

Structure Functions at HERA

Günter Grindhammer
Hans-Christian Schultz-Coulon

on behalf of H1 and ZEUS

HSQCD 08, Gatchina, July 3rd 2008

The HERA Collider Experiments



HERA
1992 - 2007

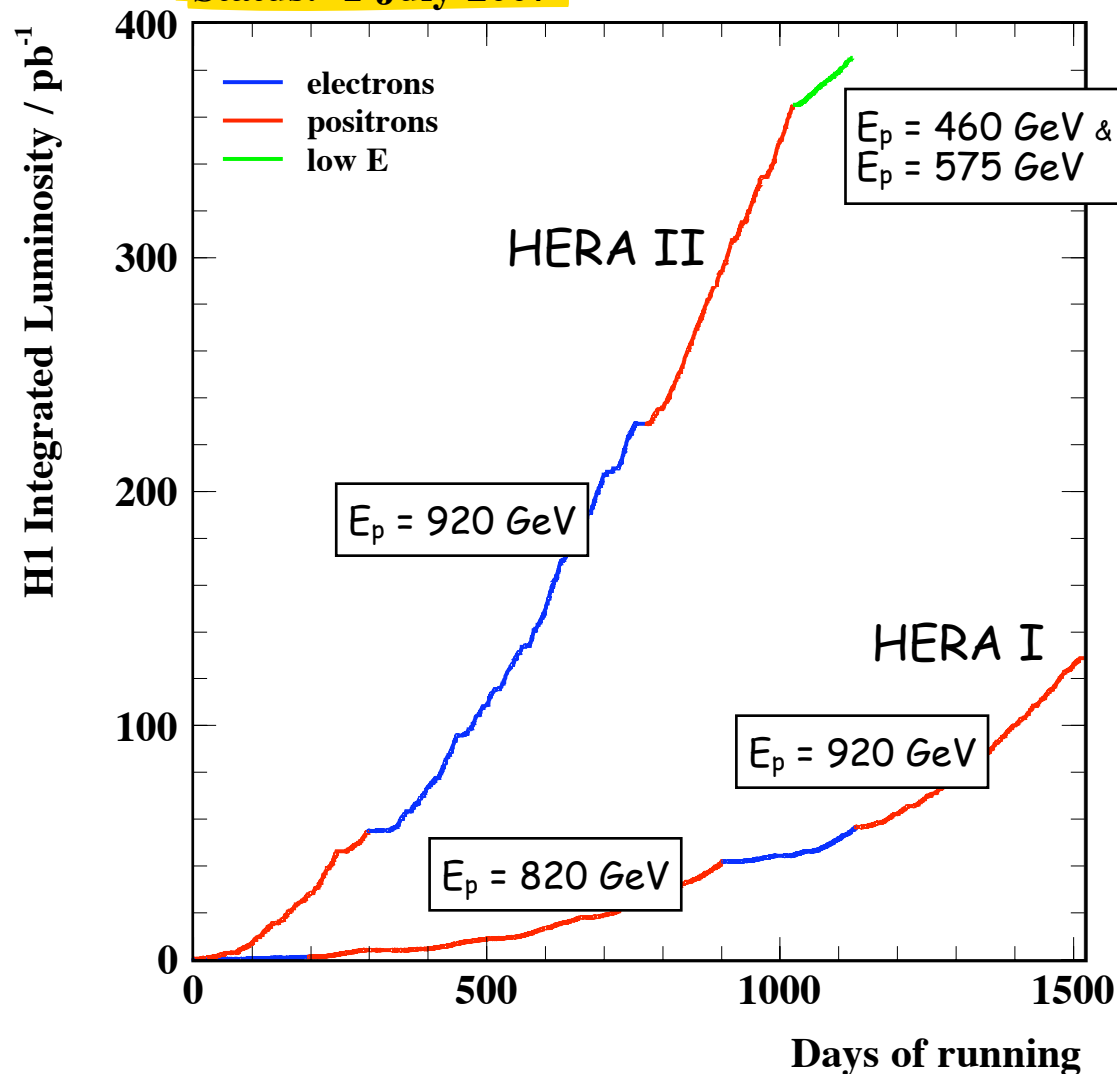
HERA



PETRA

HERA: Final Integrated Luminosity

Status: 1-July-2007



HERA I

$$e^-p : \sim 20 \text{ pb}^{-1}$$

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

+ Shift Vertex Runs
[1995 & 2000]

HERA II

$$e^-p : \sim 200 \text{ pb}^{-1}$$

$$e^+p : \sim 200 \text{ pb}^{-1}$$

+ Low Energy Runs
[@ 460 & 575 GeV]

Polarized !!

$$\text{H1 + ZEUS} : \sim 1 \text{ fb}^{-1}$$

Kinematics

$$E_e = 27.5 \text{ GeV}$$

Electron (e^\pm)

k

k'

Electron (e^\pm)
Neutrino

$$\sqrt{s} = 319 \text{ GeV}$$

$$Q^2 = -(k - k')^2$$

γ, Z^0
 W^\pm

P_q'

$P_q = xP$

$$E_p = 920 \text{ GeV}$$

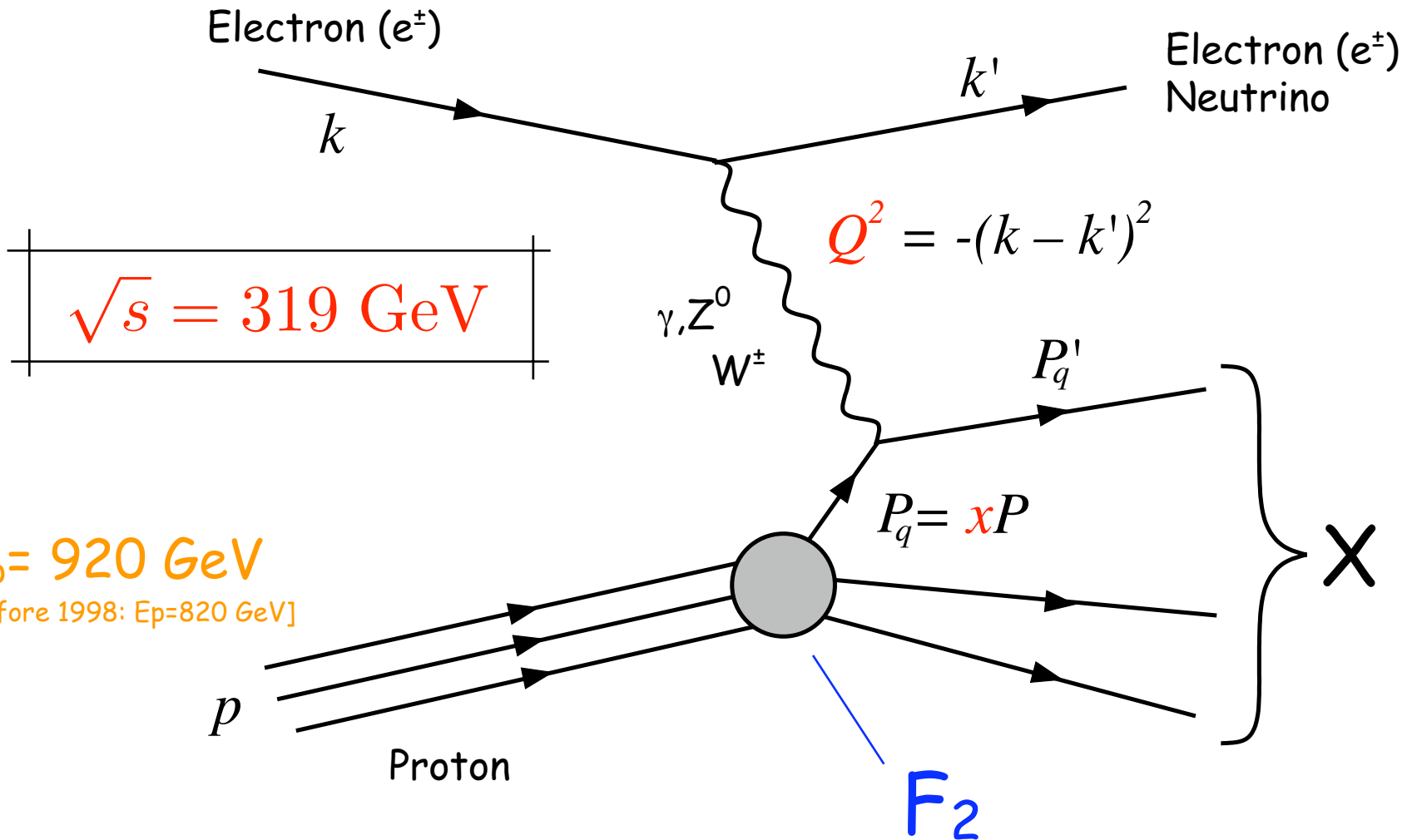
[before 1998: $E_p = 820 \text{ GeV}$]

p

Proton

F_2

X



The Structure Function F_2

Unpolarized $e^\pm p$ NC cross section:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[Y_+ F_2 \mp Y_- xF_3 - y^2 F_L \right]$$

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

$F_2 \propto \sum (q + \bar{q})$: dominates cross section

$xF_3 \propto \sum (q - \bar{q})$: contributes at high Q^2

$F_L \propto \alpha_s g(x, Q^2)$: contributes only at high y

Four-momentum
transfer:

$$Q^2 = -(k - k')^2$$

Bjorken- x :

$$x = \frac{Q^2}{2pq}$$

Inelasticity:

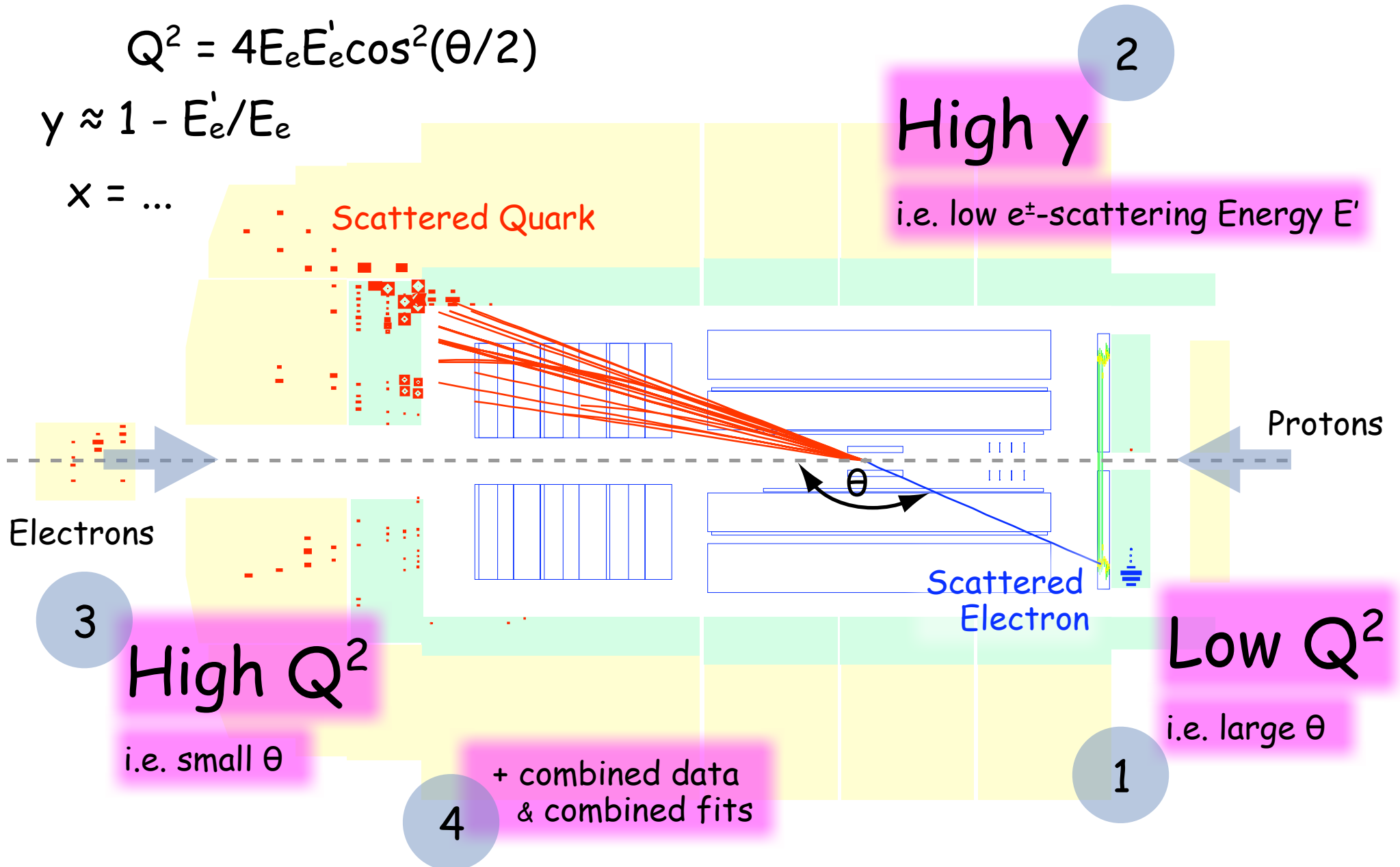
$$y = \frac{pq}{pk} = \frac{Q^2}{sx}$$

A DIS-Event in the Detector

$$Q^2 = 4E_e E_e' \cos^2(\theta/2)$$

$$y \approx 1 - E_e'/E_e$$

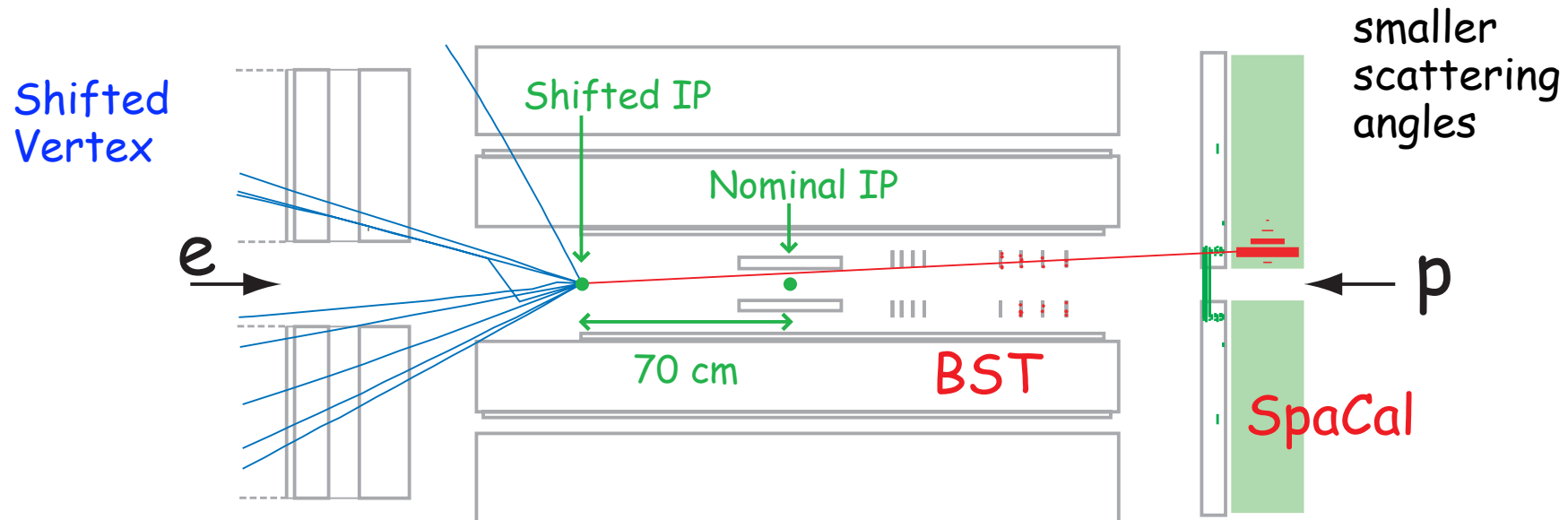
$x = \dots$



Low Q^2

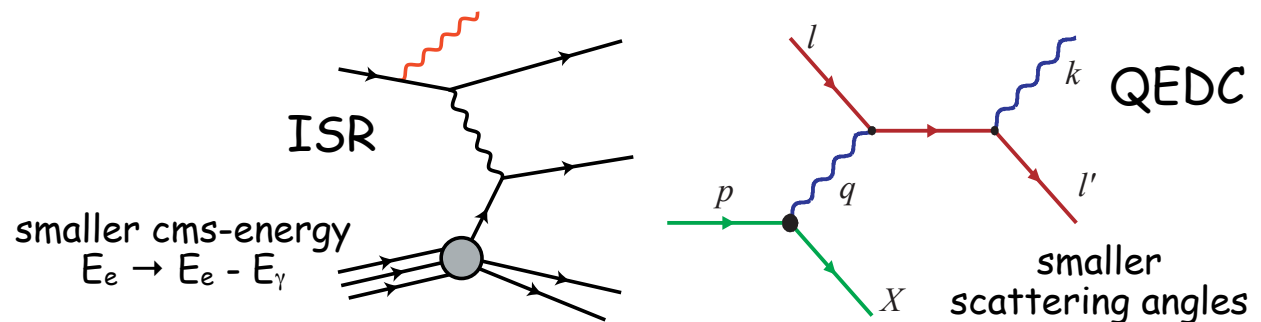
Special Experimental Techniques

- H1: shifted vertex collisions, initial state radiation (untagged ISR)
- ZEUS: low angle calorimeter & tracker (BPT), tagged ISR



... also:

Radiative events
Low angle detectors



Recent Low Q^2 Results

H1 Data:

Min Bias '97 [publ.]

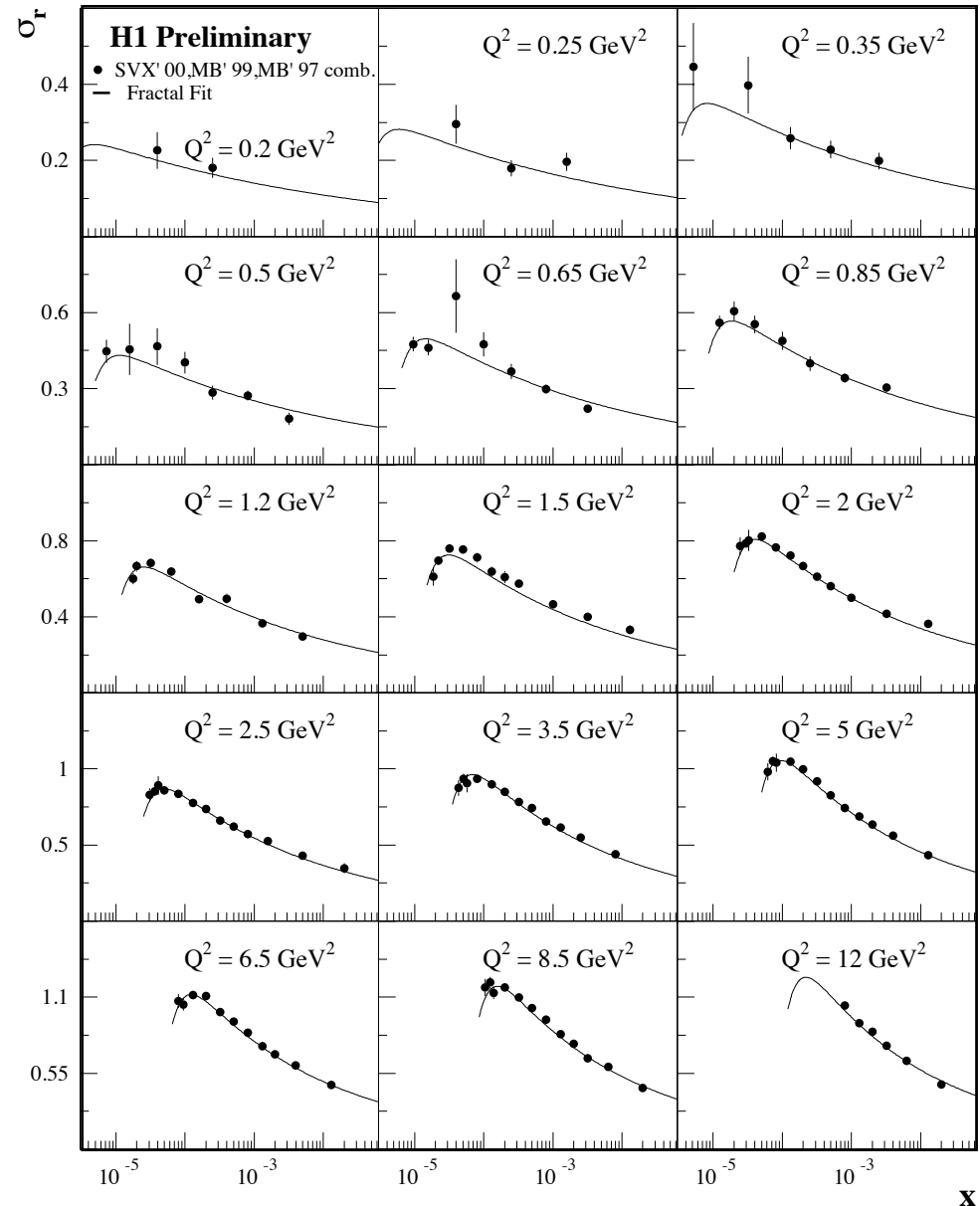
Min Bias '99 [high y]

Shifted Vtx '00 [low Q^2]

Combined

Precision: up to 1.5%

[for $Q^2 > 5 \text{ GeV}^2$]

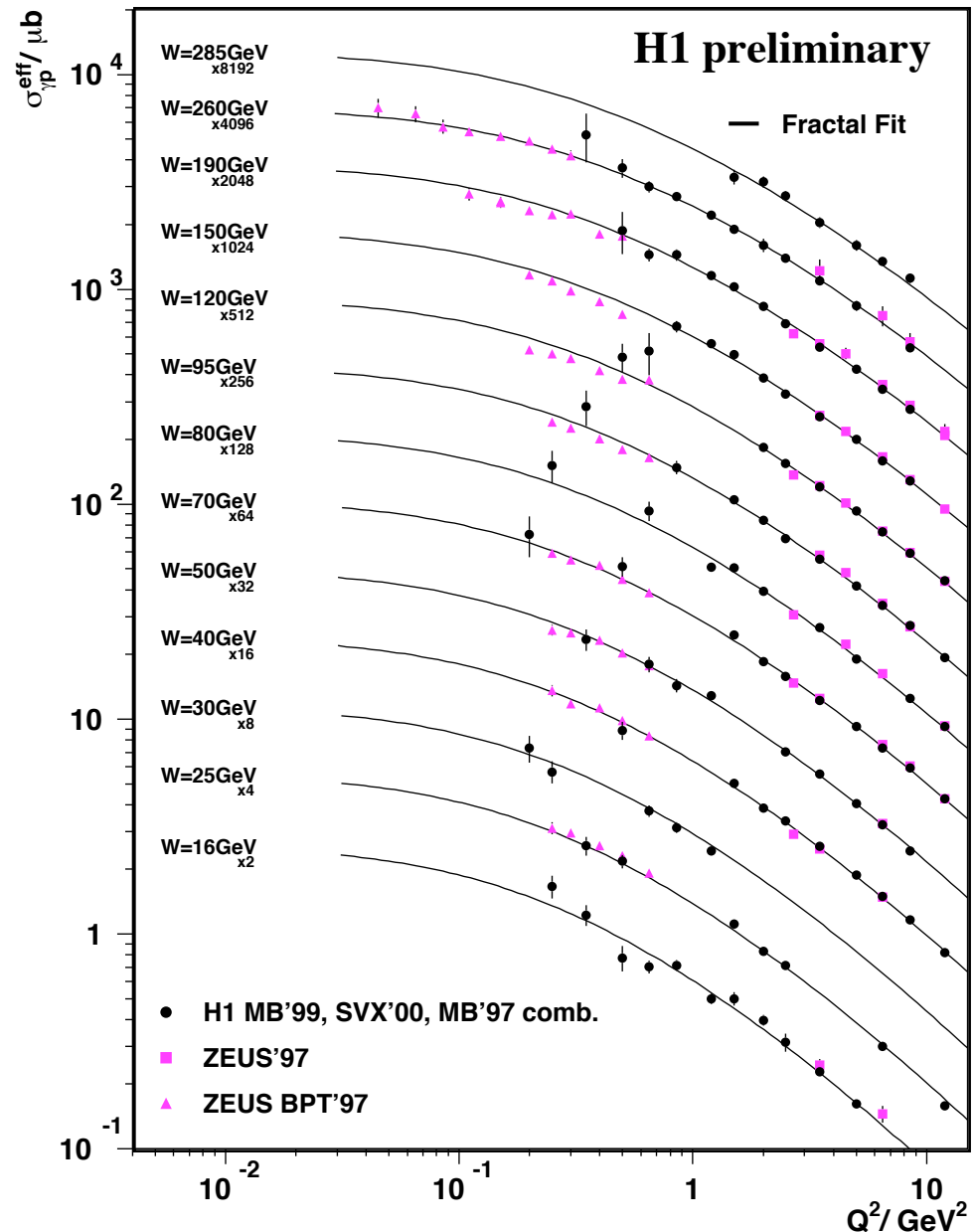


Recent Low Q^2 Results

H1 Data fill gap
in transition region

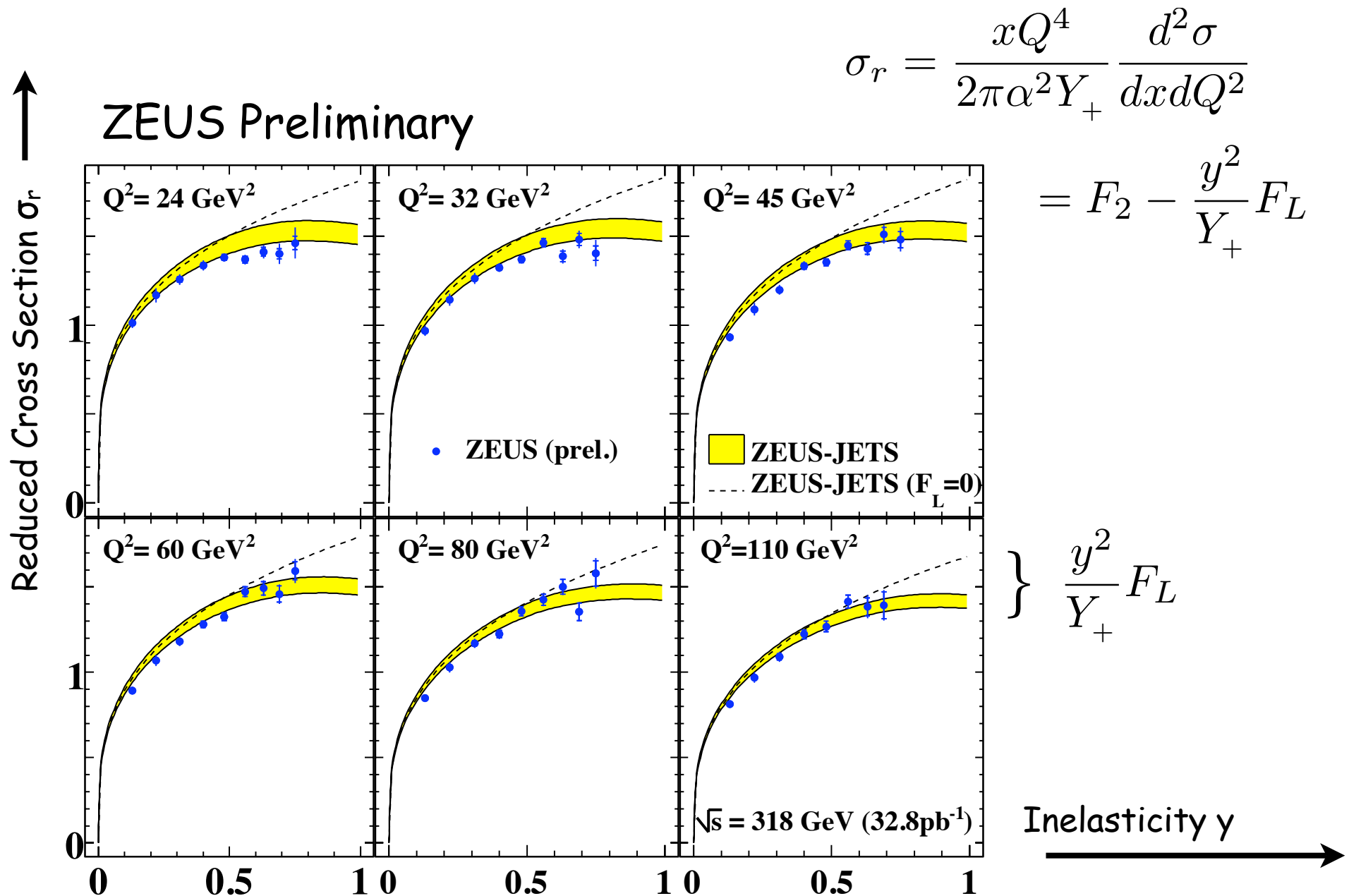
Agreement with ZEUS
in regions of overlap

Comparison to
phenomenological models
[here: fractal fit]

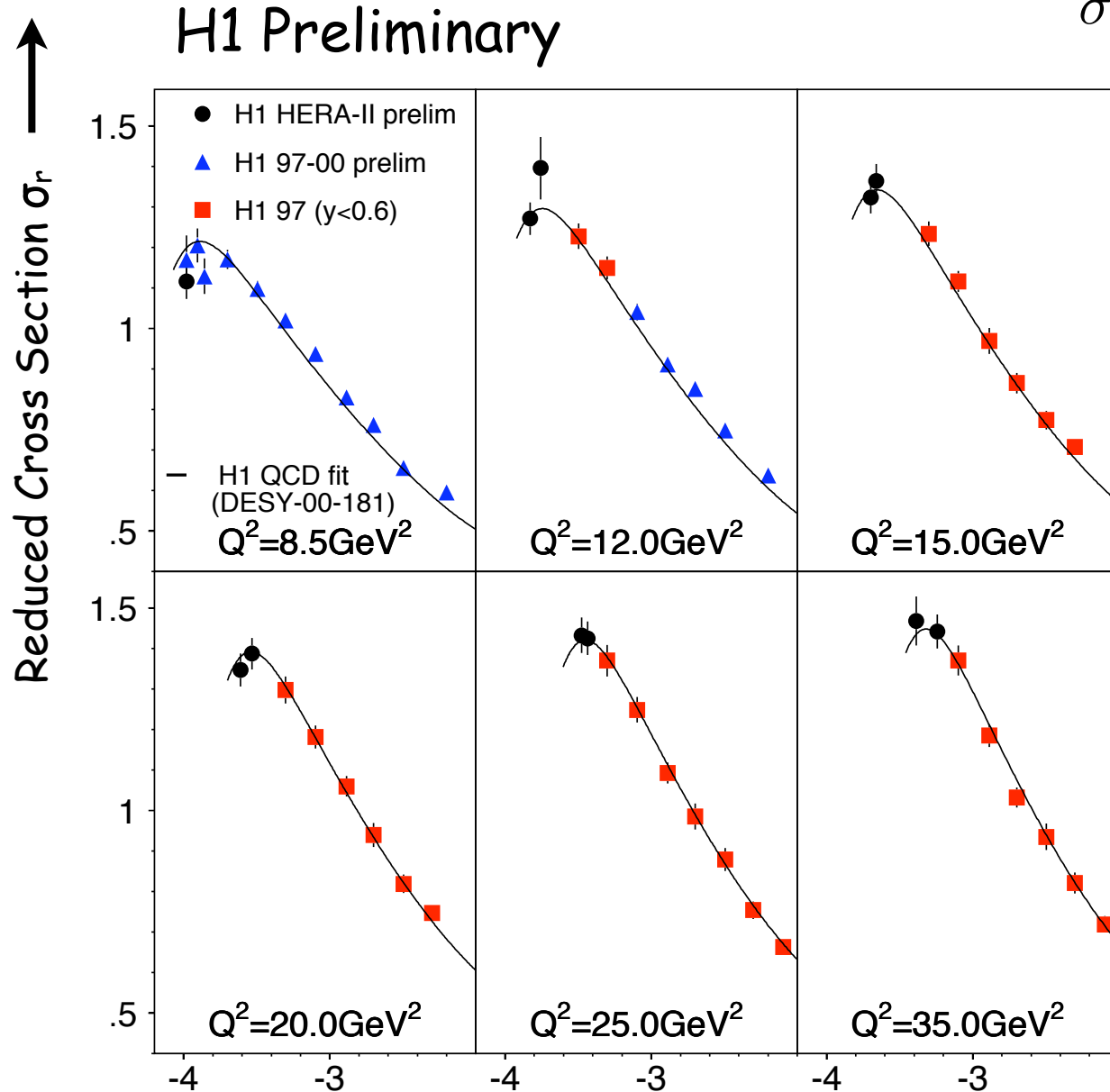


High y & F_L

Recent High γ Measurements



Recent High γ Measurements



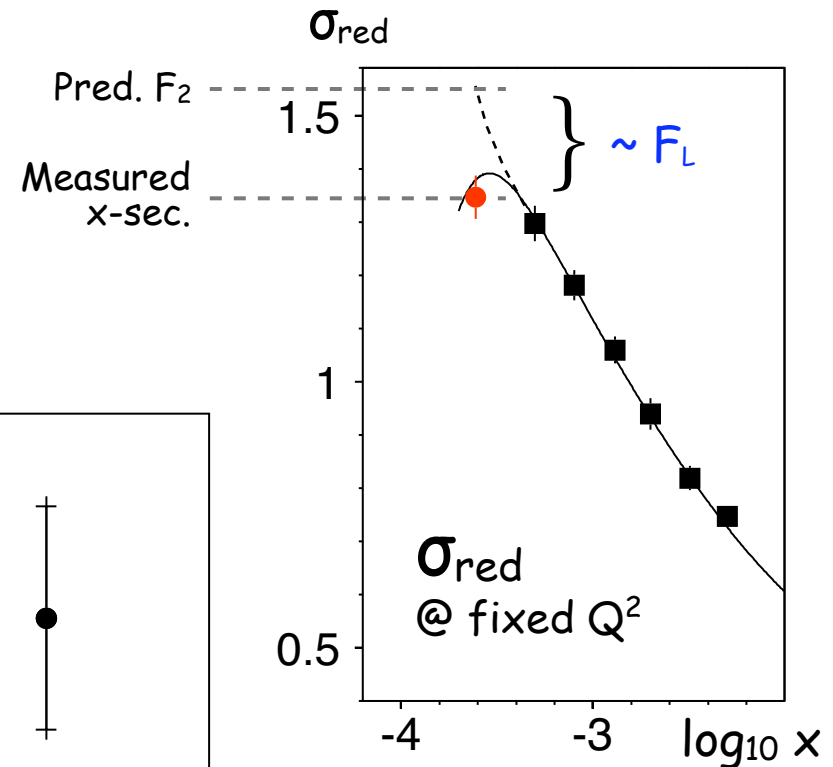
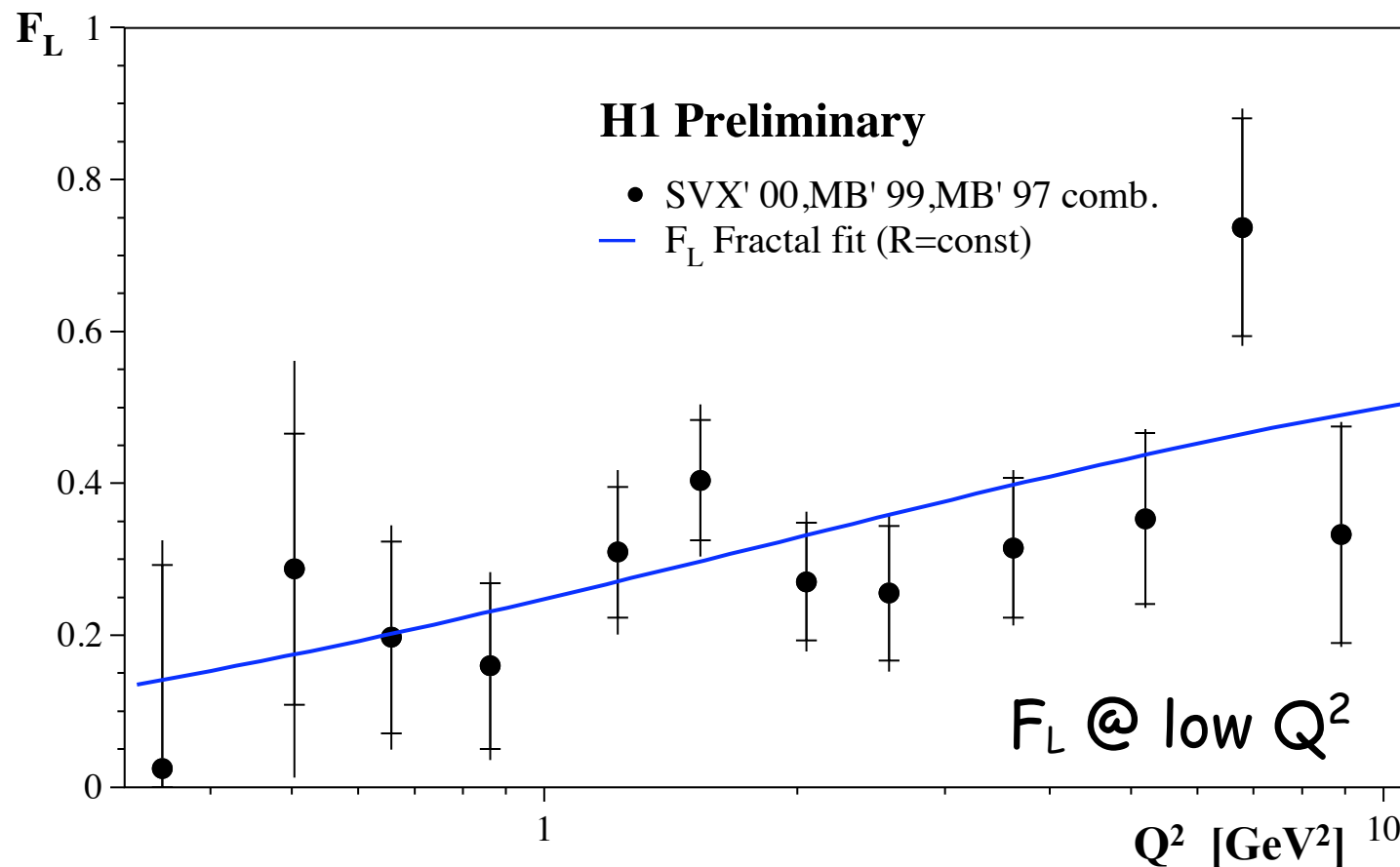
$$\sigma_r = \frac{xQ^4}{2\pi\alpha^2 Y_+} \frac{d^2\sigma}{dx dQ^2}$$

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

F_L : Indirect Determination

Extrapolate F_2 and
determine F_L via: $F_L \sim F_2 - \sigma_r$

[Drawback: Requires assumption on F_2]



Extraction via:

$$\sigma_{\text{fit}} = cx^{-\lambda} - \frac{y^2}{Y_+} F_L$$

[shape methode]

F_L : Direct Measurement

Reduced Cross Section:

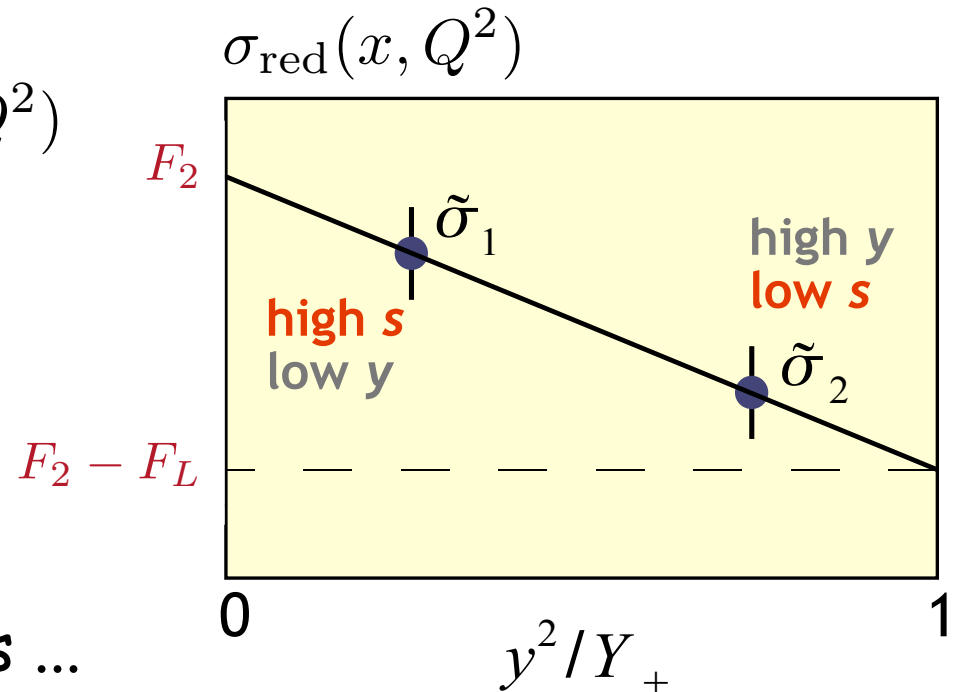
$$\sigma_{\text{red}} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

Cross section measurements
at different y -values ...

i.e. due to

$$Q^2 = sxy$$

... at different beam energies ...

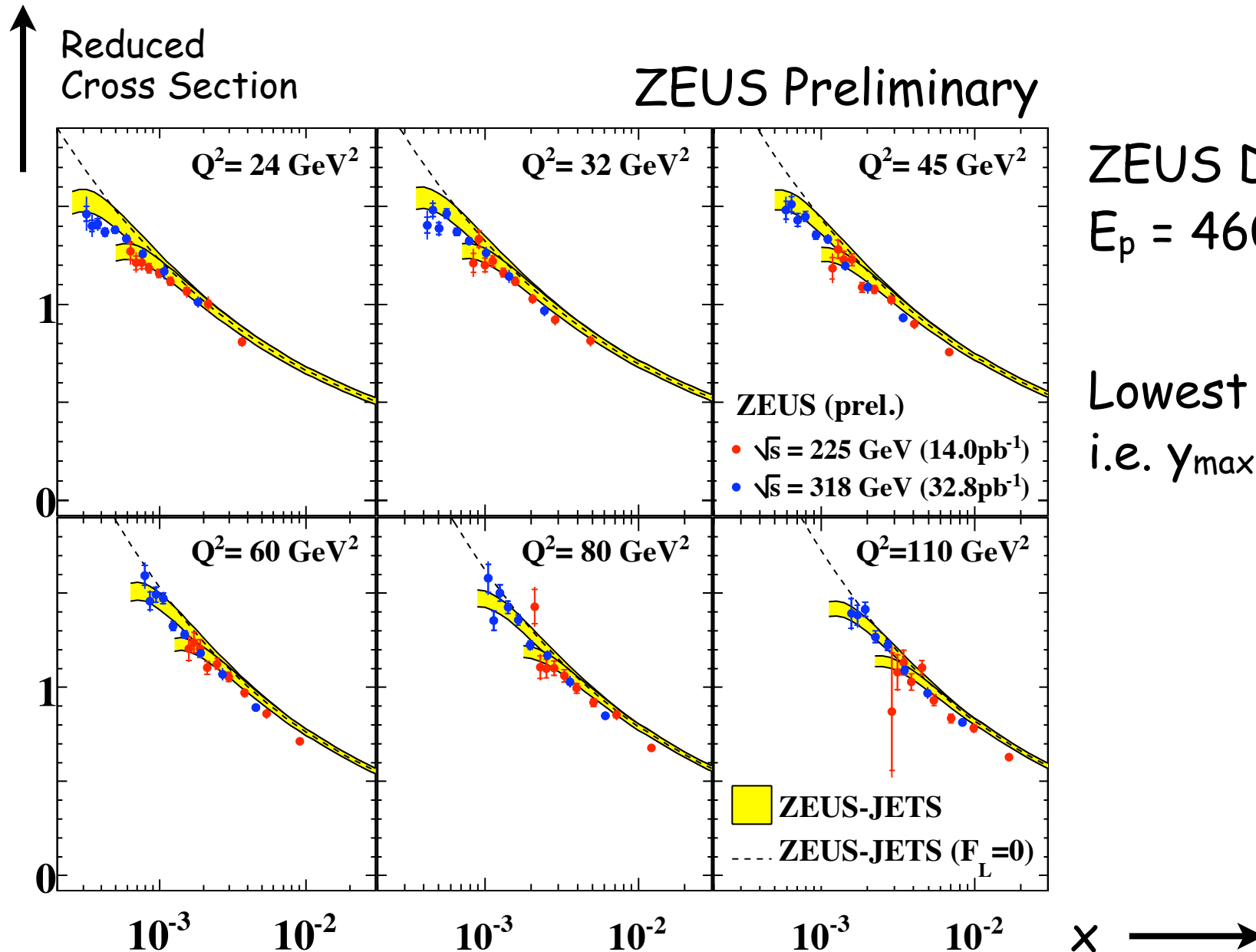


$$F_L(x, Q^2) = \frac{\sigma_{\text{red}}(x, Q^2, y_1) - \sigma_{\text{red}}(x, Q^2, y_2)}{Y_2^2/Y_{2,+} - Y_1^2/Y_{1,+}}$$

→ End of HERA II: Low energy runs @ 460 & 575 GeV

Reduced Cross Section

ZEUS

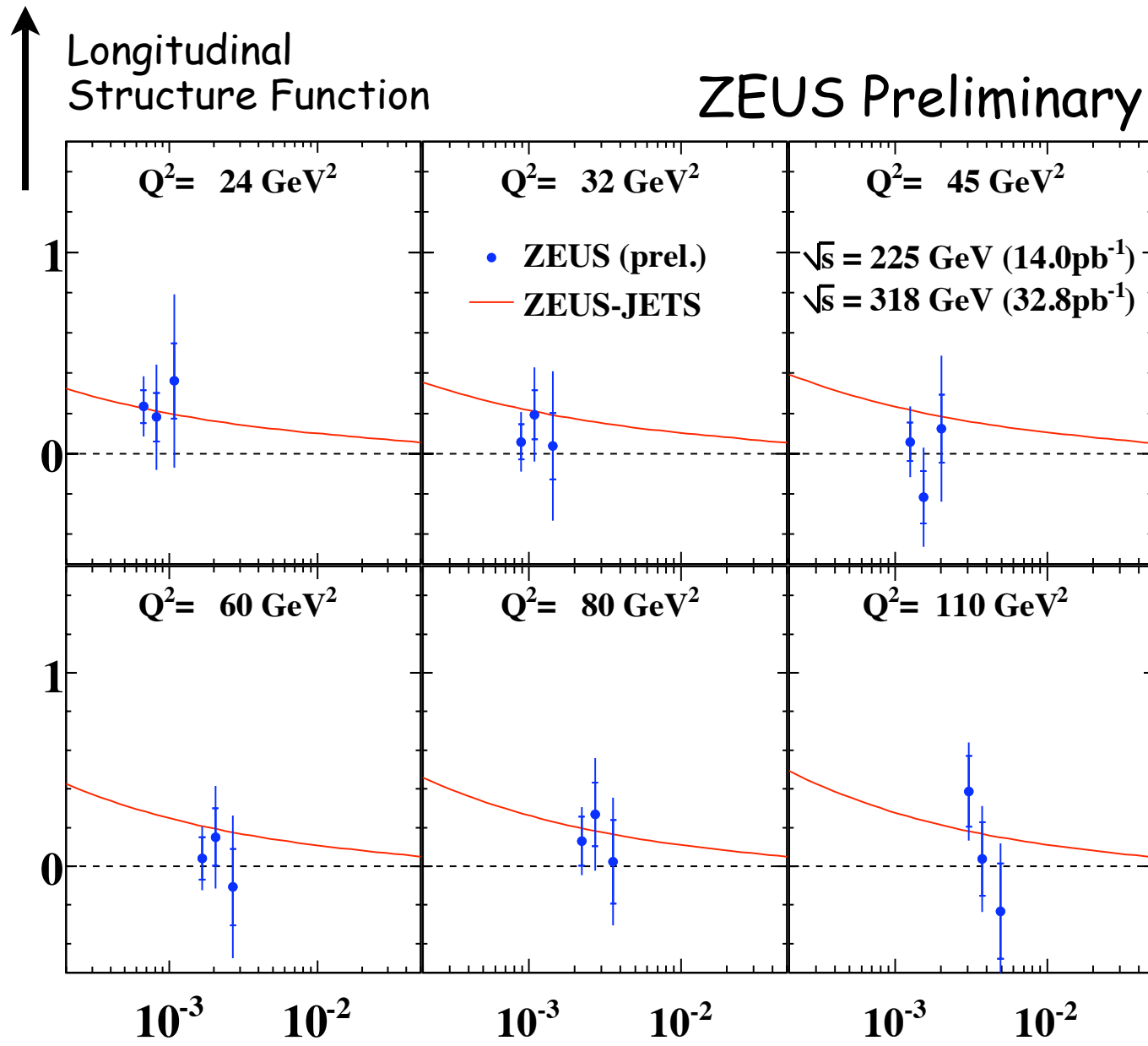


ZEUS Data @
 $E_p = 460 \text{ \& } 920 \text{ GeV}$

Lowest $E_e = 6 \text{ GeV}$
i.e. $y_{\text{max}} \sim 0.8$

Longitudinal Structure Function

ZEUS



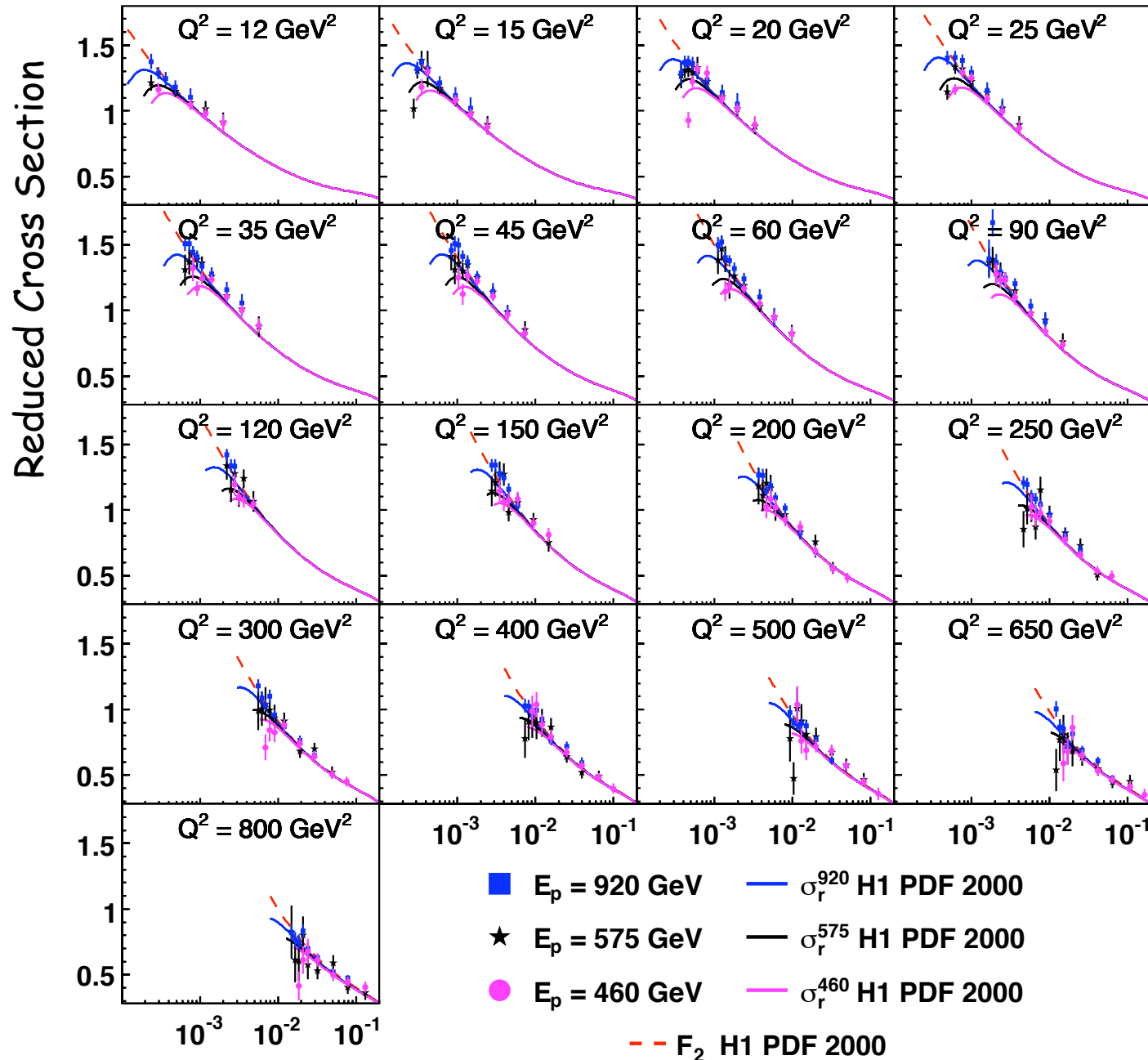
ZEUS Data @
 $E_p = 460 \text{ \& } 920 \text{ GeV}$

Lowest $E_e = 6 \text{ GeV}$
i.e. $y_{\text{max}} \sim 0.8$

Future
Improvements:
extend to higher y
incl. $E_p = 575 \text{ GeV}$ data

Reduced Cross Section

H1



H1 Preliminary

$E_p = 460 \text{ GeV}$ &
 $= 575 \text{ GeV}$ &
 $= 920 \text{ GeV}$

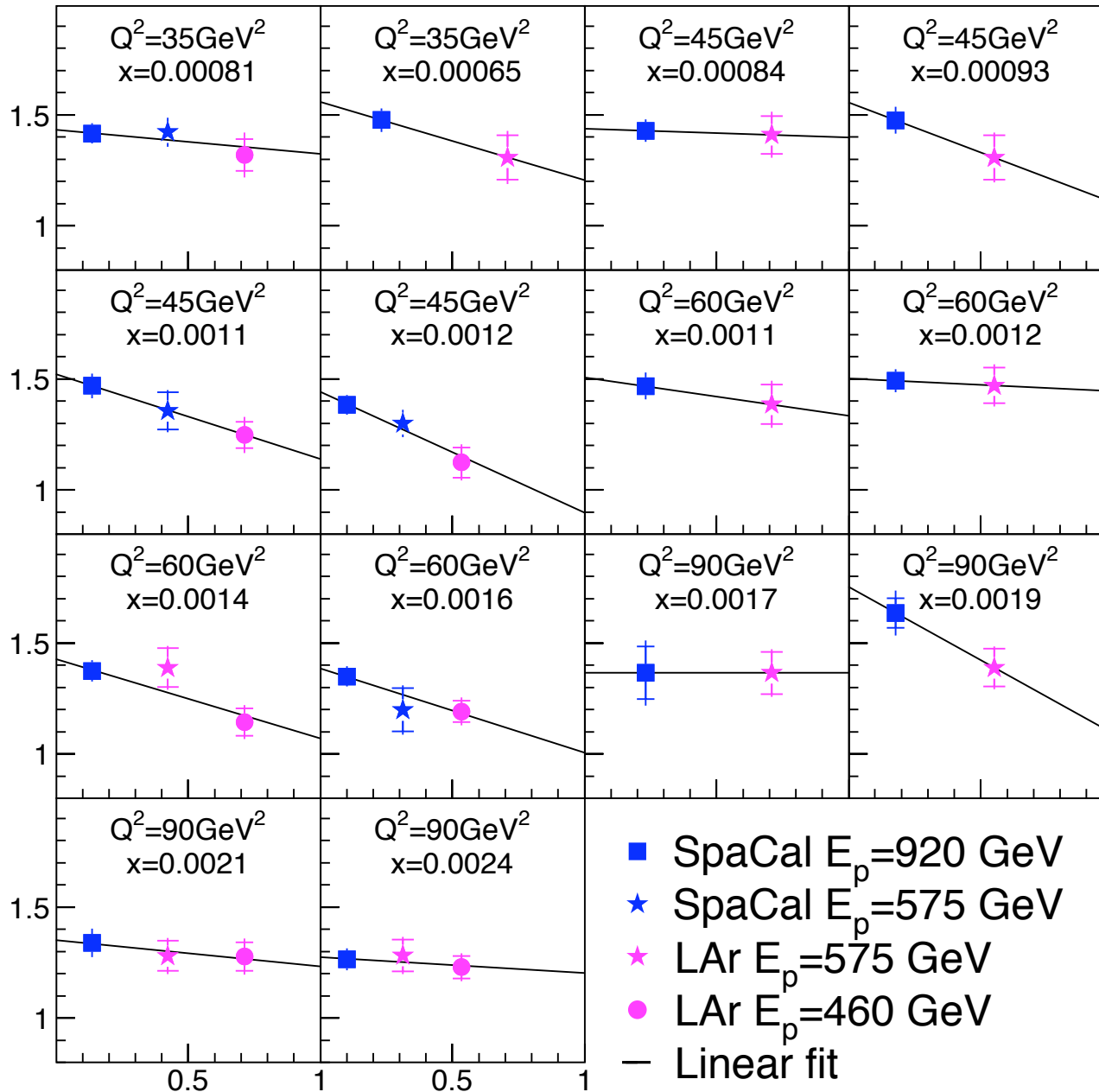
Combined
LAr & SpaCal

$y_{\text{max}} \sim 0.9$
 [@ 450 & 575 GeV]

Reduced Cross Section

H1

Reduced Cross Section



H1 Preliminary

$E_p = 460$ GeV &
 $= 575$ GeV &
 $= 920$ GeV

Linear Fit

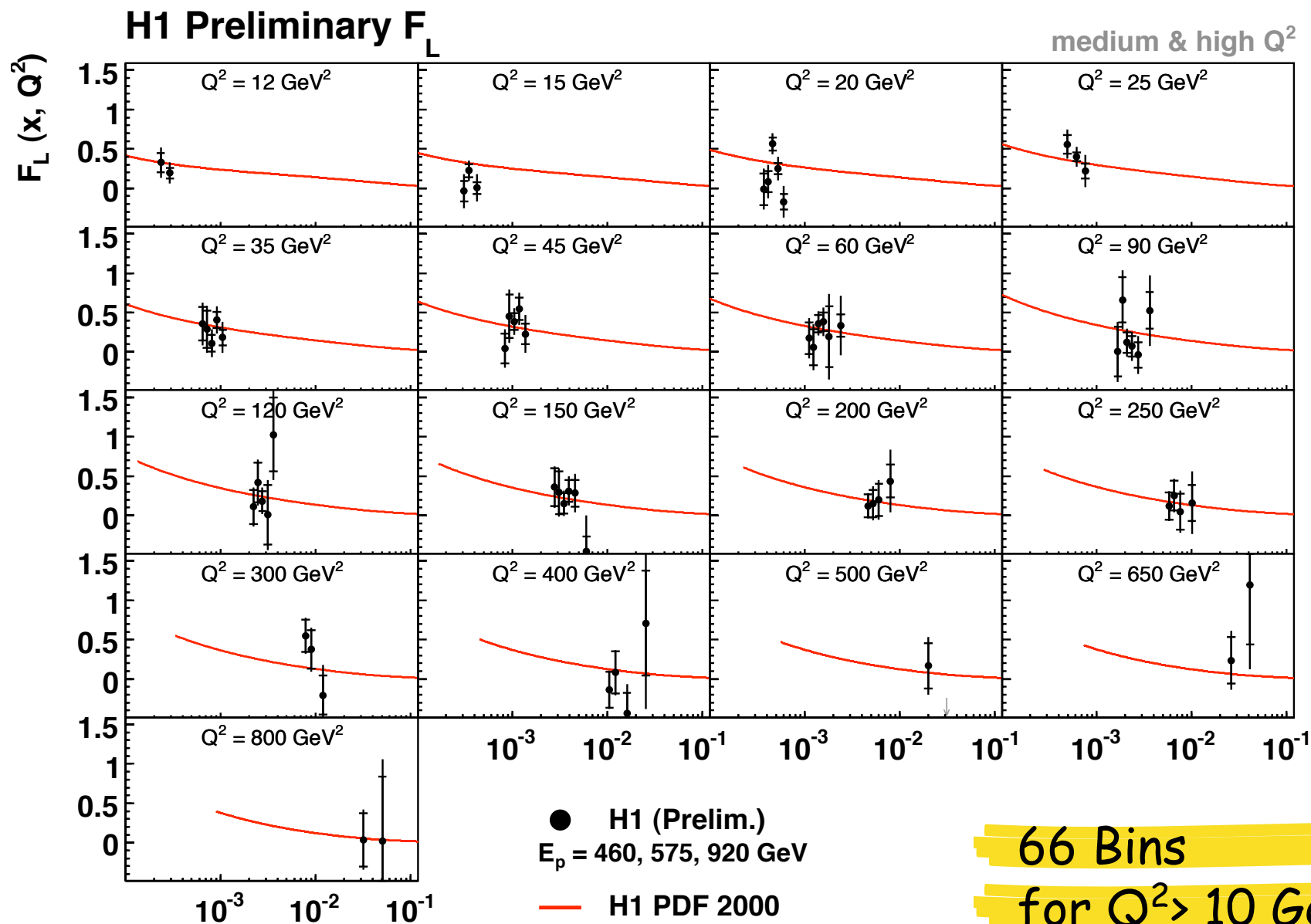
F_2 : from intercept
 F_L : from slope

y^2/Y_+



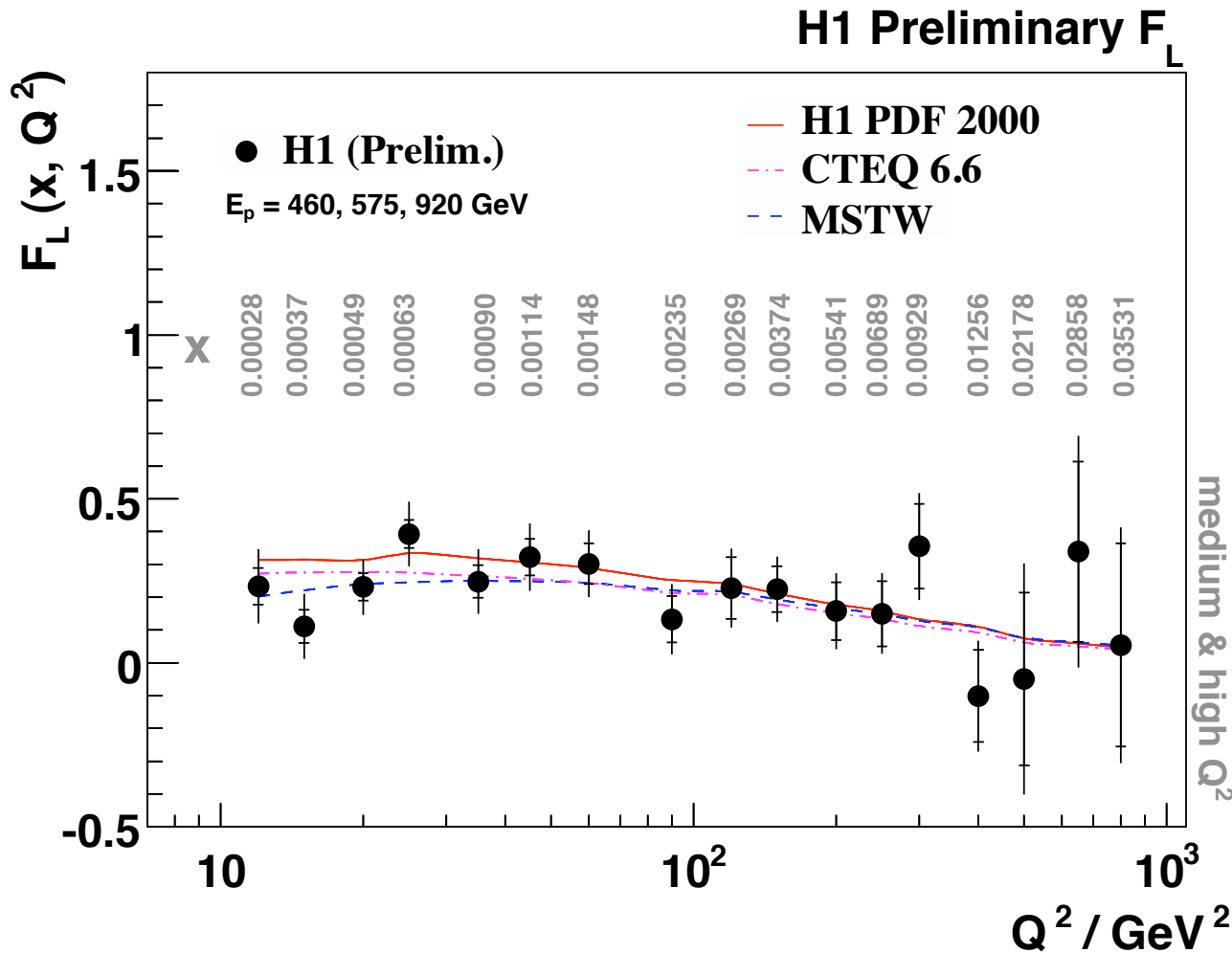
Longitudinal Structure Function

H1



x-Averaged F_L

H1



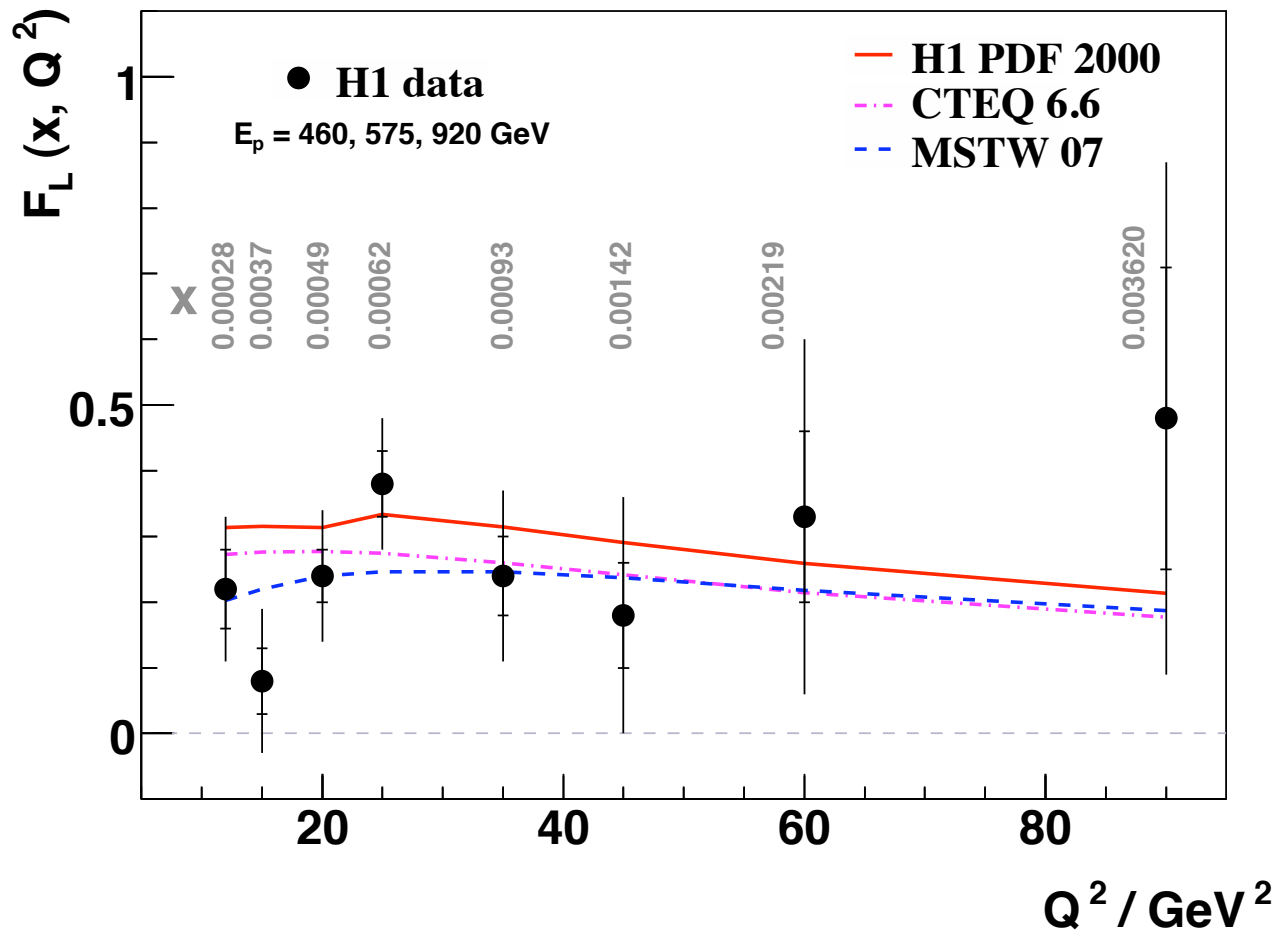
Consistent
with QCD

Extension to
lower Q^2 planned

Medium Q^2 data
published

x-Averaged F_L

H1



Consistent
with QCD

Extension to
lower Q^2 planned

Medium Q^2 data
published

High Q^2

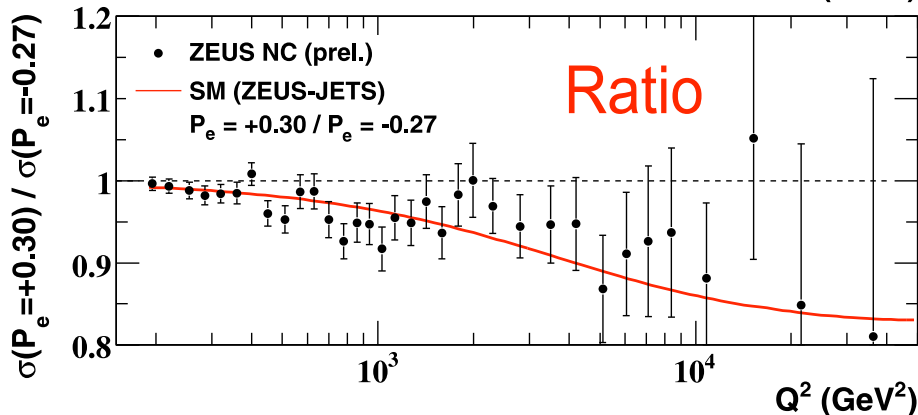
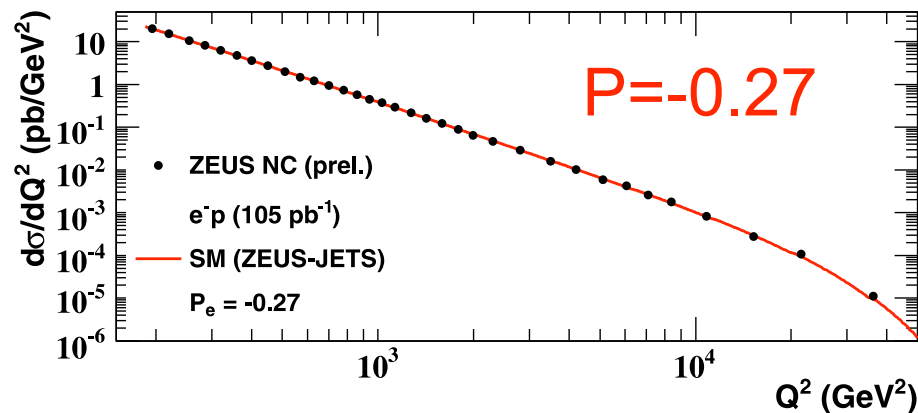
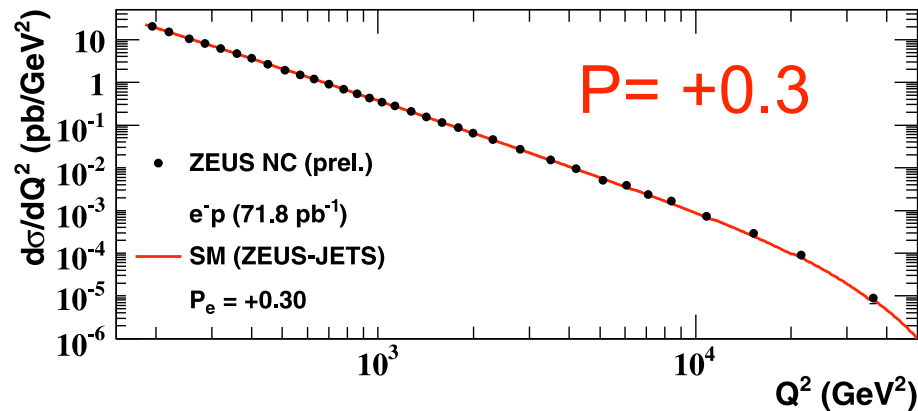
Polarized NC and CC Cross Sections

Electroweak & QCD Fits

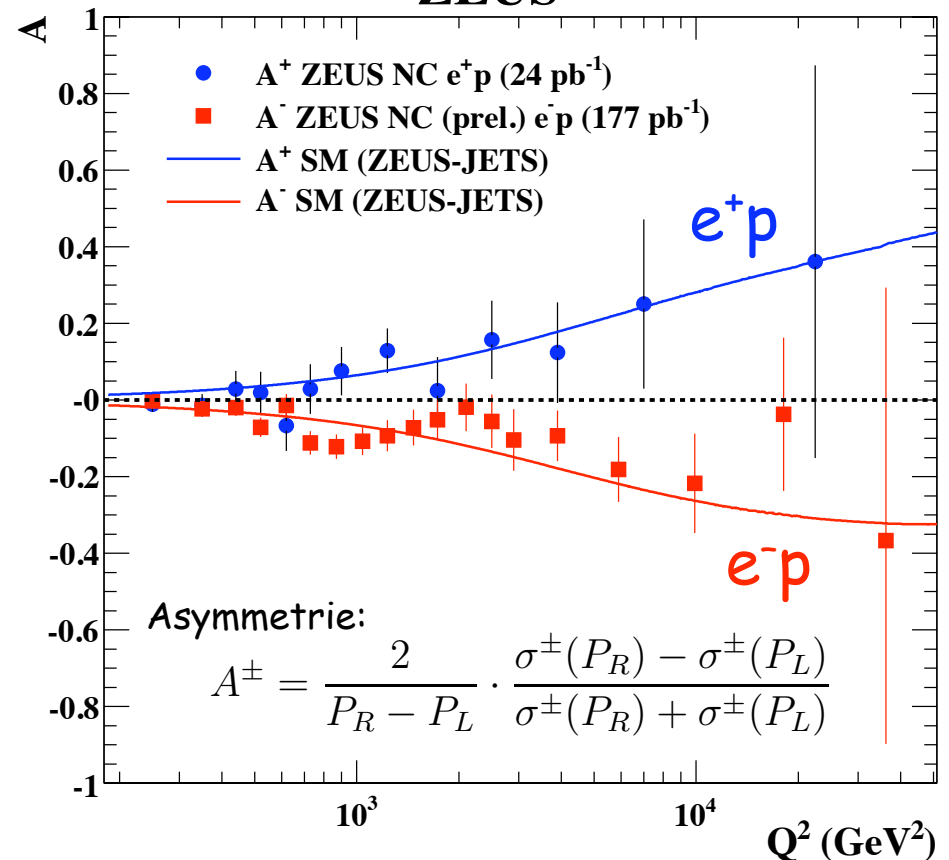
Combined HERA I Data

Polarized NC Cross Section

ZEUS

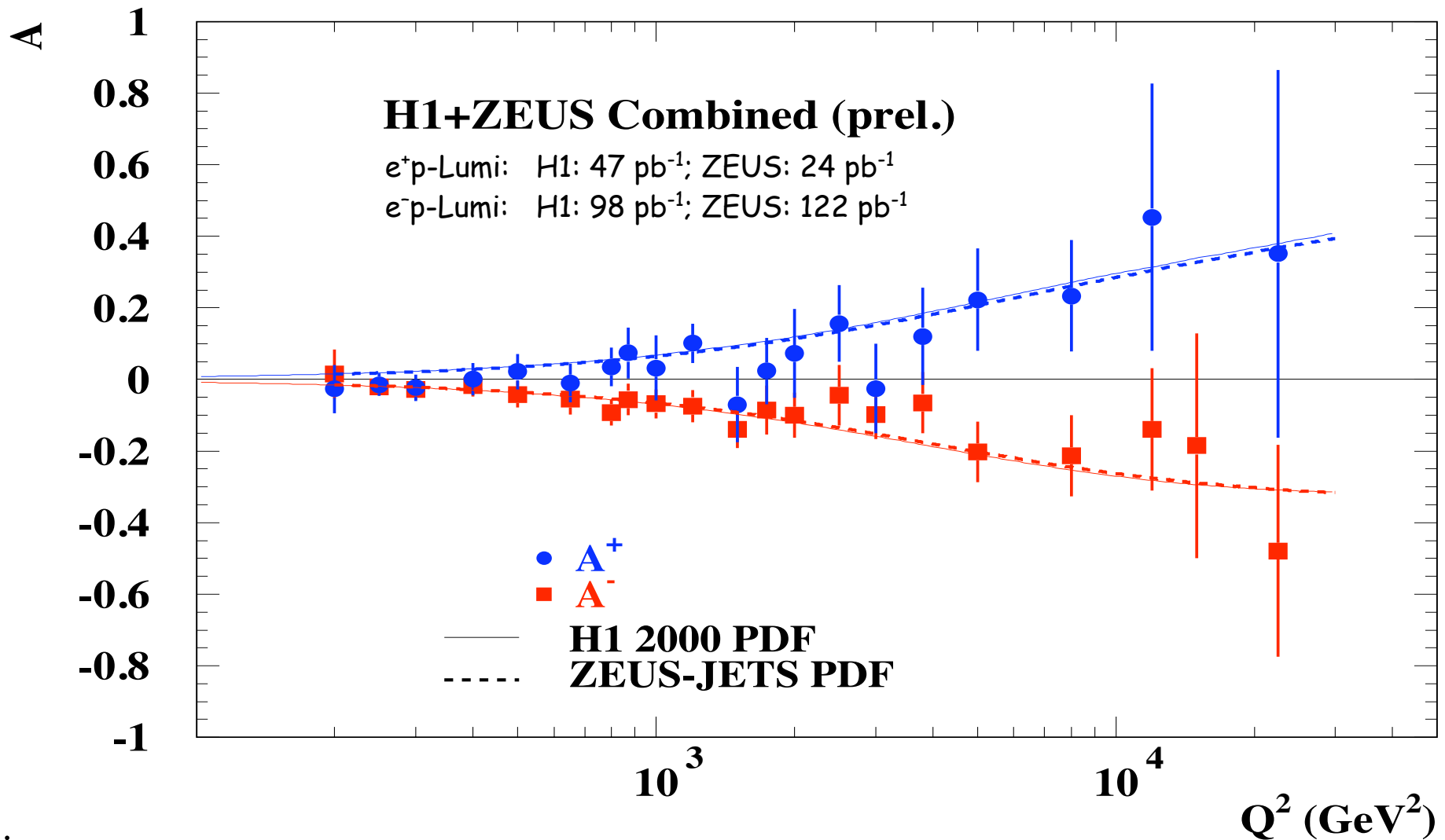


ZEUS



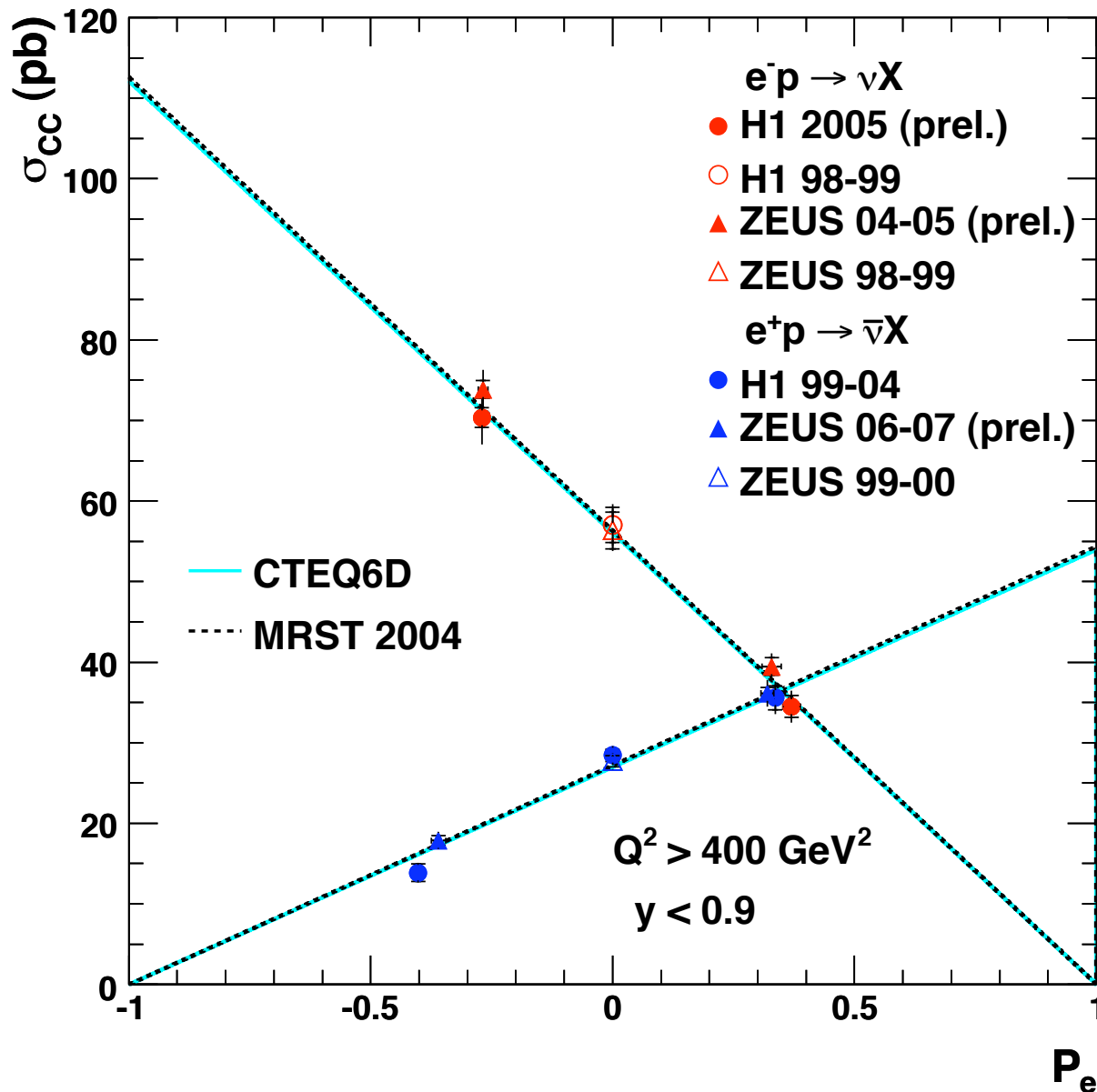
Parity violation
in NC at high Q^2

Polarized NC Cross Section



Polarized CC Cross Section

Charged Current $e^\pm p$ Scattering



$$\sigma_{CC}^{e^\pm p}(P_e) = \dots$$

$$= (1 \pm P_e) \sigma_{CC}^{e^\pm p}(P_e = 0)$$

Extrapolation:

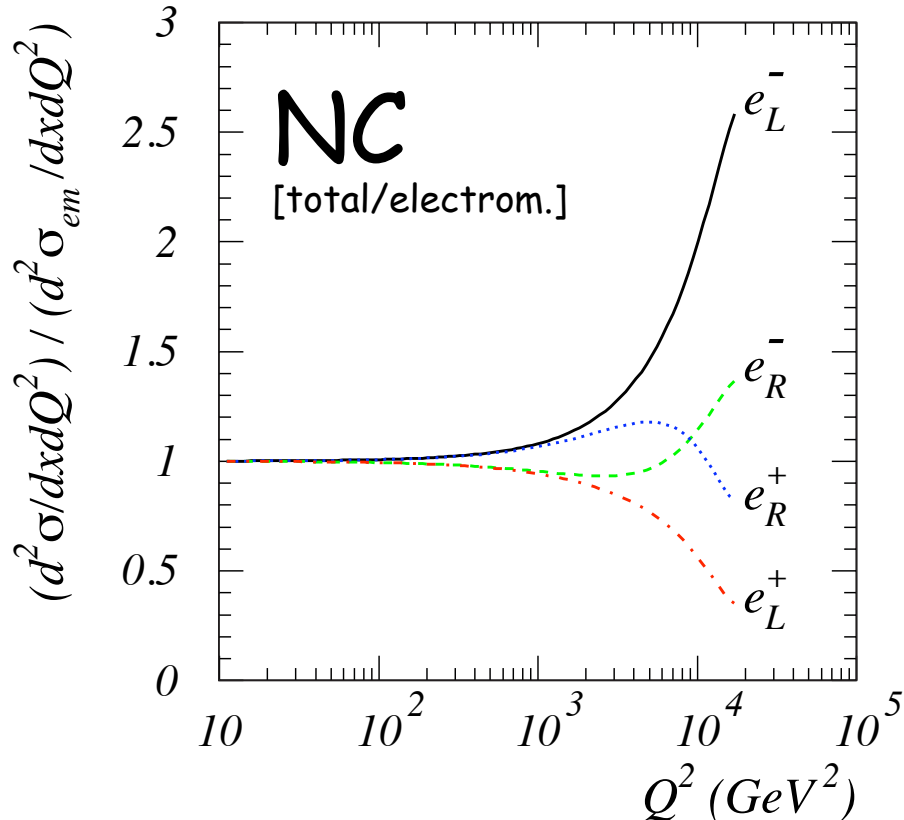
➡ No right-handed CC

H1: $\sigma_{CC,P=1} = -0.9 \pm 4.5 \text{ pb}$

ZEUS: $\sigma_{CC,P=1} = +0.8 \pm 5.9 \text{ pb}$

[Preliminary]

Electroweak & QCD Fit



Neutral current:

$$\begin{aligned}\sigma^\pm &= \sigma_{\text{NC},0}^\pm + P_e \sigma_{\text{NC},P}^\pm \\ &= f(q, \bar{q}, \text{EW couplings})\end{aligned}$$

Charged current:

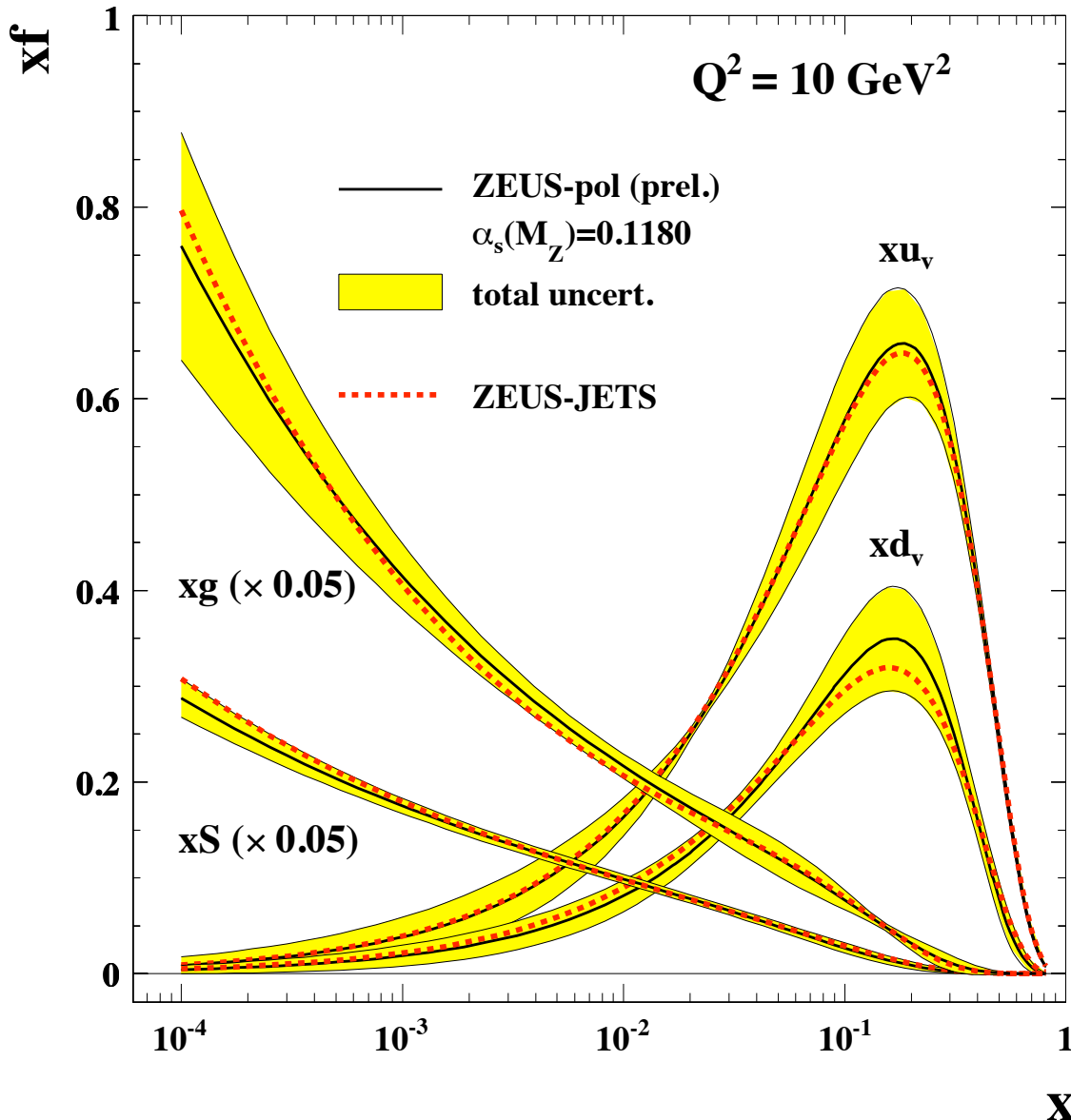
$$\sigma^\pm = (1 \pm P_e) \sigma_{\text{CC},0}^\pm$$

[e^+p : sensitive to d-quarks]

[e^-p : sensitive to u-quarks]

Use polarized NC and CC data to simultaneously determine PDFs and quark couplings v_u, v_d, a_u, a_d

Electroweak & QCD Fit



ZEUS: new PDFs
including polarized data

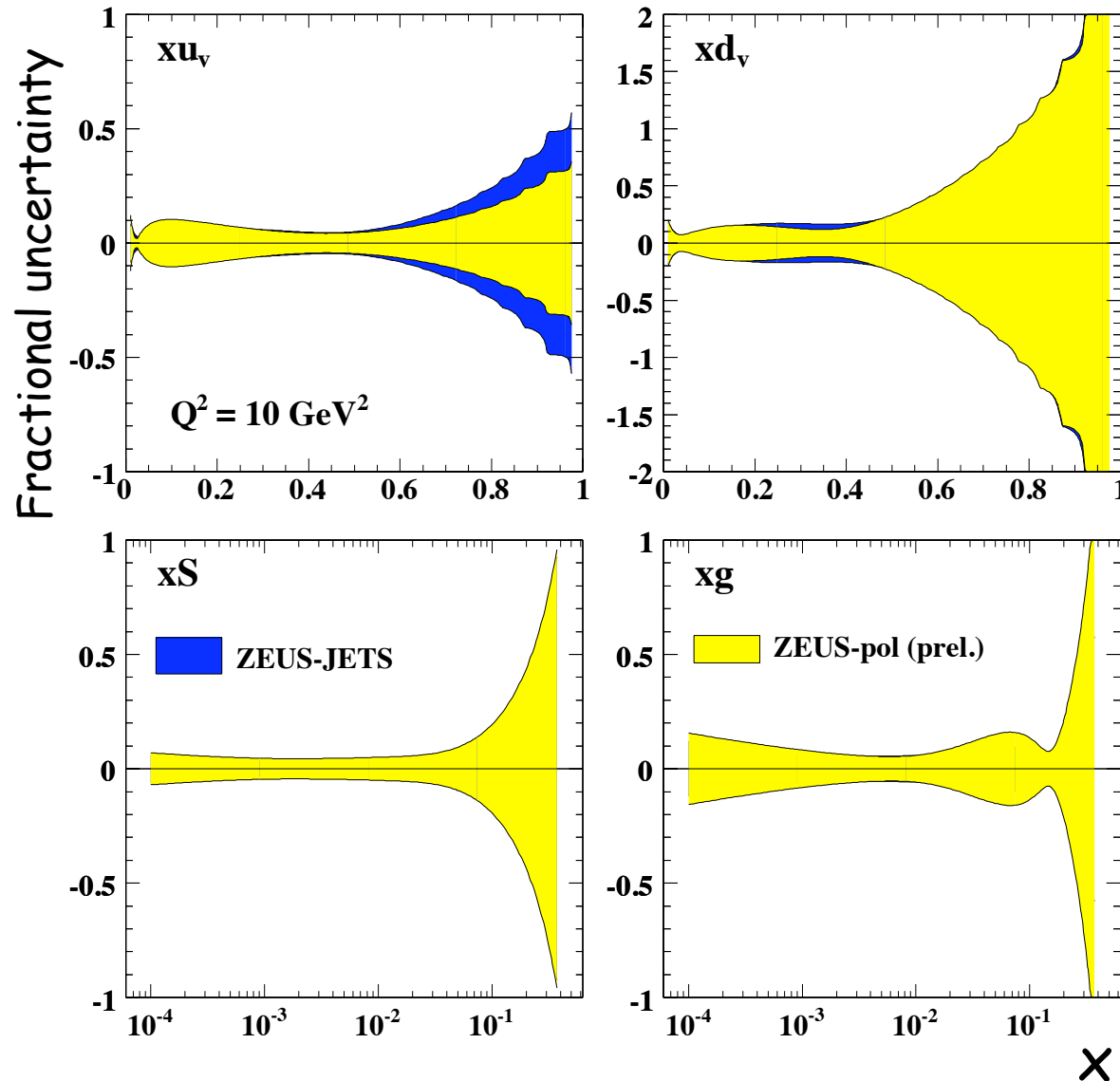
ZEUS-pol: new fit
ZEUS-jets: old fit

u_v uncertainty reduced
at high x and high Q^2

improvement up to
large Q^2 [e.g. $Q^2 = 10000 \text{ GeV}^2$]

Electroweak & QCD Fit

ZEUS



ZEUS: new PDFs
including polarized data

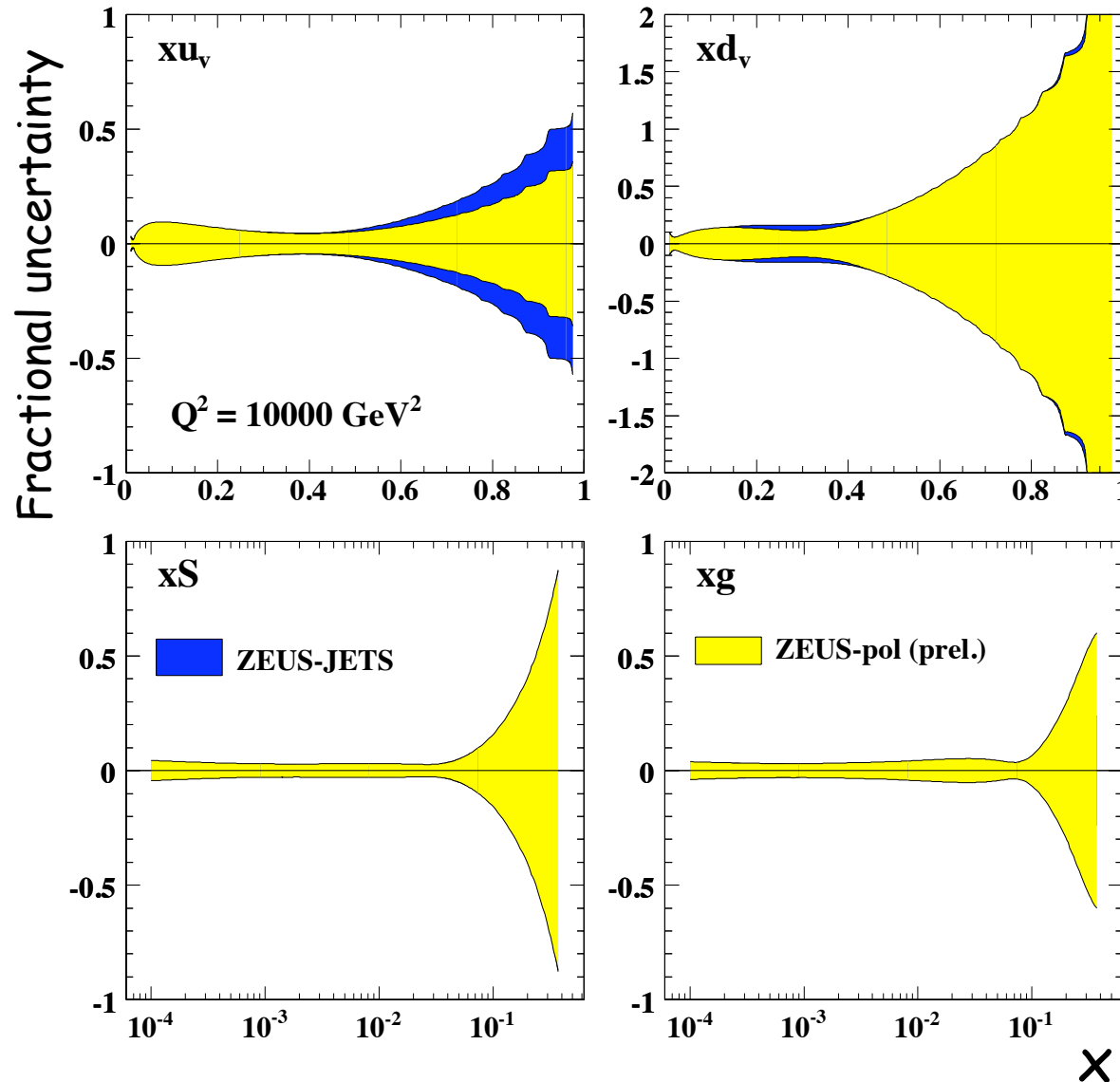
ZEUS-pol: new fit
ZEUS-jets: old fit

u_v uncertainty reduced
at high x and high Q^2

improvement up to
large Q^2 [e.g. $Q^2 = 10000 \text{ GeV}^2$]

Electroweak & QCD Fit

ZEUS



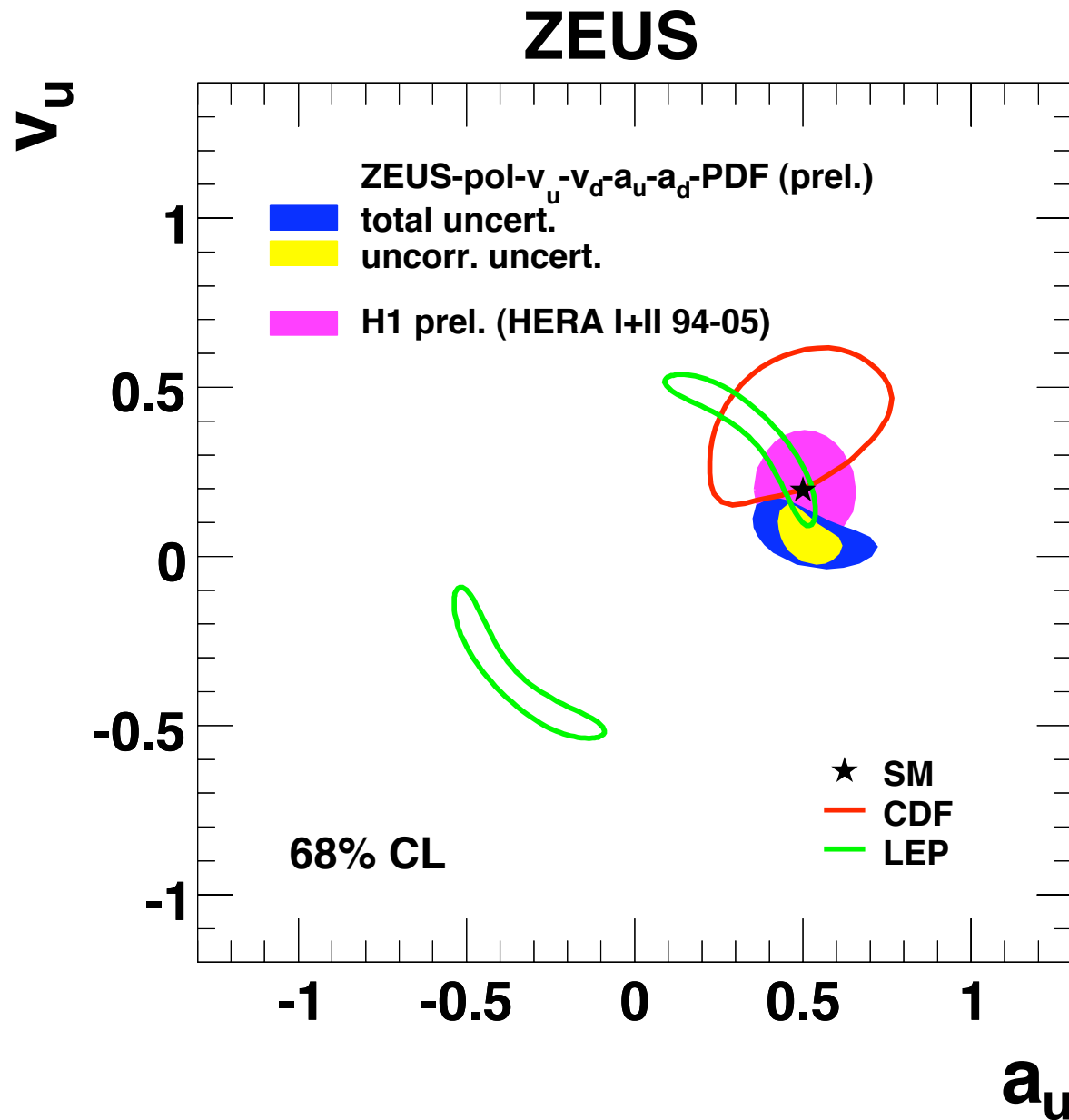
ZEUS: new PDFs
including polarized data

ZEUS-pol: new fit
ZEUS-jets: old fit

u_v uncertainty reduced
at high x and high Q^2

improvement up to
large Q^2 [e.g. $Q^2 = 10000 \text{ GeV}^2$]

Electroweak & QCD Fit



Electroweak
couplings v_u , a_u

Rem.: larger uncertainties for v_d , a_d
due to lower sensitivity of NC to d-quarks

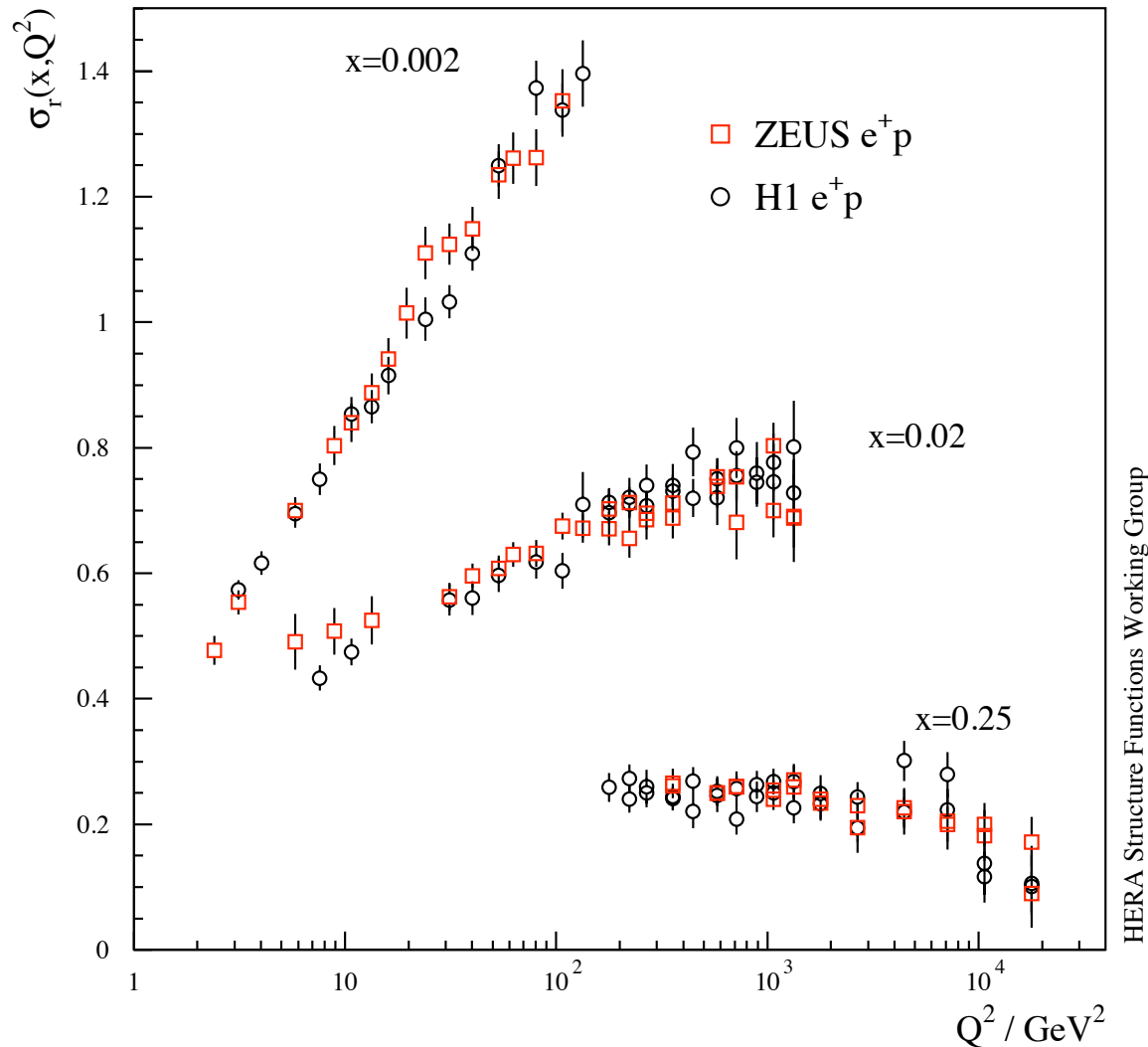
Limits competitive

HERA results
resolve LEP ambiguity

Combining Data

HERA I Combined Cross Section

HERA I e^+p Neutral Current Scattering - H1 and ZEUS



Based on
published HERA I Data

H1 NC min. bias

H1 NC low Q^2

H1 NC 94-97, 98-00

H1 CC 94-97, 98-00

ZEUS NC 96-97, 98-00

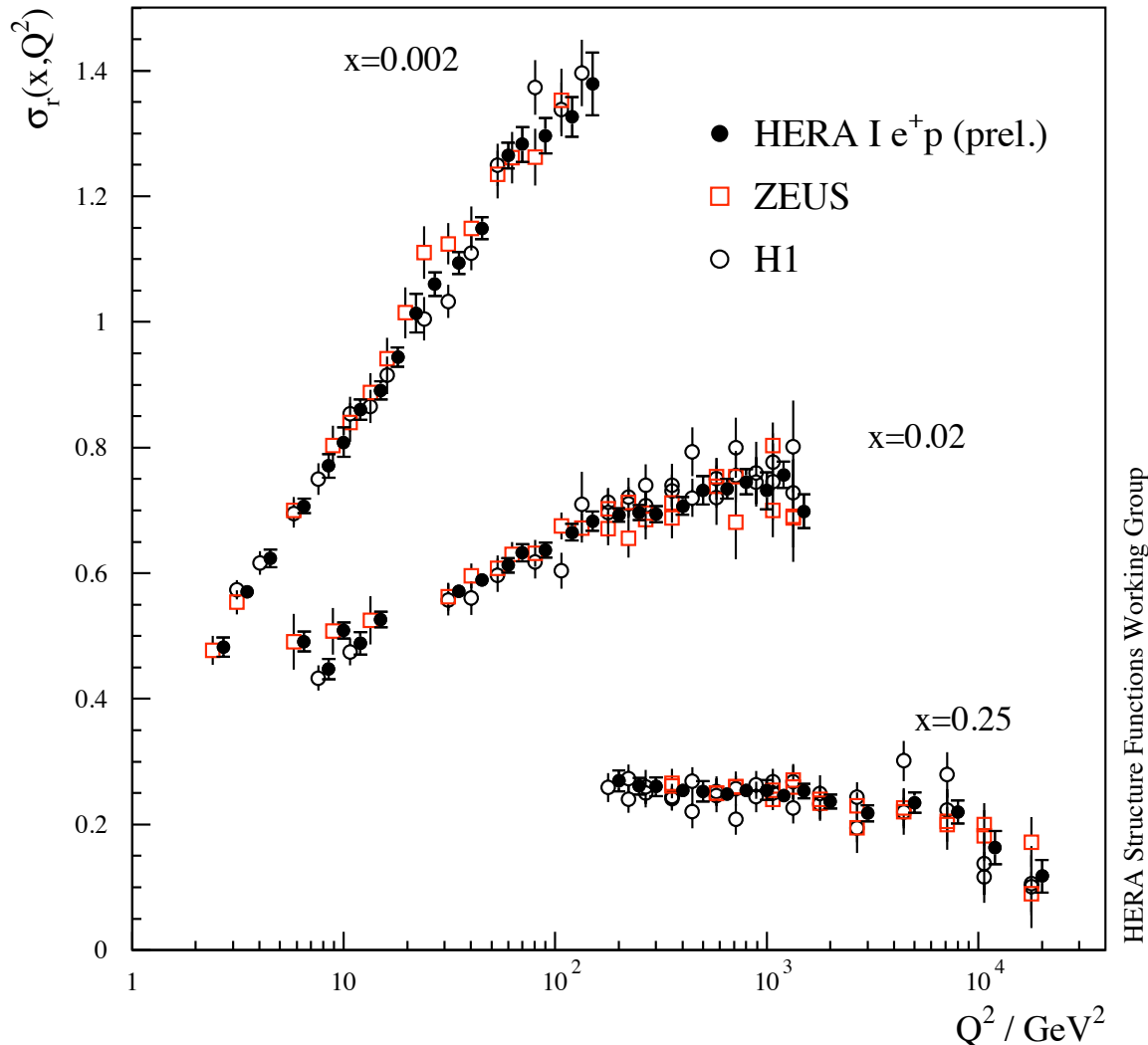
ZEUS CC 96-97, 98-00

e^+p & e^-p data

@ 820 & 920 GeV

HERA I Combined Cross Section

HERA I e^+p Neutral Current Scattering - H1 and ZEUS



Based on
published HERA I Data

Method:

Move all data
to common x - Q^2 grid

Correct for different
beam energies ...

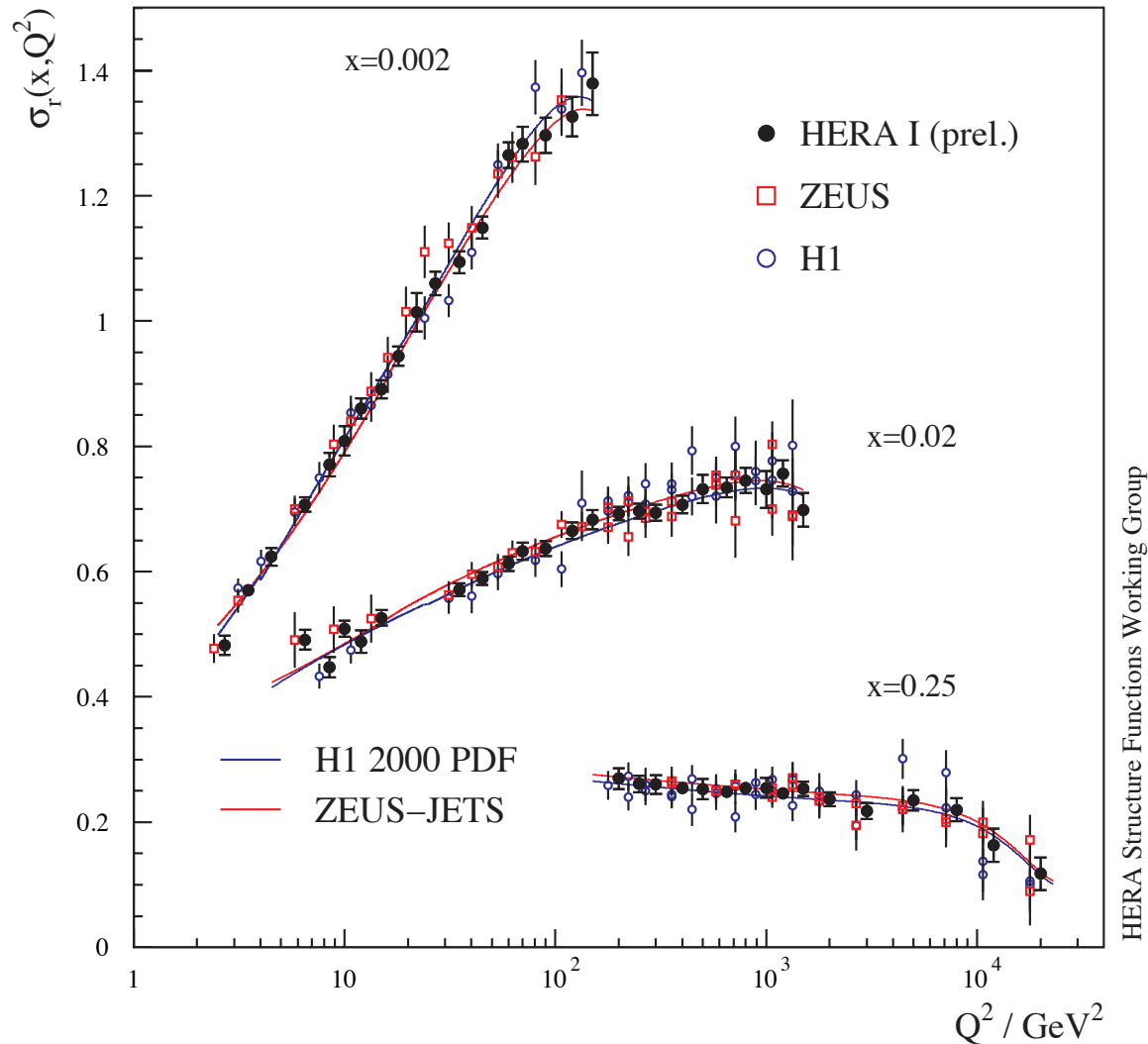
Calculate average
values using χ^2 -Method

Key assumption:

H1 & ZEUS measure
same cross section

HERA I Combined Cross Section

HERA I e^+p Neutral Current Scattering – H1 and ZEUS

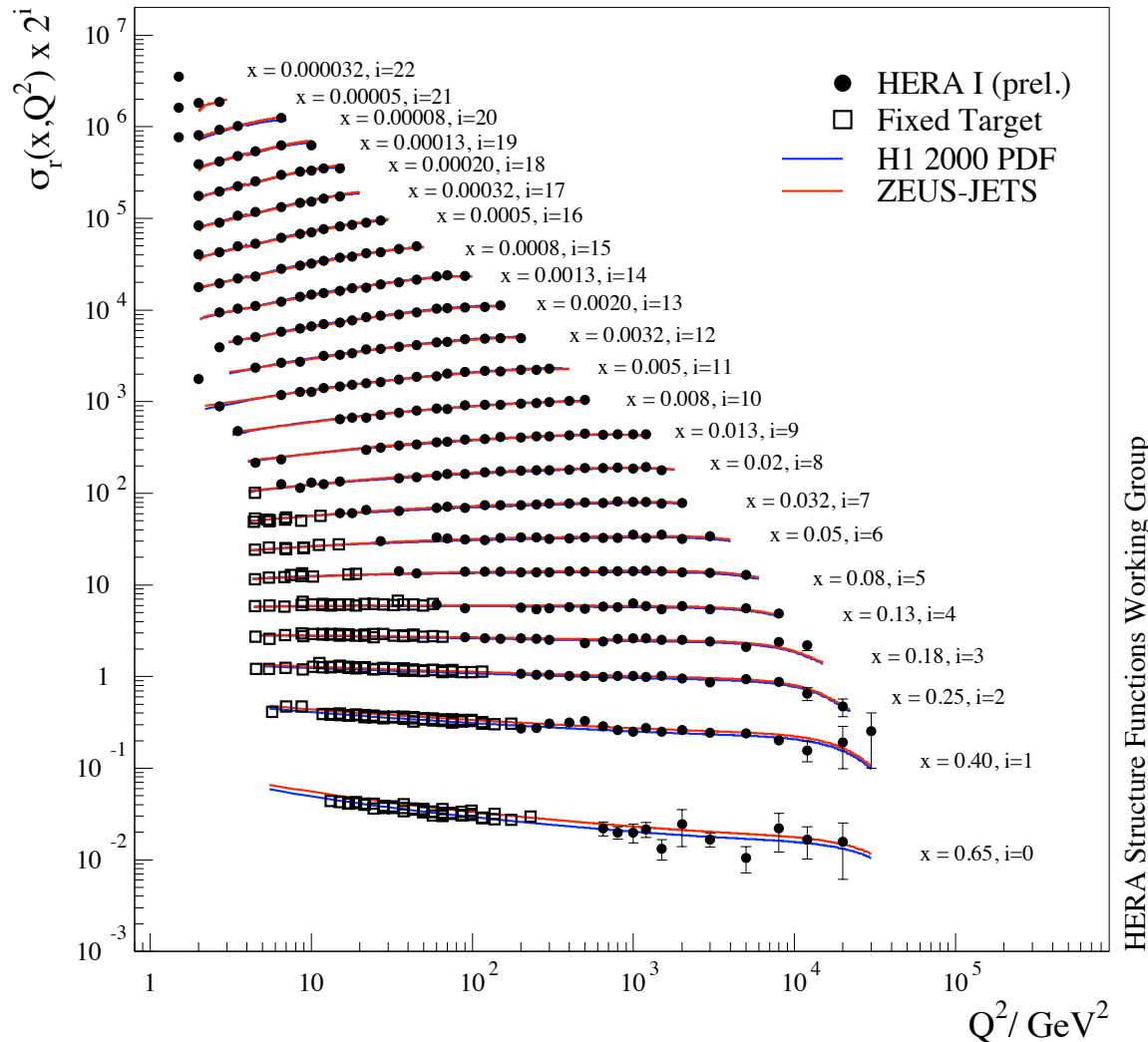


Uncertainties
greatly reduced
[Statistical & systematic]

Good agreement with
H1 and ZEUS PDF Fits

HERA I Combined Cross Section

HERA I e^+p Neutral Current Scattering - H1 and ZEUS

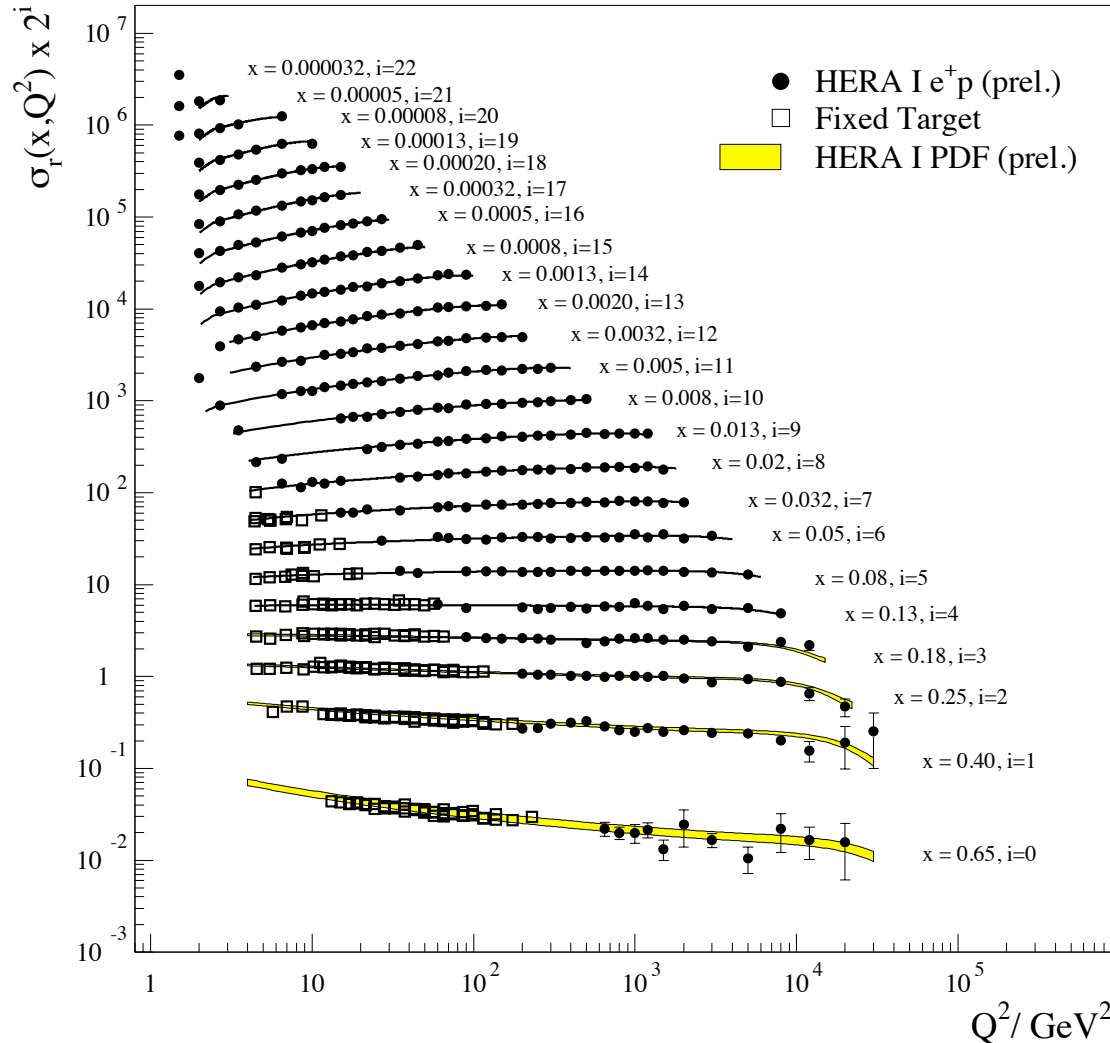


Uncertainties
 greatly reduced
 [Statistical & systematic]

Good agreement with
 H1 and ZEUS PDF Fits

HERA I Combined PDF Fit

H1 and ZEUS Combined PDF Fit

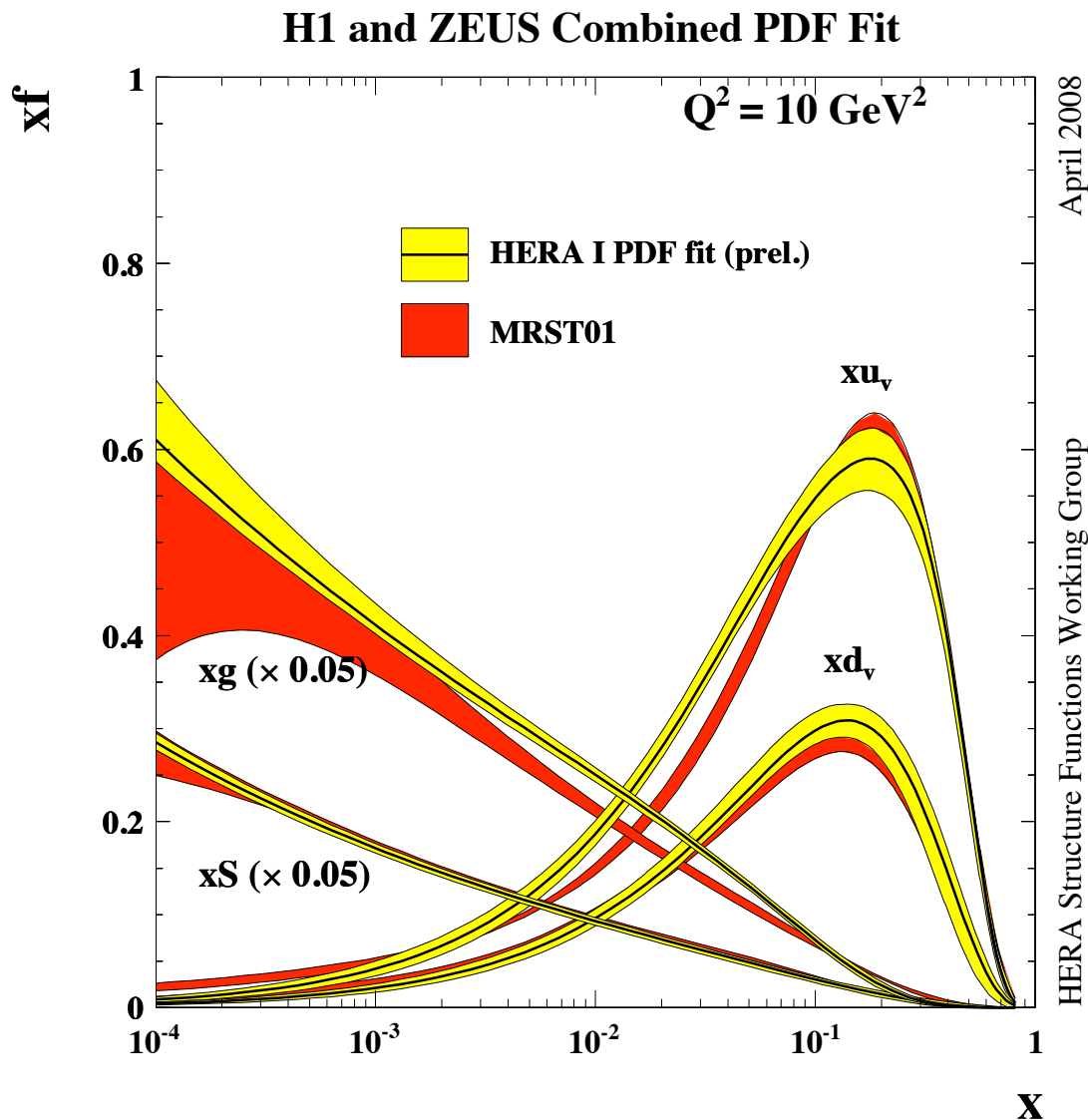


New PDFs
with reduced errors

Fits performed at NLO
[using DGLAP & ZMVFNS]

- $Q^2_{\text{min}} = 3.5 \text{ GeV}^2$
- $\chi^2/\text{ndf} = 476.7/562$

HERA I Combined PDF Fit



New PDFs
with reduced errors

Fits performed at NLO
[using DGLAP & ZMVFNS]

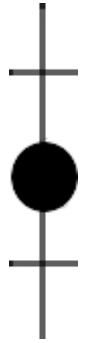
- $Q_{\min}^2 = 3.5 \text{ GeV}^2$
- $\chi^2/\text{ndf} = 476.7/562$

Summary

- 1 **Low Q^2 :** shifted vertex and min. bias data; gap in transition region filled.
- 2 **High y :** Direct & indirect F_L determination; sensitivity to gluon density.
- 3 **High Q^2 :** New polarized cross sections; combined EW & QCD Fits
- 4 **Data combination:** H1 & ZEUS NC/CC data; reduced uncertainties; combined PDF fits.

Backup Slides

H1 Data Combination



combination of data sets **requires** a proper handling of systematic & statistical errors.

Let Λ^i a set of cross section measurement, then Λ^{Ave} is obtained:

$$\chi^2(\Lambda^{Ave}, \alpha) = \sum_{k=1}^{\text{exp}} \sum_i^{\text{bins}} \frac{\left[\Lambda^{i,Ave} - \left(\Lambda_i^k + \sum_{j=1}^{\text{syst}} \frac{\partial \Lambda_i^k}{\partial \alpha_j^k} \alpha_j^k \right) \right]^2}{\sigma_{\Lambda_i^k}^2} + \sum_{k=1}^{\text{exp}} \sum_{j=1}^{\text{syst}} \frac{(\alpha_j^k)^2}{\sigma_{\alpha_j^k}^2}$$

◆ Input:

$\Lambda^i, \frac{\partial \Lambda_i}{\partial \alpha_j}, \sigma_{\Lambda,i}^2, \sigma_{\alpha_j}$ uncertainty on the source

\nwarrow sensitivity to syst \searrow stat+uncorr uncertainty

◆ Output:

Λ^{True}, α_j shift on the uncertainty of the source

Combining H1 & ZEUS Data

$$\chi^2_{\text{exp}} \left(M^{i,\text{true}}, \Delta\alpha_j \right) = \sum_i \frac{\left[M^{i,\text{true}} - \left(M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j} \Delta\alpha_j \right) \right]^2}{\sigma_i^2} + \sum_j \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

M^i measured central values

σ_i statistical and uncorrelated systematic uncertainties

$\sigma_{\alpha_j}^2$ correlated uncertainty

$\frac{\partial M^i}{\partial \alpha_j}$ sensitivity of the data to the systematic source j

$M^{i,\text{true}}$ fitted H1-ZEUS combined H1-value

$\frac{\partial M^i}{\partial \alpha_j} \Delta\alpha_j$ fitted shift of the i data due to the j sys error source

It's a cross calibration of the correlated systematics between different data sets. If $\Delta\alpha_j = 0$, it coincides with a standard average

Combining H1 & ZEUS Data

$$\chi_{\text{exp}}^2 \left(M^{i,\text{true}}, \Delta\alpha_j \right) = \sum_i \frac{\left[M^{i,\text{true}} - \left(M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j} \frac{M^{i,\text{true}}}{M^i} \Delta\alpha_j \right) \right]^2}{\left(\sigma_i \frac{M^{i,\text{true}}}{M^i} \right)^2} + \sum_j \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

Normalisation is clearly relative (multiplicative).

Are the other systematics errors additive or multiplicative ? Debatable !

Impact is mostly negligible, except at very large Q^2 and x where statistical errors and fluctuations are the largest.

At that stage : an additional uncertainty has been added.

F_L : Indirect Determination Methods

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

- Data sensitive at highest y only
- Direct measurement requires data at different $s \rightarrow$ *lower E_p runs*
- *Indirect determination at high y*

► Derivative method

$$\left. \frac{\partial \sigma_r}{\partial \ln y} \right|_{Q^2} \approx \left. \frac{\partial F_2}{\partial \ln y} \right|_{Q^2} - \frac{2y^2(2-y)}{Y_+^2} F_L$$

Derivative dominated by F_L term at high y

► Shape method

$$\sigma_{\text{fit}} = cx^{-\lambda} - \frac{y^2}{Y_+} F_L$$

Shape driven by kin. factor rather than F_L

