Deeply Inelastic Scattering: Achievements and Needs

Johannes Blümlein
DESY

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- DIS: its contribution to the Standard Model

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- DIS: its contribution to the Standard Model
- What do we know?

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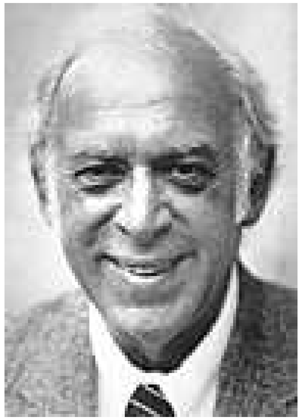
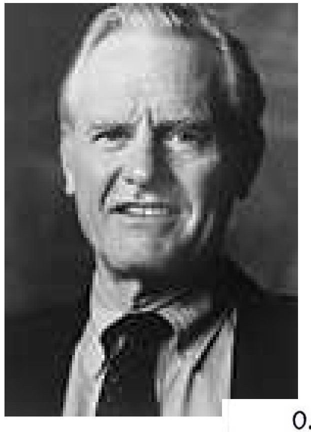
- DIS: its contribution to the Standard Model
- What do we know?
- What would we like to know?

An American Success Story:

The Discovery of Scaling





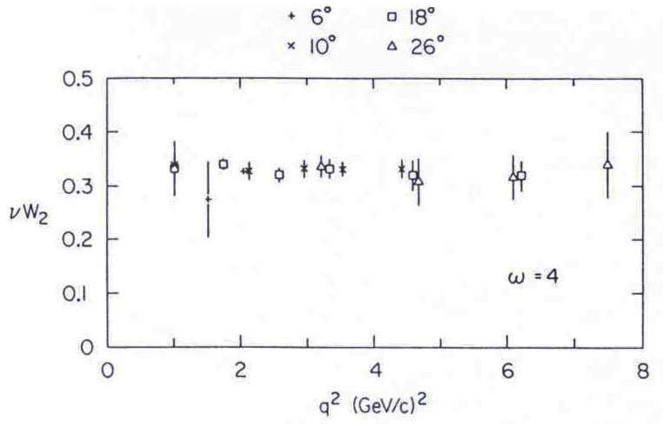


FIG. 13. An early observation of scaling: νW_2 for the proton as a function of q^2 for $W>2$ GeV, at $\omega=4$.

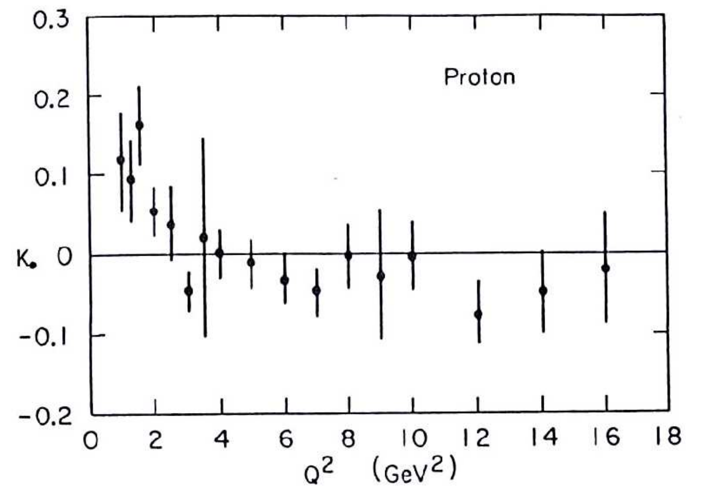


FIG. 18. The Callan-Gross relation: K_0 vs q^2, where K_0 is defined in the text. These results established the spin of the partons as 1/2.

precise measurements in a new kinematic region
confirm a theoretical prediction

scaling:

$$\lim_{Q^2,\nu\to\infty,x=\text{fixed}} F_i(\nu,Q^2) = F_i(x)$$

and find the constituents of hadrons,
the partons.

$$W_i(x,Q^2) = \sum_i dx_i \int_0^1 e_i^2 f(x_i) \delta\left(\frac{q.p_i}{M^2} - \frac{Q^2}{M^2}\right)$$

$\Longrightarrow$ **The measurement of F_L was instrumental to rule out vector-meson dominance models etc.**

Partons were soon identified with quarks (and later also gluons)
By this, quarks left their status as "pure mathematical objects".

- The GWS Standard Model could be completed:
  - hadrons could be treated at the elementary level of their constituents
  - anomaly free theory : $SU_{3c} \times SU_{2L} \times U_{1Y}$
  - asymptotic freedom : $\rightarrow$ possibility of gauge coupling unification
  - electroweak couplings in neutrino–quark scattering
- Factorization and Perturbation Theory at Short Distances
- Clear theoretical predictions for hard processes
- Inevitably necessary for:
  - top quark discovery
  - future Higgs particle discovery

DIS: Microscopy of the Nucleon

- determination of all quark densities and the gluon distribution
- determination of all polarized parton densities

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DIS: Fundamental Tests of QCD

- precision measurement of Λ_{QCD} and $\alpha_s(M_Z^2)$
- Thorough verification of the prediction of the light cone expansion: to higher twist
- Test of linear and non-linear resummations

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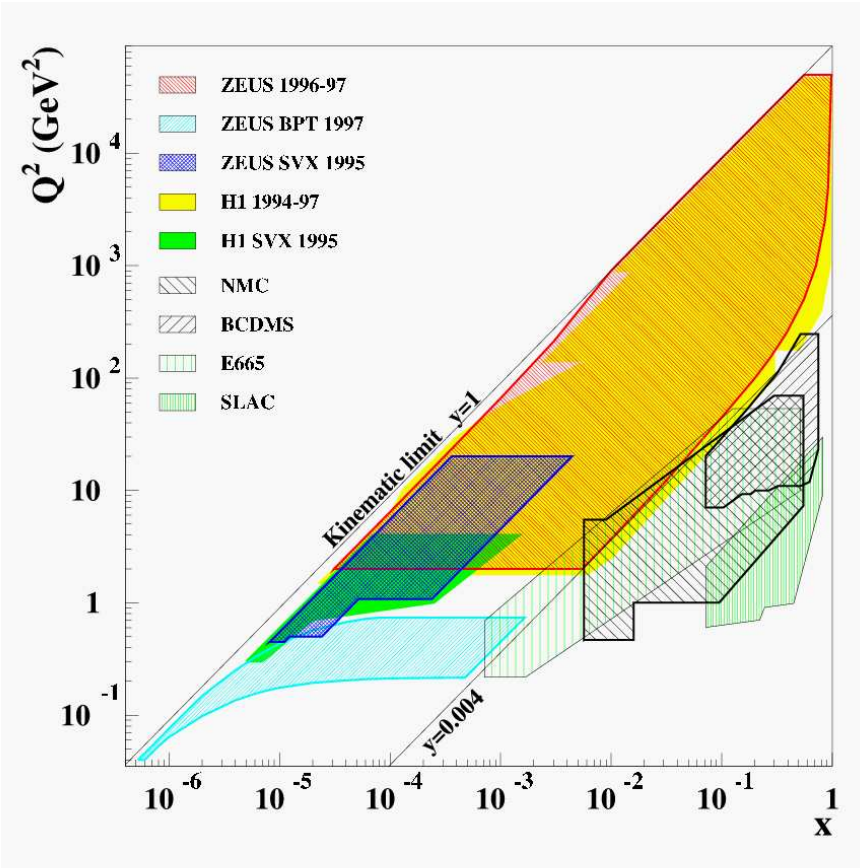
Challenges for Theory:
perturbative and non-perturbative

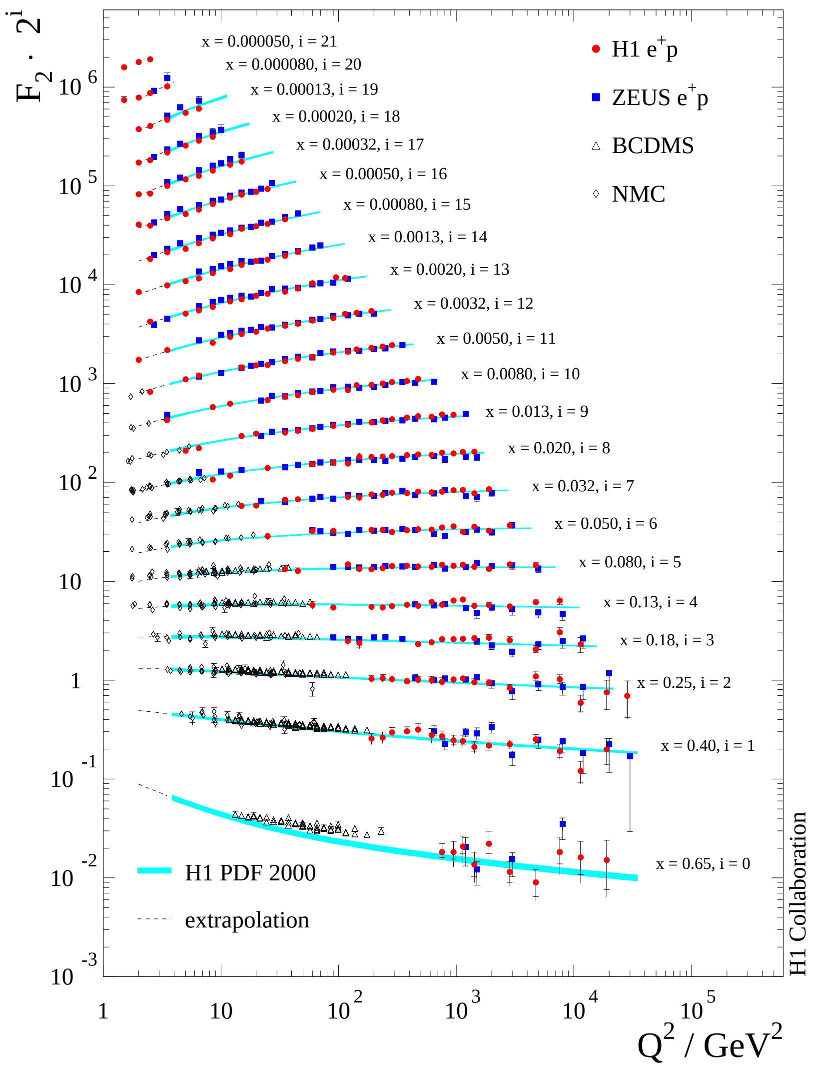
- higher order precision calculations and data analysis
- Lattice gauge theory results for hadronic matrix elements

2. The Achievements : What do we know ?

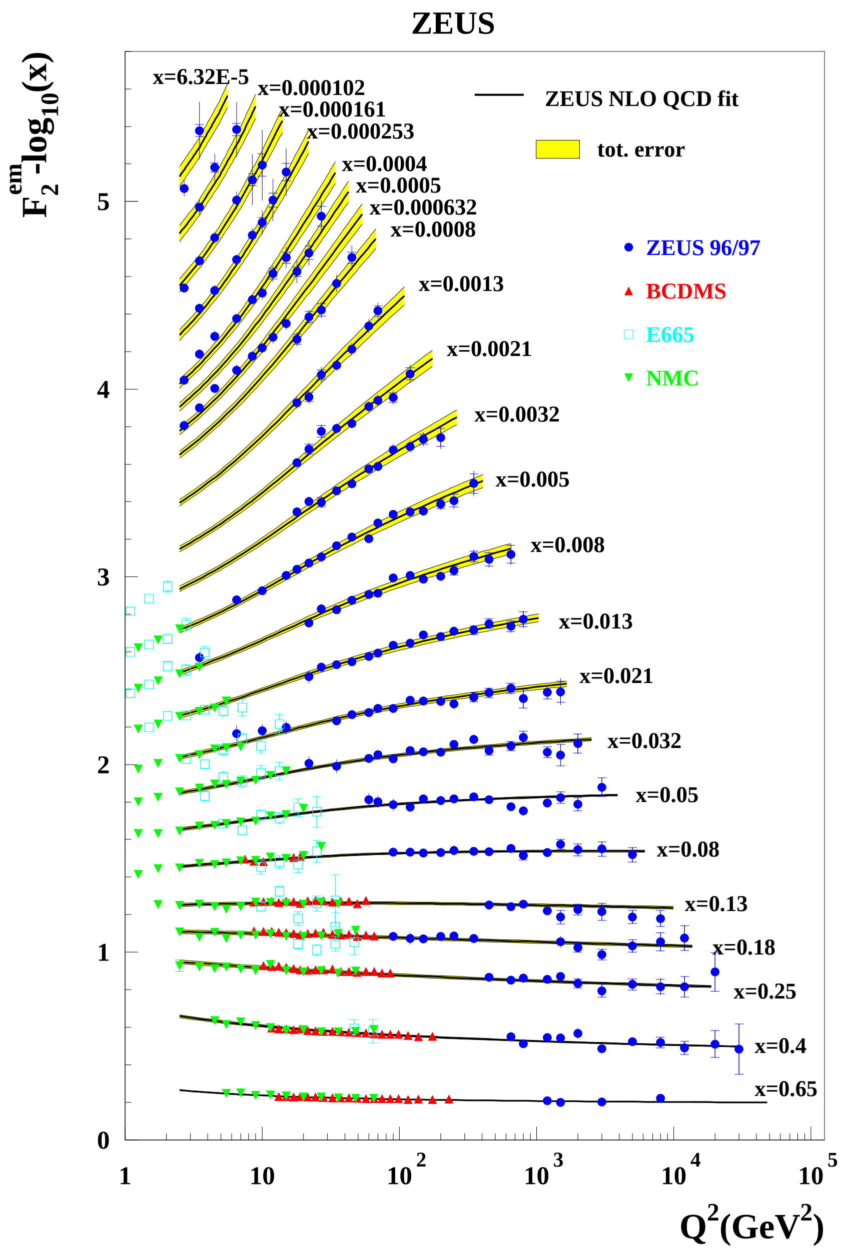
DIS range
Nucleon structure:

$10^{-5} < x < 0.9$,
$1 < Q^2 < 50.000 \mathrm{GeV}^2$



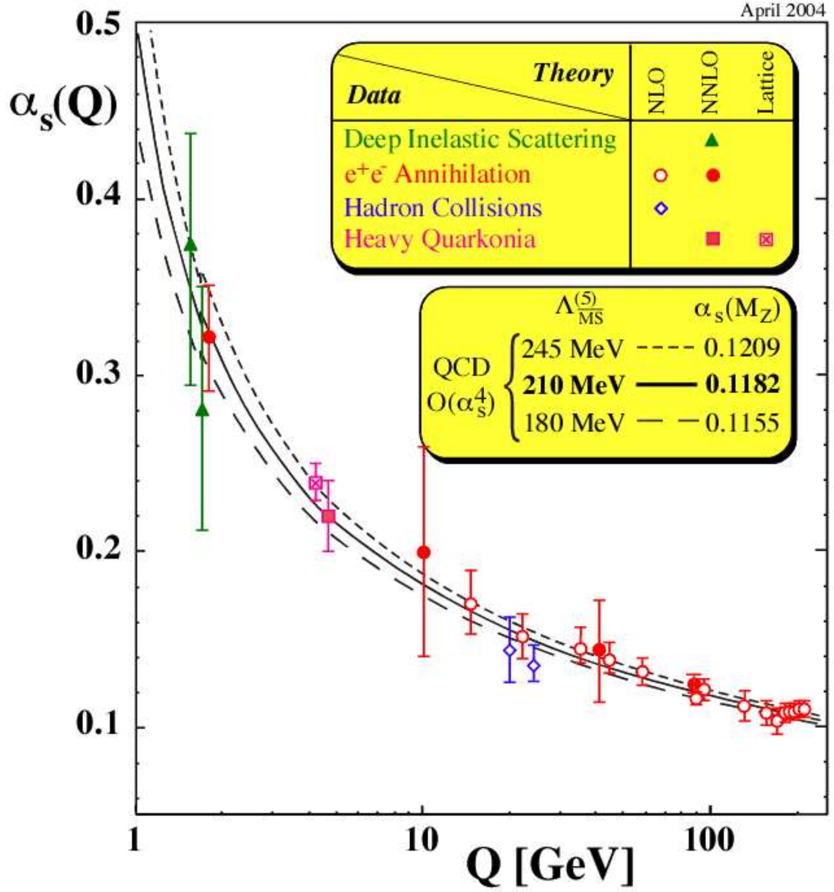


x = 0.000050, i = 21
x = 0.000080, i = 20
x = 0.00013, i = 19
x = 0.00020, i = 18
x = 0.00032, i = 17
x = 0.00050, i = 16
x = 0.00080, i = 15
x = 0.0013, i = 14
x = 0.0020, i = 13
x = 0.0032, i = 12
x = 0.0050, i = 11
x = 0.0080, i = 10
x = 0.013, i = 9
x = 0.020, i = 8
x = 0.032, i = 7
x = 0.050, i = 6
x = 0.080, i = 5
x = 0.13, i = 4
x = 0.18, i = 3
x = 0.25, i = 2
x = 0.40, i = 1
x = 0.65, i = 0
H1 e+p
ZEUS e+p
BCDMS
NMC
H1 PDF 2000
extrapolation
H1 Collaboration
F2 · 2i
Q2 / GeV2



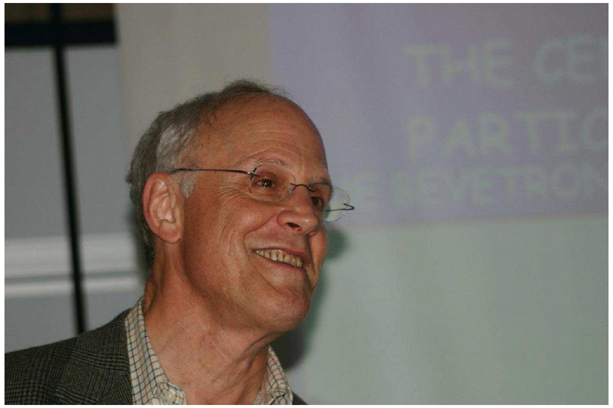
ZEUS
ZEUS NLO QCD fit
tot. error
ZEUS 96/97
BCDMS
E665
NMC
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
F2em-log10(x)
Q2(GeV2)

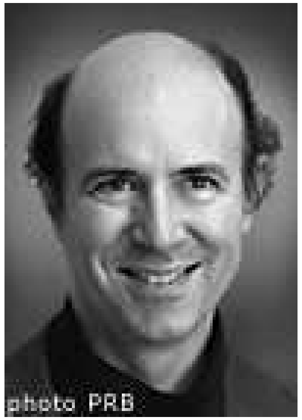
Asymptotic Freedom:

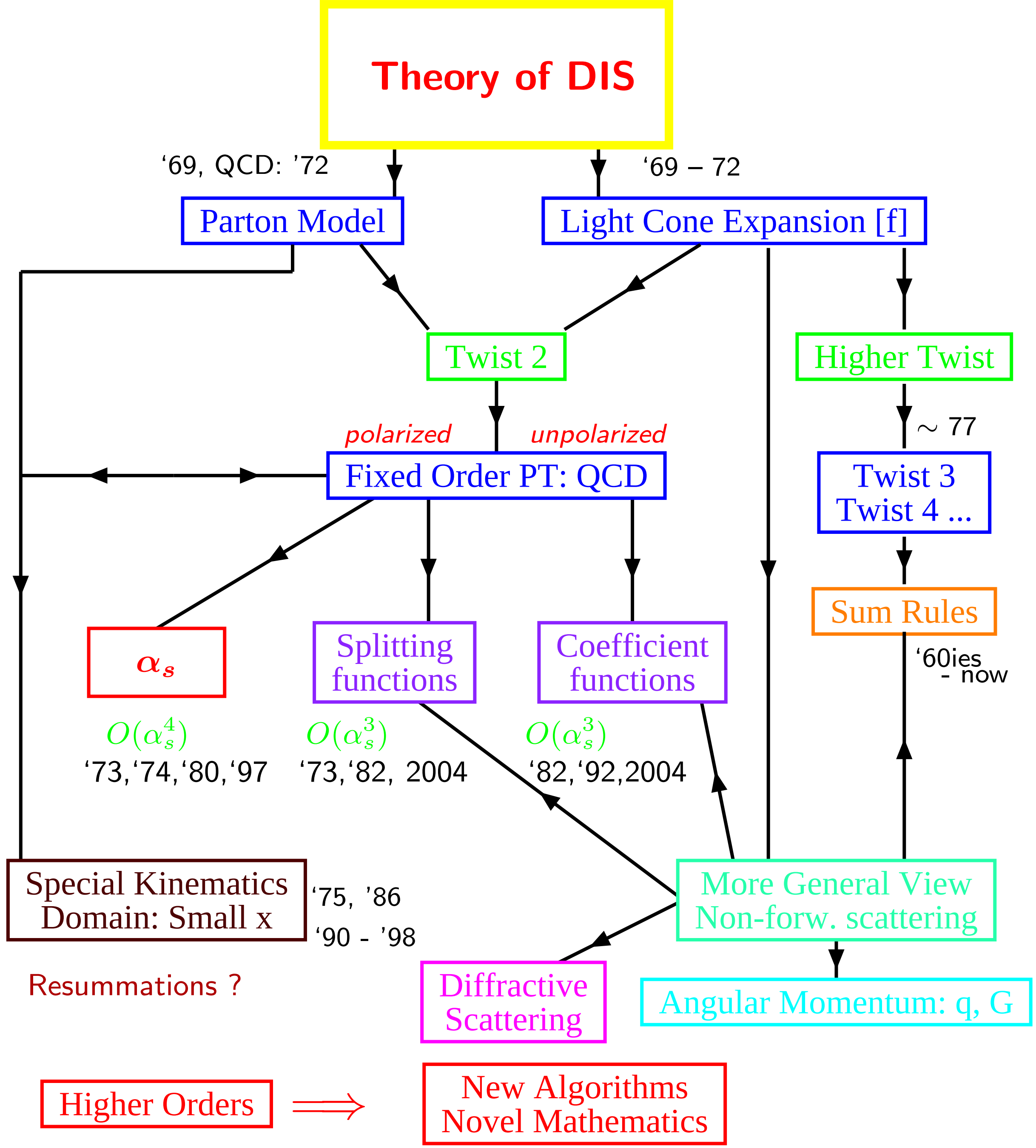


well established

Nobel prize 2004

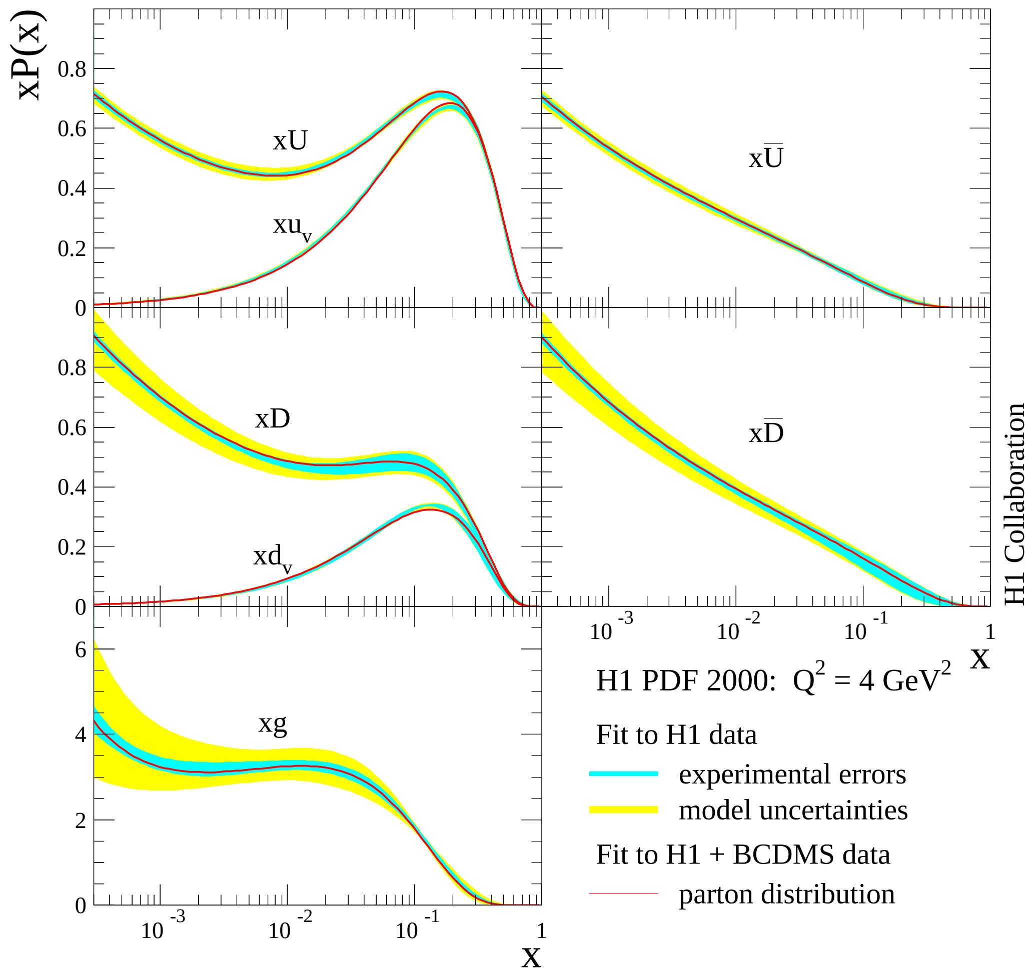




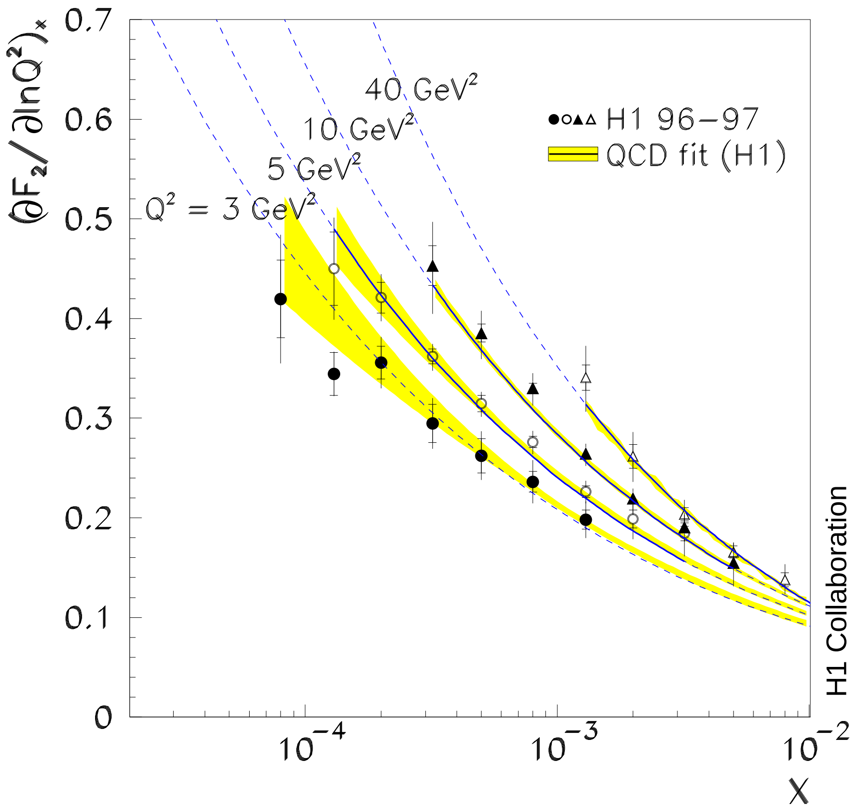
Theory of DIS
'69, QCD: '72
'69 – 72
Parton Model
Light Cone Expansion [f]
Twist 2
Higher Twist
polarized
unpolarized
Fixed Order PT: QCD
~ 77
Twist 3
Twist 4 ...
Sum Rules
'60ies - now
α_s
Splitting functions
Coefficient functions
$O(\alpha_s^4)$
'73,'74,'80,'97
$O(\alpha_s^3)$
'73,'82, 2004
$O(\alpha_s^3)$
'82,'92,2004
Special Kinematics Domain: Small x
'75, '86
'90 - '98
More General View Non-forw. scattering
Resummations ?
Diffractive Scattering
Angular Momentum: q, G
Higher Orders
$\Longrightarrow$
New Algorithms Novel Mathematics

Parton Distributions

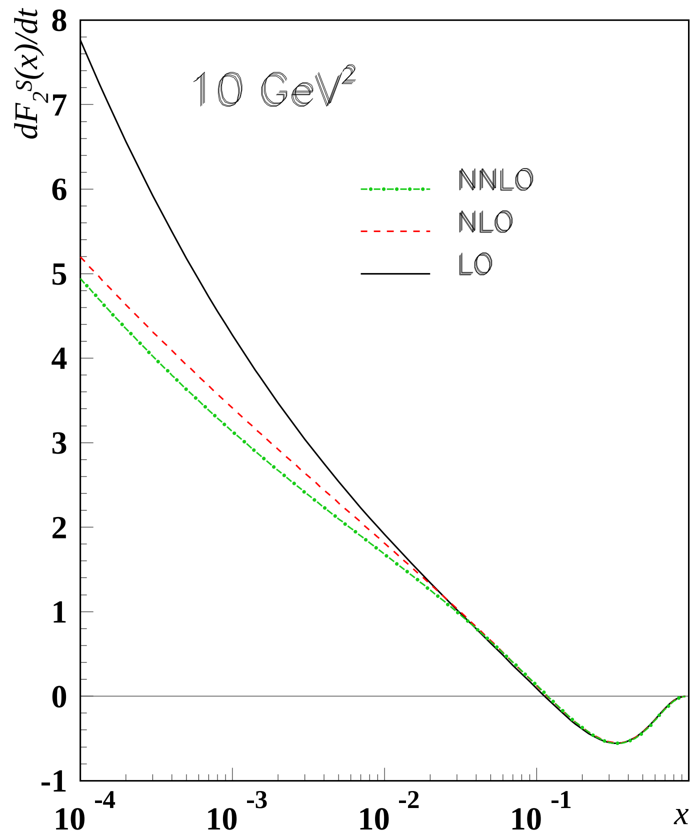


H1

Slope of F_2 at low x



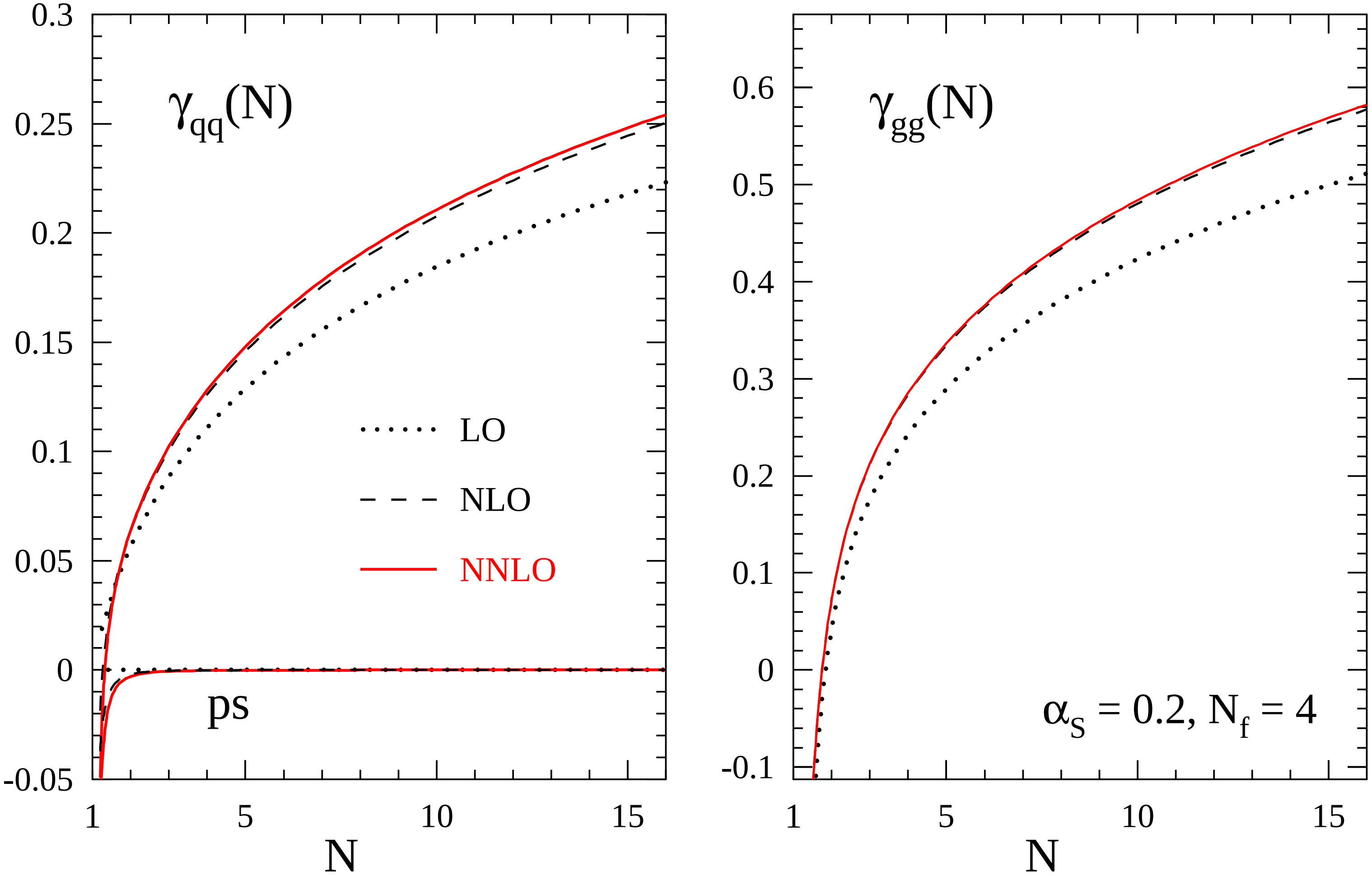
H1



J.B., A. Guffanti 2005

Very likely, that the $\overline{\rm MS}$–gluon is remains positive!

3 Loop Splitting Functions



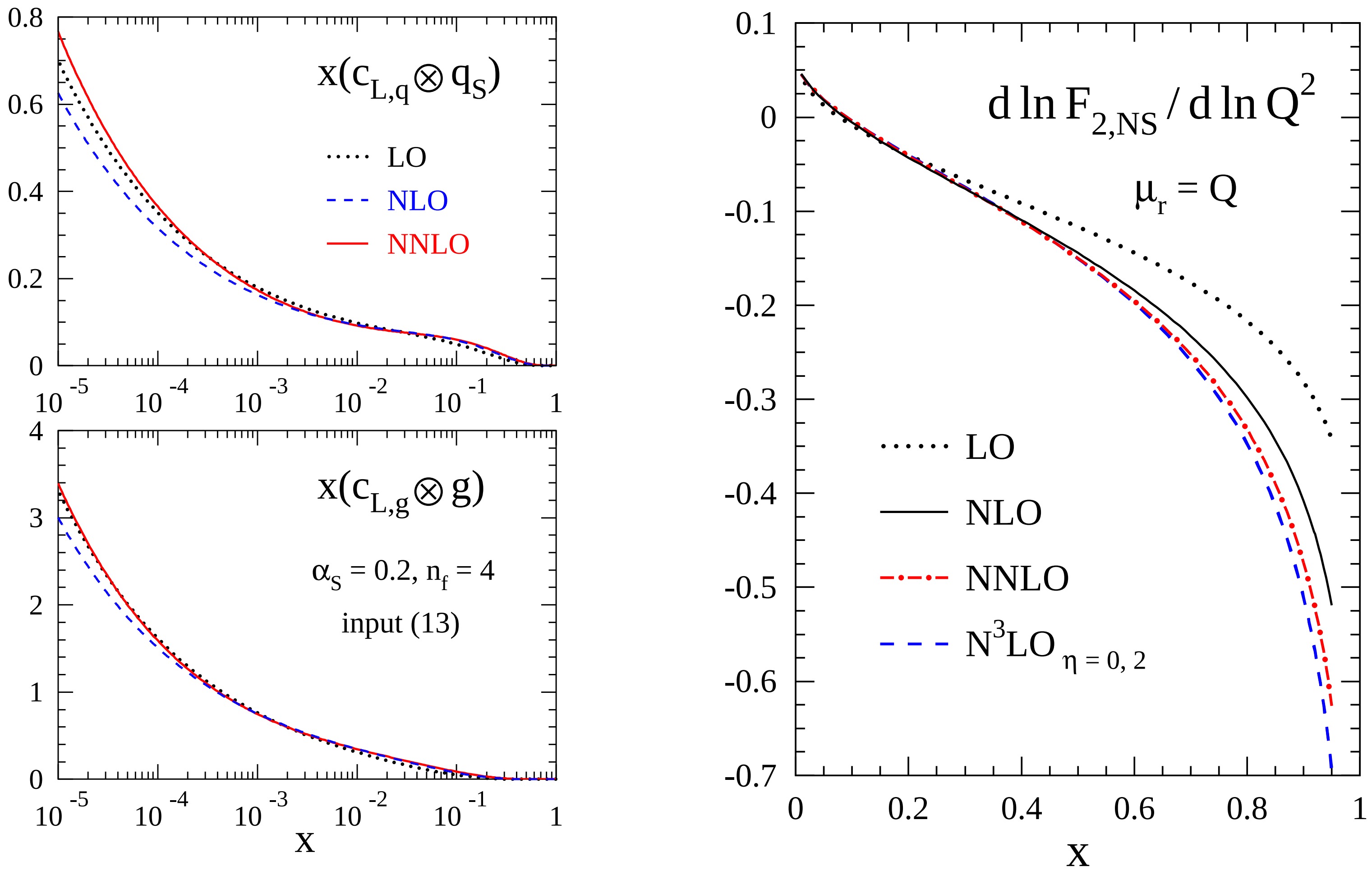
Moch, Vermasern, Vogt, 2004

Moments: 3 Loop Coefficient Functions

Example : J.B., Vermaseren, 2004

$$
\begin{aligned}
C_2^{\mathrm{NS},16}(a_s) \;=\;& \frac{4047739719}{190590400}\, C_F\, a_s \\
&+ \Bigg[\Bigg(\frac{4442667416304442887936697012 7}{3219318469217479564615680 00}\;\frac{24439538}{255255}\,\zeta_3 \Bigg) {C_F}^2 \\
&+ \Bigg(\frac{1791830840849829422278308 7}{594227058731828121600 00} - \frac{113298677}{1021020}\,\zeta_3 \Bigg) C_F\, C_A \\
&- \frac{1435683727619074721111 77}{27589113441120591360 00}\, C_F\, N_F \Bigg] {a_s}^2 \\
&+ \Bigg[\Bigg(\frac{59290512768143}{3127445521200}\,\zeta_4 - \frac{27643576}{21879}\,\zeta_5 \\
&+ \frac{303681339759950972508467729384250597655916168 9}{803445801604077593342164786340334796800000 0} \\
&+ \frac{1494341926940450865387403}{5956740402060127680 00}\,\zeta_3 \Bigg) {C_F}^3 \\
&+ \Bigg(\frac{59290512768143}{6254891042400}\,\zeta_4 + \frac{2628653778834757265588009355150331903 33}{5664680585250384867102104371200000 0} \\
&+ \frac{47187263}{51051}\,\zeta_5 - \frac{1535505046917148231 3}{4991403051835200}\,\zeta_3 \Bigg) C_F\, {C_A}^2 \\
&+ \Bigg(\frac{7227384935999670312318789884999}{76056398835262954714045440000} + \frac{64419601}{20675655}\,\zeta_3 \Bigg) C_F\, {N_F}^2 \\
&+ \Bigg(\frac{775002662711876875284509176089005146524274 1}{165250062032924227343102588716646400000 0} \\
&- \frac{2849482004138921491531}{6741167121672984000}\,\zeta_3 + \frac{983963}{21879}\,\zeta_5 \\
&- \frac{59290512768143}{2084963680800}\,\zeta_4 \Bigg) {C_F}^2 C_A + \Bigg(- \frac{552298563960959}{4021001384400}\,\zeta_3 \\
&- \frac{407320724134849319615222207993355752 9}{352977746994455372827884887040000 0} + \frac{64419601}{1531530}\,\zeta_4 \Bigg) {C_F}^2 N_F \\
&+ \Bigg(\frac{598788865585667}{1850495446800}\,\zeta_3 - \frac{64419601}{1531530}\,\zeta_4 \\
&- \frac{582811634921542995647179358698536547}{404620041803598919078721740800000} \Bigg) C_F\, C_A\, N_F \Bigg] {a_s}^3
\end{aligned}
$$

3 Loop Coefficient Functions



Moch, Vermasern, Vogt, 2004/05

Mathematical structure of HO QCD

Massless QCD, single-scale quantities :

can be described by a very small set of basic functions

Crucial : Mellin space representation.

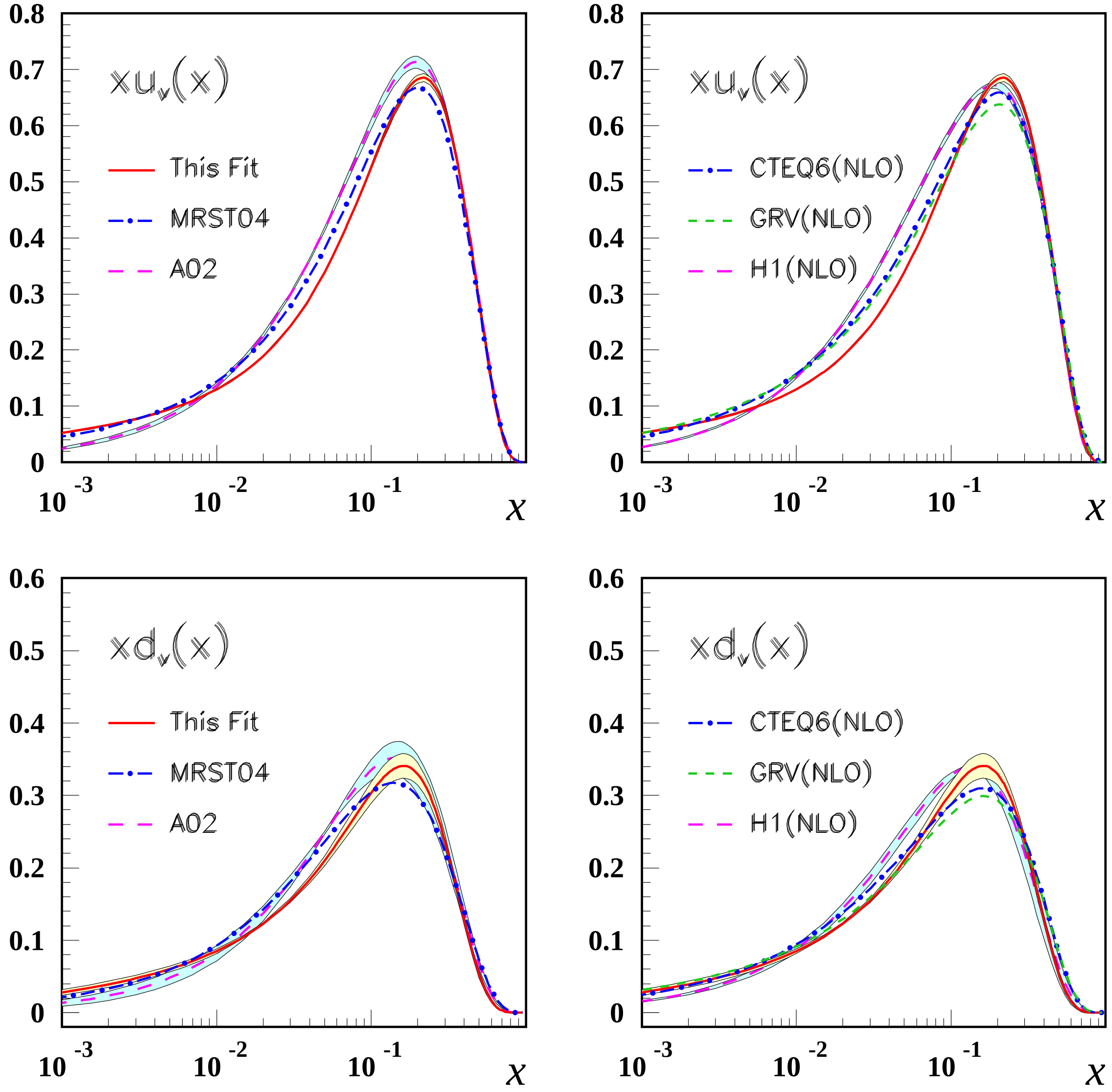
J.B., 2000,2005; J.B., V. Ravindran, 2004, J.B., S. Moch, 2004/05

Precise numerical representations derived.

Weight	Sums	a-basic	Sums $\neg -1$	a-basic	str. Rel.	Fraction
1	2	2	1	0	0	0.0
2	6	3	3	0	0	0.0
3	18	8	7	2	2	0.1111
4	54	18	17	5	3	0.0555
5	162	48	41	14	8	0.0494
6	486	116	99	28	?	$<$0.0576
	728	195	168	49	$<$41	$<$0.0563

Only 14 functions and their derivatives span the QCD single scale quantities to 3 Loops.

Valence Distributions



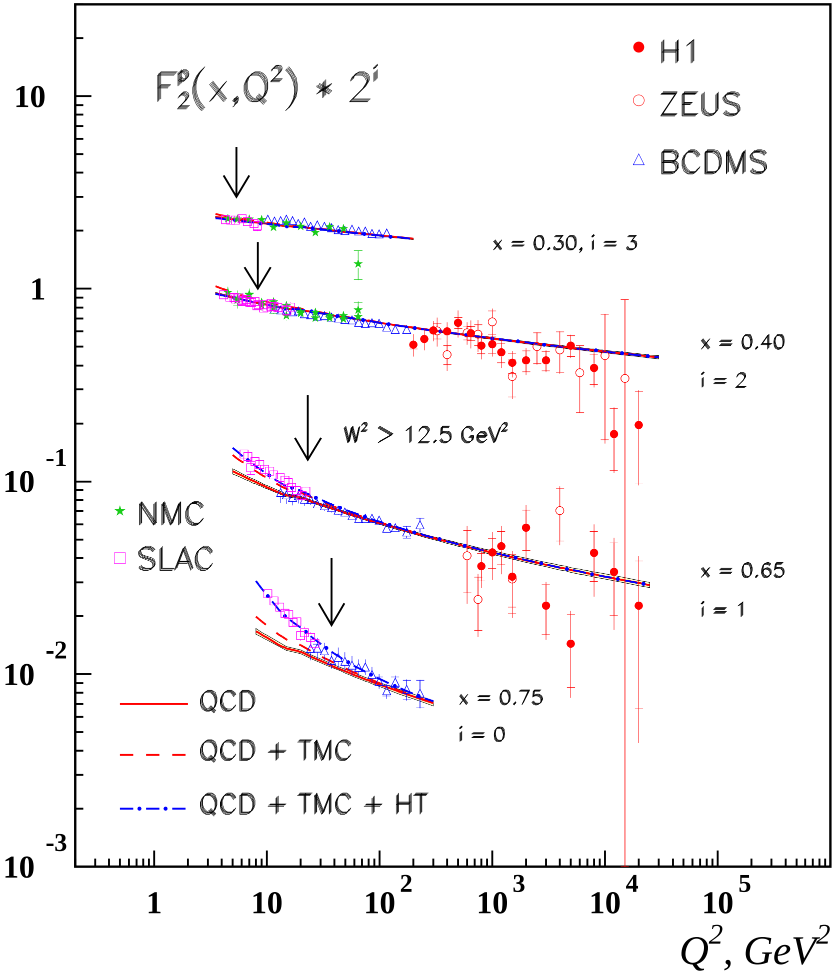
World data:
NS-analysis
$W^2 > 12.5$ GeV^2, $Q^2 > 4$ GeV^2

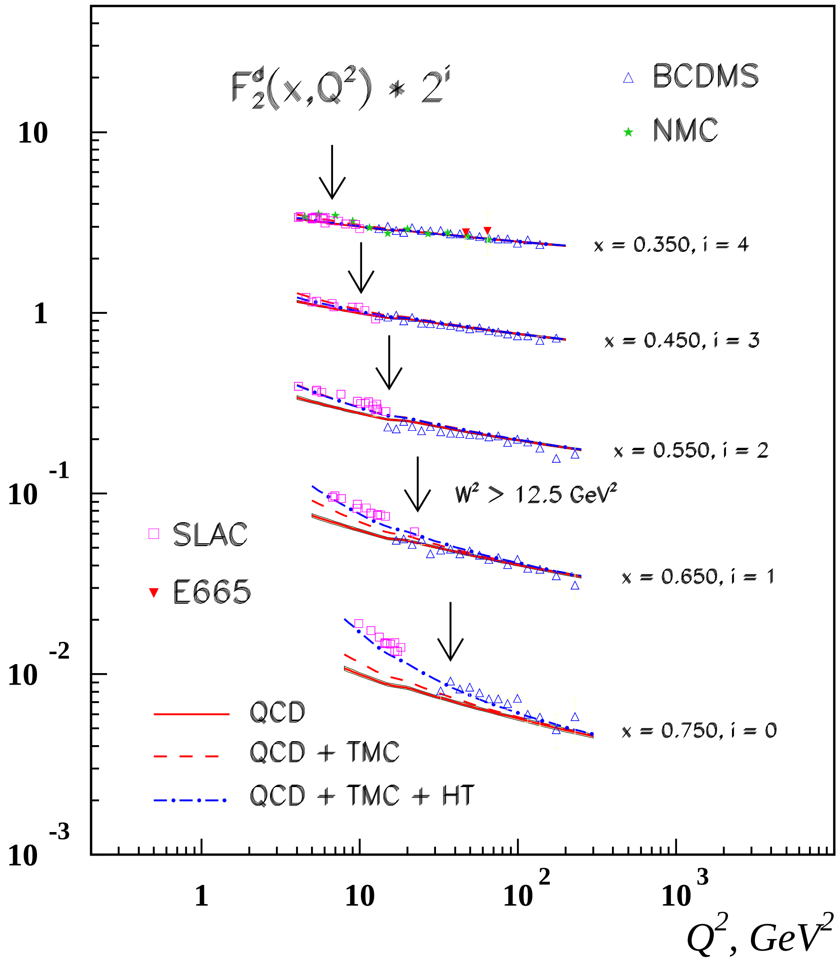
NNLO :

$\alpha_s(M_Z^2) = 0.1139^{+0.0026}_{-0.0028}$

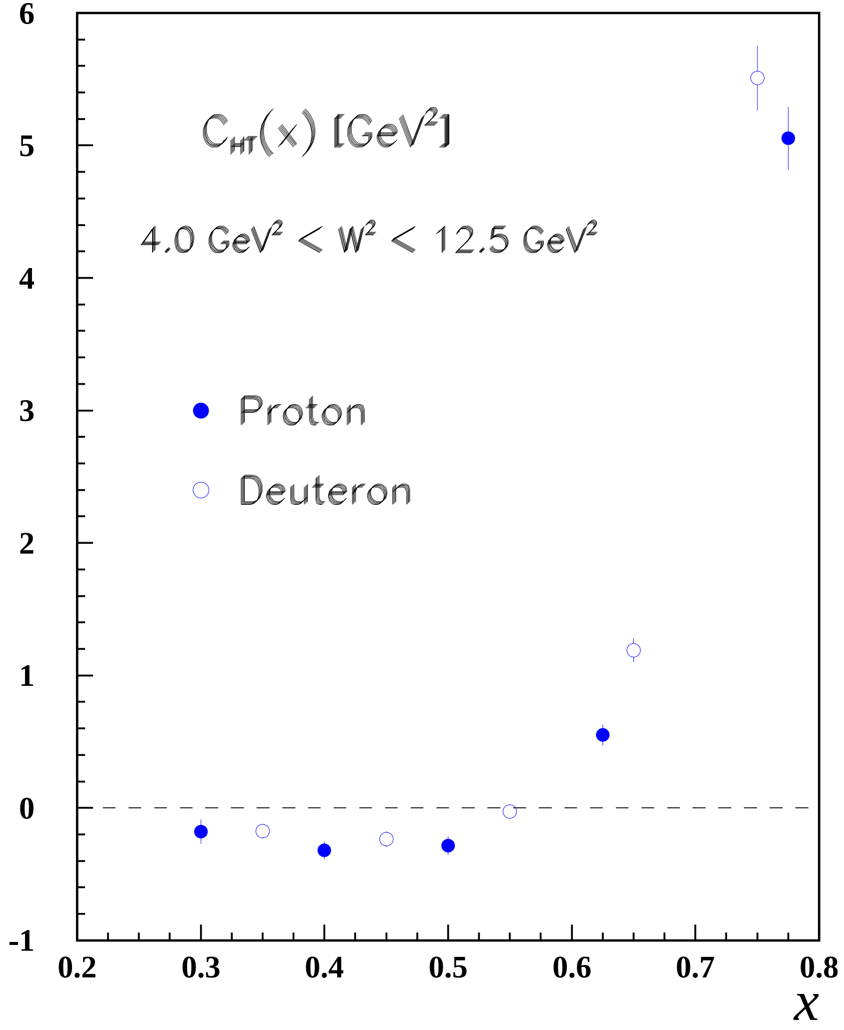
J.B., H. Böttcher,
A. Guffanti, 2004

Valence Distributions



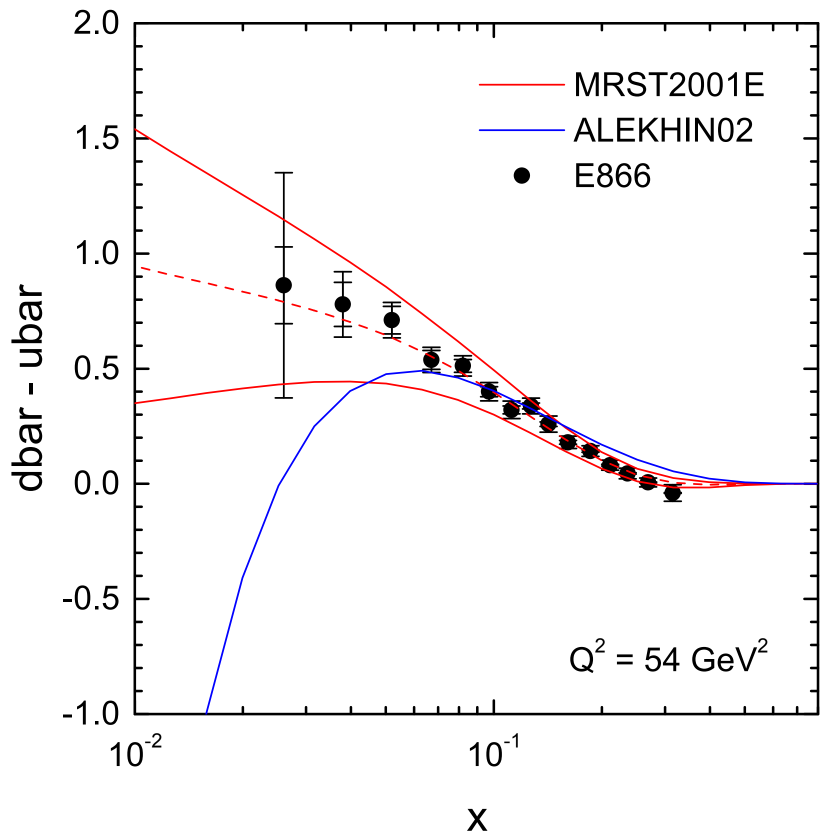


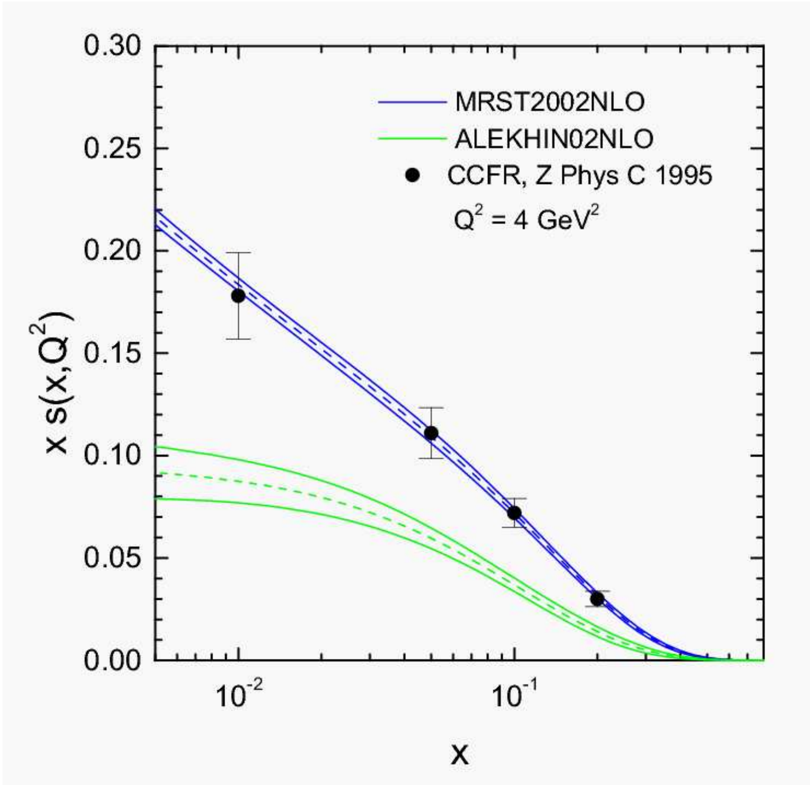
Valence Distributions: higher twist



- agreement between p and d analysis
- LGT determination of interest

Flavor distributions: light quarks



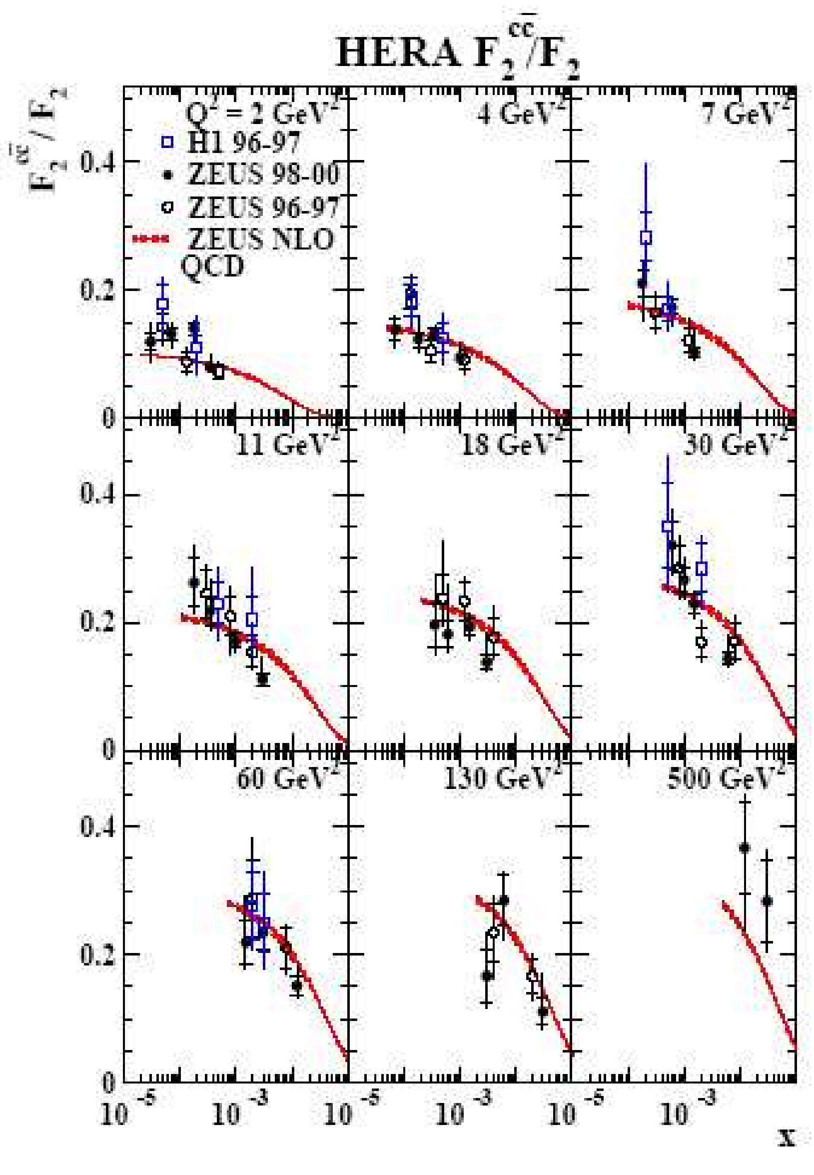


J. Stirling, 2004

More work needed.

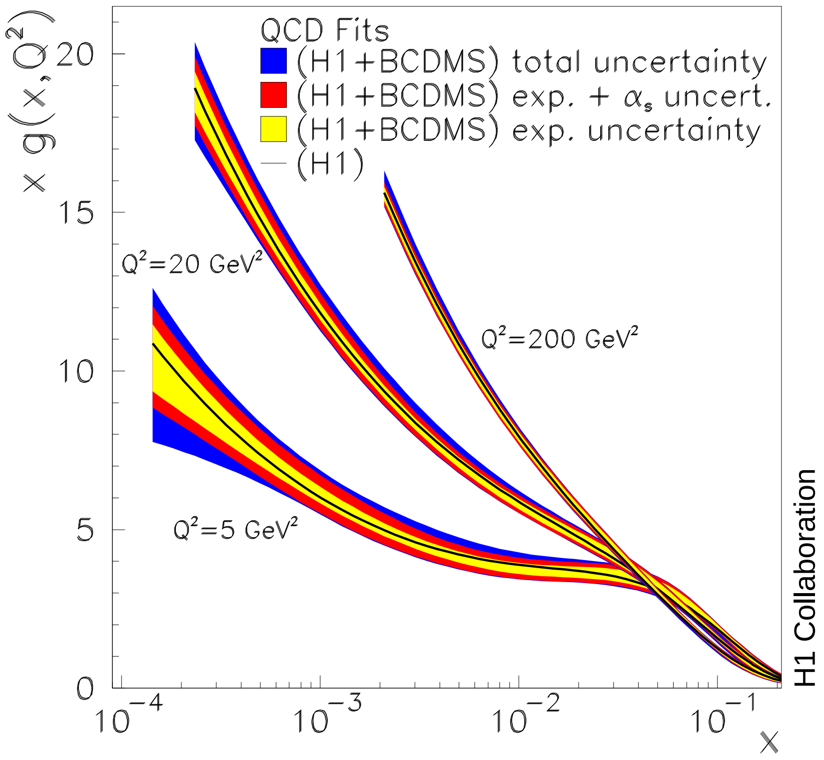
HERMES probably could measure $s(x, Q^2)$ in an independent way.

Charm

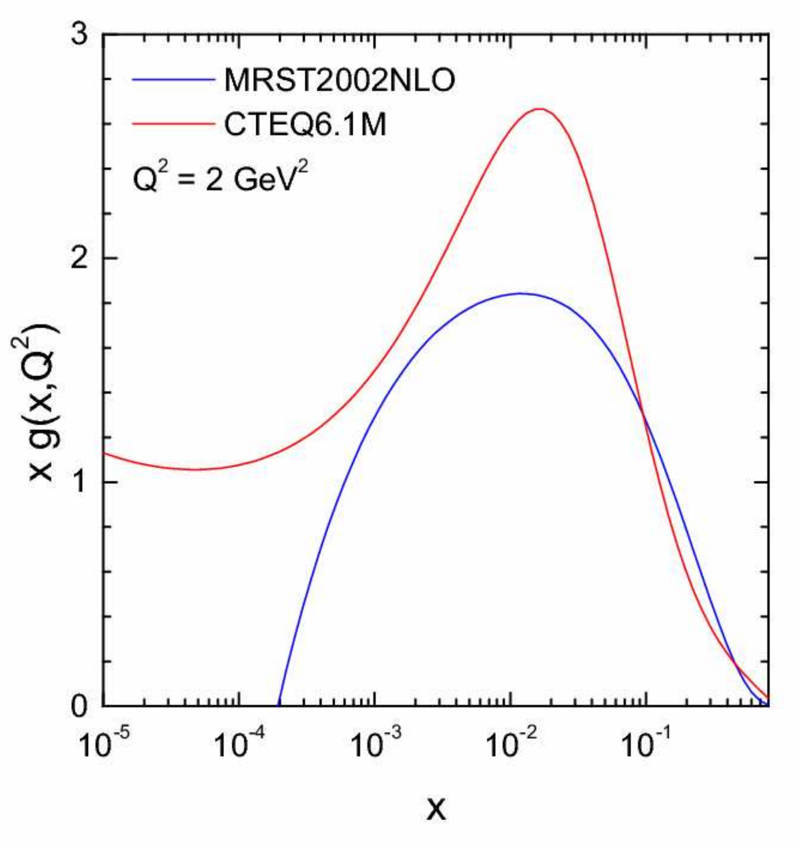


$F_2^{c\bar{c}}(x, Q^2)$ will be very well measured at HERA.

Gluon Density



H1

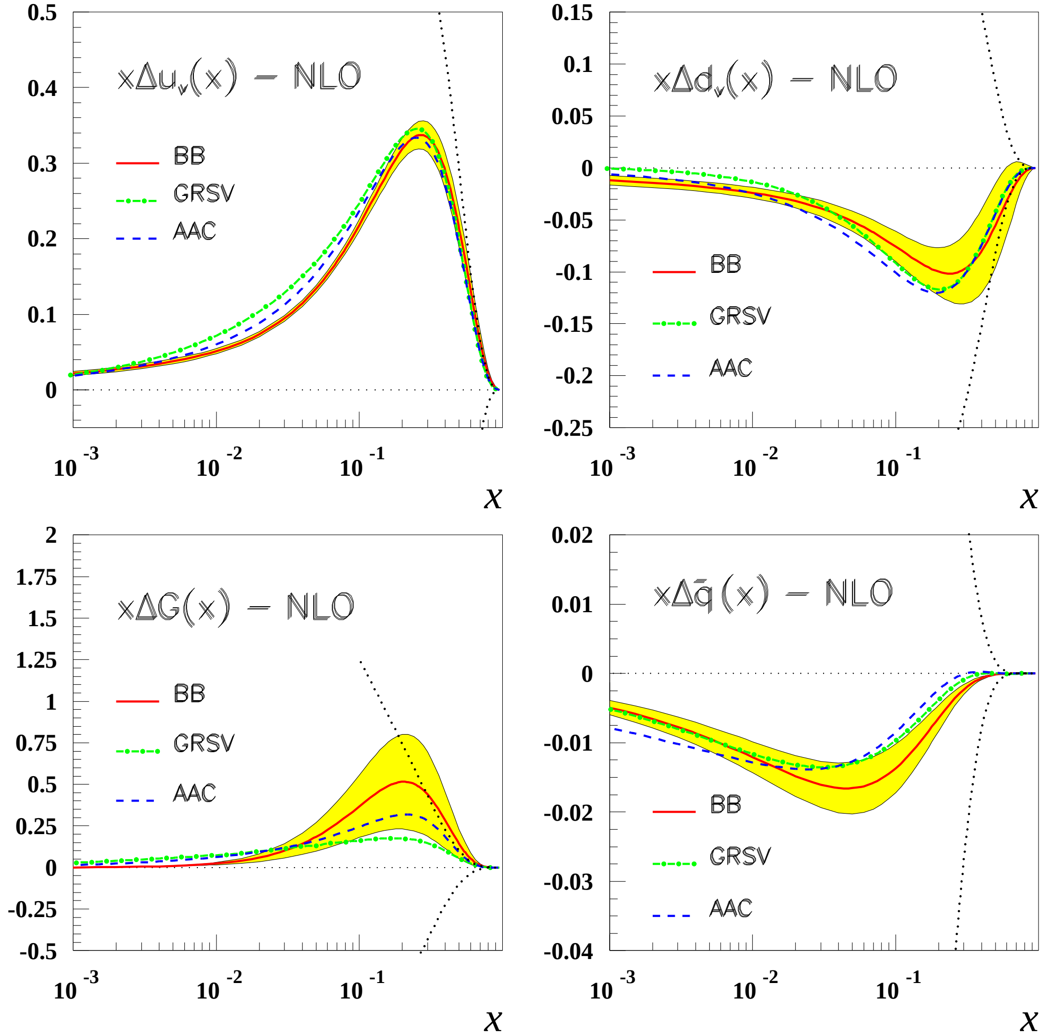


MRST 02

More work needed; MS– vs scheme-invariant evolution.

$F_L(x,Q^2)$ could be decisive.

Polarized Parton Densities

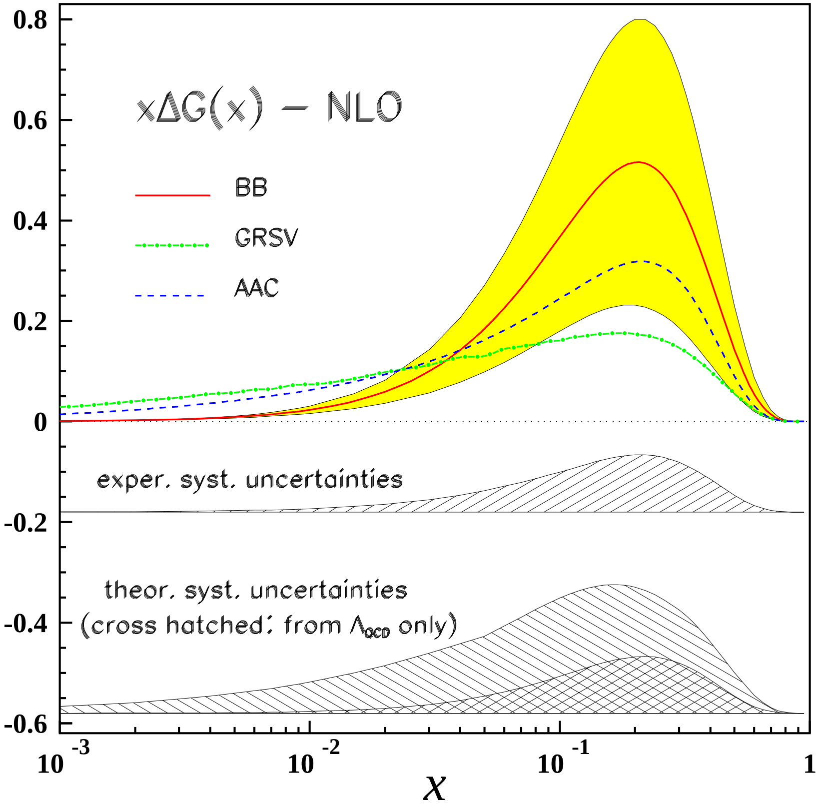


Flavor separation:
HERMES first results

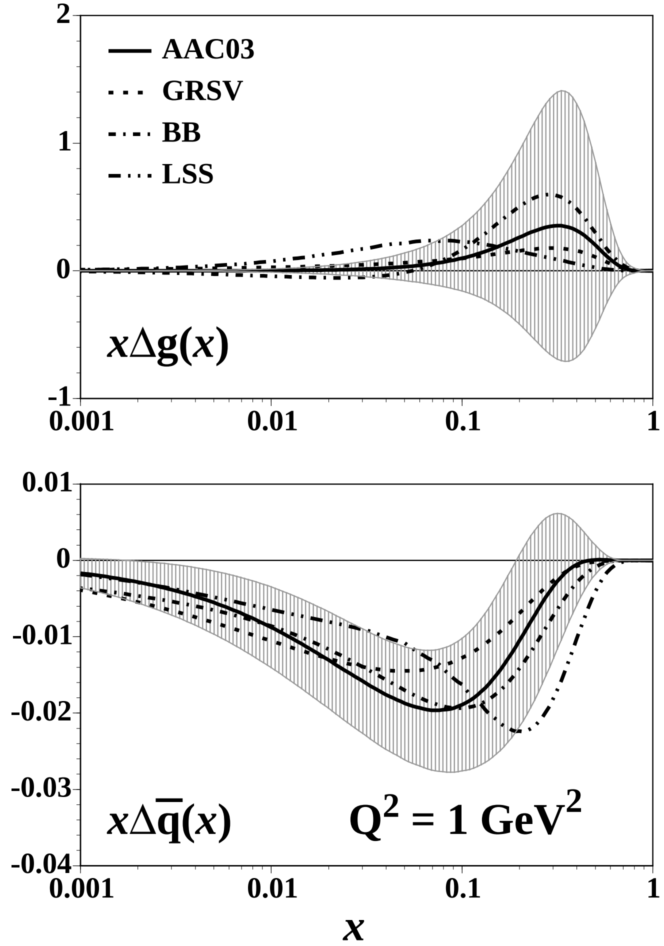
charm: COMPASS

J.B., H. Böttcher, 2002

Polarized Gluon Density



J.B., H. Böttcher, 2002



AAC

$\Longrightarrow$ Currently slight move towards lower values.

Moments of PDF's: PT + data

f	n	This Fit	MRST04	A02
u_v	2	0.288 ± 0.003	0.285	0.304
	3	0.084 ± 0.001	0.082	0.087
	4	0.0319 ± 0.0004	0.032	0.033
d_v	2	0.113 ± 0.004	0.115	0.120
	3	0.026 ± 0.001	0.028	0.028
	4	0.0078 ± 0.0004	0.009	0.010
$u_v - d_v$	2	0.175 ± 0.004	0.171	0.184
	3	0.058 ± 0.001	0.055	0.059
	4	0.0241 ± 0.0005	0.022	0.024

J.B., H. Böttcher, A. Guffanti, 2004

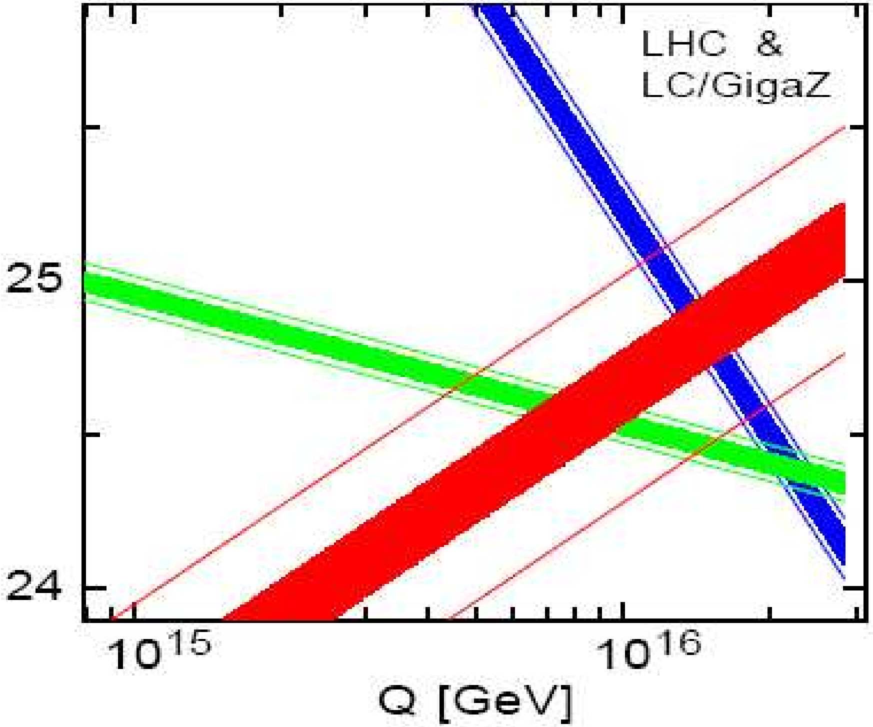
	Moment	BB, NLO
Δu_v	0	0.926
	1	0.163 ± 0.014
	2	0.055 ± 0.006
Δd_v	0	-0.341
	1	-0.047 ± 0.021
	2	-0.015 ± 0.009
$\Delta u_v - \Delta d_v$	0	1.267
	1	0.210 ± 0.025
	2	0.070 ± 0.011

J.B., H. Böttcher, 2002

Lattice Results : developping; different fermion-types studied.
Low values of m_π crucial; values approach 270 MeV now.

Λ_{QCD} and $\alpha_s(M_Z^2)$

$$\frac{\delta\alpha_{\rm em}(0)}{\alpha_{\rm em}(0)} \sim 3\cdot 10^{-11} \qquad \frac{\delta\alpha_{\rm weak}}{\alpha_{\rm weak}} \sim 7\cdot 10^{-4} \qquad \frac{\delta\alpha_s(M_Z^2)}{\alpha_s(M_Z^2)} > 2\cdot 10^{-2}$$



P. Zerwas, 2004

$\alpha_s(M_Z^2)$

NLO	$\alpha_s(M_Z^2)$	expt	theory	Ref.
CTEQ6	0.1165	± 0.0065		[1]
MRST03	0.1165	± 0.0020	± 0.0030	[2]
A02	0.1171	± 0.0015	± 0.0033	[3]
ZEUS	0.1166	± 0.0049		[4]
H1	0.1150	± 0.0017	± 0.0050	[5]
BCDMS	0.110	± 0.006		[6]
BB (pol)	0.113	± 0.004	$^{+0.009}_{-0.006}$	[7]

NLO

NNLO	$\alpha_s(M_Z^2)$	expt	theory	Ref.
MRST03	0.1153	± 0.0020	± 0.0030	[2]
A02	0.1143	± 0.0014	± 0.0009	[3]
SY01(ep)	0.1166	± 0.0013		[8]
SY01(νN)	0.1153	± 0.0063		[8]
BBG	0.1139	$+0.0026/-0.0028$		[9]

NNLO

BBG: $N_f = 4$: non-singlet data-analysis at $O(\alpha_s^3)$: $\Lambda = 233 \pm 30$ MeV

Lattice results :

Alpha Collab: $N_f = 2$ Lattice; non-pert. renormalization $\Lambda = 245 \pm 16 \pm 16$ MeV

QCDSF Collab: $N_f = 2$ Lattice, pert. reno. $\Lambda = 261 \pm 17 \pm 26$ MeV

3. The Needs : What would we like to know ?

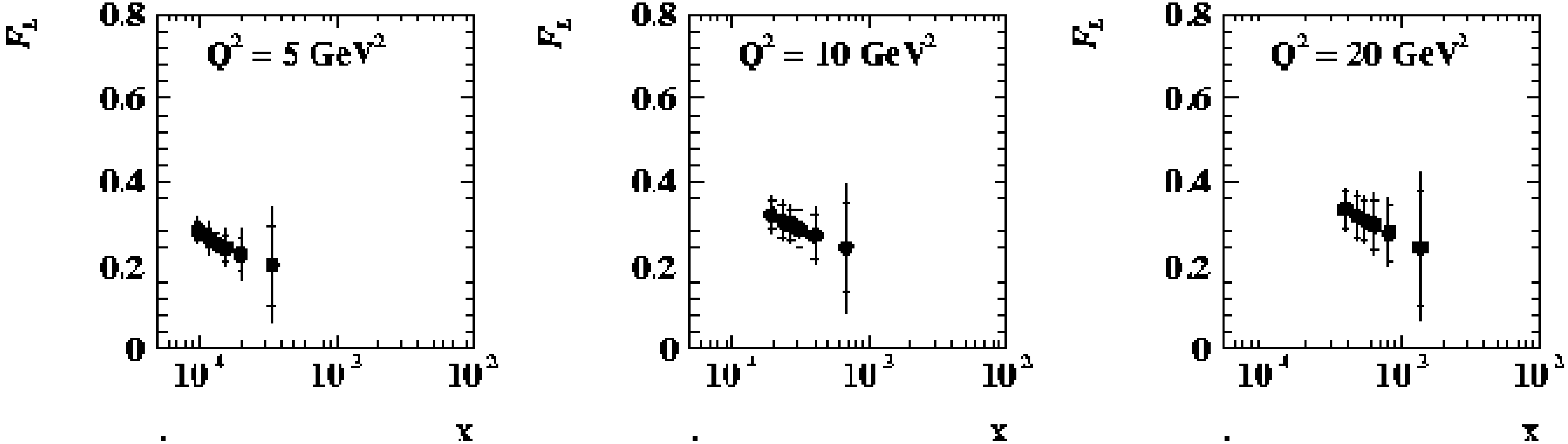
HERA:

- Collect high luminosity for $F_2(x,Q^2)$, $F_2^{c\bar{c}}(x,Q^2)$, $g_2^{c\bar{c}}(x,Q^2)$, and measure $h_1(x,Q^2)$.
- Measure : $F_L(x,Q^2)$. This is a key-question for HERA.

$F_L(x, Q^2)$

M. Klein, 2004: Projection for a possible measurement at HERA

$\Longrightarrow$ of central importance to study the small x behaviour of the gluon distribution



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- Measure : $F_L(x,Q^2)$. This is a key-question for HERA.

RHIC & LHC:

- Improve constraints on gluon and sea–quarks: polarized and unpolarized. DIS PDF's $\Longleftrightarrow$ Collider PDF's

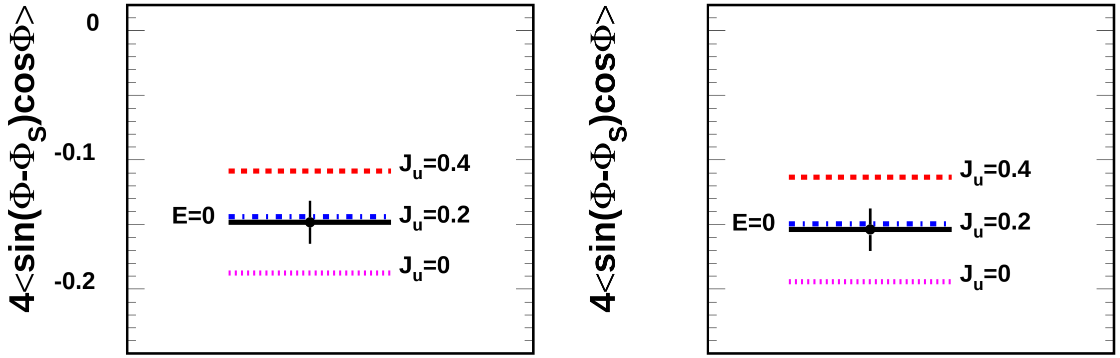
JLAB:

- High precision measurements in the large x domain at unpolarized and polarized targets; supplements HERA's high precision measurements at small x.

L_q from DVCS

- HERA and JLAB : Improve DVCS data

Theory widely developed, cf. rev. Belitsky & Radyushkin, 2005



Expected DVCS asymmetry $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ with $b_v = 1$, $b_s = \infty$, $J_u = 0.4(0.2, 0.0)$, $J_d = 0.0$ in the Regge (left panel) and factorized (right panel) ansatz, at the average kinematics of the full measurement. $E = 0$ denotes zero effective contribution from the GPD E. The projected statistical error for 8M DIS events is shown. The systematic error is expected to not exceed the statistical one.

F. Ellinghaus et al., preliminary

The measurement of L_q off data is model–dependent at the moment.
Lattice calculations at low pion masses are needed to complete the picture

Graph Resummation and Saturation

Further study of proposed mechanisms needed: RHIC, LHC for nucleus-nucleus collisions.

ep scattering: partly different mechanisms

more studies would be welcome; link to higher twist contributions in gluon–dynamics

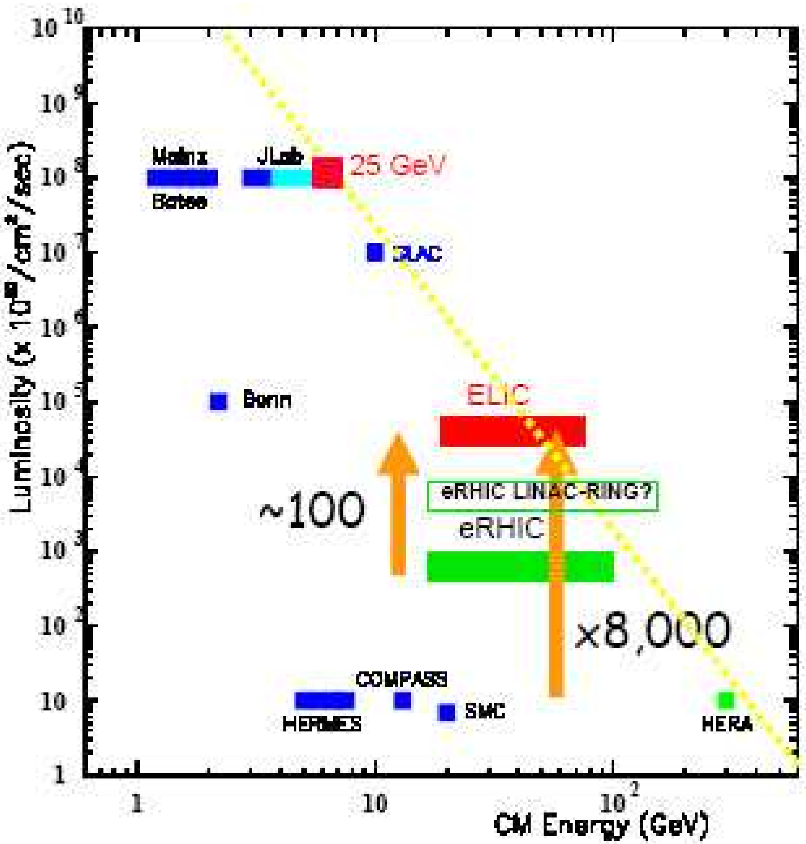
How do the non-perturbative and perturbative parts factorize ?

Conservation laws and interplay between the small x and medium x range behaviour

New DIS Machines

Where to go ?

- High energies : small x, large Q^2 $\Longrightarrow$ talk M. Klein
- High luminosities : ELIC: $\sqrt{s}$ between CERN and HERA energies



R. Ent,2004
high precision physics
polarized and unpolarized

Would be an important extension of the present programmes in many respects.

Enhancing Precision Further...

- What is the correct value of $\alpha_s(M_z^2)$? $\overline{\mathrm{MS}}$-analysis vs. scheme-invariant evolution helps. Compare non–singlet and singlet analysis; careful treatment of heavy flavor. (Theory & Experiment)
- Flavor Structure of Sea-Quarks: More studies needed.(All Experiments)
- Revisit polarized data upon arrival of the 3-loop anomalous dimensions; NLO heavy flavor contributions needed. (Theory)
- QCD at Twist 3: $g_2(x, Q^2)$, semi–exclusive Reactions, Transversity, diffraction in polarized scattering (HERMES, High Precision polarized experiments, JLAB, ELIC)
- Comparison with Lattice Results: α_s, Moments of Parton Distributions, Angular Momentum.

Enhancing Precision Further...

- Calculation of more hard scattering reactions at the 3–loop level: ILC, LHC
- Further perfection of the mathematical tools:
  $\Longrightarrow$ Algorithmic simplification of Perturbation theory in higher orders.
- Even higher order corrections needed ?