Hadron Collider Physics: Issues on PDFs

Hadron Collider Physics at Tevatron and LHC:
what's the difference from the PDF perspective?

Review of global QCD analysis of PDFs in general:
challenges and open issues.

Global QCD analysis issues at Tevatron Run II

What about LHC? and Tevatron for LHC?

Significant Recent Progress in PQCD Physics

Quantitative (NLO) treatment of general processes:

- Systematic NLO Calculation of Multi-particle (W/Z, γ, jets) final states;
- Development of NLO MC event generators;
- Better understanding of heavy quark production and decay; ....

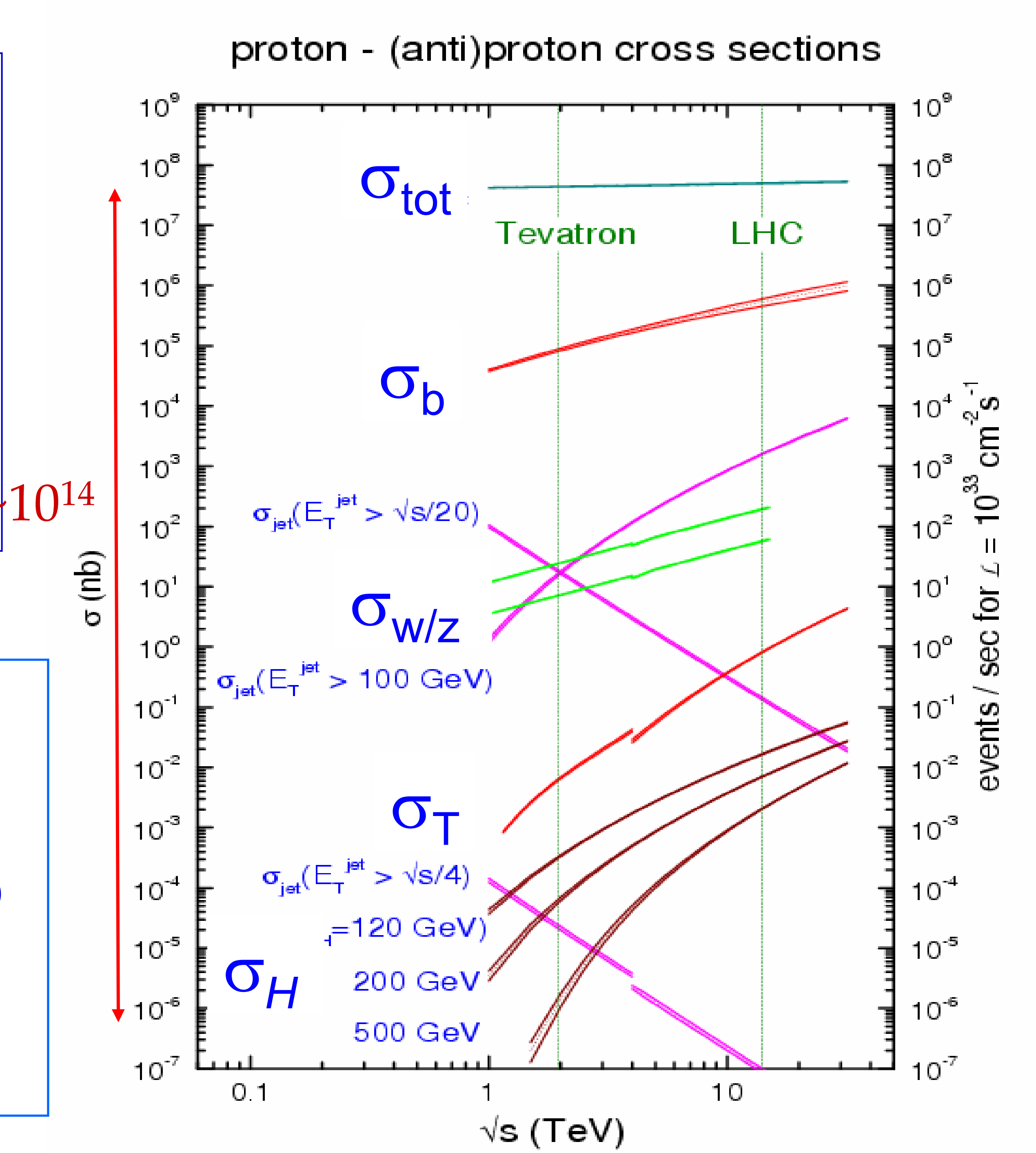
Precision (NNLO) Study of critical processes:

- (3-loop) evolution kernel ;
- Z, W, γ, rapidity distributions ;
- Higgs production; ....

Various resummation schemes for multi-scale problems

Unfortunately, no time in this talk to discuss these topics.

Representative Standard Model processes—cross sections and event rates at the Tevatron and LHC

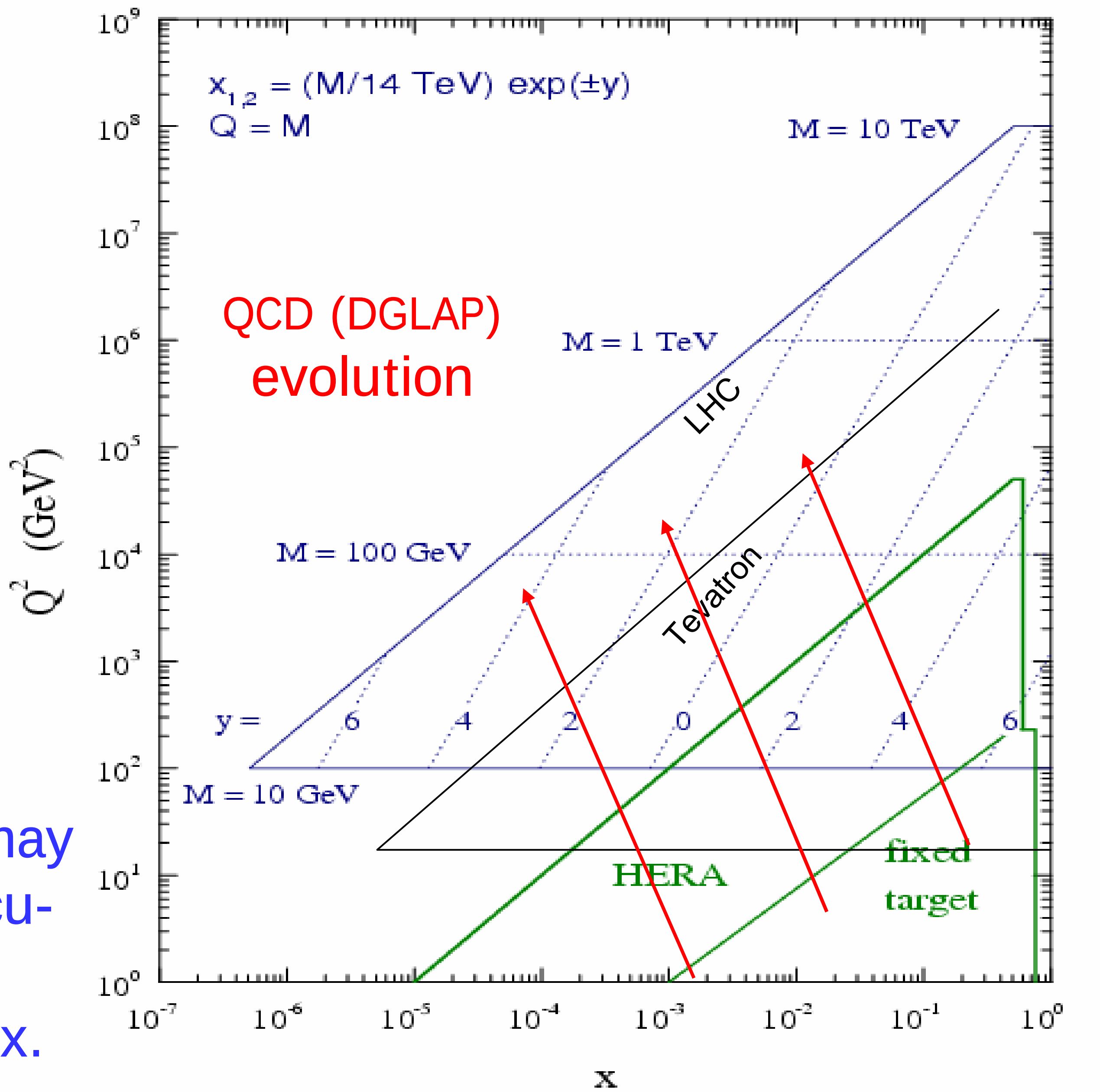


New Physics signals, if present, are generally quite low, and difficult to disentangle from the QCD and EW "backgrounds".

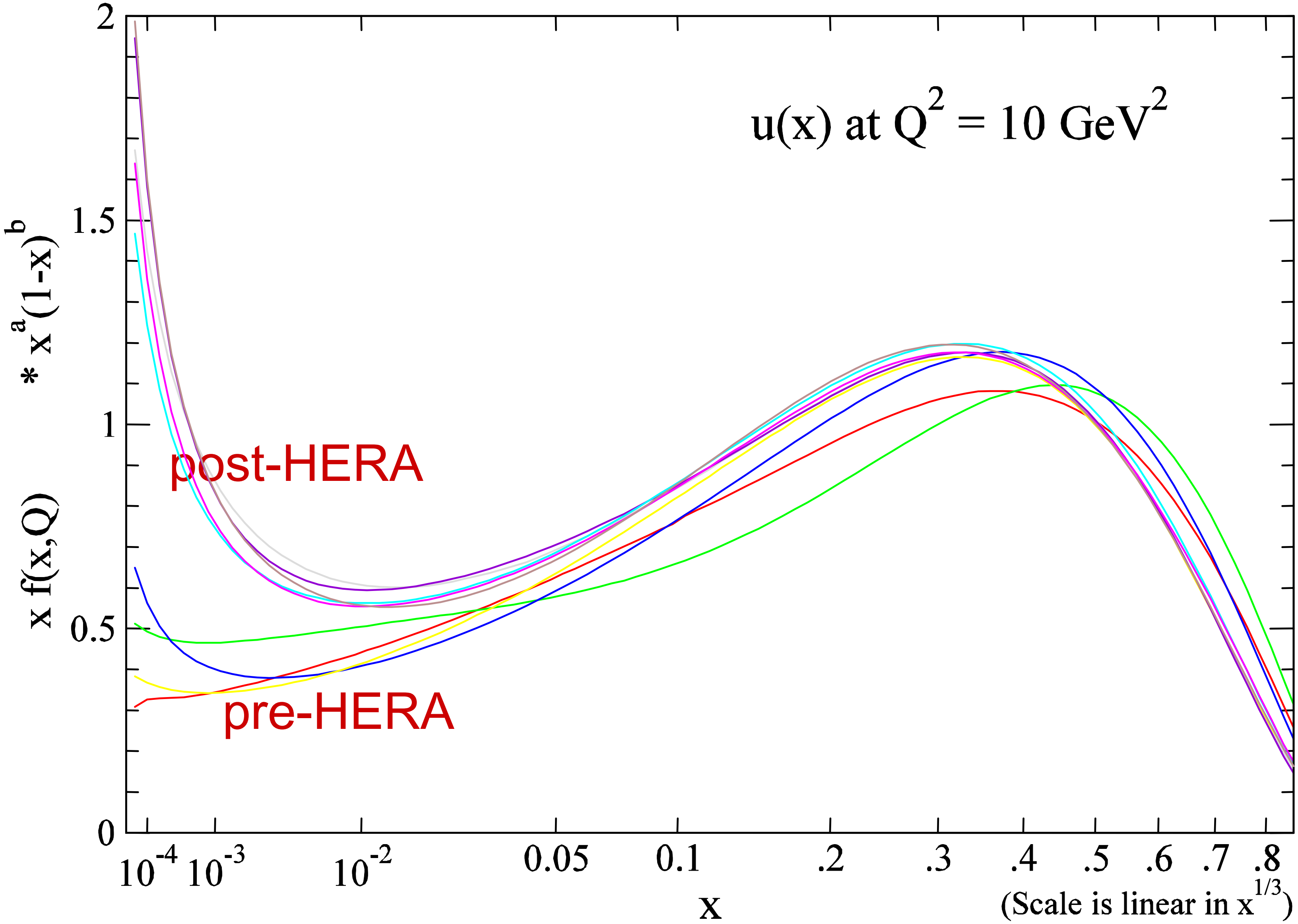
Kinematics of Parton variables

Predictive power of global analysis of PDFs is based on the renormalization group properties of the universal Parton Distributions f(x,Q).

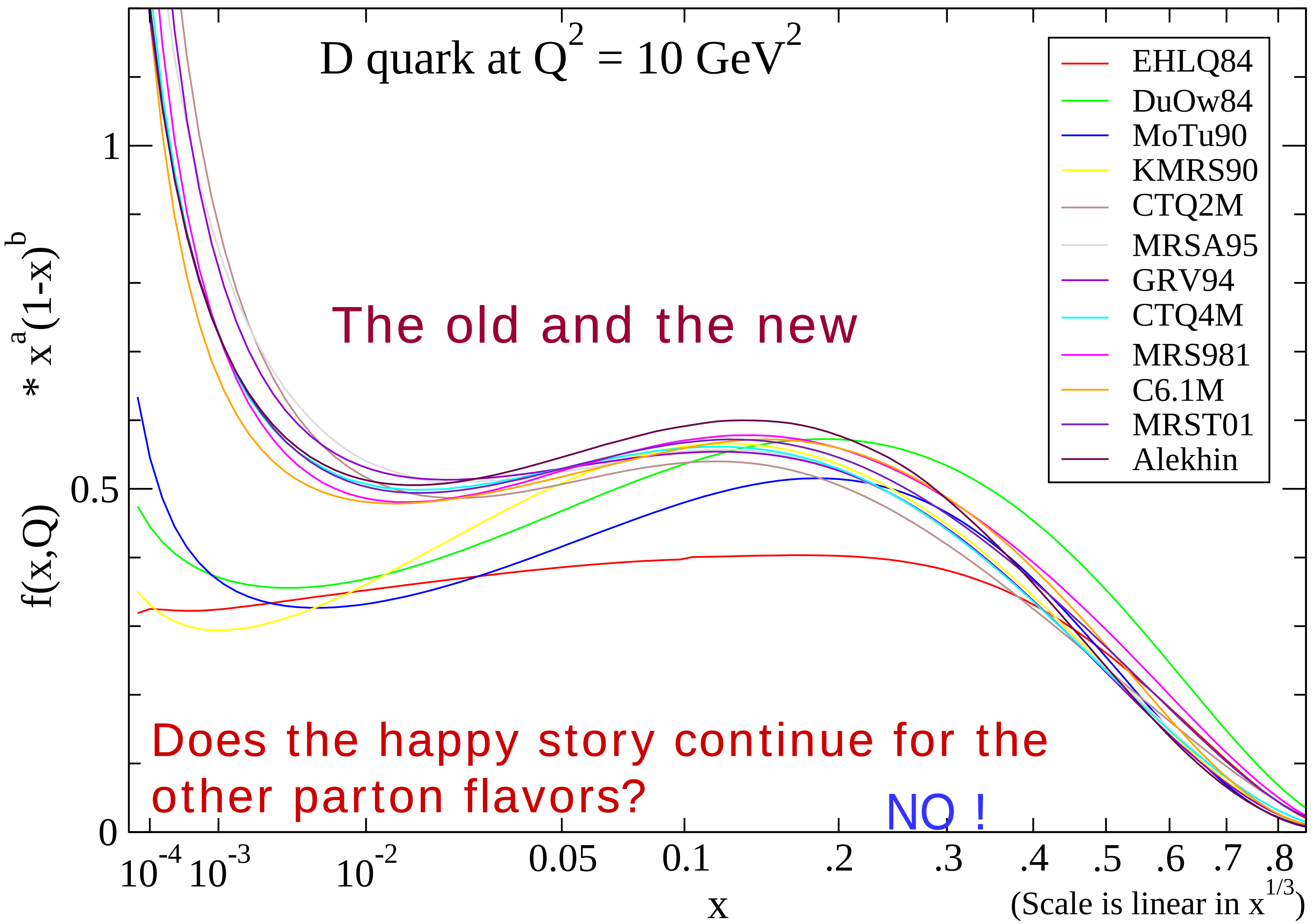
"Feed-down" effect may affect anticipated accuracy of predictions at both small and large x.

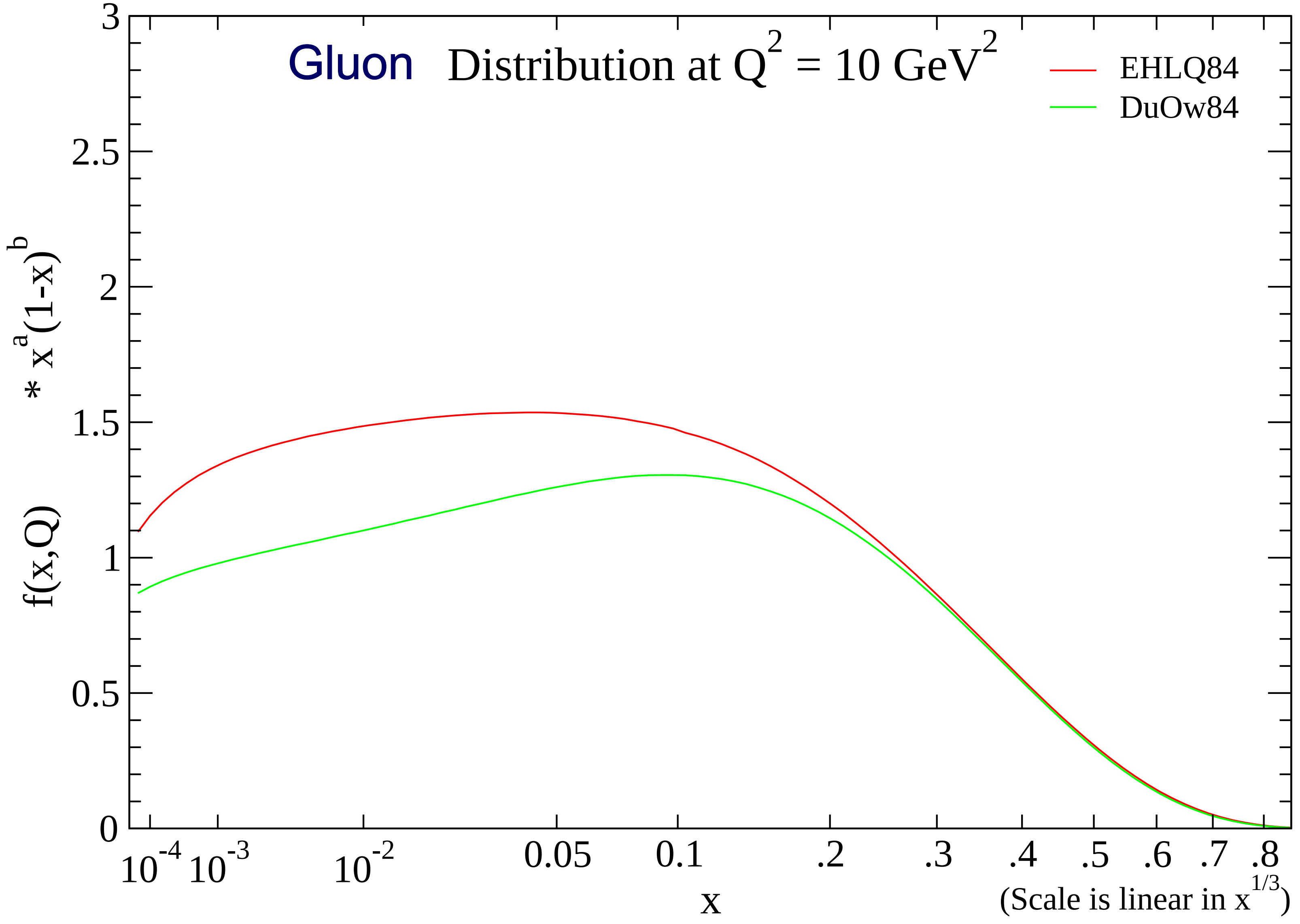


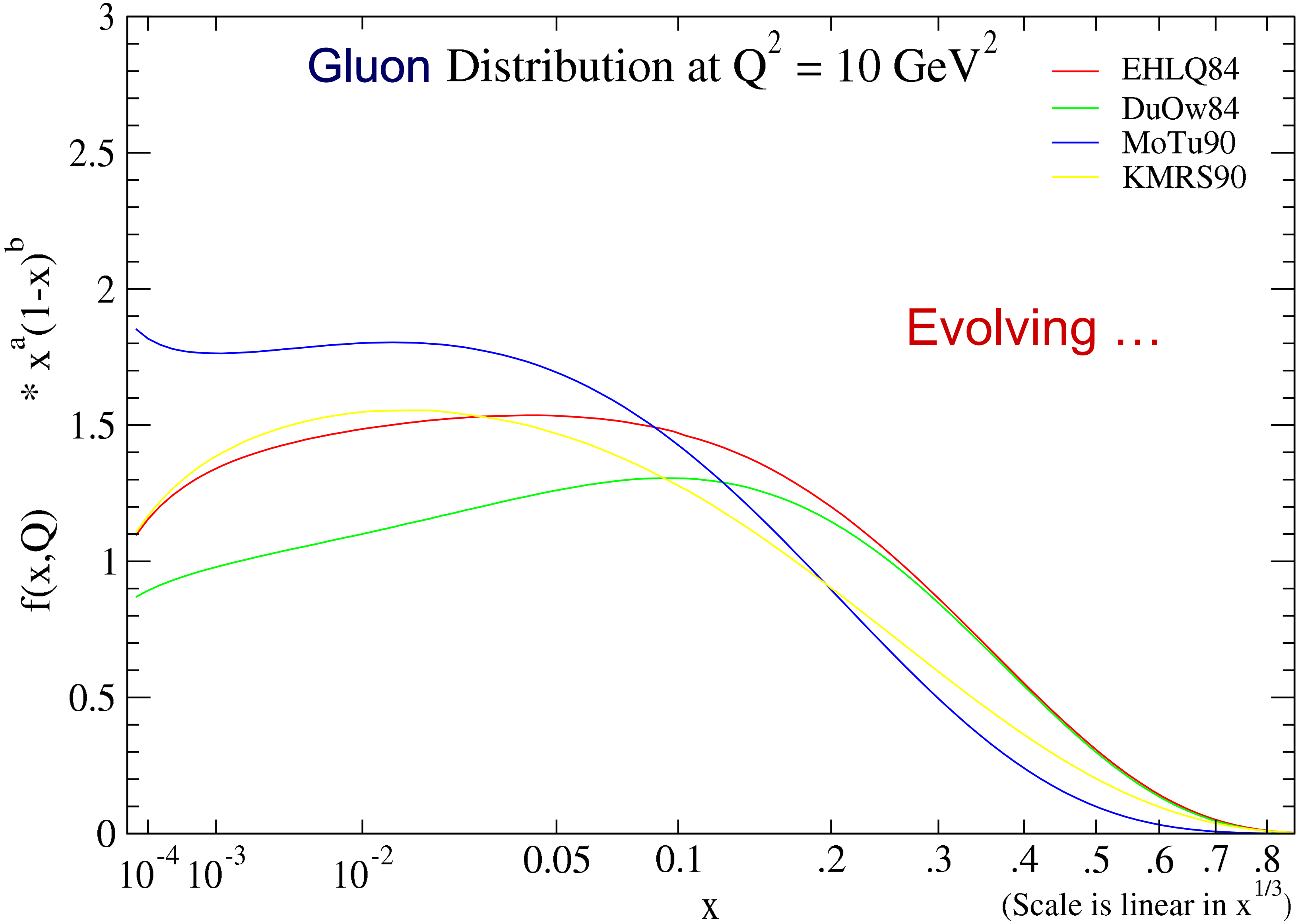
Progress in the determination (time evolution) of the u-quark distribution

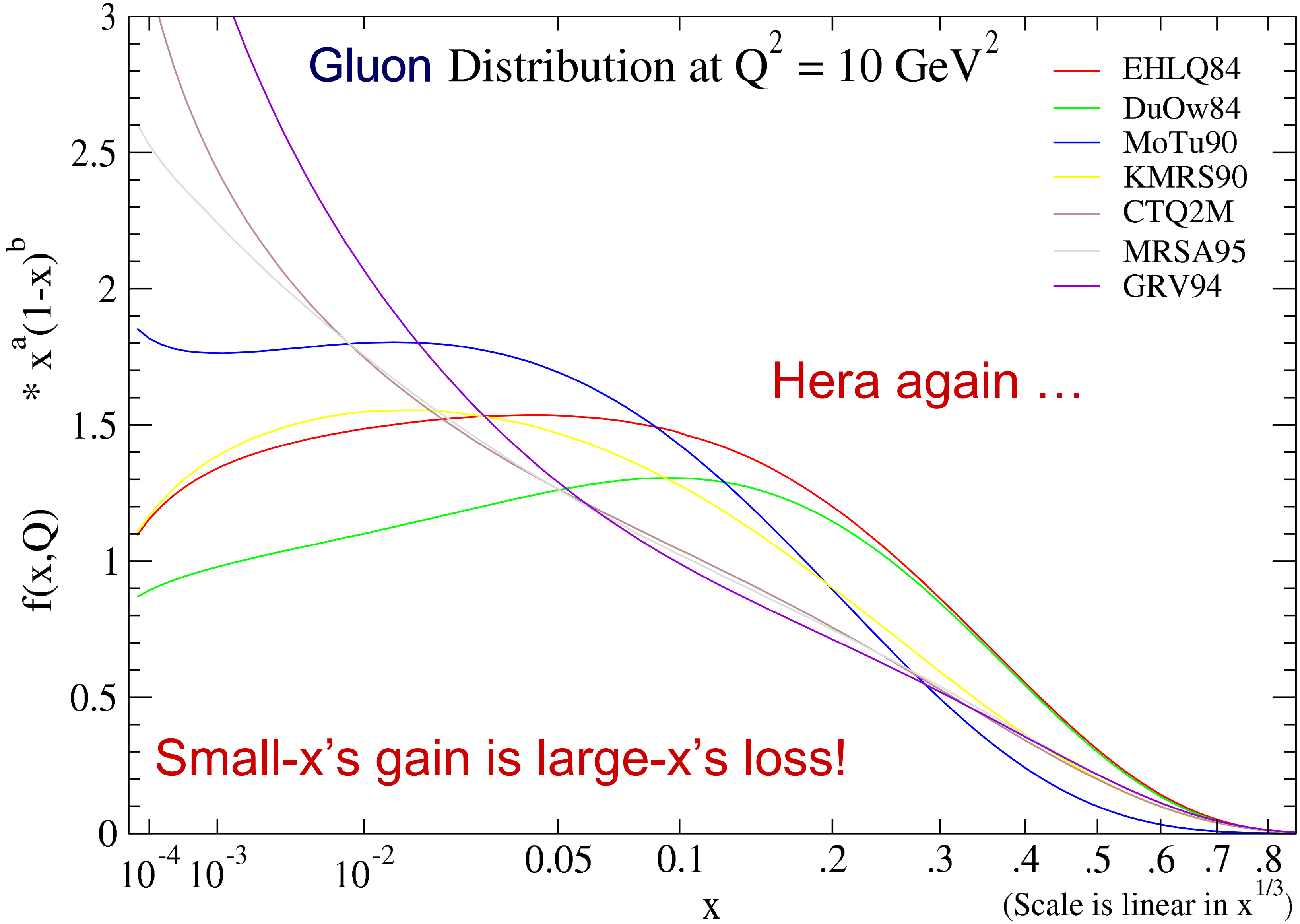


The d-quark story

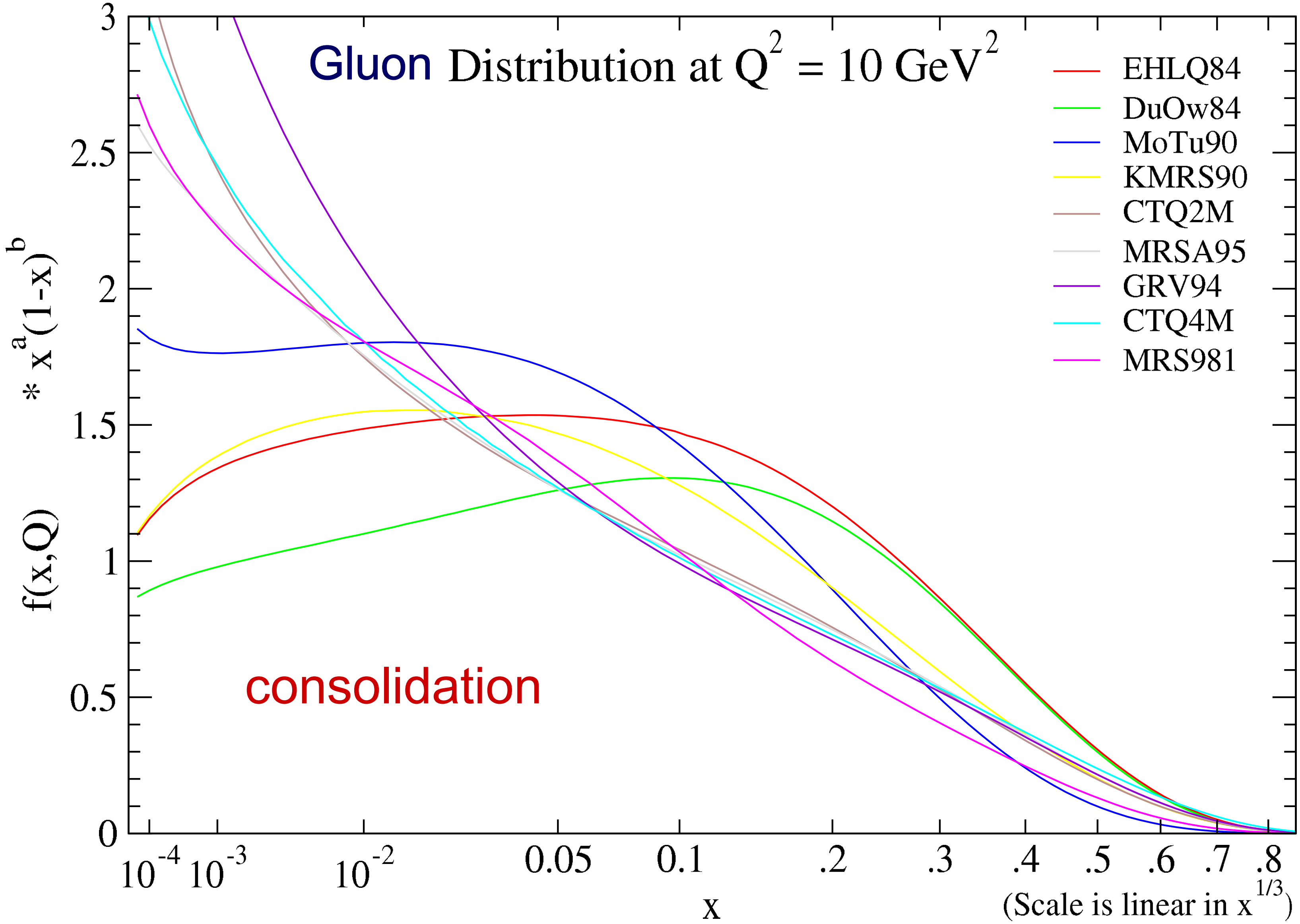



Gluon Distribution at Q^2 = 10 GeV^2
EHLQ84
DuOw84
f(x,Q) * $x^a(1-x)^b$
3
2.5
2
1.5
1
0.5
0
10^{-4} 10^{-3} 10^{-2} 0.05 0.1 .2 .3 .4 .5 .6 .7 .8
x
(Scale is linear in $x^{1/3}$)

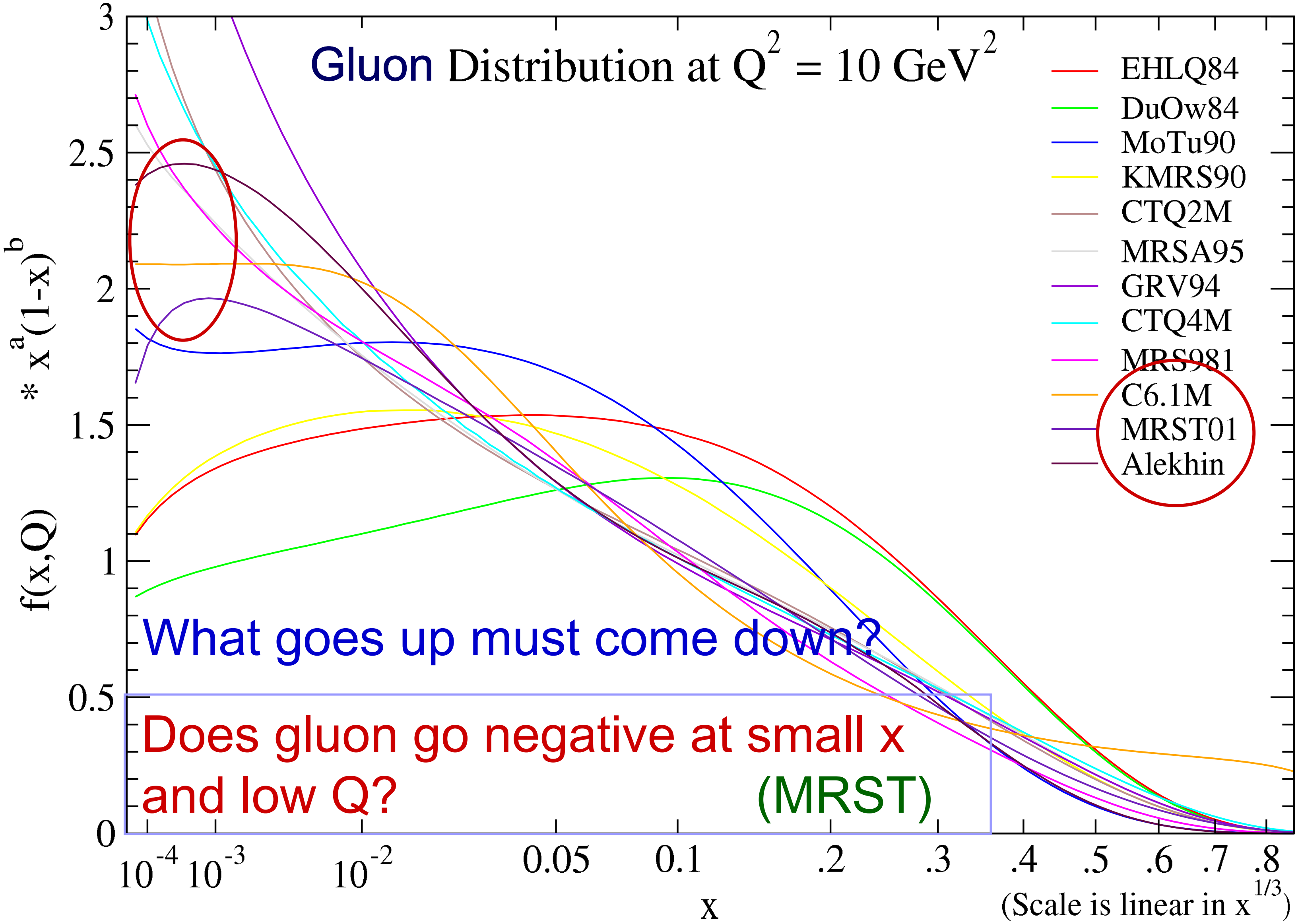

Gluon Distribution at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
Evolving …
f(x,Q) * x^a(1-x)^b
3
2.5
2
1.5
1
0.5
0
10^-4
10^-3
10^-2
0.05
0.1
.2
.3
.4
.5
.6
.7
.8
x
(Scale is linear in x^1/3)



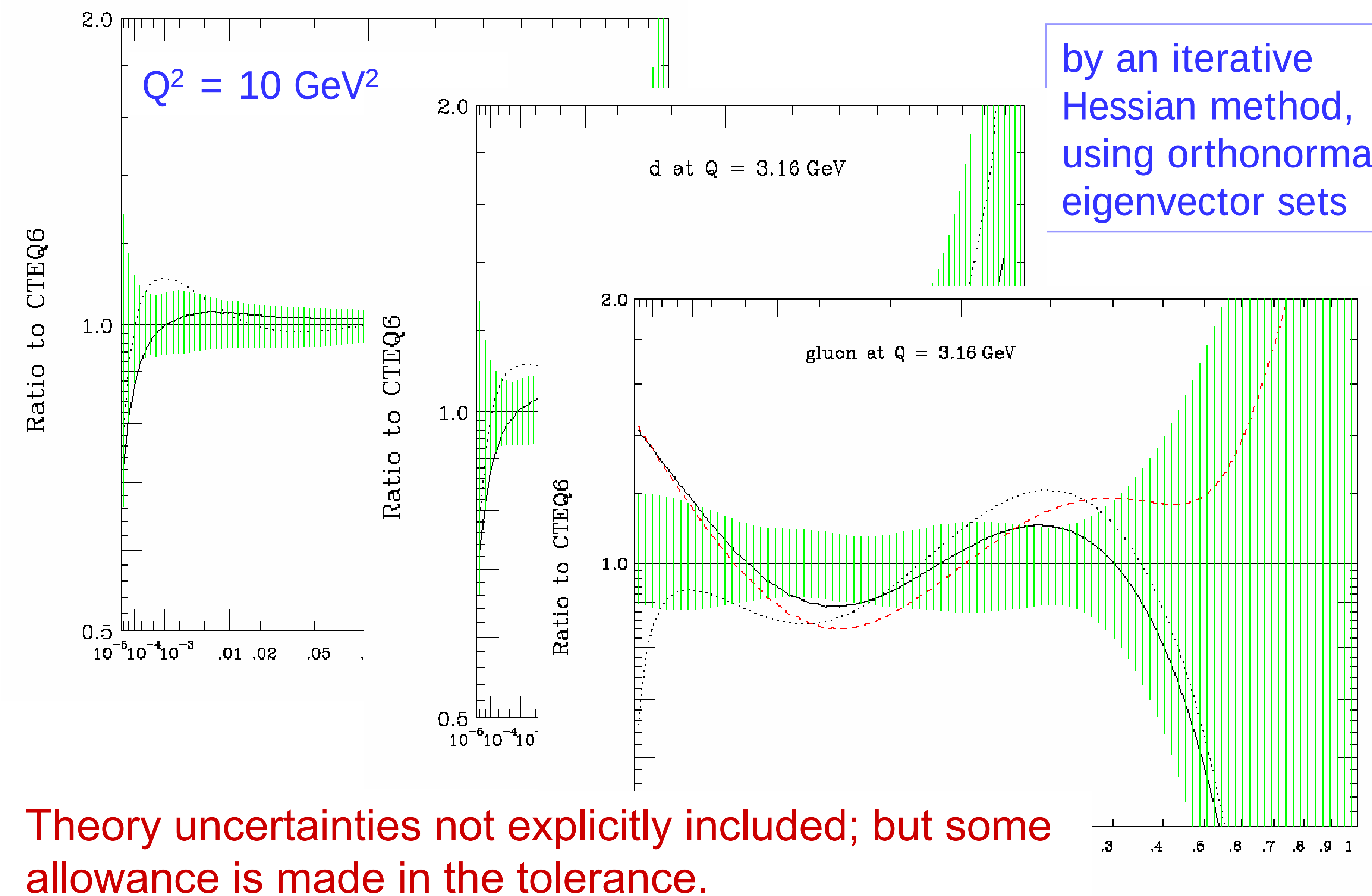
Gluon Distribution at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
Hera again …
Small-x's gain is large-x's loss!
f(x,Q) * x^a(1-x)^b
x
(Scale is linear in x^1/3)
0
0.5
1
1.5
2
2.5
3
10^-4
10^-3
10^-2
0.05
0.1
.2
.3
.4
.5
.6
.7
.8



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
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)
What goes up must come down?
Does gluon go negative at small x
and low Q?
(MRST)

Uncertainties of PDFs: CTEQ6



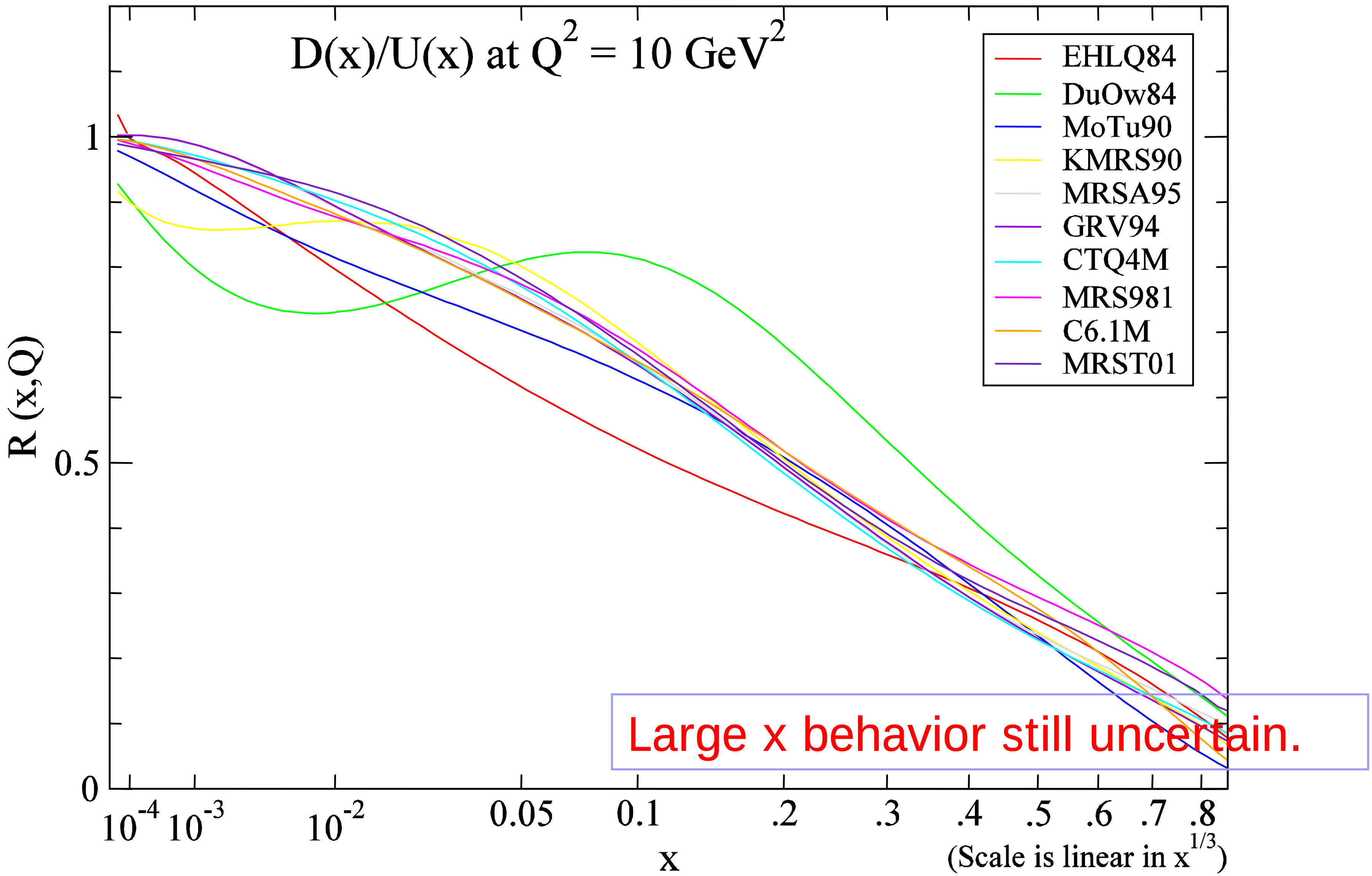
by an iterative Hessian method, using orthonormal eigenvector sets

Theory uncertainties not explicitly included; but some allowance is made in the tolerance.

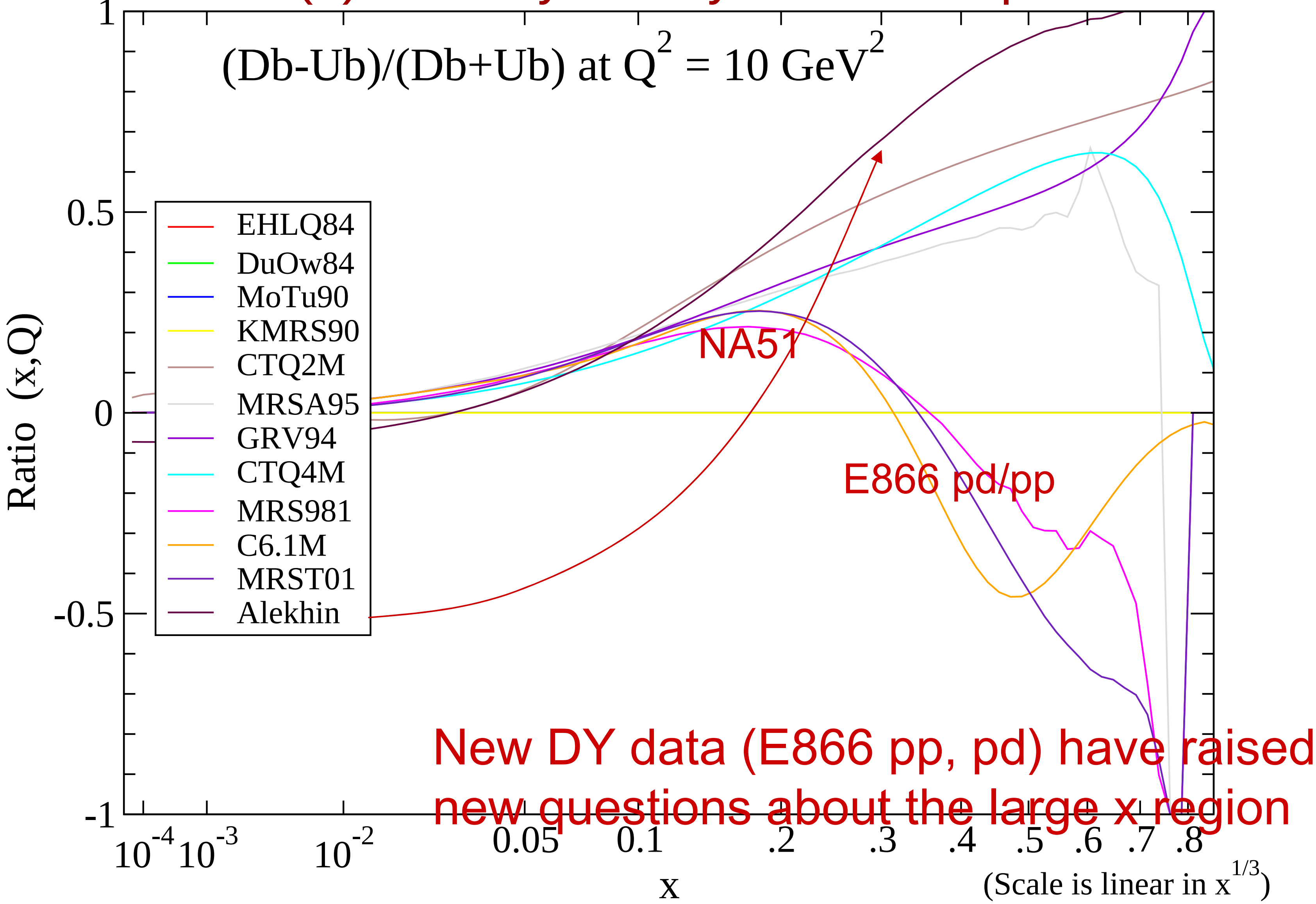
Valence and Sea Quark distributions of the Nucleon

How does the d(x)/u(x) ratio behave?

Do the sea quarks observe SU(2) isospin symmetry ($\bar{u} = \bar{d}$)?


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)
Large x behavior still uncertain.

SU(2) flavor symmetry of the sea quarks



Caution: “Modern fit” without DY and Collider input:

Valence and Sea Quark distributions of the Nucleon

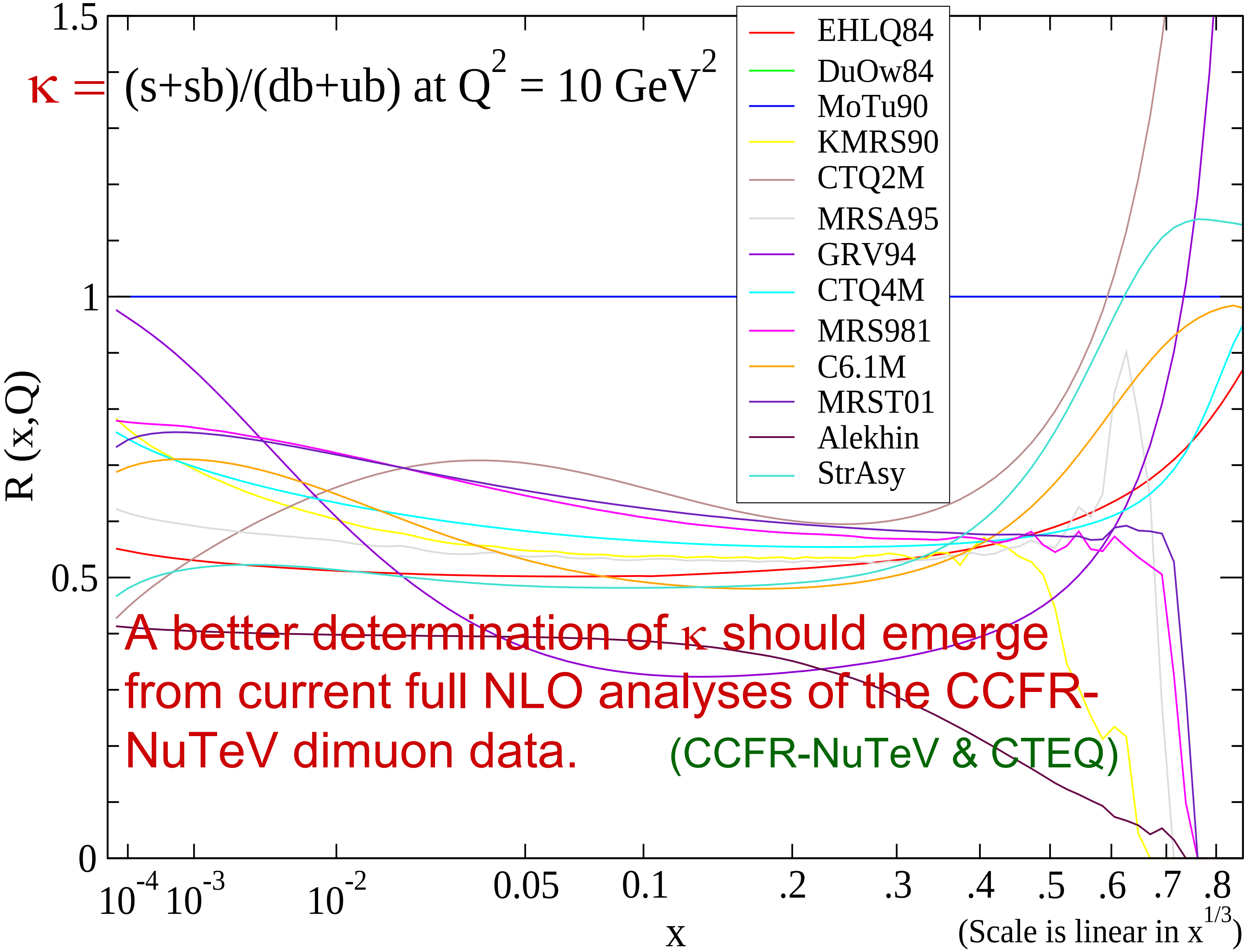
How does the d(x)/u(x) ratio behave? Low/medium x behavior well determined; Large-x behavior open.

Do the sea quarks observe SU(2) isospin symmetry?

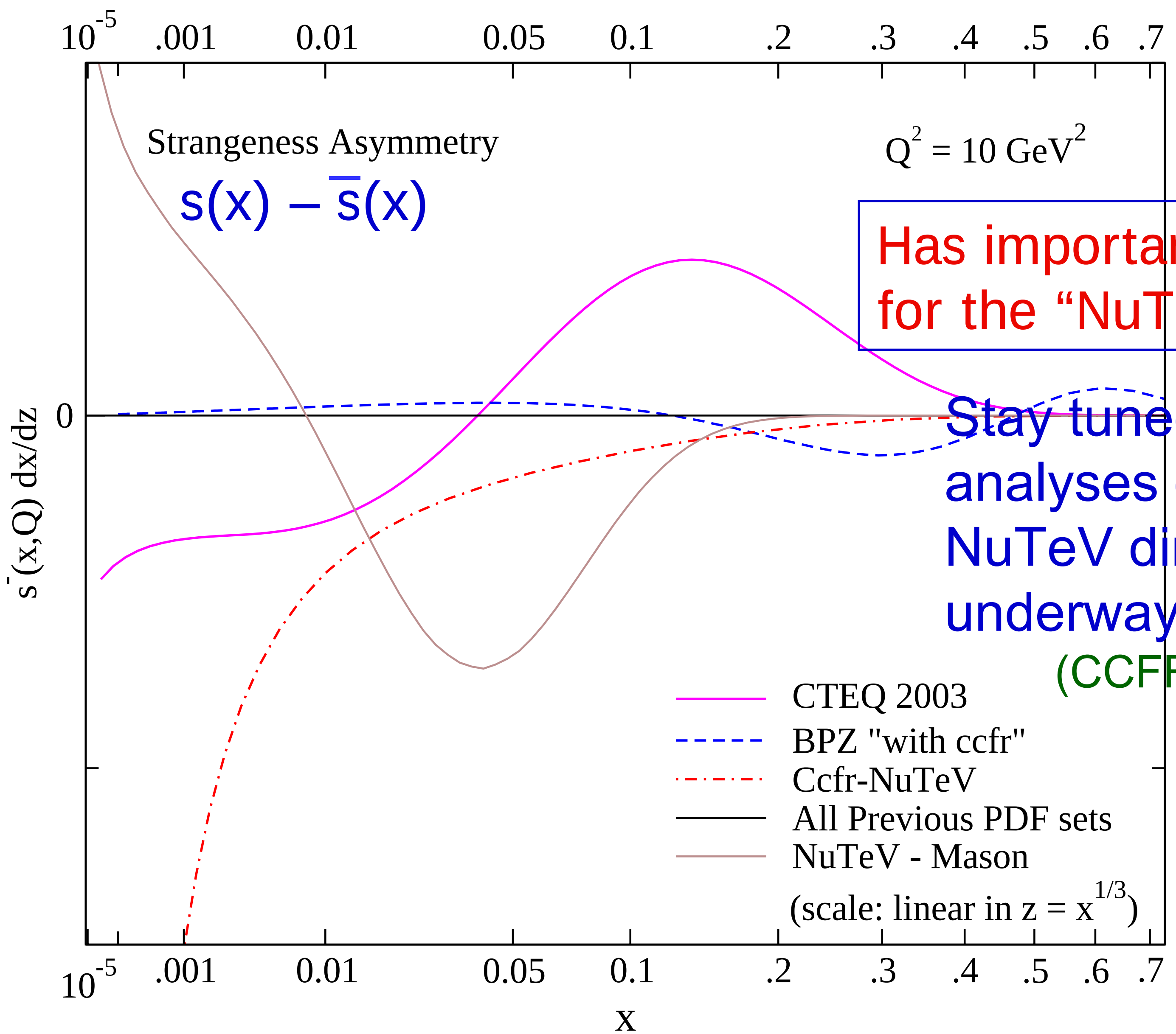
Certainly not! Large-x behavior open.

How about (flavor) SU(3) symmetry ($s+\bar{s} = \bar{u}+\bar{d}$)?

Is the strange sea charge symmetric ($s = \bar{s}$)?



κ = (s+sb)/(db+ub) at Q^2 = 10 GeV^2
EHLQ84
DuOw84
MoTu90
KMRS90
CTQ2M
MRSA95
GRV94
CTQ4M
MRS981
C6.1M
MRST01
Alekhin
StrAsy
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)
A better determination of κ should emerge from current full NLO analyses of the CCFR-NuTeV dimuon data.
(CCFR-NuTeV & CTEQ)



Has important implications for the “NuTeV anomaly”

Stay tuned …. Full NLO analyses of the CCFR-NuTeV dimuon data underway.

(CCFR-NuTeV & CTEQ)

Valence and Sea Quark distributions of the Nucleon

How does the d(x)/u(x) ratio behave? Low/medium x behavior well determined; Large-x behavior open.

Do the sea quarks observe SU(2) isospin symmetry?

Certainly not! Large-x behavior open.

How about (flavor) SU(3) symmetry (s+sb=ub+db)?

Certainly not! $\kappa \sim 0.4$ more precise value to come.

Is the strange sea charge symmetric (s = sb)?

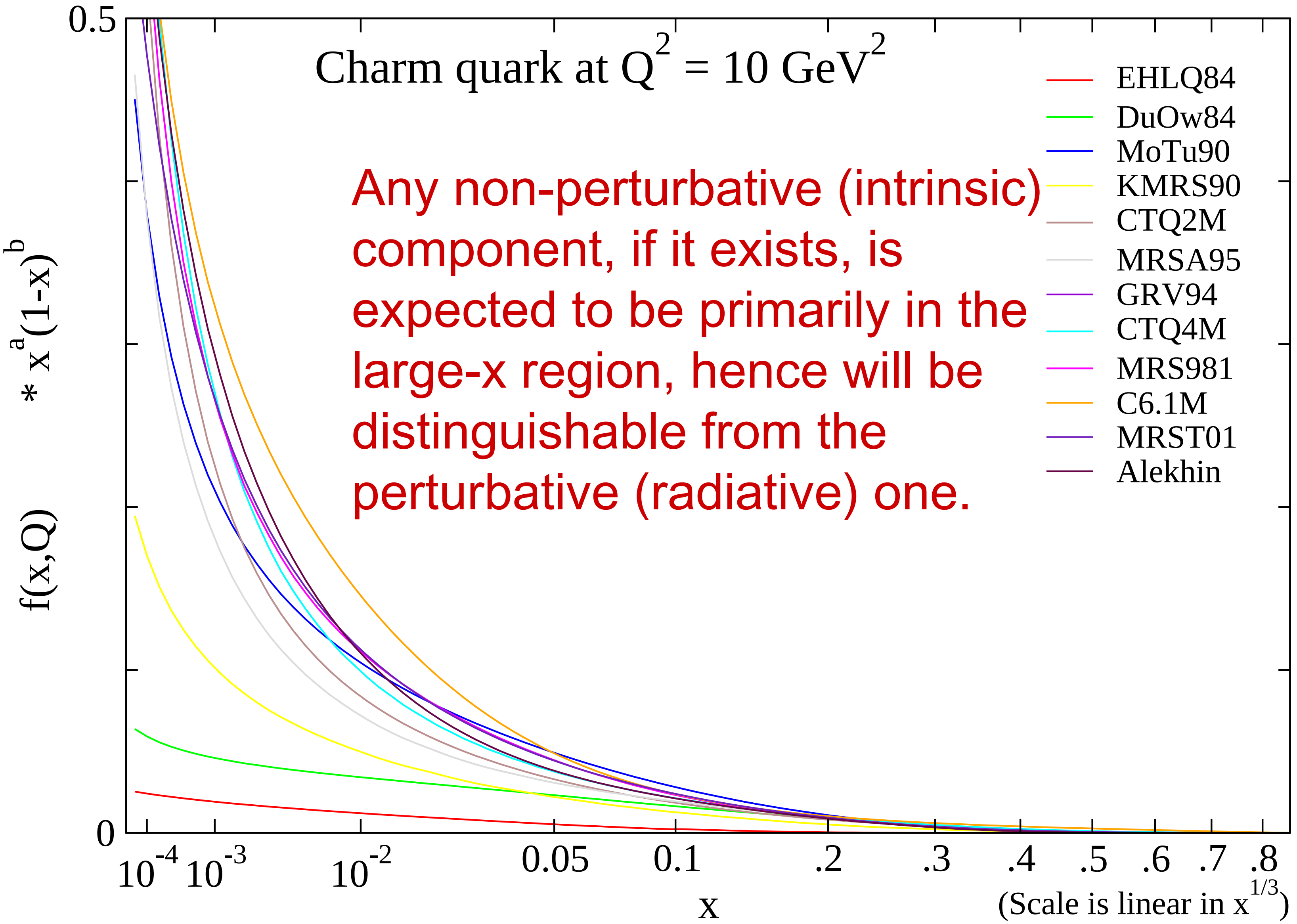
Jury is still out. Has important implications on the NuTeV anomaly.

What about heavy quark distributions?

What do we know about heavy quark distributions?

- There is yet very little direct experimental input.
- Theory formulation further depends 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.
- Open question: 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.

Mini Summary on current status of PDF Analysis

- A great deal of progress has been made since the first LO analyses were make;
- But, many areas of uncertainties and uncharted territories remain.

Yet to be done: (before we can really understand the parton structure of nucleon, and are able to make reliable predictions)

- Reliable methods of quantifying uncertainties; (several groups)
- Gluons at large and small x; (all groups)
- *d/u* at large *x*; *(db-ub)/(db+ub)* at large *x*; (CTEQ)
  Isospin violation (i.e. d_n .ne. u_p); (MRST-DIS04)
- Strangeness s(x); and strangeness asymmetry; (CTEQ, NuTeV)
- Heavy quark (c and b) parton distributions. (CTEQ)

Collider Physics Issues related to Global QCD Analysis

- Standard Candle Processes:
  W/Z total cross-section predictions;
- Precision PQCD phenomenological analyses (Tevatron):
  W/Z rapidity distribution;
  W/Z transverse momentum distribution;
  W-mass measurement;
  W/Z + Jet differential cross sections;
  Top physics
  ... (Echo precision DIS phenomenology of the 1990's)

Top-EW WG

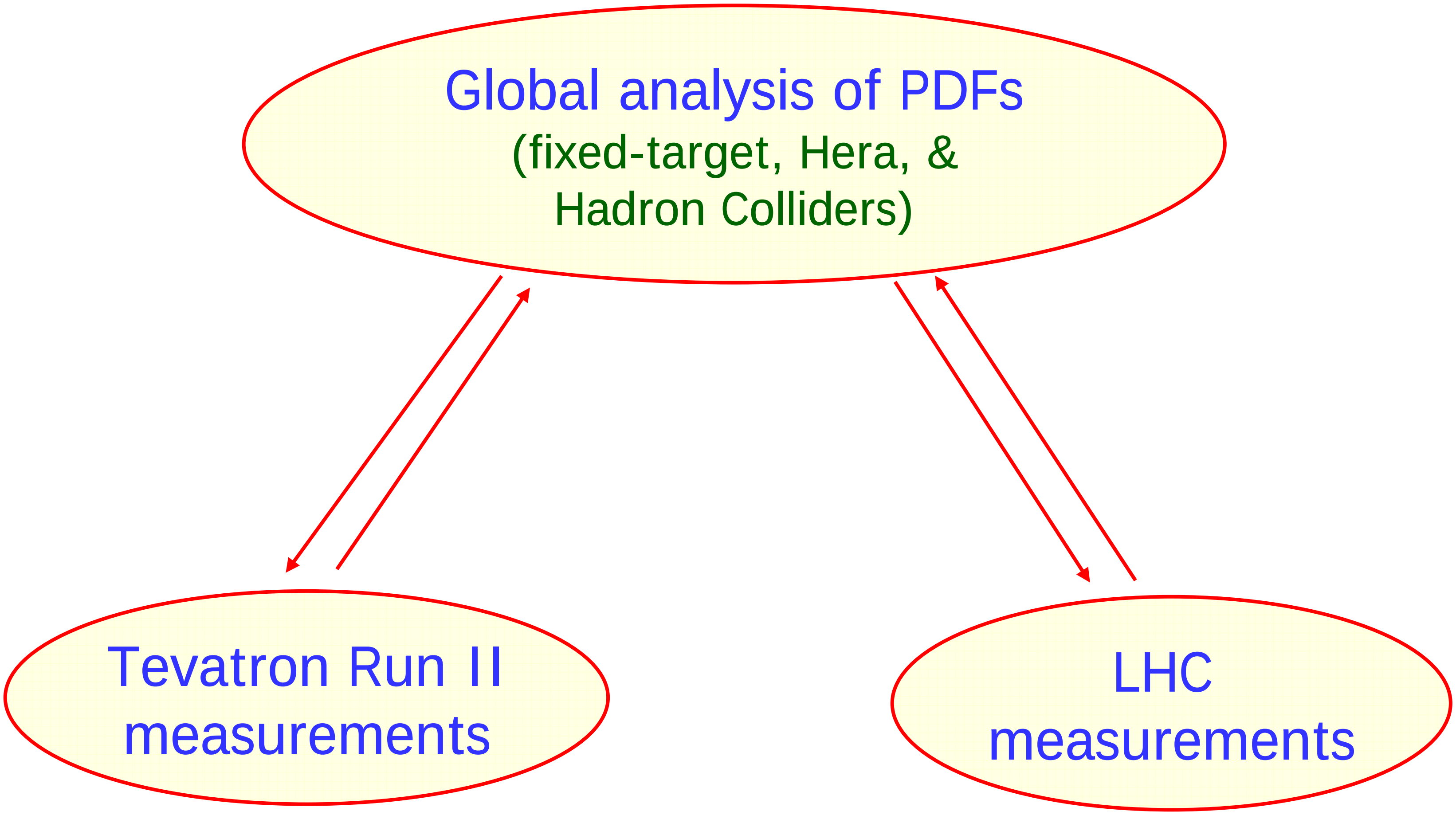
- Precision Top and Higgs Phenomenology (LHC):
  predictions and measurement of SM parameters.

Higgs WG

- Predictions on possible New Physics Discoveries:
  SUSY, Technicolor and other strong dynamics, Extra Dimensions ...

Landscape WG

PDFs, Tevatron and LHC



The precision phenomenology issues are intimately tied to:
How well do we understand the uncertainties of PDFs?

Uncertainties due to exptl input to the global analysis:

- Have been the focus of much work by several groups (exptl and theory); (Alekhin, GKK, H1, Zeus, Cteq, Mrst)
- Issues are complex; most recent, practical approaches are: (i) an iterative Hessian method (eigenvector solutions.); (ii) a Lagrange Multiplier method---developed by Stump, Pumplin etal (MSU/CTEQ) (adopted by Mrst)
- The main difficulty is not with the theory of statistical methods; rather it is with developing sensible ways to treat nominally incompatible experimental data sets used in the global analysis. ⇒ There are no rigorous answers; some subjective judgment must be involved. ⇒ differences in estimated uncertainties among groups.

Theoretical uncertainties (at small x and low Q):

(No less difficult to quantify. Studied empirically by varying kinematic cuts used in the global analysis.)

These issues were studied in CTEQ1,2 analyses. The stable cuts found then have been left unchanged since.

Recent study by MRST revived the interest on this issue, particularly because of its findings, that the cuts have an important impact on predictions for the PDFs, and their Tevatron Run II and LHC predictions.

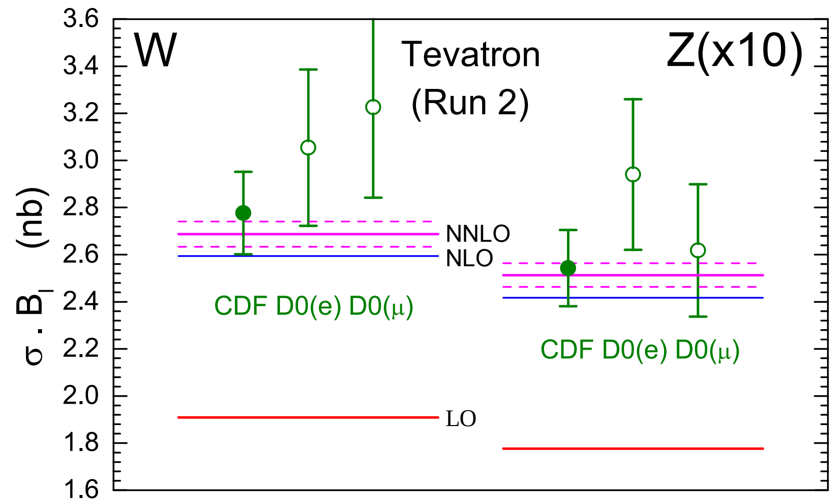
hep-ph/0308087

Important for Tevatron II and LHC physics:
Are these indications supported also by current CTEQ analysis?

(This recent study spear-headed by Joey Huston)

Standard Candle:

σ(W) and σ(Z) : precision predictions and measurements at Tevatron Run 2 and the LHC.



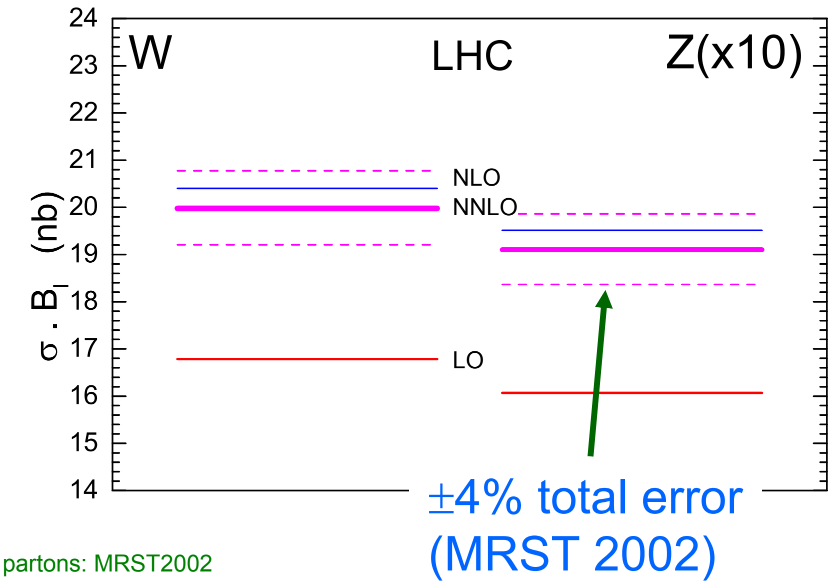
Exptl uncertainties:

LHC	$\sigma_{NLO}(W)$ (nb)
MRST2002	204 ± 4 (expt)
CTEQ6	205 ± 8 (expt)
Alekhin02	215 ± 6 (tot)

similar partons

different $\Delta\chi^2$

different partons

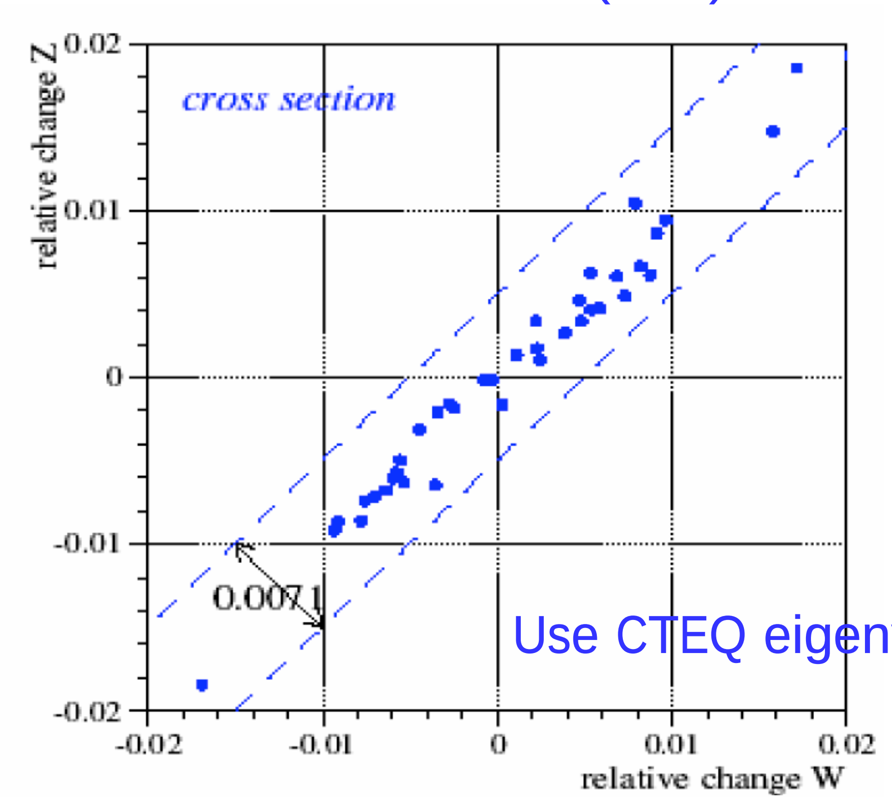


partons: MRST2002
NNLO evolution: van Neerven, Vogt approximation to Vermaseren et al. moments
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

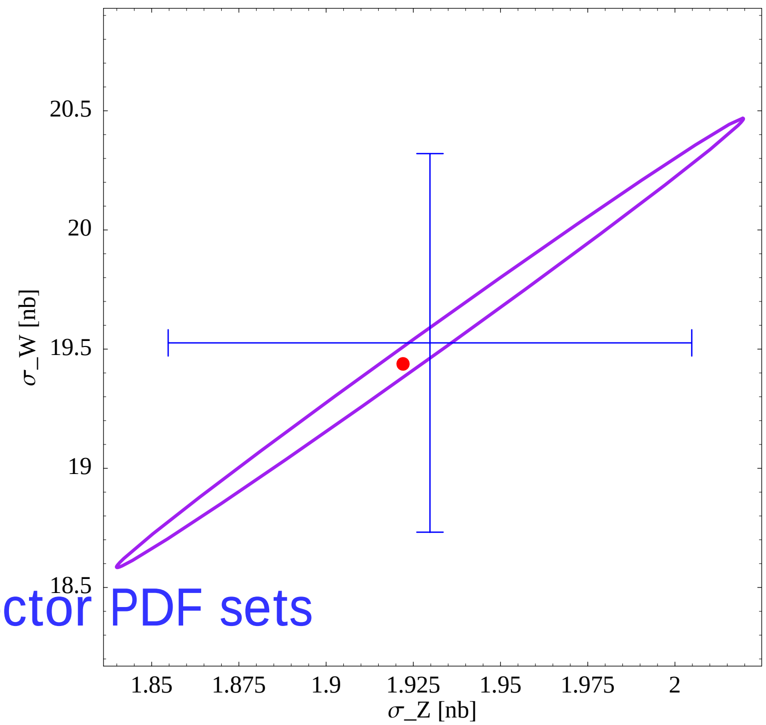
(Stirling, HeraLhc Workshop 2004)

σ_W and σ_Z ranges due to PDF uncertainties

Tevatron (CDF)



LHC (CTEQ)



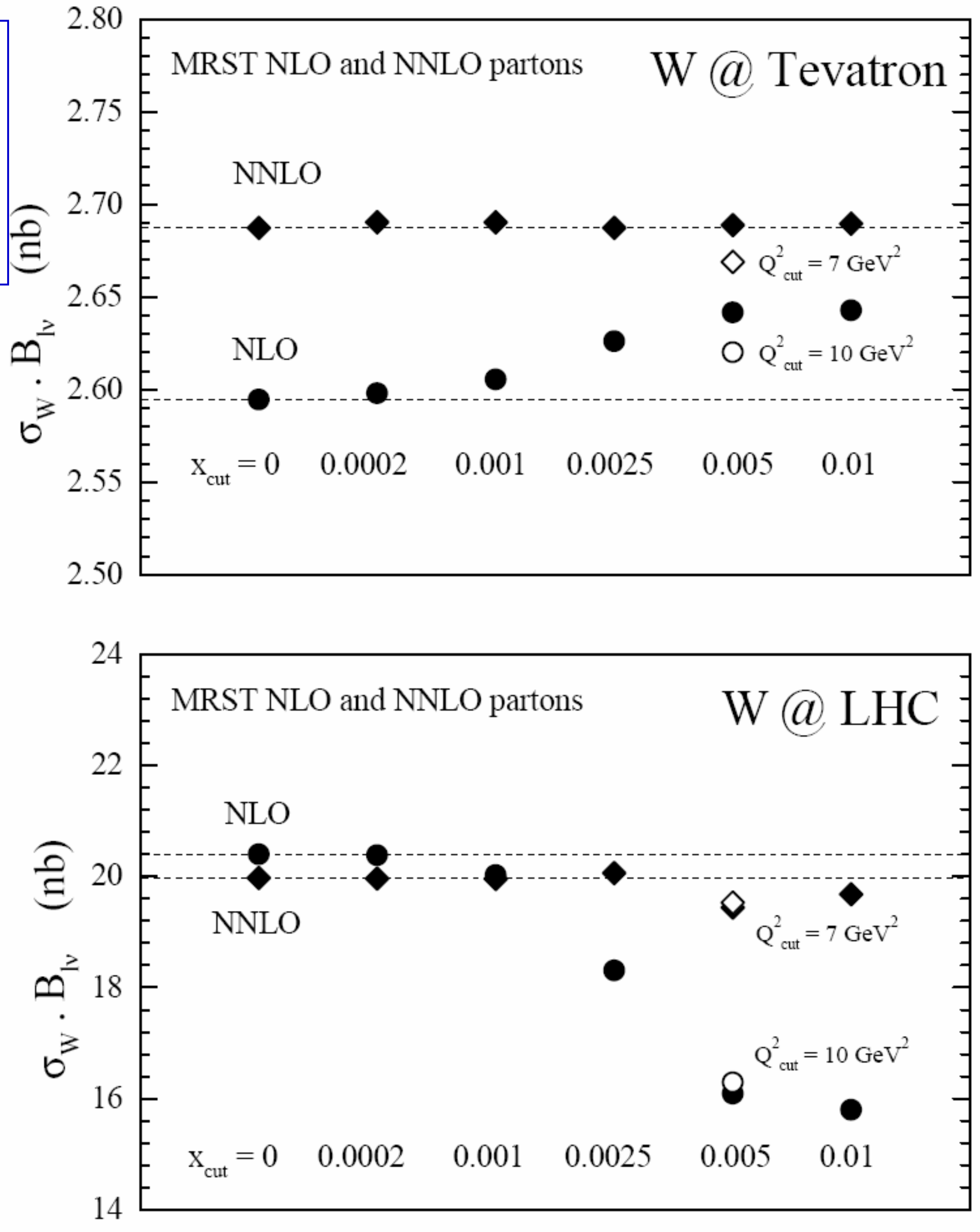
Use CTEQ eigenvector PDF sets

Error range: 2 – 5 %;

W-, Z- cross sections are highly correlated;

MRST "Theory" Uncertainty (varying cuts in global fits) (2003)

Alarm bell?
Instability at NLO !

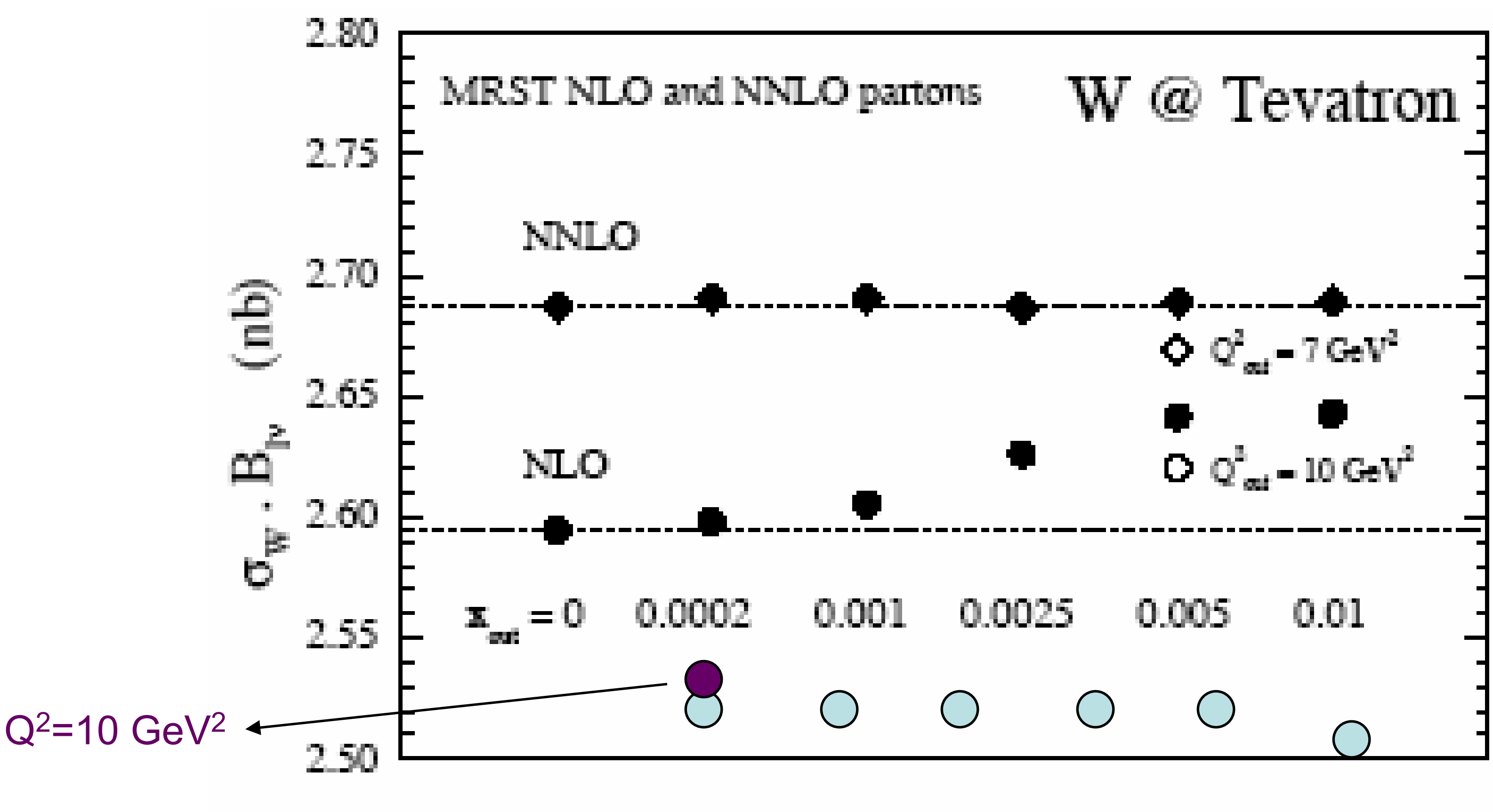


Are these findings disturbing?

- Are theory uncertainties really so large at NLO–so much larger than NNLO corrections at LHC?
- Is stability reached *only* at NNLO?

CTEQ studied this issue ...

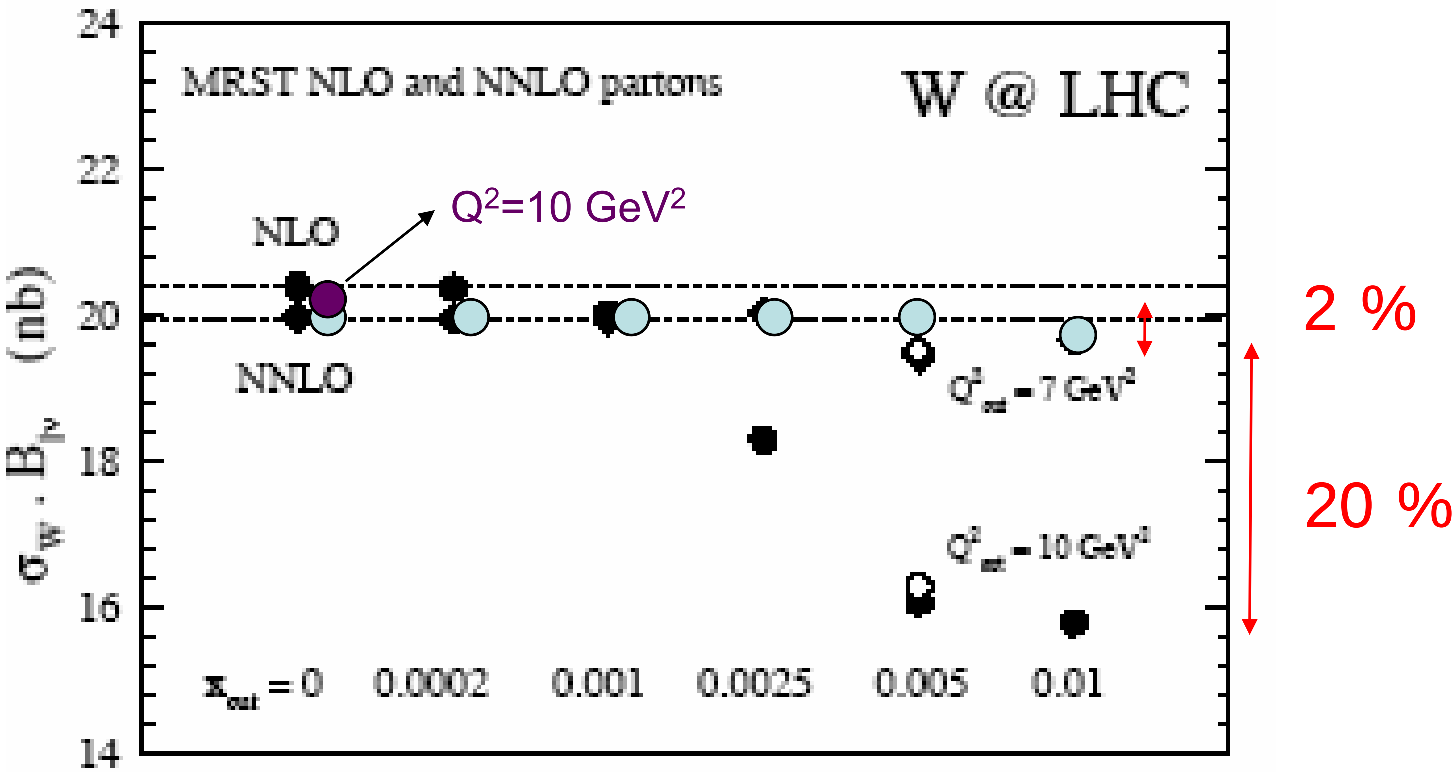
σ_W at the Tevatron



○ shows the results of applying x cuts to the CTEQ6 data set and performing a NLO fit

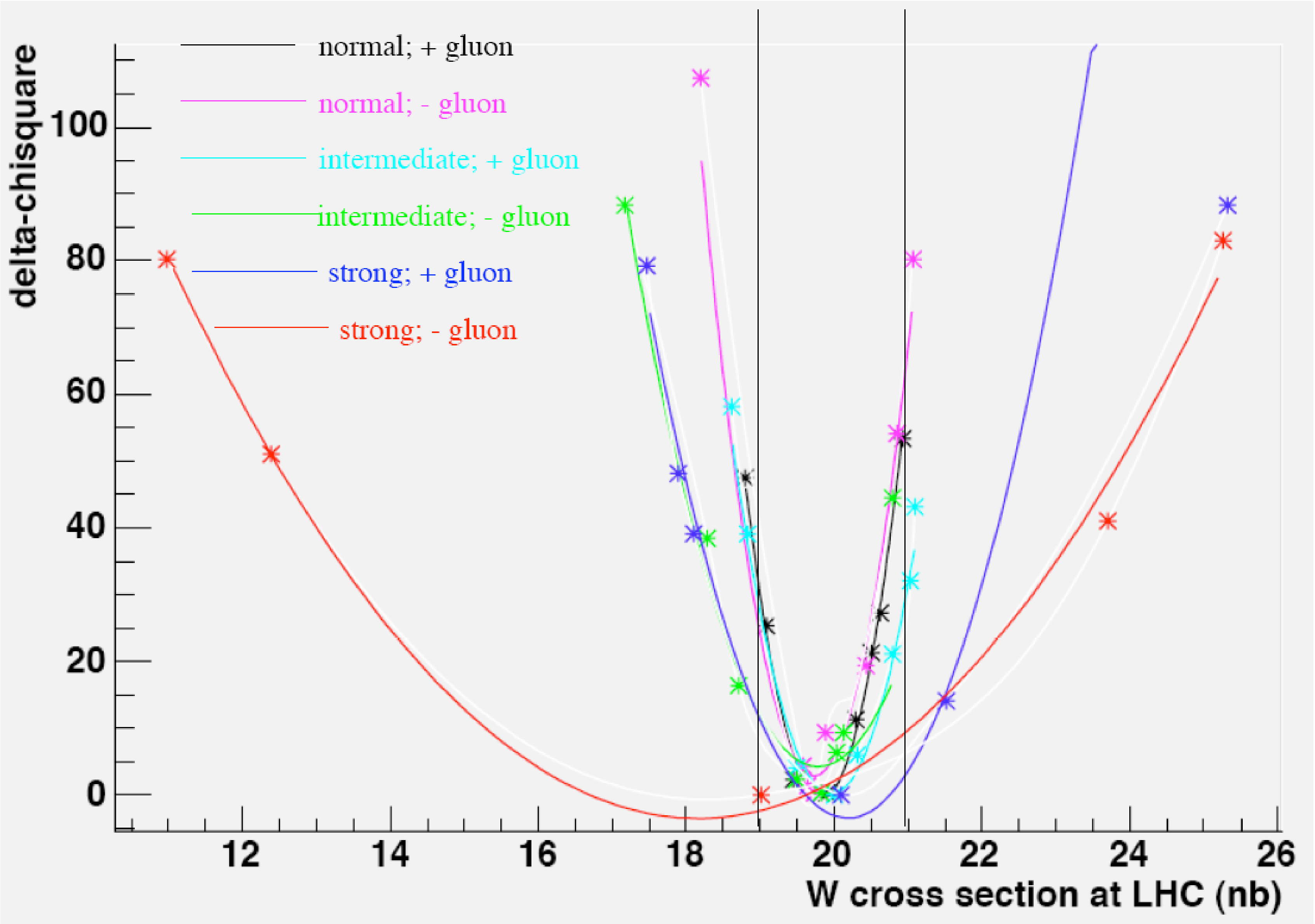
No significant instability found in the CTEQ NLO analysis. (Huston)

W total cross section at the LHC



○ shows the results of applying x cuts to the CTEQ6 data set and performing a NLO fit.

We found that NLO σ_W is quite stable w.r.t. "theory uncertainties". Aside from an overall k-fac of ~1.04, NNLO is not needed to lend stability to the calculations.

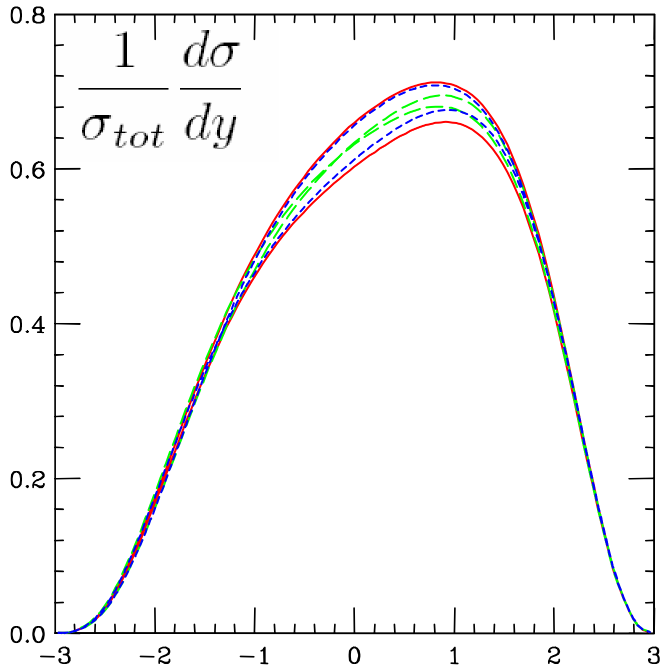


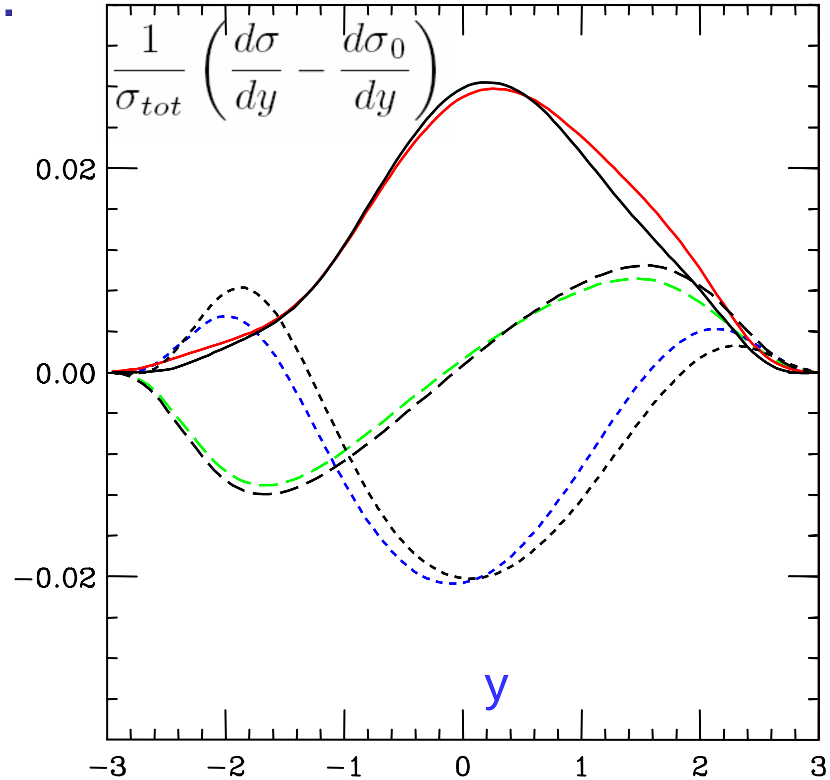
normal; + gluon
normal; - gluon
intermediate; + gluon
intermediate; - gluon
strong; + gluon
strong; - gluon
delta-chisquare
0
20
40
60
80
100
12
14
16
18
20
22
24
26
W cross section at LHC (nb)

Precision PQCD phenomenology:
W rapidity distribution at the Tevatron

- Uniquely sensitive to x-dependence of d(x)/u(x)
(Can be important for precision W-mass measurement);
- Have been studied systematically by both the Hessian and the Lagrange methods (CTEQ).

Range of uncertainty





Hessian and Lagrange methods yield the same results.

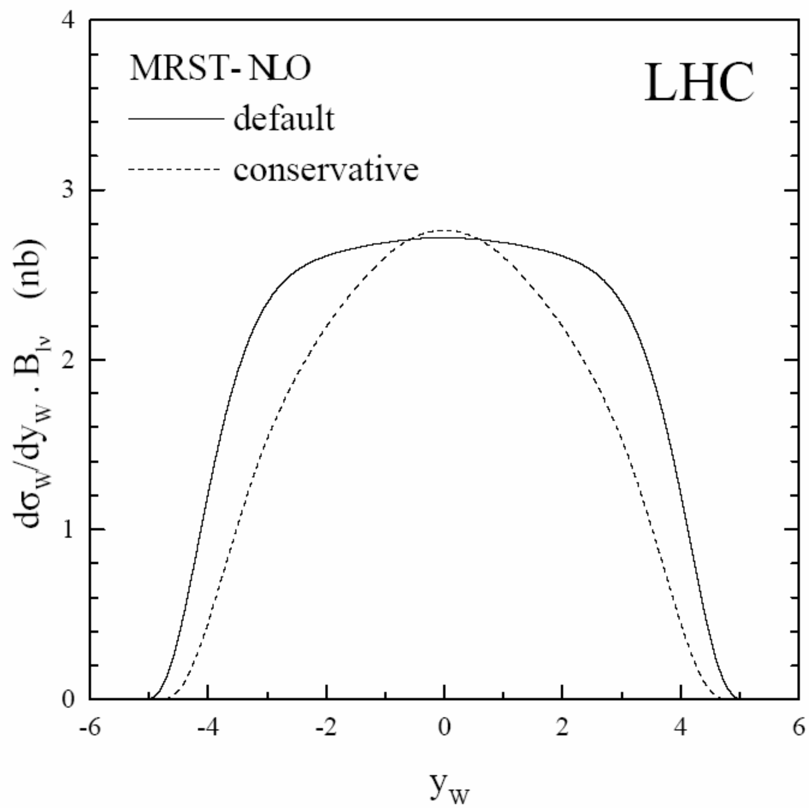
Precision PQCD phenomenology: W rapidity distribution at LHC

NLO instability again?

Comparison of prediction for $(d\sigma_W/dy_W)$ for the standard MRST partons and the conservative set. The reduction in the total cross-section in the latter case is clearly due to the huge reduction at high y_W and represents the possible type of theoretical uncertainty in this region when working at NLO.

Note a slight increase in cross-section for $y_W = 0$ $(x = 0.006)$. Due to increased evolution of quarks here.

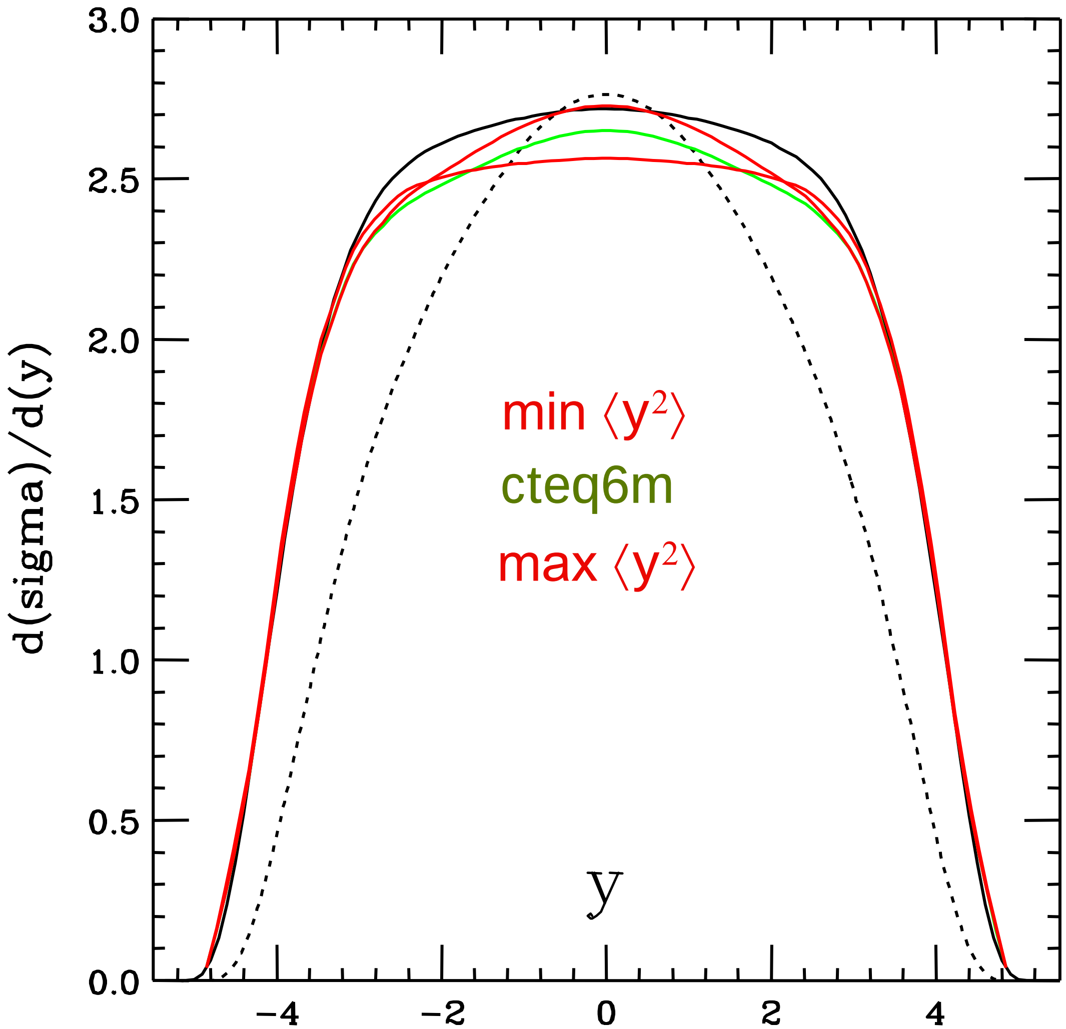
(Thorne Hera-Lhc Workshop)



Questions: (i) Is the conservative set better (more reliable) than the standard set? (ii) Again, is NLO QCD predictions so unstable w.r.t. cuts in global analysis?

CTEQ study of the W rapidity distribution at LHC (Pumplin)

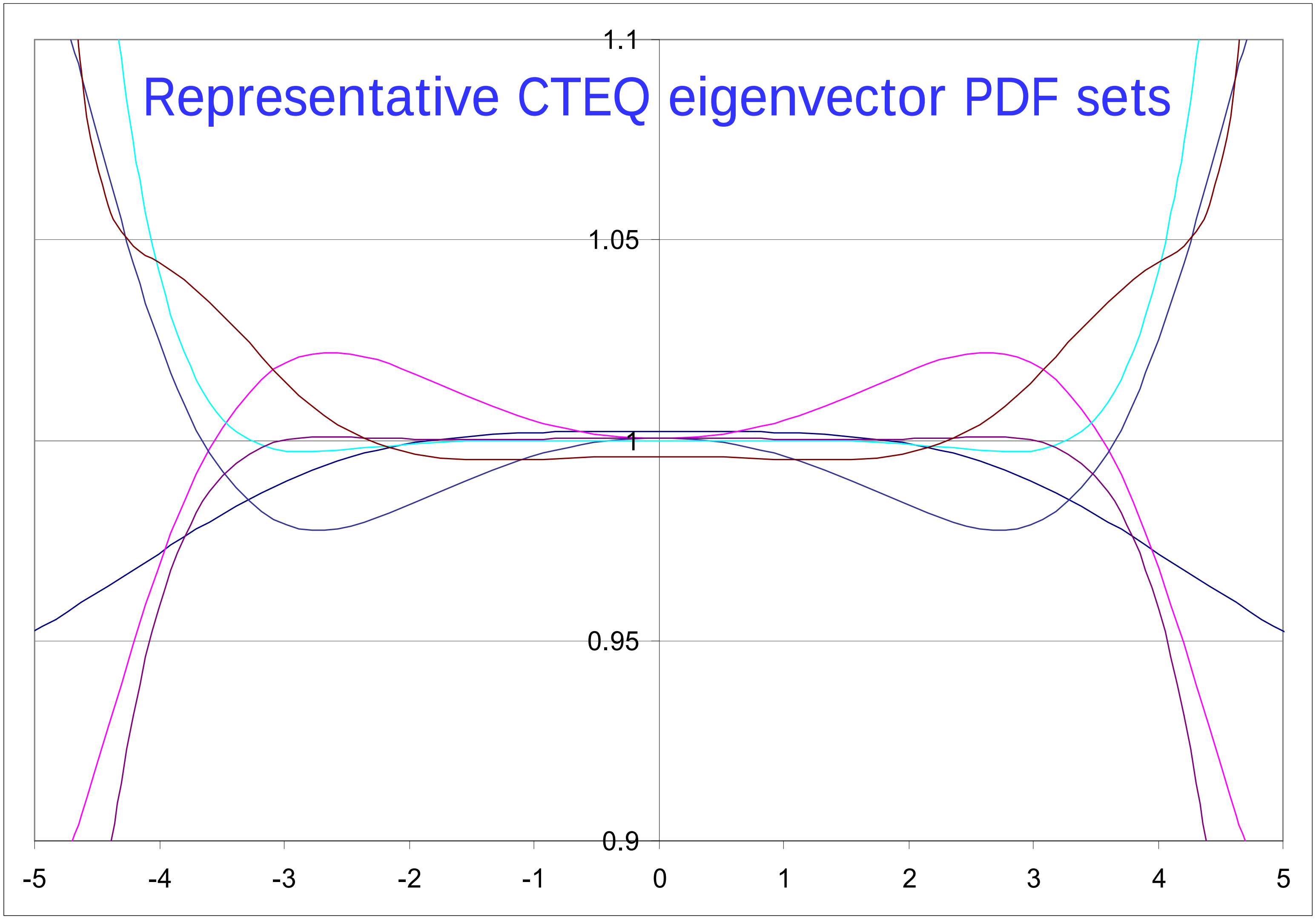
- Search in the parton parameter space, using eigenvector solutions in the improved Hessian approach, to probe the extremes in predicted shape–max/min $\langle y^2 \rangle$.



Surely experiment can tell the differences!?

"Yes, within the first 5 minutes at LHC." -- Joey Huston

$\sigma(y)_{W+} / \sigma(y)_{W-}$ at LHC



(True uncertainties are bigger, especially at large y)

What can HCP contribute to Global QCD Analysis of nuclear structure (i.e. PDFs)

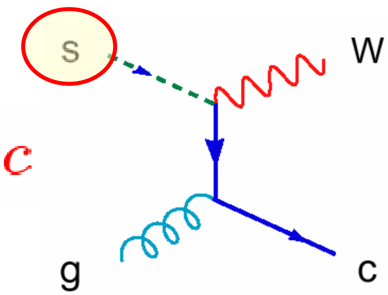
- In general: next generation of colliders are W/Z factories; many processes can provide new information on PDFs.
- More specifically:
  - Many gluon-sensitive processes can help narrow the large uncertainties on $g(x,Q_0)$;
  - W/Z rapidity distributions, $R(W_+/W_-)$, … can provide needed information on SU(2) flavor dependence of partons;
  - New channels to study heavy quark distributions.

- All these can have significant feedback on precision measurement of m_W, and top, Higgs parameters.

Probing the Sea Quark PDFs: s, c, b using tagged final states $W/Z/\gamma + c/b$?

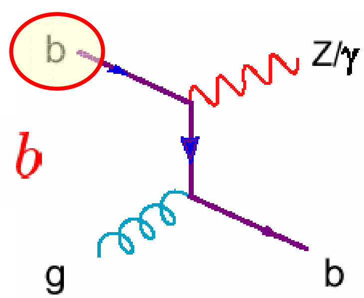
$s(x, Q)$:

$g + s \rightarrow W + c$



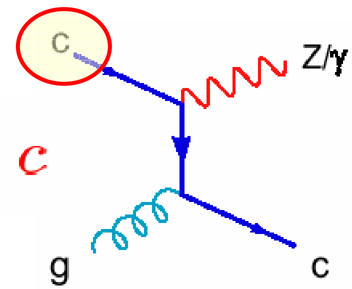
$b(x, Q)$:

$g + b \rightarrow Z/\gamma + b$

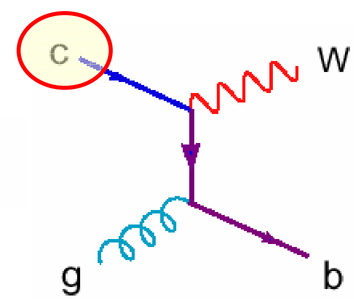


$c(x, Q)$:

$g + c \rightarrow Z/\gamma + c$

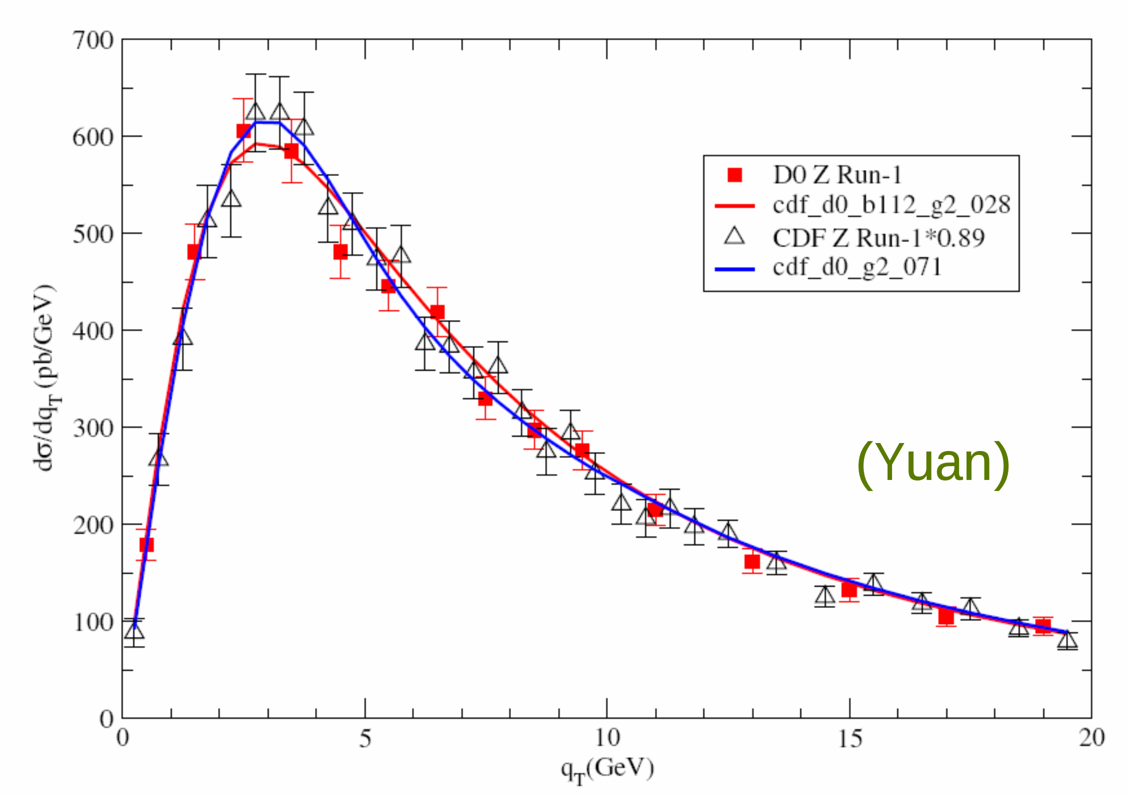


$g + c \rightarrow W + b$



P_T distribution and resumed PQCD

Cf. Nadolsky talk



- Resummation essential — a new frontier in precision PQCD phenomenology;
- Sensitivity to PDFs has not yet been studied in any systematic way;
- Important for pinning down Δm_W due to PDFs —a major source of m_W measurement error.

Non-perturbative parameters in the Sudakov exponent factor can be studied in combined fits to collider W/Z and lower energy DY data.

Systematic study of sensitivities of W/Z p_t distributions to PDF and non-perturbative parameters uncertainties is now underway.

Top Cross section at the Tevatron

M. Cacciari, S. Frixione, M.L. Mangano, P. Nason , G. Ridolfi

CTEQ PDF uncertainties

$\sqrt{S}$	m_{top}	σ_{min}	$\sigma_{ref}(\mathbf{6M})$	σ_{max}
1800	170	5.29	6.10	6.63
1800	175	4.51	5.19	5.64
1800	180	3.85	4.43	4.81
1960	170	6.79	7.83	8.54
1960	175	5.82	6.70	7.30
1960	180	5.00	5.75	6.25

MRST PDF uncertainties

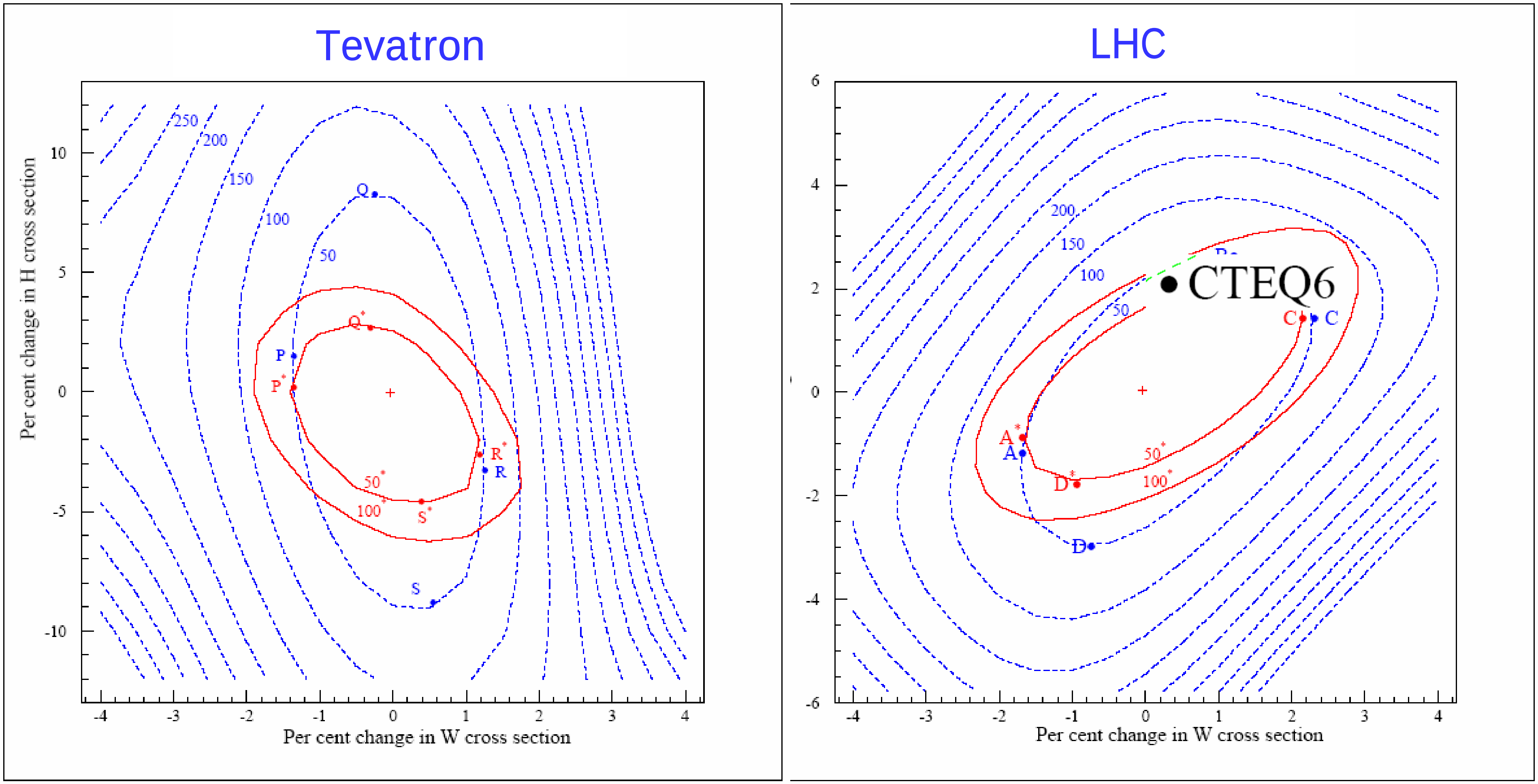
$\sqrt{S}$	m_{top}	σ_{min}	$\sigma_{ref}(\mathbf{0})$	σ_{max}
1800	170	5.52	6.13	6.44
1800	175	4.69	5.21	5.47
1800	180	4.00	4.44	4.67
1960	170	7.11	7.90	8.31
1960	175	6.08	6.76	7.10
1960	180	5.21	5.79	6.08

MRST PDF uncertainties
+ scale dependence

$\sqrt{S}$	m_{top}	$\sigma_{min}\ (r_\mu = 2,\ \mathbf{A01L})$	$\sigma_{ref}(r_\mu = 1,\ \mathbf{0})$	$\sigma_{max}\ (r_\mu = 0.5,\ \mathbf{J01})$
1800	170	5.48	6.13	6.72
1800	175	4.66	5.21	5.71
1800	180	3.98	4.44	4.86
1960	170	7.04	7.90	8.69
1960	175	6.03	6.76	7.41
1960	180	5.17	5.79	6.34

Higgs Physics

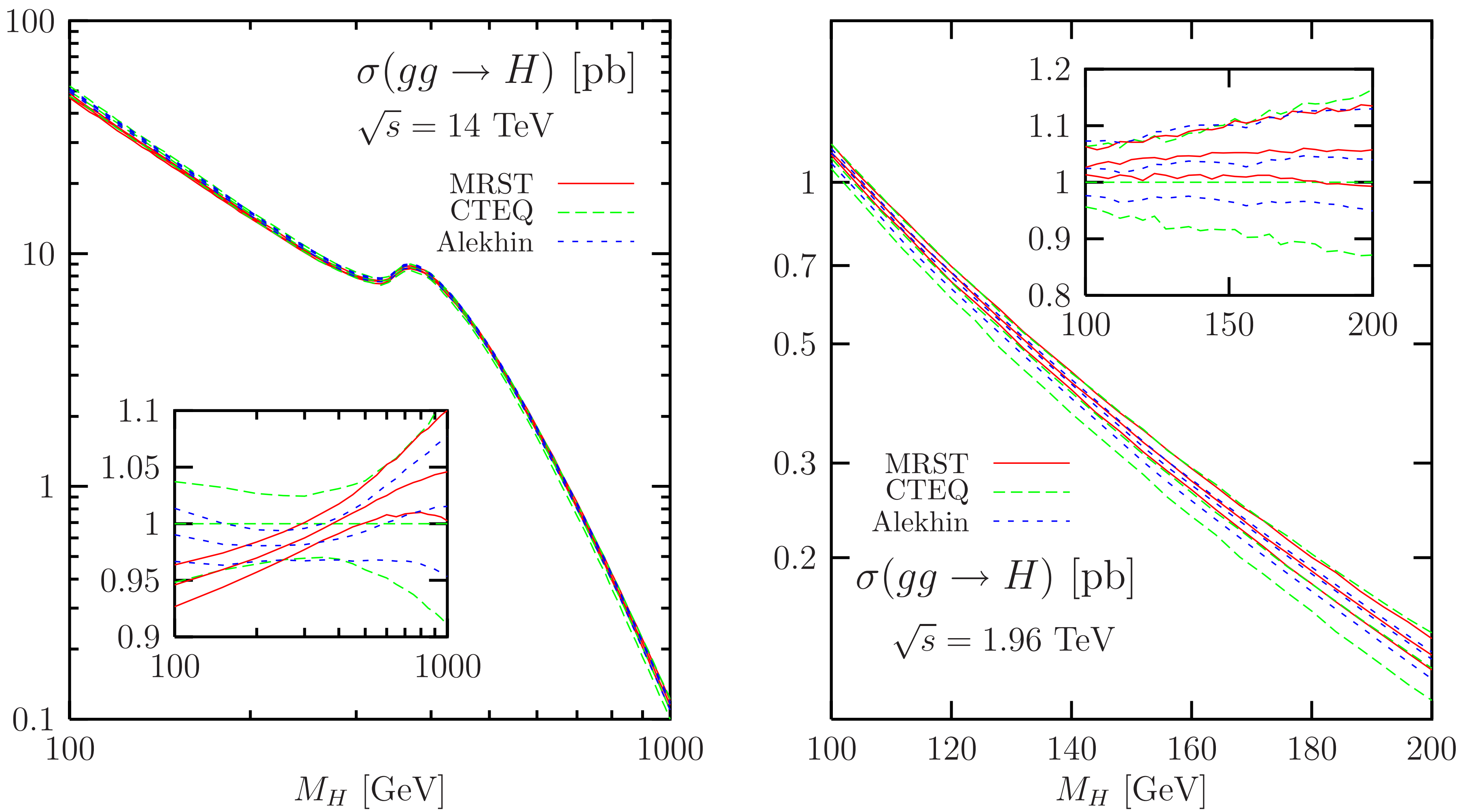
Contour plots of χ^2 in the σ_H-σ_W plane MRST



χ^2-plots for W and Higgs (120GeV) production at the Tevatron and LHC α_S free (blue) and fixed (red) at $\alpha_S = 0.119$.

Higgs Physics at the Tevatron and LHC

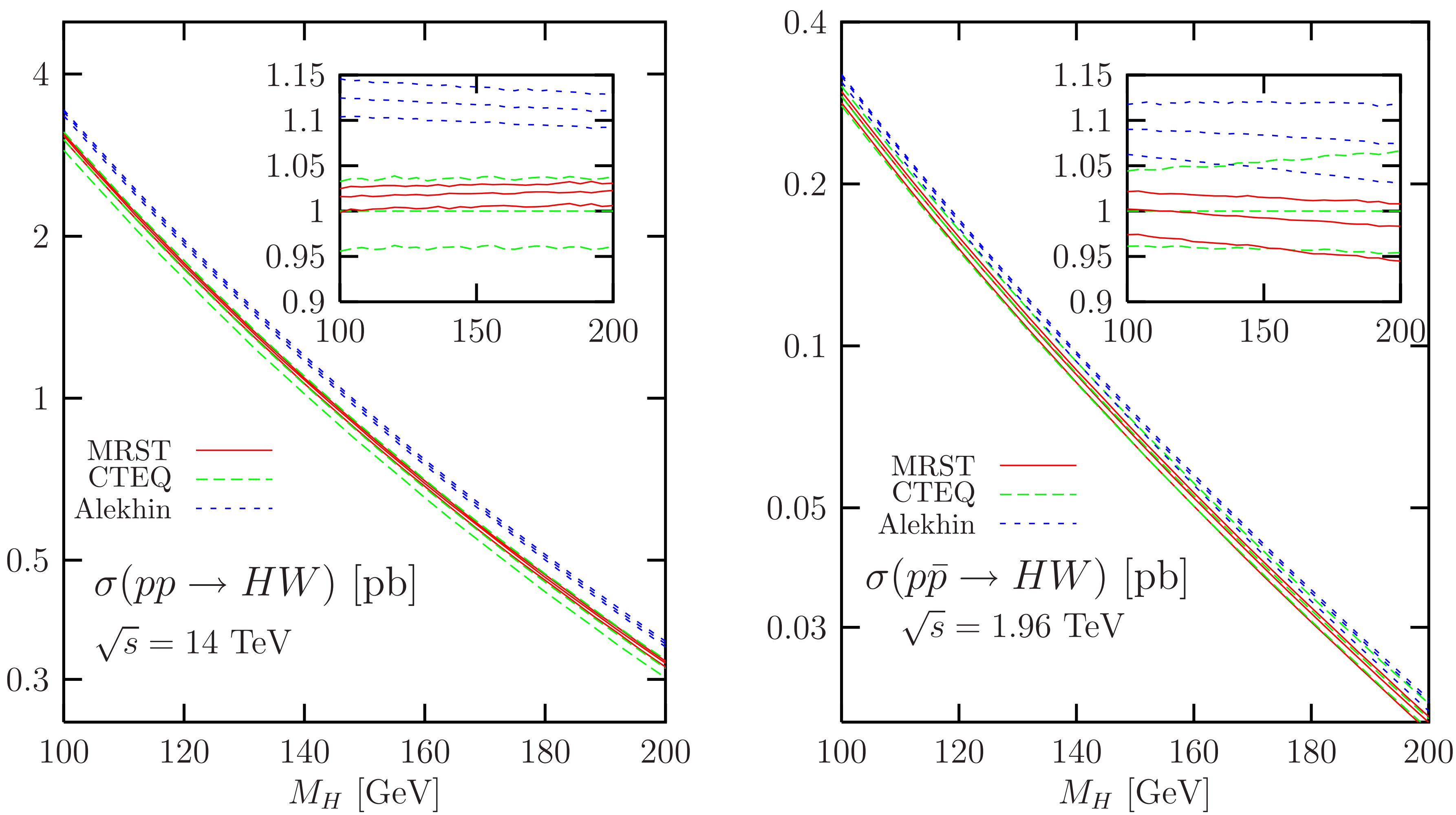
- Uncertainties due to PDFs for $gg \to H$



Djouadi & Ferrag, hep-ph/0310209

Higgs Physics at the Tevatron and LHC

• Uncertainties due to PDFs for *pp → H W*



Djouadi & Ferrag, hep-ph/0310209

Two FAQs deliberately left out of this talk:

- Can we calculate "1-σ errors" on our measurement due to PDF uncertainties?
  More specifically, do the CTEQ 40 sets of eigenvector PDFs yield 1-σ errors?

No. (to both questions)

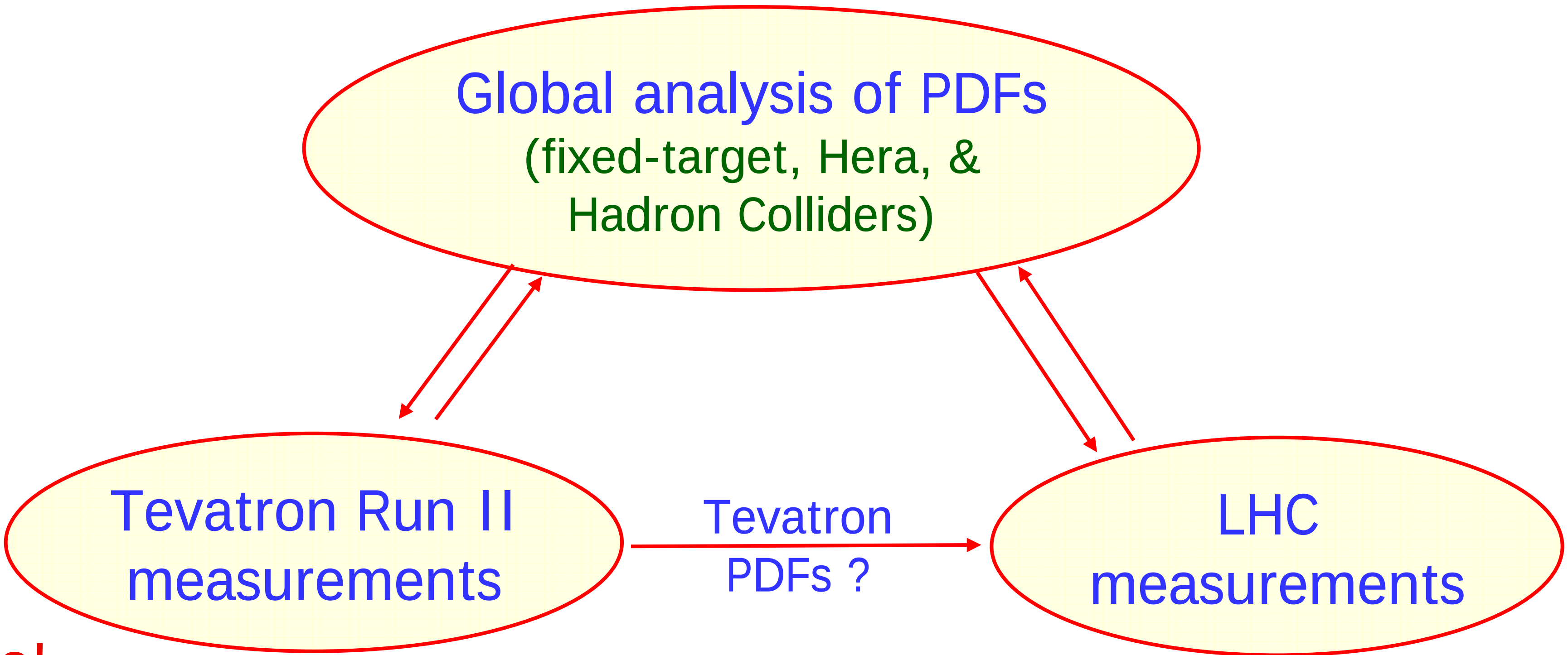
Why? Need another talk to explain.

- How do we produce "Tevatron-only" PDFs, to be used at LHC?

What for? To reduce systematic errors ("collider only")?

Question does not make much sense; but ...

Tevatron PDFs for LHC ?



No!

PDFs are *universal*; *true* PDFs must fit data for *all* processes.

However, Correlation between Tevatron and LHC measurements *can* be studied *in the global QCD analysis context*, e.g. by using the CTEQ Hessian and Lagrange Multiplier methods, with suitable emphasis factors.

Uncertainties of PDFs and their Physical Predictions---propagation of exptl errors

- The statistical principles and methods for uncertainty analyses are well established in principle: Likelihood, χ^2, … etc.---all textbook stuff.
- The real world of Global Analysis is, however, imperfect and rather more complex:
  - Unknown *theoretical uncertainties*;
  - Un-understood experimental *inconsistencies—unknown underlying sources of uncertainties.*

  – matters that textbook recipes are inadequate!
- To face this reality, and make progress, physics judgments (subjectivity) and development of *effective and flexible* statistical analysis tools are *required*.

Reality : compatibility of experiments

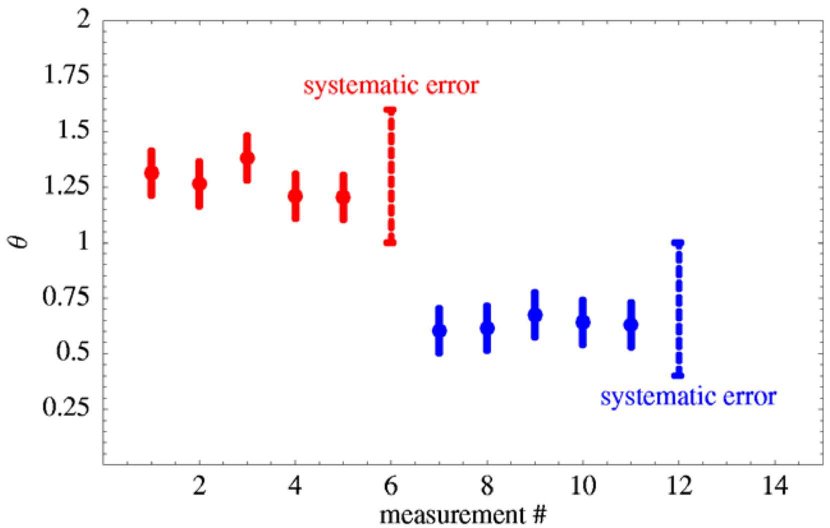
	H1	BCDMS	E665	ZEUS	NMC	LEP
H1-MRST set	-	67%	21%	0.5%	<0.1%	31%
BCDMS-MRST set	85%	-	23%	1.5%	<0.1%	0.5%
E665-MRST set	30%	82%	-	1.6%	1.0%	99%
ZEUS-MRST set	22%	<0.1%	5.0%	-	<0.1%	24%
NMC-MRST set	<0.1%	28%	1.5%	<0.1%	-	3.2%

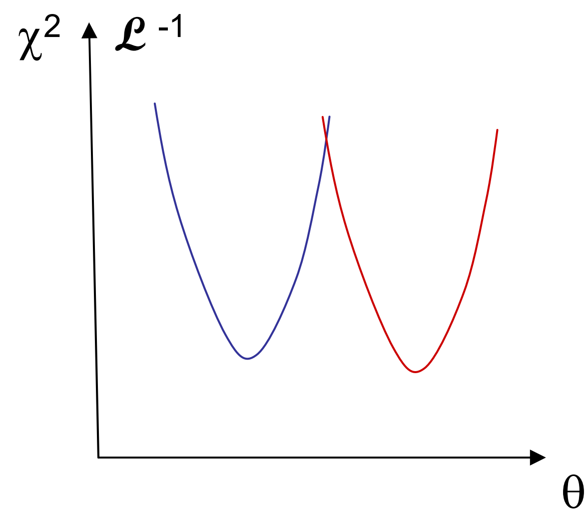
Table 2: The confidence level of each experiment given the different sets. The name of the set is composed of all included experiments and the PDF parameterization choice.

(Giele etal, 2001)

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

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





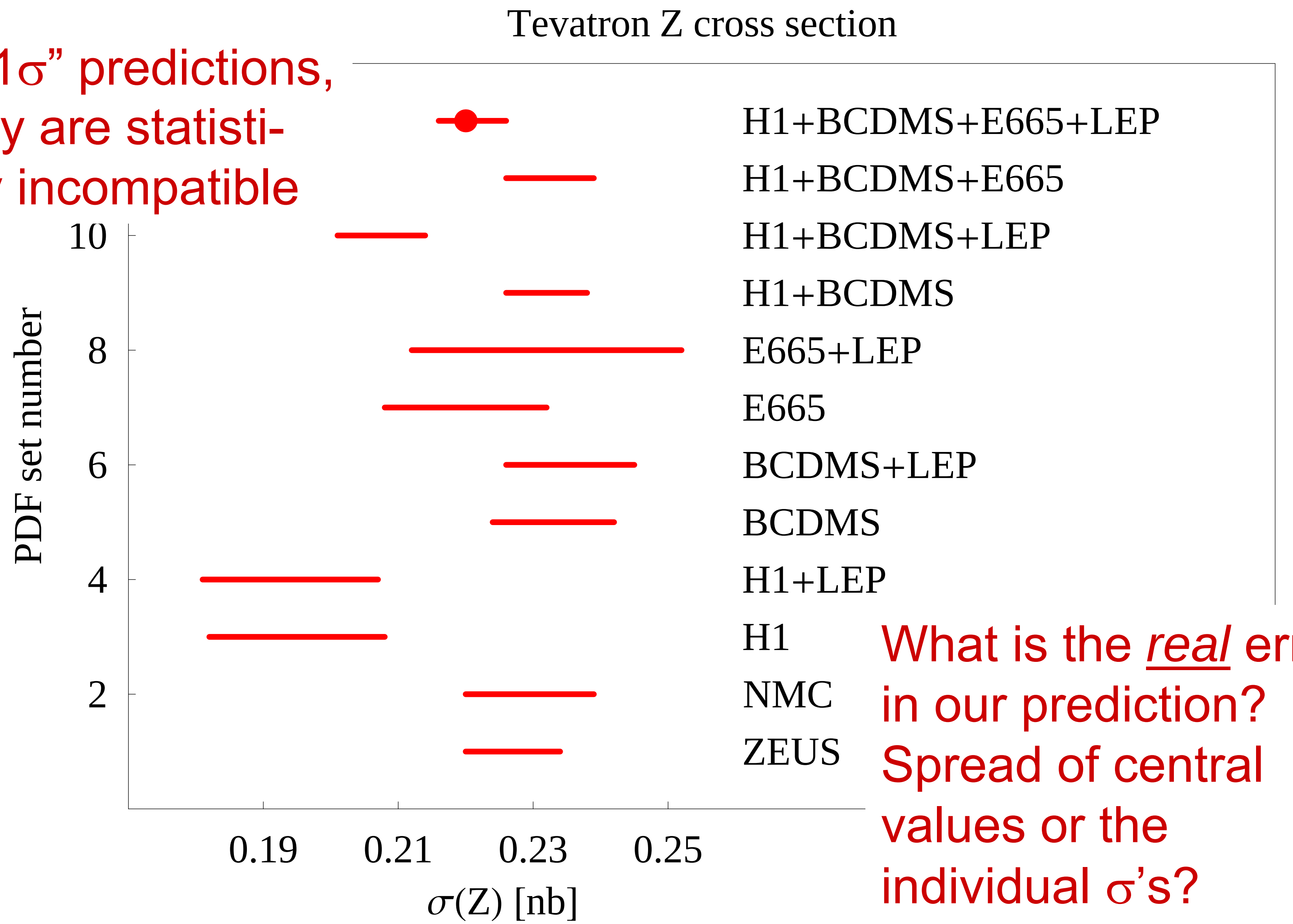
What is the value of θ?   What do confidence levels mean?

Is it possible to fit **any** parameters with "**1-σ error**"? NO!

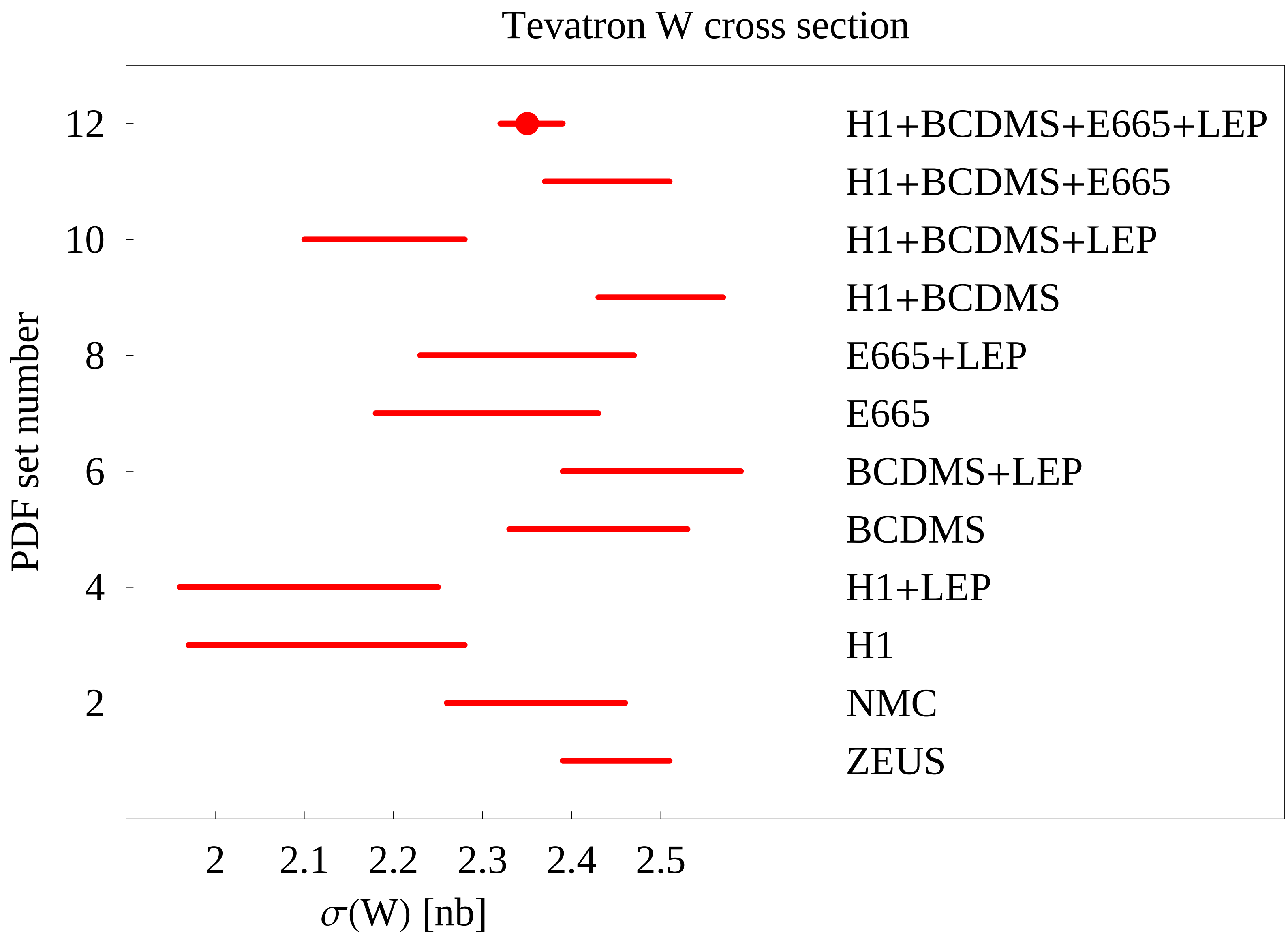
Natural question: Are all experimental errors understood?
Should the errors always be taken at face value? (Old)

Illustration: Prediction of W,Z Xsec. (GKK)

12 "1σ" predictions, many are statistically incompatible

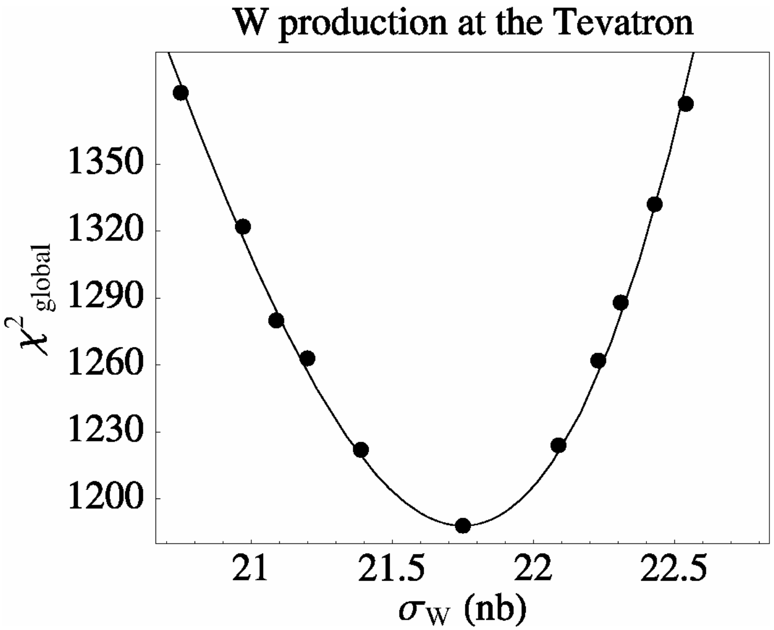


What is the *real* error in our prediction? Spread of central values or the individual σ's?

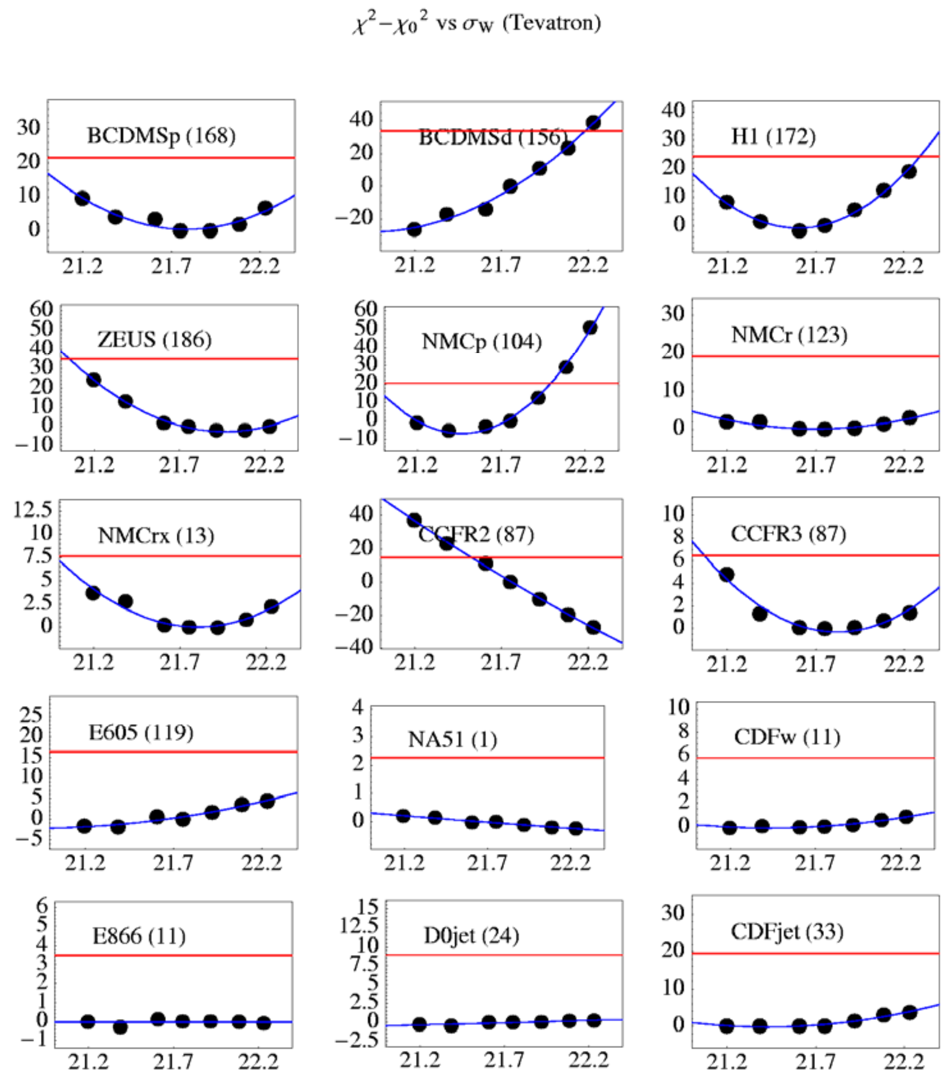

Tevatron W cross section
PDF set number
12
10
8
6
4
2
2
2.1
2.2
2.3
2.4
2.5
σ(W) [nb]
H1+BCDMS+E665+LEP
H1+BCDMS+E665
H1+BCDMS+LEP
H1+BCDMS
E665+LEP
E665
BCDMS+LEP
BCDMS
H1+LEP
H1
NMC
ZEUS

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

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



global χ^2

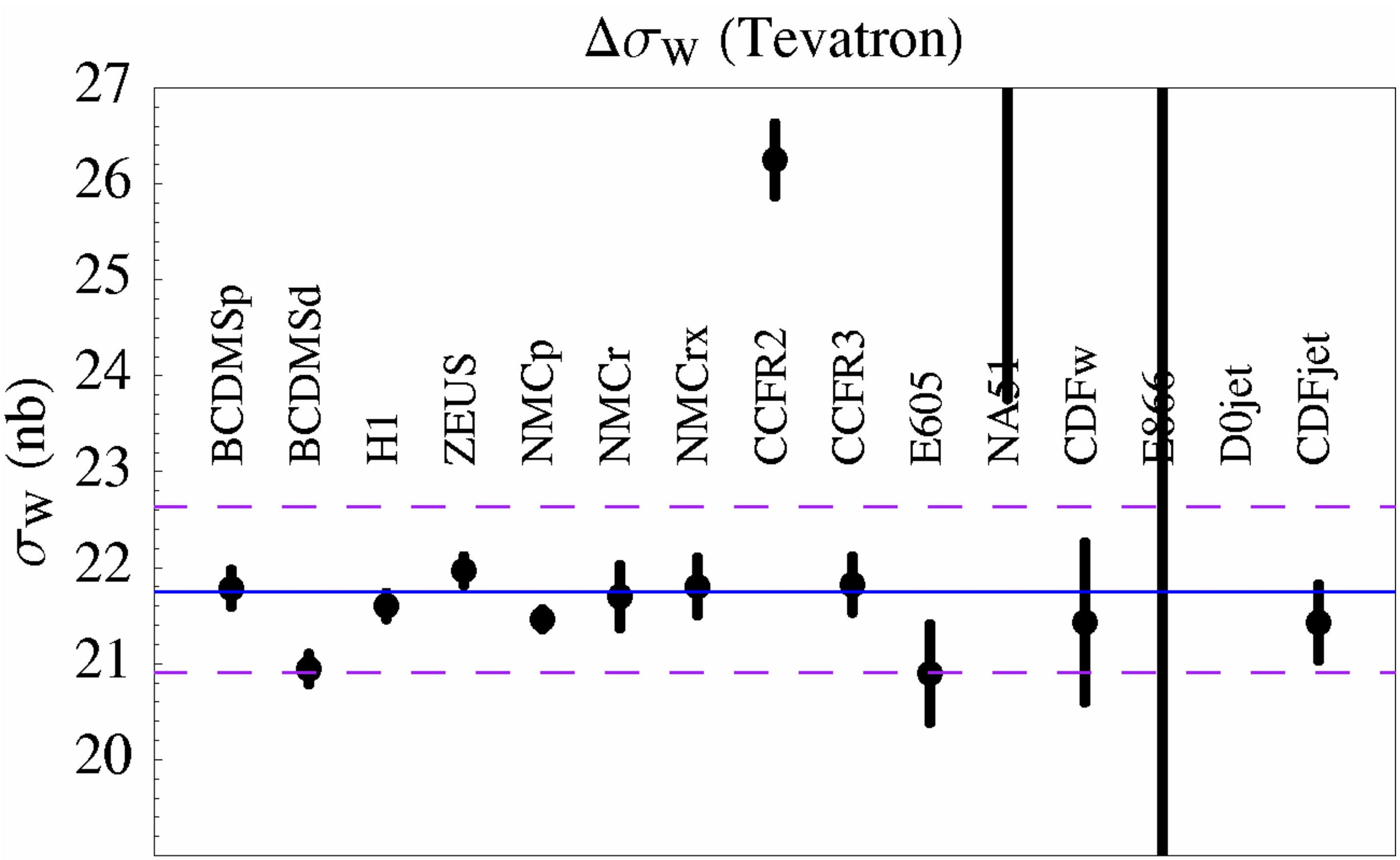


local χ^2's

Examine the quality of fit to individual experiments:

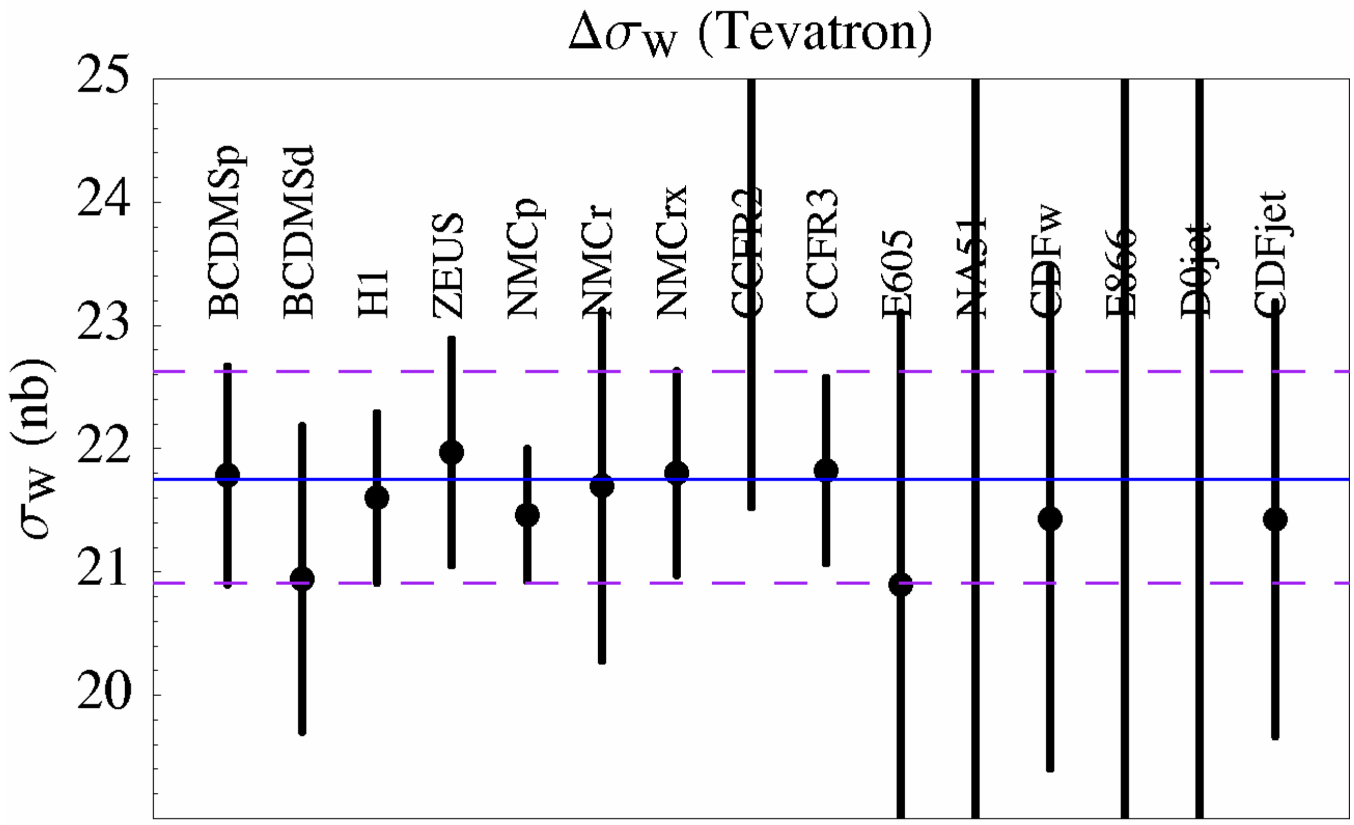
Each experiment defines a central value and a range.

This figure shows the $\Delta\chi^2 = 1$ ranges.



Is $\Delta\chi^2 = 1$ the appropriate criterion?

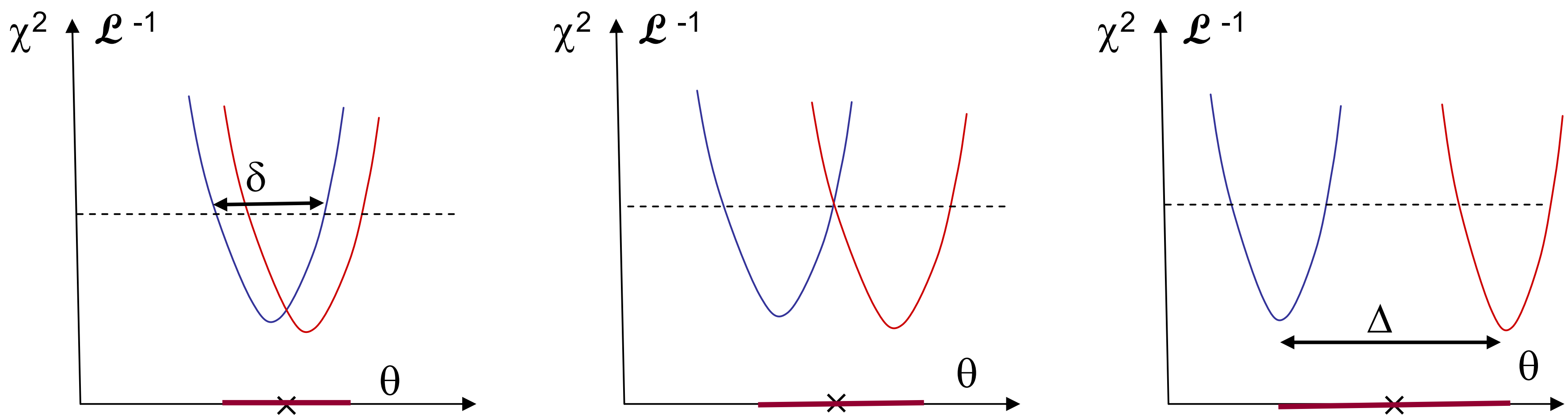
Alternatively, this figure shows broader ranges for each experiment based on the "90% confidence level" (cumulative distribution function of the rescaled χ^2).



Now we see the possibility of a consensus central value and a "90% confidence level" range of predictions.

"Uncertainties" in 3 scenarios (all which occur in the real global analysis world)

(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, such as in the last page, 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", $\Delta\chi^2$

Where do we stand?

My take …

- The important issue is not about methodology: all textbook methods are equivalent in the ideal world of perfect measurements and theory;

- 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.

Examples of such practical tools

- The improved Hessian method: iterative method to diagonalize the Hessian matrix and generate stable, physically meaningful error ranges;
- The Lagrange multiplier method to make robust estimates of uncertainties of individual parameters and predicted physical quantities;
- Alternative Hessian methods to study the compatibility between experiments and answer specific questions such as how many parameters (and which ones) are significantly constrained by a give experimental set or sets.

(Jon Pumplin, Hera-LHC workshop)