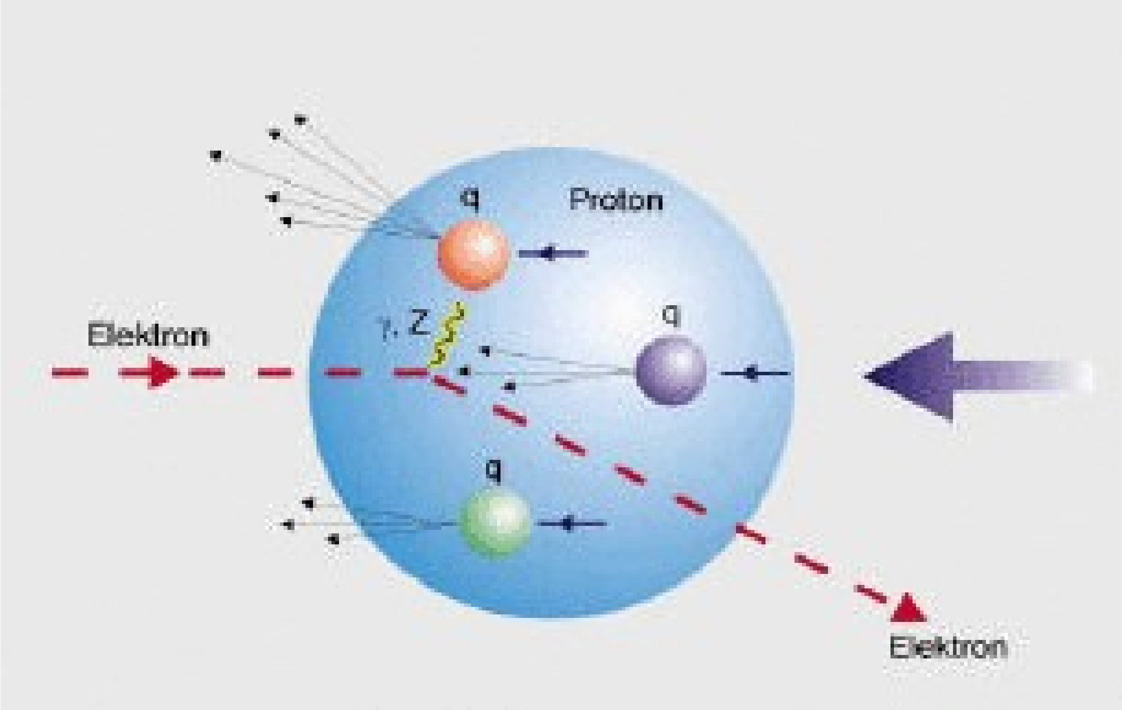
4th Particle Physics Workshop

National Center for Physics, Islamabad

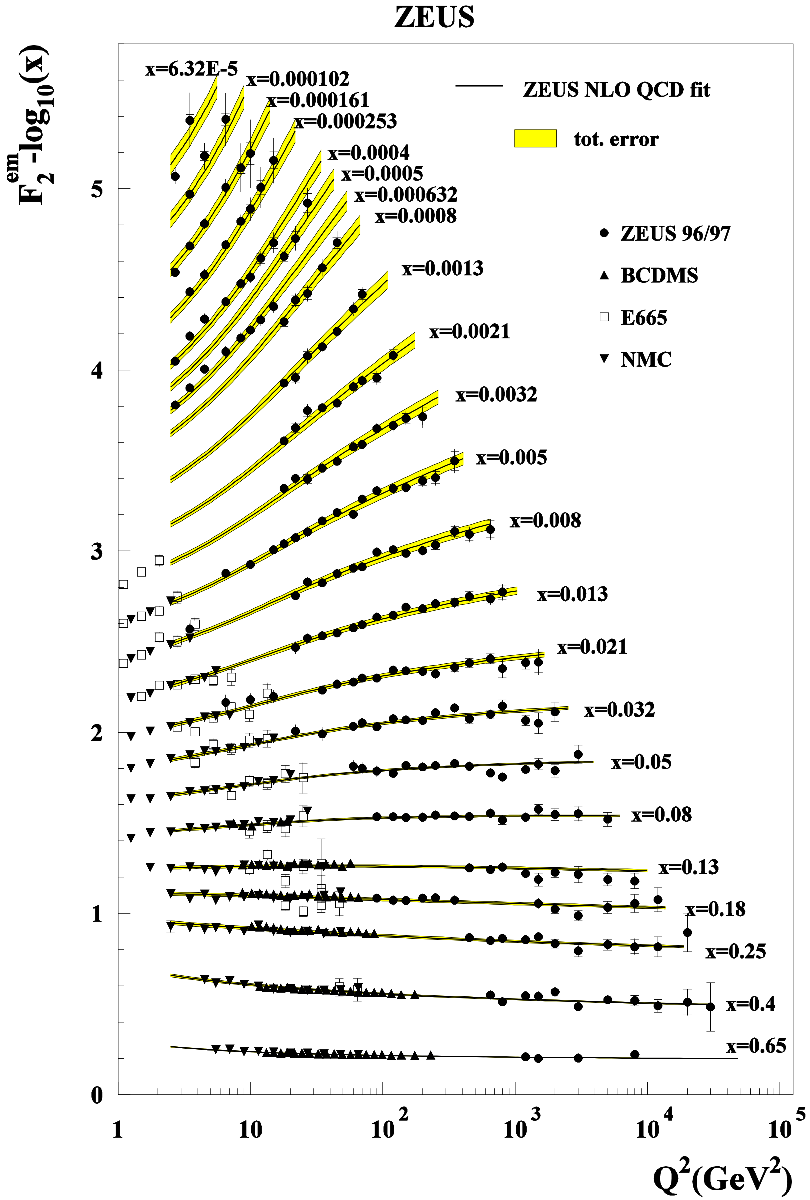
Proton Structure and QCD tests at HERA

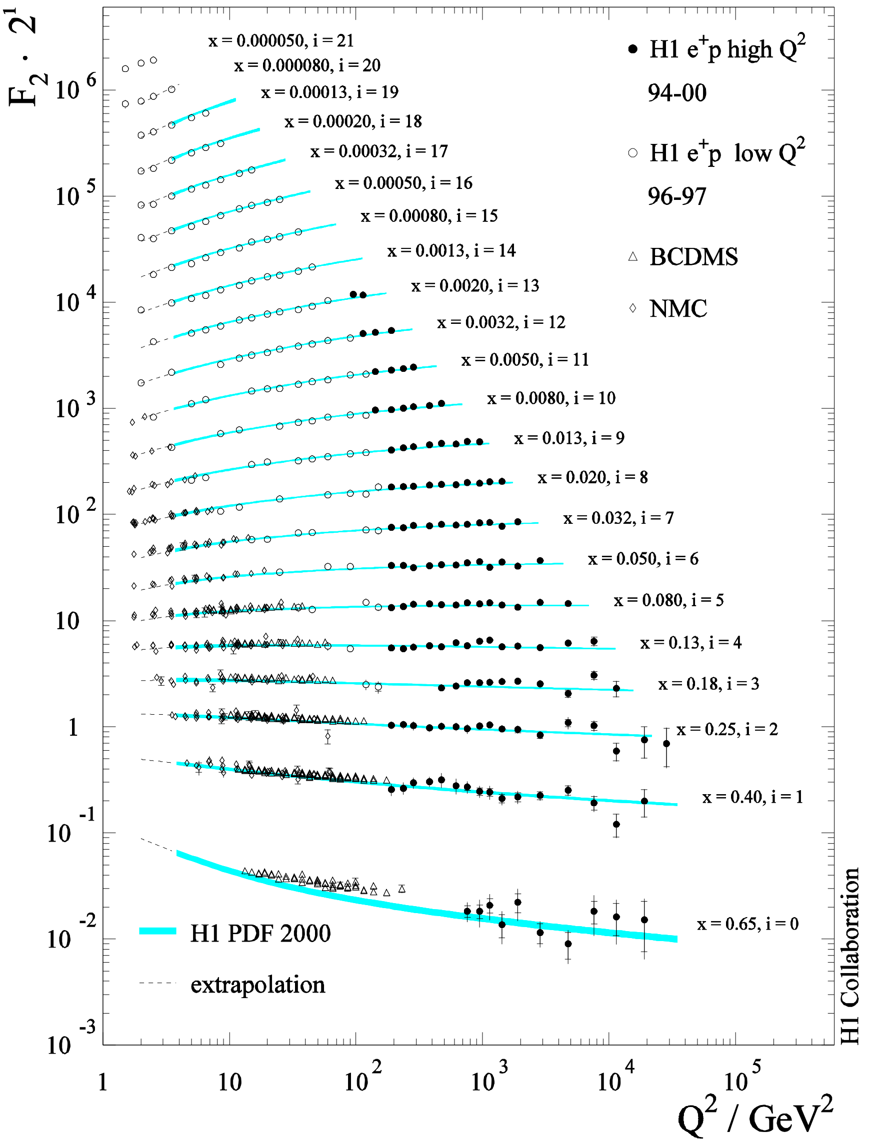
Jan Olsson, DESY

Part 2



The proton structure function F_2

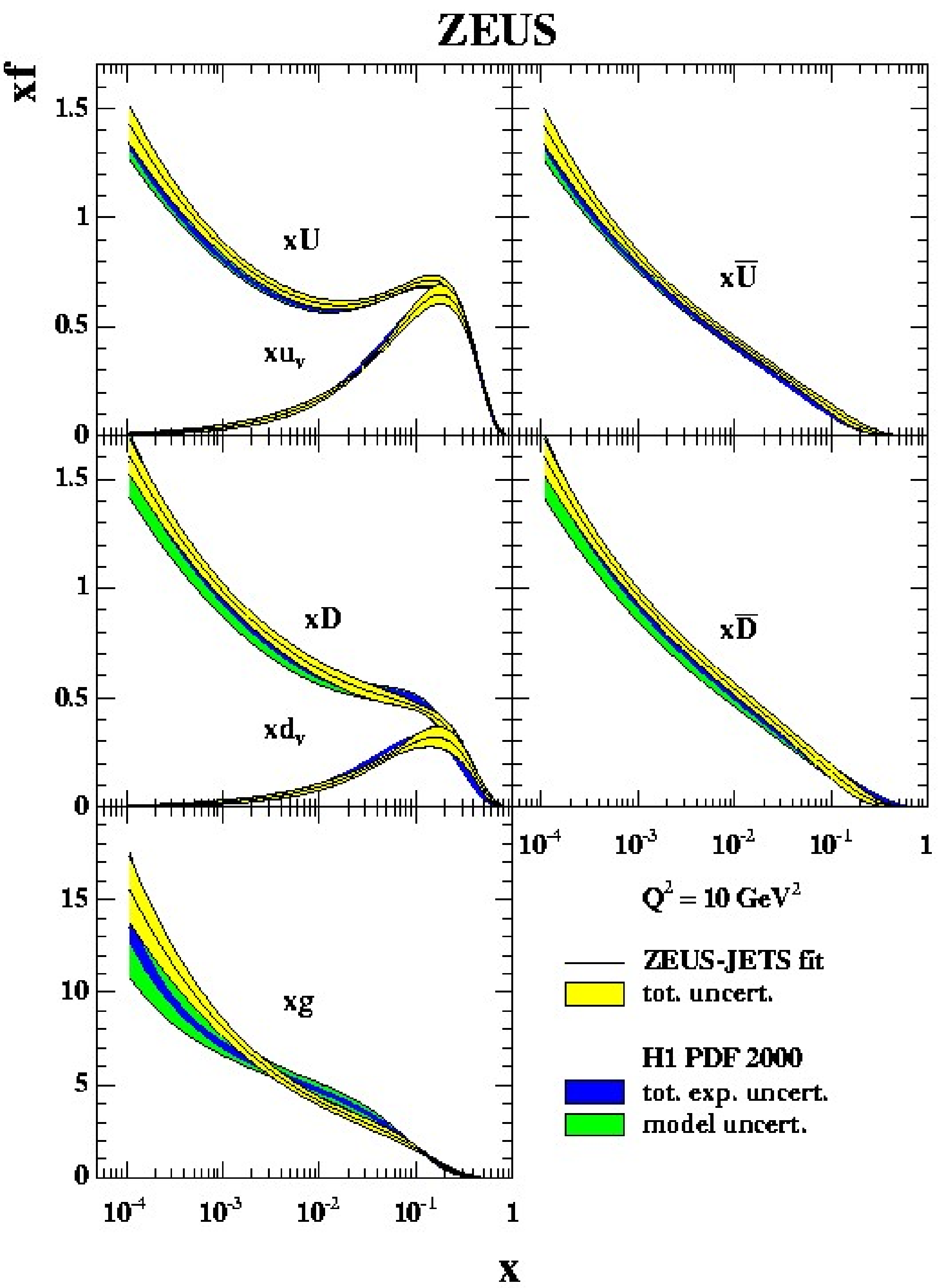


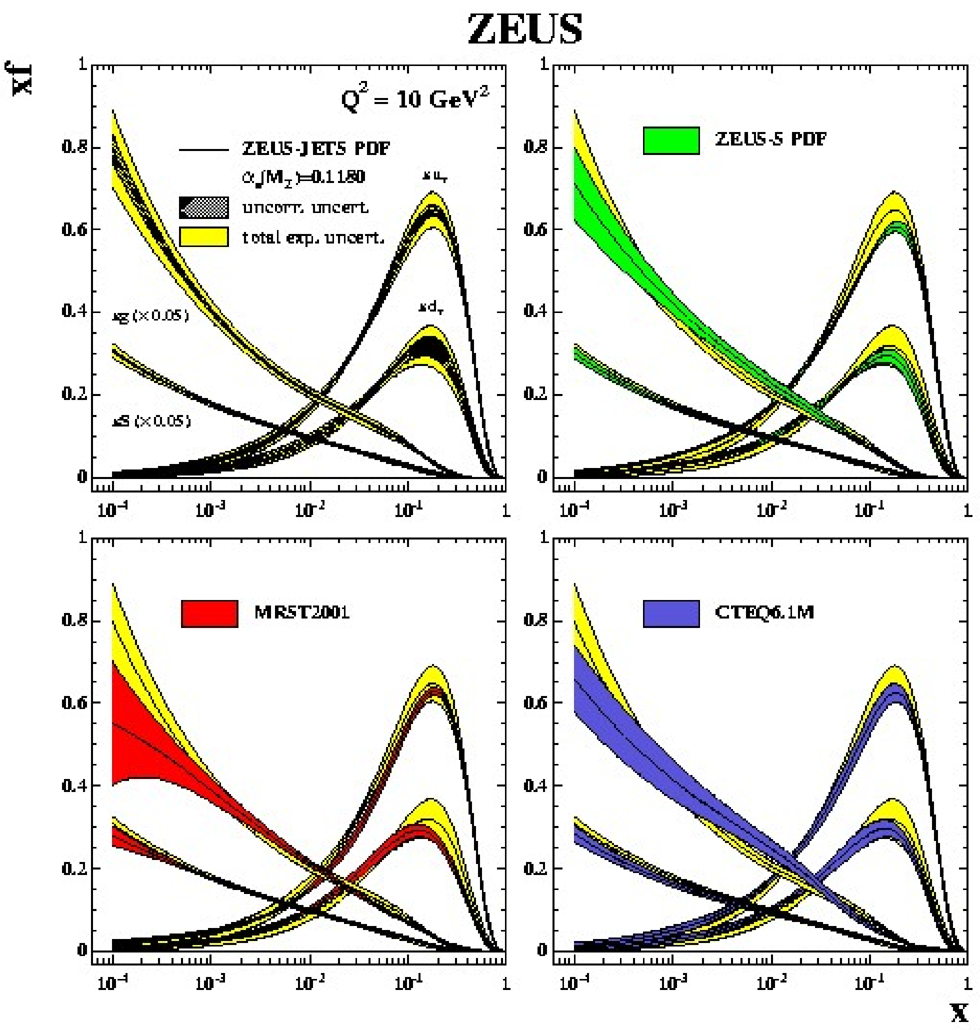


NLO QCD describes data over >4 orders of magnitude in Q^2 and x !

Fit works well even for very low Q^2 and x ! (~1 GeV², ~0.00005)

Including Jet data: The ZEUS-JETS NLO-QCD fit





Reasonable agreement:

With H1 PDF2000, MRST2001, CTEQ6

The global fits and their data

MRST

Martin,Roberts,Stirling,Thorne

CTEQ

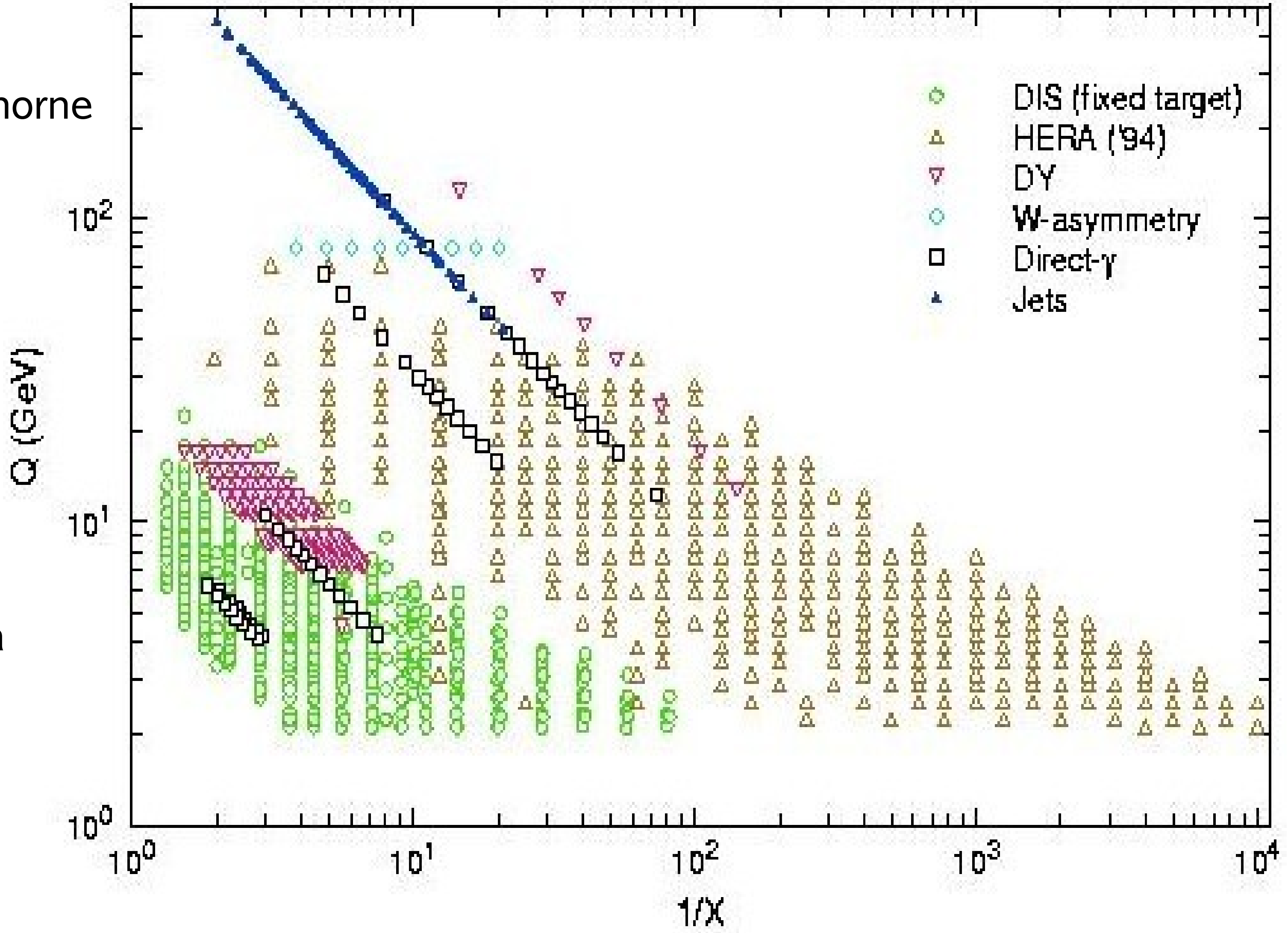
Pumplin et al.

GRV

Glueck, Reya, Vogt

H1 and ZEUS,

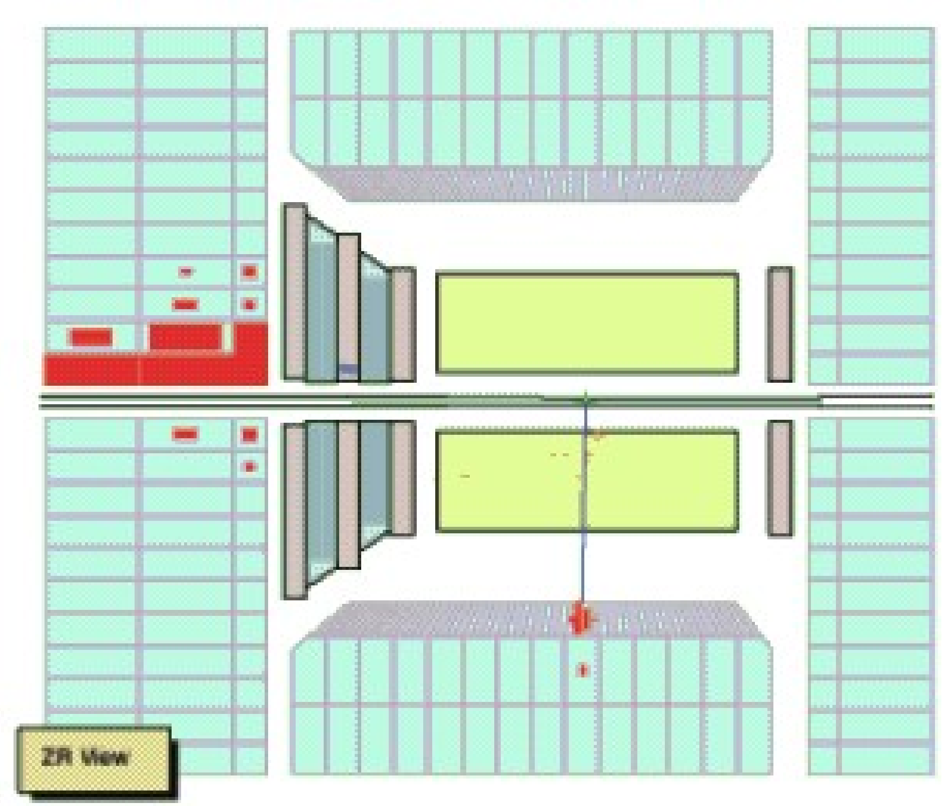
using mainly HERA data

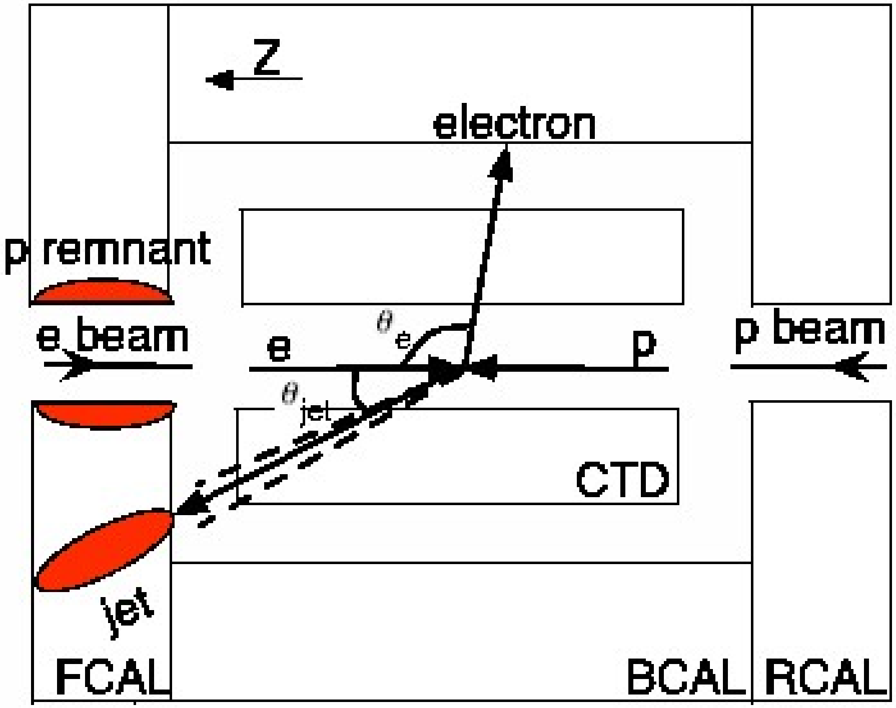


A great triumph and success for NLO QCD!

Such a big diversity of data,
all very well described,
with a common set of parameters,
and with a fit based only on pQCD and DGLAP!

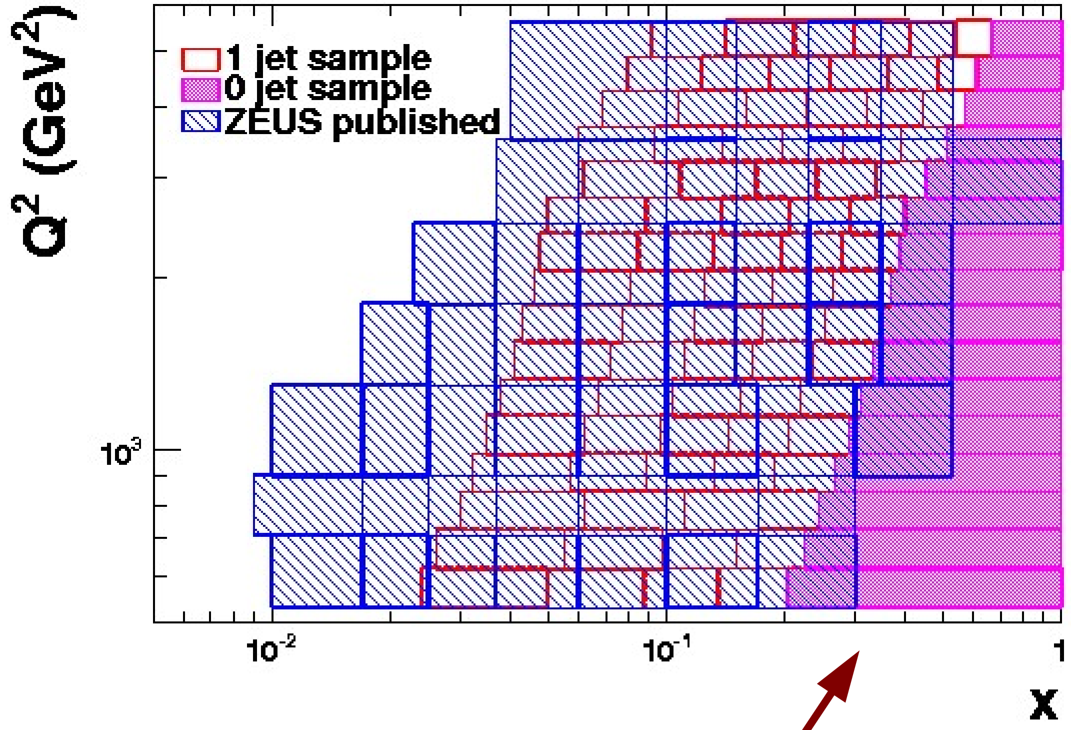
ZEUS: NC events at high x

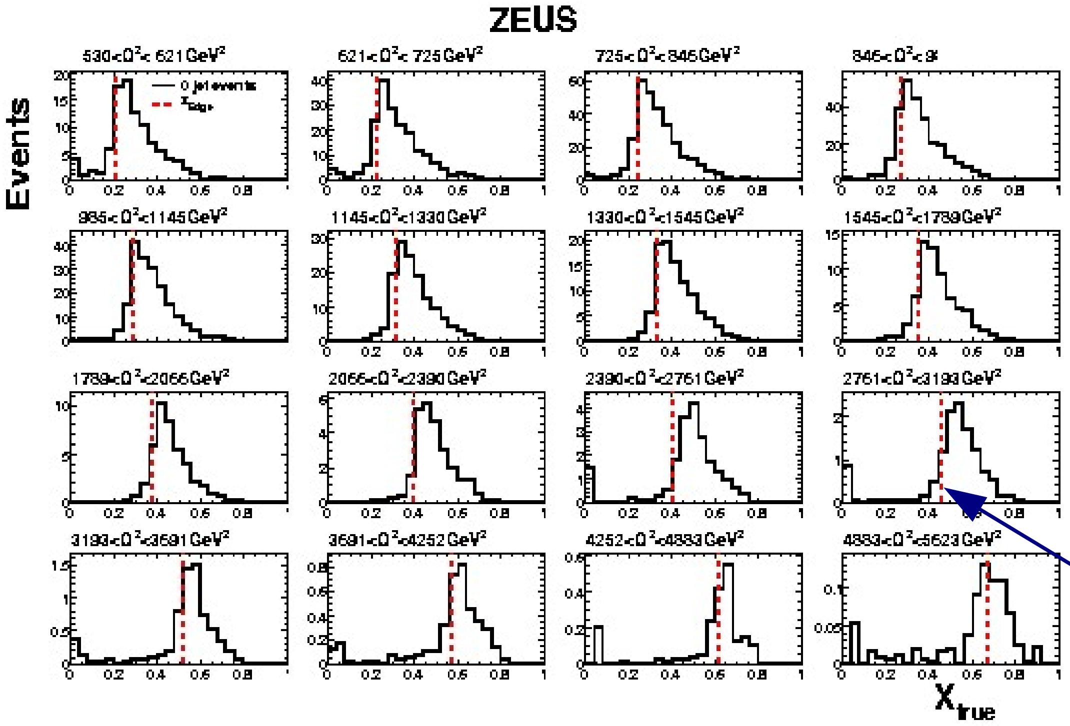




Aim: Access data at x values higher than ever reached before
Previous HERA measurements reach 0.65
Fixed Target DIS data extend to 0.75 (BCDMS)

ZEUS: NC events at high x





$$\frac{\int_{x_{\max}}^{1} dx \, \frac{d^2\sigma}{dx\,dQ^2}}{1 - x_{\max}}$$

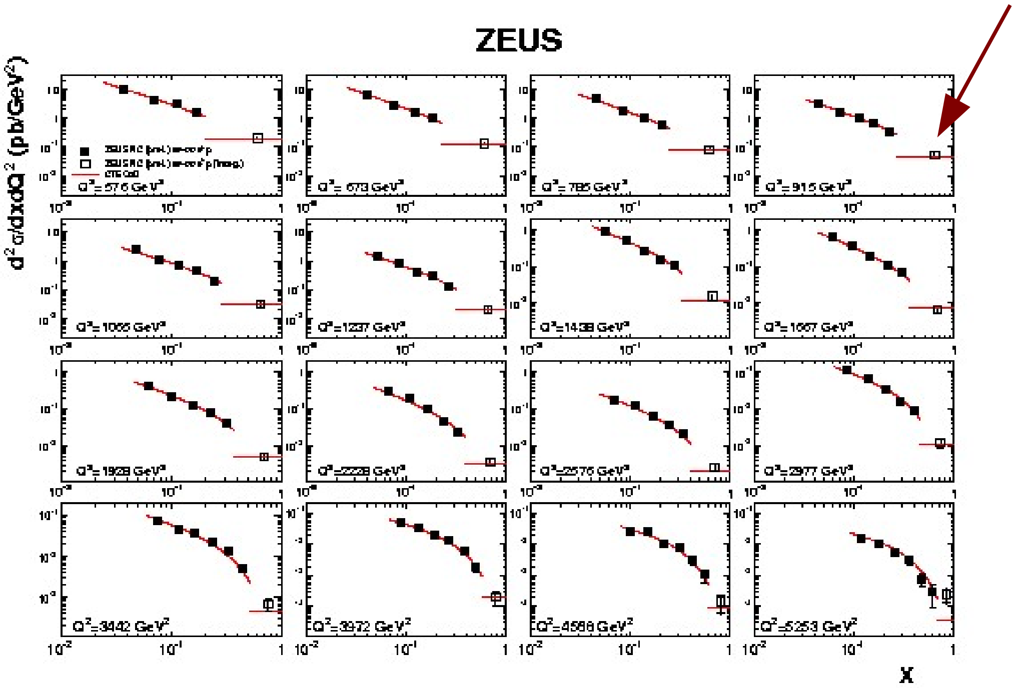
Cross section in the highest x bin
“0-jet” events

MC simulation: High purity!

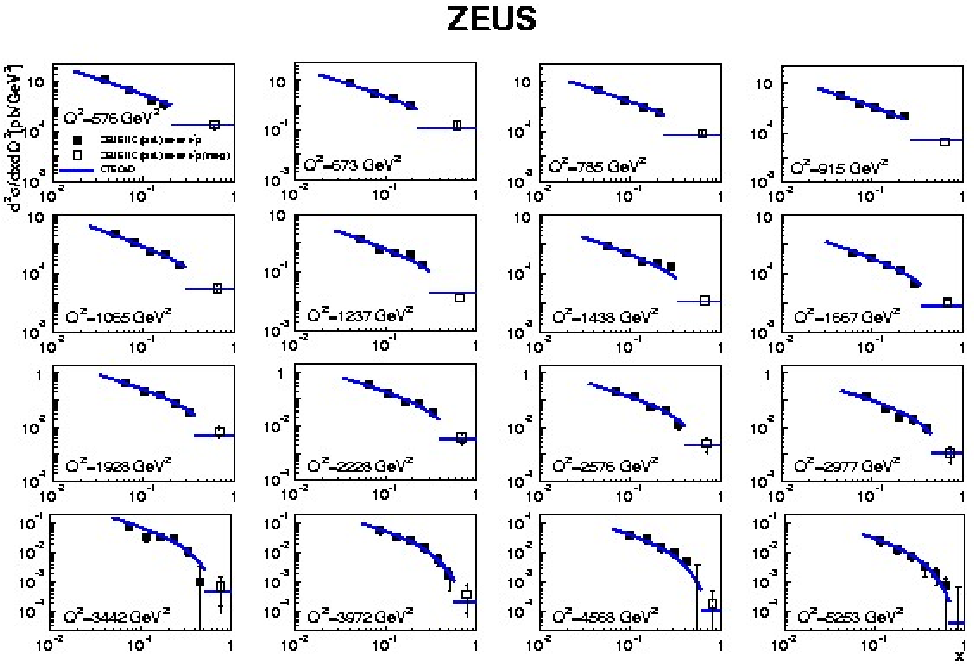
Lower edge, x_{max},
of highest bin

ZEUS: NC events at high x

Integral, divided by bin width



e^+p

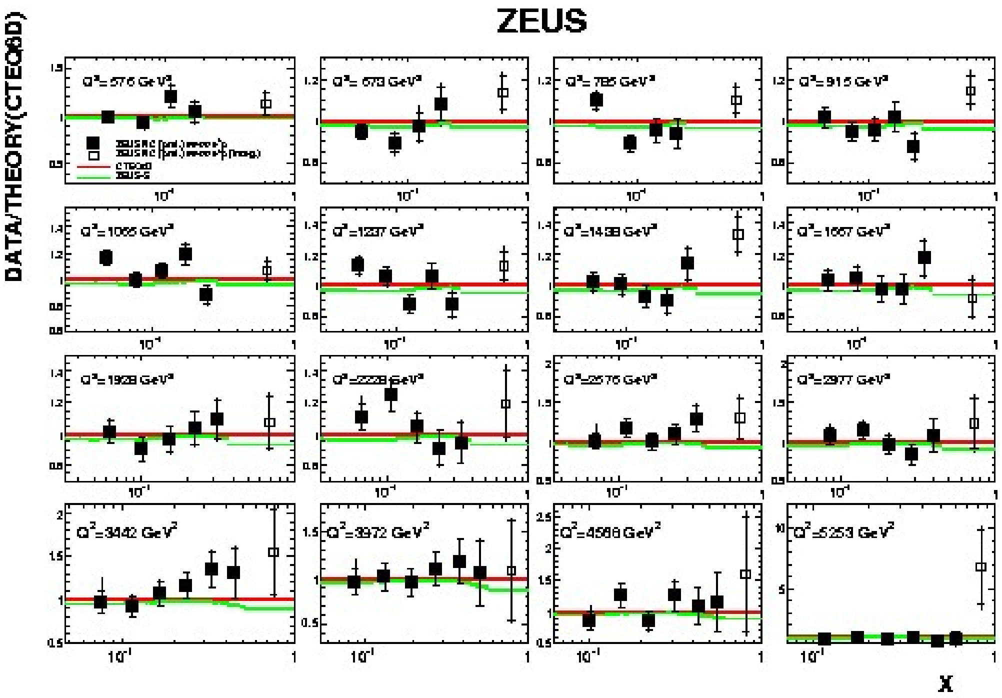


e^-p

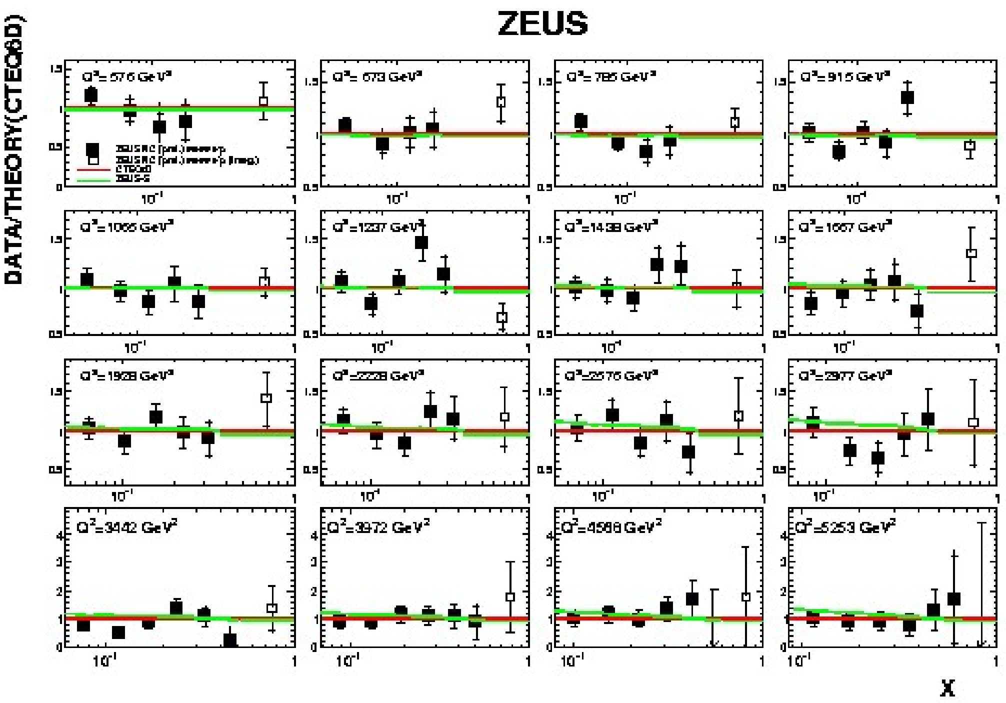
Curves from Standard Model (CTEQ6D), describe data well (?)
===> look at ratio

ZEUS: NC events at high x

Ratio of measured cross sections to
the Standard Model expectations, CTEQ6D



e^+p

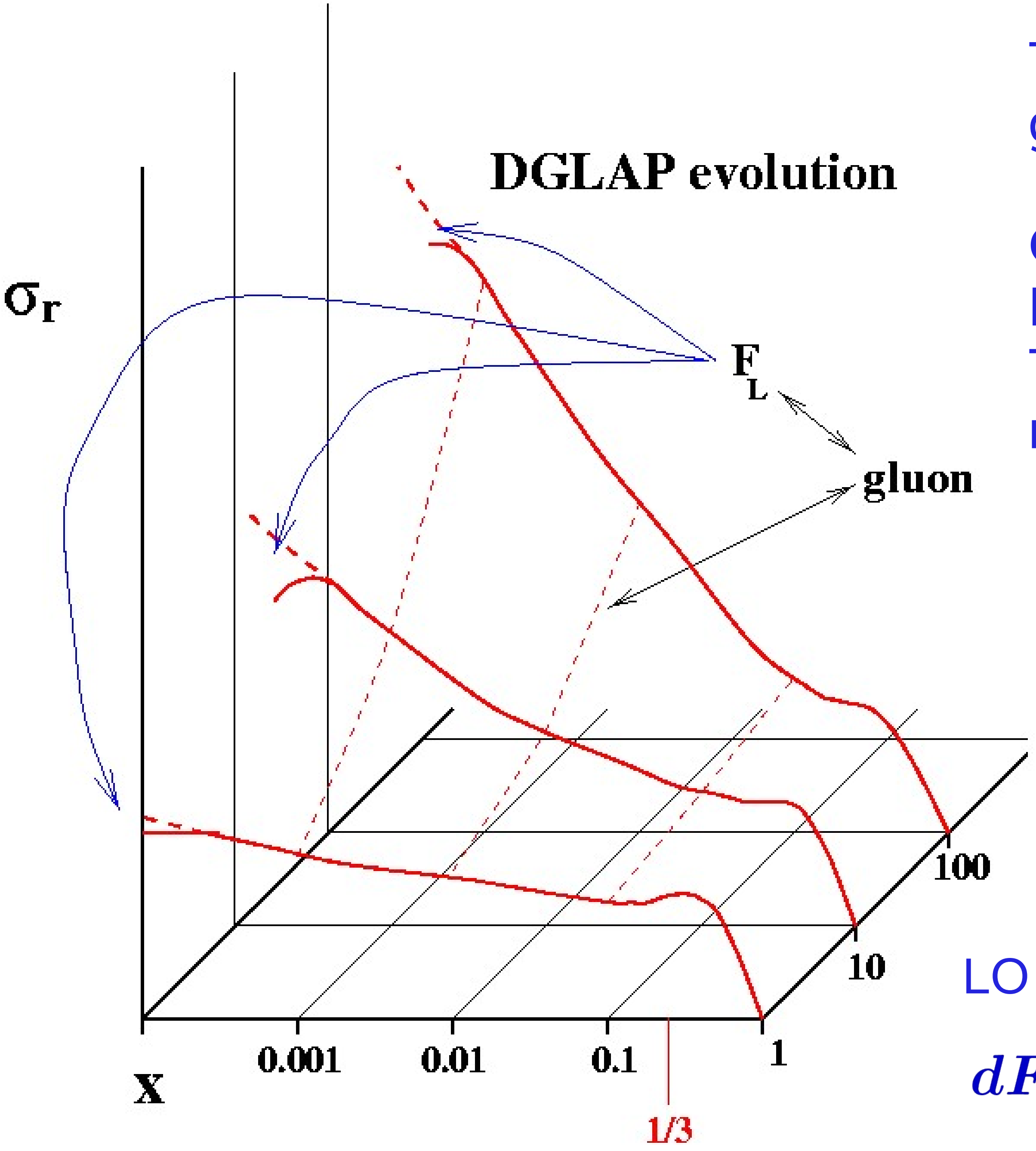


e^-p

Deviations from SM seen at highest x

==> Expect impact from these data on future PDF fits!

Proton Structure at low x



The larger Q^2 is, the more gluons are seen at low x

Gluons split into $q\bar{q}$
But $F_2 \propto x(q+\bar{q})$
Thus the gluon "drives" the rise of F_2 at low x

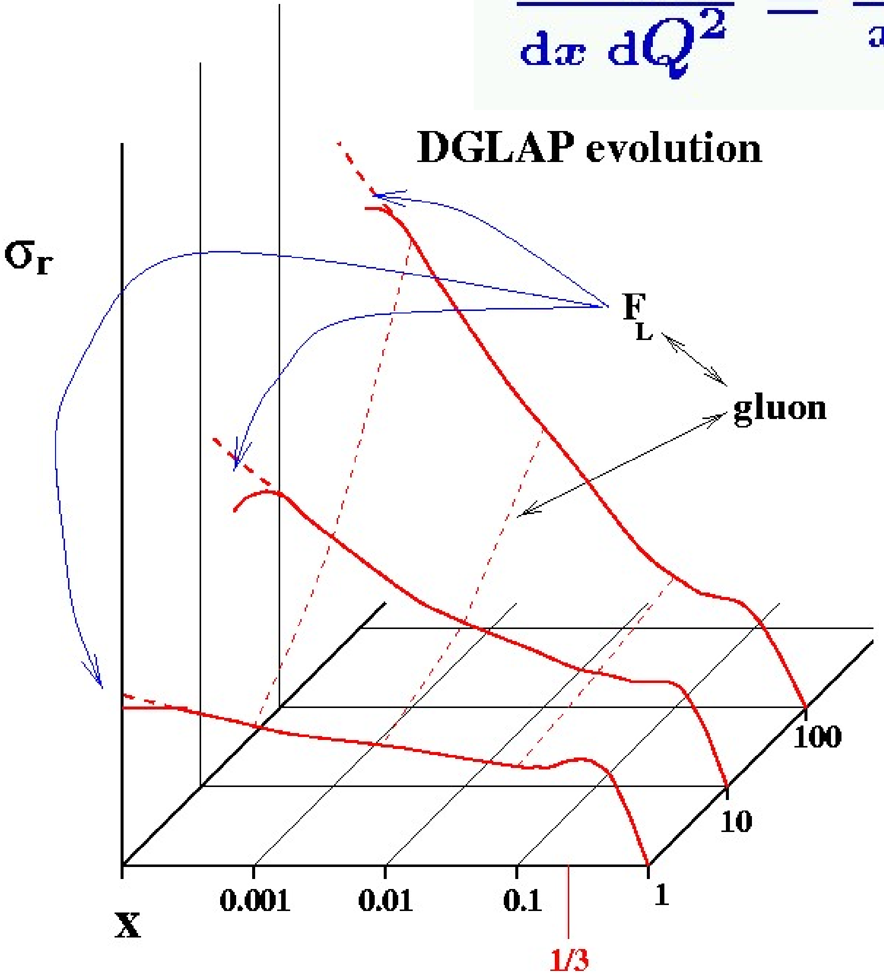
The dotted lines represent the Scaling Violations, given by the increasing gluon density

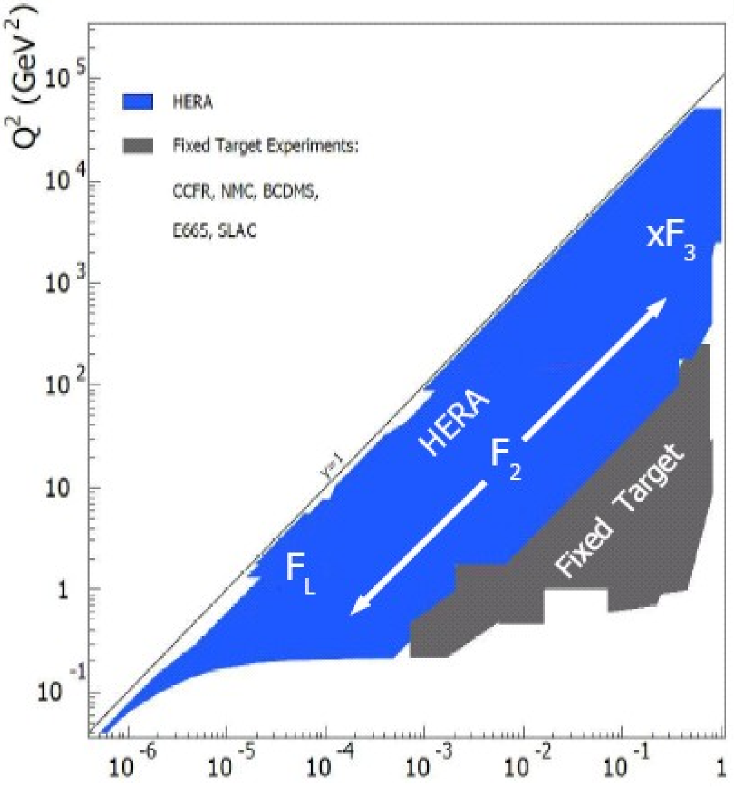
LO DGLAP, low x:

$$dF_2/d\ln Q^2 \sim \alpha_s x g(x)$$

The proton longitudinal structure function F_L

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

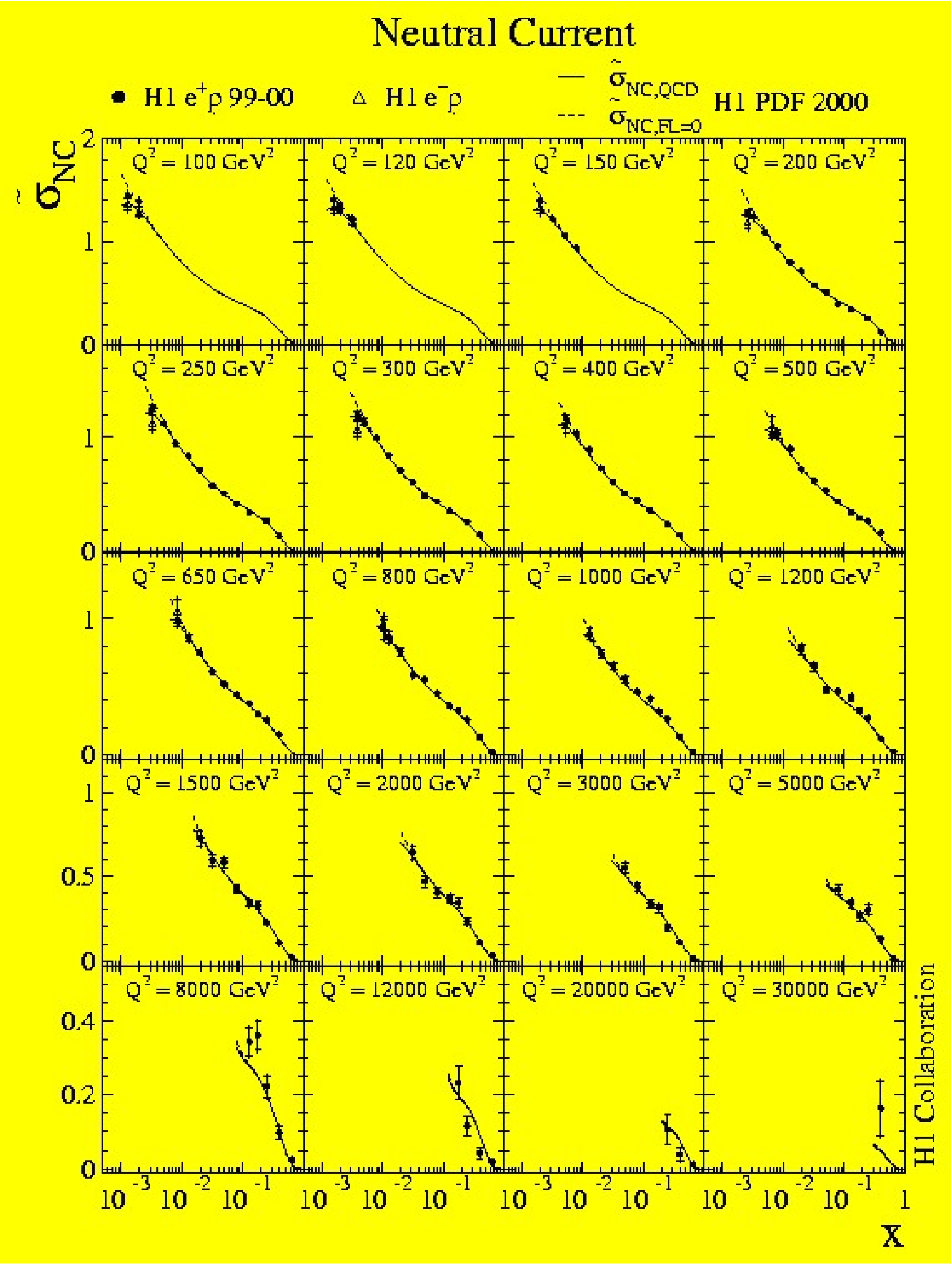


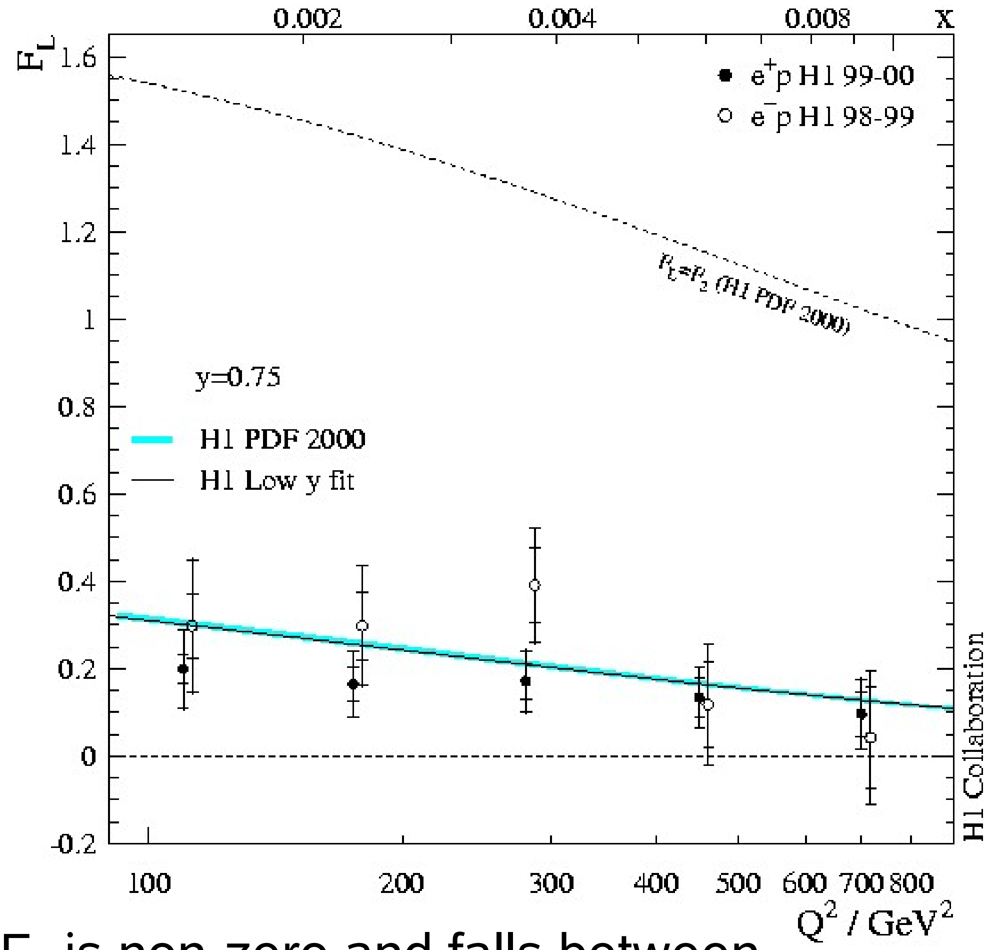


$$F_L = \frac{Y_+}{y^2}\left(F_2^{QCD-fit} - \tilde{\sigma}_r\right)$$

Neglect the small electroweak contributions in this region of the kinematic plane ===> Extract F_L from data

Extraction of F_L at high Q^2



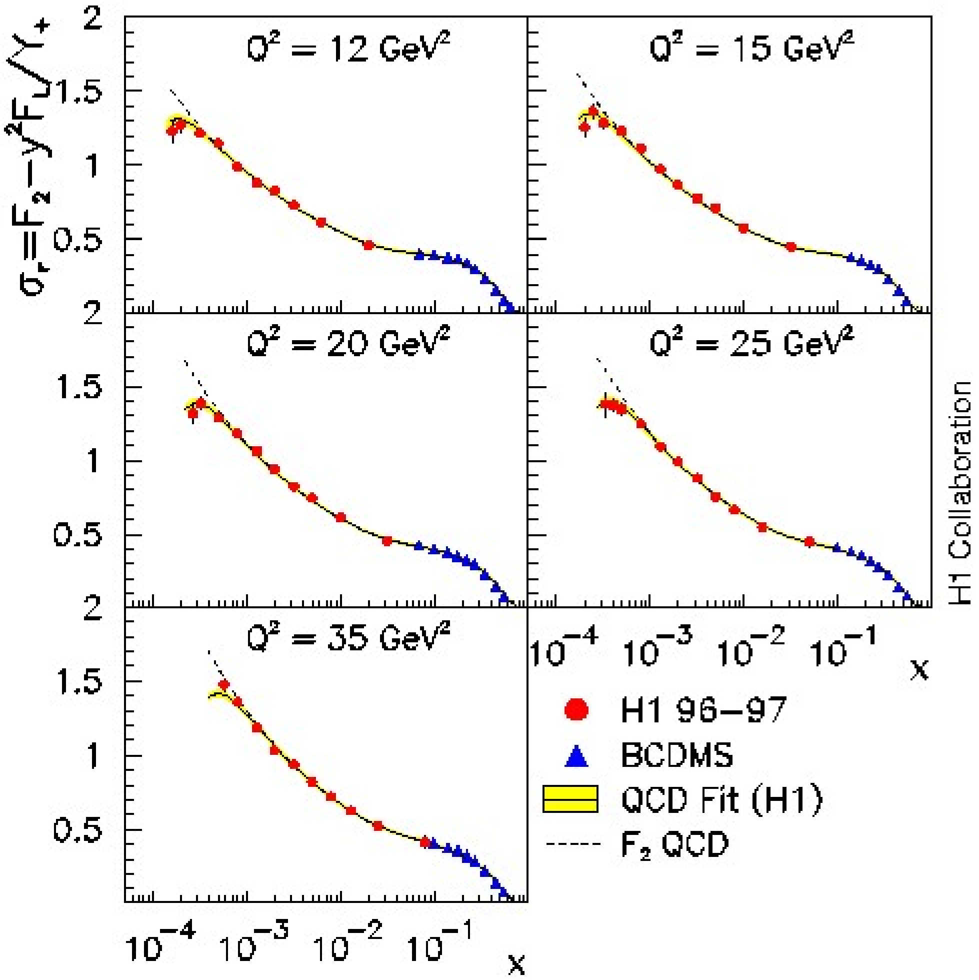


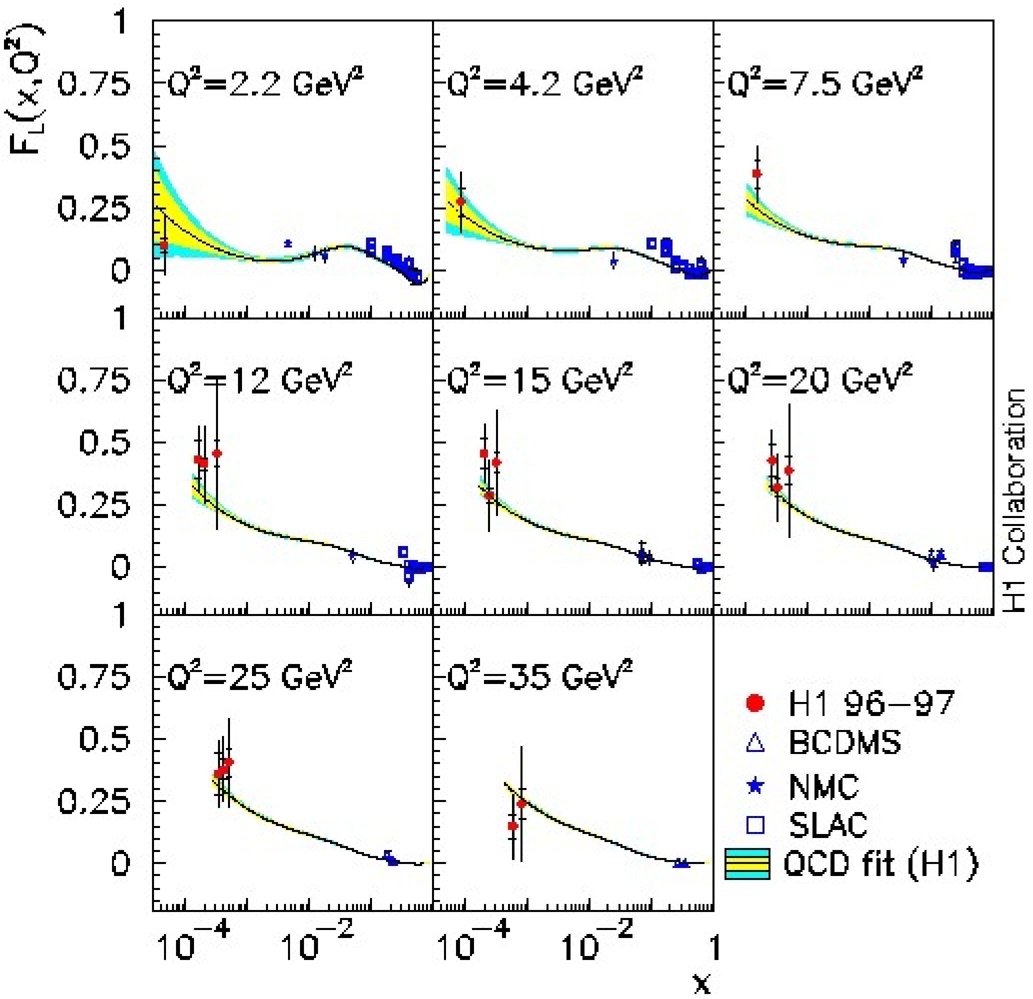
F_L is non-zero and falls between the extreme values of 0 and F2 (low *y* fit)

e⁺ and e⁻ results compatible

The *x*-dependence cannot be extracted, data cover too small a region

Extraction of F_L at low Q^2





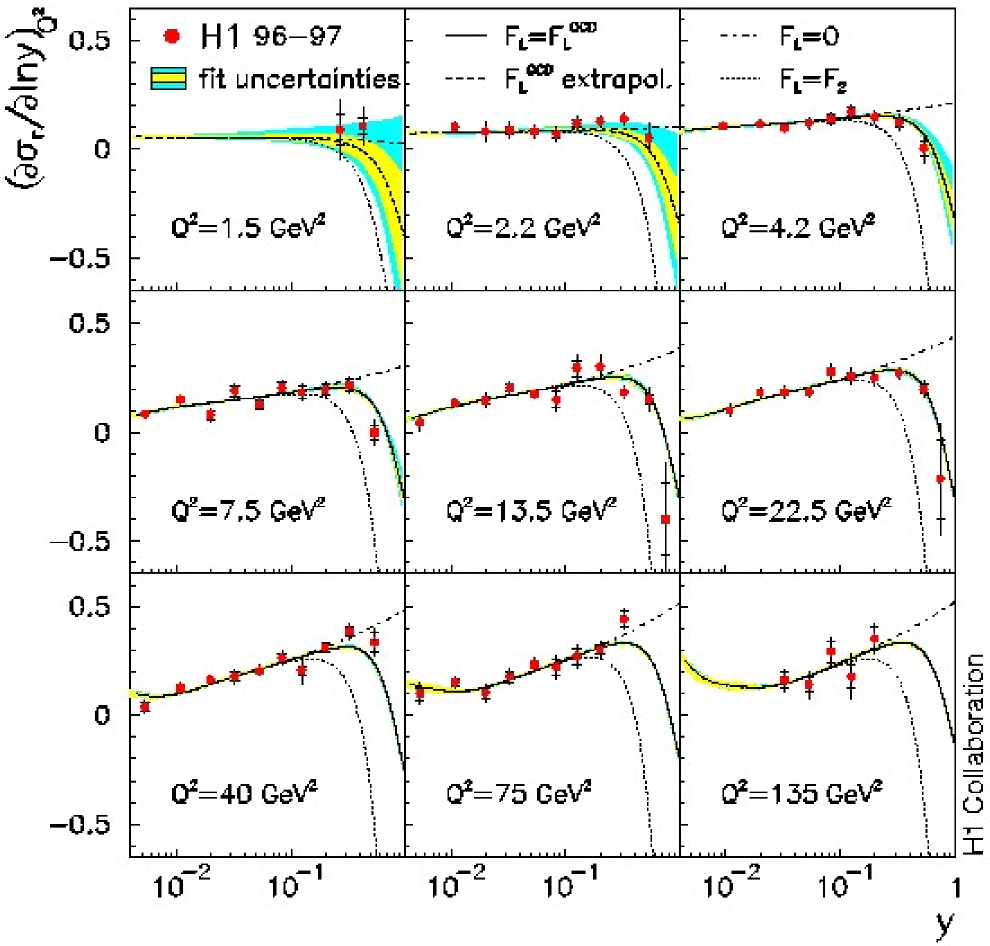
2 Methods are used for the extraction of F_L:

- Extrapolation method
- Derivative method

Consistent results in overlap region

Extraction of F_L at low Q^2, Derivative method

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



- form derivatives w.r.t. $\ln y$ from σ_r in bins of Q^2 and y:

$$\frac{\partial\sigma_r}{\partial\ln y} = \frac{\partial F_2}{\partial\ln y} - F_L\cdot 2y^2\cdot\frac{(2-y)}{Y_+^2} - \frac{\partial F_L}{\partial\ln y}\cdot\frac{y^2}{Y_+^2}$$

- $y\to 1 \quad\Rightarrow\quad \partial\sigma_r/\partial\ln y \approx \partial F_2/\partial\ln y - 2\cdot F_L$

  ($\partial F_L/\partial\ln y$ neglected, uncertainty included in error)
- for given $Q^2 \;\Rightarrow\; F_2 \sim x^{-\lambda} \sim e^{\lambda\ln y}$

  low $Q^2 \Rightarrow$ small λ : $\frac{\partial F_2}{\partial\ln y}$ linear in $\ln y$ to good approximation

  $\Rightarrow$ confirmed with QCD fit and deviations included in error
- straight-line fit to $\partial\sigma_r/\partial\ln y$ in bins of Q^2 for $y < 0.2$
- extrapolate the fitted line to high y
- subtract $\frac{\partial\sigma_r}{\partial\ln y} \quad\Rightarrow\quad F_L$

Note: It is assumed that *dF_2/dlny* is linear also at high *y*

Extraction, but not a measurement !

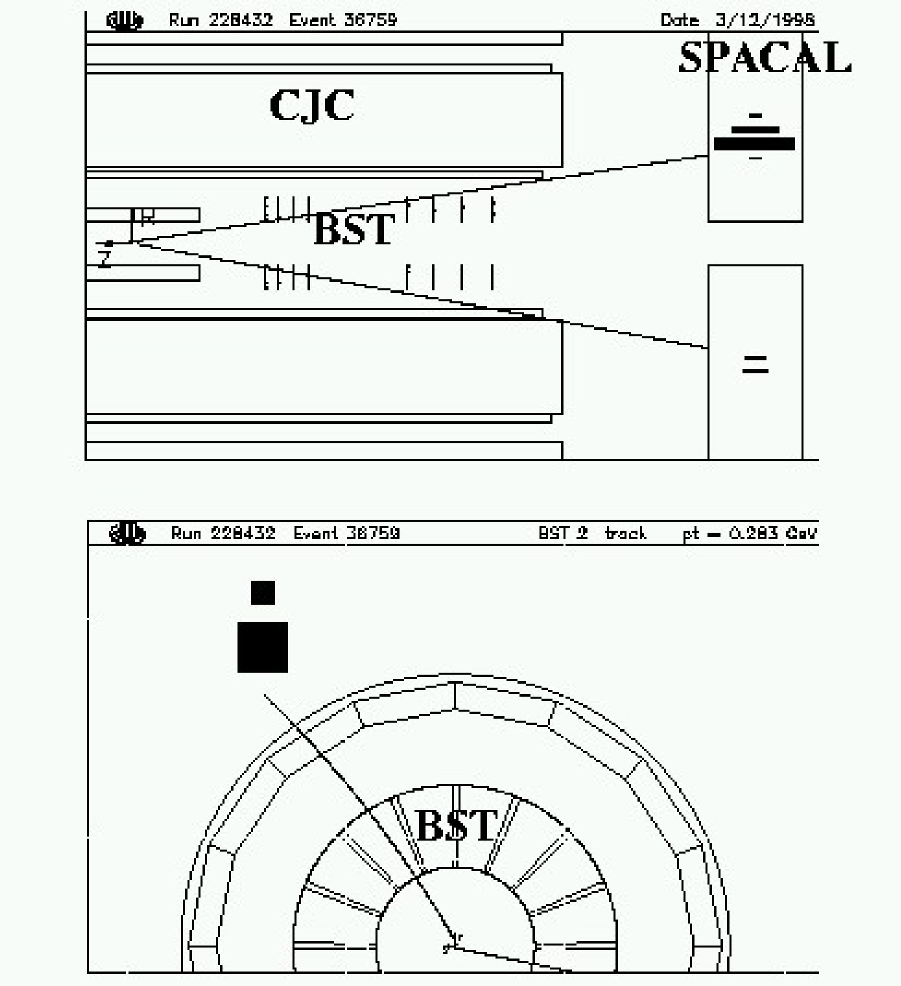
Data at very high y

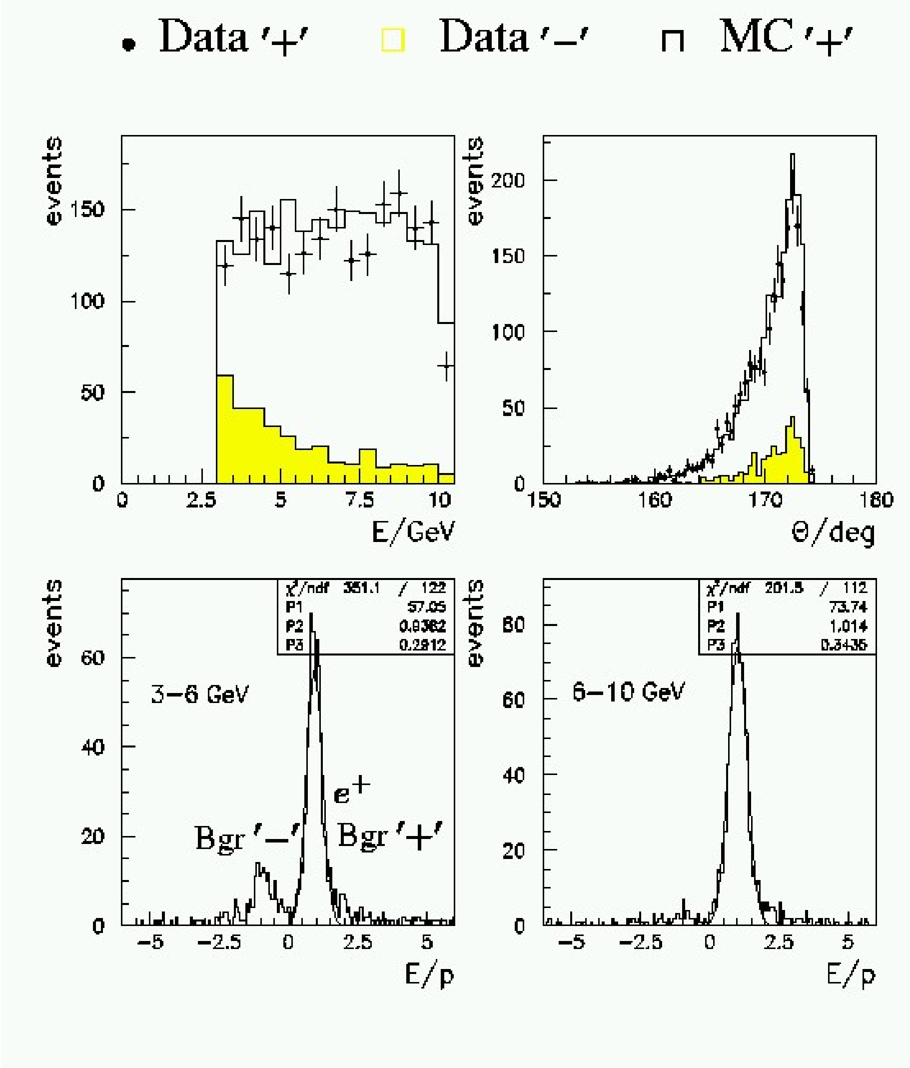
$y = 0.89 \iff E_e = 3$ GeV

To obtain data at very high y values, one must detect low energy electrons

==> Photoproduction background!

Estimate this background with opposite sign electrons





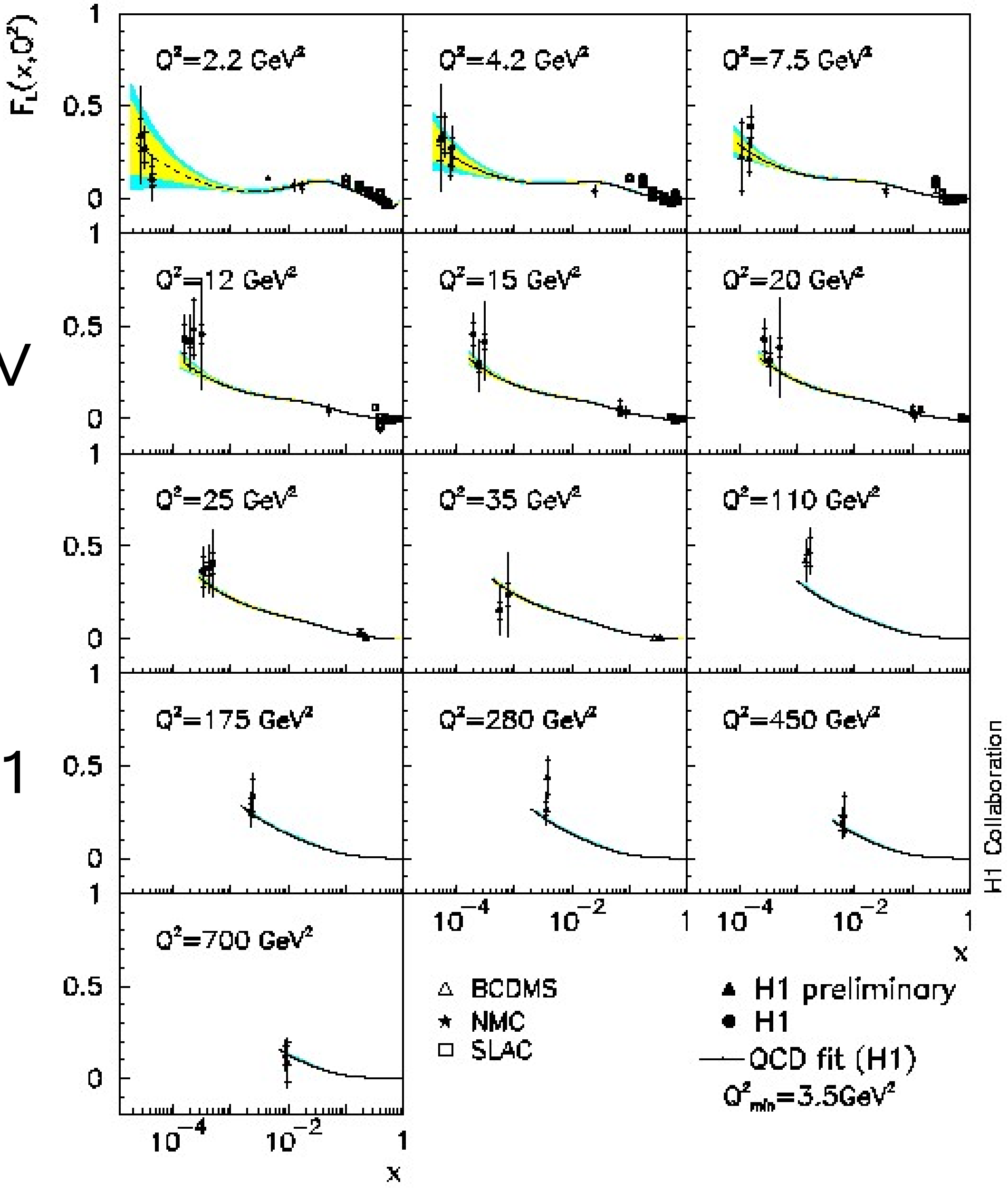
Summary I: F_L extractions

Minimum Bias low Q^2 data from 1996/97 and 1999/2000

Results extend to lower x, since proton energy increased to 920 GeV

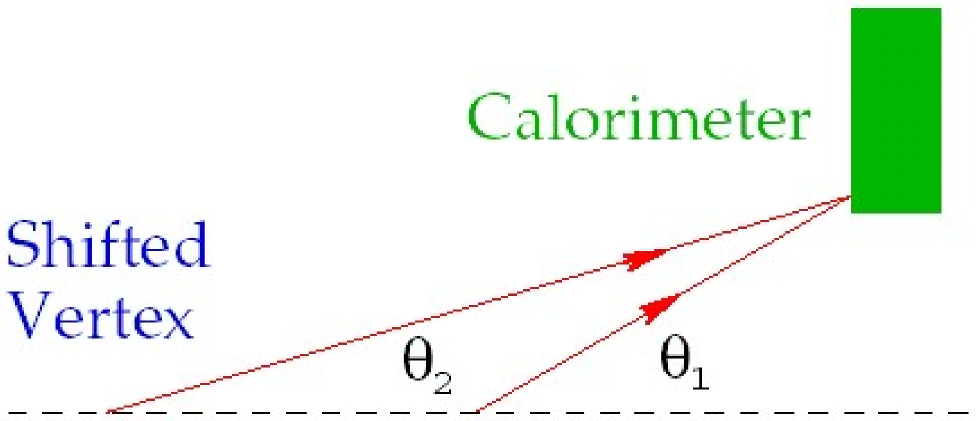
Results extracted, using
"Subtraction method"
"Derivative method"

Results agree with the QCD fit of H1

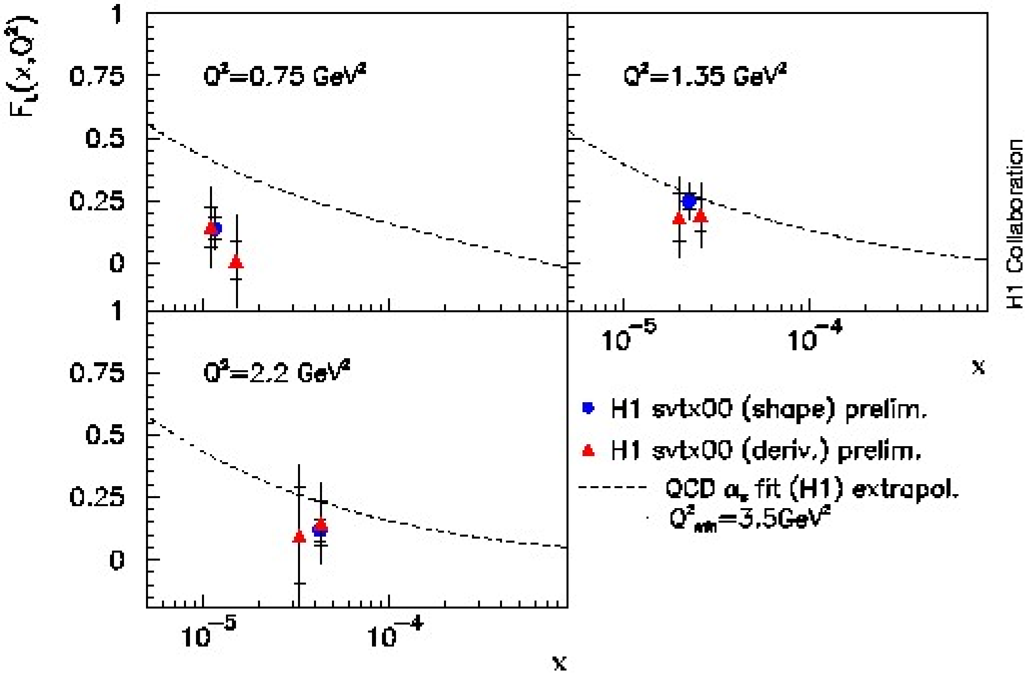


Data at low Q^2, “Shifted Vertex”

By shifting the interaction point
by +70 cm (in the proton direction)
lower electron scattering angles can be
detected, giving access to
still lower Q^2 and x values



Also with this data sample,
F_L was extracted,
using the derivative method



However, one can do better!

The “shape method” gives smaller errors than the “derivative method”

Extraction of F_L, using the “Shape method”

Criticism of the “derivative method”:

- assumes a linear behaviour of $dF_2/d\ln y$ with lny and extrapolates the information about F_2 from the low y region to the high y region.
- It does not make full use of the information provided by the cross section measurement in the intermediate y region
- Thus, for the linear fit the lowest points in y are used, and F_L extracted only for the highest points in y.
- The result on F_L consists in a few points very close in y, and with sizeable errors.
- The x-dependence of F_L is not resolved

Better:

The “Shape Method”, so called since it utilizes the shape of the reduced cross section in a given Q^2 bin. The shape is driven by the kinematic factor y^2/Y_+

2 Assumptions:

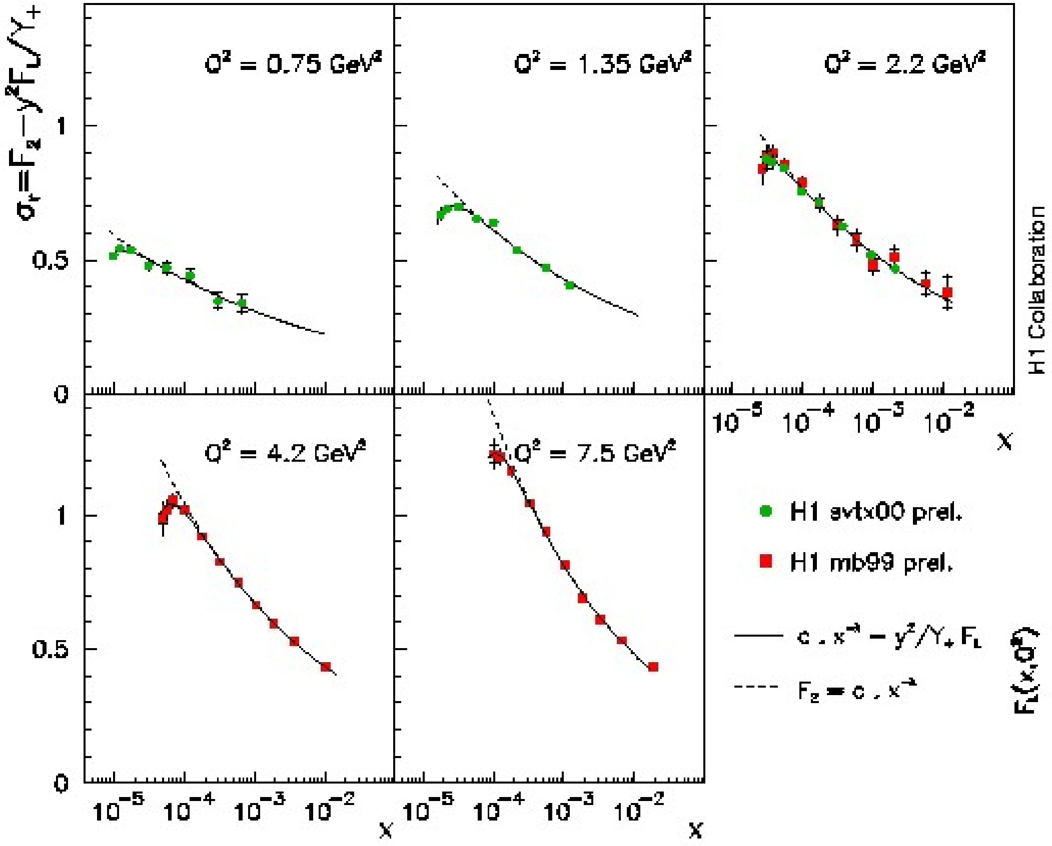
F_L is constant in each Q^2 bin in high y range of sensitivity to F_L via the y^2 term.

F_2 behaves like a power of x at fixed Q^2

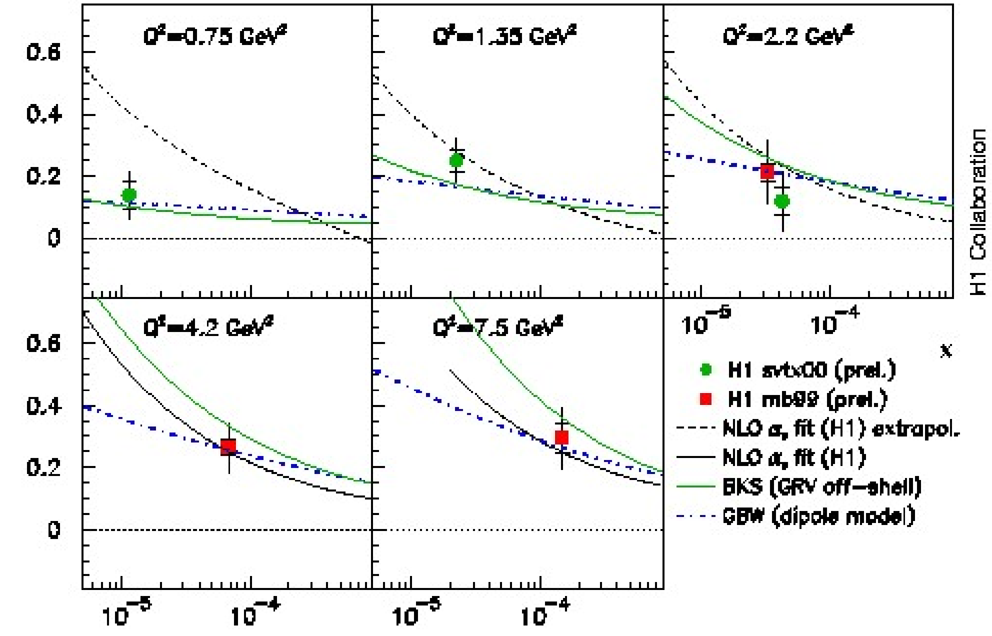
$$\sigma_{\mathrm{FIT}} = \mathbf{c} \cdot \mathbf{x}^{-\lambda} - \frac{\mathbf{y}^2}{1 + (1-\mathbf{y})^2} \mathbf{F_L}$$

Fit to data, extract c, lambda and F_L

Extraction of F_L at low Q^2, using the “Shape method”



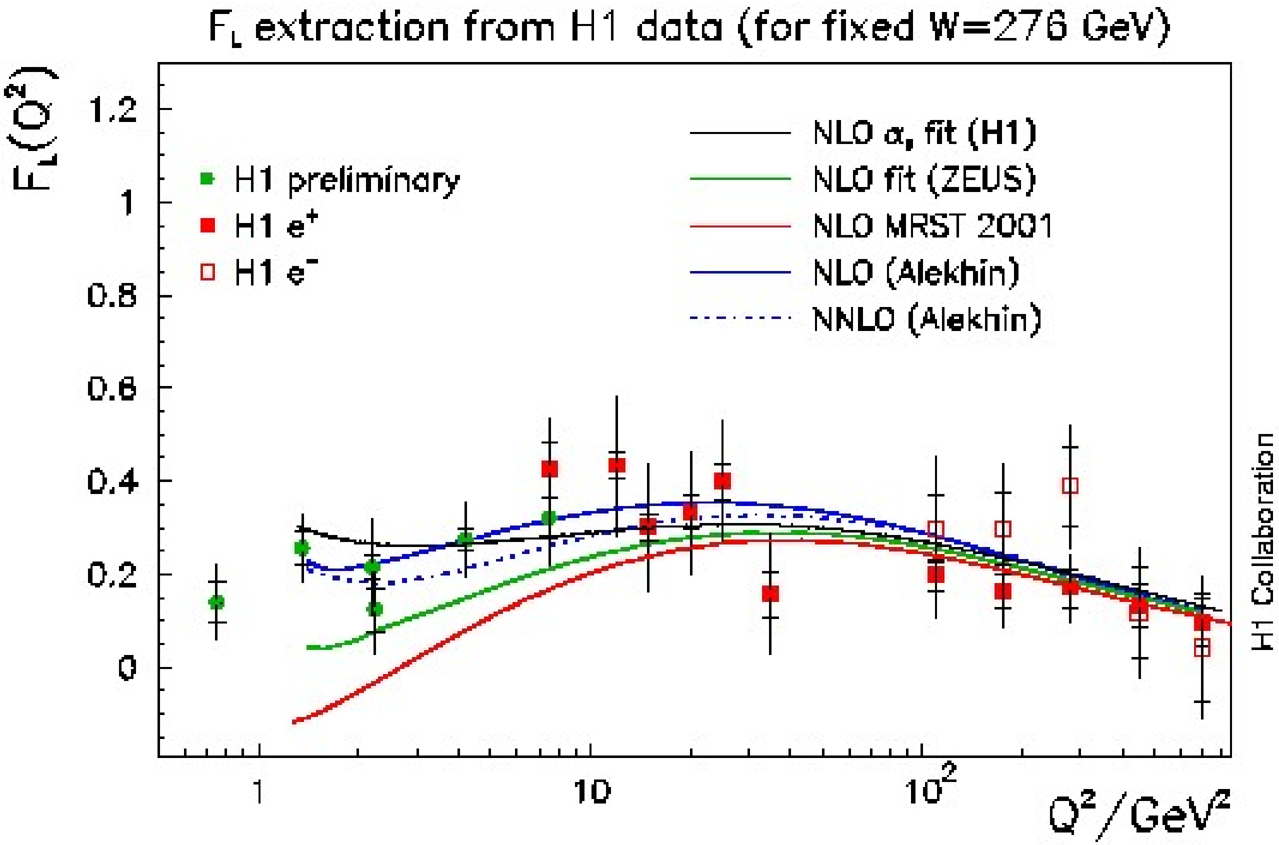
Shifted Vertex and MB99 data



Summary II: Extraction of F_L in H1 data

3 orders of magnitude in Q^2

Reasonable agreement with NLO and NNLO pQCD



But, the x-dependence cannot be determined!

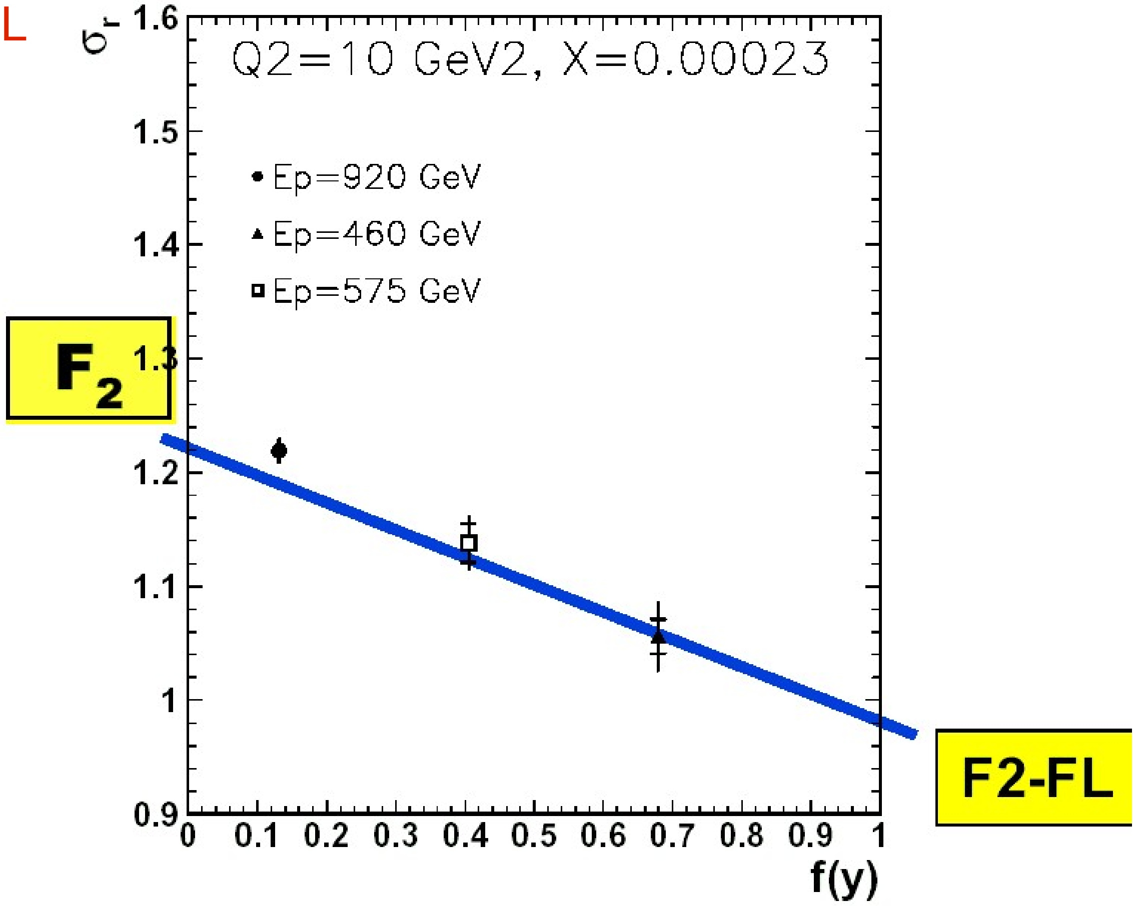
These are extractions! Need a direct measurement!

Measurement of F_L

Reduce the beam energies
(e.g. E_p to 500 GeV)
--> new value of CM energy^2 s

Measure the cross section at same values of Q^2 and x, for **both** beam energies

Since $Q^2 = x\,y\,s$
==> different value of y,
for same values of Q^2 and x

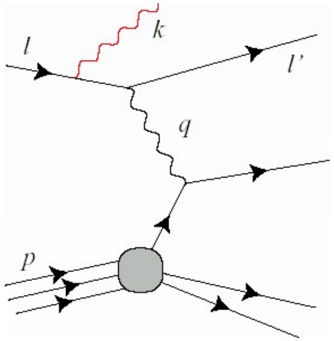


$$\sigma_1 - \sigma_2 = [(y^2/Y_+)_1 - (y^2/Y_+)_2] \cdot F_L$$

Better still: measure at several different beam energies, and fit the cross sections!

Will this happen before the end of HERA operations, i.e. before July 2007 ?

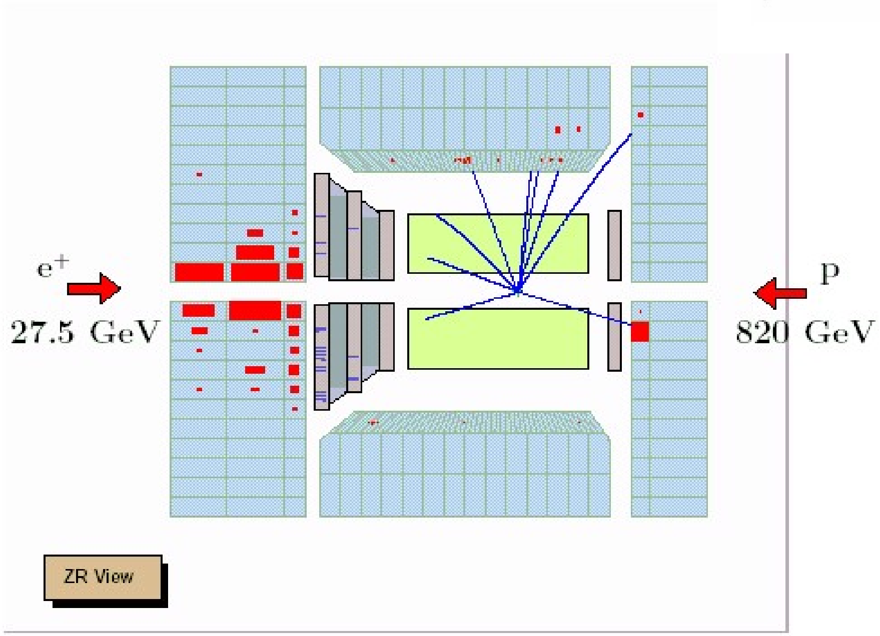
Changing electron beam energy via ISR

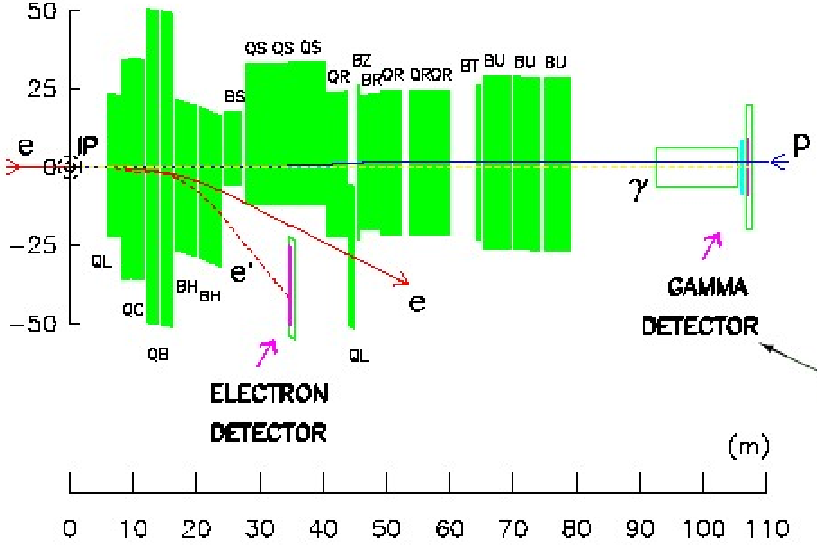


Jo Cole DIS03, St. Petersburg

Identifying ISR Events with the ZEUS Detector

- ▷ Standard DIS event selection:
  - – identify scattered positron in main detector
- ▷ Identify ISR photon in luminosity monitor





Normally used identify photon in $ep \rightarrow ep\gamma$

Structure Function measurements using ISR events 4

ZEUS: Measure F_L with ISR events

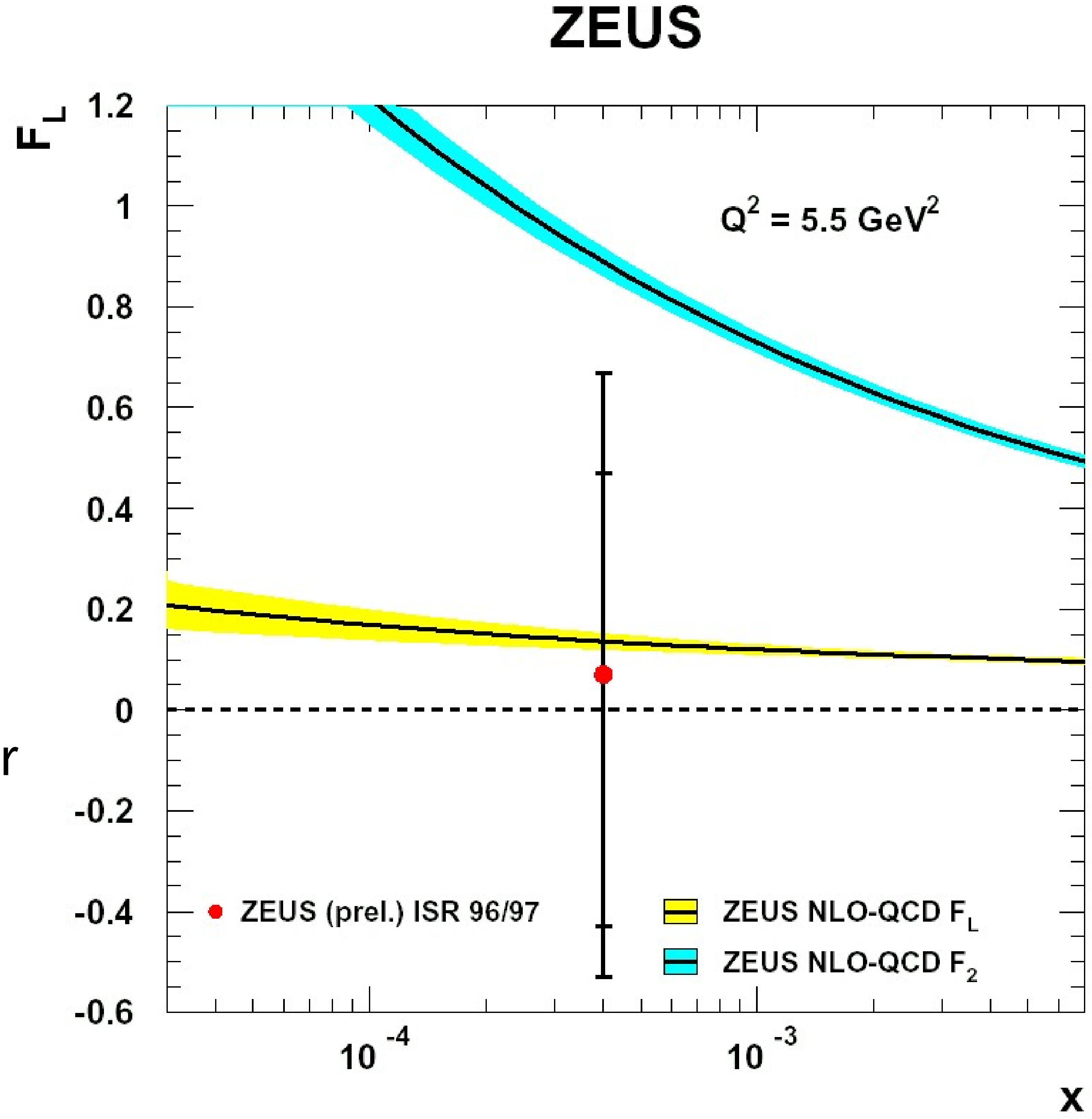
It is a measurement!

BUT:

Need in fact very large statistics (200 pb^{-1})

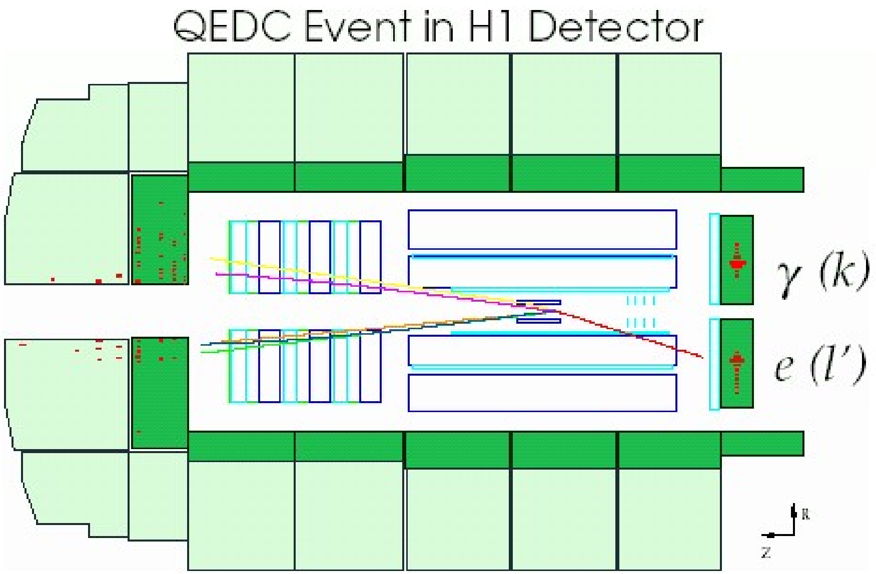
Overlap at the same x and Q^2 is in fact not very big

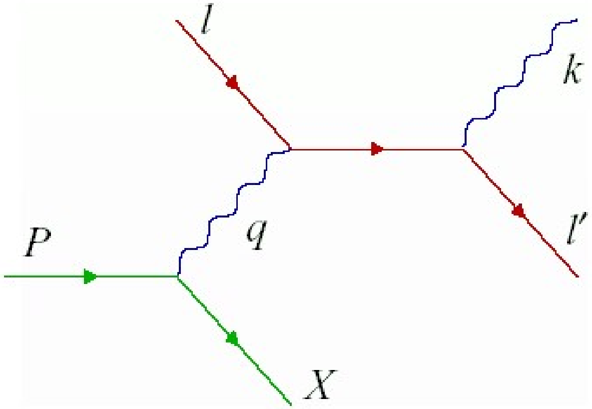
Pile-up of Bethe-Heitler events in photon detector is a problem
--> huge errors!



Measurement of F_2 at low Q^2 and low x

H1: QED Compton events and F_2 at low Q^2





Modified kinematics

Access lower Q^2 and higher x

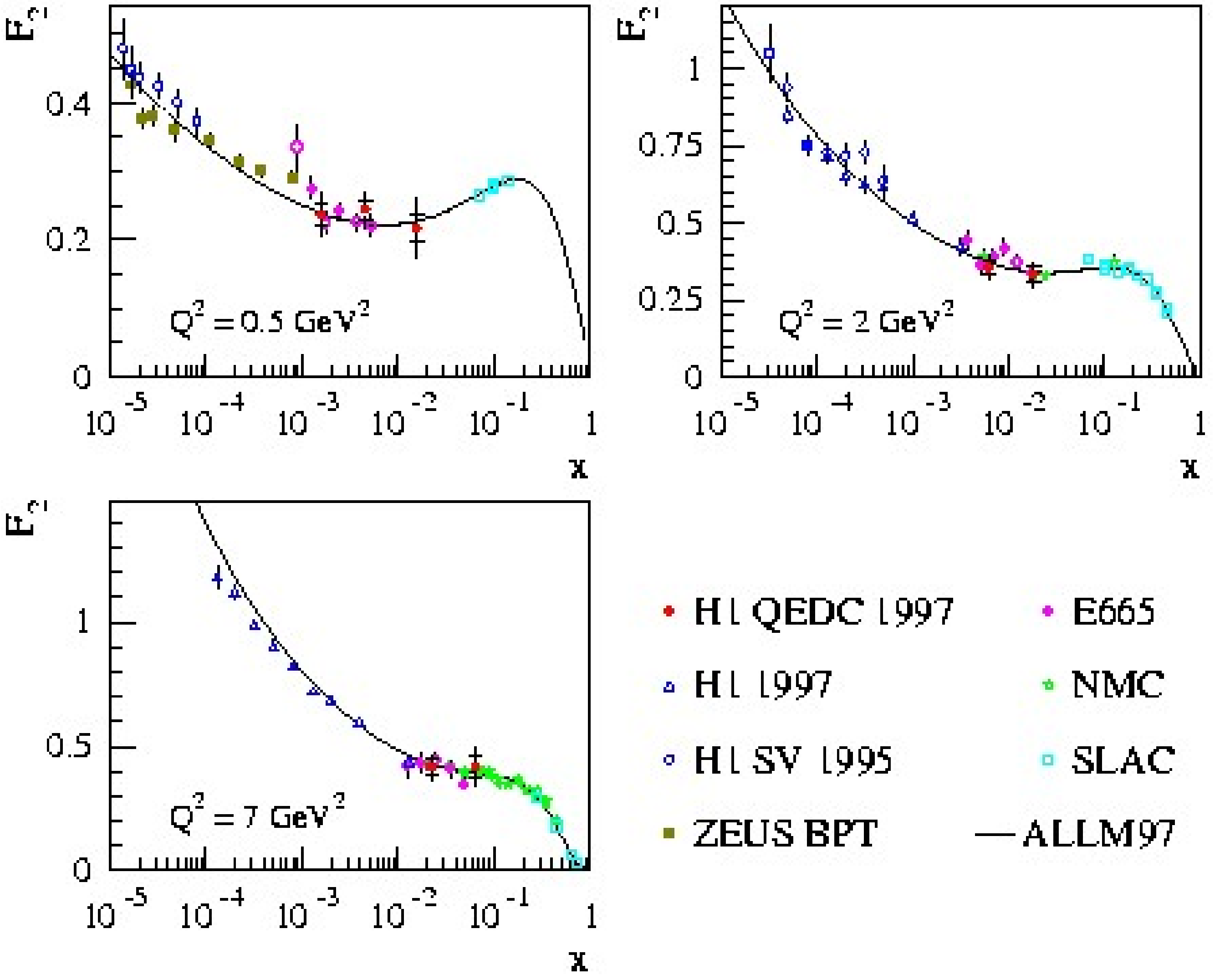
$$Q^2 = -q^2 = -(l - l' - k)^2 \,,$$

$$x = \frac{Q^2}{2P \cdot (l - l' - k)}$$

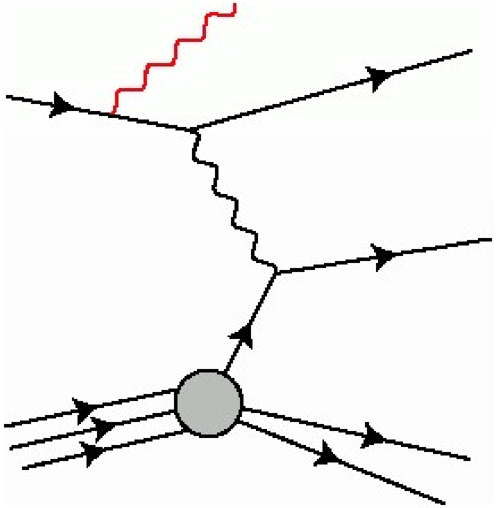
F_2 measurement with QEDC events

Low Q^2 but higher x

Good agreement with the fixed target experiment results



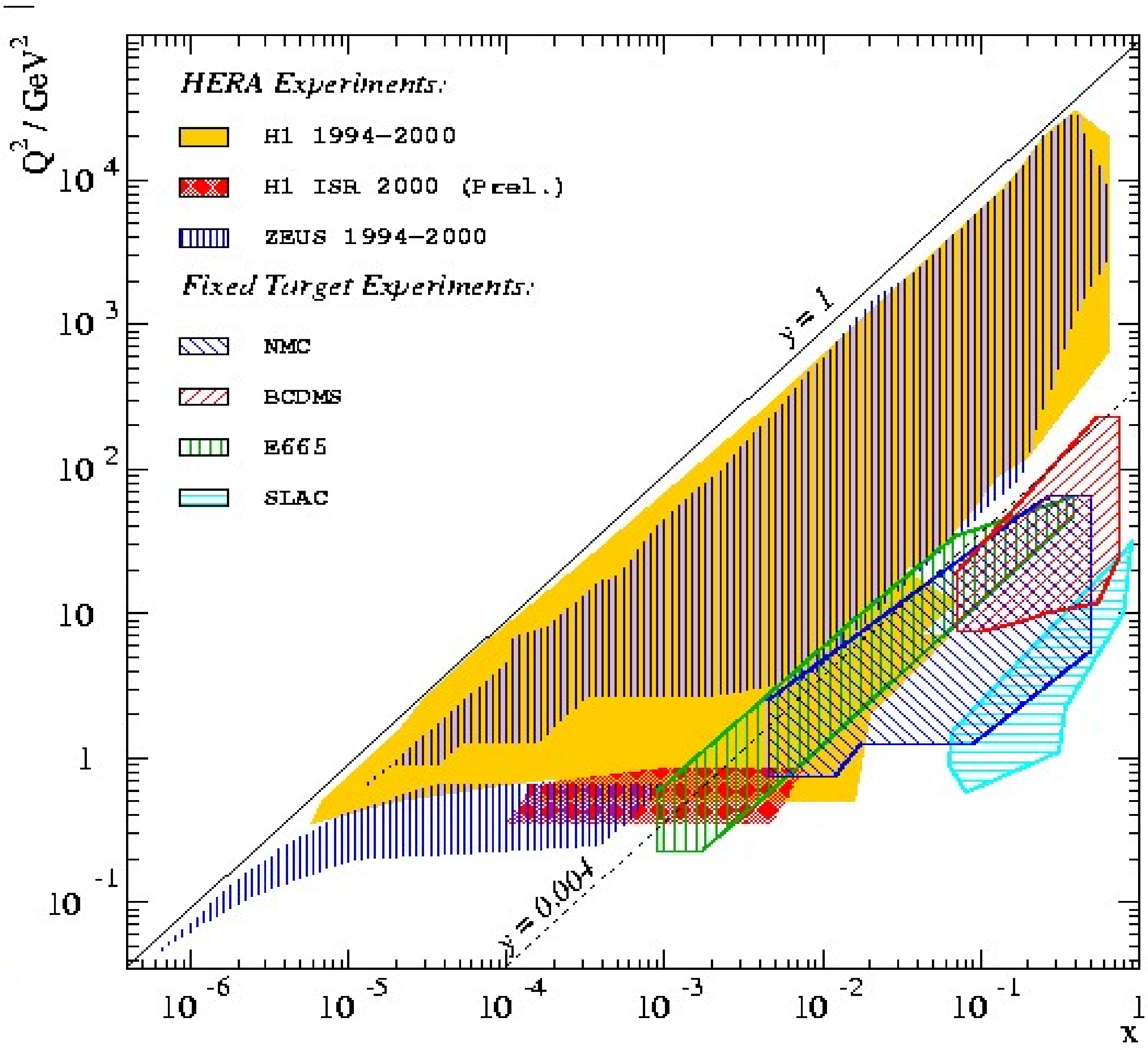
Low Q^2 but higher x, with SVTX00 ISR events



Equivalent to inclusive DIS at reduced s

$$Q^2 = xys$$

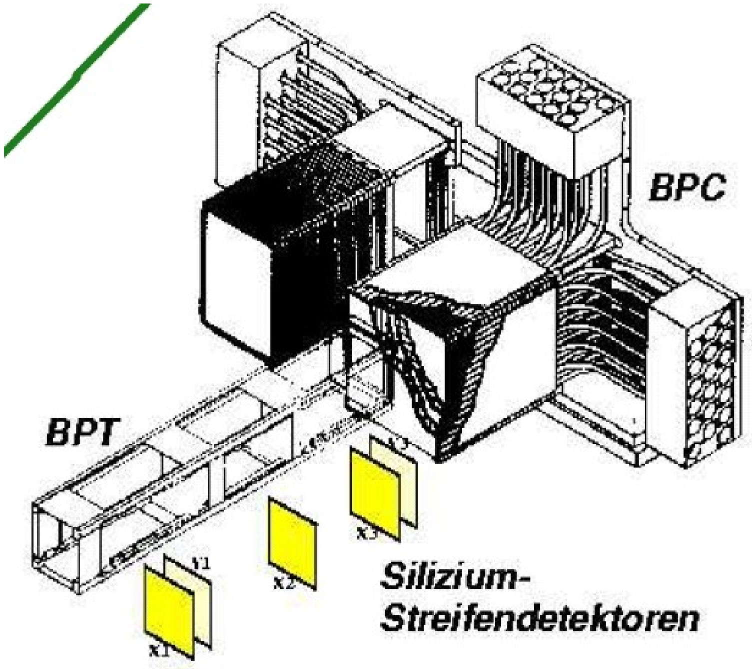
Access higher x

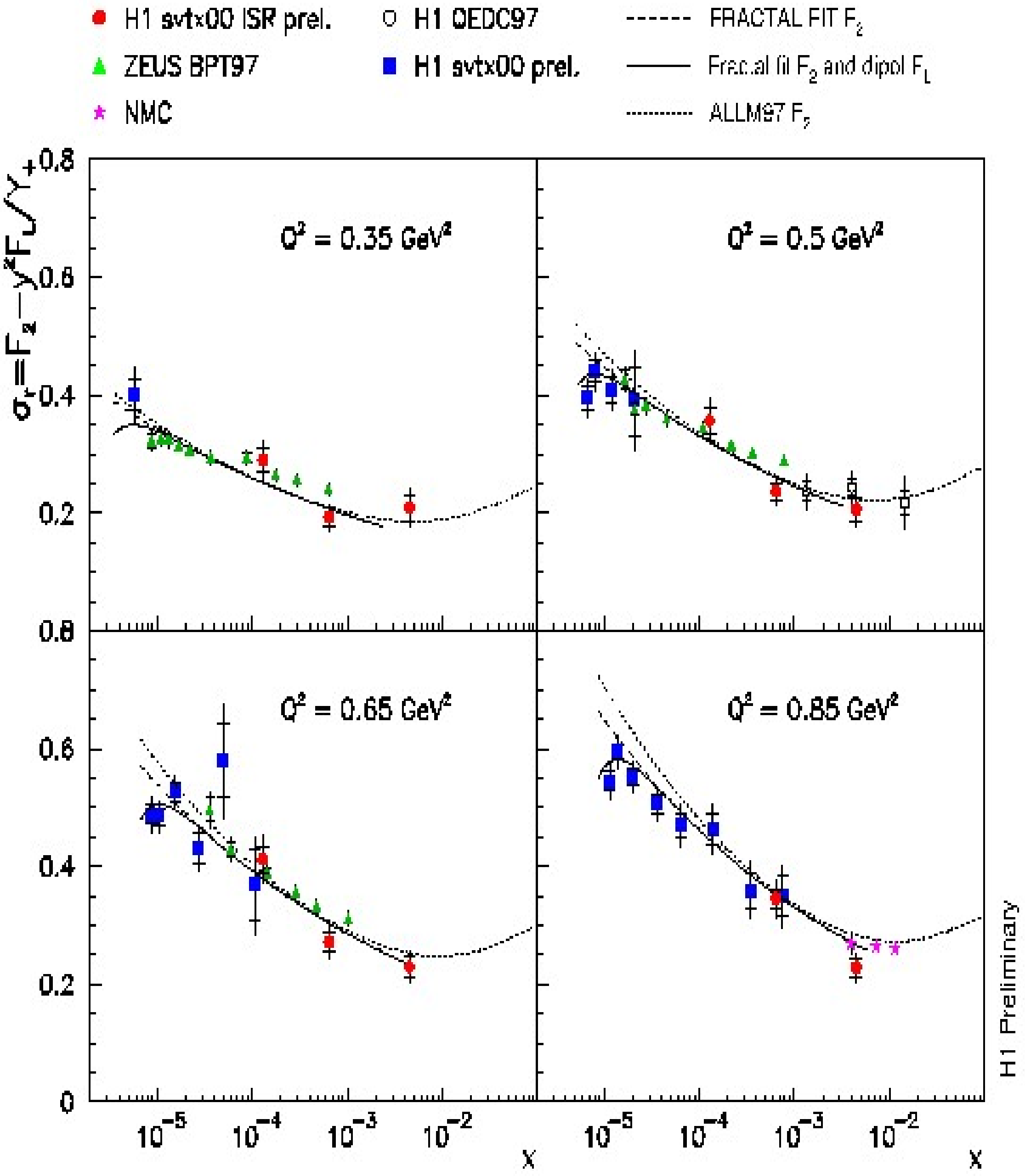


Measurement of F_2 with SVTX00 ISR events

Very low Q^2

Small overlap with Fixed Target data





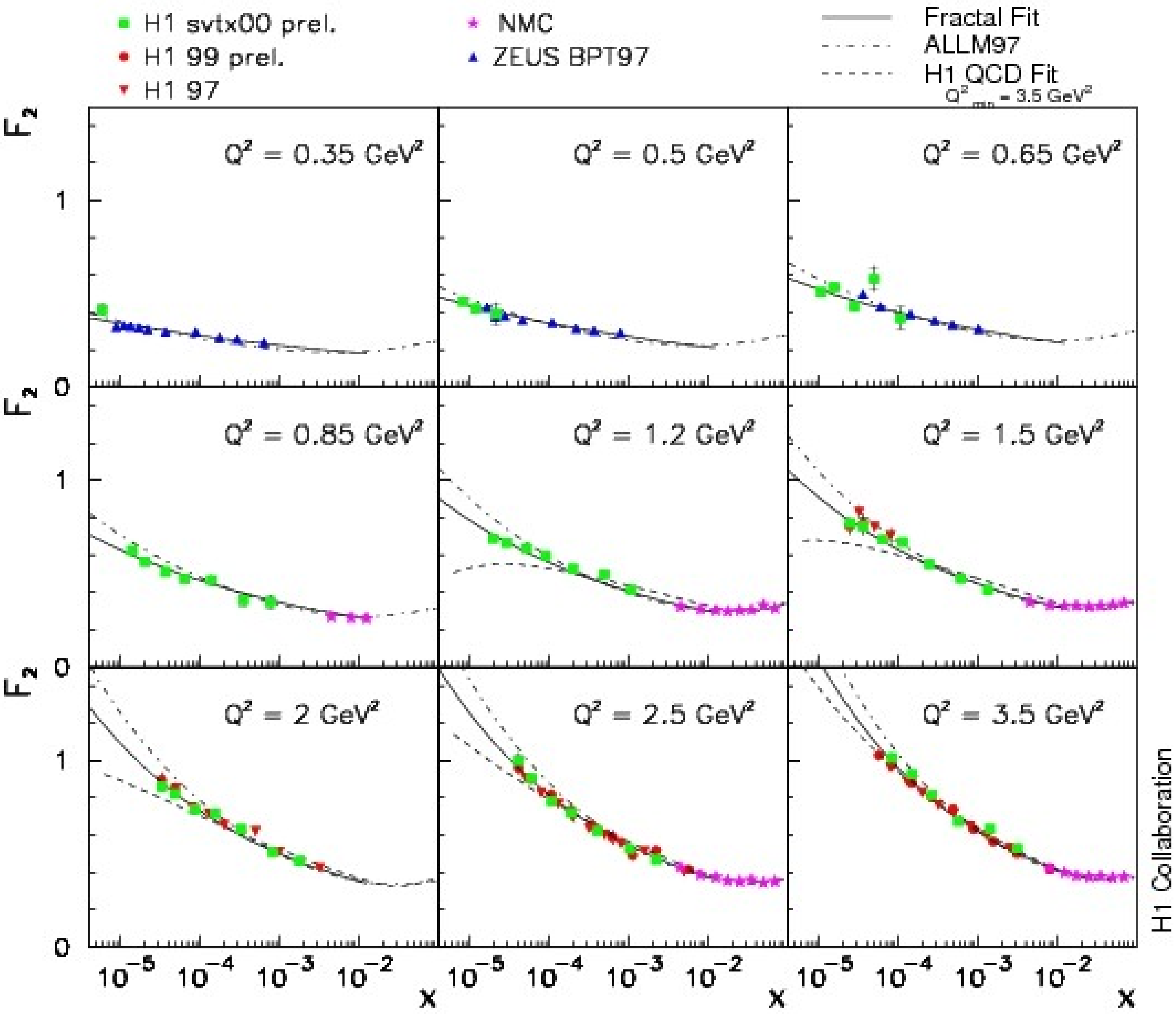
Measurements of F_2 at lowest Q^2

Extrapolation of
H1 QCD Fit into
the low Q^2 region

Fit uses data with
$Q^2 > 3.5$ GeV^2

Undershoots data

NLO QCD not
expected to work
at these low Q^2 values



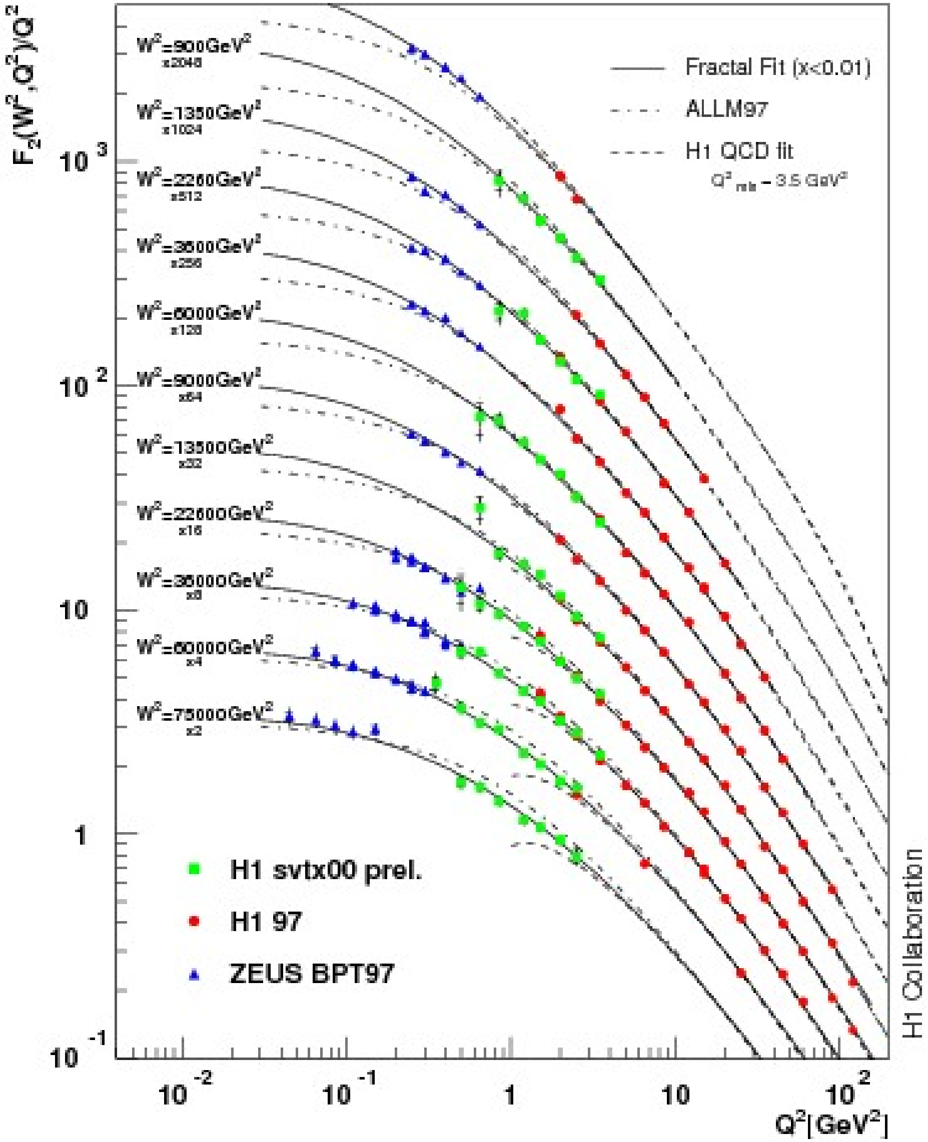
Measurements of F_2 at lowest Q^2

Virtual photon cross section,

$$\sigma_{\gamma^* p} \propto F_2/Q^2$$

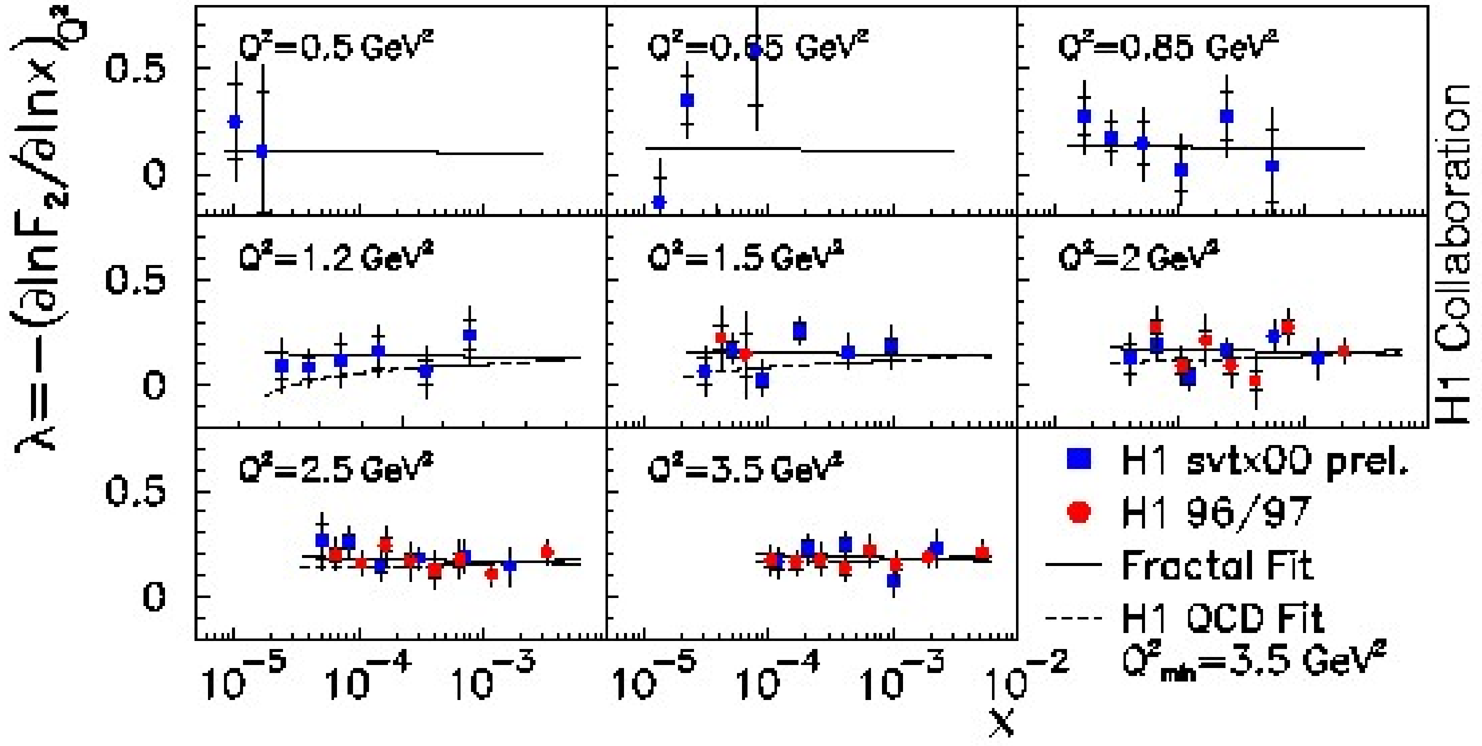
as function of Q^2 at fixed

$$W^2 \simeq sy$$



Measurements of F_2 at lowest Q^2

Take the derivative $(d \ln F_2(x, Q^2)/d \ln x)_{Q^2} = -\lambda(x, Q^2)$



Constant in x, at any given Q^2

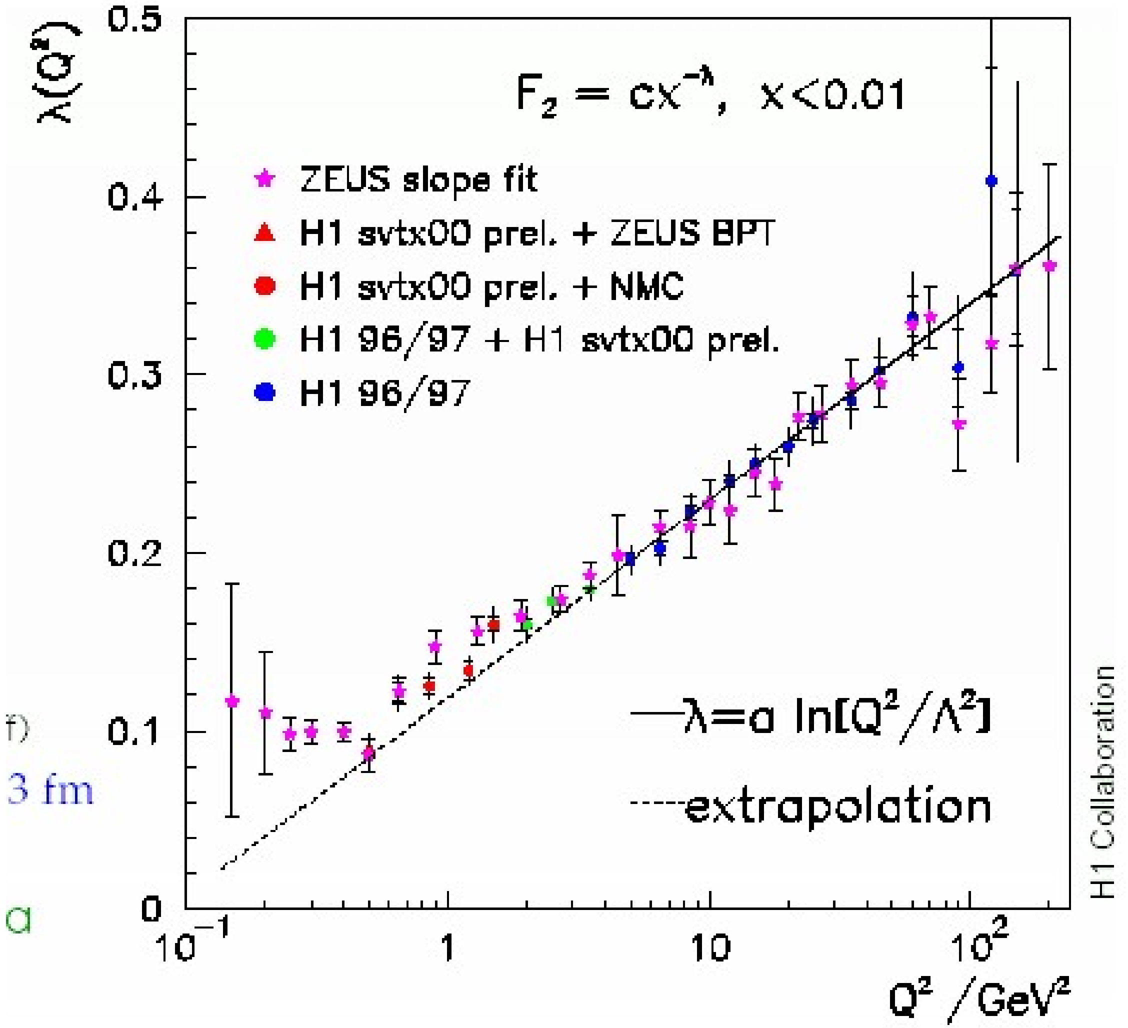
$\lambda(x, Q^2)$ ==> Function of Q^2 only

F_2 at low Q^2

Rise of F_2 at low x can be parameterised as

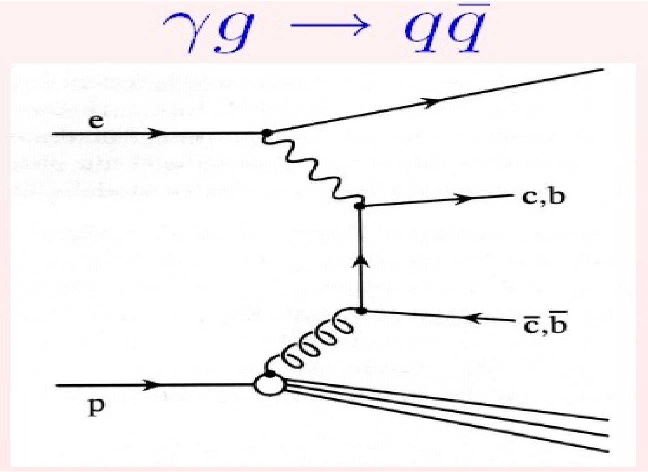
$$F_2(x,Q^2) = c(Q^2)x^{-\lambda(Q^2)}$$

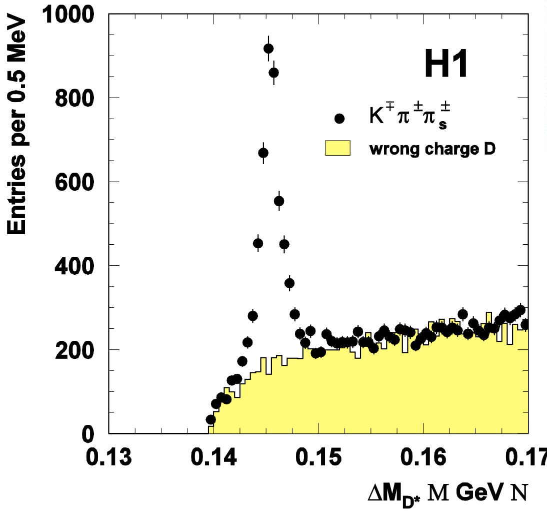
$\lambda(Q^2)$ is ~ ln Q^2 above 3 GeV^2

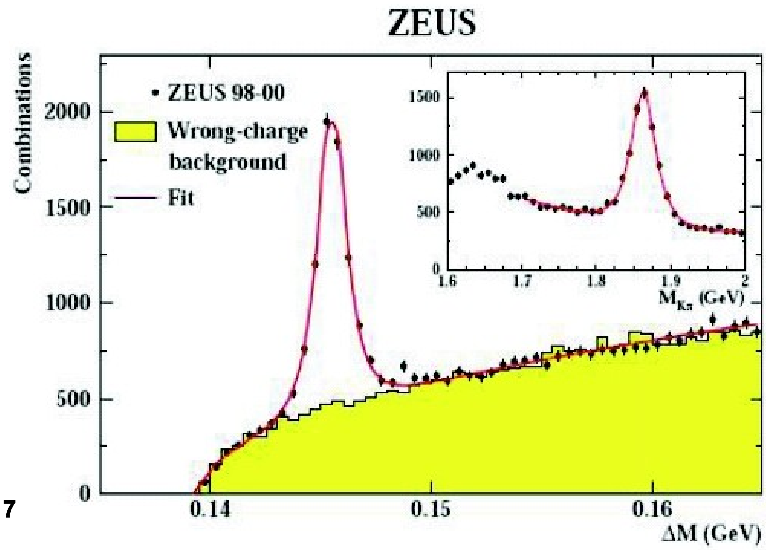


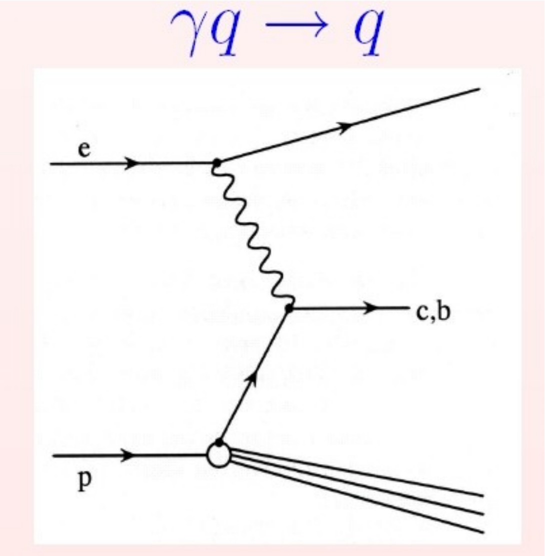
$\lambda(Q^2)$ approaches the value 0.08 at lowest Q^2 -- Transition to “soft physics”

F_2 for heavy quarks, c and b









Theoretical description complicated by the presence of several “hard scales”, Q^2, m^2_Q and p_T^2

Variable Flavour number schemes

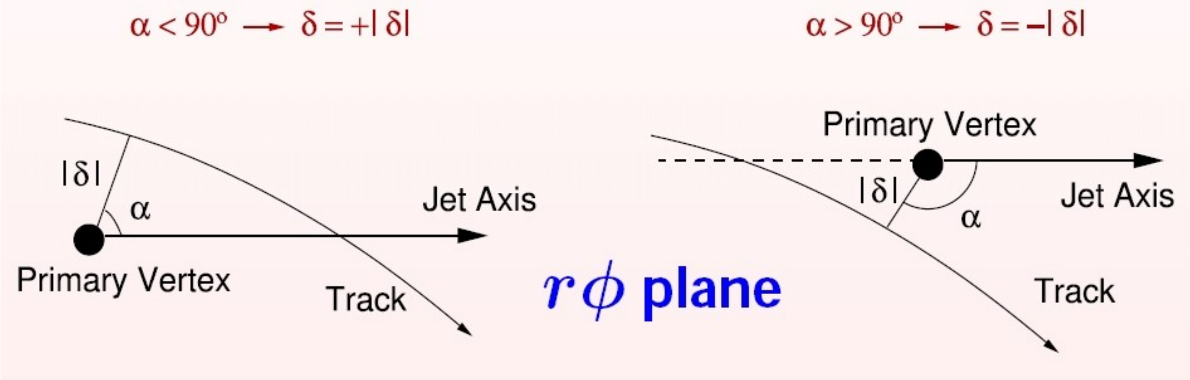
Sensitivity to gluon distribution in proton (at high Q^2 up to 35% charm content!)

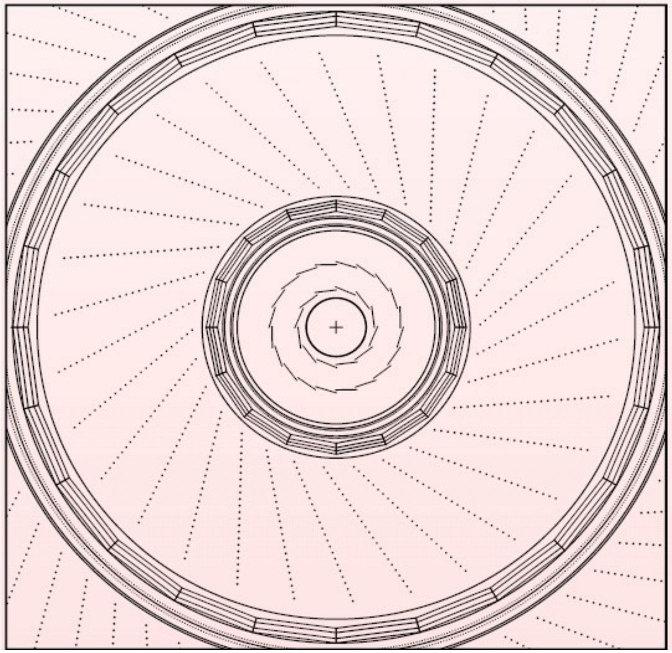
F_2 for heavy quarks, c and b


H1 CST

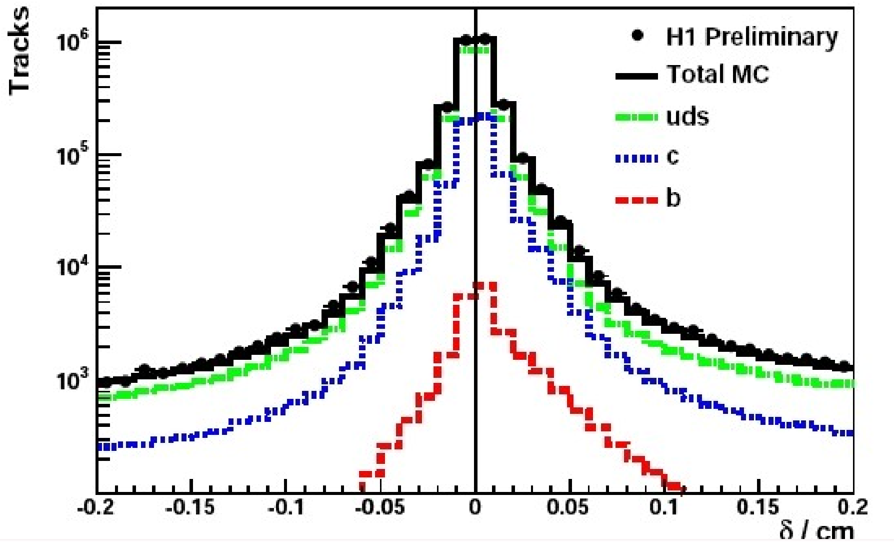
Vertex tracking to determine impact parameters of tracks

Determine signed impact parameter δ
(Distance of Closest Approach)
and its Significance $S_i = \delta/\sigma(\delta)$



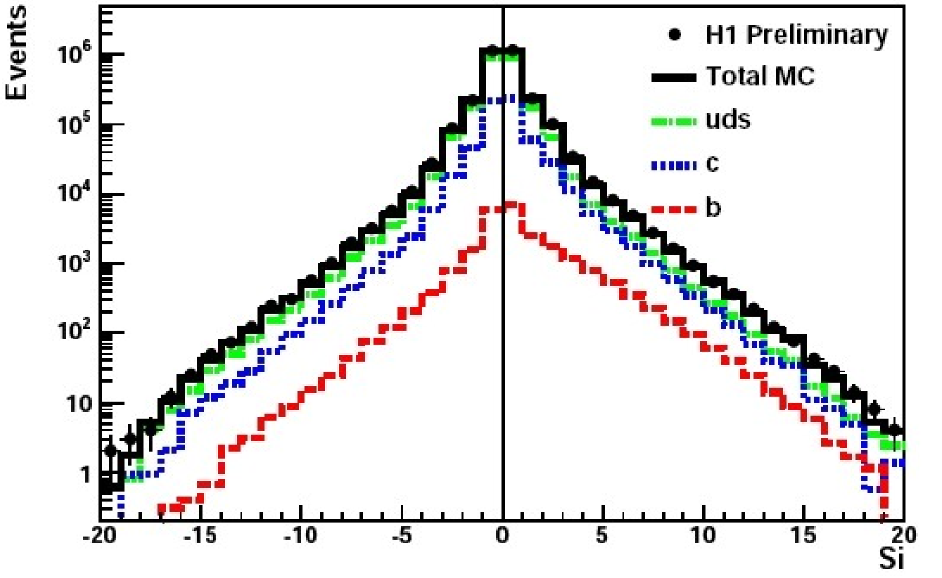


F_2 for heavy quarks, c and b



Define S_1, S_2, S_3
for the most significant track,
2nd most significant, etc.

In principle, heavy quark fractions can be fitted from these distributions

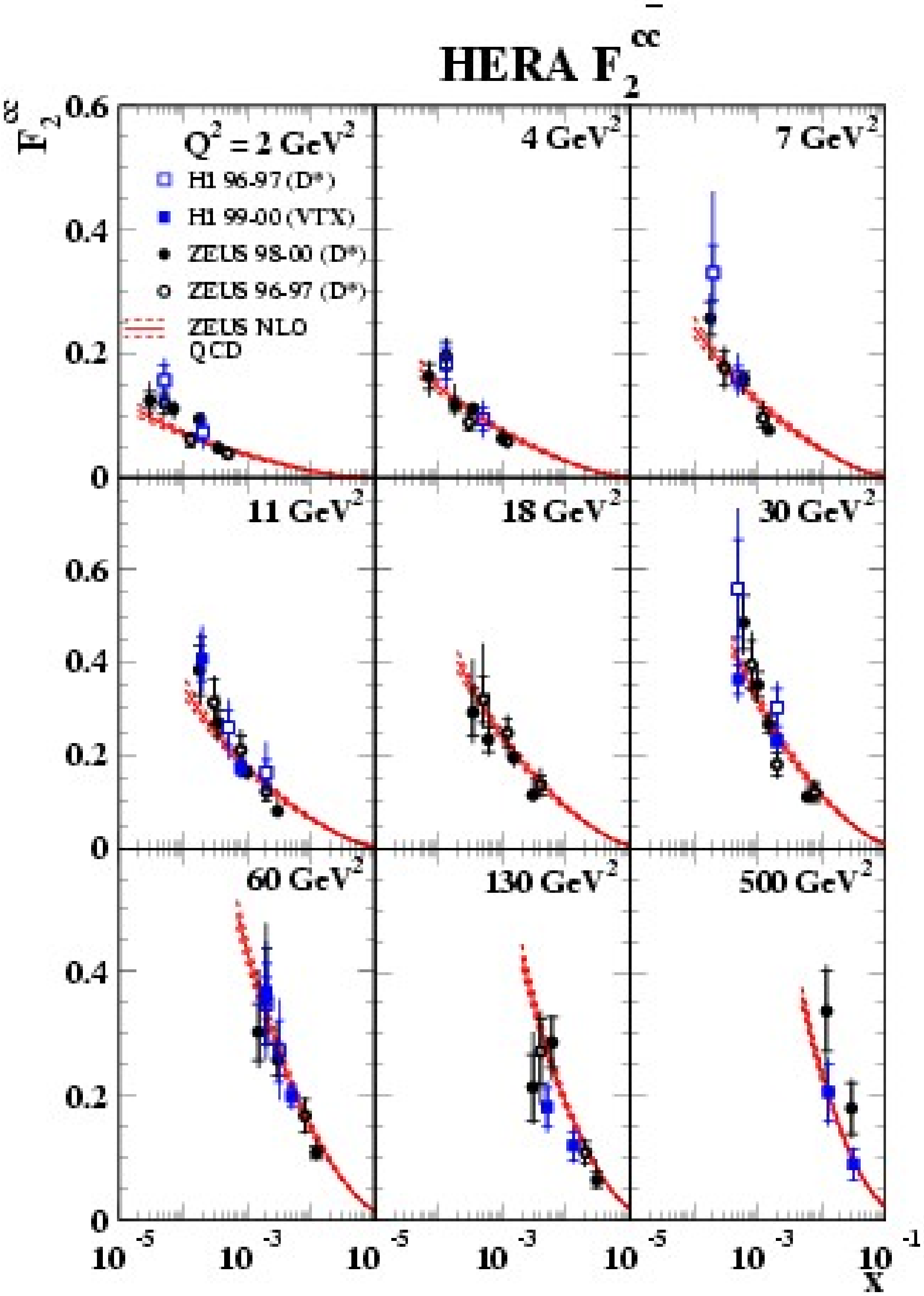


From the fitted fractions of events, the $c\bar{c}$ and $b\bar{b}$ cross sections can be determined, as functions of x and Q^2.
From these cross section measurements, $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ can be evaluated.
(The F_L contribution is estimated from the NLO QCD expectation)

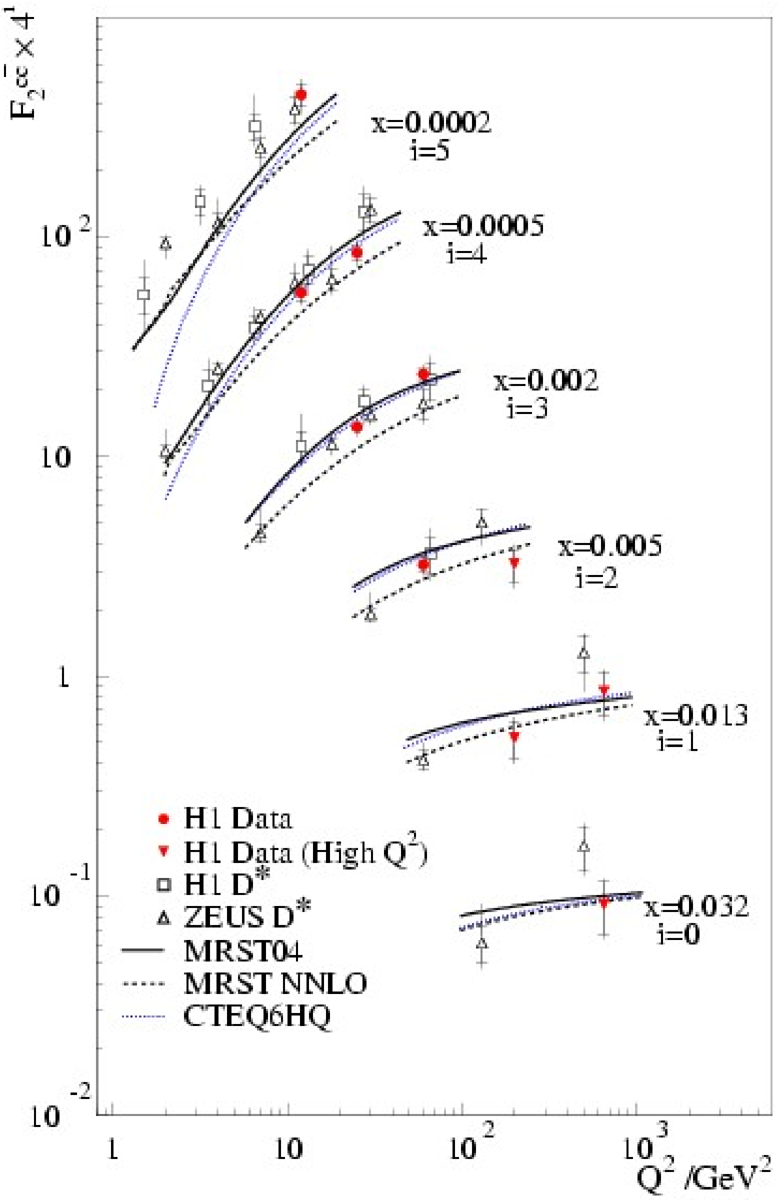
F_2 for heavy quarks, c and b

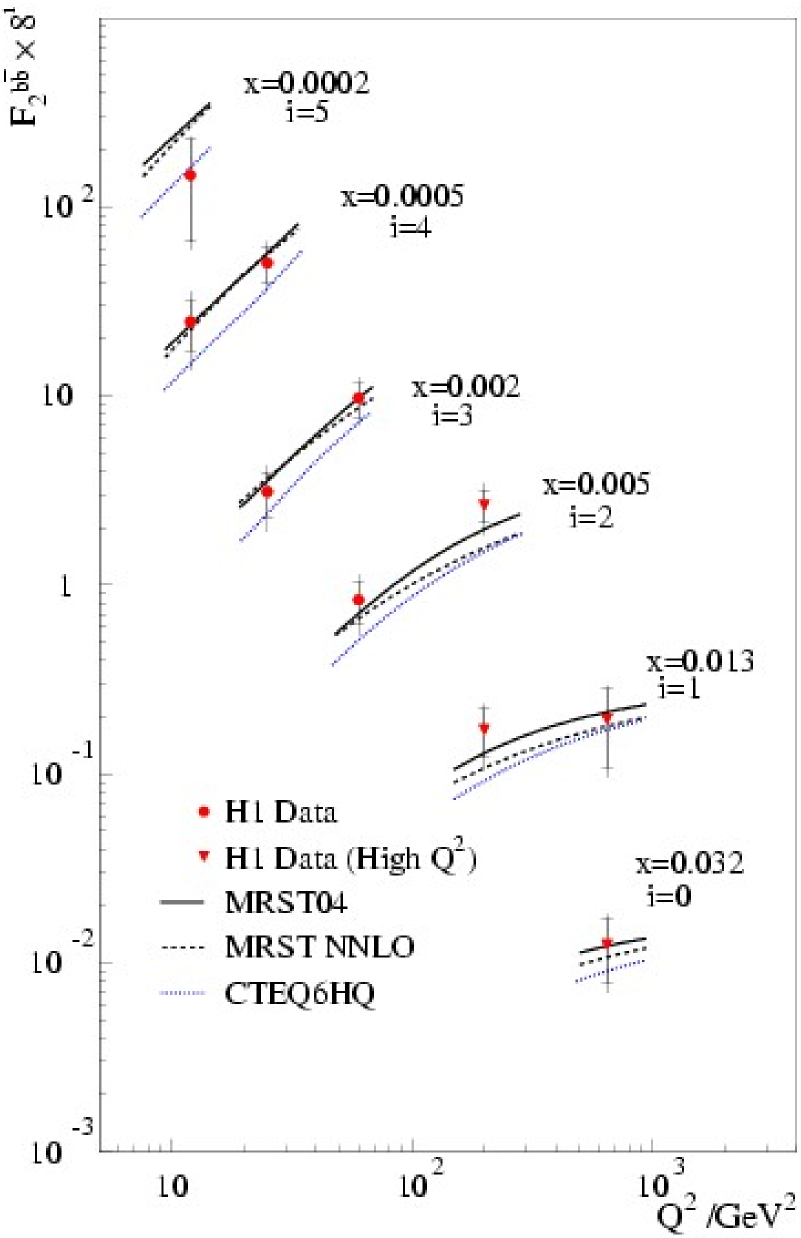
Consistent with the NLO QCD fit predictions

Shows the same features as F_2 for the light quarks



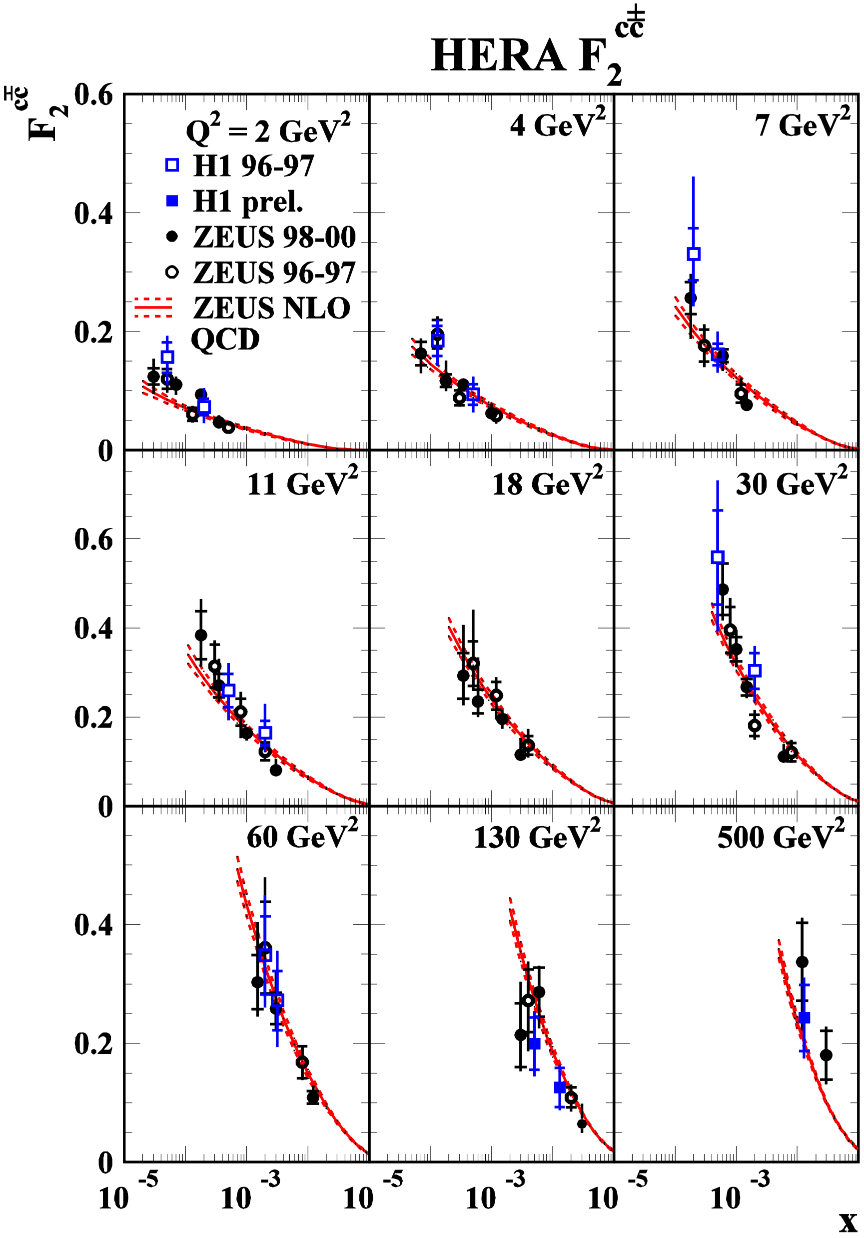
F_2 for heavy quarks, c and b

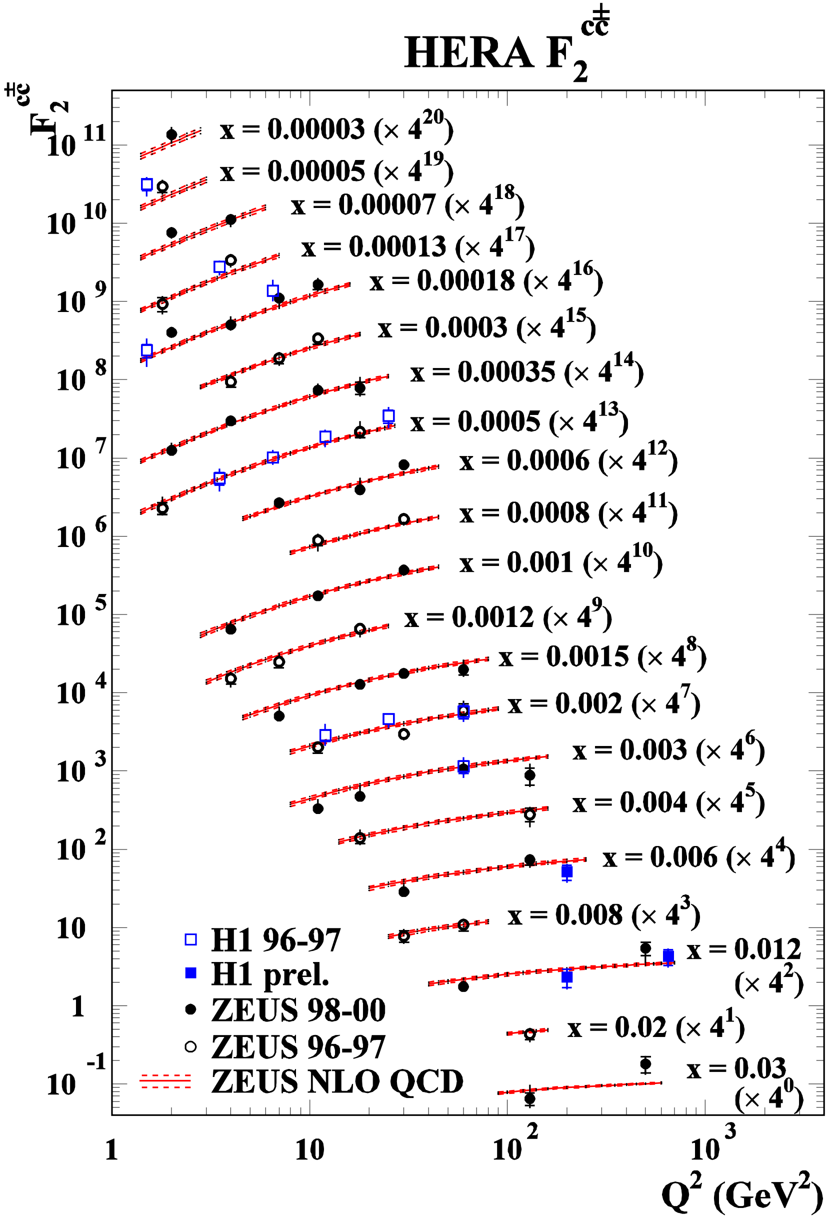




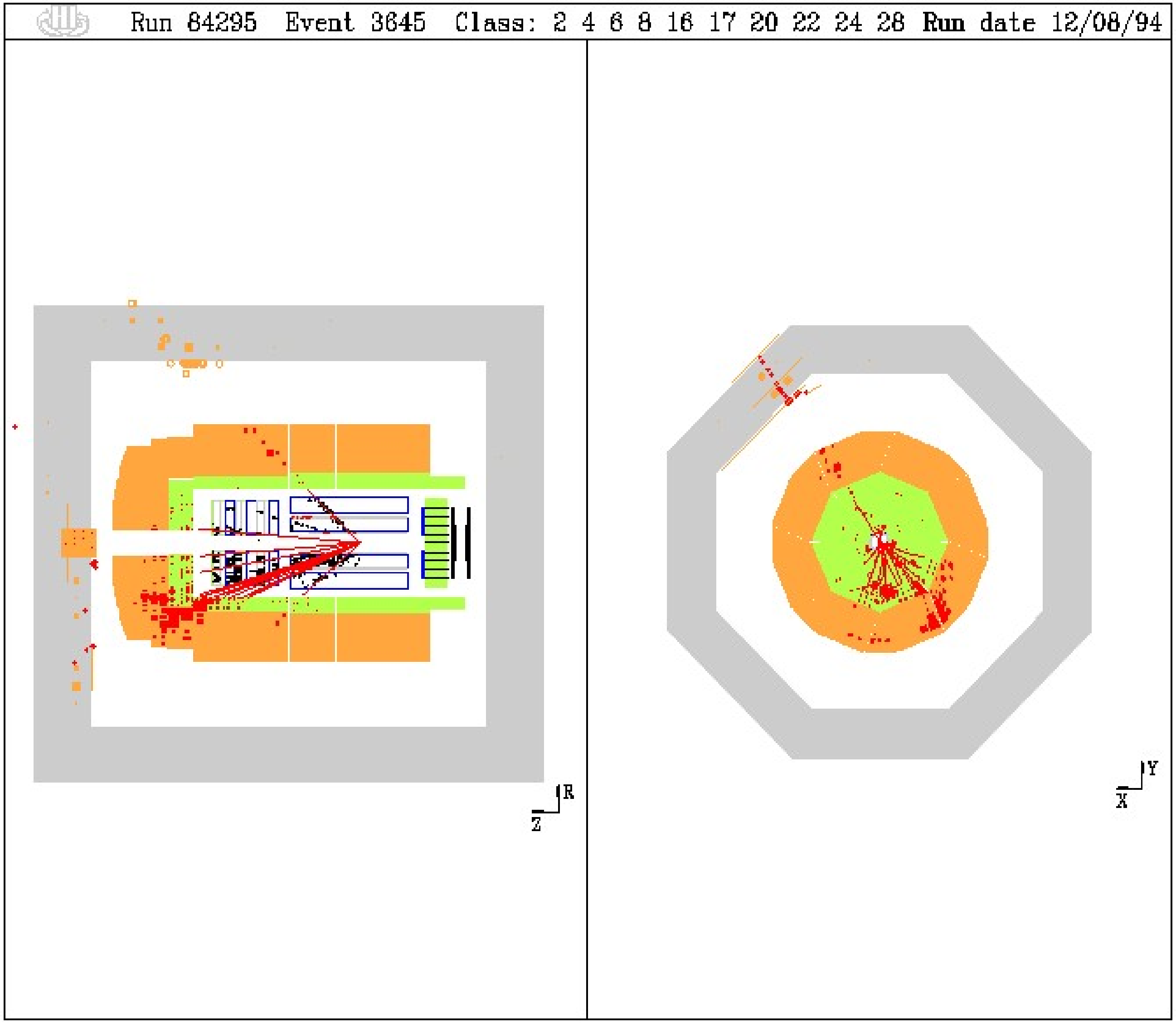
F_2 for heavy quarks, c and b

Summary of charm structure from HERA



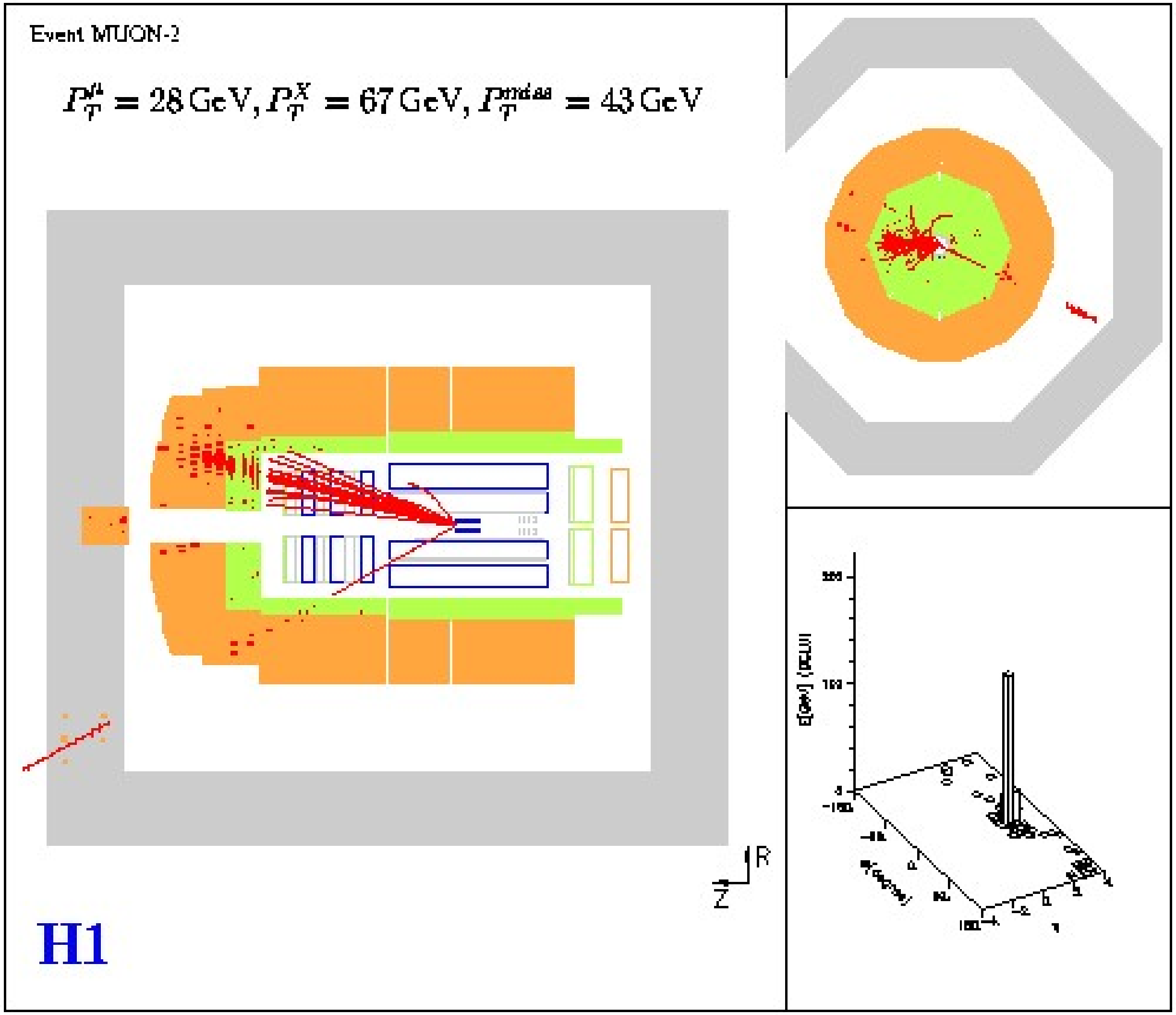


Events with isolated lepton and missing p_T



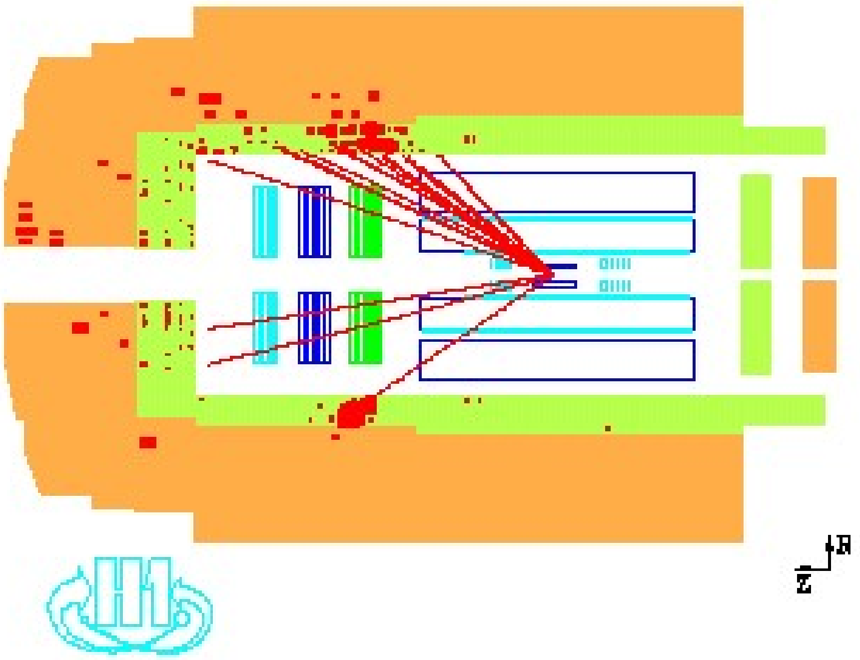
Events with isolated lepton and missing p_T

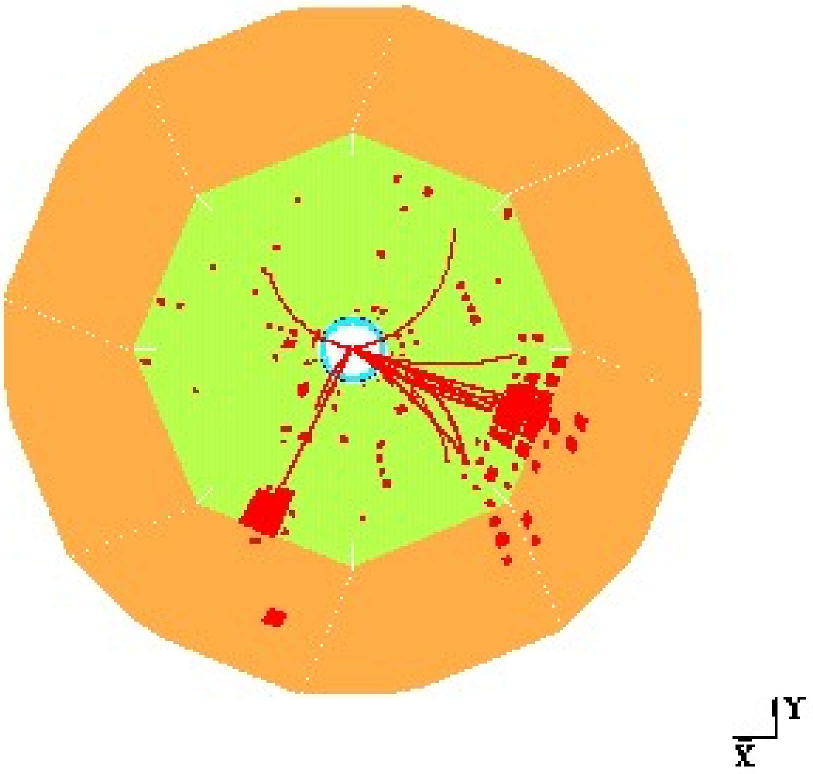
$$e^+p \rightarrow \mu^+X$$



$P_T^{\mu} = 28\,\mathrm{GeV}, P_T^{X} = 67\,\mathrm{GeV}, P_T^{miss} = 43\,\mathrm{GeV}$

Events with isolated lepton and missing p_T



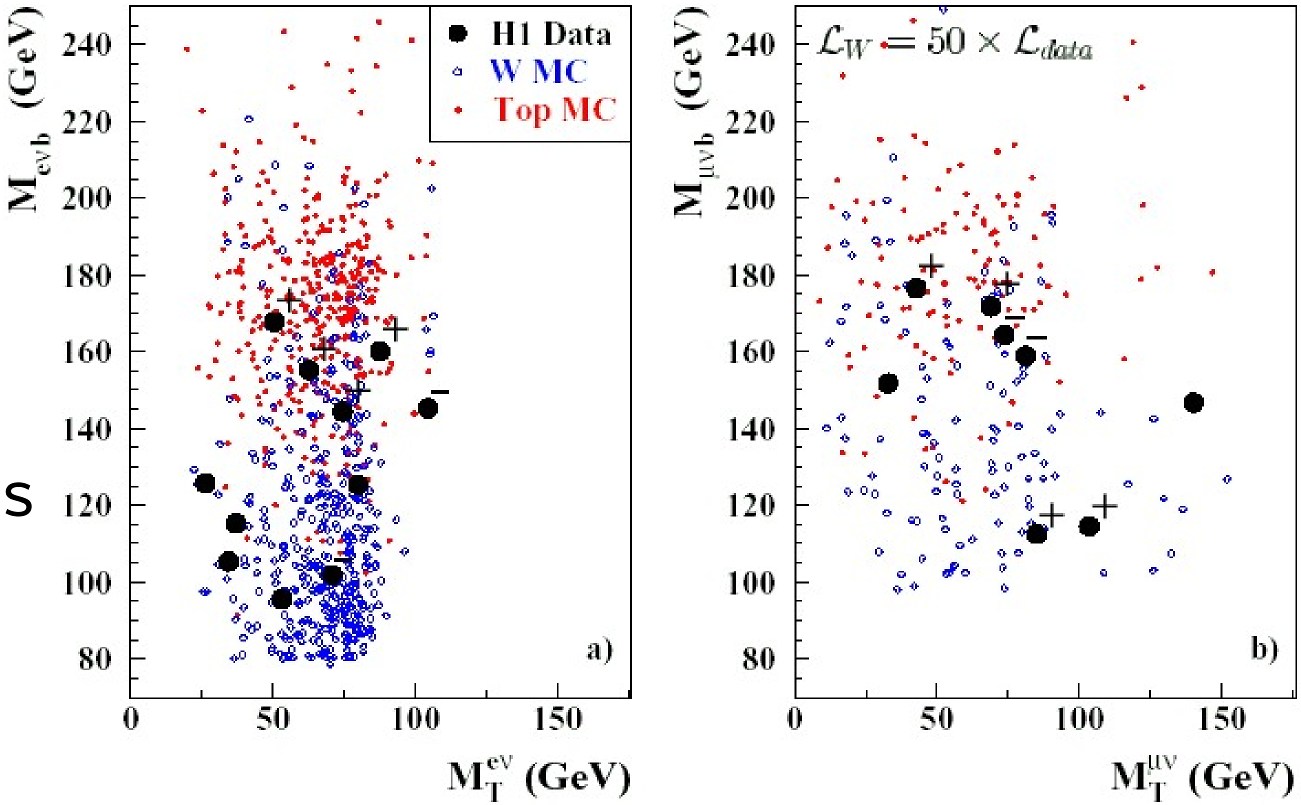


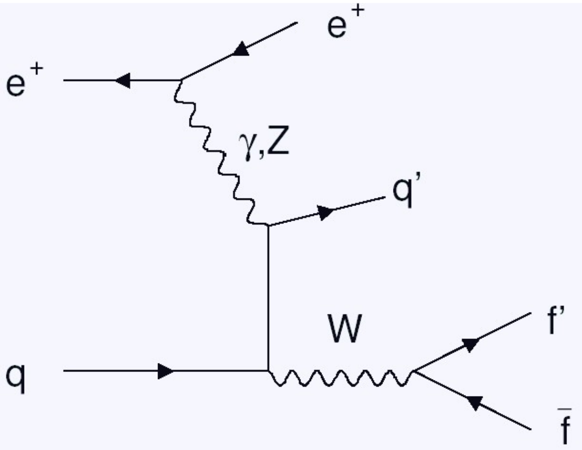
Events with isolated lepton and missing p_T

Some events agree with the SM process of W-production

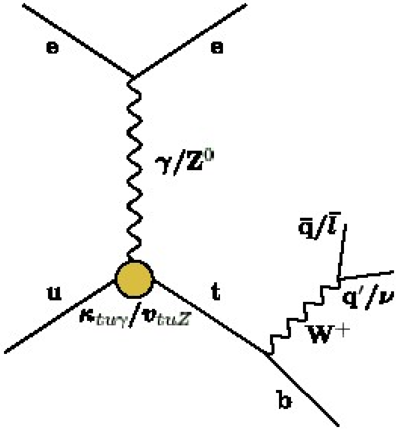
Others do not agree with the expected kinematics of this process

(simulation data correspond to 500 times greater luminosity than the real data have)



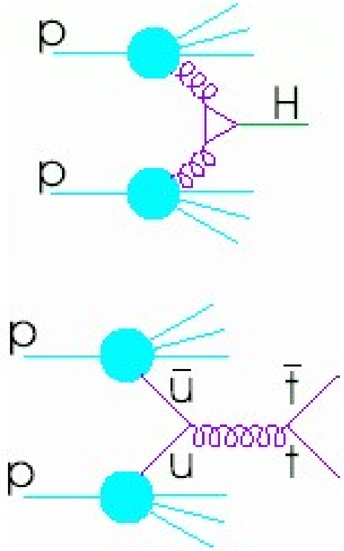


Exotic, non-SM process: Anomalous top-quark production?

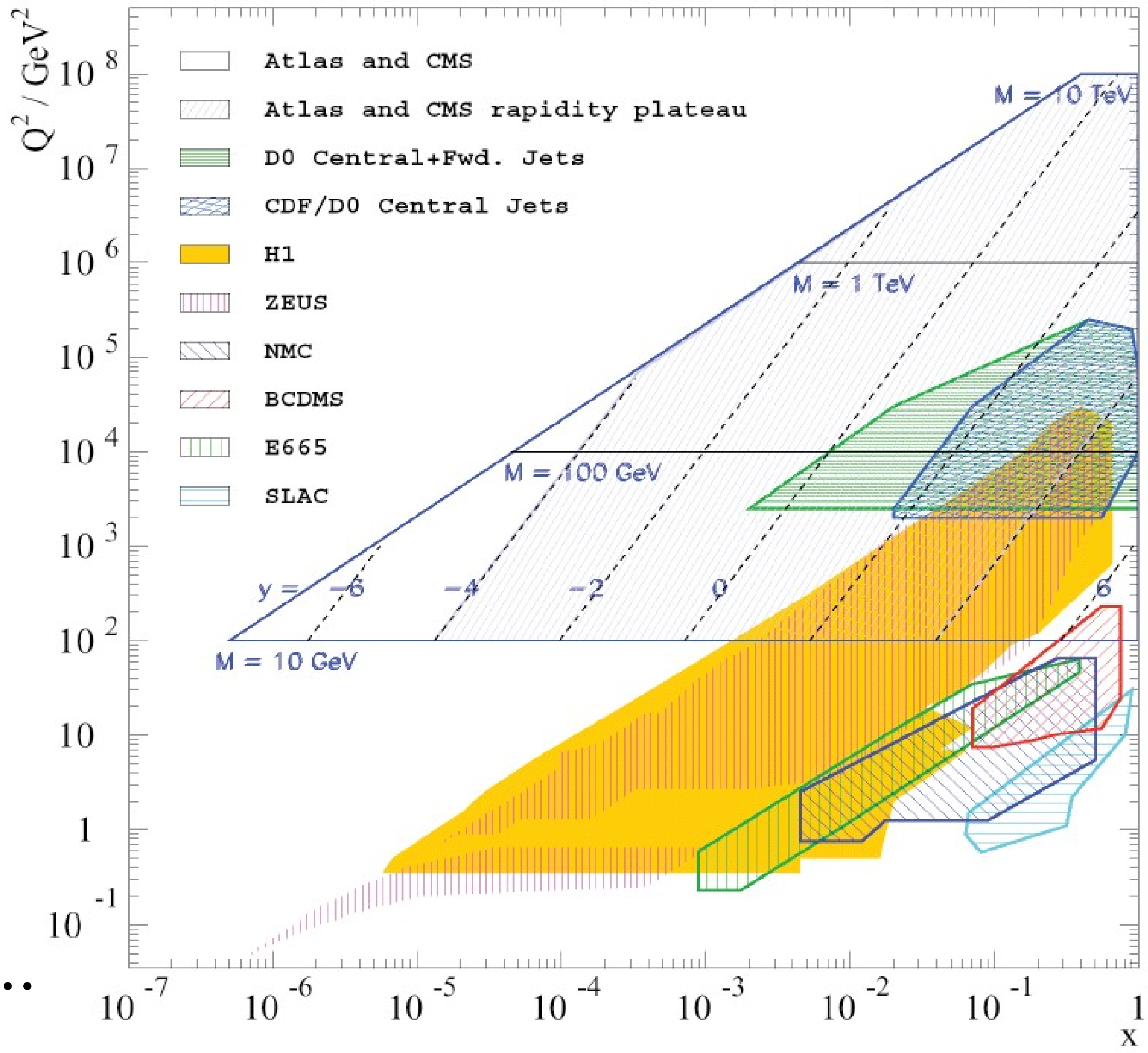


Why is Proton Structure important ?

HERA and LHC: The importance of proton PDF's



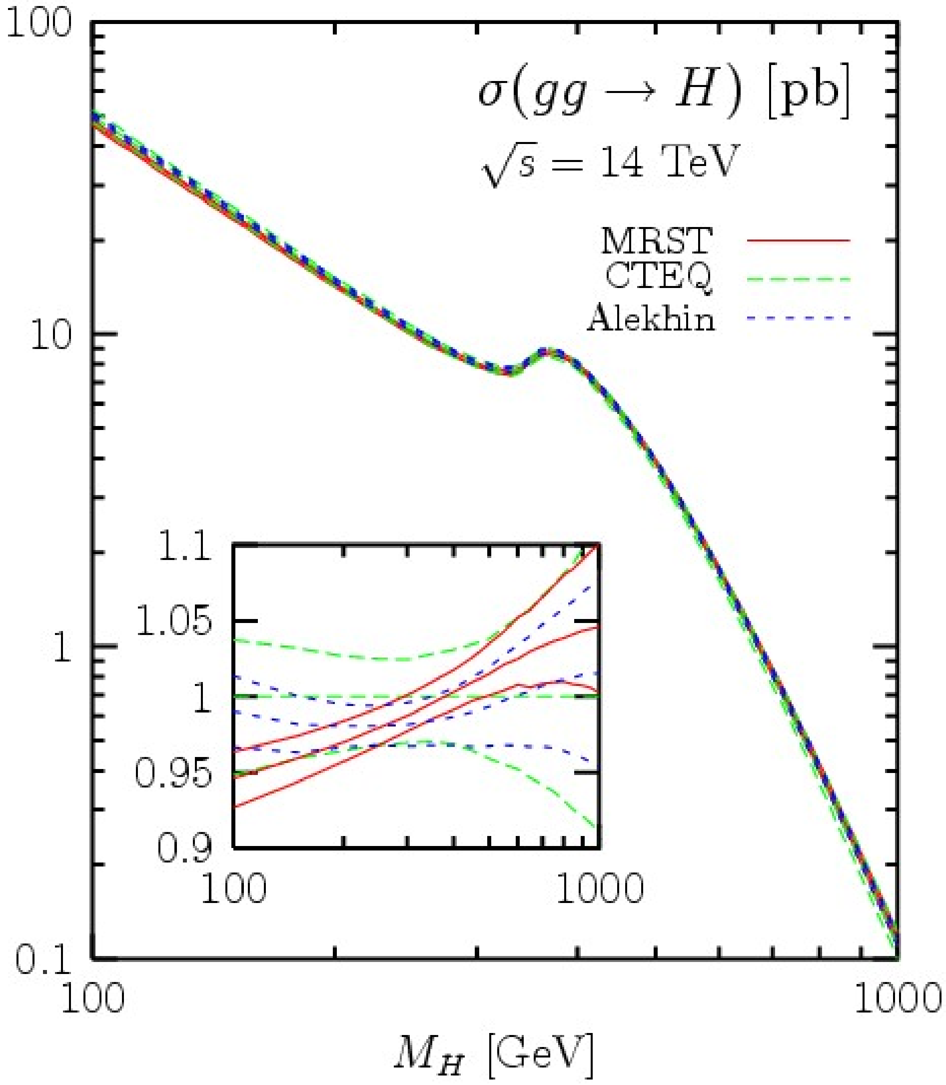
Production of
Higgs boson,
top-antitop quark pairs...



HERA and LHC: The importance of proton PDF's

To see the Higgs boson,
you must know the
background !

Proton structure,
as explored at HERA,
is absolutely vital for the
discovery of the Higgs boson!



We wish the National Centre for Physics at Islamabad
all the best for a bright future and a great success
in their taking part in the LHC adventure at CERN