TMD distributions: collinear PDFs and flavour dependence

Ignazio Scimemi, Pia Zurita

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

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

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IPARCOS

LP!

TMD factorization

The factorization of cross section and the evolution of TMD are milestones of recent years

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

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

- Its range of applicability is provided by $\delta = \dfrac{q_T}{Q} \ll 1$, 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 refactorization of TMD at large transverse momentum in Wilson coefficients (now at N3LO!!) and PDF (now at NNLO!!)
- PDF are just part of a model

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

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

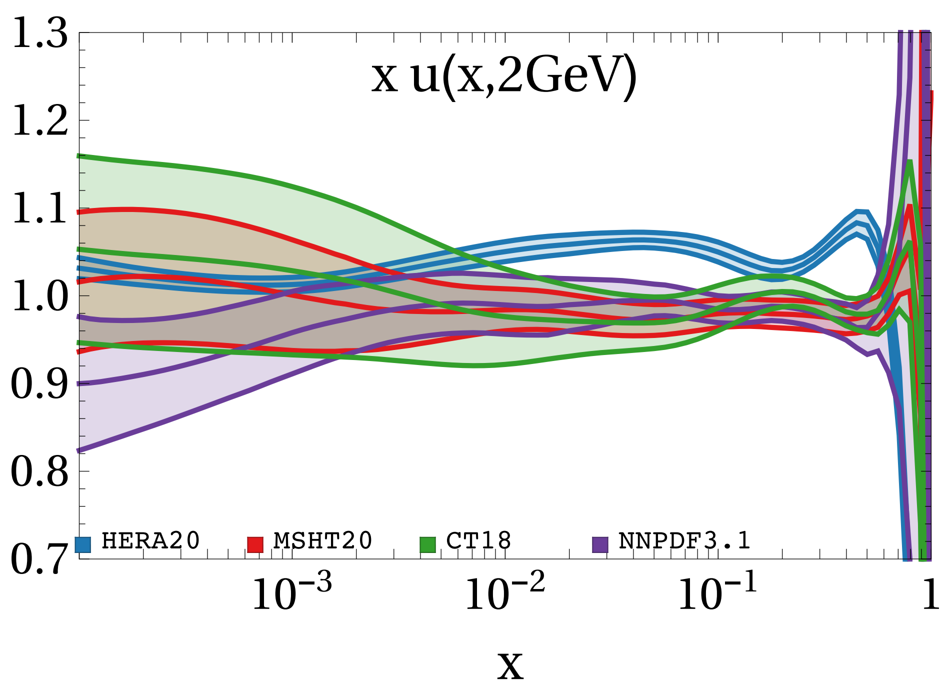
The PDF bias

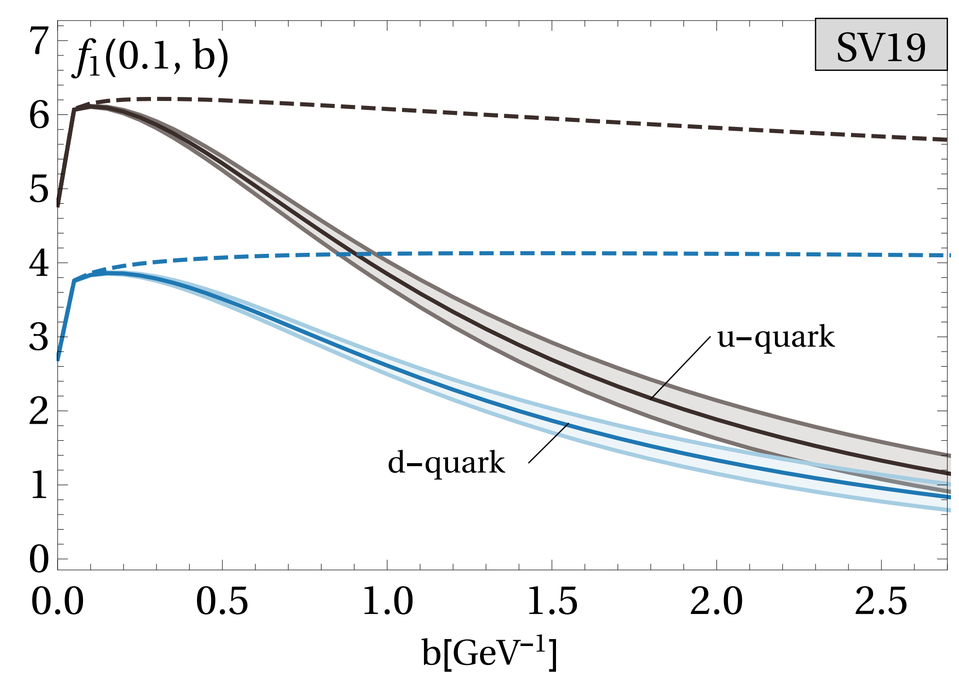
- In SV19 they tried with several PDF sets

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

- ***PDF bias***: with the same fitting strategy different sets of PDFs give different quality fits. And ***shapes***!

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



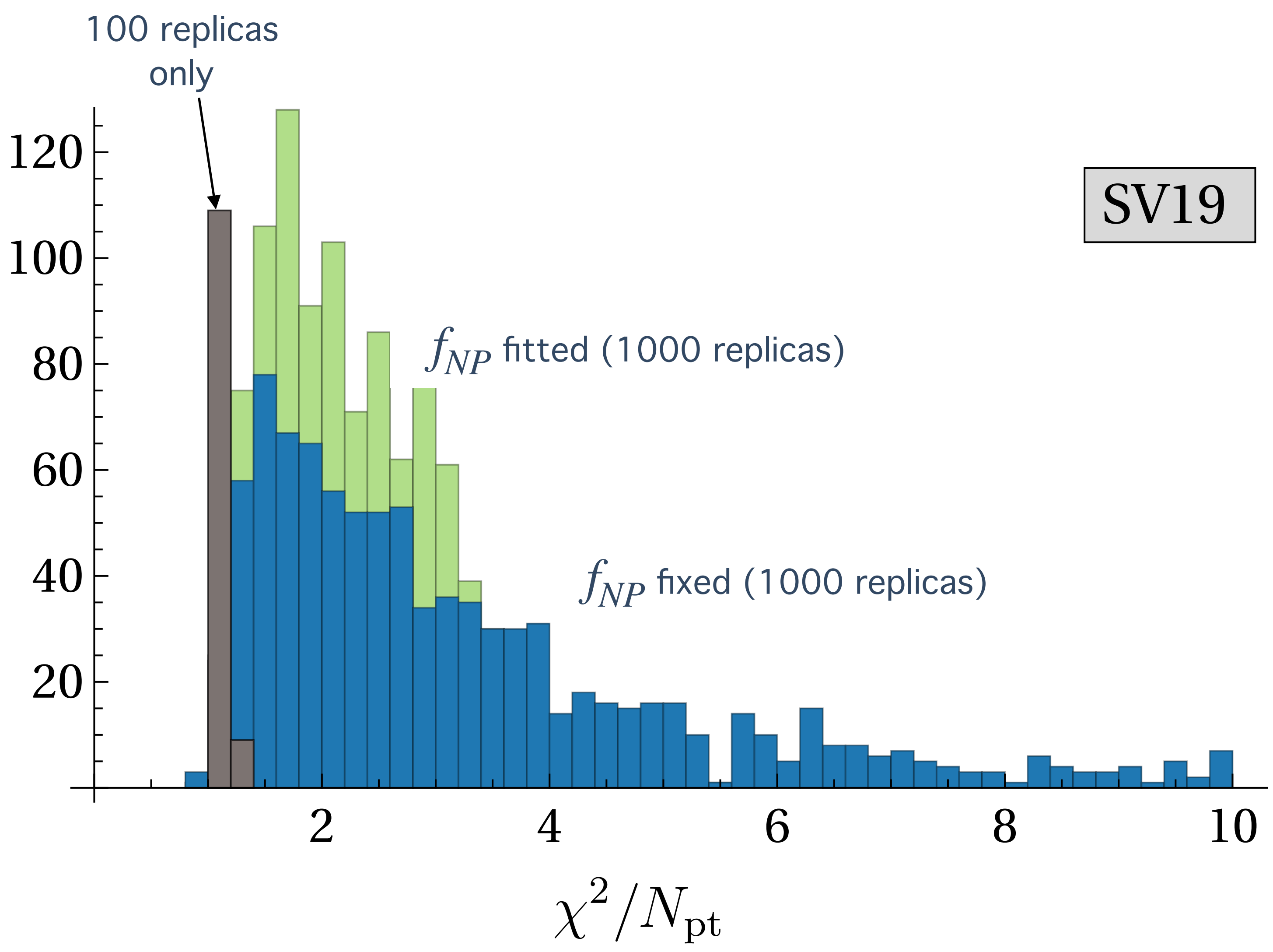


The PDF bias

- 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?

Most of replicas have a very big χ^2: reweighing is problematic

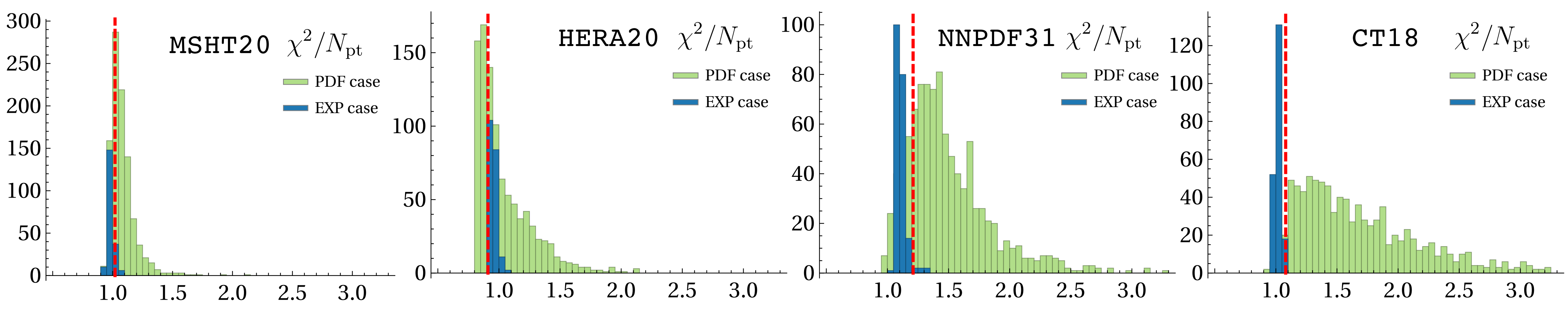


PDF uncertainties and flavour dependence

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

- Answer to question number 1: allow for some flavor separation.

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



- 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)

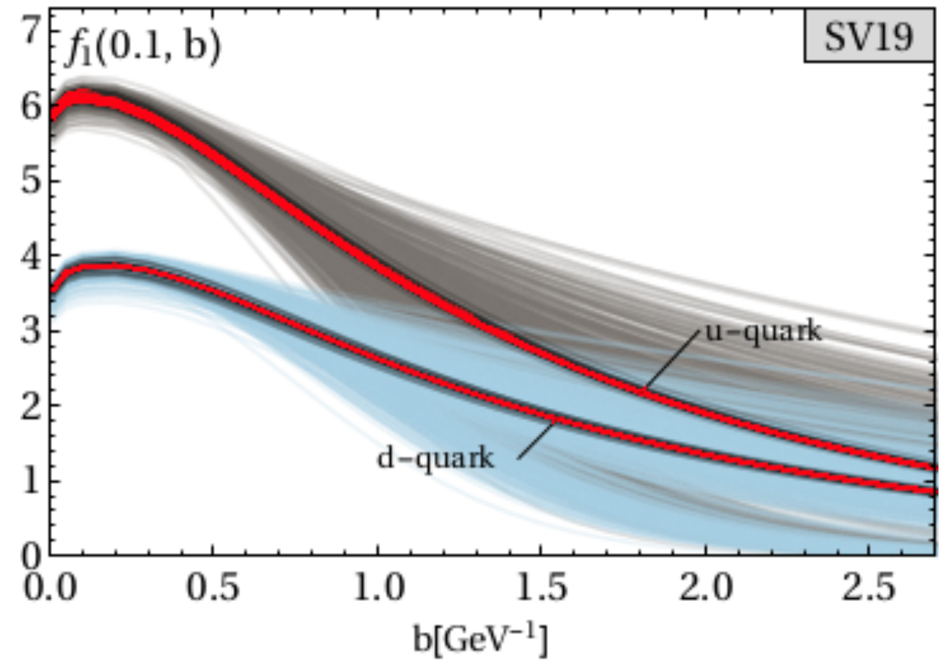
PDF uncertainties and flavour dependence

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

- Answer to question number 2: include the PDF uncertainties while keeping f_{NP} fixed.

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

- We get reasonable uncertainty bands.



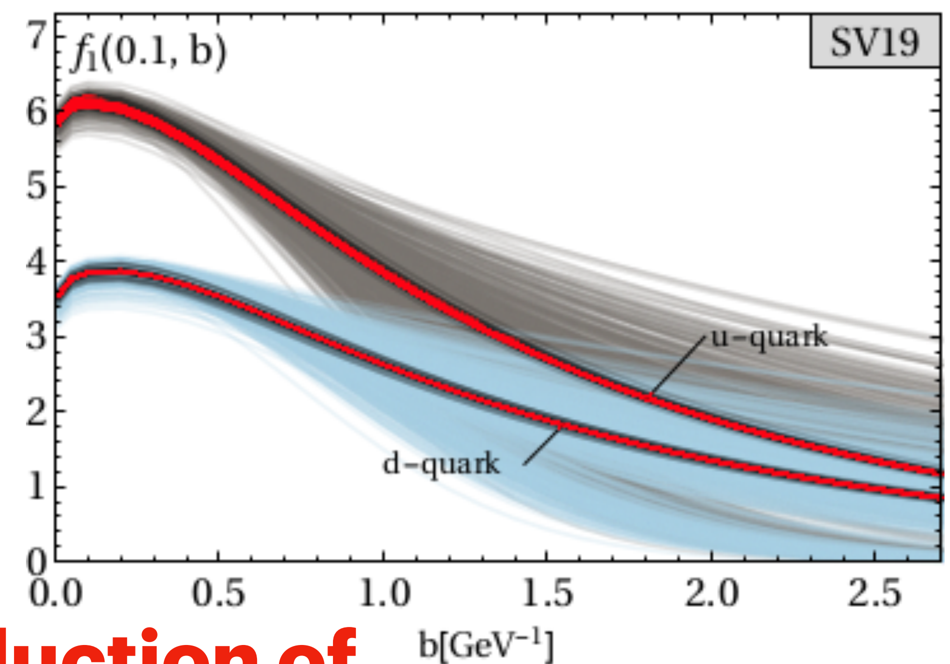
PDF uncertainties and flavour dependence

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

- Answer to question number 2: include the PDF uncertainties while keeping f_{NP} fixed.

- We had to re-fit, for each PDF replica, the TMD.

- And so we got reasonable uncertainty bands.

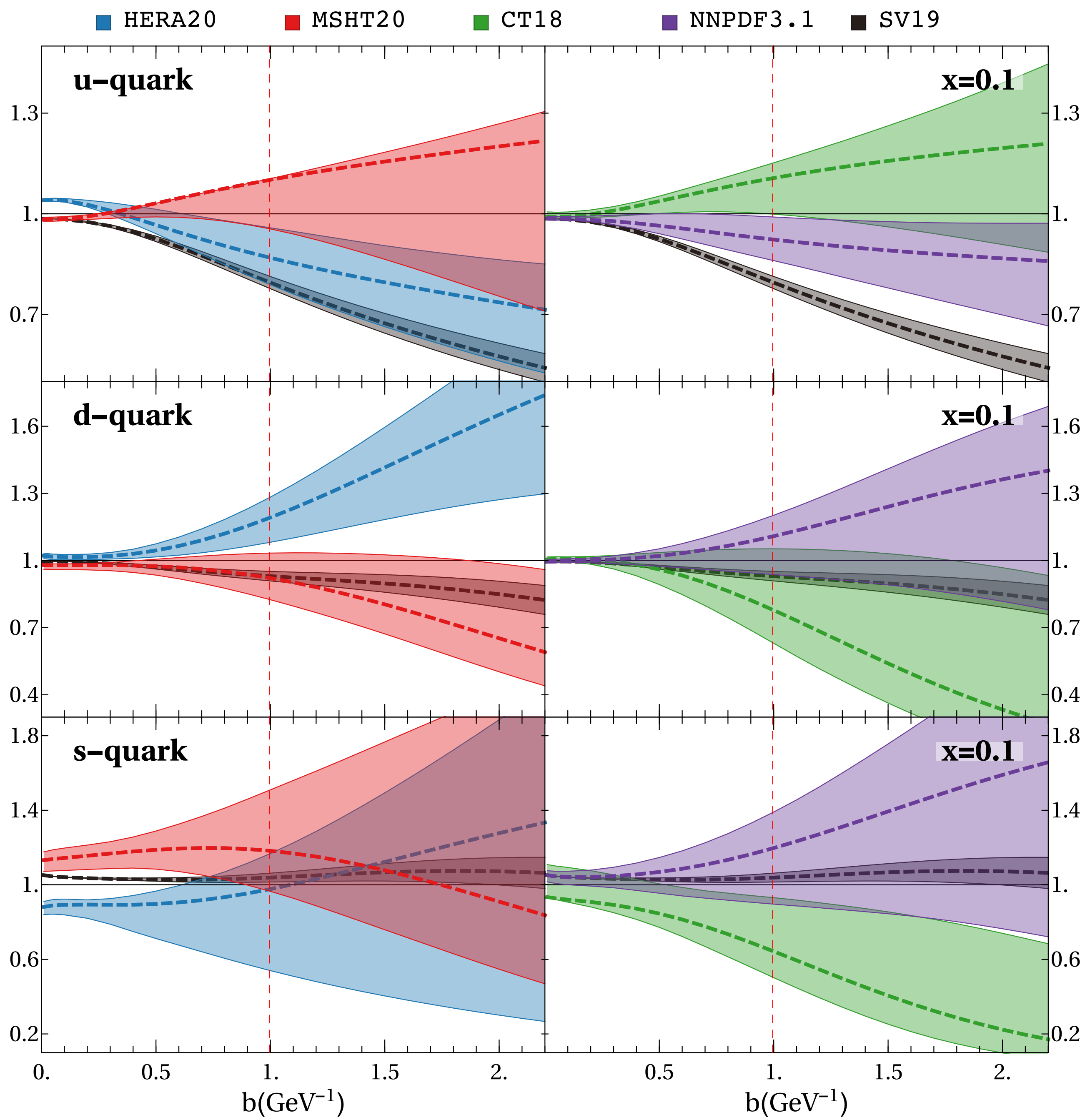


the simultaneous introduction of both improvements is crucial!

PDF uncertainties and flavour dependence

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

- Answer to question number 3: it definitely becomes better.



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ART23 >> SV19 🙂

- Higher flexibility + 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

$$\mathcal{D}(b,\mu) = \mathcal{D}_{\text{small-b}}(b^*,\mu^*) + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'} \Gamma_{\text{cusp}}(\mu') + \mathcal{D}_{\text{NP}}(b) \qquad b^*(b) = \frac{b}{\sqrt{1+\frac{\vec{b}^2}{B_{\text{NP}}^2}}} = \frac{2e^{-\gamma_E}}{\mu^*}$$

- We discover that we are sensitive to log corrections to the NP part of the evolution kernel $\mathcal{D}_{\text{NP}}(b) = bb^*\left[c_0 + c_1 \ln\left(\frac{b^*}{B_{\text{NP}}}\right)\right]$

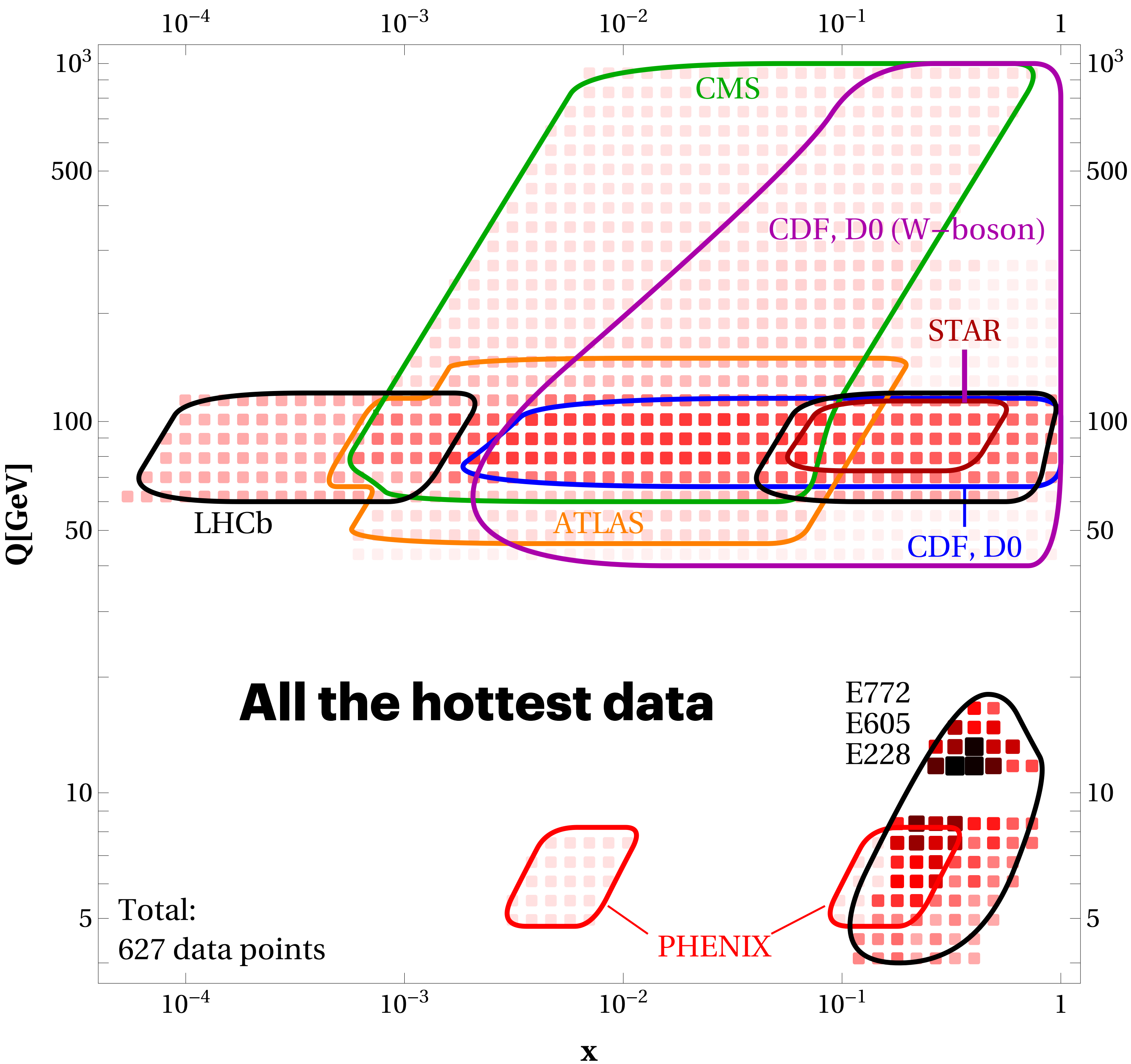
ART23: details

- Parameterization: $f^{f}_{NP}(x,b) = \dfrac{1}{\cosh\left(\left(\lambda_1^f(1-x)+\lambda_2^f x\right)b\right)}$ $\quad f = u, \bar{u}, d, \bar{d}, sea$

- In total, 13 parameters

- Reference PDFs: MSHT20

ART23: details



627 data points

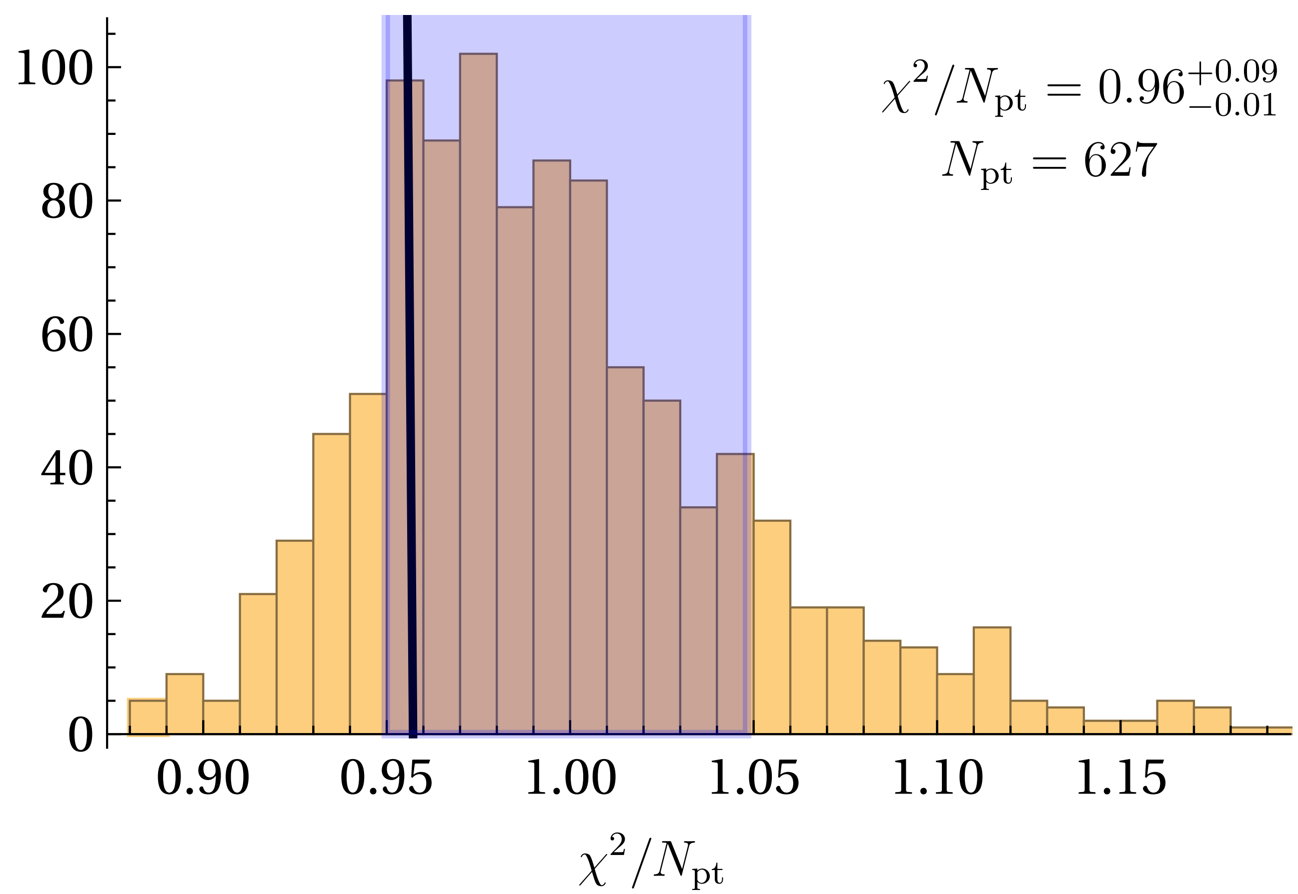
New in!

- **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 deem to be 1000.



ART23: results

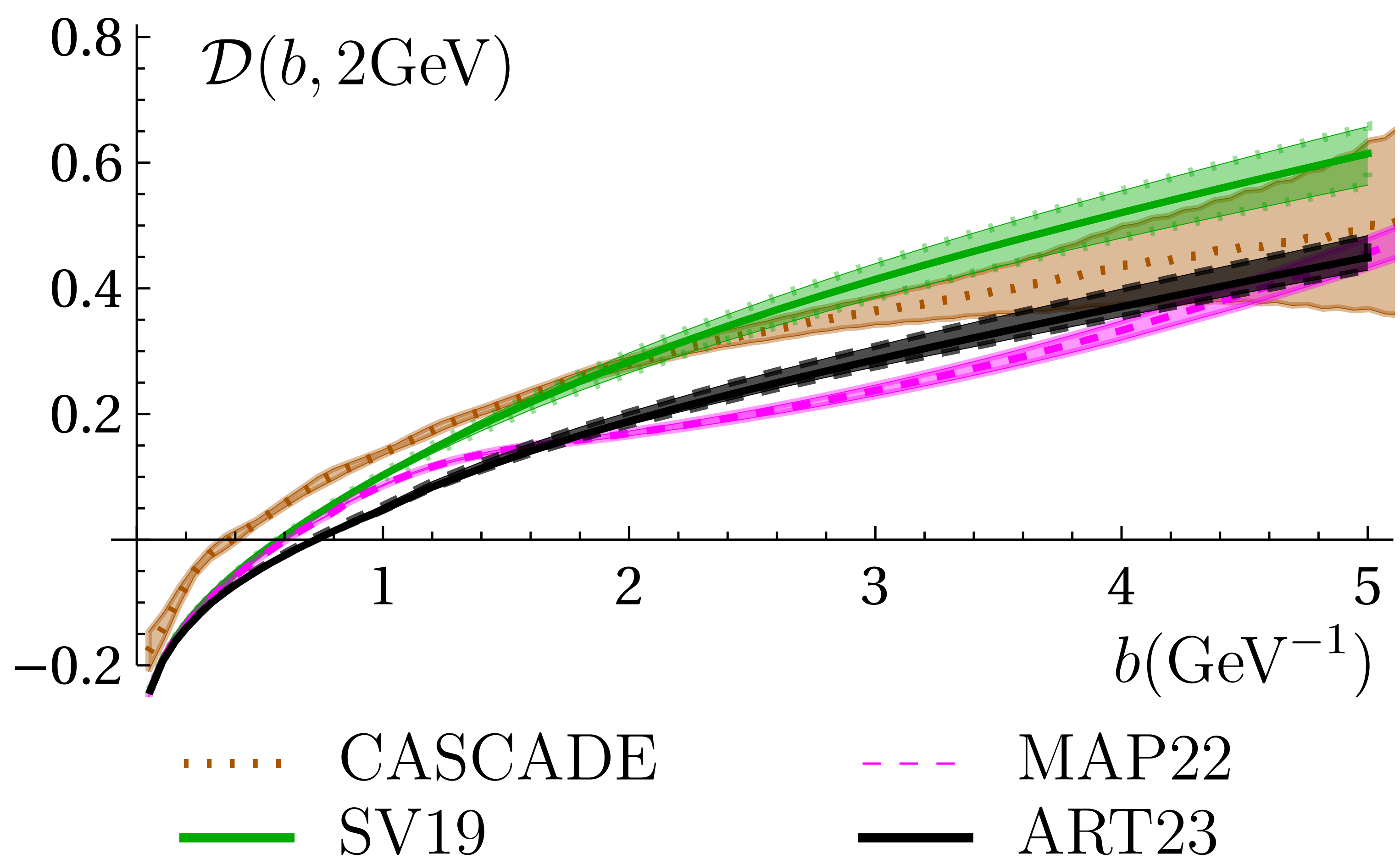
- $\chi^2/N_{pt} = 0.93$ (0.957 for the mean prediction)
- 68%CI (0.950, 1.048)
- overall improvement w.r.t. SV19. Specially for the LHC data. Higher precision plays a key role here.
- more realistic uncertainty bands than in SV19.

CS kernel close to the one from the global fit MAP22

$$B_{\rm NP} = 1.56^{+0.13}_{-0.09}\,\text{GeV}$$

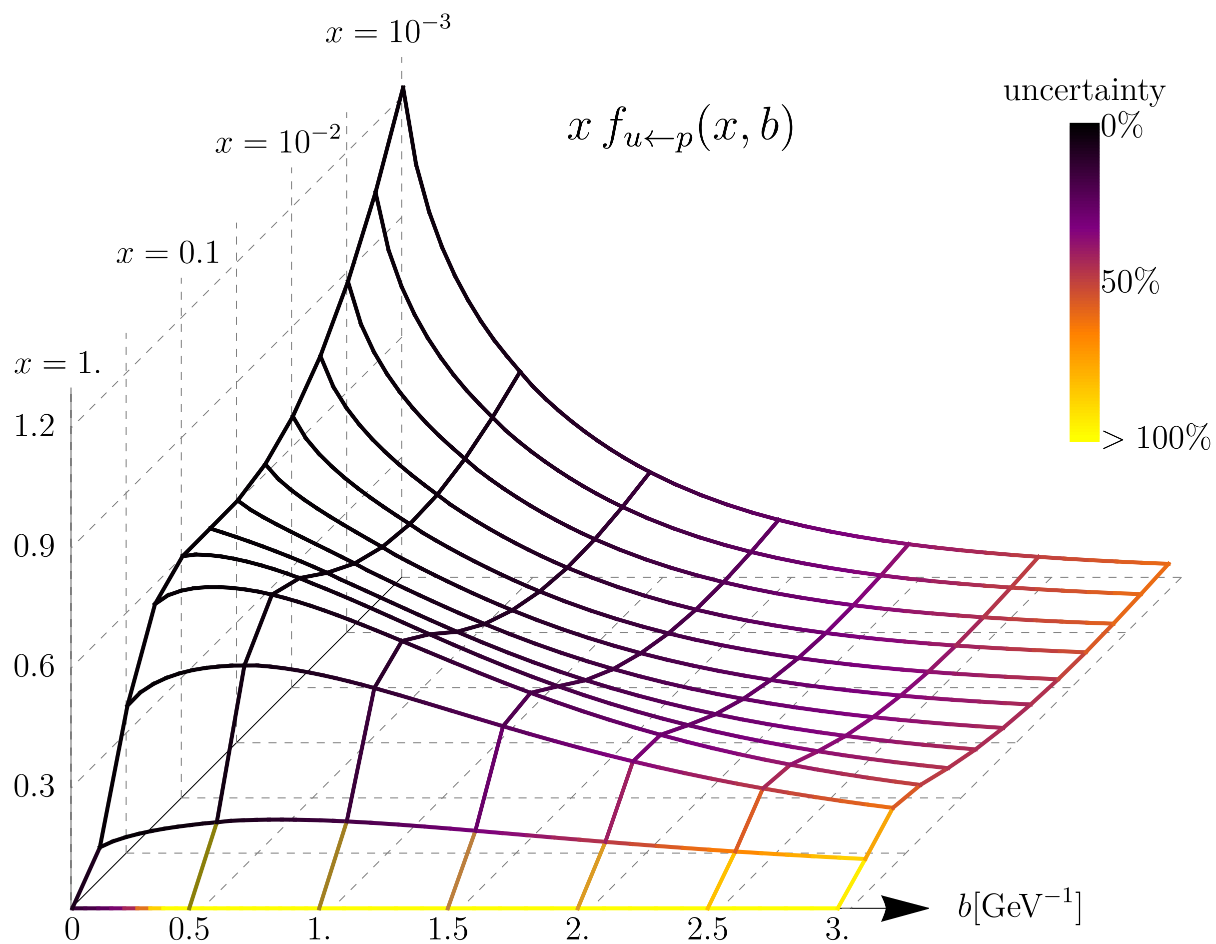
$$c_0 = 3.69^{+0.65}_{-0.61} \cdot 10^{-2}$$

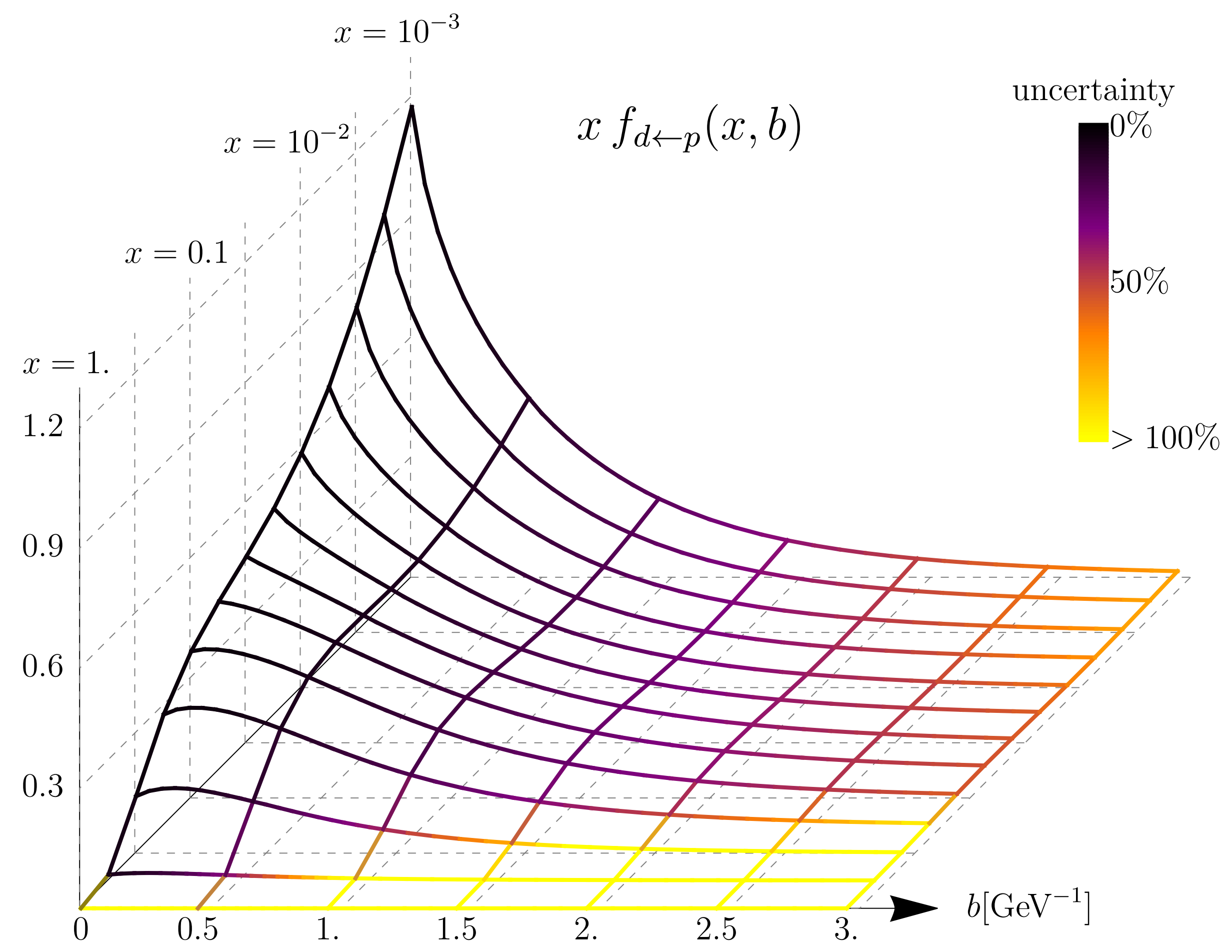
$$c_1 = 5.82^{+0.64}_{-0.88} \cdot 10^{-2}$$



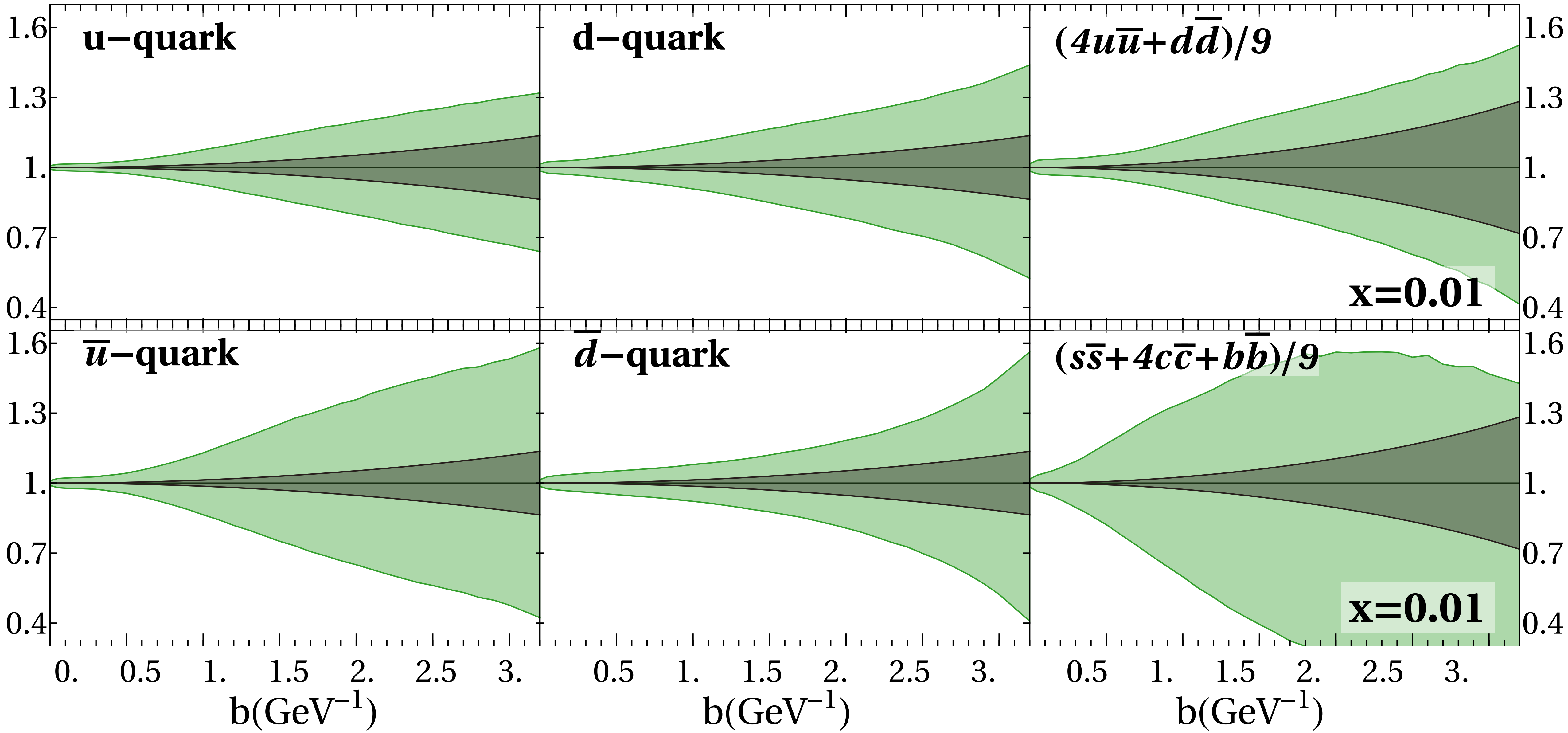
ART23: results

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



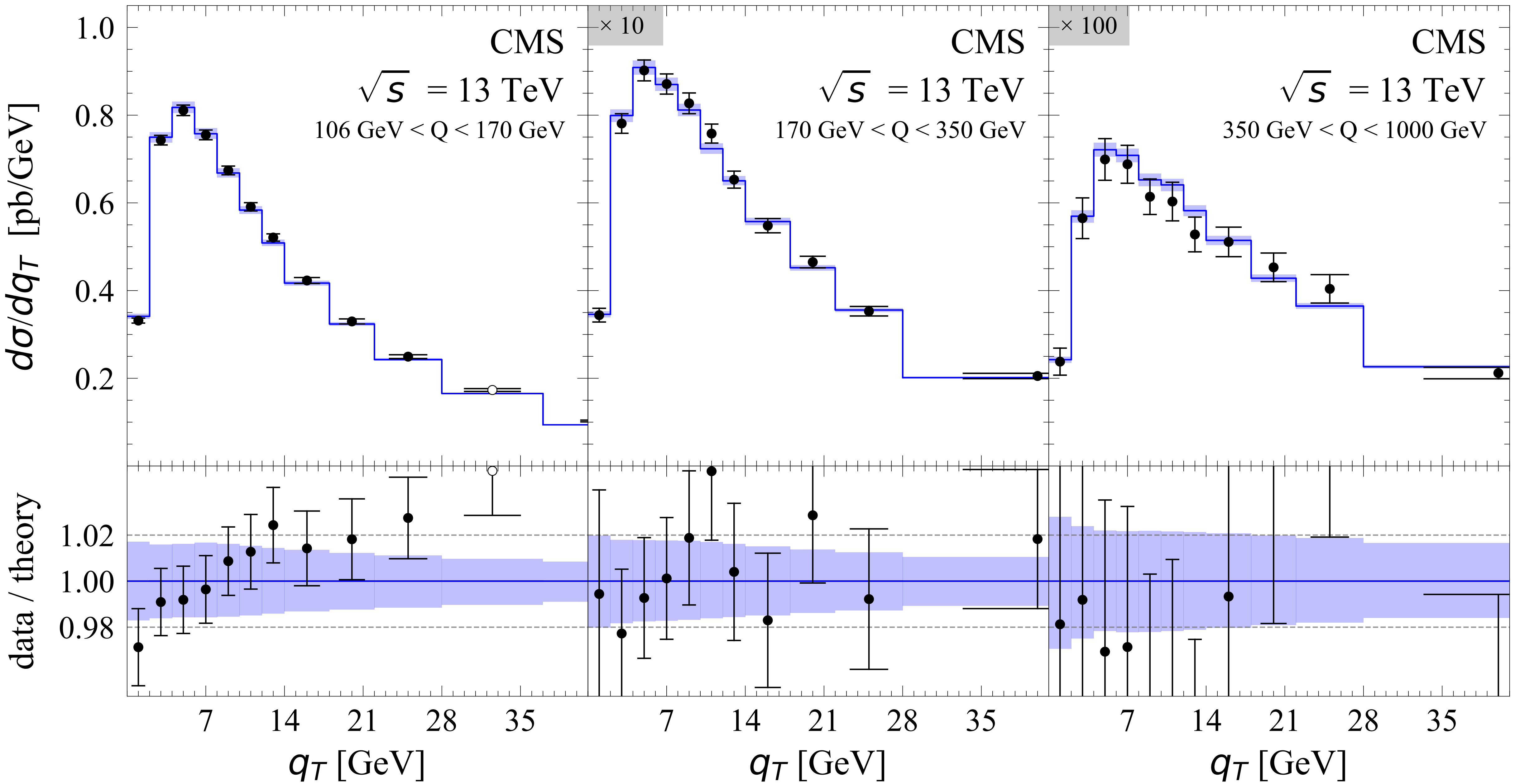


ART23: results



green: ART23
grey: SV19

ART23: results



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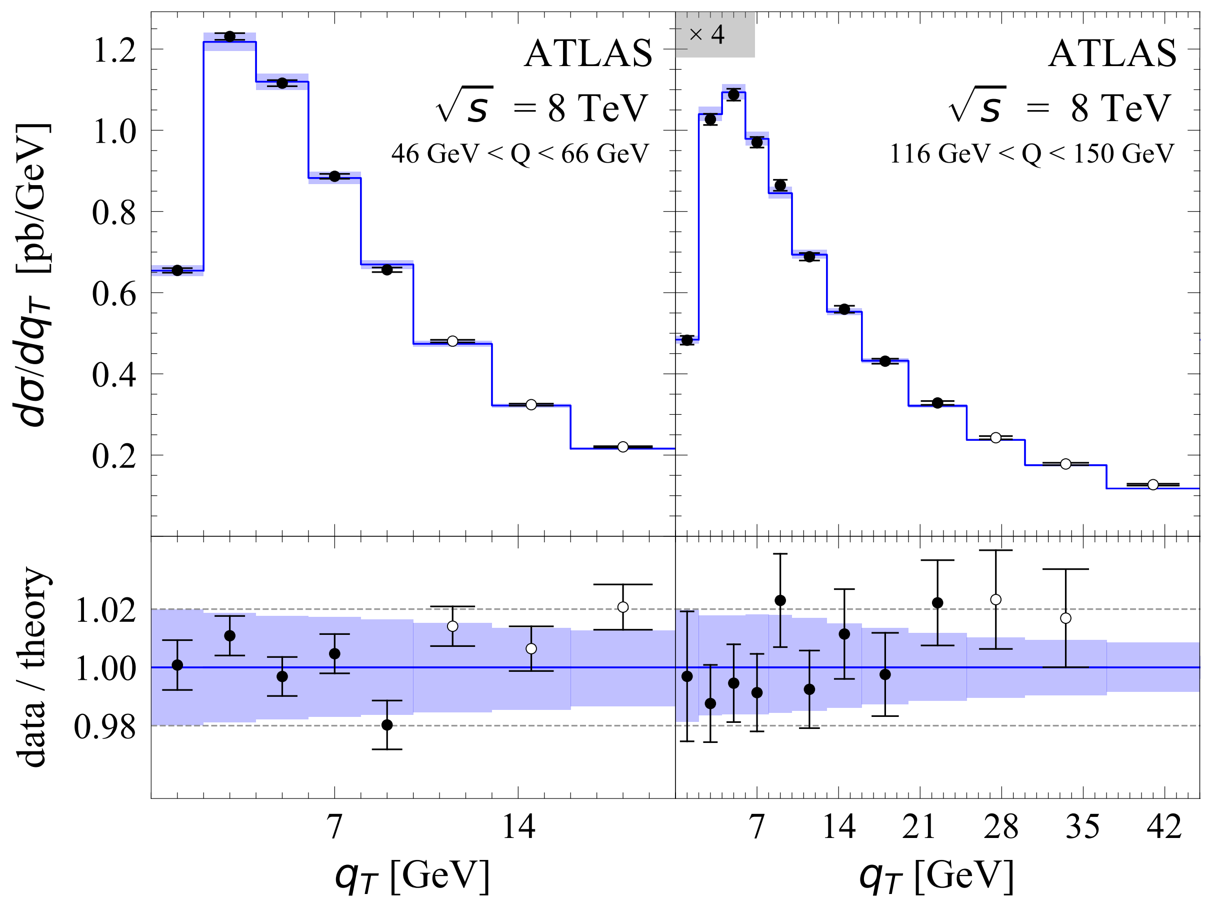

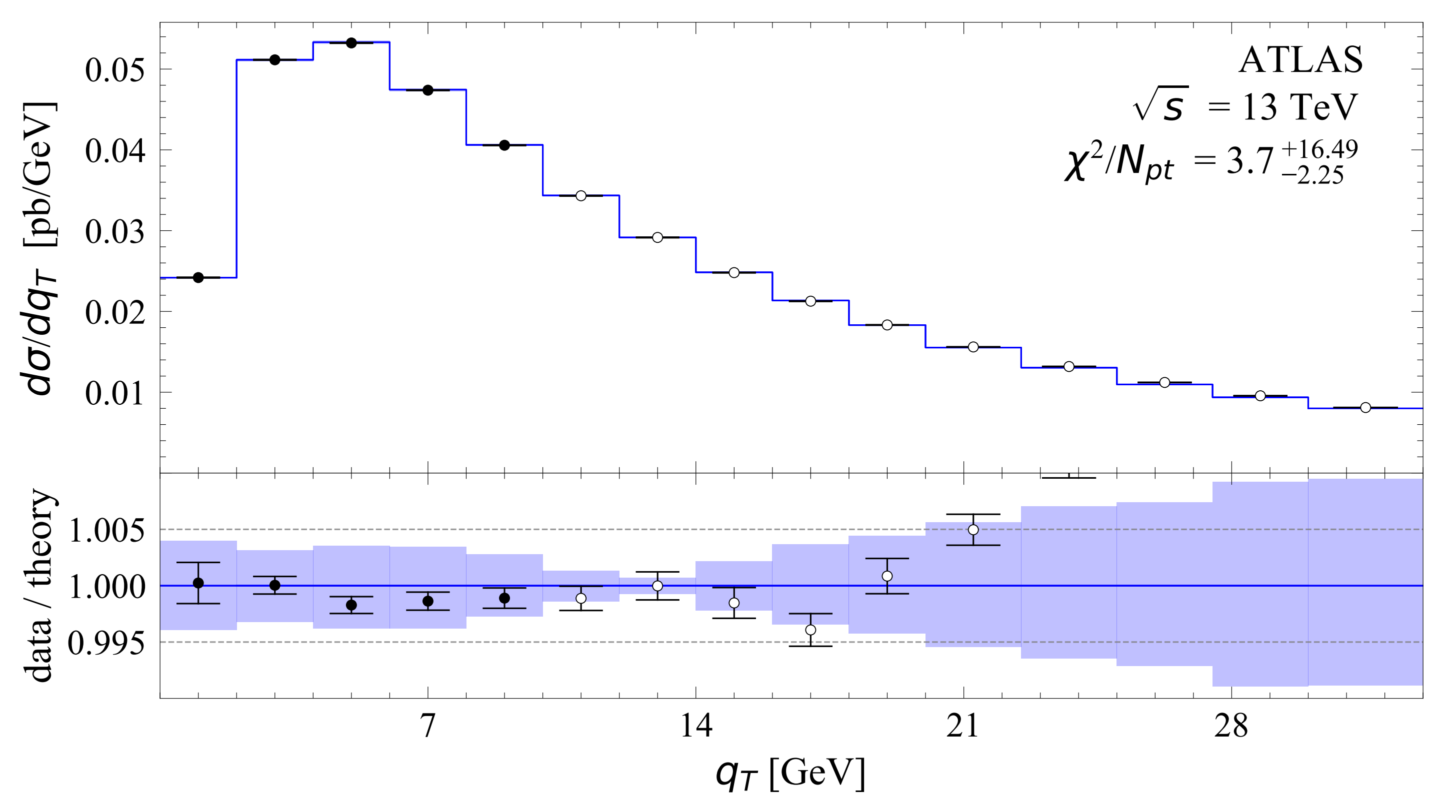

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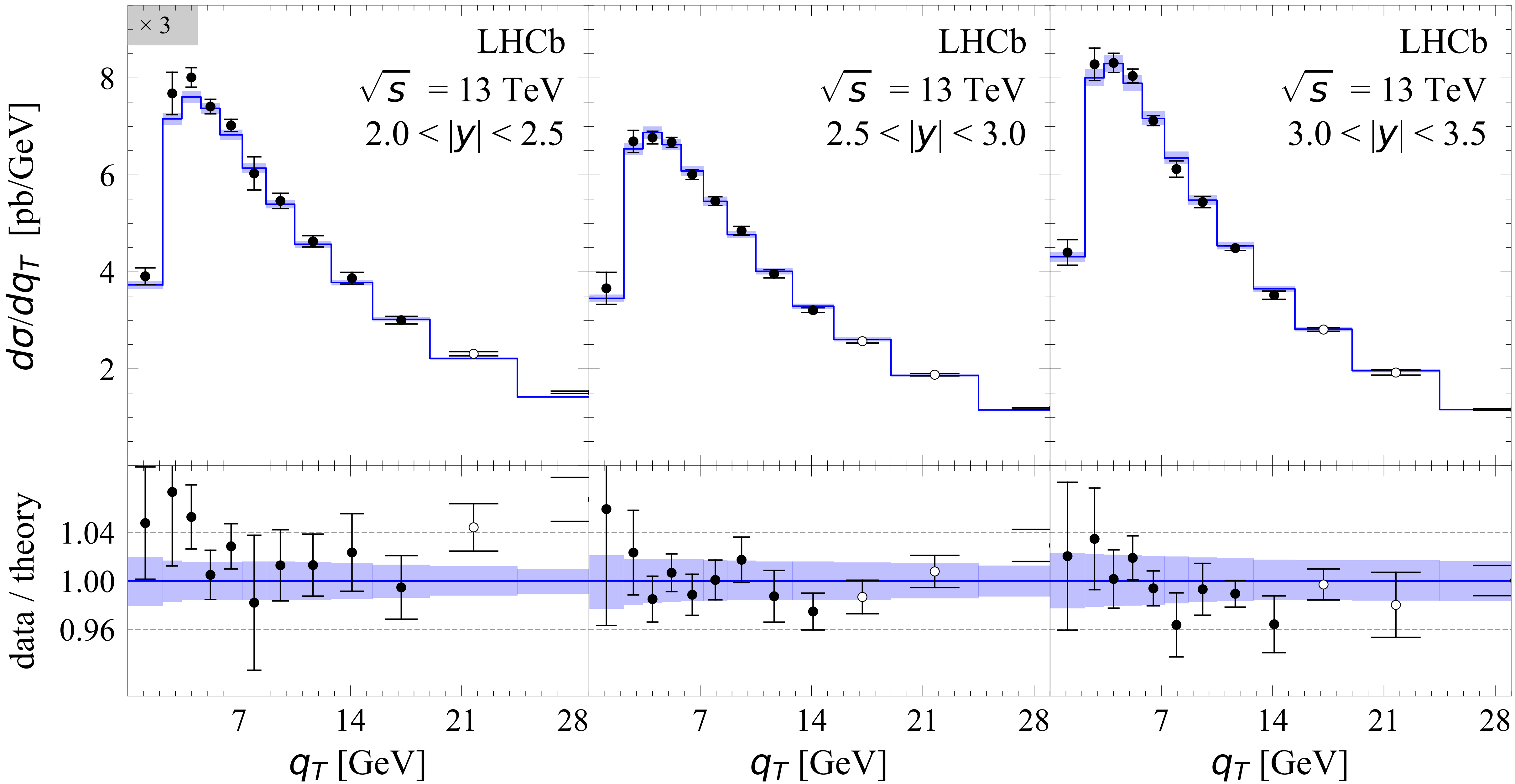

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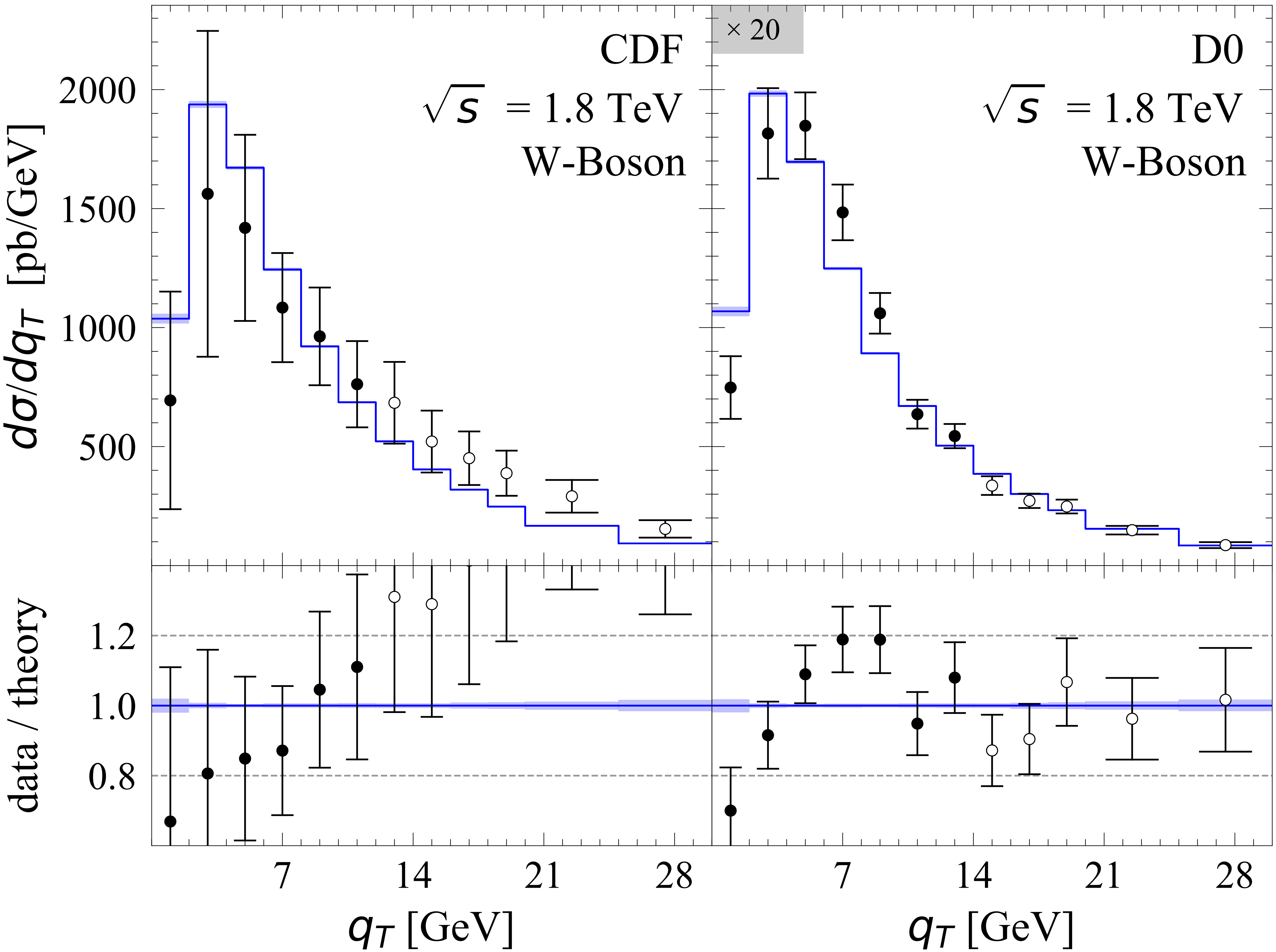

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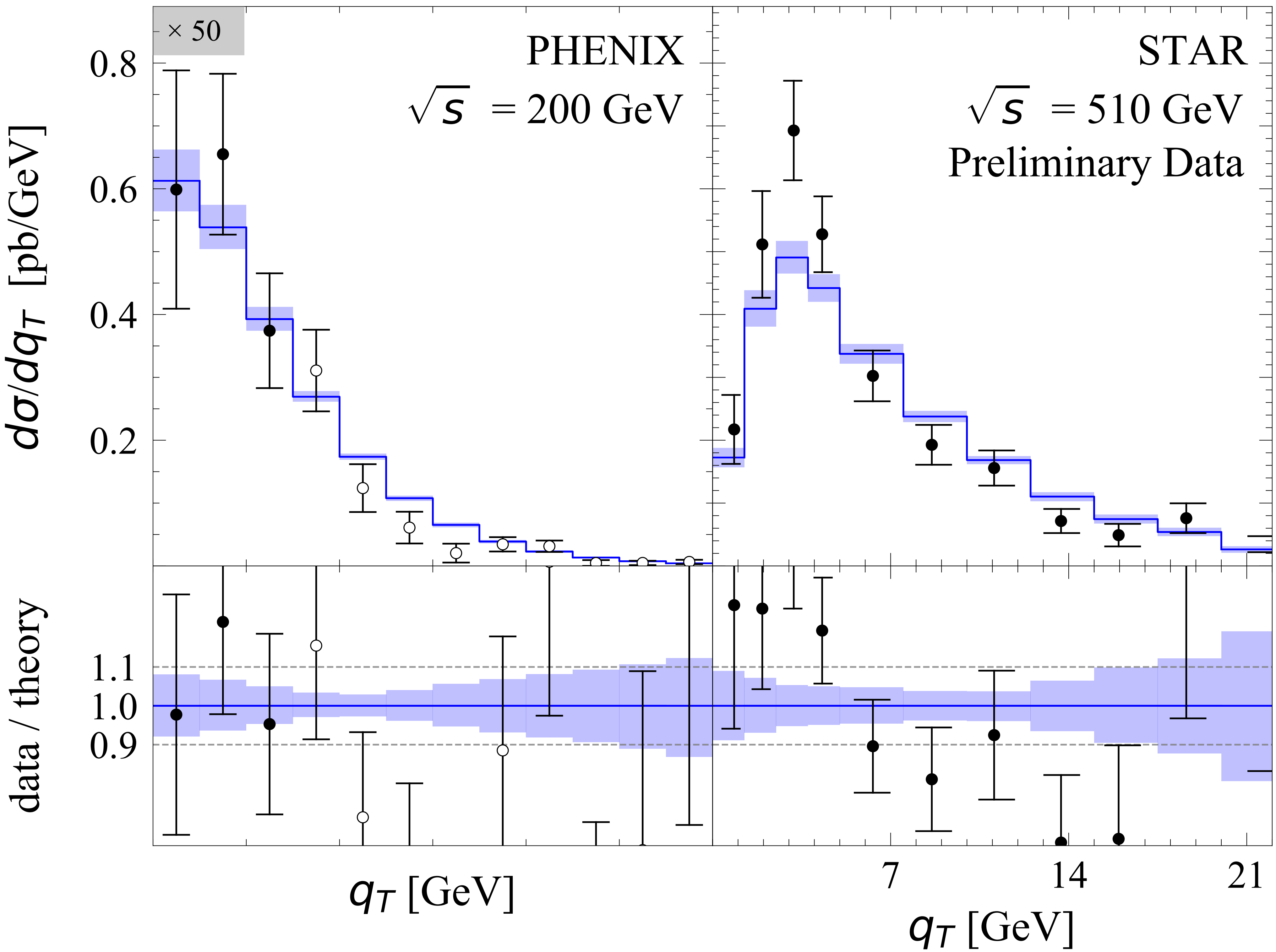

Summary

- 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