DESY, HERA Symposium, 5 July '11

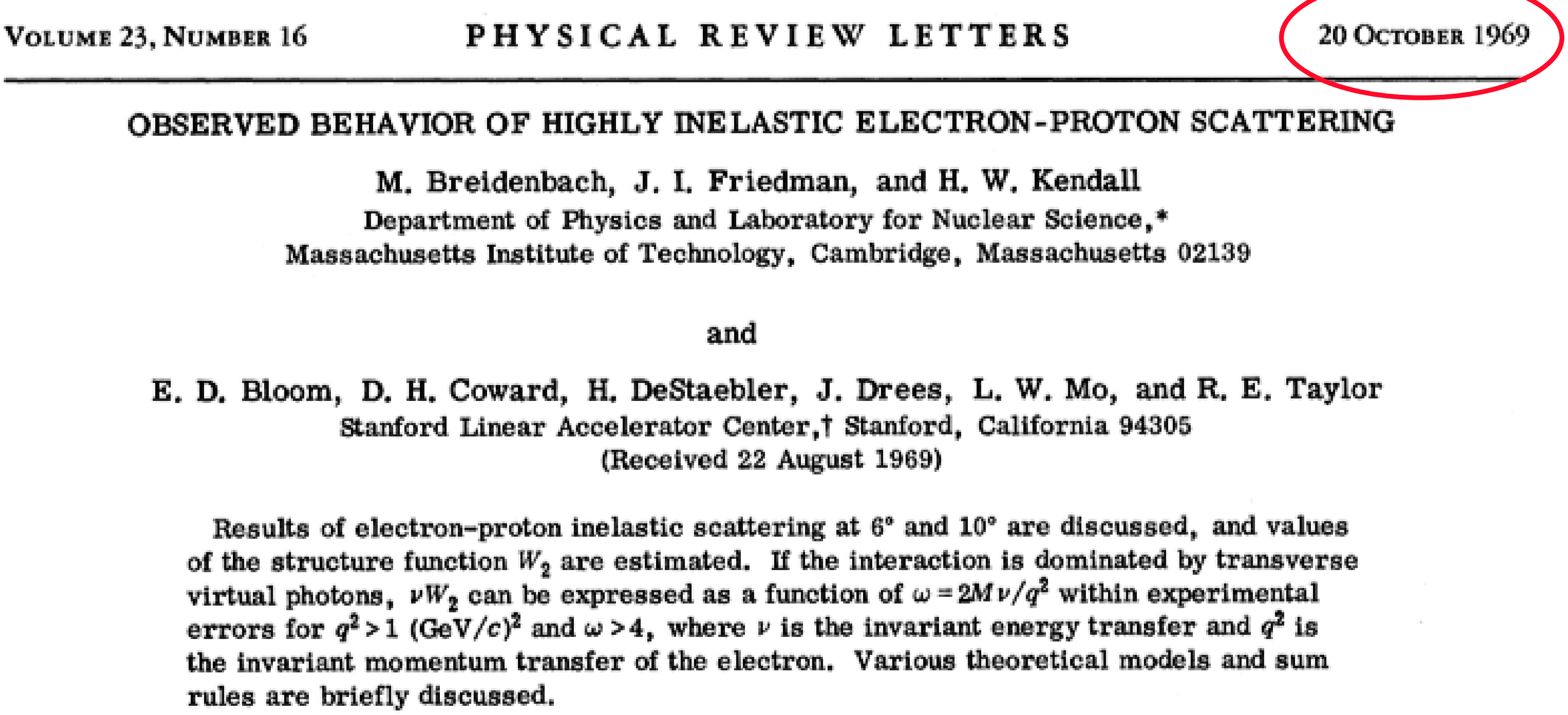
Overview of Deep Inelastic Scattering Physics

Past, Present and Future of DIS

Guido Altarelli

Universita' di Roma Tre and CERN

DIS is >40 years old!



VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

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Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

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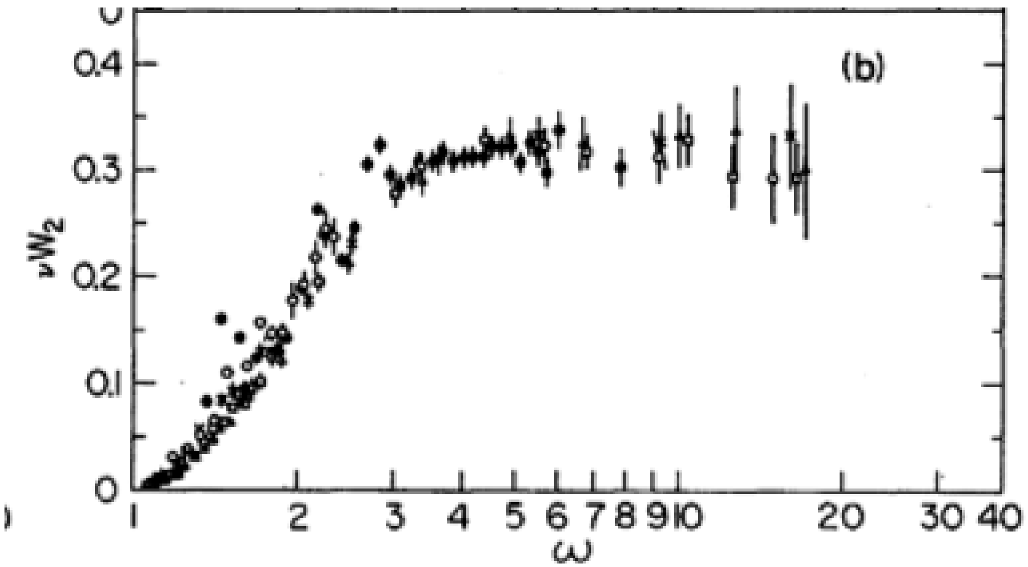
(Received 22 August 1969)

Results of electron-proton inelastic scattering at 6° and 10° are discussed, and values of the structure function W_2 are estimated. If the interaction is dominated by transverse virtual photons, νW_2 can be expressed as a function of $\omega = 2M\nu/q^2$ within experimental errors for $q^2 > 1$ $(\mathrm{GeV}/c)^2$ and $\omega > 4$, where ν is the invariant energy transfer and q^2 is the invariant momentum transfer of the electron. Various theoretical models and sum rules are briefly discussed.

1969: first evidence of approximate Bjorken scaling



Ever since
Deep Inelastic Scattering has
played a capital role in the
development of QCD

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

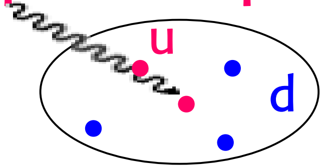
- Many structure functions
- $F_i(x,Q^2)$: two variables
- Neutral currents, charged currents
- Different beams and targets
- Different polarization

From the beginning: Establishing quarks and gluons as partons
Constructing a field theory of strong int.ns
and 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, e g:
Structure functions at small x; heavy flavour structure functions;
polarized parton densities, g_1, g_2, h_1...; non forward pdf's
Diffraction

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:

$\sigma_L \sim 0$

$F=2F_1 \sim F_2/x$

...... = small sea

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

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

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

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

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

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

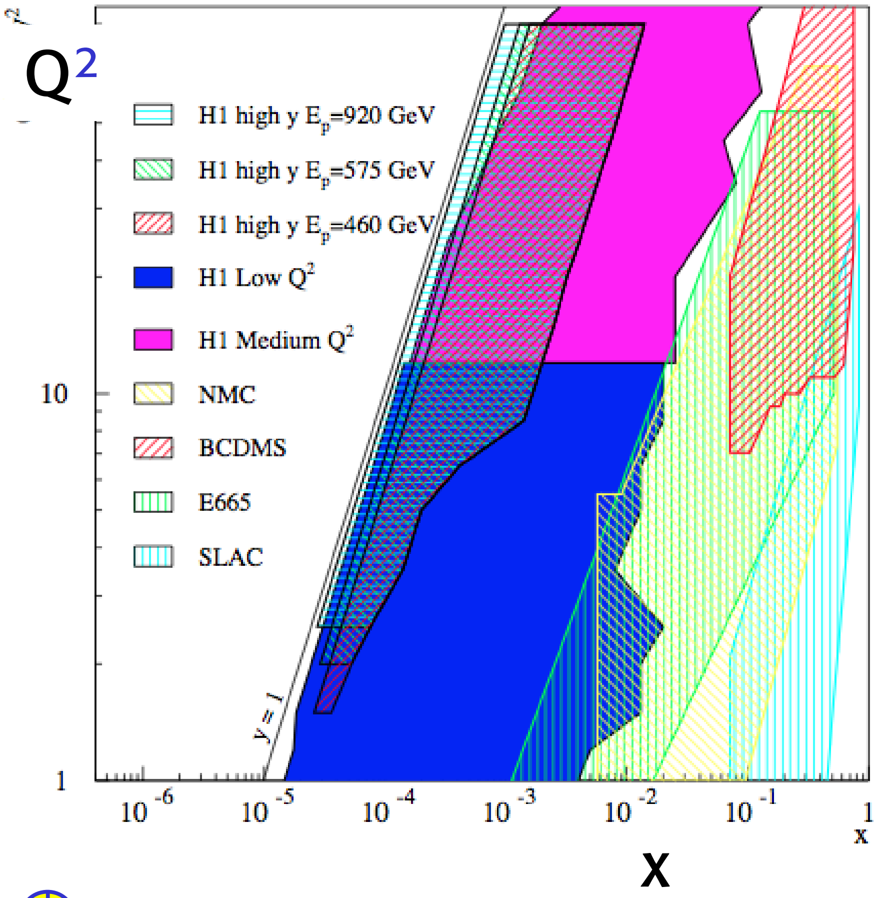
$$\int(s-\bar{s})dx = 0$$

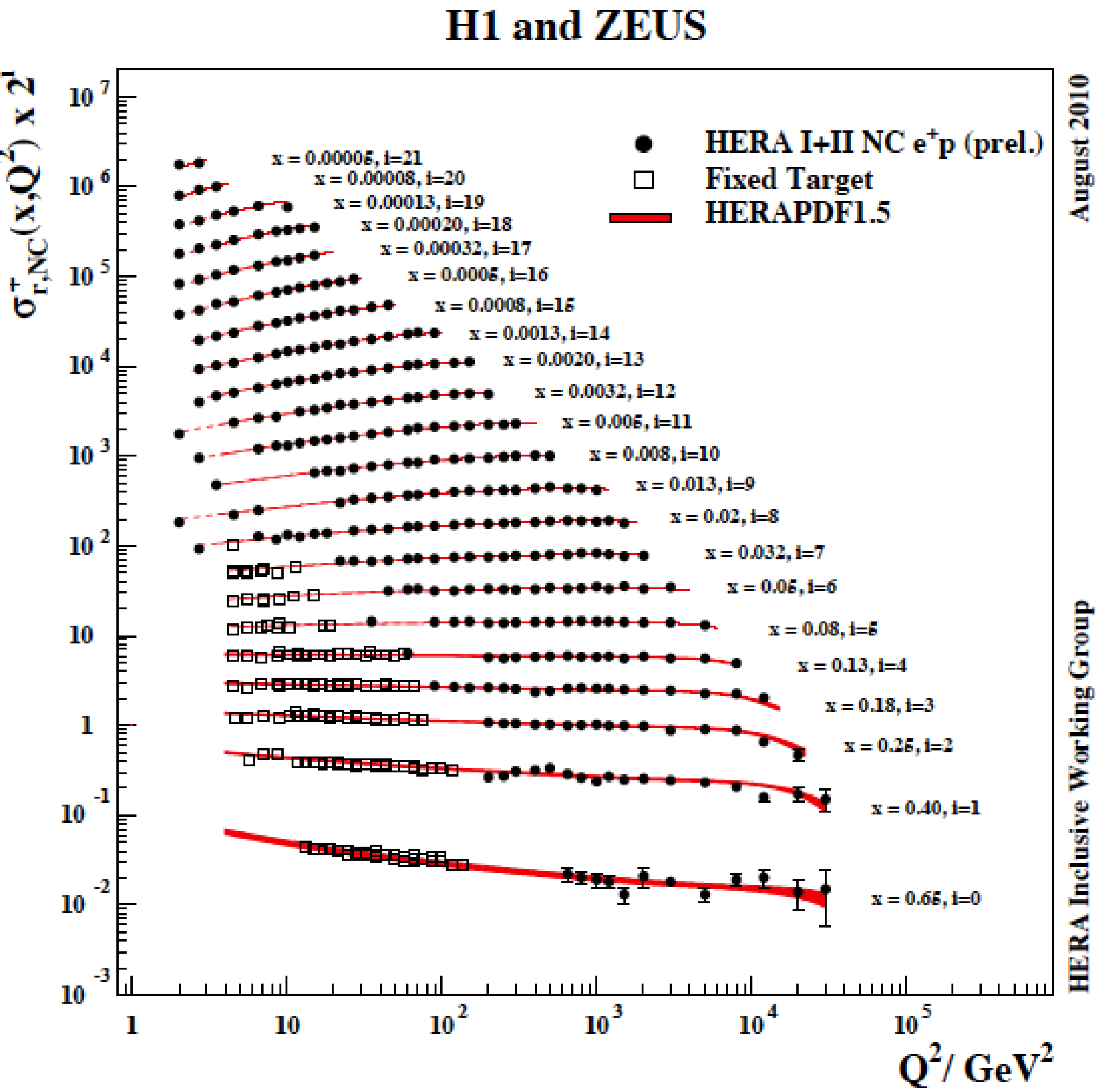
F= F(x), u=u(x), d= d(x):
naive parton model (scaling)

Over the years a magnificent work
both experimental and theoretical

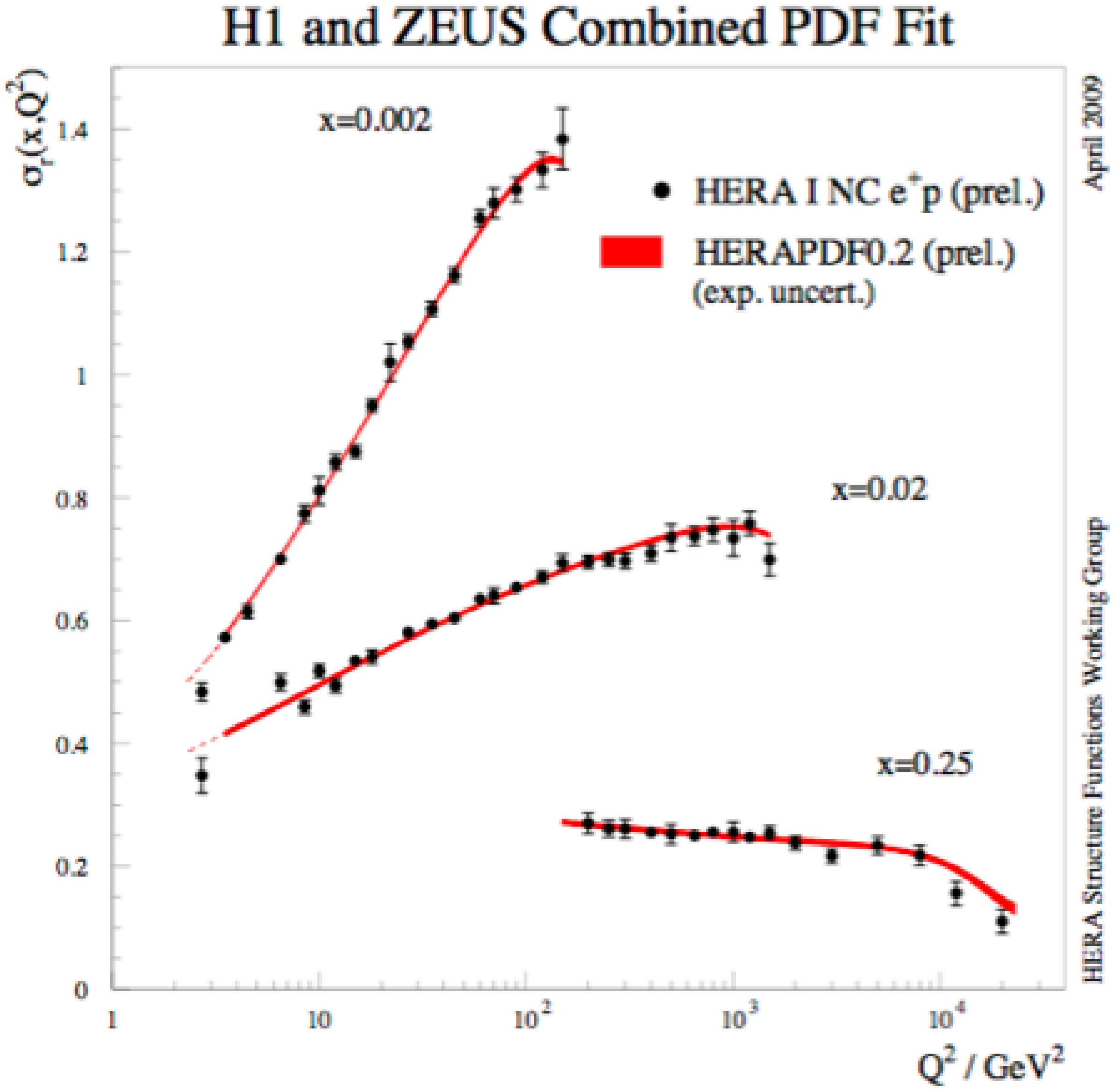
Great progress in the DIS data culminated at HERA

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

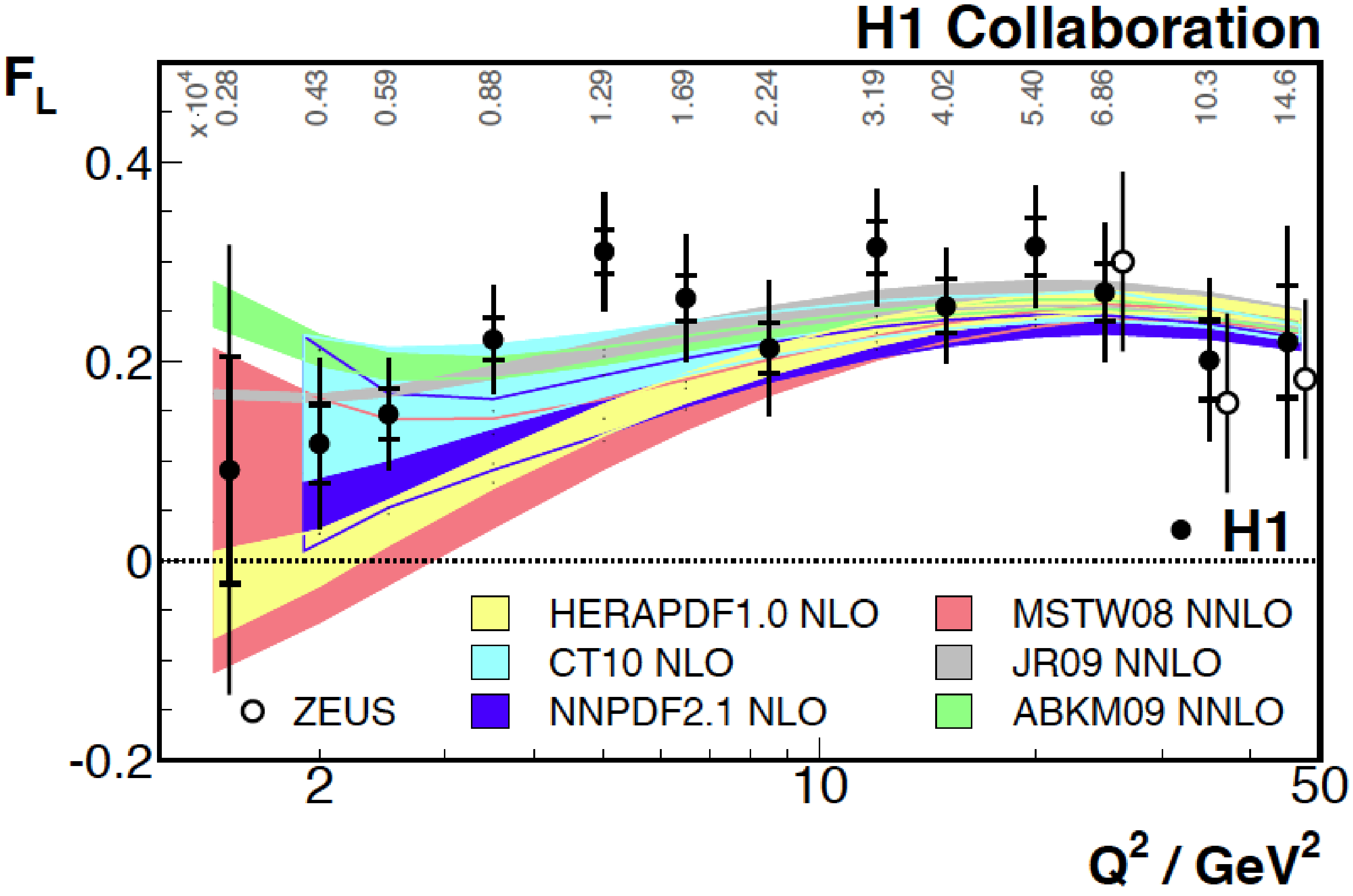




This is how the scaling violations appear in 2011 after >40 years



It took ~40 years to get meaningful data on the longitudinal structure function!!

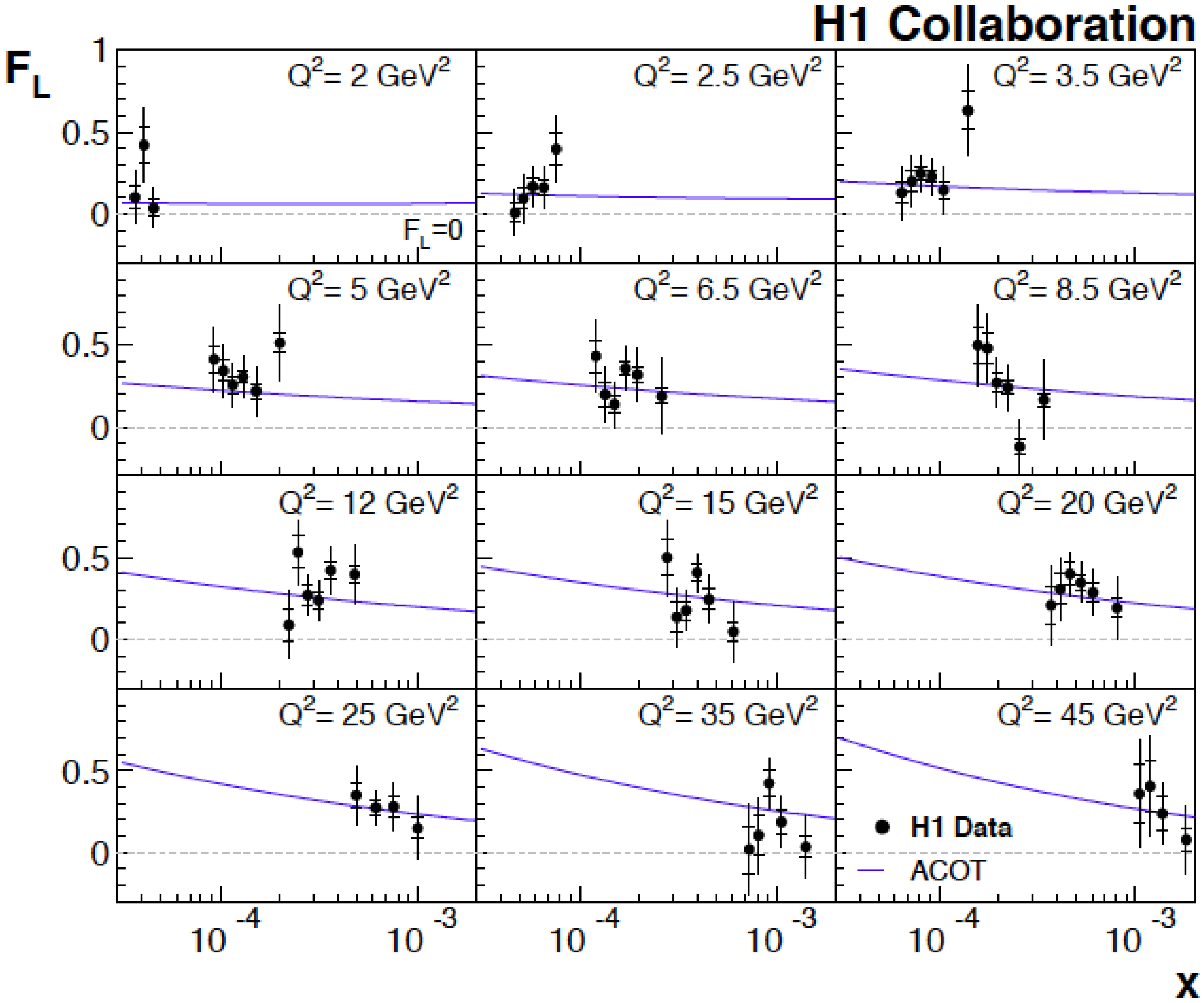


But better data would be highly desirable

Altarelli, Martinelli '78

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

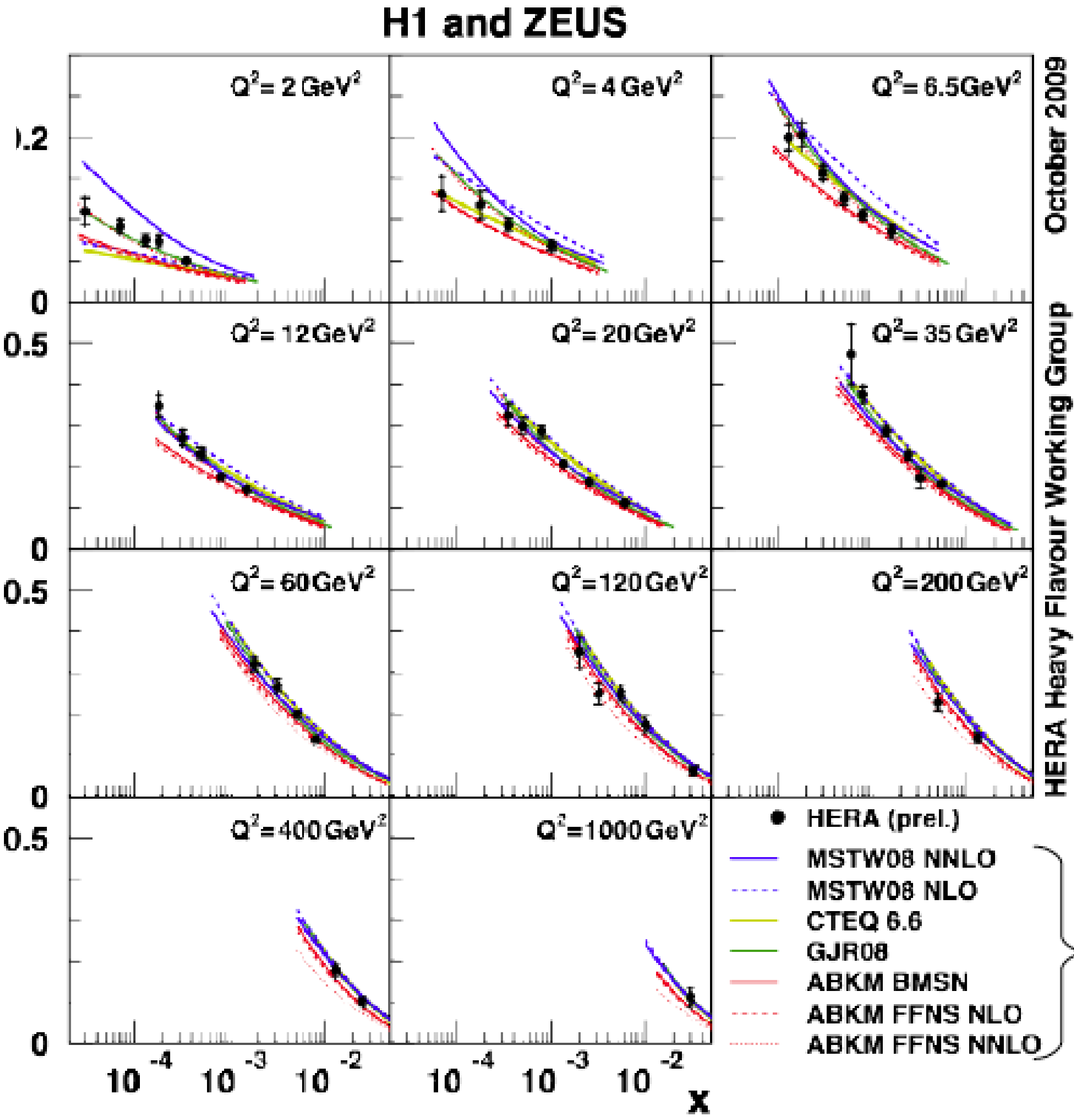
F_L vs x, Q^2



NLO QCD & ACOT

Heavy flavoured structure functions

F_2^{cc}

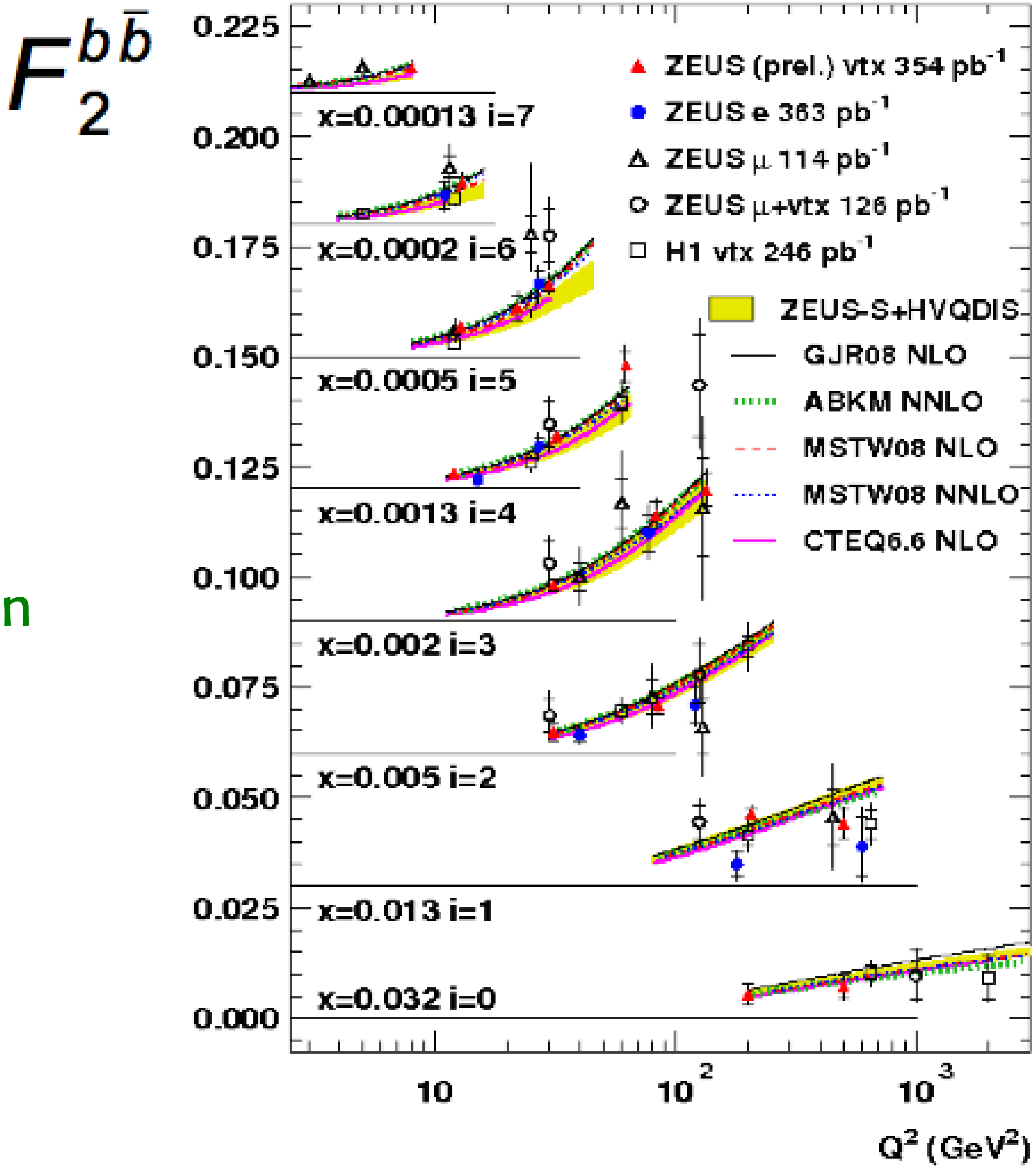


The charm component of F_2 measured

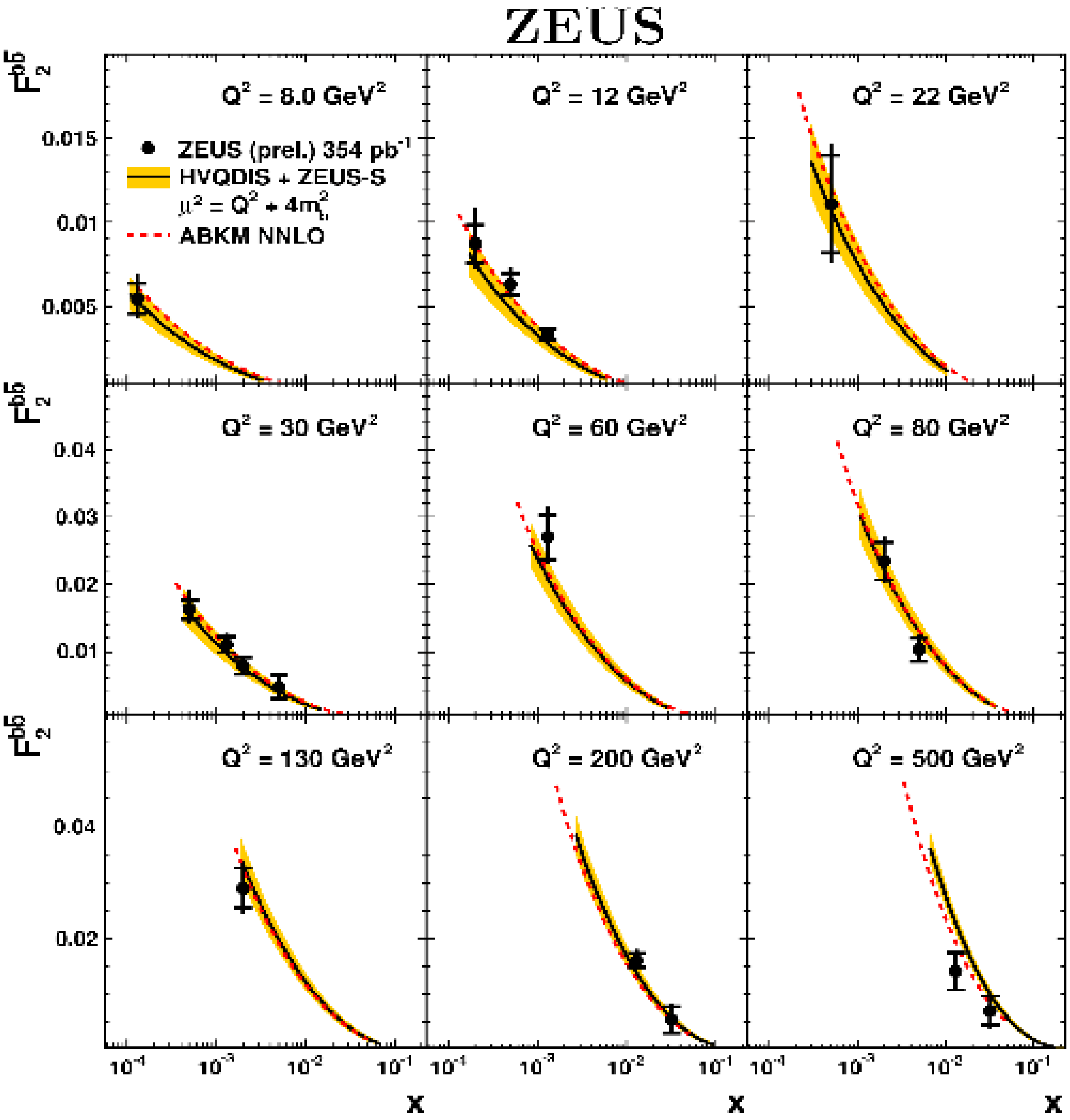
A great job at HERA!

different HQ schemes

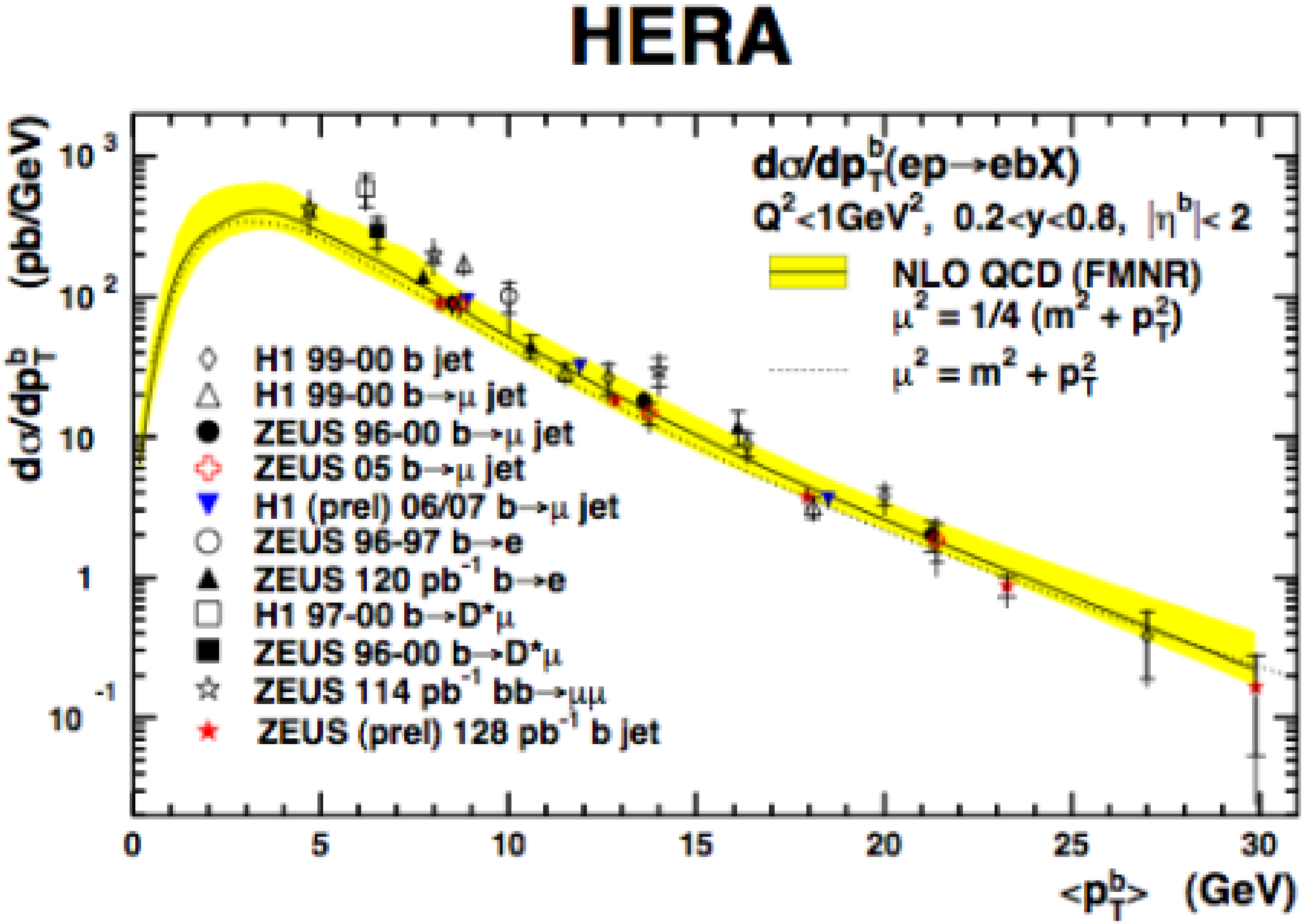
And also the b quark contribution to F2 has been measured



$F_2^{b\bar{b}}$


ZEUS
$F_2^{b\bar{b}}$
Q^2 = 8.0 GeV^2
ZEUS (prel.) 354 pb^{-1}
HVQDIS + ZEUS-S
$\mu^2 = Q^2 + 4m_b^2$
ABKM NNLO
Q^2 = 12 GeV^2
Q^2 = 22 GeV^2
0.015
0.01
0.005
Q^2 = 30 GeV^2
Q^2 = 60 GeV^2
Q^2 = 80 GeV^2
0.04
0.03
0.02
0.01
Q^2 = 130 GeV^2
Q^2 = 200 GeV^2
Q^2 = 500 GeV^2
0.04
0.02
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

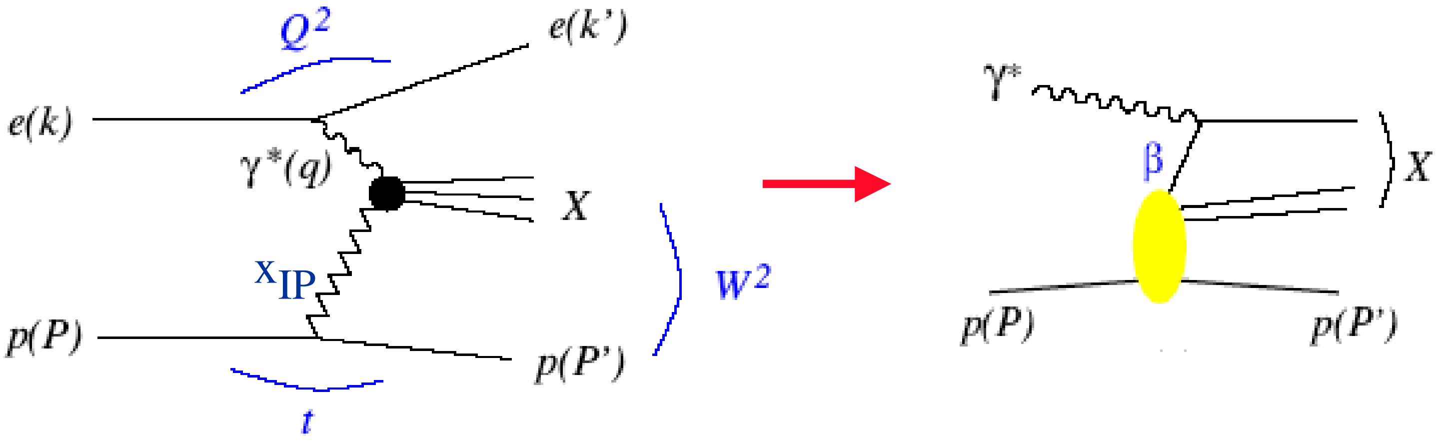
b photoproduction



Fair agreement with NLO QCD

Diffractive structure functions

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

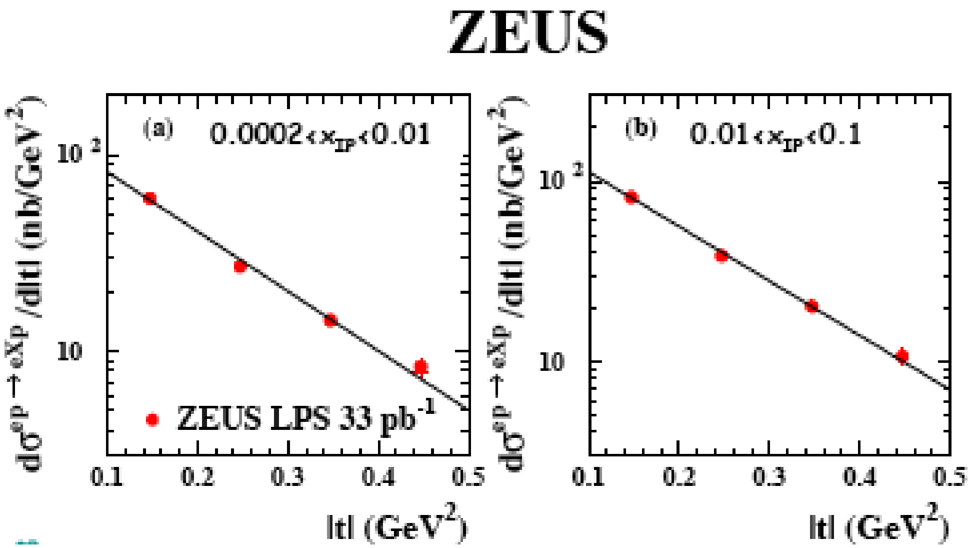
$$\frac{d\sigma^{ep\to eXp}}{d\beta\, dQ^2\, dx_{I\!P}\, dt} = \frac{4\pi\alpha_{\rm em}^2}{\beta Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D(4)}(\beta,Q^2,x_{I\!P},t) - \frac{y^2}{2}F_L^{D(4)}(\beta,Q^2,x_{I\!P},t)\right]$$

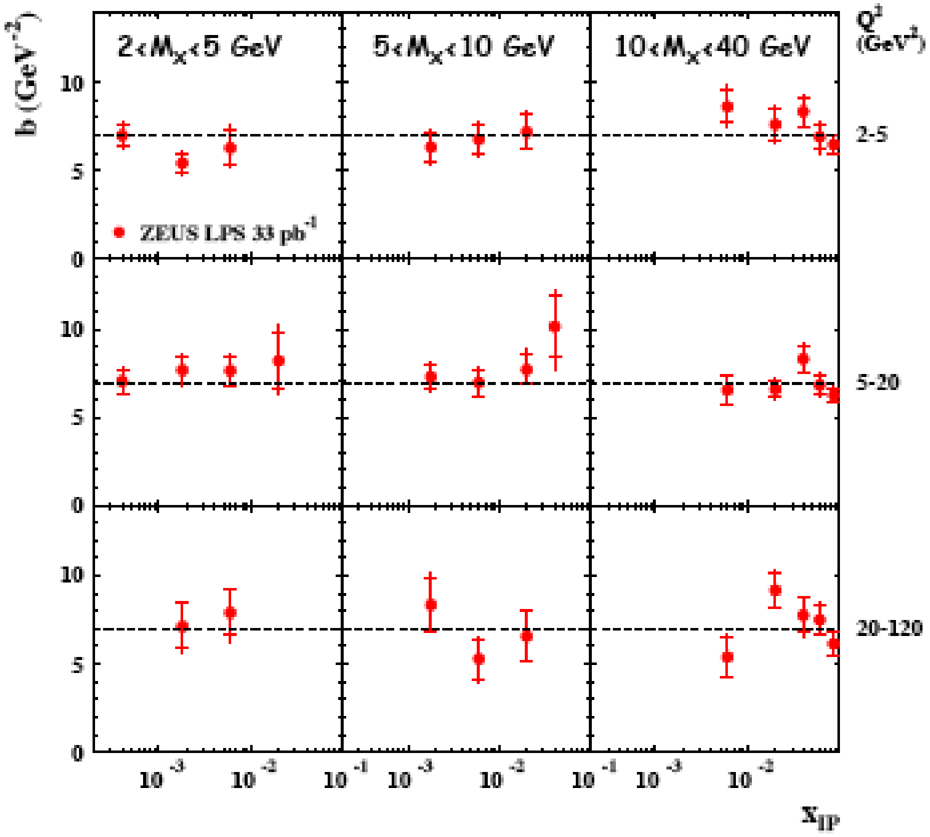
QCD evolution

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)

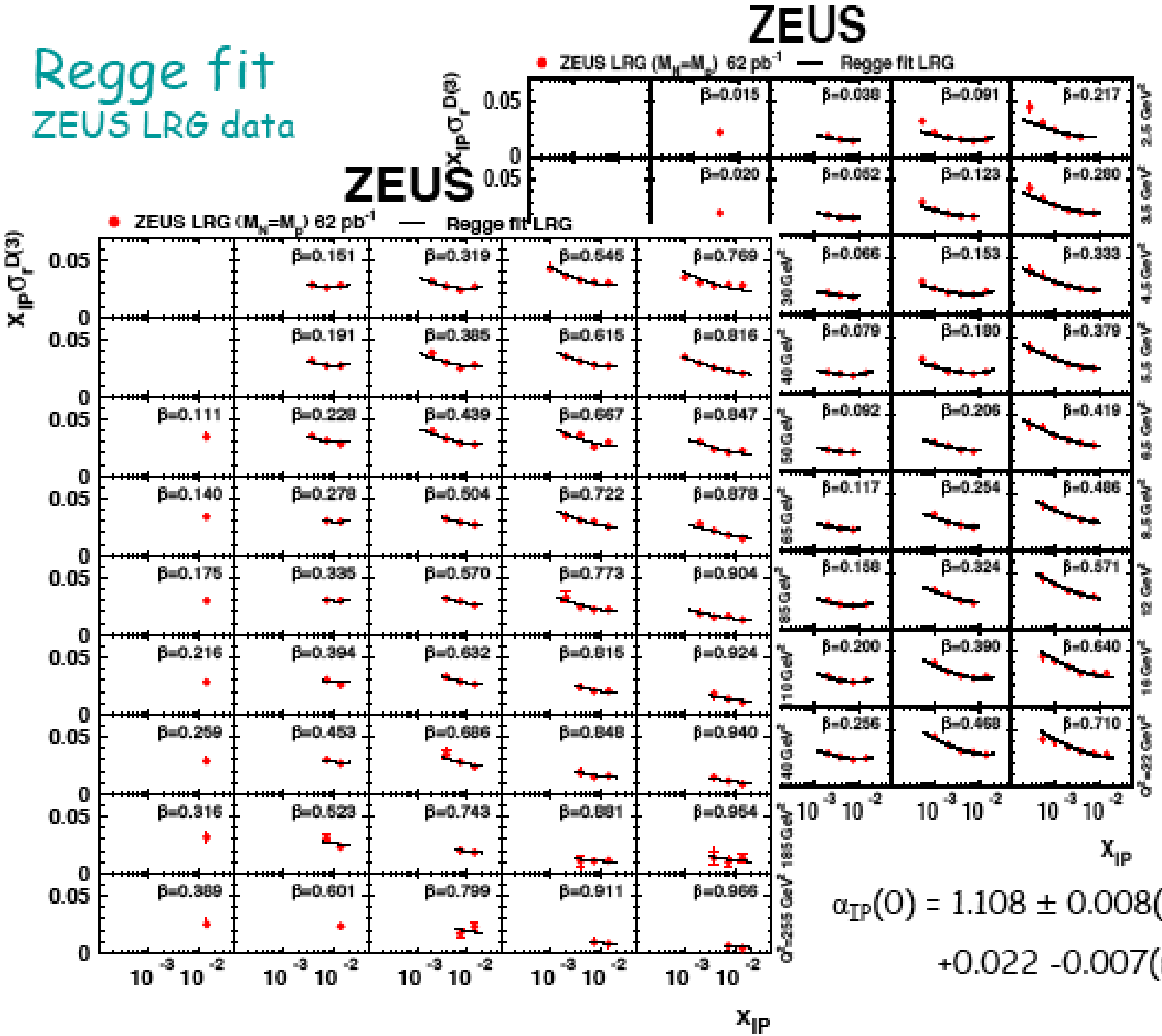




Fit to $e^{-b|t|}$ → $b = 7.0 \pm 0.4$ GeV^{-2}

Regge fit

ZEUS LRG data

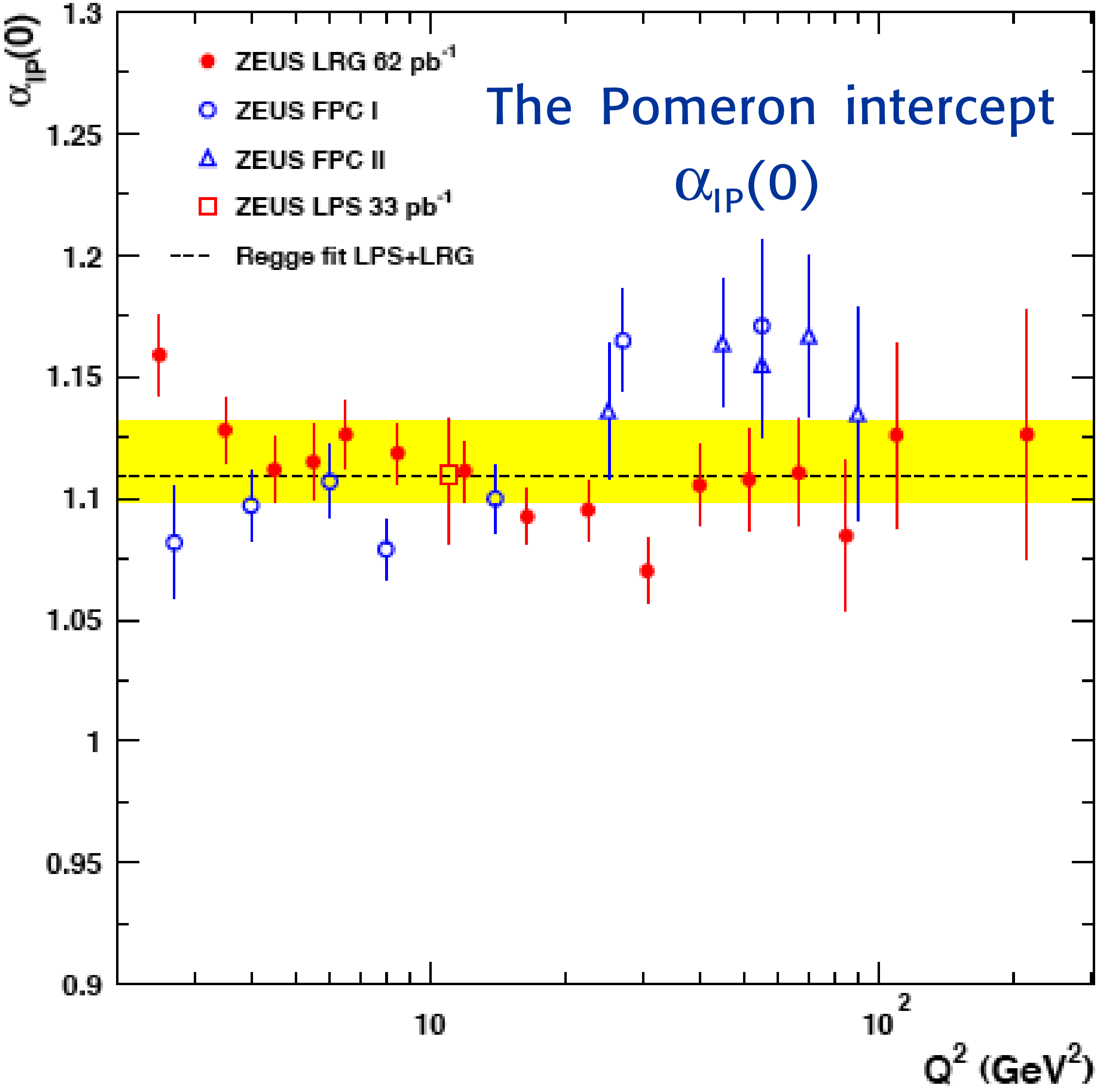


$\alpha_{IP}(0)$ = 1.108 ± 0.008(stat+syst)

+0.022 -0.007(model)

→ Assumption of Regge factorisation works

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



constant in Q^2

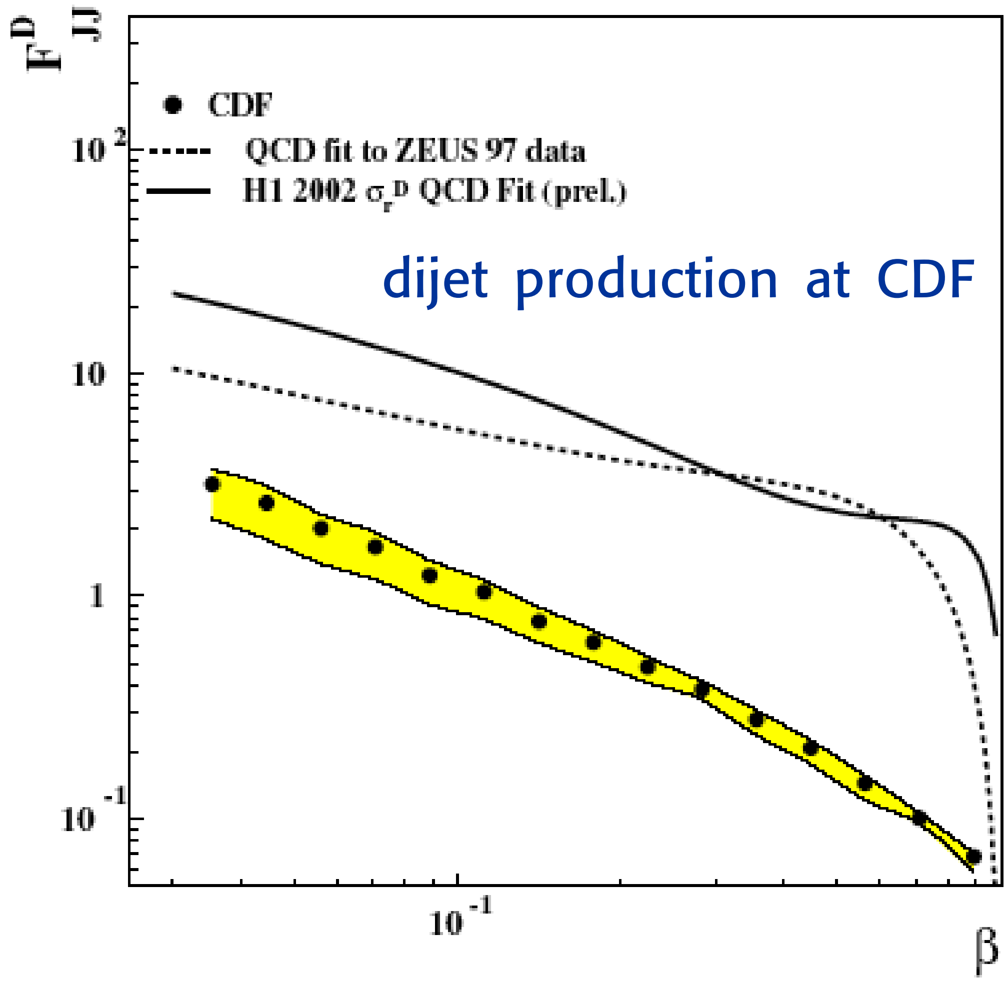
$\alpha_{IP}(0)>1$

(maybe 1

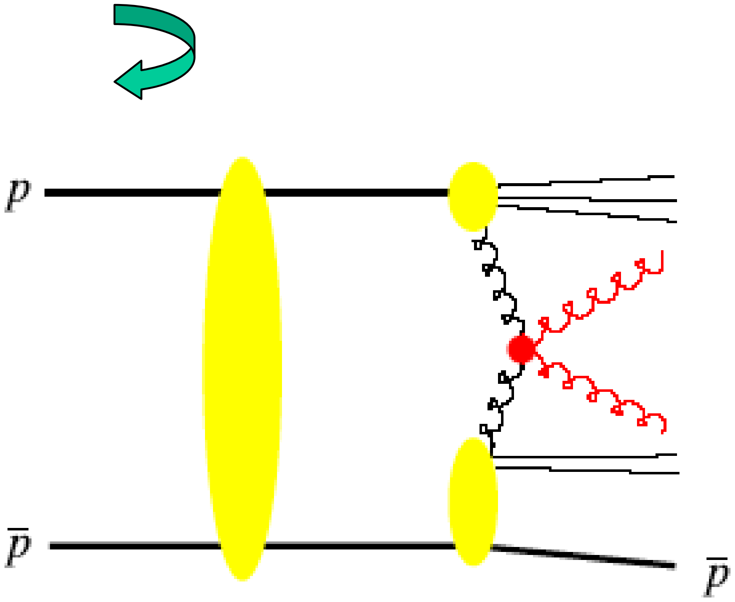
modulo logs)

Diffractive parton densities do not factorize outside eP!

Berera, Soper '95
Collins '97



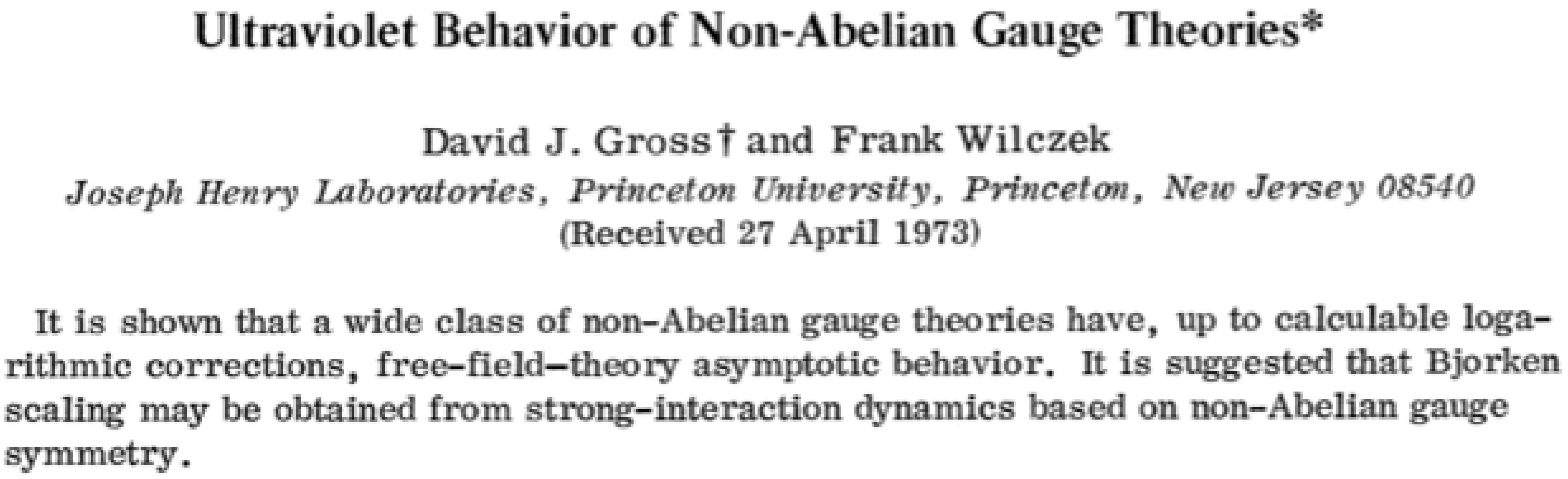
dijet production at CDF



Progress in experiment has been matched by impressive achievements in theory

For example in the theory of scaling violations

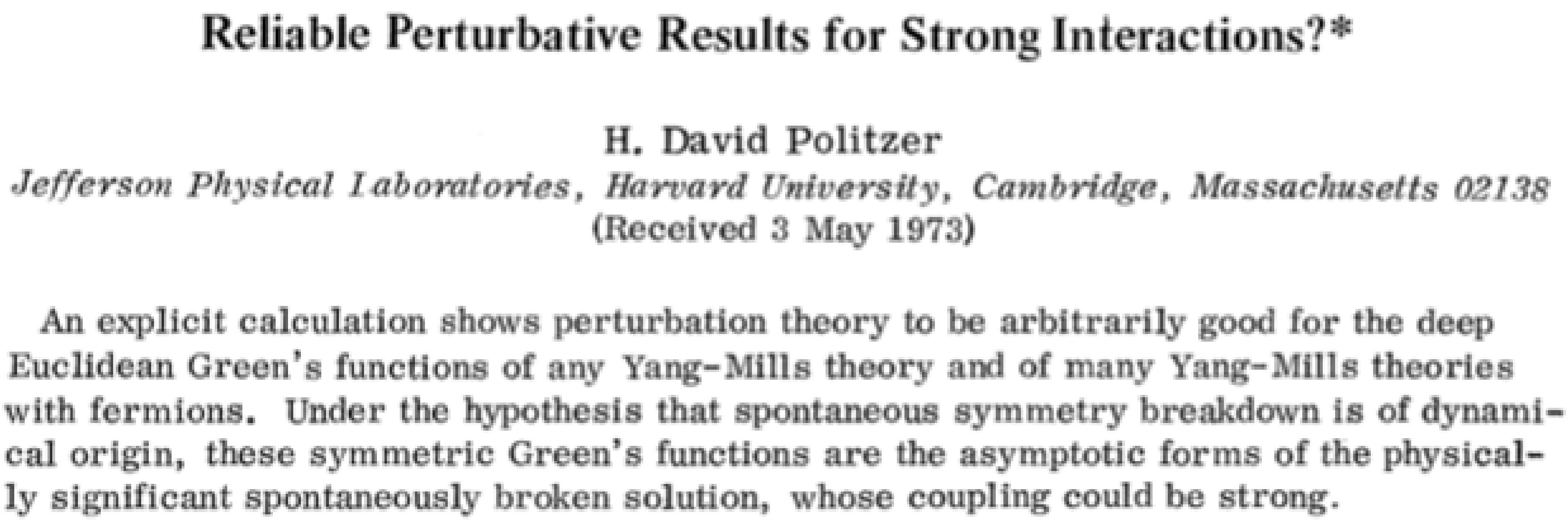
One can say that the application of QCD starts with the Nobel winner papers by Gross & Wilczek and by Politzer in 1973



Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

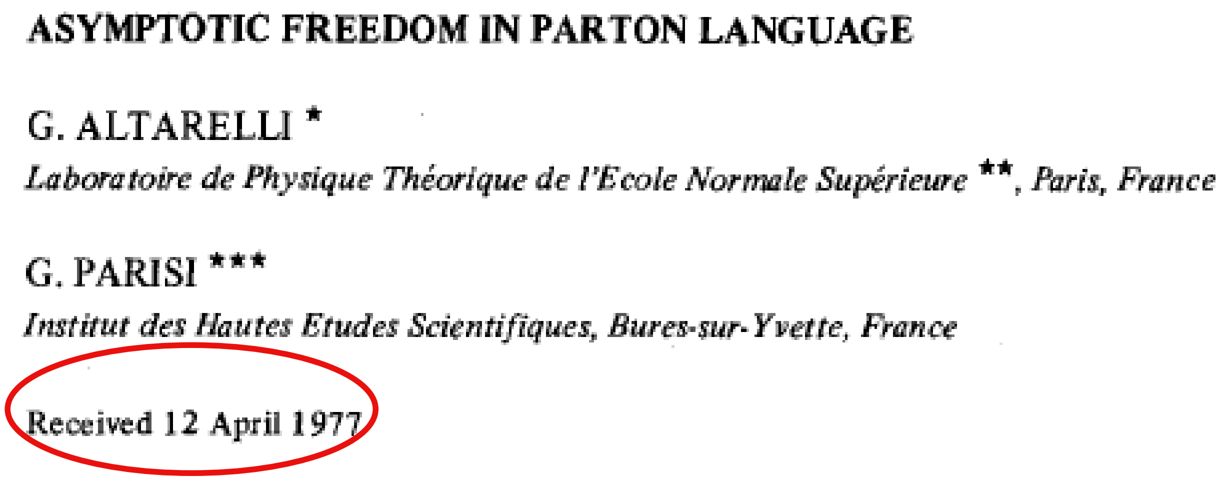


Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

In few years the QCD improved parton model was developed



ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *

Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, *Paris, France*

G. PARISI ***

Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{q^i q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^i G}\left(\frac{x}{y}\right)\right] \qquad (22)$$

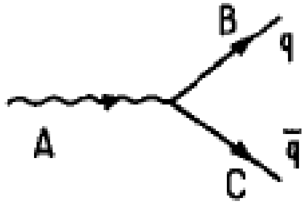
$t = \ln Q^2/\mu^2$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{Gq^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right] \qquad (23)$$

The QCD evolution equations hand-written by me on the '77 preprint (scanned by KEK)

In our paper, formulated in parton language but with running coupling, the splitting functions are derived directly from the QCD vertices, making clear they are the same for all processes (factorisation)

$$P_{\mathrm{BA}}(z) = \tfrac{1}{2}\, z(1-z) \overline{\sum_{\text{spins}}} \frac{|V_{\mathrm{A}\to\mathrm{B}+\mathrm{C}}|^2}{p_\perp^2} \qquad (z<1)$$



$$\overline{\sum_{\text{pol}}} |V_{\mathrm{q}\to\mathrm{G}+\mathrm{q}}|^2 = \frac{2p_\perp^2}{z(1-z)} \frac{1+(1-z)^2}{z} C_2(\mathrm{R})$$

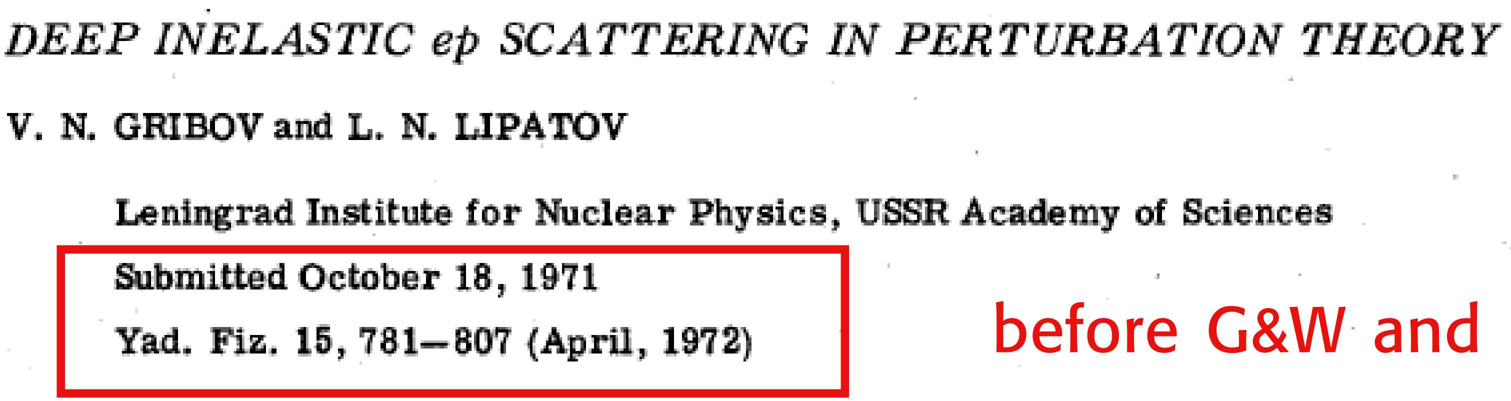
$$P_{\mathrm{Gq}}(z) = C_2(\mathrm{R}) \frac{1+(1-z)^2}{z}$$

$$P_{\mathrm{qq}}(z) = C_2(\mathrm{R}) \frac{1+z^2}{1-z} \qquad (z<1)$$

$$P_{\mathrm{qq}}(z) = C_2(\mathrm{R}) \left[\frac{1+z^2}{(1-z)_+} + \tfrac{3}{2}\,\delta(z-1) \right]$$

The evolution is described as a branching process with probabilities determined by the splitting functions

The evolution equations are now often called DGLAP



DEEP INELASTIC *ep* SCATTERING IN PERTURBATION THEORY

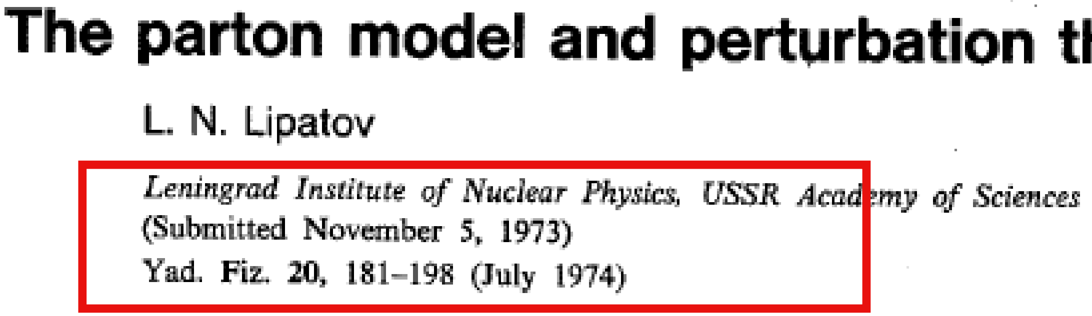
V. N. GRIBOV and L. N. LIPATOV

Leningrad Institute for Nuclear Physics, USSR Academy of Sciences

Submitted October 18, 1971

Yad. Fiz. 15, 781—807 (April, 1972)

before G&W and P!

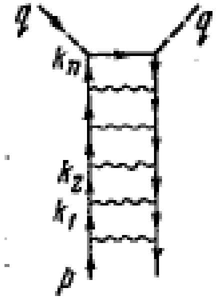


The parton model and perturbation theory

L. N. Lipatov

Leningrad Institute of Nuclear Physics, USSR Academy of Sciences
(Submitted November 5, 1973)
Yad. Fiz. 20, 181–198 (July 1974)

These papers refer to an abelian vector theory [presented together with a pseudoscalar theory] $H_{int} = g\bar{\psi}\gamma_\mu\psi V_\mu$



They ask the right question and extract the relevant terms from the dominant class of diagrams

But from their presentation it is very difficult to extract the useful results (in the vector theory section).

$$\frac{dD_i^j(x)}{\partial\Lambda} = -D_i^j(x)\,w_j(g_\Lambda^2)\frac{1}{\Lambda} + \sum_{j'}\int_x^1 dx' D_i^{j'}(x')\,w_{j'\to j}(x',x)\frac{1}{\Lambda},$$

$$D_i^j(x)|_{\Lambda=m^2} = \delta(x-1)\delta_{ij},$$

$$w_{N\to N}(x_j' x_N) = w_{\bar{N}\to\bar{N}}(x', x_N) = \frac{g_\Lambda^2}{16\pi^2}2\frac{1}{(x')^2}\frac{x'^2+x_N^2}{x'-x_N}$$

$$w_{N\to M}(x', x_M) = w_{\bar{N}\to M}(x', x_M) = \frac{g_\Lambda^2}{16\pi^2}2\frac{1}{(x')^2}\frac{x'^2+(x'-x_M)^2}{x_M}.$$

Calculation of structure functions of deep-inelastic scattering and e^+e^- annihilation by perturbation theory in quantum chromodynamics

Yu. L. Dokshitser

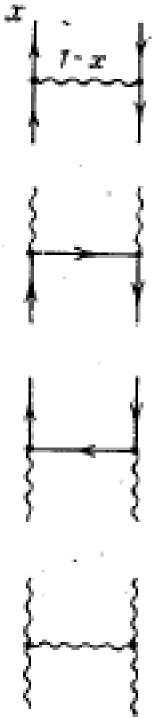
Leningrad Institute of Nuclear Physics, USSR Academy of Sciences

(Submitted April 20, 1977)
Zh. Eksp. Teor. Fiz. 73, 1216–1240 (October 1977)

Exactly contemporary to us

The limit x->1 is not made explicit

More explicit than G&L



$$\equiv V_F^F(x) = 2\,\frac{1+x^2}{1-x},$$

$$\equiv V_F^G(x) = 2\,\frac{1+(1-x)^2}{x},$$

$$\equiv V_G^F(x) = 2[x^2+(1-x)^2],$$

$$\equiv V_G^G(x) = 4x(1-x)\left[1+\frac{1}{x^2}+\frac{1}{(1-x)^2}\right]$$

non abelian

He knew G&L who are quoted in the refs.:

[7] V. N. Gribov and L. N. Liparov, Yad. Fiz. **15**, 781, 1218 (1972) [Sov. J. Nucl. Phys. **15**, 438, 675 (1972)].

[8] L. N. Lipatov, Yad. Fiz. **20**, 181 (1974) [Sov. J. Nucl. Phys. **20**, 94 (1975)].

This is the D. result “equivalent” to the evolution equations

$$W_q(\omega_k, \xi_k; \xi) = \frac{e_q^2}{d_F(\xi)} \delta\left(1 - \frac{1}{\omega_k}\right) + \int_{\xi_k}^{\xi} d\xi' \int_0^1 \frac{dx}{x} \Phi_F^F(x) \cdot$$

$$W_q(x\omega_k, \xi'; \xi) + \int_{\xi_k}^{\xi} d\xi' \frac{d_G(\xi')}{d_F(\xi')} \int_0^1 \frac{dx}{x} \Phi_F^G(x) \tilde{W}(x\omega_k, \xi'; \xi),$$

$$\tilde{W}(\omega_k, \xi_k; \xi) = \int_{\xi_k}^{\xi} d\xi' \int_0^1 \frac{dx}{x} \Phi_G^G(x) \tilde{W}(x\omega_k, \xi'; \xi)$$

$$\xi = \frac{1}{16\pi^2} \int_{\mu^2}^{|q^2|} \frac{dk^2}{k^2} \bar{g}^2(k^2)$$

$$+ \int_{\xi_k}^{\xi} d\xi' \frac{d_F(\xi')}{d_G(\xi')} \int_0^1 \frac{dx}{x} \Phi_G^F(k) \sum_{q,\bar{q}=1}^{n_f} [W_q(x\omega_k, \xi'; \xi) + W_{\bar{q}}].$$

Note: $d_G/d_F \tilde{W}$ is what we call the gluon density in terms of partons

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

For nearly 20 years all splitting funct.s P have been known to only NLO accuracy: $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + \ldots\ldots$

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 $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + \alpha_s^3 P_3 + \ldots\ldots$

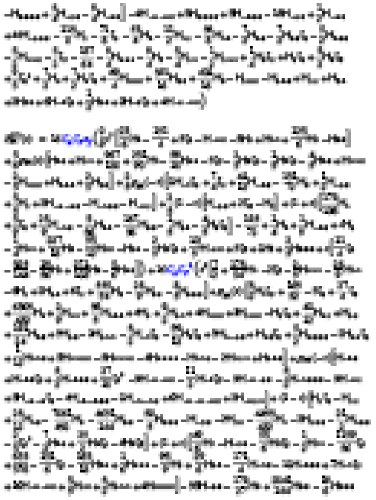
Moch, Vermaseren, Vogt '04

A really monumental, fully analytic, computation

NNLO singlet splitting functions   A completely analytical result

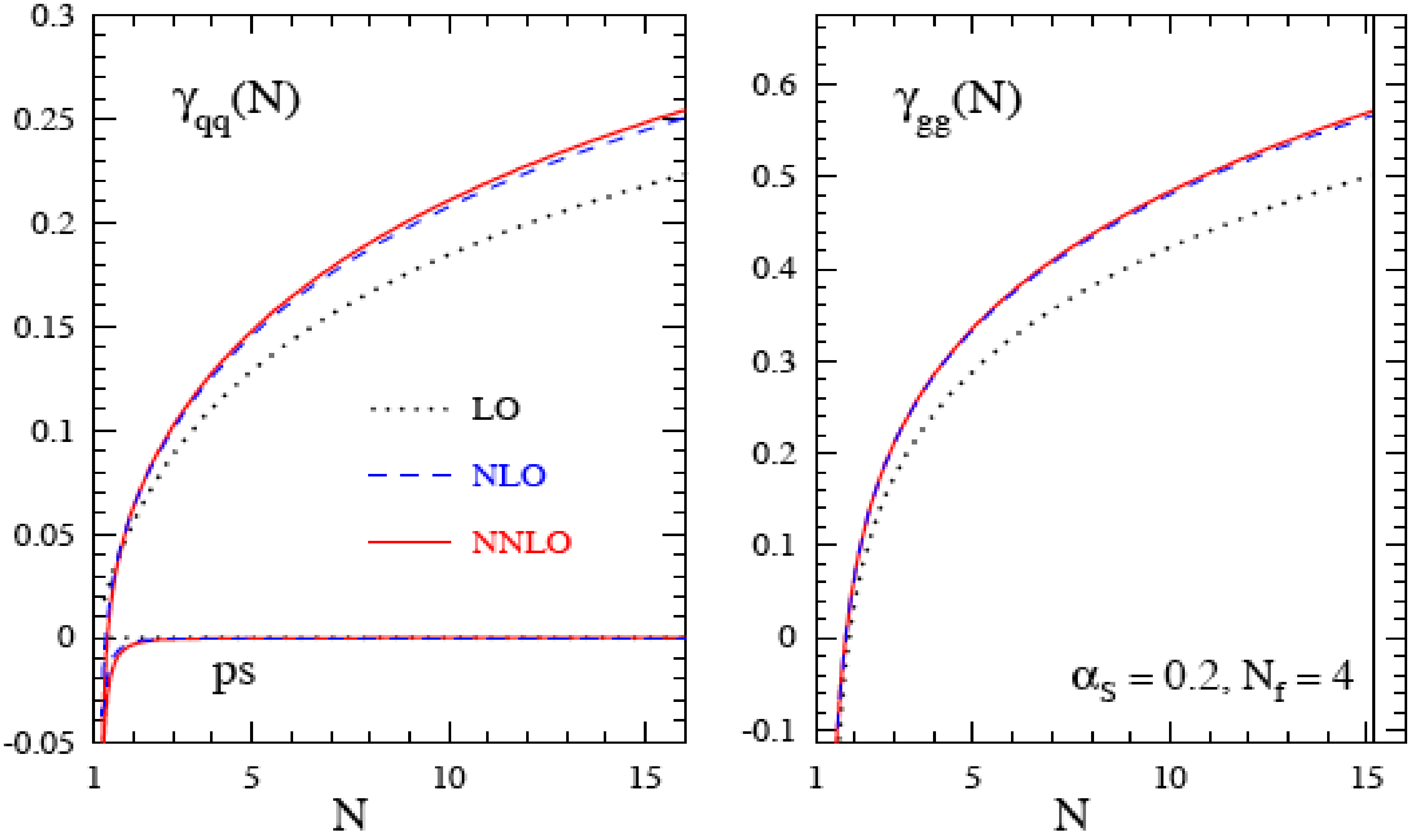
Moch, Vermaseren, Vogt '04





Anomalous dimensions vs N, the Mellin index

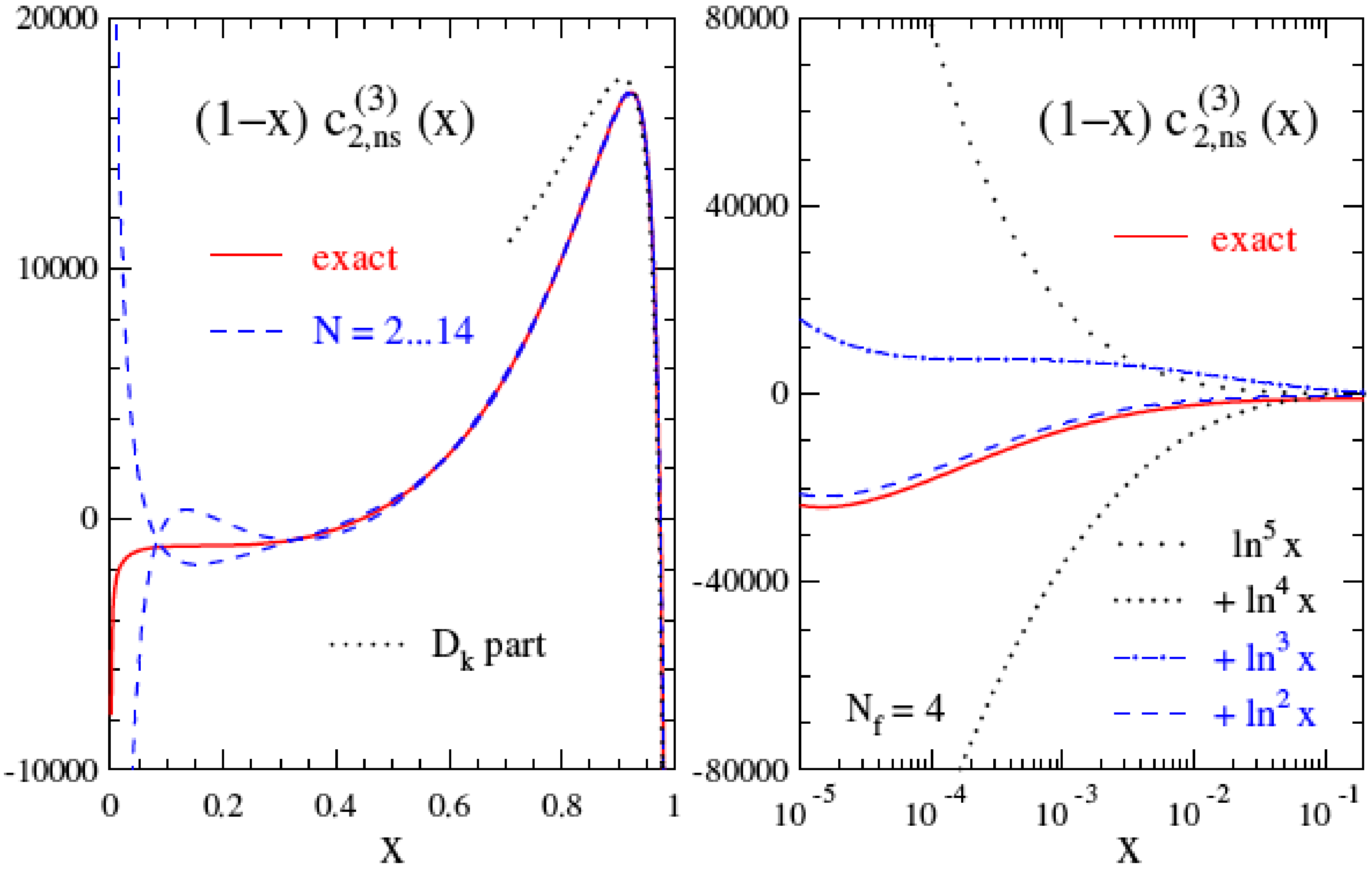


⊕ Good convergence is apparent

Now also the α_s^3 coefficient functions are known

(eg the NNLO calculation of F_L completed)

Moch, Vermaseren, Vogt '05



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 (CCSS)
Altarelli, Ball, Forte (ABF); White, Thorne

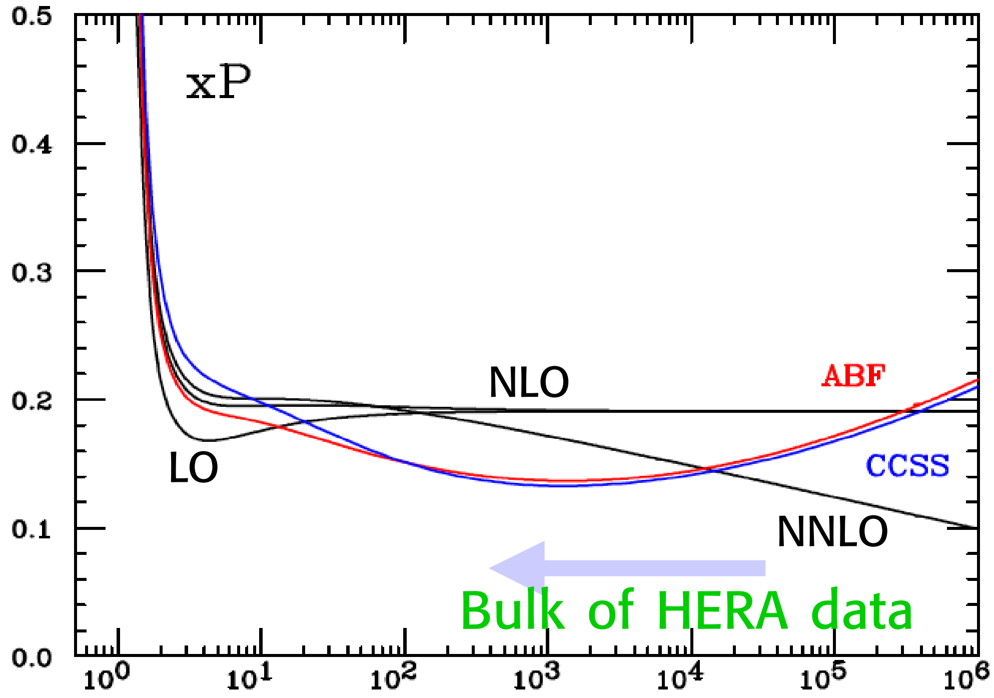
Momentum cons.+ symmetry + running coupling effect

→ soft simple pole in anom. dim

- BFKL sharp rise tamed

- resummed result close to NLO in HERA region

- new expansion stable



Note that the NNLO evolution goes crazy in the HERA range. As a result, NNLO fits are less good than NLO fits. Resummation cannot be ignored.

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).

However, the behaviour at small x has not yet been fully implemented in the evolution codes used in fitting the data.

This introduces a bias that could be avoided which affects the determination of pdf's and $\alpha_s(Q^2)$

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
- Neutrino structure functions not good enough
- ONLY NOW (!) some reasonable data on F_L are been obtained (H1 and ZEUS)
- Polarized DIS
- • • •

What is the value of α_s from DIS?

The measurement of $\alpha_s(m_Z)$ is very important.
In my opinion one should adopt as alpha-meters those processes where the theory is fully under control:
(all other processes should be taken as tests of QCD)

Totally inclusive processes with light cone operator expansion: e+e- total hadron cross-section, Z and τ decay and 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)

more questionable as m_τ is small

Davier et al '08

DIS is the next "golden" channel to consider

α_s from DIS : more complicated

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 the difference,
- $F_{3\nu N}$ is not terribly precise

  (ν data only from CCFR, NuTeV)

- neglecting sea and glue in F_2 for $x > x_0$ decreases

⊕ the sample and introduces a dependence on x_0

Non singlet electron/muon production

From a recent analysis of eP and eD data, neglecting sea and gluons at $x > 0.3$ (error to be evaluated)

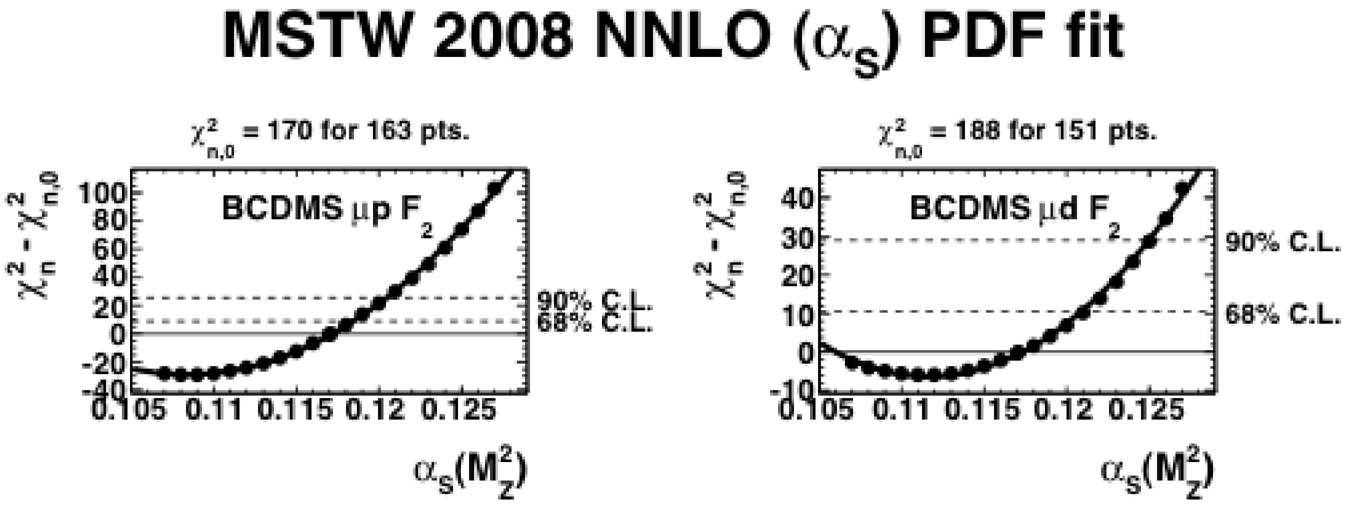
- Non singlet DIS: $\alpha_s(m_Z)=0.1148\pm0.0019$ (exp)+? (NLO)
  $\alpha_s(m_Z)=0.1134\pm0.0020$ (exp)+? (NNLO)

Bluemlein, Bottcher, Guffanti '07

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

According to Watt the contribution of singlet to F2 at x ~ 0.3 is still ~ 10%

BCDMS data push towards small α_s



According to Watt 162/280 exp points at $x > 0.3$ are from BCDMS

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

$\alpha_s \longleftrightarrow$ gluon correlation $dF/d\log Q^2 \sim \alpha_s\, g$

There is a strong feedback on α_s of the parametrisation of g.

A too rigid param'n of gluon may strongly bias α_s

The Neural Network approach may suppress g parametrization errors (The NNPDF Coll. '10)

DIS only $\alpha_s(m_Z)=0.1177\pm0.0009(\mathrm{exp})$ +? (th) (NNLO)

It appears that including Tevatron jets is important to constrain g at large x (and then, via momentum conservation, also at small x). But jets rates only known at NLO accuracy

Recent $\alpha_s(m_Z)$ determinations from DIS at NNLO

Ambiguities:

- Heavy quarks
- F_L
- Higher orders

$$\alpha_s(m_Z) = 0.1129 \pm 0.0014\ (exp)+?$$

Alekhin, Blumlein, Klein, Moch ‘09

$$\alpha_s(m_Z) = 0.1158 \pm 0.0035\ (exp)+?$$

Jimenez-Delgado, Reya ‘08

From combined H1+ZEUS data

$$\alpha_s(m_Z) = 0.1147 \pm 0.0012\ (exp)+?$$

Alekhin, Blumlein, Moch ‘10

For HERA data the NLO evolution should be improved by a correct treatment of small x effects (negative g at small x and Q^2 is a symptom)

Global fit to α_s and PDF

dominated by DIS but not only DIS

$\alpha_s(m_Z) = 0.1171 \pm 0.0014(\text{exp}) + ?$ (NNLO)

Martin, Stirling, Thorne, Watt ‘09

MRST attribute their larger value of α_s to a more flexible parametrisation of the gluon and claim that the Tevatron jets are needed to fix g at large x

In conclusion, for $\alpha_s(m_Z)$ from DIS

Bethke takes $\alpha_s(m_Z) = 0.1142 \pm 0.0023$ from non-singlet and this is what he puts in his average from DIS

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

Bluemlein, Bottcher, Guffanti '07

Problems: neglect singlet at $x>x_0$, small data sample, BCDMS...

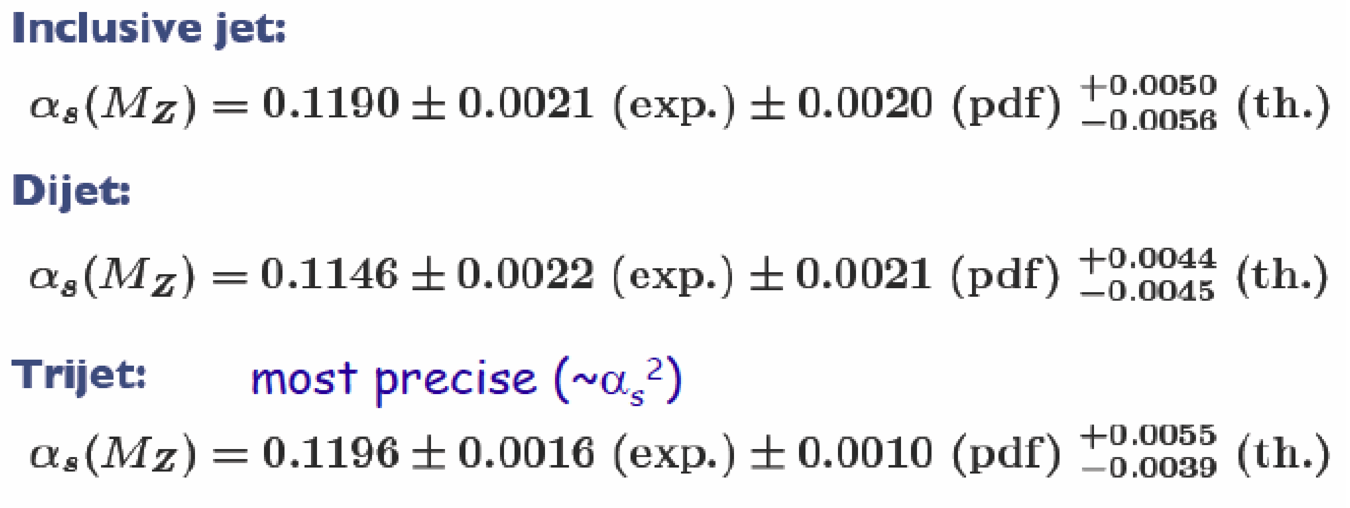
From the previous discussion it appears that for singlet there are problems related to the gluon determination and parametrization

$\alpha_s(m_Z)$ tends to slide towards low values if the g problem is not fixed [$\alpha_s(m_Z) \sim 0.113$-0.116]

The NNPDF approach or fixing the g on the Tevatron jets increases $\alpha_s(m_Z)$ [$\alpha_s(m_Z) \sim 0.117$-0.118]

Still an open problem!

At HERA $\alpha_s(m_Z)$ can also be measured from jets in DIS but the TH error is large and dominant



Inclusive jet:

$$\alpha_s(M_Z) = 0.1190 \pm 0.0021\ (\mathrm{exp.}) \pm 0.0020\ (\mathrm{pdf})\ ^{+0.0050}_{-0.0056}\ (\mathrm{th.})$$

Dijet:

$$\alpha_s(M_Z) = 0.1146 \pm 0.0022\ (\mathrm{exp.}) \pm 0.0021\ (\mathrm{pdf})\ ^{+0.0044}_{-0.0045}\ (\mathrm{th.})$$

Trijet: most precise ($\sim\alpha_s^2$)

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016\ (\mathrm{exp.}) \pm 0.0010\ (\mathrm{pdf})\ ^{+0.0055}_{-0.0039}\ (\mathrm{th.})$$

H1

By comparison in e+e- the recent determinations from non completely inclusive channels are allegedly very precise (looks too precise….)

- Event shapes:

$\alpha_s(m_Z)$=0.1135±0.0011+? (N^3LO)

Abbate et al ‘10

$\alpha_s(m_Z)$=0.1153±0.0017+? (N^3LO)

Gehrmann et al ‘10

Polarized Structure Functions

A subject where our knowledge is still far from satisfactory

Who carries the proton spin?

$$\frac{1}{2}\Delta\Sigma + \Delta g + \Delta L_z = \frac{1}{2}$$

typically $\Delta\Sigma_{exp} \sim 0.24$

What is missing must be either $\Delta g+\Delta L_z$ or $\Delta\Sigma$ terms at small x (below the measured range)

First moments

$$\Delta q \equiv \Delta q + \Delta \bar{q}$$

$$a_3 = \Delta u - \Delta d = (F + D)(1 + \varepsilon_2) = 1.269 \pm 0.003$$

SU(2) breaking

$$a_8 = \Delta u + \Delta d - 2\Delta s = (3F - D)(1 + \varepsilon_3) = 0.586 \pm 0.031$$

SU(3) breaking

$$\Gamma_1 = \int dx g_1(x) = \frac{1}{12}[a_3 + \frac{1}{3}(a_8 + 4a_0)]$$

From Γ_1 we get a_0

$$a_0 \equiv \Delta\Sigma = \Delta u + \Delta d + \Delta s = a_8 + 3\Delta s \approx 0.24$$

at $Q^2 = 1$ GeV^2

⇒

for ε_2, ε_3=0

$$\Delta u \simeq 0.81$$

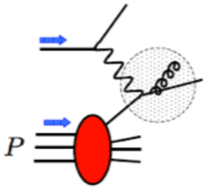
$$\Delta d \simeq -0.46$$

$$\Delta s \simeq -0.12$$

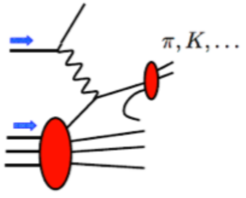
This is a strong result!
Given F, D and Γ_1 we know Δu, Δd, Δs, $\Delta\Sigma$ in the SU(3) limit

A beautiful set of data

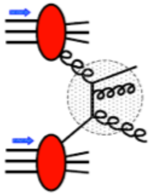
spin asymmetries in inclusive DIS



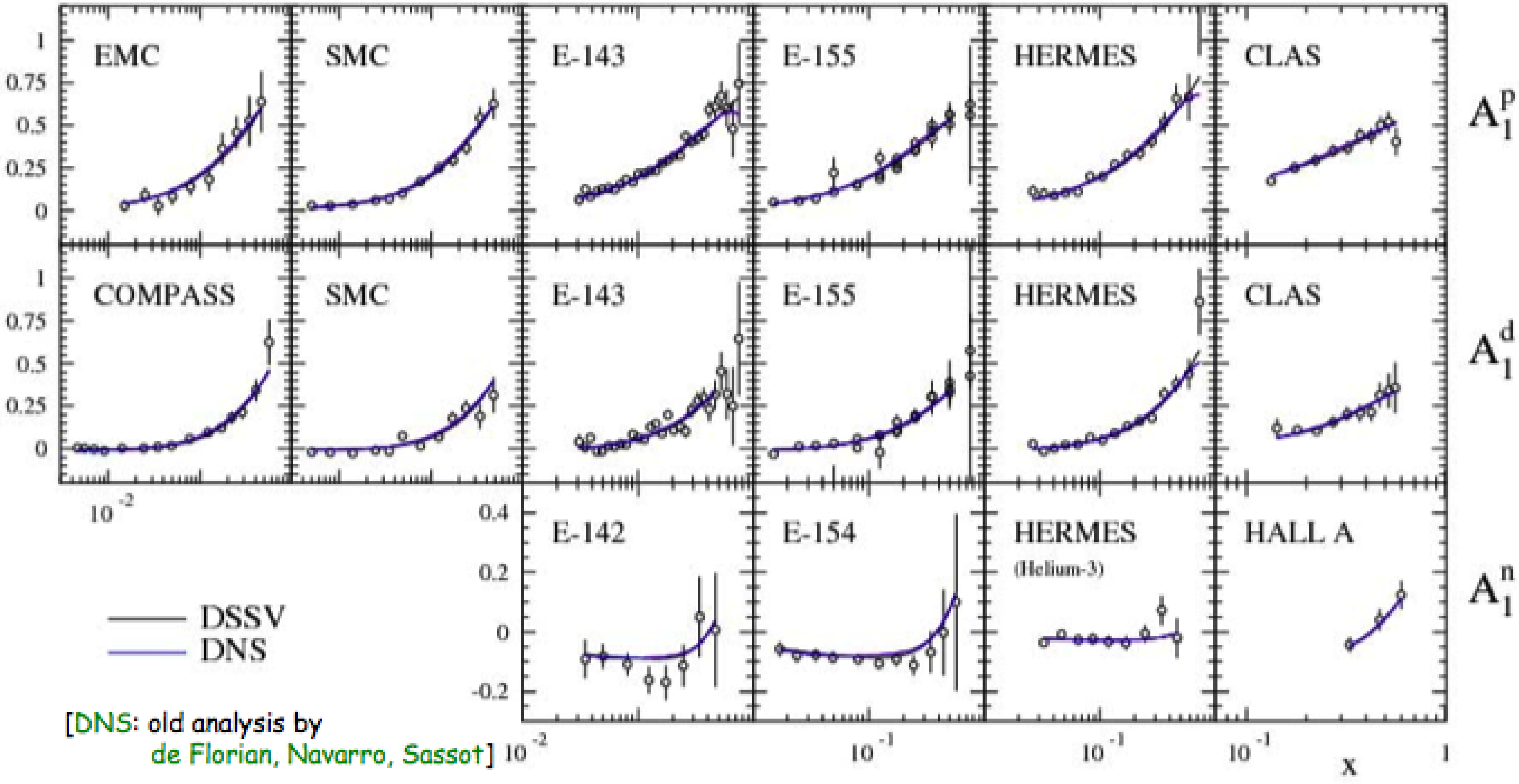
DIS



SIDIS



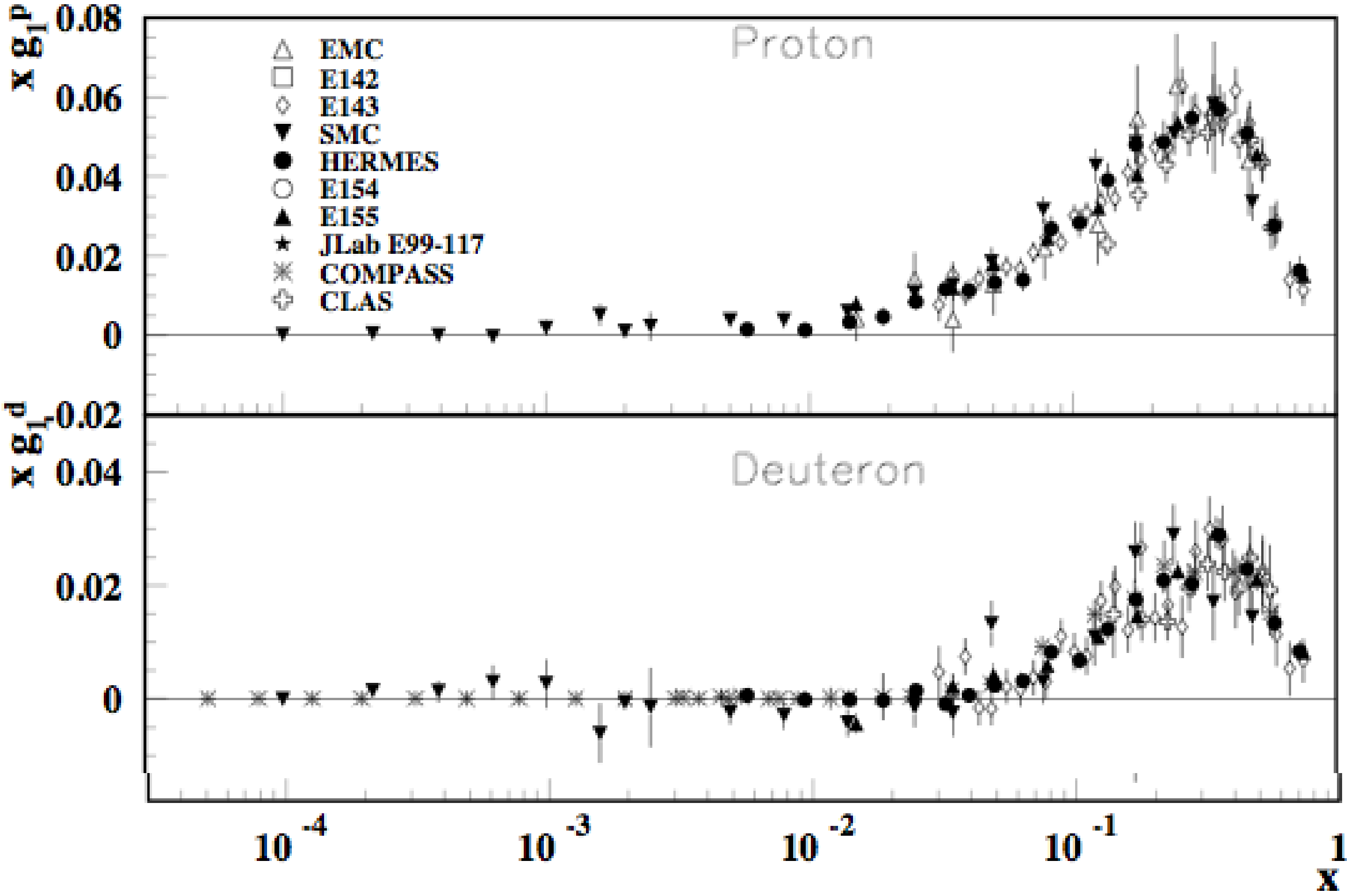
hadron-hadron



[DNS: old analysis by
de Florian, Navarro, Sassot]

The 1st moment of g_1 does not seem to get much at small x

Theory: Ermolaev, Greco, Troyan



In massless QCD in perturbation theory at LO:

- $\Delta\Sigma$ is conserved
- $\Delta g \sim 1/\alpha_s(Q^2) \sim \log Q^2$
- $\Delta g + \Delta L_z$ is conserved

$$\underbrace{\frac{1}{2}\Delta\Sigma}_{\substack{\text{const}\\ \sim 0.12}} + \underbrace{\underset{\log Q^2}{\Delta g} + \underset{\log Q^2}{\Delta L_z}}_{\text{const}} = \frac{1}{2}$$

while at NLO

- $\Delta\Sigma'$ is conserved: $\Delta\Sigma = \Delta\Sigma' - N_f \frac{\alpha_s(Q^2)}{2\pi}\Delta g$

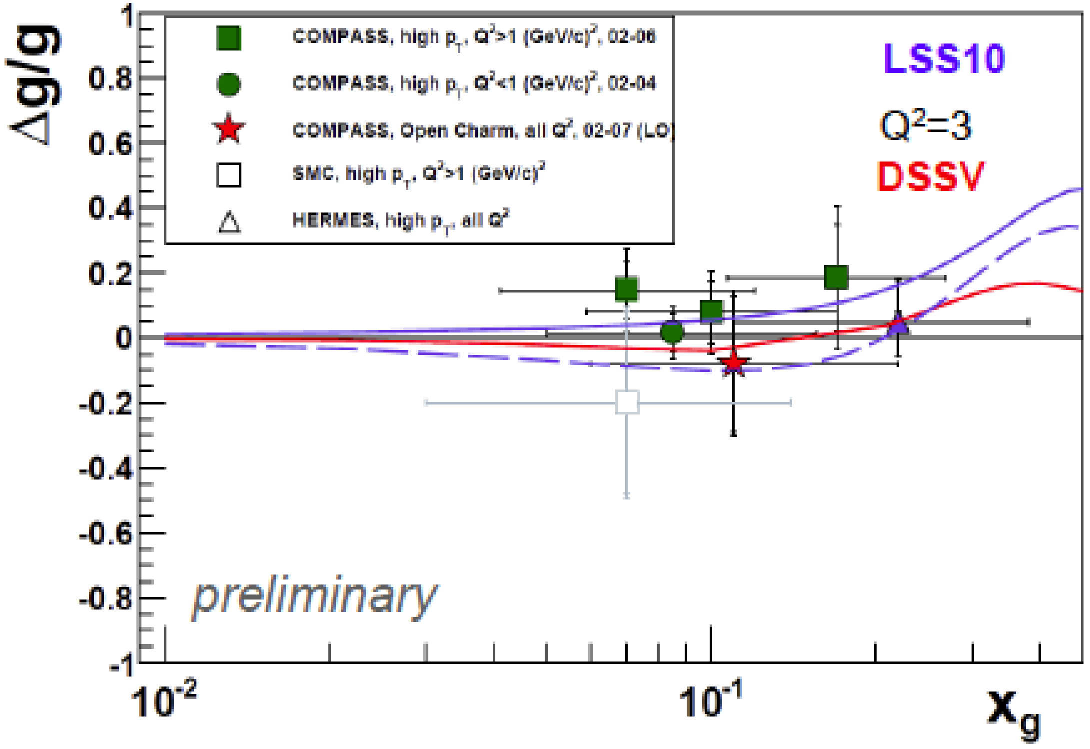
In principle the gluon could explain the smallness of $\Delta\Sigma$

Δg measured indirectly from scaling violations, directly from asymmetries, e.g. in cc production

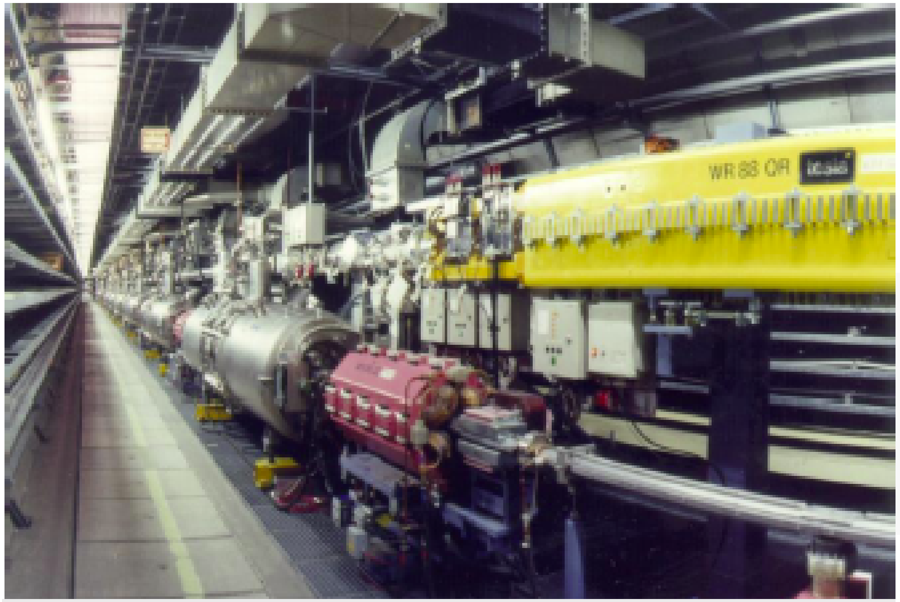
Existing direct measurements HERMES, COMPASS, CLAS, RHIC still very crude. No hint of large Δg at large x.

Experimental data on Δg

SMC
COMPASS
HERMES
SLAC
RHIC



HERMES at DESY



HERA e^+ & e^- 27 GeV

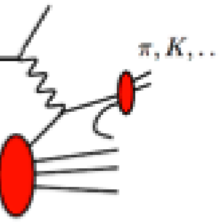
longitudinally polarized ~ 54%

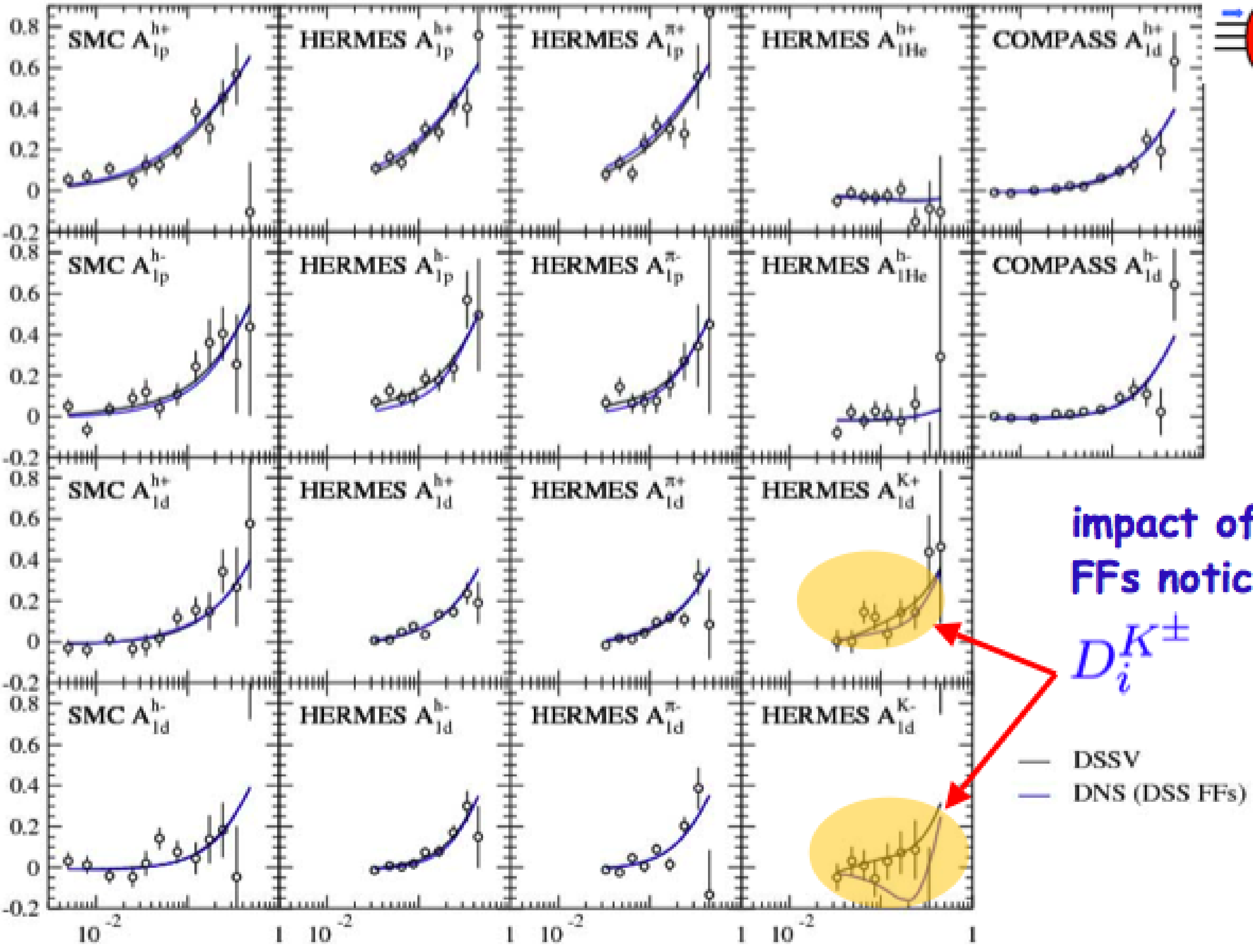
LSS10, ΔG~ + 0.32 at Q^2= 4

LSS10, ΔG~ - 0.33 (node)

DSSV, ΔG= 0.02 at Q^2=3

spin asymmetries in semi-inclusive DIS





impact of new FFs noticeable!

$D_i^{K^\pm}$

The fit to all data leads to puzzling results

Tension between the 1st moments from SU(3) and from fitting the actual data (x>0.001) which fix the moments only thru a possibly too rigid parametrization assumed

de Florian et al '08

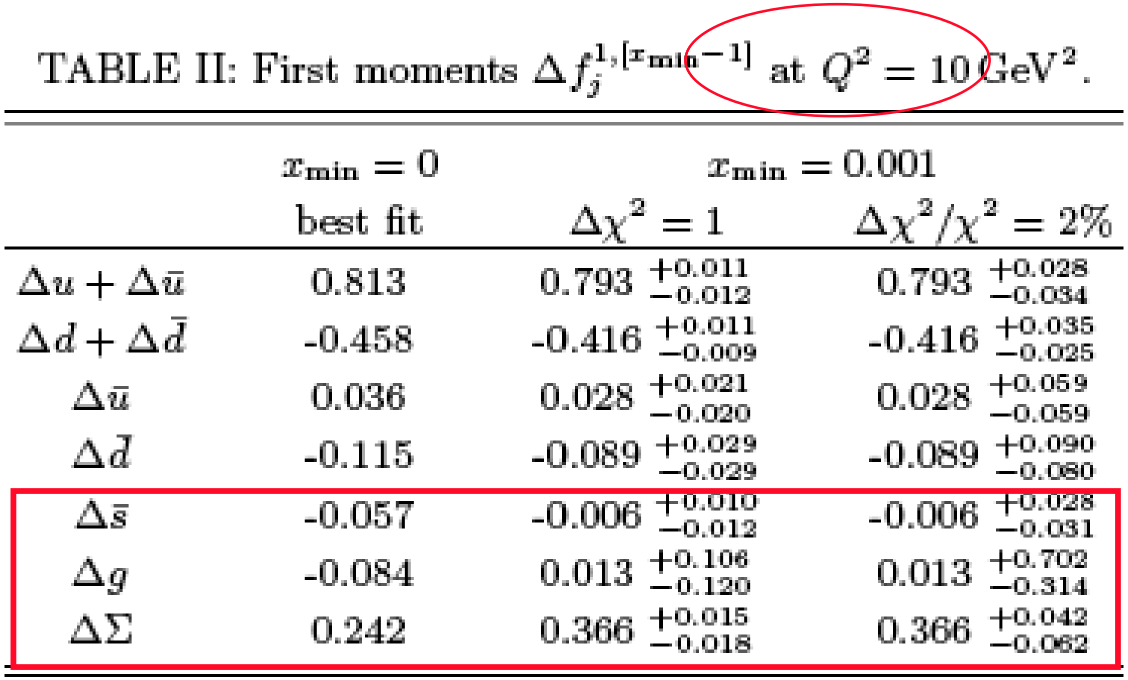


TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793^{+0.011}_{-0.012}$	$0.793^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416^{+0.011}_{-0.009}$	$-0.416^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028^{+0.021}_{-0.020}$	$0.028^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089^{+0.029}_{-0.029}$	$-0.089^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006^{+0.010}_{-0.012}$	$-0.006^{+0.028}_{-0.031}$
Δg	-0.084	$0.013^{+0.106}_{-0.120}$	$0.013^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366^{+0.015}_{-0.018}$	$0.366^{+0.042}_{-0.062}$

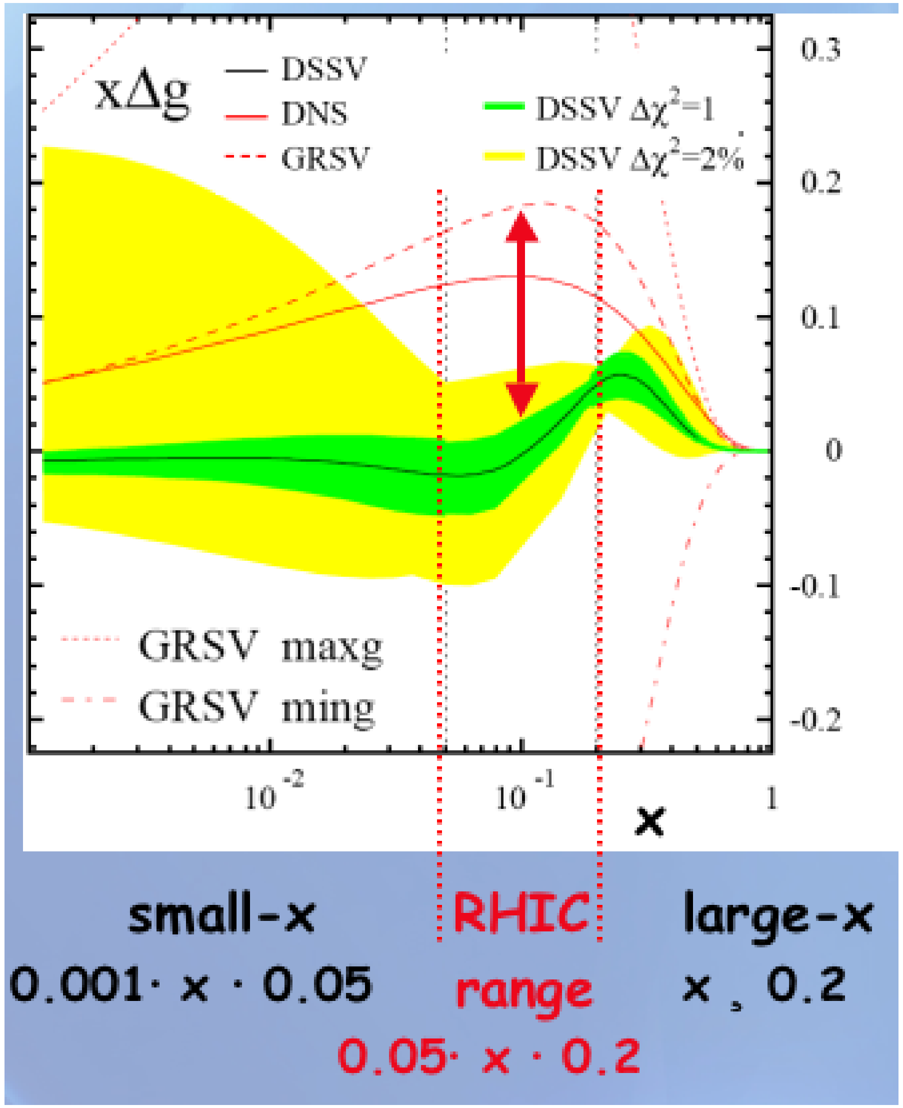
SU(3)

Parametrization?
Recall NNPDF s_+
The error from small x probably large

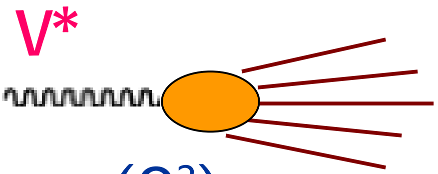
Kaon SIDIS fixes Δs but is questionable

Still
large ambiguities
at small x
in unmeasured region

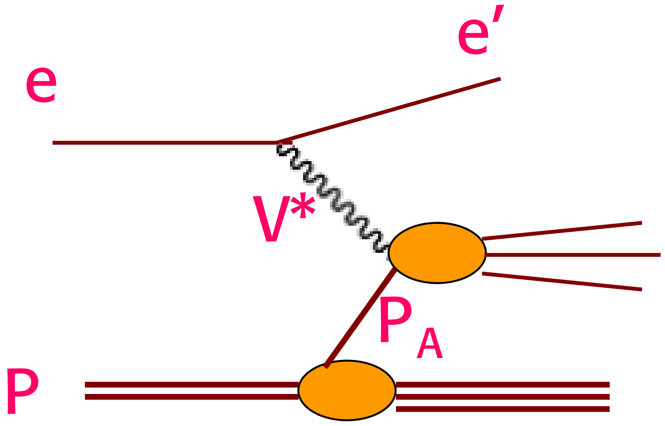
Much of Δg could be
hidden at small x



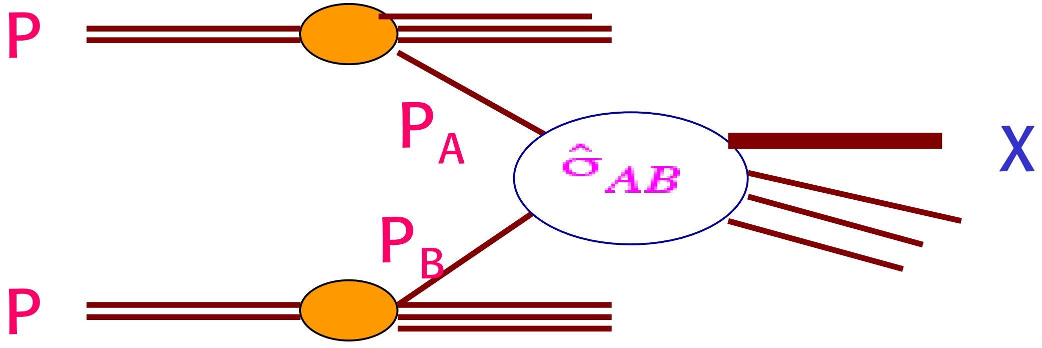
Complementary tools for particle physics



$\alpha_s(Q^2)$



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



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

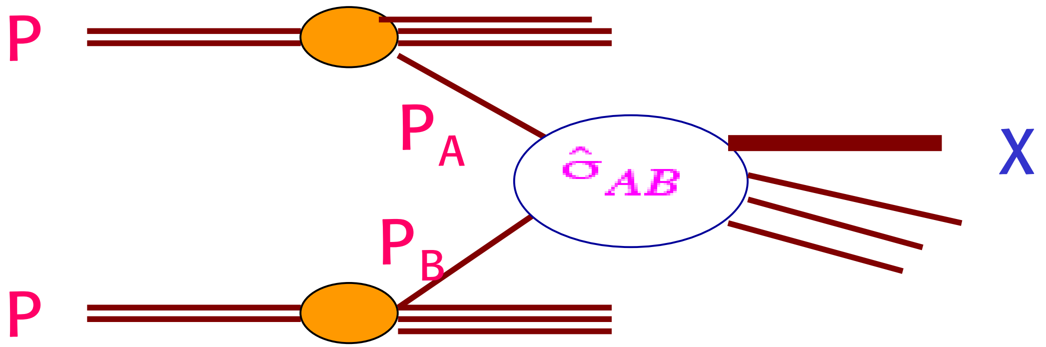
Parton densities extracted from DIS are used to compute hard processes, via the Factorisation Theorem:

density of parton A

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

reduced X-section

For example, at hadron colliders



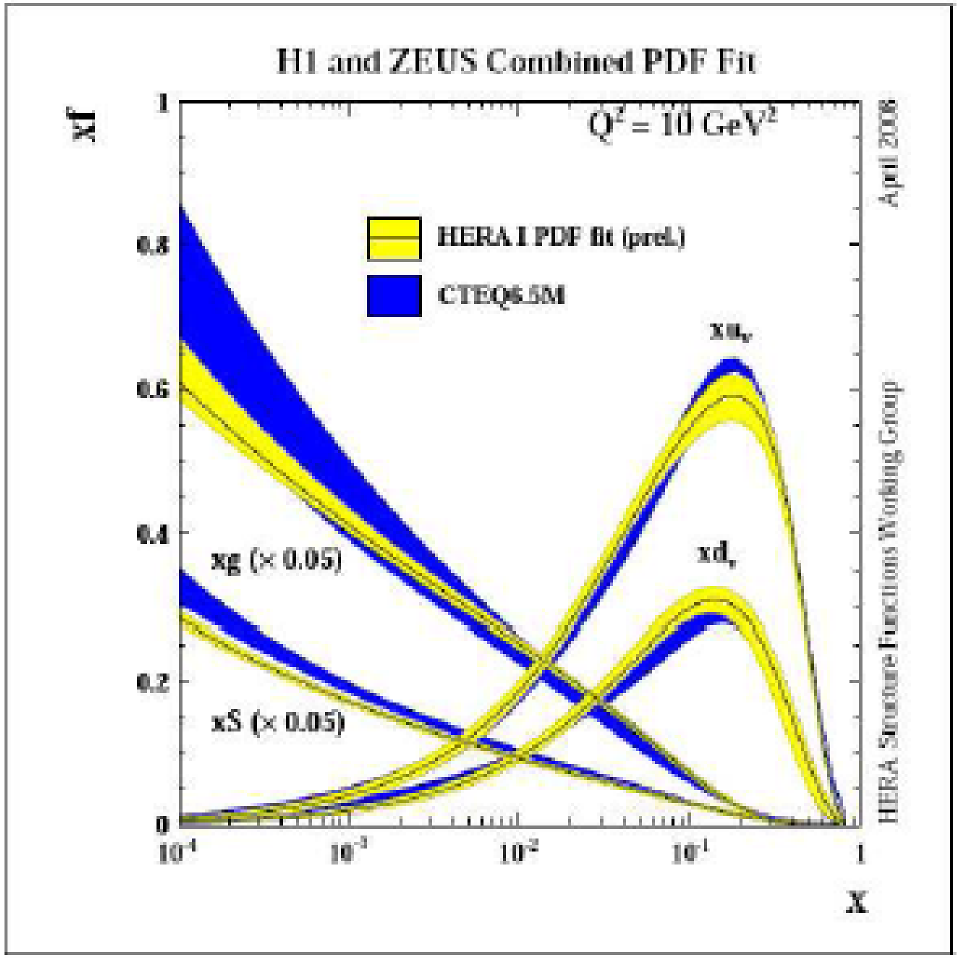
V=γ*,W,Z

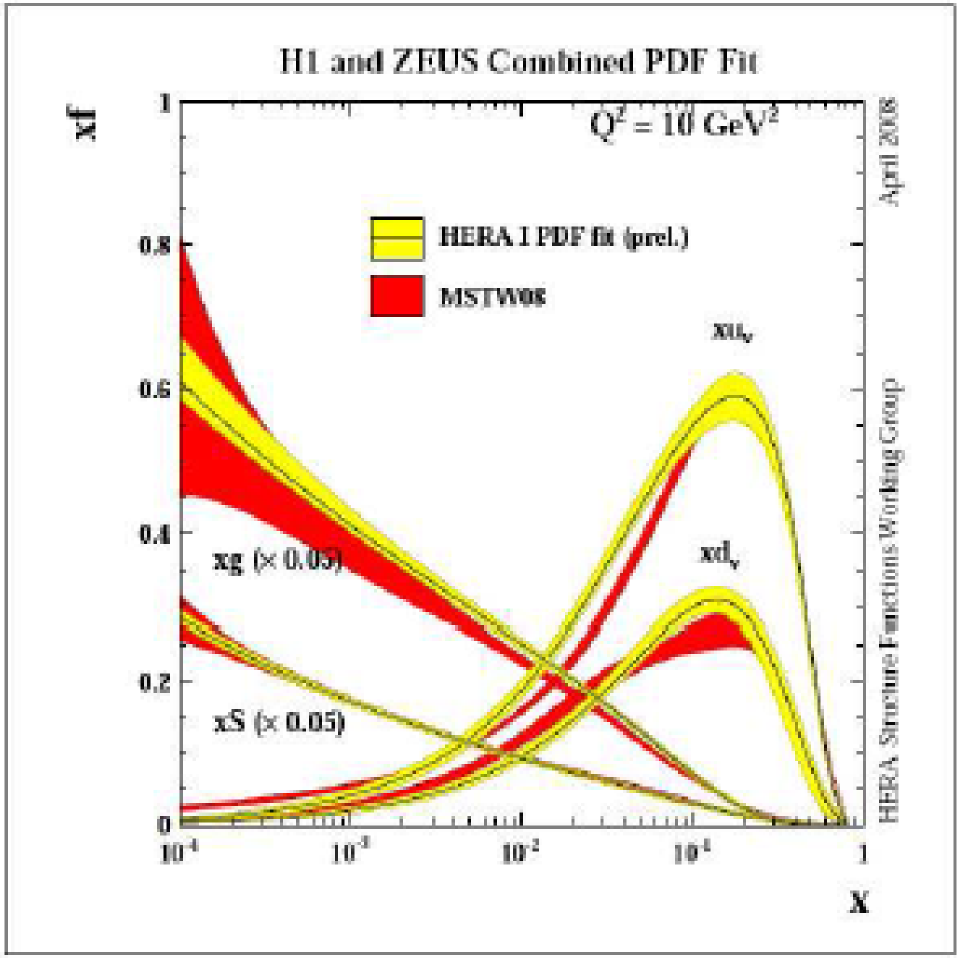
X=V, jets, QQ, H.....

Q=b,c,t

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

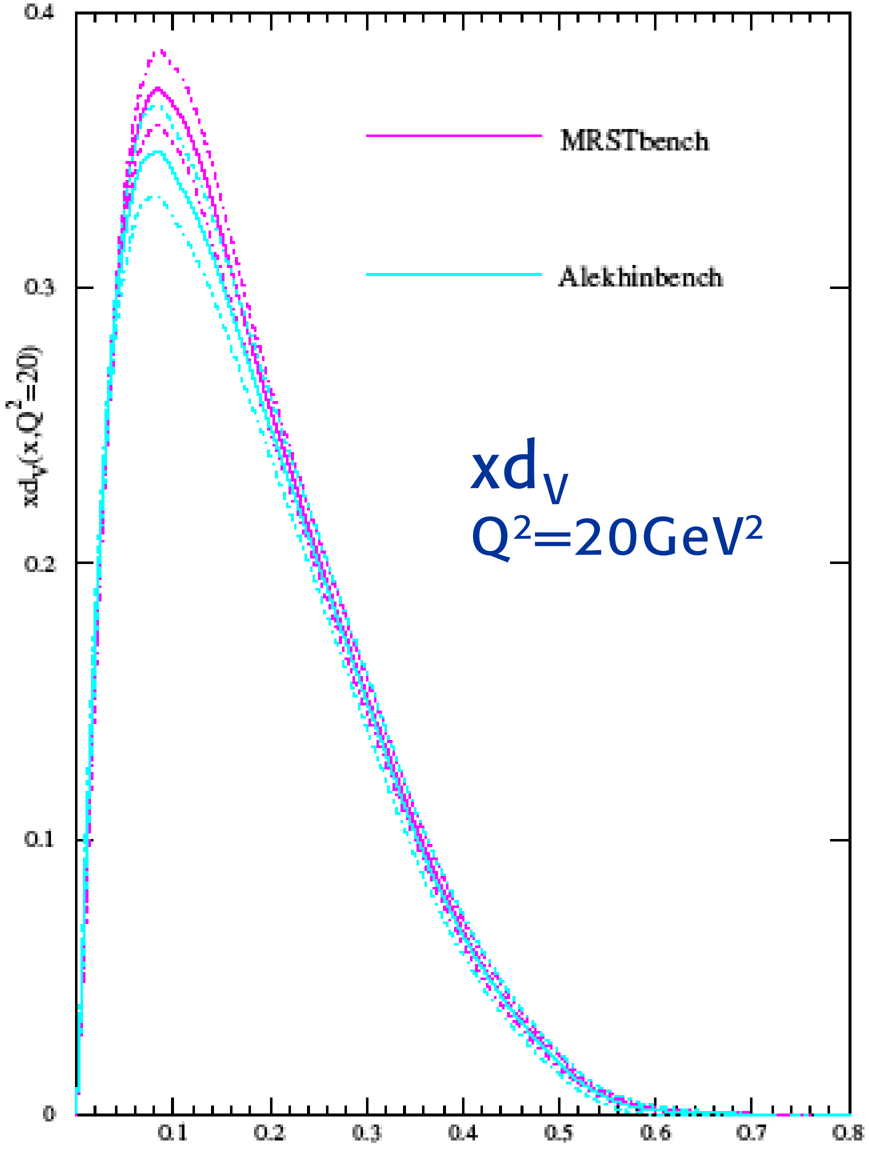
HERA is a main source of information on pdf's for LHC





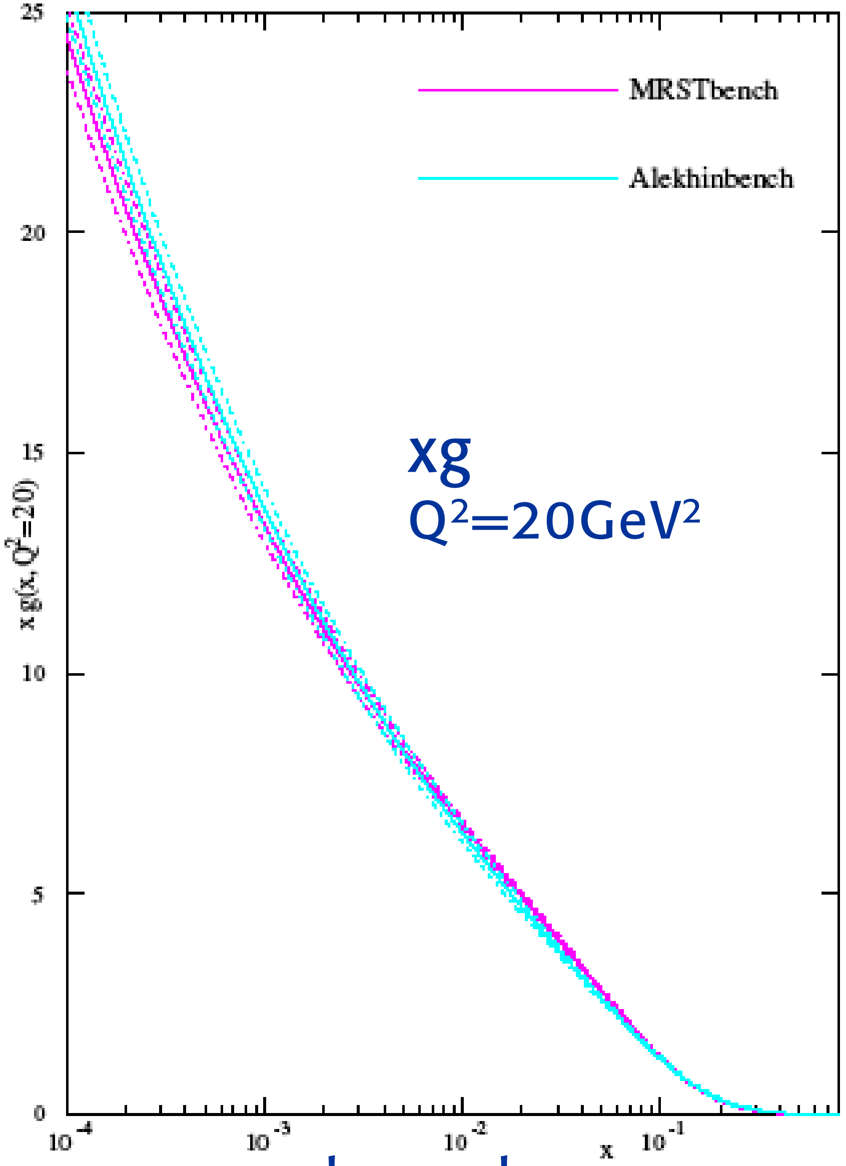
Different fits to same DIS data are comparable

HERA LHC Workshop ‘06



xd_V
Q^2=20GeV^2

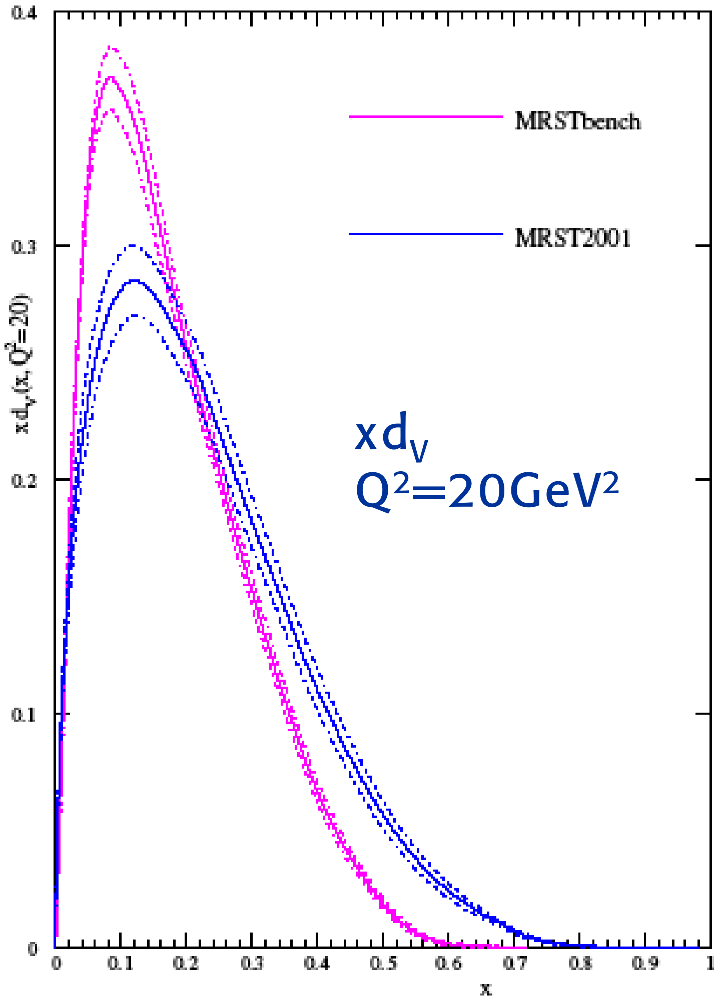
x: linear scale



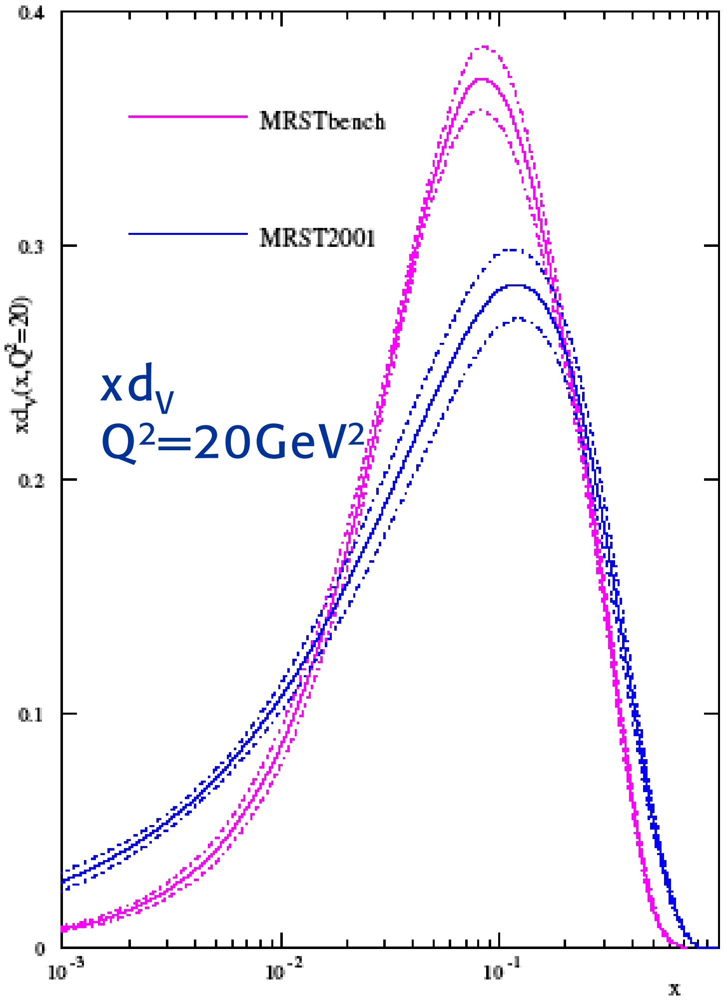
xg
Q^2=20GeV^2

x: log scale

But differ from those obtained from all the data



x: linear scale

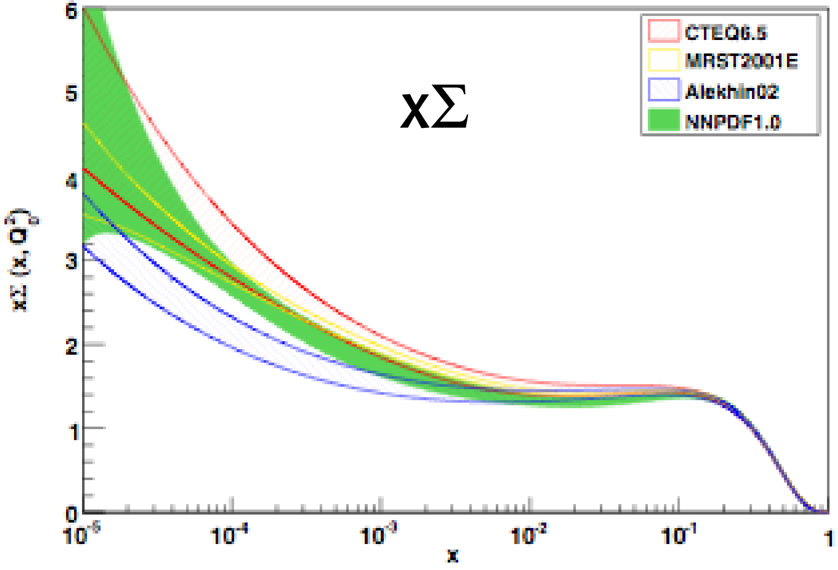


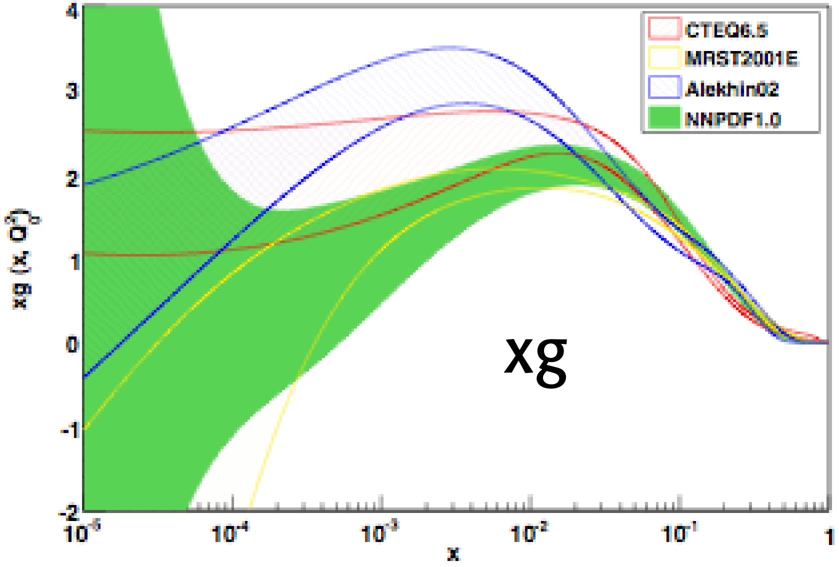
x: log scale

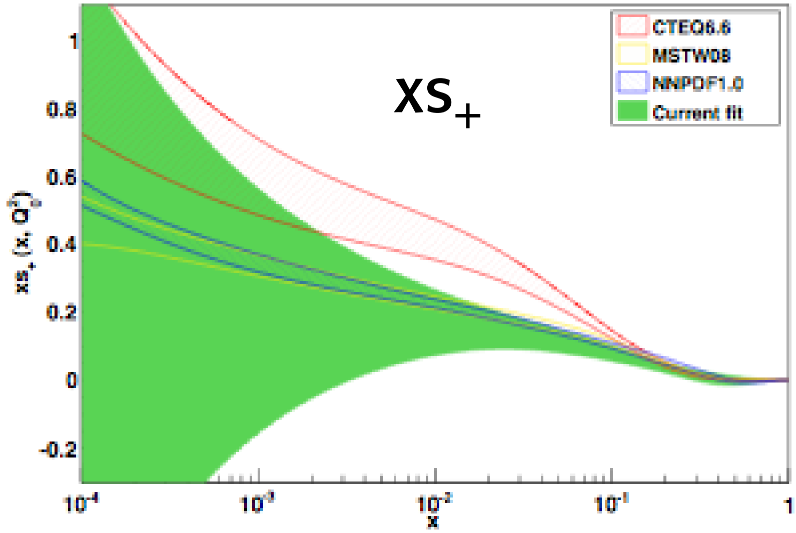
- This shows that extrapolation from one data set to another is dangerous

NNPDF: R. Ball et al ‘08

M. Ubiali







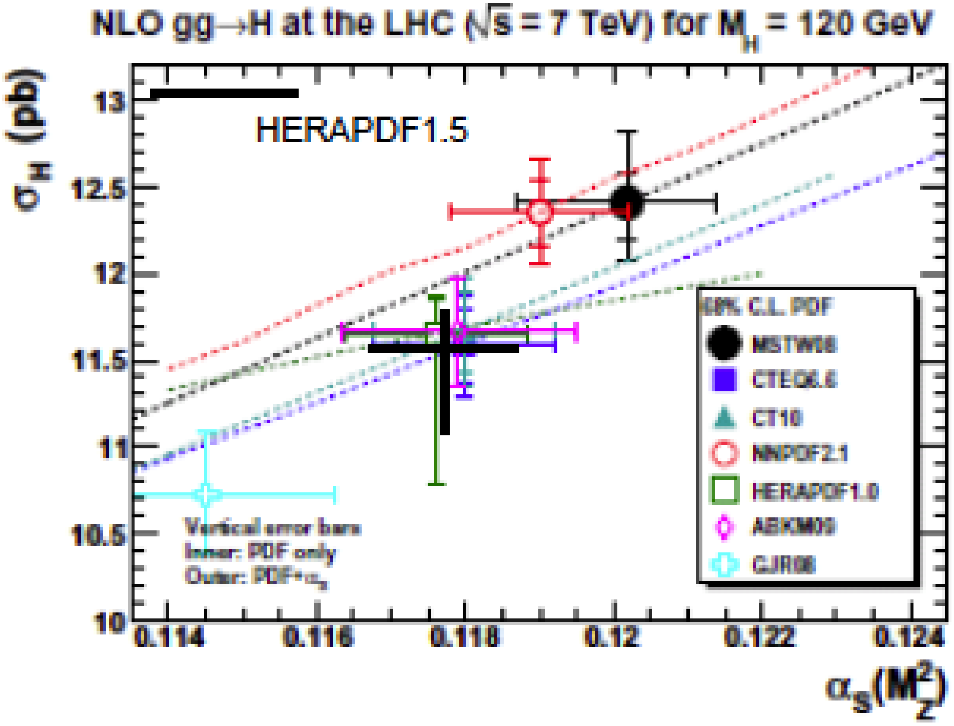
J. Rojo

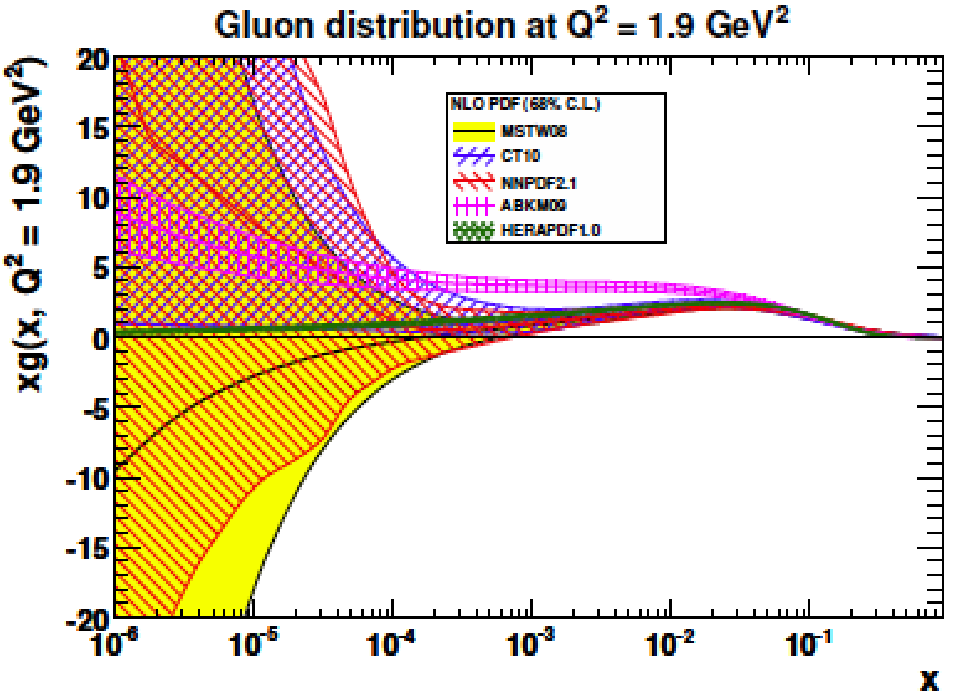
Neural Network pdf
less dep on parametrization.

a large ensemble of pdf allowed

Uncertainties larger than for
CTEQ, MRST, Alekhin
in unmeasured region

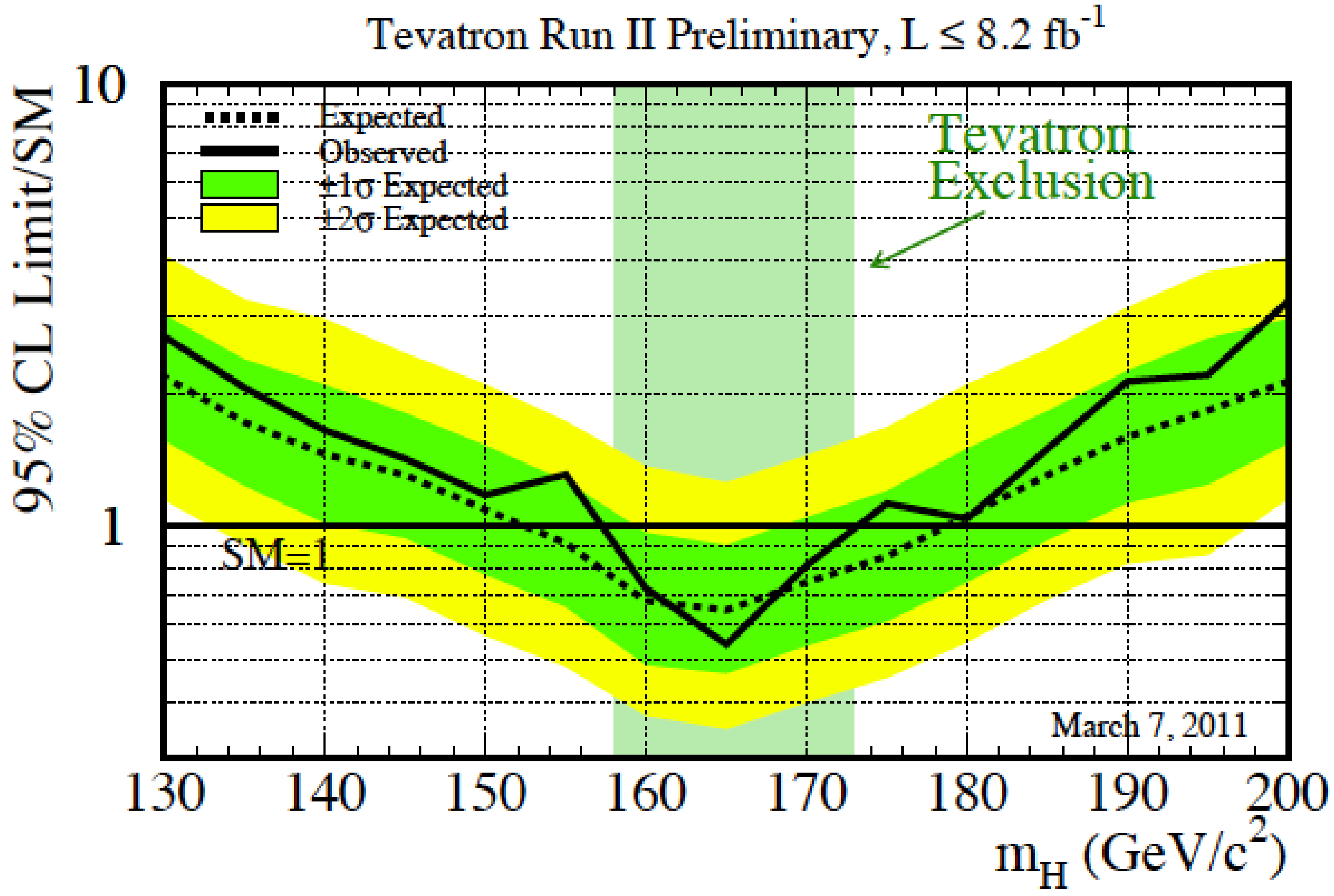
gluon pdf and $\alpha_s(m_Z)$ crucial for Higgs production at the LHC





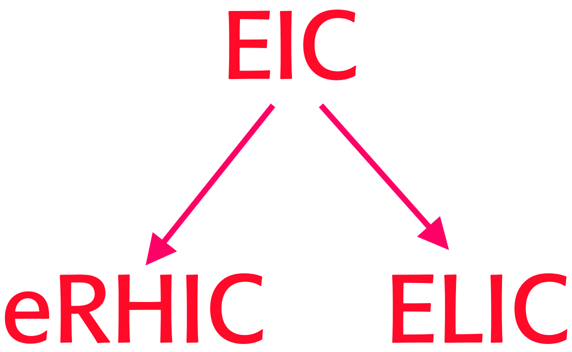
gluon pdf and $\alpha_s(m_Z)$ crucial for Higgs production at the LHC

Here is the Tevatron case



What future for DIS and PDF’s?

- Jefferson Lab (12 GeV, ELIC?)
- Brookhaven (RHIC, eRHIC?)
- CERN (COMPASS, LHeC?)



Electron Ion Collider	Large Hadron e-Collider
• Lumi > 10^{33} cm^{-2} sec^{-1}	• Lumi ~ 10^{33} cm^{-2} sec^{-1}
• CM Energy 30-100 GeV	• CM Energy 1.4 TeV
• Polarized protons & heavy ions (A=p-U)	• Un-polarized protons and heavy ions (A=p-Pb)
• Science focus: QCD, EW(?) & Nucleon Spin	• Science Focus: QCD , EW and BSM Physics

LHeC

60 GeV $e^{\pm}$ <--> 7 TeV p -----> $2E_{CM} \sim 1.3$ TeV

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

Luminosity ~ 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (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 ~ $\gamma \sim 2.7$

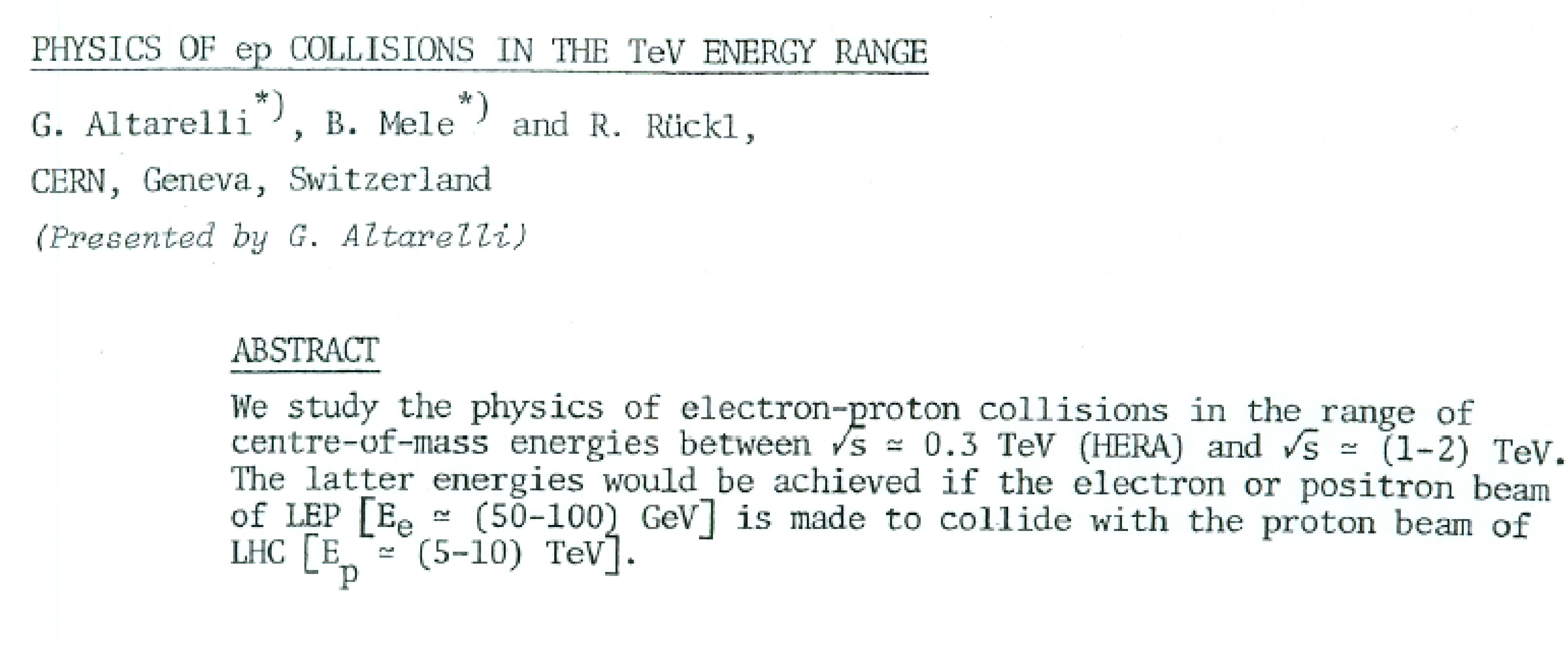
$e^{\pm}$ polarization possible

⊕ Simultaneous running of eP with PP or eA with AA

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

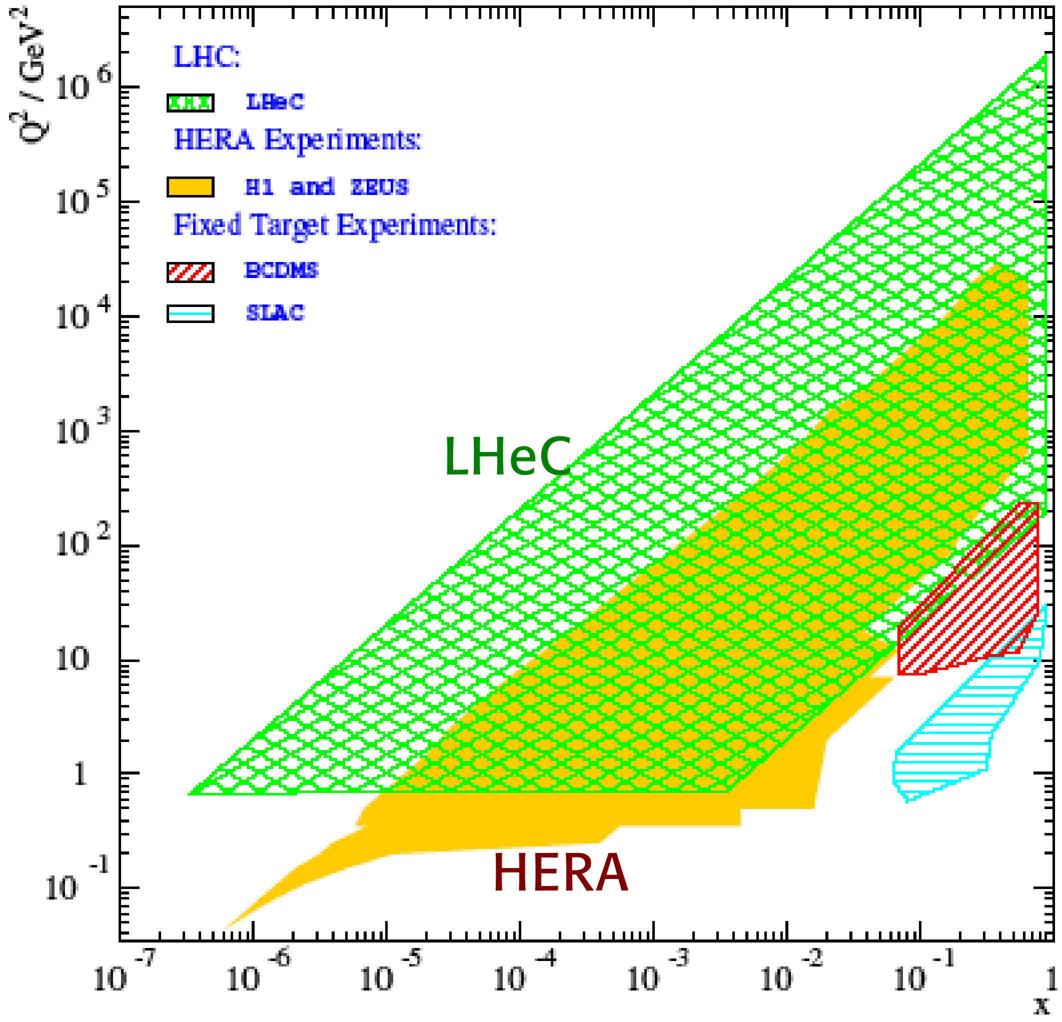
G. Altarelli*), B. Mele*) and R. Rückl,

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

Broad physics goals

- Proton structure and precision QCD physics in the domain of x and Q^2 of LHC experiments
- Small-x physics in eP and eA collisions
- Probing the e±-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…

Conclusion

DIS is a very fundamental process in particle physics

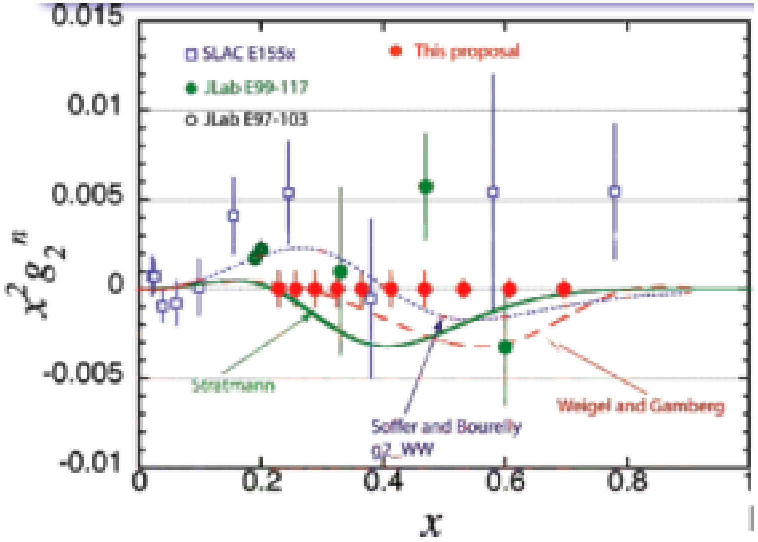
HERA has very much contributed to our knowledge on the proton structure

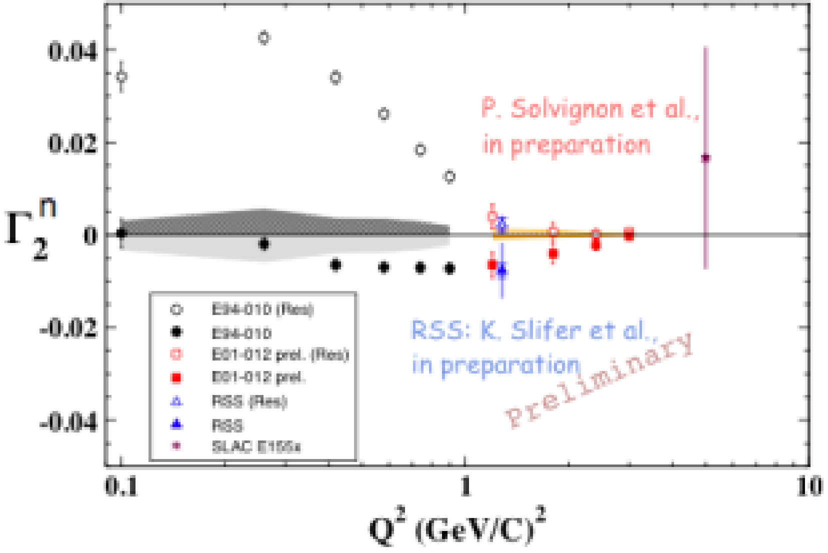
A large number of open questions remain in this domain in particular at small x

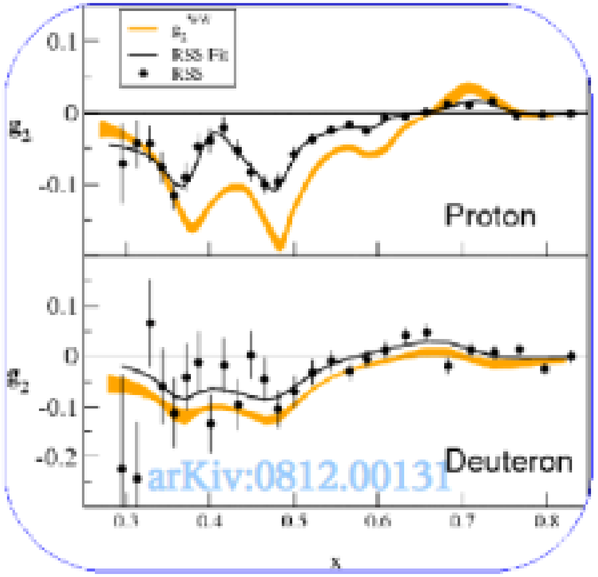
Additional issues will certainly be prompted by the LHC data and discoveries

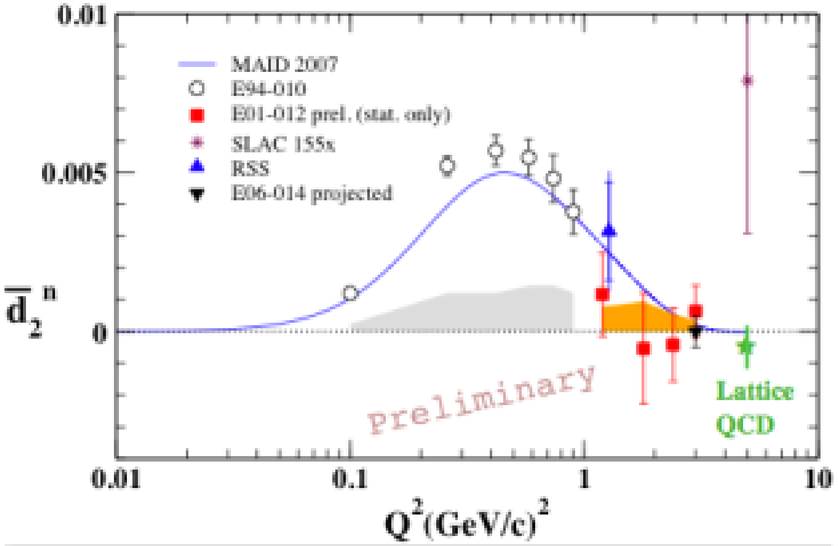
It would be a waste not to exploit the 7 TeV beams for eP and eA physics at some stage during the LHC time

Data on g_2 support the BC sum rule and show departures from the WW sum rule

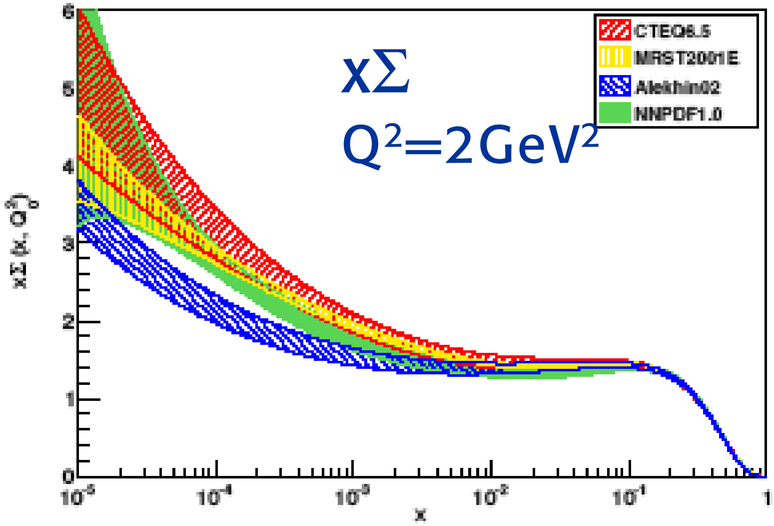




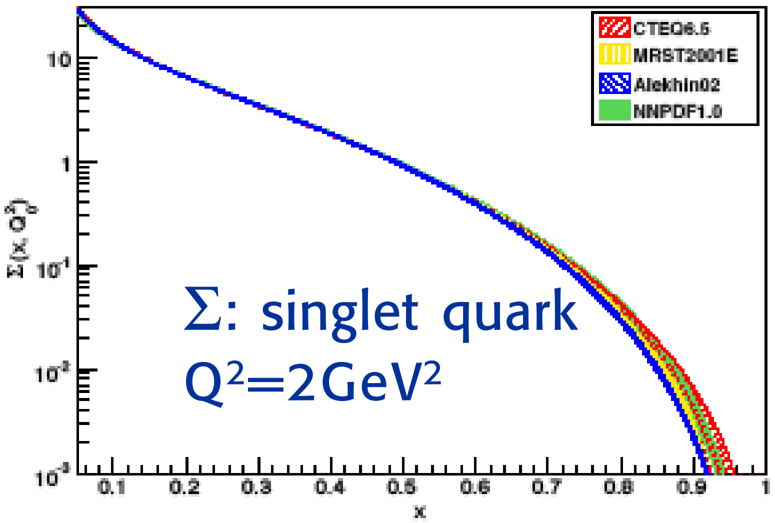




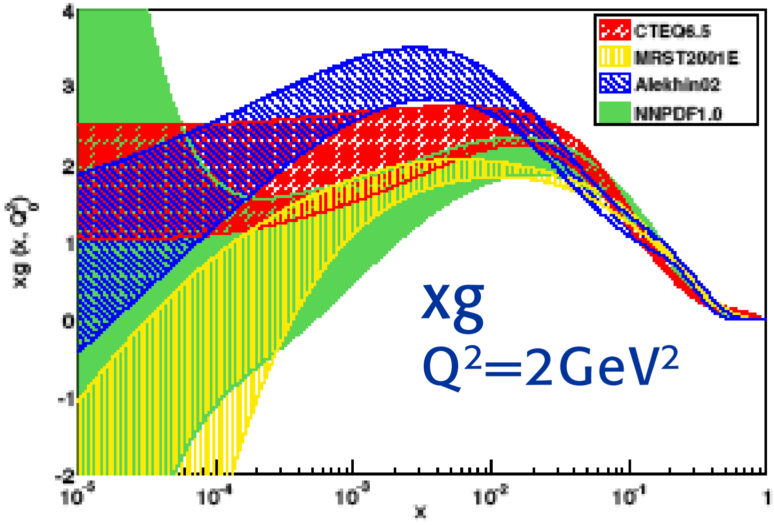
NNPDF: R. Ball et al ‘08


$x\Sigma$

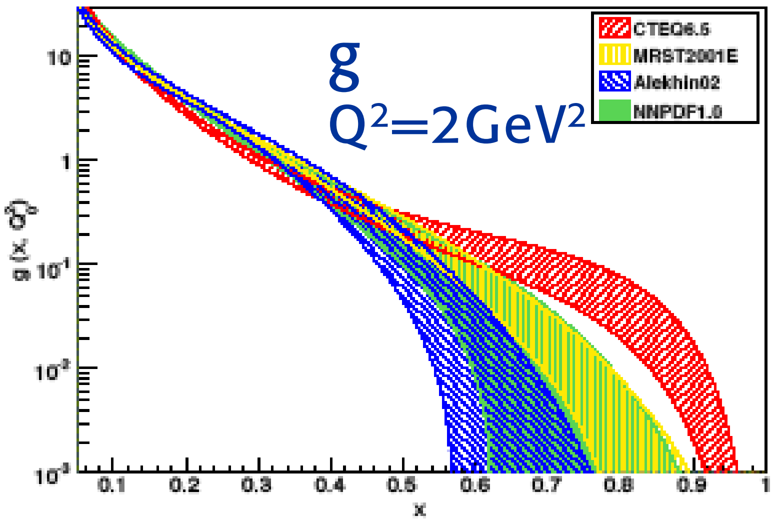
$Q^2=2GeV^2$


Σ: singlet quark

$Q^2=2GeV^2$


xg

$Q^2=2GeV^2$


g

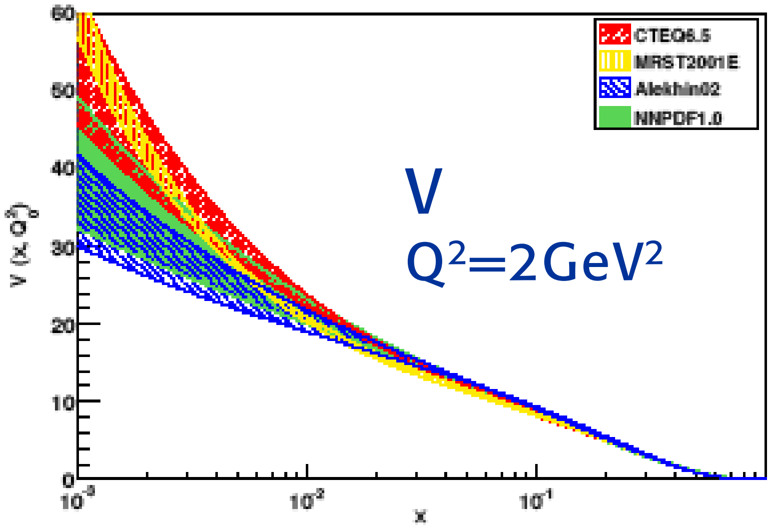
$Q^2=2GeV^2$

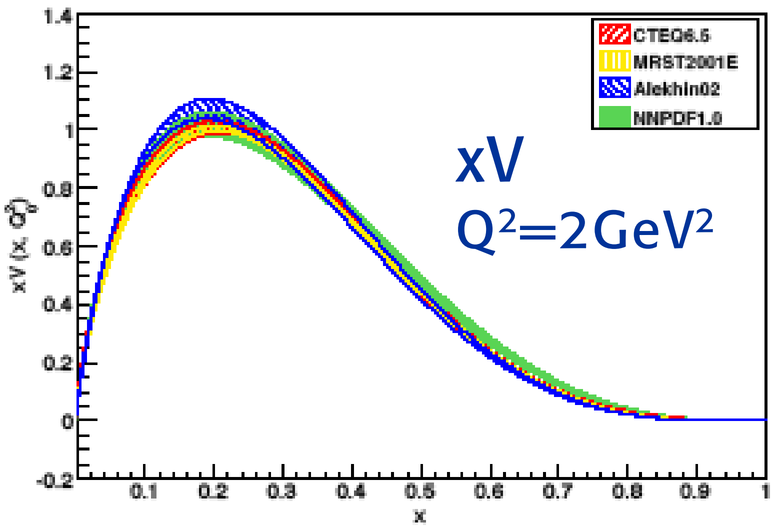
x: log scale

x: linear scale

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

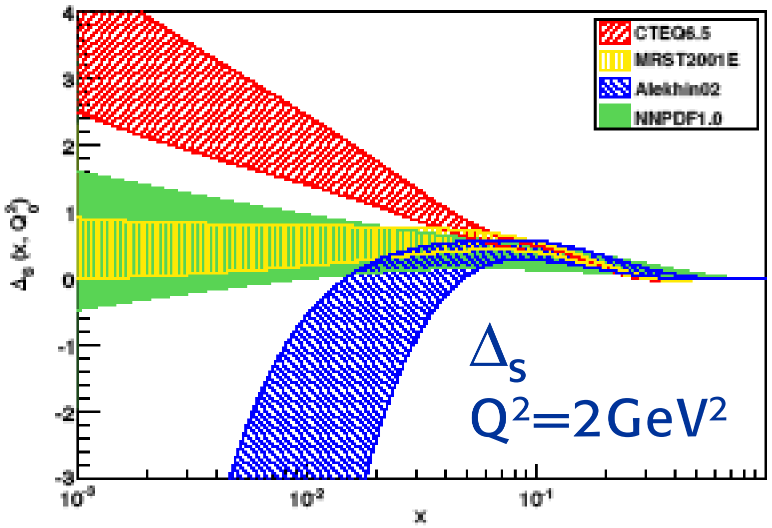
NNPDF: R. Ball et al '08

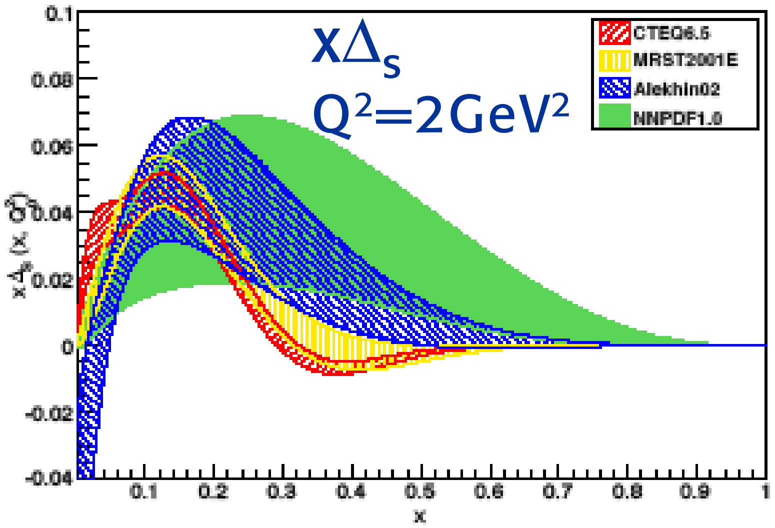




x: log scale

x: linear scale

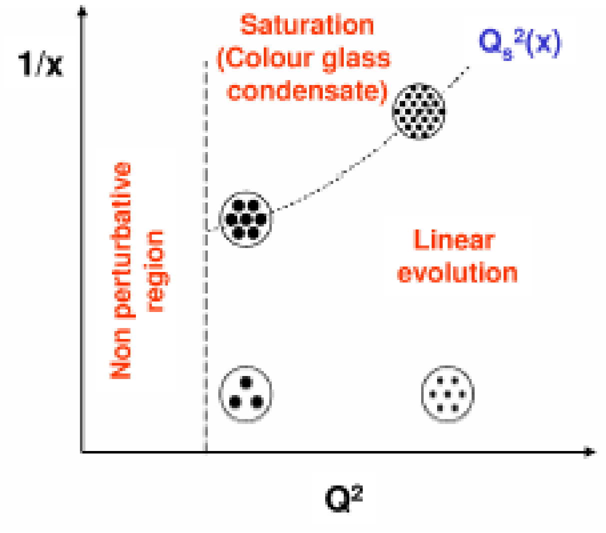




$$\Delta_S(x) \equiv \bar{d}(x) - \bar{u}(x)$$

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