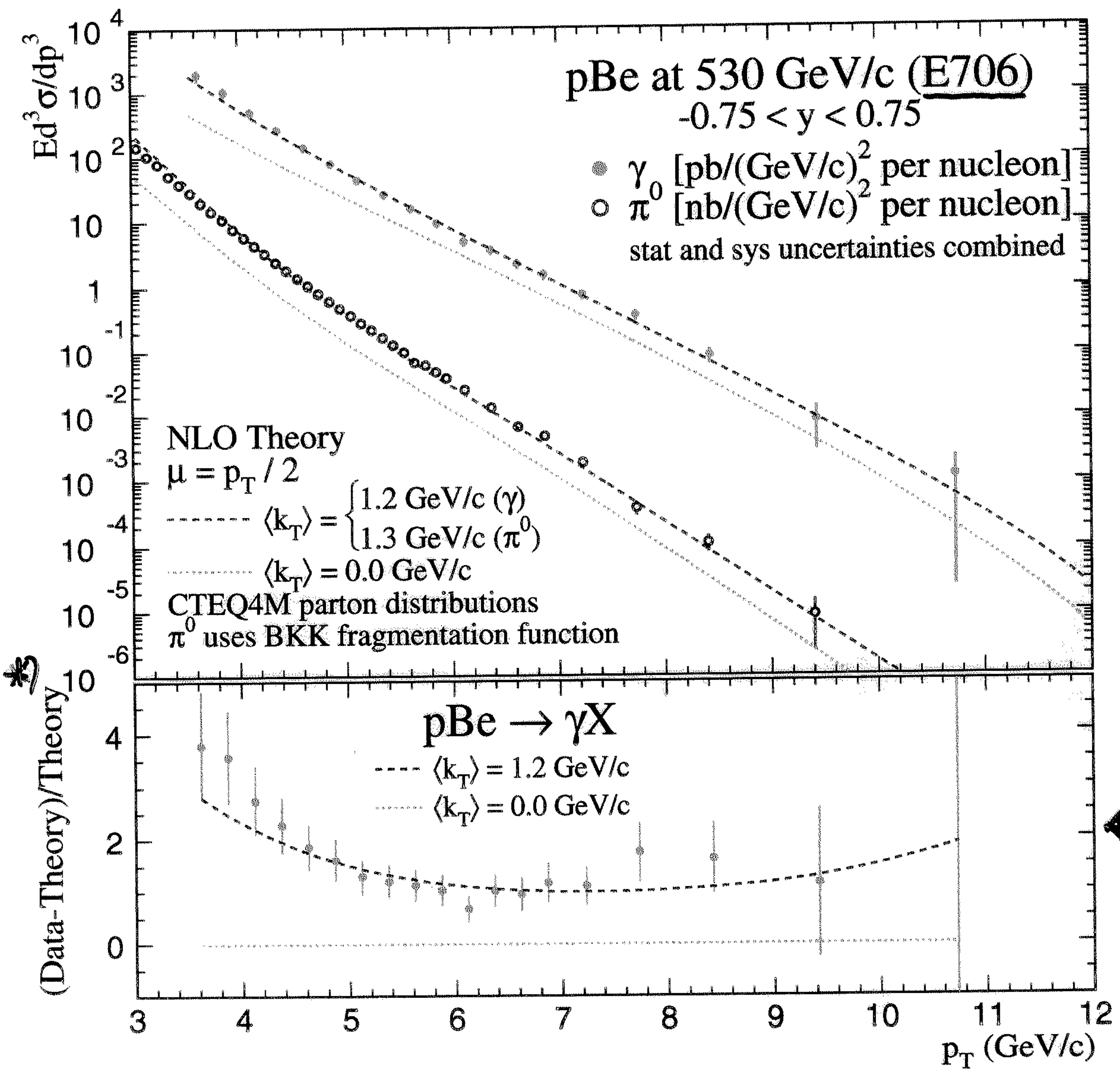
quark-gluon Compton scattering



- xg at large x (Halzen, Scott 1980) but initial state gluon emission (Feynman, Field, Fox 1978)
- UA6, WA70, E706, CDF, DØ

  ↳ will extend to ~100 GeV $p_\perp$

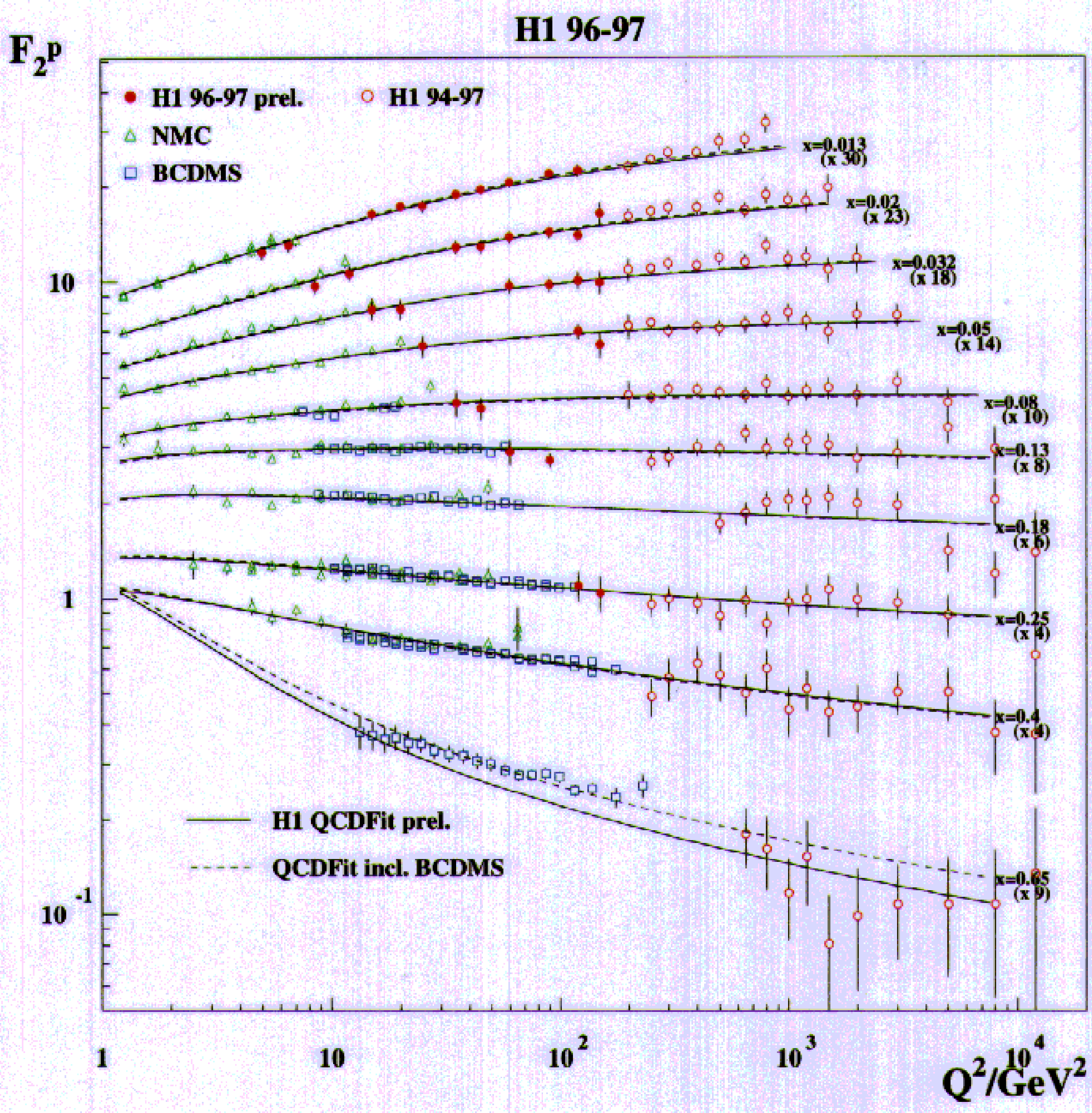
L. Apanasevich et al., PRL 81 (1998) 2642



← 2!

- LO x sections ⊗ Gaussian $k_\perp$ smearing: $k_\perp$ enhanced NLO thy[+)] . $k_\perp \sim 1$ GeV > $k_\perp^{intrinsic}$

PRD59,074007



high x to be measured at HERA with $\mathcal{L}\uparrow$

α_s in DIS

- $\delta\alpha_s \sim 0.001$ precision HERA & fixed target — HERA workshop95 Botje, Pascaud, MK.
- requires NNLO, miss 3 loop terms of splitting functions cf. v Neerven, Vogt -ph/9907472
- revival of moment analyses (2n Mellin: Larin et al.)

J. Santiago, F. Yndurain hep-ph/9907387 Bernstein

$\alpha_s^{NNLO}(M_Z^2) = 0.1163 \pm 0.0023$ NLO + 0.0012

SLAC, BCDMS, E665, H1, ZEUS & xg

A. Kataev, G. Parente, A. Sidorov hep-ph/9907310 Jacobi

$\alpha_s^{NNLO}(M_Z^2) = 0.118 \pm 0.002_{st} \pm 0.005_{sy} \pm 0.003_{thy}$ NLO + .002

xF_3, CCFR

S. Forte et al : truncated moments $\int_{x_{min}}^{1}$

- NLO S. Alekhin hep-ph/9907350

  $\alpha_s^{NLO} = 0.1183 \pm 0.0021_{exp} \pm 0.0013_{thy}$

  higher twist $h(x)/Q^2$

- J. Blümlein, A. Vogt DIS99: replace xg by $\partial F_2/\partial \ln Q^2$ in evolution equ's.

major future projects in DIS

- ν

MINOS$_{near}$ — E_ν up to 25GeV, $4 \cdot 10^6$ events/year, main injector at Fermilab

↳ 1km, 17m long Fe (+A) / Sc spectrometer

measure all $\nu, \bar{\nu}$ structure functions and A dep.

cf. J. Morfin DIS99

- μ collider hep-ex/9907033 B. King (MURINE).

- HERA

luminosity upgrade during 2000

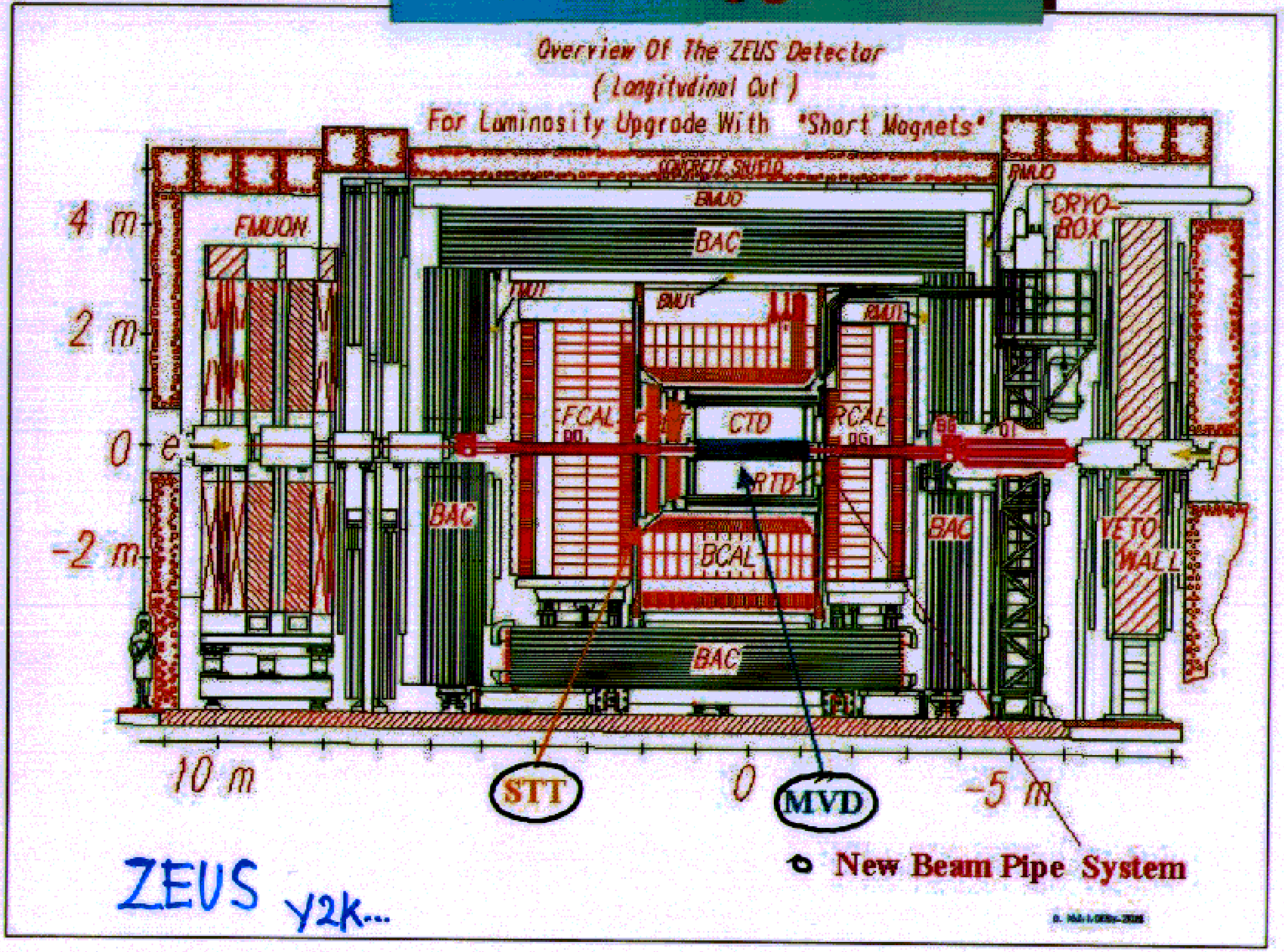
restart early 2001 after shutdown in May ... 2000

- high precision at high Q^2 — $150 pb^{-1}$ / year

$E_{e,p}$ variations. — $\int_{HERA} \mathcal{L} dt \sim 1 fb^{-1}$

- options.
  D, A, $\vec{p}$

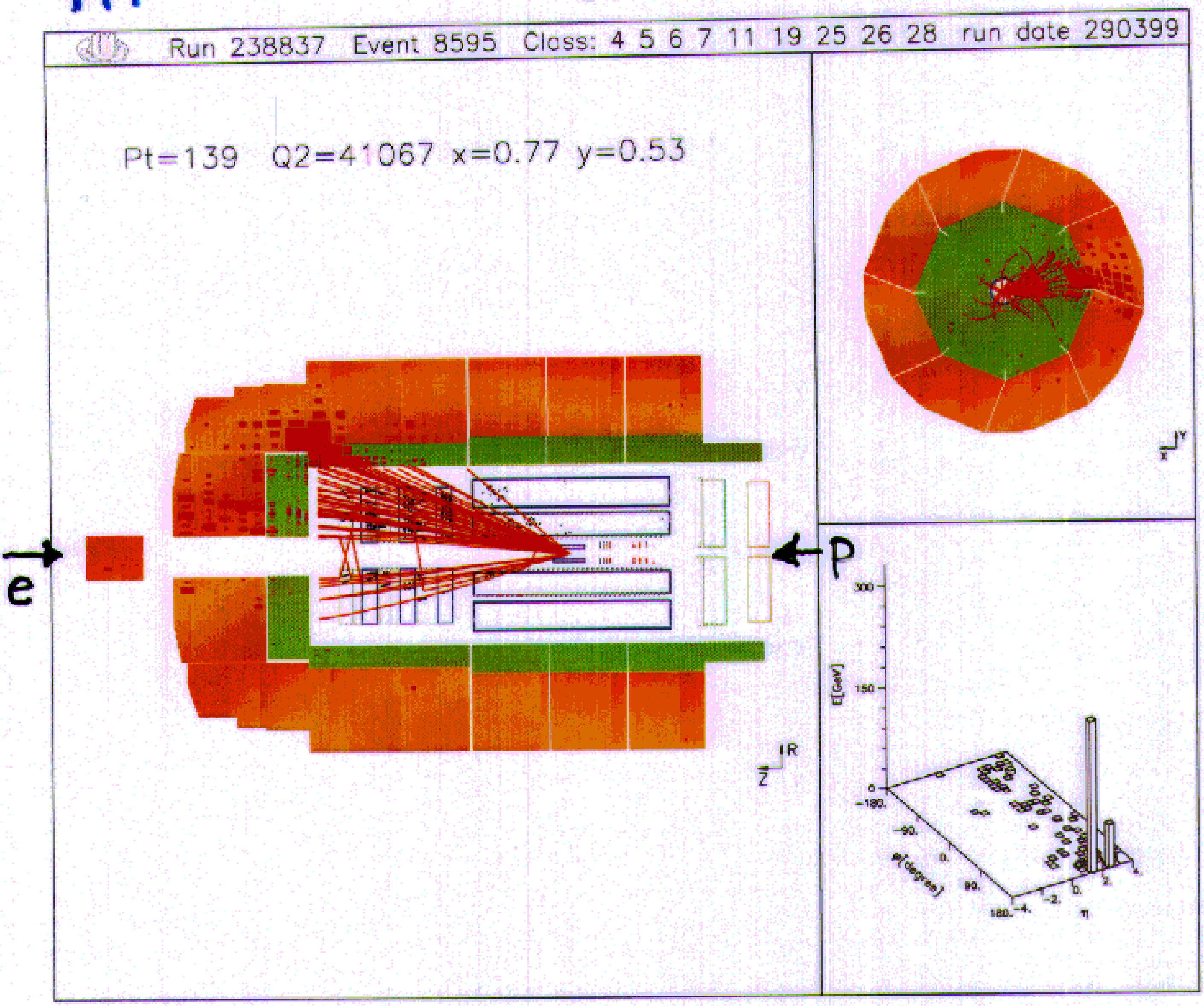
Future upgrades



polarimeter (with H1) .

H1

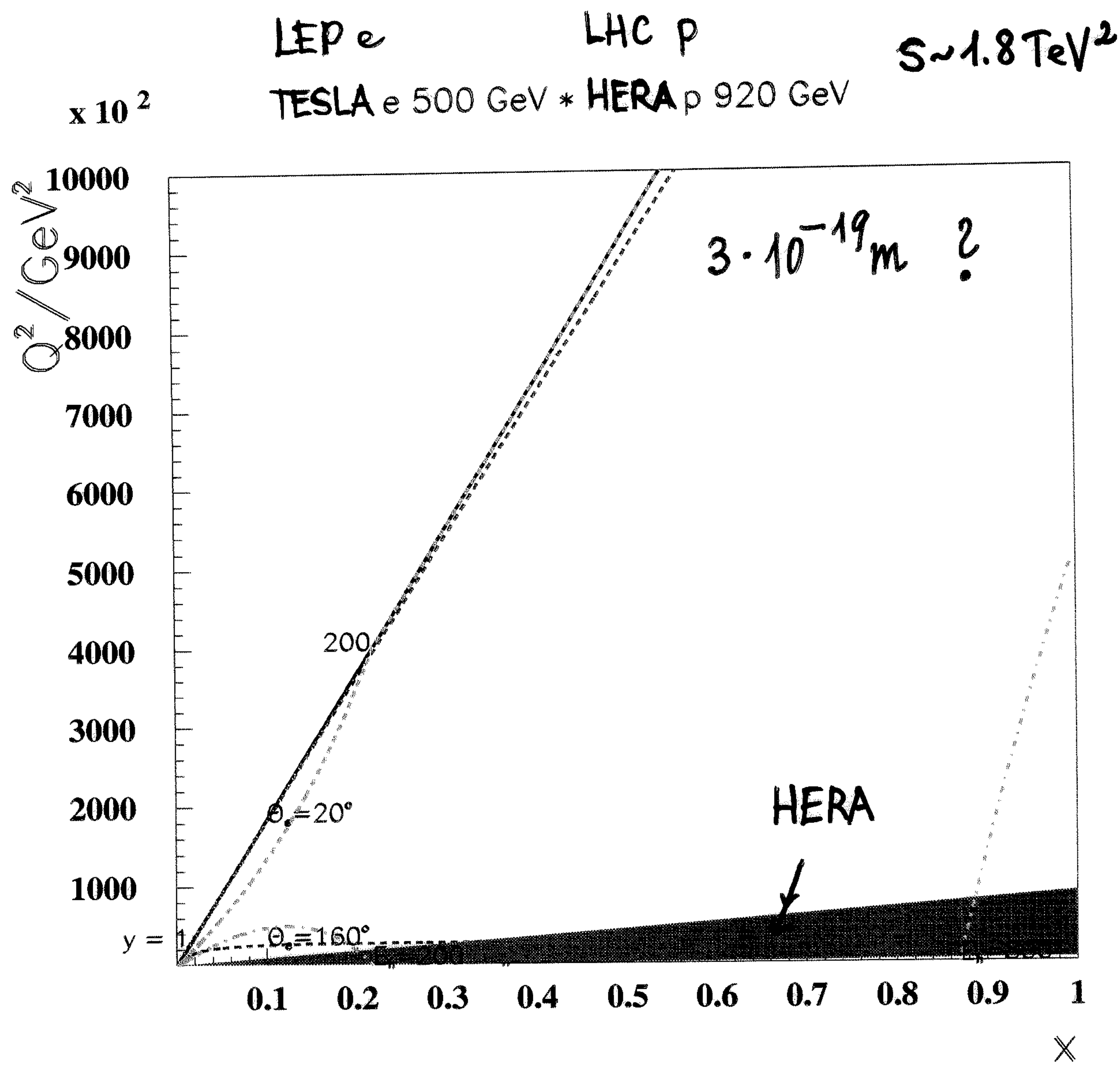
CC event $Q^2 = 41000\ GeV^2$, $x = 0.77$



- forward Silicon tracker
- upgraded forward tracker
- new inner trigger chamber
- ⋮

H1 $\mathcal{L}$ upgrade

deep- inelastic scattering



has an exciting future

instead of listening to a summary

please think a moment about

Bjoern Wiik.

thank you.

many thanks to

members of the H1 structure function group

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R. Towell, WK. Tung, A. Wagner, J. Whitmore
U.K Yang, R. Yoshida ...