



Parton Distributions at High Energy Colliders

C.-P. Yuan

Michigan State University

In collaboration with

CTEQ-TEA

9th Workshop of TeV Physics WG
May 15-18, 2014@ Sun Yat-sen Univ.,
Guangzhou, China

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.)

Tie-Jiun Hou (Academia Sinica, Taipei)

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

Michigan State Univ. -- Jon Pumplin, Dan Stump, Carl Schmidt, CPY

Back to 2012

- March 8, 2012: Daya Bay Neutrino Experiment; θ_{13}
- July 4: Higgs Discovery at LHC
- November 12-15: 7th TeV Workshop



清华大学
Tsinghua University

Center for High Energy Physics Tsinghua University

7th Workshop on TeV Physics

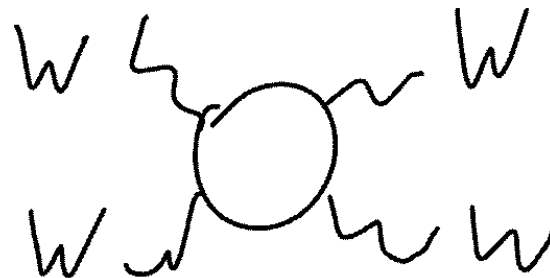
In honor of Prof Yu-Ping Kuang

2012 November (12-15th)



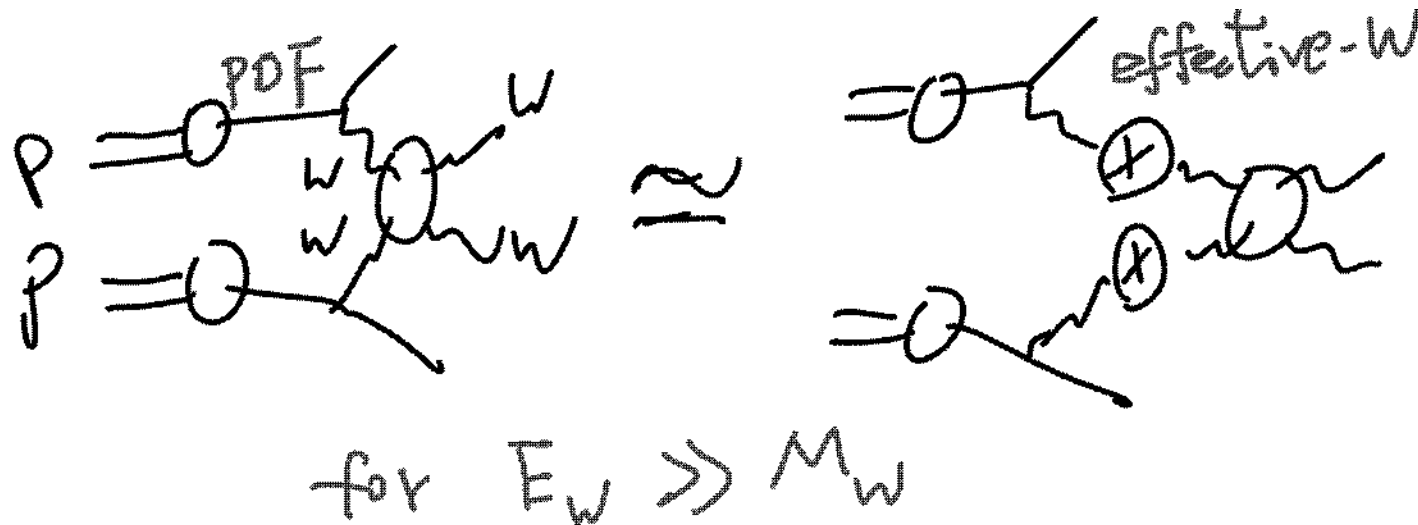
A Long Time Ago

- 1984-1985: Prof. Gordy Kane asked me to compare parton luminosities at various pp or p-pbar collider energies; to compare their physics potential, particularly, on probing the Electroweak Symmetry Breaking sector via studying



Need to know

- Parton Distribution Functions
- Effective W approximation



Another important ingredient

- Goldstone Boson Equivalence Theorem

for $E_W \gg M_W$

- In general, the modification factor $C(\text{mod})$ is not 1 beyond the tree level.

York-Peng Yao and CPY; PRD 38 (1988) 2237

J. Bagger and C. Schmidt; PRD 41 (1990) 264

- $C(\text{mod})$ can be made to be 1 in a special renormalization scheme. (See next slide.)

Prof. Yu-Ping Kuang and me

- 1992: referee of **PRL 69 (1992) 2619**
“On the precise formulation of equivalence theorem”, by
Hong-Jian He, Yu-Ping Kuang and Xiao-Yuan Li
- 1993: my first trip to China (CCAST); followed by many collaborations on studying the Electroweak Symmetry Breaking sector.
- 1997-2000: Hong-Jian He joined MSU, as a postdoc; initiating further collaborations.

$$WW \rightarrow WW$$

- In the SM, Higgs boson ensures its unitarity.
- If the coupling of H-W-W deviates from the SM, then unitarity is violated.

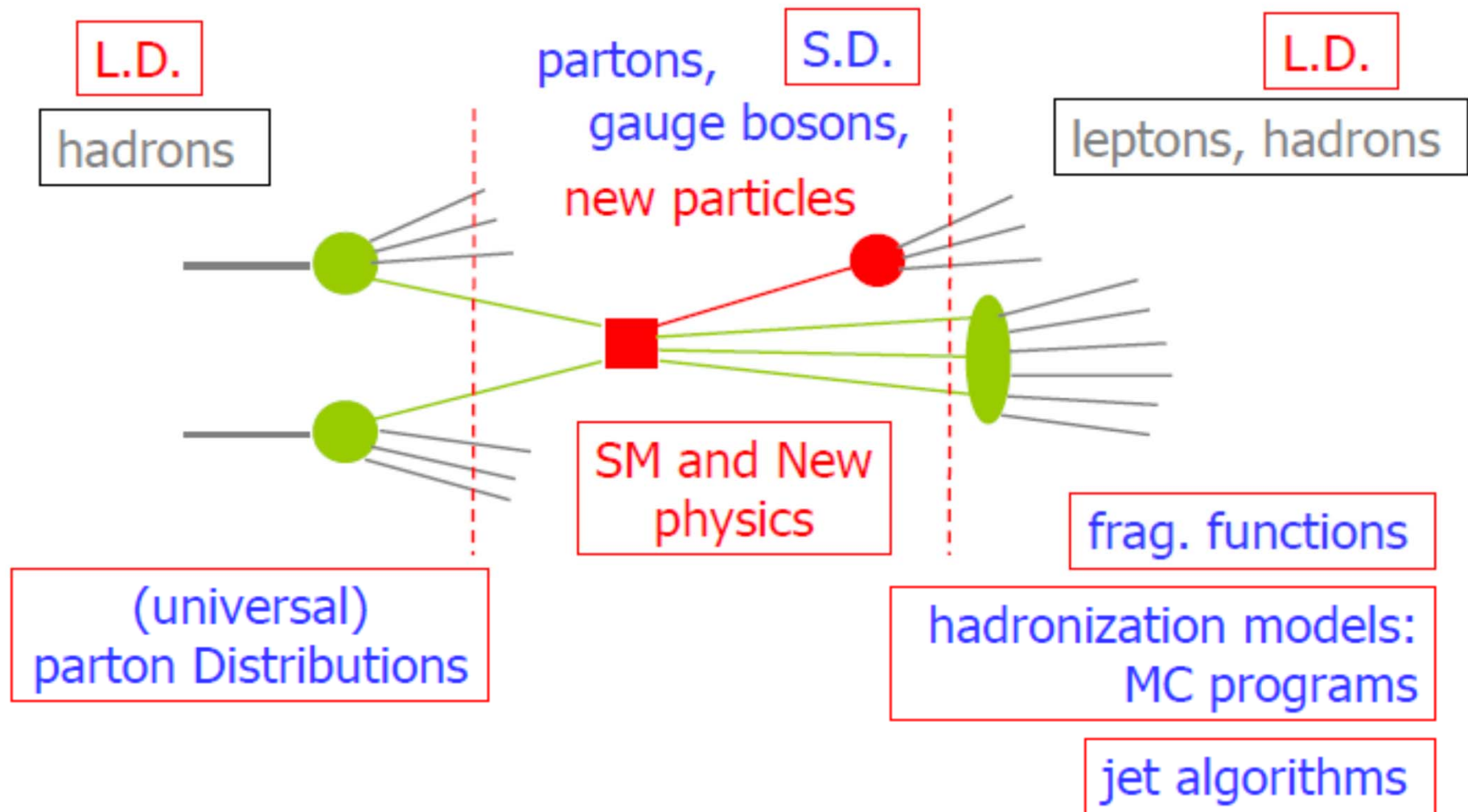
Bin Zhang, Yu-Ping Kuang, Hong-Jian He, CPY; PRD 67 (2003)
114024

- Require New Physics to restore unitarity up to some higher energy scale. It generally implies new resonance states, such as scalar, vector, tensor, or fermion states.

Parton Distribution Functions

Needed for making theoretical
calculations to compare with
experimental data

Hadron Collider Physics



CT10 NNLO update and QED effects in PDFs

Carl Schmidt

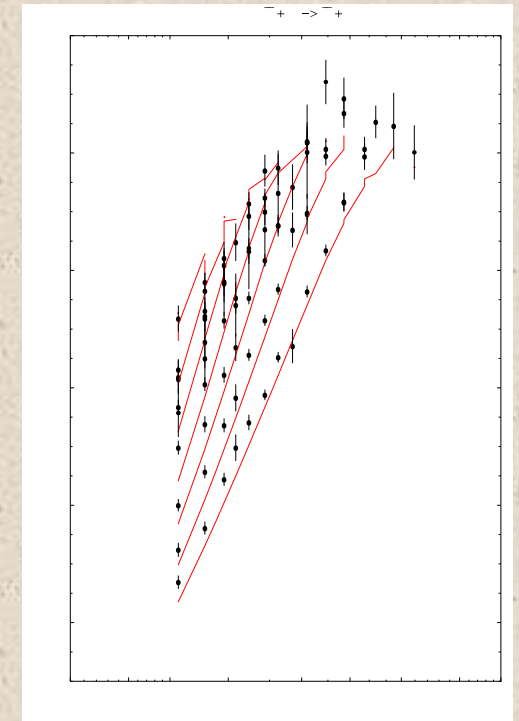
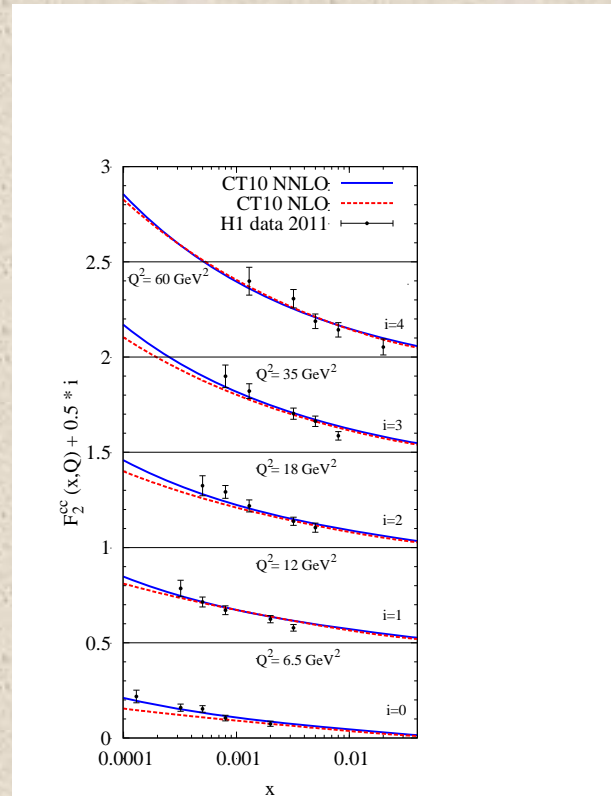
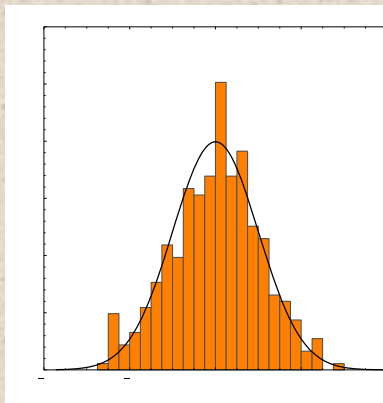
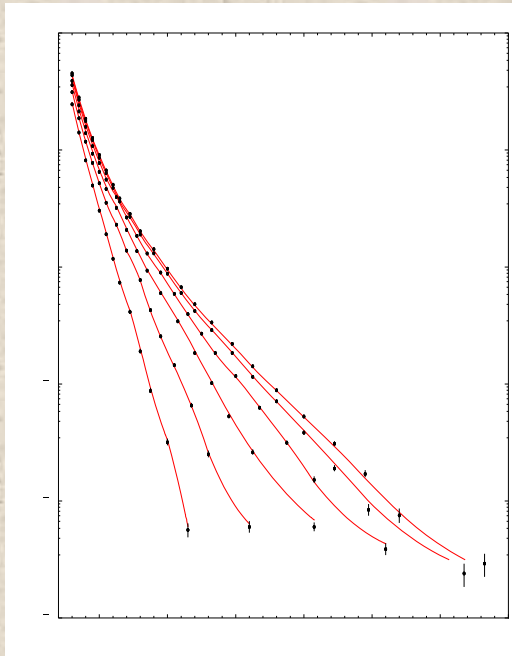
Michigan State University

On behalf of CTEQ-TEA group

April 29, 2014

DIS2014, Warsaw, Poland

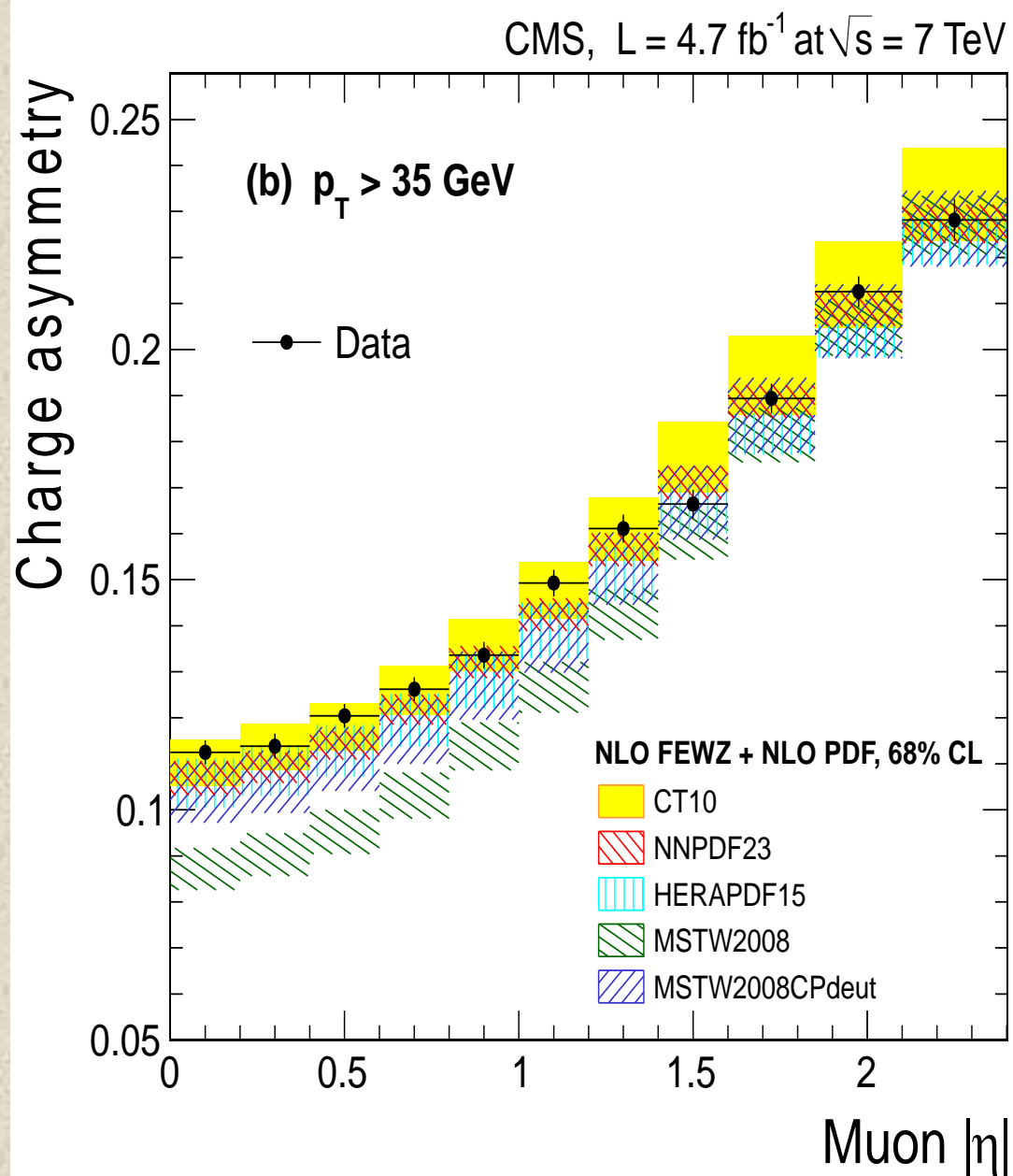
CT10NNLO vs. fitted data



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

CT10, CT1X, 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
- 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.

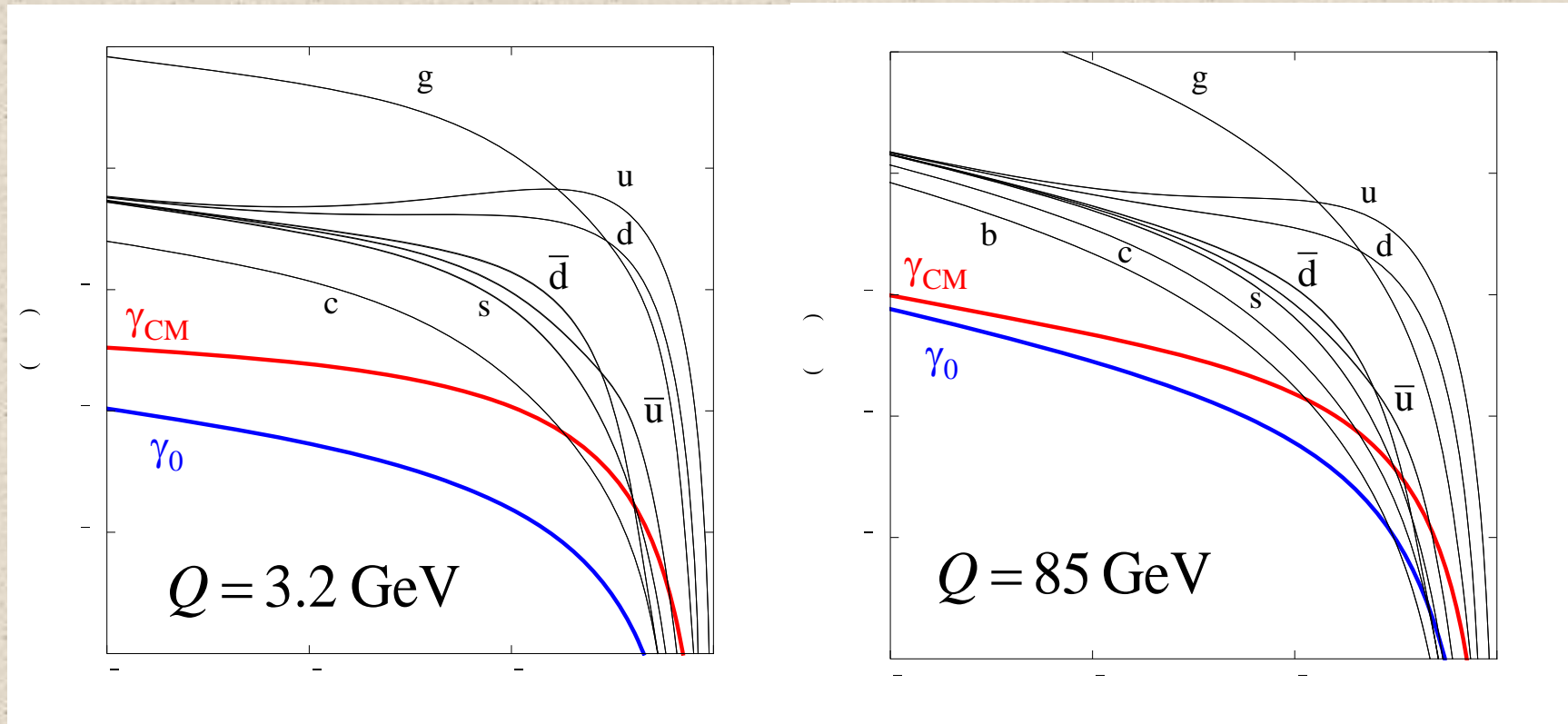


Data is already more precise than current PDF uncertainty.

Will help to determine PDFs in small x region.

Most useful for determining $d\bar{u}/u\bar{d}$.

Photon PDFs (in proton)



γ momentum fraction:

$p^\gamma(Q)$	$\gamma(x, Q_0) = 0$	$\gamma(x, Q_0)_{\text{CM}}$
$Q = 3.2 \text{ GeV}$	0.05%	0.34%
$Q = 85 \text{ GeV}$	0.22%	0.51%

Photon PDF can be larger than sea quarks at large x !

Initial Photon PDF still
← significant at large Q .

Uncertainties on H and $t\bar{t}$ Predictions at the LHC (and update on Intrinsic Charm)

Carl Schmidt

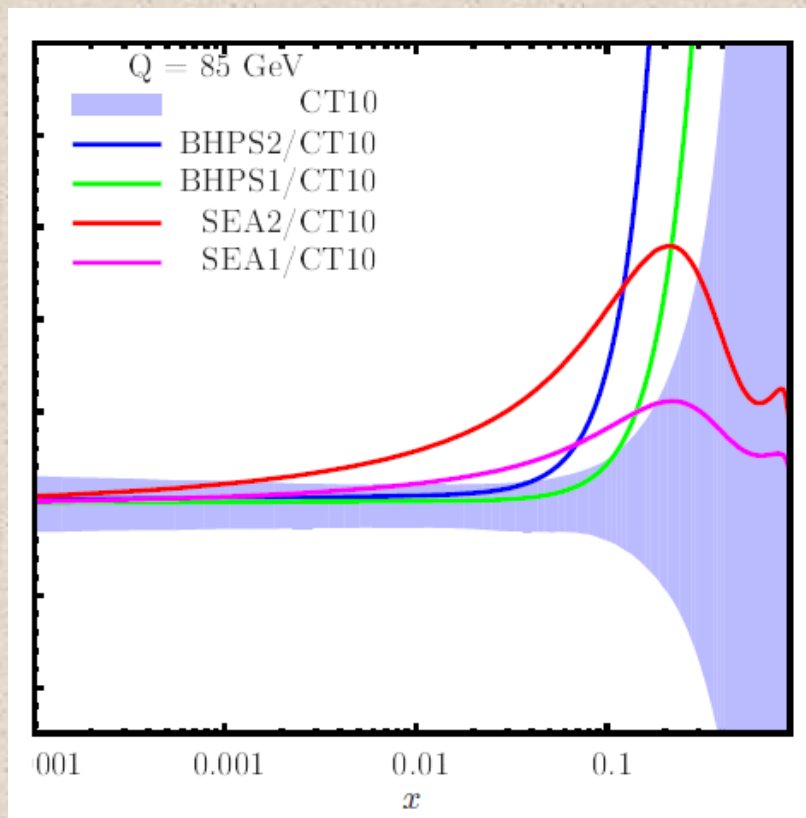
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Intrinsic Charm at LHC

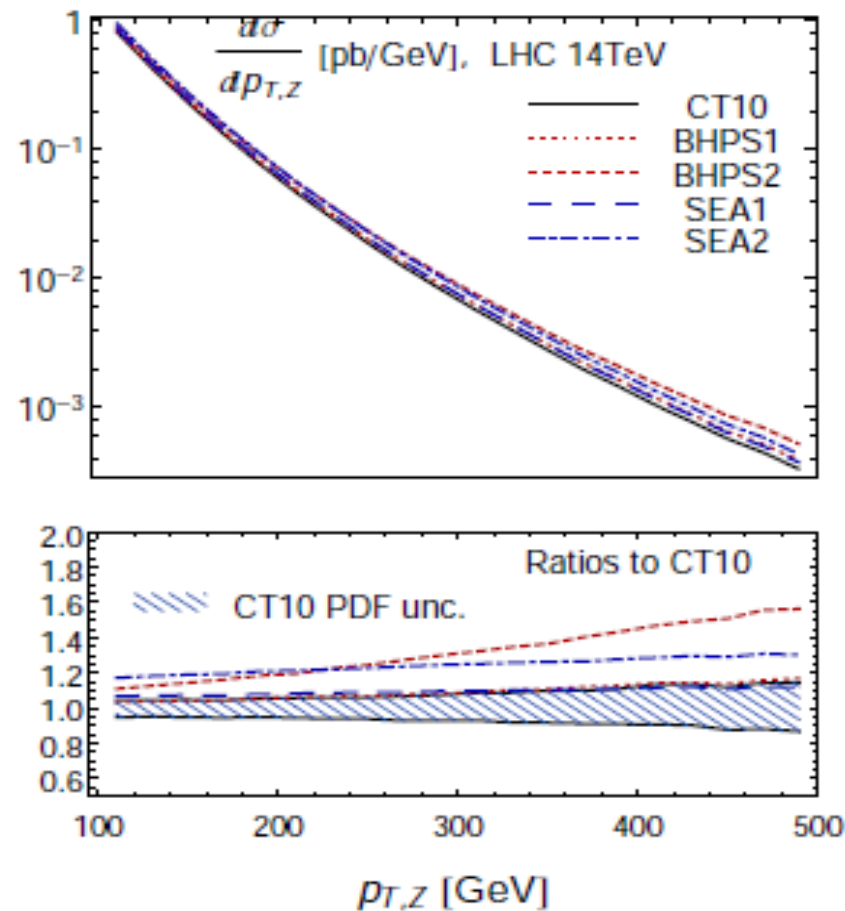


IC vs CT10 charm PDF

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

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

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



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

Some basics about PDFs

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

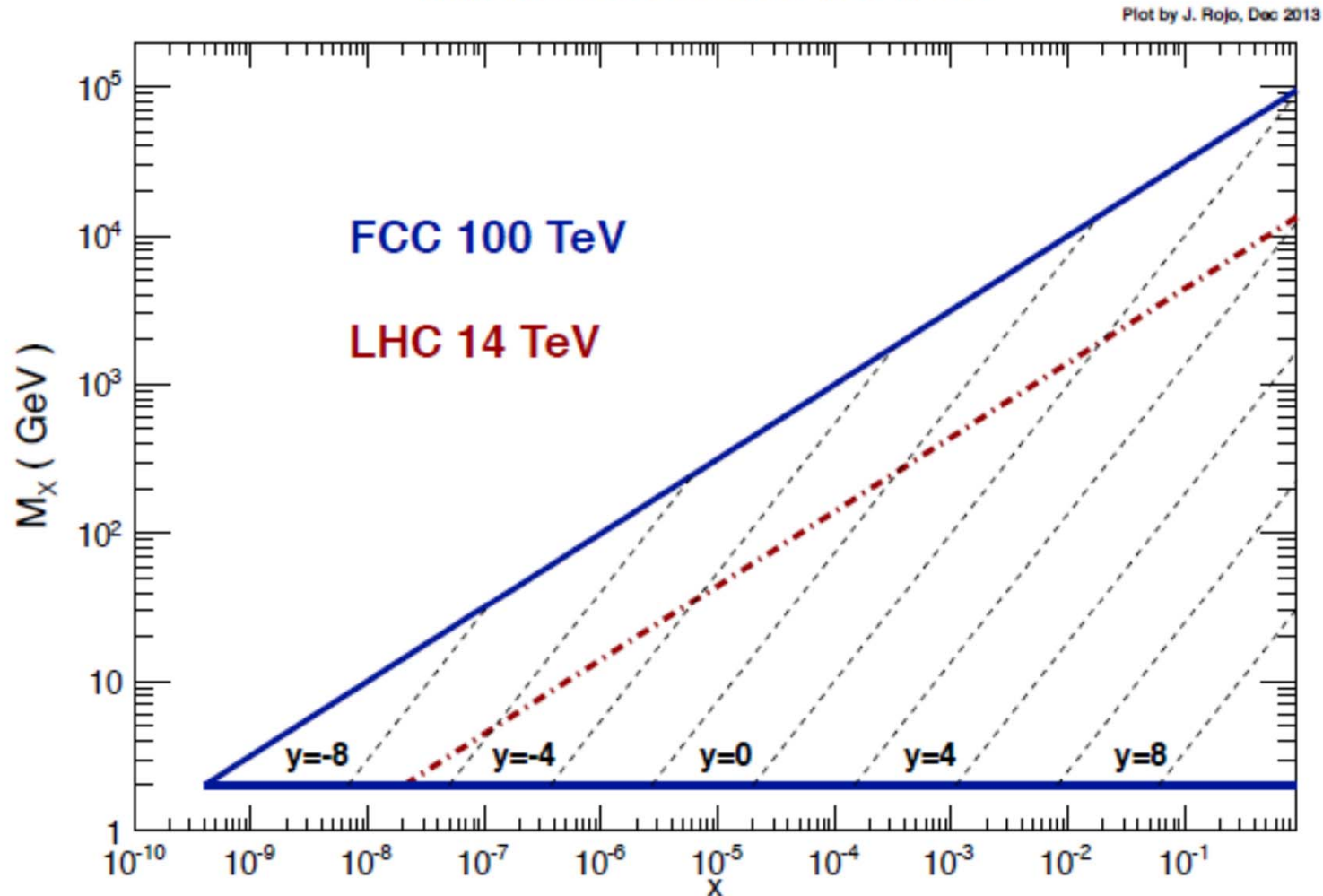
$$\langle x \rangle = \frac{Q}{\sqrt{S}} \quad \text{at central rapidity } (y=0)$$

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

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

Kinematics of a 100 TeV SppC

Kinematics of a 100 TeV FCC



- 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 $1E-4$

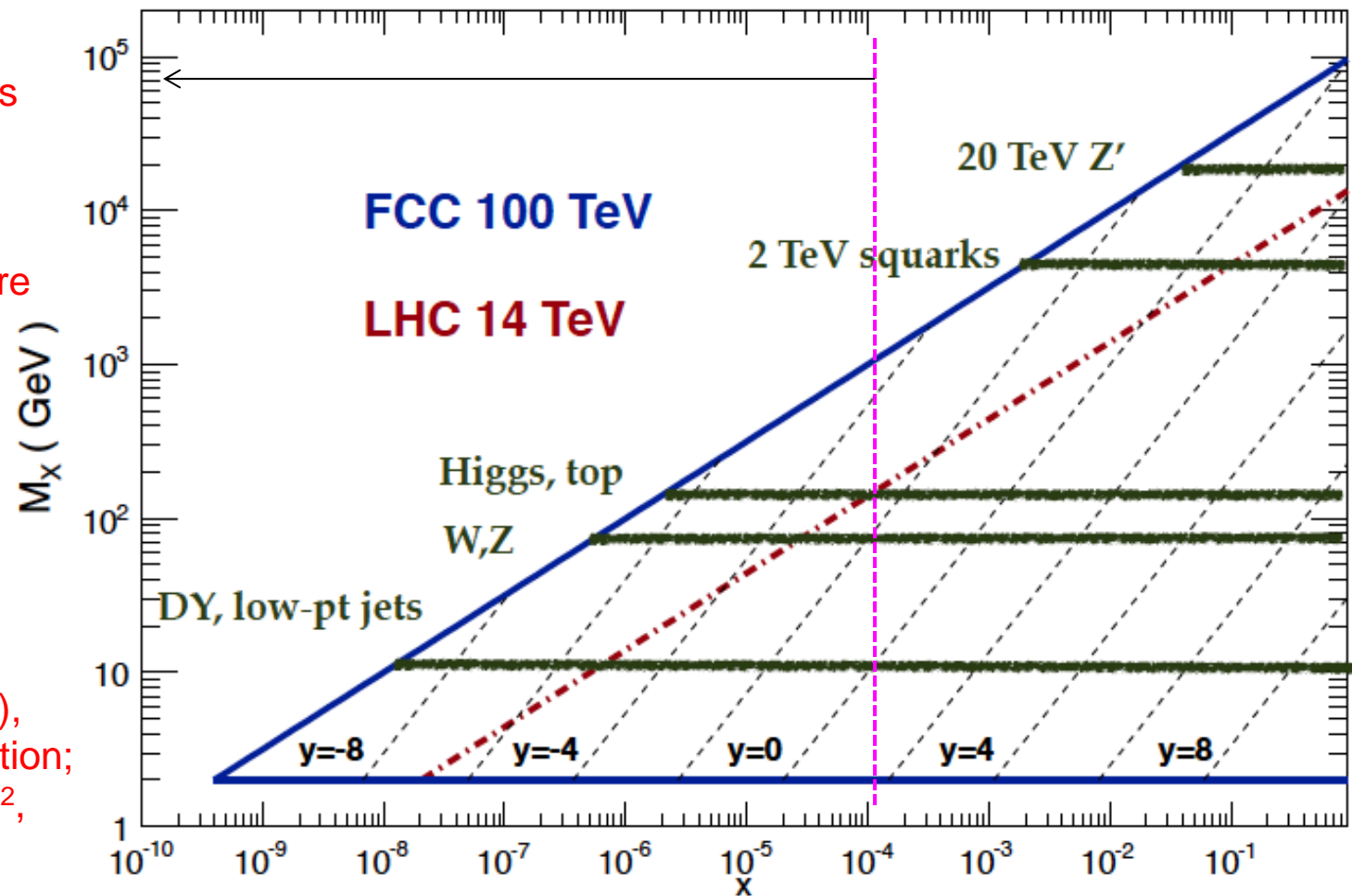
we don't know where at low x , BFKL effects start to become important

poor constraints (still) as well for high x PDFs

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

Kinematics of a 100 TeV FCC

Plot by J. Rojo, Dec 2013

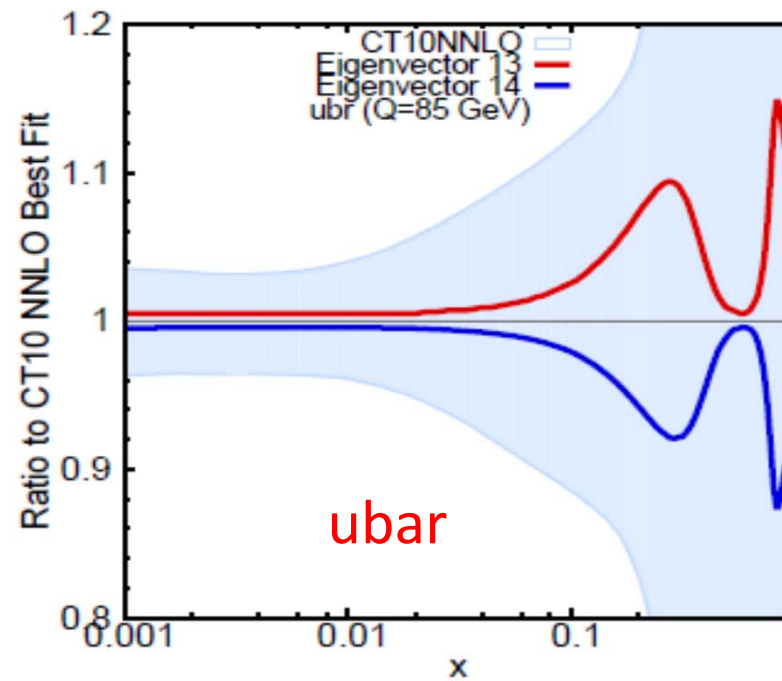
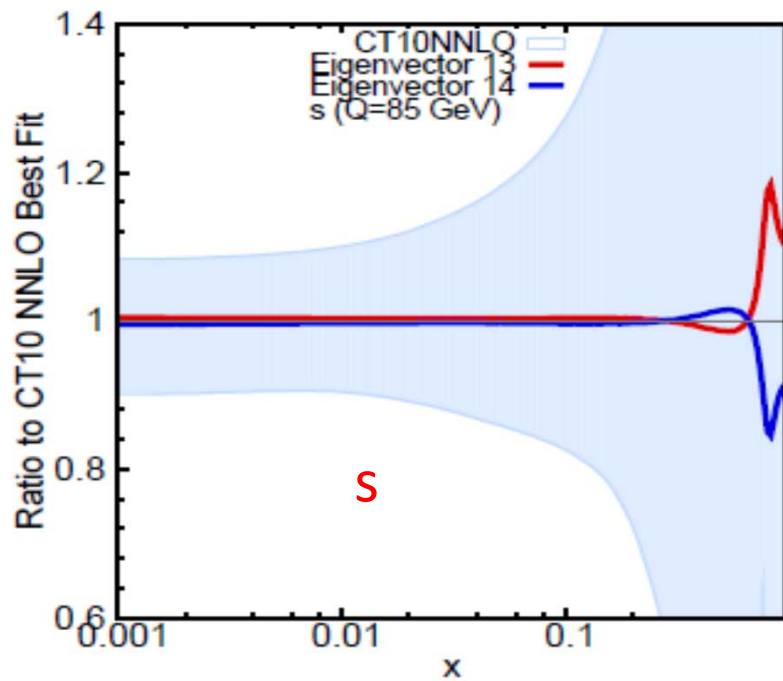
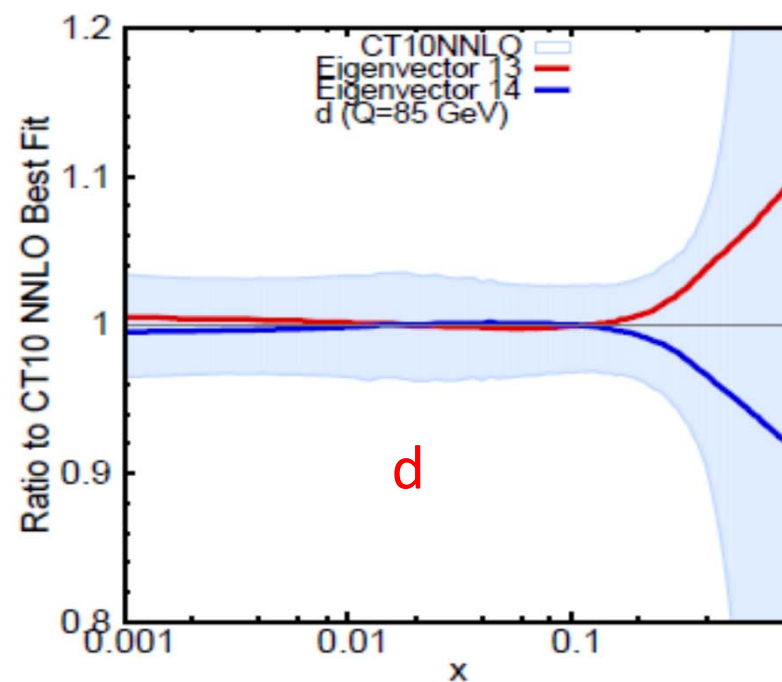
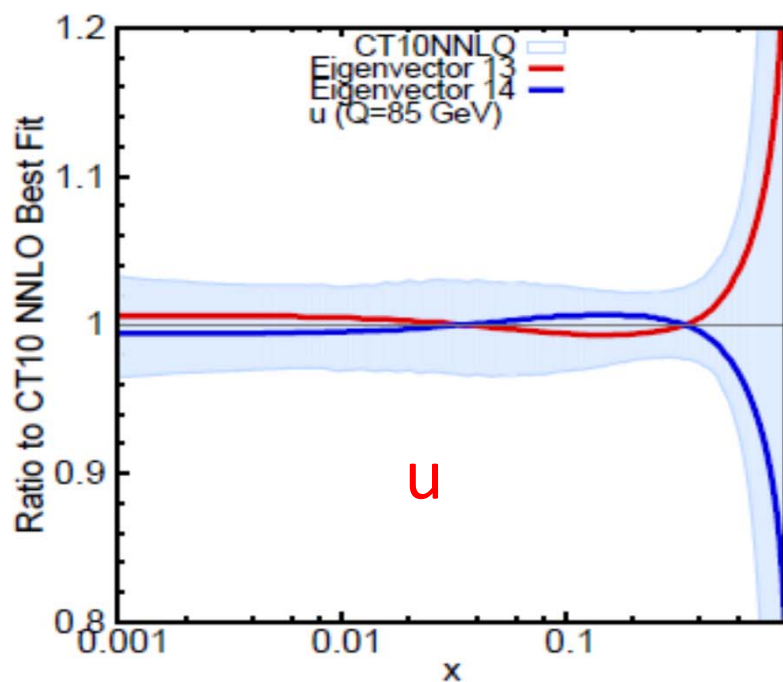


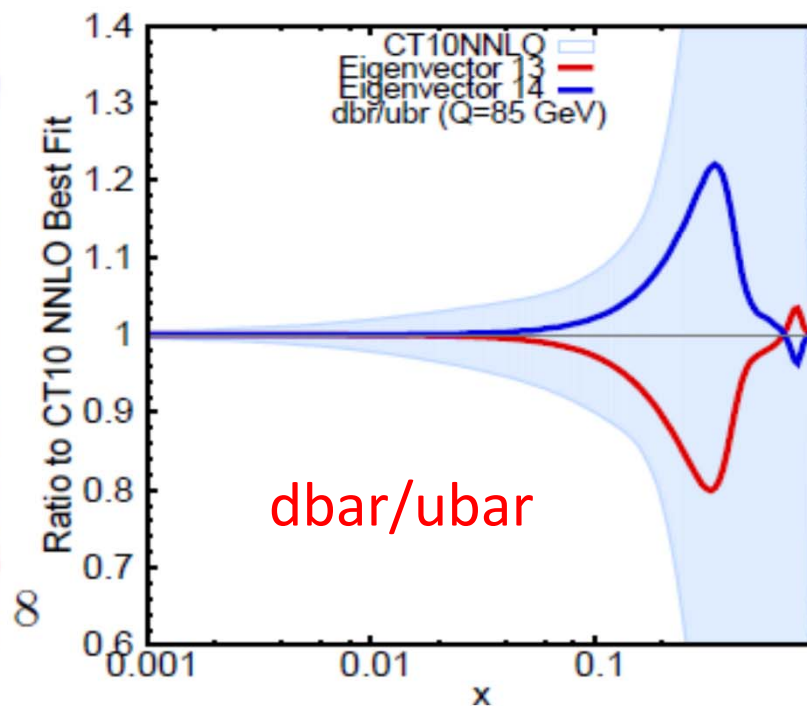
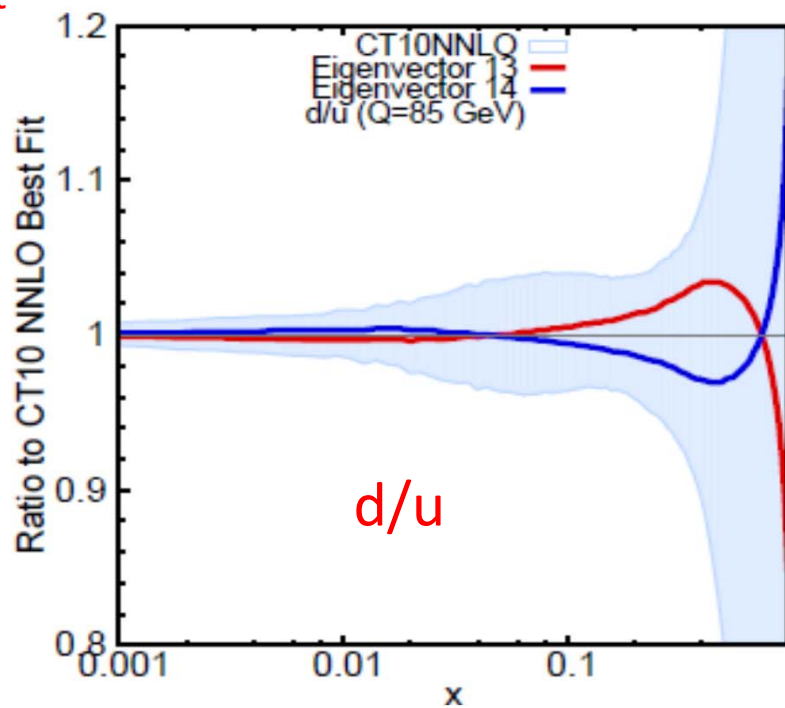
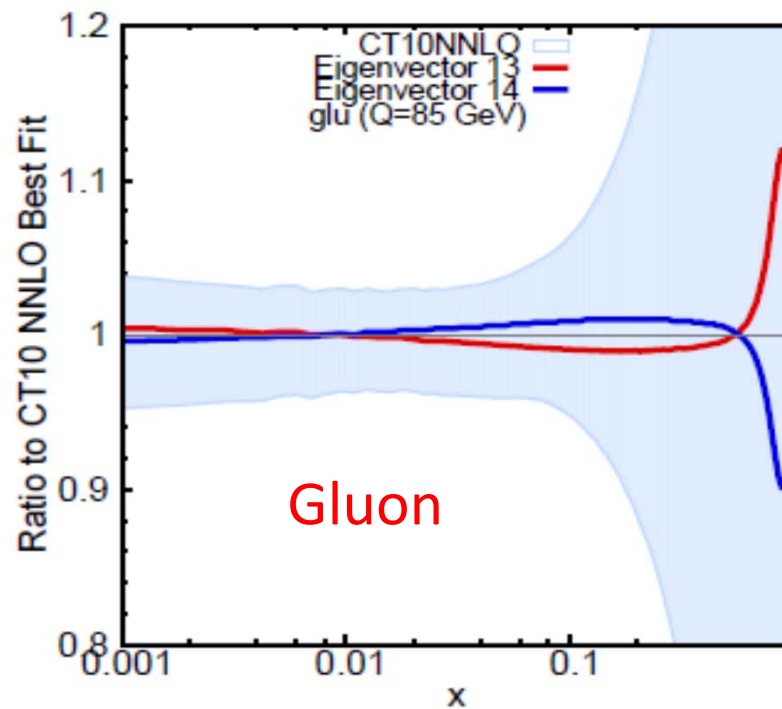
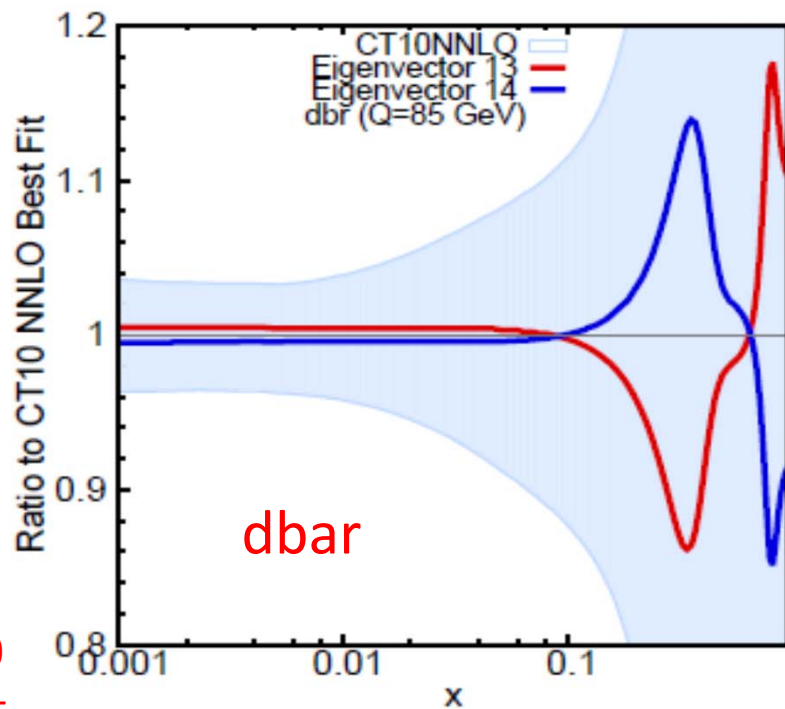
CT10 NNLO PDFs

- 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., \bar{u} and \bar{d}) 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 \bar{d}/\bar{u} ; hence, W asymmetry data at Tevatron and LHC.)

7th CT10
Eigenset



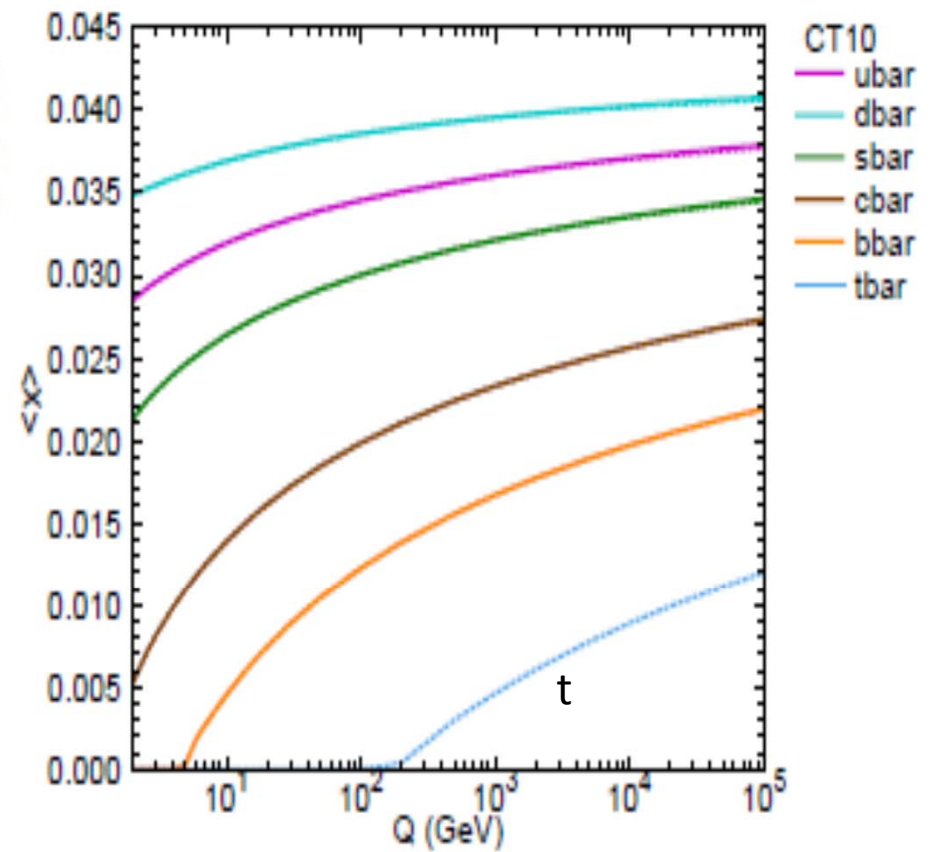
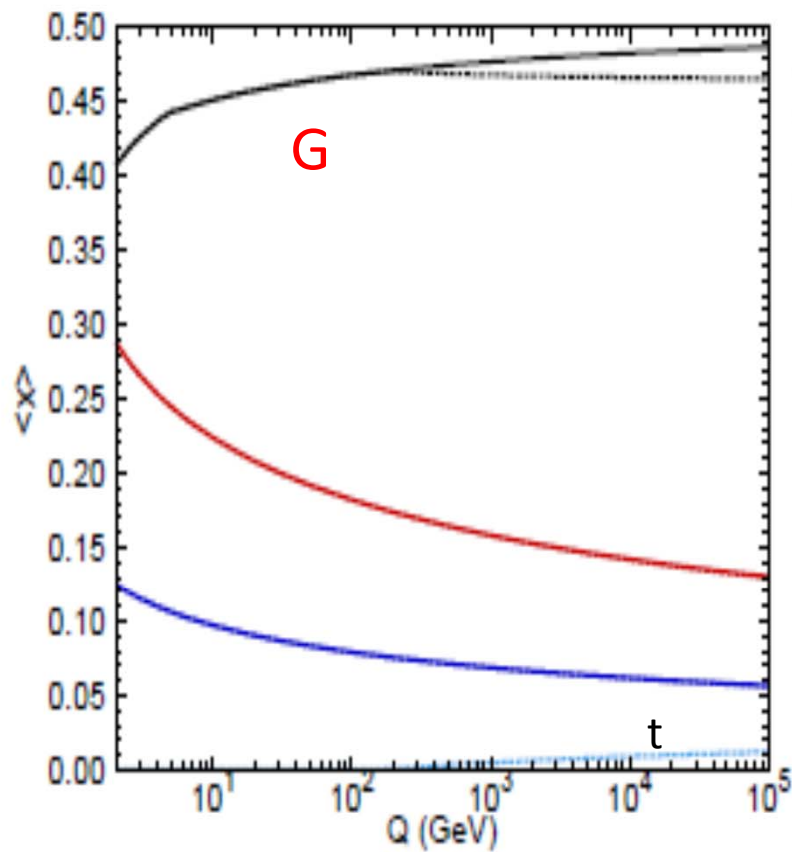


7th CT10
Eigenset

Top quark as a parton

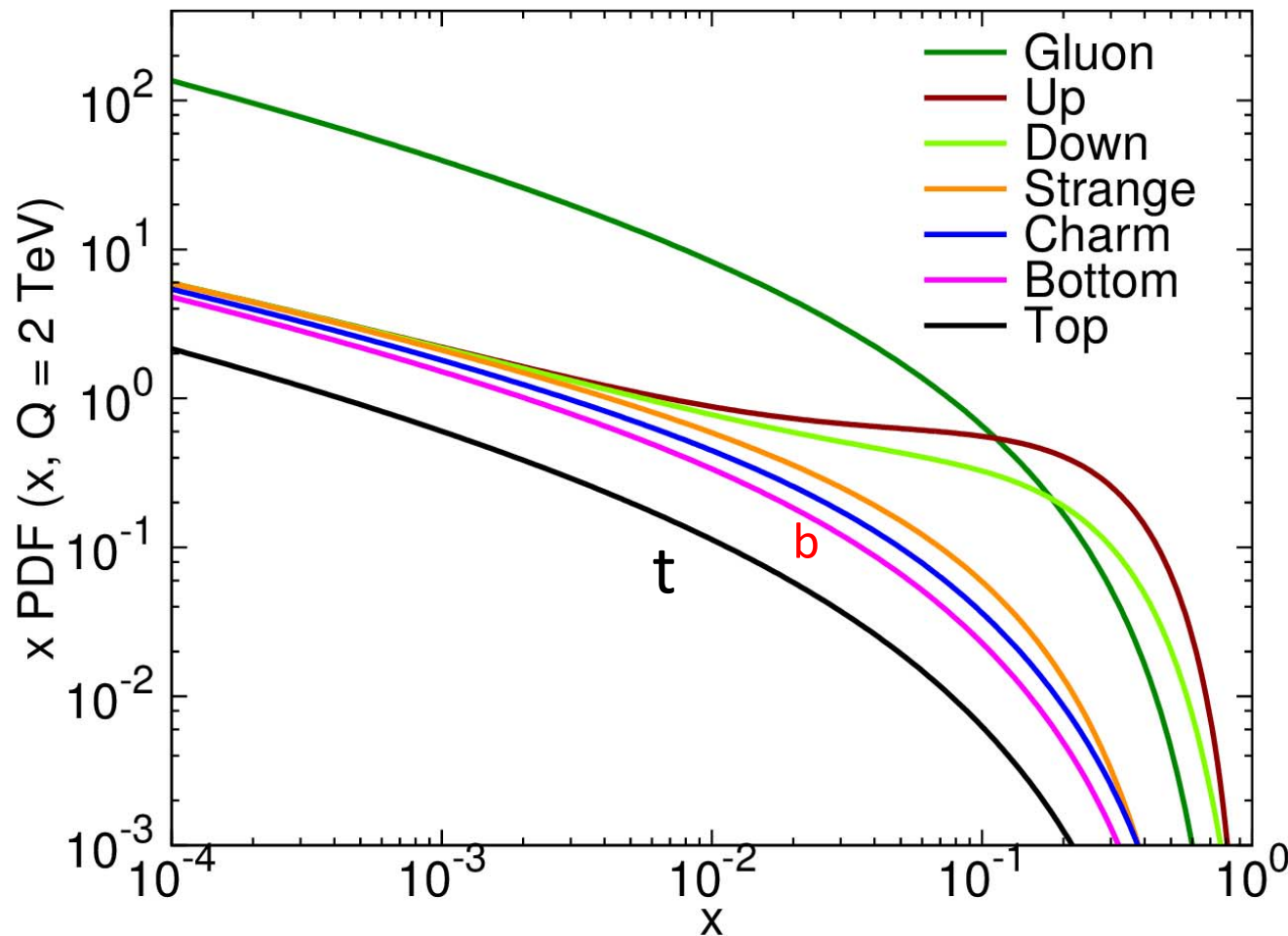
- For a 100 TeV SppC, top mass (172 GeV) can be ignored; top quark, just like bottom quark, can be a parton of proton.
- Top parton will take away some of the momentum of proton, mostly, from gluon (at NLO).
- Need to use s-ACOT scheme to calculate hard part matrix elements, to be consistent with CT10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

Momentum fraction inside proton

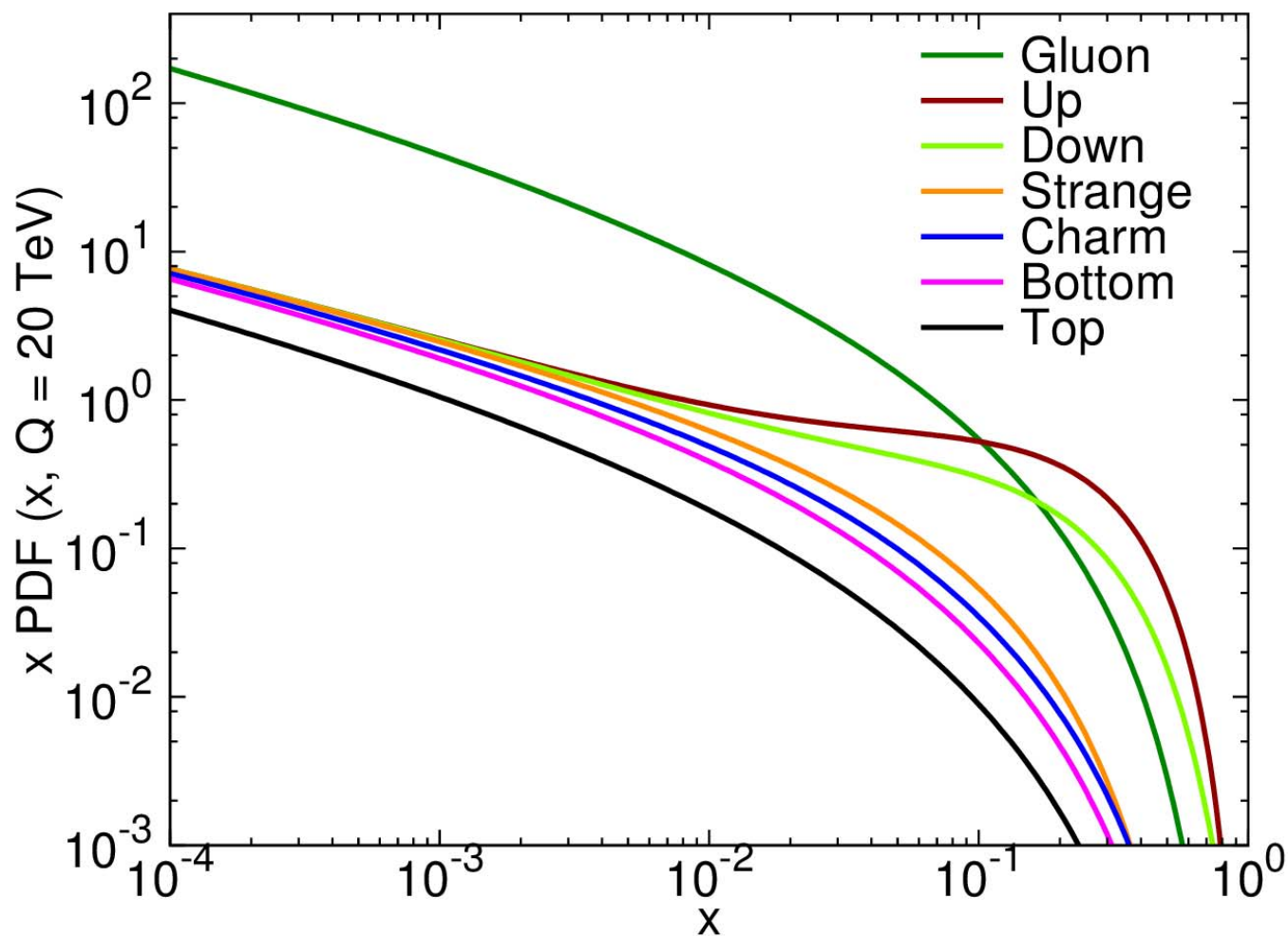


CT10 Top PDFs ($Q=2$ TeV)

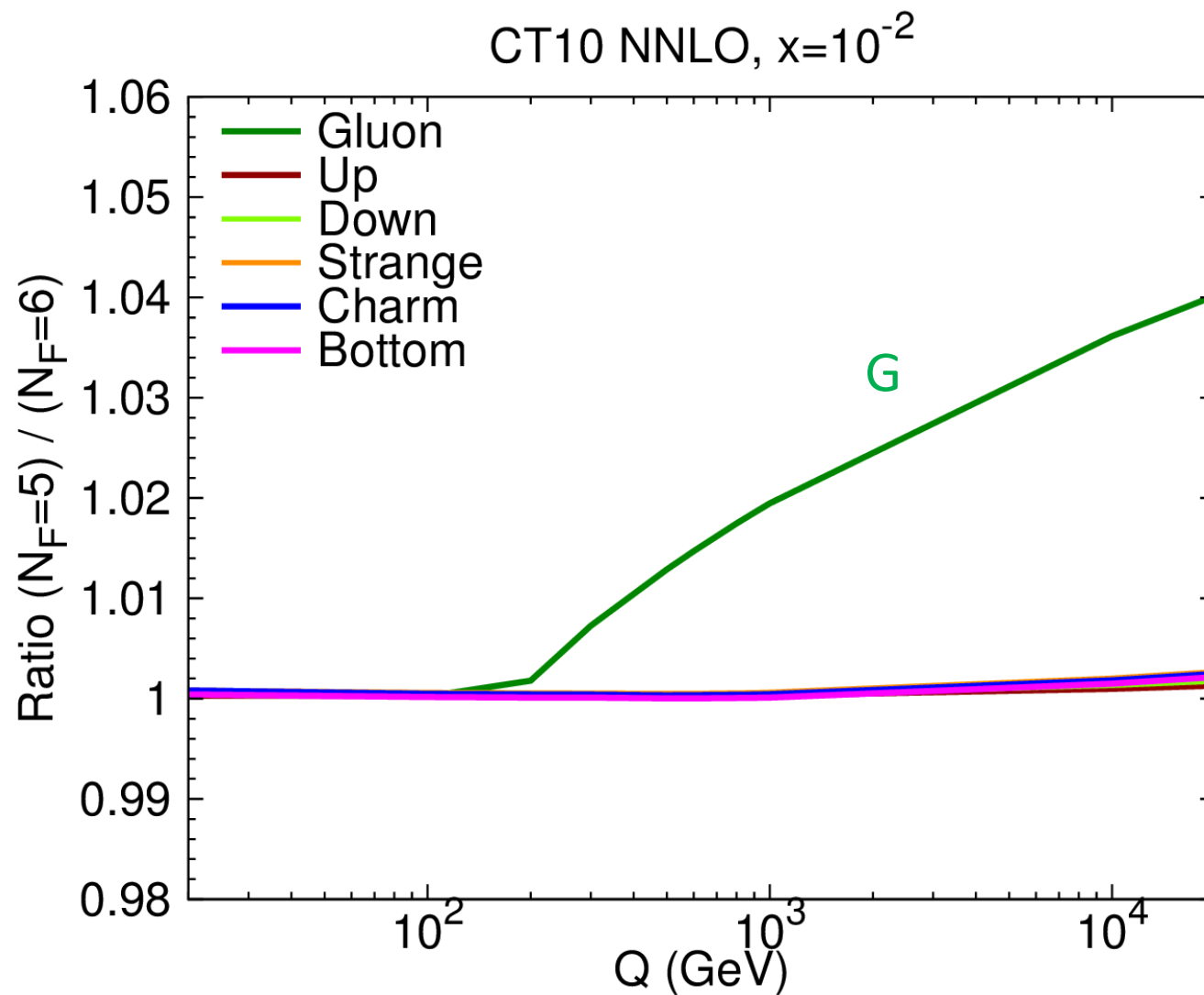
CT10 NNLO, $N_F = 6$



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

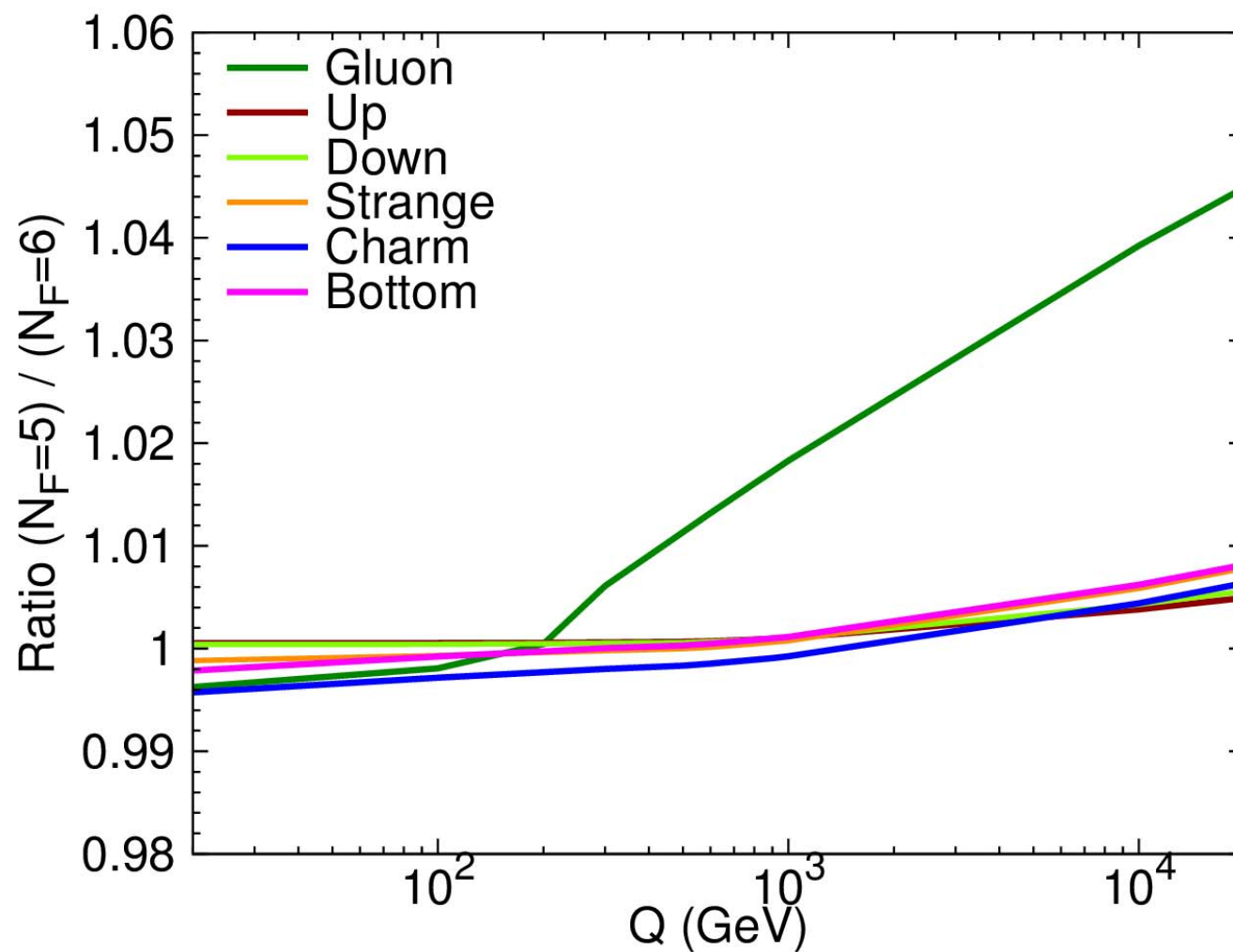
CT10 NNLO, $N_F = 6$ 

CT10Top PDFs



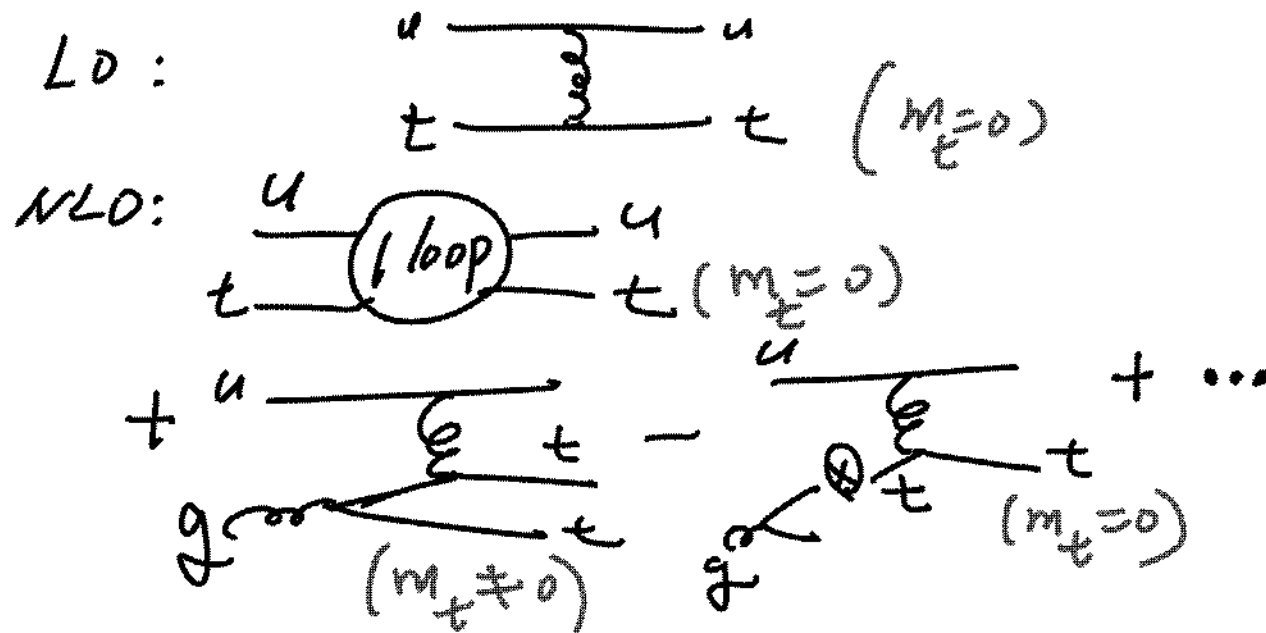
CT10Top PDFs

CT10 NNLO, $x=0.2$



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.
- Photon can be treated as a parton inside proton.
- In a 100TeV SppC, top quark can be a parton of proton, consistent hard part calculations are needed.