COLLINEAR PROTON PDFS
AND
THE Z TRANSVERSE MOMENTUM DISTRIBUTION

Maria Ubiali

Royal Society Dorothy Hodgkin Research Fellow
University of Cambridge

Mw topical workshop, CERN theory institute

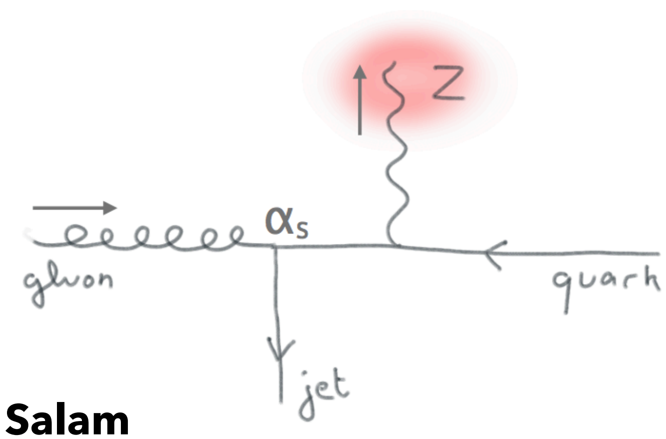
22nd June 2017

Outline of the talk

- Z transverse momentum distributions
  - ➡ Experimental measurements
  - ➡ Theoretical predictions
- The analysis
  - ➡ Impact of ZpT data in NNPDF3.0
  - ➡ Inclusion of ZpT data in NNPDF3.1
  - ➡ Study of small pT data
- Conclusions and outlook

Transverse momentum distributions

- Z boson production & decay into leptons benchmark SM process at the LHC.
- Z pT spectrum used to calibrate W pT spectrum for W mass measurement
- Can be measured very accurately at LHC thanks to large production rate and clean signature
- Can be calculated to high accuracy within the SM
  - ✓ $O(\alpha_S^2)$ total xsec prediction - **Hamberg et al (1991)**
  - ✓ $O(\alpha_S^2)$ differential xsec - **Anastasiou et al (2004), Melnikov et al (2006), Catani et al (2009)**
  - ✓ $O(\alpha_S^3)$ differential xsec - **Boughezal et al (2016), Gehrmann-De Ridder et al (2016)**
- Combination of precise experimental data and accurate theory allows this process to be used to determine quantities of fundamental importance, such as PDFs or α_S



G. Salam

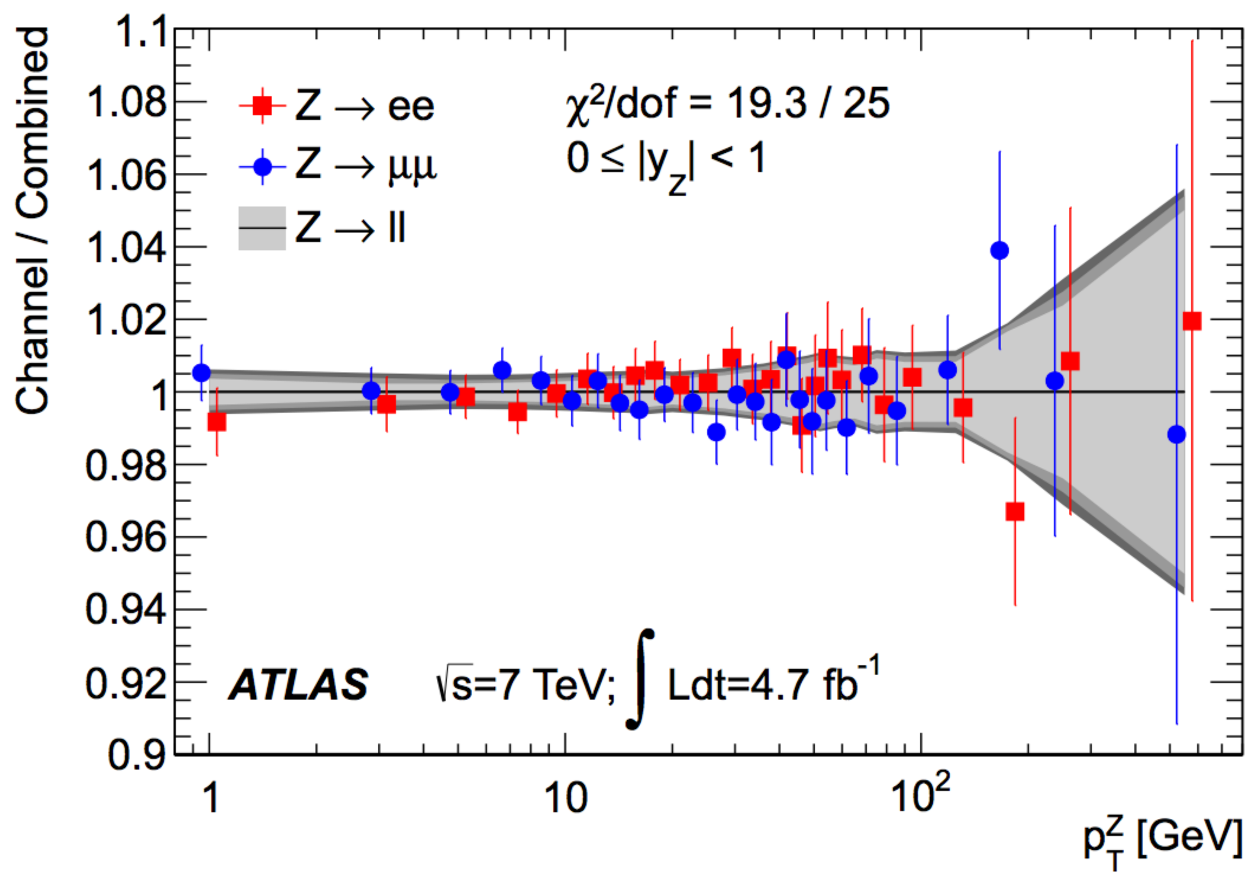
Topic of my talk

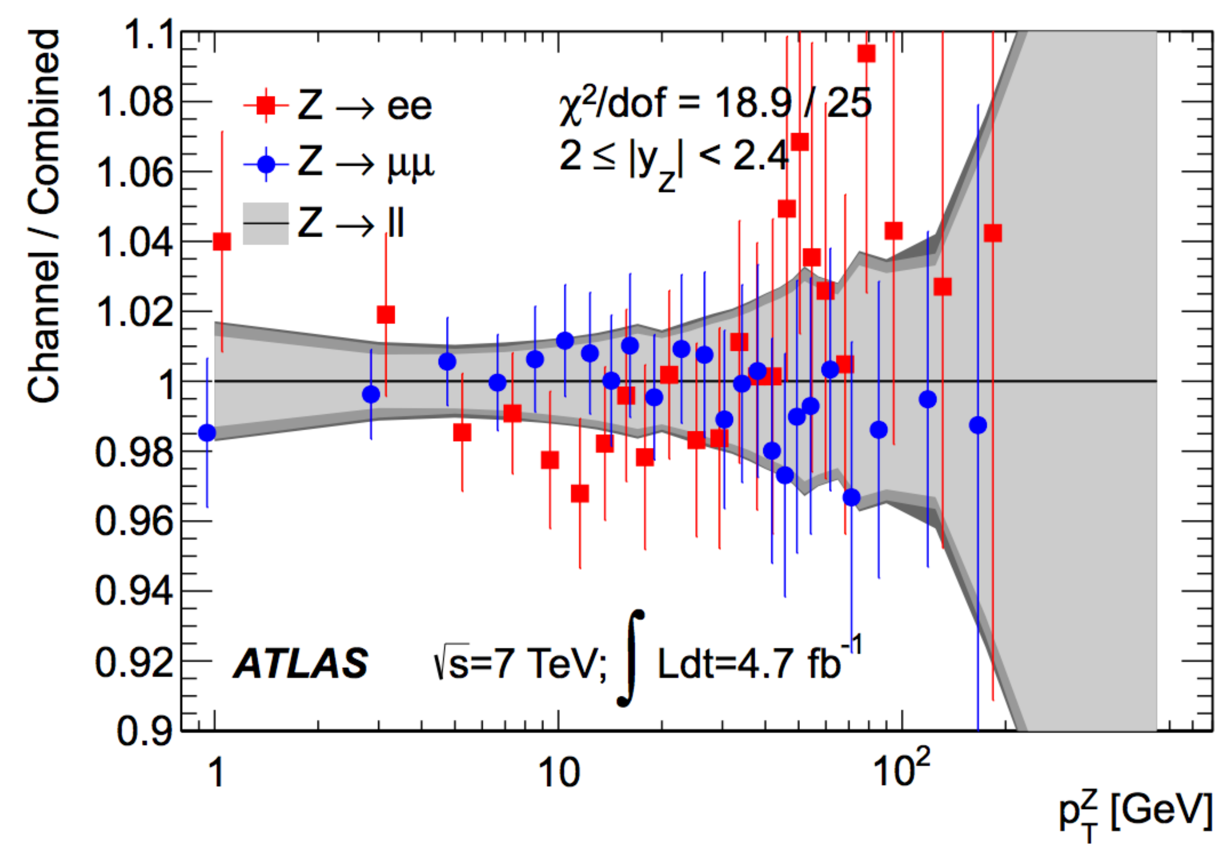
Boughezal, Guffanti, Petriello, MU -1705.00343

Ball et al - 1706.00428

Experimental Data

- Experimental precision < 1% up to pT~200 GeV
- Data hugely dominate by correlated systematic uncertainties





- Normalised distributions only
- Three rapidity bins

  0.0 < Y <1.0

  1.0 < Y < 2.0

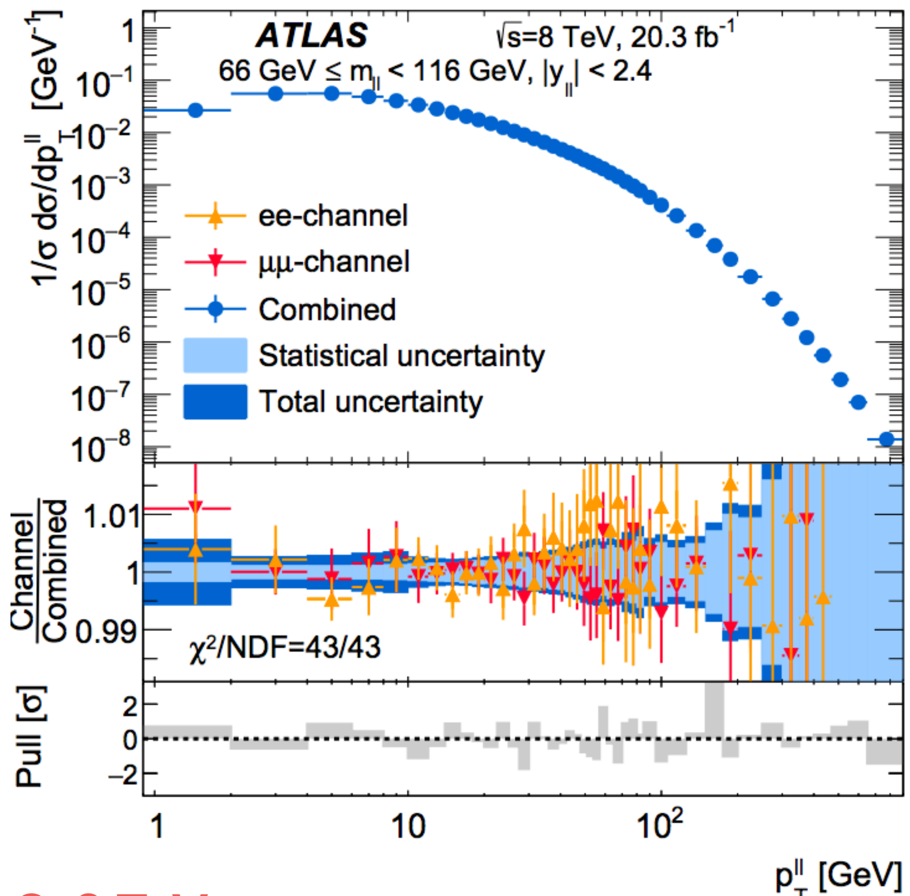
  2.0 < Y < 2.4

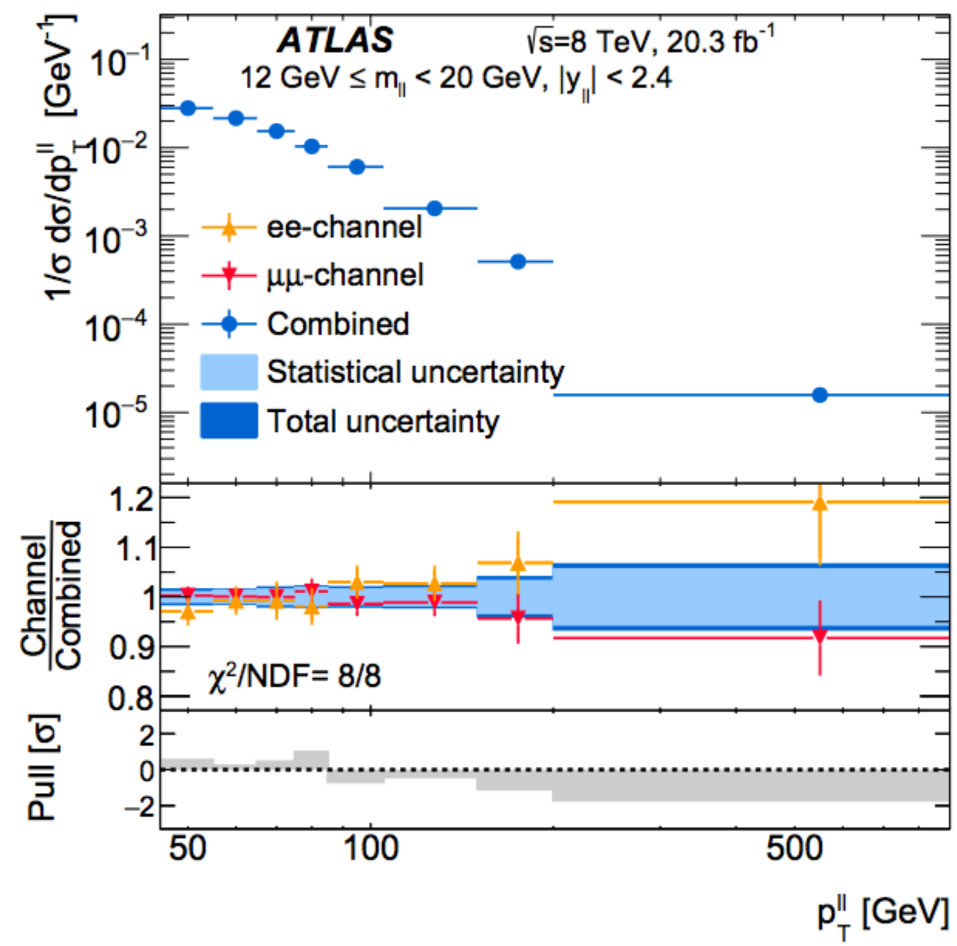
➡ **64(39)** data points (with pT > 30 GeV)

ATLAS 7 TeV measurements
ArXiv:1406.3660

Experimental Data

- Experimental precision < 1% up to pT~200 GeV
- Data hugely dominate by correlated systematic uncertainties





ATLAS 8 TeV measurements
arXiv: 1512.02192

- Normalised and Unnormalised
- Six rapidity bins in Z peak region

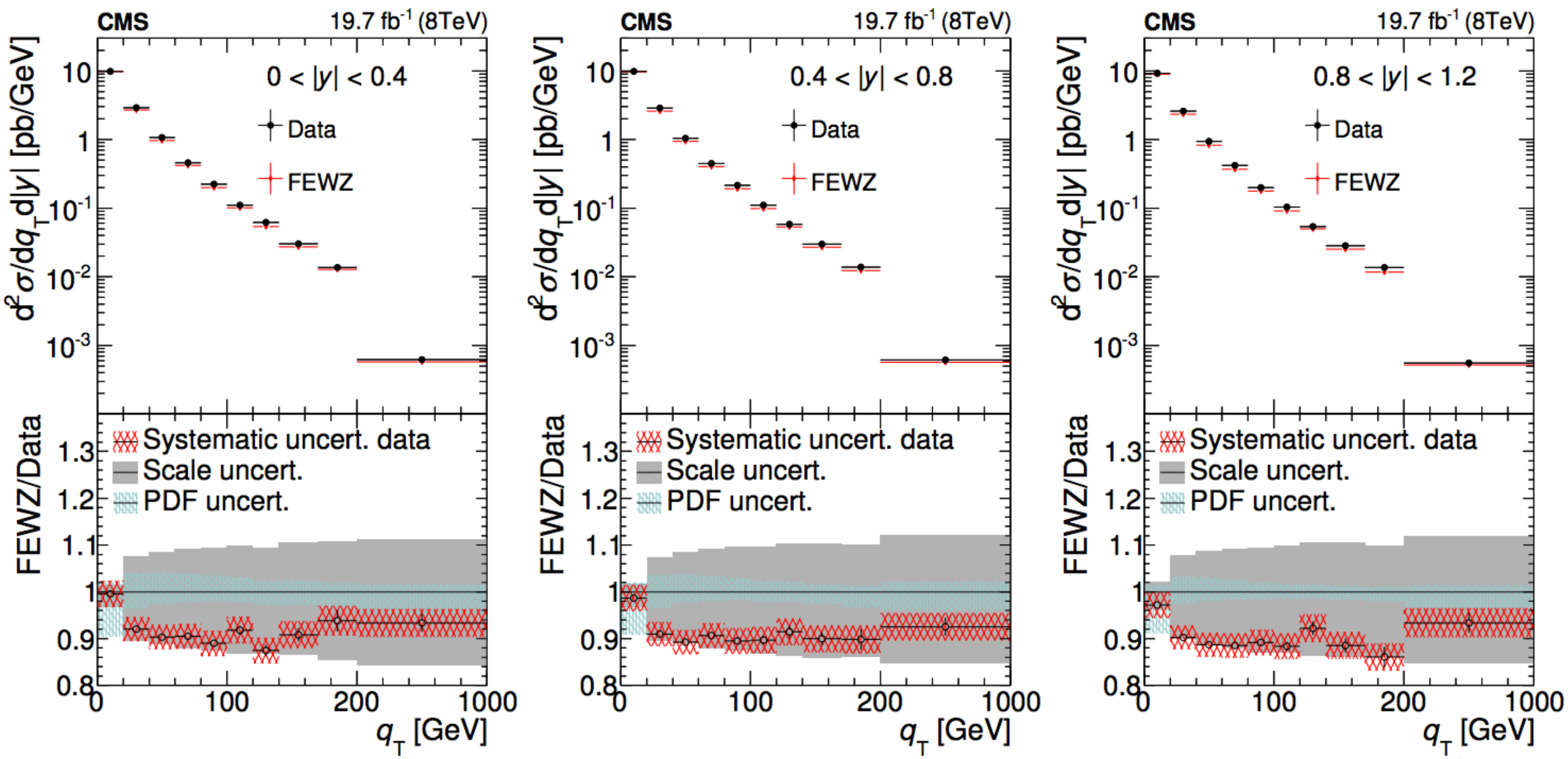
0.0 < Y < 0.4 - 0.4 < Y < 0.8
0.8 < Y < 1.2 - 1.2 < Y < 1.6
1.6 < Y < 2.0 - 2.0 < Y < 2.4

- Four low-invariant mass bins
(12,20) (20,30) (30,46) (46,66) GeV
- One high-invariant mass bin (116,150) GeV

➡ **184(94)** datapoints (with pT > 30 GeV)

Experimental Data

- Experimental precision < 1% up to pT~200 GeV
- Data hugely dominate by correlated systematic uncertainties



- Normalised and un-normalised
- Five rapidity bins in Z peak region
  0.0 < Y < 0.4, 0.4 < Y < 0.8, 0.8 < Y < 1.2
  1.2 < Y < 1.6, 1.6 < Y < 2.0

➡ **50(28)** datapoints (with pT > 30 GeV)

CMS 8 TeV measurements
arXiv: 1504.03511

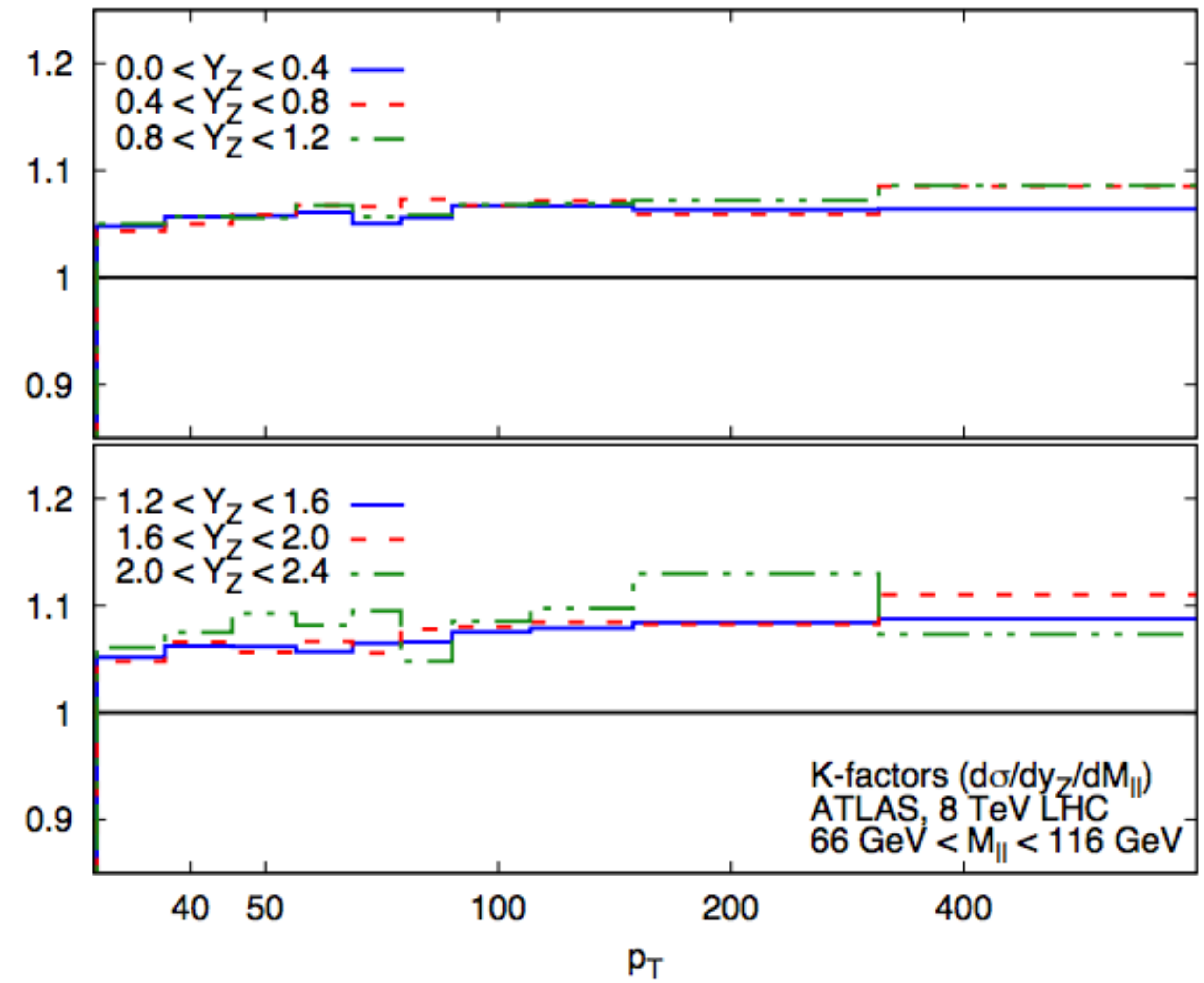
total 300 (161)
precise datapoints

Theoretical predictions

- NNLO calculation performed using N-jettiness subtraction scheme, by using recent calculation of Z+j at NNLO and relaxing cuts on final state jet

$$\mu_R = \mu_F = \sqrt{(p_T^Z)^2 + M_{ll}^2}$$

- NNLO/NLO K-factors 5% - 10% depending on the rapidity and invariant mass region
- Imposed $p_T > 30$ GeV cut and verified stability upon raising the cut to 50 GeV
- Evaluated impact of approximate EW corrections **(Pozzorini et al)** cross-checked against exact **(Denner et al)**

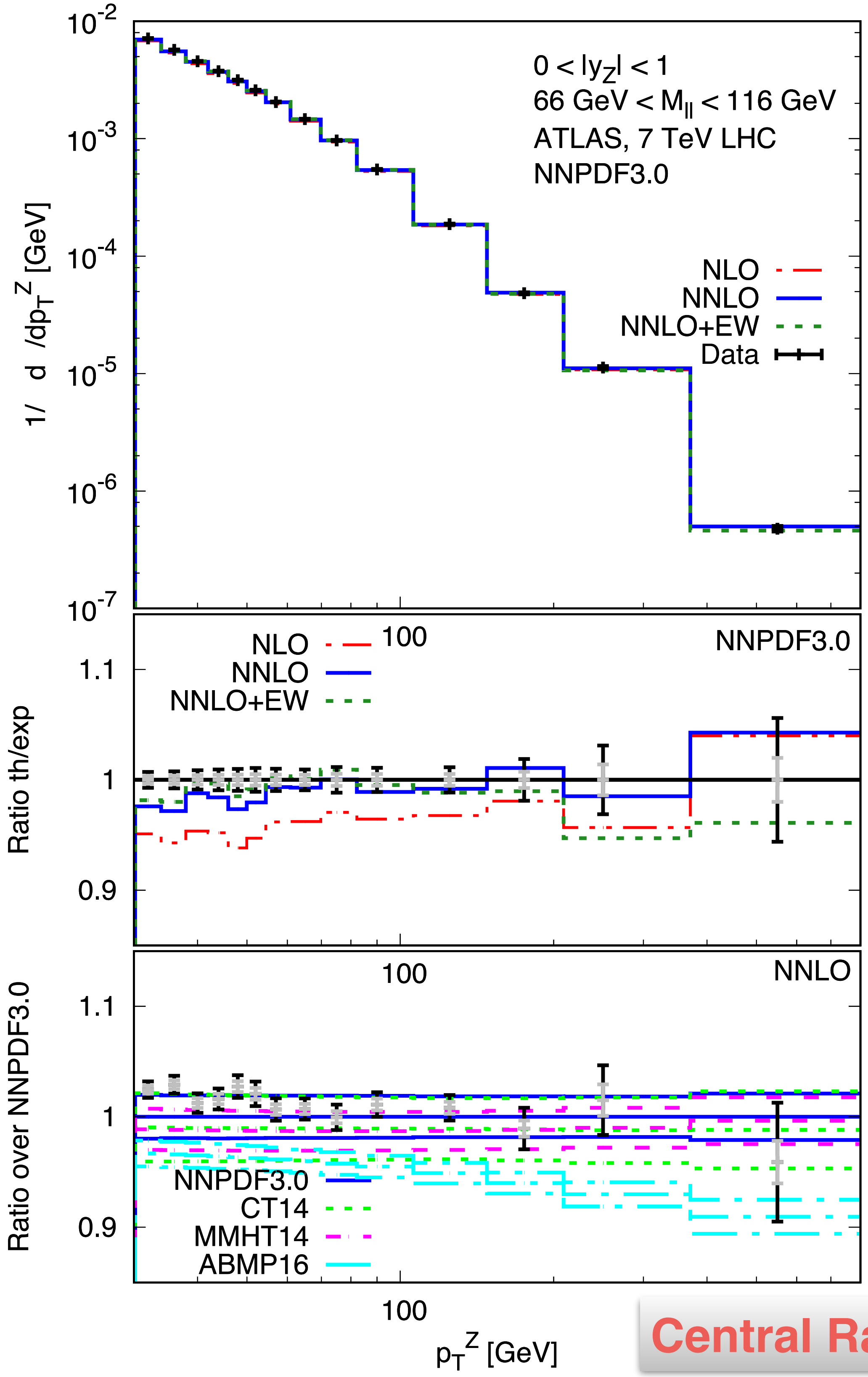


Boughezal, Guffanti, Petriello, MU -1705.00343

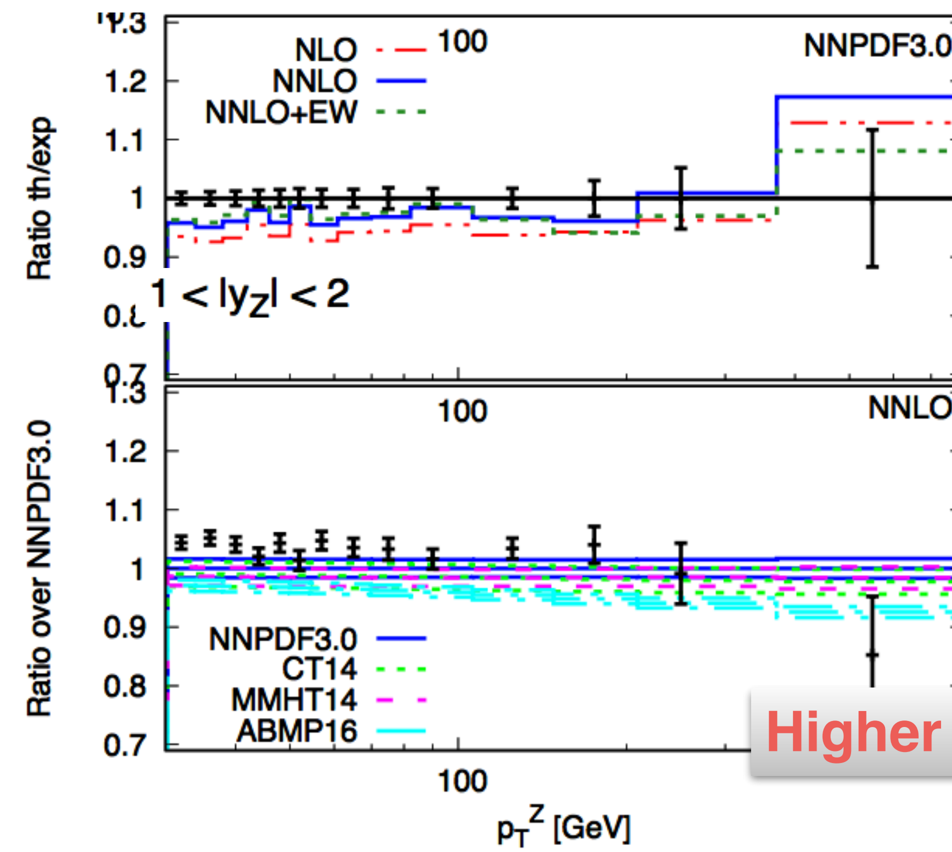
Data-theory comparison

ATLAS 7 TeV

Boughezal, Guffanti, Petriello, MU -1705.00343



Central Rapidity



Higher Rapidity

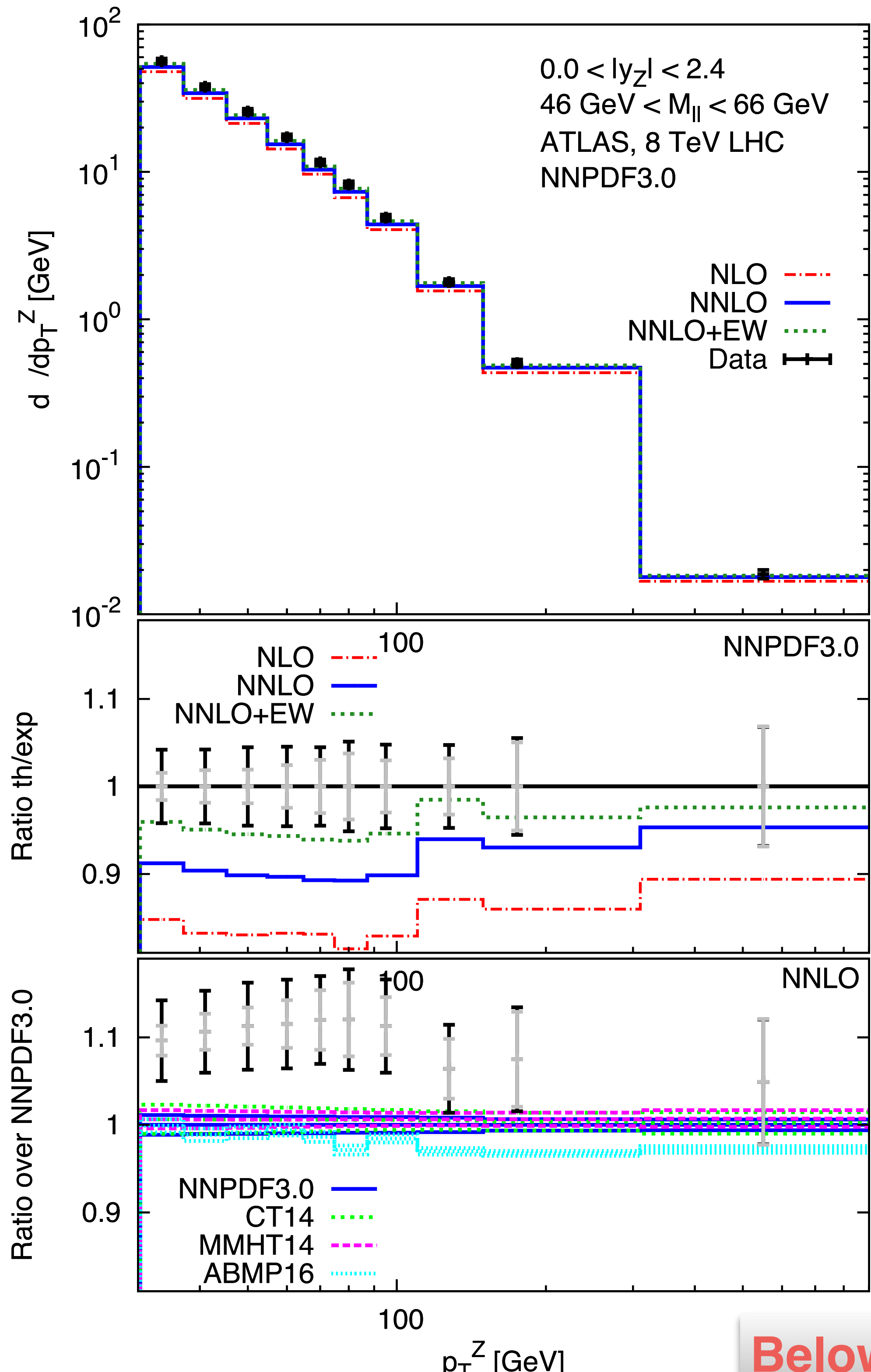
χ^2 / d.o.f.	NLO (NNPDF3.0)	NNLO (NNPDF3.0)	NNLO + EW (NNPDF3.0)	NNLO (ABMP16)
0<Y<1	10	2.2	1.3	11
1<Y<2	13	5.6	3.9	12

NNLO(+EW) improve agreement with data

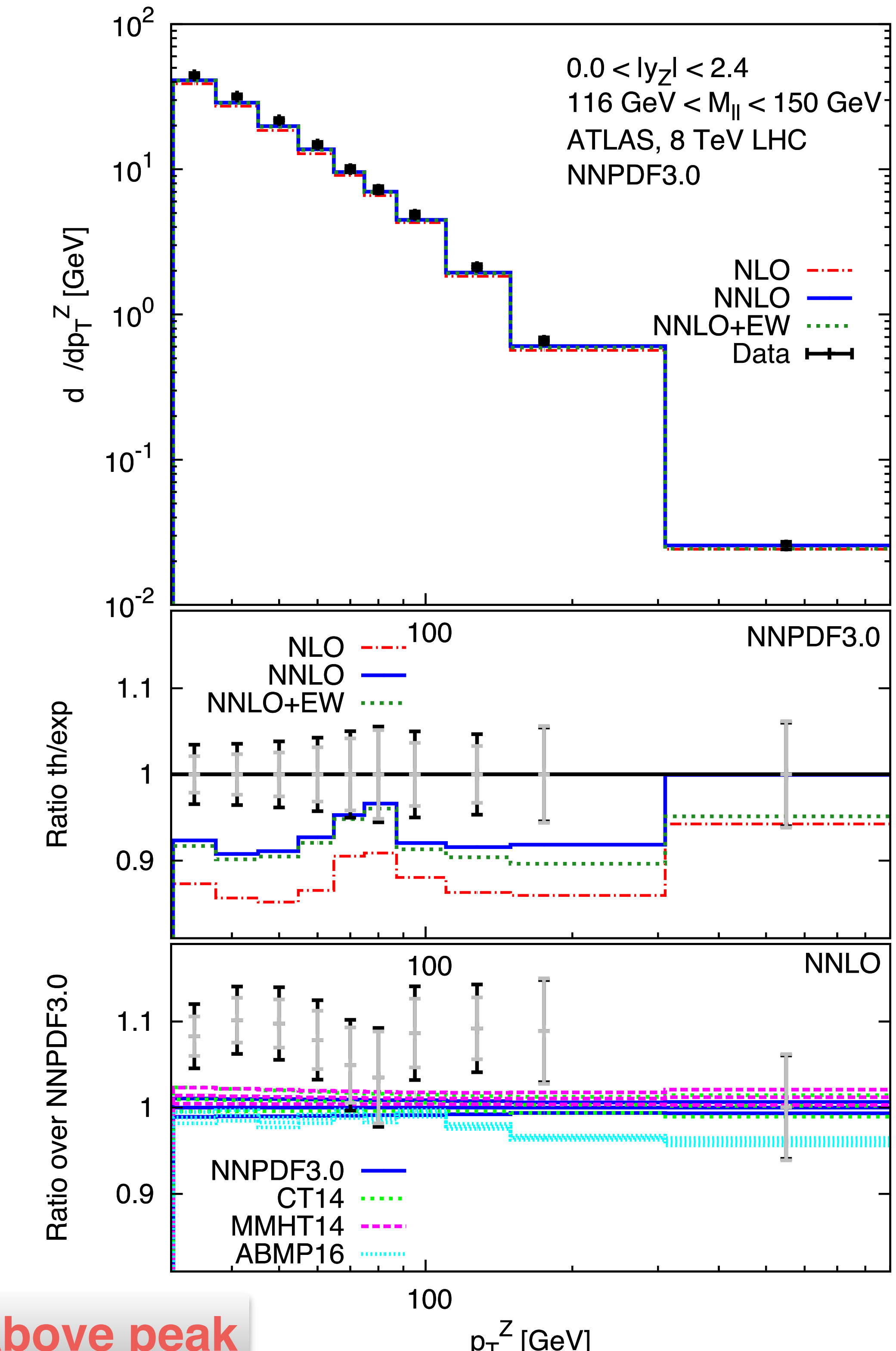
Data-theory comparison

ATLAS 8 TeV

Boughezal, Guffanti, Petriello, MU -1705.00343



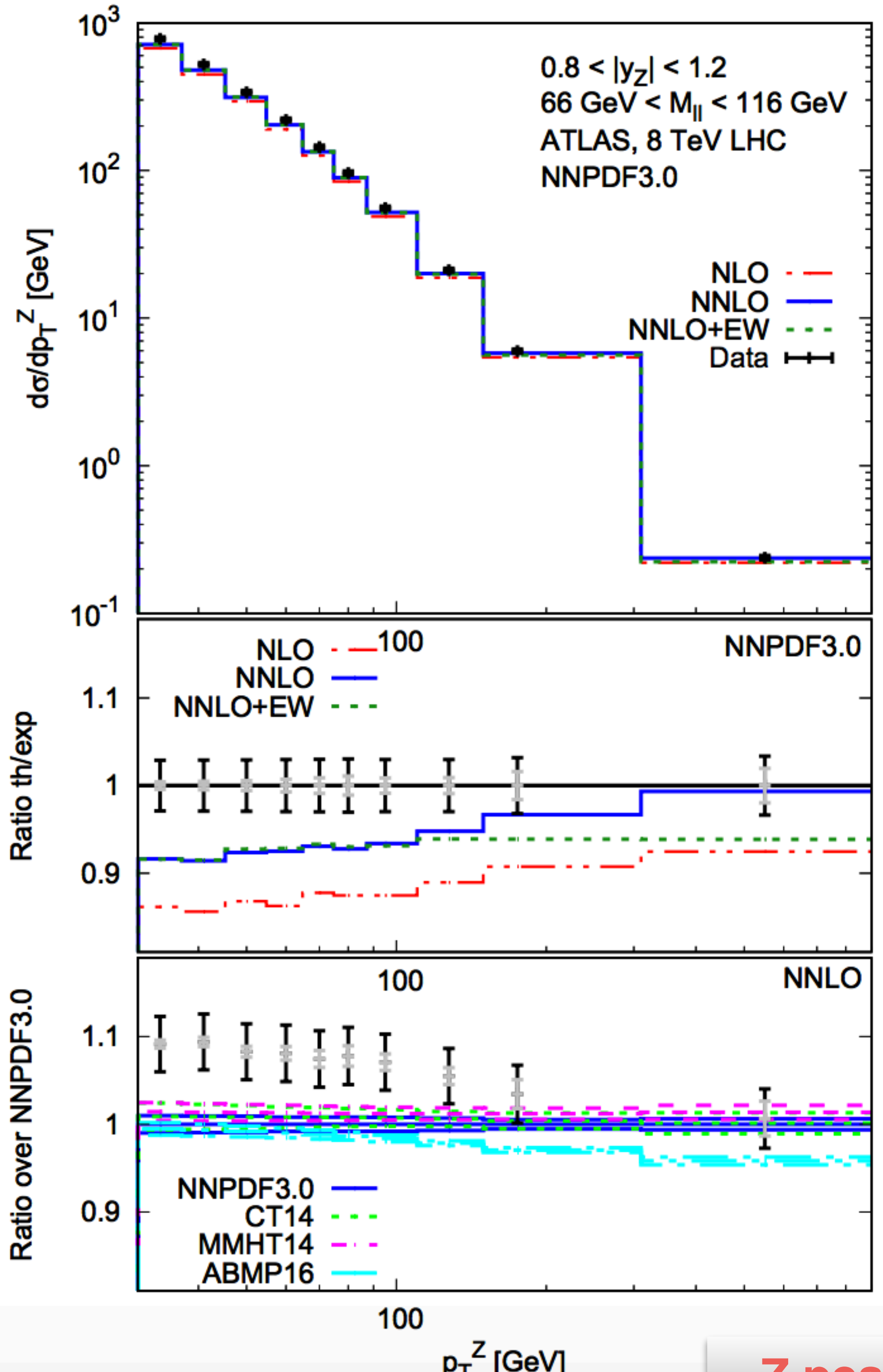
Below peak



Above peak

Data-theory comparison

ATLAS 8 TeV



Z peak

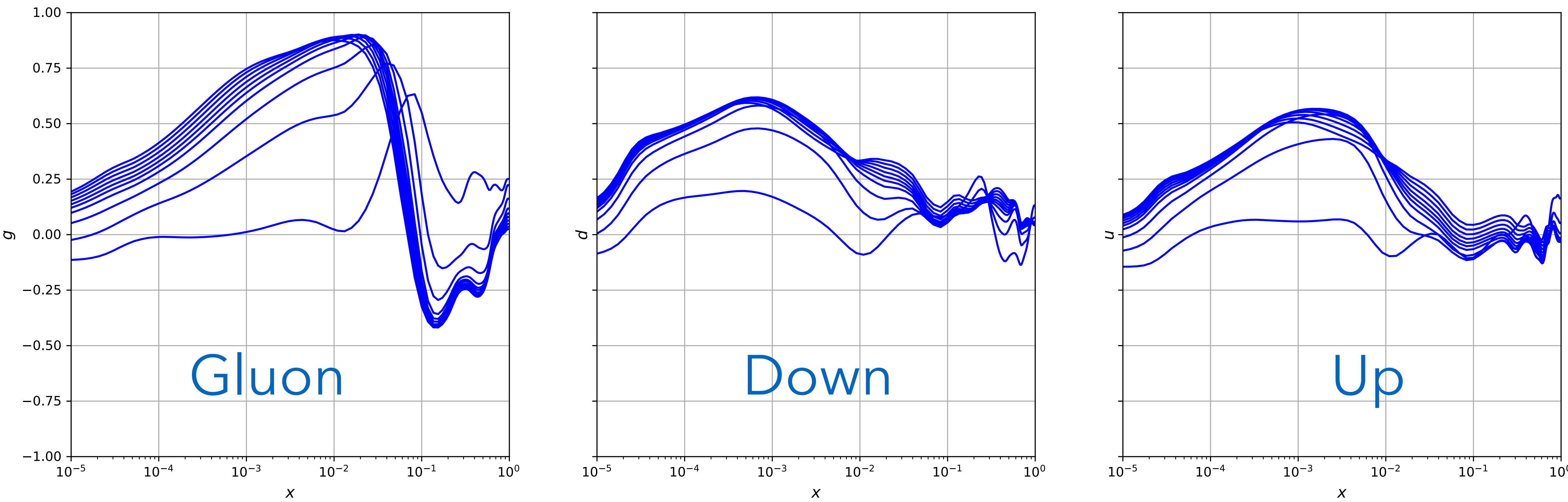
Boughezal, Guffanti, Petriello, MU -1705.00343

- Good example of correlation-dominated observable. Data-theory comparison does not reflect actual value of the χ^2
- NNLO correction generally improves agreement (before fit)
- EW corrections only relevant for the two highest p_T bins in the Z-mass peak
- Similar picture for CMS data (Y < 1.6)

χ^2 / d.o.f.	NLO (NNPDF3.0)	NNLO (NNPDF3.0)	NNLO + EW (NNPDF3.0)	NNLO (ABMP16)
0.8< Y < 1.2	5.8	4.7	2.3	2.1

Correlations with PDFs

ATLASZPT8TEVYDIST - Bin 1 **Boughezal, Guffanti, Petriello, MU -1705.00343**



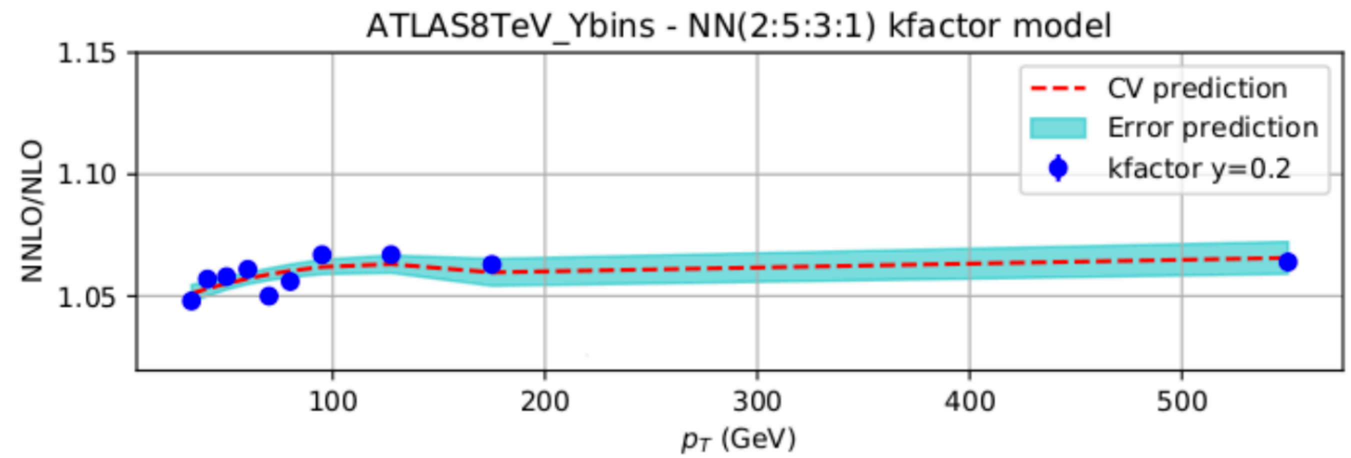
- Inclusion of Z pT data at NNLO excluding pT bins below 30 GeV and the one/two largest pT bins affected by small- / large-pT enhancements
- Expect constraint to intermediate-x gluon and light quark distributions

NNLO fit cuts

30 GeV < p_T^Z < 500 GeV (ATLAS 7 TeV)
30 GeV < p_T^Z < 150 GeV (ATLAS 8 TeV, on peak)
30 GeV < p_T^Z < 170 GeV (CMS 8 TeV)

Extra-statistical uncertainty

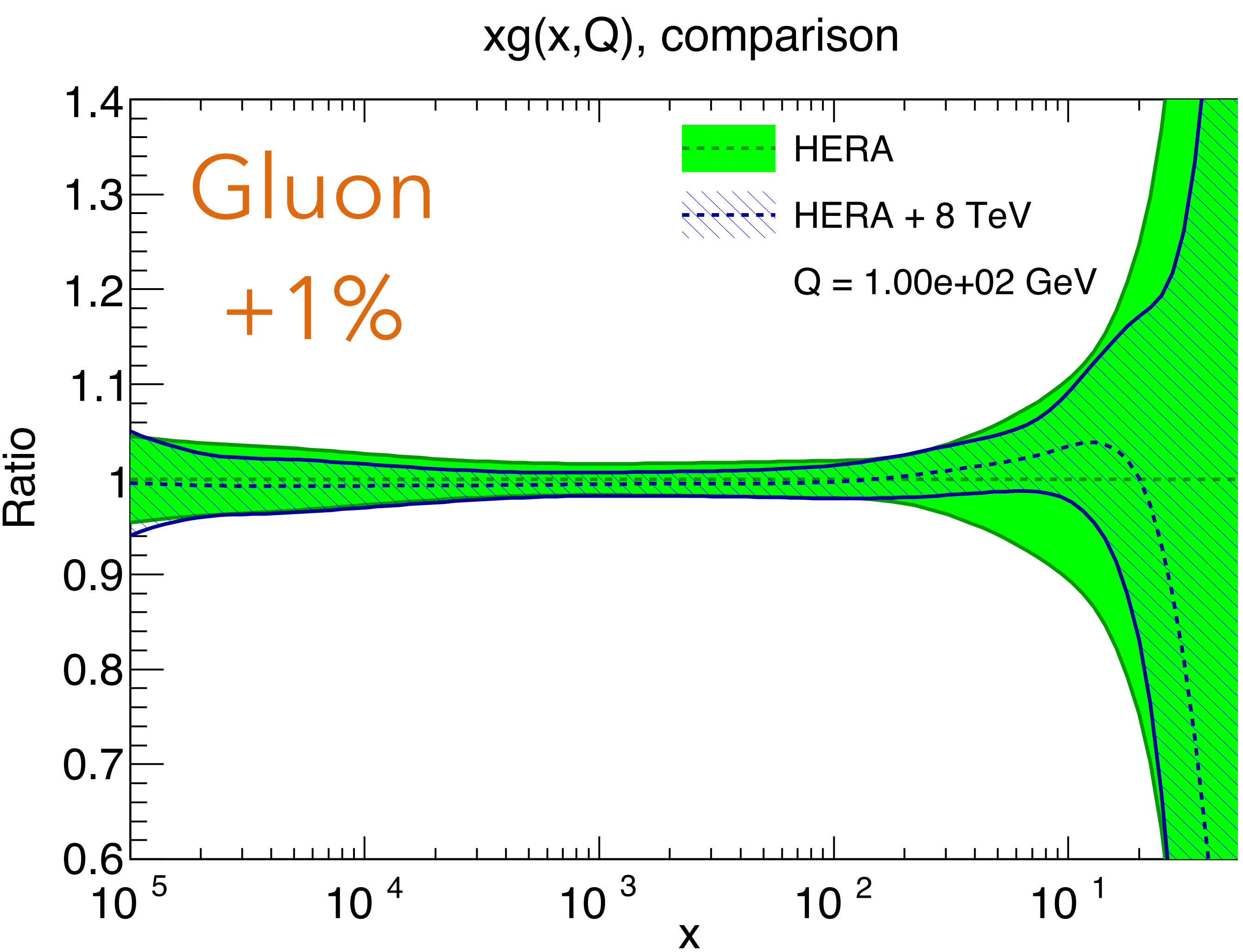
- NNLO theory predictions affected by non-negligible Monte Carlo uncertainties
- Numerical uncertainties in theoretical predictions estimated by comparing fluctuations with respect to smooth interpolation
- Explore 0%, 0.5% and 1% hypothesis

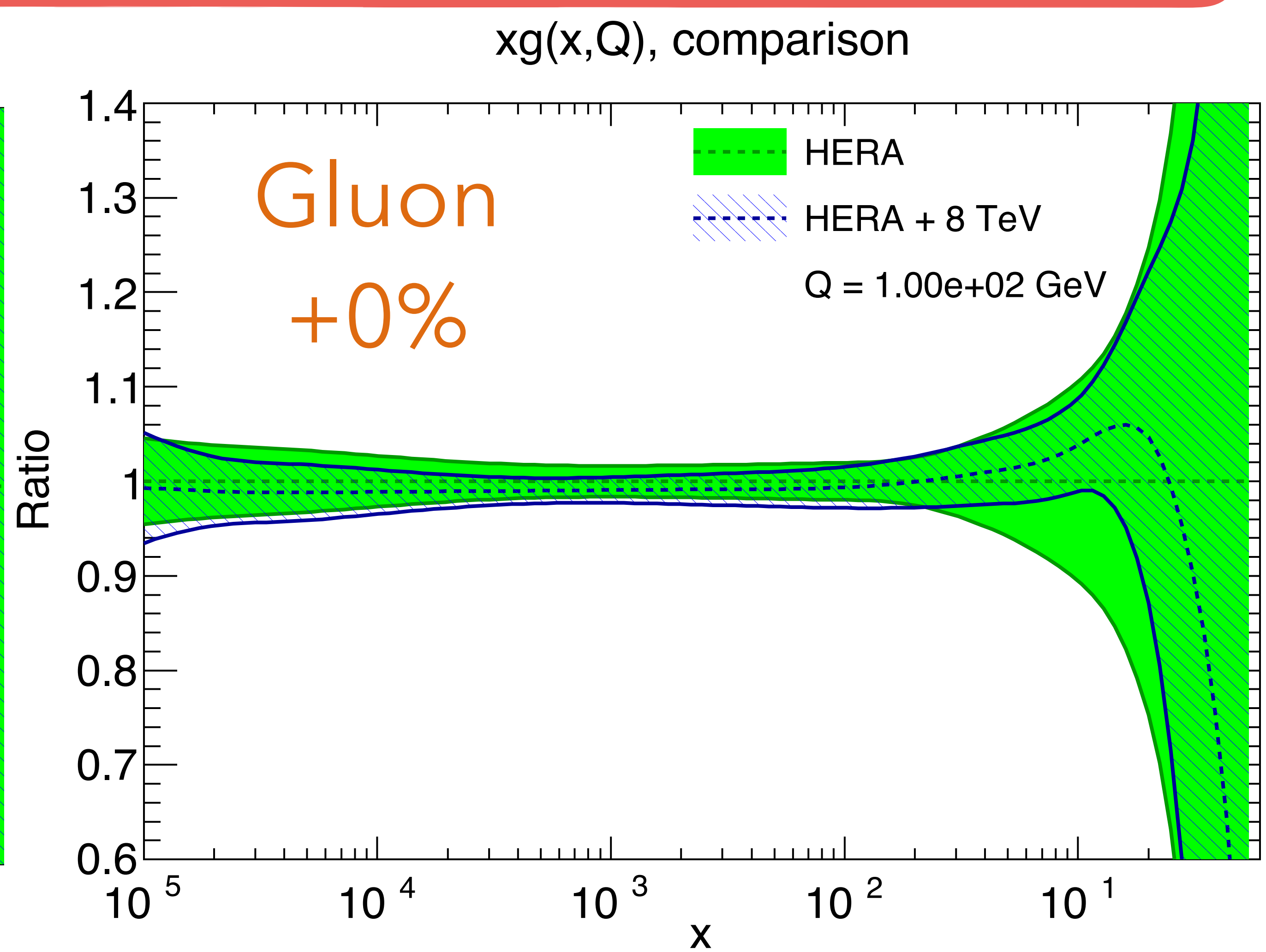


HERA + 8 TeV ZpT data fits

Extra Δ	χ^2 ATLAS 7 TeV	χ^2 ATLAS 8 TeV (M)	χ^2 ATLAS 8 TeV (Y)	χ^2 CMS 8 TeV (Y)
1%	(18)	0.90	0.77	1.42
No	(25)	1.03	2.09	3.59

Impact of 8 TeV Z p_T distributions (HERA)

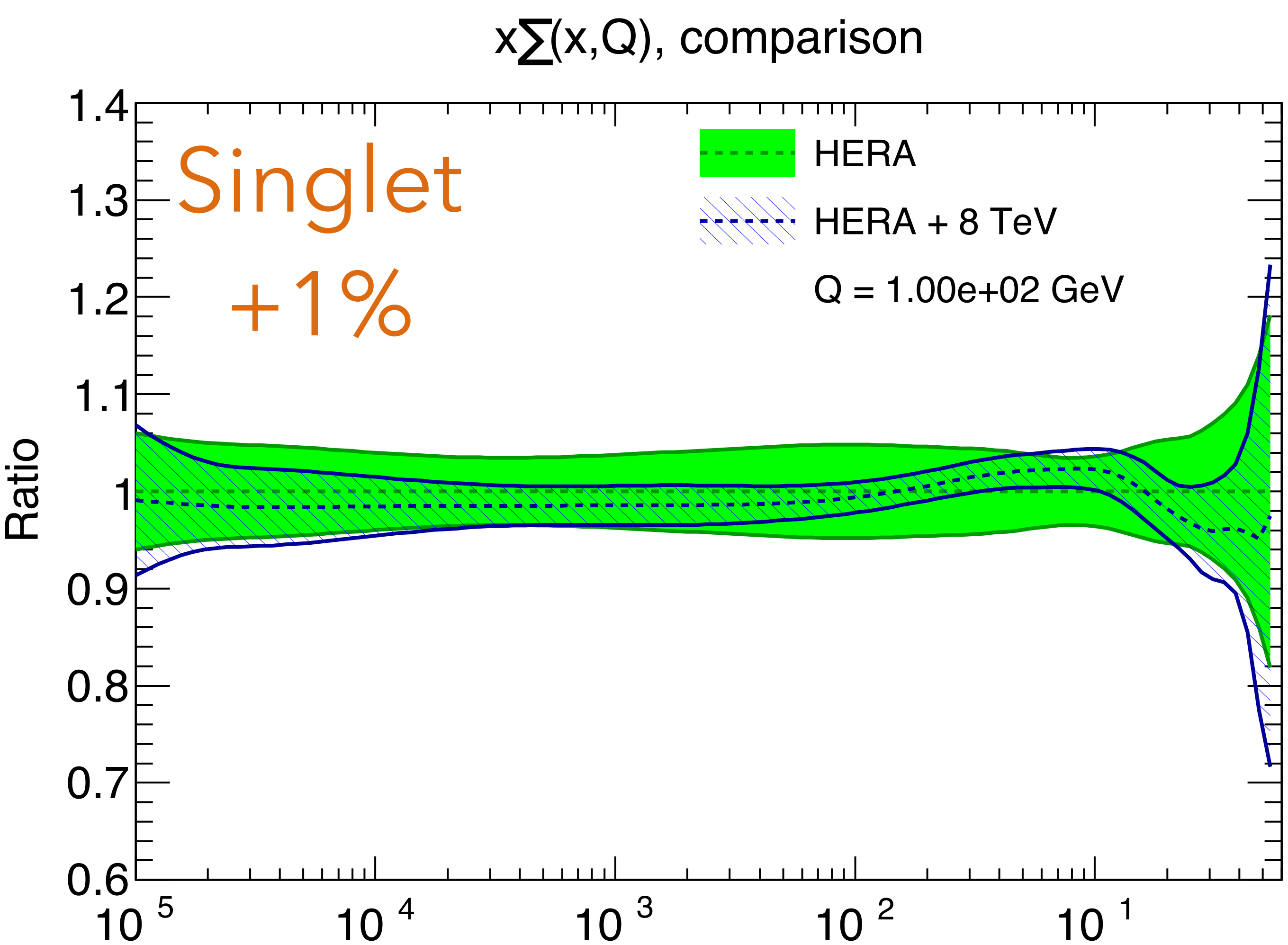


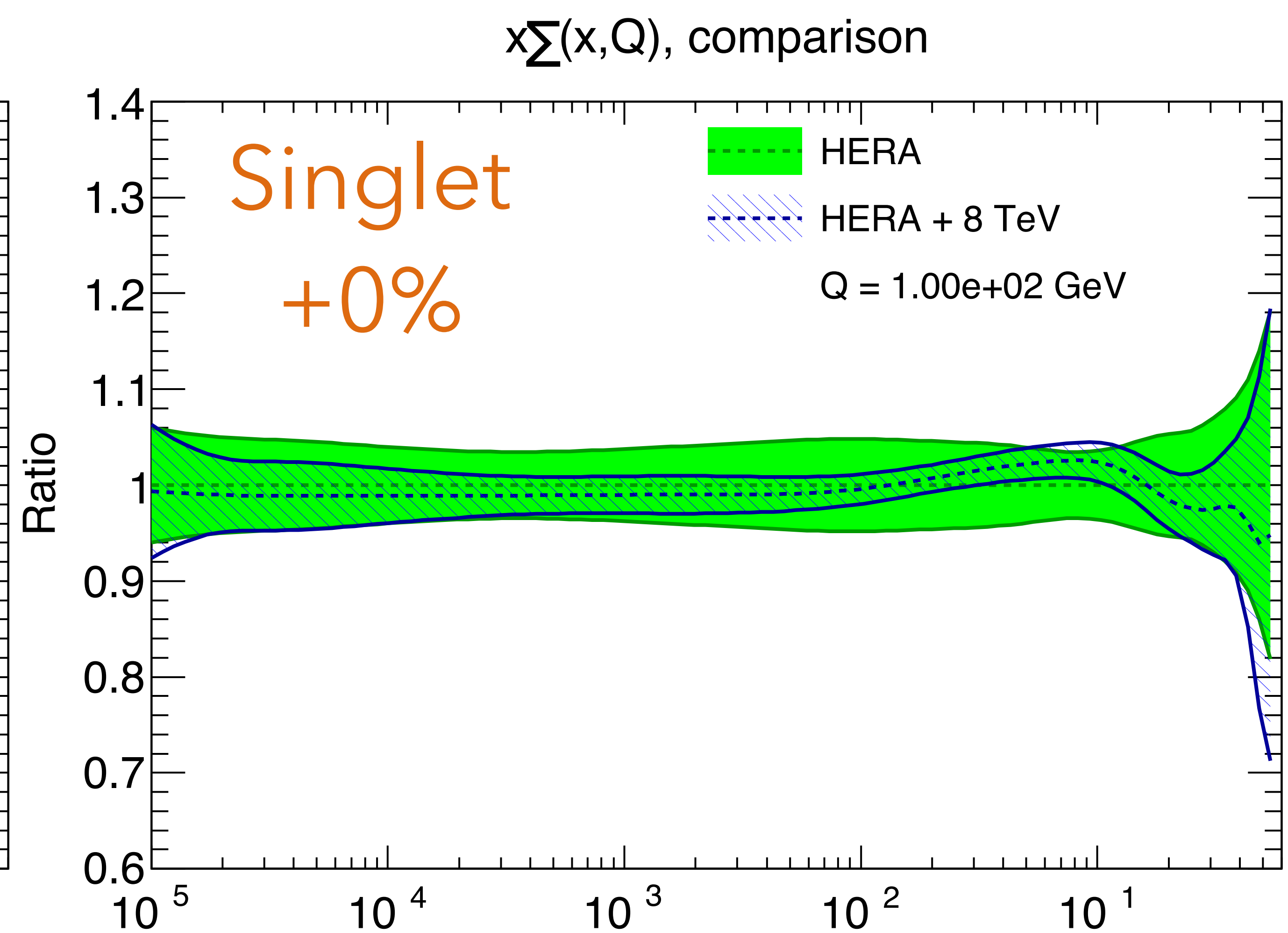


- Impact of Z pT distributions is quite strong on light quarks and gluon
- ATLAS and CMS data at 8 TeV (unnormalised) decrease uncertainty of gluon and light quark distributions at both in HERA-only fits and in global fits
- PDFs stable under extra uncorrelated uncertainty included in the fit (only slightly smaller PDF error reduction when no extra uncertainty is included - barely visible)

Boughezal, Guffanti, Petriello, MU -1705.00343

Impact of 8 TeV Z p_T distributions (HERA)

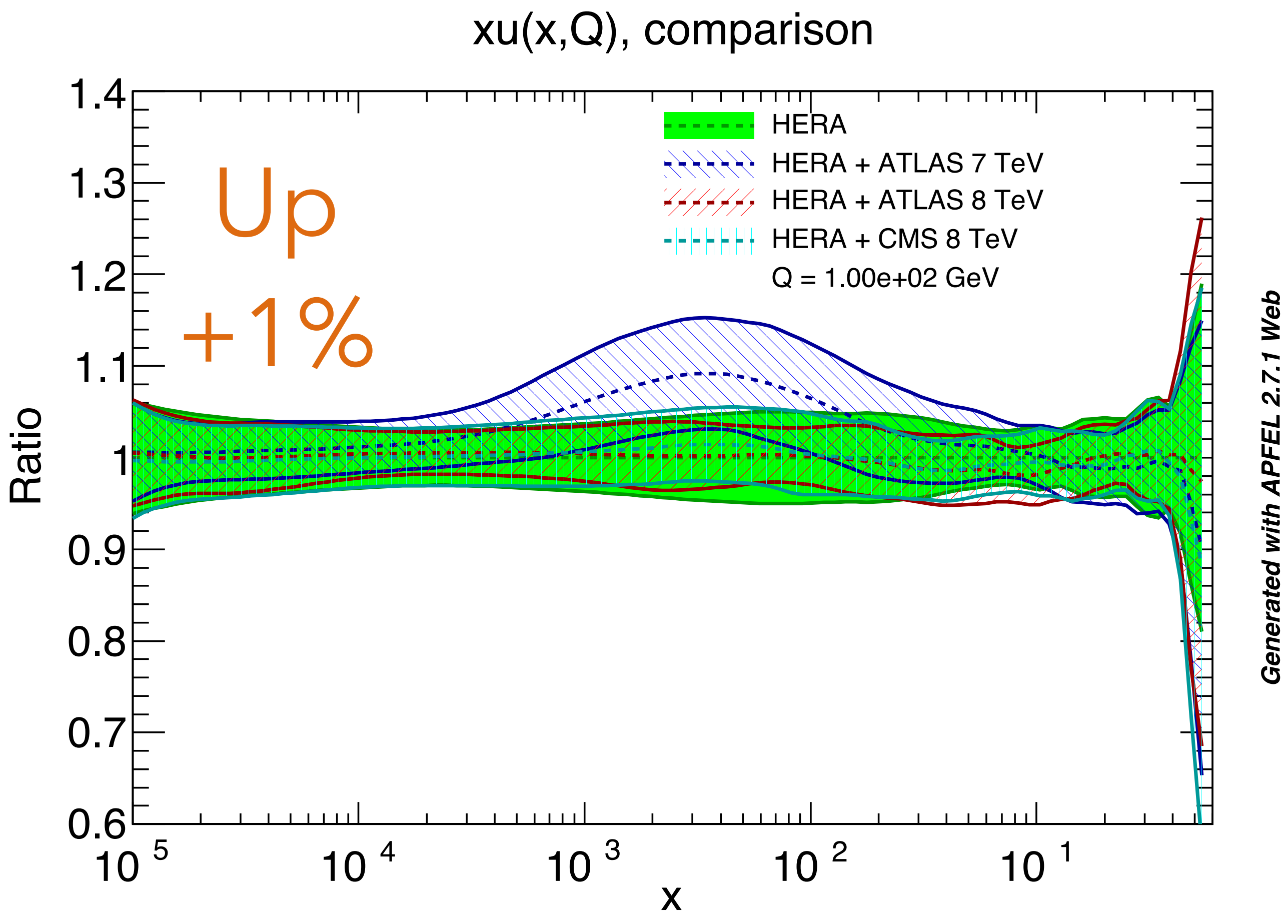


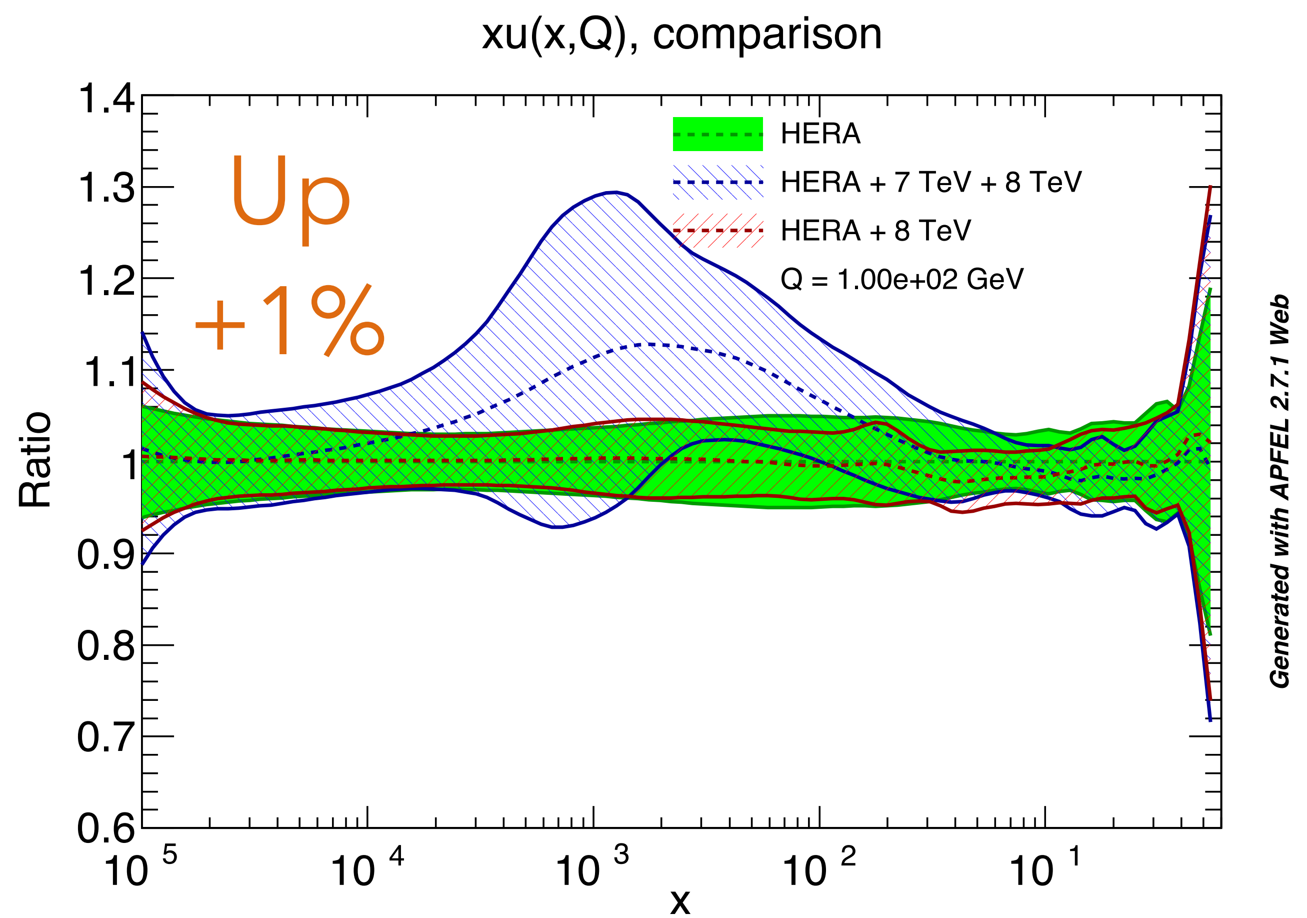


- Impact of Z pT distributions is quite strong on light quarks and gluon
- ATLAS and CMS data at 8 TeV (unnormalised) decrease uncertainty of gluon and light quark distributions at both in HERA-only fits and in global fits
- PDFs stable under extra uncorrelated uncertainty included in the fit (only slightly smaller PDF error reduction when no extra uncertainty is included - barely visible)

Boughezal, Guffanti, Petriello, MU -1705.00343

Issues with normalised distributions

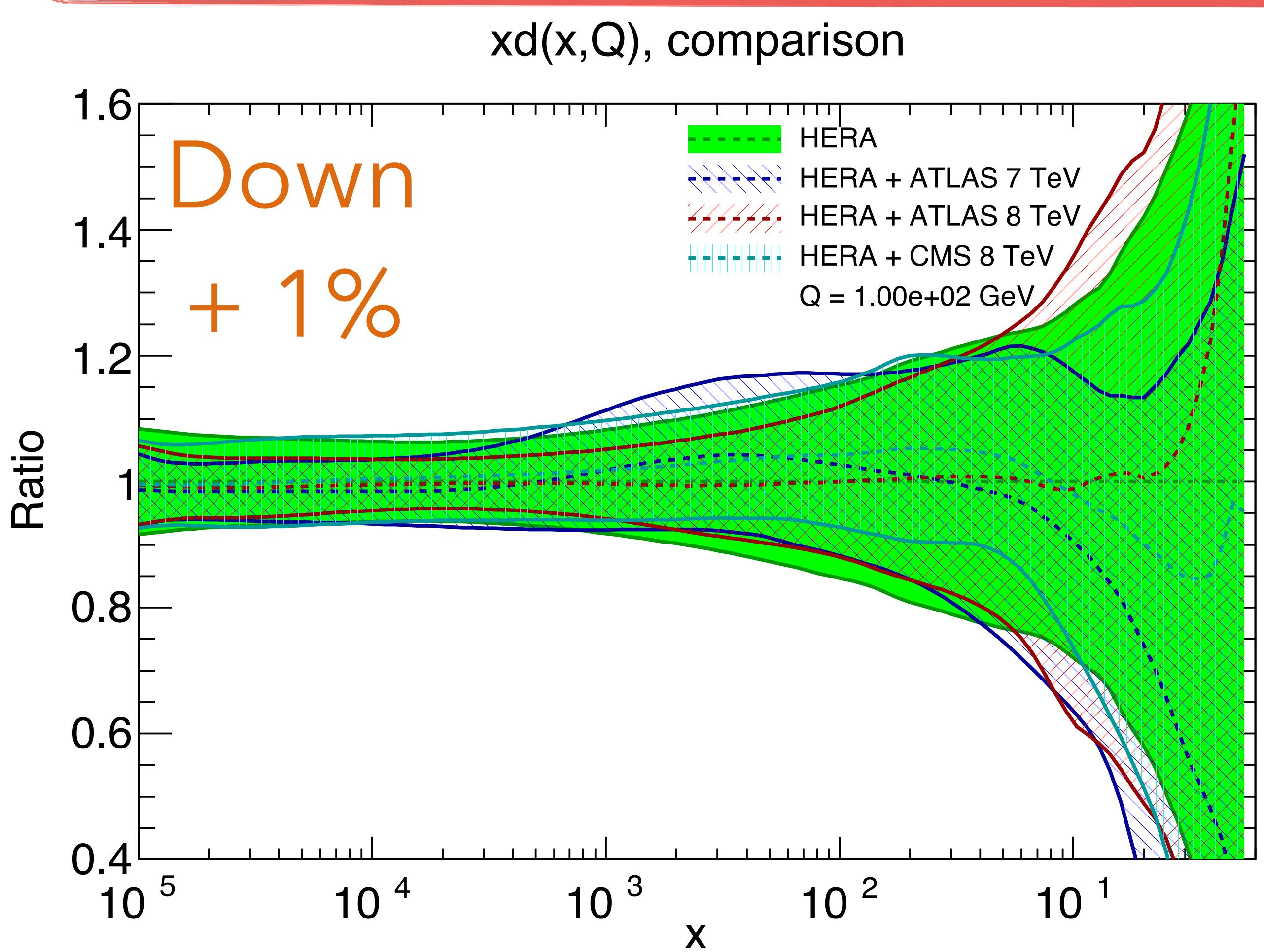


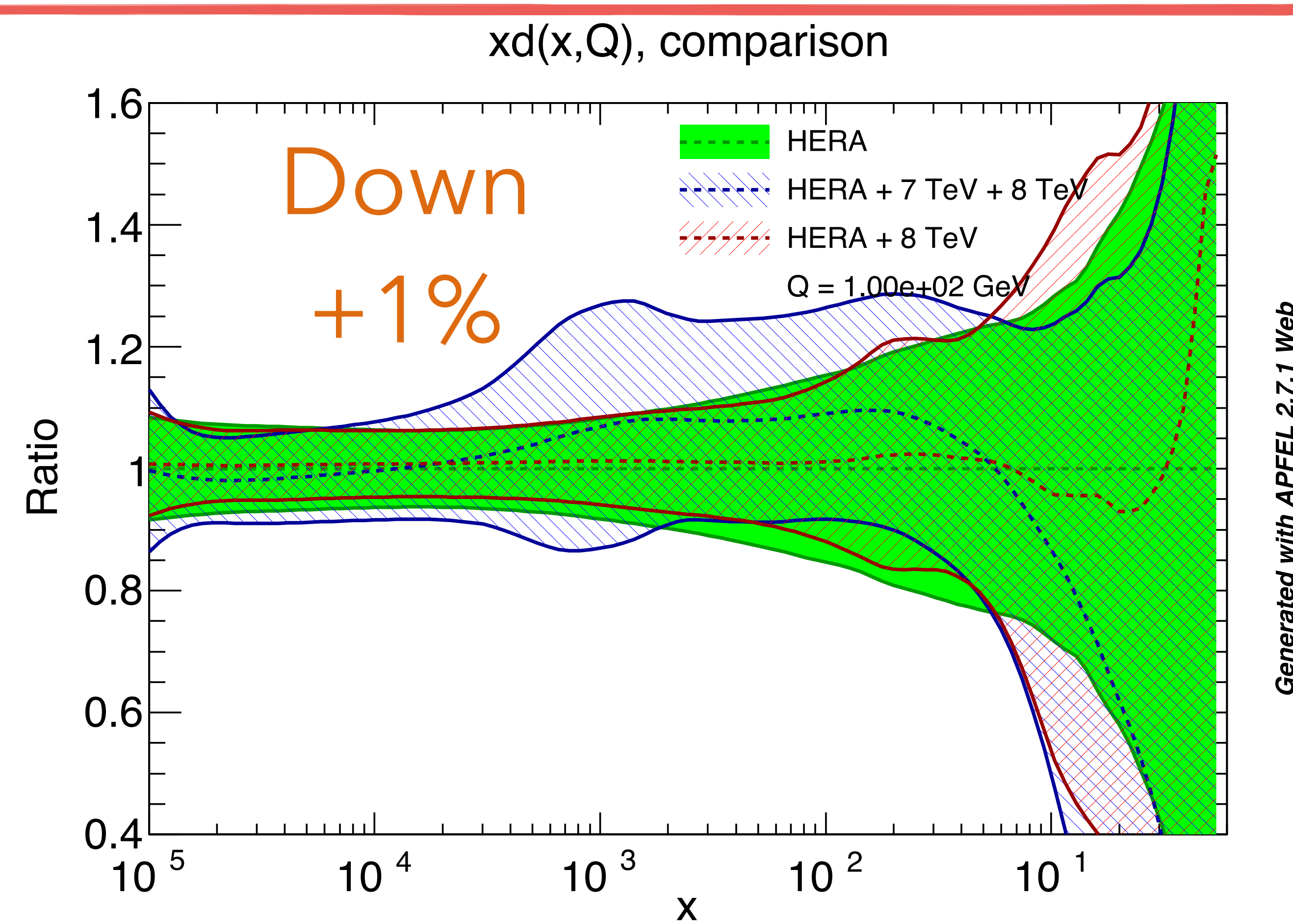


- ATLAS 7 TeV data (normalised) can be fitted individually but point to a different minimum, so when data added together uncertainty increases!
- Normalised data correlate small pT range with the high pT range used in the analysis

Extra Δ	χ^2 ATLAS 7 TeV	χ^2 ATLAS 8 TeV (M)	χ^2 ATLAS 8 TeV (Y)	χ^2 CMS 8 TeV (Y)
1%	1.4	(1.4)	(2.0)	(1.4)
1%	1.7	1.0	1.2	1.3

Issues with normalised distributions



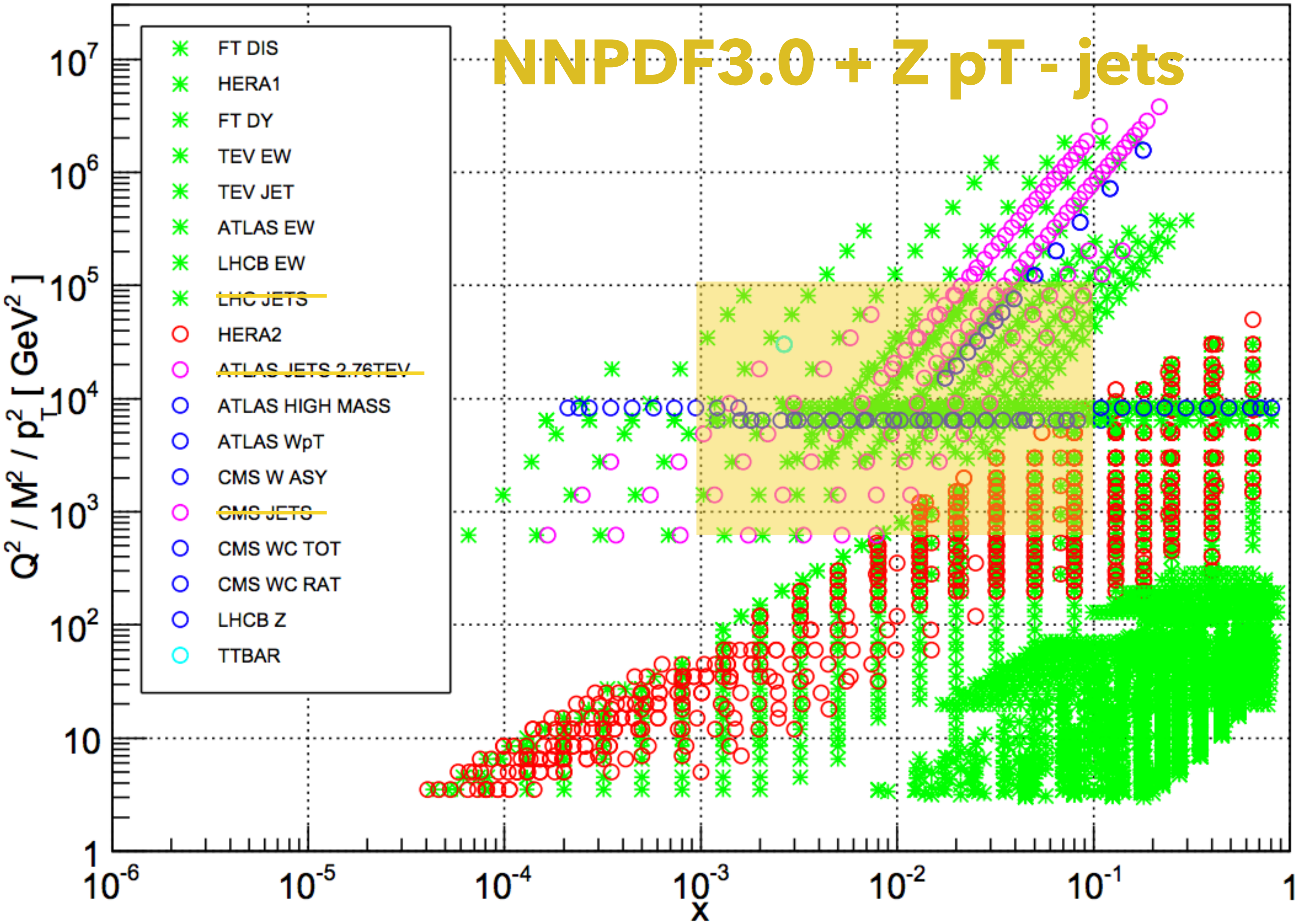


- ATLAS 7 TeV data (normalised) can be fitted individually but point to a different minimum, so when data added together uncertainty increases!
- Normalised data correlate small pT range with the high pT range used in the analysis

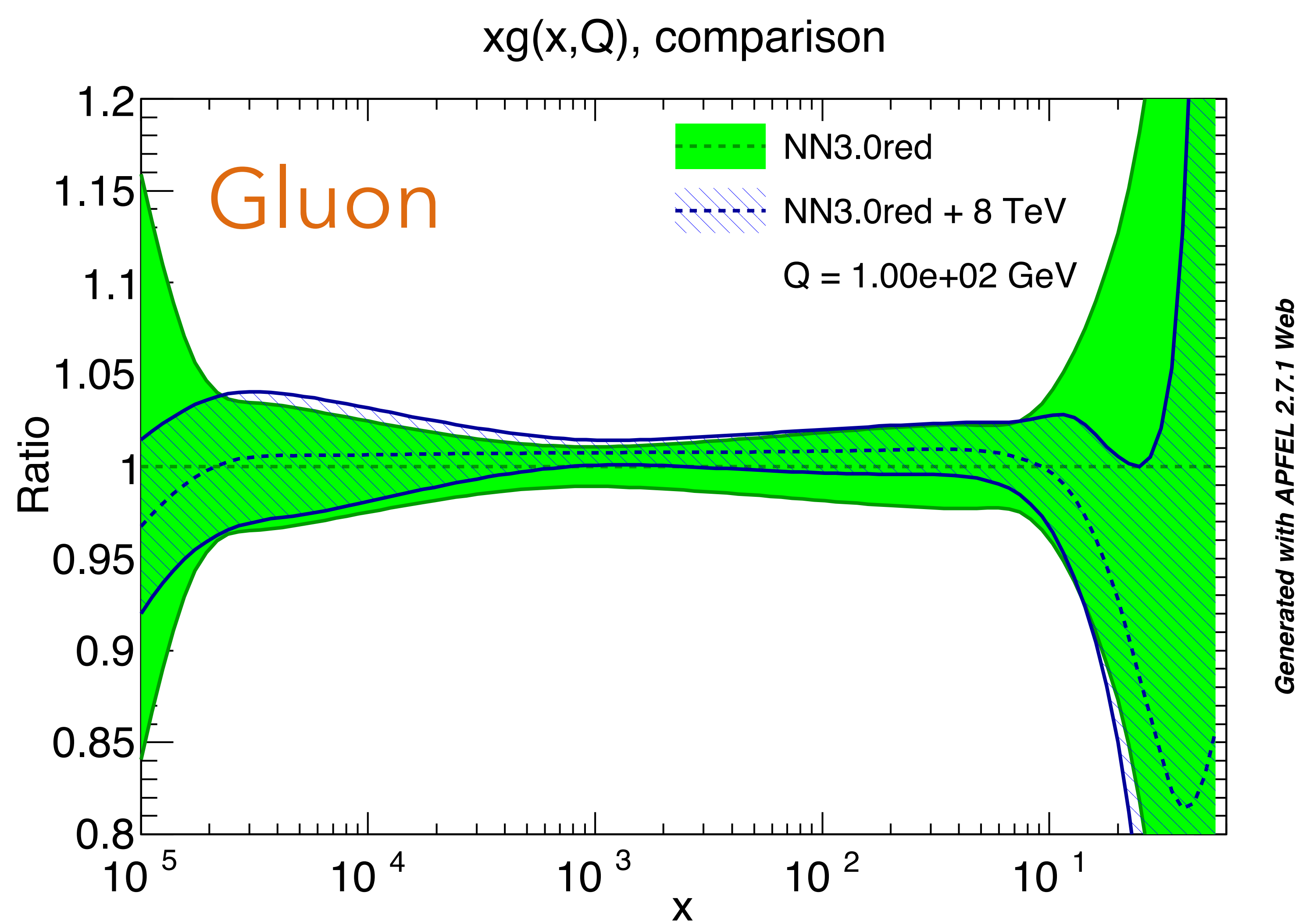
Extra **Δ**	χ^2 ATLAS 7 TeV	χ^2 ATLAS 8 TeV (M)	χ^2 ATLAS 8 TeV (Y)	χ^2 CMS 8 TeV (Y)
1%	1.4	(1.4)	(2.0)	(1.4)
1%	1.7	1.0	1.2	1.3

The NNPDF3.0 global PDF analysis

- Baseline: NNPDF3.0red with HERA I+II combined data and <u>without</u> jets data

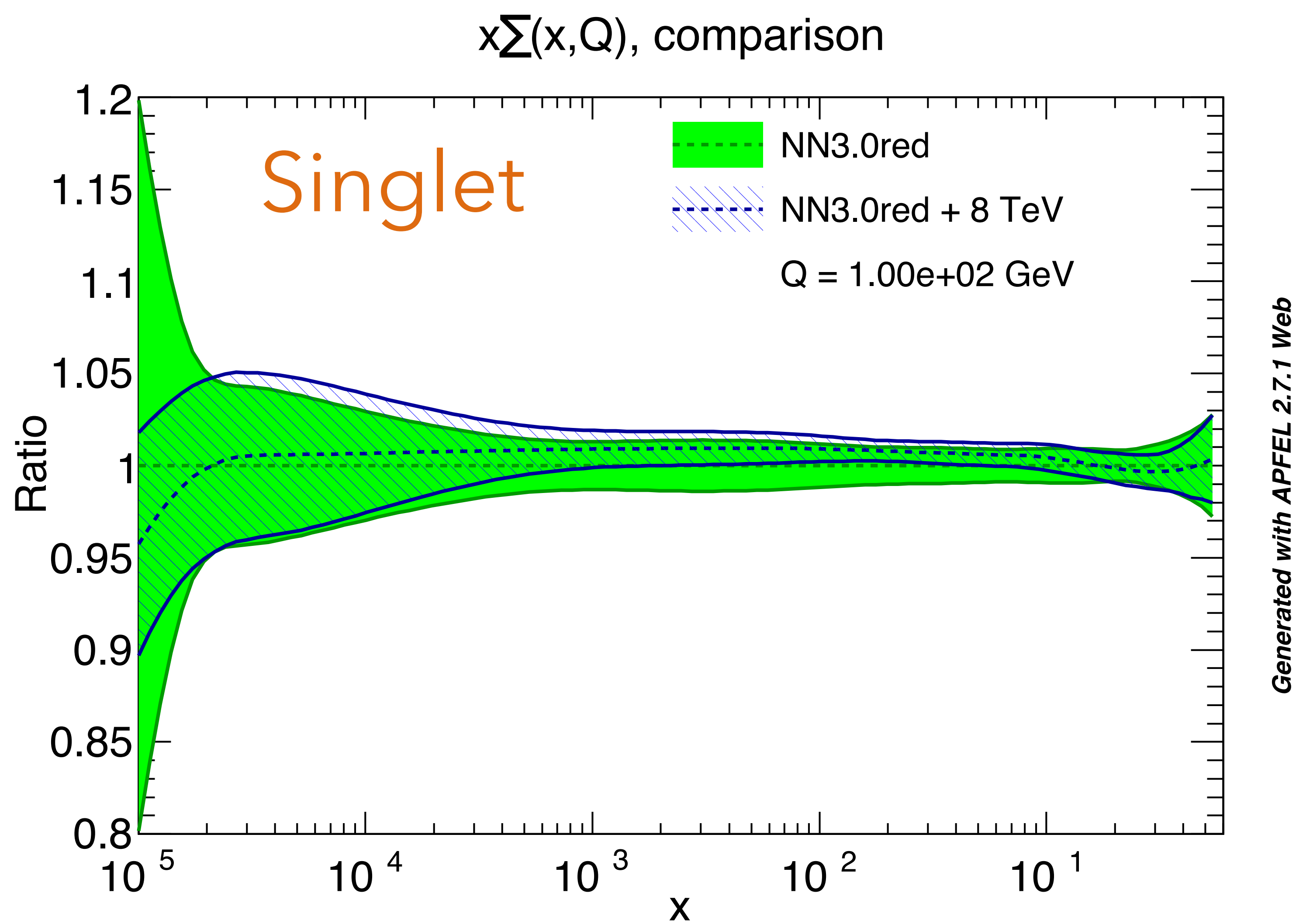


Impact of Z p_T distributions (global 3.0)



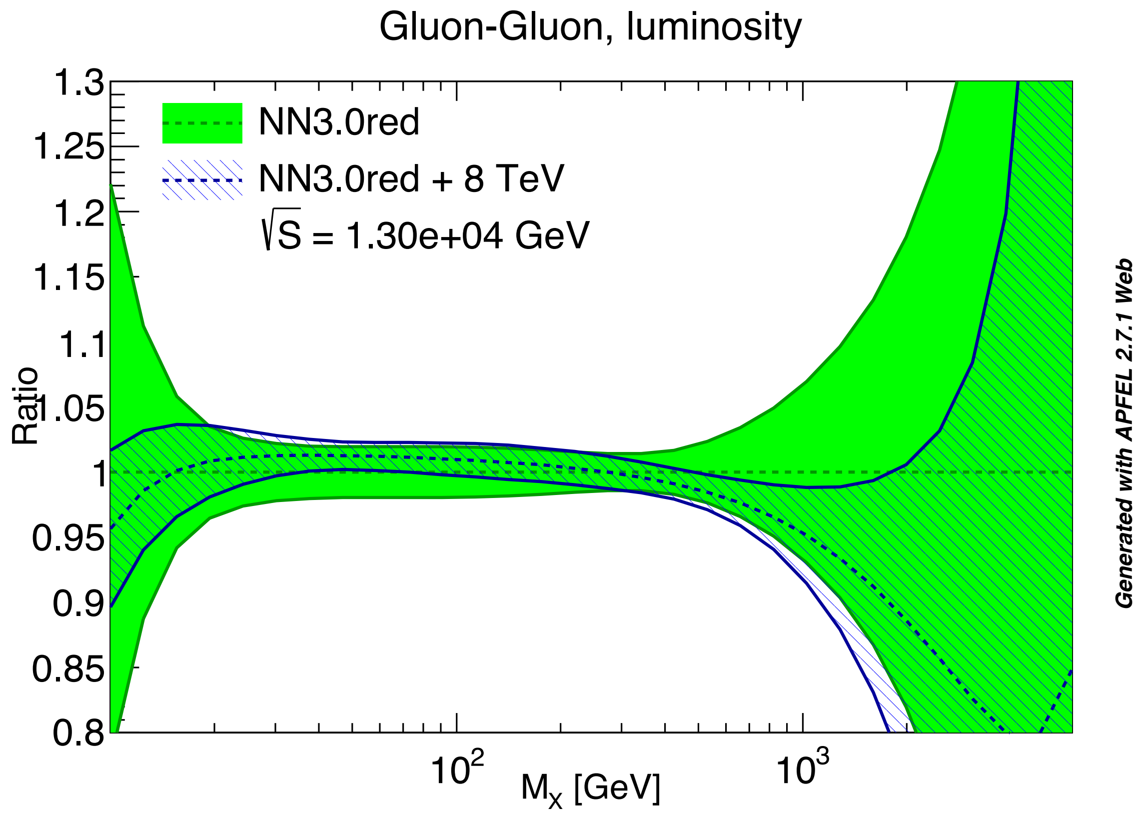
Fit (extra Δ=1%)	χ^2 ATLAS 7 TeV	χ^2 ATLAS 8 TeV (M)	χ^2 ATLAS 8 TeV (Y)	χ^2 CMS 8 TeV (Y)
NNPDF3.0red	(7.0)	(1.0)	(1.1)	(1.4)
NNPDF3.0red + ZpT 8 TeV	(7.9)	1.0	0.9	1.3

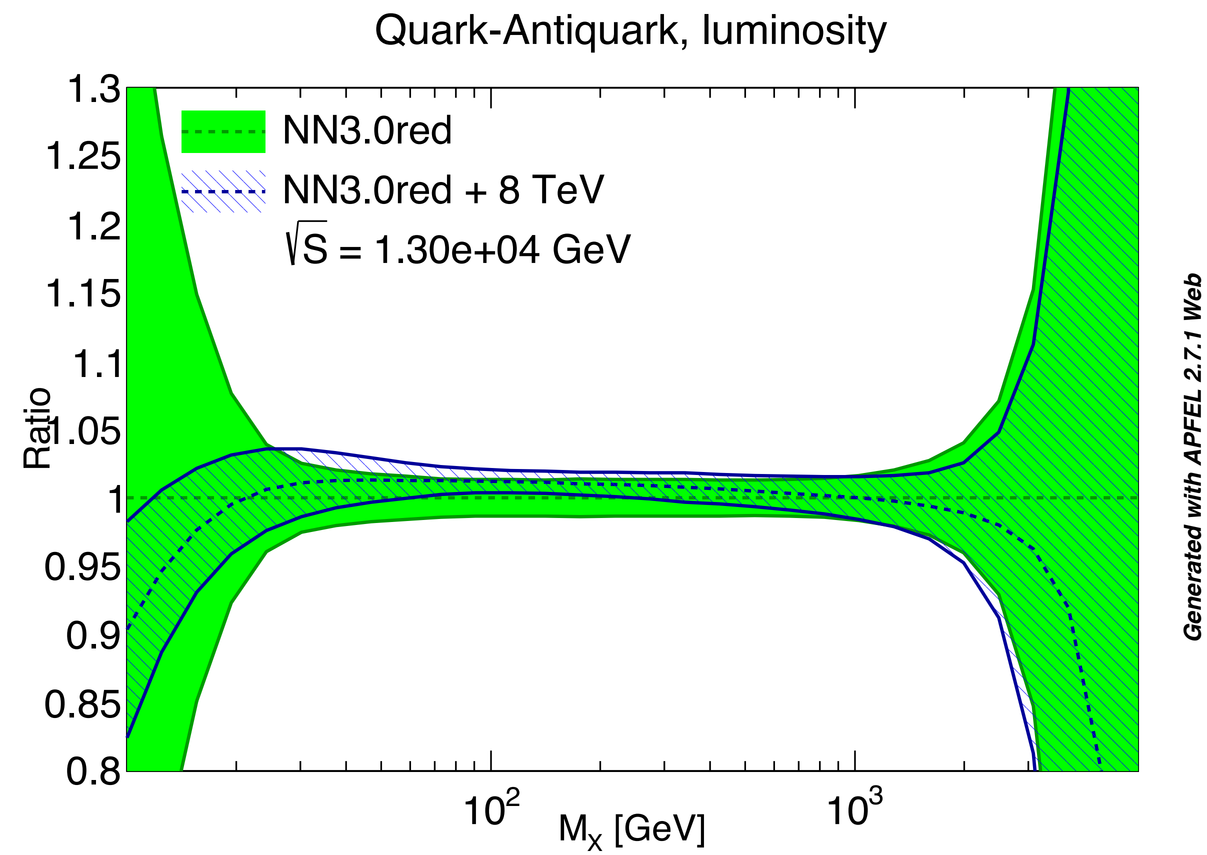
Impact of Z p_T distributions (global 3.0)

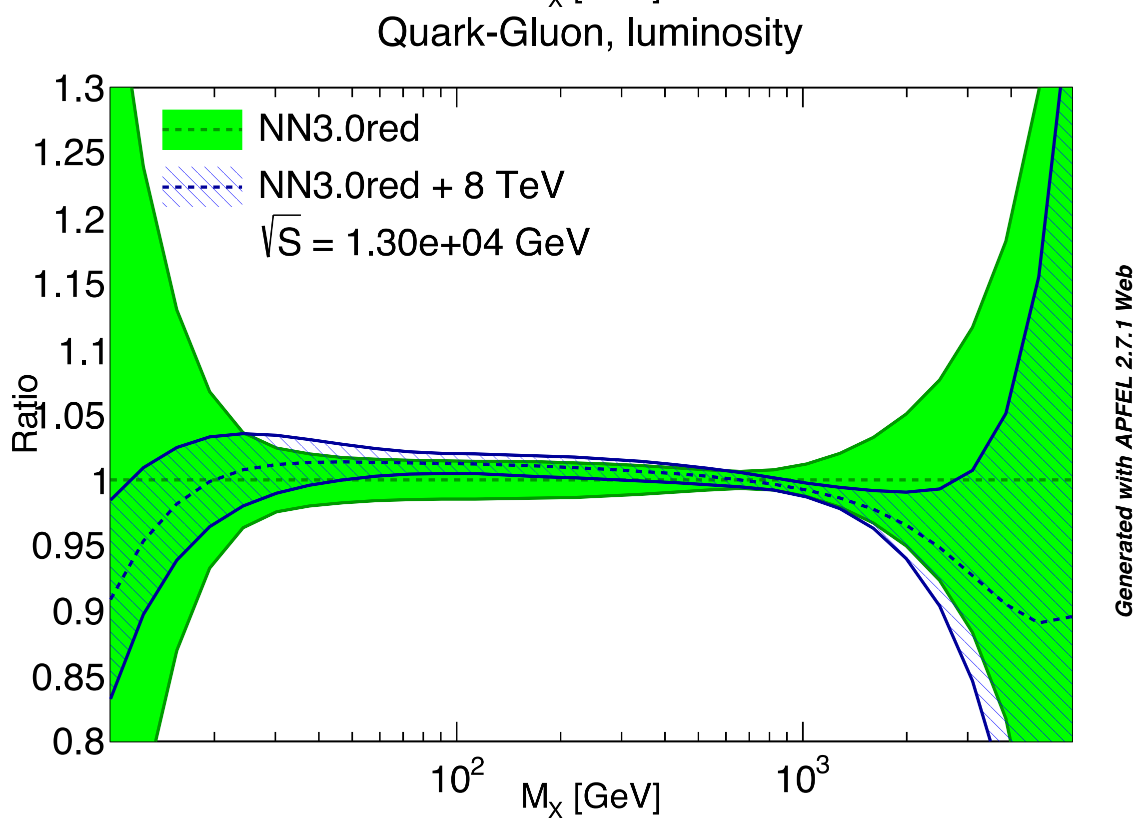


Fit (extra Δ=1%)	χ^2 ATLAS 7 TeV	χ^2 ATLAS 8 TeV (M)	χ^2 ATLAS 8 TeV (Y)	χ^2 CMS 8 TeV (Y)
NNPDF3.0red	(7.0)	(1.0)	(1.1)	(1.4)
NNPDF3.0red + ZpT 8 TeV	(7.9)	1.0	0.9	1.3

Phenomenological implications



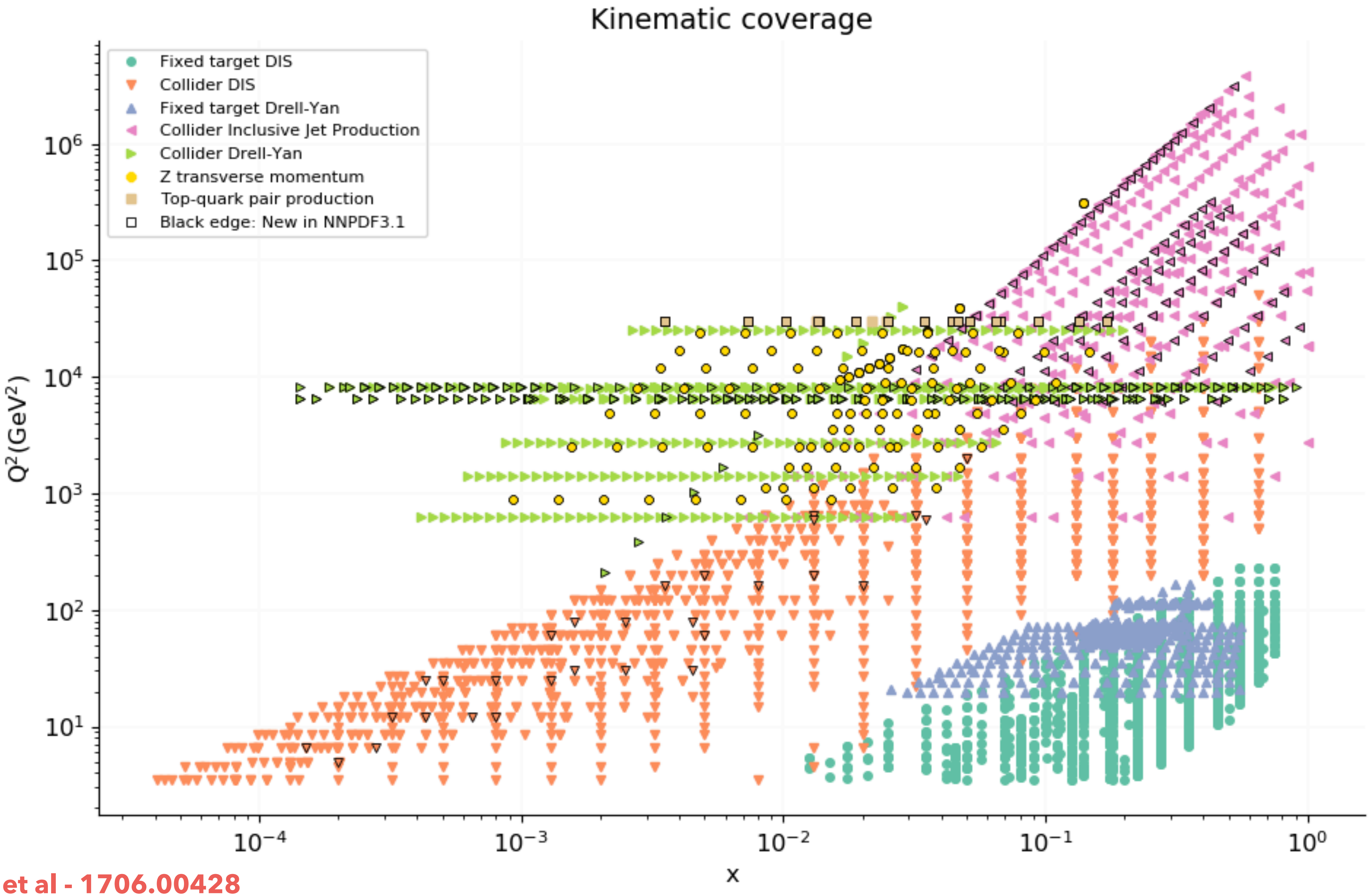




Implication for Higgs physics

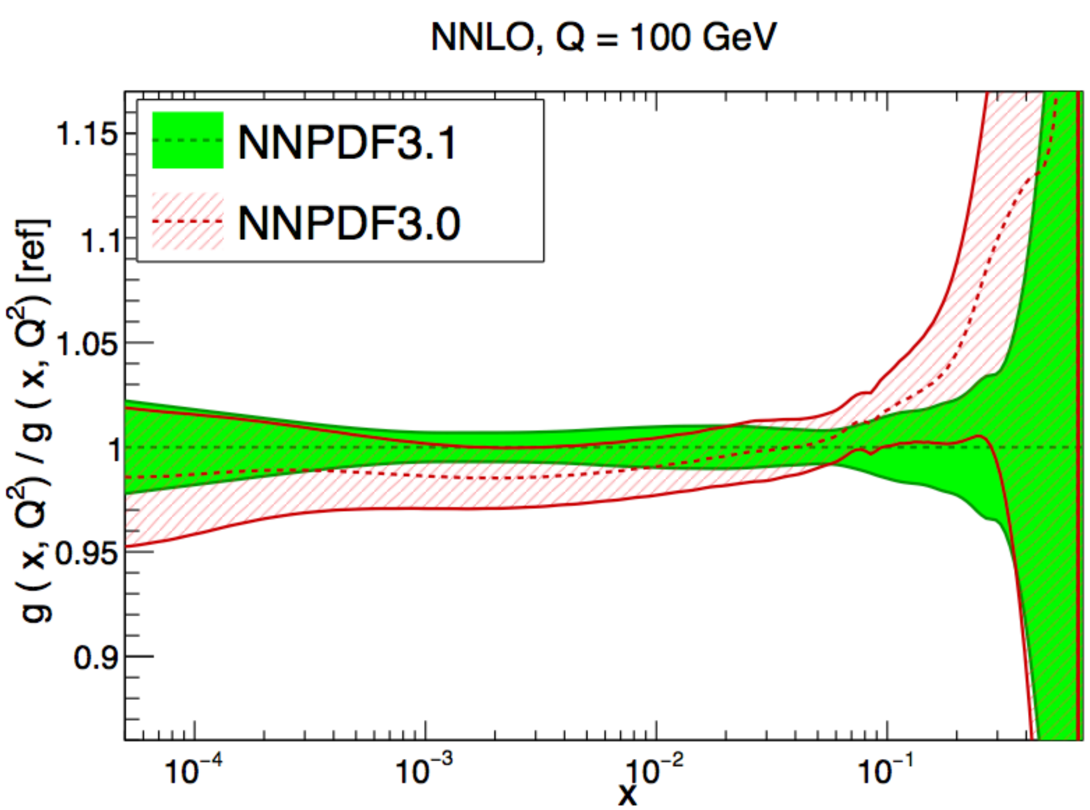
	Before ZpT data	After ZpT data
H(ggF)	48.22 ± 0.89 (1.8%)	48.61 ± 0.61 (1.3%)
H(VBF)	3.92 ± 0.06 (1.5%)	3.96 ± 0.04 (1.0%)

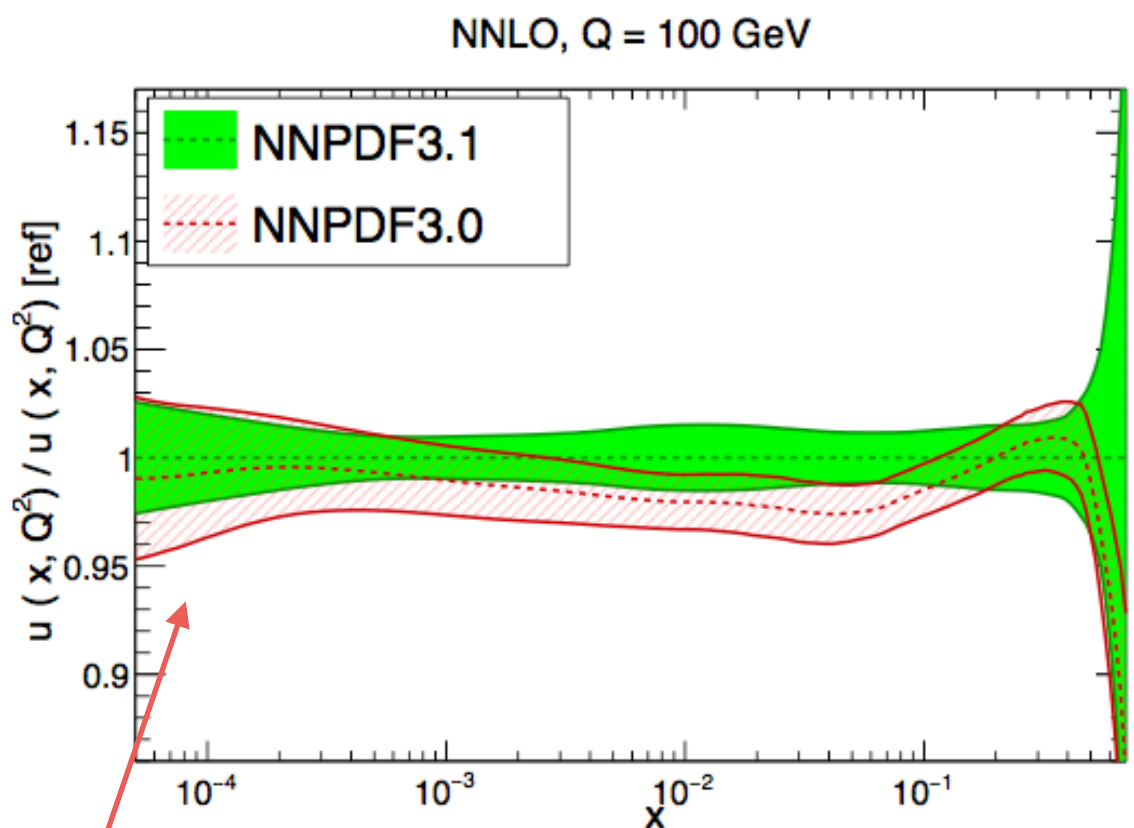
NNPDF3.1

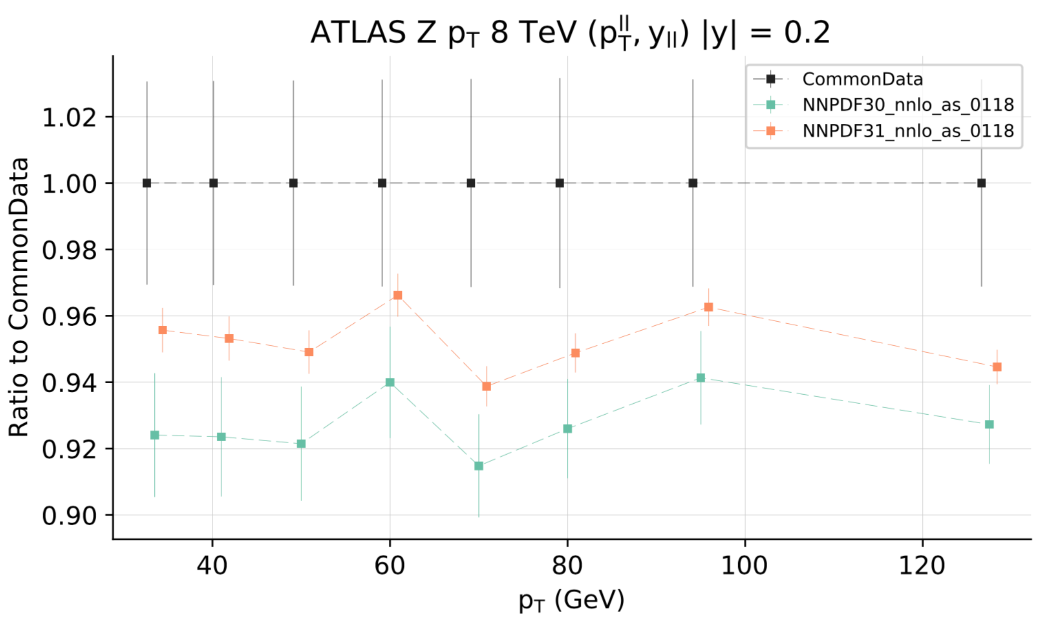


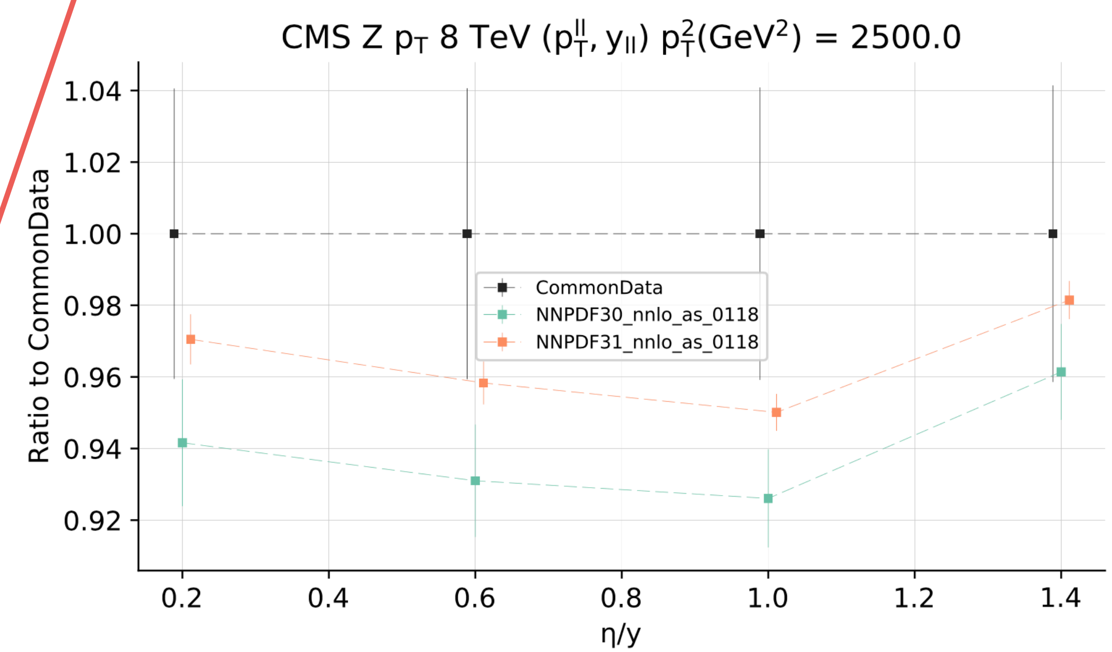
Ball et al - 1706.00428

NNPDF3.1



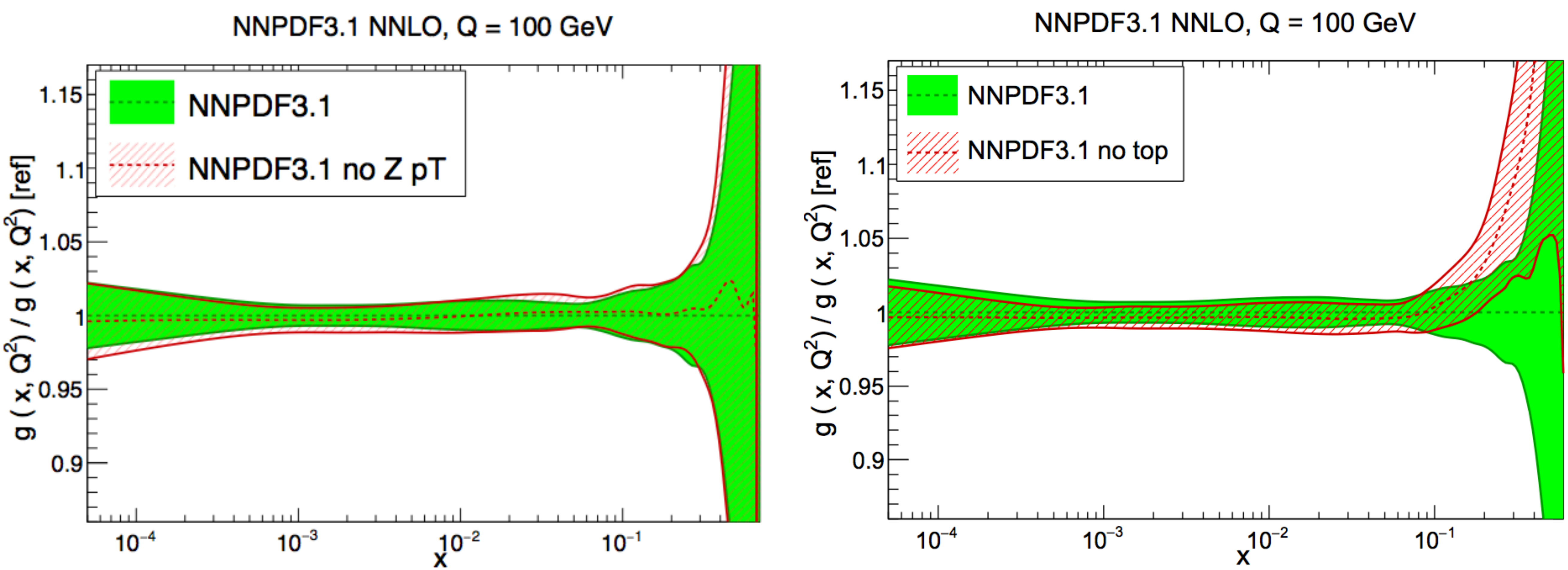






Shift in light quarks mostly driven by LHCb data and ATLAS W/Z data

Impact of ZpT data on NNPDF3.1

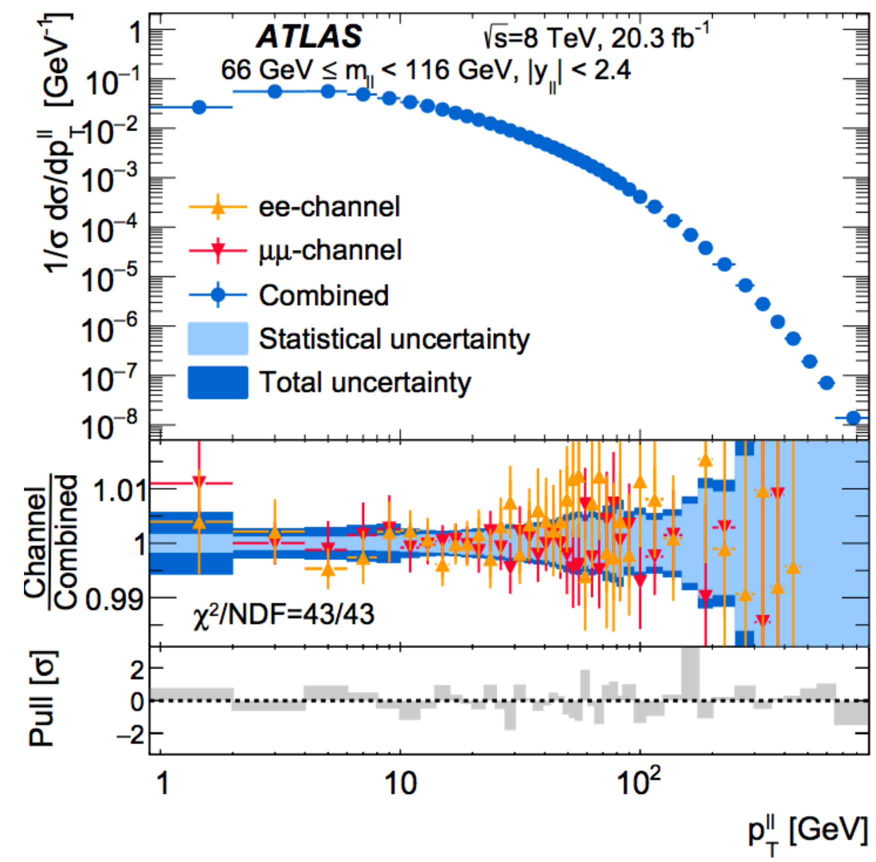


Ball et al - 1706.00428

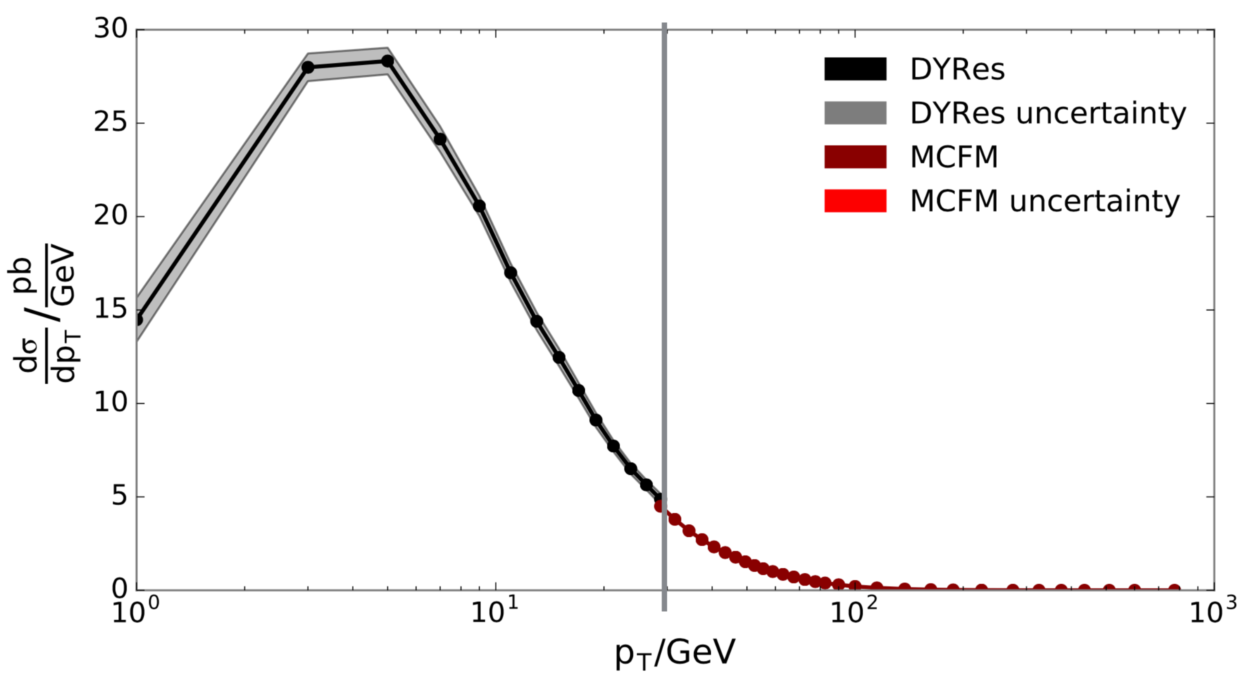
- NNPDF3.1 first analysis to include top differential distributions, ZpT distributions and jets data (NLO supplemented by theory uncertainty)
- ZpT data already well described by NNPDF3.1 before their inclusion thanks to compatibility with pull of precise top differential distribution data and V production data at the LHC
- Moderate but significant impact of ZpT data on gluon (stronger than top at intermediate x and smaller at larger x). Top + ZpT impact competitive with jets data!

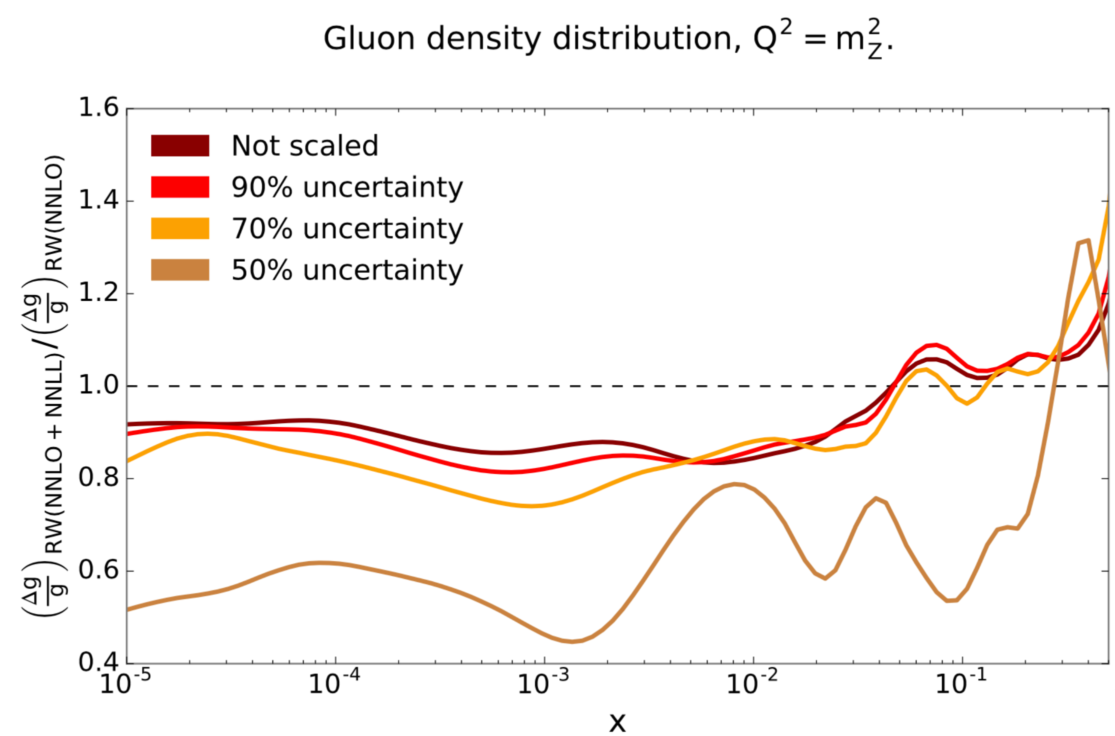
Food for thoughts: the small ZpT region

- Data below pT~ 30 GeV excluded from fixed order PDF fits are the most precise
- Can we include small pT data into PDF fit by including resummed predictions?
- What is the size of NP corrections? What are the most accurate predictions? Should they be supplemented by theoretical uncertainties (scales, resummation scales, NP corrections)?
- What is the actual gain?



H. Gormsen





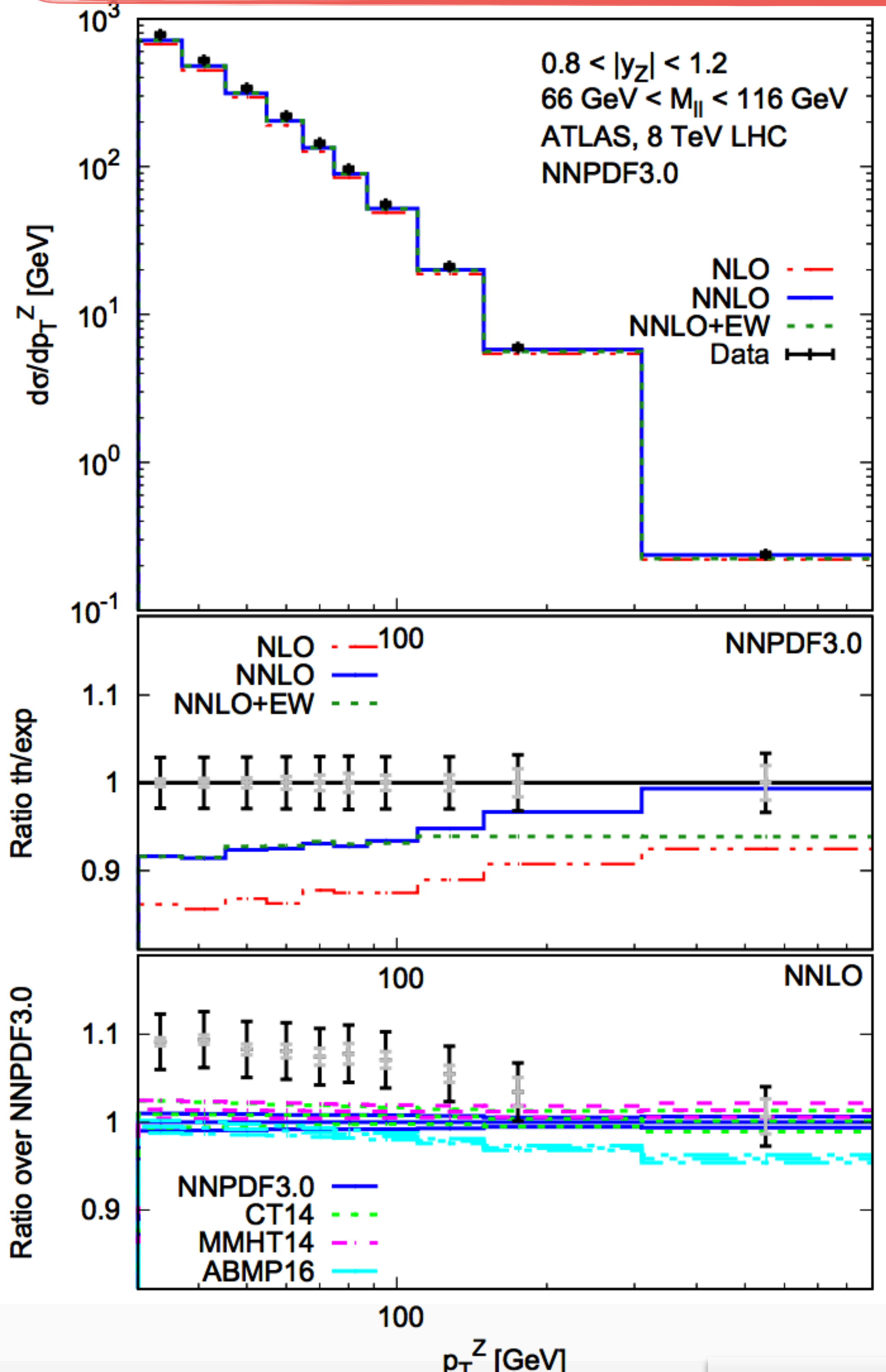
Conclusions

- Z boson production & decay into leptons benchmark Standard Model (SM) process at LHC
- Combination of precise experimental data and theory allows this process to be used to determine PDFs
- CMS and ATLAS data at 8 TeV (unnormalised) are compatible and lead to reduction in PDF uncertainties. ATLAS 7 TeV data (normalised data in general) can be fitted individually but points to a different minimum. Covariance matrix for normalised experiments built for the whole pT spectrum, pT cuts modify correlations between bins.
- Z pT spectrum sensitive to both soft QCD radiation (at small p_T) and to large electroweak Sudakov logarithms (at large p_T), interesting to see whether it can be fitted in fixed-order fit and what is the pT range
- In the future: test inclusion of pT resummation, check impact of non-perturbative effects, look at ϕ^* distributions

Extra- material

Data-theory comparison

ATLAS 8 TeV



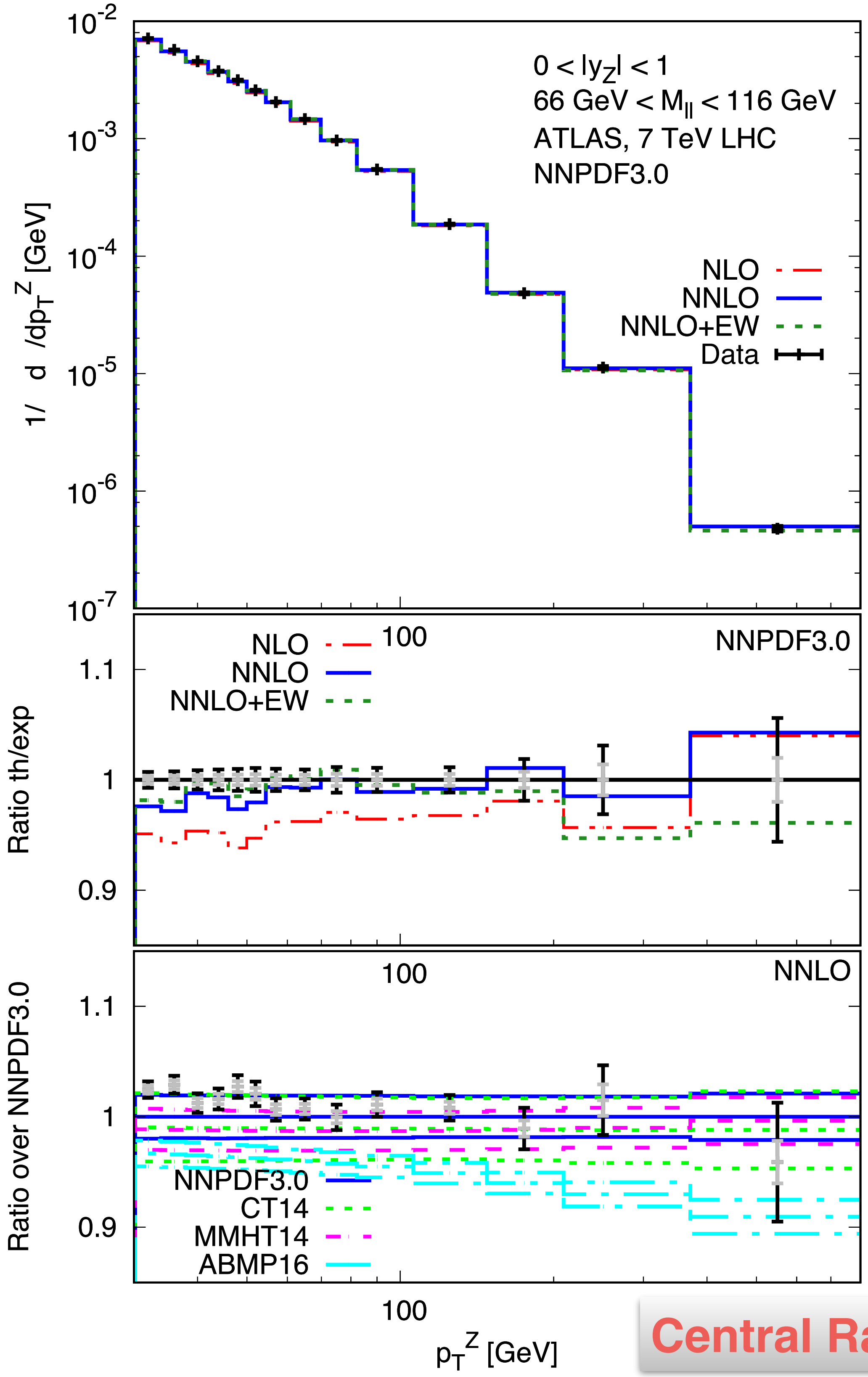
Bin	Order	$N_{\rm dat}$	$\chi^2_{\rm d.o.f.}$ (NN30)	$\chi^2_{\rm d.o.f.}$ (CT14)	$\chi^2_{\rm d.o.f.}$ (MMHT14)	$\chi^2_{\rm d.o.f.}$ (ABMP16)
$0.0 < y_Z < 0.4$	NLO	10	4.0	3.2	2.4	n.a.
	NNLO	10	2.7	2.7	2.6	2.7
	NNLO+EW	10	3.4	3.2	3.1	5.4
$0.4 < y_Z < 0.8$	NLO	10	5.6	4.6	3.8	n.a.
	NNLO	10	5.4	5.2	5.3	3.3
	NNLO+EW	10	4.0	3.9	3.7	3.8
$0.8 < y_Z < 1.2$	NLO	10	5.8	3.8	3.0	n.a.
	NNLO	10	4.7	4.0	4.3	2.1
	NNLO+EW	10	2.3	2.0	1.9	1.7
$1.2 < y_Z < 1.6$	NLO	10	4.5	3.2	2.5	n.a.
	NNLO	10	5.1	4.0	4.6	3.0
	NNLO+EW	10	3.3	2.6	2.7	2.5
$1.6 < y_Z < 2.0$	NLO	10	4.4	3.2	2.4	n.a.
	NNLO	10	5.4	4.3	5.0	3.7
	NNLO+EW	10	3.9	3.2	3.4	3.0
$2.0 < y_Z < 2.4$	NLO	10	4.1	3.2	2.4	n.a.
	NNLO	10	3.4	3.1	3.3	3.2
	NNLO+EW	10	2.6	2.3	2.4	2.5

- Good example of correlation-dominated observable. Data-theory comparison does not reflect actual value of the χ^2
- NNLO correction generally improves agreement (before fit)
- EW corrections only relevant for the two highest p_T bins in the Z-mass peak
- Similar picture for CMS data (Y < 1.6)

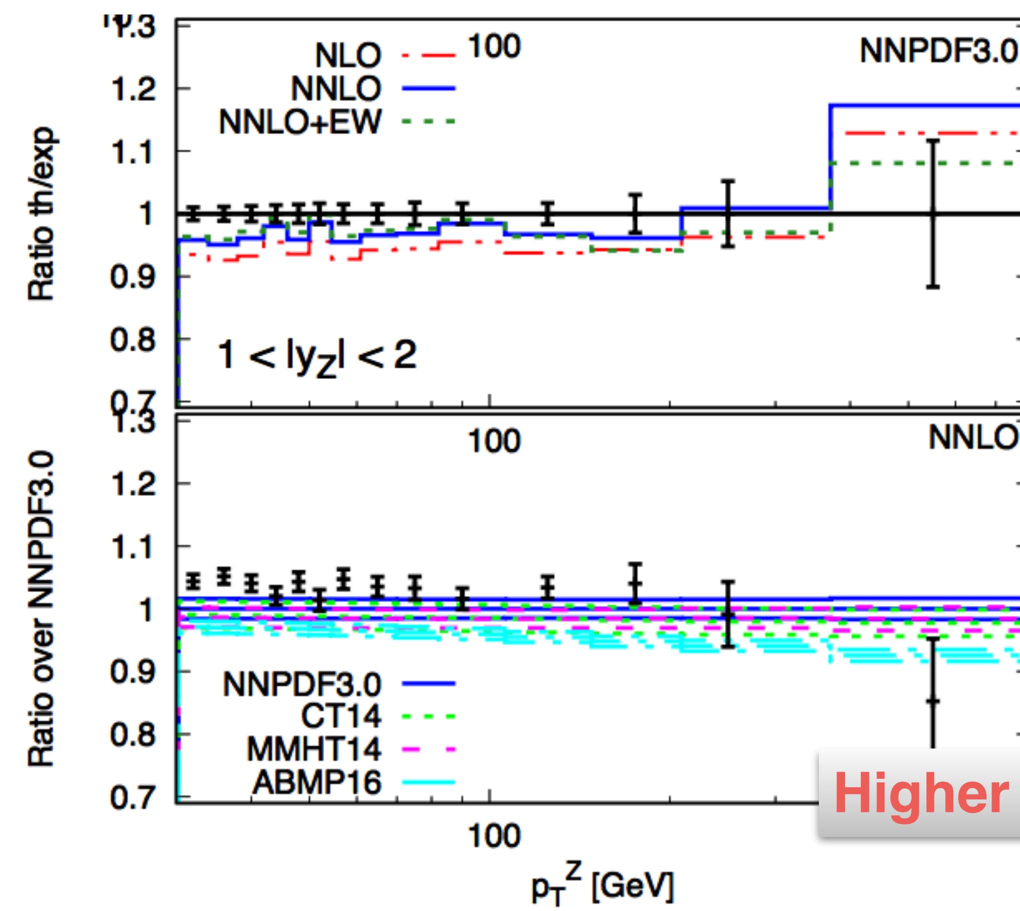
Z peak

Data-theory comparison

ATLAS 7 TeV



Central Rapidity

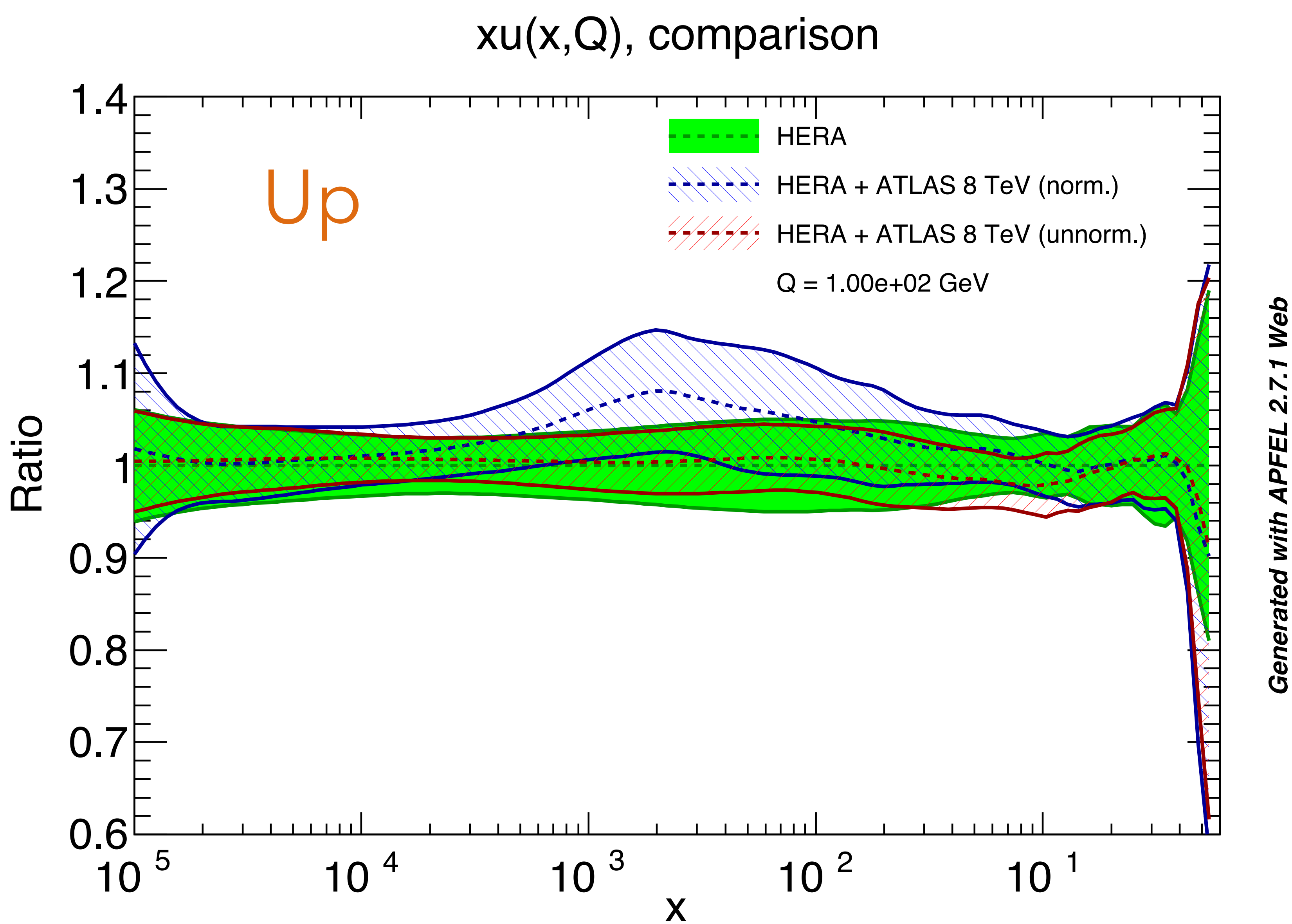


Higher Rapidity

Bin	Order	$N_{\rm dat}$	$\chi^2_{\rm d.o.f.}$ (NNPDF3.0)	$\chi^2_{\rm d.o.f.}$ (CT14)	$\chi^2_{\rm d.o.f.}$ (MMHT14)	$\chi^2_{\rm d.o.f.}$ (ABMP16)
$0.0 < y_Z < 1.0$	NLO	14	10	21	9.2	n.a.
	NNLO	14	2.2	3.8	4.3	11
	NNLO+EW	14	1.3	2.3	2.6	9.1
$1.0 < y_Z < 2.0$	NLO	14	13	18	12	n.a.
	NNLO	14	5.6	8.2	9.3	15.
	NNLO+EW	14	3.9	6.0	6.8	12.
$2.0 < y_Z < 2.4$	NLO	14	7.0	7.1	6.0	n.a.
	NNLO	14	7.0	8.2	8.7	11.
	NNLO+EW	14	5.9	7.1	7.5	9.5

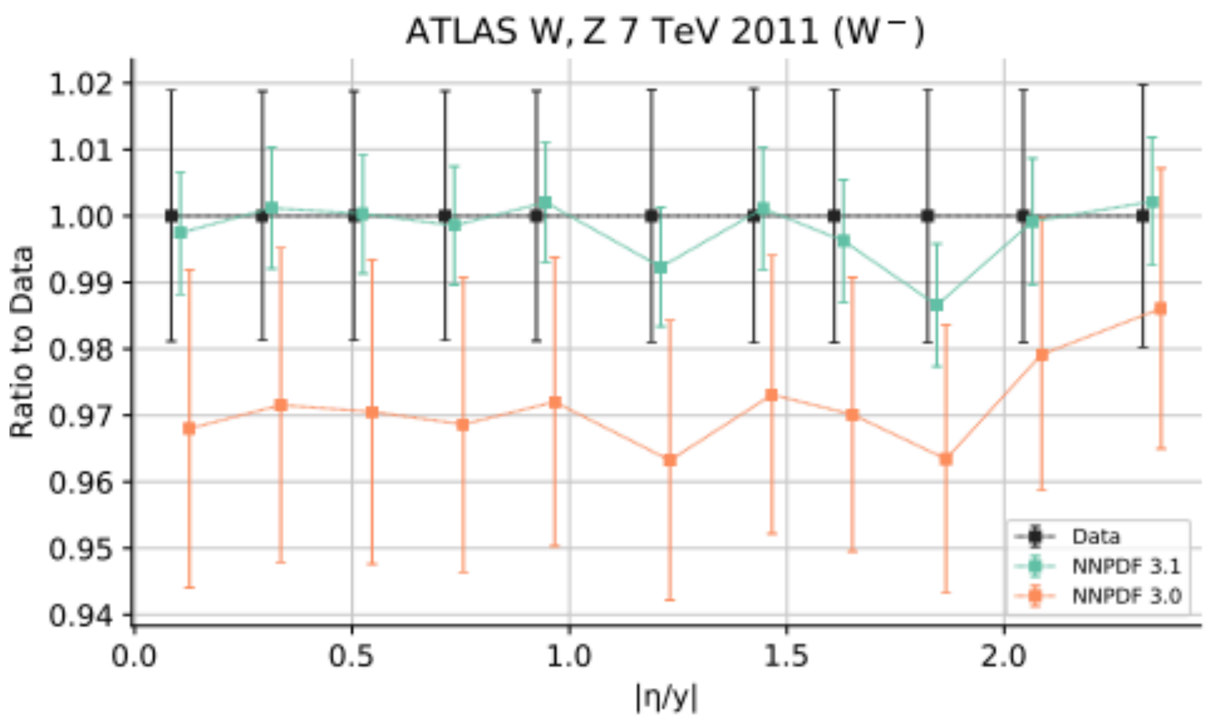
NNLO(+EW) needed to get agreement with data

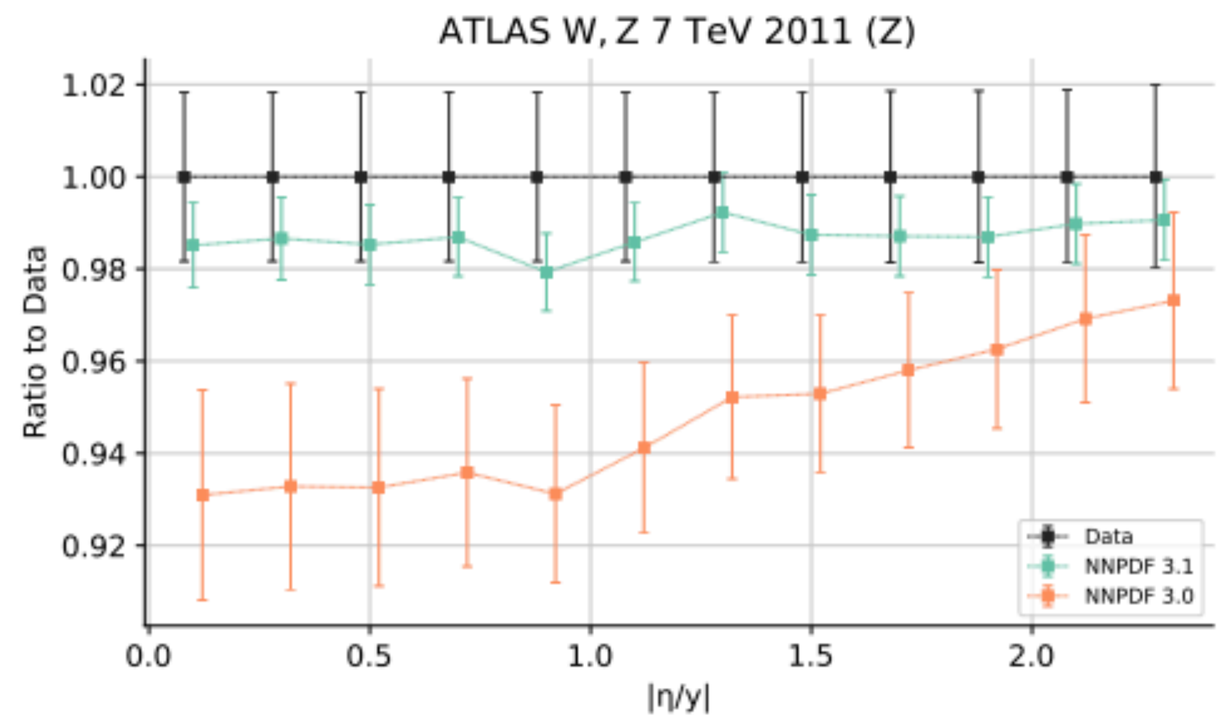
Test the normalised 8 TeV distributions

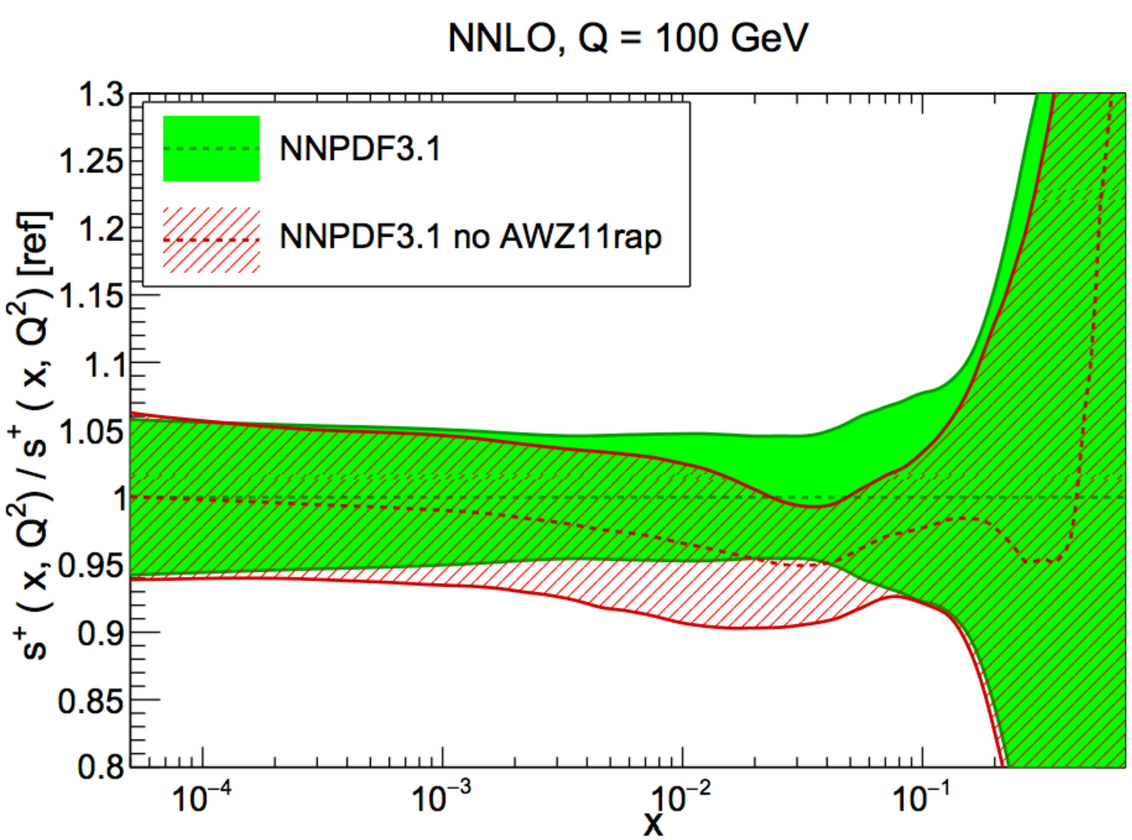


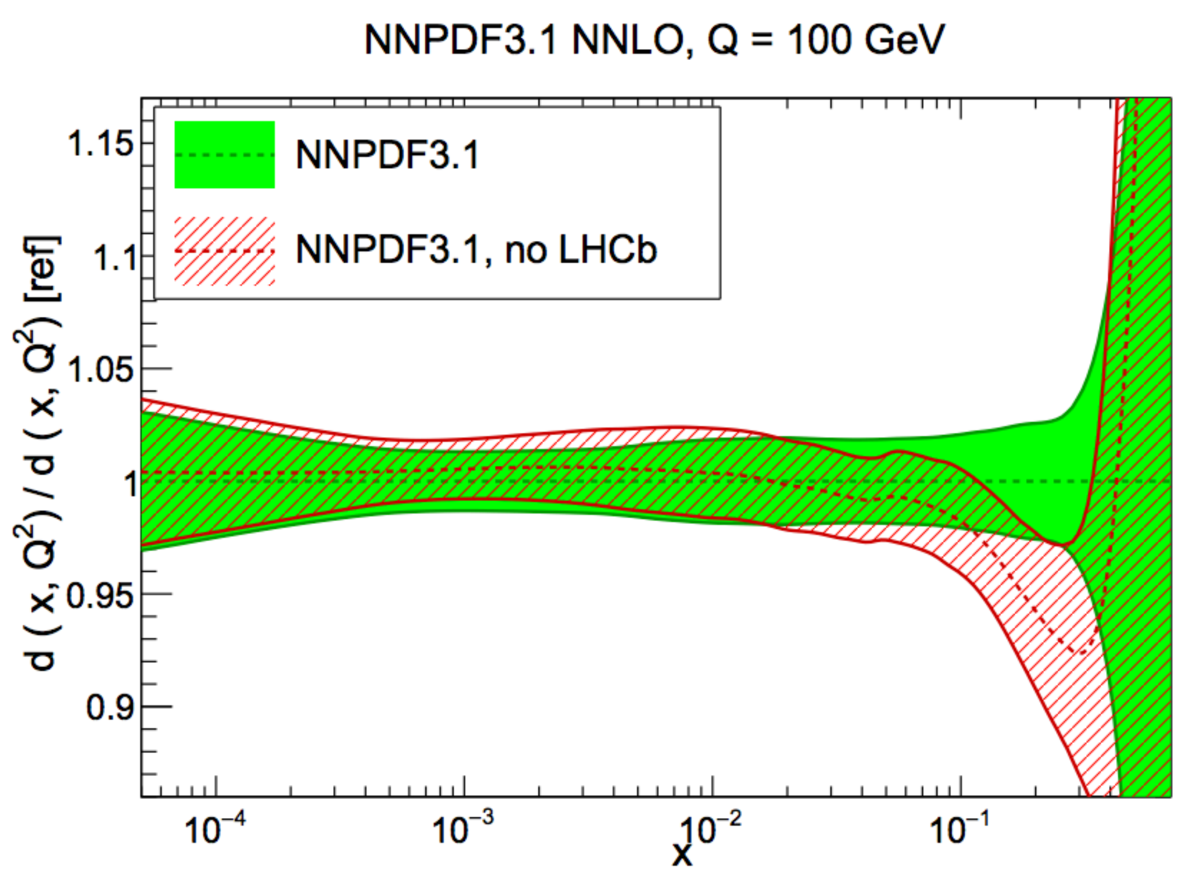
- Using the normalised ATLAS 8 TeV data has the same effect as using the normalised ATLAS 7 TeV data
- For this observable we observe a issue in using normalised data which are normalised over a pT range different from the one used in the fit

Impact of ATLAS Z/W data

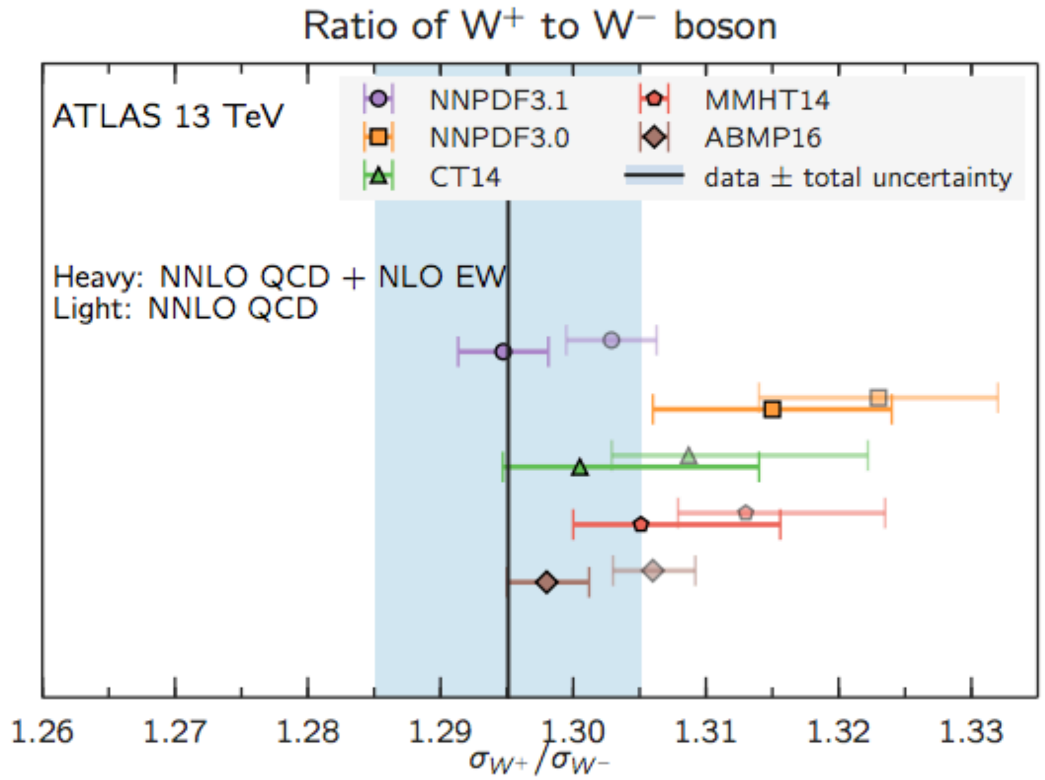


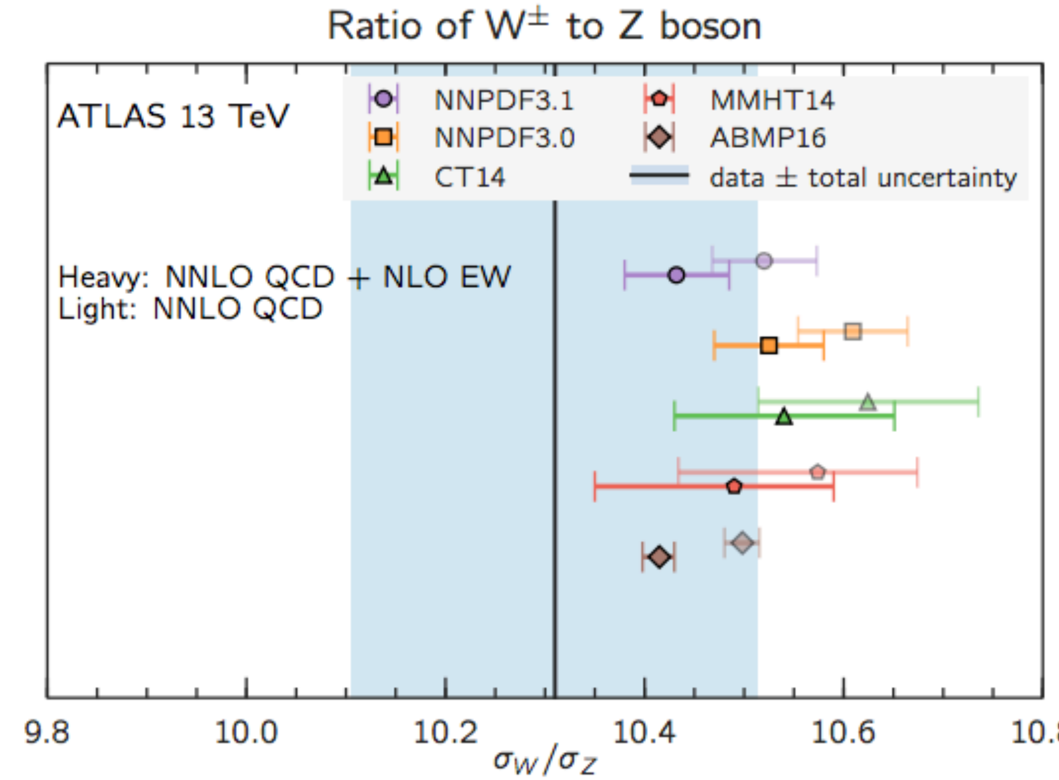


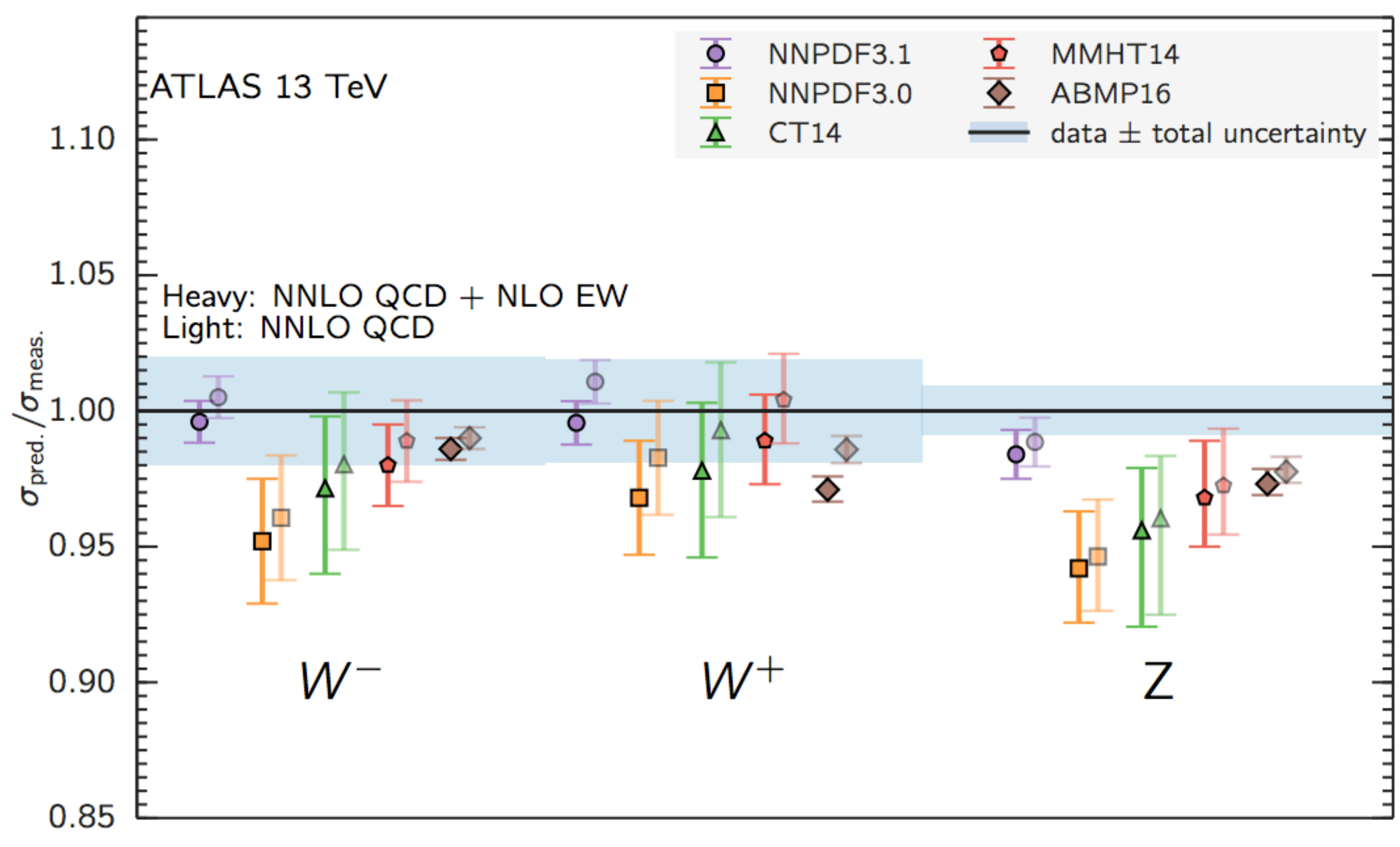




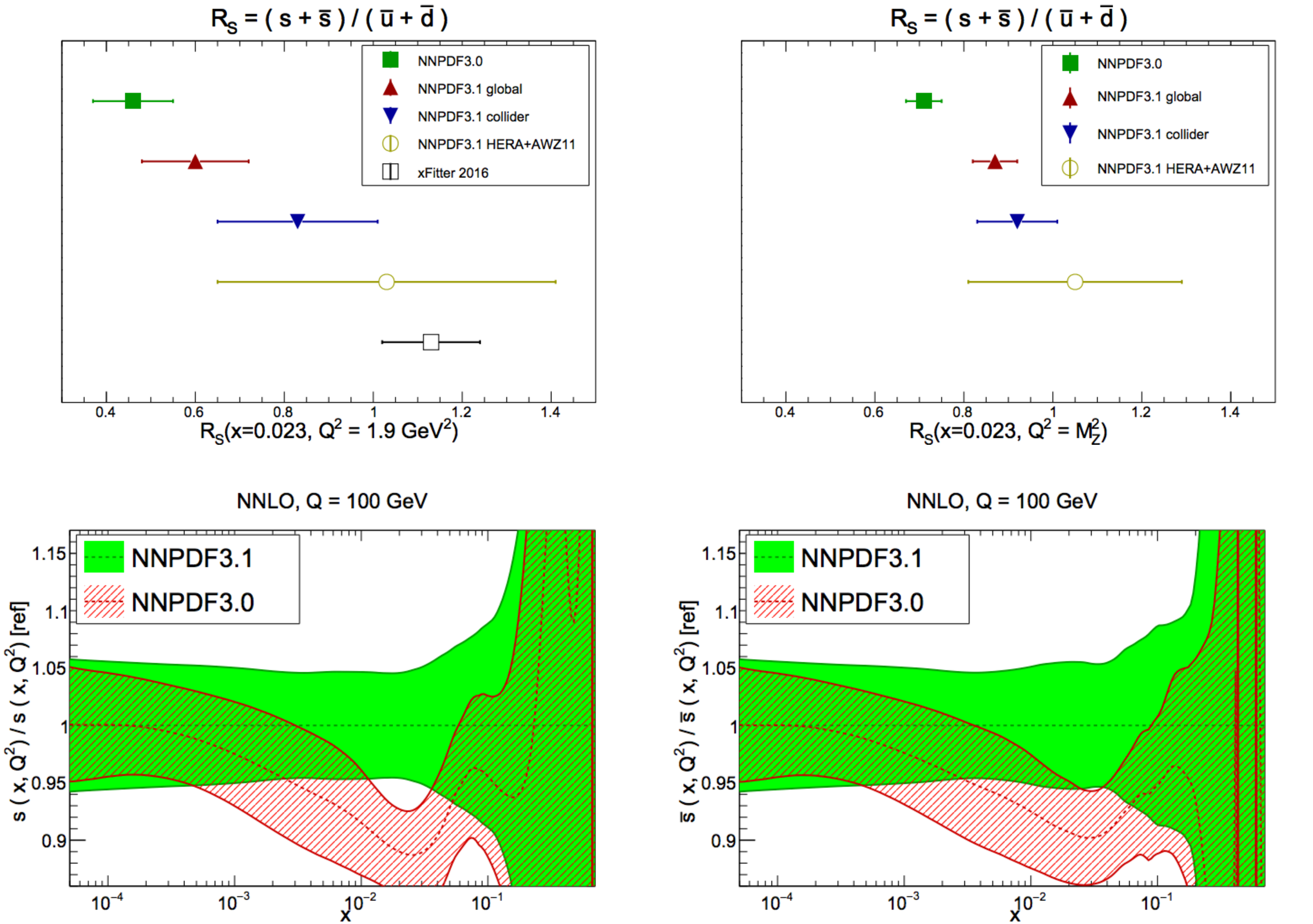
W/Z ratios after NNPDF3.1



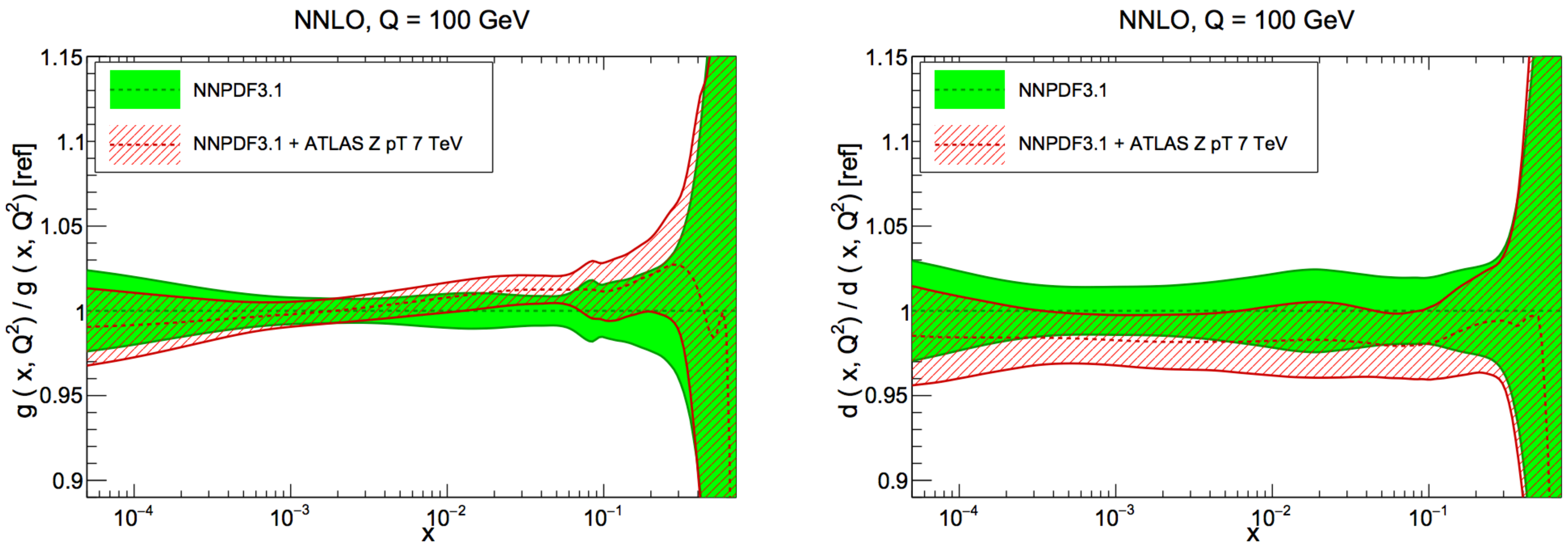




Strangeness in NNPDF3.1

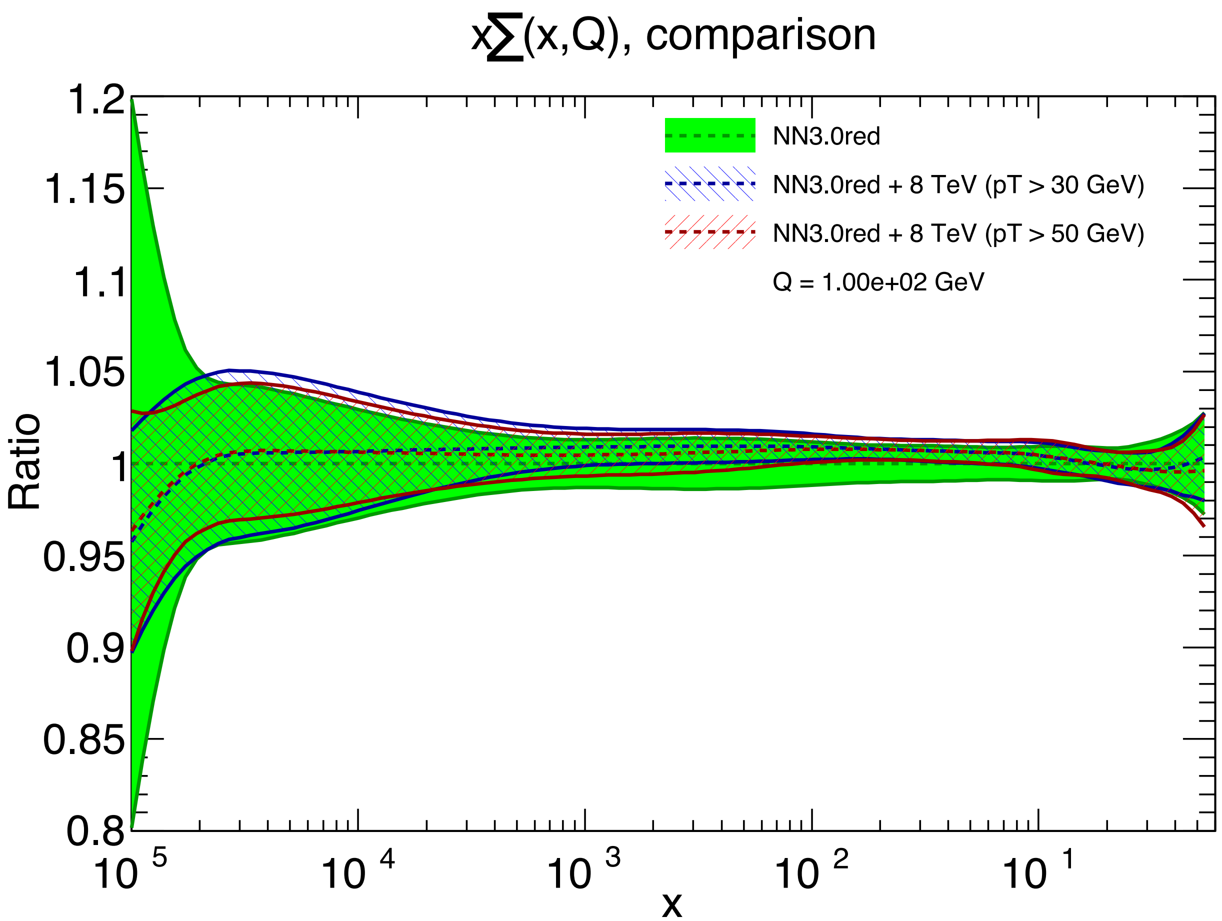


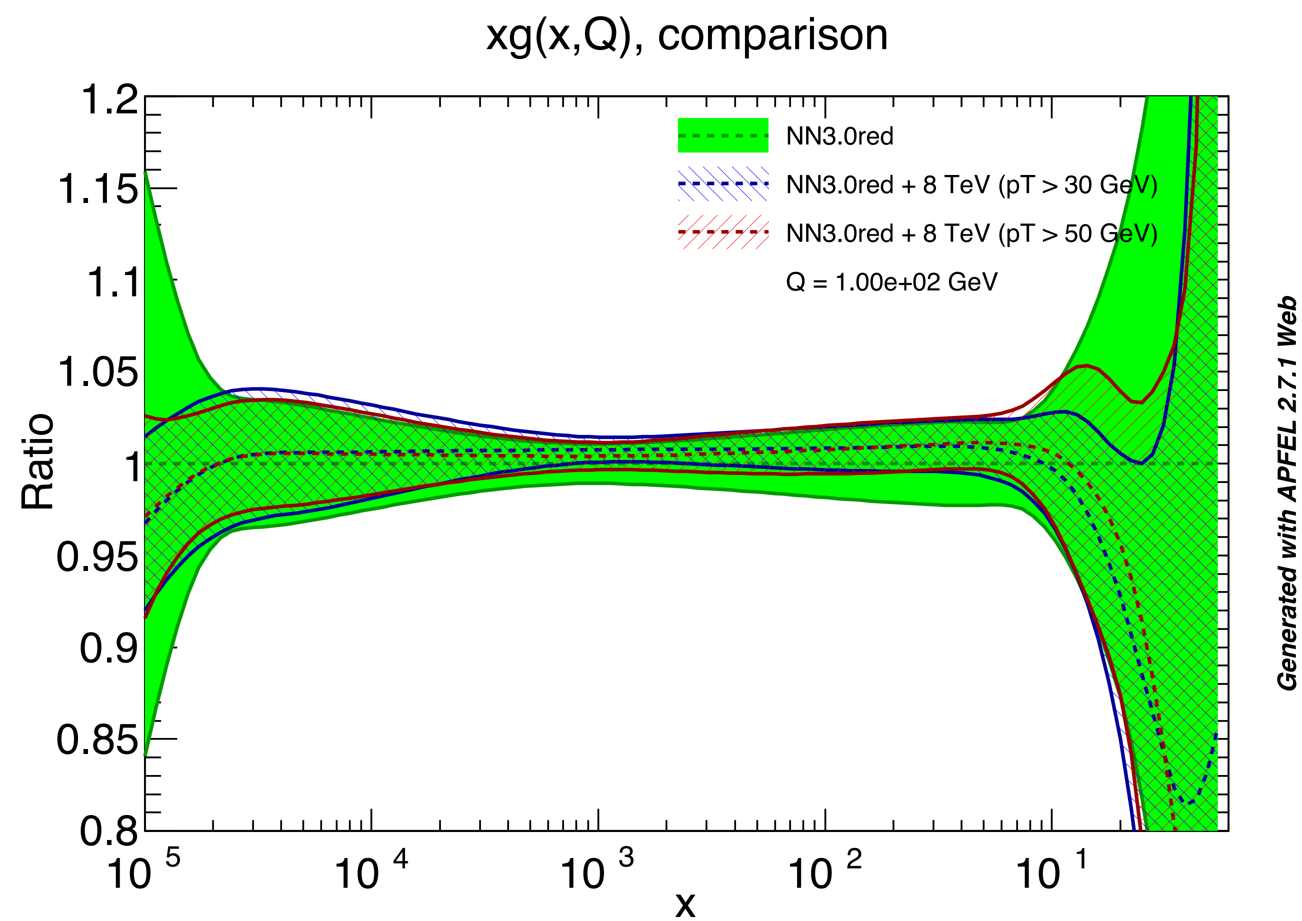
ATLAS 7 TeV in NNPDF3.1



	NNPDF3.1 NNLO	+ ATLAS Z p_T 7 TeV data
ATLAS Z p_T 7 TeV (p_T^{ll}, y_{ll})	[6.78]	3.40
ATLAS Z p_T 8 TeV (p_T^{ll}, M_{ll})	0.93	0.98
ATLAS Z p_T 8 TeV (p_T^{ll}, y_{ll})	0.93	1.17
CMS Z p_T 8 TeV (p_T^{ll}, M_{ll})	1.32	1.33

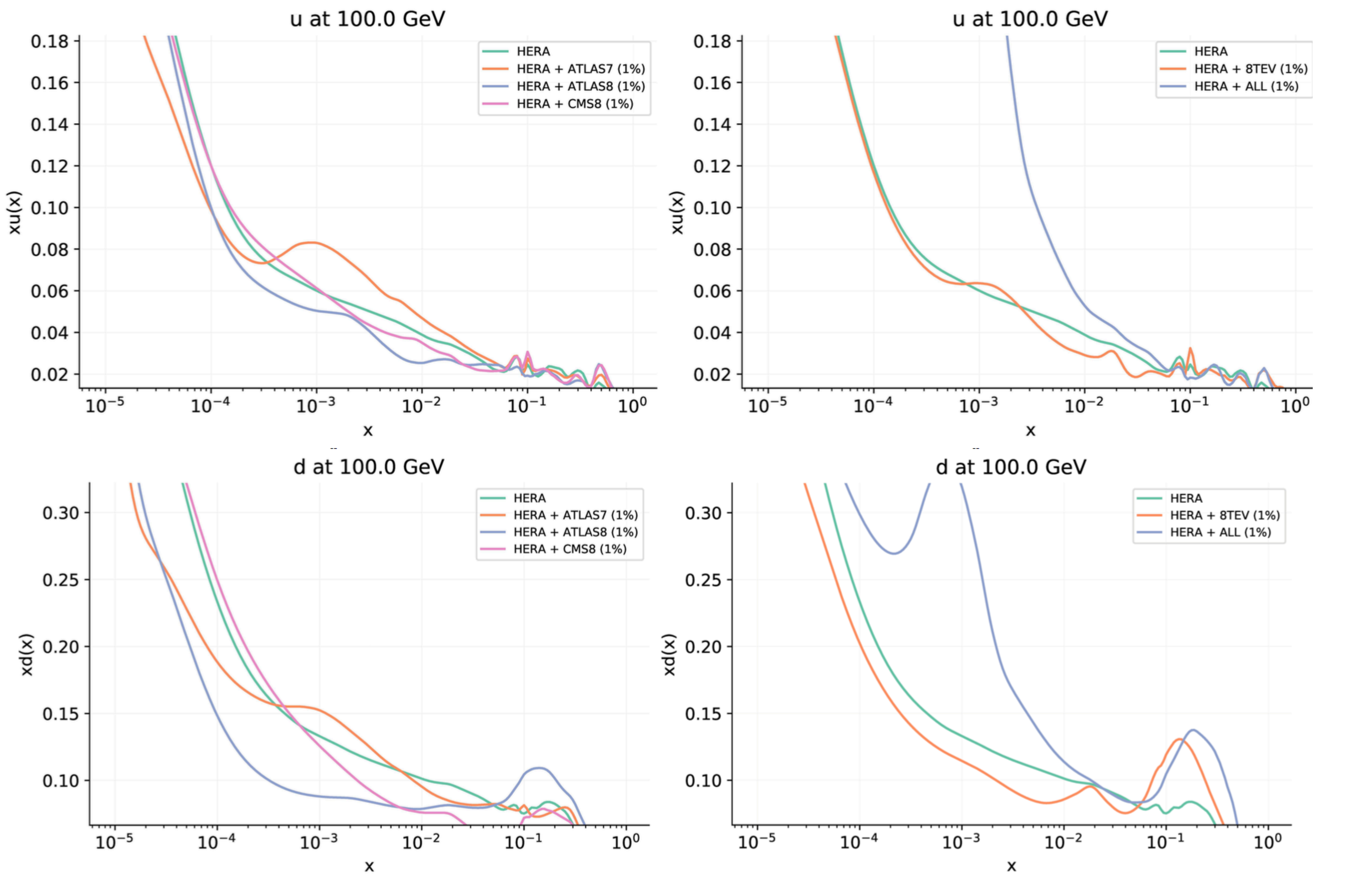
Stability under small pT cut



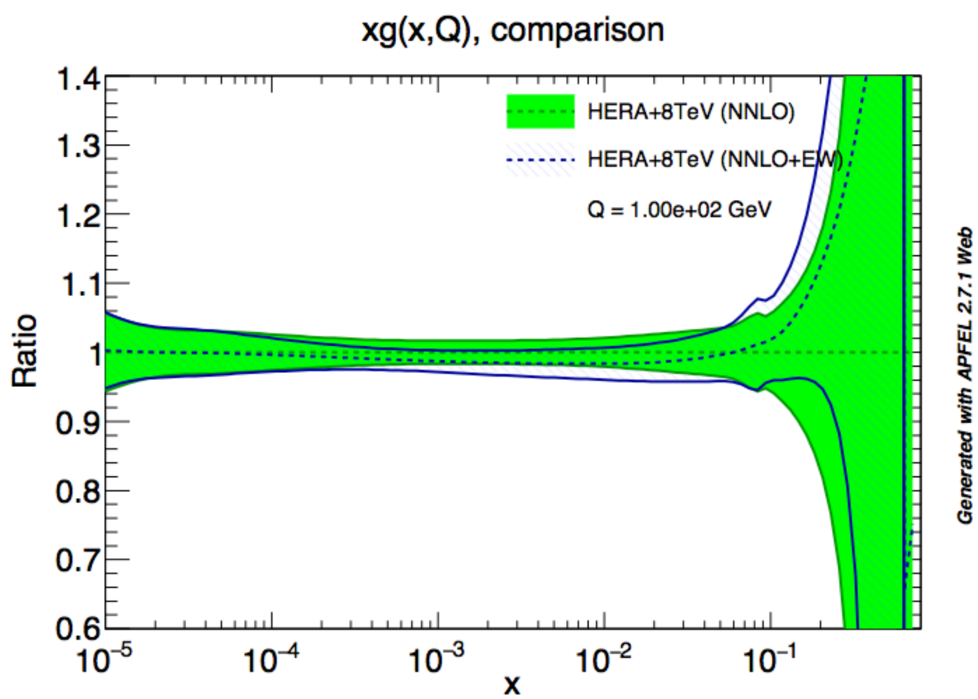


pT > 30 GeV → pT > 50 GeV

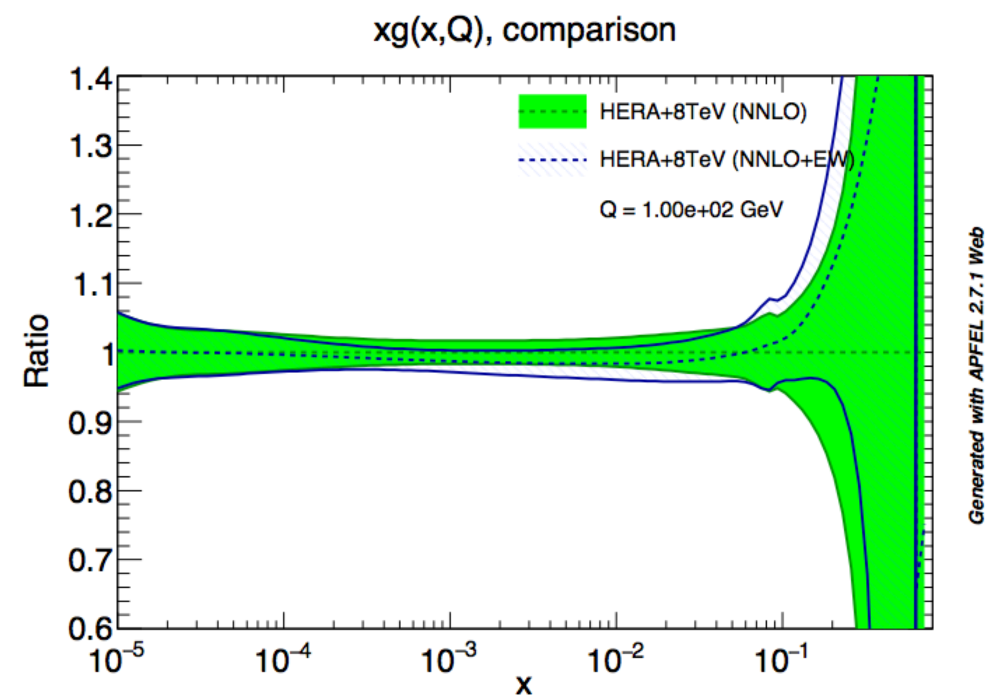
Error reduction



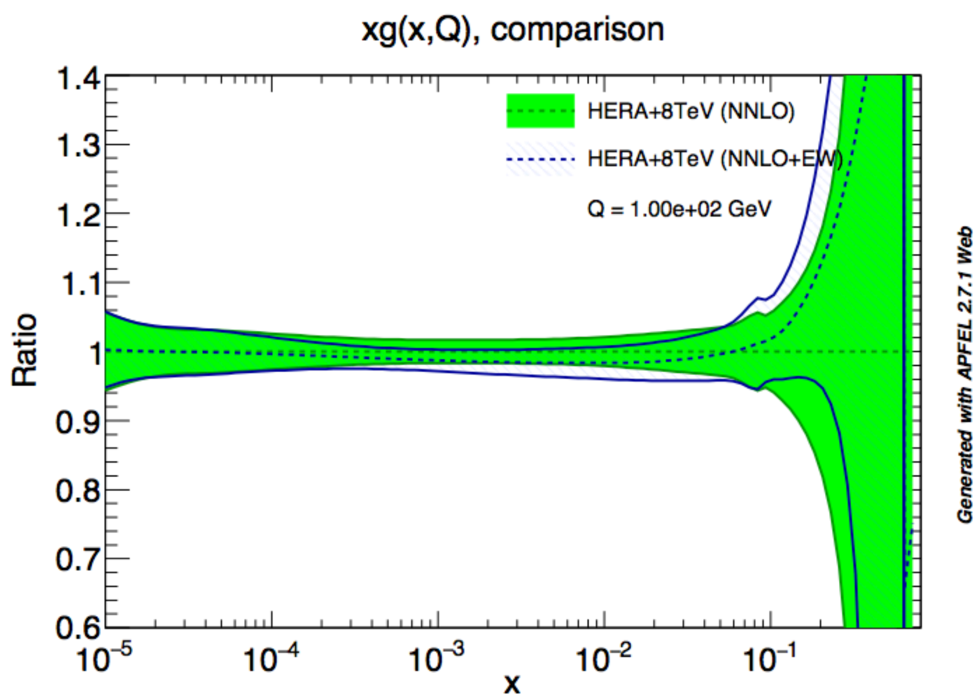
NNLO + EW fit



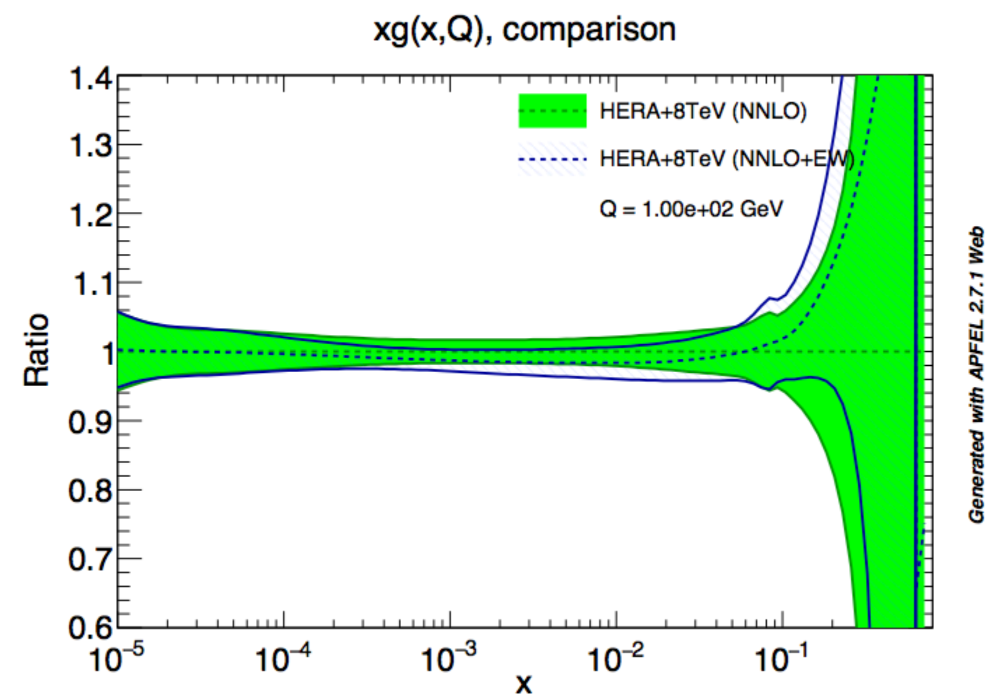
xg(x,Q), comparison
HERA+8TeV (NNLO)
HERA+8TeV (NNLO+EW)
Q = 1.00e+02 GeV
Ratio
x
Generated with APFEL 2.7.1 Web



xg(x,Q), comparison
HERA+8TeV (NNLO)
HERA+8TeV (NNLO+EW)
Q = 1.00e+02 GeV
Ratio
x
Generated with APFEL 2.7.1 Web



xg(x,Q), comparison
HERA+8TeV (NNLO)
HERA+8TeV (NNLO+EW)
Q = 1.00e+02 GeV
Ratio
x
Generated with APFEL 2.7.1 Web



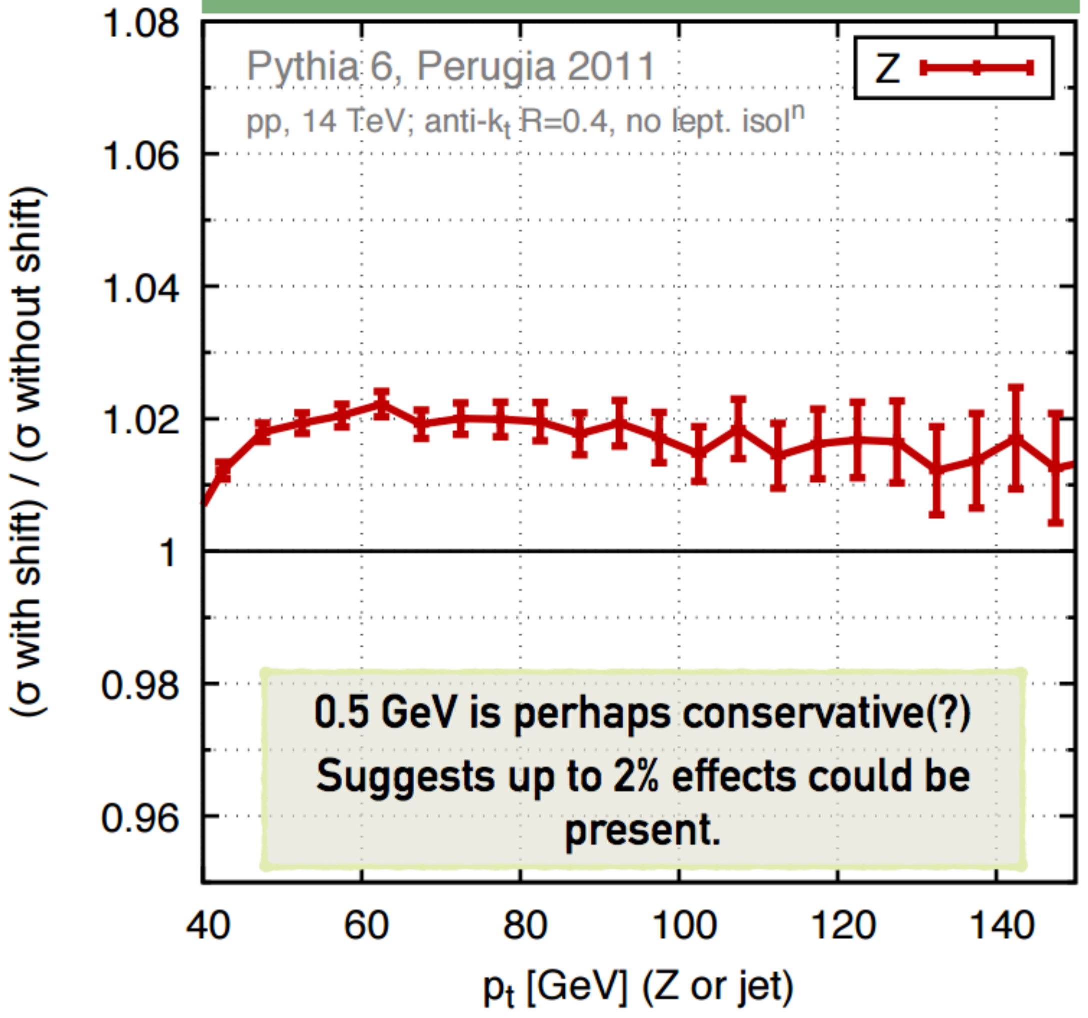
xg(x,Q), comparison
HERA+8TeV (NNLO)
HERA+8TeV (NNLO+EW)
Q = 1.00e+02 GeV
Ratio
x
Generated with APFEL 2.7.1 Web

Non-perturbative effects

Non-perturbative effects in Z p_T

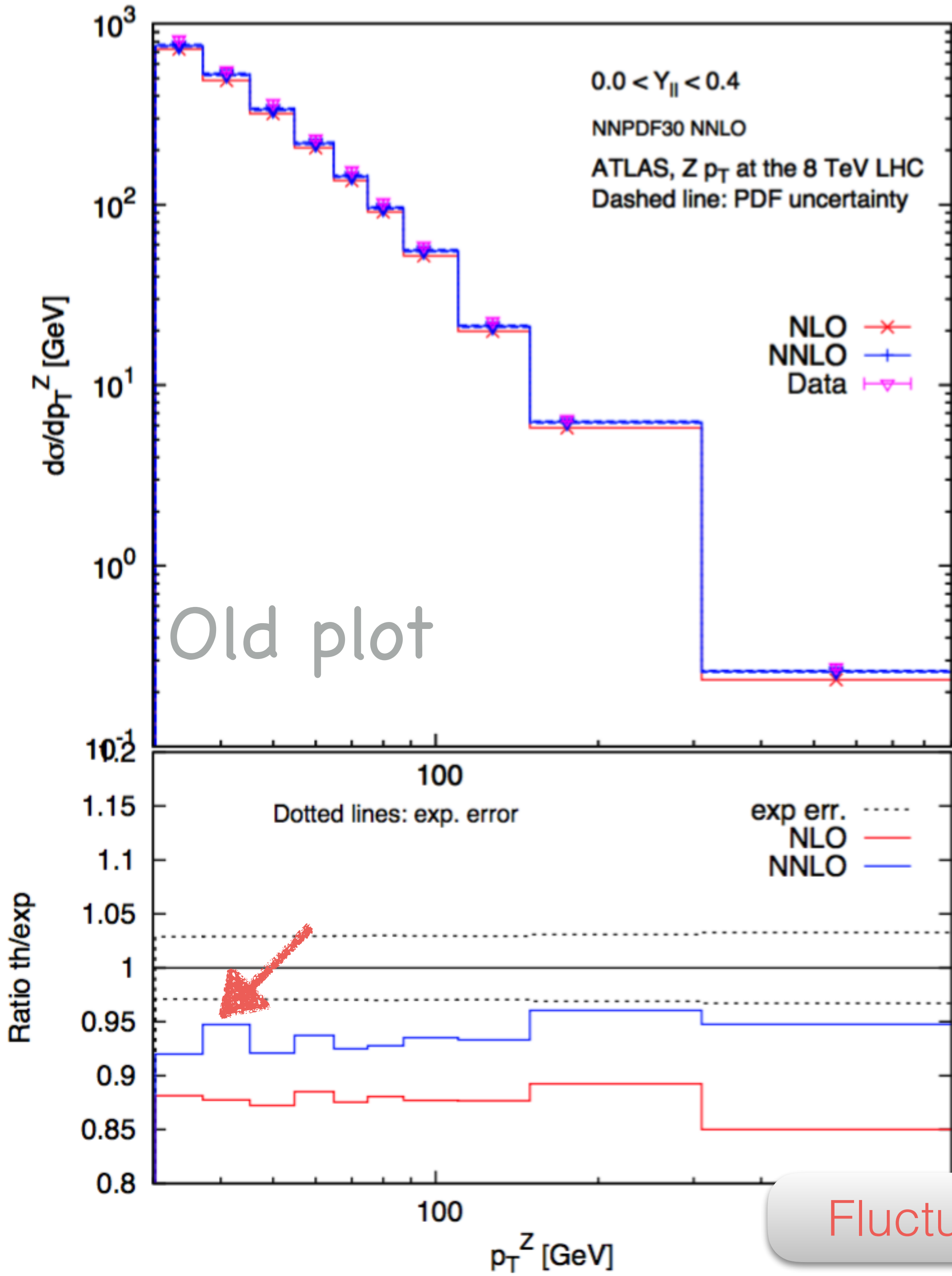
- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

impact of 0.5 GeV shift of Z p_T



G. Salam, talk at KITP 2016

Very high stat. NNLO calculation needed



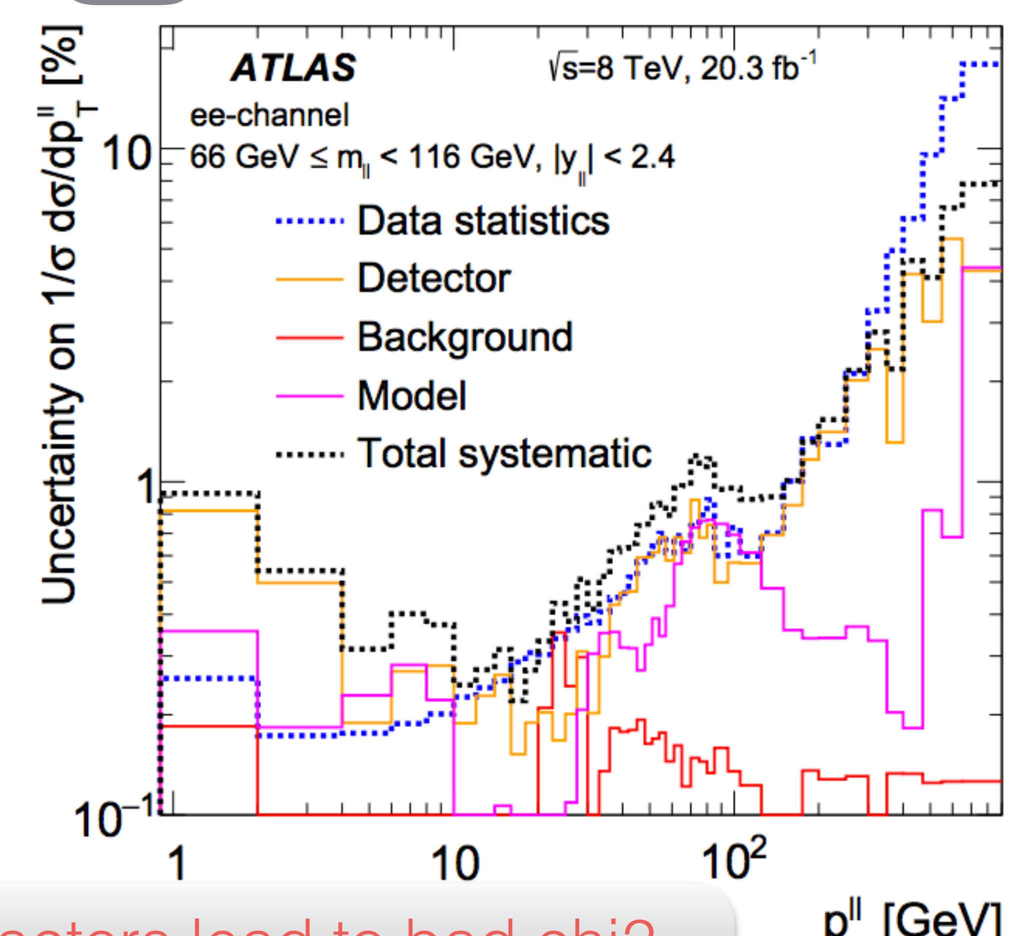
NLO

$$\chi^2_{\rm stat} = 140$$
$$\chi^2_{\rm uncor} = 115$$
$$\chi^2_{\rm diag} = 1.70$$
$$\chi^2_{\rm full} = 2.80$$

NNLO

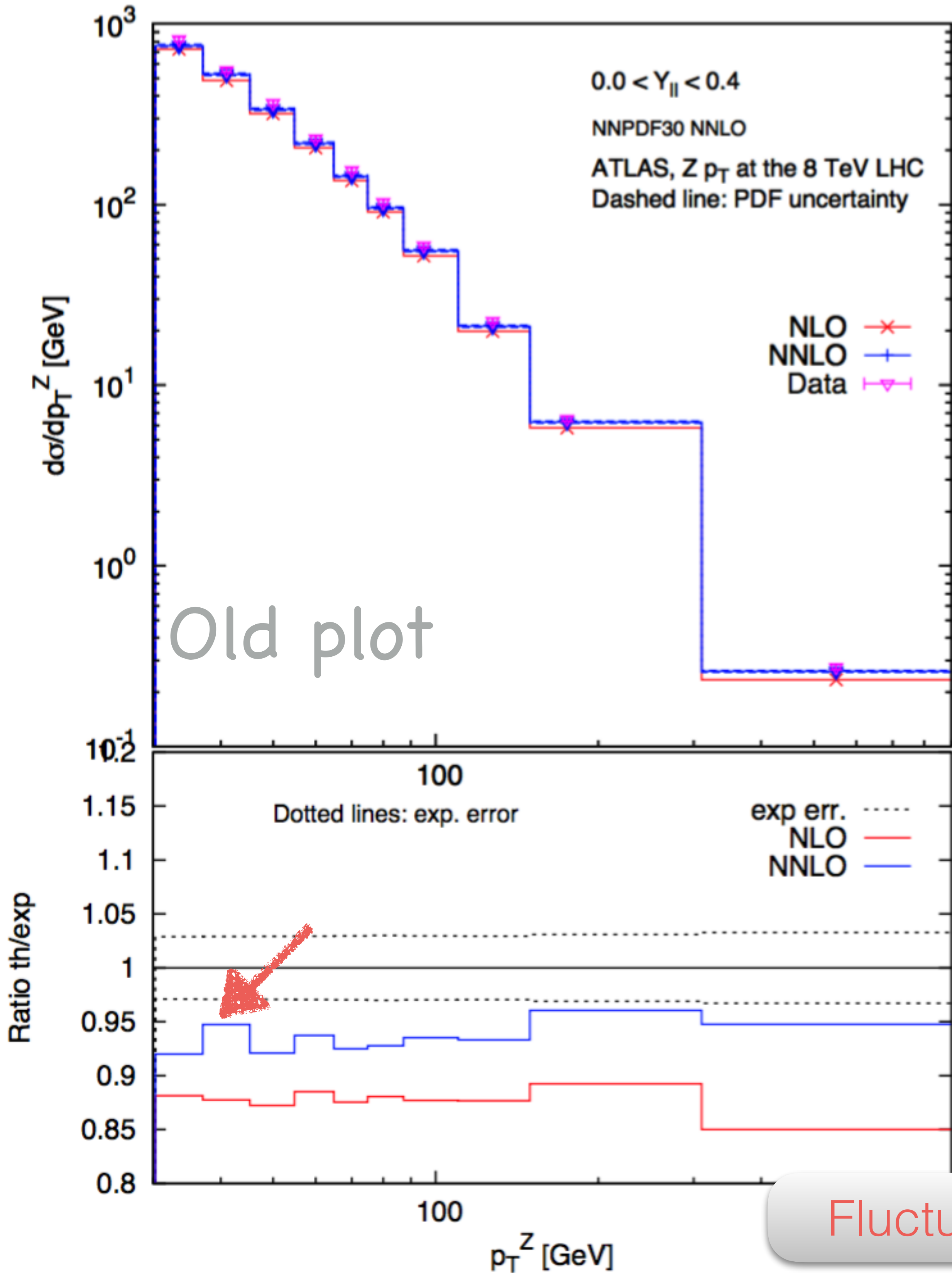
$$\chi^2_{\rm stat} = 51.$$
$$\chi^2_{\rm uncor} = 42.$$
$$\chi^2_{\rm diag} = 0.62$$
$$\chi^2_{\rm full} = 5.61$$

/d.o.f.



Fluctuations in K-factors lead to bad chi2

Very high stat. NNLO calculation needed



NLO	NNLO	
$\chi^2_{\rm stat} = 140$	$\chi^2_{\rm stat} = 51.$	/d.o.f.
$\chi^2_{\rm uncor} = 115$	$\chi^2_{\rm uncor} = 42.$	
$\chi^2_{\rm diag} = 1.70$	$\chi^2_{\rm diag} = 0.62$	
$\chi^2_{\rm full} = 2.80$	$\chi^2_{\rm full} = 5.61$	

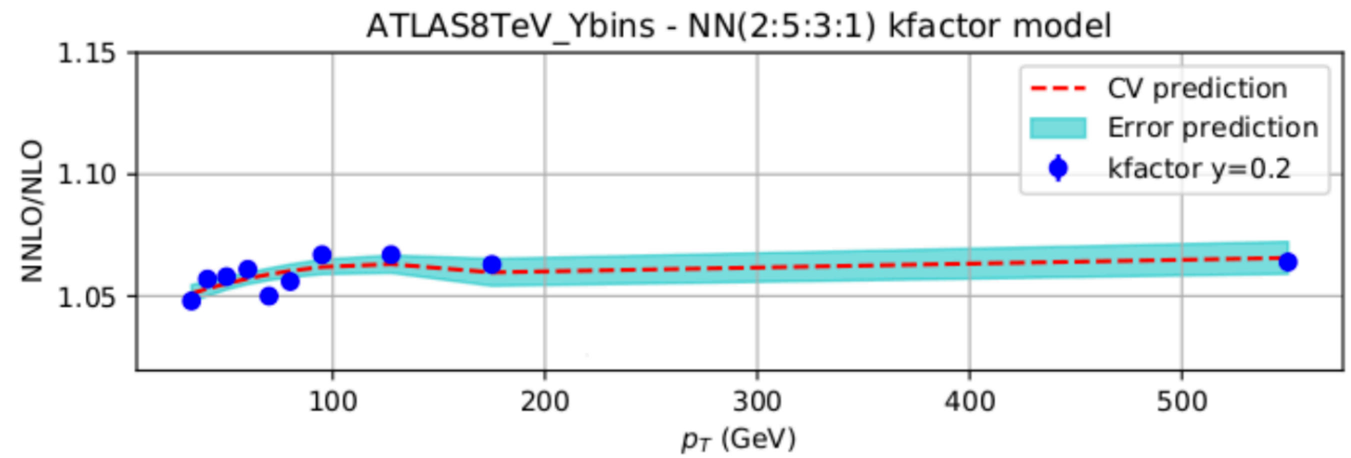
10x more statistics

2.0

Fluctuations in K-factors lead to bad chi2

Extra-statistical uncertainty

- NNLO theory predictions affected by non-negligible Monte Carlo uncertainties
- Numerical uncertainties in theoretical predictions estimated by comparing fluctuations with respect to smooth interpolation
- Explore 0%, 0.5% and 1% hypothesis



HERA + 8 TeV ZpT data fits

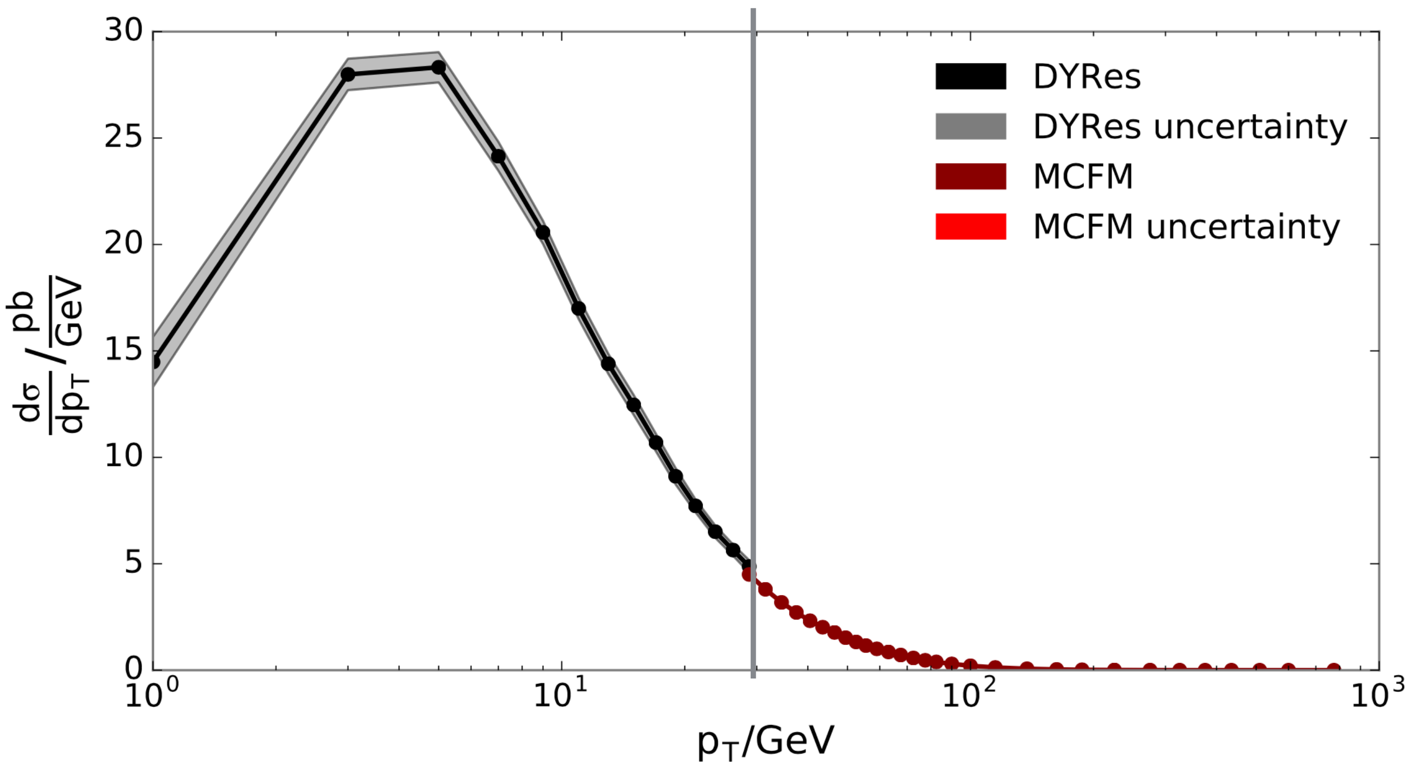
extra Δ	$\chi^2_{\text{ATLAS7tev}}$	$\chi^2_{\text{ATLAS8tev,m}}$	$\chi^2_{\text{ATLAS8tev,y}}$	χ^2_{CMS8tev}
1%	(21.8)	(1.00)	(1.56)	(1.55)
1%	(19.6)	0.91	0.70	(1.61)
1%	(16.2)	(1.04)	(1.56)	1.21
1%	(18.0)	0.90	0.77	1.42
0.5%	(27.6)	(1.10)	(2.83)	(2.46)
0.5%	(23.0)	0.99	1.05	(3.01)
0.5%	(20.5)	(1.13)	(3.15)	1.91
0.5%	(21.4)	0.99	1.29	2.44
no	(30.6)	(1.15)	(4.65)	(3.46)
no	(25.5)	1.02	1.66	(4.79)
no	(19.5)	(1.28)	(5.44)	2.51
no	(24.5)	1.03	2.09	3.59

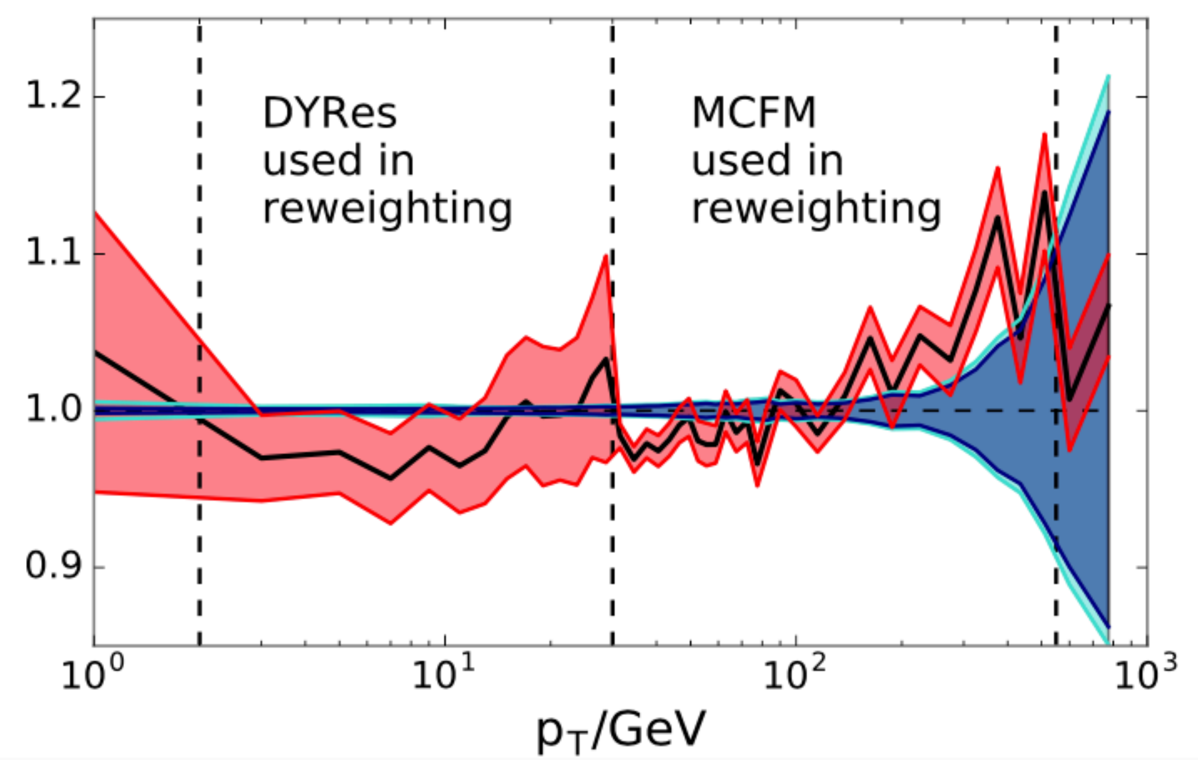
+ 1% extra uncorrelated uncertainty

no extra uncorrelated uncertainty

Fit ATLAS 8 TeV   Fit CMS 8 TeV   Fit both

Including the small ZpT region





Gluon density distribution, $Q^2 = m_Z^2$.