QCD EVOLUTION 2021

Using TMD formalism for predictions of W and Z spectrum

Ignazio Scimemi, in collaboration with D. Gutierrez-Reyes, S. Leal-Gomez, hep-ph/2011.05351

10-14/05/2021

Outline

- Status of the extraction of unpolarized TMD: DY, SIDIS (see talk of A. Vladimirov).
- Predictions for unexplored boson spectrum: Errors
- Predictions for W (Z) spectrum
- Surprise!!

General considerations on TMD extraction

Factorization

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

Separation of NP effects in evolution kernel and TMD

ζ-prescription

Scale-independent Factors!

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

3 independent functions.
All functions are scale independent in

Data selection

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

Statistical methods: replicas of exp

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

RESULTS

Unpolarized TMDPDF

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

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

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

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

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

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

NNLO-PDF

NLO-FF

Bottleneck!!!

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

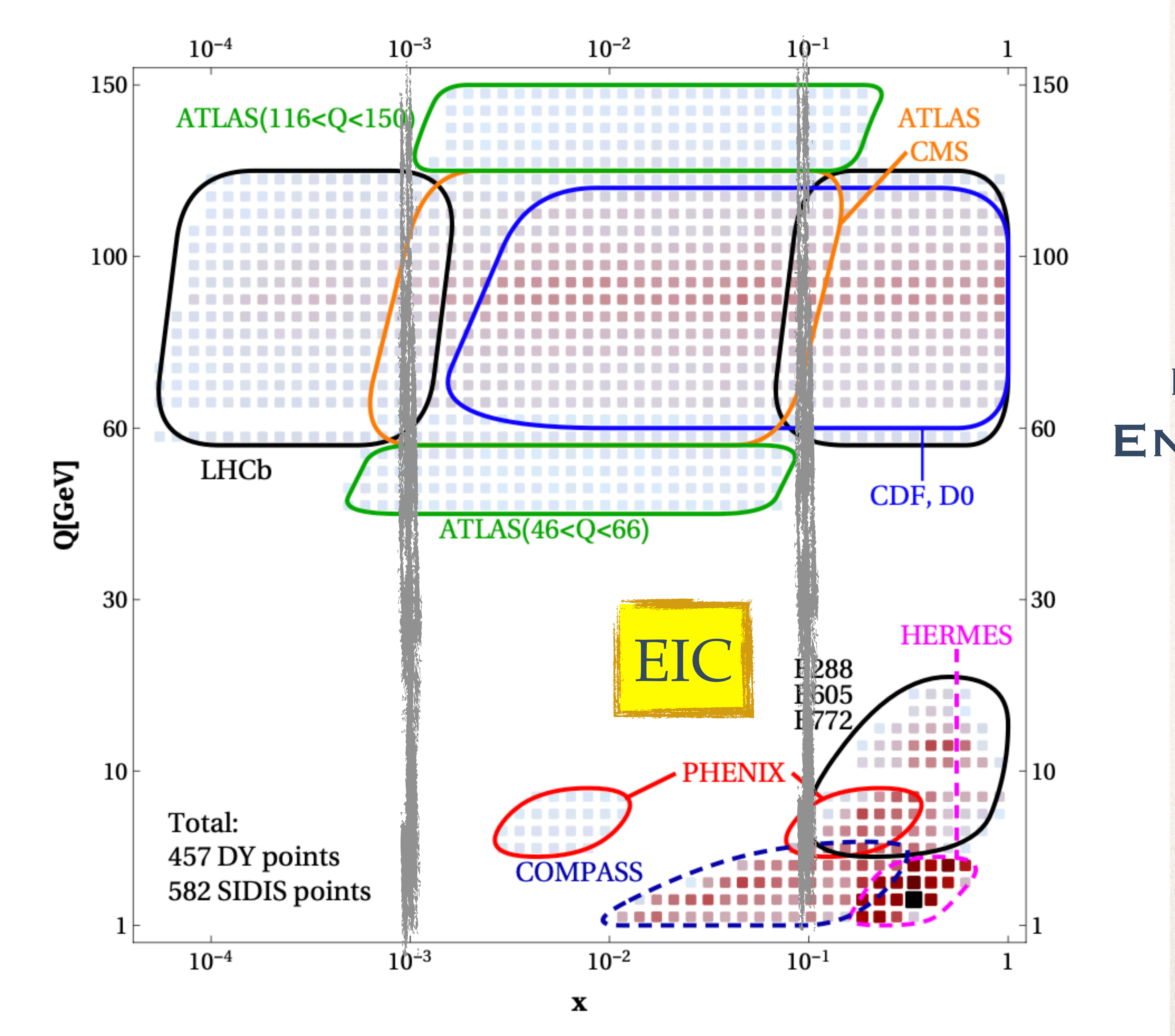
$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right),$$

Ansatz for Artemide in SV19

Data sets distributions

High Energy (only DY):
LHC+TeVatron

Low Energy (DY+SIDIS)



DY+SIDIS data depend on several flavor combination: Enough for predictions

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)

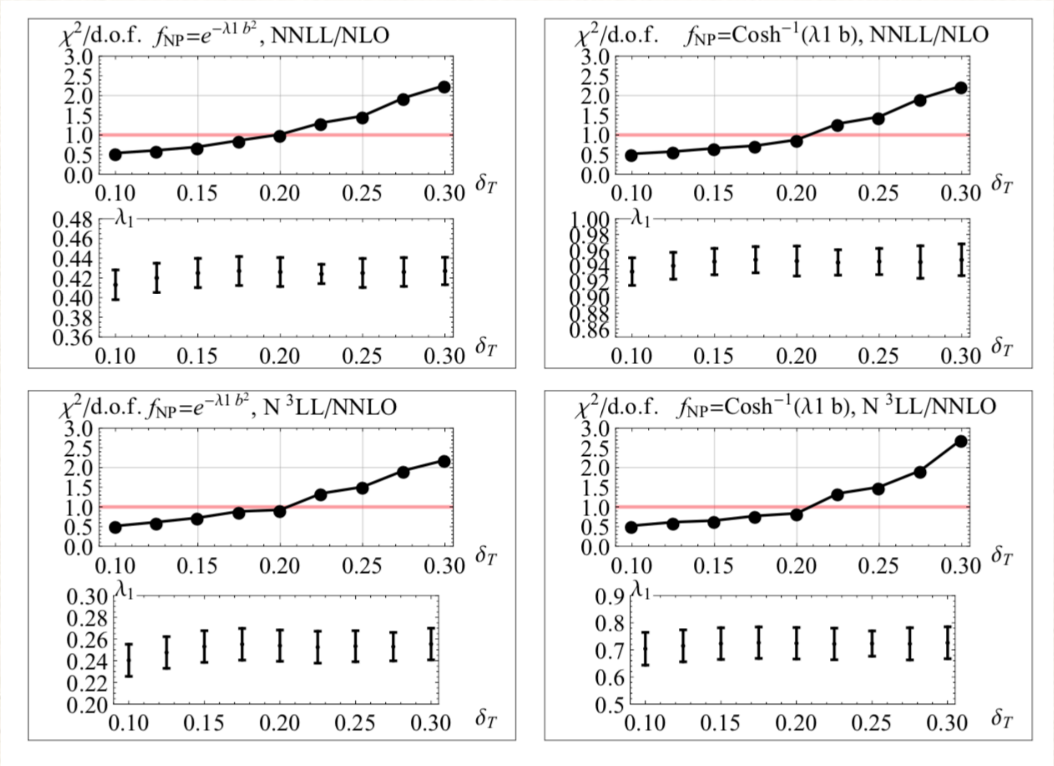
V. Bertone et at. JHEP07(2020) 117 (Nangaparbat) (Pavia19)

M. Bury et al. In progress

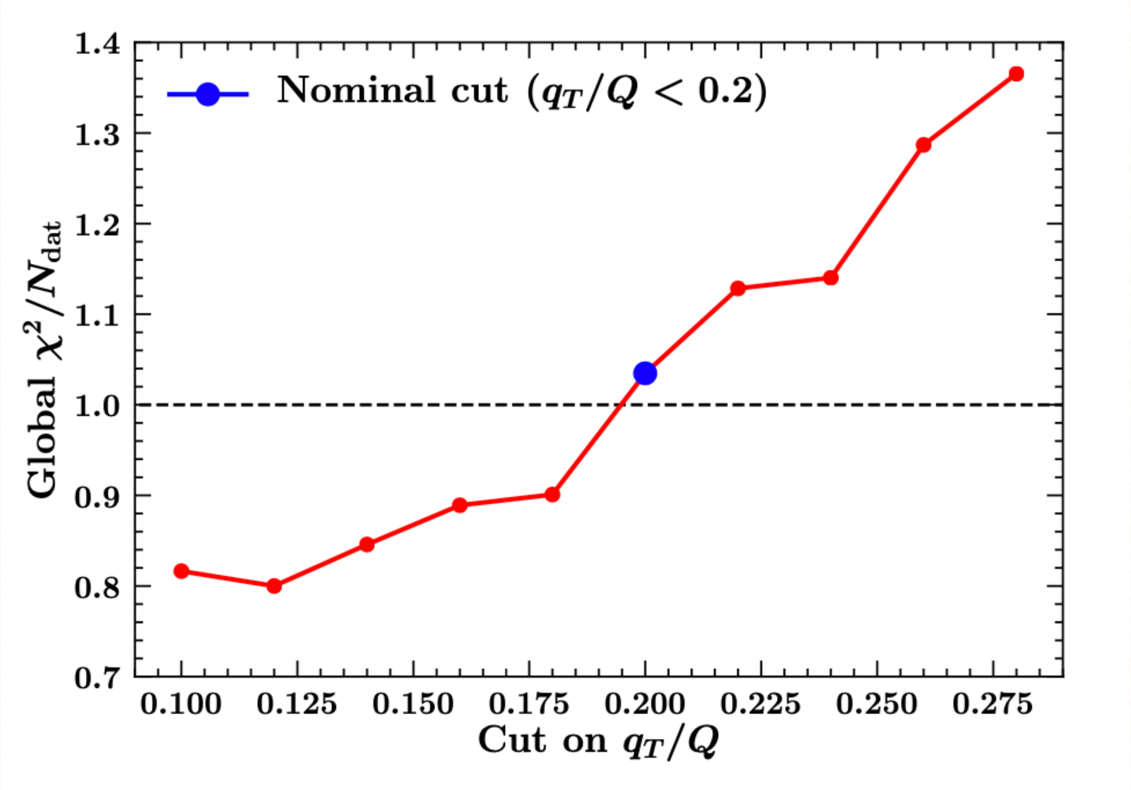
Fit from DY+SIDIS: I. S., A.Vladimirov JHEP06 (2020) 137(SV19)

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

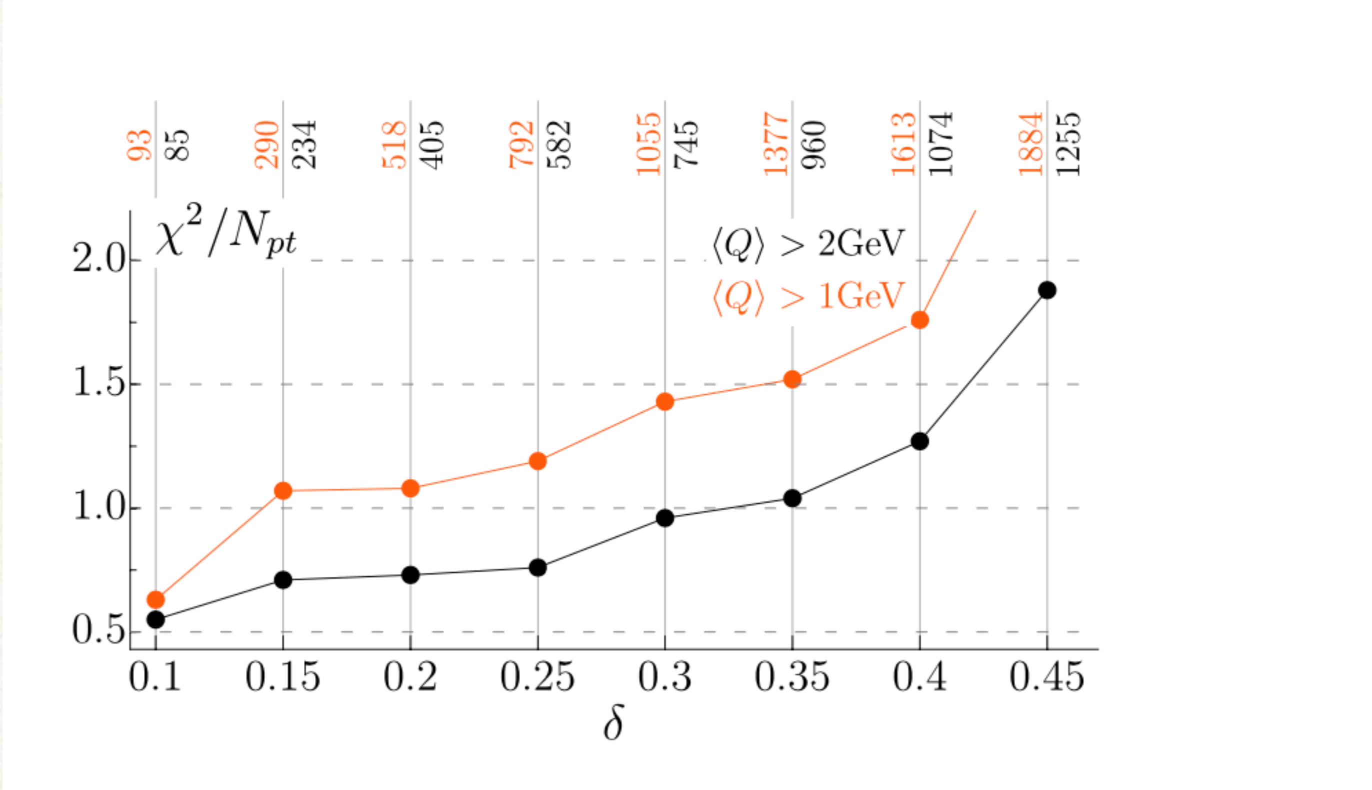
TMD validity range



SV17, DY



Pavia19, DY



SV19, SIDIS

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

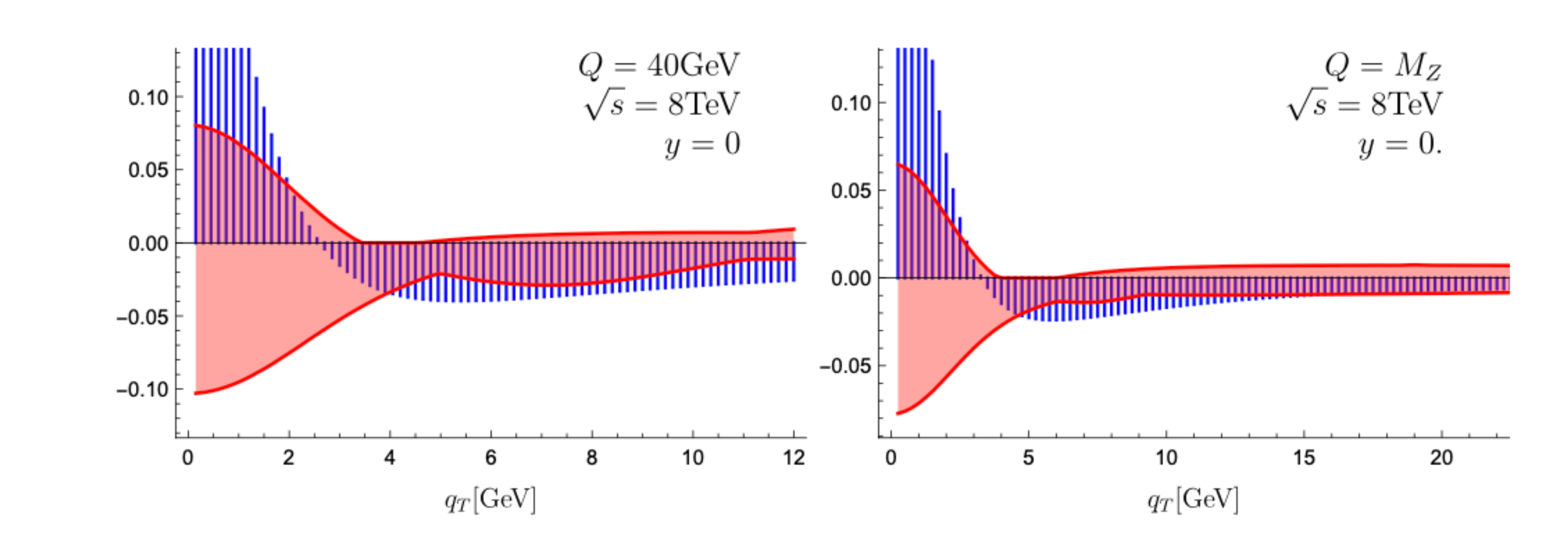
In SIDIS $\quad q_T \simeq p_\perp/z \to \delta = \dfrac{q_T}{Q} \simeq \dfrac{p_\perp}{zQ} < 0.25$

HERA data excluded, EIC necessary

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

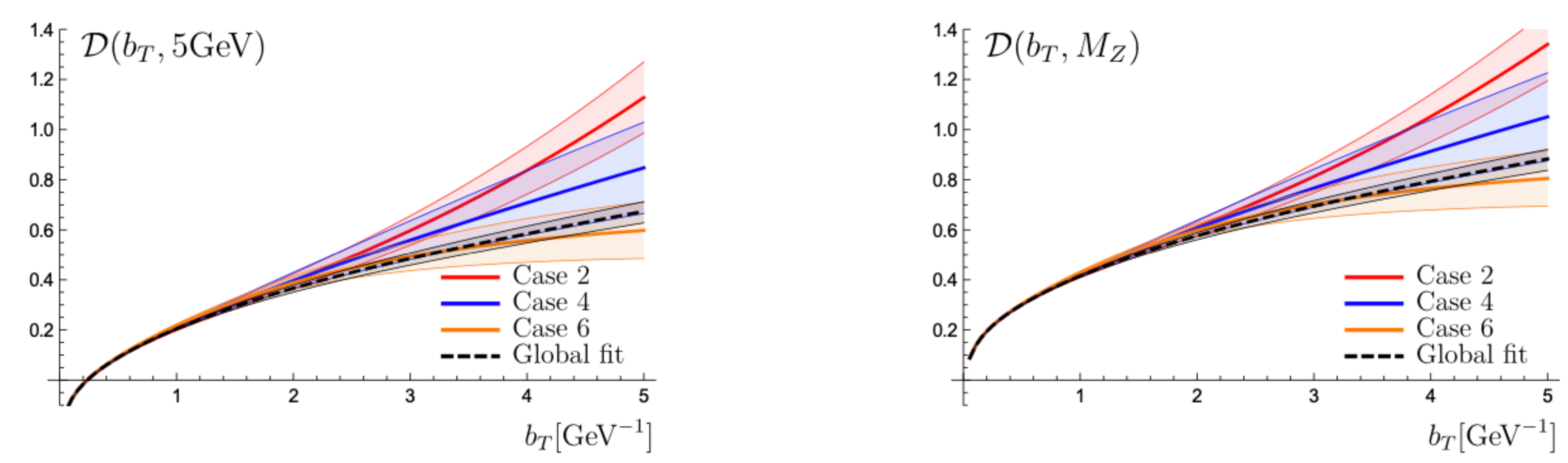
Non perturbative TMD effects at LHC

We have tested several simple models 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



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

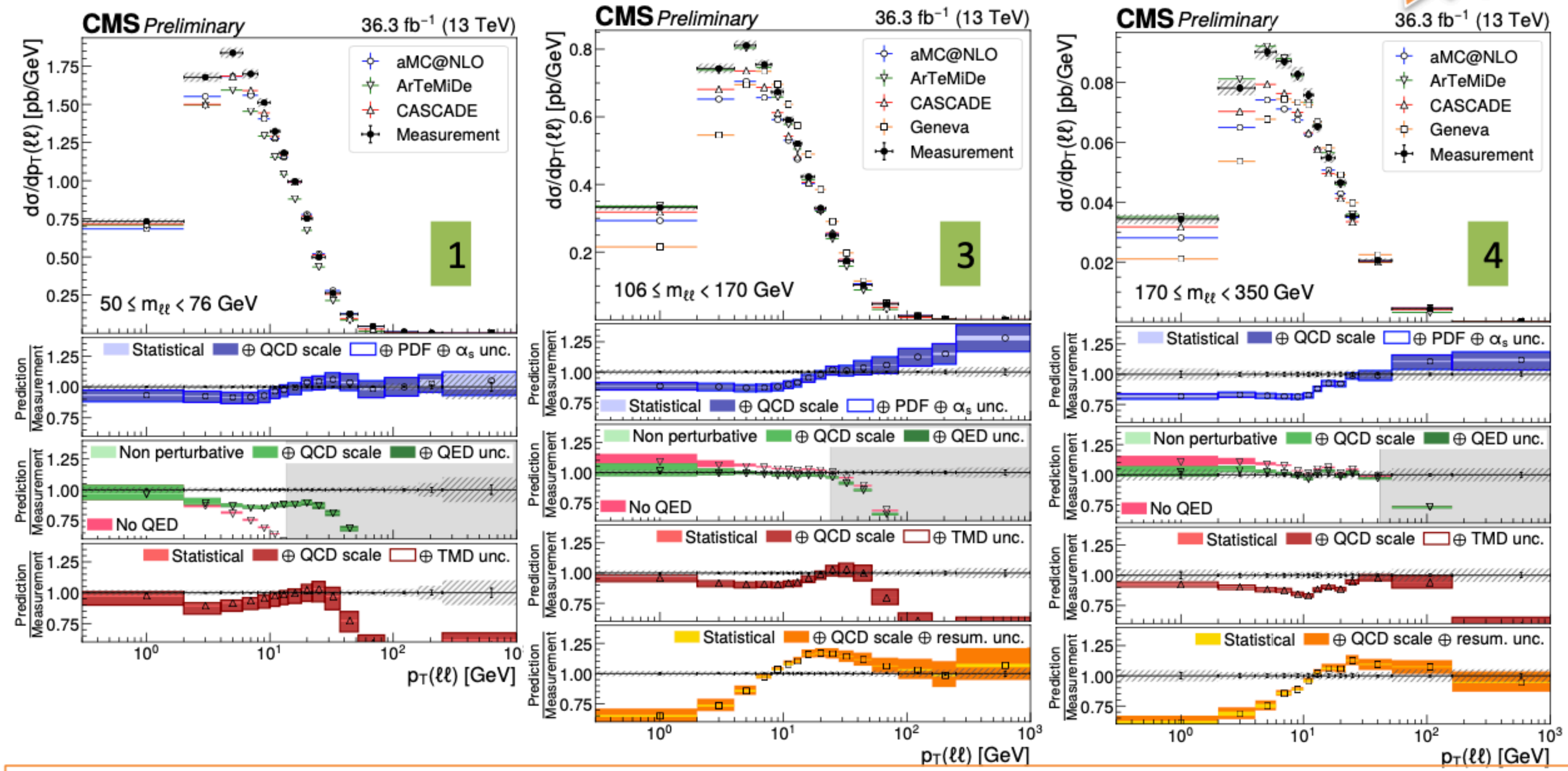
Drell-Yan pT dependence over a wide mass range

PAS-SMP-20-003

36.3 fb^{-1}

Unfolded to fiducial space

NEW



See talk of Louis Moureaux

→ amc@NLO+ Pyhthia8 gives overall good description

→ Failing to describe the low p_T, failure increasing for higher m(ll)

→ Cascade (amc@NLO 0j + PBTMD) describes the low p_T better fails at high p_T due to missing orders in ME

→ ArTeMiDe gives the best description in its validity region

→ GENEVA predicts a harder p_T spectrum (α_s choice)

B. Bilin DIS2021

W production

$h_1 h_2 \to W^+(W^-) \to l^+(l^-) + \nu_l(\bar{\nu}_l)$

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

- We need to control the ratio qT/Q
- The fiducial cross section

$$\frac{d\sigma}{dm_T^2 dy dq_T^2} = \int_0^\infty \frac{dQ^2}{Q^4} \frac{8}{N_c} \frac{\alpha_{\text{em}}^2}{s} I_W(Q^2, q_T, m_T^2) \frac{1}{(4s_W^2)^2} \frac{Q^4}{(Q^2 - M_W^2)^2 + \Gamma_W^2 M_W^2}$$
$$\times \sum_{ff'} |V_{ff'}|^2 e_f e_{f'} W_{f_1 f_1}^{ff'}(Q^2, q_T, x_1, x_2).$$

Transverse mass definition in the leptonic tensor

$$I_W(Q^2, m_T^2, q_T) = \int \frac{d^3 l}{2E} \frac{d^3 l'}{2E'} [ll' - (ll')_T] \theta(\text{cuts}) \delta^{(4)}(l + l' - q) \delta(Q^2 - m_T^2 - f(l, l'))$$

W production

$$h_1 h_2 \to W^+(W^-) \to l^+(l^-) + \nu_l(\bar{\nu}_l)$$

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

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Hadronic tensor

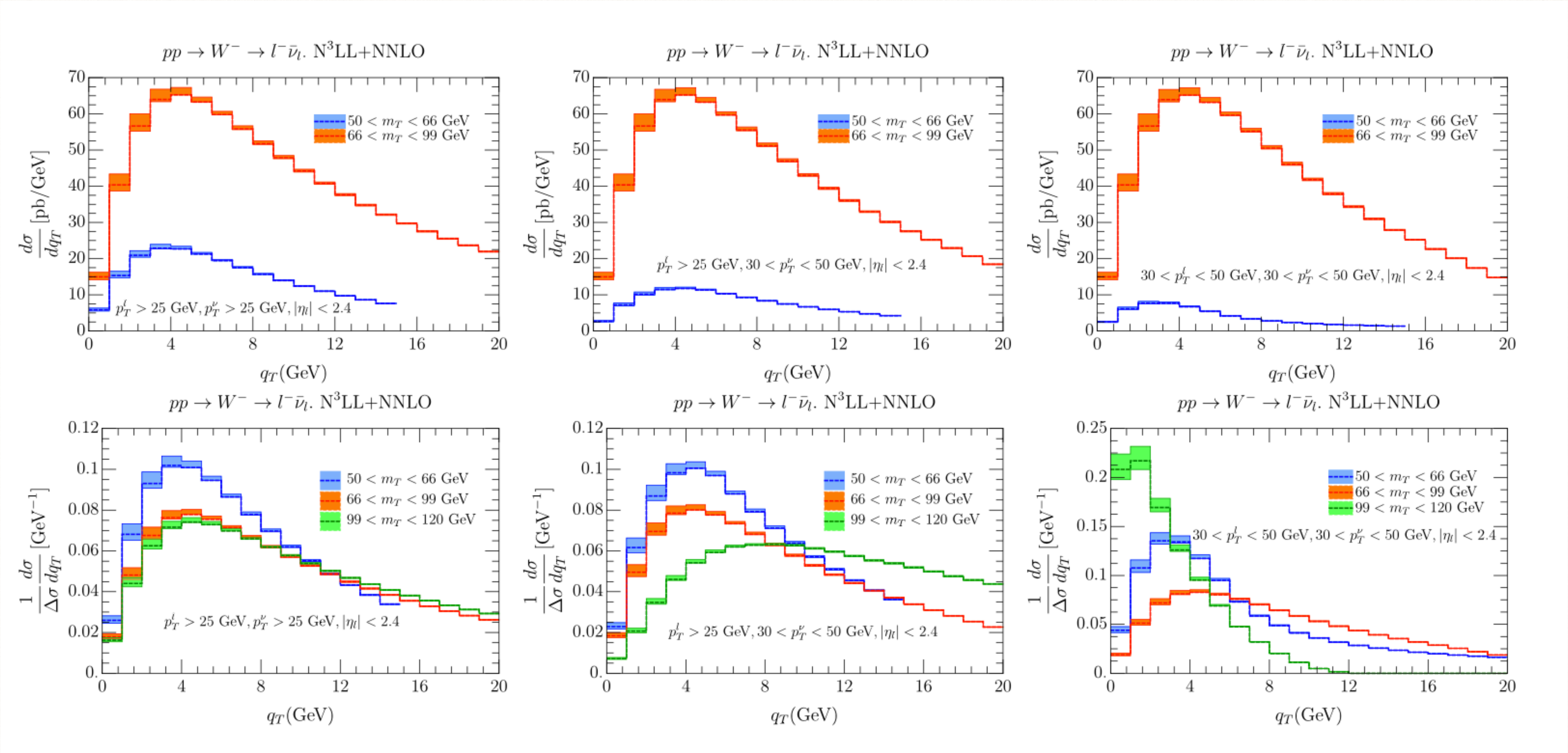
$$W_{f_1 f_1}^{ff'}(Q, q_T, x_1, x_2, \mu, \zeta) = \int \frac{|\mathbf{b}| d|\mathbf{b}|}{2} J_0(|\mathbf{b}||\mathbf{q}|) f_{1,f\leftarrow q}(x_1, \mathbf{b}, \mu, \zeta) f_{1,f'\leftarrow q}(x_2, \mathbf{b}, \mu, \zeta)$$

W production

$$h_1 h_2 \to W^+(W^-) \to l^+(l^-) + \nu_l(\bar{\nu}_l)$$

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

- We need to control the ratio qT/Q
- The fiducial cross section
- Relevant intervals (for reference ATLAS 13 TeV)



Theoretical errors…

…Theoretical uncertainties in QCD analysis (classical)…

MATCHING SCALES

Hard Scale

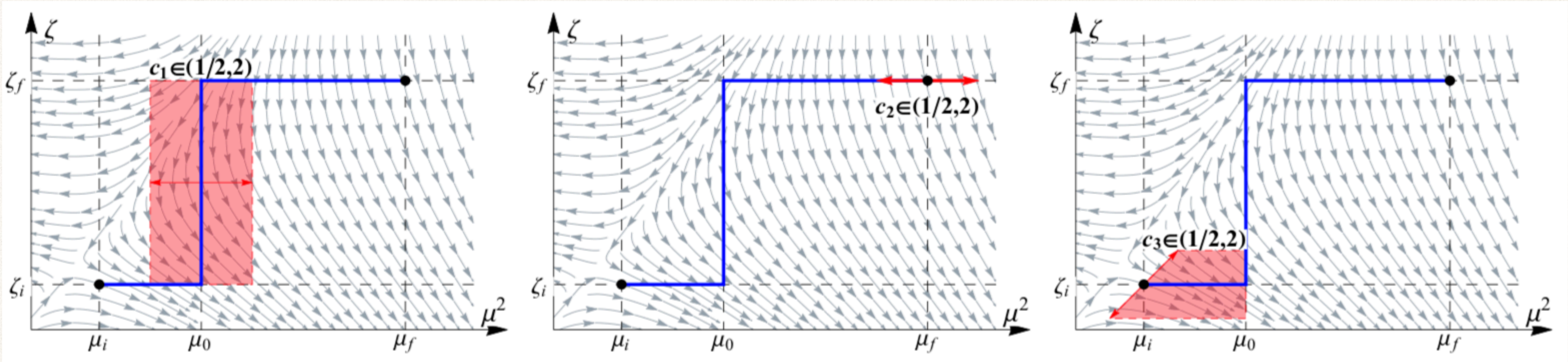
Low Scale

$$\frac{d\sigma}{dQ^2 dy d(q_T^2)} = \frac{4\pi}{3N_c}\frac{\mathcal{P}}{sQ^2}\sum_{GG'} z_{ll'}^{GG'}(q)\sum_{ff'} z_{ff'}^{GG'}\int\frac{d^2\vec{b}}{4\pi}e^{i(\vec{b}\vec{q})}|C_V(Q,c_2Q)|^2\Big\{R^f[\vec{b};(c_2Q,Q^2)\to(c_3\mu_i,\zeta_{c_3\mu_i});c_1\mu_i]\Big\}$$
$$\times F_{f\leftarrow h_1}(x,\vec{b};c_4\mu_{\mathrm{OPE}},\zeta_{c_4\mu_{\mathrm{OPE}}})F_{f'\leftarrow h_2}(x,\vec{b};c_4\mu_{\mathrm{OPE}},\zeta_{c_4\mu_{\mathrm{OPE}}})$$

Rapidity Evolution

Small b Scale

Scale variations in zeta-prescription



- ~~c_1 measure only solution dependence~~
- c_2 measure mismatch between H and R + solution dependence
- ~~c_3 measure mismatch between F and R + solution dependence~~
- c_4 measure mismatch between C and f

Eliminated by gamma-scenario

Included in c2 by optimal TMD definition

Matching to PDF scale variation

$$\mu_{\mathrm{OPE}} = \left(\frac{C_0}{b} + 2\right) c_4 \;(\textit{Naive, these plots: overestimate in the non-perturbative region})$$

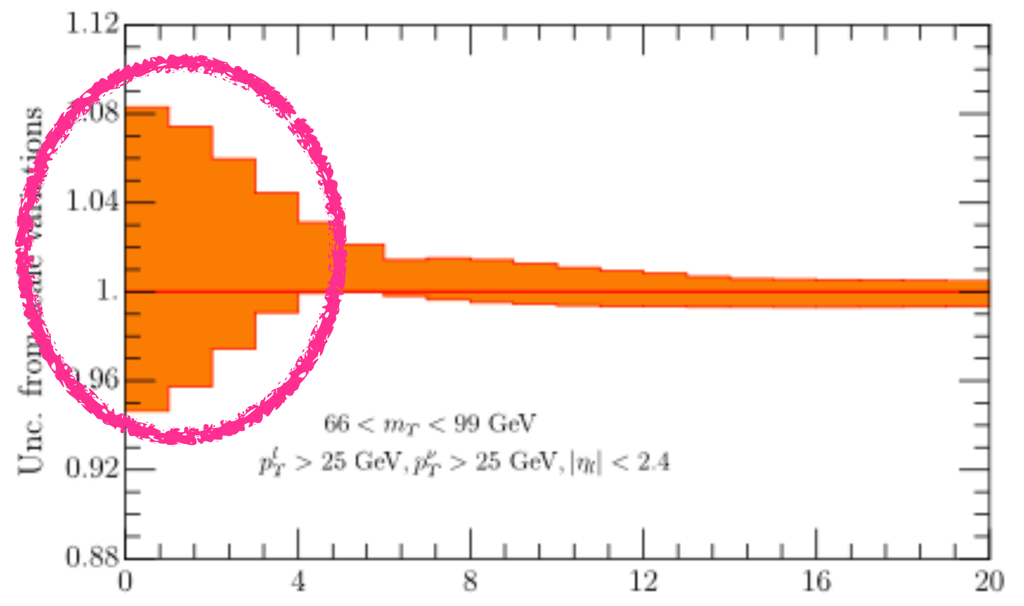
$$\mu_{\mathrm{OPE}} = \left(\frac{C_0}{b} c_4 + 2\right) \;(\textit{Future plots: error estimate in the perturbative region})$$

Input of the model

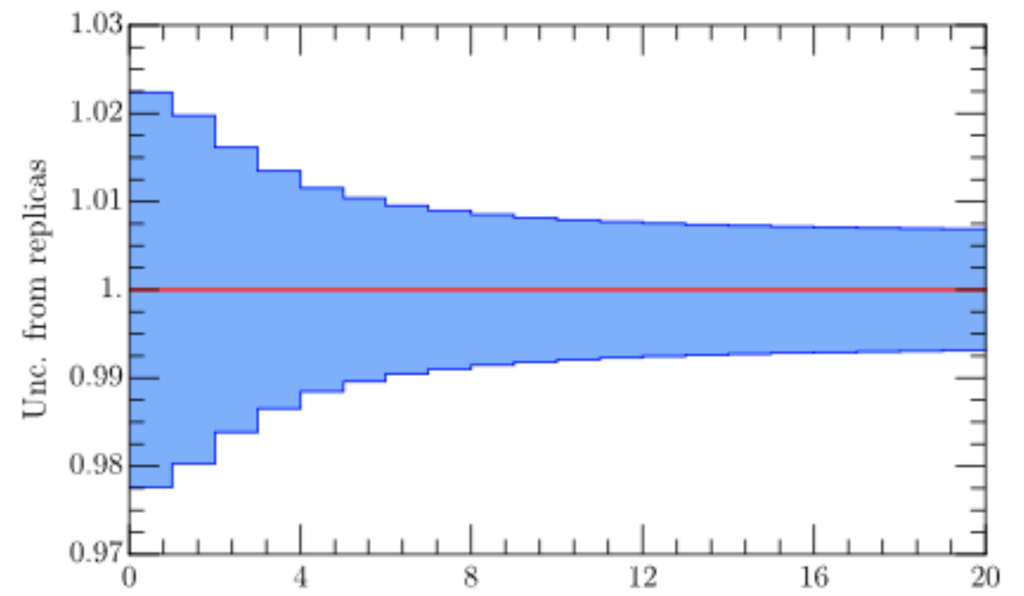
Errors in W^- spectrum

- The first 3 errors are the main ones: Work in progress to reduce some of them (scale variation, PDF sets: I. Scimemi talk at DIS2021)

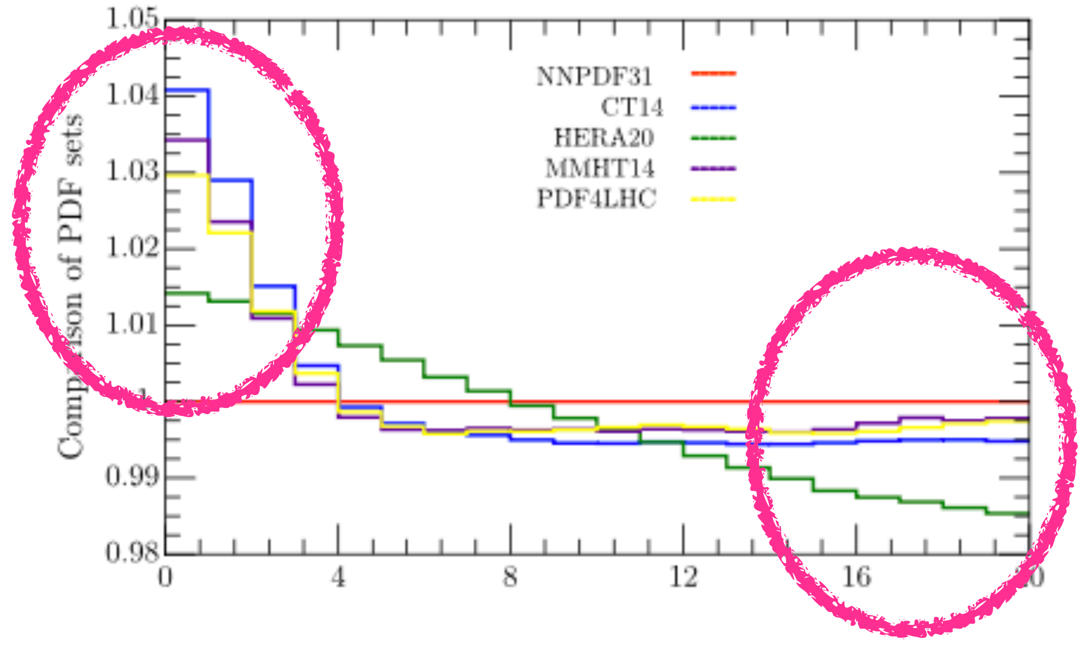
Scale variations



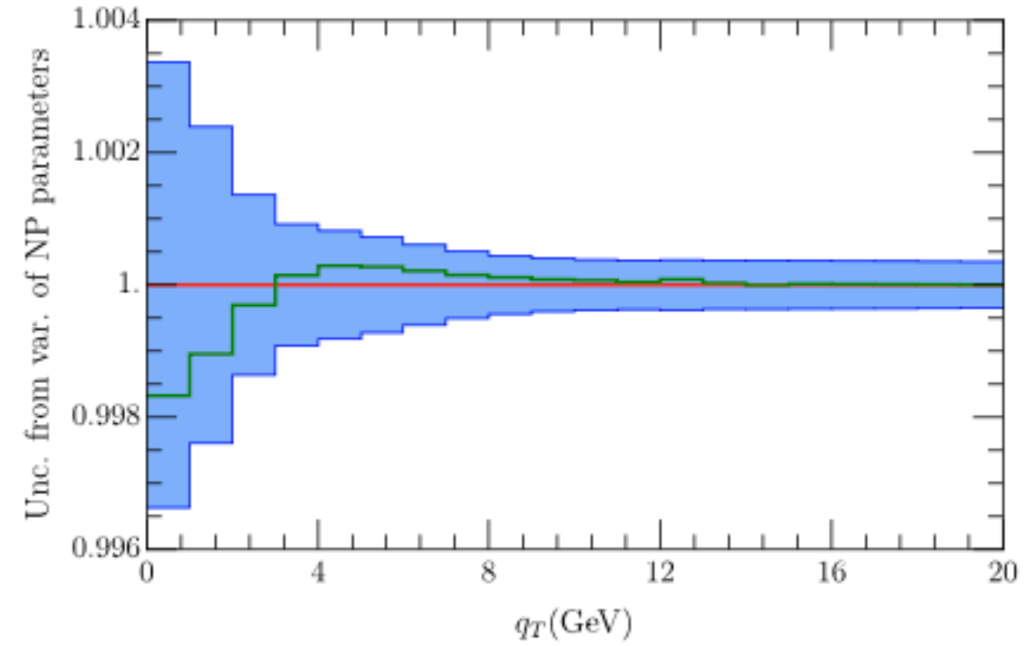
NNPDF31 replicas (1000)



PDF sets

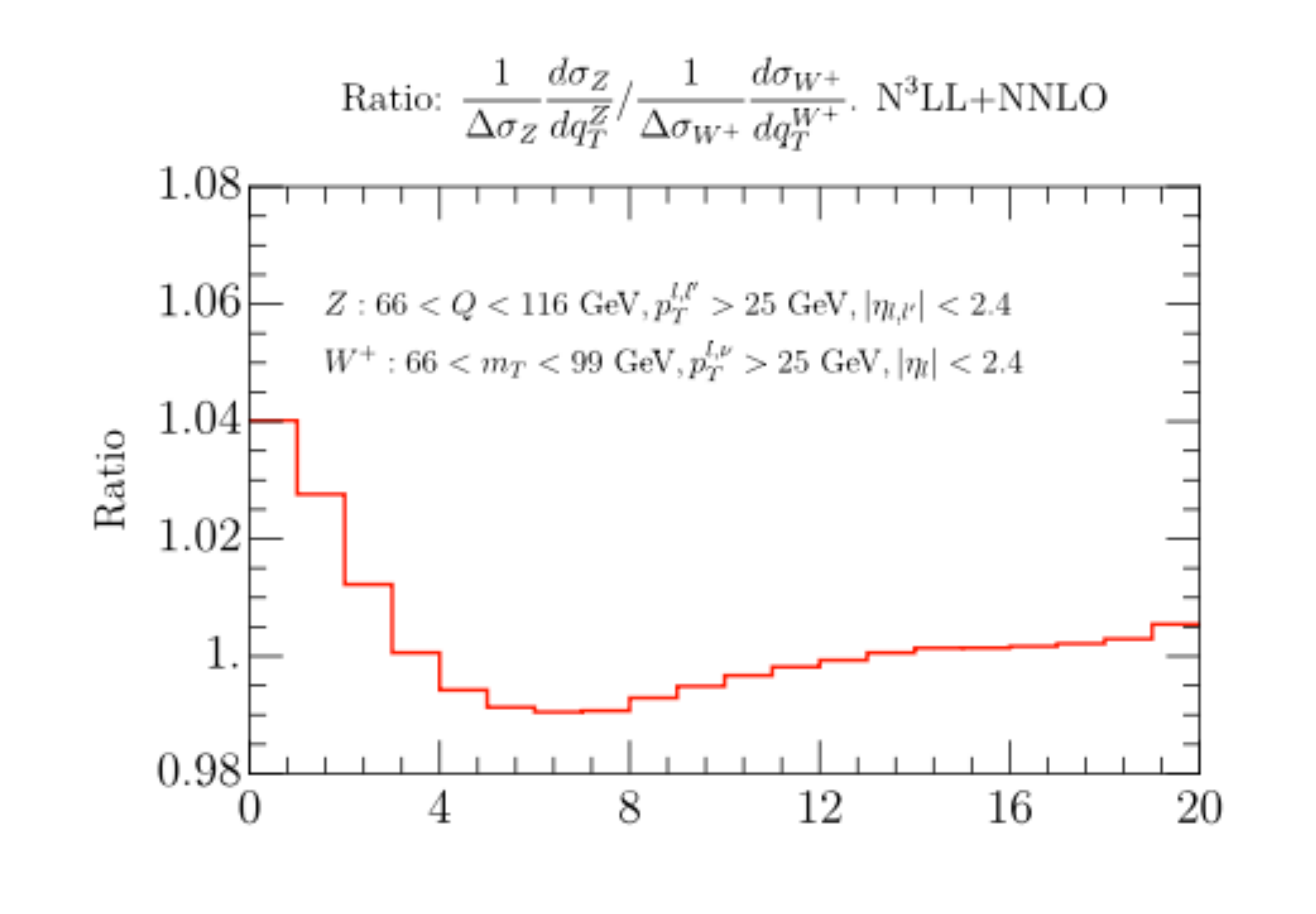


Extracted TMD parameters

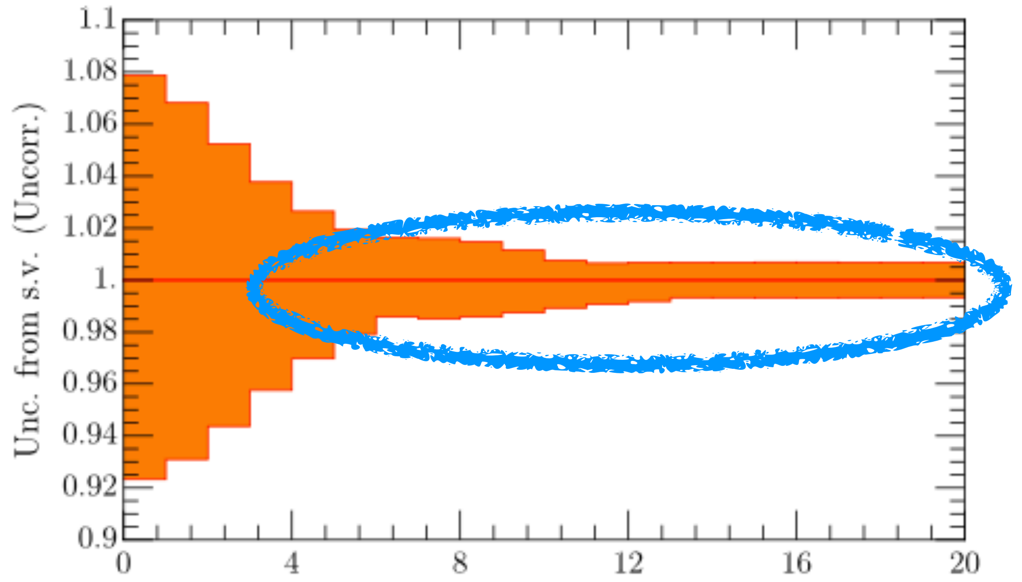


Errors in $p_T^Z/p_T^{W^+}$ spectrum

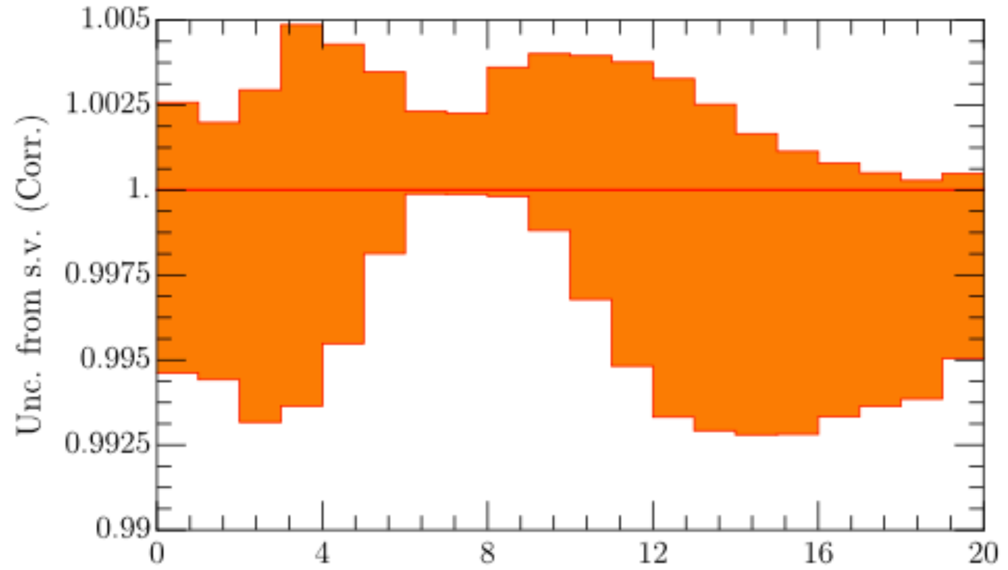
- Ongoing discussion on correlated uncorrelated error



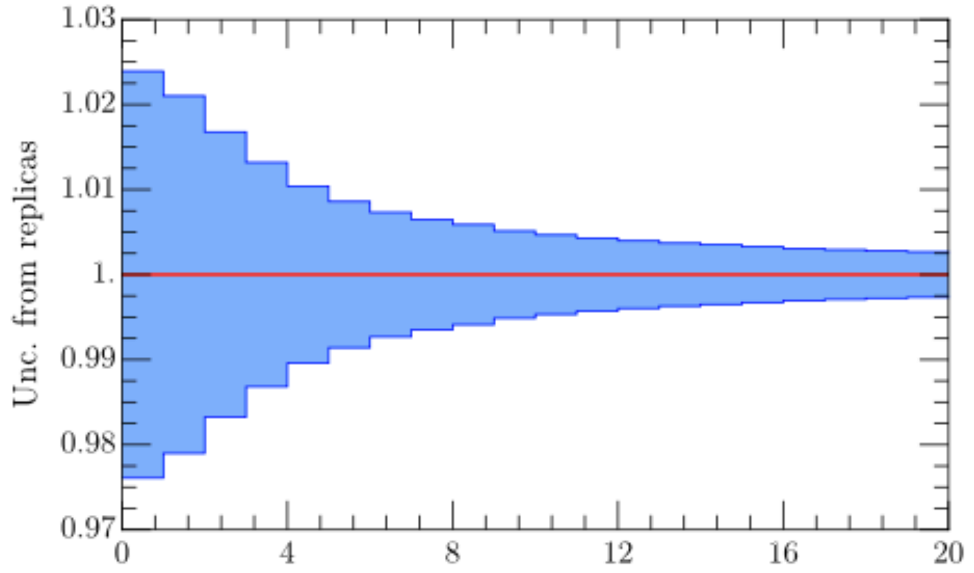
UnCorrelated Scale variations



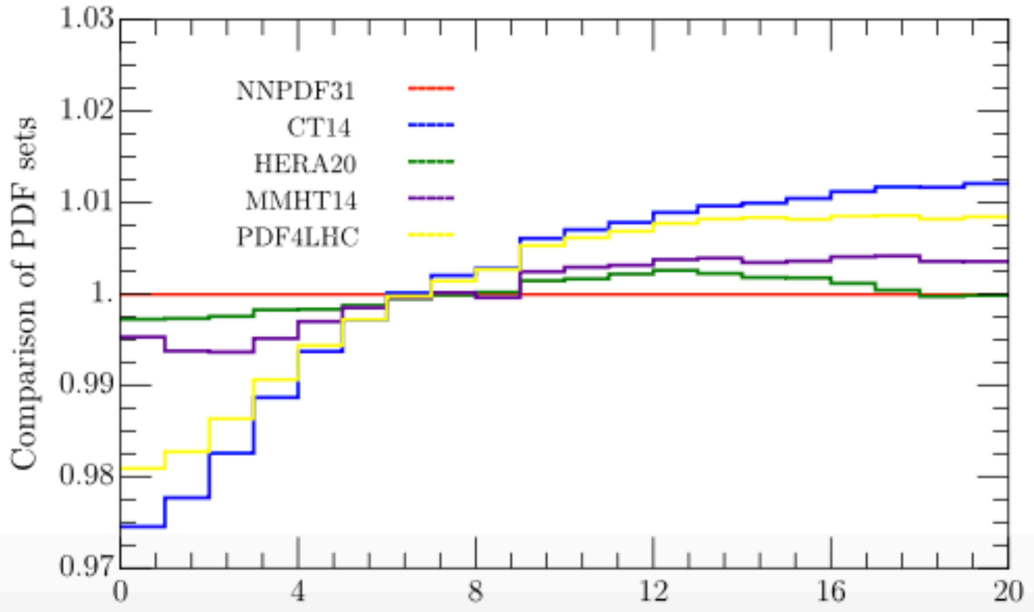
Correlated Scale variations



NNPDF31 replicas (1000)

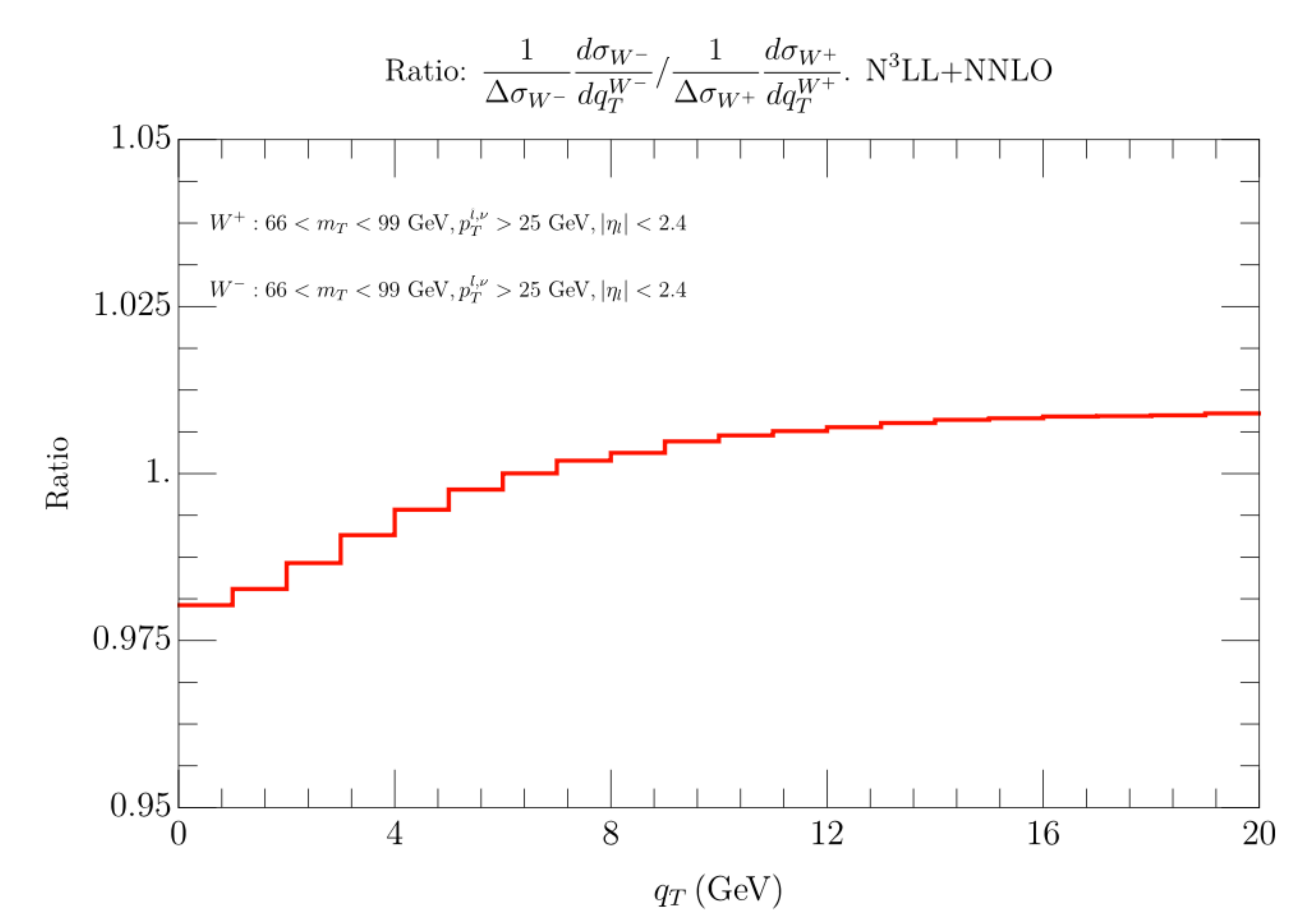


PDF sets

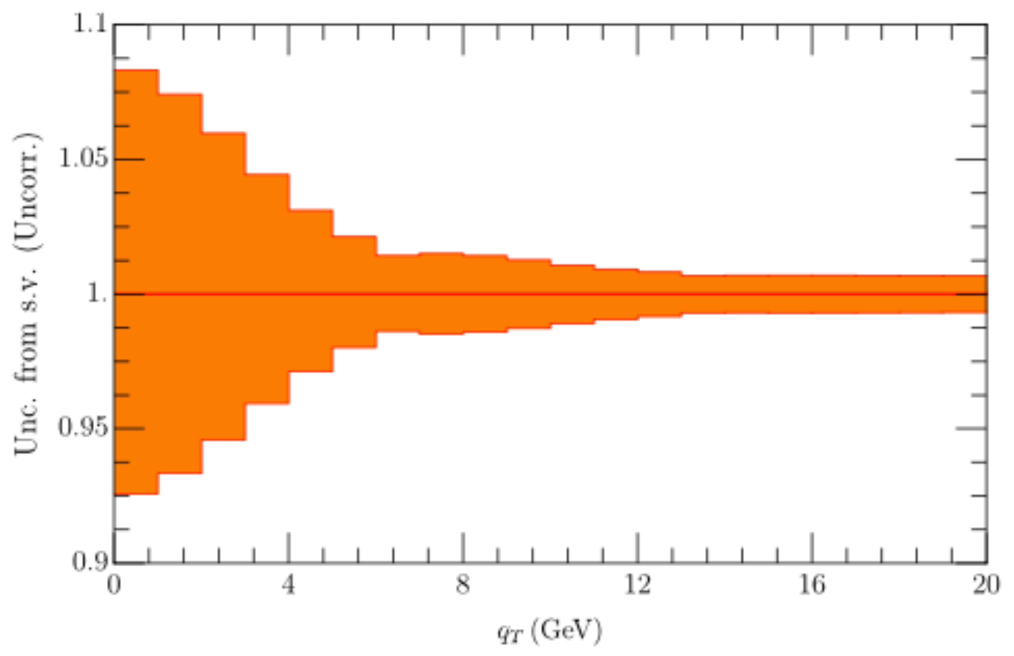


Errors in $p_T^{W^-}/p_T^{W^+}$ spectrum

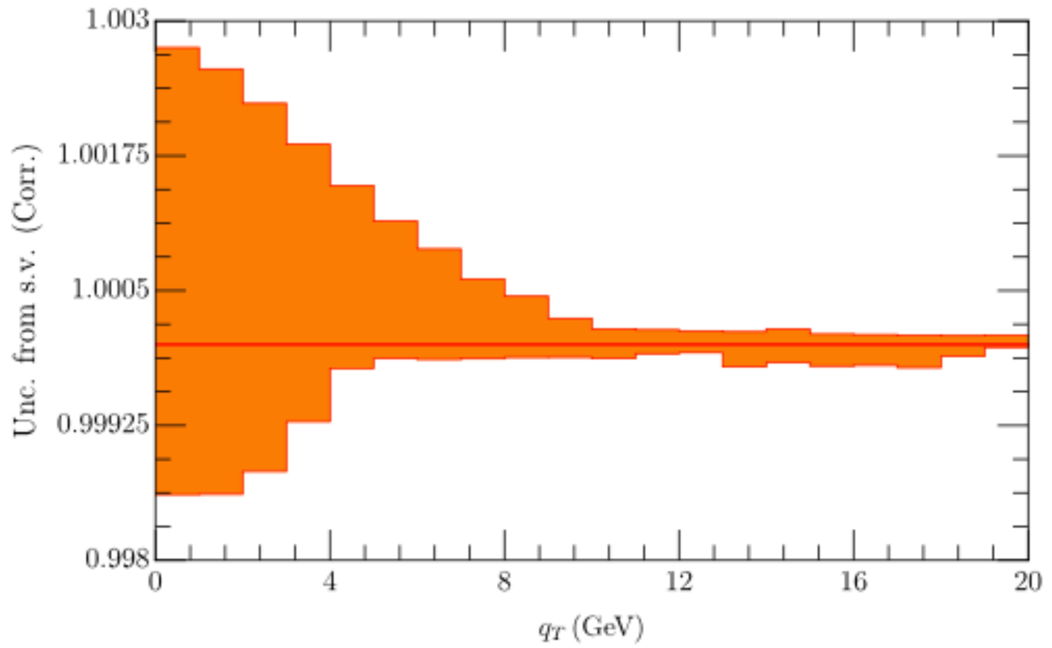
- Ongoing discussion on correlated uncorrelated error



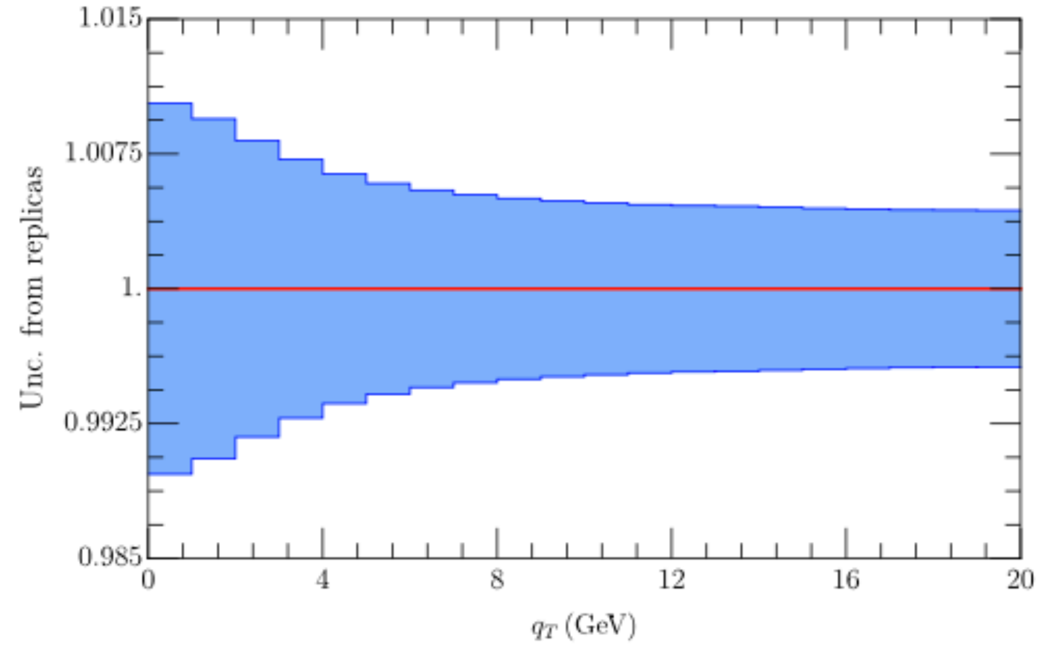
UnCorrelated Scale variations



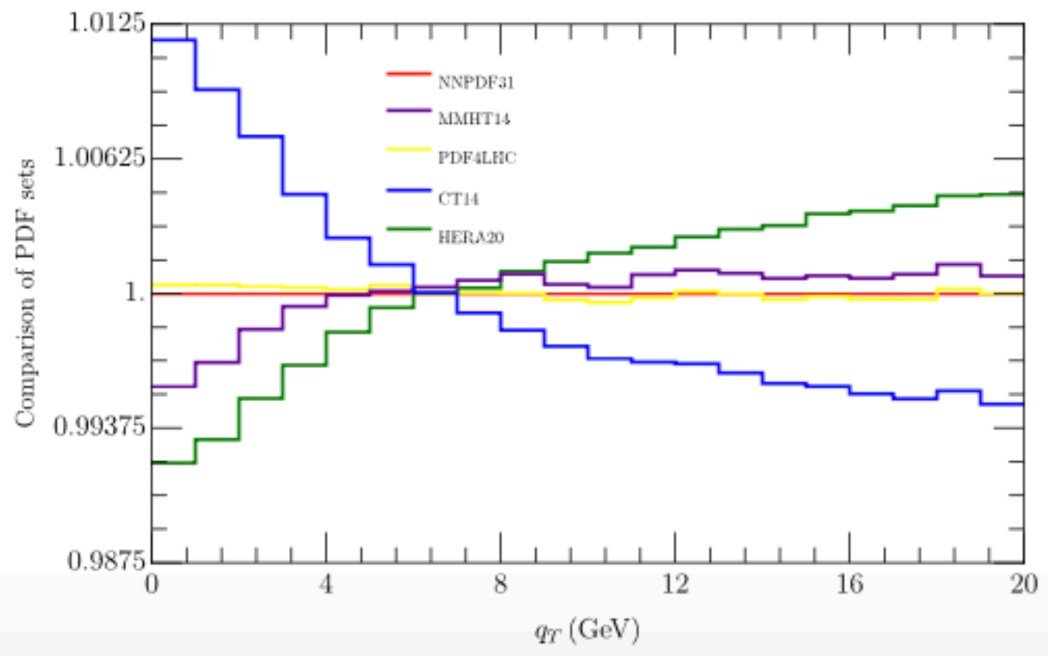
Correlated Scale variations



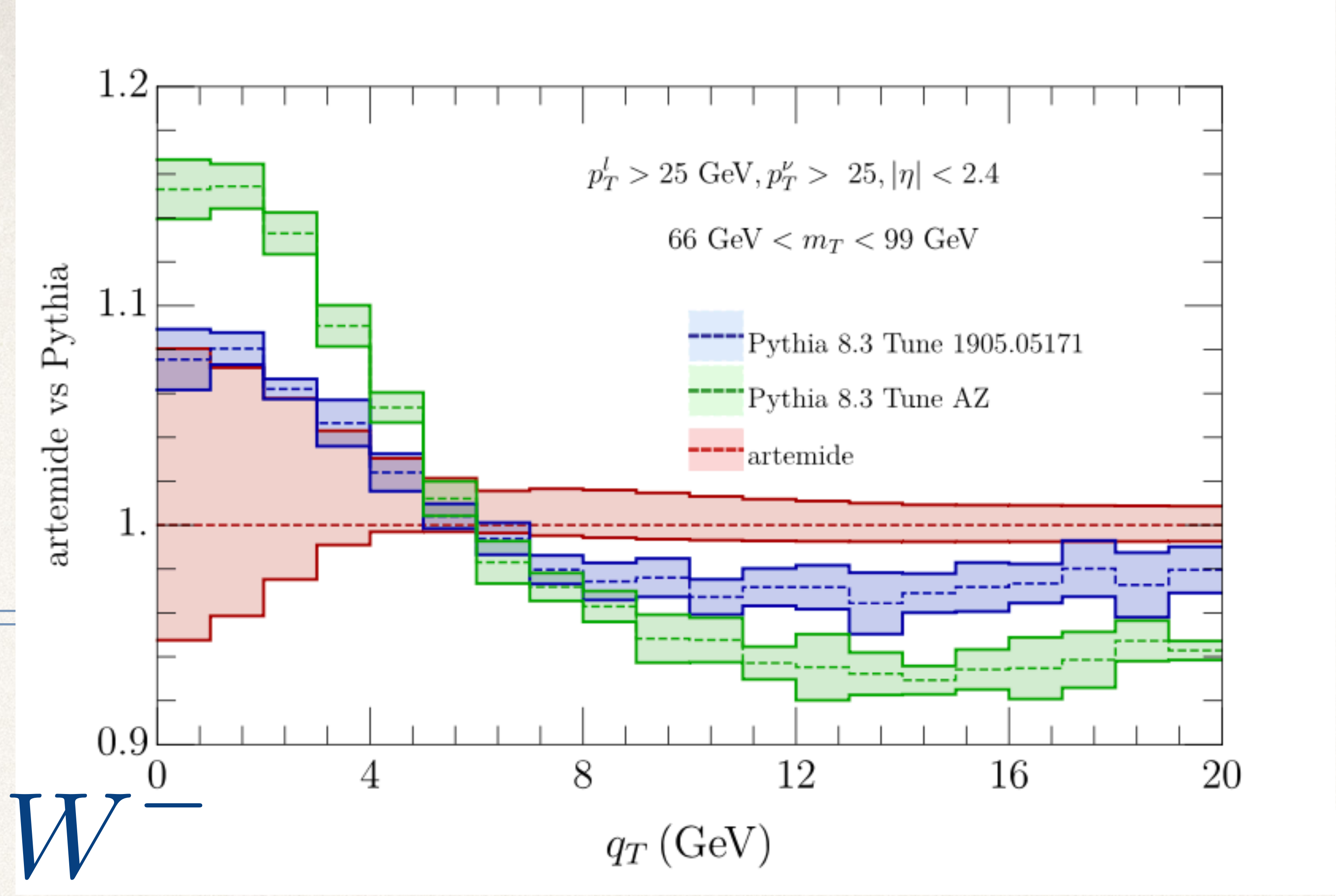
NNPDF31 replicas (1000)

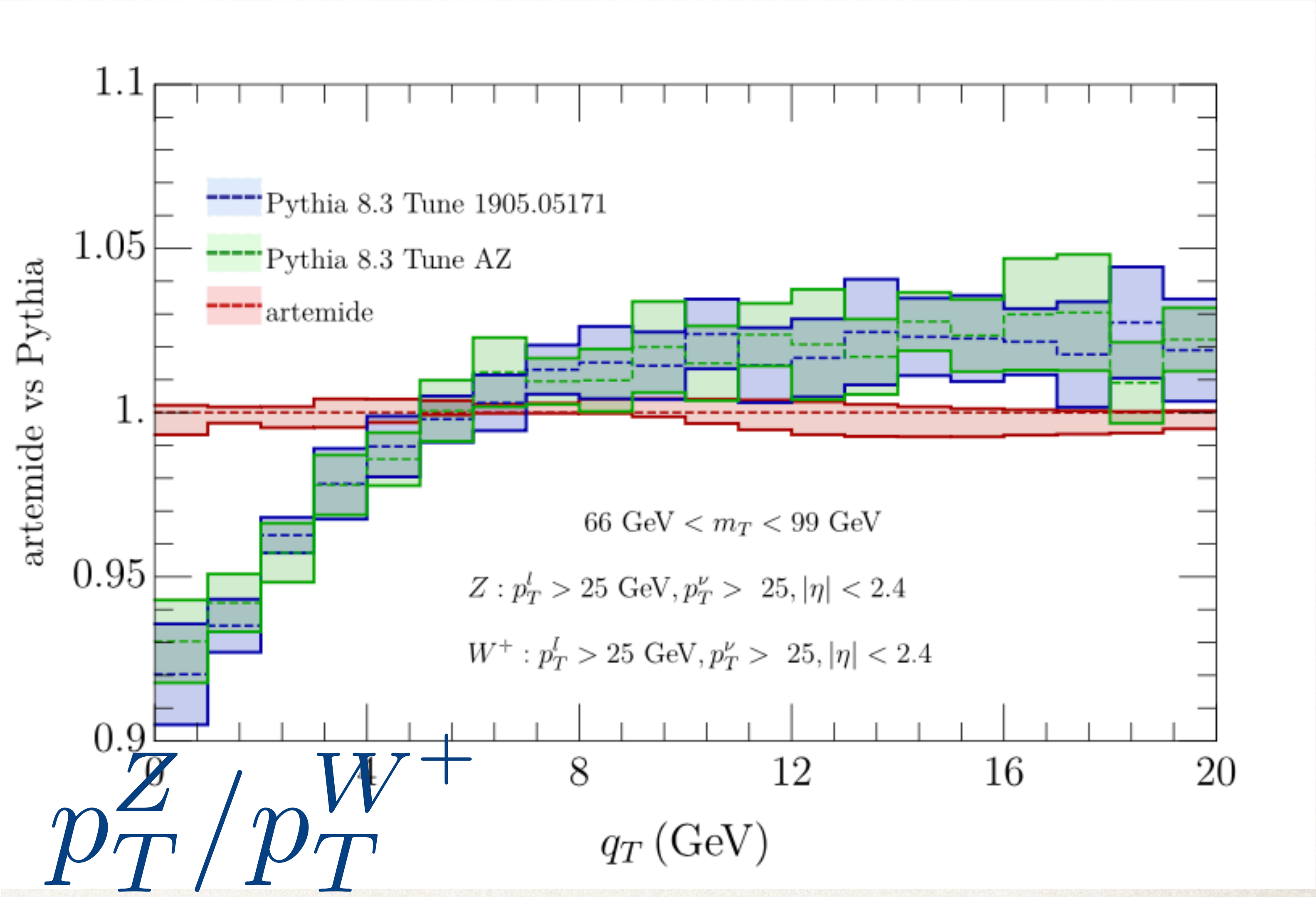


PDF sets

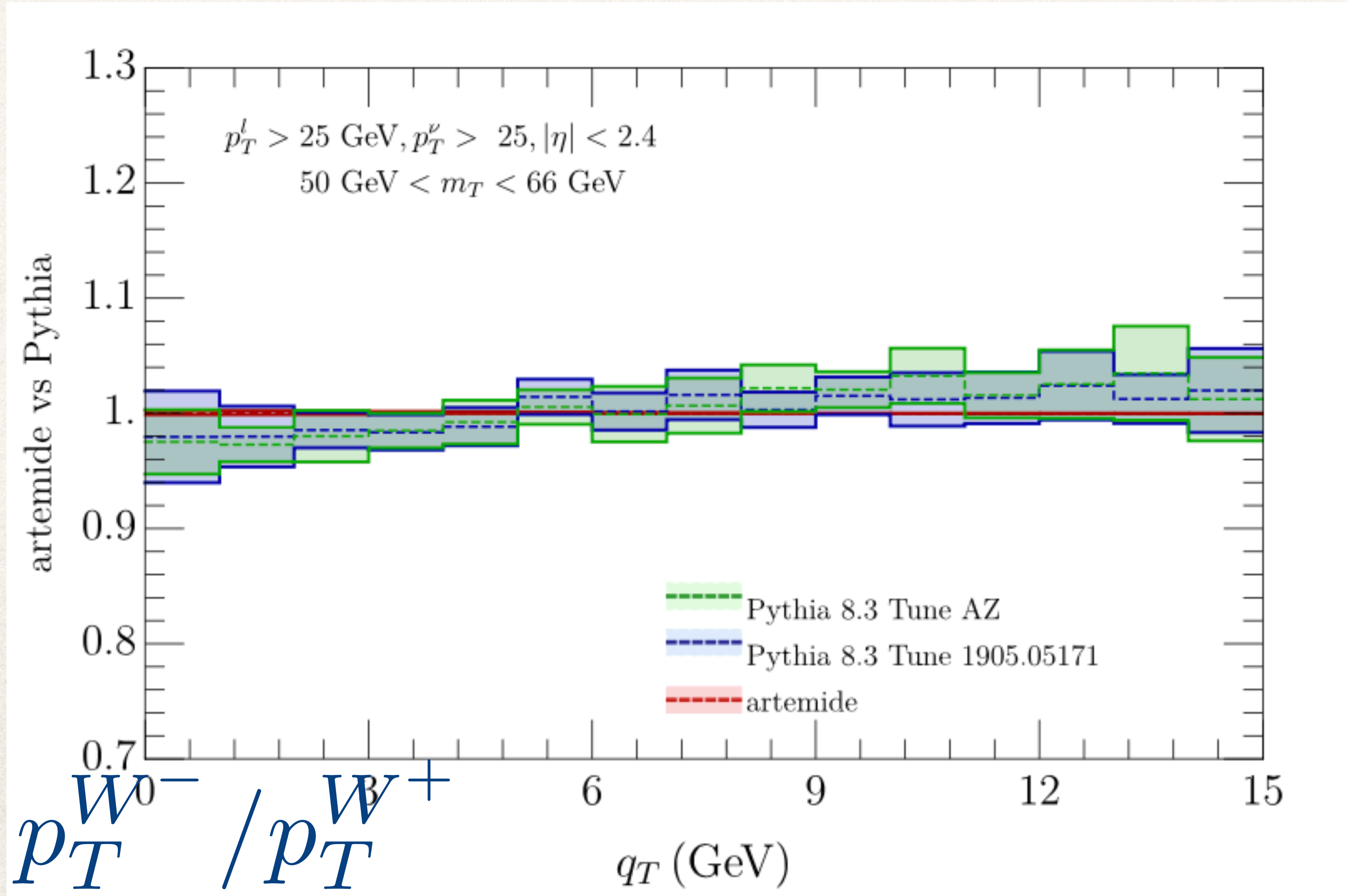


Pythia tunings

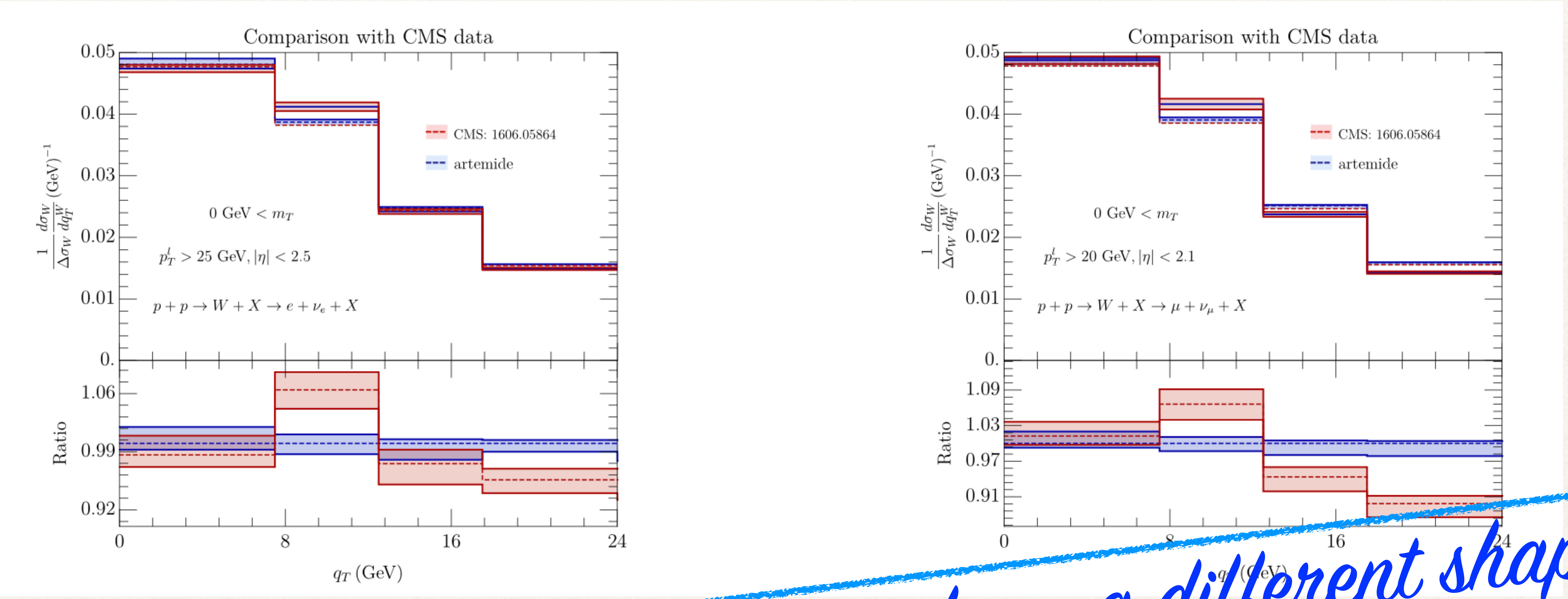




- The are noticeable differences among tunings



Comparison with data



Surprise: electrons and muons have a different shape!!

Comparison with data

	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

Surprise: electrons and muons have a different shape!!

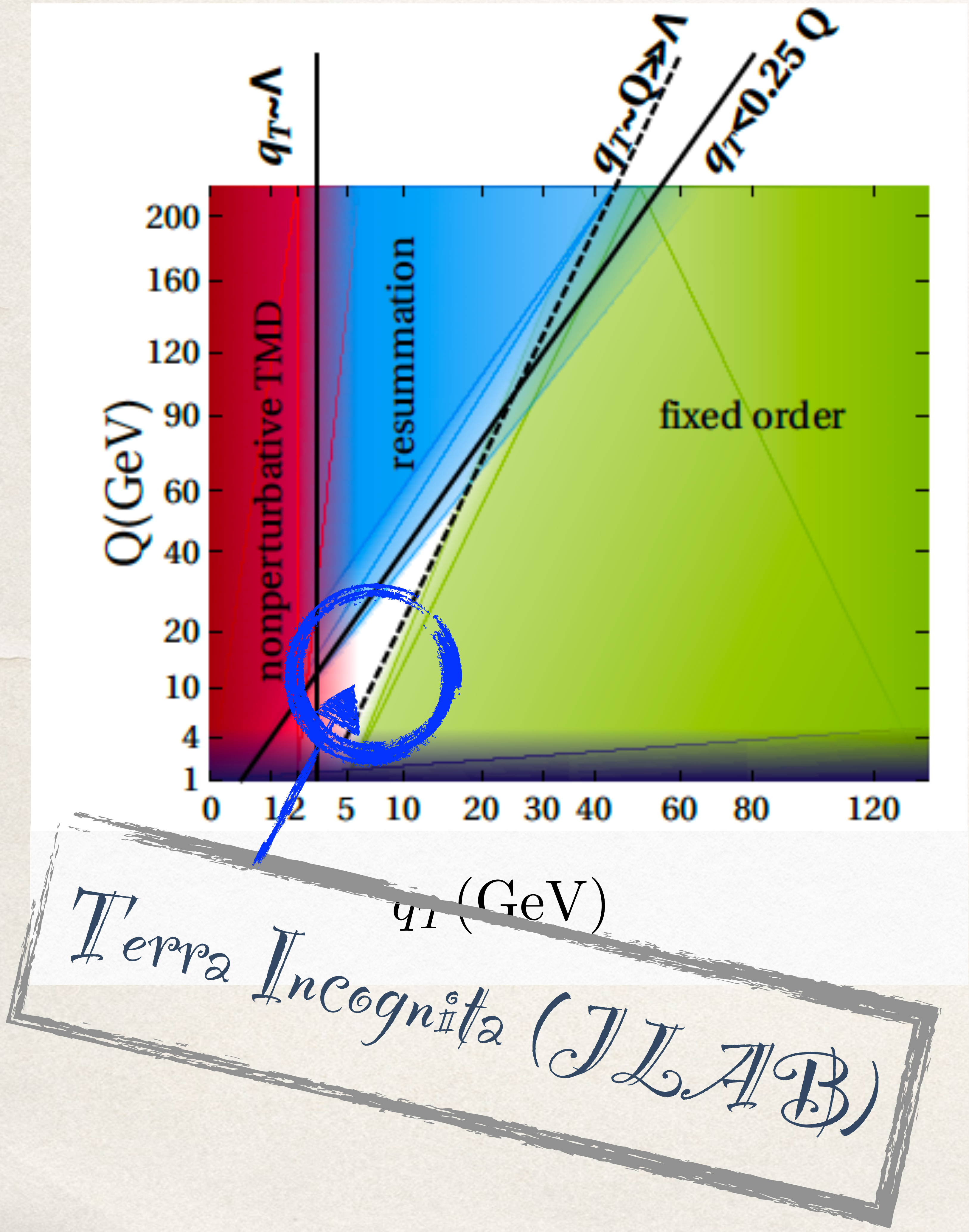
Work in progress: S. Leal-Gomez, J.J. Sanz Cillero, I. S., A. Vladimirov

Conclusions

- Great progress in the extraction of unpolarized TMD: Predictions for W, Z successful (BMS effects?)
- W production is included in Artemide. W and DY data at LHC can be largely improved looking at neglected regions of phase space and reducing the binning
- Ongoing work for reduction of errors in TMD extraction and predictions
- PDF set dependence of TMD is removed with flavor dependent models

Back slides

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 sets: bias removing

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

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:

$$\boxed{\begin{aligned} f_{NP}(x,b) &= \exp\left(-\frac{\lambda_1(1-x)+\lambda_2 x + x(1-x)\lambda_5}{\sqrt{1+\lambda_3 x^{\lambda_4}\boldsymbol{b}^2}}\boldsymbol{b}^2\right) \\ D_{NP}(x,b) &= \exp\left(-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right) \end{aligned}}$$

BHLSVZ21 ansatz:

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

$D_{NP}(x,b) = \exp\Big(-$ … $\sqrt{1+\eta_3(}$ …

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