Impact of Z-boson transverse-momentum resummation on PDF determination

ATLAS SM PDF forum

[Based on arXiv:2607.19183 with Juan M. Cruz-Martinez, P. Torrielli, and L. Rottoli]

Emanuele R. Nocera

Università degli Studi di Torino and INFN, Torino

9 October 2026

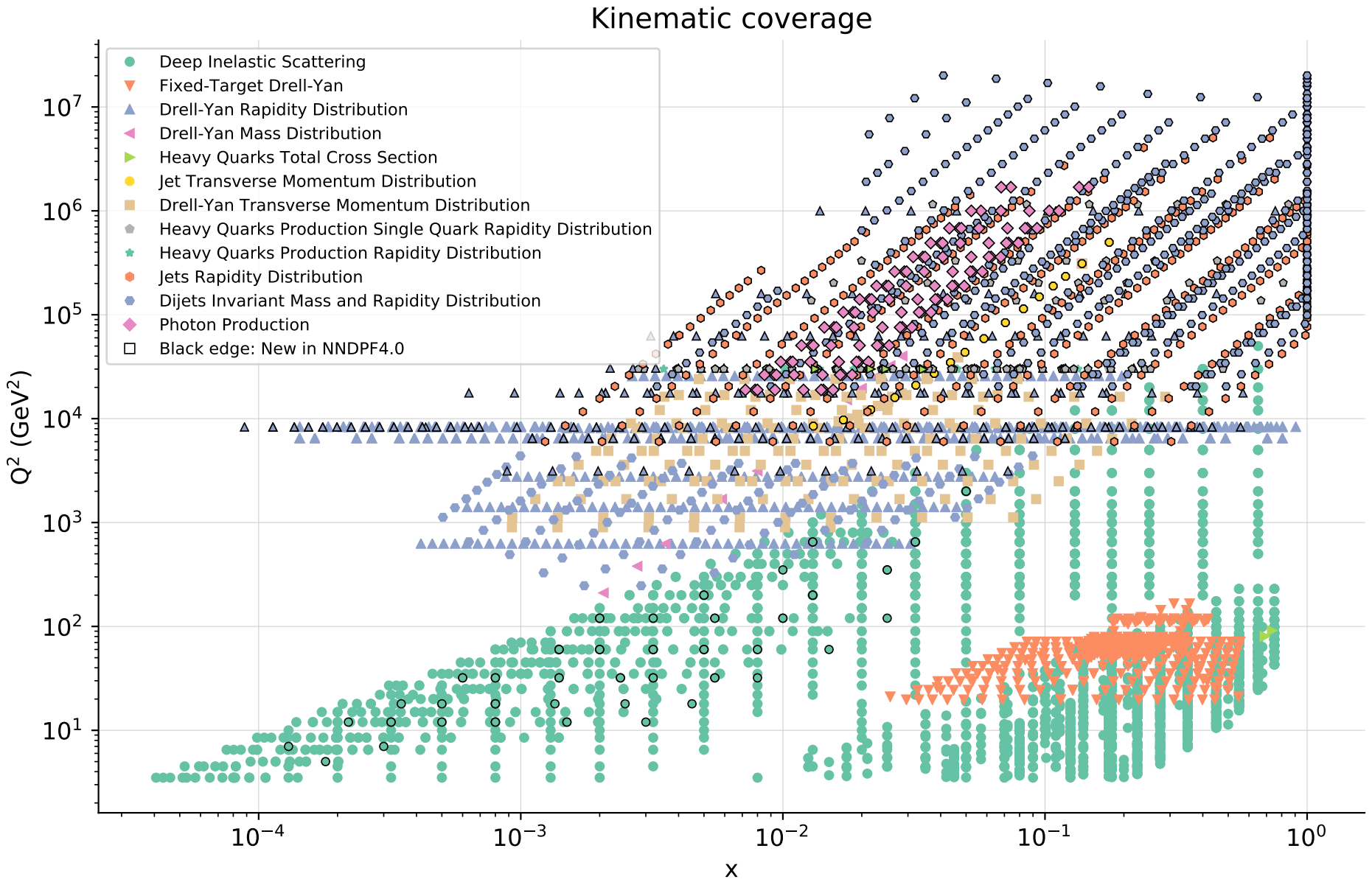






UNIVERSITÀ DI TORINO

Z-boson transverse-momentum measurements in NNPDF



$$N_{\rm dat}^{p_T^{\ell\ell}} = 120 \qquad N_{\rm dat}^{\rm tot} = 4618$$

Z-boson transverse-momentum measurements in NNPDF

Data sets first incorporated in NNPDF3.1 — unchanged in NNPDF4.0

Data set	$N_{\rm dat}$	Kinematics	NNLO K-factor
ATLAS 8 TeV $(p_T^{\ell\ell}, m_{\ell\ell})$ [EPJ C76 (2016) 291]	48	$12 \leq m_{\ell\ell} \leq 150$ GeV; $30 \leq p_T^{\ell\ell} \leq 150$ GeV	MCFM+N$_{\rm jetti}$
ATLAS 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$ [EPJ C76 (2016) 291]	44	$\lvert y_{\ell\ell}\rvert \leq 2.4$; $30 \leq p_T^{\ell\ell} \leq 150$ GeV	MCFM+N$_{\rm jetti}$
CMS 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$ [PLB 749 (2015) 187]	28	$\lvert y_{\ell\ell}\rvert \leq 1.6$; $30 \leq p_T^{\ell\ell} \leq 170$ GeV	MCFM+N$_{\rm jetti}$

Data set selection based on an earlier study in the context of NNPDF3.1 [JHEP 07 (2017) 130]

- NNLO K-factor numerically unstable: fluctuations larger than statistical uncertainties

$\rightarrow$ additional 1% theory uncertainty estimated from the variance of a fit to the K-factors

- alledged incompatibility of the highest rapidity bin of the CMS measurement

$\rightarrow$ additional cut to remove that bin

- No small-$p_T^{\ell\ell}$ resummation corrections included

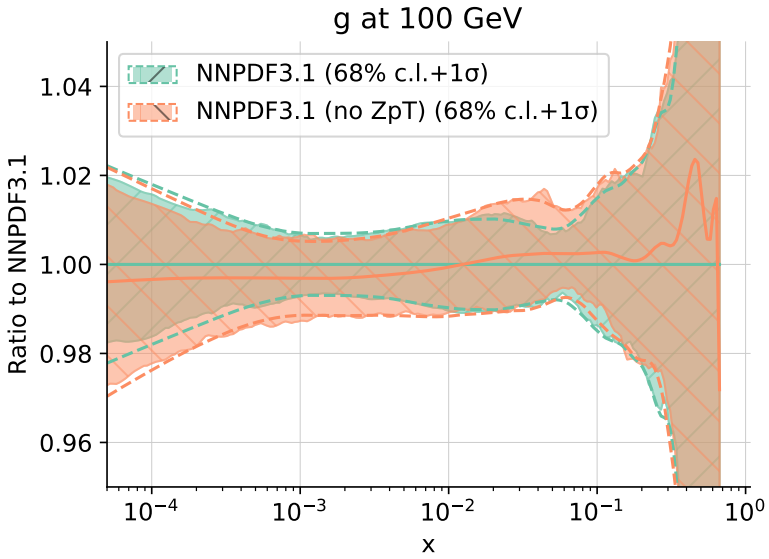
$\rightarrow$ retain only data points with $p_T^{\ell\ell} \geq 30$ GeV

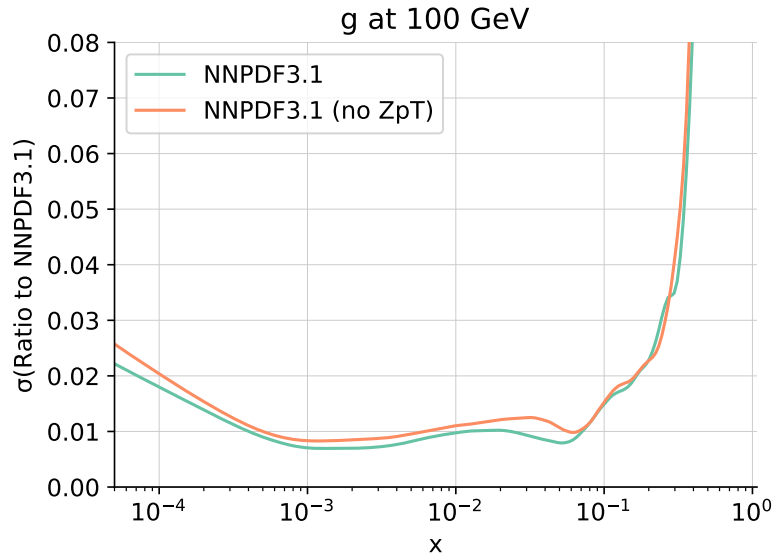
- No EW corrections included

$\rightarrow$ retain only data points with $p_T^{\ell\ell} \leq 150(170)$ GeV for ATLAS (CMS)

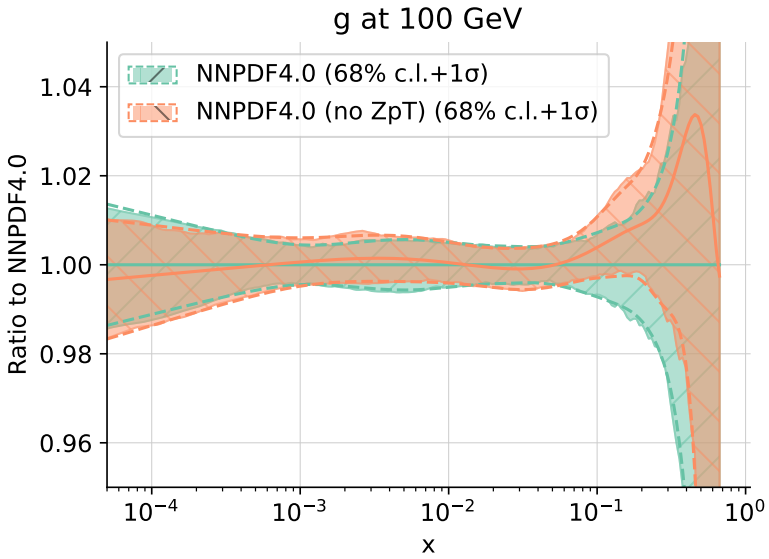
Z-boson transverse-momentum measurements in NNPDF

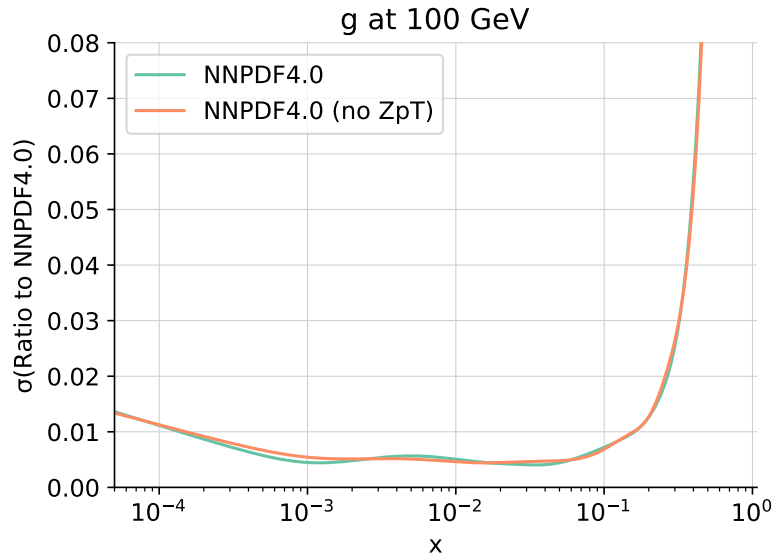
NNPDF3.1





NNPDF4.0





Updated treatment of experimental and theoretical input

Experimental input

Revision of the internal NNPDF data bookkeeping (all data included in NNPDF4.0)

$\rightarrow$ a few small bugs fixed, impact negligible [for details, see EPJ C84 540]

Theoretical input

New treatment of heavy-quark mass effects (only for subleading terms)
Use of the exact solution of the QCD renormalisation group equation

$\rightarrow$ impact negligible [for details, see EPJ C84 540]

Drop K-factors in favour of exact computations to include NNLO QCD corrections

$\rightarrow$ impact very small [see EPJ C85 (2025) 459; PoS DIS2024 (2025) 043]

Update the values of the physical parameters to the latest PDG values
Standardise renormalisation and factorisation scale choices in DY data (transverse mass)
Use the full-colour computation for dijet measurements

$\rightarrow$ impact moderate [will be documented in NNPDF4.1]

Inclusion of missing higher order uncertainties (MHOUs) via covariance matrix

$\rightarrow$ impact moderate [see EPJ C84 (2024) 517]

Move from MCFM (Njettines) to NNLOjet (antenna subtraction) for $p_T^{\ell\ell}$ data
Drop the 1% numerical uncertainty

$\rightarrow$ impact limited [see this talk]

Questions

Can we revisit the implementation of the 8 TeV data sets?

Can the numerical precision of the theoretical computation be improved?

Are the 1% numerical uncertainty and the cut of the CMS bin still justified?

Can we include the new 13 TeV $p_T^{\ell\ell}$ measurements?

Are the new measurements consistent with the NNPDF4.0 data set?

What is the impact on PDFs?

Can we consider the inclusion of small-$p_T^{\ell\ell}$ resummation?

What is the effect of resummation? Can we relax the $p_T^{\ell\ell}$ cut?

What is the interplay between resummation and MHOUs across regions of $p_T^{\ell\ell}$?

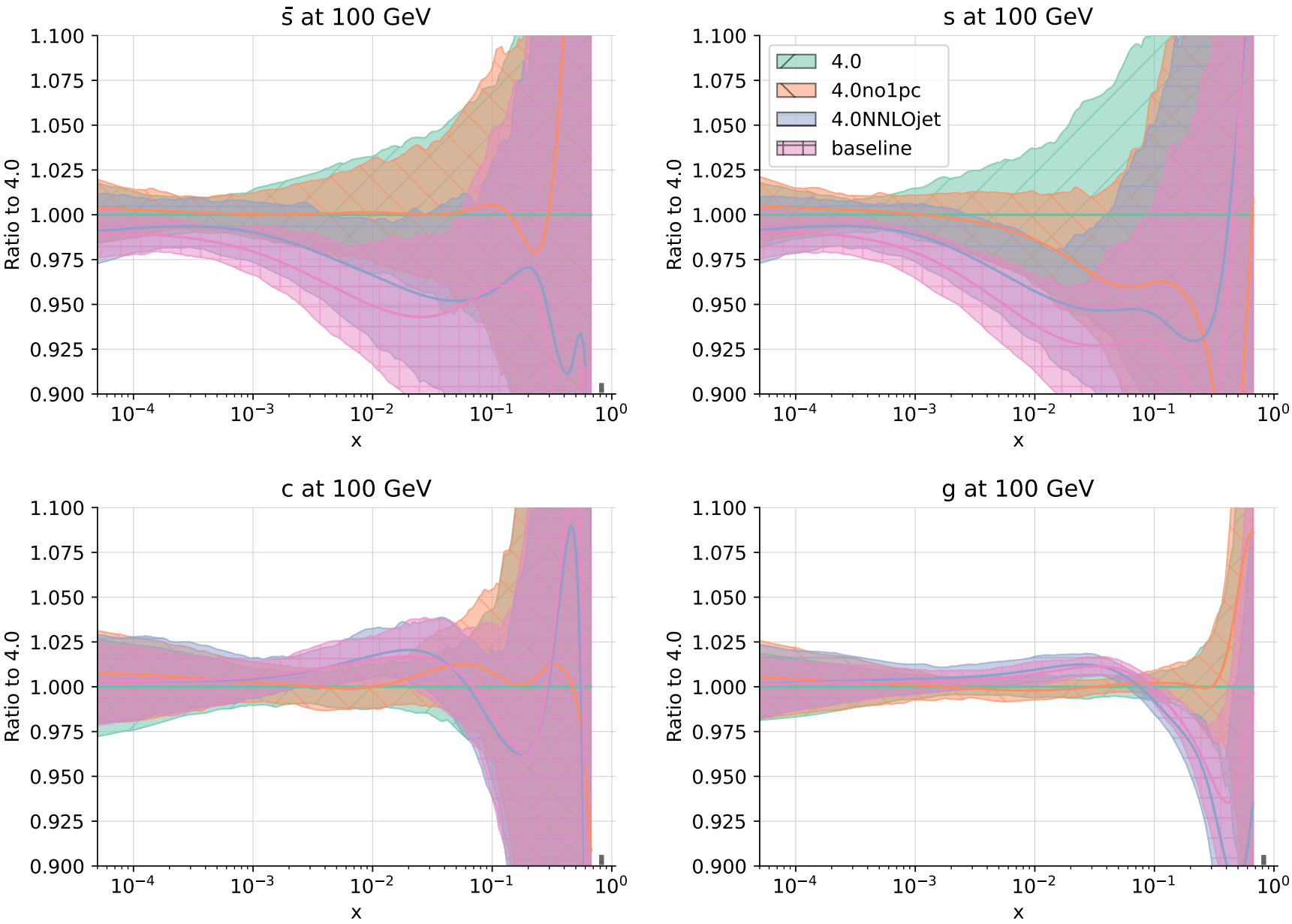
1. Can we revisit the implementation of the 8 TeV data sets?

Fits

Fit name	Fit description
4.0	same as NNPDF4.0 MHOUs, as published
4.0no1pc	same as 4.0 w/o the 1% uncertainty on the $p_T^{\ell\ell}$ data
4.0NNLOjet	same as 4.0 except for
	K-factors dismissed in favour of exact NNLO QCD corrections
	highest rapidity bin of the CMS $p_T^{\ell\ell}$ 8 TeV data set reinstated
	transverse mass for DY central scale
	full-colour computations for dijet measurements
	$p_T^{\ell\ell}$ predictions with NNLOjet
baseline	same as 4.0NNLOjet w/o the 1% uncertainty on the $p_T^{\ell\ell}$ data

Data set	$N_{\rm dat}$	4.0	4.0no1pc	4.0NNLOjet	baseline
DIS NC	2100	1.19	1.19	1.19	1.19
DIS CC	989	0.89	0.90	0.89	0.89
DY NC	671	1.15	1.35	1.05	1.23
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	44	0.92	1.06	1.08	1.24
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, m_{\ell\ell})$	48	0.69	1.97	0.65	1.97
CMS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	28	1.42	3.63	0.87	1.79
DY CC	157	1.34	1.36	1.06	1.07
top-quark pair	64	1.54	1.36	1.00	1.00
single-inclusive jets	356	0.90	0.92	0.98	0.97
dijets	144	1.65	1.65	1.54	1.52
photon	53	0.67	0.66	0.84	0.82
single top-quark	17	0.38	0.38	0.17	0.17
Total	4551	1.12	1.16	1.10	1.12

Parton distributions



2. Can we include the new 13 TeV $p_T^{\ell\ell}$ measurements?

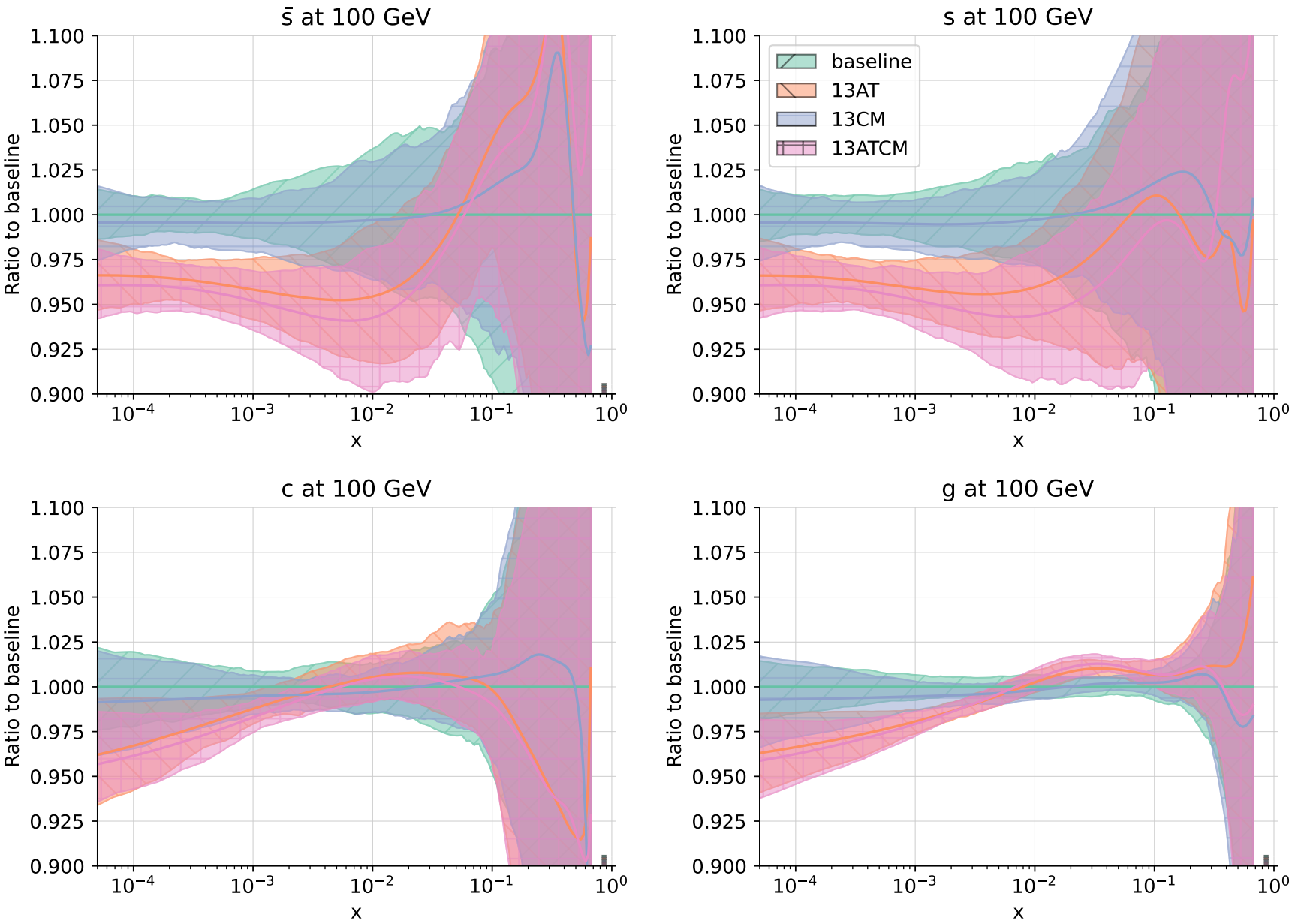
Fits

Data set	$N_{\rm dat}$	$\mathcal{L}$ [fb^{-1}]	Kinematics
ATLAS 13 TeV ($p_T^{\ell\ell}$) [EPJ C80 (2020) 616]	19	36.1	$30 \le p_T^{\ell\ell} \le 150$ GeV
CMS 13 TeV ($p_T^{\ell\ell}, m_{\ell\ell}$) [EPJ C83 (2023) 628]	16	36.3	$50 \le m_{\ell\ell} \le 1000$ GeV; $30 \le p_T^{\ell\ell} \le 150$ GeV

Fit name	Fit description
13AT	same as baseline + ATLAS 13 TeV $p_T^{\ell\ell}$ data
13CM	same as baseline + CMS 13 TeV $p_T^{\ell\ell}$ data
13ATCM	same as baseline + ATLAS and CMS 13 TeV $p_T^{\ell\ell}$ data

Data set	$N_{\rm dat}$	baseline	13AT	13CM	13ATCM
DIS NC	2100	1.19	1.21	1.20	1.20
DIS CC	989	0.89	0.89	0.89	0.89
DY NC	671	1.23	1.49	1.23	1.44
ATLAS $p_T^{\ell\ell}$ 8 TeV ($p_T^{\ell\ell}, y_{\ell\ell}$)	44	1.24	1.17	1.22	1.17
ATLAS $p_T^{\ell\ell}$ 8 TeV ($p_T^{\ell\ell}, m_{\ell\ell}$)	48	1.97	1.86	1.92	1.87
CMS $p_T^{\ell\ell}$ 8 TeV ($p_T^{\ell\ell}, y_{\ell\ell}$)	28	1.79	1.84	1.81	1.85
ATLAS $p_T^{\ell\ell}$ 13 TeV	19	—	8.22	—	7.83
CMS $p_T^{\ell\ell}$ 13 TeV	16	—	—	1.15	0.89
DY CC	157	1.07	1.06	1.07	1.05
top-quark pair	64	1.00	0.94	0.98	0.91
single-inclusive jets	356	0.97	0.99	0.98	0.99
dijets	144	1.52	1.50	1.49	1.51
photon	53	0.82	0.76	0.81	0.76
single top-quark	17	0.17	0.15	0.17	0.15
Total	4551	1.12	1.17	1.12	1.16

Parton distributions



3. Can we consider the inclusion of small-$p_T^{\ell\ell}$ resummation?

Small-$p_T^{\ell\ell}$ resummation

Resummation implemented through Radish [JHEP 07 (2024) 193]

$$\frac{\mathrm{d}\Sigma(v)}{\mathrm{d}\Phi_B} = \int \frac{\mathrm{d}k_{t1}}{k_{t1}} \mathcal{L}(k_{t1})\, \mathrm{e}^{-R(k_{t1})}\, \mathcal{F}(v, \Phi_B, k_{t1})$$

hardest radiation momentum	k_{t1}
Sudakov radiator	$R(k_{t1}) = -Lg_1(\lambda) - \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n g_{n+2}(\lambda)$
	$L = \ln(Q/k_{t1})$, $\lambda = \alpha_s\, \beta_0\, L$, $Q = m_{\ell\ell}/2$
	functions $g_{k+1}(\lambda)$ known up to $k = 3$ (N^{3}LL)
luminosity factor	$\mathcal{L}(k_{t1}) = \sum_{ijcd} \lvert\mathcal{M}_B\rvert^2_{cd} C_{ci} \otimes f_i(k_{t1}) C_{dj} \otimes f_j(k_{t1}) H$
	H is the hard virtual function at $\mathcal{O}(\alpha_s^k)$ (N^{k+1}LL effect)
number of resolved emissions	$\mathcal{F}(v, \Phi_B, k_{t1})$ known up to N^{3}LL$'$

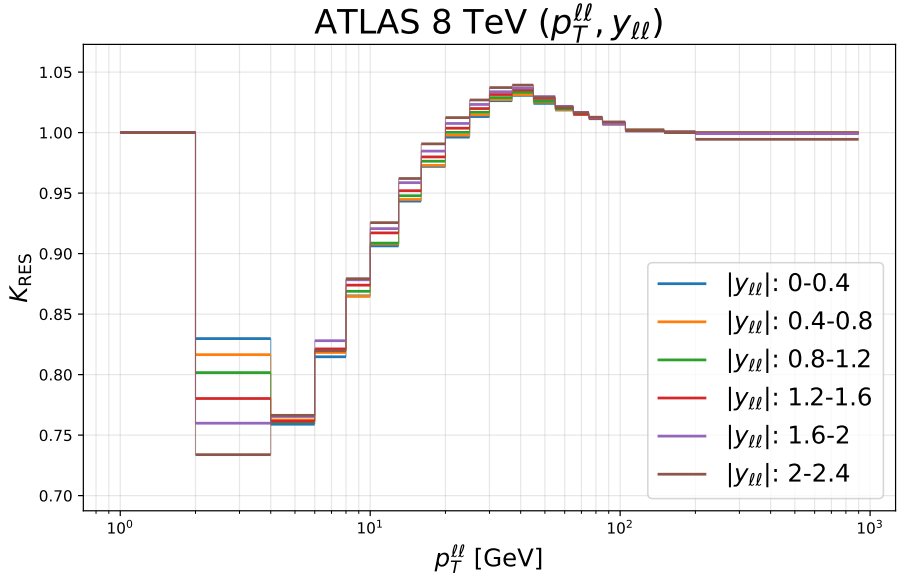
Additive matching to fixed order

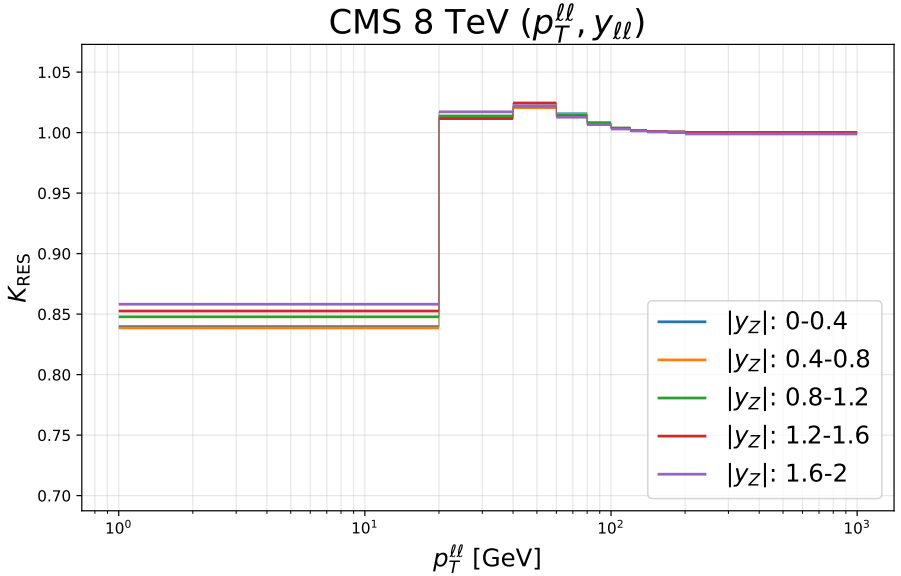
$$\frac{\mathrm{d}\sigma_{\mathrm{RES+FO}}}{\mathrm{d}p_T^{\ell\ell}} = \frac{\mathrm{d}\sigma_{\mathrm{FO}}}{\mathrm{d}p_T^{\ell\ell}} + \frac{\mathrm{d}\sigma_{\mathrm{RES}}}{\mathrm{d}p_T^{\ell\ell}} - \left[\frac{\mathrm{d}\sigma_{\mathrm{RES}}}{\mathrm{d}p_T^{\ell\ell}}\right]_{\mathrm{FO}}$$

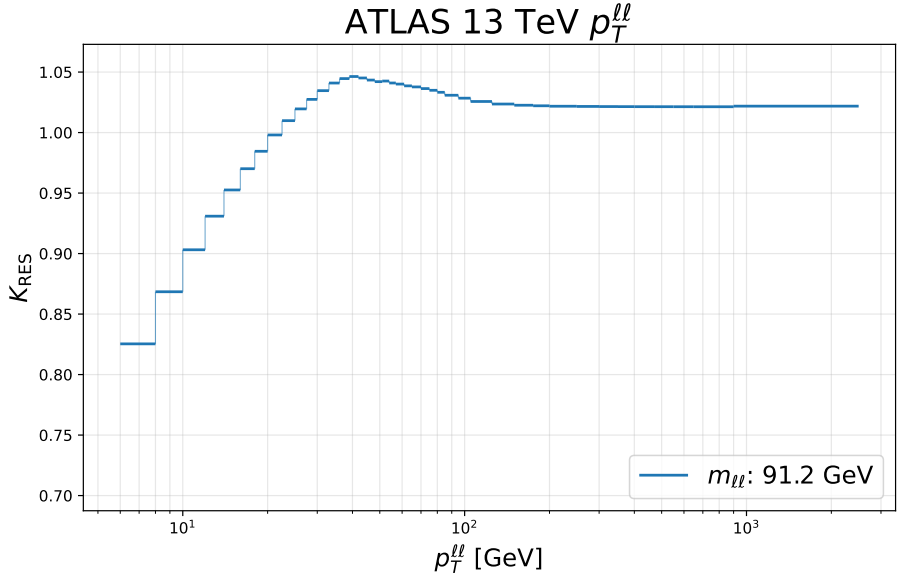
K-factors matched to fixed-order for each variation of μ_R and μ_F

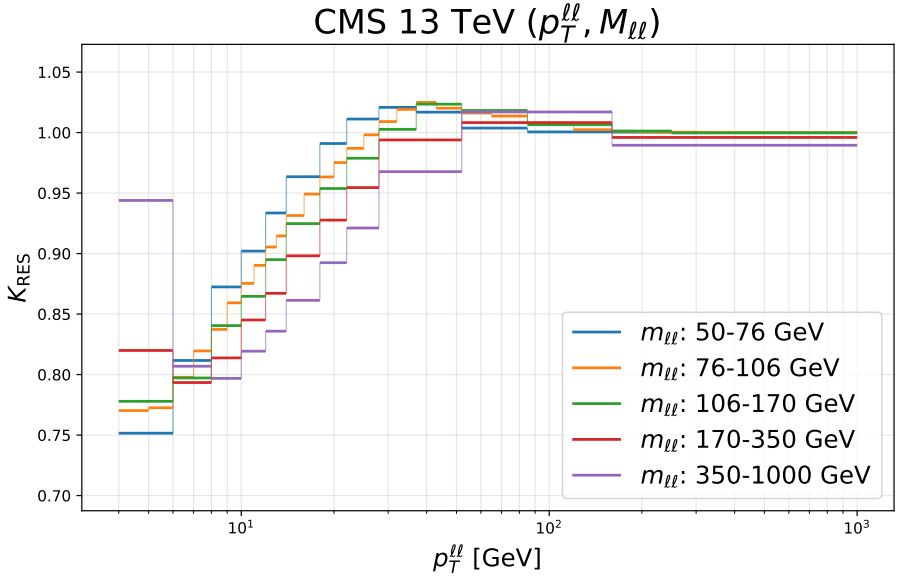
$$K_{\mathrm{RES}} = \frac{d\sigma_{\mathrm{RES+FO}}/dp_T^{\ell\ell}}{d\sigma_{\mathrm{FO}}/dp_T^{\ell\ell}}$$

Small-$p_T^{\ell\ell}$ resummation K-factors









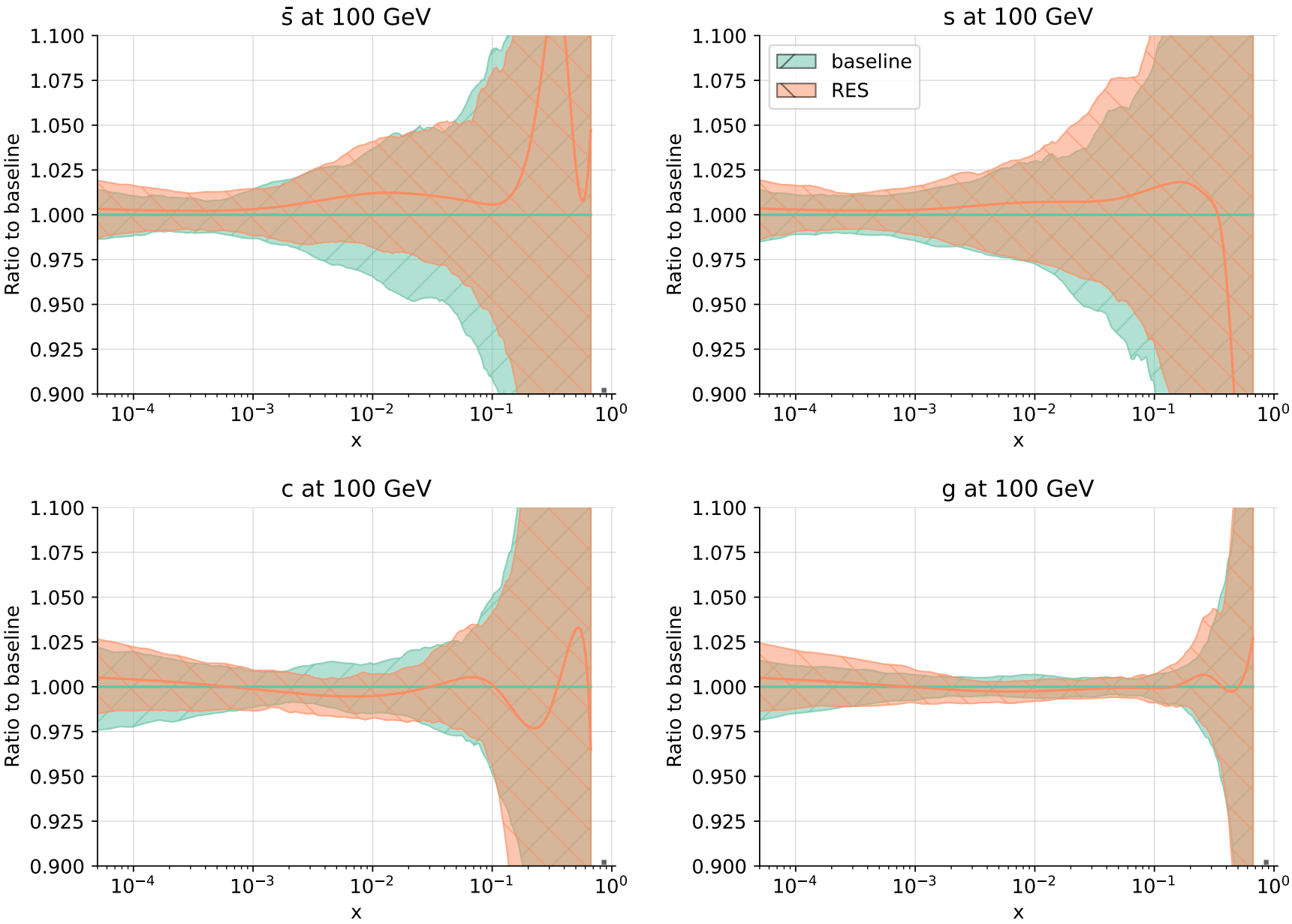
Fits

Fit name	Fit description
RES	same as baseline + resummation K-factors (only 8 TeV $p_T^{\ell\ell}$ data)
13RES	same as 13ATCM + resummation K-factors (8 and 13 TeV $p_T^{\ell\ell}$ data)
13RESAT	same as 13AT + resummation K-factors (8 TeV and ATLAS 13 TeV $p_T^{\ell\ell}$ data)
13RESCM	same as 13CM + resummation K-factors (8 TeV and CMS 13 TeV $p_T^{\ell\ell}$ data)

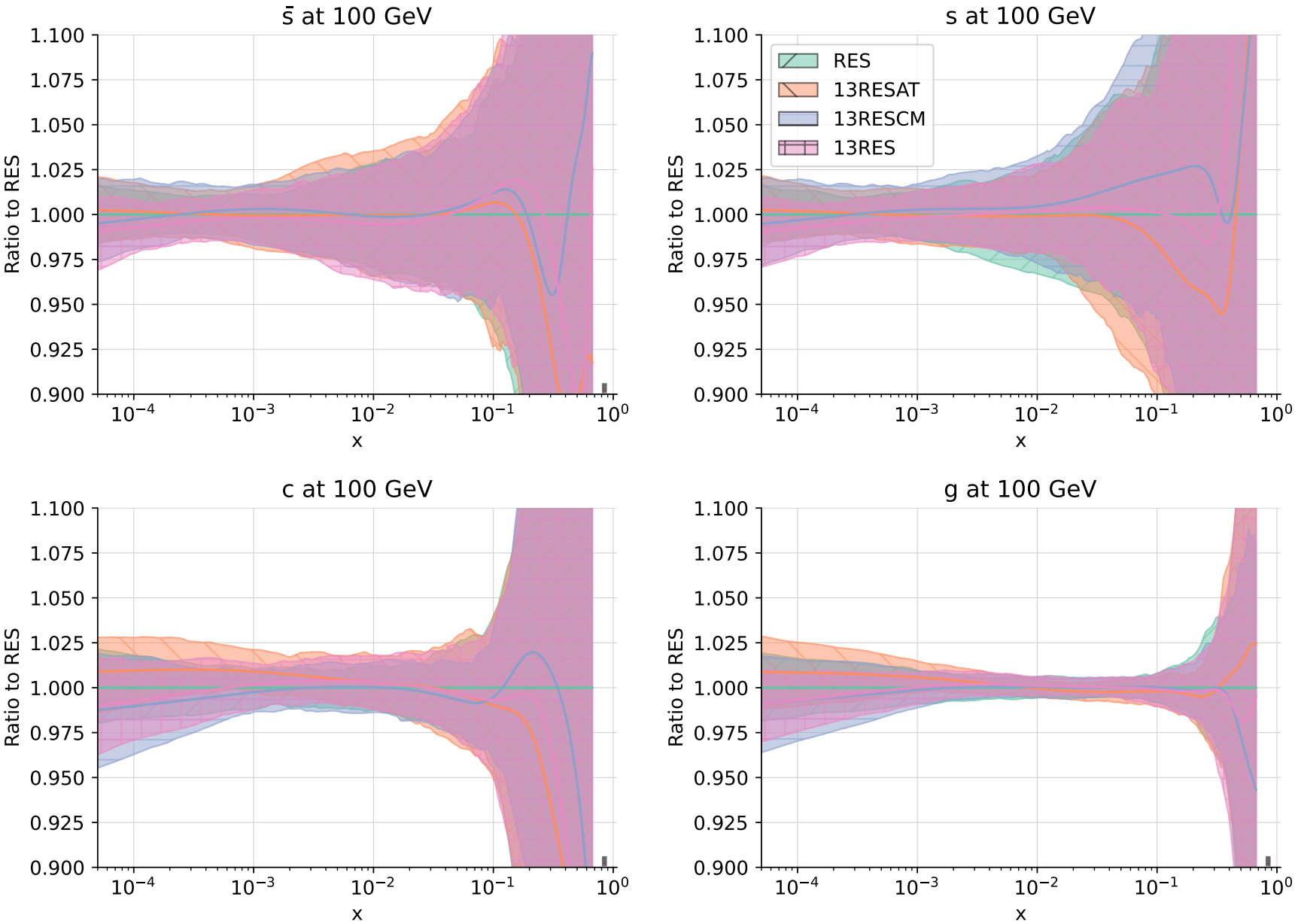
All fits have the same $p_T^{\ell\ell} \geq 30$ GeV cut

Data set	$N_{\rm dat}$	baseline	RES	13ATCM	13RES	13RESAT	13RESCM
DIS NC	2100	1.19	1.20	1.20	1.20	1.20	1.20
DIS CC	989	0.89	0.89	0.89	0.89	0.89	0.89
DY NC	671	1.23	1.19	1.44	1.25	1.28	1.17
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	44	1.24	1.23	1.17	1.21	1.24	1.22
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, m_{\ell\ell})$	48	1.97	1.62	1.87	1.62	1.64	1.63
CMS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	28	1.79	1.69	1.85	1.69	1.69	1.70
ATLAS $p_T^{\ell\ell}$ 13 TeV	19	—	—	7.83	3.94	3.94	—
CMS $p_T^{\ell\ell}$ 13 TeV	16	—	—	0.89	0.74	—	0.75
DY CC	157	1.07	1.06	1.05	1.06	1.04	1.08
top-quark pair	64	1.00	1.03	0.91	1.02	1.04	1.01
single-inclusive jets	356	0.97	0.98	0.99	0.99	0.99	0.97
dijets	144	1.52	1.50	1.51	1.51	1.51	1.50
photon	53	0.82	0.82	0.76	0.81	0.82	0.82
single top-quark	17	0.17	0.17	0.15	0.17	0.17	0.17
Total	4551	1.12	1.12	1.16	1.13	1.14	1.12

Parton distributions: 8 TeV



Parton distributions: 13 TeV

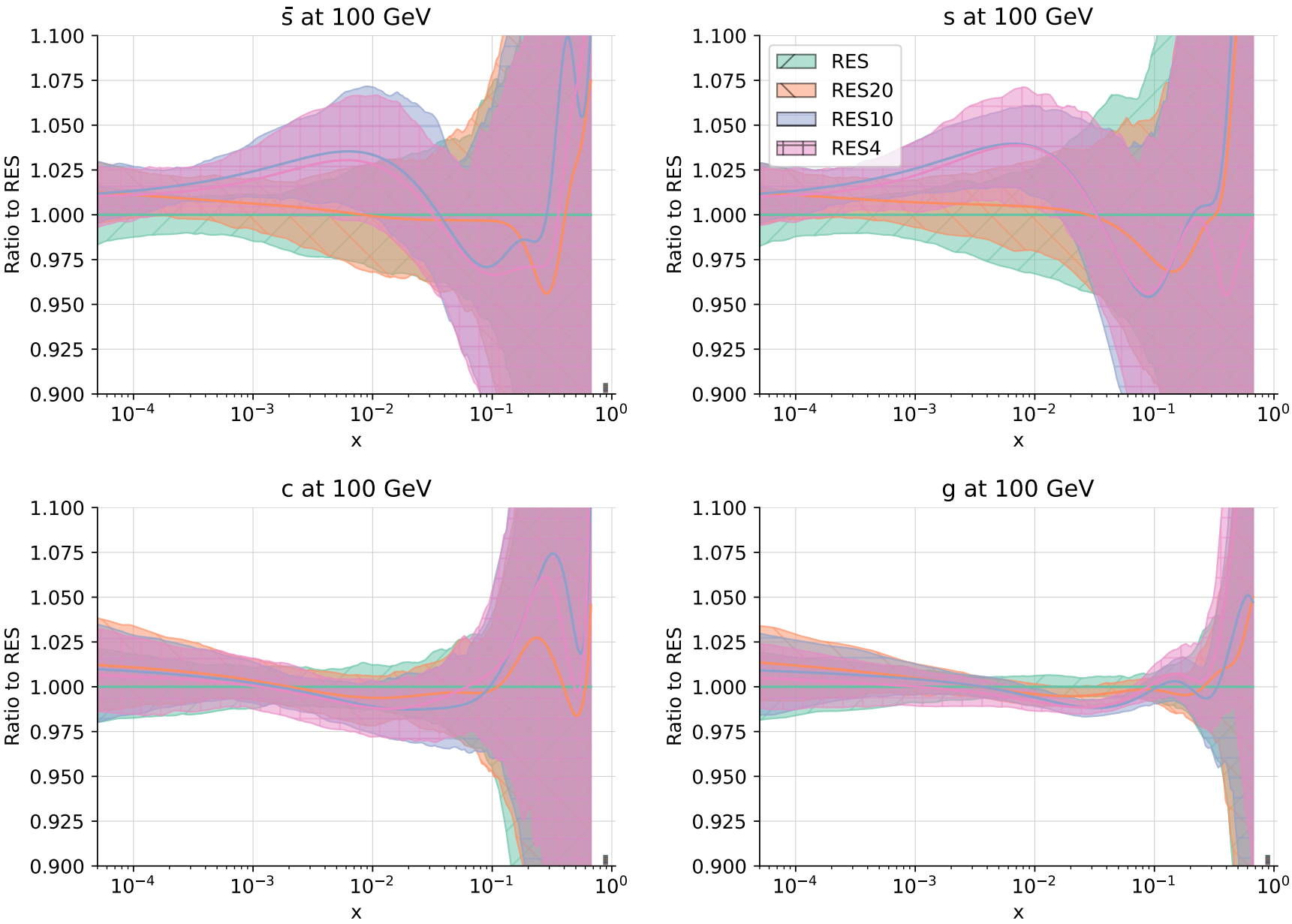


What happens if the $p_T^{\ell\ell}$ cut is lowered?

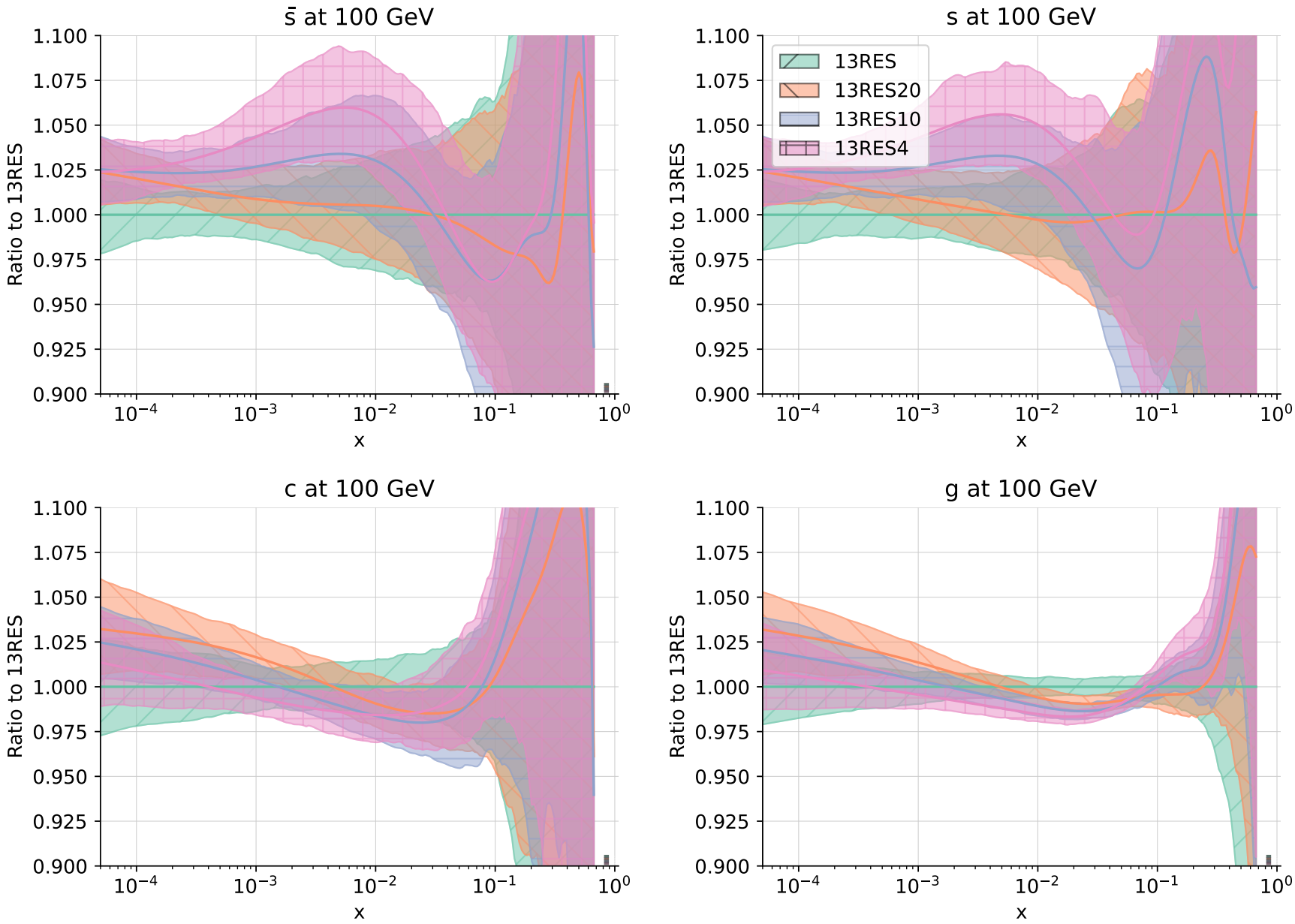
Fit name	Fit description
RES20, RES10, RES4	same as RES, with decreasing $p_T^{\ell\ell}$ cuts: $p_T^{\ell\ell} \geq 20, 10, 4$ GeV (only 8 TeV $p_T^{\ell\ell}$ data)
13RES20, 13RES10, 13RES4	same as 13RES, with decreasing $p_T^{\ell\ell}$ cuts: $p_T^{\ell\ell} \geq 20, 10, 4$ GeV (8 and 13 TeV $p_T^{\ell\ell}$ data)

Data set	$N_{\rm dat}$	RES	RES20	RES10	RES4	13RES	13RES20	13RES10	13RES4
DIS NC	2100	1.20	1.20	1.20	1.21	1.20	1.21	1.21	1.21
DIS CC	989	0.89	0.89	0.89	0.90	0.89	0.89	0.90	0.90
DY NC	671	1.19	1.41	1.74	1.90	1.25	1.62	2.29	2.64
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	44	1.23	1.24	1.24	1.22	1.21	1.27	1.23	1.21
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, m_{\ell\ell})$	48	1.62	3.71	3.78	4.40	1.62	3.65	3.56	4.31
CMS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	28	1.69	1.65	4.47	4.42	1.69	1.64	4.64	4.53
ATLAS $p_T^{\ell\ell}$ 13 TeV	19	—	—	—	—	3.94	8.42	13.5	17.6
CMS $p_T^{\ell\ell}$ 13 TeV	16	—	—	—	—	0.74	0.80	1.03	1.63
DY CC	157	1.06	1.09	1.09	1.06	1.06	1.09	1.04	1.02
top-quark pair	64	1.03	1.04	1.04	1.21	1.02	1.13	1.26	1.29
single-inclusive jets	356	0.98	0.98	0.98	0.96	0.98	0.98	0.95	0.96
dijets	144	1.50	1.52	1.52	1.51	1.51	1.51	1.48	1.46
photon	53	0.82	0.83	0.83	0.88	0.81	0.83	0.86	0.85
single top-quark	17	0.17	0.18	0.18	0.18	0.17	0.18	0.18	0.18
Total	4551	1.12	1.15	1.21	1.24	1.13	1.20	1.31	1.39

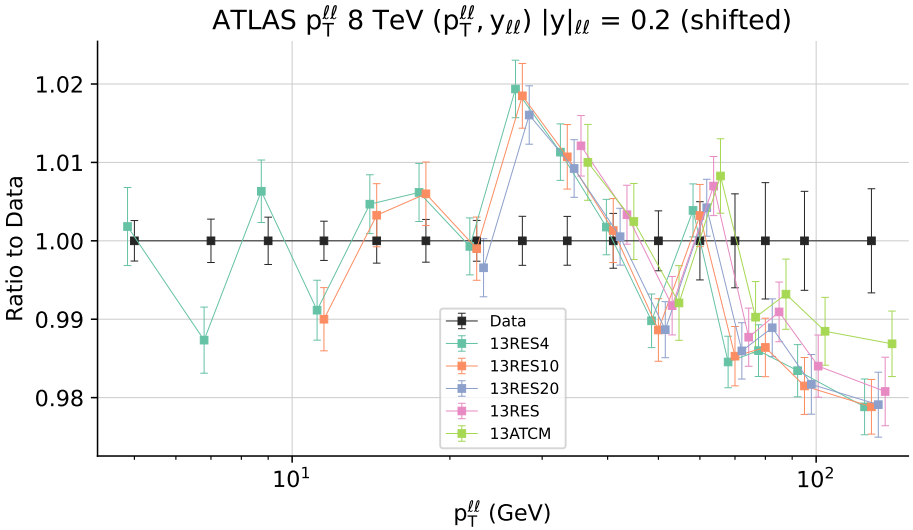
Parton distributions: 8 TeV

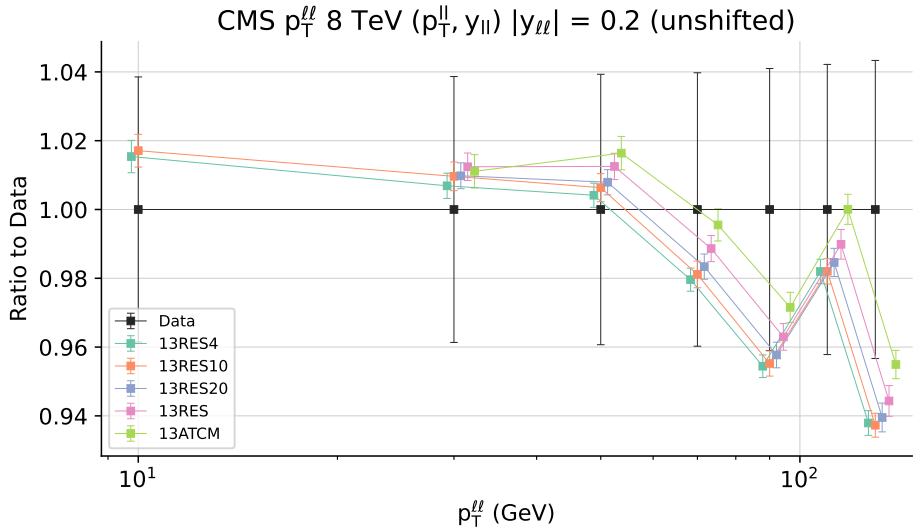


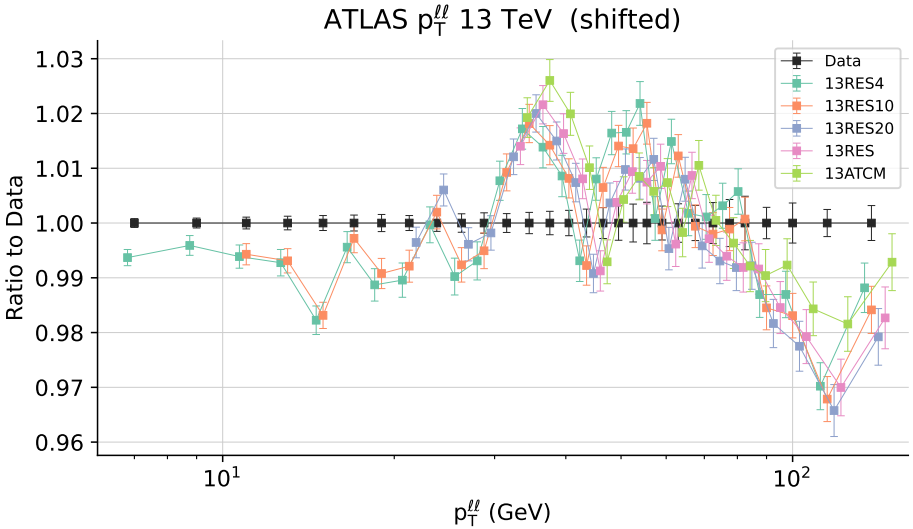
Parton distributions: 13 TeV

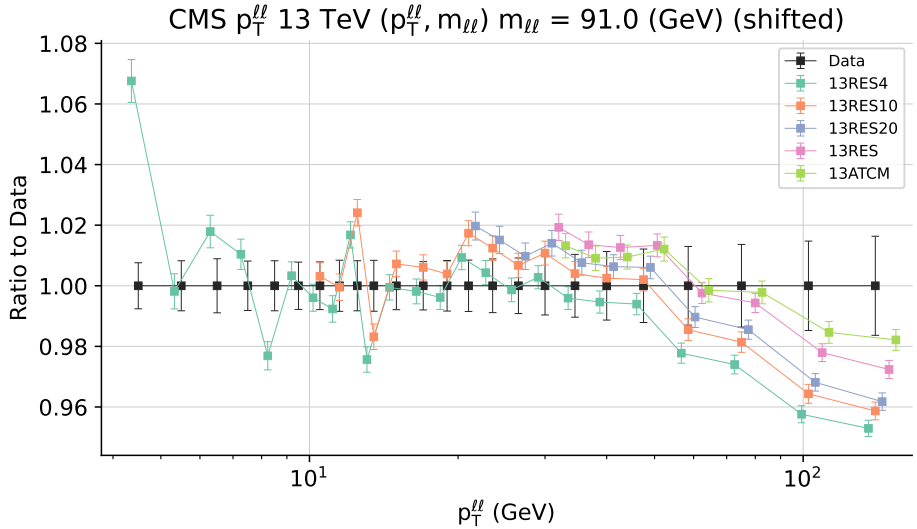


Data-theory comparison









Some additional considerations

Is the high χ^2 observed for the ATLAS 13 TeV data
driven by a nearly singular experimental covariance matrix?

No — we have explicitly checked that the χ^2 does not change upon regularisation

Is the inclusion of the resummation correction via a K-factor a good approximation?

Very likely yes, if this is small (of the order of few percent) — as for QCD

What if the resummed computation was matched on the N^{3}LO?

Difficult to say, but χ^2 values do not change if recomputed with aN^{3}LO PDFs

Do scale variations provide a good estimate of MHOUs across the entire $p_T^{\ell\ell}$ range?

Difficult to say, but correlations certainly matter a lot

Data set	$N_{\rm dat}$	13RES	13RES20	13RES10	13RES4	13RES	13RES20	13RES10	13RES4
		diagonal prescription				envelope prescription			
ATLAS $p_T^{\ell\ell}$ 8 TeV ($p_T^{\ell\ell}, y_{\ell\ell}$)	44	0.62	0.64	0.63	0.61	0.53	0.55	0.54	0.53
ATLAS $p_T^{\ell\ell}$ 8 TeV ($p_T^{\ell\ell}, m_{\ell\ell}$)	48	0.39	0.44	0.39	0.35	0.28	0.32	0.29	0.26
CMS $p_T^{\ell\ell}$ 8 TeV ($p_T^{\ell\ell}, y_{\ell\ell}$)	28	0.30	0.37	0.60	0.71	0.18	0.24	0.39	0.47
ATLAS $p_T^{\ell\ell}$ 13 TeV	19	0.39	0.42	0.49	0.47	0.29	0.32	0.35	0.33
CMS $p_T^{\ell\ell}$ 13 TeV	16	0.61	0.73	0.71	0.75	0.52	0.62	0.63	0.70

4. Conclusions

Summary

Can we revisit the implementation of the 8 TeV data sets?

Numerically stable NNLO predictions make the additional 1% uncertainty unnecessary

The revised treatment supports restoring the highest CMS rapidity bin

Can we include the new 13 TeV measurements?

CMS is well described; ATLAS exposes limitations of the fixed-order description

Resummation improves the ATLAS description substantially

Resummation largely removes the PDF shifts induced by ATLAS at fixed order, while a discrepancy in the data description remains

Can we include small-$p_T^{\ell\ell}$ resummation and relax the cut?

Resummation matters even above $p_T^{\ell\ell} = 30$ GeV

Lowering the cut worsens fit quality: extending the fitted region is not yet justified

The conclusions depend on the treatment of correlations in MHOUs

Summary

Can we revisit the implementation of the 8 TeV data sets?

Numerically stable NNLO predictions make the additional 1% uncertainty unnecessary

The revised treatment supports restoring the highest CMS rapidity bin

Can we include the new 13 TeV measurements?

CMS is well described; ATLAS exposes limitations of the fixed-order description

Resummation improves the ATLAS description substantially

Resummation largely removes the PDF shifts induced by ATLAS at fixed order, while a discrepancy in the data description remains

Can we include small-$p_T^{\ell\ell}$ resummation and relax the cut?

Resummation matters even above $p_T^{\ell\ell} = 30$ GeV

Lowering the cut worsens fit quality: extending the fitted region is not yet justified

The conclusions depend on the treatment of correlations in MHOUs

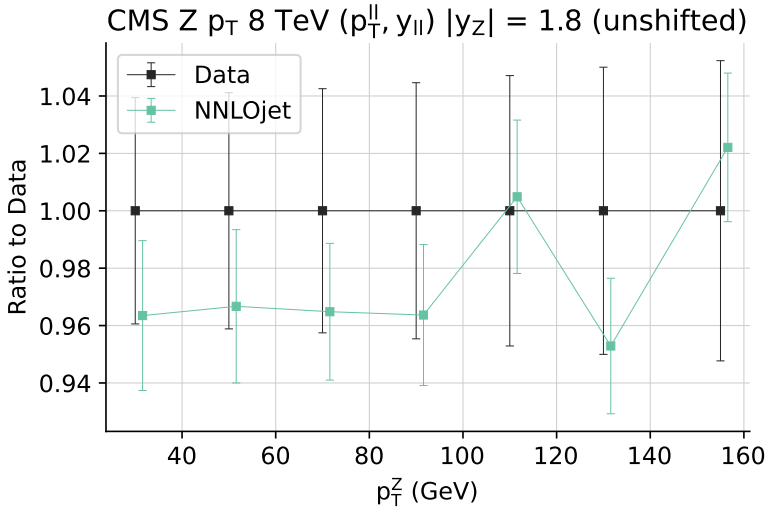
Thank you

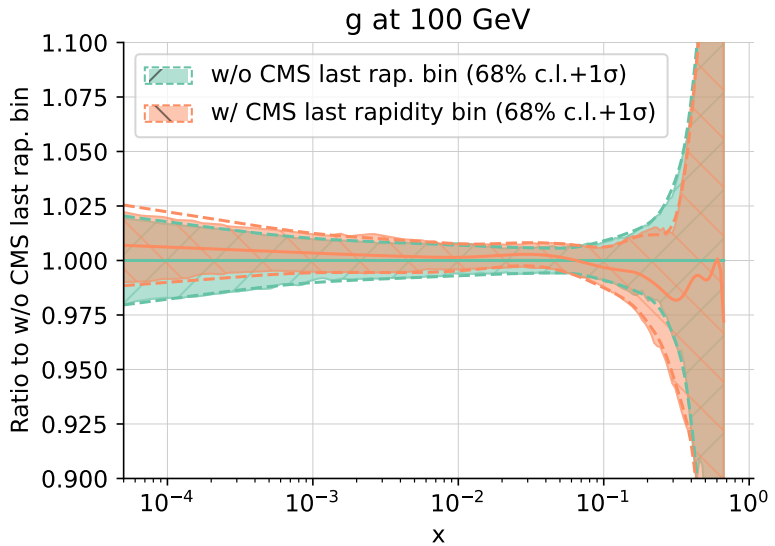
5. Backup

Cuts: CMS largest rapidity bin

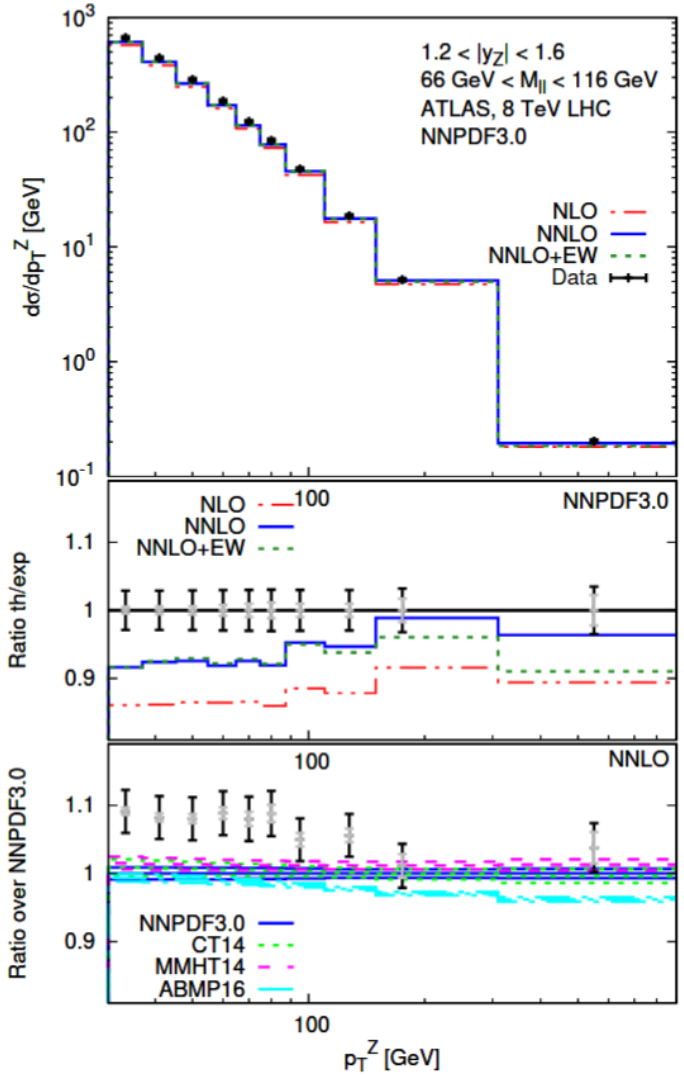
Let's revisit the CMS largest rapidity bin and let's refit the PDFs

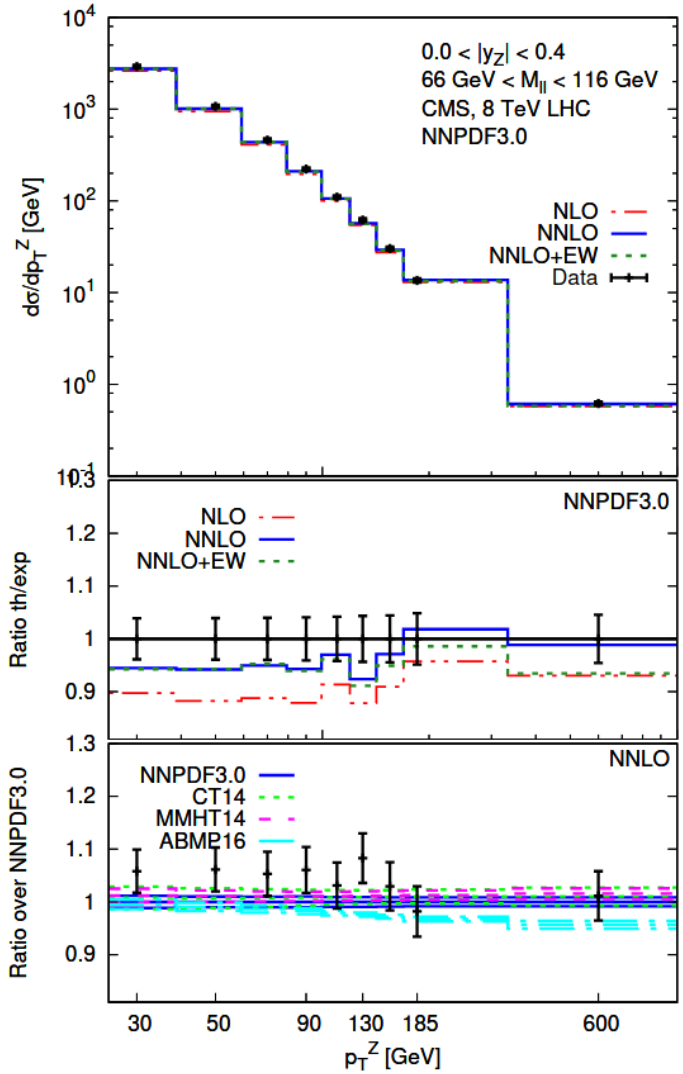
		NNLO jet w/o 1% w/o CMS bin		NNLO jet w/o 1% w/o CMS bin reg.		NNLO jet w/o 1% w/ CMS bin		NNLO jet w/o 1% w/ CMS bin reg.	
		ndata	χ^2/ *ndata*	ndata	χ^2/ *ndata*	ndata	χ^2/ *ndata*	ndata	χ^2/ *ndata*
DY NC	Total	120	1.643	120	1.229	127	1.559	127	1.200
	ATLAS_Z0J_8TEV_PT-M	44	1.256	44	1.256	44	1.268	44	1.268
	ATLAS_Z0J_8TEV_PT-Y	48	2.025	48	1.340	48	1.901	48	1.292
	CMS_Z0J_8TEV_PT-Y	28	1.965	28	1.288	35	1.706	35	1.170
Total	Total	120	1.643	120	1.229	127	1.559	127	1.200





Cuts: EW corrections



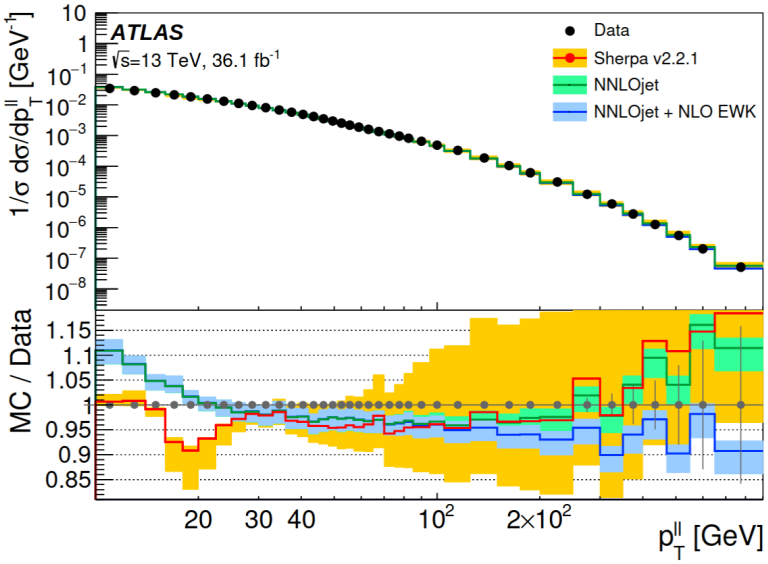


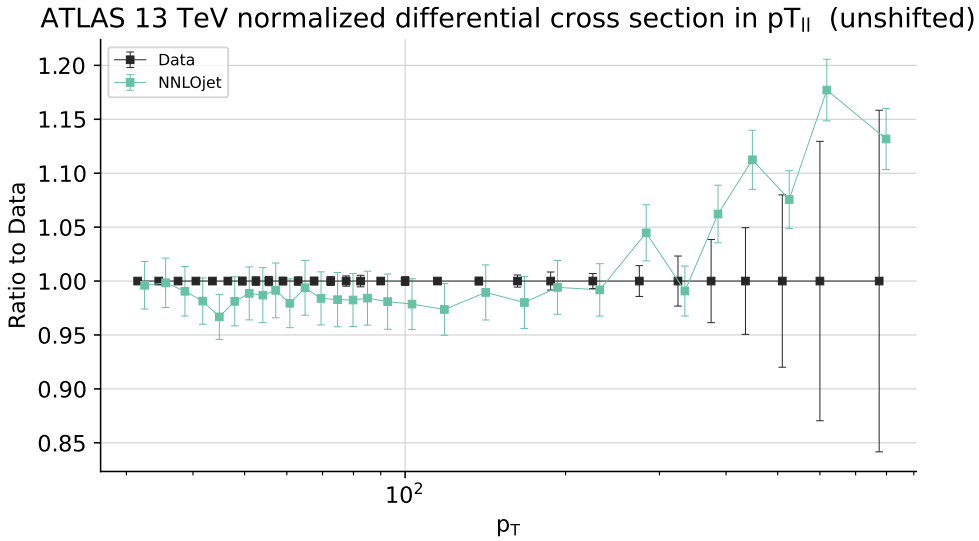
[Plots from JHEP 07 (2017) 130]

We confirm that a cut $p_T^Z \leq 150$ (170) GeV be adequate for ATLAS (CMS)

Are there bugs still around?

Is our data-theory comparison similar to the one reported in the ATLAS paper?





Consistency check: is the r.h.s. plot qualitatively consistent with a $\chi^2/N_{\rm dat} \sim 7$?

		Default		Default+th.decorr.	
		ndata	χ^2/*ndata*	ndata	χ^2/*ndata*
DY NC	Total	58	3.983	58	0.9014
	ATLAS_Z0J_13TEV_PT_LL	29	6.658	29	0.8426
	CMS_Z0J_13TEV_PT-M	29	1.336	29	0.9602
Total	Total	58	3.983	58	0.9014

Weighted fit

Data set	$N_{\rm dat}$	13RES	13RESwg
DIS NC	2100	1.20	1.30
DIS CC	989	0.89	1.34
DY NC	671	1.25	1.66
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	44	1.21	1.33
ATLAS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, m_{\ell\ell})$	48	1.62	1.89
CMS $p_T^{\ell\ell}$ 8 TeV $(p_T^{\ell\ell}, y_{\ell\ell})$	28	1.69	1.51
ATLAS $p_T^{\ell\ell}$ 13 TeV	19	3.94	3.57
CMS $p_T^{\ell\ell}$ 13 TeV	16	0.74	0.88
DY CC	157	1.06	1.62
top-quark pair	64	1.02	1.08
single-inclusive jets	356	0.89	1.45
dijets	144	1.51	1.70
photon	53	0.81	0.74
single top-quark	17	0.17	0.70
Total	4551	1.13	1.42

