XXVIII DIS2021

Extraction of TMD with Drell-Yan and Sidis data

Ignazio Scimemi, Work in progress with M. Bury, F. Hautmann, S. Leal Gomez, A. Vladimirov, P. Zurita

13-16/05/2021

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

TMD extraction

Factorization

$$\frac{d\sigma}{dQ^2dydq_T^2} = \sigma_0 \sum_{f_1,f_2} \int \frac{d^2\boldsymbol{b}}{4\pi} e^{i(\boldsymbol{b}\cdot\boldsymbol{q}_T)} H_{f_1f_2}(Q,\mu) F_{f_1\leftarrow h_1}(x_1,\boldsymbol{b};\mu,\zeta_1) F_{f_2\leftarrow h_2}(x_2,\boldsymbol{b};\mu,\zeta_2).$$

Scale-independent Factors!

$$\frac{d\sigma}{dQ^2dydq_T^2} = \sigma_0 \sum_{f_1,f_2} \int \frac{d^2\boldsymbol{b}}{4\pi} e^{i(\boldsymbol{b}\cdot\boldsymbol{q}_T)} H_{f_1f_2}(Q,Q) \{R[\boldsymbol{b};(Q,Q^2)]\}^2 F_{f_1\leftarrow h_1}(x_1,\boldsymbol{b}) F_{f_2\leftarrow h_2}(x_2,\boldsymbol{b})$$

3 independent functions.
All functions are scale independent in

ζ-prescription

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

TMDPDF: T. Gehrmann et al. JHEP 06 (2014) 155,

TMDPDF and TMDFF: M.G. Echevarria et al. Phys. Rev. D93 (2016) 011502, JHEP 09 (2016) 004

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

TMDFF: M. Ebert et al. e-Print:2012.07853

F

Unpolarized TMDPDF

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

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PDF ARE PART OF THE MODEL

NNLO TMDPDF: T. Gehrmann et al. JHEP 06 (2014) 155,
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TMDFF: M. Ebert et al. e-Print:2012.07853

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

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

NNLO-PDF

NLO-FF

Bottleneck!!!

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

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

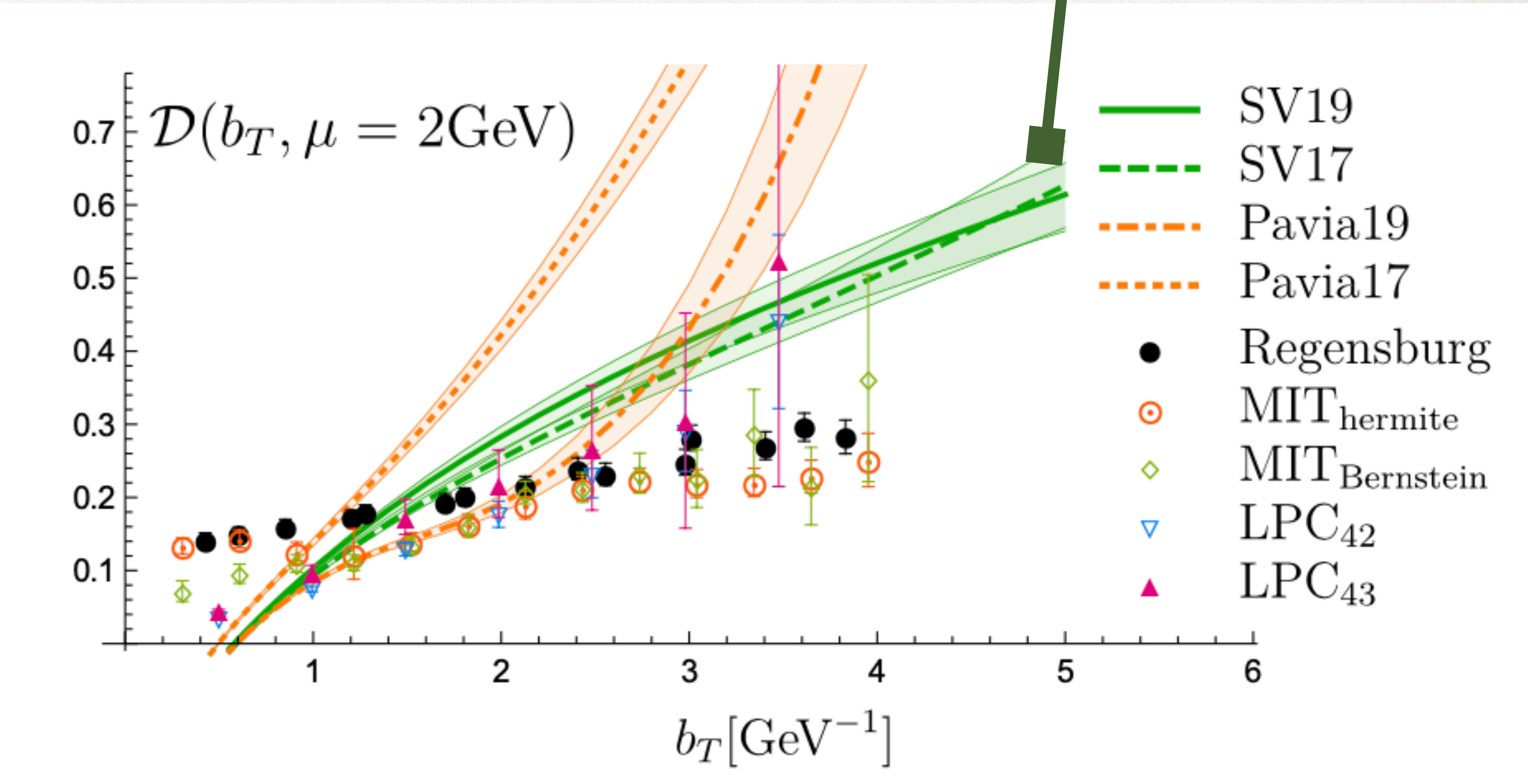
Ansatz for Artemide in SV19

The evolution

$$R(b, Q, \mu) = \left(\frac{Q^2}{\zeta_\mu[\mathcal{D}(b, \mu)]} \right)^{-2\mathcal{D}(b,\mu)}$$

$$\mathcal{D}(b, \mu) = \mathcal{D}_{\text{pert}}(b, \mu) + d_{\text{NP}}(b)$$

Consistency of extractions
Of the evolution kernel
In DY and DY+SIDIS



N3LO:
Y. Li, H.X. Zhu, Phys. Rev. Lett. 118, 022004 (2017)
A. Vladimirov, Phys. Rev. Lett. 118 (2017) 6, 062001

Unpolarized TMD and data

Fit from DY:

D'Alesio et al. JHEP11 (2014) 098 (Evolution kernel)

Bacchetta et al, JHEP06 (2017)081

I. S., A. Vladimirov Eur. Phys. J. C. 78 (2018) 2, 89 (Artemide)

V. Bertone, I.S., A. Vladimirov JHEP06 (2019) 028

A.Vladimirov JHEP10 (2019)090 (pion-proton)

V. Bertone et at. JHEP07(2020) 117 (Nangaparbat) (Pavia19)

M. Bury et al. In progress

Fit from DY+SIDIS: I. S., A.Vladimirov JHEP06 (2020) 137(SV19)

W-production: D. Gutierrez-Reyes, S. Leal-Gomez, I.S. e-print 2011.05351 [hep-ph]

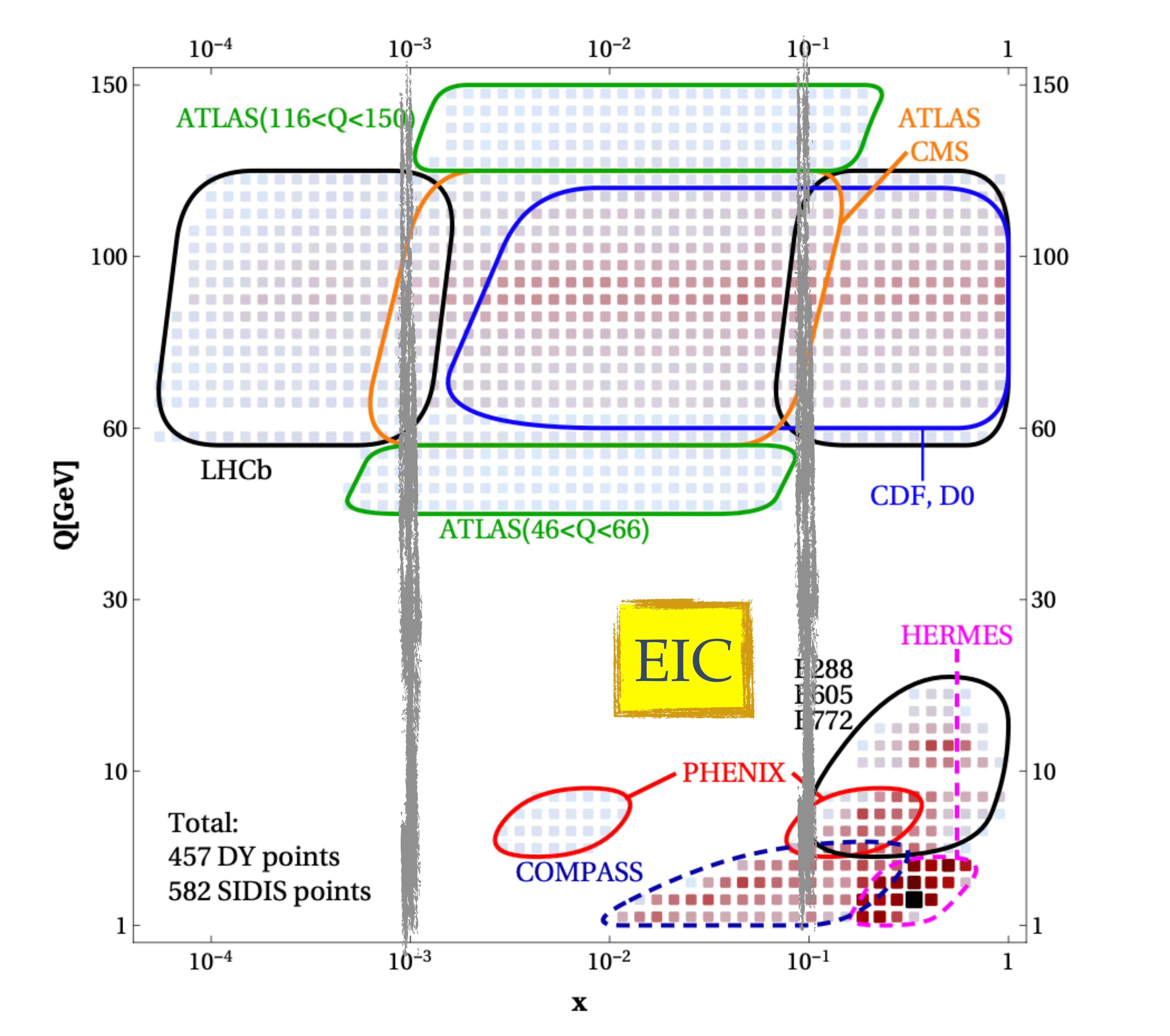
Open questions

- 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?

Data sets distributions

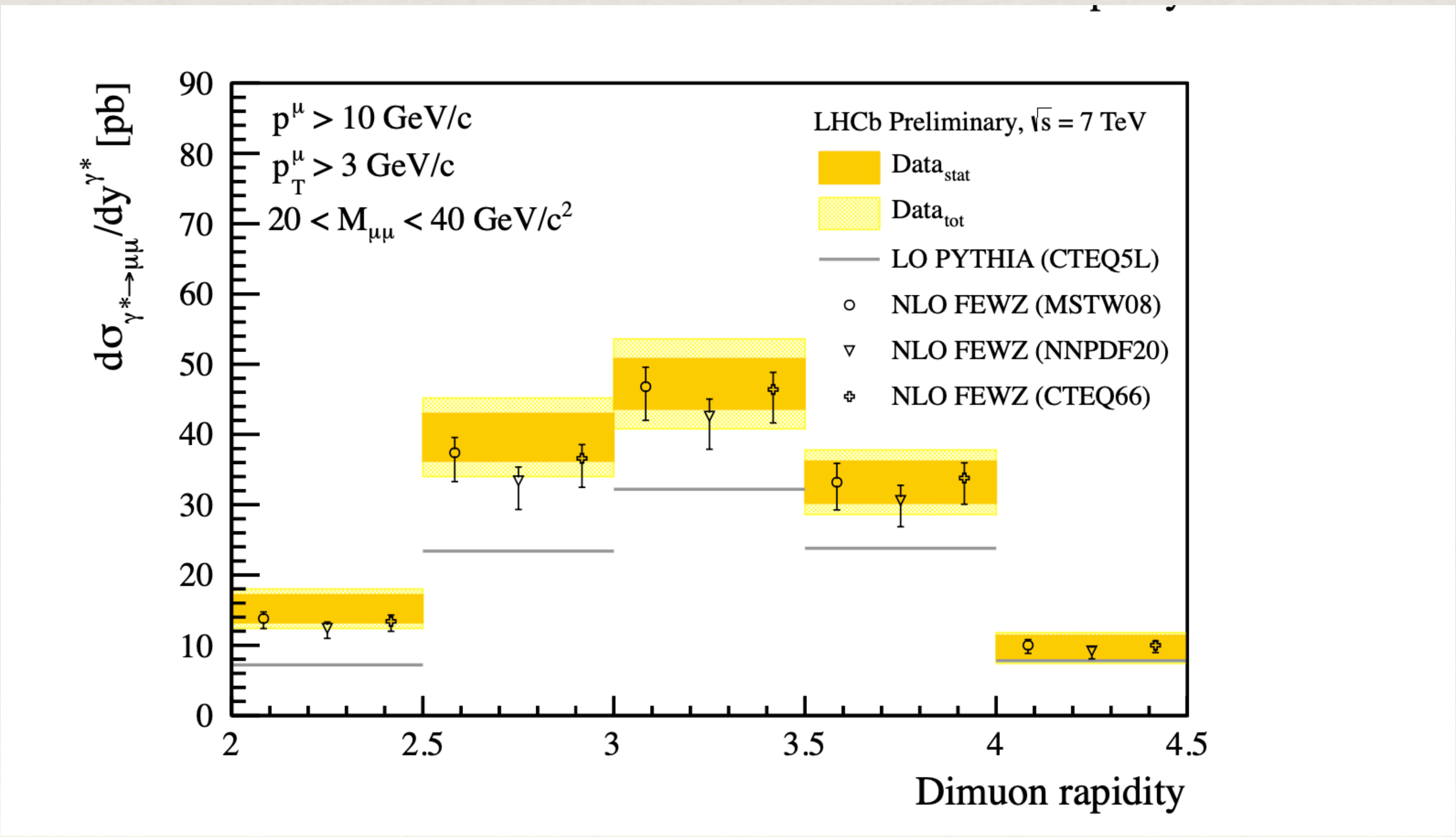
High Energy (only DY):
LHC+TeVatron

Low Energy (DY+SIDIS)



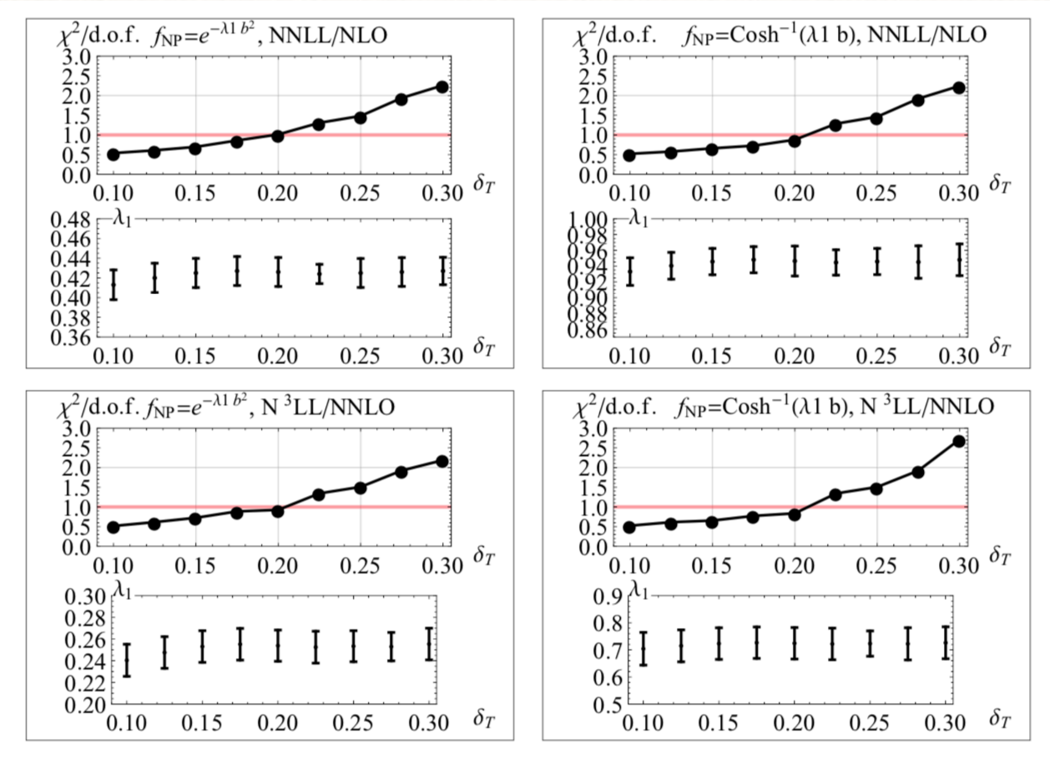
Forgotten data at LHC?

For TMD we need LHC data with low boson mass: ex. LHCb-CONF-2012-013 ; CERN-LHCb-CONF-2012-013

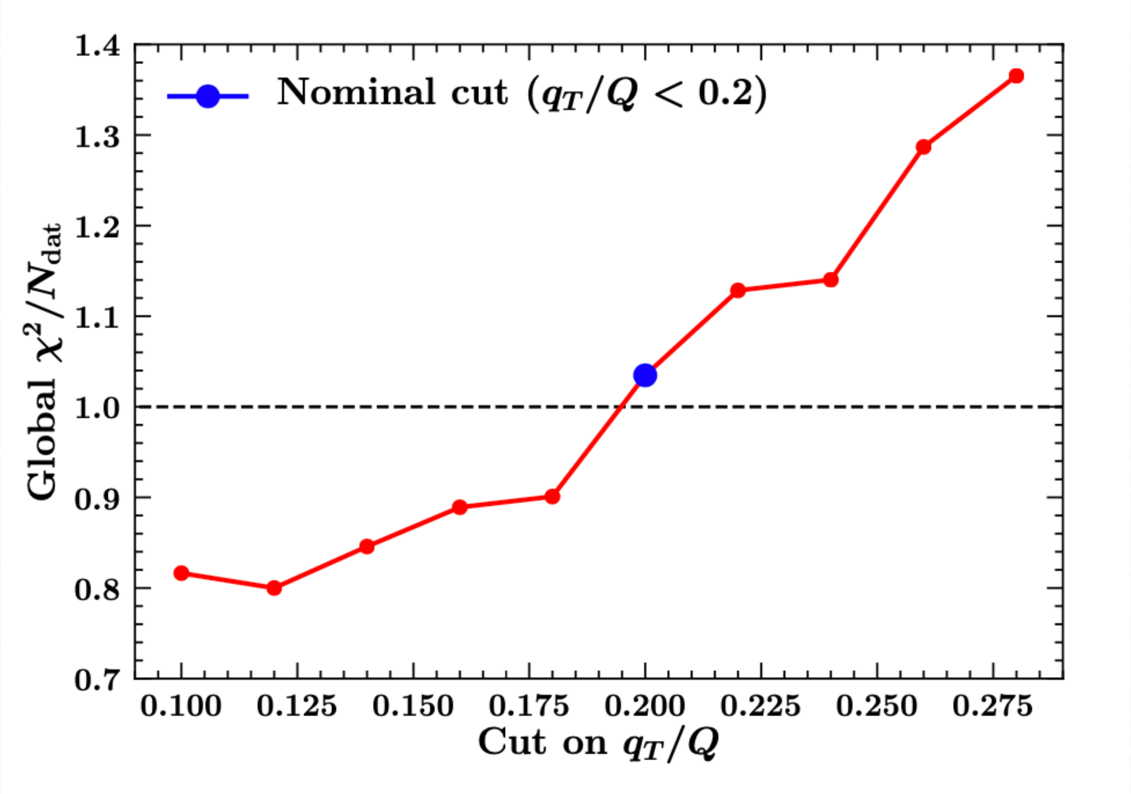


Please address trigger problem at ATLAS, CMS

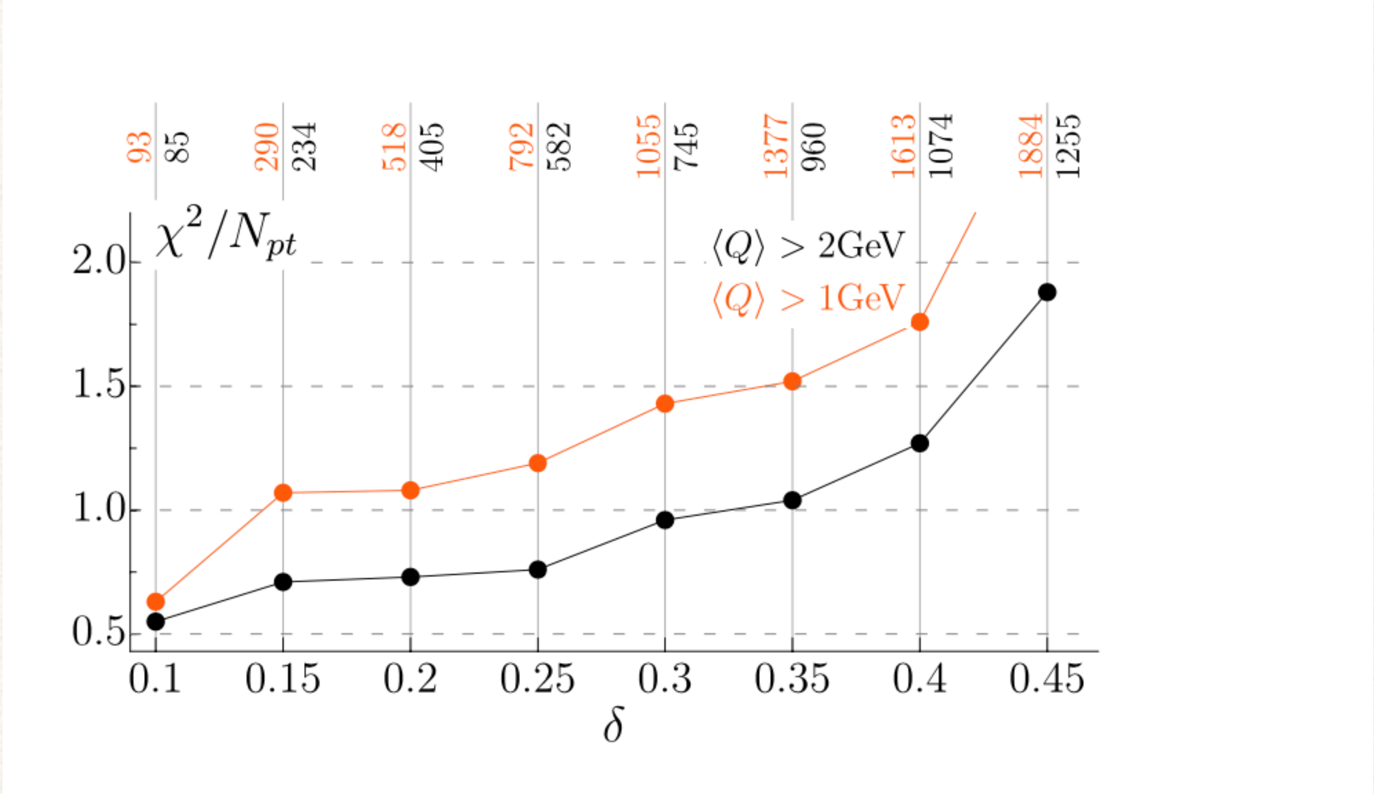
TMD validity range



SV17, DY



Pavia19, DY



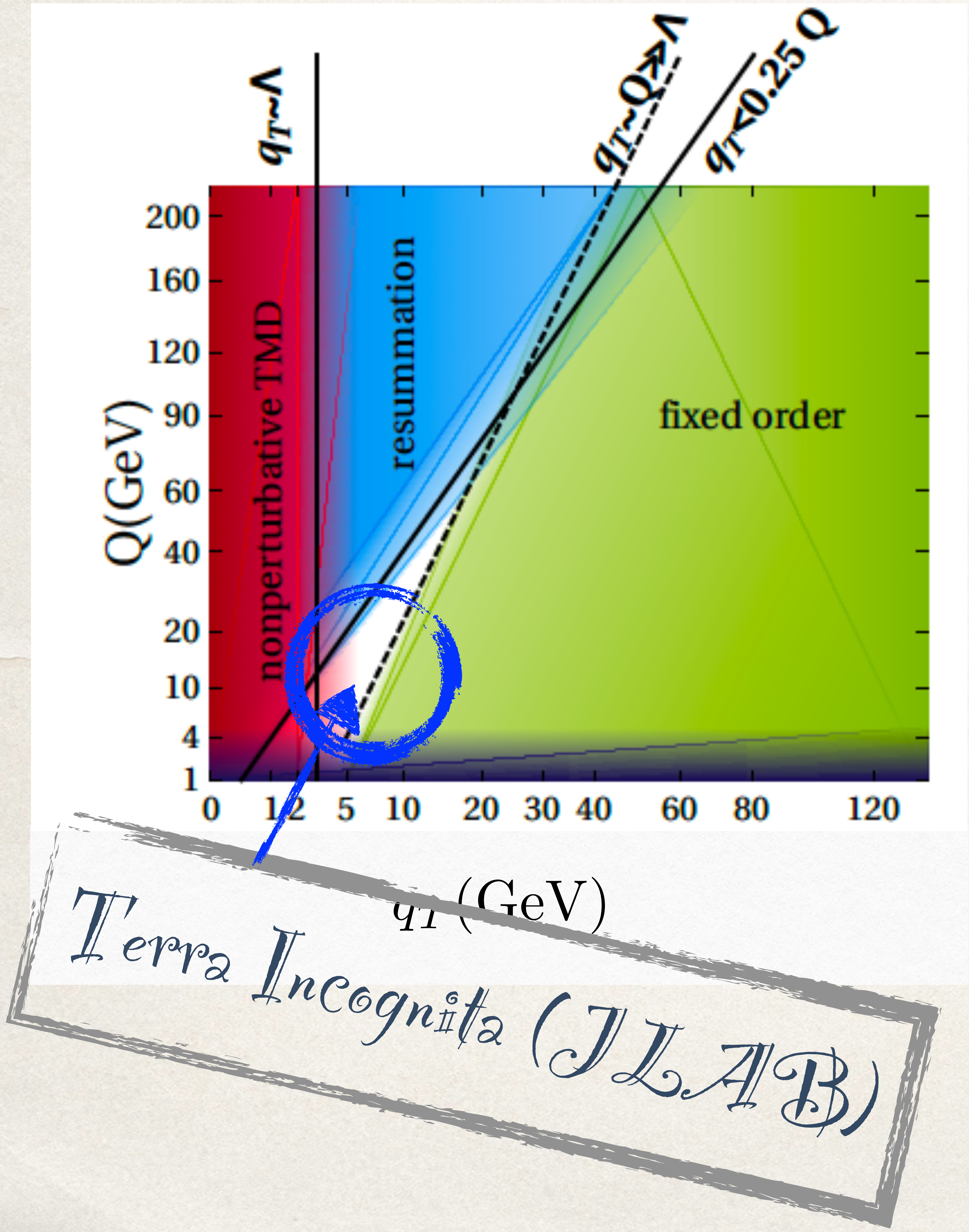
SV19, SIDIS

The range of validity of TMD is independent of models, implementation, perturbative order, experiment type

In SIDIS $\quad q_T \simeq p_\perp/z \to \delta = \dfrac{q_T}{Q} \simeq \dfrac{p_\perp}{zQ} < 0.25$

HERA data excluded, EIC necessary

TMD validity range



$q_T/Q \lesssim 0.25$

Resummation region

$q_T/Q \lesssim 0.25$ & $q_T/\Lambda \gg 1$ TMD factorization valid and dominated by perturbative effects

Non-perturbative TMD region

$q_T/Q \lesssim 0.25$ & $q_T/\Lambda \sim 1$ TMD factorization valid and dominated by non-perturbative effects

TMD and PDF

Do TMD fit quality depend on PDF set choice?
In principle the TMD is independent but …

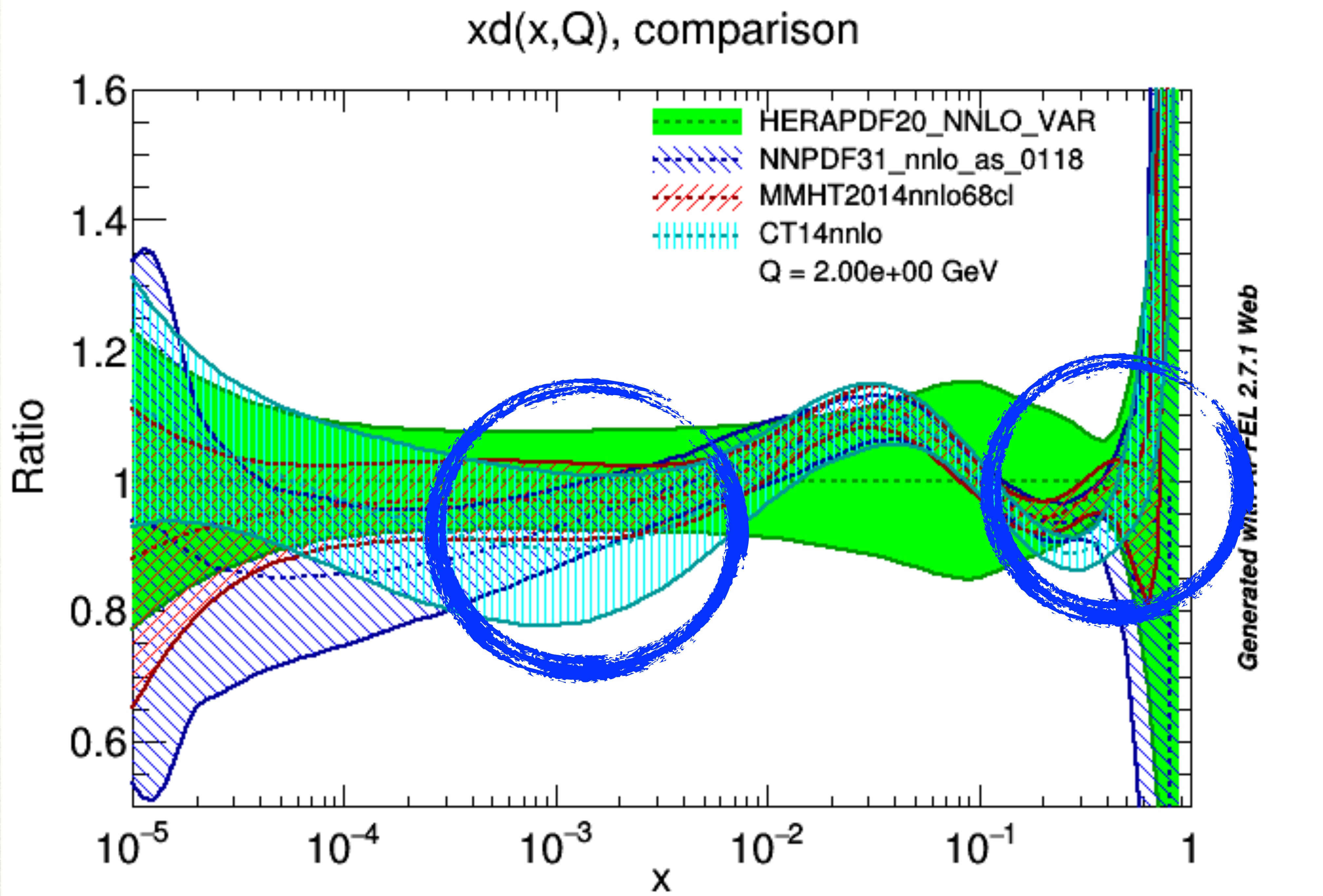
$$F_{f\leftarrow h}(x,\mathbf{b}) = \sum_{f'}\int_x^1 \frac{dy}{y} C_{f\leftarrow f'}(y, \mathbf{L}_{\mu_{\rm OPE}}, a_s(\mu_{\rm OPE})) f_{f'\leftarrow h}\left(\frac{x}{y}, \mu_{\rm OPE}\right) f_{\rm NP}(x,b)$$

Matching (Wilson) coefficient NNLO

PDF

Gaussian?
Exponential?

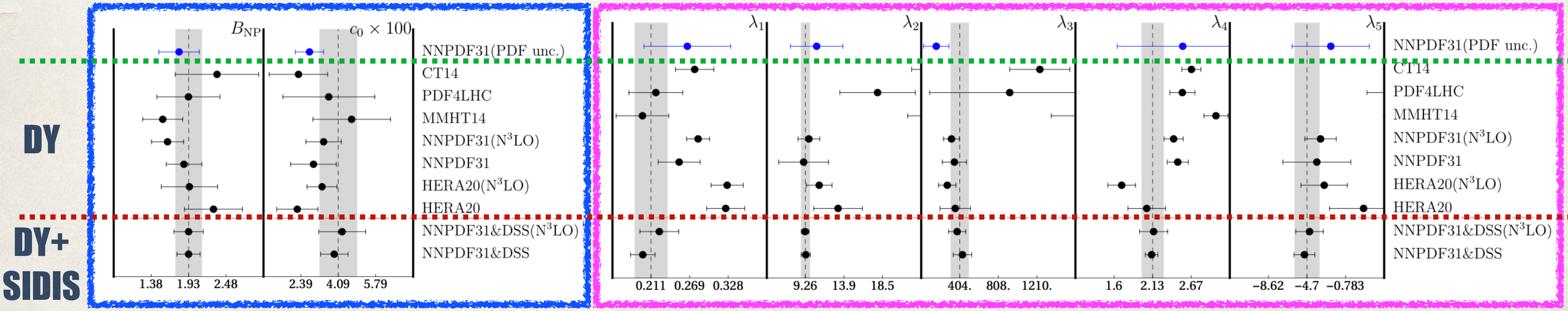
- Every PDF set has its own error band
- Spread among different sets



Differences among PDF sets are visible in TMD physics

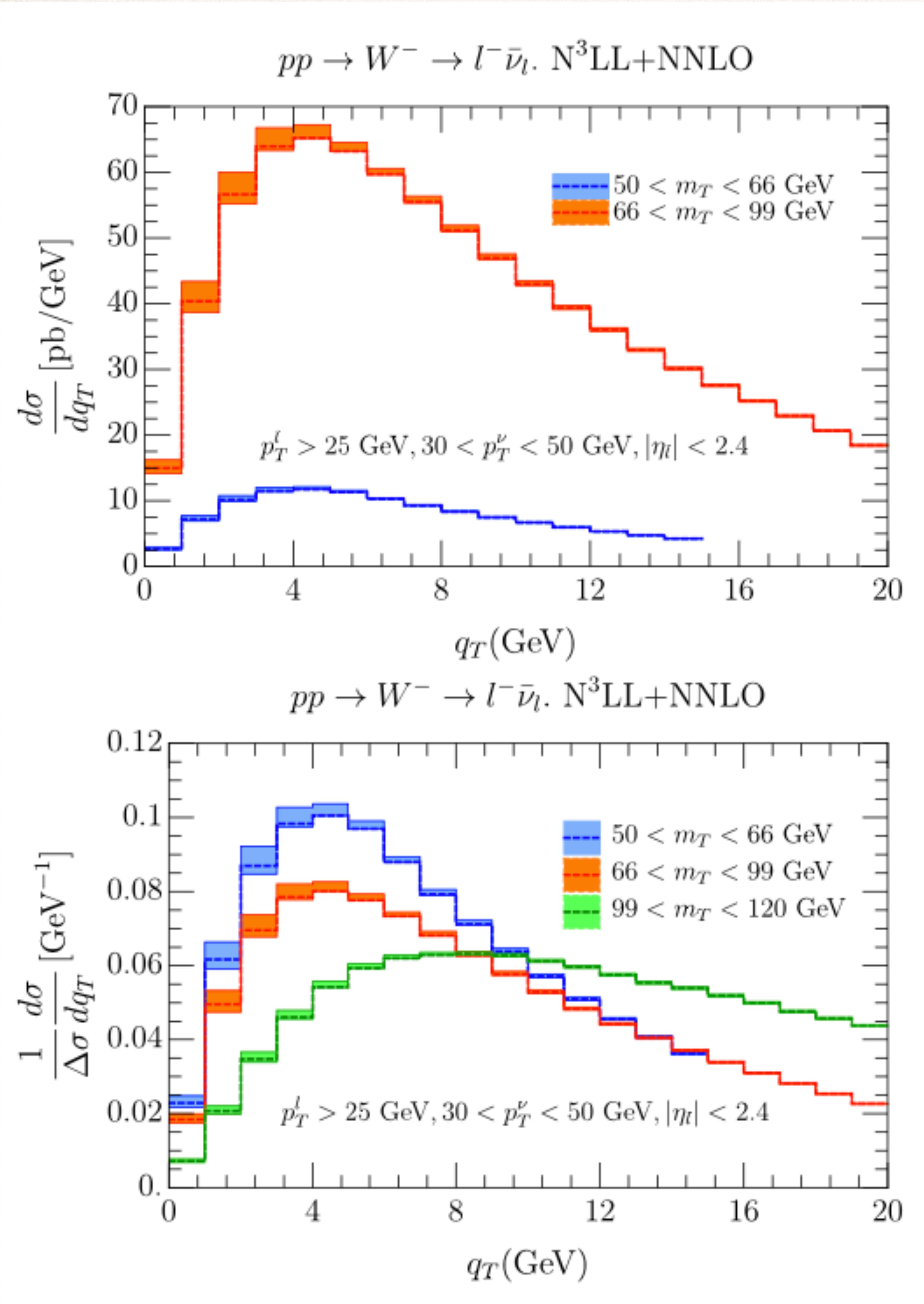
DY fit from I.S., A. Vladimirov *JHEP* 06 (2020) 137

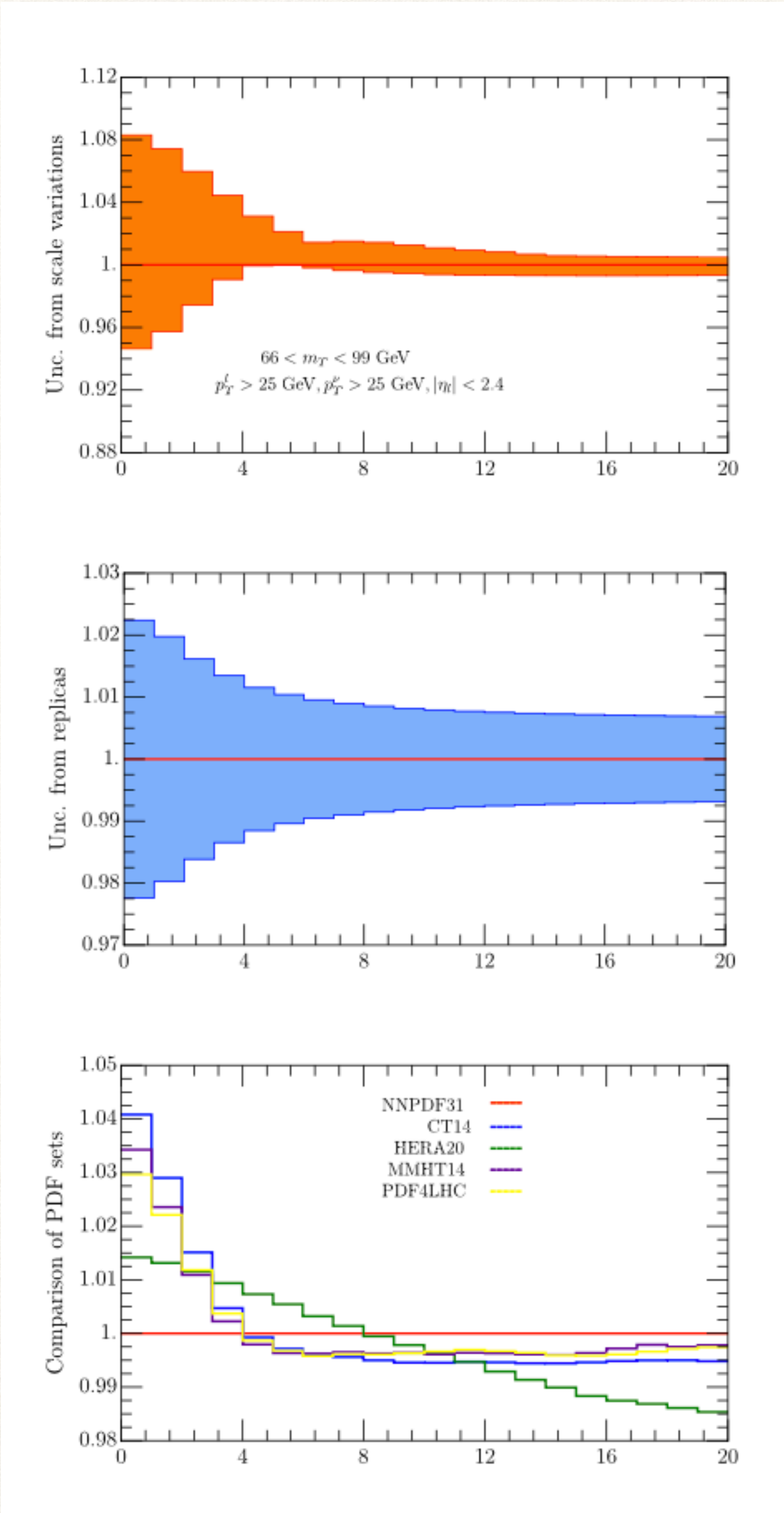
PDF set	χ^2/N_{pt}	Parameters for $\mathcal{D}$	Parameters for f_1	
HERA20	0.97	$B_{\rm NP} = 2.29 \pm 0.43$ $c_0 = (2.22 \pm 0.93) \cdot 10^{-2}$	$\lambda_1 = 0.324 \pm 0.029$ $\lambda_2 = 13.2 \pm 2.9$	$\lambda_3 = (3.56 \pm 1.59) \cdot 10^2$ $\lambda_4 = 2.05 \pm 0.26$ $\lambda_5 = -10.4 \pm 3.5$
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	$B_{\rm NP} = 2.35 \pm 0.61$ $c_0 = (2.27 \pm 1.33) \cdot 10^{-2}$	$\lambda_1 = 0.277 \pm 0.029$ $\lambda_2 = 24.9 \pm 2.9$	$\lambda_3 = (12.4 \pm 3.2) \cdot 10^3$ $\lambda_4 = 2.67 \pm 0.13$ $\lambda_5 = -23.8 \pm 2.9$



TMD uncertainties in W production

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





Scale uncertainty
(More study in the future)

Replicas for
NNPDF31_nnlo_118

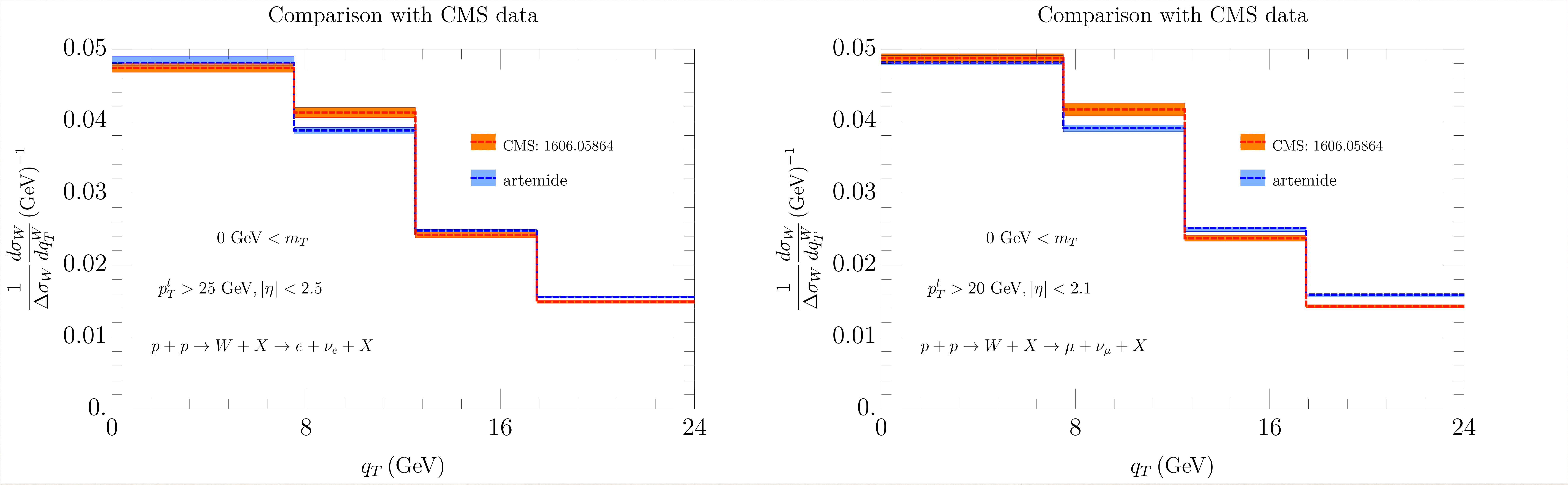
PDF sets

TMD uncertainties in W production

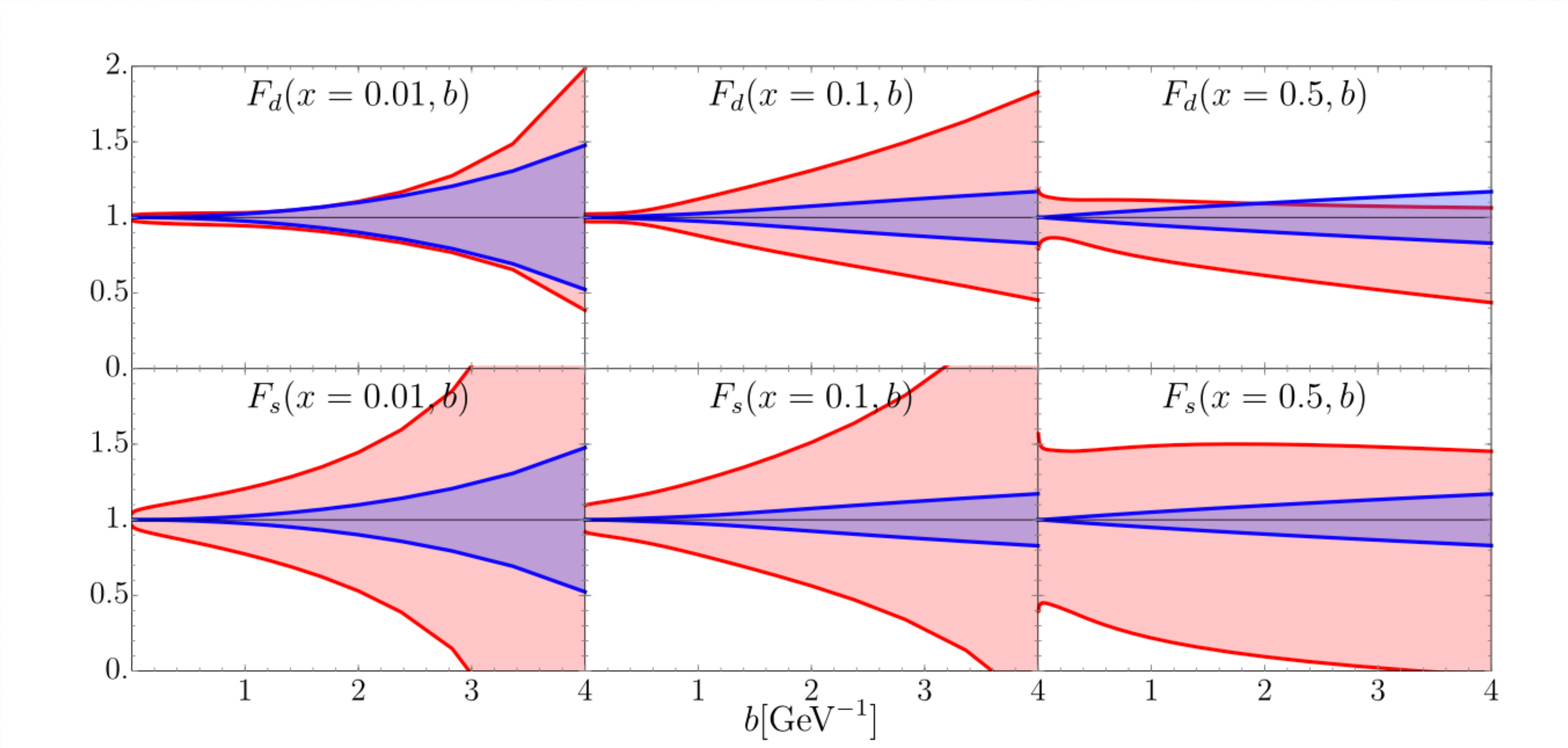
D. Gutierrez-Reyes,
S. Leal-Gomez, I.S.
arXiv: 2011.05351

χ^2/N includes PDF, data and theoretical error

	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	4
NNPDF31	0.540	1.485	0.463	1.674	3.165
HERA20	0.469	1.591	0.271	1.563	3.721



TMD uncertainties from a single PDF set



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

Experimental uncertainty

PDF uncertainty (replicas, NNPDF31_nnlo_118)

TMD and PDF sets: bias removing

- Spread among different sets

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

SV19 ansatz:

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

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

BHLSVZ21 ansatz:

$f_{NP}(x,b)$ … $\lambda_2 x + x(1-x)\lambda_5\, \boldsymbol{b}^2$ …

$D_{NP}(x,b) = \exp\left(-\frac{\ldots}{\sqrt{1+\eta_3(\ldots}}\right.$ …

Top Secret: Preliminary

The non-perturbative ansatz used in previous fits is too rigid:

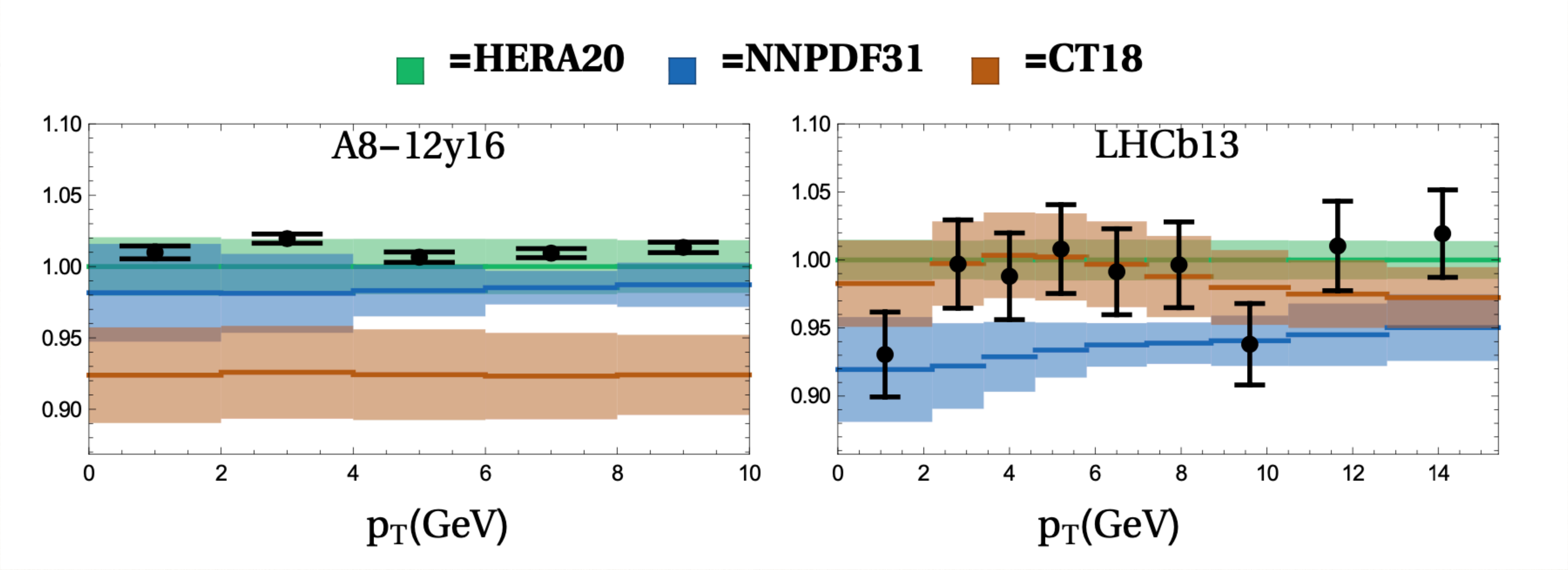
We need flavor dependence of the ansatz to compensate the differences in different PDF sets

TMD and PDF sets: preliminary results

PDF	χ^2/N
NNPDF31	0.97
HERA20	0.90
CT18	0.98
MSHT20	0.88

The spread in the fit quality does not depend on PDF sets

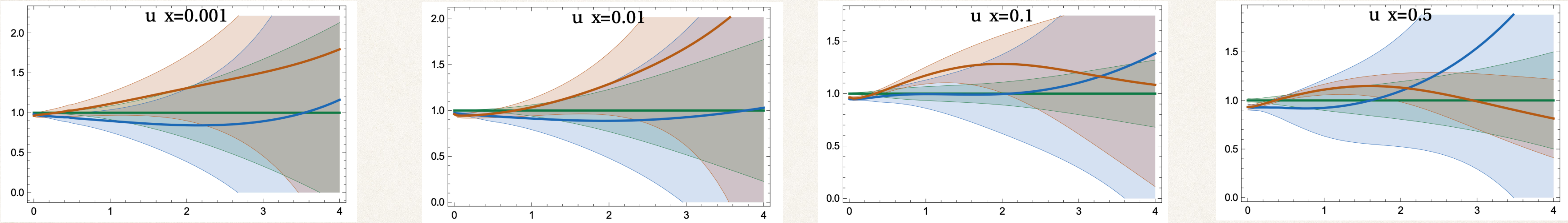
TMD uncertainties from PDF sets



The goodness of a set depends on x

TMD uncertainties from PDF sets

TMD(PDF set)/TMD(HERA) vs b



Conclusions

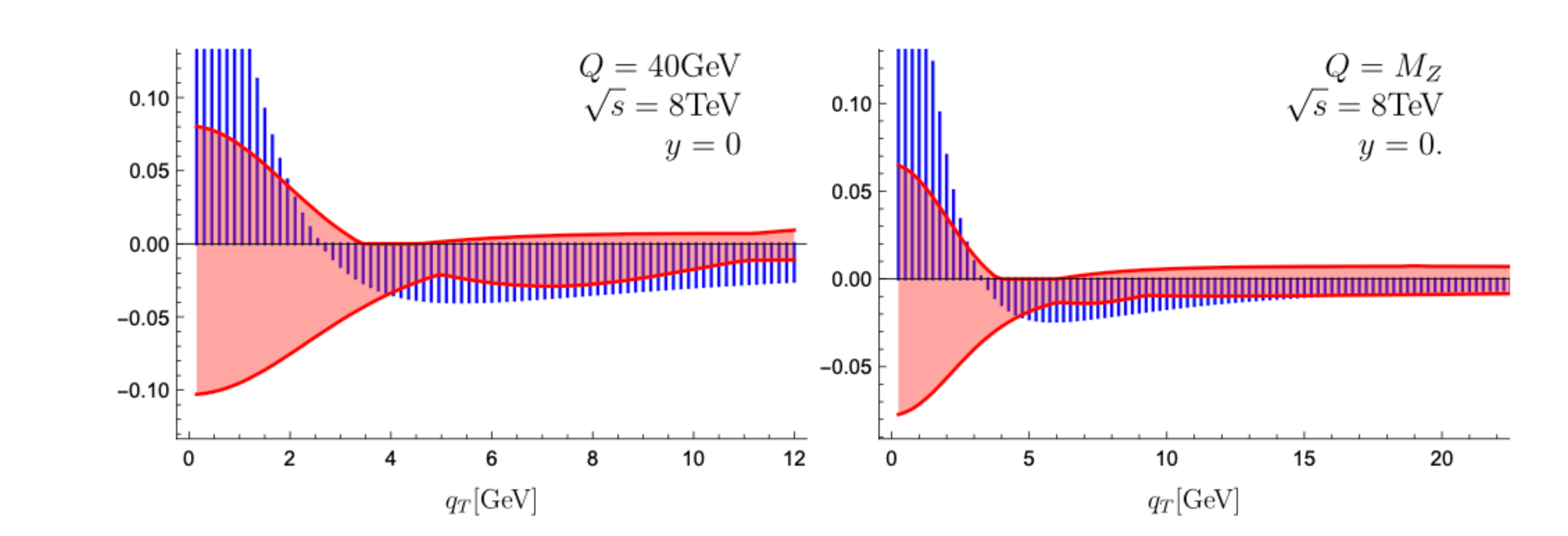
- Great progress in the extraction of unpolarized TMD: Higher order perturbative extractions available. The critical point is the inclusion of collinear functions in TMD extractions (NNLO fragmentation functions are needed)
- W production is included in Artemide. W and DY data at LHC can be largely improved looking at neglected regions of phase space
- JLAB and EIC are/will be exploring fundamental regions of phase space
- PDF set dependence of TMD is removed with flavor dependent models

Back slides

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

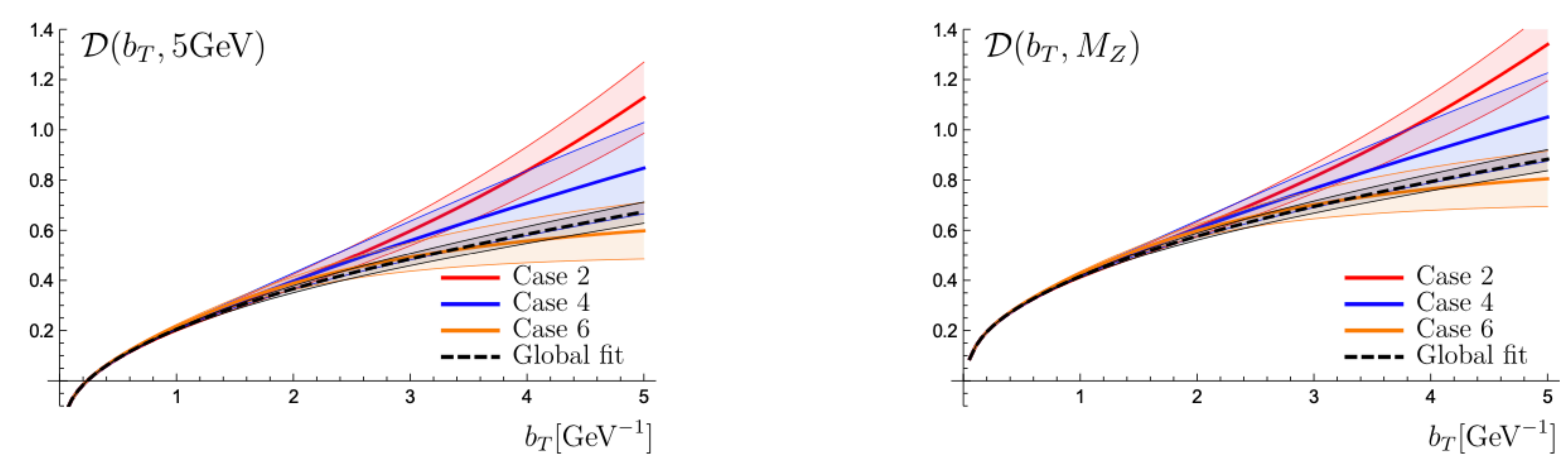


F. Hautmann, I.S., A. Vladimirov *Phys.Lett.B* 806 (2020) 135478

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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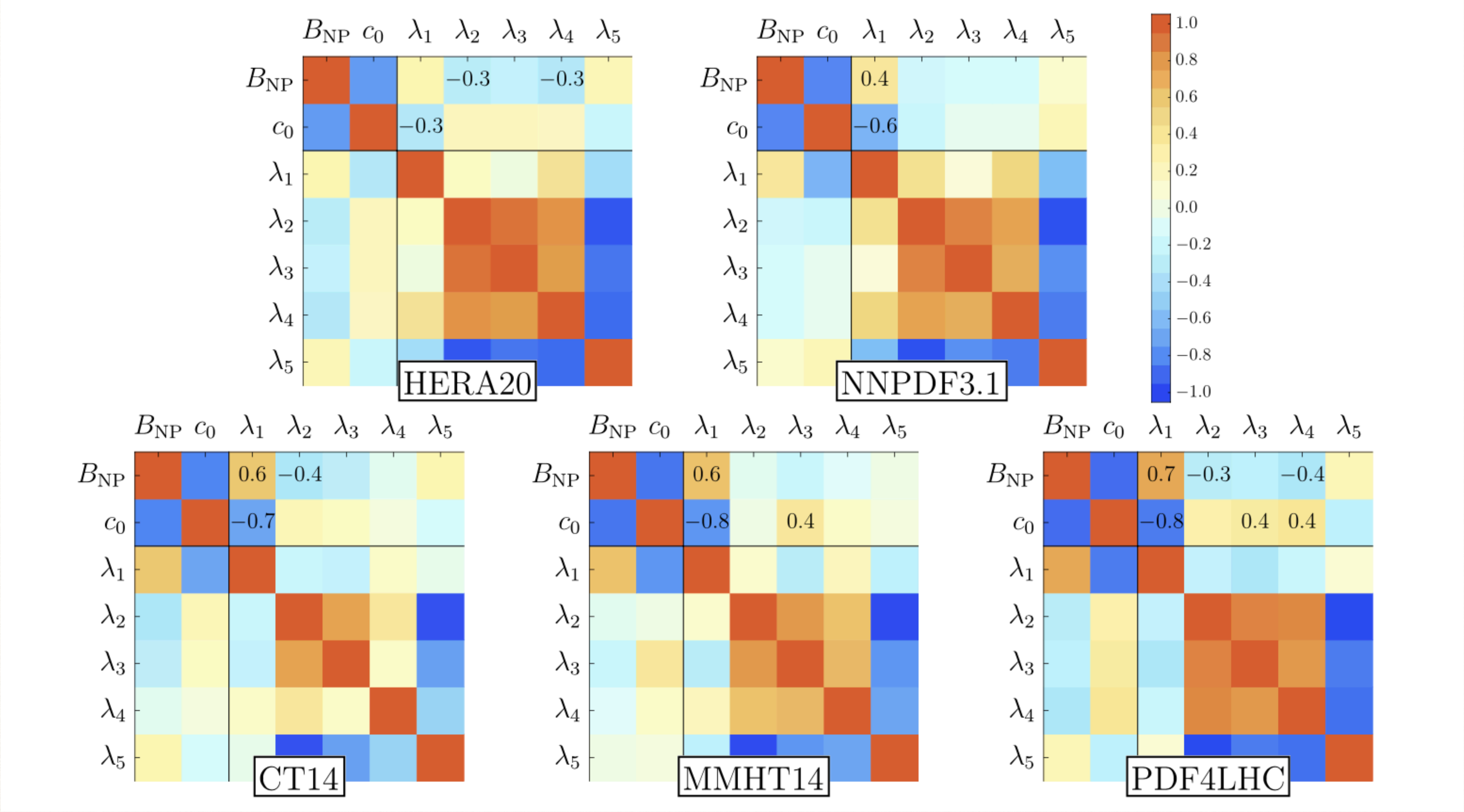
Correlation of parameters



F. Hautmann, I.S., A. Vladimirov *Phys.Lett.B* 806 (2020) 135478