TMD DISTRIBUTIONS AT N4LLL

arXiv:2305.07473 [hep-ph] in collaboration with V. Moos, A. Vladimirov and P. Zurita

And *JHEP* 10 (2022) 118 M. Bury et al.

Sar Wors 2023, 4–7 June 2023, Cagliari

TMD FACTORIZATION

LP!

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

In recent years we have learnt a lot about this formula. For instance:

- Its range of applicability is provided by $\delta = \frac{q_T}{Q} \ll 1$, fixed-$q_T$, $\delta \sim 0.25$
- We have a non-perturbative evolution kernel (whose perturbative part is known at N3LO!!). We can work with different schemes (CSS, ζ-prescription, ..).
- We have a re-factorization of TMD at large transverse momentum in Wilson coefficients (now at N3LO!!) and PDF (now at NNLO!!)
- PDF are just part of a model

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

TMD FACTORIZATION

We can :

- Perform an extraction of TMD at N4LL (higher order than PDF..)
- Analyze the source of errors
- Be ready for NLP corrections

In this talk I will consider the first two points

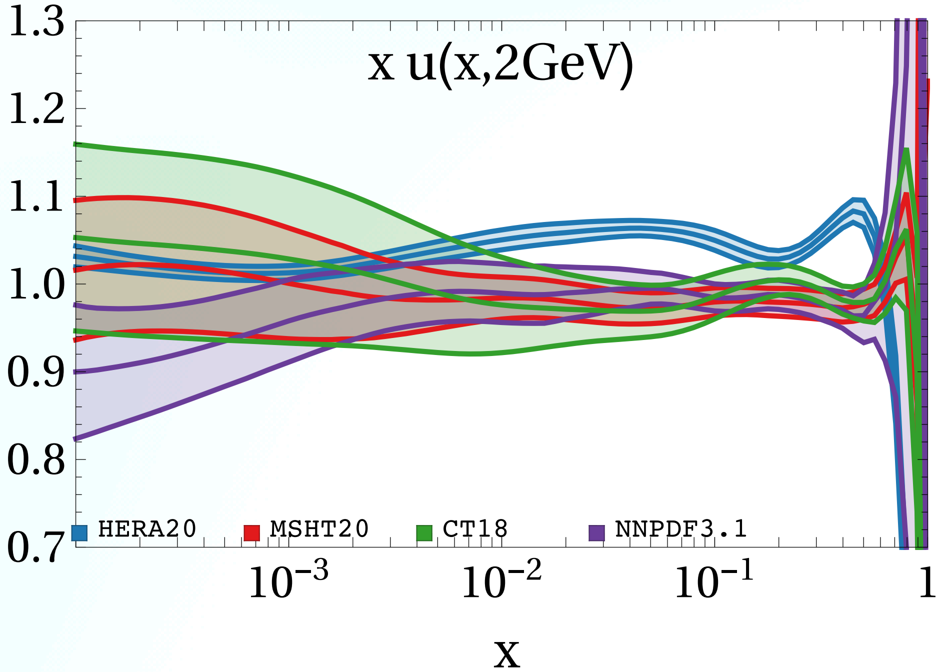
We call the new Artemide code extraction

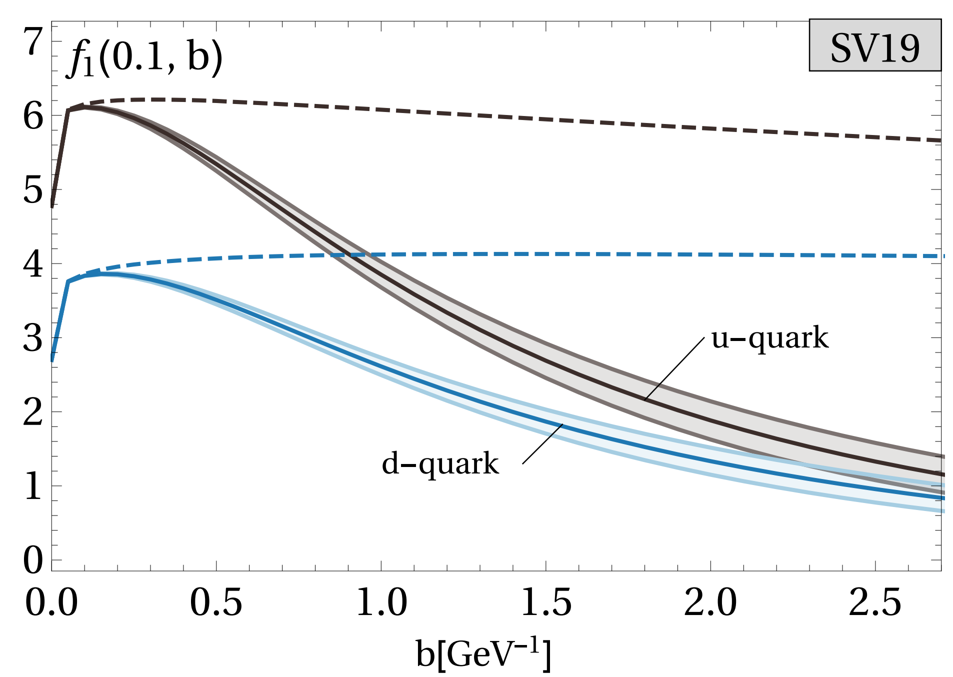
ART23

In SV19 we tried with several PDF sets

PDF set	χ^2_{DY}/N_{pt}
CT14	1,59
HERAPDF2.0	0,97
MMHT14	1,34
NNPDF3.1	1,14
PDF4LHC15	1,53

Also, in SV19, for $b \to 0$, the uncertainty bands $\to 0$.





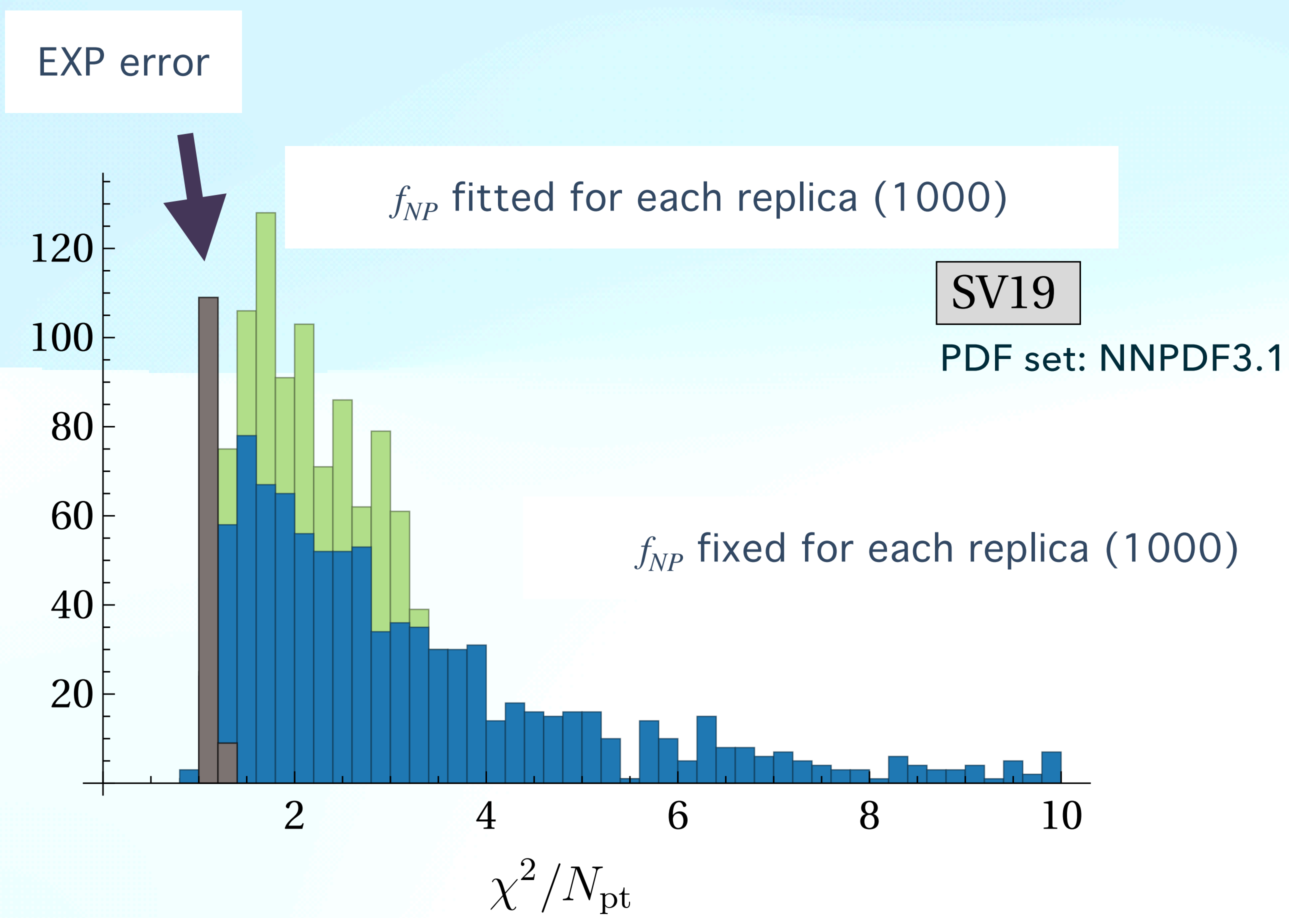
THE PDF BIAS

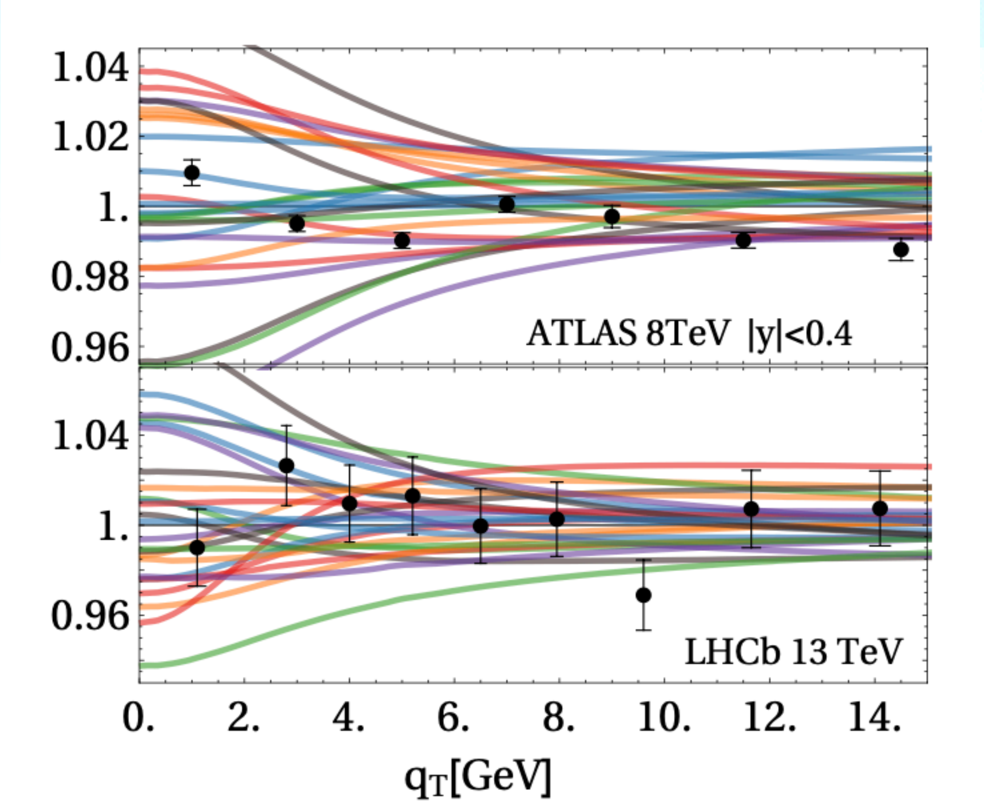
- So we have some questions to answer:

1. Can we get ***good TMD fits*** for different collinear PDFs?
2. Would they have sensible uncertainty bands?
3. Would they the consistent with each other?

FLAVOR INDEPENDENT $\mathcal{F}_{NP}$

Most of replicas (64%) have $\chi^2/N>2$.
Each replica has a peculiar shape



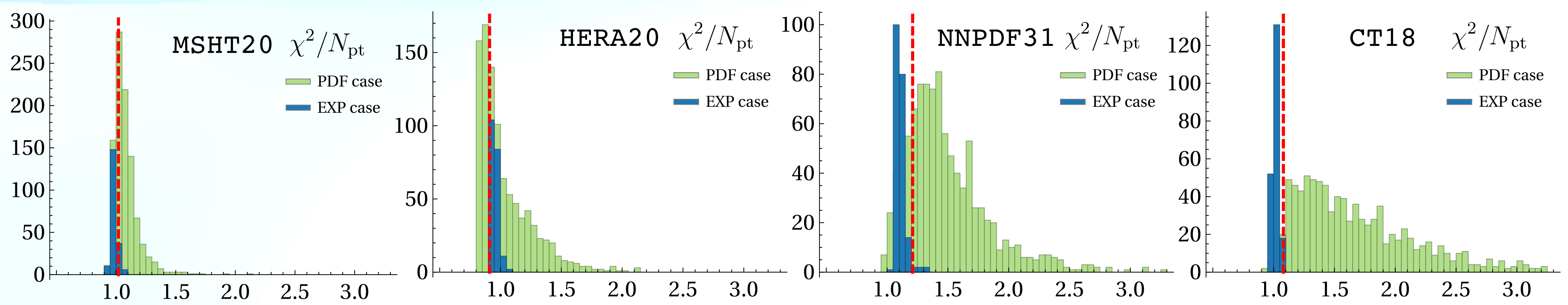


PDF UNCERTAINTIES AND FLAVOUR DEPENDENCE

M. Bury, F. Hautmann, S. Leal-Gomez, I. Scimemi, A. Vladimirov, PZ, **JHEP 10 (2022) 118**

- **Flavor separation make fits more PDF set independent and modeling simpler**

$$f_{NP}^{f}(x,b) = \exp\left(-\frac{\lambda_1^f(1-x)+\lambda_2^f x}{\sqrt{1+\lambda_0 x^2 \mathbf{b}^2}}\mathbf{b}^2\right) \qquad f = u, \bar{u}, d, \bar{d}, sea$$



- All PDF distributions have similar χ^2
- The spread of χ^2 of PDF replica is highly reduced
- Final χ^2: MSHT20 (1.12), HERA20 (0.91), NNPDF31(1.21), CT18 (1.08)

PDF UNCERTAINTIES AND FLAVOUR DEPENDENCE

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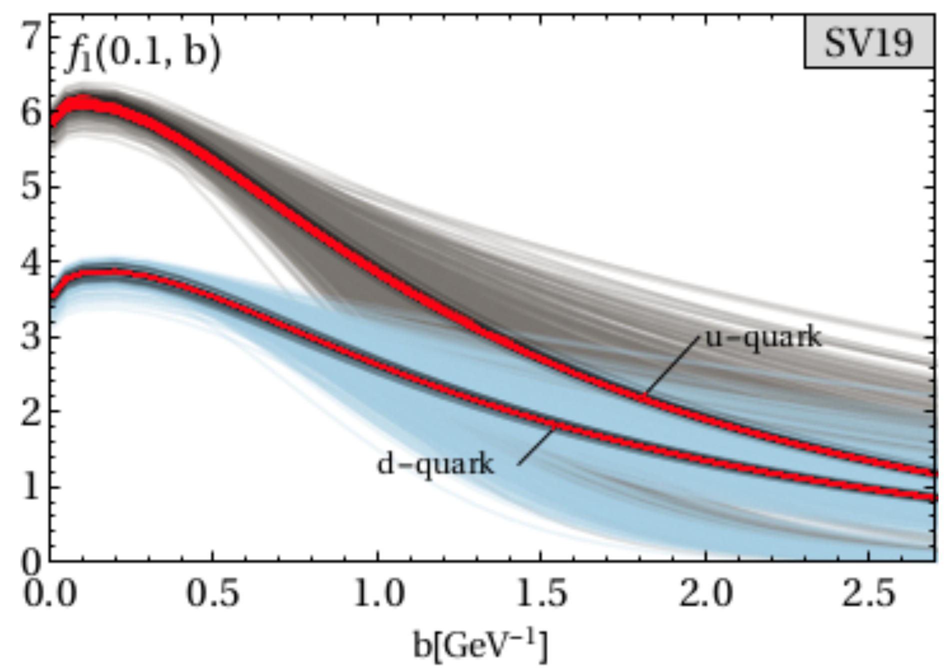
- **We include the PDF uncertainties while keeping f_{NP} fixed.**

- **We re-fit TMD, for each PDF replica.**

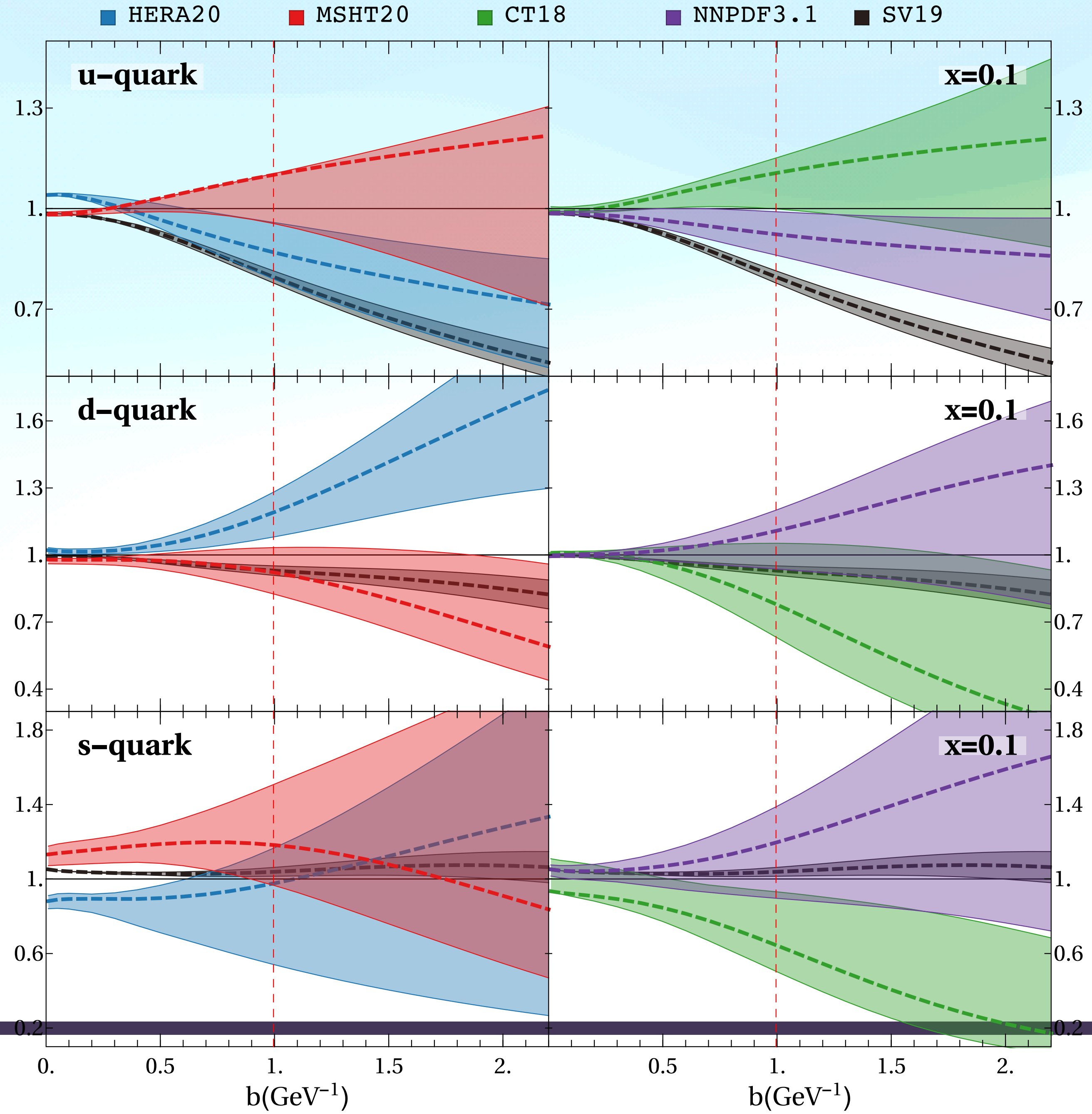
- **We get reasonable uncertainty bands.**



PDF UNCERTAINTIES AND FLAVOUR DEPENDENCE

M. Bury, F. Hautmann, S. Leal-Gomez, I. Scimemi, A. Vladimirov, PZ, **JHEP 10 (2022) 118**

- **The TMD obtained from different sets agree reasonably**



ART23

- **Flavor dependence.**
- **All the latest datasets!**
- **W-boson production!**
- **Increased perturbative accuracy! (N^4LL)**
- **Includes collinear PDF uncertainties!**
- **A full new fit to Drell-Yan data.**

ART23: DETAILS

Evolution:

- **We use the ζ prescription** (I.S., A. Vladimirov *JHEP* 08 (2018) 003)
- **We use the integral form of the evolution kernel to introduce a scale dependence similar to CSS for direct comparison**

$$\mathscr{D}(b,\mu) = \mathscr{D}_{\textbf{small-b}}(b^*,\mu^*) + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'}\Gamma_{\textbf{cusp}}(\mu') + \mathscr{D}_{\textbf{NP}}(b) \qquad b^*(b) = \frac{b}{\sqrt{1+\frac{b^2}{\mathbf{B}_{\mathrm{NP}}^2}}} = \frac{2e^{-\gamma_E}}{\mu^*}$$

- **We discover that we are sensitive to log corrections to the NP part of the evolution kernel**

$$\mathscr{D}_{\mathrm{NP}}(b) = bb^*\left[c_0 + c_1 \ln\left(\frac{b^*}{B_{\mathrm{NP}}}\right)\right]$$

ART23: DETAILS

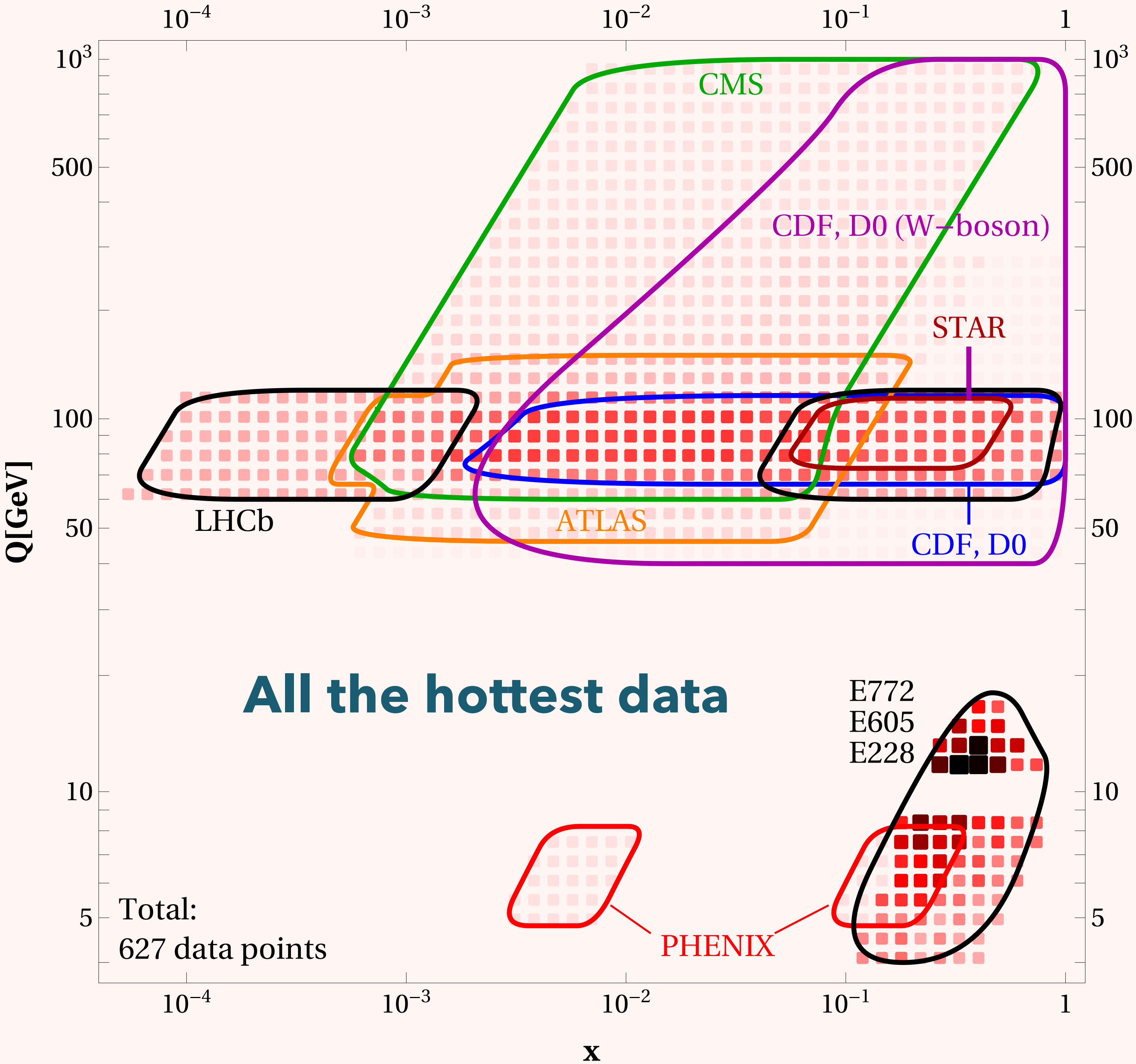
- **Simple Parameterization:** $$f_{NP}^{f}(x,b) = \frac{1}{\cosh\left(\left(\lambda_1^f(1-x)+\lambda_2^f x\right)b\right)}$$

$$f = u,\ \bar{u},\ d,\ \bar{d},\ sea$$

- **In total, 13 parameters**

- **Reference PDFs: MSHT20**

ART23: DETAILS



All the hottest data

627 data points

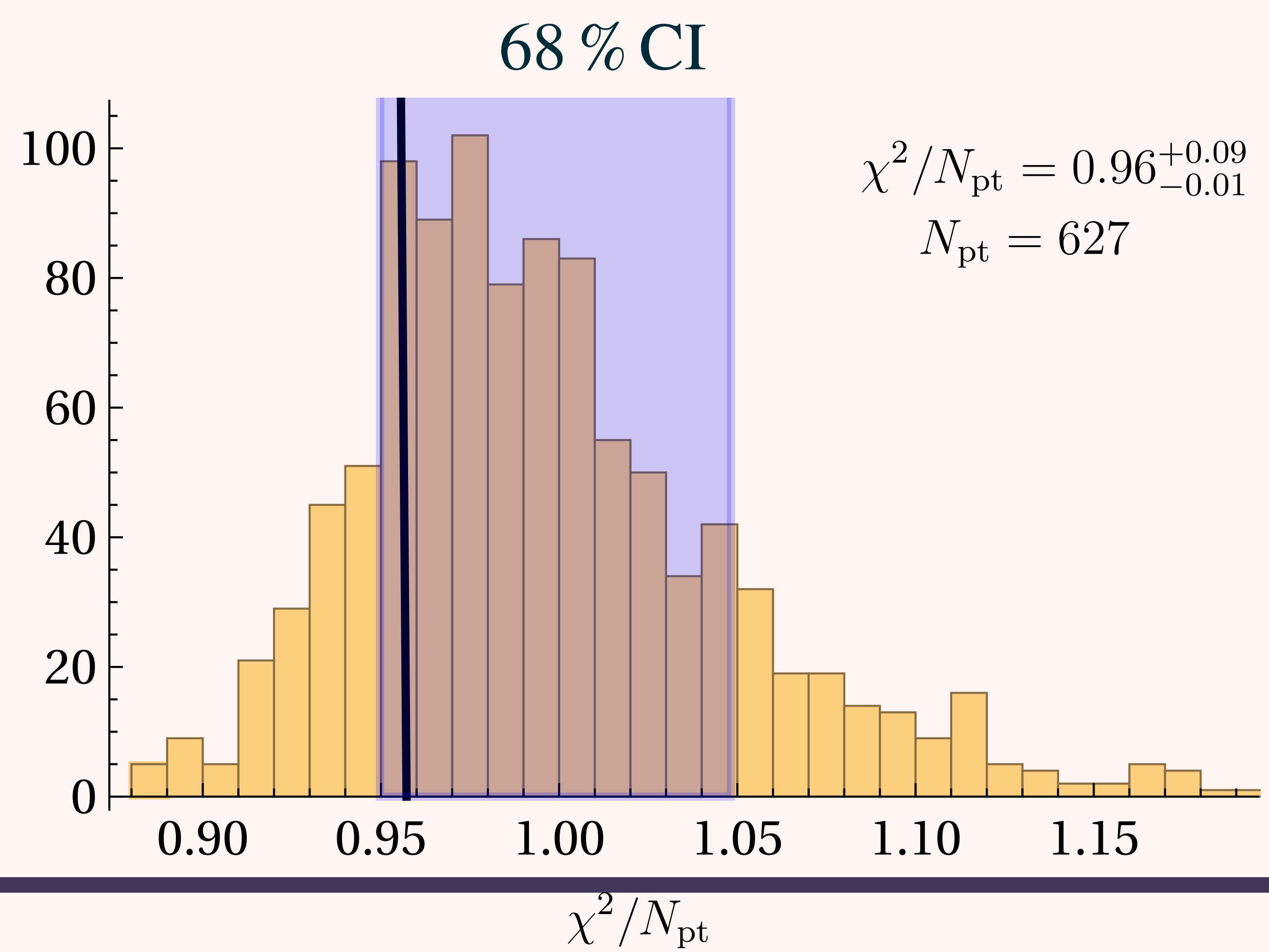
New in!

- **PHENIX: DY data at $\sqrt{s} = 200$ GeV**
- **STAR: Z/γ-boson production at $\sqrt{s} = 510$ GeV (preliminary).**
- **CMS and LHCb: y-differential Z-boson production at $\sqrt{s} = 13$ TeV.**
- **ATLAS: high precision differential Z-boson cross-section.**
- **CMS: high-Q neutral-boson production.**
- **Tevatron: W-boson production.**

ART23: DETAILS

- Fitting procedure: construct simultaneous replicas of the **data** AND the **PDFs**. Then fit.

- The number of replicas needed to have a faithful representation of the TMDPDF distribution was deemed to be 1000.



ART23: RESULTS

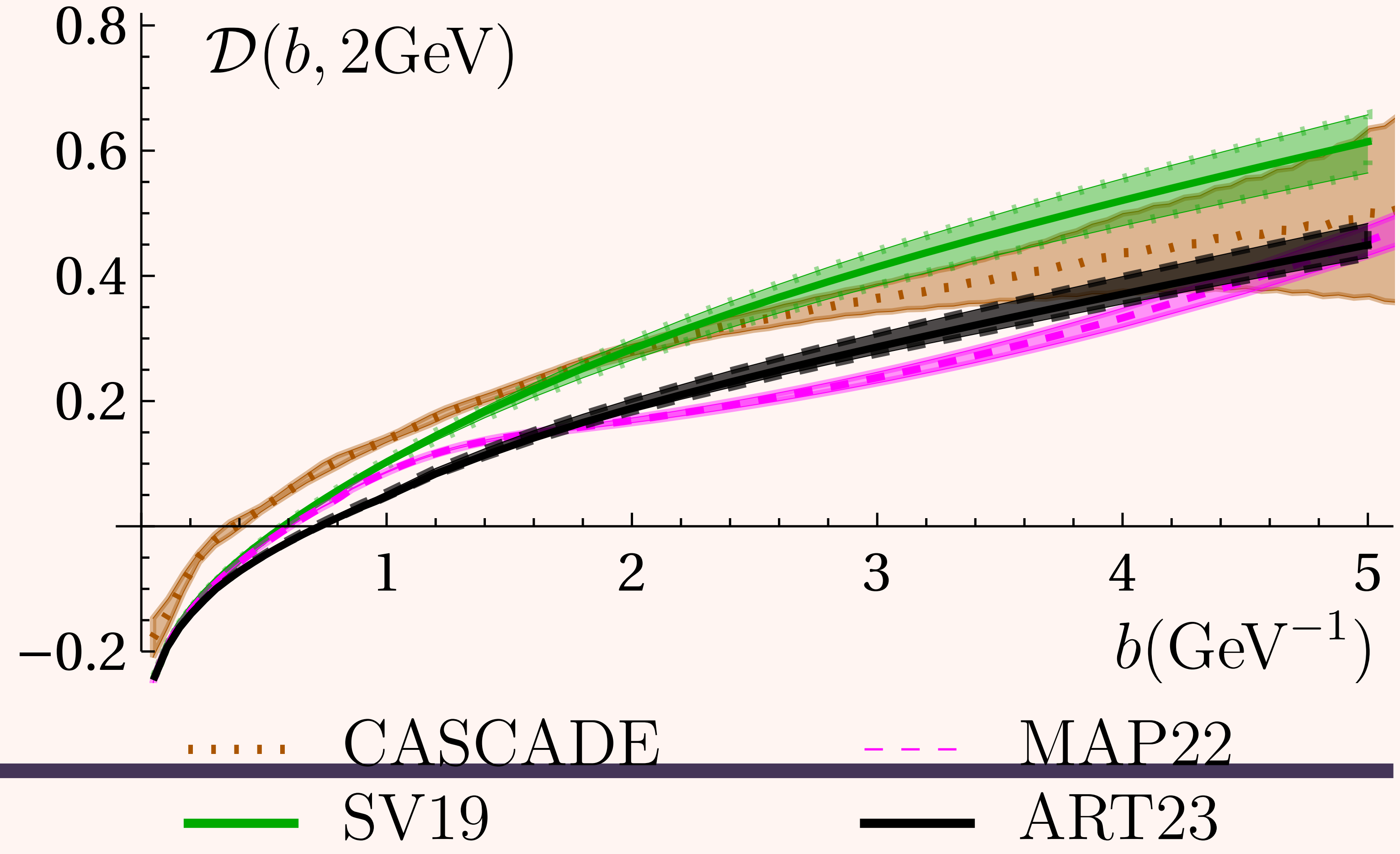
- overall improvement w.r.t. SV19. Specially for the LHC data. Higher precision plays a key role here.
- more realistic uncertainty bands than in SV19.

CS kernel close to the one from the global fit MAP22

$$B_{\mathrm{NP}} = 1.56^{+0.13}_{-0.09}\mathrm{GeV}$$

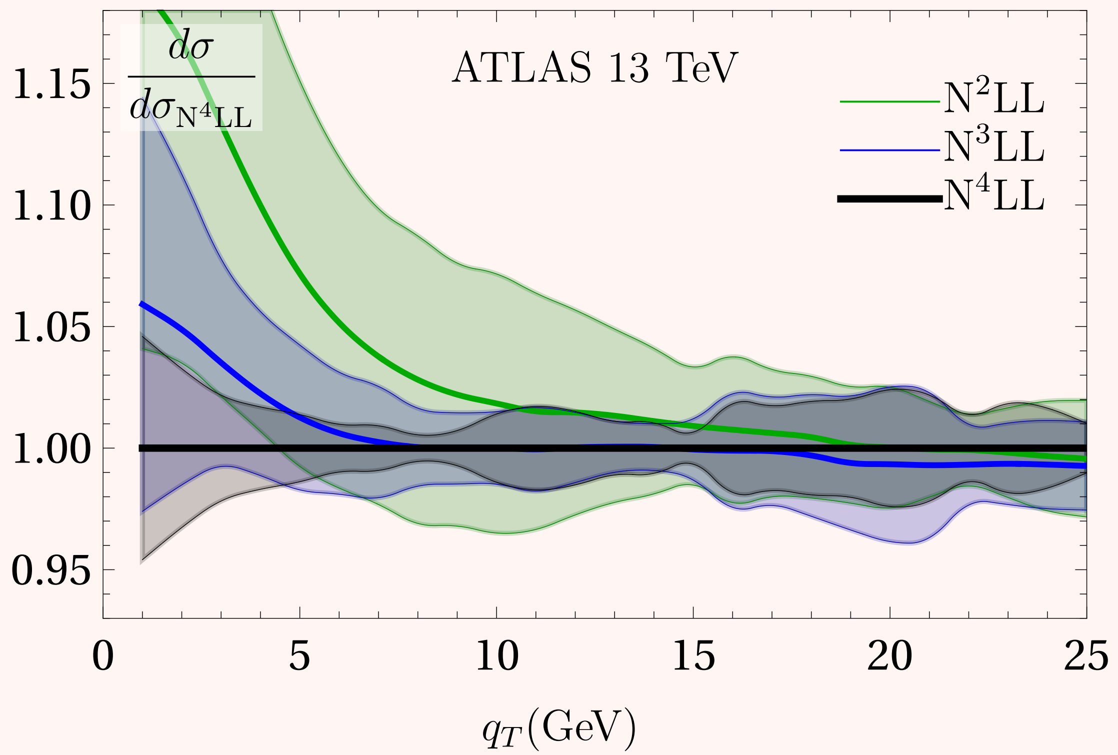
$$c_0 = 3.69^{+0.65}_{-0.61} \cdot 10^{-2}$$

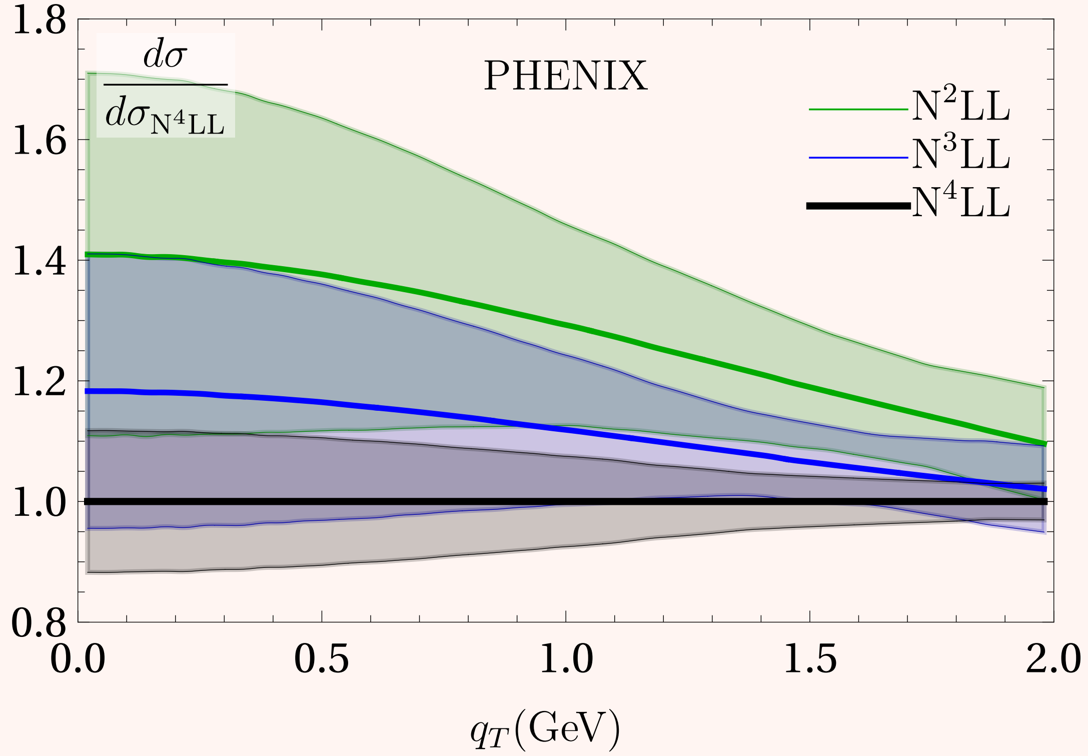
$$c_1 = 5.82^{+0.64}_{-0.88} \cdot 10^{-2}$$



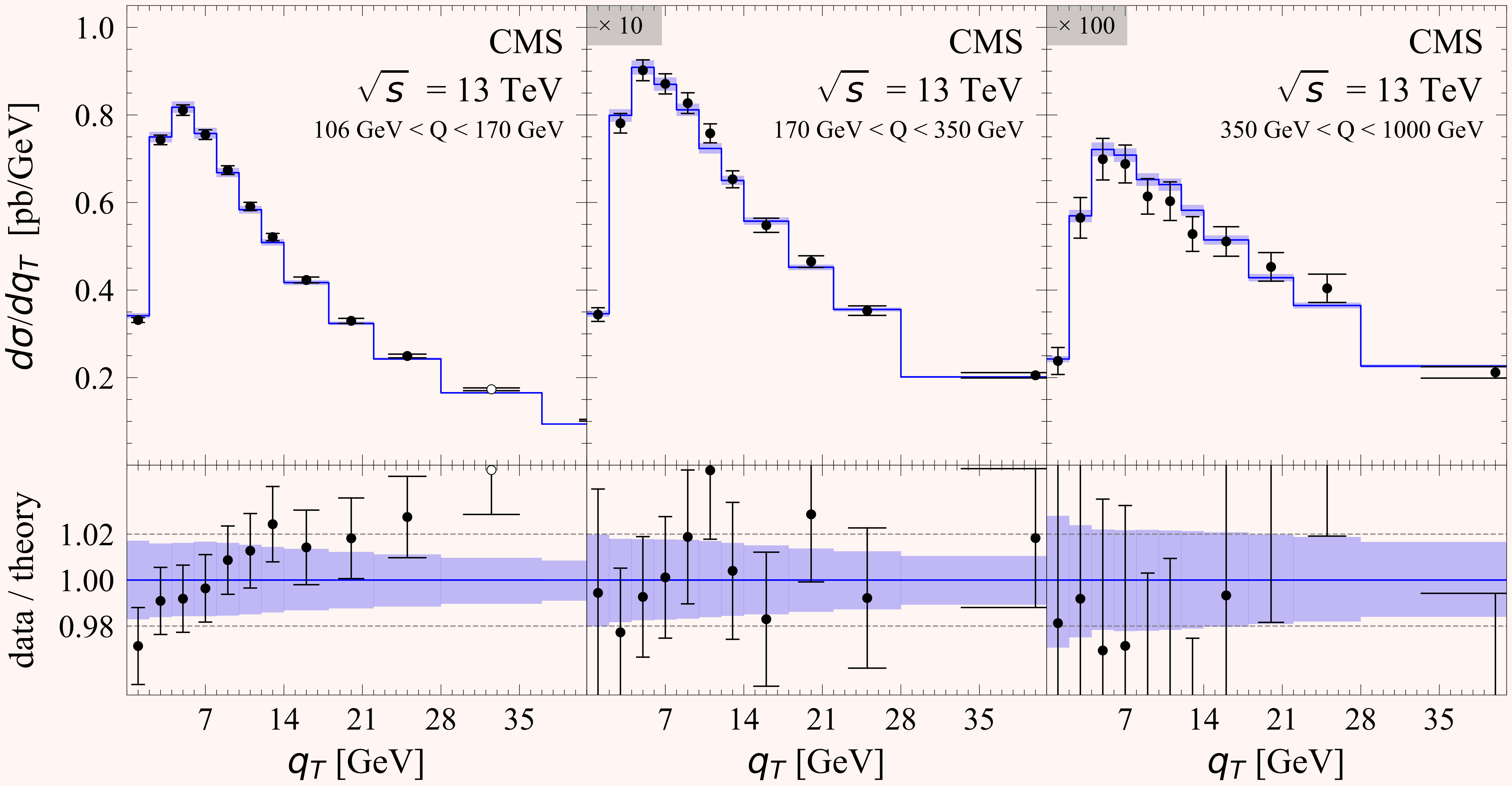
ART23: RESULTS

Scale variations $\left\{\mu \to s_2\mu, \mu* \to s_3\mu*, \mu_{\text{OPE}} \to s_4\frac{2e^{-\gamma_E}}{b} + 2\text{GeV}\right\}.$





ART23: RESULTS



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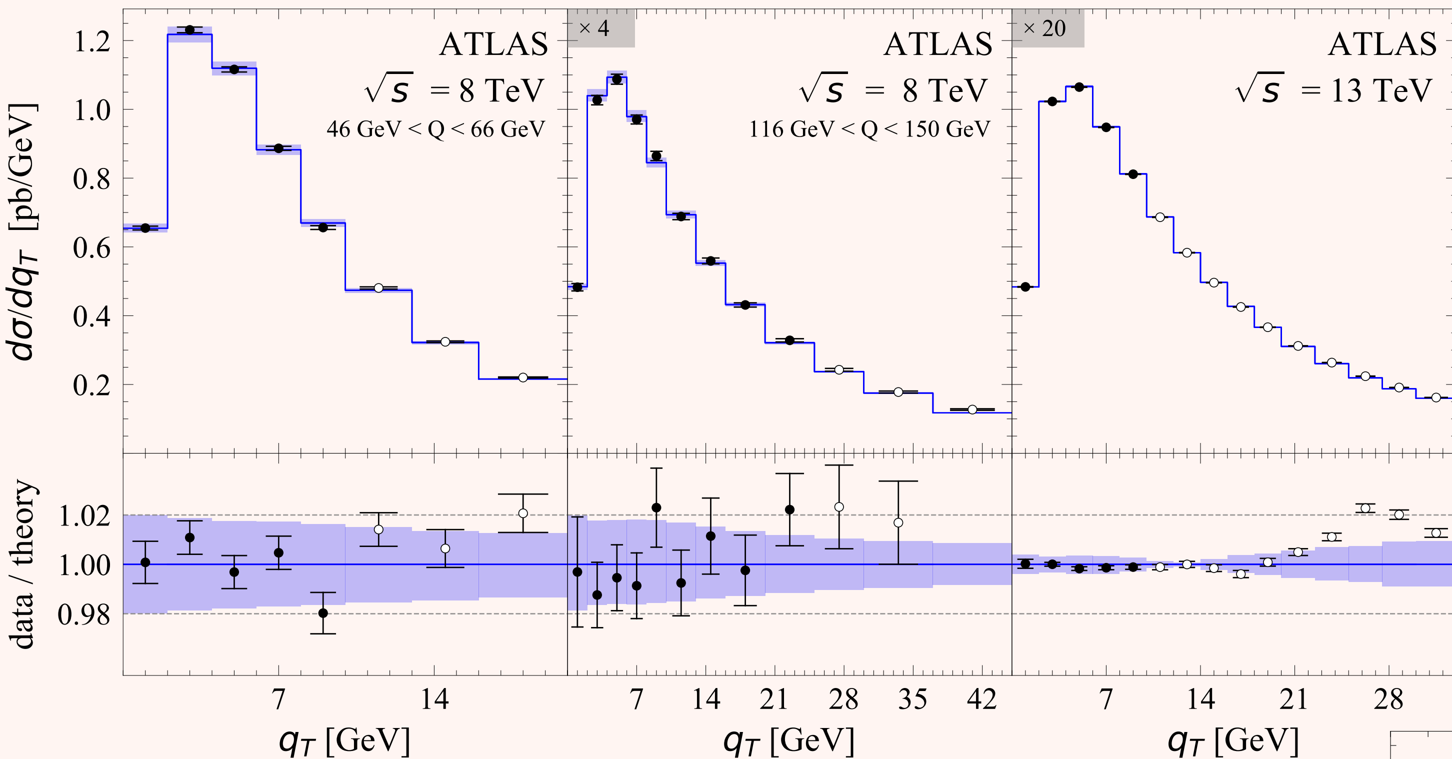

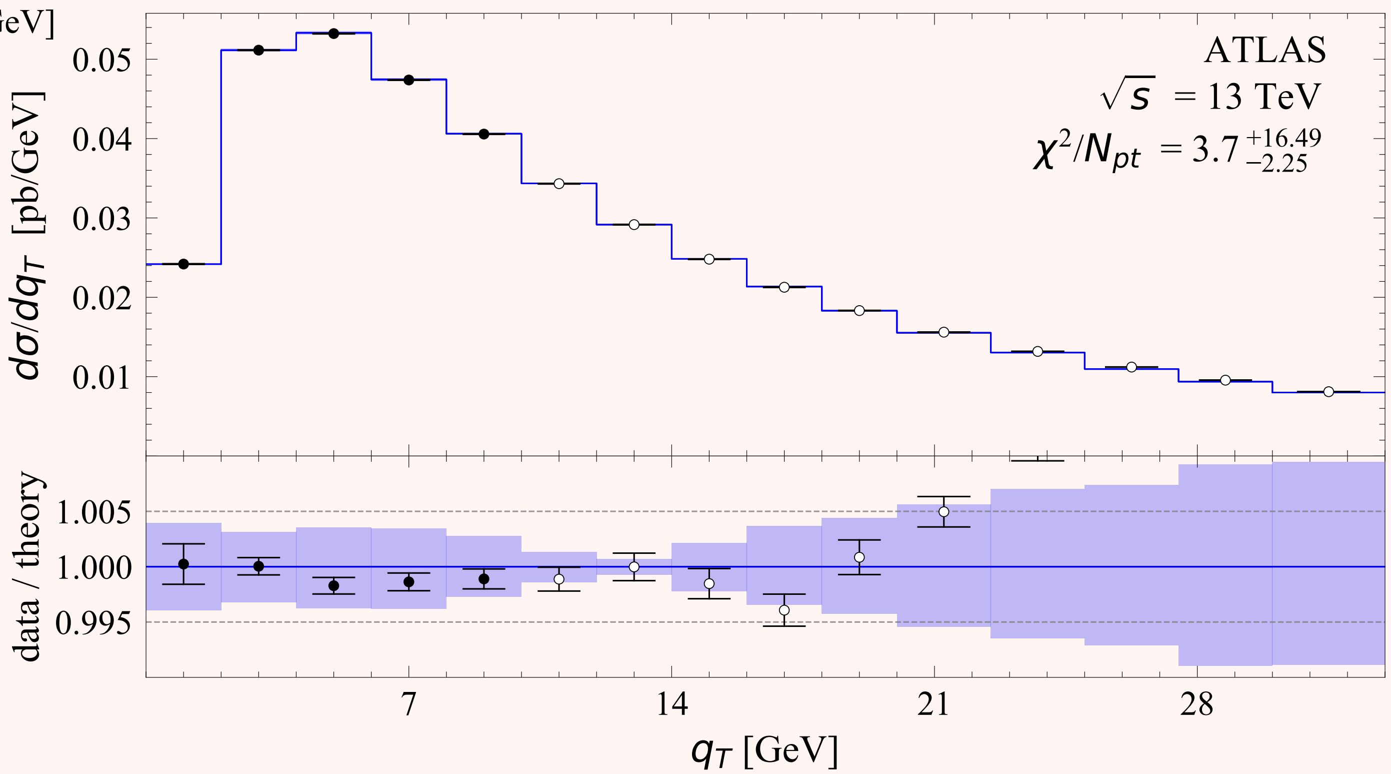

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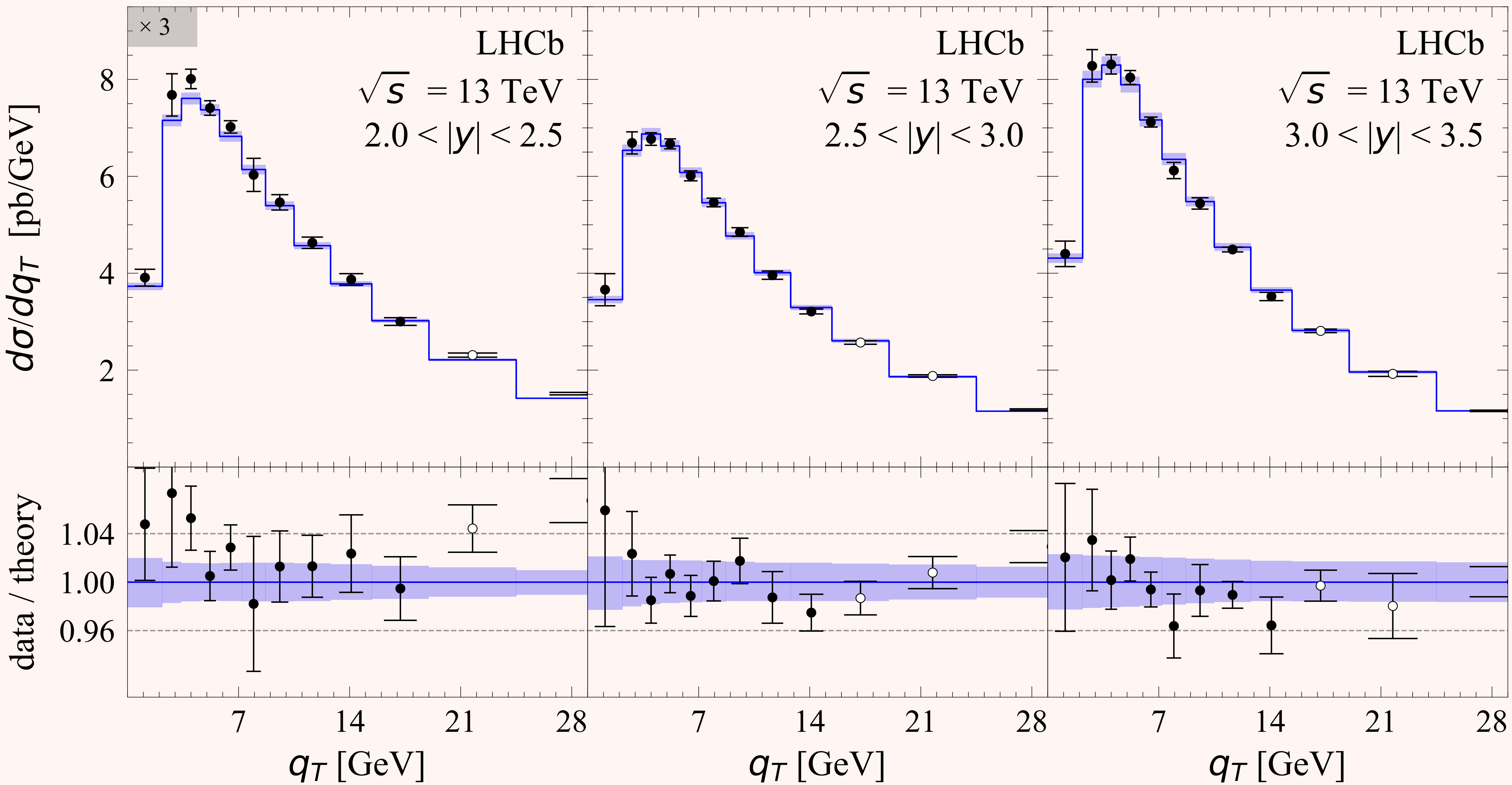

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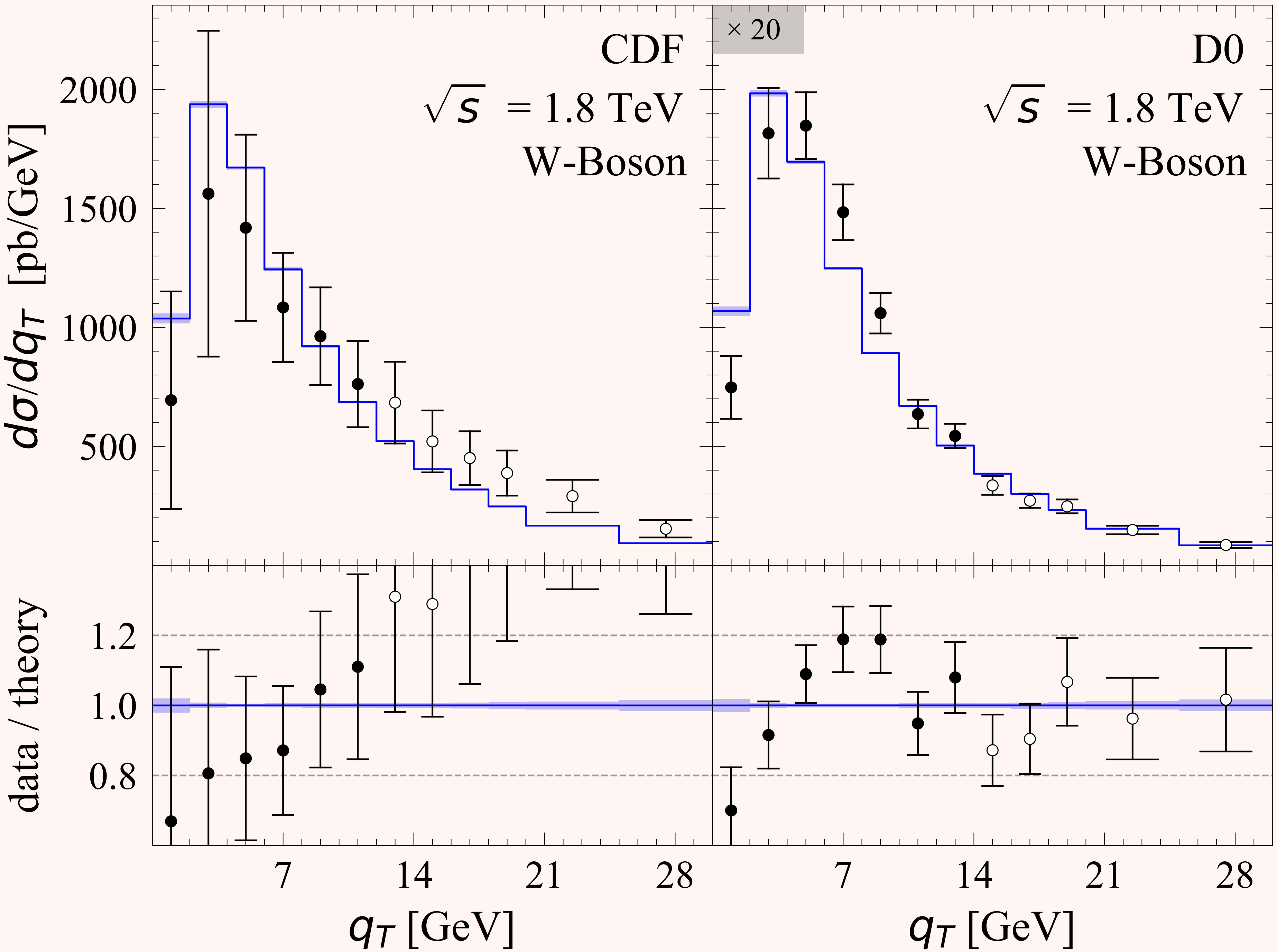
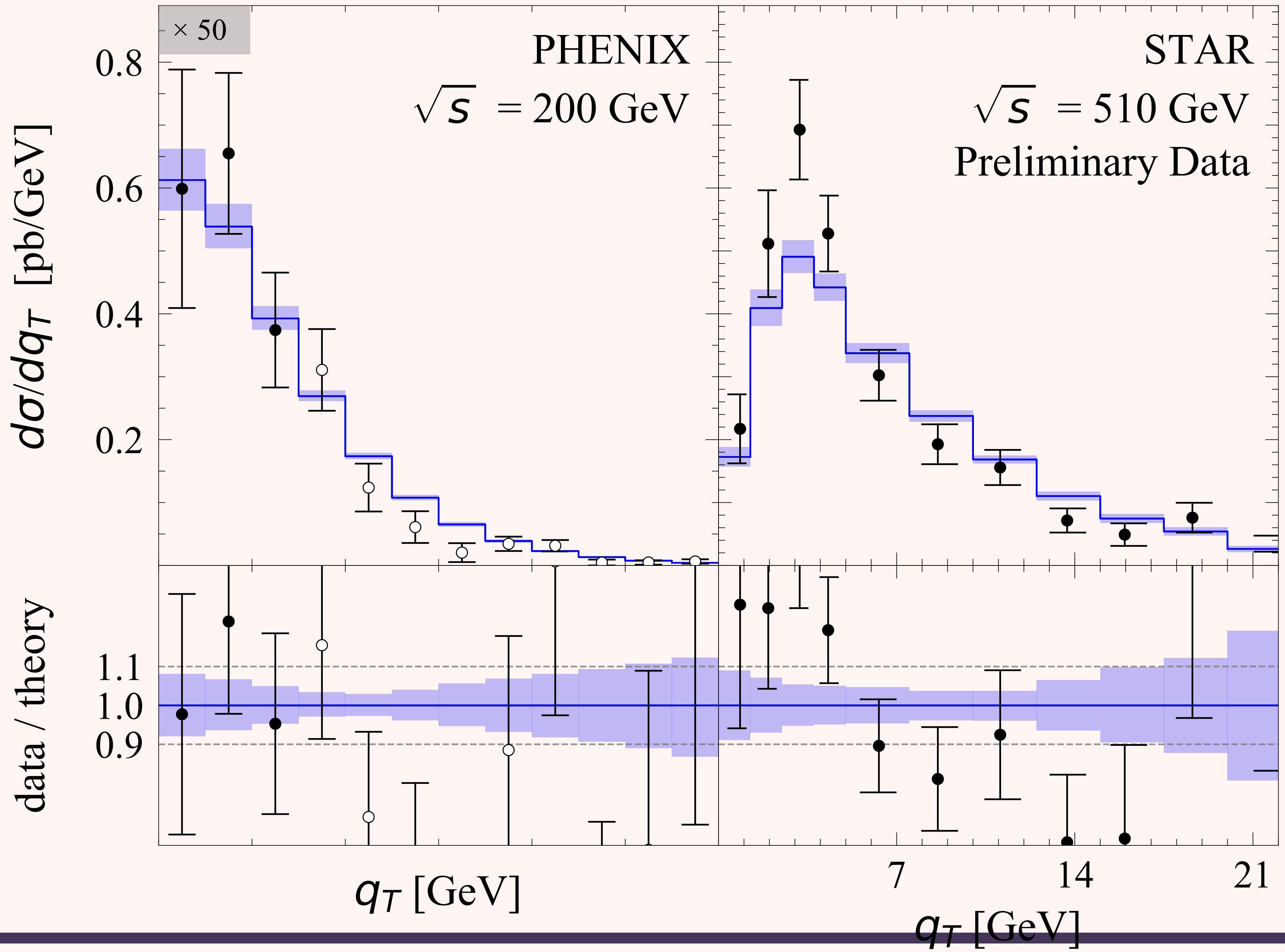
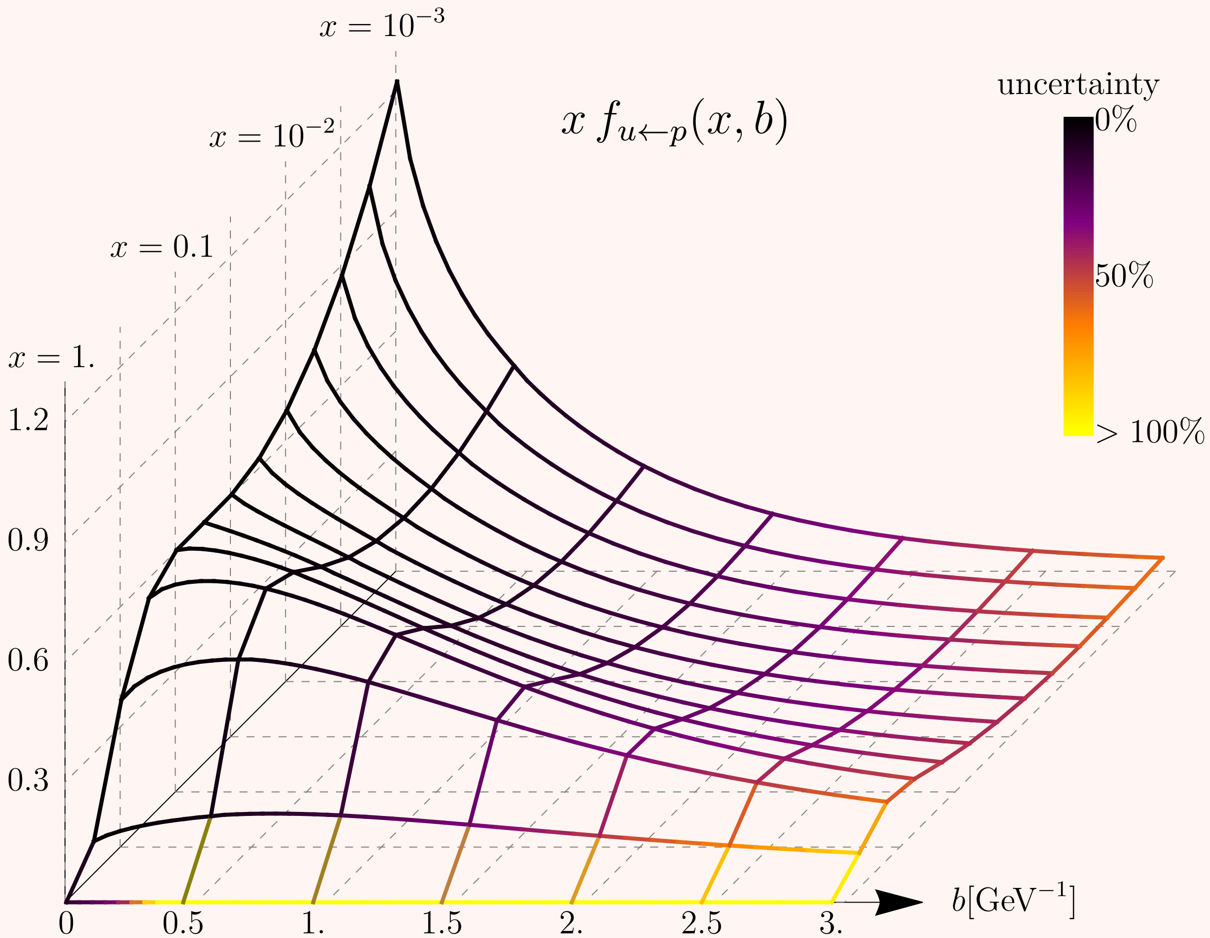


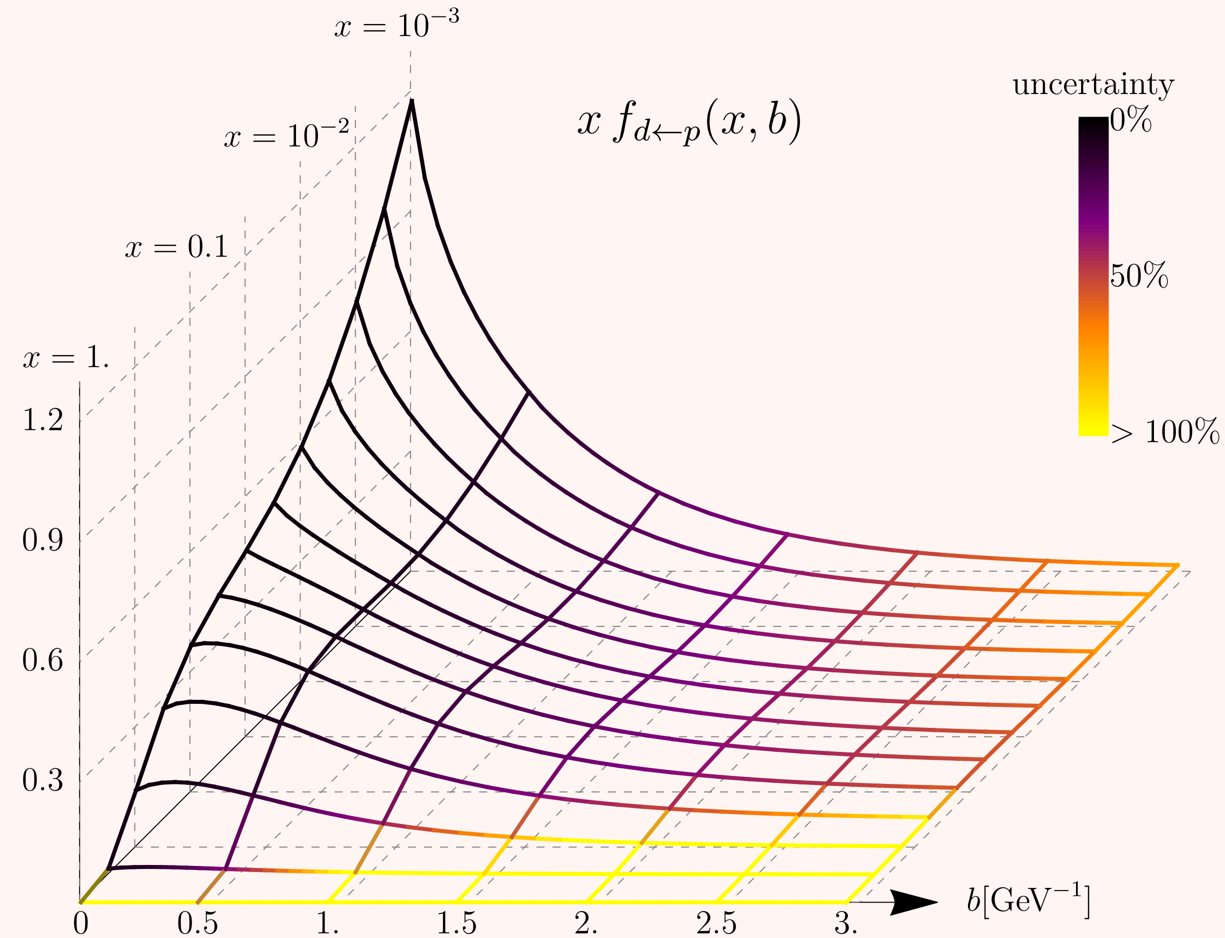
ART23: RESULTS



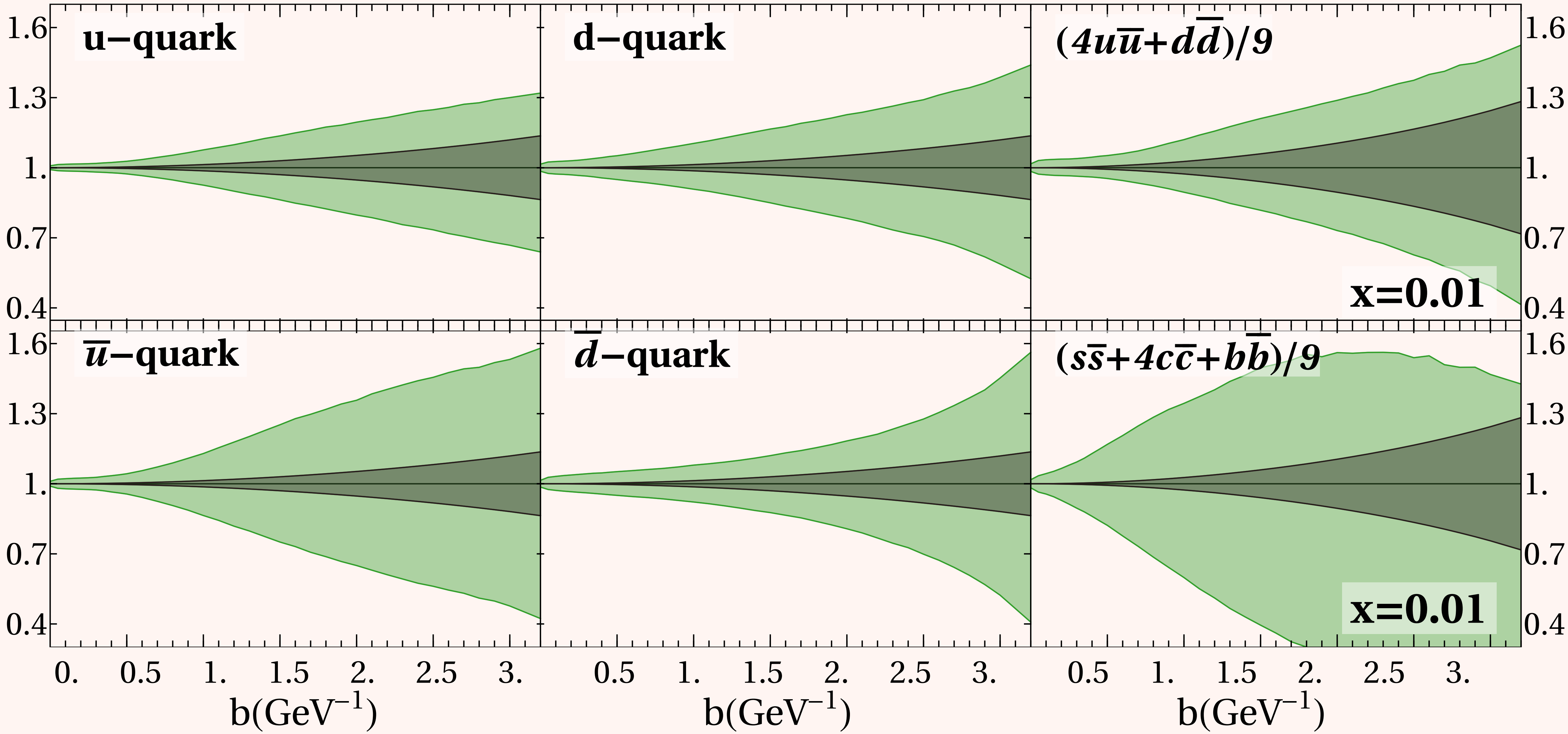
ART23: RESULTS

$$\lambda_1^u = 0.87^{+0.10}_{-0.10}, \qquad \lambda_2^u = 0.91^{+0.33}_{-0.29},$$
$$\lambda_1^d = 0.99^{+0.09}_{-0.12}, \qquad \lambda_2^d = 6.06^{+1.36}_{-1.34},$$
$$\lambda_1^{\bar{u}} = 0.35^{+0.23}_{-0.22}, \qquad \lambda_2^{\bar{u}} = 46.6^{+7.9}_{-8.1},$$
$$\lambda_1^{\bar{d}} = 0.12^{+0.13}_{-0.11}, \qquad \lambda_2^{\bar{d}} = 1.53^{+0.54}_{-0.17},$$
$$\lambda_1^{sea} = 1.32^{+0.23}_{-0.24}, \qquad \lambda_2^{sea} = 0.46^{+0.13}_{-0.45},$$





ART23: RESULTS



green: ART23
grey: SV19

SUMMARY

- We have performed a novel TMDPDF extraction: ***ART23*.**
- We used all the newest measurements and also W-boson production data, finding a good description.
- For the first time, the PDF uncertainties are systematically included. And we have realistic uncertainty bands.
- The flavor dependence in the NP ansatz is crucial to reduce the PDF bias.
- The global fit (including SIDIS data) is … closer

BACK-UP

NNPDF3.1: COMPARISON