REF2020, EDINBURGH

Uncertainties and challenges in TMD extraction

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7-11/12/2020

TMD extraction

Factorization

$$\frac{d\sigma}{dQ^2 dy dq_T^2} = \sigma_0 \sum_{f_1,f_2} \int \frac{d^2\boldsymbol{b}}{4\pi} e^{i(\boldsymbol{b}\cdot\boldsymbol{q}_T)} H_{f_1 f_2}(Q,\mu) F_{f_1\leftarrow h_1}(x_1,\boldsymbol{b};\mu,\zeta_1) F_{f_2\leftarrow h_2}(x_2,\boldsymbol{b};\mu,\zeta_2).$$

Scale-independent Factors!

$$\frac{d\sigma}{dQ^2 dy dq_T^2} = \sigma_0 \sum_{f_1,f_2} \int \frac{d^2\boldsymbol{b}}{4\pi} e^{i(\boldsymbol{b}\cdot\boldsymbol{q}_T)} H_{f_1 f_2}(Q,Q) \{R[\boldsymbol{b};(Q,Q^2)]\}^2 F_{f_1\leftarrow h_1}(x_1,\boldsymbol{b}) F_{f_2\leftarrow h_2}(x_2,\boldsymbol{b})$$

Separation of NP effects in evolution kernel and TMD

ζ-prescription

Data selection

E288(200)			CMS (7TeV)
E288(300)		ATLAS (7TeV)	CMS (8TeV)
E288(400)	CDF (run1)	ATLAS (8TeV)	LHCb (7TeV)
	CDF (run2)		
E605	D0 (run1)	ATLAS (8TeV)	LHCb (8TeV)
	D0 (run2)		
E772	D0 (run2)	ATLAS (8TeV)	LHCb (13TeV)

Statistical methods: replicas of exp

$$V_{ij} = \left(\sigma_{i,\text{stat}}^2 + \sigma_{i,\text{unc}}^2\right)\delta_{ij} + \sum_{l=1}^{k} \sigma_{i,\text{corr}}^{(l)} \sigma_{j,\text{corr}}^{(l)}$$

RESULTS

Unpolarized TMDPDF

$\zeta-$prescription *JHEP* 08 (2018) 003

$$\lim_{b\to 0} f_{1,f\leftarrow h}(x,b) = \sum_{f'}\int_x^1 \frac{dy}{y} C_{f\leftarrow f'}\left(\frac{x}{y}, \mathbf{L}_{\mu_{\text{OPE}}}, a_s(\mu_{\text{OPE}})\right) f_{1,f'\leftarrow h}(y,\mu_{\text{OPE}}),$$

$$\lim_{b\to 0} D_{1,f\to h}(z,b) = \sum_{f'}\int_z^1 \frac{dy}{y} \mathbb{C}_{f\to f'}\left(\frac{z}{y}, \mathbf{L}_{\mu_{\text{OPE}}}, a_s(\mu_{\text{OPE}})\right) \frac{d_{1,f'\to h}(y,\mu_{\text{OPE}})}{y^2},$$

PDF ARE PART OF THE MODEL

NNLO

T. Gehrmann et al. JHEP 06 (2014) 155,
M.G. Echevarria et al. Phys. Rev. D93 (2016) 011502, JHEP 09 (2016) 004

NNNLO

M. X. Luo et al. Phys.Rev.Lett. 124 (2020) 9, 092001
M. Ebert et al. JHEP 09 (2020) 146

$$f_{1,f\leftarrow h}(x,b) = \int_x^1 \frac{dy}{y}\sum_{f'} C_{f\leftarrow f'}\left(y, \mathbf{L}_{\mu_{\text{OPE}}}, a_s(\mu_{\text{OPE}})\right) f_{1,f'\leftarrow h}\left(\frac{x}{y},\mu_{\text{OPE}}\right) f_{\text{NP}}(x,b),$$

$$D_{1,f\to h}(z,b) = \frac{1}{z^2}\int_z^1 \frac{dy}{y}\sum_{f'} y^2\mathbb{C}_{f\to f'}\left(y, \mathbf{L}_{\mu_{\text{OPE}}}, a_s(\mu_{\text{OPE}})\right) d_{1,f'\to h}\left(\frac{z}{y},\mu_{\text{OPE}}\right) D_{\text{NP}}(z,b)$$

$$f_{NP}(x,b) = \exp\left(-\frac{\lambda_1(1-x)+\lambda_2 x + x(1-x)\lambda_5}{\sqrt{1+\lambda_3 x^{\lambda_4}\boldsymbol{b}^2}}\boldsymbol{b}^2\right)$$

$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right),$$

Ansatz for Artemide

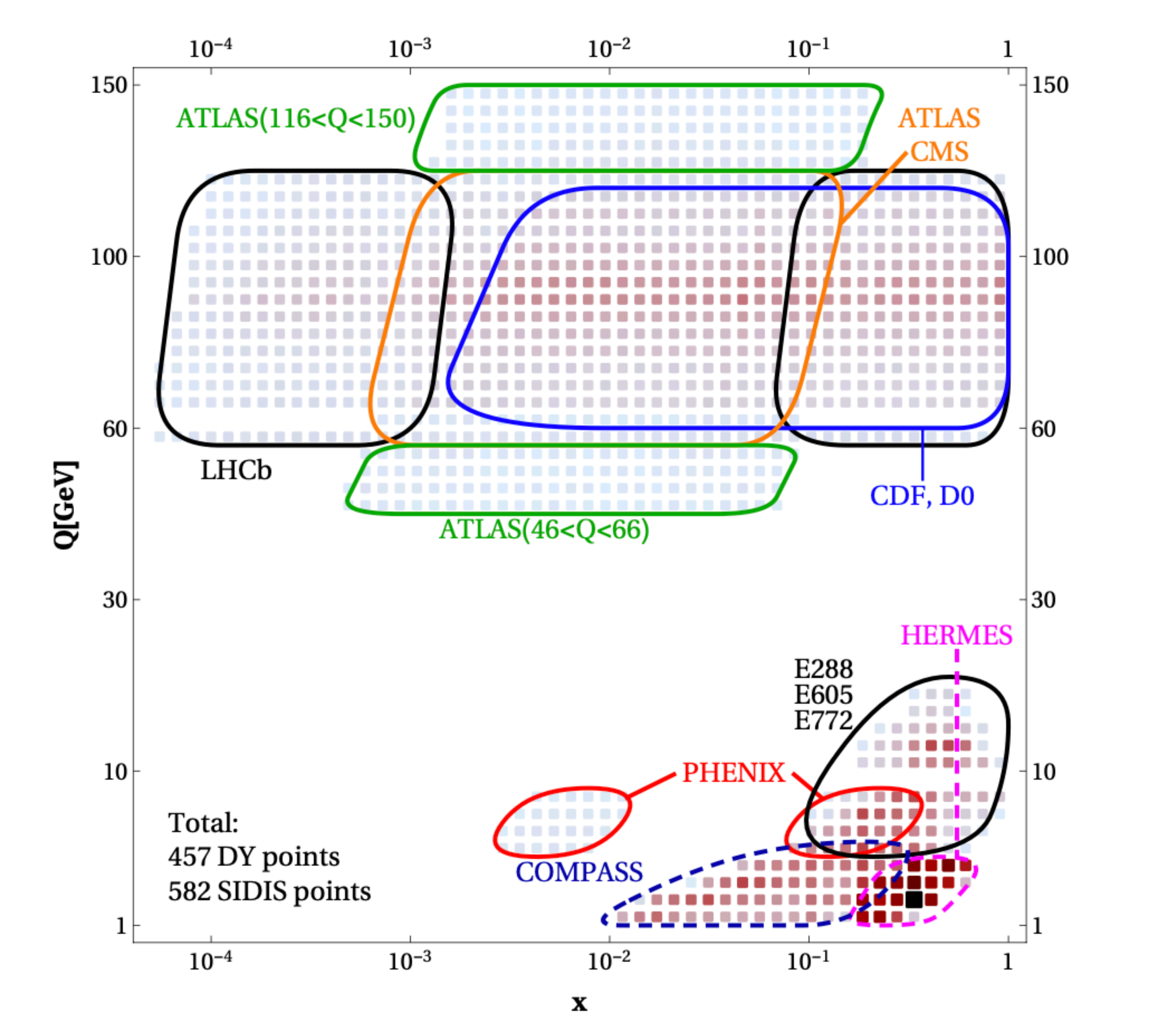
Open questions

- Which data are sensitive to TMD?
- Do TMD fits depend on the choice of PDF sets?
- Do we have a unique f_{NP} for all sets of PDF?
- Do we need to reweigh the PDF sets?
- Do f_{NP} models depend of flavor?
- Can we give sense to the extraction of PDF when including low qT data?

Data sets distributions

High Energy (only DY):
LHC+TeVatron

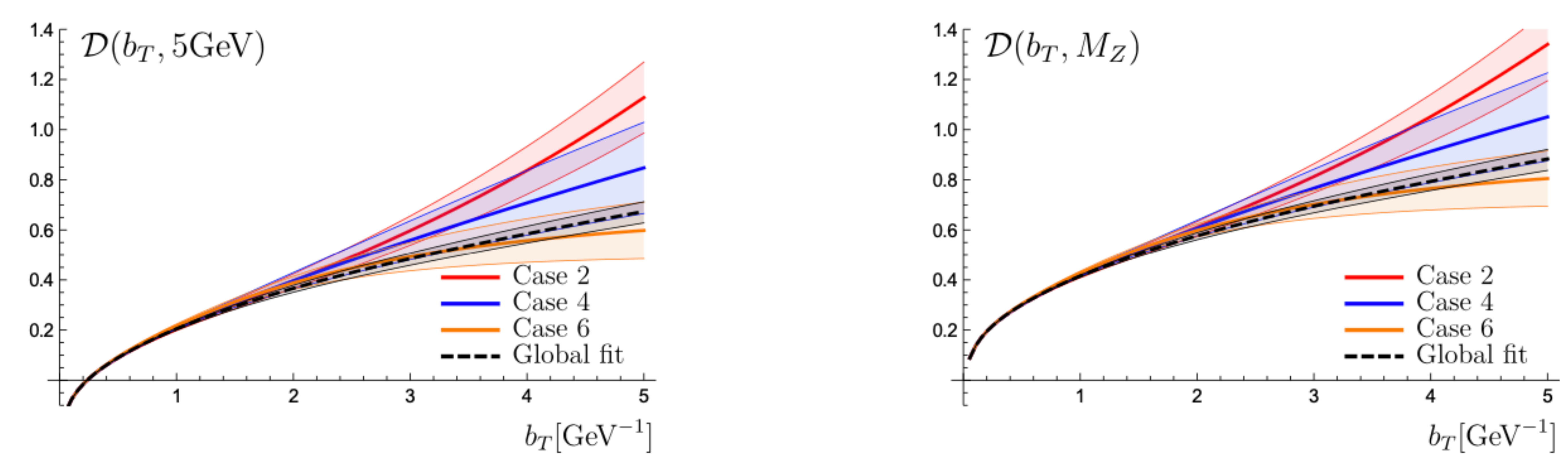
Low Energy (DY+SIDIS)



Non perturbative TMD effects at LHC

We have tested several simple modeles for LHC with/without NP effects in TMD.
A non-perturbative part on evolution kernel is always necessary and it is present in every code. We tested several possibilities.
Models with an fNP different from 1 give better agreement with LHC data.

Case	B_{NP}	g_K	λ_1 ($f_{NP} = \exp -\lambda_1 b^2$)	χ^2/dof	χ^2/dof(norm.)
1	5.5 (max)	0.116 ± 0.002	10^{-3}(fixed)	3.29	3.04
2	2.2 ± 0.4	0.032 ± 0.006	0.29 ± 0.02	1.50	1.28
Case	B_{NP}	c_0	λ_1	χ^2/dof	χ^2/dof(norm.)
3	1. (min)	0.016 ± 0.001	10^{-3}(fixed)	2.21	1.99
4	3.0 ± 1.5	0.04 ± 0.02	0.27 ± 0.04	1.61	1.36
Case	B_{NP}	g_K^*	λ_1	χ^2/dof	χ^2/dof(norm.)
5	1.34 ± 0.01	0.16 ± 0.01	10^{-3}(fixed)	1.70	1.52
6	2.43 ± 0.66	0.05 ± 0.02	0.24 ± 0.04	1.49	1.28



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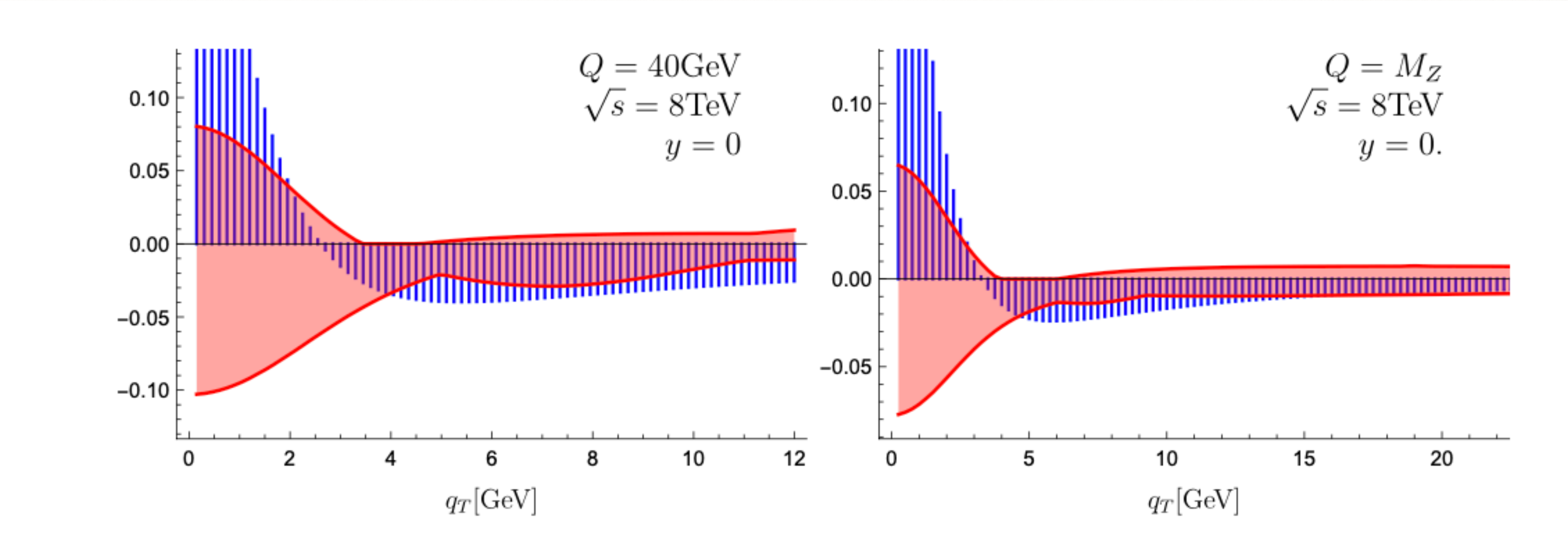
Non perturbative TMD effects at LHC

$$R_\sigma = 2\frac{d\sigma_{\text{test}} - d\sigma_{\text{TMD}}}{d\sigma_{\text{test}} + d\sigma_{\text{TMD}}}$$

Scales uncertainty



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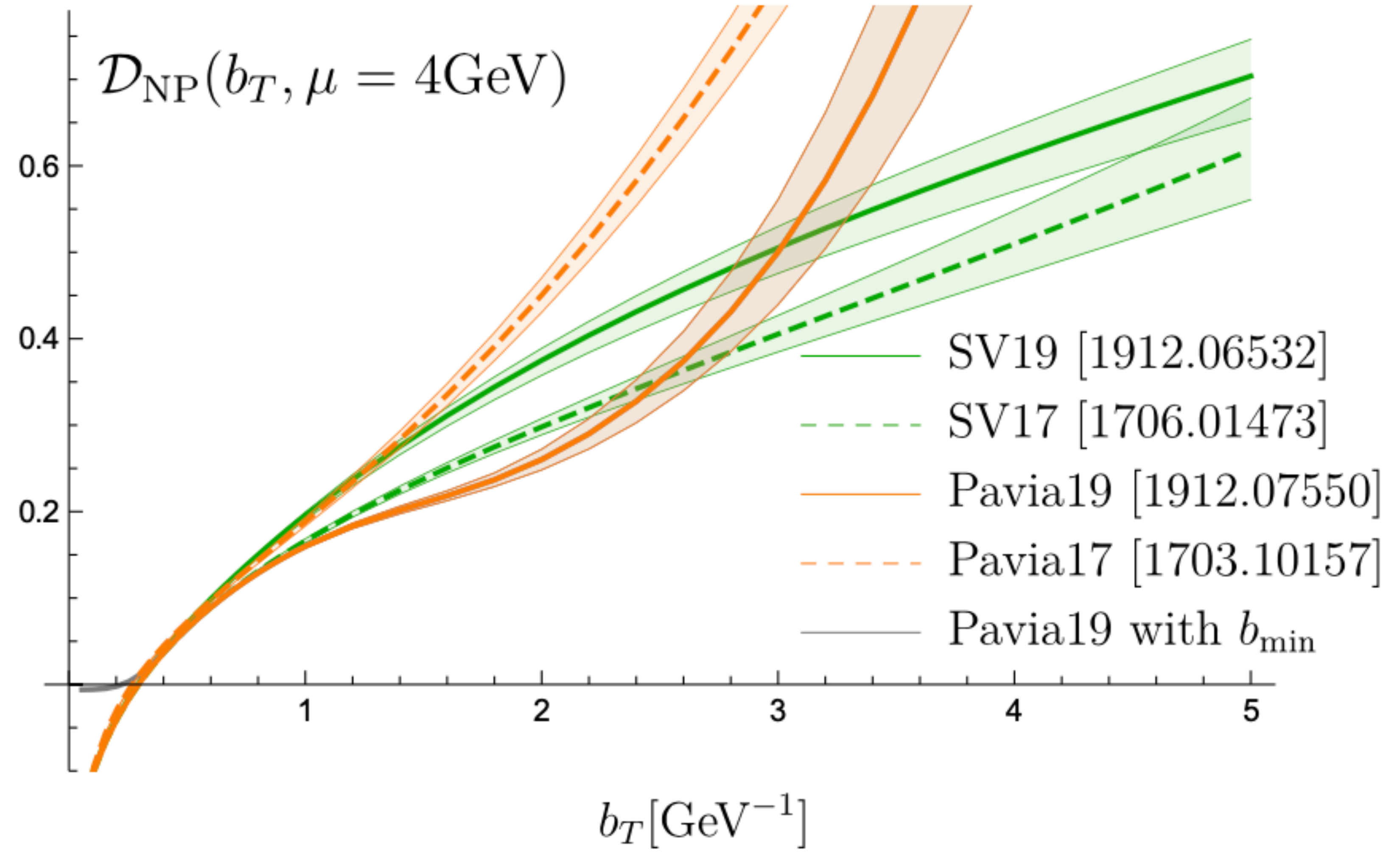
Evolution kernel from global fits

Recent extractions

Name	Order	Data set	Model	Comm.
Pavia17	LO	DY+SIDIS	$\mathcal{D}_{\text{pert}}(\mu, b) + g_2 \frac{b^2}{2}$	$b_{\text{min}}^{\text{max}}$-prescription
SV17	NNLO	DY	$\mathcal{D}_{\text{pert}}(\mu, b) + c_0 b^2$	ζ-prescription
SV19	NNLO/N^{3}LO	DY+SIDIS	$\mathcal{D}_{\text{resum}}(\mu, b^*) + c_0 b b^*$	ζ-prescription
Pavia19	NNNLO	DY	$\mathcal{D}_{\text{pert}}(\mu, b) + g_2 \frac{b^2}{4} + g_{2b} \frac{b^4}{4}$	$b_{\text{min}}^{\text{max}}$-prescription



Slide from A. Vladimirov

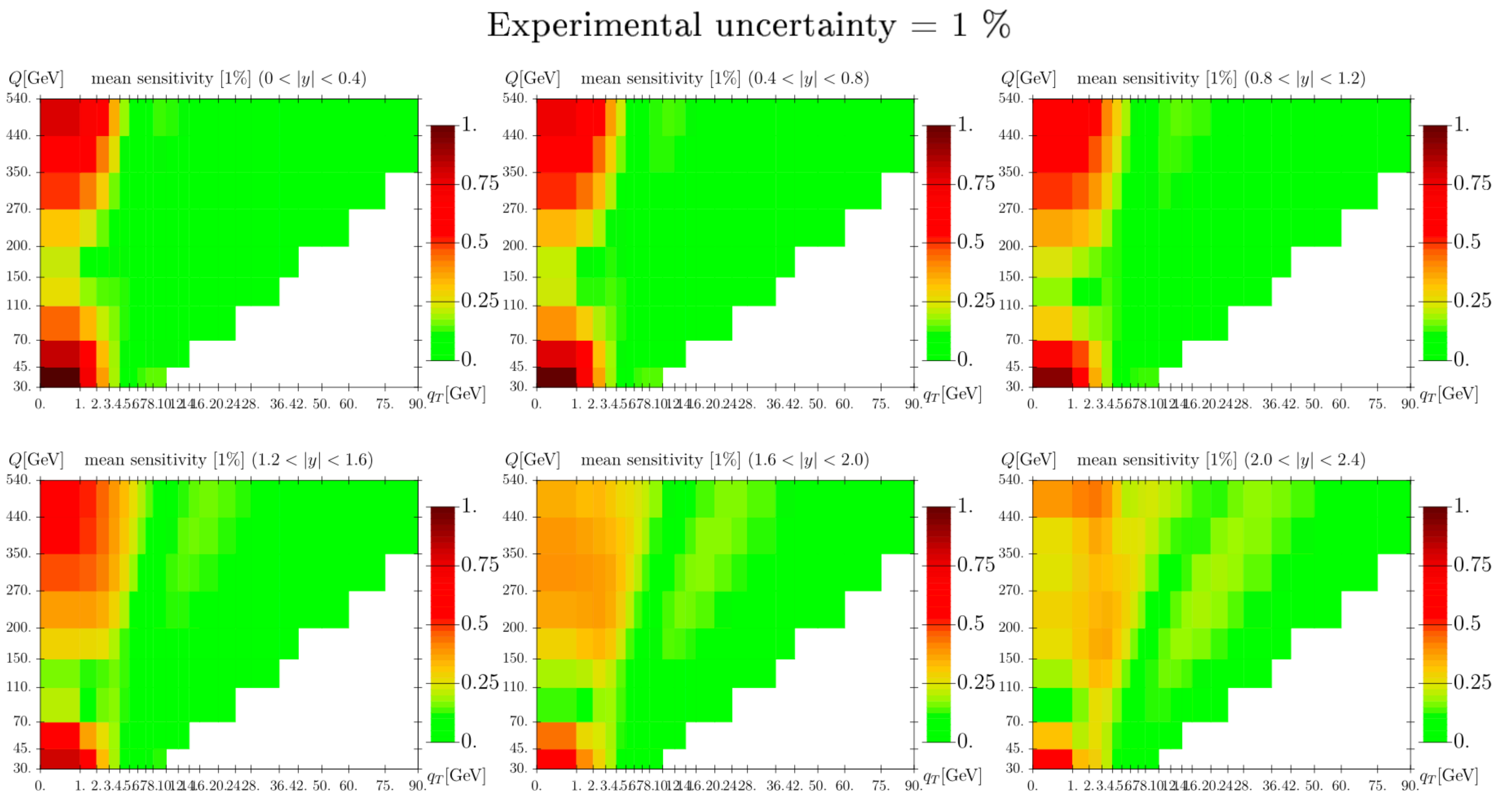
Data sensitivity:

$$\text{Correlation coefficient} = \rho[\sigma, O] = \frac{\langle \sigma O \rangle - \langle \sigma \rangle \langle O \rangle}{\Delta\sigma \Delta O}$$

measures correlation between NP-parameter and cross-section

$$\text{Sensitivity coefficient} = S[\sigma, O] = \rho[\sigma, O] \frac{\Delta O}{\Delta O_{\text{exp.}}}$$

reweigh the correlation by expected experimental uncertainty and shows feasible regions



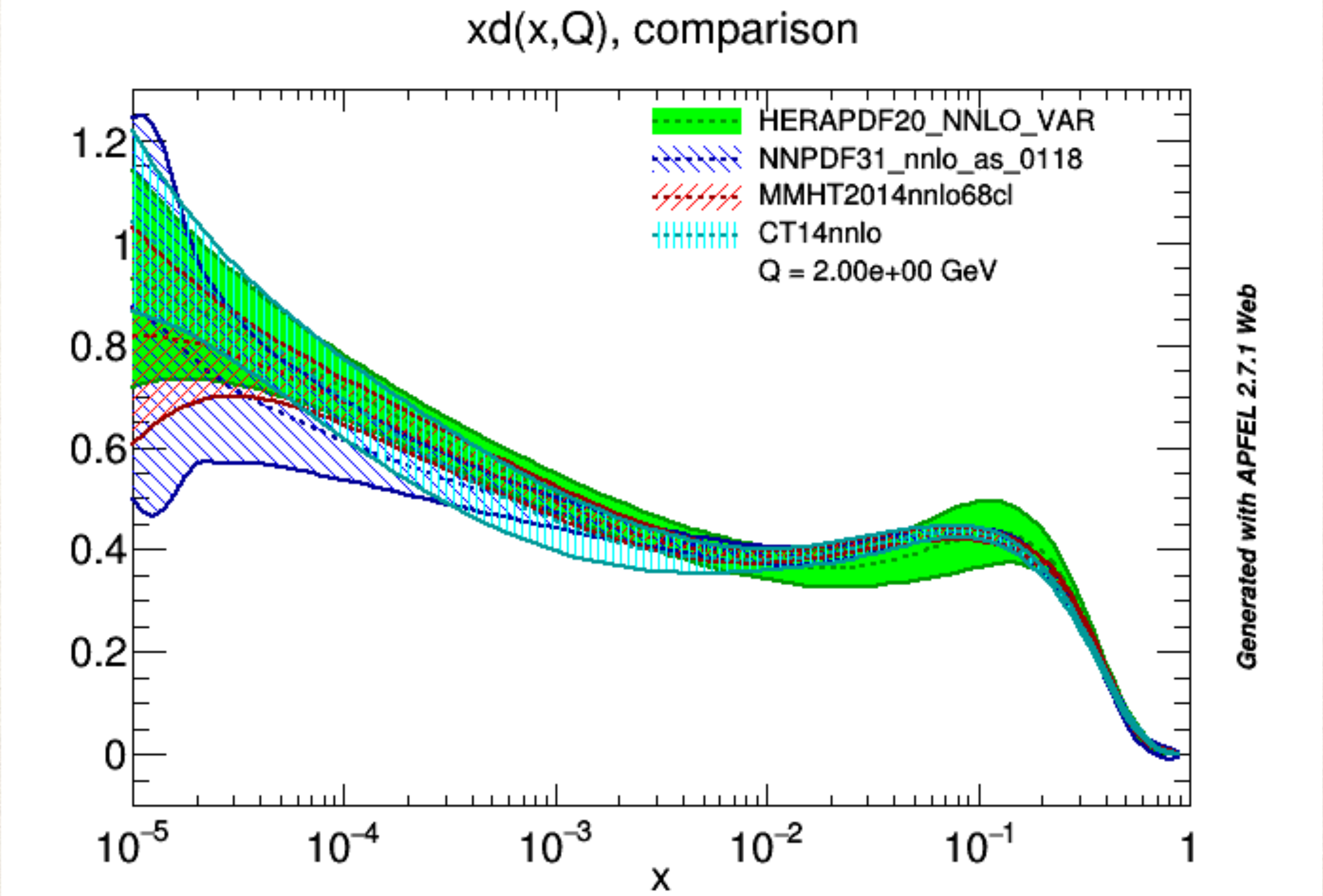
$$F_{f\leftarrow h}(x,\mathbf{b}) = \sum_{f'}\int_x^1 \frac{dy}{y} C_{f\leftarrow f'}(y, \mathbf{L}_{\mu_{\rm OPE}}, a_s(\mu_{\rm OPE})) f_{f'\leftarrow h}\left(\frac{x}{y}, \mu_{\rm OPE}\right) f_{\rm NP}(x,b)$$

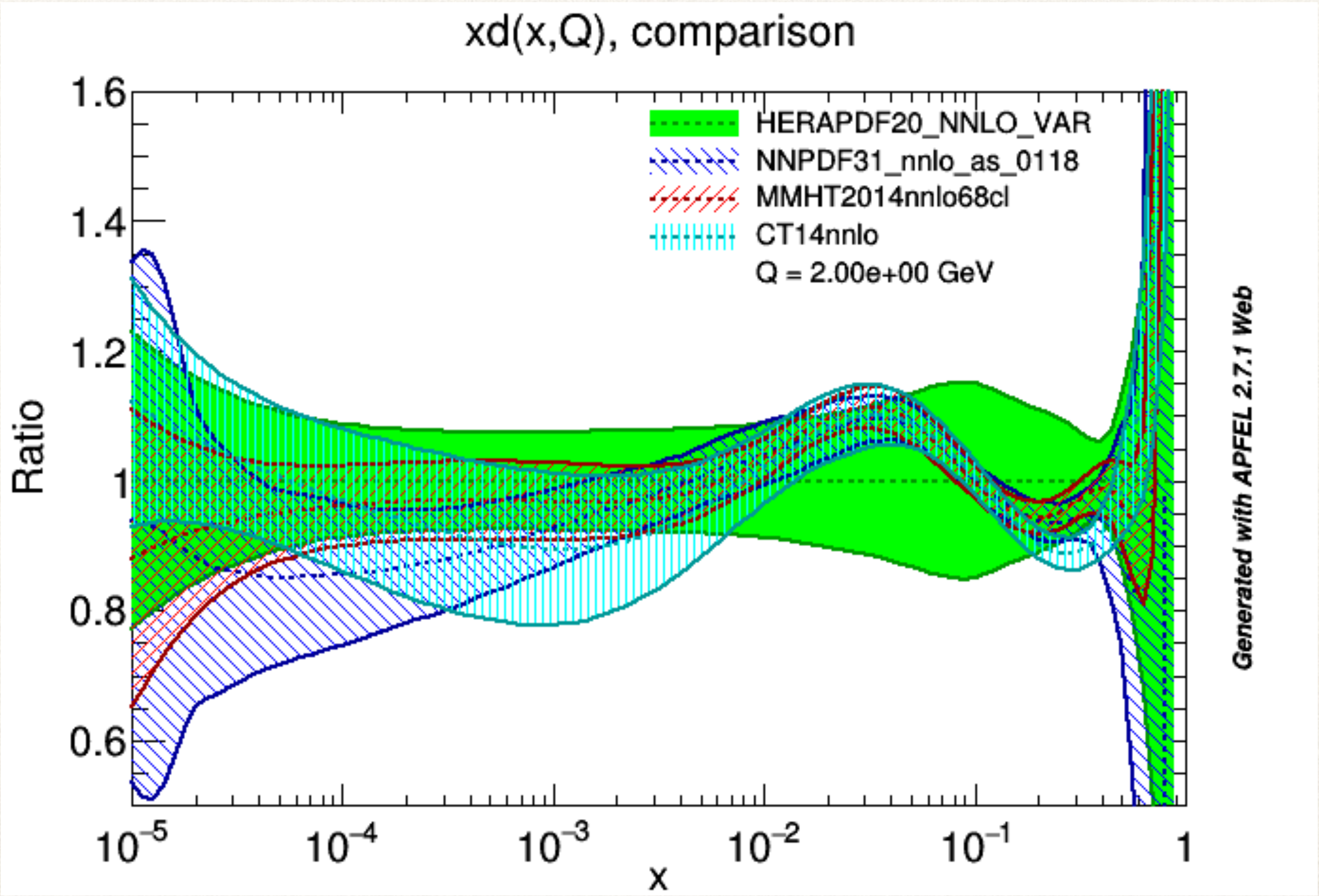
Matching (Wilson) coefficient NNLO

PDF

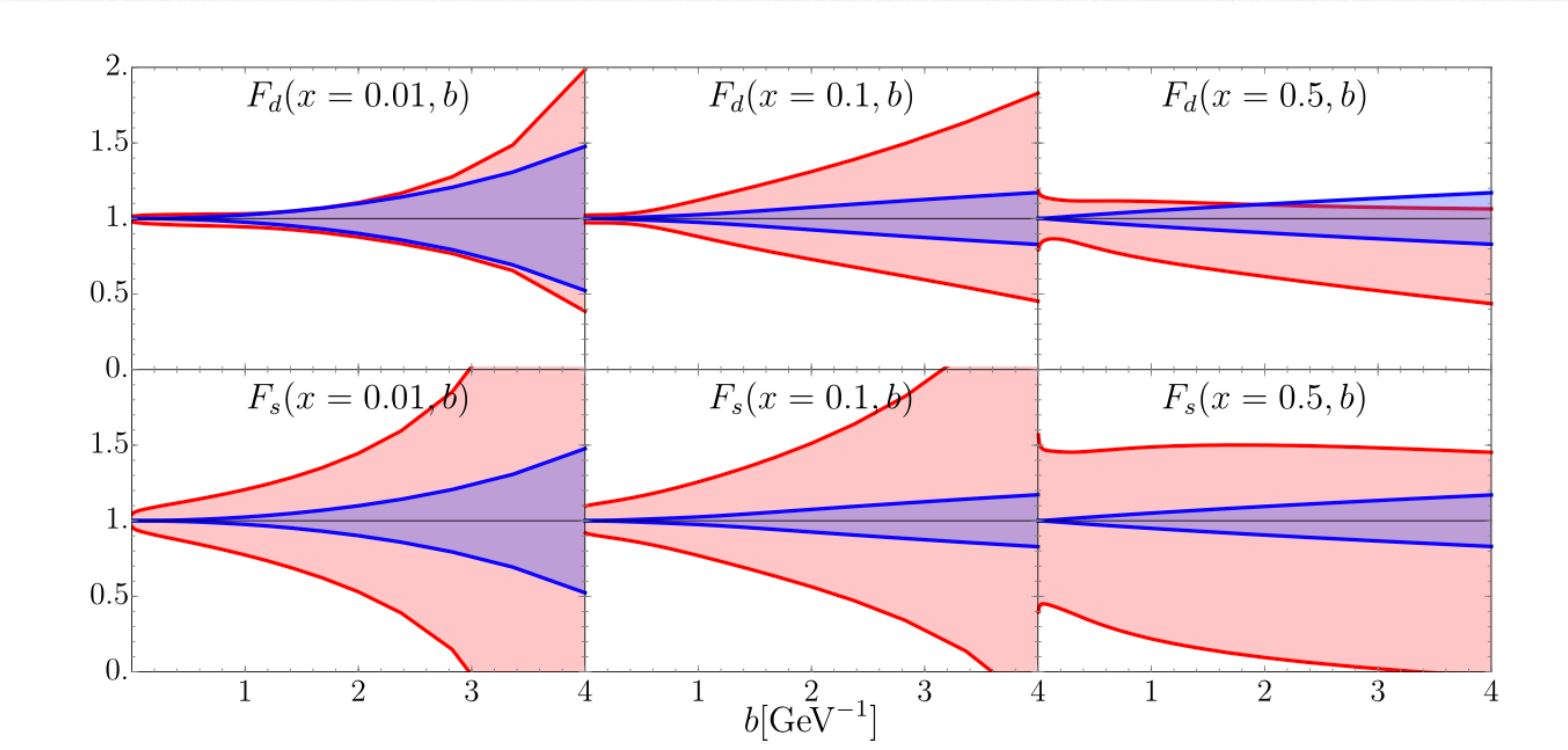
Gaussian?
Exponential?

Why do TMD depend on PDF set choice?
In principle the TMD is independent but …





TMD uncertainties from PDF uncertainties

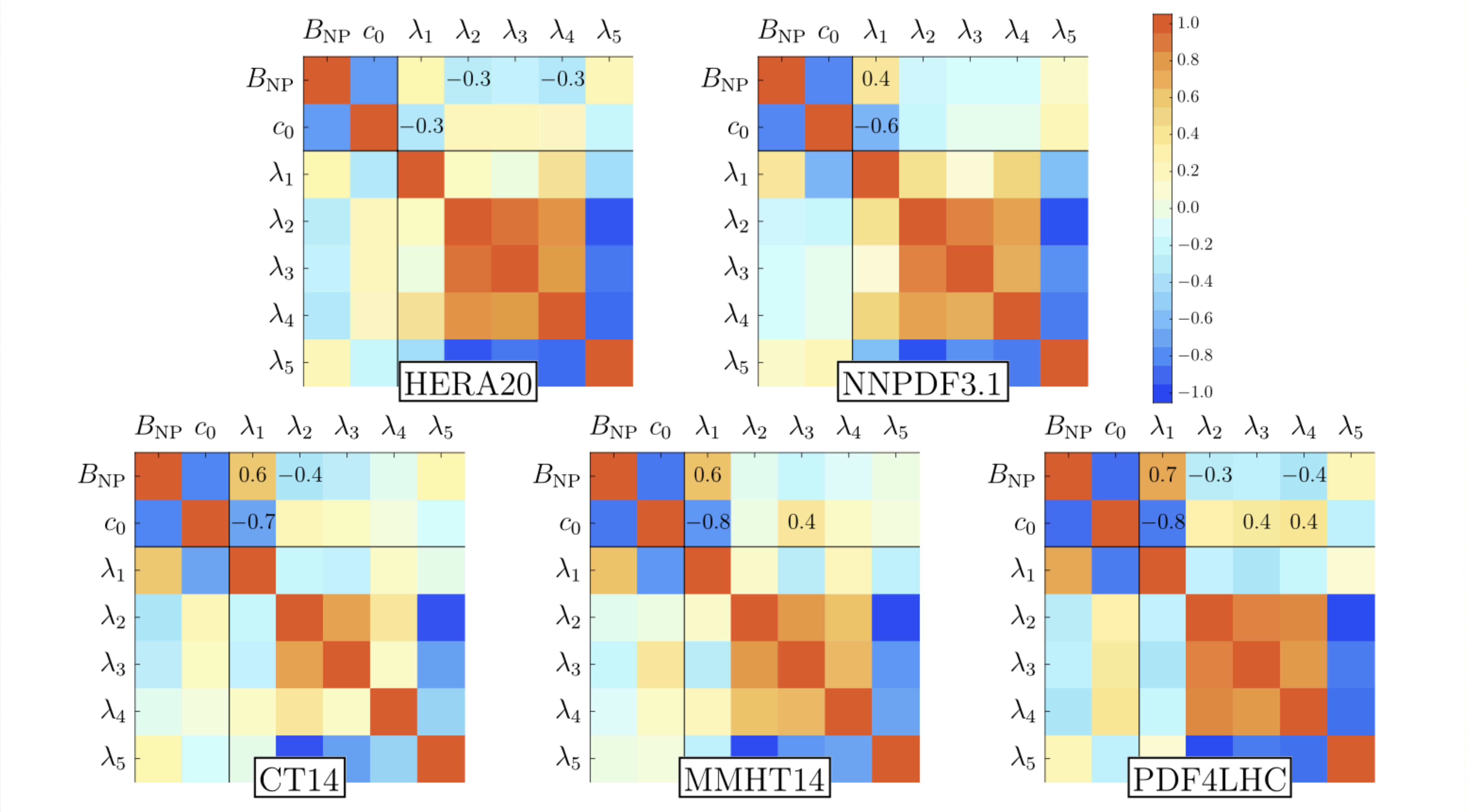


I.S., A. Vladimirov *JHEP* 06 (2020) 137

Experimental uncertainty

PDF uncertainty (replicas, NNPDF31_nnlo_118)

Correlation of parameters



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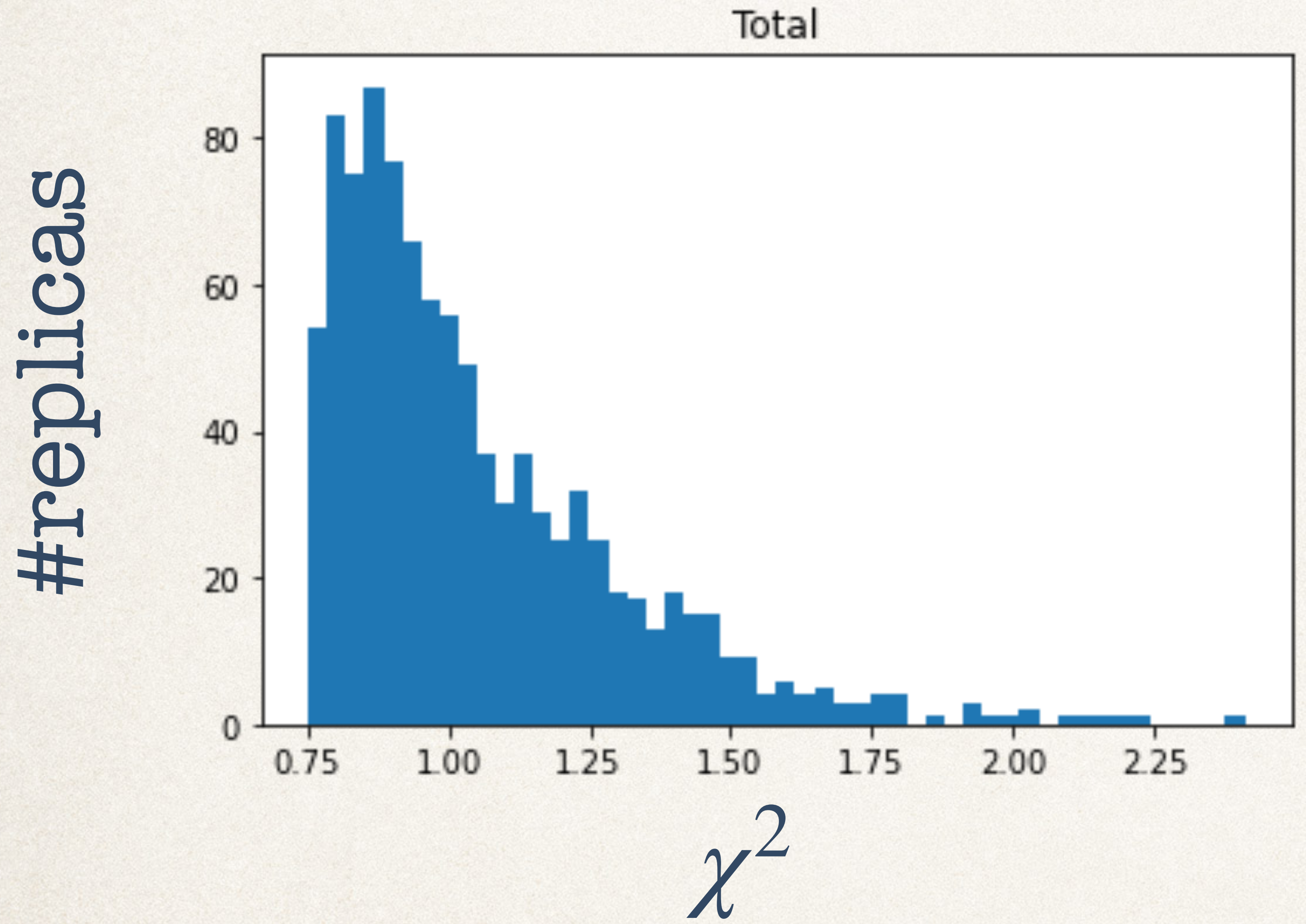
Differences among PDF sets are visible in TMD physics

DY fit from I.S., A. Vladimirov *JHEP* 06 (2020) 137

PDF set	χ^2/N_{pt}	Parameters for $\mathcal{D}$	Parameters for f_1	
HERA20	0.97	$B_{\rm NP} = 2.29 \pm 0.43$ $c_0 = (2.22 \pm 0.93) \cdot 10^{-2}$	$\lambda_1 = 0.324 \pm 0.029$ $\lambda_2 = 13.2 \pm 2.9$	$\lambda_3 = (3.56 \pm 1.59) \cdot 10^2$ $\lambda_4 = 2.05 \pm 0.26$ $\lambda_5 = -10.4 \pm 3.5$
NNPDF31	1.14	$B_{\rm NP} = 1.86 \pm 0.30$ $c_0 = (2.96 \pm 1.04) \cdot 10^{-2}$	$\lambda_1 = 0.253 \pm 0.032$ $\lambda_2 = 9.0 \pm 3.0$	$\lambda_3 = (3.47 \pm 1.16) \cdot 10^2$ $\lambda_4 = 2.48 \pm 0.15$ $\lambda_5 = -5.7 \pm 3.4$
MMHT14	1.34	$B_{\rm NP} = 1.55 \pm 0.29$ $c_0 = (4.70 \pm 1.77) \cdot 10^{-2}$	$\lambda_1 = 0.198 \pm 0.040$ $\lambda_2 = 26.4 \pm 4.9$	$\lambda_3 = (26.8 \pm 13.2) \cdot 10^3$ $\lambda_4 = 3.01 \pm 0.17$ $\lambda_5 = -23.4 \pm 5.4$
PDF4LHC	1.53	$B_{\rm NP} = 1.93 \pm 0.47$ $c_0 = (3.66 \pm 2.09) \cdot 10^{-2}$	$\lambda_1 = 0.218 \pm 0.041$ $\lambda_2 = 17.9 \pm 4.5$	$\lambda_3 = (9.26 \pm 8.38) \cdot 10^2$ $\lambda_4 = 2.54 \pm 0.17$ $\lambda_5 = -15.5 \pm 4.7$
CT14	1.59	$B_{\rm NP} = 2.35 \pm 0.61$ $c_0 = (2.27 \pm 1.33) \cdot 10^{-2}$	$\lambda_1 = 0.277 \pm 0.029$ $\lambda_2 = 24.9 \pm 2.9$	$\lambda_3 = (12.4 \pm 3.2) \cdot 10^3$ $\lambda_4 = 2.67 \pm 0.13$ $\lambda_5 = -23.8 \pm 2.9$

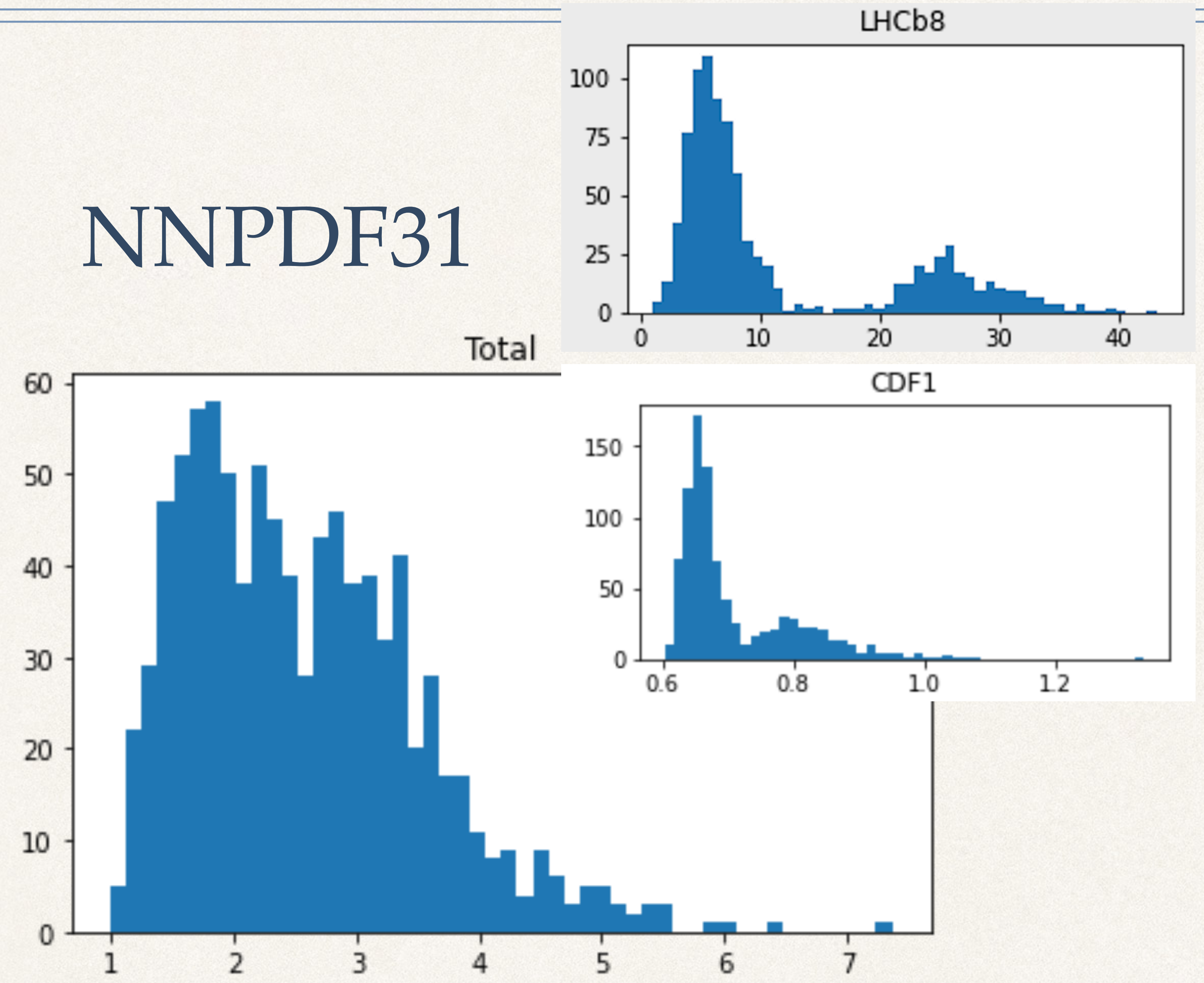
χ^2 for several sets

HERA2020



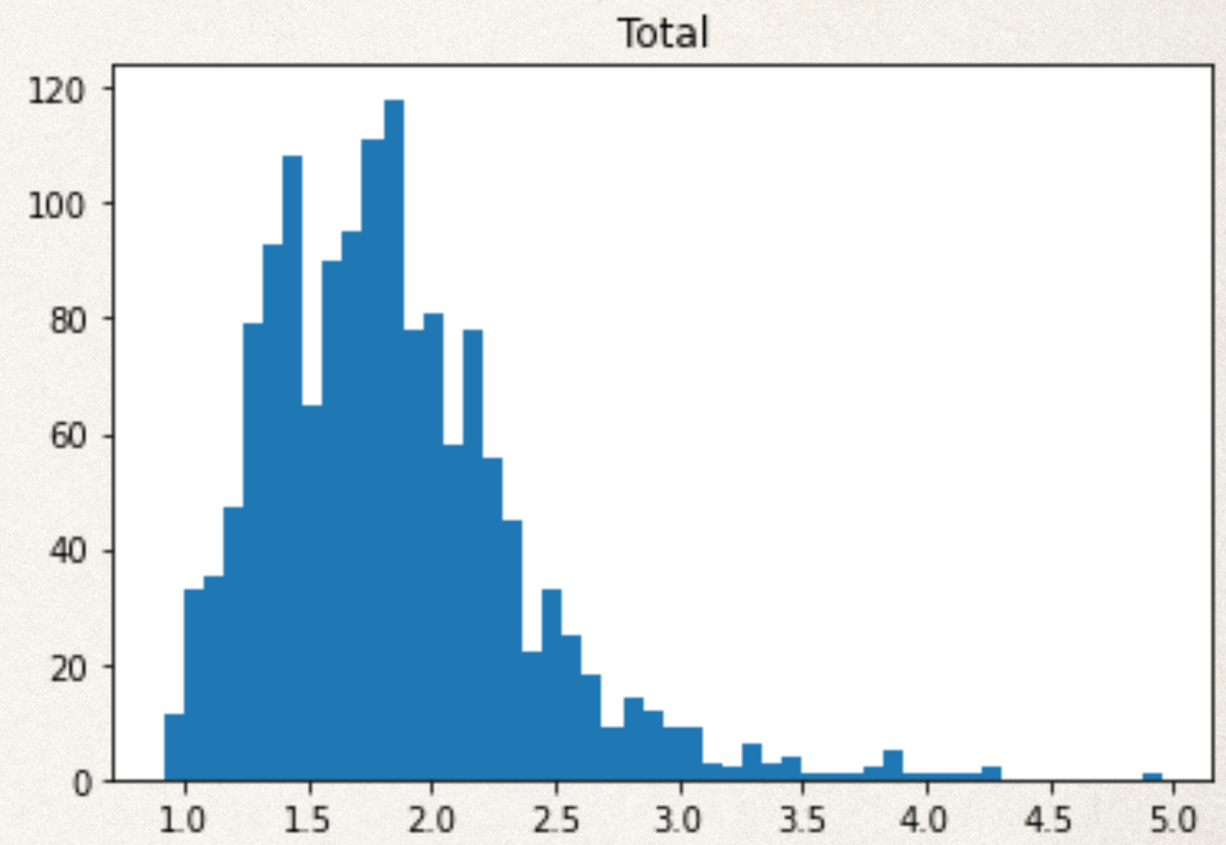
Peaked around <1

NNPDF31



Double peaked

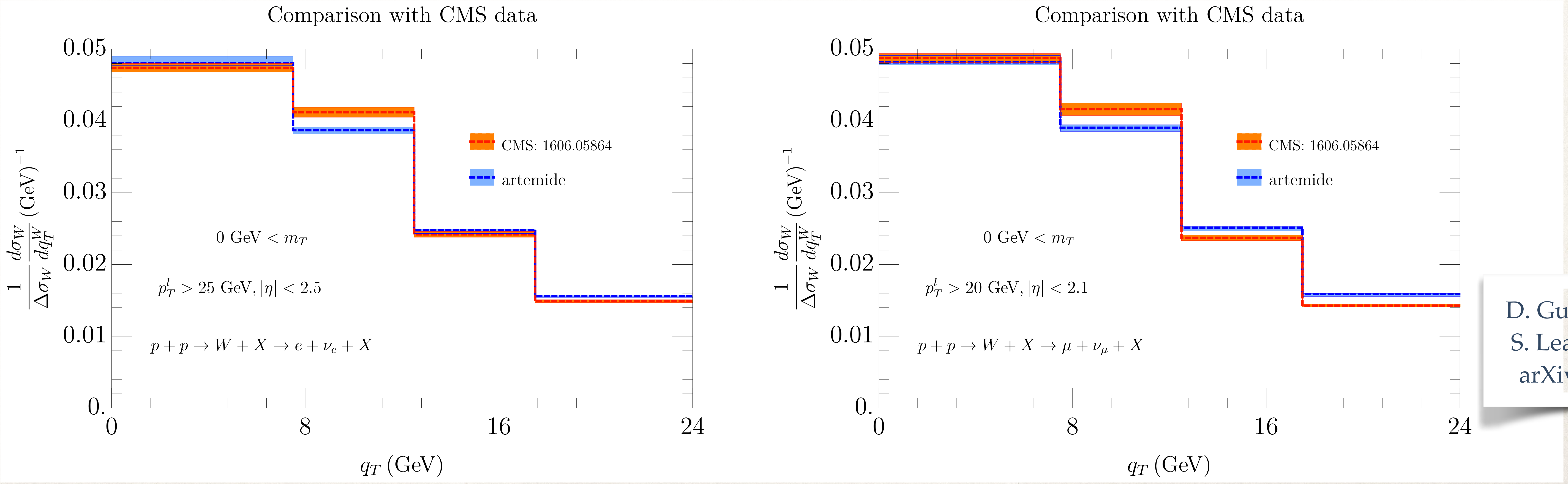
CT14



Broad peak

Predictions coming from fits using different data sets for W boson q_T spectrum

	CDF $\sqrt{s} = 1.8$ TeV	D0 $\sqrt{s} = 1.8$ TeV	ATLAS	CMS $e\nu$	CMS $\mu\nu$
Number of points	10	10	2	4(3)	4
NNPDF31	0.650	1.845	1.565	7.284 (1.694)	21.502
HERA20	0.617	2.009	0.853	6.024(0.310)	16.090
MMHT14	0.667	2.166	1.406	7.465(1.505)	21.751
CT14	0.677	2.608	1.324	7.974 (1.482)	21.972
PDF4LHC	0.660	2.061	1.405	7.733(1.605)	22.075



D. Gutierrez-Reyes, S. Leal-Gomez, I.S. arXiv: 2011.05351

Conclusions

The goal is a consistent description of TMDs

TMD affect qT spectrum at all energies for low qT

Up to now all fits are done with a single model of TMD for all PDF sets and show differences among PDF sets.

It is not clear where problems are located and the answer can depend on the PDF set.

Study is progress arXiv:21XX.YYYYY