

Global QCD Analysis and Hadron Collider Physics

The role of QCD, and global QCD analysis in Hadron Collider Physics

Global QCD analysis:

- **Progress:** how far have we come along?
- **Open Issues:** how far do we have to go?
 - Experimental and theoretical uncertainties
 - Gluon; flavor SU(2) structure
 - Strangeness and heavy quark structure

What can global QCD analysis do for hadron collider physics?

- Standard Candle processes
- Precision W/Z/jet phenomenology
- Precision Top/Higgs phenomenology
- Predictions on New Physics processes

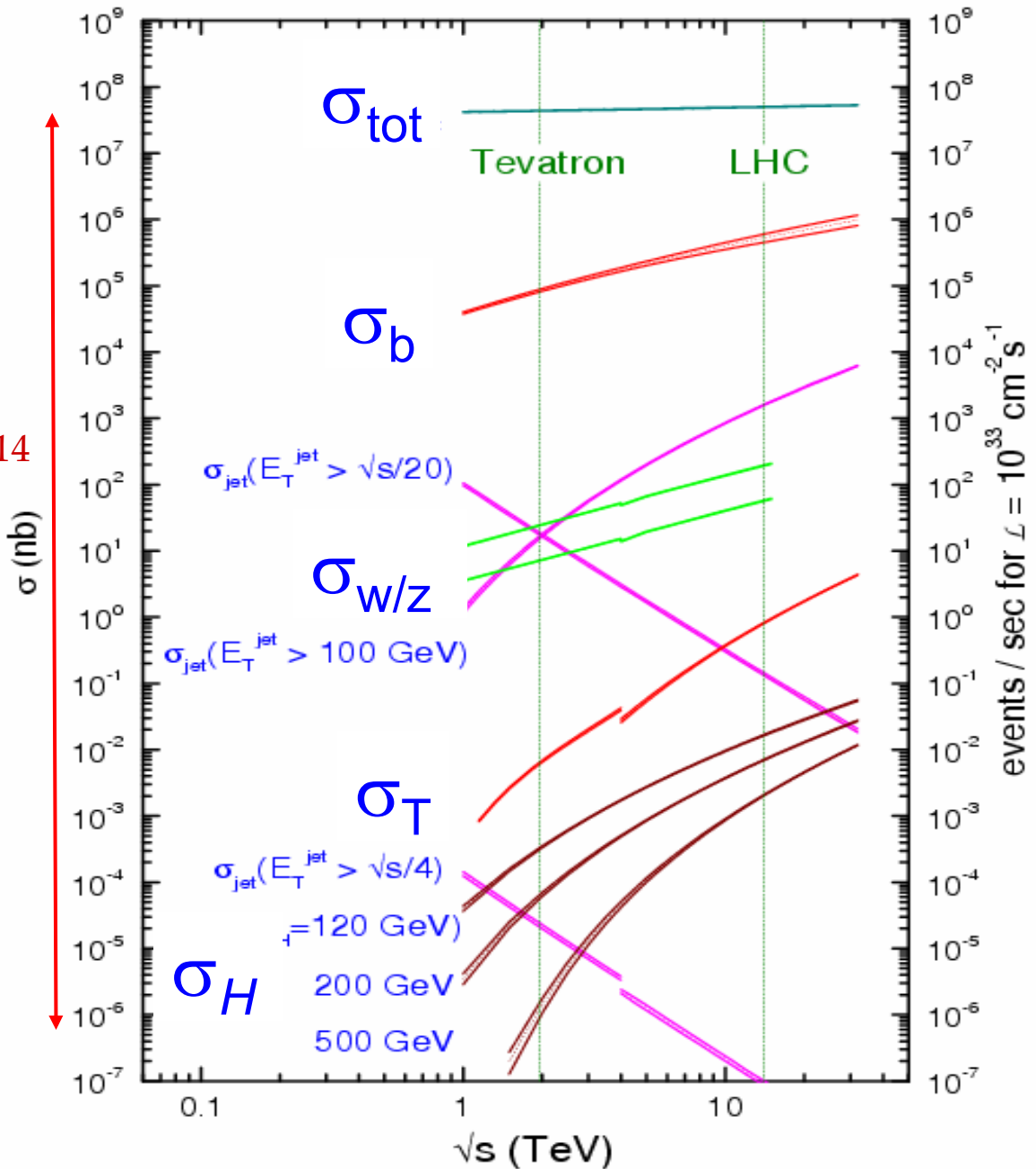
How can hadron collider physics contribute to global QCD analysis of nucleon structure?

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”.

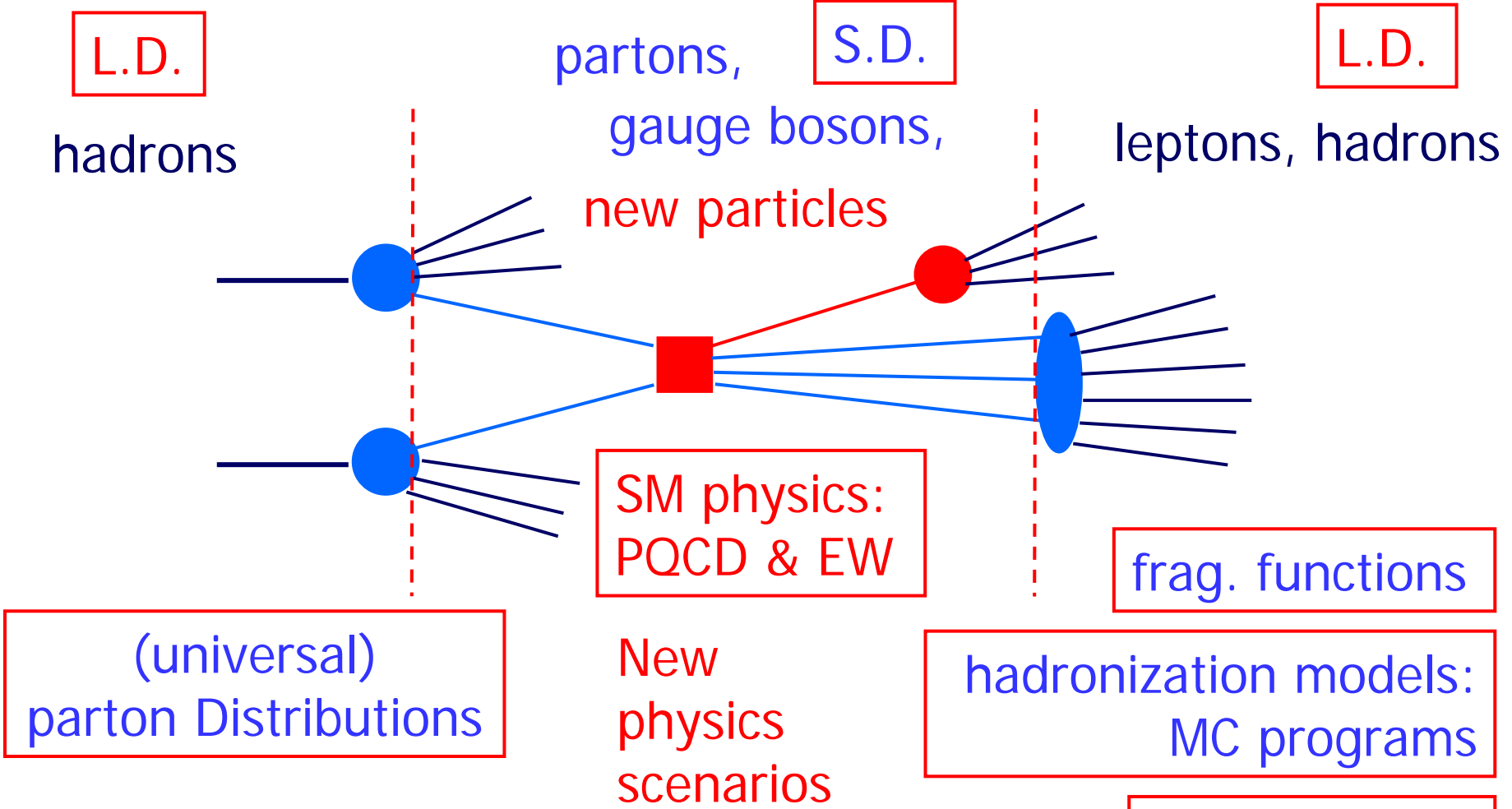
$\sim 10^{14}$

proton - (anti)proton cross sections



The many faces of QCD in Hadron Collider Physics

Asymptotic Freedom and Factorization of QCD:



QCD enters in all aspects of HCP (red boxes).

Significant Recent Progress in PQCD Physics

Quantitative (NLO) treatment of general processes:

- Systematic NLO Calculation of Multi-particle ($W/Z, \gamma, \text{jets}$) final states;
 - Development of NLO MC event generators;
 - Better understanding of heavy quark production and decay;
-

Precision (NNLO) Study of critical processes:

- Evolution kernel ;
 - $Z, W, \gamma, \text{rapidity distributions}$;
 - Higgs production;
-

Various resummation schemes for multi-scale problems

Cf. talks by Kunzst, Laenen, Frixione

This talk will be concerned with ...

Global QCD Analysis of Parton Structure of the Nucleon

- **Intrinsic interest:** QCD dynamics at short distance, PQCD; fundamental structure of the nucleon (non-perturbative) — QCD dynamics at the confinement scale;
- **Practical importance:** essential ingredient that connects the hadron world to the parton world for all SM and New physics processes in hadron colliders.
(Crucial to understanding both the signal and the background of most processes of interest.)

Survey:

- How far have we come along, 20 years after EHLQ and Duke-Owens (when SSC was the big dream) ?
- How much more do we have to go (in order to realize the full potential of Tevatron and LHC) ?

Two Topcite papers that started global analysis at the dawn of the SSC dream in 1984:

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

By [D.W. Duke](#), [J.F. Owens](#) , FSU-HEP-831115, Nov 1983. Phys.Rev.D30:49,1984

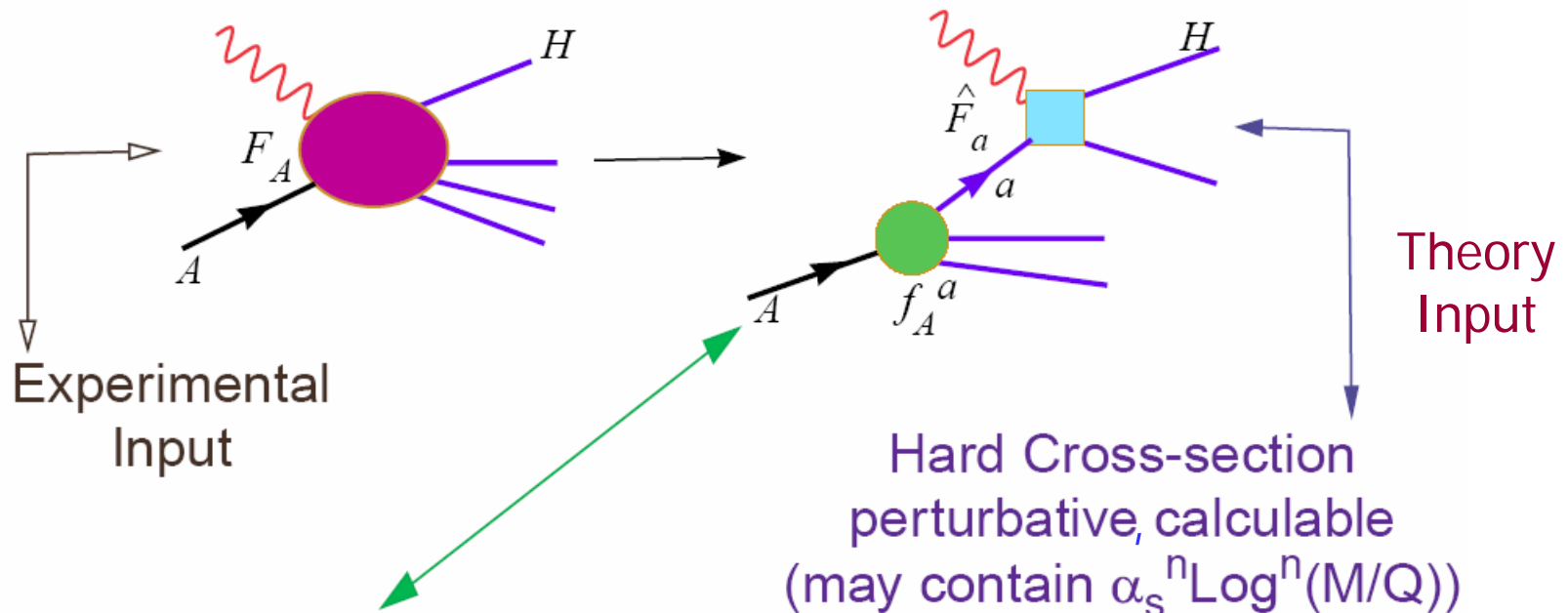
SUPER COLLIDER PHYSICS.

By [E. Eichten](#), [I. Hinchliffe](#), [Kenneth D. Lane](#) , [C. Quigg](#),. Feb 1984. 550pp. 1667 citations
Rev.Mod.Phys.56:579,1984

Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model
– the Factorization Theorem

$$F_A^\lambda(x, \frac{m}{Q}, \frac{M}{Q}) = \sum_a f_A^a(x, \frac{m}{\mu}) \otimes \hat{F}_a^\lambda(x, \frac{Q}{\mu}, \frac{M}{Q}) + \mathcal{O}((\frac{\Lambda}{Q})^2)$$



universal Parton Dist. Fn.

Non-Perturbative Parametrization at Q_0

GLAP Evolution to Q

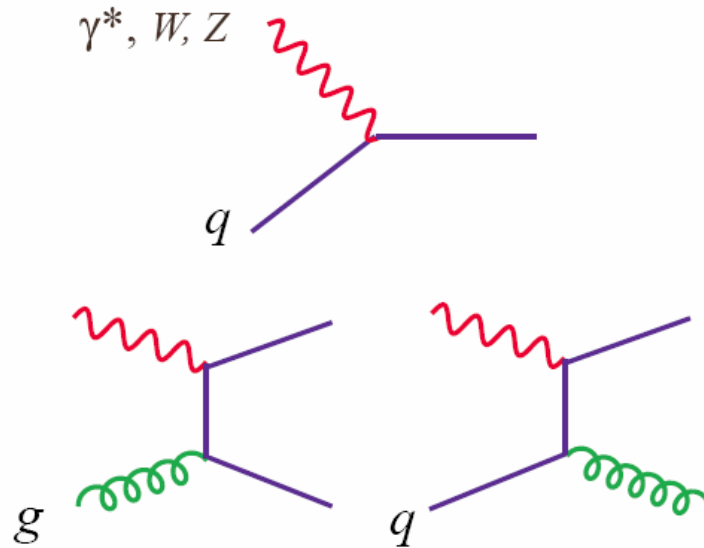
extracted by global analysis

Experimental Input: Physical Processes & Experiments

DIS

$e N$
 μN

νN
 $\bar{\nu} N$

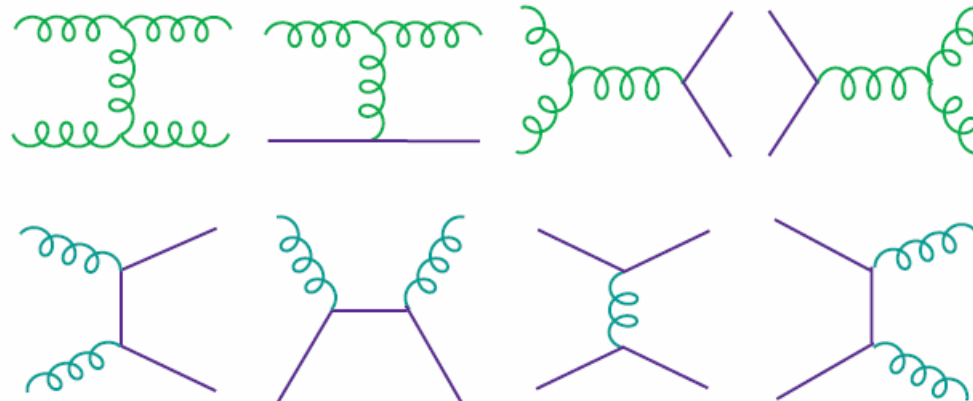


SLAC
BCDMS
NMC, E665
H1, ZEUS

CDHS, CHARM
CCFR
CHORUS

Jet Inc.

$\bar{p} p$



CDF, D0

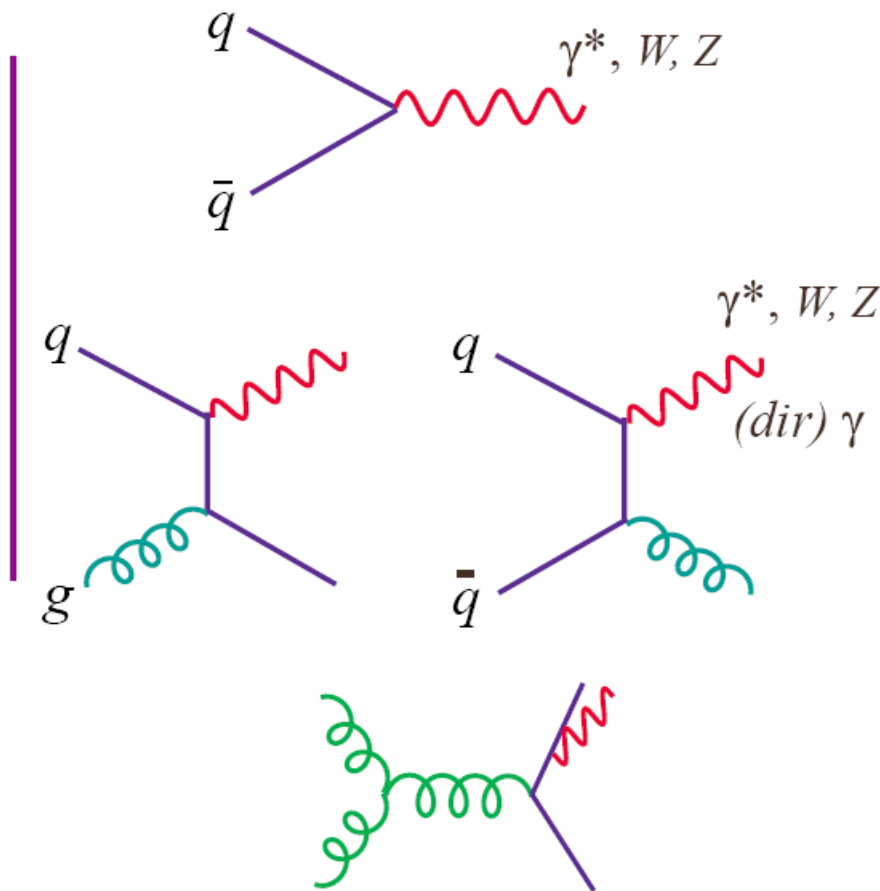
Experimental input (continued)

DY

$p N$
 πN
 $k N$
 $\bar{p} N$

(Dir.Ph.)

$p N$
 πN
 $k N$
 $\bar{p} N$



E605, E772
 NA51
E866

CDF, D0

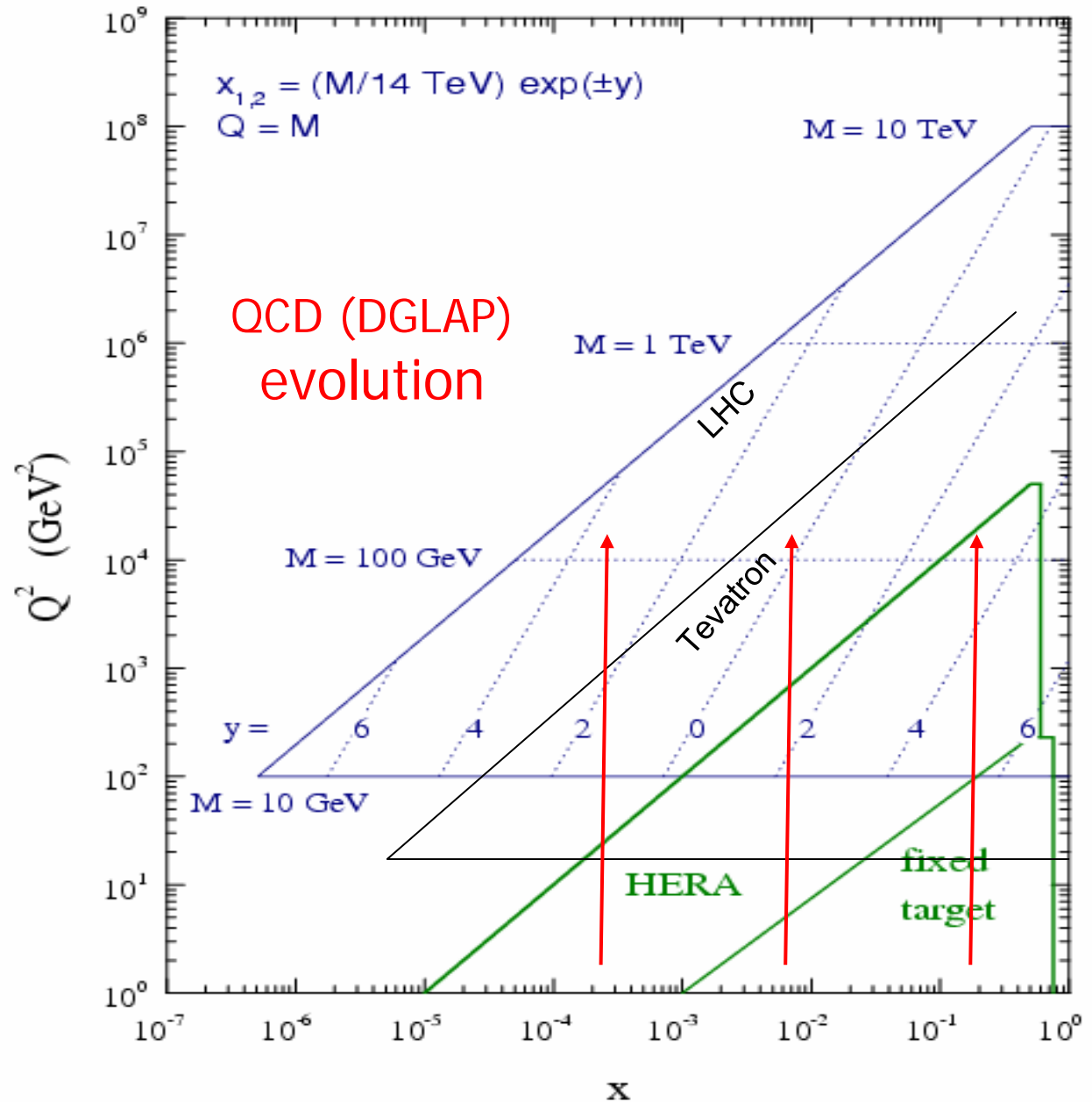
WA70, UA6
 E706

CDF, D0

(DIS jets, heavy quark prod. ...)

Kinematics of Parton variables

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



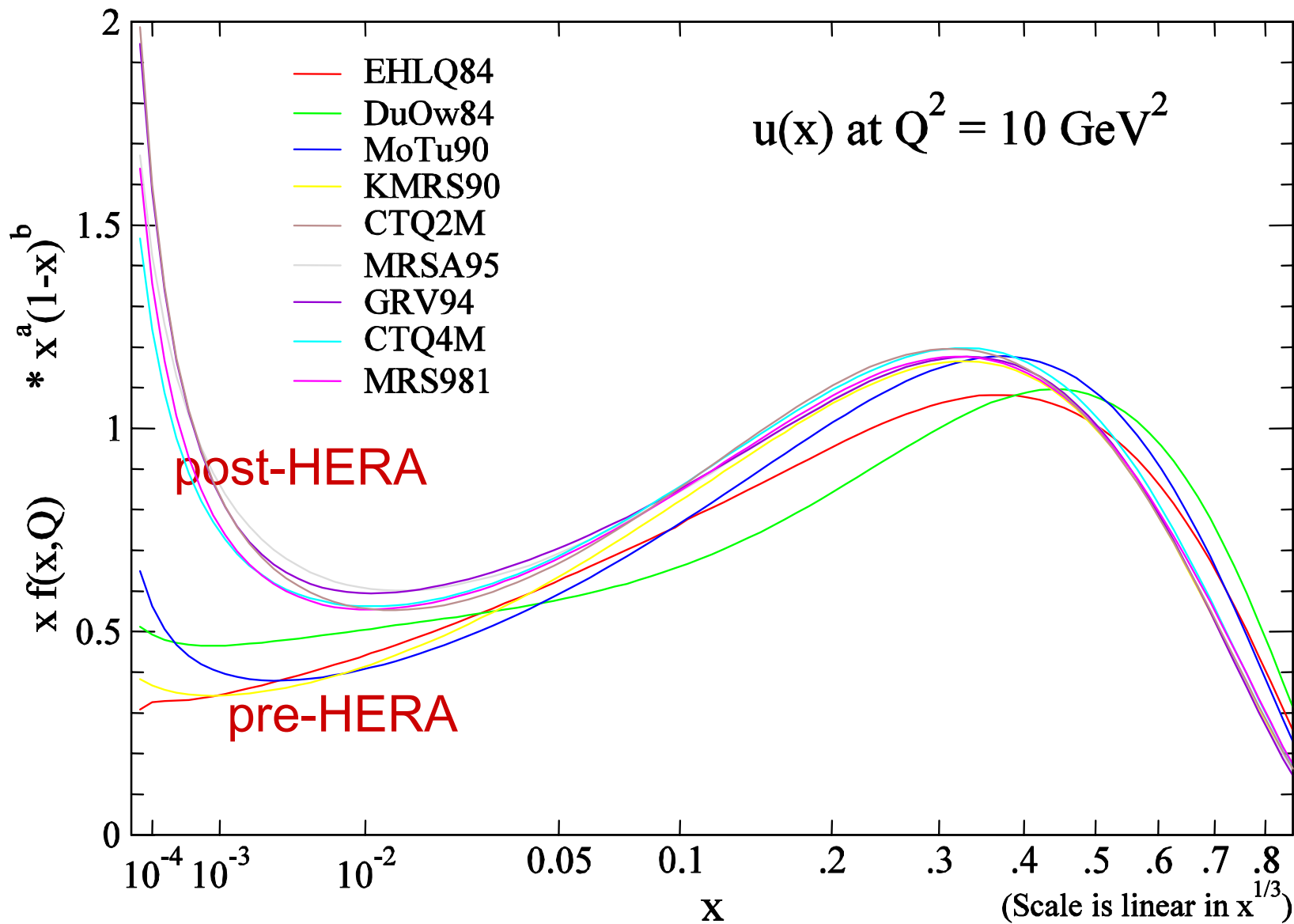
How far have we come?

Some **quantitative measure** of the progress made over the years (illustrative of historical trend only)

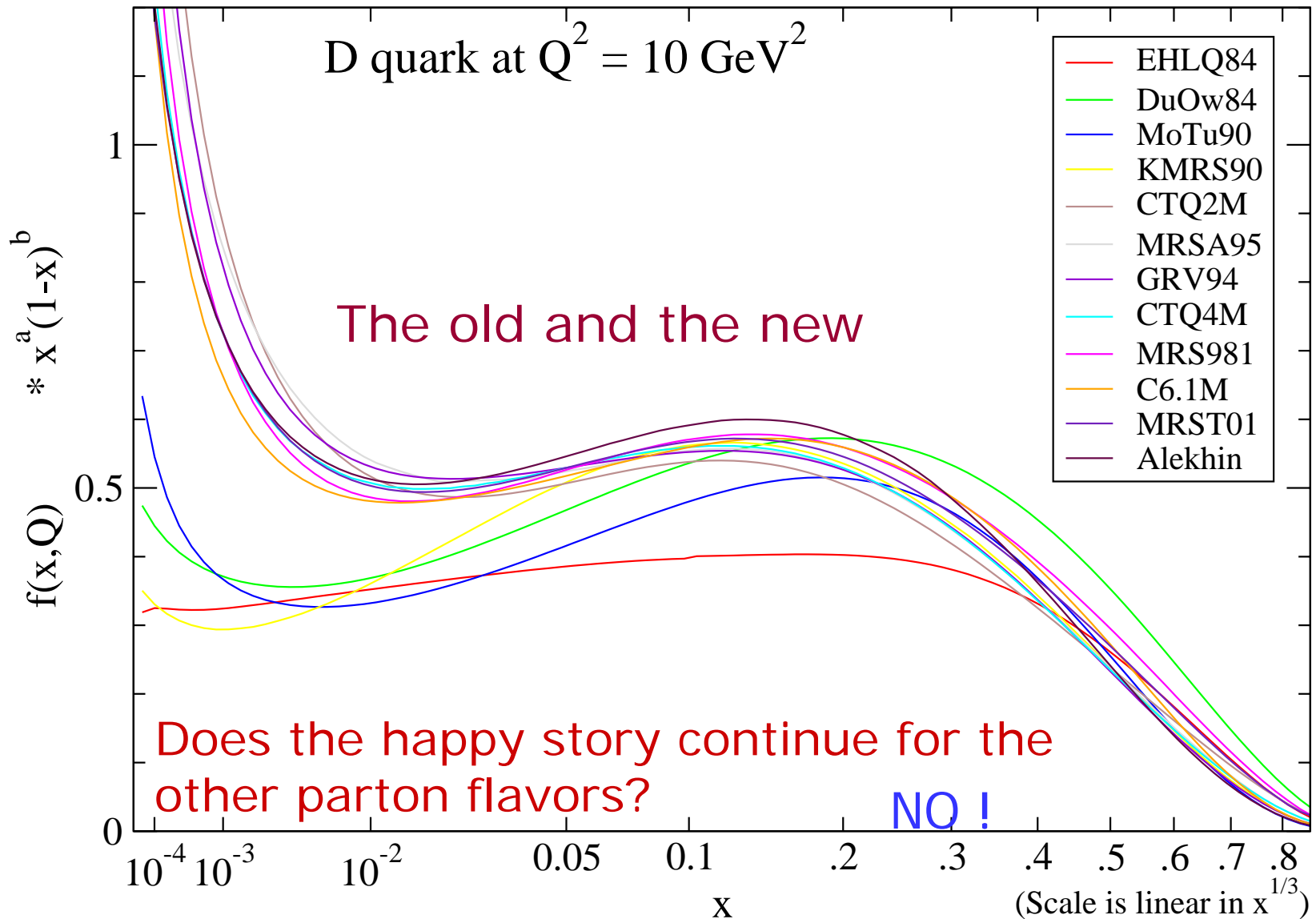
	Fixed-tgt	HERA	DY-W	Jets	Total	χ^2/dof
# Expt pts.	1070	484	145	123	1822	
EHLQ '84	11475	7750	2373	331	21929	10
DuOw '84	8308	5005	1599	275	15187	
MoTu ~'90	3551	3707	857	218	8333	4.5
KMRS ~'90	1815	7109	577	280	10381	
CTQ2M ~'94	1531	1241	646	224	3642	2
MRSTA ~'94	1590	983	249	231	3054	
GRV94 ~'94	1497	3779	302	213	5791	
CTQ4M ~'98	1414	666	227	206	2513	
MRS981 ~'98	1398	659	111	227	2396	1.3
CTQ6M 02	1239	508	159	123	2029	~1.1
MRST01 01	1378	530	120	236	2264	
Alekhin 03	1576	572	892	270	3309	1.5

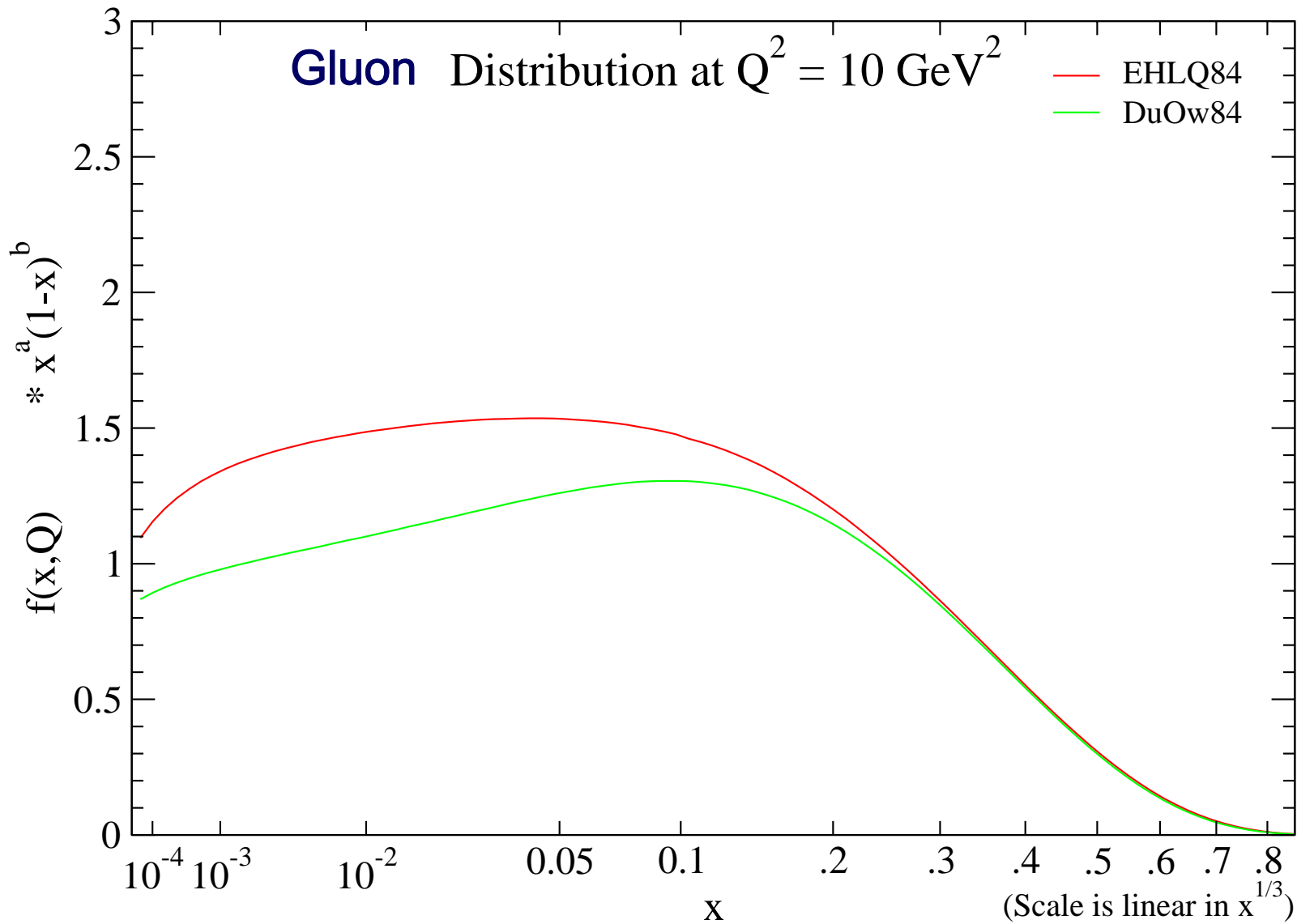
χ^2 values evaluated on common data sets based on the respective PDFs, using the CTEQ fitting program.

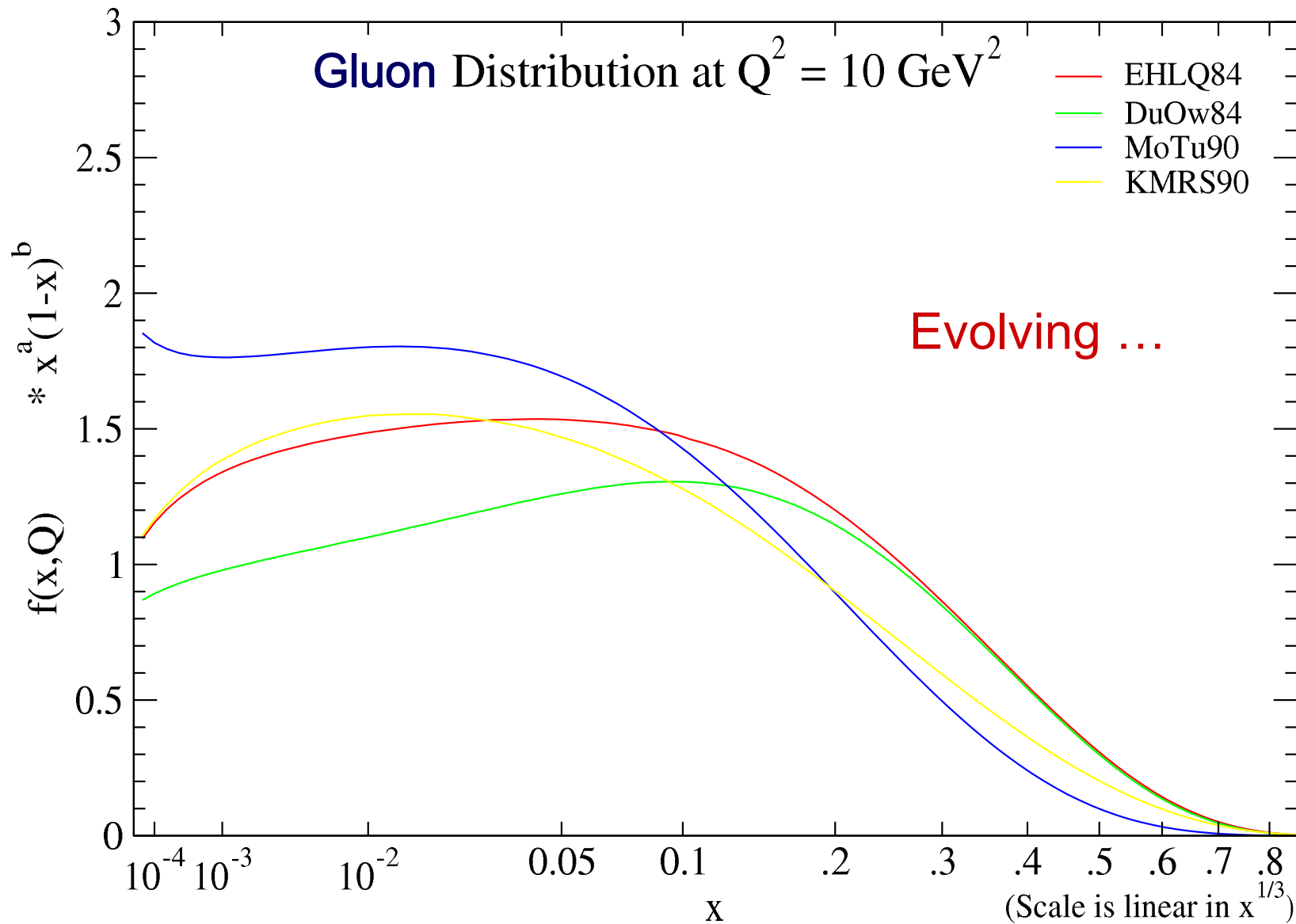
Progress in the determination (time evolution) of the u-quark distribution

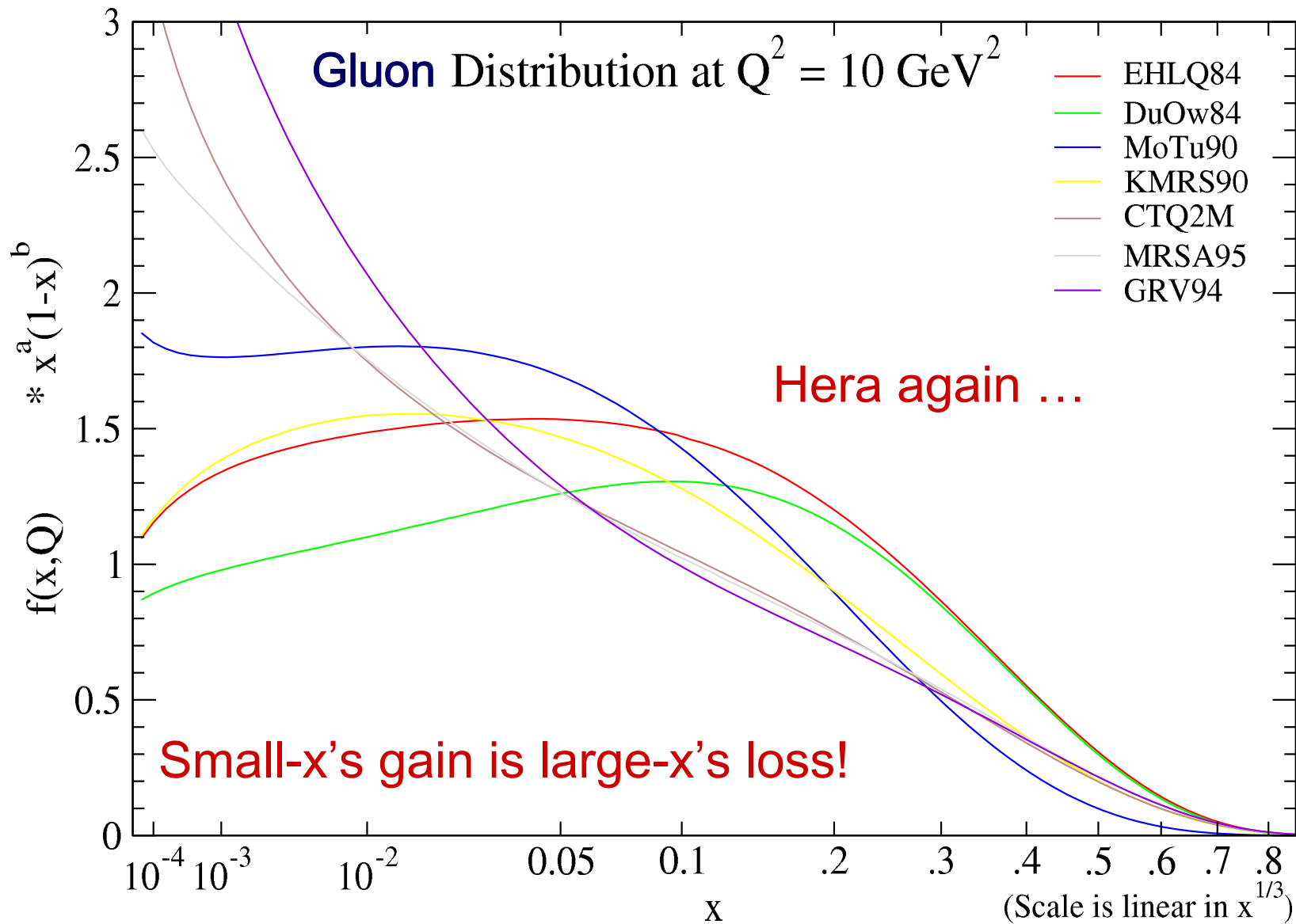


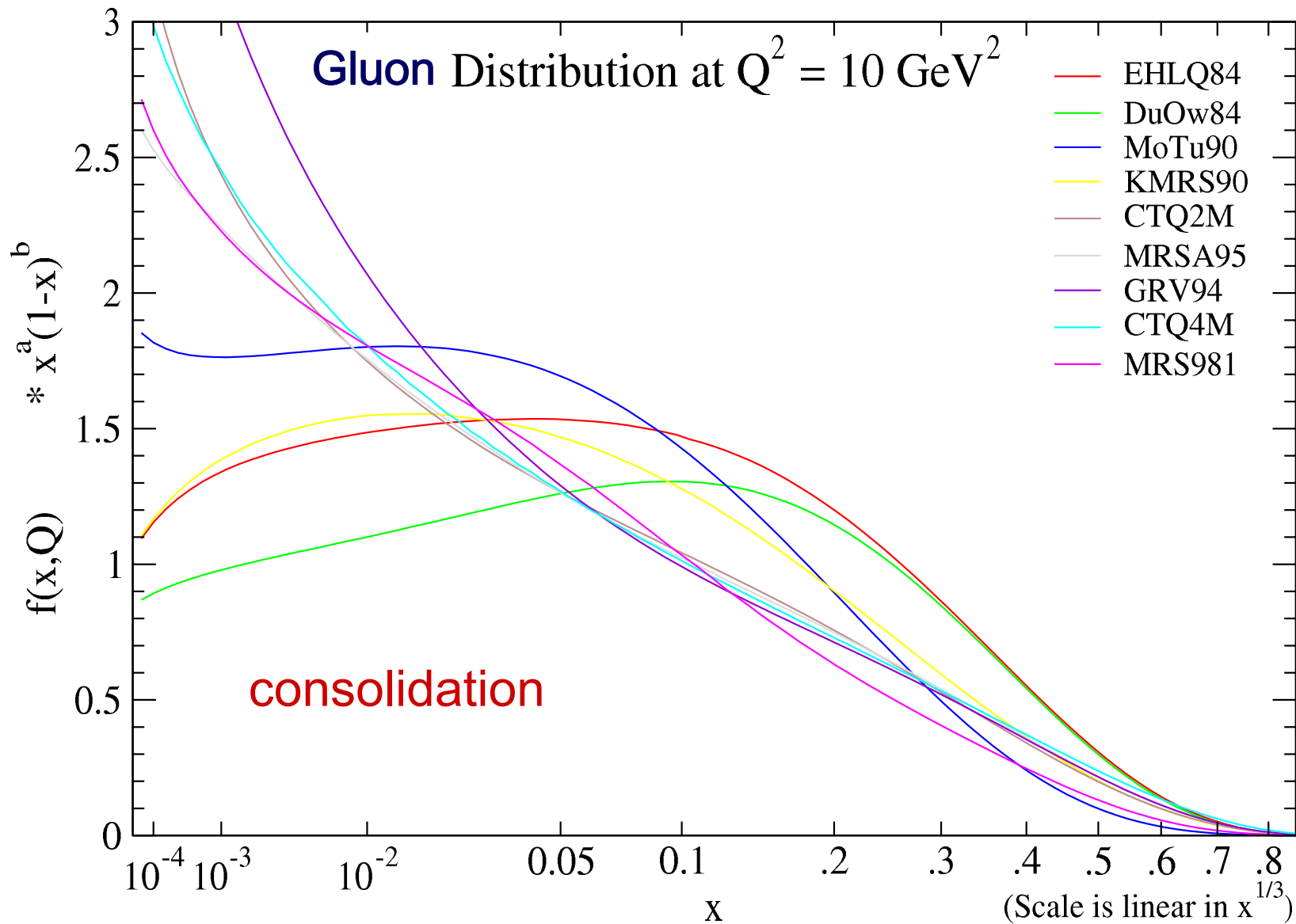
The d-quark story



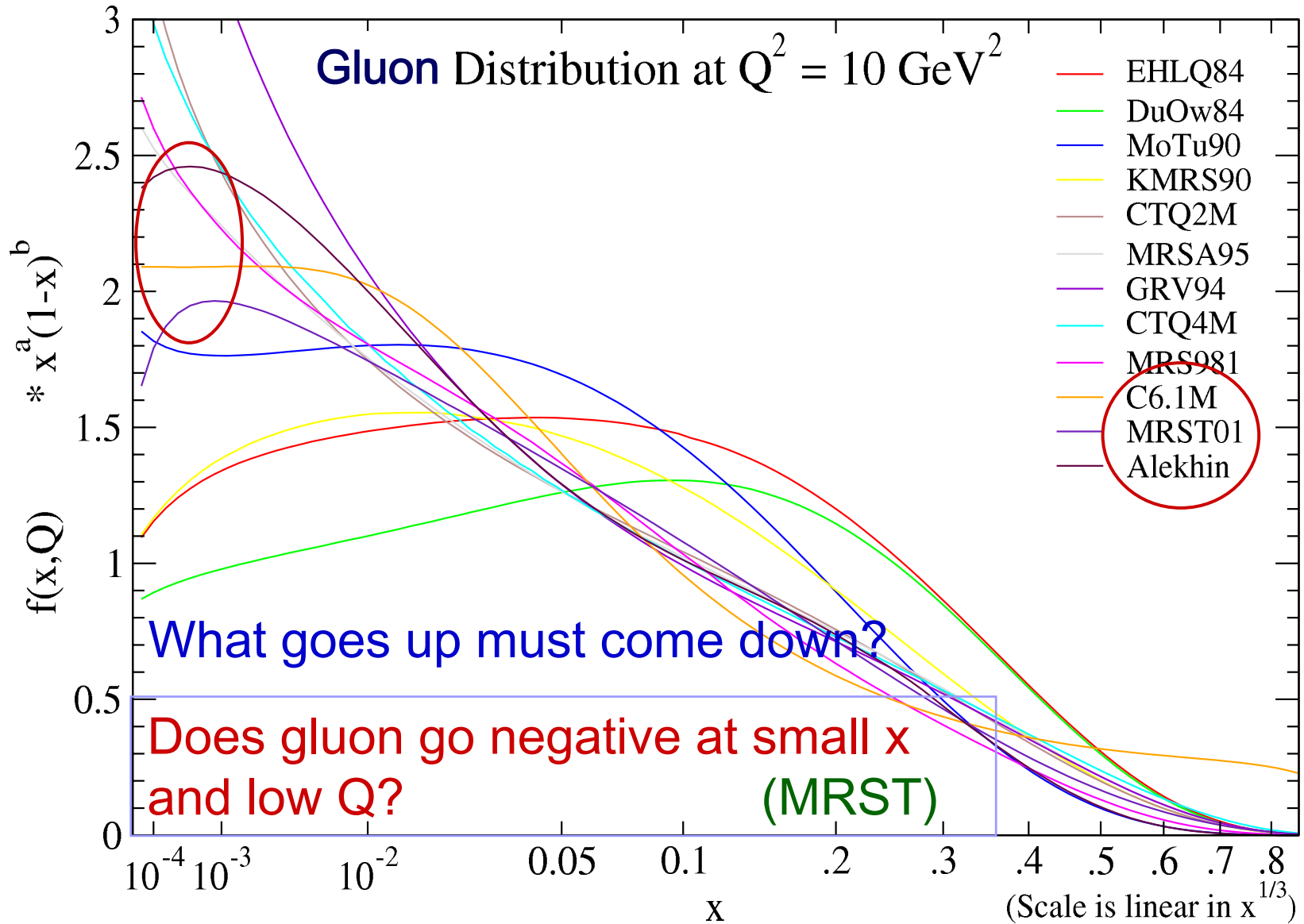








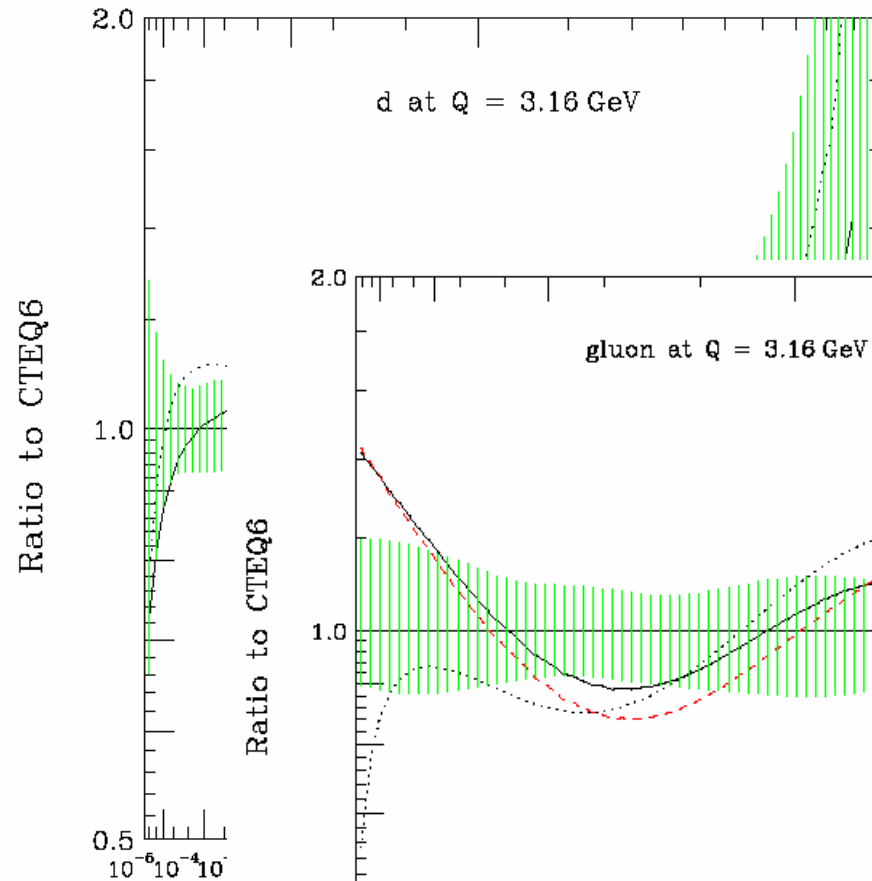
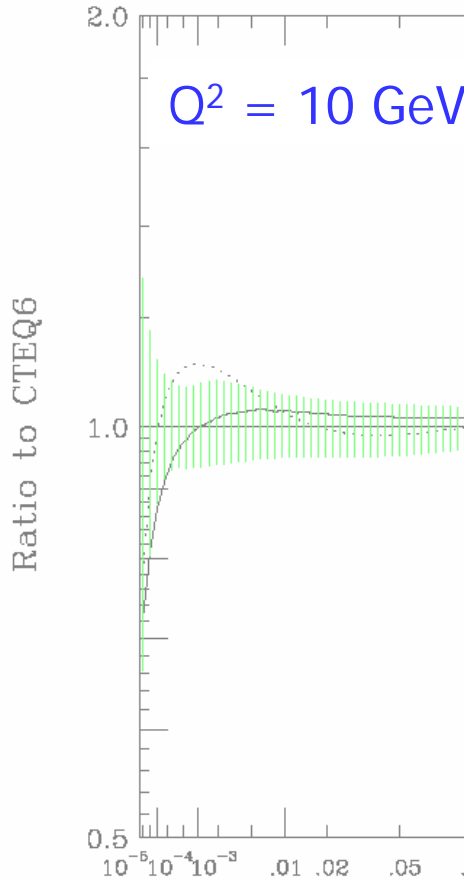
Gluon Distribution at $Q^2 = 10 \text{ GeV}^2$



Uncertainties of PDFs:

CTEQ6

$Q^2 = 10 \text{ GeV}^2$



by an iterative Hessian method, using orthonormal eigenvector sets

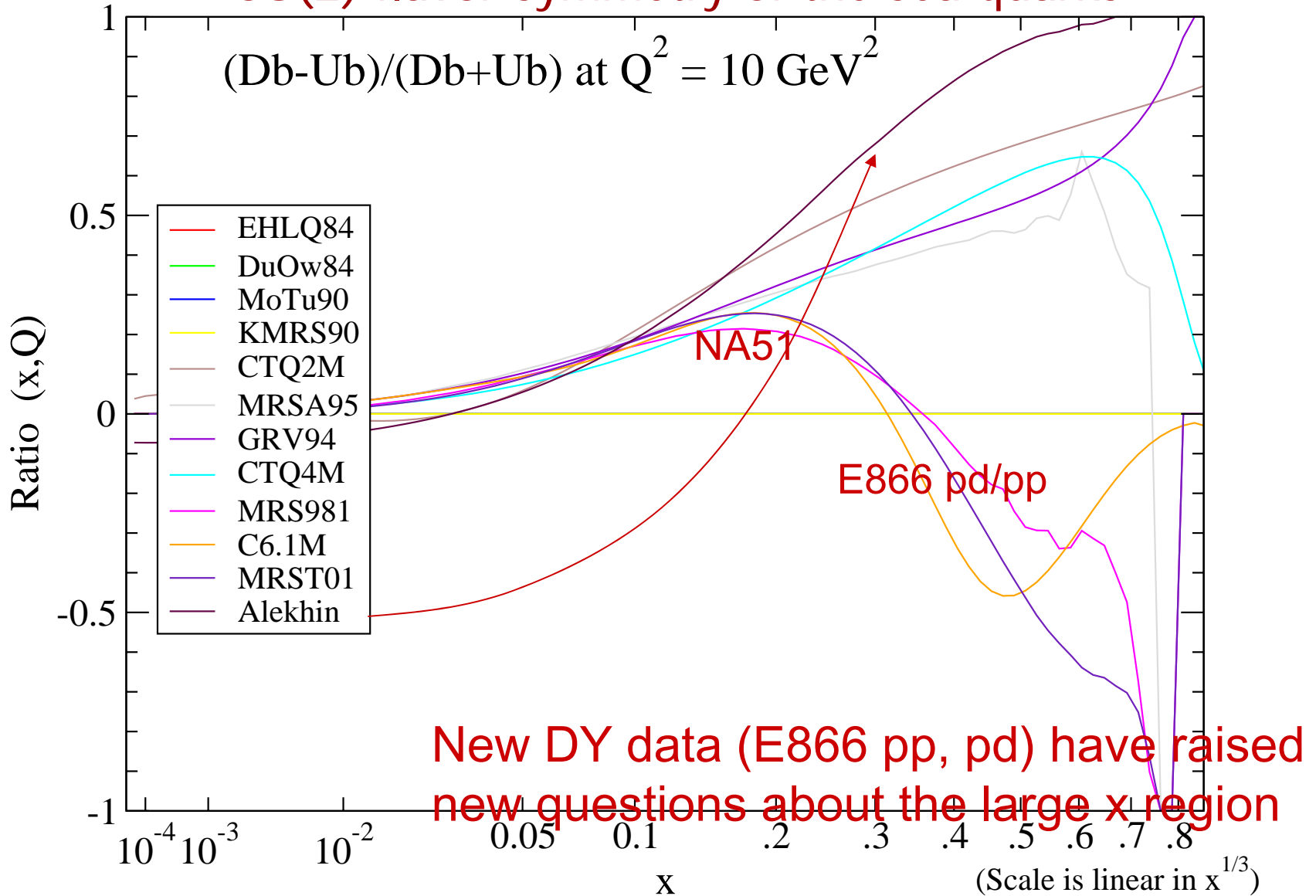
Theory uncertainties not explicitly included; but some allowance is made in the tolerance.

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
($\bar{u} = \bar{d}$)?

SU(2) flavor symmetry of the sea quarks



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

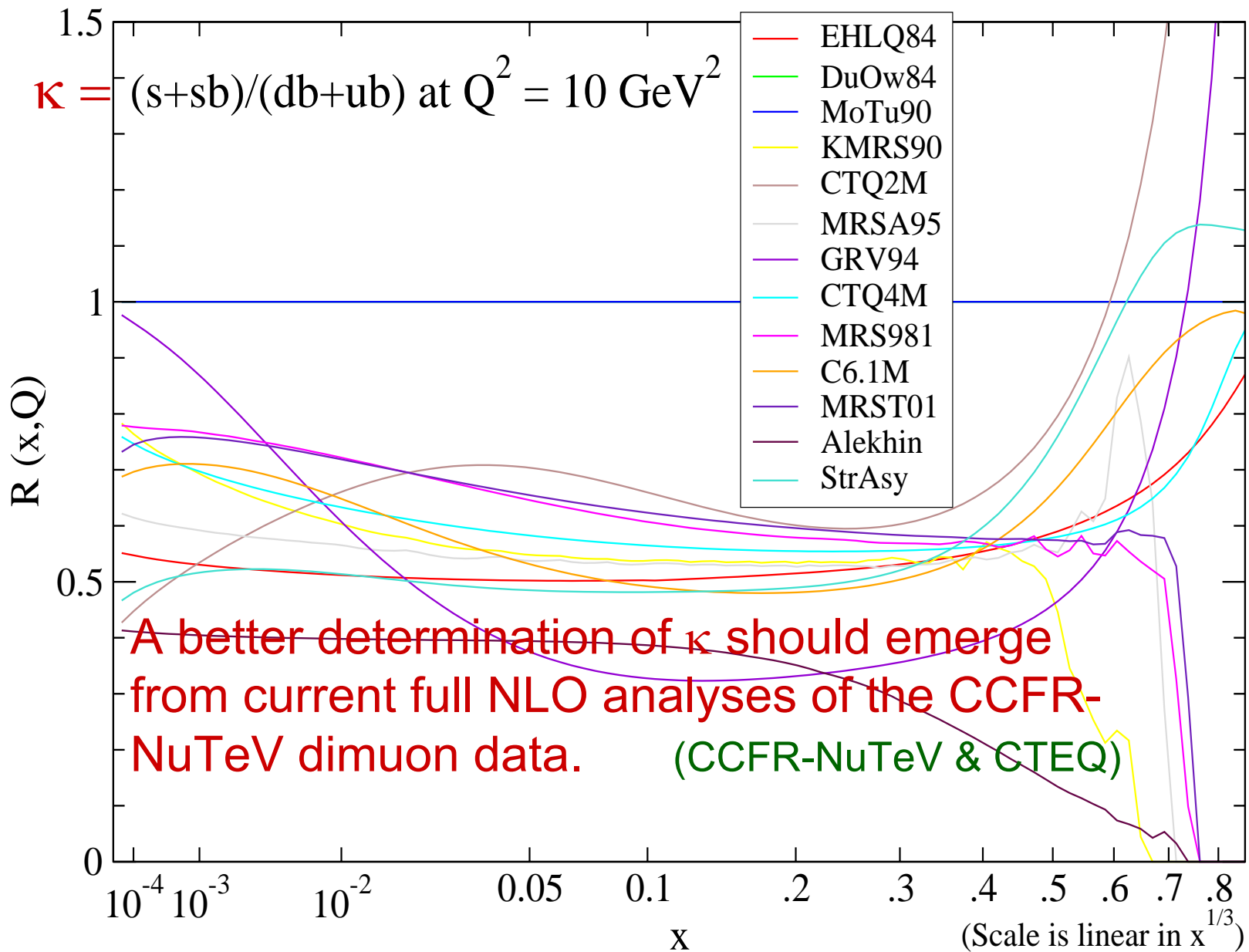
Valence and Sea Quark distributions of the Nucleon

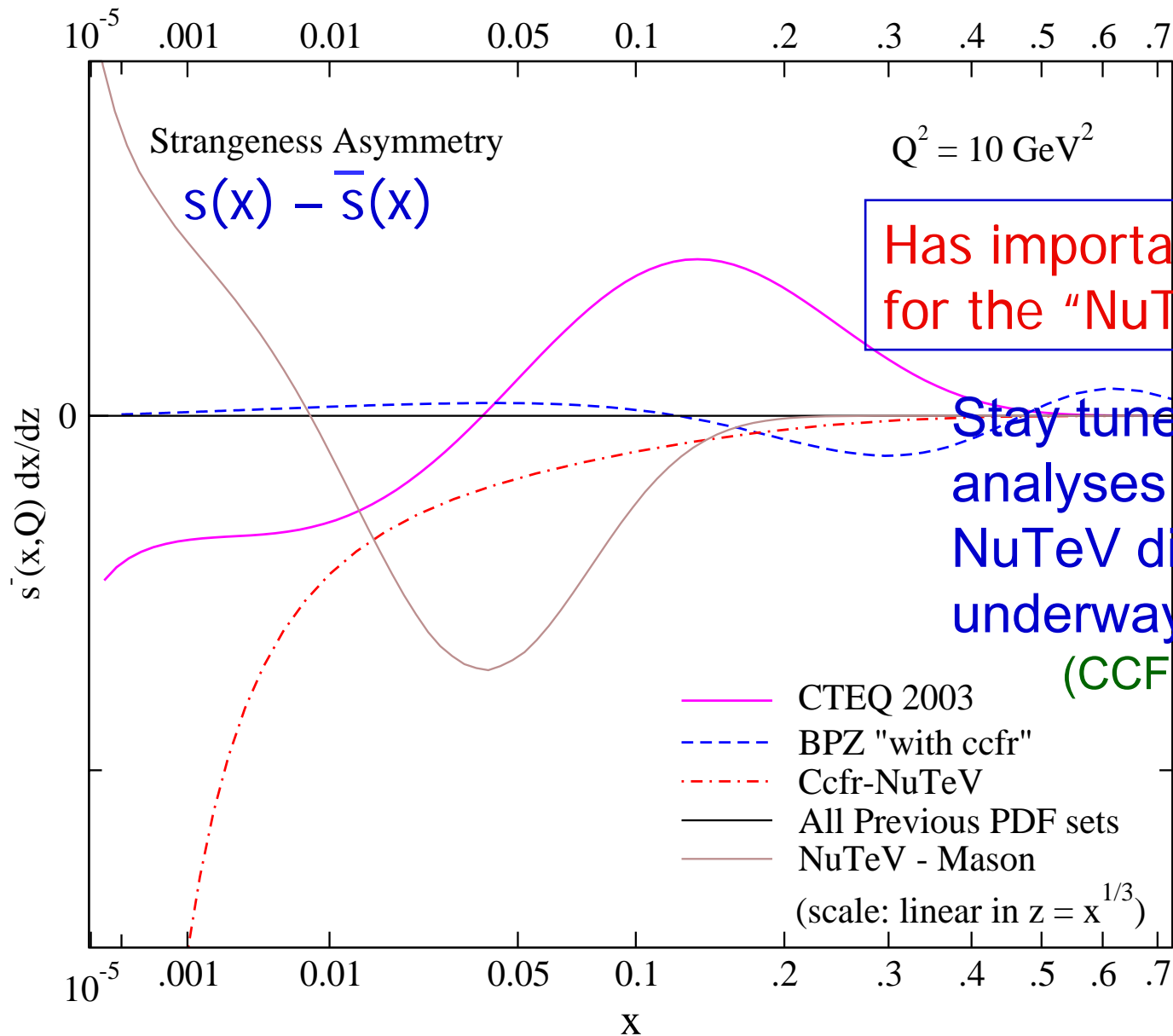
How does the $d(x)/u(x)$ ratio behave? Low/medium x
behavior well determined; Large- x behavior open.

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 ($s = \bar{s}$)?





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 ($s+s_b=u_b+d_b$)?
Certainly not! $\kappa \sim 0.4$ more precise value to come.

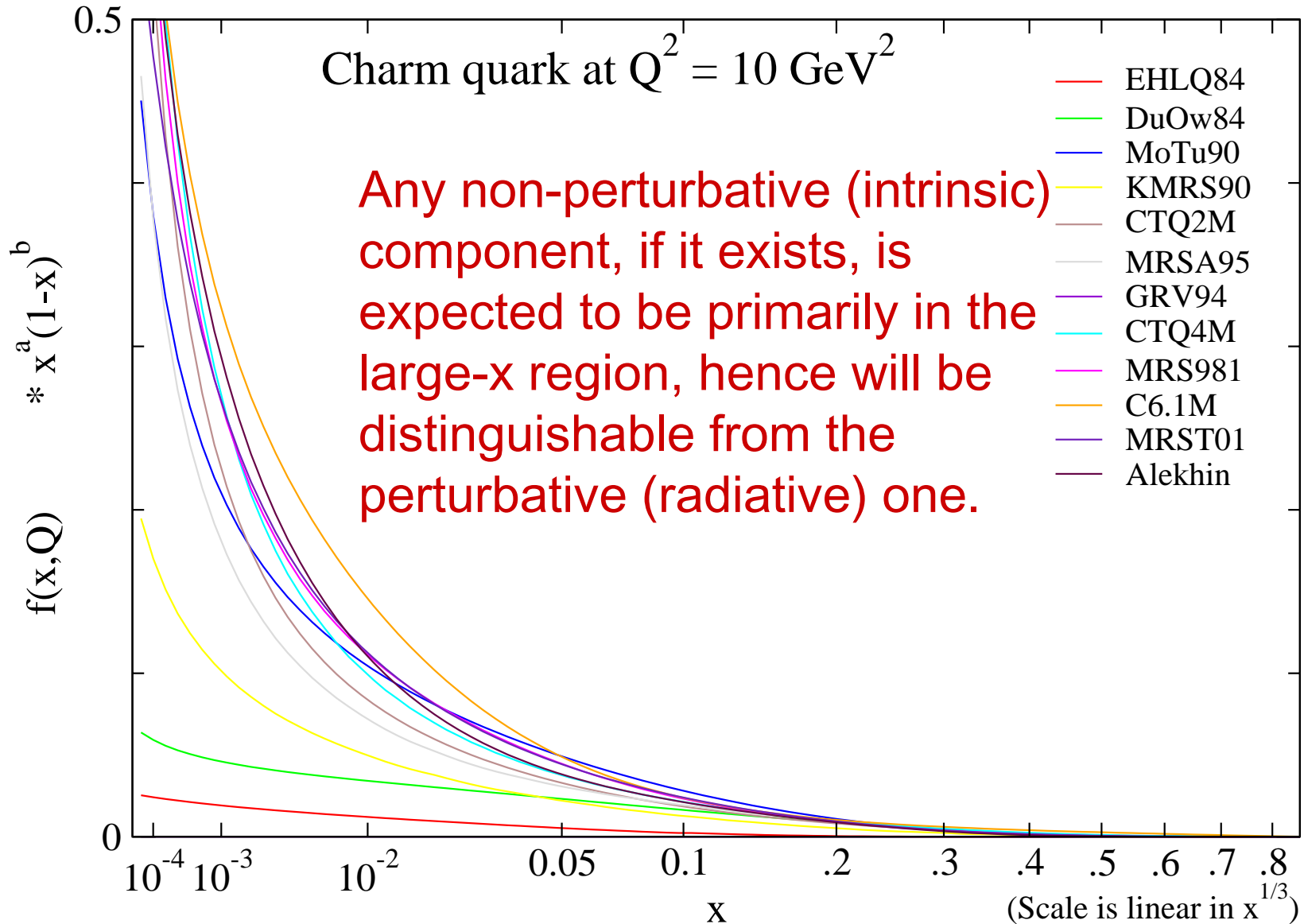
Is the strange sea charge symmetric ($s = s_b$)?
Jury is still out. Has important implications on the
NuTeV anomaly.

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 ...



Mini Summary on Global QCD Analysis

- A great deal of progress has been made since the first LO analyses were made;
- 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:**
W/Z rapidity distribution;
W/Z transverse momentum distribution; Nadolsky,
Campbell
W-mass measurement;
W/Z + Jet differential cross sections;
... (Echo precision DIS phenomenology of the 1990's)
- **Precision Top and Higgs Phenomenology:** Tait, Kilgore
predictions and measurement of SM parameters.
- **Predictions on possible New Physics Discoveries:** Belyaev. ...
SUSY, Technicolor and other strong dynamics, Extra
Dimensions ...

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. \Rightarrow There are no rigorous answers; some subjective judgment must be involved. \Rightarrow 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](https://arxiv.org/abs/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:

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

Exptl uncertainties:

LHC

MRST2002

CTEQ6

Alekhin02

$\sigma_{\text{NLO}}(W)$ (nb)

204 ± 4 (expt)

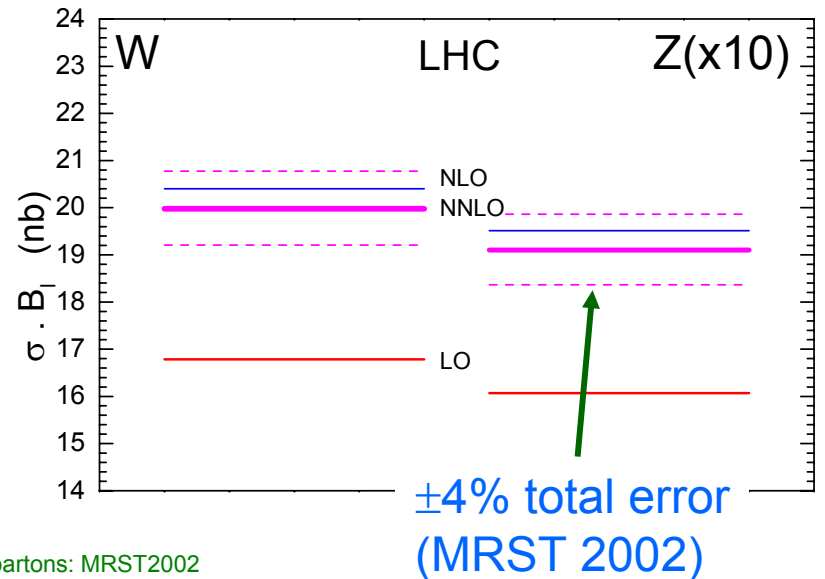
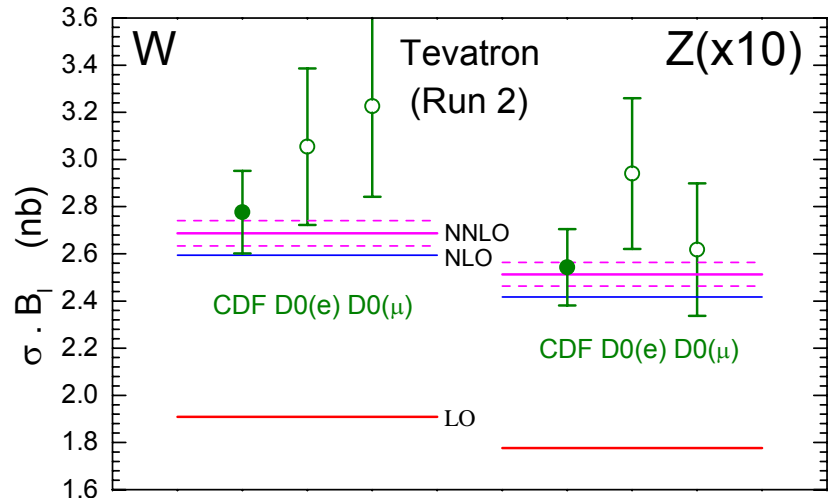
205 ± 8 (expt)

215 ± 6 (tot)

similar partons

different $\Delta\chi^2$

different partons



partons: MRST2002

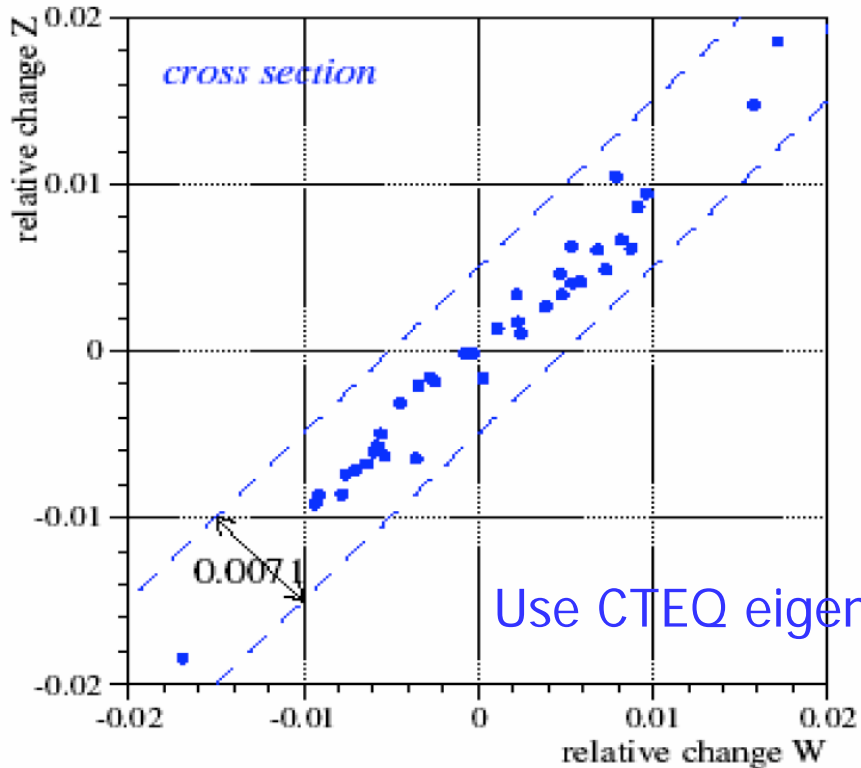
NNLO evolution: van Neerven, Vogt approximation to vermaasereen et al. moments

NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

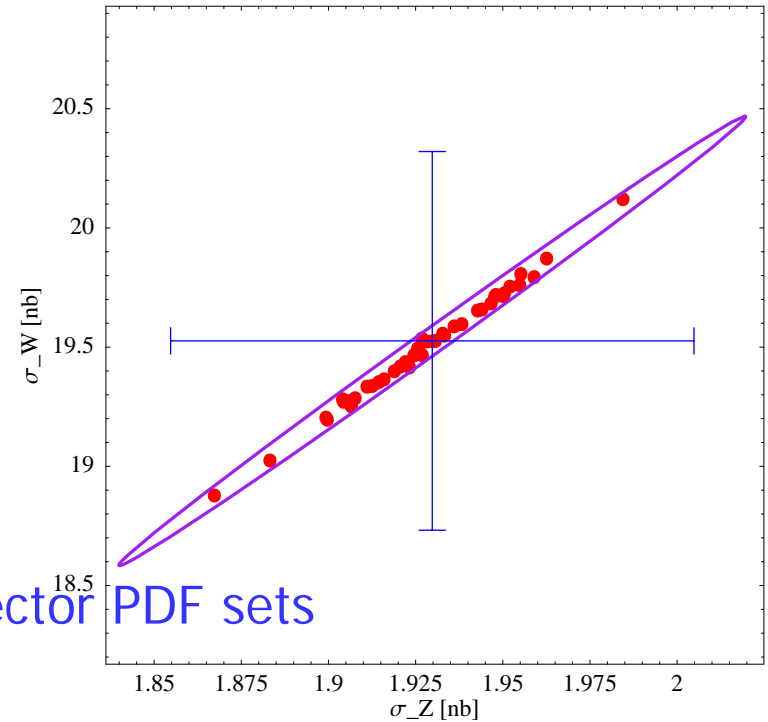
(Stirling, HeraLhc Workshop 2004)

σ_W and σ_Z ranges due to PDF uncertainties

Tevatron (CDF)



LHC (CTEQ)



Error range: 2 – 5 %;
W-, Z- cross sections are highly correlated;

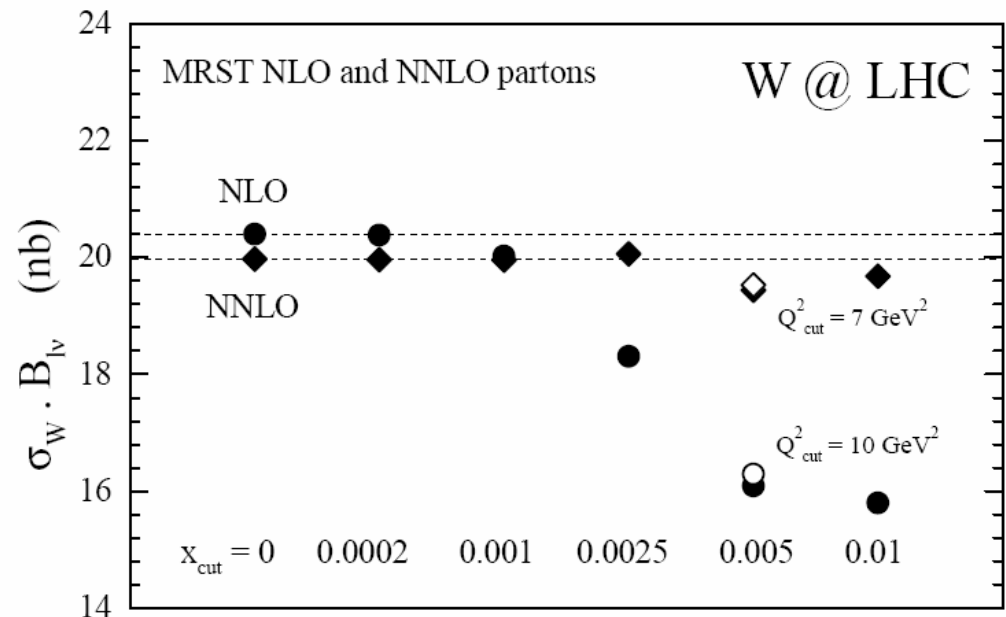
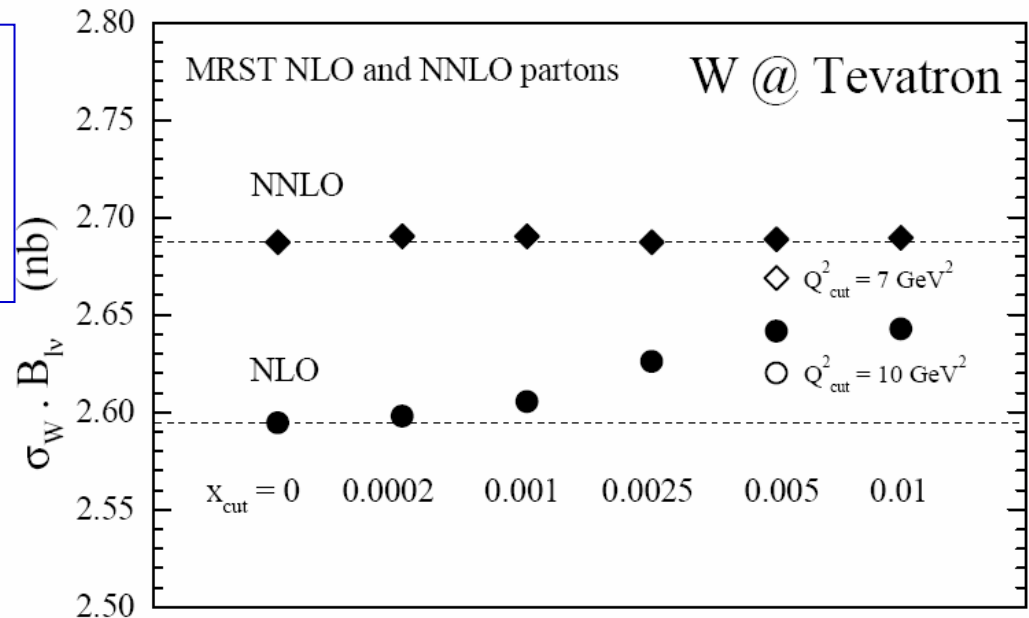
MRST "Theory" Uncertainty
(varying cuts in global fits)
(2003)

Alarm bell?
Instability at NLO !

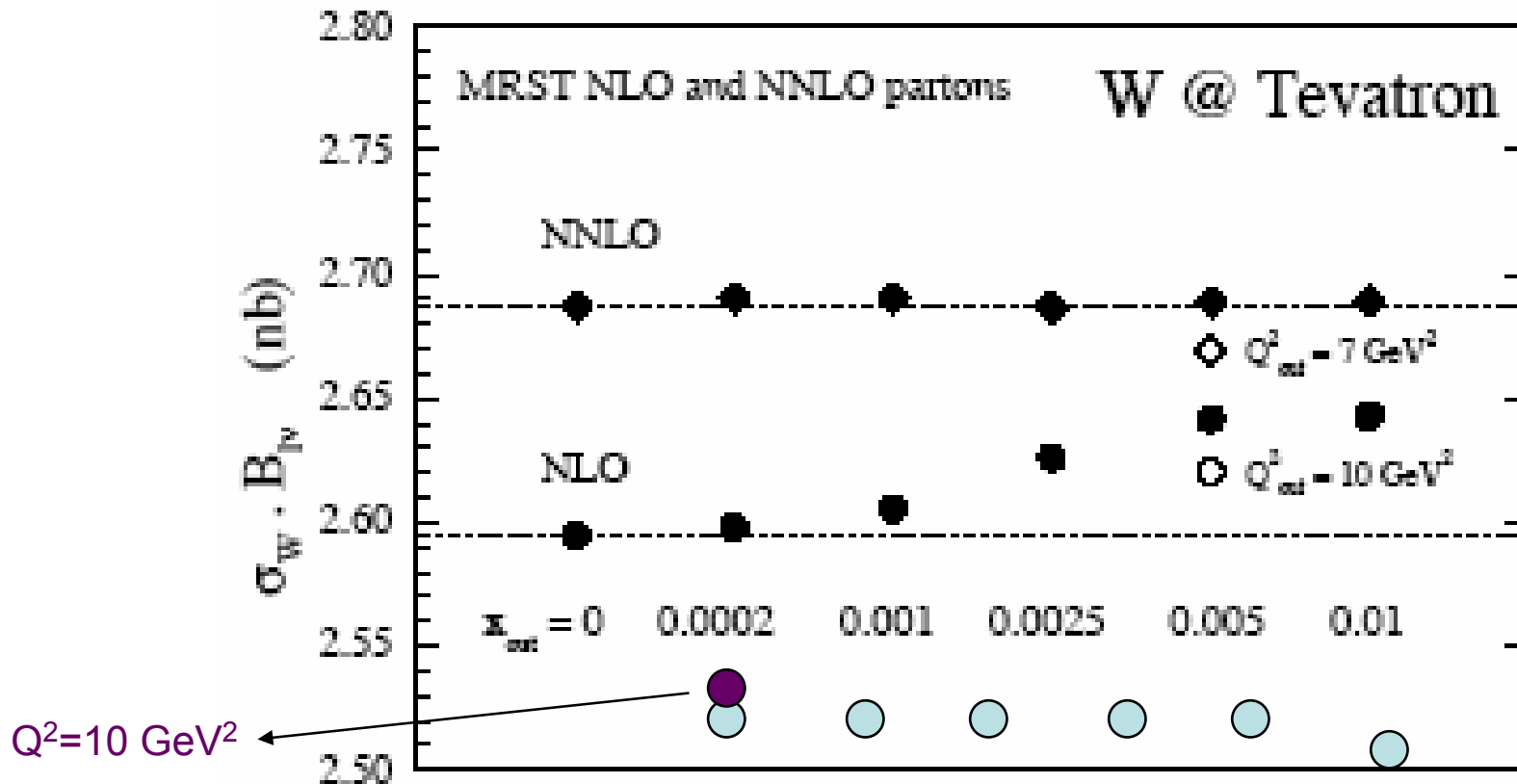
Are these findings disturbing?

- 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 ...



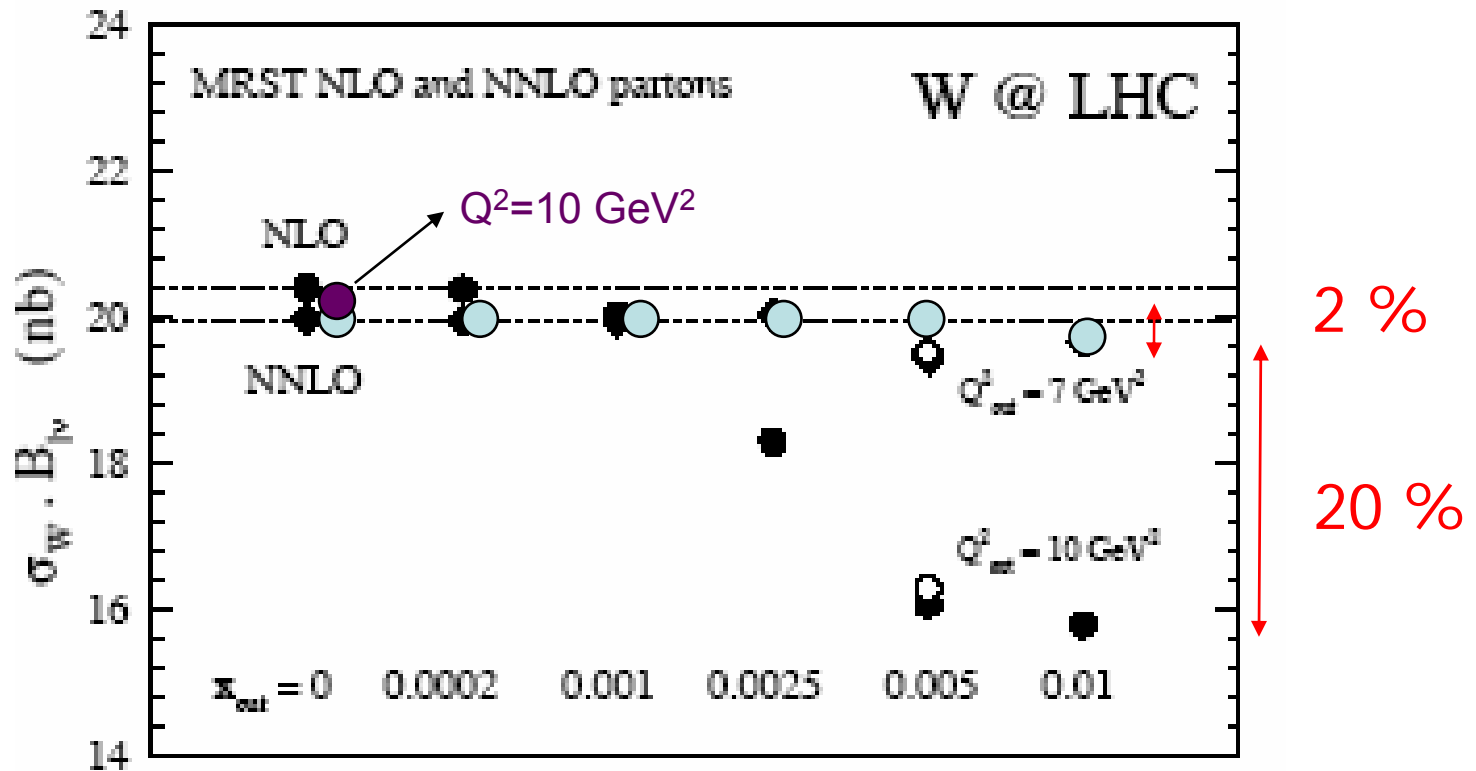
σ_W at the Tevatron



○ 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



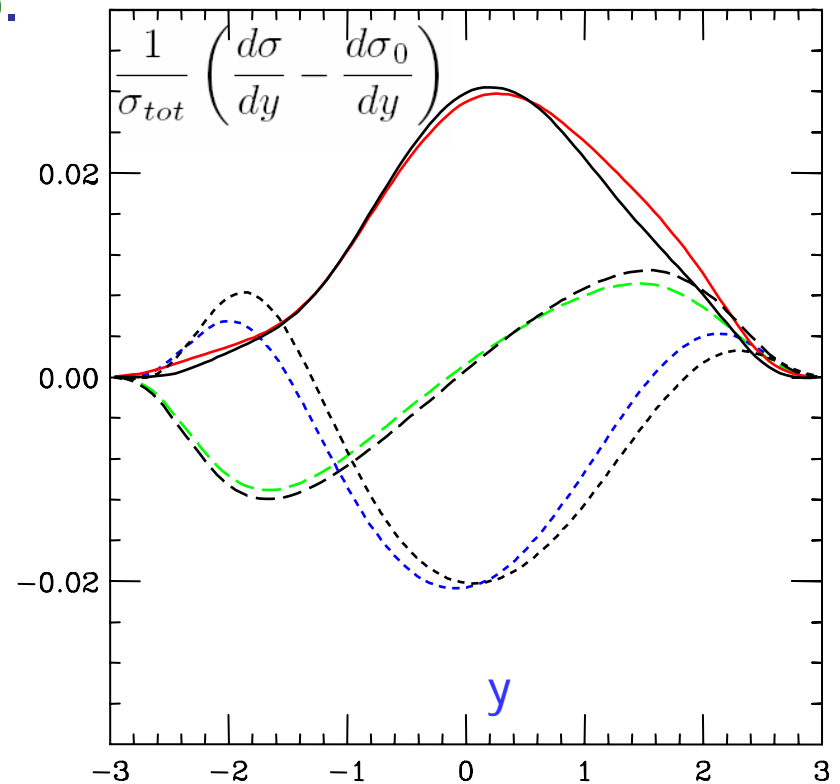
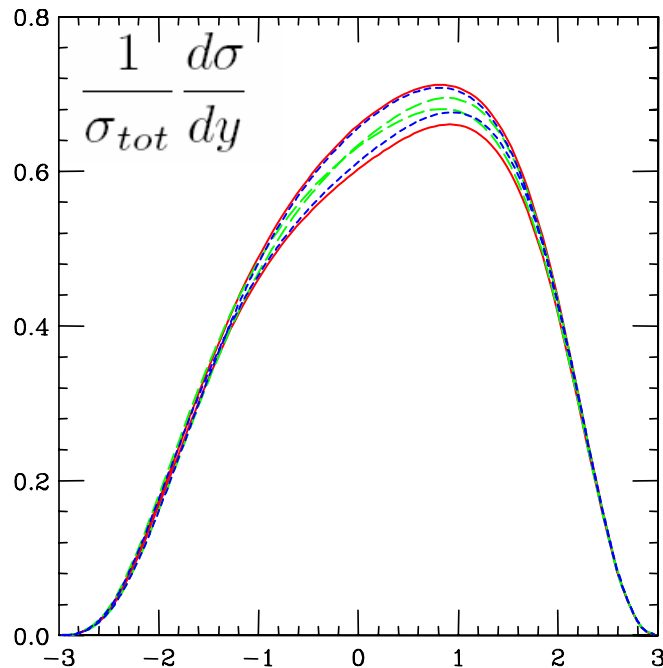
- shows the results of applying x cuts to the CTEQ6 data set and performing a NLO fit.

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.

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.

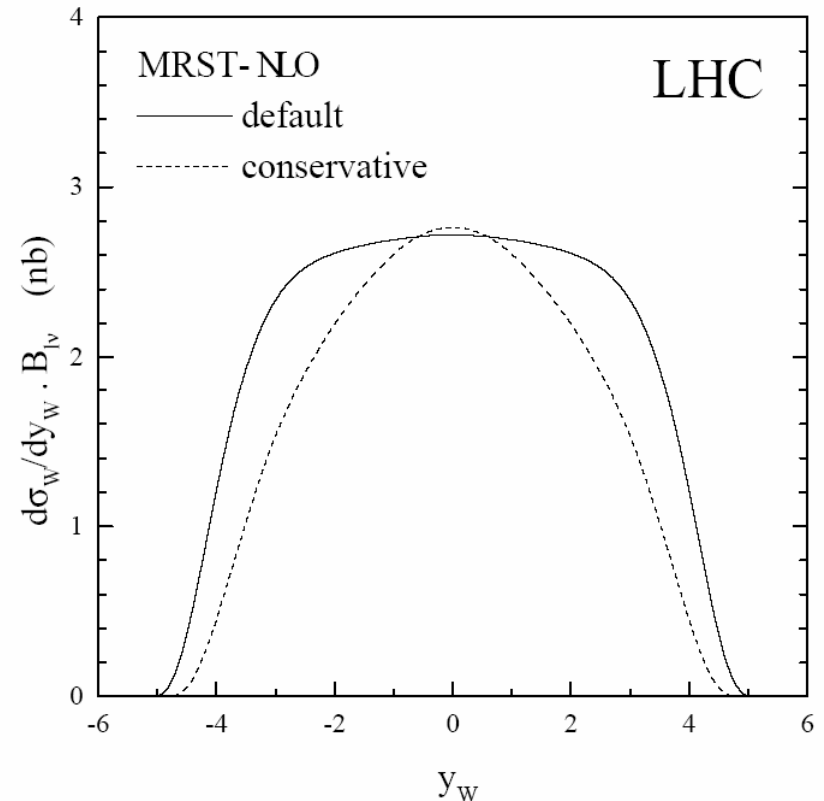
Precision PQCD phenomenology: W rapidity distribution at LHC

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.

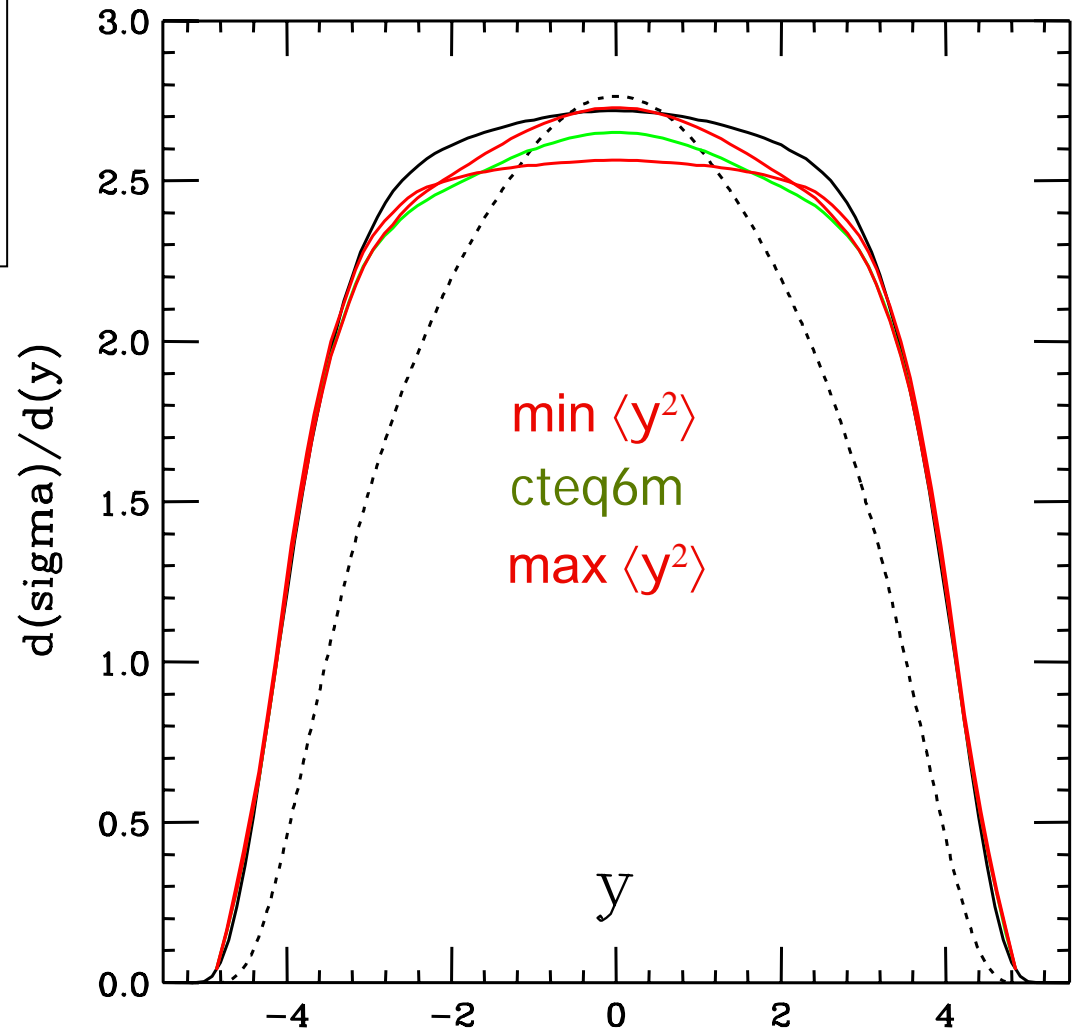
(Thorne Hera-Lhc Workshop)



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)

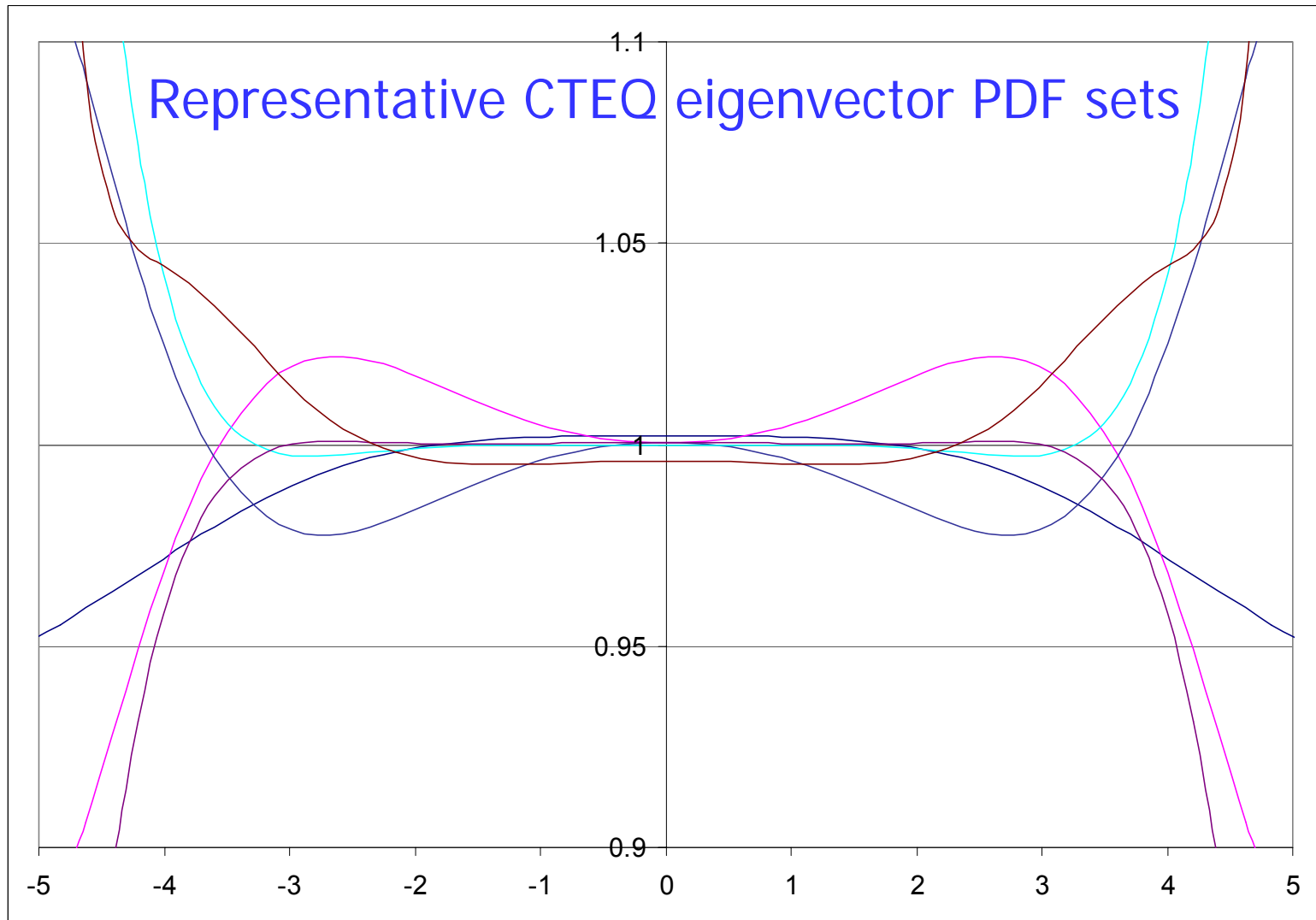
- Search in the parton parameter space, using eigenvector solutions in the improved Hessian approach, to probe the extremes in predicted shape—max/min $\langle y^2 \rangle$.



Surely experiment can tell the differences!?

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

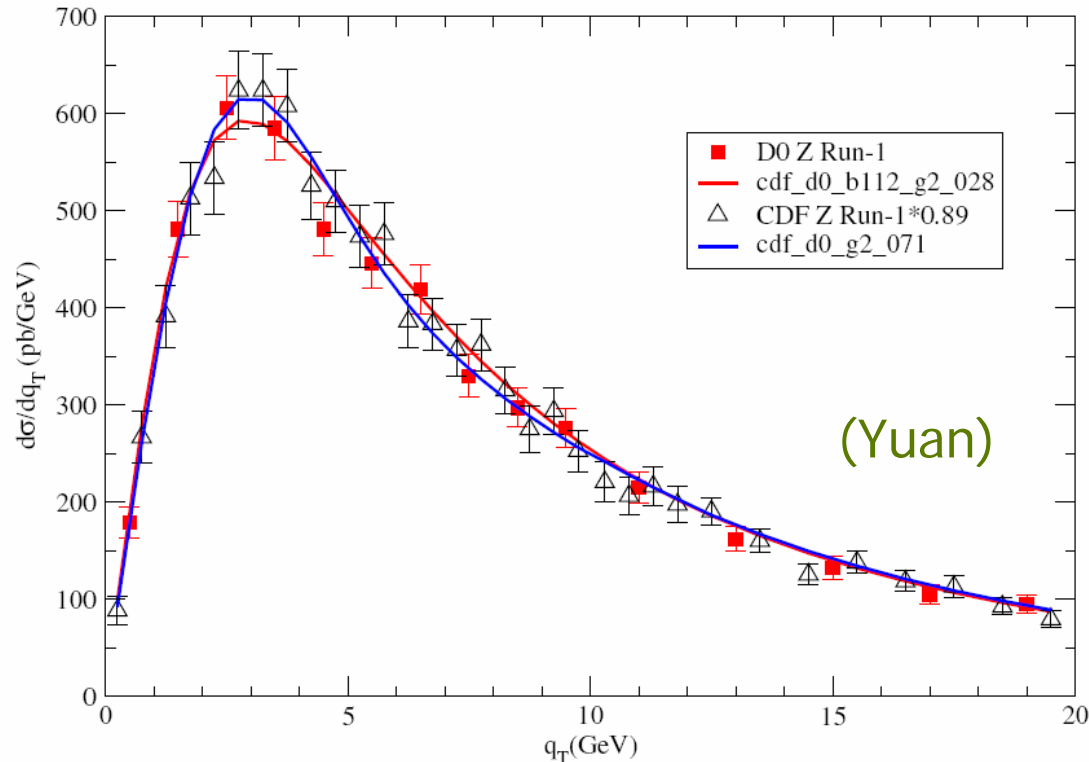
$$\sigma(y)_{w^+} / \sigma(y)_{w^-} \text{ at LHC}$$



(True uncertainties are bigger, especially at large y)

P_T distribution and resummed 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

\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

\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

CTEQ PDF uncertainties

MRST PDF uncertainties

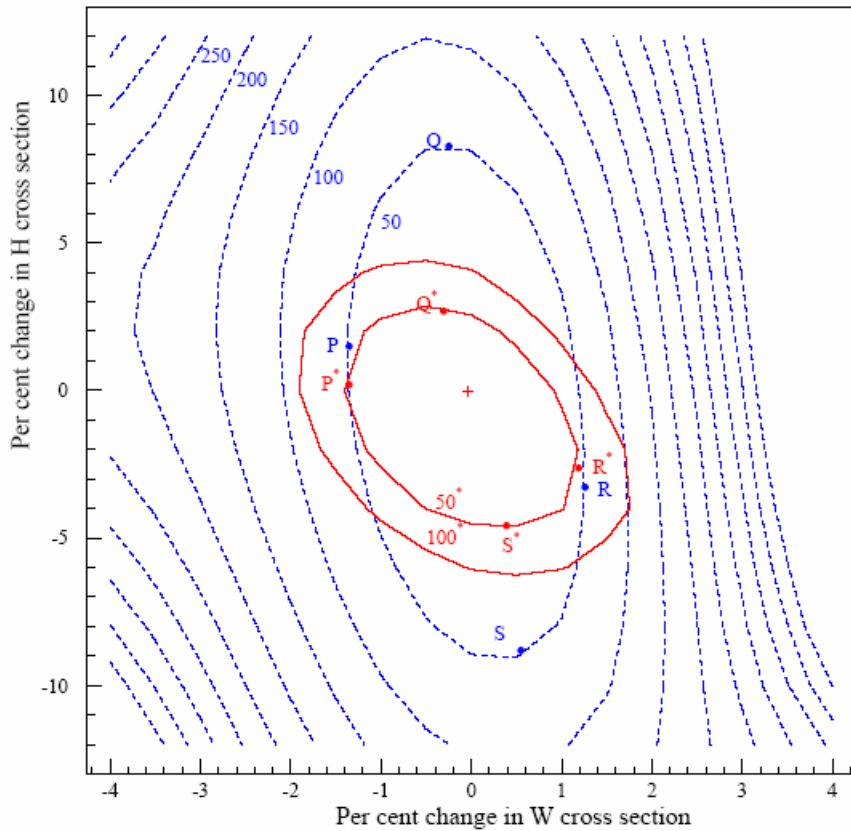
\sqrt{S}	m_{top}	$\sigma_{min} (r_\mu = 2, \mathbf{A01L})$	$\sigma_{ref}(r_\mu = 1, \mathbf{0})$	$\sigma_{max} (r_\mu = 0.5, \mathbf{J01})$
1800	170	5.48	6.13	6.72
1800	175	4.66	5.21	5.71
1800	180	3.98	4.44	4.86
1960	170	7.04	7.90	8.69
1960	175	6.03	6.76	7.41
1960	180	5.17	5.79	6.34

MRST PDF uncertainties
+ scale dependence

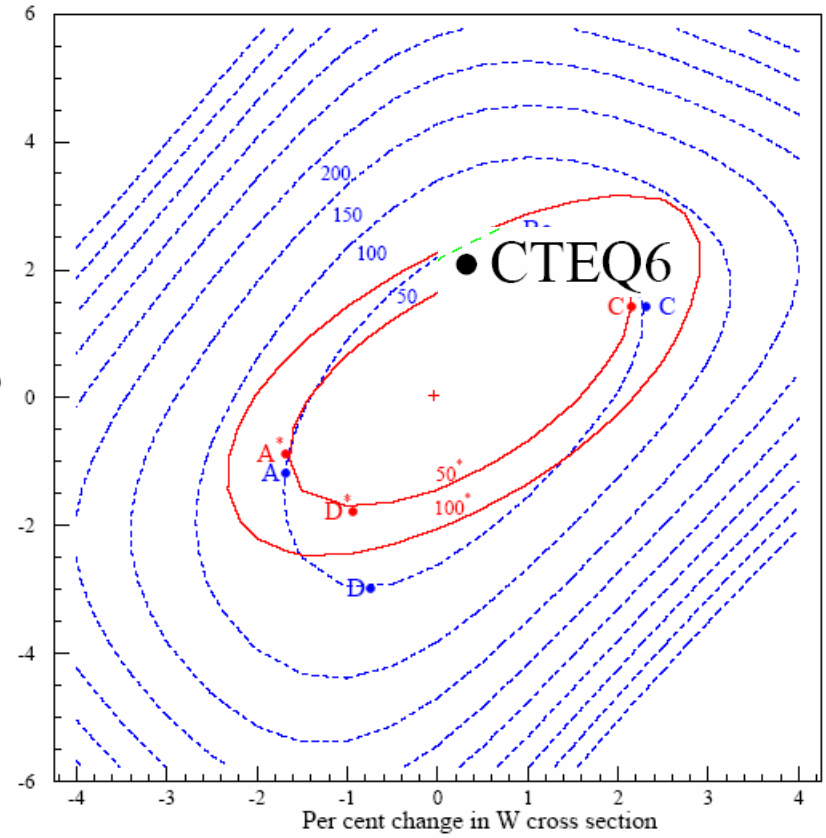
Higgs Physics

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

Tevatron



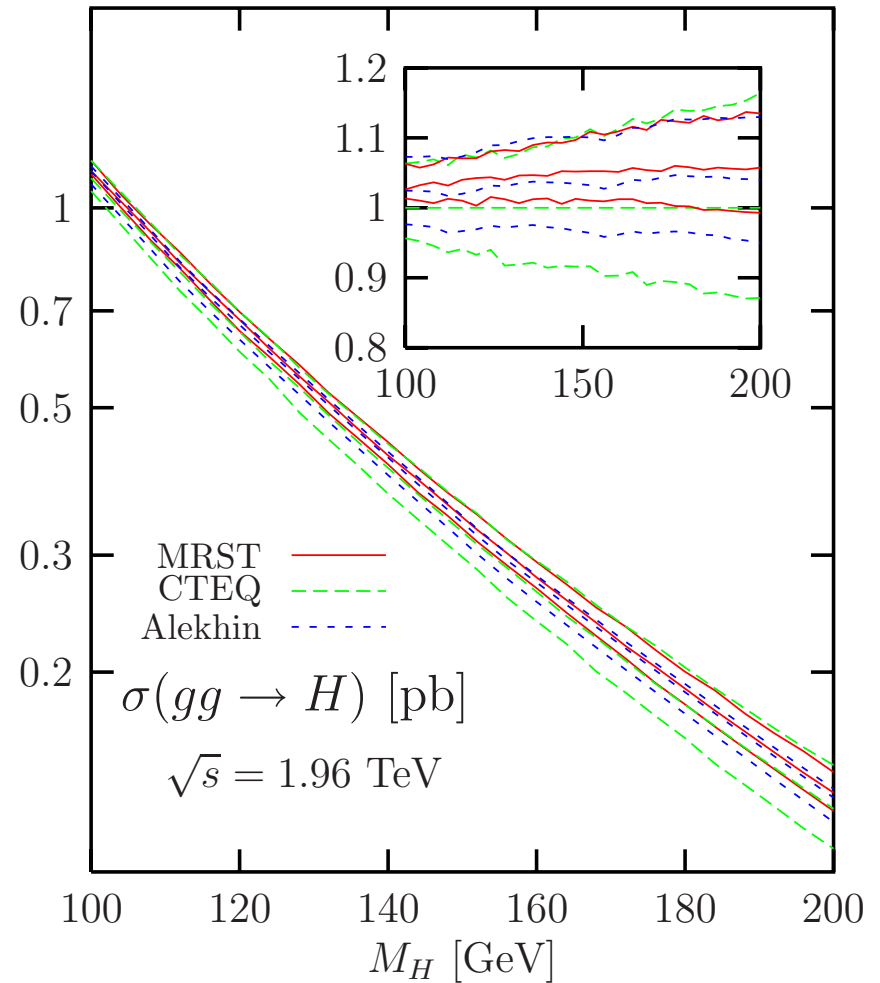
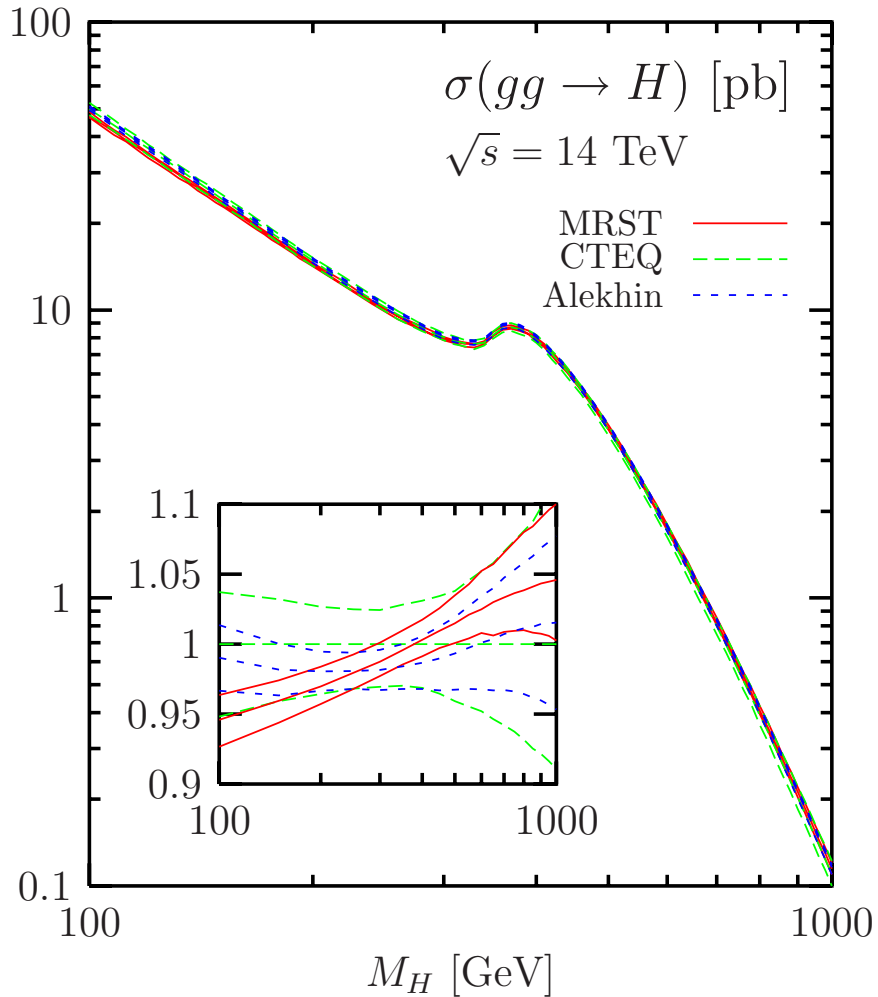
LHC



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

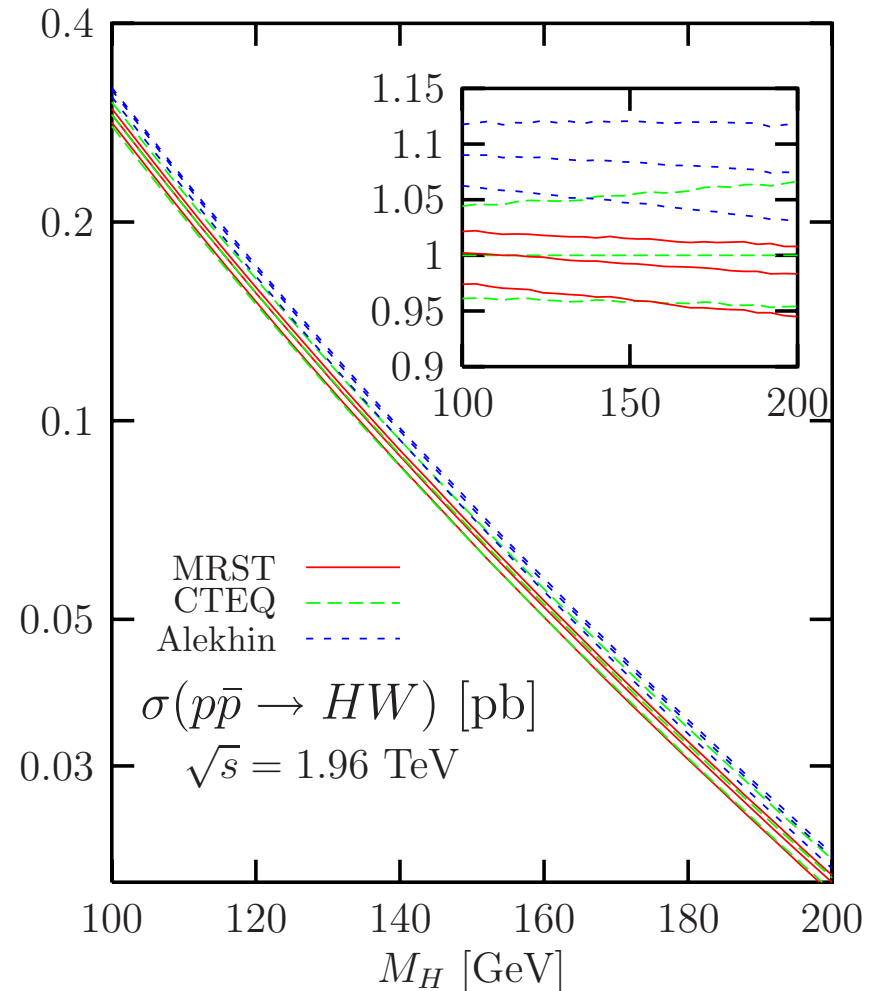
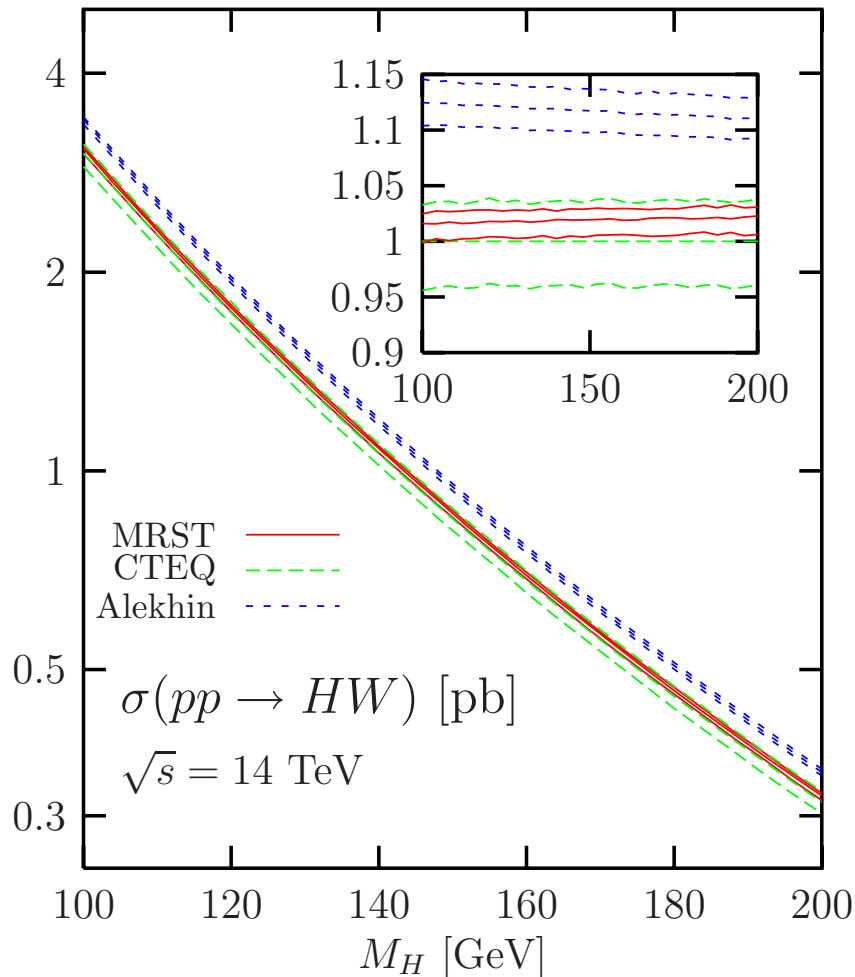
Higgs Physics at the Tevatron and LHC

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



Higgs Physics at the Tevatron and LHC

- Uncertainties due to PDFs for $pp \rightarrow HW$



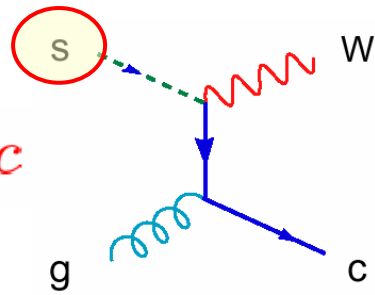
What can HCP contribute to Global QCD Analysis of nuclear structure (i.e. PDFs)

- **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 $W/Z/\gamma + c/b$?

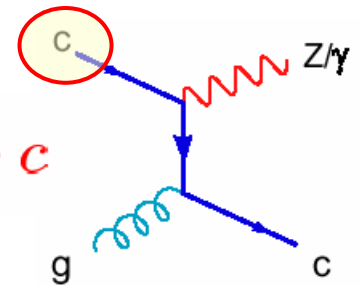
$s(x, Q)$:

$$g + s \rightarrow W + c$$



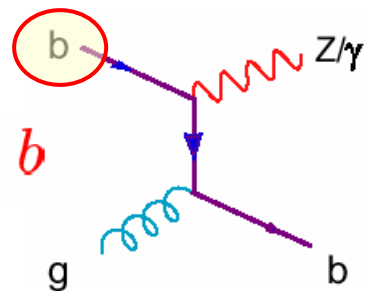
$c(x, Q)$:

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

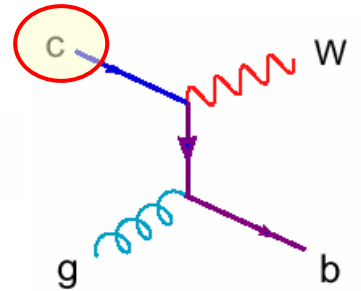


$b(x, Q)$:

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



$$g + c \rightarrow W + b$$



Global QCD Analysis and Hadron Collider Physics

The role of QCD, and global QCD analysis in Hadron Collider Physics

Ubiquitous

Global QCD analysis:

- **Progress:** how far have we come along? A lot
- **Open Issues:** how far do we have to go?
 - Experimental and theoretical uncertainties
 - Gluon; flavor SU(2) structure
 - Strangeness and heavy quark structure

A lot, on all these fronts

What can global QCD analysis do for hadron collider physics?

- Standard Candle processes
- Precision W/Z/jet phenomenology
- Precision Top/Higgs phenomenology
- Predictions on New Physics processes

Significantly for all these tasks

How can hadron collider physics contribute to global QCD analysis of nucleon structure?

A great deal