4th Hi-X workshop, Frascati, November 21, 2014

CT10, CT14 and META parton distributions

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On behalf of CTEQ-TEA group
S. Dulat, J. Gao, M. Guzzi, T.-J. Hou, J. Huston, J. Pumplin, C. Schmidt, D. Stump, C. -P. Yuan

I wish to thank the organizers for a stimulating and enjoyable workshop. I will address the interesting points raised by A. Accardi, S. Brodsky, K. McFarland, J. Owens, J.-C. Peng, and others

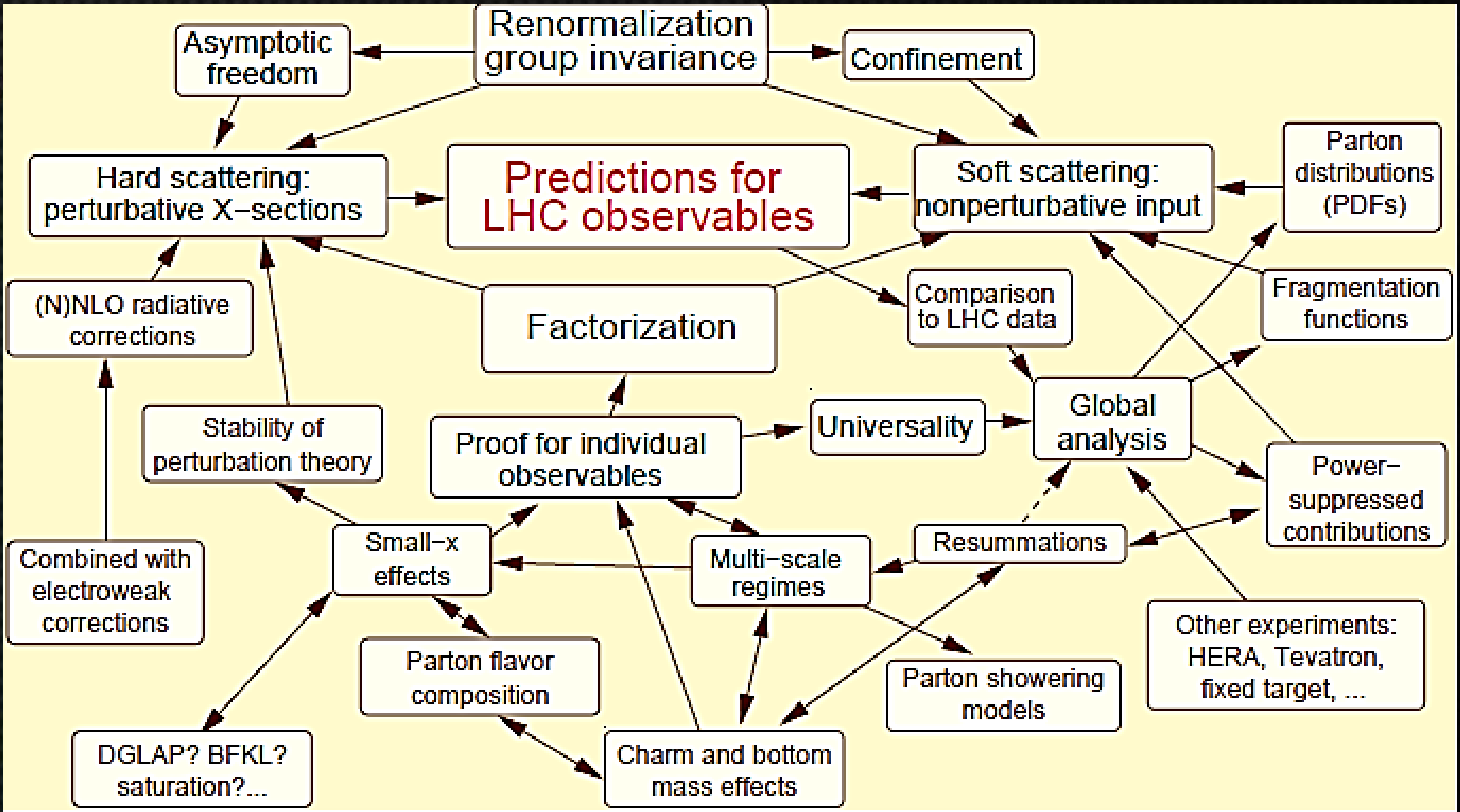
The objective of the CTEQ-TEA global analysis

The CTEQ-TEA analysis aims to provide PDFs for perturbative QCD calculations for high-energy proton scattering at the Large Hadron Collider and elsewhere, at the accuracy that matches unprecedented quality of the LHC data and revolutionary advancements in predictions of hard QCD cross sections

CT10 and CT14 PDFs

- Our most recent published PDF ensembles, **CT10/CT10W NLO** [arXiv:1007.2241] and **CT10 NNLO** [arXiv:1302.6246] are in good agreement with LHC Run-1 data
- The soon-to-be-released CT14 ensemble will be based on new HERA and LHC data and improved techniques
- The long-term target is to obtain "**PDFs that achieve 1% accuracy**" in LHC processes

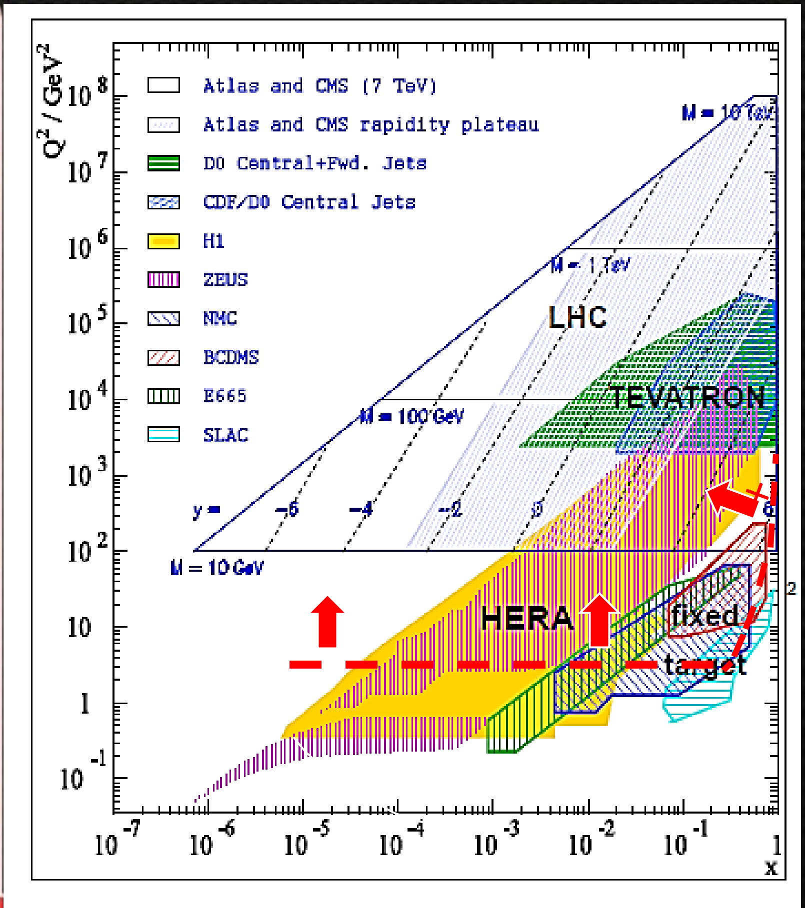
Full richness of QCD theory comes into play in the global QCD analysis at 1% resolution



Concept map (c. 2007), even more relevant now

Selection of experiments

Experimental measurements are selected so as to reduce dependence on any theoretical input beyond the leading power in perturbative QCD



Only DIS data with $Q^2 > 4\ GeV^2$, $W^2 > 12.25\ \ GeV^2$ (above the red line) are accepted to ensure stable perturbative predictions

When possible, data from DIS and DY on **nuclear targets** will be **replaced by** comparable LHC/Tevatron measurements on **the proton**

Selection of experiments

Experimental measurements are selected so as to reduce dependence on any theoretical input beyond the leading power in perturbative QCD

Data sets and $\chi^2/d.o.f.$ in CT10 NNLO and CT10W NLO analyses

Experimental data set	N_{pt}	CT10NNLO	CT10W
Combined HERA1 NC and CC DIS [74]	579	1.07	1.17
BCDMS F_2^p [75]	339	1.16	1.14
BCDMS F_2^d [76]	251	1.16	1.12
NMC F_2^p [77]	201	1.66	1.71
NMC F_2^d/F_2^p [77]	123	1.23	1.28
CDHSW F_2^p [78]	85	0.83	0.66
CDHSW F_3^p [78]	96	0.81	0.75
CCFR F_2^p [79]	69	0.98	1.02
CCFR xF_3^p [80]	86	0.40	0.59
NuTeV neutrino dimuon SIDIS [81]	38	0.78	0.94
NuTeV antineutrino dimuon SIDIS [81]	33	0.86	0.91
CCFR neutrino dimuon SIDIS [82]	40	1.20	1.25
CCFR antineutrino dimuon SIDIS [82]	38	0.70	0.78
H1 F_L^p [83]	8	1.17	1.26
H1 σ_r^c for $c\bar{c}$ [59, 84]	10	1.63	1.54
ZEUS F_2^c [57]	18	0.74	0.90
ZEUS F_2^c [58]	27	0.62	0.76
E605 Drell-Yan process, $\sigma(pA)$ [85]	119	0.80	0.81
E866 Drell Yan process, $\sigma(pd)/(2\sigma(pp))$ [86]	15	0.65	0.64
E866 Drell-Yan process, $\sigma(pp)$ [87]	184	1.27	1.21
CDF Run-1 W charge asymmetry [88]	11	1.22	1.24
CDF Run-2 W charge asymmetry [89]	11	1.04	1.02
D0 Run-2 $W \to e\nu_e$ charge asymmetry [90]	12	2.17	2.11
D0 Run-2 $W \to \mu\nu_\mu$ charge asymmetry [91]	9	1.65	1.49
D0 Run-2 Z rapidity distribution [92]	28	0.56	0.54
CDF Run-2 Z rapidity distribution [93]	29	1.60	1.44
CDF Run-2 inclusive jet production [94]	72	1.42	1.55
D0 Run-2 inclusive jet production [95]	110	1.04	1.13
Total:	2641	1.11	1.13

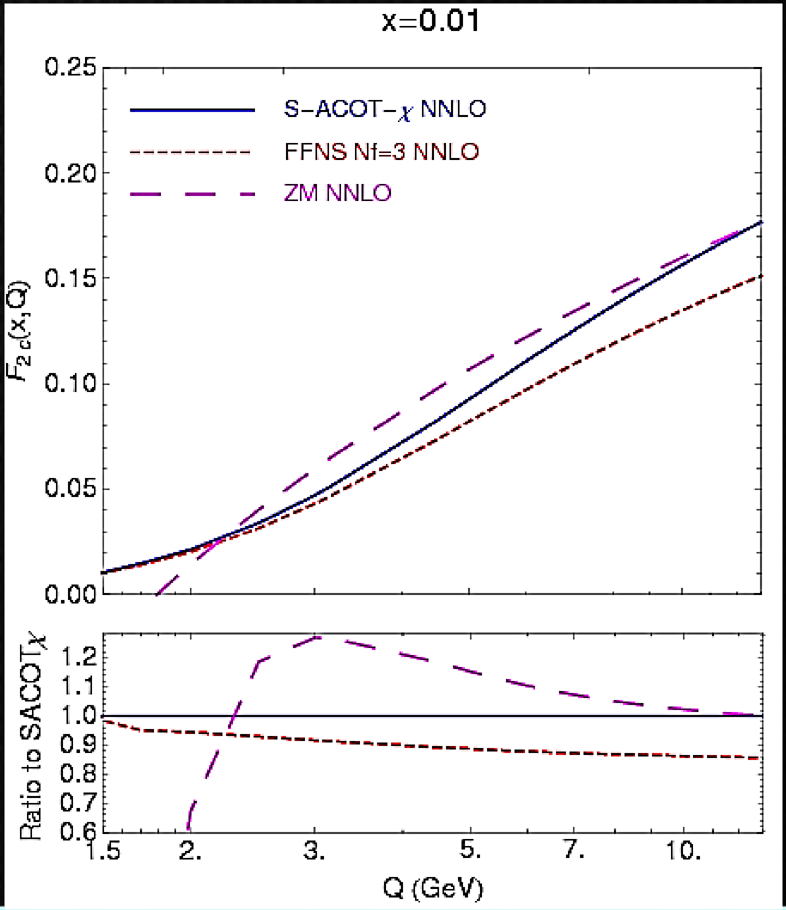
New sets in CT14

1. HERA-2 $F_{2c}(x,Q)$
2. ATLAS W/Z cross sections
3. ATLAS low mass/high mass DY
4. CMS W asymmetry, 4.7 fb^{-1}
5. LHCb 7 TeV W asymmetry
6. ATLAS inclusive jet 7 TeV R=0.6
7. CMS inclusive jet 7 TeV R=0.7
8. ATLAS jet ratio 2.76 TeV/7 TeV R=0.6

NNLO cross sections in a general-mass scheme

NC DIS and DY cross sections are evaluated at NNLO in the general-mass scheme *(Guzzi, Lai, P.N., Yuan, arXiv:1108.5112)*

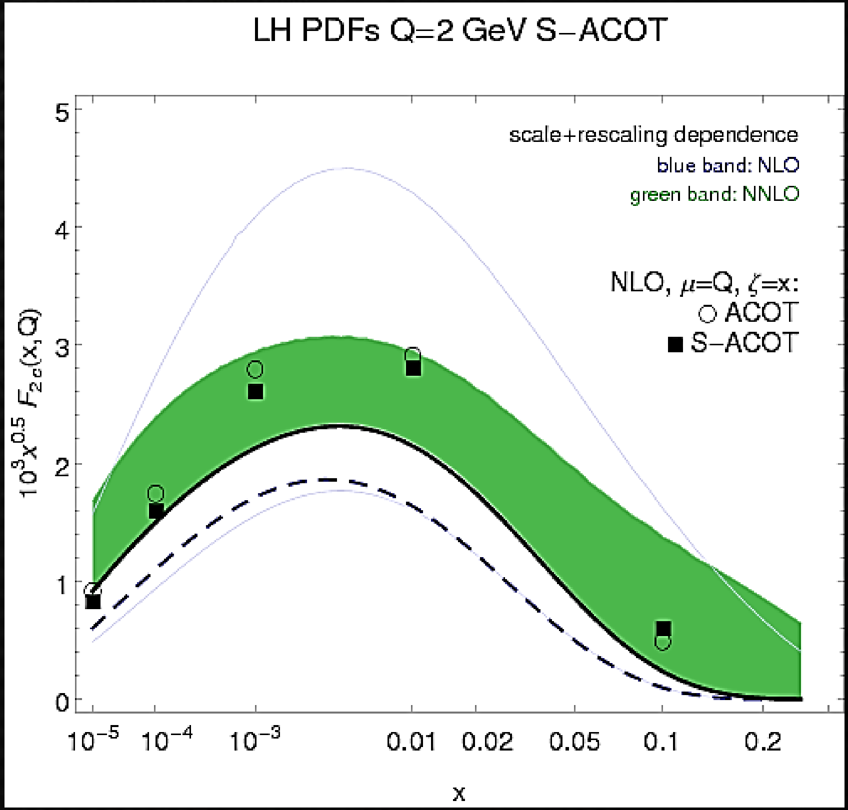
Effects of heavy-quark masses are included at all Q.



NNLO cross sections in a general-mass scheme

NC DIS and DY cross sections are evaluated at NNLO in the general-mass scheme *(Guzzi, Lai, P.N., Yuan, arXiv:1108.5112)*

Dependence on QCD scales and threshold matching conditions is reduced compared to NLO



Benchmark comparisons of NNLO cross sections

Most NNLO cross sections in the CT14 fit are benchmarked against cross sections from other groups.

This is important. Some changes in $g(x, Q)$ and $s(x, Q)$ expected in the CT14 ensemble are due to the improved numerical calculation of CC DIS cross sections and NLO jet cross sections

Benchmark comparisons of PDF analyses

1. J. Gao et al., MEKS: a program for computation of inclusive jet cross sections at hadron colliders , arXiv:1207.0513

Codes for NLO jet production

2. R. Ball et al., Parton Distribution benchmarking with LHC data, arXiv:1211.5142

(N)NLO LHC cross sections

3. S. Alekhin et al., ABM11 PDFs and the cross section benchmarks in NNLO, arXiv:1302.1516; The ABM parton distributions tuned to LHC data; arXiv:1310.3059

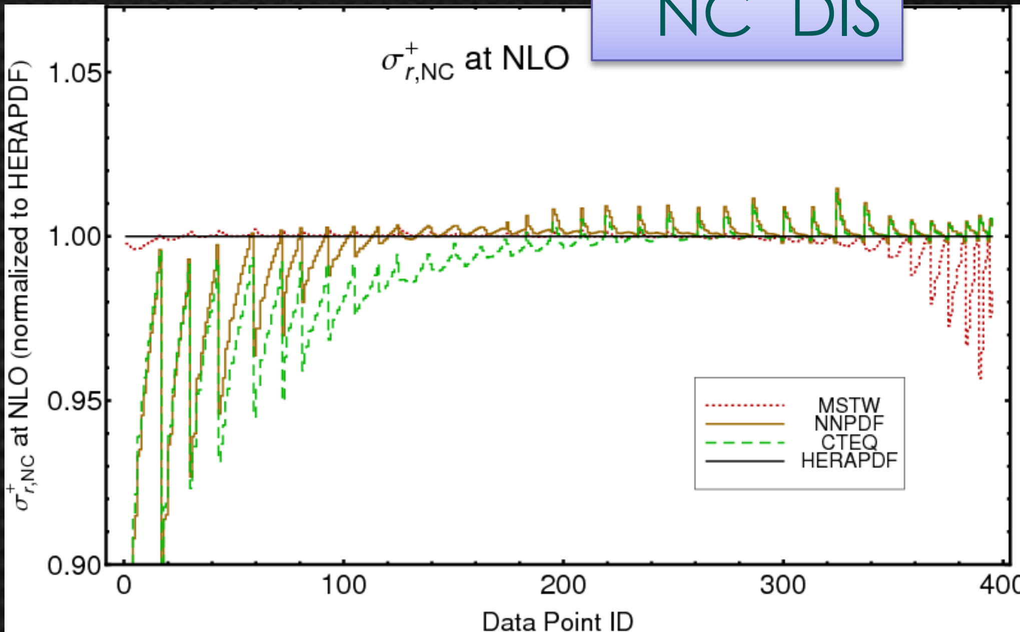
W/Z, $t\bar{t}$,…

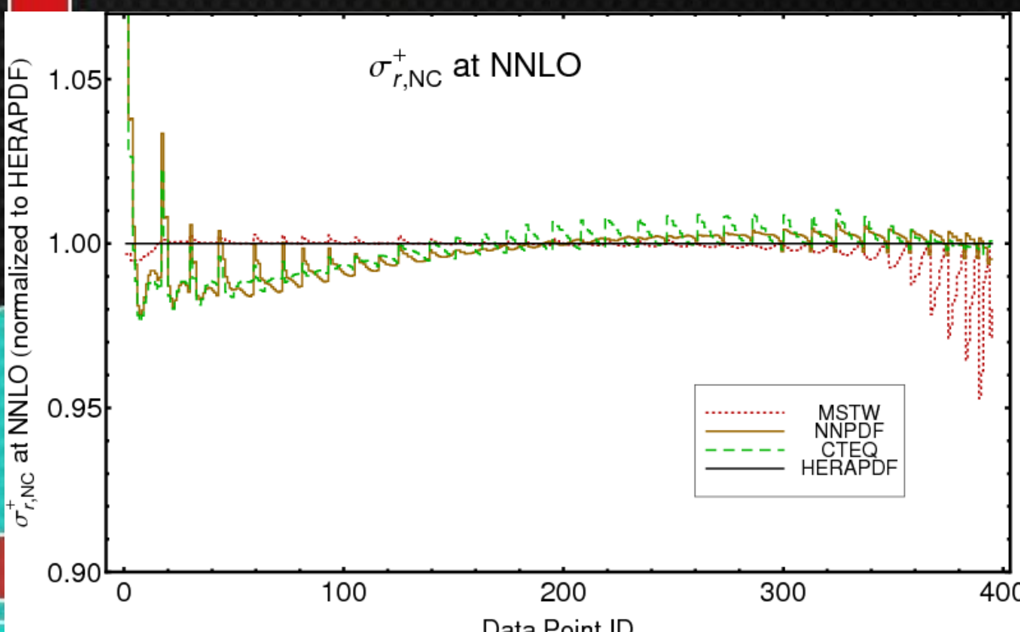
4. A.Cooper-Sarkar et al., PDF dependence of the Higgs production cross section in gluon fusion from HERA data, 2013 Les Houches Proceedings, arXiv:1405.1067, p. 37

NC DIS; CC DIS (in progress)

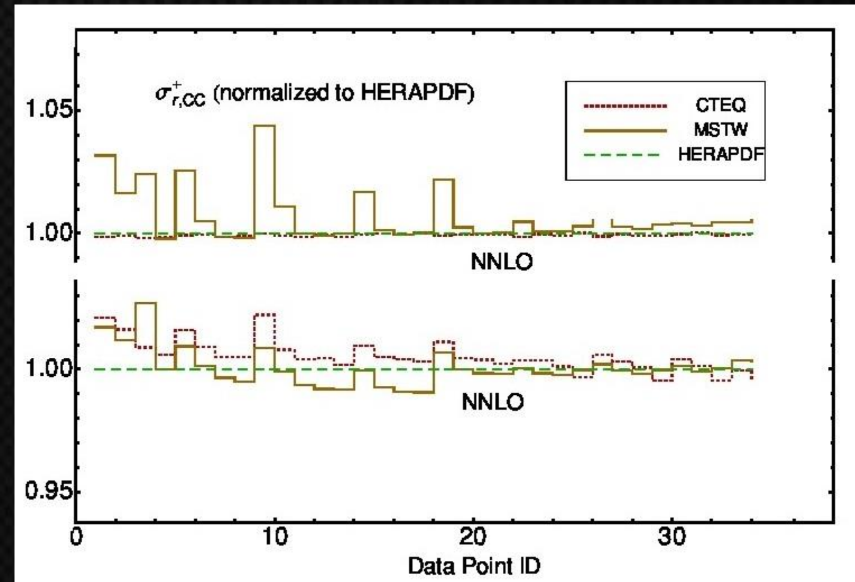
5. S. Forte and J. Rojo, Dataset sensitivity of the gg->H cross-section in the NNPDF analysis, arXiv:1405.1067, p. 56

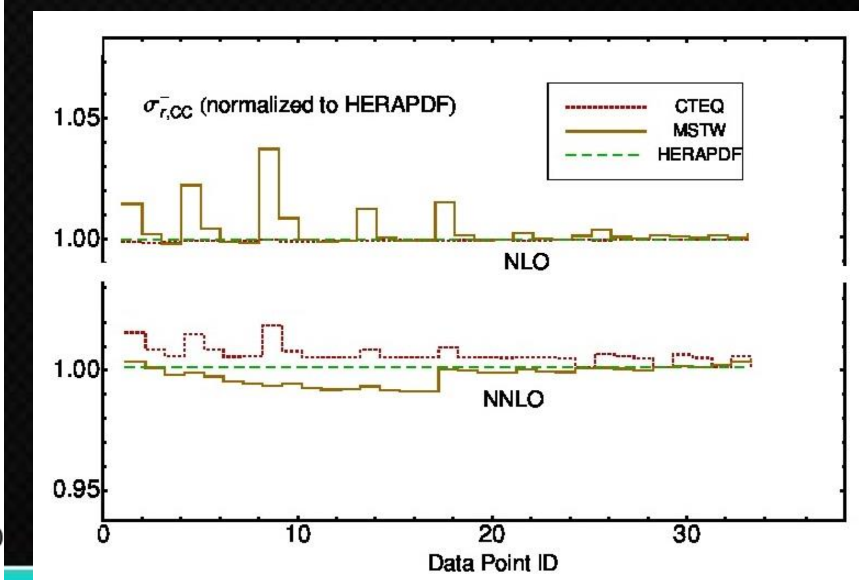
NC DIS





CC DIS (preliminary)



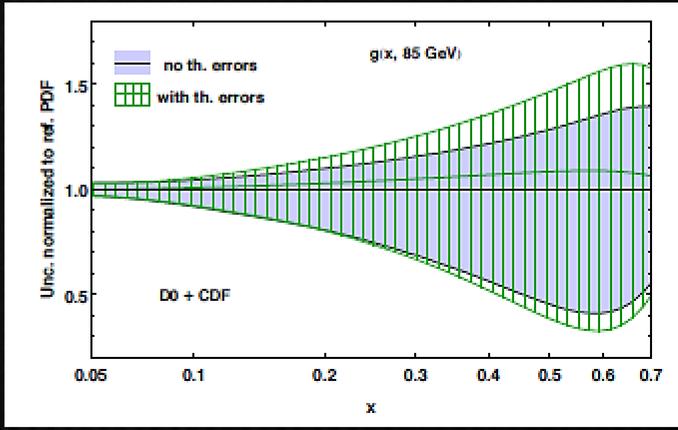


Residual uncertainty in NLO cross sections

CC DIS and jet production hard cross sections are still computed at NLO

In the CT14 study, we estimate the theoretical uncertainty in the PDFs from the QCD scale dependence and normalization variations in the jet cross sections due to the missing NNLO contributions.

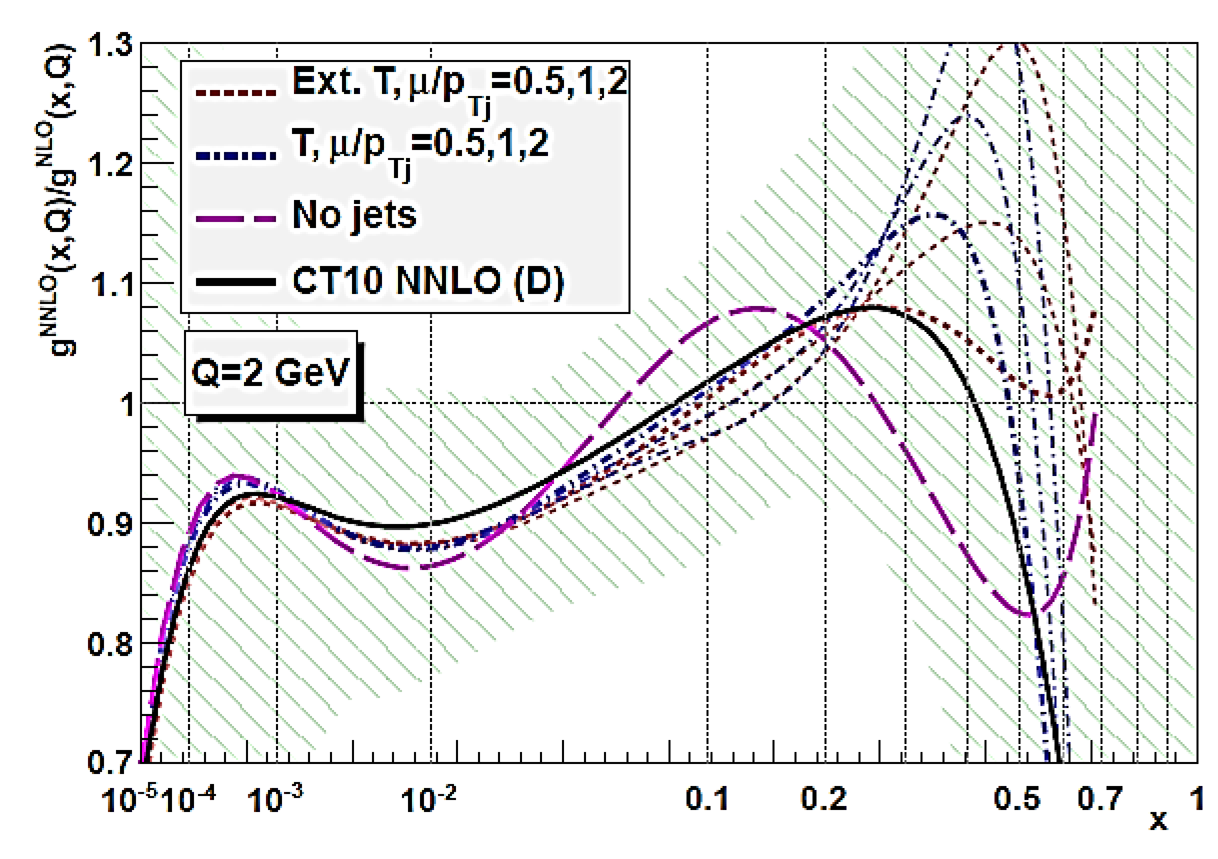
This uncertainty is small compared to the experimental uncertainty.



- About 20% increase of the gluon PDF uncertainty in large-x region and 10% in the Higgs mass region, for a fit with only Tevatron jet data included (+DIS+…)
- Similar results are observed when also including the LHC jet data or using different criteria for the determination of PDF uncertainties

Jun Gao, 2014

Role of correlated systematic errors



One of the objectives of the CT10 NNLO study was to investigate the role of correlated systematic errors and theoretical uncertainties

For example, the large-x g(x,Q) depends on the implementation of corr. syst. errors in Tevatron jet experiments, as well as on the assumptions about QCD scales. The CT10 NNLO gluon error sets are constructed so as to span the full range of uncertainty due to experimental errors, corr. syst. errors, and various scale choices

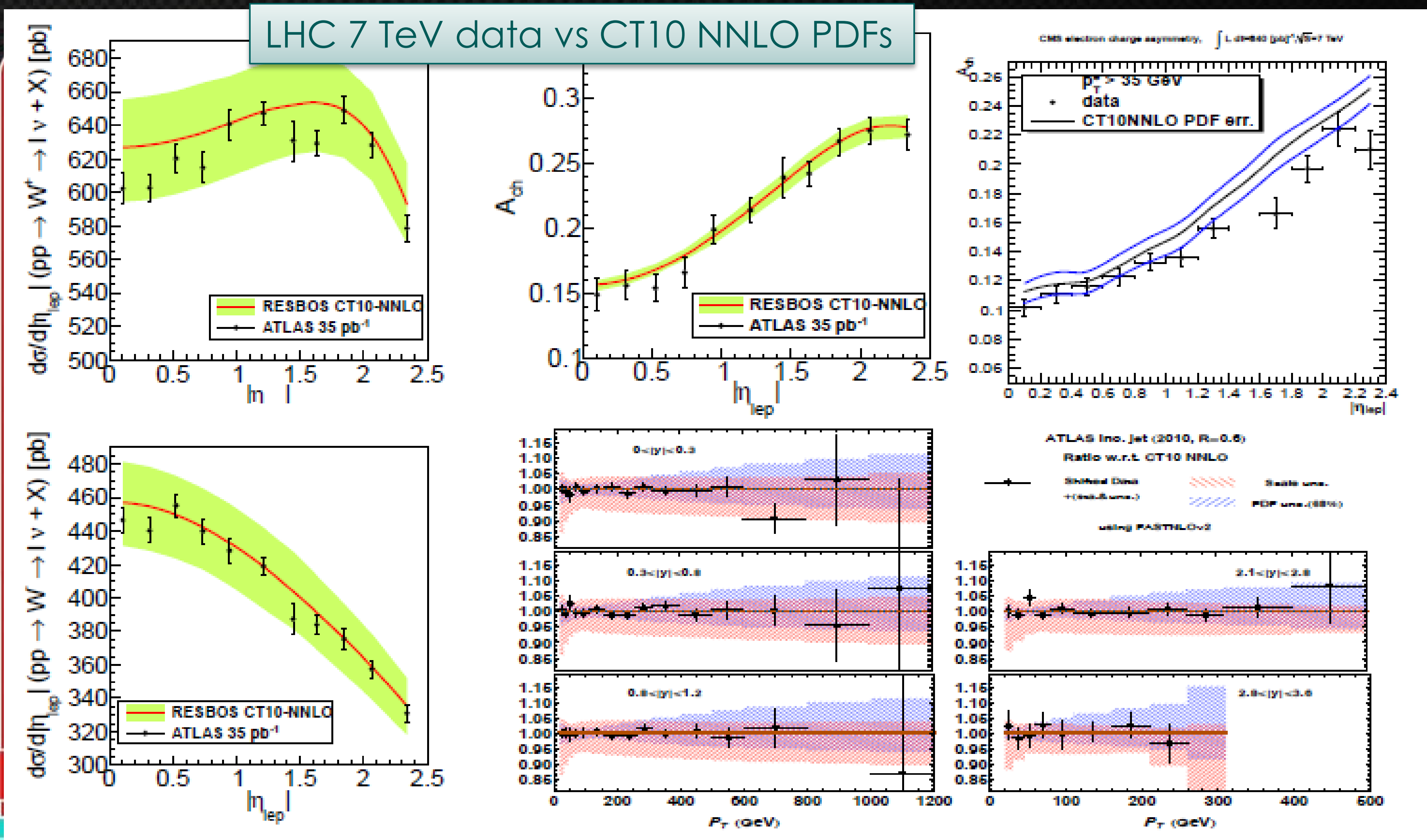
CT14: new parametrization forms

- CT14 relaxes restrictions on several PDF combinations that were enforced in CT10. [These combinations were not constrained by the pre-LHC data.]
  - The assumptions $\frac{\bar{d}(x,Q_0)}{\bar{u}(x,Q_0)} \to 1$, $u_v(x,Q_0) \sim d_v(x,Q_0) \propto x^{A_{1v}}$ with $A_{1v} \approx -\frac{1}{2}$ at $x < 10^{-3}$ are relaxed once LHC W/Z data are included
  - CT14 parametrization for $s(x,Q)$ includes extra parameters
- Candidate CT14 fits have 30-35 free parameters
- In general, $\mathrm{f_a}\,(\mathrm{x}, \mathrm{Q_0}) = \mathrm{Ax^{a_1}}\,(1-\mathrm{x})^{\mathrm{a_2}}\mathrm{P_a}(\mathrm{x})$
- CT10 assumed $P_a(x) = \exp(a_0 + a_3\sqrt{x} + a_4 x + a_5\, x^2)$
  - exponential form conveniently enforces positive definite behavior
  - but power law behaviors from a_1 and a_2 may not dominate
- In CT14, $\mathrm{P_a(x) = G_a(x)F_a(z)}$, where $\mathrm{G_a(x)}$ is a smooth factor
  - $\mathrm{z = 1 - 1(1-\sqrt{x})^{a_3}}$ preserves desired Regge-like behavior at low x and high x (with a_3>0)
- Express $F_a(z)$ as a linear combination of Bernstein polynomials:

$$z^4, 4z^3(1-z), 6z^2(1-z)^2, 4z(1-z)^3, (1-z)^4$$

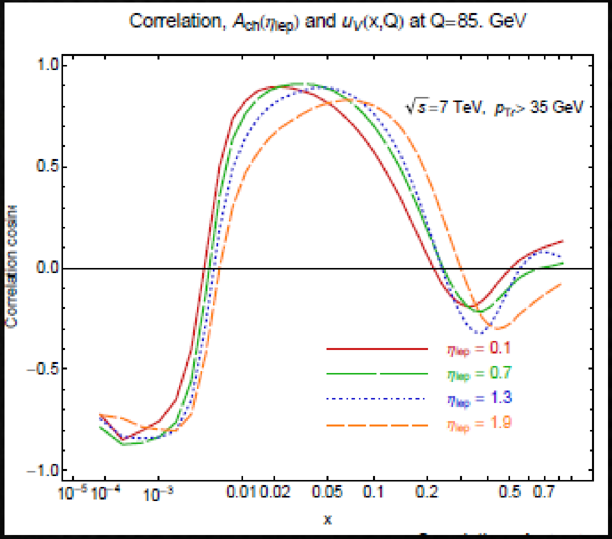
  - each basis polynomial has a single peak, with peaks at different values of z; reduces correlations among parameters

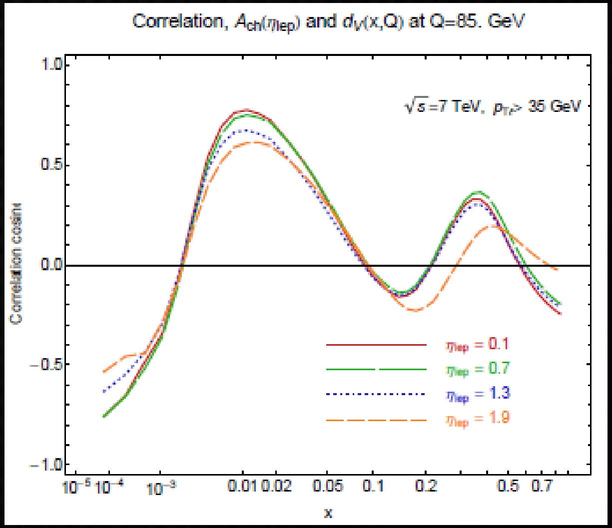
CT10 NNLO PDFs are in a very good agreement with a variety of LHC observables



CT14: direct tests of flavor composition

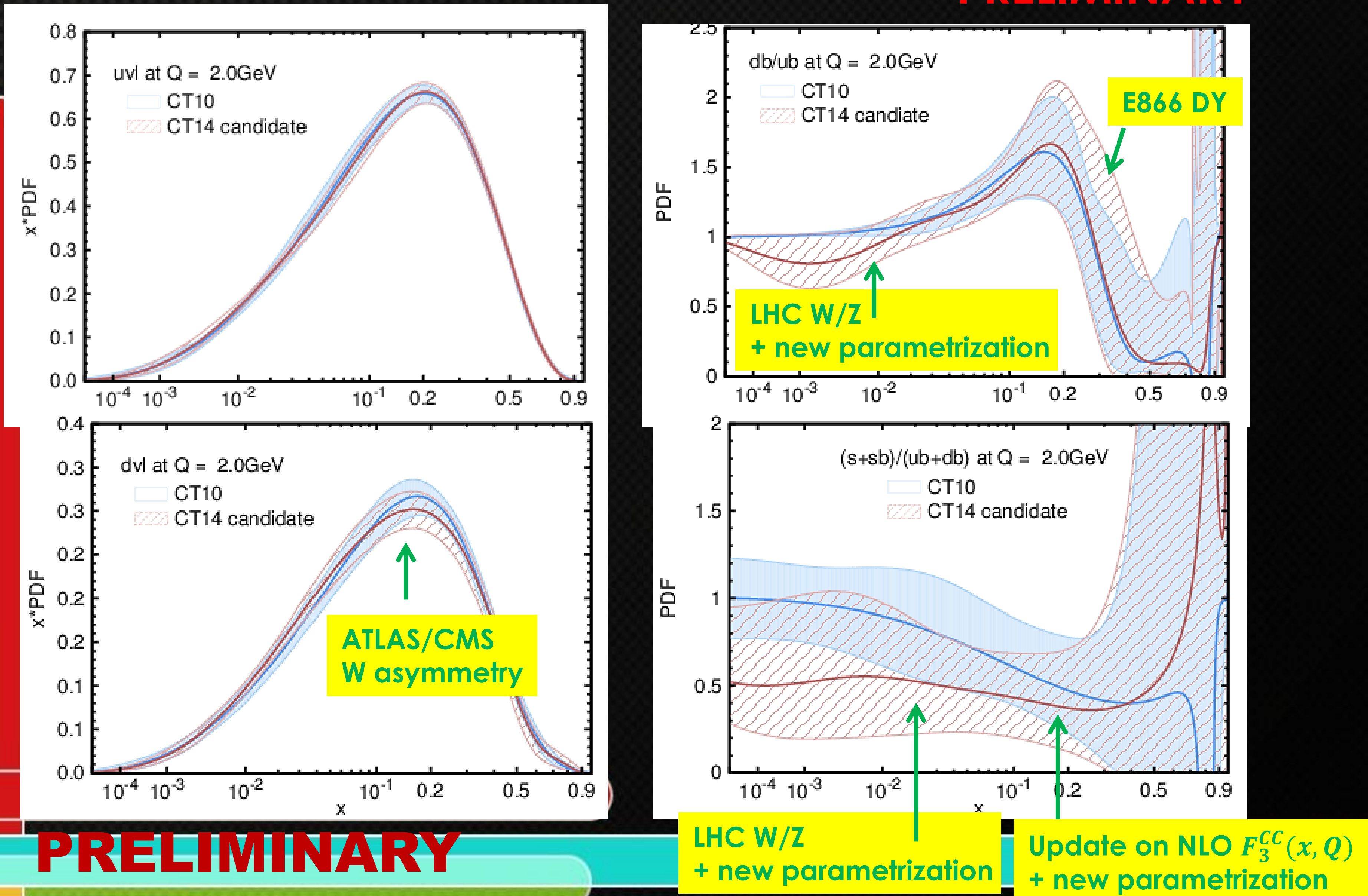
- LHC measurements impose some unique constraints on parton flavor composition (on g, u_v and d_v, $\frac{s+\bar{s}}{\bar{u}+\bar{d}}$,...) that will strengthen soon. We finalize revisions in the CT14 parametrization forms in order to account for new constraints on flavor separation with the current and upcoming sets of the LHC data.



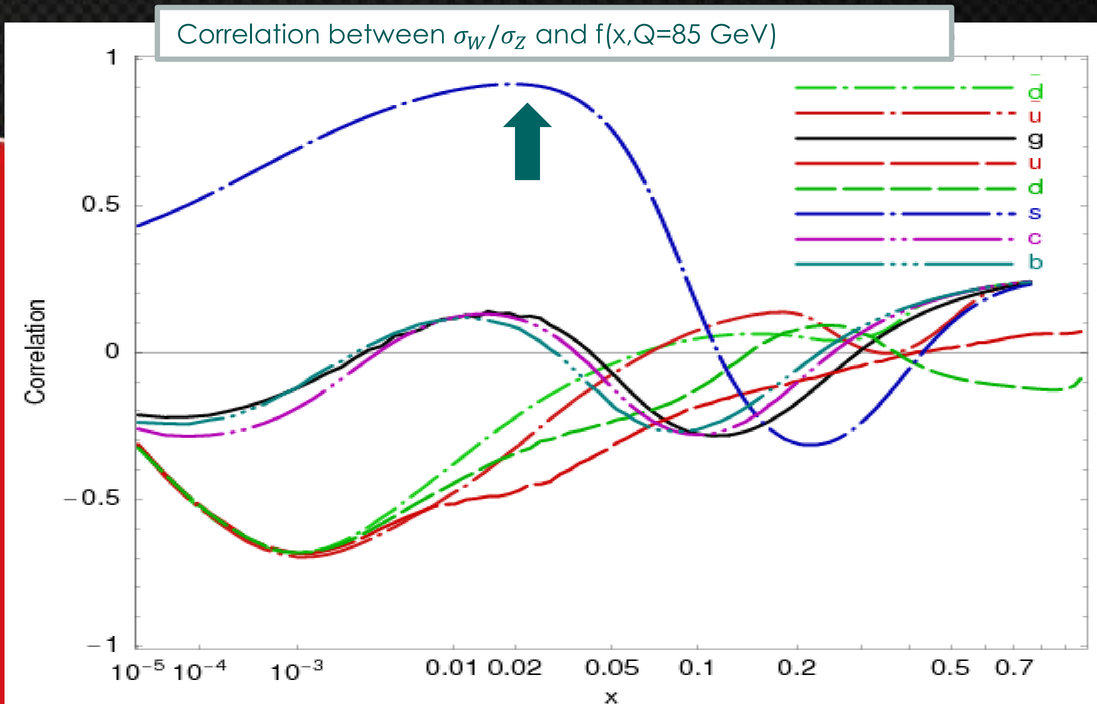


Effects on the candidate quark PDFs

PRELIMINARY

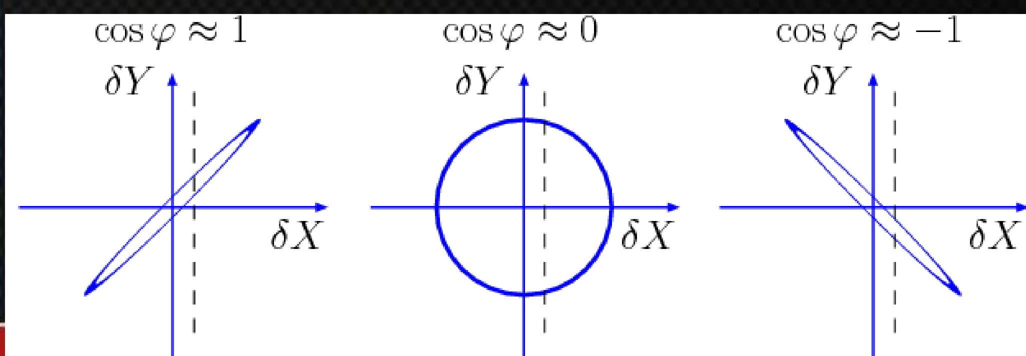


Constraining strangeness PDF by LHC W and Z cross sections



2008, CTEQ6.6 (arXiv:0802.0007): the ratio σ_W/σ_Z at LHC must be sensitive to the strange PDF $s(x,Q)$

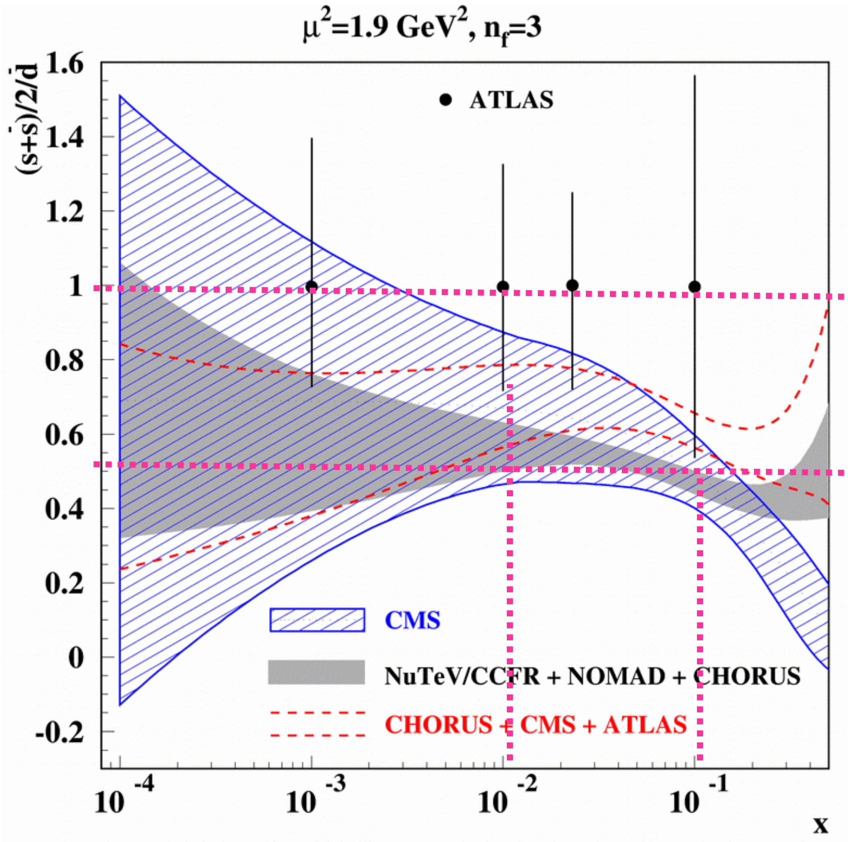
The uncertainty on $s(x,Q)$ limits the accuracy of the W boson mass measurement at the LHC



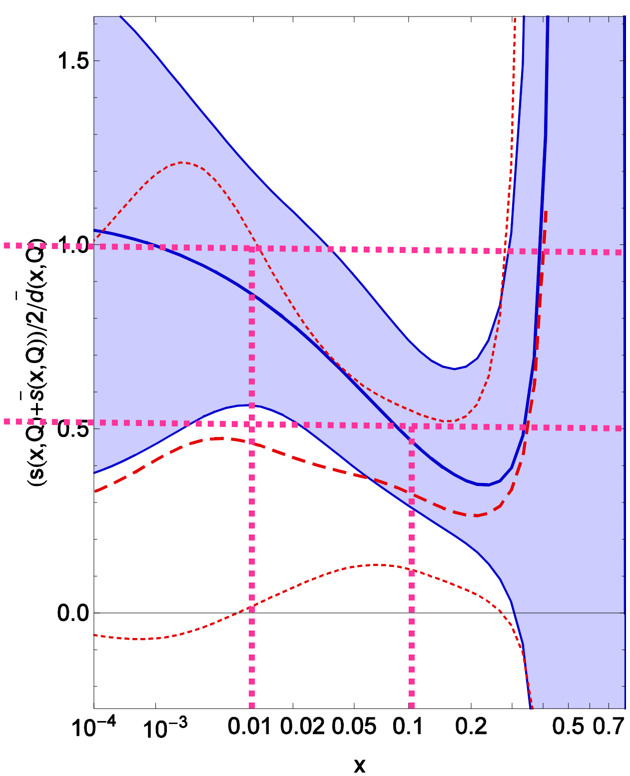
Correlation cosine $\cos\varphi \approx \pm 1$:

⇔ Measurement of X imposes tight constraints on Y

Strangeness PDF from ABM and CT14

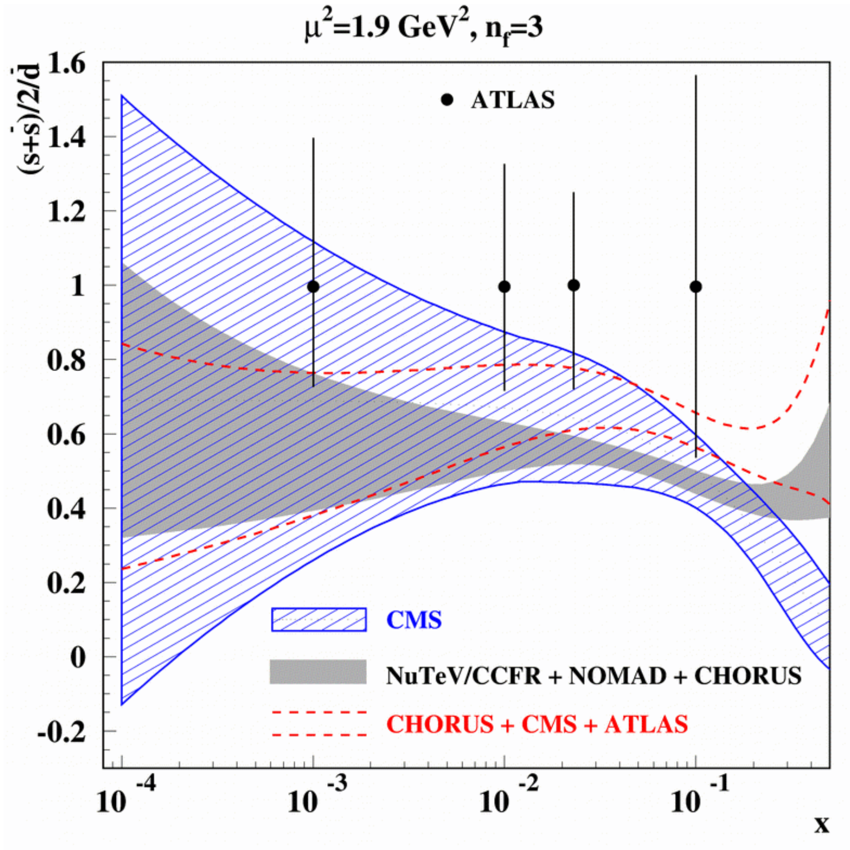


Alekhin et al., hep-ph/1404.6469
68%c.l. errors, $\Delta\chi^2 = 1$

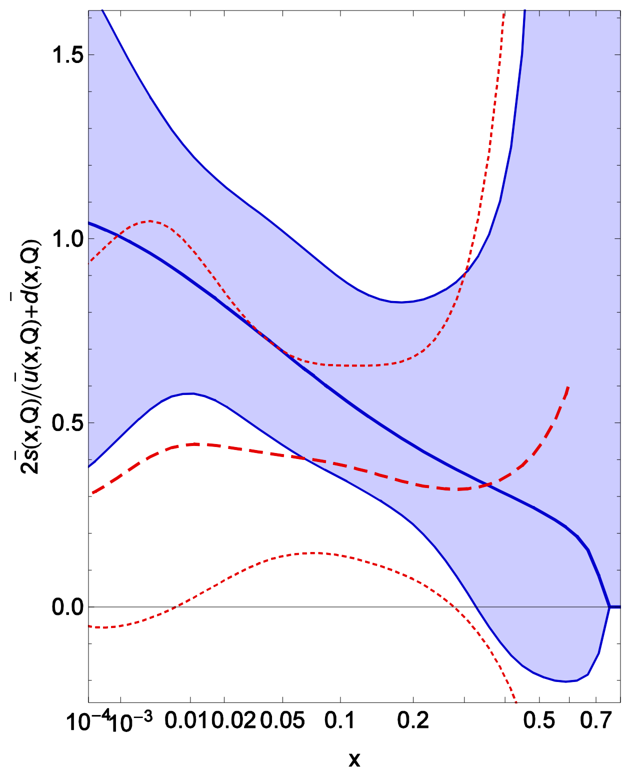


$(s + \bar{s})/(2\bar{d})$.
90% c.l. errors

Strangeness PDF from ABM and CT14

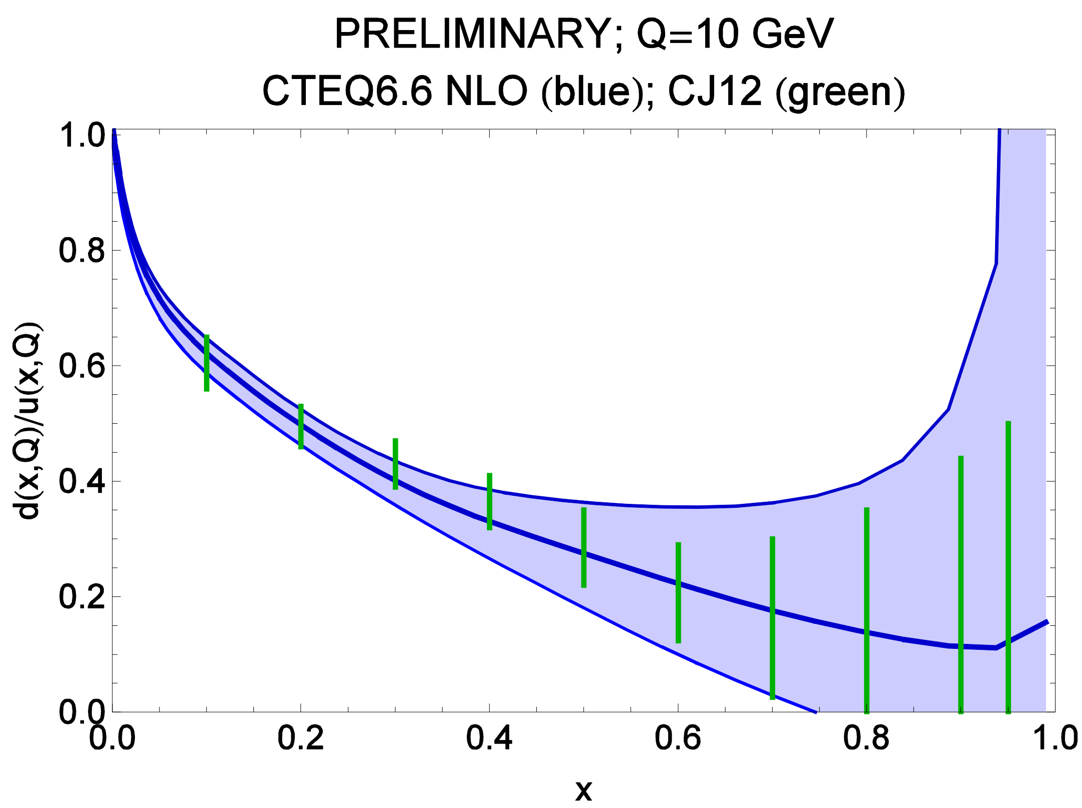


Alekhin et al., hep-ph/1404.6469



$(s+\bar{s})/(\bar{u}+\bar{d})$

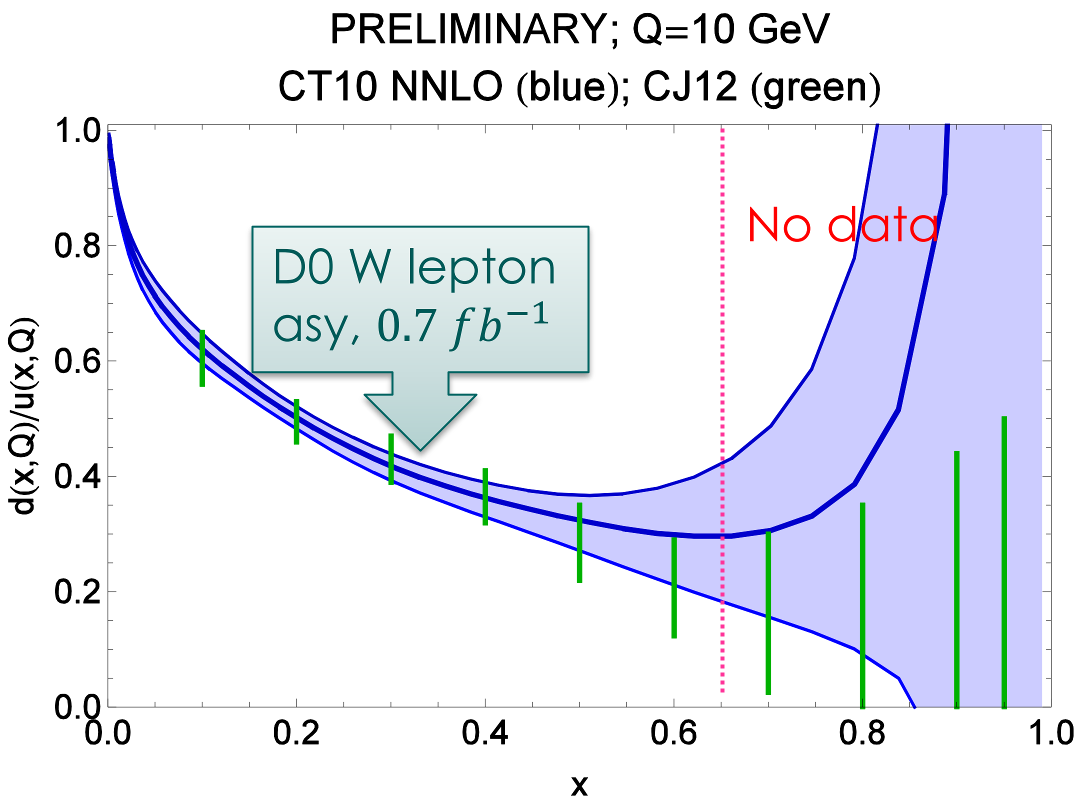
$d(x,Q)/u(x,Q)$ at $x \to 1$



- **Blue: CTEQ6.6 NLO**
- **Green: CJ 12 NLO**

(Owens et al., 1212.1702)

$d(x,Q)/u(x,Q)$ at $x \to 1$

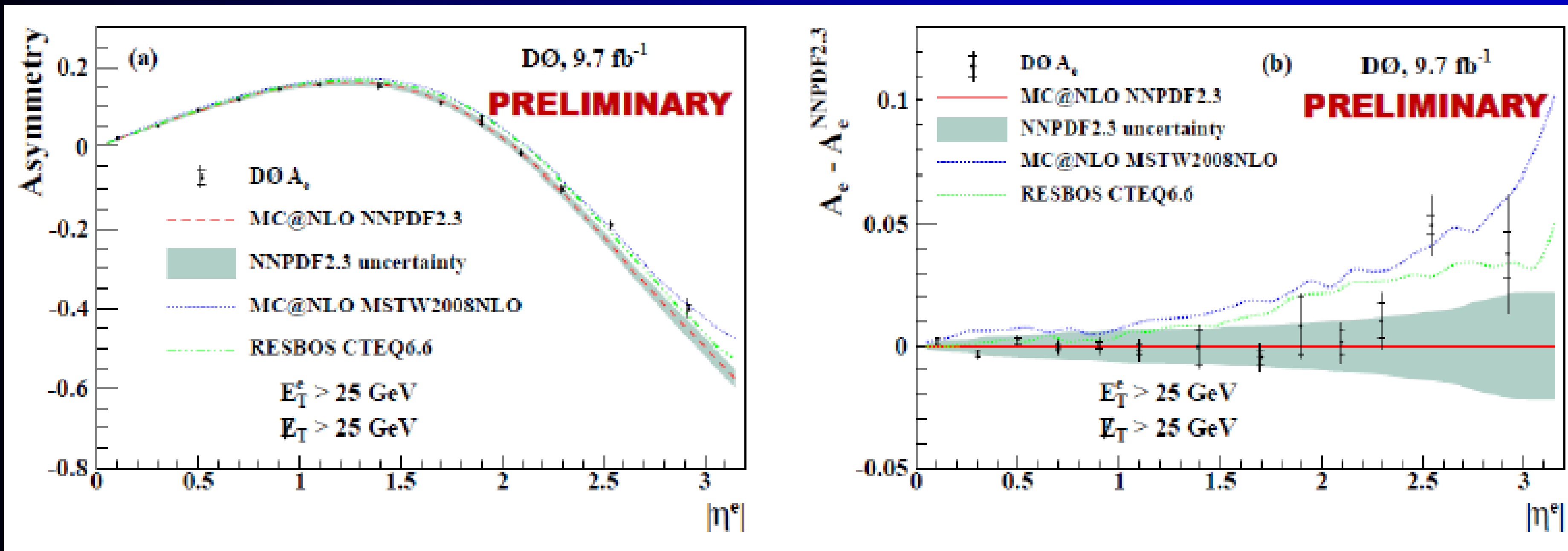


D0 $0.7\ fb^{-1}$ W lepton asymmetry (in CT10) is to be superseded by $9.7\ fb^{-1}$ data, possibly preferring a different d/u shape

- **Blue: CT10 NNLO**
- **Green: CJ 12 NLO**

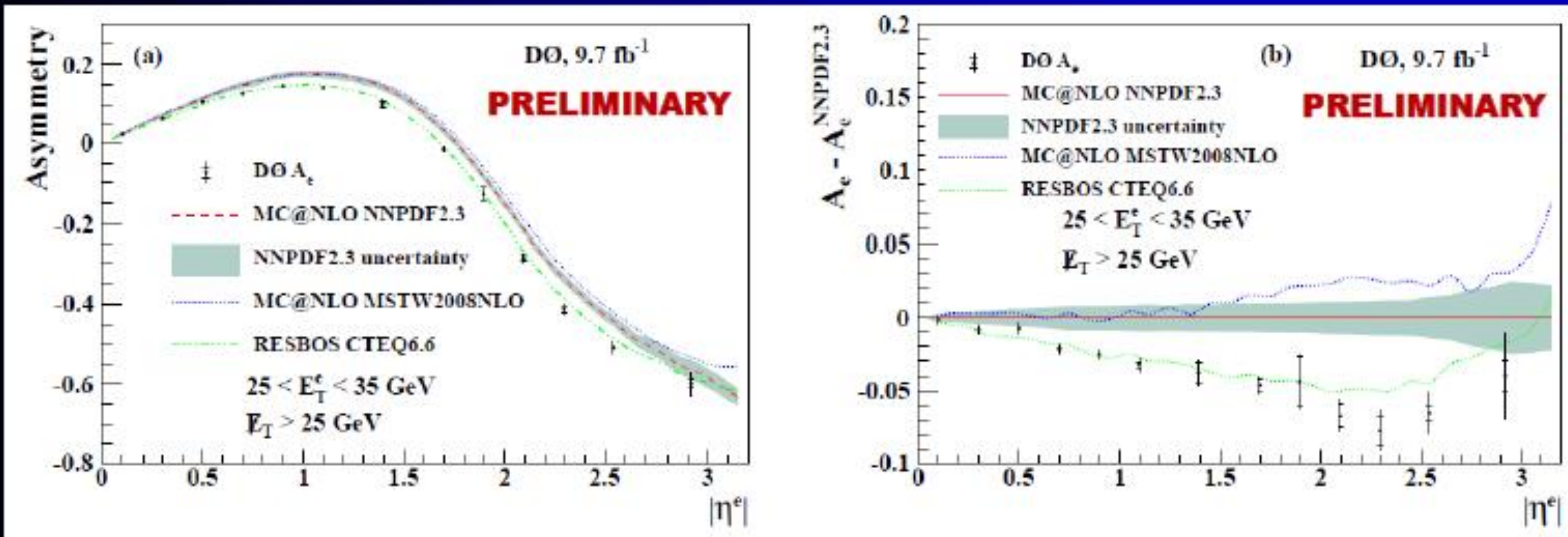
(Owens et al., 1212.1702)

A: e Charge Asymmetry Results

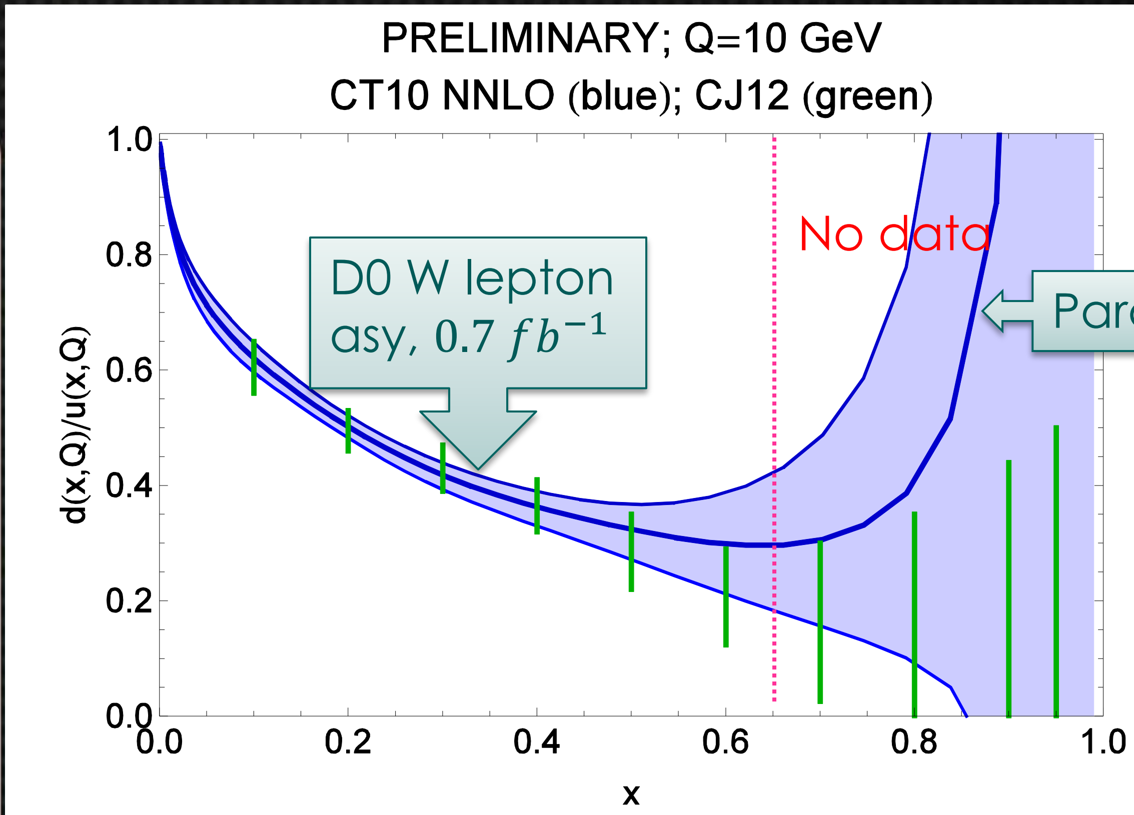


- **These results supersede previous D0 0.7 fb^{-1} measurement**
  - Old result lacked improved calibrations, *the* $K_{eff}^{\pm}$ correction, and additional systematic uncertainties included in the current analysis
- **Submission to PRD very soon**

A: e Charge Asymmetry Results



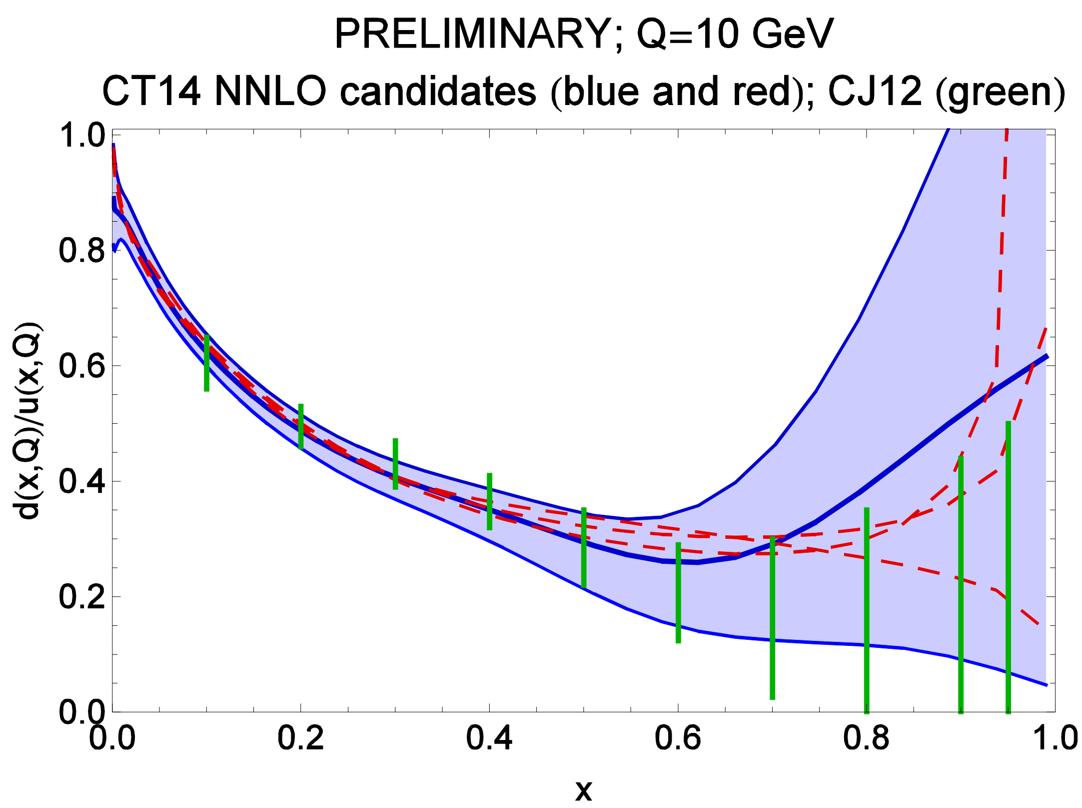
$d(x, Q)/u(x, Q)$ at $x \to 1$



- **Blue: CT10 NNLO**
- **Green: CJ 12 NLO**

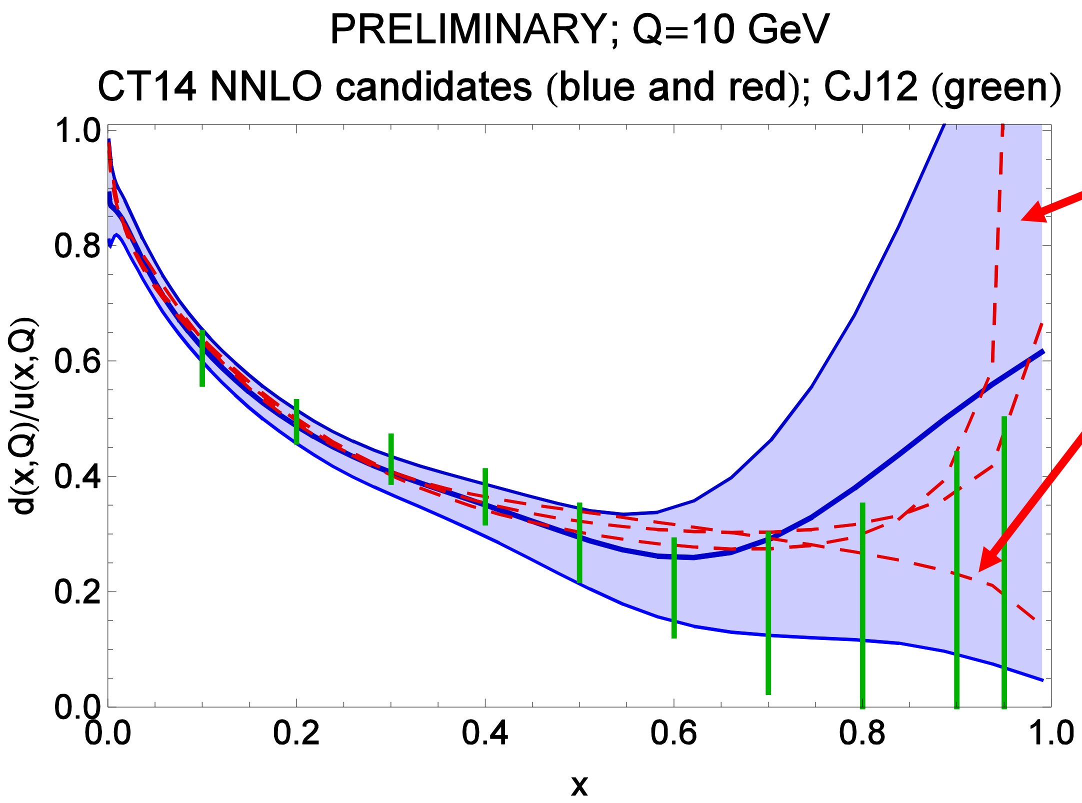
(Owens et al., 1212.1702)

$d(x,Q)/u(x,Q)$ at $x \to 1$



- **Blue and red:** **CT14 NNLO candidates**
- **Green: CJ 12 NLO** (Owens et al., 1212.1702)

$d(x,Q)/u(x,Q)$ at $x \to 1$



CT10-like or…

…spectator counting rules

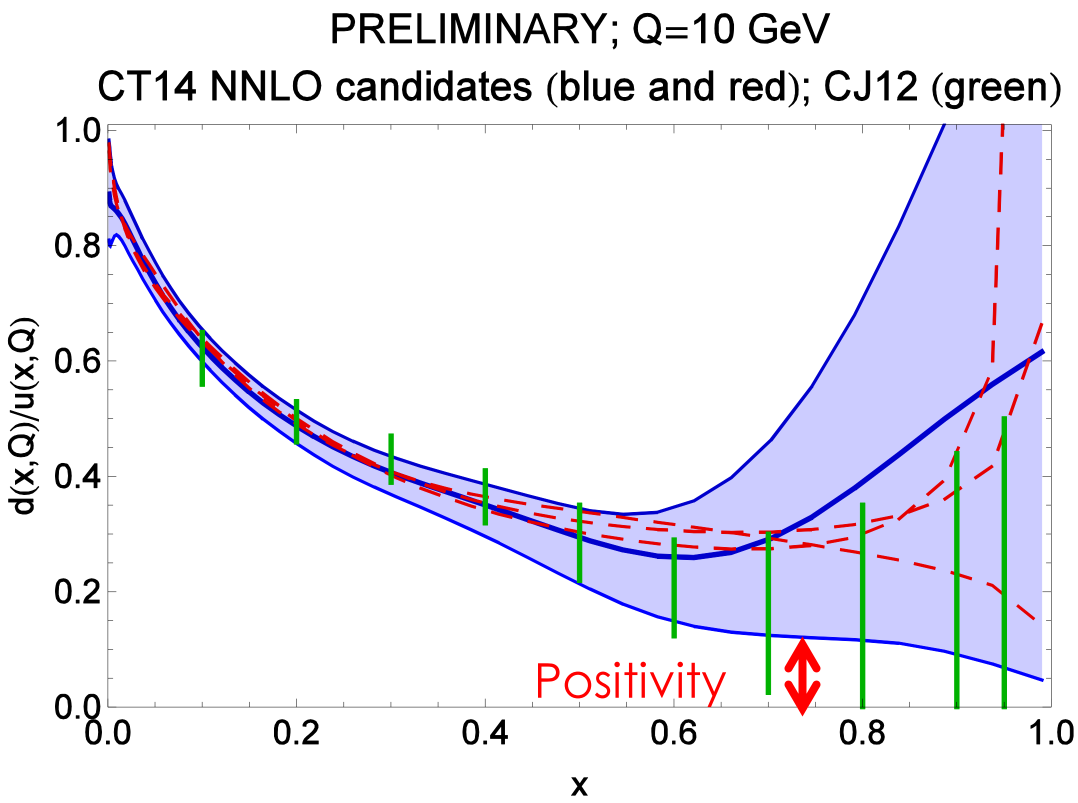
- **Blue and red:**

CT14 NNLO candidates

- **Green: CJ 12 NLO**

(Owens et al., 1212.1702)

$d(x,Q)/u(x,Q)$ at $x \to 1$



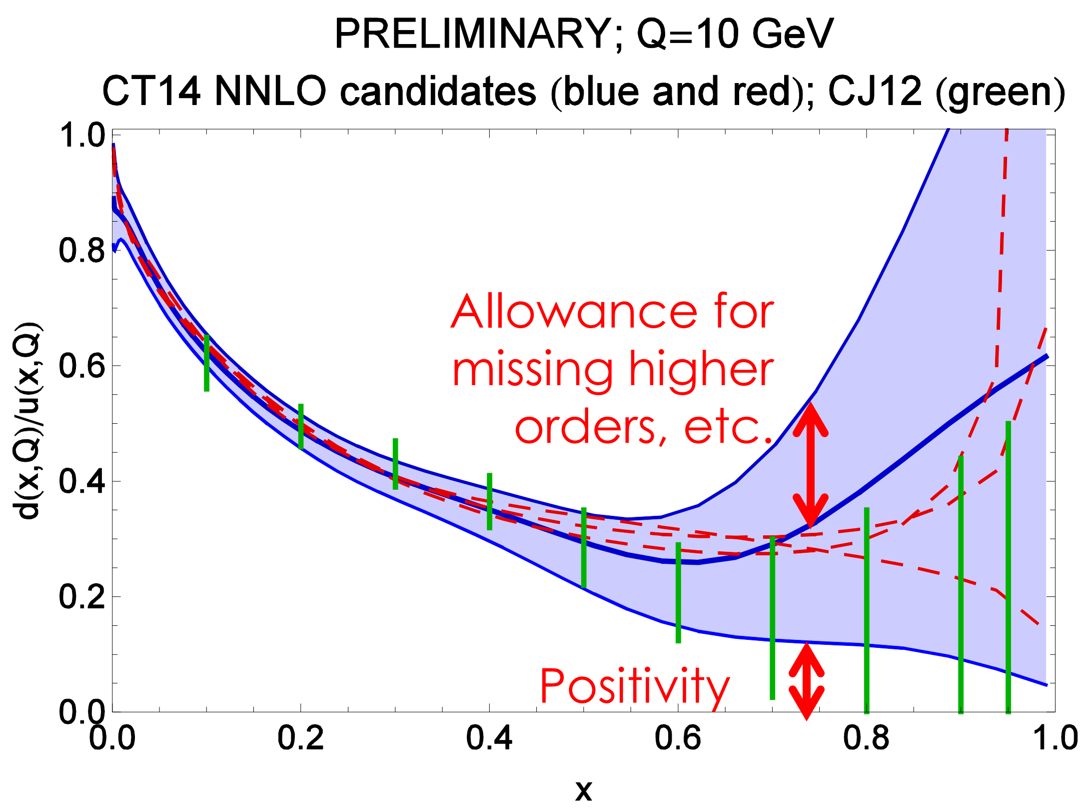
- **Blue and red:**

CT14 NNLO candidates

- **Green: CJ 12 NLO**

(Owens et al., 1212.1702)

$d(x,Q)/u(x,Q)$ at $x \to 1$



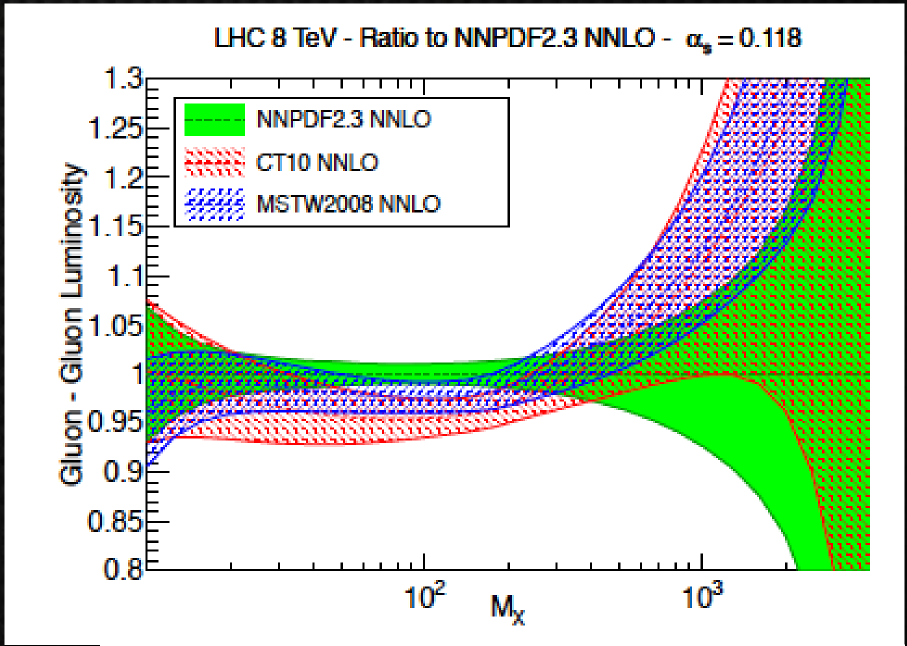
- **Blue and red:** **CT14 NNLO candidates**
- **Green: CJ 12 NLO** (Owens et al., 1212.1702)

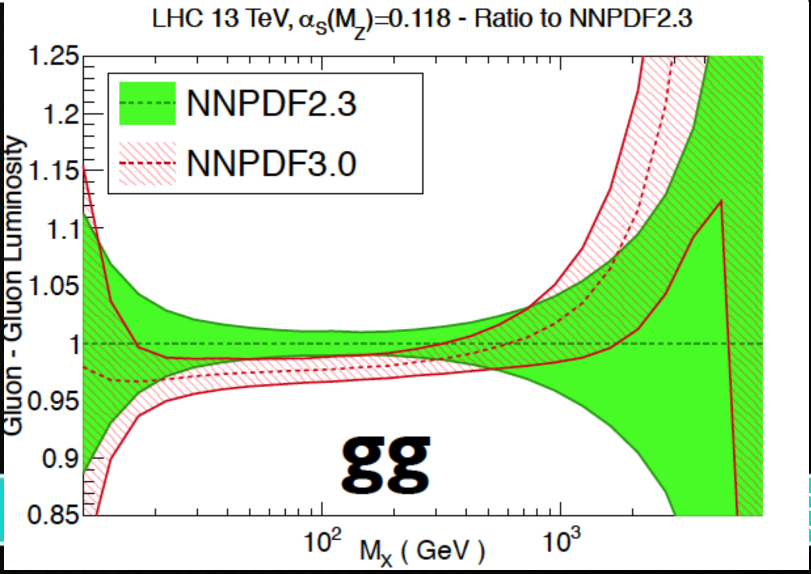
Now to CT14 gluon distribution

- Reminder: CT10 gg luminosity forms lower bound for LHC combination, for m< 400 GeV
  - NNPDF3.0 decreases by 2-3% compared to NNPDF2.3
- CT14 predictions for Higgs cross sections at 8, 14 TeV will increase by 1-1.5%, thus further reducing the size of the envelope (assuming MTXX14 doesn't move much)
  - parameterization, new data
- Top cross sections will increase by roughly 2%

	CT10	CT14
7 TeV	172.5 pb	176.1 pb
8 TeV	246.3 pb	251.3 pb
13 TeV	805.7 pb	819.6 pb

J. Gao top++ m_{top}=173.3 GeV



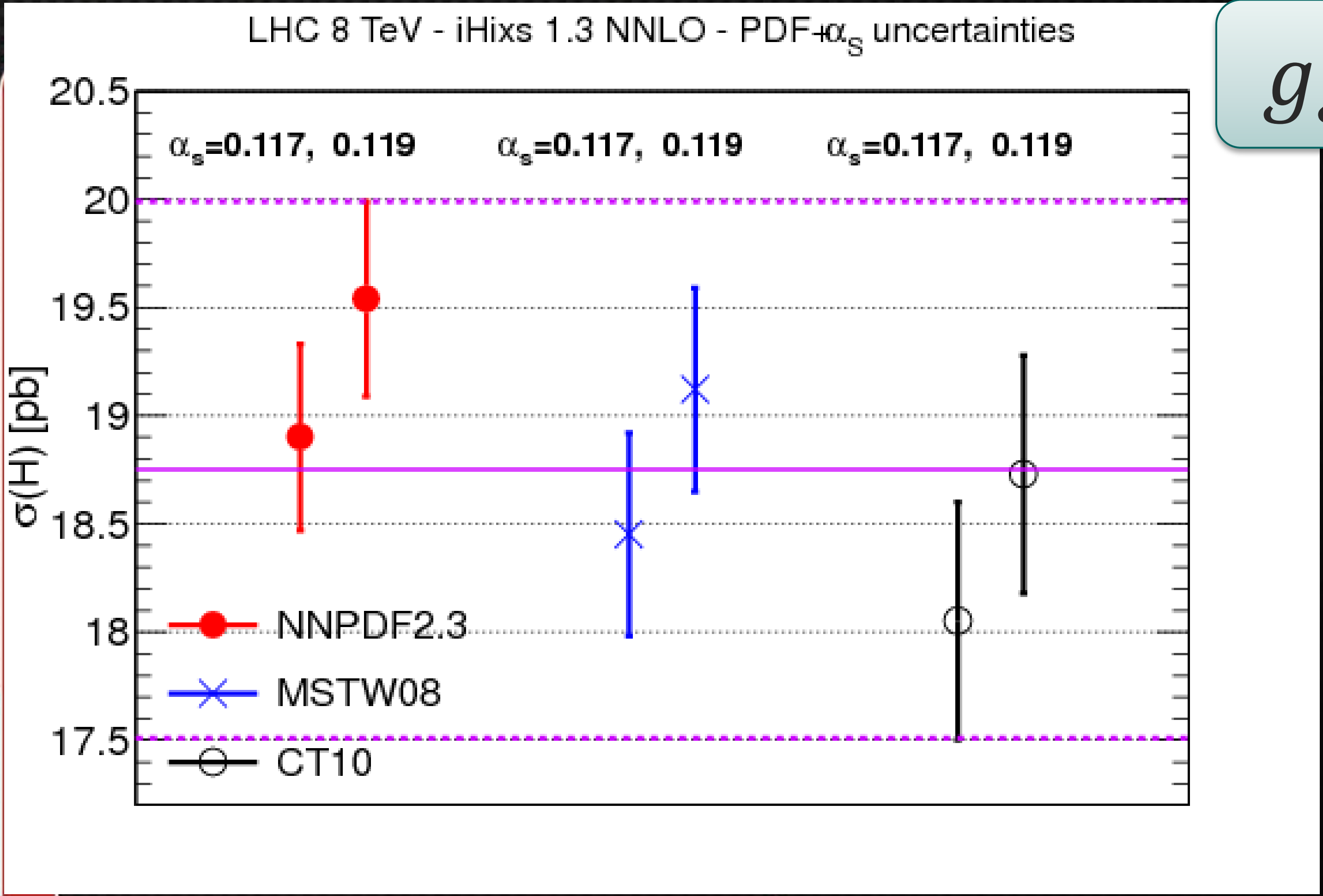


A meta-PDF method for combination of PDF ensembles

Jun Gao, P. N. arXiv:1401.0013,Gao, Huston, P.N., arXiv:1410.xxxx

An alternative to the PDF4LHC convention

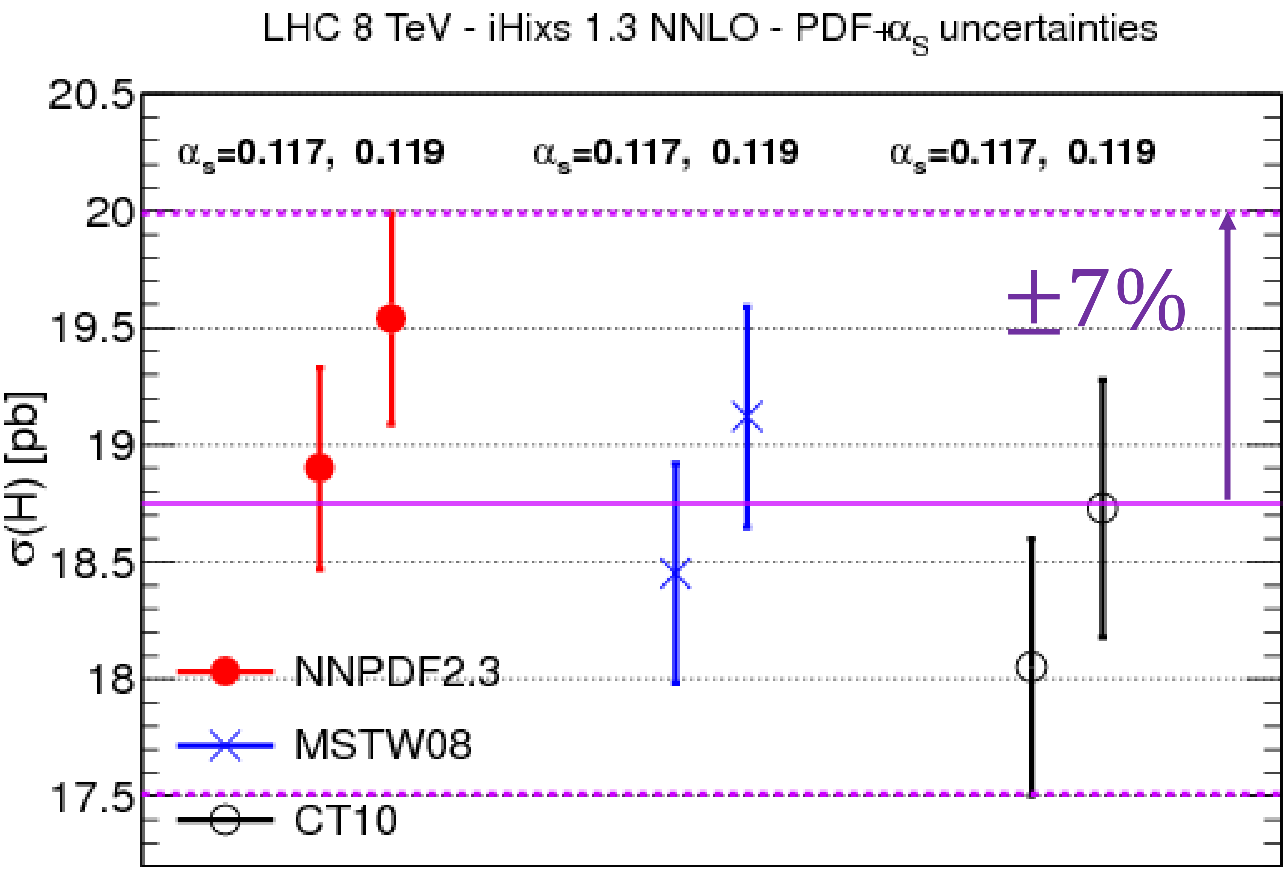
2014: the typical NNLO PDF+α_s uncertainty is larger than 1%



$$gg \to H^0_{SM}$$

R. Ball et al., Parton Distribution benchmarking with LHC data **arXiv:1211.5142**

2014: the typical NNLO PDF+α_s uncertainty is larger than 1%

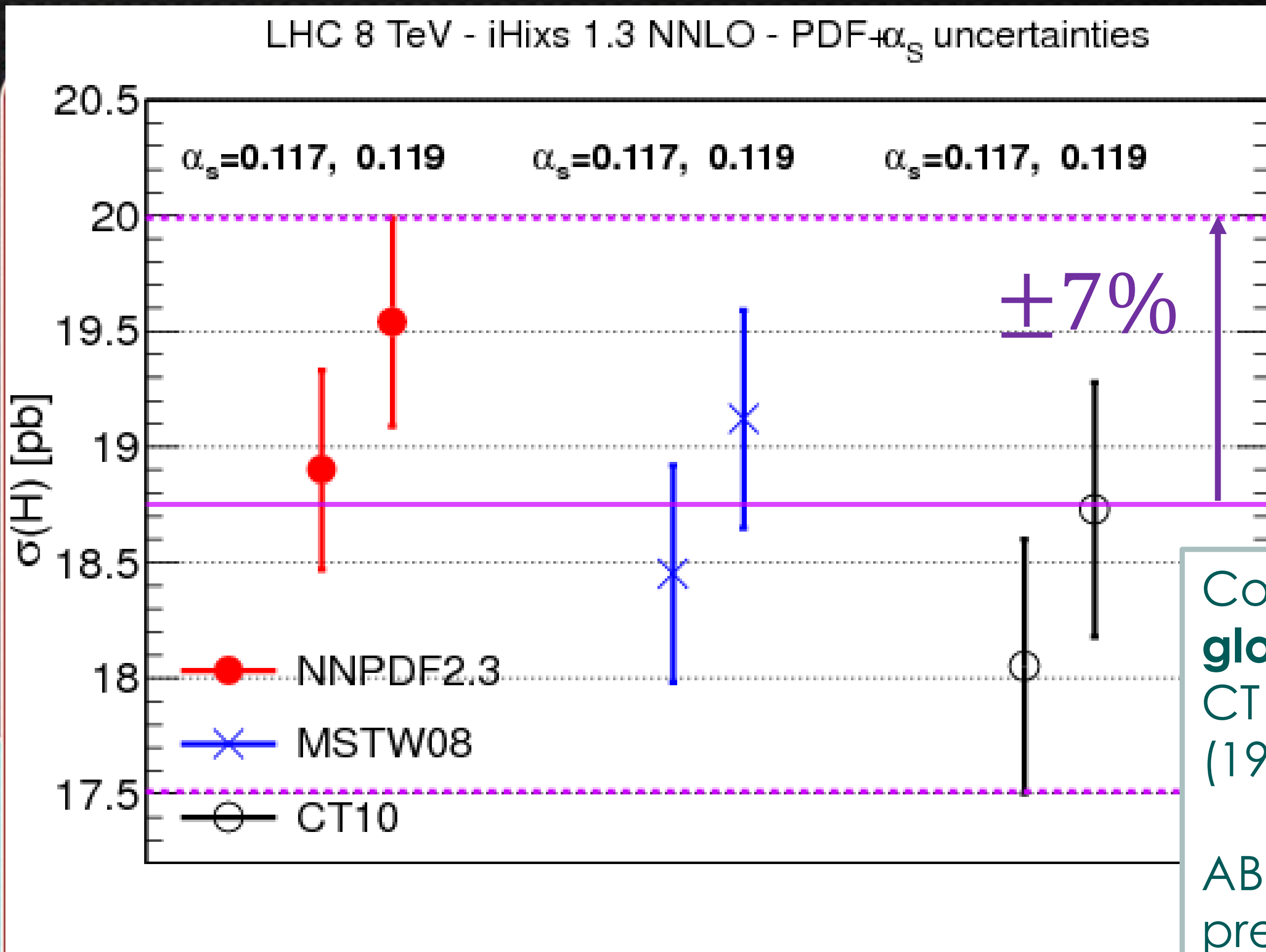


$gg \rightarrow H^0_{SM}$

1σ combined PDF+α_s uncertainty, using PDF4LHC convention (Botje et al., arxiv:1101.0538)

R. Ball et al., Parton Distribution benchmarking with LHC data **arXiv:1211.5142**

2014: the typical NNLO PDF+α_s uncertainty is larger than 1%



$gg \to H^0_{SM}$

1σ combined PDF+α_s uncertainty, using PDF4LHC convention (Botje et al., arxiv:1101.0538)

Combination of three **global** PDF ensembles CT10, MSTW08, NNPDF2.3 (190 error sets)

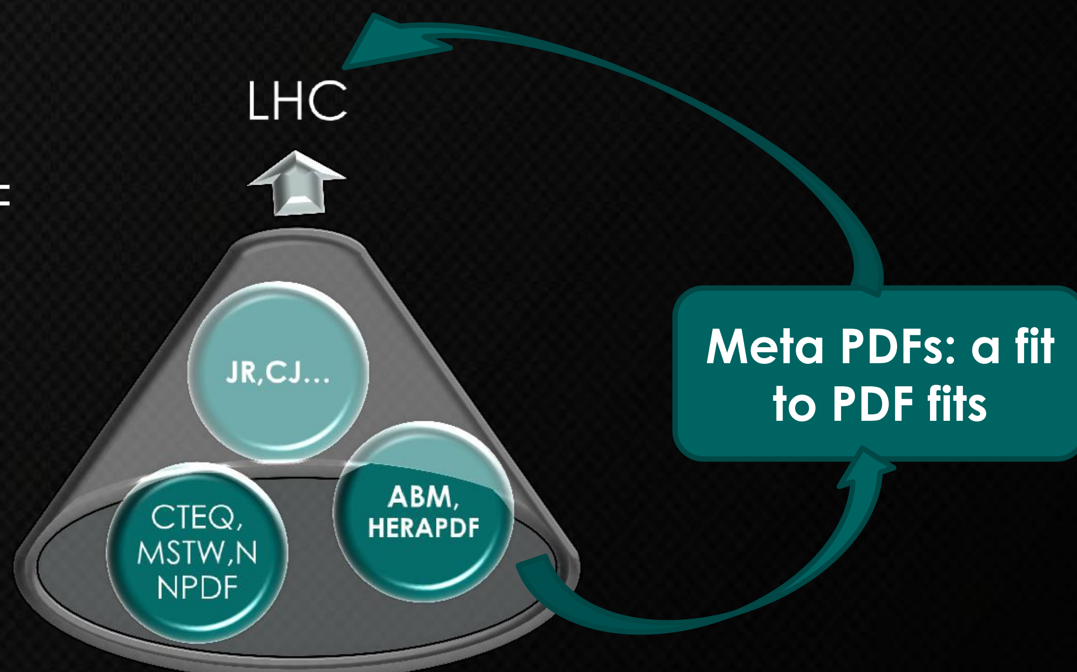
ABM, CJ, GJR, HERA PDF predictions not included

R. Ball et al., Parton Distribution benchmarking with LHC data **arXiv:1211.5142**

What is the PDF meta-analysis?

A meta-analysis compares and combines LHC predictions based on several PDF ensembles. It serves the same purpose as the PDF4LHC prescription. It combines the PDFs directly in space of PDF parameters. It can significantly reduce the number of error PDF sets needed for computing PDF uncertainties and PDF-induced correlations.

The number of input PDF ensembles that can be combined is almost unlimited



META1.0 PDFs: A working example of a meta-analysis

See arXiv:1401.0013 for details

1. Select the input PDF ensembles (CT, MSTW, NNPDF…)
2. Fit each PDF error set in the input ensembles by a common functional form ("**a meta-parametrization**")
3. Generate many Monte-Carlo replicas from meta-parametrizations of each set to investigate the probability distribution on the ensemble of all meta-parametrizations (as in Thorne, Watt, 1205.4024)
4. Construct a final ensemble of 68% c.l. **Hessian eigenvector sets** to propagate the PDF uncertainty from the combined ensemble of replicated meta-parametrizations into LHC predictions.

Only in the META set

Only in the META set

The logic behind the META approach

Emphasize simplicity and intuition

When expressed as the meta –parametrizations, PDF functions can be combined by averaging their meta-parameter values

Standard error propagation is more feasible, e.g., to treat the meta-parameters as discrete data in the linear (Gaussian) approximation for small variations

The Hessian analysis can be applied to the combination of all input ensembles in order to optimize uncertainties and eliminate "noise"

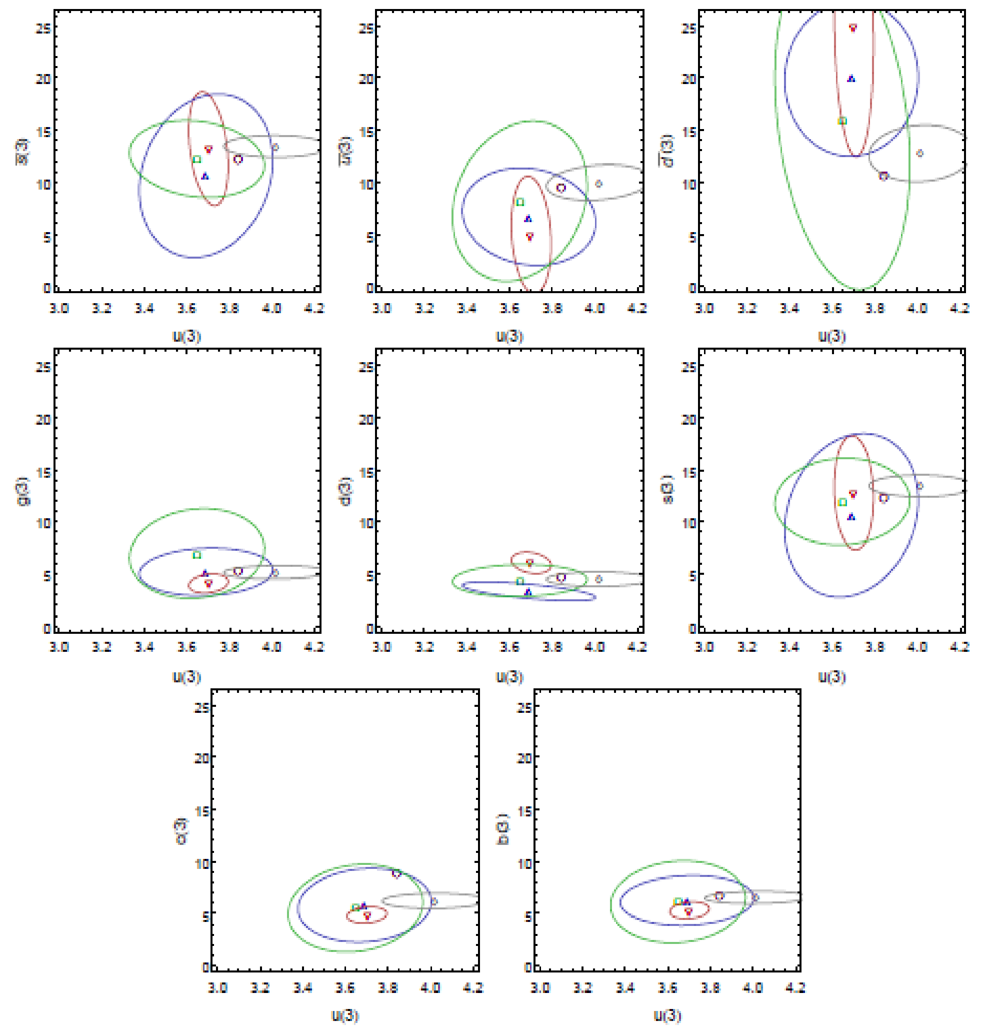


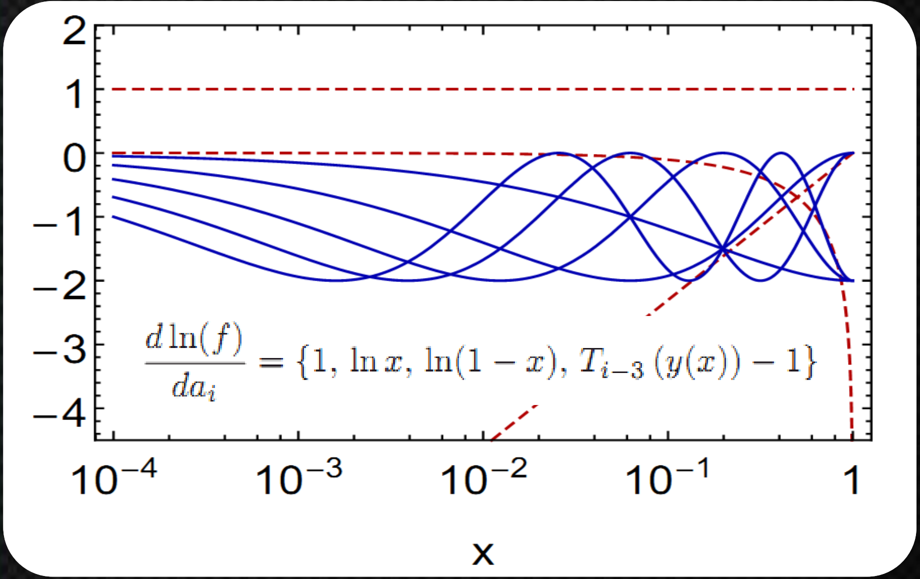
Figure 10: Fitted PDF parameters and 90% c.l. ellipses for CT10 (blue up triangle), MSTW08 (red down triangle), NNPDF2.3 (green square), HERAPDF1.5 (gray diamond) and ABM11 (magenta circle).

The functional form for the meta parametrization

$$f(x, Q_0; \{a\}) = e^{a_1} x^{a_2} (1-x)^{a_3} e^{\sum_{i\geq 4} a_i \,(T_{i-3}(y(x))-1))}$$

J. Pumplin, 0909.5176, A. Glazov, et al., 1009.6170, A. Martin, et al., 1211.1215

The initial scale of DGLAP evolution is Q_0=8 GeV. $T_i(y)$ are Chebyshev polynomials with $y(x)=\cos(\pi x^{\beta})$ and β=1/4.



The input PDFs are fitted by this form in the x regions covered by the experimental data.

Outside these x regions, the PDFs are determined by extrapolation.

Merging PDF ensembles

The ensembles can be merged by averaging their meta-parameters. For CT10, MSTW, NNPDF ensembles, unweighted averaging is reasonable, given their similarities.

For any parameter a_i , ensemble g with N_{rep} initial replicas:

$$\langle a_i \rangle_g = \frac{1}{N_{rep}} \sum_{k=1}^{N_{rep}} a_i(k),$$

Central value on g

$$\mathrm{cov}(a_i, a_j)_g = \frac{N_{rep}}{N_{rep}-1} \langle (a_i - \langle a_i \rangle_g) \cdot (a_j - \langle a_j \rangle_g) \rangle_g,$$

$$(\delta a_i)_g = \sqrt{\mathrm{cov}(a_i, a_i)_g}.$$

Standard deviation on g

Reduction of the error PDFs

The number of final error PDFs can be much smaller than in the input ensembles

In the META1.0 study:
200 CT, MSTW, NNPDF error sets

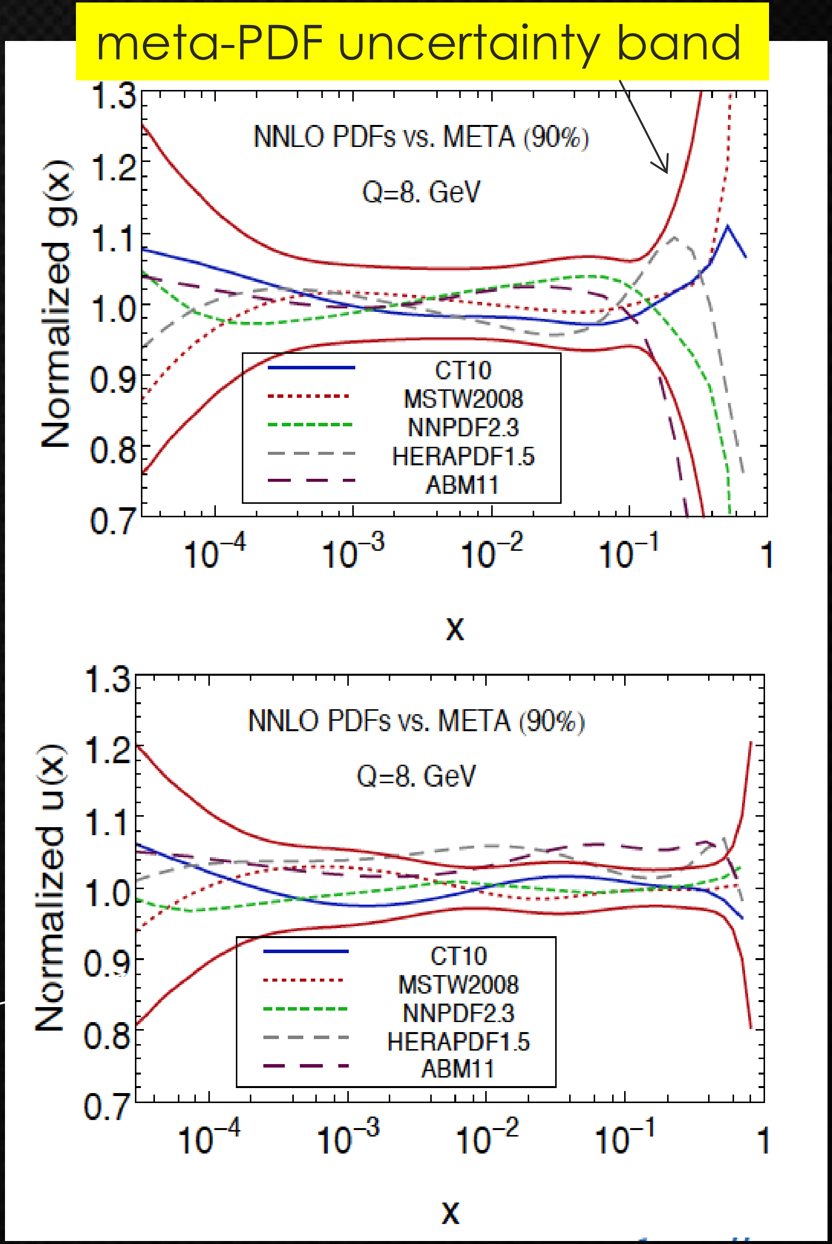
⇒ 300 MC replicas for reconstructing the combined probability distribution

⇒ 100 Hessian META sets for most LHC applications (**general-purpose** ensemble META1.0)

⇒ 13 META sets for LHC Higgs production observables (**reduced ensemble** META LHCH)

General-purpose META PDF ensemble

- 50 eigenvectors (100 error sets) provide a very good representation of the PDF uncertainties for all of the 3 PDF error families above
- The META PDFs provide both an average of the chosen central PDFs, as well as a good estimation of the 68% c.l. total PDF uncertainty
- Can re-diagonalize the Hessian matrix to get 1 orthogonal eigenvector to get the α_s uncertainty (H.-L. Lai et al., **1004.4624**)



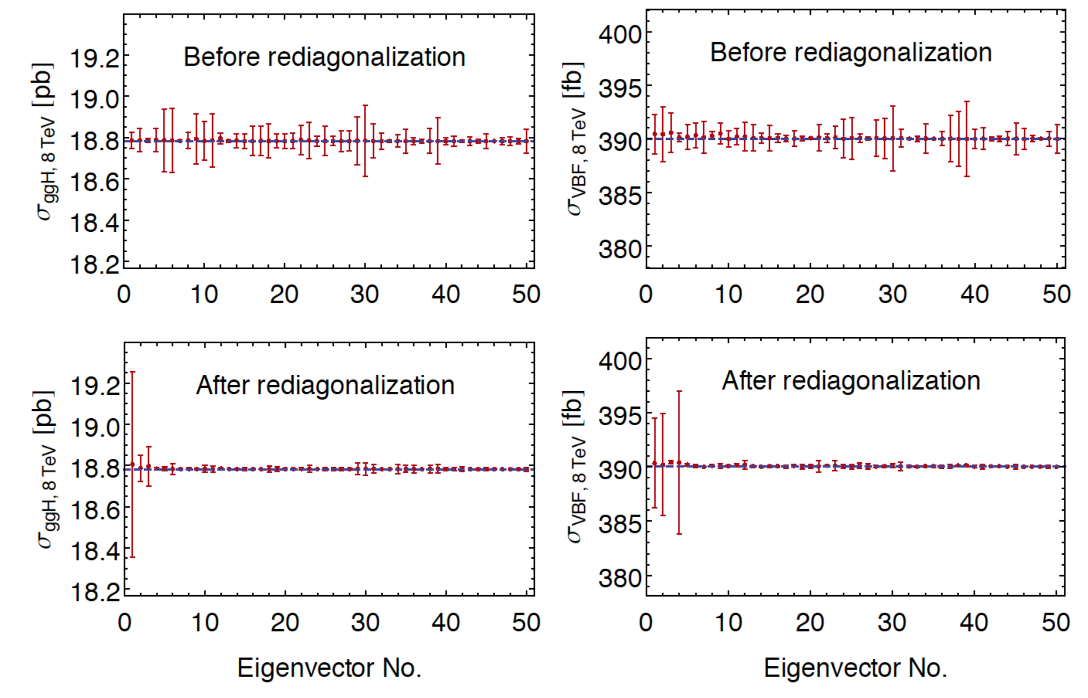
Reduced META ensemble

- Already the general-purpose ensemble reduced the number of error PDFs needed to describe the LHC physics; but we can further perform a data set diagonalization to pick out eigenvector directions important for Higgs physics or another class of LHC processes
- Select global set of Higgs cross sections at 8 and 14 TeV (46 observables in total; more can be easily added if there is motivation)

production channel	$\sigma(inc.)$	$\sigma(\lvert y_H \rvert > 1)$	$\sigma(p_{T,H} > m_H)$	scales
$gg \to H$	iHixs1.3 [32] at NNLO	MCFM6.3 [33] at LO	—	m_H
$b\bar{b} \to H$	iHixs at NNLO	—	—	m_H
VBF	VBFNLO2.6 [34] at NLO	same	same	m_W
HZ	VHNNLO1.2 [35] at NNLO	CompHEP4.5 [36] at LO	CompHEP at LO	$m_Z + m_H$
$HW^\pm$	VHNNLO at NNLO	—	—	$m_W + m_H$
HW^+	CompHEP at LO	same	same	$m_W + m_H$
HW^-	CompHEP at LO	same	same	$m_W + m_H$
$H + 1jet$	MCFM at LO	same	same	m_H
$Ht\bar{t}$	MCFM at LO	CompHEP at LO	CompHEP at LO	$2m_t + m_H$
HH	Hpair [37] at NLO	—	—	$2m_H$

Data set diagonalization (Pumplin, 0904.2424)

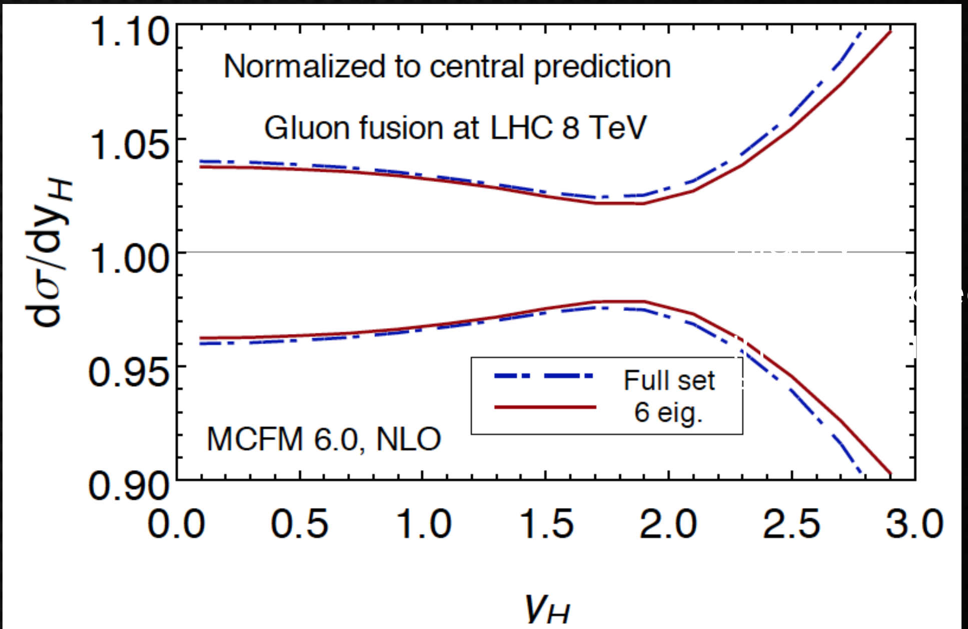
- There are 50 eigenvectors, but can rediagonalize the Hessian matrix to pick out directions important for the Higgs observables listed on previous page; with rotation of basis, 50 important eigenvectors become 6

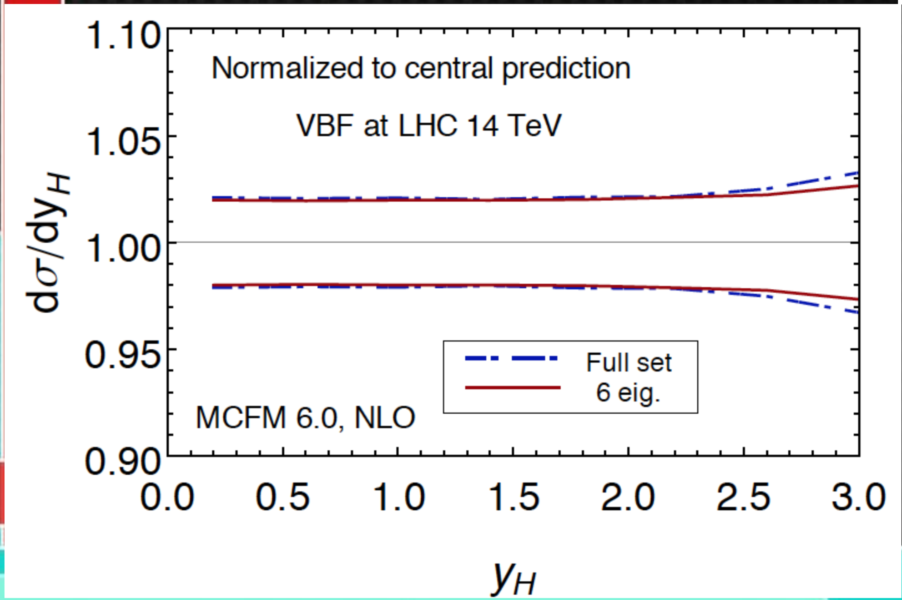


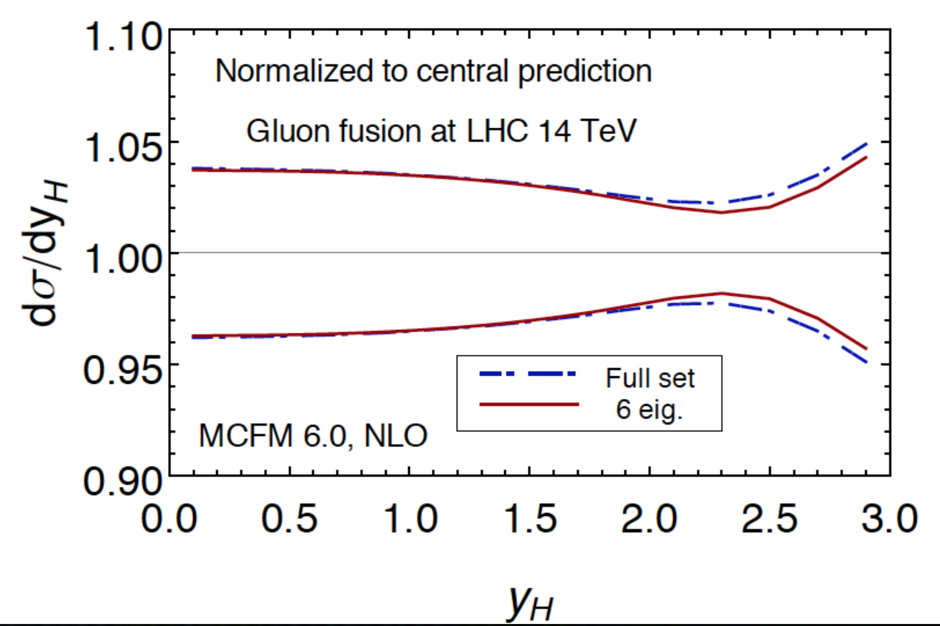
J. Gao,
J. Huston
P. Nadolsky
(in progress)

Higgs eigenvector set

- The reduced META eigenvector set does a good job of describing the uncertainties of the full set for *typical* processes such as ggF or VBF
- But actually does a good job in reproducing PDF-induced correlations and describing those LHC physics processes in which $g,\ \bar{u},\ \bar{d}$ drive the PDF uncertainty (see next slide)







process	$\sigma_{cen.}$	δ_{Full}	$\delta_{Diag.}$	$\sigma^{\alpha_s}_{0.116}$	$\sigma^{\alpha_s}_{0.12}$
$gg \to H$ [pb]	18.77	$^{+0.48}_{-0.46}$	$^{+0.48}_{-0.44}$	18.11	19.4
	43.12	$^{+1.13}_{-1.07}$	$^{+1.13}_{-1.04}$	41.68	44.6
VBF [fb]	302.5	$^{+7.8}_{-6.7}$	$^{+7.6}_{-6.7}$	303.1	301.
	878.2	$^{+19.7}_{-17.9}$	$^{+19.2}_{-17.3}$	877.3	878.
HZ [fb]	396.3	$^{+8.4}_{-7.3}$	$^{+8.1}_{-7.4}$	393.0	399.
	814.3	$^{+14.8}_{-13.2}$	$^{+13.8}_{-13.0}$	806.5	823.
$HW^{\pm}$ [fb]	703.0	$^{+14.4}_{-14.4}$	$^{+14.3}_{-14.1}$	697.4	708.
	1381	$^{+28}_{-22}$	$^{+26}_{-22}$	1368	139
HH [fb]	7.81	$^{+0.33}_{-0.30}$	$^{+0.33}_{-0.30}$	7.50	8.10
	27.35	$^{+0.78}_{-0.72}$	$^{+0.78}_{-0.68}$	26.48	28.2
$t\bar{t}$ [pb]	248.4	$^{+9.1}_{-8.2}$	$^{+9.2}_{-8.1}$	237.1	259.
	816.9	$^{+21.4}_{-19.6}$	$^{+21.4}_{-18.4}$	785.5	848.
$Z/\gamma^*(l^+l^-)$ [nb]	1.129	$^{+0.025}_{-0.023}$	$^{+0.024}_{-0.023}$	1.113	1.14
	1.925	$^{+0.043}_{-0.041}$	$^{+0.040}_{-0.037}$	1.897	1.95
$W^+(l^+\nu)$ [nb]	7.13	$^{+0.14}_{-0.14}$	$^{+0.14}_{-0.13}$	7.03	7.25
	11.64	$^{+0.24}_{-0.23}$	$^{+0.22}_{-0.21}$	11.46	11.8
$W^-(l^-\bar{\nu})$ [nb]	4.99	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	4.92	5.08
	8.59	$^{+0.21}_{-0.20}$	$^{+0.19}_{-0.18}$	8.46	8.74
W^+W^- [pb]	4.14	$^{+0.08}_{-0.08}$	$^{+0.08}_{-0.07}$	4.04	4.20
	7.54	$^{+0.15}_{-0.14}$	$^{+0.14}_{-0.12}$	7.39	7.57
ZZ [pb]	0.703	$^{+0.016}_{-0.014}$	$^{+0.015}_{-0.014}$	0.695	0.71
	1.261	$^{+0.026}_{-0.024}$	$^{+0.024}_{-0.022}$	1.256	1.27
W^+Z [pb]	1.045	$^{+0.019}_{-0.018}$	$^{+0.019}_{-0.017}$	1.039	1.06
	1.871	$^{+0.033}_{-0.031}$	$^{+0.029}_{-0.027}$	1.850	1.89
W^-Z [pb]	0.788	$^{+0.020}_{-0.019}$	$^{+0.019}_{-0.018}$	0.780	0.79
	1.522	$^{+0.034}_{-0.032}$	$^{+0.033}_{-0.031}$	1.509	1.54

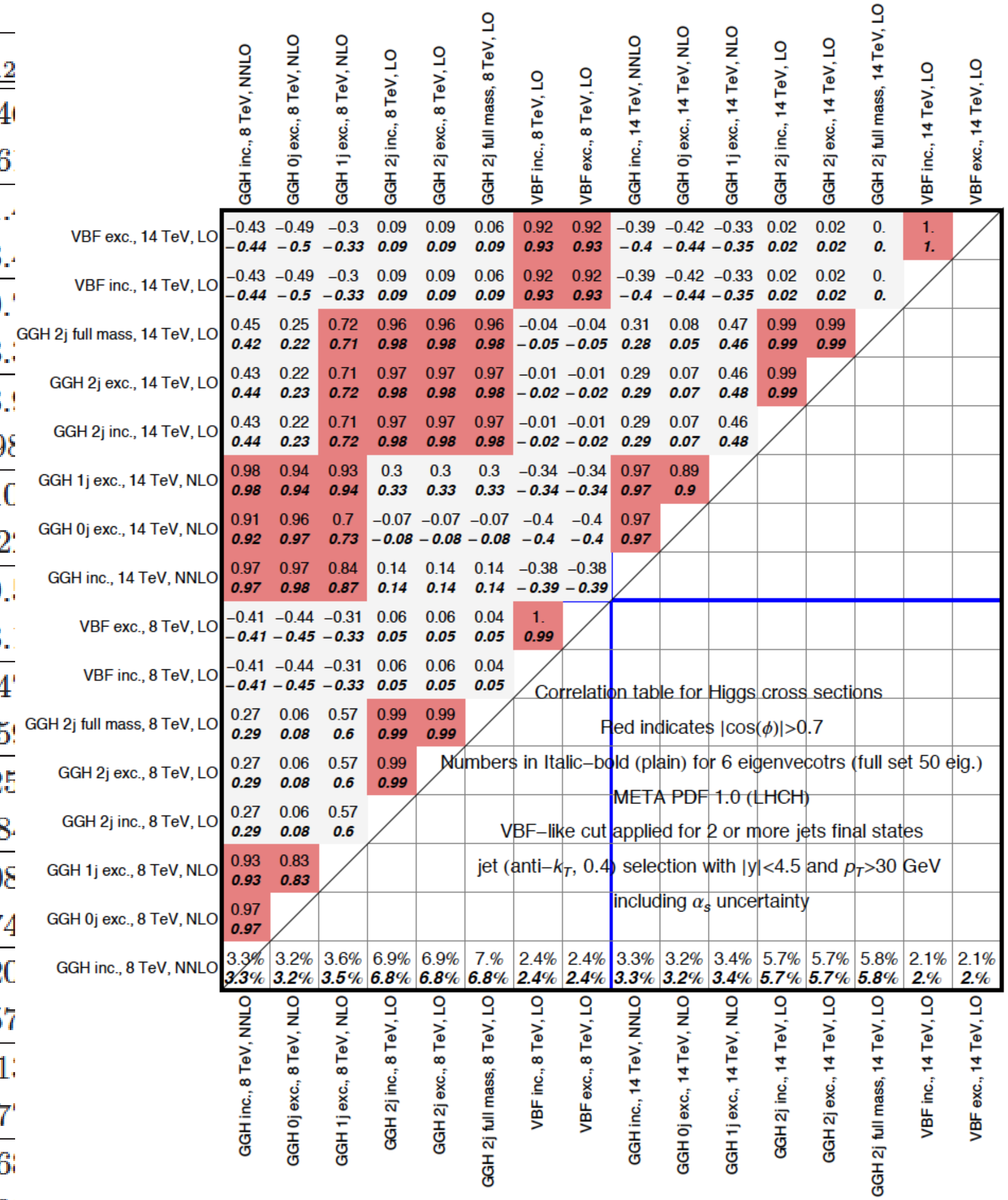


FIG. 7: Same as Fig. 5, with α_s uncertainties included by adding in quadrature.

To summarize, the meta-parametrization and Hessian method facilitate the combination of PDF ensembles even when the MC replicas are introduced at the intermediate stage

Benefits of the meta-parametrization

- The PDF parameter space of all input ensembles is visualized explicitly.
- Data combination procedures familiar from PDG can be applied to each meta-PDF parameter

To summarize, the meta-parametrization and Hessian method facilitate the combination of PDF ensembles even when the MC replicas are introduced at the intermediate stage

Benefits of the Hessian method

- It is very effective in data reduction, as it makes use of diagonalization of a semipositive-definite Hessian matrix in the Gaussian approximation. [The unweighting of MC replicas is both more detailed and nuanced.]
- Correlations between Higgs signals and backgrounds are reproduced with just 13 META PDFs. It remains to be seen how many MC replicas will be needed to reproduce the correlations in the MC compression approach.

Back-up slides

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Meta-parameters of 5 sets and META PDFs

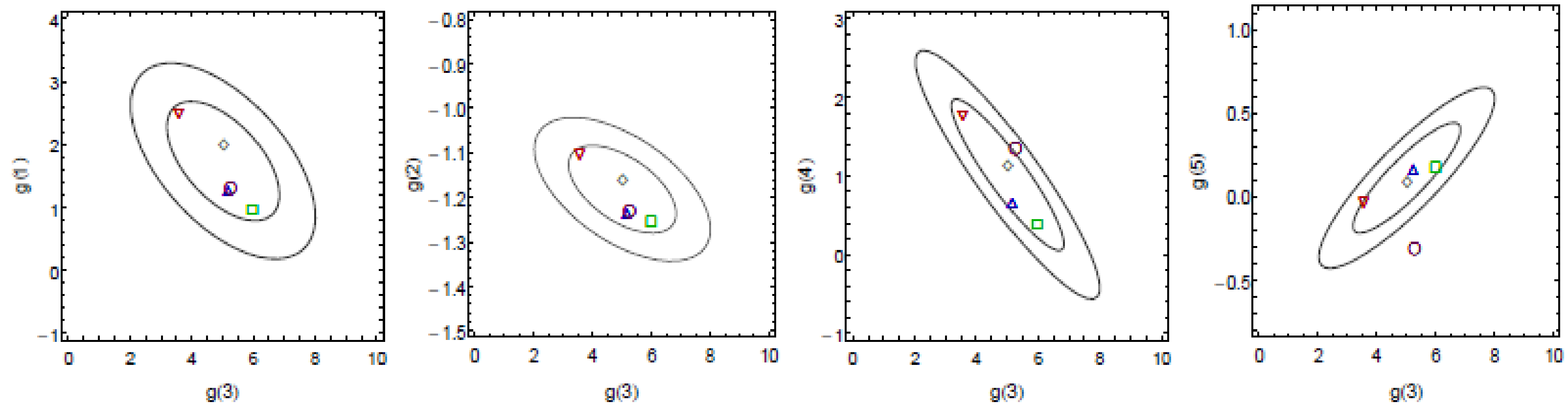


Figure 16: Comparison of META PDF confidence intervals with central NNLO PDFs of the input PDF ensembles in space of meta-parameters a_{1-5} for the gluon PDF. Up triangle, down triangle, square, diamond, and circle correspond to the best-fit PDFs from CT10, MSTW, NNPDF, HERAPDF, and ABM respectively. The ellipses correspond to 68 and 90% c.l. ellipses of META PDFs.

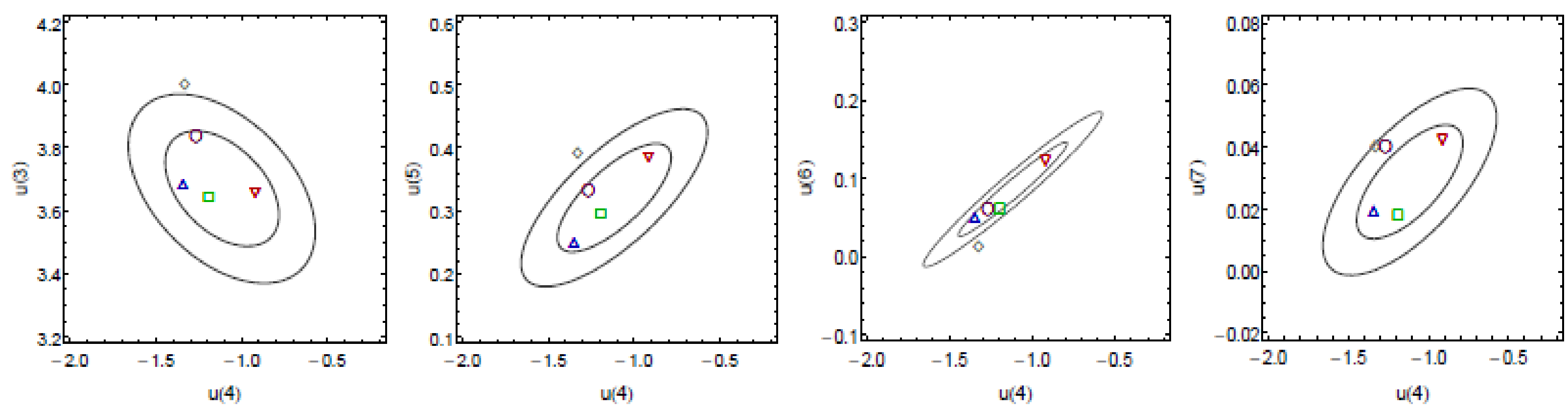
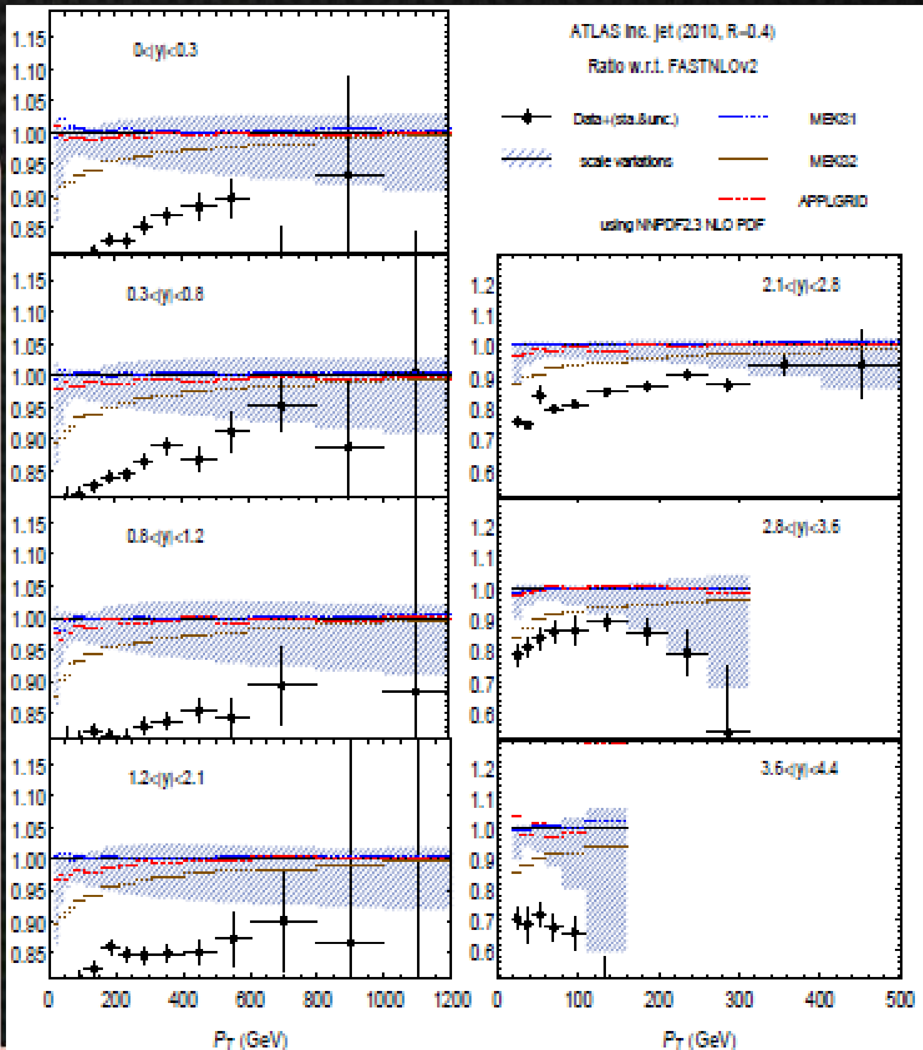


Figure 17: Same as Fig. 16, for a_{3-7} of the u quark PDF.

Advanced NLO predictions for incl. jet production



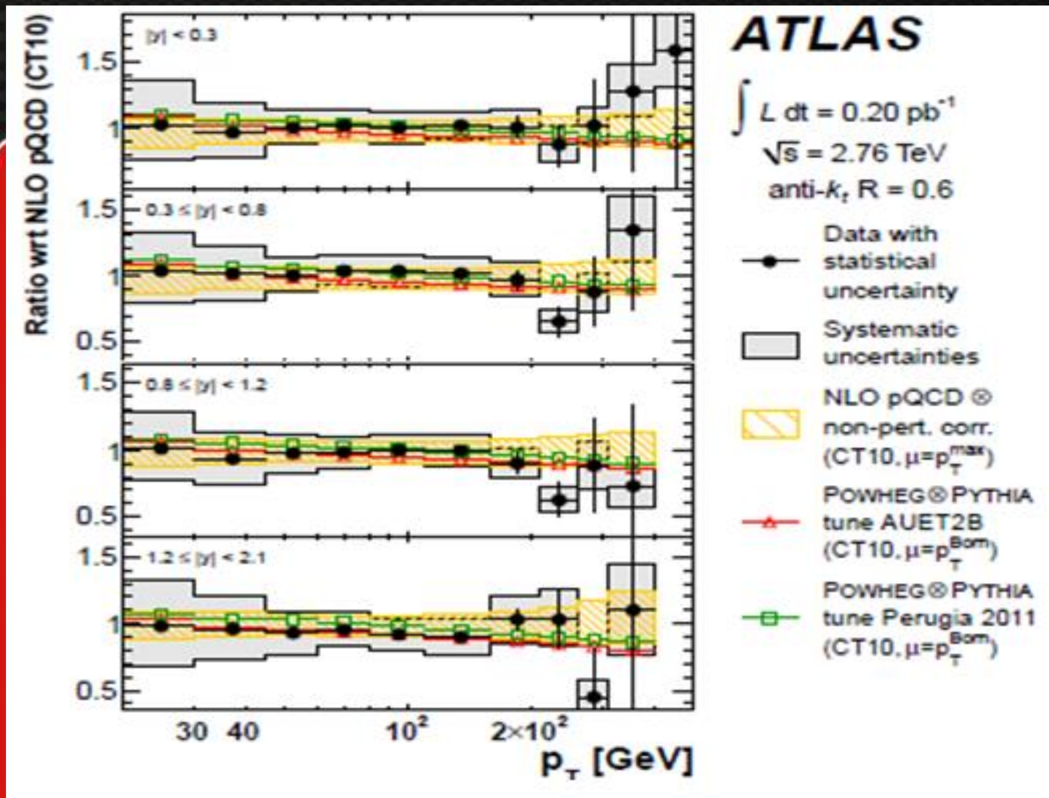
The need to have reliable predictions for LHC (di)jet production for PDF analysis inspired revisions/tuning of NLO theory calculations.

Through various tests, independent NLO codes (**NLOJet++/ApplGrid/FastNLO** and **MEKS**) **AND** NLO event generators (**MC@NLO** and **Powheg, slide 2**) were brought into excellent agreement (non-trivial!)

The range of scale uncertainty was determined

Jun Gao et al., arXiv: 1207.0513; Ball et al., 1211.5142

Advanced NLO predictions for incl. jet production



P. Starovoitov, DIS'2013

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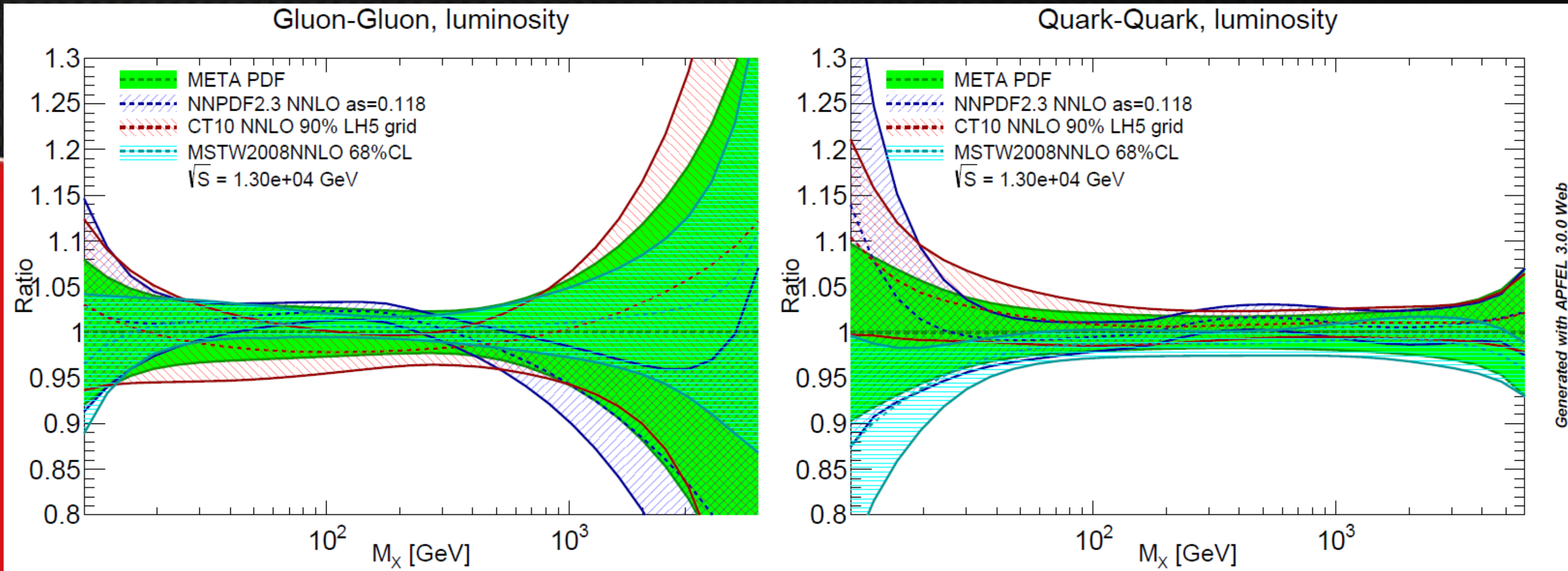
Benchmark comparisons of DIS cross sections

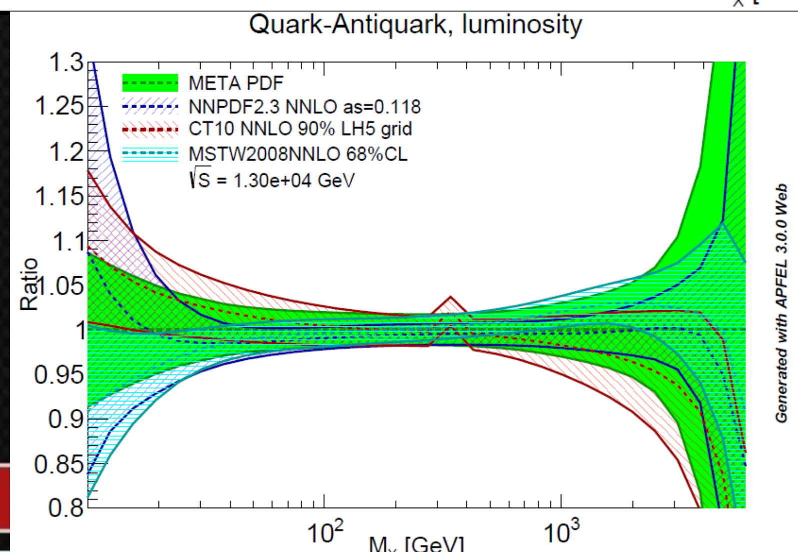
2013 Les Houches Proceedings, arXiv:1405.1067, p. 37 and 56

1. Detailed studies of reduced cross sections $\sigma^{\pm}_{r,NC}$ and structure functions $F_{1,2}$ from CT, HERA, MSTW, NNPDF
   - for neutral-current DIS (published), charged-current DIS (in progress)
   - at LO, NLO, and NNLO
   - separately for light quarks and heavy quarks
   - with Les Houches toy PDFs
   - in various heavy-quark schemes

2. Fits to HERA data only, using 4 fitting codes
   - with native and varied PDF parametrizations
   - with various Q cuts
   - with various treatment of systematic errors
   - with varied heavy-quark masses

Some parton luminosities





Plots are made with APFEL WEB (apfel.mi.infn.it; Carrazza et al., 1410.5456)

PDFs for sea quarks