PDF Summary

Robert Thorne

August 27th 2018

University College London

Dresden – Aug 2018

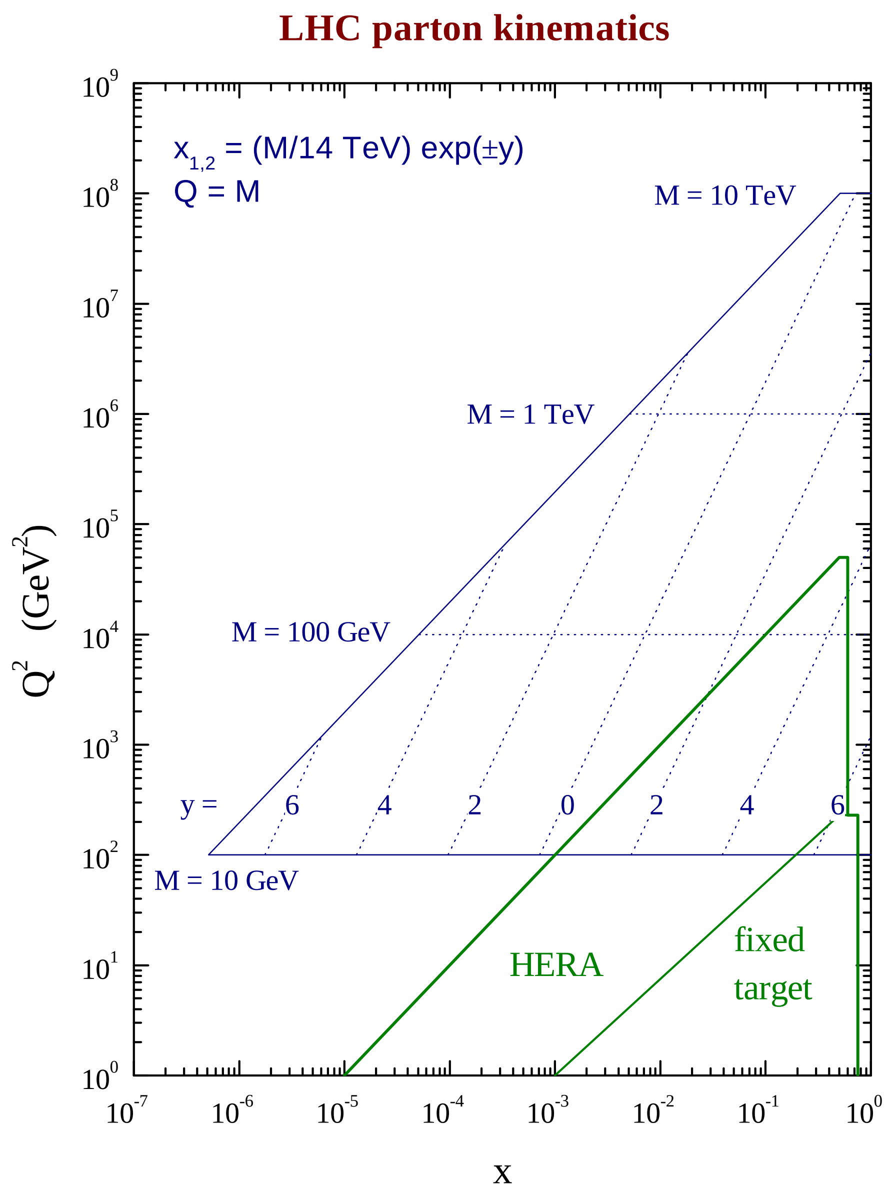
LHC **Physics**

The kinematic range for particle production at the LHC is shown.

$x_{1,2} = x_0 \exp(\pm y), \quad x_0 = \frac{M}{\sqrt{s}}$.

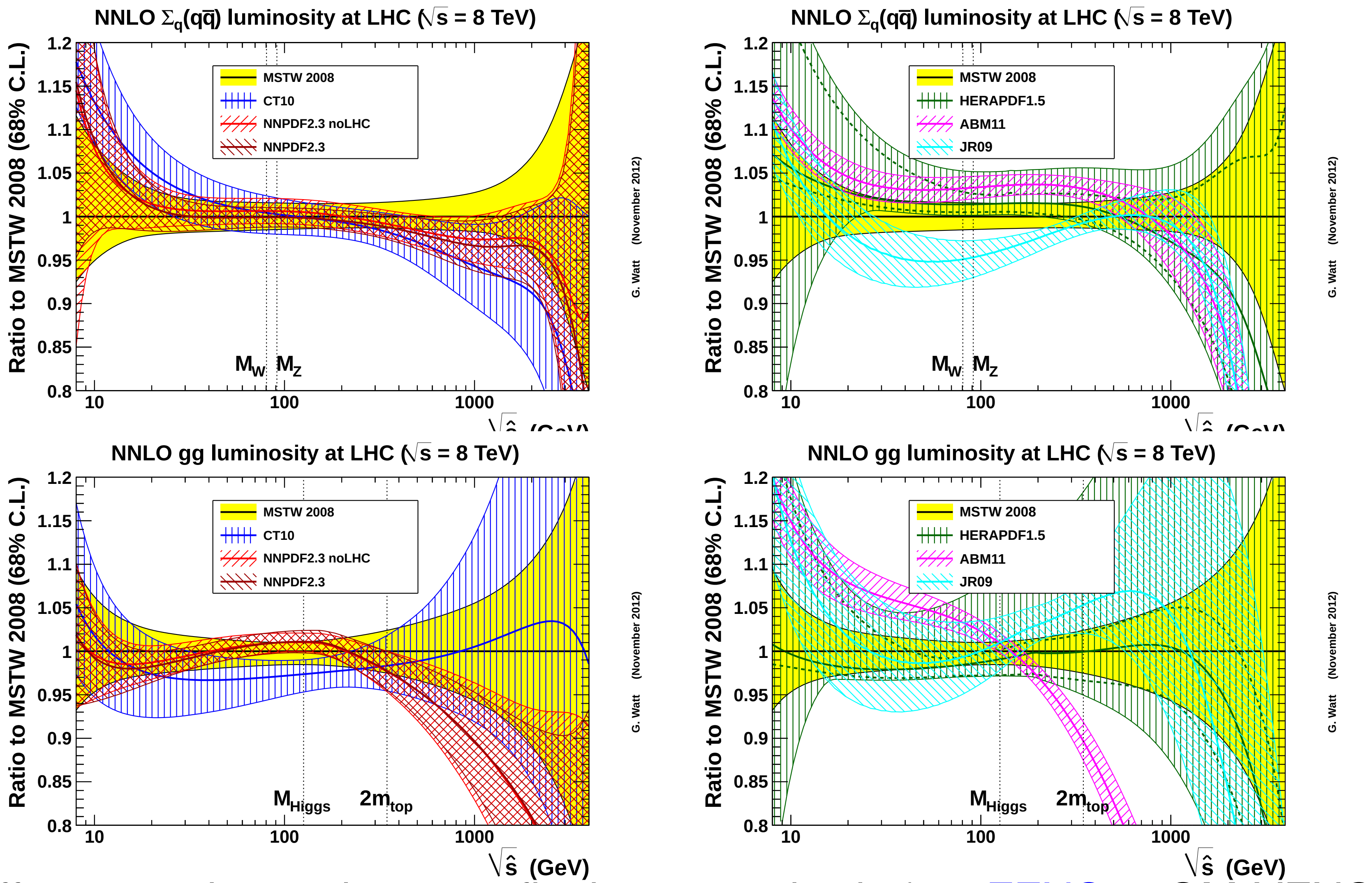
$x \sim 0.001 - 0.01$ parton distributions therefore vital for understanding standard production processes at the LHC.

However, even smaller (and higher) x required when one moves away from zero rapidity, e.g. when calculating total cross-sections.



Comparisons between different sets.

From a few years ago when LHC data started appearing. Watt



Differences due to data sets fit, theory methods (e.g FFNS or GM-VFNS for heavy flavour. Updates in the past few years have led to changes.

PDF Updates

ABM12 PDFs – Include combined HERA charm DIS data, and ATLAS, CMS, LHCb Drell-Yan data, and improved DIS charged current description at $Q^2 \gg m_c^2$. Also investigate top pair production data.

CT14 PDF sets - changes due to new data sets – including ATLAS, CMS LHCb W, Z data and initial ATLAS, CMS inclusive jet data. Also **new parameterisation** – Bernstein polynomials - peak at specific x.

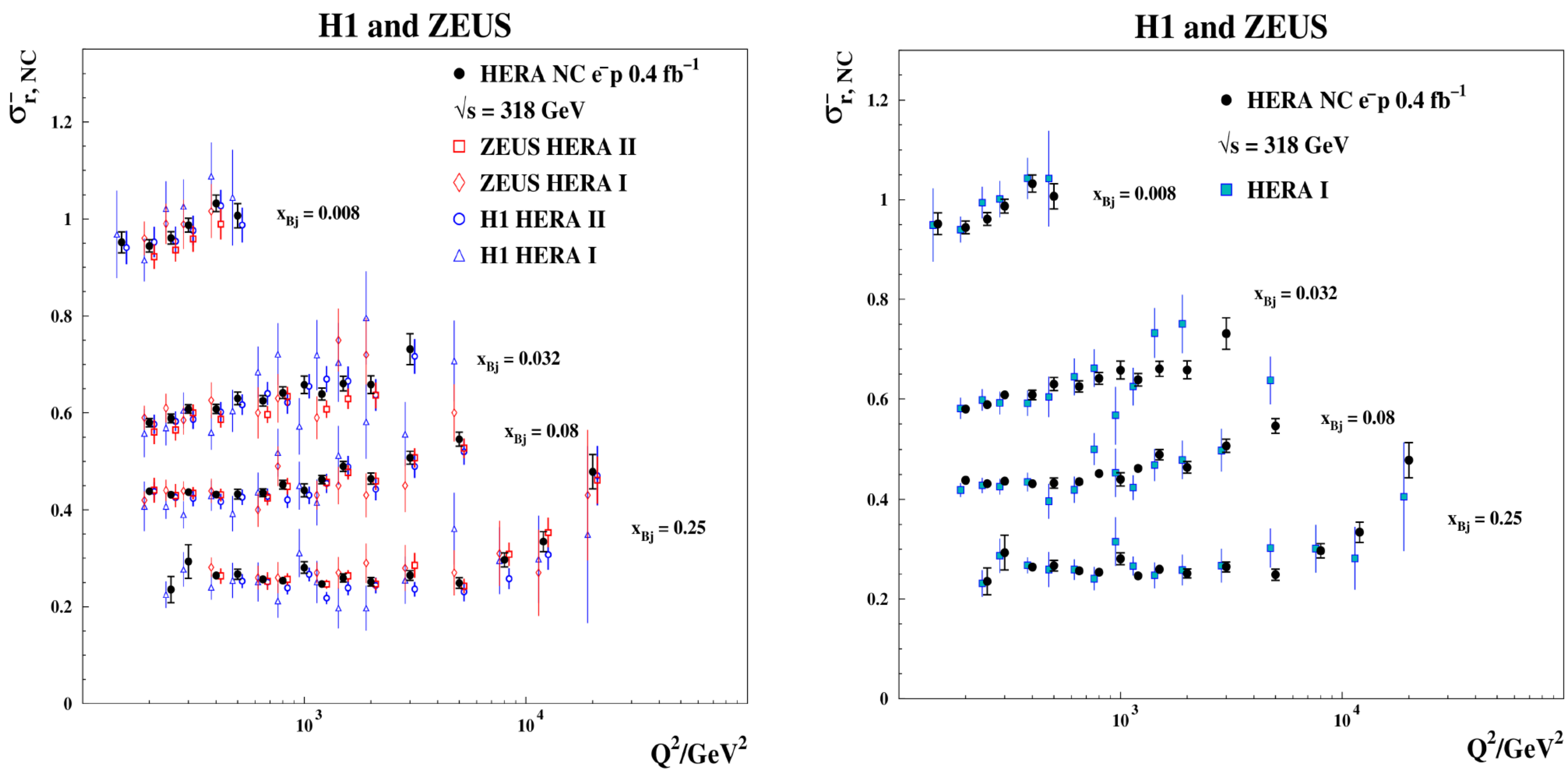
NNPDF3.0 PDFs – newer HERA data (also on charm), initial ATLAS, CMS inclusive jet data, ATLAS, CMS LHCb $W, Z, W + c, W p_T$ data and top pair production data. Also significant **improved methodology** - closure test improved procedures in finding best fit using their procedure, i.e. inputs to algorithm, training length *etc.*

MMHT2014 – Changes in theoretical procedures – parameterisation with Chebyshev polynomials, freedom in deuteron nuclear corrections; "optimal" GM-VFNS choice; improved D-meson branching ratio with error which feeds into PDFs. **Changes in data sets** - updates of HERA data and Tevatron data LHC data on W,Z top pair production data. 25 eigenvector pairs, rather than the 20 in MSTW.

Developments soon after.

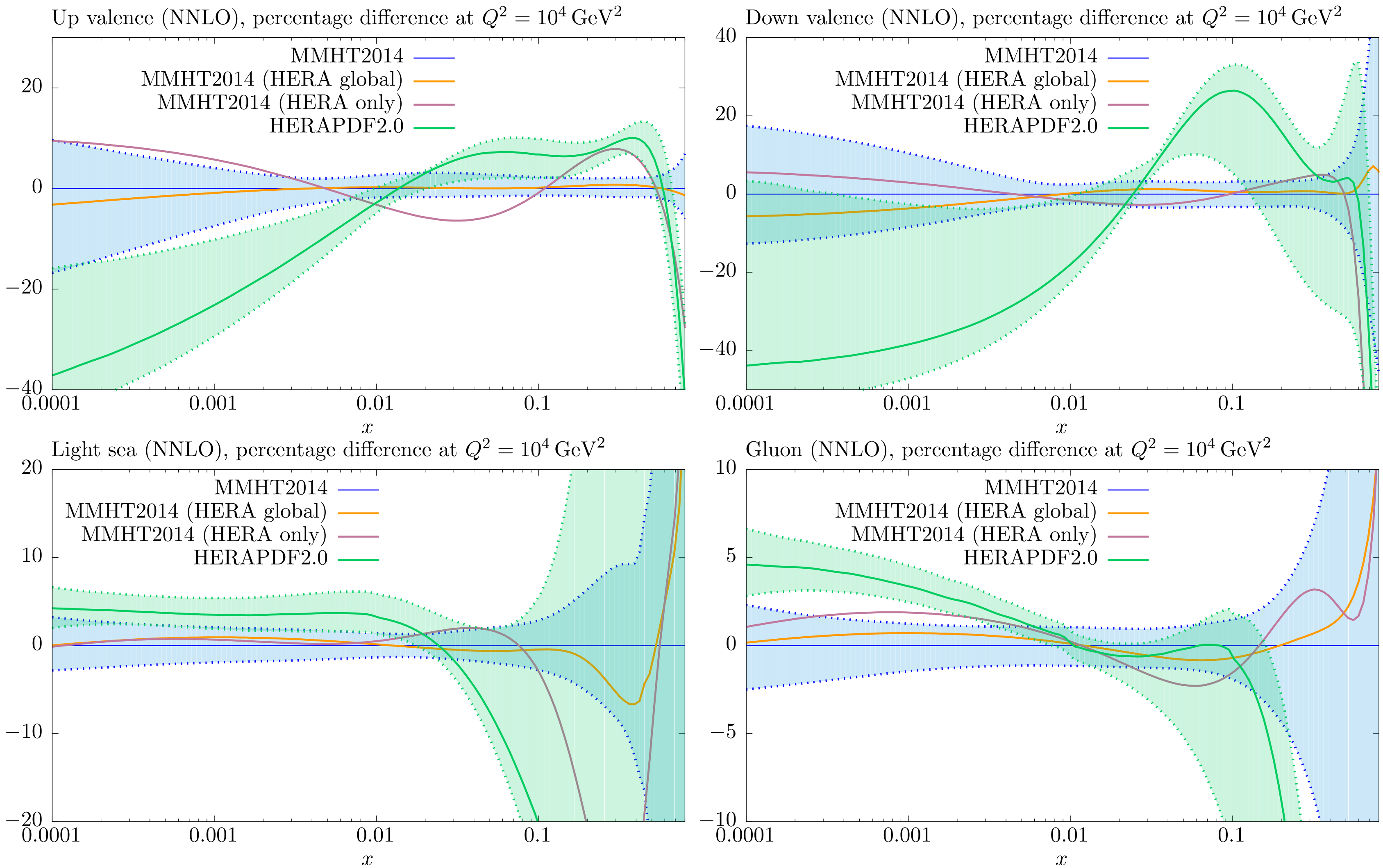
HERAI+II combination data.

Averaged cross sections: NC e⁻p



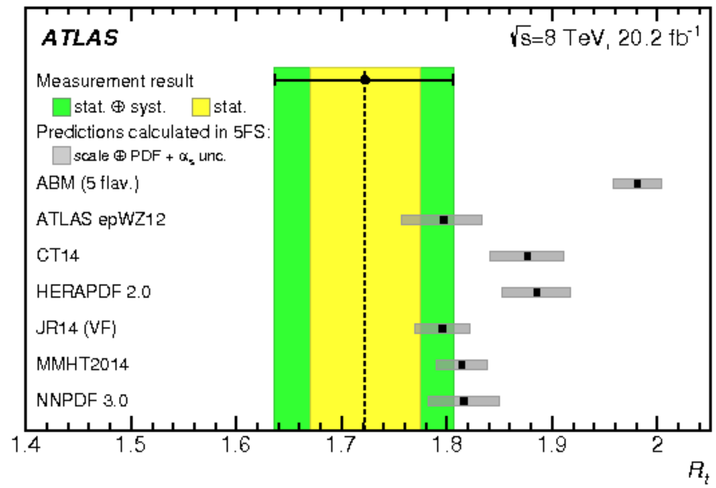
Makes HERAPDF PDFS more precise, but in general a bit further from other PDFs in some places, e.g high-x up quark.

HERA II Combined data in other PDFs

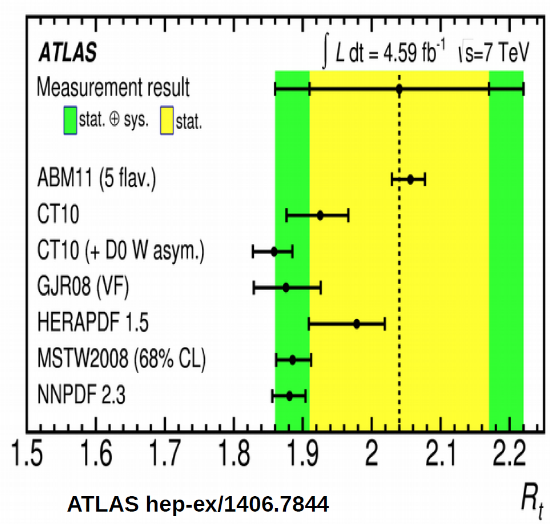


Updated PDFs very well within MMHT2014 uncertainties. PDFs from HERA II data only fit in some ways similar to HERAPDF2.0.

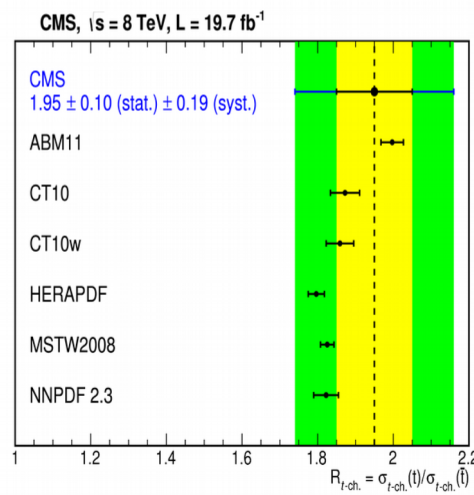
$x \sim 0.2$ enhancement in up quark preferred by HERA e^- charged-current data in tension with recent most accurate measurement of single top ratio (different to older, but less precise measurements).



Also disfavours any other reason for enhanced $u(x)/d(x)$ for $x \sim 0.1$.

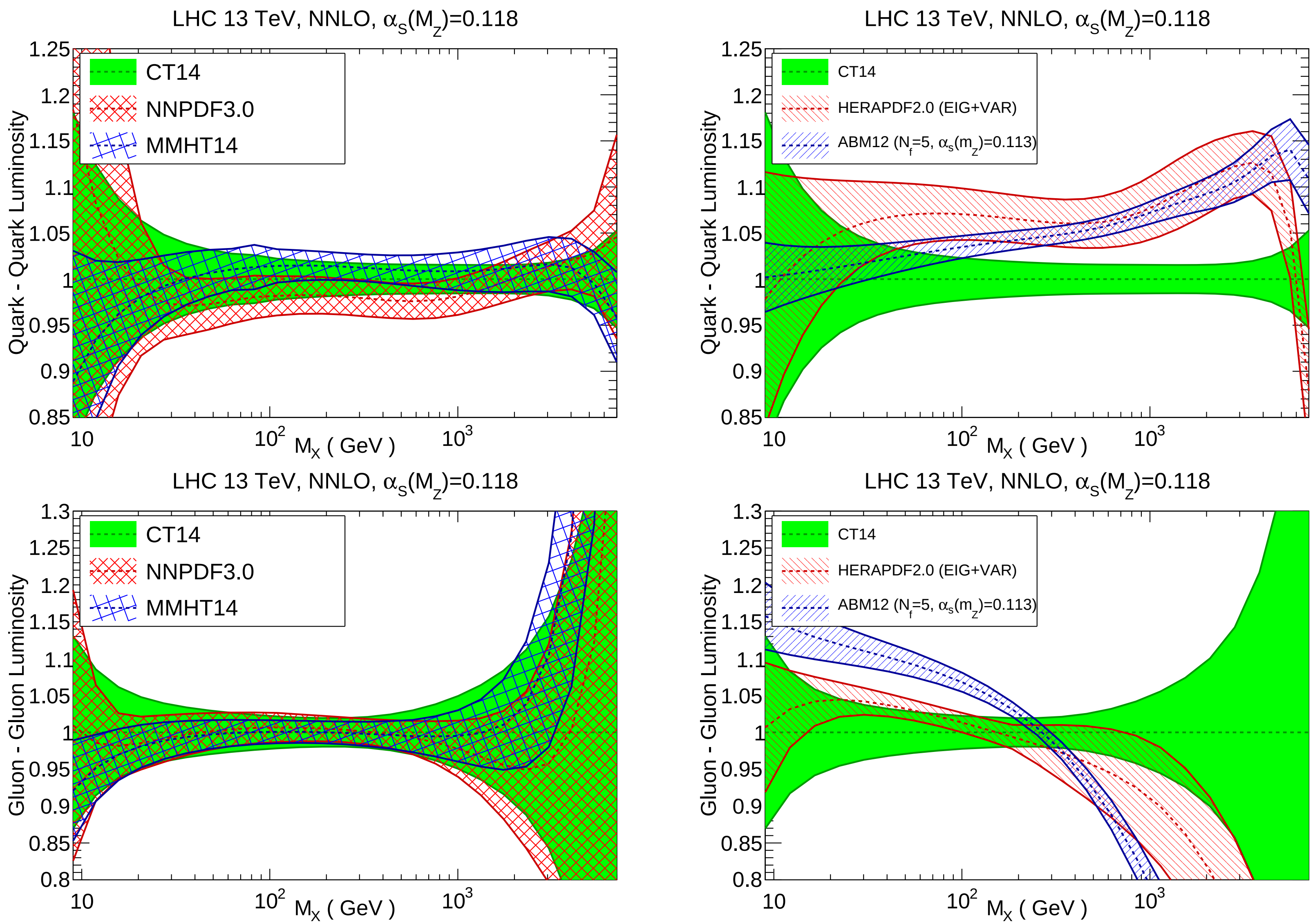


ATLAS hep-ex/1406.7844



CMS hep-ex/1403.7366

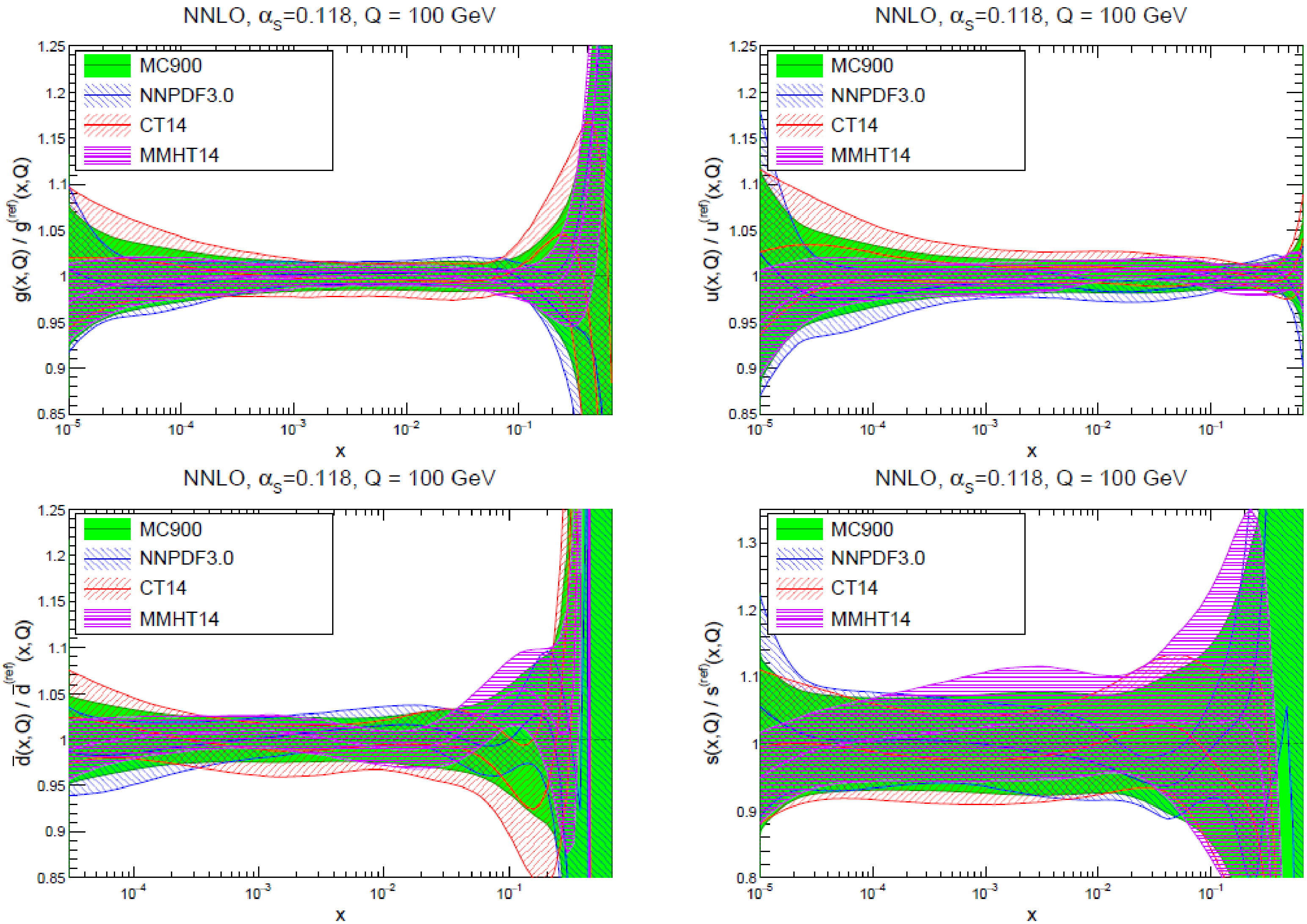
Comparison of state-of-the-art PDFs (late 2015)



Some good agreement between CT14, MMHT2014 and NNPDF3.0.

Some differences in some PDF sets in central values and uncertainty.

Comparison of Combination of CT, MMHT, NNPDF using "Monte Carlo" sets to the Individual PDFs



Works well if PDFs are fairly compatible.

The PDF4LHC Prescription

Perform a Monte Carlo combination of the included PDF sets.

Sets entering into the combination must satisfy requirements, i.e. be compatible for combination. $\alpha_S(M_Z^2) = 0.118$

Deliver a single combined PDF set - either Monte Carlo or Hessian form for combined PDF.

– Monte Carlo - A set of PDF replicas is delivered. The mean is the central value and the standard deviation the uncertainty.

– Hessian - A central set and eigenvectors representing orthogonal sources of uncertainty are delivered. Uncertainty obtained by summing each uncertainty source in quadrature.

In each case a single combined set at both $\alpha_S(M_Z^2) = 0.1165$ and $\alpha_S(M_Z^2) = 0.1195$ is provided to give $\alpha_S(M_Z^2)$ uncertainty (i.e. $\Delta\alpha_S(M_Z^2) = 0.118$) to be added in quadrature with other uncertainties.

Alternative Viewpoint put forward Eur.Phys.J. C76 (2016) no.8, 471.

Recommendations for PDF usage

Two distinct cases are considered:

I. Precision theory predictions, a class of predictions, either within or beyond SM

Recommendation: Use the individual PDF sets ABM12, CJ15, CT14, JR14, HERAPDF2.0, MMHT14 and NNPDF3.0 (or as many as possible), together with the respective uncertainties for the chosen PDF set, the strong coupling $\alpha_s(M_Z)$ and the heavy quark masses m_c, m_b and m_t.

II. Other theory predictions

Recommendation: Use any one of the PDF sets listed in `LHAPDF(v6)`.

Note: the recent developments in modern tools often allow to include different PDFs in the theory calculations via *reweighting* methodology (i.e. weights from different PDFs stored on event basis)

→ allows to evaluate effects from different PDFs in efficient way

The fit ingredients

DATA:

- DIS NC/CC inclusive (HERA I+II added, no deuteron data included)
- DIS NC charm production (HERA)
- DIS CC charm production (HERA, NOMAD, CHORUS, NuTeV/CCFR)
- fixed-target DY
- LHC DY distributions (ATLAS, CMS, LHCb)
- t-quark data from the LHC and Tevatron
- deuteron data are excluded

QCD:

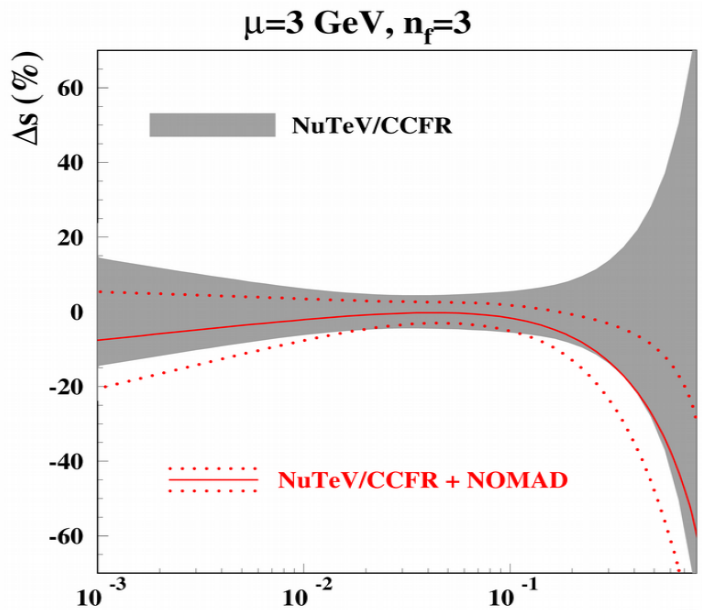
- NNLO evolution
- NNLO massless DIS and DY coefficient functions
- NLO+ massive DIS coefficient functions (**FFN scheme**)
  - – NLO + NNLO(approx.) corrections for NC
  - – NNLO CC at Q>> m_c
  - – running mass
- NNLO exclusive DY (FEWZ 3.1)
- NNLO inclusive ttbar production (pole / running mass)
- Relaxed form of (dbar-ubar) at small x

Power corrections in DIS:

- target mass effects
- dynamical twist-4 terms

Alekhin PDF4LHC 2017

NOMAD charm data



NOMAD NPB 876, 339 (2013)

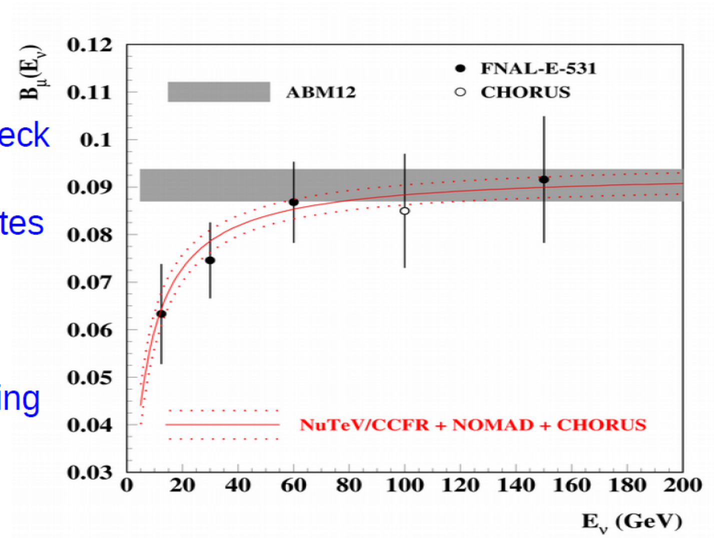
- The data on ratio 2μ/incl. CC ratio with the 2μ statistics of 15000 events (much bigger than in earlier CCFR and NuTeV samples).
- Systematics, nuclear corrections, etc. cancel in the ratio
- Pull down strange quarks at x>0.1 with a sizable uncertainty reduction

The semi-leptonic branching ratio B_μ is a bottleneck

– weighted average of the charmed-hadron rates

$$B_\mu(E_\nu)=\sum_h r^h(E_\nu)B^h_\mu = a/(1+b/E_\nu)$$

– fitted simultaneously with the PDFs, etc. using the constraint from the emulsion data



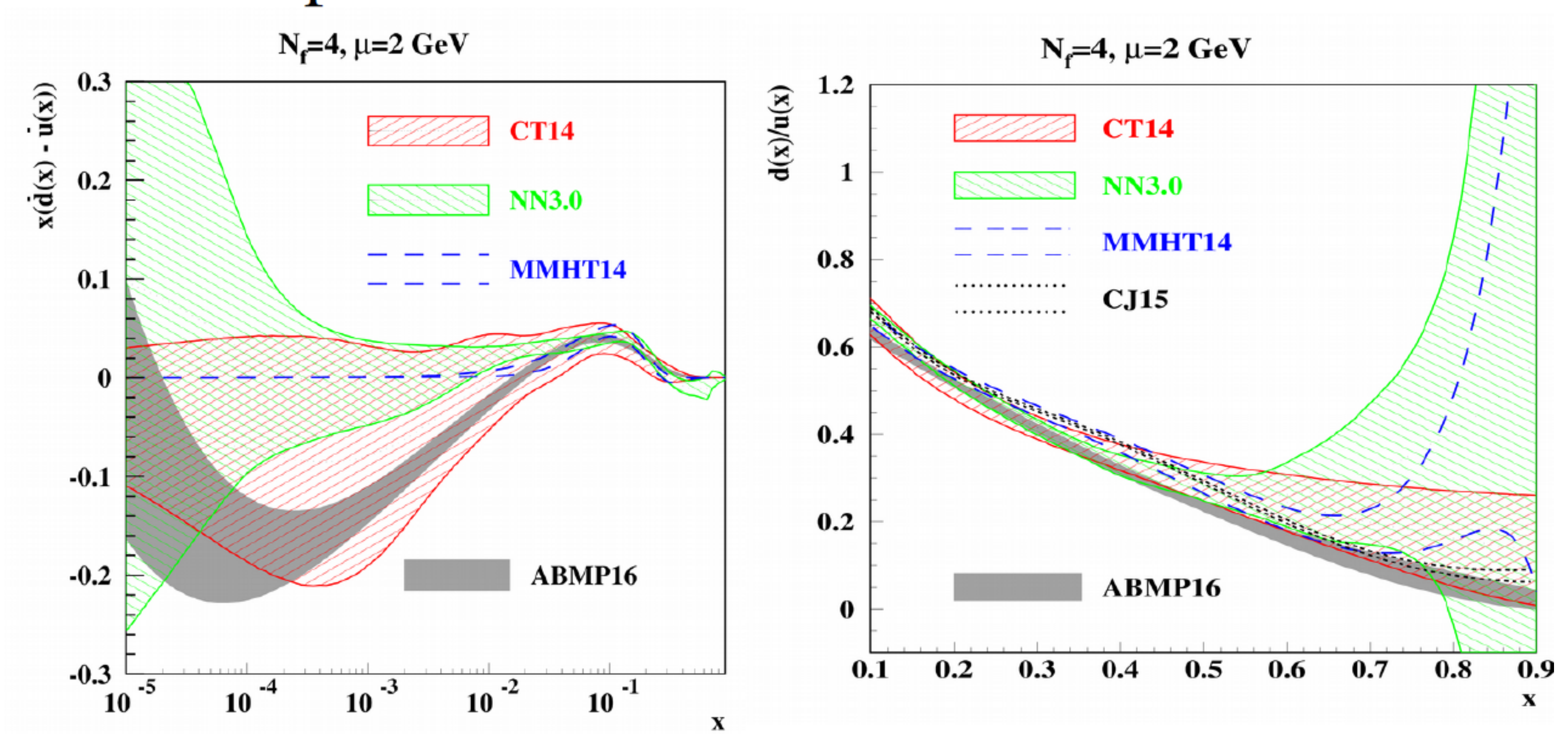
sa, Blümlein, Caminada, Lipka, Lohwasser, Moch, Petti, Plačakytė PRD 91, 094002 (2015)

5

Alekhin DIS 2018

ABMP16 PDFs – impact at high x from LHC and Tevatron data.

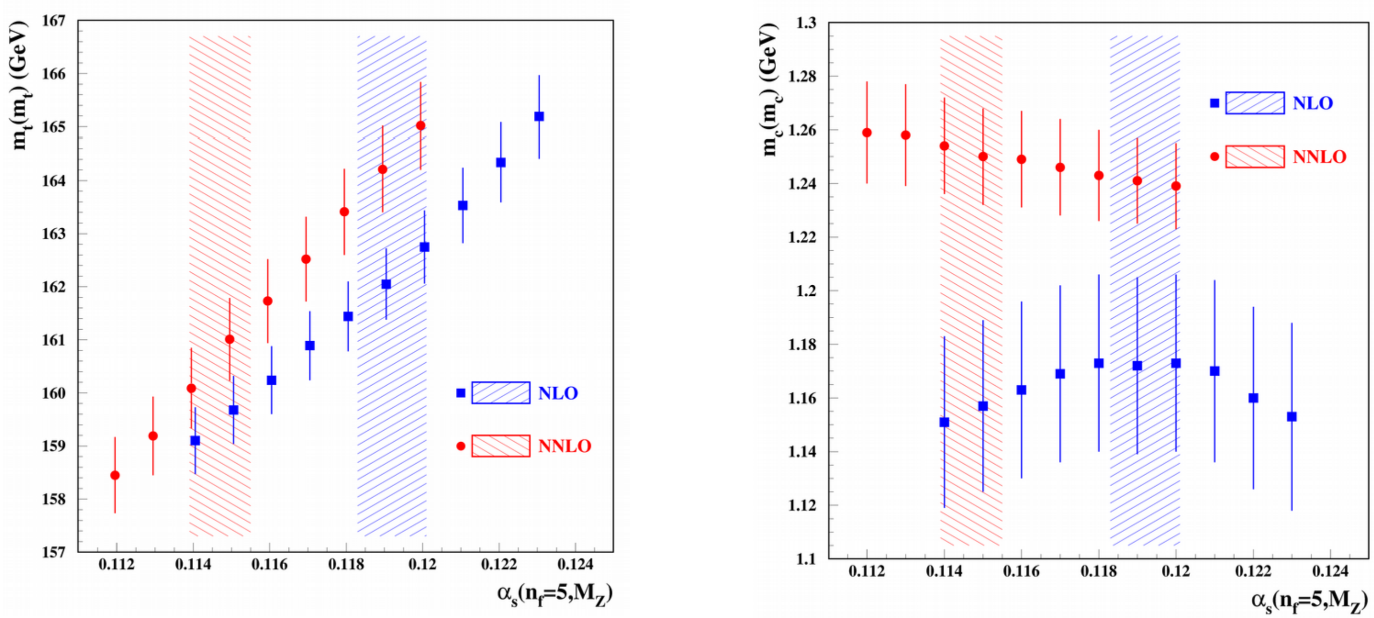
Impact of the forward Drell-Yan data



- Relaxed form of the sea iso-spin asymmetry I(x) at small x; Regge-like behaviour is recovered only at x~10^{-6}; at large x it is still defined by the phase-space constraint
- Good constraint on the d/u ratio w/o deuteron data → independent extraction of the deuteron corrections Accardi, Brady, Melnitchouk, Owens, Sato hep-ph/1602.03154;
- Big spread between different PDF sets, up to factor of 30 at large x → poor control of the background to BSM effects without constraints from the DY data

Details at high x depend on whether W or lepton data are used.

Masses and α_s



- Strong correlation between m_t and α_s
- Big difference in m_c between the orders (compensation of NNLO correction)

Consistent treatment of quark masses and α_s is needed

18

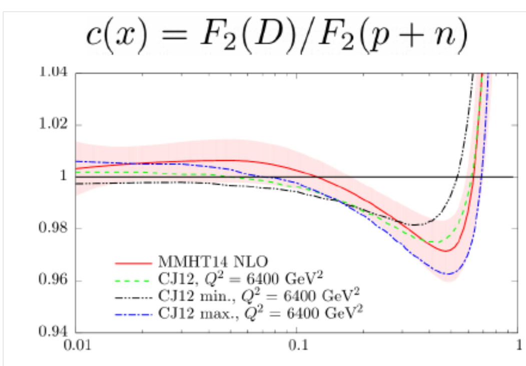
Alekhin DIS2018 2018

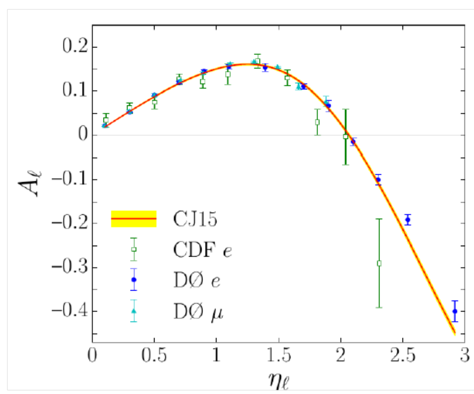
CJ15 PDFs – simultaneous study of precision proton and deuteron data fit/verify deuteron corrections.

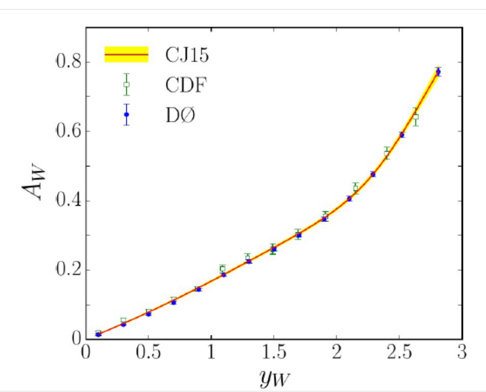
NUCL / HEP symbiosis

Observable	Experiment	# points	χ^2 LO	χ^2 NLO	χ^2 NLO (OCS)	χ^2 NLO (no nucl)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440
	BCDMS (d) [81]	254	297	**292**	289	301
	SLAC (p) [82]	564	488	**434**	435	441
	SLAC (d) [82]	582	396	**376**	380	507
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13
	DØ (μ) [17]	10	37	**20**	19	29
	DØ (e) [18]	13	20	**29**	29	14
	CDF (W) [89]	13	16	**16**	16	14
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

- Ignoring nuclear dynamics, SLAC(d) and D0(W) pull d quark in opposite directions
  - **D0 (W) data determine nuclear corrections !!**
  - other asymmetries inconclusive by themselves
  - **BONUS data validate DO(W) analysis**







NNPDF3.1 Now released.

New datasets in NNPDF3.1

Measurement	Data taking	Motivation
Combined HERA inclusive data	Run I+II	quark singlet and gluon
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive W, Z rap 7 TeV	2011	strangeness
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z pT 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-x gluon
CMS Z (pT,y) 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 2.76 TeV jets	2012	medium and large-x gluon
LHCb W,Z rapidity dists 7 TeV	2011	large-x quarks
LHCb W,Z rapidity dists 8 TeV	2012	large-x quarks

4

Juan Rojo   DIS2017, Birmingham, 04/04/2017

Rojo DIS2017

Theory developments

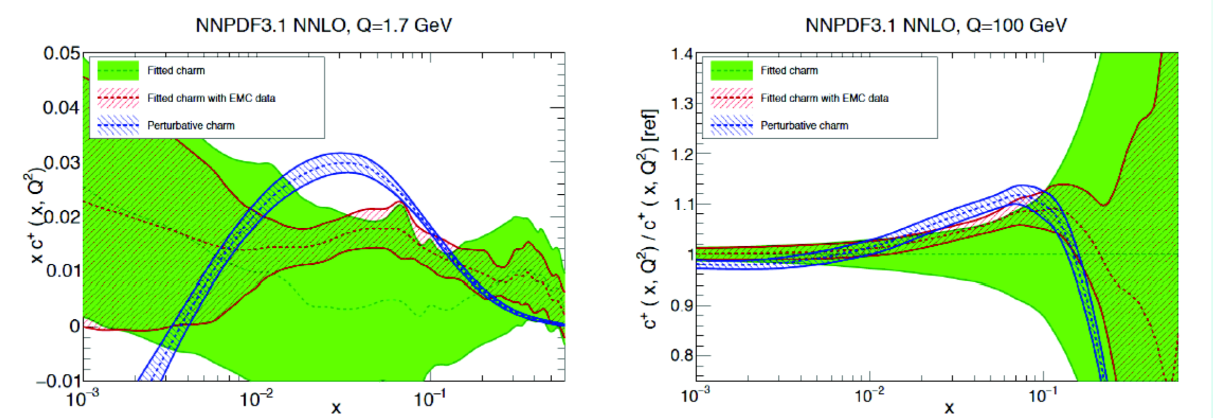
Charm content of proton revisited

- The new LHC experiments provide additional constraints on **non-perturbative charm**

- Including the EMC charm data, we find **evidence for non-perturbative charm at the 1.5 sigma level.** Even without EMC data, **non-perturbative charm bounded < 1.0 % at the 90% CL**

$$[C(Q^2)] \equiv \int_0^1 dx\ \left(xc(x,Q^2) + x\bar{c}(x,Q^2)\right)$$

PDF set	$C(Q = 1.65\ \text{GeV})$	$C(Q = 100\ \text{GeV})$
Perturbative charm	$(0.360 \pm 0.007)\%$	$(3.77 \pm 0.02)\%$
Fitted charm	$(0.45 \pm 0.40)\%$	$(3.8 \pm 0.2)\%$
Fitted charm with EMC data	$(0.52 \pm 0.14)\%$	$(3.86 \pm 0.08)\%$

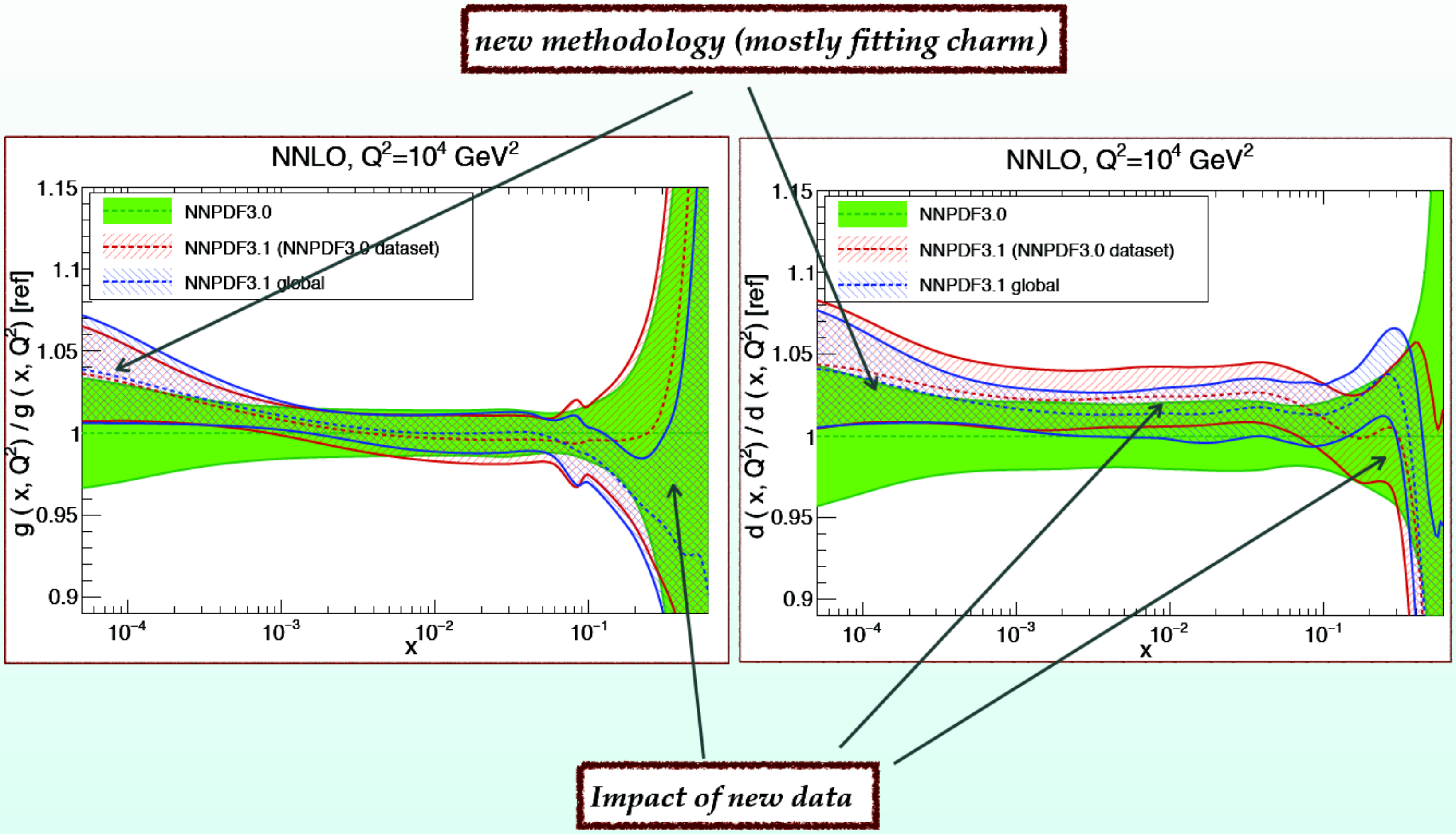


2

LHC W, Z data prefer lower charm for $0.01 < x < 0.1$.

Rojo, DIS 2017

new data vs new methodology

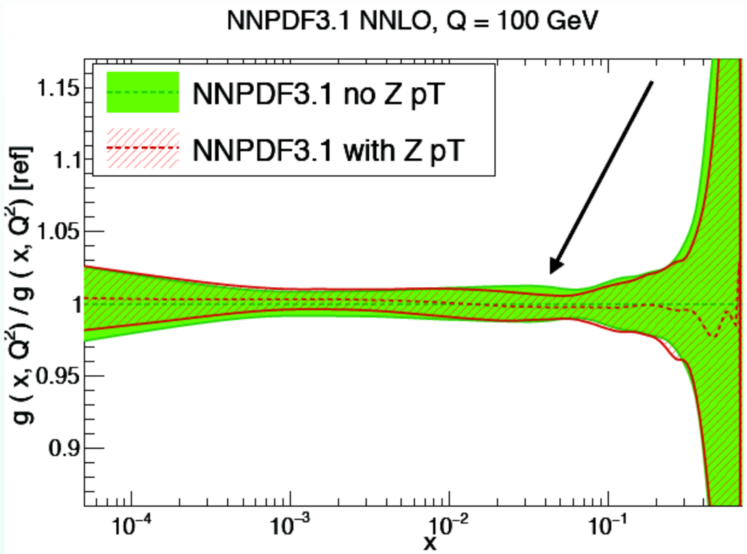


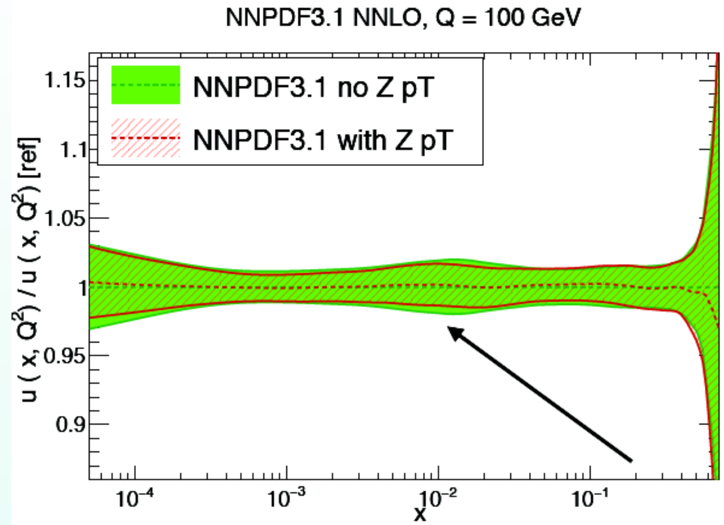
10

Juan Rojo

DIS2017, Birmingham, 04/04/2017

Impact of Z p_T data



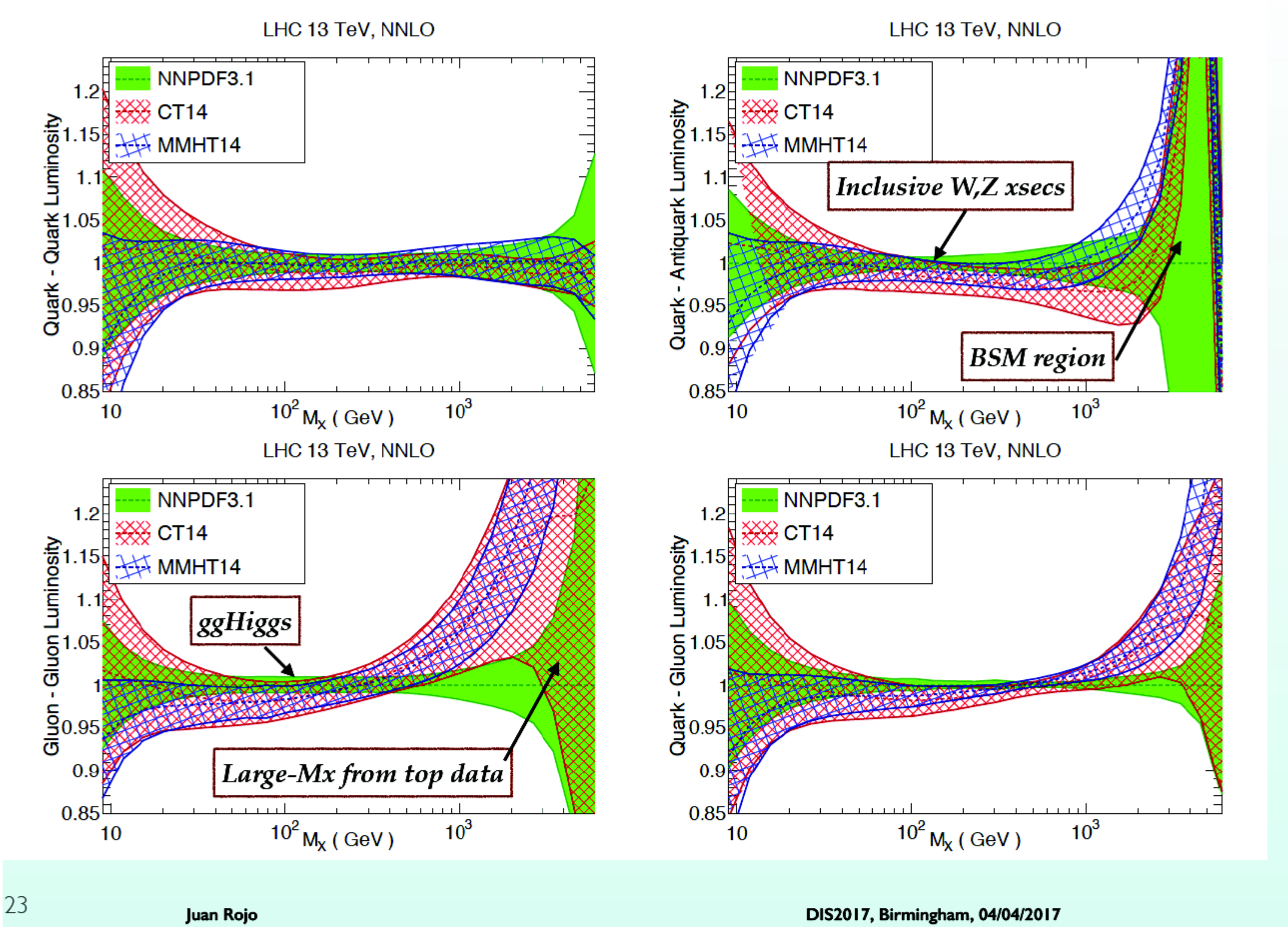


- **Moderate error reduction in the intermediate-x** region, excellent consistency with the other experiments in the global fit.
- Given very high precision (sub-percent) of these experiments, this is quite a non-trivial achievement
- The ATLAS Z p_T 7 TeV data not included in NNPDF3.1. If included, **poor data/theory agreement, χ^2 = 3.5,** and shifts in gluon and quarks. ***Tension with 8 TeV data?***

See talk by M. Ubiali

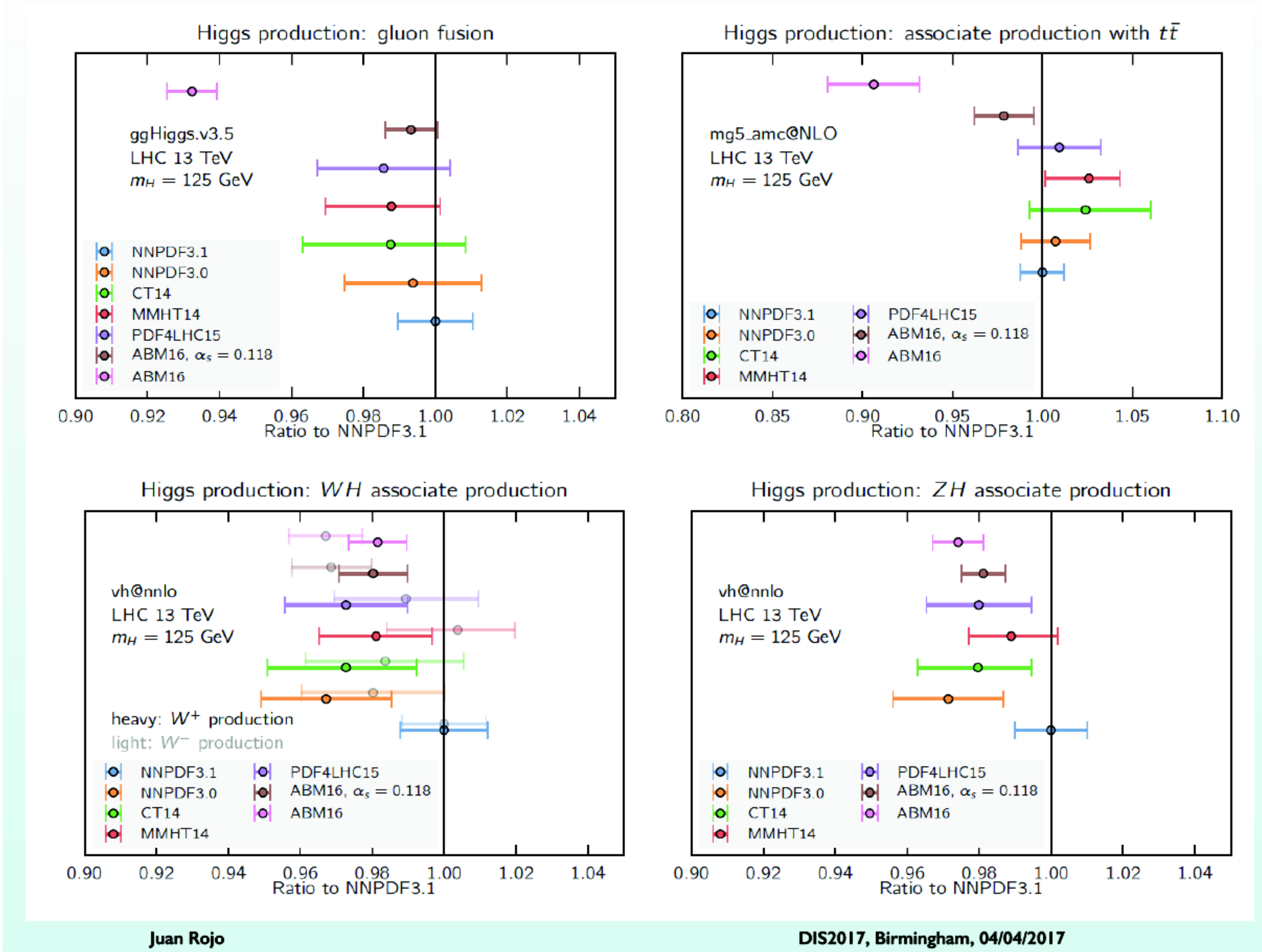
Only full study of $Z\ p_T$ data so far.

PDF luminosities



Still good agreement with CT14 and MMHT14 but change in gluon shape and quark increase.

Higgs production cross-sections



Some impact on cross sections.

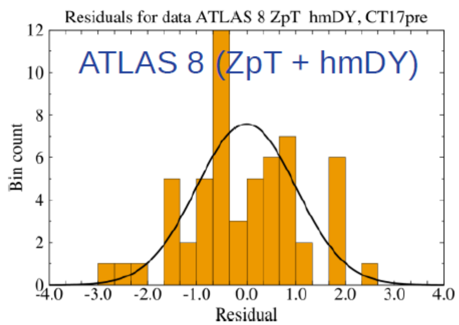
LHC data sets included in CT17pre

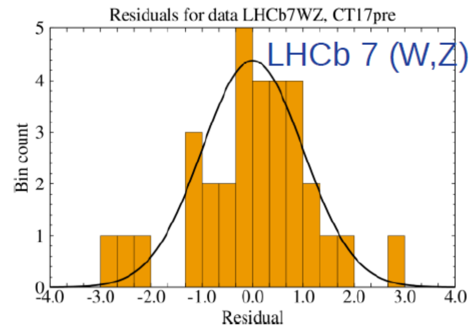
- LHCb Z (W) rapidity (muon rapidity) at 7 (applgrid); 8 TeV Z rapidity (applgrid)
- *LHCb heavy flavor (applgrid) (to be added), SACOT-chi, base on Xie, Campbell, Nadolskey, 2018*
- ATLAS W/Z lepton(s) rapidity at 7 TeV (applgrid)
- ATLAS 8 TeV DY (applgrid)
- ATLAS 7 TeV Z p_T (applgrid)
- ATLAS 8 Z p_T, as a function of mass (applgrid)
- CMS Z p_T,as a function of y, at 8 TeV (applgrid)
- CMS W lepton rapidity (asymmetry) at 8 TeV (applgrid);
- CMS W,Z p_T at 8 TeV (applgrid)
- CMS inclusive jet cross section at 7,8 TeV with R=0.7 (fastNLO)
- ATLAS inclusive jet cross section at 7 TeV with R=0.6 (applgrid)
- ATLAS and CMS 7,8 TeV tT differential distributions (fastNNLO)
- *including double differential from CMS at 8 TeV (work in progress)*
- ATLAS low mass/high mass Drell-Yan at 7 TeV (applgrid)
- CMS low mass/high mass DY at 8 TeV (applgrid)

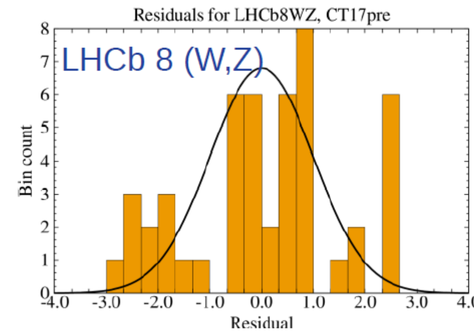
There is a lot of new data, but there is also a lot of old data already in the fit, that continues to have an impact, and will tend to dilute the impact of new data.

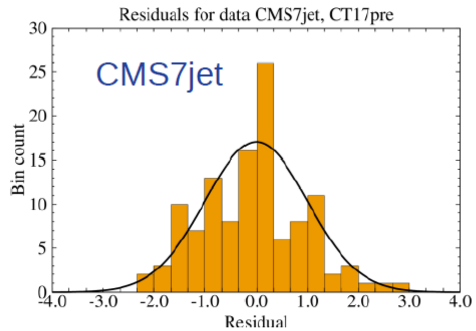
5

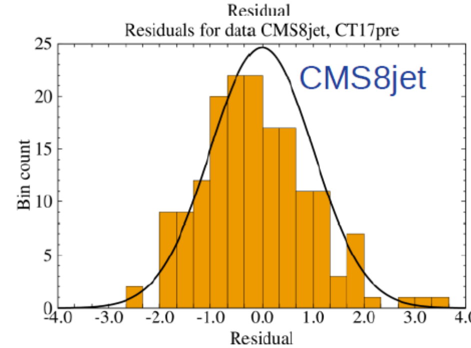
Goodness of CT17pre Fit





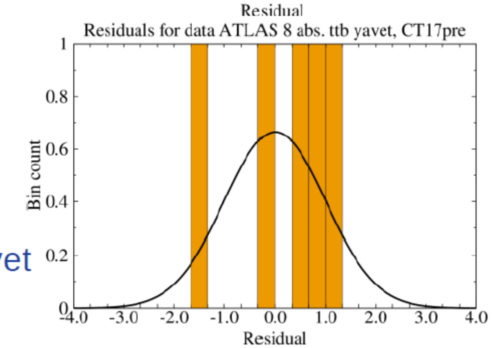


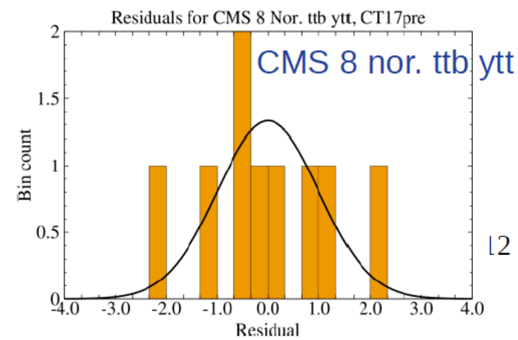




$$Residual \equiv \left(\frac{T - D_{shifted}}{\sqrt{\sigma_{stat}^2 + \sigma_{unc.\,sys}^2}} \right)$$

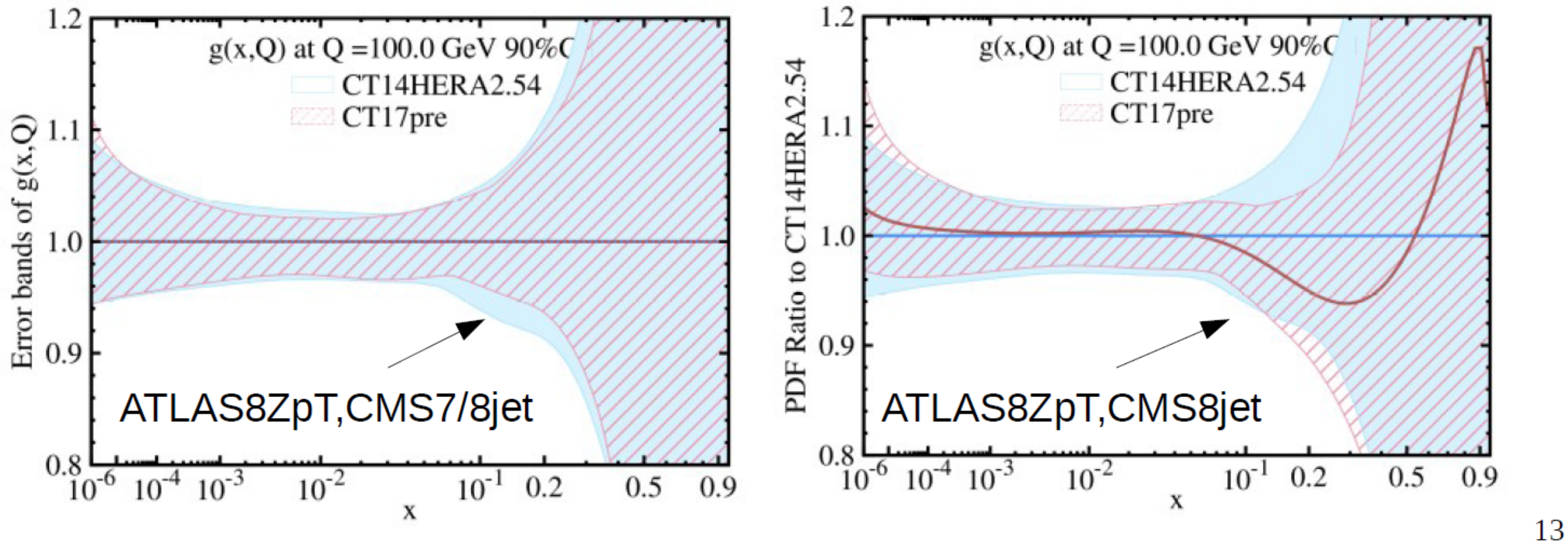
ATLAS 8 abs. ttb yavet





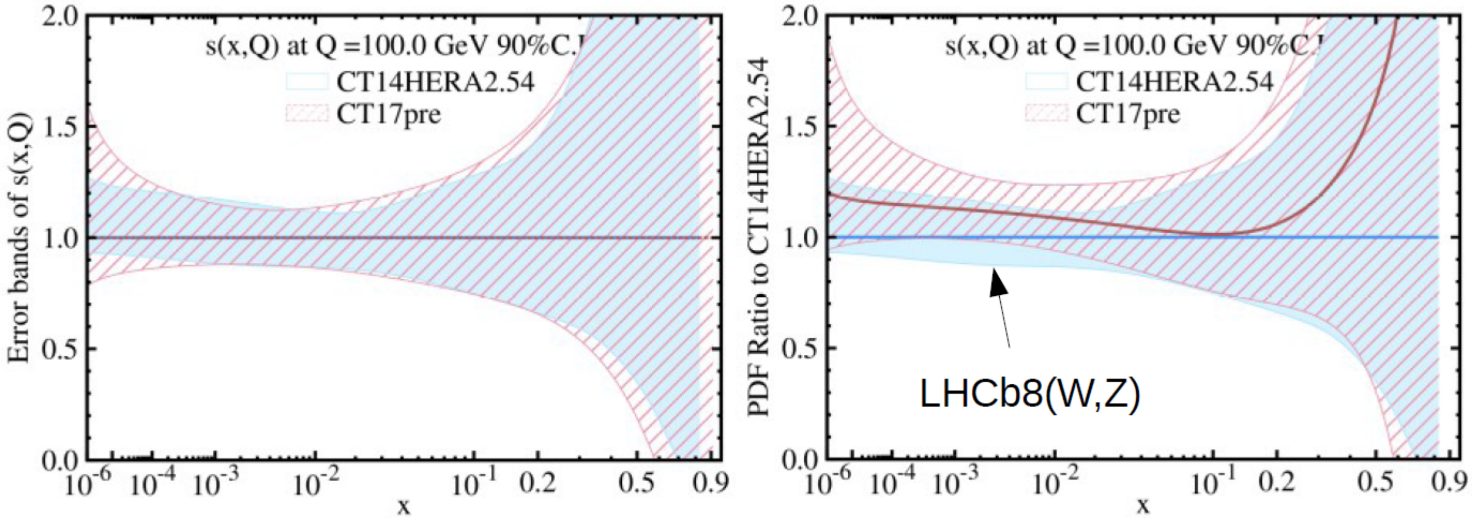
Preview of CT17pre (g-PDF)

- Improvement in gluon uncertainty for x around 0.2 dominated by the CMS 8 TeV jet data.
- Reduction of gluon central PDF for x around 0.2 is due to ATLAS 8 TeV ZpT, CMS 8 TeV jet data and ttbar distributions, ATLAS and CMS.



Preview of CT17pre (s-PDF)

- The new LHC DY and jet data have some effect on S-PDF, but mainly due to LHCb 8 TeV WZ data.
- Larger central S-PDF, though still consistent with CT14HERA2.



Update

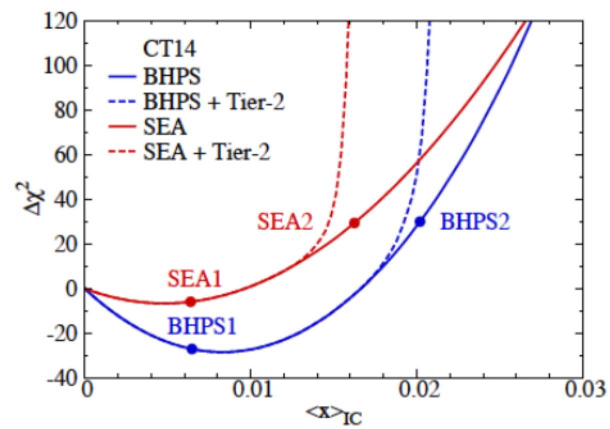
- Return to study of intrinsic charm within CT14/ CT14HERA2 framework, again with 2 models of intrinsic charm
  - Valence-like

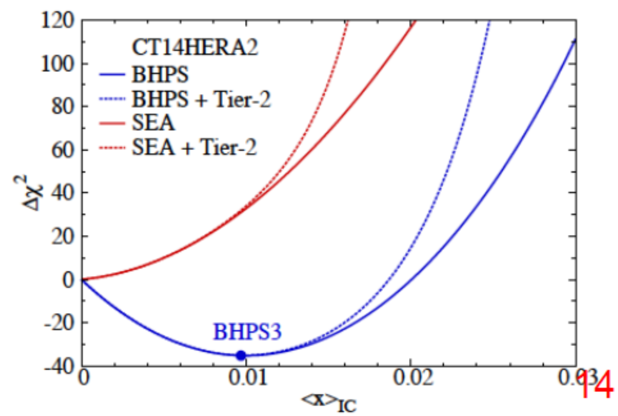
$$\hat{c}(x) = A\ x^2\left[6x(1+x)\ln x + (1-x)(1+10x+x^2)\right]$$

  - Sea-like

$$\hat{c}(x) = A\ \left(\bar{d}(x,Q_0) + \bar{u}(x,Q_0)\right)$$

- See reduction in valence-like (BHPS) models, but with the drop in c2 interesting but less than our criterion (100)
- In addition, the decrease in c2 comes primarily from BCDMS data that does not have any particular sensitivity to charm





Huston PDF4LHC 2017

MMHT preliminary set - fit to new hadron collider (mainly LHC) data

Fit new LHCb data at 7 and 8 TeV, $W + c$ jets from CMS, CMS $W^{+,-}$ data, and also the final e asymmetry data from D0.

	no. points	NLO χ^2_{pred}	NLO χ^2_{new}	NNLO χ^2_{pred}	NNLO χ^2_{new}
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W + Z$	33	50.1	45.4	46.5	42.9
LHCb 8 TeV $W + Z$	34	77.0	58.9	62.6	59.0
LHCb 8TeV e	17	37.4	33.4	30.3	28.9
CMS 8 TeV W	22	32.6	18.6	34.9	20.5
CMS 7 TeV $W + c$	10	8.5	10.0	8.7	8.0
D0 e asymmetry	13	22.2	21.5	27.3	25.8
total	3738/3405	4375.9	4336.1	3741.5	3723.7

Predictions good, and no real tension with other data when refitting, i.e. changes in PDFs relatively small, mainly in $d_V(x, Q^2)$.

Investigated more flexible $\bar{d}(x, Q^2) - \bar{u}(x, Q^2)$ parameterization.

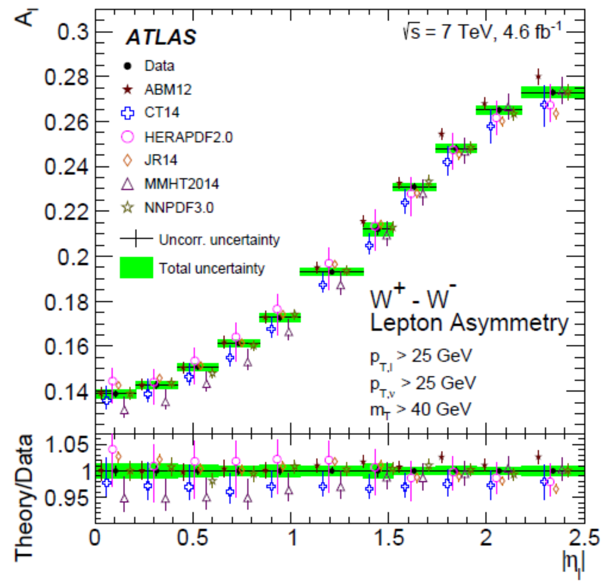
At NLO $\Delta\chi^2 = 9$ for the remainder of the data and at NNLO $\Delta\chi^2 = 8$.

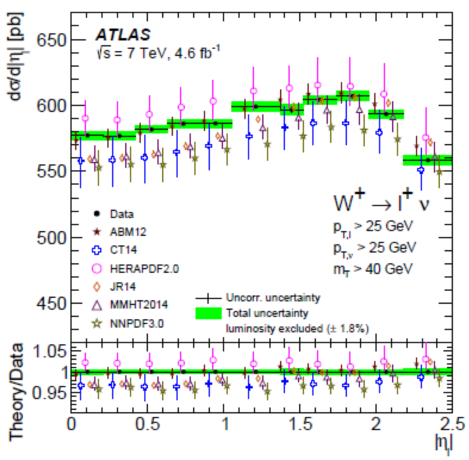
Some reduction in details of flavour decomposition uncertainties, e.g. low-x valence quarks.

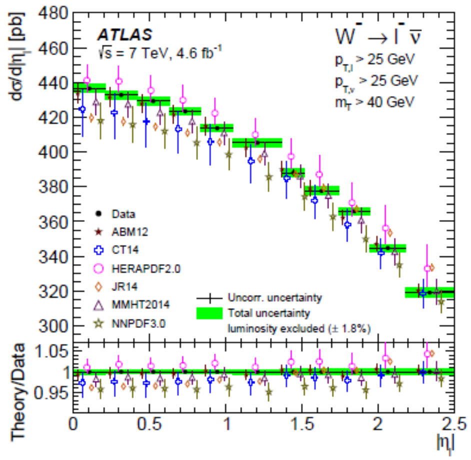
Recent extremely high precision data on W, Z from ATLAS

Differential $W \to \ell\nu$ Measurements

- shape of differential W cross sections generally well described
- particularly good description of the differential lepton charge asymmetry A_ℓ
- differences in PDF sets seen in the overall normalisation
- a precise measurement of the absolute cross section provides valuable information despite larger uncertainties

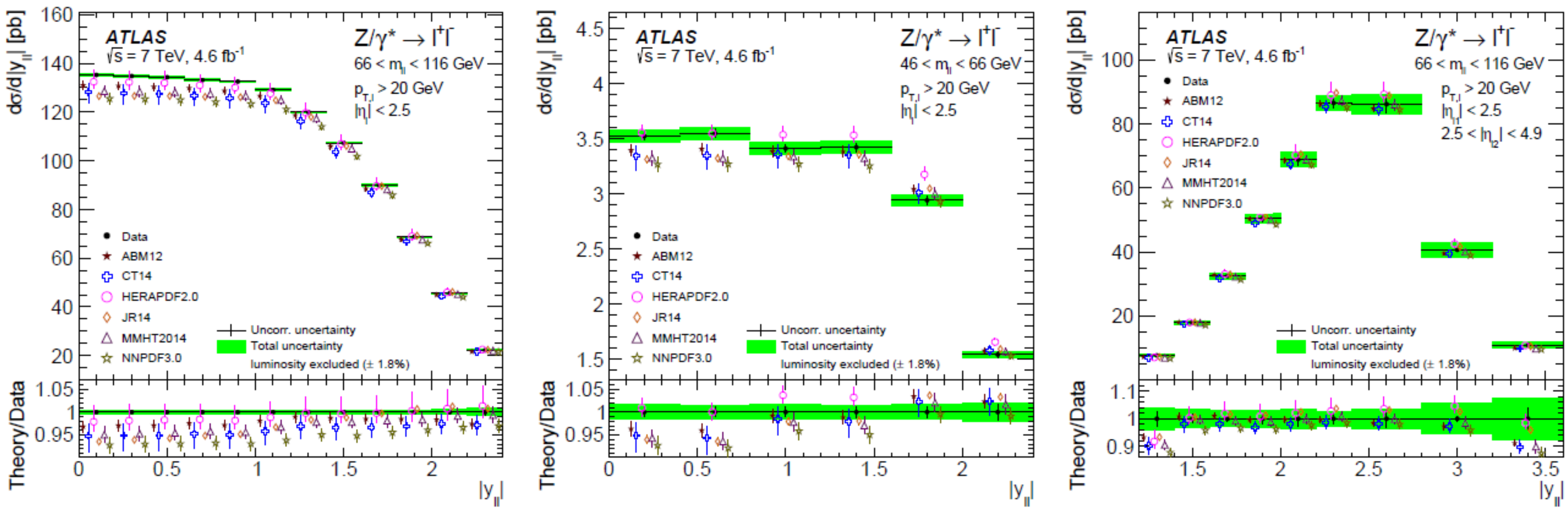






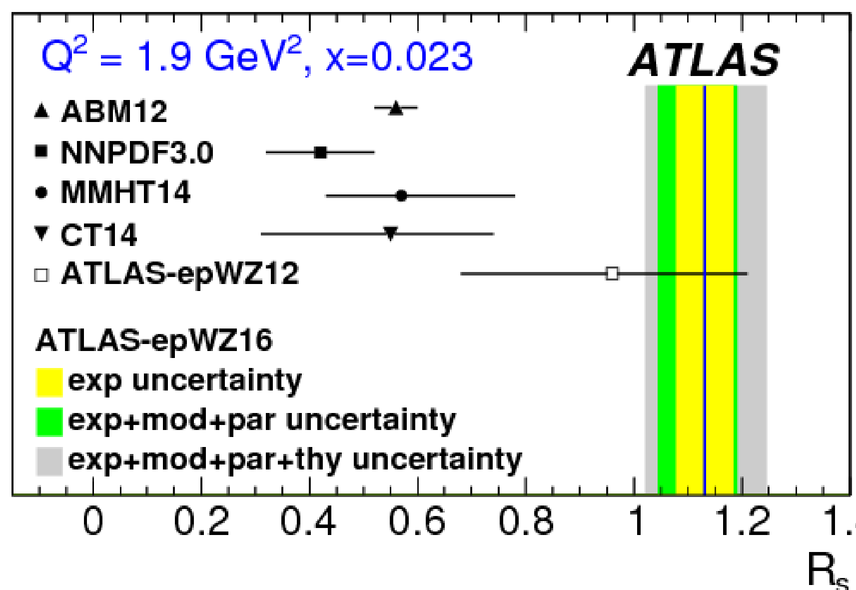
Sommer DIS2017

Differential $Z \to \ell\ell$ Measurements



- differences in the rapidity dependence between data and theoretical predictions

Fixed by increase in strange quark fraction in ATLAS study.



Studied by NNPDF - smaller strange enhancement.

PDF set	$R_s(x=0.023, Q=1.65 \text{ GeV})$	$R_s(x=0.013, Q=M_Z)$
NNPDF3.0	0.47±0.09	0.79±0.04
NNPDF3.1	0.62±0.12	0.83±0.05
NNPDF3.1 collider-only	0.86±0.17	0.94±0.07
NNPDF3.1 HERA + ATLAS W, Z	0.96±0.20	0.98±0.09
ATLAS W, Z 2011 xFitter (Ref. [93])	$1.13^{+0.11}_{-0.11}$	-
ATLAS W, Z 2010 HERAfitter (Ref. [120])	$1.00^{+0.25}_{-0.28}$ (*)	$1.00^{+0.09}_{-0.10}$ (*)

- **Confirmed the strange symmetric fit** preferred by the ATLAS W,Z 2011 measurements, though we find PDF uncertainties larger by a factor 2

- The **global fit** accommodates both the neutrino data and the ATLAS W,Z 2011 (χ^2_{nutev}**=1.1,** χ^2_{AWZ11}**=2.1**) finding a compromise value for **R_S=0.62+-0.12**

- **Mild tension** in the global fit (1.5-sigma level at most) when simultaneously included neutrino data, CMS W+charm and ATLAS W,Z 2010+2011

$\sigma_W \propto c\bar{s}$, $\sigma_Z \propto g_S * s\bar{s} + g_d * c\bar{c}$, where $g_s > g_c$.

Smaller strange correlated with smaller charm, i.e. σ_Z/σ_W rises with smaller charm.

Improved fit to older ATLAS W, Z data with larger m_c evident in MMHT2014. Usually interplay with fitting HERA data.

MMHT – updated fits also with high precision ATLAS W, Z data.

Including ATLAS W, Z data in fit goes from $\chi^2/N_{pts} \sim 387/61 \rightarrow \chi^2/N_{pts} \sim 130/61$, similar to ATLAS profiling.

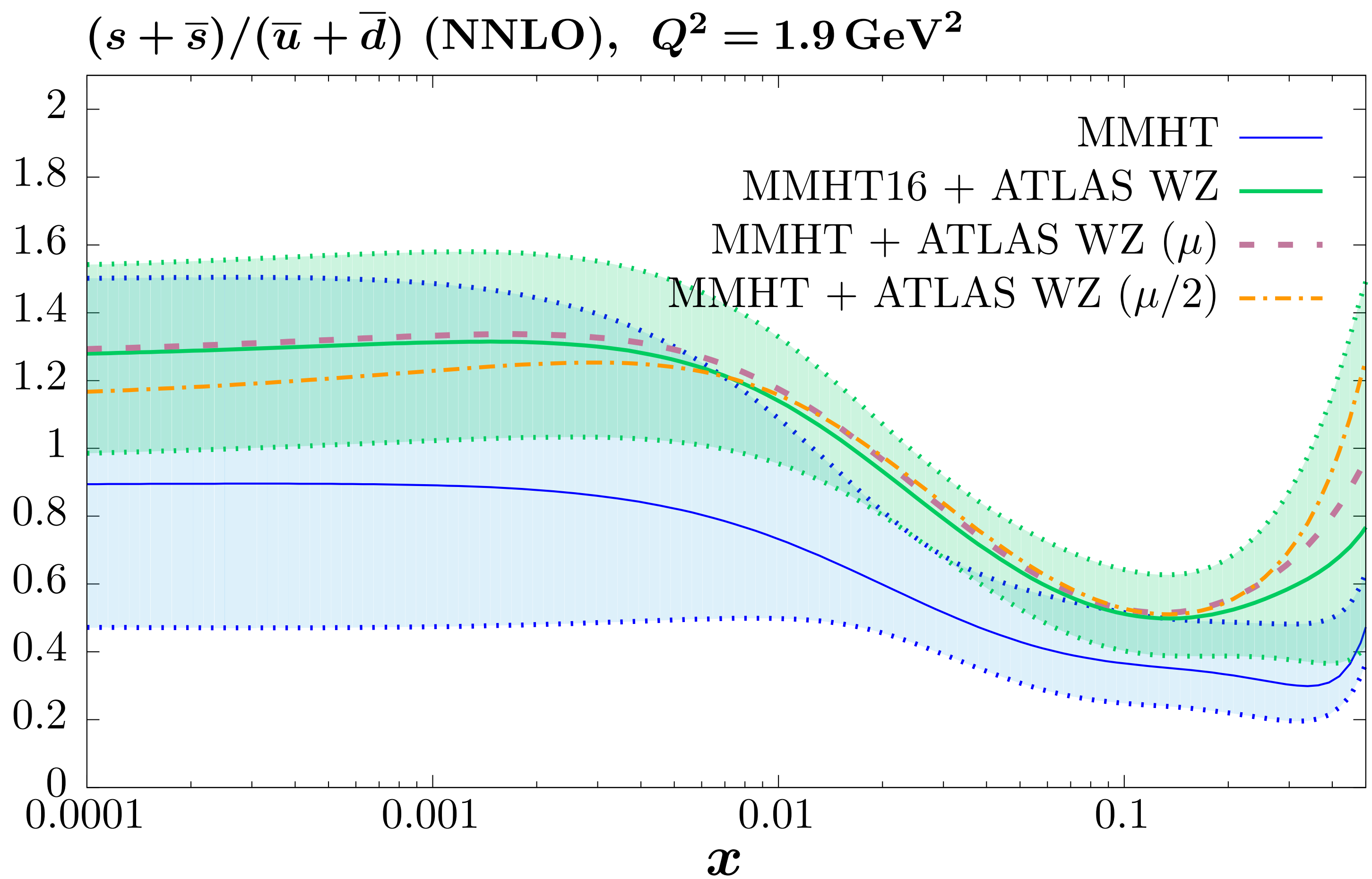
Deterioration in fit to other data $\Delta\chi^2 = 54$. CMS double differential Z/γ data ($\Delta\chi^2 = 17$) and CCFR/NuTeV dimuon data ($\Delta\chi^2 = 16$).

Also fixed target DIS , E866 Drell-Yan asymmetry and CDF W-asymmetry.

Also try fit with scales set to $\mu_{R,F} = M_{W,Z}/2$ rather than $\mu_{R,F} = M_{W,Z}$ (thanks to V. Radescu, A. Cooper-Sarkar)

As in ATLAS study find reduction in χ^2 of about 20 units.

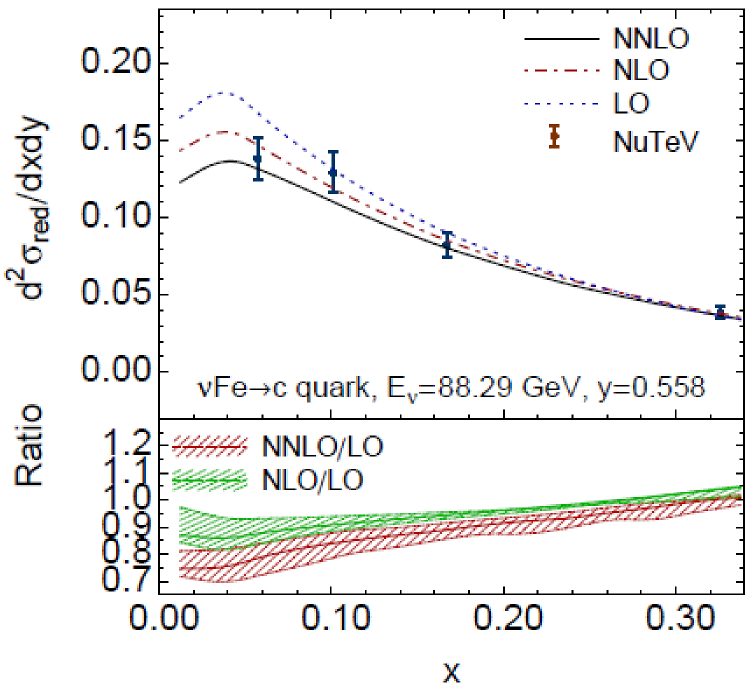
Almost no change in fit to other data or PDFs.

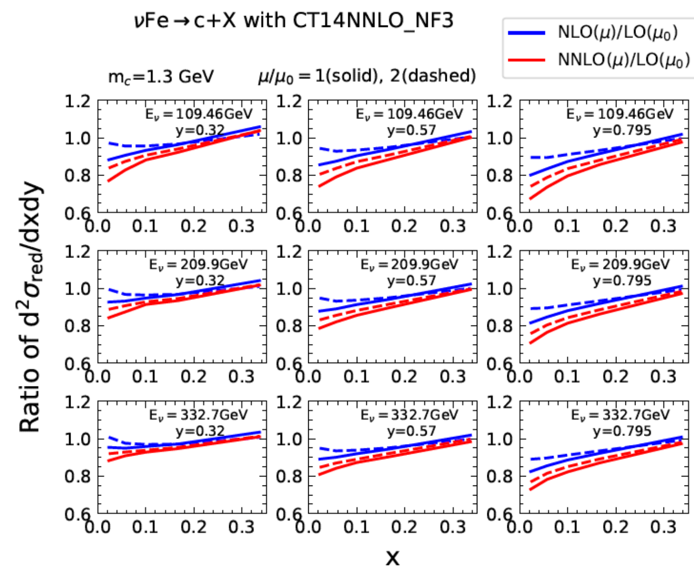


Ratio of $(s+\bar{s})$ to $\bar{u}+\bar{d}$, i.e. R_s at $Q^2 = 1.9\ \mathrm{GeV}^2$.

At $x = 0.023$ $R_s \sim 0.83 \pm 0.15$. Compare to ATLAS with $R_s = 1.13^{+0.08}_{-0.13}$

Details of tension of W, Z data may be mitigated by NNLO corrections to dimuon production (Phys. Rev. Lett. 116 (2016), Berger *et al.*, J. Gao, `arXiv:1710.04258`).

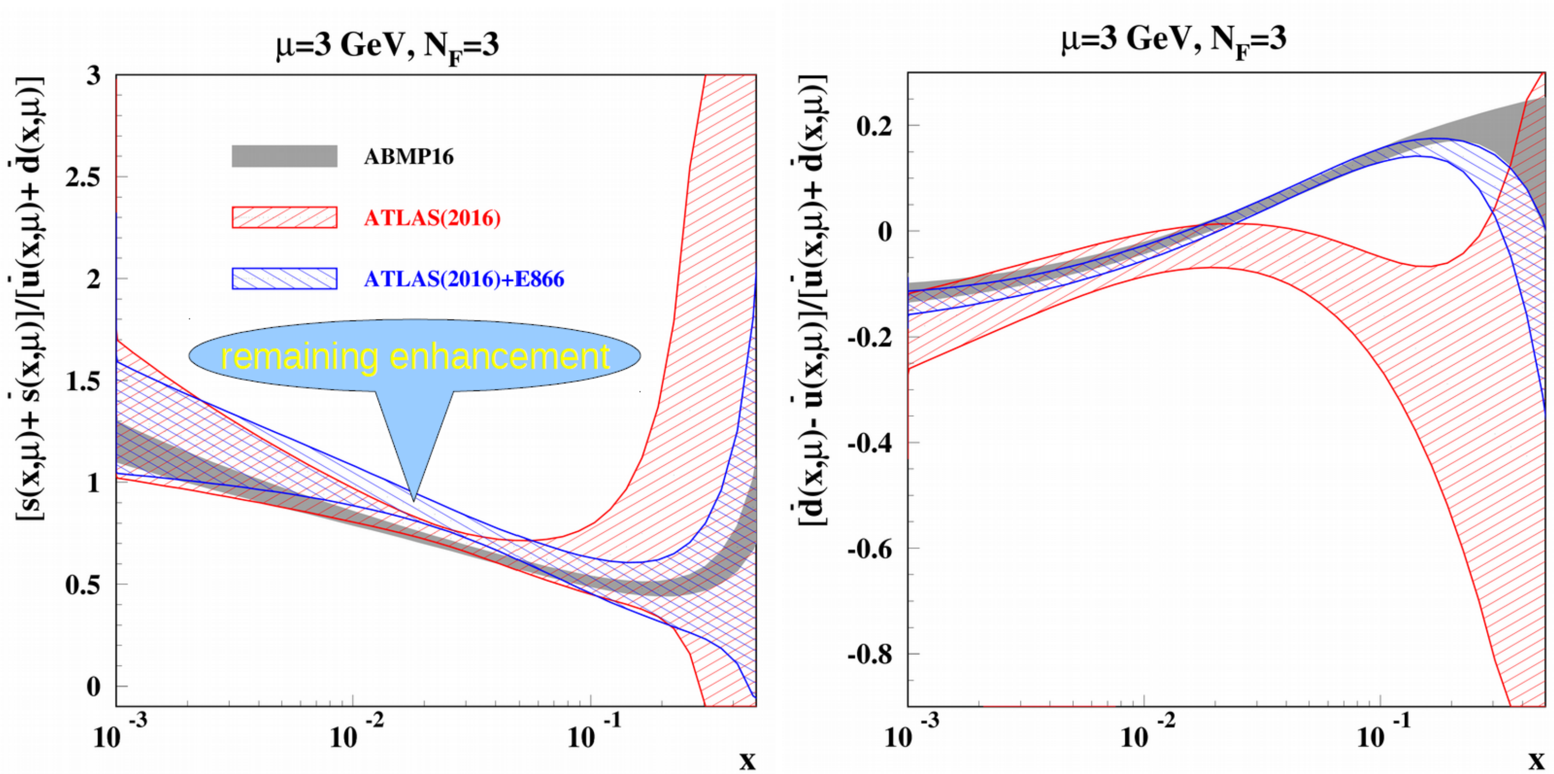




NNLO correction negative, but larger in size at lower x

Some slight increase in strange in ABM - Alekhin PDF4LHC

Strange and non-strange sea from ATLAS data



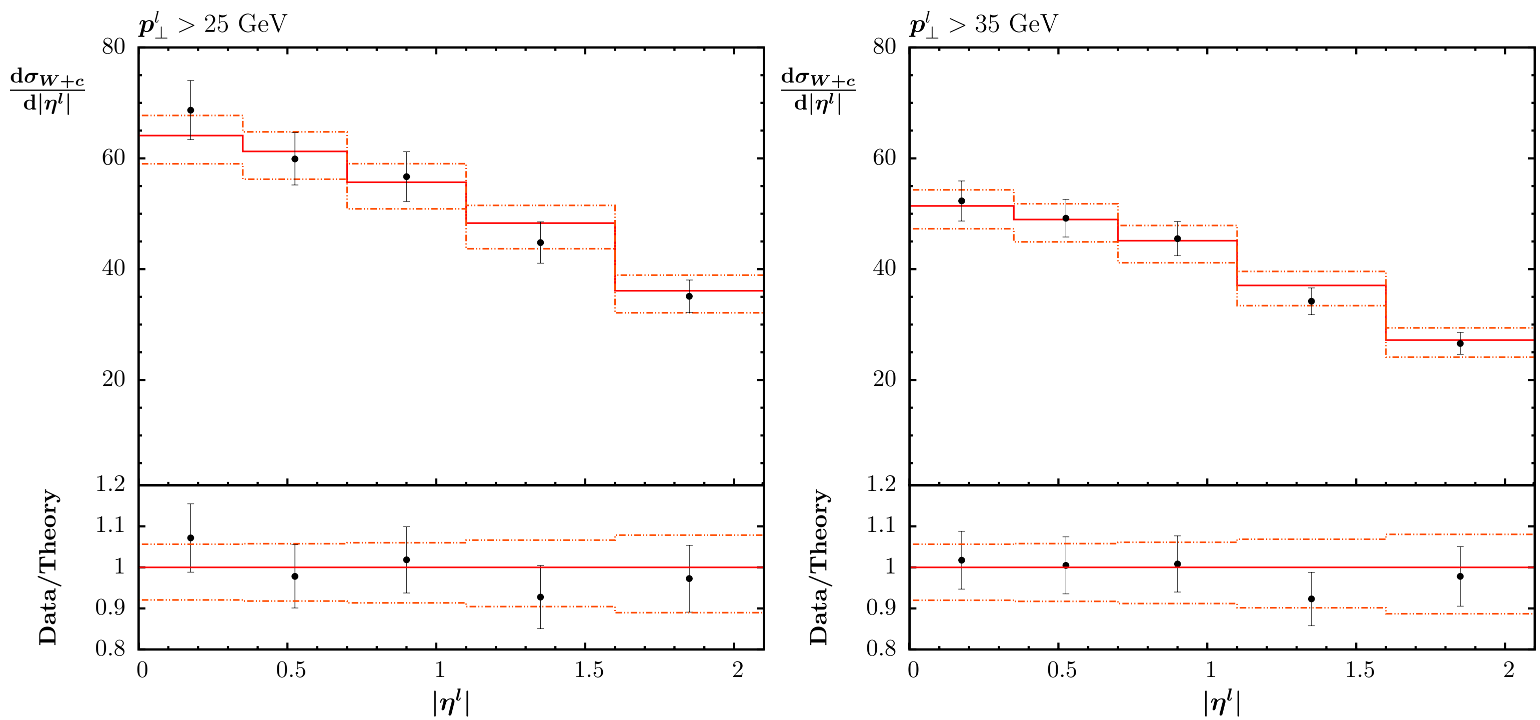
The data used in test fit: collider W&Z data except of ATLAS(2016) discarded to approach the data selection of epWZ16 fit

For the flexible PDF shape the strangeness is in a broad agreement with the ABMP16 results; the E866 data are consistent with the ATLAS(2016) set: χ^2/NDP=48/39 and 40/34, respectively.

Stress than it is shape dependent and related to $\bar{d}$ determination – ATLAS PDFs are not consistent with E866 Drell-Yan asymmetry data.

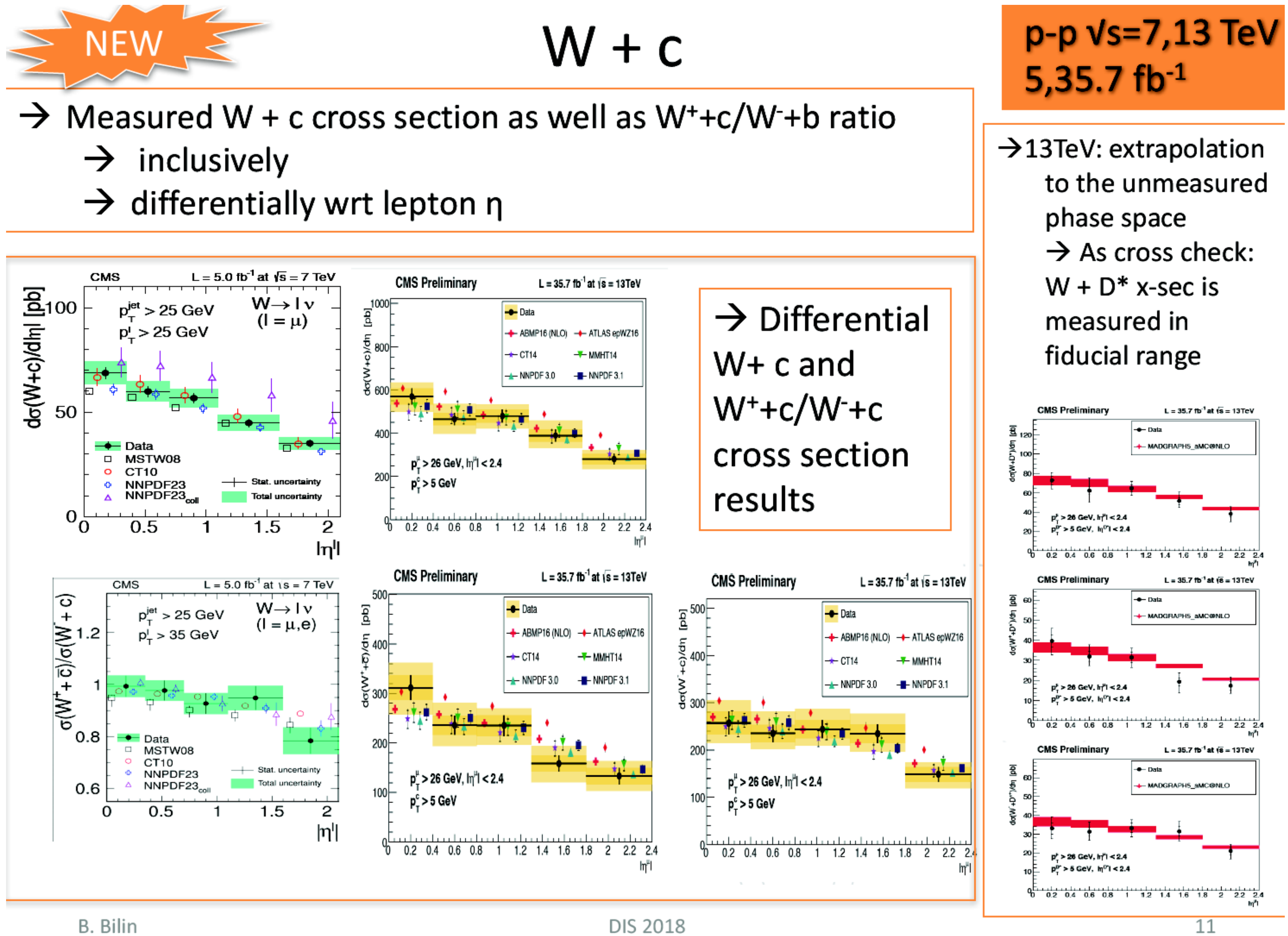
Direct constraint on Strange – $W + c$ differential distributions.

	GeV	data	MSTW2008	MMHT2014
$\sigma(W+c)$	$p_T^{\rm lep} > 25$	$107.7 \pm 3.3({\rm stat.}) \pm 6.9({\rm sys.})$	102.8 ± 1.7	110.2 ± 8.1
$\sigma(W+c)$	$p_T^{\rm lep} > 35$	$84.1 \pm 2.0({\rm stat.}) \pm 4.9({\rm sys.})$	80.4 ± 1.4	86.5 ± 6.5
$R_c^{\pm}$	$p_T^{\rm lep} > 25$	$0.954 \pm 0.025({\rm stat.}) \pm 0.004({\rm sys.})$	0.937 ± 0.029	0.924 ± 0.026
$R_c^{\pm}$	$p_T^{\rm lep} > 35$	$0.938 \pm 0.019({\rm stat.}) \pm 0.006({\rm sys.})$	0.932 ± 0.030	0.904 ± 0.027



MSTW2008 a bit low (especially for ATLAS), but MMHT2014 seems fine particularly for CMS (shown). Data will add some constraint.

Newer CMS data at 13 TeV – doesn't favour very large $s + \bar{s}$.



Fit to high luminosity ATLAS $7\ \mathrm{TeV}$ inclusive jet data – MMHT (JHEP 02 (2015) 153)

Initially take as default $R = 0.4$ and $\mu = p_{T,1}$ and work at NLO.

Prediction at NLO gives $\chi^2/N_{pts} = 413.1/140$.

Refit gives improvement only to $\chi^2/N_{pts} = 400.4/140$.

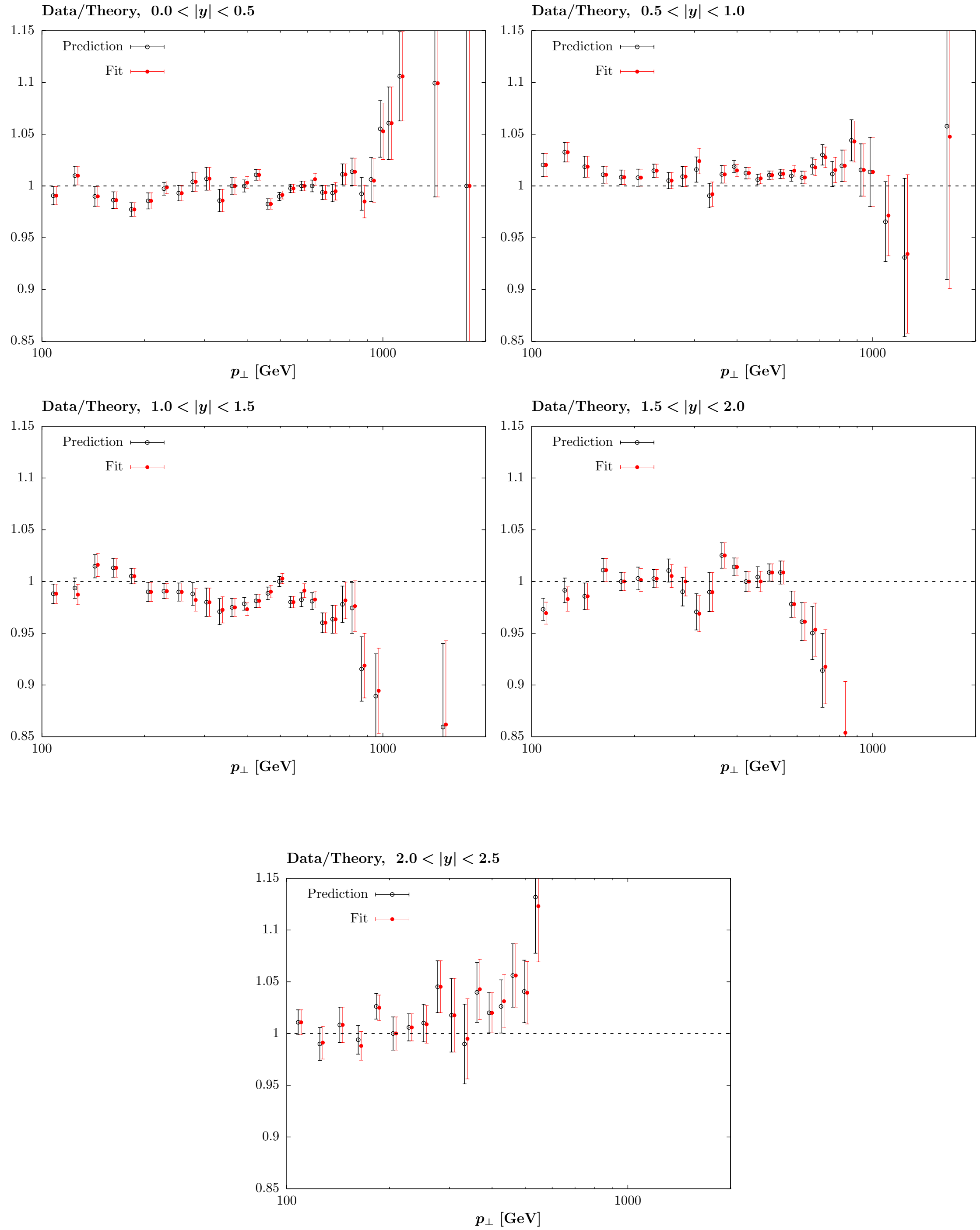
Deterioration in other data $\Delta\chi^2 \sim 3$, so no strong tensions.

Cannot simultaneously fit data in all rapidity bins. Mismatch in one bin different in form to neighbouring bin constraining PDFs of similar x, Q^2.

Similar results also seen by other groups.

Qualitative conclusion shown to be independent of jet radius R, choice of scale or inclusion of NNLO corrections.

Cannot simultaneously fit data in all bins. Mismatch in one rapidity bin different to others probing PDFs of similar flavour, x and Q^2.

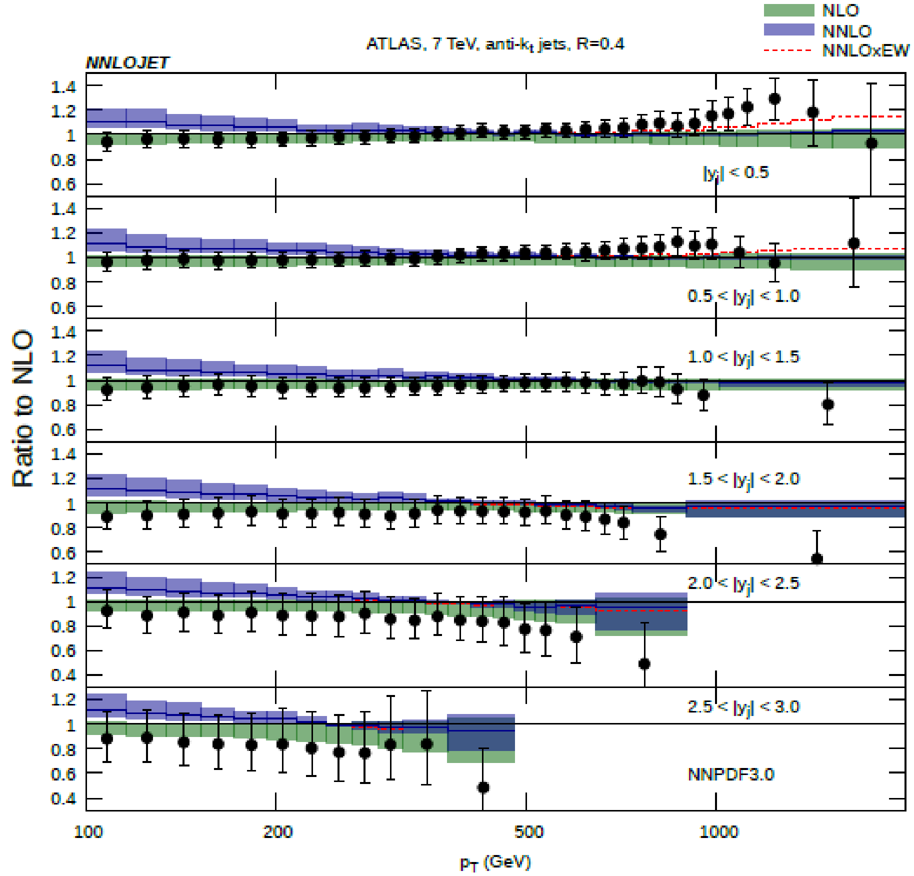


NNLO corrections

Now calculated Currie *et al* Phys.Rev.Lett. 118 (2017) 072002.

Fit quality can slightly improve or decrease compared to NLO depending on choices.

Electroweak corrections to jets different in different bins, but much smaller than systematic effect.



Exact form dependent on R and on scale choice, e.g $\mu = p_{T,1}$ or p_T. Up to 20% at low p_T. Authors now recommend using more physical scale, $\hat{p}_T$ – sum of parton p_T (arXiv:1807.03692), improved convergence criteria properties. Can also resum R dependence Liu, Moch and Ringer – Phys.Rev.Lett. 119 (2017) 212001.

Exercise on decorrelating uncertainties

We consider the effect on the χ^2 of the simultaneous fit to all data of decorrelating two uncertainty sources, i.e. making them independent between the 6 rapidity bins.

Compared to the original $\chi^2/N_{pts} = 2.85$ we get instead

	Full	21	62	21,62
$\chi^2/N_{\mathrm{pts.}}$	2.85	1.56	2.36	1.27

Very significant improvement, particularly from decorrelating jes21.

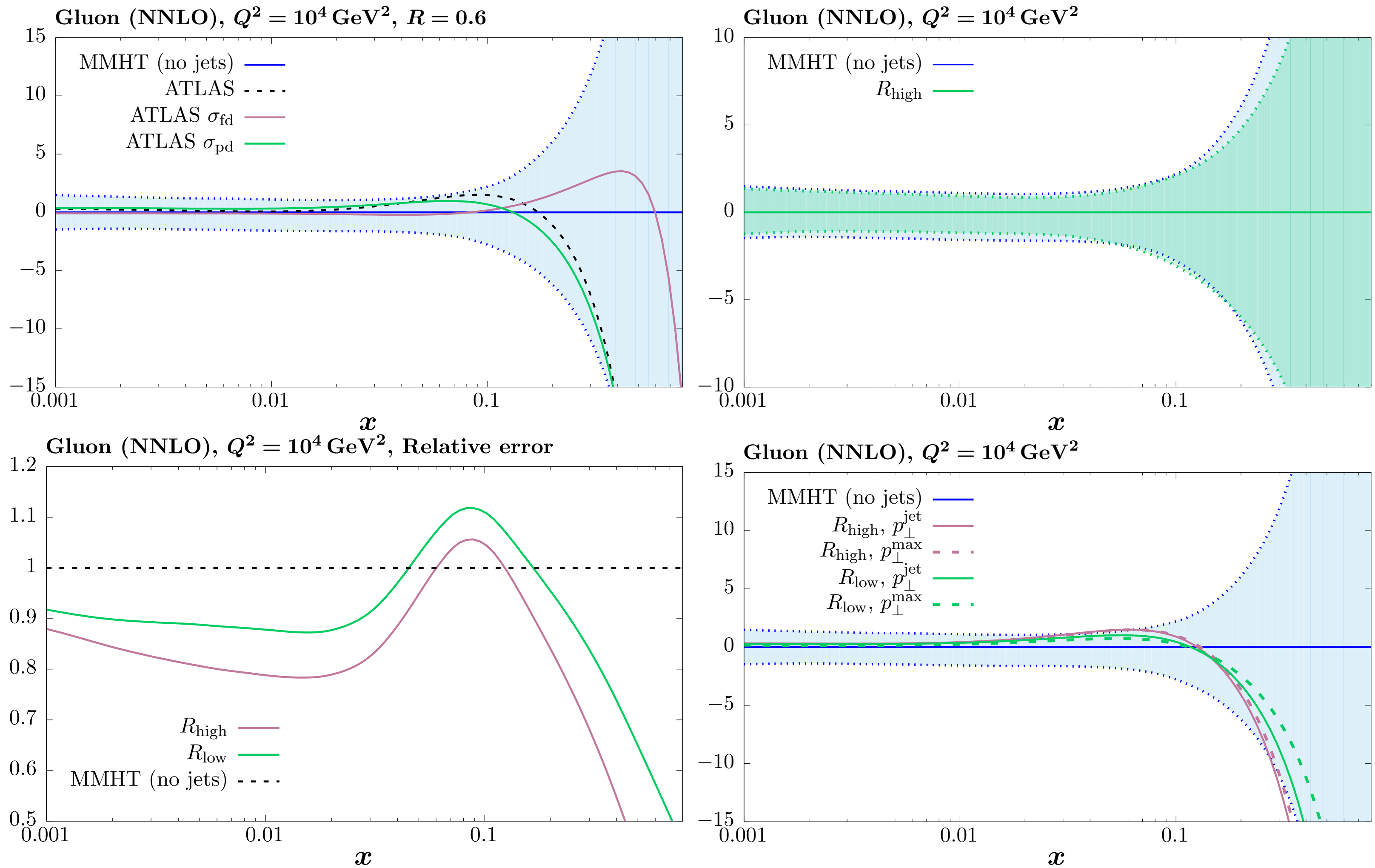
With correlations between rapidity bins relaxed for just two sources of systematics $\chi^2/N_{pts} = 178/140 = 1.27$.

More extensive decorrelation study in ATLAS – JHEP 09 020 (2017).

Similar results using new NNLO results.

	$R_{\mathrm{low}},\ p_\perp^{\mathrm{jet}}$	$R_{\mathrm{low}},\ p_\perp^{\mathrm{max}}$	$R_{\mathrm{high}},\ p_\perp^{\mathrm{jet}}$	$R_{\mathrm{high}},\ p_\perp^{\mathrm{max}}$
NLO	210.0 (187.1)	189.1 (181.7)	175.1 (193.5)	164.9 (191.2)
NNLO	172.3 (177.8)	199.3 (187.0)	149.8 (182.3)	152.5 (185.4)

New data results of fits

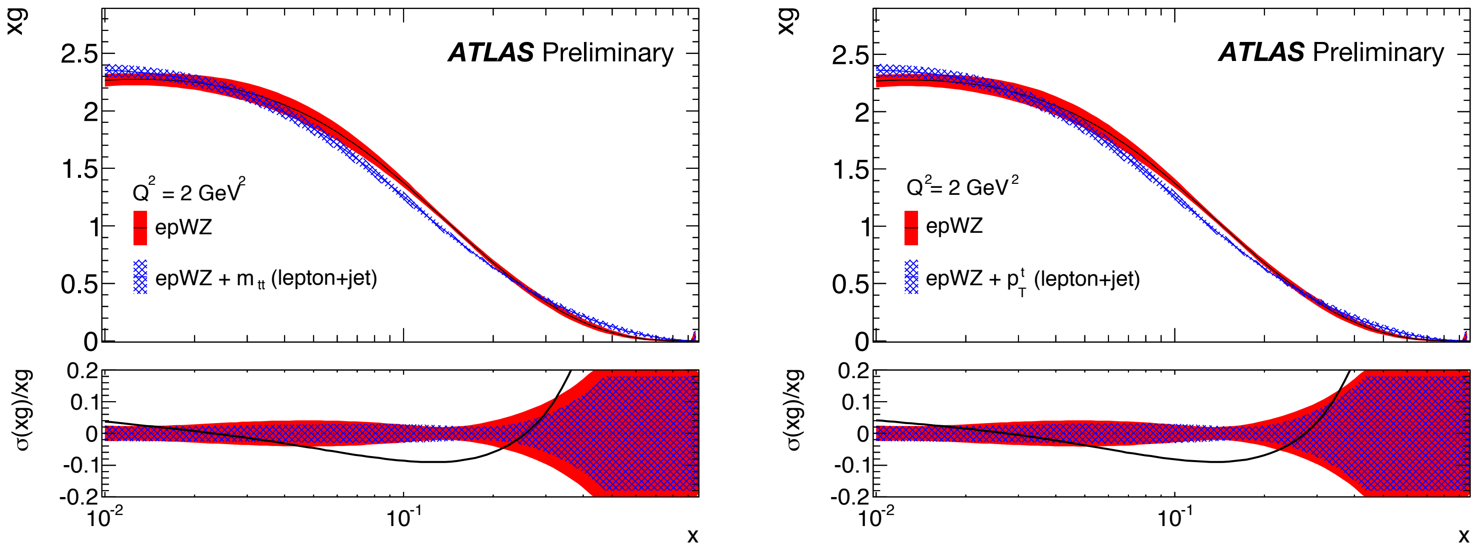


Central values and uncertainties insensitive to decorrelation of two sources between rapidity bins. Find softer gluon, reduced uncertainty.

Also relatively little sensitivity to scales and jet radius.

Differential $t\bar{t}$ data.

A similar issue noticed in ATL-PHYS-PUB-2018-017 –(NNLO Differential top-antitop production now available Czakon *et al*).



Distributions in $m_{t\bar{t}}$ and p_T^t both fit well with similar pulls on gluon.

However, χ^2 in joint fit very poor.

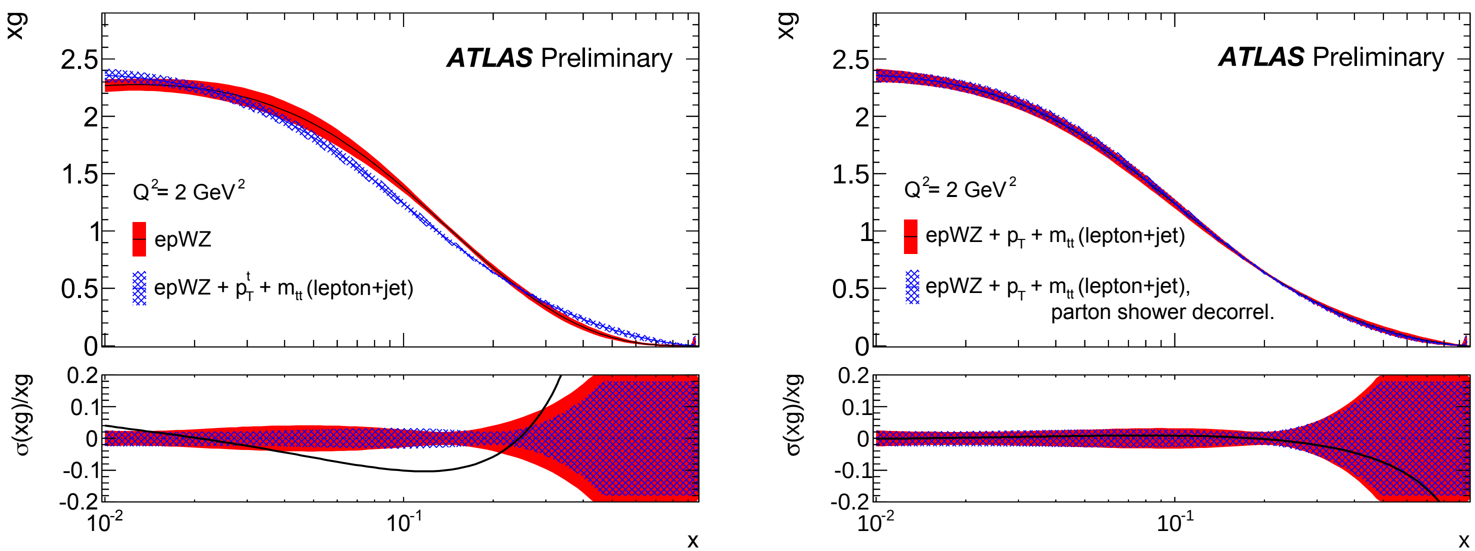
		lepton+jets spectra			
		p_T^t and y_t with statistical correlations	p_T^t and y_t without statistical correlations	p_T^t and m_{tt} with statistical correlations	p_T^t and m_{tt} without statistical correlations
Total χ^2/NDF		1264 / 1068	1260 / 1068	1290 / 1070	1287 / 1070
Partial χ^2/NDP	HERA	1148 / 1016	1147 / 1016	1162 / 1016	1162 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	82.7 / 55	83.5 / 55	83.2 / 55	83.1 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	33 / 13	30 / 13	45 / 15	42 / 15

Again because some correlated systematic uncertainties require very different pulls. All related to 2-point model uncertainties.

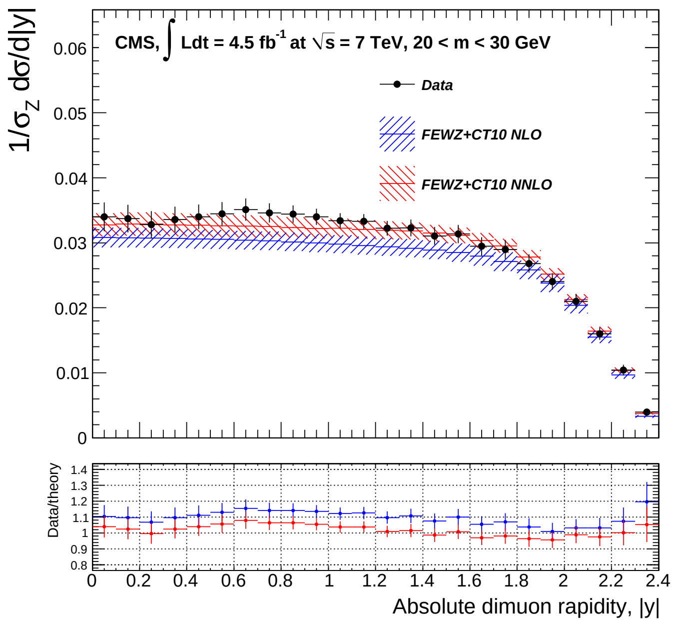
Systematic uncertainty source	lepton+jets spectrum			
	p_T^t	y_t	y_{tt}	m_{tt}
Hard scattering model	+0.74± 0.31	+0.48± 0.22	+0.92± 0.37	-0.43± 0.20
Parton shower model	-1.32± 0.43	-0.79± 0.26	-0.51± 0.17	+0.39±0.13
ISR/FSR model	-0.47± 0.18	-0.87±0.30	-1.27± 0.38	+0.33± 0.10

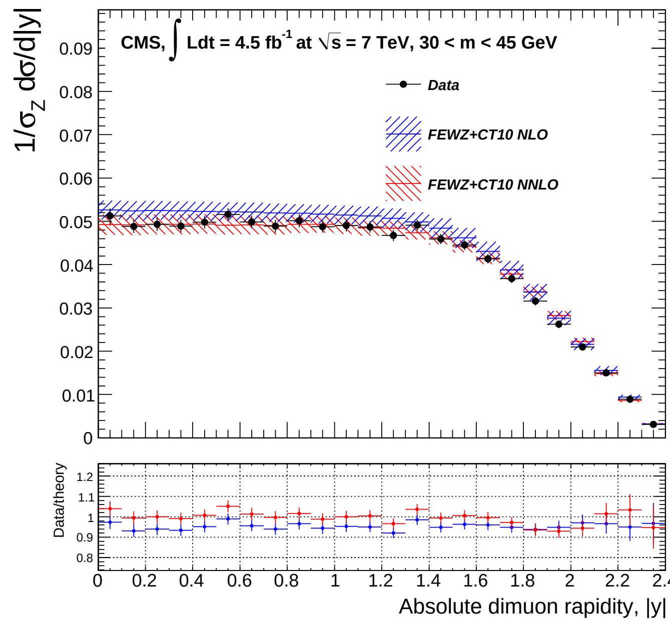
Decorrelation between distributions give much better fit but very similar effect on the gluon distribution.

		lepton+jets spectra		
		p_T^t and y_t decorrelate 2-point uncertainties	p_T^t and m_{tt} decorrelate 2-point uncertainties	p_T^t and m_{tt} decorrelate parton-shower model uncertainty
Total χ^2/NDF		1259 / 1068	1247 / 1070	1248 / 1070
Partial χ^2/NDP	HERA	1147 / 1016	1154 / 1016	1153 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	83.9 / 55	81.9 / 55	81.6 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	27.8 / 13	11.5 / 15	14.1 / 15



CMS Drell Yan data. Fit very poor at NLO in lowest mass bins (where it is effectively LO), even when data highly weighted.





Enormously better fit quality at NNLO. Potentially important to perform small-x resumed fits?

Sensitivity to strange fraction in quarks, but differs at NLO and NNLO and weak compared to direct constraint from di-muon data.

Cannot use 8 TeV data due to problems in understanding uncertainties. (Also found by CSKK - Phys.Rev. D98 (2018) 014027 study where ATLAS W, Z data dominate.)

xFitter tool for individual PDF studies

xFitter Project

www.xfitter.org

2011 Open Source Revolution:
first open source QCD Fit Platform which started the wave of sharing QCD fit codes
EPJC (2015), 75: 304

- A team of ~30 developers:
  - LHC/HERA/theory/independent
  - several releases since 2011
  - 33 publications that have used the framework [in total]

synergy between experiment and theory groups

provides a unique QCD framework to address theoretical differences:
→ benchmark exercises/collaborative efforts/topical studies
provides means to the experimentalists to optimise the measurements:
→ assess impact/consistency of new data

Dedicated studies [xFitter developers]
method in preserving correlation between PDFs extracted at different orders in pQCD
address consistency of Tevatron measurement and evaluate their collective impact on valence
determination of the running mass in $\overline{\mathrm{MS}}$ scheme

R. Plačakytė PDF4LHC, CERN, 13 Sept 2016 4

Schematic View of the xFitter Program

Main steps in QCD analysis:

Parametrise PDFs at the starting scale

→ multiple options for functional forms
  → Standard Polynomial, Chebyshev, etc

Evolve to the scale corresponding to data point

→ QCD(DGLAP) evolution codes [QCDNUM, APFEL]
→ kt ordered evolution, dipole models, QCD(DGLAP)+QED

Calculate the cross section

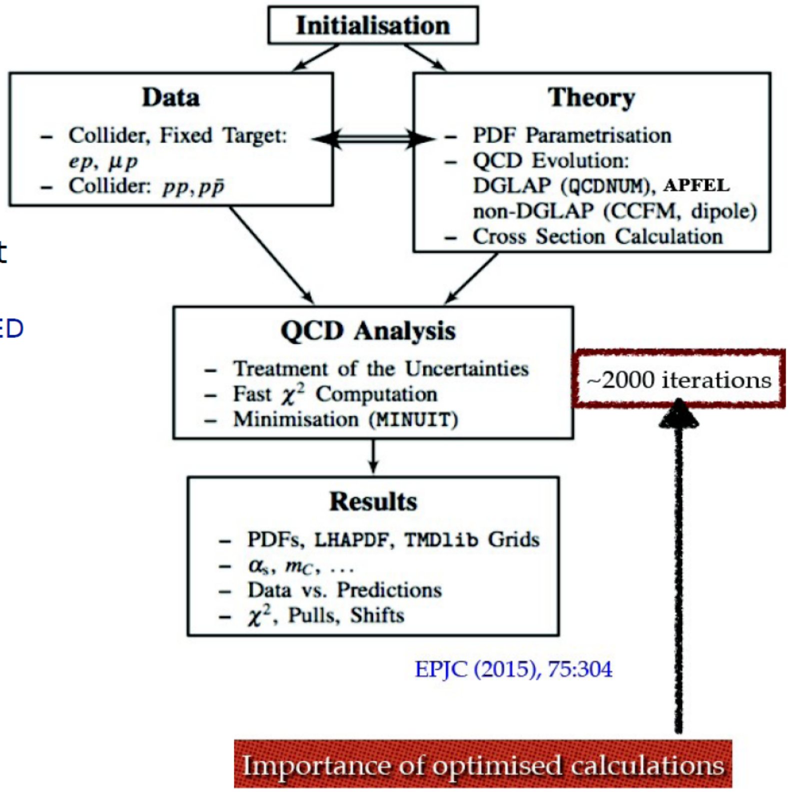
→ various heavy flavour schemes:
  → RT, ACOT, FONLL, FFNS(ABM)
→ fast grid techniques interfaced to DY:
  → APPLGRID, FASTNLO

Compare with data via χ^2:

→ multiple forms to account for correlations

Minimize χ^2 with respect to PDF parameters

→ profiling, reweighting
→ fit: MINUIT, data driven regularisation

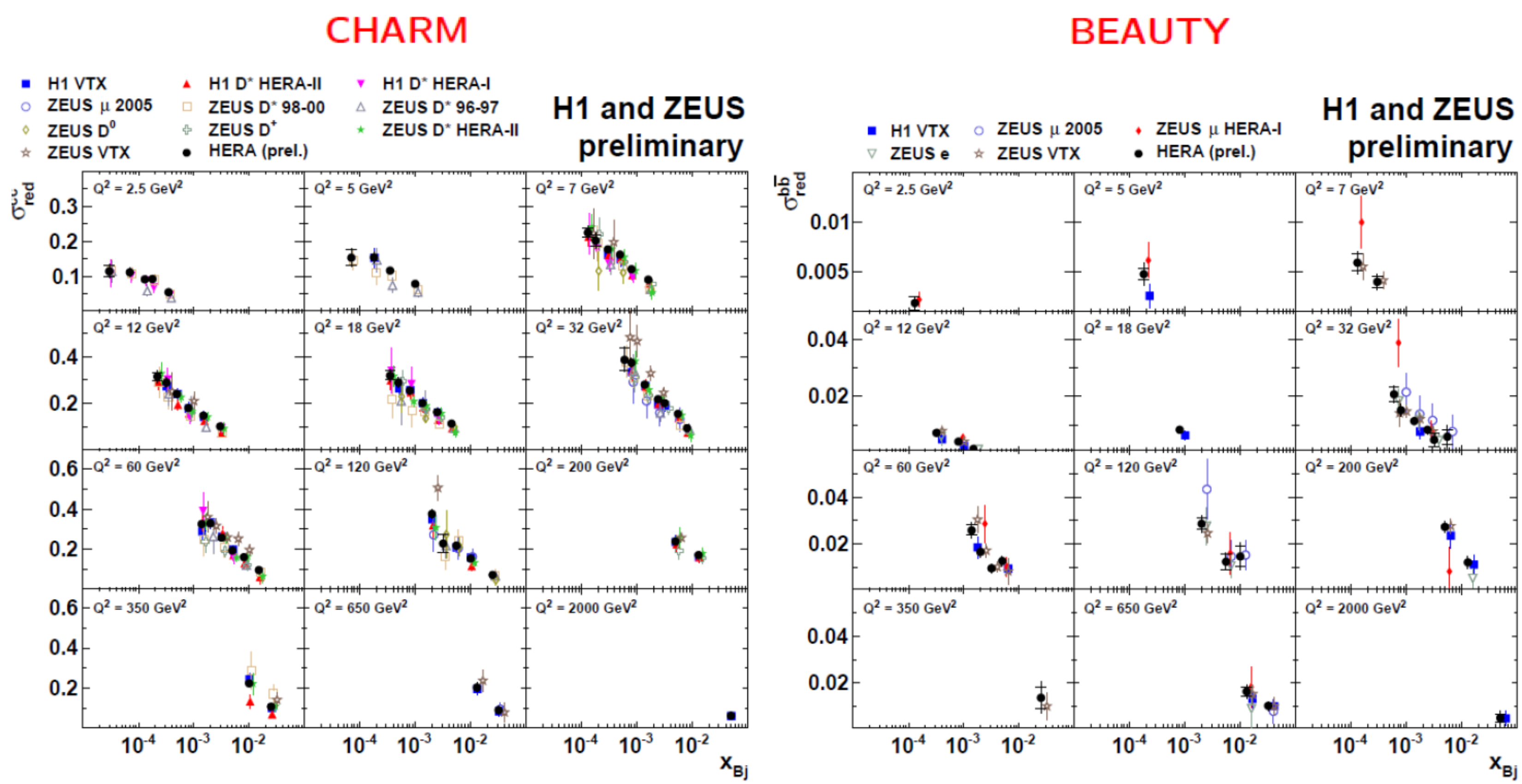


I would advise caution in use to assess "impact" of new data set.

Must consider what already constrains given PDF (not just HERA data).

Final HERA heavy flavour data – Cooper-Sarkar PDF4LHC

Combined data



χ^2/dof = 149/187, including correlations: input data are consistent

9

To be included in updated fits – some problems compared to predictions.

QCD analysis of combined charm and beauty data

Similar to HERAPDF2.0 FF:

- performed using xFitter [www.xfitter.org]
- inclusive HERA data + **new combined $c\&b$ data**
- NLO DGLAP [QCDNUM] and matrix elements [OPENQCDRAD], $n_f = 3$
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_Q^2}$ varied by factor 2 (model unc.)
- **free $m_c(m_c)$, $m_b(m_b)$**
- $\alpha_s(M_Z)^{n_f=3} = 0.106$ ($\rightarrow \alpha_s(M_Z)^{n_f=5} = 0.118$)
- HERAPDF parametrisation, 14p
- fit uncertainty using $\Delta\chi^2 = 1$
- model and parametrisation uncertainties

$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+7}_{-31}(\text{par})\ \text{MeV}$$

$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{mod})^{+1}_{-31}(\text{par})\ \text{MeV}$$

$\Rightarrow$ **determined precise HQ masses consistent with world average**

PDG2016: $m_c(m_c) = 1270 \pm 30$ MeV, $m_b(m_b) = 4180^{+40}_{-30}$ MeV

16

Important developments in other PDF tools.

motivation, and APPLfast

- **interpretation of exp. data requires fast theory predictions**
  often need **repeated computation of same cross section**, for EG: pdf uncertainties and/or alternative sets; scale variations, μ_R, μ_F; variation of $\alpha_s(M_Z)$; SM parameter fits

- **jet cross section calcs. at NLO were slow – historical reason for development of interpolation grids**
- nowadays **NNLO** in general very demanding!
- **need procedure for fast repeated computations of higher order cross sections**
  → interpolation grids using **APPLgrid** or **fastNLO**

- **APPLfast:** common project of **APPLgrid**, **fastNLO** and **NNLOJET** authors:
- **NNLOJET:** semi-automated calculation of NNLO QCD cross sections
  (authors from CERN, ETH, Zurich, IPPP, Lisbon)
- **APPLfast:** interface between **NNLOJET** and **fast grid technology**:
- implementation for both **APPLgrid** and **fastNLO**;
- aims to be as **unobtrusive** as possible, for both ends of interface;
- **flexible**; intended to be reusable by other theory codes

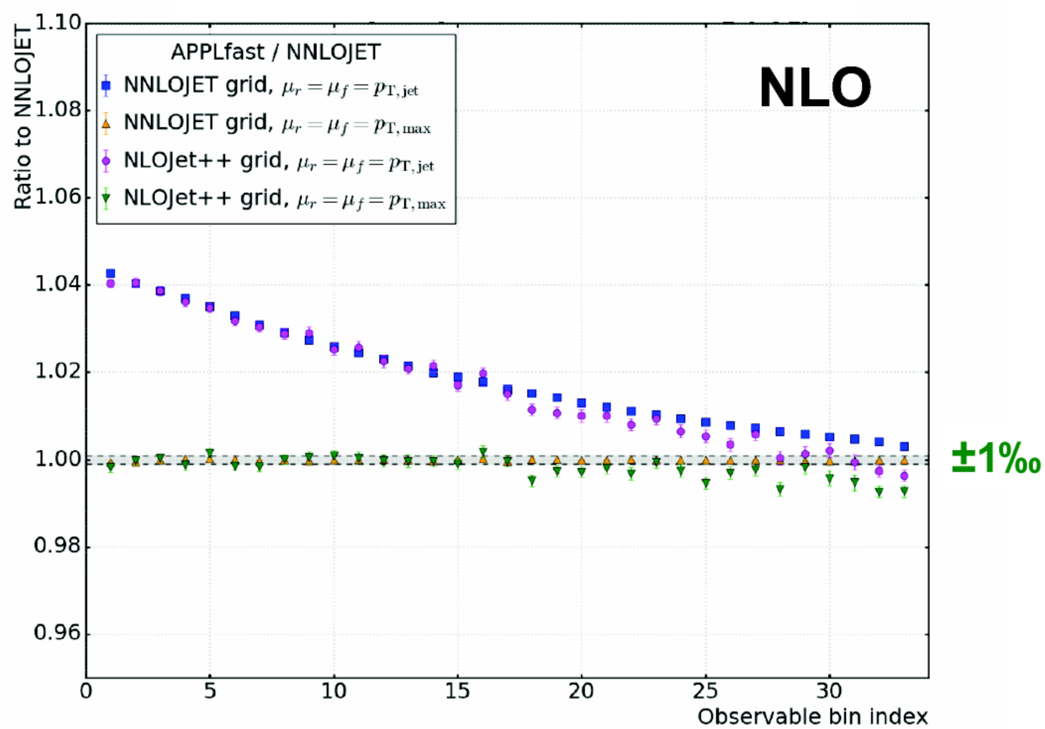
(see also write up in Les Houches proceedings, arXiv:1803.07977)

2

Gwenlan, DIS 2018

Heading towards full results for jets.

cross check with NLOJet++



ratio always to NNLOJET with scale ptmax

error bars: stat. uncertainty estimate from NNLOJET and NLOJet++

16

Gwenlan, DIS 2018

Also, new site for grids under construction.

grid distribution – Ploughshare

What is Ploughshare ?

1. **Quick to use** - a web based utility for the automated distribution of fast inperpolation grids for the high energy physcis community.
2. **Secure storage** - registered users can upload grid files and corresponding standard format configuration files to describe the grids and physics processes and these are added to a central repository.
3. **Automatic distribution** - a standard utility library will be provided to download any required grids automatically in user code.

A utility for the community Ploughshare allows users to share their grids, so it is important that the provenance of the grids is guaranteed. This is achieved by allowing only registered users to upload their validated grids. Subsequently however, anyone is free to download and use the grids as they wish.

Fast operations summary

Navigate quickly to some of the primary operations you might be interested in

Download grids
Veiw all the lovely grids which are available for download

Upload grids
Upload grids using the standard web interface

Download grid code
Get the code for the automated download of multiple grids

Settings
How to set up the automated code for the grid downloads

- **new project**; registered users can upload grids with documentation
- automated job treats upload
  - adds to appropriate location in file system
  - generates relevant lists and display web pages
- provides user interface for **automated download** with a simple line of code
- expression of interest from many stakeholders…
- proof of concept ready…
  CONTRIBUTIONS WELCOME!

21

Gwenlan, DIS 2018

Photon PDF in proton

LUXqed photon PDF (A. Manohar et al., PRL 117, 242002 (2016), JHEP 1712, 046 (2017)) relates photon to structure functions.

LUXqed

- Recent study of arXiv:1607.04266:

CERN-TH/2016-155

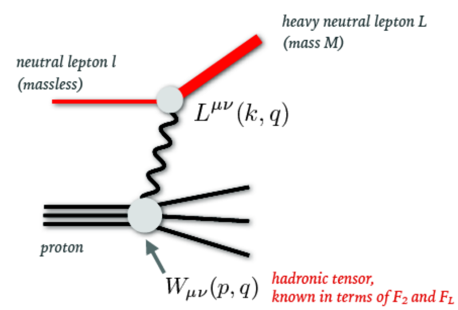
How bright is the proton?
A precise determination of the photon PDF

Aneesh Manohar,[1,2] Paolo Nason,[3] Gavin P. Salam,[2,*] and Giulia Zanderighi[2,4]

[1]*Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA*
[2]*CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[3]*INFN, Sezione di Milano Bicocca, 20126 Milan, Italy*
[4]*Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, University of Oxford, UK*

- Show how photon PDF can be expressed in terms of F_2 and F_L. Use measurements of these to provide well constrained `LUXqed` photon PDF.

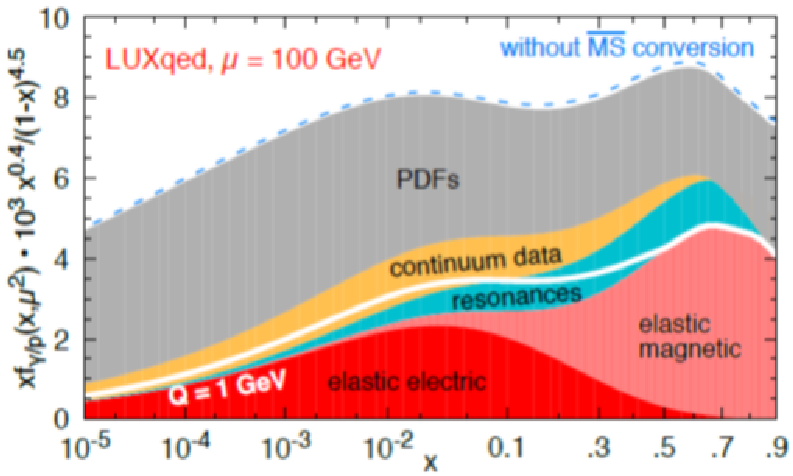
$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\}, \quad (6)$$



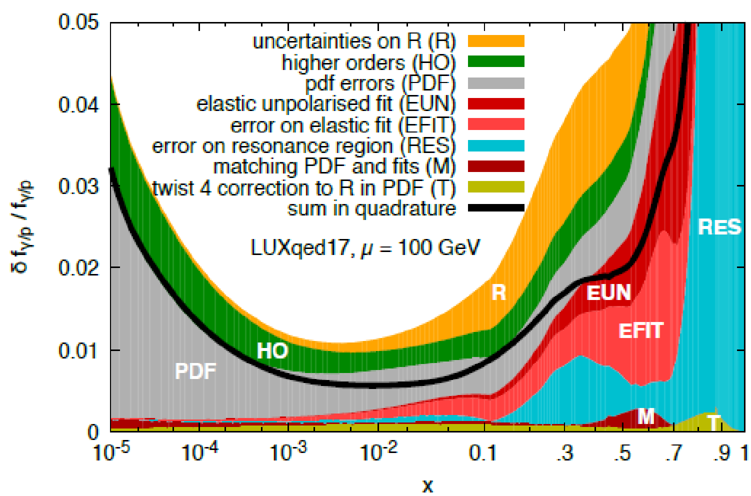
22

Breakdown into well-known elastic (coherent) contribution and moderately model dependent inelastic part Harland-Lang *et al.* PRD94 (2016) 074008. Much better constraint on input.

LUX Contributions and Uncertainties



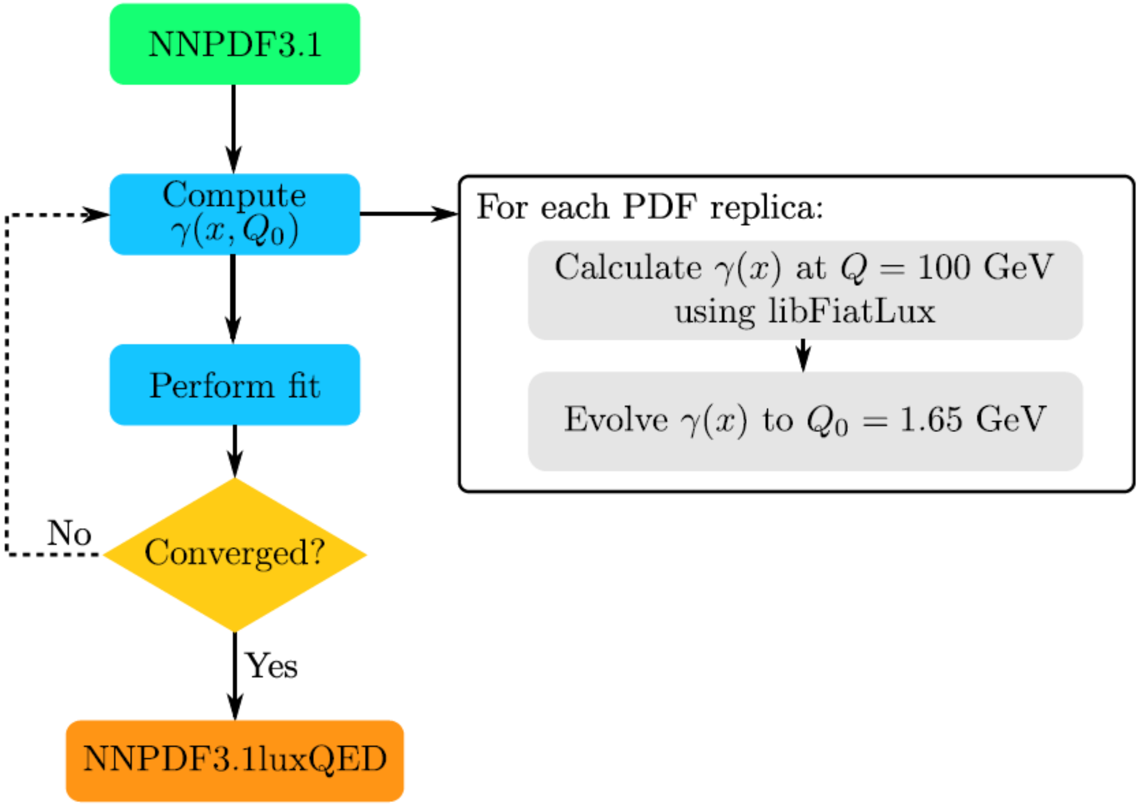
Fractional contributions to high-Q^2 photon. At high-x elastic important, at low x PDF contribution dominates.



Uncertainty contributions. Very precise up to very high x.

NNPDFLux PDFs with QED corrections

Iterative procedure starting with LUX type photon.



Calculate $\gamma(x, Q^2)$ at $Q^2 = 100\mathrm{GeV}^2$ using LUX procedure, but NNPDF PDFs.

Evolve down perturbatively to $Q_0^2 = (1.65)^2\mathrm{GeV}^2$ and use as input for new fit – iterate.

MMHT PDFs with QED corrections – Nathvani

We now base photon input for PDFs at low Q^2 on LUX.

Effect of photon evolution fully incorporated to couple with that of quarks and gluon for both proton and neutron.

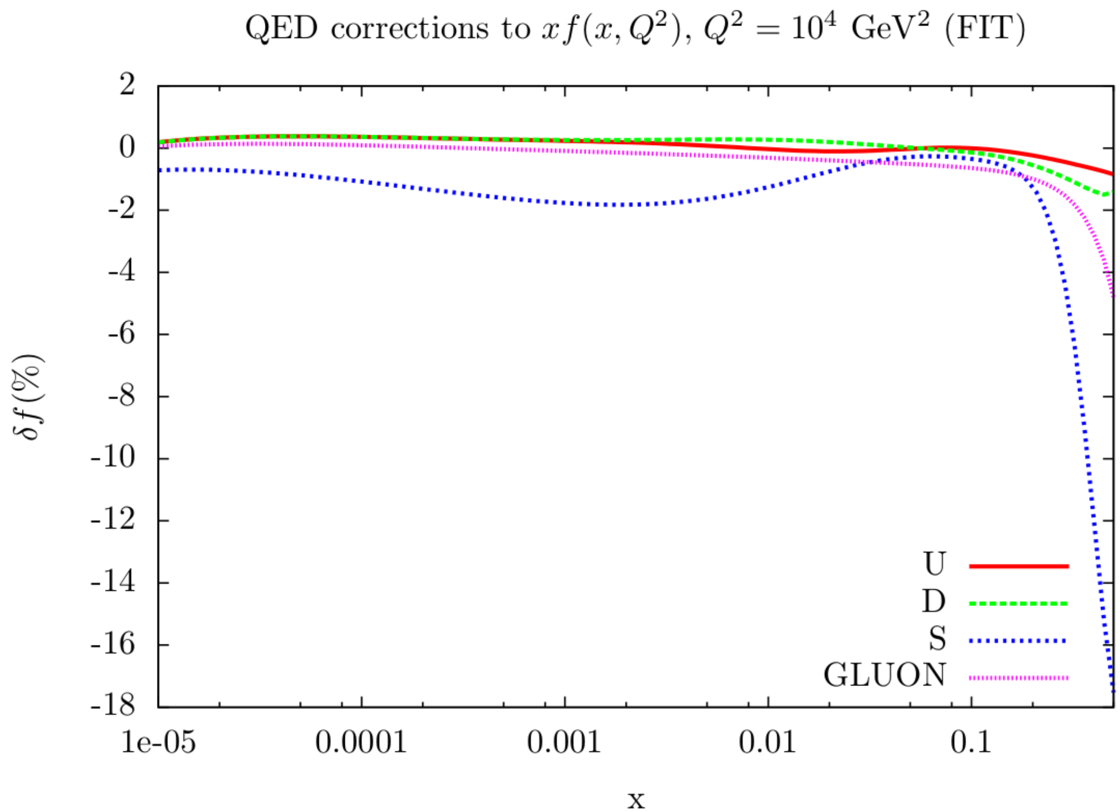
The photon input is defined at $Q_0^2 = 1\mathrm{GeV}^2$, the same as our other PDFs. Input momentum 0.00195.

Input defined by integrating LUX expression up to scale $\mu^2 = Q_0^2$. Hence contribution up to this scale should be identical. (Minor difference from using μ^2 rather than $\mu^2/(1-z)$ as integral limit, with correction in last term $\propto \alpha\ln(1-z)P_{\gamma q}$.)

PDFs evolve up using DGLAP splitting functions to given order in α_s with $\alpha, \alpha\alpha_S$ and α^2 corrections (De Florian *et al*) included.

In addition the photon receives contributions/corrections from “higher twist” sources above $Q_0^2 = 1\mathrm{GeV}^2$ – elastic, target mass, kinematic cuts, higher twist operators ......

Change in PDFs due to refit



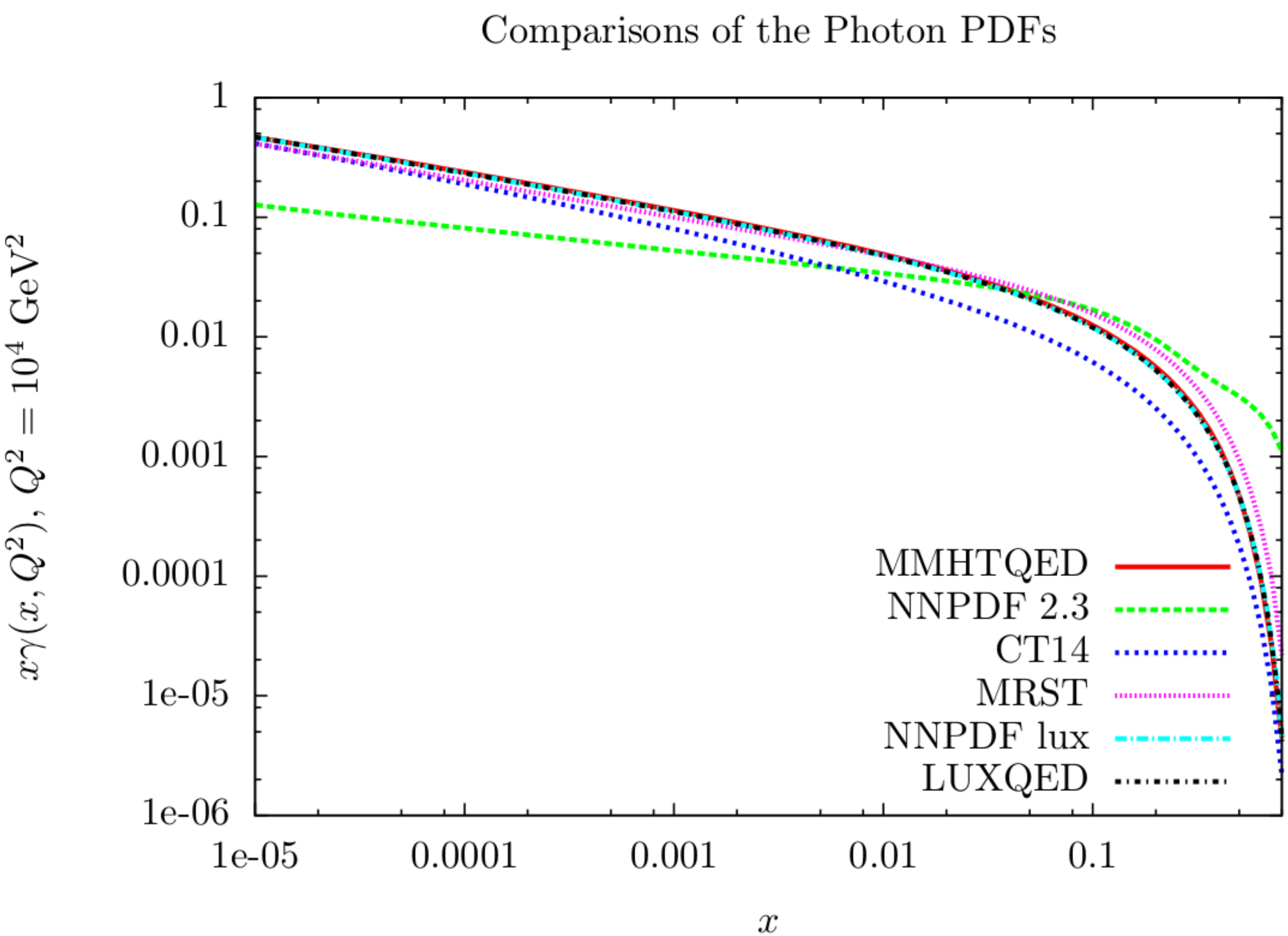
Gluon affected mainly at high x, loss of momentum.

Small x flavour rearrangement in quarks – less strange.

Quarks lose momentum at high x from QED evolution, but reduction in high Q^2 up quark less as compensated for by input.

Modern LUX-based PDFs all in excellent agreement with very small uncertainty.

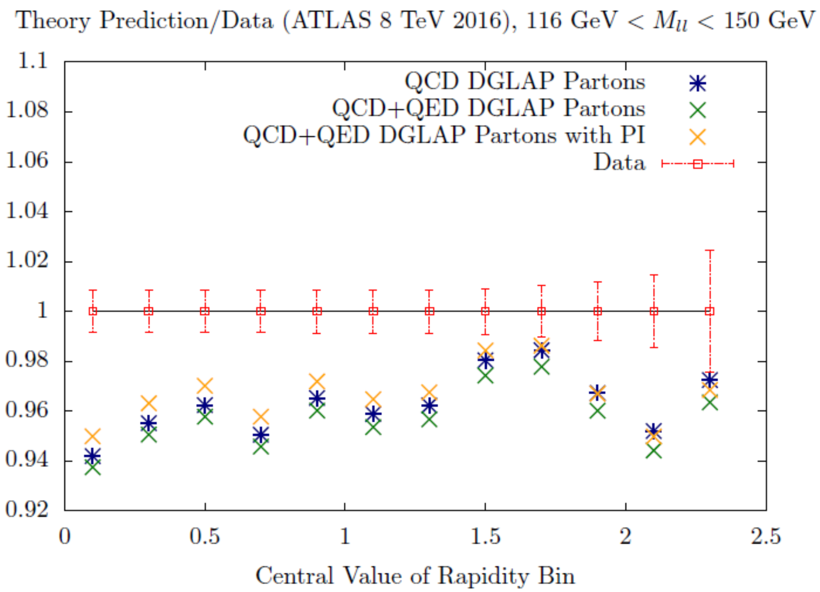
Historical photon PDFs have much more variation.

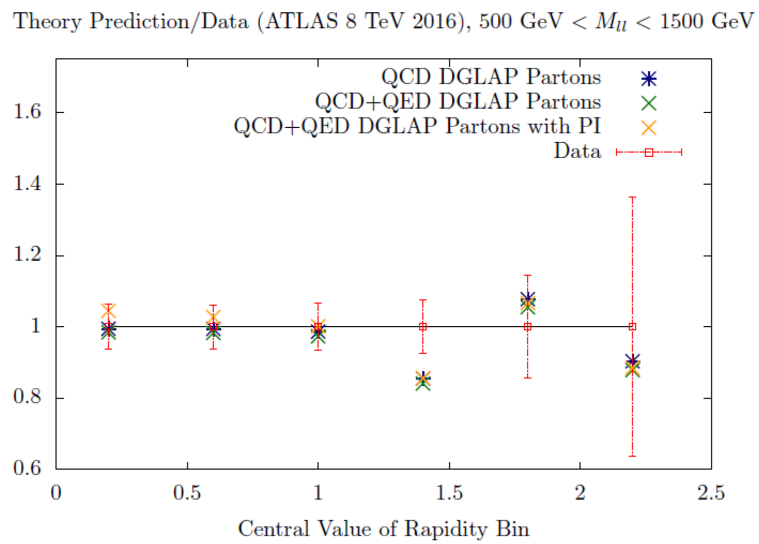


Impact on fit to ATLAS high-mass Drell-Yan data.

This data no longer constrains the photon in any meaningful way. Fit quality including photon contributions $\chi^2/\mathrm{Npts} = 65/48$.

In some bins QED-altered evolution of quarks more important than photon contribution.

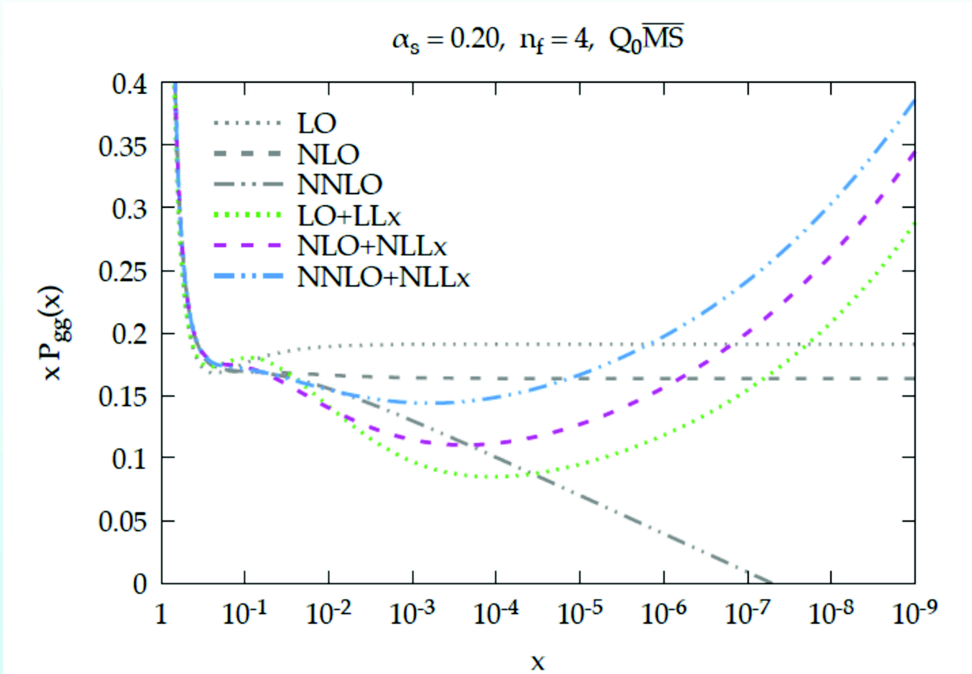




Revival of studies with $\ln(1/x)$ resummation (Fit in Eur.Phys.J. C78 (2018) no.4, 321.)

PDFs with BFKL resummation

- Ultimately, the need for (or lack of) BKFL resummation can only be assessed by performing a **global PDF analysis with (N)NLO+NLLx matched theory**
- Theoretical tools are now available: **HELL for NLLx resummation**, interfaced to the public **APFEL** code



Bonvini, Marzani, Peraro 16
Bonvini, Marzani, Muselli 17

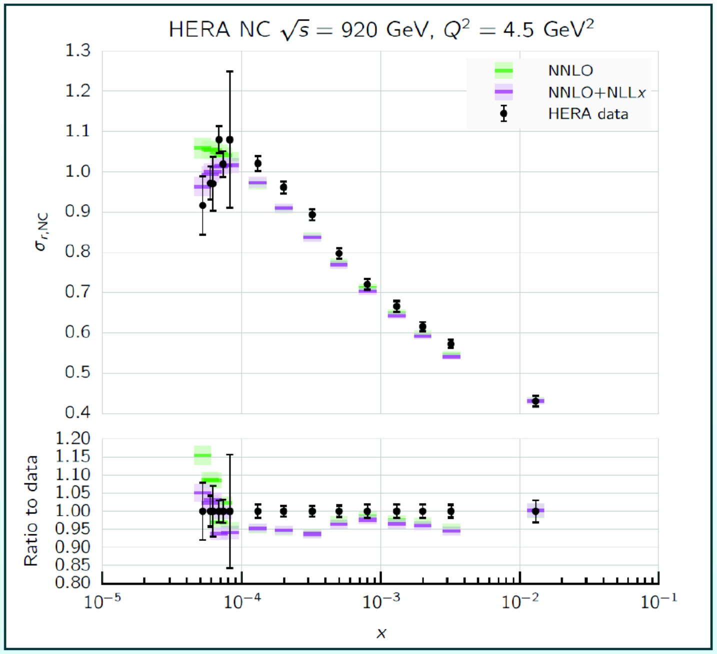
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

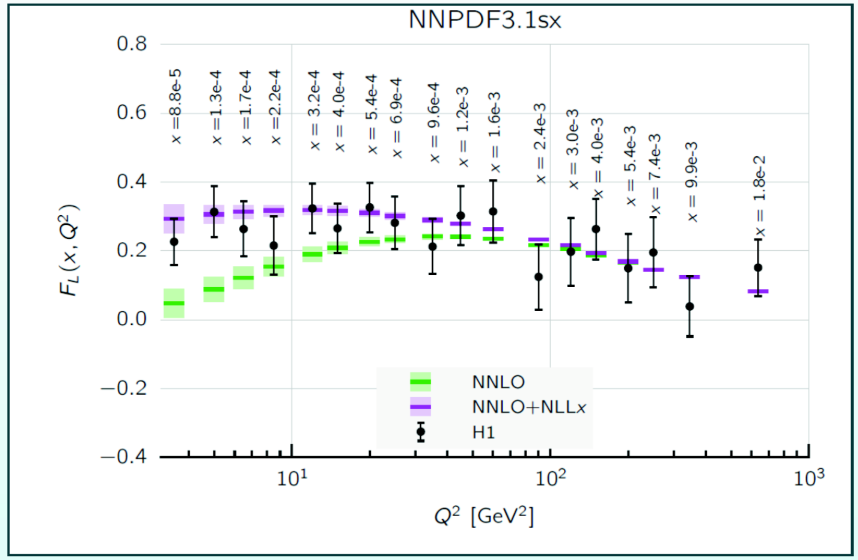
https://www.ge.infn.it/~bonvini/hell/

Juan Rojo 13 PDF4LHC WG meeting, CERN, 06/08/2017

Based on results previously obtained from studies by Altarelli, Ball, Forte, Ciafaloni, Colferai, Salam, Stasto and RT, White.

Comparison with HERA data





Using **NNLO+NLL*x* theory,** improved description of the **small-x NC cross-sections,** in particular of the change of slope

Also **improved description of F_L,** which moreover remains markedly **positive** down to the smallest values of *x* and Q probed

Juan Rojo 18 **PDF4LHC WG meeting, CERN, 06/08/2017**

Also resolves problems in fitting charm data at NNLO.

General results also found by xFitter Eur.Phys.J. C78 (2018) 621, but no issue with fit to charm data in this instance.

Data vs theory

	NNLO fit	NNLO+NLLx fit
Total χ^2/d.o.f	1446/1178	1373/1178
subset NC 920 $\tilde{\chi}^2$/n.d.p	446/377	413/377
subset NC 820 $\tilde{\chi}^2$/n.d.p	70/70	65/70
subset charm $\tilde{\chi}^2$/n.d.p	48/47	49/47
correlated shifts inclusive	102	77
correlated shifts charm	15	11
log term inclusive	20	−3
log term charm	−2	−1

$$\chi^2 = \sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,\mathrm{unc}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,\mathrm{unc}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{unc}} D_i^2 + \delta^2_{i,\mathrm{stat}} D_i^2},$$

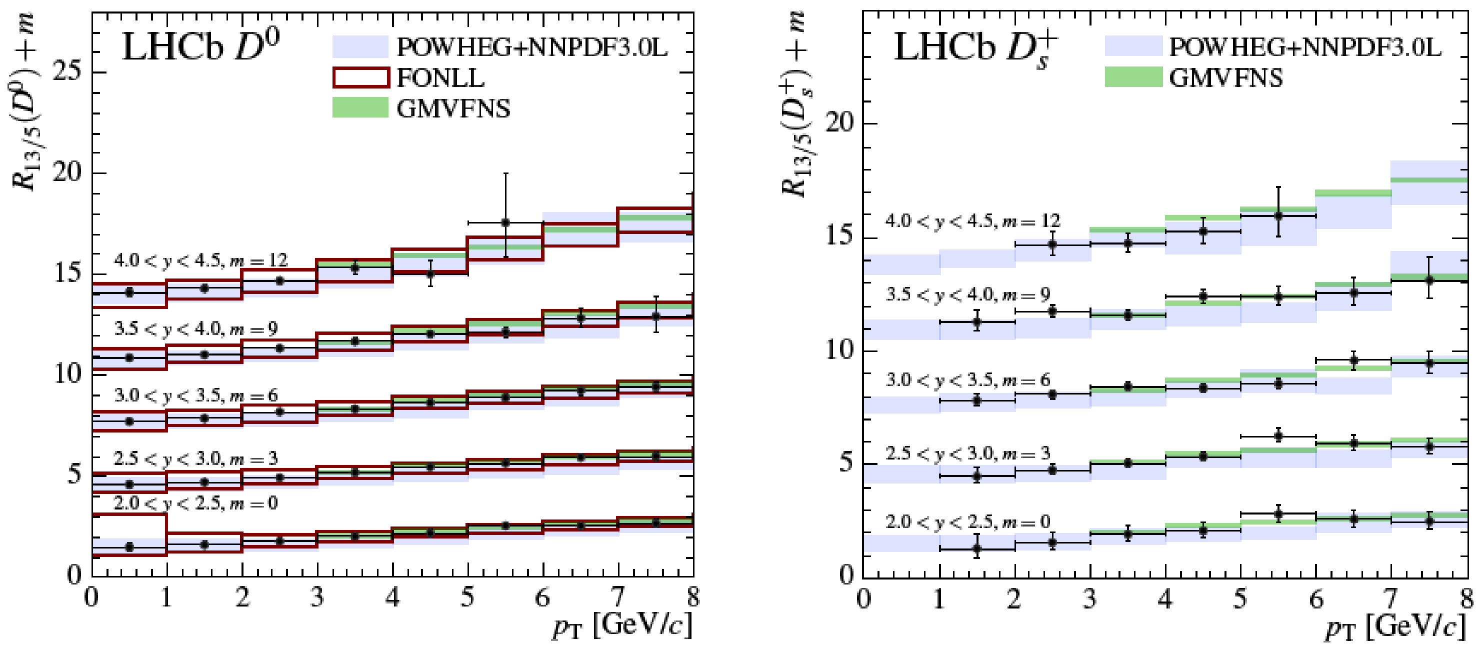
→ largest improvements in the χ^2 are observed for the precise $E_p = 920$ GeV set as well as for correlated systematic uncertainties and log-penalty term.

Bertone, DIS 20178

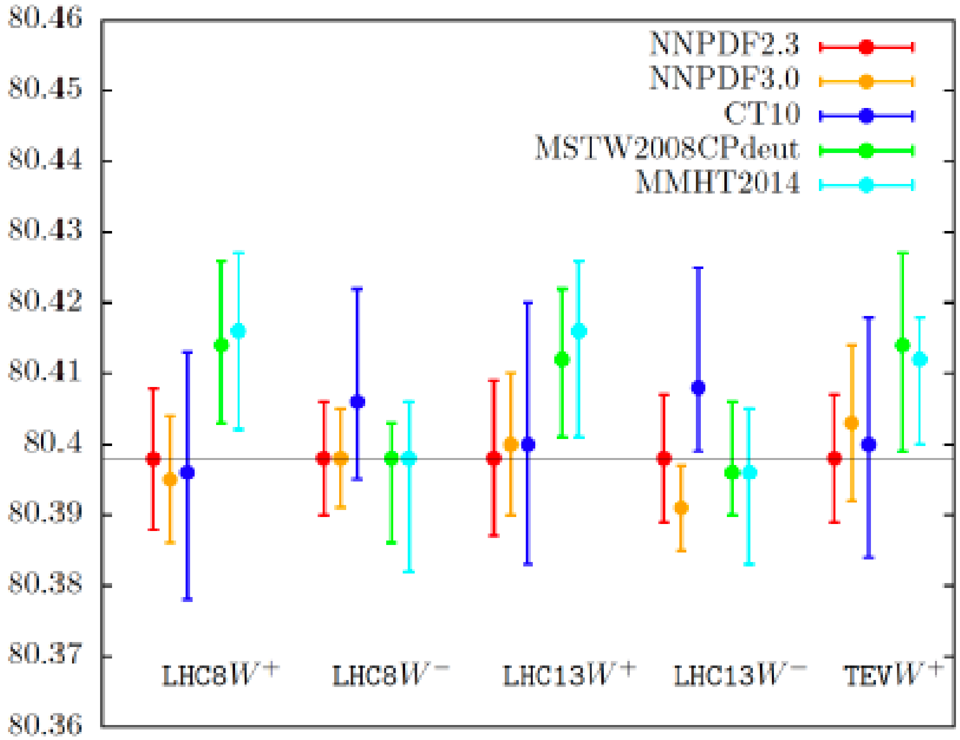
LHCb heavy flavour data potentially constrains this region

Open charm production

JHEP03(2016)159, JHEP05(2017)074, JHEP06(2017)147



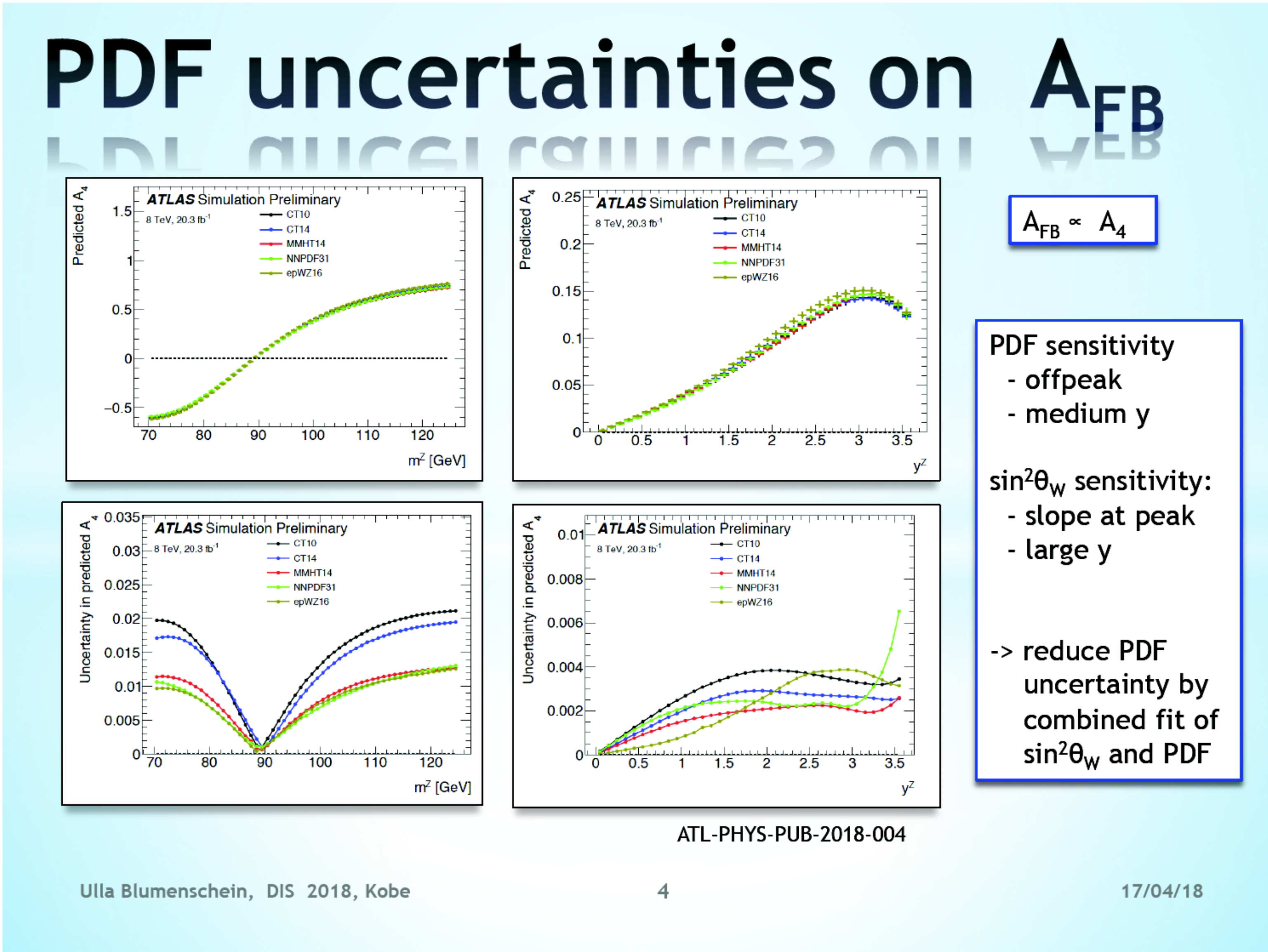
PDFs the dominant uncertainty source for M_W determination.
Bozzi *et al*, Phys. Rev. D91 (11) (2015) 113005.



Significant variation between some PDF sets depending on whether W^+ or W^- used.

There will be some impact for the most recently incorporated LHC data, and from some methodology changes.

Also playing and important role in $\sin^2\theta_W$ extraction.



Very recent study on potential impact of High Lumi LHC on PDFs – Bailey, Gao, Harland-Lang, Khalek, Rojo.

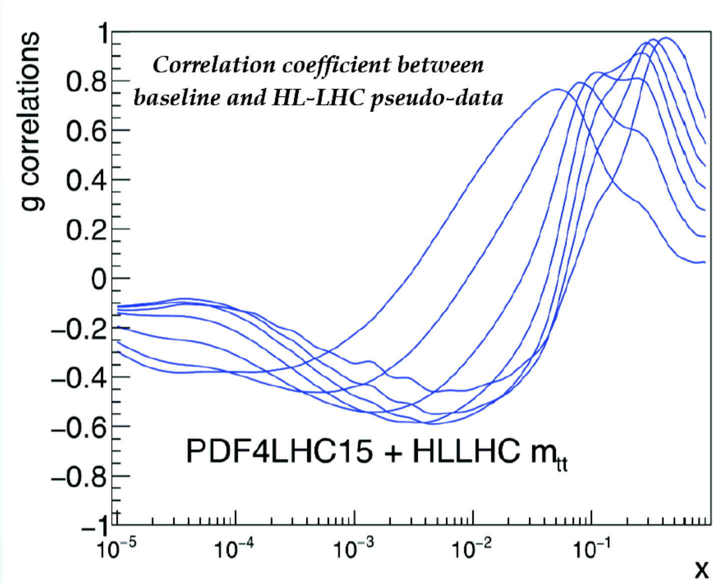
PDF-sensitive processes at the HL-LHC

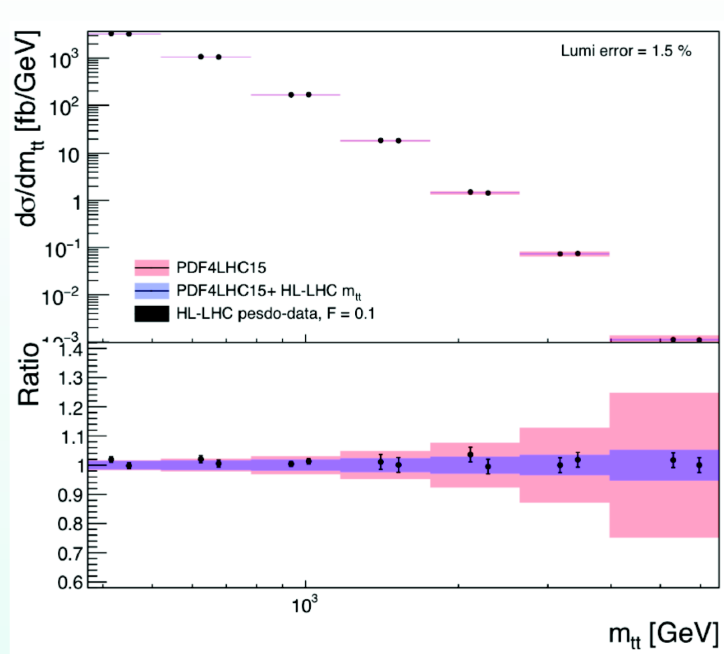
Our analysis is based on a **non-exhaustive** list of **PDF-sensitive processes** at the HL-LHC, with emphasis on **high-p_T region,** and on measurements that are not already **limited by systematic uncertainties**

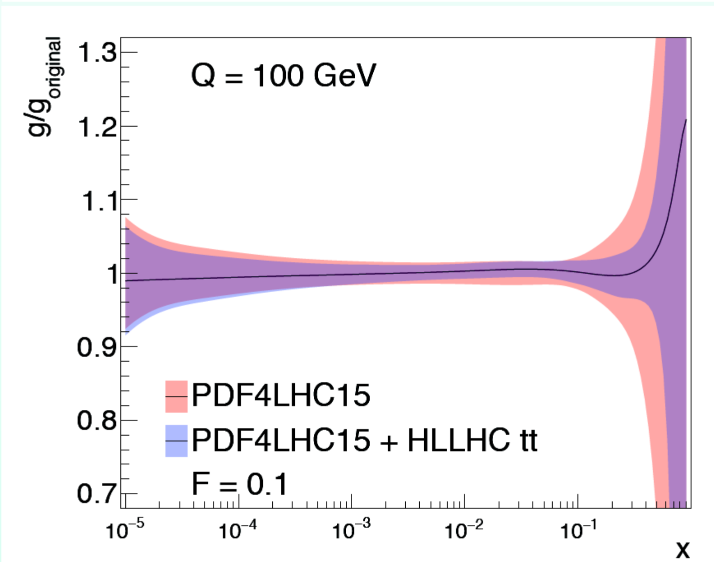
Process	Kinematics	$N_{\rm dat}$	Sensitivity
$Z\ p_T$	$20\,\mathrm{GeV} \le p_T^{ll} \lesssim 3.5$ TeV $12\,\mathrm{GeV} \le m_{ll} \le 150$ GeV $\lvert y_{ll}\rvert \le 2.4$	130	*medium-x gluon*
high-mass Drell-Yan	$m_{ll} \ge 116\,\mathrm{GeV},\ \lvert\eta_l\rvert < 2.5$ $p_T^{l1(2)} \ge 40\ (30)$	21	*antiquarks*
top quark pair	$m_{t\bar{t}} \lesssim 5$ TeV, $\lvert y_t\rvert \le 2.5$	26	*large-x gluon*
W+charm (central)	$p_T^\mu \ge 26\,\mathrm{GeV},\ p_T^c \ge 5\,\mathrm{GeV},$ $\lvert\eta^\mu\rvert \le 2.4$	6	*strangeness*
W+charm (forward)	$p_T^\mu \ge 20\,\mathrm{GeV},\ p_T^c \ge 20\,\mathrm{GeV},\ p_T^{\mu+c} \ge 20\,\mathrm{GeV},$ $2 \le \eta^\mu \le 2.4,\ 2.2 \le \eta^c \le 3.2$	12	*strangeness*
Direct photon	$E_T^\gamma \lesssim 3$ TeV, $\lvert\eta_\gamma\rvert \le 2.5$	60	*medium-x gluon*
Forward W, Z	$p_T^l \ge 20\,\mathrm{GeV},\ 2.0 < \eta_l < 4.5$ $60 < m_{ll} < 120\,\mathrm{GeV},\ 2.0 < y_{ll} < 4.5$	90	*antiquarks*
Inclusive jets ($R = 0.4$)	$\lvert y_{\rm jet}\rvert \le 3,\ p_T^{\rm jet} \lesssim 4$ TeV	54	*large-x gluon*

4 **Juan Rojo** **CERN TH Institute, 17/07/2018**

Top quark pair production



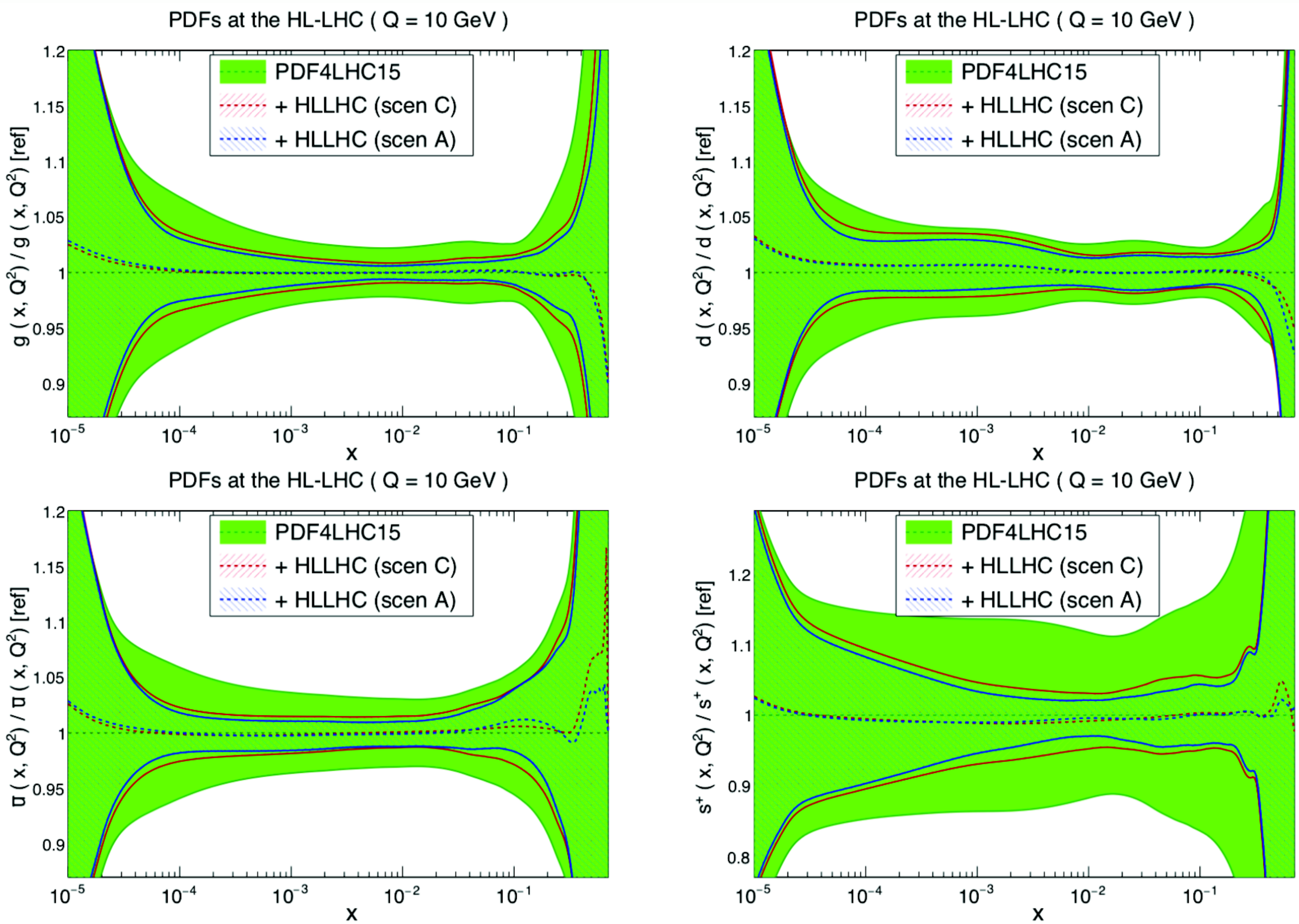




- Instrumental to pin down the **gluon at very large *x*** (m_{tt} reach up to **6 TeV**)
- The kinematical coverage can extend up to **several TeV** at the HL-LHC
- Promising results even without assuming any reduction in systematic errors

Juan Rojo **CERN TH Institute, 17/07/2018**

Parton distributions at the HL-LHC



- **Scenario A: optimistic** (assume systematic uncertainty reduction by factor 2.5)
- **Scenario B: Conservative** (assume no reduction in systematic errors)

10

Juan Rojo **CERN TH Institute, 17/07/2018**

Partonic luminosities at the HL-LHC

Uncertainty reduction in PDF luminosities as compared to the baseline (current situation)

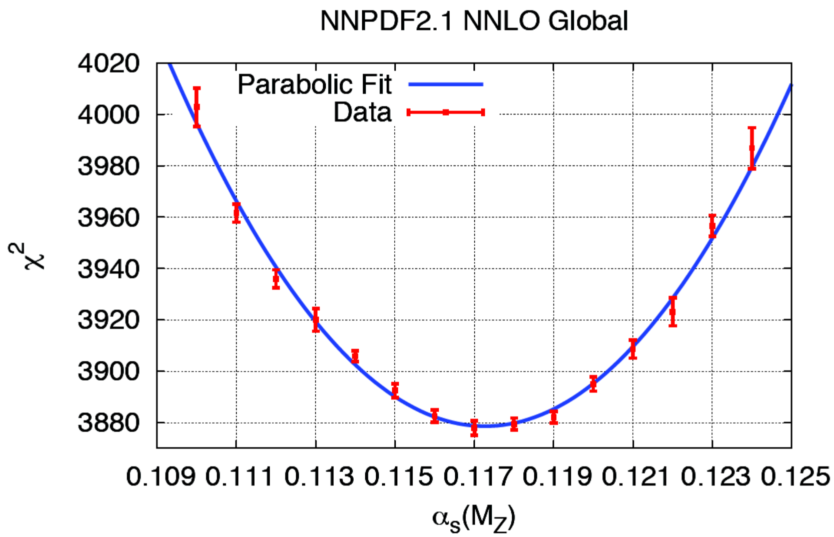
PDF uncertainties HLLHC / Current	10 GeV < M_X < 40 GeV	40 GeV < M_X < 1 TeV	1 TeV < M_X < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)
up-strange luminosity	0.73 (0.67)	0.38 (0.27)	0.42 (0.38)

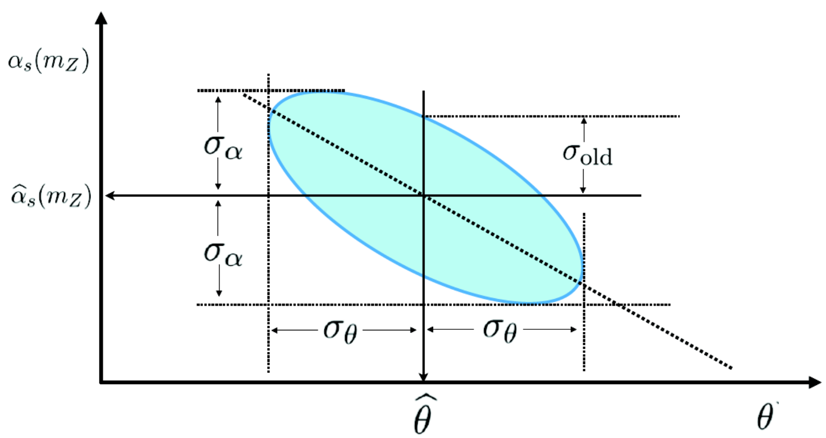
- In the region **M_X > 40 GeV**, the constraints from the HL-LHC can lead to a reduction of the PDF uncertainties in the partonic lumis of **up to a factor 4 in the optimistic scenario**
- Even with rather conservative assumptions, a **PDF error reduction between a factor 2 and 3** can be expected
- Moreover, these results are mostly likely **upper bounds** on the HL-LHC potential, since we have not included other PDF-sensitive processes (dijets, single top, low-mass DY, charged meson production, …)

Studies on best-fit $\alpha_S(M_Z^2)$

DETERMINING ALPHAS FROM A GLOBAL FIT

[1802.03398]





Previous NNPDF determination Based on a scan of NNPDF2.1
[1110.2483]

Measure the χ^2 of best fit PDF parameters as a function of α_S

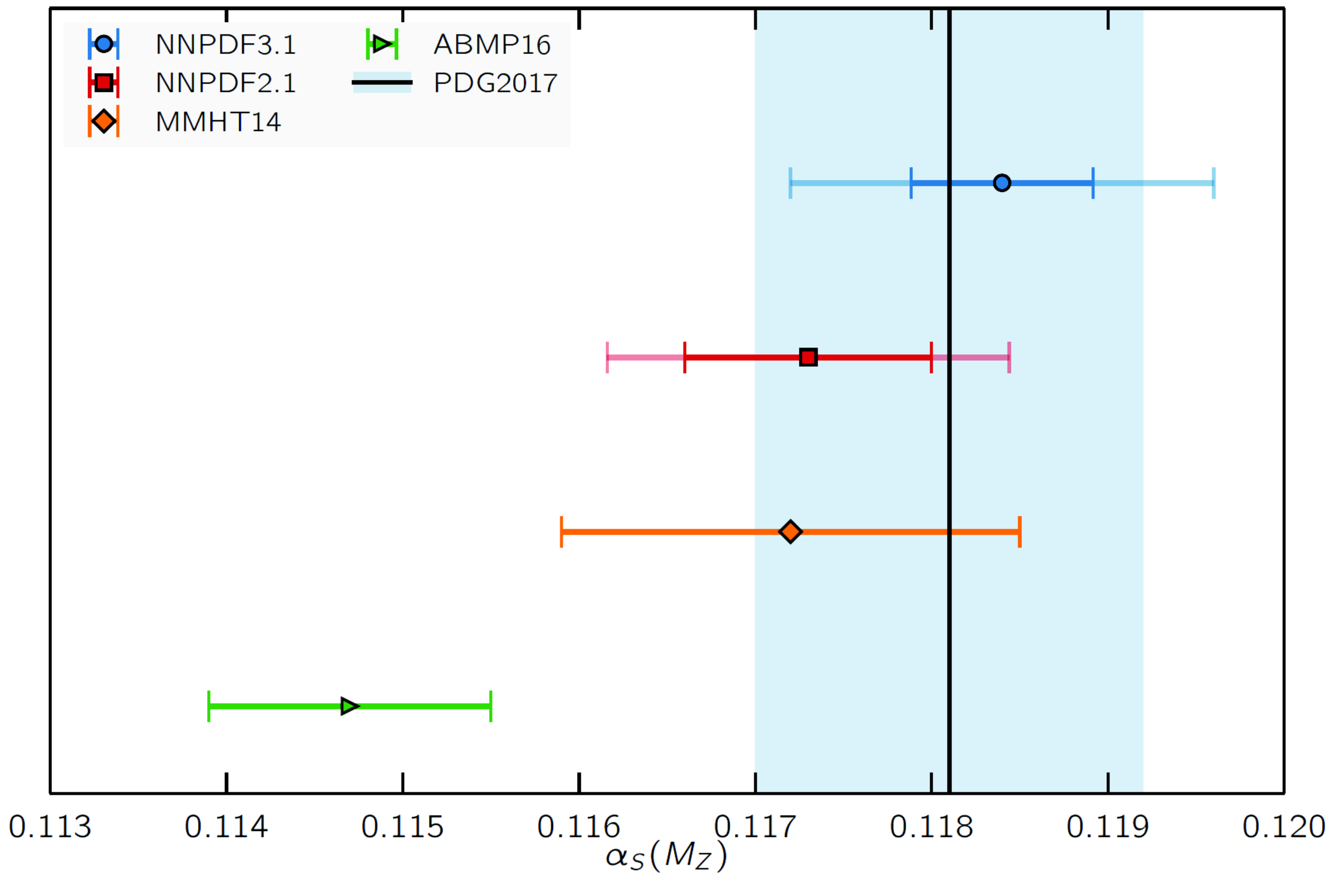
Neglects correlations with PDF fit parameters (θ) - important when experimental uncertainties are small

Ideally one should minimise PDFs and α_S simultaneously

RESULTS

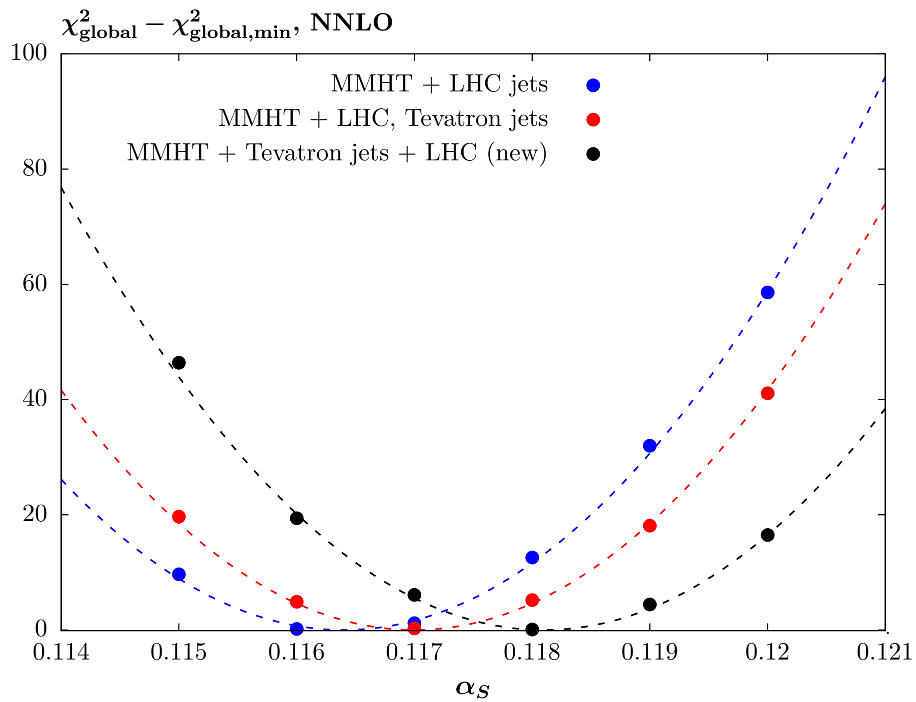
[1802.03398]

$$\alpha_s^{\rm NNLO}(m_Z) = 0.1185 \pm 0.0005^{\rm exp} \pm 0.0001^{\rm meth} \pm 0.0011^{\rm th} = 0.1185 \pm 0.0012 \;(1\%)$$



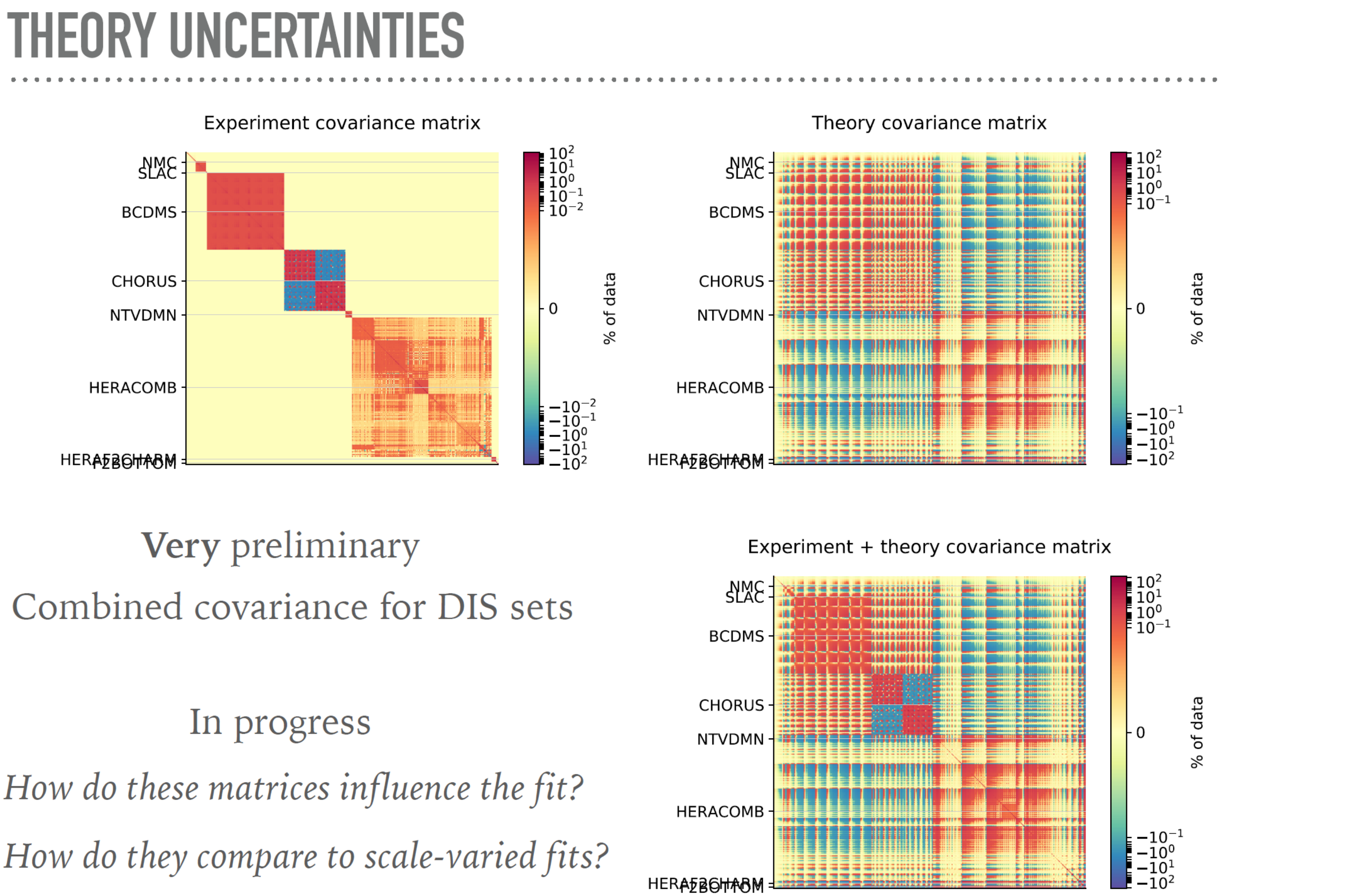
For MMHT2014 $\alpha_S(M_Z^2) = 0.1172 \pm 0.0013$ ($\alpha_S(M_Z^2) = 0.1178$ when world average added as data point). With 8 TeV data on $\sigma_{\bar{t}t}$ and final HERA data went to $\alpha_S(M_Z^2) = 0.118$.

For further addition of LHC jets and removal of Tevatron jet data, $\alpha_S(M_Z^2) = 0.1164$. When Tevatron jets also added back $\alpha_S(M_Z^2) = 0.1173$



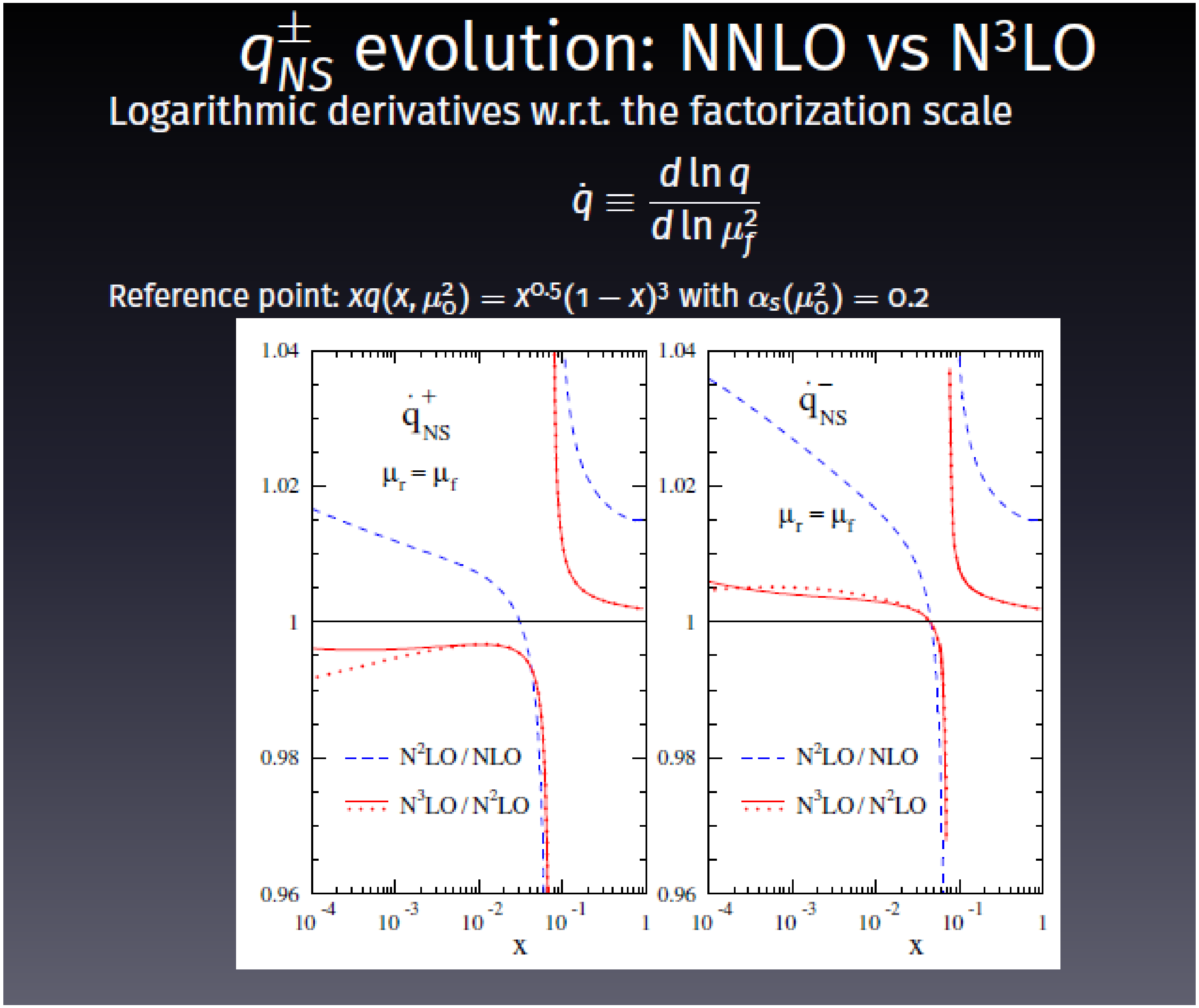
Also look at inclusion of newer W, Z data from ATLAS, CMS, LHCb. Without newer LHC jet data $\alpha_S(M_Z^2) = 0.1179$ but with these data $\alpha_S(M_Z^2) = 0.1176$.

Reaching the point where theory unrelated related to PDFs becoming vital. First attempts by varying scales by NNPDF.



Uncertainties **related to** PDFs not the same as uncertainties **on** PDFs.

However, also some progress on explicitly obtaining higher corrections
Ueda, *et al.*



or on calculating PDFs in a complete different manner, i.e. lattice.

Mom.	Collab.	Ref.	N_f	Status	Disc	QM	FV	Ren	ES		Value
$\langle x \rangle_{u^+ - d^+}$	LHPC 14	[249]	2+1	P	■	★	★	★	★		0.140(21)
	ETMC 17	[250]	2	P	■	★	■	★	★	*	0.194(9)(11)
	RQCD 14	[251]	2	P	■	■	○	★	★	**	0.217(9)
$\langle x \rangle_{u^+}$	ETMC 17	[250]	2	P	■	★	■	★	★	*▷	0.453(57)(48)
$\langle x \rangle_{d^+}$	ETMC 17	[250]	2	P	■	★	■	★	★	*▷	0.259(57)(47)
$\langle x \rangle_{s^+}$	ETMC 17	[250]	2	P	■	★	■	★	★	*▷	0.092(41)(0)
$\langle x \rangle_{g}$	ETMC 17	[250]	2	P	■	★	■	○	★	*	0.267(22)(27)

* Study employing a single physical pion mass ensemble.
** Study employing a single ensemble with $m_\pi = 150$ MeV.
▷ Nonsinglet renormalization is applied.

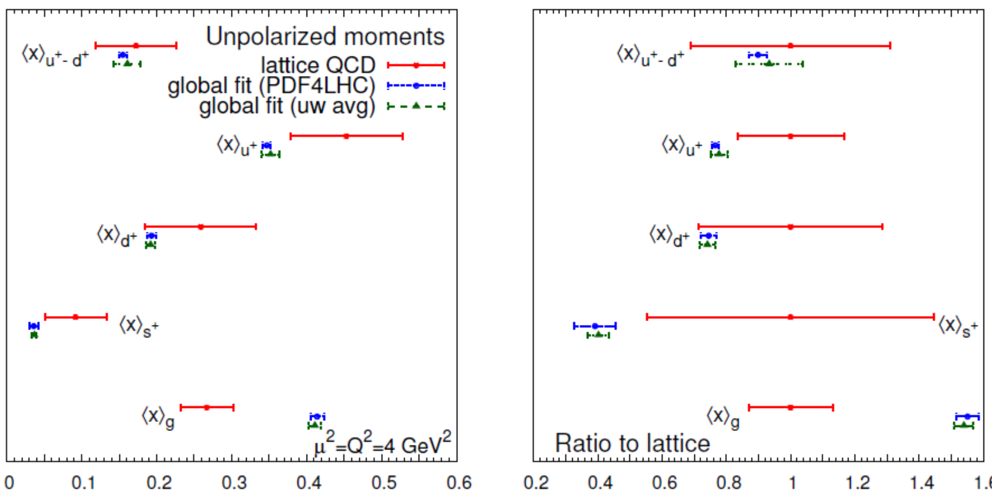


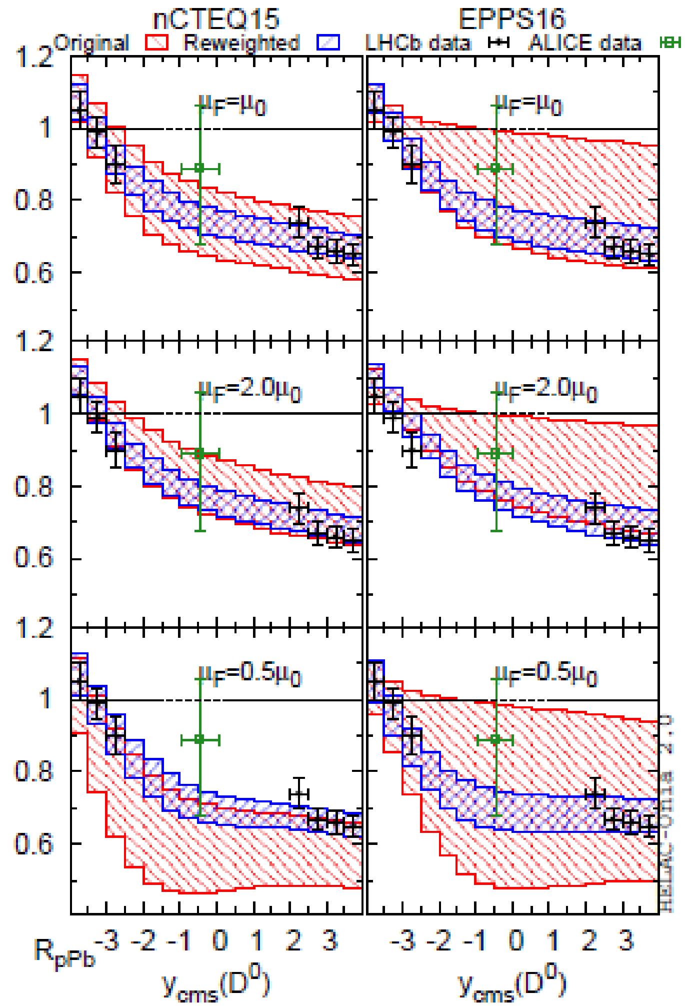
Figure 3.2: A comparison of the unpolarized PDF benchmark moments between the lattice QCD computations and global fit determinations. Results are displayed both in terms of absolute values (left) and ratios to the lattice values (right) at $\mu^2 = 4$ GeV^2.

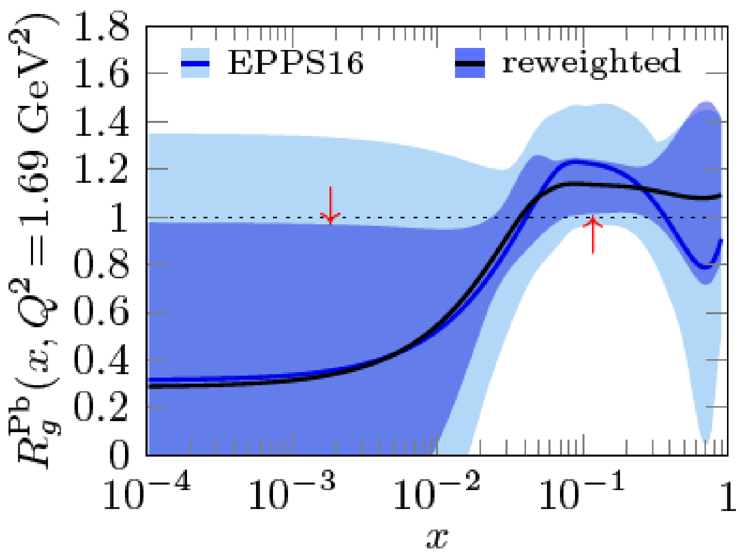
Nuclear PDFs

Main recent result, evidence for gluon shadowing at small-x from heavy meson production (right Kusina DIS2018) and jets (below Paakkinen DIS2018).

Also results on W, Z production.
Information on flavour.

Reweighting with D^0 data





Conclusions

LHC data starting to have a significant impact on PDF extractions.

Theory catching up for fitting precision data, e.g NNLO jets, differential top, ...

Significant changes in strange distribution most likely first major change (uncertainty and/or central value).

Many new tools becoming available – practical and potentially theoretical.

Precision data and theory throwing up problems in cases where correlated systematics are important. Improved interplay between theory/experiment on these seems a priority.

Back-up

Parton Fits and Uncertainties. Two main approaches.

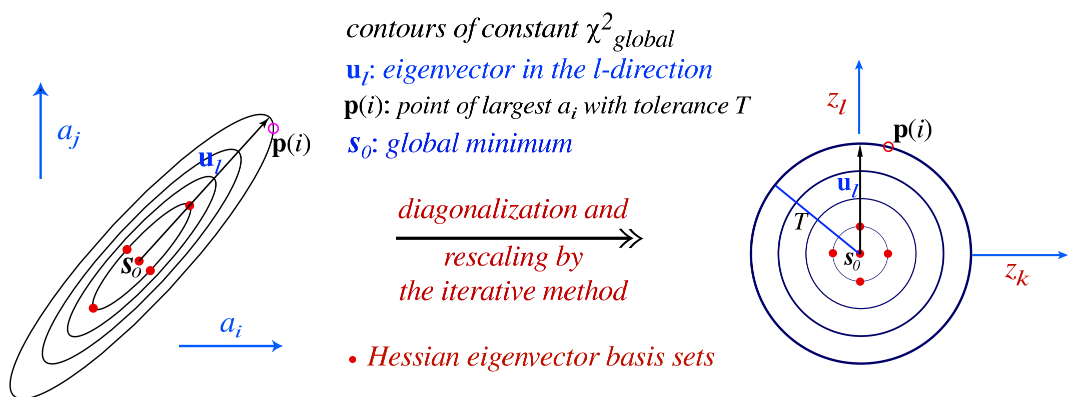
Most groups use a parton parameterization and Hessian approach.

$$\chi^2 - \chi^2_{min} \equiv \Delta\chi^2 = \sum_{i,j} H_{ij}(a_i - a_i^{(0)})(a_j - a_j^{(0)})$$

Often $\Delta\chi^2 > 1$ to account for inconsistencies between data sets (or other sources), e.g *dynamical tolerance*.

Can find and rescale eigenvectors of H leading to $\Delta\chi^2 = \sum_i z_i^2$

2-dim (i,j) rendition of d-dim (~20) PDF parameter space



(a)
Original parameter basis

(b)
Orthonormal eigenvector basis

Uncertainty on physical quantity then given by

$$(\Delta F)^2 = 0.5 * \sum_i \left(F(S_i^{(+)}) - F(S_i^{(-)})\right)^2,$$

where $S_i^{(+)}$ and $S_i^{(-)}$ are PDF "error sets". (Can also allow for asymmetric uncertainties.)

Neural Network group (Ball *et al.*) limit parameterization dependence. Leads to alternative approach to "best fit" and uncertainties.

First part of approach, no longer perturb about best fit.

- Generate artificial data according to distribution

$$O_i^{(art)\,(k)} = (1 + r_N^{(k)}\,\sigma_N)\left[O_i^{(exp)} + \sum_{p=1}^{N_{sys}} r_p^{(k)}\,\sigma_{i,p} + r_{i,s}^{(k)}\,\sigma_s^i\right]$$

Where $r_p^{(k)}$ are random numbers following Gaussian distribution.

Fit to the data replicas obtaining PDF replicas $q_i^{(net)(k)}$ (follows Giele *et al.*)

Mean μ_O and deviation σ_O of observable O then given by

$$\mu_O = \frac{1}{N_{rep}} \sum_1^{N_{rep}} O[q_i^{(net)(k)}], \quad \sigma_O^2 = \frac{1}{N_{rep}} \sum_1^{N_{rep}} (O[q_i^{(net)(k)}] - \mu_O)^2.$$

Eliminates parameterisation dependence by using a neural net which undergoes a series of (mutations via genetic algorithm) to find the best fit. In effect is a much larger sets of parameters – ~ 37 per distribution.

However, can now generate "Monte Carlo" PDF sets from eigenvectors directly, and *vice versa*.

Choices for Heavy Flavours in DIS.

Near threshold $Q^2 \sim m_H^2$ massive quarks not partons. Created in final state. Described using **Fixed Flavour Number Scheme** FFNS (used in ABM(P) PDF determination).

$$F(x, Q^2) = C_k^{FF,n_f}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2)$$

Does not sum $\alpha_S^n \ln^n Q^2/m_H^2$ terms in perturbative expansion.

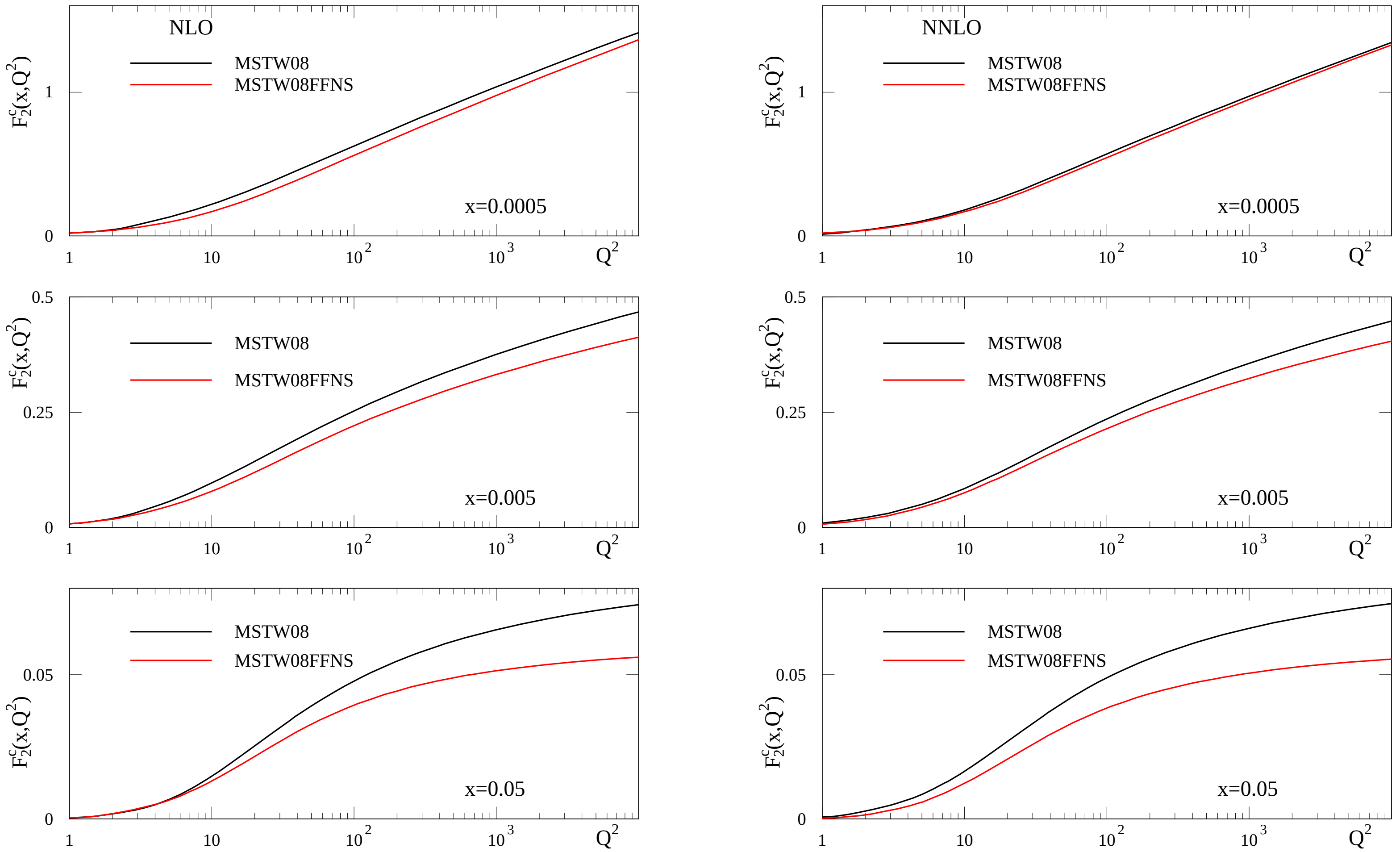
Variable Flavour - at high scales $Q^2 \gg m_H^2$ heavy quarks behave like massless partons. Sum $\ln(Q^2/m_H^2)$ terms via evolution. Partons in different number regions related to each other perturbatively.

$$f_j^{n_f+1}(Q^2) = A_{jk}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2),$$

Can define a **General-Mass Variable Flavour Number Scheme** taking one from $Q^2 \leq m_H^2$ to $Q^2 \gg m_H^2$ in a well-defined manner.

Variants used in CT, HERA, MMHT, NNPDF fits. Different versions converge at higher orders.

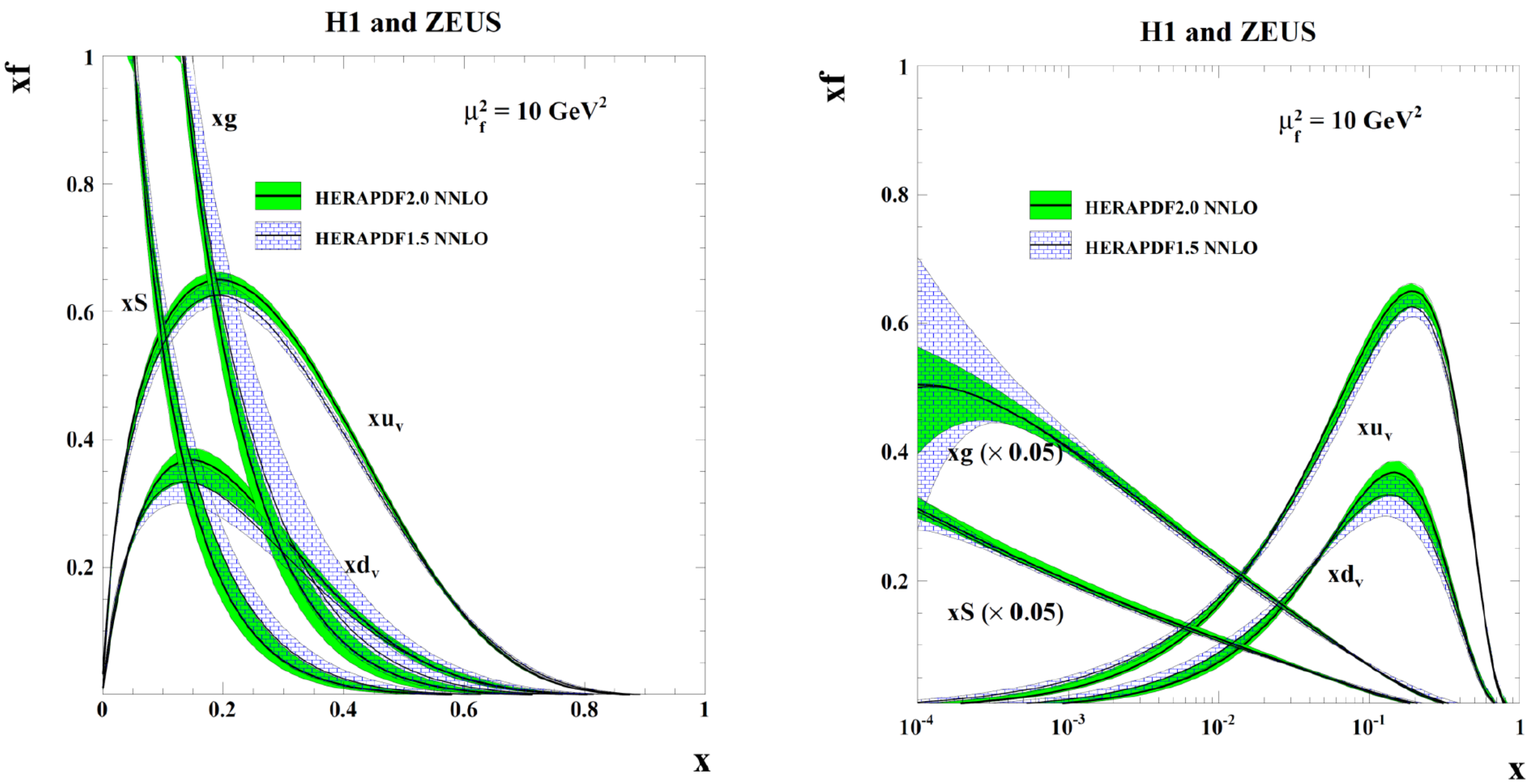
Difference between FFNS and GM-VFNS



At higher Q^2 charm structure function for FFNS nearly always lower than any GM-VFNS. NNLO uses $\mathcal{O}(\alpha_S^2)$ coefficient functions for $F_2^c(x, Q^2)$.

Included in HERAPF2.0 fits. A.M. Cooper-Sarkar

Compare HERAPDF2.0 to HERAPDF1.5 at NNLO



Make HERAPDF PDFS more precise, but in general a bit further from other PDFs in some places, e.g high-x up quark.

There are basically two kinds of situation. The recommendation advises:

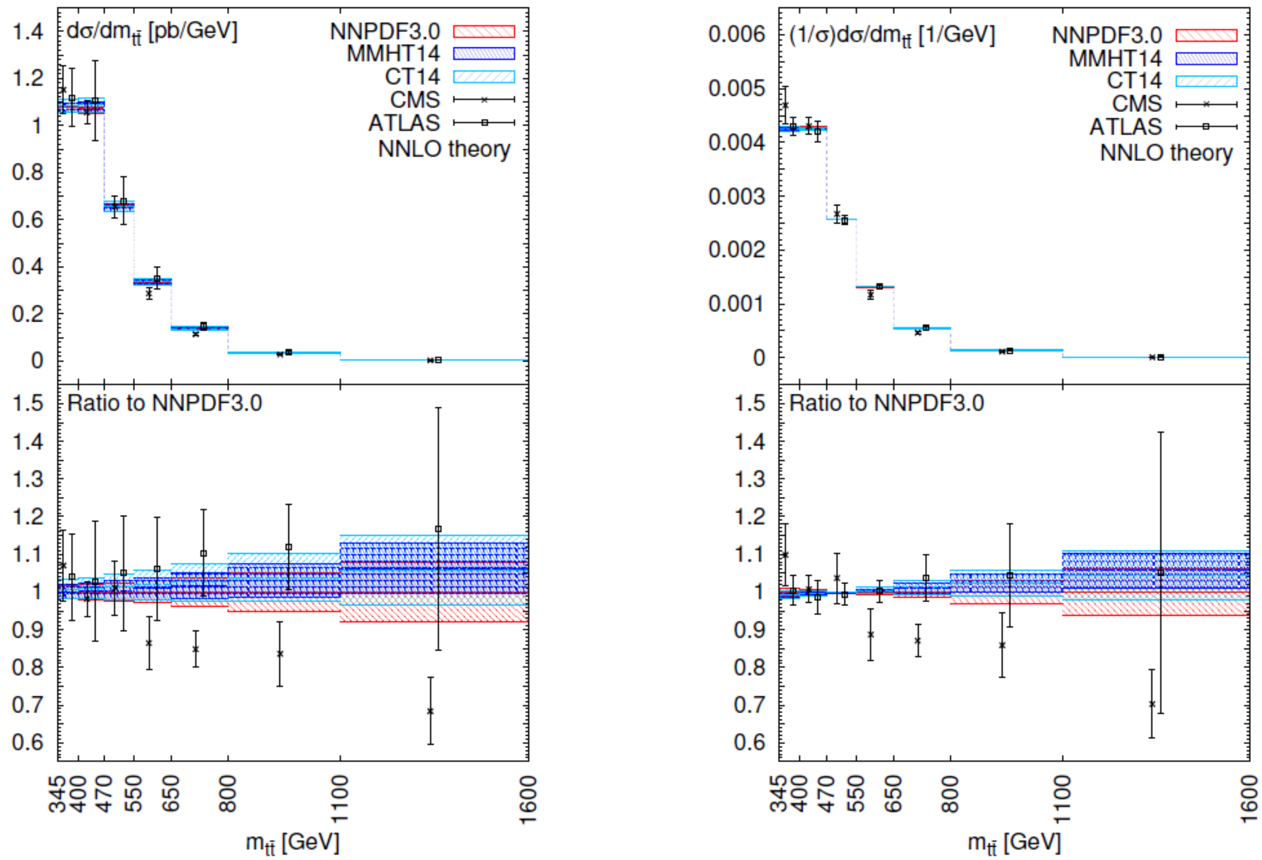
- For assessment of the PDF uncertainty in searches, discovery, acceptance corrections . . . (e.g. Higgs, Susy). Use the PDF4LHC prescription.

- When comparing predictions to theory in well-determined standard model processes, e.g. jets, W, Z distributions, top pair cross sections . . .. Use the individual PDF sets (ABM, CT, HERAPDF, JR, MMHT, NNPDF)

An alternative viewpoint soon after in Accardi *et al.*, Eur.Phys.J. C76 (2016) 471.

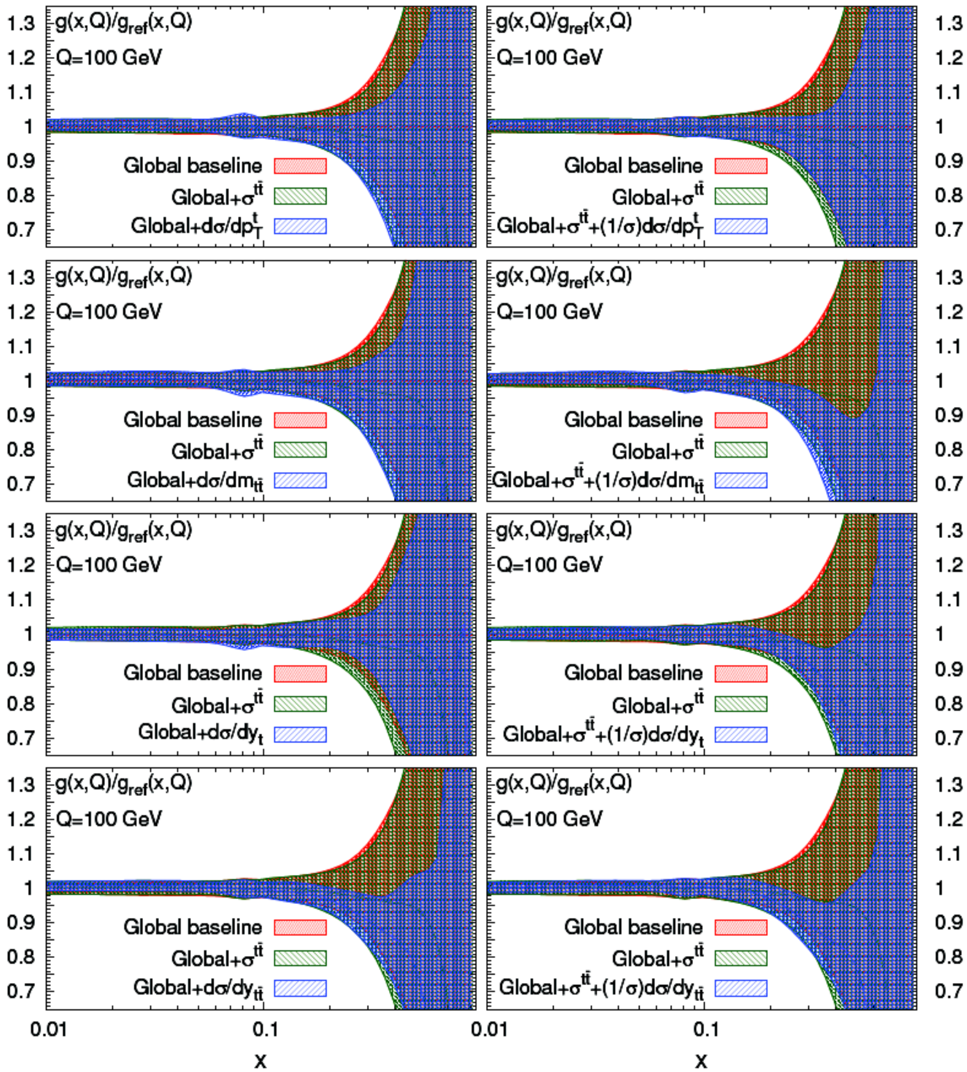
NNLO Differential top-antitop production now available and studied in Czakon *et al*. JHEP 1704 (2017) 044.

Data/Theory comparison: $m_{t\bar{t}}$



Incompatibility between distributions and some very difficult to fit. Overall imply softer gluon and slightly reduced high-x uncertainty.

Impact of $t\bar{t}$ distributions on the gluon PDF at large x



Significant reduction in the gluon uncertainty at large x

Affected kinematic region as expected from the correlation coefficients $(0.1 \lesssim x \lesssim 0.7)$

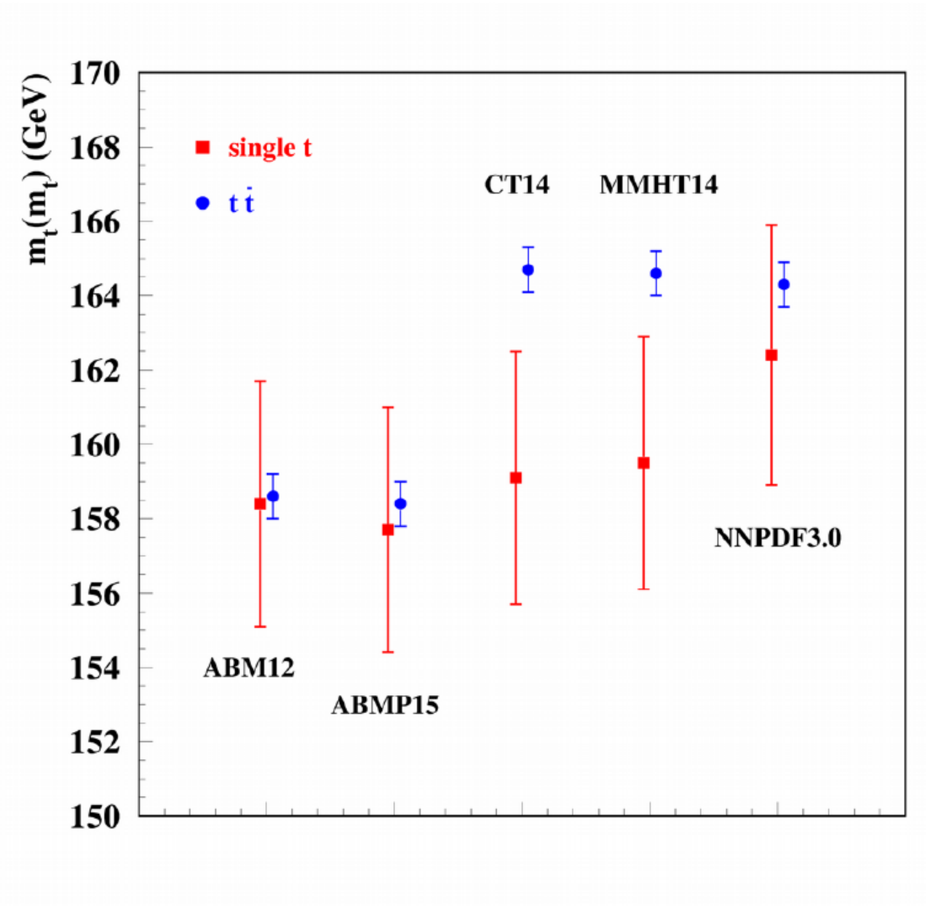
Gluon remarkably consistent in the fit across the choice of distributions

Normalised distributions appear to lead to a greater reduction of uncertainties

Almost negligible impact of total inclusive cross sections (in green)

Settle on using ATLAS y_t distribution and CMS $y_{t\bar{t}}$ distribution, both normalised.

t-quark mass from the single-top data



- Electroweak production → reduced impact of α_s and the PDF umcertainties
- HATHOR framework
  t-channel: NNLO
  Brucherseifer, Caola, Melnikov PLB 736, 58 (2014)
  s-channel: NNLO threshold. resum.
  sa, Moch, Thier hep-ph/1608.05212
- Different PDFs prefer value of

  $m_t(m_t)$ ~160± 3.5 GeV

NNPDF goes higher by 3 GeV.

- The CT14 and MMHT14 go higher by 3 GeV with the ttbar channel

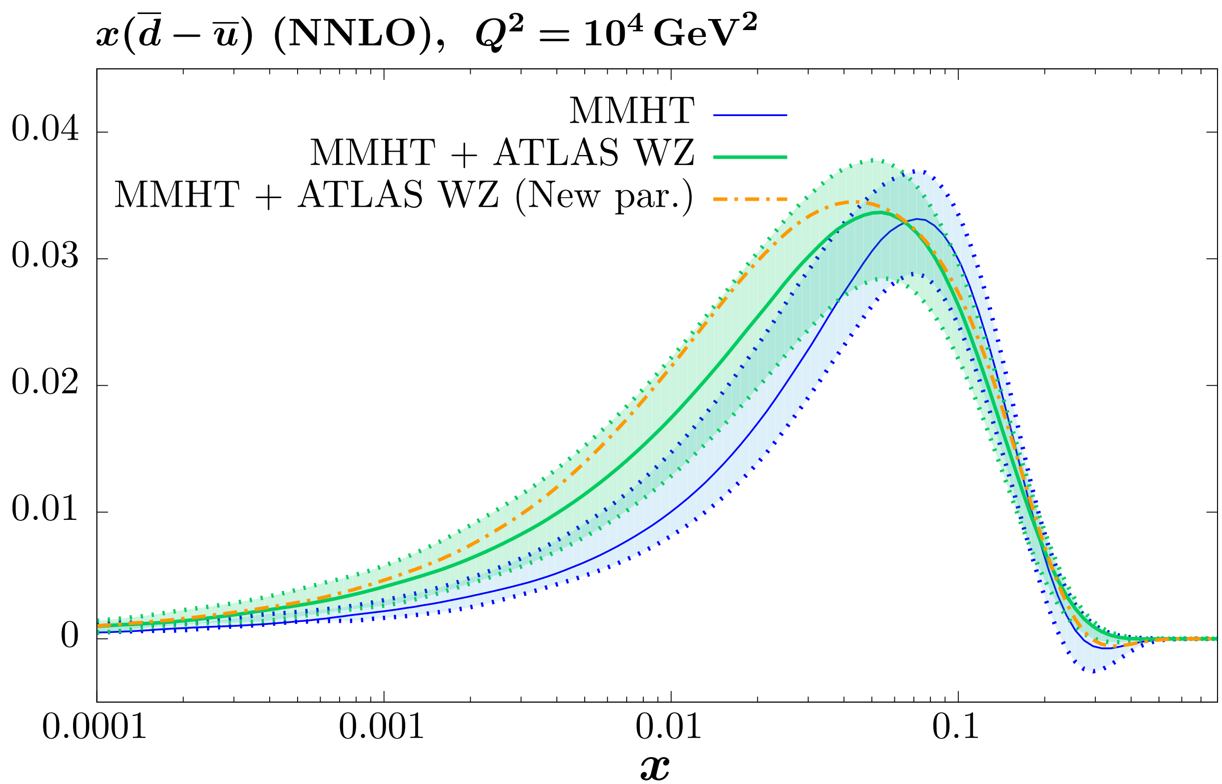
Still lower $\alpha_S(M_Z^2)$ (0.1147) and different gluon shape.

Extension of $\bar{d} - \bar{u}$ parameterisation.

Currently use 3 parameters, $(\bar{d}-\bar{u})(x,Q_0^2) = A(1-x)^{\eta_{sea}+2}x^{\delta}(1+\gamma x + \Delta x^2)$,

Extend to $(\bar{d}-\bar{u})(x,Q_0^2) = A(1-x)^{\eta_{sea}+2}x^{\delta}(1+\sum_{i=1}^{4} a_i T_i(1-2x^{\frac{1}{2}}))$,

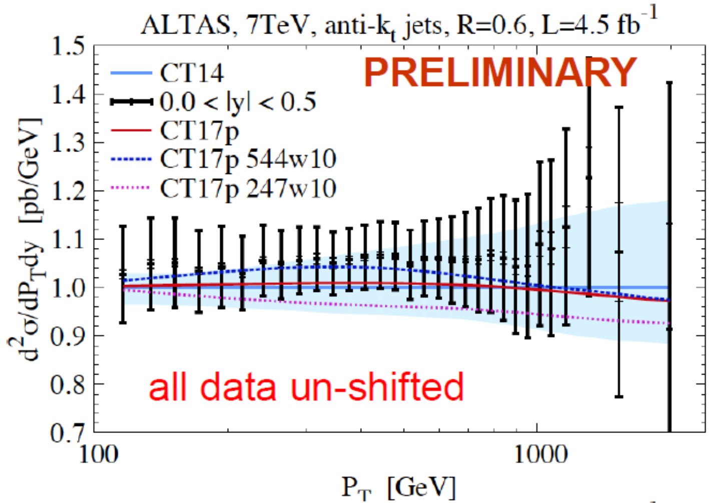
where $T_i(1-2x^{\frac{1}{2}})$ are Chebyshev polynomials. So 5 free parameters. Easily allows multiple turning points (seen in first fit iteration).

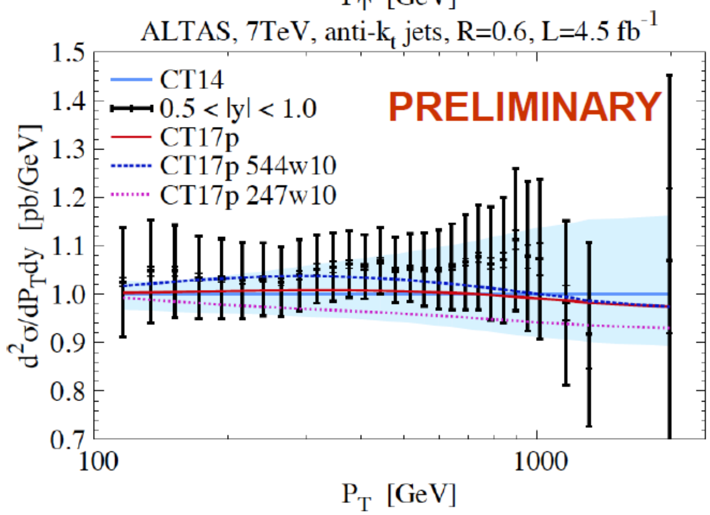


All groups have difficulties with the ATLAS jets Huston - PDF4LHC.

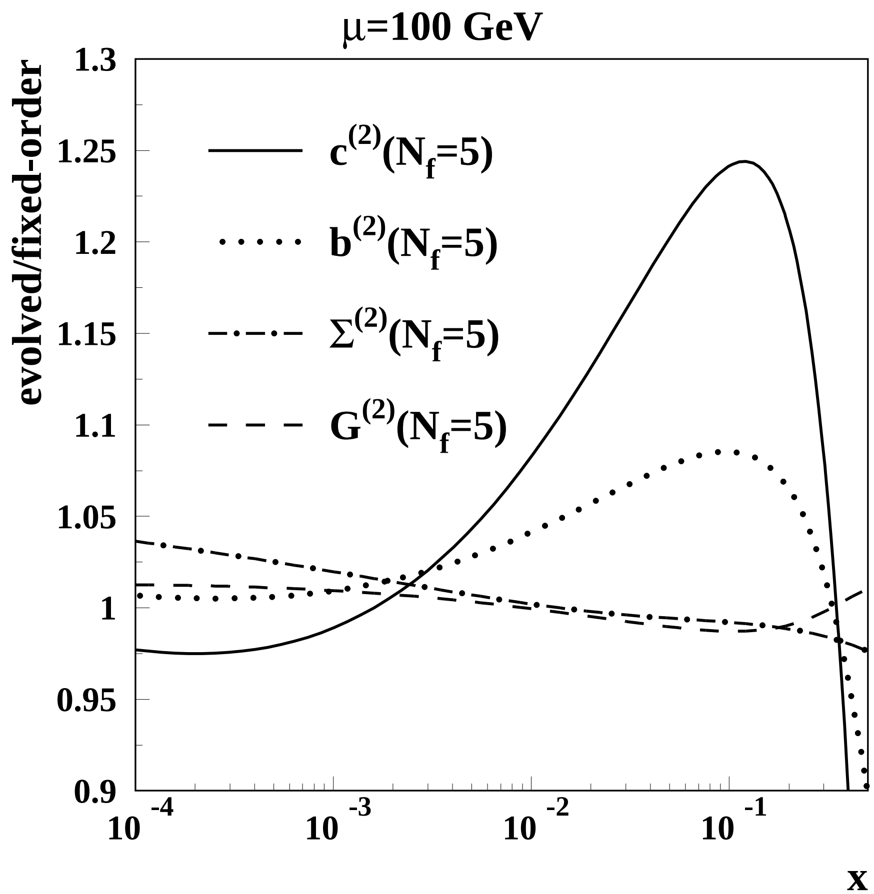
CT17p: ATLAS 7 TeV jet data

- Cannot get a good fit simultaneously to all rapidity bins: χ^2/DOF>2, even with weight 10 for combined jet data
  - outer error bars are with stat and syst errors added in quadrature; inner error bars are uncorrelated errors alone
- Individual rapidity bins can be fit better
- First 2 rapidity bins can be fit together reasonably ok (χ^2=102 for 60 data points with a Spartyness of 3.3; nb, no NNLO MC statistical error applied to this particular calculation)
- CMS 7 TeV jet data fit better, with the exception of the last rapidity bin





Recent proposals by ATLAS to alleviate this.



Results for $F_2^c(x, Q^2)$ in GM-VFNS compared to those for FFNS similar to results for PDFs by Alekhin *et al.* in Phys.Rev. D81 (2010) 014032 comparing NNLO evolution to the fixed order result up to $\mathcal{O}(\alpha_S^2)$.

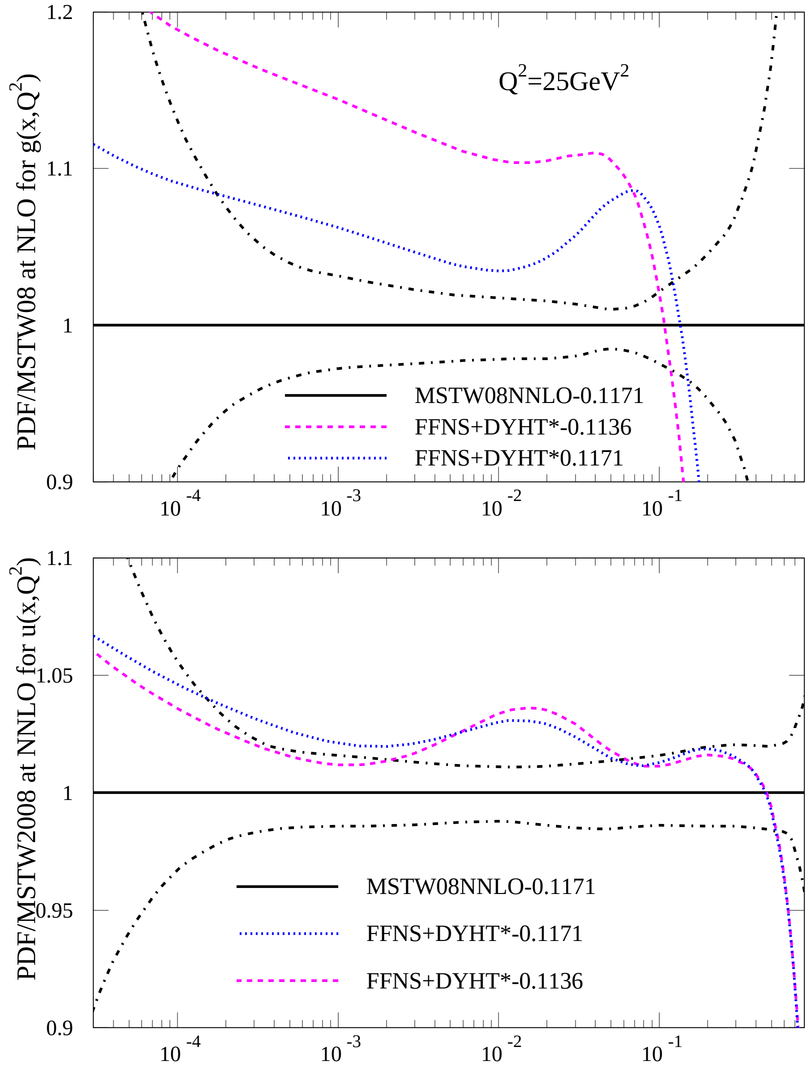
Use of FFNS rather than GM-VFNS leads to smaller high-x gluon and smaller α_S (RT, Eur.Phys.J. C74 (2014) 2958).

Why is α_S lower in FFNS?

Look at parton ratios at lower Q^2 where evolution must match data, and respective $\alpha_S(M_Z^2)$ values are 0.1171 and 0.1136.

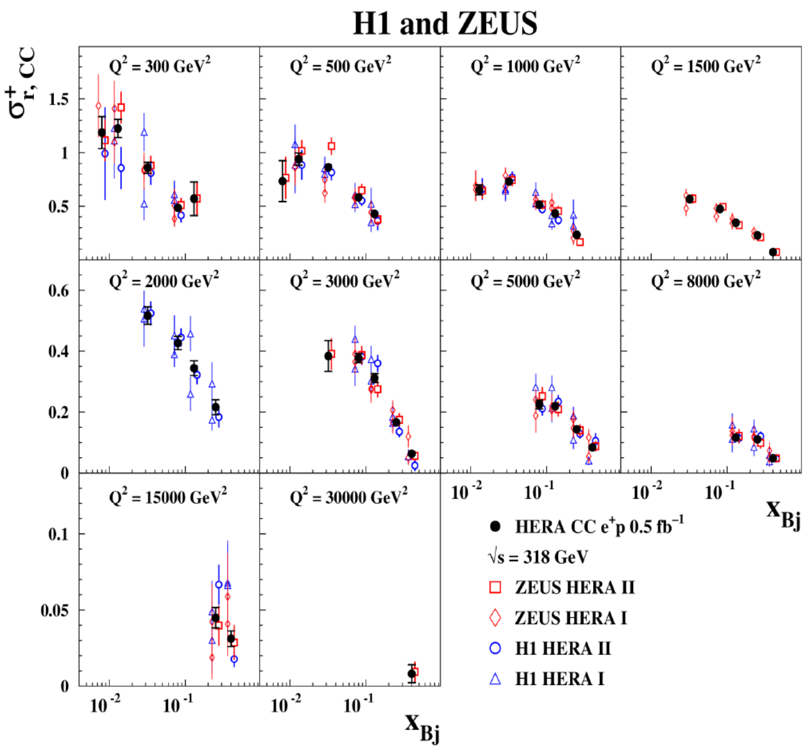
Gluon needs to be bigger at $x \sim 0.001\text{-}0.1$ – smaller at high x – to fit data. Feeds to lower x at higher Q^2.

Inverse correlation between high-x gluon and α_S. Without high-x gluon quark evolution too quick.

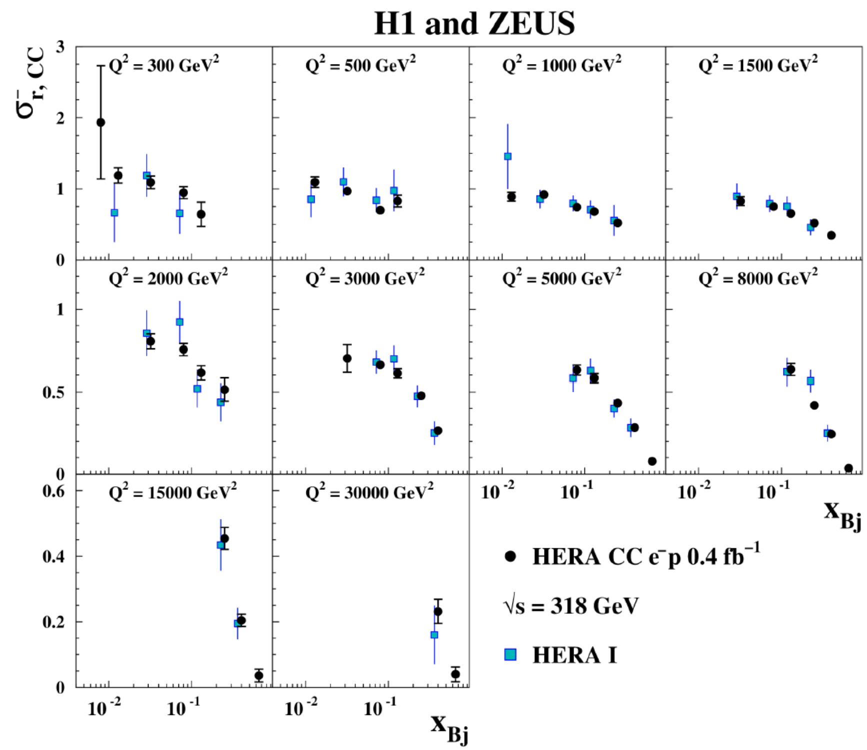


Averaged cross sections: CC e±p

CC e⁺p



CC e⁻p



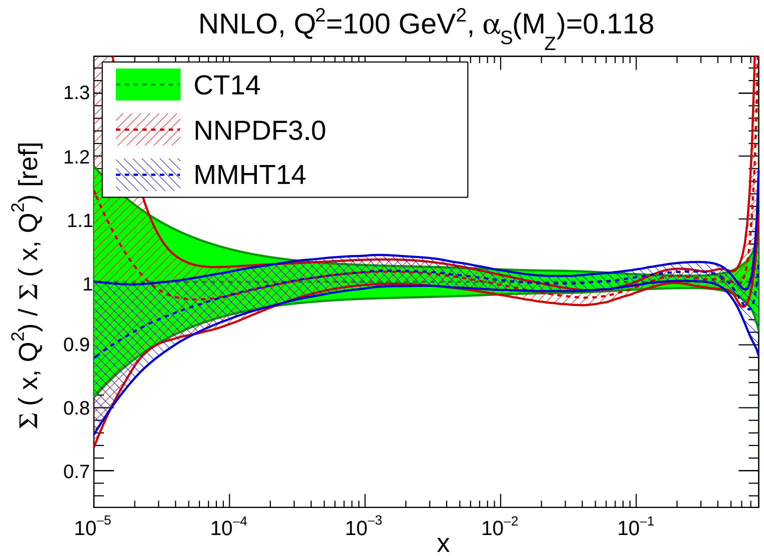
Easier to see impact in predictions for benchmark cross sections.

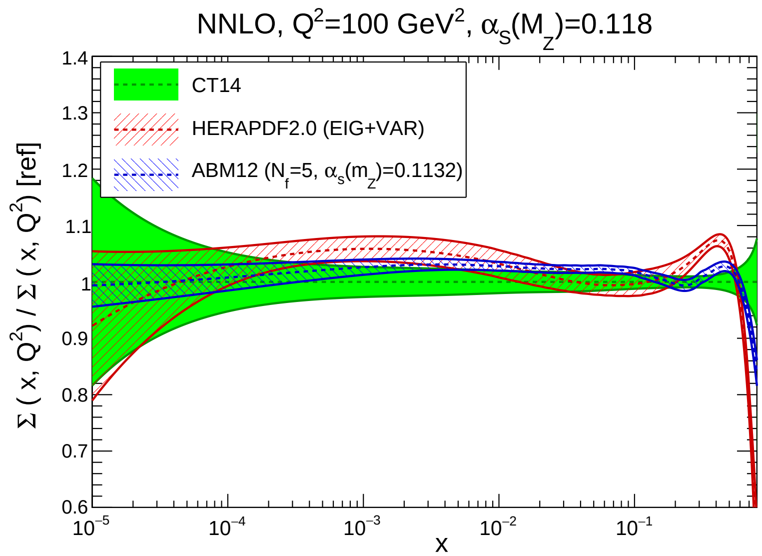
	MMHT14	MMHT14 (HERA global)
W Tevatron (1.96 TeV)	$2.782^{+0.056}_{-0.056}$ $\binom{+2.0\%}{-2.0\%}$	$2.789^{+0.050}_{-0.050}$ $\binom{+1.8\%}{-1.8\%}$
Z Tevatron (1.96 TeV)	$0.2559^{+0.0052}_{-0.0046}$ $\binom{+2.0\%}{-1.8\%}$	$0.2563^{+0.0047}_{-0.0047}$ $\binom{+1.8\%}{-1.8\%}$
W^+ LHC (7 TeV)	$6.197^{+0.103}_{-0.092}$ $\binom{+1.7\%}{-1.5\%}$	$6.221^{+0.100}_{-0.096}$ $\binom{+1.6\%}{-1.5\%}$
W^- LHC (7 TeV)	$4.306^{+0.067}_{-0.076}$ $\binom{+1.6\%}{-1.8\%}$	$4.320^{+0.064}_{-0.070}$ $\binom{+1.5\%}{-1.6\%}$
Z LHC (7 TeV)	$0.9638^{+0.014}_{-0.013}$ $\binom{+1.5\%}{-1.3\%}$	$0.9663^{+0.015}_{-0.013}$ $\binom{+1.6\%}{-1.3\%}$
W^+ LHC (14 TeV)	$12.48^{+0.22}_{-0.18}$ $\binom{+1.8\%}{-1.4\%}$	$12.52^{+0.22}_{-0.18}$ $\binom{+1.8\%}{-1.4\%}$
W^- LHC (14 TeV)	$9.32^{+0.15}_{-0.14}$ $\binom{+1.6\%}{-1.5\%}$	$9.36^{+0.14}_{-0.13}$ $\binom{+1.5\%}{-1.4\%}$
Z LHC (14 TeV)	$2.065^{+0.035}_{-0.030}$ $\binom{+1.7\%}{-1.5\%}$	$2.073^{+0.036}_{-0.026}$ $\binom{+1.7\%}{-1.3\%}$
Higgs Tevatron	$0.874^{+0.024}_{-0.030}$ $\binom{+2.7\%}{-3.4\%}$	$0.866^{+0.019}_{-0.023}$ $\binom{+2.2\%}{-2.7\%}$
Higgs LHC (7 TeV)	$14.56^{+0.21}_{-0.29}$ $\binom{+1.4\%}{-2.0\%}$	$14.52^{+0.19}_{-0.24}$ $\binom{+1.3\%}{-1.7\%}$
Higgs LHC (14 TeV)	$47.69^{+0.63}_{-0.88}$ $\binom{+1.3\%}{-1.8\%}$	$47.75^{+0.59}_{-0.72}$ $\binom{+1.2\%}{-1.5\%}$
$t\bar{t}$ Tevatron	$7.51^{+0.21}_{-0.20}$ $\binom{+2.8\%}{-2.7\%}$	$7.57^{+0.18}_{-0.18}$ $\binom{+2.4\%}{-2.4\%}$
$t\bar{t}$ LHC (7 TeV)	$175.9^{+3.9}_{-5.5}$ $\binom{+2.2\%}{-3.1\%}$	$174.8^{+3.3}_{-5.3}$ $\binom{+1.9\%}{-3.0\%}$
$t\bar{t}$ LHC (14 TeV)	969.9^{+16}_{-20} $\binom{+1.6\%}{-2.1\%}$	964.2^{+13}_{-19} $\binom{+1.3\%}{-2.0\%}$

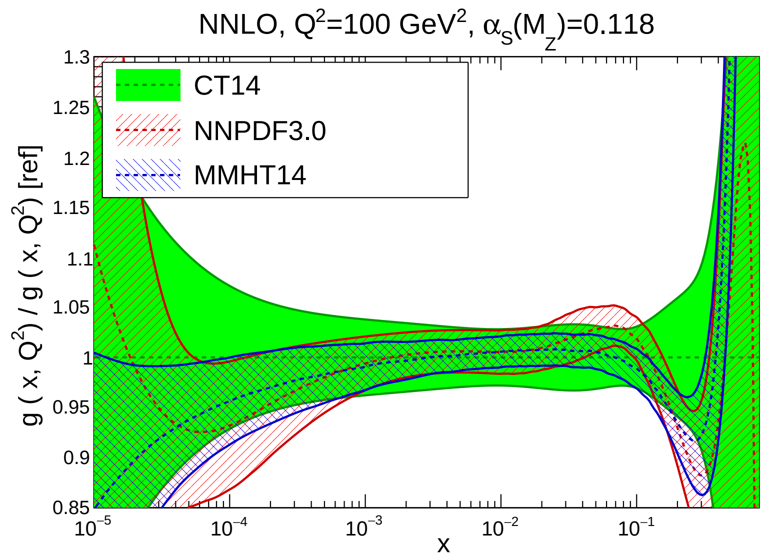
Table 2: The values of various cross sections (in nb) obtained with the NNLO MMHT 2014 sets, with and without the final HERA combination data set included. PDF uncertainties only are shown.

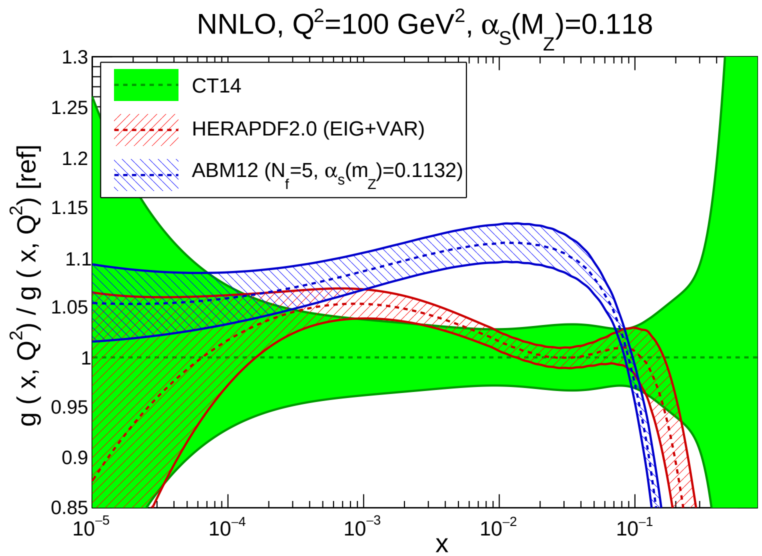
For MMHT very little change in central values. Up to about 10% improvement in uncertainty for $\sigma_{\bar{t}t}$ and $\sigma(gg \to h)$, i.e. in gluon dominated processes. Less in (anti)quark initiated final states.

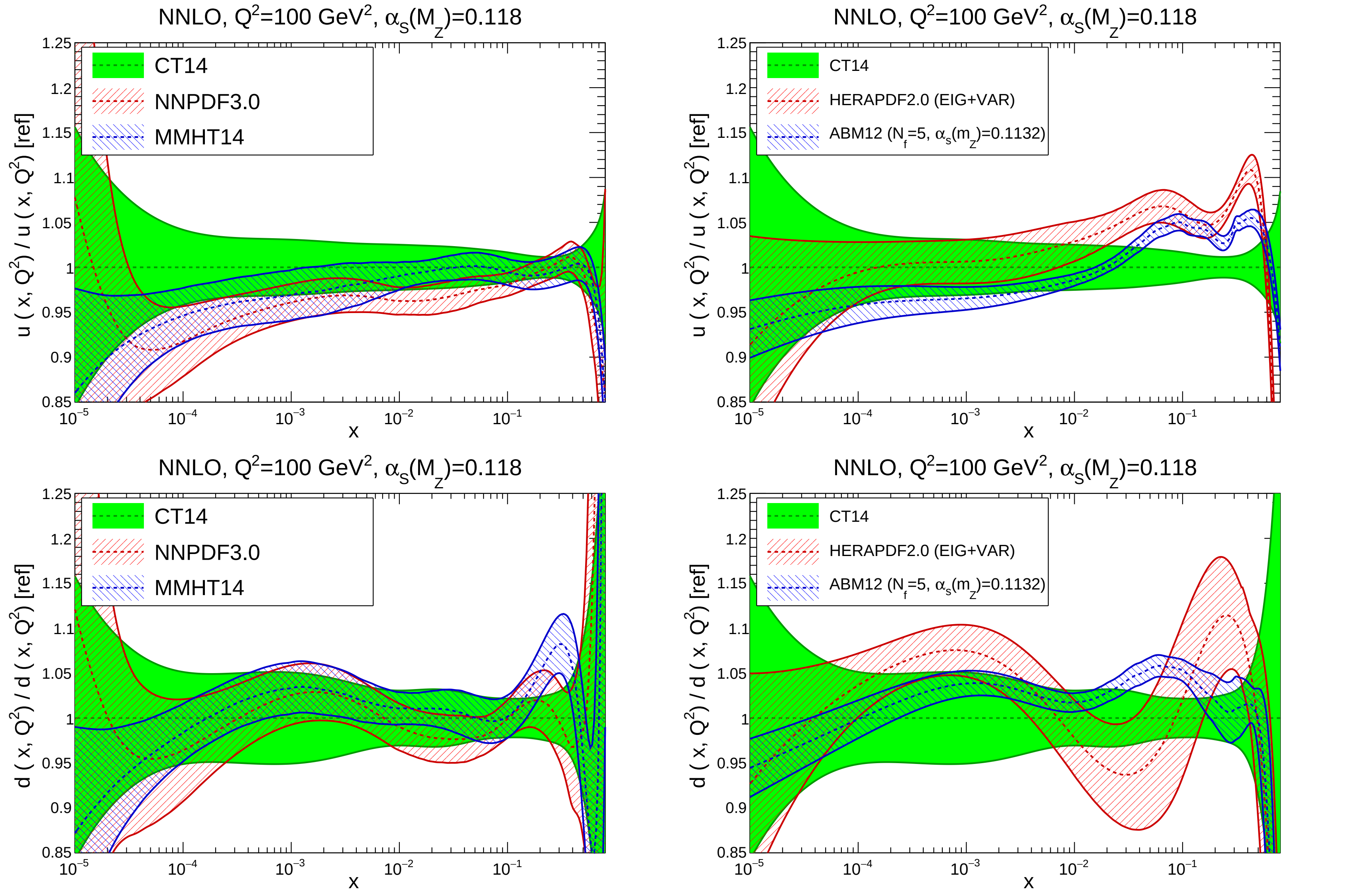
Comparison of PDFs










NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
NNPDF3.0
MMHT14
u (x, Q^2) / u (x, Q^2) [ref]
x
NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
HERAPDF2.0 (EIG+VAR)
ABM12 (N_f=5, $\alpha_s(m_Z)$=0.1132)
u (x, Q^2) / u (x, Q^2) [ref]
x
NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
NNPDF3.0
MMHT14
d (x, Q^2) / d (x, Q^2) [ref]
x
NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
HERAPDF2.0 (EIG+VAR)
ABM12 (N_f=5, $\alpha_s(m_Z)$=0.1132)
d (x, Q^2) / d (x, Q^2) [ref]
x

Three Options Provided

PDF4LHC15-mc: A compressed **Monte Carlo** set with $N_{\rm rep} = 100$.

PDF4LHC15-30: A symmetric **Hessian** set with $N_{\rm eig} = 30$. (Meta-PDF approach - refit combination to functional form.)

PDF4LHC15-100: A symmetric **Hessian** set with $N_{\rm eig} = 100$. (MC-H representing eigenvectors on linear basis of replica.)

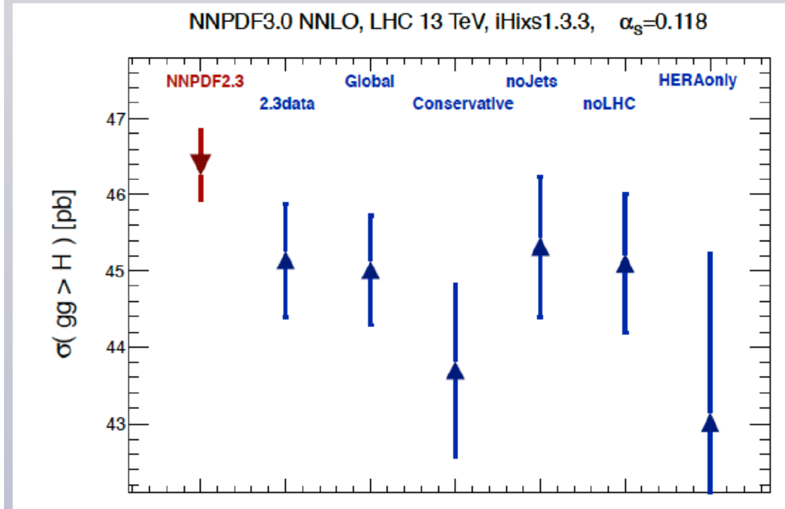
Some suggestions for which ones to use

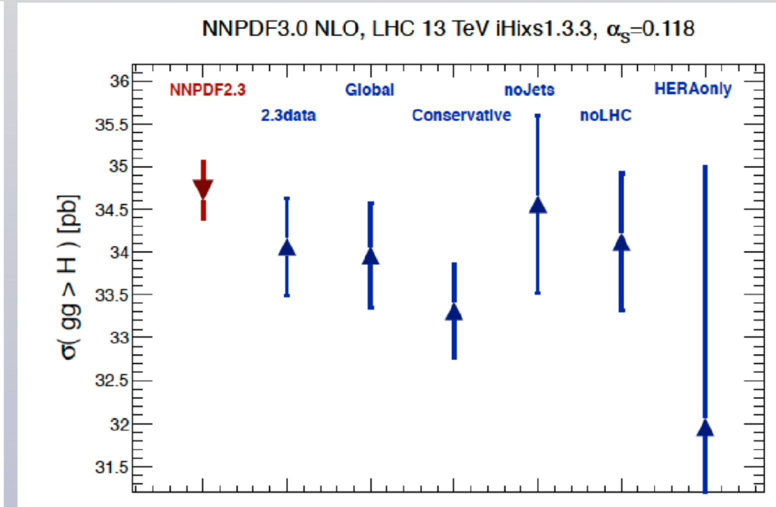
Monte Carlo contains non-gaussian features – important for searches at high masses (high x).

Hessian 30 set has good precision and useful for many experimental needs and when using nuisance parameters.

Hessian 100 set has optimal precision if running time not a problem or extreme accuracy needed.

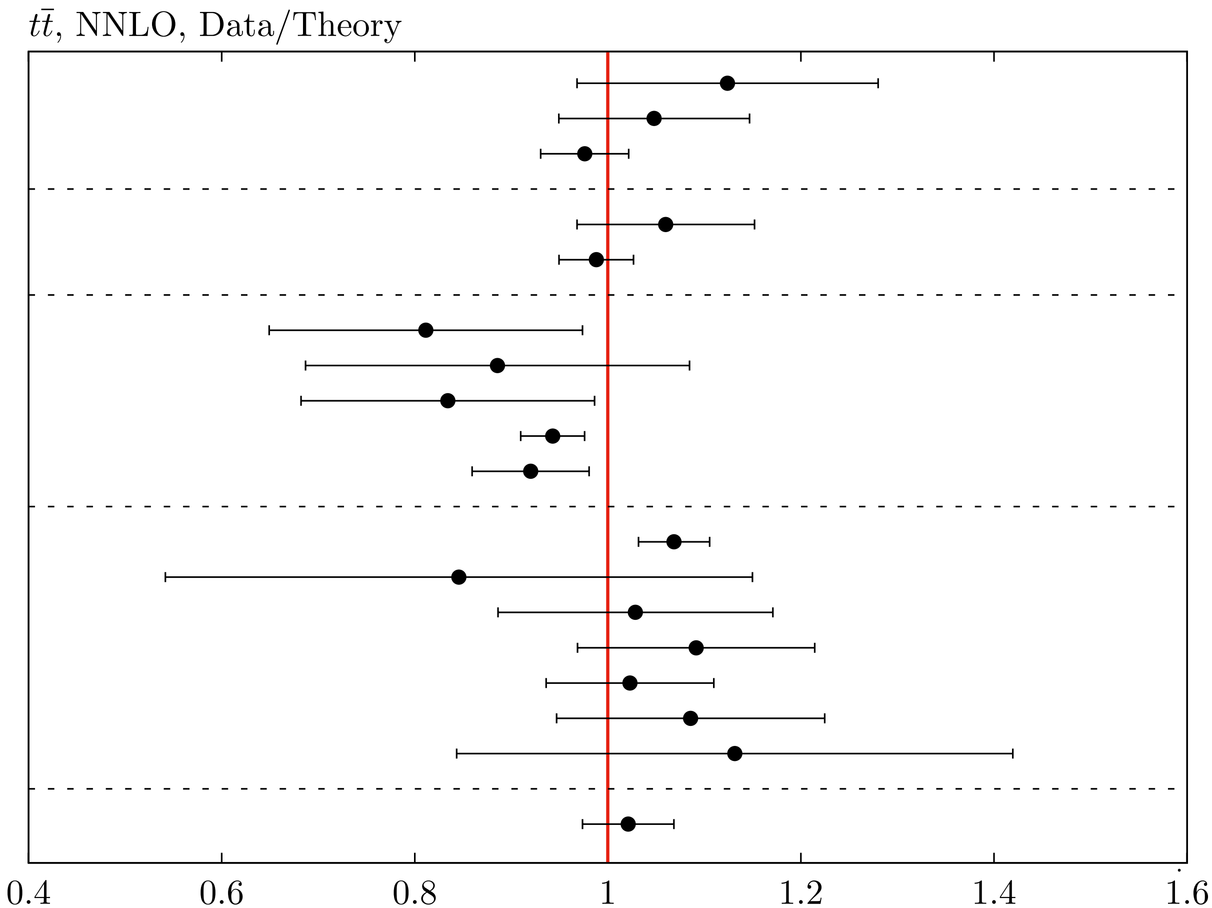
Higgs production in gluon fusion





- The softer **gg luminosity** in NNPDF3.0 leads to a **decrease in the ggH xsec** at the LHC 13 TeV
- The effect is more marked at NLO and NNLO, though even in the latter the pull is only **P ~1.5**
- The ggH process is different from many other LHC xsecs because there are **no direct experimental constraints on the gluon at x ~ 0.01**, and thus predictions for **ggH** are more sensitive to modifications in the methodology or in the choice of dataset (that indirectly affects g(x) for **x ~ 0.01**)
- In NNPDF3.0, the changes in the **ggH xsec arise mostly from** the **improved fitting methodology**, validated on the closure tests

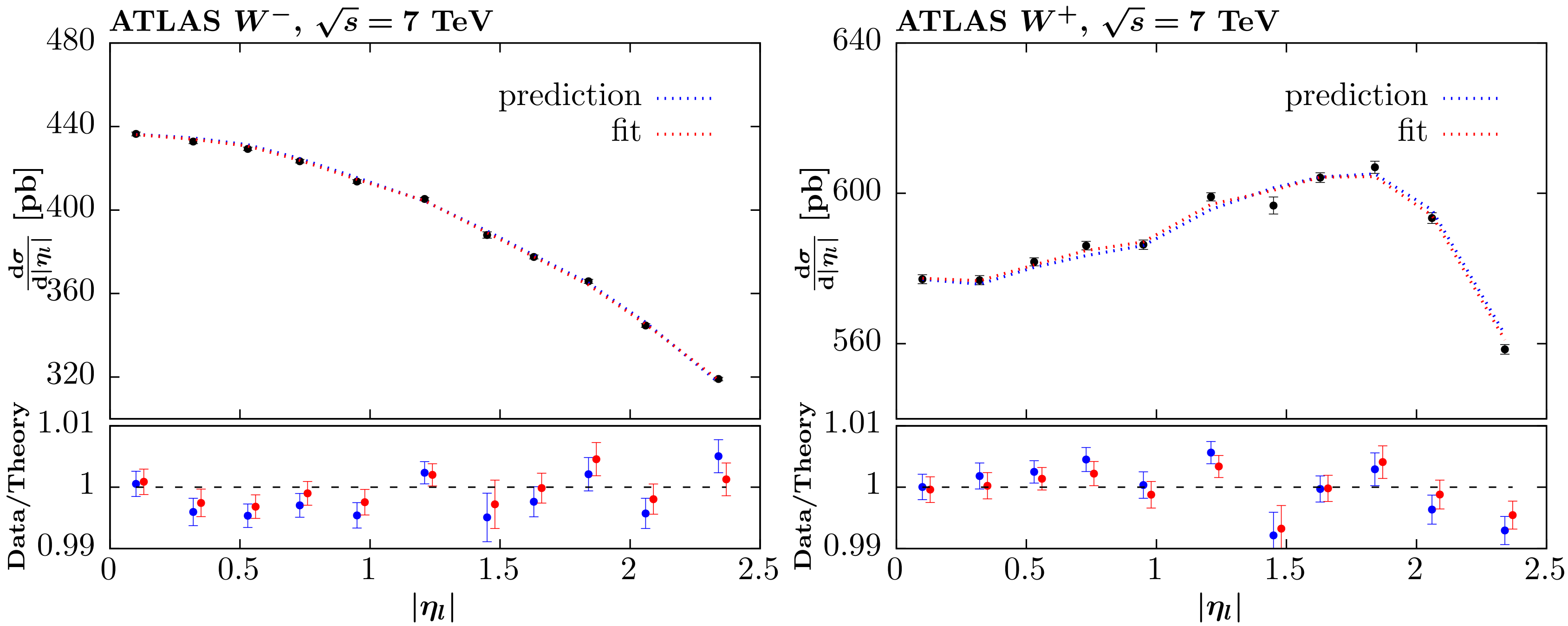
MMHT Included some more up-to-date results on $\sigma_{\bar{t}t}$.



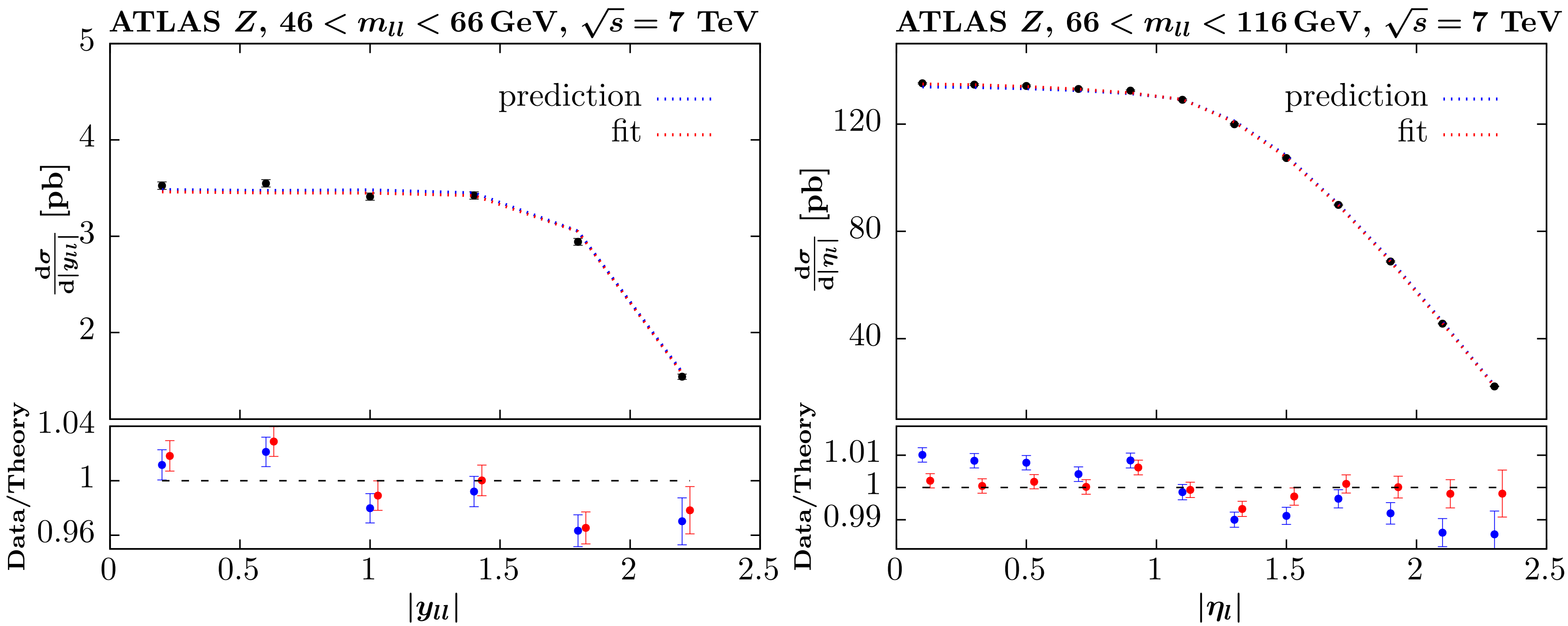
Fit very good and with $\alpha_S(M_Z^2) = 0.118$ the fitted $m_t^{pole} = 173.4$ GeV. At NLO $m_t^{pole} = 170.2$ GeV. MMHT values $m_t^{pole} = 174.2$ GeV and $m_t^{pole} = 171.7$ GeV

Helps drive slight increase in $\alpha_S(M_Z^2)$

Prediction and Fit to data



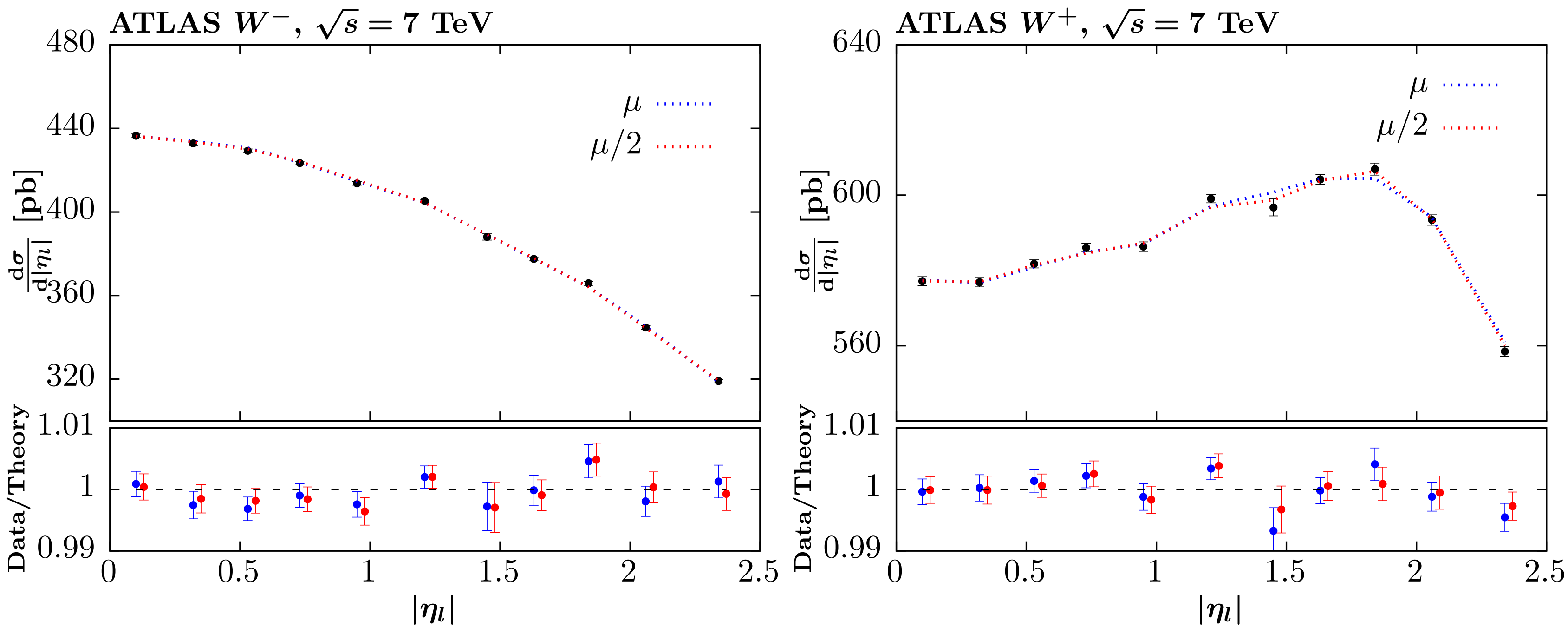
Slight reduction in lower $|\eta|$ W^- required and opposite for W^+.



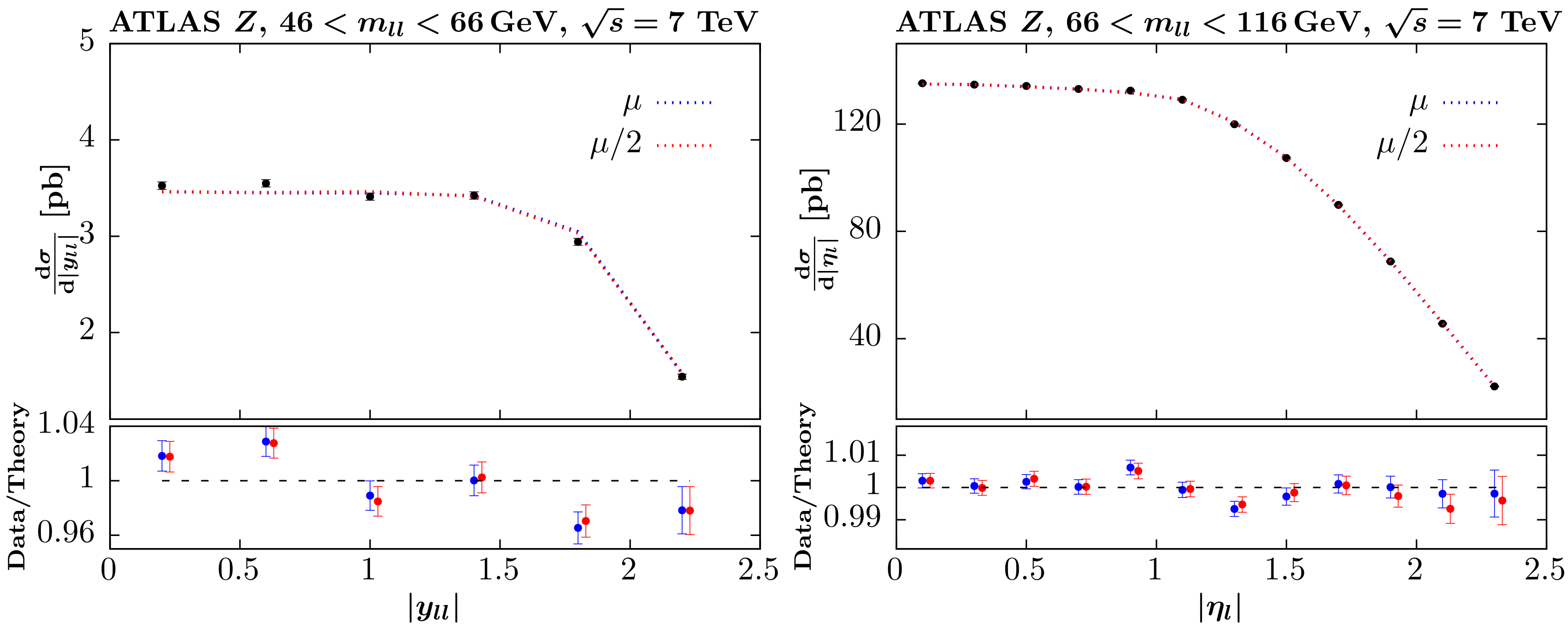
Significant change in shape required for Z production, Higher at low $|\eta|$ and lower at high $|\eta|$

Even with fit difficulty in shape for lower mass data.

Change scales to $\mu_{R,F} = M_{W,Z}/2$



More noticeable improvement for W^+.

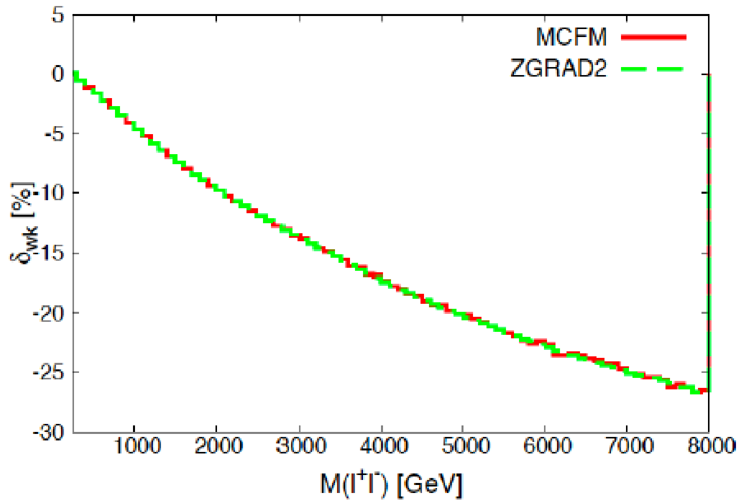


Marginal improvement in shape problem at lower mass.

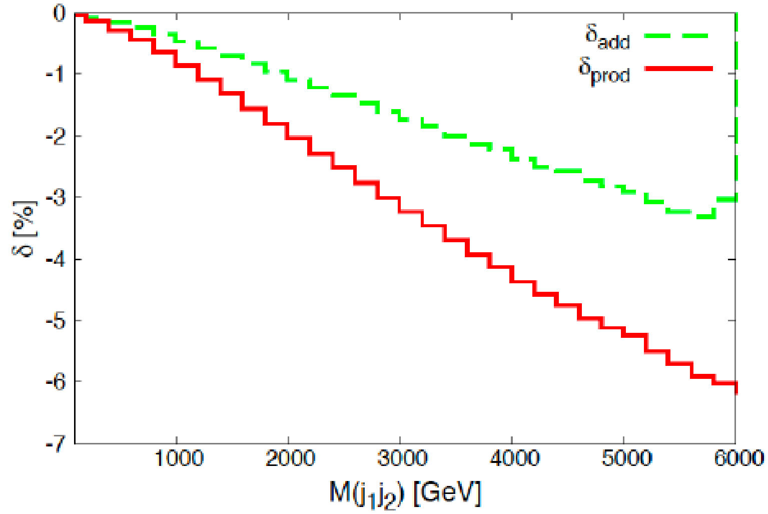
Less fluctuation for Z peak rapidity distribution.

Electroweak corrections

Inclusive Z production



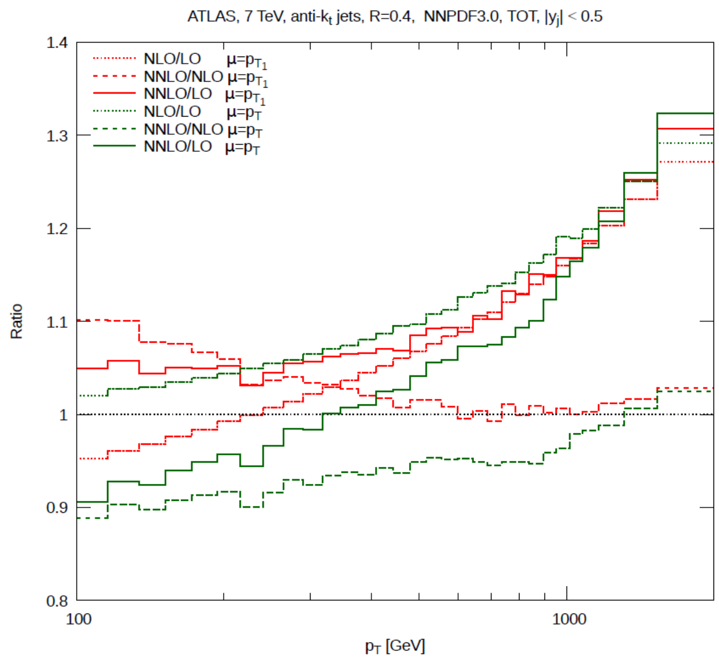
Dijet production

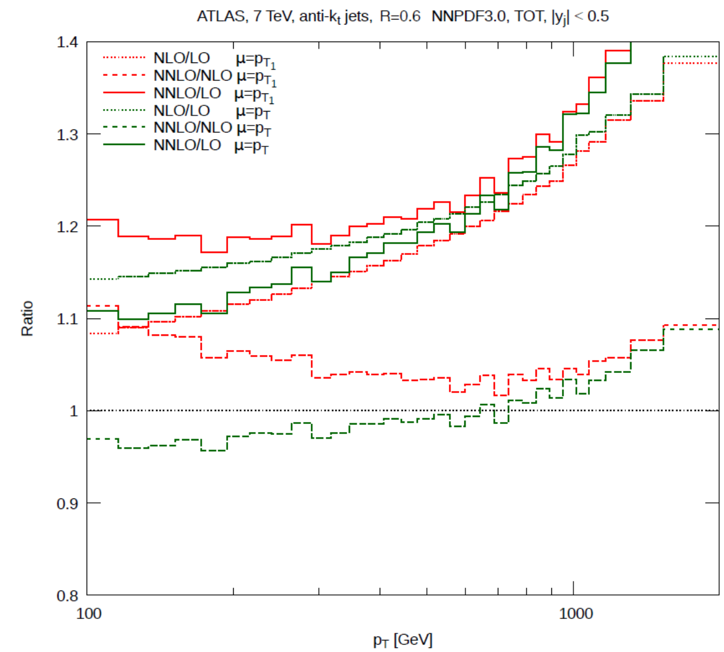


CMS 7 TeV jets.

Here take as default $R = 0.7$ and $\mu = p_T$.

Larger R, and $\mu = p_T$ rather than $\mu = p_{T1}$, lead to more stable NNLO corrections.



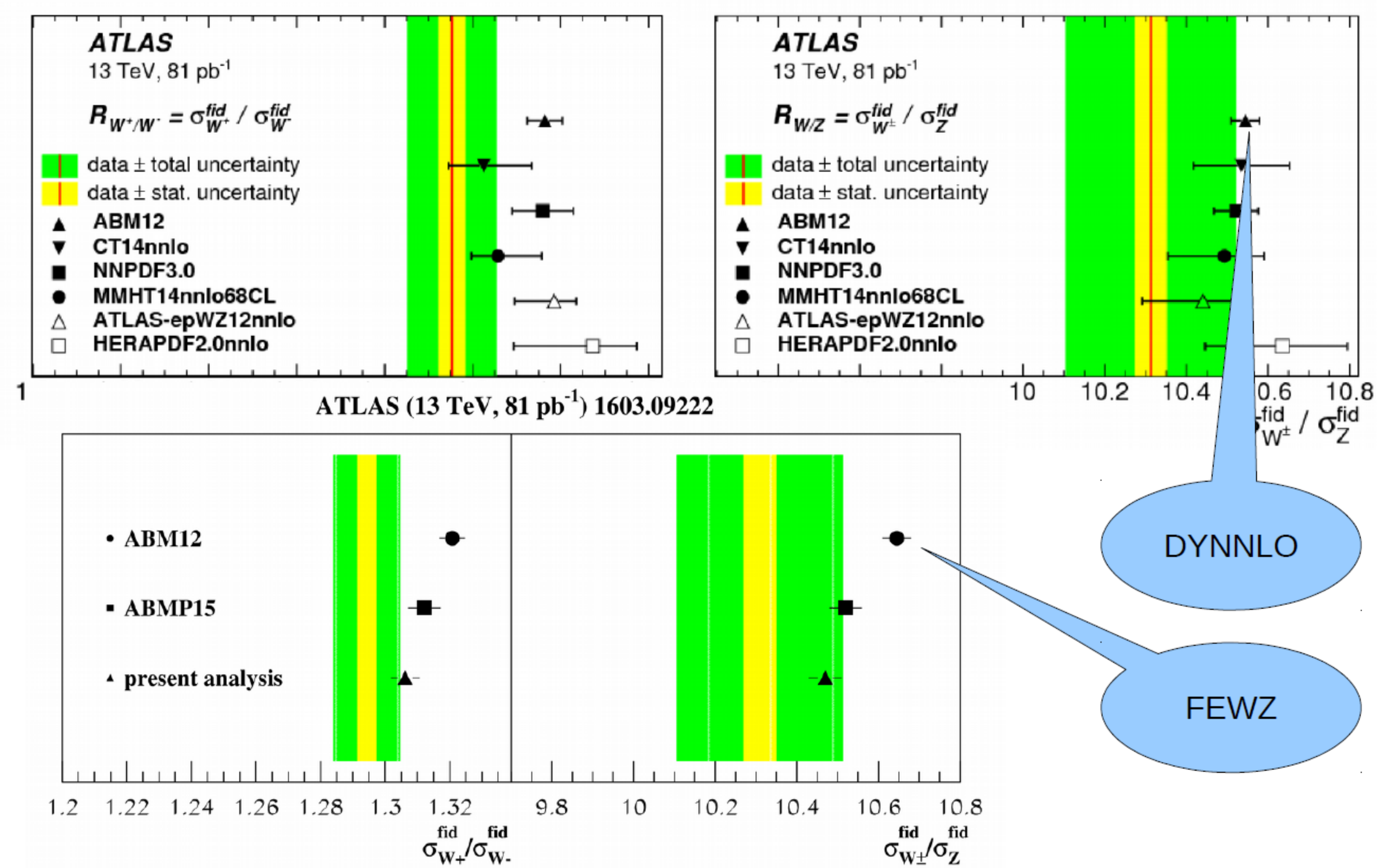


Therefore good NLO fit maintained at NNLO and little change in gluon.

More stability from NLO to NNLO expected for ATLAS jets if larger R and different scale chosen for fit?

ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222

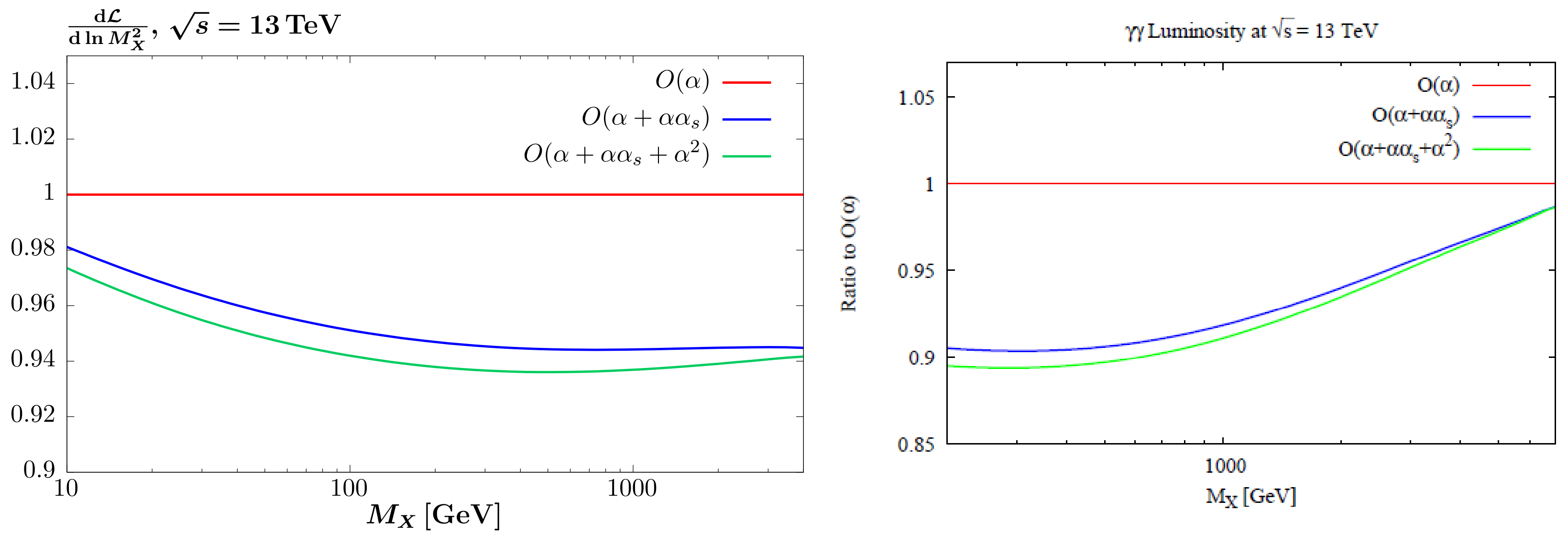


Data are well accommodated into the fit χ^2/NDP=9/6

3

Some changes in quark decomposition.

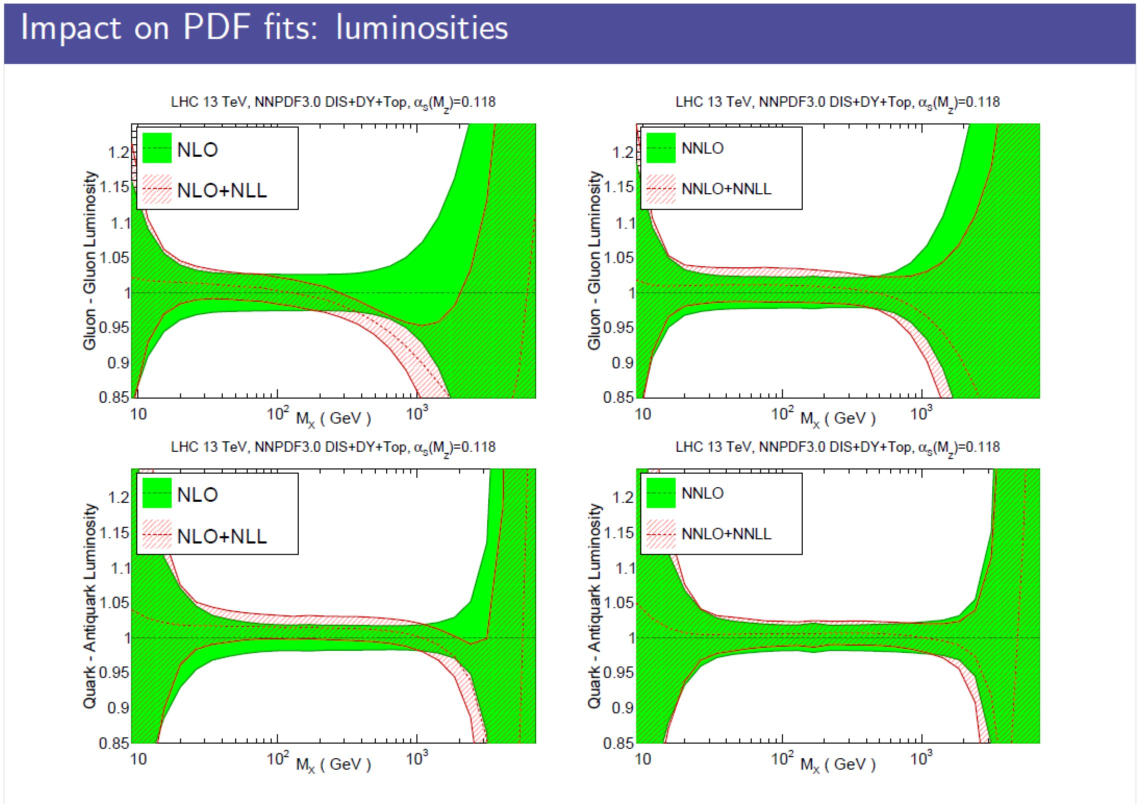
Photon-Photon Luminosity



Smaller effect than for NNPDF3.0 photon (right), F. Giuli, *et al*, EPJC77 (2017) 400.

(Note different scale on horizontal axes.)

Threshold resummations Bonvini.



Larger at NLO than NNLO. Also some effect from data missed out in the fit. Correct PDFs bring cross section back slightly towards fixed order.