IMPACT OF THE INCLUSION OF PRECISE Z PT DISTRIBUTIONS IN A PDF FIT

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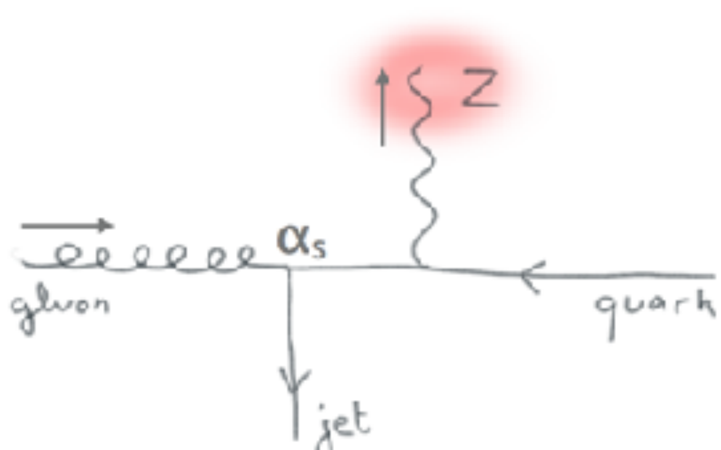
Transverse momentum distributions

- Z boson production & decay into leptons benchmark Standard Model (SM) process at the LHC.
- Can be measured very accurately by the LHC experiments thanks to large production rate and clean signature
- Can be calculated to high accuracy within the Standard Model
  - ✓ $O(\alpha_S^2)$ 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 highly-developed theory allows this process to be used to determine quantities of fundamental importance, such as PDFs or α_S



G. Salam

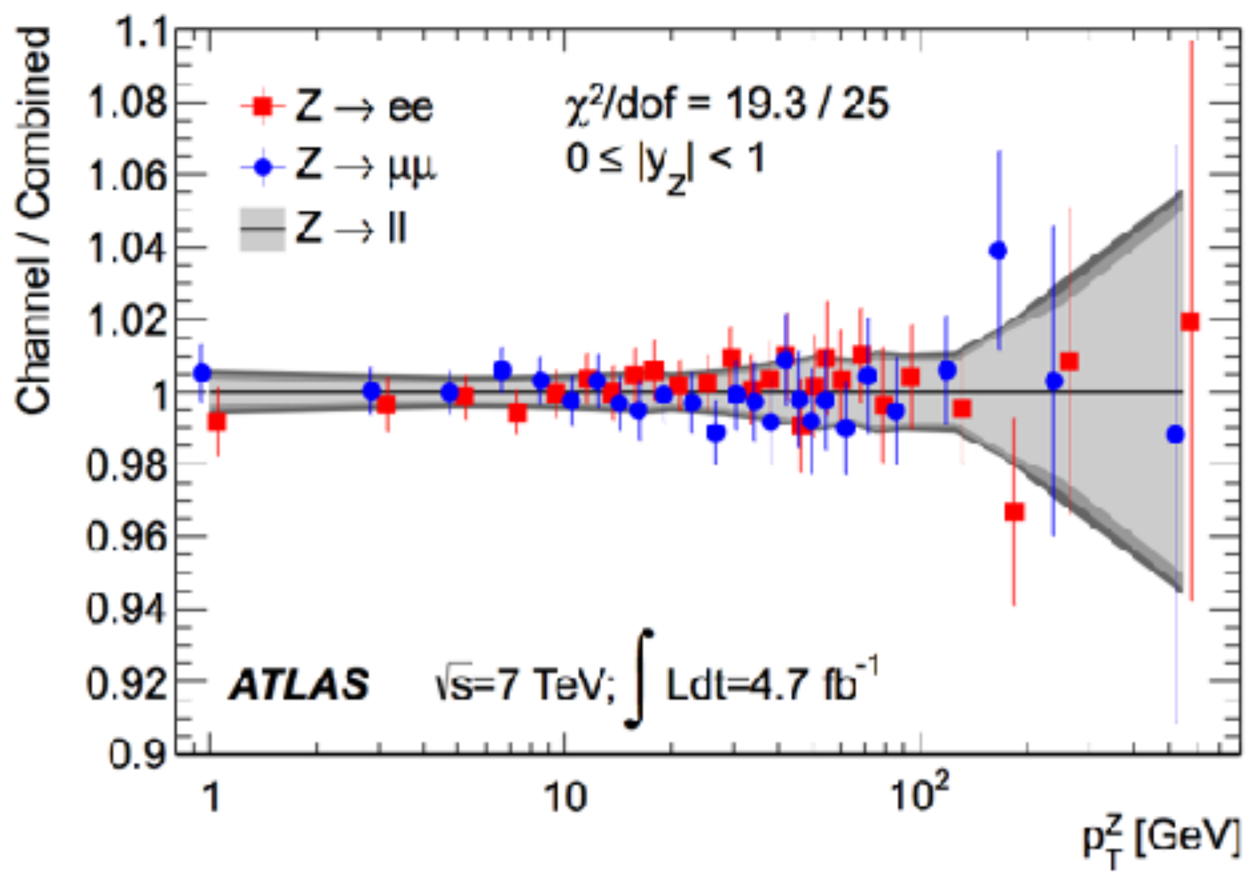
Topic of my talk
Boughezal, Guffanti, Petriello, MU - arXiv:1704.xxxxx

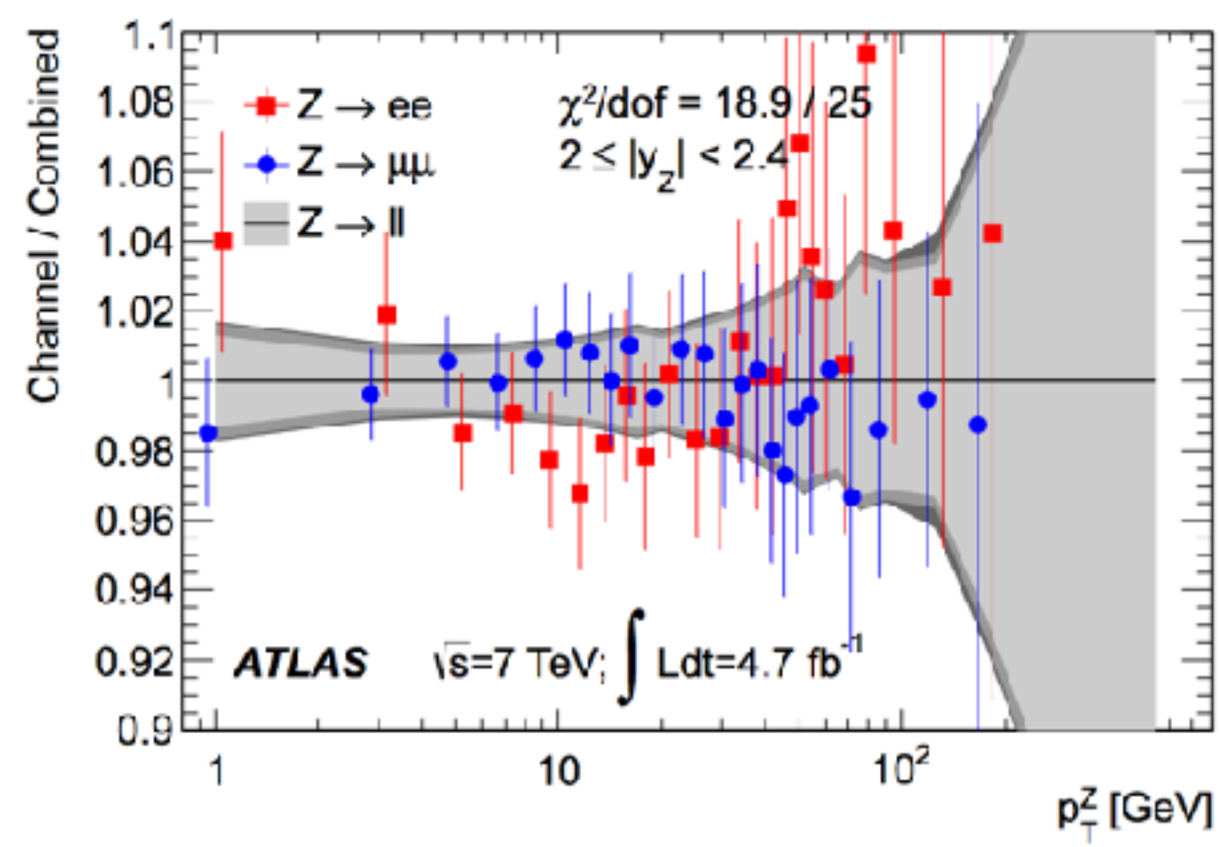
Outline of the talk

- Z transverse momentum distributions
    - ➡ Experimental measurements
    - ➡ Theoretical predictions
- The analysis
    - ➡ Inclusion of ZpT data in a HERA-only fit
    - ➡ Inclusion of ZpT data in global analysis
    - ➡ The NNPDF3.1 global set
- Conclusions and outlook

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

➡ **O(50)** data points with pT > 30 GeV

ATLAS 7 TeV measurements
ArXiv:1406.3660

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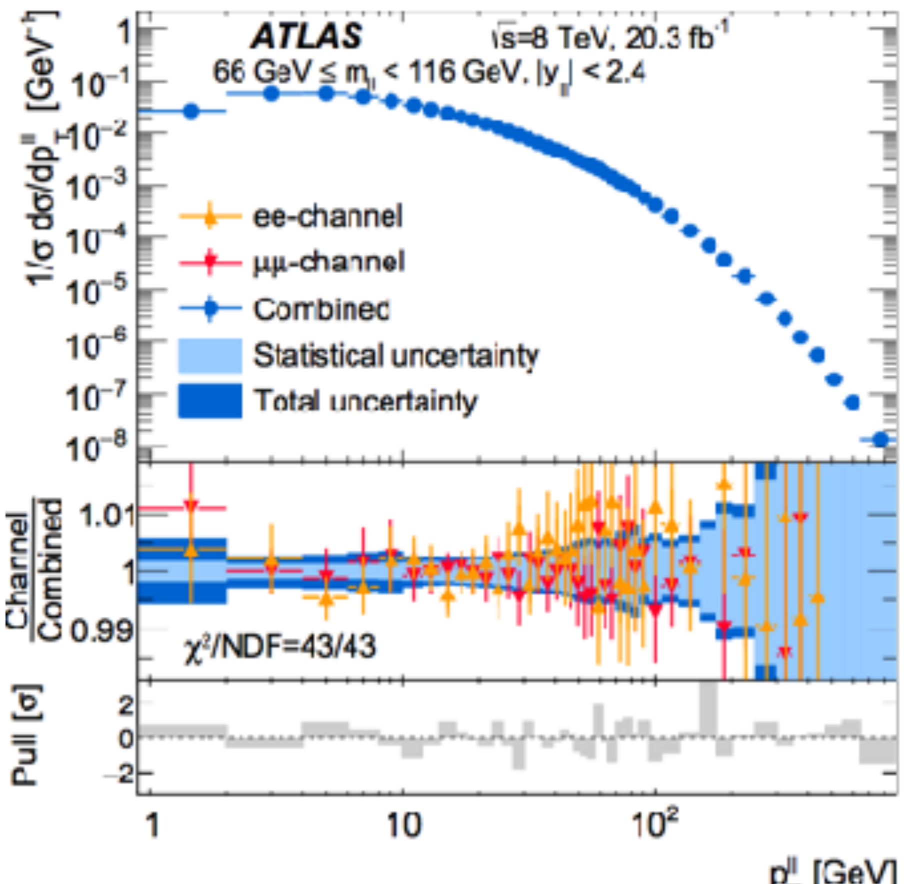
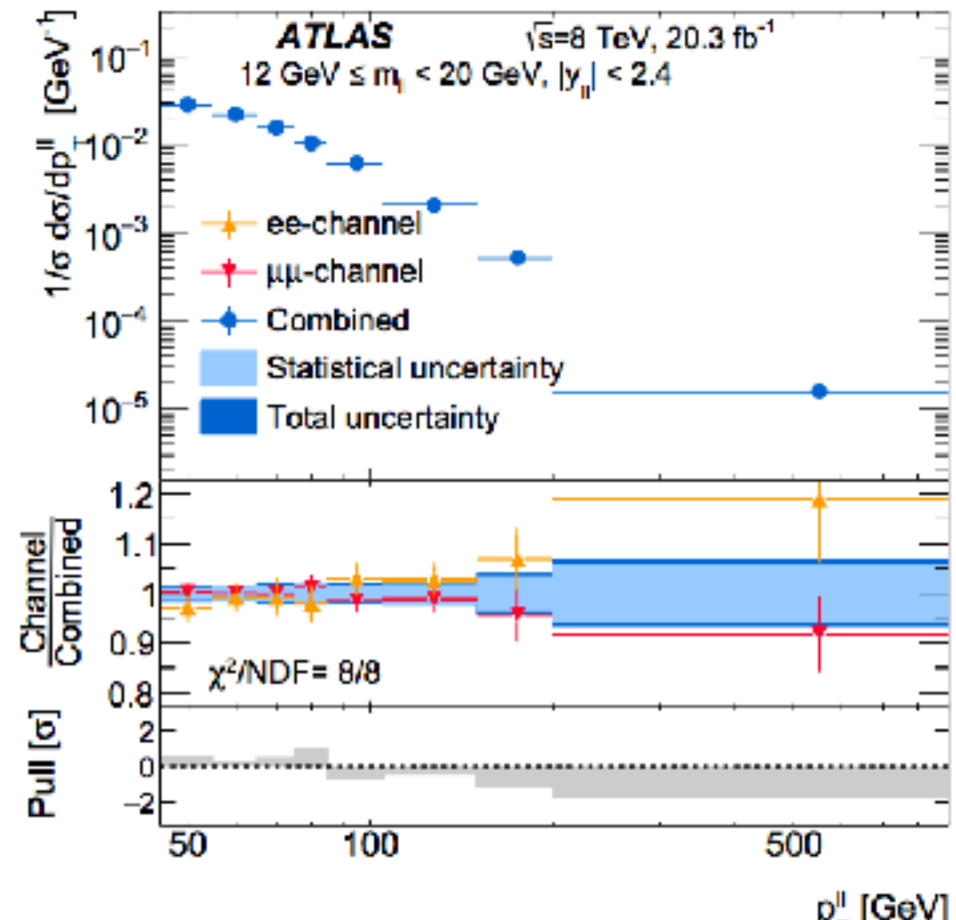


ATLAS 8 TeV measurements
arXiv: 1512.02192

- 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

➡ **O(150)** datapoints with pT > 30 GeV

Experimental Data

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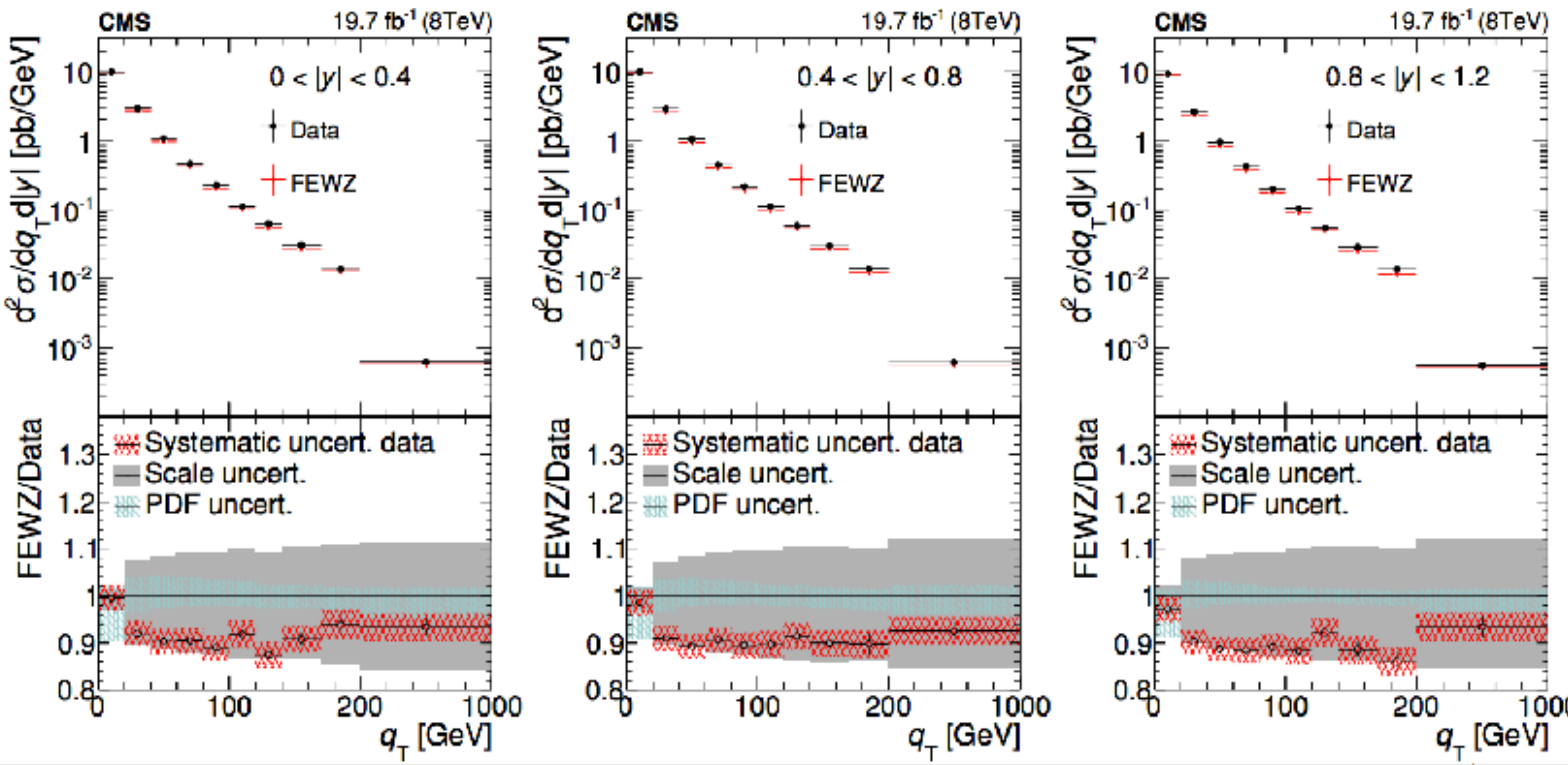


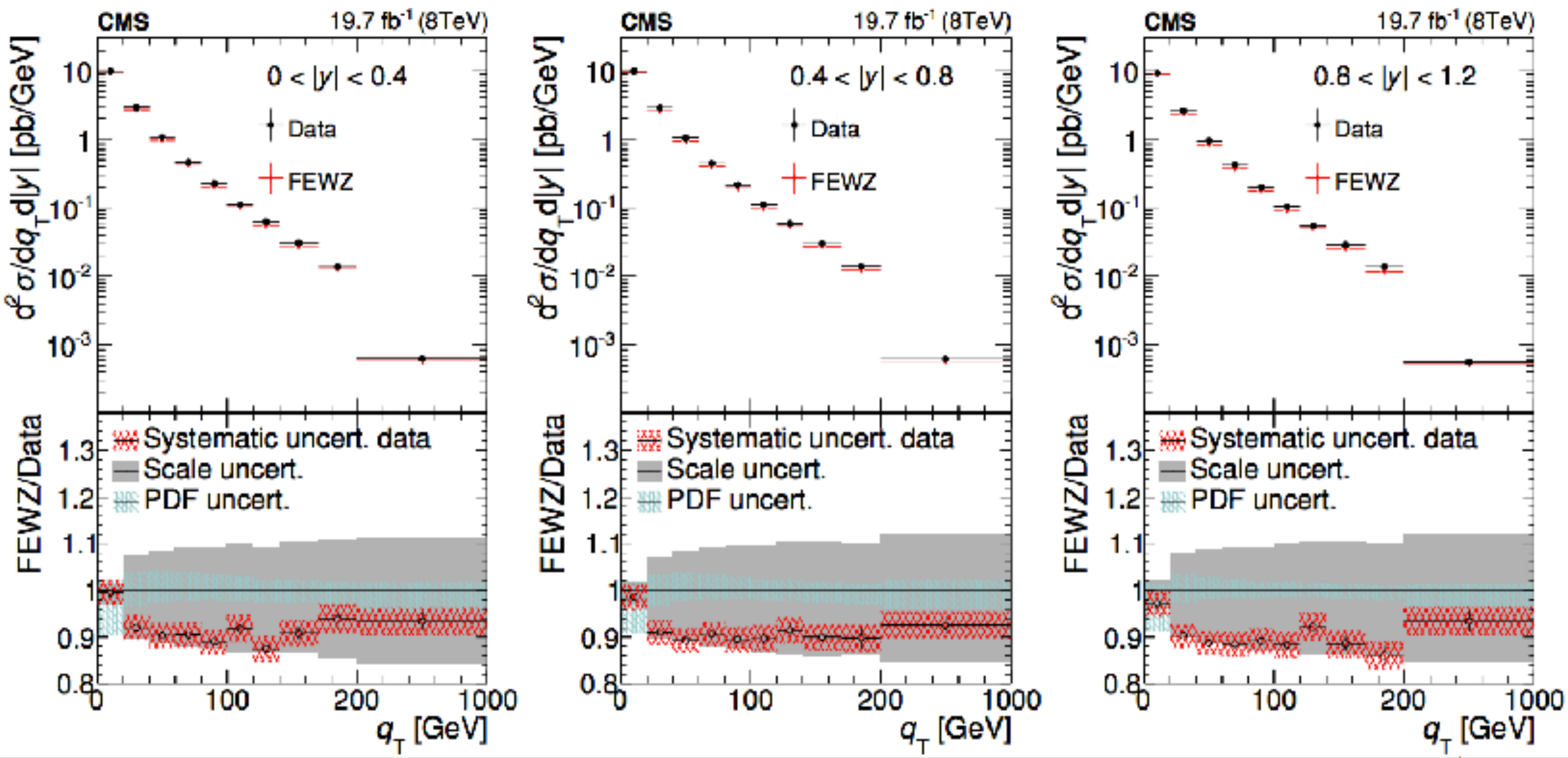
- Normalised and un-normalised
- Five rapidity bins in Z peak region
  0.0 < Y < 0.4, 0.4 < Y < 0.8, 0.8 < Y < 1.2
  1.2 < Y < 1.6, 1.6 < Y < 2.0

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

CMS 8 TeV measurements
arXiv: 1504.03511

Experimental Data

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



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

CMS 8 TeV measurements
arXiv: 1504.03511

250 precise datapoints

Theoretical predictions

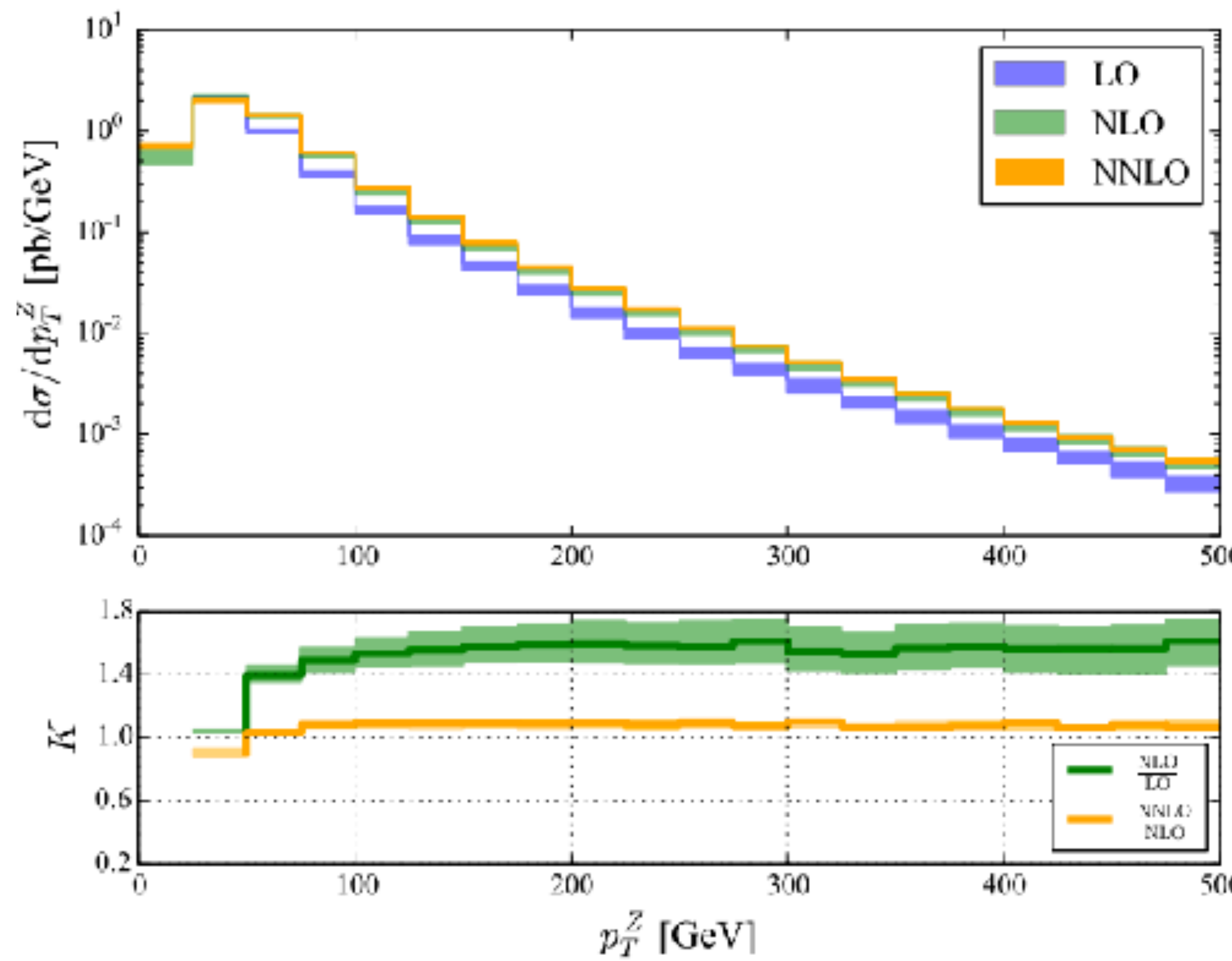
- NNLO calculation performed using N-jettiness subtraction scheme, by using recent calculation of Z+j at NNLO and relaxing cut on final state jet

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

- NNLO/NLO K-factors 5% - 10% depending on the rapidity and invariant mass region

- Included $p_T > 30$ GeV and verified stability upon raising the cut

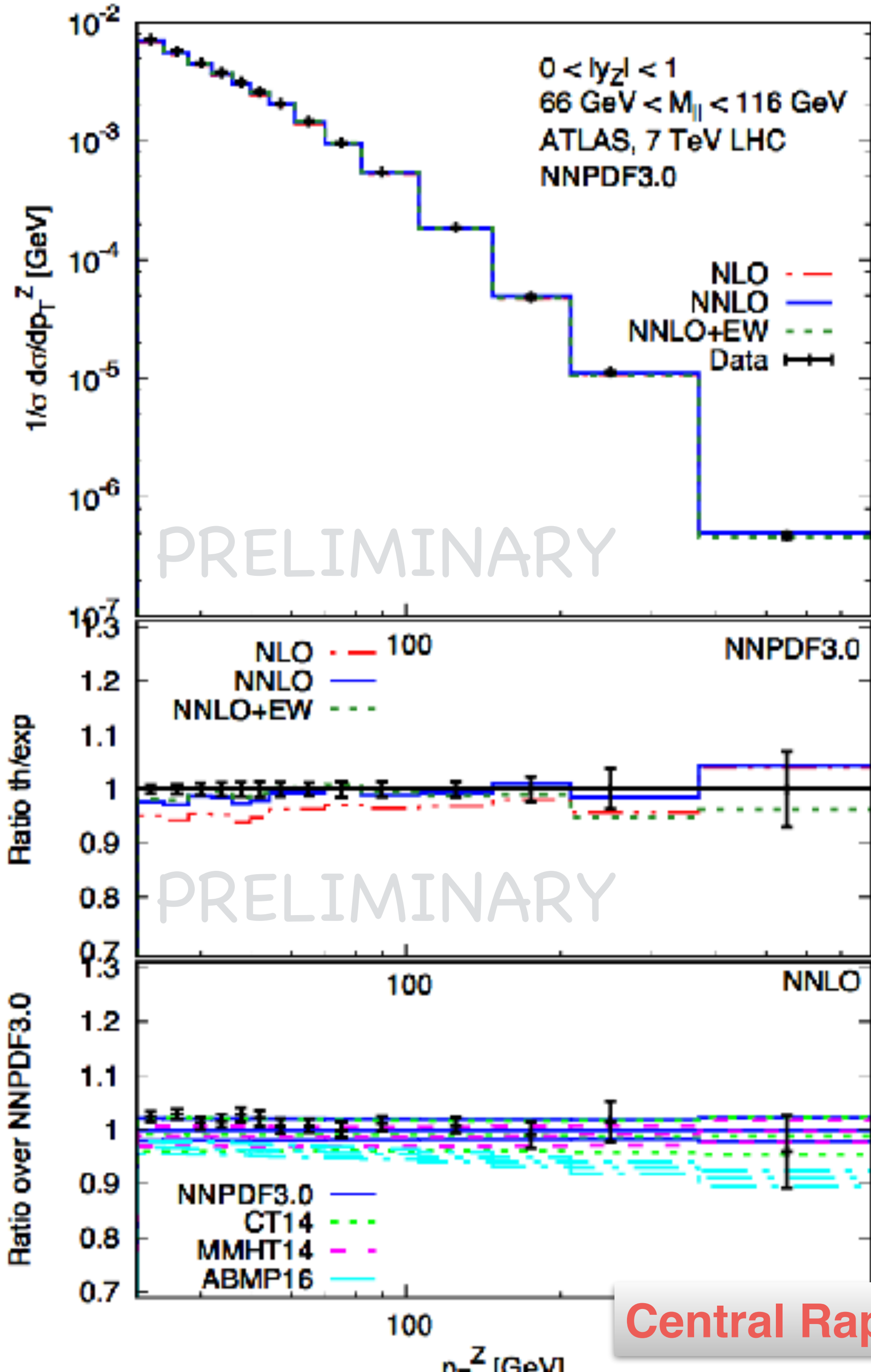
- NLO approximated EW corrections relevant for the highest p_T bins in the Z-mass peak and for off-peak measurements



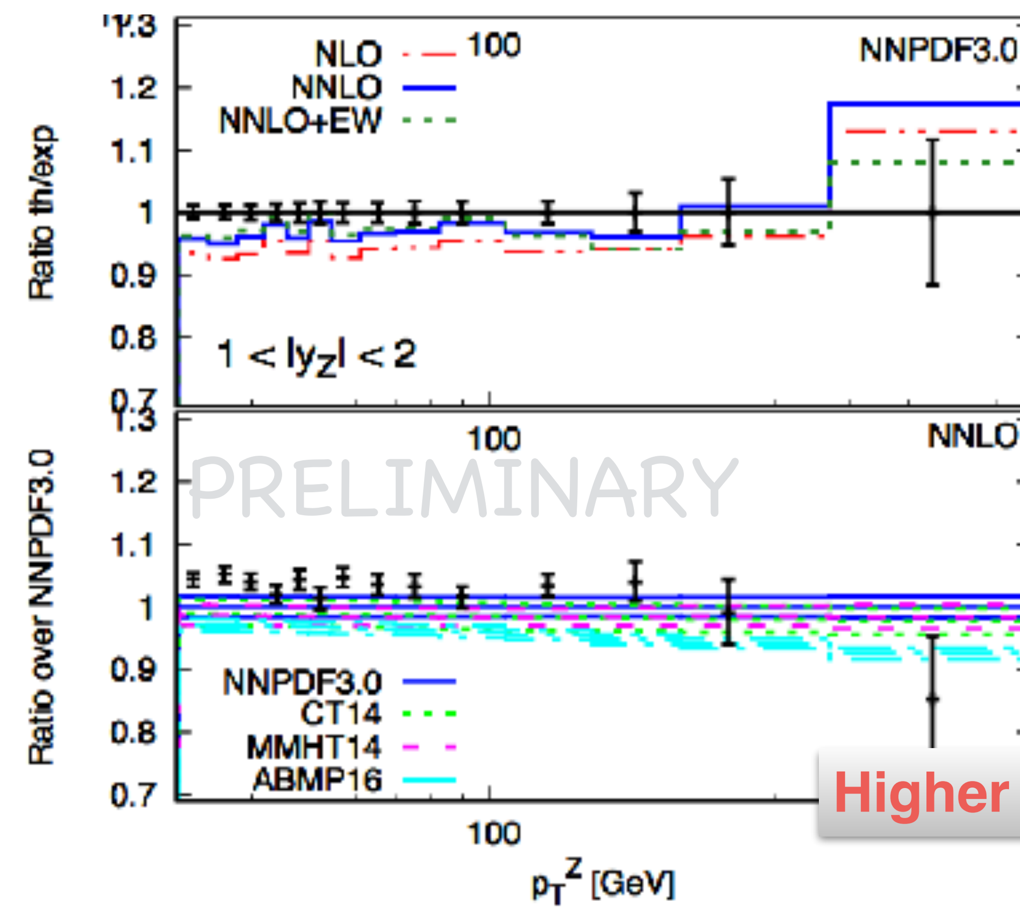
Boughezal et al, PRL 116 (2016)
Boughezal et al, PRD 94 (2016)

Theoretical predictions

ATLAS 7 TeV



Central Rapidity



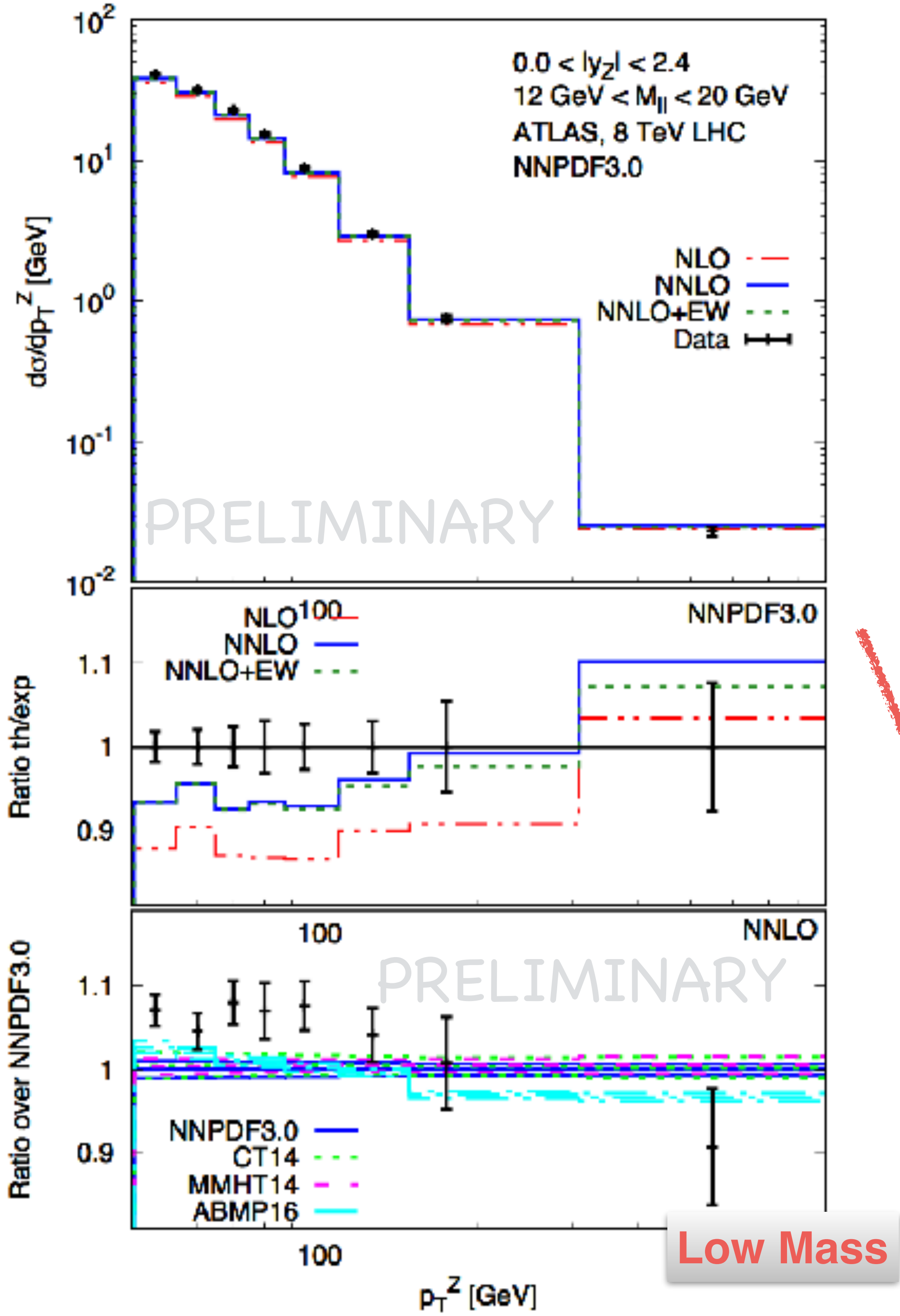
Higher Rapidity

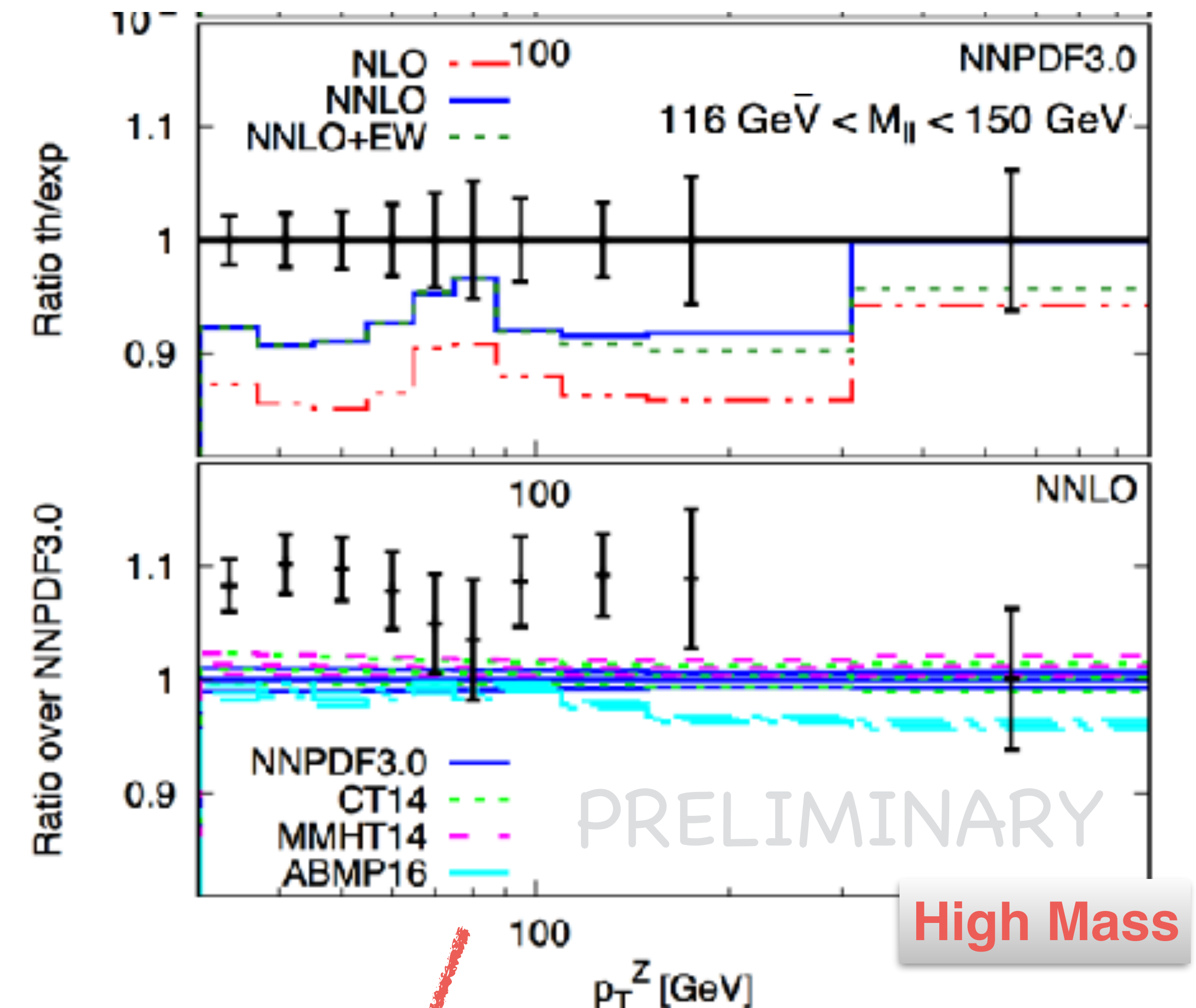
Bin	Order	N_{dat}	$\chi^2_{d.o.f.}$ (NNPDF3.0)	$\chi^2_{d.o.f.}$ (CT14)	$\chi^2_{d.o.f.}$ (MMHT14)	$\chi^2_{d.o.f.}$ (ABMP16)
$0.0 < y_Z < 1.0$	NLO	14	10	21	9.2	n.a.
	NNLO	14	2.2	3.8	4.3	11
	NNLO+EW	14	1.3	2.3	2.6	9.1
$1.0 < y_Z < 2.0$	NLO	14	13	18	12	n.a.
	NNLO	14	5.6	8.2	9.3	15.
	NNLO+EW	14	3.9	6.0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

Theoretical predictions

ATLAS 8 TeV

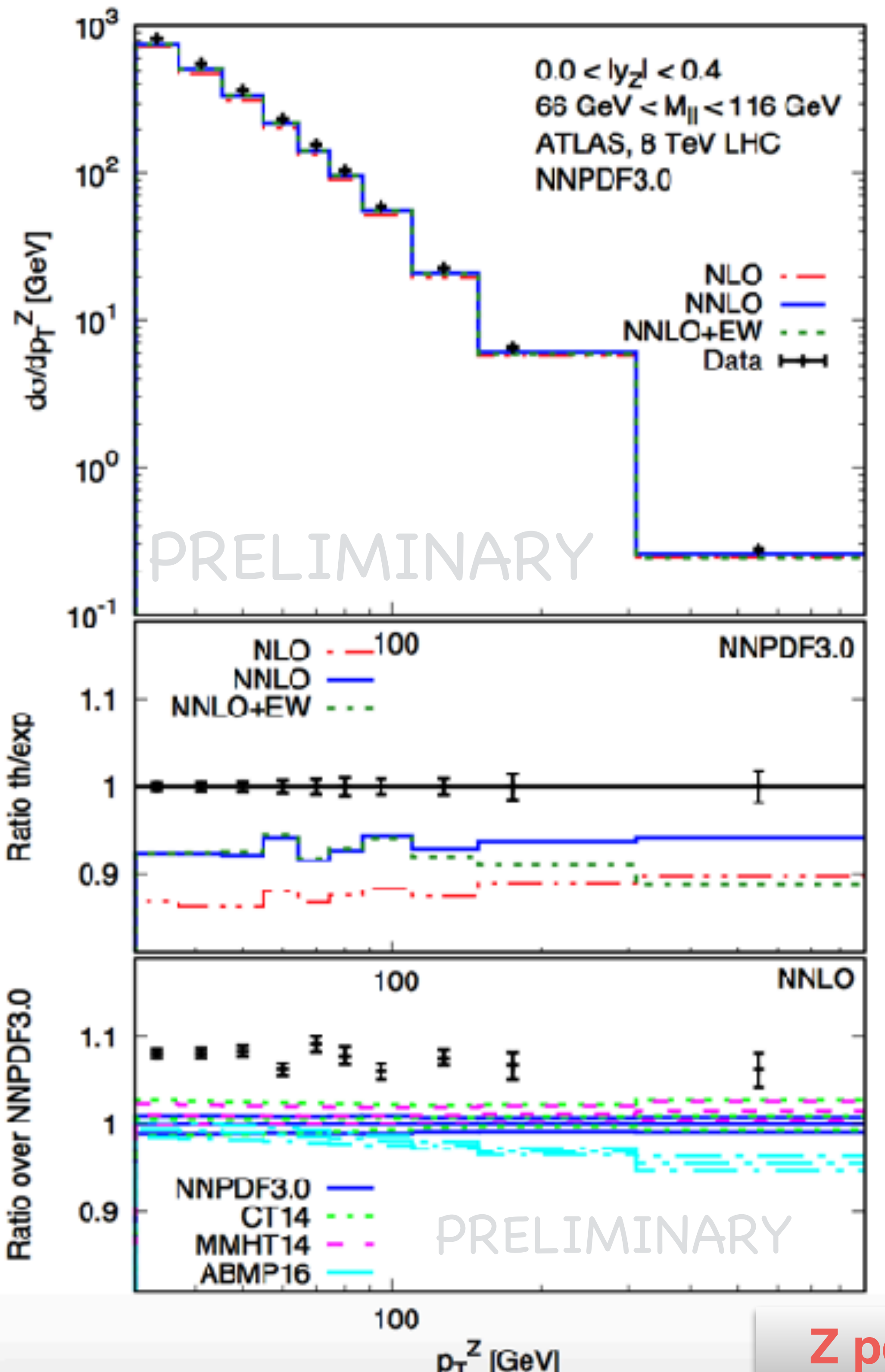




Order	N_{dat}	$\chi^2_{d.o.f.}$ (NNPDF3.0)	$\chi^2_{d.o.f.}$ (CT14)	$\chi^2_{d.o.f.}$ (MMHT14)	$\chi^2_{d.o.f.}$ (ABMP16)
NLO	8	2.5	2.2	1.9	n.a.
NNLO	8	1.7	1.6	1.7	1.1
NNLO+EW	8	1.4	1.3	1.3	1.0
NLO	10	2.3	2.1	1.6	n.a
NNLO	10	1.2	1.0	1.0	1.3
NNLO+EW	10	1.1	1.0	0.9	1.4

Theoretical predictions

ATLAS 8 TeV

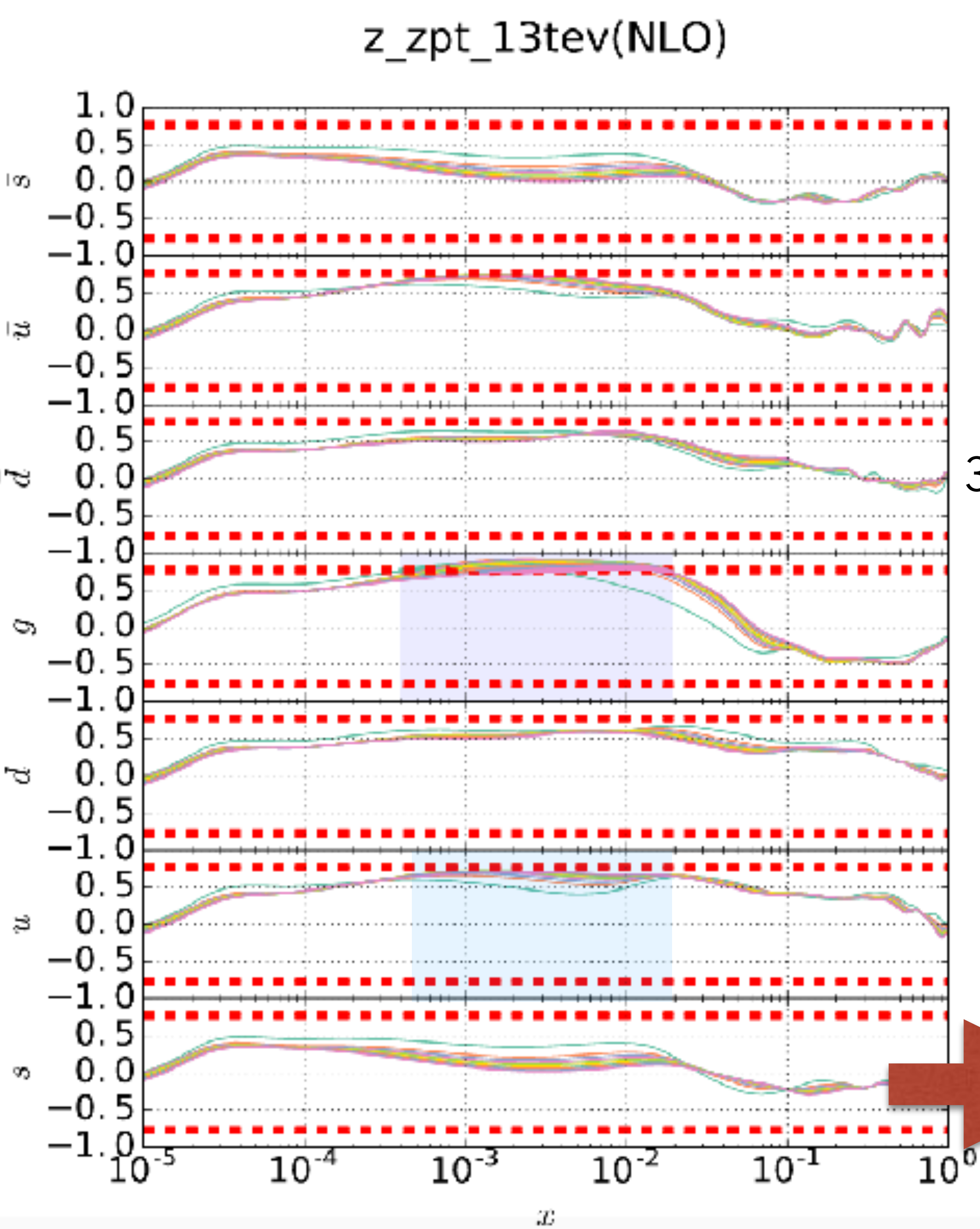


Z peak

Bin	Order	N_{dat}	$\chi^2_{d.o.f.}$ (NNPDF3.0)	$\chi^2_{d.o.f.}$ (CT14)	$\chi^2_{d.o.f.}$ (MMHT14)	$\chi^2_{d.o.f.}$ (ABMP16)
$0.0 < y_Z < 0.4$ GeV	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
$0.4 < y_Z < 0.8$ GeV	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
$0.8 < y_Z < 1.2$ GeV	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
$1.2 < y_Z < 1.6$ GeV	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
$1.6 < y_Z < 2.0$ GeV	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
$2.0 < y_Z < 2.4$ GeV	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 improves agreement (before fit) especially at central rapidities
- EW corrections only relevant for the two highest p_T bins in the Z-mass peak
- Similar picture for CMS data (Y < 1.6)

Correlation with PDFs



- 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

$$30\text{ GeV} < \begin{array}{lll} p_T^Z & < 500\,\mathrm{GeV} & (\mathrm{ATLAS\ 7\ TeV}) \\ p_T^Z & < 150\,\mathrm{GeV} & (\mathrm{ATLAS\ 8\ TeV - Z - peak\ region}) \\ p_T^Z & < 170\,\mathrm{GeV} & (\mathrm{CMS\ 8\ TeV}) \end{array}$$

- Expect constraint to intermediate-x gluon and light quark distributions

Generated with SM-PDF web interface using NLO observable and NNLO PDFs
https://smpdf.mi.infn.it/
Carrazza, Kassabov 1606.09248

Extra-statistical uncertainty

- NNLO theory predictions affected by Monte Carlo uncertainties
- Good fit quality only if uncertainties in theoretical predictions are estimated by comparing fluctuations with respect to smooth interpolation
- Explore 0%, 0.5% and 1% hypothesis

HERA + ZpT data fits

$\chi^2_{\mathrm{ATLAS7tev}}$	$\chi^2_{\mathrm{ATLAS8tev,m}}$	$\chi^2_{\mathrm{ATLAS8tev,y}}$	$\chi^2_{\mathrm{CMS8tev}}$	χ^2_{tot}
(21.8)	(1.00)	(1.56)	(1.55)	1.168
1.39	(1.39)	(2.04)	(1.41)	1.176
(19.6)	0.91	0.70	(1.61)	1.146
(16.2)	(1.04)	(1.56)	1.21	1.176
(18.0)	0.90	0.77	1.42	1.156
1.64	1.05	1.17	1.27	1.171
(27.6)	(1.10)	(2.83)	(2.46)	1.168
1.58	(1.54)	(3.36)	(2.11)	1.186
(23.0)	0.99	1.05	(3.01)	1.168
(20.5)	(1.13)	(3.15)	1.91	1.198
(21.4)	0.99	1.29	2.44	1.207
2.13	1.18	1.98	2.21	1.253
(30.6)	(1.15)	(4.65)	(3.46)	1.168
1.74	(1.69)	(4.79)	(3.06)	1.185
(25.5)	1.02	1.66	(4.79)	1.193
(19.5)	(1.28)	(5.44)	2.51	1.225
(24.5)	1.03	2.09	3.59	1.251
2.35	1.24	2.81	3.19	1.301

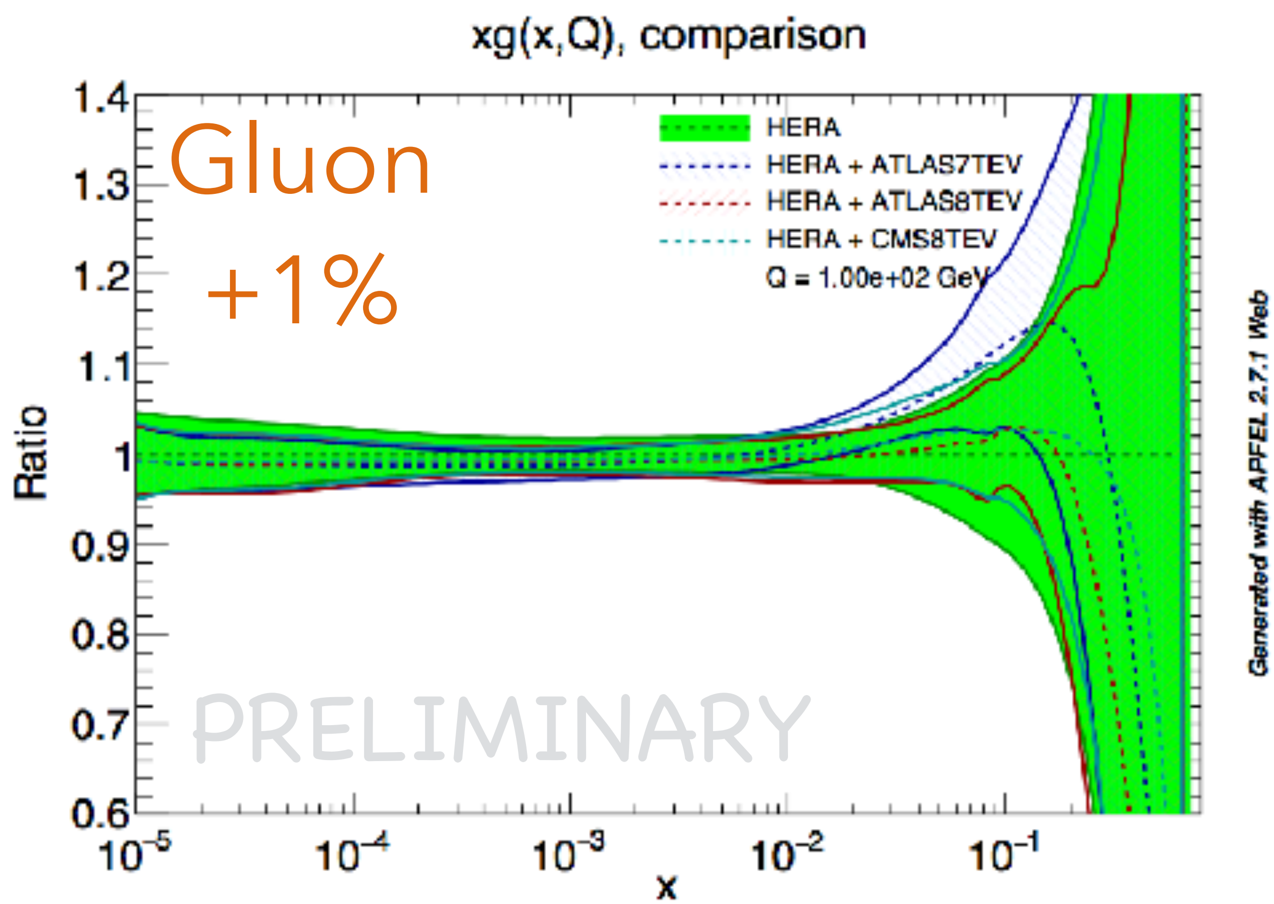
+ 1% uncorrelated uncertainty

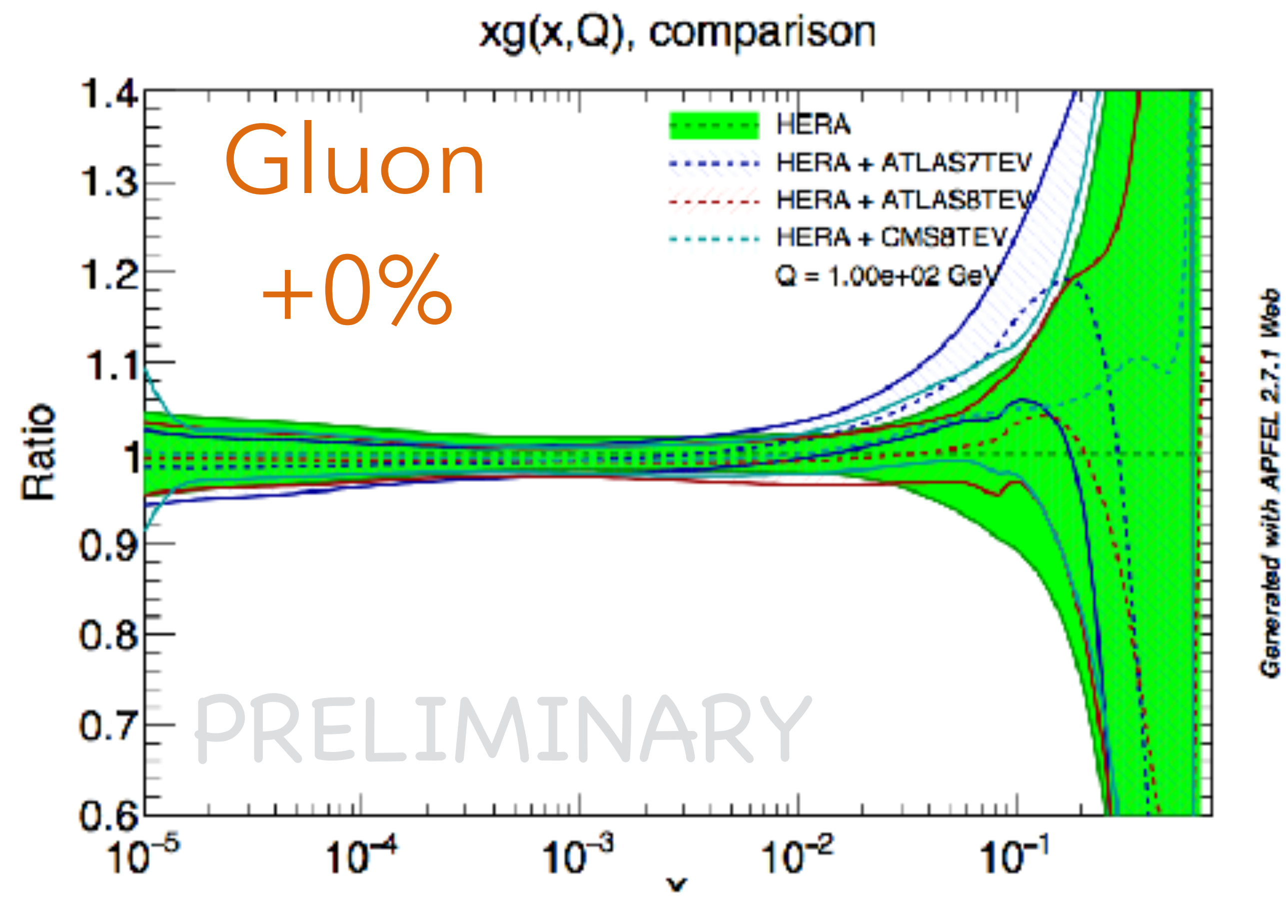
+ 0.5% uncorrelated uncertainty

+ 0% uncorrelated uncertainty

PRELIMINARY

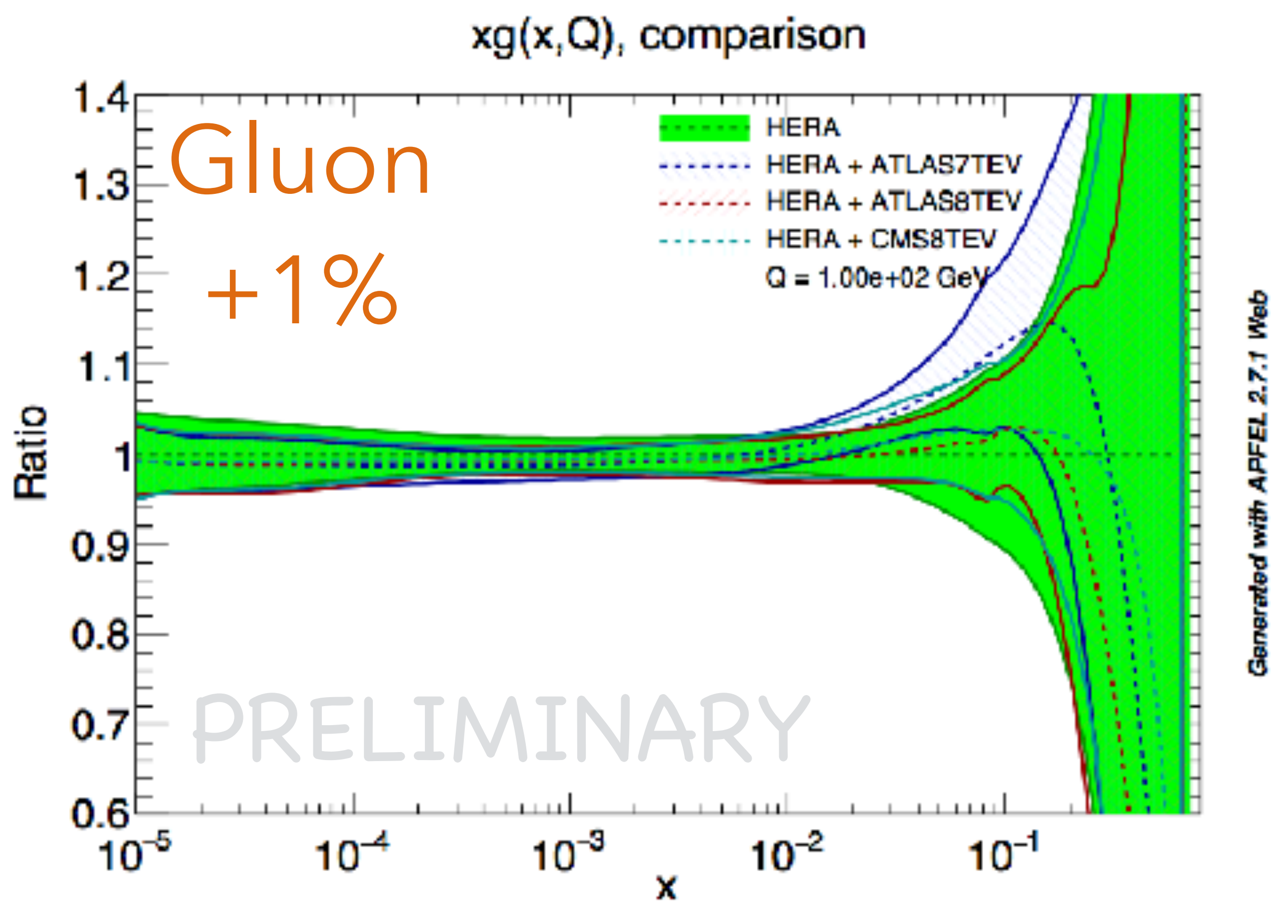
Impact of Z p_T distributions (HERA fits)

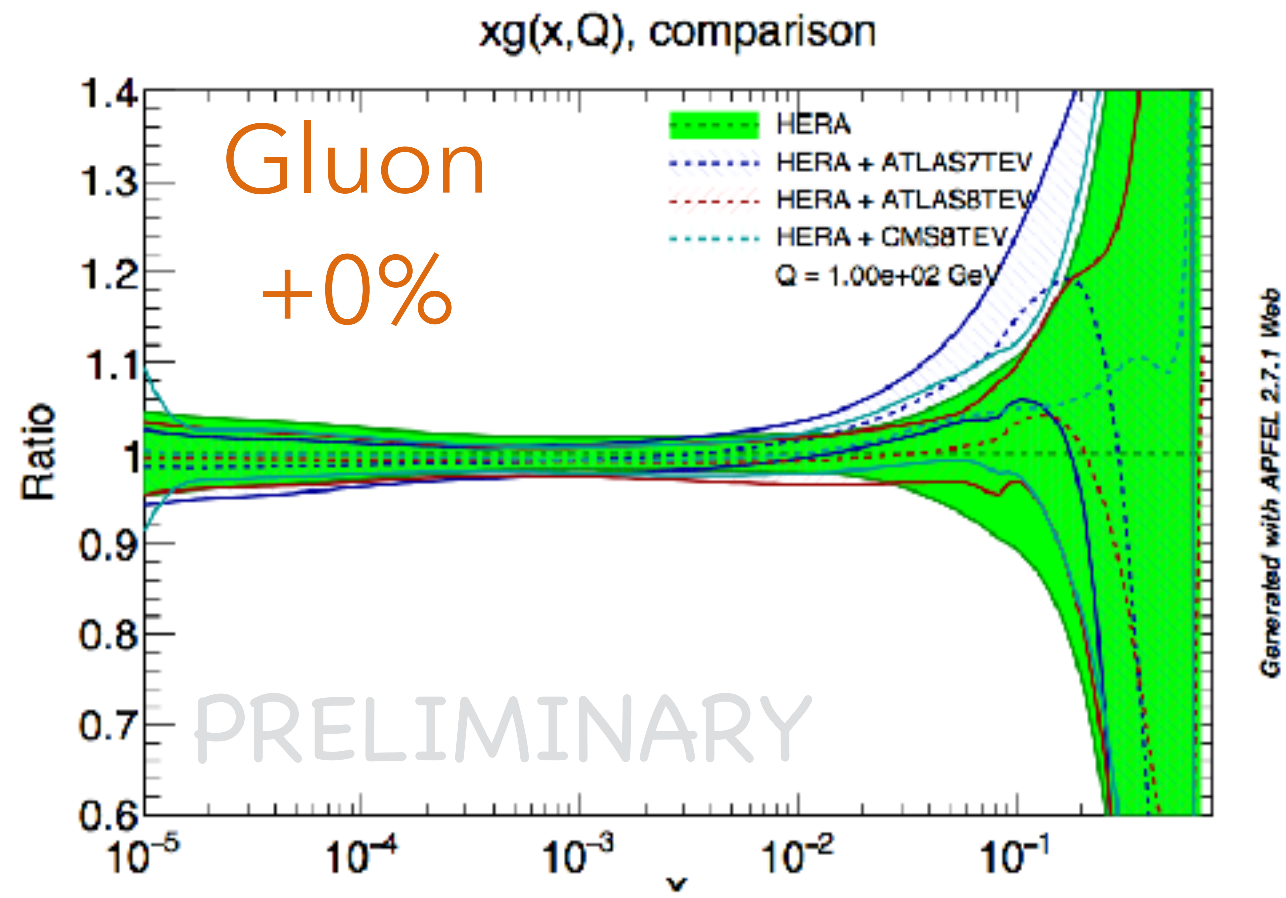


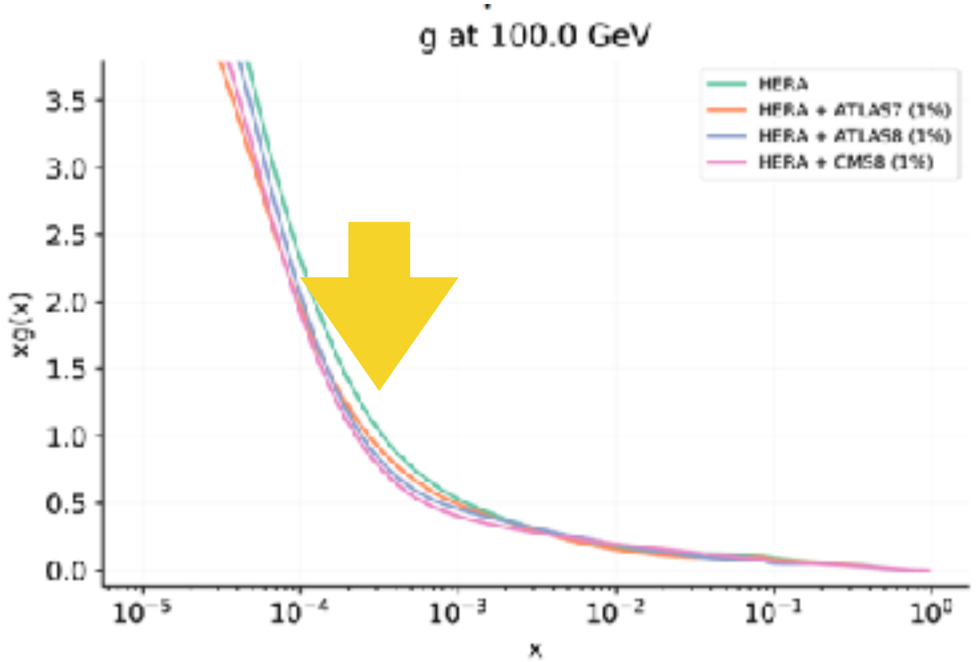


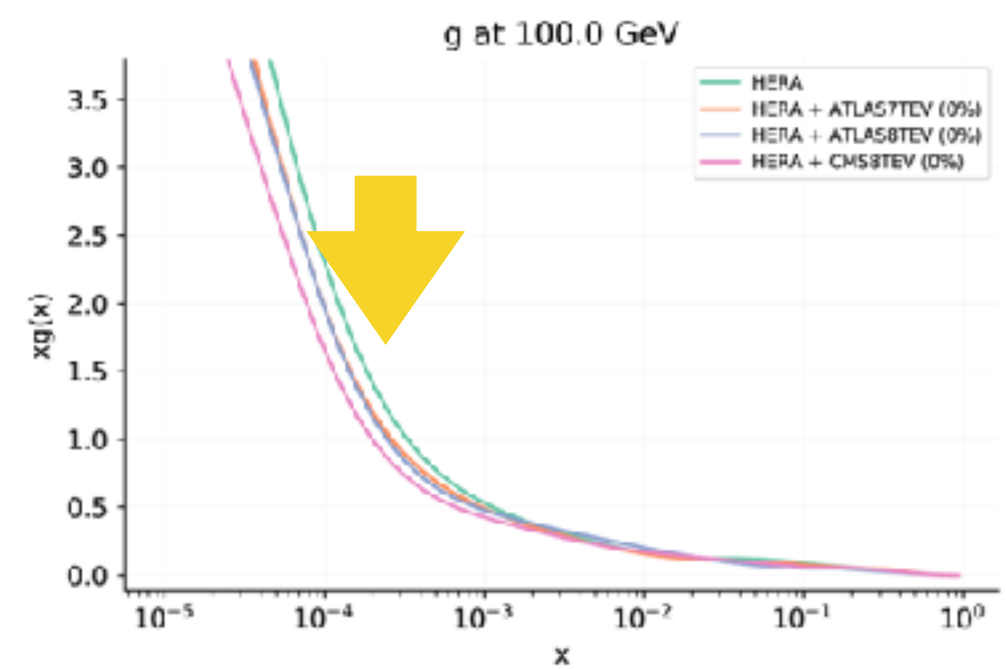
- PDFs stable under extra statistical uncertainty included in the fit (only slightly smaller PDF error reduction when no extra uncertainty is included - barely visible)

Impact of Z p_T distributions (HERA fits)

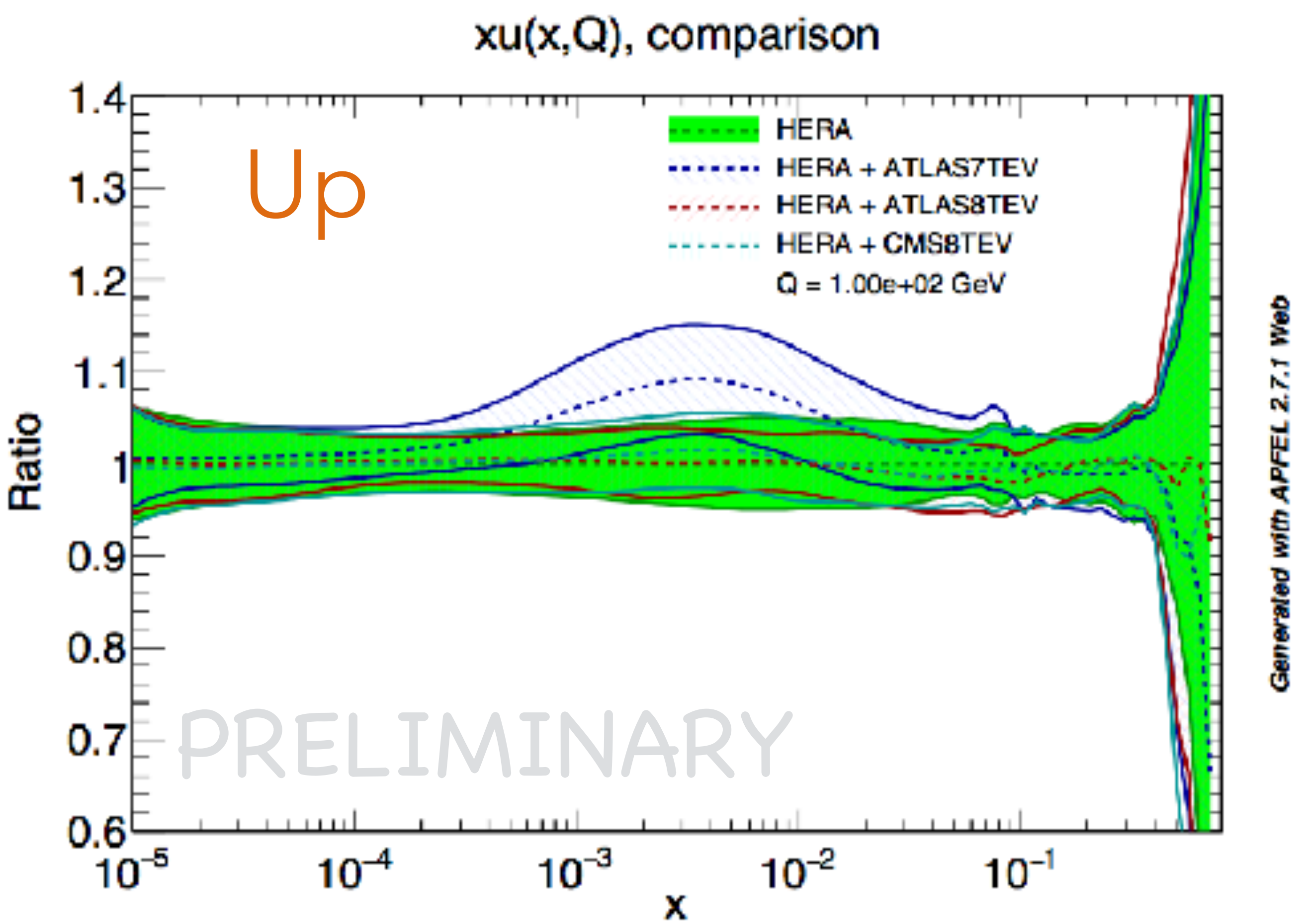


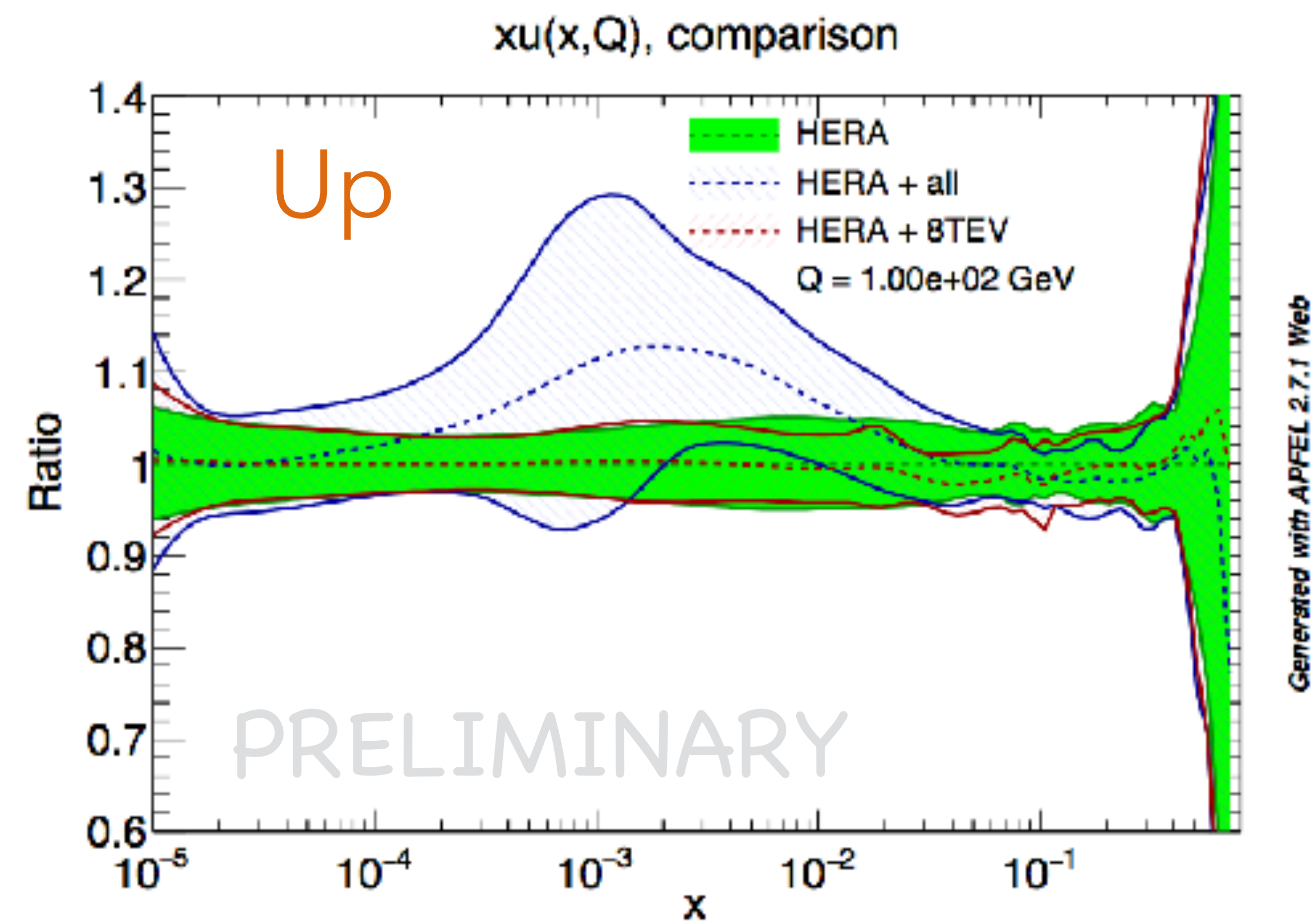






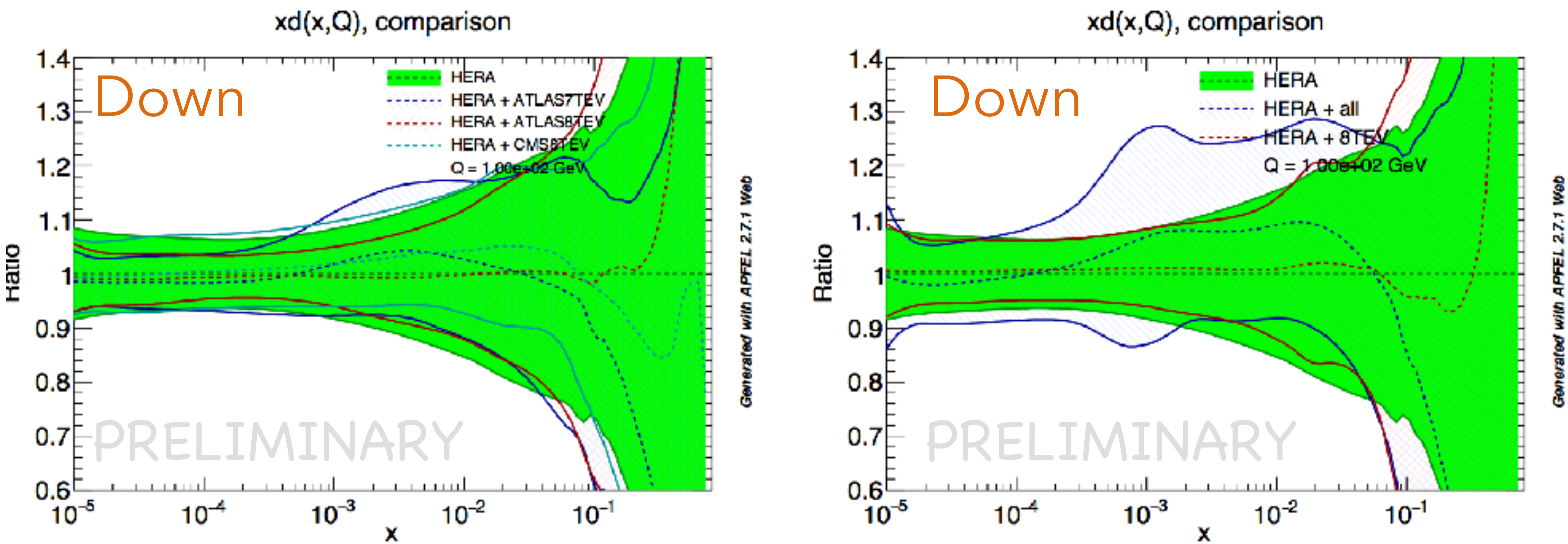
Impact of Z p_T distributions (HERA fits)





- Impact of Z pT distributions is quite strong, they increase the light quark distributions in regions in which we expect them to be correlated with measurement
- 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.
- ATLAS 7 TeV data (normalised) can be fitted individually but point to a different minimum, when added together uncertainty increases!

Impact of Z p_T distributions (HERA fits)



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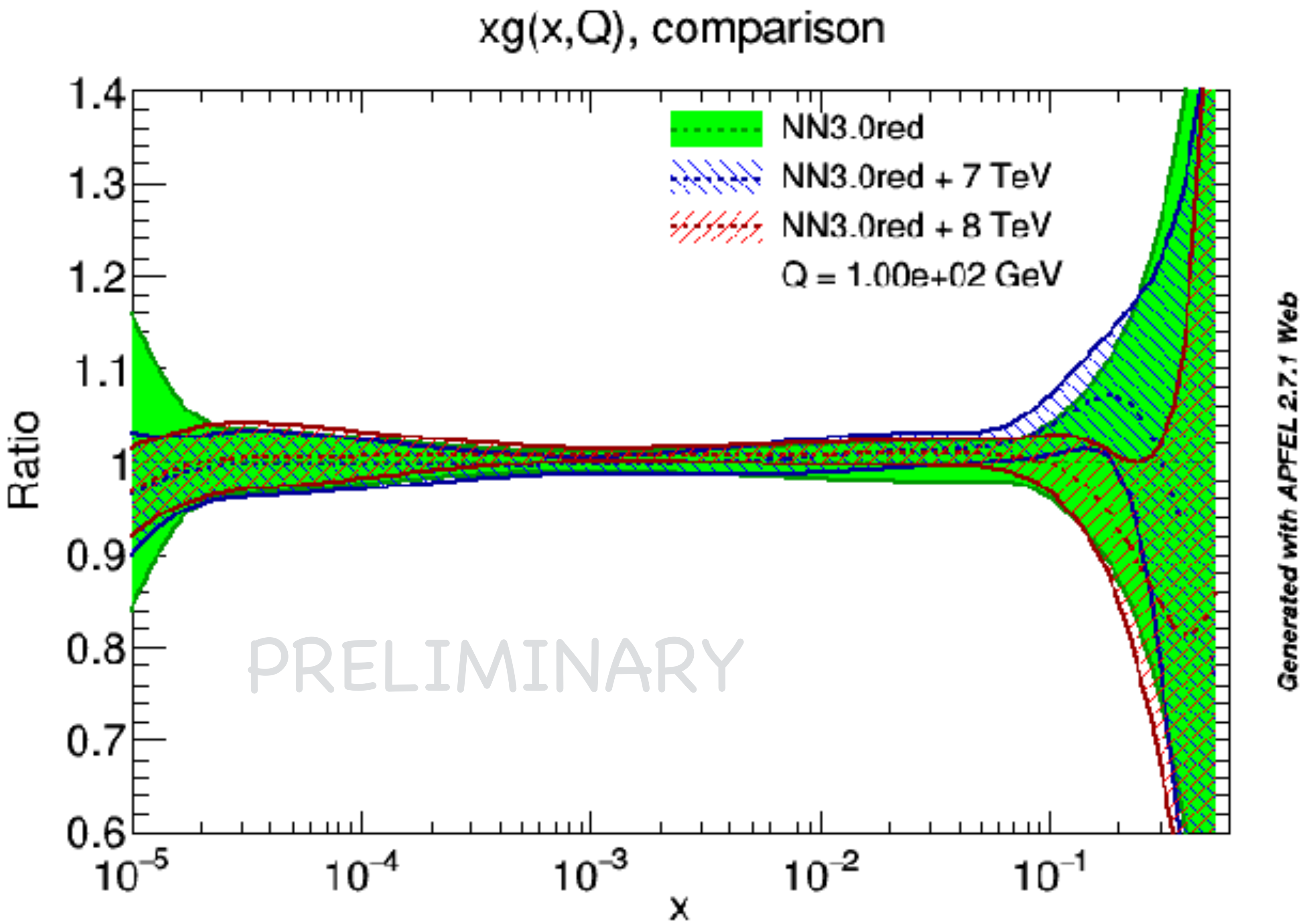
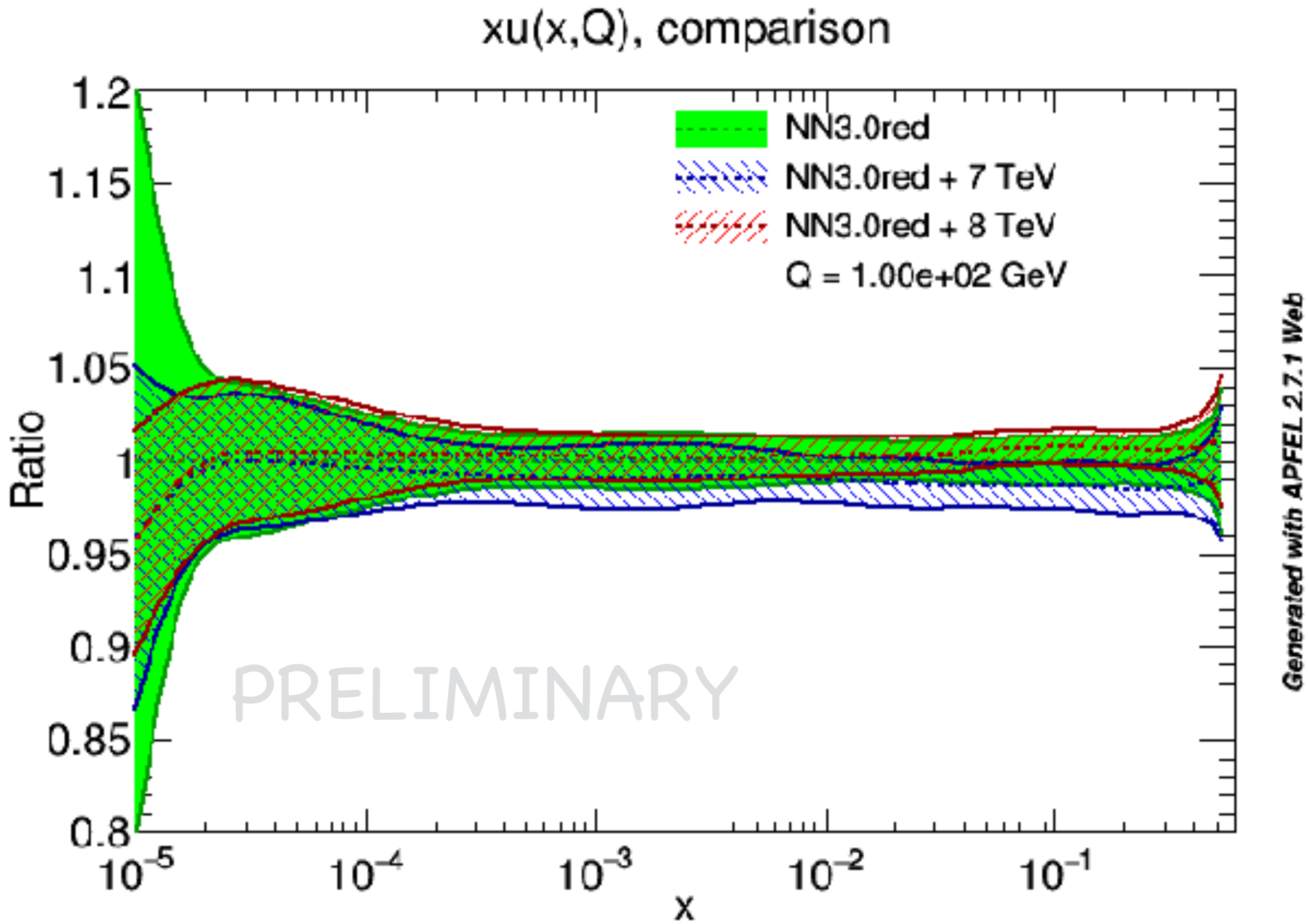
Impact of Z p_T distributions (global 3.0)



- Baseline: NNPDF3.0red with HERA I+II combined data (instead of separated sets) and without jets data
- Perturbative charm

fit id	extra Δ	$\chi^2_{\mathrm{ATLAS7tev}}$	$\chi^2_{\mathrm{ATLAS8tev,mdist}}$	$\chi^2_{\mathrm{ATLAS8tev,ydist}}$	$\chi^2_{\mathrm{CMS8tev}}$	χ^2_{tot}
(aa)	1%	(6.93)	(0.98)	(1.06)	(1.41)	1.17677
(bb)	1%	3.20	(1.03)	(1.40)	(1.47)	1.17641
(cc)	1%	(7.87)	0.96	0.88	1.32	1.17690
(dd)	1%	3.45	1.01	1.26	1.36	1.17969

Impact of Z p_T distributions (global 3.0)



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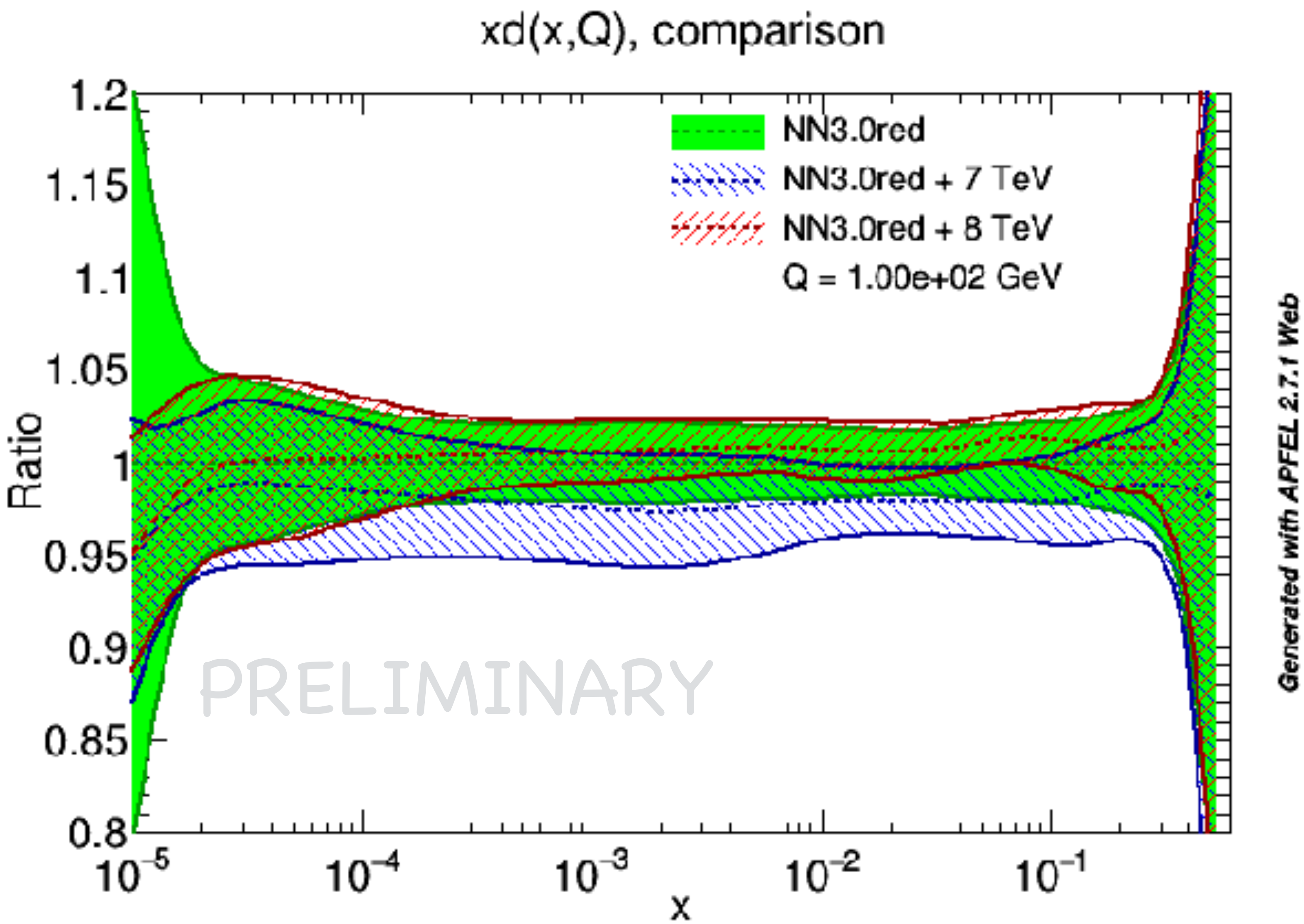

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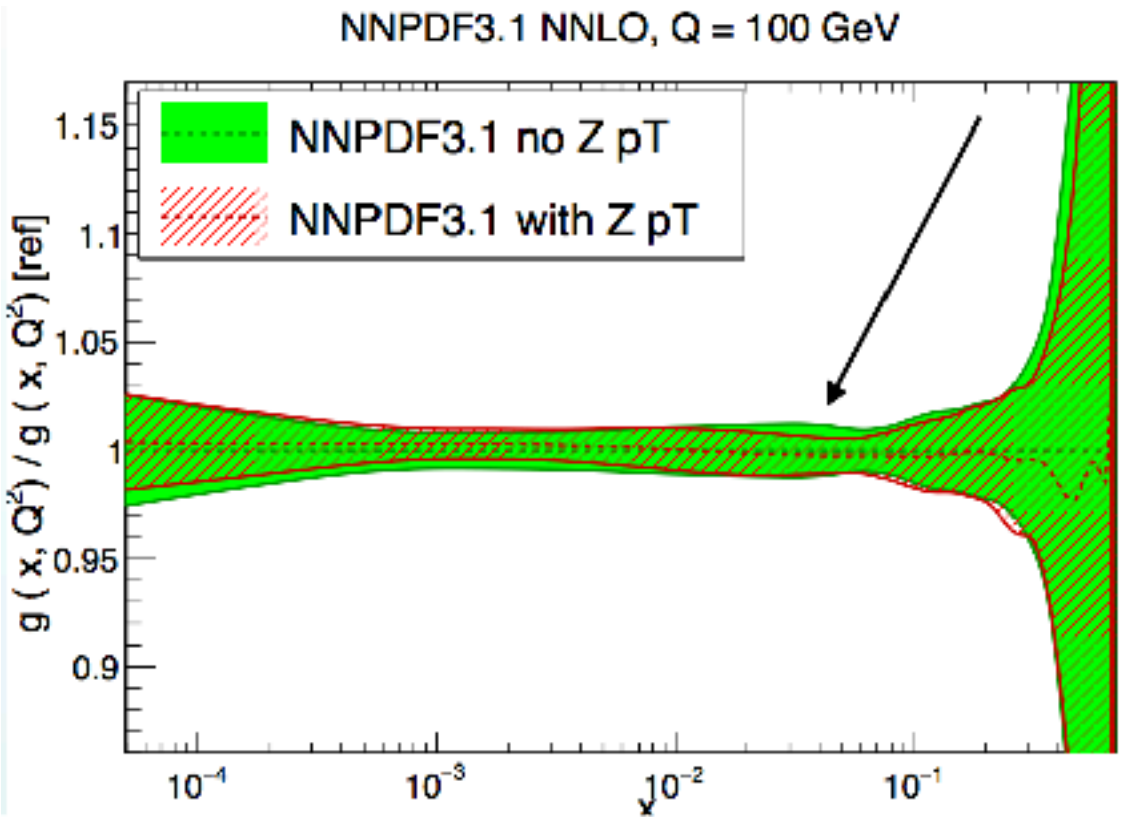
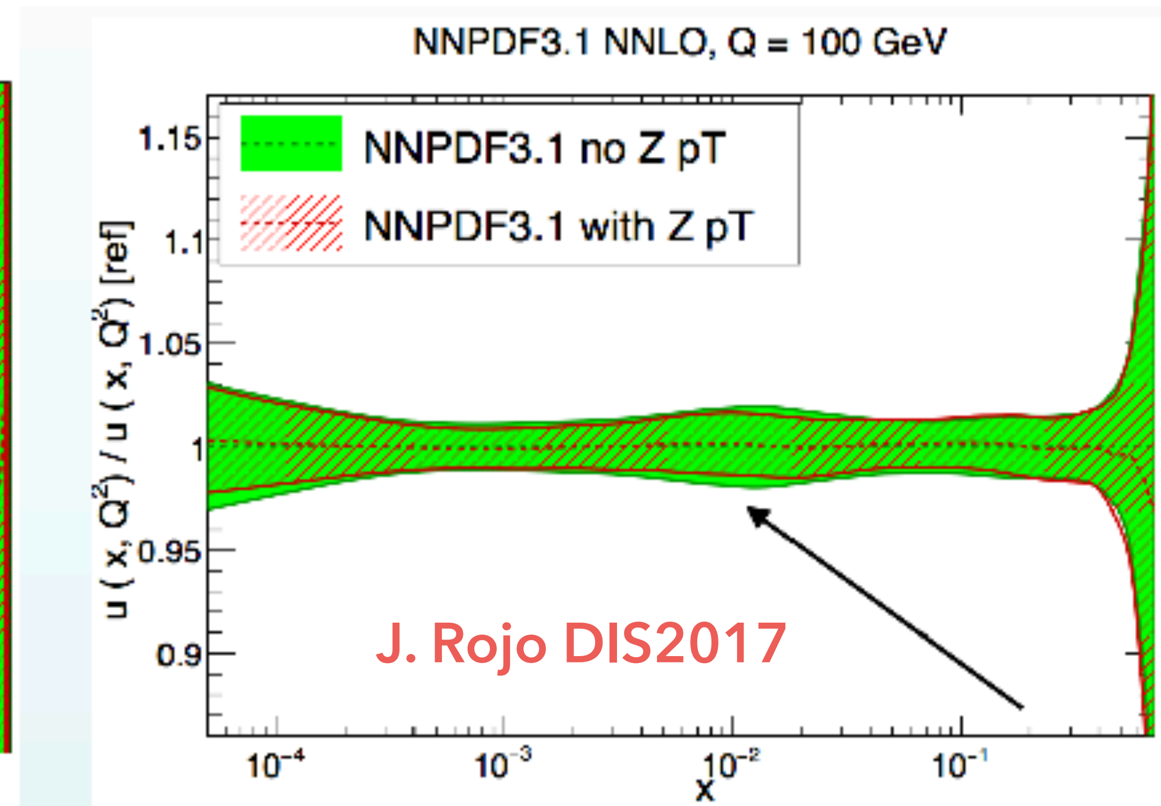
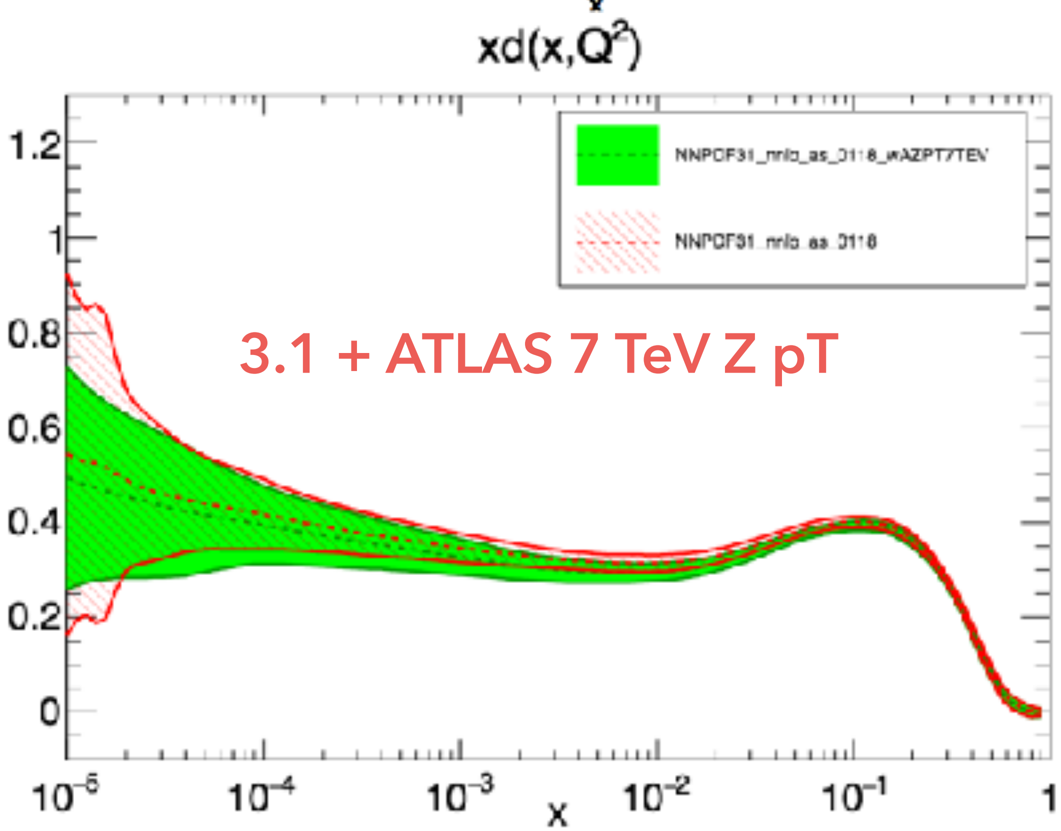
Impact of Z p_T distributions (NNPDF3.1)







- NNPDF3.1 analysis confirms our results
- 8 TeV data included reduce uncertainties without moving central value
- 7 TeV data would cause a downwards shift and no error reduction

Conclusions

- Z boson production & decay into leptons benchmark Standard Model (SM) process at LHC.
- Combination of precise experimental data and highly-developed theory allows this process to be used to determine PDFs
- 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 fitter in fixed-order fit and what is the pT range
- For first time need to include MC statistical uncertainty to get good chi2. PDFs stable under choice of MC statistical uncertainty (within reasonable range)
- CMS and ATLAS data at 8 TeV (unnormalised) are compatible and lead to significant reduction in PDF uncertainties
- ATLAS 7 TeV data (normalised) can be fitted individually but seems to point to a different minimum. Covariance matrix for normalised experiments built for the whole pT spectrum, pT cuts modify correlations between bins. Need pT resummation?
- In the future, lots of interesting physics studies: test inclusion of pT resummation, check impact of non-perturbative effects, look at ϕ^* distributions, impact on the determination of α_S

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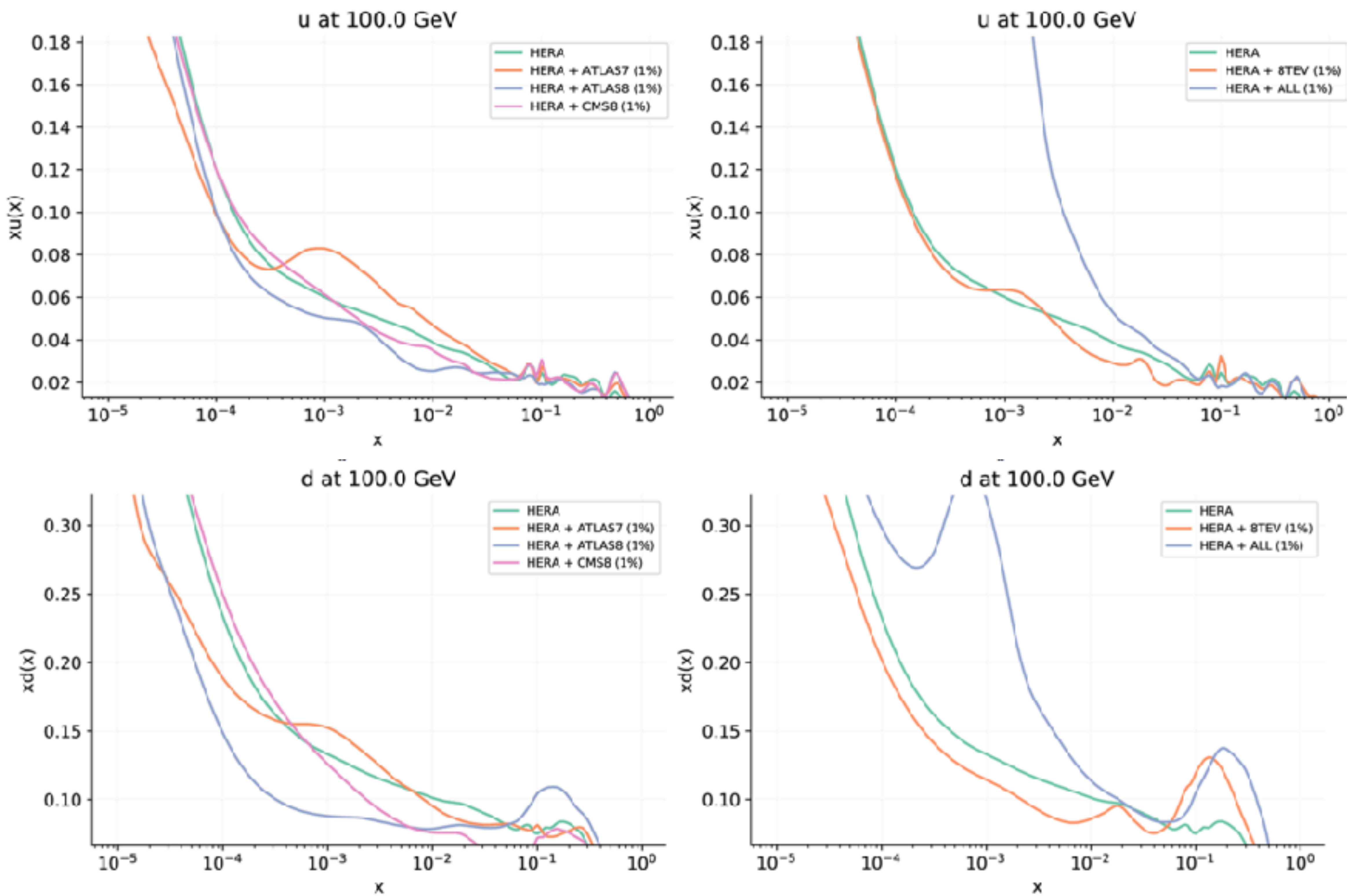
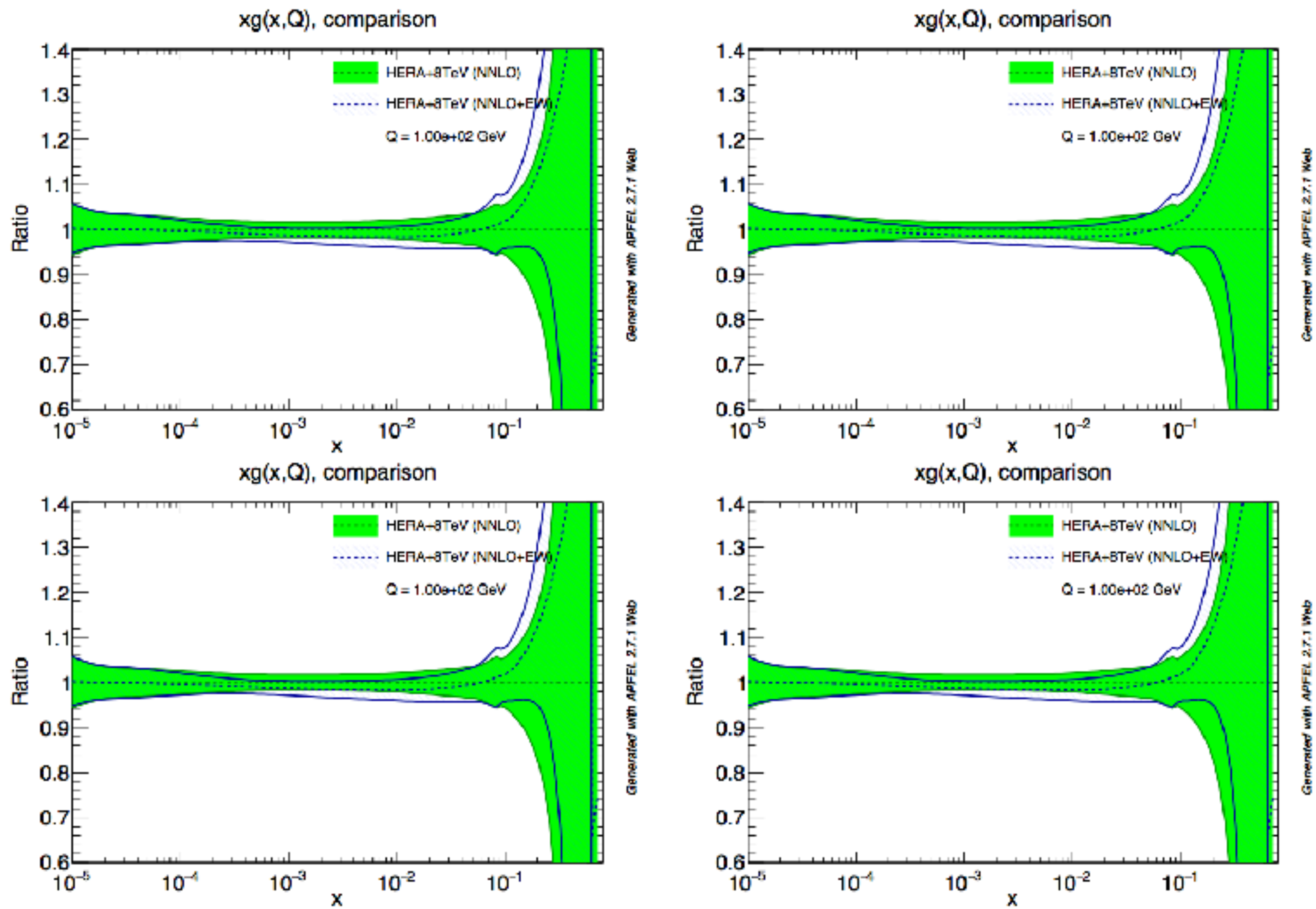
Thanks for your attention!!

Extra- material

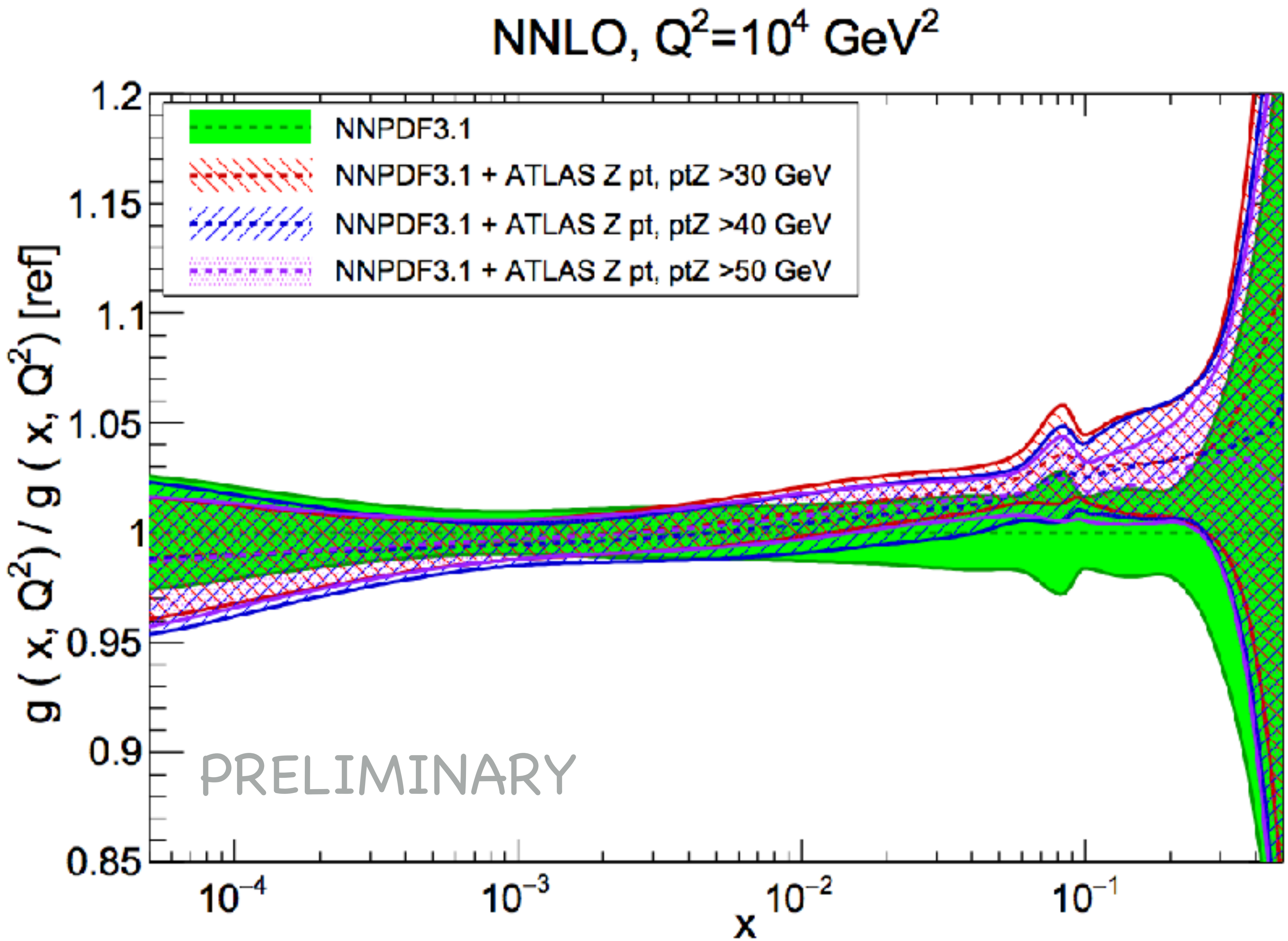
Error reduction



NNLO + EW fit

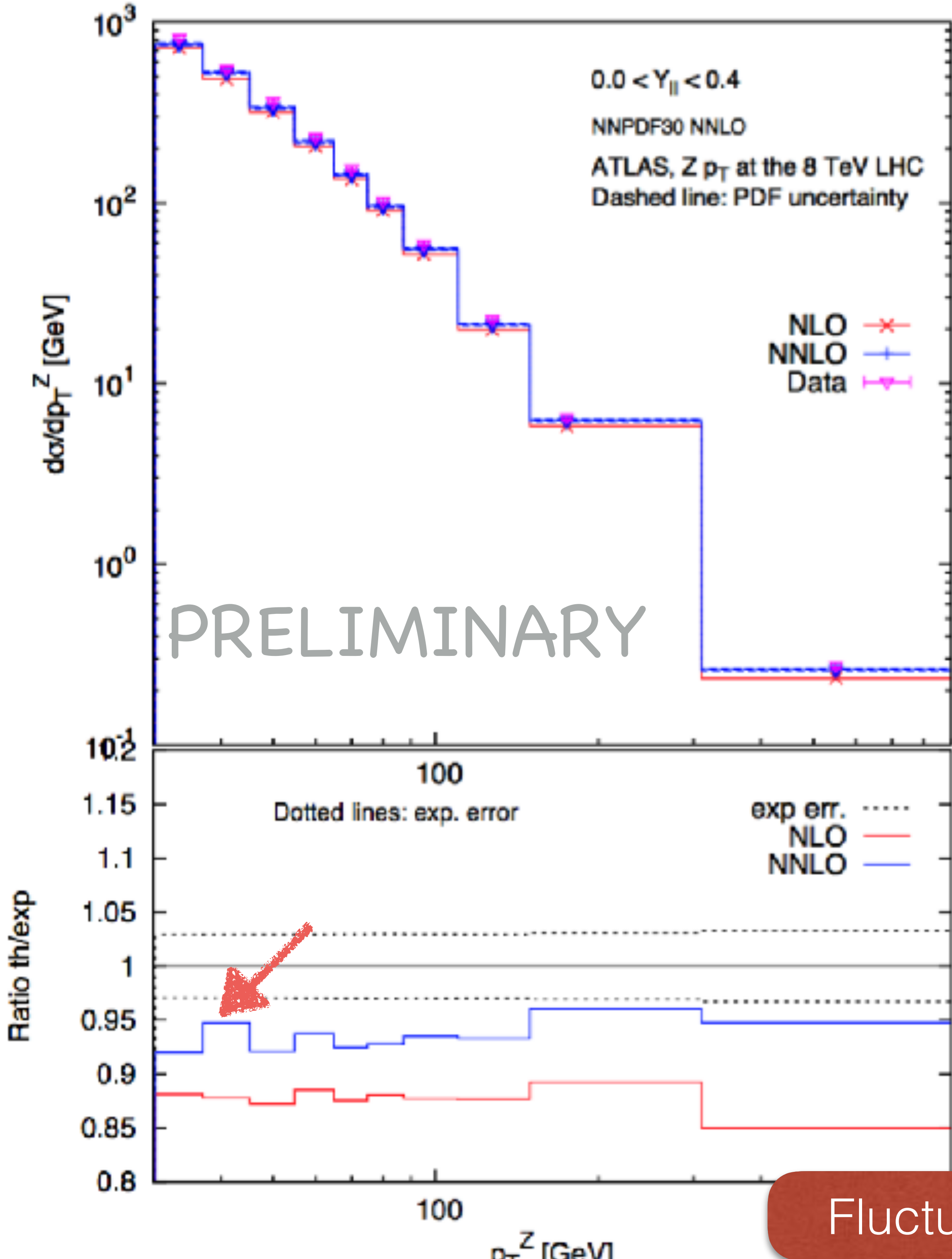

xg(x,Q), comparison
HERA+8TeV (NNLO)
HERA+8TeV (NNLO+EW)
Q = 1.00e+02 GeV
Ratio
x
Generated with APFEL 2.7.1 Web

Z pT data



NNLO, $Q^2=10^4$ GeV^2
NNPDF3.1
NNPDF3.1 + ATLAS Z pt, ptZ >30 GeV
NNPDF3.1 + ATLAS Z pt, ptZ >40 GeV
NNPDF3.1 + ATLAS Z pt, ptZ >50 GeV
g (x, Q^2) / g (x, Q^2) [ref]
x
PRELIMINARY

Z p_T distributions



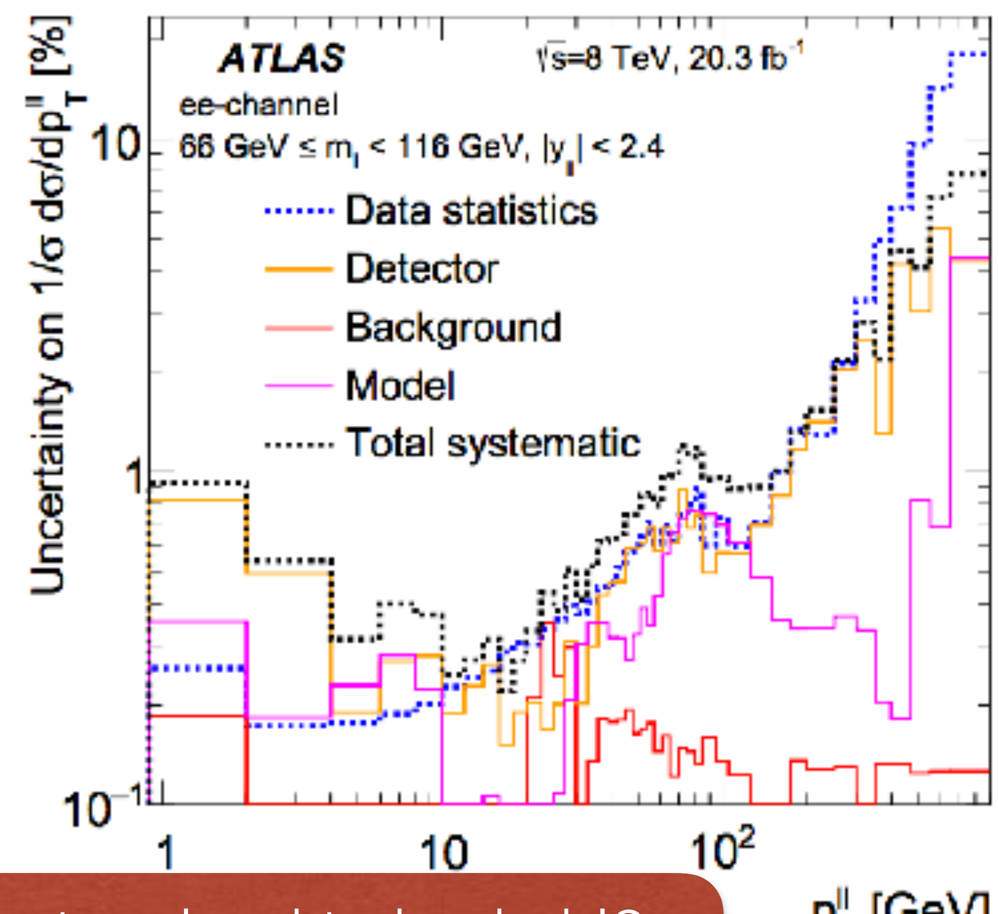
NLO

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

NNLO

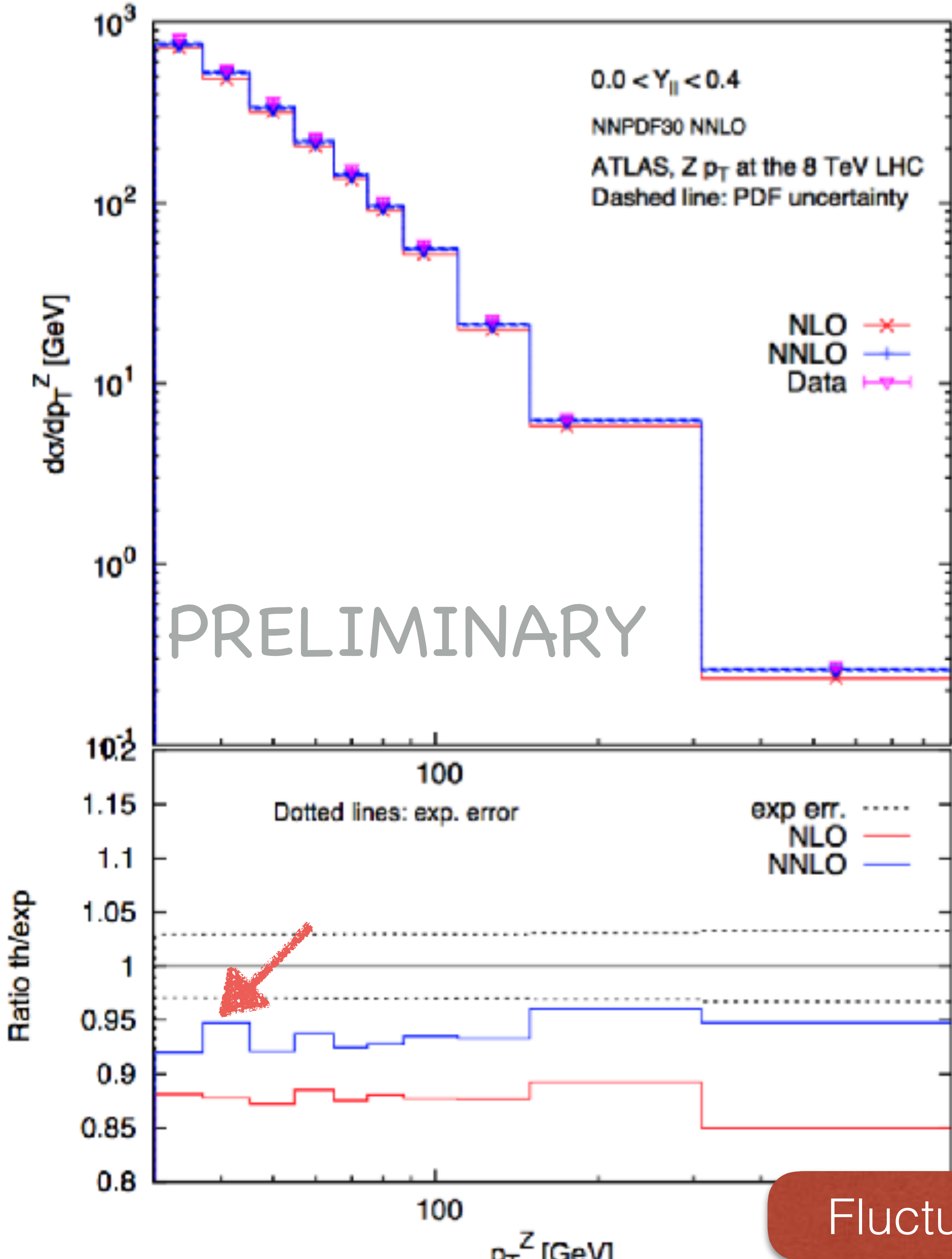
$$\chi^2_{\rm stat} = 51.$$
$$\chi^2_{\rm uncor} = 42.$$
$$\chi^2_{\rm diag} = 0.62$$
$$\chi^2_{\rm full} = \boxed{5.61}$$

/d.o.f.



Fluctuations in K-factors lead to bad chi2

Z p_T distributions



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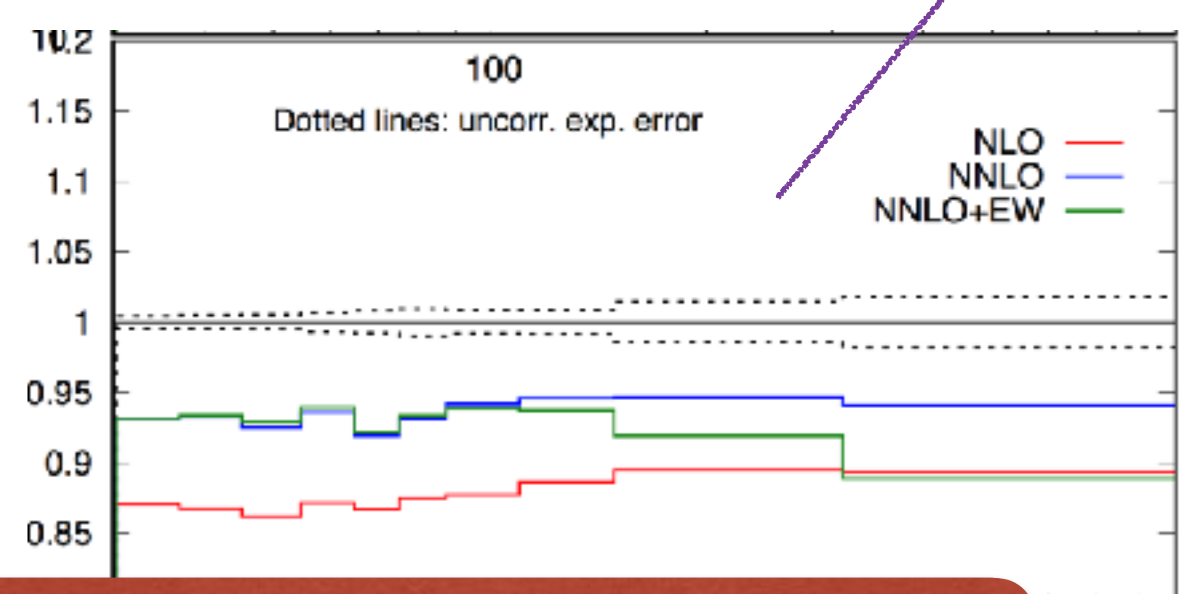
/d.o.f.

$\boxed{2.0}$

10x more statistics

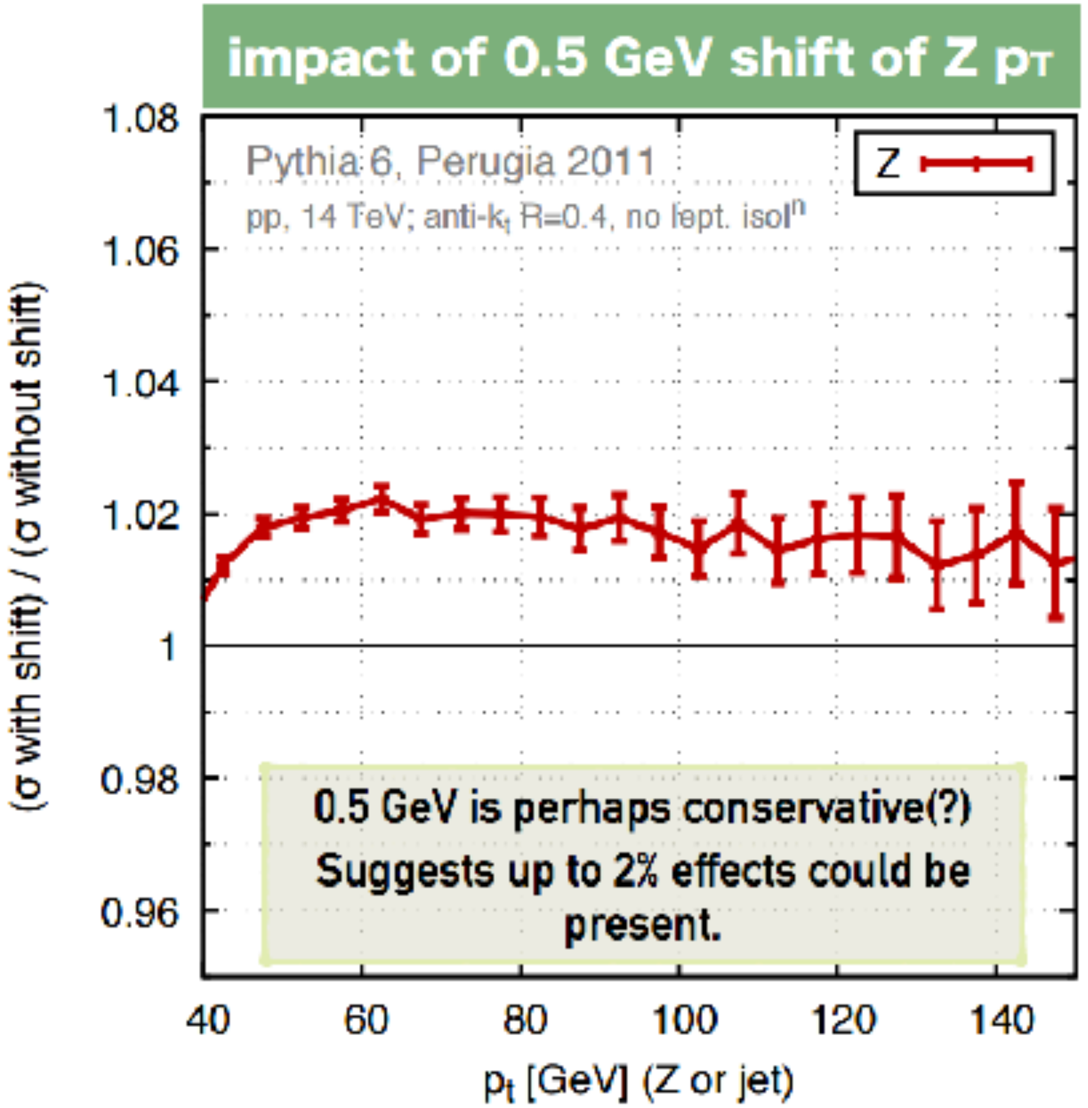


Fluctuations in K-factors lead to bad chi2

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



G. Salam, talk at KITP 2016