Introduction to Deep Inelastic Scattering (DIS)

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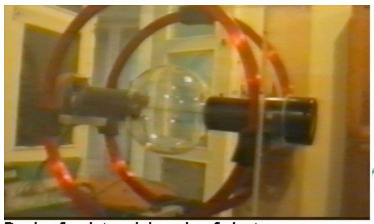
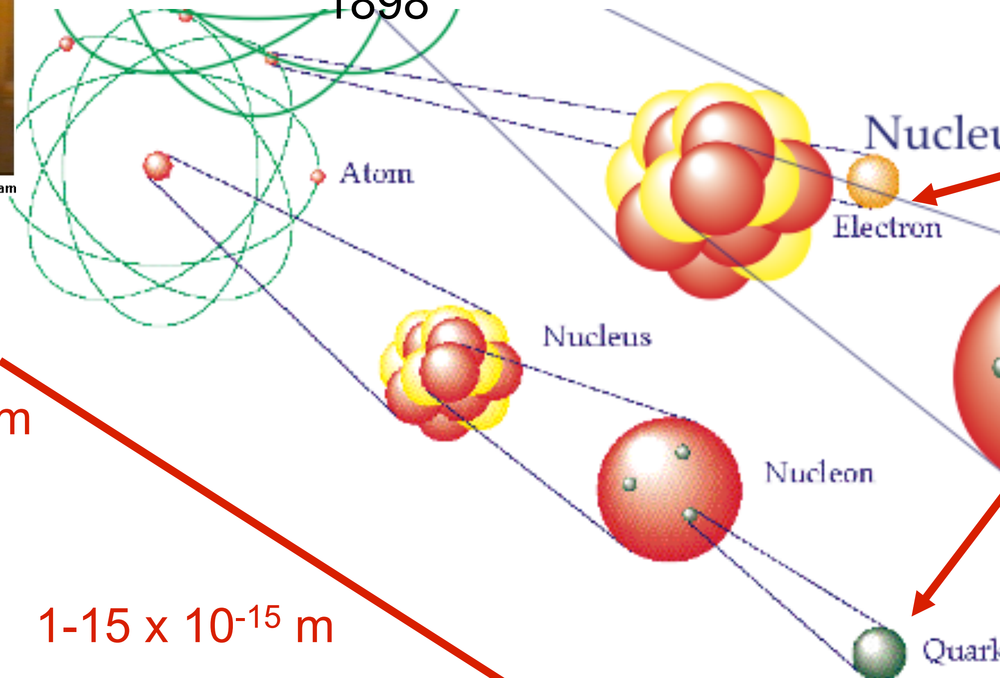
2009 CTEQ Summer School
Madison, WI

Inelastic Scattering – Probing the Structure of Matter



Device for determining q/m of electrons photo-Team

1898



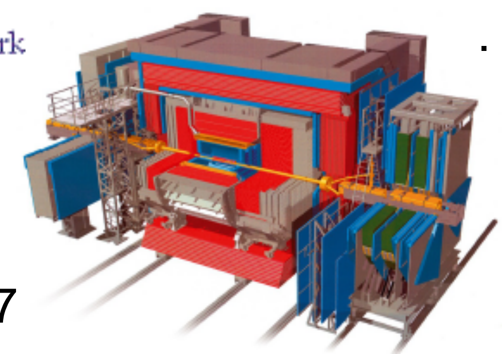
Pointlike?
$< 10^{-18}$ m

~few 10^{-10} m

1-15 x 10^{-15} m

~ 10^{-15} m

ZEUS detector:



1992-2007

Quark-Parton Model (QPM) of DIS

Feynman's QPM explanation of DIS : the nucleon is made up of point-like, spin-1/2, non-interacting constituents – the quarks as partons. DIS is the *incoherent* sum of elastic scattering from these quarks.

Furthermore, the probability f(x) for the quark f to carry a fraction x of the nucleon momentum is an intrinsic property of the nucleon and is *process independent*.

We now know that QCD describes quark interactions with the addition of another "parton" - the gluon (QCD-improved QPM).

- Nucleons are just a "beam of partons" (*incoherent*).
- The f(x)s, the "beam parameters", could be measured in some other process (*process independent*).

Quarks and Gluons as Partons

$u(x)$: up quark distribution
$\bar{u}(x)$: up anti-quark distribution
etc. (d,s,c,b,t) and
$g(x)$: gluon (spin-1)

Momentum has to add up to 1 ("momentum sum rule") :

$$\int x[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)+s(x)+\bar{s}(x)+\ldots+g(x)]dx = 1$$

Quantum numbers of the nucleon have to be right :

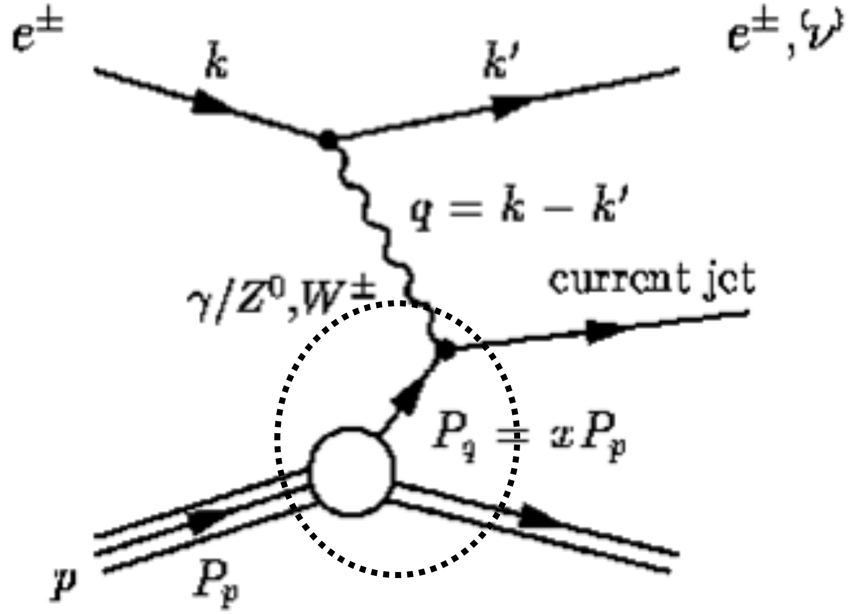
So for a proton :

$\int[u(x)-\bar{u}(x)]dx=2$ # u_{val} $\int[d(x)-\bar{d}(x)]dx=1$ # d_{val}

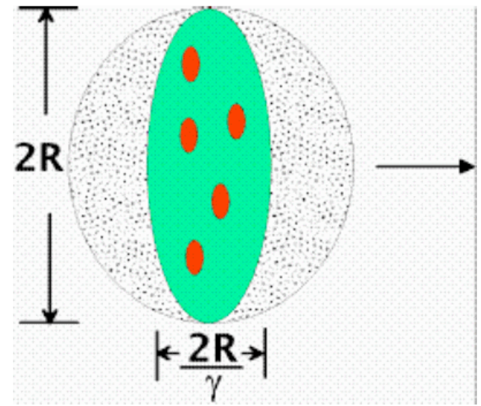
$\int[s(x)-\bar{s}(x)+\ldots\ldots]dx=0$ "sea" quark contribution

DIS Kinematics – Scattering Variables

ep scattering



proton in "∞" momentum frame



No transverse momentum

$\boxed{0 \le x \le 1}$

x = fractional longitudinal momentum carried by the struck parton

y = fractional energy transfer

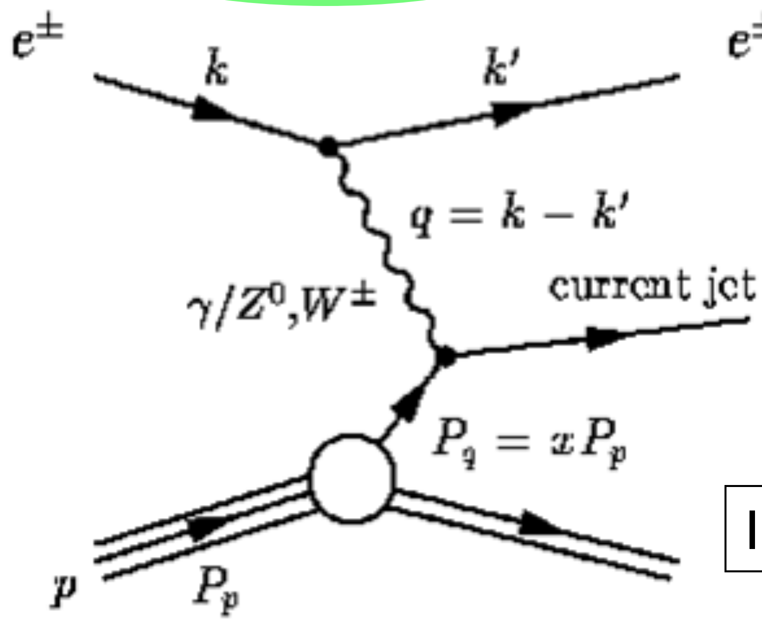
$\boxed{0 \le y \le 1}$

$\sqrt{s}$ = ep cms energy

$Q^2 = -q^2$ = 4-momentum transfer squared = sxy
(or virtuality of the "photon")

DIS Kinematics – Experimental Variables

ep scattering



Final electron energy

Initial electron energy

$$Q^2 = -q^2 = -(k-k')^2 = 2E_e E'_e(1+\cos\theta_e)$$

$$x = Q^2/2p\bullet q = \frac{E_e}{E_P}\,\frac{E'_e\,(1+\cos\theta_e)}{2E_e - E'_e(1-\cos\theta_e)}$$

Initial proton energy

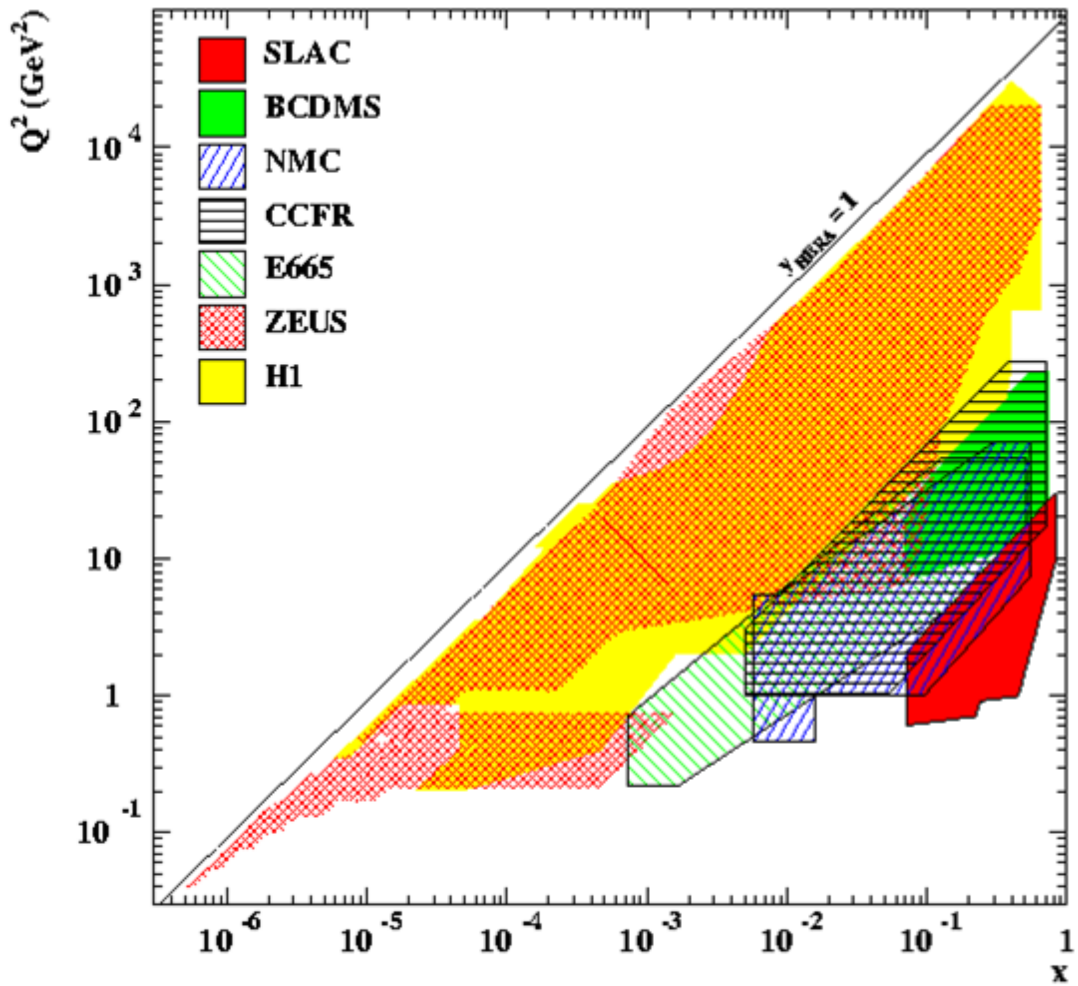
Electron scattering angle

E_e', θ_e : electron method

E_h, γ_h : Jacquet-Blondel method (energy, angle of struck quark)

θ_e, γ_h : Double-Angle method (angles of scattered electron, struck quark)

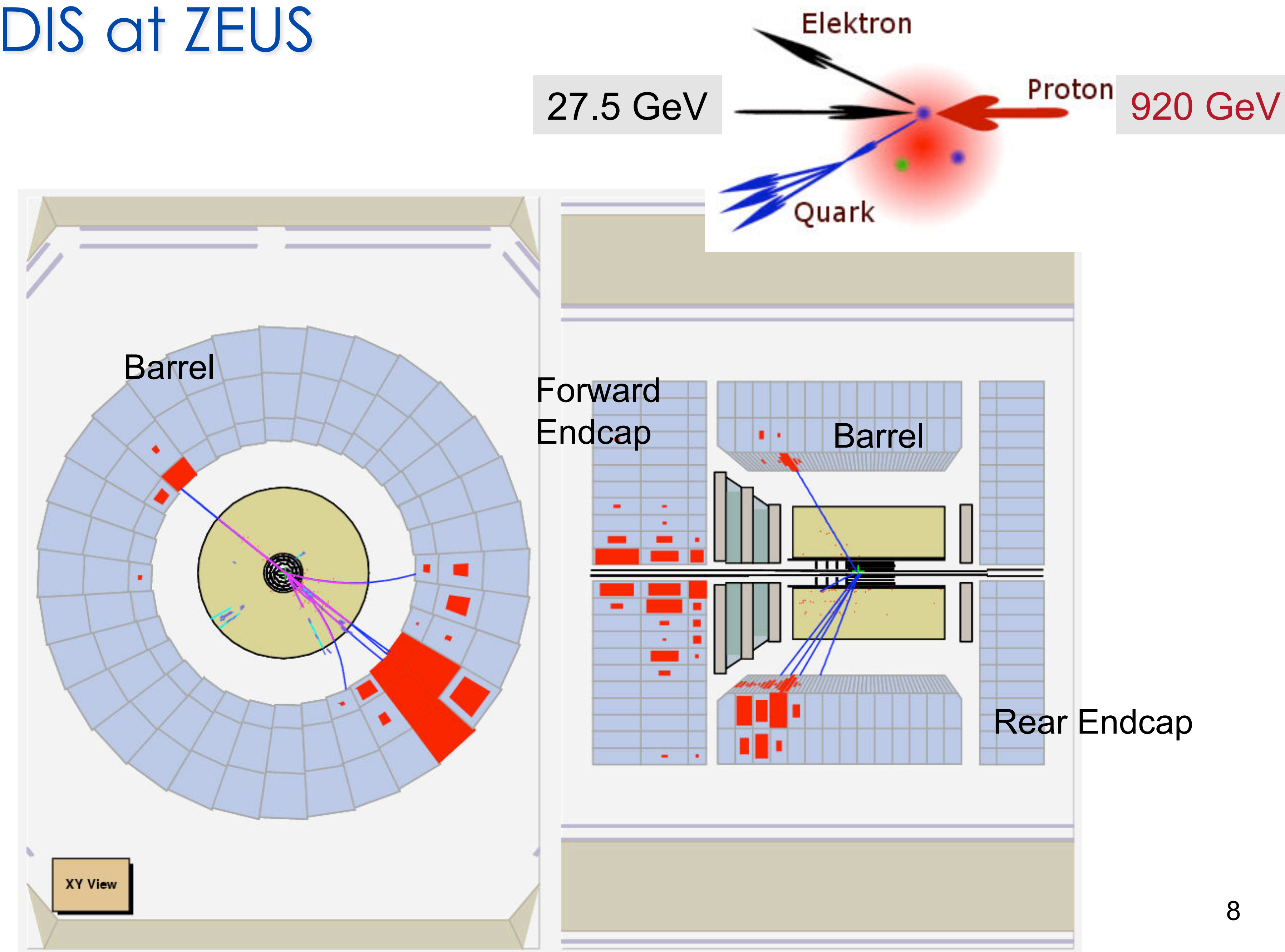
Kinematics of DIS Experiments



HERA collider :
H1 and ZEUS
1992 – 2007

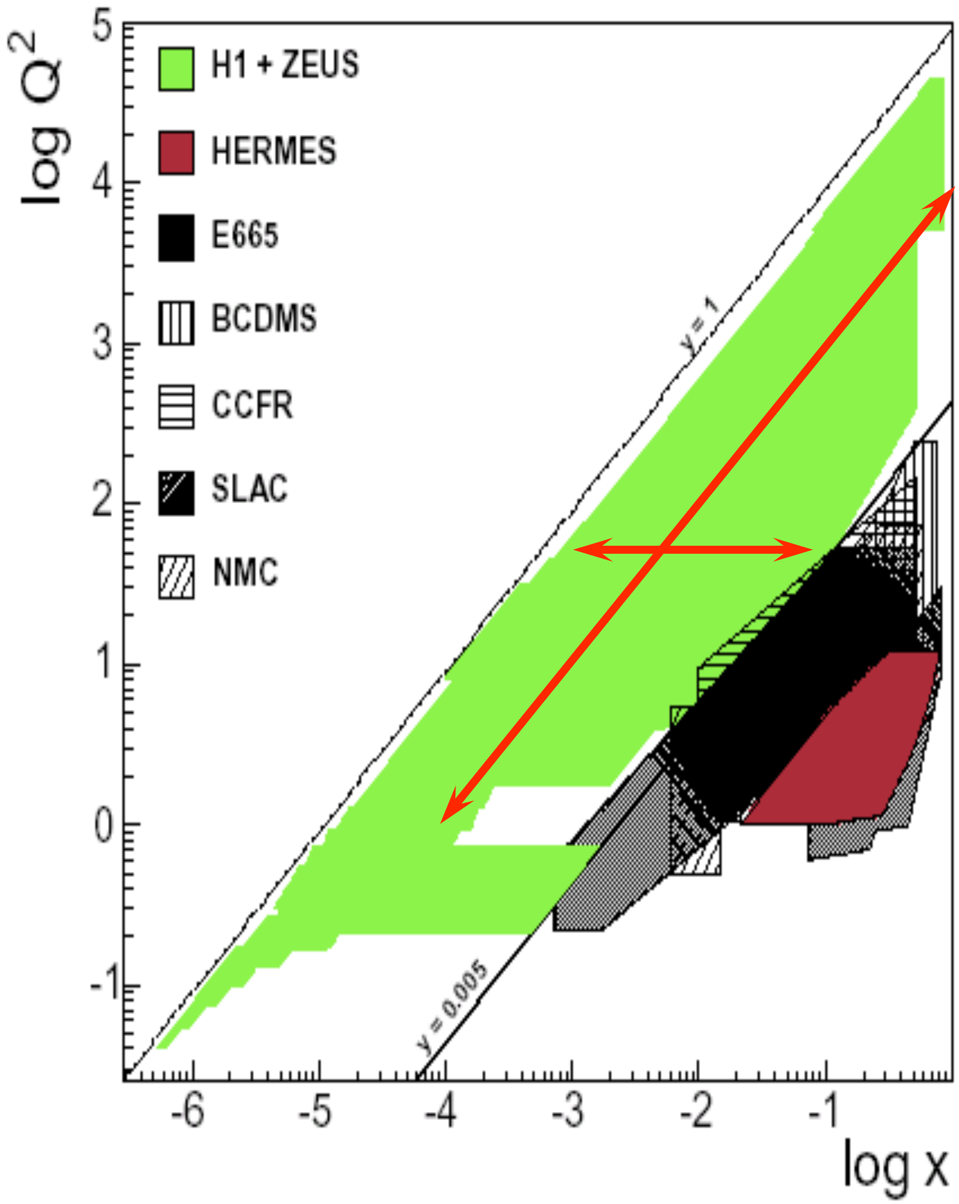
Fixed target :
SLAC, FNAL and CERN
completed ~10-20 years ago

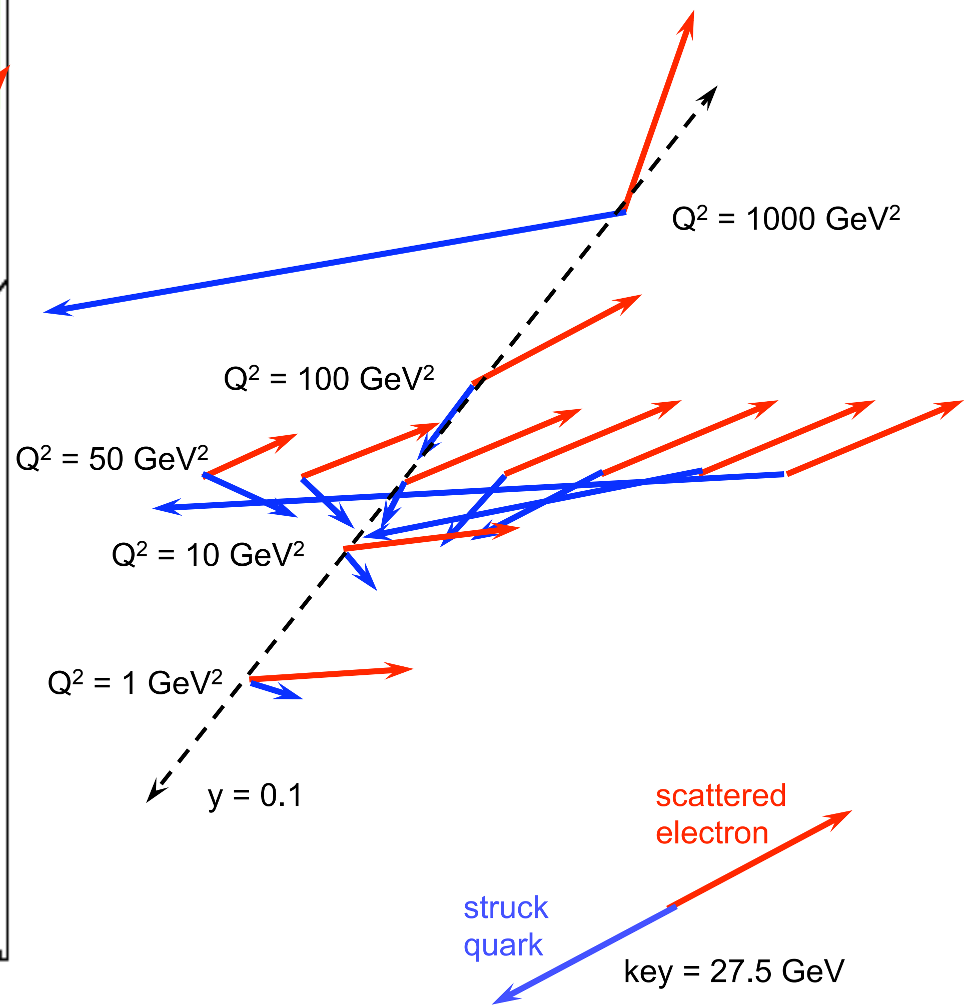
DIS at ZEUS



Elektron
27.5 GeV
Proton
920 GeV
Quark
Barrel
XY View
Forward
Endcap
Barrel
Rear Endcap

Event Topology at the HERA Collider





ep Neutral Current (γ^*,Z) Cross Section

$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+ F_2 - y^2 F_L \mp Y_- xF_3\right)$$

$Y_\pm = (1 \pm (1-y)^2)$, **the inelasticity parameter**

The structure functions of the proton are :

$F_2(x,Q^2) = x \sum_q e_q^2 \left(q(x,Q^2) + \bar{q}(x,Q^2)\right)$

- the sum of the quark and anti-quark densities

$xF_3(x,Q^2) = x \sum_q e_q^2 \left(q(x,Q^2) - \bar{q}(x,Q^2)\right)$

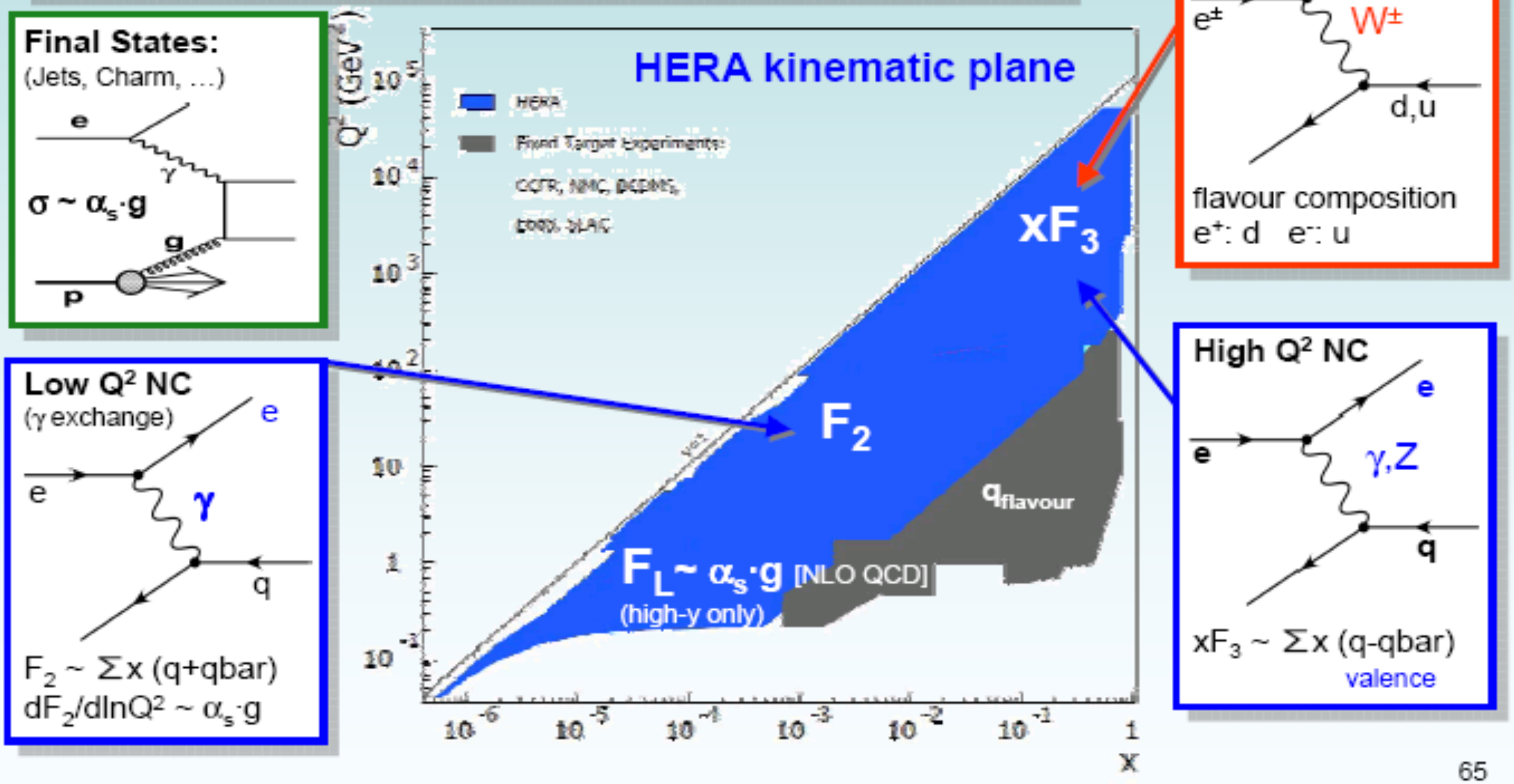
- the difference of the quark and anti-quark densities, small for $Q^2 \ll M_Z^2$

$F_L(x,Q^2) \sim F_2 - xg(x,Q^2)$

- the longitudinal structure function which vanishes at LO in QCD and is damped by y^2 in the cross section

HERA and PDFs: a rough guide

NC DIS: $$\tilde{\sigma}^{\pm} = \frac{d^2\sigma^{\pm}}{dx\,dQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^{\pm} \mp \frac{Y_-}{Y_+} x\tilde{F}_3^{\pm} - \frac{y^2}{Y_+}\tilde{F}_L^{\pm}$$



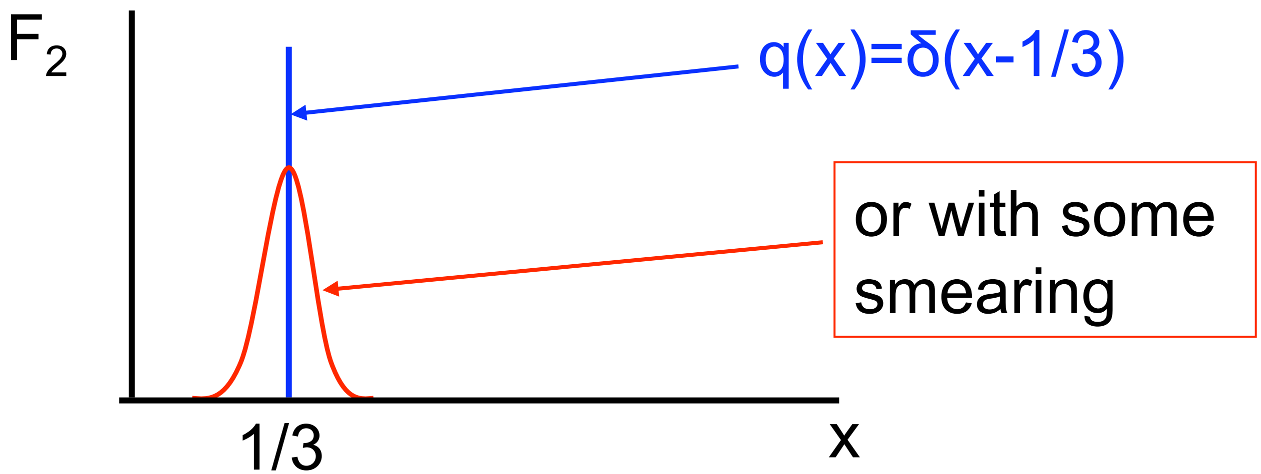
From C. Gwenlan

We will start with the structure function F2 :

IF, proton was made of 3 quarks each with 1/3 of proton's momentum:

no anti-quark!

$$F_2 = x\sum_q e_q^{\,2}\,(q(x) + \cancel{\bar{q}(x)})$$

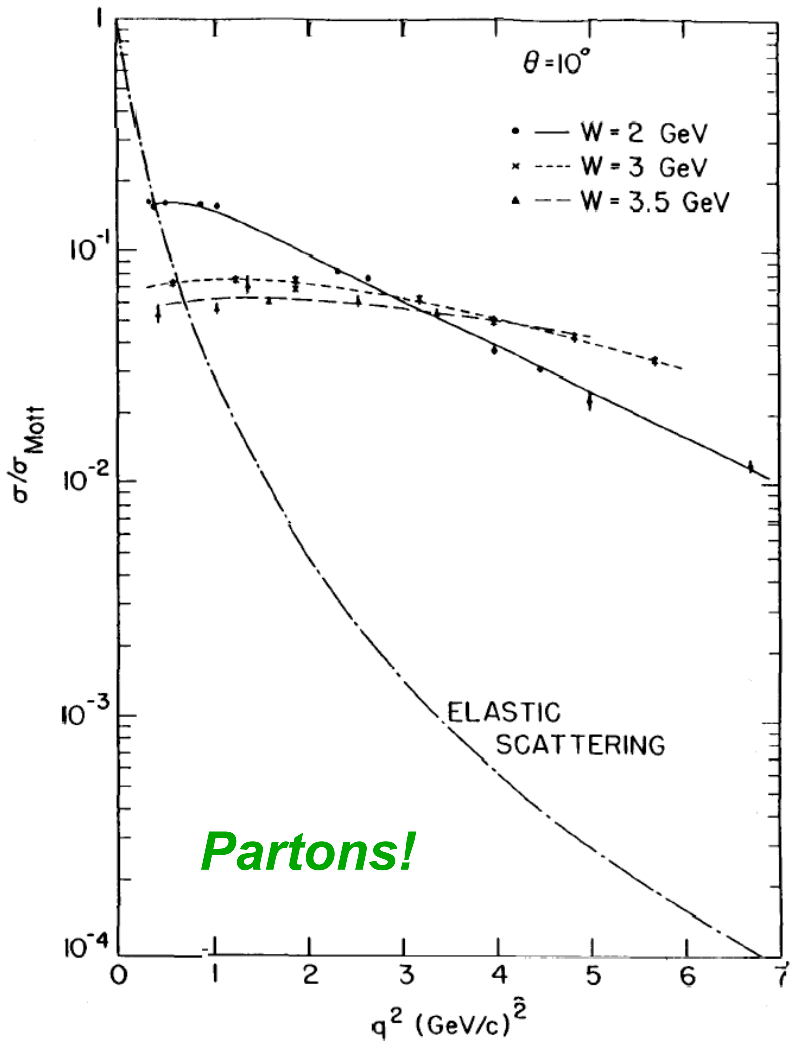


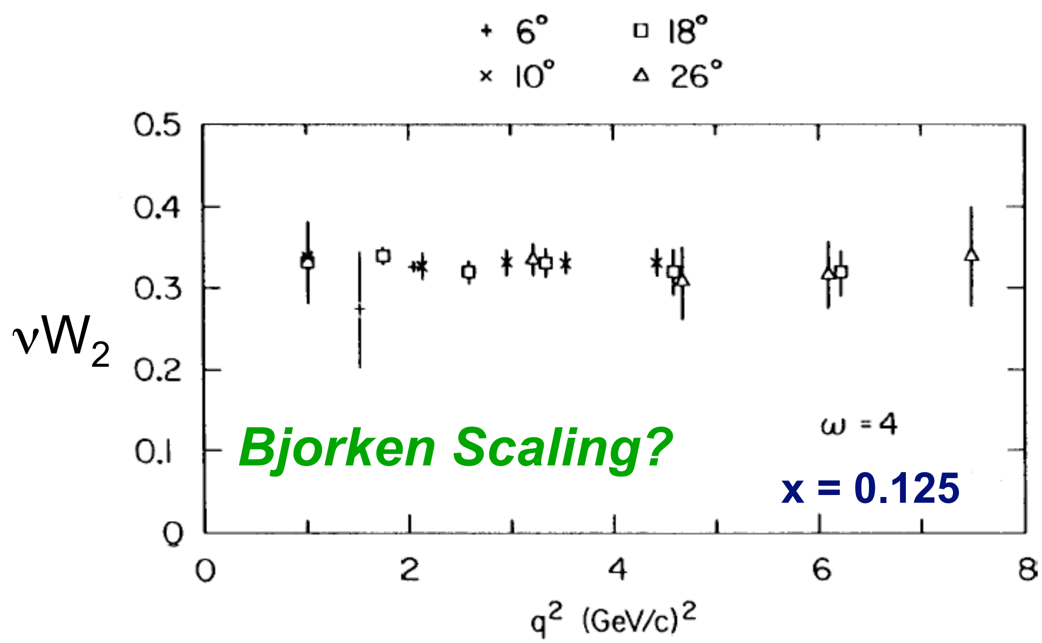
The partons are *point-like* and *incoherent* - F_2 should be independent of Q^2.

→ Bjorken scaling : F_2 has no Q^2 dependence.

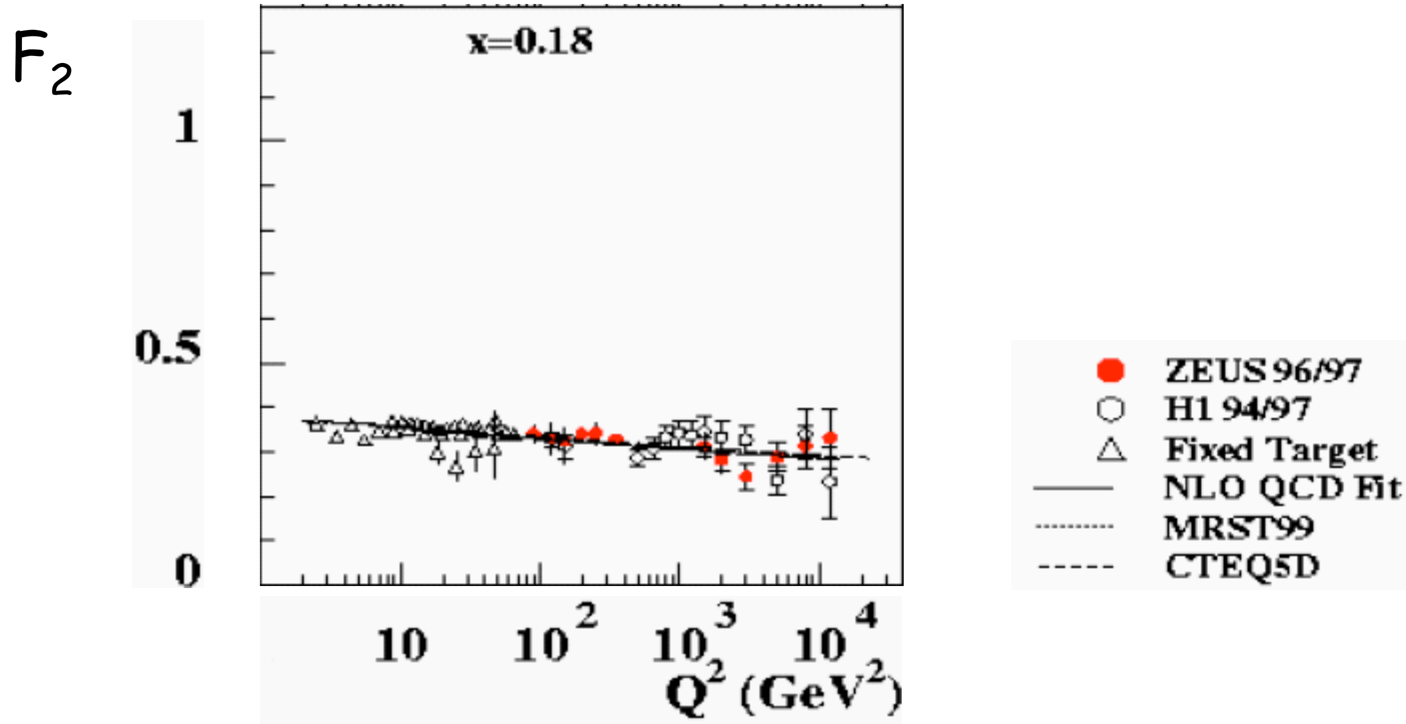
Does the data support this? →

SLAC-MIT Results (1969)





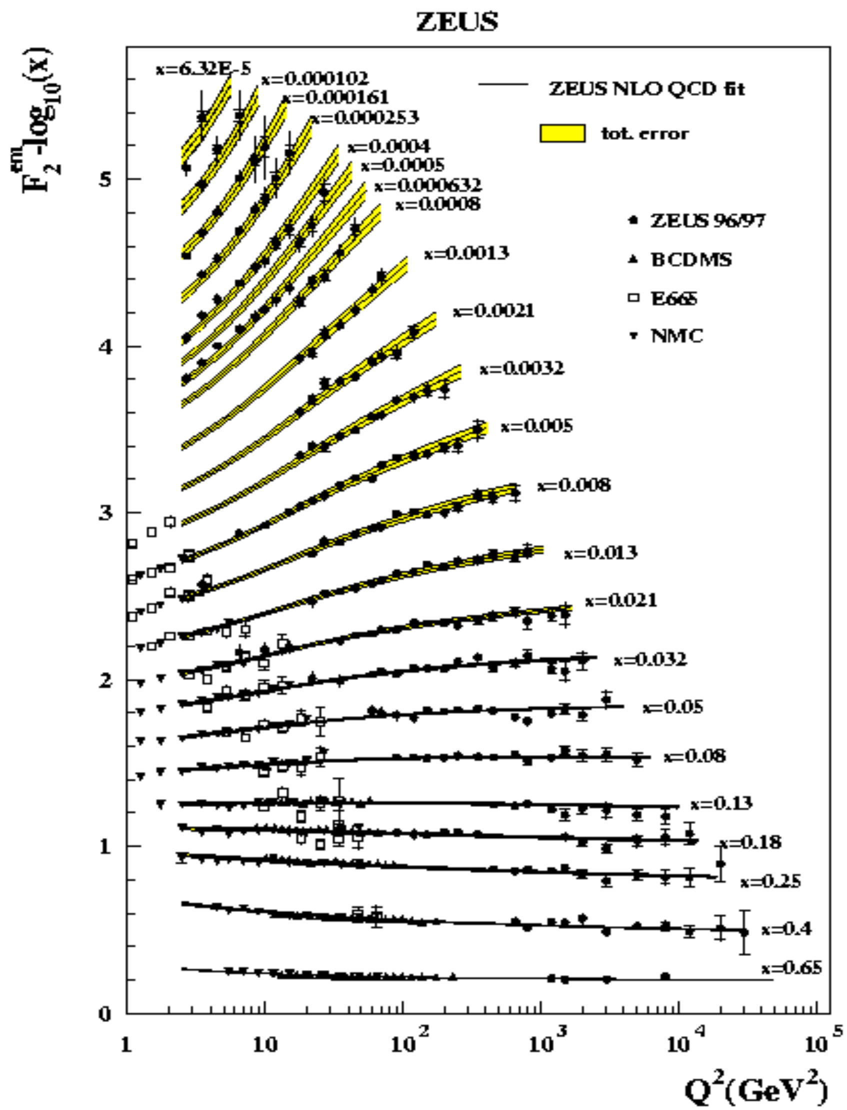
Proton Structure Function F_2



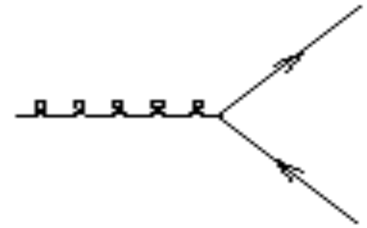
Bjorken scaling is …. NOT seen at all x!

QCD – F_2 violates Bjorken Scaling

$$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g$$

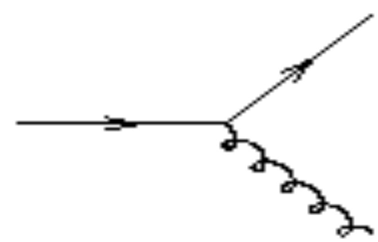


At low x :



Gluon splitting enhances quark density
➔ F_2 rises with Q^2

At high x :



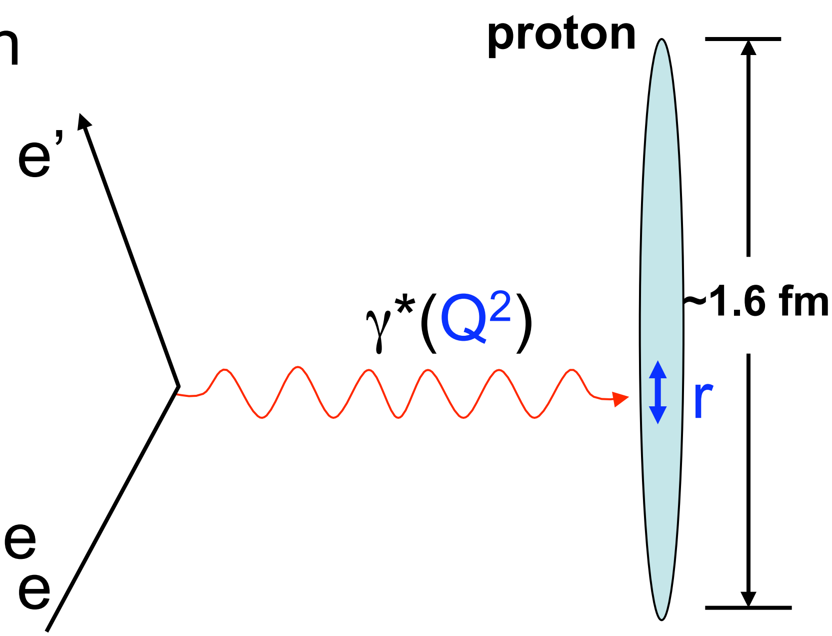
Gluon radiation shifts quark to lower x
➔ F_2 falls with Q^2

Proton probe with a photon of virtuality Q^2

- Distance scale r at which proton is probed :

  $r \approx hc/Q = 0.2\text{fm}/Q[\text{GeV}]$

- Because the virtual photon is absorbed in a time much shorter than the characteristic time of parton-parton interactions (Impulse Approximation), the DIS cross section factorizes as :

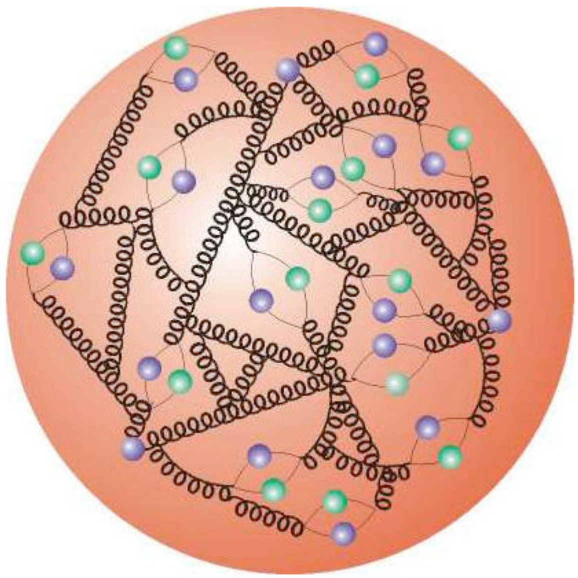


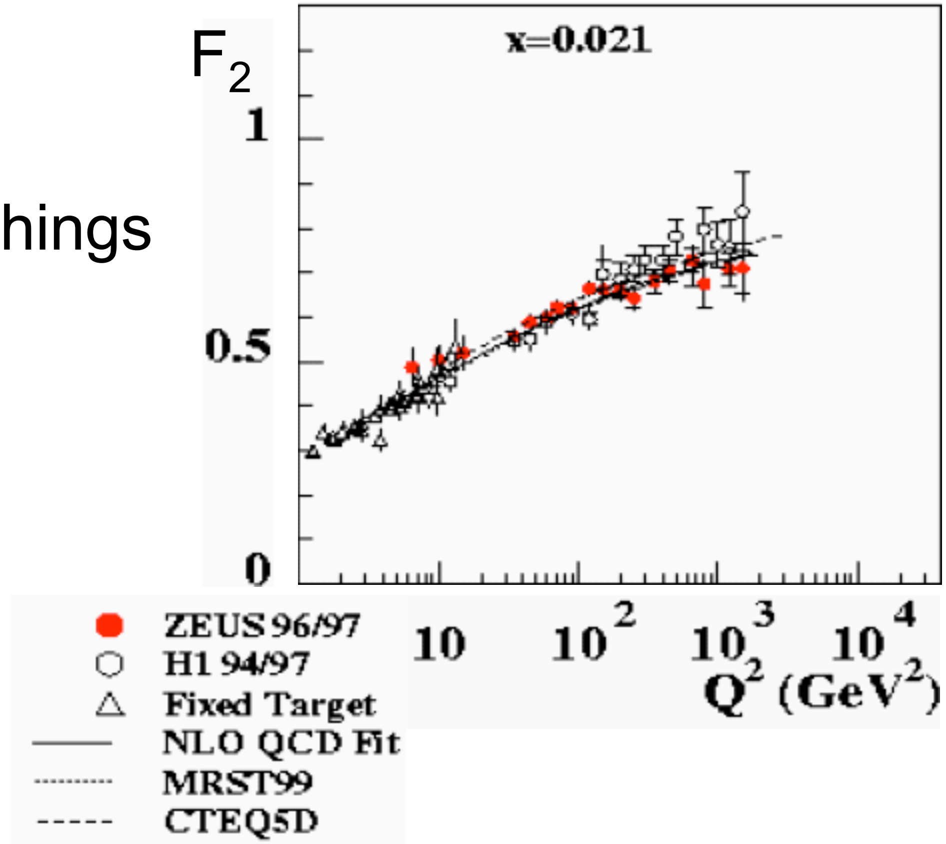
$$\sigma_{DIS} \sim f_p(x) \otimes \sigma$$

$f_p(x)$: (universal) parton density functions in the proton

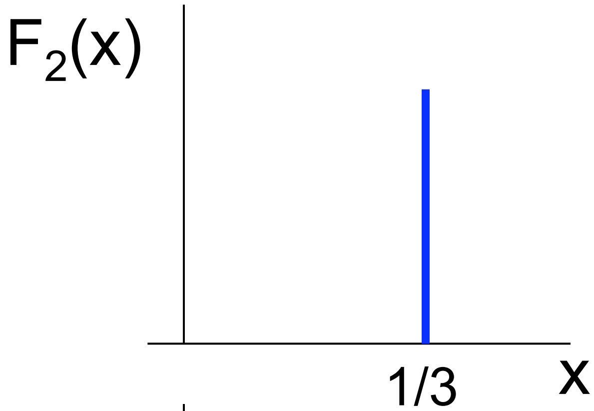
σ : hard scattering partonic cross section → pQCD

Higher the resolution (i.e. higher the Q^2) more branchings to lower x we "see".

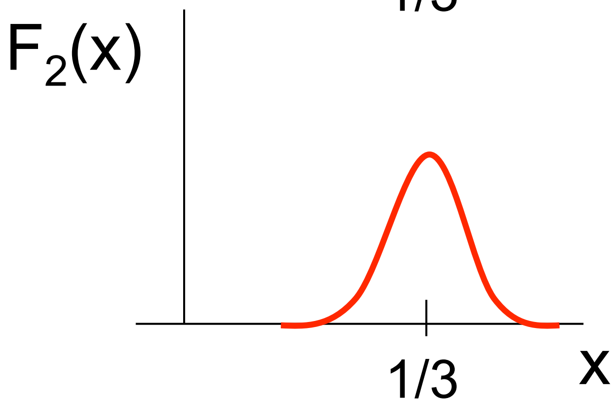




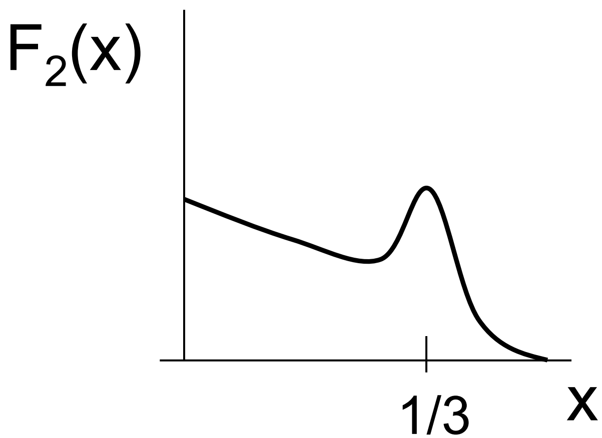
So what do we expect F_2 as a function of x at a fixed Q^2 to look like?



Three quarks with 1/3 of total proton momentum each.



Three quarks with some momentum smearing.

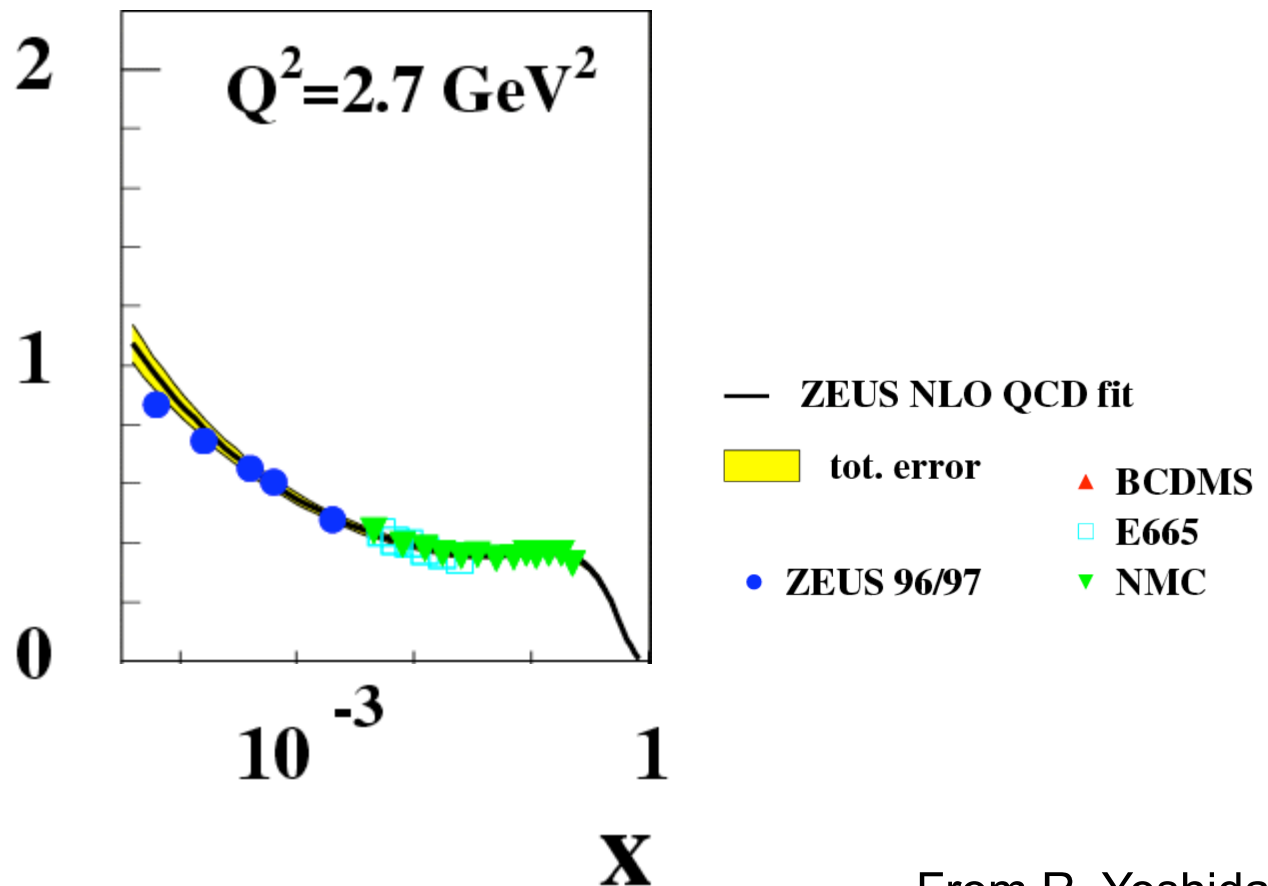


The three quarks radiate partons at low x.

Proton Structure Function F_2 – Q^2 Evolution

Q^2 dependence quantitatively described by :

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations



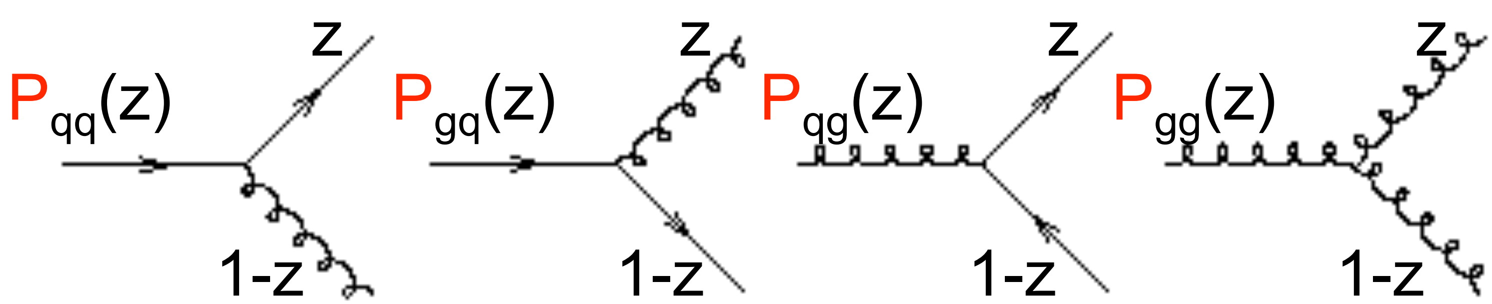
From R. Yoshida

DGLAP Equations

The evolution of the parton densities with Q^2 is given by the DGLAP equations :

$$\partial \boldsymbol{f}_p \,/\, \partial \ln Q^2 \sim \boldsymbol{f}_p \otimes \mathbf{P}$$

First, **P** represents the four "splitting functions" :



$\mathbf{P}_{ba}(z)$: probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

So, the DGLAP equations, $\partial f_p / \partial \ln Q^2 \sim f_p \otimes P$ for quarks and gluons are :

$$\frac{\partial}{\partial \ln Q^2} \Sigma(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \left([\Sigma \otimes P_{qq}] + [g \otimes 2n_f P_{qg}] \right)$$

where $\Sigma(x,Q^2) = \sum_i (q_i(x,Q^2) + \bar{q}_i(x,Q^2))$ is the quark density summed over all (active) flavors

And for the gluon :

$$\frac{\partial}{\partial \ln Q^2} g(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \left([\Sigma \otimes P_{gq}] + [g \otimes P_{gg}] \right)$$

Parton Density Functions (PDFs) Extraction

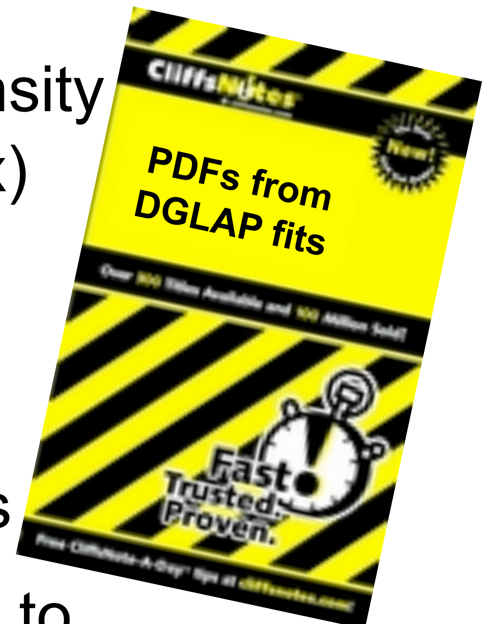
DGLAP fit (or QCD fit) extracts the parton distributions from measurements.

(Lectures on Friday and Saturday by Pavel Nadolsky)

The Cliffs Notes version :

Step 1: parametrize the parton momentum density $f(x)$ at some Q^2 -> $f(x)=p_1x^{p2}(1-x)^{p3}(1+p_4\sqrt{x}+p_5x)$

$u_v(x)$ u-valence
$d_v(x)$ d-valence } "The original three quarks"
$g(x)$ gluon
$S(x)$ sum of all "sea" (non valence) quarks



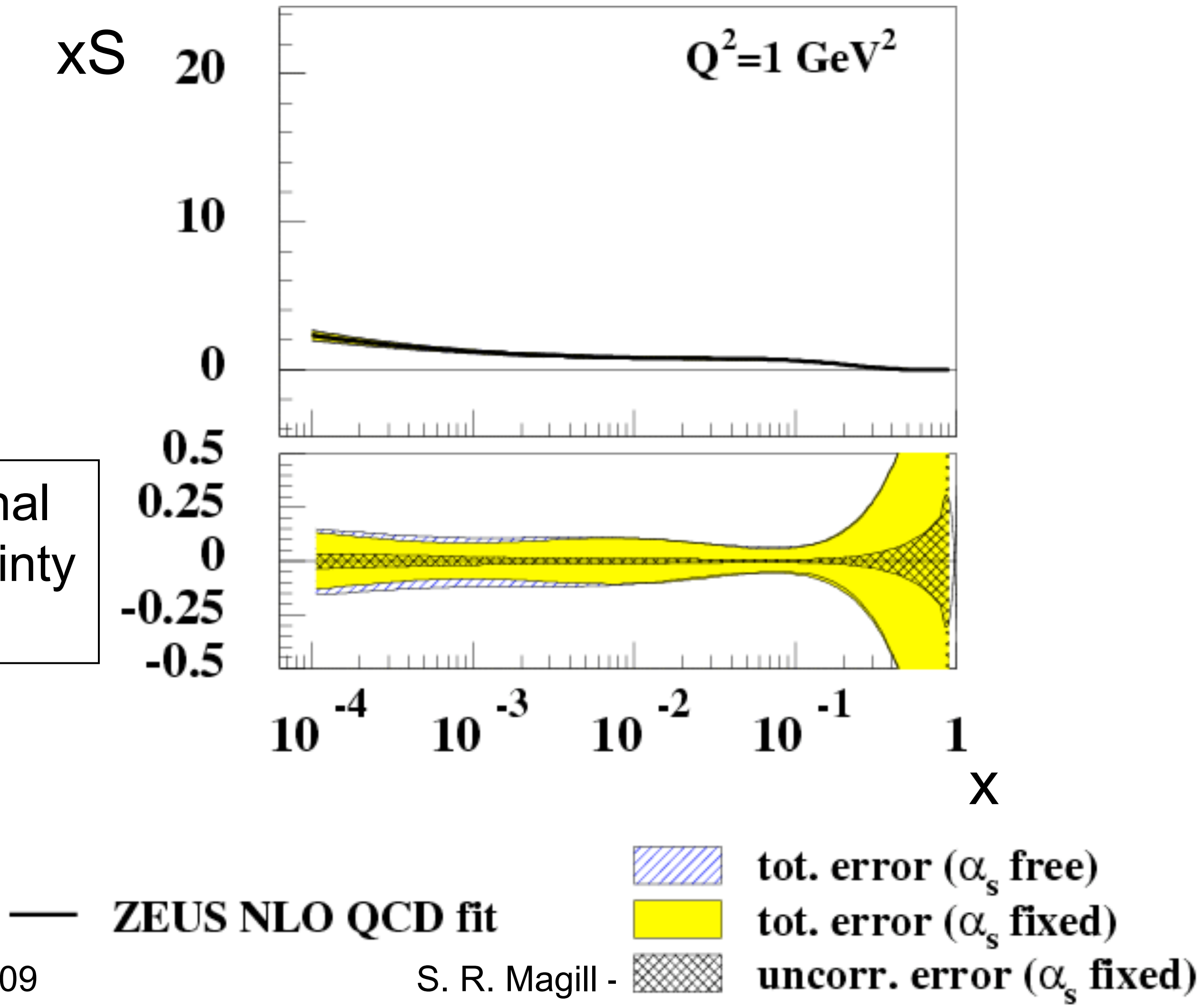
Step 2: find the parameters (p_1 -> p_5) by fitting to DIS (and other) data using the DGLAP equations to evolve $f(x)$ in Q^2.

At x<<1/3, quarks and (anti-quarks) are all "sea".

Since $F_2 = e_q^2 \sum x(q + \bar{q})$, xS is very much like F_2

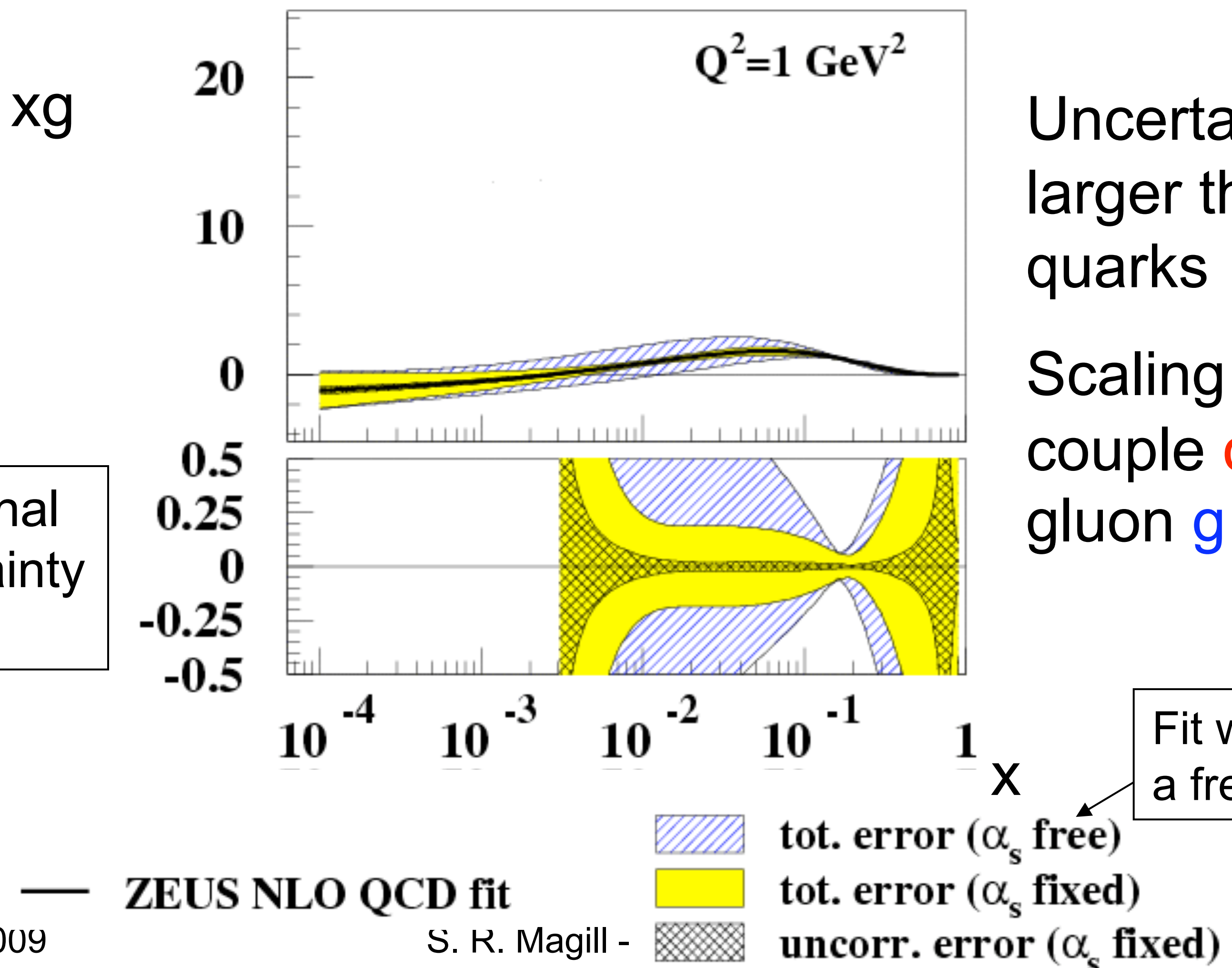
Sea PDF

Fractional uncertainty bands



The gluon pdf is determined from scaling violations, $dF_2/d\ln Q^2$ via the DGLAP equations.

Gluon PDF



Fractional uncertainty bands

Uncertainties are larger than for quarks

Scaling violations couple α_s and gluon g

Fit with α_s also a free parameter

Summarizing so far:

$F_2 \sim \sum(q+\bar{q}) \approx S$ (sea quarks) measured directly in NC DIS

Scaling violations

$dF_2/d\ln Q^2 \sim \alpha_s \bullet g$ Scaling violations gives gluons (times α_s). DGLAP equations.

What about valence quarks?

$\sum(q-\bar{q}) = u_v + d_v$ can we determine them separately?

Can we decouple α_s and g ?

Proton Structure Function xF_3

Back to the NC cross section :

$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+ F_2 - y^2 F_L \mp Y_- xF_3)$$

$Y_\pm = (1 \pm (1-y)^2)$, **the inelasticity parameter**

$xF_3 = \sum_i (q_i(x,Q^2) - \bar{q}_i(x,Q^2)) \times B_q$ ~The valence quarks!

$$B_q = \underbrace{-2e_q a_q a_e x_z}_{\boxed{\gamma\text{-Z interference}}} + \underbrace{4v_q a_q v_e a_e x_z^2}_{\boxed{\text{Z-exchange}}}$$

$x_z \propto Q^2/(M_z^2+Q^2)$

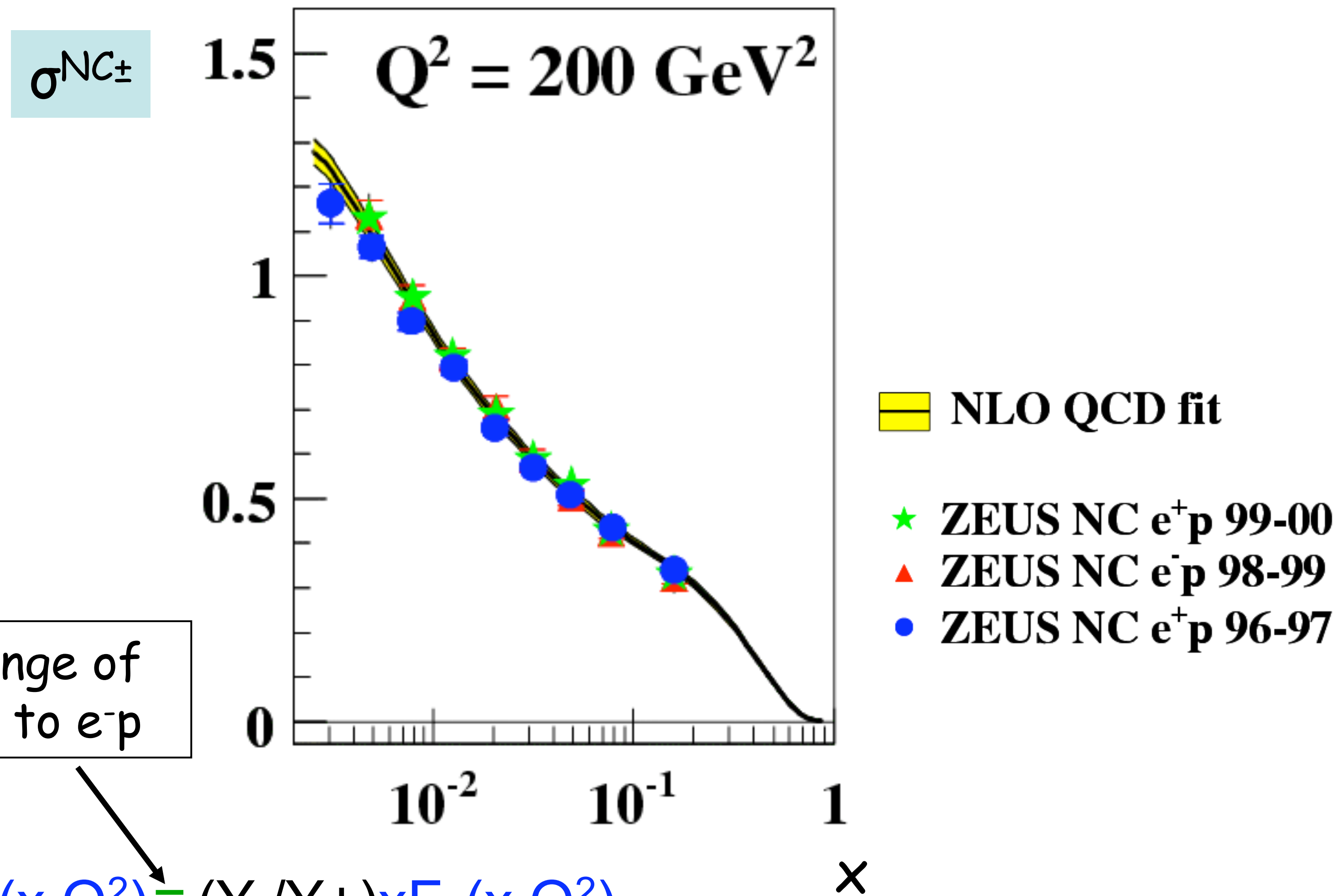
-> xF_3 small if $Q<M_Z$

e_q: electric charge of a quark

$a_q v_q$: axial-vector and vector couplings of a quark

$a_e v_e$: axial-vector and vector couplings of an electron

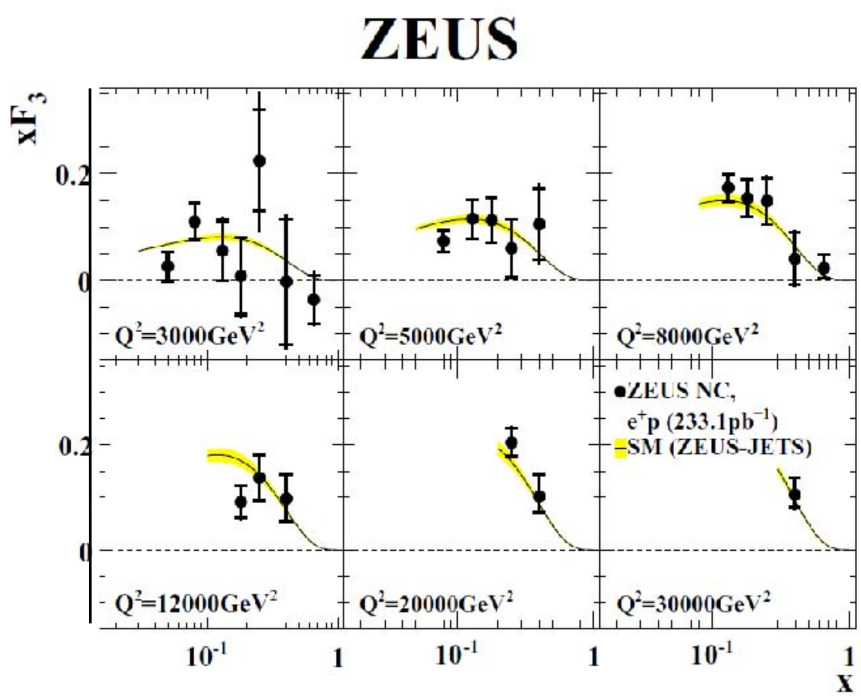
Reduced Neutral Current Cross-section

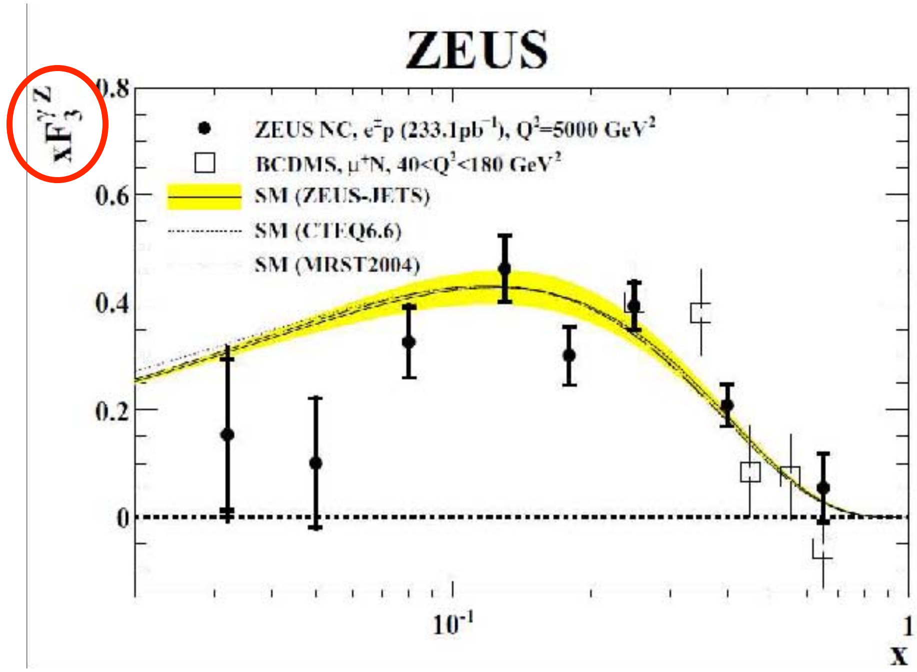


Note the change of sign from e^+p to e^-p

$$\sigma^{NC\pm} = F_2(x,Q^2) \mp (Y-/Y+)xF_3(x,Q^2)$$

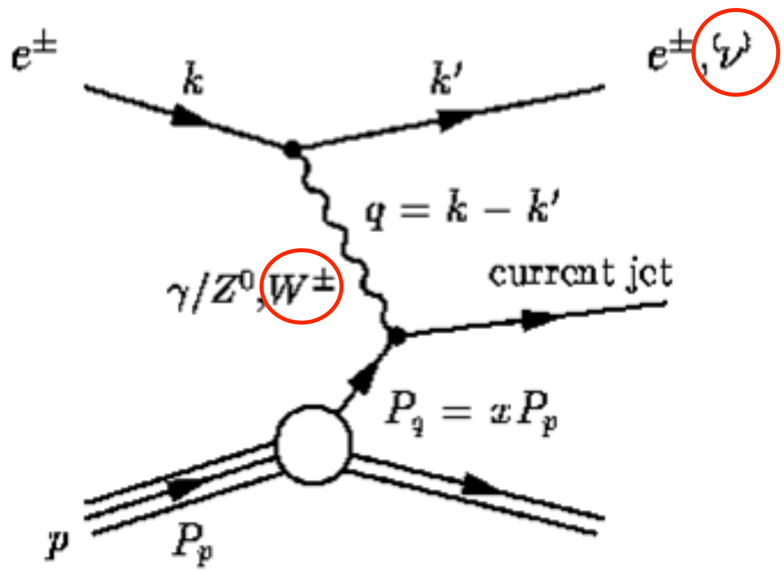
Recent xF_3 (DIS 09) Results from HERA

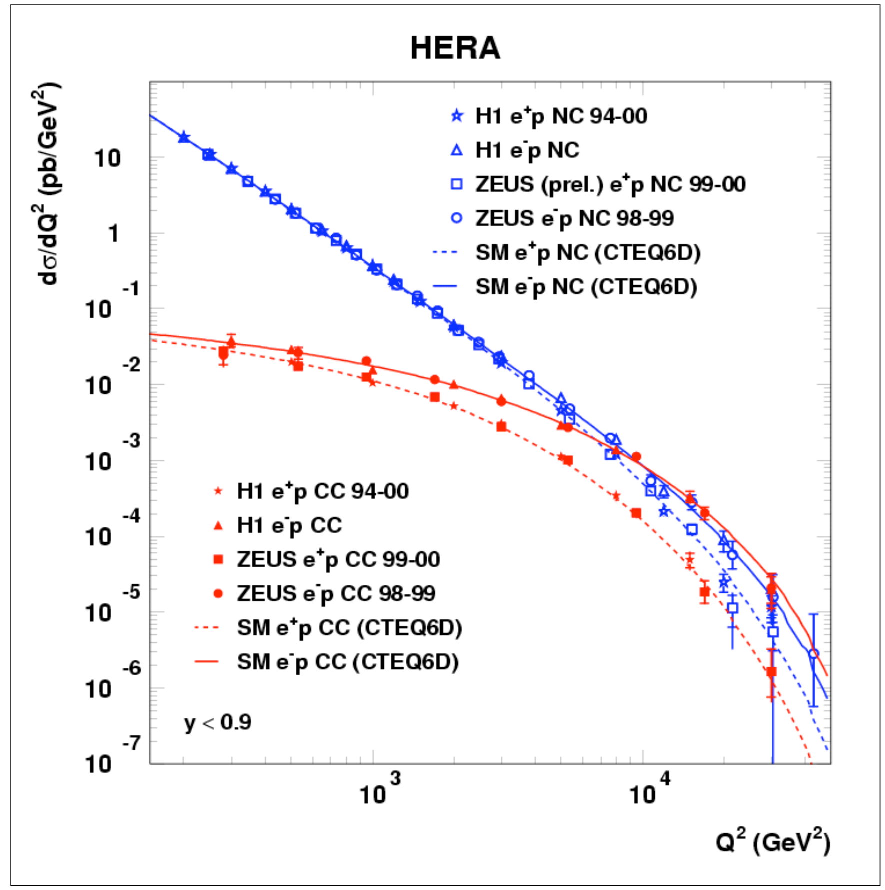




γZ interference term larger than Z exchange

Neutral and Charged Current Cross-Sections





$$\frac{d\sigma^{CC}(e^{\pm}p)}{dx\,dQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \sigma^{CC\pm}$$

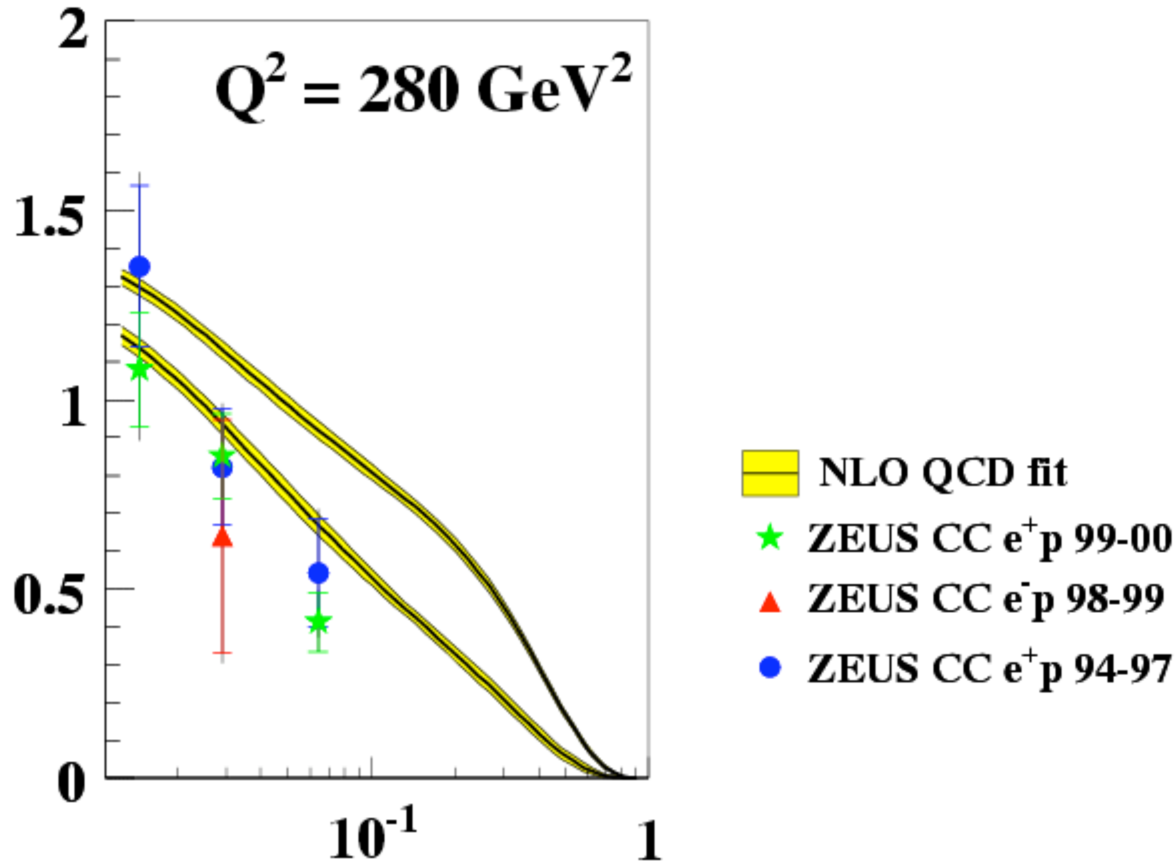
$$\sigma^{CC+} = x\,[\bar{u} + \bar{c} + (1 - y)^2(d + s)] \quad \sim d$$

$$\sigma^{CC-} = x\,[u + c + (1 - y)^2(\bar{d} + \bar{s})] \quad \sim u$$

charm

Reduced Charged Current Cross-Section

$\sigma^{CC\pm}$

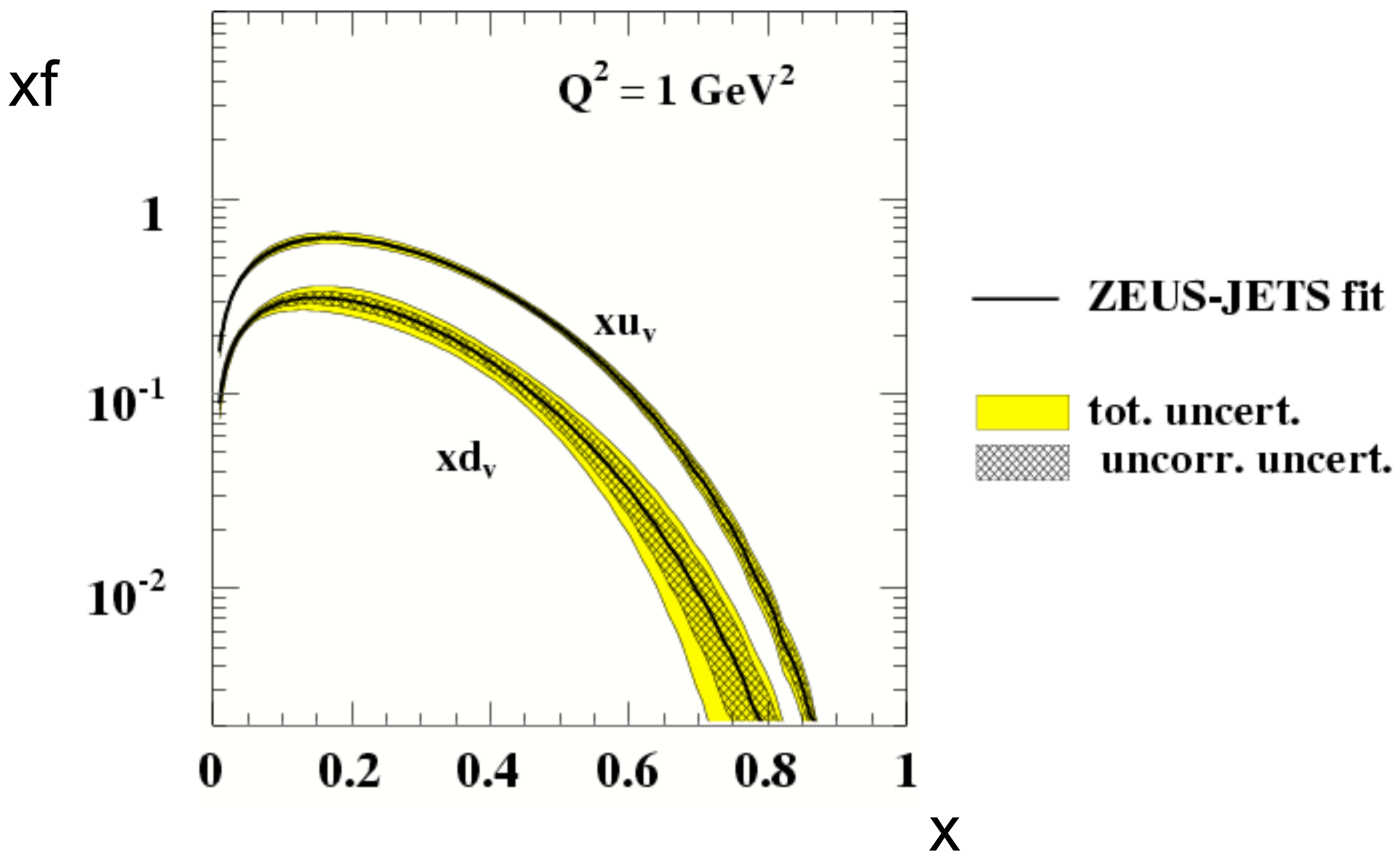


$\sigma^{CC+} \sim d$

$\sigma^{CC-} \sim u$

x

Valence PDFs from QCD Fit

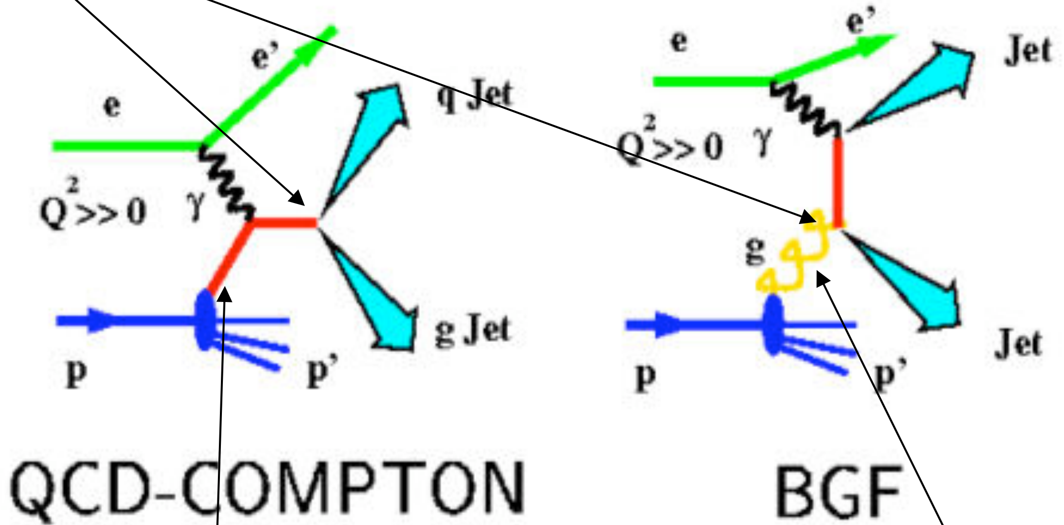


The momenta from valence quarks are producing gluons and sea quarks at low x

Jet production in DIS (HERA)

Sensitive to α_s

$\sigma_{jet} \sim \alpha_s \bullet f(x)$



Sensitive to quarks
$\sim 10^{-2} < x < \sim 10^{-1}$

Same range as NC and CC

Sensitive to gluon
$\sim 10^{-3} < x < \sim 10^{-2}$

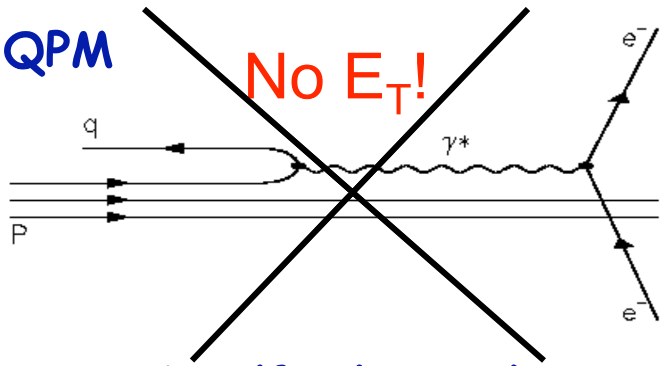
complementary
to gluon from F_2

Jet Measurements in the Breit Frame

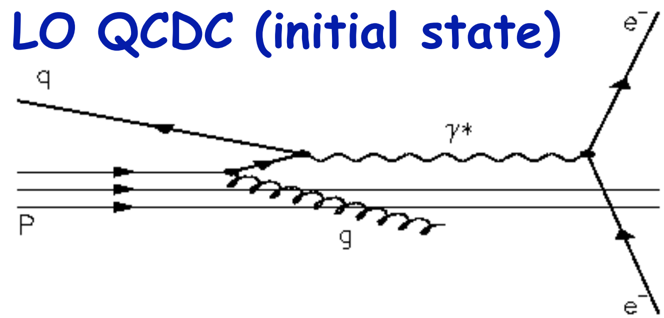
Some definitions :

+z from IP in proton direction – *Target Region*
-z from IP in γ^* direction – *Current Region*
γ^* has 4-vector q = (0,0,0,-Q)
Struck quark in QPM carries away momentum –Q/2

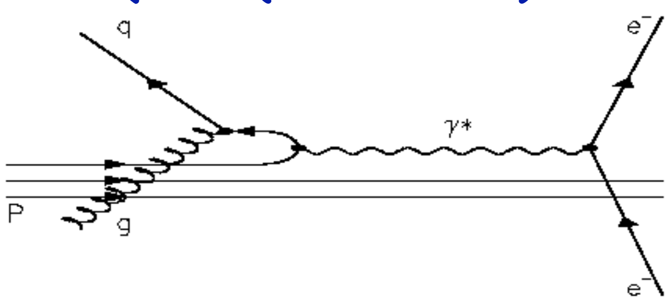
QPM



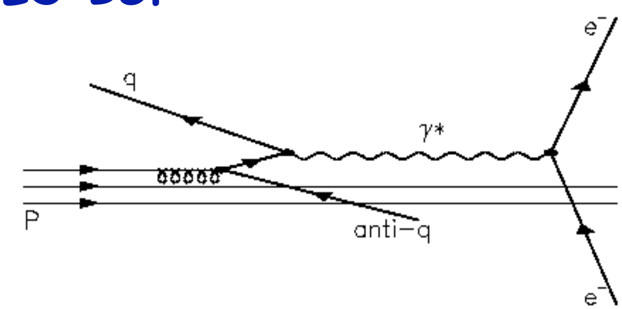
LO QCDC (initial state)



LO QCDC (final state)



LO BGF



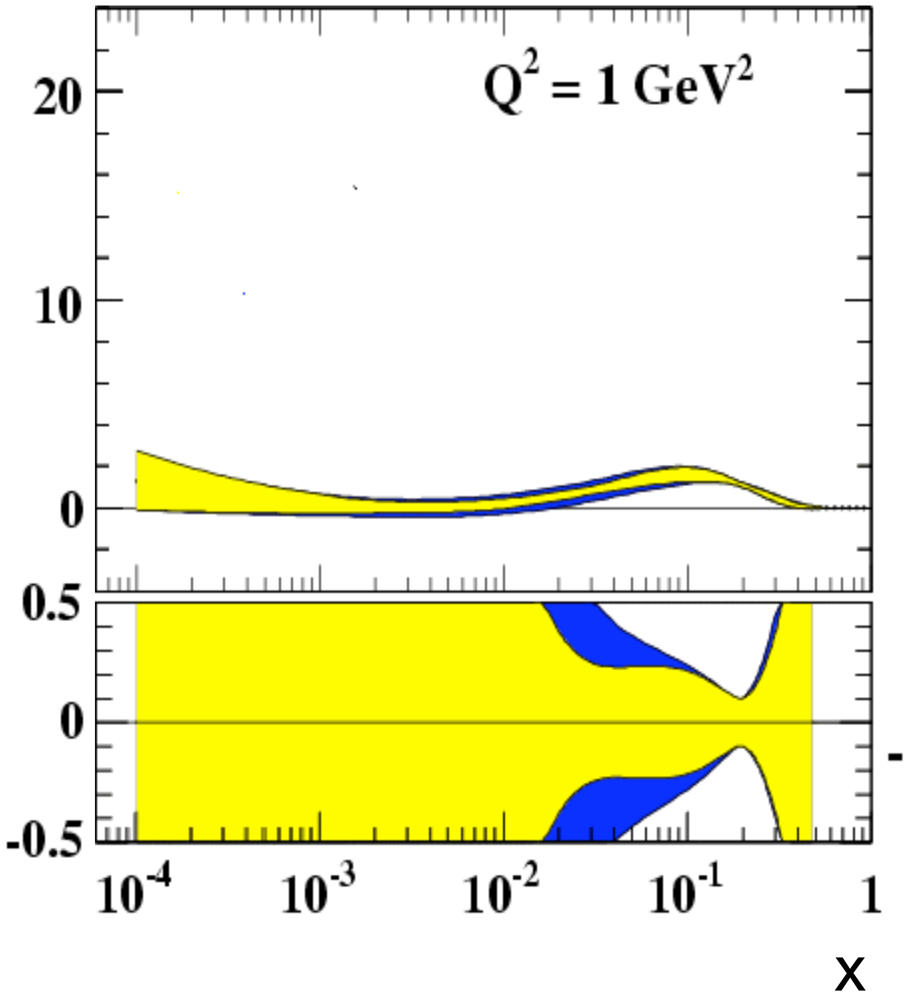
Hard Scale Q = E_t

→ *High Q^2*

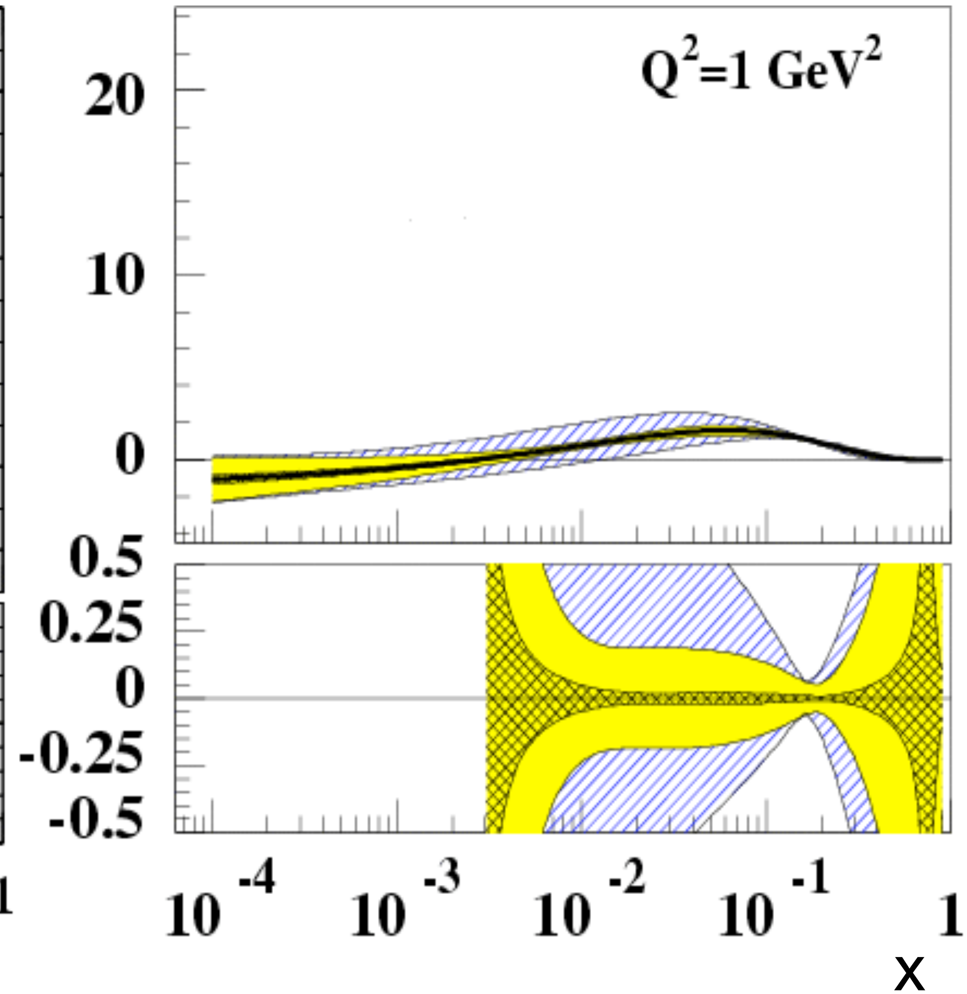
Hard Scale E_t (>Q)

→ *Low Q^2*

Gluon distributions



Using only HERA (ZEUS) data including NC,CC and jets



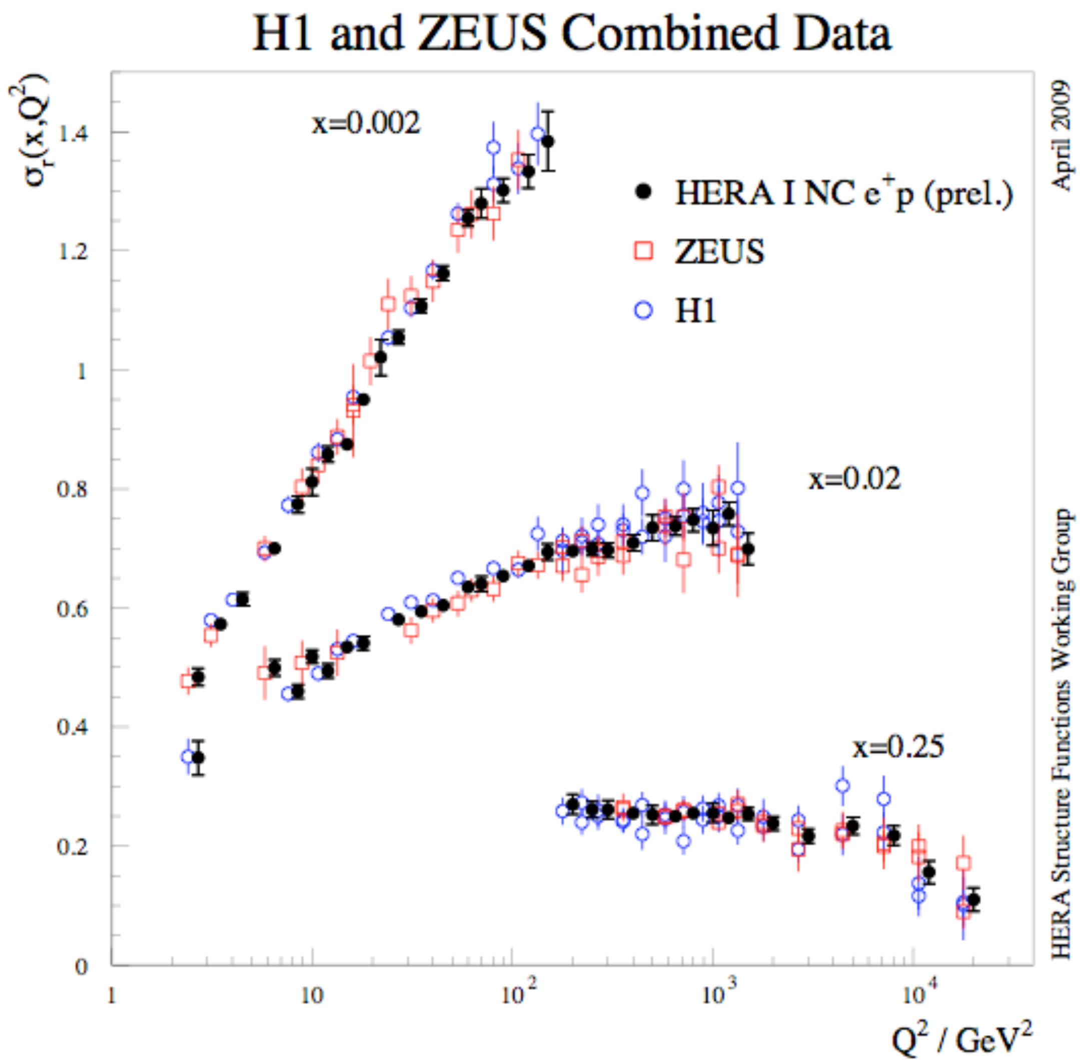
Using HERA (ZEUS) F_2 data and FNAL, CERN fixed tgt

Combined PDFs from HERA – DIS Precision

Combine the measured H1 and ZEUS cross sections. Double statistics and take advantage of complementary measurement techniques which result in reduced systematic uncertainties.

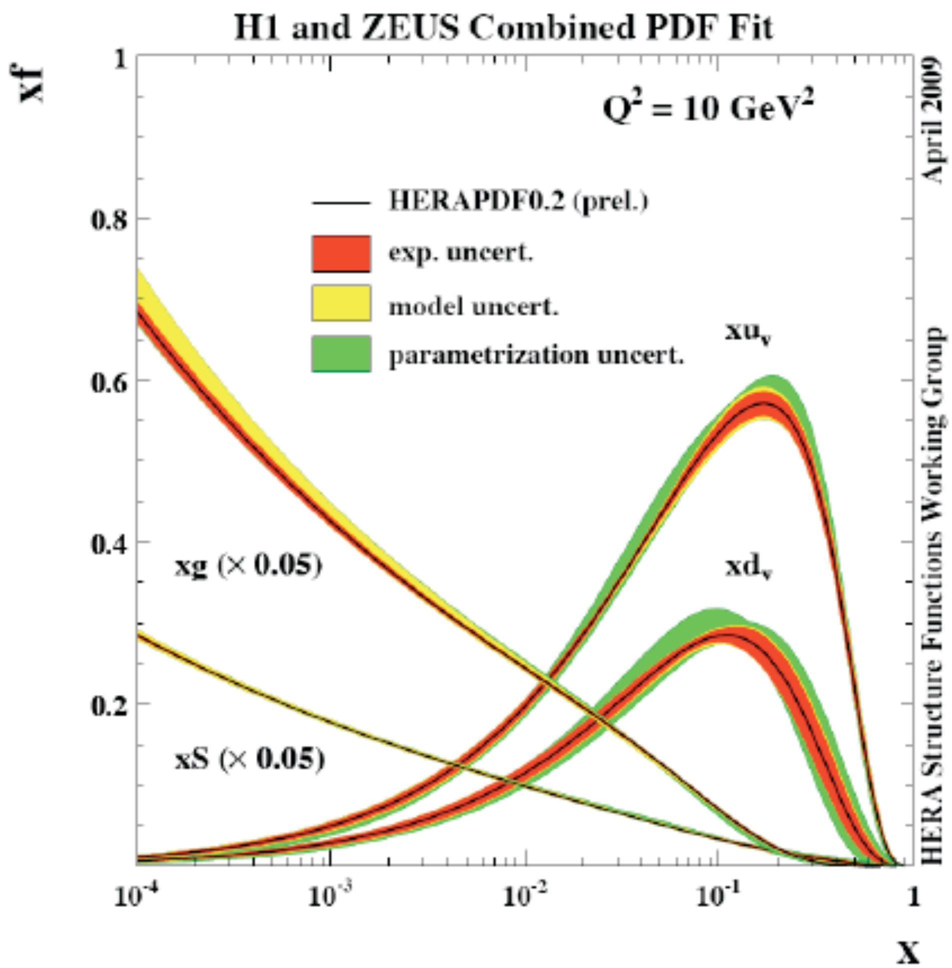
Sample of NC e^+p data showing the ZEUS and H1 data and the combined data as a result of the averaging procedure

Statistical errors shown



HERAPDF0.2

- Red: experimental uncertainties
- Yellow: model uncertainties
- Green: pdf parametrization uncertainties

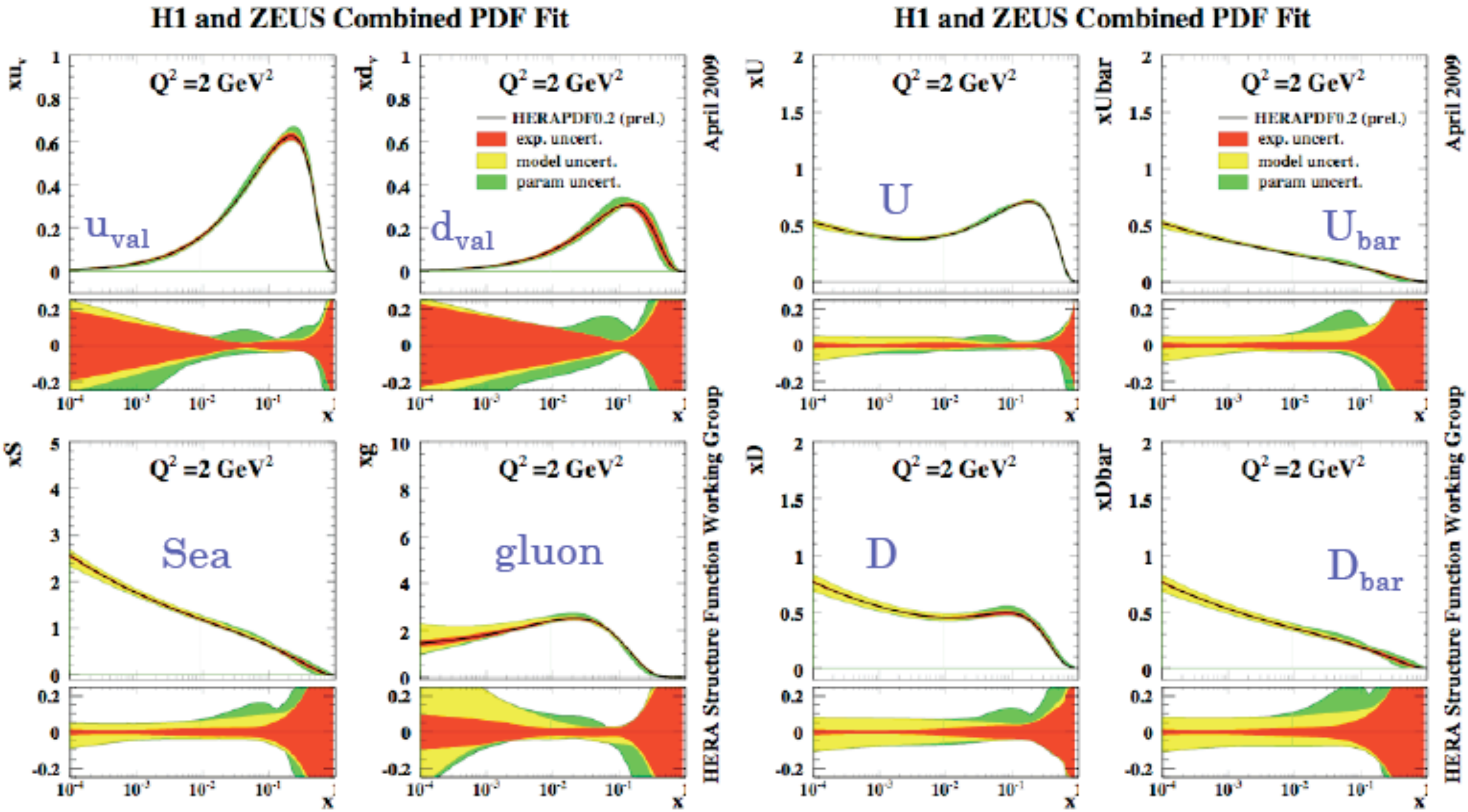


Observations:

- High-x and valence are mostly affected by the PDF parametrisation
  - The procedure to estimate PDF parametrisation uncertainty addresses the high-x region
  - Low-x region interesting to investigate

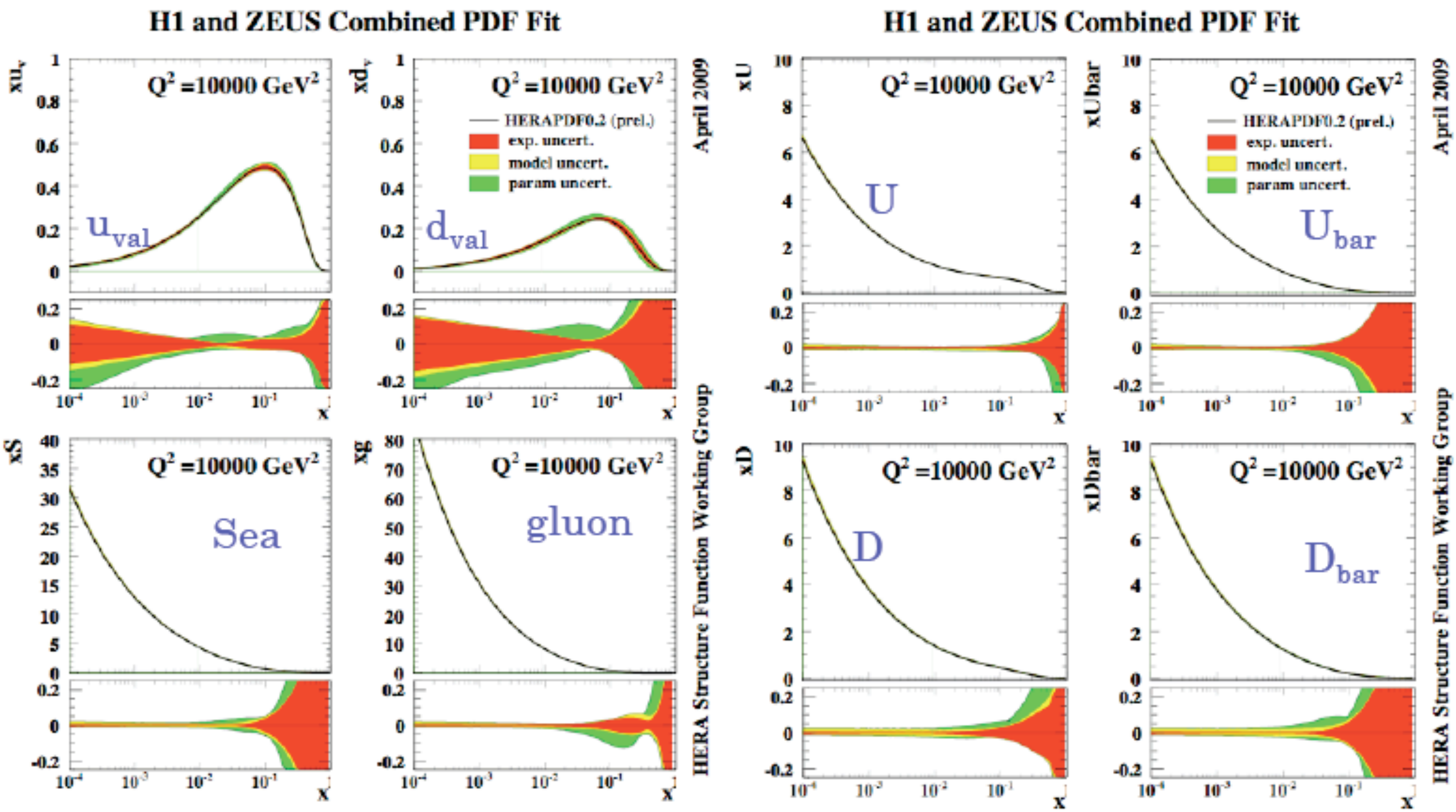
HERAPDF0.2 at Q^2=2 GeV^2

- At the starting scale gluon is valence like
- Q_0^2, Q^2_{min} dominate the model uncertainty of gluon and valence PDFs
- PDF parametrisation uncertainty dominates valence PDFs and high x region

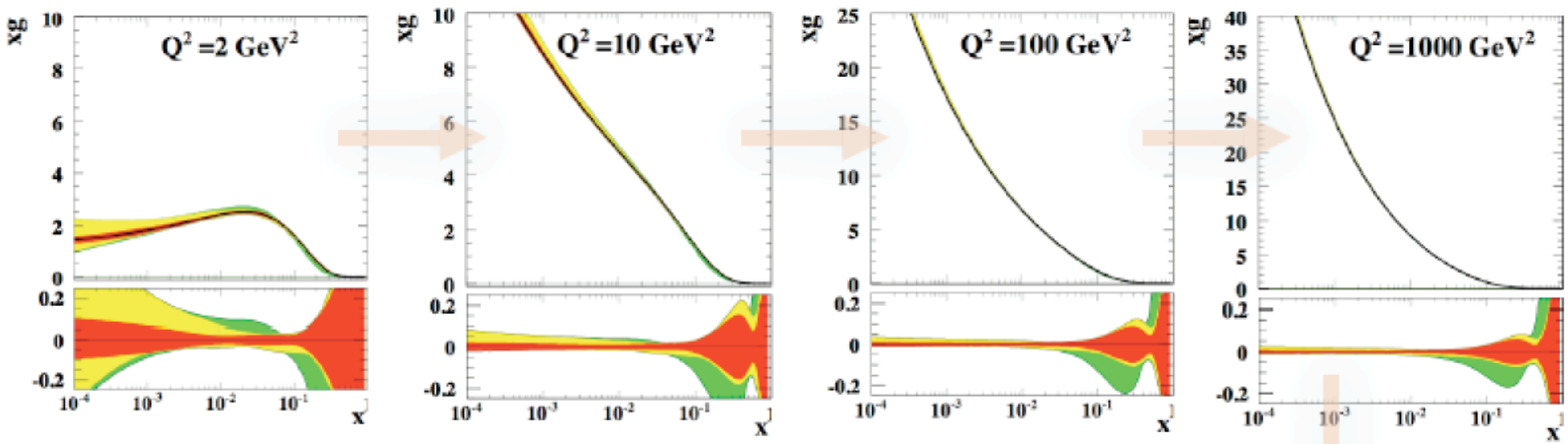


HERAPDF0.2 at Q^2=10000 GeV^2

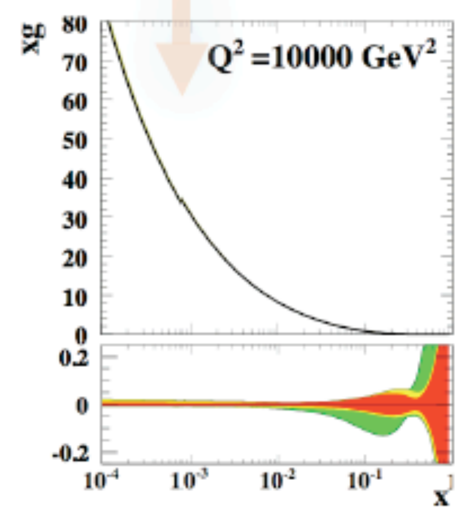
- PDF parametrisation uncertainty dominates valence PDFs and high x region
- Impressive precision at the scale relevant to LHC



Gluon Evolution



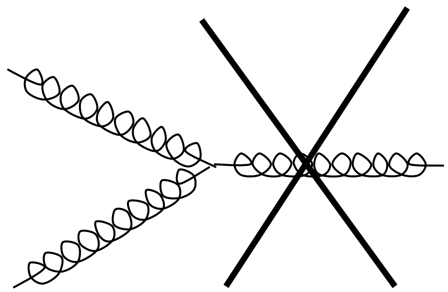
- Near the starting scale gluon is valence like
  - The model uncertainties are large in low x region
    - Mostly due to Q_0^2 variations
  - The PDF param. uncertainty dominates high x



- Impressive precision at higher Q^2

Understanding DGLAP equations – pdf evolution :

The “incoherence” of the original parton model is preserved. i.e. a parton doesn’t know anything about its neighbor.



never happens

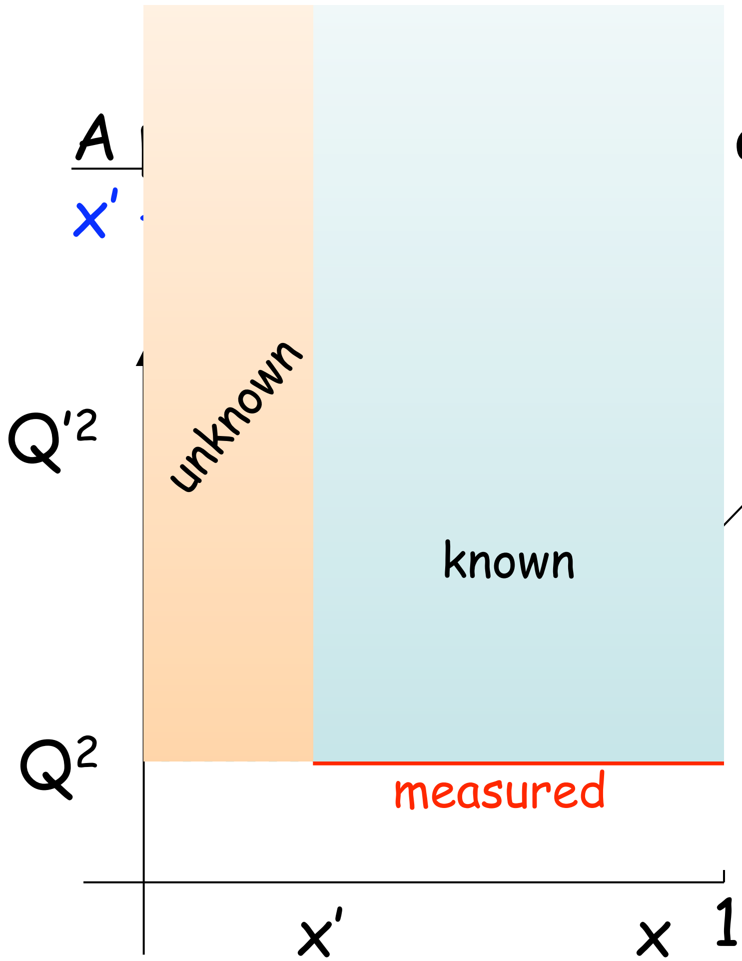
The “process independent” partons also survive.

But now parton densities must be “evolved” in Q^2.

An example for future analyses →

A a source of partons at

x'

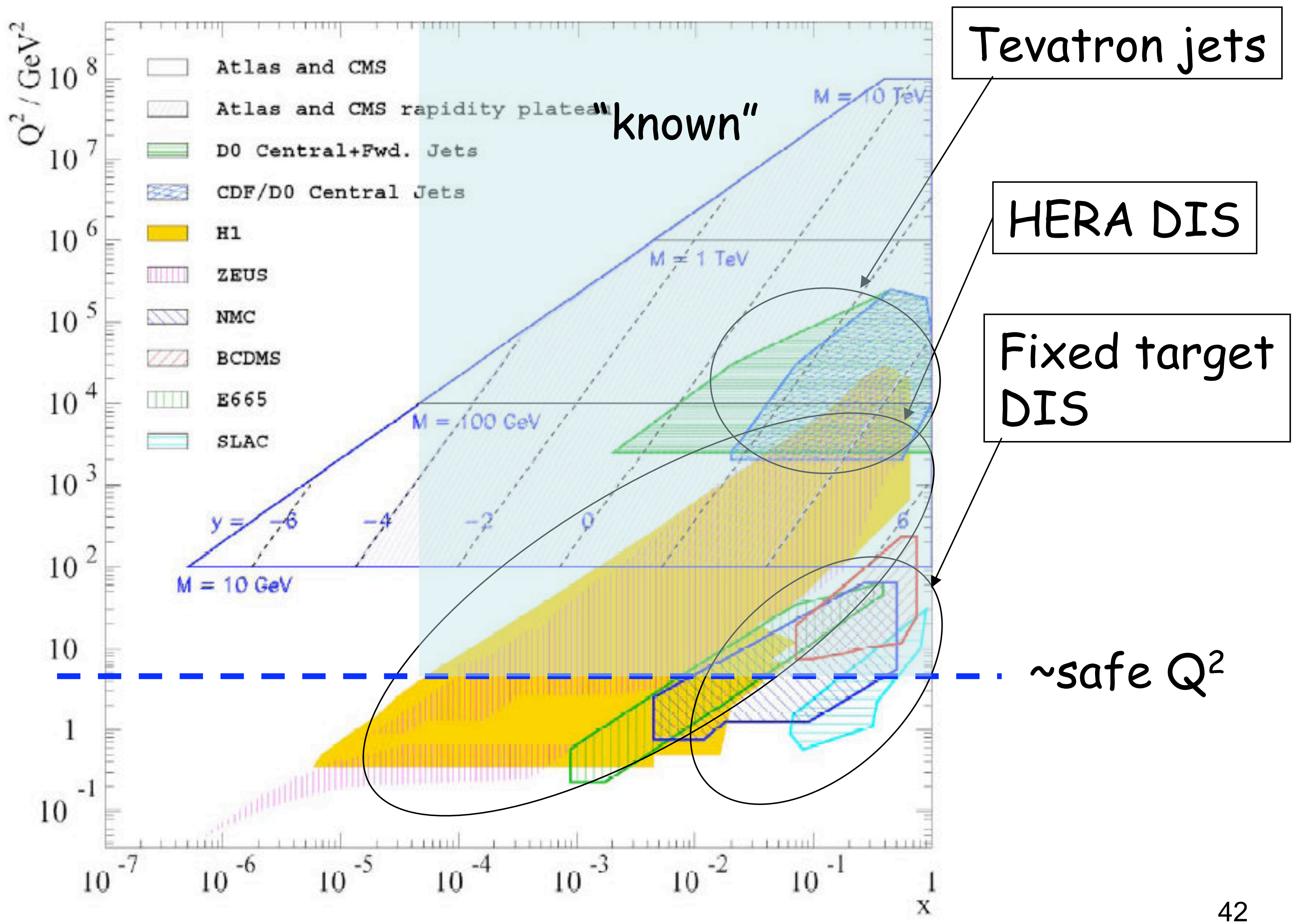


In fact, any parton at $x > x'$ at Q^2 is a source.

To know the parton density at x', Q'^2 it's necessary (and sufficient) to know the parton density in the range: $x' \leq x \leq 1$ at some lower Q^2

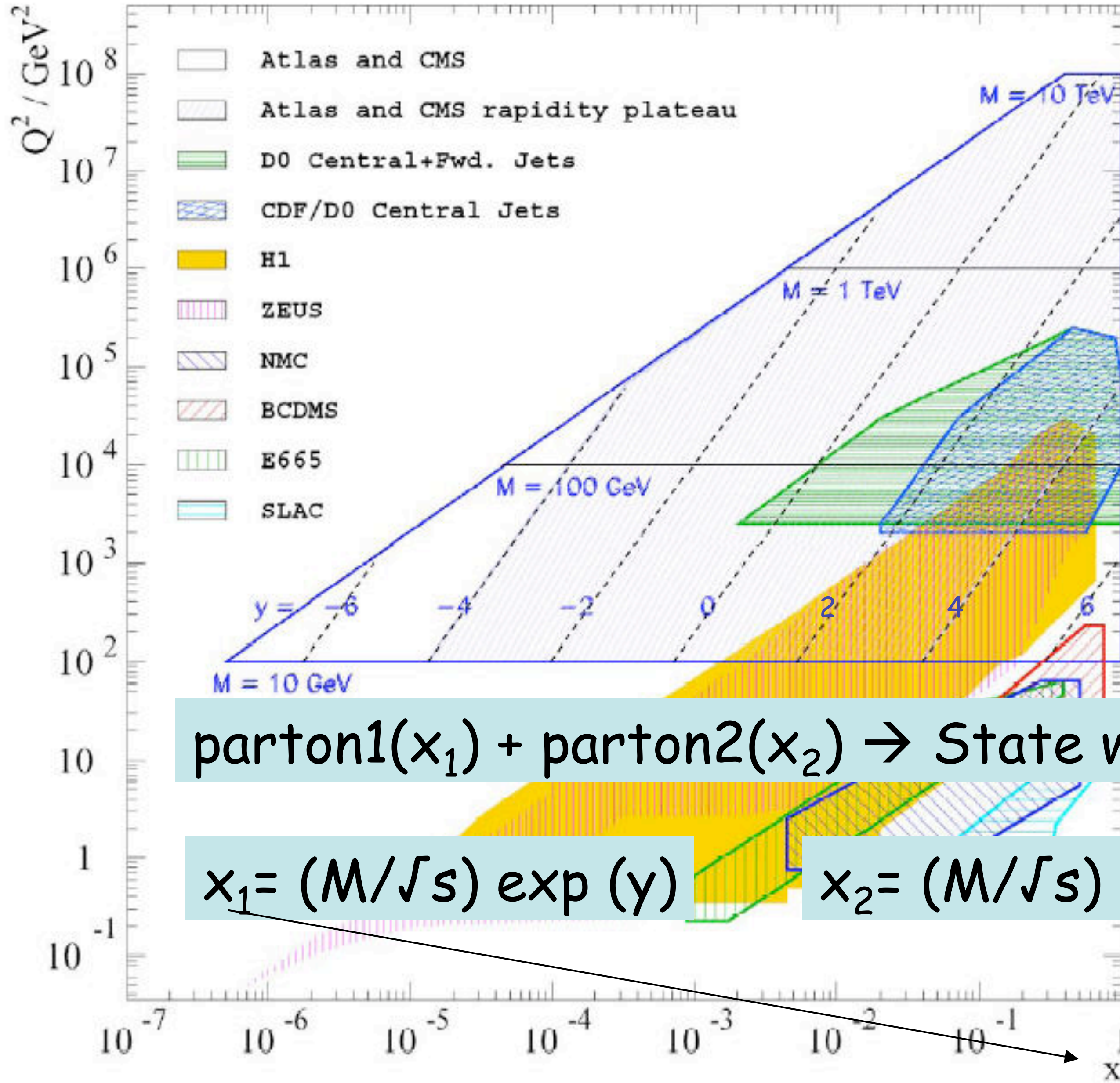
If you know the partons in range $x' \leq x \leq 1$ at some Q^2, then you know the partons in the range $x' \leq x \leq 1$ for all $Q'^2 > Q^2$.

What does this mean for the LHC? →



Tevatron jets
HERA DIS
Fixed target DIS
"known"
~safe Q^2
Q^2 / GeV^2
Atlas and CMS
Atlas and CMS rapidity plateau
D0 Central+Fwd. Jets
CDF/D0 Central Jets
H1
ZEUS
NMC
BCDMS
E665
SLAC
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = -6 -4 -2 0 2 4 6
x

LHC (or hadron-hadron) parton kinematics



rapidity:

$$y = \frac{1}{2}\ln\left(\frac{E+P_Z}{E-P_Z}\right)$$

pseudo-rapidity:

$$\eta = -\ln \tan(\theta/2)$$

angle wrt beam

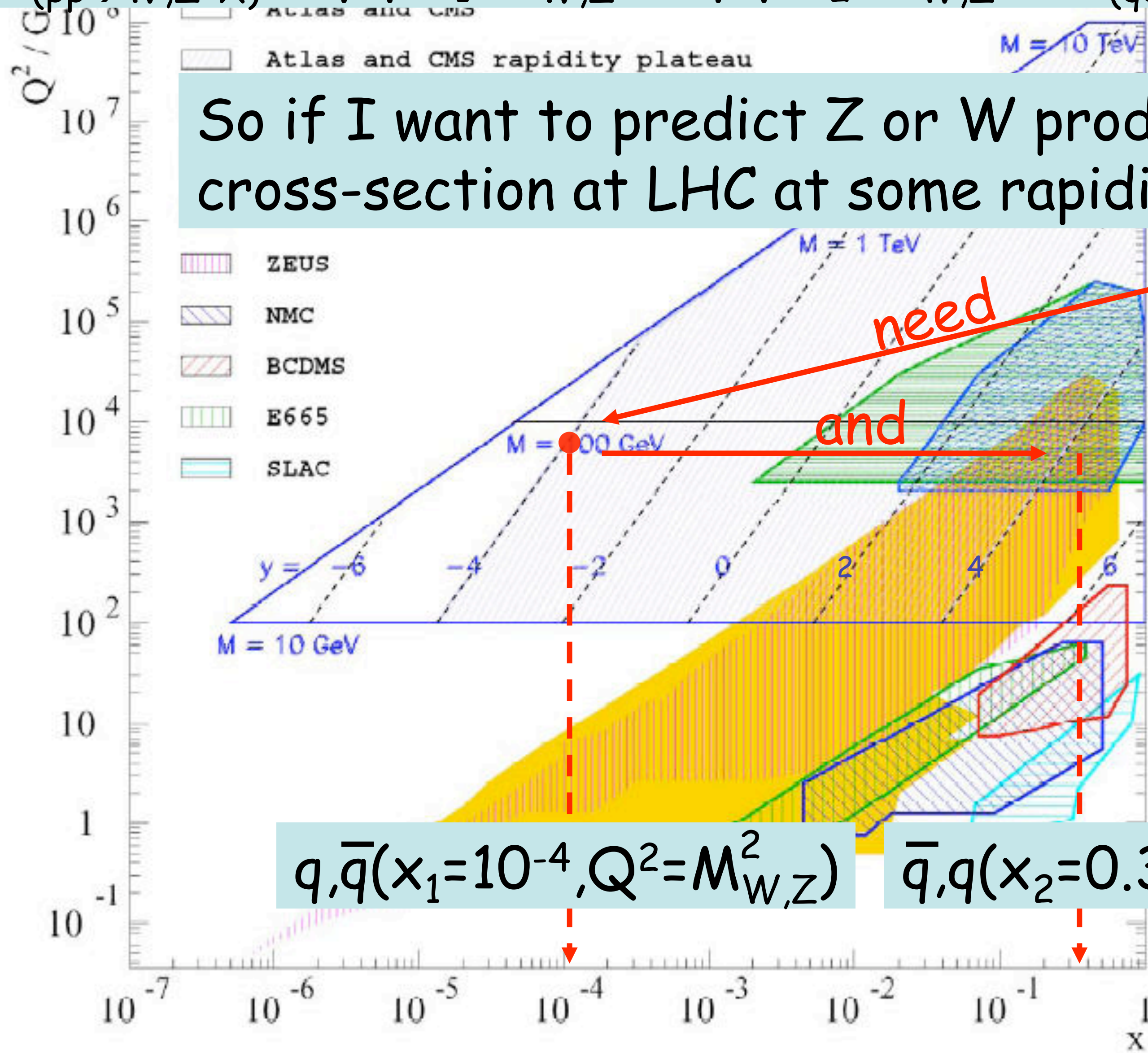
parton1(x_1) + parton2(x_2) → State with mass M

$x_1 = (M/\sqrt{s}) \exp(y)$

$x_2 = (M/\sqrt{s}) \exp(-y)$

$$\sigma_{(pp\to W,Z+X)} \sim q,\bar{q}(x_1,M^2_{W,Z}) \times \bar{q},q(x_2,M^2_{W,Z}) \times \sigma_{(q\bar{q}\to W,Z)}$$

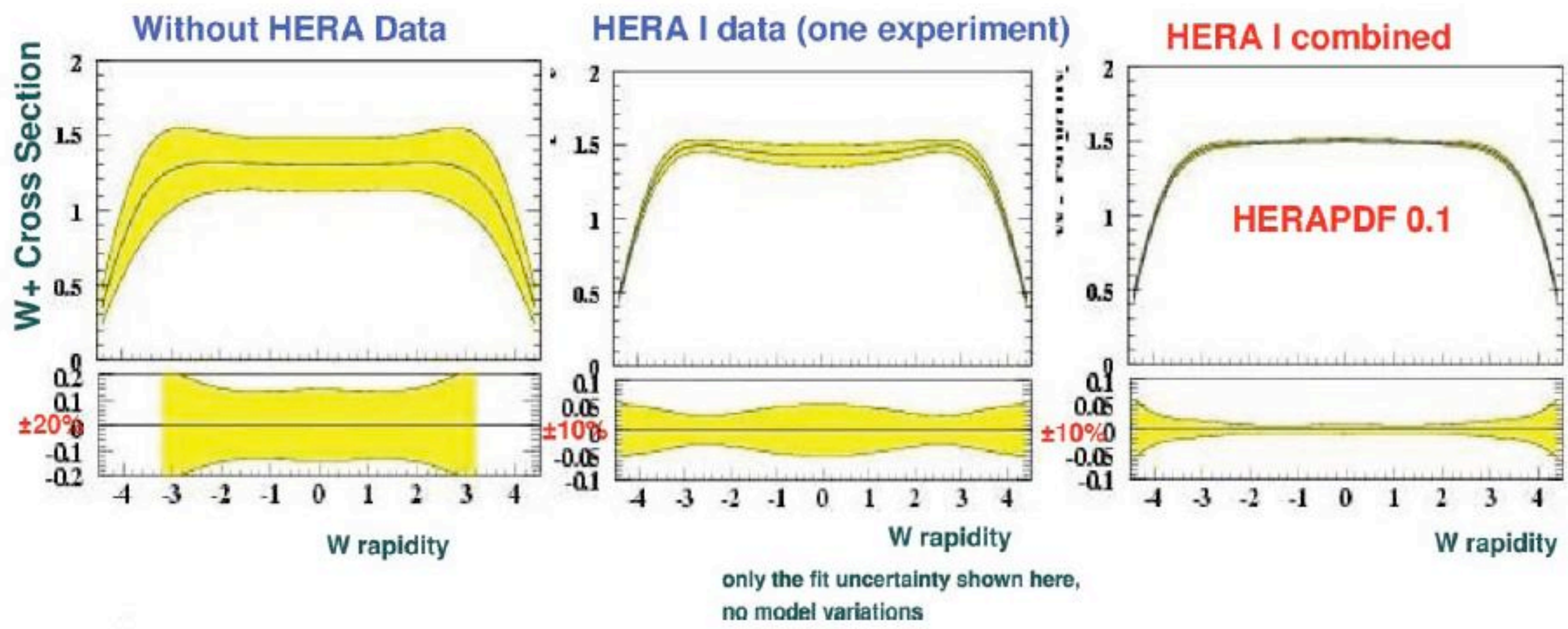
So if I want to predict Z or W production cross-section at LHC at some rapidity y, say, -4:



$q,\bar{q}(x_1=10^{-4},Q^2=M^2_{W,Z})$

$\bar{q},q(x_2=0.3,Q^2=M^2_{W,Z})$

Parton densities from combined data



A test on a standard candle process at LHC

HERA PDFs 0.1 available in LHAPDF

HERAPDF0.2 has factor of 2 smaller uncertainty than 0.1 (more data) at low x
Available soon in LHAPDF

With DIS data up to now :

$F_2 \sim \sum(q+\bar{q}) \approx S$ (sea quarks) measured in NC DIS

From scaling violations in F_2

$dF_2/d\ln Q^2 \sim \alpha_s \cdot g$ sensitive to gluons (times α_s)

$xF_3 \sim \sum(q-\bar{q}) = u_v + d_v$ valence quarks

Use jet cross sections to decouple α_s and g

DGLAP fits with all of the above -> precise predictions at LHC

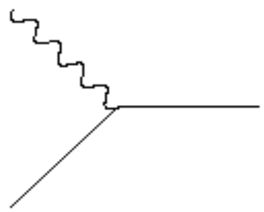
Now, for the last piece – the longitudinal structure function F_L to give us direct access to the gluons ->

Longitudinal Structure Function F_L

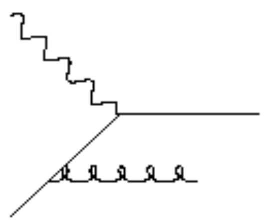
- F_L corresponds to absorption of longitudinally polarized virtual photon.

$F_L = (Q^2/4\pi^2\alpha)\ \sigma_L$

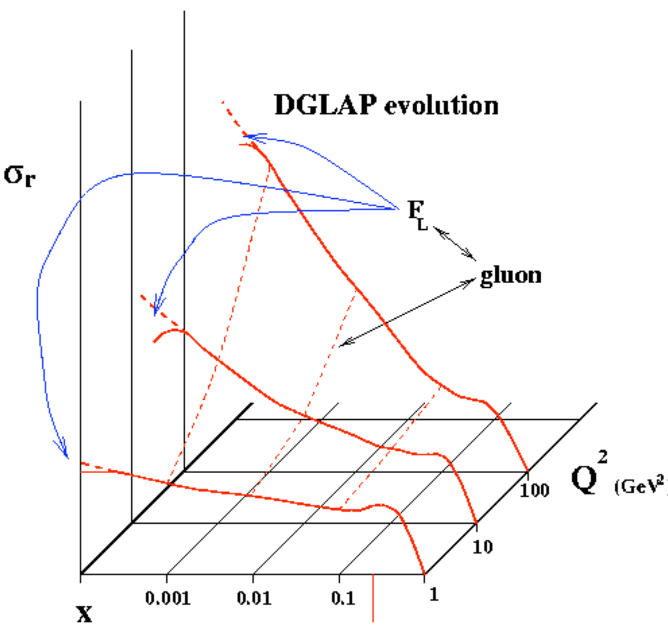
- Spin 1/2 quarks (with no transverse momentum) cannot absorb a longitudinally polarized boson.



LO: $k_T=0$, $F_L=0$ σ_r



NLO: $k_T \neq 0$, $F_L \neq 0$



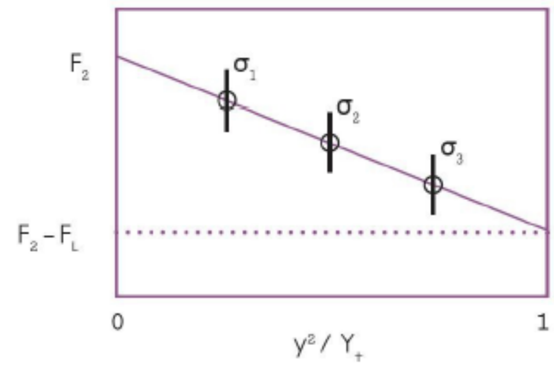
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) zg \right]$$

Analysis strategy

- Direct F_L measurement requires measurement of the reduced cross sections at **same x and Q^2 but different y:**

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

- Larger difference in y → better sensitivity to F_L (bigger "lever arm")

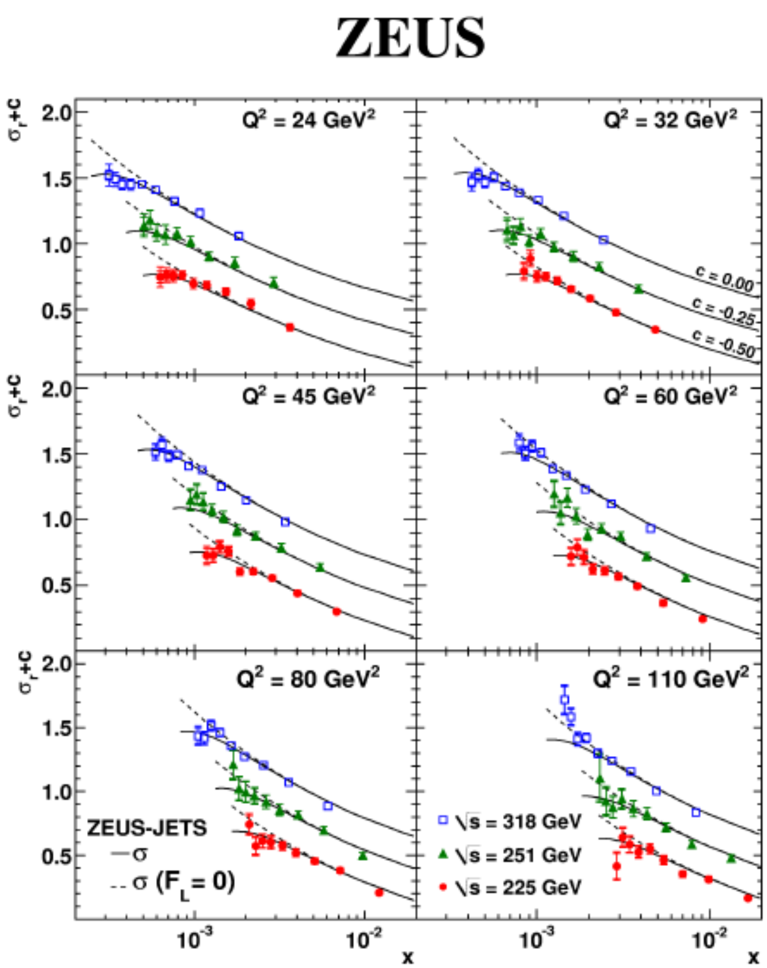


At given x and Q^2:
→ F_2 is the intercept at y-axis
→ F_L is the negative slope

- $Q^2 = xys$: different y → different s → different beam energies
- Direct F_L measurement only possible if HERA operates with different proton beam energies

DIS09 conference, Madrid, Spain. 27 April 2009 Julia Grebenyuk. F_L measurement with ZEUS detector. 5

Measured reduced cross sections



Kinematic region:

20 GeV^2 < Q^2 < 130 GeV^2

$5 \cdot 10^{-4} < x < 7 \cdot 10^{-3}$

- First ZEUS F_L publication available
- Most precise cross section measurement from ZEUS in the kinematic region studied
- Measured cross sections are published and available for fits
- Measured cross sections compared to ZEUS-JETS with and without F_L
- **Turnover at low x small but visible**

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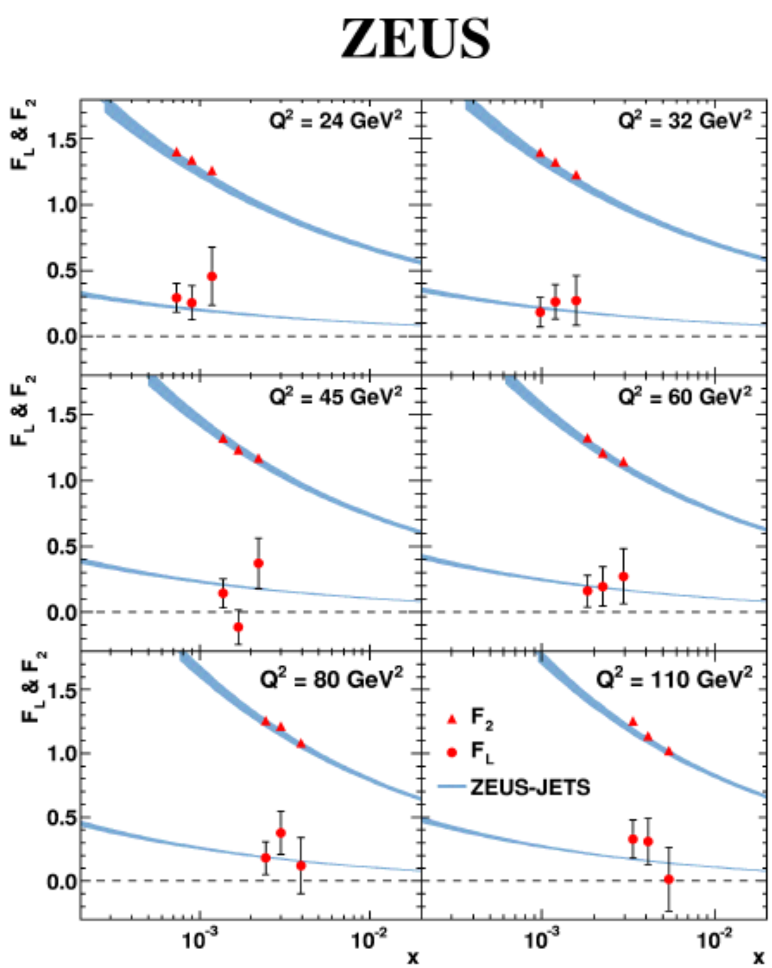
Extracted F_L and F_2



- **Most precise F_2 measurement from ZEUS at kinematic region studied**
- **First F_2 measurement without assumptions on F_L**

- Data support a non-zero F_L
- Predictions for F2 and FL are consistent with data

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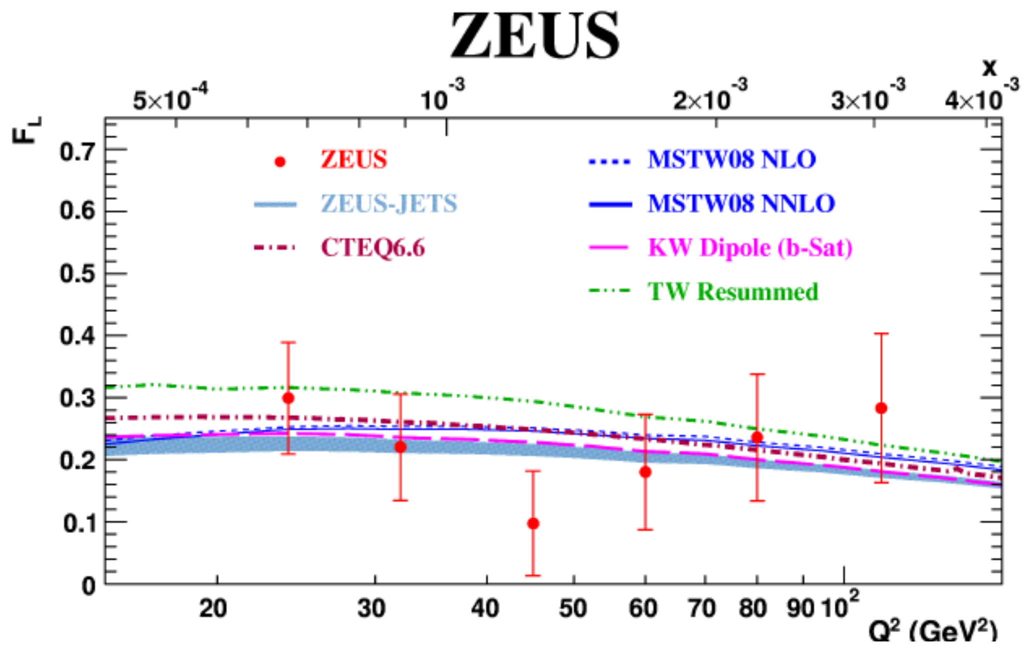

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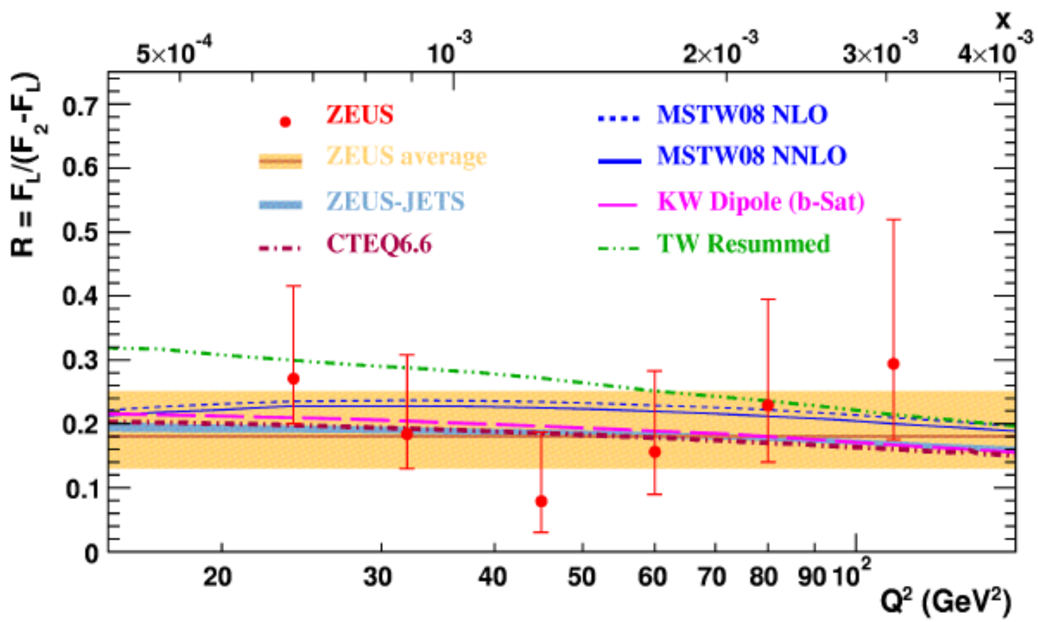


Ratio R is fitted:

$$R = F_L/(F_2 + F_L)$$

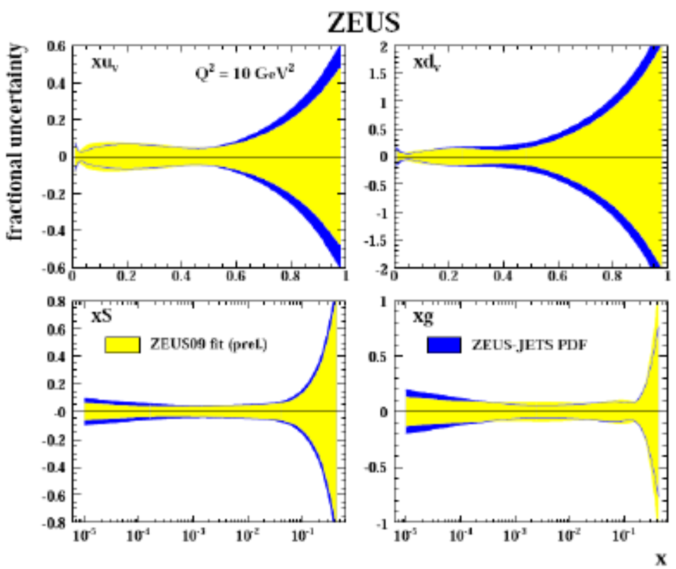
Average R from all data:

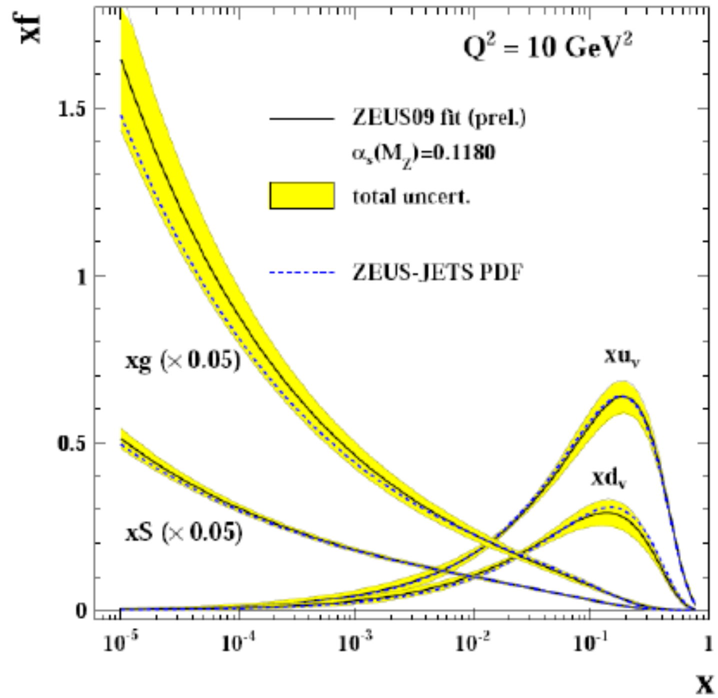
$R = 0.18^{+0.07}_{-0.05}$

PDF fits with F_L data included

- Measured coss sections for 3 data sets (HER, LER, MER) are included in ZEUS PDF fits
- Data has impact on the low x:
  - Steeper rise of gluon at low x
  - Sea and gluon uncertainty reduced

→ **For more details see talk of A. Cooper-Sarkar**





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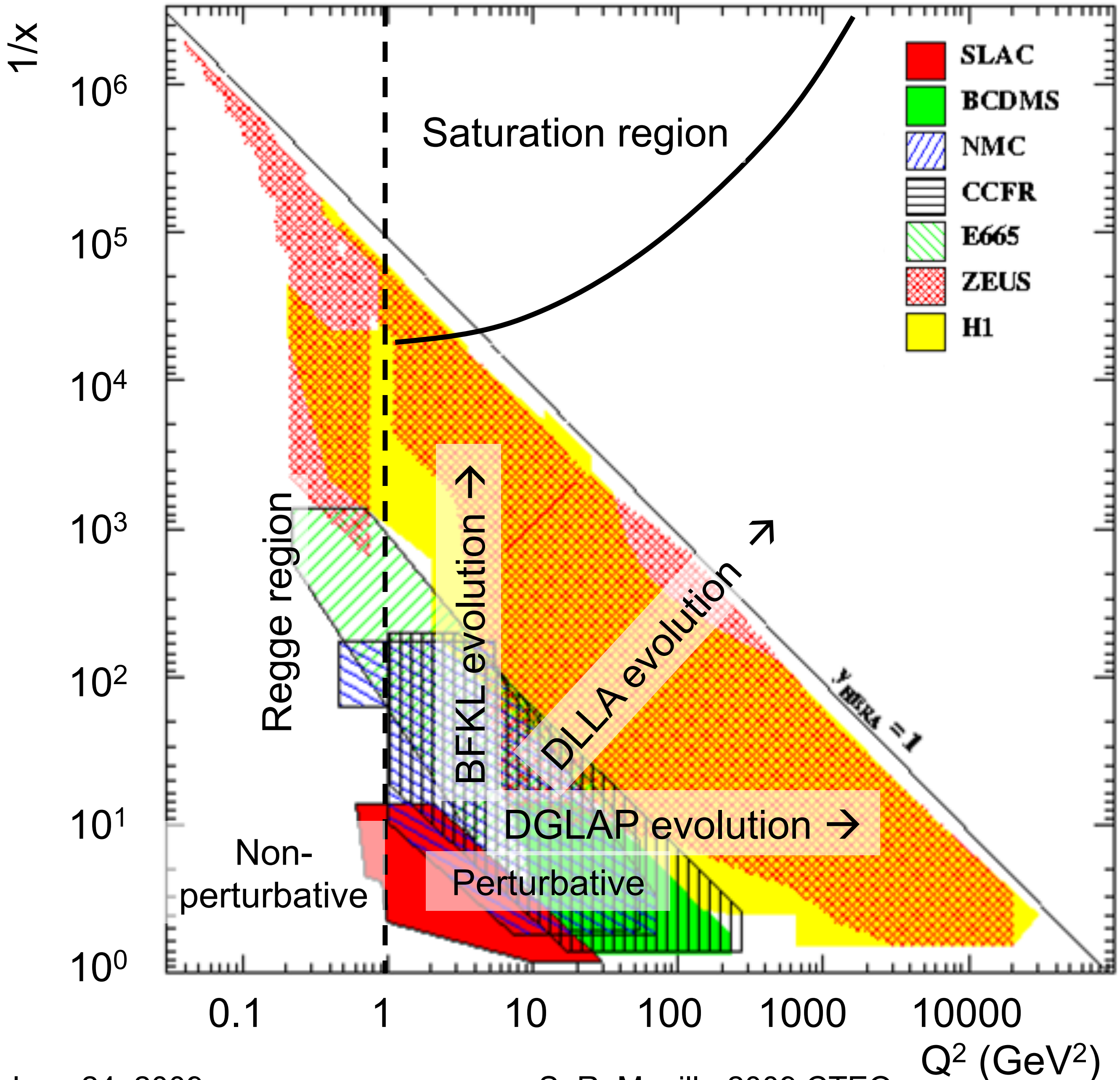
1/x
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0.1
1
10
100
1000
10000
Q^2 (GeV^2)
Saturation region
SLAC
BCDMS
NMC
CCFR
E665
ZEUS
H1
Regge region
BFKL evolution →
DLLA evolution →
DGLAP evolution →
Non-perturbative
Perturbative
y_HERA = 1