1984 – 2004:
20 Years of Global QCD Analysis of the Parton Structure of Nucleon

– A survey of open issues through the historical perspective

DIS04 Strbske Pleso Tung

The two Topcite papers that started this journey in 1984:

*Q**2 DEPENDENT PARAMETRIZATIONS OF PARTON DISTRIBUTION FUNCTIONS*.1092 citations

By D.W. Duke, J.F. Owens (Florida State U.),. FSU-HEP-831115, Nov 1983. Phys.Rev.D30:49,1984

SUPER COLLIDER PHYSICS.
By E. Eichten, I. Hinchliffe, Kenneth D. Lane , C. Quigg,. Feb 1984. 550pp. 1667 citations
Rev.Mod.Phys.56:579,1984

How far have we come along?

What still remains unclear?

How far do we still to go?

Agenda

- The Valence quarks
- The Gluon
- The Sea quarks
  - Breaking of Isospin Symmetry
  - Breaking of flavor SU(3)
  - Strangeness Asymmetry?
  - Iso-spin Violation?
  - Heavy Quark Parton Distributions
- Uncertainties of
  - Parton Distributions, and
  - Their Physical Predictions

First, some quantitative measure of the progress made over the years (illustrative only)

	Fixed-tgt	HERA	DY-W	Jets	Total
# Expt pts.	1070	484	145	123	1822
EHLQ '84					
DuOw '84					
MoTu ~'90					
KMRS ~'90					
CTQ2M ~'94					
MRSTA ~'94					
GRV94 ~'94					
CTQ4M ~'98					
MRS981 ~'98					
CTQ6M 02					
MRST01 01					
Alekhin 03					

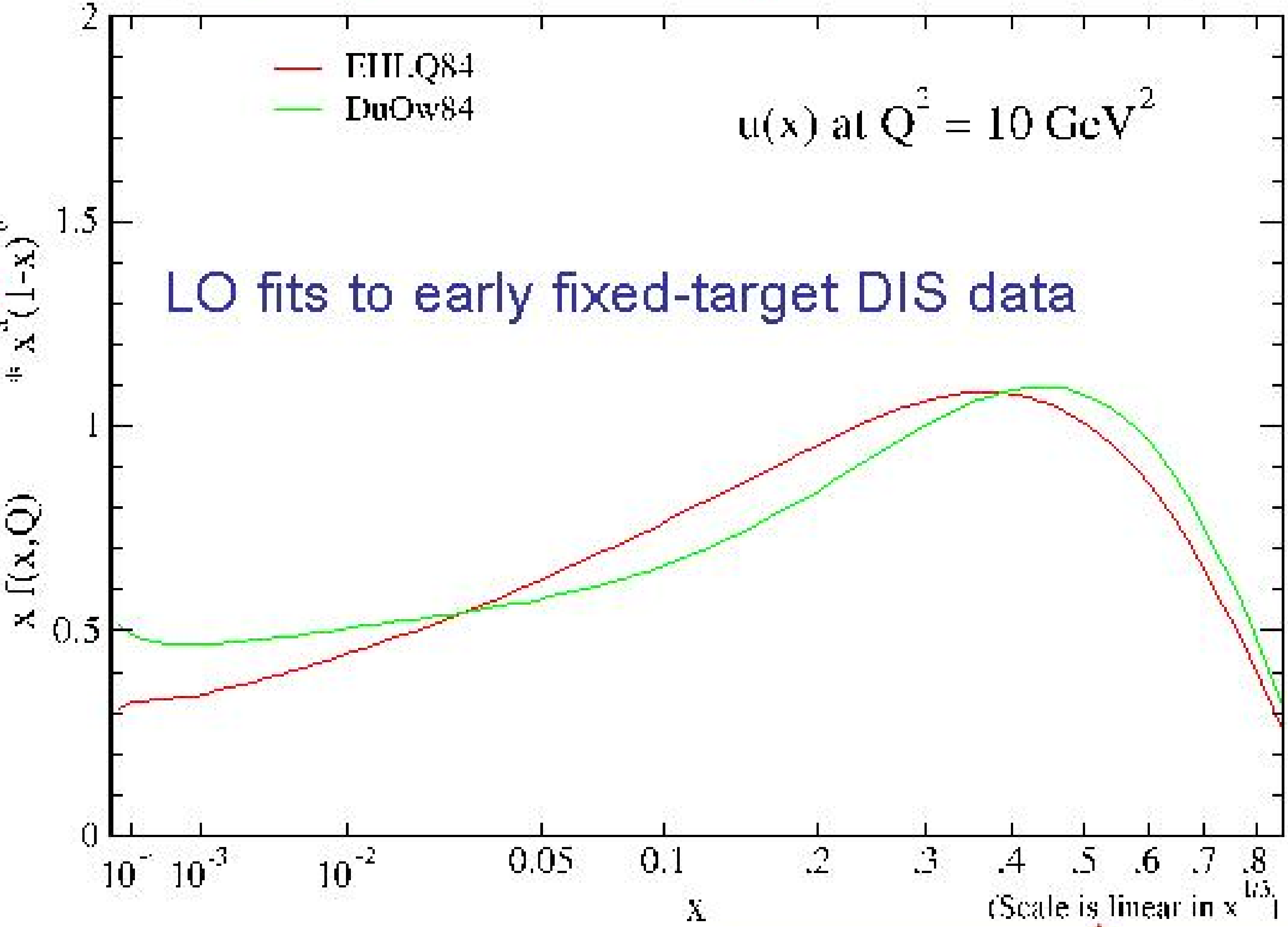
χ^2 values evaluated on common data sets based on the respective PDFs, using the CTEQ fitting program.

First, some quantitative measure of the progress made over the years (illustrative only)

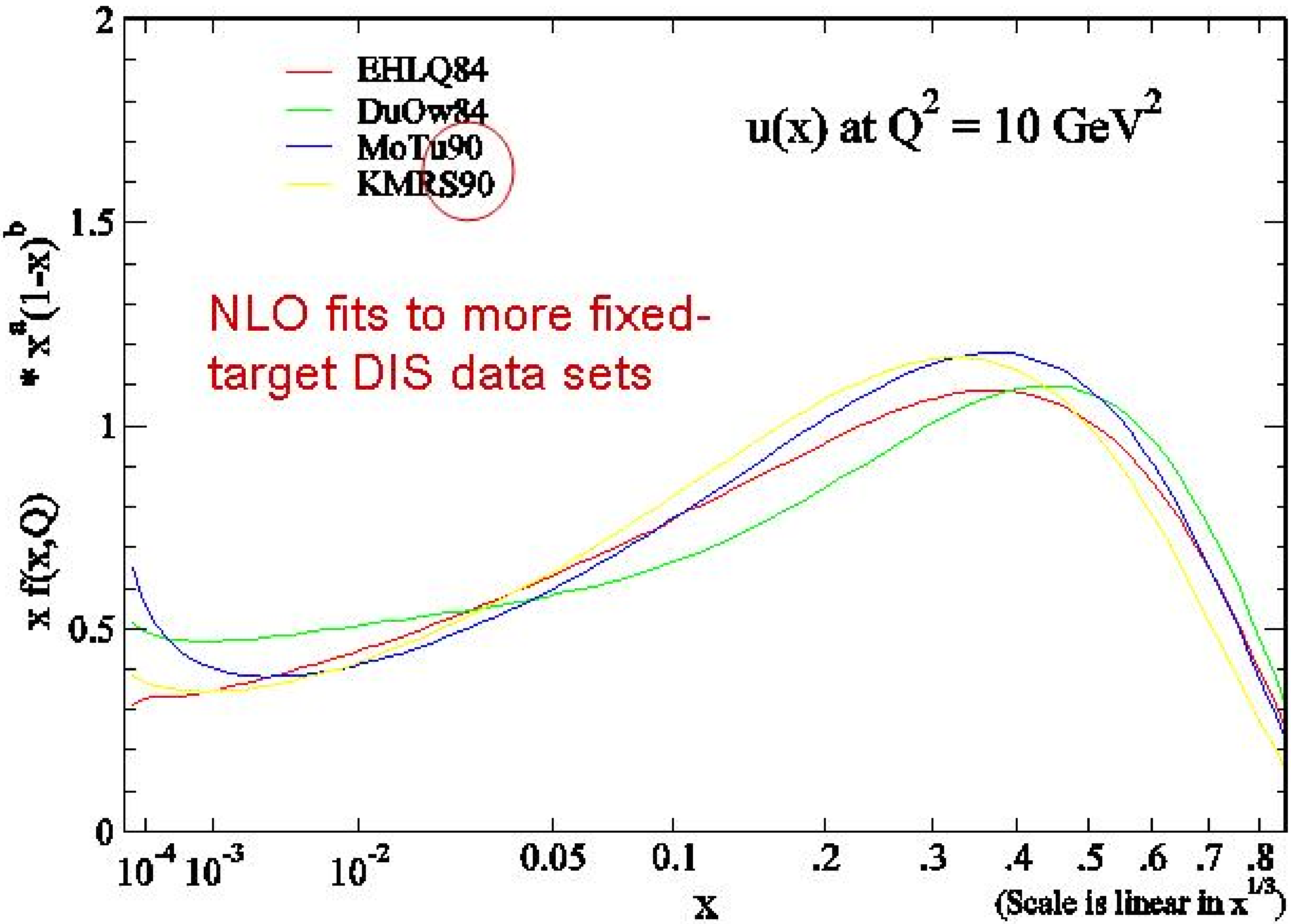
	Fixed-tgt	HERA	DY-W	Jets	Total
# Expt pts.	1070	484	145	123	1822
EHLQ '84	11475	7750	2373	331	21929
DuOw '84	8308	5005	1599	275	15187
MoTu ~'90	3551	3707	857	218	8333
KMRS ~'90	1815	7709	577	280	10381
CTQ2M ~'94	1531	1241	646	224	3642
MRSTA ~'94	1590	983	249	231	3054
GRV94 ~'94	1497	3779	302	213	5791
CTQ4M ~'98	1414	666	227	206	2513
MRS981 ~'98	1398	659	111	227	2396
CTQ6M 02	1239	508	159	123	2029
MRST01 01	1378	530	120	236	2264
Alekhin 03	1576	572	892	270	3309

The Valence u Quark: progression of improvements

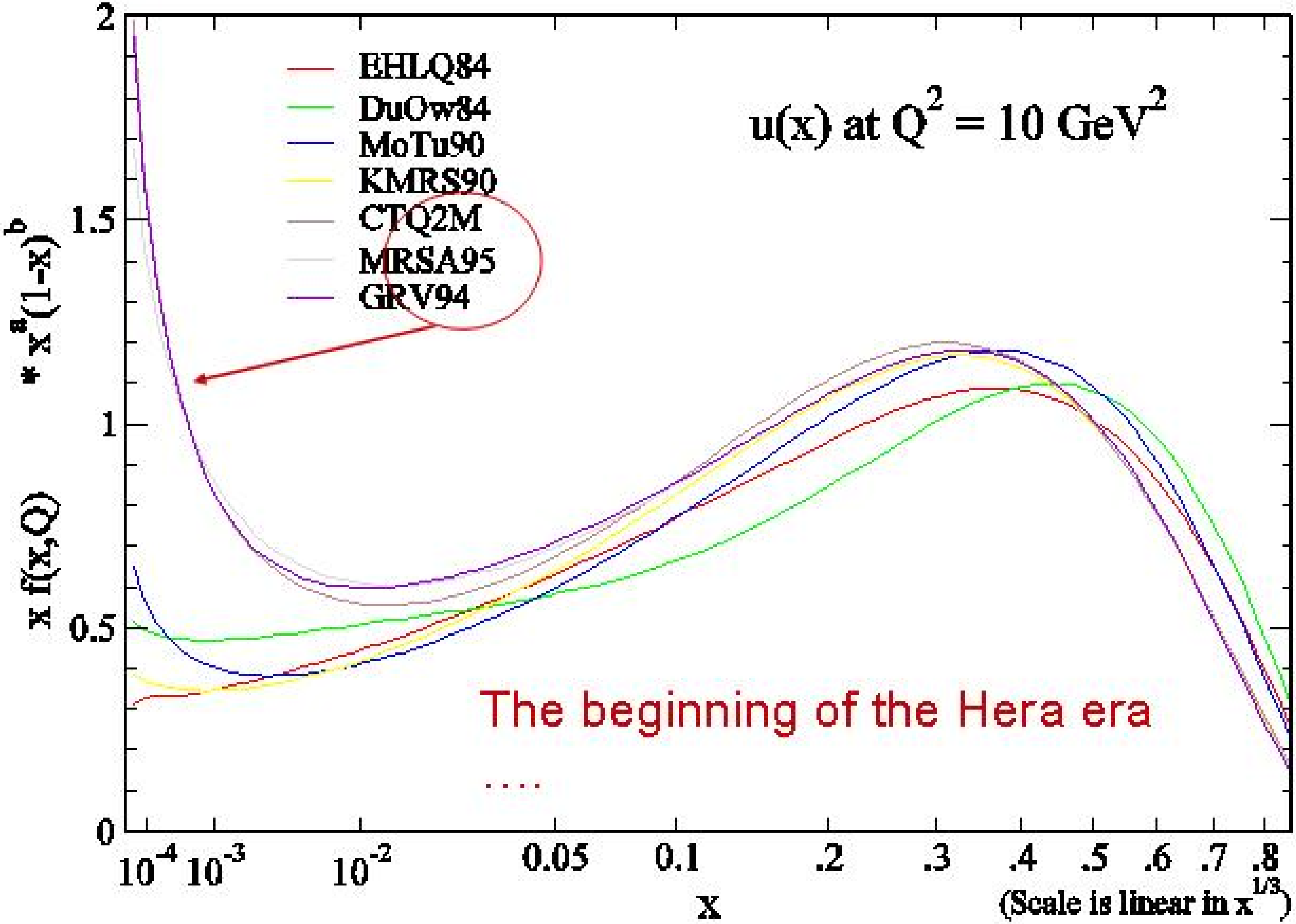
To reveal the difference in both large and small x regions

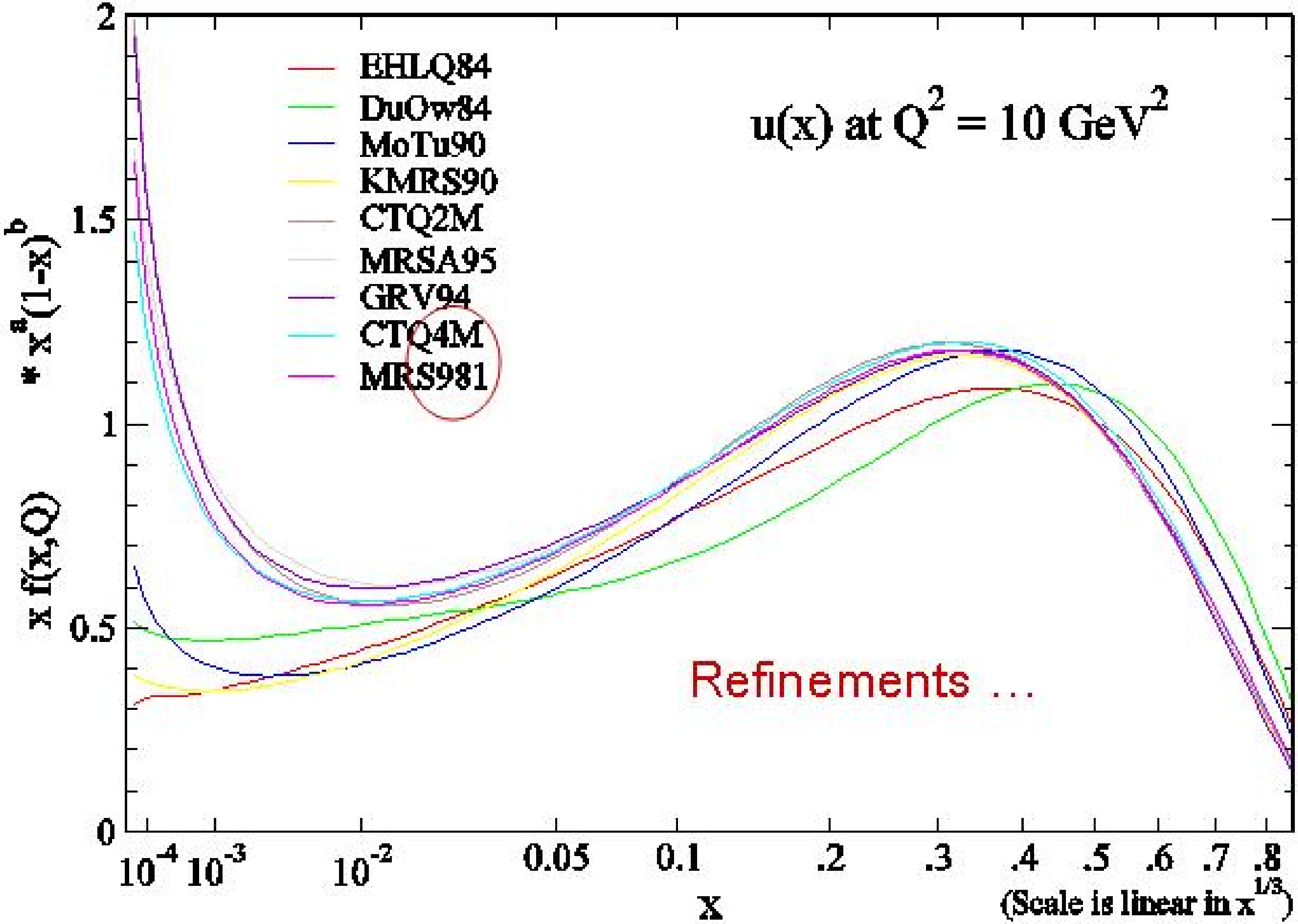


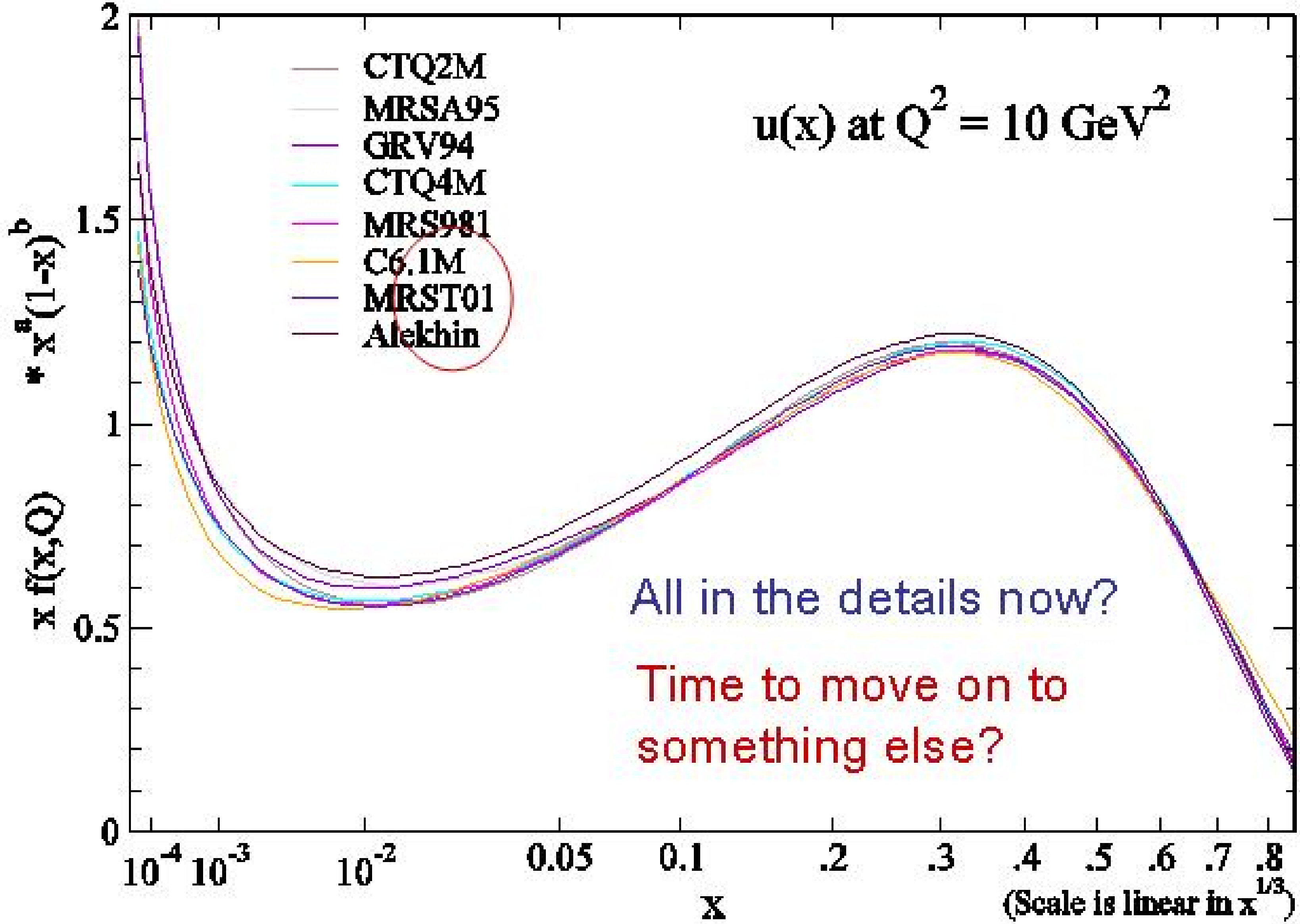
To view small and large x in one plot



EHLQ84
DuOw84
MoTu90
KMRS90
u(x) at Q^2 = 10 GeV^2
NLO fits to more fixed-target DIS data sets
x f(x,Q) * x^a (1-x)^b
x
(Scale is linear in x^1/3)
2
1.5
1
0.5
0
10^-4
10^-3
10^-2
0.05
0.1
.2
.3
.4
.5
.6
.7
.8

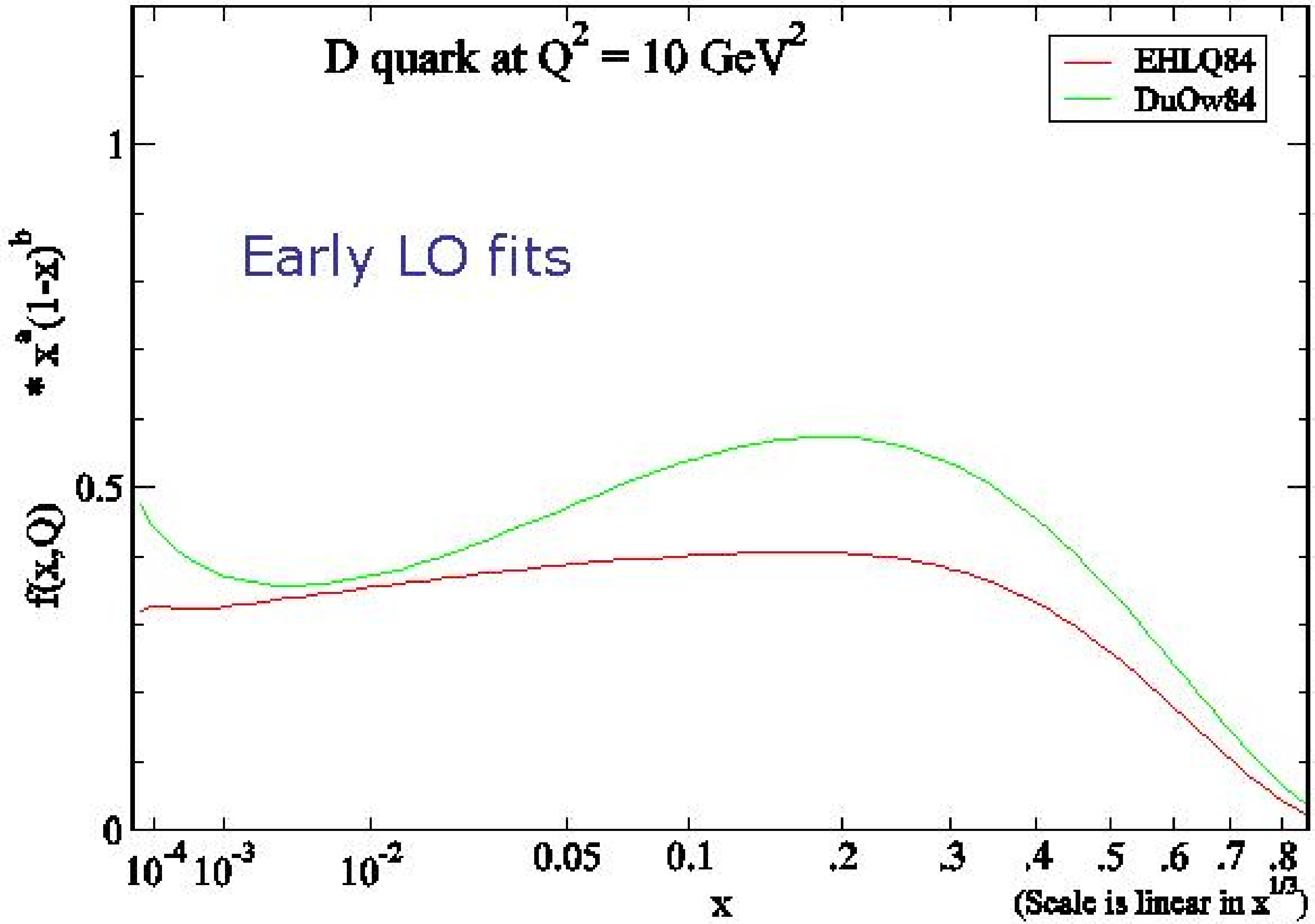

EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
u(x) at Q2 = 10 GeV2
x f(x,Q) * x^a (1-x)^b
x
(Scale is linear in x^1/3)
The beginning of the Hera era
....

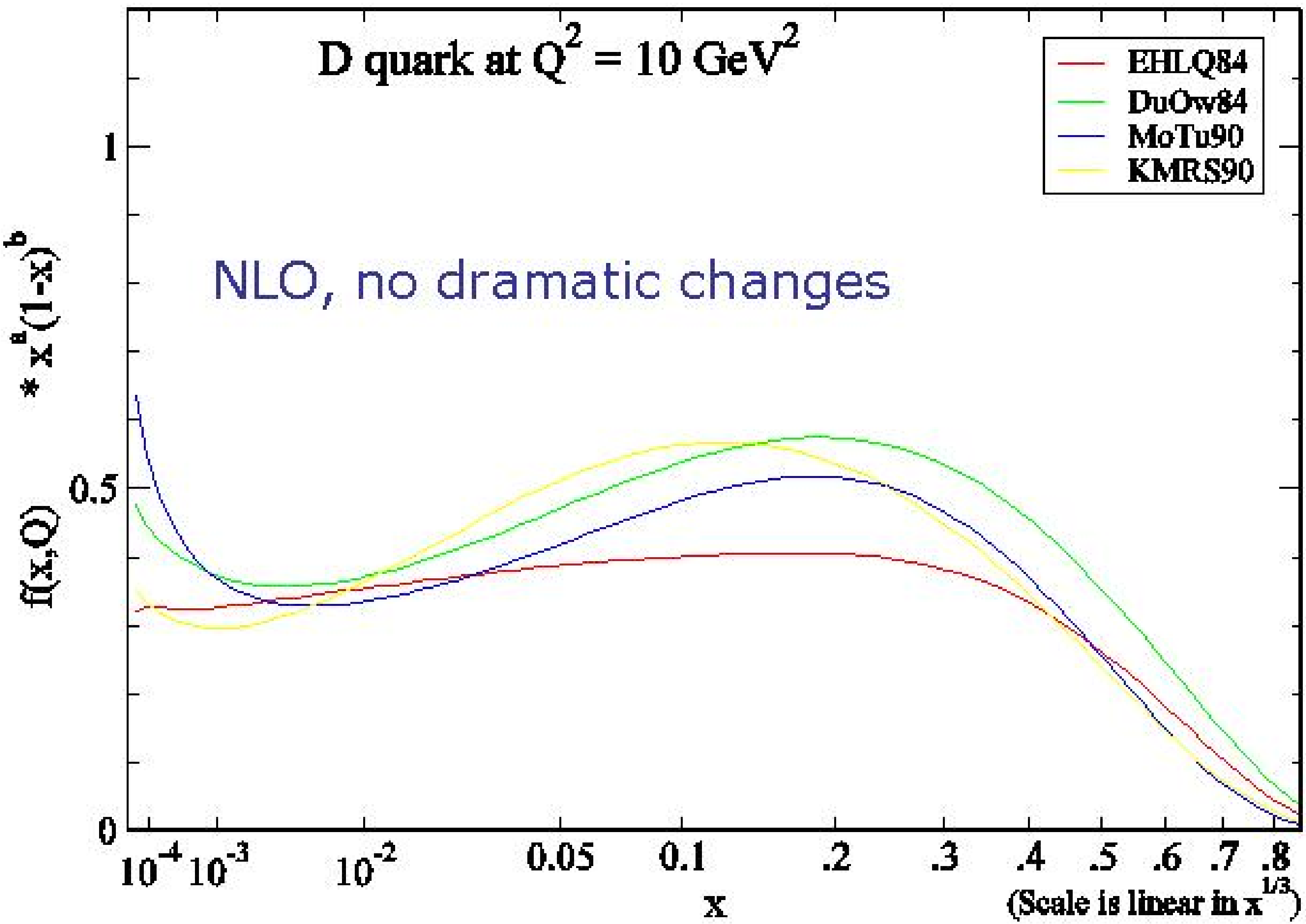

EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
CTQ4M
MRS981
u(x) at Q^2 = 10 GeV^2
x f(x,Q) * x^a (1-x)^b
Refinements ...
0
0.5
1
1.5
2
10^-4
10^-3
10^-2
0.05
0.1
.2
.3
.4
.5
.6
.7
.8
x
(Scale is linear in x^1/3)



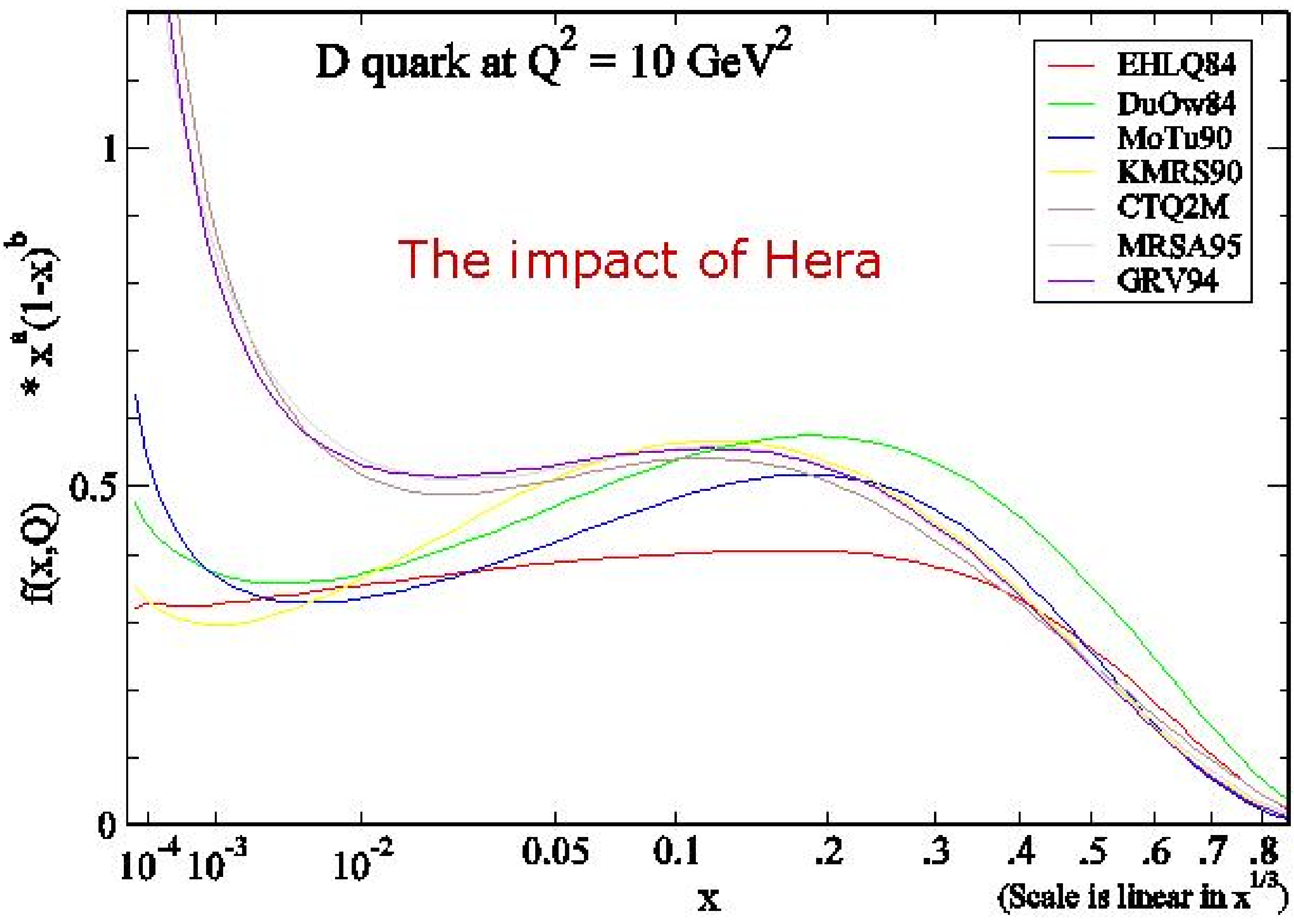
CTQ2M
MRSA95
GRV94
CTQ4M
MRS981
C6.1M
MRST01
Alekhin
u(x) at Q^2 = 10 GeV^2
x f(x,Q) * x^a (1-x)^b
All in the details now?
Time to move on to
something else?
x
(Scale is linear in x^1/3)

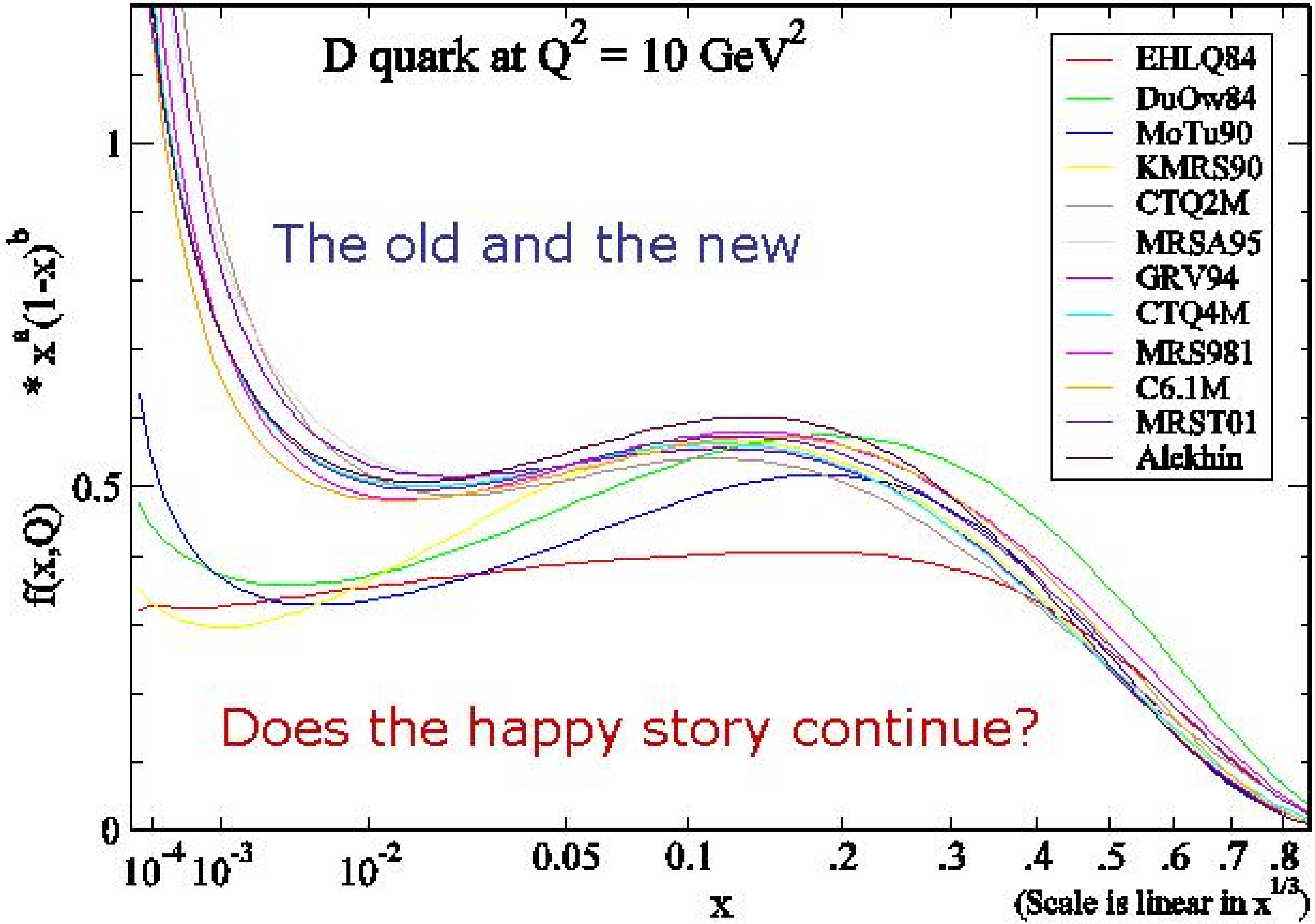
D quark, the other twin:





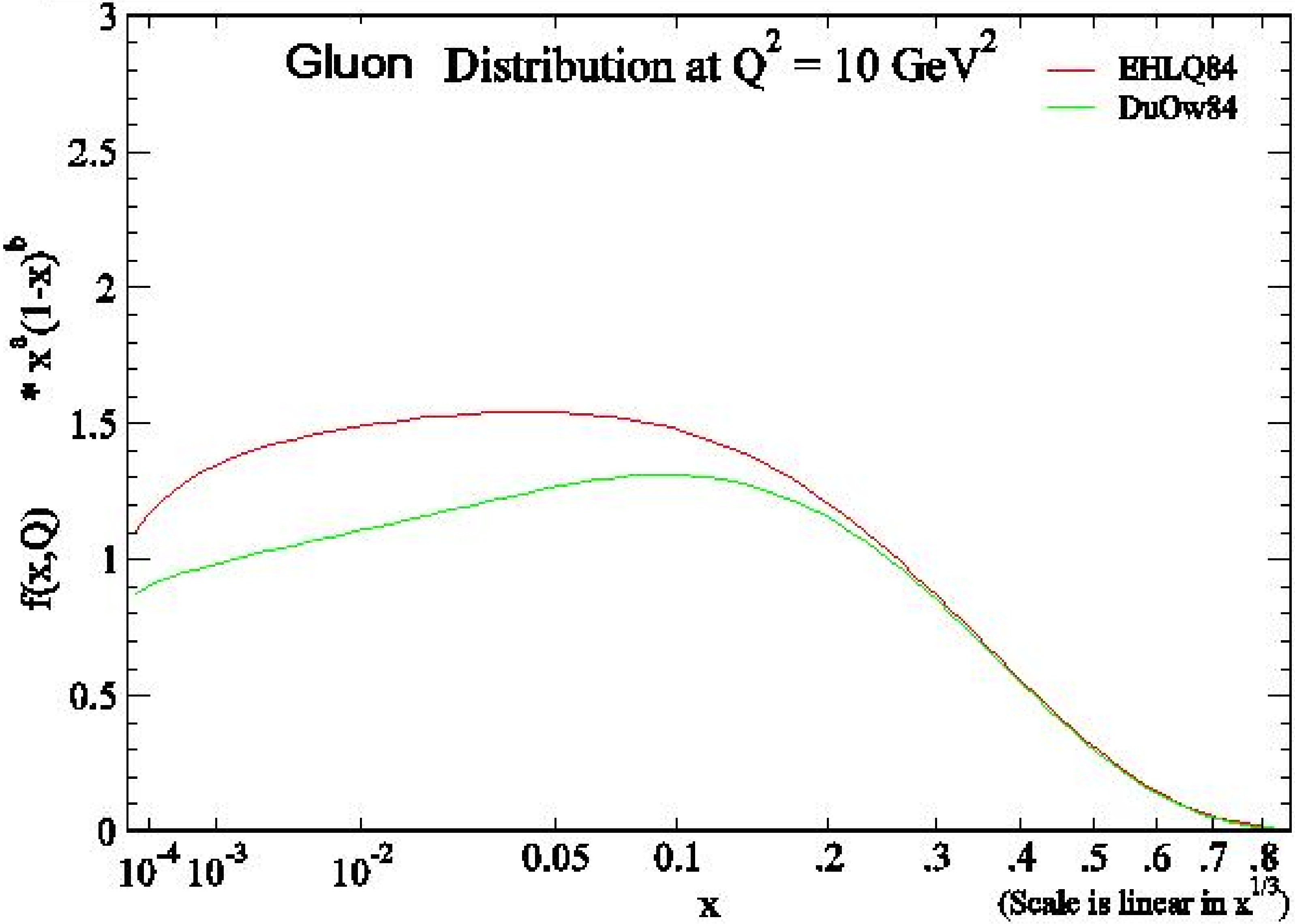
D quark at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
NLO, no dramatic changes
f(x,Q) * x^a (1-x)^b
1
0.5
0
10^-4 10^-3 10^-2 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in x^1/3)

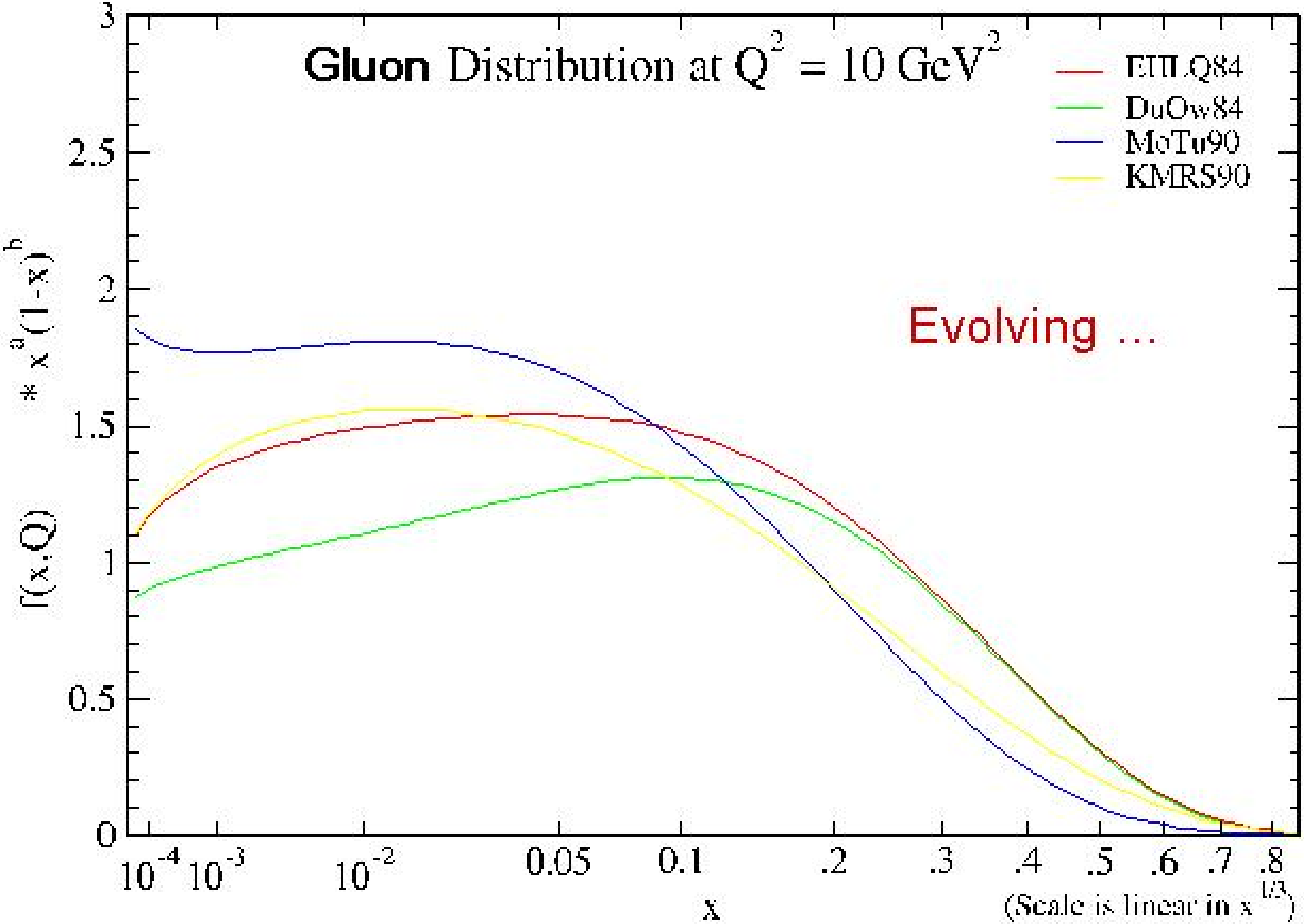

D quark at Q^2 = 10 GeV^2
The impact of Hera
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
f(x,Q) * x^a(1-x)^b
1
0.5
0
10^{-4} 10^{-3} 10^{-2} 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in x$^{1/3}$)

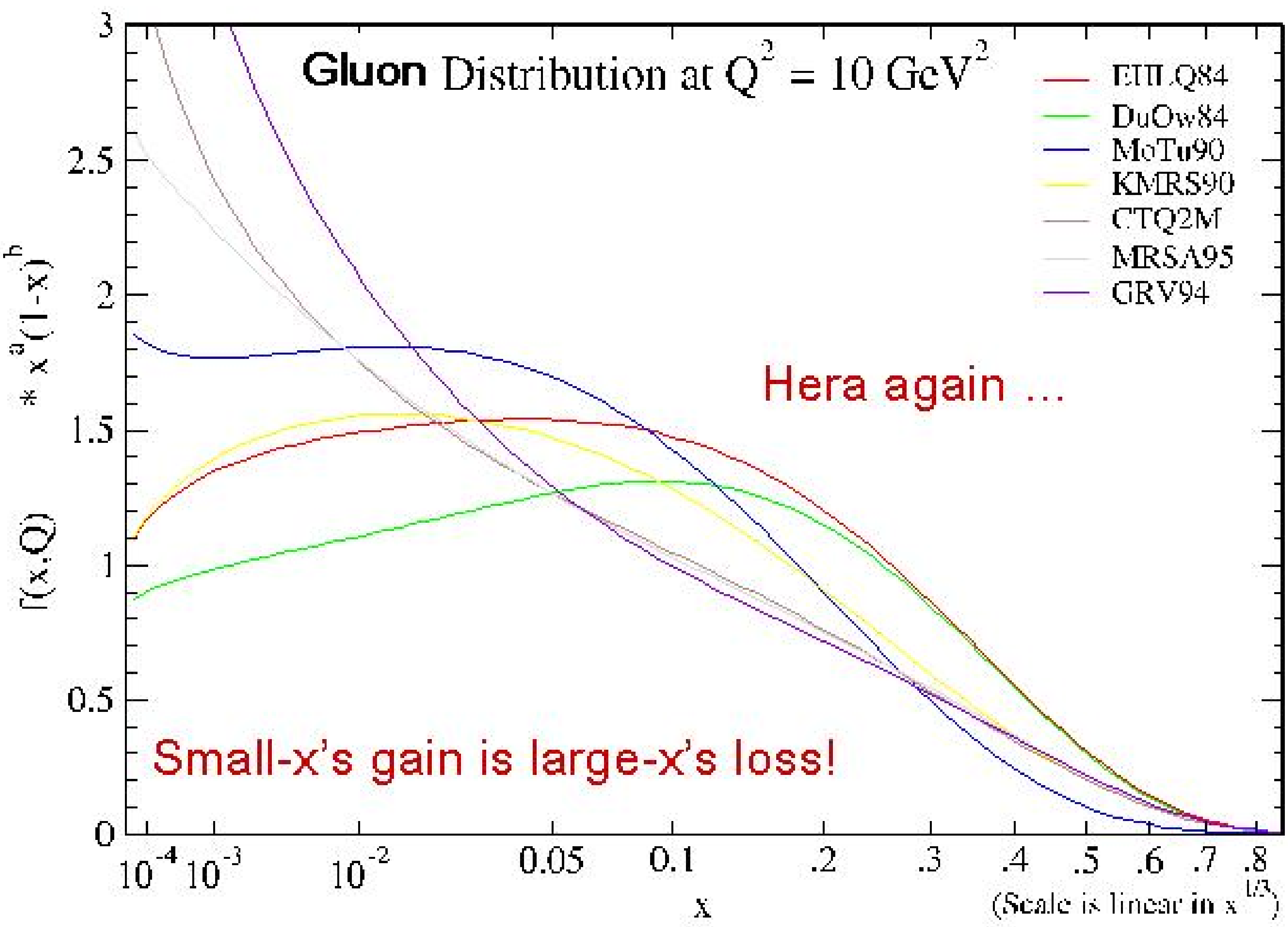


D quark at Q^2 = 10 GeV^2
The old and the new
Does the happy story continue?
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
CTQ4M
MRS981
C6.1M
MRST01
Alekhin
f(x,Q) * x^a (1-x)^b
1
0.5
0
10^-4 10^-3 10^-2 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in x^1/3)

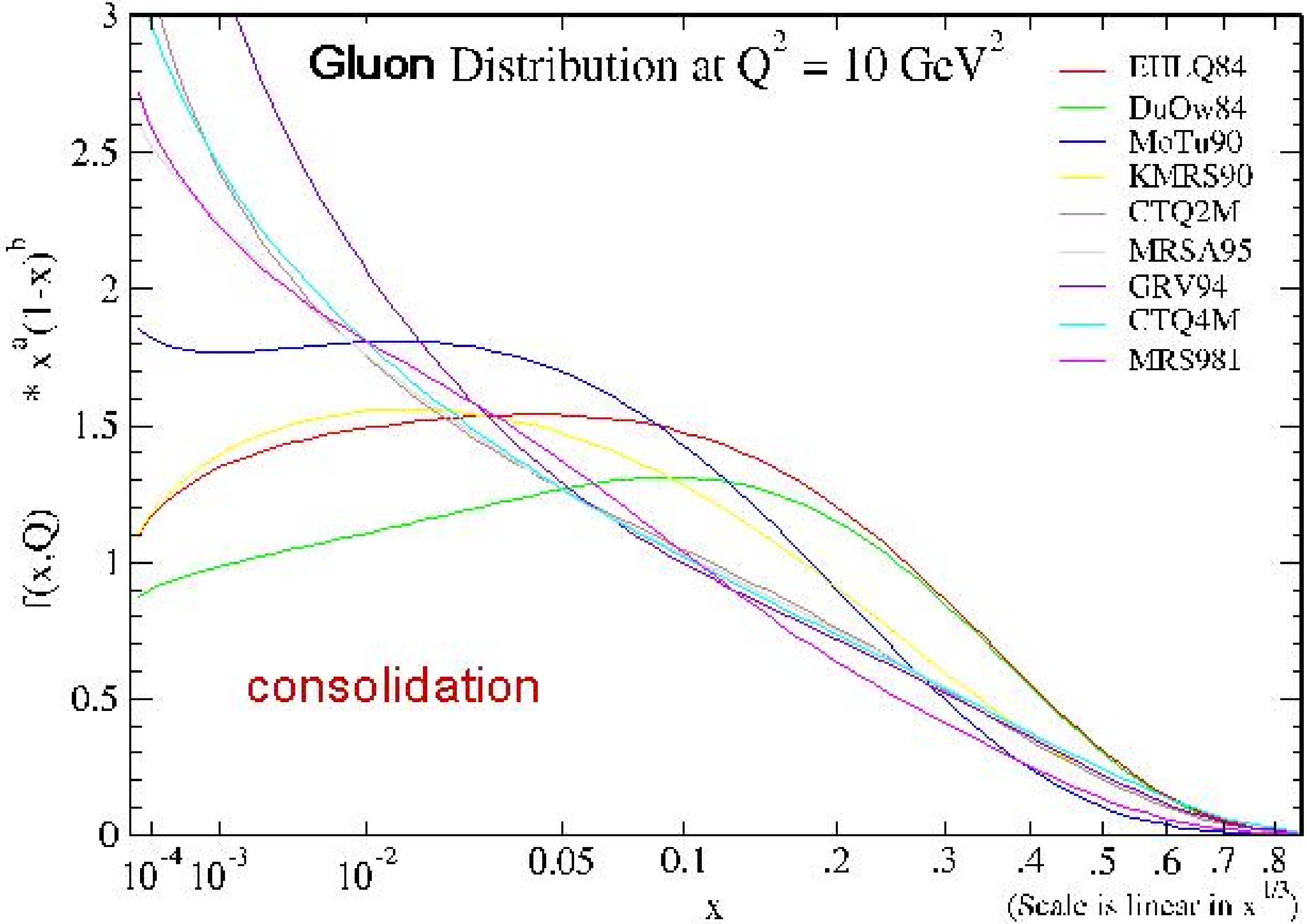
The story about the gluon is more interesting, and not as happy ...



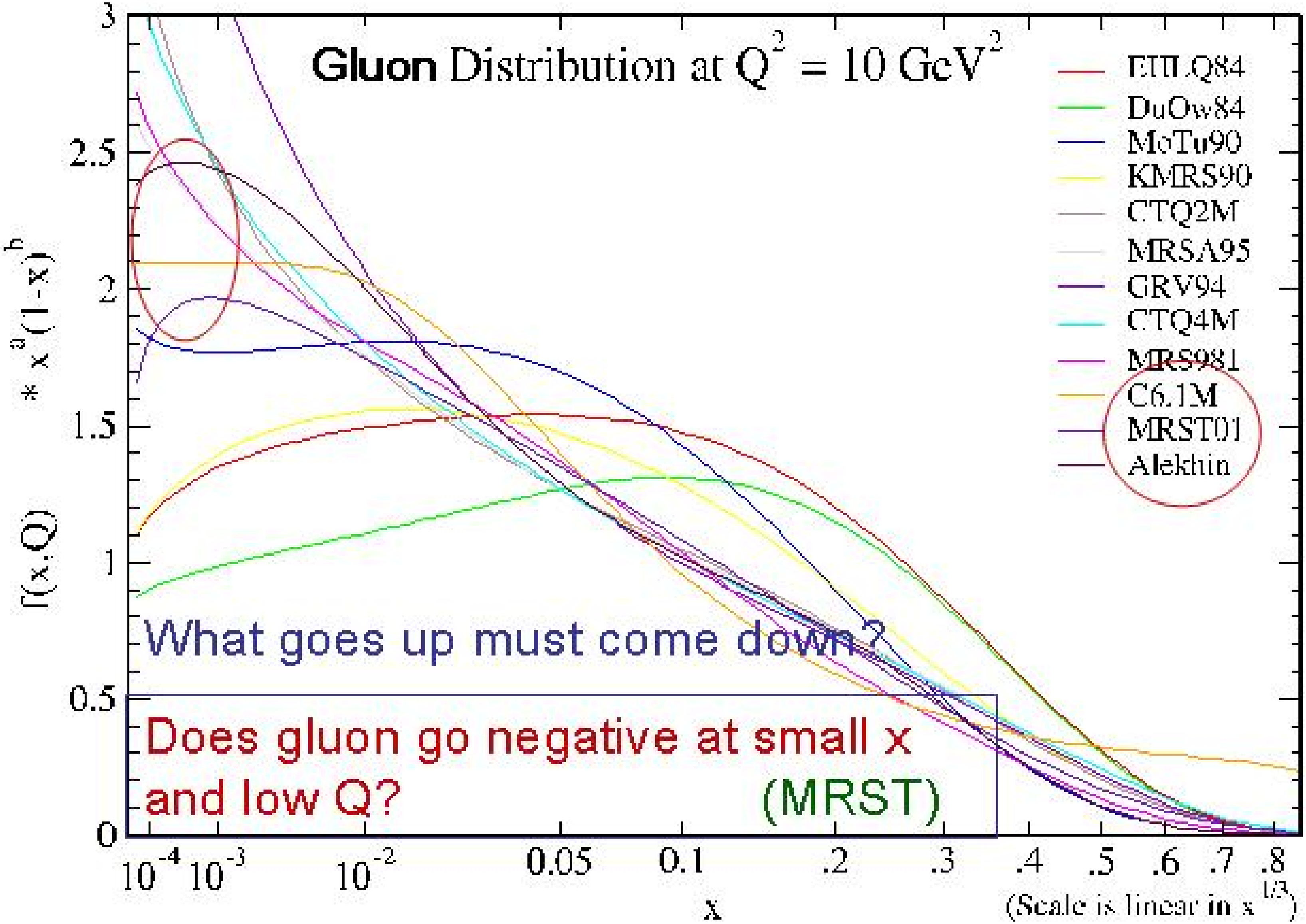

Gluon Distribution at $Q^2 = 10$ GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
Evolving ...
f(x,Q) * $x^a(1-x)^b$
x
(Scale is linear in $x^{1/3}$)



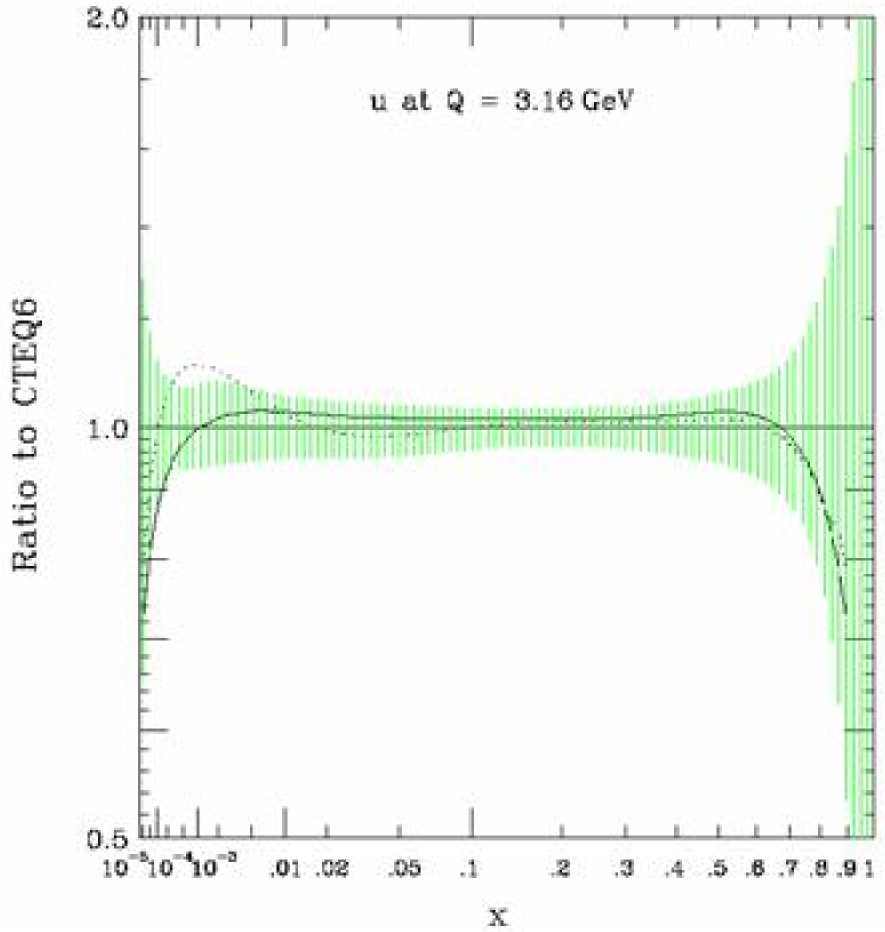
Gluon Distribution at $Q^2 = 10 \text{ GeV}^2$
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
Hera again …
Small-x's gain is large-x's loss!
$f(x,Q) * x^a (1-x)^b$
x
(Scale is linear in $x^{1/3}$)



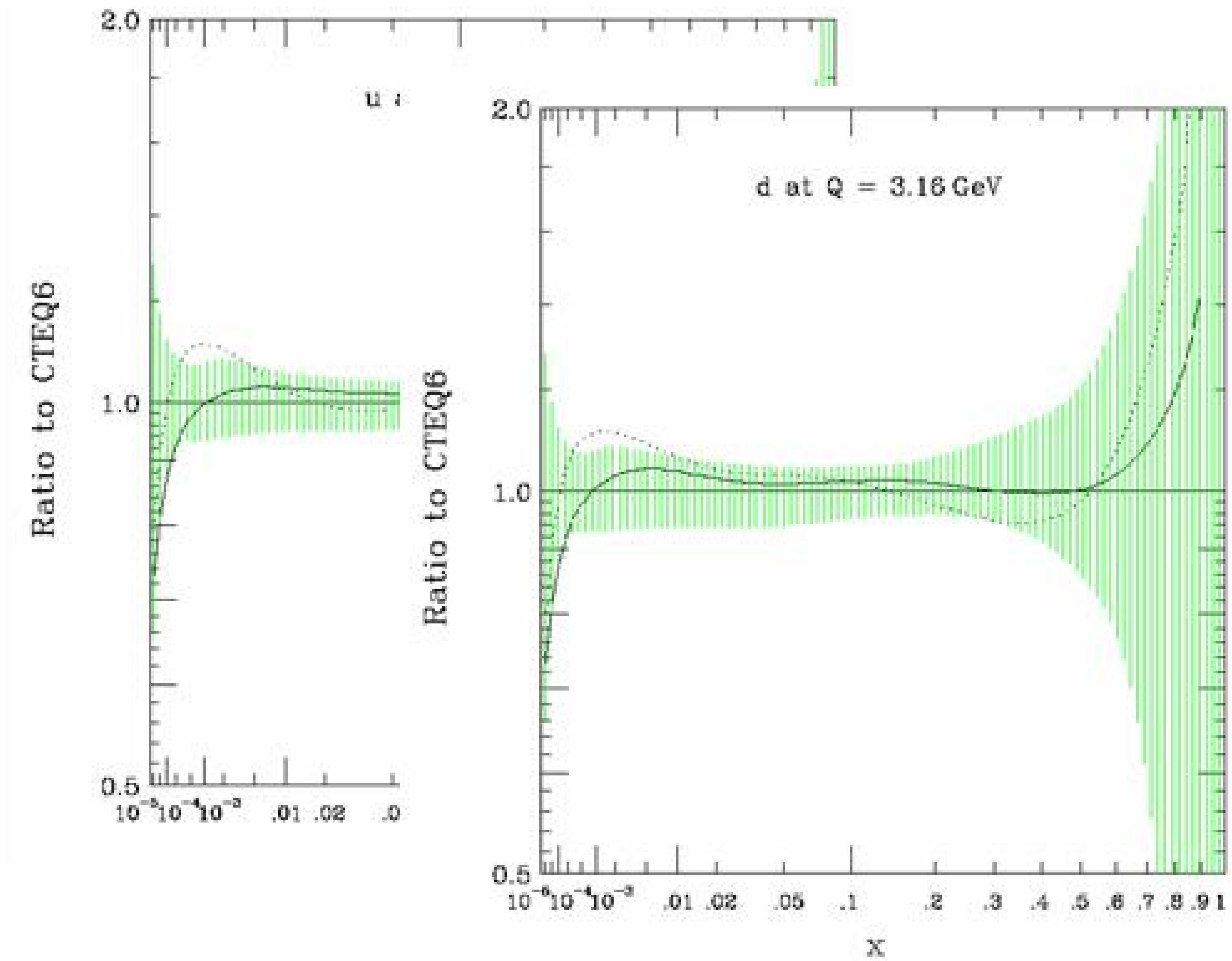
Gluon Distribution at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
CTQ4M
MRS981
f(x,Q) * x^a (1-x)^b
consolidation
3
2.5
2
1.5
1
0.5
0
10^-4
10^-3
10^-2
0.05
0.1
.2
.3
.4
.5
.6
.7
.8
x
(Scale is linear in x^1/3)


Gluon Distribution at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
CTQ4M
MRS981
C6.1M
MRST01
Alekhin
f(x,Q) * x^a (1-x)^b
x
(Scale is linear in x^1/3)
What goes up must come down?
Does gluon go negative at small x
and low Q?
(MRST)

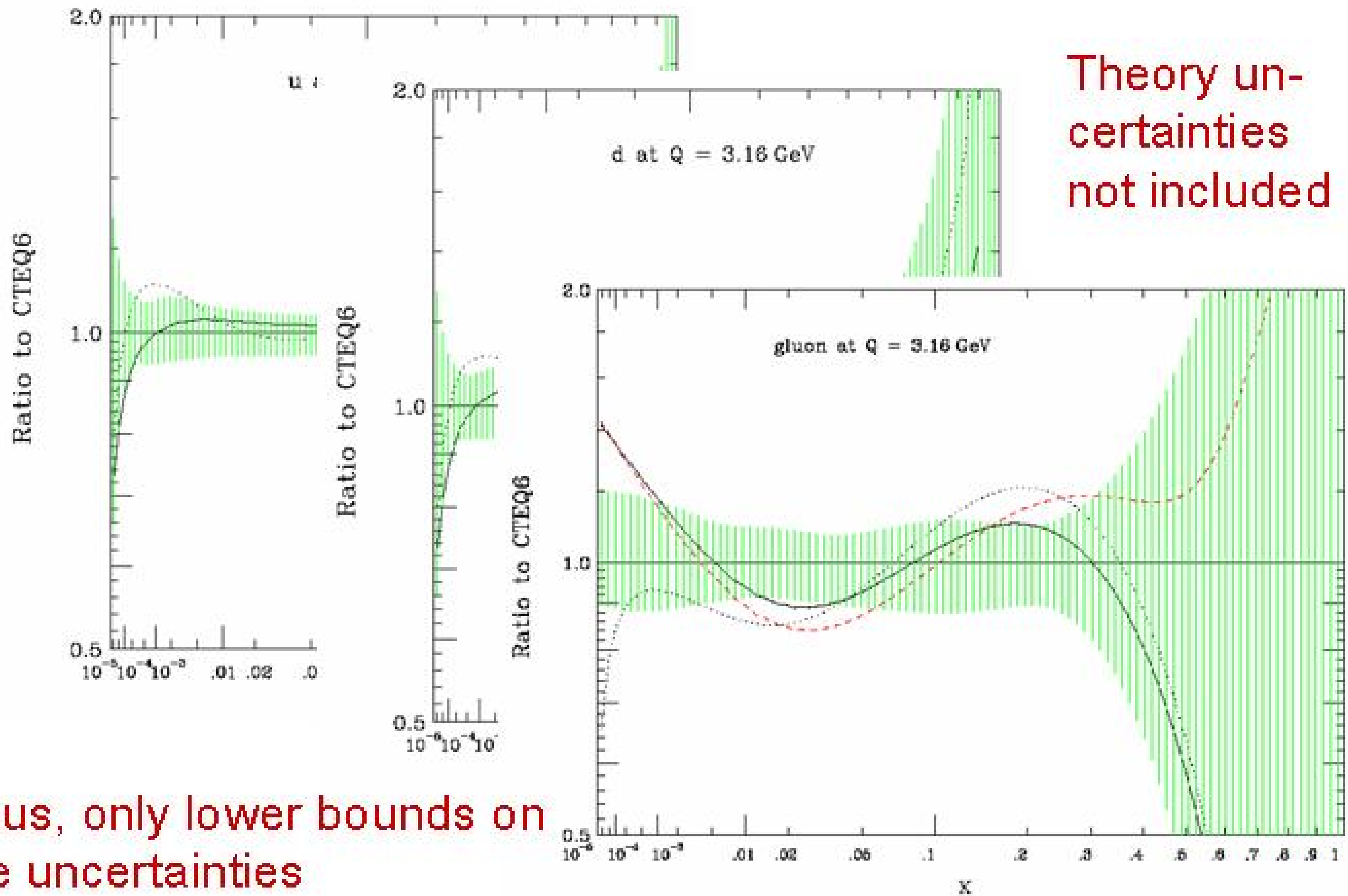
Uncertainties of PDFs: CTEQ6



Uncertainties of PDFs: CTEQ6



Uncertainties of PDFs: CTEQ6



Theory uncertainties not included

Thus, only lower bounds on the uncertainties

Two potential Direct* Measurements of the Gluon Distribution

(* processes in which the dominant contribution at LO is gluon-initiated.)

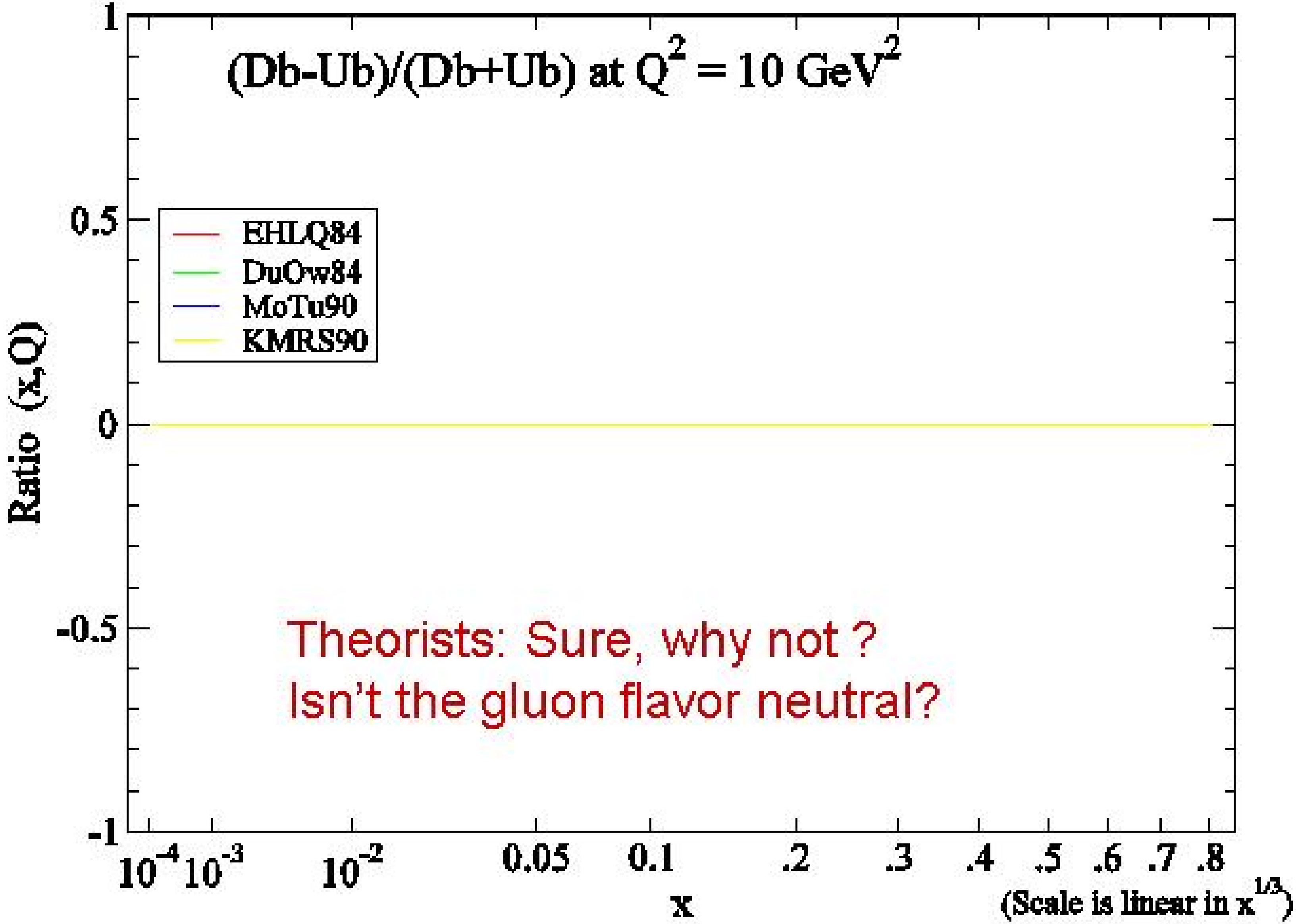
- Measurement of the longitudinal Structure Function in DIS.

  Crucial. Still possible at Hera?

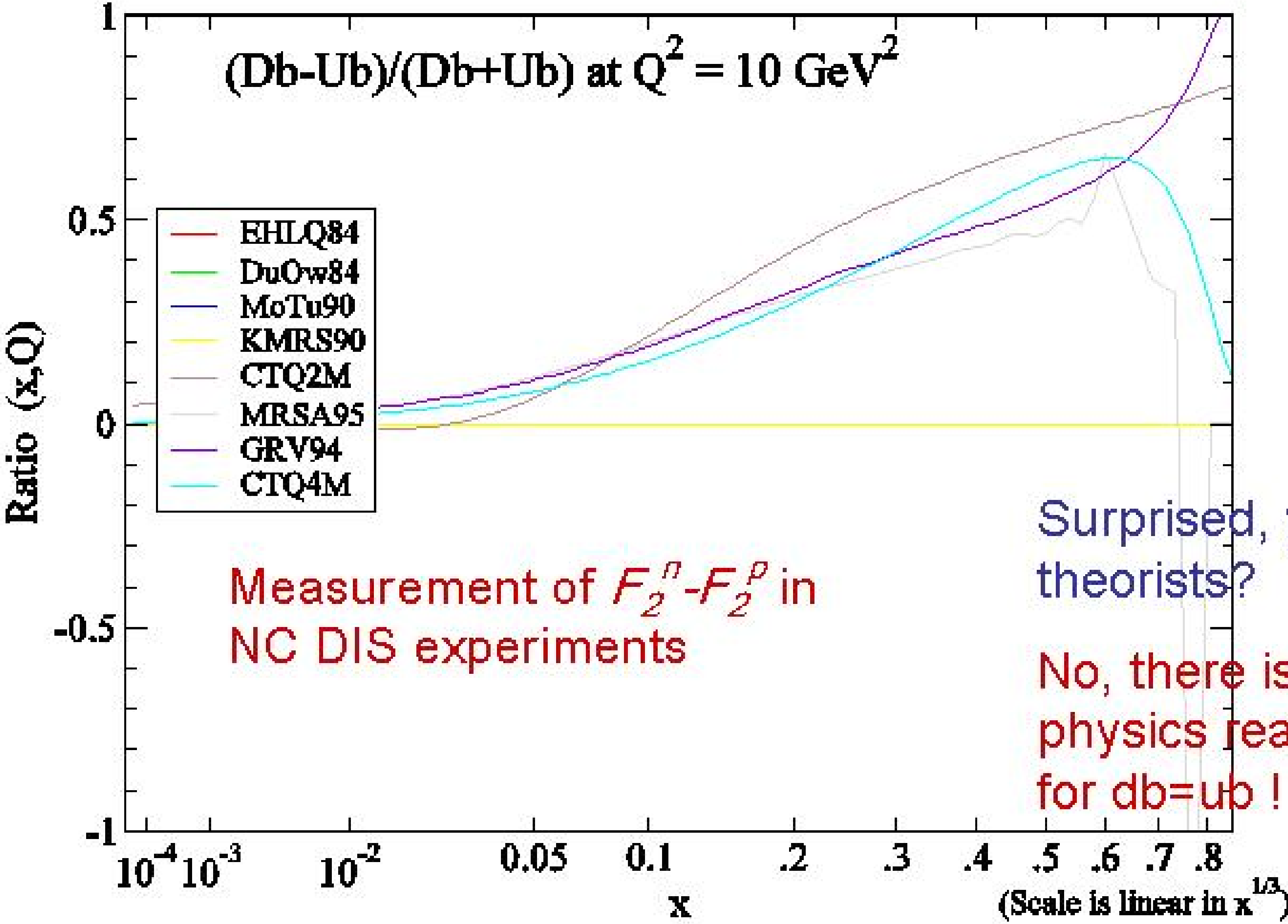
- Direct Photon Production in Hadron Collisions
  - Data exist–but not always consistent with each other (WA70 and E706);
  - Theoretical uncertainties in NLO QCD overwhelming; Resummed QCD promising, but has not delivered so far.

- Jet production at Hera and Hadron colliders too.

The non-strange sea quarks: do they observe isospin symmetry?



Experimentalists: Let Nature speak for him/herself!

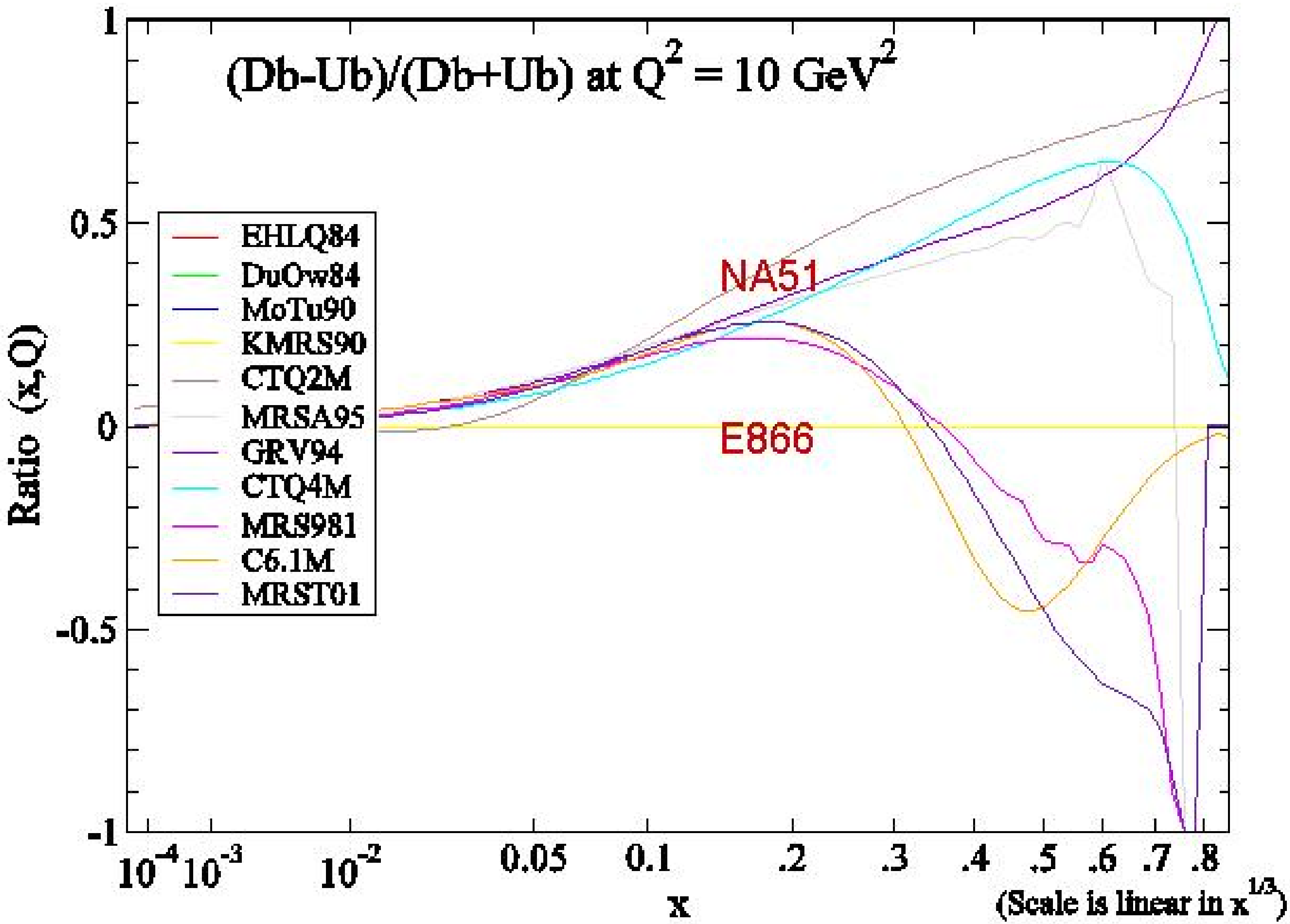


Measurement of F_2^n-F_2^p in NC DIS experiments

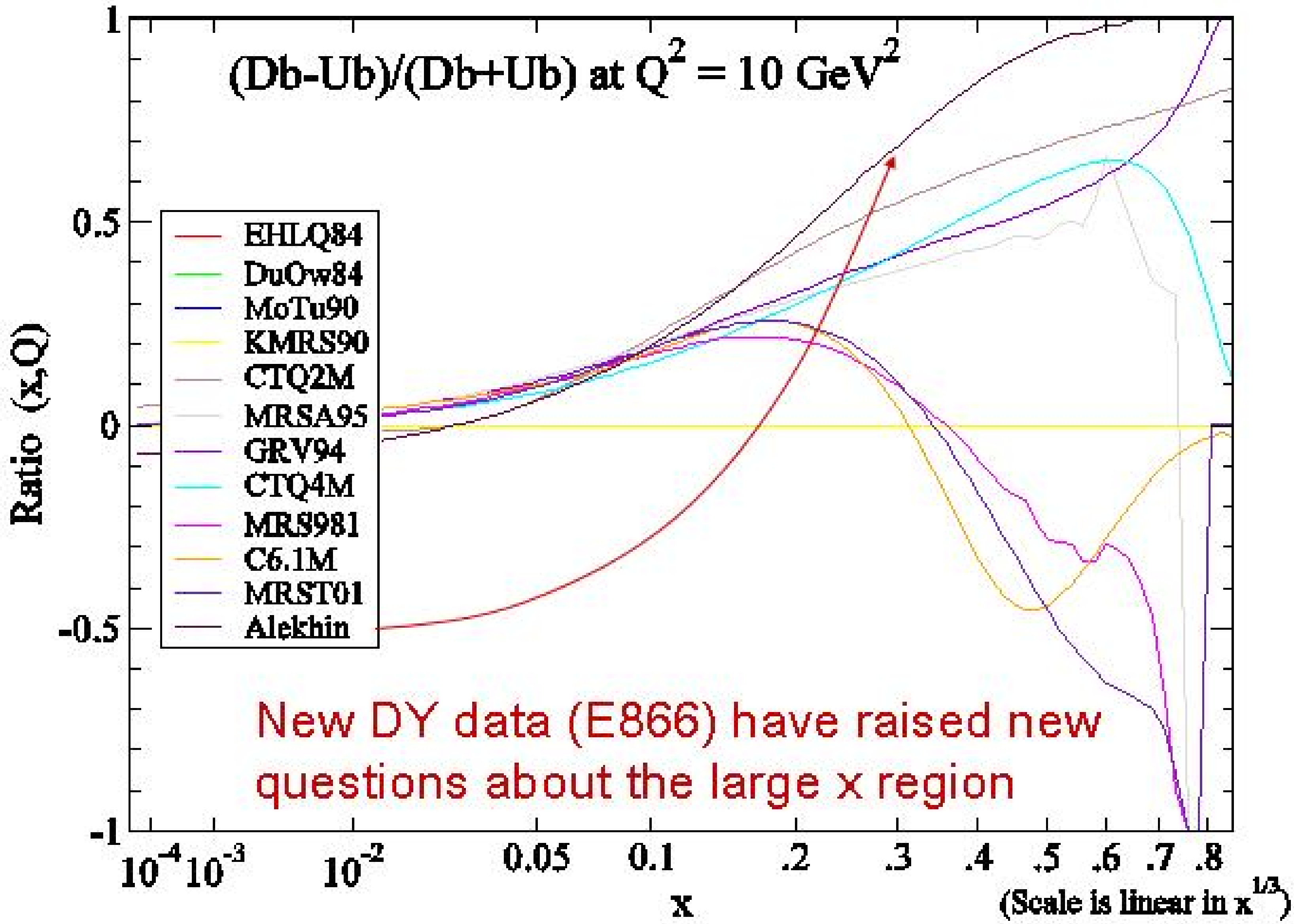
Surprised, you theorists?

No, there is no physics reason for db=ub !

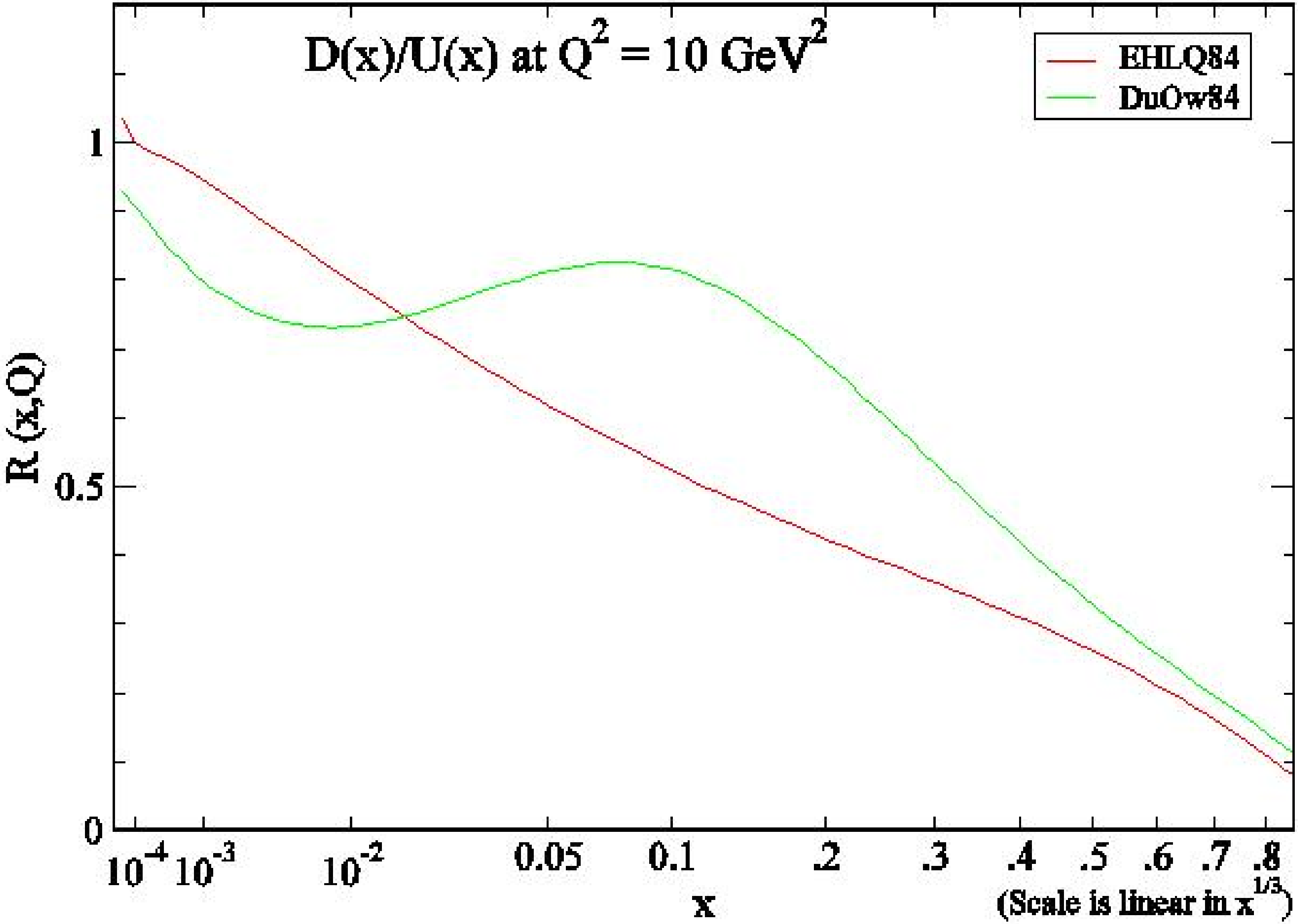
More experimental inputs: (mostly DY asymmetry)

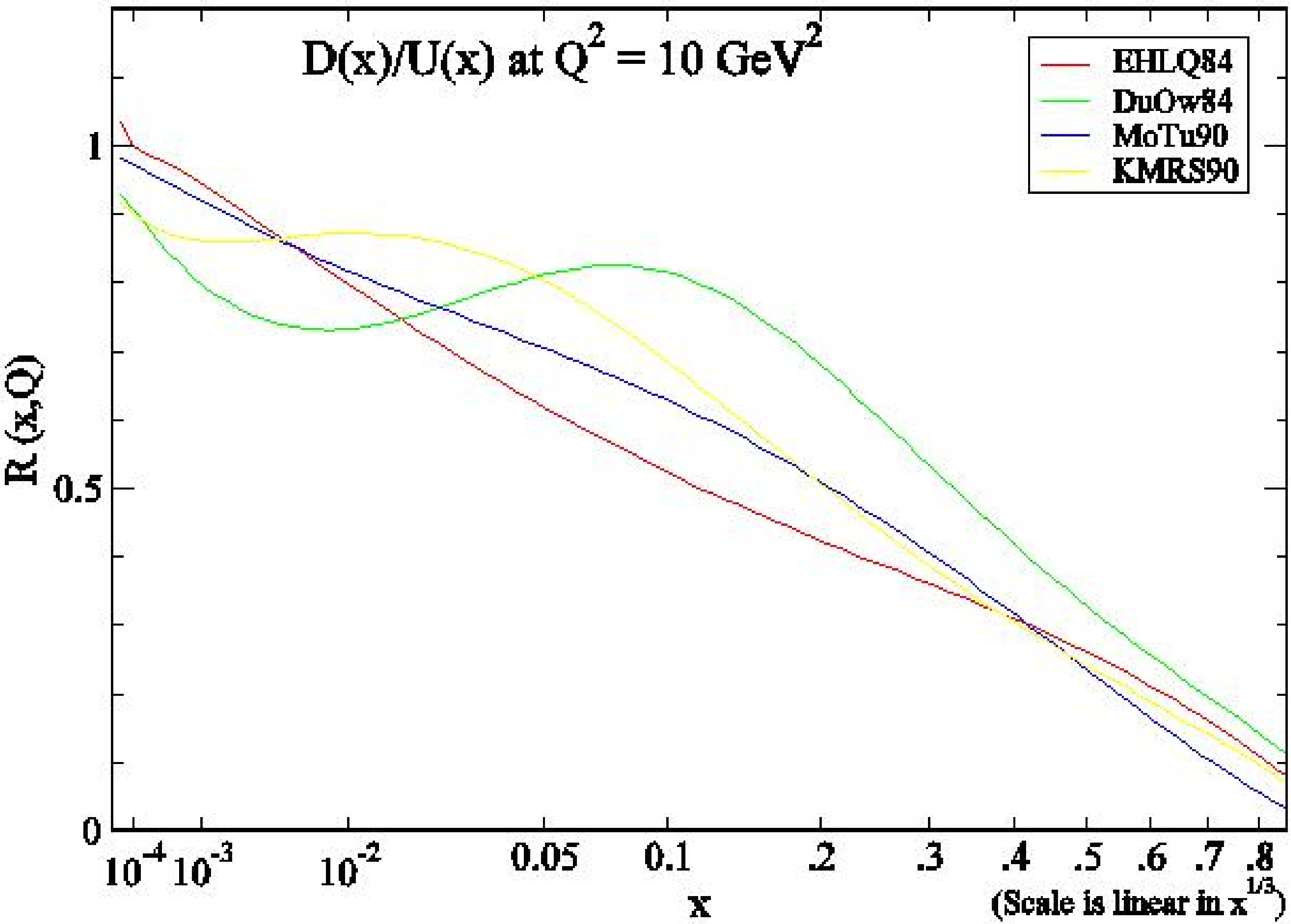


Caution: "Modern fit" without DY and Collider input:

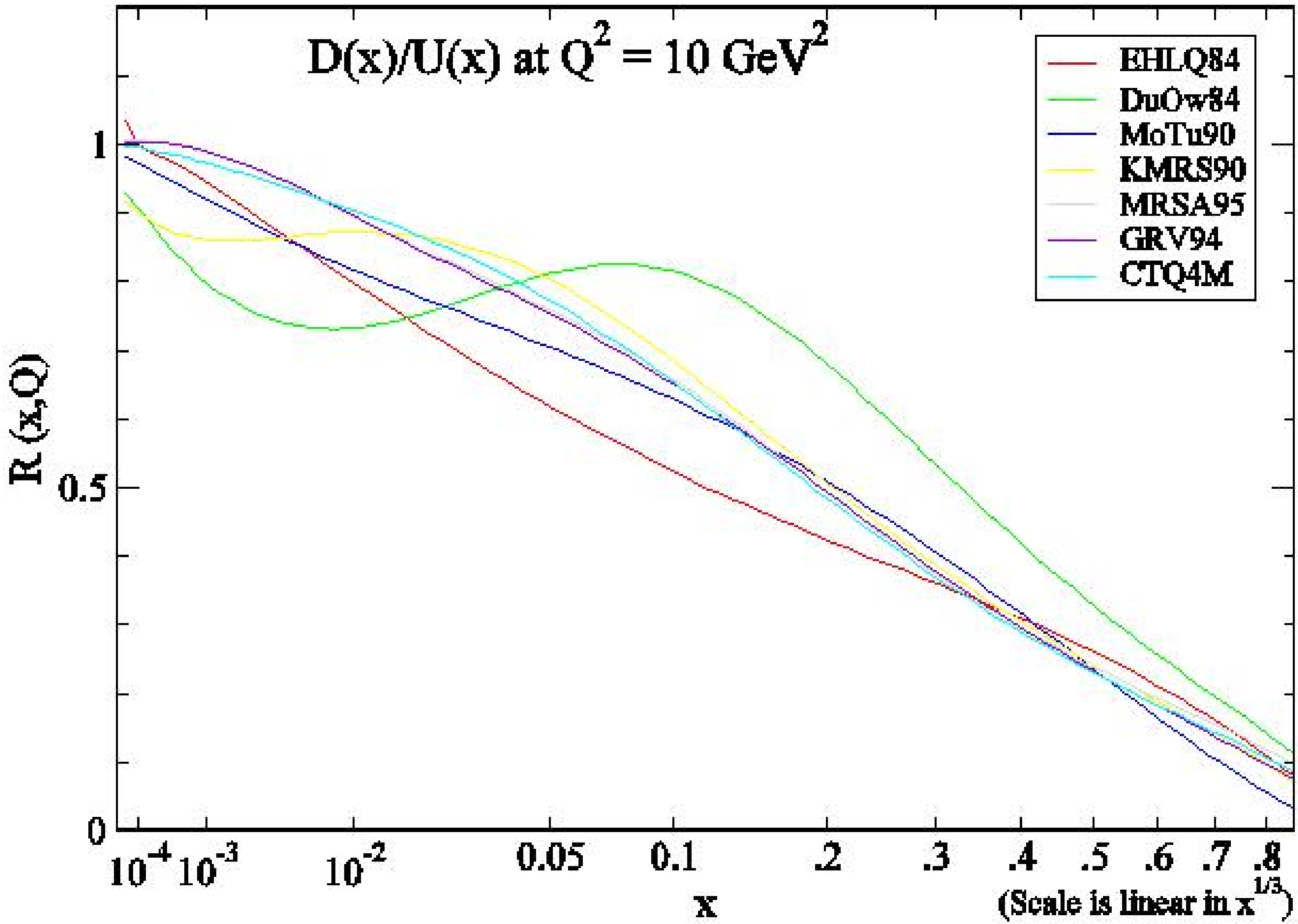


Comparing the Valence Quarks of the Nucleon:

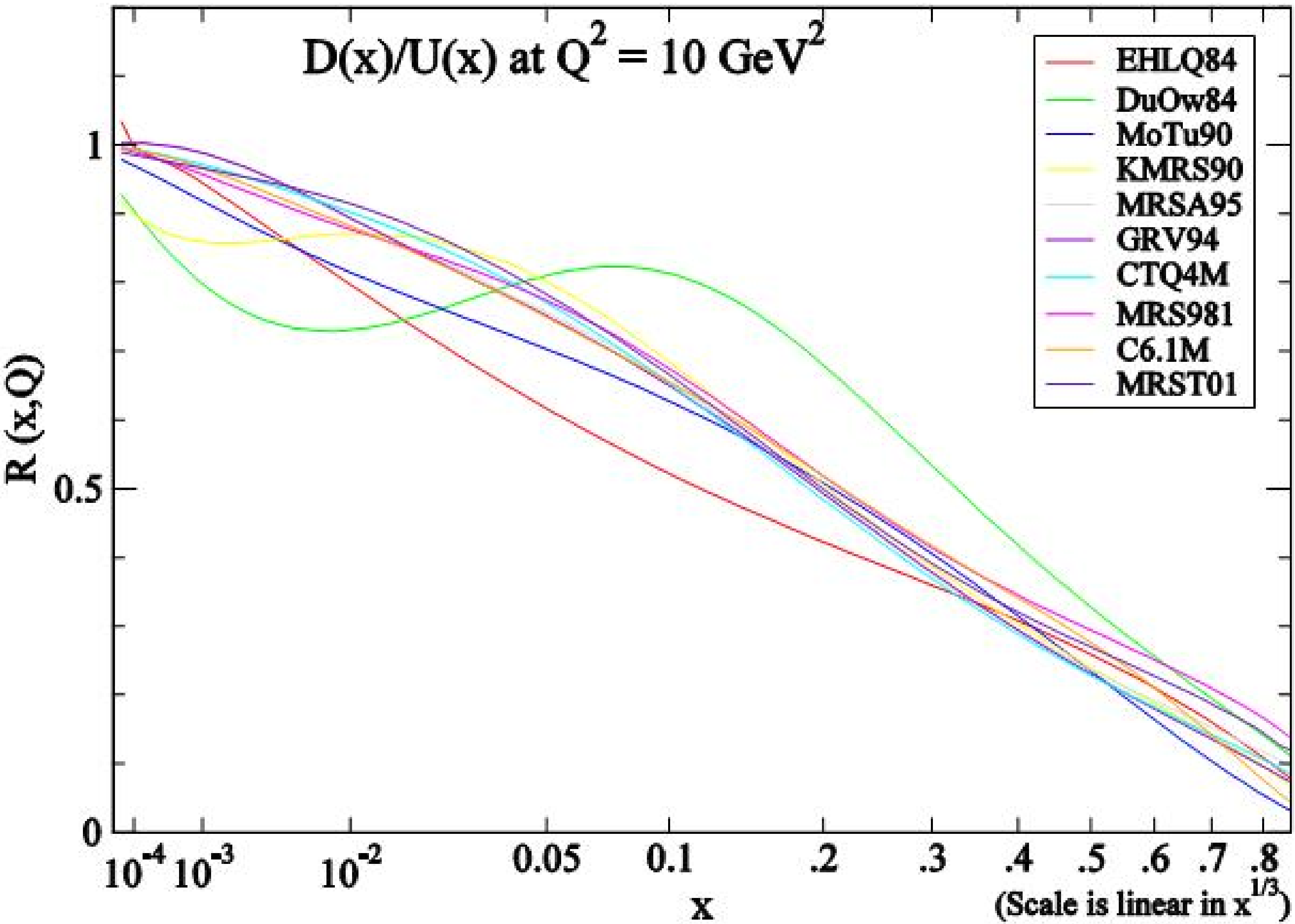


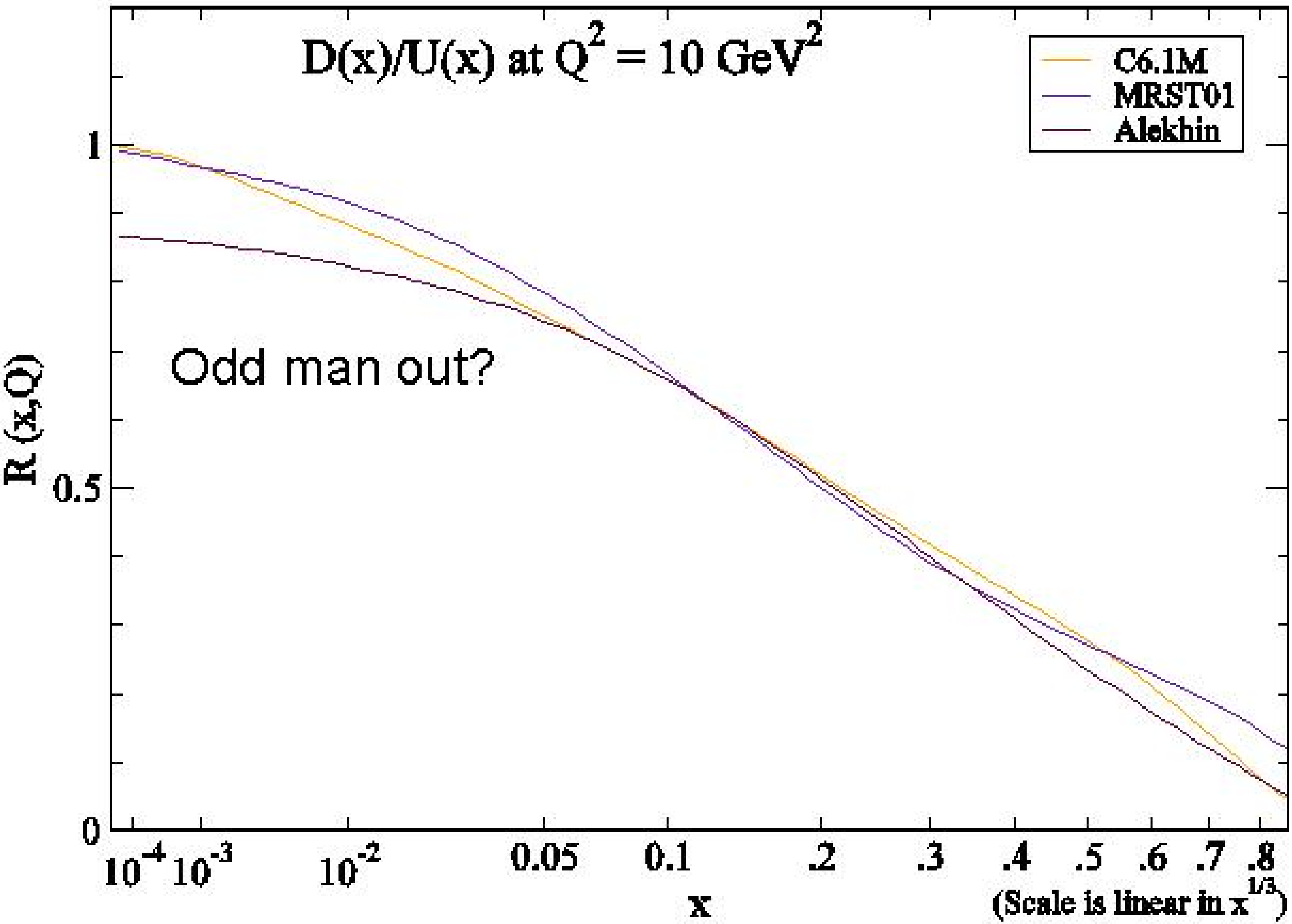


D(x)/U(x) at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
R (x,Q)
1
0.5
0
10^-4 10^-3 10^-2 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in x^1/3)



D(x)/U(x) at Q² = 10 GeV²
EHLQ84
DuOw84
MoTu90
KMRS90
MRSA95
GRV94
CTQ4M
R (x,Q)
1
0.5
0
10⁻⁴
10⁻³
10⁻²
0.05
0.1
.2
.3
.4
.5
.6
.7
.8
x
(Scale is linear in x^1/3)


D(x)/U(x) at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
MRSA95
GRV94
CTQ4M
MRS981
C6.1M
MRST01
R (x,Q)
1
0.5
0
10^{-4}
10^{-3}
10^{-2}
0.05
0.1
.2
.3
.4
.5
.6
.7
.8
x
(Scale is linear in $x^{1/3}$)


D(x)/U(x) at Q^2 = 10 GeV^2
C6.1M
MRST01
Alekhin
Odd man out?
R (x,Q)
1
0.5
0
10^{-4} 10^{-3} 10^{-2} 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in $x^{1/3}$)

Comments on D/U ratio determination

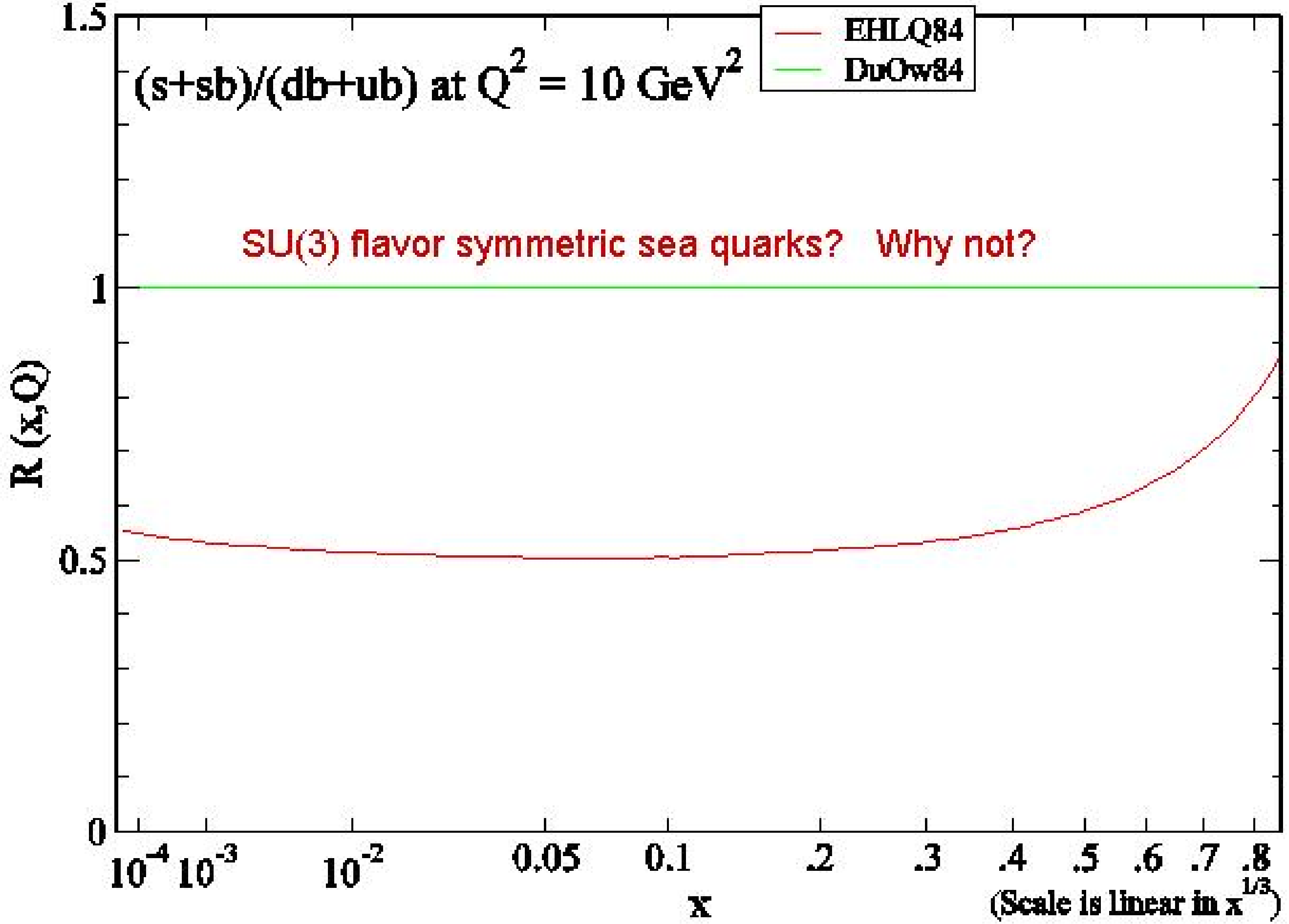
CDF W lepton asymmetry played an important role in existing analyses.

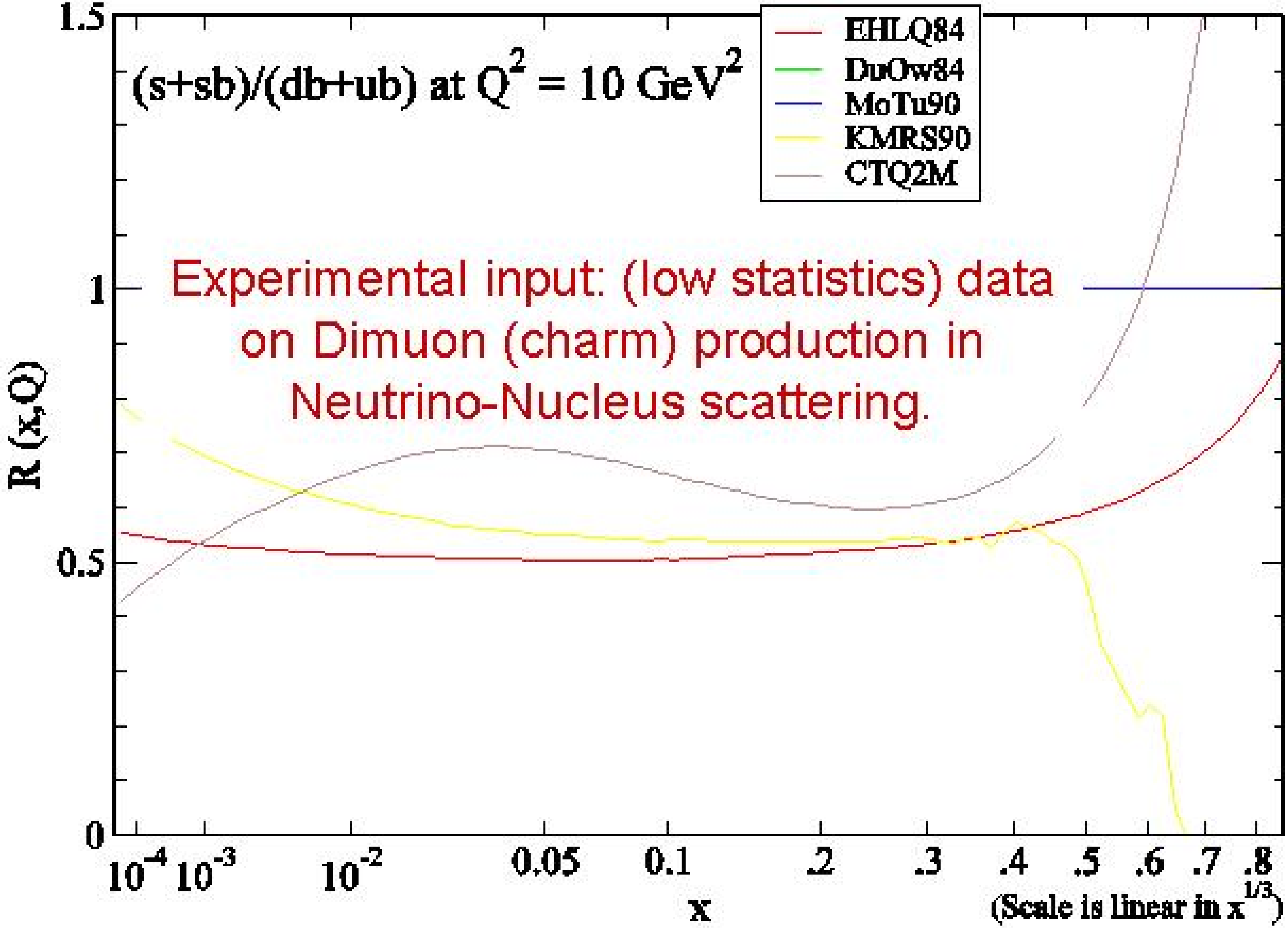
Preliminary results of E866 pp pd cross section data threw some doubt on current PDFs. But data remain preliminary. (See WG1 talk.)

Charged Current cross sections measured at HERA will provide the cleanest determination of this ratio.

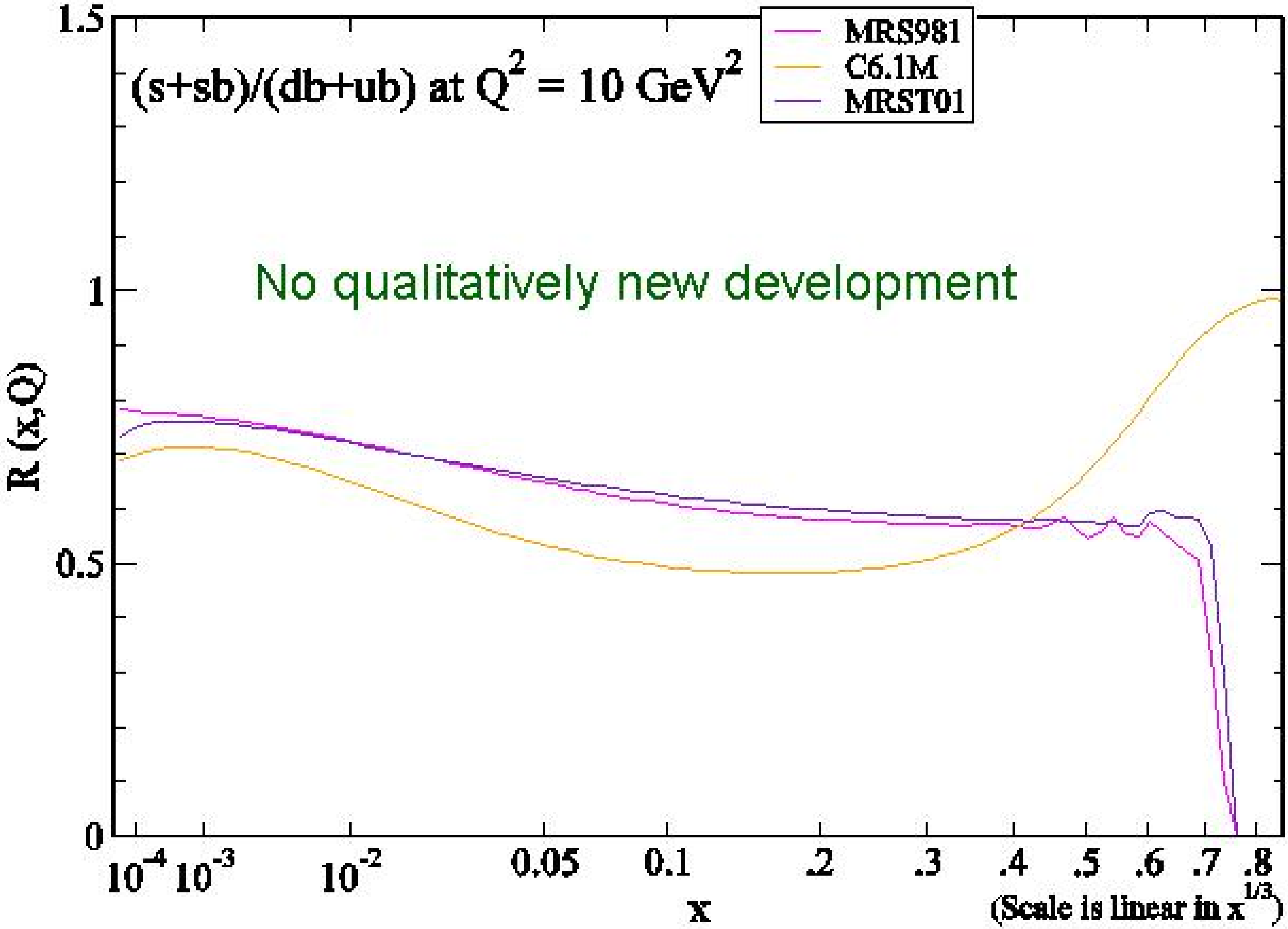
W+/W- ratio at LHC will provide precise input to future analysis of this quantity.

Strange Content of the Nucleon Structure

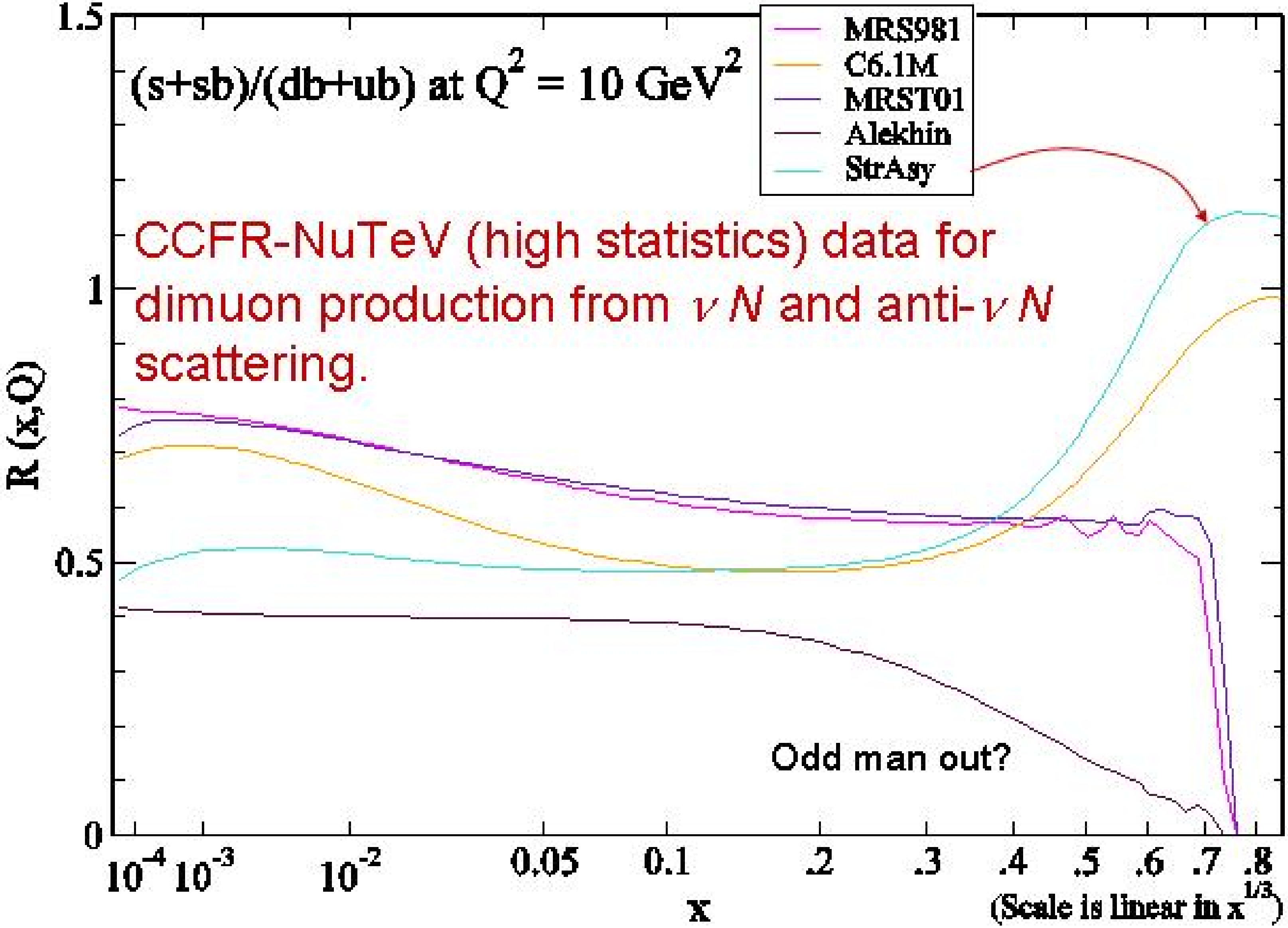




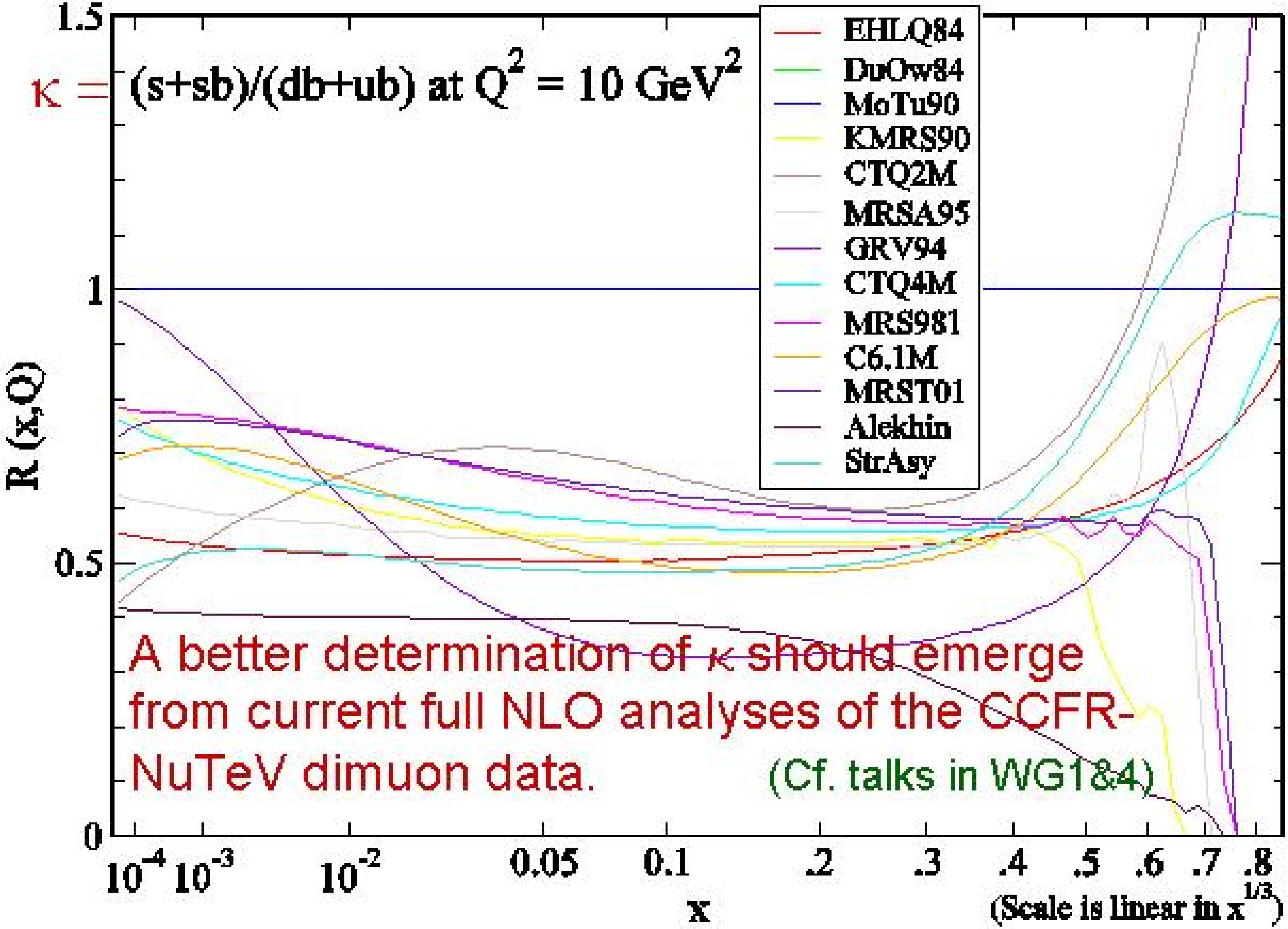
(s+sb)/(db+ub) at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
Experimental input: (low statistics) data
on Dimuon (charm) production in
Neutrino-Nucleus scattering.
R (x,Q)
1.5
1
0.5
0
10^-4 10^-3 10^-2 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in x^1/3)



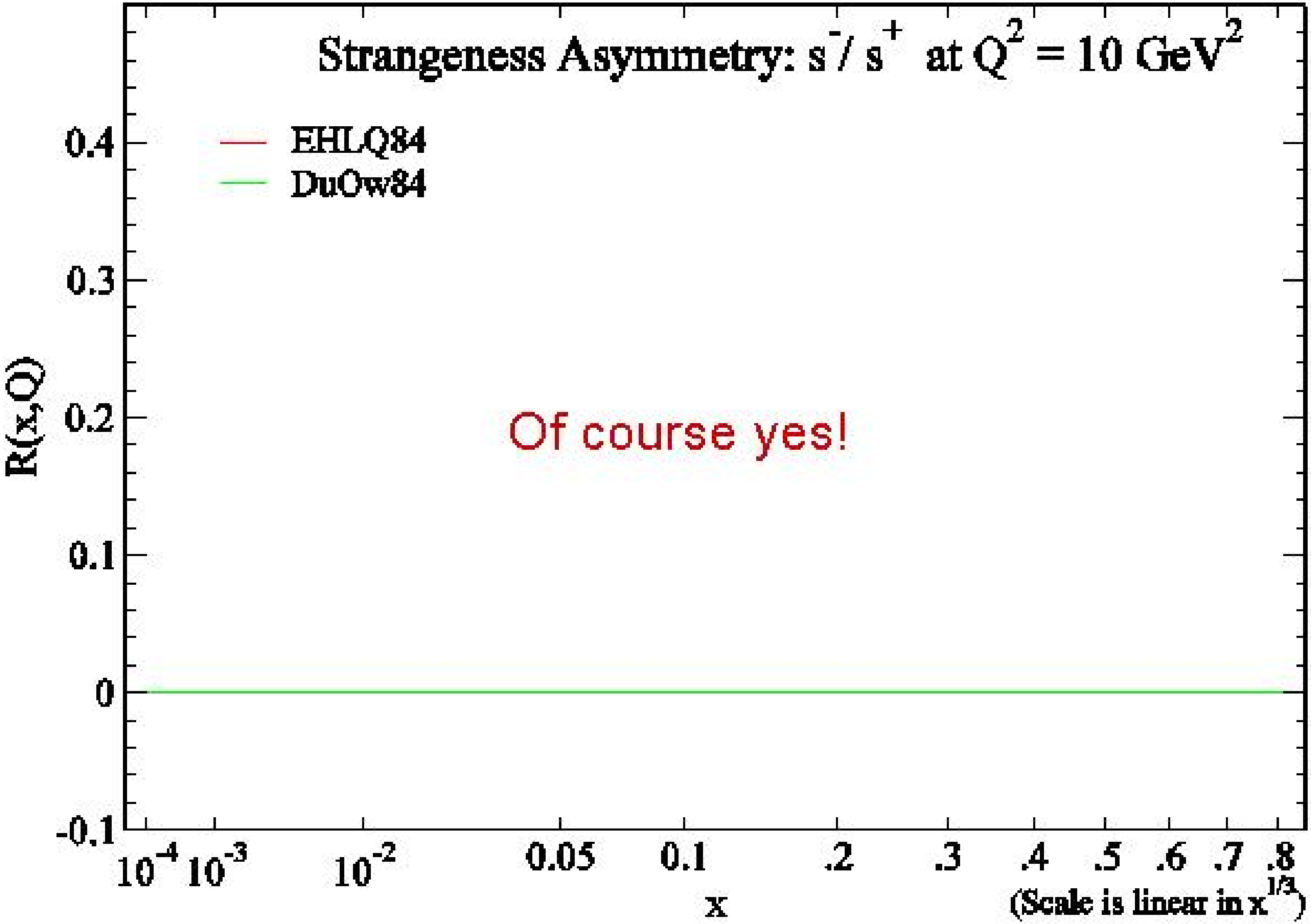
(s+sb)/(db+ub) at Q² = 10 GeV²
MRS981
C6.1M
MRST01
No qualitatively new development
R (x,Q)
1.5
1
0.5
0
10⁻⁴ 10⁻³
10⁻²
0.05
0.1
.2
.3
.4
.5
.6
.7
.8
x
(Scale is linear in x^1/3)

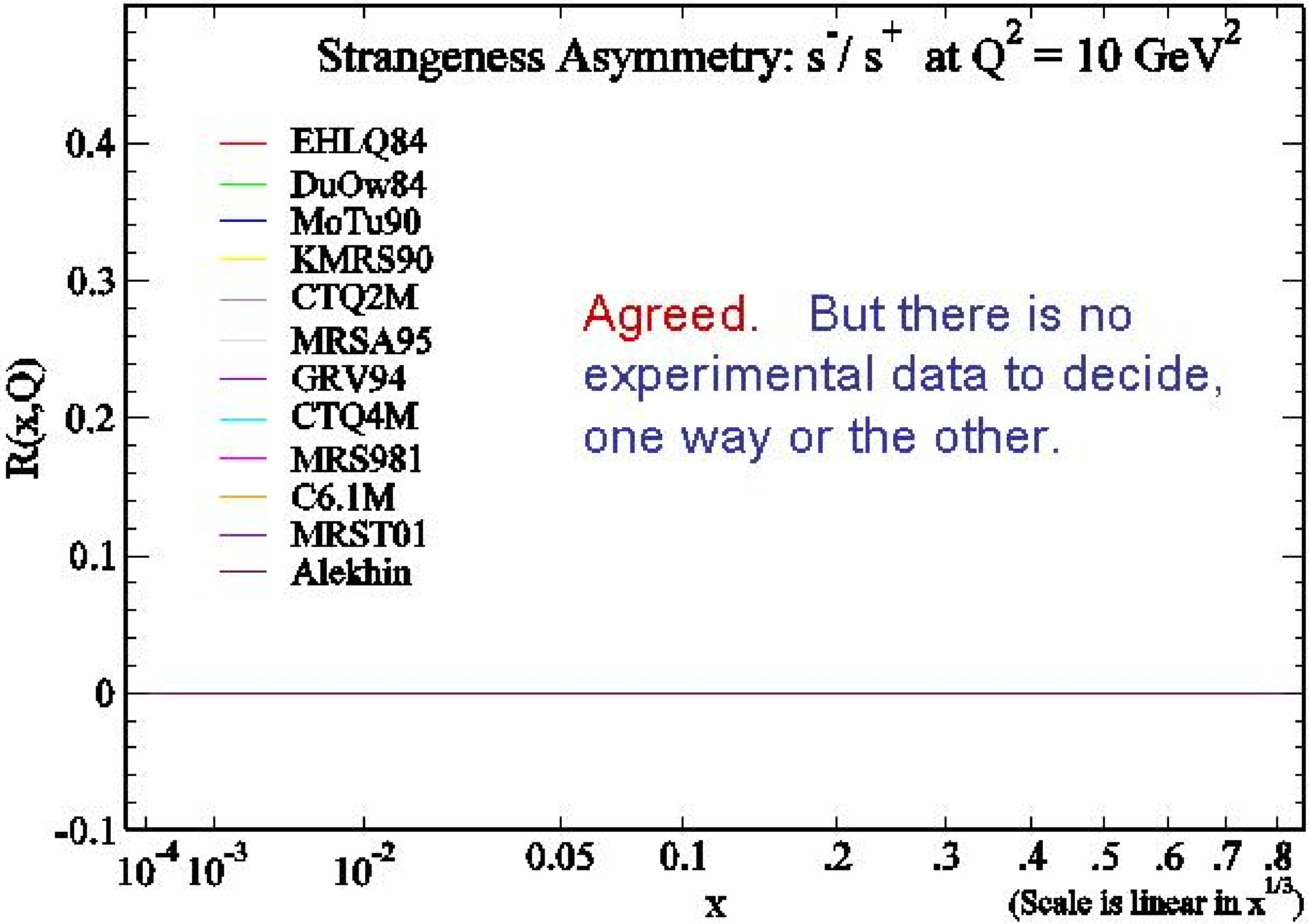

MRS981
C6.1M
MRST01
Alekhin
StrAsy
(s+sb)/(db+ub) at Q^2 = 10 GeV^2
CCFR-NuTeV (high statistics) data for dimuon production from ν N and anti-ν N scattering.
R (x,Q)
Odd man out?
1.5
1
0.5
0
10^-4 10^-3 10^-2 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in x^1/3)

All together:



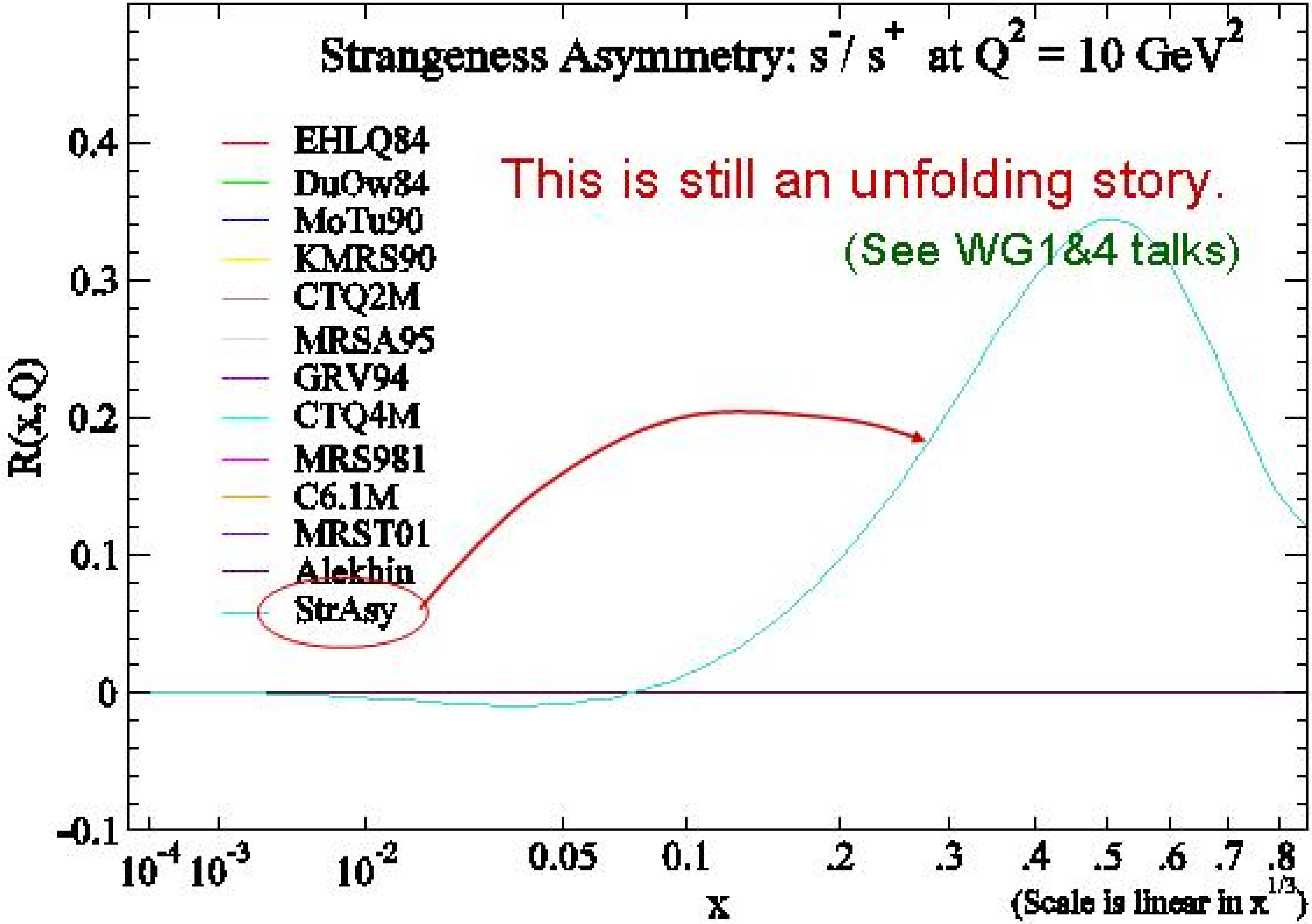
Is the strangeness sector charge symmetric?





Agreed. But there is no experimental data to decide, one way or the other.

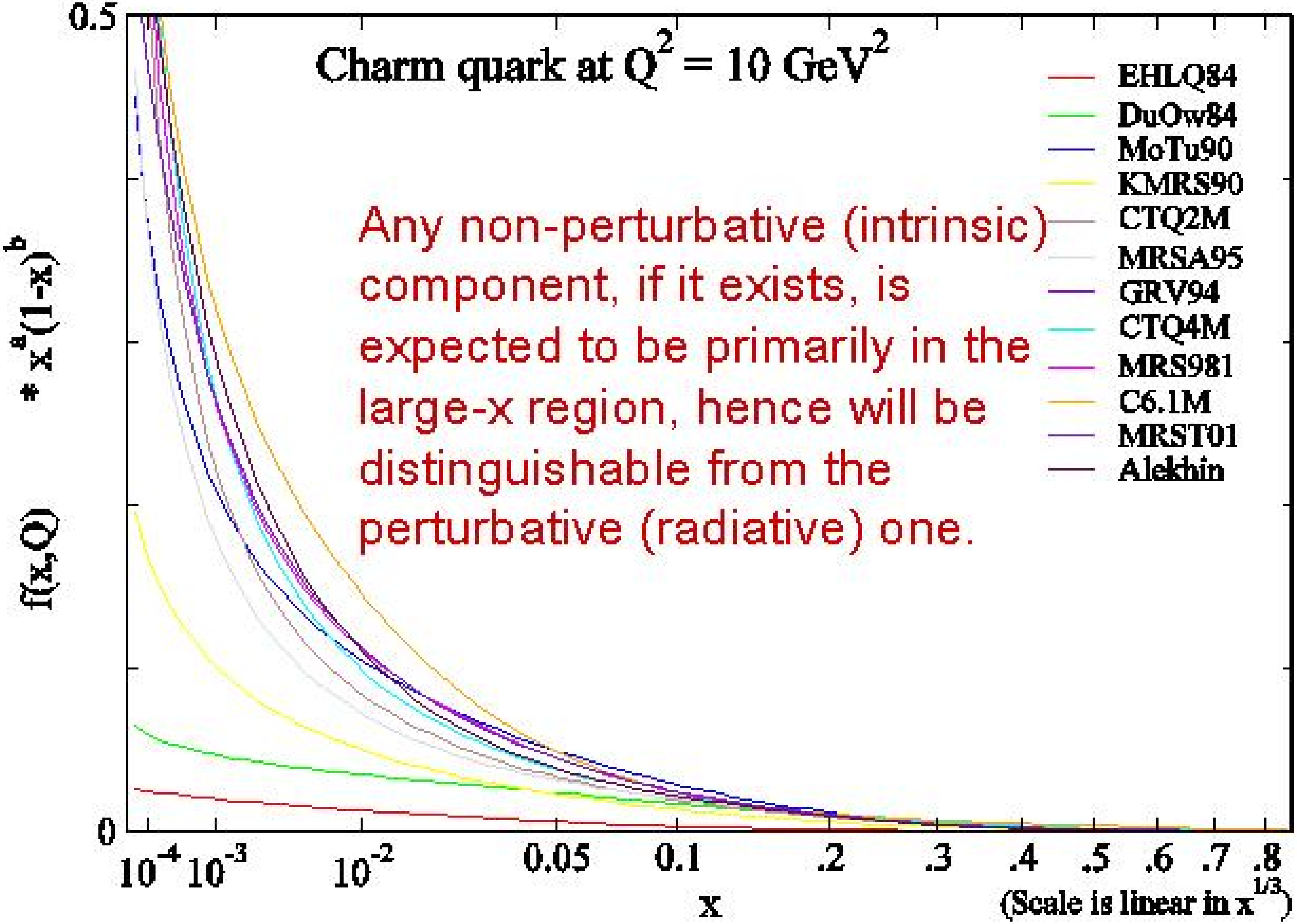
Now, there are new CCFR-NuTeV dimuon data that can, in principle, determine s(x) and sbar(x) separately!



What do we know about heavy quark distributions?

- There is yet very little direct experimental input.
- Theory formulation further depend on the "scheme" chosen to handle heavy quark effects in PQCD–fixed-flavor-number (FFN) vs. variable-flavor-number (VFN) schemes, threshold suppression prescriptions, … etc.
- All c(x,Q) and b(x,Q) found in existing PDF sets are based on "radiatively generated" heavy flavors.
- Are there any "intrinsic" heavy quarks?

Yet unexplored Territories ...



Any non-perturbative (intrinsic) component, if it exists, is expected to be primarily in the large-x region, hence will be distinguishable from the perturbative (radiative) one.

Important issue: Uncertainties of PDFs and their Physical Predictions

- The statistical principles and methods for uncertainty analyses are well established in principle: Likelihood, χ^2, … etc.---all textbook stuff. Nothing extraordinary, no particular insight required.
- The real world is not textbook-like! The world of Global Analysis (being rather complex and imperfect) has many
  - Unknown *theoretical uncertainties*;
  - Un-understood experimental *inconsistencies—unknown underlying sources of uncertainties*.

  – matters that textbooks offer little immediate help!
- To face this reality, and make progress, physics judgments (subjectivity) and development of *effective and flexible* statistical analysis tools are *required*.

Reality #1 : compatibility of experiments

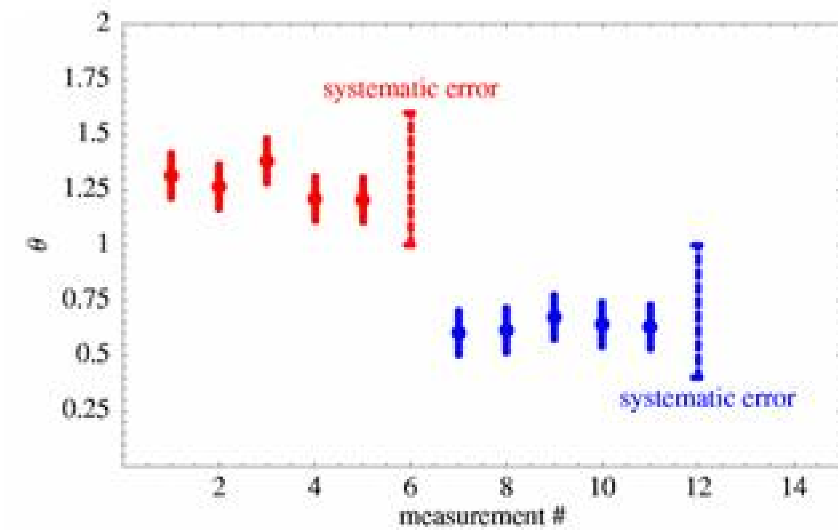
	H1	BCDMS	E665	ZEUS	NMC	LEP
H1-MRST set	-	67%	21%	0.5%	<0.1%	31%
BCDMS-MRST set	85%	-	23%	1.5%	<0.1%	0.5%
E665-MRST set	30%	82%	-	1.6%	1.0%	99%
ZEUS-MRST set	22%	<0.1%	5.0%	-	<0.1%	24%
NMC-MRST set	<0.1%	28%	1.5%	<0.1%	-	3.2%

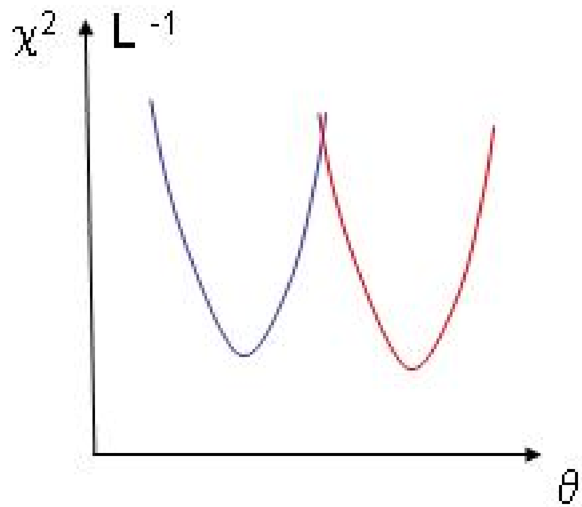
Table 2: The confidence level of each experiment given the different sets. The name of the set is composed of all included experiments and the PDF parameterization choice.

(Giele etal, 2001)

Basic dilemma:
What is the *real uncertainty* on a measured quantity due to apparently incompatible experimental results?

Imagine that two experimental groups have measured a quantity θ, with the results shown.





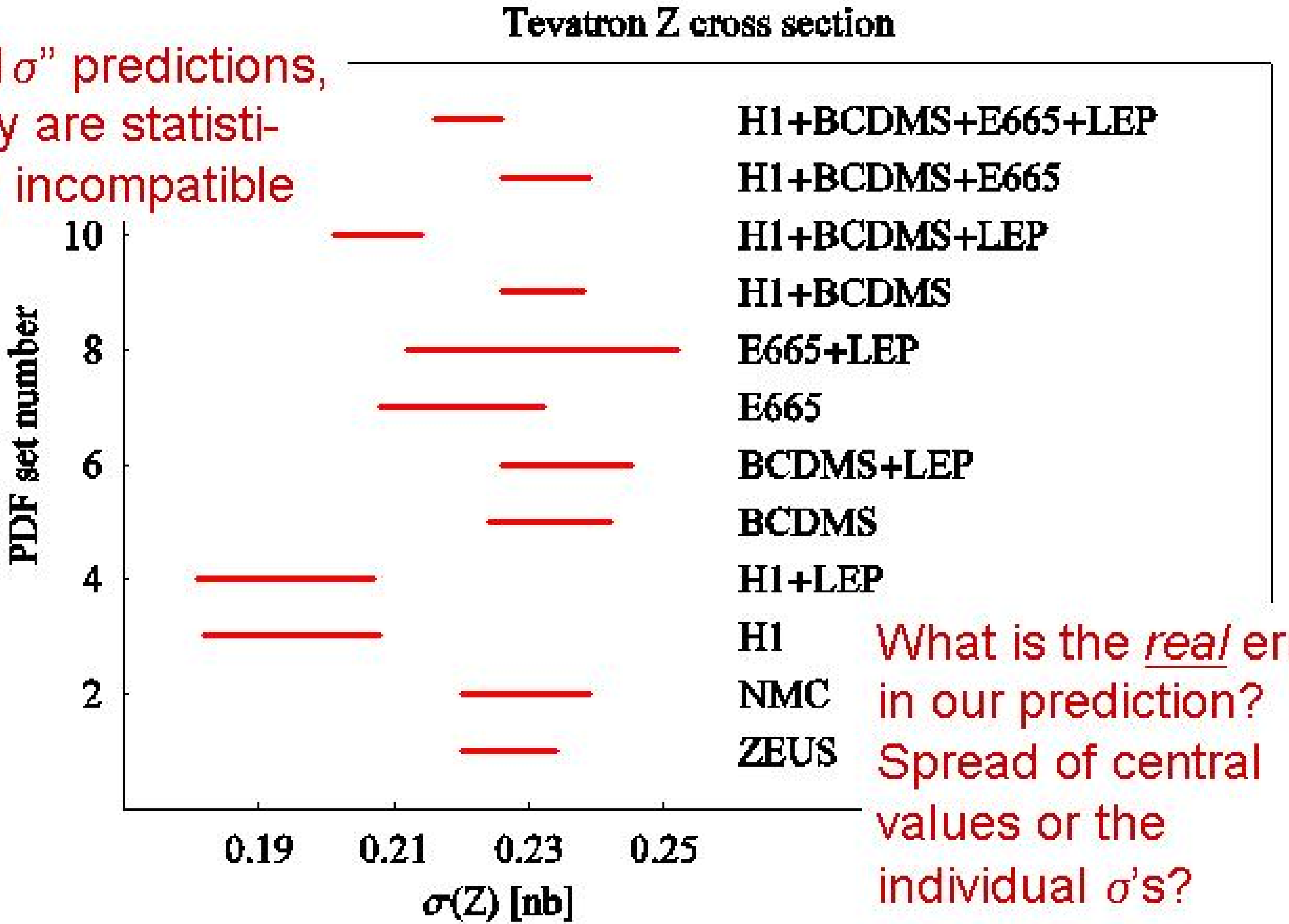
What is the value of θ? What do confidence levels mean?

(This is common occurrence in the real world.)

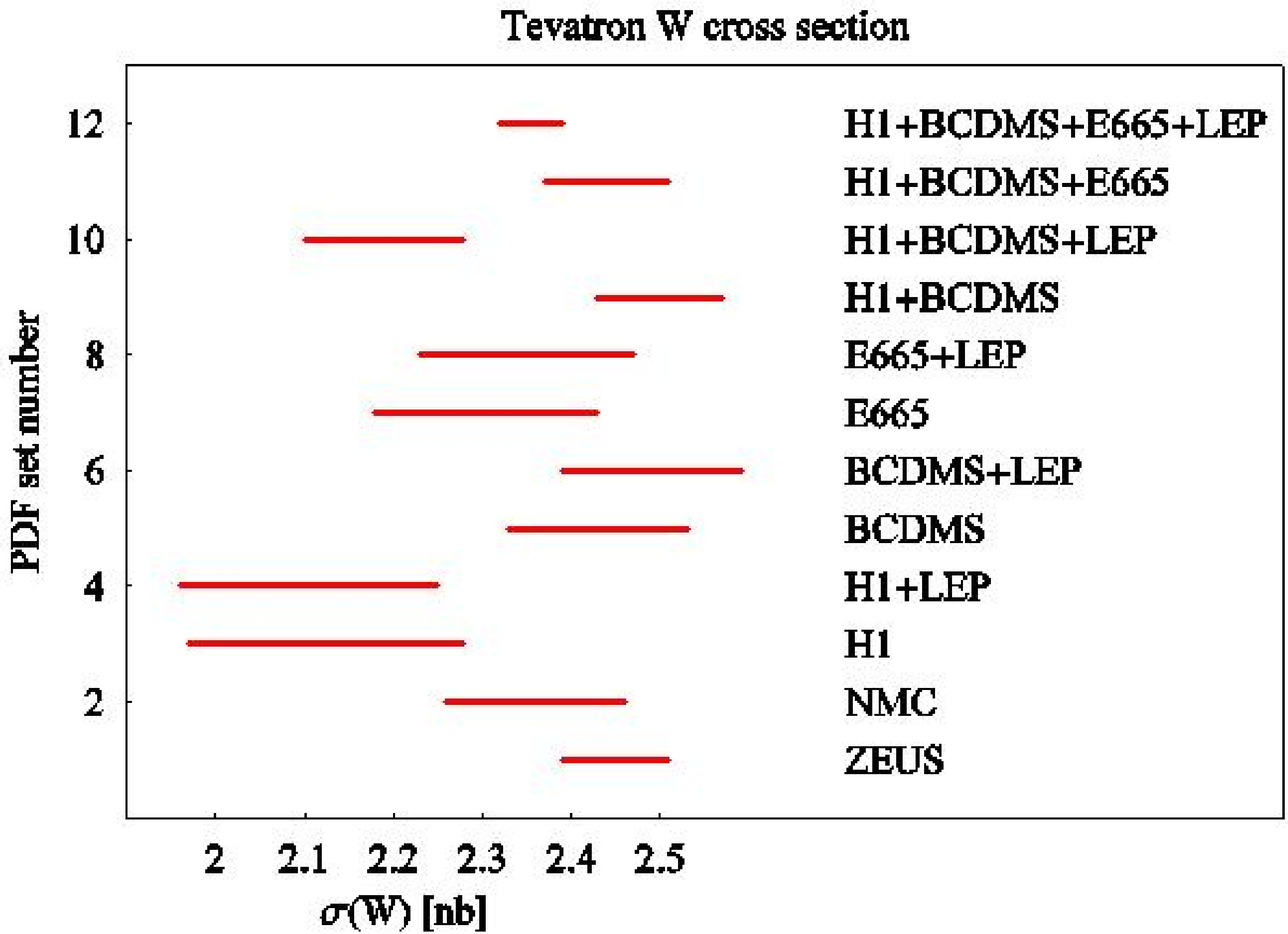
Are all experimental errors understood? Should the errors be taken at face value?

Realistic Case: Prediction of W,Z Xsec. (GKK)

12 "1σ" predictions, many are statistically incompatible



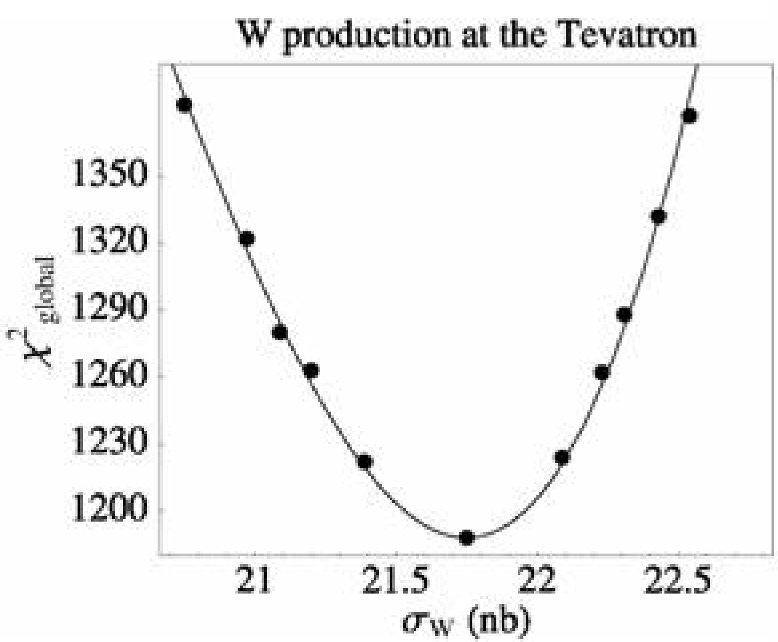
What is the *real* error in our prediction? Spread of central values or the individual σ's?



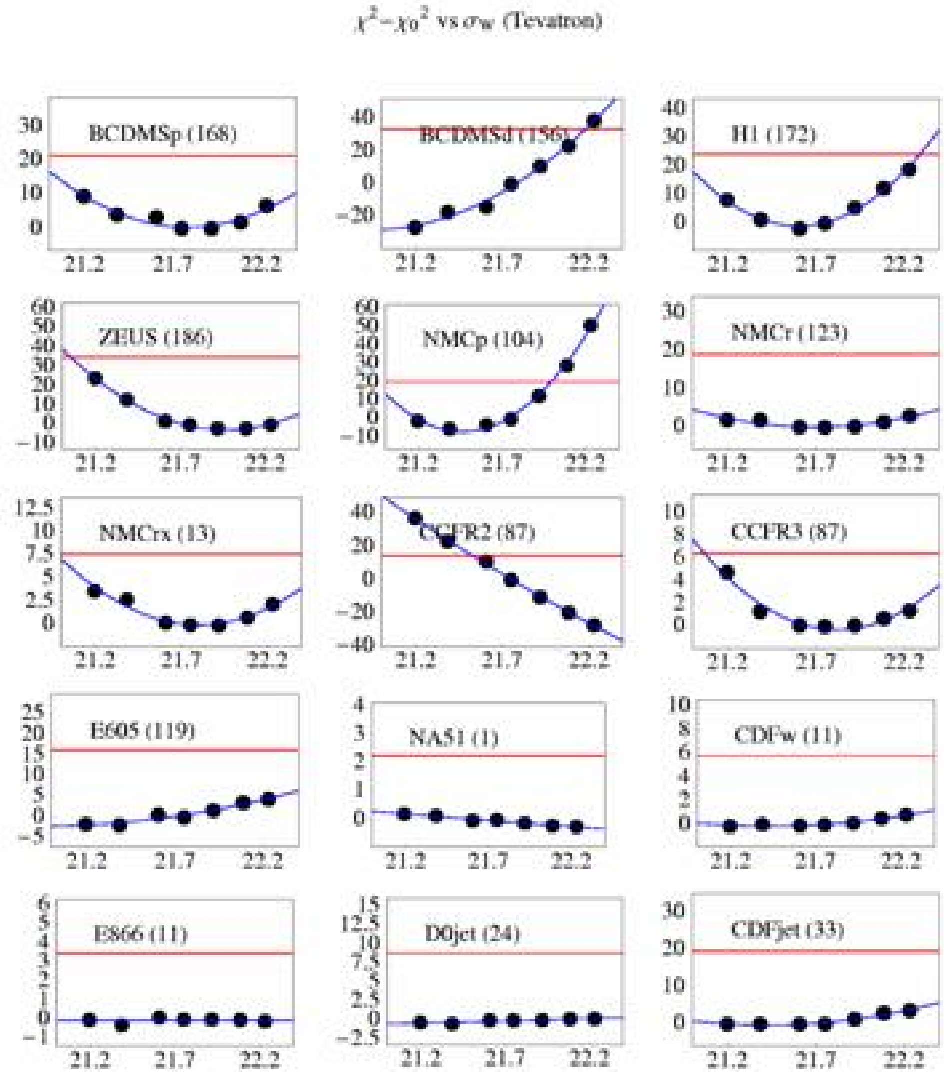
Tevatron W cross section
PDF set number
12
10
8
6
4
2
H1+BCDMS+E665+LEP
H1+BCDMS+E665
H1+BCDMS+LEP
H1+BCDMS
E665+LEP
E665
BCDMS+LEP
BCDMS
H1+LEP
H1
NMC
ZEUS
2
2.1
2.2
2.3
2.4
2.5
σ(W) [nb]

Case study: CTEQ global analysis of σ_W (χ^2 method)

Estimate the uncertainty on the predicted cross section for $p p_{bar} \rightarrow W+X$ at the Tevatron collider.

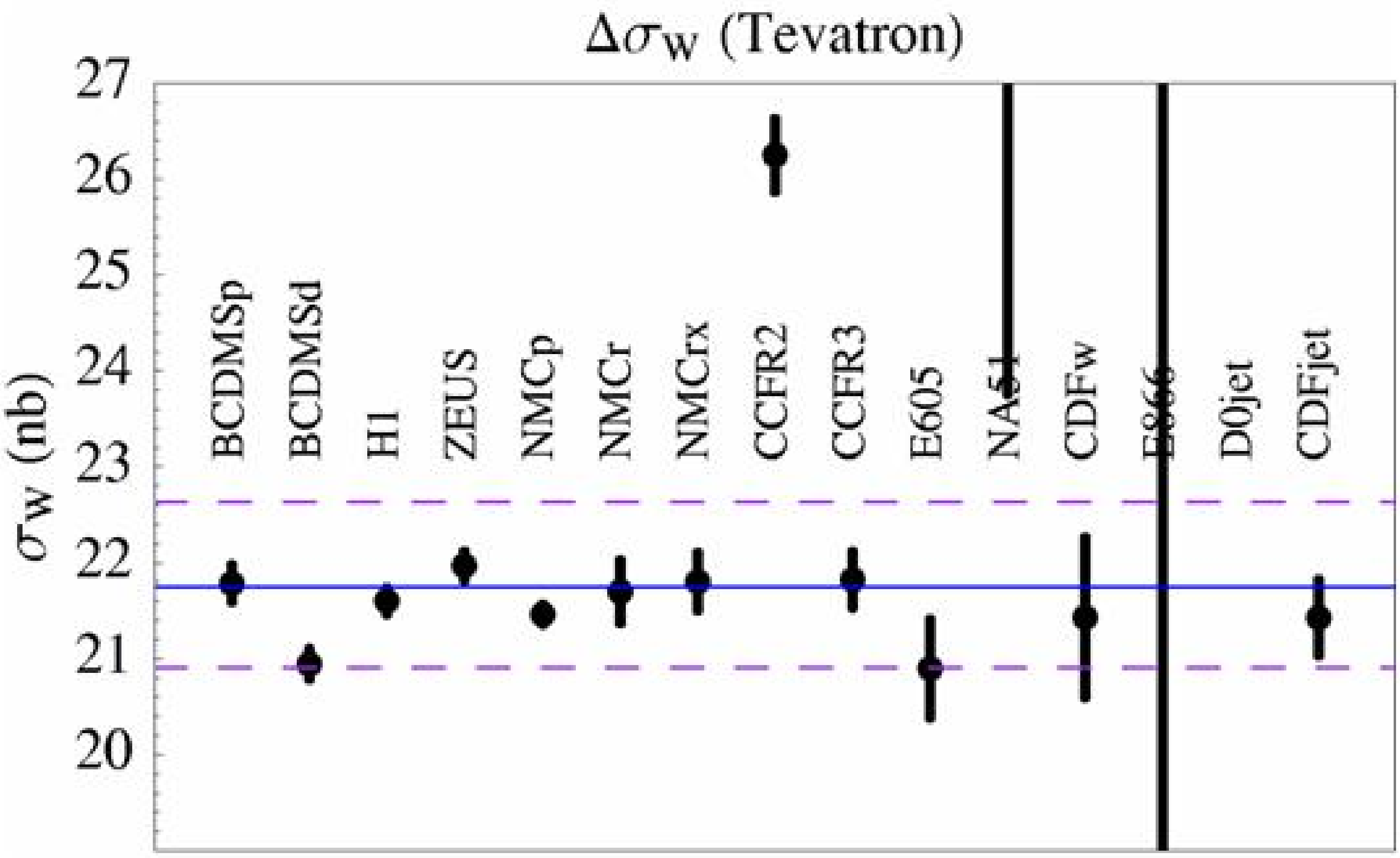


global χ^2

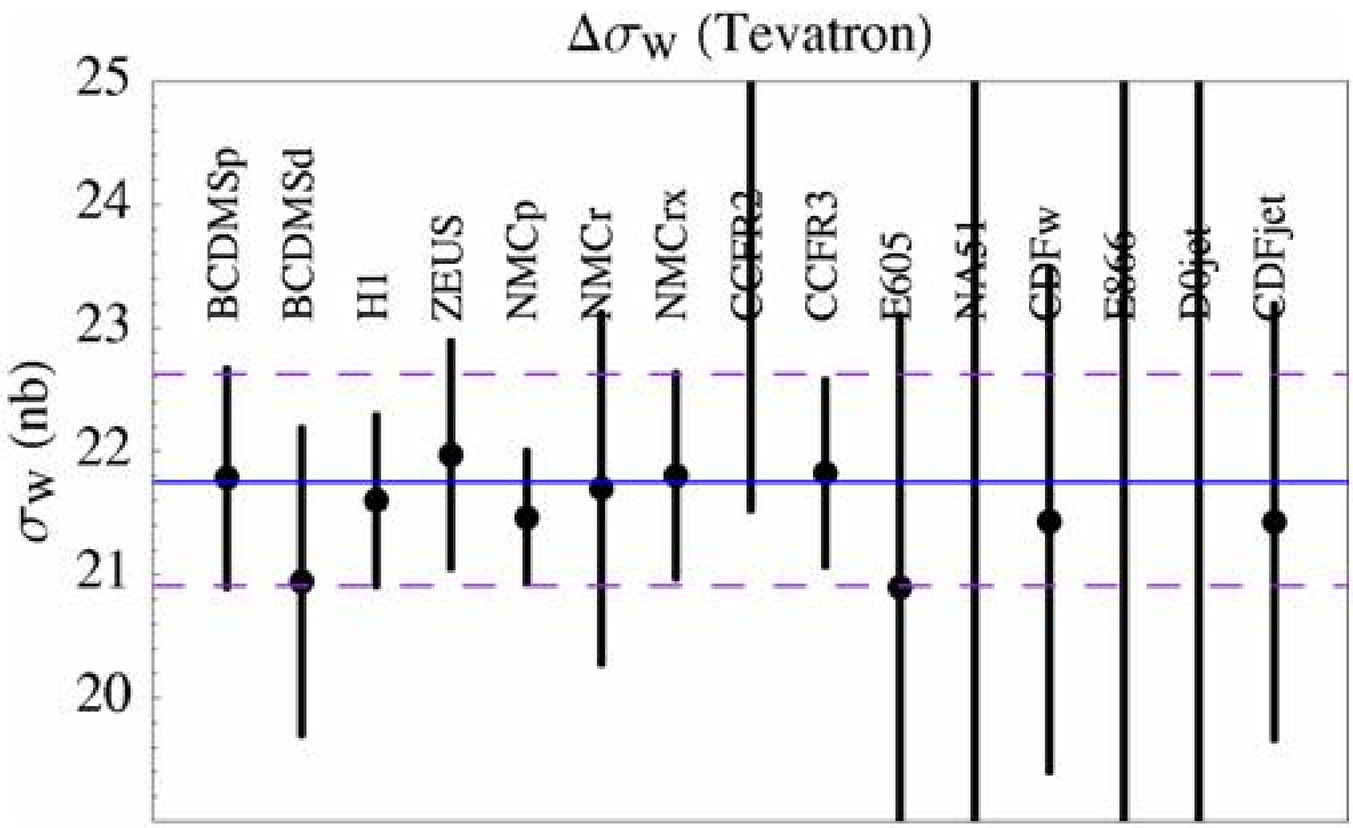


local χ^2's

Each experiment defines a "prediction" and a "range".
This figure shows the $\Delta\chi^2 = 1$ ranges.

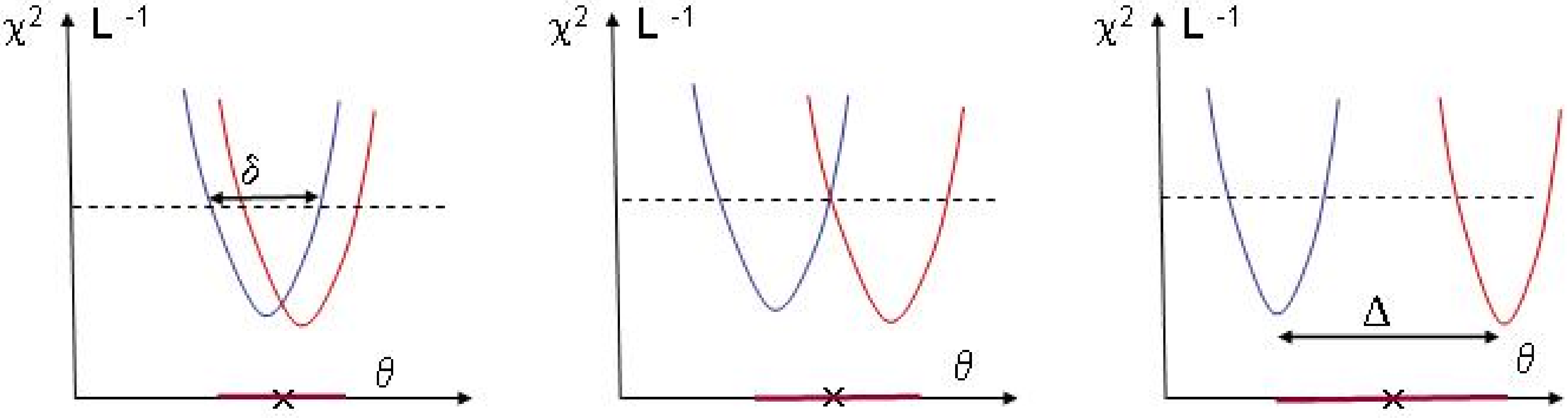


This figure shows broader ranges for each experiment based on the "90% confidence level" (cumulative distribution function of the rescaled χ^2).



"Uncertainty" in 3 scenarios

(either directly measured or indirectly inferred physical quantity θ)



Uncertainty dominated by:

δ	$\Delta \otimes \delta$	Δ

- Only case I is textbook safe; but II and III are "real".
- There are commonly used prescriptions for dealing with II and III; but none can be rigorously justified.
- Over time, inconsistencies are eliminated by refined experiments and analyses

This is the Source of large "tolerance", $\Delta\chi^2$

Quantifying uncertainties, experimental and theoretical, has been, and continues to be, an active area of current research.

For concrete examples, case studies, comparison between different approaches, cf. WG 1 talk(s) and discussions.

But, where do we stand?

My take …

- The important issue is not about methodology: likelihood vs. χ^2; or Monte Carlo sampling or Hessian approximation, …
  They are all equivalent, given consistent theoretical and experimental input.
- The challenges concern:
  - Refrain from the ideological (aka "rigorous") stance that confuse the scene (since the world is not perfect);
  - Develop effective, flexible statistical tools tailored to cope with the complex issues of Global analysis, with the goals:
    - to allow sensible estimates of "90 %" confidence uncertainty ranges (rather than "1-σ error limits").
    - to help pin-point the sources of existing trouble spots.

(continued)

Even so, the ultimate goal surely has to be: to eliminate all experimental incompatibilities and theoretical uncertainties, so we can have 1-σ errors on parton distributions and their predictions?

The question is ruled out of order:

Before we get anywhere, on the time scale it requires to think about this goal, New Physics surely would have been discovered; and we would be much too busy asking, and answering, other questions.

Agenda for studying Nucleon Structure and Collider Physics

- Large x behavior of *G(x,Q)*, *u(x,Q)* and *d(x,Q)*;

New frontiers on detailed flavor structure of the nucleon:

- Pinning down the strangeness sector of nucleon structure;
- Understanding the charm content of the nucleon;

Precision W/Z phenomenology at the Tevatron and LHC

- Predictions by and feedback to global analysis
- Transverse momentum, resummation and W-mass
- NNLO analysis
- Higgs, Top, and Beyond SM Phenomenology