Divonne, 1 September '08

Deep inelastic scattering in the LHC era

Guido Altarelli

Universita' di Roma Tre
and CERN

Deep Inelastic Scattering

$l + N \to l' + X, \qquad l = e, \mu, \nu$

- Many structure functions
- $F_i(x,Q^2)$: two variables
- Neutral currents, charged currents
- Different beams and targets
- Different polarization

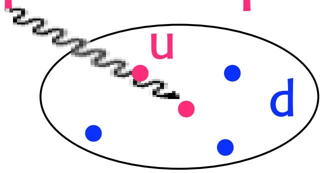
A fundamental role in the development of QCD:

from the beginning: Establishing quarks and gluons as partons
Constructing a field theory of strong int.ns
along the years: Quantitative testing of QCD
Totally inclusive
QCD theory of scaling violations crystal clear
(based on ren. group and operator exp.)
Q^2 dependence tested at each x value)
Measuring q and g densities in the nucleon
Instrumental to compute all hard processes
Measuring α_s
Always presenting new challenges:
Structure functions at small x
Polarized parton densities

In the '70's a great role in establishing QCD

- Approximate Scaling
- Success of Naive Parton Model Bjorken, Feynman

From constituent quarks (real? fictitious?) to parton quarks (real!)



- R= σ_L/σ_T ---> 0 Spin 1/2 quarks
- ~50% of momentum carried by neutrals Gluons
- Quark charges:

$F=2F_1 \sim F_2/x$ $\sigma_L \sim 0$

...... = small sea

$F\gamma p = 4/9\ u(x) + 1/9\ d(x) + \ldots\ldots$

$F\gamma n = 4/9\ d(x) + 1/9\ u(x) + \ldots\ldots$

$F\nu p \sim F\bar{\nu}n = 2\ d(x) + \ldots\ldots$

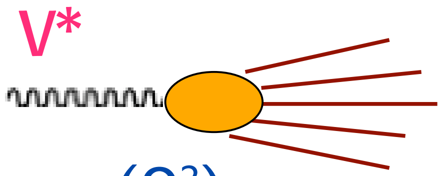
$F\nu n \sim F\bar{\nu}p = 2\ u(x) + \ldots\ldots$

$$\int (u-\bar{u})dx = 2$$

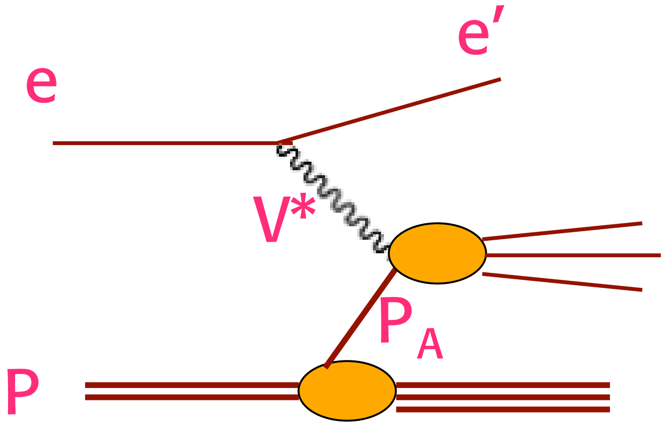
$$\int (d-\bar{d})dx = 1$$

$$\int (s-\bar{s})dx = 0$$

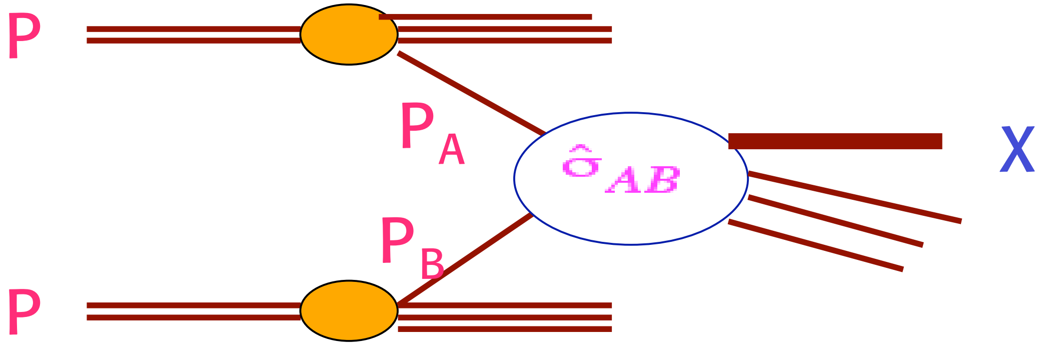
F= F(x), u=u(x), d= d(x):
naive parton model (scaling)



$\alpha_s(Q^2)$



$\alpha_s(Q^2)$ & $q(x,Q^2)$, $g(x,Q^2)$



The basic experimental set ups:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (....SppS, Tevatron, LHC)

Progress in particle physics needs their continuous interplay to take full advantage of their complementarity

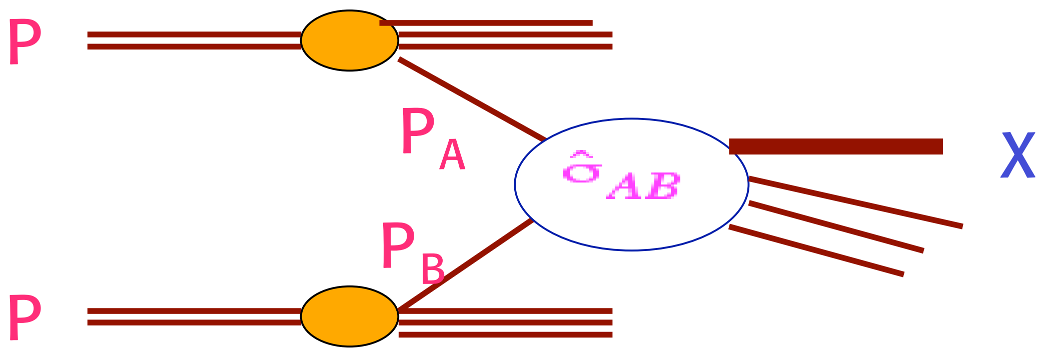
Parton densities extracted from DIS are used to compute hard processes, via the Factorisation Theorem:

x times density of parton A

$$\sigma(s) = \sum_{A,B} \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} p_A(x_1,Q^2) p_B(x_2,Q^2) \hat{\sigma}_{AB}(x_1 x_2 s, Q^2)$$

reduced X-section

For example, at hadron colliders



V=γ*,W,Z

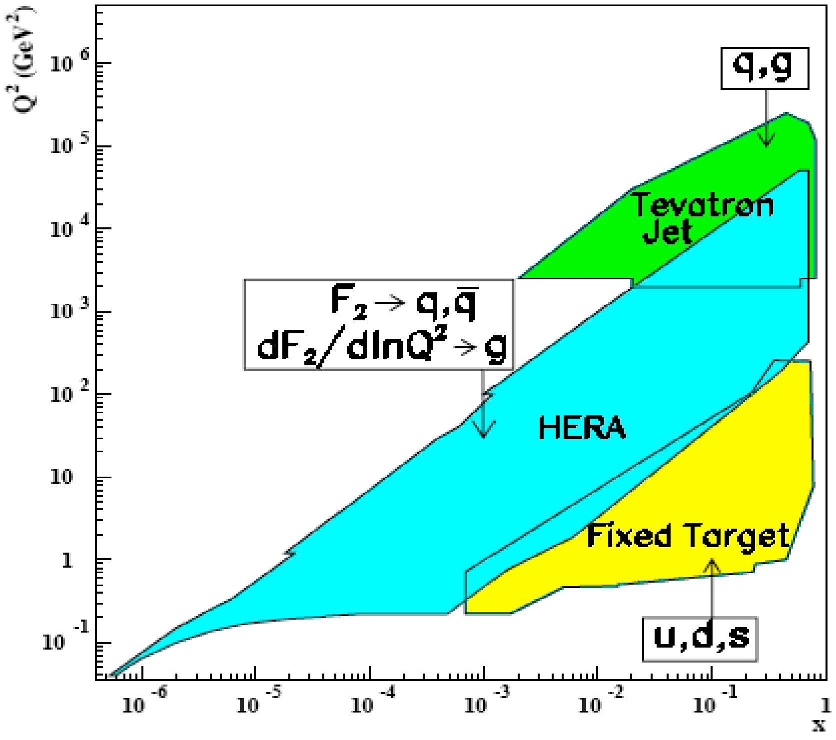
X=V, jets, QQ, H.....

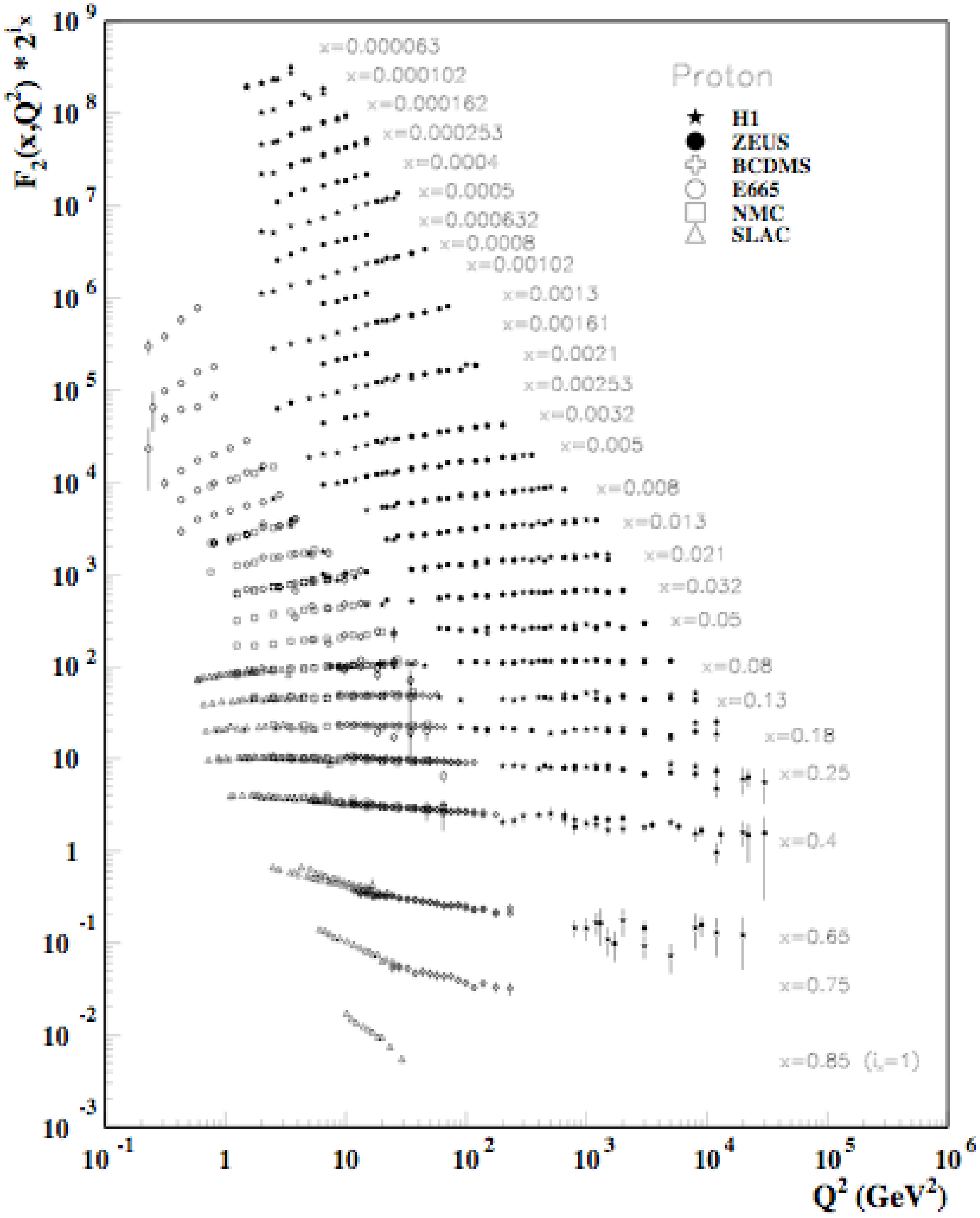
Q=b,c,t

- Very stringent tests of QCD
- Feedback on constraining parton densities

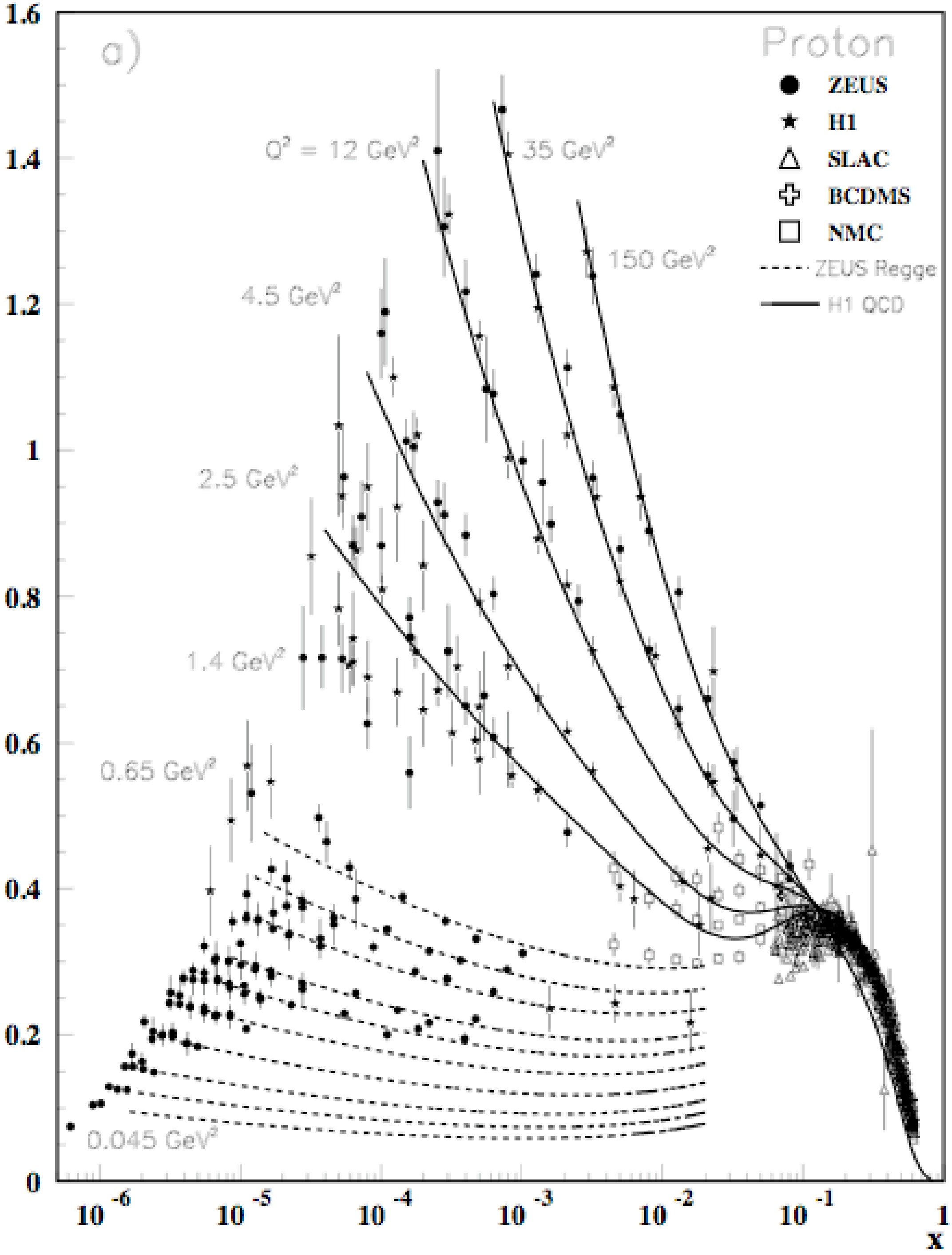
Great progress in the DIS data culminated at HERA

Proton Structure Function $F_2(x,Q^2)$





$F_2(x,Q^2)$ proton



Progress in experiment has been matched by impressive achievements in theory

For example in the theory of scaling violations

The scaling violations are clearly observed
and the (N)NLO QCD fits are remarkably good.

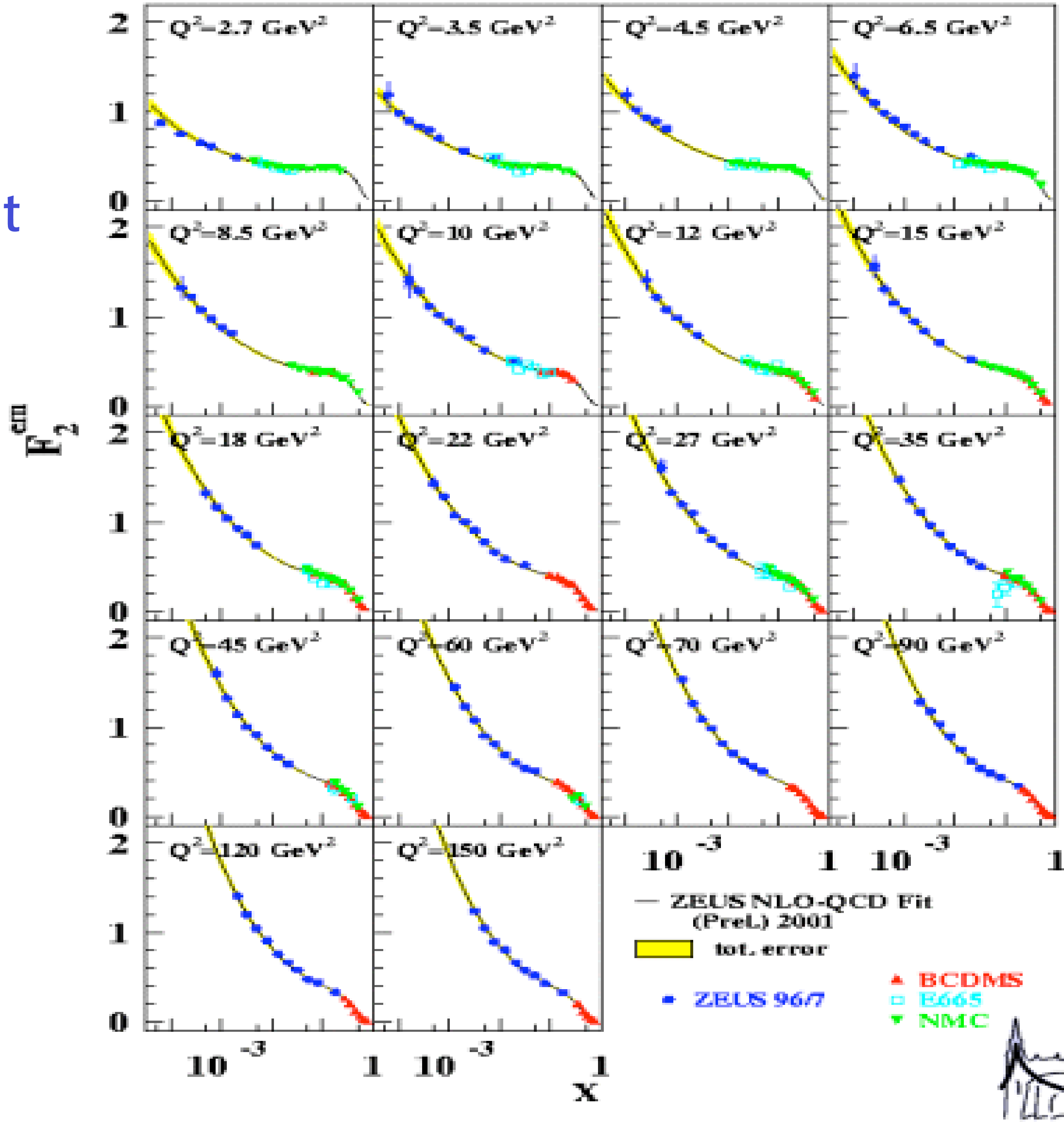
These fits to $F_i(x,Q^2)$ provide

- an impressive set of QCD tests
- measurements of $q(x,Q^2)$, $g(x,Q^2)$
- measurements of $\alpha_s(Q^2)$

$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{q_iq_j}(y,\alpha_S)q_j(\frac{x}{y},Q^2)\ +\ P_{q_ig}(y,\alpha_S)g(\frac{x}{y},Q^2)\right\}$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq_j}(y,\alpha_S)q_j(\frac{x}{y},Q^2)\ +\ P_{gg}(y,\alpha_S)g(\frac{x}{y},Q^2)\right\}$$

Example of NLO QCD evolution fit



Incr.
Q^2

Splitting functions stimulated the development of the most advanced computational techniques over the years

For over a decade all splitting funct.s P have been known to only NLO accuracy: $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + ...$

Floratos et al; Gonzales-Arroyo et al; Curci et al; Furmanski et al

Then the complete, analytic NNLO results have been derived for the first few moments (N<13,14).

Larin, van Ritbergen, Vermaseren+Nogueira

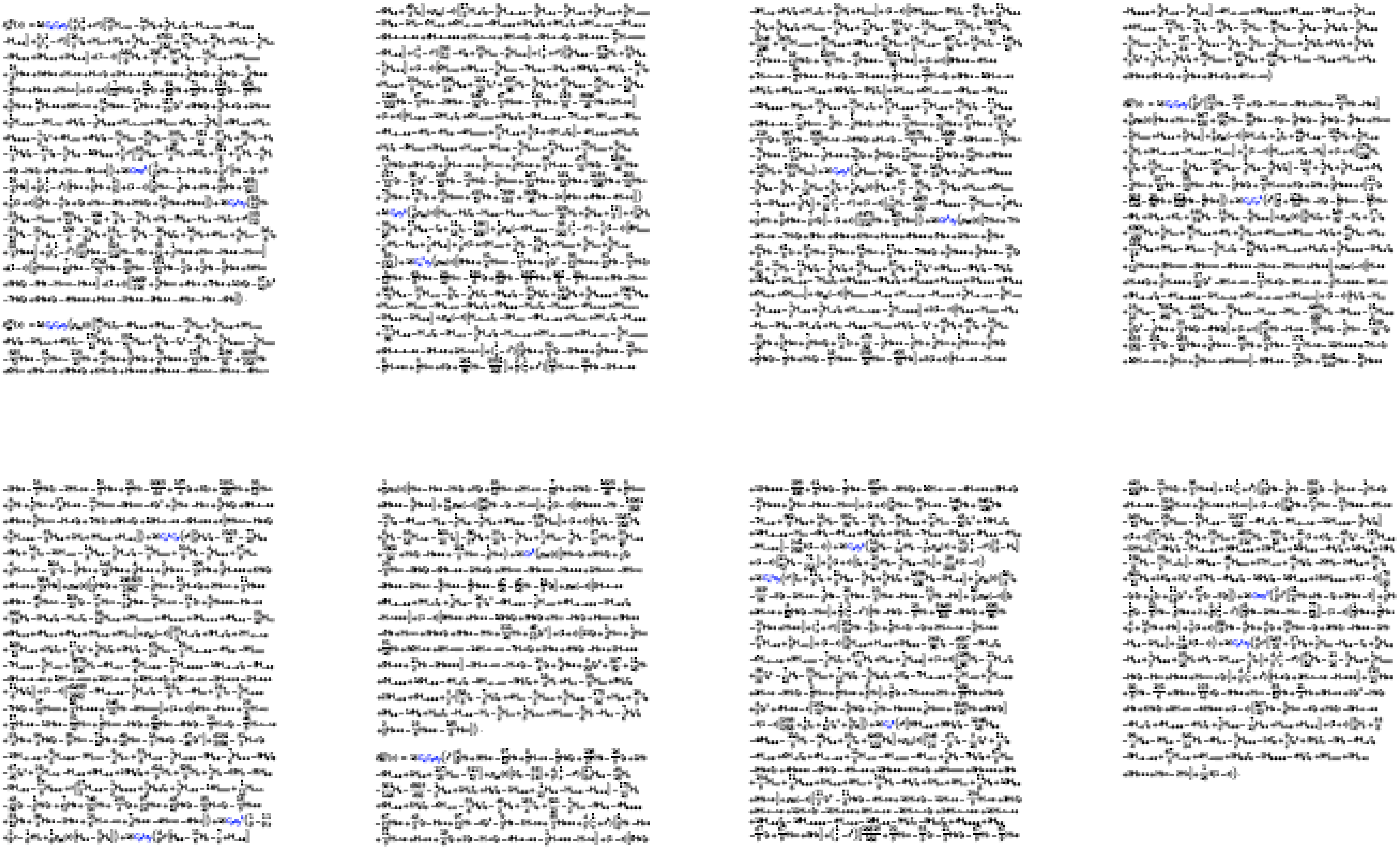
Finally, in 2004, the calculation of the NNLO splitting functions has been totally completed $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + \alpha_s^3 P_3 + ...$

Moch, Vermaseren, Vogt ‘04

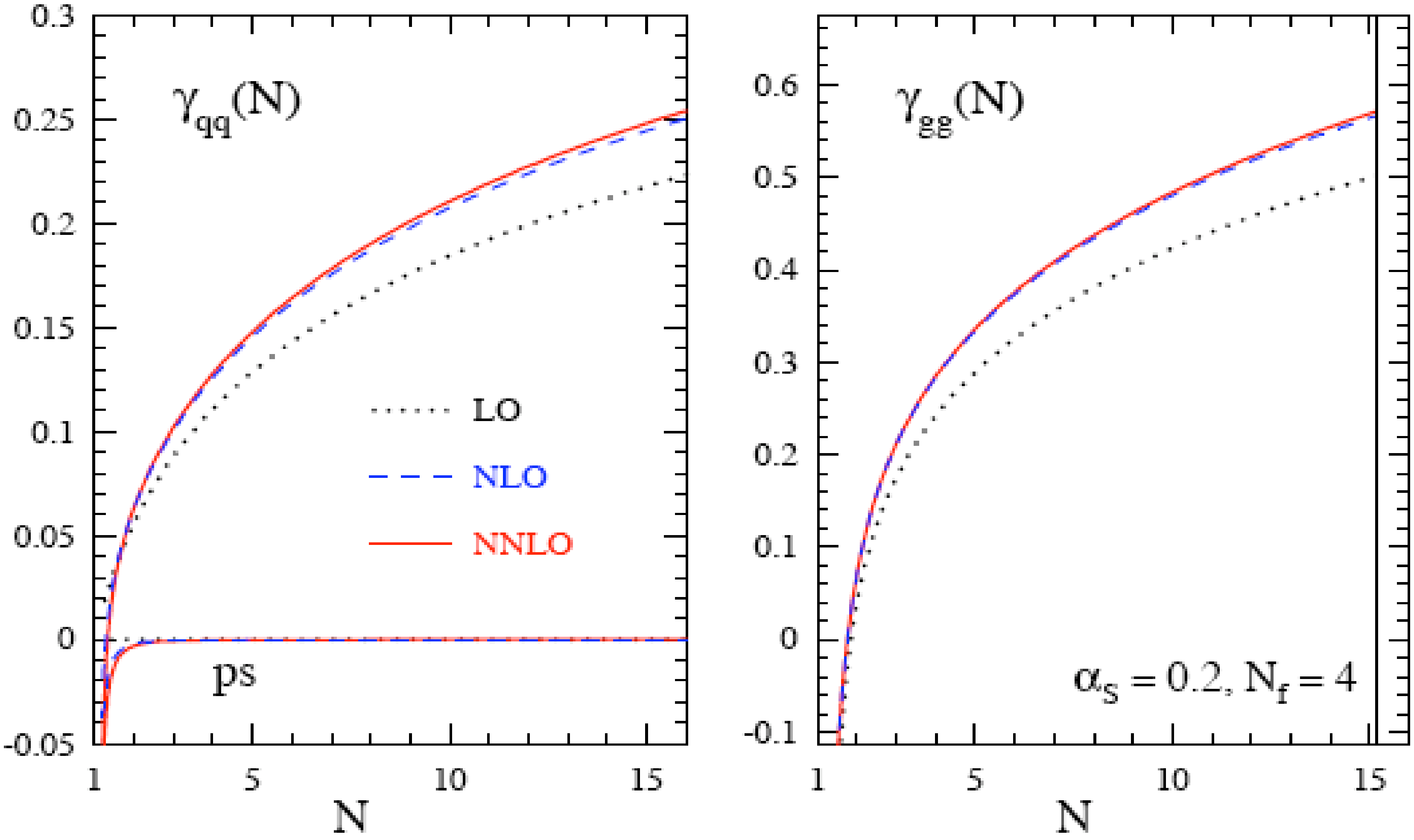
⊕ A really monumental, fully analytic, computation

NNLO singlet splitting functions   A completely analytical result

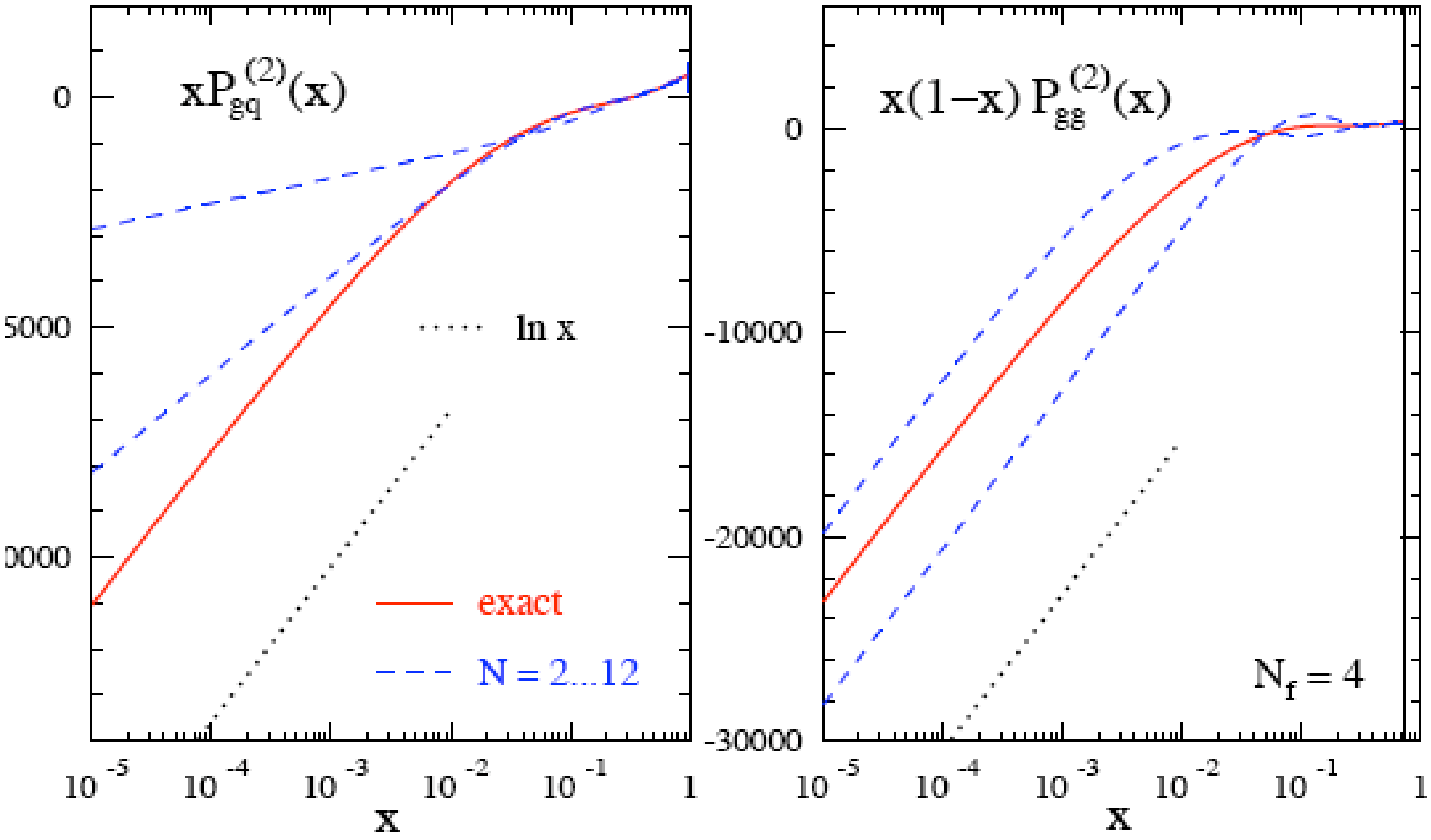
Moch, Vermaseren, Vogt '04



Anomalous dimensions vs N, the Mellin index



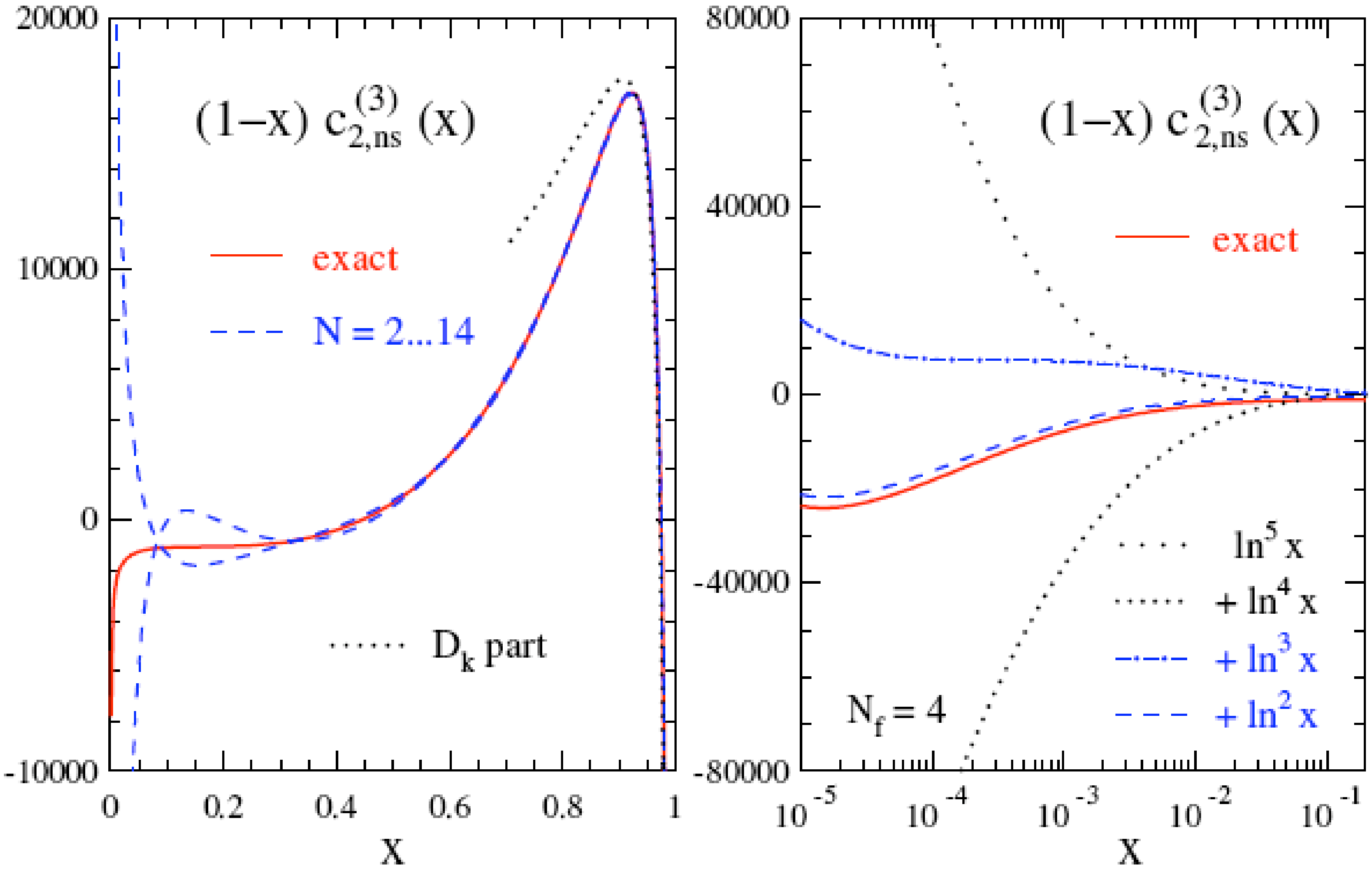
Good convergence is apparent



- Exact result, estimates from fixed moments and leading small-x term
- Splitting function $P_{gq}^{(2)}$ (left) and $P_{gg}^{(2)}$ (right)

Also the α_s^3 coefficient functions are known

Moch, Vermaseren, Vogt '05



- (eg the NNLO calculation of F_L completed)

LHeC

70 GeV $e^{\pm}$ <--> 7 TeV p -----> $2E_{CM} \sim 1.4$ TeV

compare with HERA $2E_{CM} \sim 0.3$ TeV

Luminosity ~ 10^{33} $cm^{-2}s^{-1}$ (3-30 fb^{-1} per year)

HERA ~ 0.12-0.3 fb^{-1} per year

γ of eP system: $\gamma \sim E/m_{eP} \sim 5$

HERA ~ $\gamma \sim 2.7$

$e^{\pm}$ polarization possible

Simultaneous running of eP with PP or eA with AA

What is the price in Euros or Sfr?

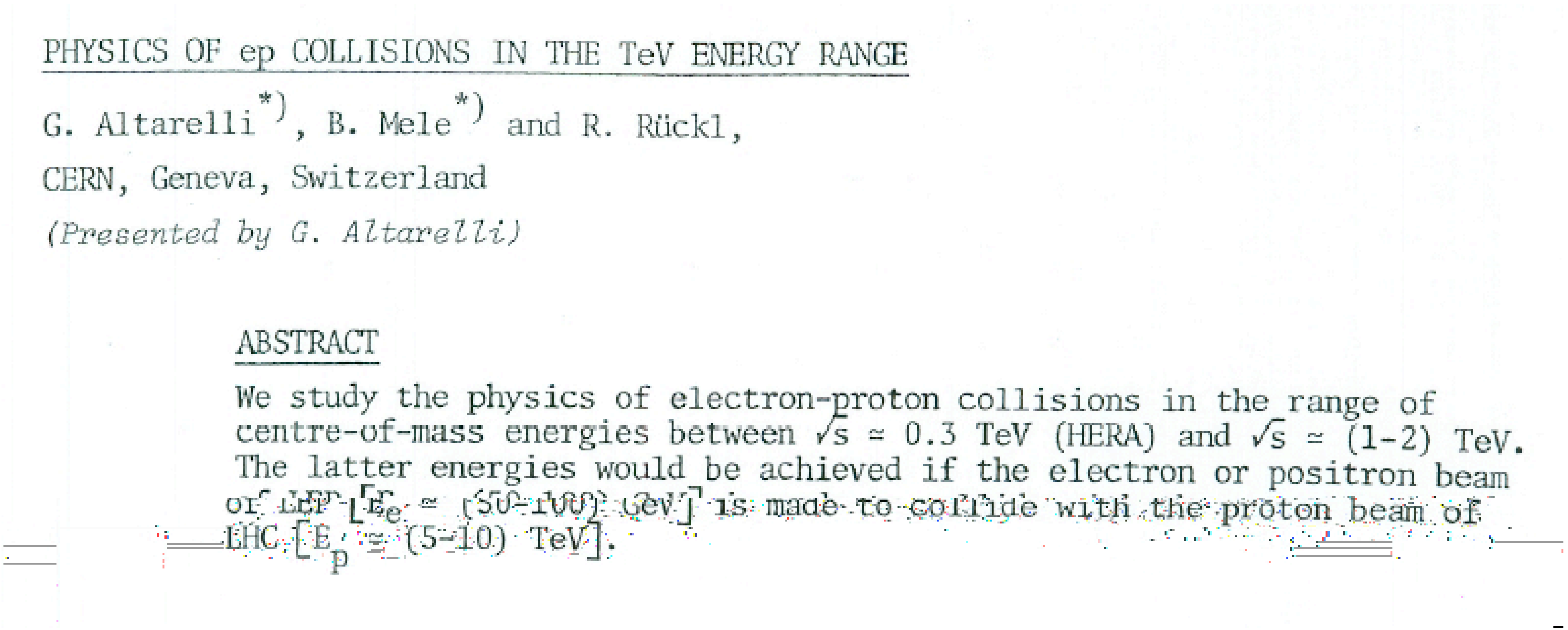
We are only discussing the physics here.

But in the end the balance between cost and benefit will be very essential .

The eP option was present since the beginning of the LHC

ECFA-CERN Workshop
Large Hadron Collider in the LEP Tunnel
Lausanne March ‘84

Published in CERN-ECFA Wkshp.1984:0549 (QCD183:E2:1984)

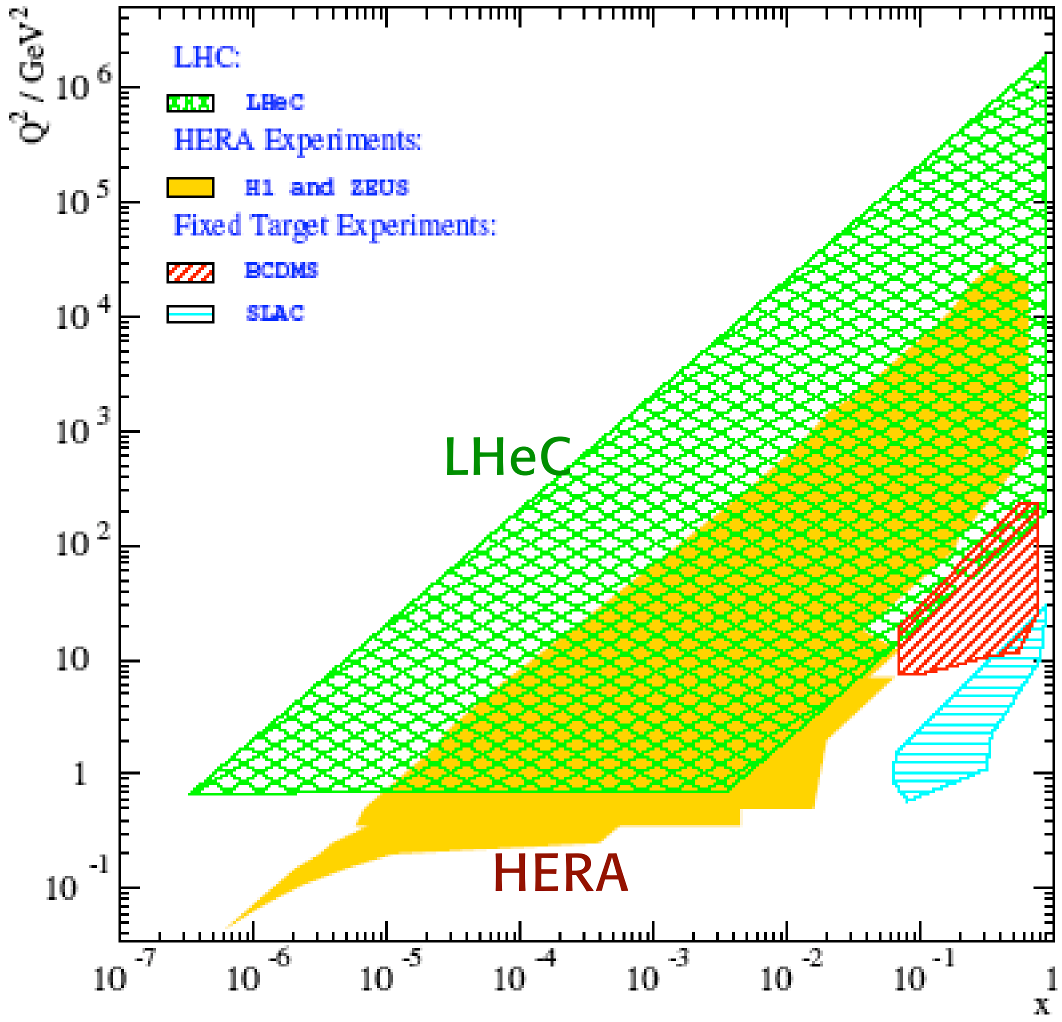


PHYSICS OF ep COLLISIONS IN THE TeV ENERGY RANGE

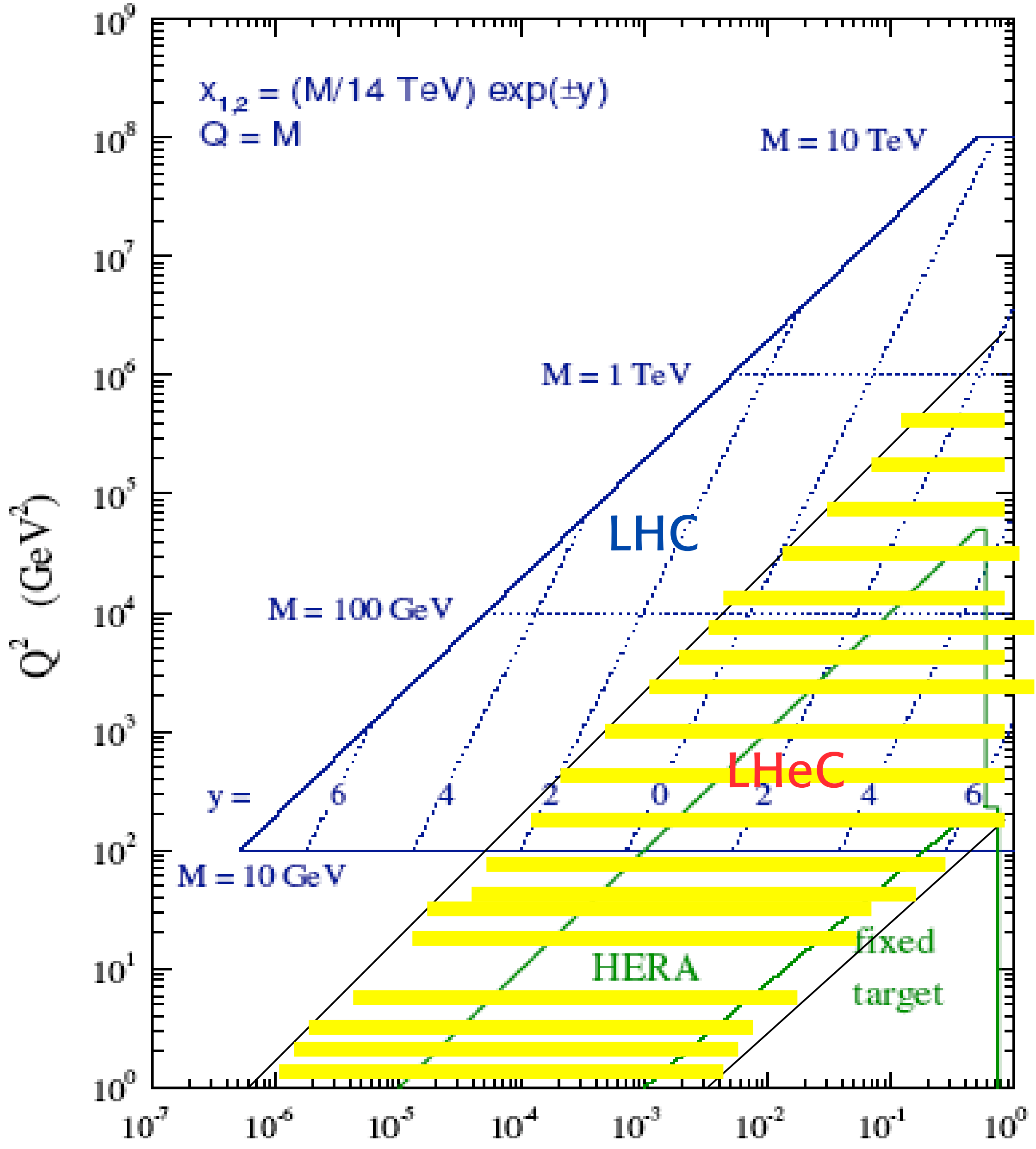
G. Altarelli*), B. Mele*) and R. Rückl,
CERN, Geneva, Switzerland
(Presented by G. Altarelli)

ABSTRACT

We study the physics of electron-proton collisions in the range of centre-of-mass energies between $\sqrt{s} \simeq 0.3$ TeV (HERA) and $\sqrt{s} \simeq (1-2)$ TeV. The latter energies would be achieved if the electron or positron beam of LEP $[E_e \simeq (50-100)$ GeV$]$ is made to collide with the proton beam of LHC $[E_p \simeq (5-10)$ TeV$]$.



LHC:
LHeC
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
BCDMS
SLAC
LHeC
HERA
Q^2 / GeV^2
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x



A larger overlap with the LHC domain than for HERA

Broad physics goals (to be discussed at the Workshop)

- Proton structure and QCD physics in the domain of x and Q^2 of LHC experiments
- Small-x physics in eP and eA collisions
- Probing the $e^{\pm}$-quark system at ~TeV energy

  eg leptoquarks, excited e*'s, mirror e, SUSY with no R-parity......
- Searching for new EW currents

  eg RH W's,
  effective eeqq contact interactions...

Why the LHeC after HERA? A main question for this Workshop

In spite of the large effort in theory and experiment over ~40 years still our knowledge is in many respects surprisingly not satisfactory

Some examples:

- The determination of α_s from DIS
- Ambiguities on the pdf's
- ONLY NOW (!) some reasonable data on F_L are been obtained (H1 and ZEUS)

• • • •

What is the value of α_s from DIS?

From LEP we have the best values to compare with:

- Z inclusive decay: $\alpha_s(m_Z)=0.1191\pm0.0027$ (N^3LO)
- τ inclusive decay: $\alpha_s(m_Z)=0.1212\pm0.0011$ (N^3LO)

Davier et al '08

(I do not believe this small error, but this is not an issue here)

- Event shapes: $\alpha_s(m_Z)=0.1240\pm0.0034$ (N^3LO)

Dissertori et al '08

DIS is the next "golden" channel to consider

QCD predicts the Q^2 dependence of $F(x, Q^2)$ not the x shape. But the Q^2 dependence is related to the x shape by the QCD evolution eqs.

For each x-bin approx. a straight line in $d\log F(x, Q^2)/d\log Q^2$: the log slope.

[Q^2 span and precision of data not much sensitive to curvature]

The scaling violations of non-singlet str. functs. would be ideal: less dependence on input parton densities

$$\frac{d}{dt}\log F(x, t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 dy \frac{F(y, t)}{yF(x, t)} P_{qq}\left(\frac{x}{y}\right)$$

But for F_p-F_n exp. errors add up in difference, and $F_{3\nu N}$ not terribly precise (and come essentially from only one experiment CCFR)

Neutrinos. For xF_3 at NNLO:

Using Bernstein moments

A combination of Mellin moments which emphasizes a value of x and a given spread in order to be sensitive to the interval where the measured points are

- $\alpha_s(m_Z)=0.1153\pm0.0063$

Santiago, Yndurain ‘01

- $\alpha_s(m_Z)=0.1174\pm0.0043$

Maxwell, Mirjalili ‘02

Here the error from scale dep. not included (a model dep. scale fixing is chosen)

Using Mellin moments

- $\alpha_s(m_Z)=0.1190\pm0.0060$

Kataev, Parente, Sidorov ‘02

Good overall agreement. Not very precise: (as expected from ν’s) Total error ~±0.006

electron/muon production

From a recent analysis of eP and eD data, neglecting sea and gluons at $x > 0.3$

- Non singlet DIS: $\alpha_s(m_Z)=0.1148\pm0.0019$ (exp)+? (NLO)
  $\alpha_s(m_Z)=0.1134\pm0.0020$ (exp)+? (NNLO)

Blumlein et al '06

- a rather small central value
- not much difference between NLO and NNLO

When one measures α_s from scaling viols. in F_2 from e or μ beams, data are abundant, exp. errors small but:

α_s ↔ gluon correlation

$dF/d\log Q^2 \to \alpha_s g$

- Using data on P from SLAC, BCDMS, E665 and HERA, NNLO [Bernstein moments] :

$\alpha_s(m_Z)=0.1166\pm0.0013$ (!!th error?)

Santiago, Yndurain '01

- Or using data on p from SLAC, BCDMS, NMC and HERA, NNLO [Mellin moments]:

$\alpha_s(m_Z)=0.1143\pm0.0014$ (exp) ±0.0013 (th)

Alekhin '02

The difference in central values between these nominally most precise determinations suggests a total error ~±0.003

Other analyses (NLO vs NNLO generally close) based on different methods and data sets offer a spread of central values suggesting larger errors

- Using data on p from BCDMS and NMC, NLO kernels, truncated moments

Moments from x_0 to 1 in measured range, coupled eqs.

$$\alpha_s(m_Z)=0.122\pm0.006$$

Forte, Latorre, Magnea, Piccione '02

- H1 only or H1+BCDMS, NLO

$$\alpha_s(m_Z)=0.1185\pm0.002\ (\mathrm{exp})\ \pm0.005$$
$$\alpha_s(m_Z)=0.1150\pm0.002\ (\mathrm{exp})$$

- ZEUS, NLO $\alpha_s(m_Z)=0.1166\pm0.0049\ (\mathrm{exp})\ \pm0.0018$

- Proton data, Nachtmann moments including soft gluon resumm. at large x and estimate of higher twist

$$\alpha_s(m_Z)=0.1188\pm0.0017\ (\mathrm{exp})$$ Simula, Osipenko '03

Summary

- Z inclusive decay: $\alpha_s(m_Z)=0.1191\pm0.0027$ (N^3LO)
- τ inclusive decay: $\alpha_s(m_Z)=0.1212\pm0.0011$ (N^3LO)

Davier et al ‘08

(I do not believe this error, but this is not an issue here)

- Event shapes: $\alpha_s(m_Z)=0.1240\pm0.0034$ (N^3LO)

Dissertori et al ‘08

- Non singlet DIS: $\alpha_s(m_Z)=0.1148\pm0.0019$ (exp)+? (NLO)

  $\alpha_s(m_Z)=0.1134\pm0.0020$ (exp)+? (NNLO)

  Blumlein et al ‘06

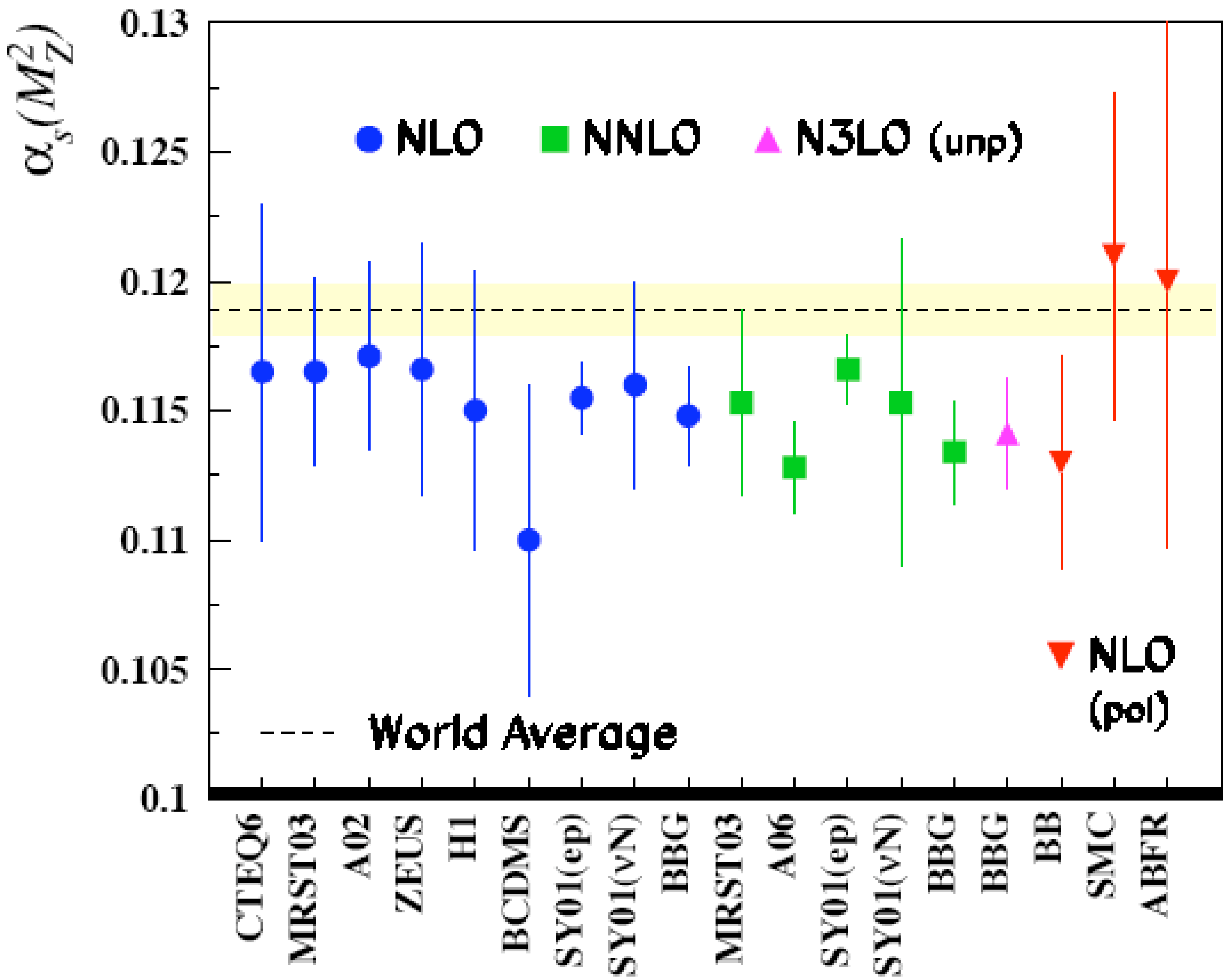
- All DIS eP: $\alpha_s(m_Z)=0.1166\pm0.0013$ (th error?) (NNLO)

  Santiago, Yndurain ’01

  $\alpha_s(m_Z)=0.1143\pm0.0014$ (exp) ±0.0013 (th) (NNLO)

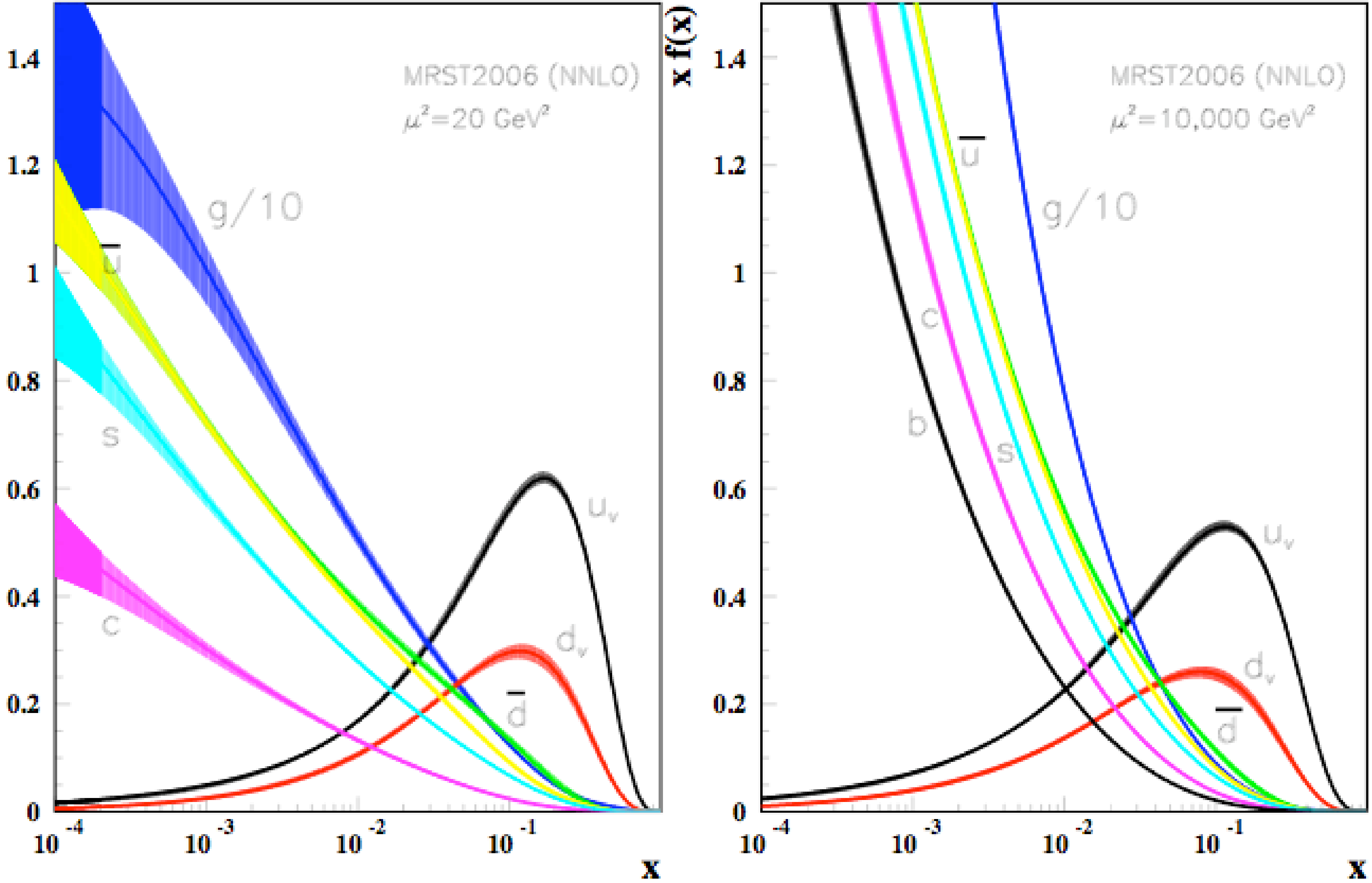
  Alekhin ‘02

Blumlein et al ‘06



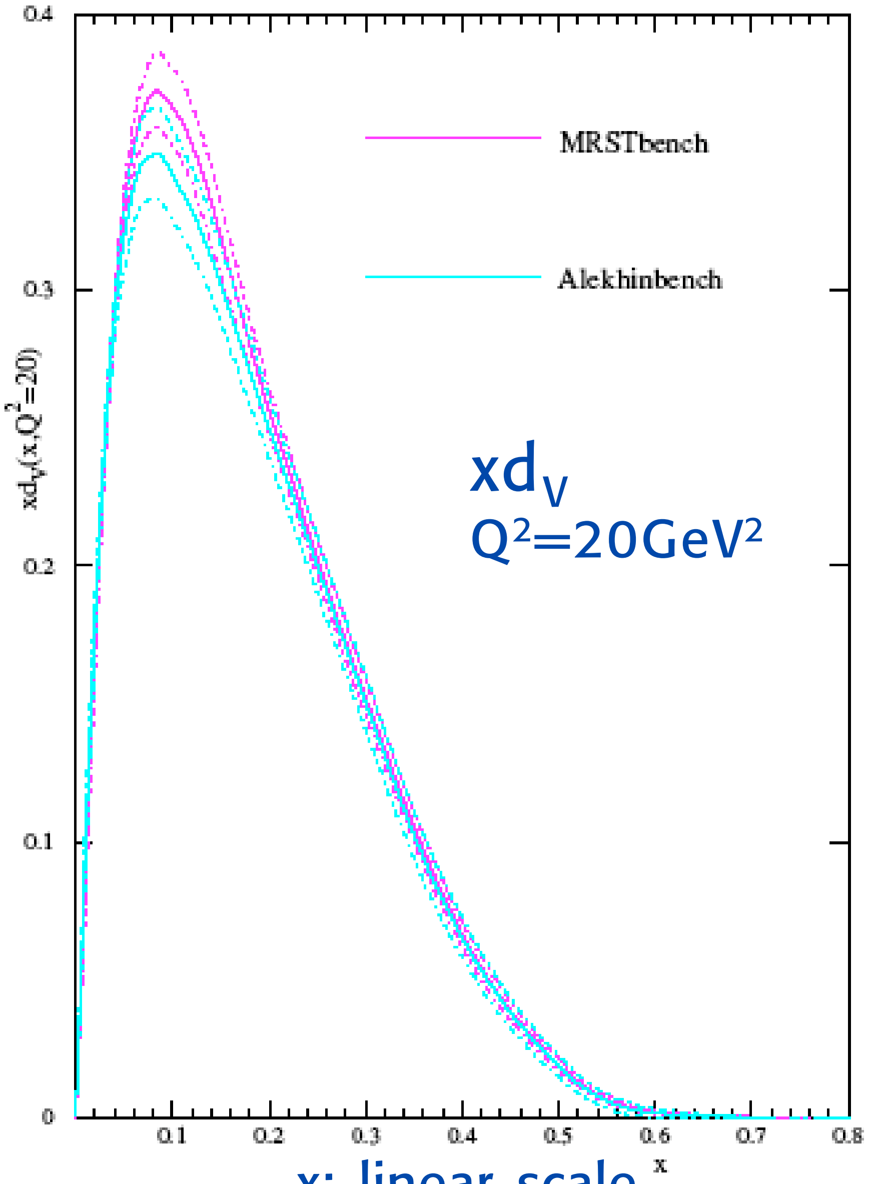
- DIS results tend to be on the low side. Can the LHeC help?

Are the parton densities known well enough?

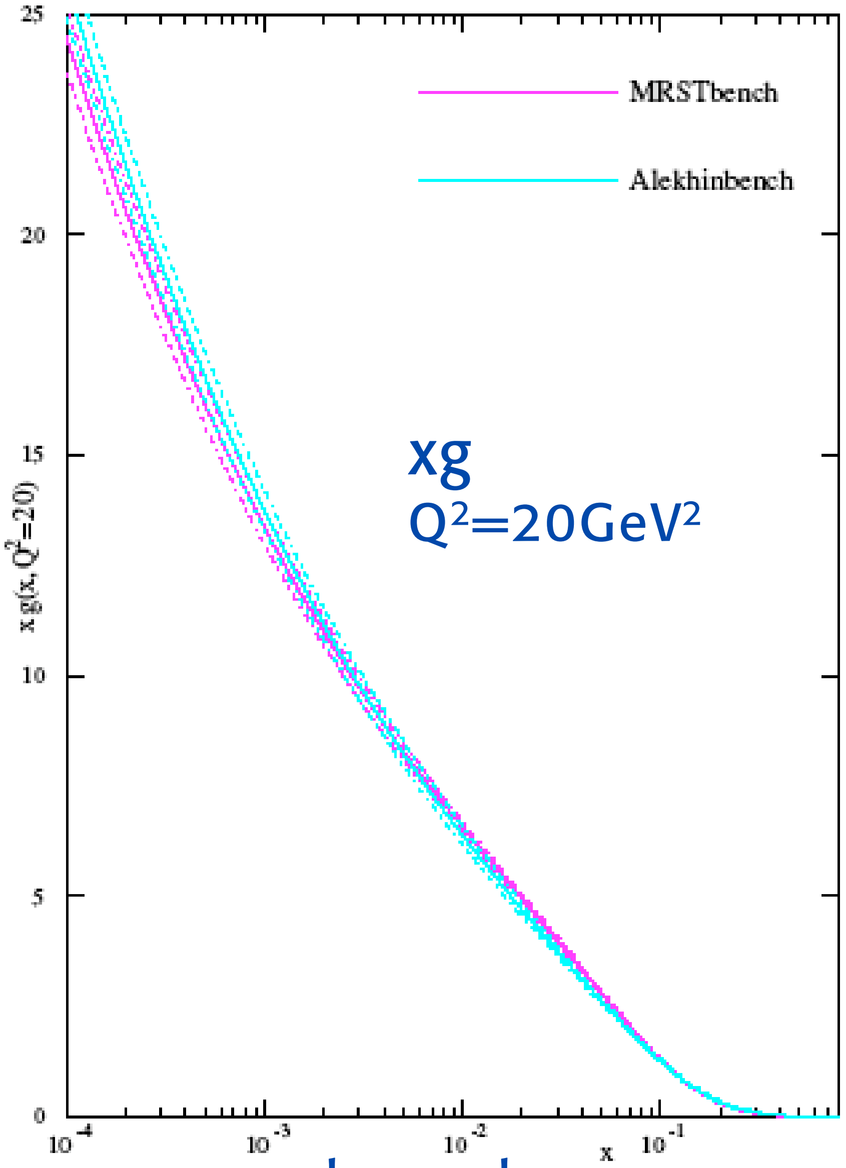


Different fits to same DIS data are comparable

HERA LHC Workshop '06

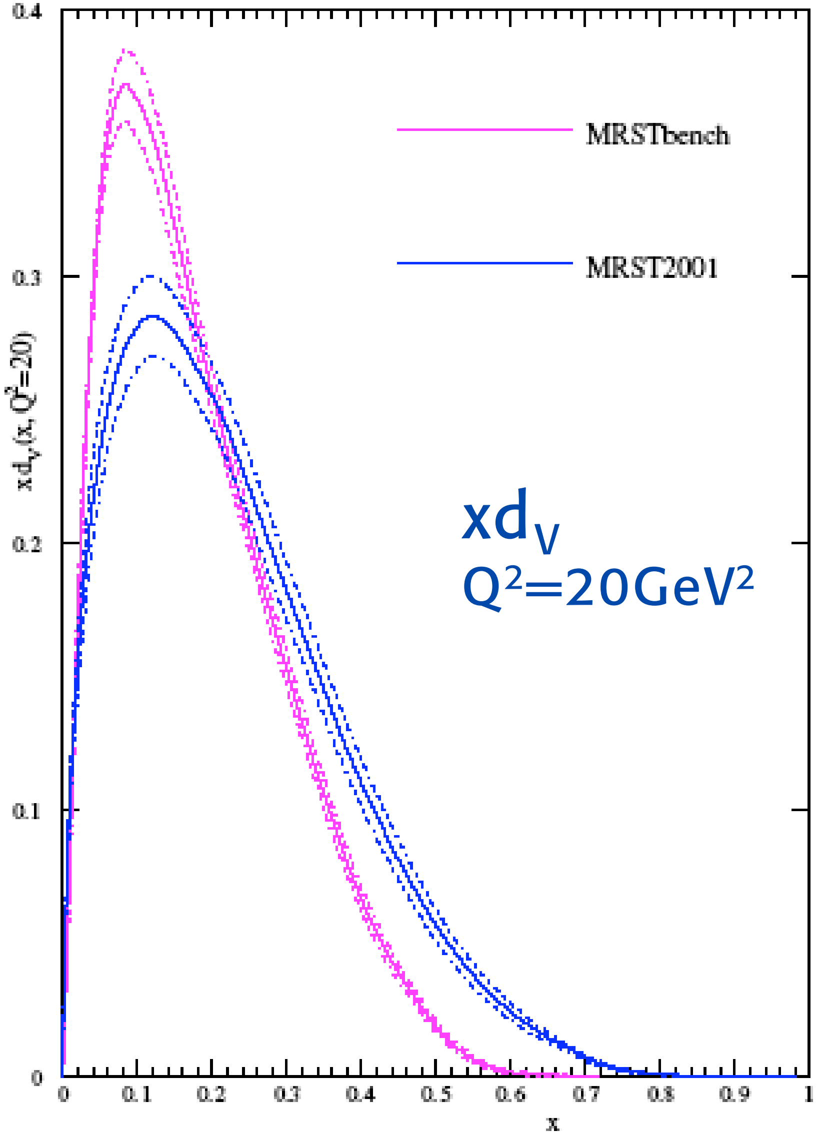


x: linear scale



x: log scale

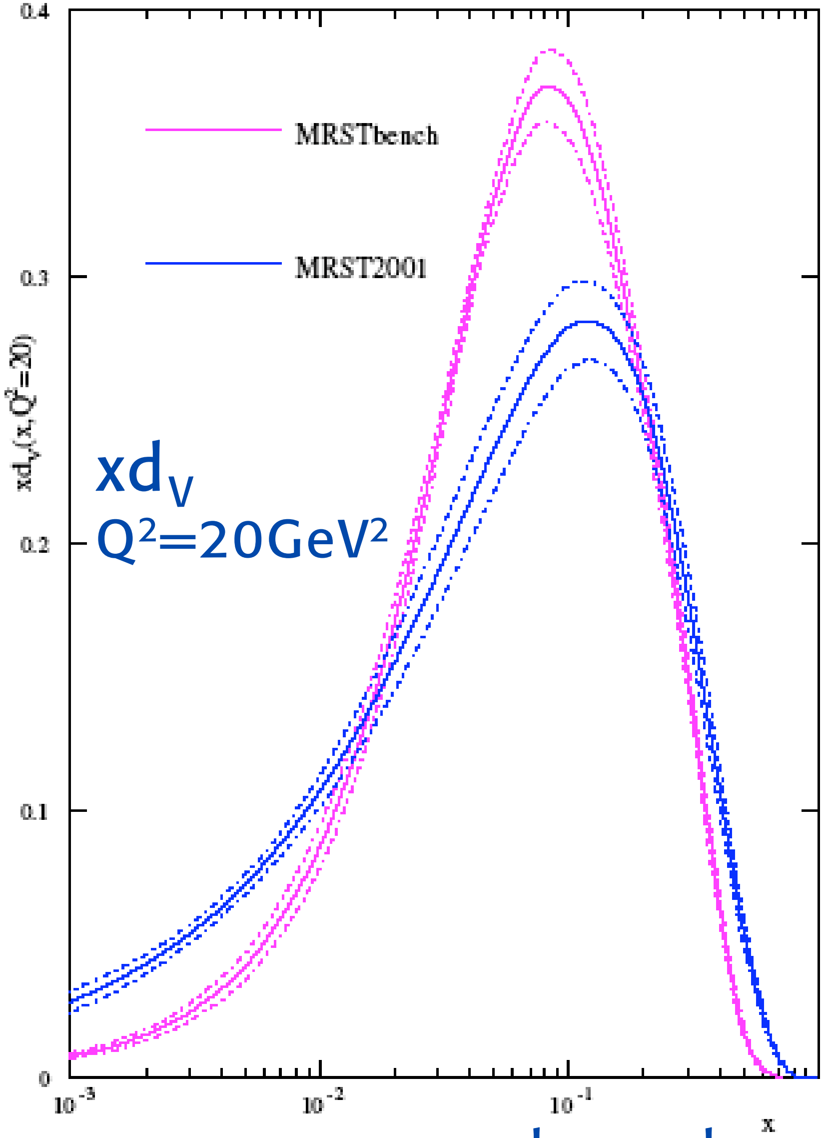
But differ from those obtained from all the data



xd_V

Q^2=20GeV^2

x: linear scale

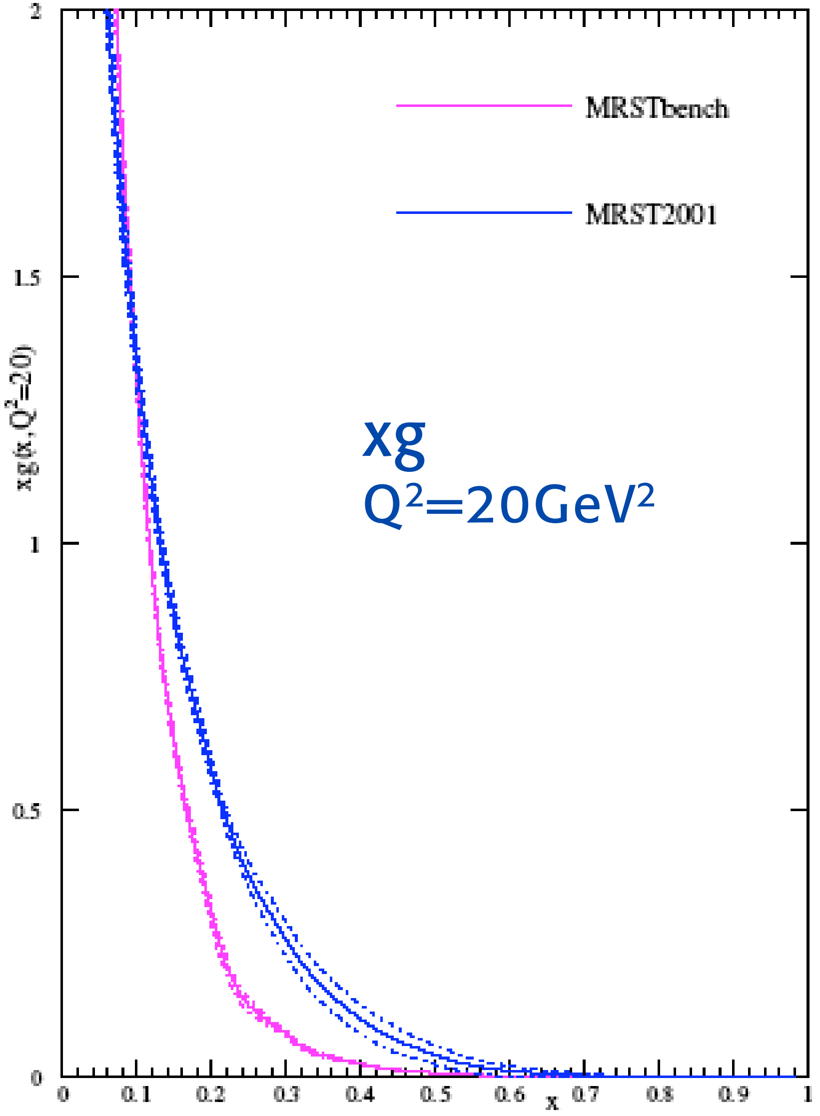


xd_V

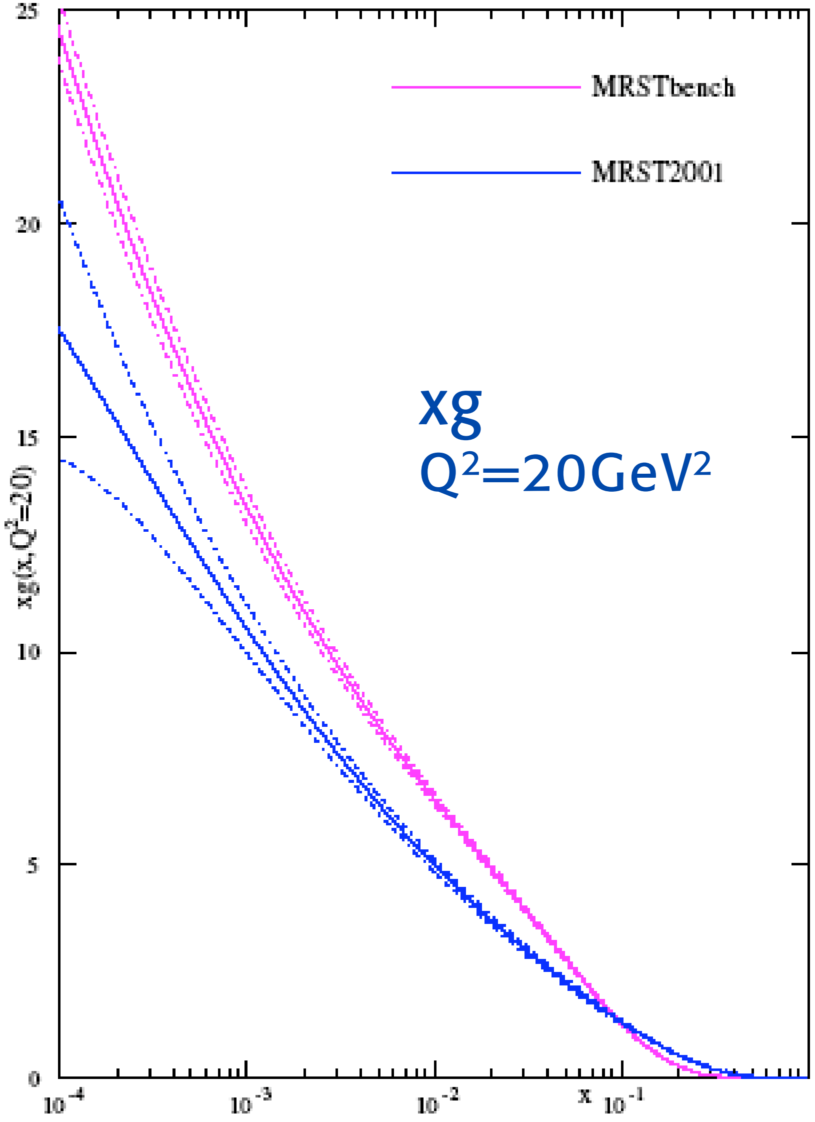
Q^2=20GeV^2

x: log scale

This shows that extrapolation from one data set to another is dangerous

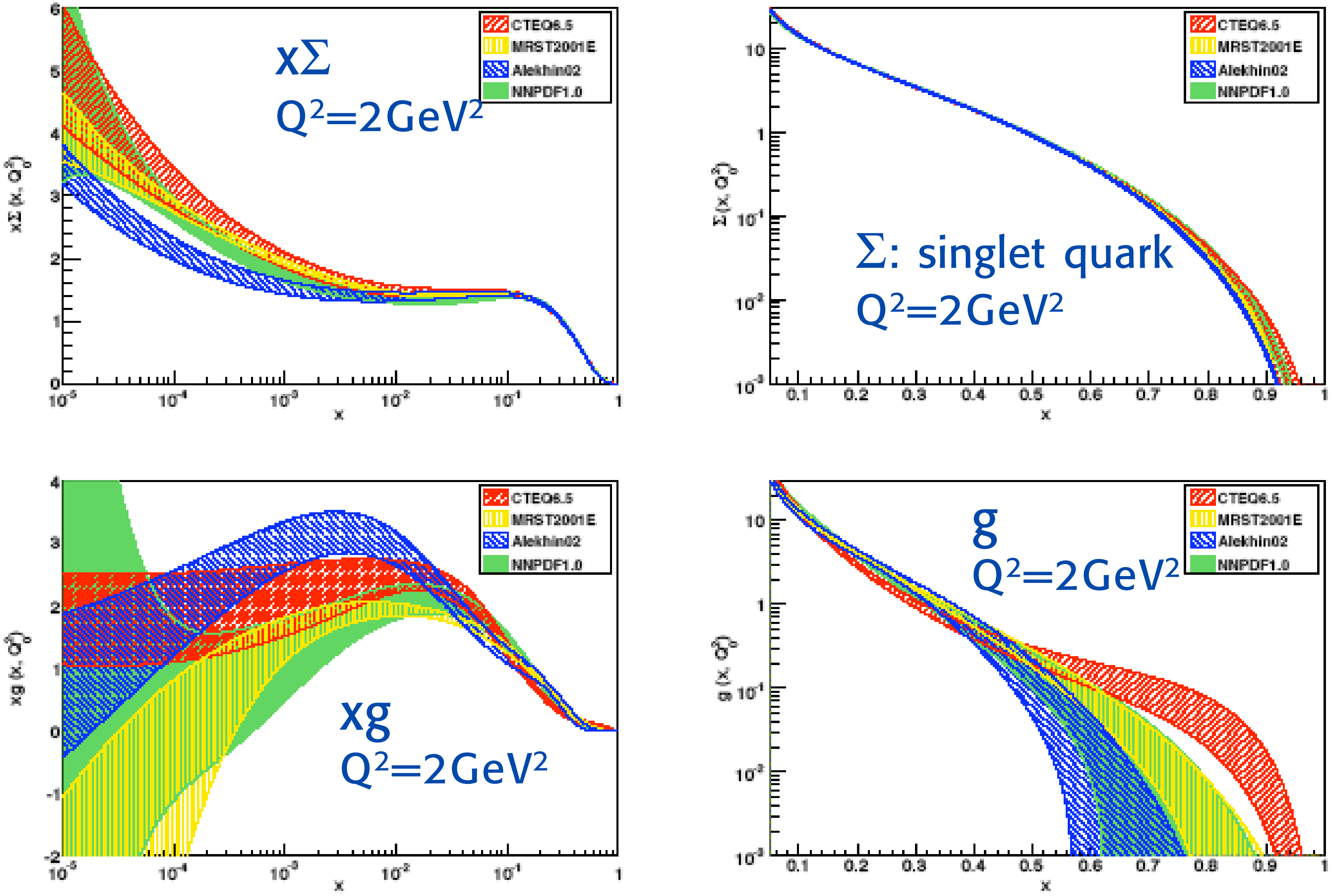


x: linear scale



x: log scale

NNPDF: R. Ball et al '08

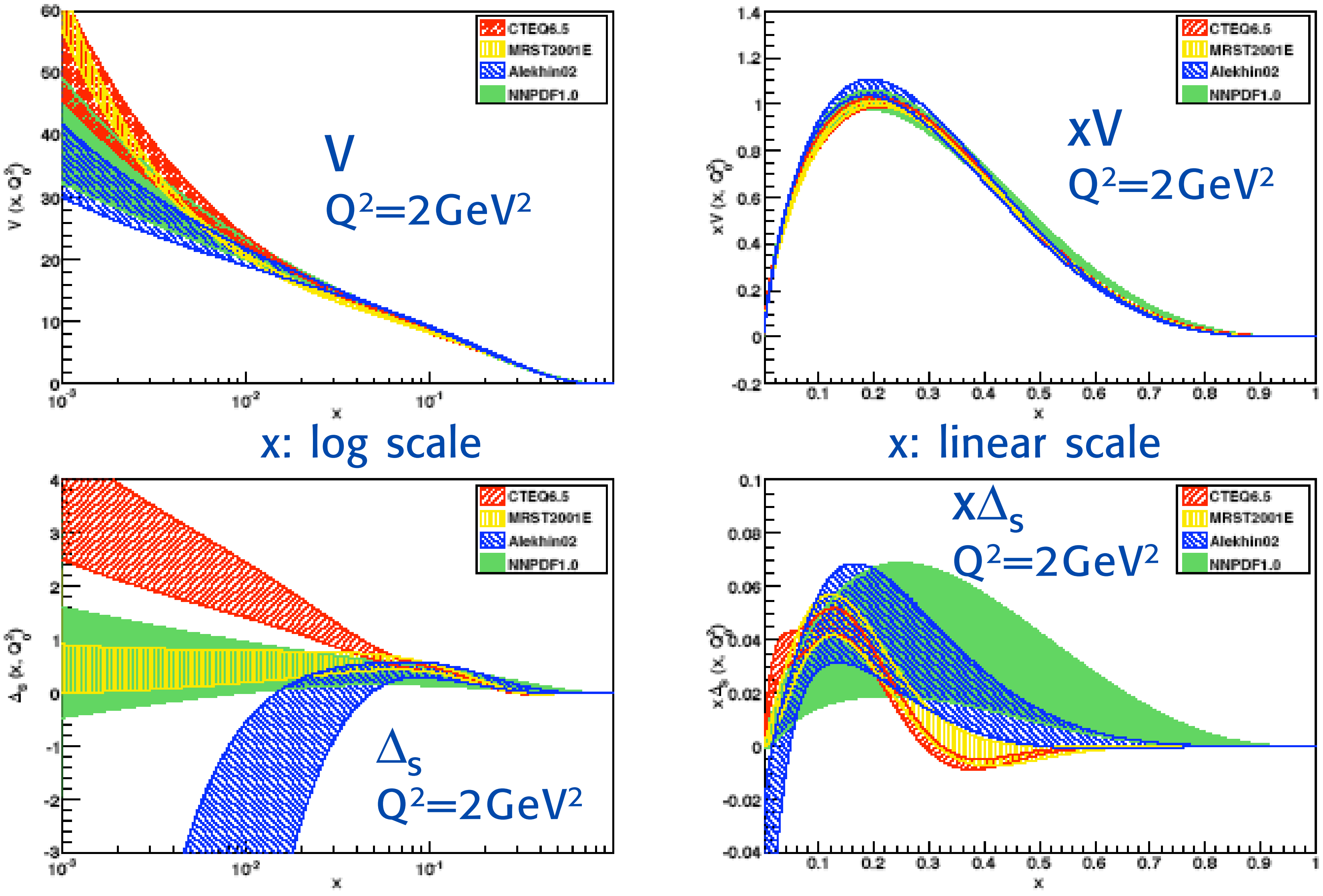


x: log scale

x: linear scale

$$V(x) \equiv \sum_{i=1}^{n_f} (q_i(x) - \bar{q}_i(x))$$

NNPDF: R. Ball et al '08



x: log scale

x: linear scale

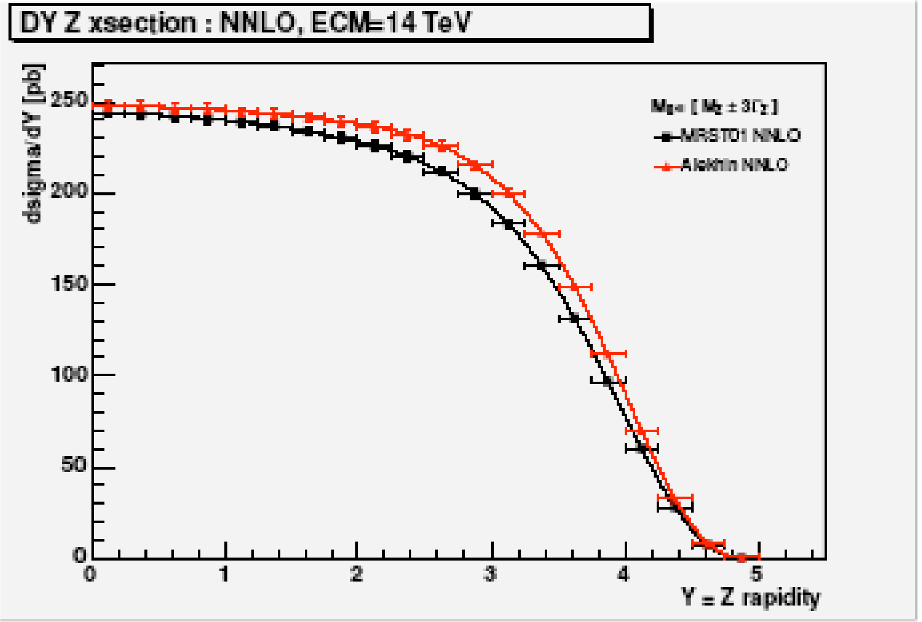
$$\Delta_S(x) \equiv \bar{d}(x) - \bar{u}(x)$$

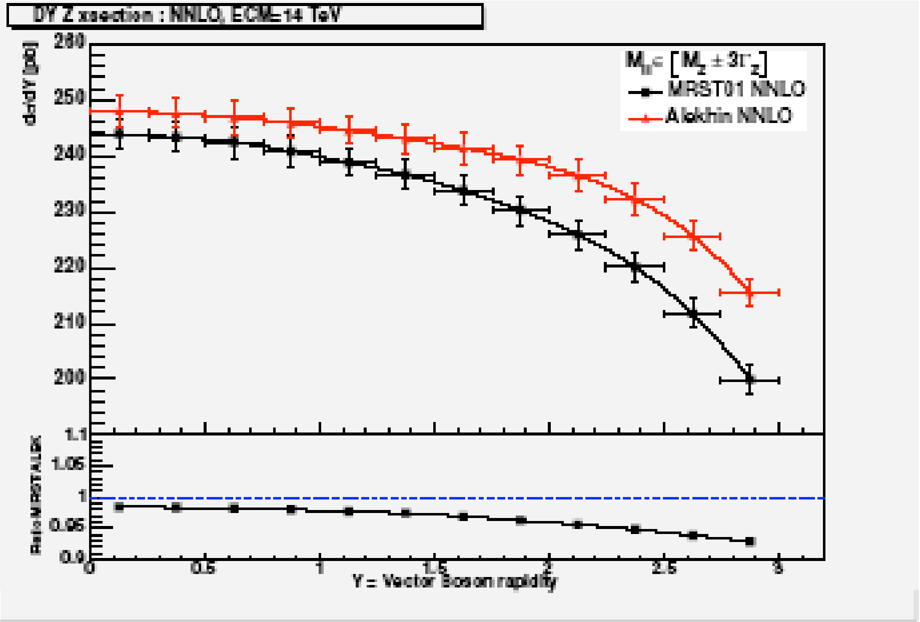
W, Z production cross sections at the LHC

Table 1: LHC W/Z cross-sections for decay via the lepton mode, for various PDFs

PDF Set	$\sigma(W^+).B(W^+ \to l^+\nu_l)$	$\sigma(W^-).B(W^- \to l^-\bar{\nu}_l)$	$\sigma(Z).B(Z \to l^+l^-)$
ZEUS-S no HERA	10.63 ± 1.73 nb	7.80 ± 1.18 nb	1.69 ± 0.23 nb
ZEUS-S	12.07 ± 0.41 nb	8.76 ± 0.30 nb	1.89 ± 0.06 nb
CTEQ6.1	11.66 ± 0.56 nb	8.58 ± 0.43 nb	1.92 ± 0.08 nb
MRST01	11.72 ± 0.23 nb	8.72 ± 0.16 nb	1.96 ± 0.03 nb

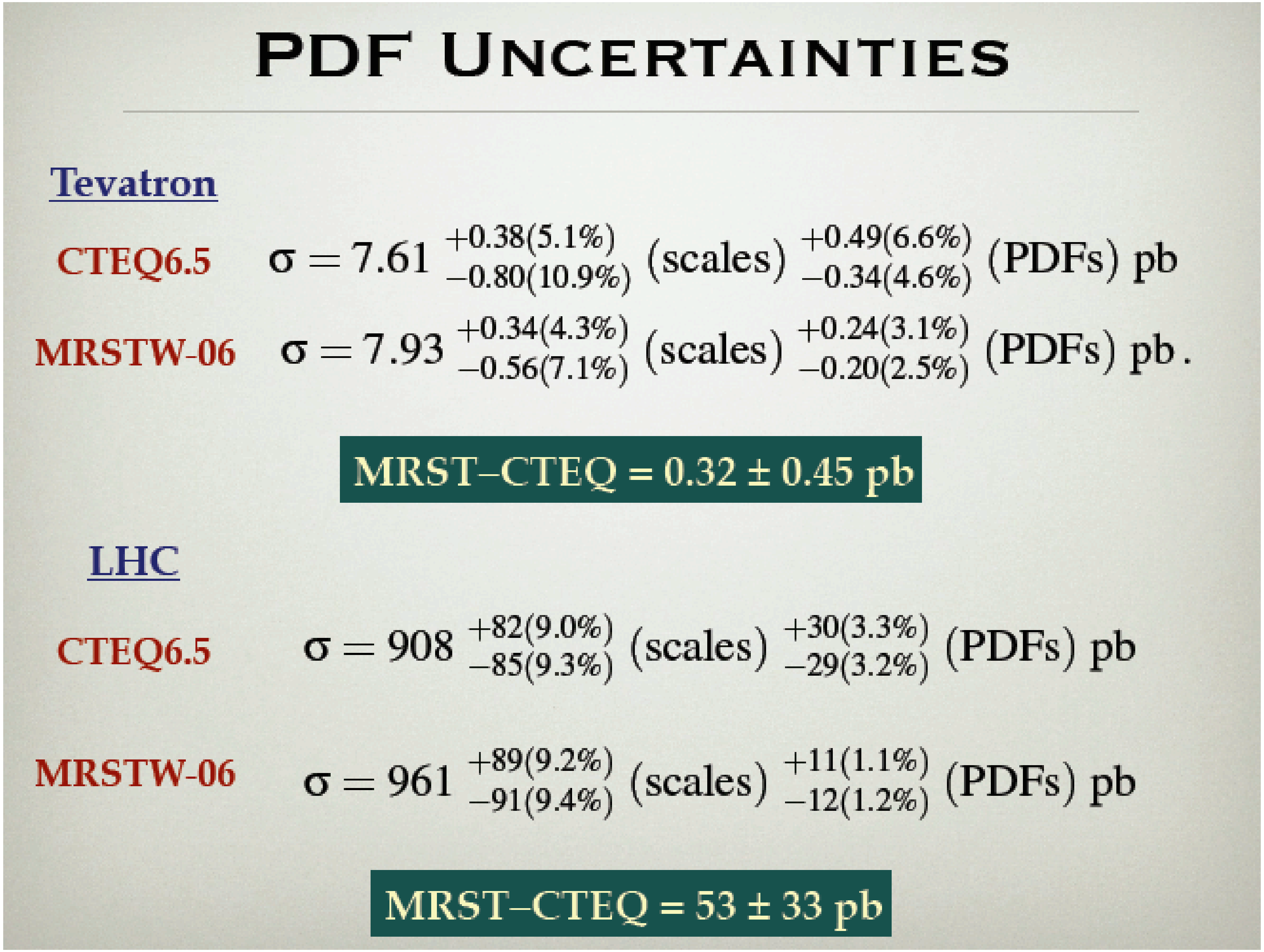
a few % uncertainty from the pdf





Top pair production cross section

M. Mangano '08



PDF UNCERTAINTIES

Tevatron

CTEQ6.5 $\sigma = 7.61\,^{+0.38(5.1\%)}_{-0.80(10.9\%)}\,(\text{scales})\,^{+0.49(6.6\%)}_{-0.34(4.6\%)}\,(\text{PDFs})\ \text{pb}$

MRSTW-06 $\sigma = 7.93\,^{+0.34(4.3\%)}_{-0.56(7.1\%)}\,(\text{scales})\,^{+0.24(3.1\%)}_{-0.20(2.5\%)}\,(\text{PDFs})\ \text{pb}\,.$

MRST–CTEQ = 0.32 ± 0.45 pb

LHC

CTEQ6.5 $\sigma = 908\,^{+82(9.0\%)}_{-85(9.3\%)}\,(\text{scales})\,^{+30(3.3\%)}_{-29(3.2\%)}\,(\text{PDFs})\ \text{pb}$

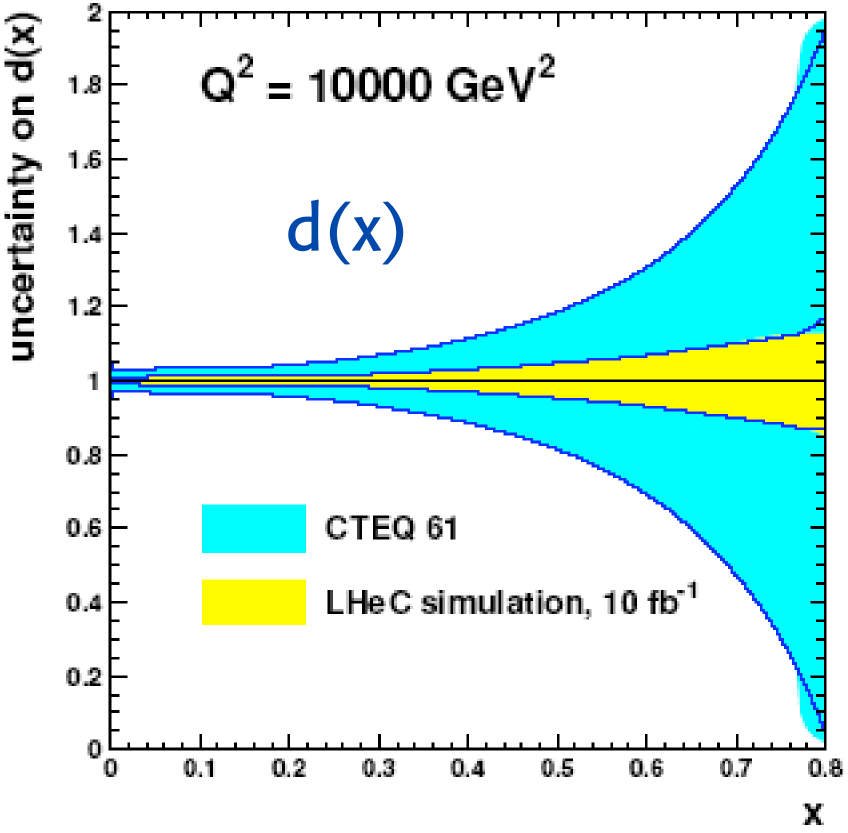
MRSTW-06 $\sigma = 961\,^{+89(9.2\%)}_{-91(9.4\%)}\,(\text{scales})\,^{+11(1.1\%)}_{-12(1.2\%)}\,(\text{PDFs})\ \text{pb}$

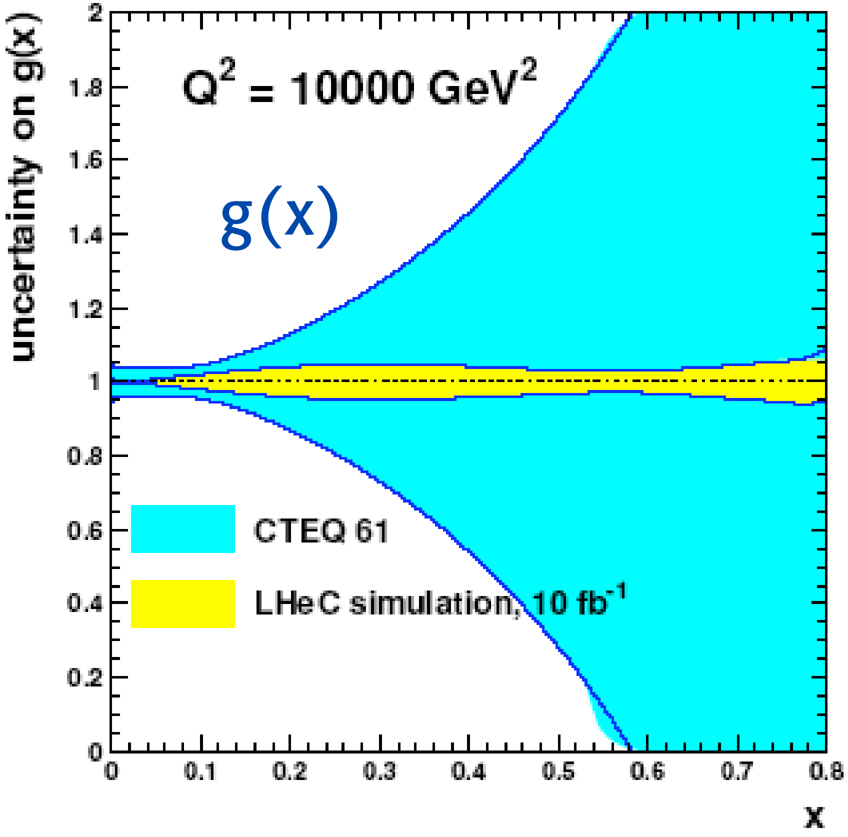
MRST–CTEQ = 53 ± 33 pb

Ambiguity at large x now and after LHeC

Important for production at the LHC of heavy particles
(eg multi TeV Z’, W’....)

E. Perez ‘07

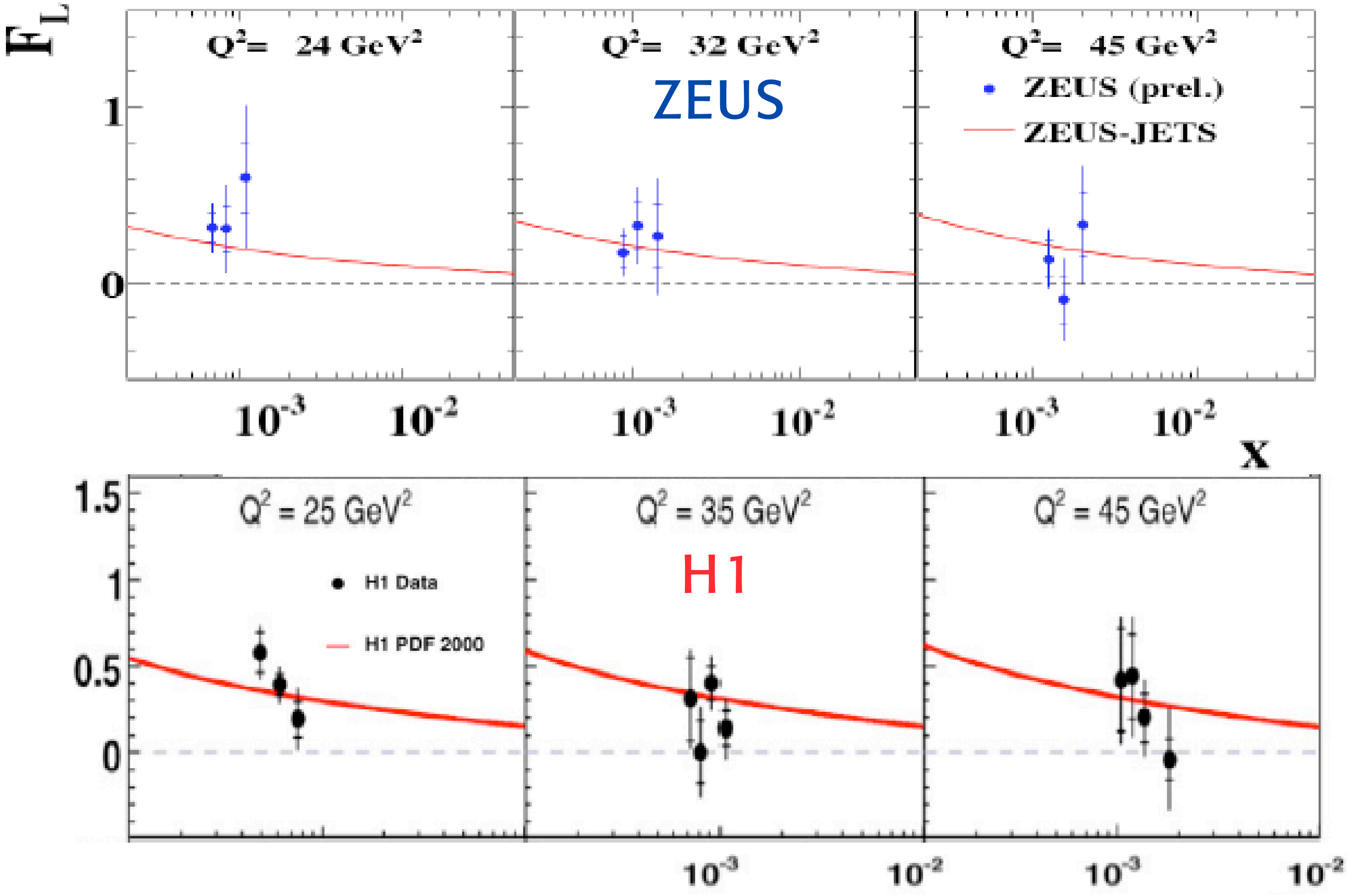




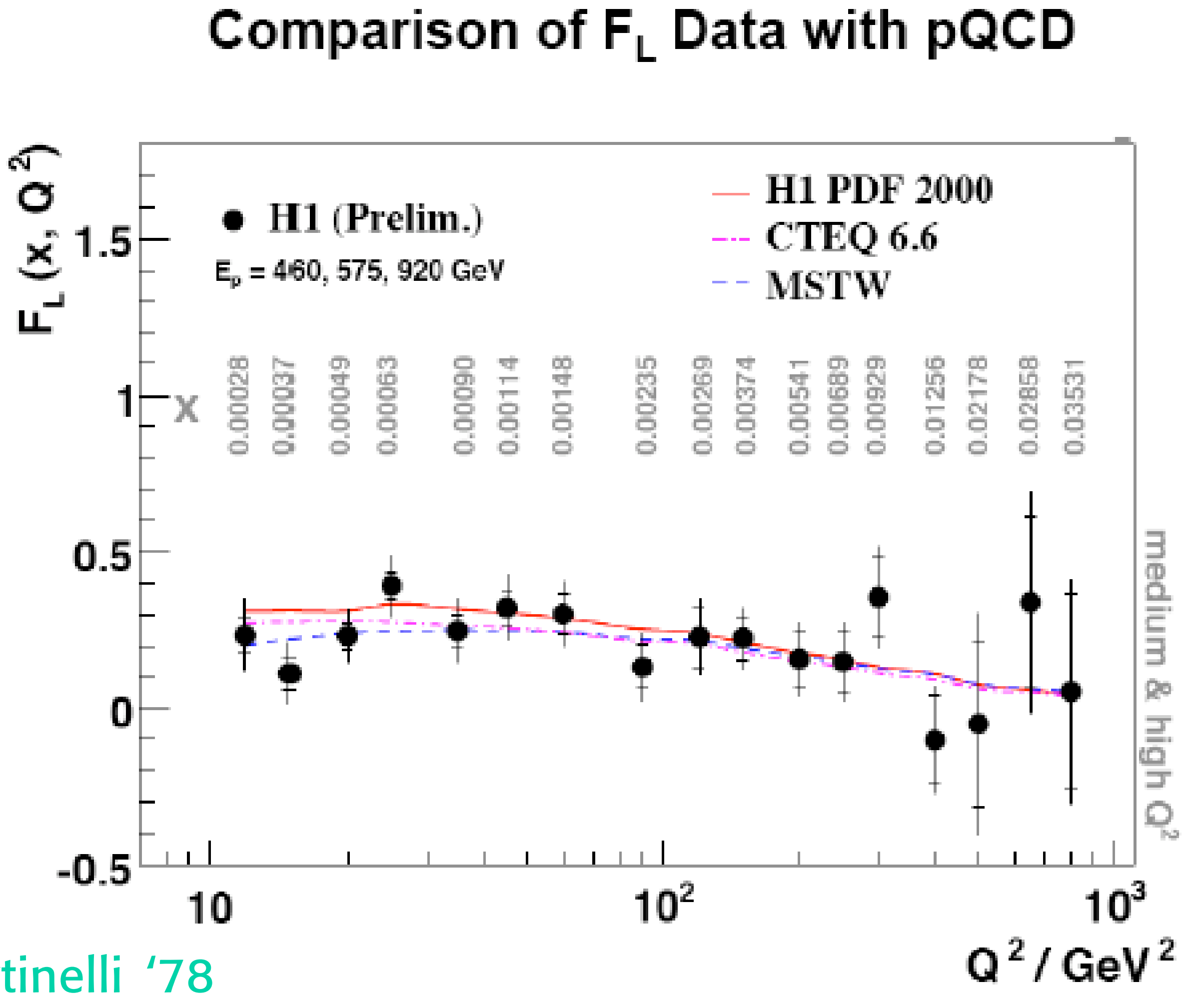
On PDF’s:

We hope that the HERA - TeVatron interplay will succesfully continue into a LHeC - LHC feedback

New data on F_L, the longitudinal structure function



A fundamental QCD prediction still awaiting for a precise test


Comparison of F_L Data with pQCD

Altarelli, Martinelli '78

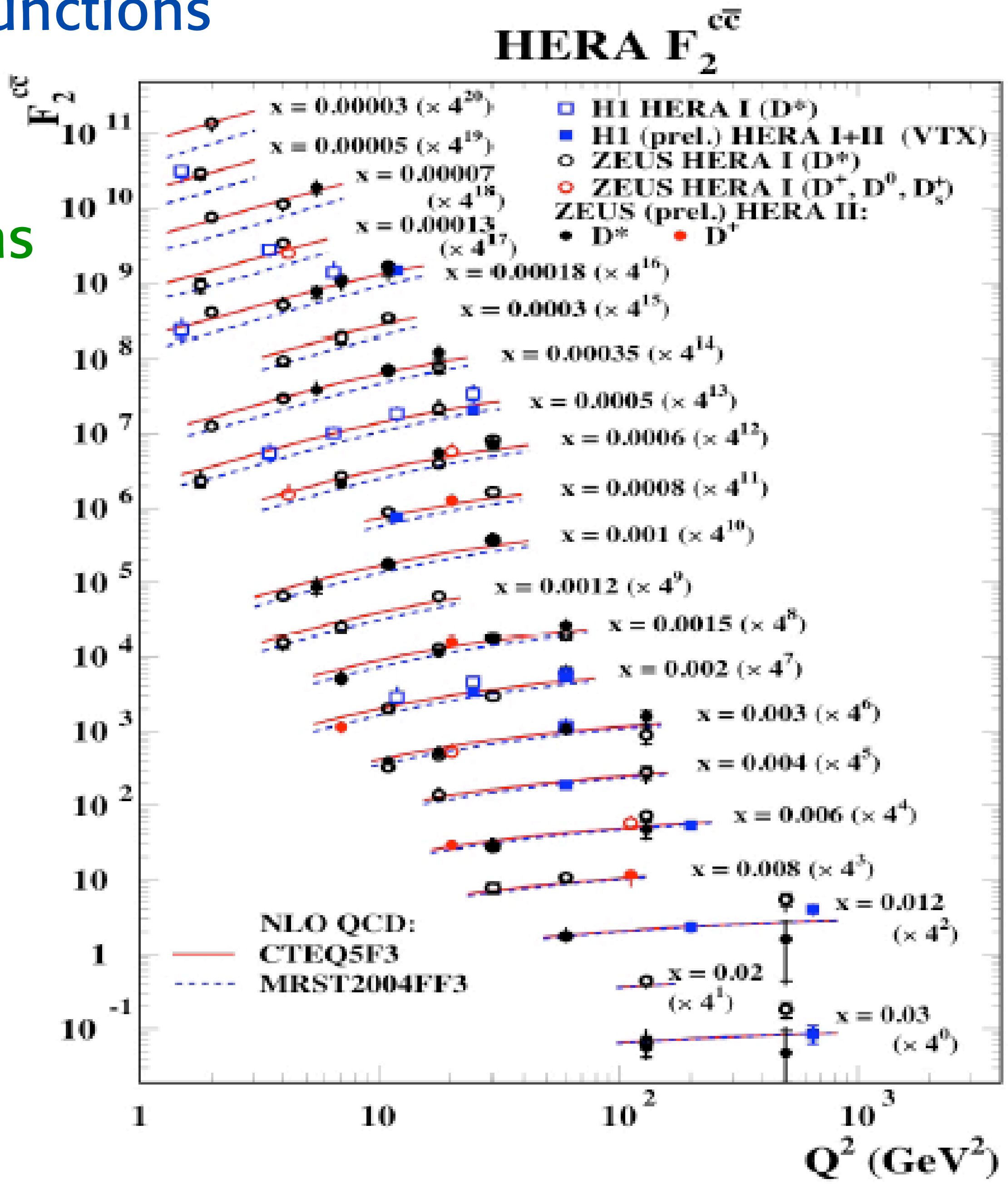
$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} x^2 \int_x^1 \frac{dy}{y^3} \left[\frac{8}{3} F_2(y,Q^2) + \frac{40}{9} yg(y,Q^2)(1-\frac{x}{y}) \right]_{n_f=4}$$

Heavy flavoured structure functions

Another kind of gluon
sensitive structure functions

A great job at HERA!

At the LHeC the increased phase space will allow detailed c and b production studies

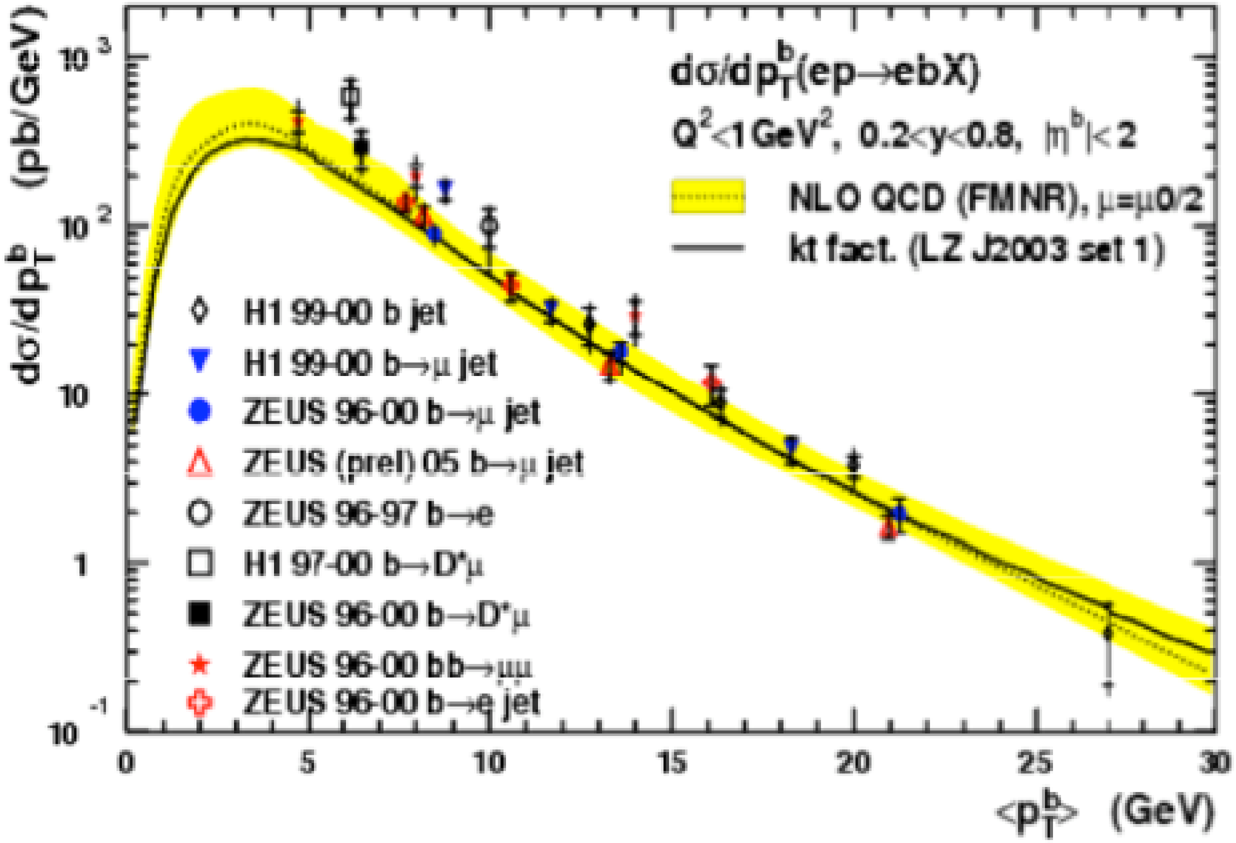


b photoproduction

Boutle '08

HERA

2008:

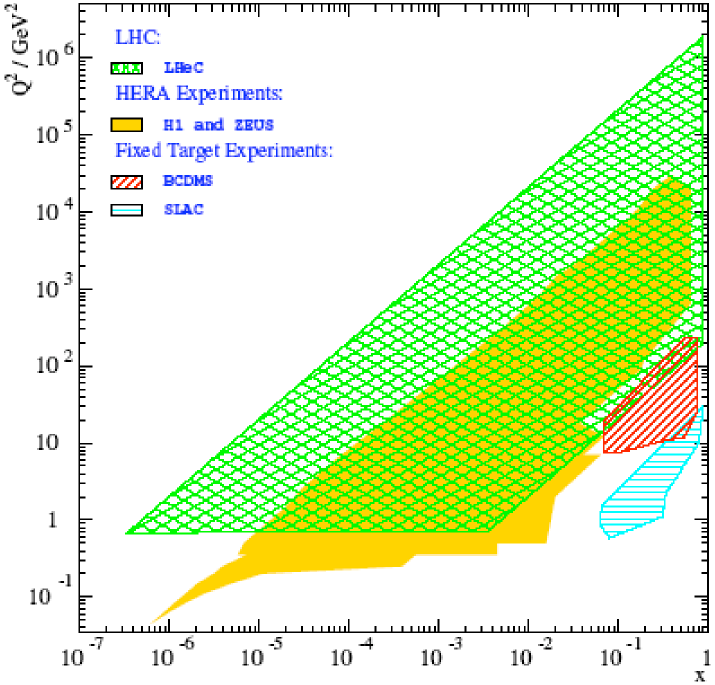


Fair agreement with NLO QCD

Structure functions at small x

At fixed Q^2, also considering the larger luminosity, LHeC can go more than 2 orders of magnitude lower in x than HERA.

This is an interesting perspective both for eP and eA



In eP, contrary to some occasional statements, there is no compelling evidence for deviations from leading twist perturbative (but resummed) evolution (no saturation, no parton recombination....).

For example, geometrical scaling, invoked as a sign, is not an evidence for saturation (at Q > ~2 GeV).

Caola, Forte '08

Singlet splitting function at small x

Resum $(\alpha_s \log 1/x)^n$

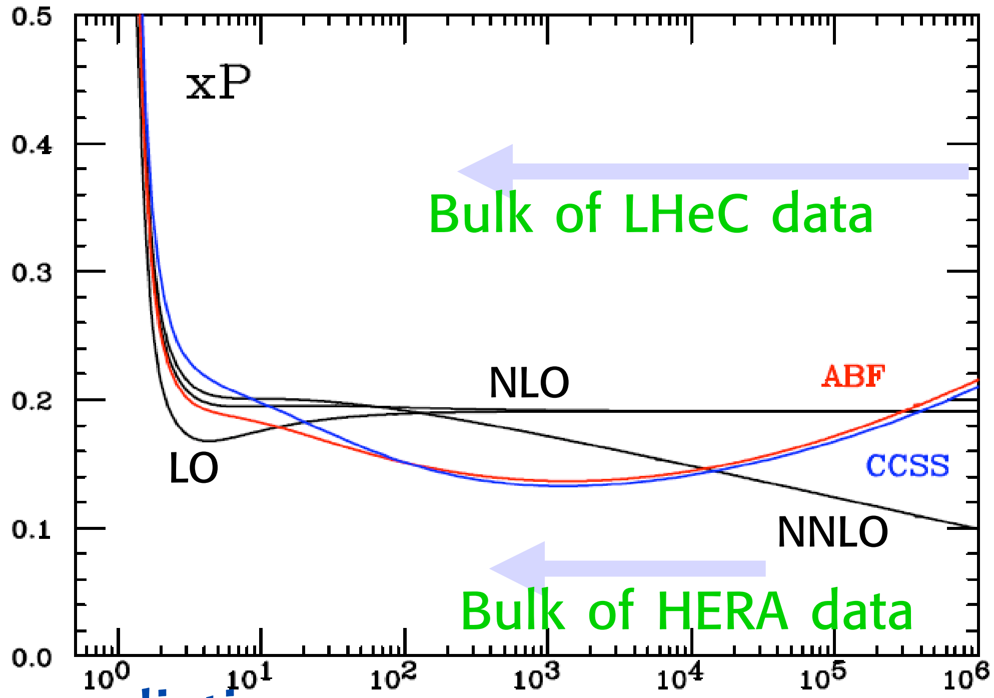
The problem of correctly including BFKL at small x has been solved

Ciafaloni, Colferai, Salam, Stasto ‘07 (CCSS)
Altarelli, Ball, Forte ‘07 (ABF); see also White, Thorne’06

Momentum cons.+ symmetry + running coupling effect

→ soft simple pole in anom. dim

- BFKL sharp rise tamed
- resummed result close to NLO in HERA region
- new expansion stable



Makes the ground solid for LHC predictions (eg b production)

$$x_1 x_2 s = (2m_b)^2 \Rightarrow \bar{x} = \sqrt{x_1 x_2} \sim \frac{2m_b}{\sqrt{s}} \sim 0.7 \cdot 10^{-3}$$

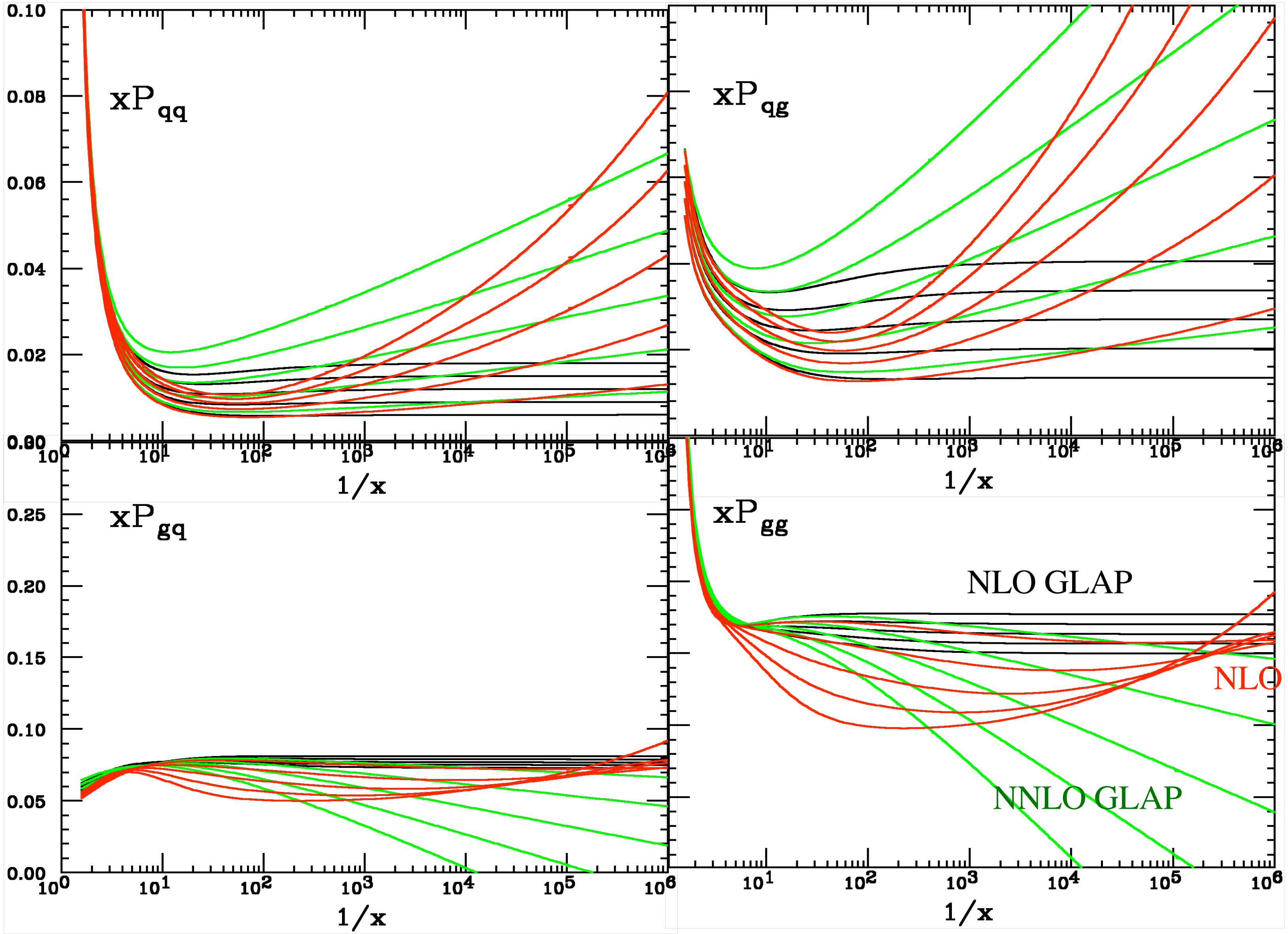
Due to the dip there is less scaling violations at HERA than from NLO

Fitting α_s from NLO one would obtain a smaller value than the true value (for the same gluon).

May be that the small value of α_s from DIS is mainly due to a combination of some systematics in BCDMS and to this effect for HERA data

$Q_0\overline{MS}$ Splitting Functions: $\alpha_s = 0.1, 0.15, 0.2, 0.25, 0.3$

$n_f = 4$



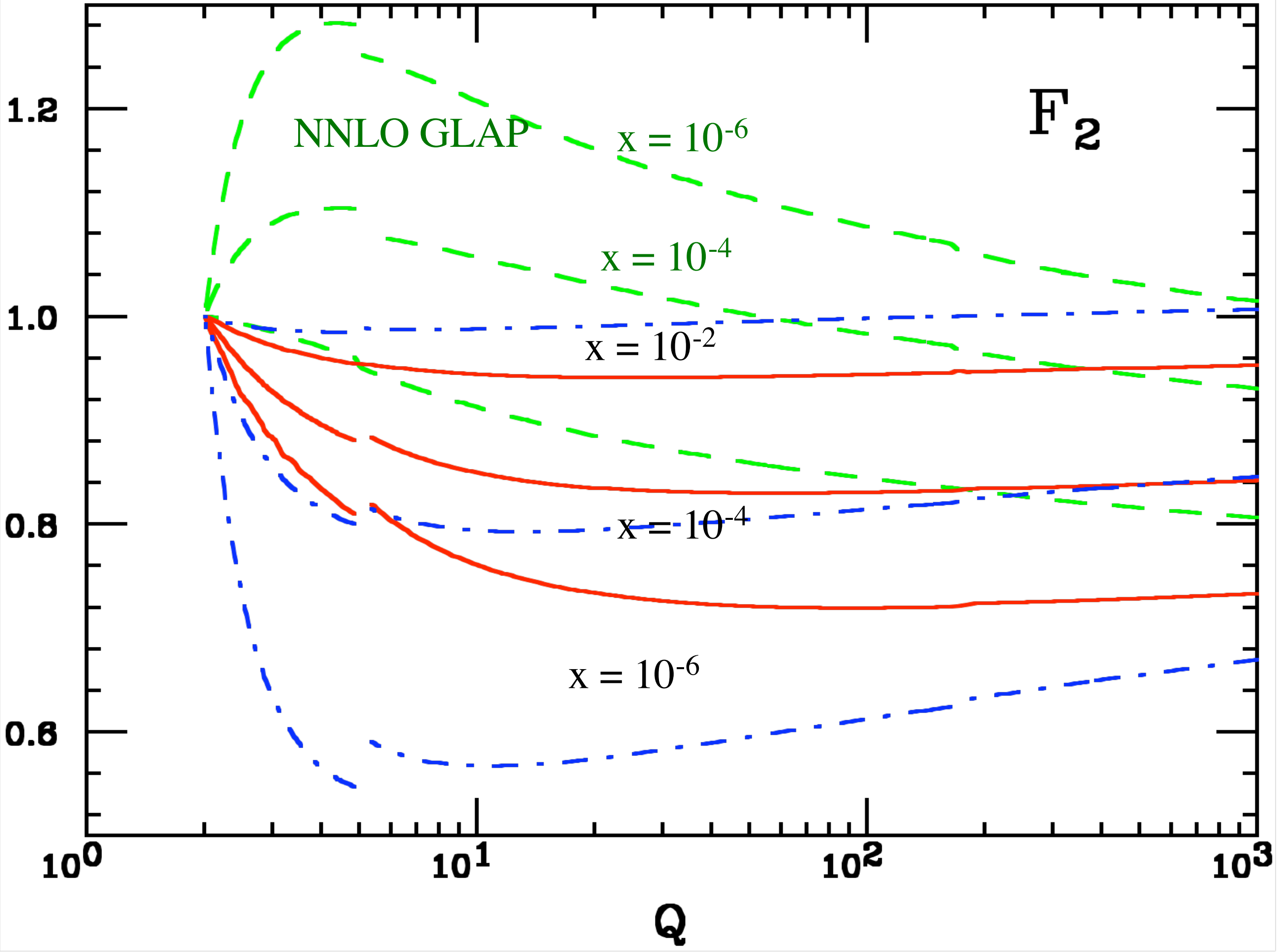
All curves rescaled by $0.2/\alpha_s$

As an effect of the dip there is less evolution for F_2 than at NLO (while for NNLO the opposite is true)

Initial pdfs at Q_0 = 2GeV adjusted so that $F_2^{Res} = F_2^{NLO}$ etc.

ABF '08

$$K \equiv \frac{F_2^{Res}}{F_2^{NLO}}$$



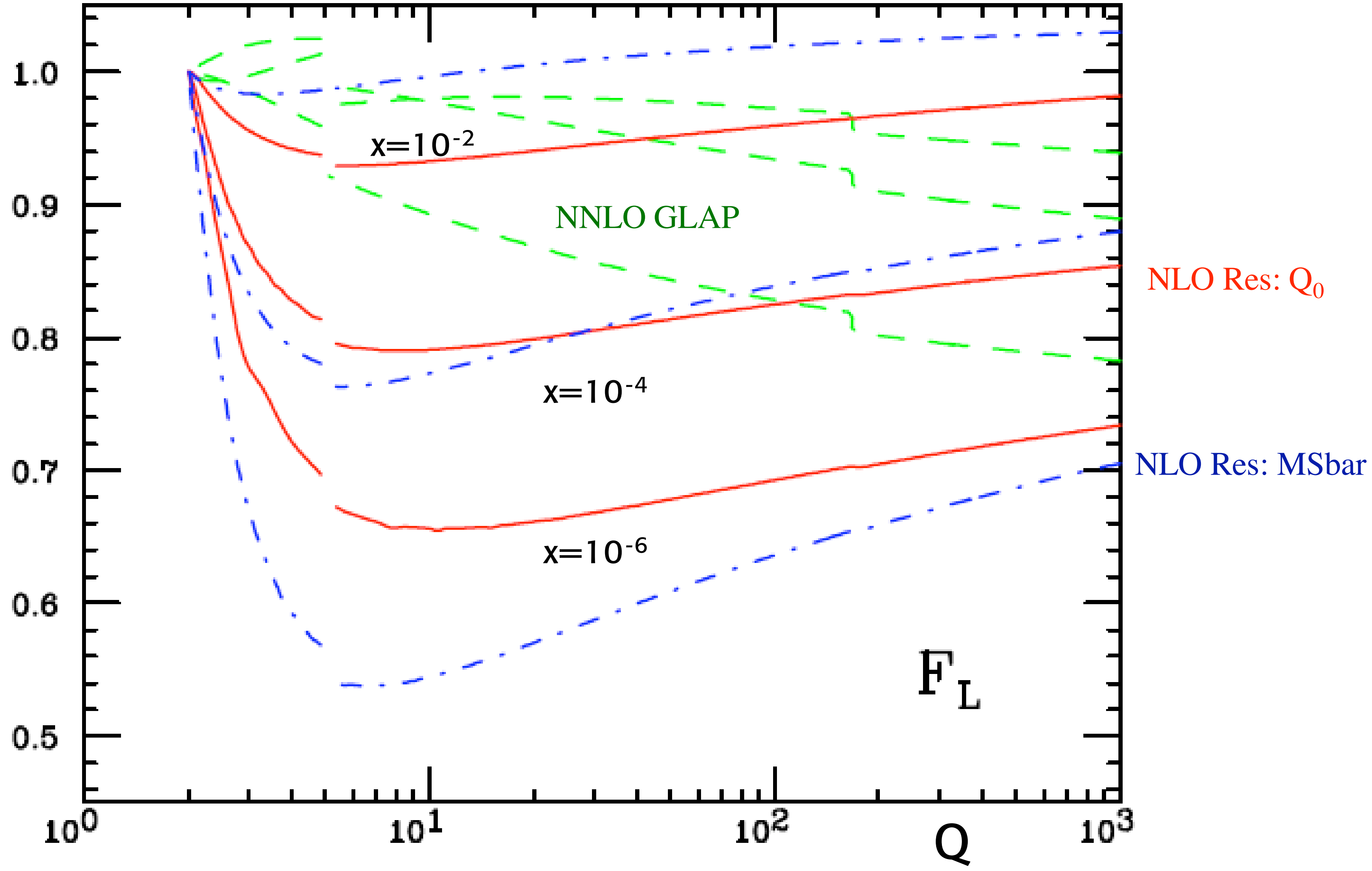
NLO Res: Q_0

NLO Res: MSbar

Effect of
resummation
opposite
to NNLO

The longitudinal structure function F_L

ABF ‘08

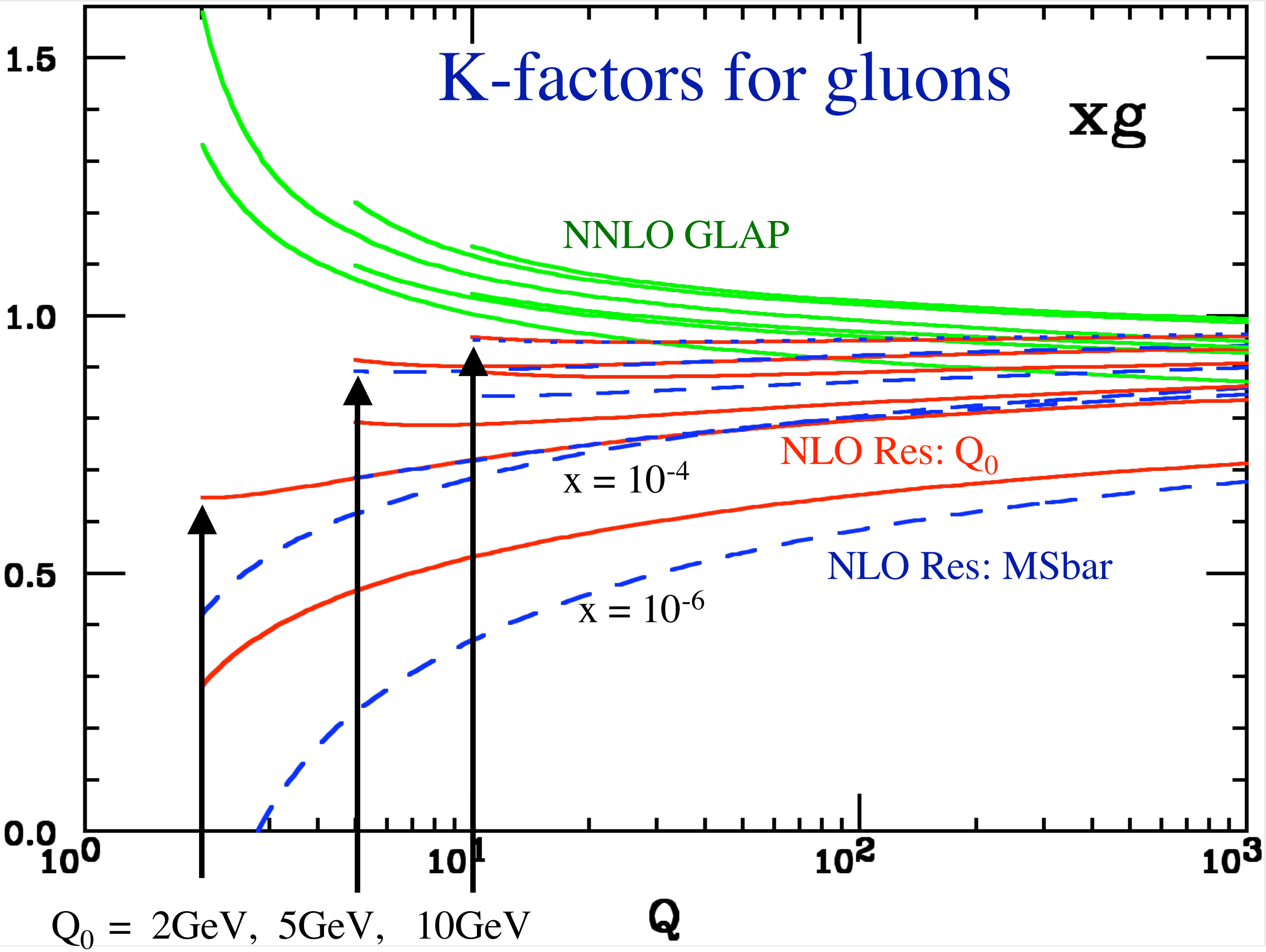


Neglecting resummation makes a 10-20% error on pdf’s in going from HERA to the LHC

Initial pdfs at Q_0 = 2, 5 and 10GeV adjusted so that $F_2^{Res} = F_2^{NLO}$ etc.

$$K \equiv \frac{g^{Res}}{g^{NLO}}$$

Resummation:
fewer gluons
at LHC



These K-factors could be tested at the LHeC

Getting ready to fit the data

We have just produced very dense numerical grids of $P_{ij}^{improved} = P_{ij}^{NLO} + K_{ij}$, and similarly for coefficients c_{ij}^{2}, c_{ij}^{L}.

The eight grids contain 60 by 60 values of the resummation corrections K in uniform steps in logx (for x between 1 and 10^{-6}) and α_s (between 0.08 and 0.36) with n_f fixed, in $Q_0 MS^{bar}$ scheme, sufficient to interpolate for any value of x and α_s in these ranges.

CTEQ will soon include $P_{ij}^{improved}$ in their fitting machine

P. Nadolsky

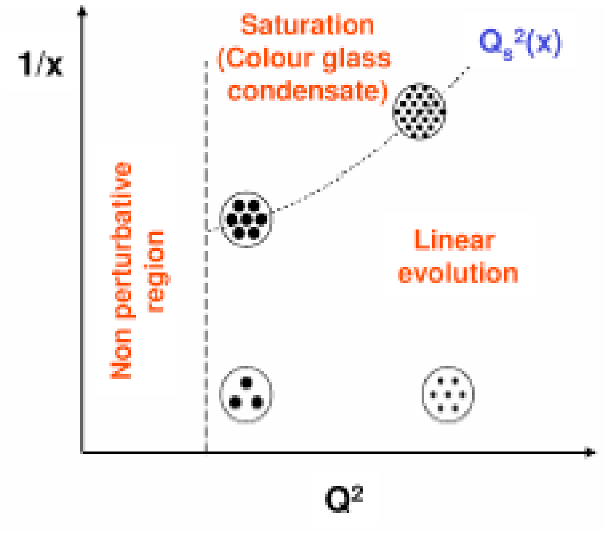
and also in publicly available evolution codes

J. Rojo

The region where we expect the leading twist perturbative regime to fail is at very small x where the singlet splitting functions finally take off

This is at the boundary of the LHeC domain

Saturation: when in a sphere of r=o(1/Q) there are too many gluons (large Q, small x) --> colour glass condensate

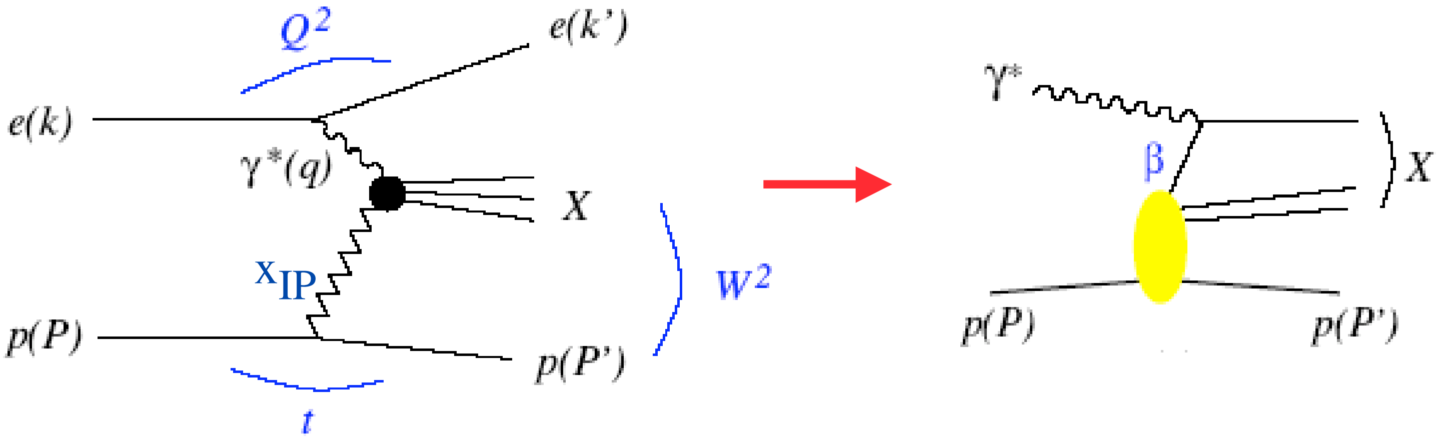


At the LHeC one goes deeper in the small-x region and it should be possible to test the details of the resummed evolution and of the transition region

- The ion beam will enhance the potentialities for saturation

Diffractive structure functions: an opportunity at the LHeC

QCD partons and Pomeron phenomenology



Arneodo, Diehl '06

$$x_{I\!P} = \frac{(P-P')\cdot q}{P\cdot q} \qquad \beta = \frac{Q^2}{2(P-P')\cdot q} \qquad \beta x_{I\!P} = x$$

x_{IP} ~0.001-0.02

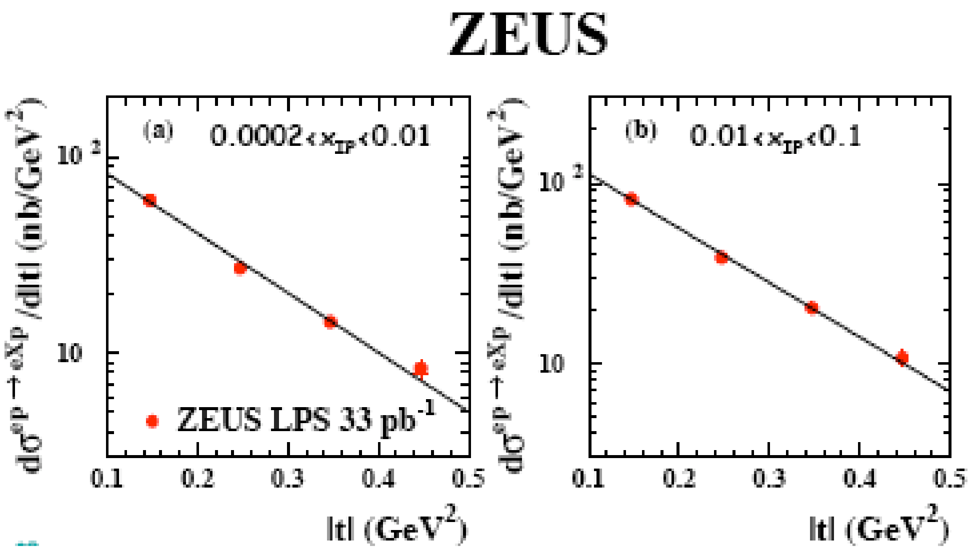
$$\frac{d\sigma^{ep\to eXp}}{d\beta\, dQ^2\, dx_{I\!P}\, dt} = \frac{4\pi\alpha_{\rm em}^2}{\beta Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D(4)}(\beta,Q^2,x_{I\!P},t) - \frac{y^2}{2}F_L^{D(4)}(\beta,Q^2,x_{I\!P},t)\right]$$

QCD evolution

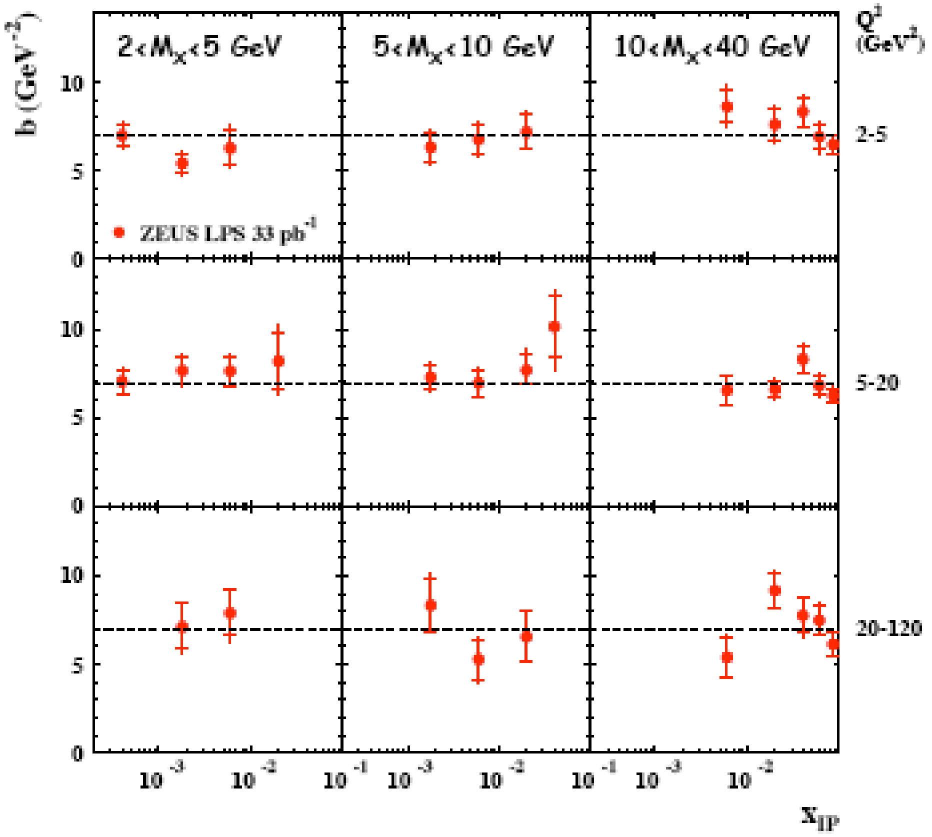
factorization

$$F_2^{D(4)}(\beta,Q^2,x_{I\!P},t) = \sum_i \int_\beta^1 \frac{dz}{z}\, C_i\!\left(\frac{\beta}{z}\right) f_i^D(z,x_{I\!P},t;Q^2)$$

t dependence is exponential (typical of diffraction)

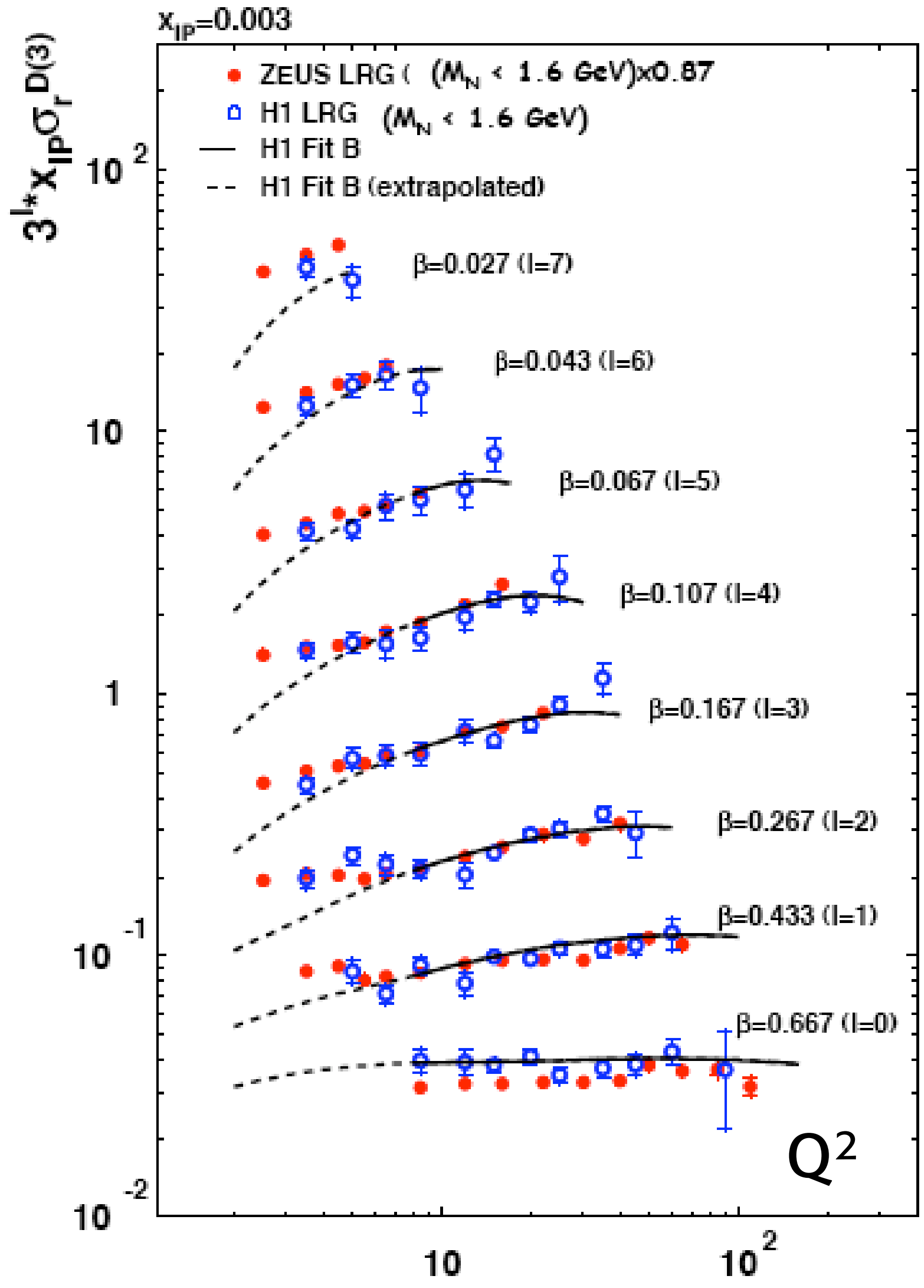


M. Ruspa '08 HERA-LHC Workshop

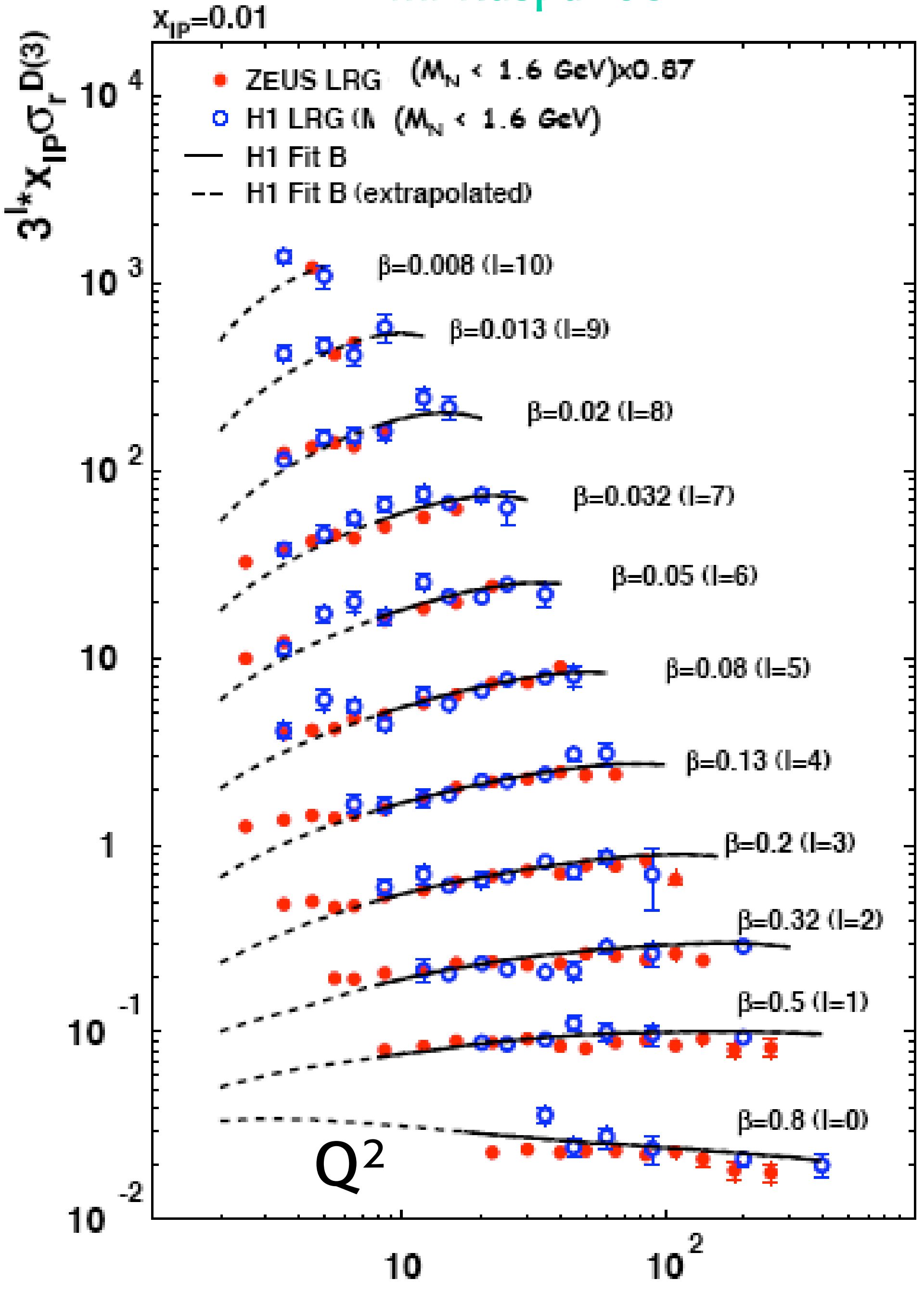


Fit to $e^{-b|t|}$ → $b = 7.0 \pm 0.4$ GeV^{-2}

M. Ruspa '08



x_{IP}=0.003
$3^l * x_{IP}\sigma_r^{D(3)}$
ZEUS LRG ((M_N < 1.6 GeV)x0.87
H1 LRG (M_N < 1.6 GeV)
H1 Fit B
H1 Fit B (extrapolated)
β=0.027 (l=7)
β=0.043 (l=6)
β=0.067 (l=5)
β=0.107 (l=4)
β=0.167 (l=3)
β=0.267 (l=2)
β=0.433 (l=1)
β=0.667 (l=0)
10^2
10
1
10^{-1}
10^{-2}
10
10^2
Q^2

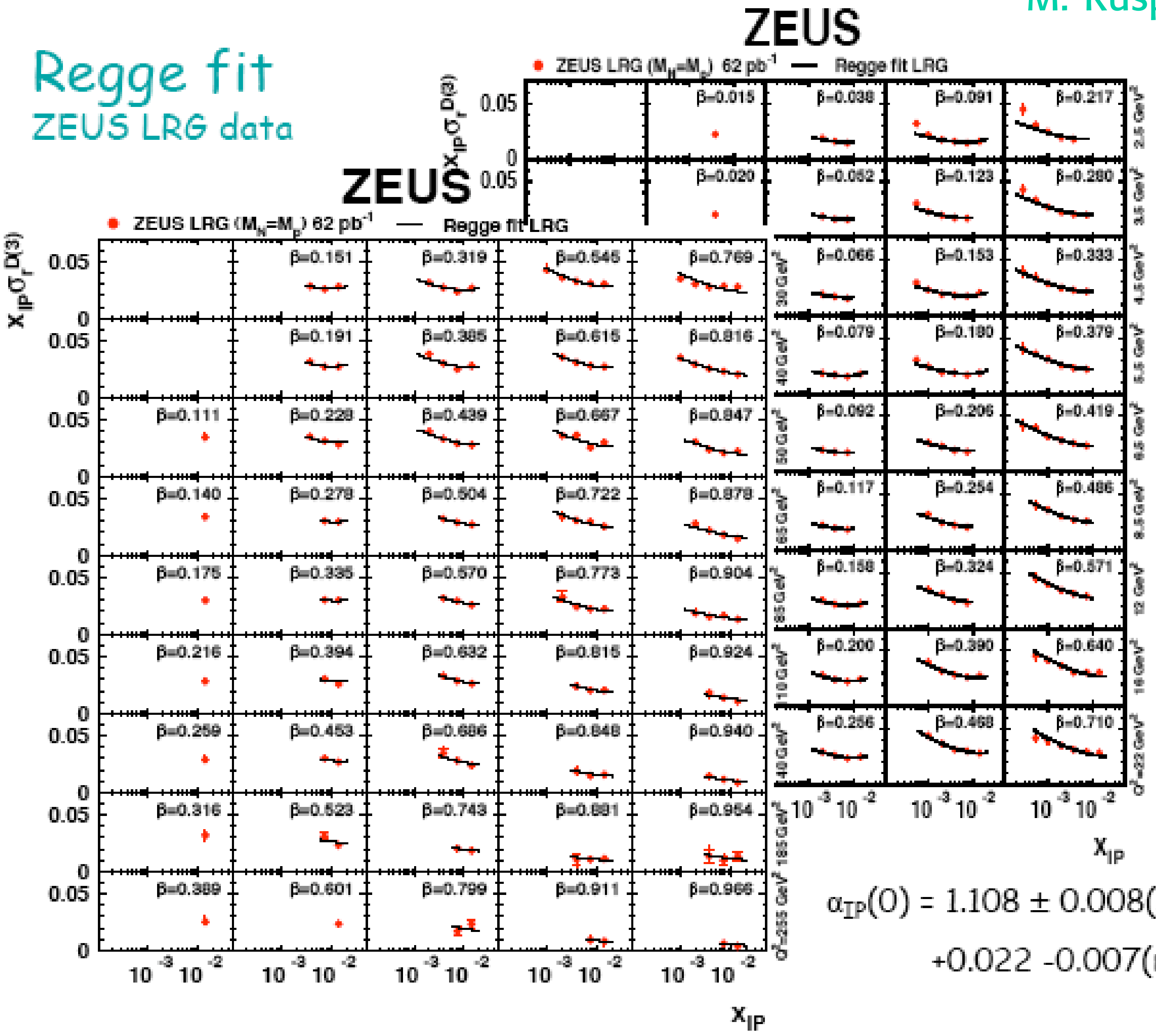


x_{IP}=0.01
$3^l * x_{IP}\sigma_r^{D(3)}$
ZEUS LRG (M_N < 1.6 GeV)x0.87
H1 LRG (M (M_N < 1.6 GeV)
H1 Fit B
H1 Fit B (extrapolated)
β=0.008 (l=10)
β=0.013 (l=9)
β=0.02 (l=8)
β=0.032 (l=7)
β=0.05 (l=6)
β=0.08 (l=5)
β=0.13 (l=4)
β=0.2 (l=3)
β=0.32 (l=2)
β=0.5 (l=1)
β=0.8 (l=0)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10
10^2
Q^2

M. Ruspa ‘08

Regge fit

ZEUS LRG data



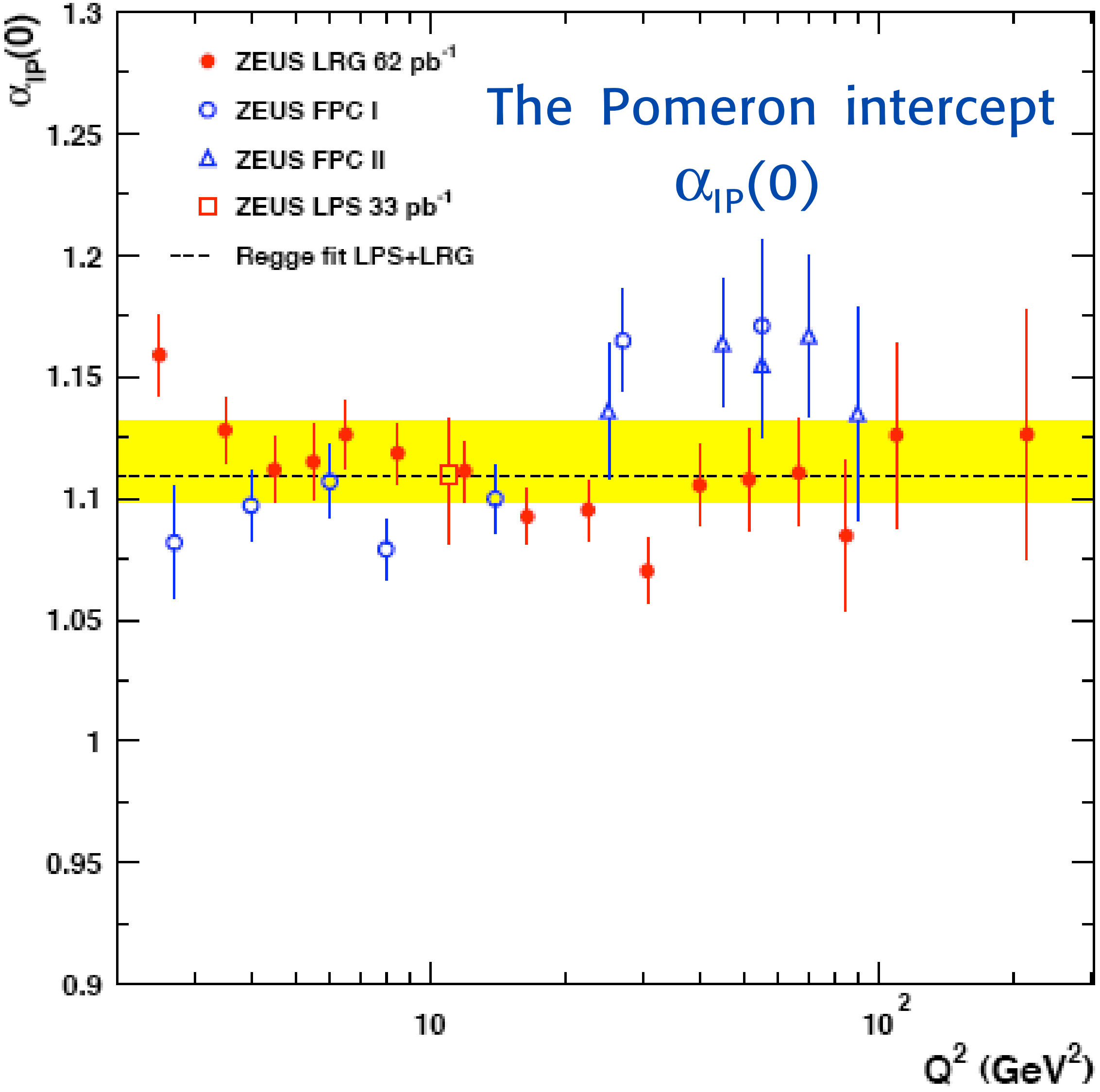
$\alpha_{IP}(0) = 1.108 \pm 0.008(\text{stat+syst})$

$+0.022\ -0.007(\text{model})$

→ Assumption of Regge factorisation works

M. Ruspa '08

The Pomeron intercept $\alpha_{IP}(0)$



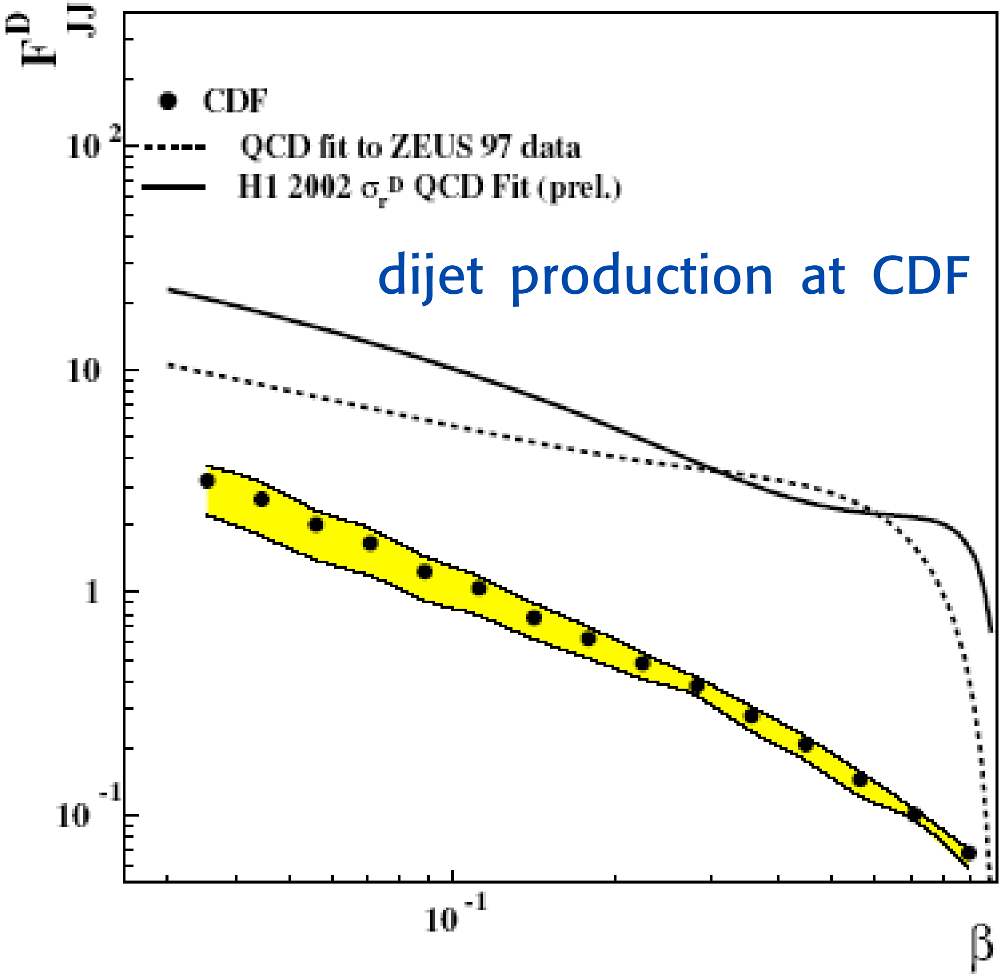
constant in Q^2

$\alpha_{IP}(0)>1$

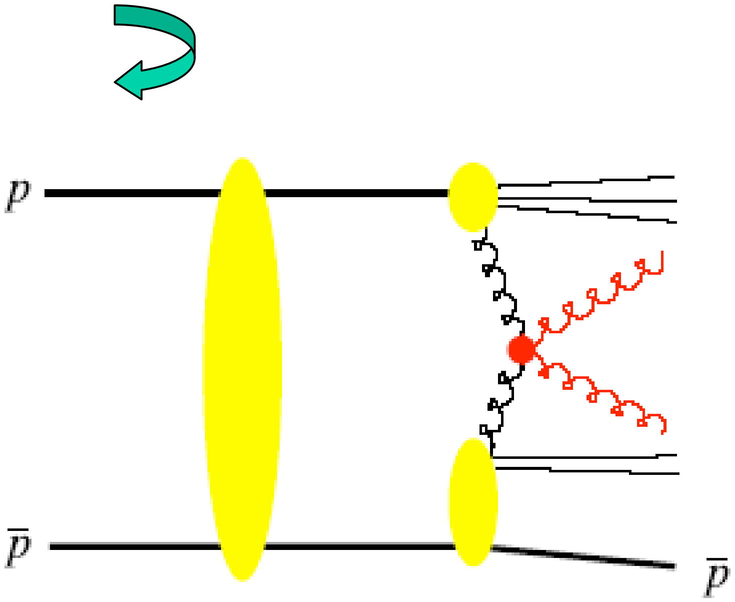
(maybe 1 modulo logs)

Diffractive parton densities do not factorize outside eP!

Berera, Soper '95
Collins '97

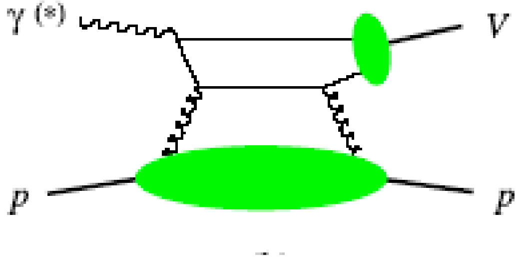


dijet production at CDF

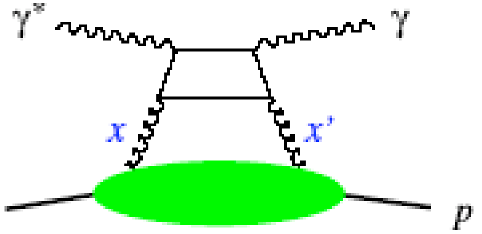


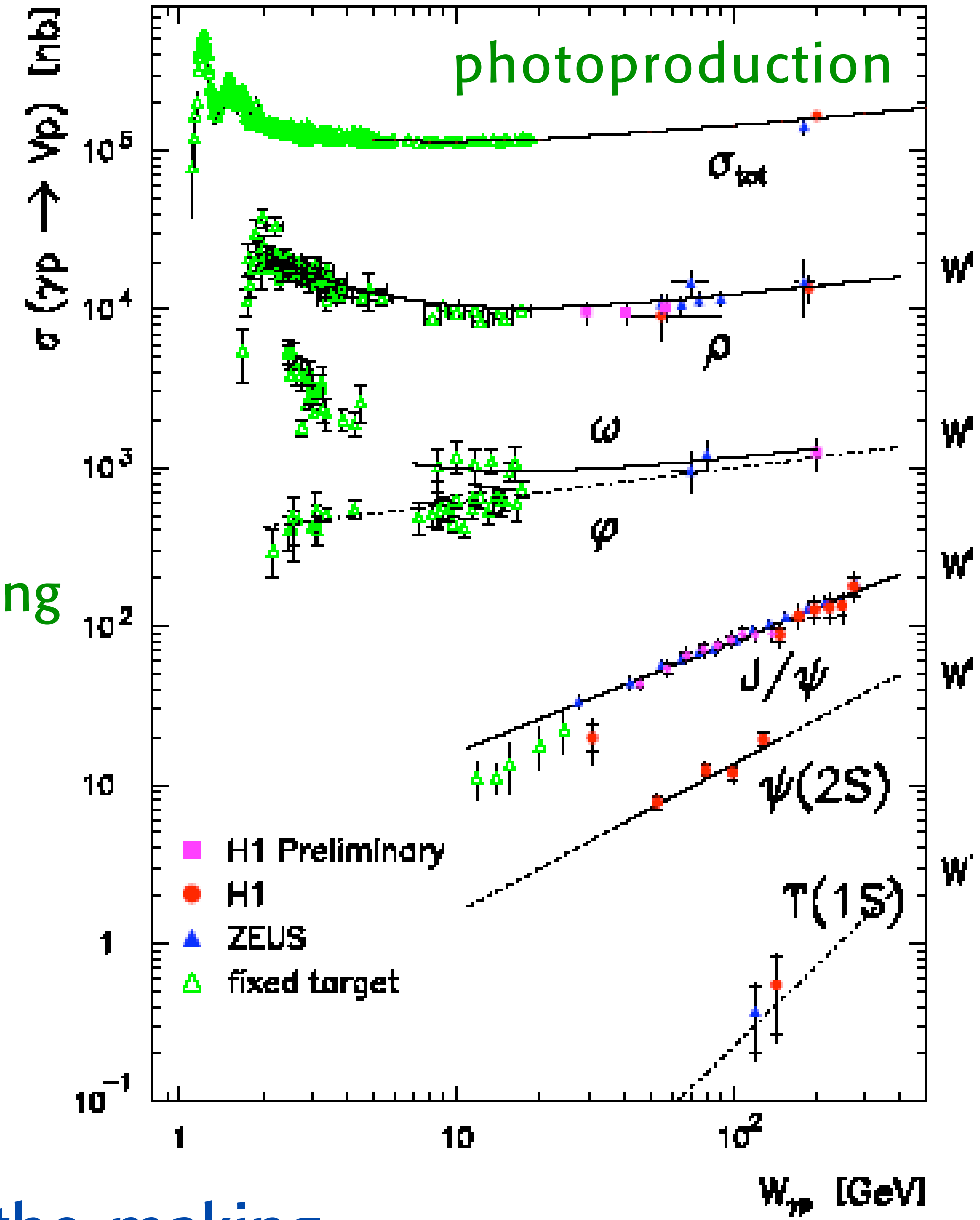
Exclusive diffractive processes

Vector meson production



Deeply virtual Compton Scattering



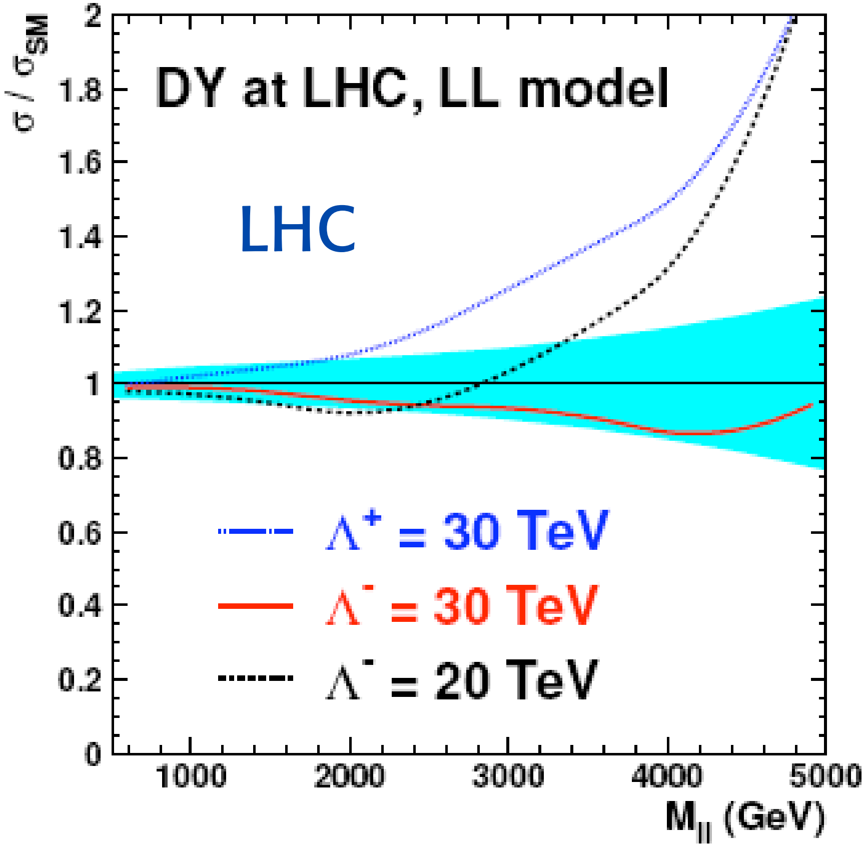


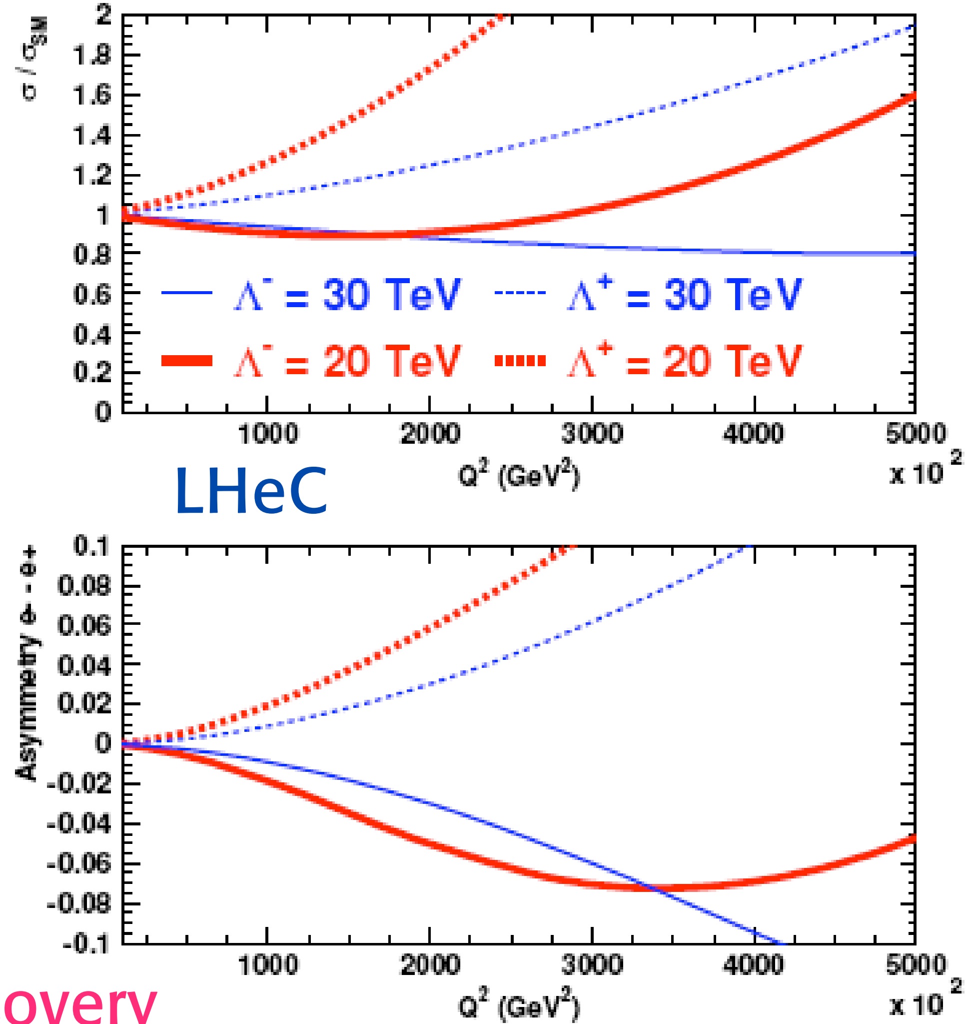
- A lot of physics still in the making

In some cases the LHeC can be useful to interpret new signals at the LHC

Example: contact interaction eeqq

E. Perez '07





- In general unlikely that a discovery at the LHeC is invisible at the LHC

A set of questions for the Workshop:

How well can the LHeC do on

- measuring α_s in DIS
- sharpening our grasp on pdf's
- measuring F_L
- studying heavy flavour production, eg $F^{cc}_{2,L}$, $F^{bb}_{2,L}$
- clarifying the small-x domain
  - disentangling resummation effects
  - approaching the saturation regime
  - studying inclusive/exclusive diffraction,
  - deep virtual Compton & non forward pdf
- achieving the goals of $e^{\pm}$-ion collisions
- studying electroweak processes
- complementing the LHC on new physics

Conclusion

HERA has very much contributed to our knowledge on the proton structure

A large number of open questions remain in this domain in particular at small x

Additional issues will certainly be prompted by the LHC data and discoveries

It would be a waste not to exploit the 7 TeV beams for eP and eA physics at some stage during the LHC time

I am sure that at this Workshop the physics case for the LHeC will become even more clear!