SM Measurements and PDF

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In collaboration with
CTEQ-TEA

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Exploring the Physics Frontier with Circular Colliders, Aspen

CTEQ-TEA group

- CTEQ – Tung et al. (TEA)

  in memory of Prof. Wu-Ki Tung, who established CTEQ Collaboration in early 90's

- Current members:

Sayipjamal Dulat (Xinjiang Univ.)

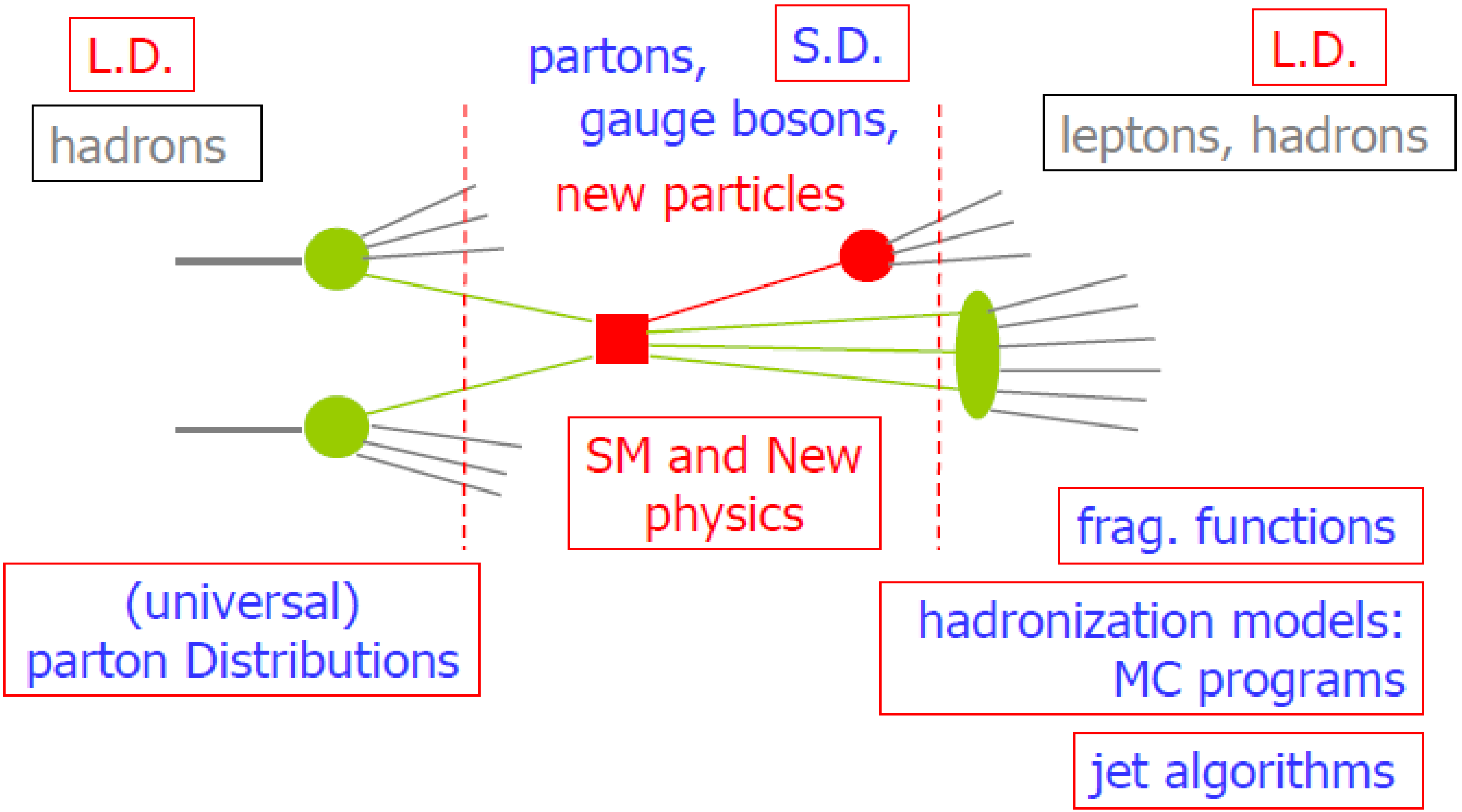
Southern Methodist Univ. -- Pavel Nadolsky, Jun Gao, Marco Guzzi, Tie-Jiun Hou

Michigan State Univ. -- Joey Huston, Jon Pumplin, Dan Stump, Carl Schmidt, C.-P. Yuan

Parton Distribution Functions

Needed for making theoretical calculations to compare with experimental data

Hadron Collider Physics



Outline

1) CT10 NLO/NNLO PDFs review and update

   Gao et al, PRD **89**, 033009 (2014)

2) Update of Intrinsic Charm Analysis

   Dulat et al, PRD **89**, 073004 (2014)

4) Lagrange Multiplier (LM) Uncertainty Analysis on gg->H

   Dulat et al, arXiv:1309.0025[hep-ph]

5) Lagrange Multiplier (LM) Uncertainty Analysis on gg-> t tbar

6) PDF Benchmarking

7) PDFs for Future Hadron Collider

CT10 NNLO PDFs and Beyond

CT10 NNLO error PDFs

Available at http://hep.pa.msu.edu/cteq/public/ct10_2012.html**;**
LHAPDF;

Complements the CT10/CT10W NLO PDF sets *(Lai et al., PRD82, 074024 (2010))*

- **Includes only "pre-LHC" CT10 data.** Can be used to predict LHC cross sections based on pre-LHC experimental inputs
- Same input parameters, functional forms for input PDFs as in the CT10 NLO PDFs
  - $\alpha_s(M_Z) = 0.118 \pm 0.002$, $m_c^{pole} = 1.3$ GeV, $m_b^{pole} = 4.75$ GeV
  - Simpler assumptions about the PDF flavor composition at $\mu_0 = m_c^{pole} = 1.3$ GeV, e.g., $\bar{u}(x)/\bar{d}(x) \to 1$ as $x \to 0$

CT10 NNLO PDFs

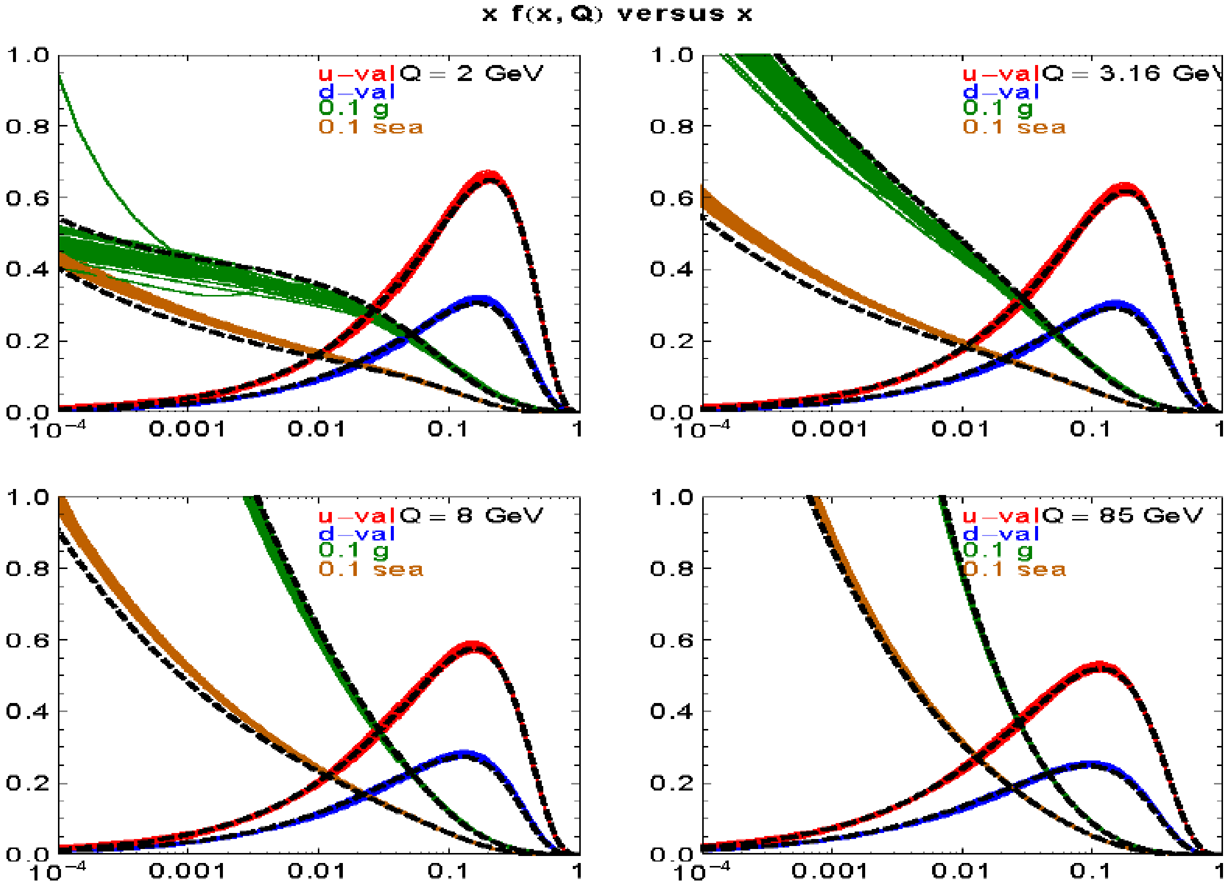


Figure 3: CT10-NNLO parton distribution functions. These figures show the *alternate fits* for the CT10-NNLO analysis. Each graph shows $x\, u_{\text{valence}} = x(u - \overline{u})$, $x\, d_{\text{valence}} = x(d - \overline{d})$, $0.10\, x\, g$ and $0.10\, x\, \overline{q}$sea as functions of x for a fixed value of Q. The values of Q are $2, 3.16, 8, 85$ GeV. Sea $= 2(\overline{d} + \overline{u} + \overline{s})$. The dashed curves are the central NLO fit, CT10.

DGLAP evolution for PDFs

- Non-perturbative PDFs are determined at the scale of Q=1.3 GeV.

- PDFs at any other scale Q can be obtained from pQCD,
via solving DGLAp evolution equations.

- Due to DGLAP evolution, the PDF error band becomes smaller
when the energy scale Q increases.

- The evolution effect is large in low Q region, say,
from 1.3 GeV to 8 GeV.

The CT10-NNLO global analysis of QCD

Parametrization of PDFs at Q = 1.3 GeV, with 25 parameter values to be chosen; there are from 4 to 6 parameters for each parton type.

Many data sets, for short distance interactions.

Perturbative QCD, using NNLO approximations wherever available.

Taking account of ***experimental errors***, statistical and systematic.

(Not so strong on systematic ***theoretical errors***.)

Heavy flavor mass effects are included using the ***S-ACOT-χ*** factorization formalism (extended to NNLO).

Details of the CT10 NNLO computation

- **NNLO hard-scattering contributions in DIS** (in the S-ACOT-χ mass scheme) and **vector boson production** (NNLO K factors from FEWZ for $d\sigma/dy$; NNLL/NLO+K from ResBos for W charge asymmetry)

- NNLO evolution for α_s and PDFs (HOPPET)
  - matching coefficients relating the PDFs in N_f and N_{f+1} schemes *(Smith, van Neerven, et al.)*

- Pole quark masses or $\overline{MS}$ quark masses as an input
  - CT10 NNLO: pole masses $m_c = 1.3$ GeV, $m_b = 4.75$ GeV

28 data sets used for the CT10-NNLO global analysis

CT10-NNLO Table	Ndp	Chi^2	Nsy	
1/ 159 HERA1X0	579	617.	114	Combined HERA1 NC+CC DIS (2009)
2/ 101 BcdF2pCor	339	392.	5	BCDMS collaboration
3/ 102 BcdF2dCor	251	291.	5	BCDMS collaboration
4/ 103 NmcF2pCor	201	333.	11	NMC collaboration
5/ 104 NmcRatCor	123	151.	5	NMC collaboration
6/ 108 cdhswf2	85	70.5	0	P Berge et al Z Phys C49 187 (1991)
7/ 109 cdhswf3	96	77.9	0	P Berge et al Z Phys C49 187 (1991)
8/ 110 ccfrf2.mi	69	67.8	5	Yang&Bodek model-independent
9/ 111 ccfrf3.md	86	34.8	0	Shaevitz&Seligman model-dependent processed by SK
10/ 201 e605	119	95.7	0	DY Q^3 dSig/dQ dy proton on heavy target
11/ 203 e866f	15	9.7	0	E866 experiment: pd / 2pp
12/ 225 cdfLasy	11	13.4		W production: decay lepton asymmetry CDF Run-1
13/ 140 HN+67F2c	8	9.3	0	H1 neutral current charm
14/ 143 HN+90X0c	10	16.3	8	H1 neutral current charm
15/ 156 ZN+67F2c	18	13.4	0	ZEUS neutral current charm
16/ 157 ZN+80F2c	27	16.7	0	ZEUS neutral current charm
17/ 124 NuTvNuChXN	38	29.6	0	NuTev Neutrino Dimuon Reduced xSec
18/ 125 NuTvNbChXN	33	28.4	0	NuTev Neutrino Dimuon Reduced xSec
19/ 126 CcfrNuChXN	40	48.0	0	Ccfr Neutrino Dimuon Reduced xSec
20/ 127 CcfrNbChXN	38	26.4	0	Ccfr Neutrino Dimuon Reduced xSec
21/ 204 e866ppxf	184	234.	0	E866 experiment: DY pp: Q^3 dSig/dQ dxf
22/ 260 ZyD02a	28	15.6	6	Z rapidity dist. (D0 TeV II-a)
23/ 261 ZyCDF2	29	46.5	6	Z rapidity dist. (CDF TeV II)
24/ 227 cdfLasy2	11	11.4	0	W production: decay lepton asymmetry CDF Run-2
25/ 231 d02Easy1	12	26.0	0	W production: decay elec asymmetry D0 Run-2 Pt>25
26/ 234 d02Masy1	9	14.8	0	W production: decay muon asymmetry D0 Run-2 Pt>20
27/ 504 cdf2jtCor2	72	101.	24	(run II: cor.err; ptmin & ptmax)
28/ 514 d02jtCor2	110	114.	23	(run II: cor.err; ptmin & ptmax)

Experimental "Errors" (or, Uncertainties)

An experiment publishes N measurements,

$\{M_i\ ;\ i = 1,2,3,\ldots,N\}$.

Each measurement has several parts,

$M_i = \{D_i\ ;\ \sigma_{0i}\ ;\ \{\sigma_{1i}, \sigma_{2i}, \sigma_{3i}, \ldots\}\}$

= {central value; SD of statistical error; SDs of correlated systematic errors};

that is,

$$D_i = \quad True_i + \sigma_{0i}\ r_{0i} + \sum_{k=1}^{Nsy} \sigma_{ki}\ r_k$$

…where r_{0i} and $\{r_k\}$ are random variables (gaussian?)

Define $$\chi^2 = \sum_i \ (D_i - \sum_k \sigma_{ki} r_k - T_i)^2 / \sigma_{0i}^2 + \sum_k r_k^2$$

…and minimize with respect to both the normalized systematic shifts $\{r_k\}$ and the theory parameters.

HERA : ē P → ē X

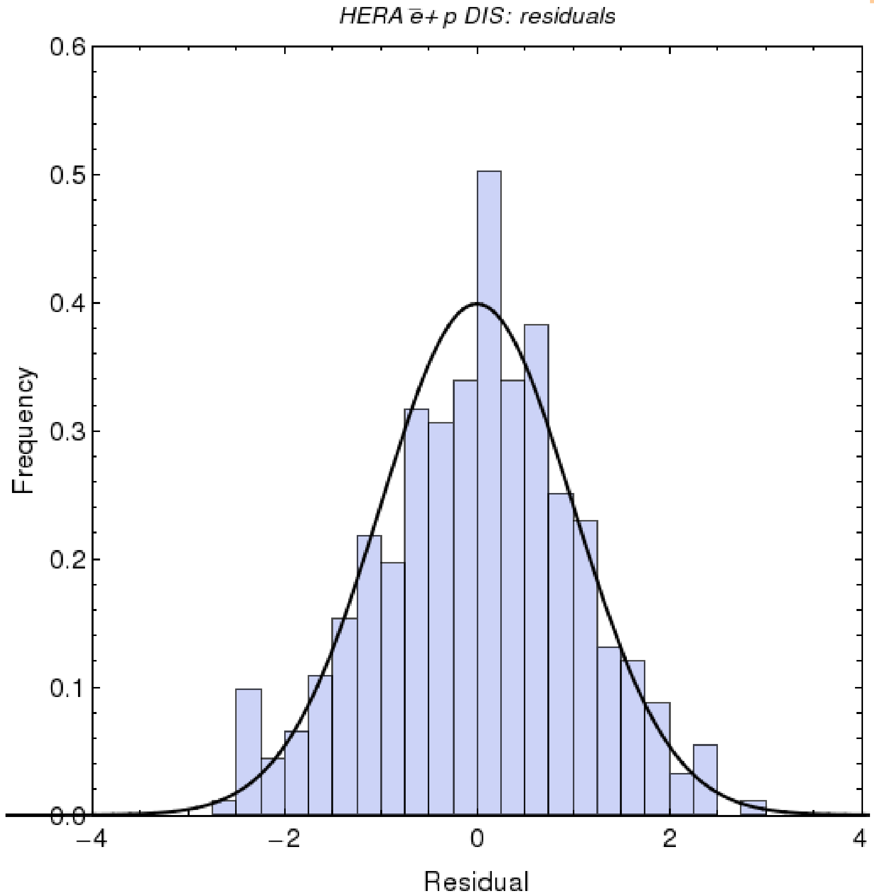
"Histogram of Residuals"

We define the *residual* by

$$\text{Residual}_{\,\text{i}} = \frac{sD_i - T_i}{\sigma_{0i}}$$

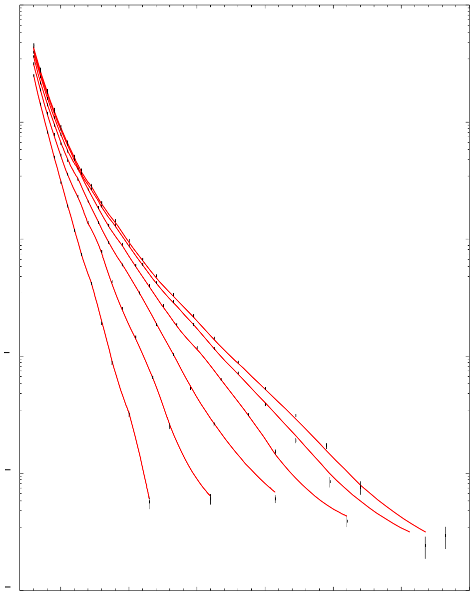
(i = 1, 2, 3, …, NDP)

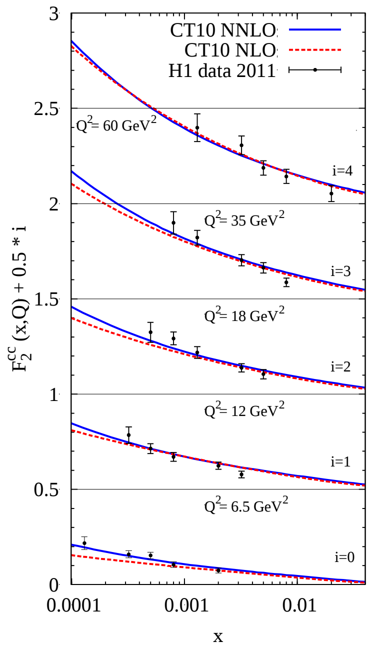
For good agreement between data and theory , the residuals should have a Gaussian distribution with mean = 0 and standard deviation = 1.

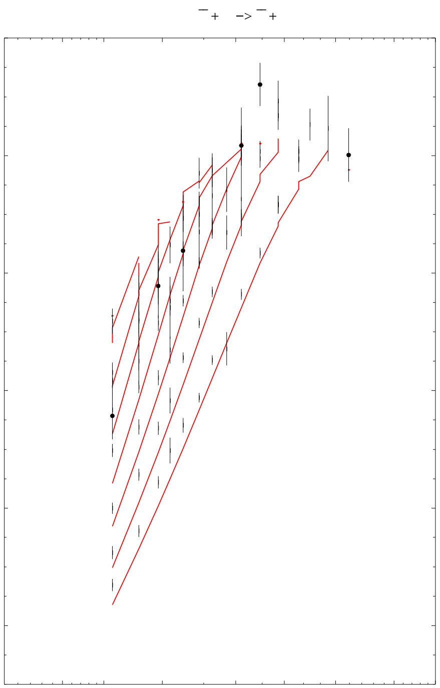


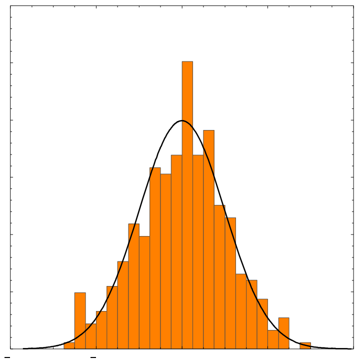
Theory = CT10-NNLO, i.e., ***<u>the central fit</u>***;
sData = Data ***MINUS*** the optimized systematic errors;
Black curve = ideal Gaussian distribution

CT10NNLO vs. fitted data







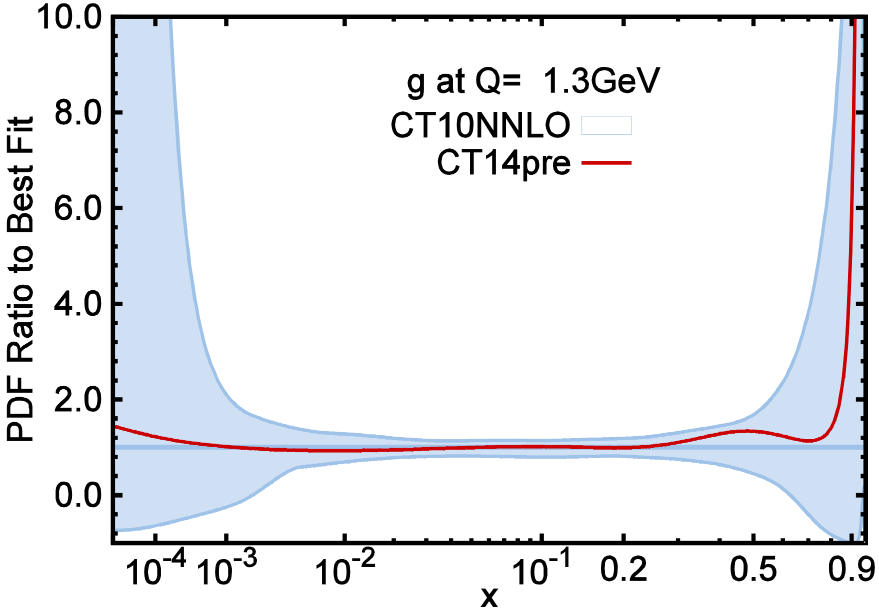


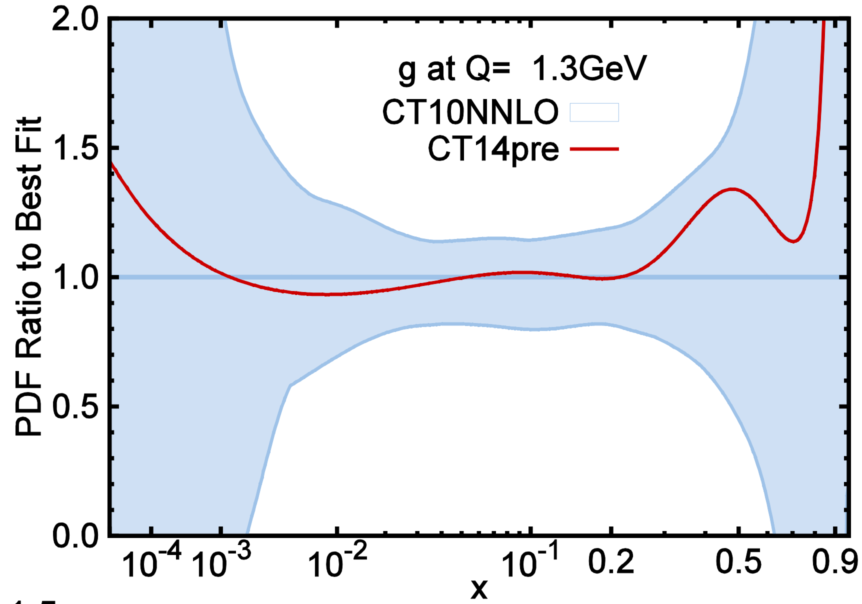
Fits well: $\chi^2 / N_{pt} = 2950/2641 = 1.11$

CT10 NNLO PDFs

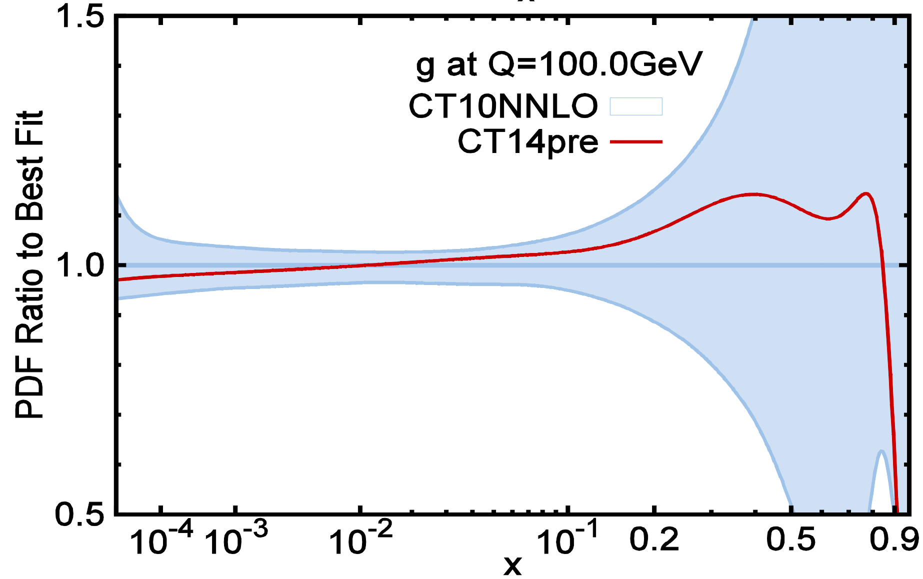
- PDF error bands
  - u and d PDFs are best known
  - currently no constraint for x below 1E-4
  - large error for x above 0.3
  - larger sea (e.g., ubar and dbar) quark uncertainties in large x region
  - with non-perturbative parametrization form dependence in small and large x regions
- PDF eigensets
  - useful for calculating PDF induced uncertainty
  - sensitive to some special (combination of) parton flavor(s).
  - (e.g., eigenset 7 is sensitive to d/u or dbar/ubar; hence, W asymmetry data at Tevatron and LHC.)

CT10 and CT14 NNLO PDFs

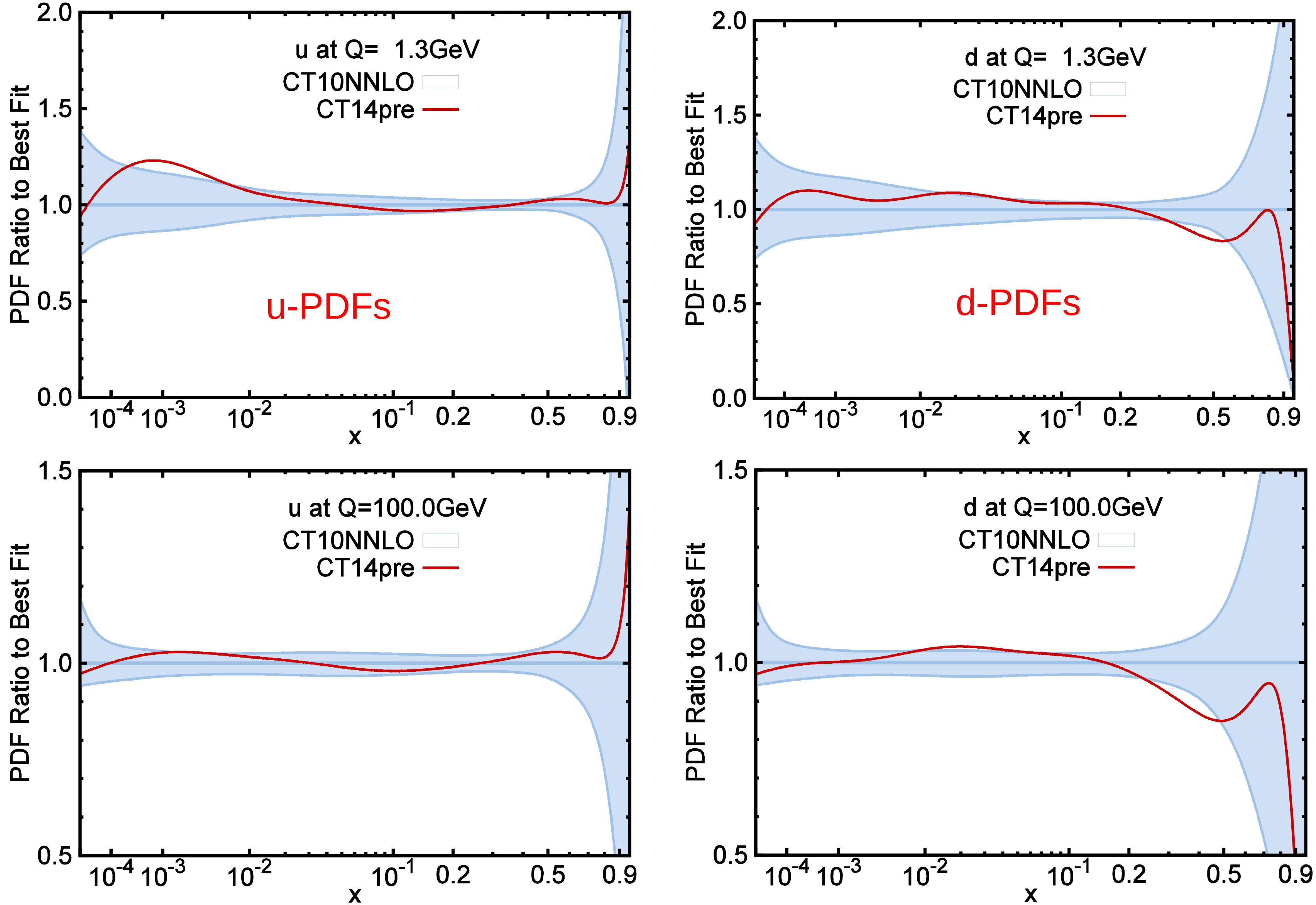




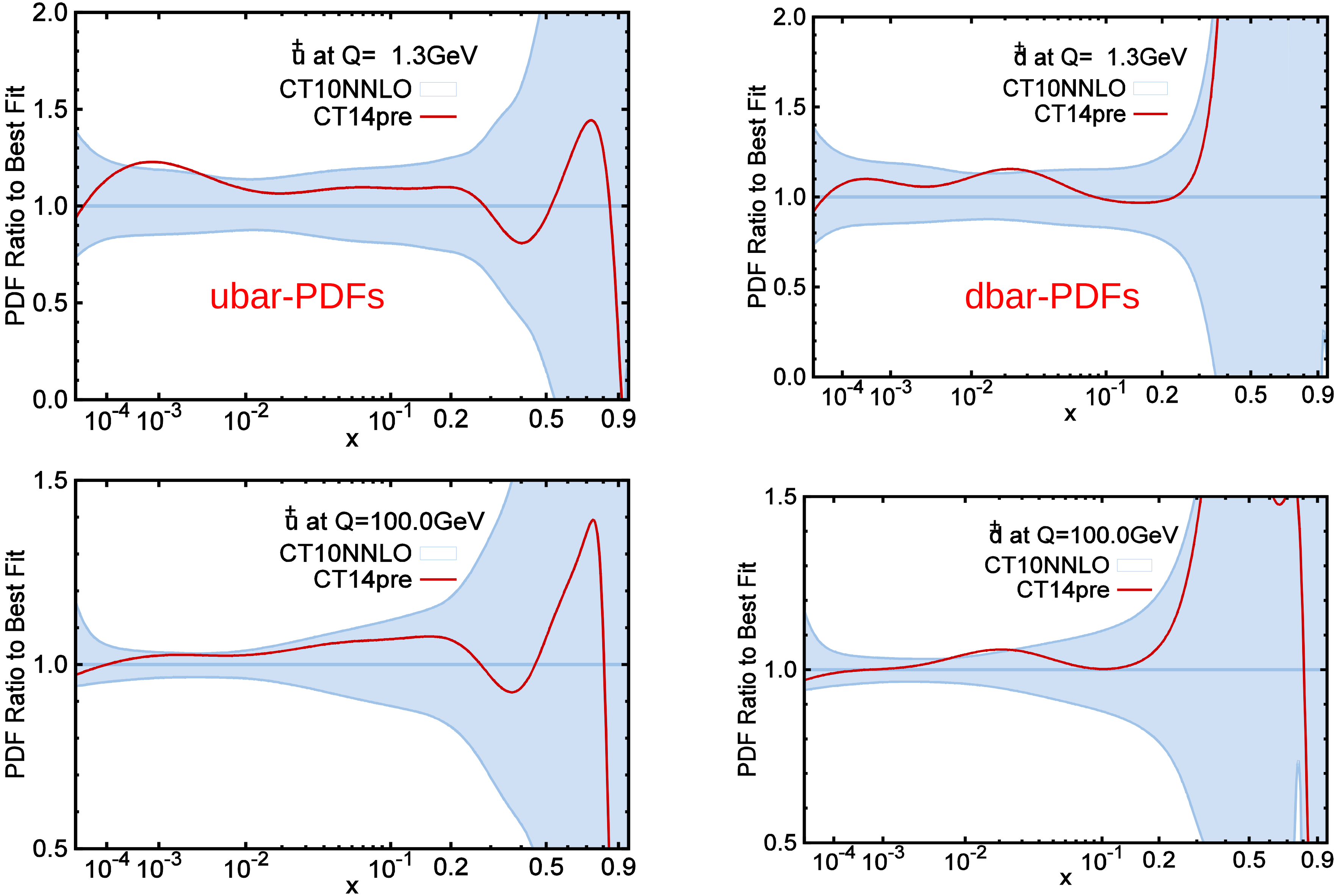
Gluon PDFs



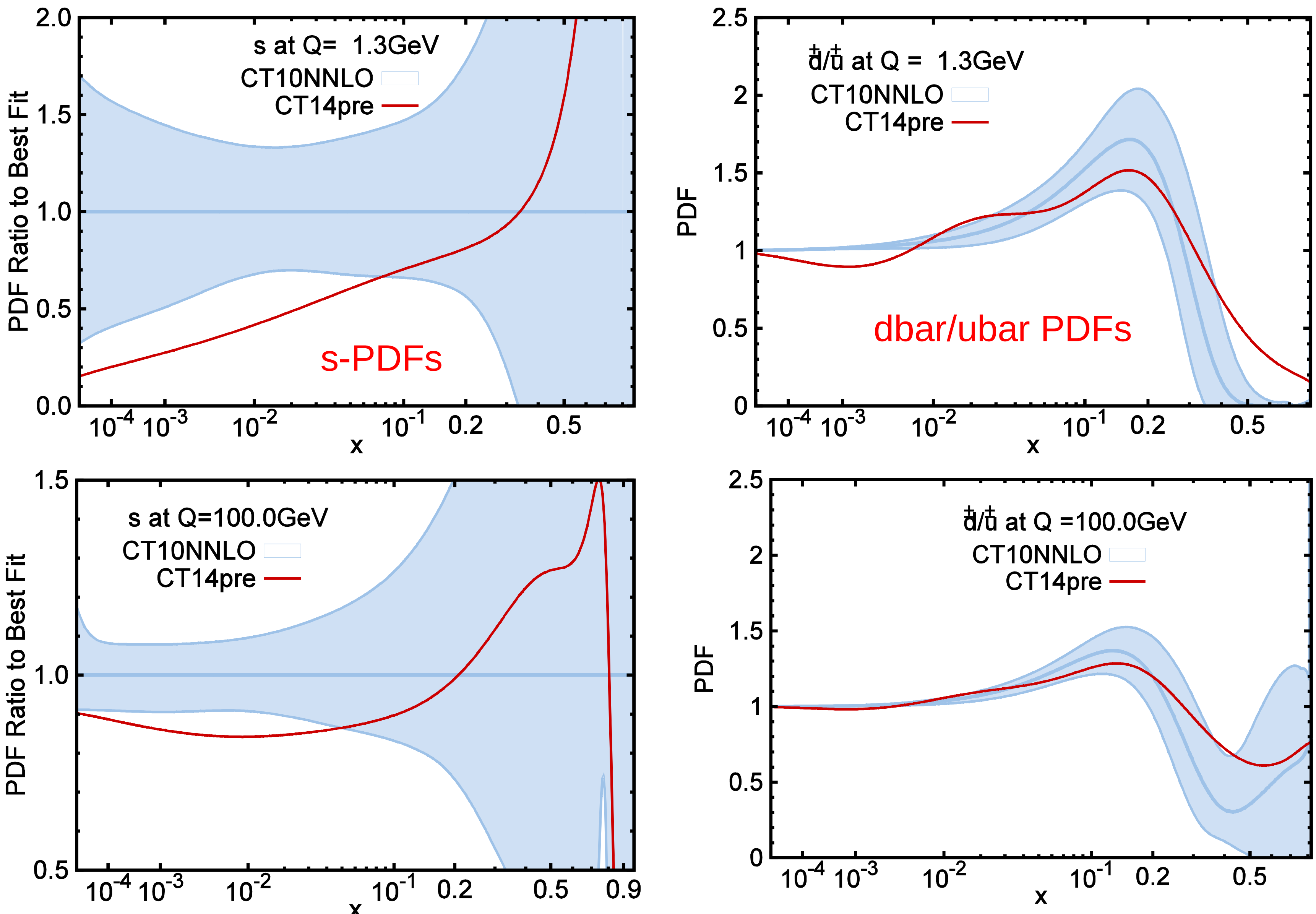
CT10 and CT14 NNLO PDFs



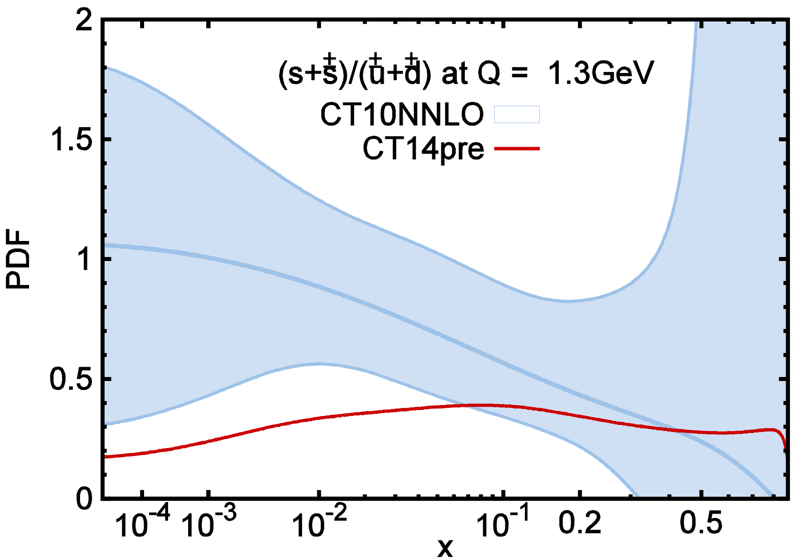
CT10 and CT14 NNLO PDFs

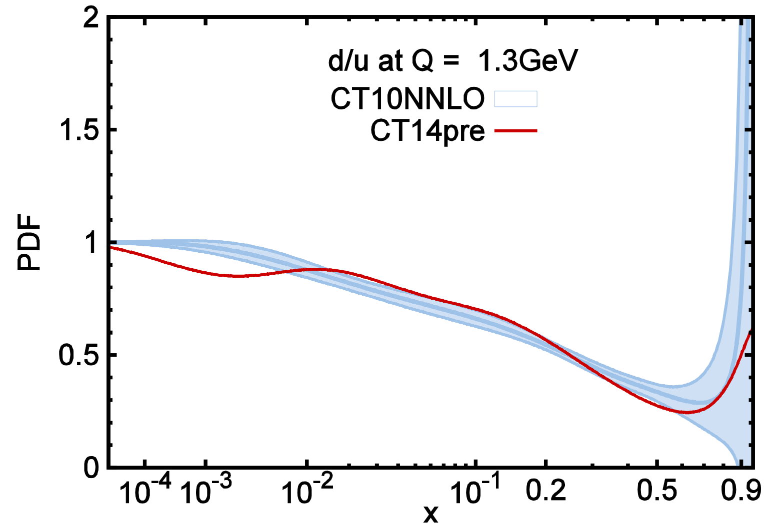


CT10 and CT14 NNLO PDFs



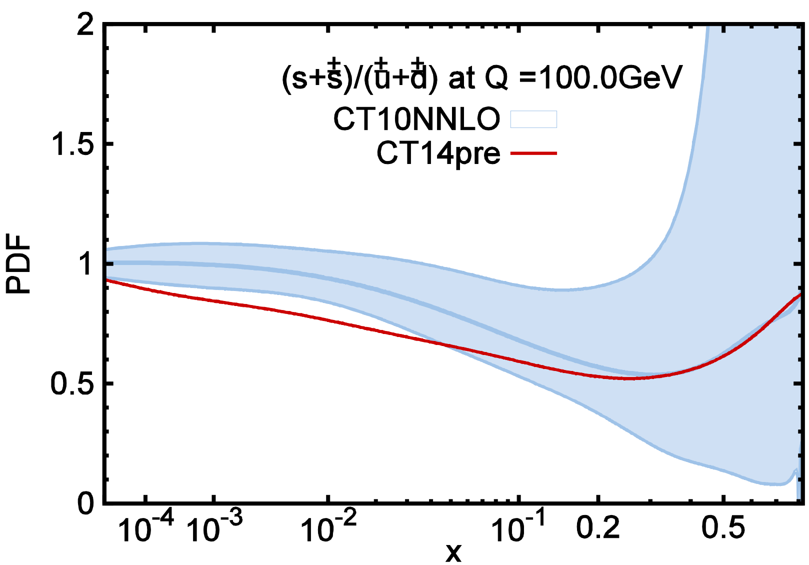
CT10 and CT14 NNLO PDFs

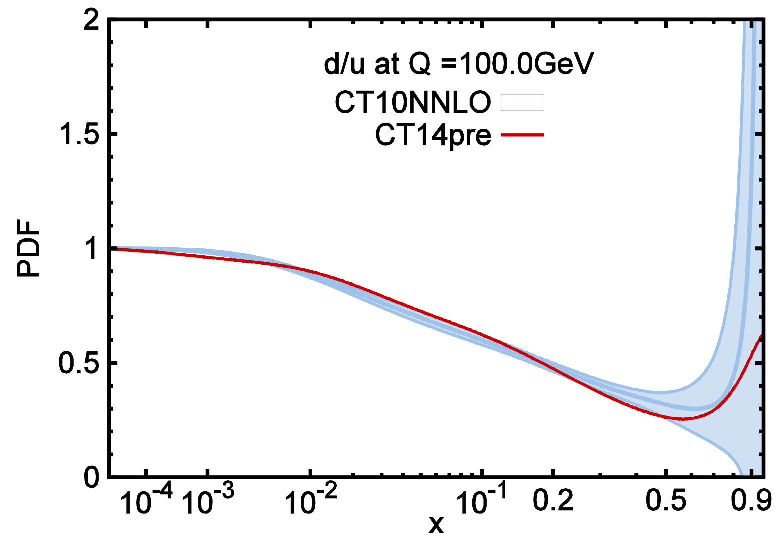




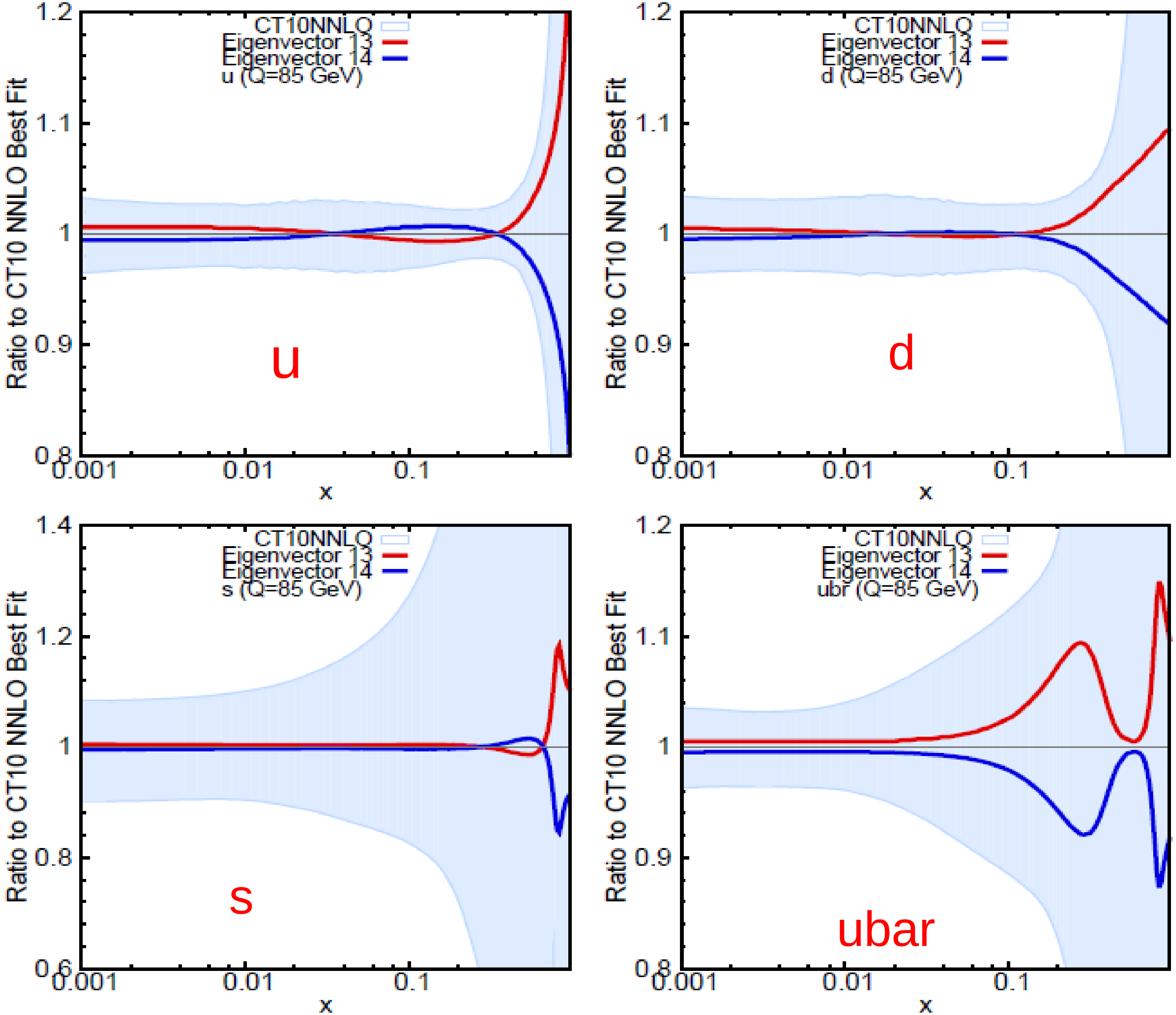
(s+sbar)/(ubar+dbar) PDFs

d/u PDFs

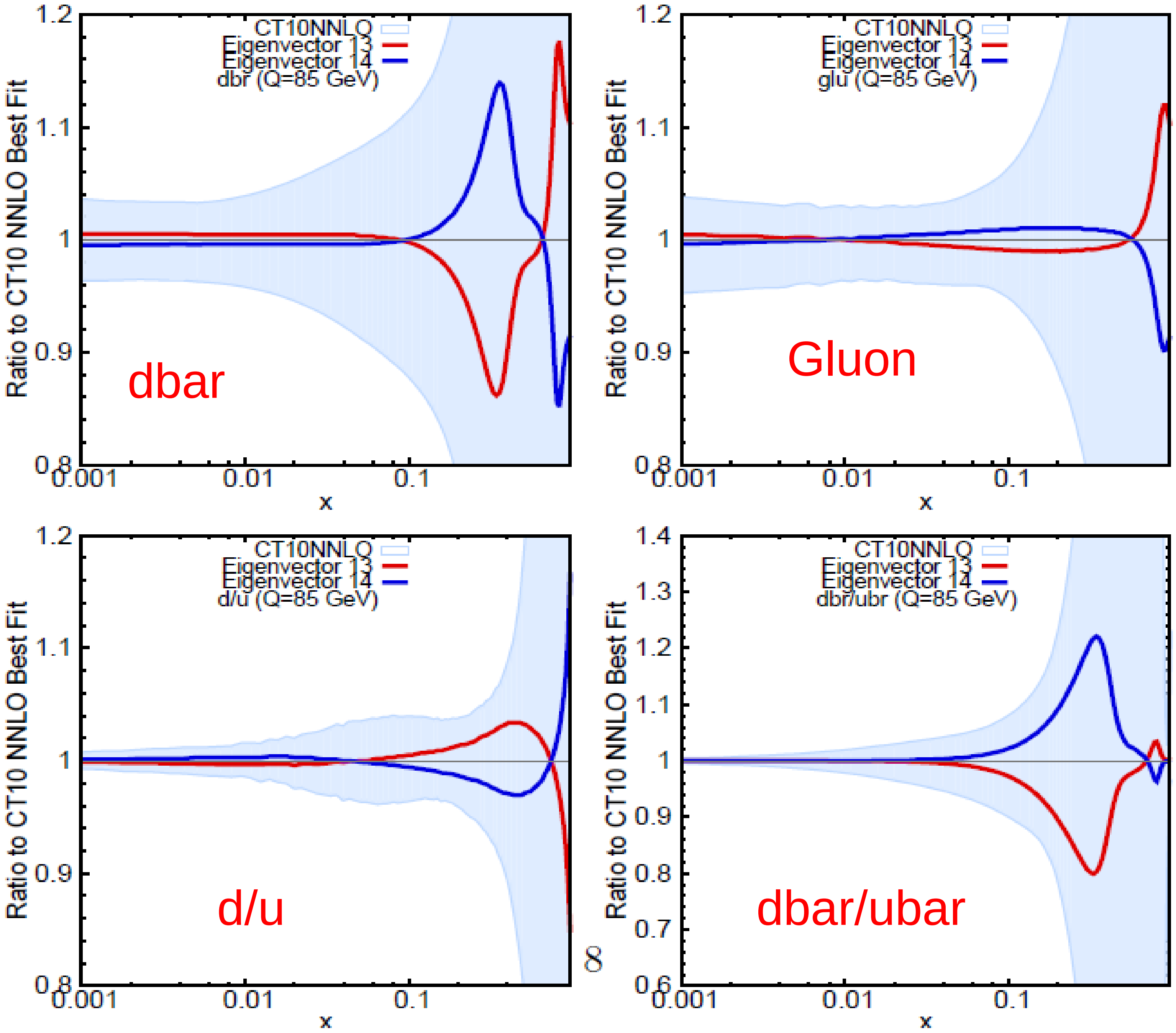




7th CT10 Eigenset

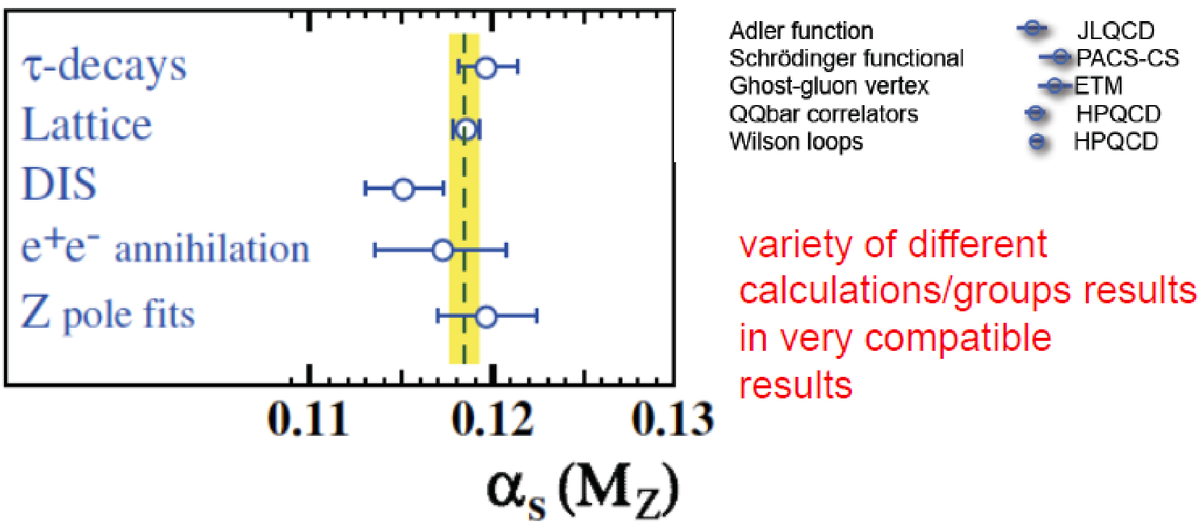


7th CT10 Eigenset



$\alpha_s(m_Z)$

- Right now the Higgs Cross Section Working Group is using a mean value for $\alpha_s(m_Z)$ of 0.118 with 90% CL error of 0.002 (68%CL error of 0.0012), or an inflation of the world average uncertainties; the α_s error is added in quadrature with the PDF error
- The world average is dominated by lattice results



variety of different calculations/groups results in very compatible results

Figure 1-1. *Summary of values of $\alpha_s(M_Z^2)$ obtained for various sub-classes of measurements. The world average value of $\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$ is indicated by the dashed line and the shaded band. Figure taken from [1].*

NNLO cross section and PDF induced uncertainty for gg->H (using ResBos2 program)

$$\Delta\sigma_{\rm PDF} = \frac{1}{2}\sqrt{\sum_{i=1}^{d}\left(\sigma_i^{(+)} - \sigma_i^{(-)}\right)^2}.$$

$\alpha_S(M_Z) = 0.118$

arXiv:1205.4311 [hep-ph]

M=125 GeV

	CTEQ6.6	CT10 NLO	CT10W NLO	CT10 NNLO	MSTW2008NNLO	NNPDF2.3NNLO
Tevatron	$0.77 \pm 6.9\%$	$0.77 \pm 6.9\%$	$0.76 \pm 7.0\%$	$0.77 \pm 6.9\%$	$0.78 \pm 6.4\%$	$0.80 \pm 4.6\%$
LHC 7 TeV	$12.80 \pm 6.1\%$	$13.33 \pm 6.1\%$	$12.82 \pm 5.1\%$	$12.65 \pm 5.8\%$	$12.69 \pm 4.5\%$	$13.73 \pm 3.0\%$
LHC 8 TeV	$16.31 \pm 5.5\%$	$16.53 \pm 5.5\%$	$16.95 \pm 4.8\%$	$16.63 \pm 5.6\%$	$16.30 \pm 4.5\%$	$16.90 \pm 5.5\%$
LHC 14 TeV	$42.39 \pm 8.5\%$	$42.64 \pm 8.5\%$	$42.91 \pm 7.1\%$	$41.87 \pm 7.7\%$	$43.10 \pm 6.4\%$	$43.28 \pm 5.9\%$

TABLE II: The total cross sections (in pb) for Higgs boson production via $g + g \to H + X$ at the Tevatron (1.96 TeV) and LHC (7 TeV, 8 TeV and 14 TeV) by using different PDF sets in ResBos2. The PDF induced uncertainties are estimated at 90% confidence-level, and expressed in the form of percentages.

Uncertainties of cross sections for gg->H (using ResBos2 program)

$$\Delta\sigma_{\alpha_s} = \frac{1}{2}\sqrt{[\sigma_0(A_{-2}) - \sigma_0(A_2)]^2}.$$

(at 90% CL, with the range of 0.116 to 0.120)

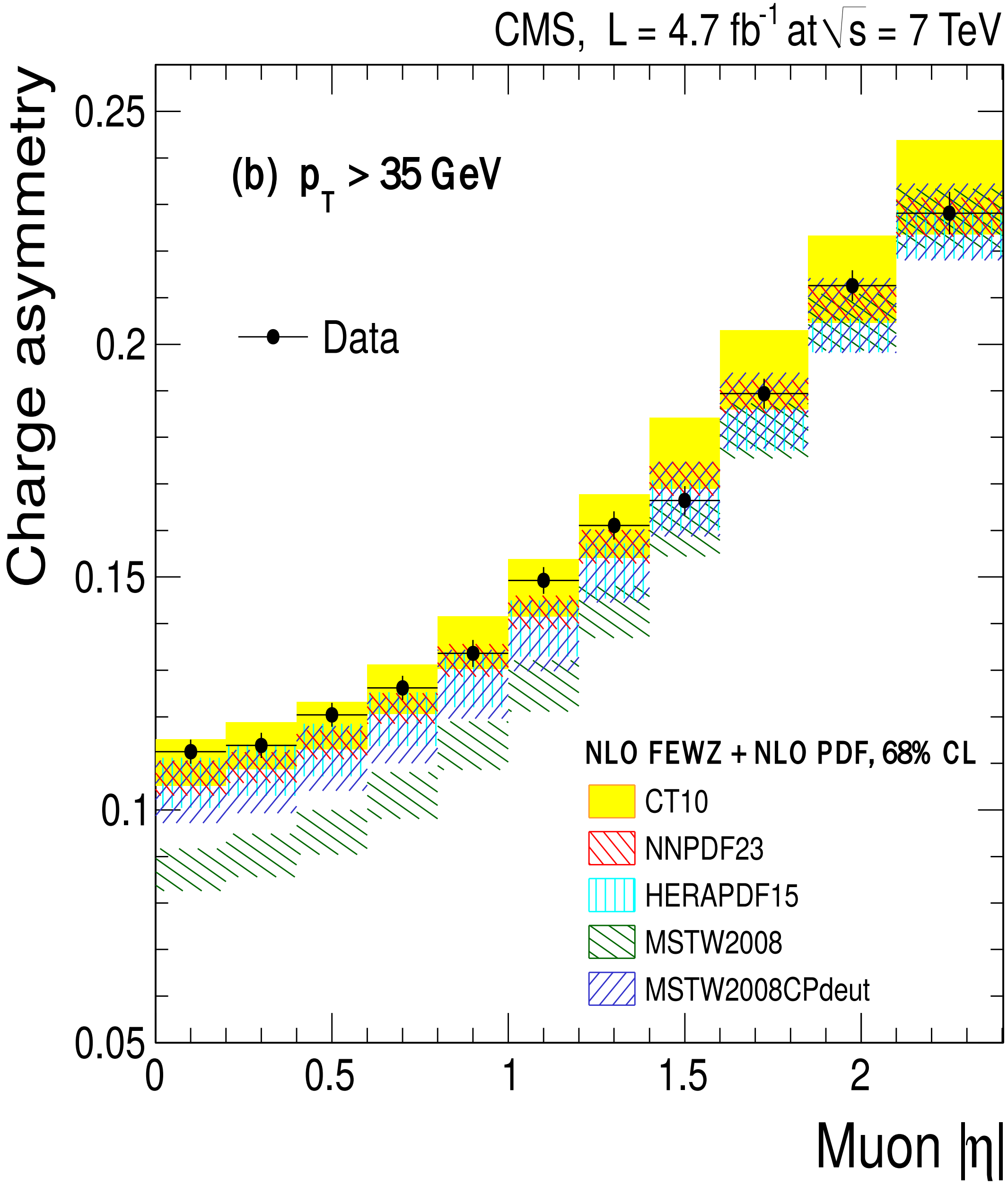
$\alpha_S(M_Z)$

CT10AS PDF sets

$$(\Delta\sigma)^2 = (\Delta\sigma_{\rm PDF})^2 + (\Delta\sigma_{\alpha_s})^2\,.$$

M=125 GeV

CT10-NNLO	σ_0	$\Delta\sigma_{\rm PDF}$	$\Delta\sigma_{\alpha_s}$	$\Delta\sigma = \sqrt{(\Delta\sigma_{\rm PDF})^2 + (\Delta\sigma_{\alpha_s})^2}$
Tevatron	0.77	$\pm 6.9\%$	$\pm 1.8\%$	$\pm 7.1\%$
LHC 7 TeV	12.65	$\pm 5.8\%$	$\pm 2.5\%$	$\pm 6.3\%$
LHC 8 TeV	16.63	$\pm 5.6\%$	$\pm 3.5\%$	$\pm 6.6\%$
LHC 14 TeV	41.87	$\pm 7.7\%$	$\pm 5.3\%$	$\pm 9.3\%$



Data is already more precise than current PDF uncertainty.

Will help to determine PDFs in small x region.

Most useful for determining dbar/ubar.

Intrinsic Charm and CT10IC

1) Update of CTEQ6.5 IC study from 2007 to CT10NNLO
   - includes combined H1 and ZEUS data, HERA inclusive charm

2) Recent CT10 global analysis study of charm quark mass:
   $m_c(m_c) = 1.15^{+0.18}_{-0.12}$ GeV   Gao et al, Eur.Phys.J. C73 (2013) 2541
   Use m_c(pole)=1.3 GeV for this study
   - some correlation between m_c and IC

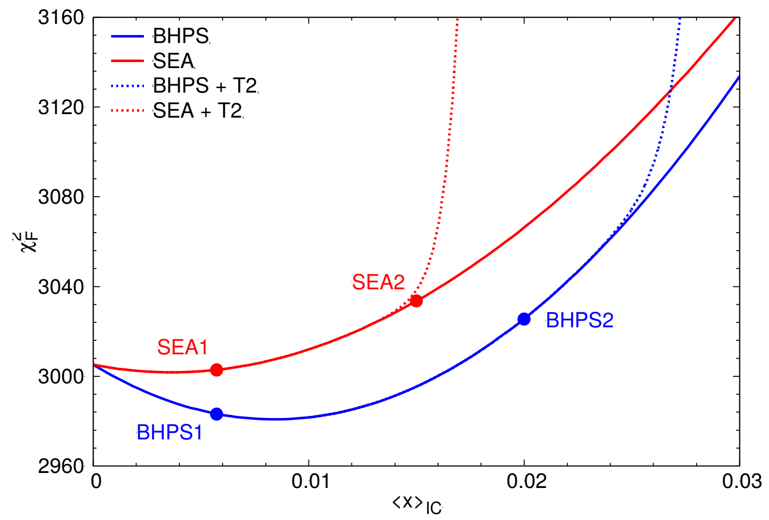
3) Two model Intrinsic Charm distributions at Q_c=1.3 GeV
   - BHPS valence-like model (Brodsky et al, Phys. Lett. **93B**, 451 (1980))
   - SEA-like model

$$\langle x \rangle_{\rm IC} = \int_0^1 x[\, c(x,Q_c) + \bar{c}(x,Q_c)]\, dx$$

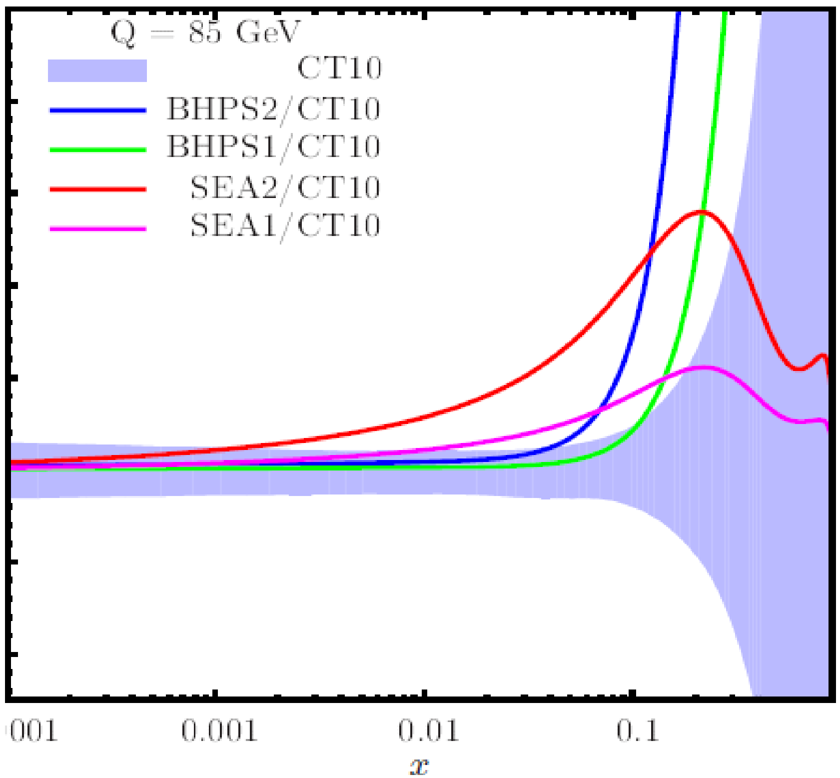
4) 90% CL limits:

$$\langle x \rangle_{\rm IC} \leq 0.025 \quad \text{BHPS}$$

$$\langle x \rangle_{\rm IC} \leq 0.015 \quad \text{SEA}$$



Intrinsic Charm at LHC

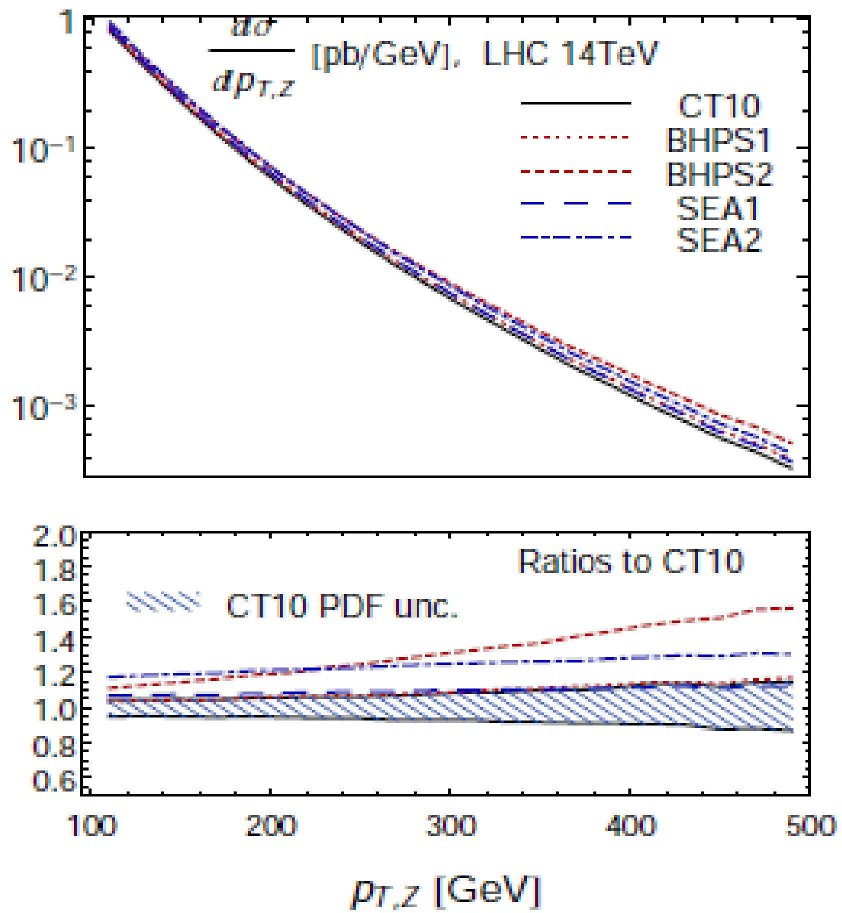


IC vs CT10 charm PDF

SEA1/BHPS1: $\langle x \rangle_{\mathrm{IC}} = 0.57\%$

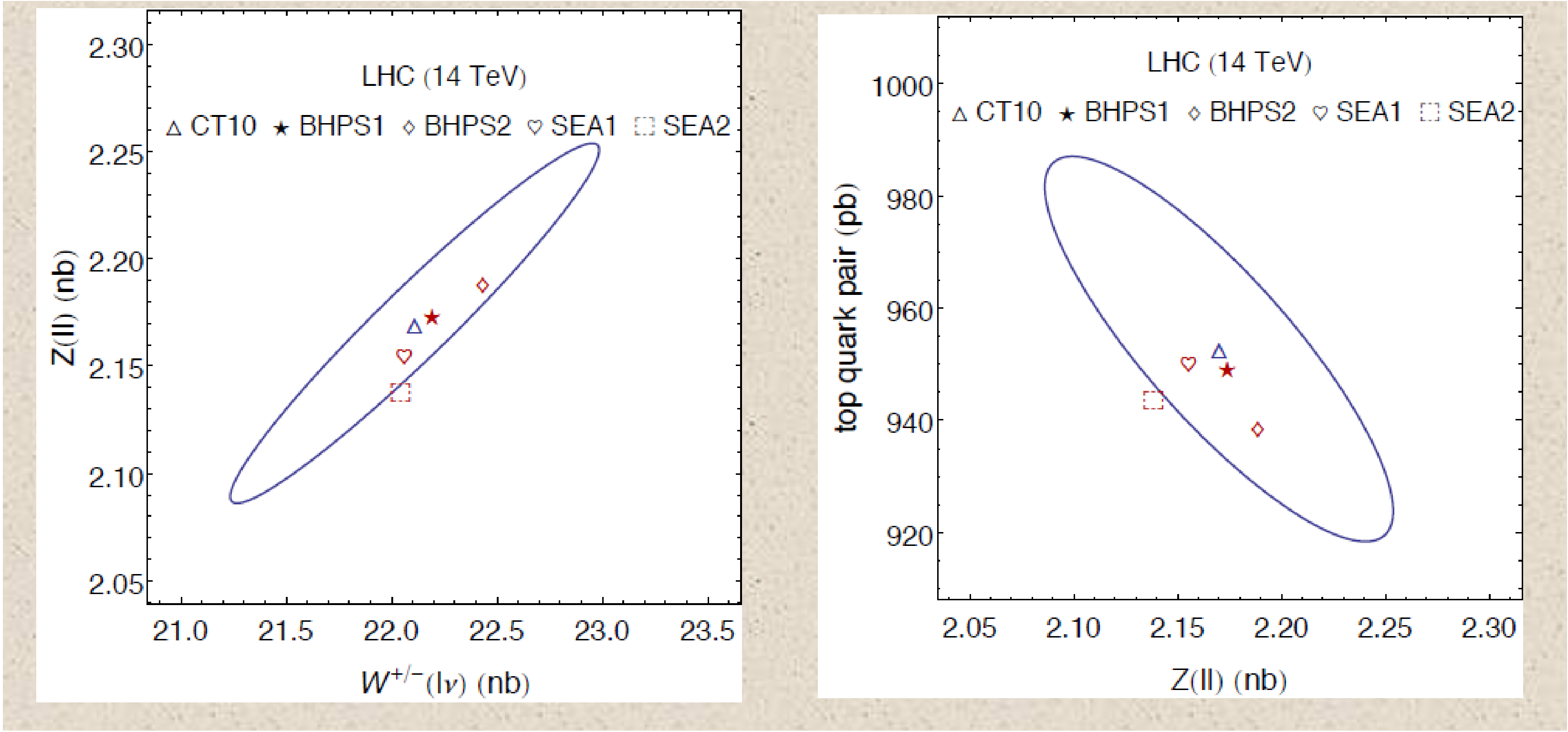
SEA2: $\langle x \rangle_{\mathrm{IC}} = 1.5\%$

BHPS2: $\langle x \rangle_{\mathrm{IC}} = 2.0\%$



$pp \rightarrow Zc$ at LHC may further constrain valence-like model

CT10 IC at LHC



W, *Z* and top production at LHC

CT10 IC distributions publicly available

PDF uncertainties in gg→H

1) Most analyses use Hessian Method (n error PDF sets)

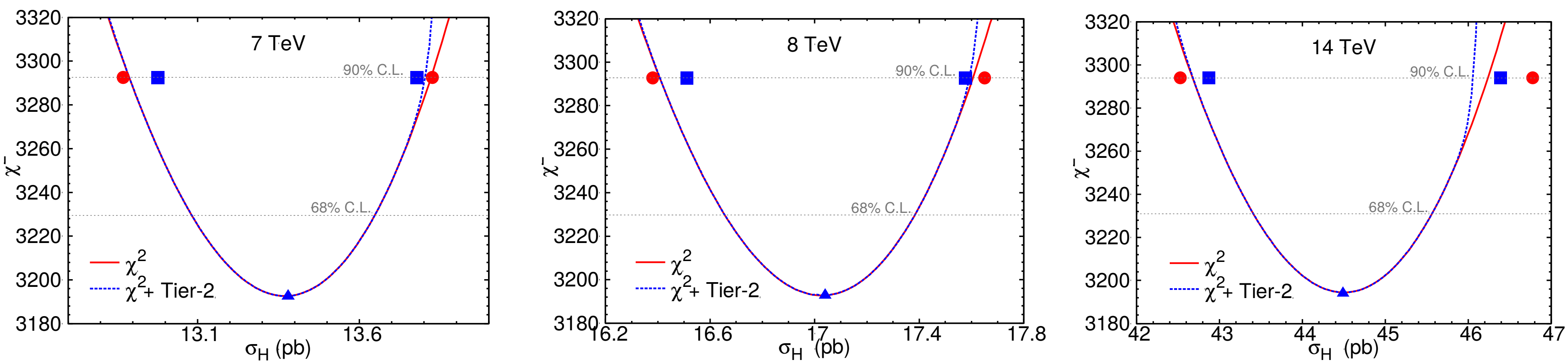
$$\left(\delta X\right)^2 = \frac{1}{4}\sum_{k=1}^{n}\left(X(a_k^+) - X(a_k^-)\right)^2$$

- Error sets can be used by anyone for any observable
- Assume quadratic and linear dependence of χ^2, X on a_k

2) Lagrange Multiplier (LM) method is more robust

- Find best fit for each constrained value of observable X
- No assumptions on dependence of χ^2, X on a_k
- Can validate Hessian method
- Can display correlations between PDFs and Observable
- Must calculate separately for each observable

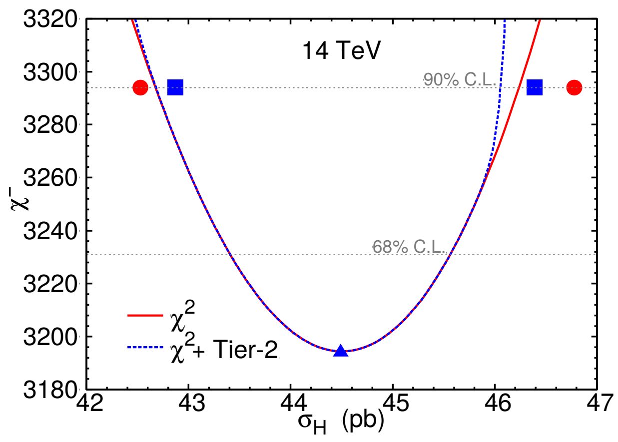
Uncertainties in gg→H

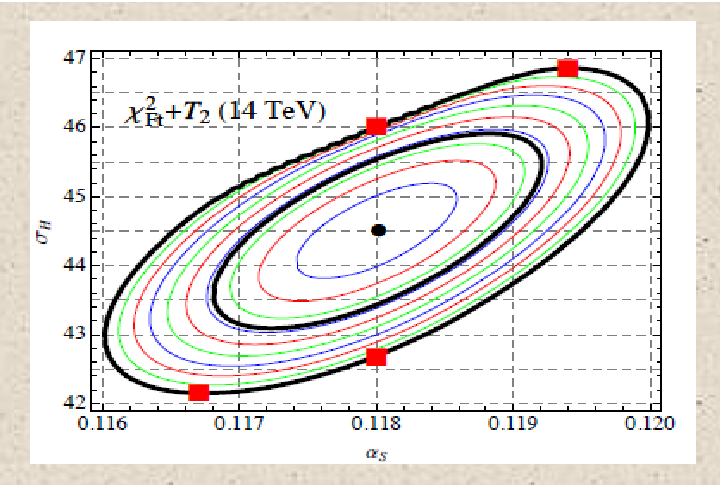


- Curves are LM, circles/squares are Hessian
- Red use χ^2
- Blue add Tier-2 penalty to ensure no specific experiment is too badly fit
- Allowed Tolerance is 100 at 90% CL

- Small differences in asymmetries, but in general the two methods agree well for this observable

LM Uncertainty in gg→H

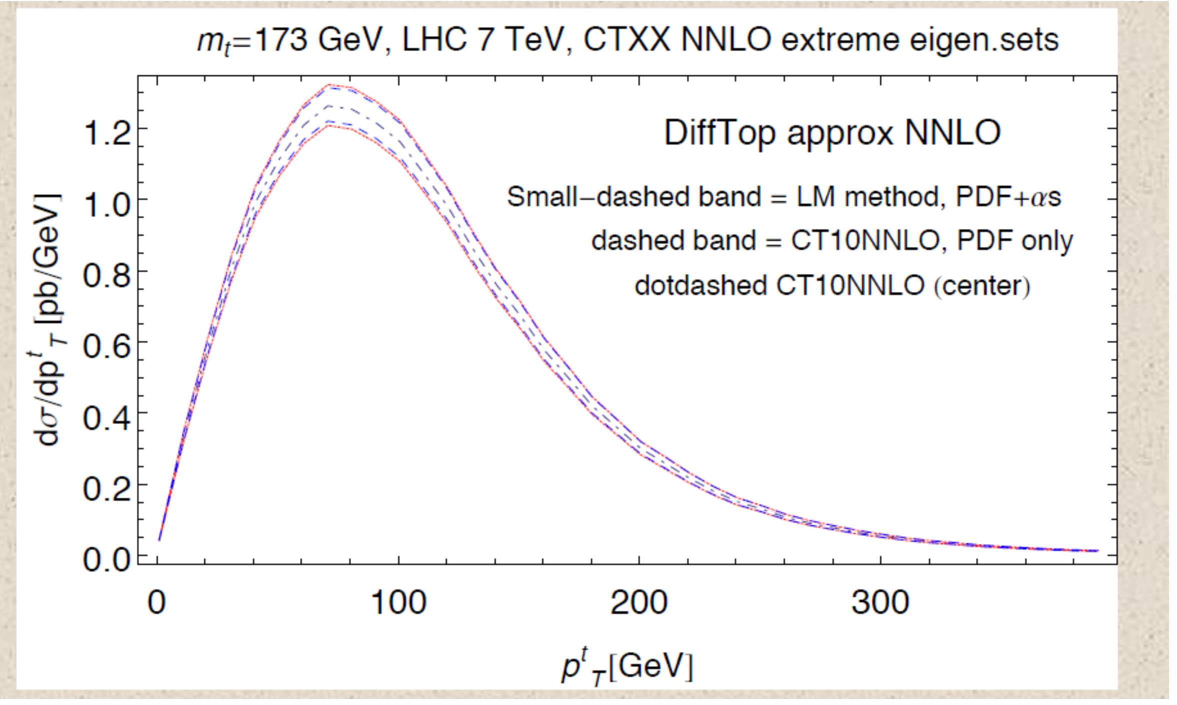




- Lagrange Multiplier method more robust than Hessian Method
- PDF uncertainly only or PDF+α_s uncertainty
- But must check for each process
- For Higgs cross section they agree well

- PDF sets that give extreme values of Higgs cross section at 90% CL are publically available as CT10H sets. It contains the combined effect from α_s and PDF uncertainties.
- Shown on contour plot as Red squares
- Useful for efficient $gg \to H$ analyses

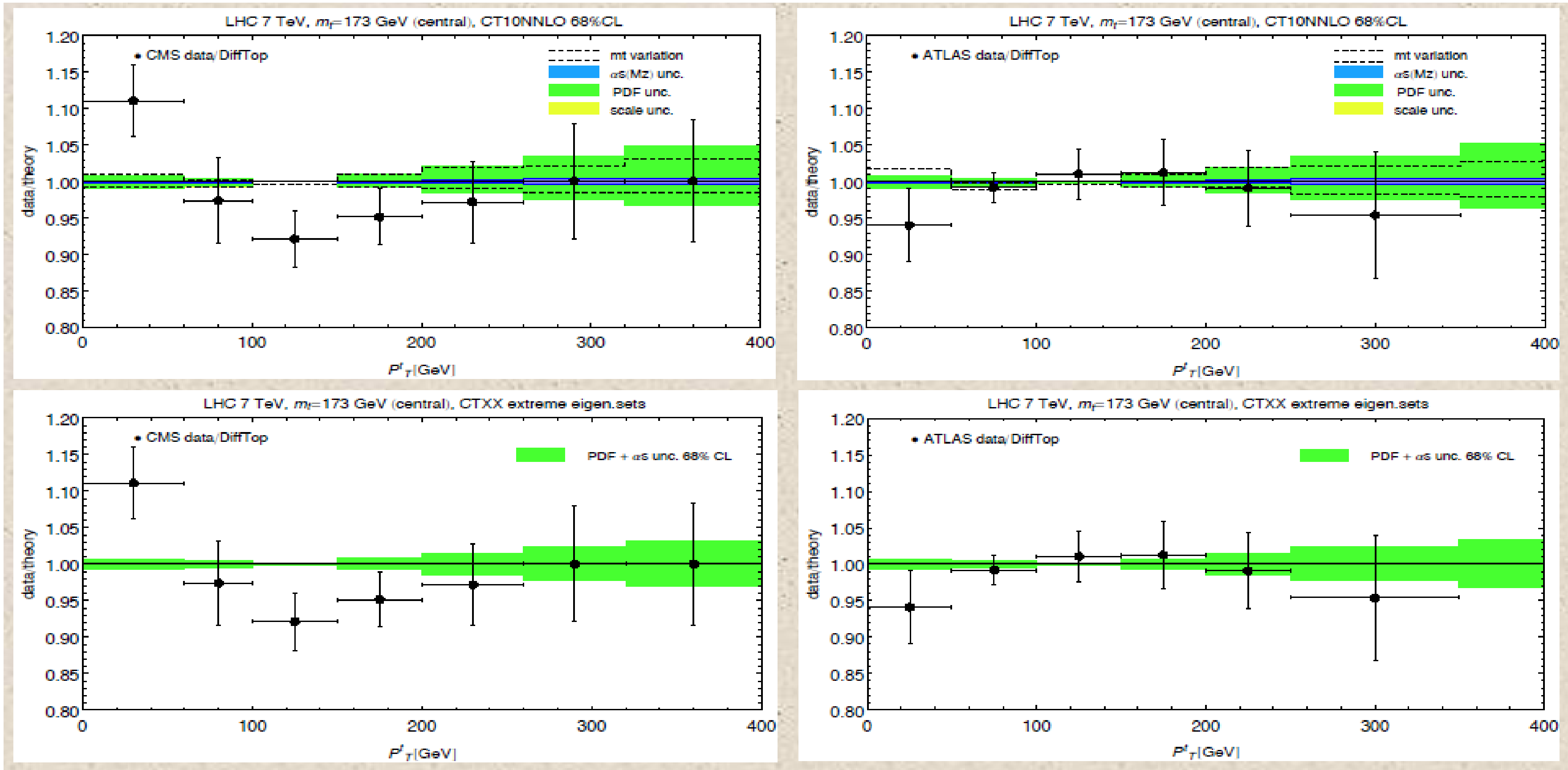
CT10tt extreme sets



- Pairs of CT10tt extreme sets (PDF, PDF+α_s) to be released
  - for focused ttbar analyses

Results provided by DiffTop group (M. Guzzi, K. Lipka, S. Moch)

CT10tt extreme sets



- Comparison with CMS (left) and ATLAS (right) data
- Hessian top, LM extreme sets bottom
- Extreme sets useful if highly correlated with inclusive ttbar (note high p_T)

Results provided by DiffTop group (M. Guzzi, K. Lipka, S. Moch)

Recap

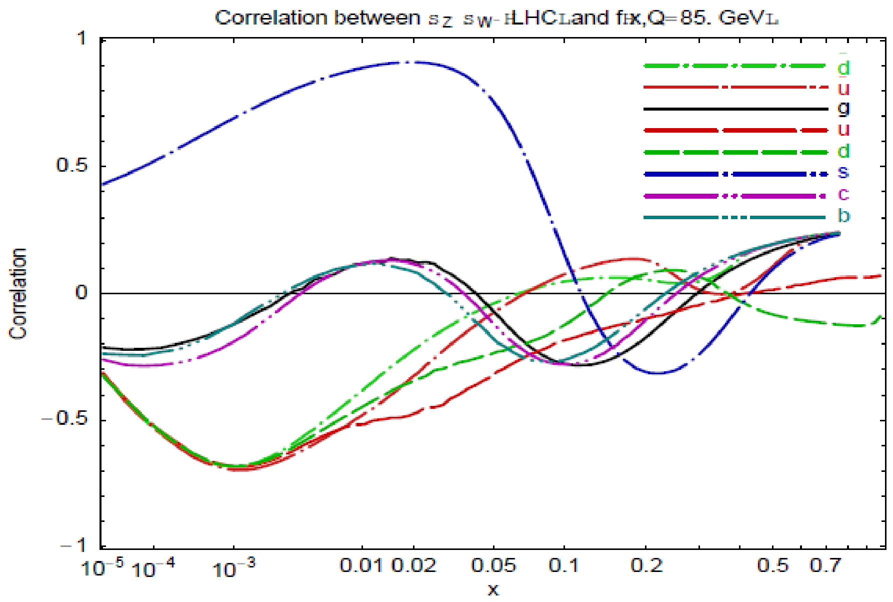
- Intrinsic Charm
    - Limits on valence-like and sea-like IC
    - CT10IC PDFs available for further study
    - LHC will probe further
- Lagrange Multiplier Uncertainty analysis
    - Less dependent on assumptions than Hessian analysis
    - Allows study of data correlations with particular observable
    - Test of Hessian results
        - Consistent with Hessian results for both Higgs and ttbar
    - CT10H extreme sets available for focused studies

      (CT10tt extreme sets to come)

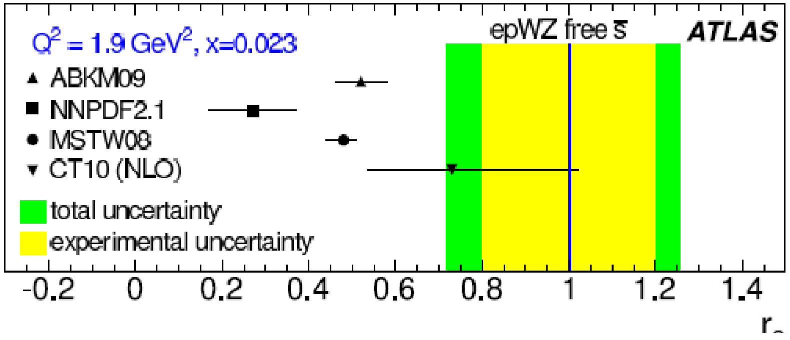
CT10, CT14, and LHC data

- We have since included early (7 TeV) LHC data: Atlas W/Z production and asymmetry at 7 TeV, Atlas single jet inclusive, CMS W asymmetry, HERA F_L and F_2^c
- New D0 (9.7 1/fb) W-electron rapidity asymmetry data.
- More flexible parametrization – gluon, d/u at large x and both, d/u and dbar/ubar at small x, strangeness, and s - sbar.
- Improvements modest so far, but expectation from ttbar, W/Z, Higgs, etc.

Strangeness in CT10 PDFs and LHC W/Z Data



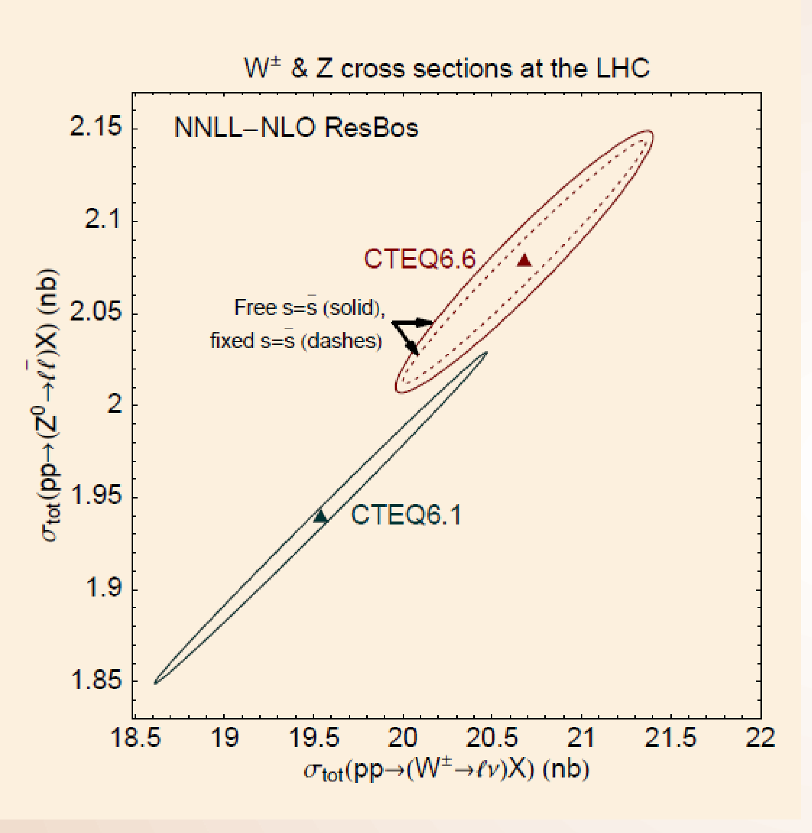
In 2008, our CTEQ6.6 PDF correlation analysis pointed out the sensitivity of ratios σ_W/σ_Z at the LHC to the strangeness PDF, with implications to EW precision measurements *(Nadolsky, Lai, Cao, Huston, Pumplin, Tung, Yuan, PRD, 78 (2008) 013004)*.

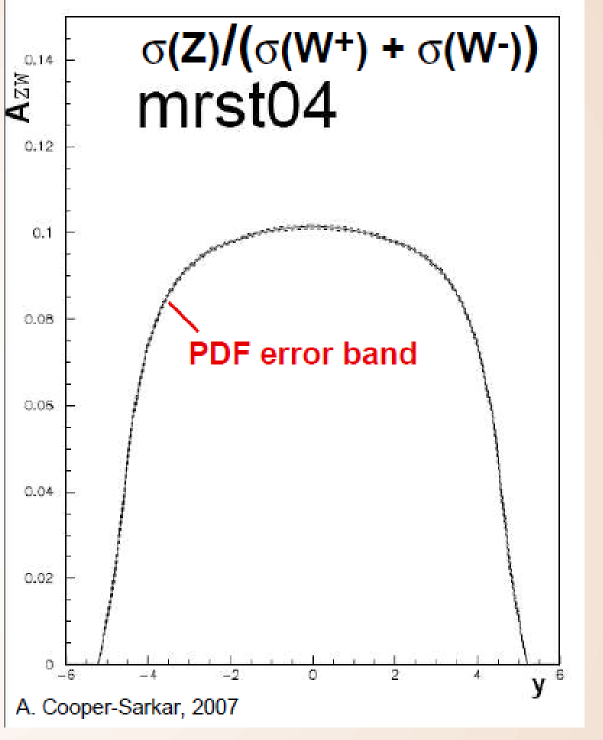


The ATLAS analysis (arXiv:1203.4051) of W and Z production suggests that $\bar{s}(x,Q)/\bar{d}(x,Q) = 1.00^{+0.25}_{-0.28}$ at $x = 0.023$ and $Q^2 = 1.9$ GeV^2

CTEQ6.6 vs. CTEQ6.1

Correlations and ratio of W and Z cross sections





Radiative contributions, PDF dependence have similar structure in W, Z, and alike cross sections; cancel well in Xsection ratios

Correlation analysis for collider observables

(J. Pumplin et al., PRD 65, 014013 (2002); P.N. and Z. Sullivan, hep-ph/0110378)

A technique based on the Hessian method

For $2N$ PDF eigensets and two cross sections X and Y:

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)^2}$$

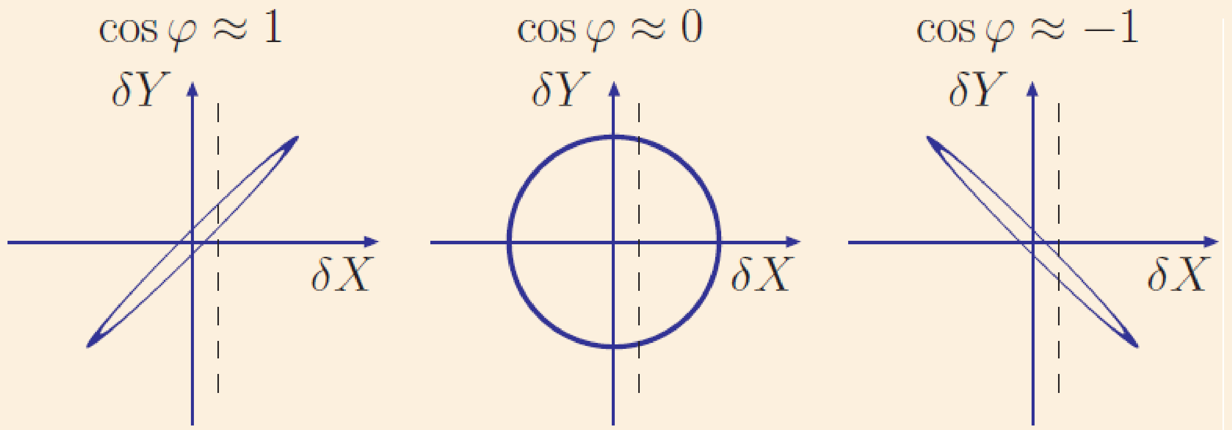
$$\cos\varphi = \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

$X_i^{(\pm)}$ are maximal (minimal) values of X_i tolerated along the i-th PDF eigenvector direction; $N = 22$ for the CTEQ6.6 set

Correlation angle φ

Determines the parametric form of the $X - Y$ correlation ellipse

$$
\begin{aligned}
X &= X_0 + \Delta X \cos\theta \\
Y &= Y_0 + \Delta Y \cos(\theta + \varphi)
\end{aligned}
$$



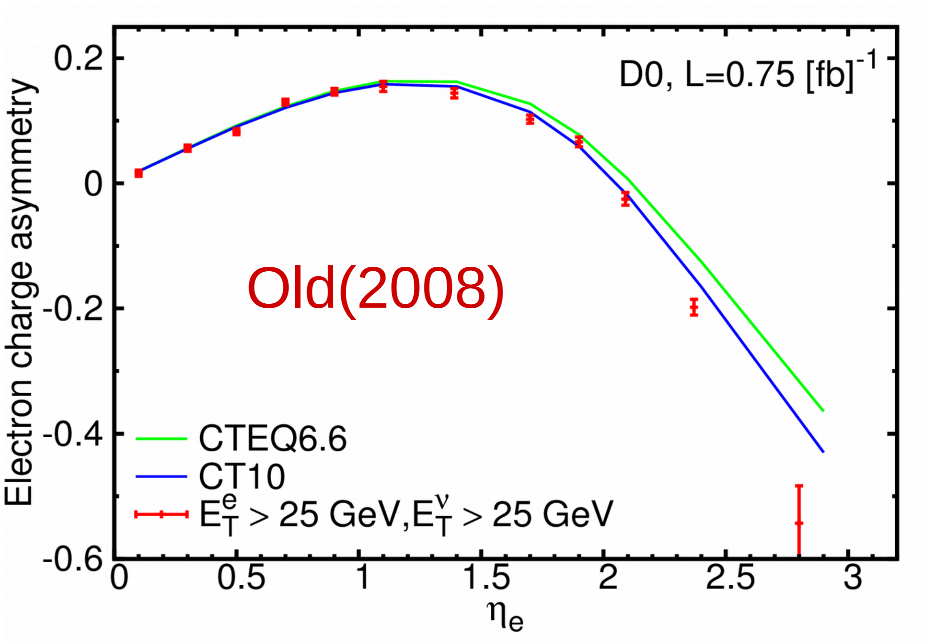
X_0, Y_0: best-fit values

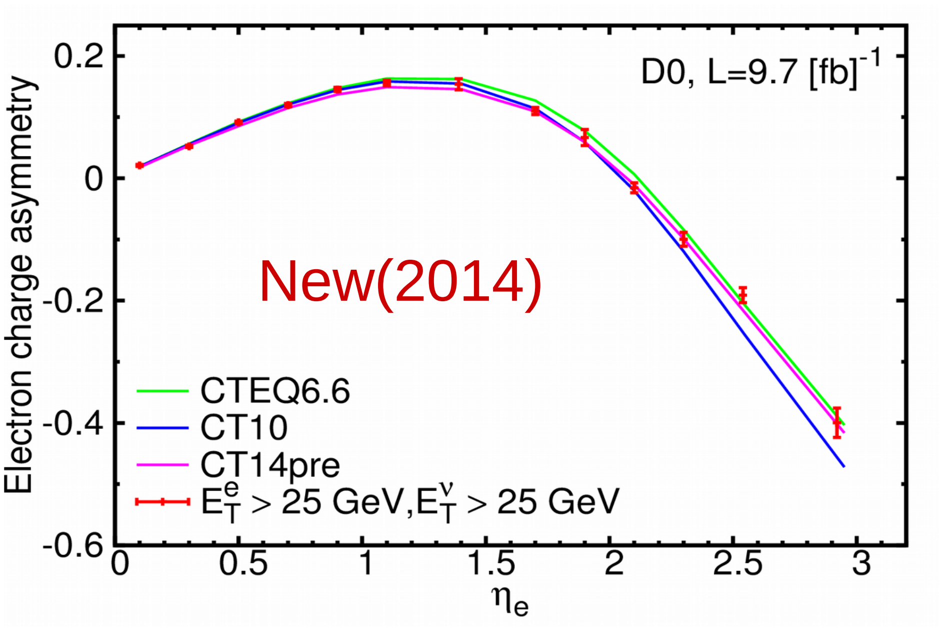
$\Delta X, \Delta Y$: PDF errors

$\cos\varphi \approx \pm 1$: Measurement of X imposes tight constraints on Y

$\cos\varphi \approx 0$: Measurement of X imposes loose constraints on Y

Compare Old and New D0 W-electron charged asymmetry Data

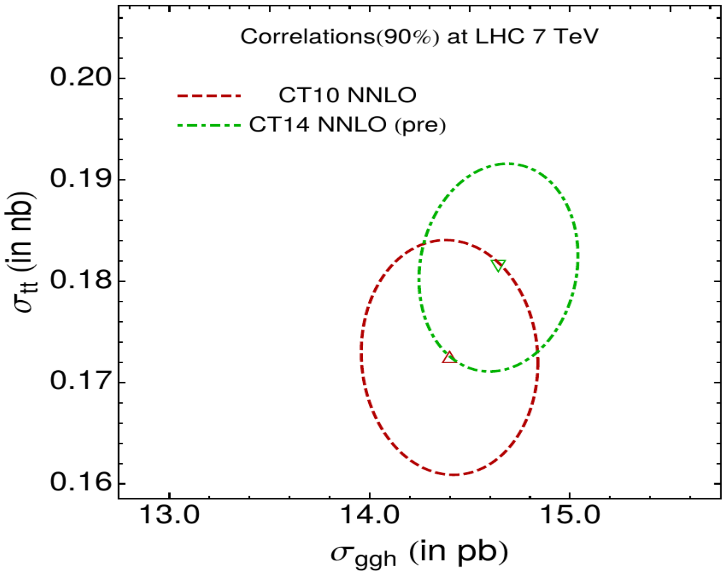




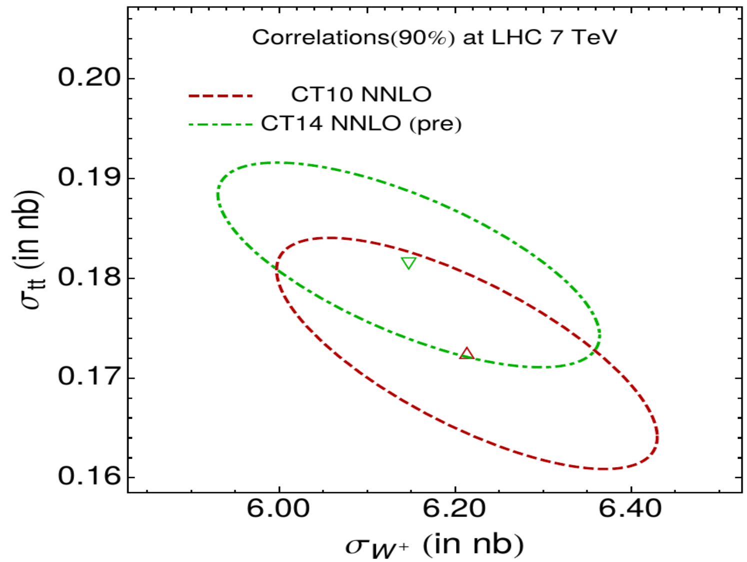
Old D0 data disfavor CTEQ6.6 and requires CT10.

New D0 data disfavor CT10 and requires CT14.

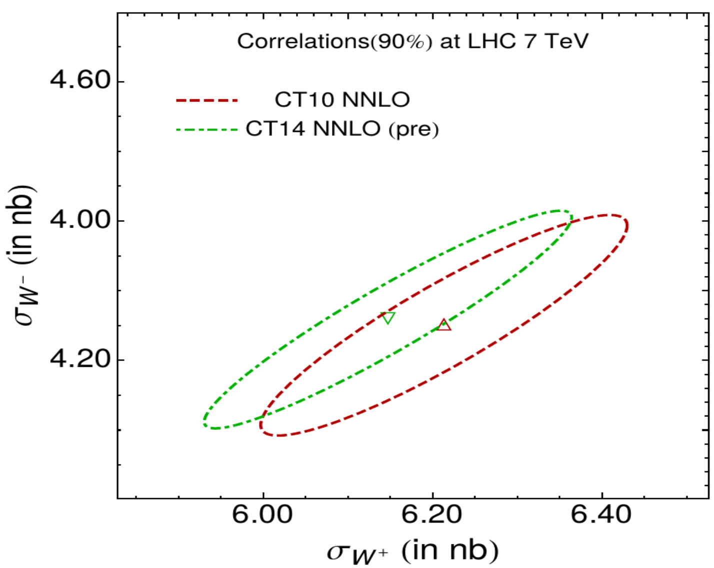
LHC 7 TeV



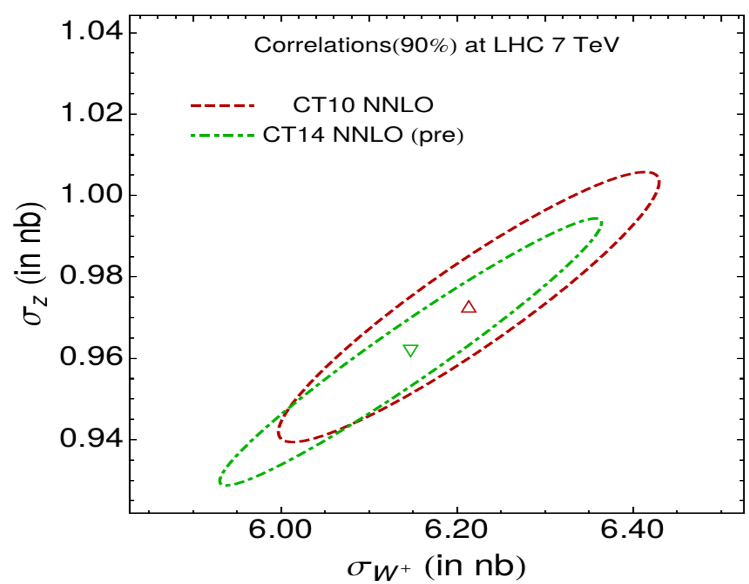
Correlations(90%) at LHC 7 TeV
CT10 NNLO
CT14 NNLO (pre)
0.20
0.19
0.18
0.17
0.16
σ_{tt} (in nb)
13.0
14.0
15.0
σ_{ggh} (in pb)



Correlations(90%) at LHC 7 TeV
CT10 NNLO
CT14 NNLO (pre)
0.20
0.19
0.18
0.17
0.16
σ_{tt} (in nb)
6.00
6.20
6.40
σ_{W^+} (in nb)

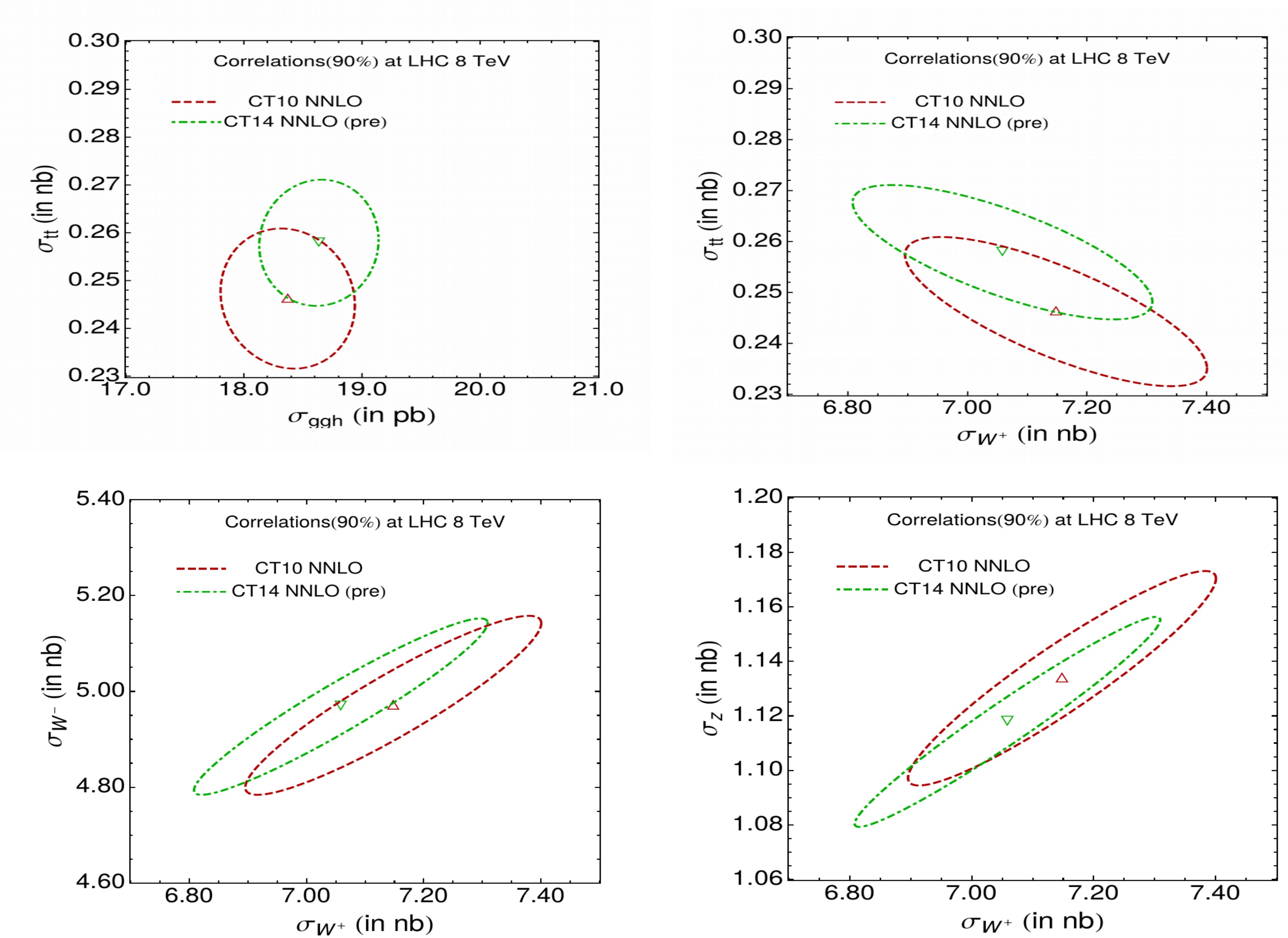


Correlations(90%) at LHC 7 TeV
CT10 NNLO
CT14 NNLO (pre)
4.60
4.00
4.20
σ_{W^-} (in nb)
6.00
6.20
6.40
σ_{W^+} (in nb)



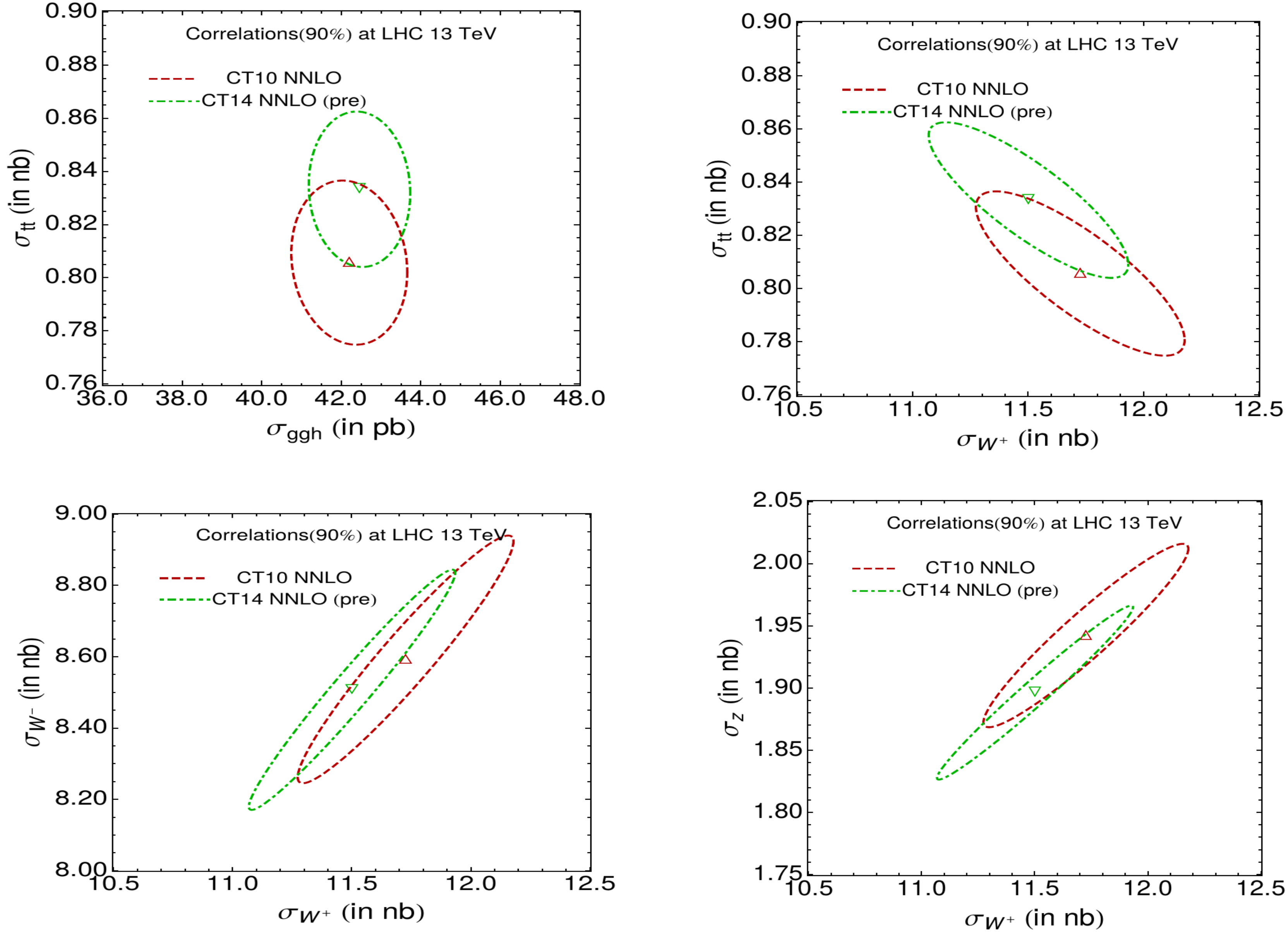
Correlations(90%) at LHC 7 TeV
CT10 NNLO
CT14 NNLO (pre)
1.04
1.02
1.00
0.98
0.96
0.94
σ_Z (in nb)
6.00
6.20
6.40
σ_{W^+} (in nb)

LHC 8 TeV



Correlations(90%) at LHC 8 TeV
CT10 NNLO
CT14 NNLO (pre)
$\sigma_{t\bar{t}}$ (in nb)
σ_{ggh} (in pb)
σ_{W^+} (in nb)
σ_{W^-} (in nb)
σ_Z (in nb)

LHC 13 TeV

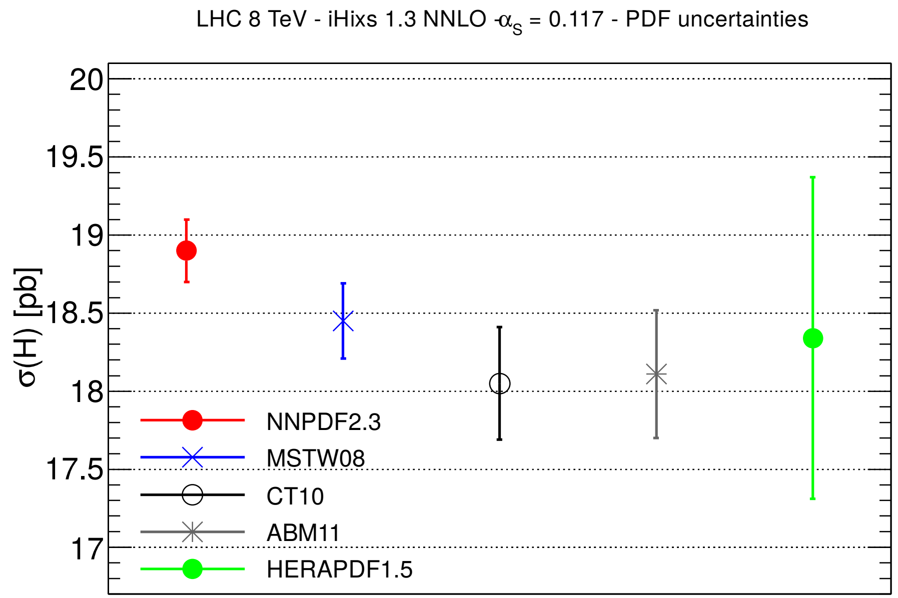


Correlations(90%) at LHC 13 TeV
CT10 NNLO
CT14 NNLO (pre)
$\sigma_{t\bar{t}}$ (in nb)
σ_{ggh} (in pb)
0.90
0.88
0.86
0.84
0.82
0.80
0.78
0.76
36.0
38.0
40.0
42.0
44.0
46.0
48.0
Correlations(90%) at LHC 13 TeV
CT10 NNLO
CT14 NNLO (pre)
$\sigma_{t\bar{t}}$ (in nb)
σ_{W^+} (in nb)
10.5
11.0
11.5
12.0
12.5
Correlations(90%) at LHC 13 TeV
CT10 NNLO
CT14 NNLO (pre)
σ_{W^-} (in nb)
σ_{W^+} (in nb)
9.00
8.80
8.60
8.40
8.20
8.00
Correlations(90%) at LHC 13 TeV
CT10 NNLO
CT14 NNLO (pre)
σ_Z (in nb)
σ_{W^+} (in nb)
2.05
2.00
1.95
1.90
1.85
1.80
1.75

PDF Benchmarking: compared with other PDF global analysis groups

PDF Benchmarking

gg -> H cross section

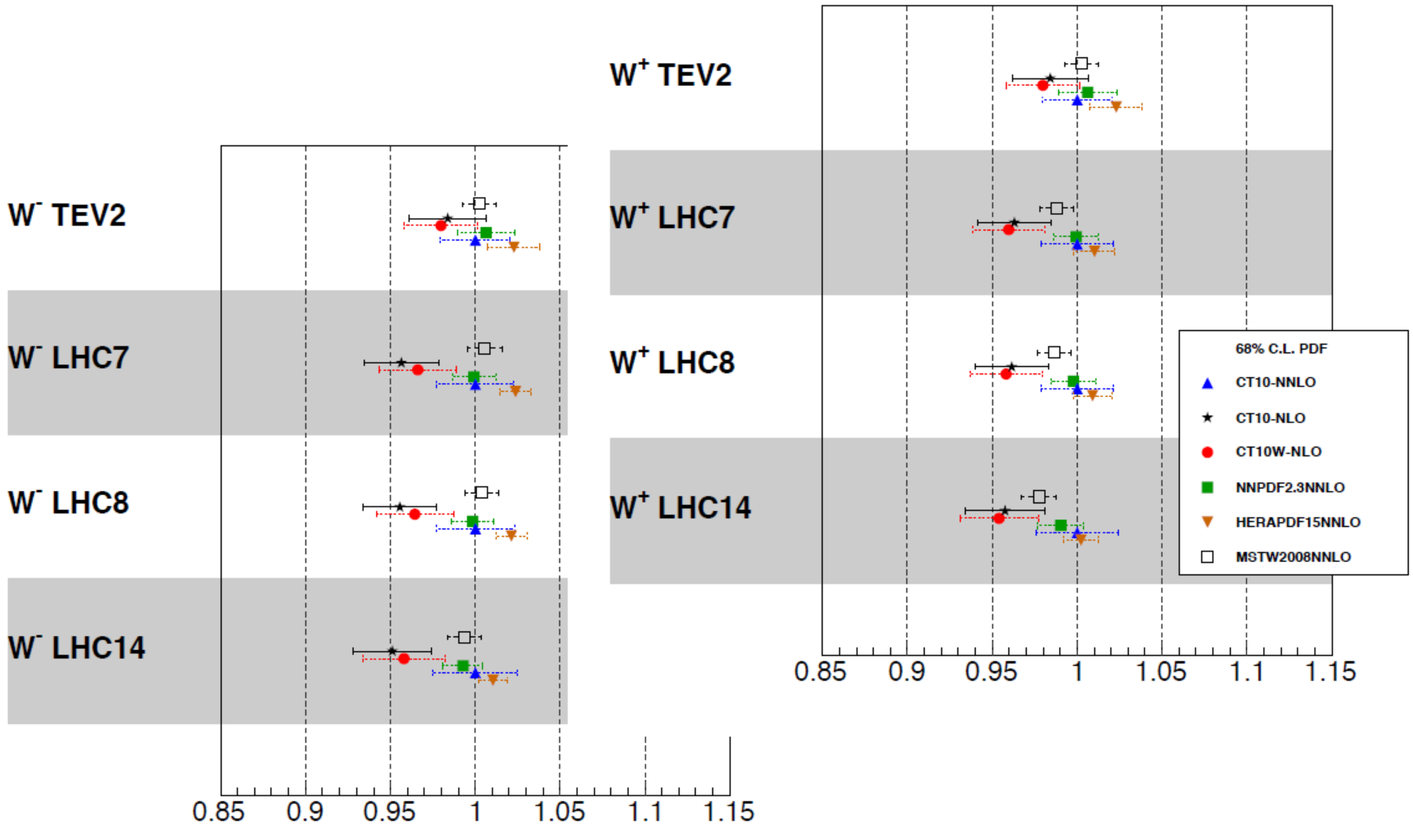


Benchmarking-

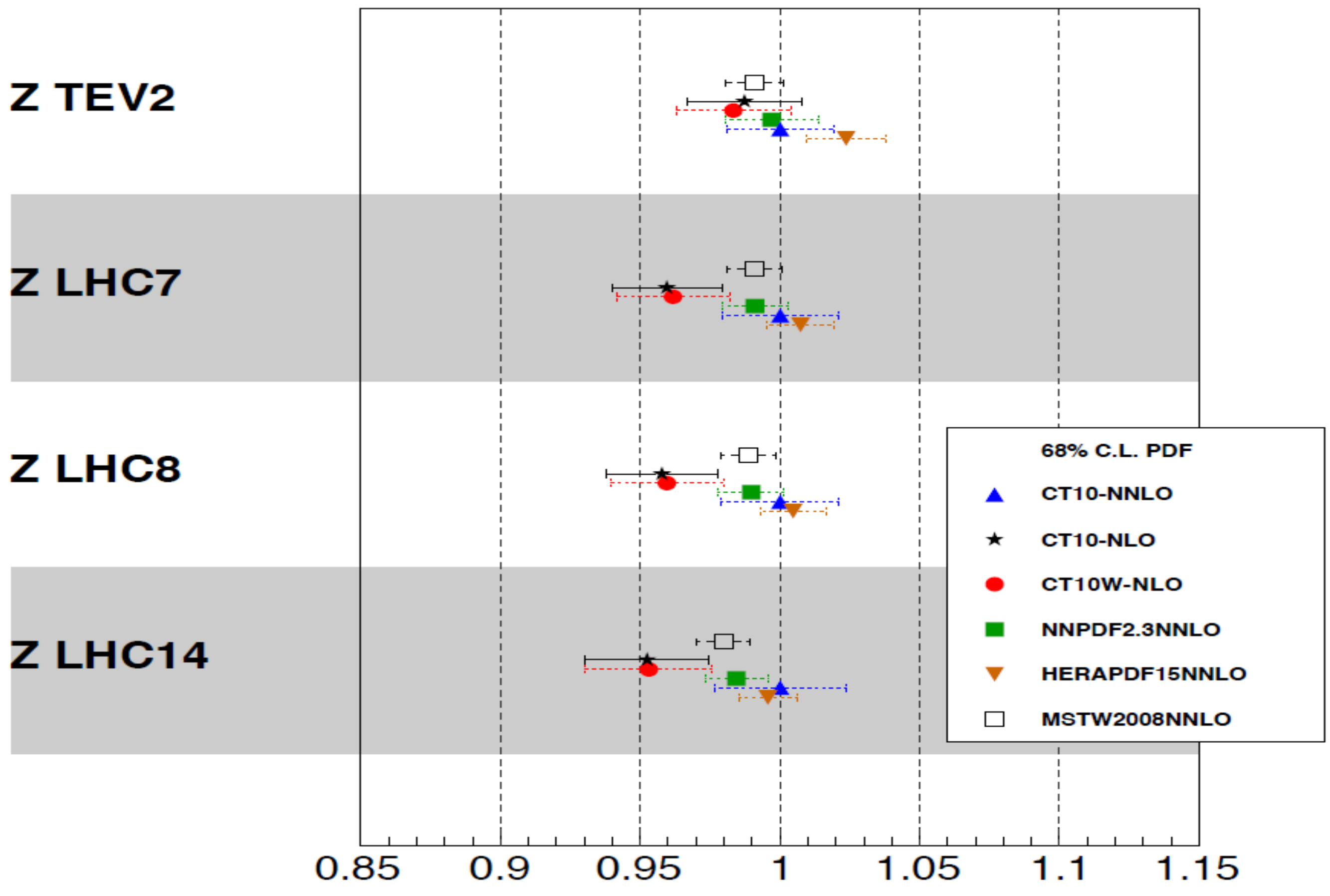
Ongoing study to compare and understand differences in PDF predictions at LHC

Ball et al, JHEP 1304 (2013) 125

CT10-NNLO compared with other PDFs for W boson production (NNLO)

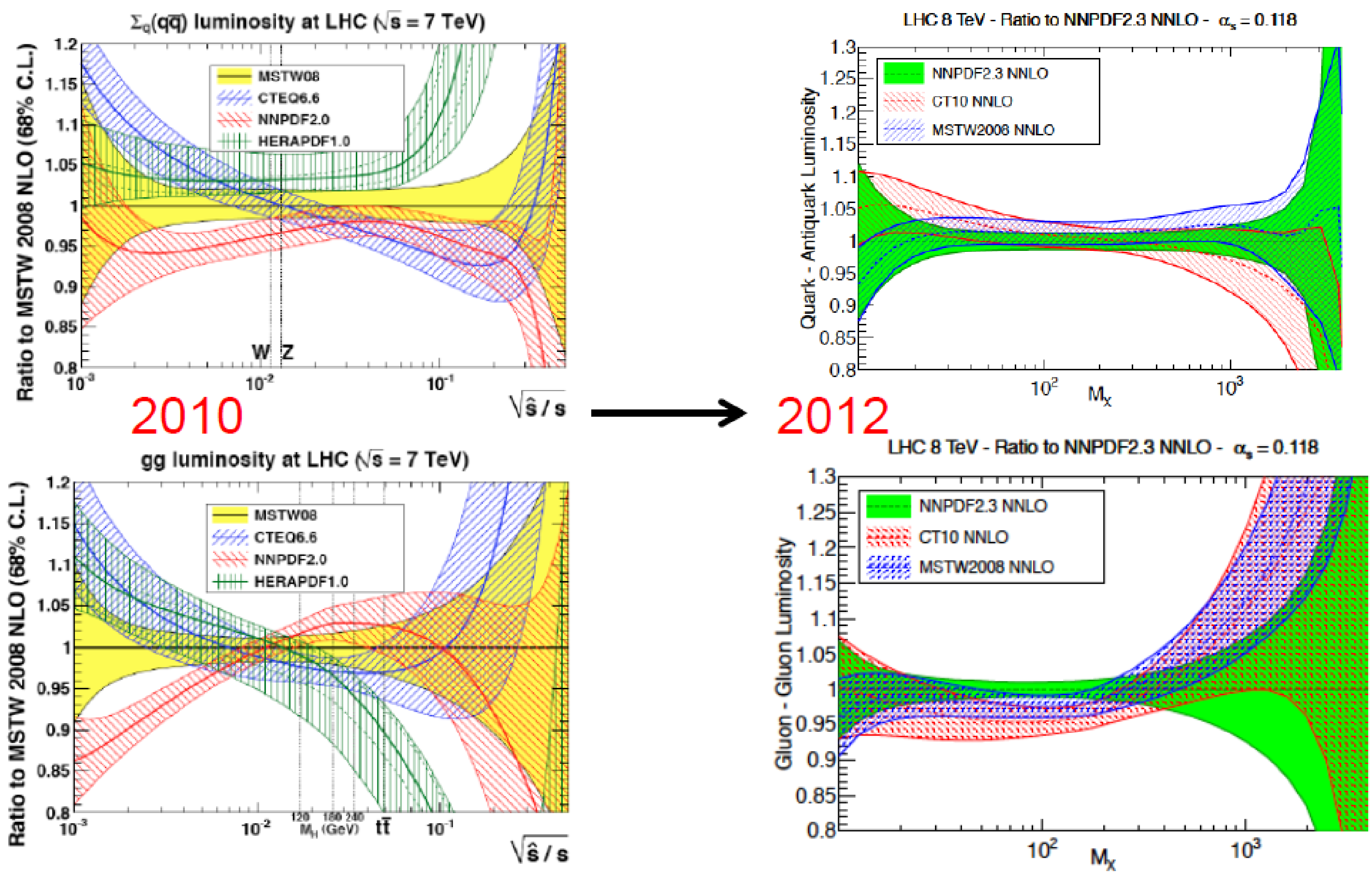


CT10-NNLO compared with other PDFs for Z boson production (NNLO)



Uncertainties did improve

- …with additional data and in going from NLO to NNLO (and other theory improvements)



PDFs
for
Future Hadron Colliders

Some basics about PDFs

- Parton Distribution Function $f(x, \mathrm{Q})$
- Given a heavy resonance with mass Q produced at hadron collider with c.m. energy $\sqrt{S}$
- What's the typical x value?

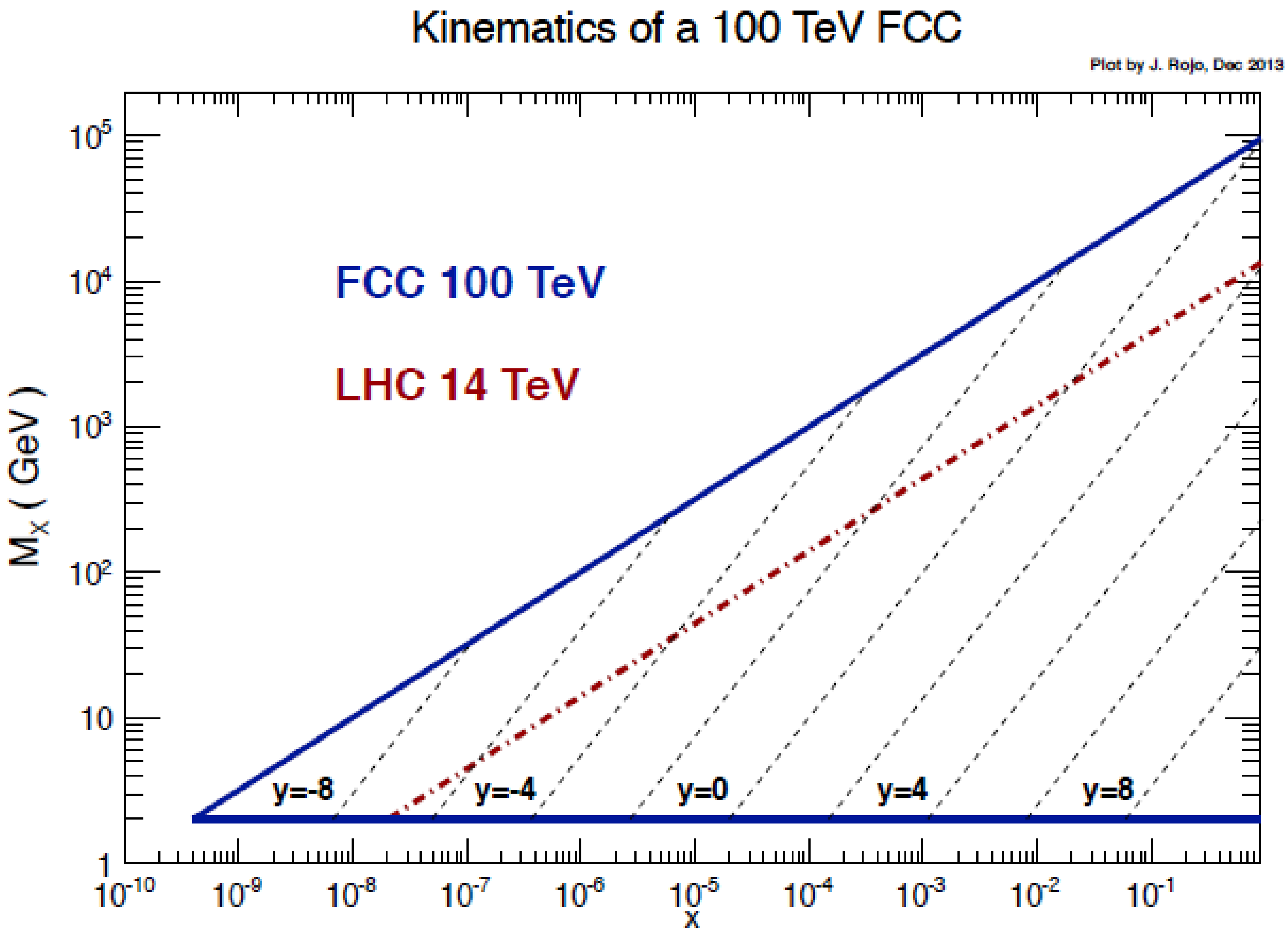
$$< x >= \frac{Q}{\sqrt{S}}$$

at central rapidity (y=0)

- Generally, $x_1 = \frac{Q}{\sqrt{S}} e^{y}$ *and* $x_2 = \frac{Q}{\sqrt{S}} e^{-y}$

$$x_1 + x_2 = 2\frac{Q}{\sqrt{S}} \cosh(\mathrm{y}) \quad \Longrightarrow \quad y_{\mathrm{max}} : \; x_1 + x_2 = 1$$

Kinematics of a 100 TeV SppC



- J. Rojo: kickoff meeting for FCC at CERN, Feb. 2014

On to a 100 TeV SppC

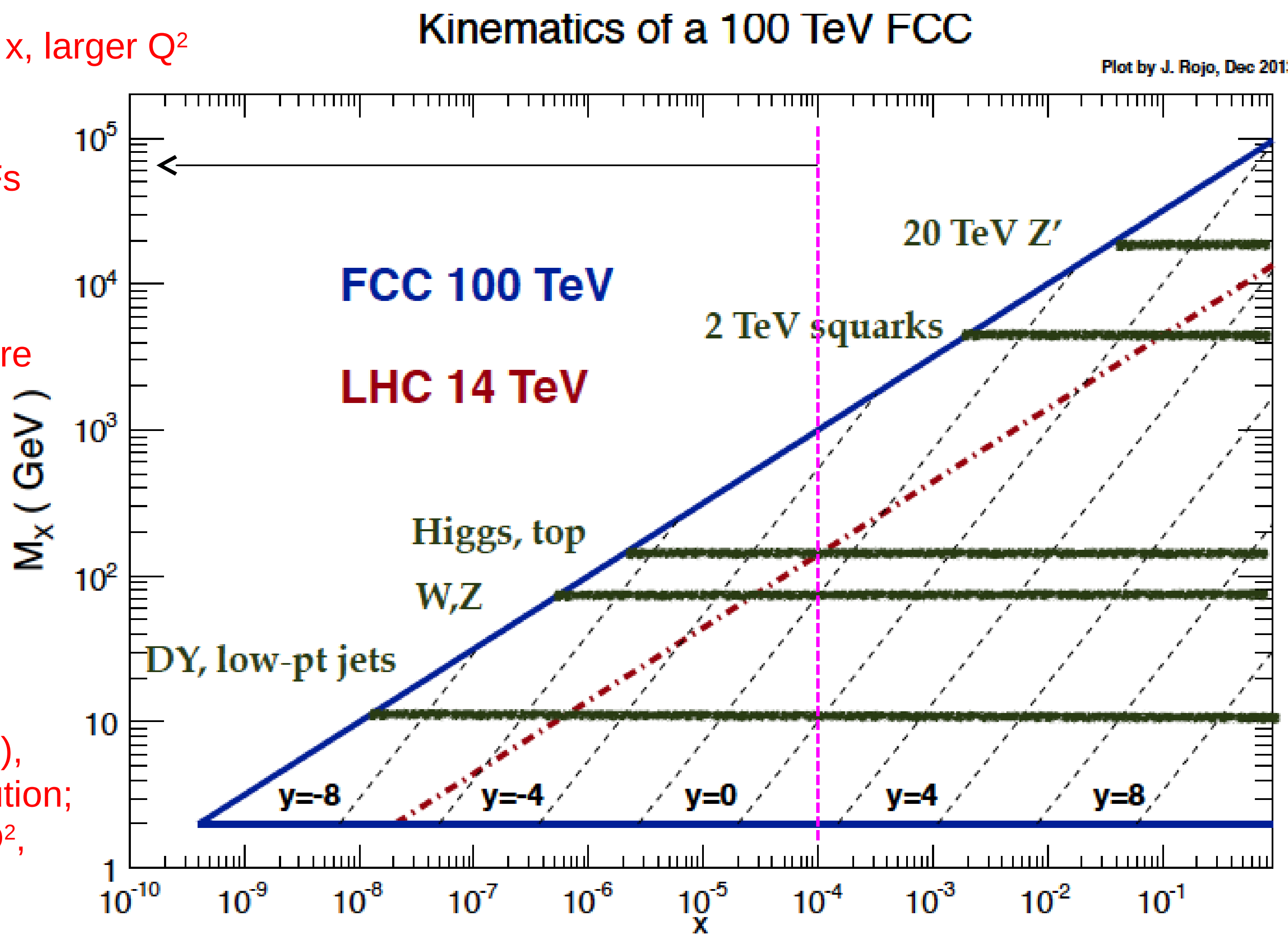
will access smaller x, larger Q^2

currently have no constraints on PDFs for x values below 1E-4

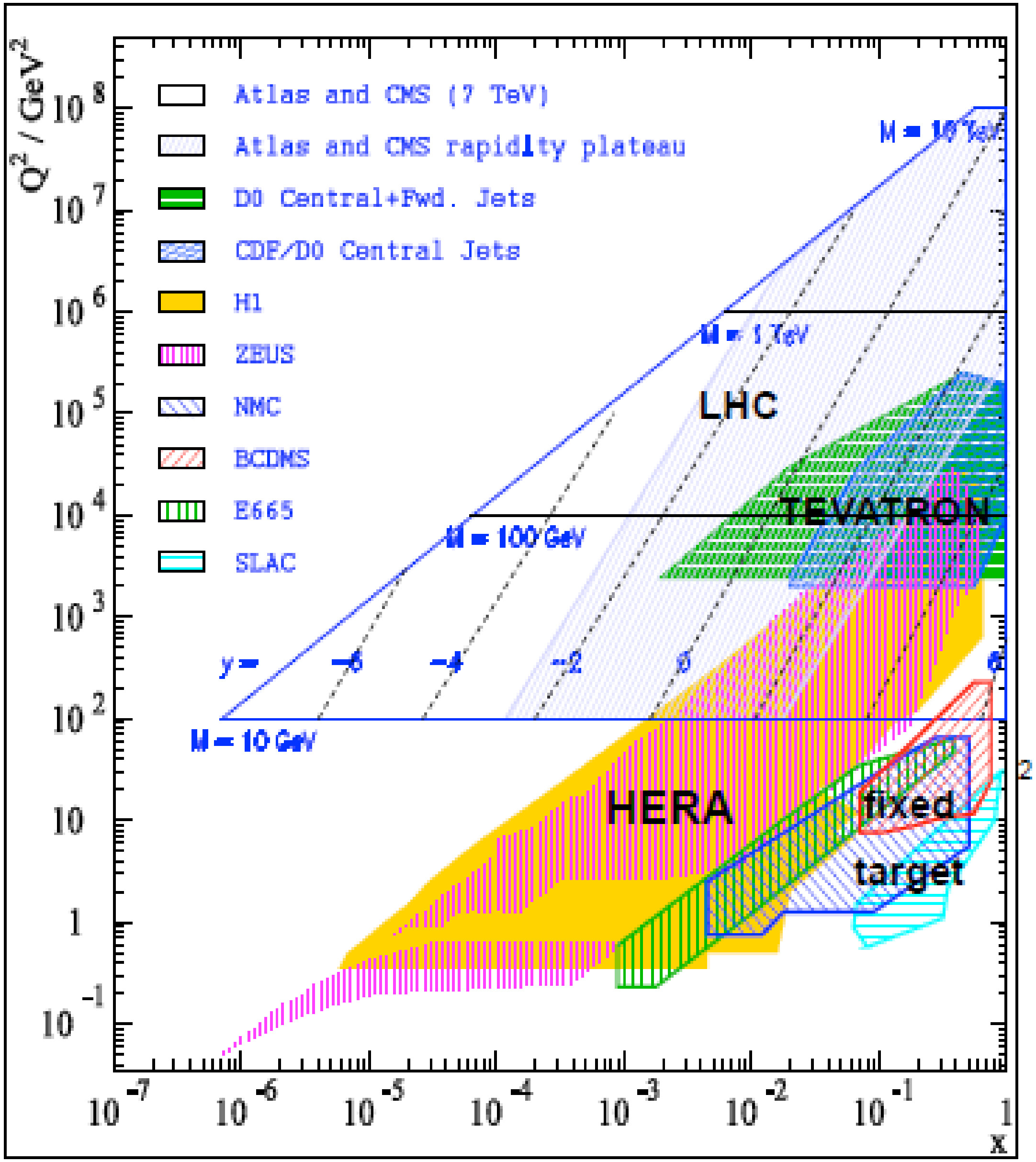
we don't know where at low x, BFKL effects start to become important

poor constraints (still) as well for high x PDFs

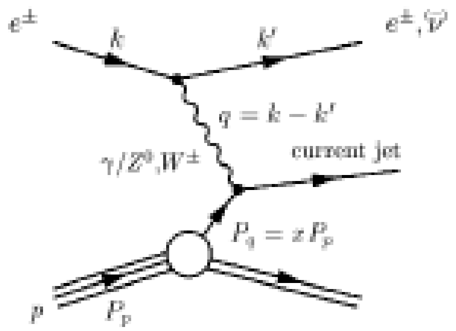
at high masses (Q^2), rely on DLAP evolution; we know at large Q^2, EW effects also become important



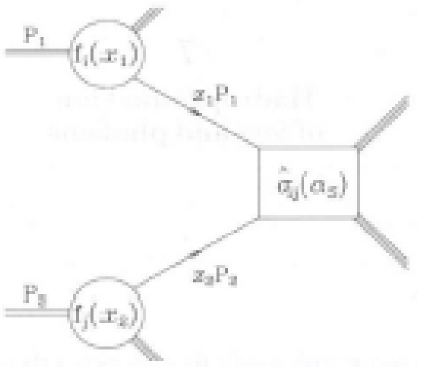
Experimental access to the proton structure



HERA: low and medium x



LHC: important constraints on g(x), flavour separation

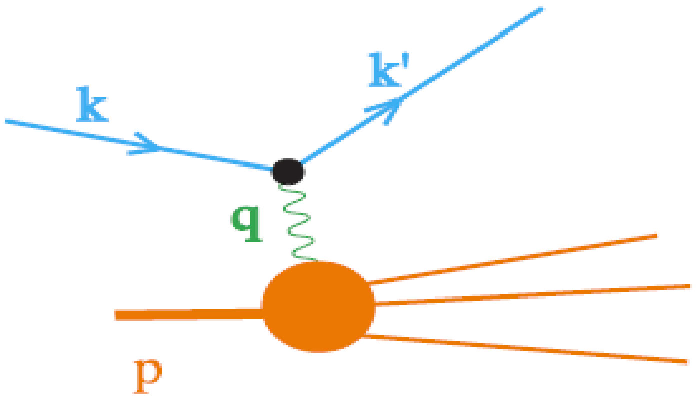


Fixed Target: high x, nuclear PDFs

Kinematics of deep inelastic lepton scattering

$$\ell(k) + h(p) \rightarrow \ell'(k') + X.$$

$$\begin{aligned} q^\mu &= k^\mu - k'^\mu \\ Q^2 &= -q^2 \\ x &= \frac{Q^2}{2p\cdot q} \text{ or } A\frac{Q^2}{2p\cdot q} \\ y &= \frac{p\cdot q}{p\cdot k}. \end{aligned}$$



"Deep Inelastic" $\Rightarrow Q^2 \rightarrow \infty$, x fixed.

Then also $W^2 = (p+q)^2 = m_h^2 + \frac{1-x}{x}Q^2 \rightarrow \infty$.

Included here: γ, W and Z exchanges.

In CT analysis, we imposed cuts:
$Q > 2$ GeV and $W^2 > 12$ GeV^2
e.g., $Q=2$ GeV, $x < 0.25$
Namely, large-x data are not included in the analysis, to avoid large non-perturbative, higher twist, contributions.

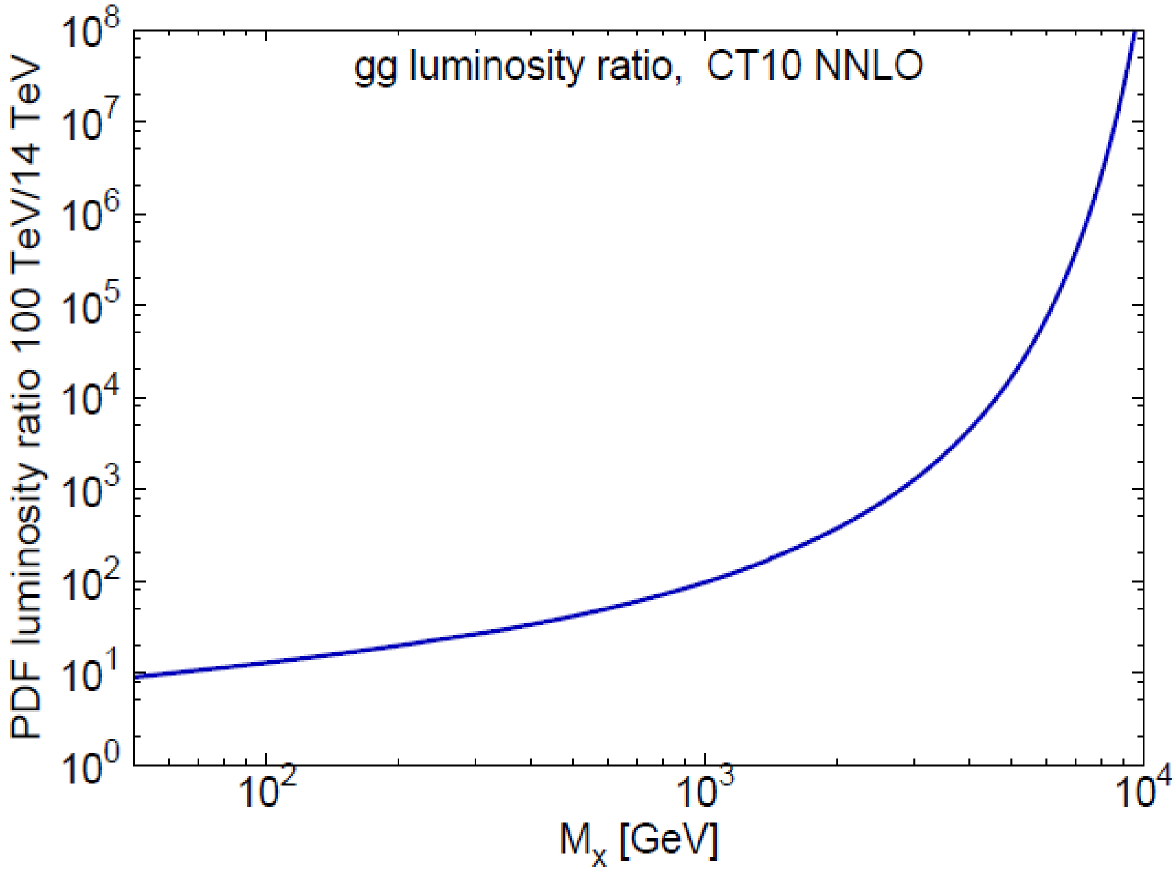
PDF luminosities

$$\sigma = \int dx_1 dx_2 \; g(x_1, M) g(x_2, M) \hat{\sigma}(M)$$

$$= \int d\tau dy \; g(x_1, M) g(x_2, M) \hat{\sigma}(M)$$

$$\equiv \int dM^2 \frac{dL}{dM^2} \hat{\sigma}(M)$$

PDF Luminosity



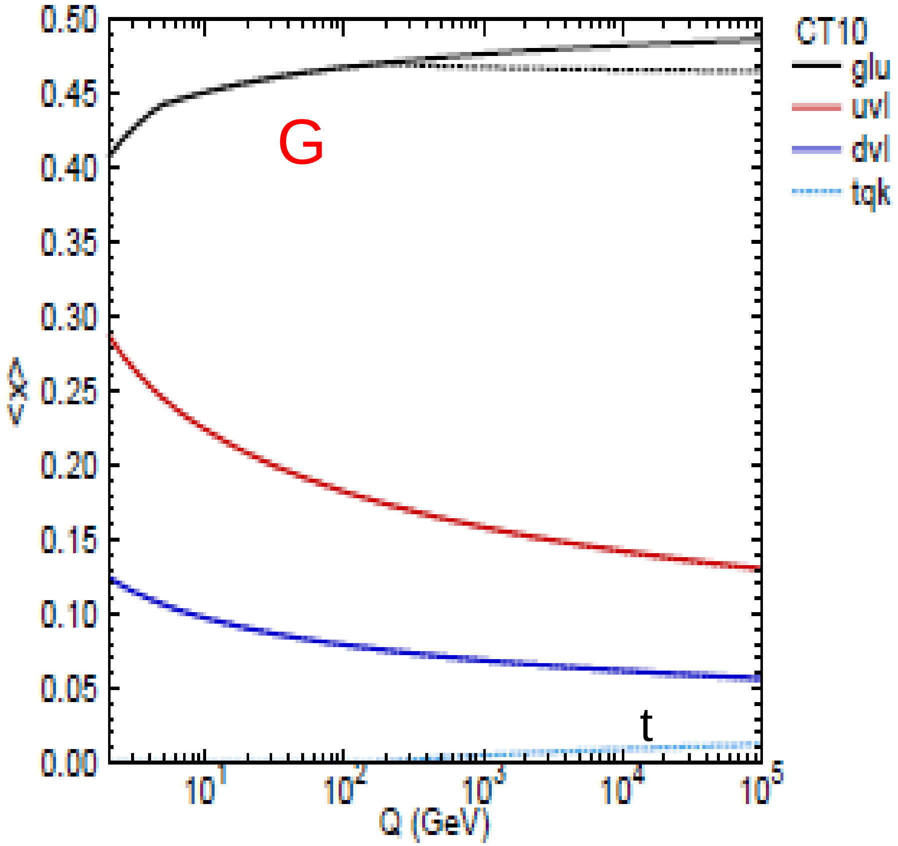
$$\tau = x_1 x_2$$

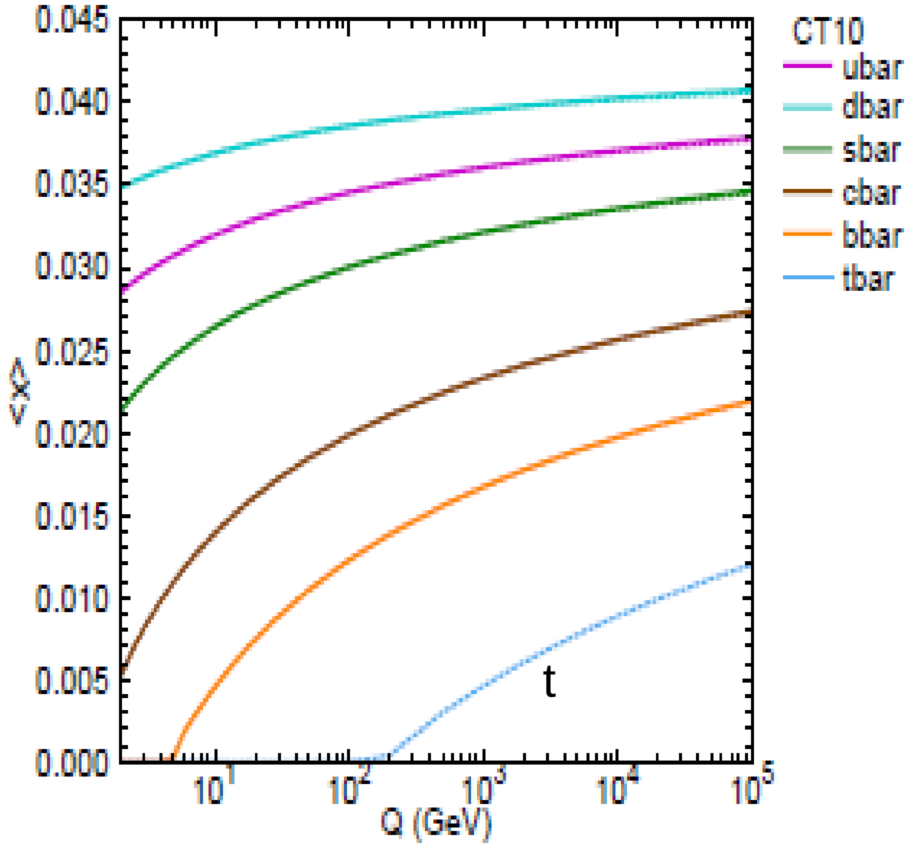
$$y = \frac{1}{2} \ln\left(\frac{x_1}{x_2} \right)$$

Top quark as a parton

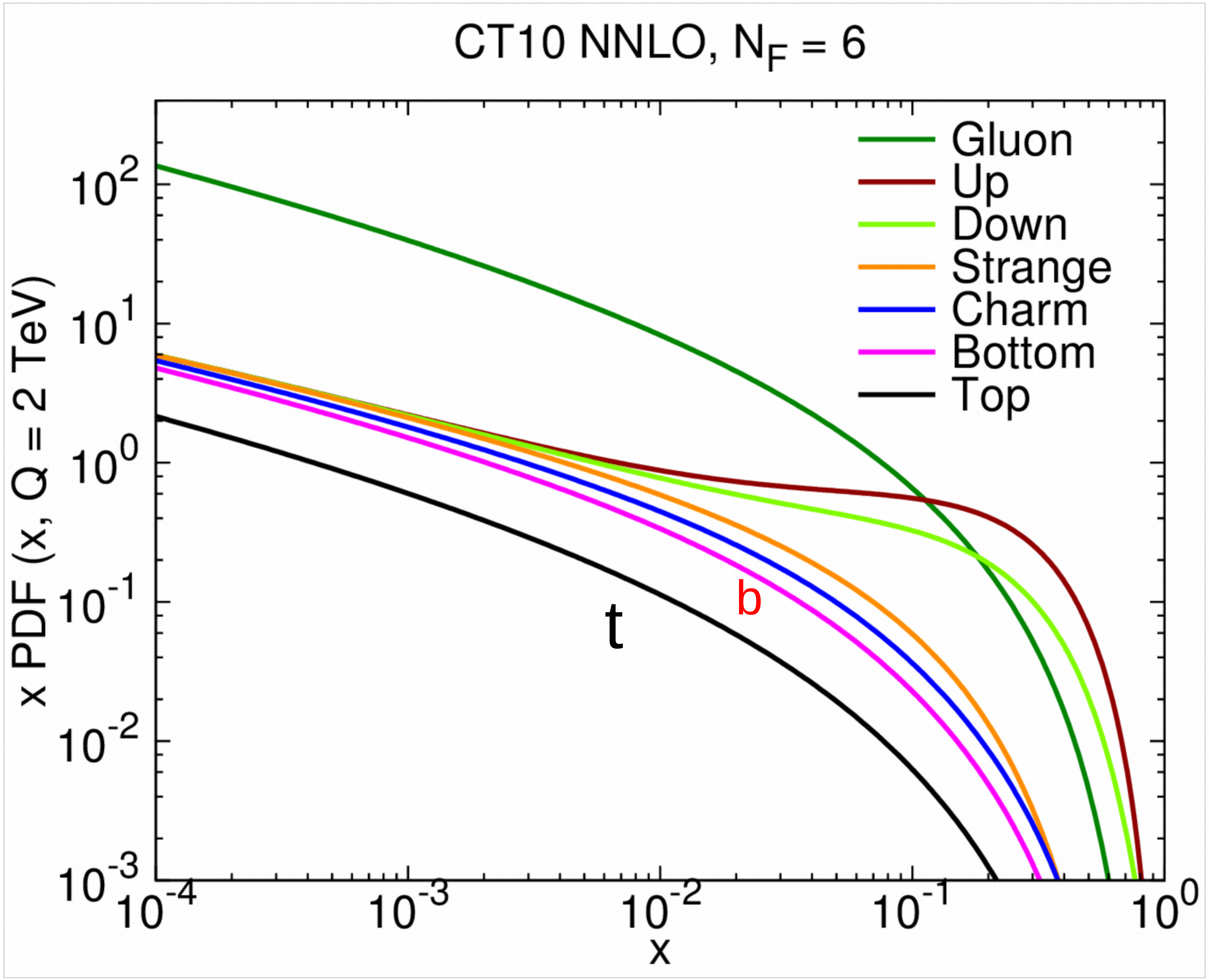
- For a 100 TeV SppC, top mass (172 GeV) can be ignored; top quark, just like bottom quark, can be a parton of proton.
- Top parton will take away some of the momentum of proton, mostly, from gluon (at NLO).
- Need to use s-ACOT scheme to calculate hard part matrix elements, to be consistent with CT10 PDFs.

Momentum fraction inside proton



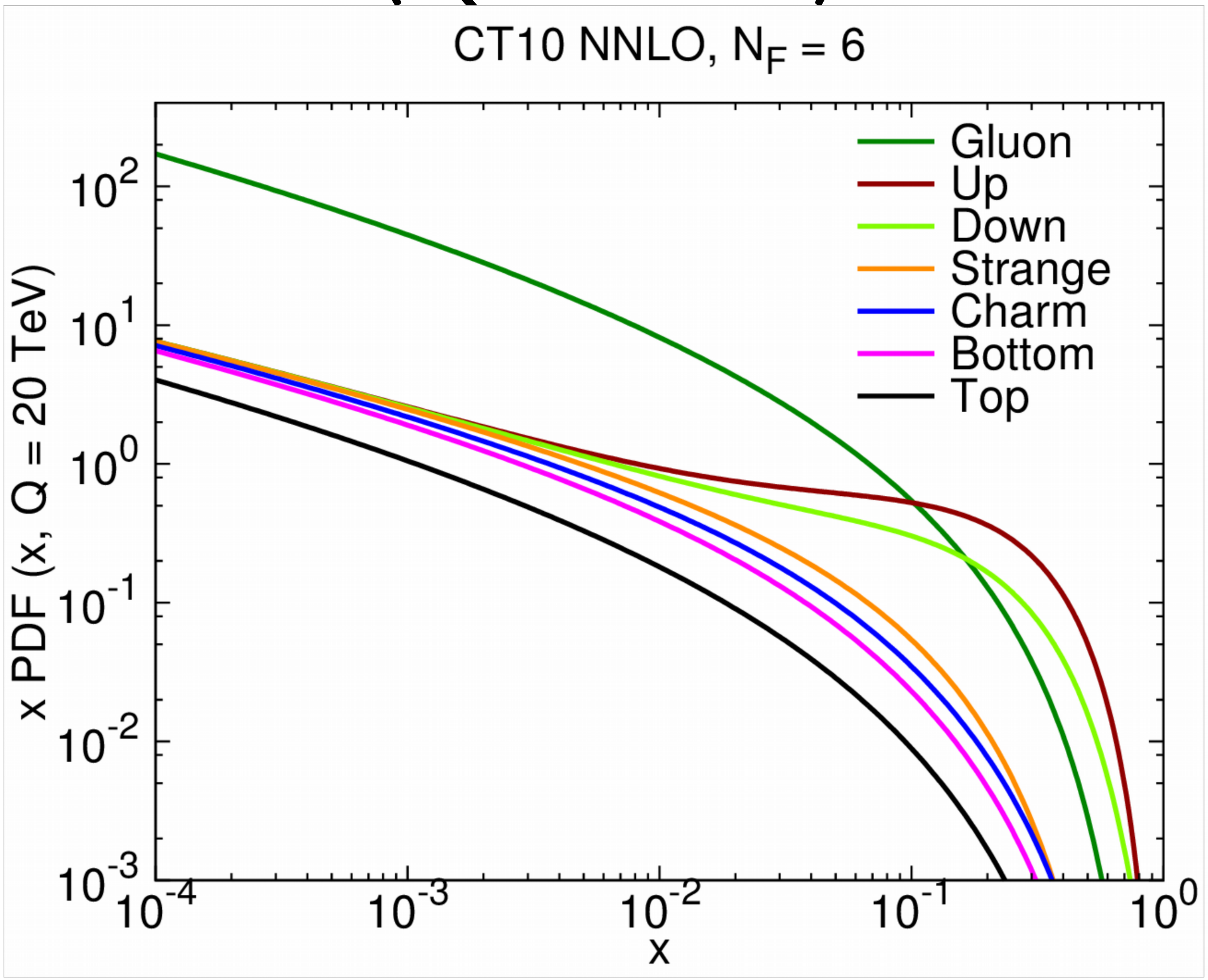


CT10 Top PDFs (Q=2 TeV)

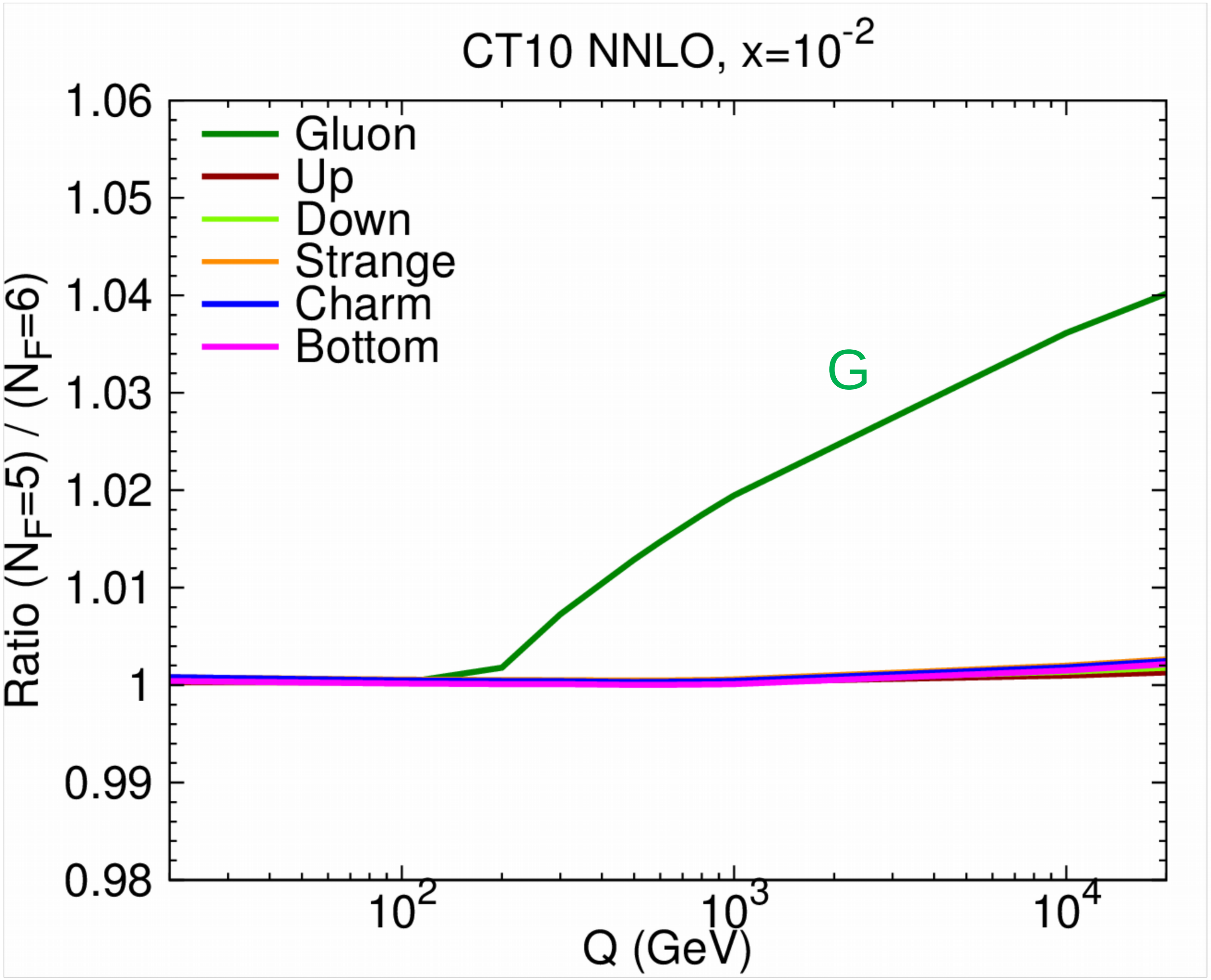


Top PDF is only a factor of 2 smaller than b PDF

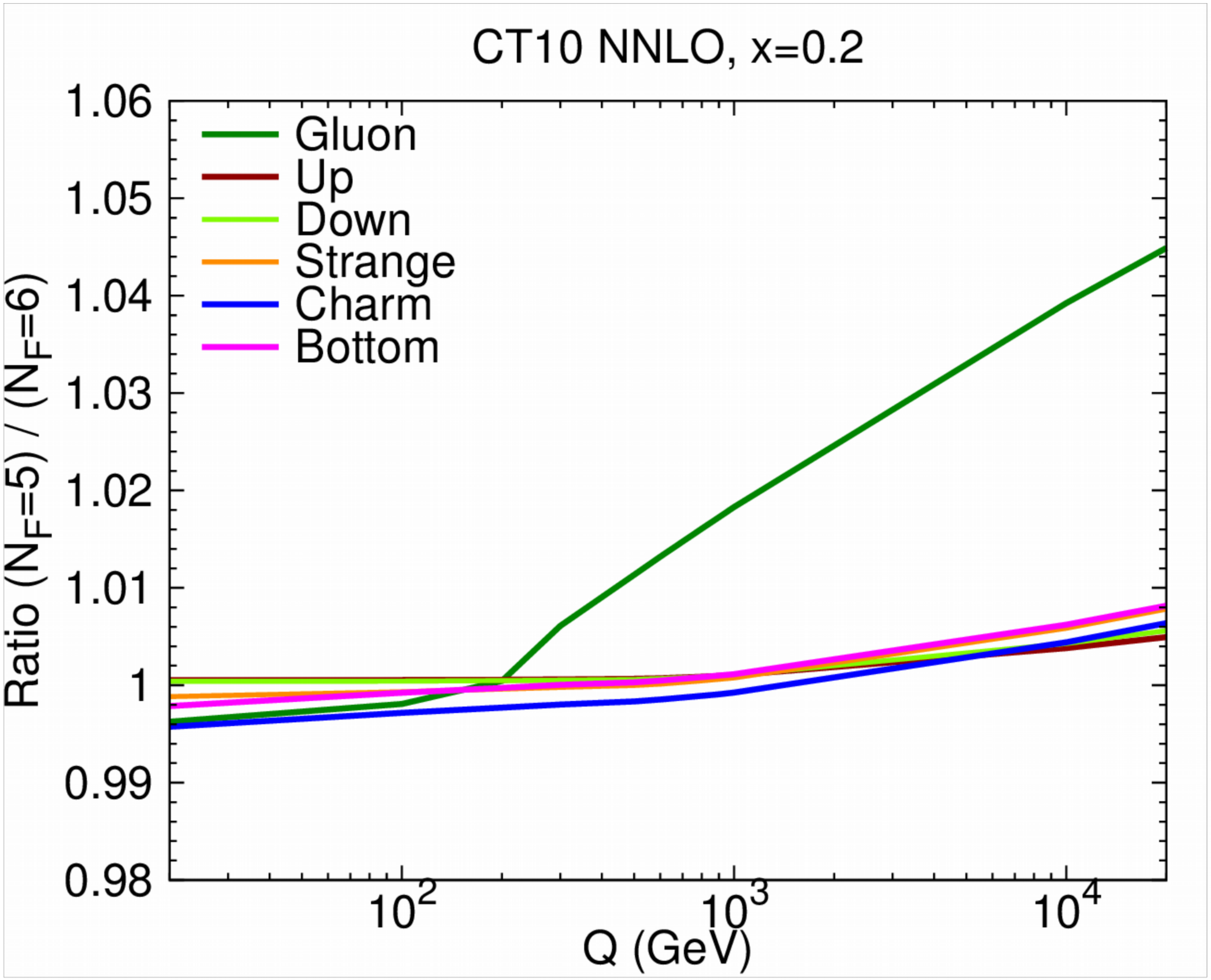
CT10 Top PDFs (Q=20 TeV)



CT10Top PDFs

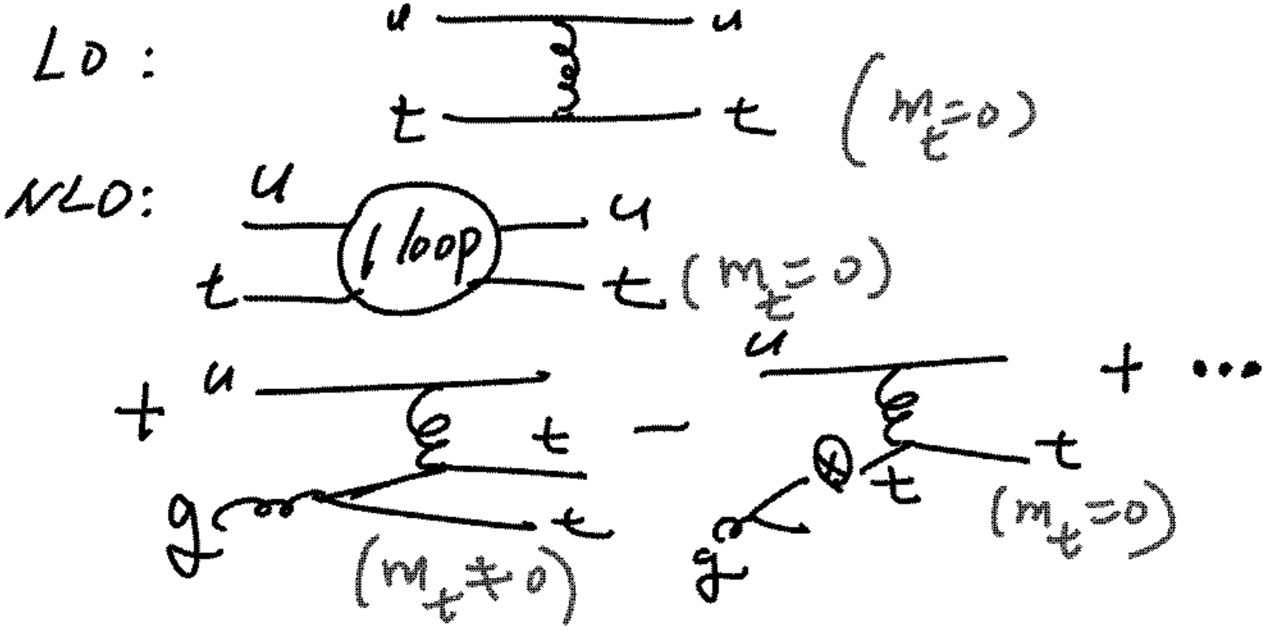


CT10Top PDFs



Hard part calculation

- S-ACOT scheme
- Example: single-top production



Summary

- PDFs have larger uncertainties in both small x and large x regions.
- PDFs will be further determined by LHC data.
- In a 100TeV SppC, top quark can be a parton of proton, consistent hard part calculations are needed.