PDF at LHC and 100 TeV Collider

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In collaboration with
CTEQ-TEA

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CTEQ-TEA group

- CTEQ – Tung et al. (TEA)

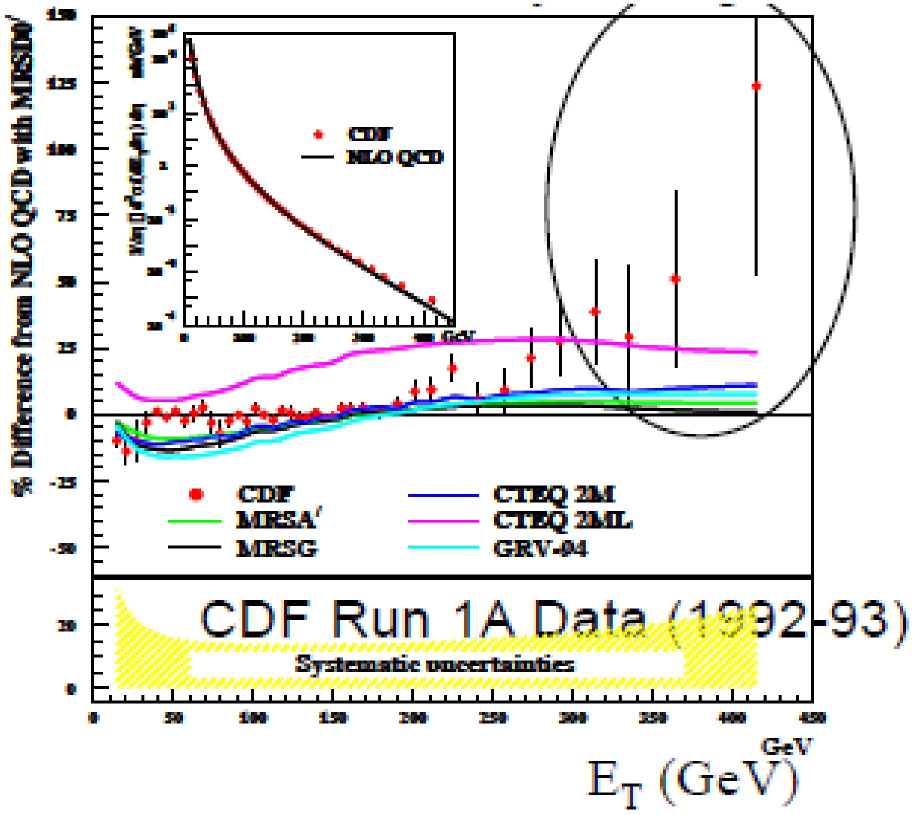
in memory of Prof. Wu-Ki Tung,
who established CTEQ Collaboration in early 90's

The Coordinated Theoretical-Experimental project on QCD

- Current members:

Sayipjamal Dulat (Xinjiang U.),
Tie-Jiun Hou, Pavel Nadolsky (Southern Methodist U.), Jun Gao (Argonne Nat. Lab.), Marco Guzzi (U. of Manchester), Joey Huston, Jon Pumplin, Dan Stump, Carl Schmidt, CPY (Michigan State U.)

New Physics Found (20 years ago)?

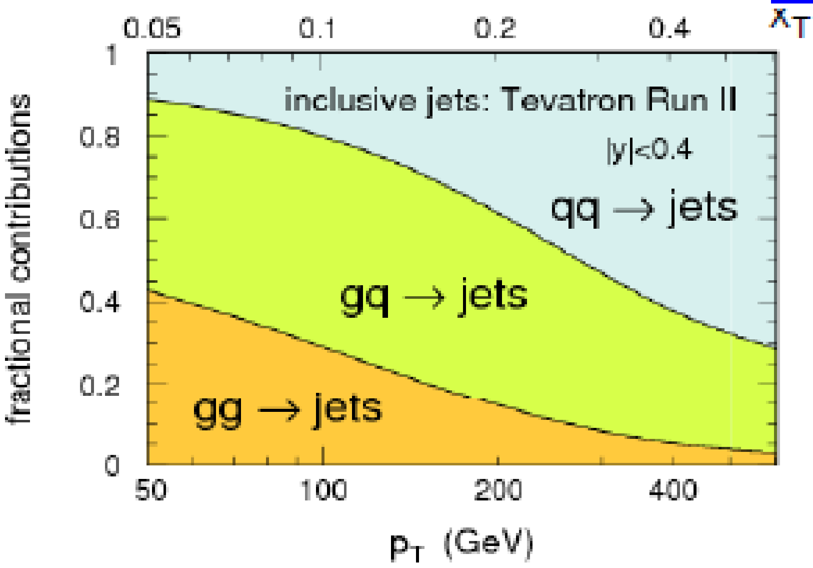


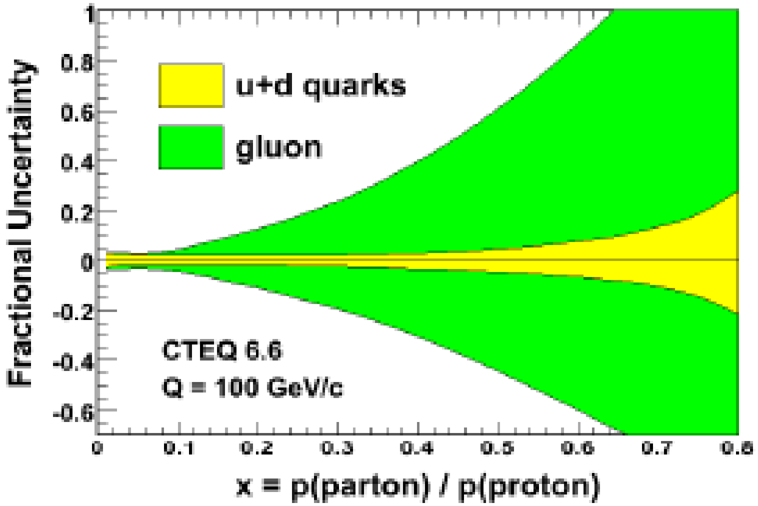
CDF Run 1A Data (1992-93)

Phys. Rev. Lett. 77, 438 (1996)

High-x gluon not well known

...can be accommodated in the Standard Model

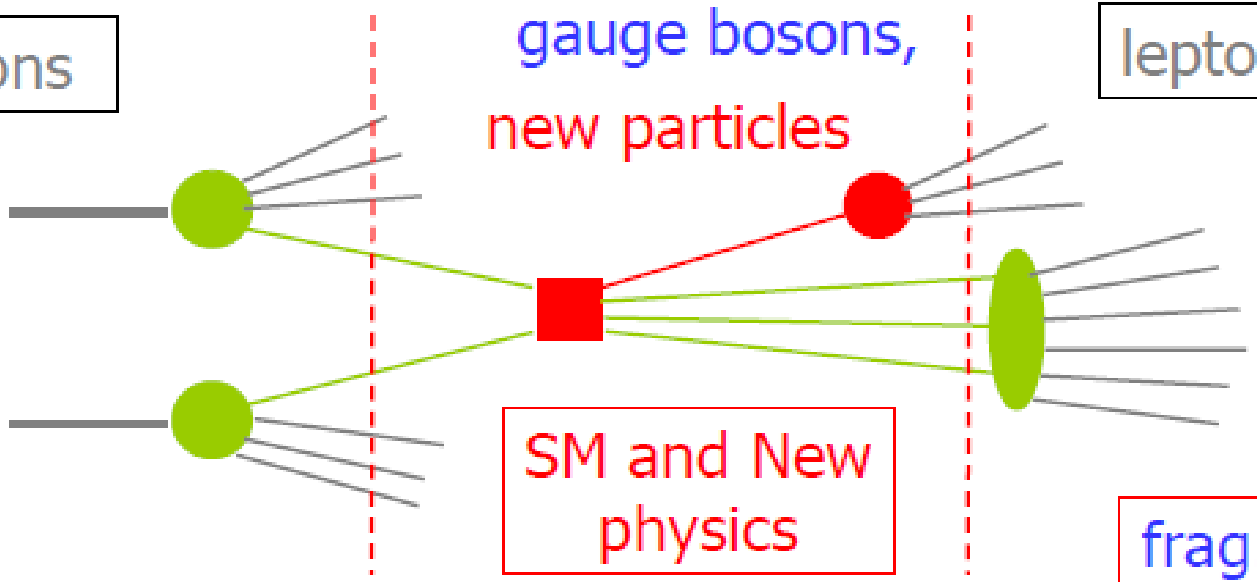




Parton Distribution Functions

Needed for making theoretical calculations to compare with experimental data

Hadron Collider Physics



L.D.

hadrons

partons,

gauge bosons,

new particles

S.D.

L.D.

leptons, hadrons

SM and New physics

frag. functions

(universal) parton Distributions

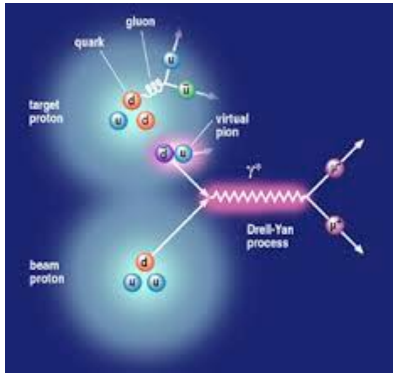
hadronization models: MC programs

jet algorithms

Parton Distribution Functions (PDFs)

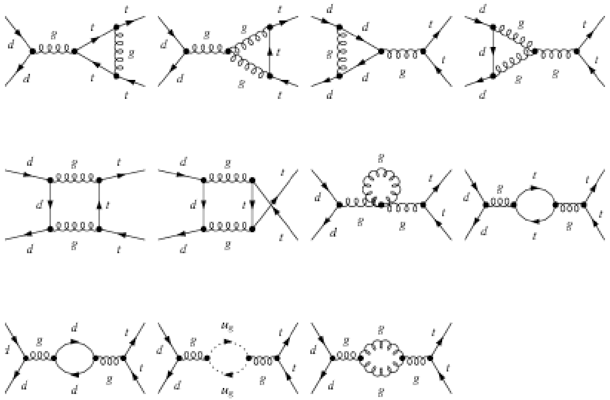
Factorization Theorem (QCD improved parton model)

$$\sigma(\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)) = \sum_{a,b}\int_0^1 dx_1 dx_2 f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2)\ \hat{\sigma}^{a,b}(x_1,x_2;\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{Q^2}\right)$$



Long distance, nonperturbative

Hard scattering cross section (short distance, perturbative):



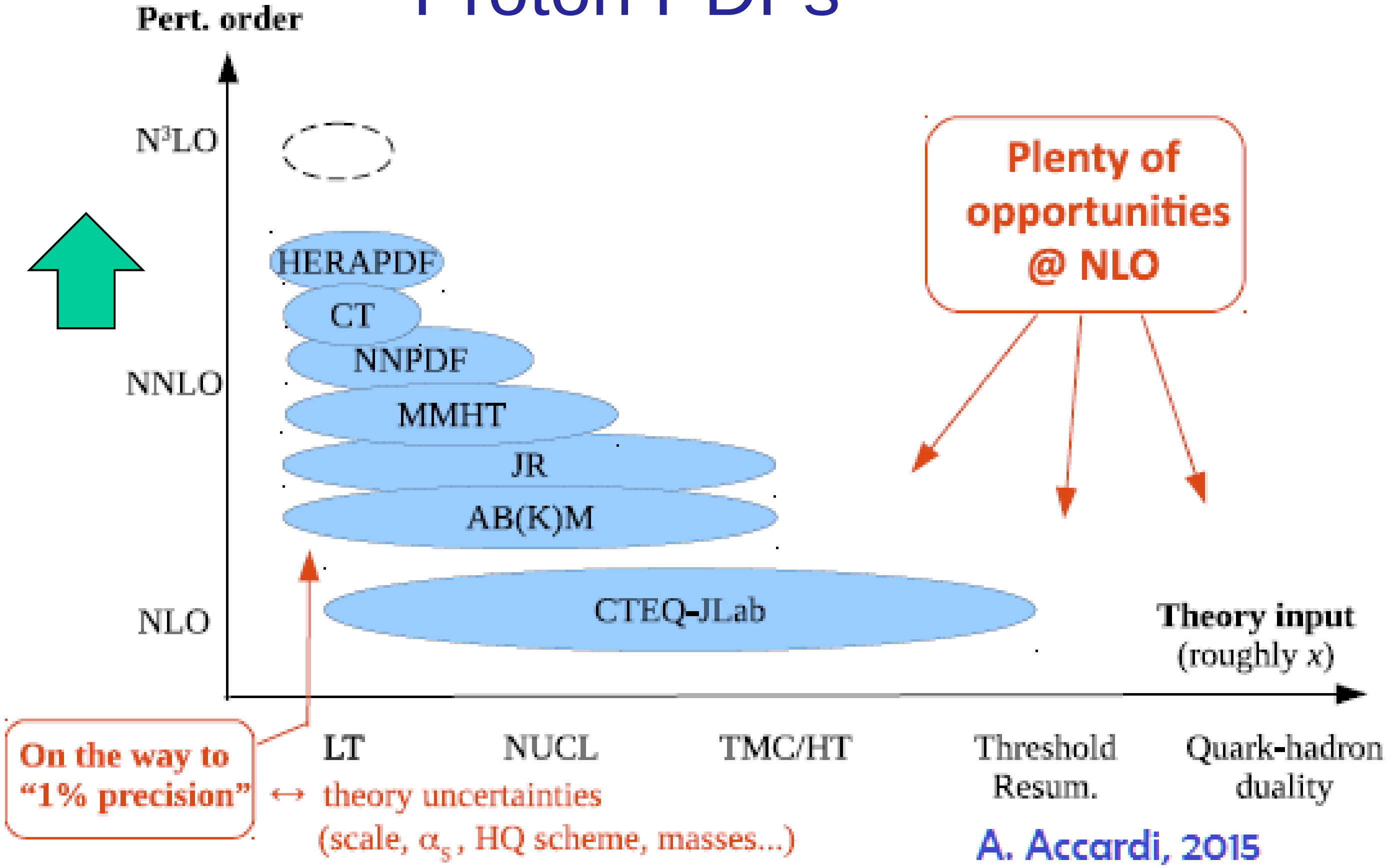
$$\frac{d\ f_a(x,\mu_F^2)}{d\log\mu_F^2} = \sum_{b=q,\bar{q},g}\int_x^1 \frac{dz}{z} P_{ab}\left(\frac{x}{z};\mu_F^2\right) f_b(z,\mu_F^2)$$

PDFs depend on energy scale:
RG evolution (DGLAP)

Parton Distribution Functions (PDFs) of the proton map out the longitudinal momentum distribution of proton’s constituent quarks and gluons.

Two trends in the modern PDF analysis

Proton PDFs



Plenty of opportunities @ NLO

On the way to "1% precision" ↔ theory uncertainties (scale, α_s, HQ scheme, masses...)

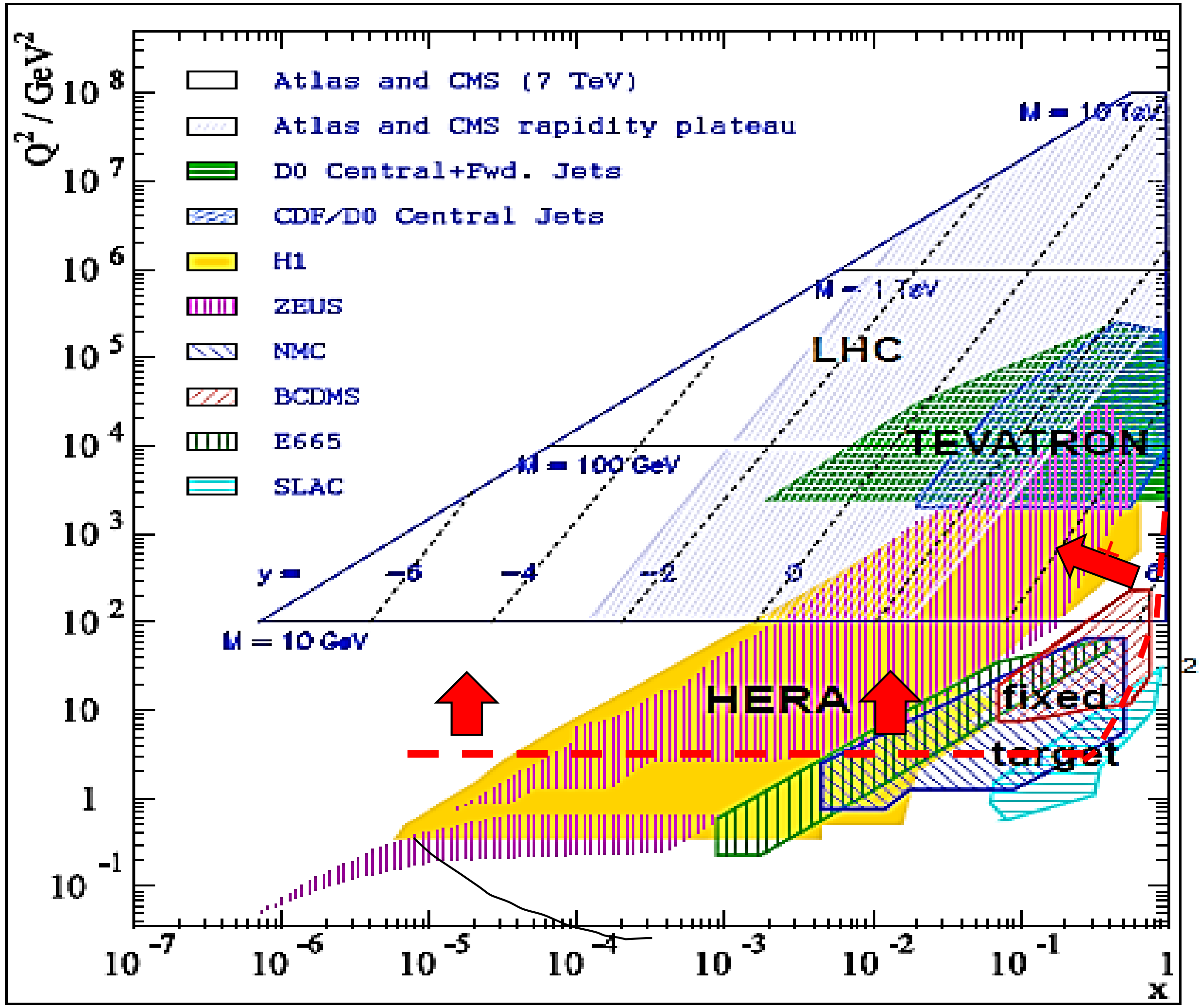
A. Accardi, 2015

For general-purpose **nucleon** PDFs, the goal is to determine very precise parametrizations for pQCD calculations up to (N)(N)NLO in α_s. The focus is on the high-Q data that is not sensitive to nuclear (NUCL), target mass corrections (TMC) and higher twists (HT) effects.

⇒ CT, MMHT, NNPDF PDFs for studying LHC physics.

Selected Experimental Data in Global analysis

For nucleon PDFs, experimental measurements are selected so as to reduce dependence on theoretical input beyond the leading power in perturbative QCD

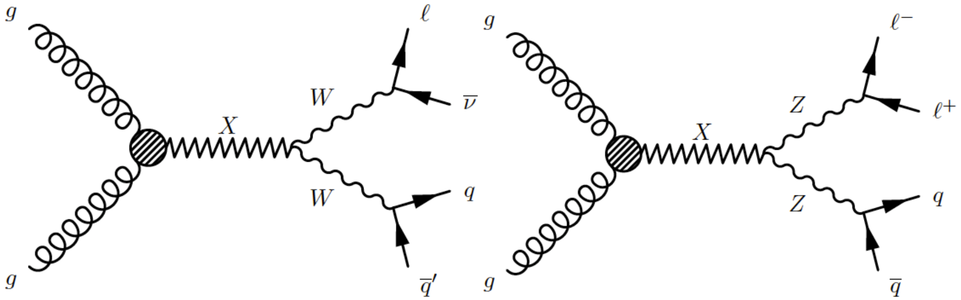


CT14:

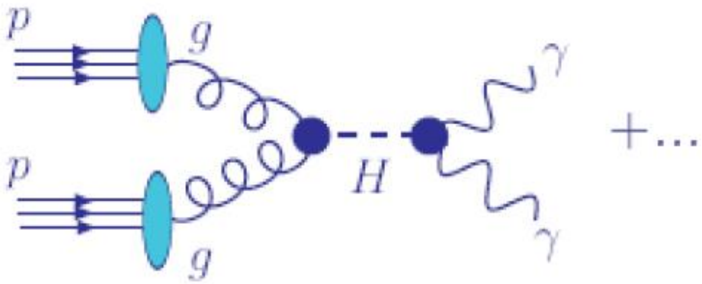
only DIS data with $Q^2 > 4\ GeV^2$, $W^2 > 12.5\ \ GeV^2$ (above the red line) are accepted to ensure stable perturbative predictions

Still using data from DIS and DY on **nuclear targets. CT14HERA2** does not use NMC DIS **on deuteron,** will be replaced by comparable future LHC/Tevatron measurements on **the proton**

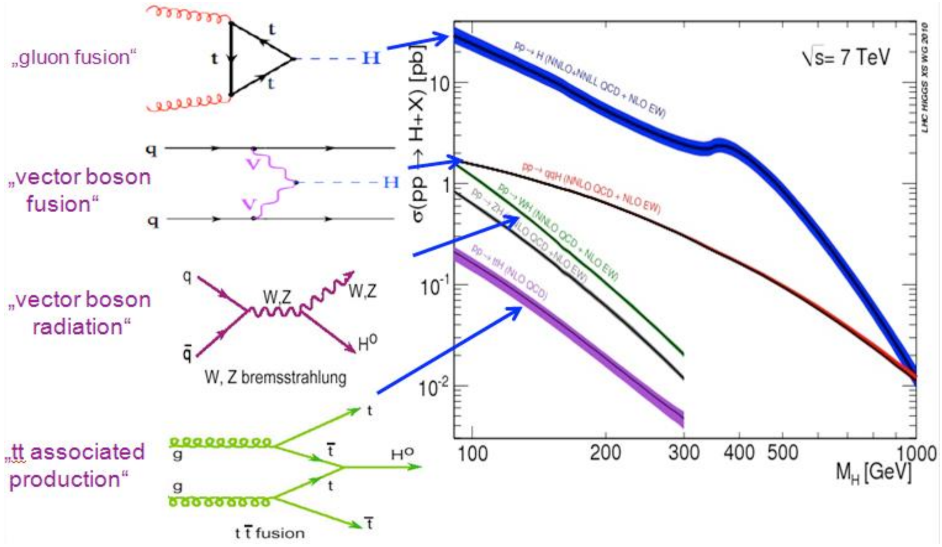
Precise knowledge of PDFs is important



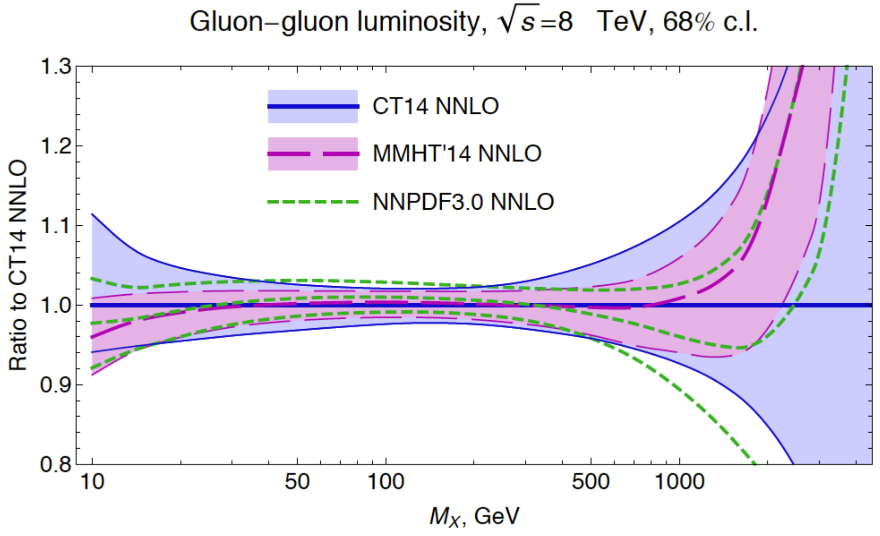
Gluon-gluon channel for the production of a generic resonance X decaying to WW and ZZ diboson pairs.



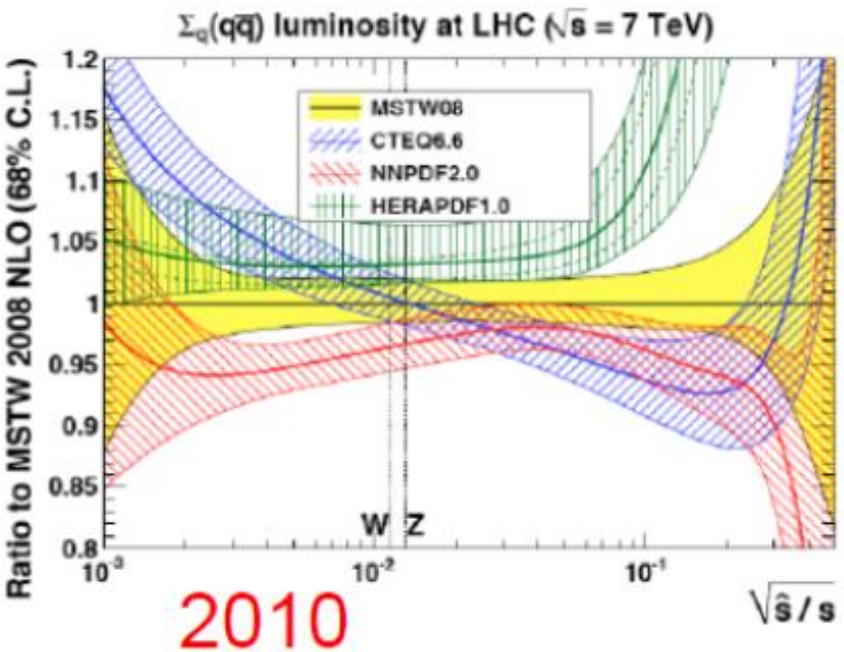
Higgs boson production



SENSITIVITY TO GLUON PDFs

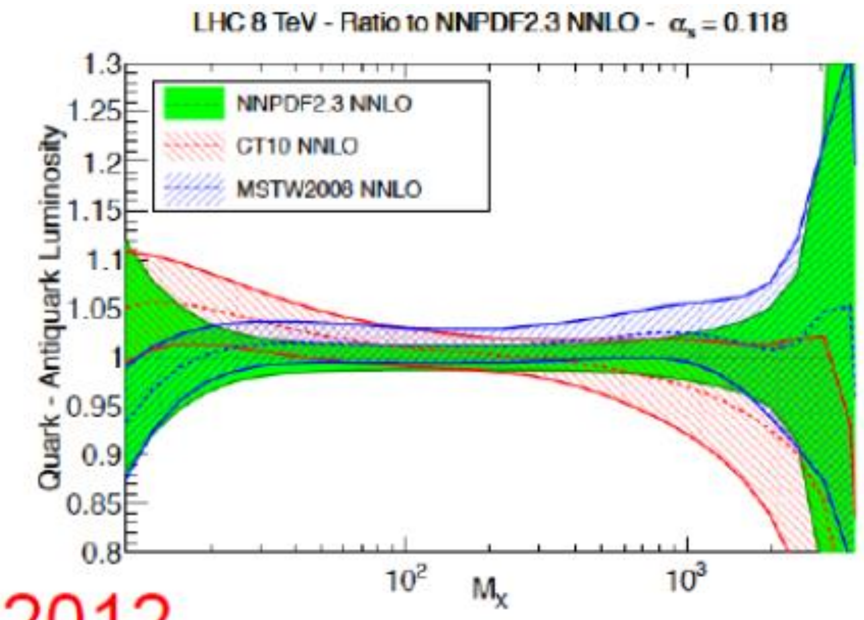


CT14 PDFs:1506.07443

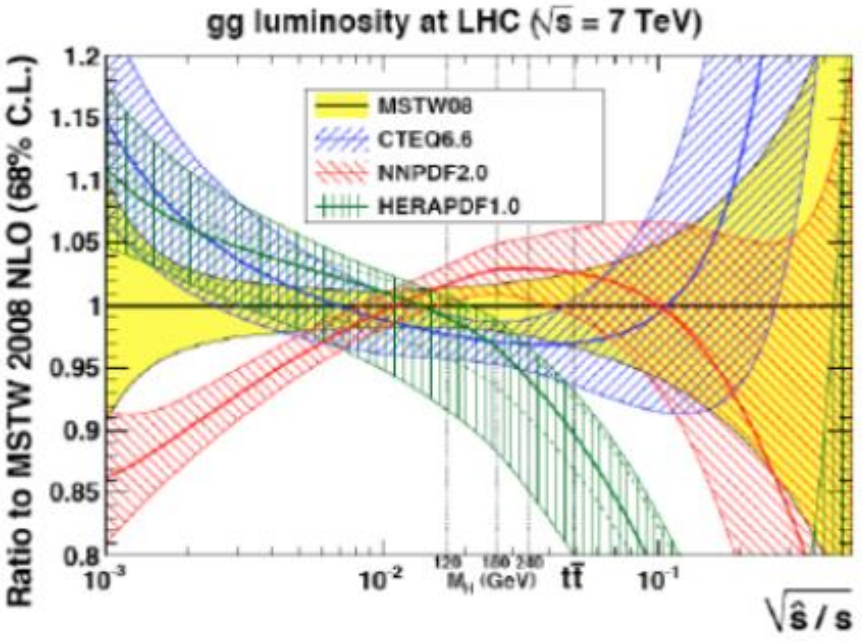


2010

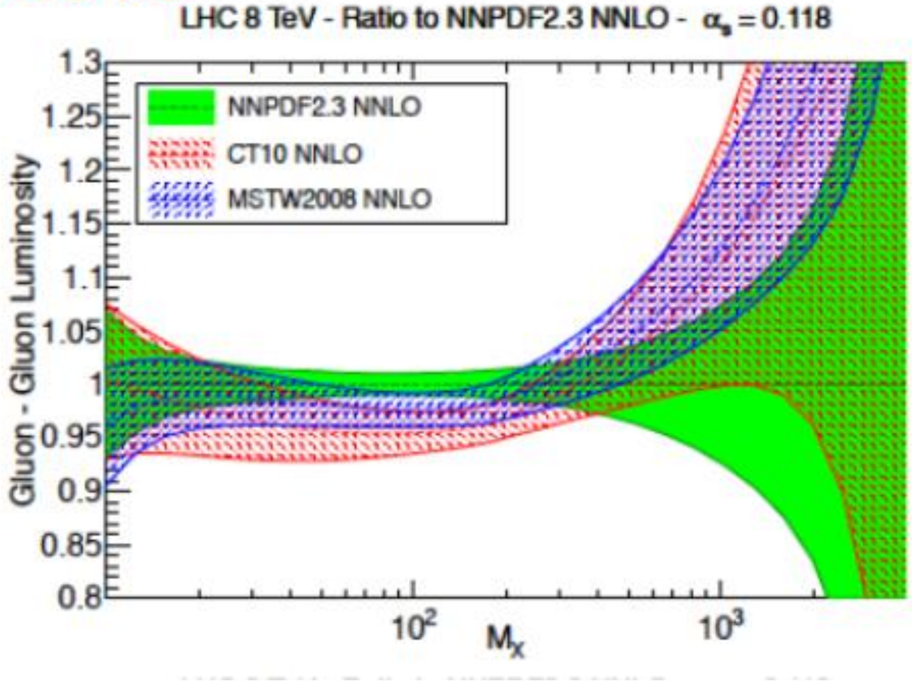
q-qbar

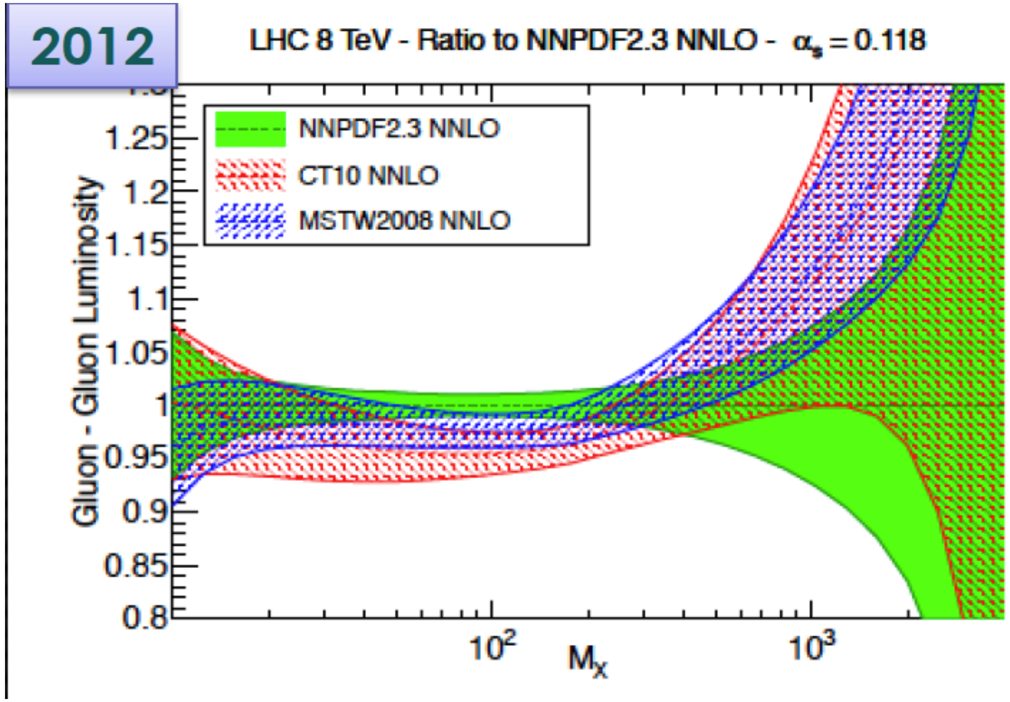


2012



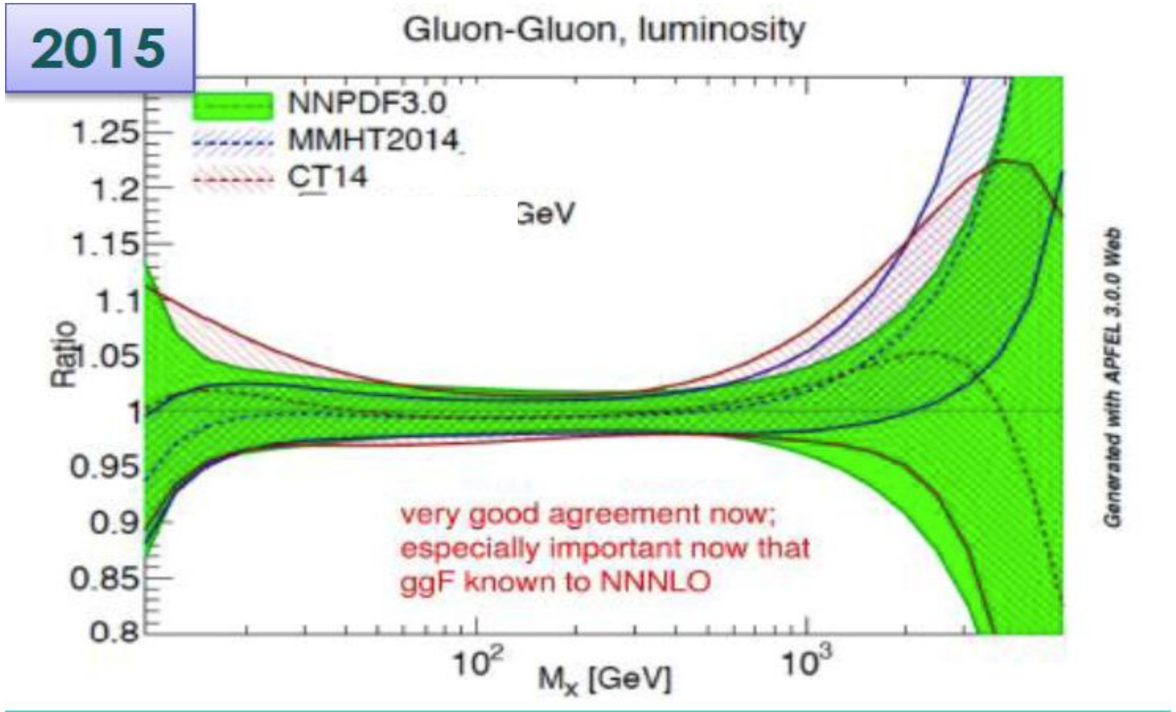
G-G





LHC run 1 data have some impact in recent global analyses.

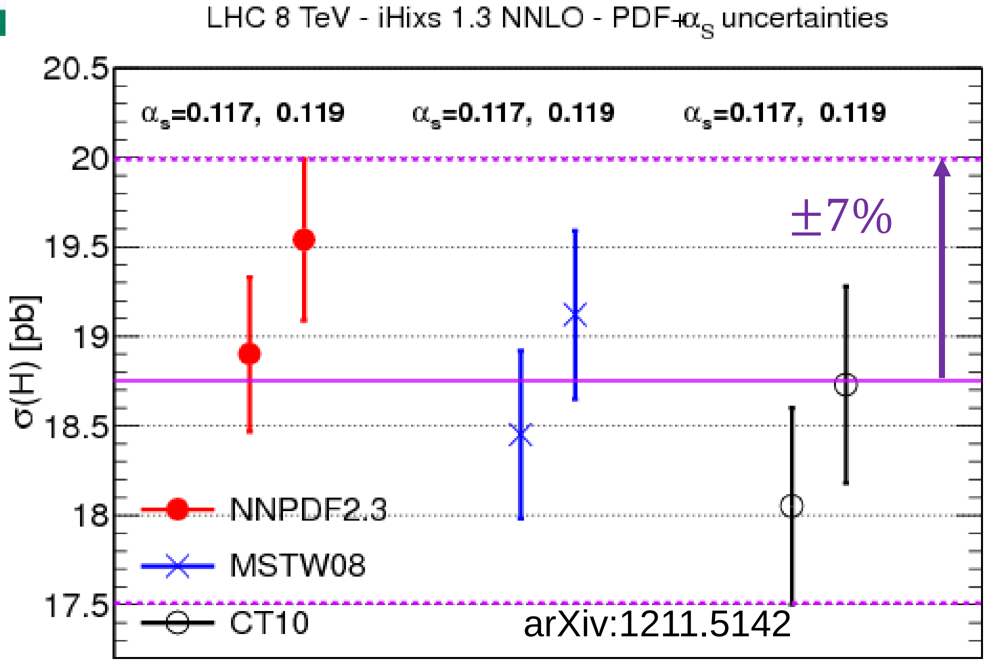
A lot of efforts in the past 2 years went into comparisons and benchmarking: “PDF4LHC recommendations for LHC run II”, arXiv: 1510.03865



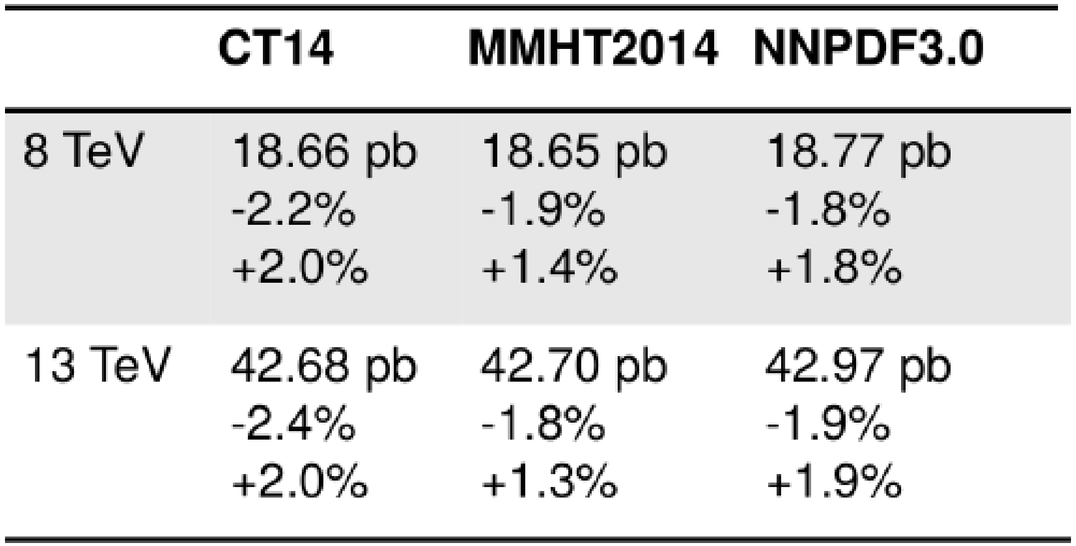
Comparison of PDFs at
Q^2 = 10^2 GeV^2
between the NNPDF3.0,
CT14 and MMHT14 sets at NNLO,
with *αs* (M_Z) = 0.118.

From PDF4LHC
arXiv: 1507.00556 (July 2015)

Example: $gg \to H^0_{SM}$ at the LHC



2012



	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

2015 J.Huston, PDF4LHC, April 2015

For example, δ_{PDF} on Higgs cross sections based on 3 **latest** global fits has reduced from 7% to within 3%, i.e., the PDF uncertainty is now of order of N3LO QCD scale uncertainty

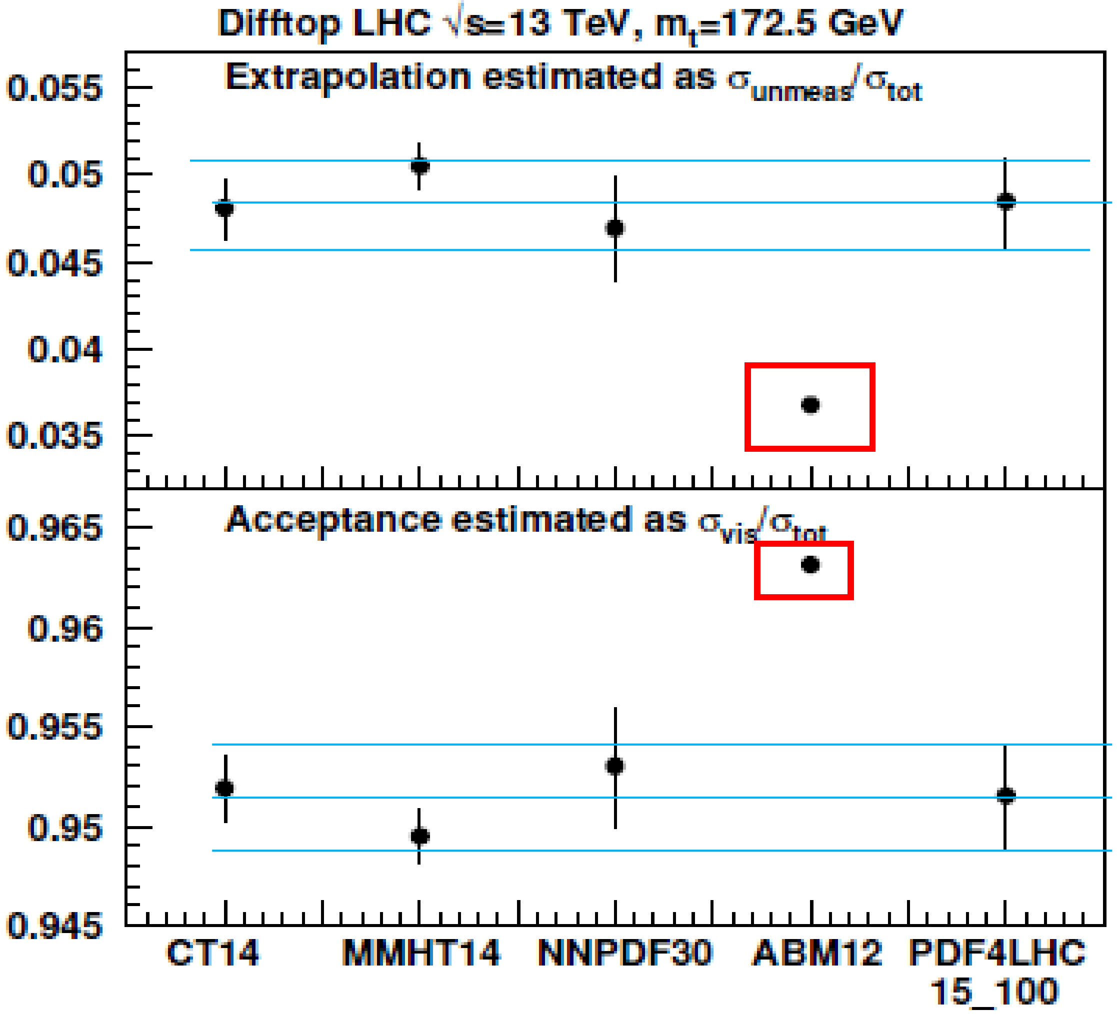
This improvement is due to benchmarking of general-mass factorization schemes; but can there be hidden sources of uncertainties on $\sigma(gg \to H)$, e.g., associated with massive charm DIS contributions, cf. arXiv:1603.08906?

Which PDF set to be used for

Making central prediction and
Estimating its uncertainty due to PDF and α_s

Estimation of PDF uncertainties on LHC observables

$pp \to t\bar{t}X$



The procedure for computing the PDF uncertainty must vary depending on the goals. The options may include

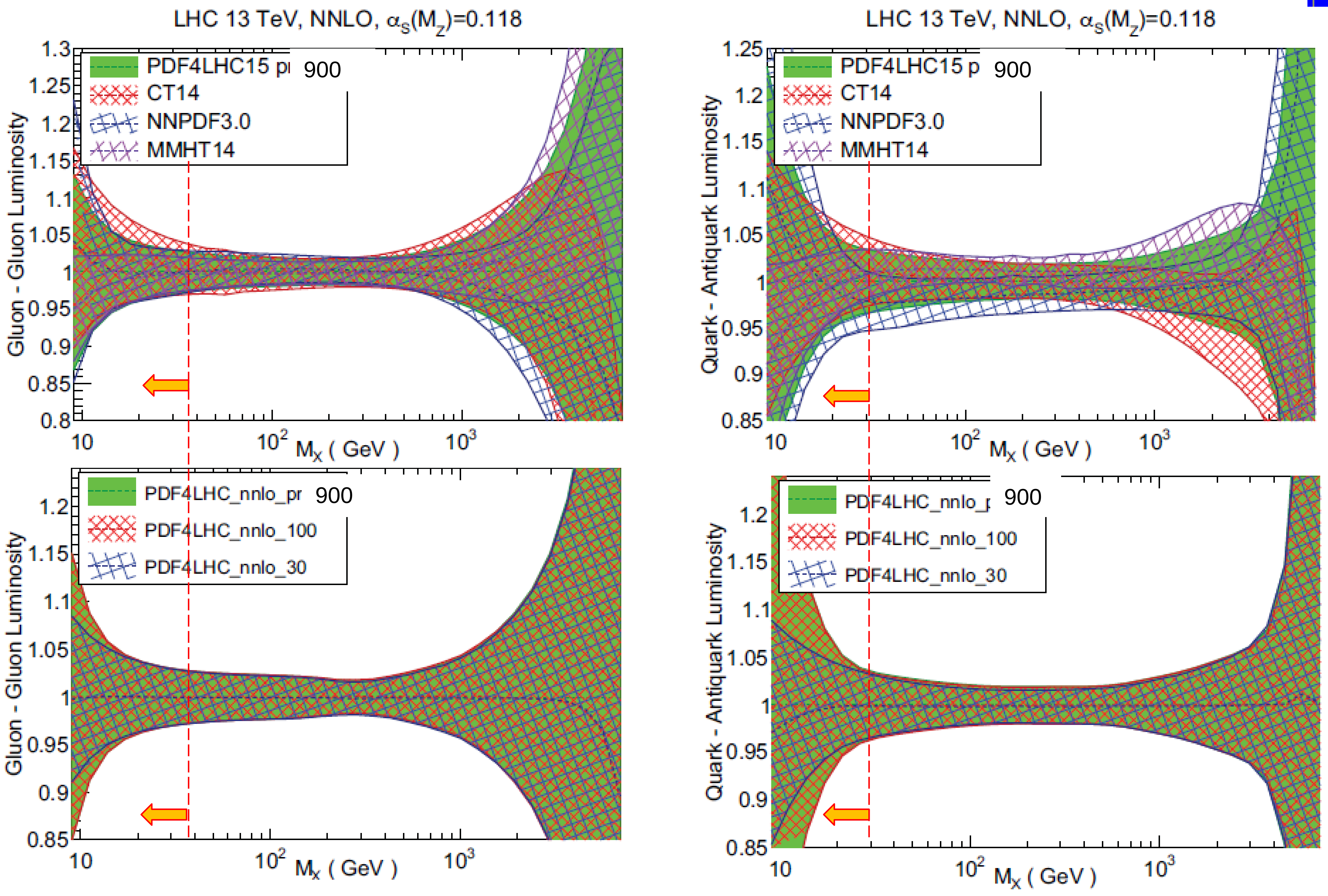
a) Using one individual set out of several similar ones (e.g., CT, MMHT, or NNPDF)

b) Using an envelope of all sets, including the outlier sets

c) New (arXiv:1510.03865)**:** using a combined PDF4LHC15 set constructed from CT14, MMHT14, NNPDF3.0

- A statistical combination of 3 sets
- Reproduces the total uncertainty with only 30-100 error sets
- Eliminates redundant comparisons of 3 global sets
- can be used in many (not all) cases.

PDF4LHC15 combined sets (900, 100, 30 replicas) vs. CT14, MMHT, NNPDF

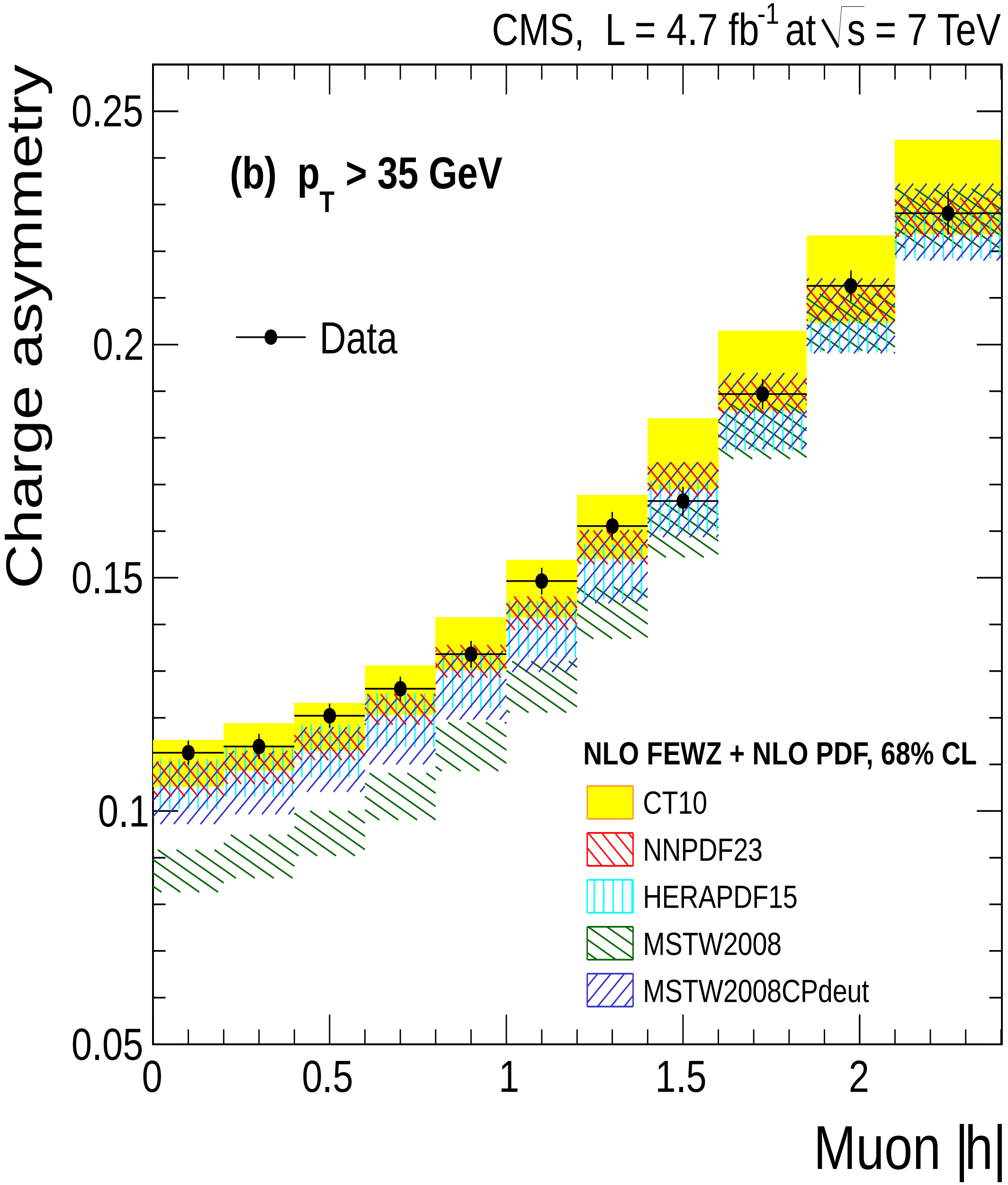


CT, MMHT, NNPDF

- Provide the central set (giving the best fit to global analysis) of the PDFs
- Provide eigensets (or replica sets) to allow estimation of uncertainty induced by PDF errors for predicting any experimental observable.
- Provide information on (anti-) correlations among various parton flavors (quarks or gluon) at given x and Q values.
- Trying their best to estimate the PDF errors in the small and large x regions, where PDFs are not yet well determined.

Though they are generally in good agreement, some noticeable difference can appear in experimental observables, sensitive to some special combination of different parton flavors.

LHC Run 1 Data matters



- Data is already more precise than CT10, NNPDF2.3 and MSTW2008 PDF uncertainties.
- Will help to determine u,d,ubar and dbar PDFs.
- Most useful for determining d/u and dbar/ubar.
- MSTW2008 NNLO PDFs are disfavored by this data set

CT14 Global QCD Analysis

Recent results

CT14NNLO

CT14NLO

CT14LO

CT14IC

CT14HERA2

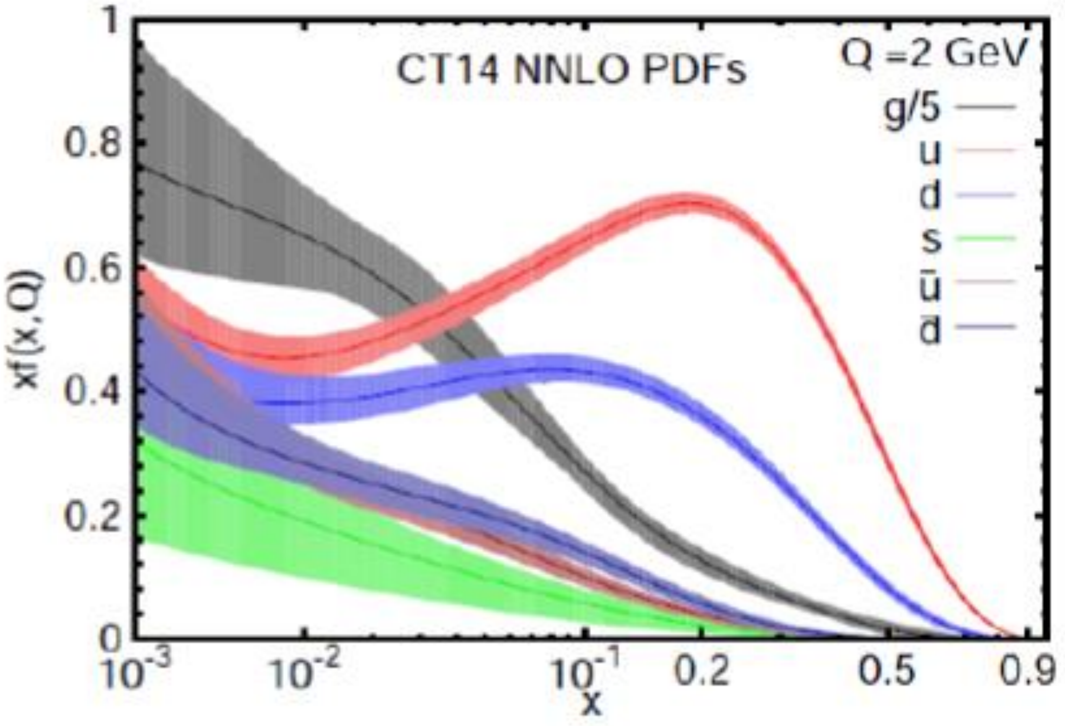
CT14MC

CT14QED

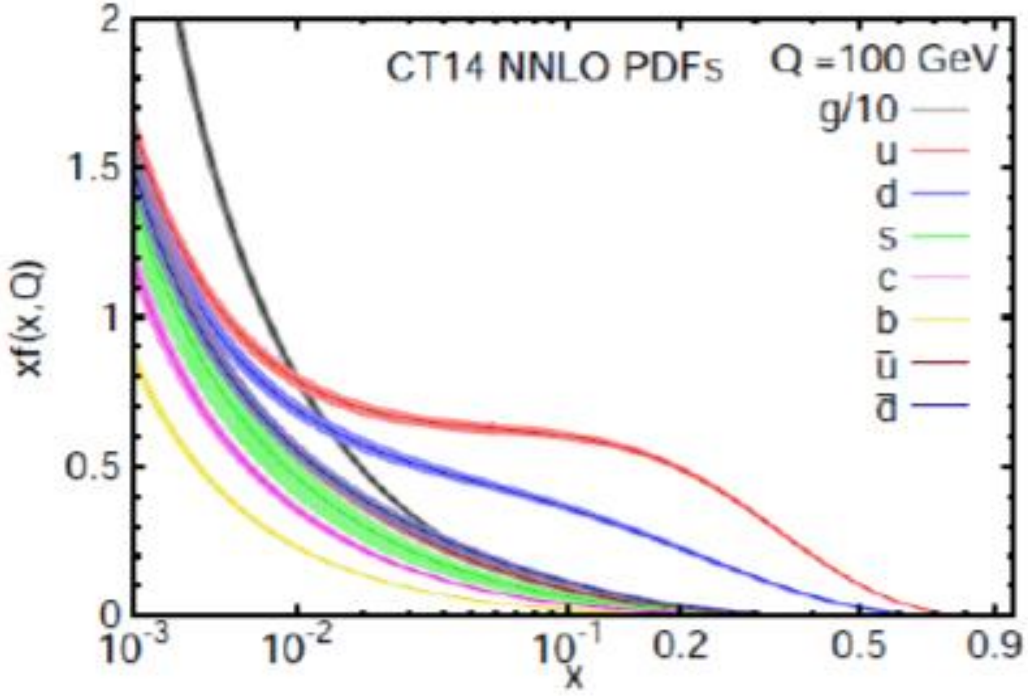
CT14 PDFs

Phenomenological parametrizations of PDFs are provided with estimated uncertainties of multiple origins (uncertainties of measurement, theoretical model, parametrization form, statistical analysis, …)

The shape of PDFs is optimized w.r.t. hundreds of **nuisance parameters**



Q= 2 GeV



Q= 100 GeV

Overview of CT14 analysis

- CT10 includes only pre-LHC data
- CT14 is the first CT analysis including LHC Run 1 data
- CT14 also includes the new Tevatron D0 Run 2 data on W-electron charge asymmetry
- CT14 uses a more flexible parametrization in the non-perturbative PDFs.
- We have published its results at NNLO, NLO and LO.

Produce 90% C.L. error PDF sets from Hessian method, scaled by 1/1.645 to obtain 68% C.L. eigenvector sets.
For NNLO, Chi^2/d.o.f is about 1.1 for about 3000 data points included in the fits.

Theory Analysis in CT14

- CT14 has 26 shape parameters, plus four extreme sets for describing s- and g-PDFs in small-x region. In comparison, CT10 has 24 shape parameters, plus two extreme sets for describing g-PDFs in small-x region.
- More flexible parametrization – gluon, d/u at large x, and both d/u and dbar/ubar at small x, strangeness (assuming sbar = s)
- Non-perturbative parametrization form:

$$x\, f_a(x) = x^{a_1}\,(1-x)^{a_2}\, P_a(x)$$

where $P_a(x)$ is expressed as a linear combination of Bernstein polynomials to reduce the correlation among its coefficients.

Theory Analysis in CT14

- Choose experimental data with $Q^2 > 4$ GeV^2 and $W^2 > 12.5$ GeV^2 to minimize high-twist, nuclear correction, etc., and focus on perturbative QCD predictions.
- PDFs are parametrized at Q=1.3 GeV.
- Take $\alpha_s(Mz) = 0.118$, but also provide α_s-series PDFs.
- Use s-ACOT-χ prescription for heavy quark partons, and take pole mass M_c =1.3 GeV and M_b=4.75 GeV
- NNLO calculations for DIS, DY, W, Z, except jet (at NLO).
- Correlated systematic errors are taken into account.
- Check Hessian method results by Lagrangian Multiplier method which does not assume quadratic approximation in chi-square.

What's new in CT14 NNLO PDFs

CT14 differs from CT10 PDFs in several respects:

pre-LHC

new HERA data:

- Combined HERA charm production measurements ($F_2^{(c)}$)
- measurements of the longitudinal $F_L(x, Q^2)$ in DIS neutral currents

new Tevatron data:

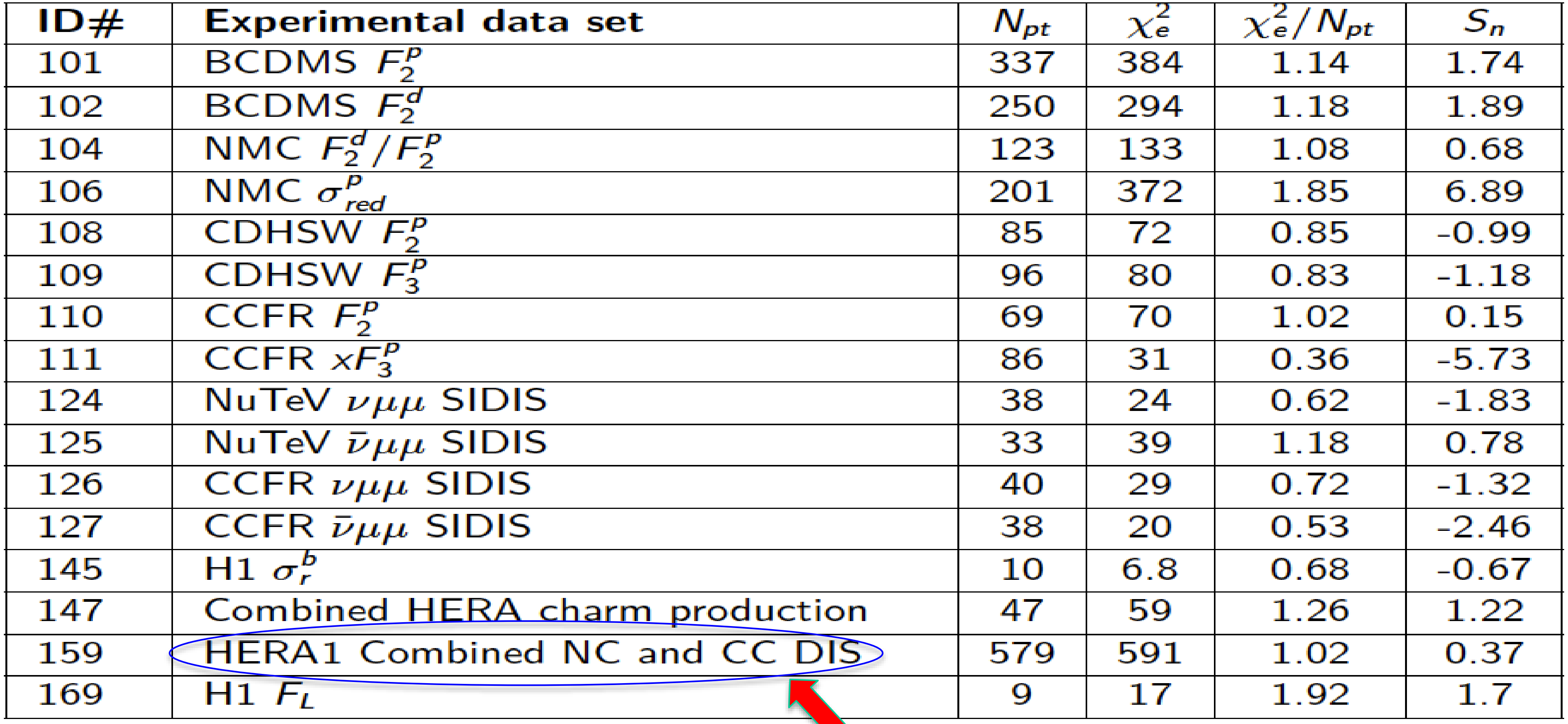
- Tevatron Run 1 CDF and D0 inclusive jet data are dropped,
- old D0 data (0.75 fb^{-1}) superseded by the new D0 (9.7 fb^{-1}) W-electron rapidity asymmetry data.

LHC 7 TeV run I data included

- ATLAS and LHCb W and Z production,
- ATLAS, CMS and LHCb W-lepton charge asymmetry,
- ATLAS and CMS inclusive jet data.

CT14 has ≈3000 data points

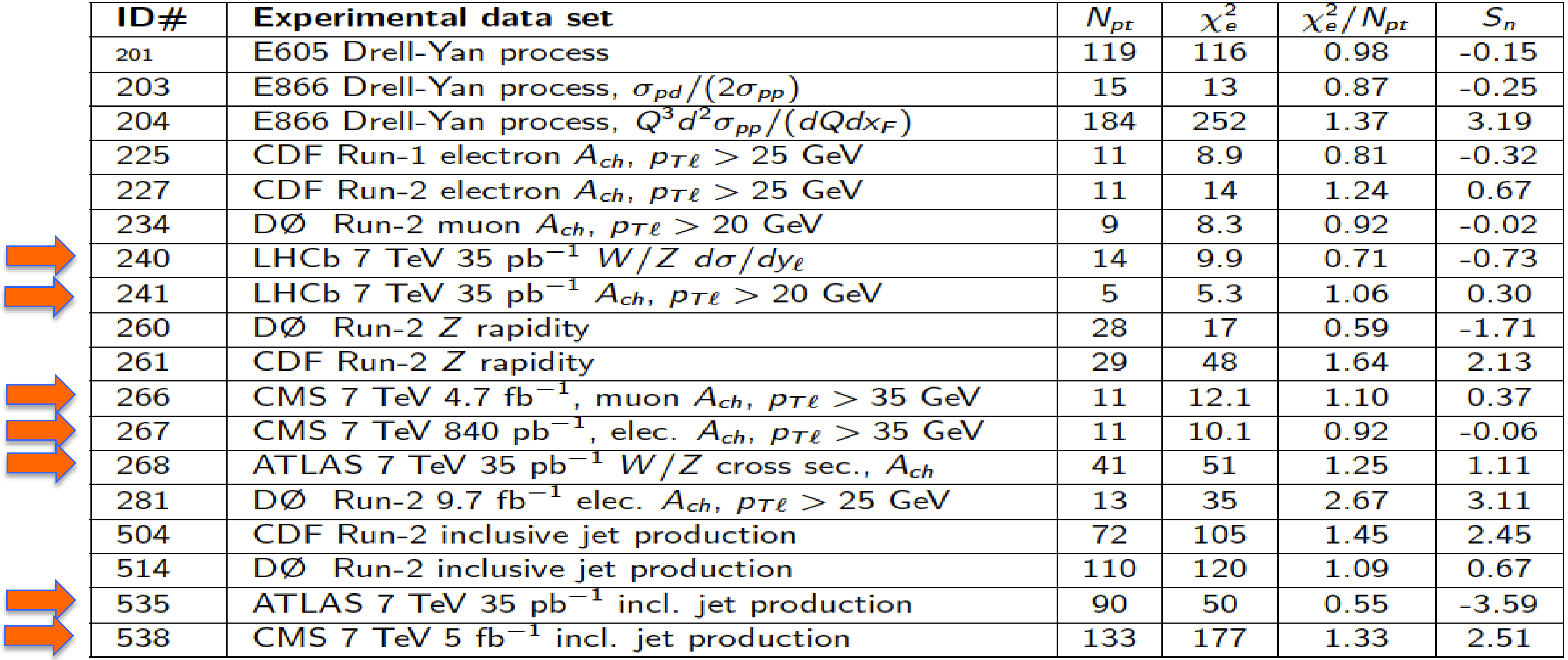
CT14 Data sets ensemble I



ID#	Experimental data set	N_{pt}	χ_e^2	χ_e^2/N_{pt}	S_n
101	BCDMS F_2^p	337	384	1.14	1.74
102	BCDMS F_2^d	250	294	1.18	1.89
104	NMC F_2^d/F_2^p	123	133	1.08	0.68
106	NMC σ_{red}^p	201	372	1.85	6.89
108	CDHSW F_2^p	85	72	0.85	-0.99
109	CDHSW F_3^p	96	80	0.83	-1.18
110	CCFR F_2^p	69	70	1.02	0.15
111	CCFR xF_3^p	86	31	0.36	-5.73
124	NuTeV $\nu\mu\mu$ SIDIS	38	24	0.62	-1.83
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	33	39	1.18	0.78
126	CCFR $\nu\mu\mu$ SIDIS	40	29	0.72	-1.32
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	38	20	0.53	-2.46
145	H1 σ_r^b	10	6.8	0.68	-0.67
147	Combined HERA charm production	47	59	1.26	1.22
159	HERA1 Combined NC and CC DIS	579	591	1.02	0.37
169	H1 F_L	9	17	1.92	1.7

Very important for PDF determination

CT14 Data sets ensemble II



	ID#	Experimental data set	N_{pt}	χ^2_e	χ^2_e/N_{pt}	S_n
	201	E605 Drell-Yan process	119	116	0.98	-0.15
	203	E866 Drell-Yan process, $\sigma_{pd}/(2\sigma_{pp})$	15	13	0.87	-0.25
	204	E866 Drell-Yan process, $Q^3 d^2\sigma_{pp}/(dQdx_F)$	184	252	1.37	3.19
	225	CDF Run-1 electron A_{ch}, $p_{T\ell} > 25$ GeV	11	8.9	0.81	-0.32
	227	CDF Run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV	11	14	1.24	0.67
	234	DØ Run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV	9	8.3	0.92	-0.02
➡	240	LHCb 7 TeV 35 pb^{-1} W/Z $d\sigma/dy_\ell$	14	9.9	0.71	-0.73
➡	241	LHCb 7 TeV 35 pb^{-1} A_{ch}, $p_{T\ell} > 20$ GeV	5	5.3	1.06	0.30
	260	DØ Run-2 Z rapidity	28	17	0.59	-1.71
	261	CDF Run-2 Z rapidity	29	48	1.64	2.13
➡	266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	11	12.1	1.10	0.37
➡	267	CMS 7 TeV 840 pb^{-1}, elec. A_{ch}, $p_{T\ell} > 35$ GeV	11	10.1	0.92	-0.06
➡	268	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	41	51	1.25	1.11
	281	DØ Run-2 9.7 fb^{-1} elec. A_{ch}, $p_{T\ell} > 25$ GeV	13	35	2.67	3.11
	504	CDF Run-2 inclusive jet production	72	105	1.45	2.45
	514	DØ Run-2 inclusive jet production	110	120	1.09	0.67
➡	535	ATLAS 7 TeV 35 pb^{-1} incl. jet production	90	50	0.55	-3.59
➡	538	CMS 7 TeV 5 fb^{-1} incl. jet production	133	177	1.33	2.51

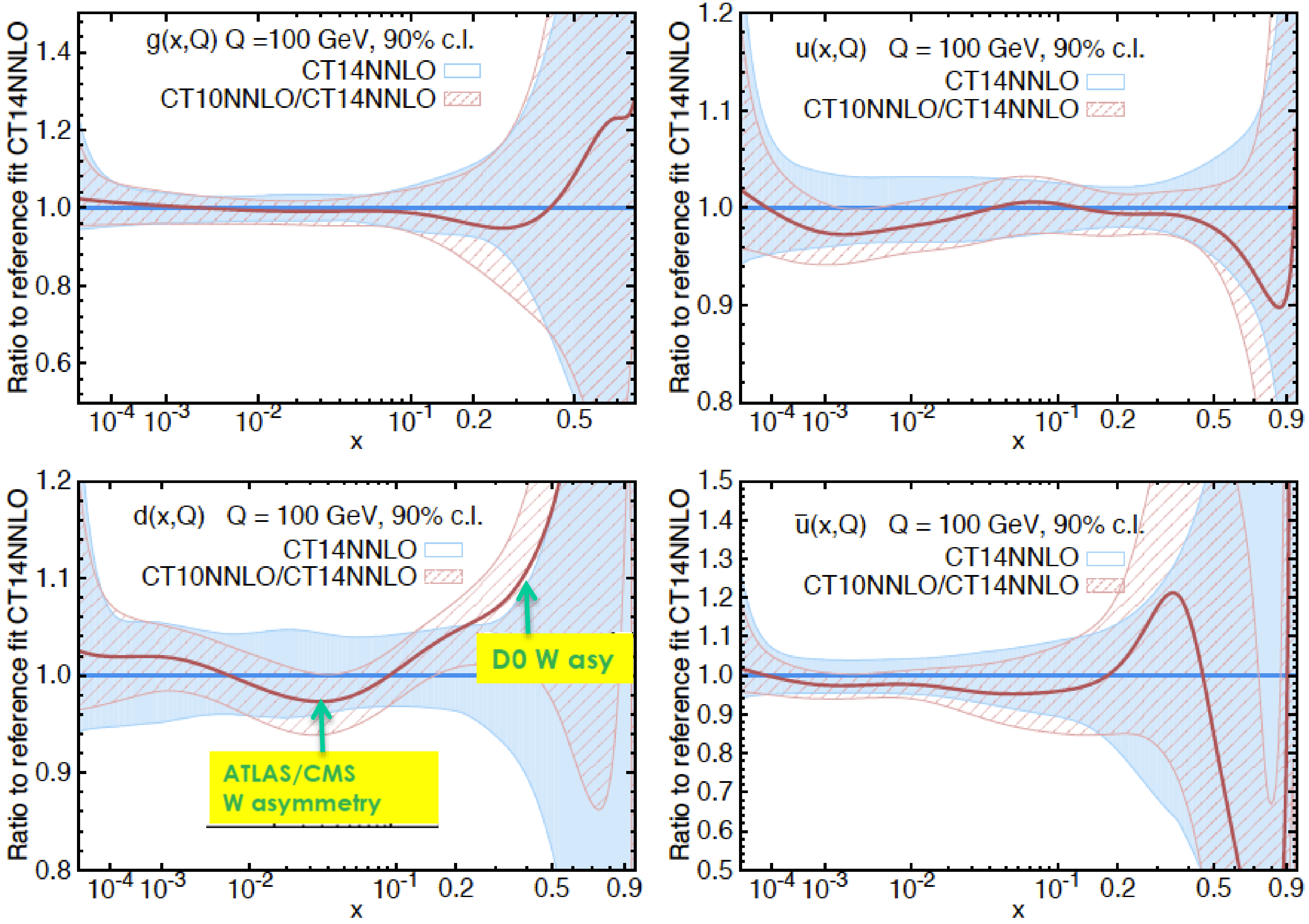
Aspects of the CT14 analysis: $\alpha_s(M_Z)$

- central value of $\alpha_s(M_Z) = 0.118$ has been assumed in the global fits at NLO and NNLO, but
- PDF sets at alternative values of $\alpha_s(M_Z)$ are provided.
- CT14 prefers $\alpha_s(M_Z) = 0.115^{+0.006}_{-0.004}$ at NNLO (0.117 ± 0.005 at NLO) at 90 % confidence level (C.L.).

Uncertainties from the global QCD fits are larger than those of the data from LEP and other experiments included into the world average *Chin.Phys.C* (2014).

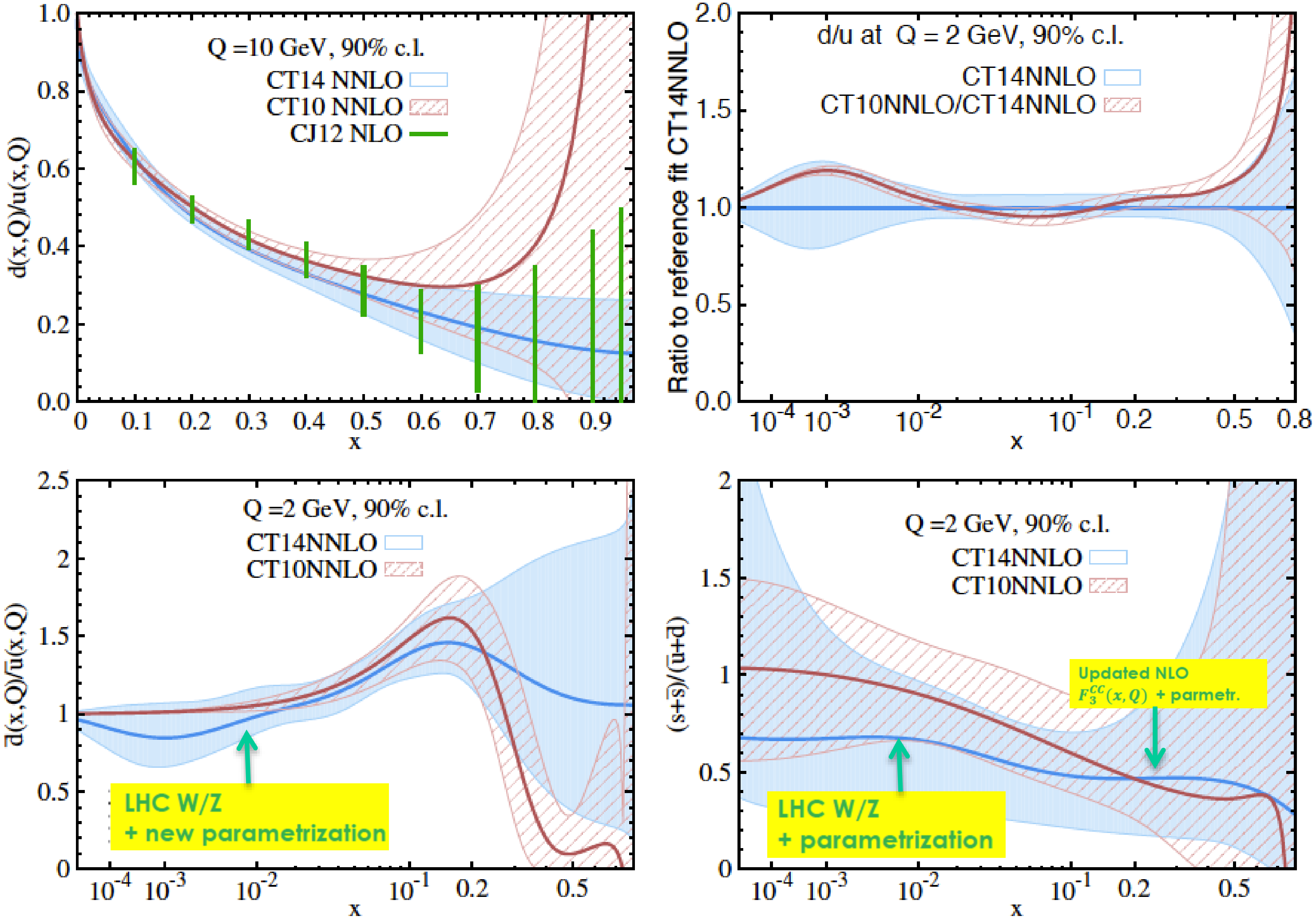
CT14 $\alpha_s(M_Z)$ central is consistent with the world average value.

CT14 vs CT10 at NNLO 90% C.L.



- ATLAS, CMS 7 TeV W/Z prod. $\Rightarrow$ d-quark increased by 5% at $x \approx 0.05$.
- D0 ele charge asy data $\Rightarrow$ d highly reduced at $x \geq 0.1$ and u moderately increased.

CT14 $d(x,Q)/u(x,Q)$ ratios



LHC W/Z
+ new parametrization

LHC W/Z
+ parametrization

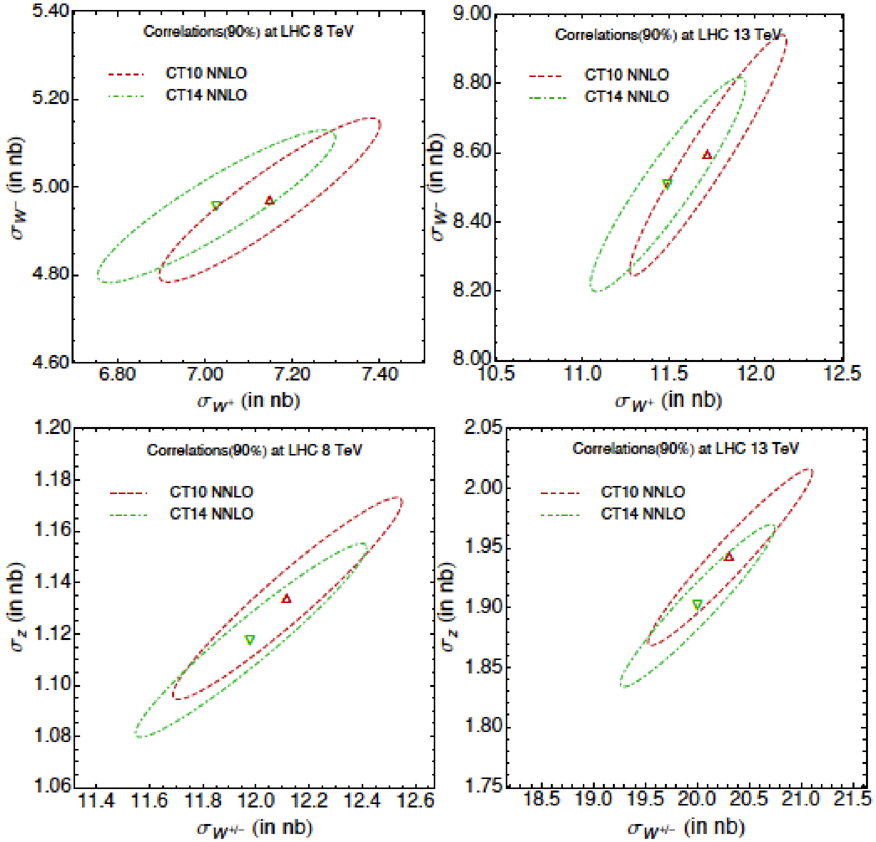
Updated NLO
$F_3^{cc}(x,Q)$ + parmetr.

- 9.7 fb^{-1} D0 charge asy ⇒ reduction of the central ratio at $x > 0.1$,
- new parametrization form ⇒ increased uncertainty at $x < 0.05$
- s reduction at $x > 0.01$ ⇒ smaller ratio $(s+\bar{s})/(\bar{u}+\bar{d})$. The $SU(3)$-symmetric asymptotic solution at $x \to 0$ is still allowed in CT14: bigger unc. $x \approx 10^{-5}$.

CT14 NNLO: agreement with data

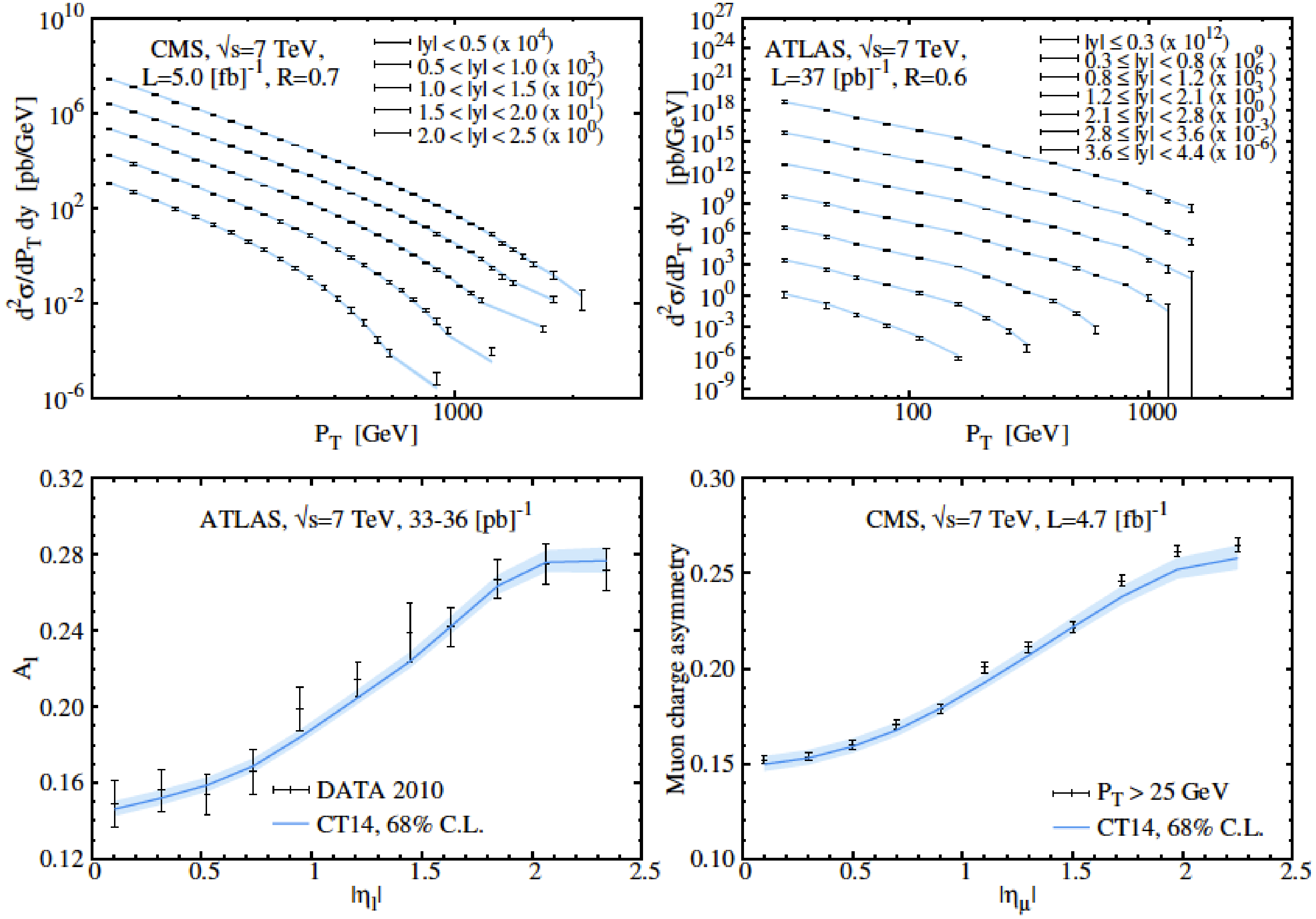
Total of 2947 data points from 33 experiments $\chi^2 = 3252$ at the best fit CT14 NNLO, $\chi^2/N_{pt} = 1.10$.

Data and theory are in reasonable good agreement for most experiments (next slides)



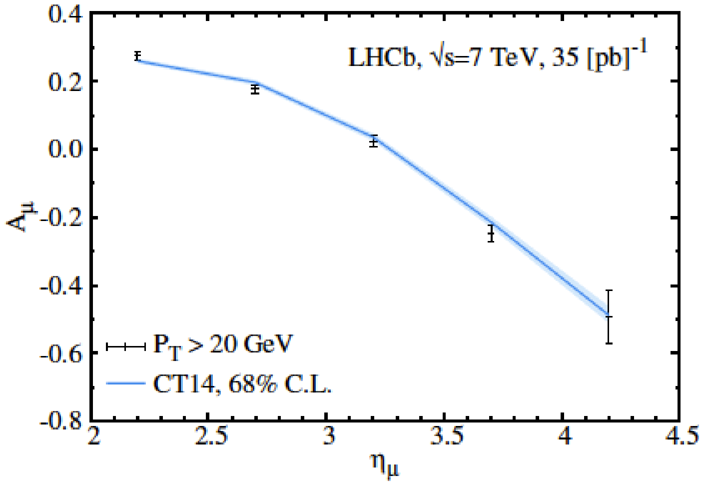
W/Z Correlations plots CT14 vs CT10 @ NNLO

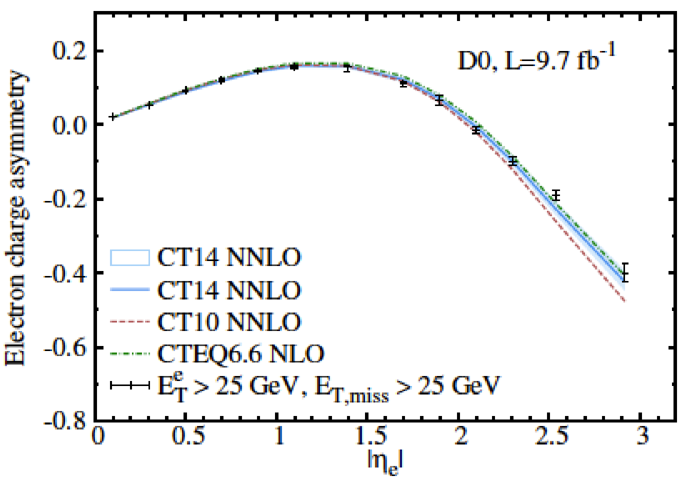
CT14 NNLO: agreement with data

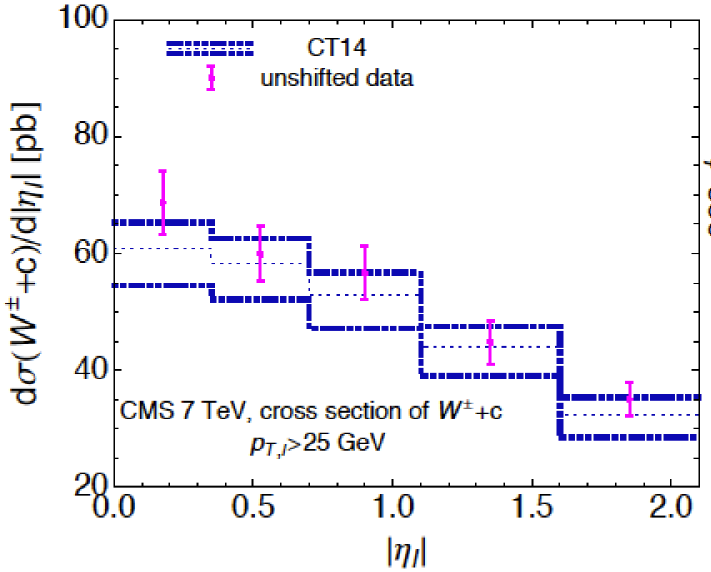


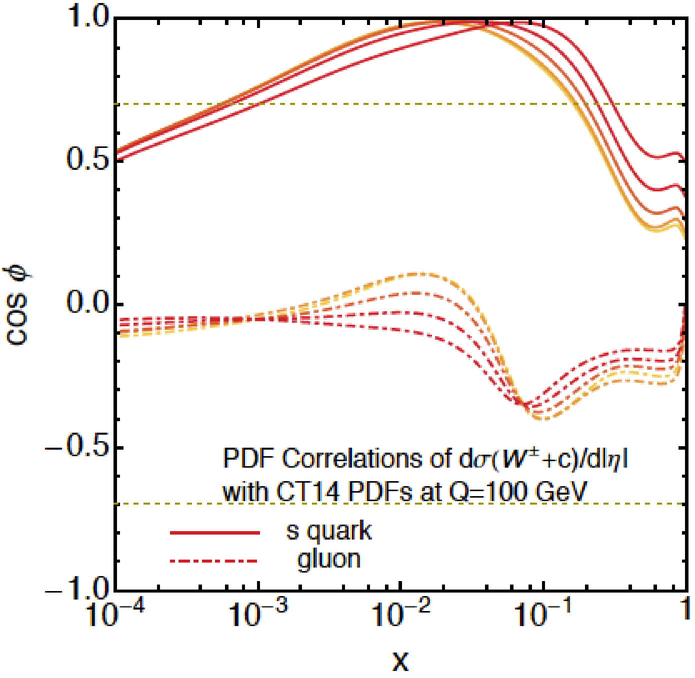
Inclusive jet production and *W* lepton charge asymmetry at the LHC 7 TeV

CT14 NNLO: agreement with data





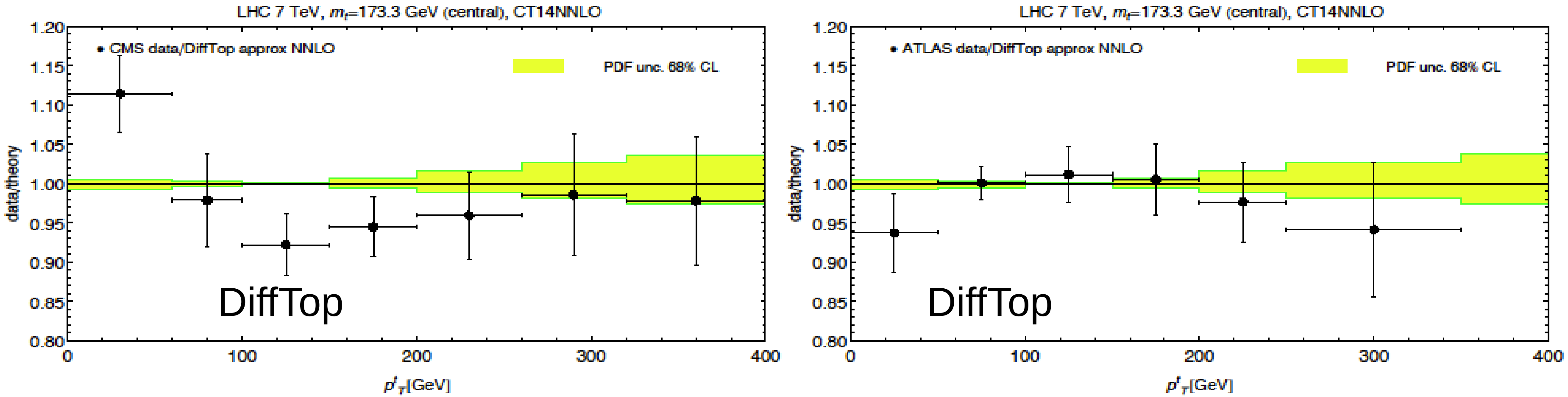




CT14 NNLO: agreement with data

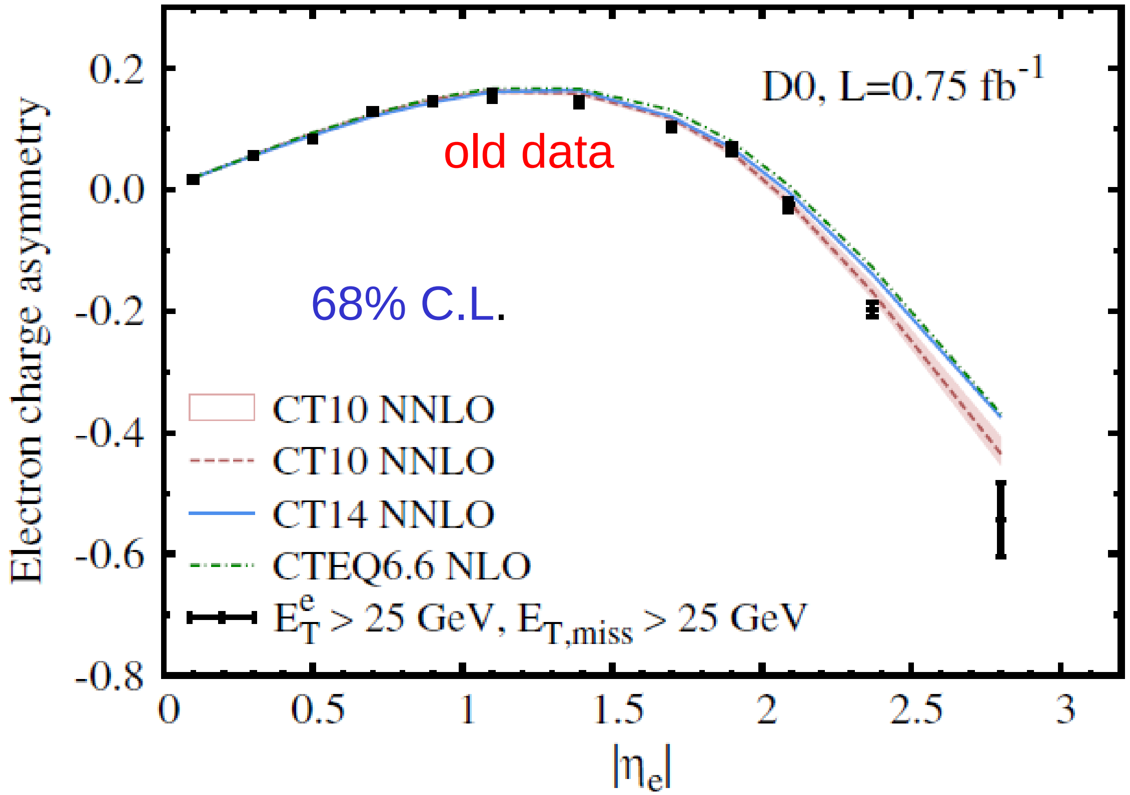
Total inclusive $t\bar{t}$ cross section at NNLO in QCD with TOP++, (Czakon, Mitov, CPC 2014)

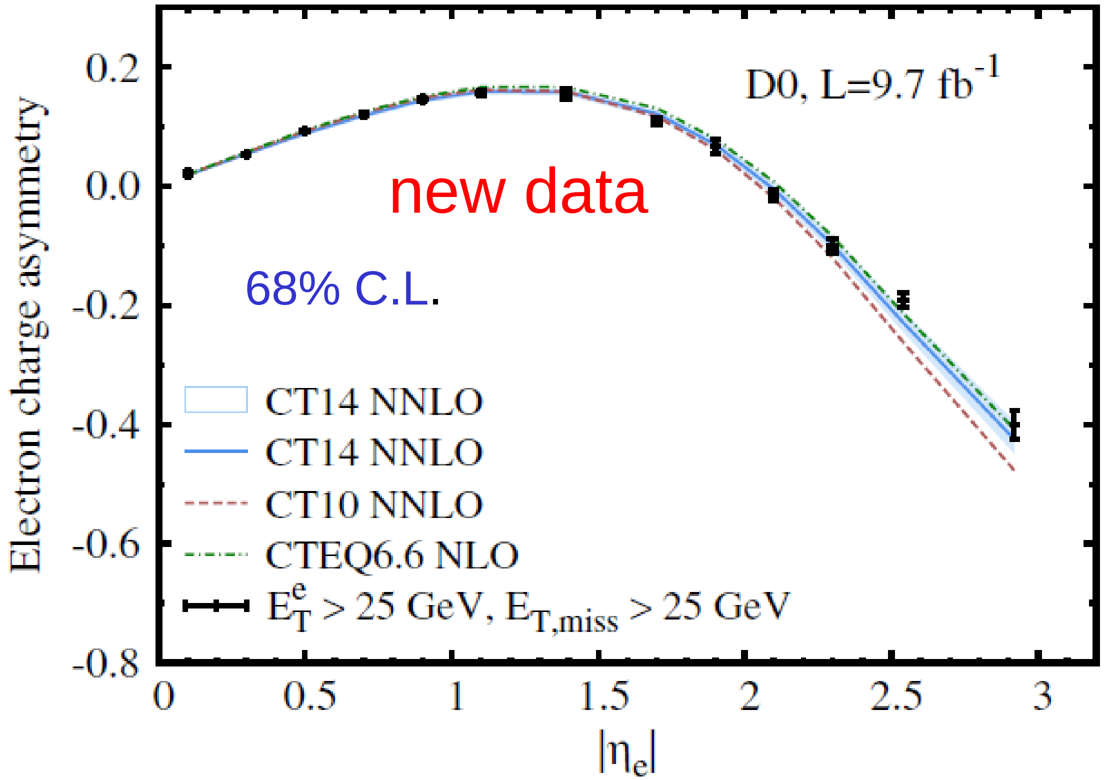
$pp \to t\bar{t}$ (pb), PDF unc., $\alpha_s = 0.118$	7 TeV	8 TeV	13 TeV
68% C.L. (Hessian)	$177 + 4.8\% - 3.9\%$	$250 + 3.9\% - 3.5\%$	$820 + 2.6\% - 2.7\%$
68% C.L. (LM)		$+4.8\% - 4.6\%$	$+2.9\% - 2.9\%$
$pp \to t\bar{t}$ (pb), PDF+α_s	7 TeV	8 TeV	13 TeV
68% C.L. (Hessian)	$+5.5\% - 4.6\%$	$+5.2\% - 4.4\%$	$+3.6\% - 3.5\%$
68% C.L. (LM)		$+5.1\% - 4.7\%$	$+3.6\% - 3.5\%$



Approx NNLO p_T spectrum for the final state top-quark with DIFFTOP (M.G., Lipka, Moch, JHEP 2015)

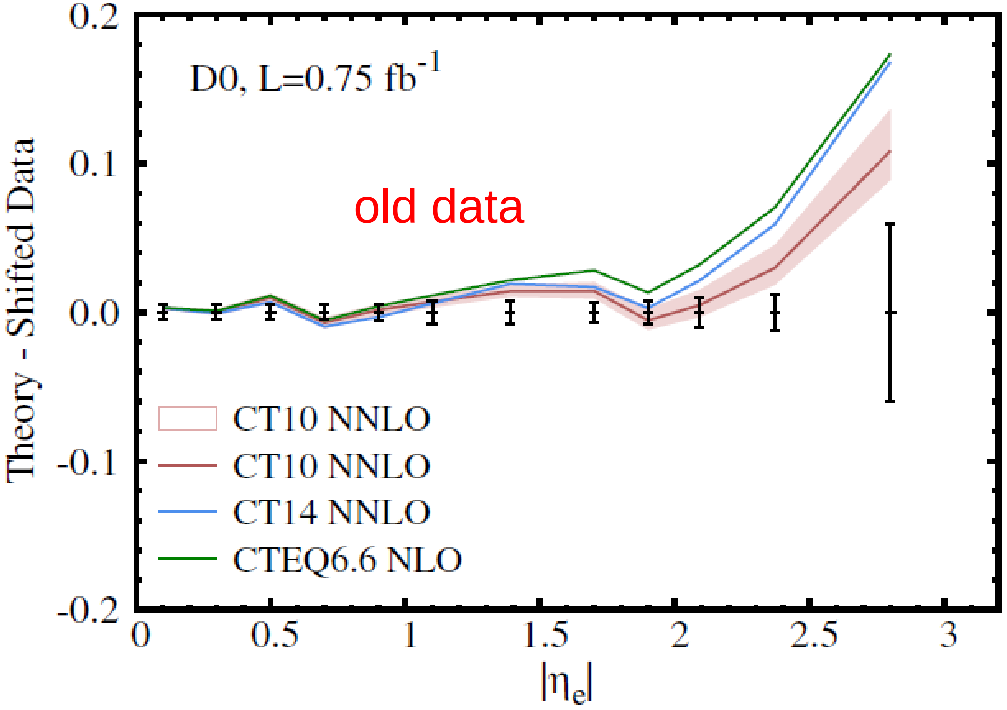
Story about D0 Run 2
W-electron rapidity asymmetry data

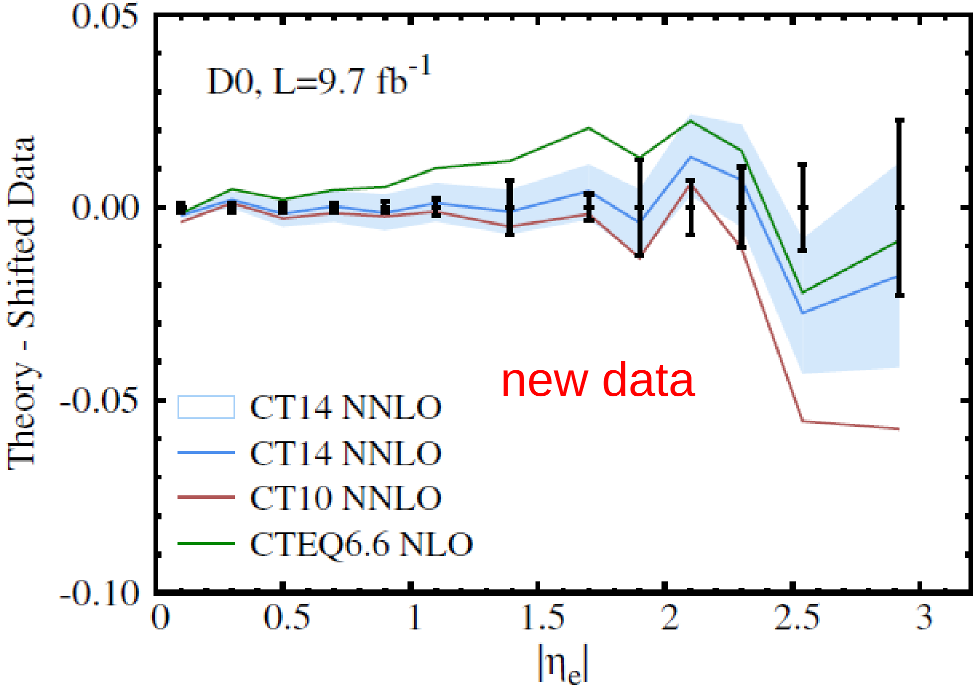




CT10 was produced by fitting to old D0 data.
CT14 uses new D0 data, closer to CTEQ6.6
than CT10 predictions in large rapidity.

Story about D0 Run 2
W-electron rapidity asymmetry data





Old D0 data disfavor CTEQ6.6 and requires CT10.
New D0 data disfavor CT10 and requires CT14.

CT14IC

Intrinsic Charm PDFs

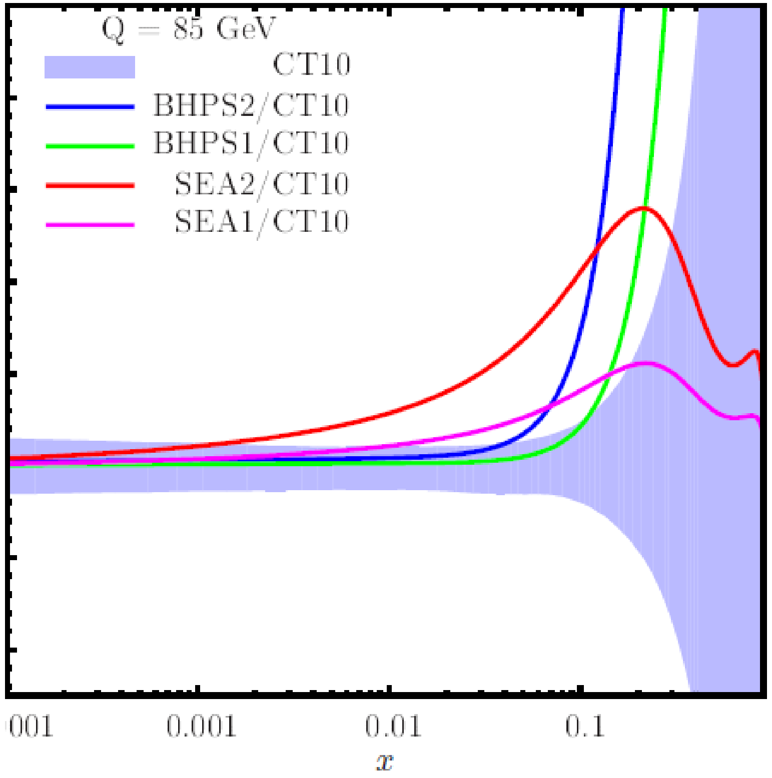
Intrinsic Charm: CT10IC and CT14IC

C T E Q

- Update of CTEQ6.5 IC study from 2007 to CT14NNLO
  - includes combined H1 and ZEUS data, HERA inclusive charm.
  - include LHC RUN I data.
- 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.
- Two model Intrinsic Charm distributions at $Q_0 = 1.3$GeV
  - BHPS valence-like model (Brodsky et al. Phys. Lett. 93B, 451(1980))
  - SEA-like model

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

CT10IC PDFs

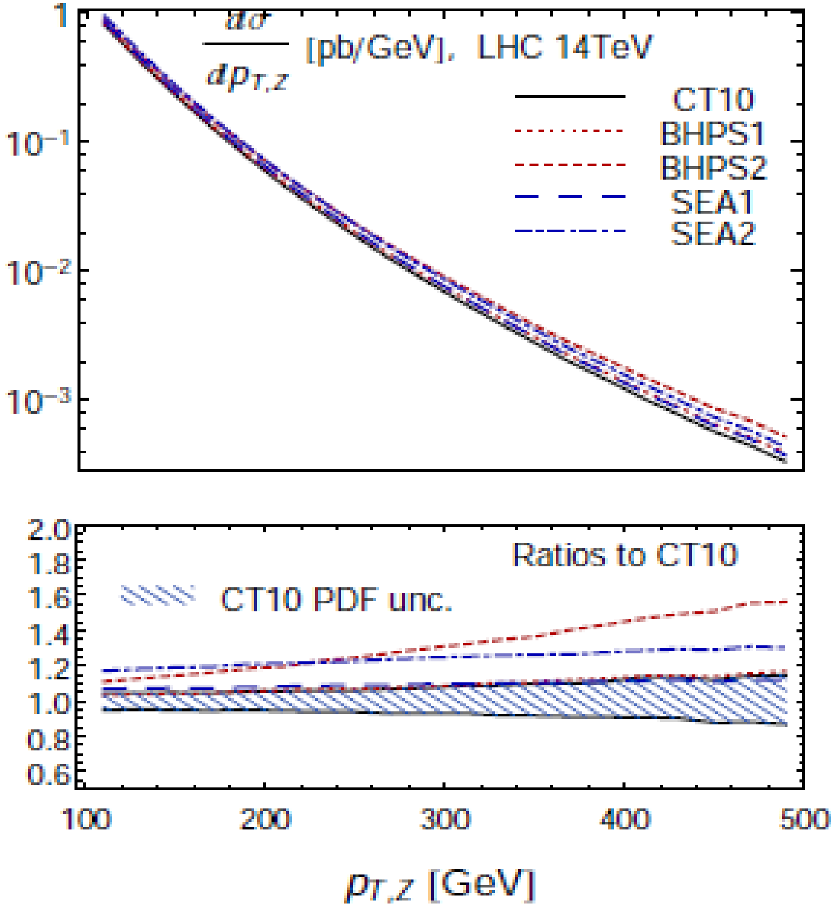


IC vs CT10 charm PDF

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

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

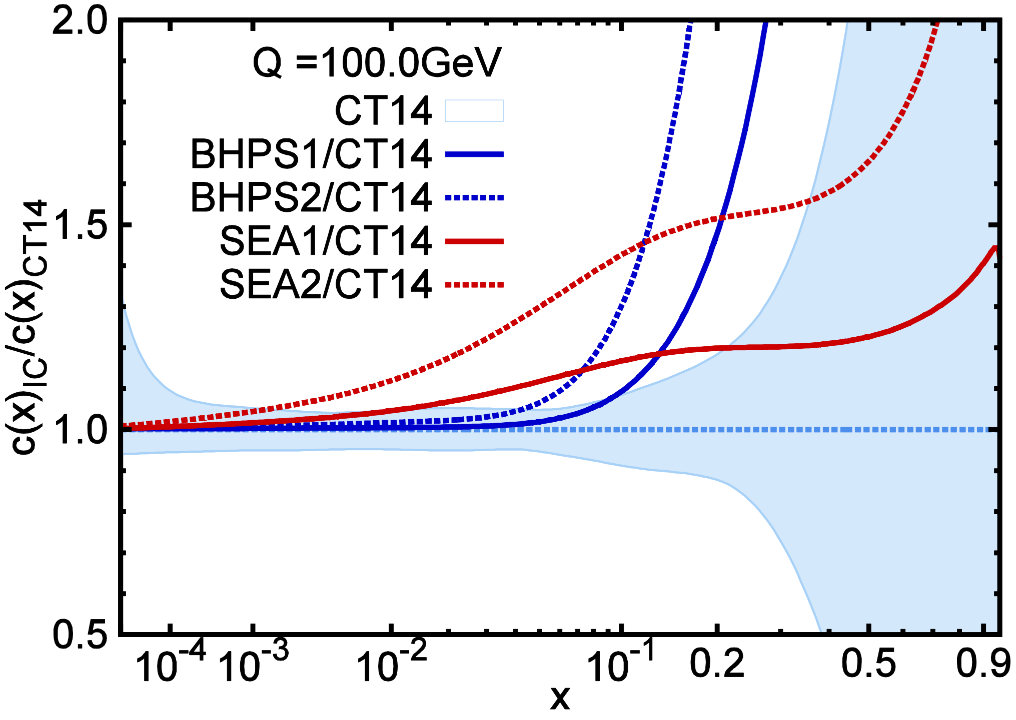
BHPS2: $\langle x\rangle_{\mathrm{IC}} = 2.0\%$

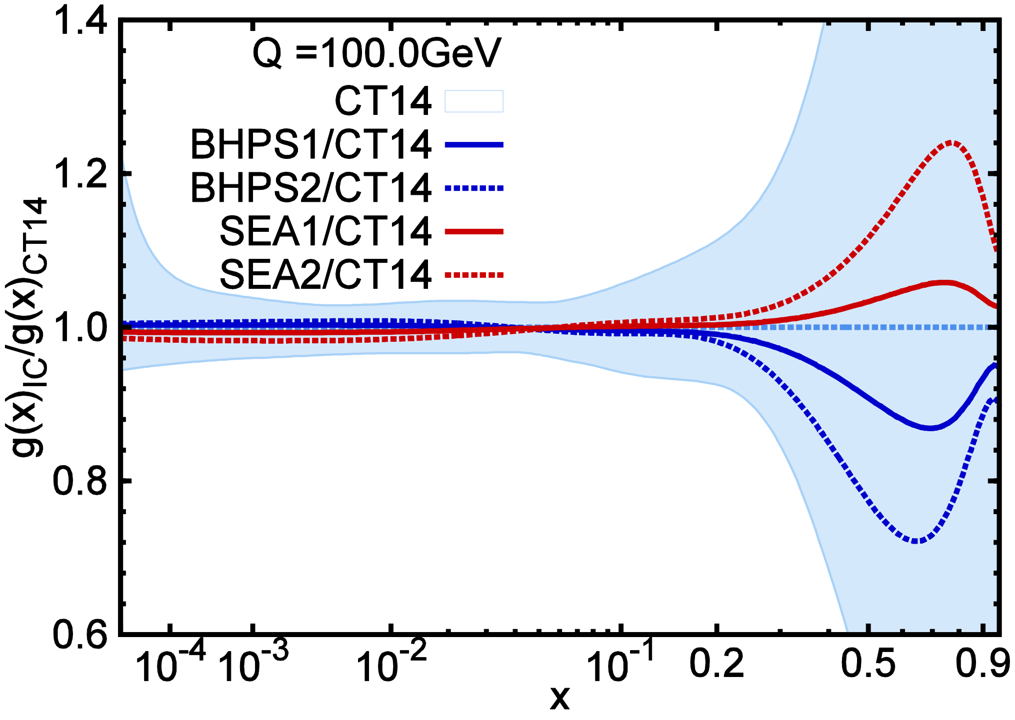


$pp \to Zc$ at LHC may further constrain valence-like model

arXiv:1309.0025

CT14IC PDFs





Charm PDFs

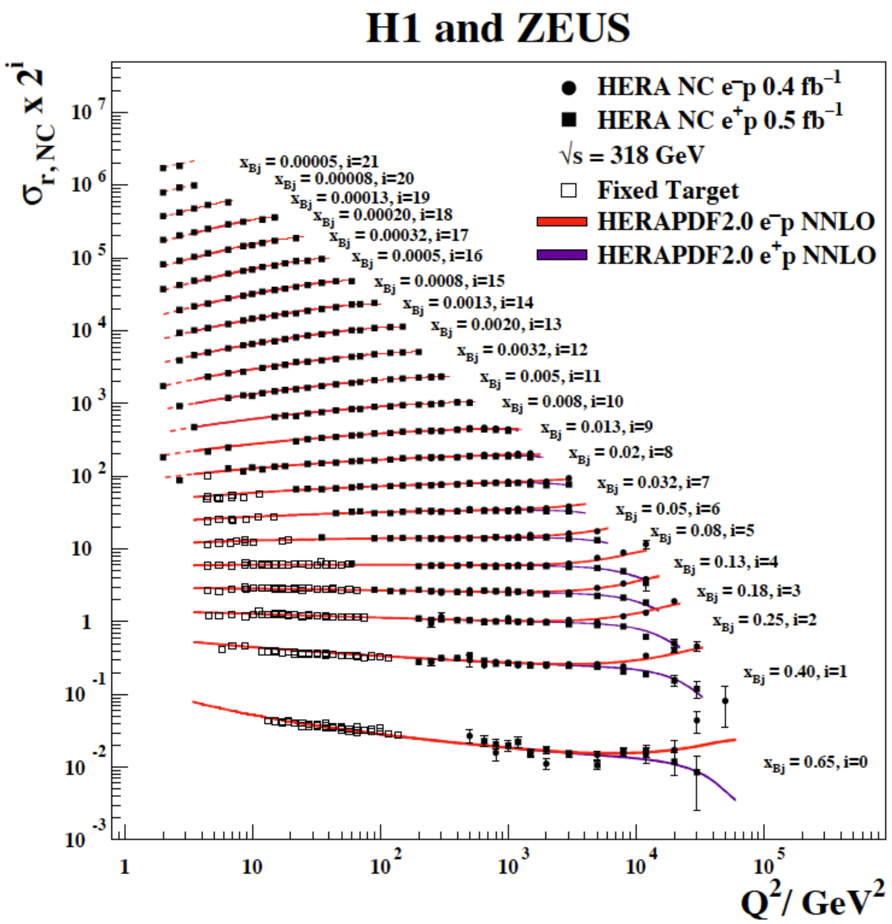
Gluon PDFs

CT14HERA2

Impact of HERA combined Run 1 and Run 2 data to CT14 PDFs

Impact of the new HERA run I+II measurements

CT14HERA2



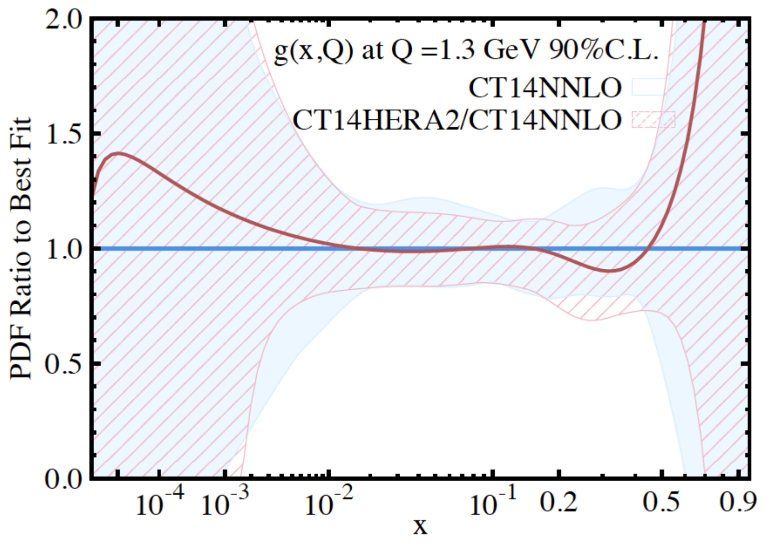
H1 and ZEUS combination of DIS cross sections for NC and CC
H1 and ZEUS Coll. 1506.06042 EPJ2015

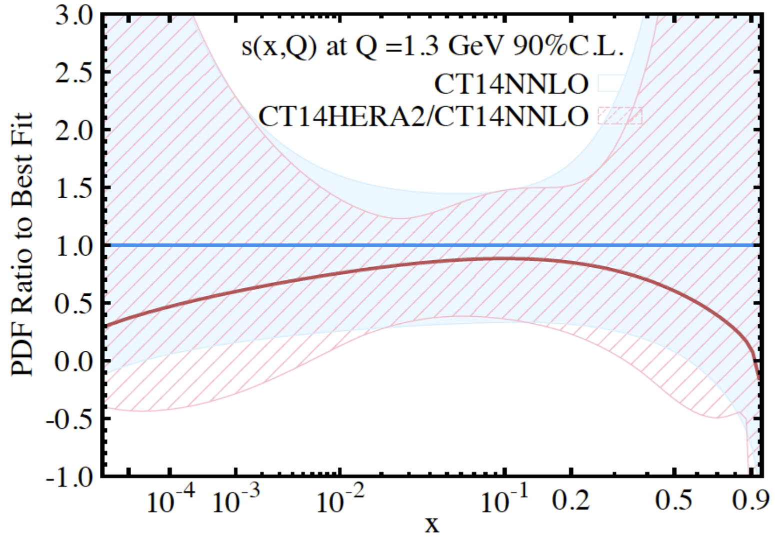
So far, the most important measurements for PDF determination

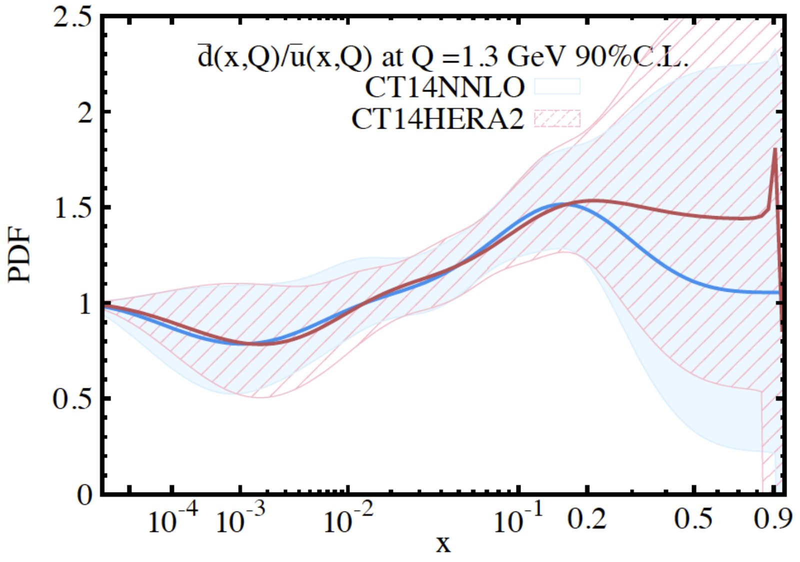
	Neutral Current	Charged Current
e-p	[Ep=920 GeV]	[Ep=920 GeV]
e+p	[Ep=920 GeV]	[Ep=920 GeV]
e+p	[Ep=460 GeV]	
e+p	[Ep=575 GeV]	
e+p	[Ep=820 GeV]	

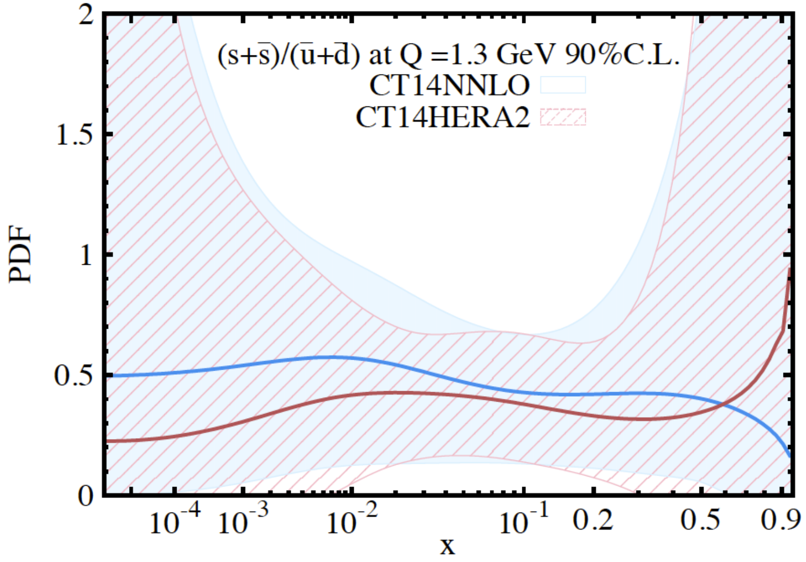
$$\chi^2_{\mathrm{CT14_{HERA2},NNLO}}/N_{pts} = 3596/3287 = 1.09 \qquad \chi^2_{\mathrm{CT14,NNLO}}/N_{pts} = 3250/2947 = 1.10$$

Most relevant changes due to HERA2 data in the PDFs and their ratios









CT14MC

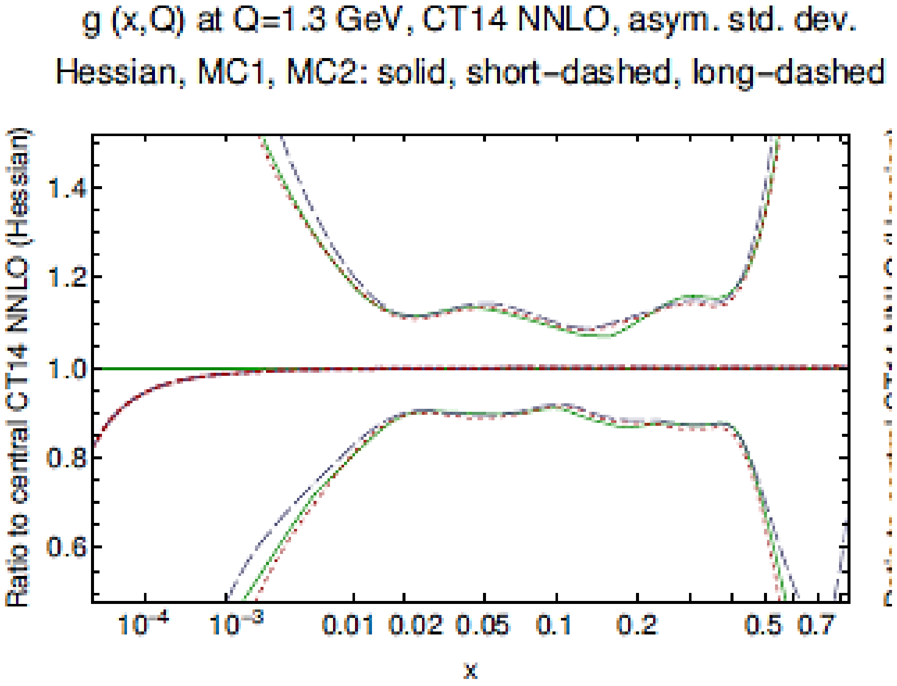
Replica sets for CT14 PDFs

CT14 Monte-Carlo replica PDFs

Tie-Jiun Hou, et al., arXiv:1607.06066

mcgen: a public code to convert Hessian eigenvector ensembles into Monte-Carlo replica ensembles with several methods (http://metapdf.hepforge.org/mcgen/)

CT14 MC1 and MC2: ensembles of PDF replicas ($N_{rep} = 1000$) generated from CT14 Hessian ensemble



Green: Hessian 68% c.l. errors
Blue and red: Asymmetric MC1 and MC2 replicas

Asymmetric standard deviations of CT14 MC ensembles reproduce **asymmetric** CT14 Hessian uncertainties

CT14 MC2 replicas are non-negative: lead to positive physical cross sections

Can be used for combinations of PDF ensembles and PDF reweighting

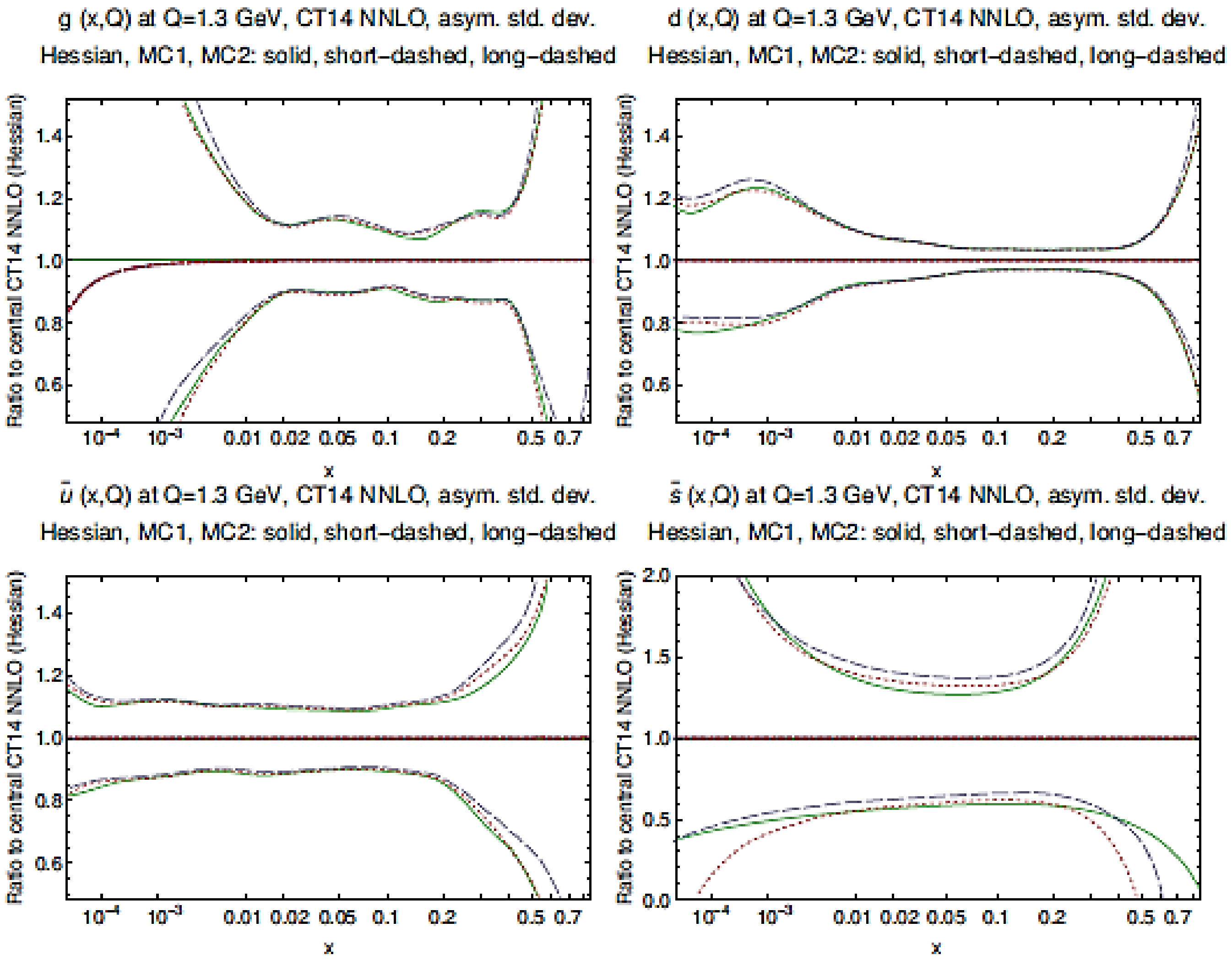


FIG. 3: The mean values and asymmetric standard deviations (20), (21) of the CT14 NNLO MC1 (short-dashed) and MC2 (long-dashed) PDFs, compared to the mean and 68% c.l. uncertainty (Eq. (10), solid) of the CT14 NNLO Hessian PDF. The PDFs are shown as ratios to the central CT14 fit. Upper panel: $g(x,Q_0)$ and $d(x,Q_0)$. Lower panel: $\bar{u}(x,Q_0)$ and $\bar{s}(x,Q_0)$.

CT14 MC2 replicas satisfy positivity

Scaled ratios of replicas to central CT14 Hessian

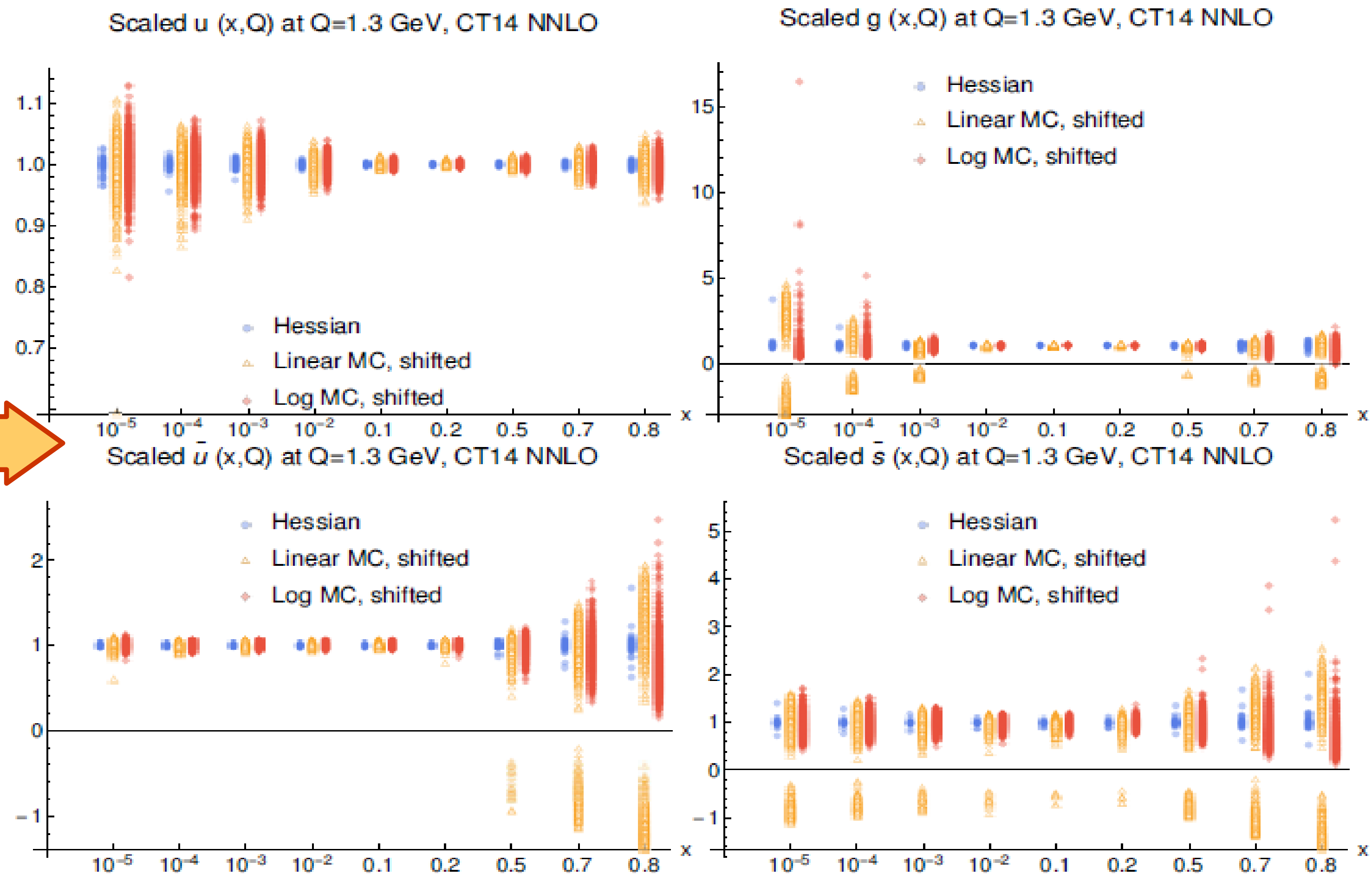
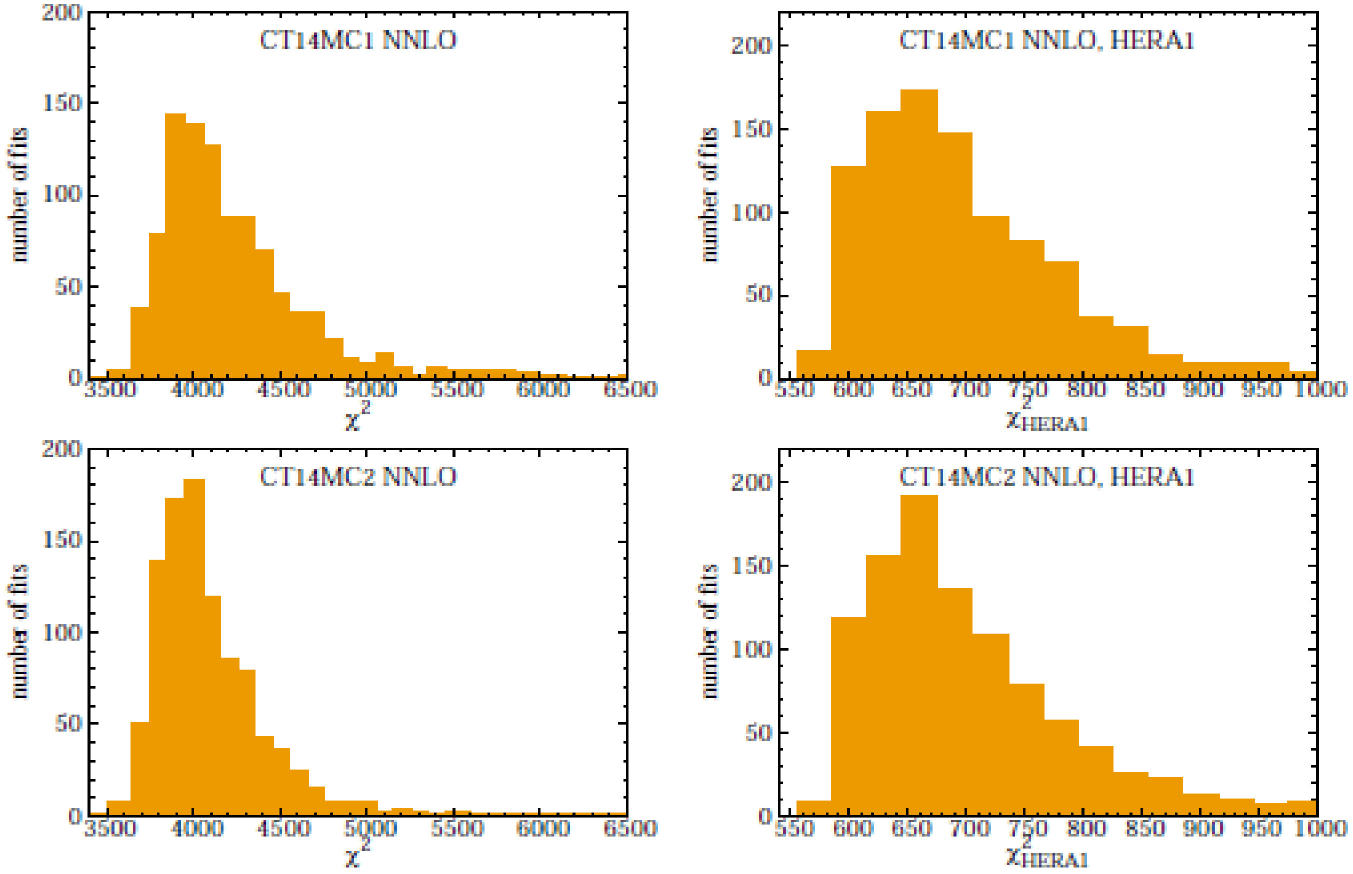


FIG. 2: Distributions of individual replicas for MC1 (linear MC, shifted) and MC2 (log MC, shifted) ensembles.

Large χ^2 in replicas



Typical CT14MC replicas sets have large χ^2. Here, we show χ^2 distributions for 1000 replicas, with about 3000 data points (579 for HERA-I) included in the CT14 fit.

CT14QED
and
CT14QED_inc

- Photon as a parton inside proton
- Evolved at the NLO QED plus LO QED
- CT14QED for inelastic contribution
- CT14QED_inc for inclusive contribution

Photon PDFs

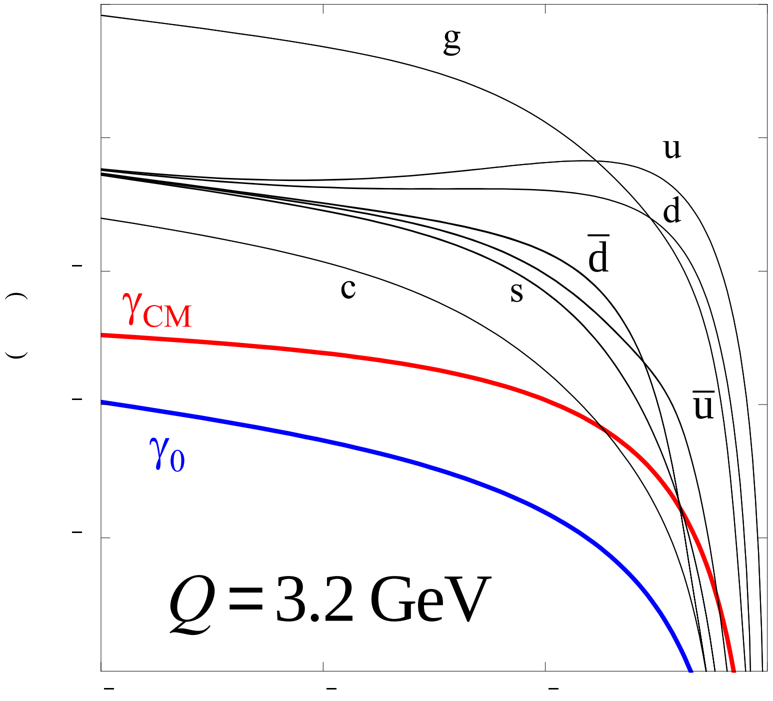
CT14QED

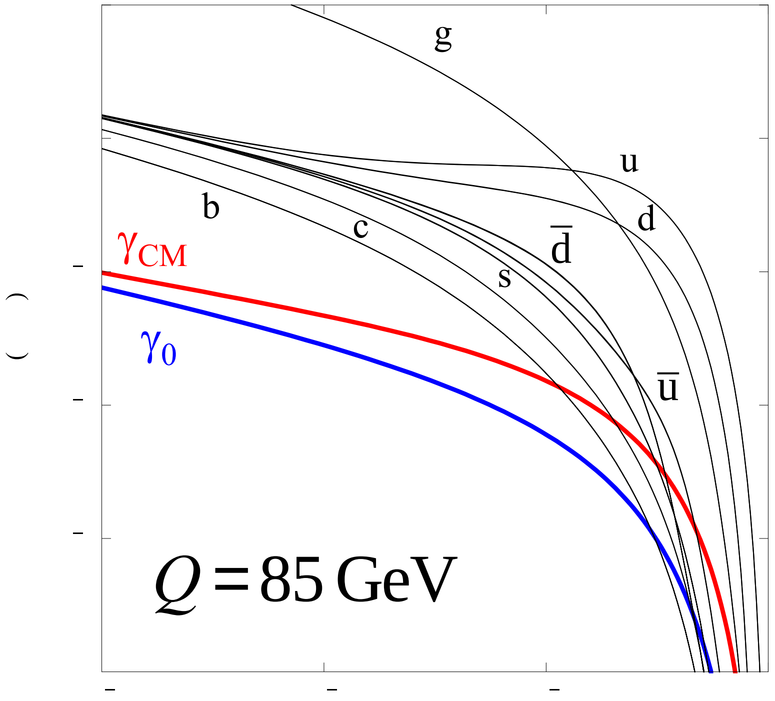
1) Previous studies
    a) MRST Martin et al., EPJC 39 (2005) 155
        - Radiation off "primordial current quark" distributions
    b) NNPDF Ball et al., Nuc. Phys. B 877 (2013) 290
        - parametrized fit, predominantly constrained by W, Z, γ^* Drell-Yan
    c) Sadykov arXiv:1401.1133
        - photon evolution in QCDNum

2) Photon evolution at LO in α and NLO in α_S currently implemented in CTEQ-TEA global analysis package
    a) Alternative parametrization approach
    b) Constrain with DIS + photon data

arXiv:1509.02905

CT14QED
Photon PDFs (in proton)





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

γ momentum fraction:

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

Initial Photon PDF still
← significant at large *Q*.

arXiv:1509.02905

Photon-Photon Luminosity
CT14QED_inc PDFs

arXiv:1603.04874

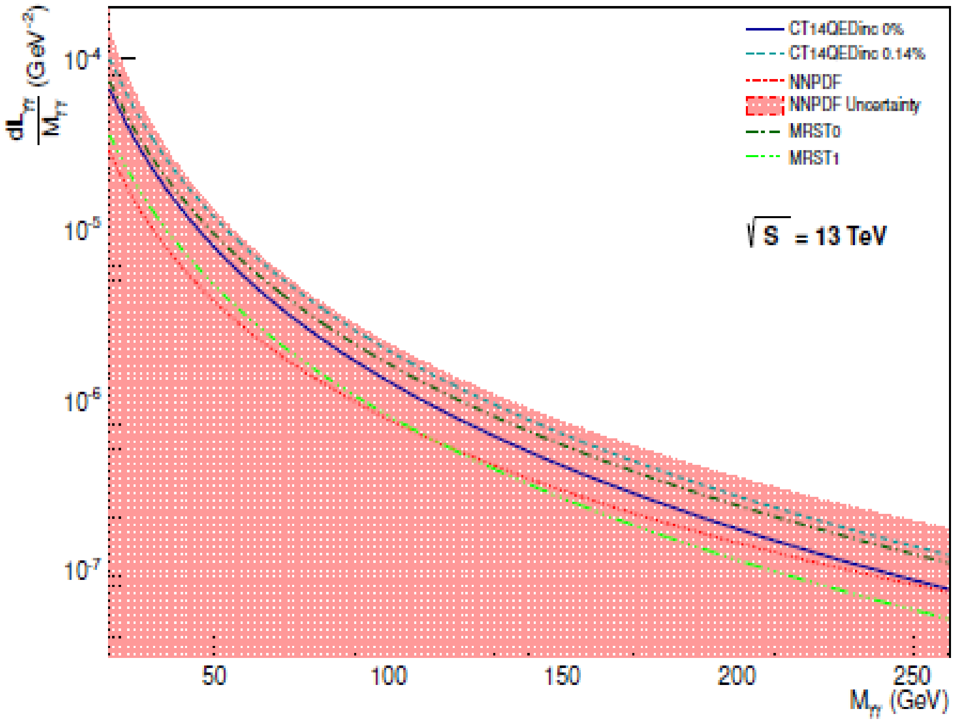


FIG. 5: Photon-photon luminosity for an invariant mass of 20 GeV to 500 GeV for 13 TeV collider energy

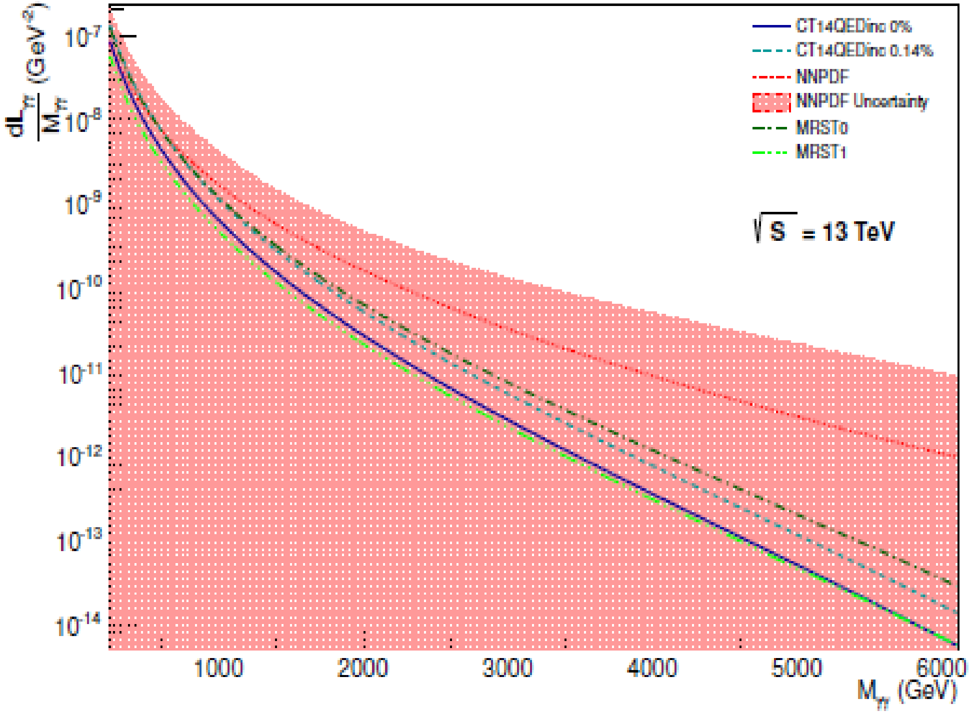


FIG. 6: Photon-photon luminosity for and invariant mass of 500 GeV to 6000 GeV for 13 TeV collider energy

Some useful information for PDF users

For LHC and 100 TeV Collider

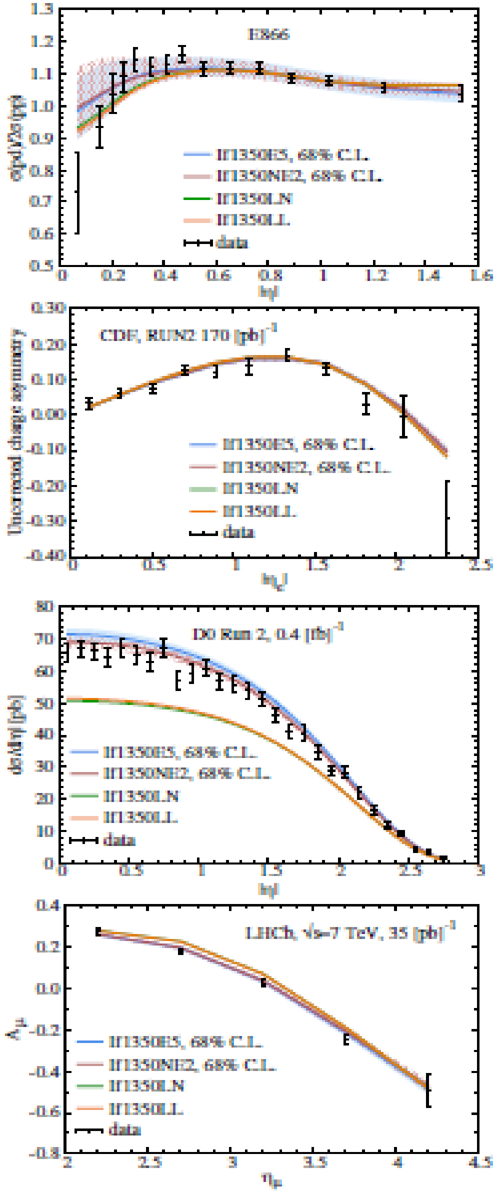
CT14 NNLO PDFs

- 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).

When is LO PDFs to be used?

- LO PDFs were obtained in the global fits by using LO hard part cross sections. Hence, if you want to describe the fitted data using the LO calculation, you have to use LO PDFs. Similar arguments apply to NLO and NNLO PDFs.
- However, if you are studying a new physics process, or some process not been included in our global fits, you might argue to use NLO or NNLO PDFs in the LO calculation by noting that whatever the difference is at higher order (than LO prediction).
- CT14LO PDFs were obtained by fitting to the same set of LHC run-1 data as done for CT14NLO and CT14NNLO.
- LO PDFs have much worse χ^2 in global fits than NLO and NNLO fits which have about the same χ^2 . Also, with much larger PDF errors.

CT14 LO vs. NLO and NNLO fits



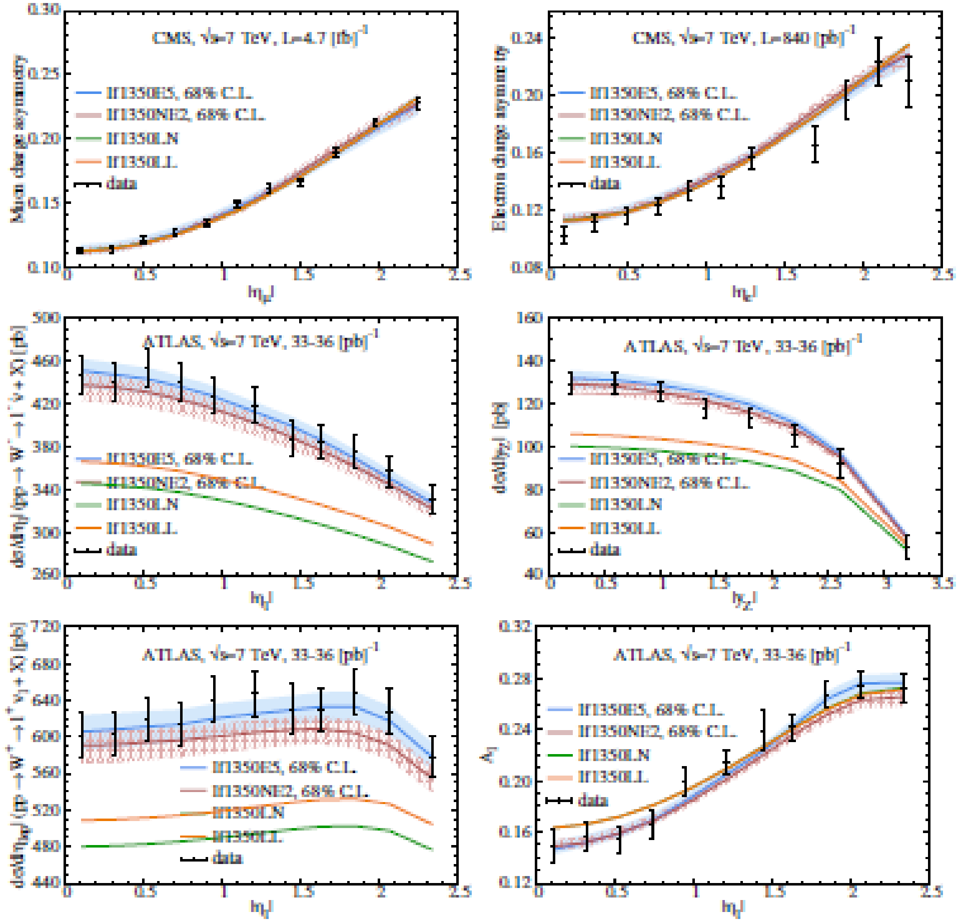


Figure 2:

2

MICHIGAN STATE

C T E Q

Impact of PDF uncertainty to New Physics Search

For LHC and 100 TeV Collider

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?

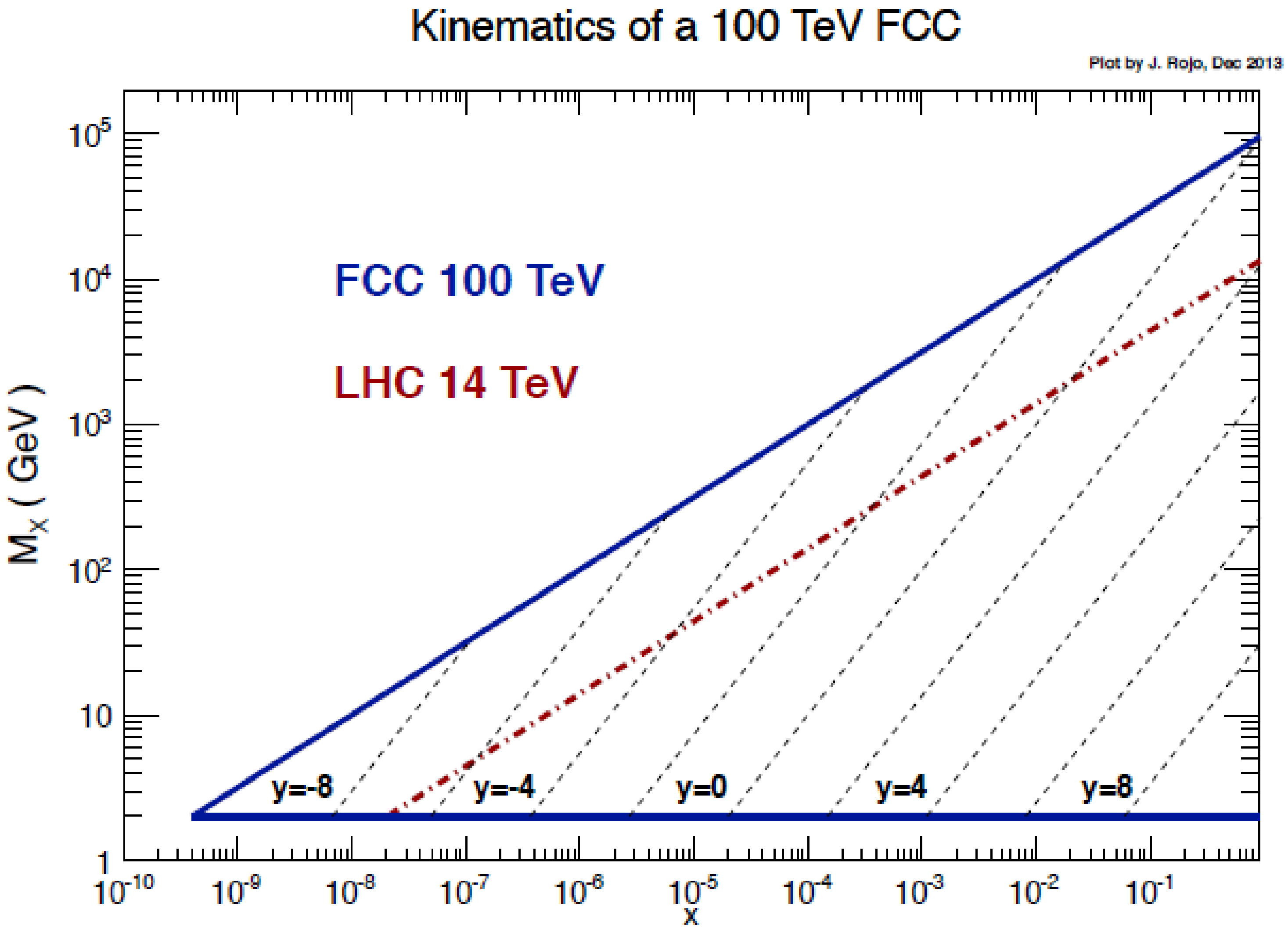
$$<x>=\frac{Q}{\sqrt{S}}$$

at central rapidity (y=0)

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

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

Kinematics of a 100 TeV SppC



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

On to a 100 TeV FCC

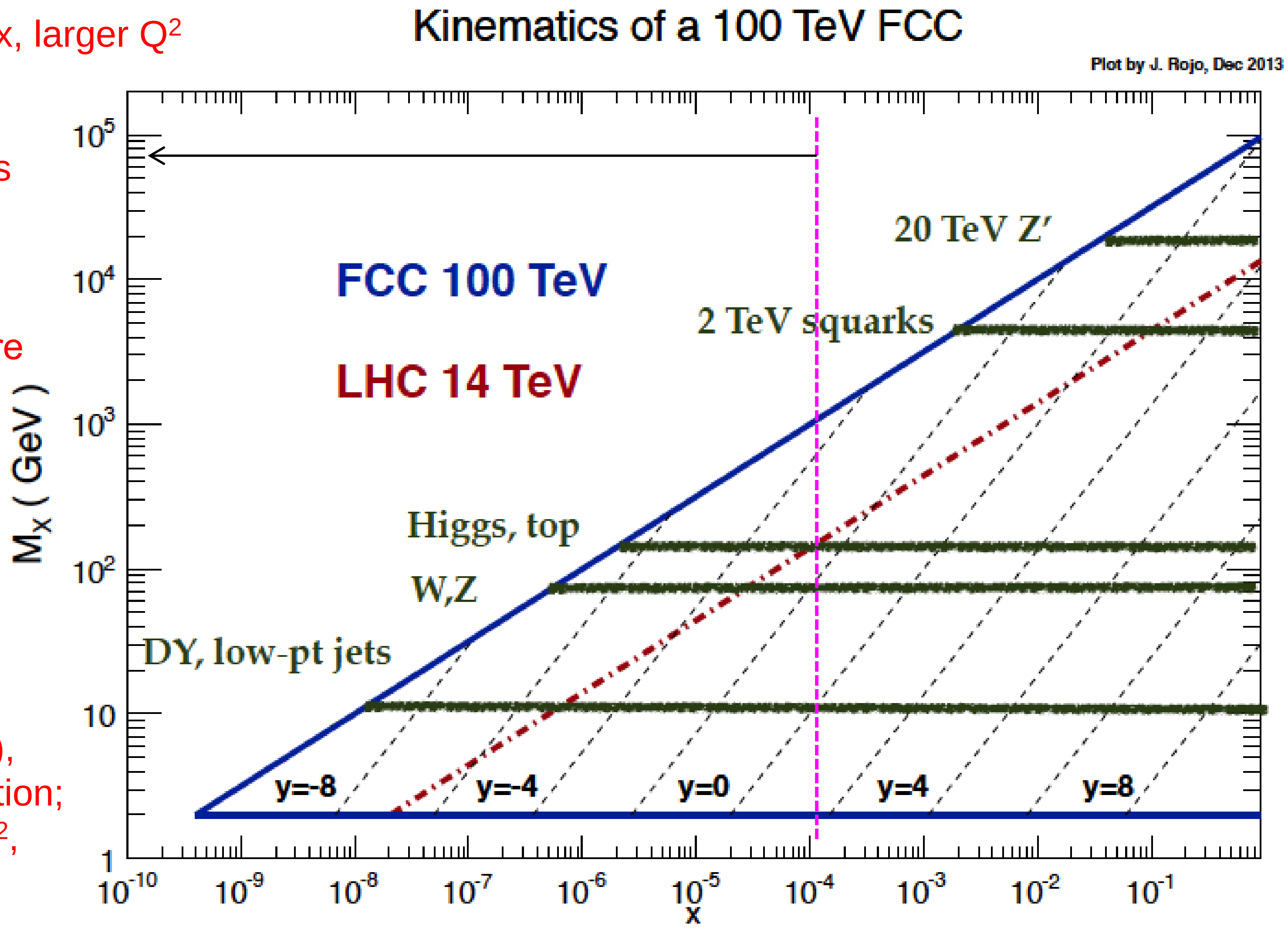
will access smaller x, larger Q^2

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



PDF luminosities

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

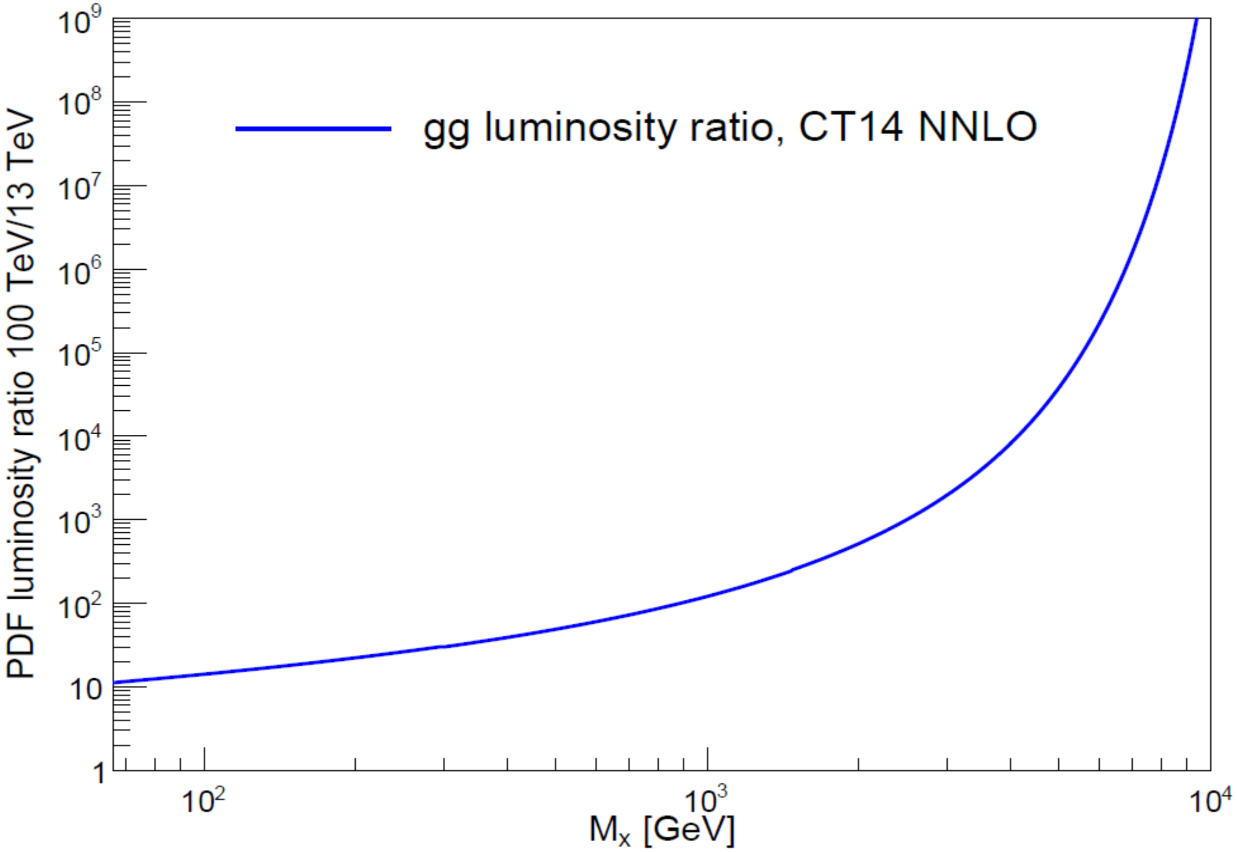
$$= \int d\tau dy \; g(x_1, M) g(x_2, M) \hat{\sigma}(M)$$

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

PDF Luminosity

$$\tau = \mathrm{x}_1 \mathrm{x}_2$$

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



Uncertainties in physical cross sections induced by PDFs also vary.

Conclusions

- LHC unprecedented energies brought us in a new precision era.
- Massive efforts are going on to constrain proton structure:

PDF uncertainties still remain a limiting factor for precision at the LHC.

- Finding new, highly sensitive measurements for constraining PDFs:
  - Less inclusive, yet clean, processes *(e.g.* $Z\ pT$ *at NNLO…etc.)*
  - Better constraints at $x > 0.3$
  - Reliable flavor separation
- High precision data ⇒ control on subleading effects (NLO EM corrections, photon PDFs, off-shell resonant production…) and theoretical uncertainties (scale dependence, heavy-quark schemes)