Structure Functions
From HERA to LHC

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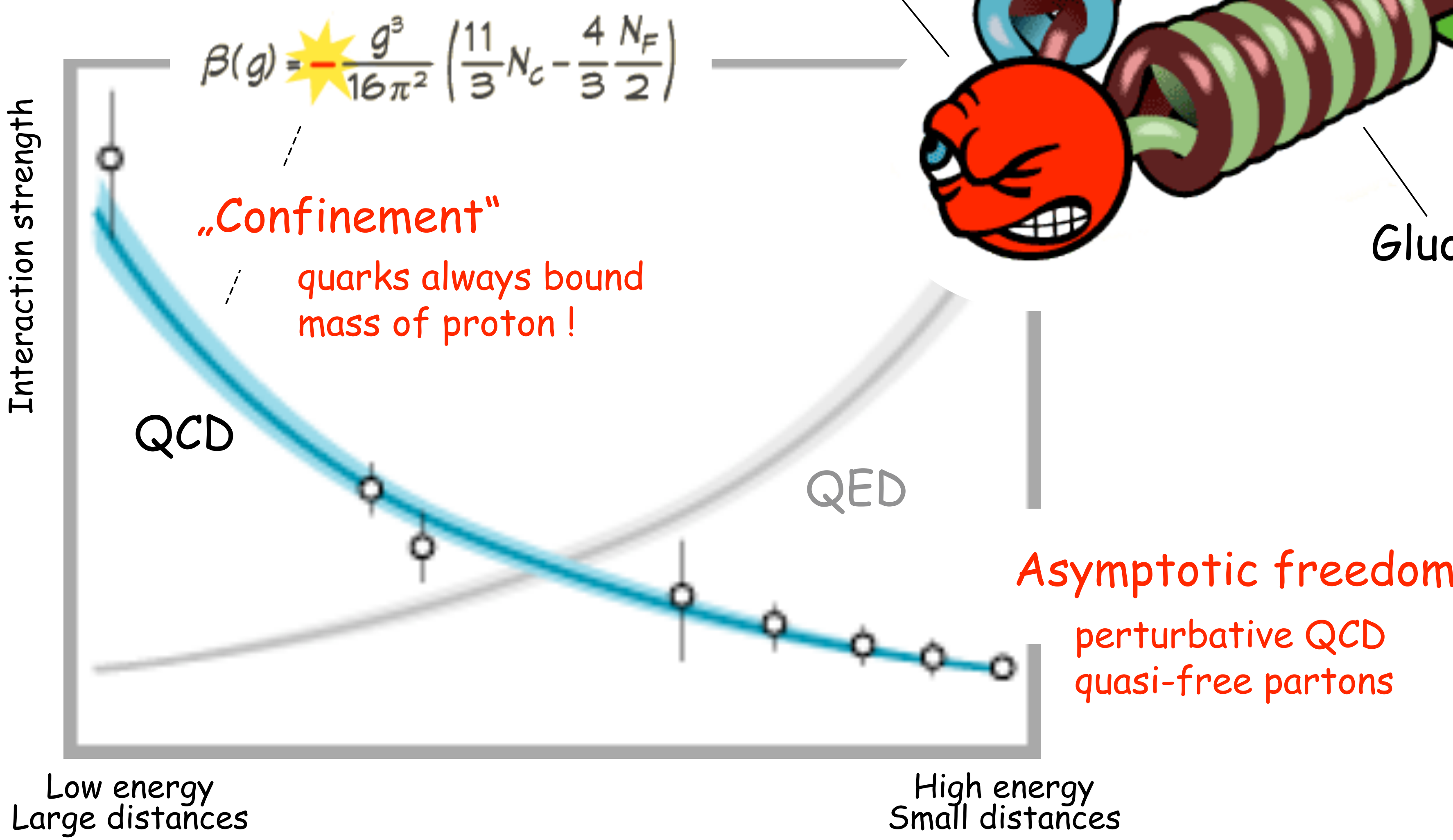
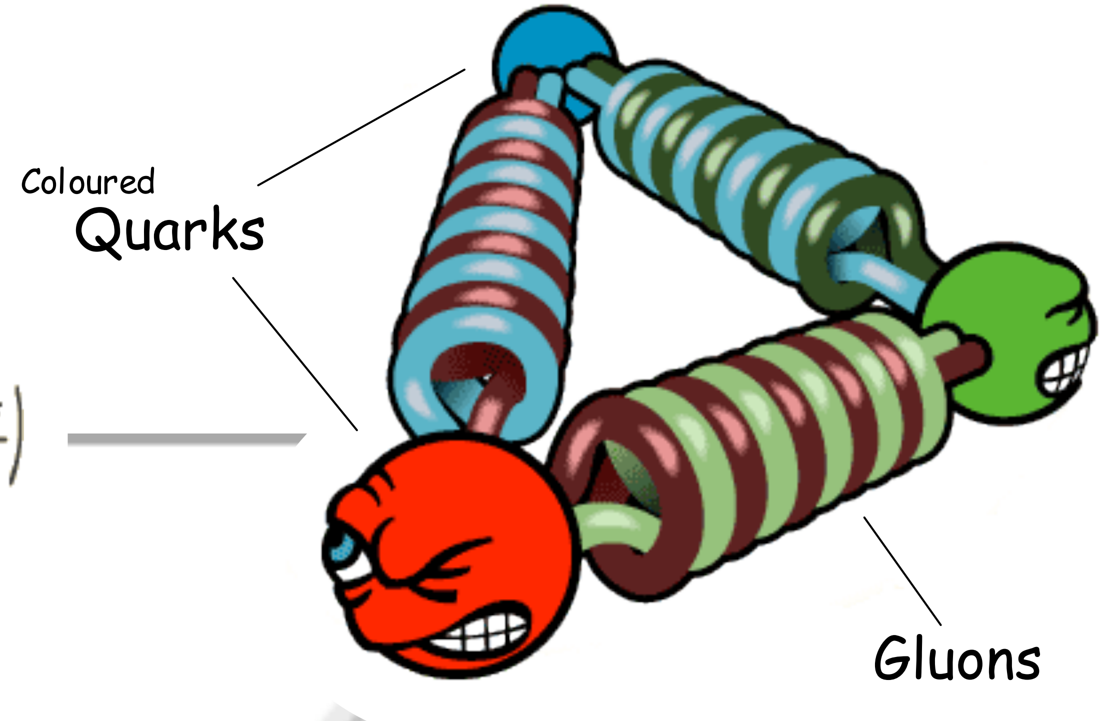
Workshop on Hard Processes
Graduiertenkolleg

Dortmund, October 13th, 2005

Nobelprize 2004

D.J.Gross, H.D. Politzer & F. Wilczek





http://nobelprize.org/physics/laureates/2004/illpres

We know: QCD is the theory of the strong interactions !

Why then QCD at HERA ?

and elsewhere ... ?

Because:

... the strong coupling α_s is the least well known of the coupling constants

... we do not understand how partons are put together to make hadrons

... we need to understand future high energy experiments at the LHC

...

QCD @ HERA ...

Today!

- proton structure F_2

  quark- & gluon-PDFs (→ LHC), $\Delta\alpha_s/\alpha_s \sim 1\%$ (NNLO)
  F_2 at small Q^2, x → non-perturbative QCD
  xF_3, PDFs at large x (HERA II !) ...

- heavy quarks

  universality of proton structure (gluon-PDF!)
  fragmentation, production mechanisms, c/b-PDFs ...

- diffraction and low-x physics

  QCD dynamics at high parton densities ...
  structure of diffractive interactions, factorization
  DVCS → parton-parton correlations (GPDs)

- jet physics

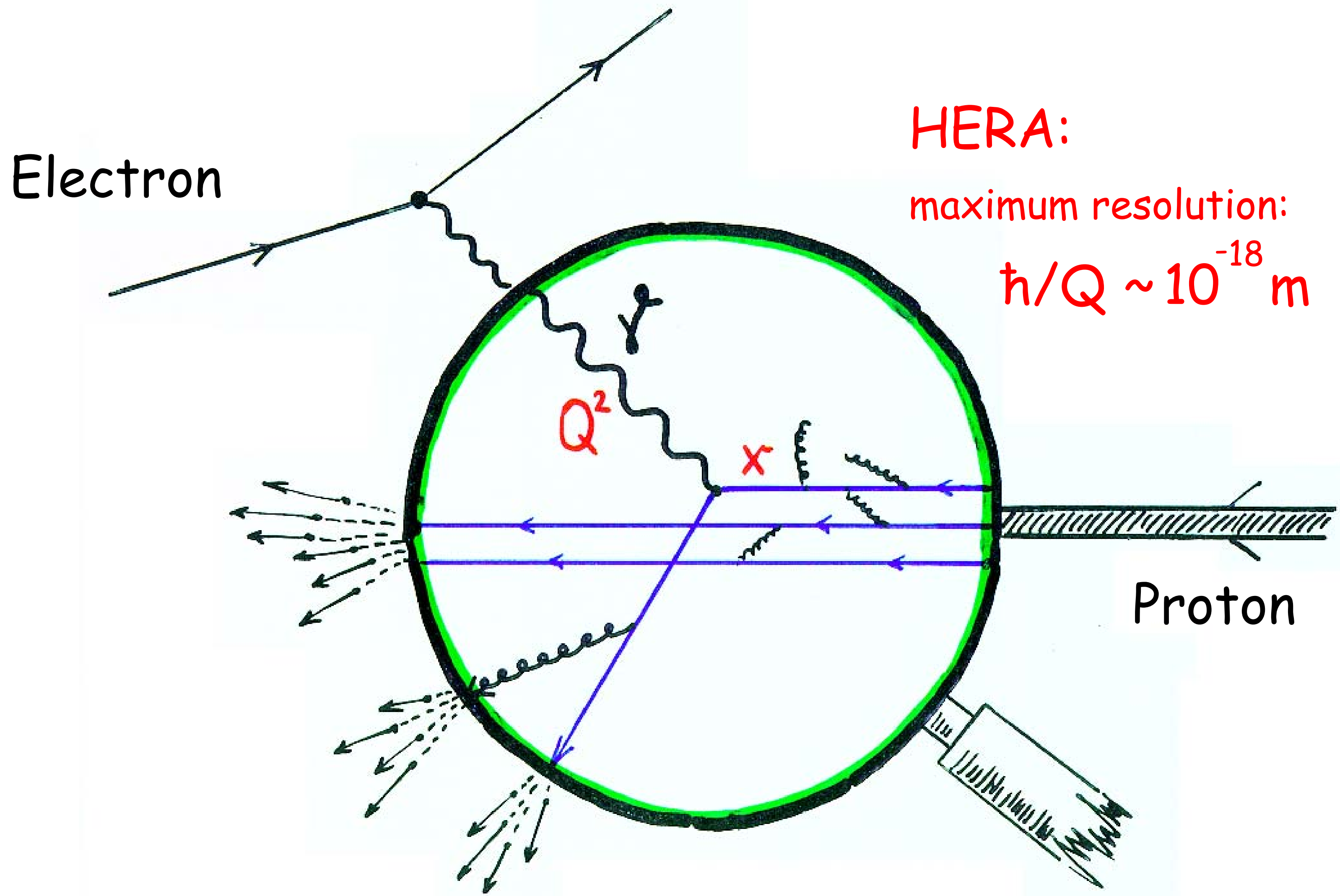
  universality of proton structure (gluon-PDF!)
  parton dynamics, measurement of α_s

- spectroscopy

  pentaquarks ...

Structure Functions

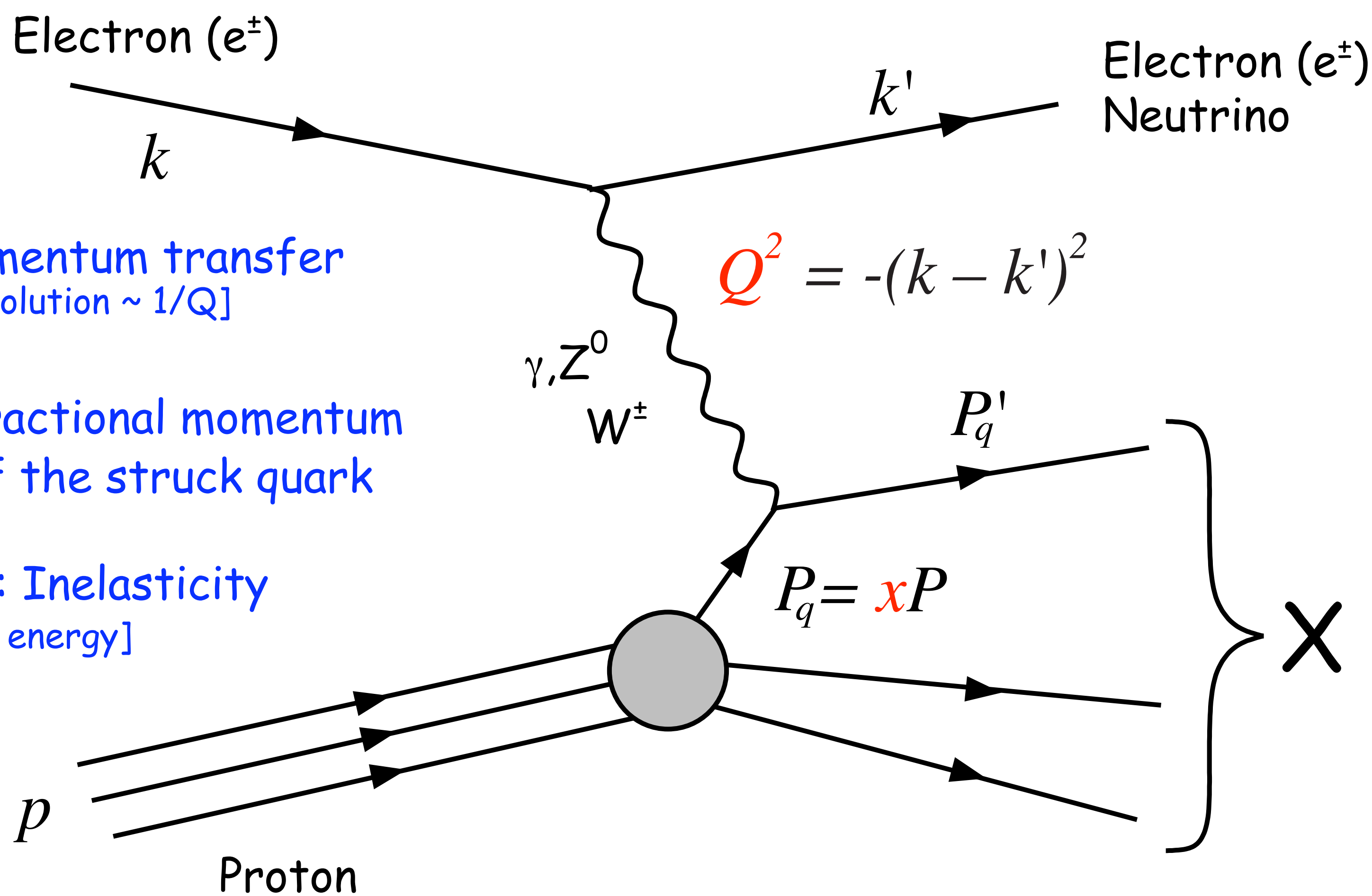
Basics



Ideal QCD laboratory

HERA Kinematics

E_e=27.5 GeV



Q^2: four-momentum transfer
[spatial resolution ~ 1/Q]

x: fractional momentum of the struck quark

$y = Q^2/sx$: Inelasticity
[$\sqrt{s}$: cms energy]

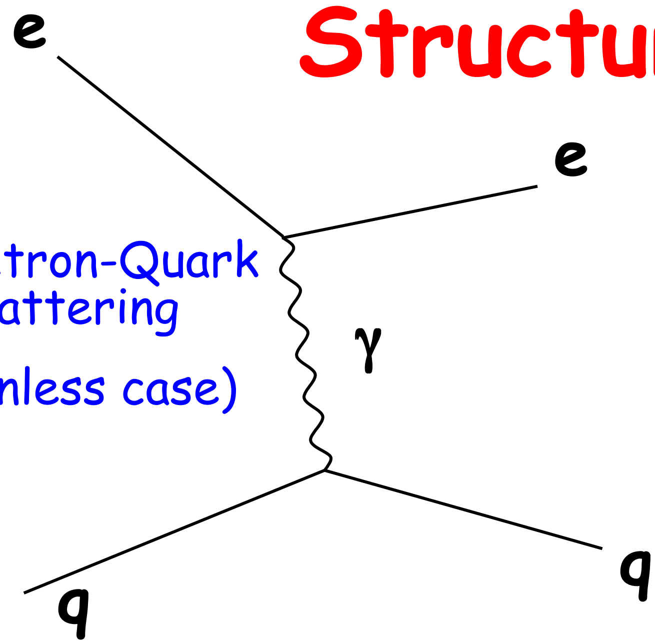
E_p=920 GeV
[before 1998: E_p=820 GeV]

Structure Function F_2

Naive
QPM

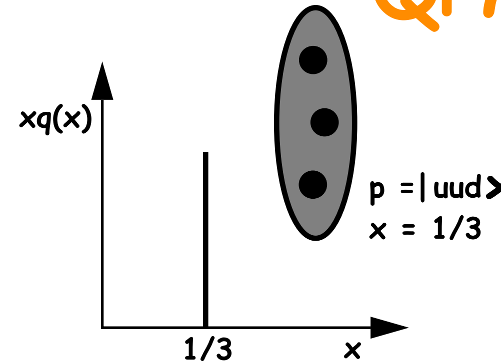
Electron-Quark scattering

(spinless case)



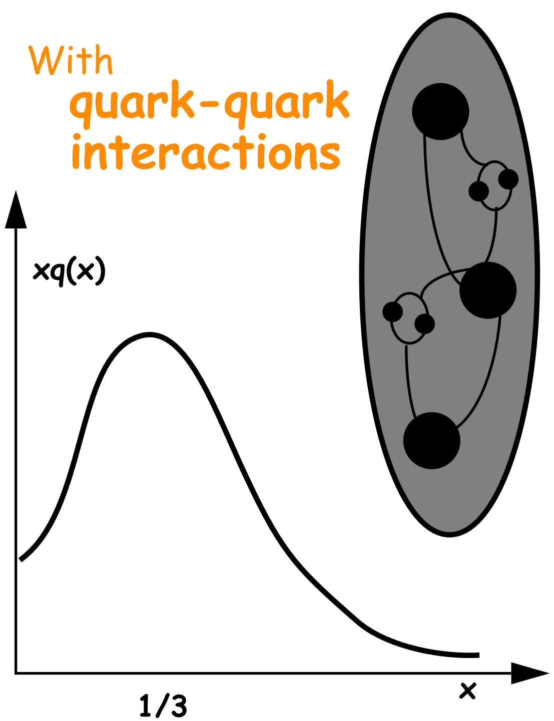
$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

Rutherford scattering on pointlike target



$$\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4}[2e_u^2 + e_d^2] = \frac{4\pi\alpha^2}{q^4}$$

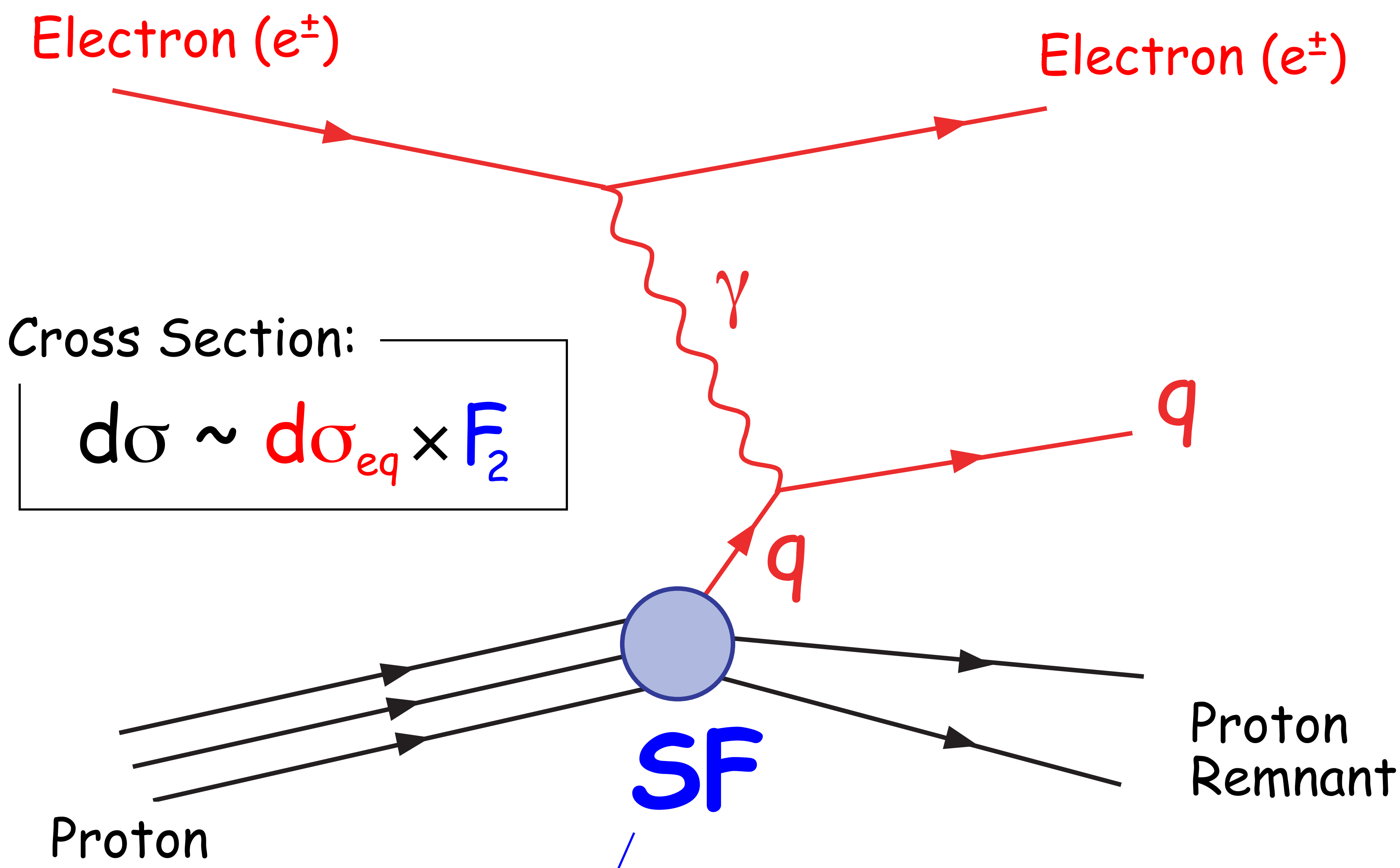
With **quark-quark interactions**



$$\frac{d\sigma(ep)}{dx\,dq^2} = \frac{4\pi\alpha^2}{q^4}[e_u^2 u(x) + e_d^2 d(x) + \ldots]$$

$$= \frac{4\pi\alpha^2}{q^4} \frac{F_2(x)}{x}$$

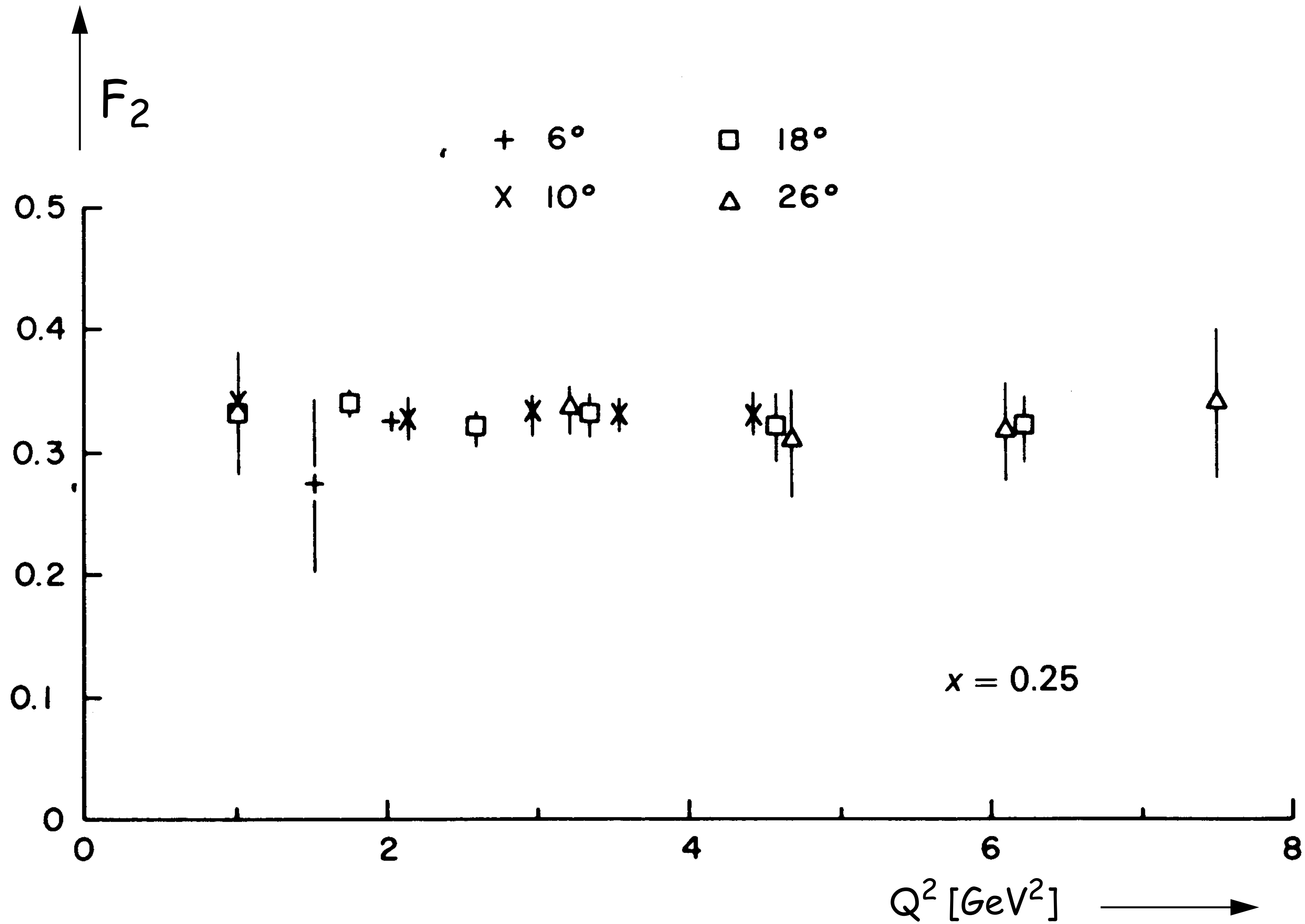
QPM: Structure Function F_2 independent of Q^2



$$F_2 = \sum e_q^2 \, x q(x)$$

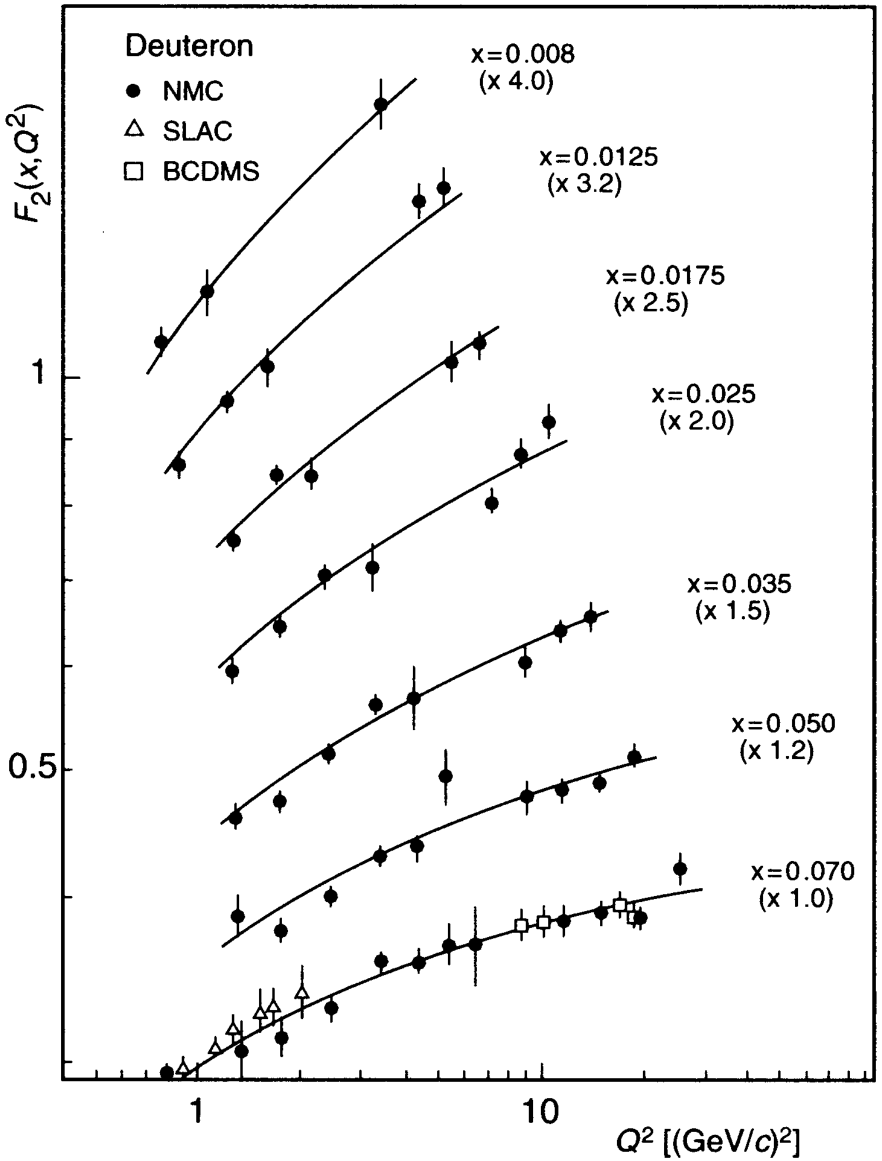
- describes structure of proton
- probability to find quark with momentum fraction x
- QPM: independent of Q^2. Correct?

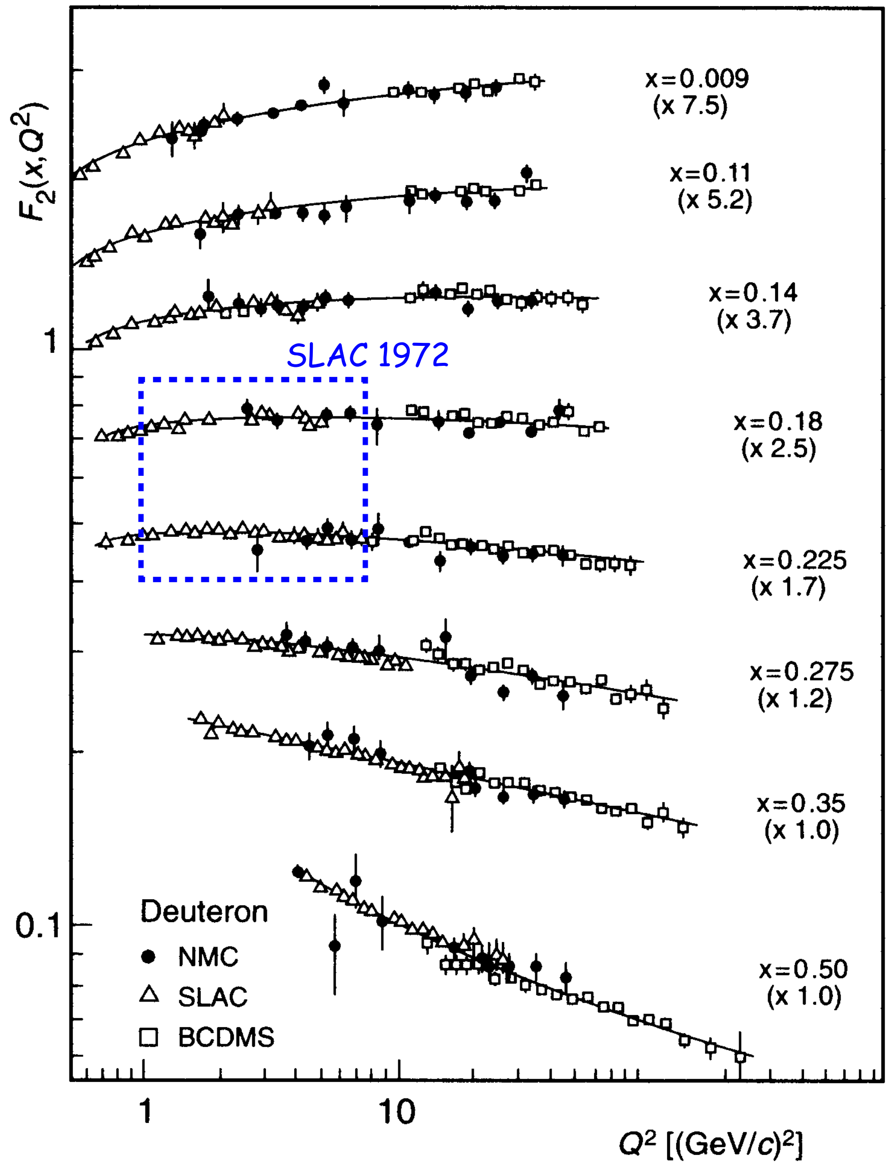
Scaling [SLAC 1972]



Scaling Violations [1990++]

$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$

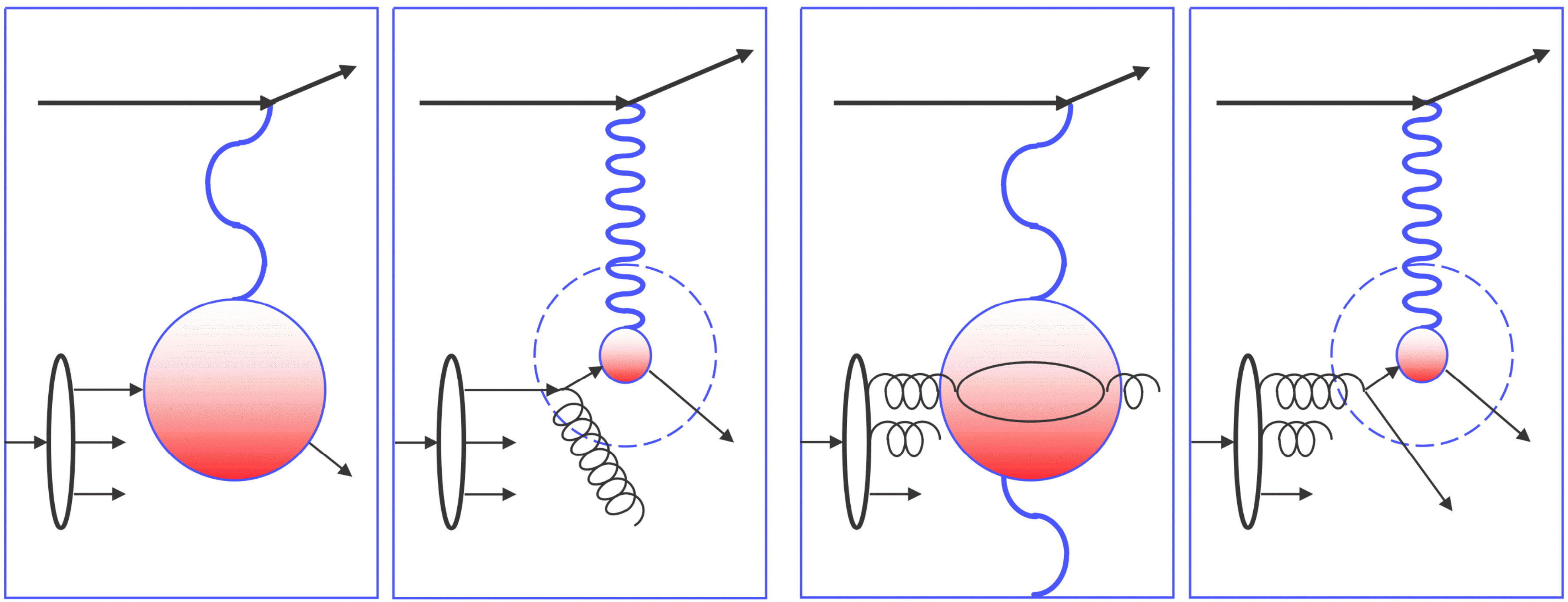




The QCD Picture of Scaling Violation

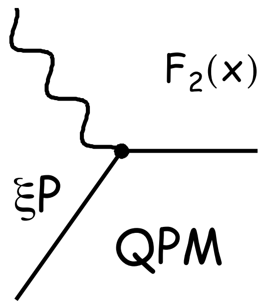
- Proton quark dominated:
  $Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

- Proton gluon dominated:
  $Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x



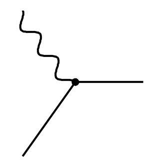
Q^2-evolution described by DGLAP equations

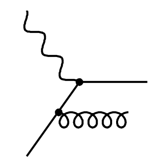
QCD Improved Parton Model

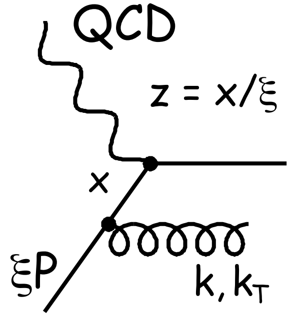


$$F_2(x) = x\sum_q \int_0^1 e_q^2\, d\xi\, q(\xi)\,\delta(x-\xi) = x\sum_q e_q^2 q(x)$$

$$F_2(x) = x\sum e_q^2 \int_x^1 \frac{d\xi}{\xi} q(\xi)\left[\delta\left(1-\frac{x}{\xi}\right) + \frac{\alpha_s}{2\pi} P_{qq}\left(\frac{x}{\xi}\right)\log\frac{Q^2}{\mu_0^2}\right]$$







μ_0: cutoff parameter

$$\sigma_{\gamma^* q \to qg} \sim \frac{\alpha_s}{2\pi} P_{qq}(z) \int_{\mu_0^2}^{Q^2} \frac{dk_T^2}{k_T^2}$$

$$\sim \frac{\alpha_s}{2\pi} P_{qq}(z) \log\frac{Q^2}{\mu_0^2}$$

Splitting function:

Probability to find quark with momentum fraction z of a parent quark having emitted a gluon with momentum (1-z)

$$q(x,Q^2) = q(x) + \frac{\alpha_s}{2\pi}\log\frac{Q^2}{\mu_0^2}\int_x^1 \frac{dz}{z} P_{qq}(z)\, q(x/z) \qquad \text{(A)}$$

$$q(x,\mu^2) = q(x) + \frac{\alpha_s}{2\pi}\log\frac{\mu^2}{\mu_0^2}\int_x^1 \frac{dz}{z} P_{qq}(z)\, q(x/z) \qquad \text{(B)}$$

(A)-(B)

$$q(x,Q^2) = q(x,\mu^2) + \frac{\alpha_s}{2\pi}\log\frac{Q^2}{\mu^2}\int_x^1 \frac{dz}{z} P_{qq}(z)\, q(x/z)$$

DGLAP Equations

DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

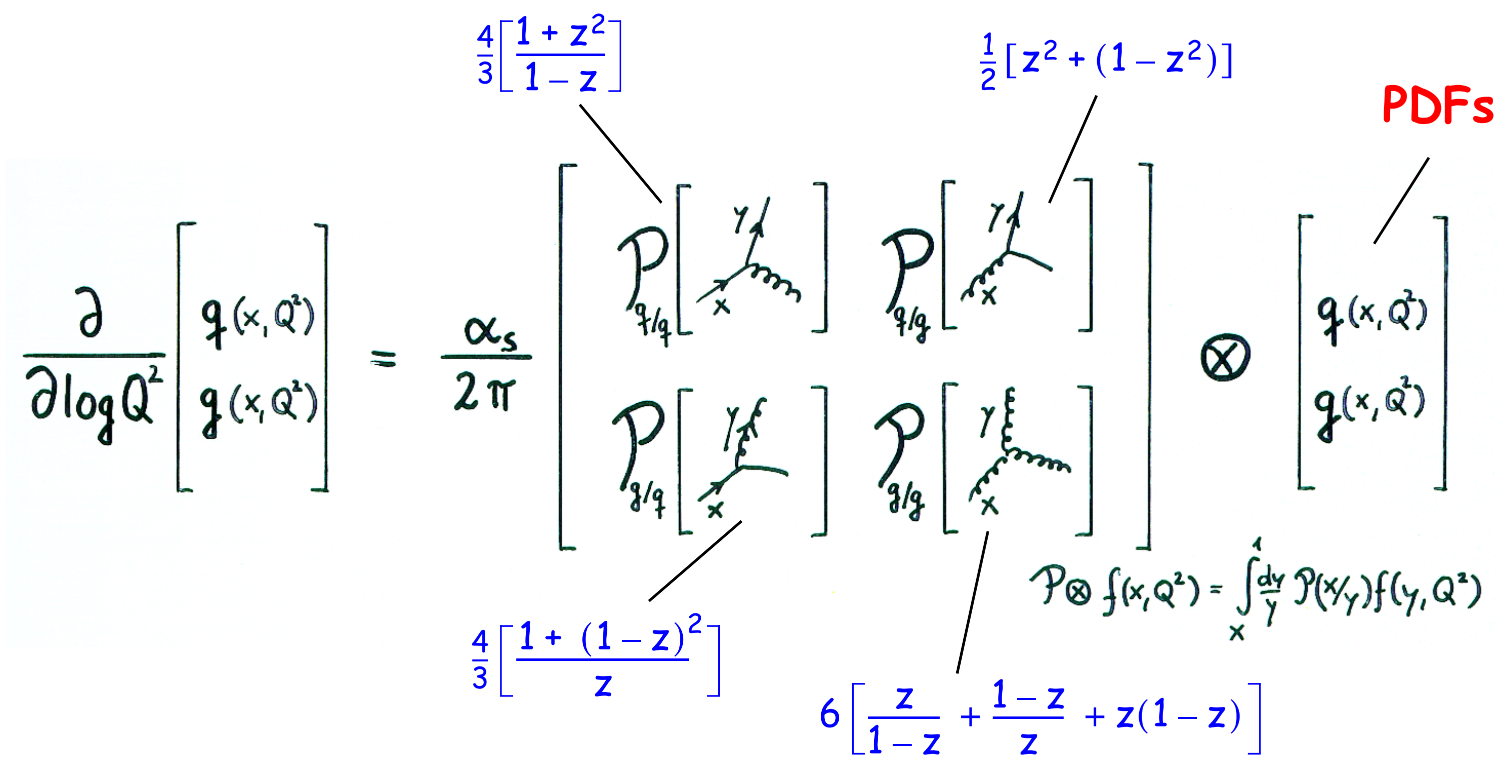
DGLAP evolution equations arise from requirement that $q(x,Q^2)$ should not depend on the choice of scale μ:

$$q(x,Q^2) = q(x,\mu^2) + \frac{\alpha_s}{2\pi}\log\frac{Q^2}{\mu^2}\int_x^1 \frac{dz}{z}P_{qq}(z)\,q(x/z)$$

$$\& \quad \frac{dq(x,Q^2)}{d\log\mu^2} = \frac{dq(x,\mu^2)}{d\log\mu^2} - \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}P_{qq}(z)\,q(x/z) \stackrel{!}{=} 0$$

$$\frac{dq(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}P_{qq}(z)\,q(x/z,\mu^2)$$

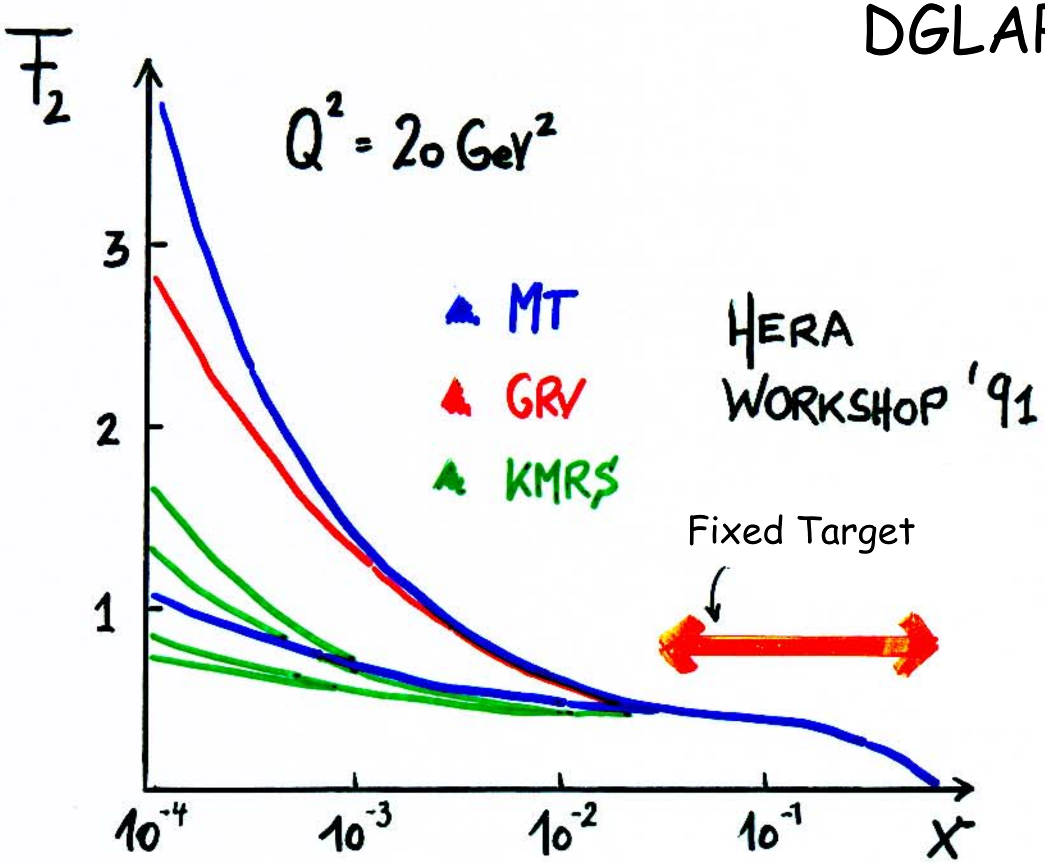
From iteration



F_2 at Low Bjorken-x

[Pre-HERA Knowledge]

$$\frac{\partial}{\partial \log Q^2}\begin{pmatrix} q \\ g \end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{bmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{bmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$



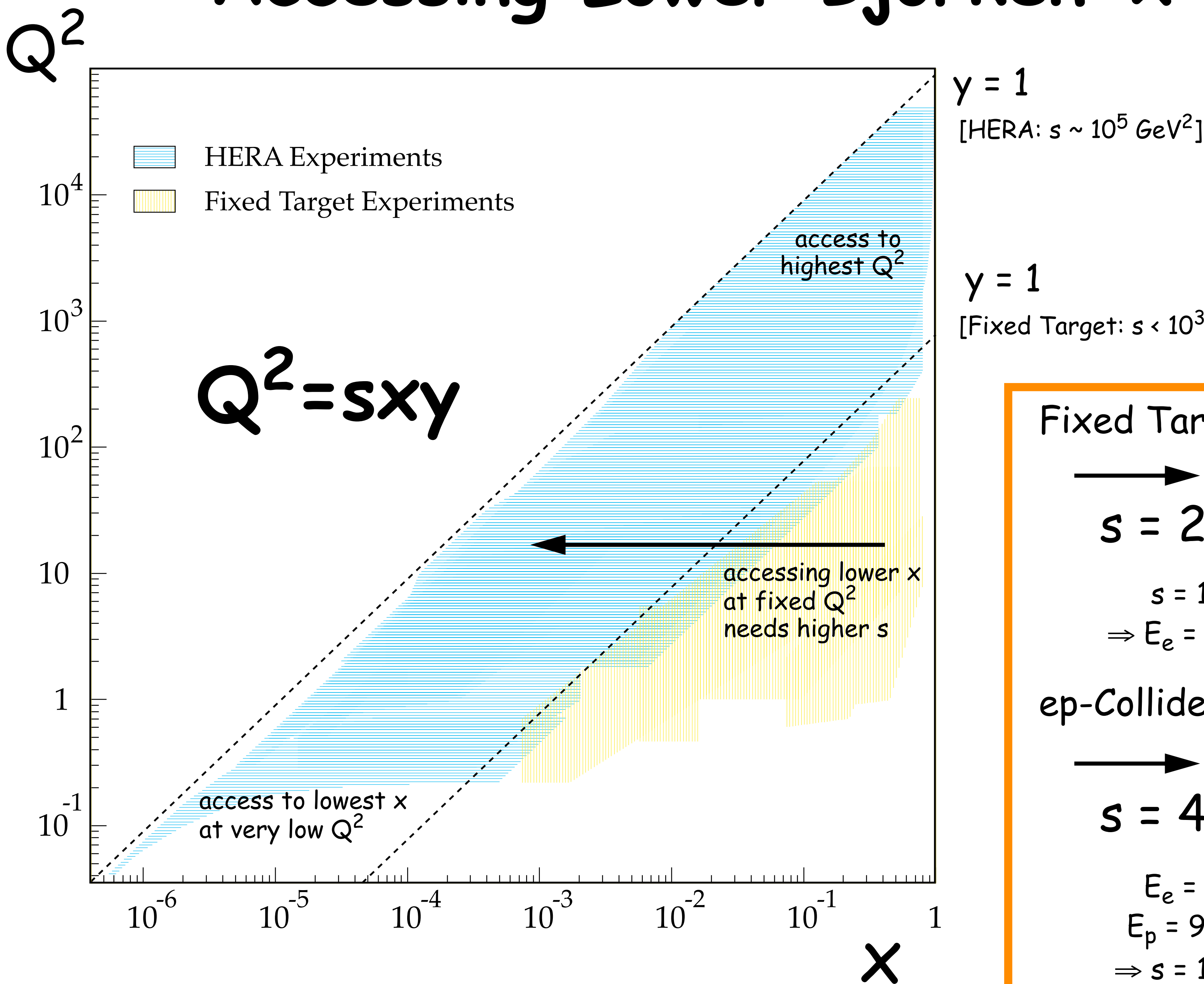
DGLAP: No prediction for the x-dependence of F_2

[except asymptotic behaviour]

A. De Rujula et.al. 1974

Measure !!

Accessing Lower Bjorken-x



Fixed Target:

$$s = 2M_pE_e$$

$s = 10^5$ GeV

$\Rightarrow E_e = 50$ TeV

ep-Collider:

$$s = 4E_pE_e$$

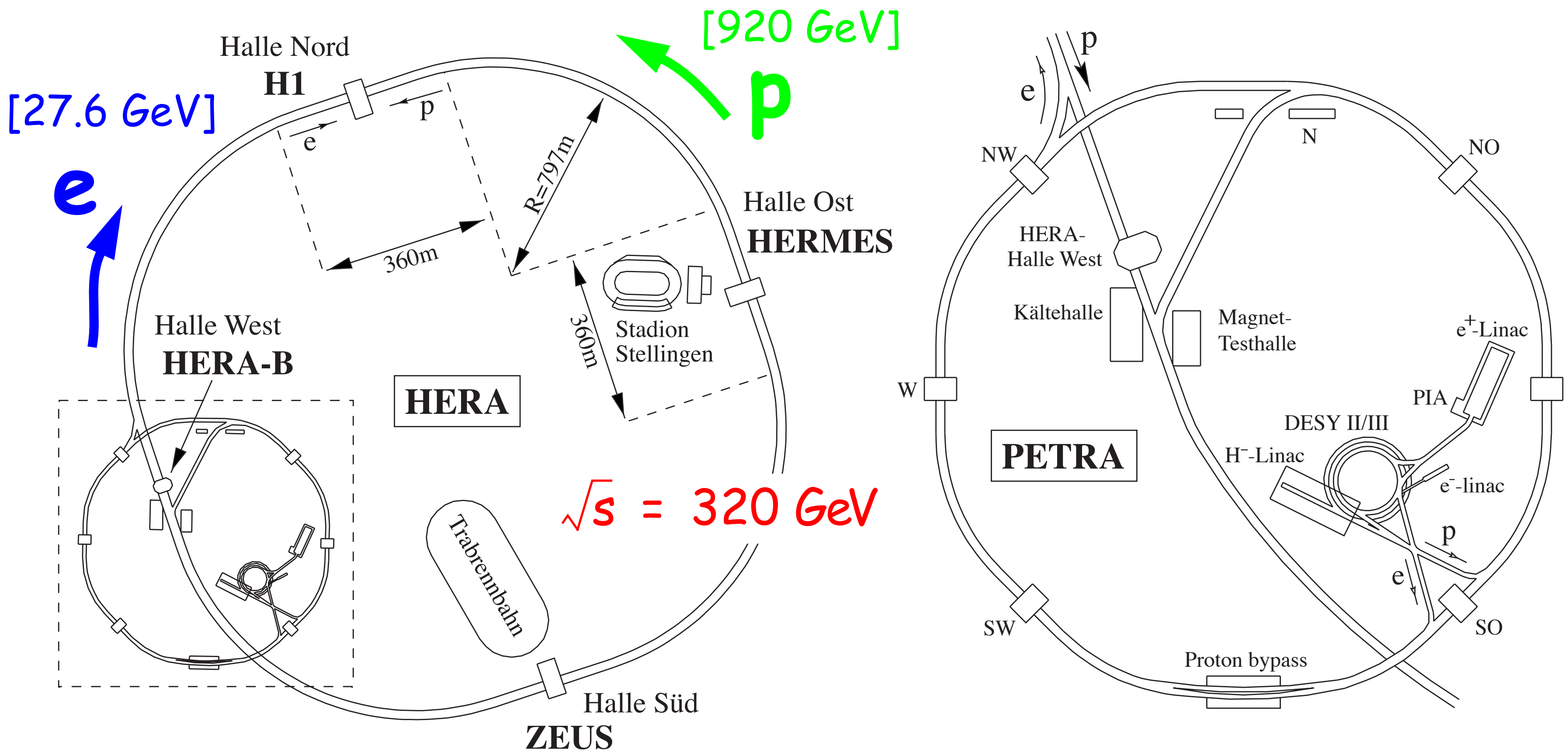
$E_e = 30$ GeV

$E_p = 900$ GeV

$\Rightarrow s = 10^5$ GeV


HERA
PETRA

The HERA Accelerator Complex



Proton ring:

- Energy*: 920 GeV
- Mag. Field: 4.682 T
- Current: ~ 100 mA

* before 1998: 820 GeV

Electron ring:

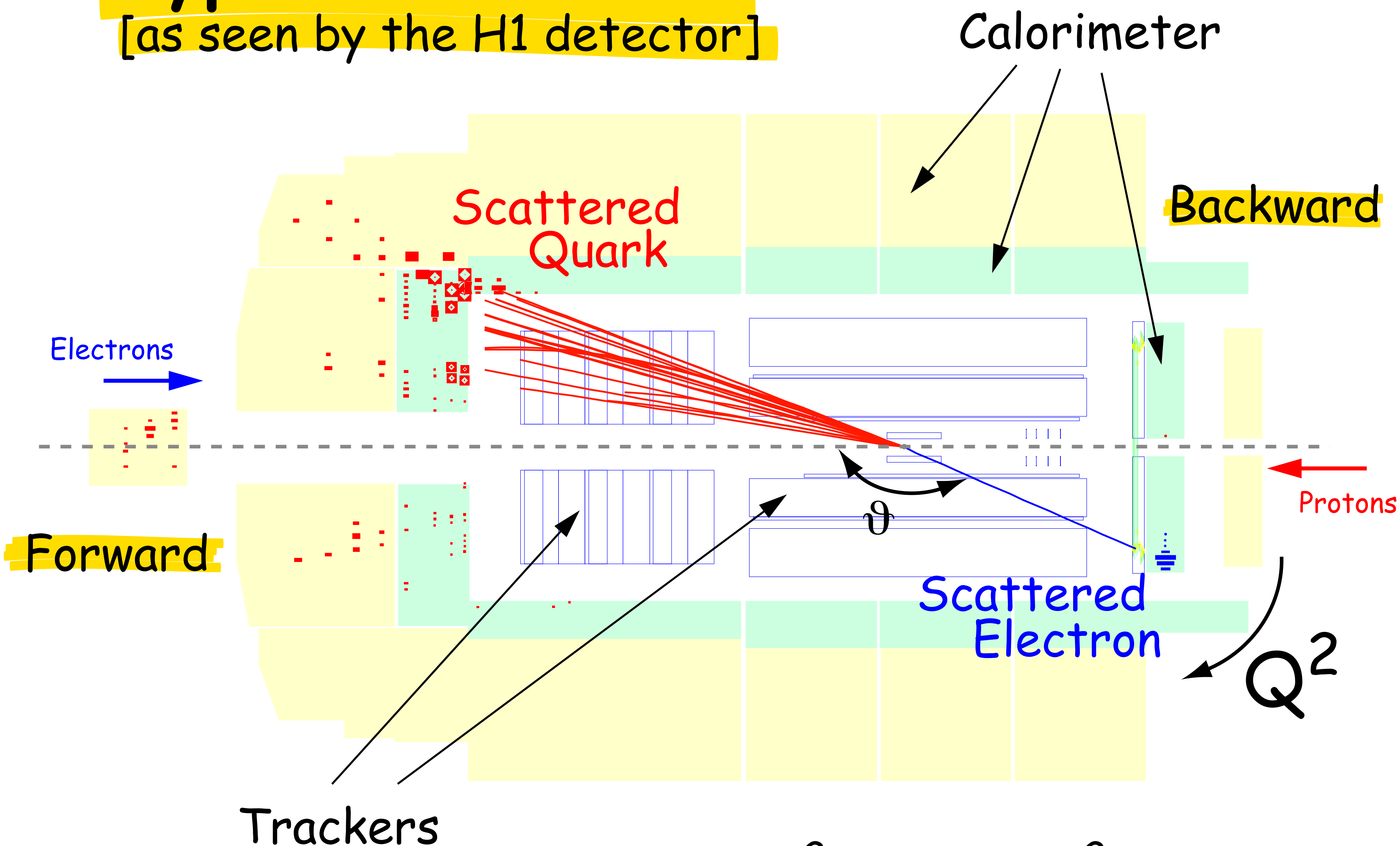
- Energy: 27.5 GeV
- Mag. Field: 0.164 T
- Current: ~ 40 mA

General:

- Energy in cms: 318 GeV
- Circumference: 6.3 km
- BX rate: 10.4 MHz
- Lumi: $1.5 \cdot 10^{31}$ $cm^{-2}s^{-1}$

Typical DIS-Event

[as seen by the H1 detector]



$$Q^2 = 4E_eE_e'\cos^2(\vartheta/2)$$

ep Cross Section [low Q^2 approximation]

Proton Structure

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

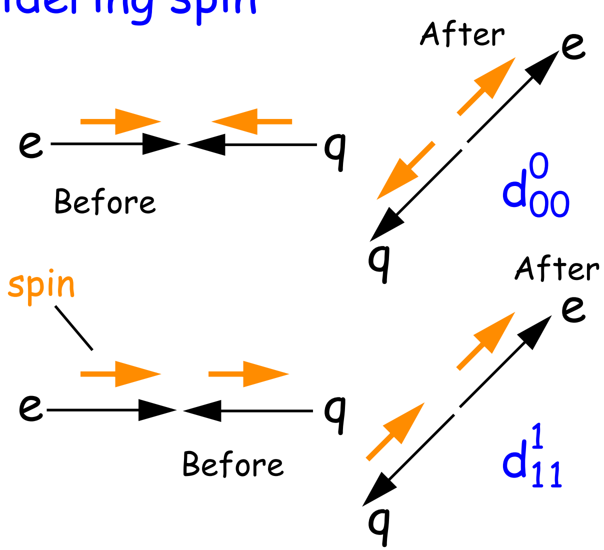
Evolution according to DGLAP

Rutherford

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4} F_2(x,Q^2) \cdot \tfrac{1}{2}[1 + (1-y)^2] - y^2 F_L$$

$y^2 F_L \sim 0$: influence small, related to gluon density [contribution only @ high y] [LO: F_L=0]

Considering spin



$$M^2 \propto |d^J_{\lambda,\lambda'}|^2 \qquad d^0_{0,0} = 1 \qquad d^1_{1,1} = \frac{1+\cos\theta^*}{2}$$

$$y = \frac{pq}{pk} = \frac{E_p E_e (1-\cos\theta^*)}{2E_p E_e} = \frac{(1-\cos\theta^*)}{2}$$

$$\longrightarrow M^2 \propto 1 + (1-y)^2$$

y-dependence describes helicity structure of interaction

Structure Function F_2

[Principle of Measurement]

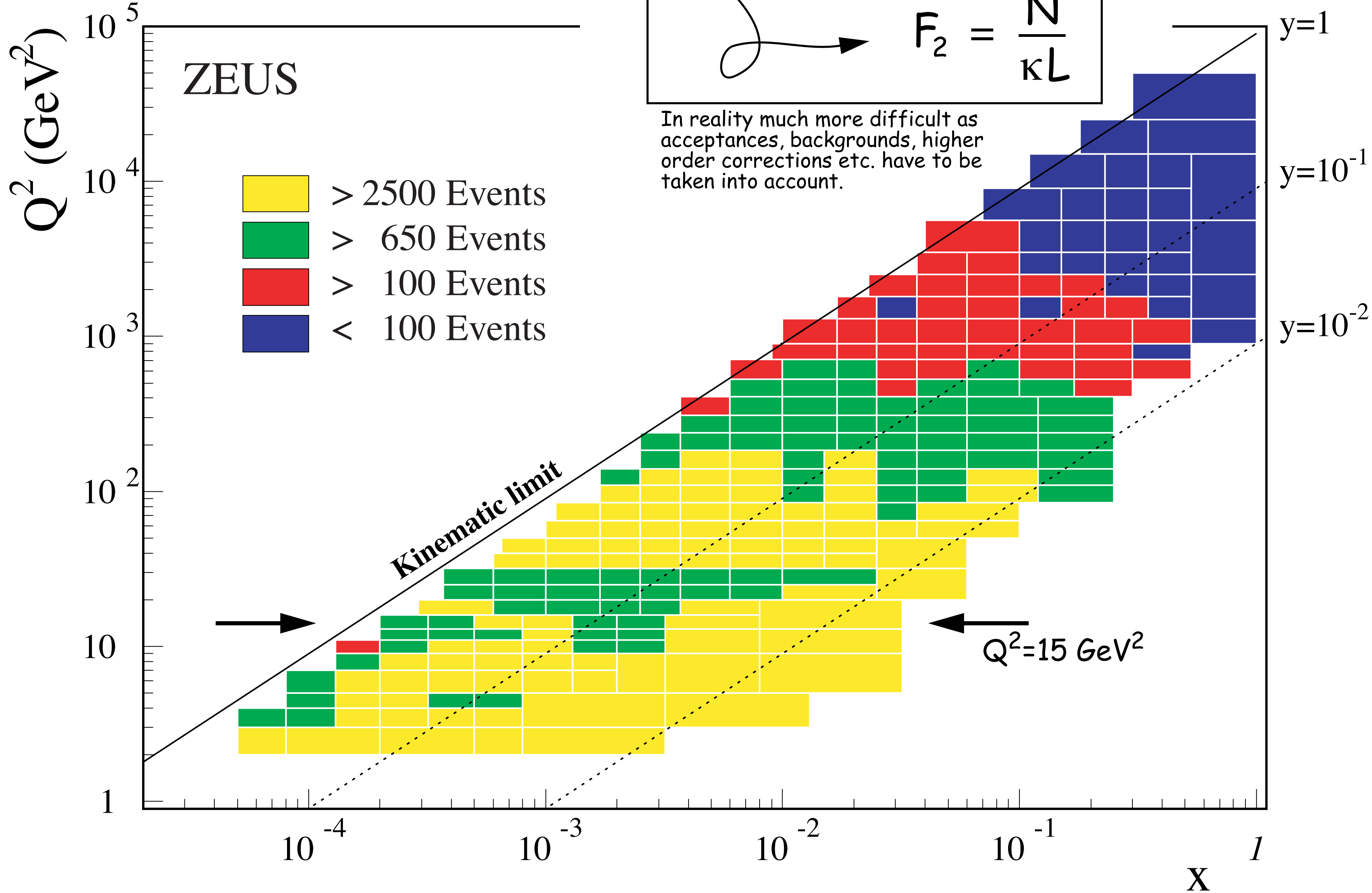
Basic (simplified) Procedure:

$$\sigma \sim \underbrace{\frac{4\pi\alpha^2}{xQ^4}}_{\kappa} F_2 \quad \text{and} \quad \sigma = N/L$$

$$F_2 = \frac{N}{\kappa L}$$

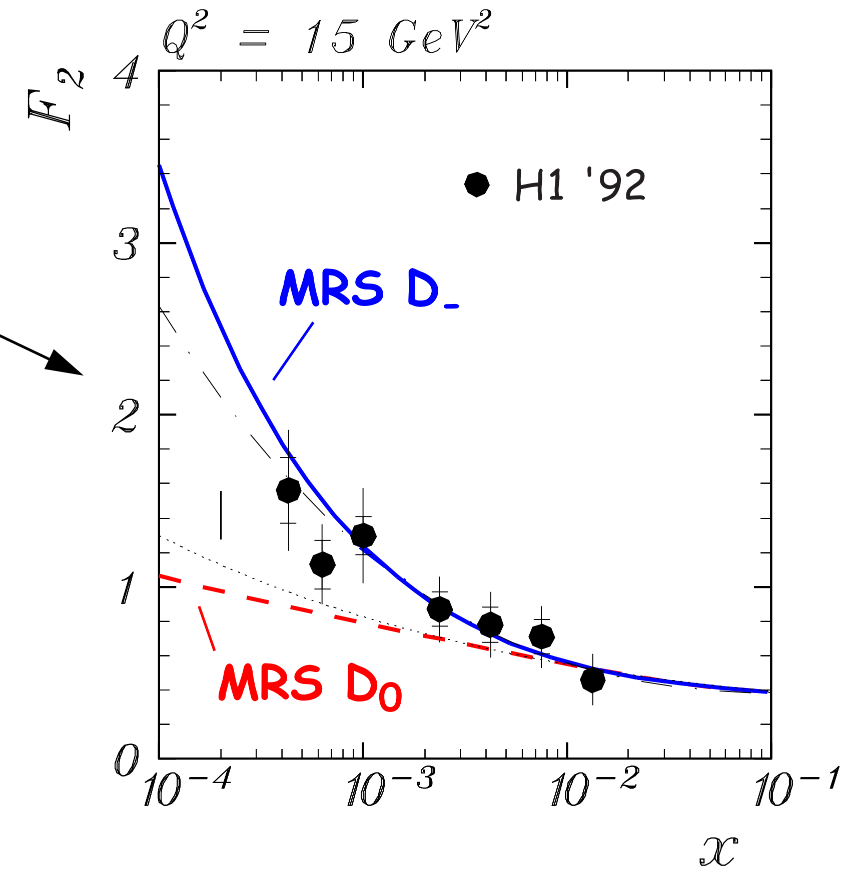
N: Number of events
L : Luminosity

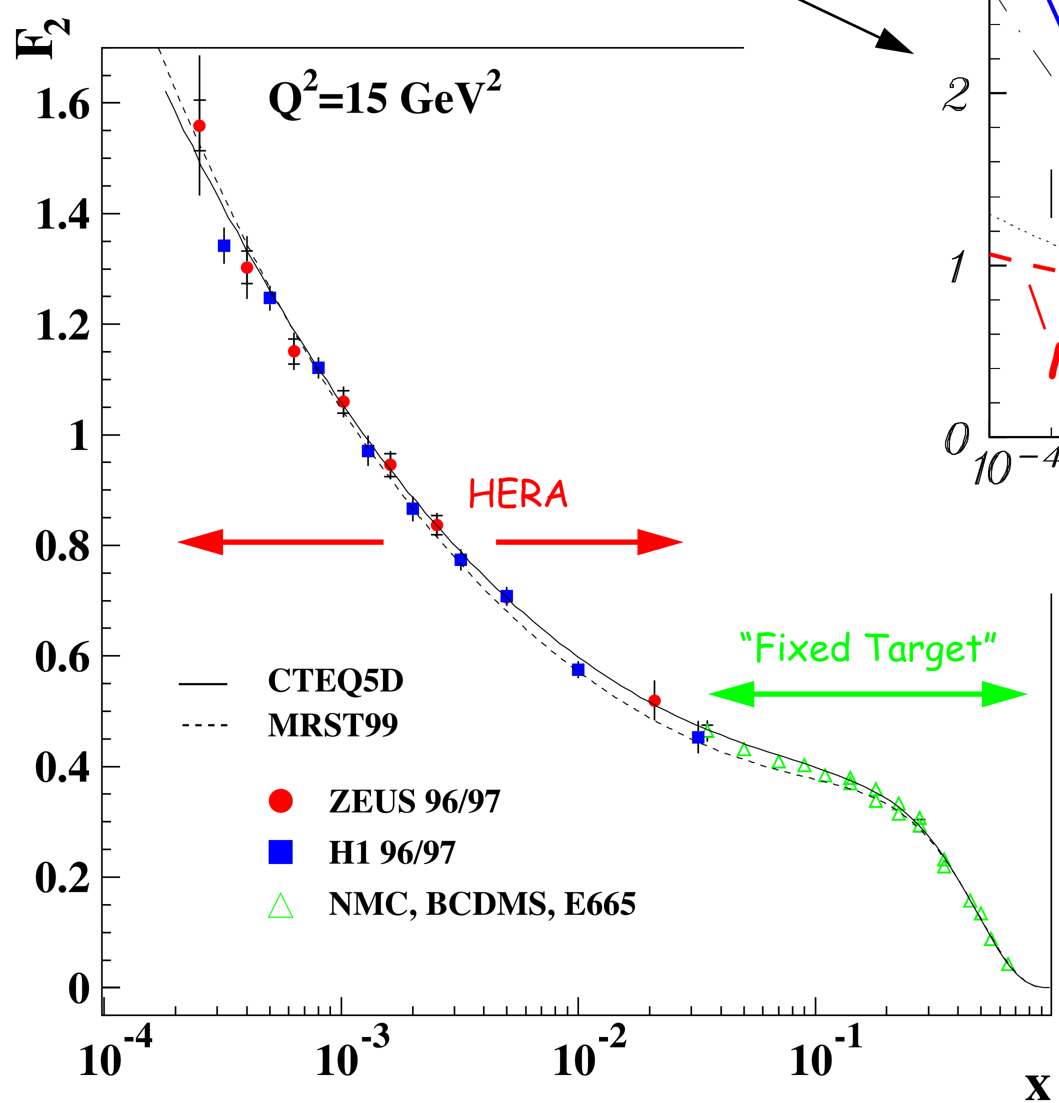
In reality much more difficult as acceptances, backgrounds, higher order corrections etc. have to be taken into account.



MRS D_0,D_-:

- Fit to fixed target data only
- Different assumptions on $xg(x,Q^2)$

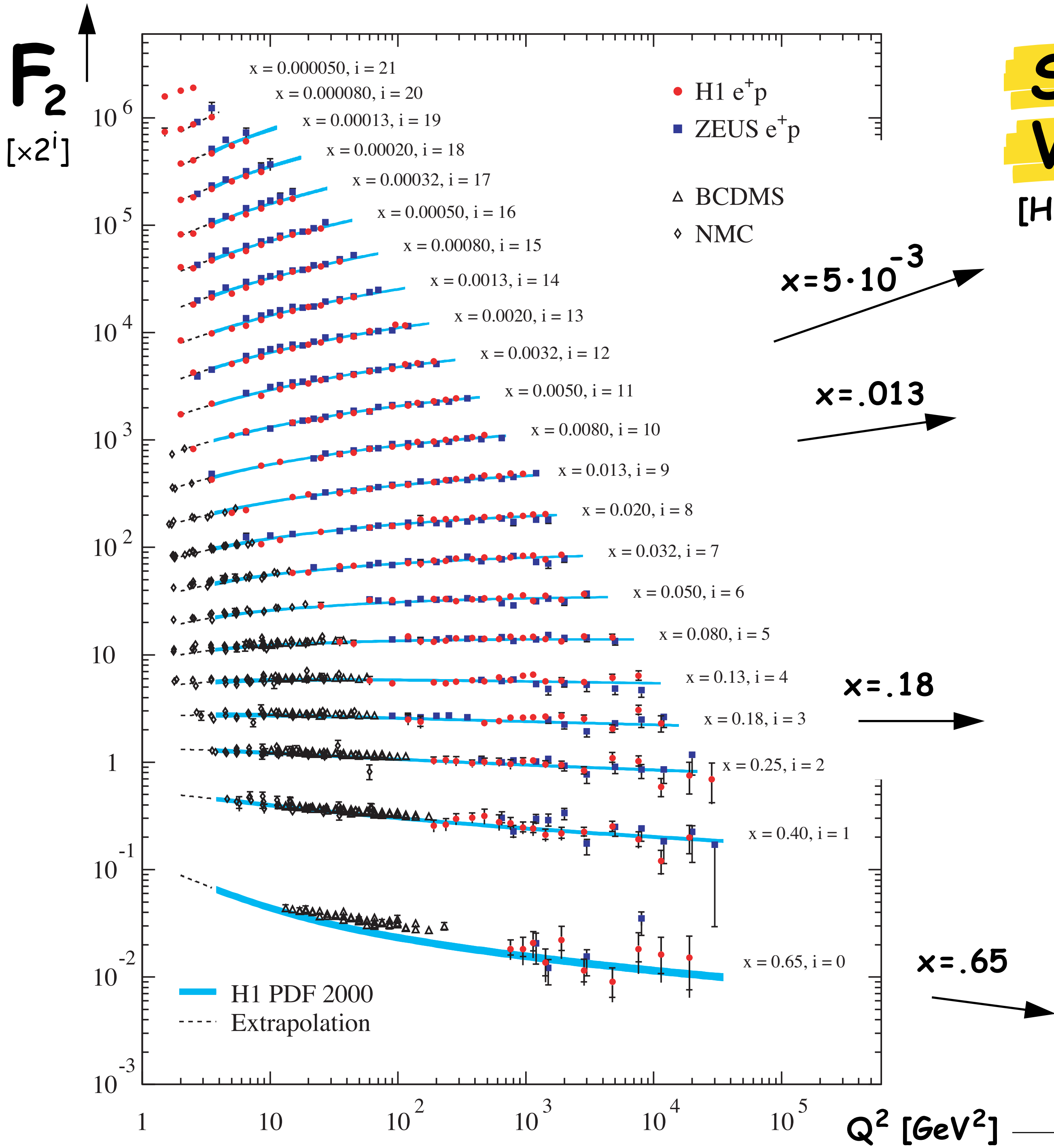




2-3%
Precision

Scaling Violations

[HERA & fixed target data]



Precision: 2-3%
[bulk region]

For $x < 10^{-2}$:

$$\frac{dF_2}{d\log Q^2} \sim g(x,Q^2)\cdot\alpha_s(Q^2)$$

NLO QCD Fits:

Quark densities
Gluon density
Strong coupling α_s

QCD Fits: Principle

Fit Procedure

- Parametrize parton distribution functions (PDFs) at starting scale $Q^2 = Q_0^2$ as function of x.
- Perform QCD evolution using DGLAP equations. [usually NLO, special treatment of heavy quark PDFs]
- Calculate predictions for experimental observables. [cross sections, structure functions, ...]
- Determine PDF parameters from χ^2-fit to experimental data.

For $p = u_v, d_v, \sum(q+\bar{q}), g$ or $p = \bar{u}+\bar{d}, \bar{u}-\bar{d}, s$:

$$xp(x, Q_0^2) = A_p x^{a_p} (1-x)^{b_p} P(x; c_p, \ldots)$$

characterizes PDFs at x = 0.
[sea: $a_p<0$, valence: $a_p>0$]

characterizes PDFs at x = 1.
[$b_p>0$ for all PDFs]

weakly x-dependent function.
["fine tuning"]

QCD Fits: Inputs

- Fixed target data — $\ell p \rightarrow \ell p$: BCDMS, NMC, E665 ...
  $\ell p \rightarrow \nu p$: CCFR, CDHS, BEBC ...
- H1, ZEUS data — structure function and cross section measurements

- Sum rules: $\int u_v(x)dx = 2, \int d_v(x)dx = 1,$ — Valence quarks

$$\int dx\, x \left\{ g(x) + \sum [q(x) + \bar{q}(x)] \right\} = 1,$$ — Momentum sum rule

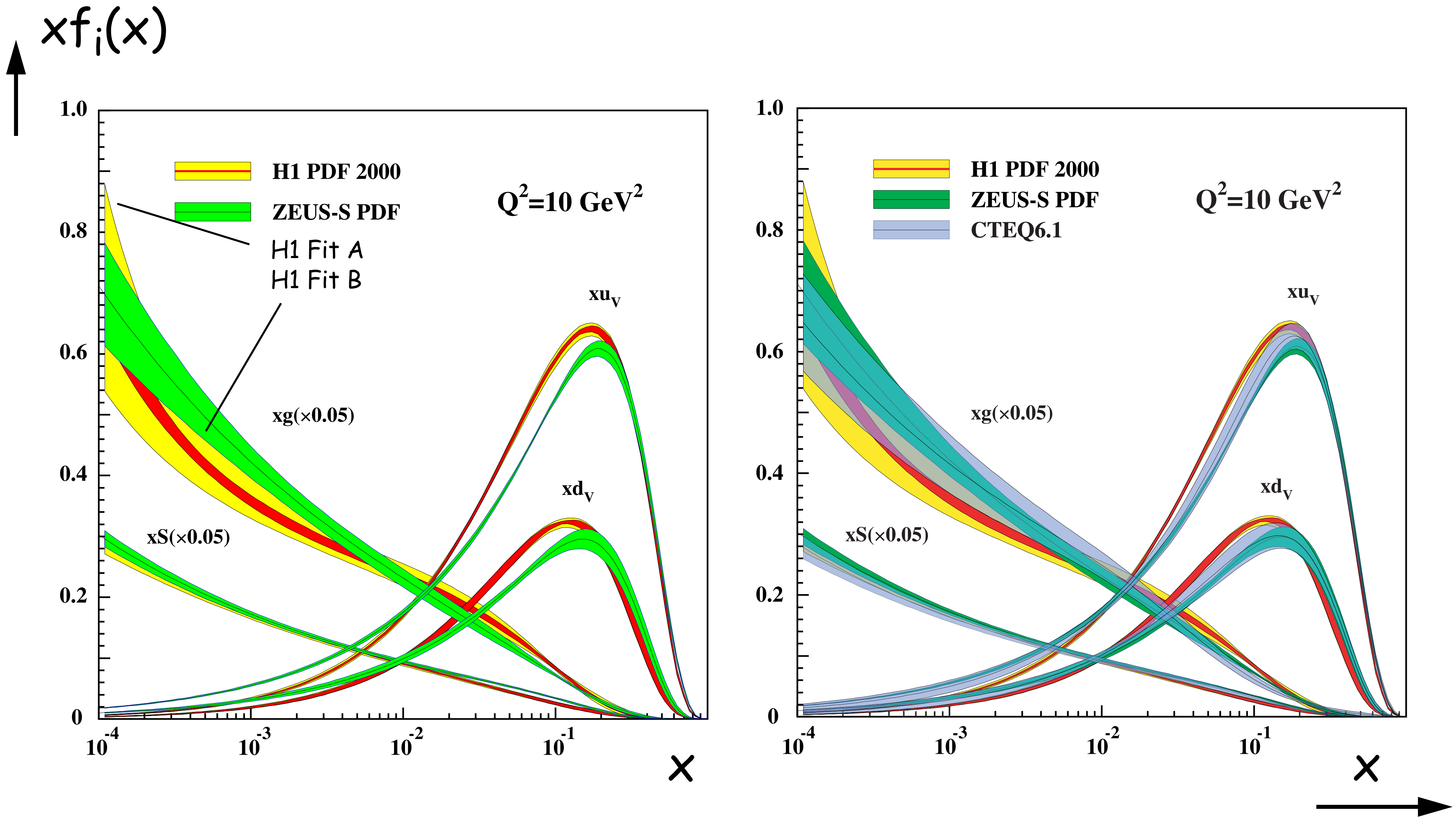
$$I_G = \int dx\, (F_2^{\ell p} - F_2^{\ell n}) = \frac{1}{3} + \frac{2}{3} \int dx\, (\bar{u} - \bar{d}).$$ — Gottfried sum rule

[Experiment (NMC): $I_G = 0.235 \pm 0.026 \rightarrow \bar{u} > \bar{d}$]

- Other experimental data:

$p\bar{p} \rightarrow W + X$	$q\bar{q} \rightarrow W$	u, d, u/d
$\nu N \rightarrow \mu^+\mu^- + X$	$\nu s \rightarrow \mu c$	s
$pp, pN \rightarrow \ell^+\ell^- + X$	$q\bar{q} \rightarrow \ell^+\ell^-$	$\bar{d}/\bar{u}$
$hh \rightarrow \gamma + X$	$qg \rightarrow q\gamma$	g
$p\bar{p} \rightarrow \text{jets} \pm X$	$gg \rightarrow gg, qg \rightarrow \ldots$	g

Parton Densities — HERA Results



Comparison H1 vs. ZEUS

H1 α_s fit:

Dedicated to α_s and $g(x)$.
H1 ep NC data (low Q^2) & BCDMS μp data.
Parametrization of valence, sea quark and gluon.
Starting scale: $Q_0^2 = 4\ GeV^2$.

$$\alpha_s = 0.1150\ ^{+0.0019}_{-0.0018}\ \pm 0.005$$

scale uncertainty

exp. & model uncertainty

H1 PDF fit:

Dedicated to PDF-determination.
Fit A: H1 data only (NC, CC, low & high Q^2).
Fit B: H1 data & BCDMS μp data.
Parametrization of U, $\bar{U}$, D, $\bar{D}$ and gluon.
Starting scale: $Q_0^2 = 4\ GeV^2$.

ZEUS PDF fit:

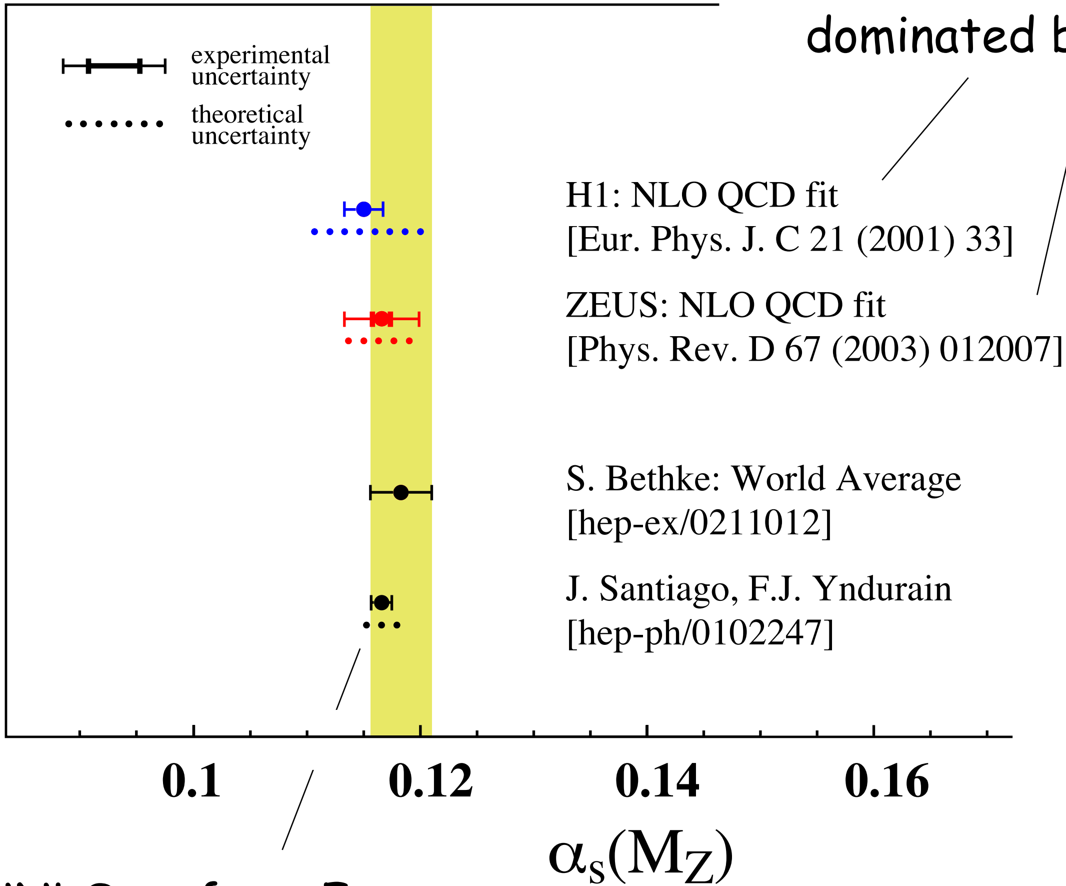
Dedicated to PDF-determination (main goal).
Simultaneous fit to strong coupling constant.
Data: ZEUS NC data, BCDMS, NMC, E665, CCFR.
Starting scale: $Q_0^2 = 7\ GeV^2$.

$$\alpha_s = 0.1166\ ^{+0.0052}_{-0.0052}\ \pm 0.004$$

exp. & model uncertainty

scale uncertainty

theoretical error
dominated by scale uncertainty



renorm. scale uncertainty

exp. & model uncertainty

ZEUS:

$$\alpha_s = 0.1166 \;{}^{+0.0052}_{-0.0052} \quad \pm 0.004$$

H1:

$$\alpha_s = 0.1150 \;{}^{+0.0019}_{-0.0018} \quad \pm 0.005$$

[World average: 0.1183 ± 0.0027]
S. Bethke: hep-ph/0211012

NNLO α_s from F_2
moment analysis based on Bernstein polynomials

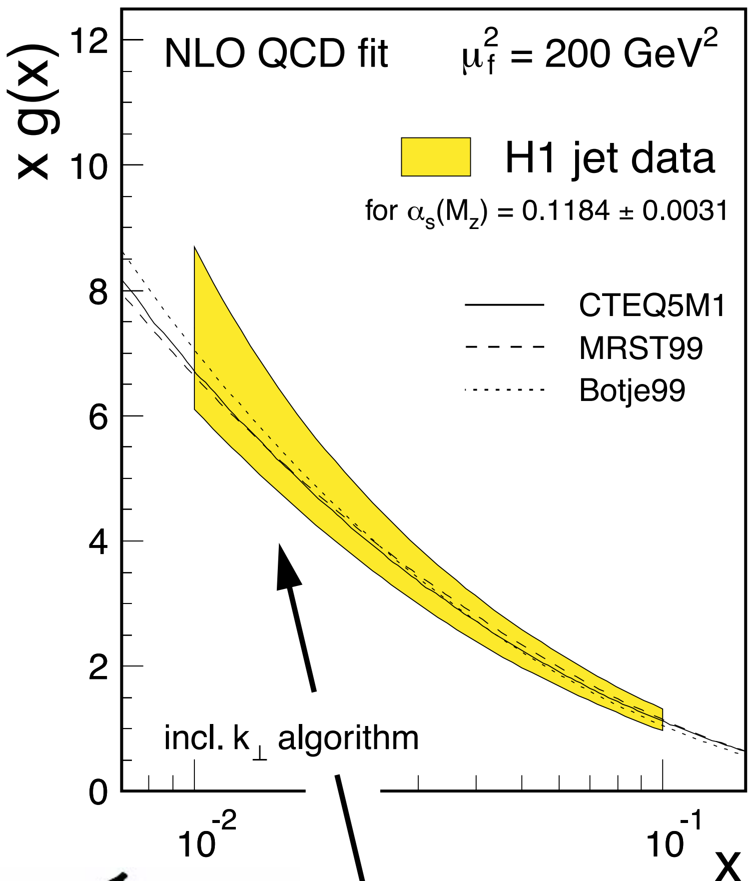
systematic error includes:
- NNNLO correction estimate
- higher twist effects

NNLO promises world beating α_s from HERA

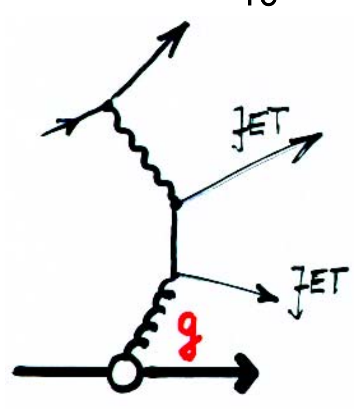
Now available:
NNLO splitting functions
[Moch, Vermaseren, Vogt]

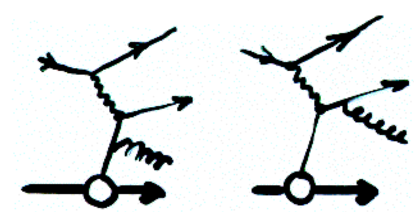
Non-singlet case: hep-ph/0403192
Singlett case: hep-ph/0404111

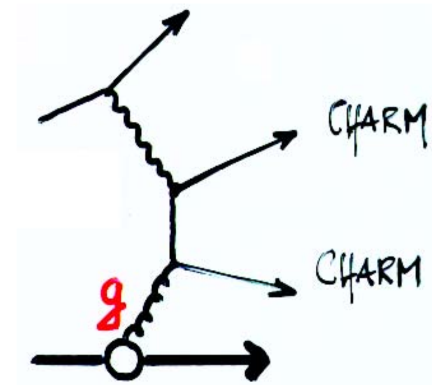
PDFs - Are they universal?



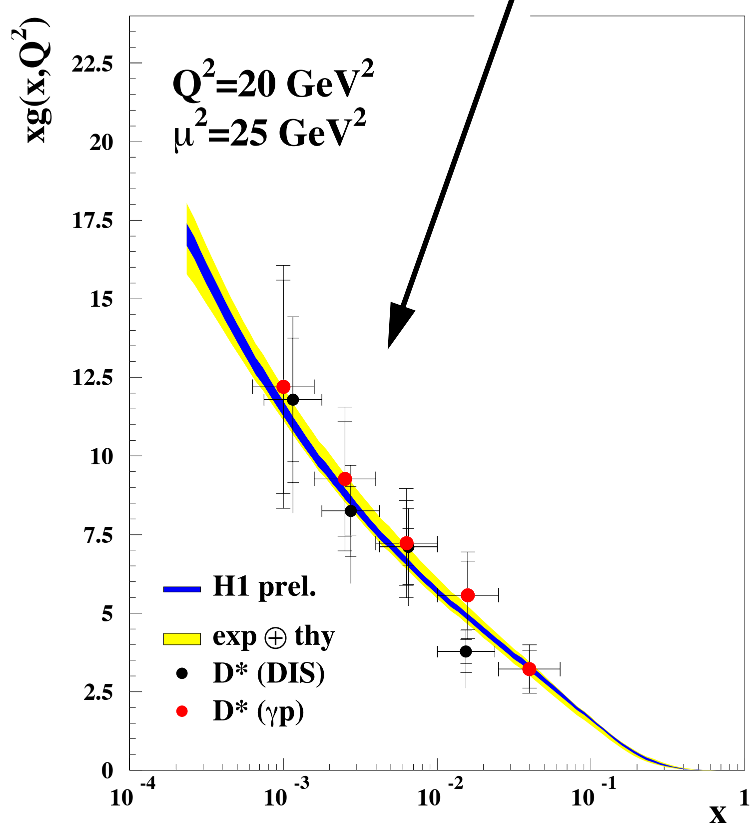
gluon
from jets





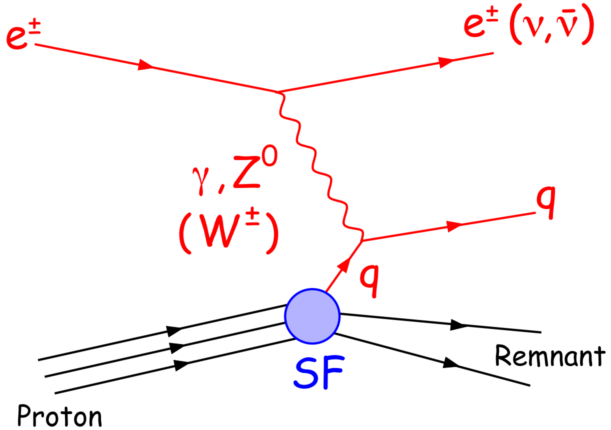


gluon
from charm



High Q^2 Physics
Constraining Valence Quarks

DIS Cross Section @ High Q^2



Influence only @ high y

$$\frac{d^2\sigma(e^\pm)}{dx\,dQ^2} \sim \xi F_2 \mp \zeta x F_3 - \eta y^2 F_L$$

different contribution from xF_3 for different lepton charge

Neutral Current:

$$F_2 \sim x\sum_i [q_i + \bar{q}_i]$$

$$xF_3 \sim x\sum_i [q_i - \bar{q}_i]$$

Use e^+p/e^-p data to extract xF_3
Sensitivity to valence quark density

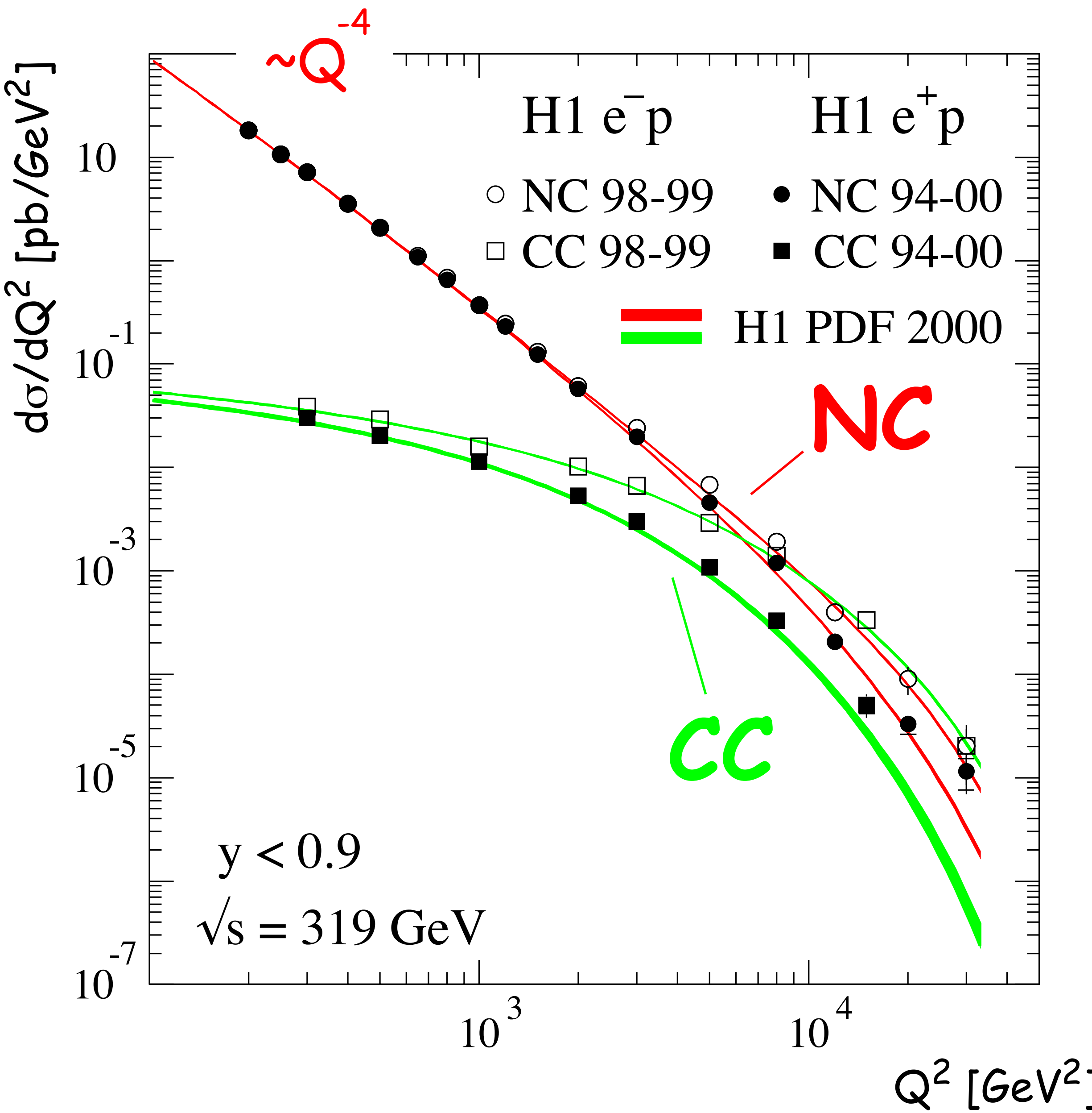
Charged Current:

$$d^2\sigma(e^+) \sim x[d + \bar{u}]$$

$$d^2\sigma(e^-) \sim x[u + \bar{d}]$$

Use e^+p/e^-p data to disentangle up-/down-quark content at high x

NC and CC Cross Sections



Standard Model describes cross sections over large range of Q^2

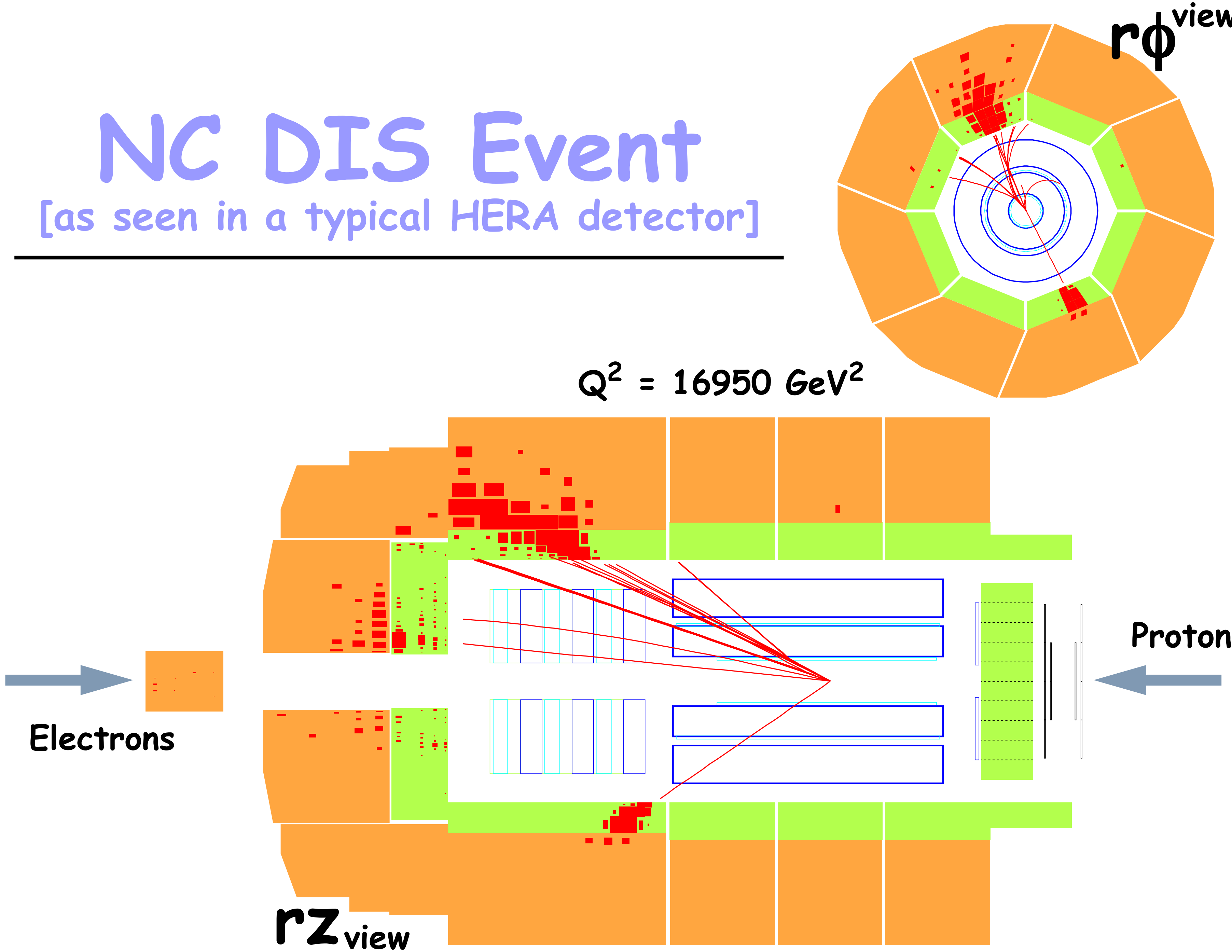
Electroweak 'unification' at large $Q^2 \sim M_Z^2$

e^+p/e^-p cross sections differ due to different

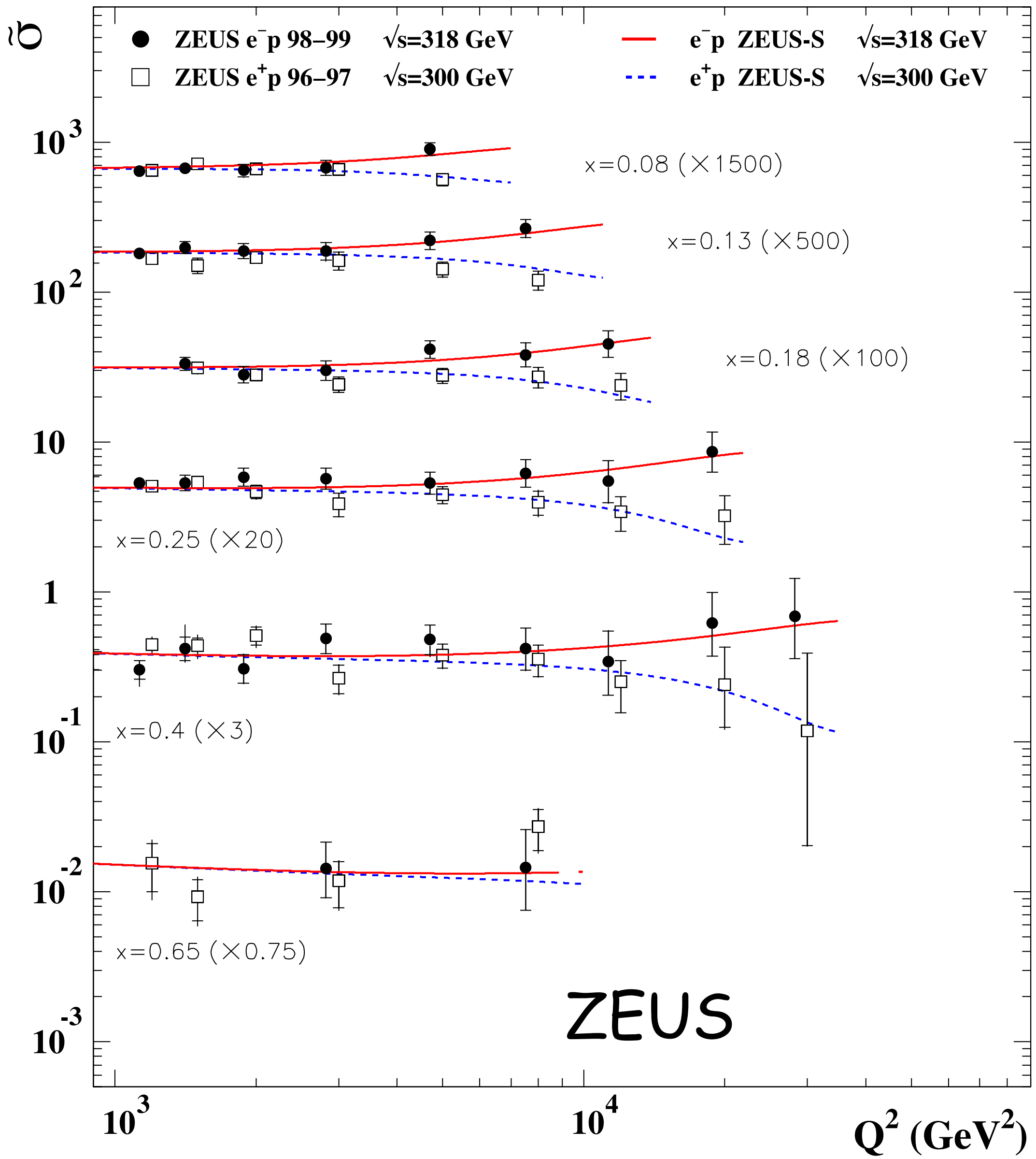
- quark contributions
- helicity structure of EW interactions

NC DIS Event

[as seen in a typical HERA detector]



NC Reduced Cross Section



$1/(xQ^4)$-dependence removed

xF_3 Extraction:

$$\tilde{\sigma}^{NC}(e^-) = \xi F_2 + \zeta x F_3$$

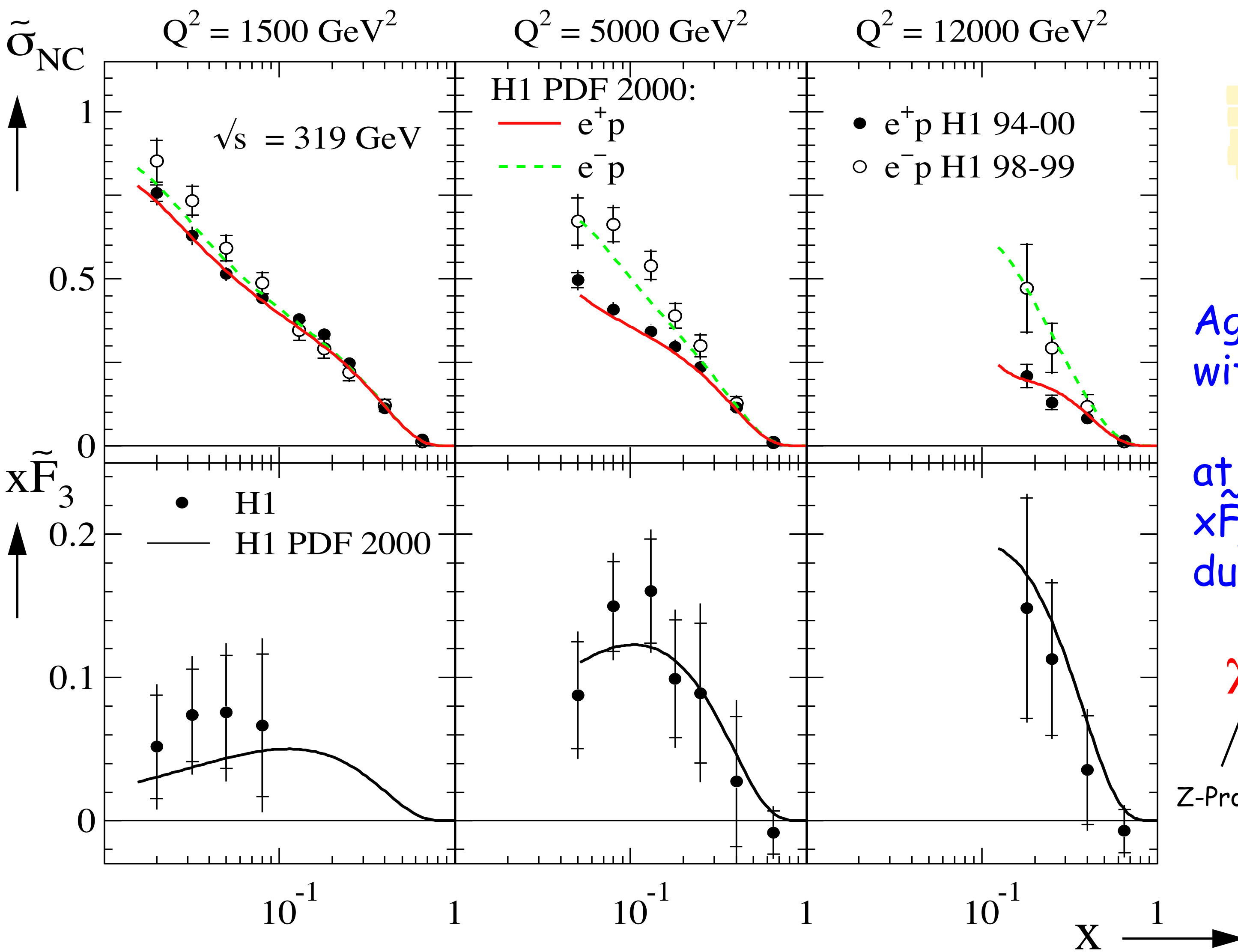
$$\tilde{\sigma}^{NC}(e^+) = \xi F_2 - \zeta x F_3$$

$$xF_3 = \frac{1}{2}\zeta^{-1}\left[\tilde{\sigma}^{NC}(e^-) - \tilde{\sigma}^{NC}(e^+)\right]$$

$$\sim \sum [q(x,Q^2) - \bar{q}(x,Q^2)]$$

At high Q^2: sensitivity to valence quark densities down to $x \sim 10^{-2}$

$x\tilde{F}_3$



Agreement of data with QCD fit

at fixed Bjorken-x $x\tilde{F}_3$ rises with Q^2 due to:

$$\chi_Z = \frac{1}{4 s_W^2 c_W^2}\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

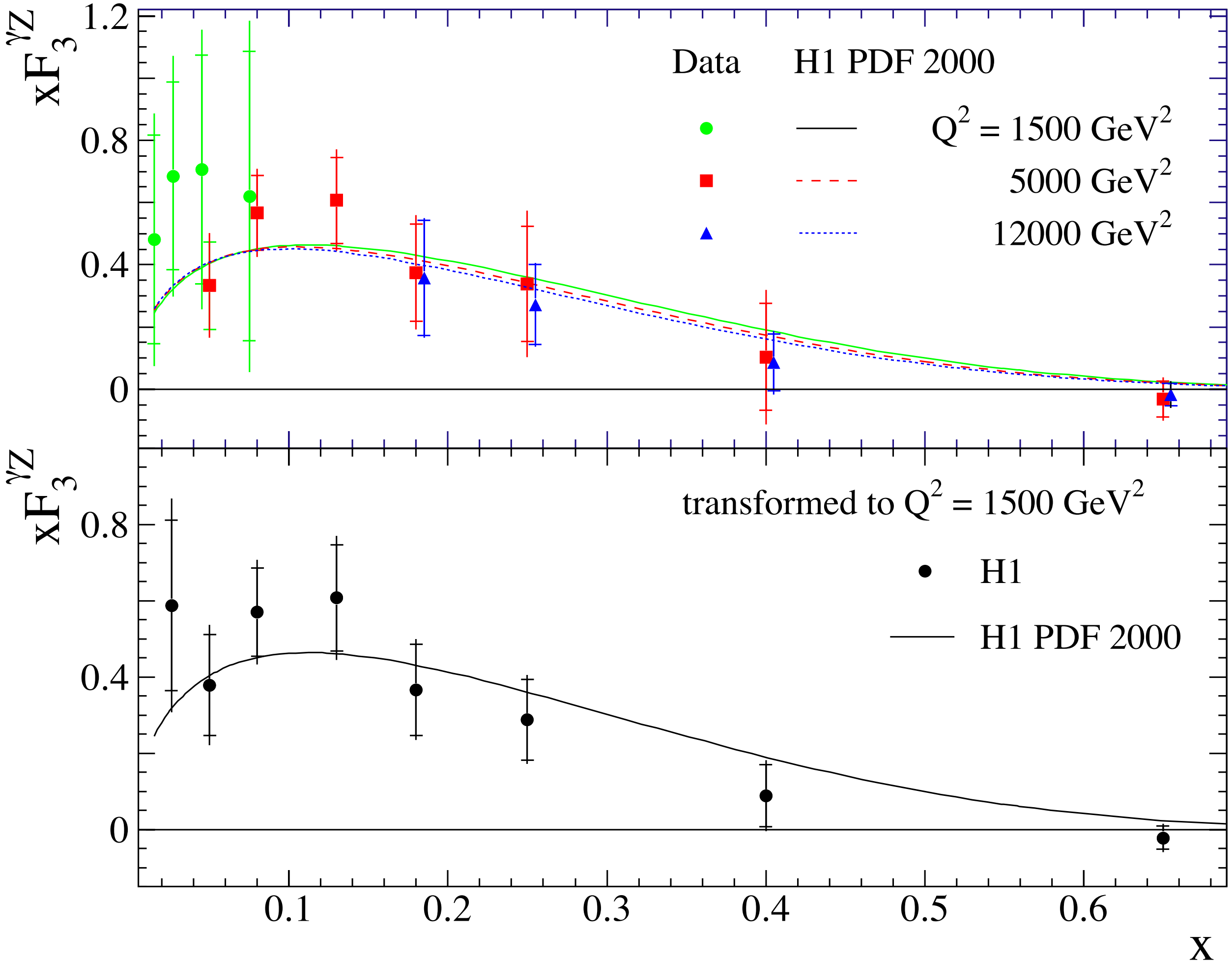
Z-Propagator

$$x\tilde{F}_3 = Q_e a_e \left\{ 2 Q_q a_q x[q_i - \bar{q}_i] \right\} \cdot \chi_Z + 2 v_e a_e \left\{ 2 v_q a_q x[q_i - \bar{q}_i] \right\} \cdot (\chi_Z)^2$$

$\sim Q_e a_e \{ x F_3^{\gamma Z} \} \cdot \chi_Z$

contribution to $x\tilde{F}_3 < 3\%$

$xF_3^{\gamma Z}$



$$\int_{0.02}^{0.65} F_3^{\gamma Z} = 1.28 \pm 0.20$$

[H1 measurement]

$$\int_{0.02}^{0.65} F_3^{\gamma Z} = 1.06 \pm 0.02$$

[H1 PDF 2000]

$$\int_0^1 F_3^{\gamma Z} = \int_0^1 2Q_q a_q [q_i - \bar{q}_i] = 2Q_u a_u N_u + 2Q_d a_d N_d = \frac{5}{3} \cdot (1 - \alpha_s/\pi)$$

[sum rule a la Gross Llewellyn-Smith]

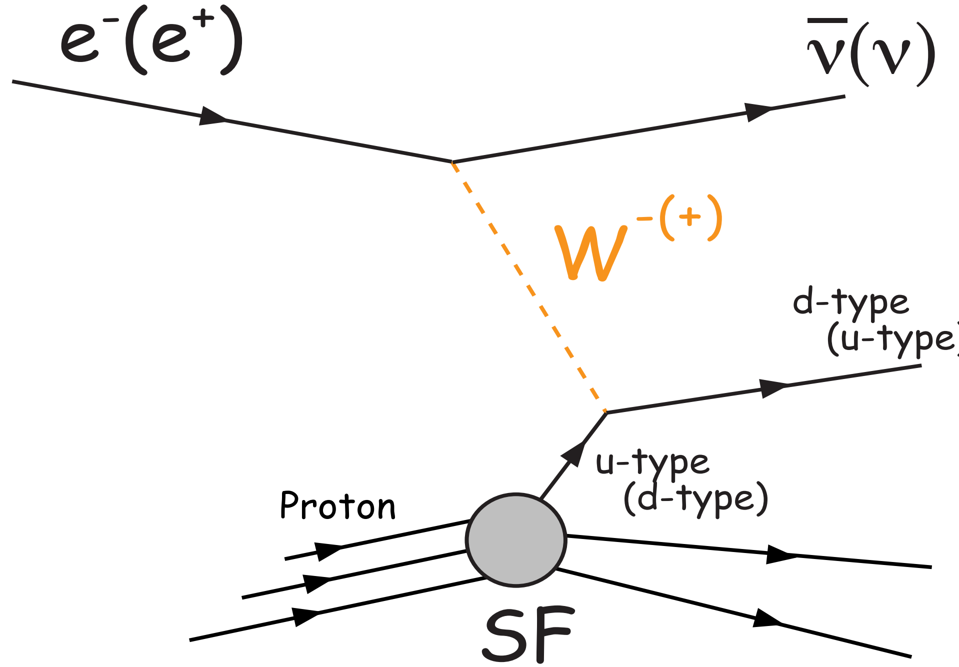
Charged Current Cross Section

$$e^- + u \rightarrow d + \bar{\nu}$$

$$e^- + \bar{d} \rightarrow \bar{u} + \bar{\nu}$$

$$e^+ + d \rightarrow u + \nu$$

$$e^+ + \bar{u} \rightarrow \bar{d} + \nu$$



$$\frac{d^2\sigma^{CC}(e^-)}{dx\,dQ^2} = \frac{\pi\alpha^2}{4s_W^2}\frac{1}{(Q^2+M_W^2)^2}\left[\underbrace{u+c}-(1-y)^2(\bar{d}+\bar{s})\right]$$

Probes u-quark density

$$\frac{d^2\sigma^{CC}(e^+)}{dx\,dQ^2} = \frac{\pi\alpha^2}{4s_W^2}\frac{1}{(Q^2+M_W^2)^2}\left[\bar{u}+\bar{c}-(1-y)^2\underbrace{(d+s)}\right]$$

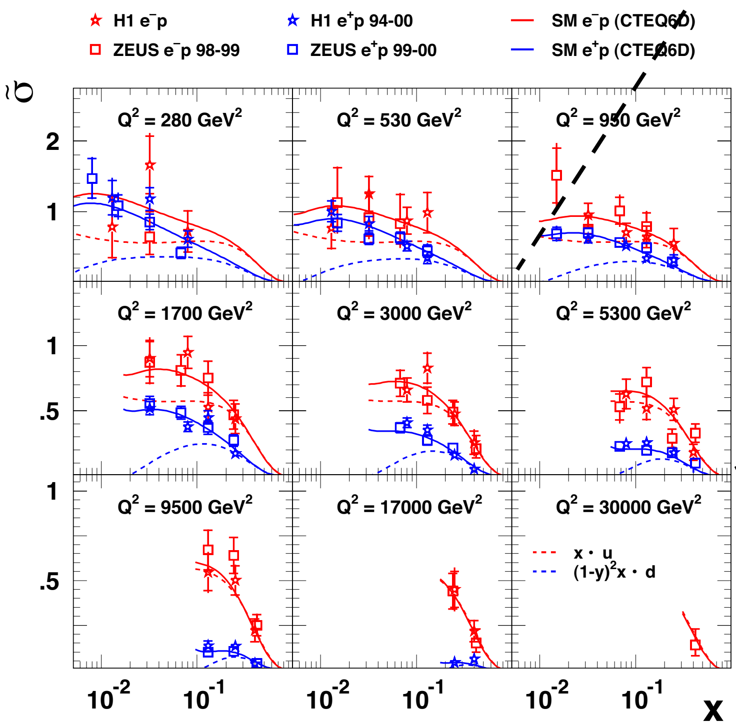
Probes d-quark density

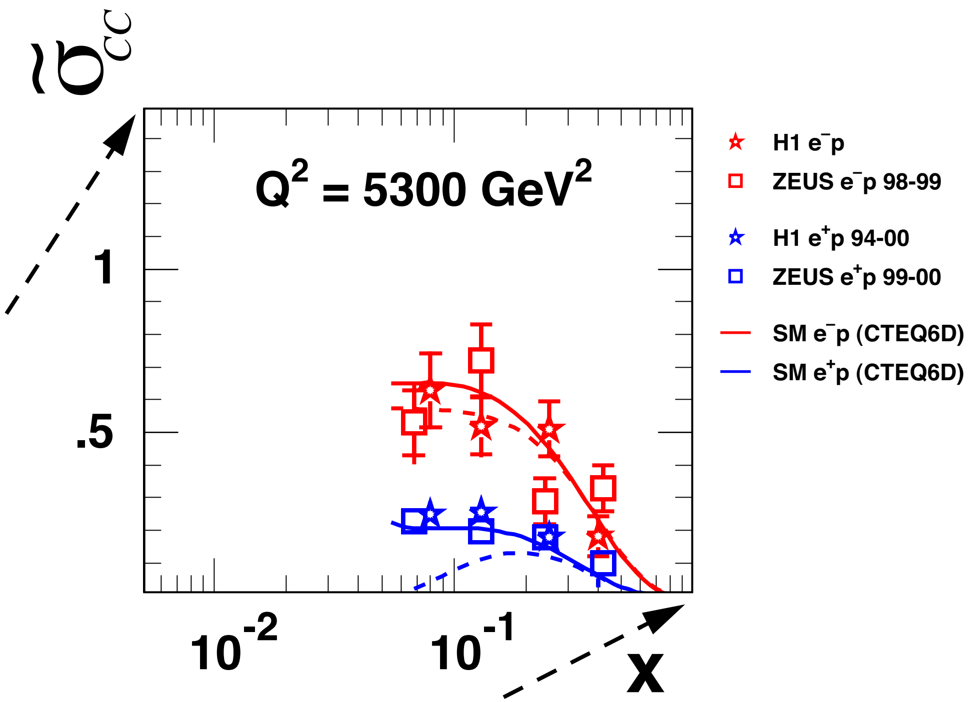
Reduced CC Cross Section

$$\tilde{\sigma}^{\pm}_{CC} = \left[\frac{4s_W^2(Q^2+M_W^2)^2}{\pi\alpha^2}\right]\frac{d^2\sigma_{CC}(e^{\pm})}{dx\,dQ^2}$$

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

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

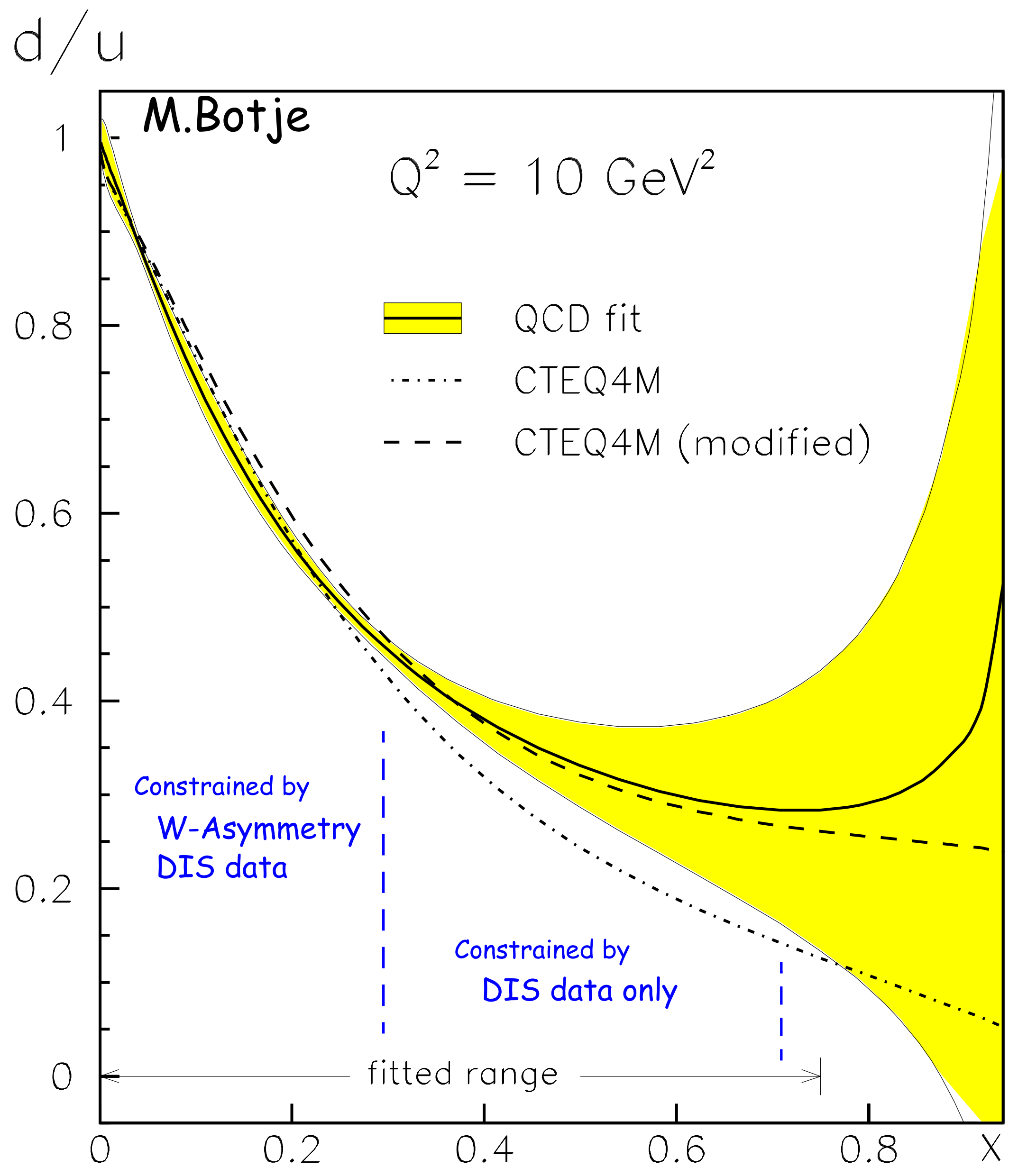




Sensitivity to
u(d)-Quark density

More statistics!
[HERA II Data]

Knowledge of d/u Ratio



Fit to

- HERA ep data [H1 1994, ZEUS 1994]
- Fixed Target proton and deuteron data [E665, NMC, BCDMS, SLAC]
- Neutrino data [CCFR]
- Drell-Yan data [E866]

Large uncertainty at high x

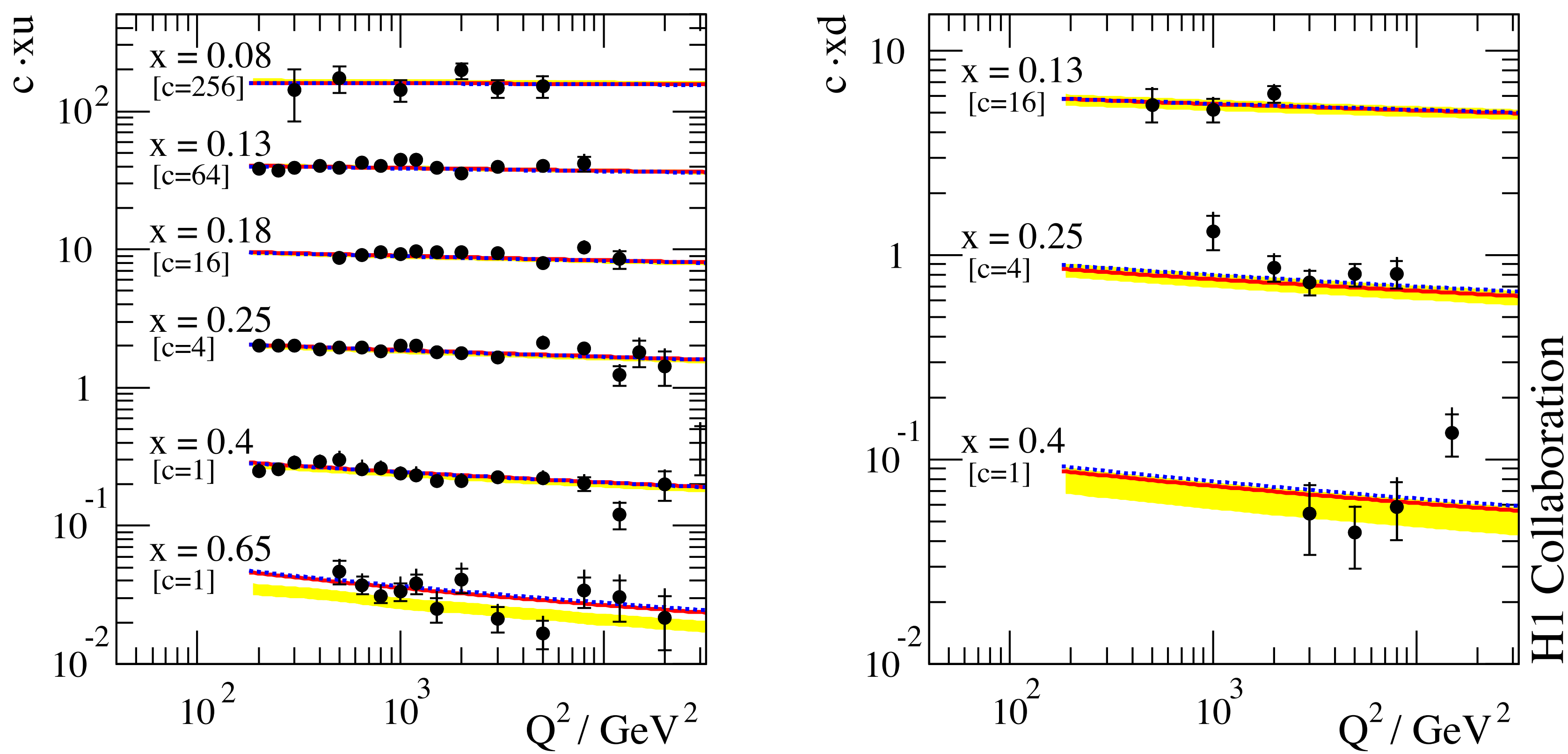
[dependence on parametrization]

[e.g. due to nuclear corrections]

Can be further constrained with NC and CC HERA data.

Valence Quark Distribution

@ high x



- - - MRST2001

.... CTEQ6

H1 PDF 2000

Uses:
H1 high-Q^2 data,
[NC/CC e^+p and e^-p data]
H1 low-Q^2 data

● H1 data points

determined via local extraction method ...

$$xq = \sigma_{meas} \, (xq/\sigma)_{fit}$$

To constrain
d, u at high x further

more statistics from HERA II

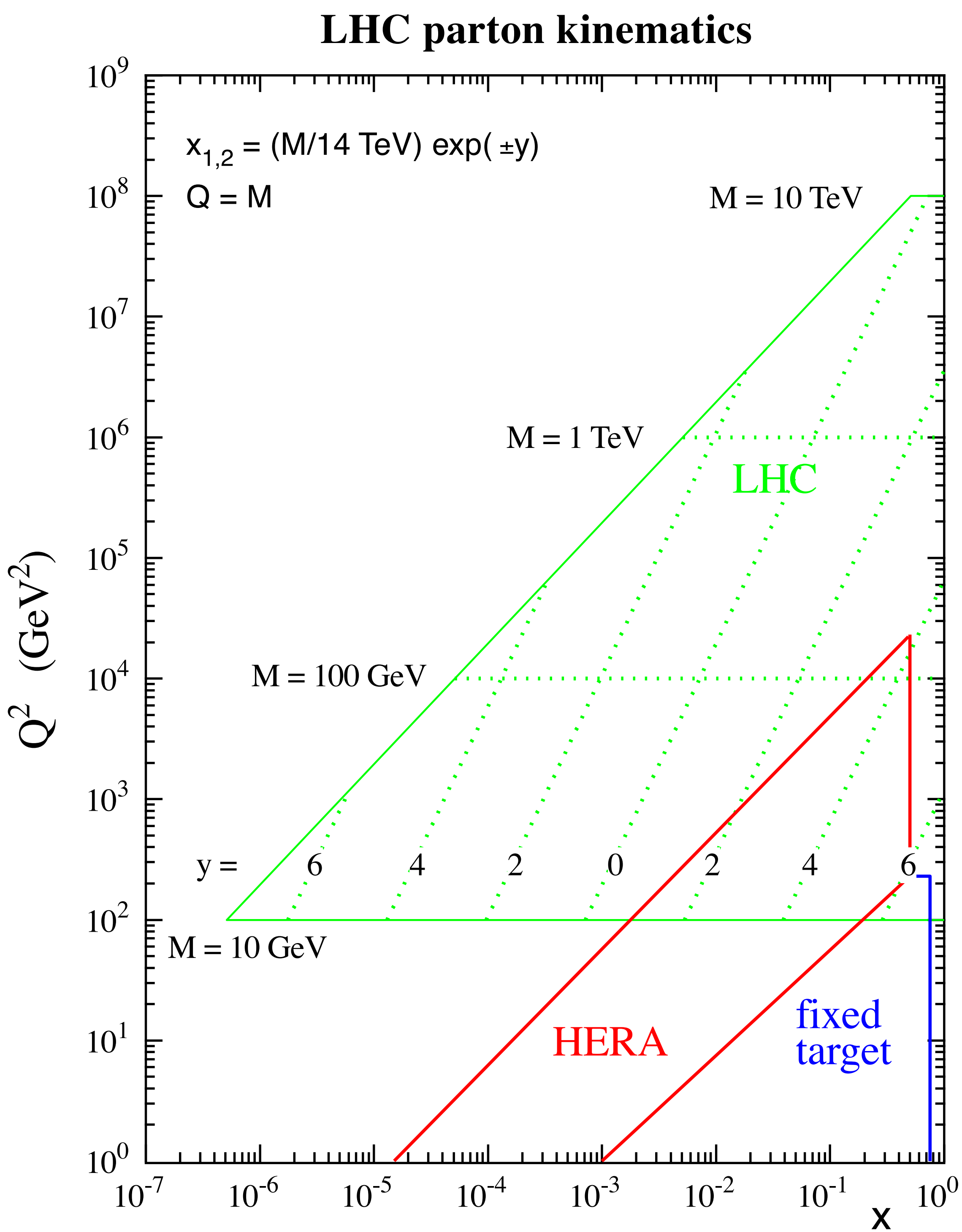
is needed.

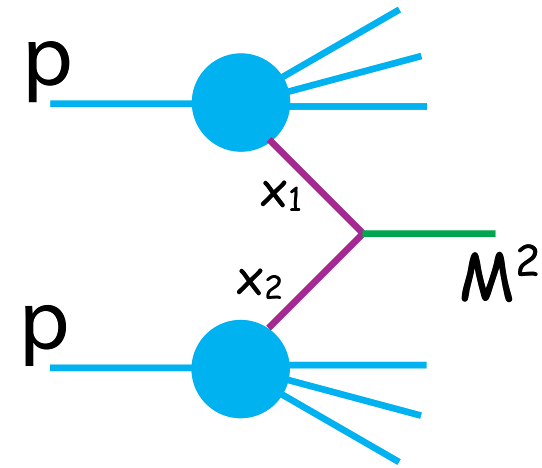
Parton Densities @ LHC

What do we need?

How well do we know them?

How to improve?





$M^2 = x_1 x_2\, s$

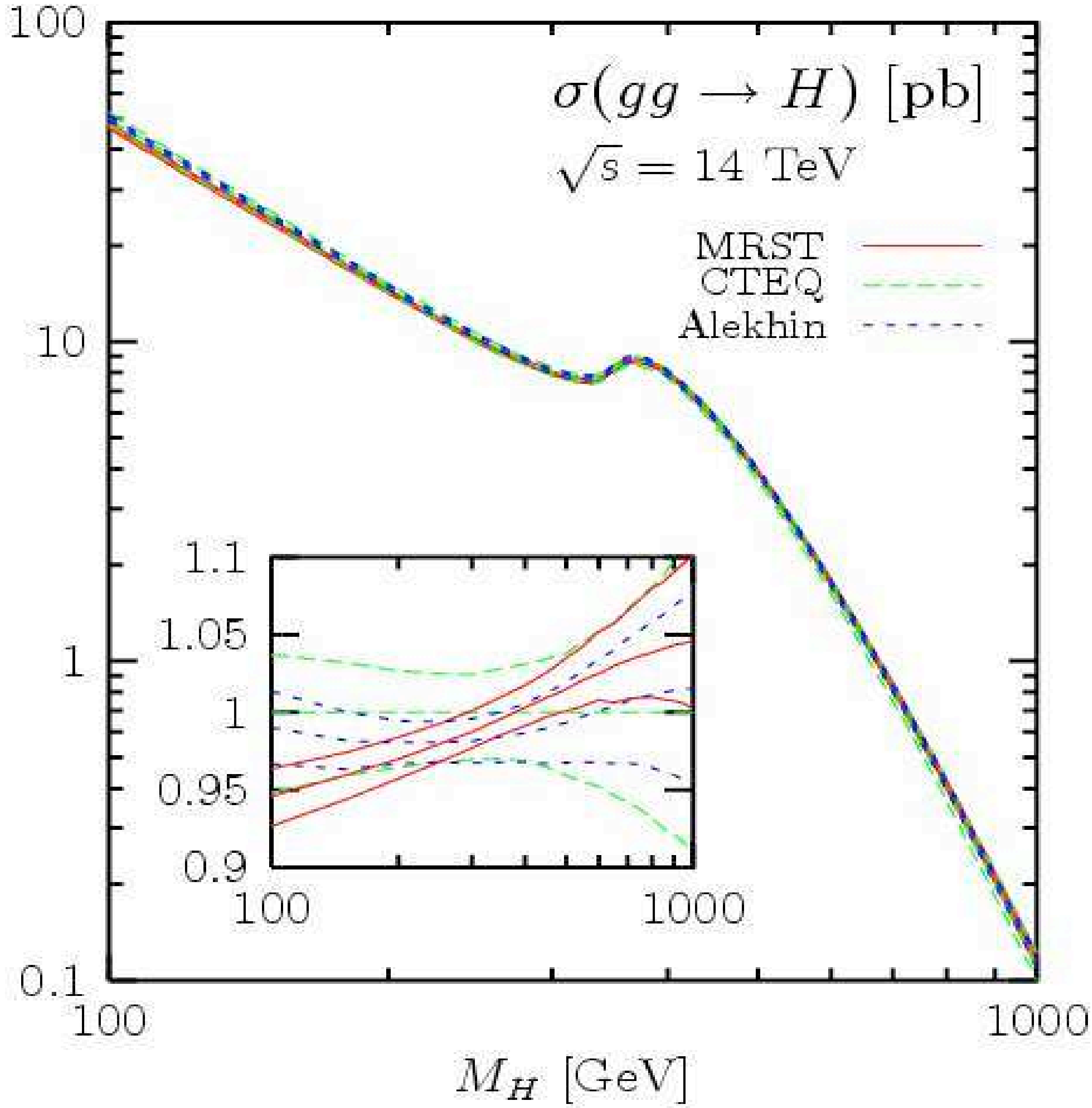
i.e. to produce a particle with mass M at LHC energies ($\sqrt{s}$ = 14 TeV)

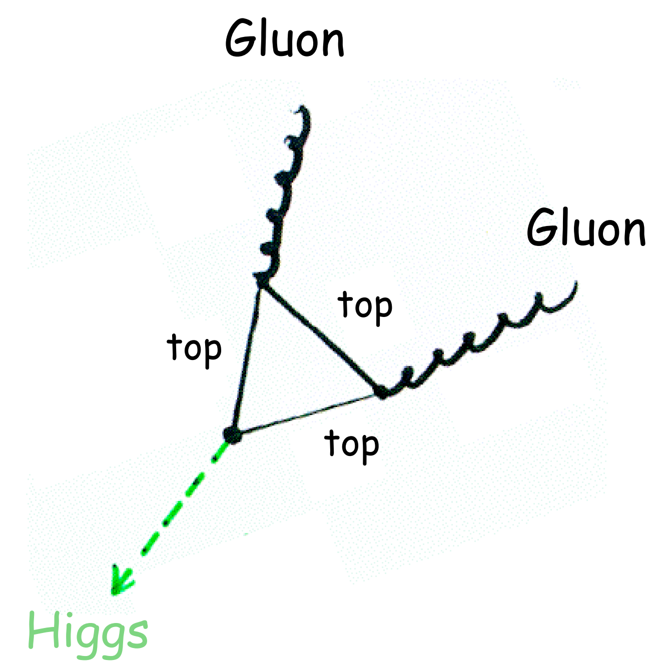
$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$

[$x_1 = x_2$: mid-rapidity]

LHC needs:

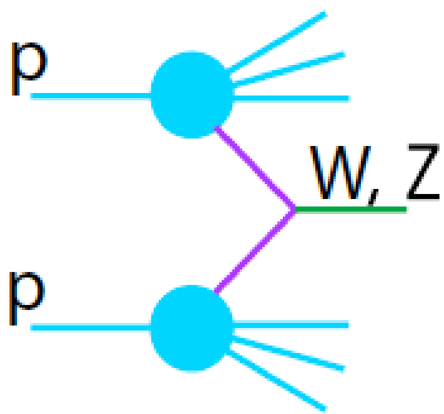
- knowledge on parton densities
- extrapolation over orders of magnitude



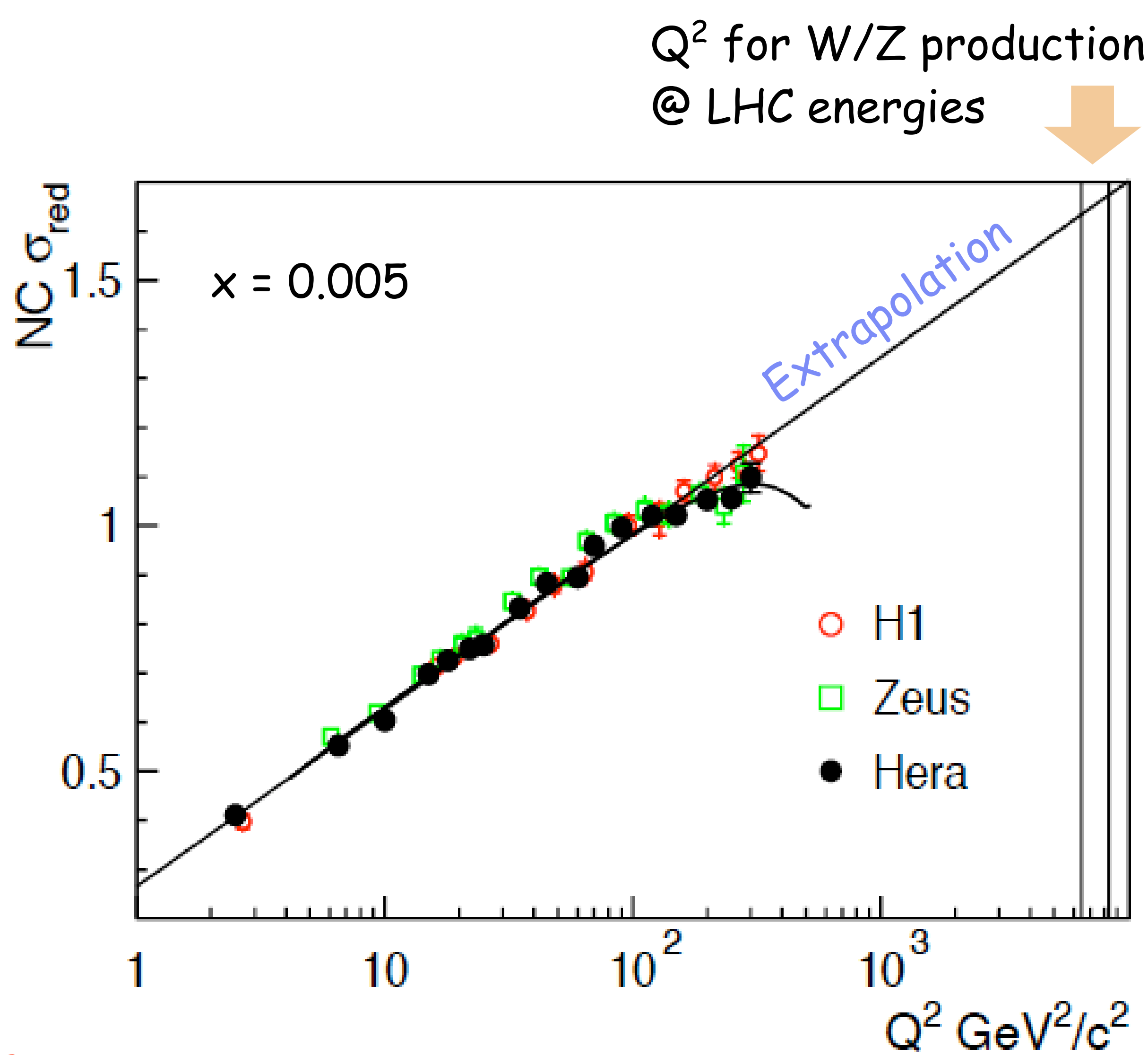


Simple spread of existing PDFs gives a 5-10% uncertainty on the Higgs cross section.

W and Z Production @ LHC



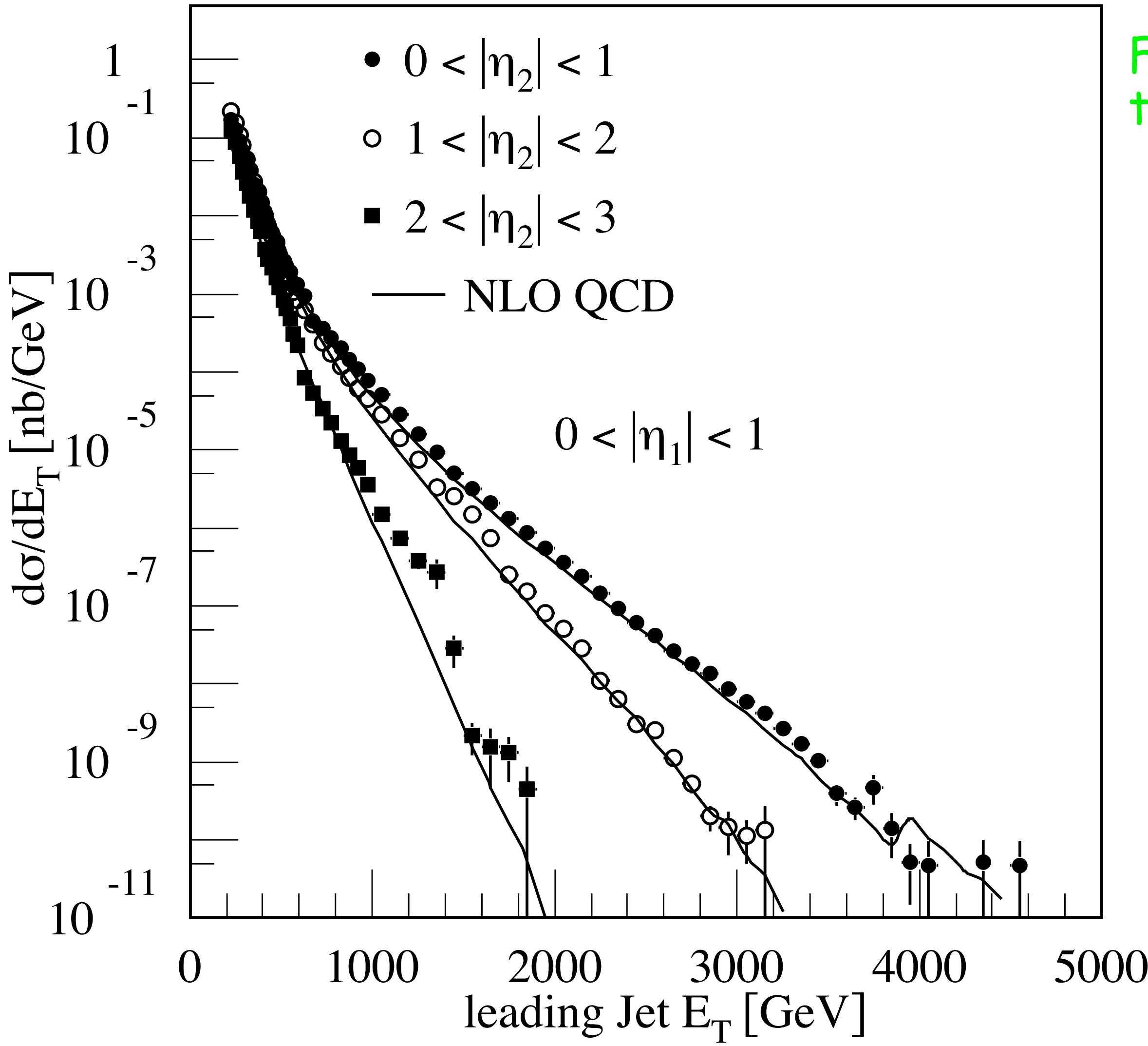
$pp \rightarrow W + X$
$pp \rightarrow Z + X$



Considered
as luminosity monitor

Jet Spectrum @ LHC

ATLAS TDR: Inclusive Jet E_T

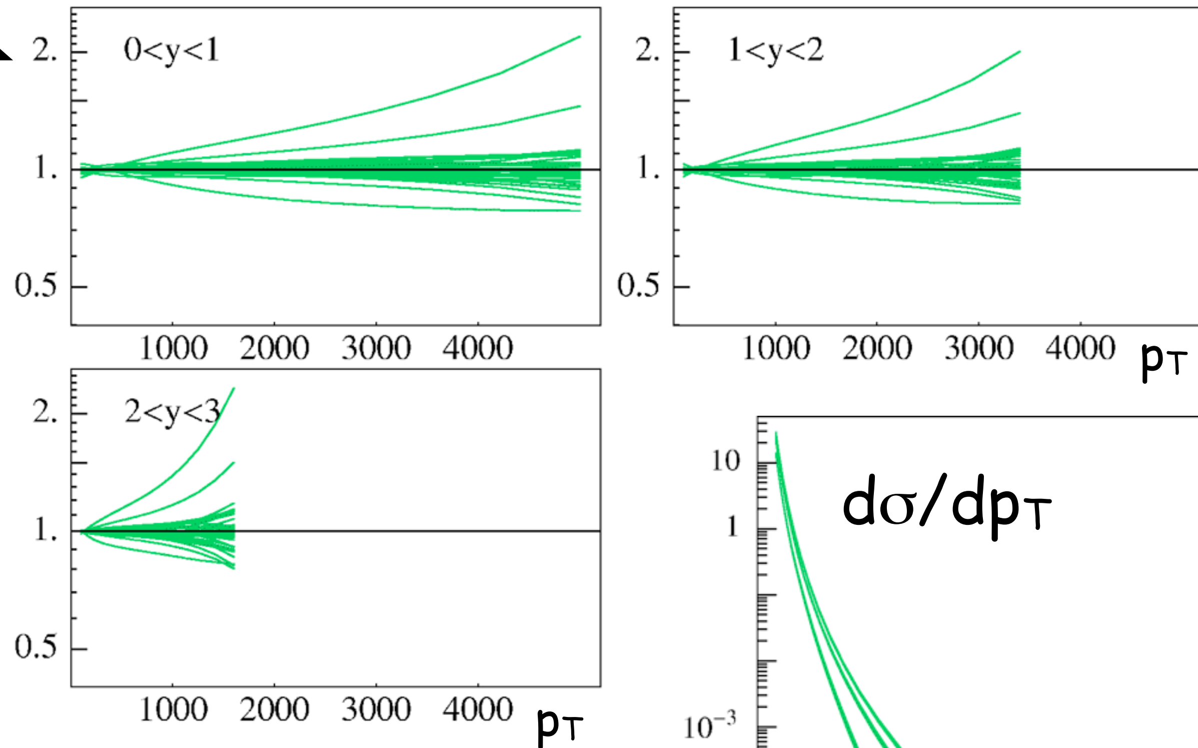


First plot
to be made at LHC

Sensitive to:

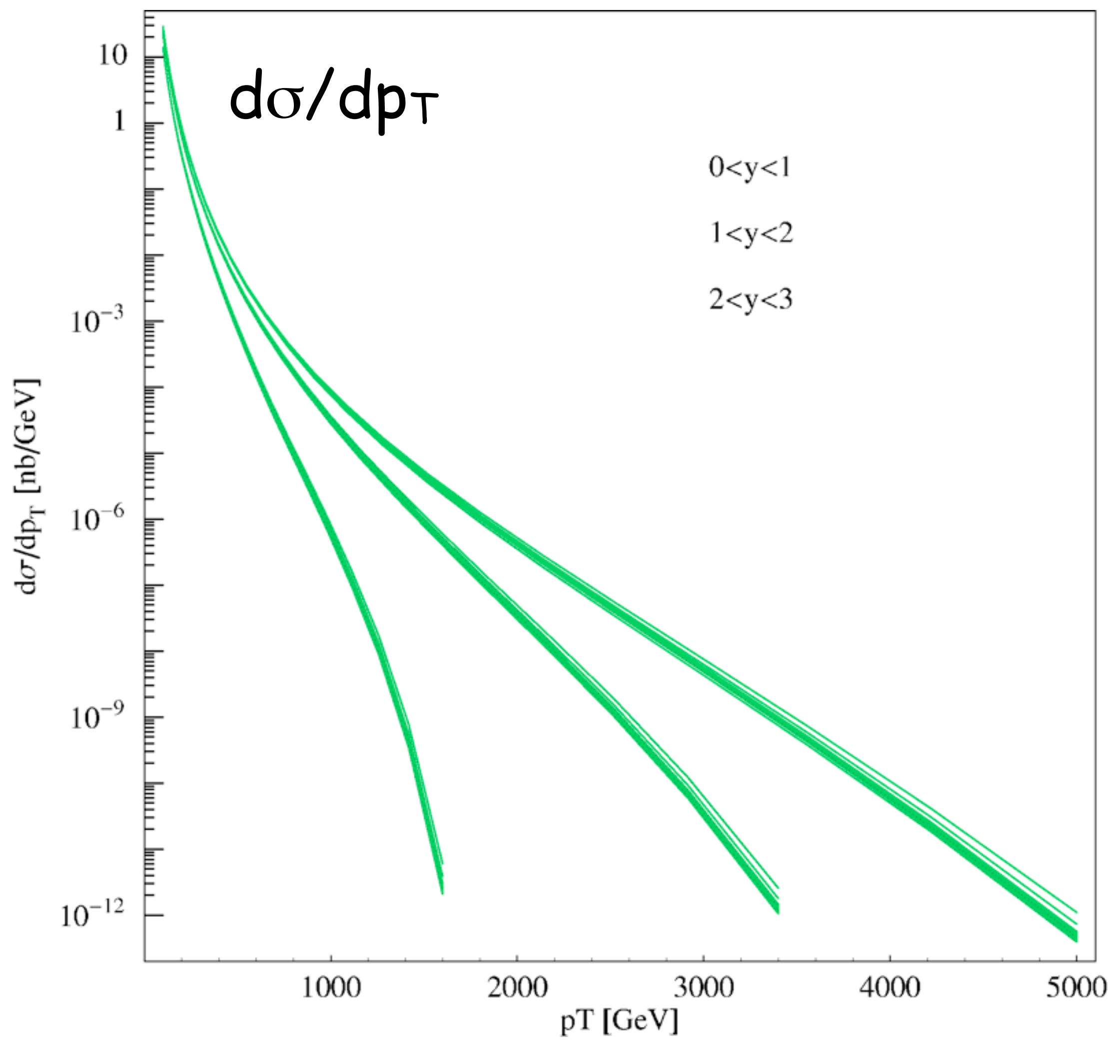
- Parton distribution functions
- Detector performance
  [Energy scale and resolution]
- New Physics

Relative Uncertainty [compared to CTEQ 6.1M]



Inclusive Jet Cross Section @ LHC

[D.Stump et al., JHEP 10 (2003) 046]



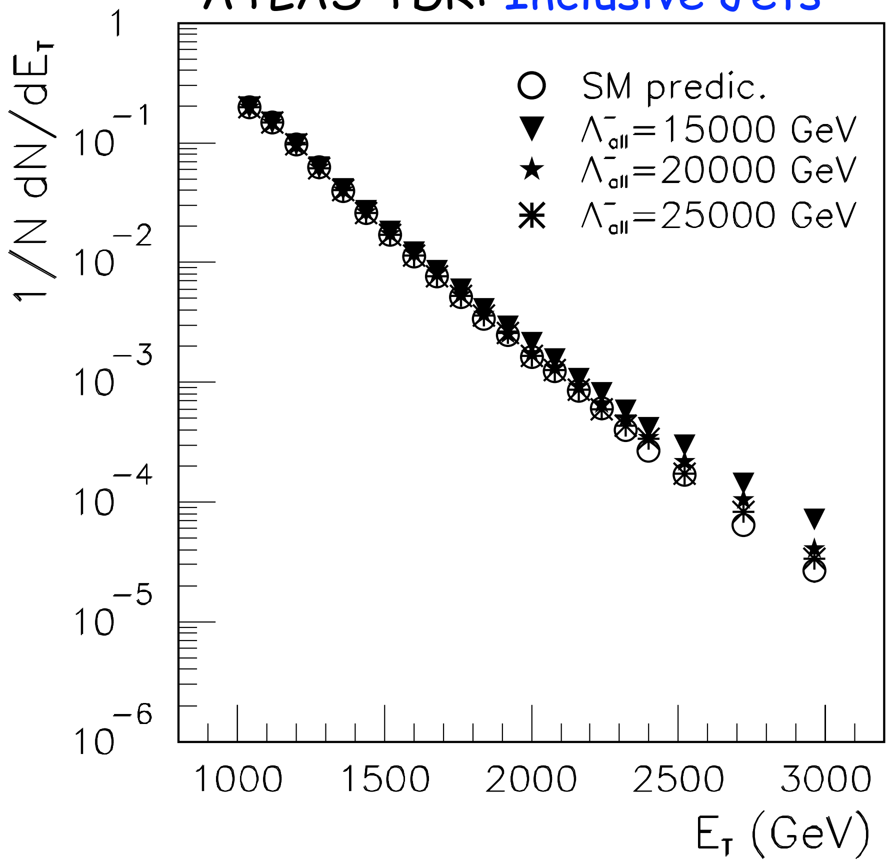
Mid-rapidity:
100 % uncertainty
@ $E_T \sim 5$ TeV

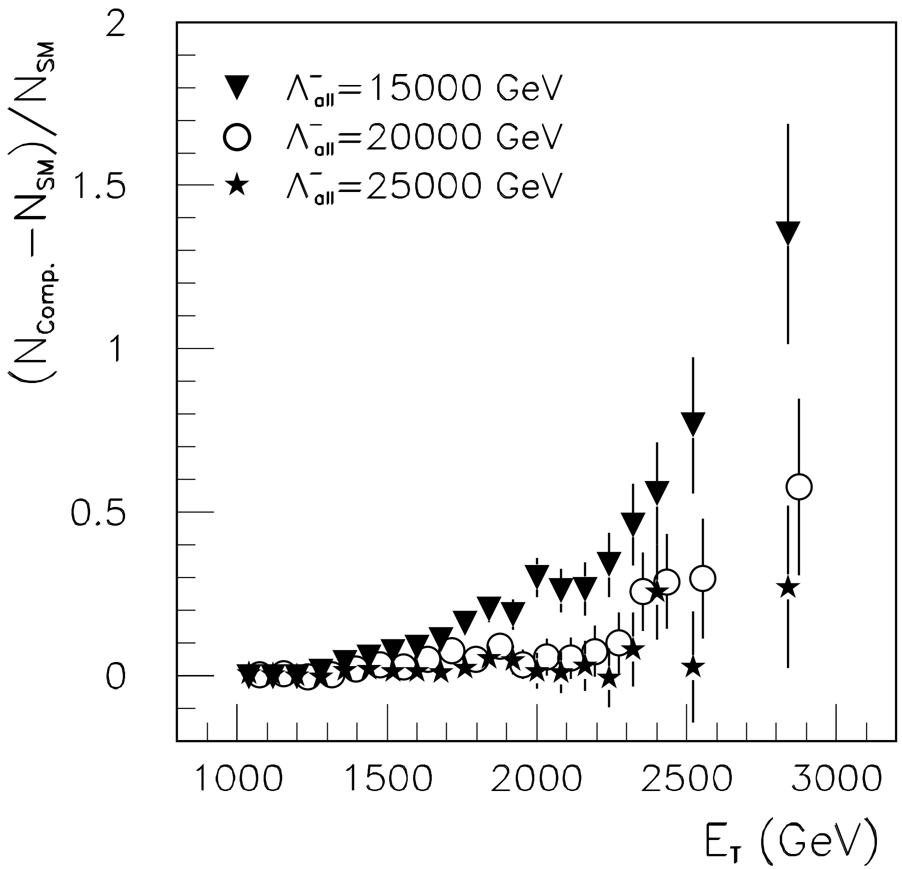
Forw. jets:
100 % uncertainty
@ $E_T \sim 2$ TeV

Quark Substructure [Compositeness]

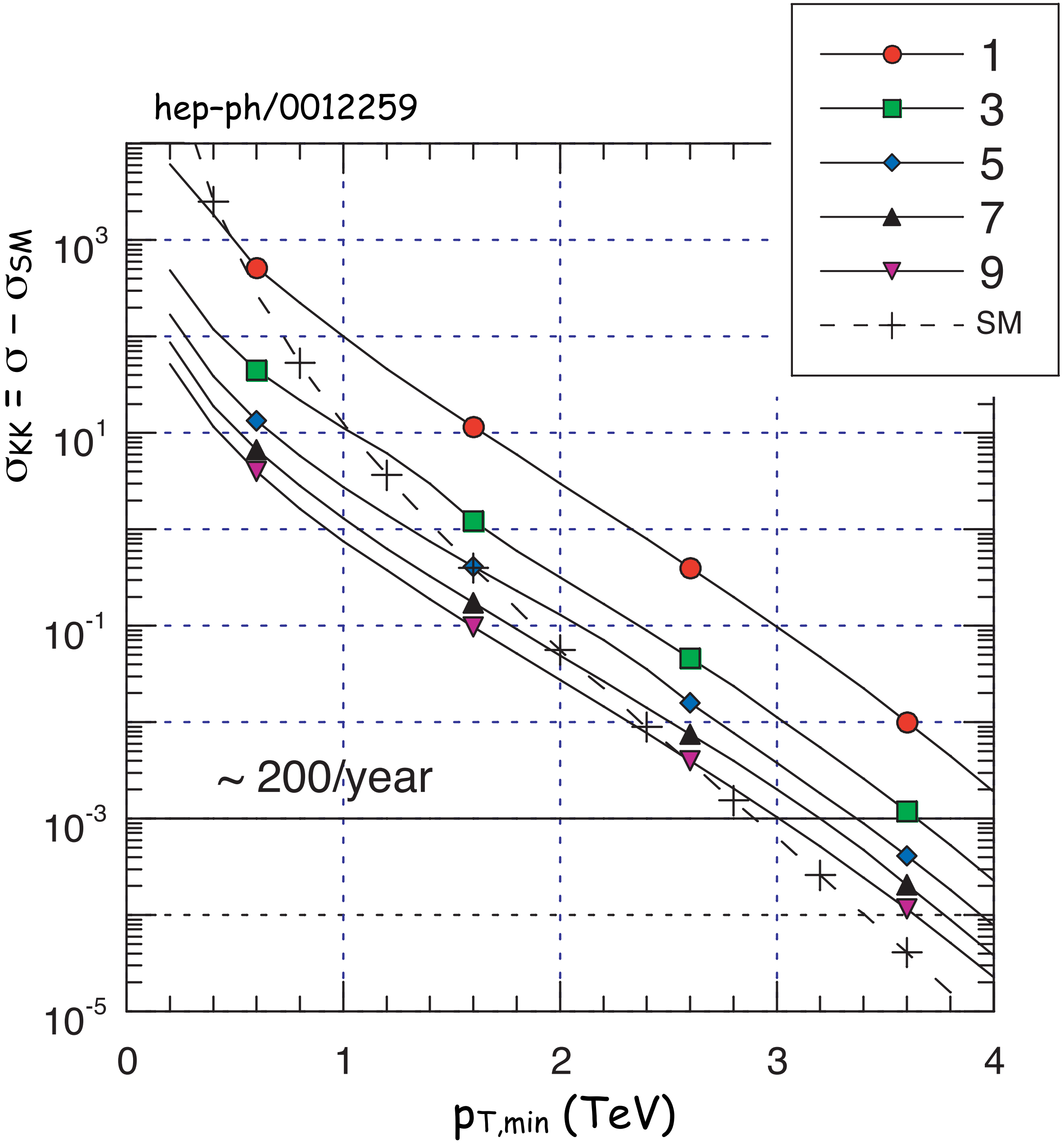
Expectation: Enhancement of σ_{jet} at high E_T

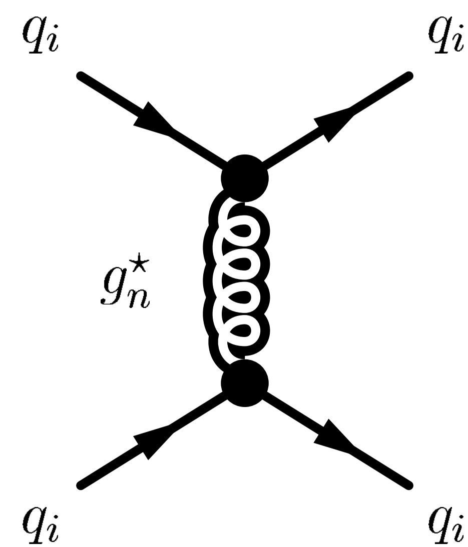
ATLAS TDR: Inclusive Jets





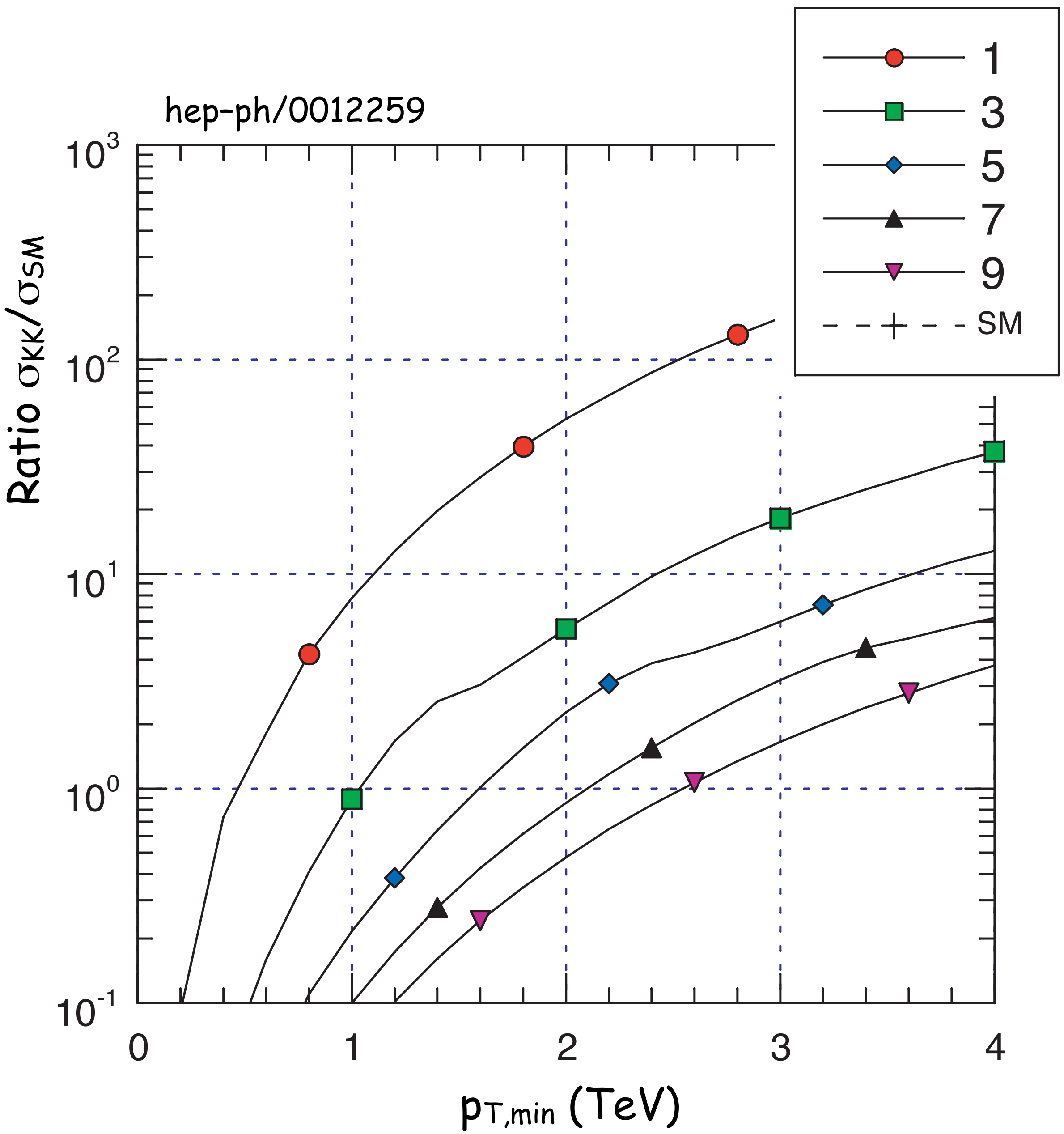
Heavy Gluons [Extra Dimensions]

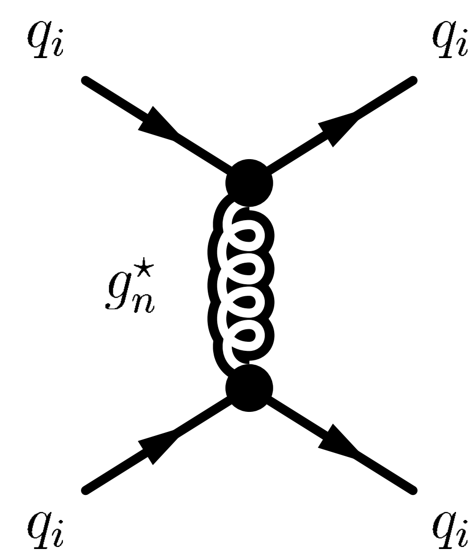




Heavy Gluons:
Kaluza Klein Excitations
of normal gluon
Mass of g*:
Scale of Extra Dimension

Heavy Gluons [Extra Dimensions]





Heavy Gluons:

Kaluza Klein Excitations of normal gluon

Mass of g*:

Scale of Extra Dimension

HERA Parton Distributions

Present Precision

Future Perspectives

Where HERA Data constrain PDFs

Valence Quarks:

High Q^2, high x
NC/CC ep cross section
[HERA I: statistics limited]

HERA II

Sea Quarks:

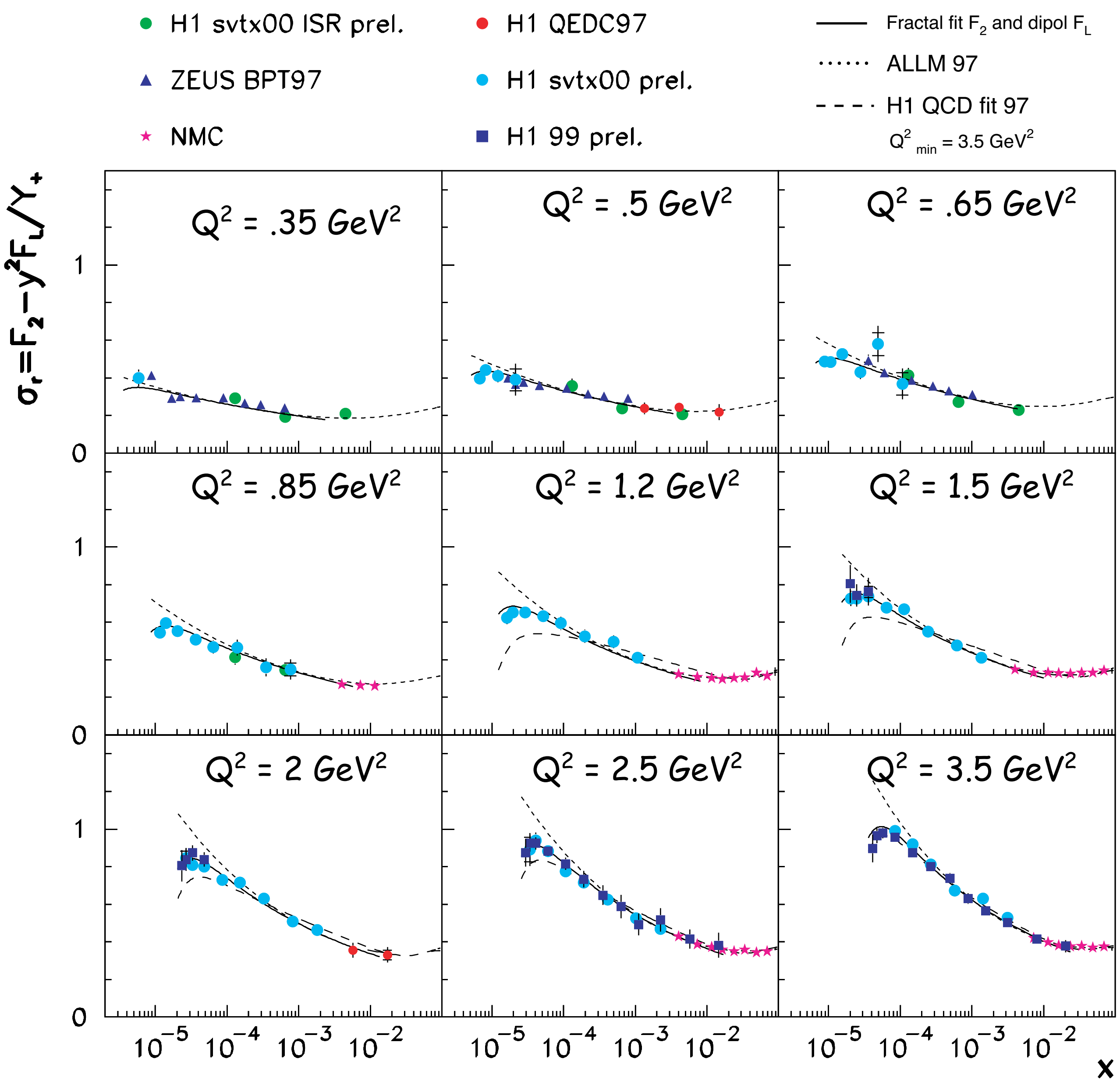
Low-x: inclusive NC DIS
[HERA I 2000 data to be published]

Gluon:

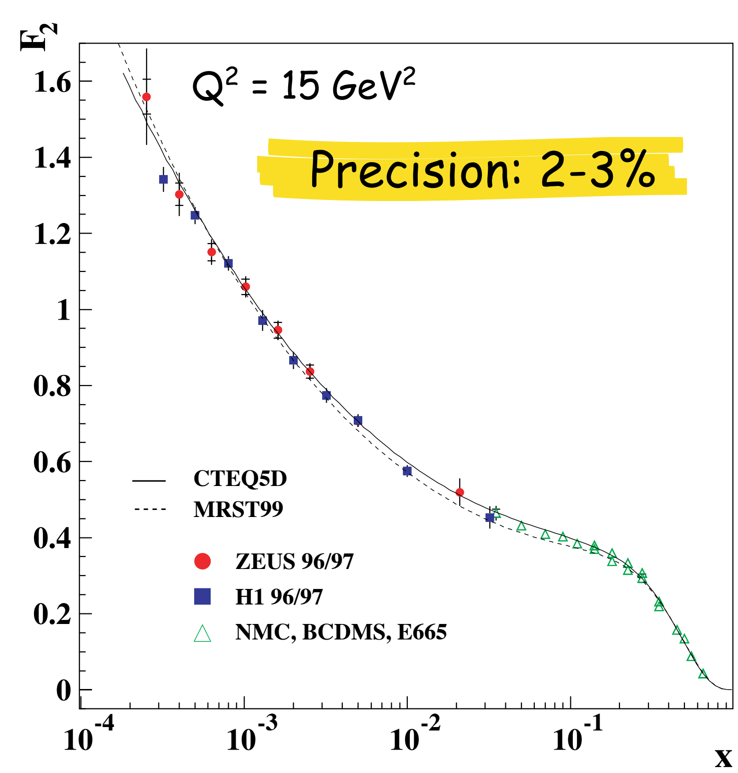
Low-x: scaling violations
Mid-x: jet data
heavy flavours
High-x: momentum sum rules
[HERA I statistics limited at high E_T]
[HERA II: jets, heavy flavours]

HERA II

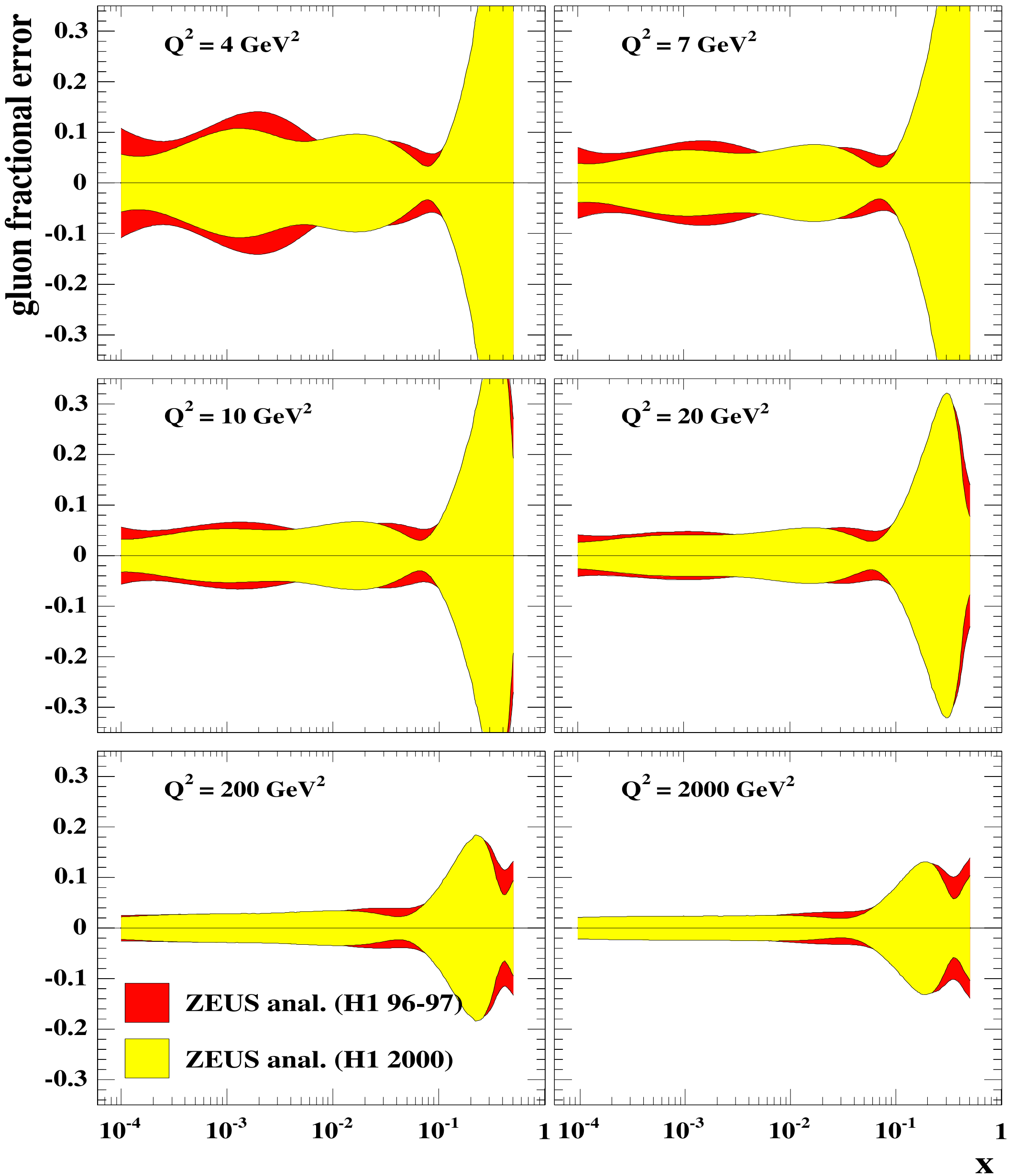
New H1 Low-Q^2 Results



Precision of 2-3% down to Q^2 =0.35



Impact of 'New' HERA low-Q^2 data



ZEUS Fit to H1 Data

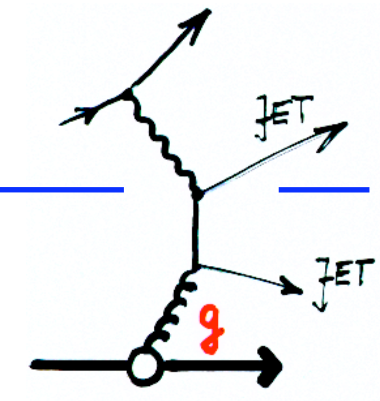
- High Q^2 NC/CC Data 94-00
  Low Q^2 NC 94-97 (published)
- High Q^2 NC/CC Data 94-00
  Low Q^2 NC 2000 (estimate)

- improved knowledge of gluon at low x and low Q^2
- some reduction also at higher x

C.Gwenlan
[HERA/LHC Workshop]

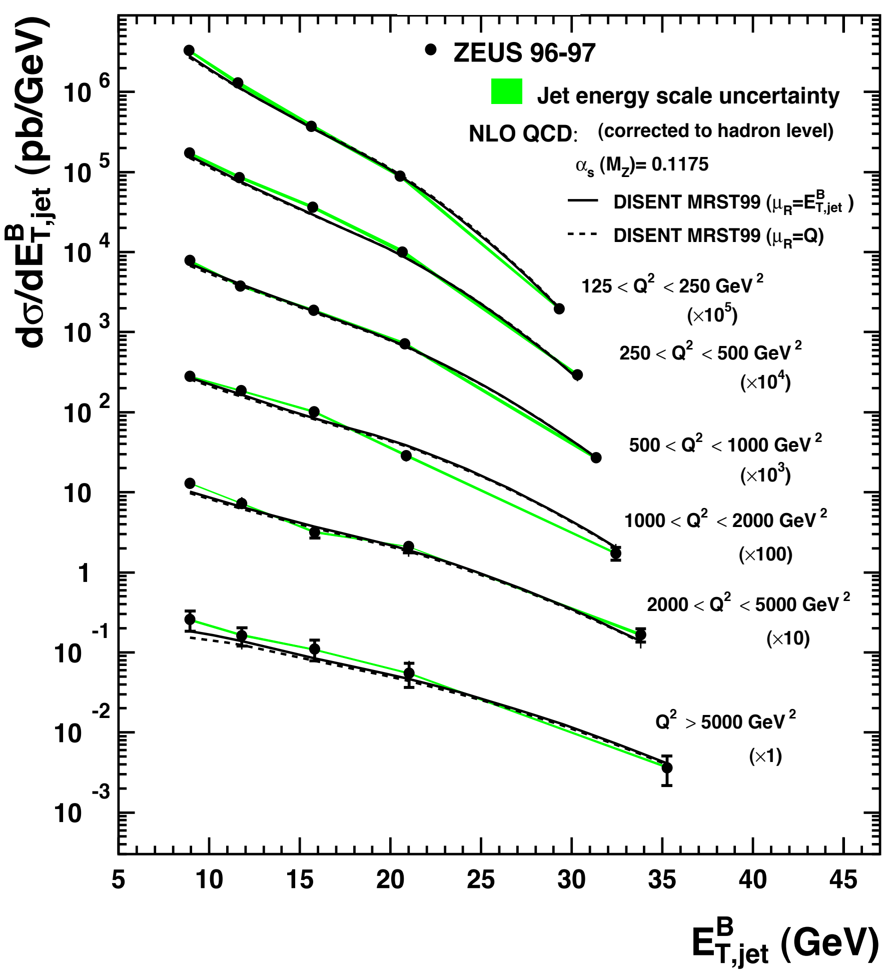
"only"
Moderate impact on xg(x)
from extra precision on low Q^2 data

Jet Data

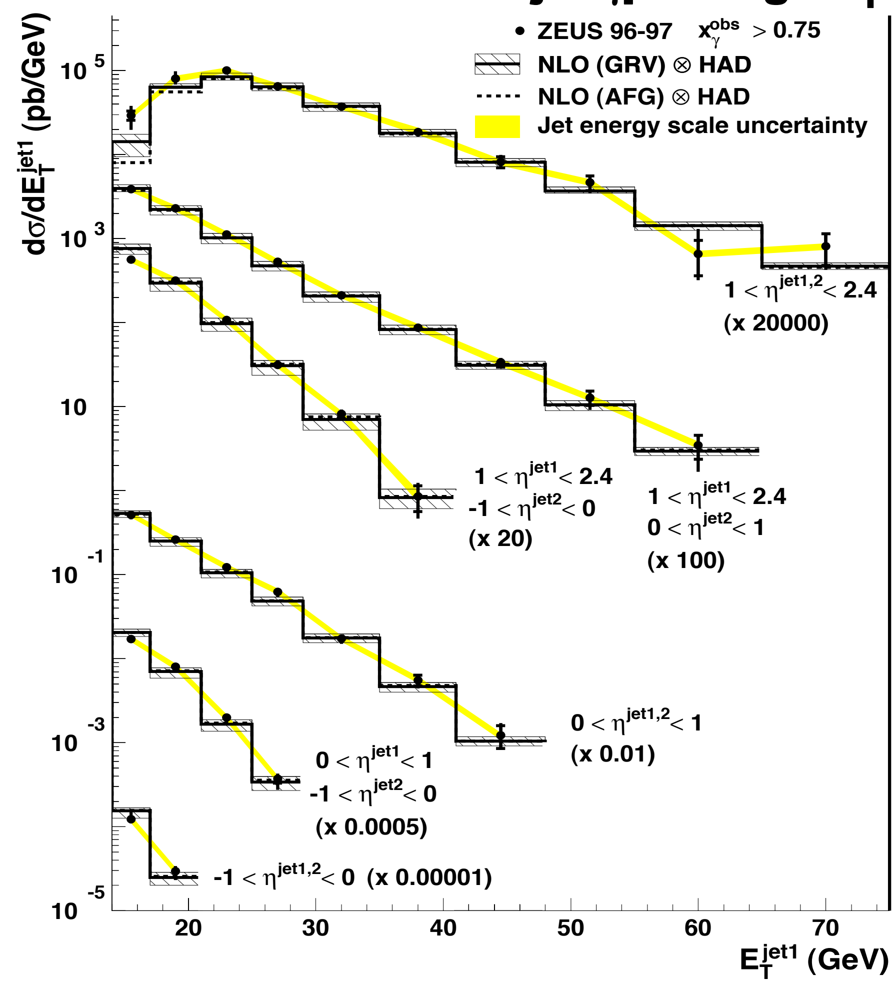


Examples: HERA-I high E_T jet measurements
in DIS and Photoproduction ($Q^2 \sim 0$)

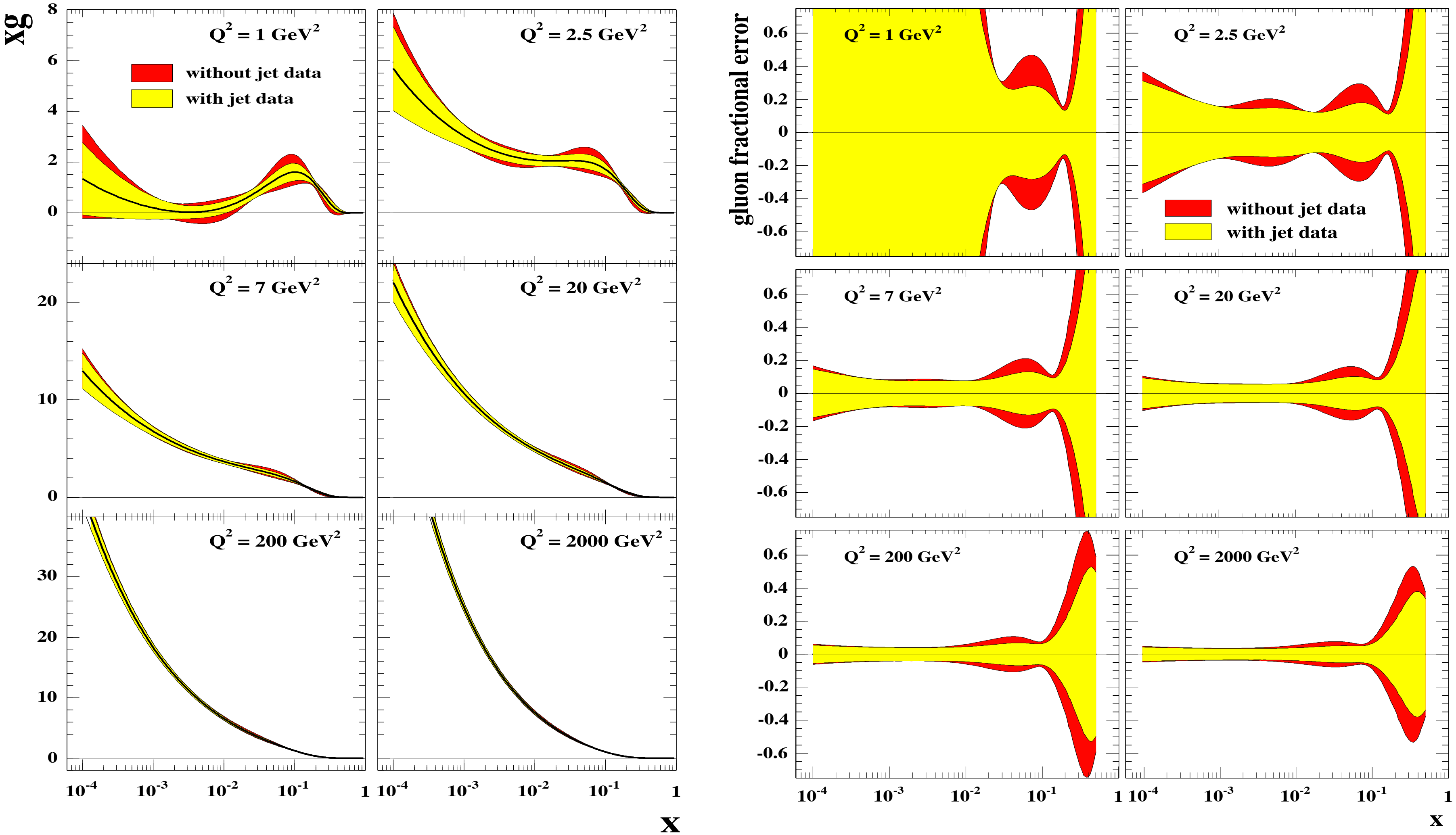
HERA-I: ZEUS inclusive jets in DIS



HERA-I: ZEUS two-jet γp at high-E_T

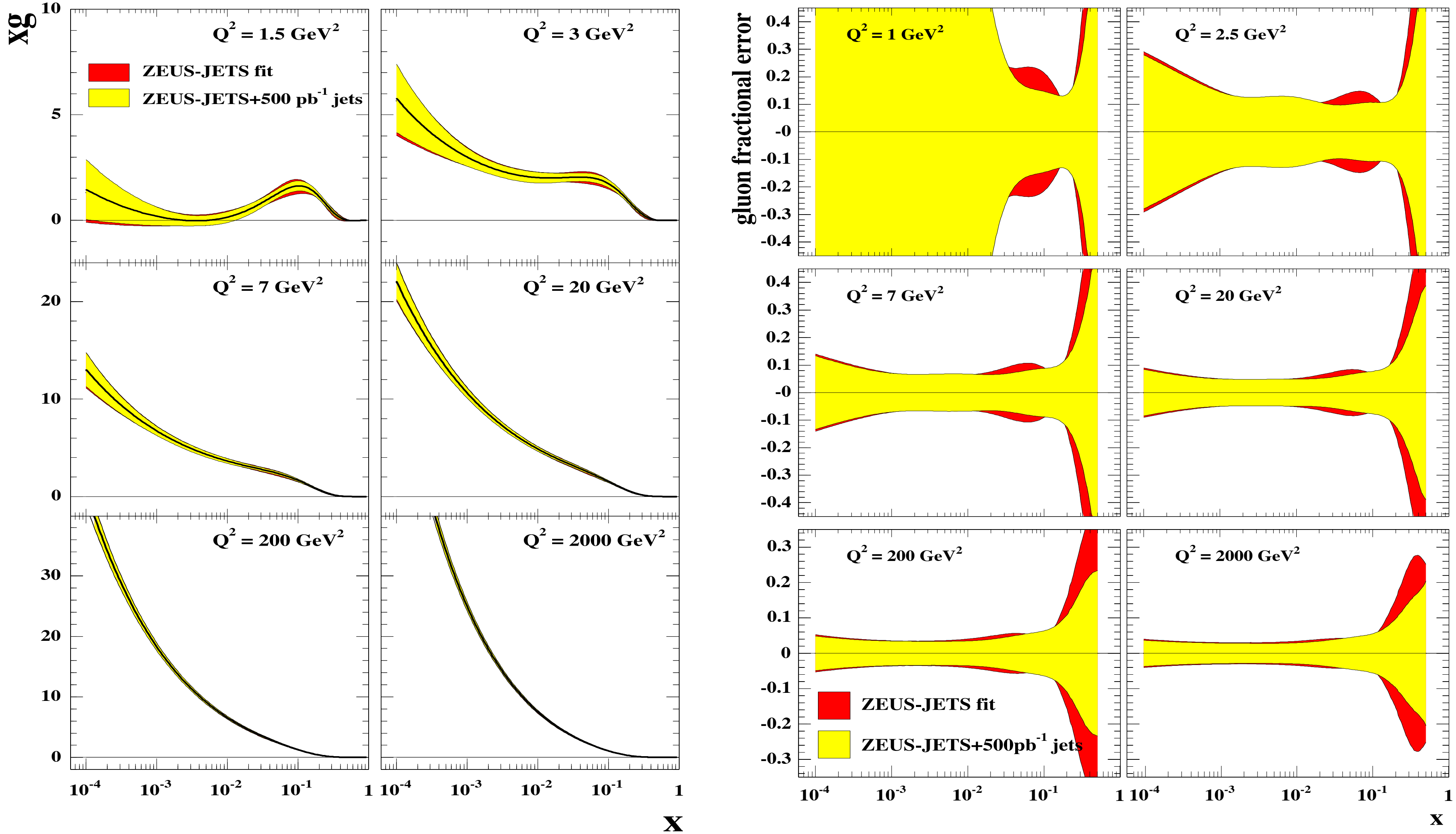


Impact of Jet Data on Gluon PDF



Clear improvement of xg(x) at x ~ 0.01 - 0.1

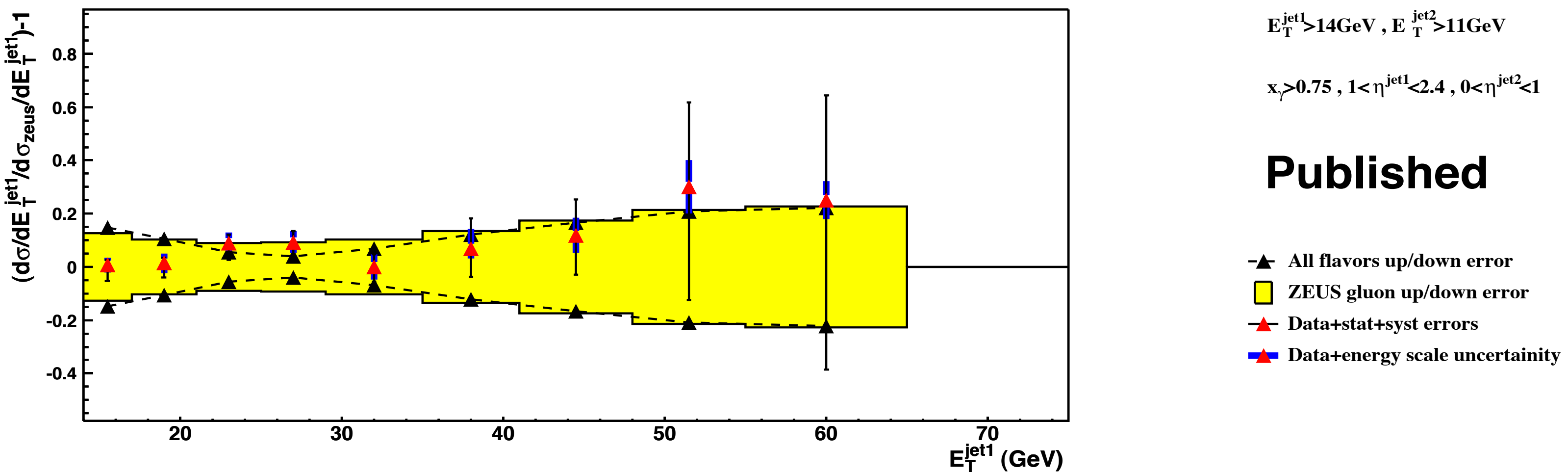
Impact of 500 pb^{-1} Jet Data

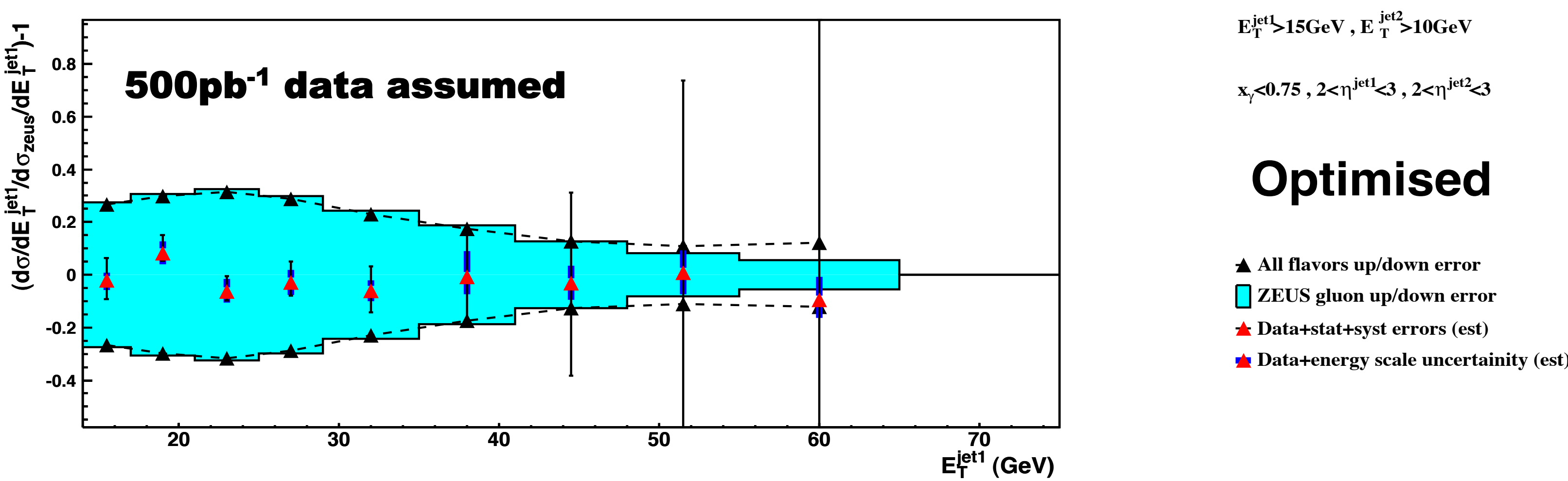


Further improvement of xg(x) at x ~ 0.01 - 0.1

HERA prospects using jets

by optimizing selection cuts





Significant improvement seems possible.

Impact of HERA II

[case study using current running scenario]

Data sample	L of HERA-I measurement (pb^{-1})	assumed L of HERA-II measurement (pb^{-1})	Central values taken from...	Systematica taken from...
High-Q^2 NC e+	63	350	existing data	existing data
High-Q^2 NC e-	16	350	existing data	existing data
High-Q^2 CC e+	61	350	existing data	existing data
High-Q^2 CC e-	16	350	existing data	existing data
Inclusive DIS jets	37	500	existing data	existing data
Dijets in γp	37	500	existing data	existing data
Optimised dijets in γp	-	500	NLO QCD	NOT INCLUDED

statistically limited data-sets

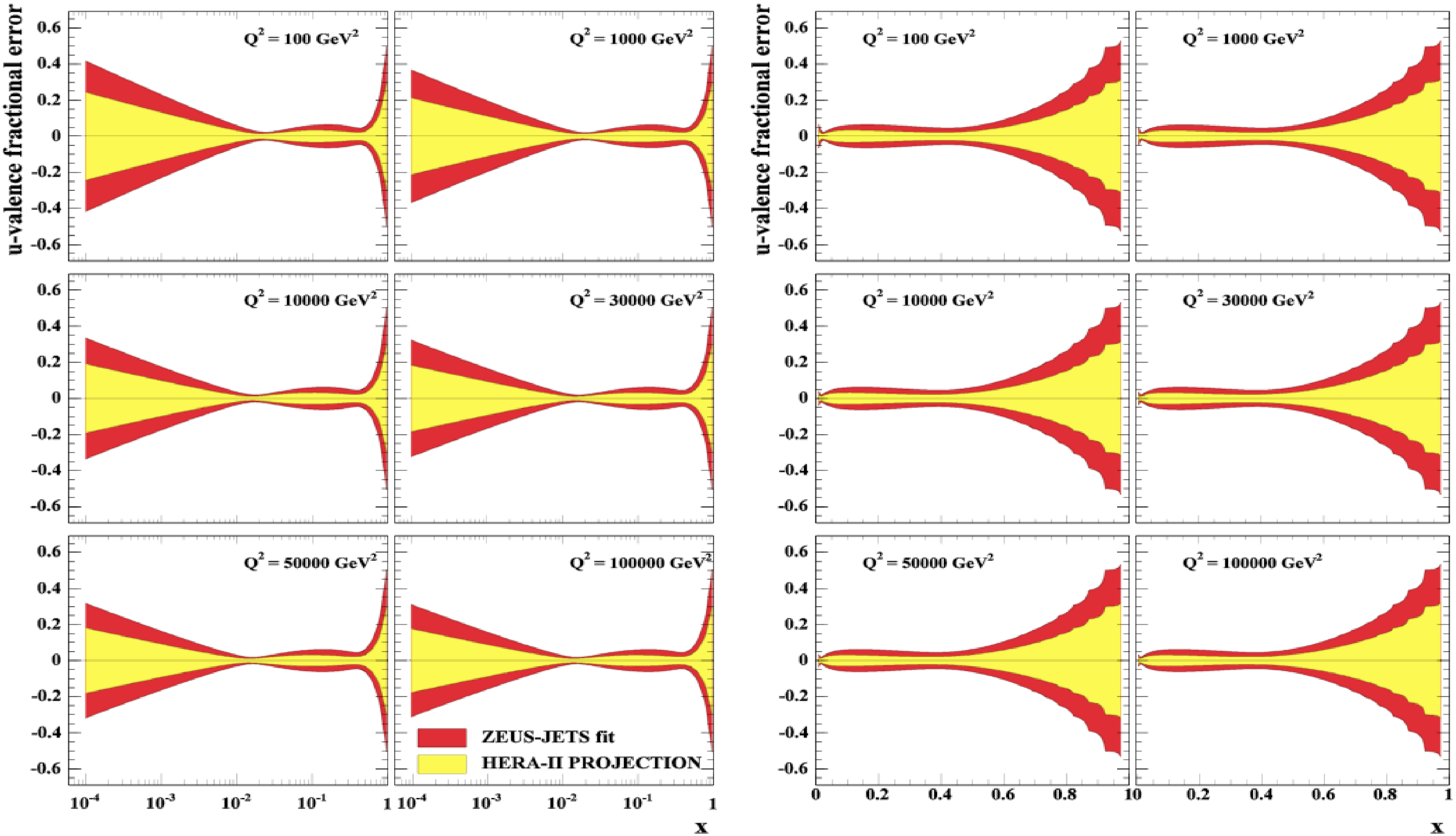
- scale statistical uncertainties on existing data assuming max. 700 pb^{-1} (equally between e+/e-)
- systematic uncertainties taken from existing data

optimised jet cross sections

- include simulated data-points from NLO QCD, statistical uncertainties assume 500 pb^{-1}
- no systematics included

u-Valence Uncertainties

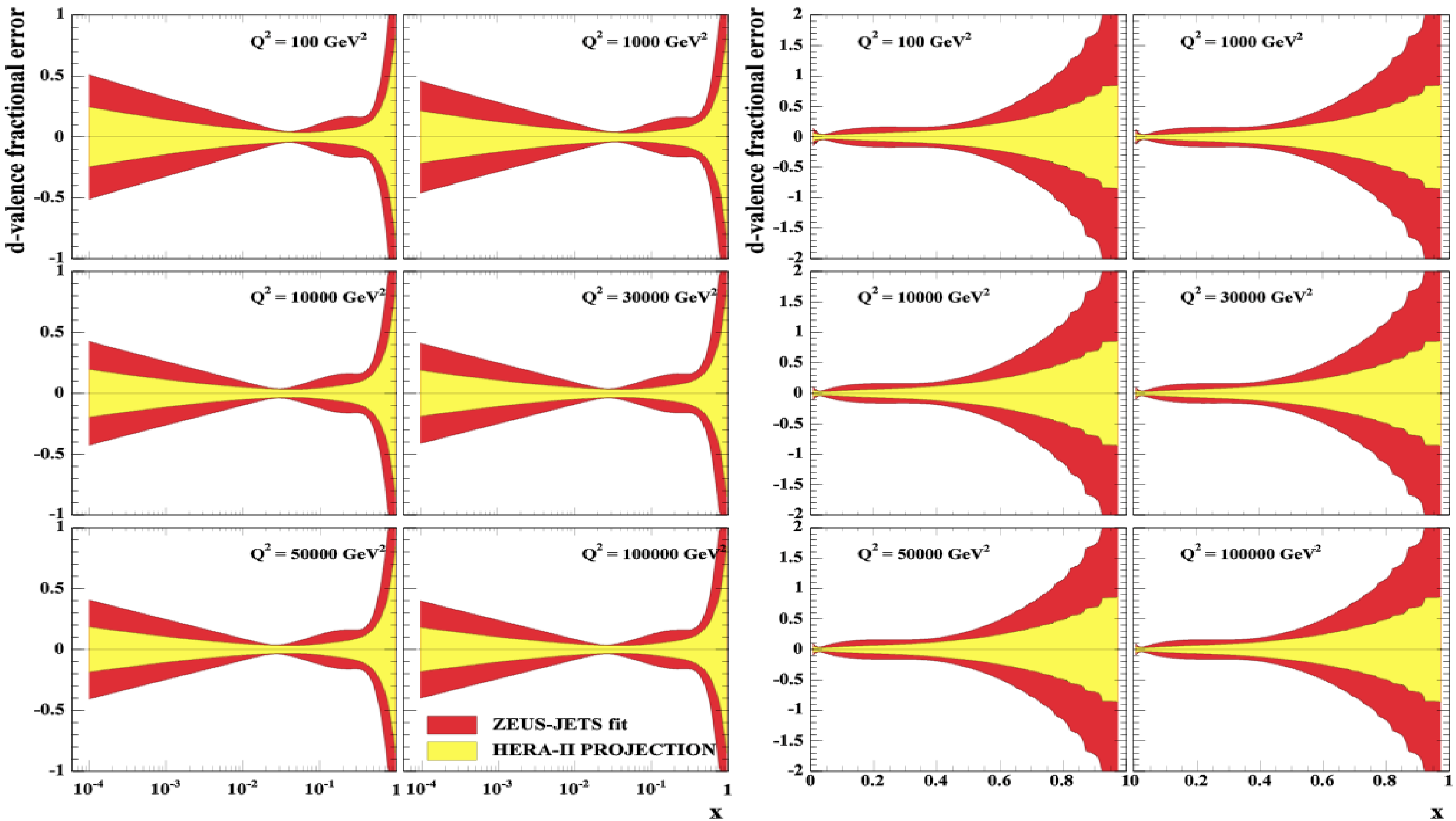
log-x scale (low-x region) | linear-x scale (high-x region)



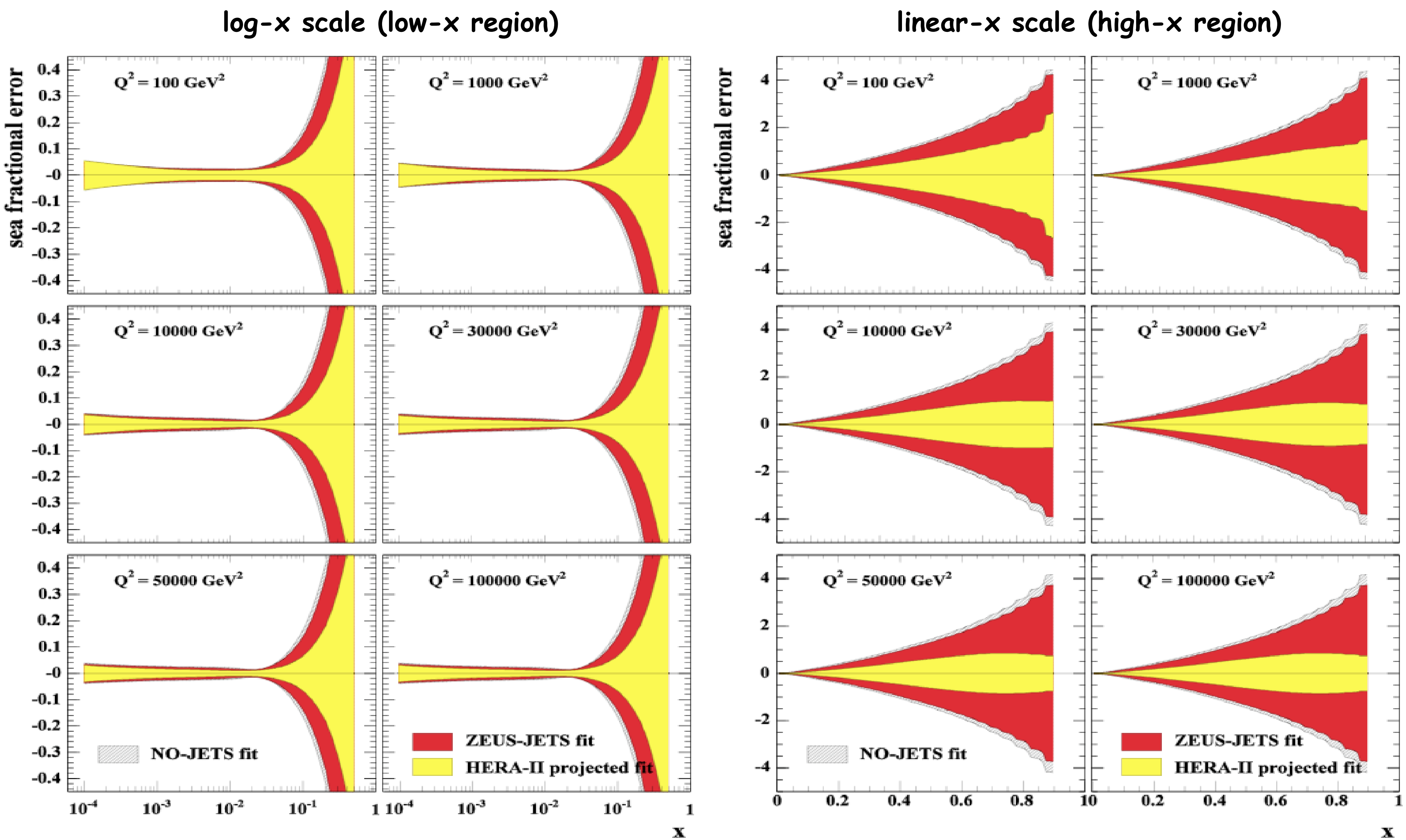
d-Valence Uncertainties

log-x scale (low-x region)

linear-x scale (high-x region)

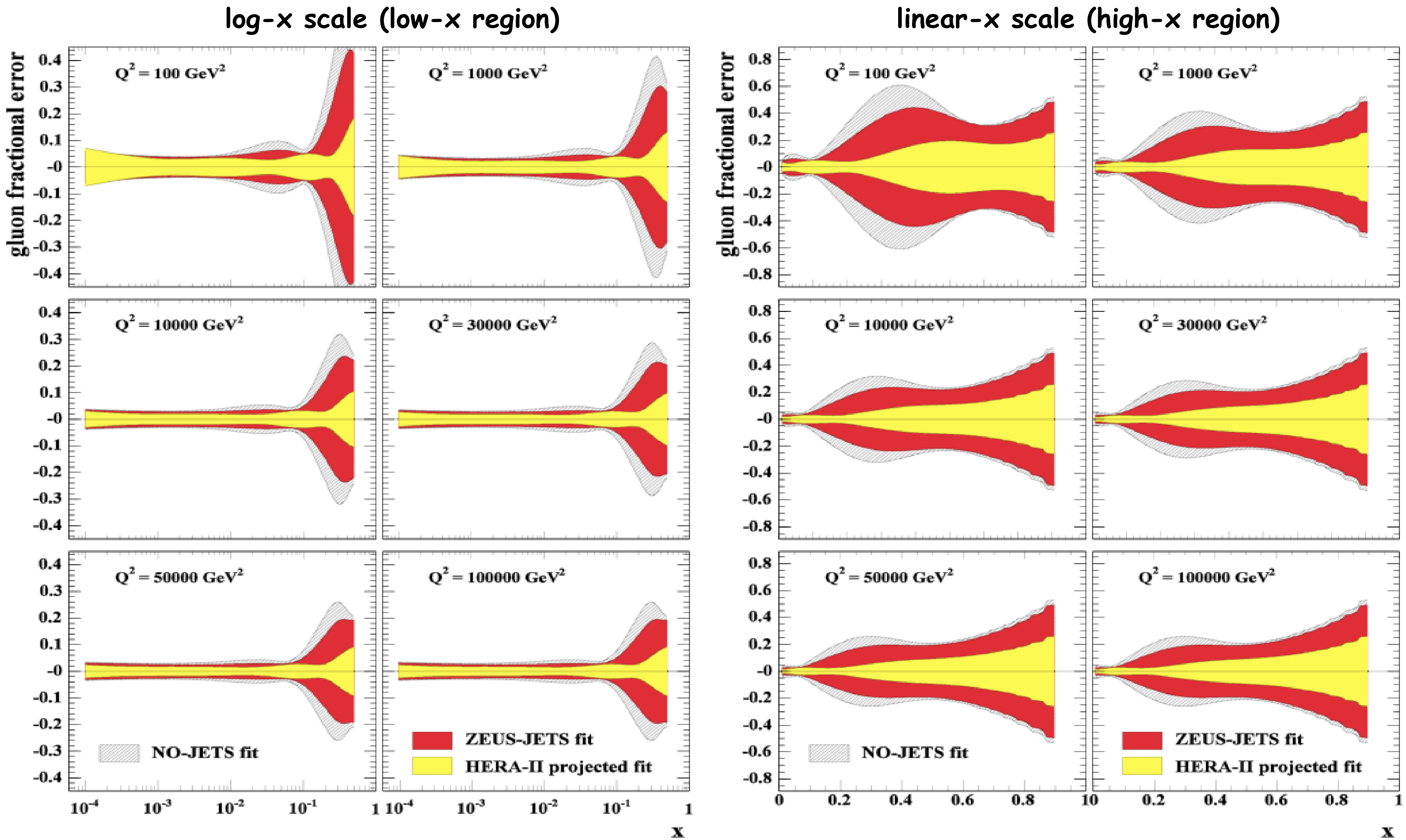


Sea Quark Uncertainties



→ most significant improvement from increased statistics at HERA-II

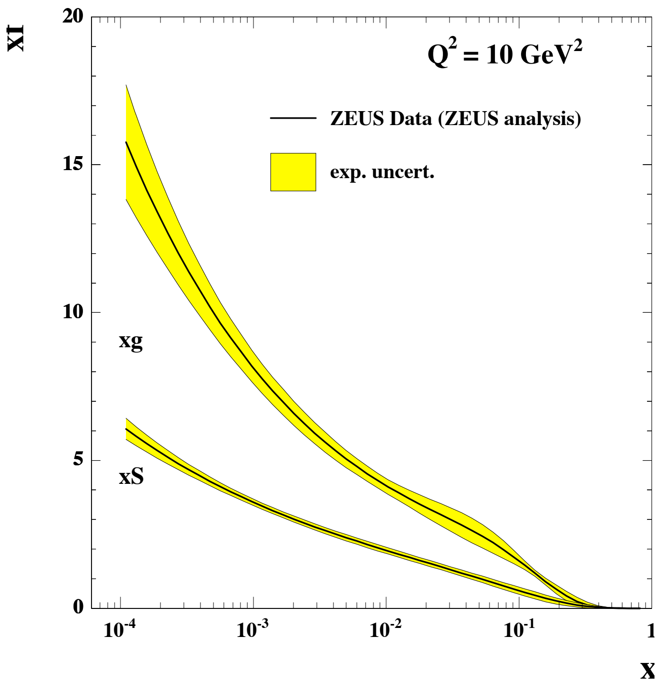
Gluon Uncertainties



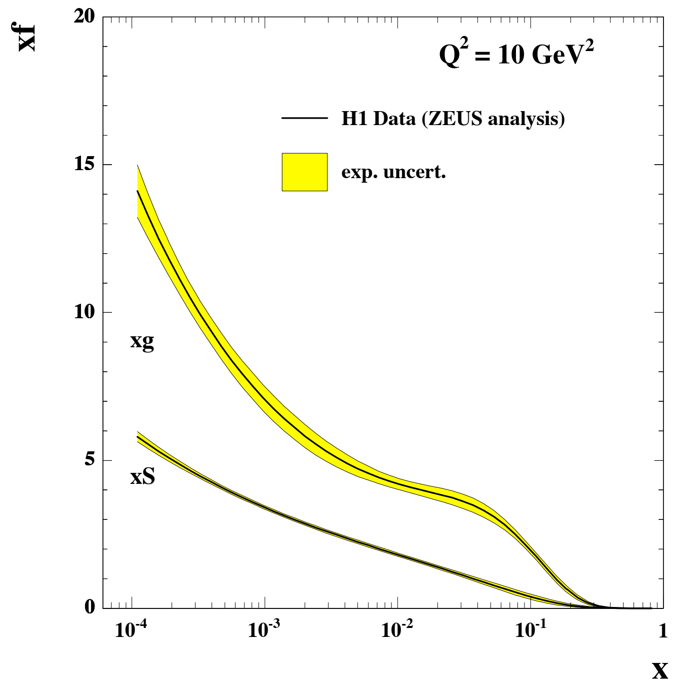
→ most significant improvement from optimized jet analysis

Caveats

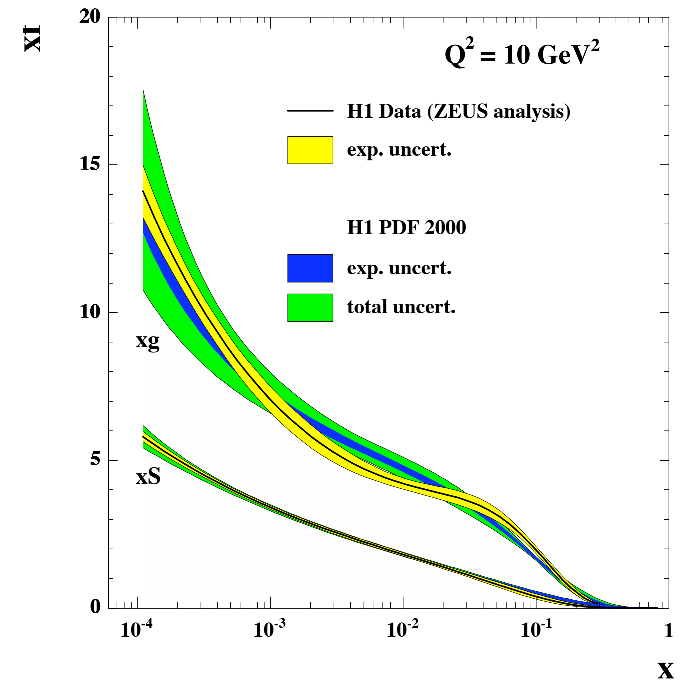
Comparison of H1 and ZEUS



ZEUS analysis/ ZEUS data



ZEUS analysis/ H1 data



ZEUS analysis/H1 data
H1 analysis/H1data

Here we see the effect of differences in the data; recall that the gluon is not directly measured (no jets).

The data differences are most notable in the large 96/97 NC samples at low-Q^2.

If a fit is done to ZEUS and H1 together the χ^2 for both these data sets rises compared to when they are fitted separately ...

Here we see the effect due to differences in the analysis choice

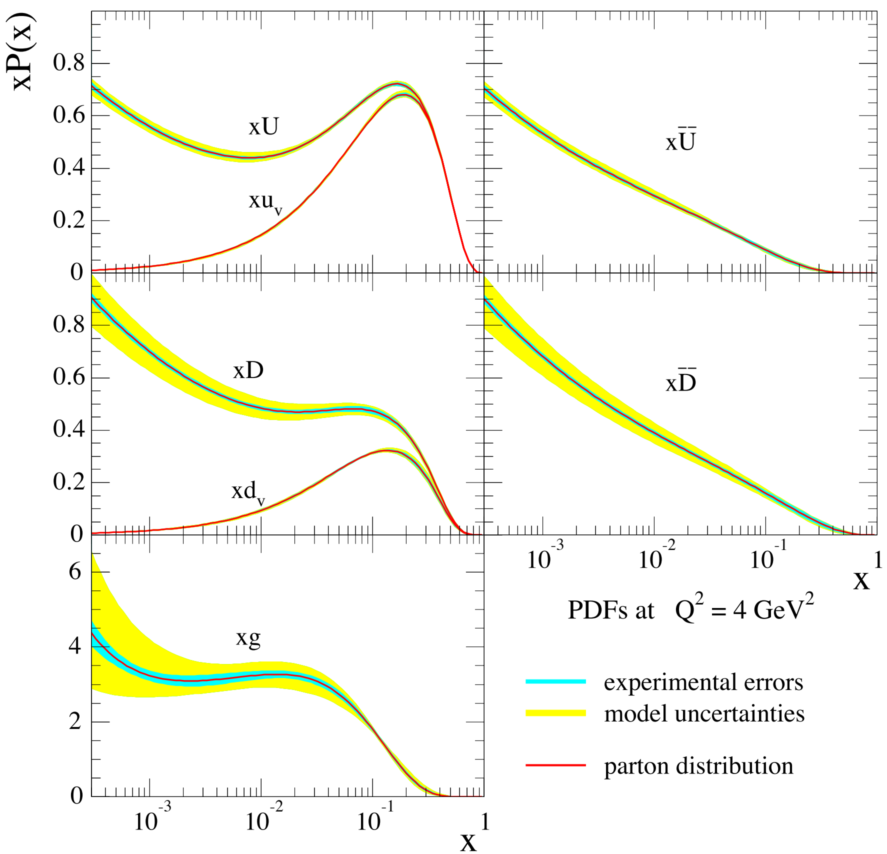
e.g. parametrization at Q_0^2 ...

[Cooper-Sarkar]

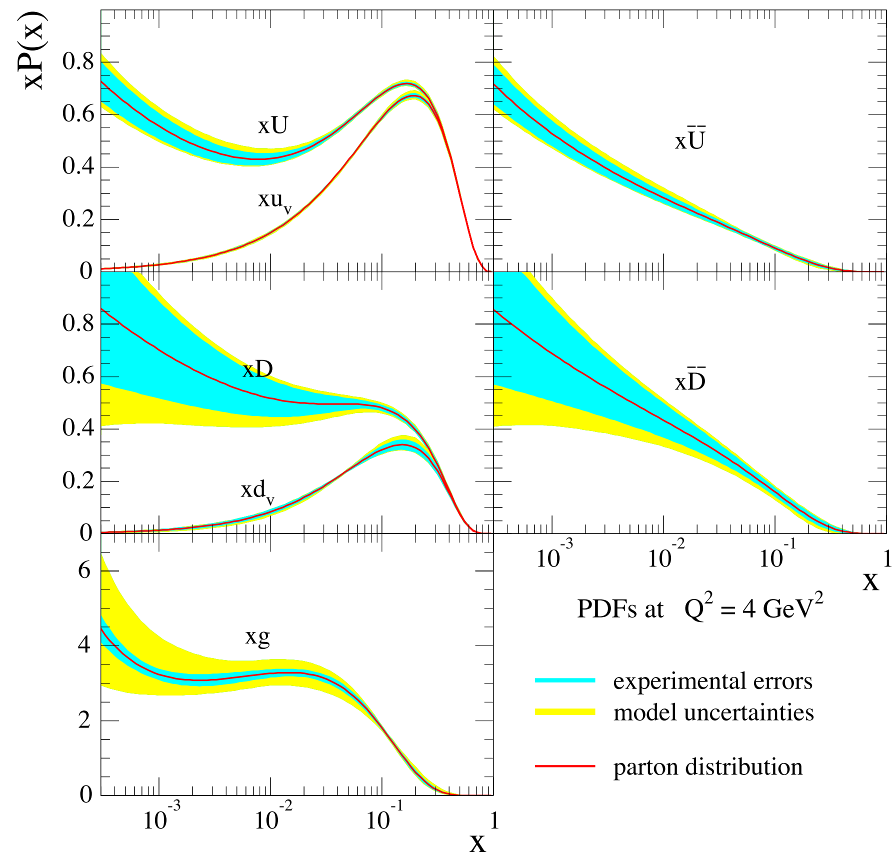
Possible

Impact of $\bar{d}$-$\bar{u}$ Asymmetries

H1 + BCDMS
[$a_{\bar{u}}$, $a_{\bar{d}}$, $b_{\bar{u}}$, $b_{\bar{d}}$ constrained]



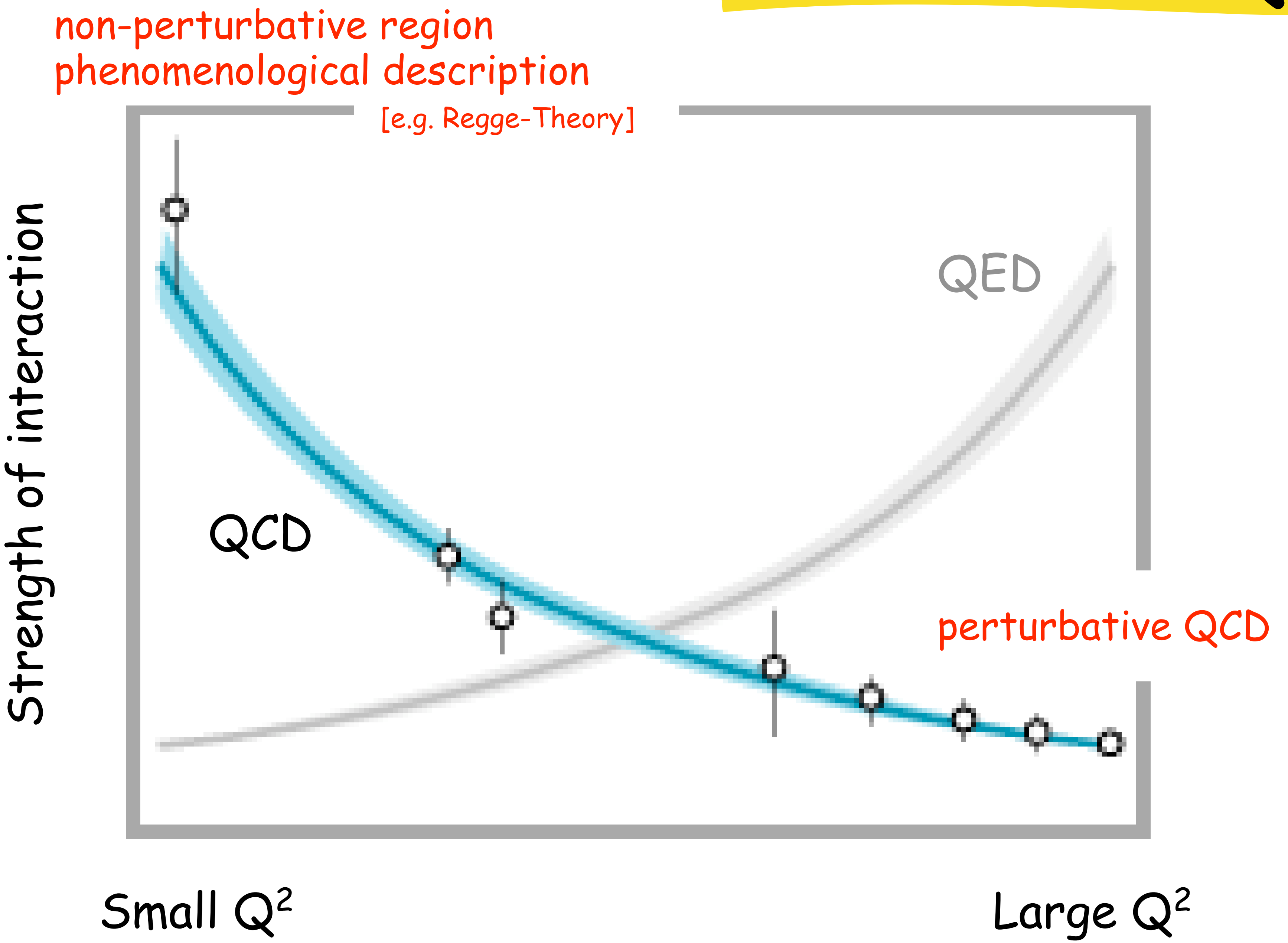
H1 + BCDMS
[$a_{\bar{u}}$, $a_{\bar{d}}$, $b_{\bar{u}}$, $b_{\bar{d}}$ unconstrained]



Enforce: $x(\bar{d} - \bar{u}) \xrightarrow{x \to 0} 0$

$a_{\bar{u}}$, $a_{\bar{d}}$, $b_{\bar{u}}$, $b_{\bar{d}}$: free parameters

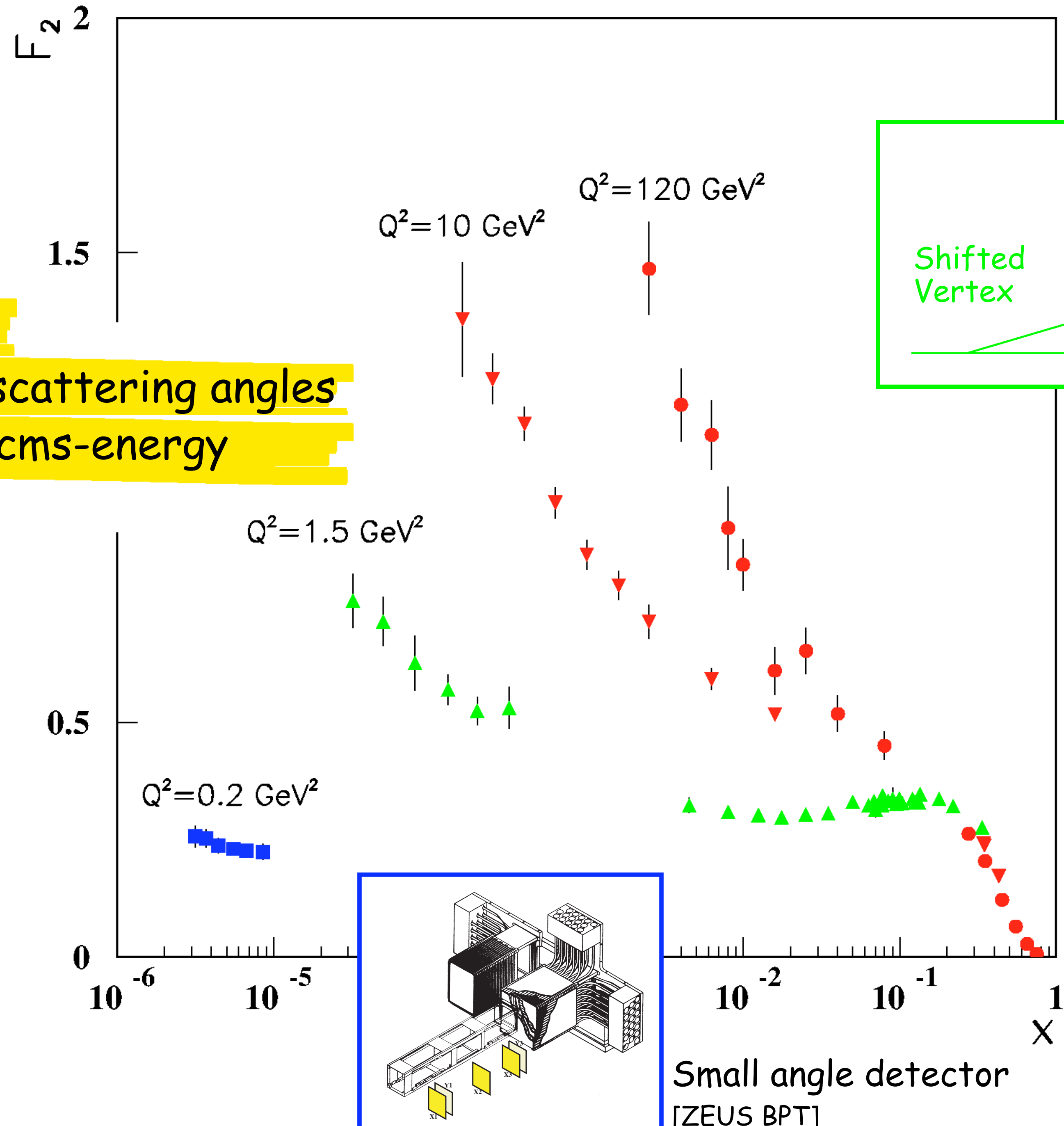
F_2 @ low Q^2

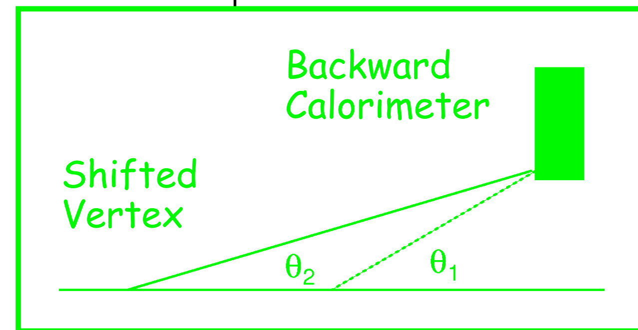

non-perturbative region
phenomenological description
[e.g. Regge-Theory]
Strength of interaction
QED
QCD
perturbative QCD
Small Q2
Large Q2

Small Q^2

↔ small scattering angles

↔ lower cms-energy





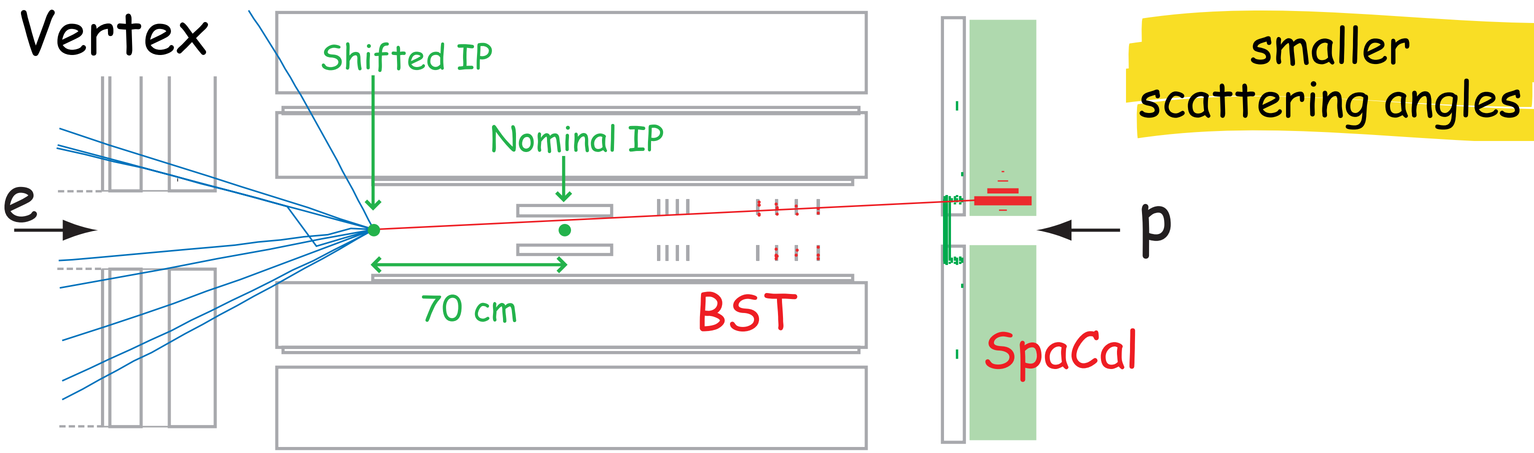
Special
data taking period
with shifted vertex

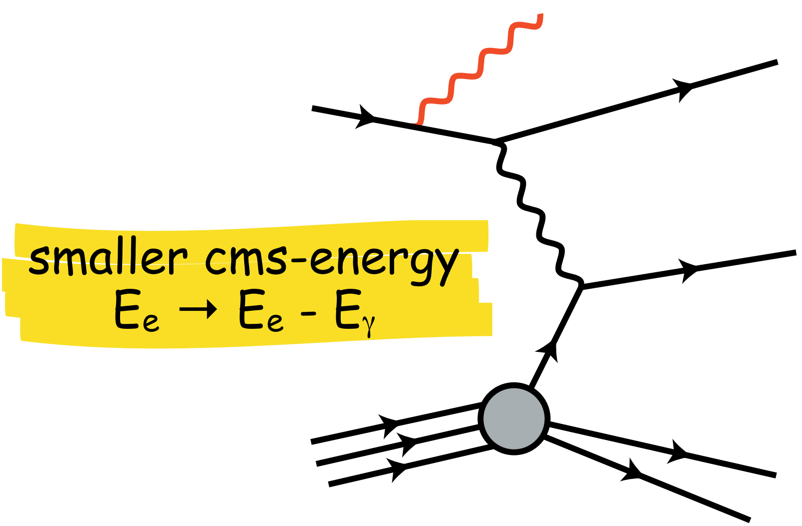
+ ISR
QEDC

Small angle detector
[ZEUS BPT]

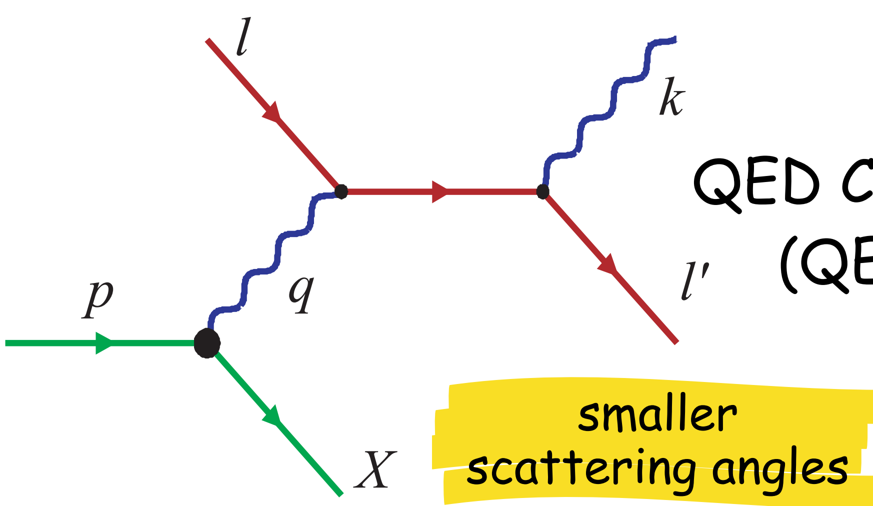
Experimental Technics [to Access Low Q^2]

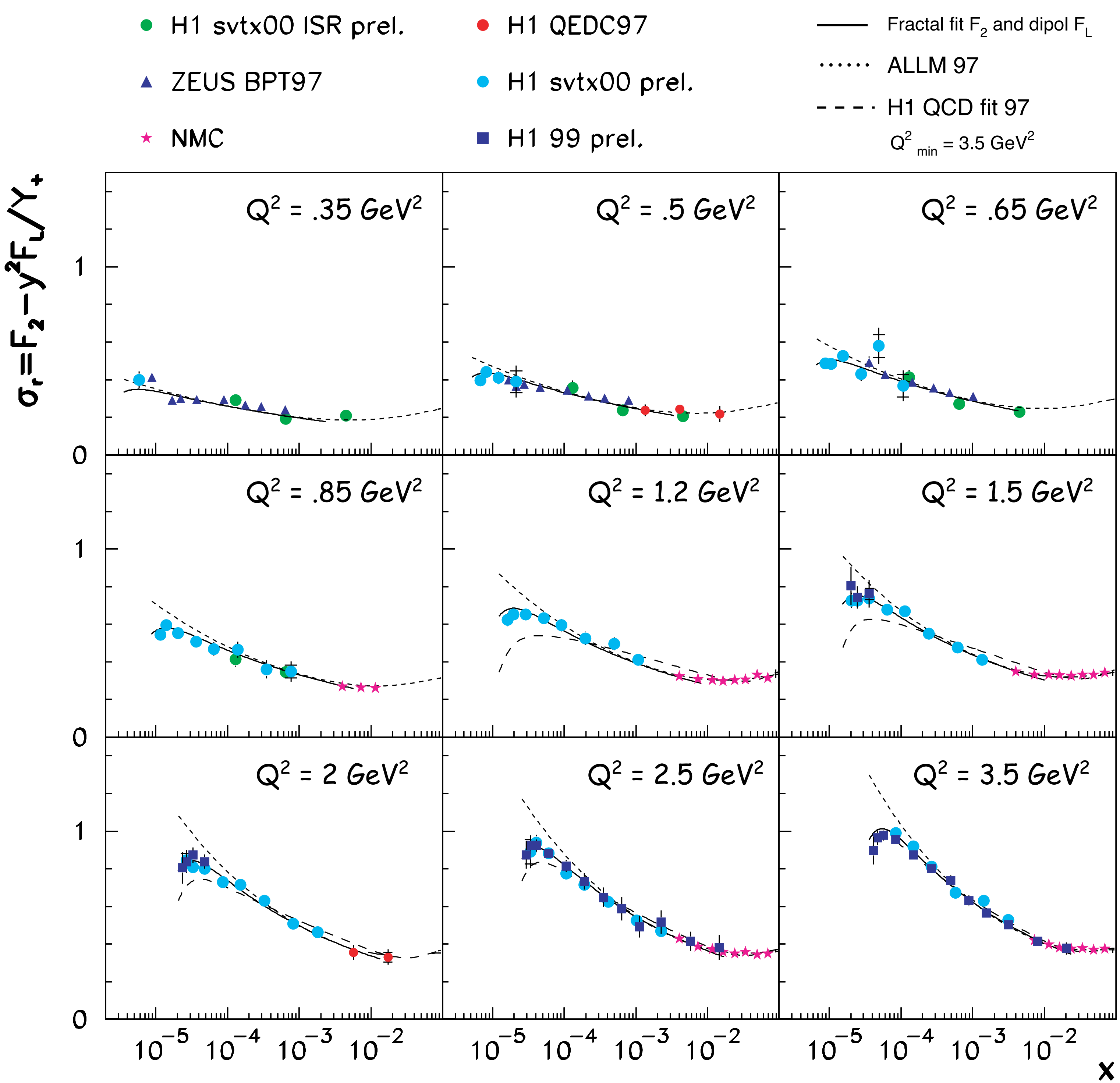
Shifted Vertex



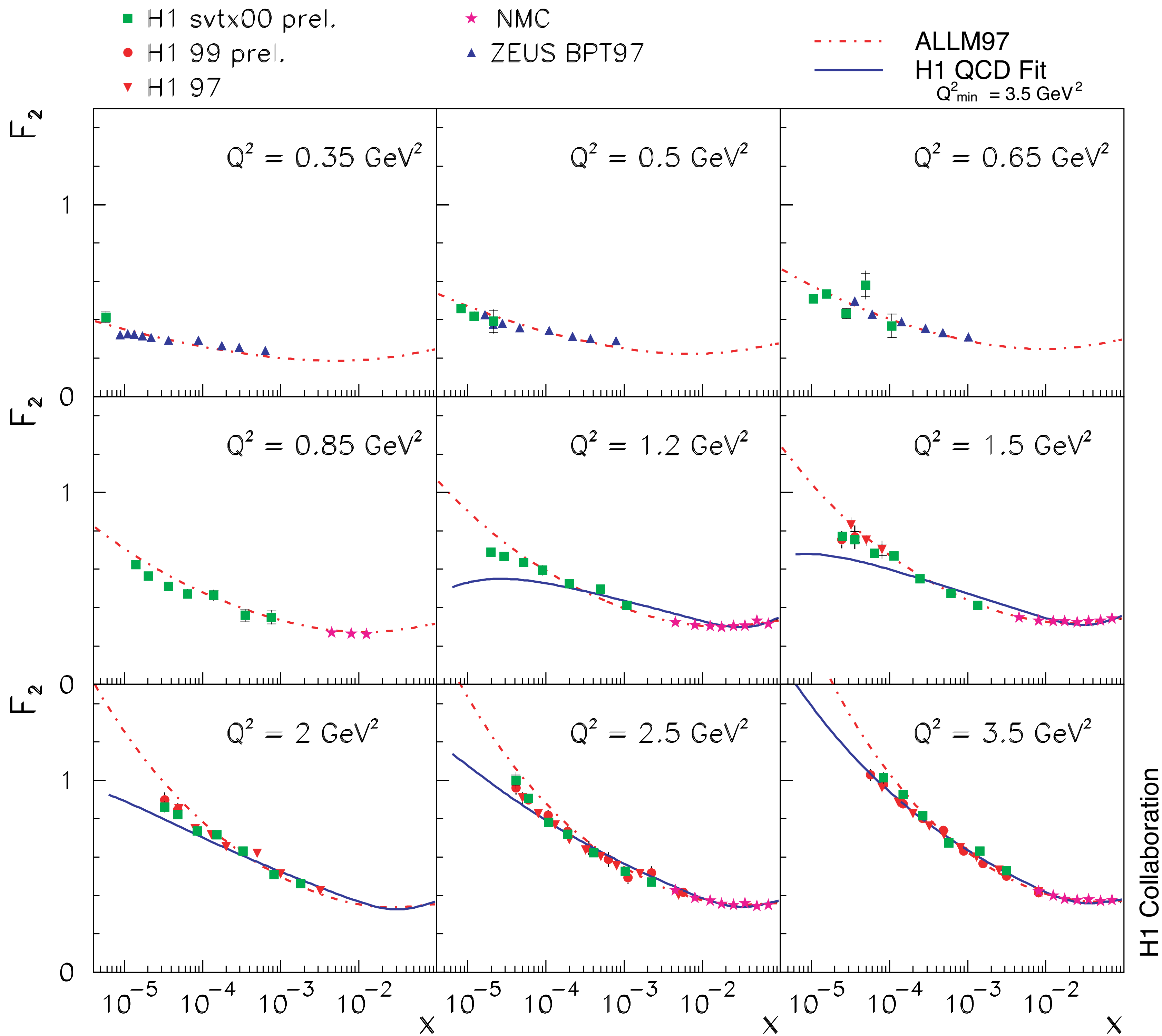


Initial State Radiation (ISR)

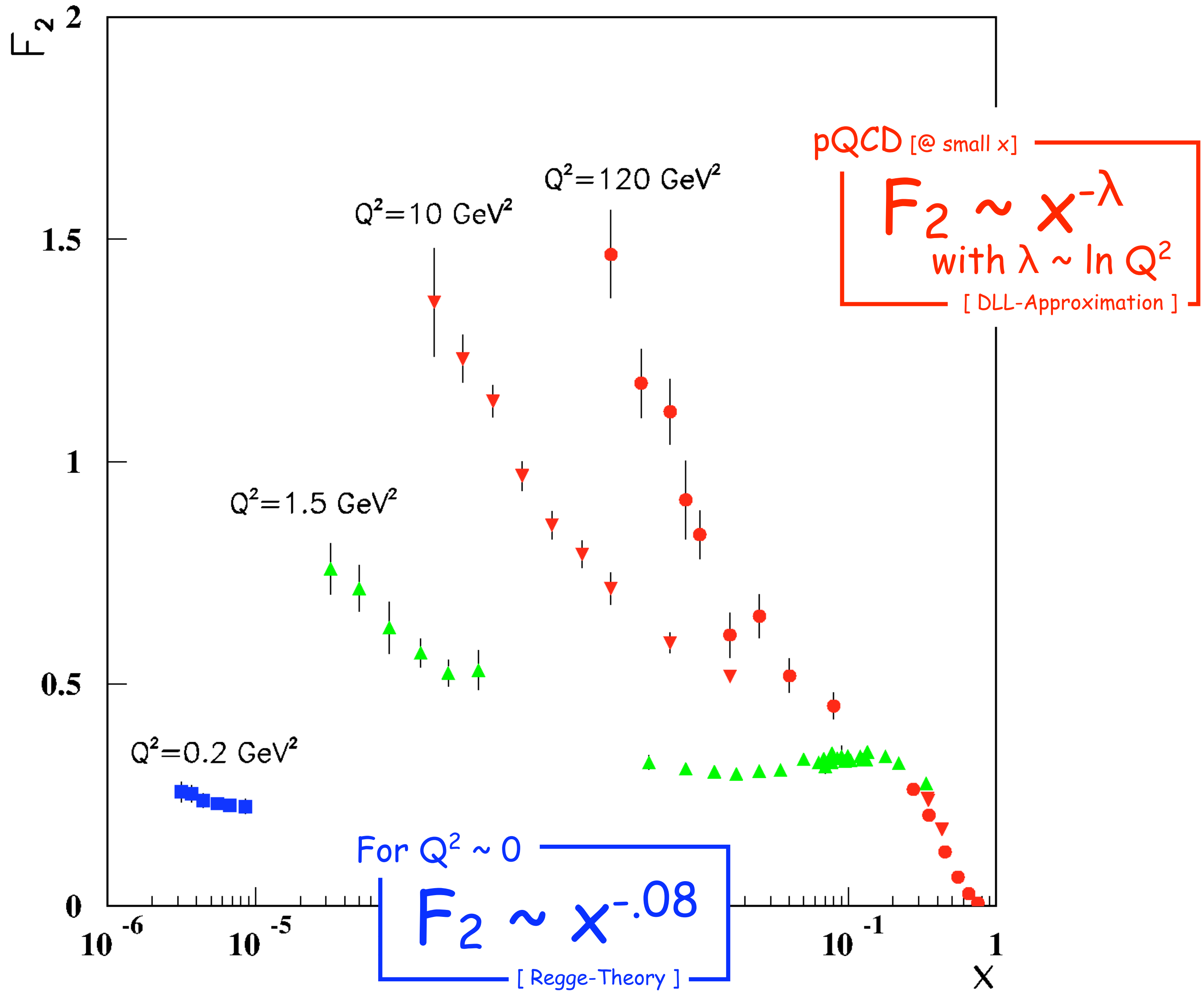




H1 svtx00 ISR prel.
ZEUS BPT97
NMC
H1 QEDC97
H1 svtx00 prel.
H1 99 prel.
Fractal fit F_2 and dipol F_L
ALLM 97
H1 QCD fit 97
$Q^2_{min} = 3.5\ GeV^2$
$\sigma_r = F_2 - y^2 F_L / Y_+$
$Q^2 = .35\ GeV^2$
$Q^2 = .5\ GeV^2$
$Q^2 = .65\ GeV^2$
$Q^2 = .85\ GeV^2$
$Q^2 = 1.2\ GeV^2$
$Q^2 = 1.5\ GeV^2$
$Q^2 = 2\ GeV^2$
$Q^2 = 2.5\ GeV^2$
$Q^2 = 3.5\ GeV^2$
0
1
10^{-5} 10^{-4} 10^{-3} 10^{-2}
x



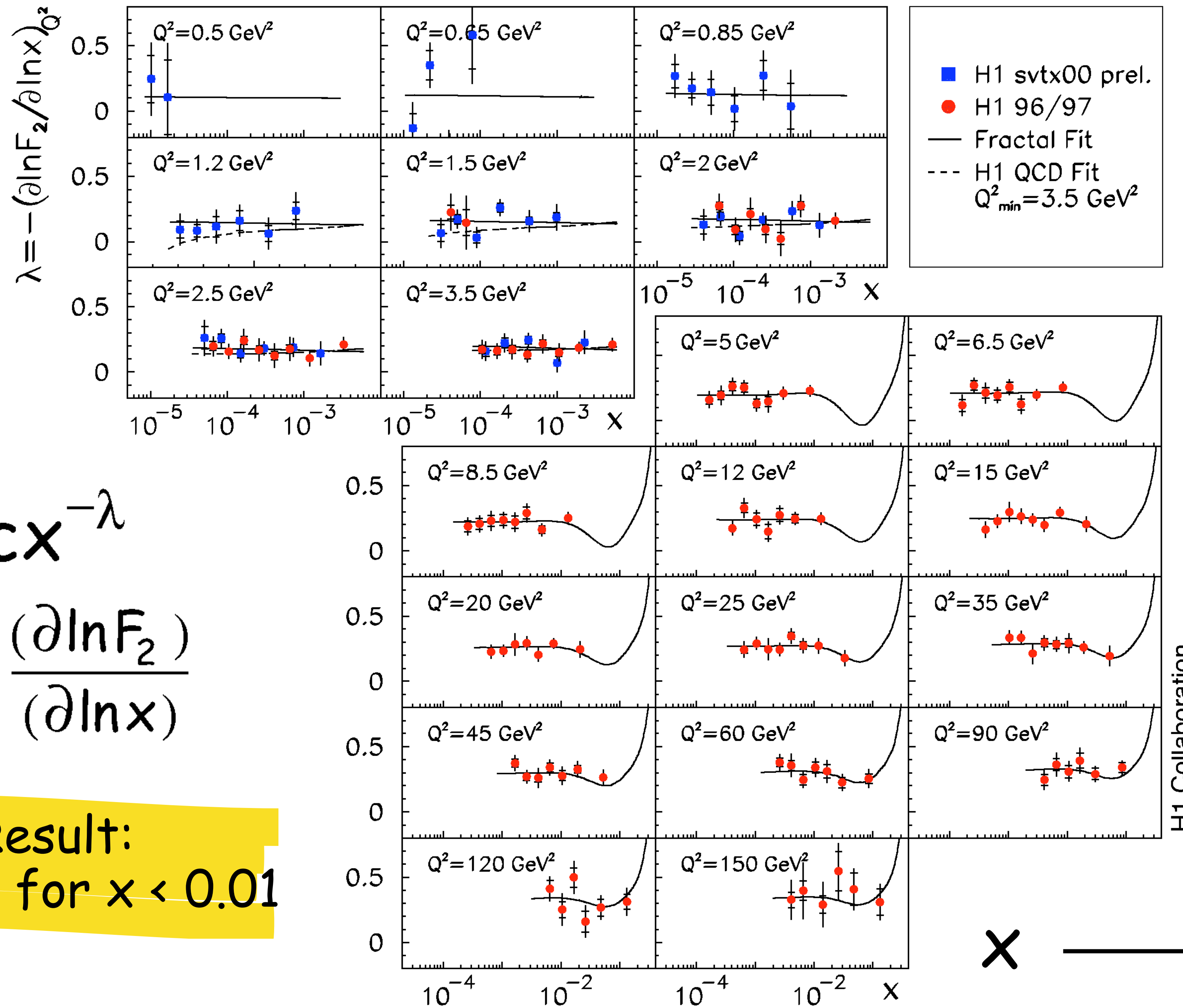
H1 svtx00 prel.
H1 99 prel.
H1 97
NMC
ZEUS BPT97
ALLM97
H1 QCD Fit
Q²min = 3.5 GeV²
F2
Q² = 0.35 GeV²
Q² = 0.5 GeV²
Q² = 0.65 GeV²
Q² = 0.85 GeV²
Q² = 1.2 GeV²
Q² = 1.5 GeV²
Q² = 2 GeV²
Q² = 2.5 GeV²
Q² = 3.5 GeV²
0
1
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻²
x
H1 Collaboration



F_2
2
1.5
1
0.5
0
10^{-6}
10^{-5}
10^{-1}
1
X
Q^2=120 GeV^2
Q^2=10 GeV^2
Q^2=1.5 GeV^2
Q^2=0.2 GeV^2
pQCD [@ small x]
$F_2 \sim x^{-\lambda}$
with $\lambda \sim \ln Q^2$
[DLL-Approximation]
For $Q^2 \sim 0$
$F_2 \sim x^{-.08}$
[Regge-Theory]

Determination of λ

λ



x

$$F_2 = cx^{-\lambda}$$

$$\hookrightarrow \lambda = -\frac{(\partial \ln F_2)}{(\partial \ln x)}$$

Result:
$F_2 \sim x^{-\lambda}$ for $x < 0.01$

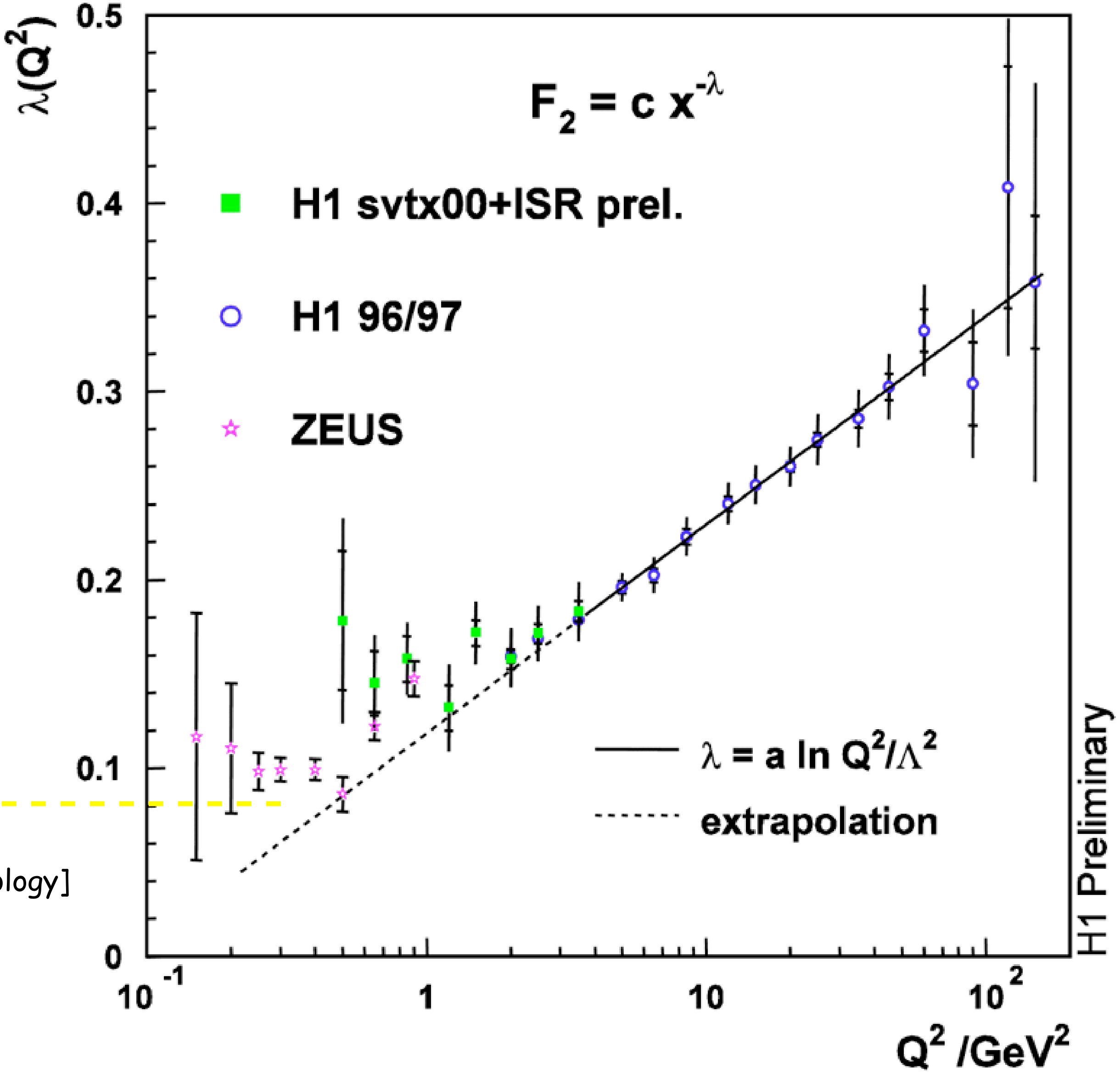
Q^2-Dependence of F_2-Slope

What happens
at $Q^2 \sim 0.5$ GeV^2?

corresponds to scale of
$r \approx \hbar/Q \approx 0.3$ fm.

proton radius: $r \approx 0.8$ fm

Evidence for non-partonic substructure within proton?



λ =0.08
[Regge phenomenology]

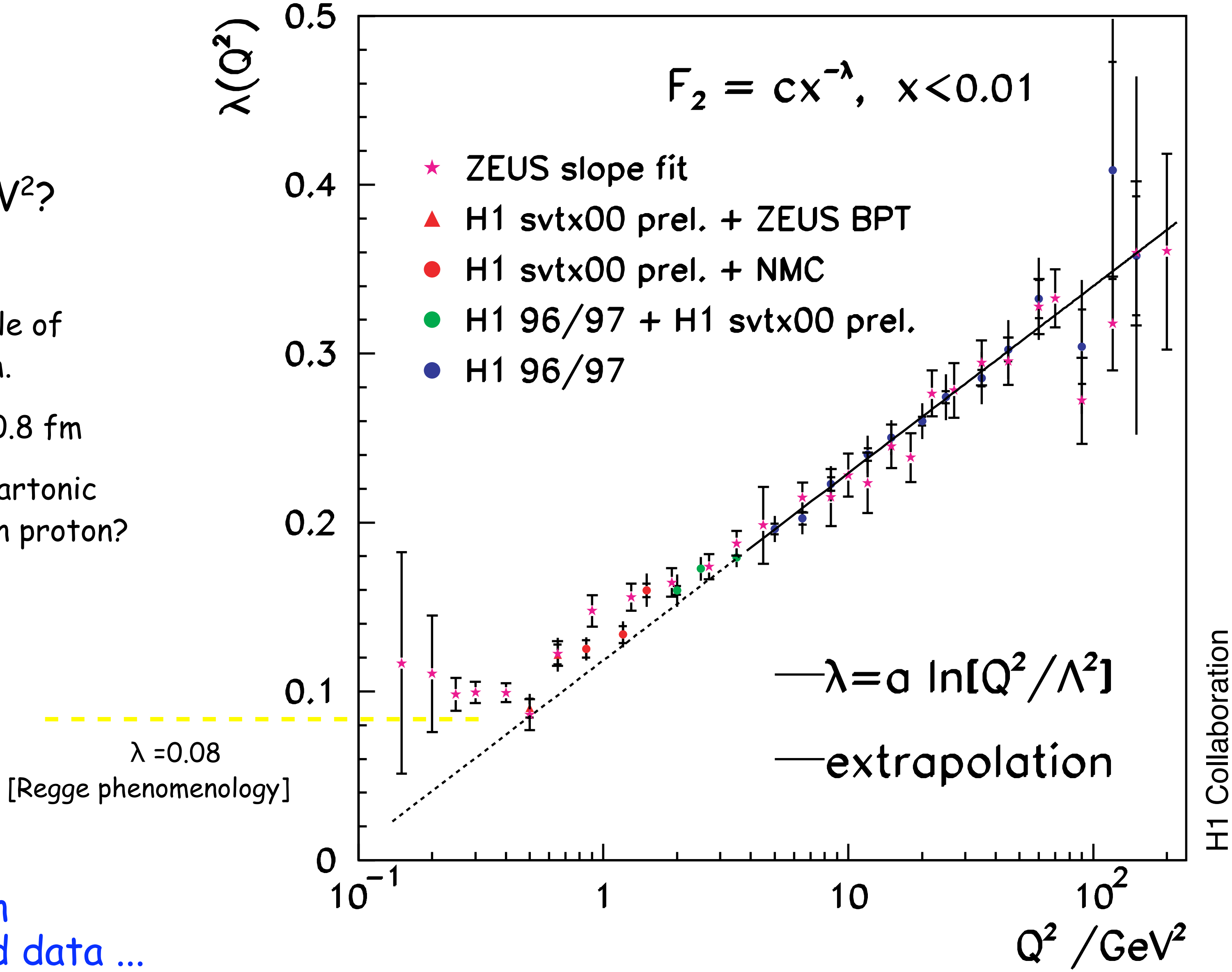
Q^2-Dependence of F_2-Slope

What happens
at Q^2 ~ 0.5 GeV^2?

corresponds to scale of
r ≈ –h/Q ≈ 0.3 fm.

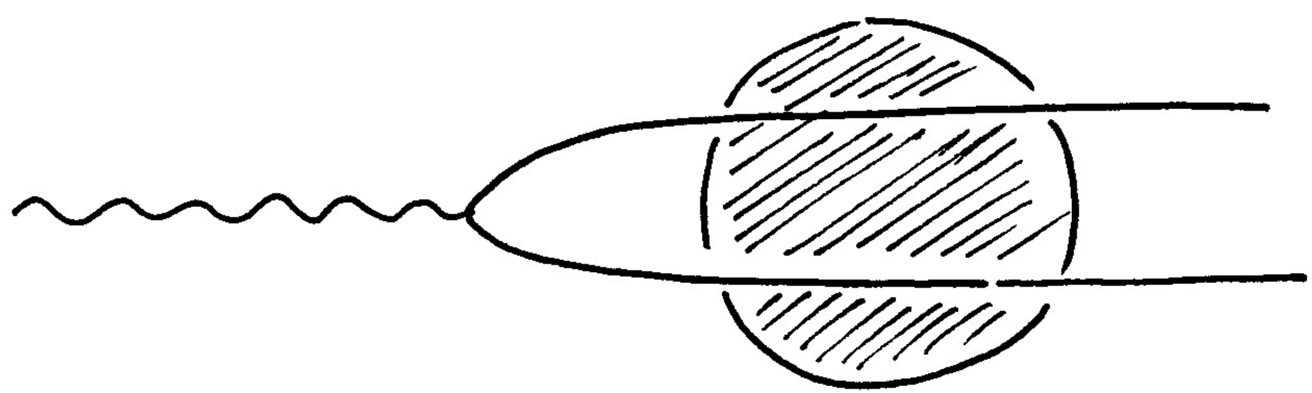
proton radius: r ≈ 0.8 fm

Evidence for non-partonic substructure within proton?

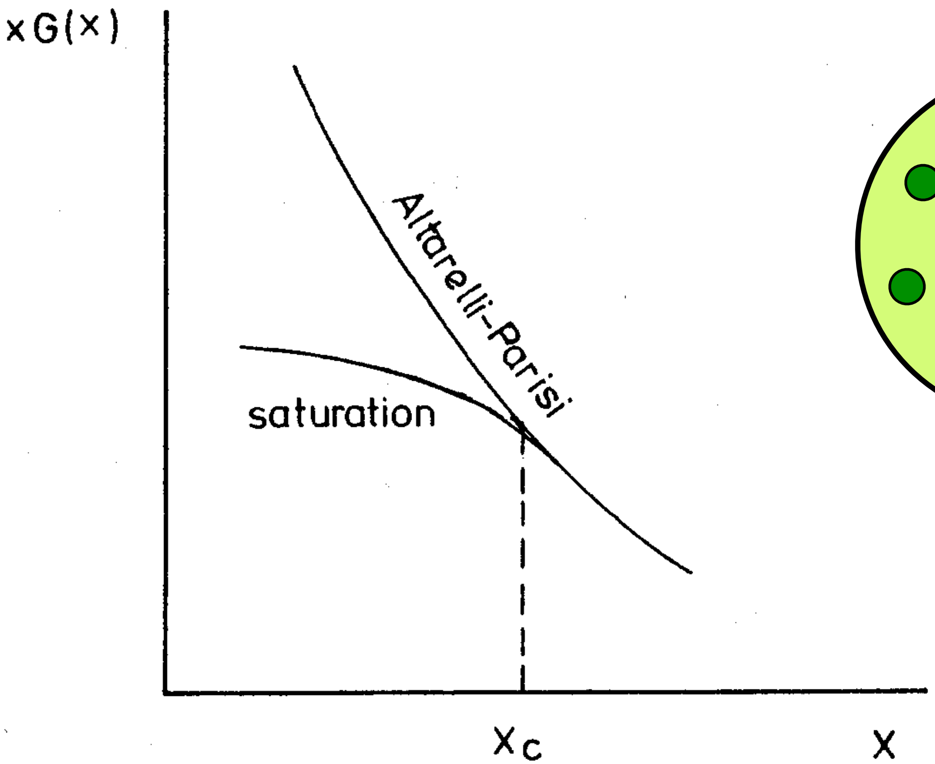


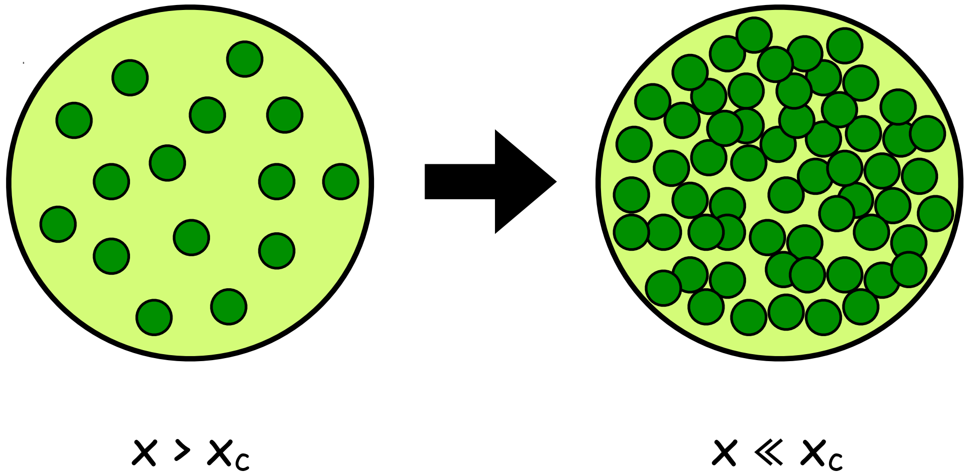
More precision
from combined data ...

From hard to soft physics
Do we see saturation?



Saturation





Expectation:

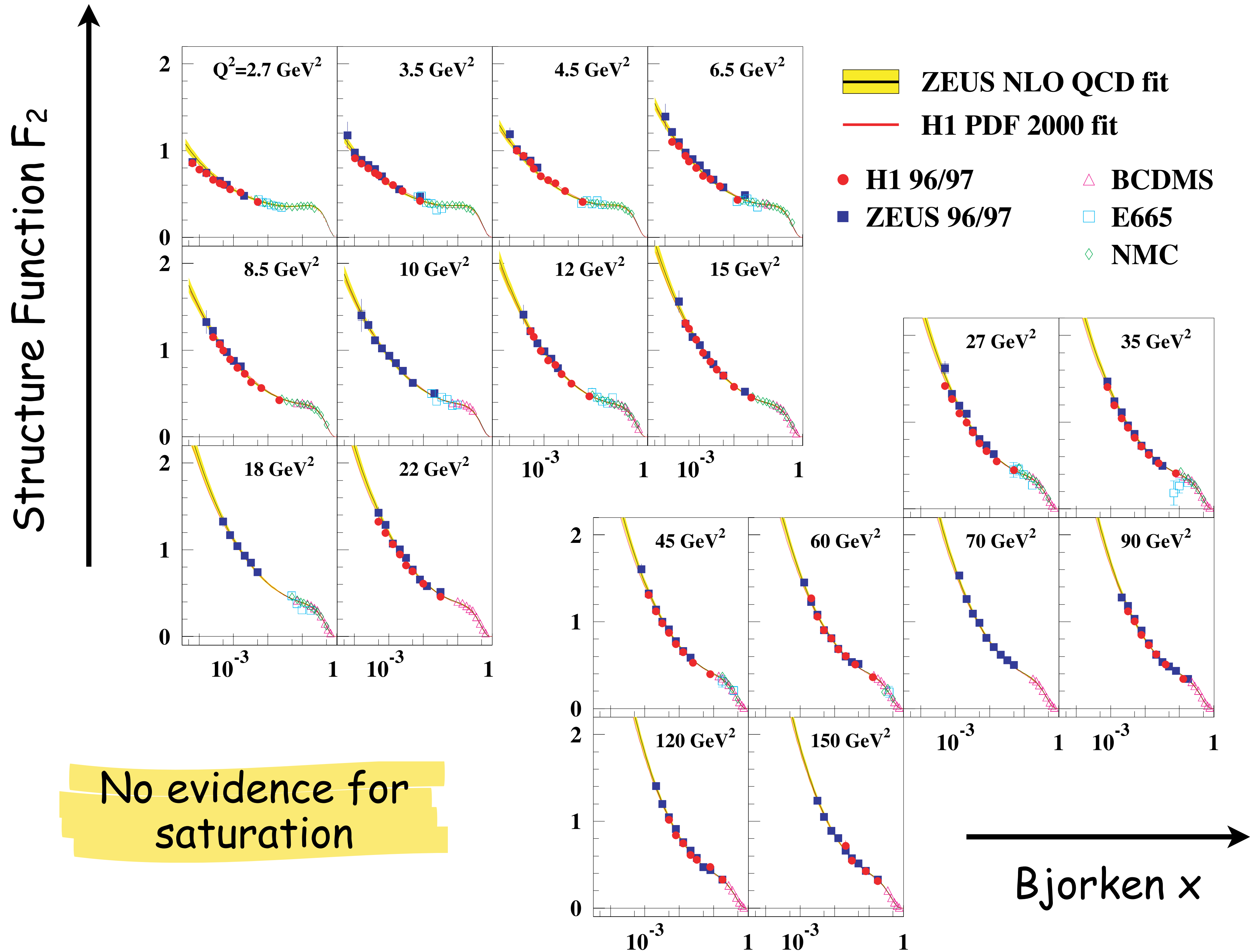
At some point number of gluons is so large that recombination becomes important

Unitarity consideration:

Rise towards small x has to stop somewhere

Possible observation:

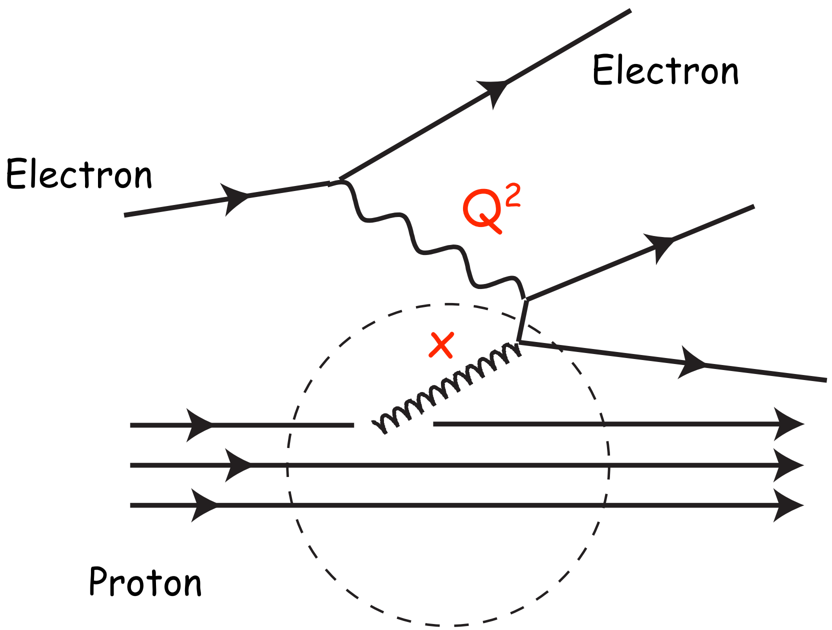
Taming of the rise of F_2 at low x



No evidence for saturation

ep-Scattering - Alternative Pictures

Infinite momentum frame

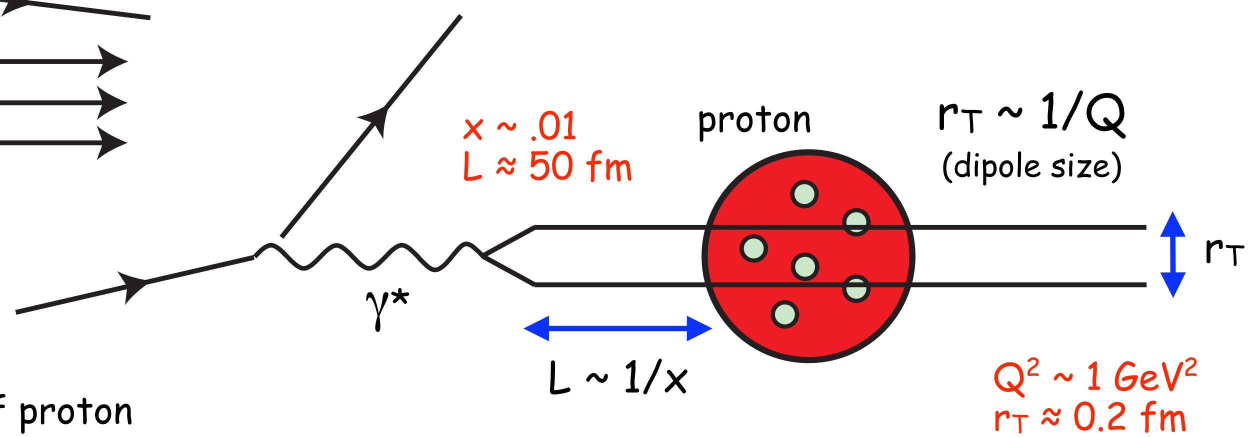


Electron interacts with quark of proton
Parton content described by F_2

Proton rest frame

A colour dipole of variable size $r_T \sim 1/Q$
interacts with the proton at high CM energy

$s^{\gamma p} = W^2 = Q^2/x$
[low x = high energy scattering!]



$$F_2(x,Q^2) = F_2(W^2,Q^2) \approx 4\pi\alpha^2 \cdot Q^2 \cdot \sigma^{\gamma^* p}(s^{\gamma p},Q^2)$$

The Saturation Model

Dipole model
γ^*p cross section
[for small x]

dipole proton x-section

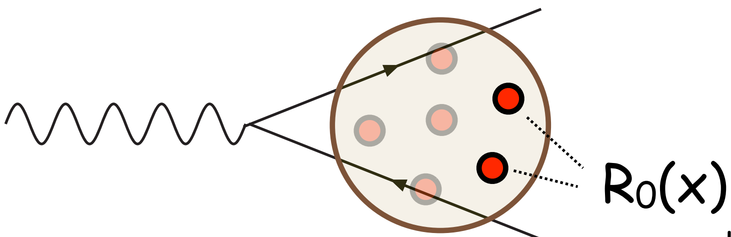
dipole wave function

$$\sigma_{T,L}^{\gamma^* p}(x,Q^2) \;=\; \int d^2r\, dz\;\; \psi^*_{T,L}(Q,r,z)\;\hat{\sigma}(x,r)\;\psi_{T,L}(Q,r,z)$$

Saturation model à la GBW:

$$\hat{\sigma}(x,r) \;=\; \sigma_0\,\left\{1 \,-\, \exp\left(-r^2/4R_0^2(x)\right)\right\}$$

$$R_0^2(x) \;=\; \frac{1}{\mathrm{GeV}^2}\,\left(\frac{x}{x_0}\right)^{\lambda}$$

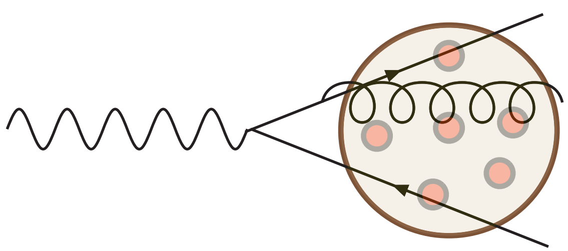


average gluon distance at which saturation sets in

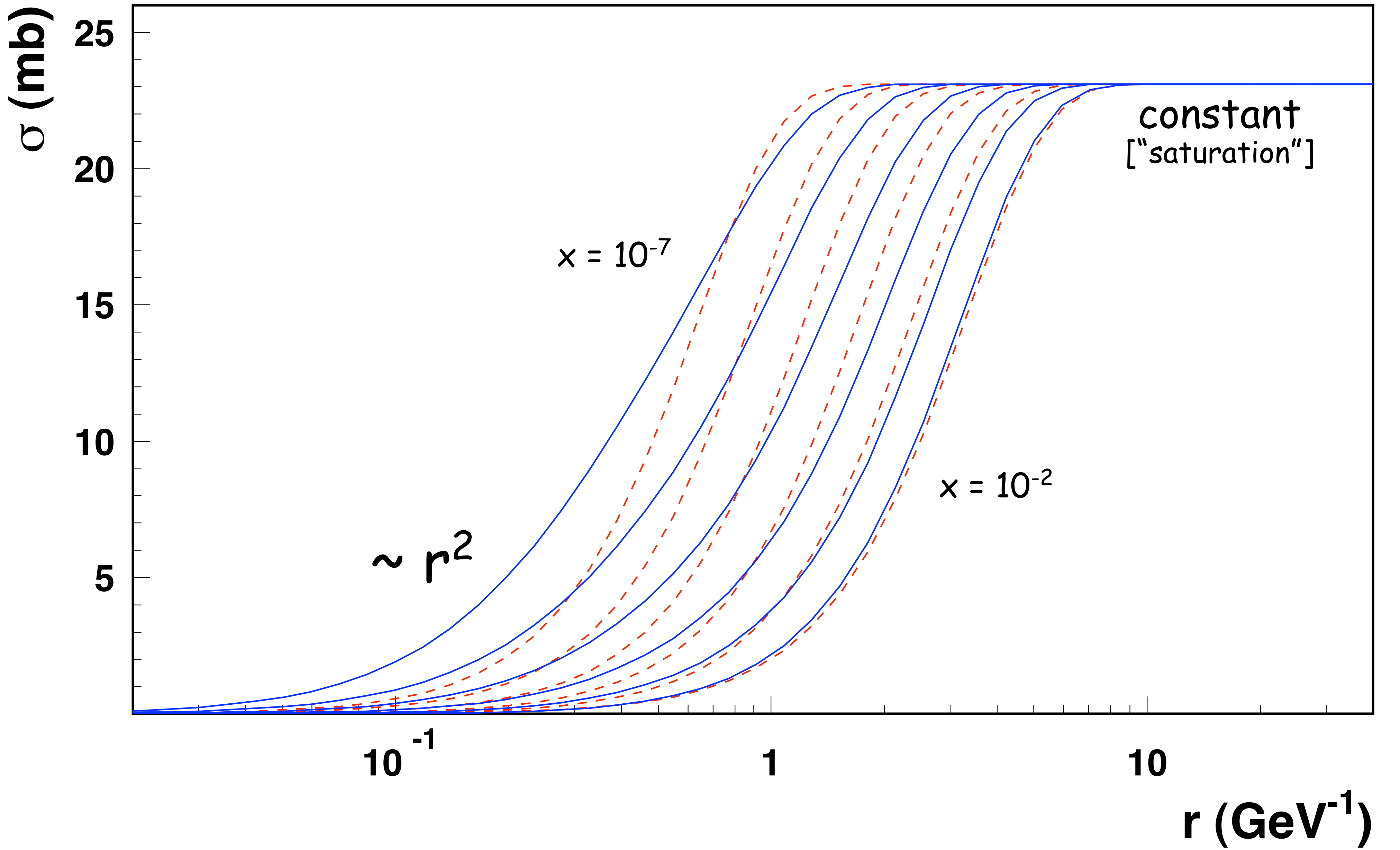
DGLAP [for small r]:

$$\left[\;\hat{\sigma}(x,r) \;\simeq\; \frac{\pi^2}{3}\, r^2\, \alpha_s\, xg(x,\mu^2)\;\right]$$

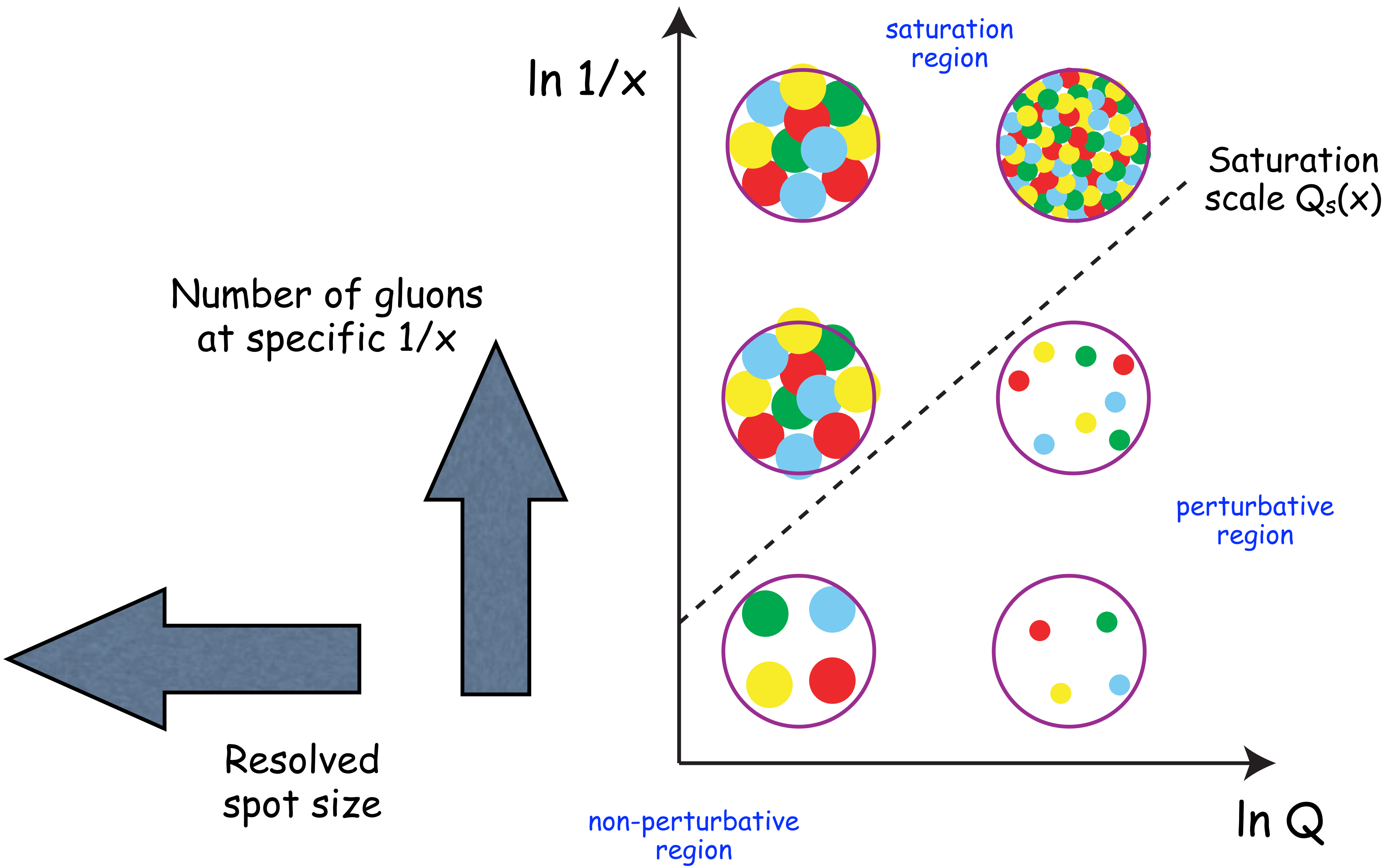
Saturation model including gluon evolution:

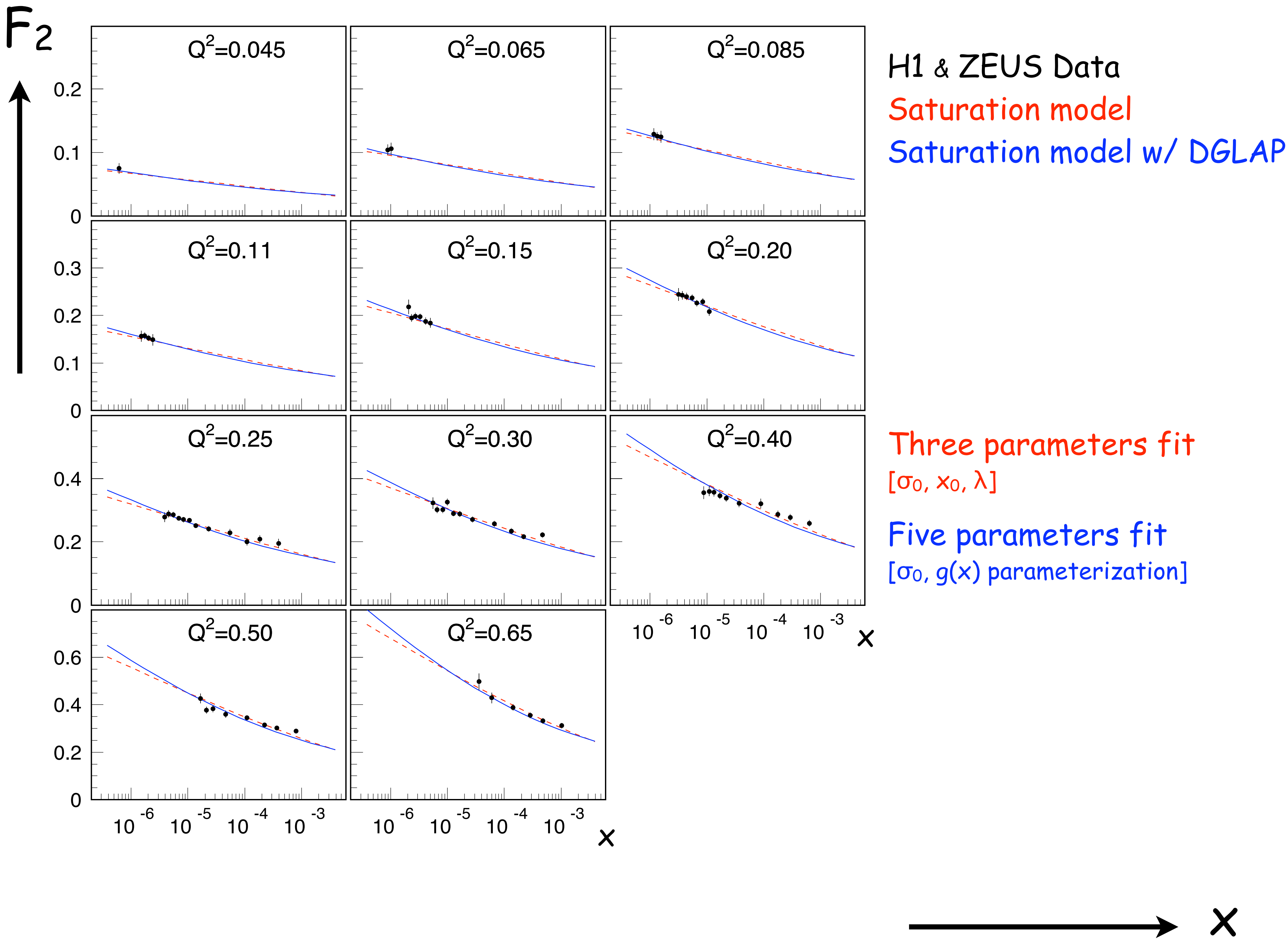


$$\hat{\sigma}(x,r) \;=\; \sigma_0\,\left\{1 \,-\, \exp\left(-\frac{\pi^2\, r^2\, \alpha_s(\mu^2)\, xg(x,\mu^2)}{3\,\sigma_0}\right)\right\}$$

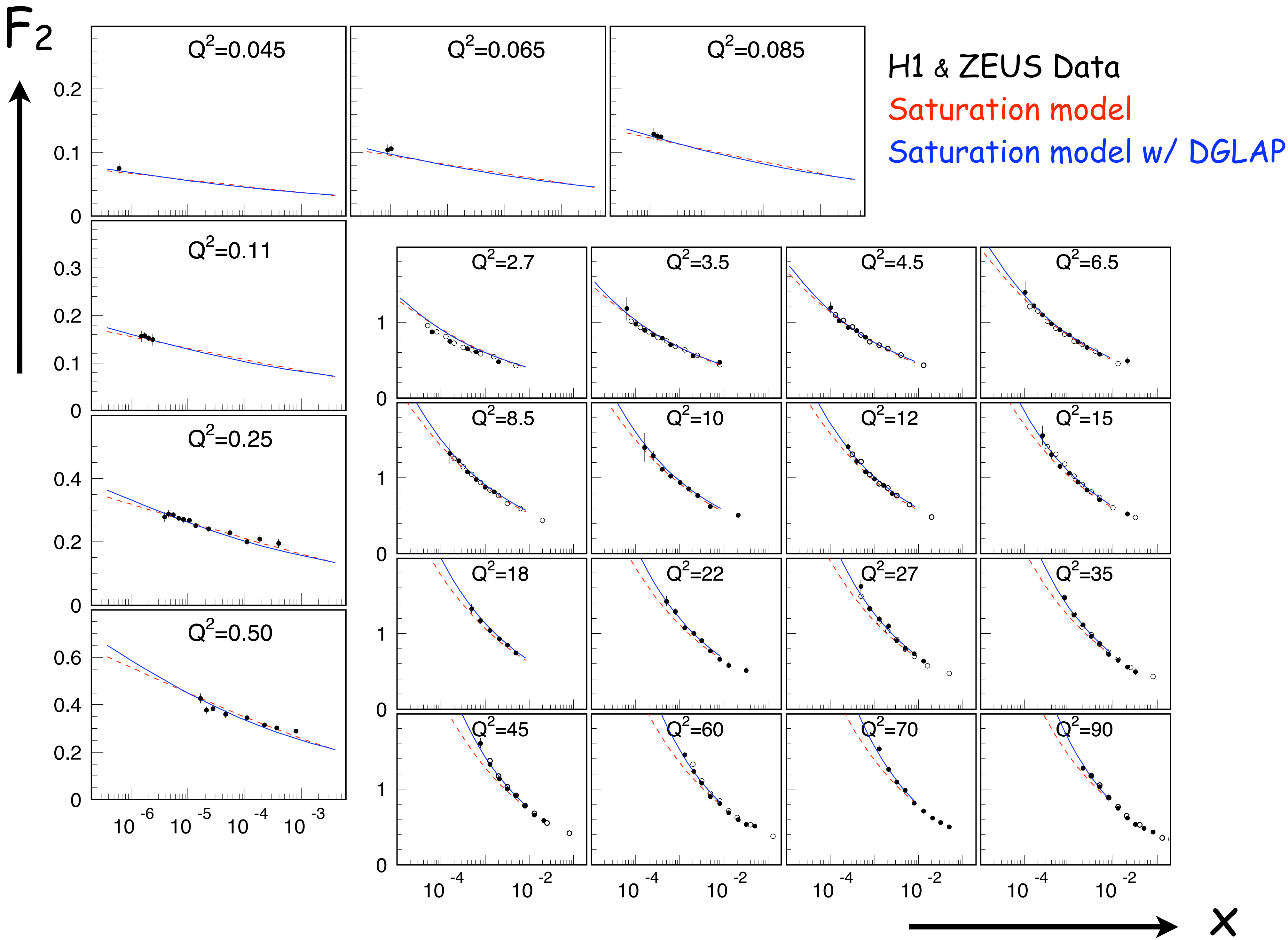

σ (mb)
25
20
15
10
5
10 -1
1
10
r (GeV-1)
constant
["saturation"]
x = 10-7
x = 10-2
~ r2

Parton Saturation

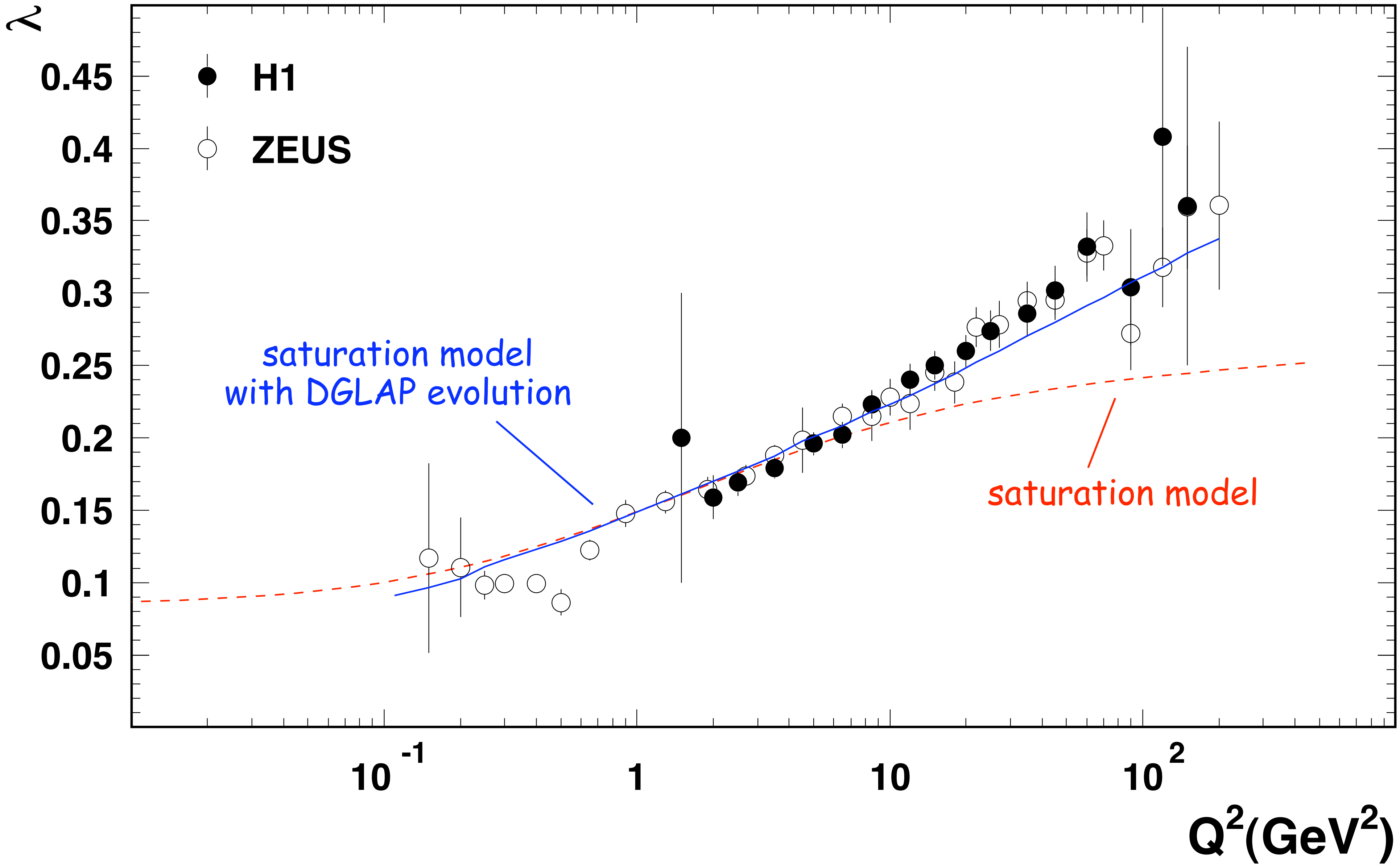




F2
Q2=0.045
Q2=0.065
Q2=0.085
Q2=0.11
Q2=0.15
Q2=0.20
Q2=0.25
Q2=0.30
Q2=0.40
Q2=0.50
Q2=0.65
H1 & ZEUS Data
Saturation model
Saturation model w/ DGLAP
Three parameters fit
[σ0, x0, λ]
Five parameters fit
[σ0, g(x) parameterization]
x

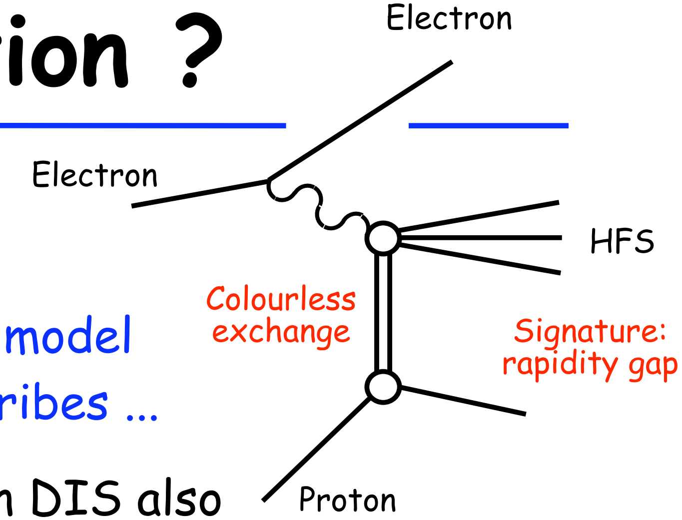


F2
H1 & ZEUS Data
Saturation model
Saturation model w/ DGLAP
Q2=0.045
Q2=0.065
Q2=0.085
Q2=0.11
Q2=0.25
Q2=0.50
Q2=2.7
Q2=3.5
Q2=4.5
Q2=6.5
Q2=8.5
Q2=10
Q2=12
Q2=15
Q2=18
Q2=22
Q2=27
Q2=35
Q2=45
Q2=60
Q2=70
Q2=90
x



Transition to soft physics described !

Do we see saturation ?

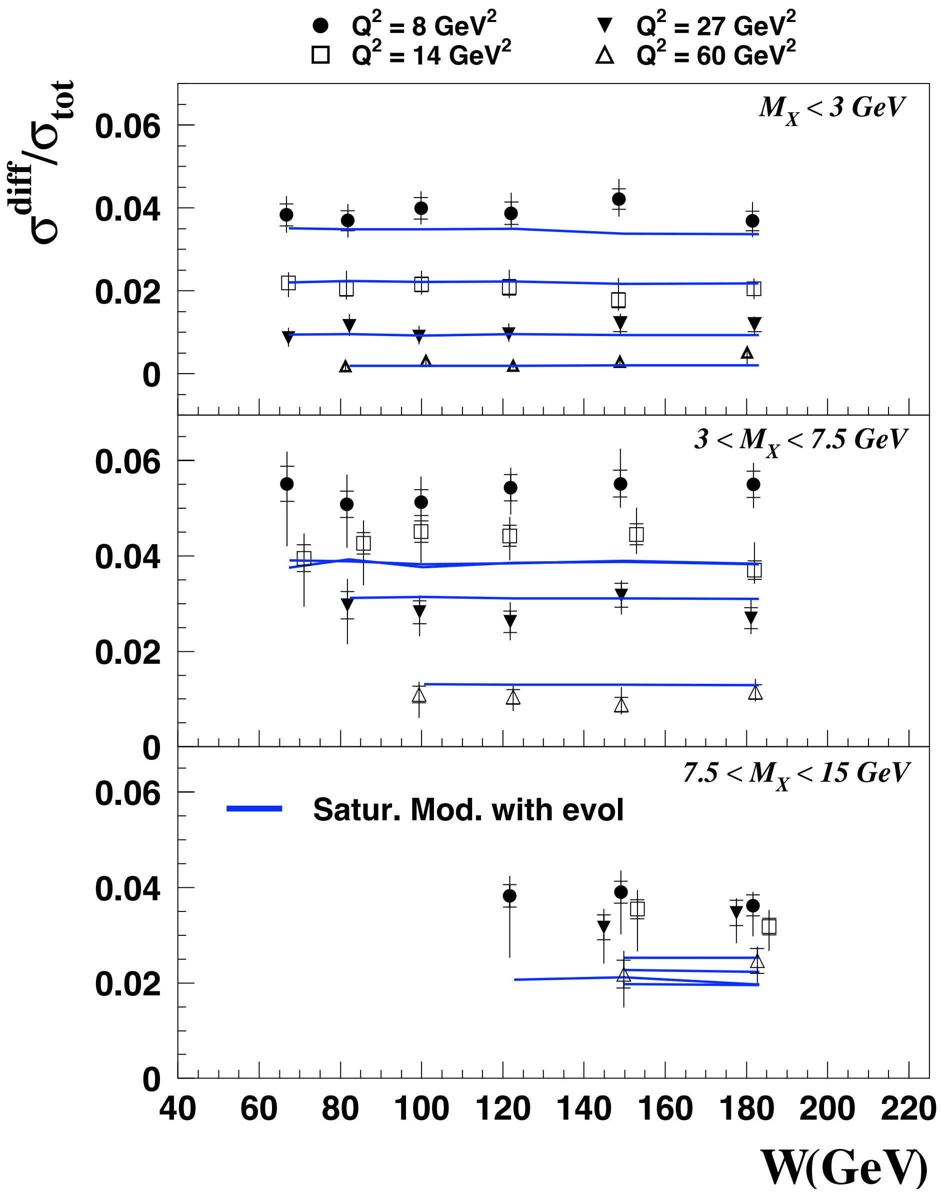


Dipole saturation model successfully describes ...

- describes F_2 in DIS also at small x and low Q2 (Fit!)
- predicts details of diffractive processes
- predicts diffractive DIS/DIS = constant
- ...

No proof of saturation, but ...

- several independent effects described
- very appealing
- also very much discussed also within Heavy Ion community (Color Glass Condensate)
- more theoretical work needed ...



Concluding Remarks

HERA provides the decisive information about
parton distributions, especially the gluon content of the proton

HERA has delivered data which guide theory to describe
low energy QCD, e.g. the transition from hard to soft physics

However, despite of large theoretical progress regarding
saturation, dynamic QCD evolution, understanding of diffraction ...

... low energy QCD is still not understood

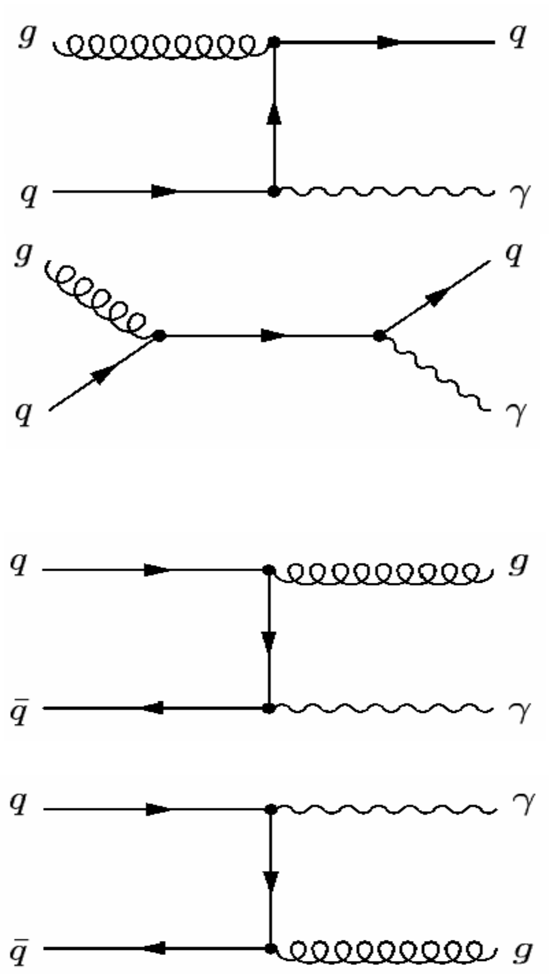
Epilogue

How to constrain PDFs at LHC

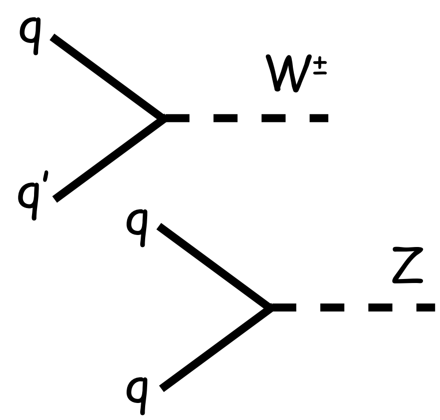
[some examples]

Vector Boson Production

Direct γ-production:



Singel W/Z production:

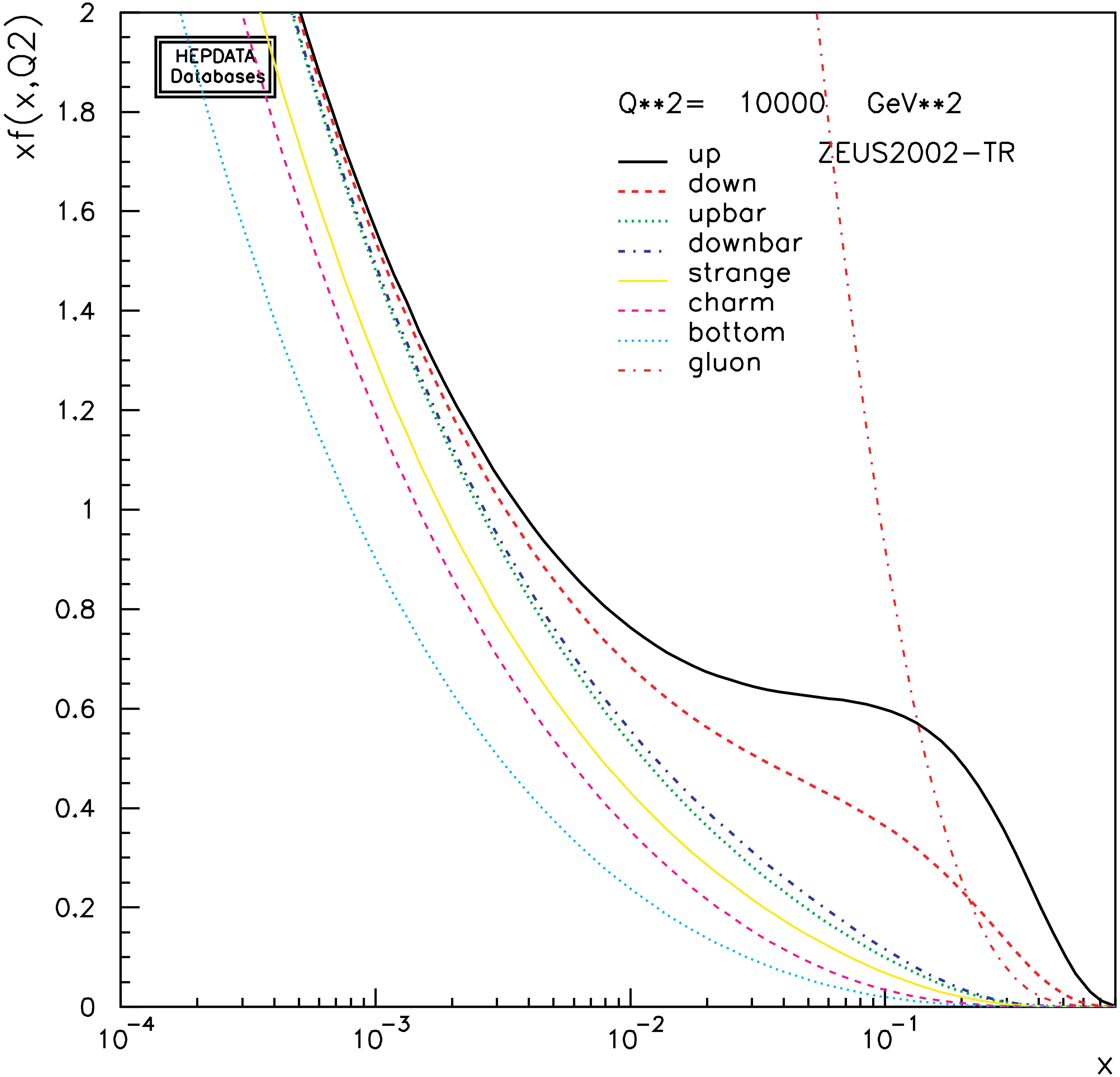


W production: (main contributions) $\begin{cases} u\bar{d} \to W^{+} \\ d\bar{u} \to W^{-} \end{cases}$

Z production: (main contributions) $\begin{cases} u\bar{u} \to Z \\ d\bar{d} \to Z \end{cases}$

- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty

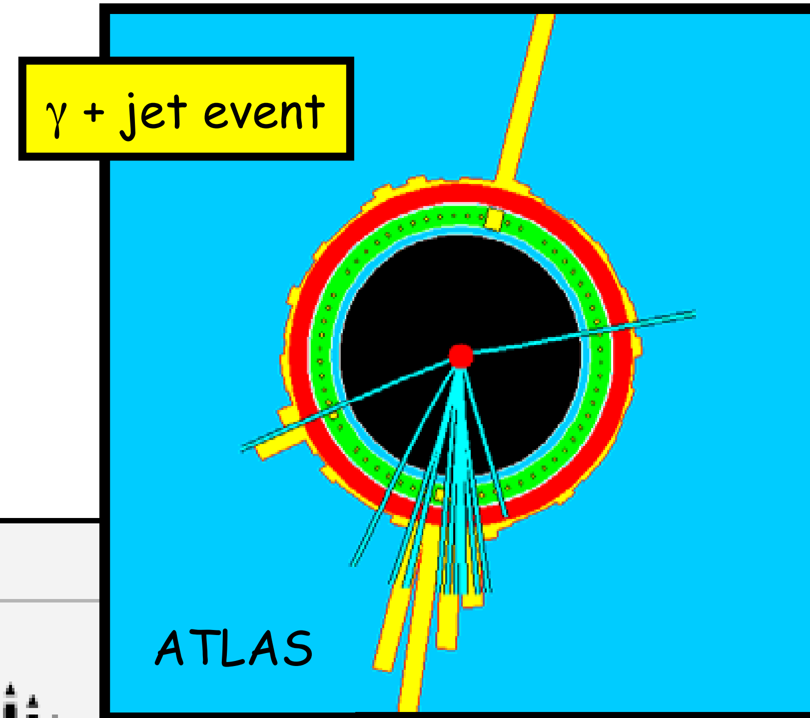
➥ Constraints on sea and gluon distributions

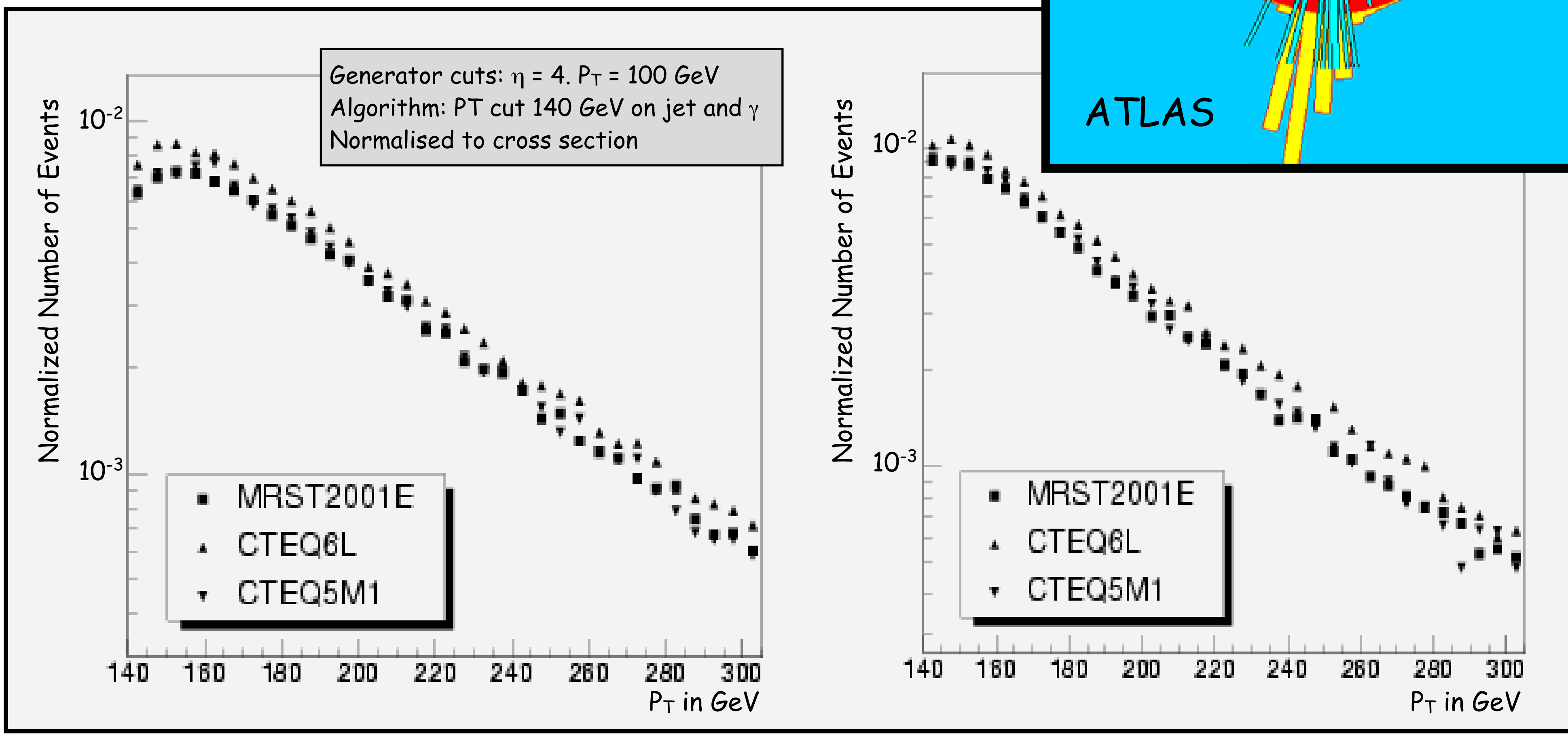


HEPDATA
Databases
Q**2= 10000 GeV**2
up
ZEUS2002-TR
down
upbar
downbar
strange
charm
bottom
gluon
xf(x,Q2)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

Direct γ Production

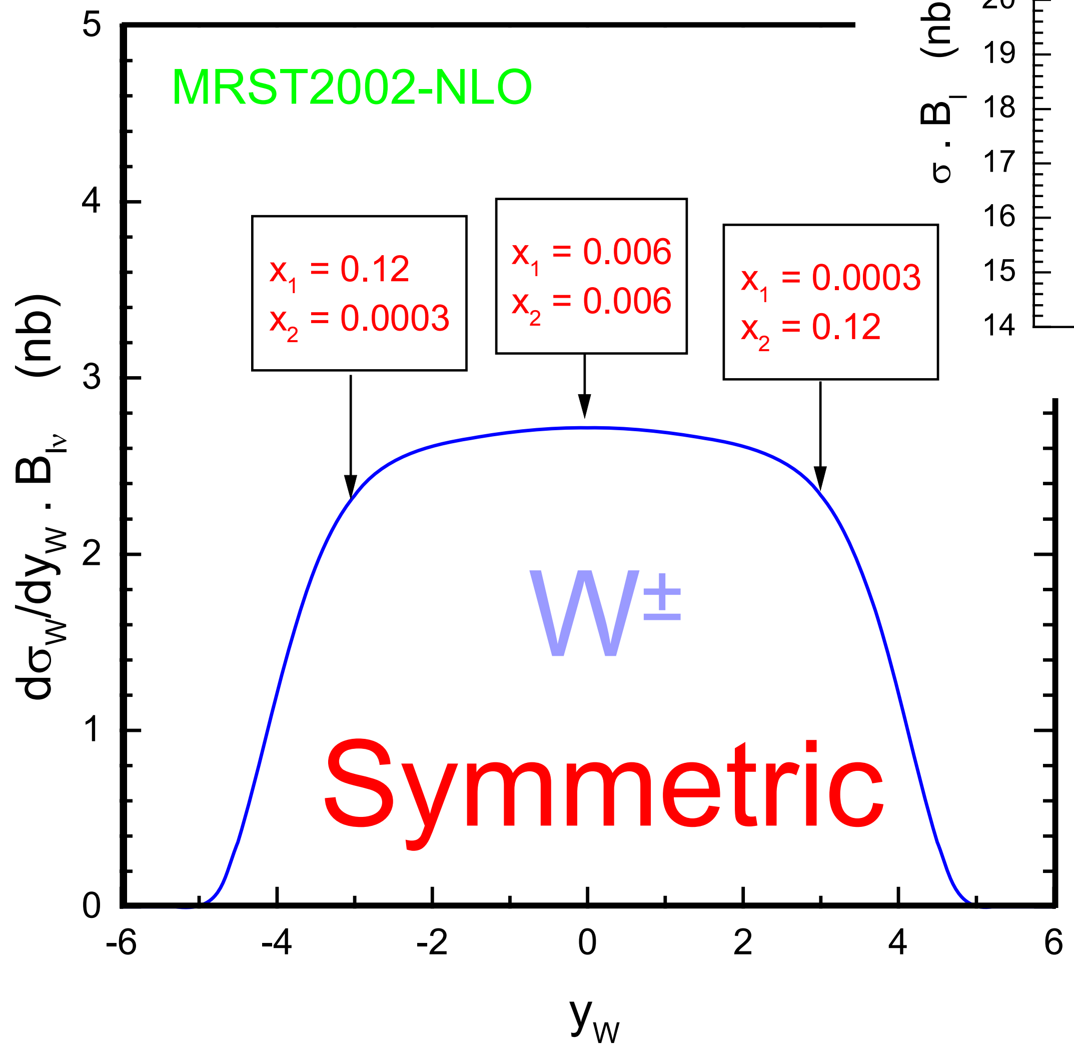
Sensitive to PDF differences
CTEQ - MRST: ± 16 -18 % disagreement
Needs good understanding of detector

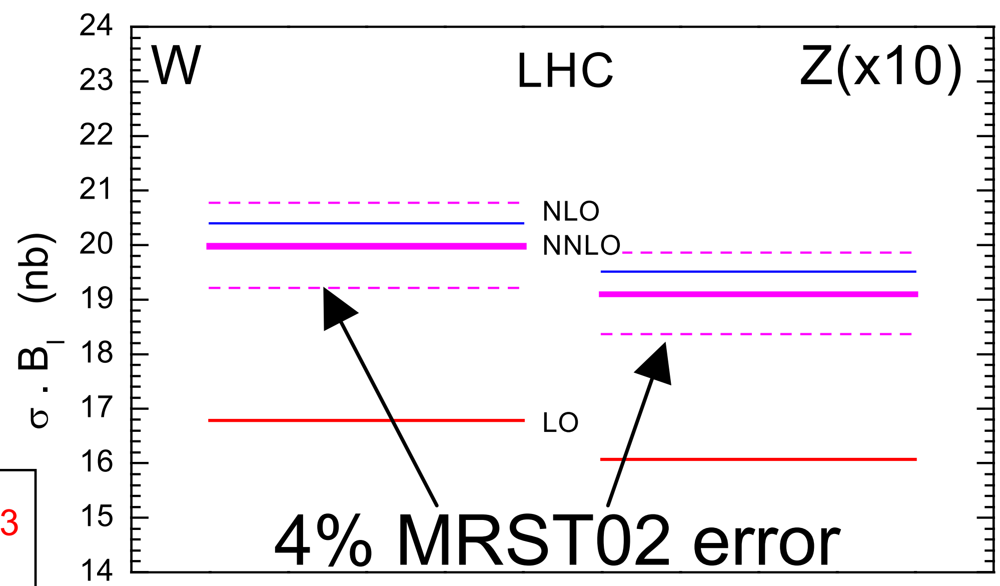




Single W and Z Production

W± rapidity distribution



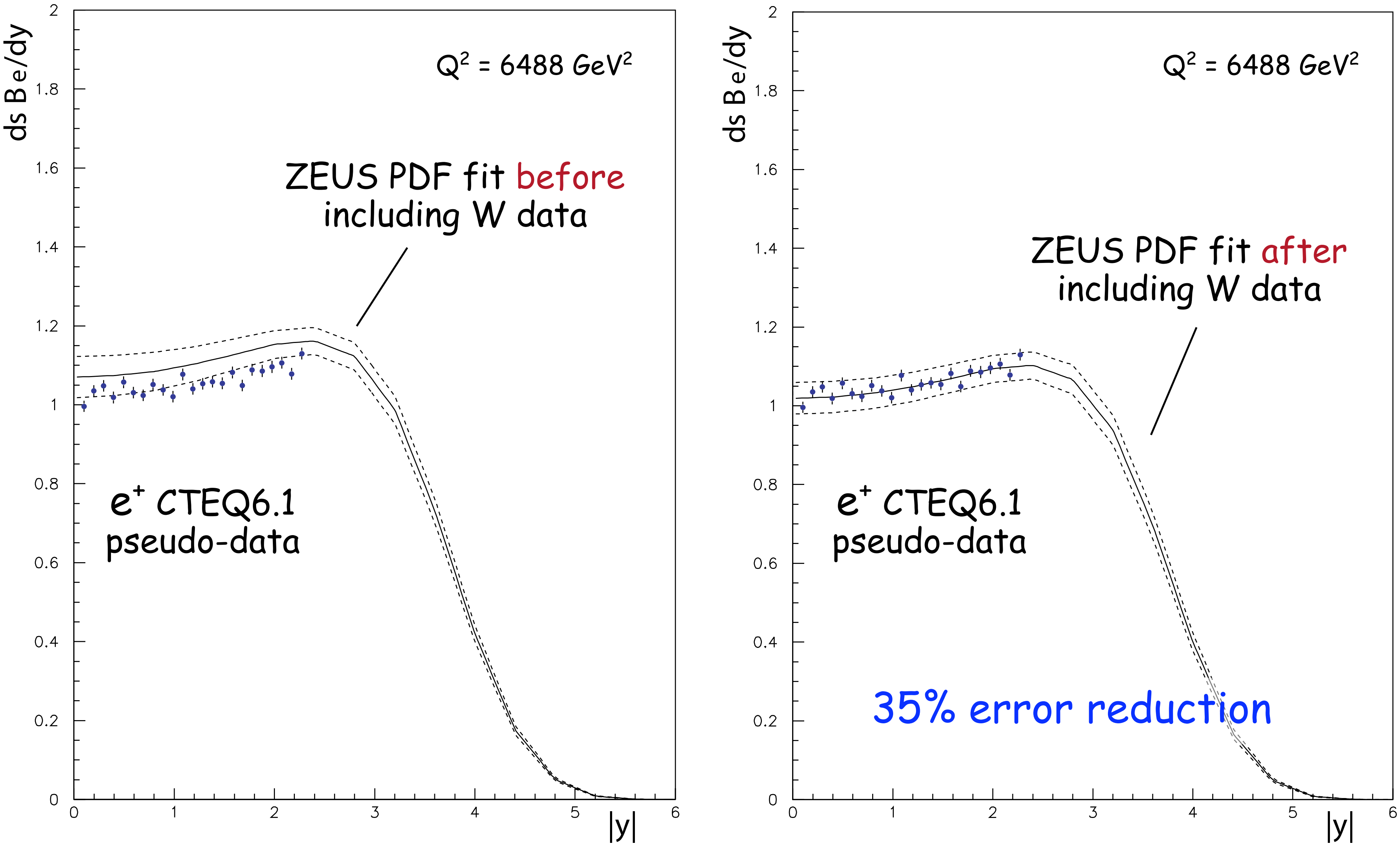


W± total cross section

Theoretical uncertainty dominated by PDFs

Extra input from LHC measurements

Effect on PDFs of LHC W data



Data Included in CTEQ Fits