Recent QCD results from HERA

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(for the H1 and ZEUS collaborations)

- Proton Structure Functions and Scaling Violations
  - F_2 (including reference to possible manifestation of non-pert. physics)
  - F_2^{charm}
- Diffractive deep inelastic scattering (very briefly)
- α_S measurement from jet rates and from scaling violations
- Photoproduction
- NC and CC cross sections and structure functions up to very high Q^2

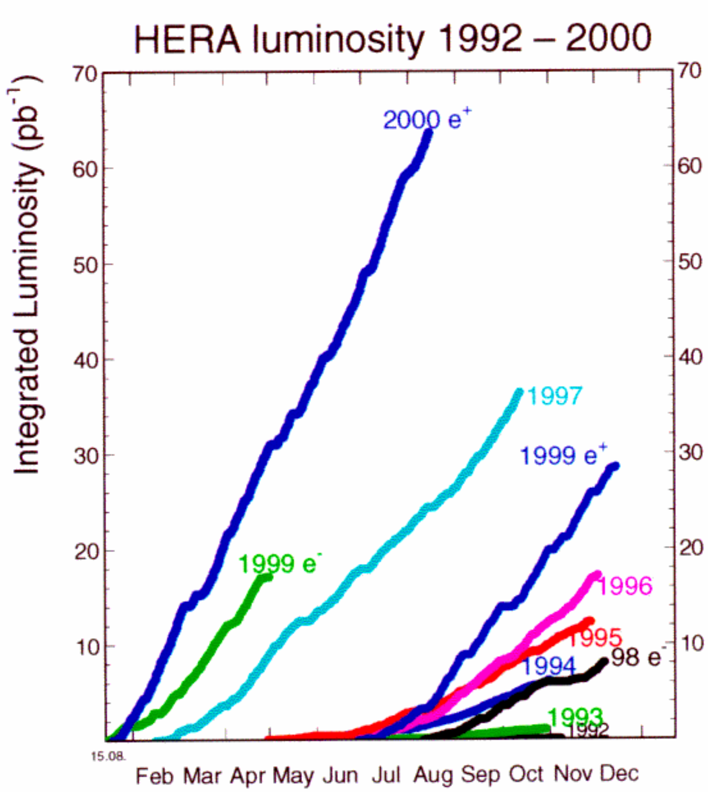
HERA: e^{+-} p collider, 27.5 x 820 (920) GeV

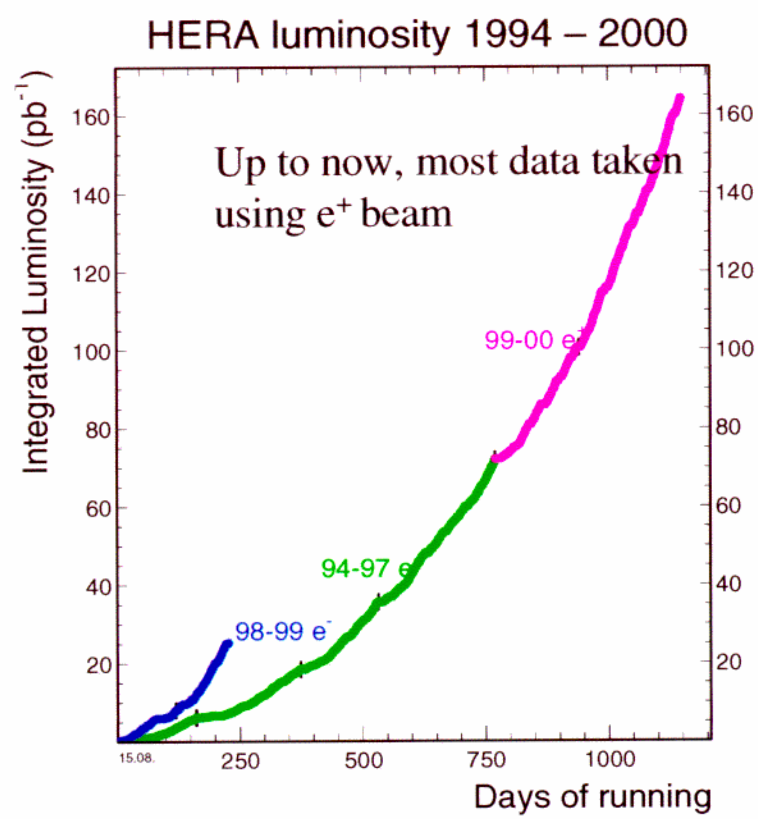
Instantaneous luminosity ~ 1.5 10^{31} cm^{-2} s^{-1}

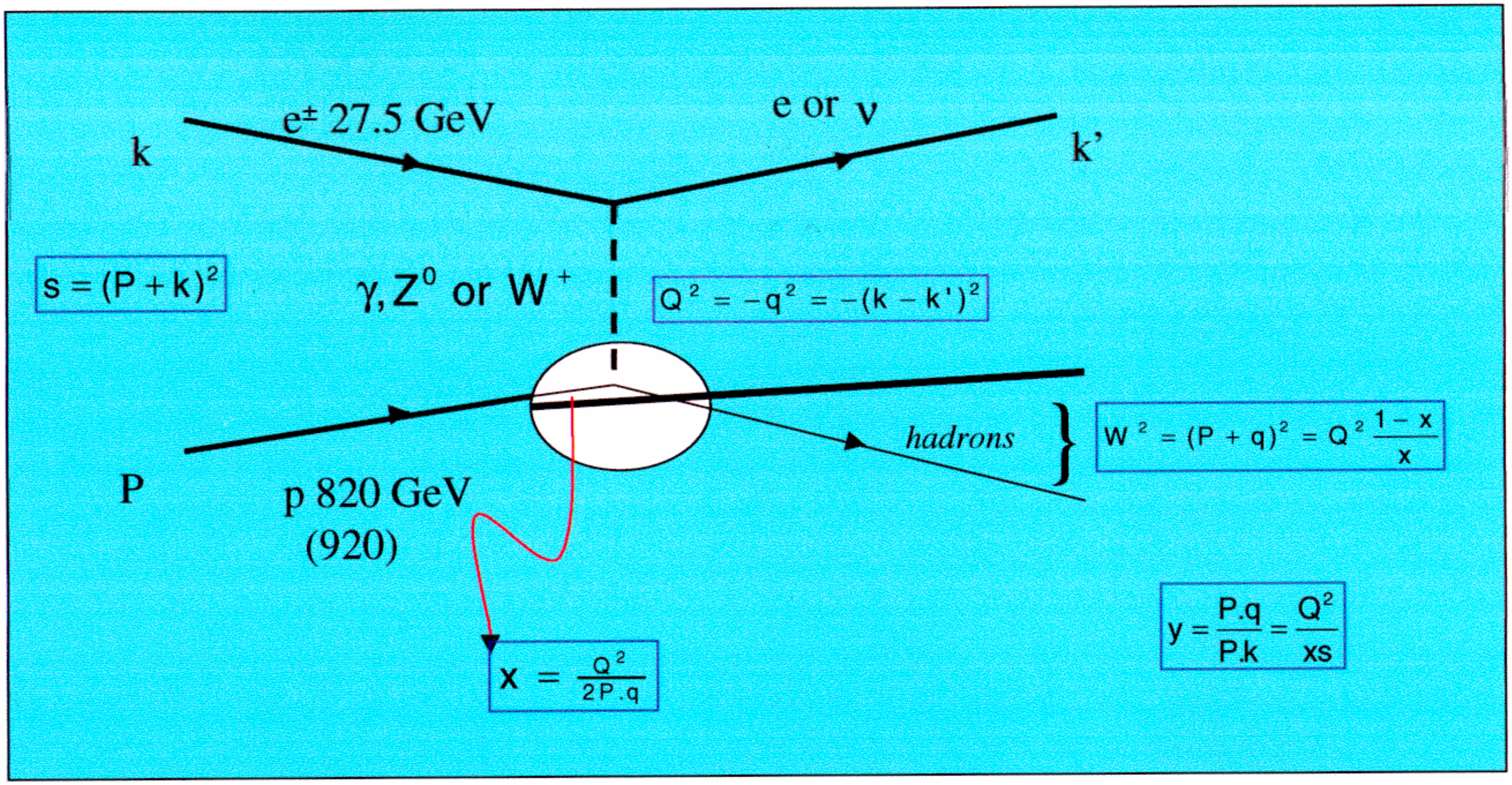
Two 'general purpose' colliding beam experiments: H1, ZEUS

One fixed target experiment, using polarized electron beam (Hermes)

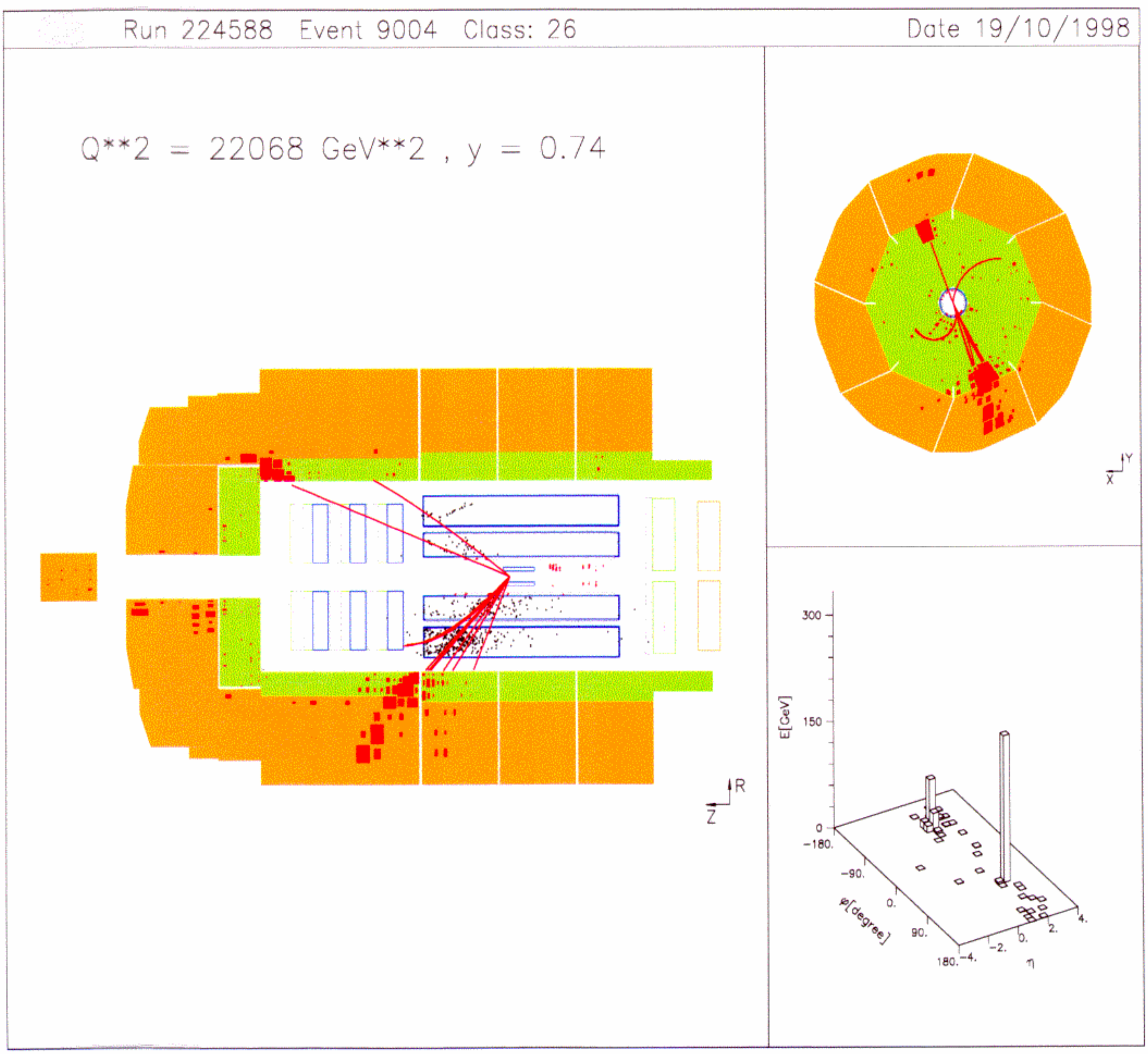
One fixed target experiment using proton beam (HERA-B)

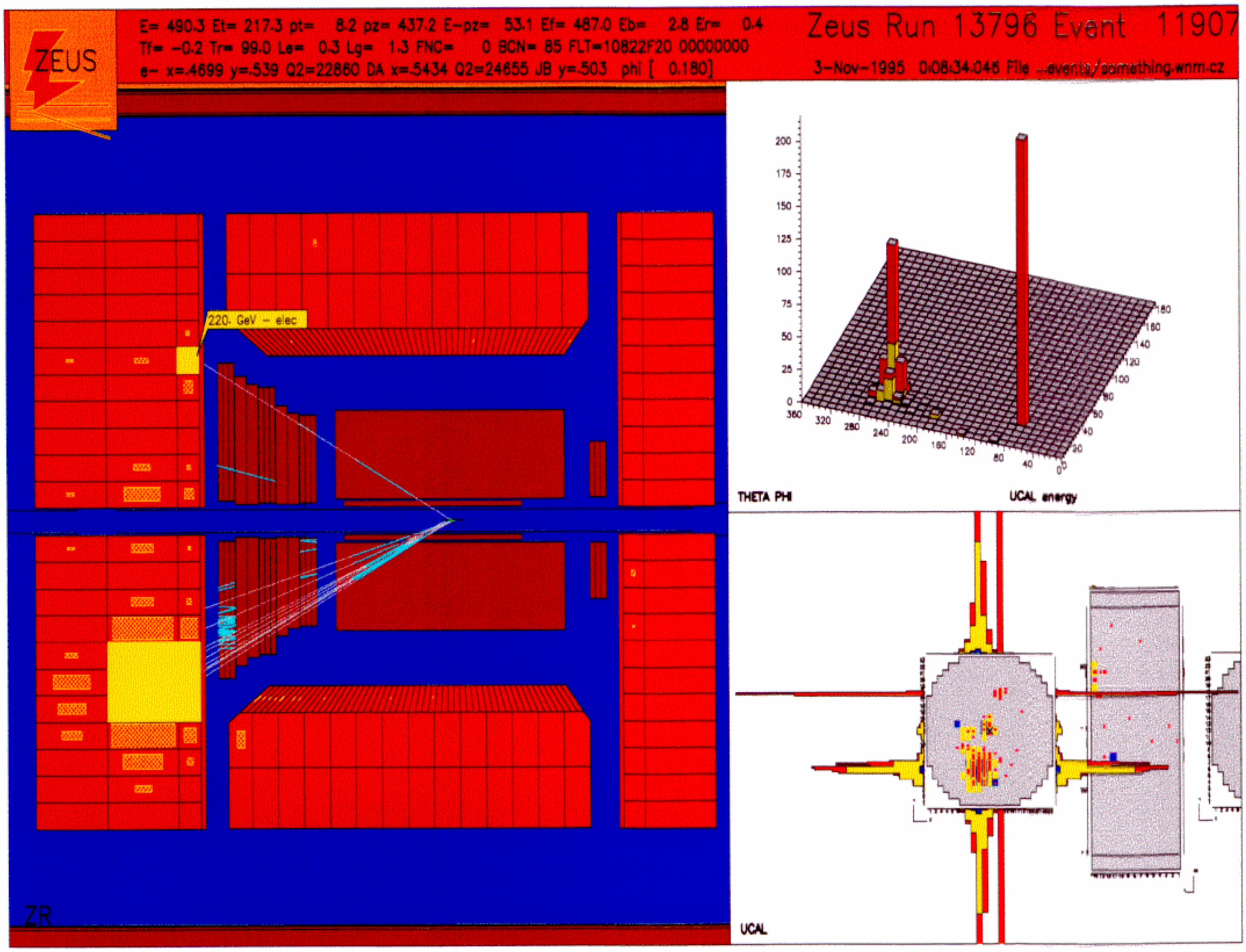






- Structure Functions $F_i(x,Q^2)$: Q^2 evolution described by pert. QCD
- Hadronic final state: governed by hard (#jets) and soft QCD (hadronization)
- $Q^2 \sim 0$: photoproduction; if hard scale present (p_T,m_Q): pert. QCD
- Hard (Q^2>>1 GeV^2) diffraction


Run 224588 Event 9004 Class: 26
Date 19/10/1998
Q**2 = 22068 GeV**2 , y = 0.74
R
Z
Y
X
E[GeV]
300
150
0
-180.
-90.
0.
90.
180.
φ[degree]
-4.
-2.
0.
2.
4.
η


E= 490.3 Et= 217.3 pt= 8.2 pz= 437.2 E-pz= 53.1 Ef= 487.0 Eb= 2.8 Er= 0.4
Tf= -0.2 Tr= 99.0 Le= 0.3 Lg= 1.3 FNC= 0 BCN= 85 FLT=10822F20 00000000
e- x=.4699 y=.539 Q2=22860 DA x=.5434 Q2=24655 JB y=.503 phi [0.180]
Zeus Run 13796 Event 11907
3-Nov-1995 0:08:34.046 File ..events/something-wnm.cz
ZEUS
220. GeV - elec
ZR
THETA PHI
UCAL energy
UCAL

Neutral current e^+p scattering:

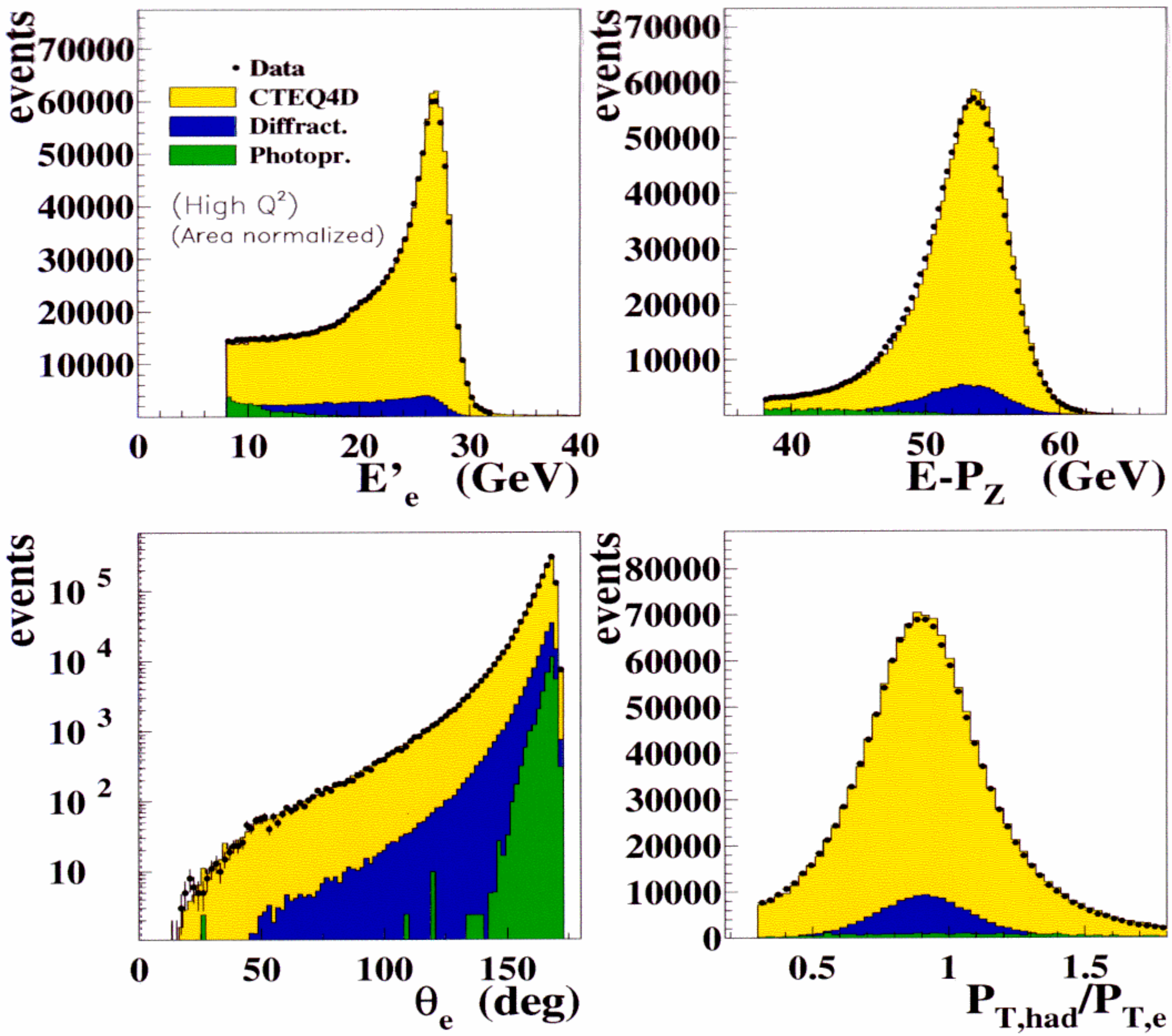
$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) - Y_-xF_3(x,Q^2)](1+\delta_r(x,Q^2))$$

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

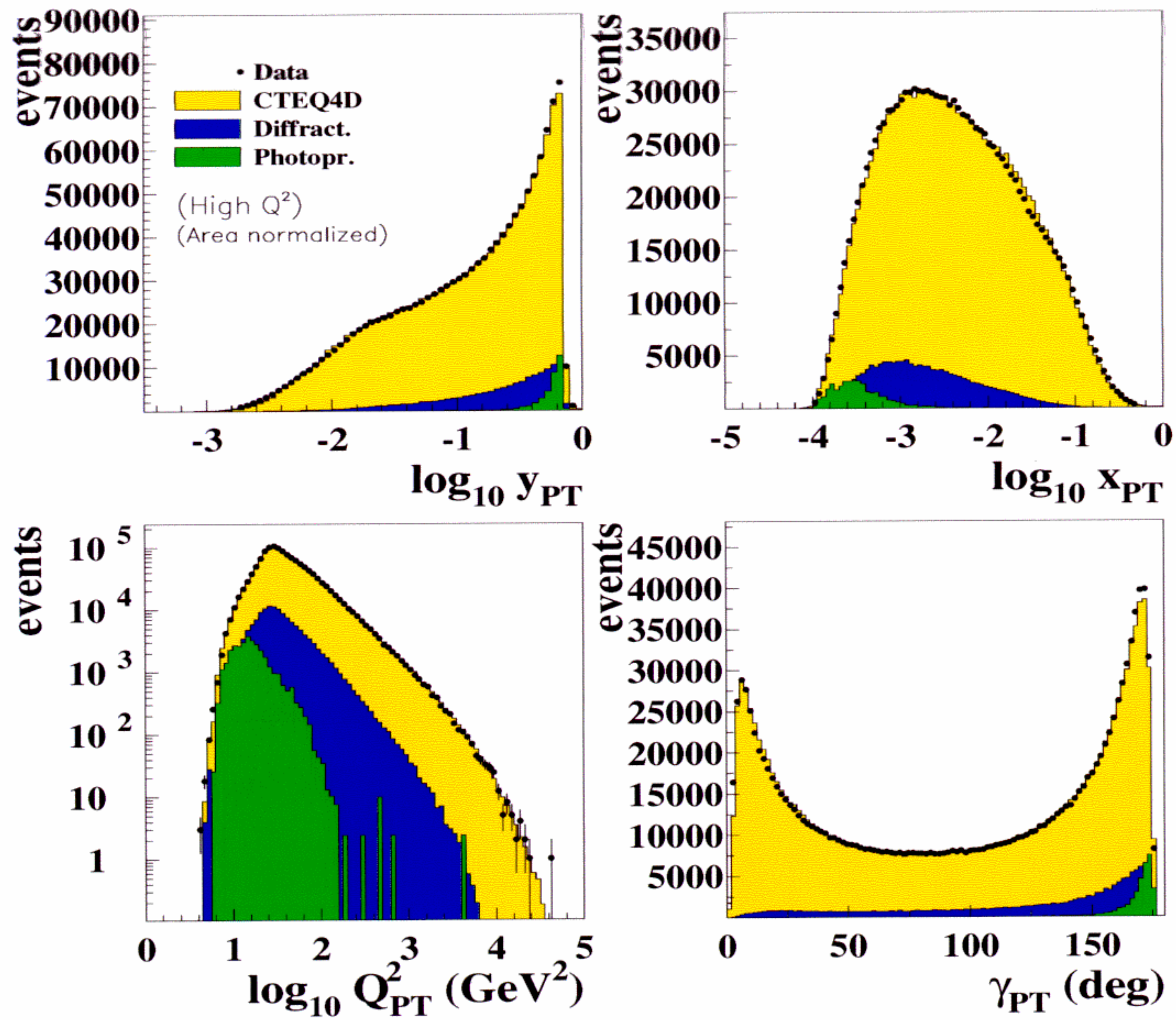
$$F_2 = F_2^{em} + \frac{Q^2}{(Q^2+M_Z^2)}F_2^{\text{int}} + \frac{Q^4}{(Q^2+M_Z^2)^2}F_2^{wk} = F_2^{em}(1+\delta_Z)$$

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}F_2^{em}(1+\delta_Z)(1-\delta_L-\delta_3)(1+\delta_r)$$

ZEUS Preliminary 1996-97



ZEUS Preliminary 1996-97



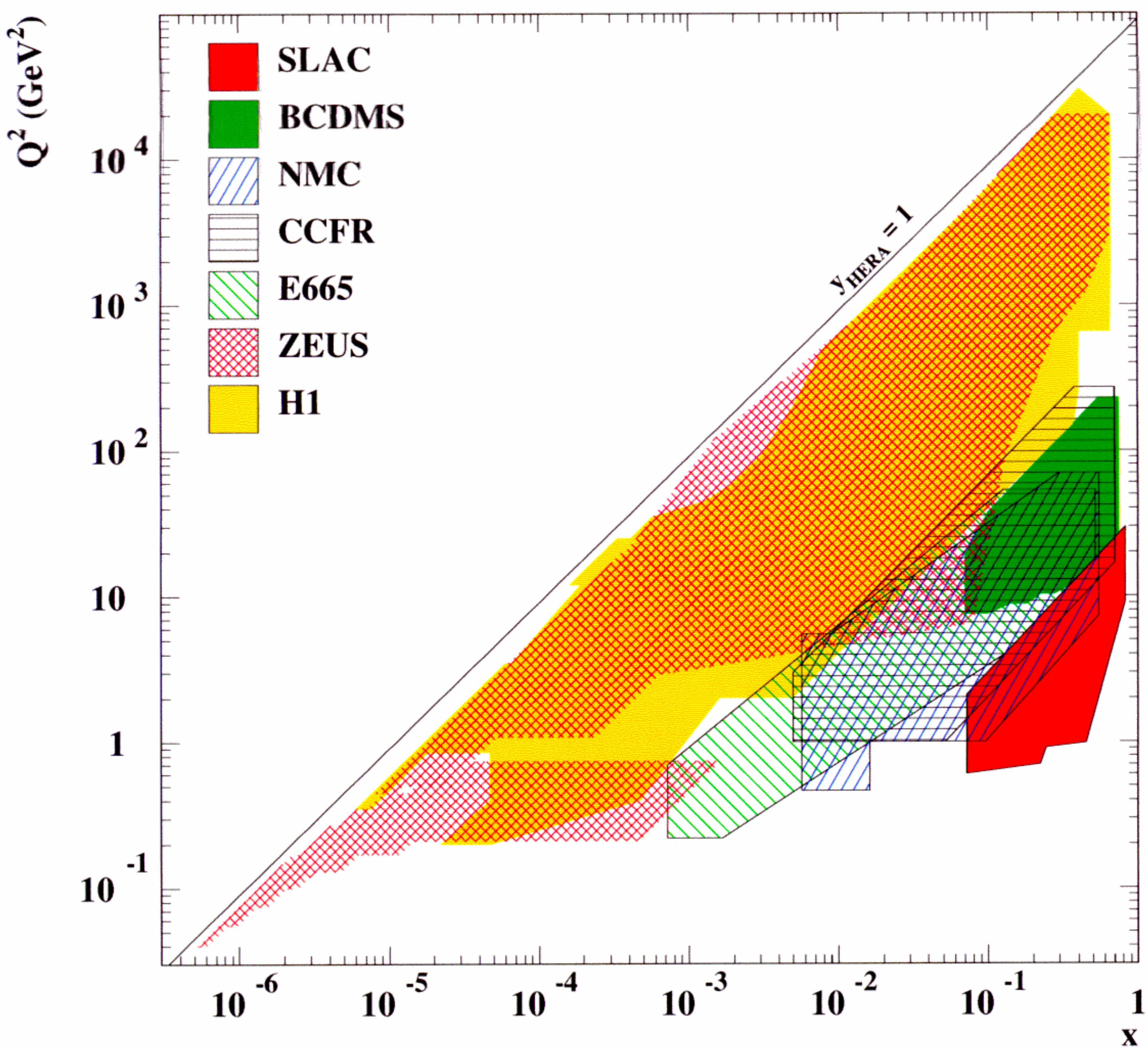
The DGLAP equations govern the Q^2 evolution of the structure functions:

$$Q^2 \frac{\partial F^{NS}}{\partial Q^2} = \frac{\alpha_S(|Q|)}{2\pi} P^{qq} * F^{NS}$$

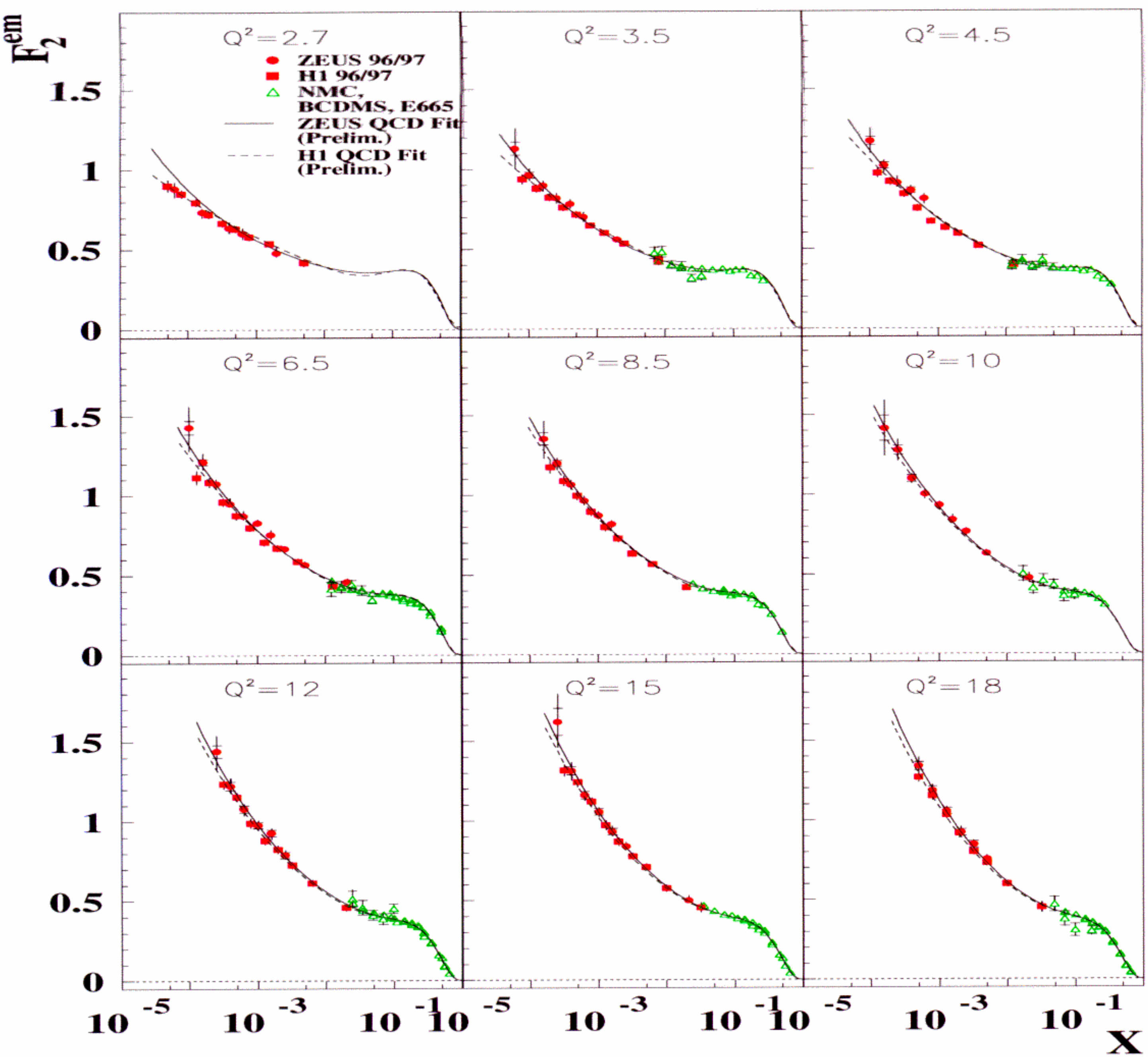
$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} F^S \\ G \end{pmatrix} = \frac{\alpha_S(|Q|)}{2\pi} \begin{pmatrix} P^{qq} & 2n_f P^{qg} \\ P^{gq} & P^{gg} \end{pmatrix} * \begin{pmatrix} F^S \\ G \end{pmatrix}$$

$$F^{NS} = q_i - q_j \quad ; \quad F^s = \sum_i (q_i + \bar{q}_i)$$

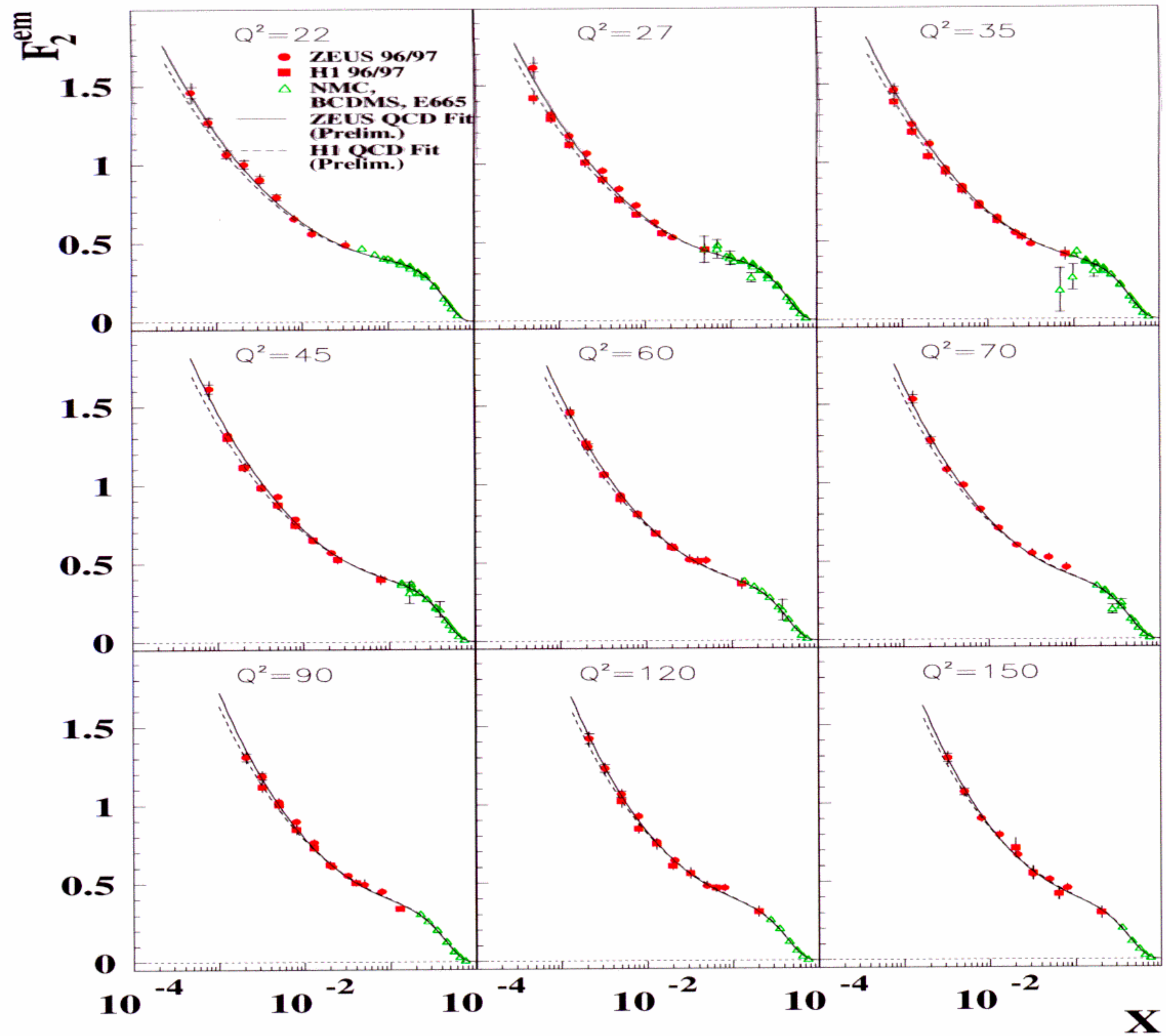
$$P * F = \int_x^1 \frac{dy}{y} P(y) F\left(\frac{x}{y}\right)$$


Q^2 (GeV^2)
10^4
10^3
10^2
10
1
10^-1
SLAC
BCDMS
NMC
CCFR
E665
ZEUS
H1
y_HERA = 1
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
x

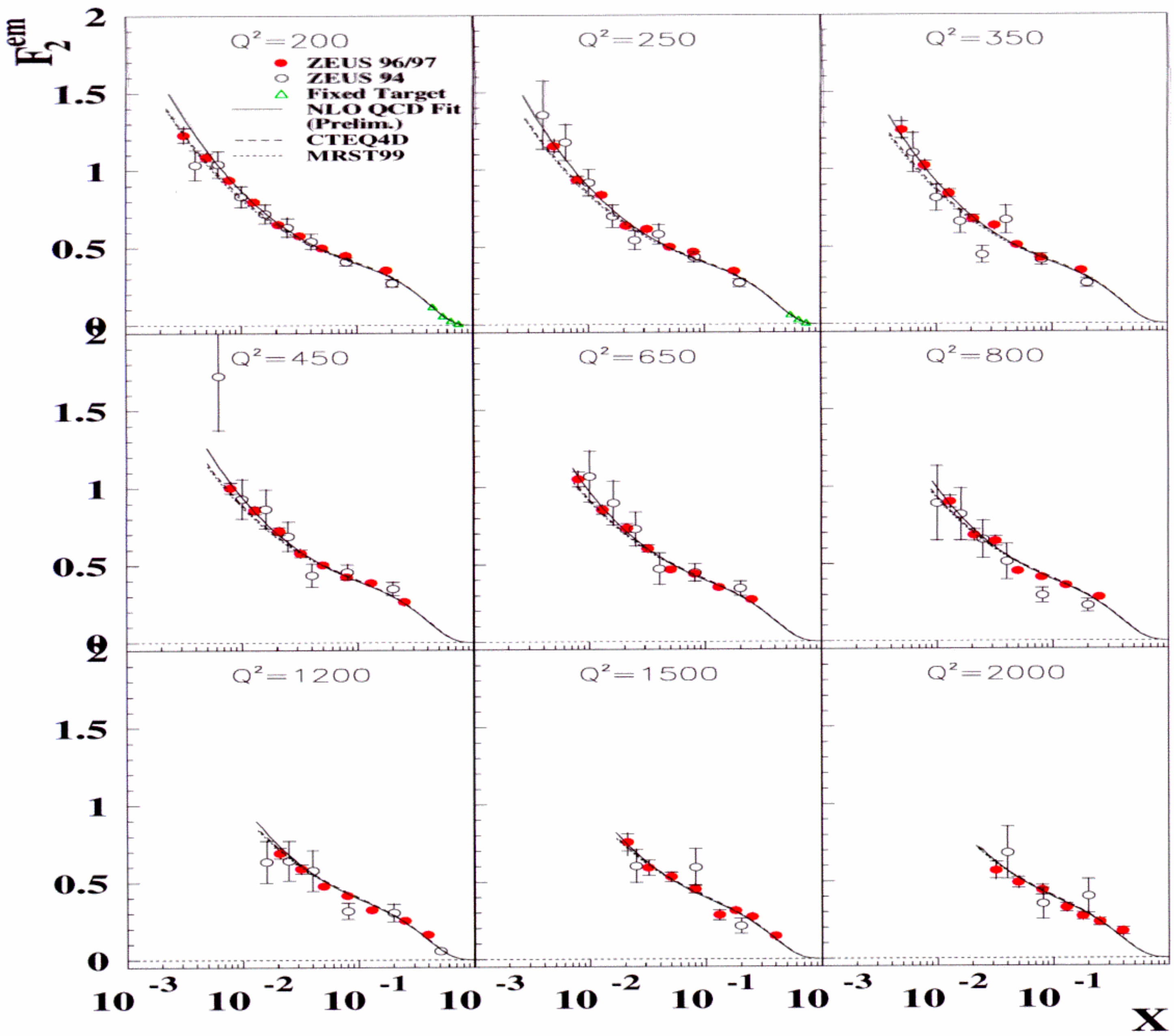
ZEUS+H1 Preliminary 96/97



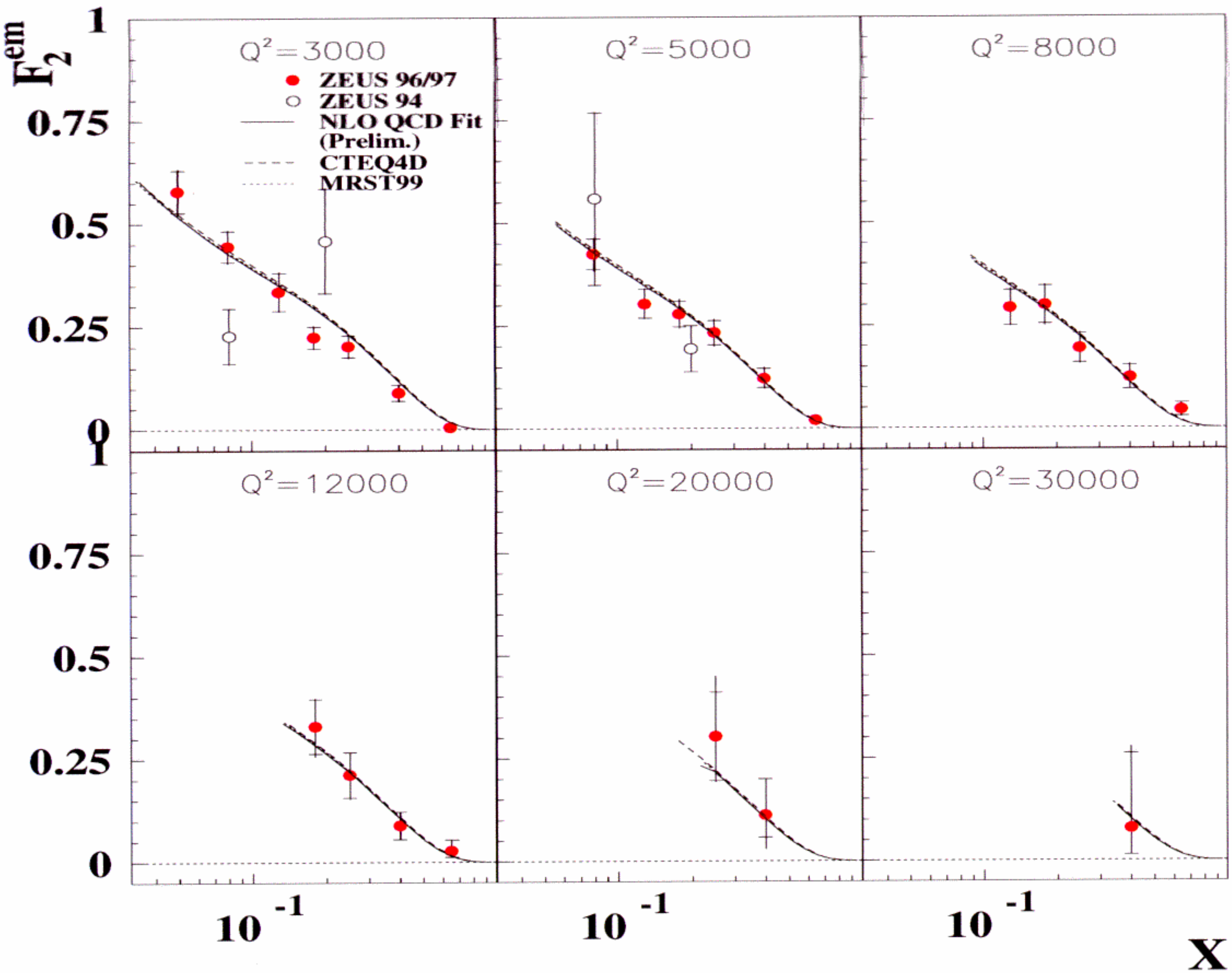
ZEUS+H1 Preliminary 96/97



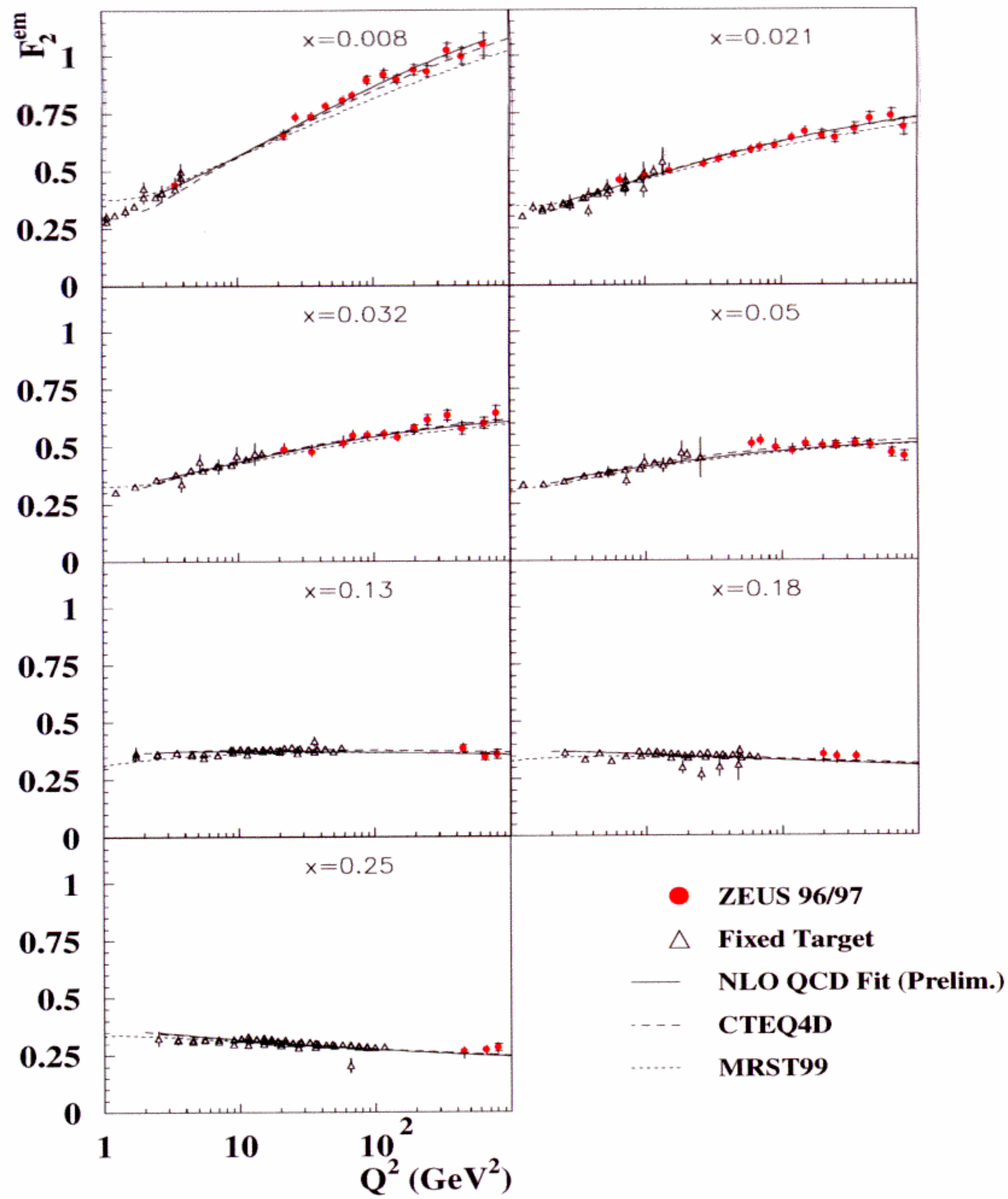
ZEUS Preliminary 96/97

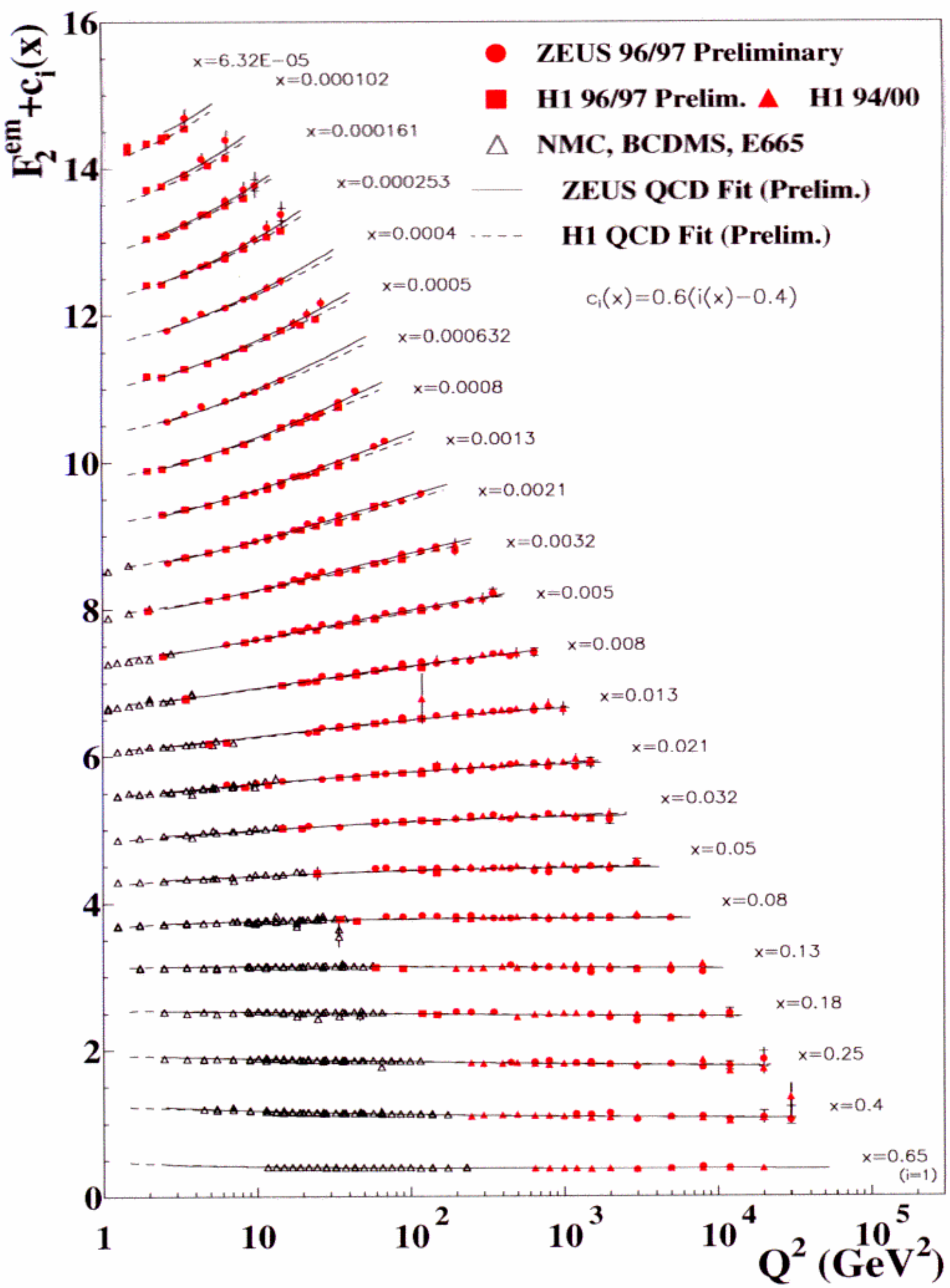


ZEUS Preliminary 96/97



ZEUS Preliminary 1996-97





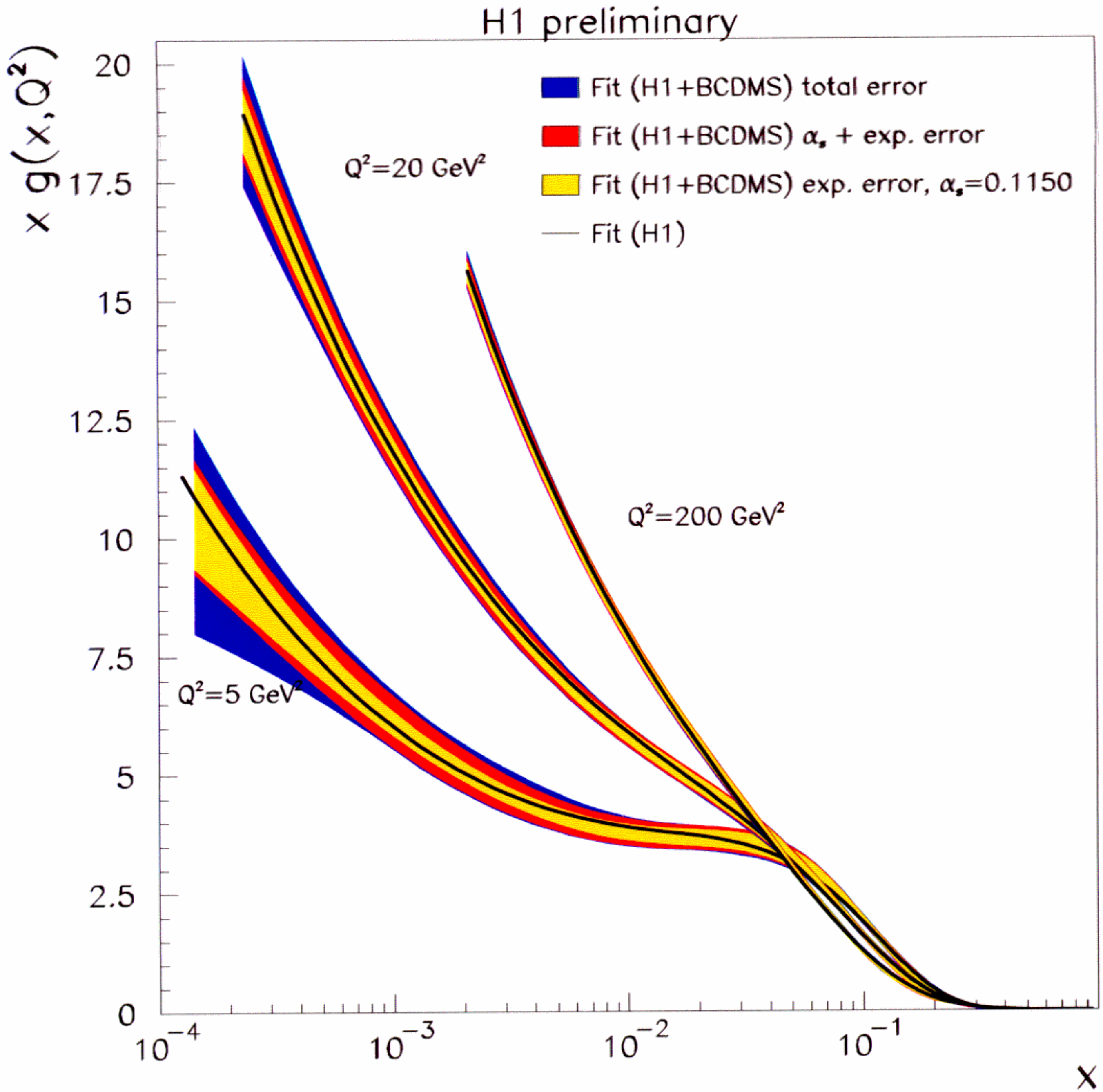
$F_2^{em}+c_i(x)$
ZEUS 96/97 Preliminary
H1 96/97 Prelim.
H1 94/00
NMC, BCDMS, E665
ZEUS QCD Fit (Prelim.)
H1 QCD Fit (Prelim.)
$c_i(x)=0.6(i(x)-0.4)$
x=6.32E−05
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
(i=1)
Q^2 (GeV^2)

F_2 fits in the framework of DGLAP Q^2 evolution

19 parameters to parameterise the parton densities as a function of x;
typically: $xq(x,Q_0^2) = Ax^{\delta}(1-x)^{\eta}(1+\gamma x)$
16 free parameters after imposing sum rules

Need high x (i.e. fixed target - NMC,SLAC,BCDMS) data for properly constraining pdf's (valence) (need to be corrected for higher twist contributions etc.)

Beautiful description of data - extraction of gluon density; delicate fit, very sensitive to scaling violations at low x -how low can one go?


H1 preliminary
x g(x,Q²)
20
17.5
15
12.5
10
7.5
5
2.5
0
Fit (H1+BCDMS) total error
Fit (H1+BCDMS) αs + exp. error
Fit (H1+BCDMS) exp. error, αs=0.1150
Fit (H1)
Q²=20 GeV²
Q²=200 GeV²
Q²=5 GeV²
10⁻⁴
10⁻³
10⁻²
10⁻¹
x

Conclusions on F_2

- F_2 determined at (better than) 5% up to Q^2~800 GeV^2
  - some overlap with fixed target data
  - systematics dominated
  - scaling violations in agreement with QCD (DGLAP)
  - extraction of gluon density and α_S (H1; ZEUS very soon)
- F_2 measured all the way up to Q^2~30,000 GeV^2

Remarks:

- measurement includes diffractive DIS; how 'universal' is F_2 (cf. pp scattering) ?
- transition into 'non-perturbative' region: where, how?
- low x region (saturation model & geometric scaling:

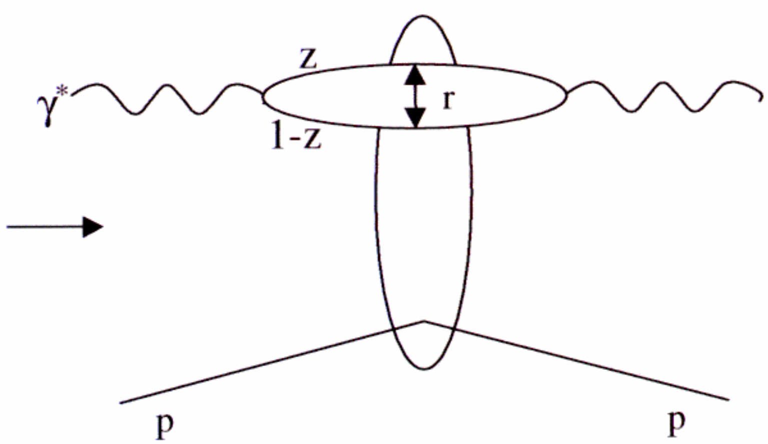
  $\gamma^* \rightarrow$q qbar dipole interacting with the proton; dipole cross section saturates for $x \rightarrow 0$;
  γ^*p cross section function of only one dimensionless variable : $Q^2 R_0^2(x)$
  (Stasto, Golec-Biernat, Kwiecinski))

} → *next*

The transition into the non-perturbative regime: not a priori clear at which Q^2.

DGLAP fits can be made to work down to Q^2~1 GeV^2; vanishing (or negative gluon distribution)…

F_2 slopes, $dF_2/d(\log Q^2)$, track the scaling violations and may be sensitive to non-perturbative effects; these slopes show a behaviour in qualitative agreement with a 'saturation' model (Golec-Biernat, Wuesthoff)



$$\sigma_{T,L}(x,Q^2) = \int d^2r \int_0^1 dz \,|\psi_{T,L}(z,r)|^2\, \hat{\sigma}(x,r^2)$$

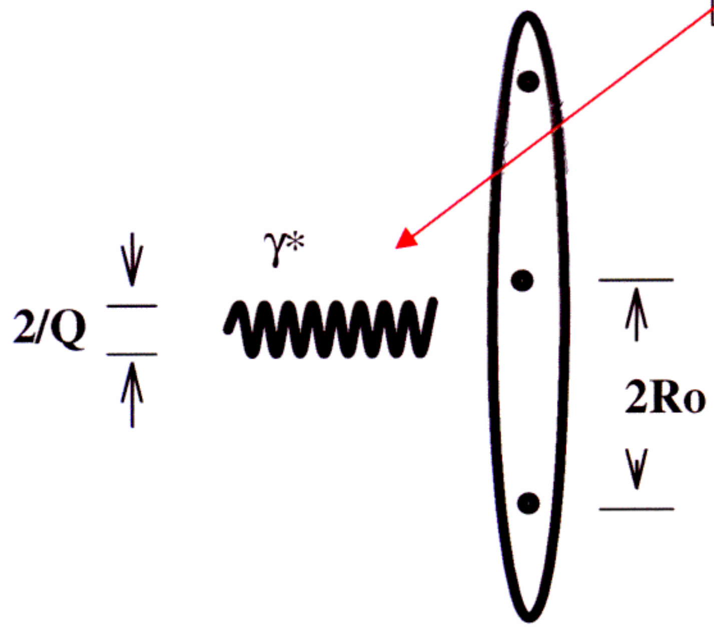
$$F_{T,L}(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}} \sigma_{T,L}(x,Q^2)$$

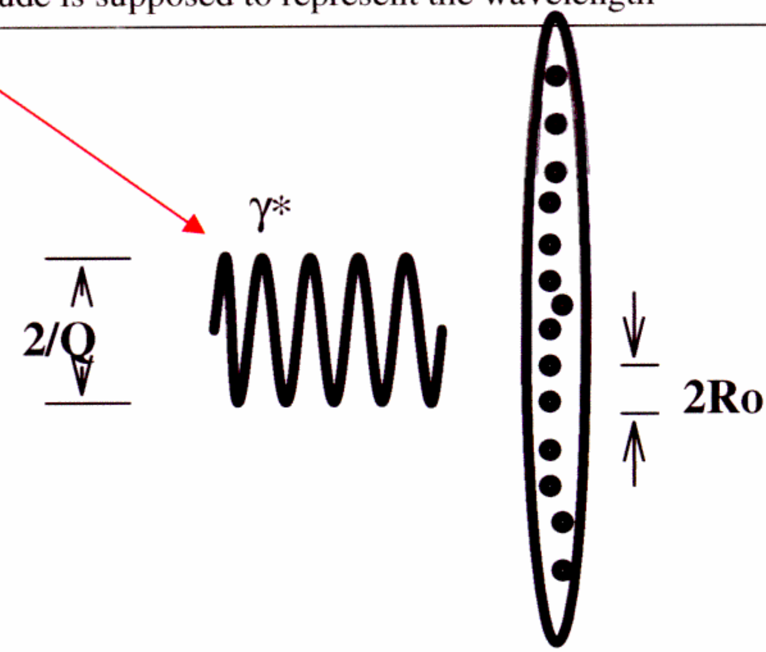
Modeling of dipole cross section, adopting an x dependent radius:

$$R_0(x) = \frac{1}{Q_0}\left(\frac{x}{x_0}\right)^{\lambda/2} \quad ; \quad \hat{\sigma}(x,r^2) = \sigma_0 g(\hat{r}^2)$$

$$\hat{r} = \frac{r}{2R_0(x)} \quad ; \quad g(\hat{r}^2) = 1 - e^{-\hat{r}^2}$$

The cartoon is somewhat misleading; what we draw as an amplitude is supposed to represent the wavelength





SCALING

$1/Q^2 << R_0^2$; $dF_2/d\log(Q^2) \sim x^{-\lambda}$

SATURATION

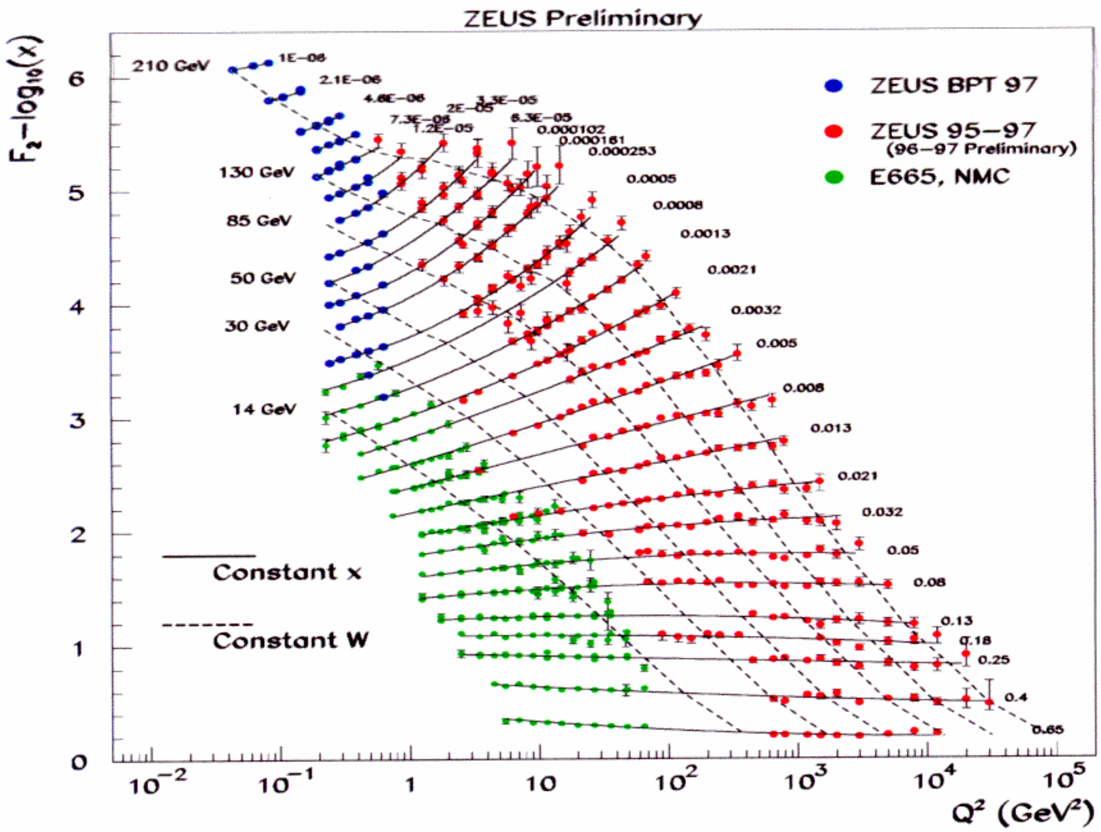
$1/Q^2 >> R_0^2$; $dF_2/d\log(Q^2) \sim Q^2\sigma_0$

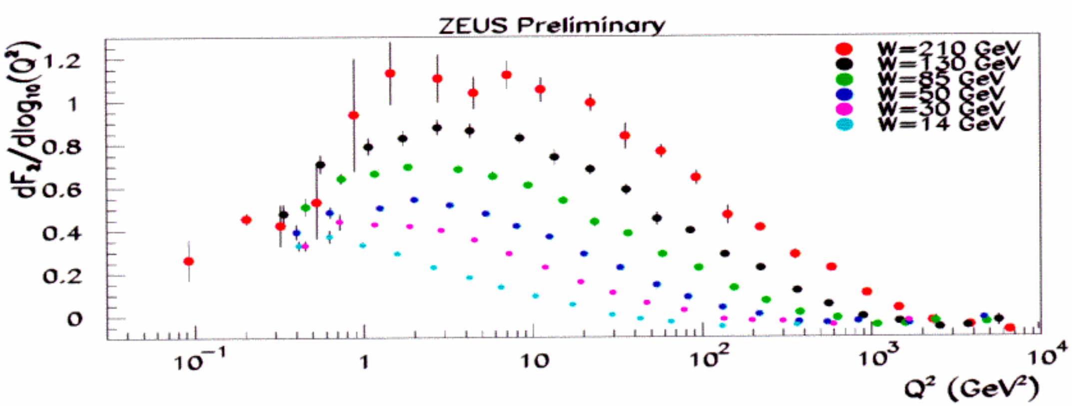
(and $1/R_0^2 \sim x^{-\lambda}$; cf. gluon density)

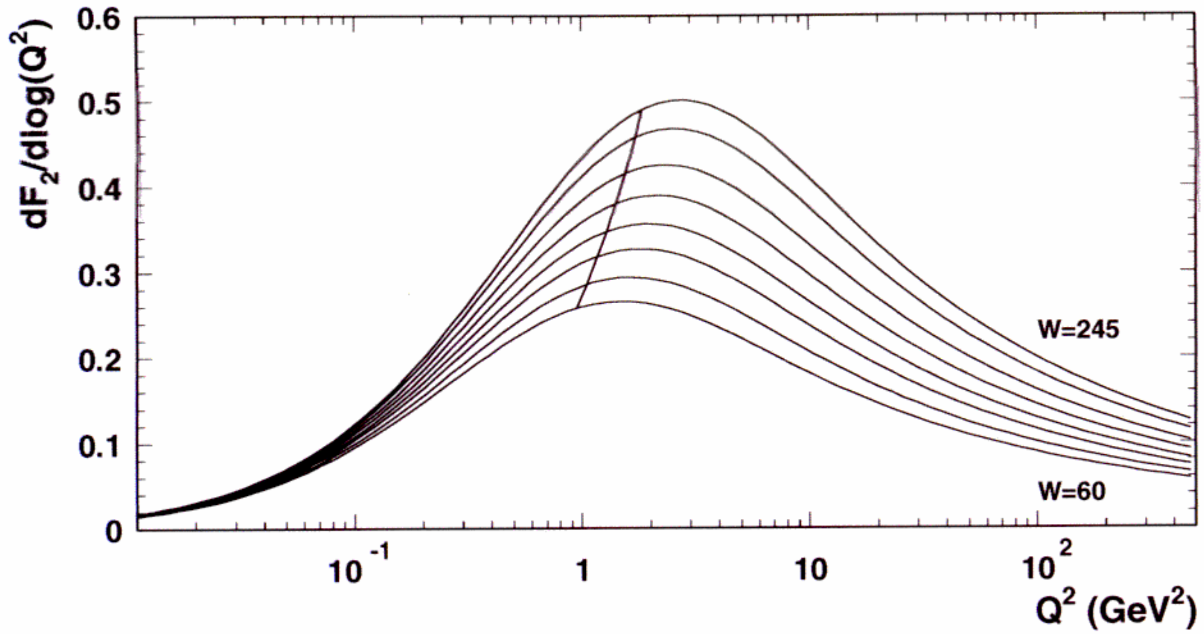
Model can also be made to work ‘naturally’ for diffraction: probabilty of hitting 2 gluons in a color singlet state

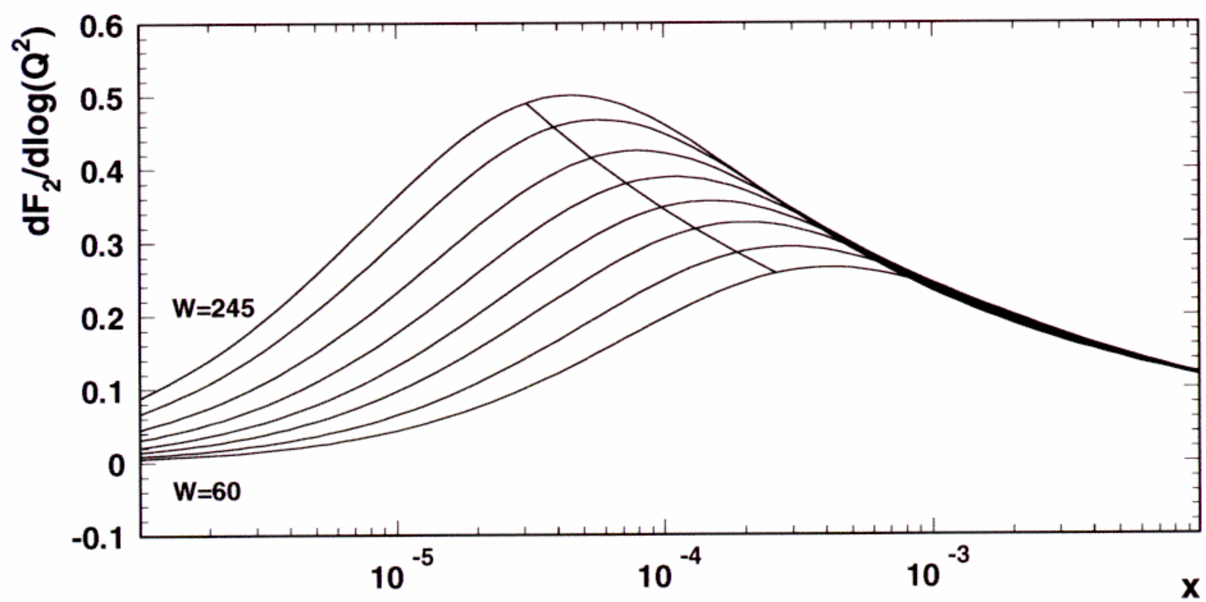
Proton F_2 scaling

Behaviour changes at low x, $Q^2 \approx 2\text{-}6\ GeV^2$







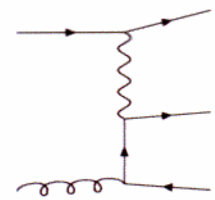


From Golec-Biernat, Wüsthof

Change of slopes in qualitative agreement with data

Charm production in DIS

- consistent with photon-gluon fusion



+HO

Two approaches:

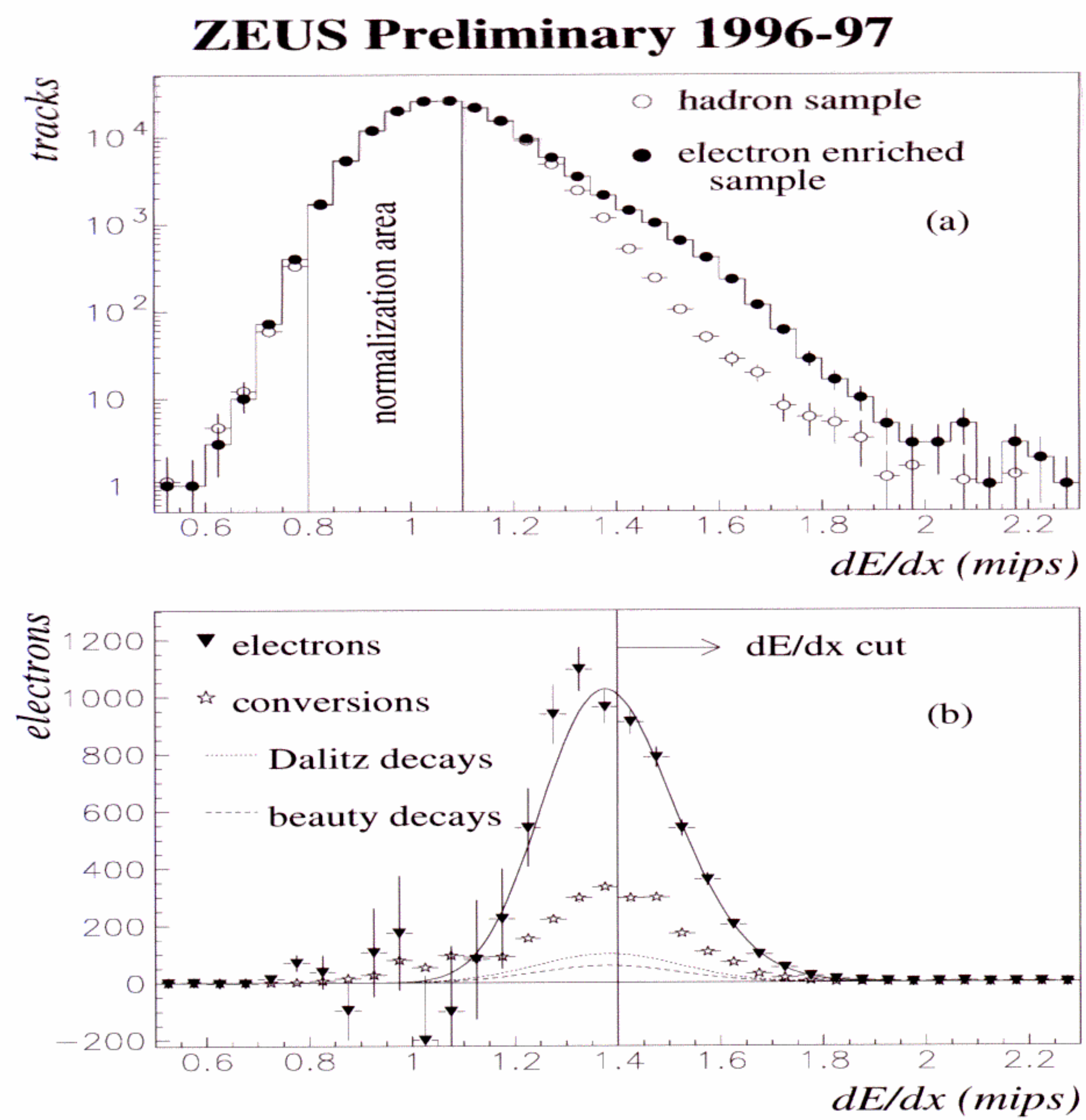
- select $D^{*\pm}$ events in the 'usual' way
- select events with 'direct electrons'

NLO calculations implemented in HVQDIS; treatment m_Q

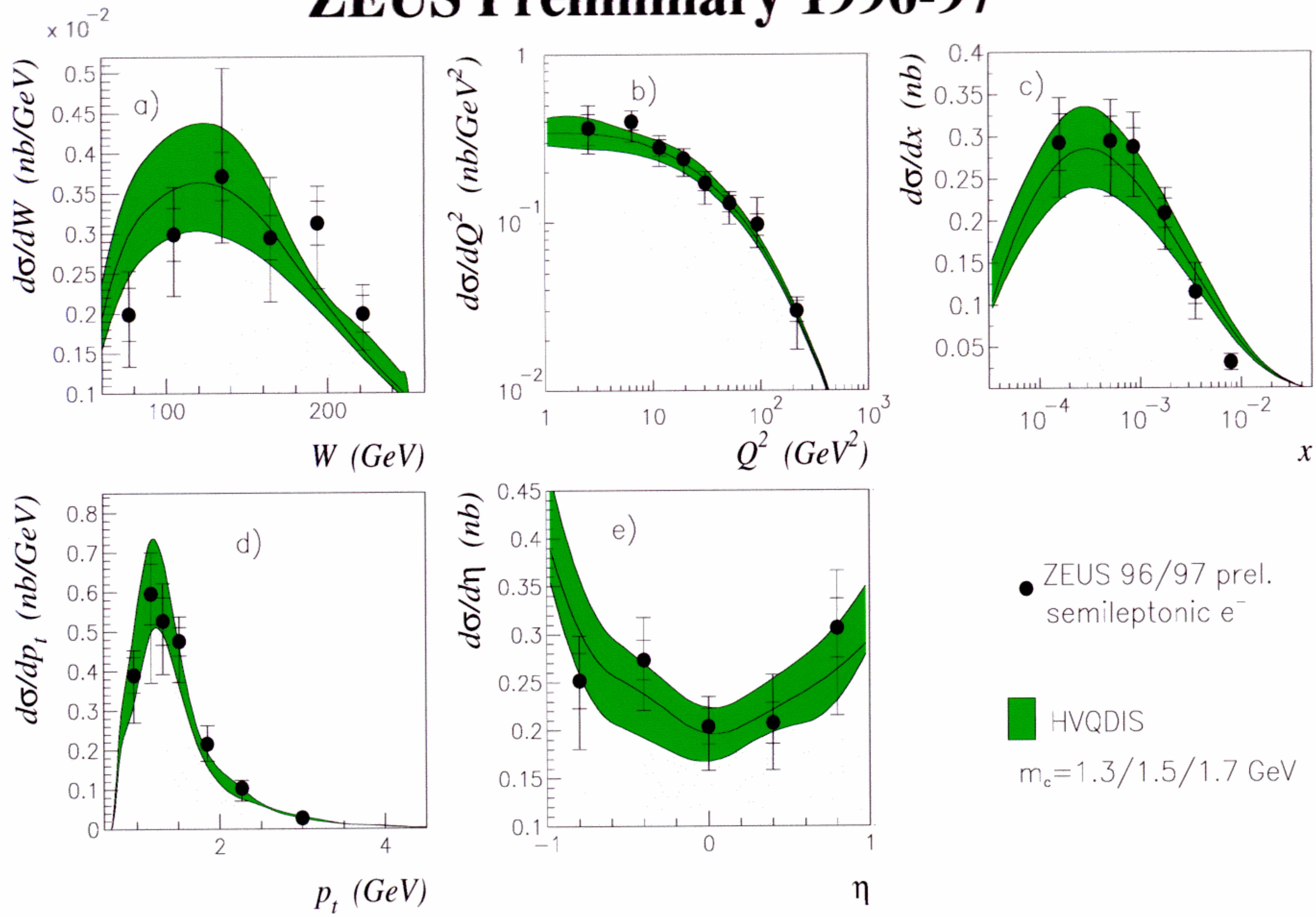
Harris, Smith + refs. to earlier work

Large extrapolations required in both cases

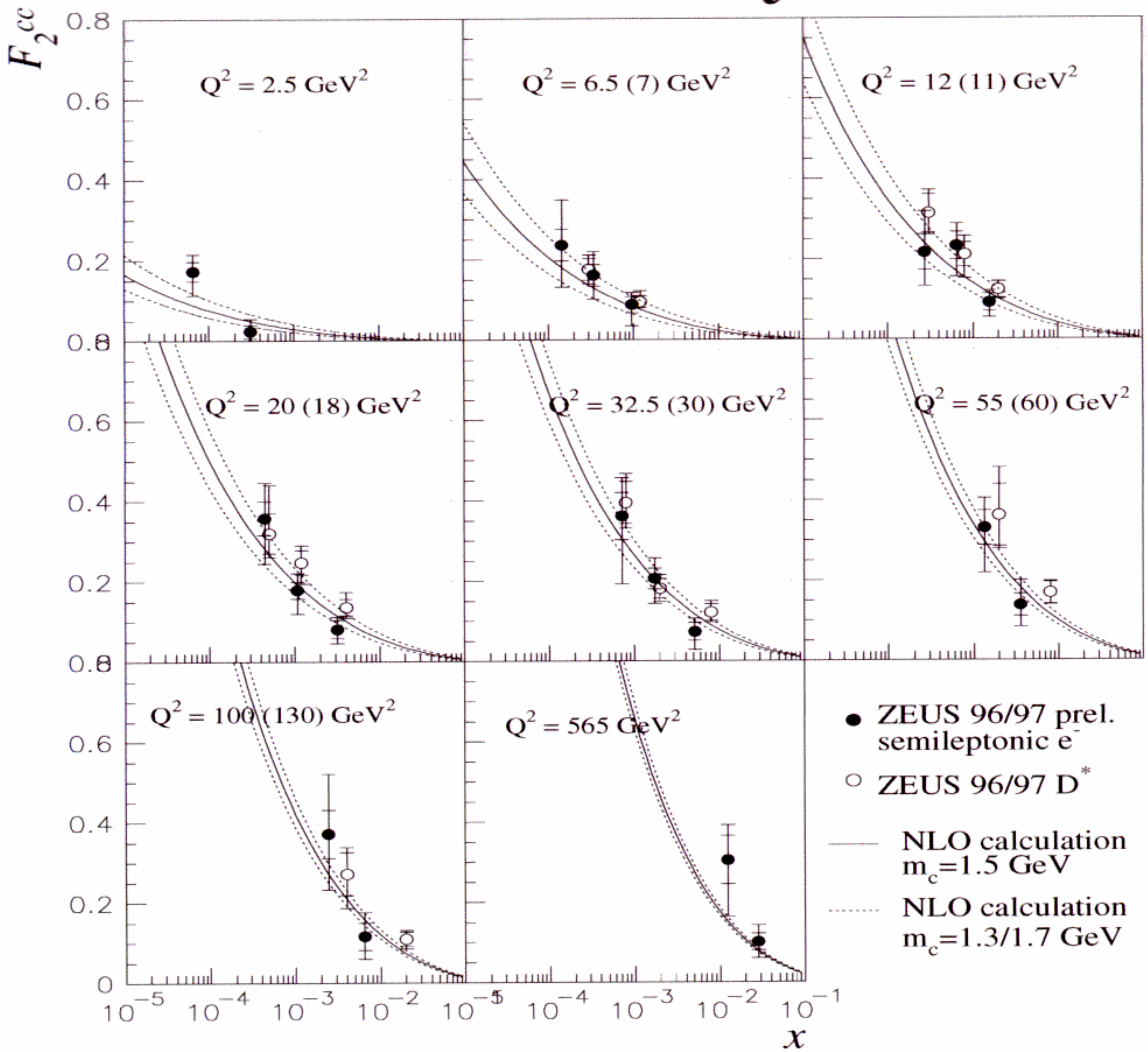
$$\frac{d^2\sigma^c}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left(1+(1-y)^2\right)F_2^c(x,Q^2)$$


ZEUS Preliminary 1996-97
tracks
10^4
10^3
10^2
10
1
hadron sample
electron enriched sample
(a)
normalization area
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
dE/dx (mips)
electrons
1200
1000
800
600
400
200
0
−200
electrons
conversions
Dalitz decays
beauty decays
dE/dx cut
(b)
dE/dx (mips)

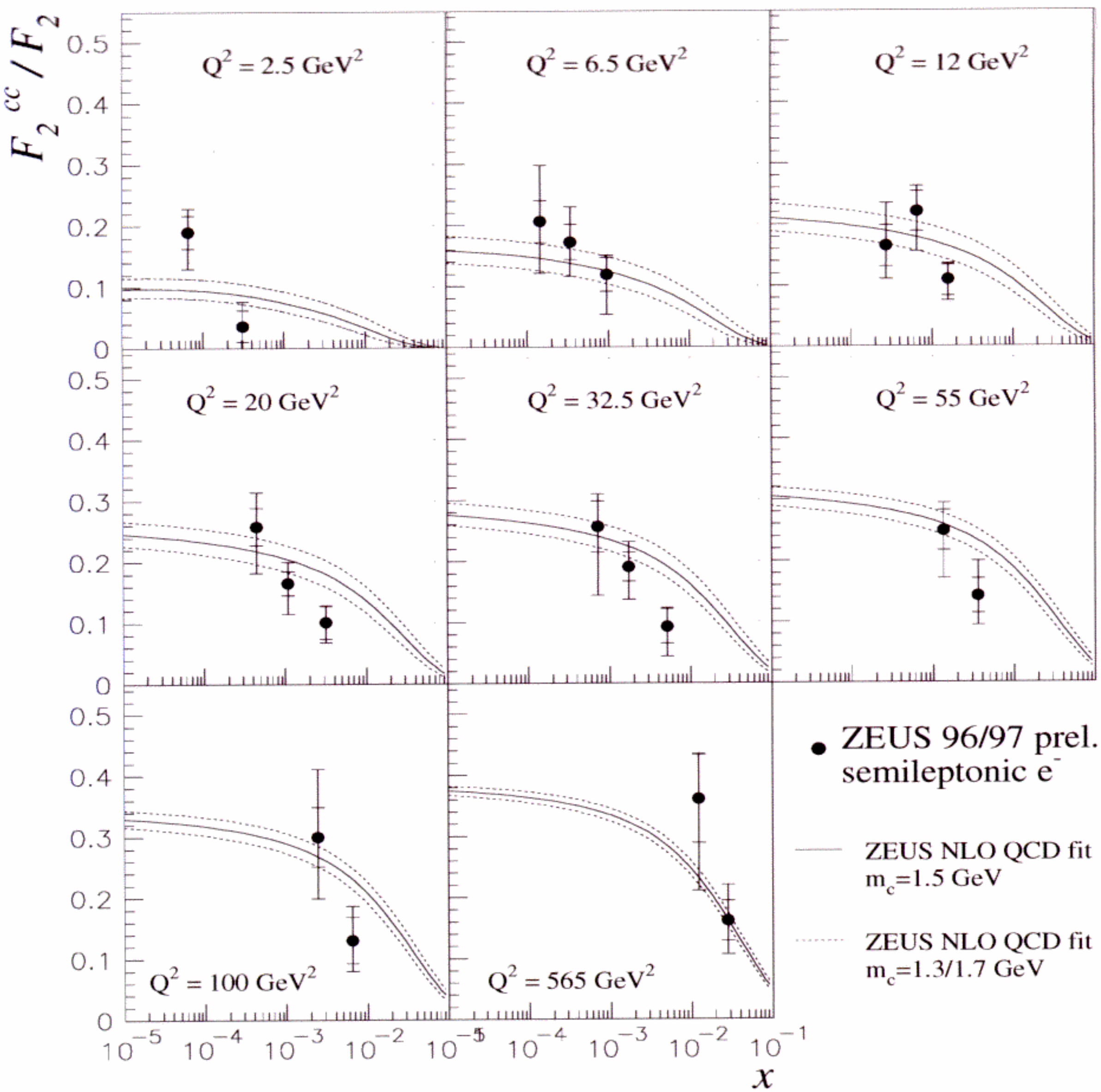
ZEUS Preliminary 1996-97

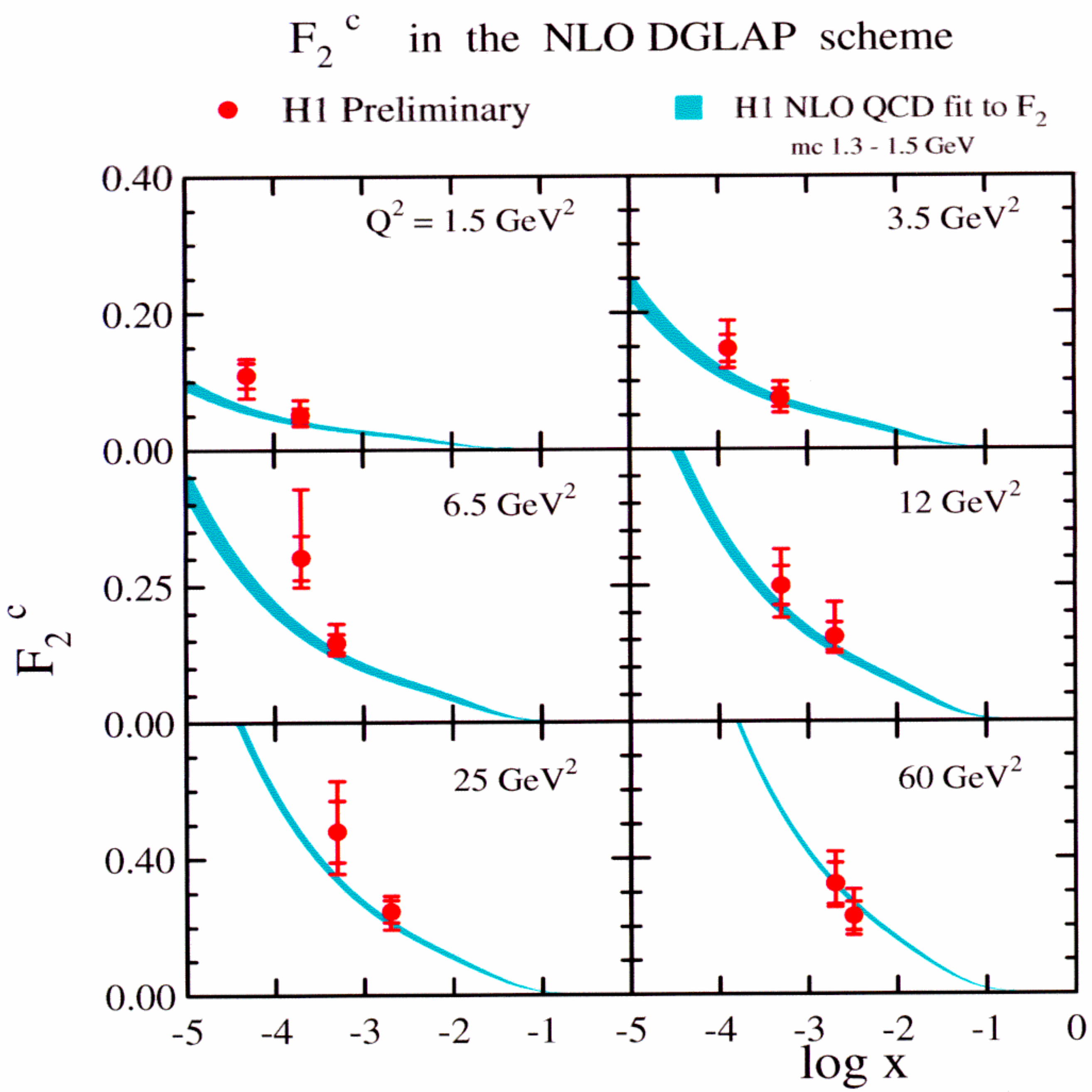


ZEUS Preliminary 1996-97

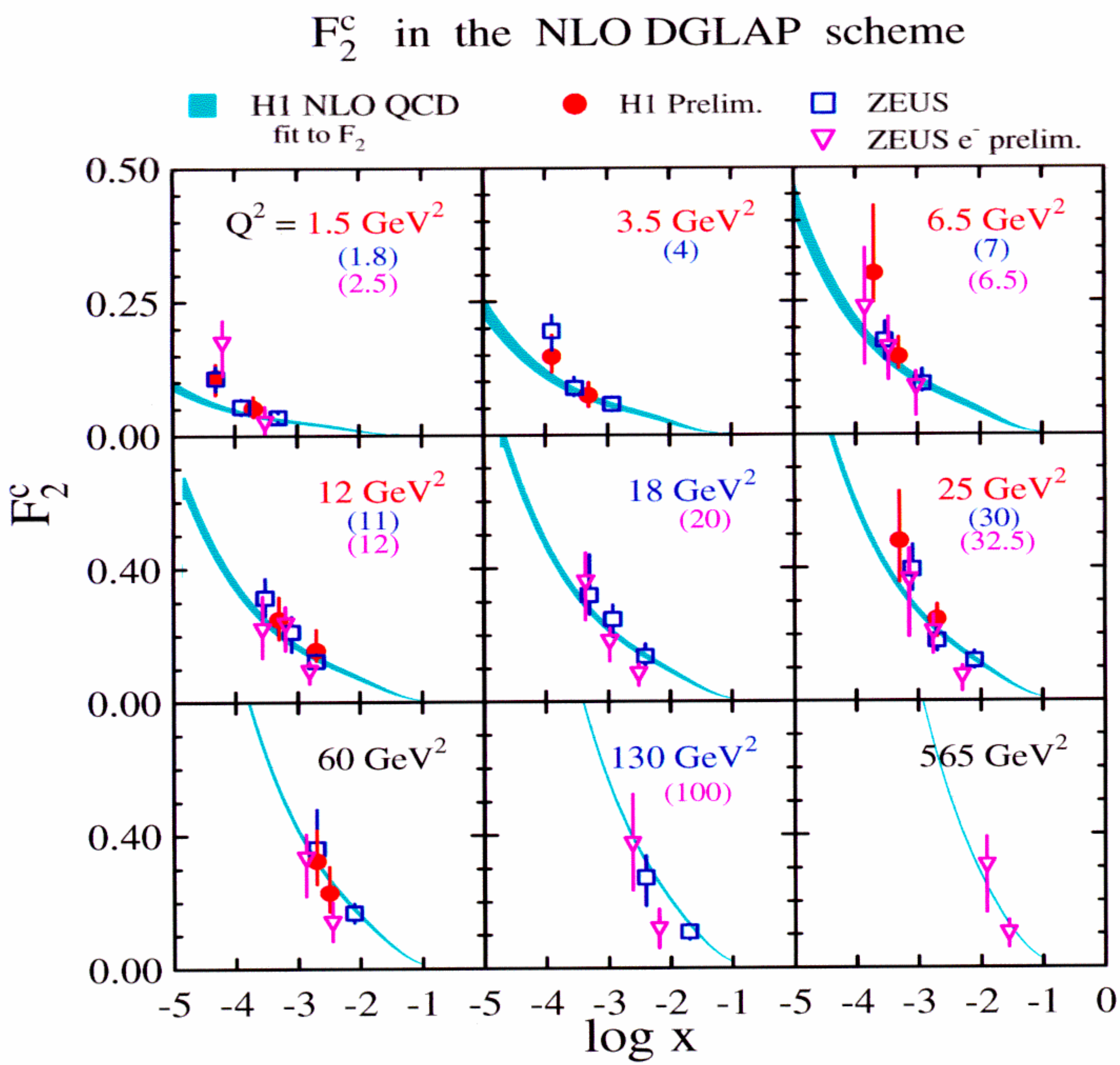


ZEUS Preliminary 1996-97

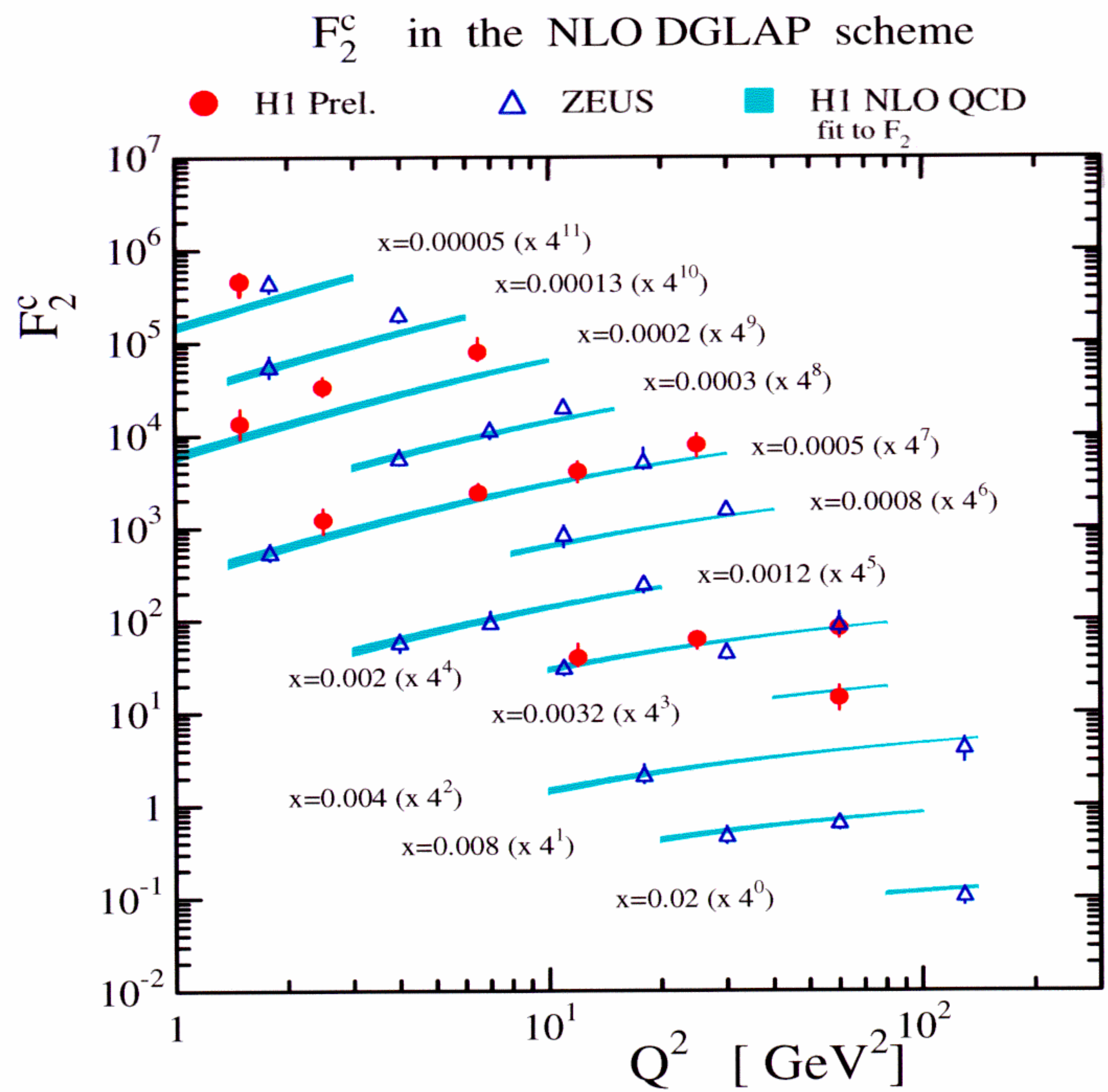




F2 c in the NLO DGLAP scheme
H1 Preliminary
H1 NLO QCD fit to F2
mc 1.3 - 1.5 GeV
Q2 = 1.5 GeV2
3.5 GeV2
6.5 GeV2
12 GeV2
25 GeV2
60 GeV2
0.40
0.20
0.00
0.25
0.00
0.40
0.00
-5
-4
-3
-2
-1
0
F2 c
log x



F_2^c in the NLO DGLAP scheme
H1 NLO QCD fit to F_2
H1 Prelim.
ZEUS
ZEUS e^- prelim.
Q^2 = 1.5 GeV^2 (1.8) (2.5)
3.5 GeV^2 (4)
6.5 GeV^2 (7) (6.5)
12 GeV^2 (11) (12)
18 GeV^2 (20)
25 GeV^2 (30) (32.5)
60 GeV^2
130 GeV^2 (100)
565 GeV^2
F_2^c
log x



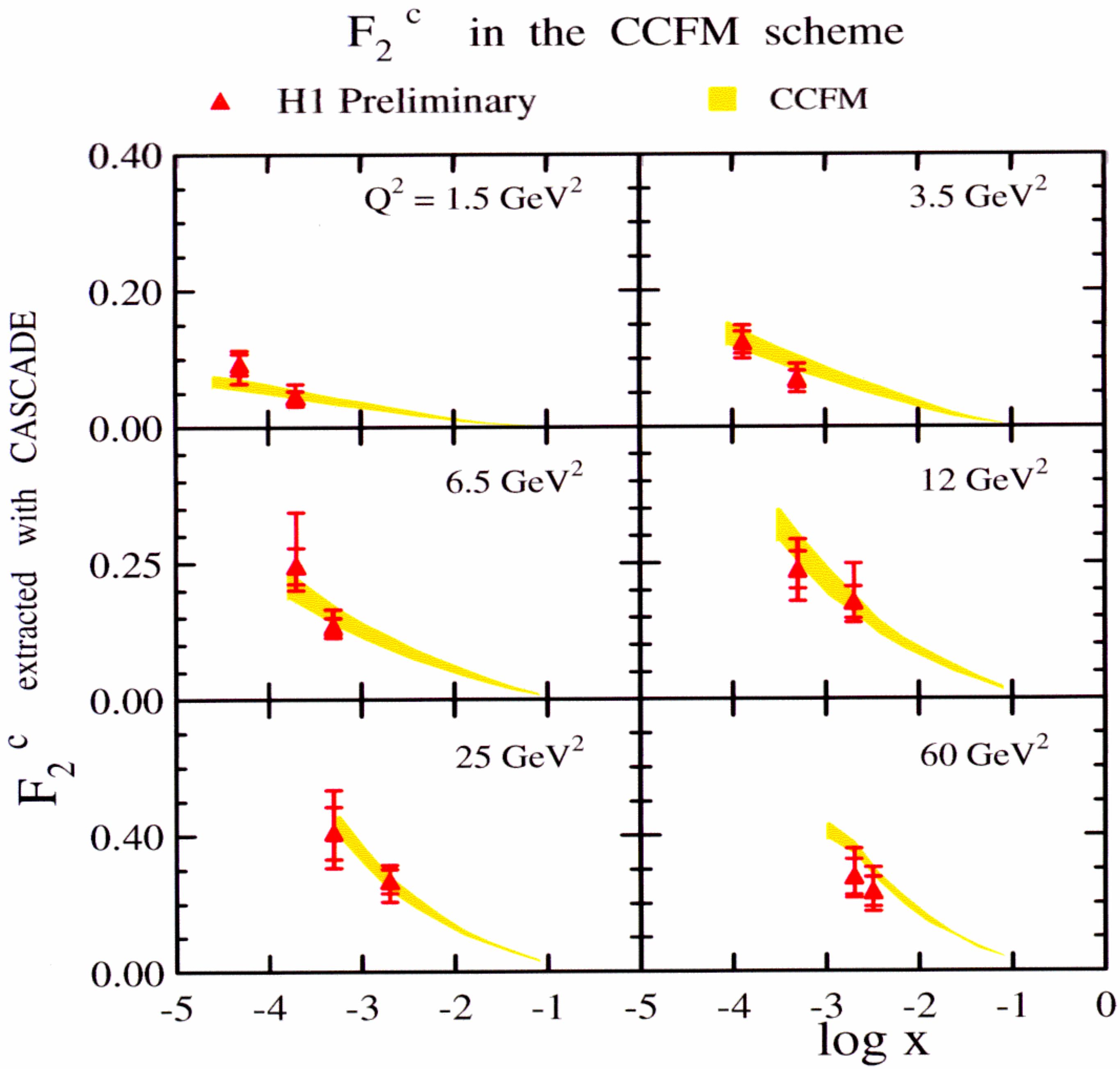
F2c in the NLO DGLAP scheme
H1 Prel.
ZEUS
H1 NLO QCD fit to F2
x=0.00005 (x 4^11)
x=0.00013 (x 4^10)
x=0.0002 (x 4^9)
x=0.0003 (x 4^8)
x=0.0005 (x 4^7)
x=0.0008 (x 4^6)
x=0.0012 (x 4^5)
x=0.002 (x 4^4)
x=0.0032 (x 4^3)
x=0.004 (x 4^2)
x=0.008 (x 4^1)
x=0.02 (x 4^0)
F2c
Q2 [GeV2]

H1 has performed an analysis of charm production in DIS in the framework of CCFM evolution, as implemented in the CASCADE programme

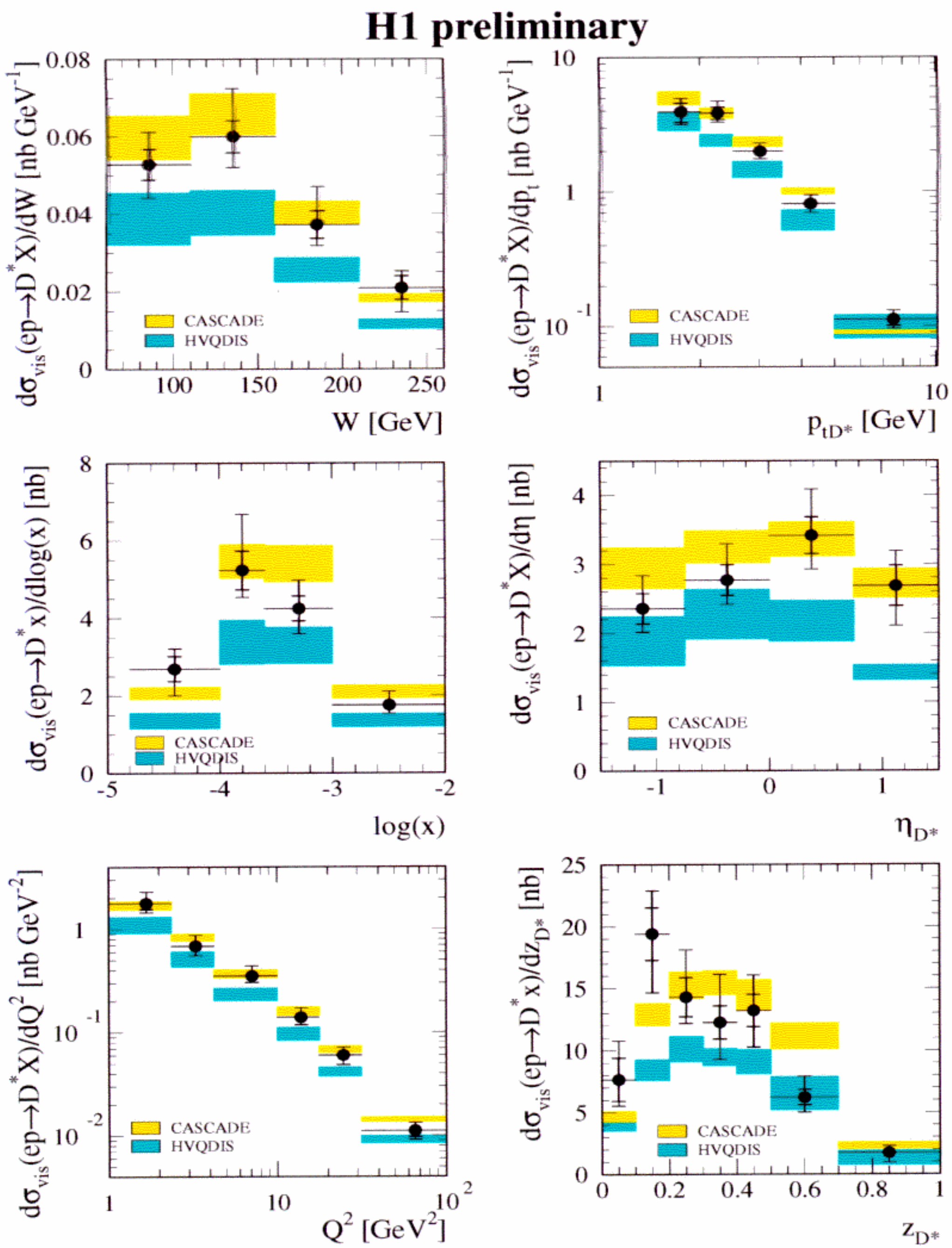
Ciafeloni, Catani, Fiorani, Marchesini   Jung

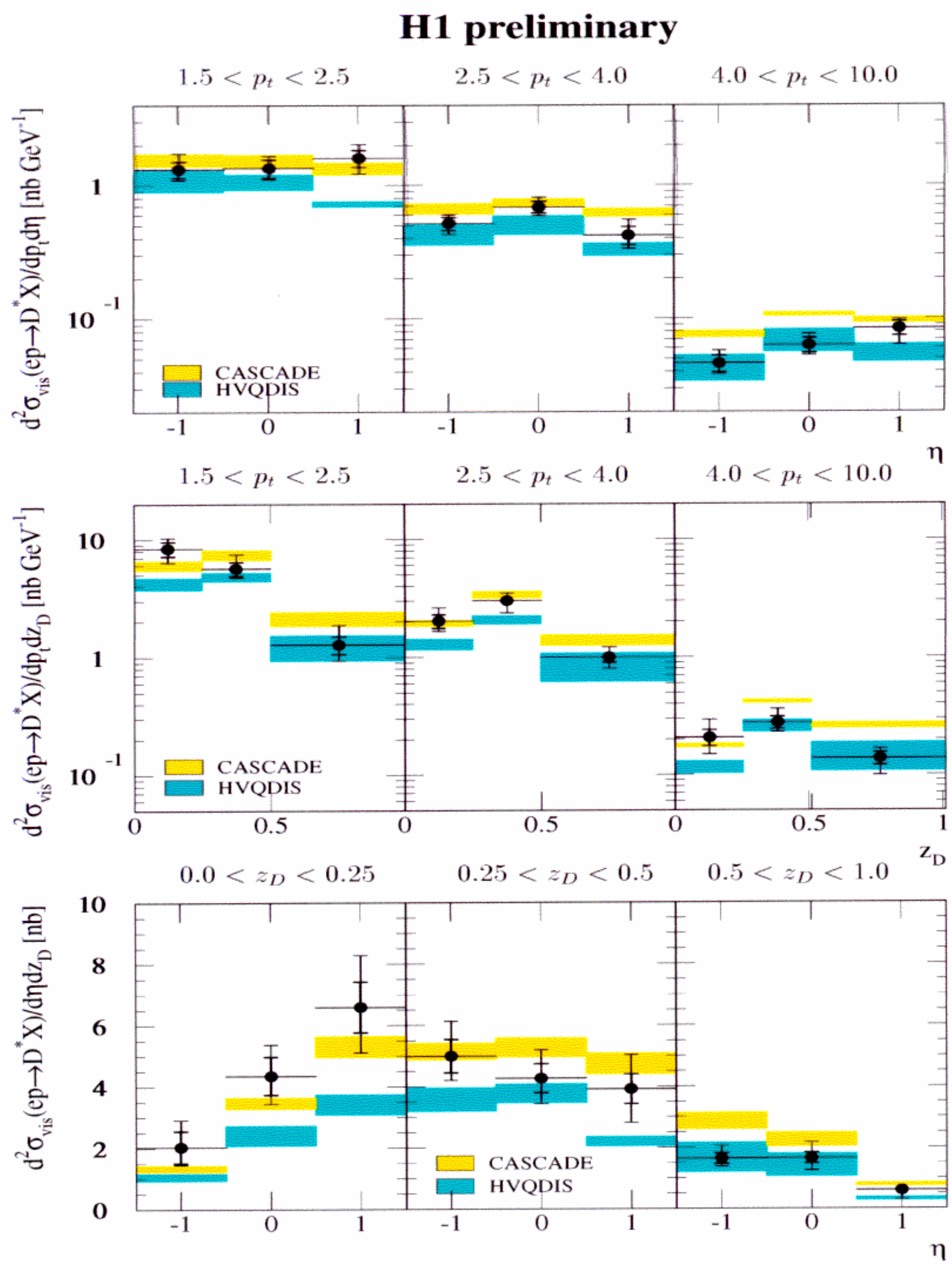
CCFM: evolution in both Q^2 and $1/x$

Good (better) description of charm production in DIS, in particular in the lower p_T region



F2 c in the CCFM scheme
H1 Preliminary
CCFM
F2 c extracted with CASCADE
Q2 = 1.5 GeV2
3.5 GeV2
6.5 GeV2
12 GeV2
25 GeV2
60 GeV2
0.40
0.20
0.00
0.25
0.00
0.40
0.00
-5
-4
-3
-2
-1
-5
-4
-3
-2
-1
0
log x


H1 preliminary
dσvis(ep→D*X)/dW [nb GeV-1]
W [GeV]
dσvis(ep→D*X)/dpt [nb GeV-1]
ptD* [GeV]
dσvis(ep→D*x)/dlog(x) [nb]
log(x)
dσvis(ep→D*X)/dη [nb]
ηD*
dσvis(ep→D*X)/dQ2 [nb GeV-2]
Q2 [GeV2]
dσvis(ep→D*x)/dzD* [nb]
zD*
CASCADE
HVQDIS



H1 preliminary
1.5 < pt < 2.5
2.5 < pt < 4.0
4.0 < pt < 10.0
d²σvis(ep→D*X)/dptdη [nb GeV⁻¹]
d²σvis(ep→D*X)/dptdzD [nb GeV⁻¹]
d²σvis(ep→D*X)/dηdzD [nb]
0.0 < zD < 0.25
0.25 < zD < 0.5
0.5 < zD < 1.0
CASCADE
HVQDIS
η
zD

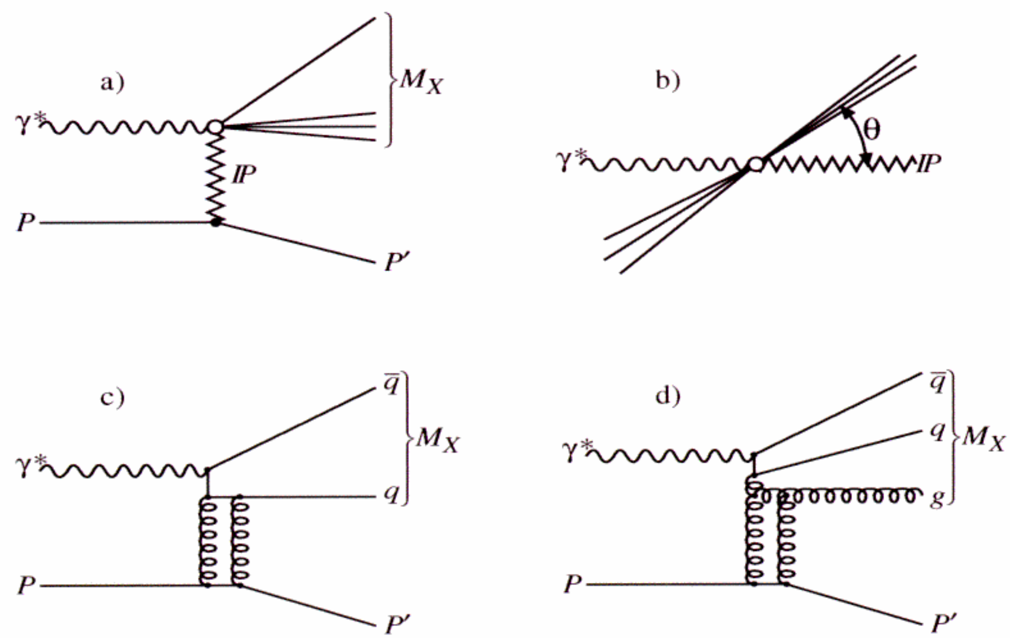
Conclusions on F_2^{charm}

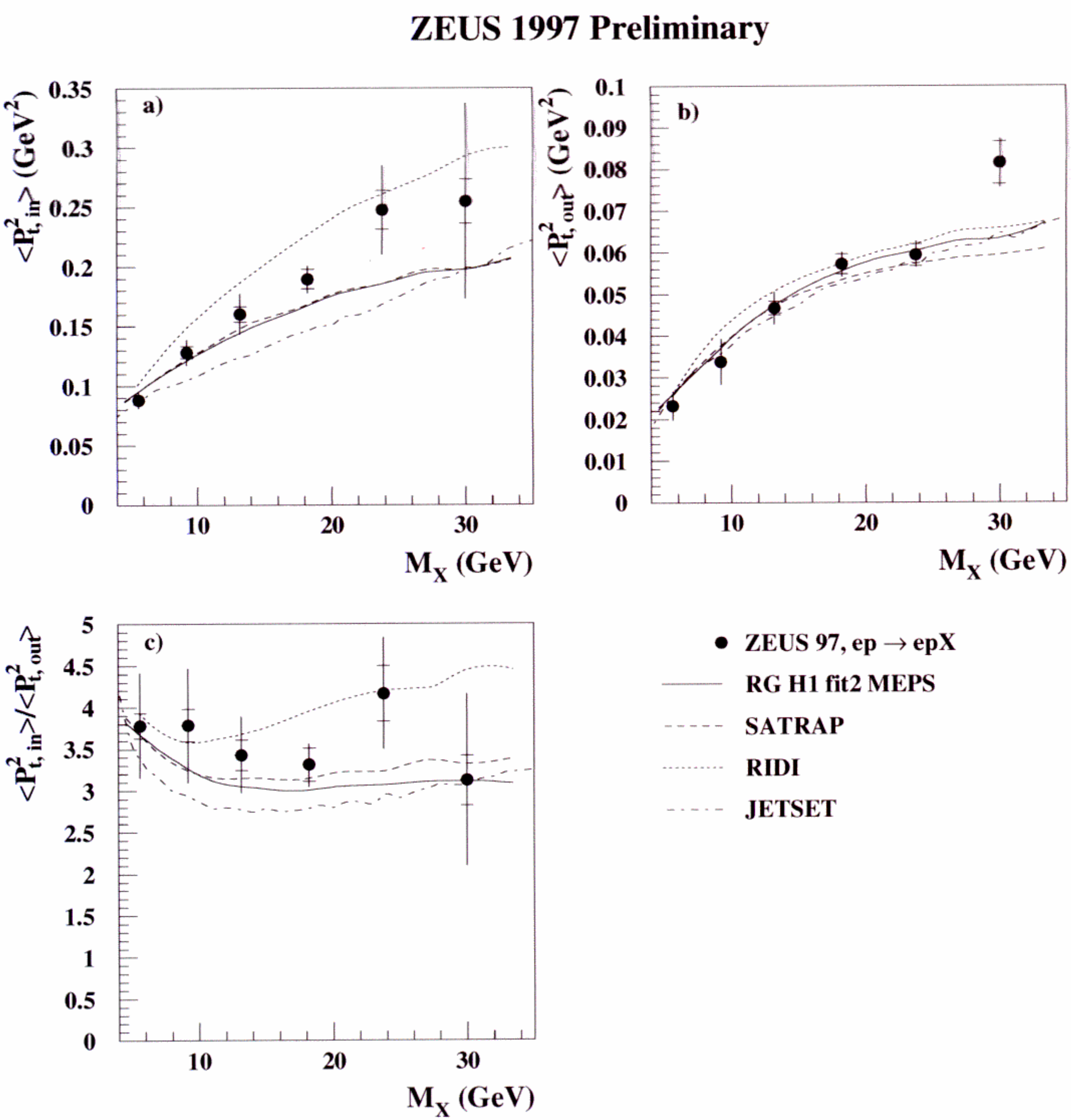
- only initial measurements; large extrapolations
- probes gluon density function
- agreement with HO pQCD calculations; various approaches to treatment of charm quark mass
- H1: indications that CFFM scheme as implemented in CASCADE gives better description of the data (at low p_T)

Diffractive DIS has been discovered at HERA; ‘Pomeron’ pdf’s have been extracted (‘gluonic’); now trying to get insight in DDIS by studying final states.

Three approaches:

- RAPGAP - γ^*IP scattering + Pomeron structure functions (H1)
  Ingelman, Schlein; Jung
- SATRAP - γ^* dissociation + coupling to proton via 2g exchange + saturation of parton densities in proton
  Bartels, Ellis, Kowalski, Wuesthof
  plus saturation
- RIDI - LLA; $\sigma \sim G^2$
  Ryskin; Ryskin, Solano





Extensive studies have been made, but definitive conclusions in favor of or against one of the models cannot be drawn yet relevant event data [59]. In particular, data from purely hadronic initial states are used as they can provide important constraints on the gluon distributions.

α_S

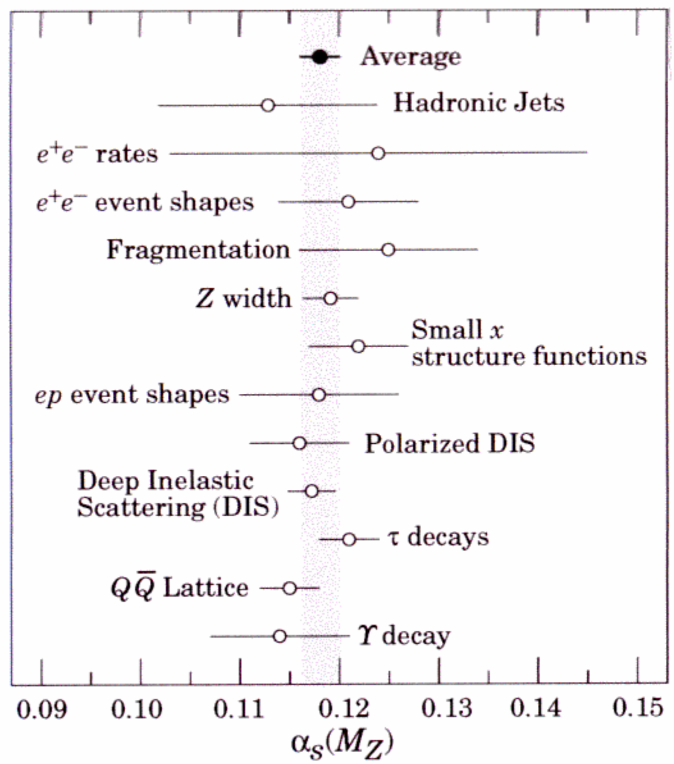
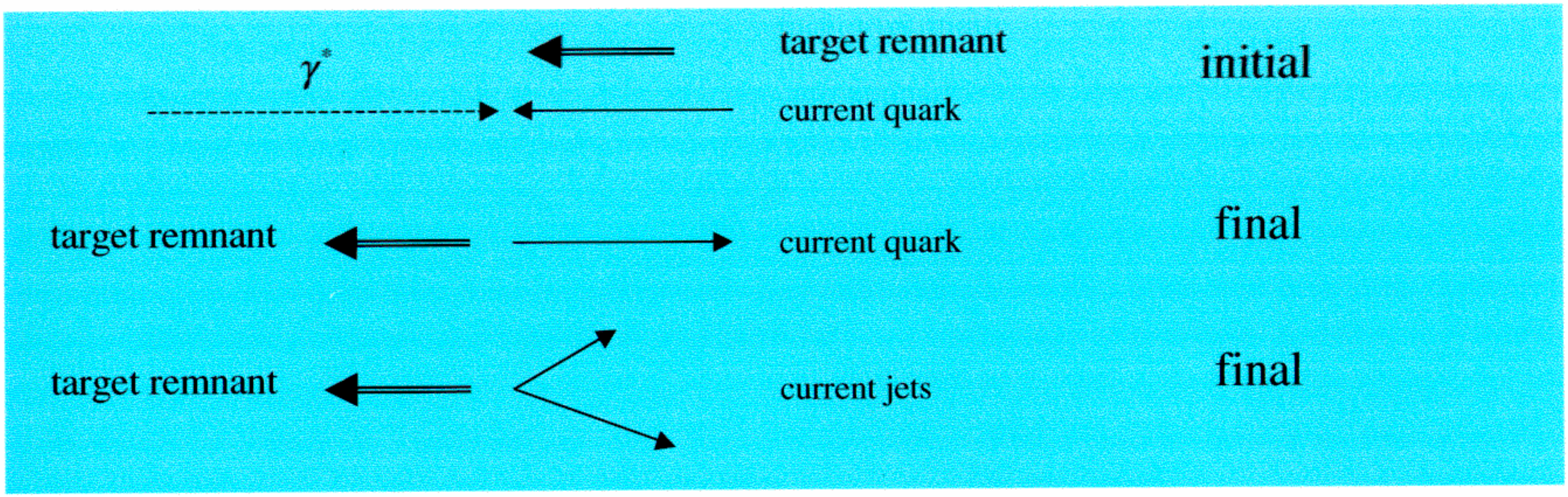


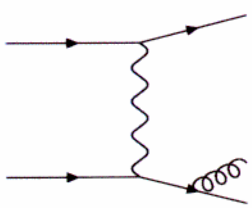
Figure 9.1: Summary of the values of $\alpha_s(M_Z)$ and $\Lambda^{(5)}$ from various processes. The values shown indicate the process and the measured value of α_s extrapolated up to $\mu = M_Z$. The error shown is the *total* error including theoretical uncertainties.

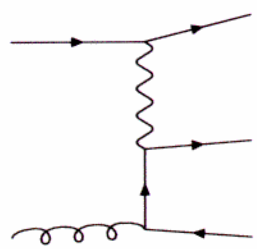
9.4. QCD in decays of the τ lepton

The semi-leptonic branching ratio of the tau ($\tau \rightarrow \nu_\tau +$ hadrons, R_τ) is an inclusive quantity. It is related to the contribution of hadrons to the imaginary part of the W self

Analysis of DIS final states in Breit frame







Jet search via k_T cluster algorithm

α_s measurement at HERA

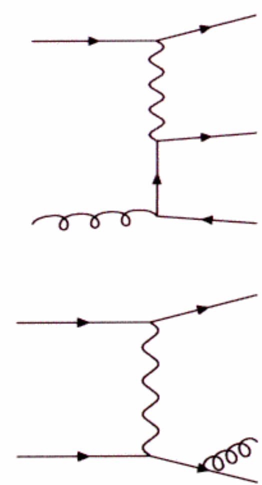
PDG: $\alpha_s(M_z) = 0.1185 \pm 0.0020$

Di-jets in NC DIS

DISENT (NLO QCD); Catani, Seymour

ZEUS: $\alpha_S(M_Z) = 0.1166 \pm 0.0019(stat) \pm^{0.0034}_{0.0043}(\exp) \pm^{0.0057}_{0.0044}(th)$

1

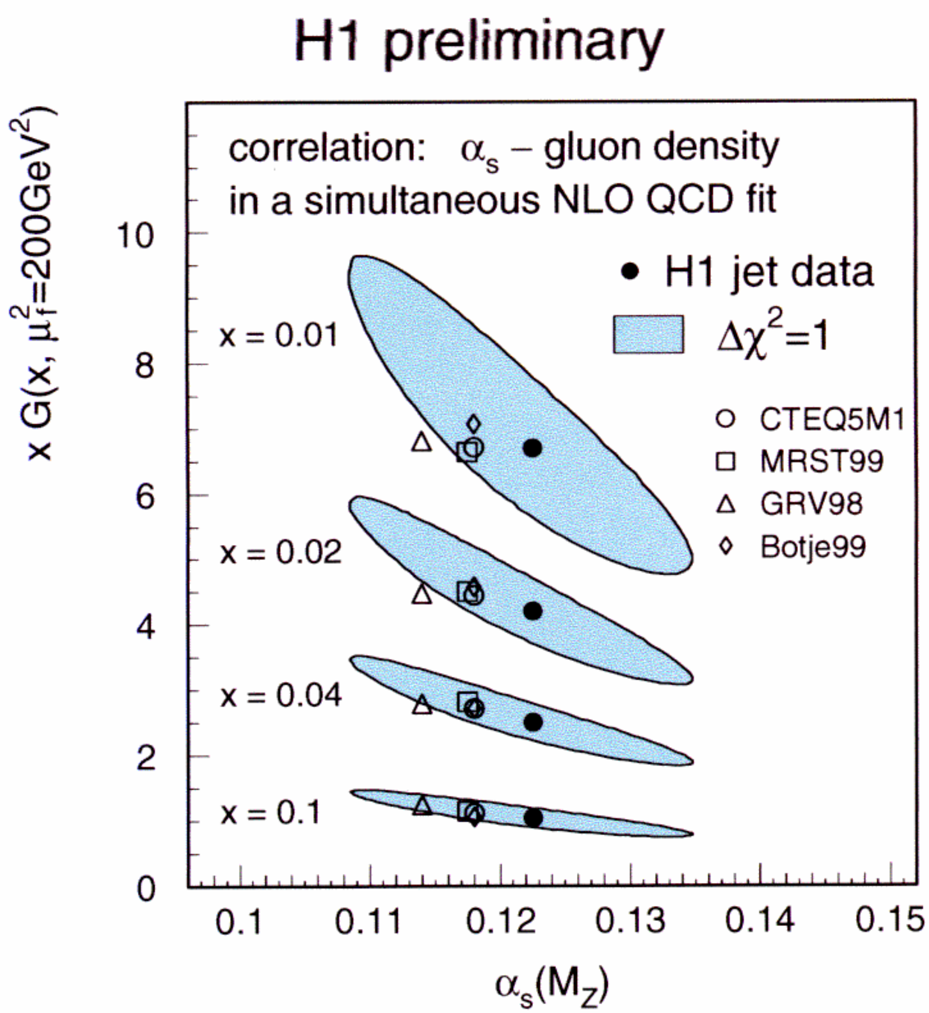


H1: $\alpha_S(M_Z) = 0.1181 \pm 0.0030(\exp) \pm^{0.0039}_{0.0046}(th) \pm^{0.0036}_{0.0015}(pdf)$ $\mu_r = E_T$

1

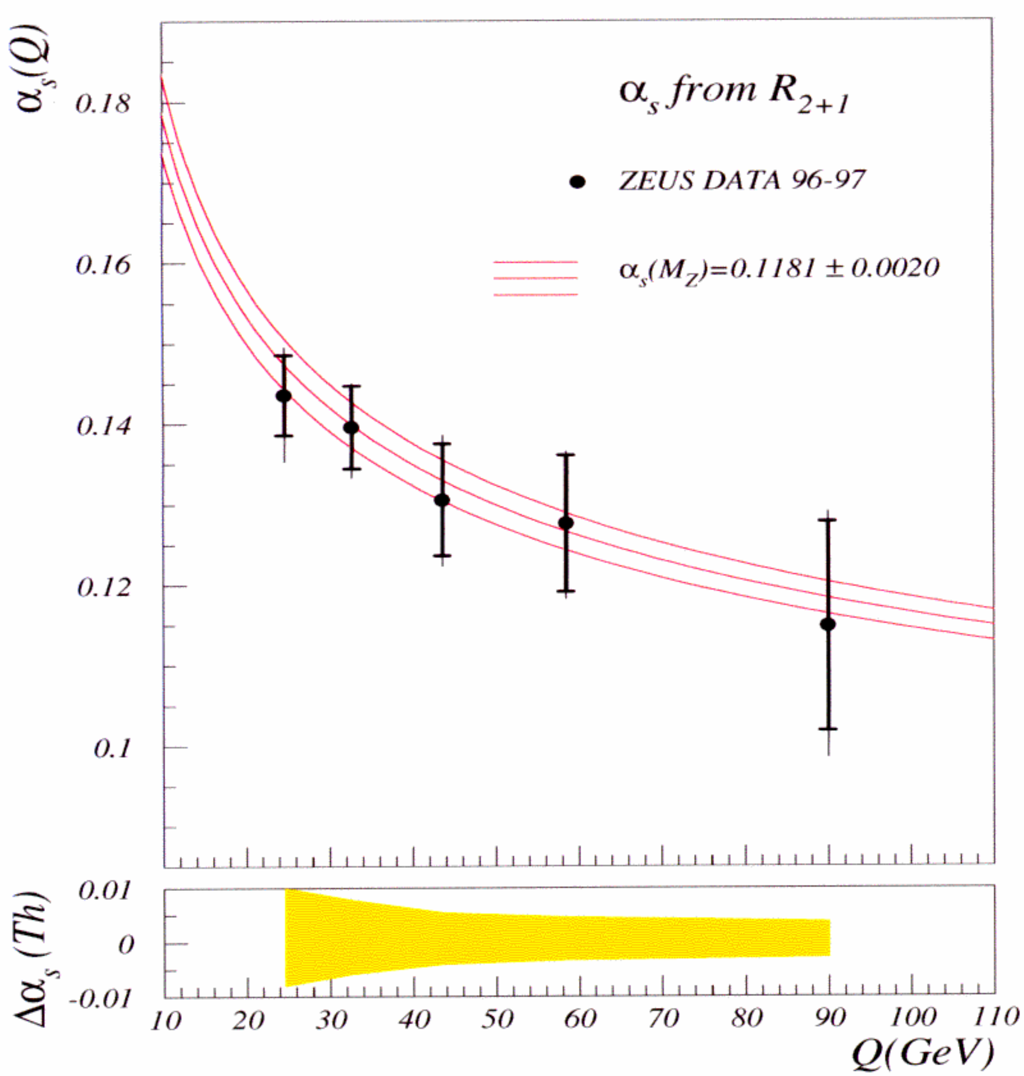
$\alpha_S(M_Z) = 0.1221 \pm 0.0034(\exp) \pm^{0.0054}_{0.0059}(th) \pm^{0.0033}_{0.0016}(pdf)$ $\mu_r = Q$

From scaling violations (low x): $\alpha_S(M_Z) = 0.1150 \pm 0.0017\ (\exp) \pm^{0.0011}_{0.0012}\ (\mathrm{mod}) \pm 0.005\ (scale)$



Using HERA (i.e. H1) data only

ZEUS 96-97 PRELIMINARY

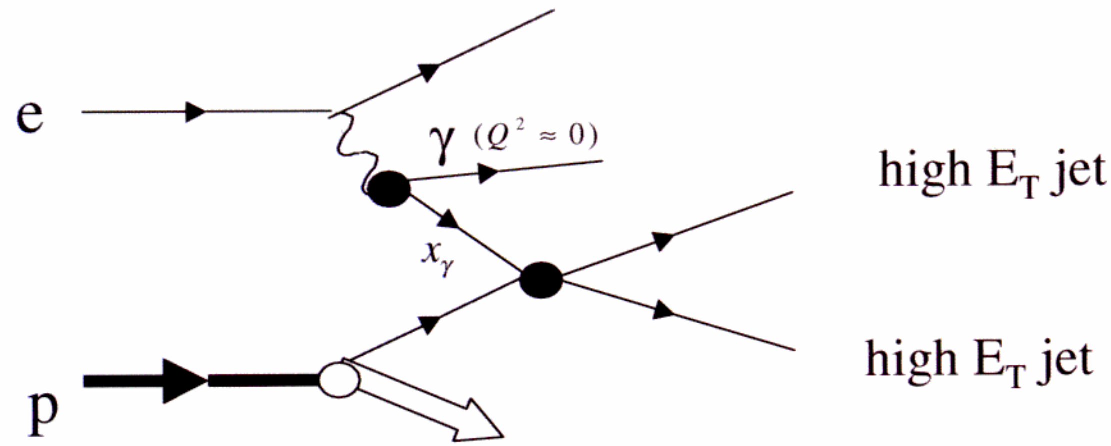


Conclusions on α_S

Precision measurements possible and achieved, both from ($\geq$) 2-jet production and from F_2 scaling violations and from a combined analysis.

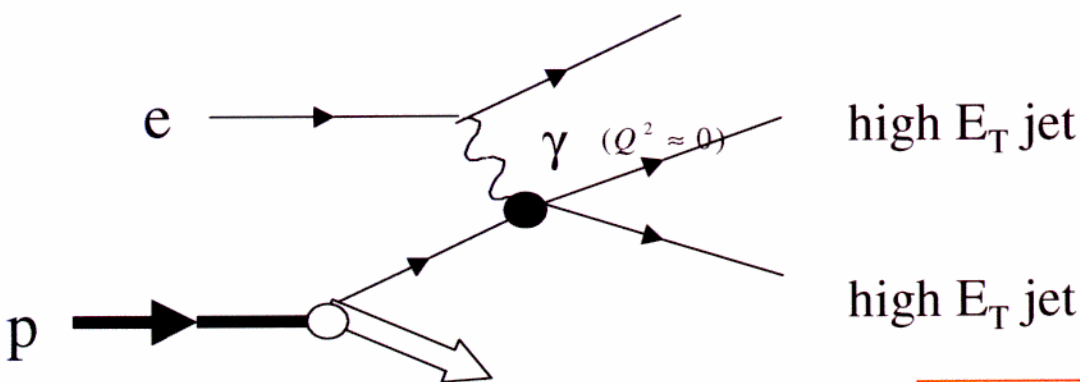
Main sources of uncertainty: choice of scale (need higher order calculations?) and the correlation of α_S and the gluon density (to be measured independently!)

Photoproduction



‘resolved’

$0 < x_\gamma < 1$

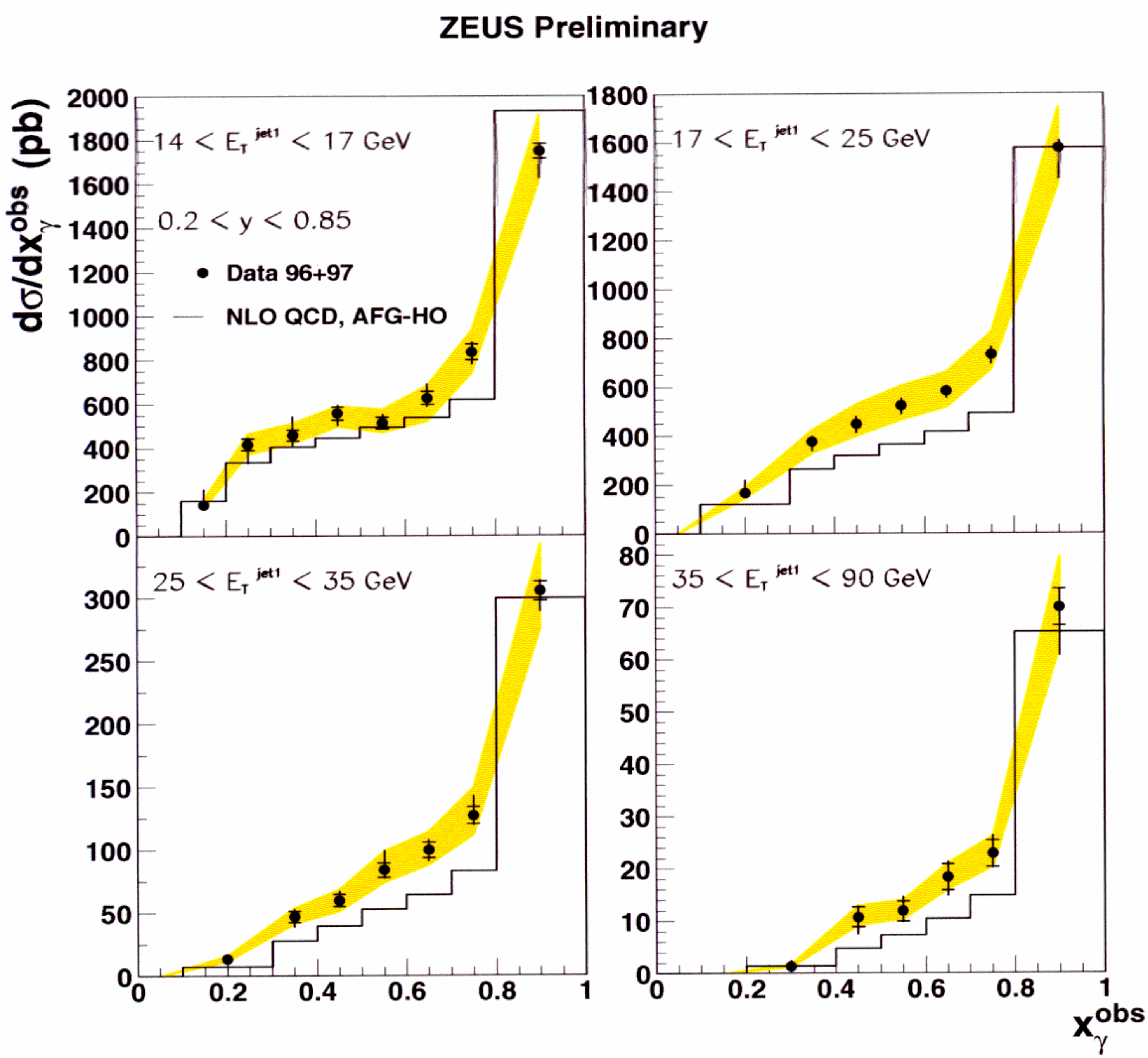


‘pointlike’

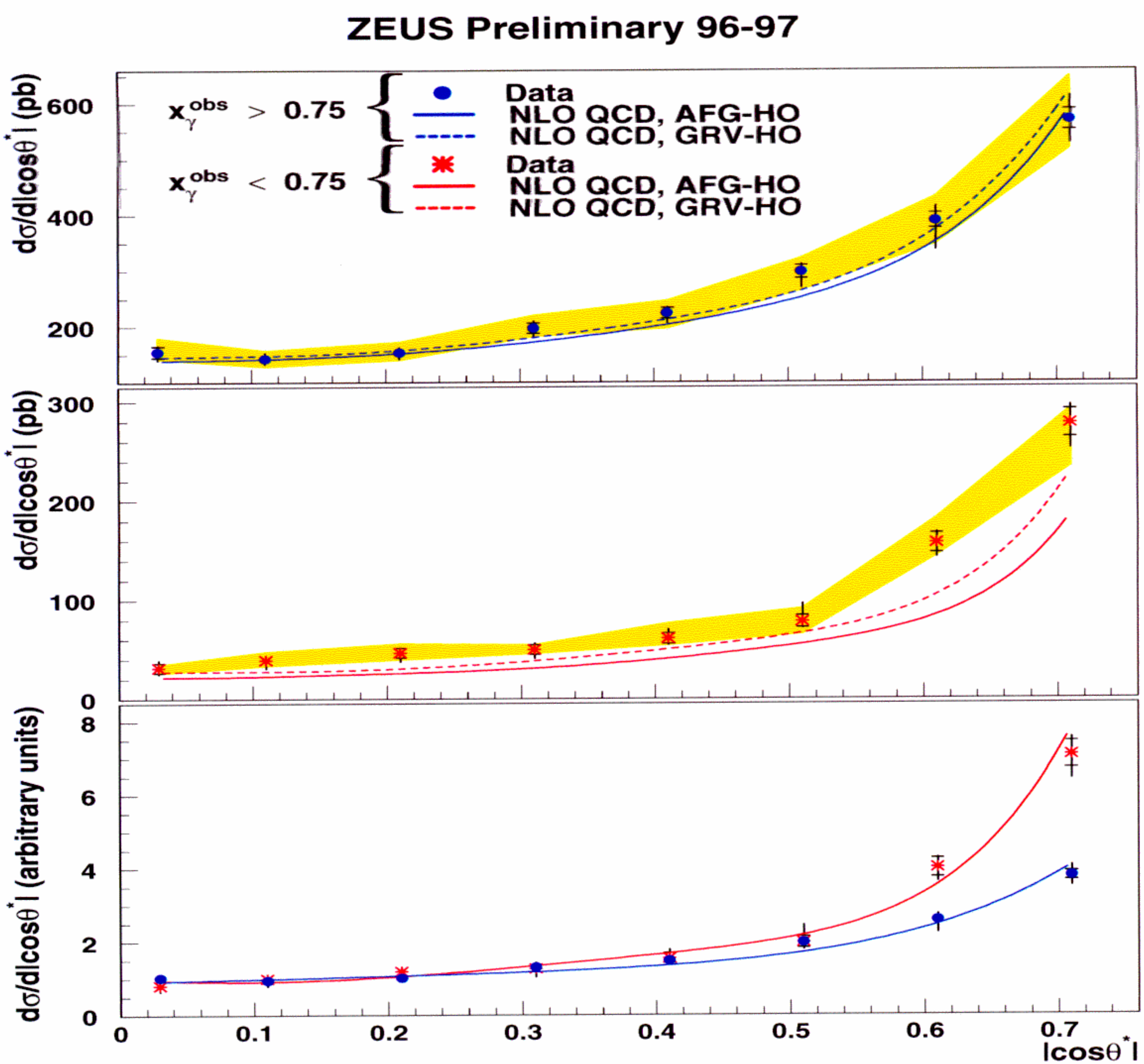
$x_\gamma = 1$

$$x_\gamma^{obs} = \frac{E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}}{2yE_e}$$

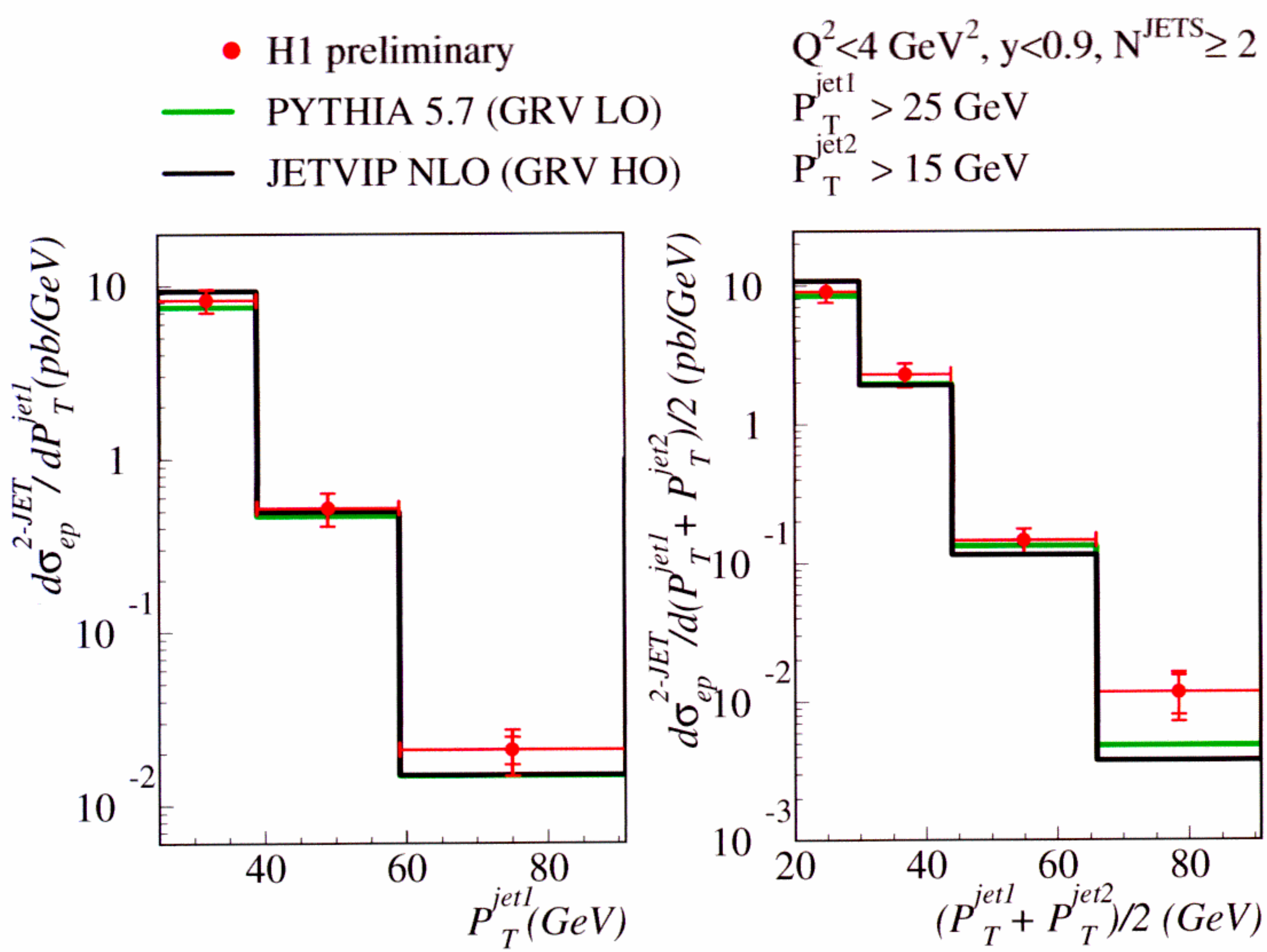
● : pert. QCD vertex



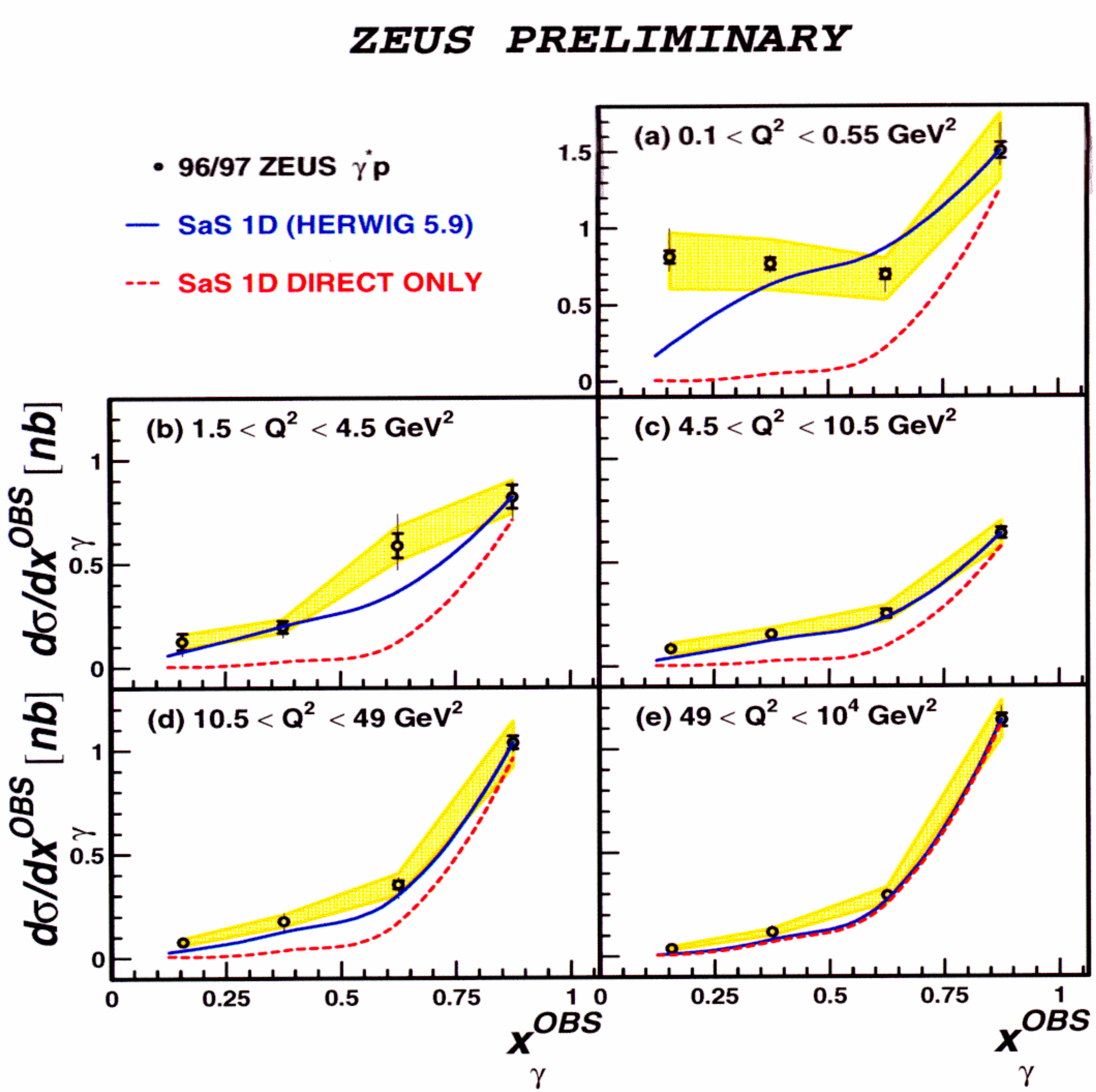
NLO QCD calulations reviewed by Harris, Klasen, Vossebeld hep-ph/9905348

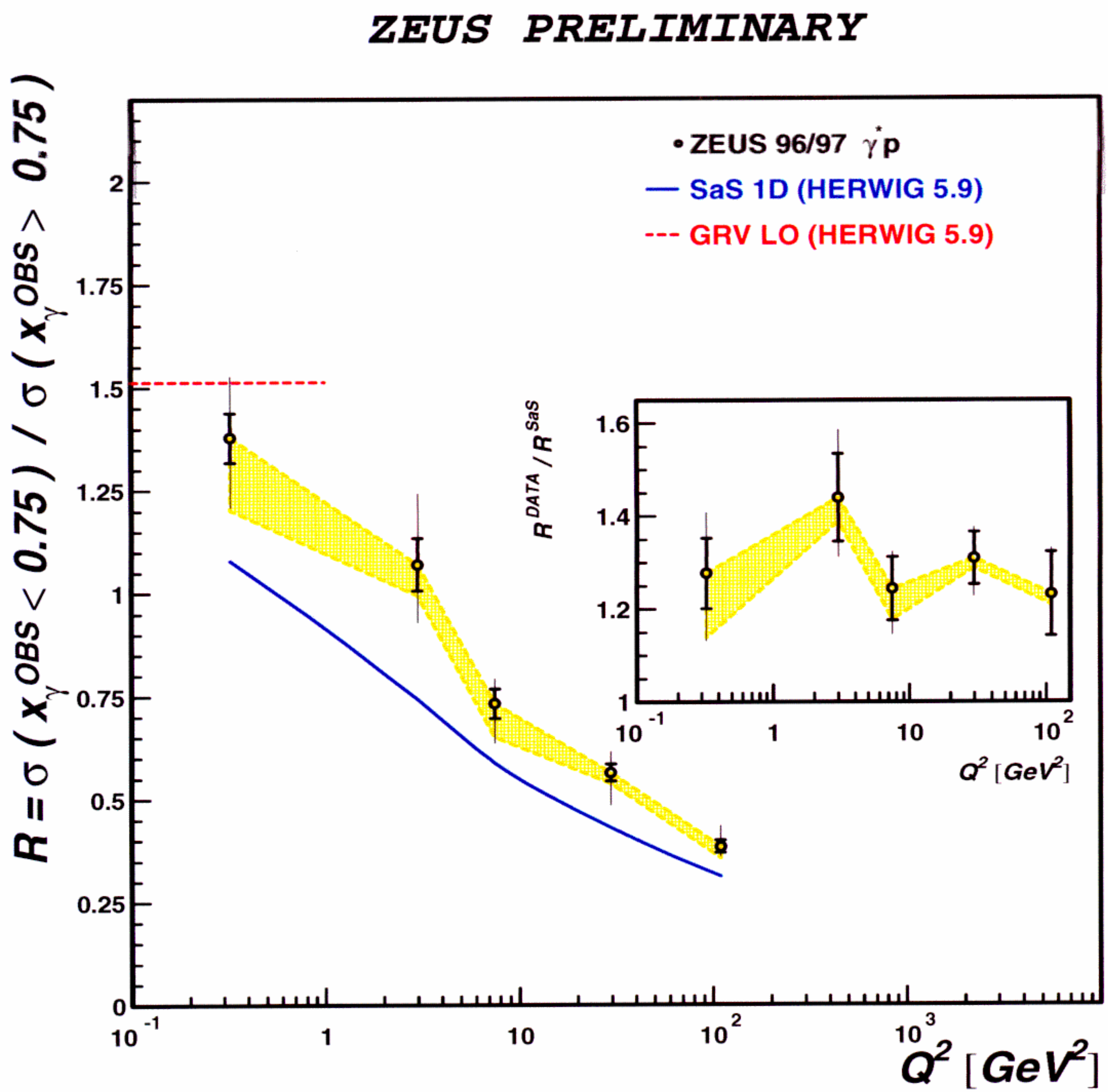


ZEUS Preliminary 96-97
$x_\gamma^{obs} > 0.75$
Data
NLO QCD, AFG-HO
NLO QCD, GRV-HO
$x_\gamma^{obs} < 0.75$
Data
NLO QCD, AFG-HO
NLO QCD, GRV-HO
$d\sigma/d|\cos\theta^*|$ (pb)
$d\sigma/d|\cos\theta^*|$ (pb)
$d\sigma/d|\cos\theta^*|$ (arbitrary units)
$|\cos\theta^*|$



H1 preliminary
PYTHIA 5.7 (GRV LO)
JETVIP NLO (GRV HO)
Q^2<4 GeV^2, y<0.9, N^JETS ≥ 2
P_T^jet1 > 25 GeV
P_T^jet2 > 15 GeV
dσ_ep^2-JET / dP_T^jet1 (pb/GeV)
P_T^jet1 (GeV)
dσ_ep^2-JET / d(P_T^jet1 + P_T^jet2)/2 (pb/GeV)
(P_T^jet1 + P_T^jet2)/2 (GeV)


ZEUS PRELIMINARY
• 96/97 ZEUS $\gamma^* p$
— SaS 1D (HERWIG 5.9)
--- SaS 1D DIRECT ONLY
(a) $0.1 < Q^2 < 0.55$ GeV^2
(b) $1.5 < Q^2 < 4.5$ GeV^2
(c) $4.5 < Q^2 < 10.5$ GeV^2
(d) $10.5 < Q^2 < 49$ GeV^2
(e) $49 < Q^2 < 10^4$ GeV^2
$d\sigma/dx_\gamma^{OBS}$ [nb]
x_γ^{OBS}
0
0.25
0.5
0.75
1
1.5


ZEUS PRELIMINARY
$R = \sigma (x_\gamma^{OBS} < 0.75) / \sigma (x_\gamma^{OBS} > 0.75)$
• ZEUS 96/97 $\gamma^* p$
— SaS 1D (HERWIG 5.9)
--- GRV LO (HERWIG 5.9)
R^{DATA} / R^{SaS}
Q^2 [GeV^2]
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
10^{-1}
1
10
10^2
10^3
1.2
1.4
1.6

Beauty Photoproduction

(in lowest order: photon-gluon fusion; NLO calculations available)

Frixione, Mangano, Nason, Ridolfi

H1: inclusive muons in di-jets; impact parameter distribution
in limited kinematic range, $\sigma_{vis}(ep \rightarrow b\ bbar\ X \rightarrow \mu\ X) = 170 \pm 25$ pb
as compared to NLO QCD prediction 104 ± 17 pb

ZEUS: inclusive electrons in di-jets

UA1, CDF, D0 find larger b cross section at colliders than predicted.

However: ZEUS finds (di-jet photoproduction) that photon pdf's need updating (↑);
should be done first before drawing conclusions on b production, but most likely
the effect of 'updated' pdf's on calculations will be (much) smaller than the presently observed difference between experiment and theory

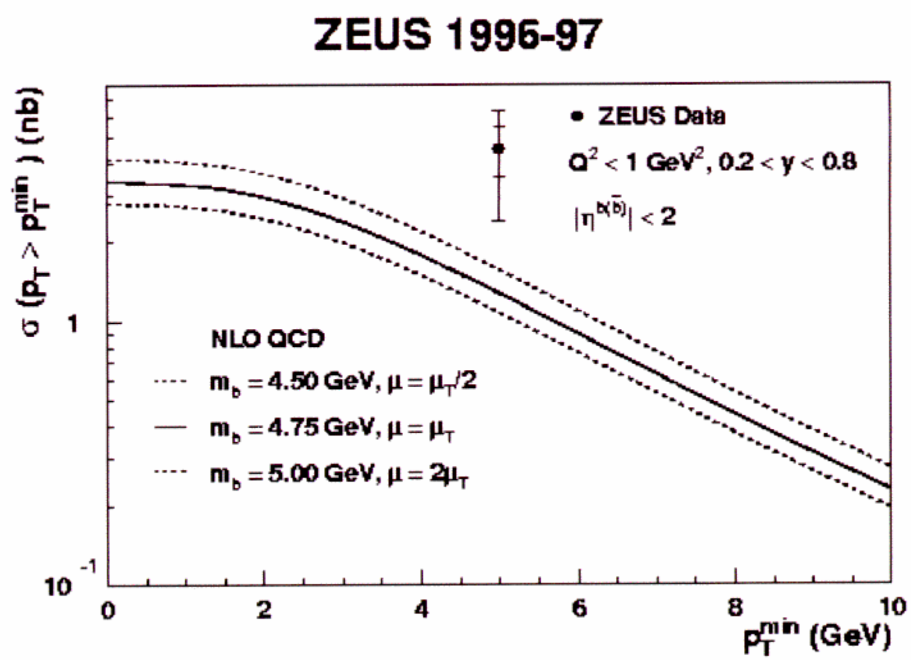


Figure 11: The extrapolated $b\bar{b}$ cross section as a function of the minimum transverse momentum, p_T^{min}. The data point is shown with statistical error (inner bar) and statistical, systematic and extrapolation errors added in quadrature and is compared with predictions from NLO-QCD.

Conclusions on Photoproduction

- Jet p_T spectra well described (H1) (at high p_T, no contradiction with)
  - GRV pdf's for proton and photon — Glueck, Reya, Vogt
  - PYTHIA 5.7 event generator (LO)
  - JetVip calculations (HO) — Potter
- NLO QCD predictions agree with data for 'pointlike' photon (ZEUS)
- NLO QCD predictions below the data for 'resolved' photon (ZEUS)
  - AFG(HO) and GRV(HO) photon pdf's
    Aurenche, Fontannaz, Guillet
  - shape of angular distributions correct, normalization not → need improved photon pdf's (i.e. include these data in future fits)
- Di-jet production in $\gamma^* p$ interactions reveals virtual photon structure
  - SaS photon pdf's — Schuler, Sjostrand
  - resolved virtual photon component up to $Q^2 \sim E_T^2 \sim 49$ GeV^2
  - $0.1 < Q^2 < 0.55$ GeV^2 not well described
  - resolved virtual photon component decreases with Q^2
- Indications that cross section for photoproduction of beauty is larger than theoretical predictions — Frixione, Mangano, Nason, Ridolfi

Neutral current $e^{\pm}p$ scattering:

$$\frac{d^2\sigma^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) \mp Y_-xF_3(x,Q^2) - y^2F_L(x,Q^2)]$$

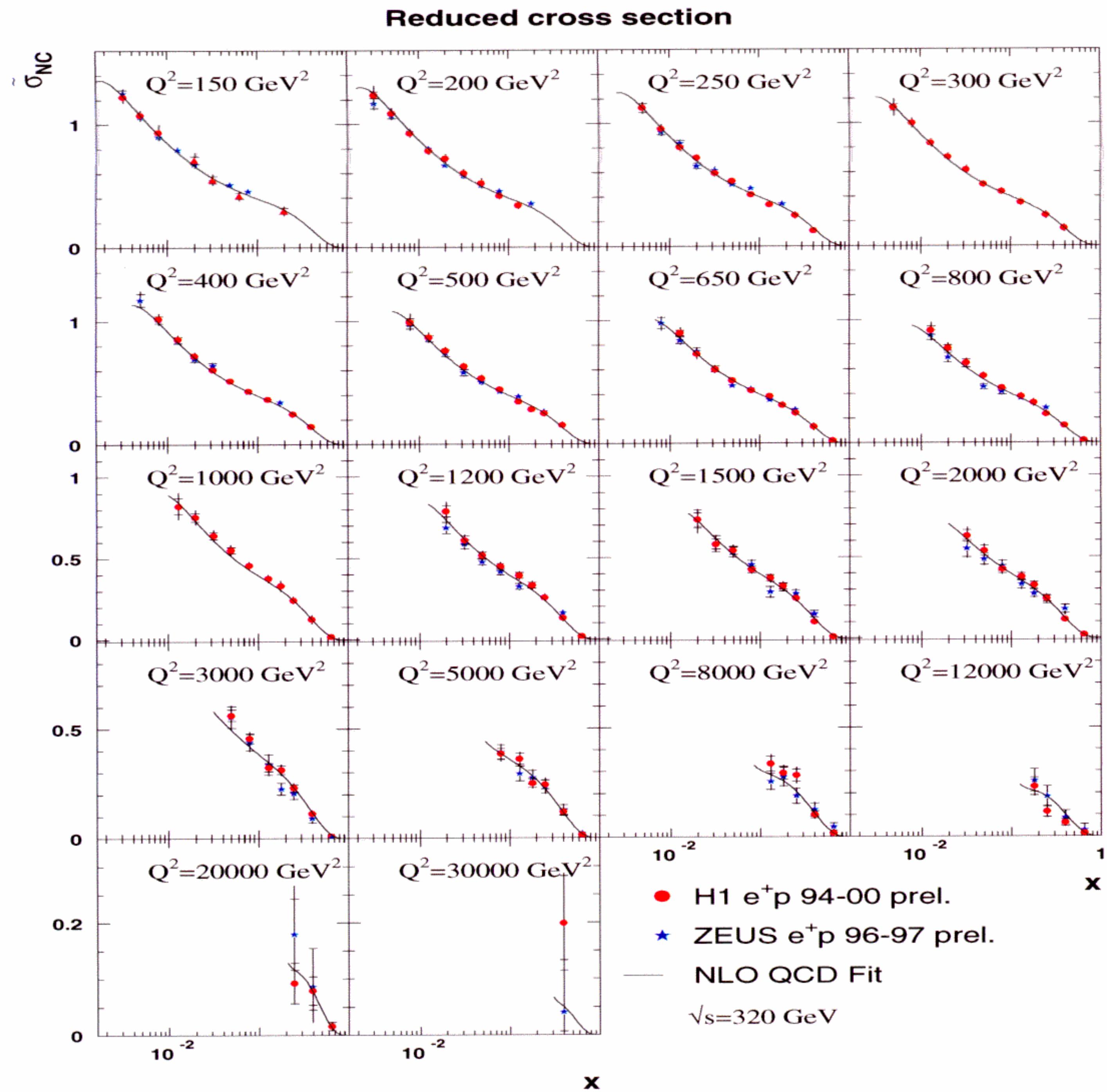
$$F_2(x,Q^2) = x\sum_f A_f(Q^2)[q_f(x,Q^2) + \bar{q}_f(x,Q^2)]$$

$$xF_3(x,Q^2) = x\sum_f B_f(Q^2)[q_f(x,Q^2) - \bar{q}_f(x,Q^2)]$$

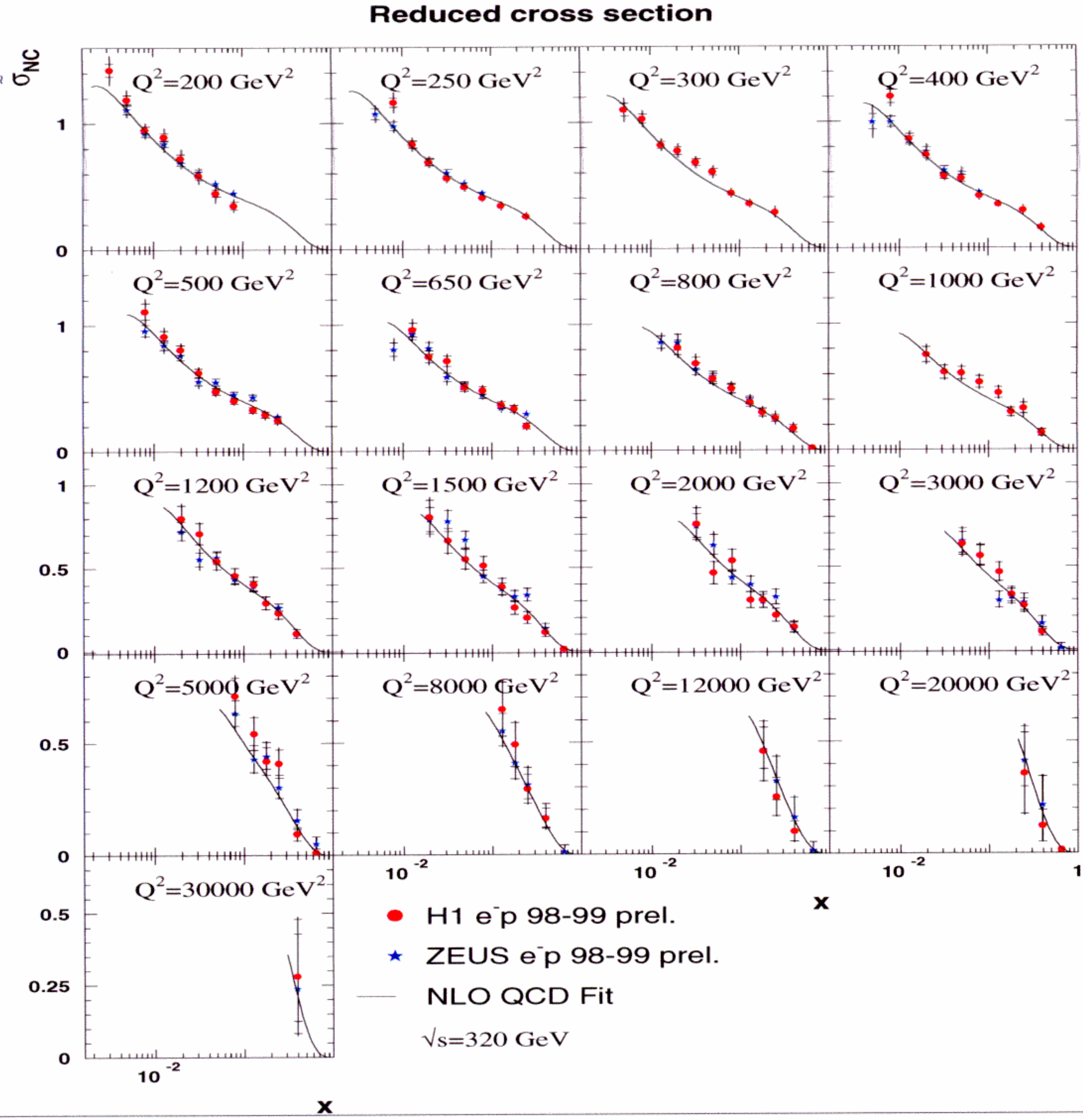
$$A_f(Q^2) = e_f^2 - 2v_e v_f e_f P_Z + (v_e^2 + a_e^2)(v_f^2 + a_f^2)P_Z^2$$

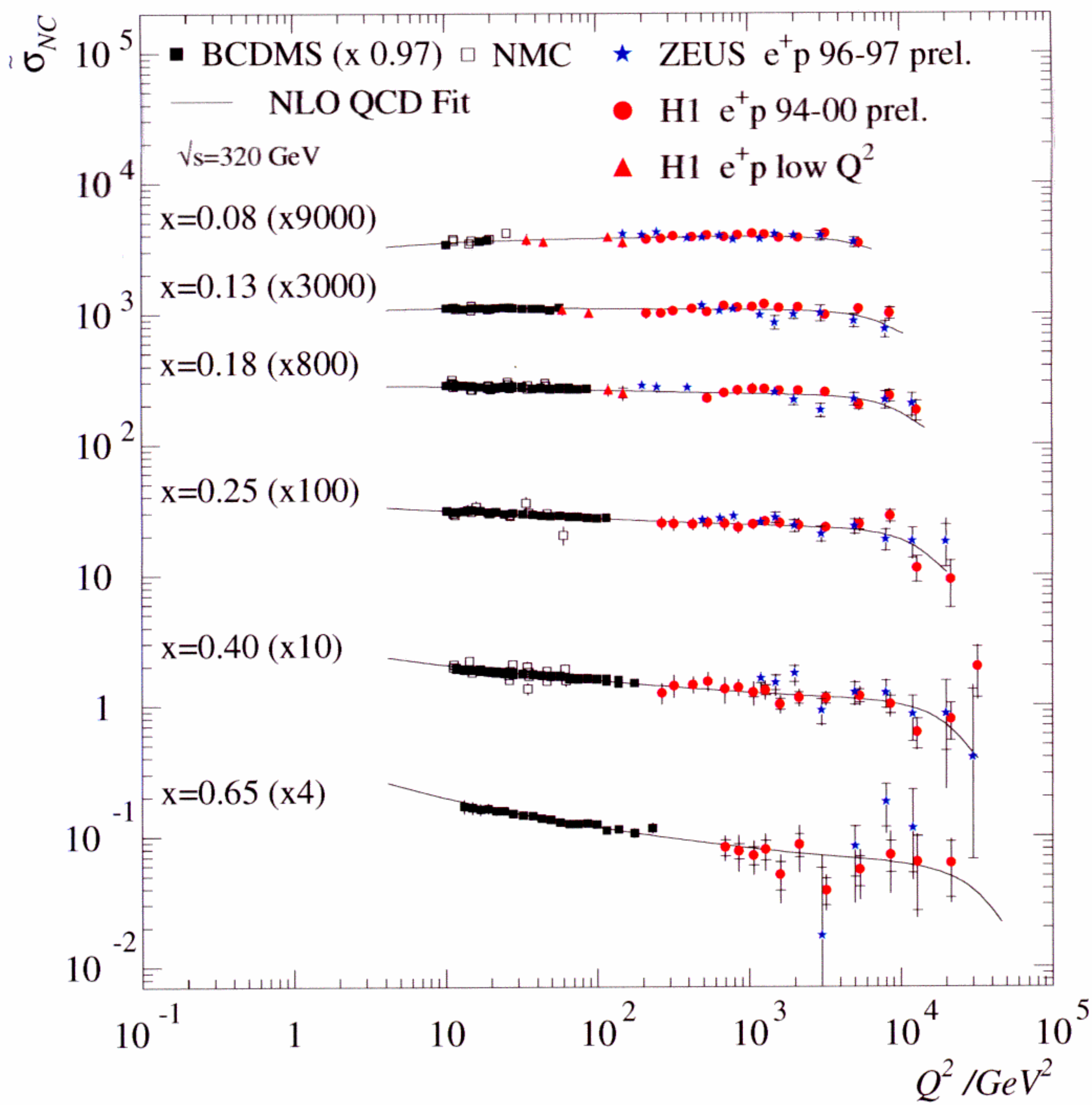
$$B_f(Q^2) = -2a_e a_f e_f P_Z + 4v_e a_e v_f a_f P_Z^2$$

$$P_Z = \frac{1}{4\sin^2\theta_W \cos^2\theta_W}\frac{Q^2}{Q^2 + M_Z^2}$$

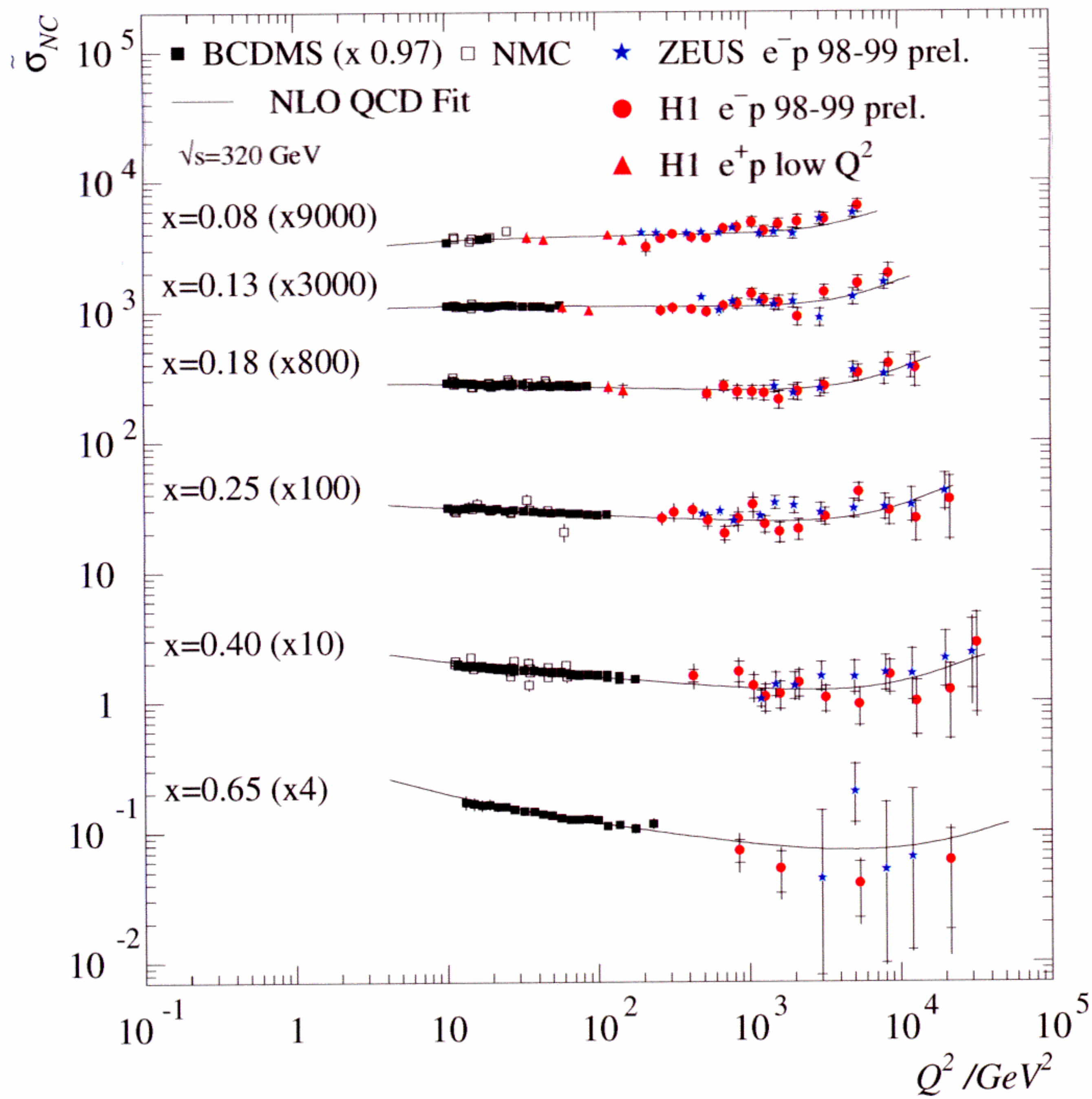


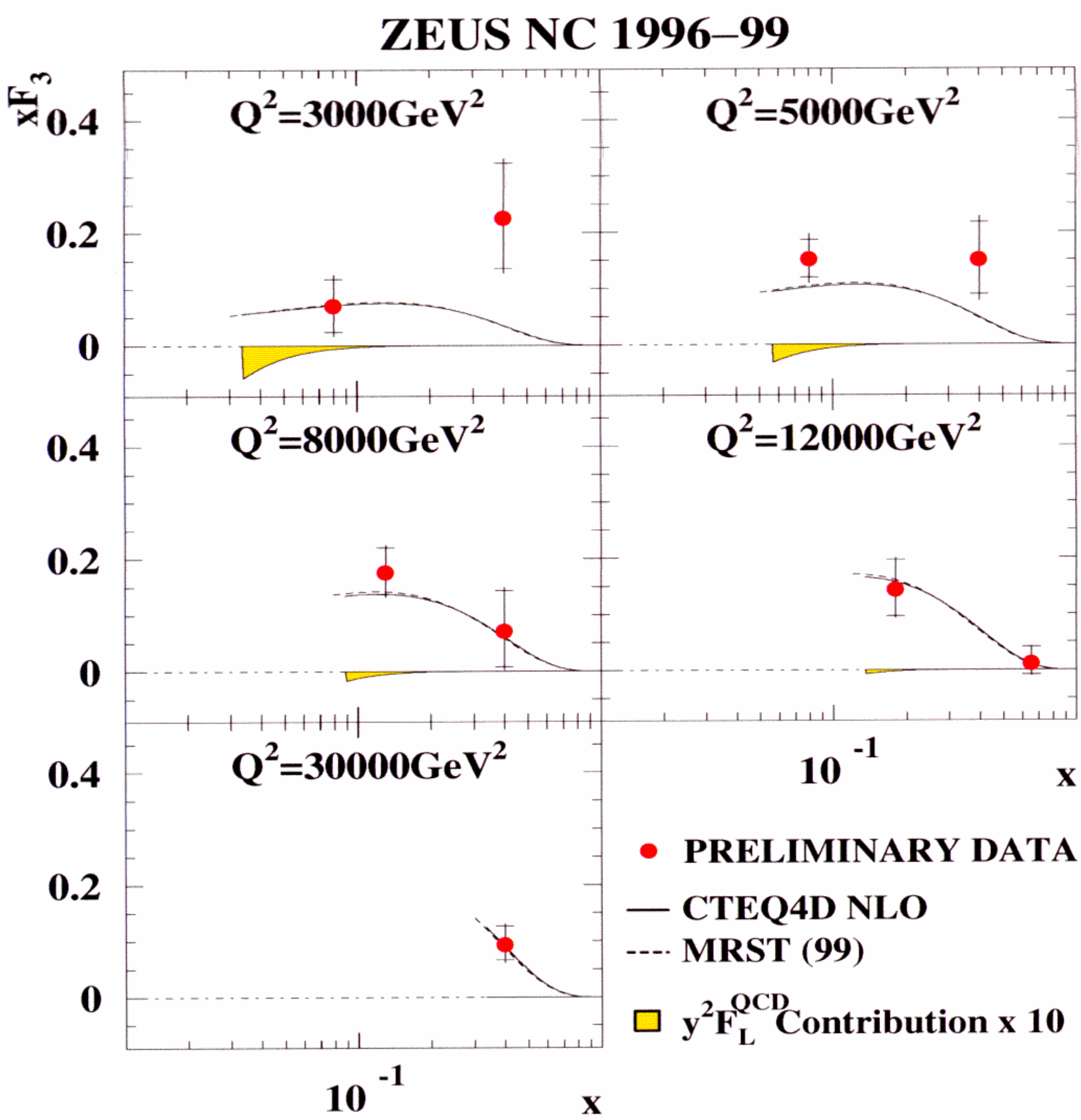
Reduced cross section
$\tilde{\sigma}_{NC}$
Q^2=150 GeV^2
Q^2=200 GeV^2
Q^2=250 GeV^2
Q^2=300 GeV^2
Q^2=400 GeV^2
Q^2=500 GeV^2
Q^2=650 GeV^2
Q^2=800 GeV^2
Q^2=1000 GeV^2
Q^2=1200 GeV^2
Q^2=1500 GeV^2
Q^2=2000 GeV^2
Q^2=3000 GeV^2
Q^2=5000 GeV^2
Q^2=8000 GeV^2
Q^2=12000 GeV^2
Q^2=20000 GeV^2
Q^2=30000 GeV^2
H1 e^+p 94-00 prel.
ZEUS e^+p 96-97 prel.
NLO QCD Fit
$\sqrt{s}$=320 GeV
x


Reduced cross section
$\tilde{\sigma}_{NC}$
Q^2=200 GeV^2
Q^2=250 GeV^2
Q^2=300 GeV^2
Q^2=400 GeV^2
Q^2=500 GeV^2
Q^2=650 GeV^2
Q^2=800 GeV^2
Q^2=1000 GeV^2
Q^2=1200 GeV^2
Q^2=1500 GeV^2
Q^2=2000 GeV^2
Q^2=3000 GeV^2
Q^2=5000 GeV^2
Q^2=8000 GeV^2
Q^2=12000 GeV^2
Q^2=20000 GeV^2
Q^2=30000 GeV^2
H1 e^-p 98-99 prel.
ZEUS e^-p 98-99 prel.
NLO QCD Fit
$\sqrt{s}$=320 GeV
x
10^{-2}
1
0
0.25
0.5

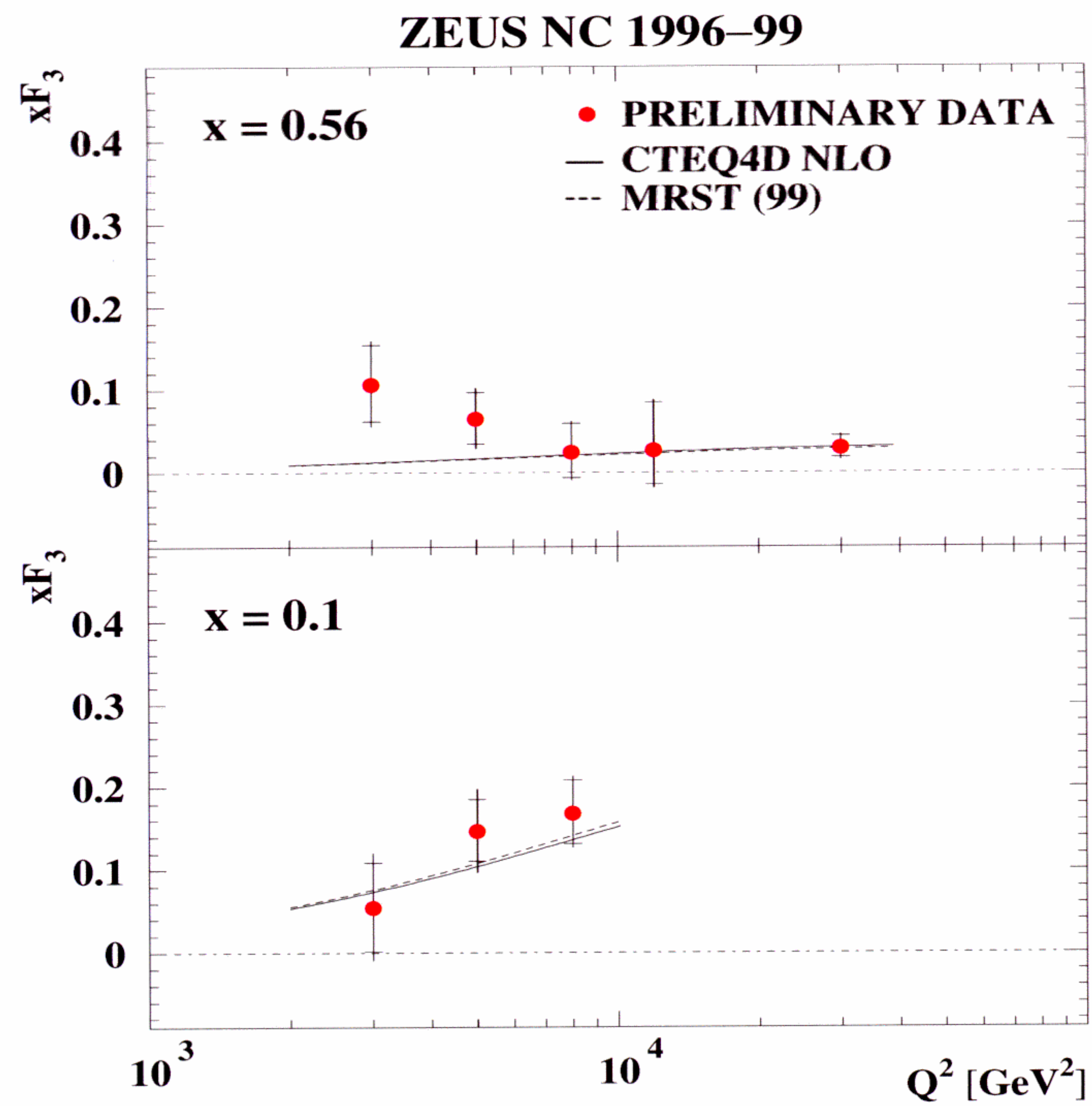


$\tilde{\sigma}_{NC}$
BCDMS (x 0.97)
NMC
ZEUS e+p 96-97 prel.
NLO QCD Fit
H1 e+p 94-00 prel.
√s=320 GeV
H1 e+p low Q2
x=0.08 (x9000)
x=0.13 (x3000)
x=0.18 (x800)
x=0.25 (x100)
x=0.40 (x10)
x=0.65 (x4)
Q^2 /GeV^2


σ̃_NC
BCDMS (x 0.97)
NMC
ZEUS e⁻p 98-99 prel.
NLO QCD Fit
H1 e⁻p 98-99 prel.
√s=320 GeV
H1 e⁺p low Q²
x=0.08 (x9000)
x=0.13 (x3000)
x=0.18 (x800)
x=0.25 (x100)
x=0.40 (x10)
x=0.65 (x4)
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
Q² /GeV²



ZEUS NC 1996–99
xF3
0.4
0.2
0
Q2=3000GeV2
Q2=5000GeV2
Q2=8000GeV2
Q2=12000GeV2
Q2=30000GeV2
10 -1
x
PRELIMINARY DATA
CTEQ4D NLO
MRST (99)
y2FLQCD Contribution x 10


ZEUS NC 1996–99
xF3
x = 0.56
PRELIMINARY DATA
CTEQ4D NLO
MRST (99)
0.4
0.3
0.2
0.1
0
xF3
x = 0.1
0.4
0.3
0.2
0.1
0
10^3
10^4
Q^2 [GeV^2]

Charged Current Scattering:

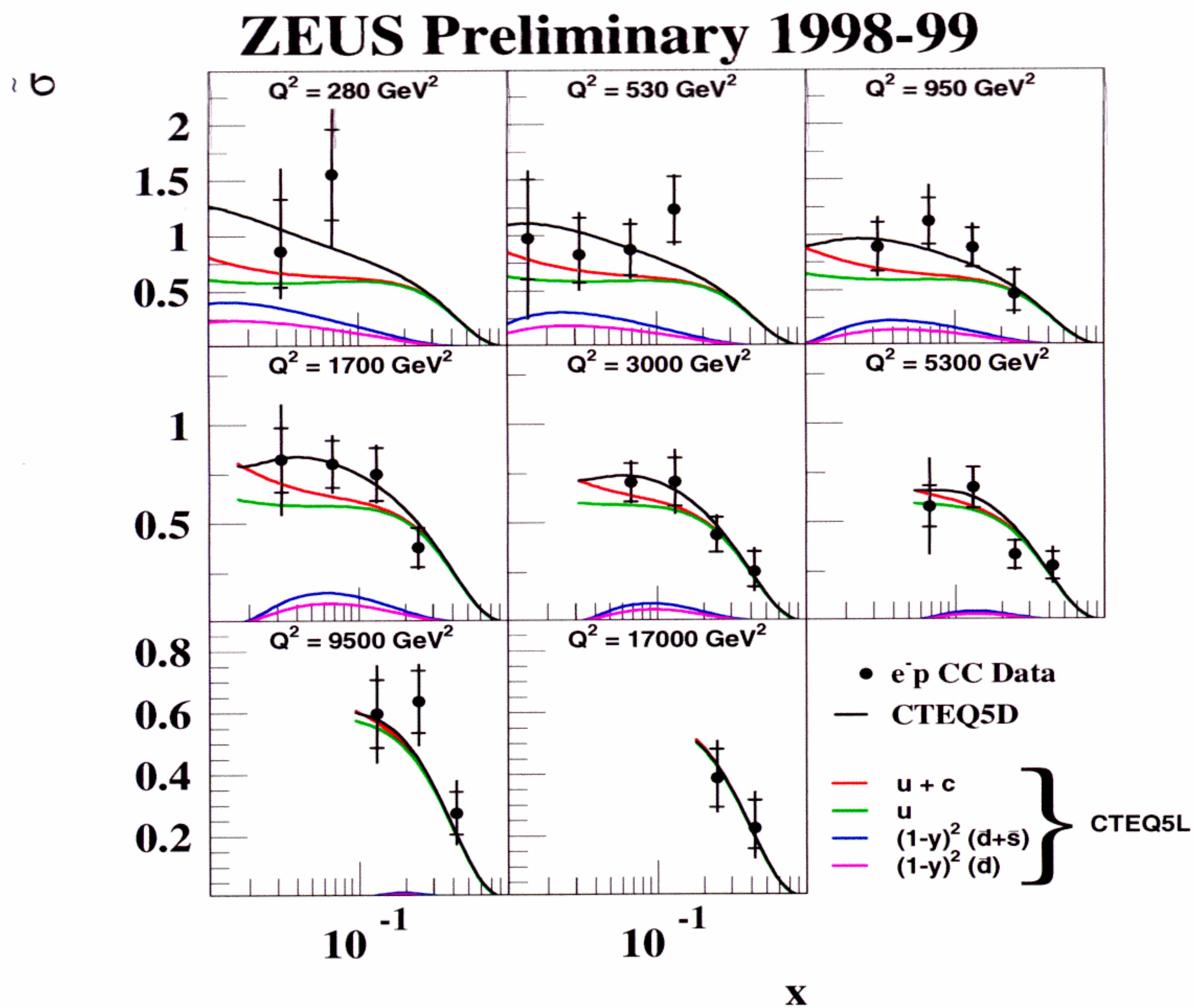
$$\frac{d^2\sigma^{e^- p\to\nu_e X}}{dx dQ^2} = \frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[xu + xc + (1-y)^2(x\bar{d} + x\bar{s})\right]$$

For e^+p CC scattering replace (u,c) by anti-(u,c) and anti-(d,s) by (d,s)

Reduced double-differential cross-sections:

$$\tilde{\sigma}^{e^- p\to\nu_e X} = \left[\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\right]^{-1}\frac{d^2\sigma}{dx dQ^2} = x[u + c + (1-y)^2(\bar{d} + \bar{s})]$$

$$\tilde{\sigma}^{e^+ p\to\bar{\nu}_e X} = x[\bar{u} + \bar{c} + (1-y)^2(d + s)]$$


ZEUS Preliminary 1998-99
$\tilde{\sigma}$
Q^2 = 280 GeV^2
Q^2 = 530 GeV^2
Q^2 = 950 GeV^2
Q^2 = 1700 GeV^2
Q^2 = 3000 GeV^2
Q^2 = 5300 GeV^2
Q^2 = 9500 GeV^2
Q^2 = 17000 GeV^2
e^-p CC Data
CTEQ5D
u + c
u
$(1-y)^2$ $(\bar{d}+\bar{s})$
$(1-y)^2$ $(\bar{d})$
CTEQ5L
10^{-1}
x

Conclusions

HERA offers excellent possibilities for studying (p)QCD

- measurements of structure functions over large range in x (down to $\leq 10^{-5}$) and Q^2 (up to 10^5 GeV^2)
- quantitative study of scaling violations
- measurement of gluon density function
- charm production in DIS
- diffractive DIS
- jet production in DIS and measurement of α_S
- photoproduction and photon structure

Progress in modeling of transition into low x, low Q^2 region: CFFM evolution; γ^*(dipole)p cross section & saturation

Outlook

HERA upgrade during shutdown 2000-2001 (luminosity *5)

Detector upgrades (Si μVTX)

- charm (beauty) in photoproduction and DIS
- high Q^2 (and high x) structure functions and pdf's
- → and ← polarised e^+ and e^- beams