Vector boson production and TMD extraction at N4LL

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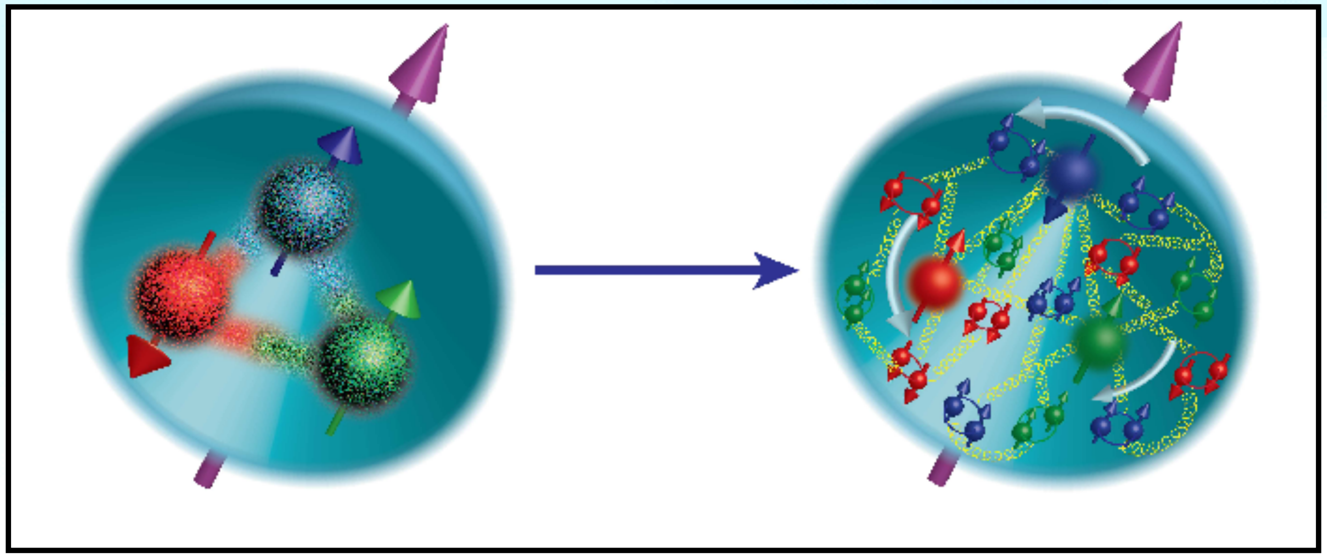
Comunidad de Madrid

IPARCOS

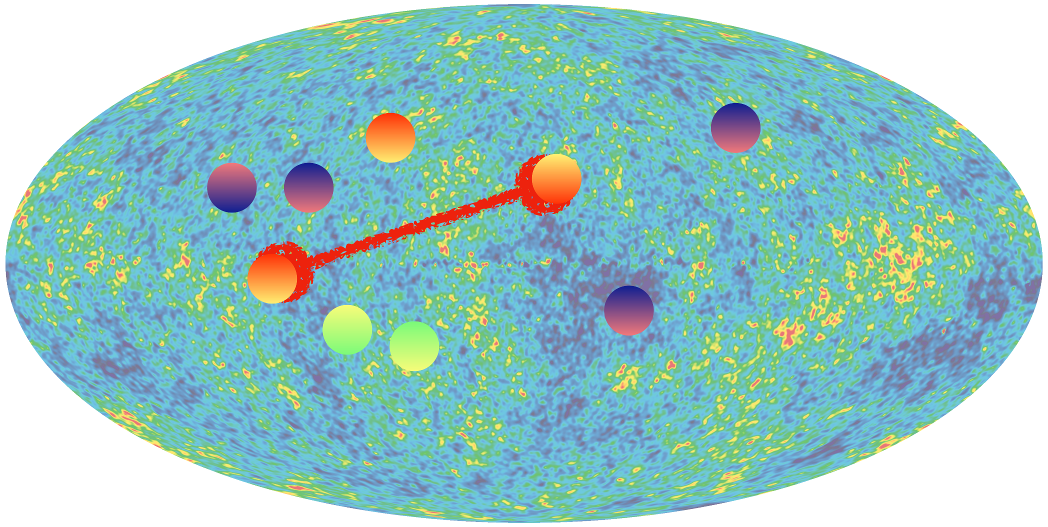
Motivation

Now suppose you have a proton.

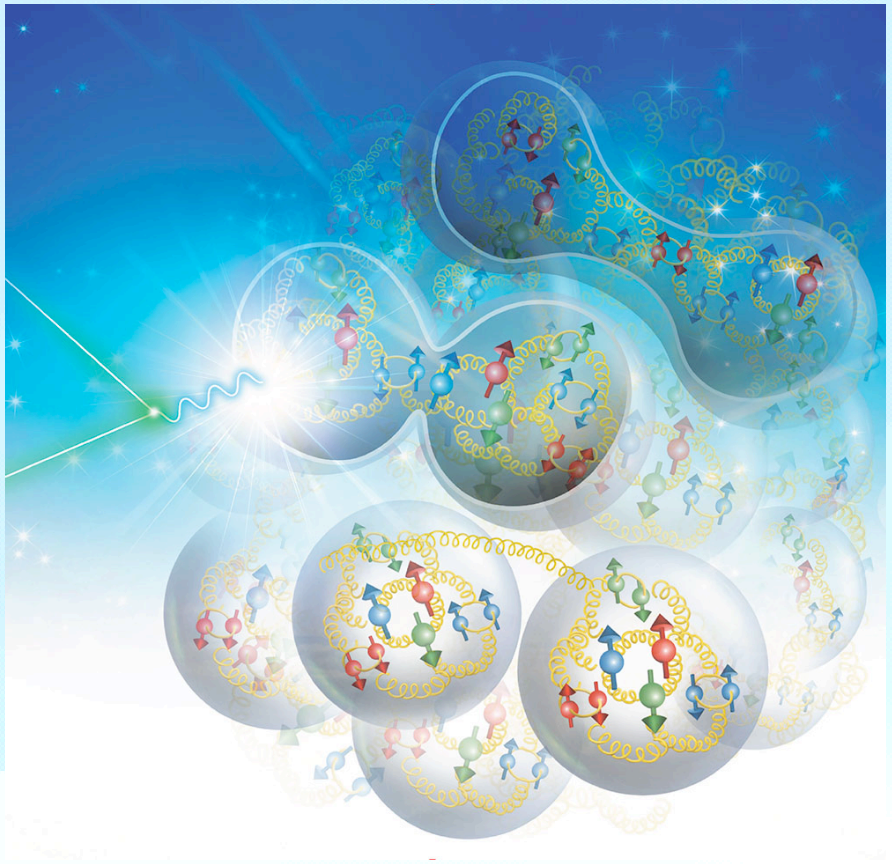
We have made *experiments* showing that we have 3 quarks + pairs of quarks-antiquarks + gluons

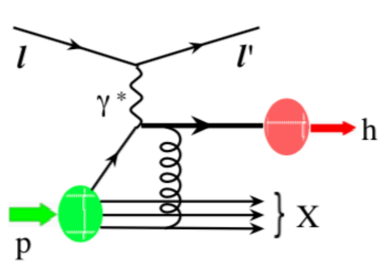


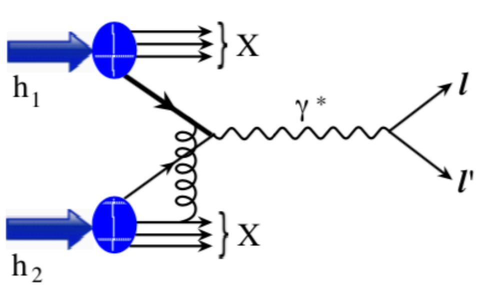
How are quarks in two distinct points correlated?Spin?



Motivation







- We need a virtual photon coupled to lepton pairs to reduce QCD uncertainties: Drell-Yan, Semi-inclusive DIS, $e^+e^- \to 2j$
- We need to address a method to identify fundamental quark distributions in the cross section: power expansion, operator product expansion (in combination with effective field theory (SCET), or background field method)
- Overcome all technical difficulties (40 years of research behind!)

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 and allows N4LL resummation). 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

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

Unpolarized TMD matching to collinear functions: DY and SIDIS in the asymptotic limit

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

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

The Wilson coefficients (C,$\mathbb{C}$) are all known at higher orders!!

NNLO TMDPDF /TMDFF: T. Gehrmann et al. JHEP 06 (2014) 155, M.G. Echevarria et al. Phys. Rev. D93 (2016) 011502, JHEP 09 (2016) 004, M. X. Luo et al. *JHEP* 01 (2020) 040, *JHEP* 10 (2019) 083

NNNL TMDPDF /TMDFF: M. X. Luo et al. Phys.Rev.Lett. 124 (2020) 9, 092001, *JHEP* 06 (2021) 115, M. Ebert et al. JHEP 09 (2020) 146

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

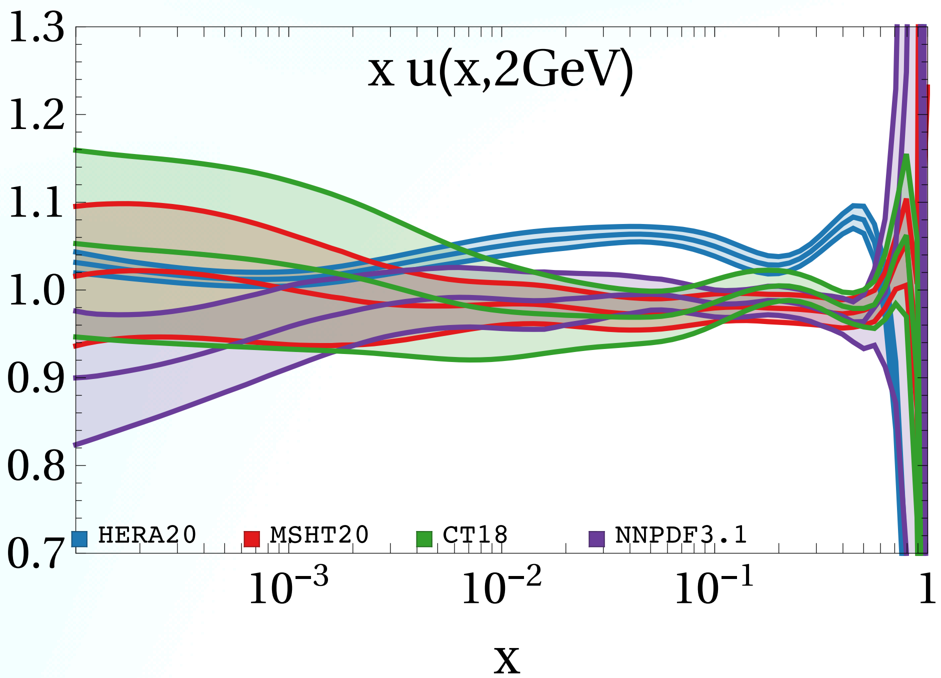
V. Moos, I.S., A. Vladimirov, P. Zurita e-Print: 2305.07473 [hep-ph]

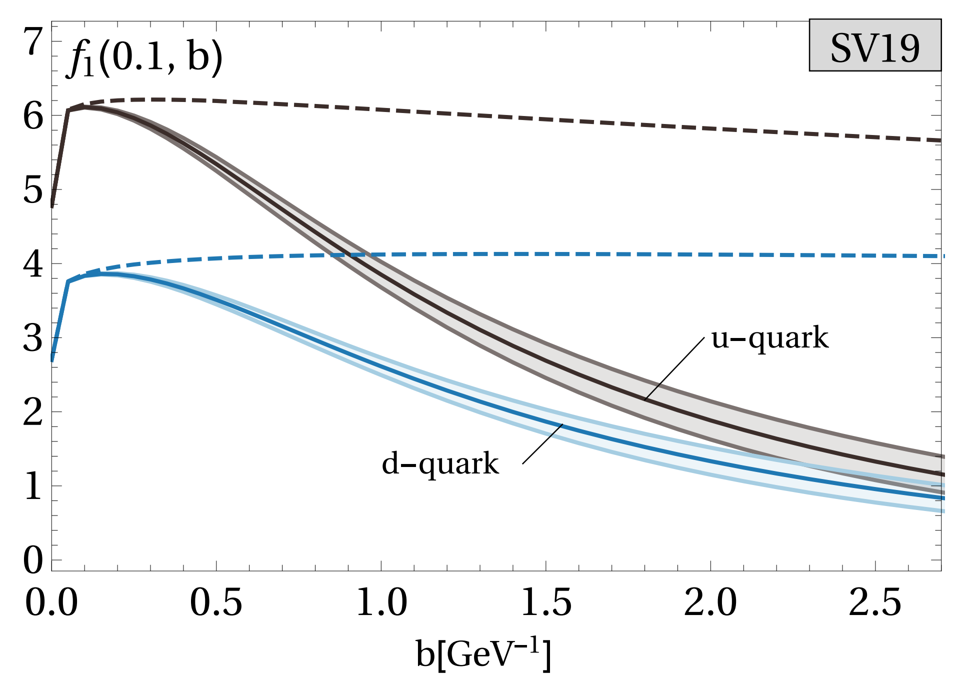
ART23

- 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 $\to 0$.





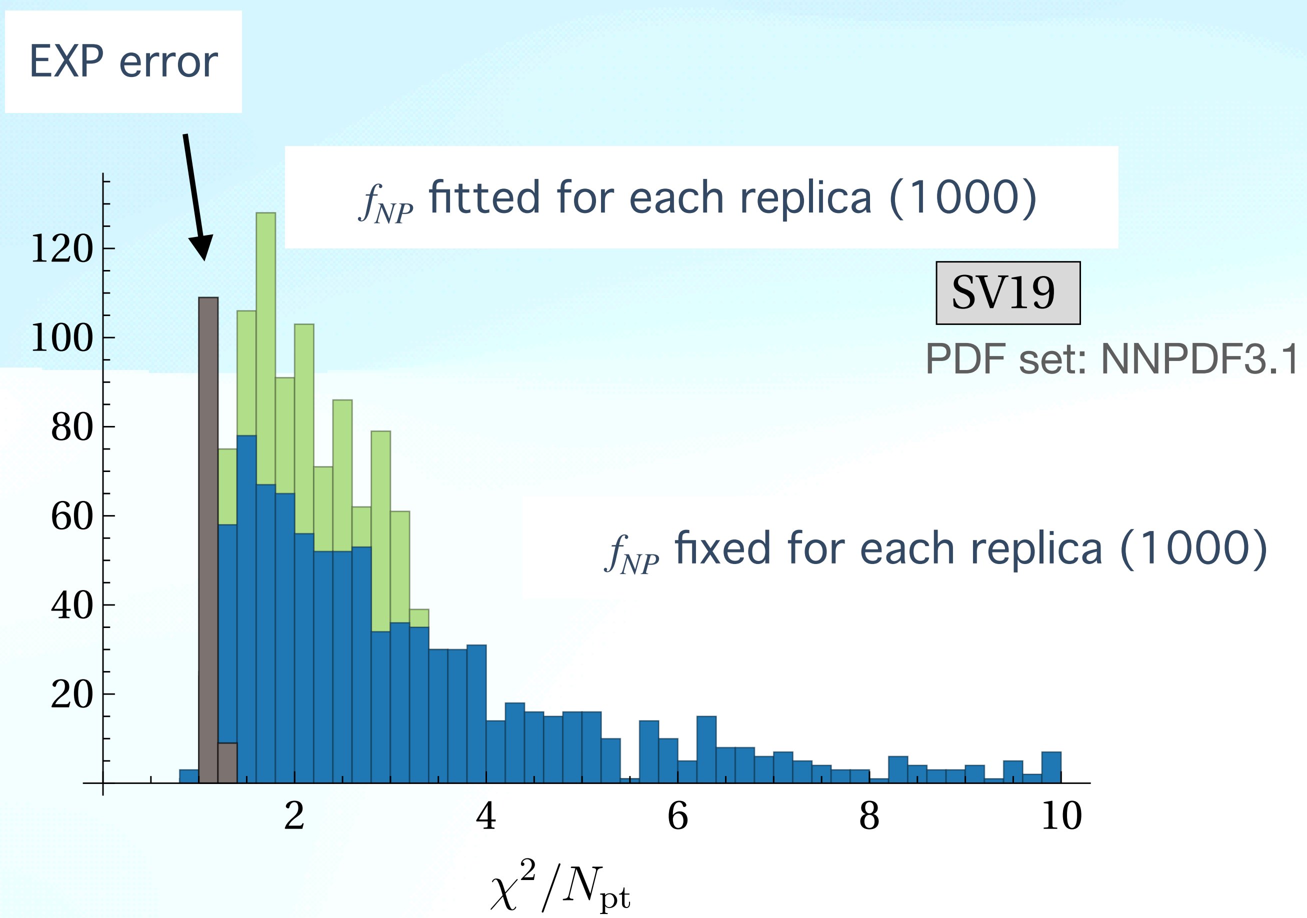
The PDF bias

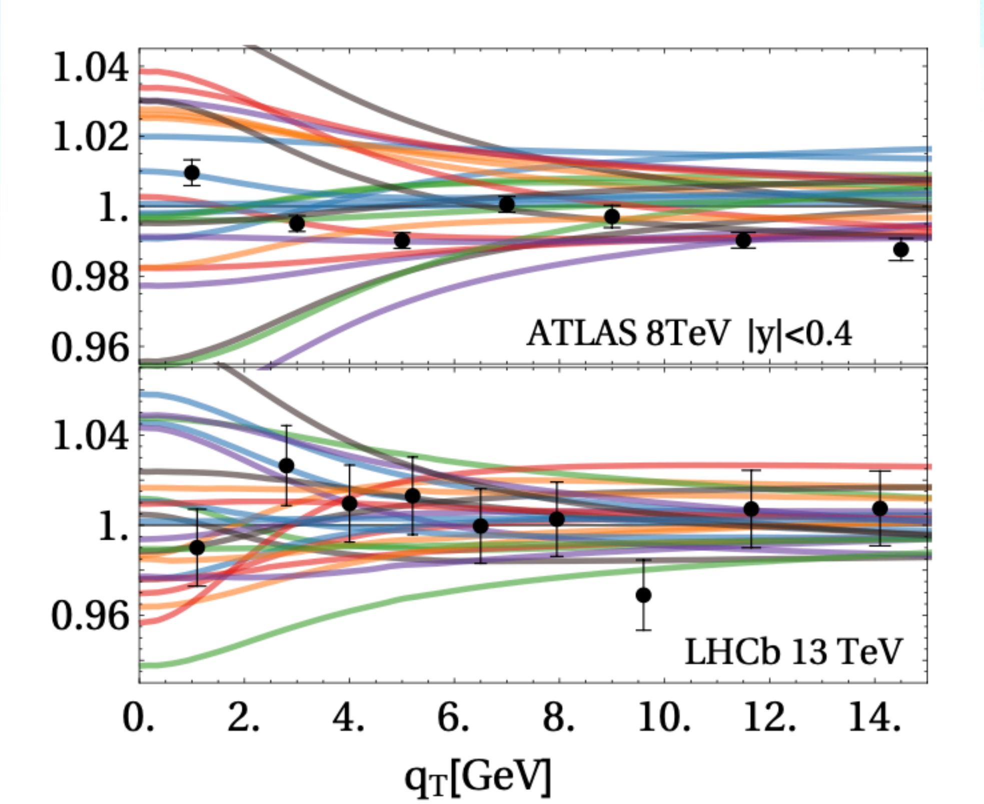
- So we have some questions to answer:

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 FNP

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



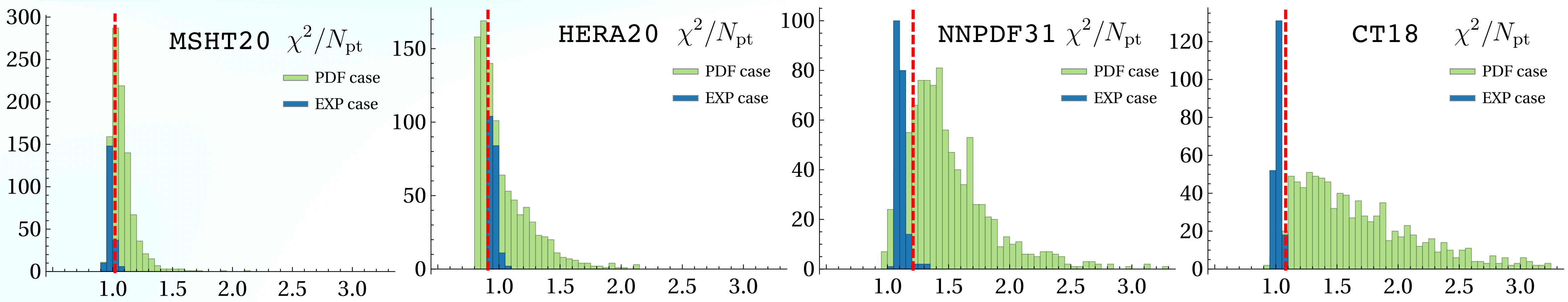


PDF uncertainties and flavour dependence

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

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



- 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)

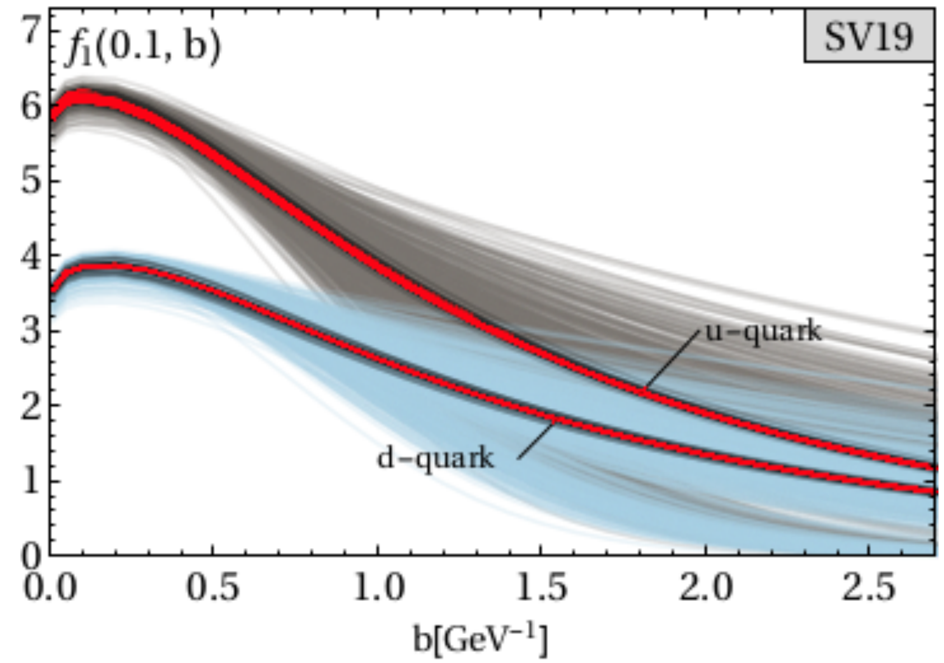
PDF uncertainties and flavour dependence

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

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

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

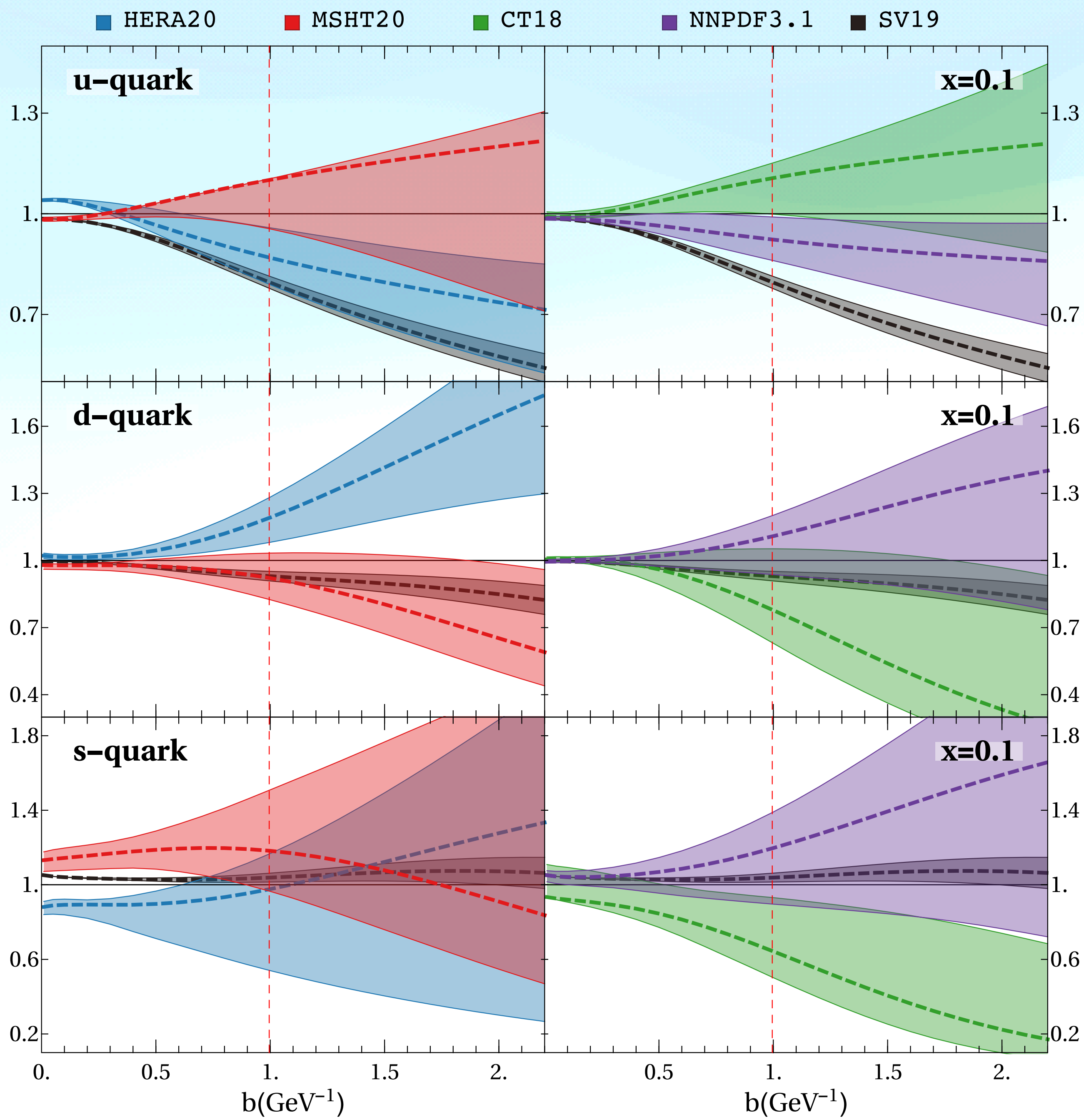
- We get reasonable uncertainty bands.



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



V. Moos, I. Scimemi, A. Vladimirov, PZ, **arXiv:2305.07473 [hep-ph]**

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

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

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

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

ART23: details

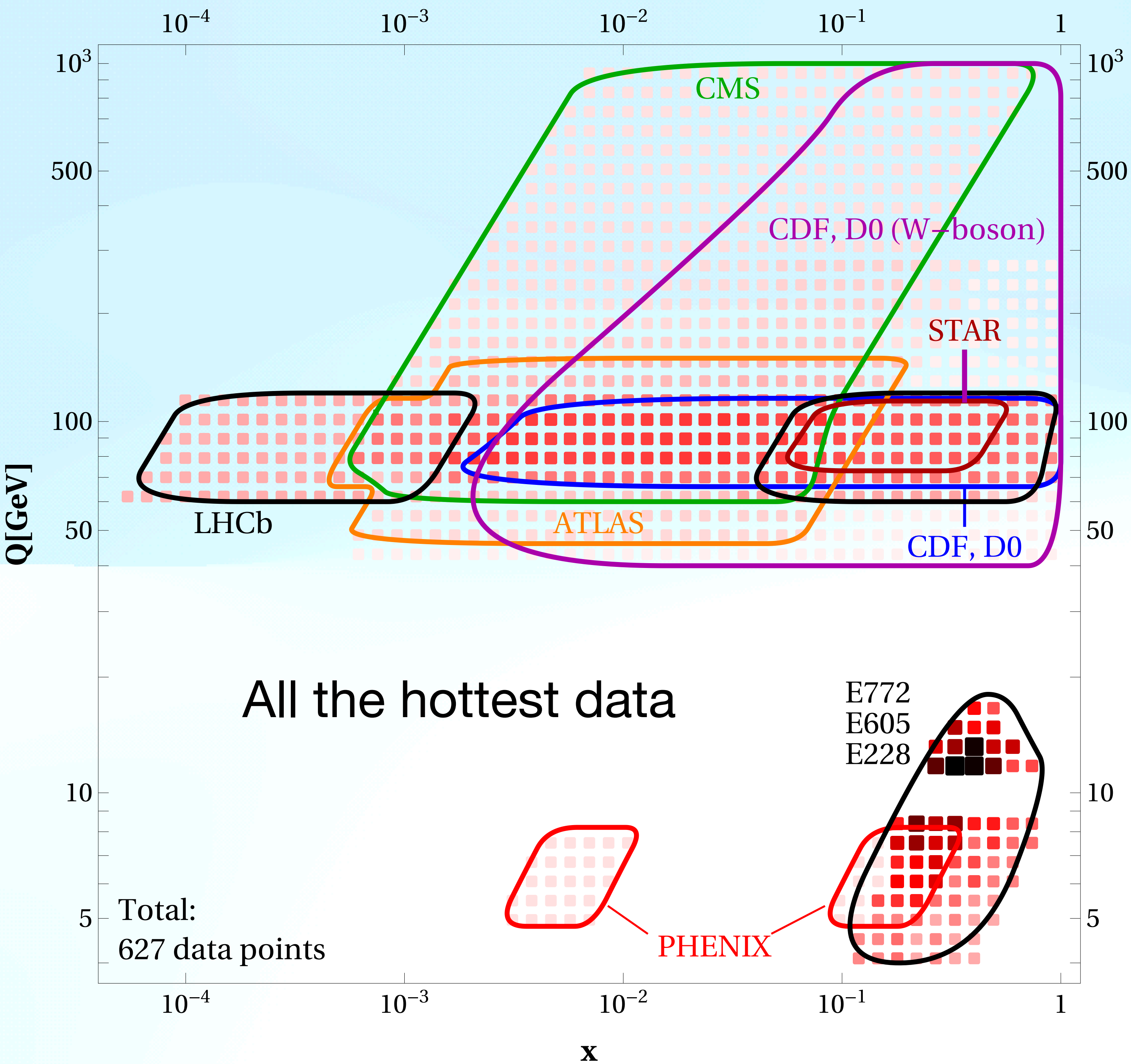
- Simple Parameterization: $f_{NP}^{f}(x,b) = \dfrac{1}{\cosh\left(\left(\lambda_1^f(1-x)+\lambda_2^f x\right)b\right)}$

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

- In total, 13 parameters

- Reference PDFs: MSHT20

ART23: details



All the hottest data

627 data points

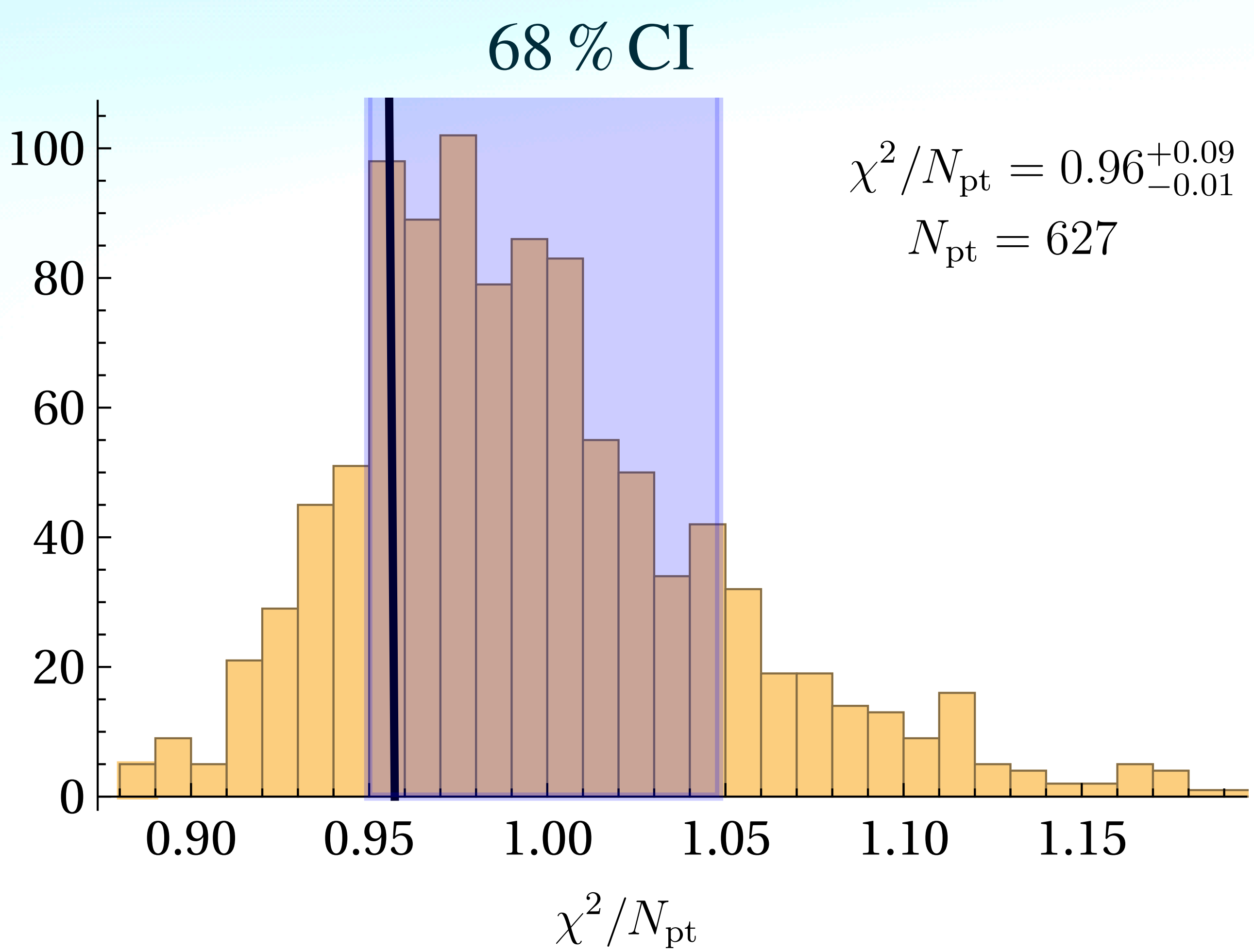
New in!

- **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

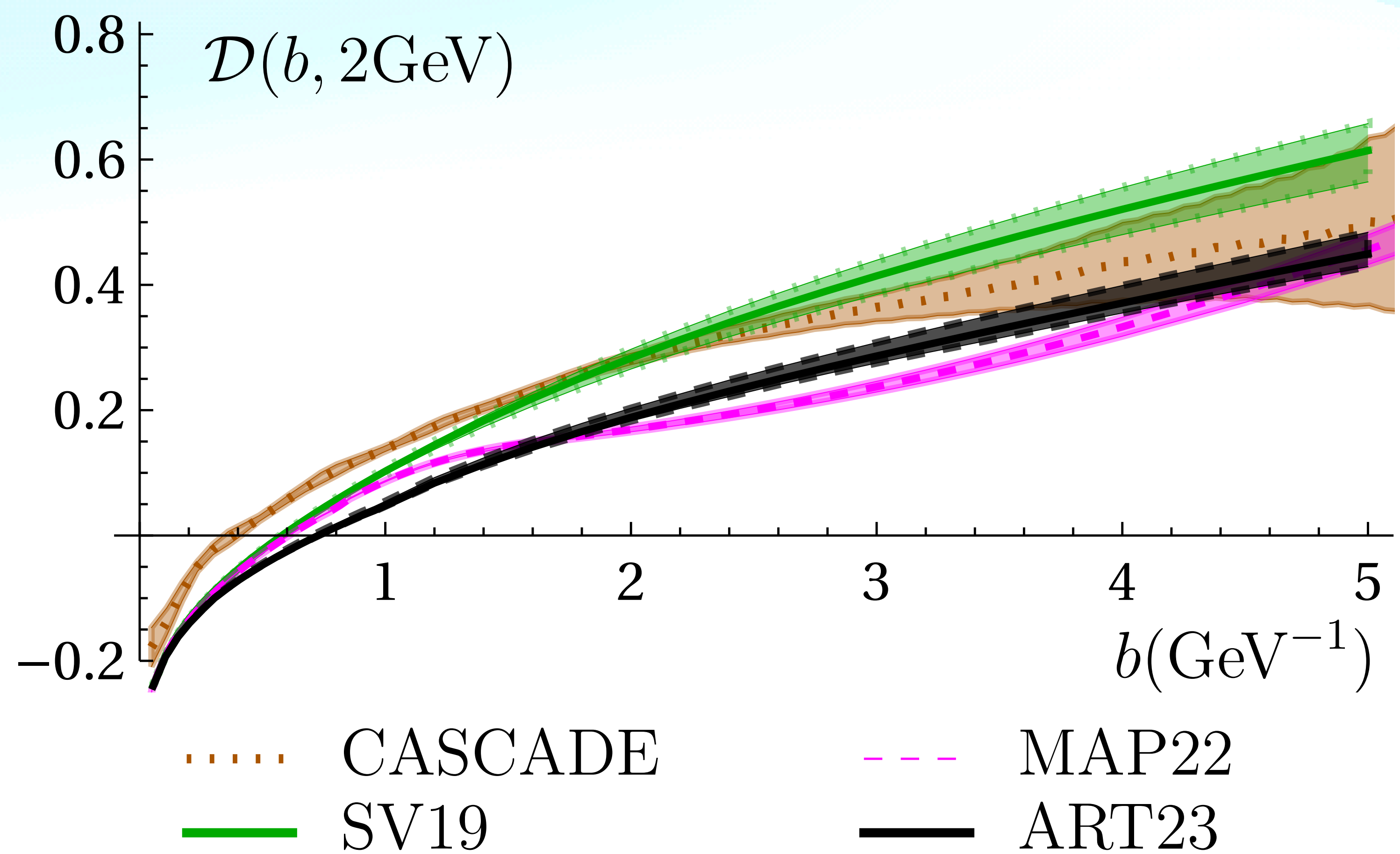
- overall improvement w.r.t. SV19. Specially for the LHC data. Higher precision plays a key role here.
- more realistic uncertainty bands than in SV19.

CS kernel close to the one from the global fit MAP22

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

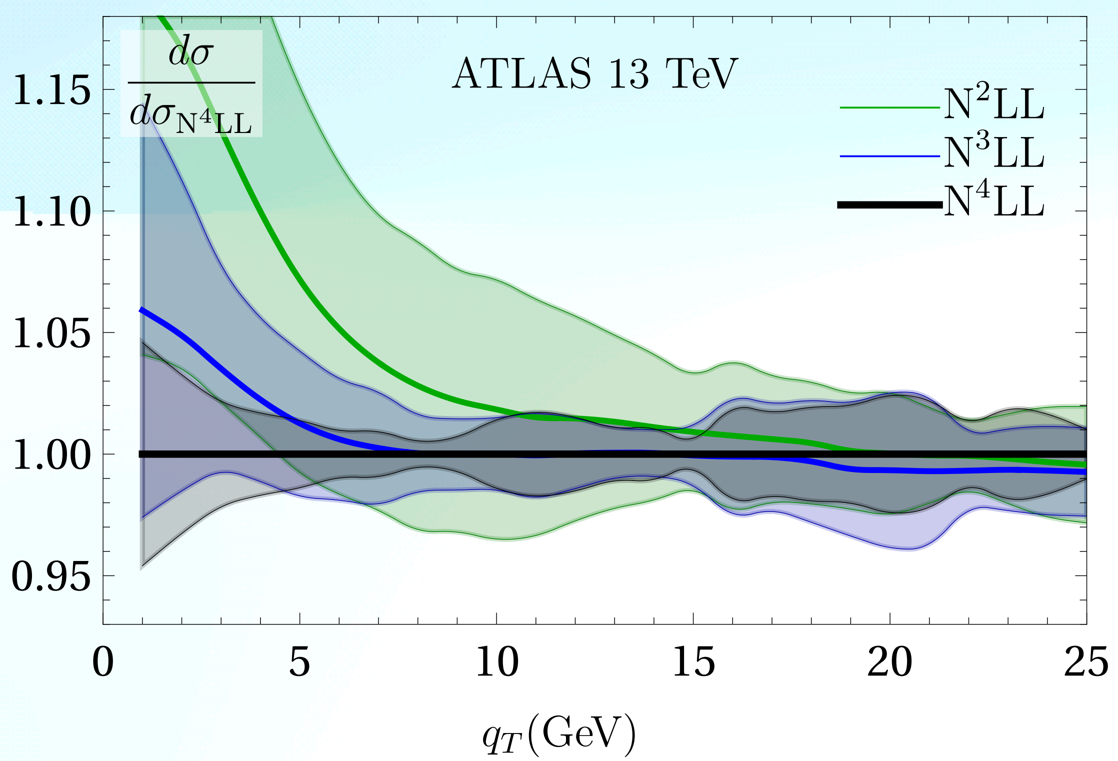
$$c_0 = 3.69^{+0.65}_{-0.61}\cdot 10^{-2}$$

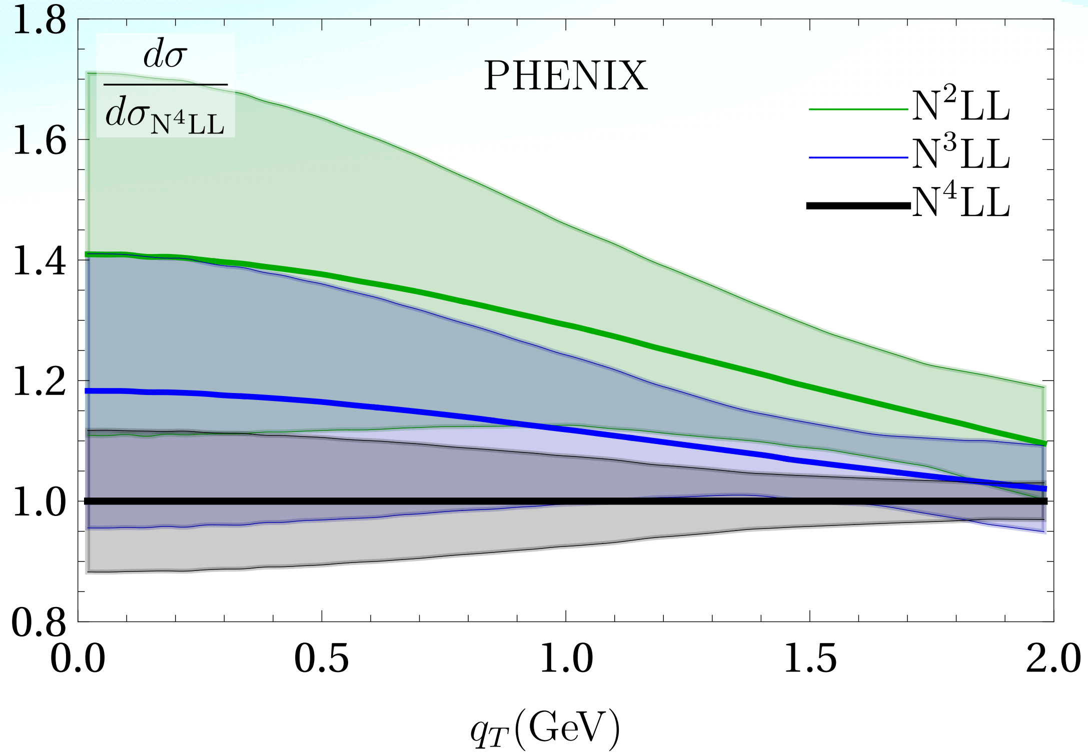
$$c_1 = 5.82^{+0.64}_{-0.88}\cdot 10^{-2}$$



ART23: results

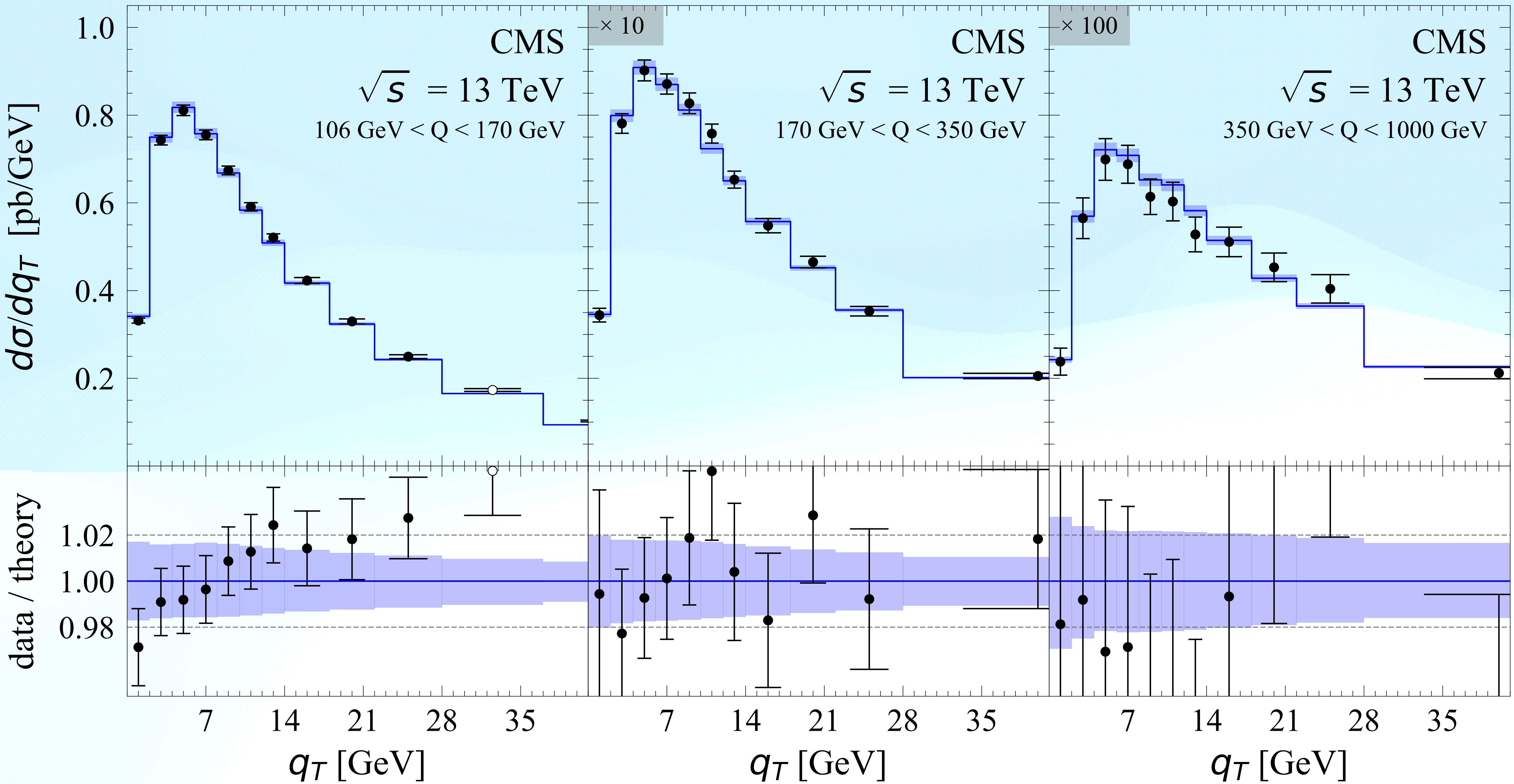
Scale variations $\left\{\mu \to s_2\mu, \mu^* \to s_3\mu^*, \mu_{\text{OPE}} \to s_4\frac{2e^{-\gamma_E}}{b} + 2\text{GeV}\right\}.$



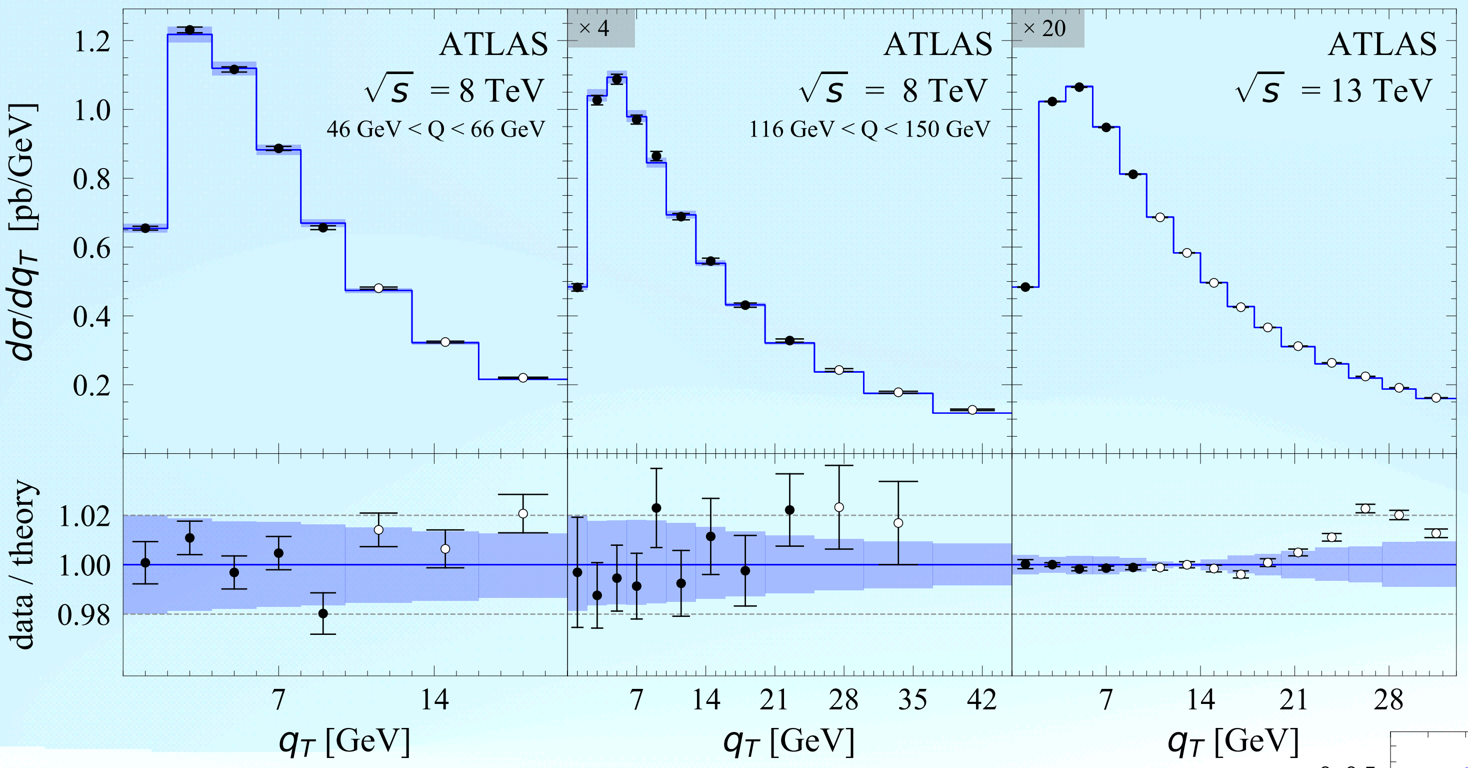


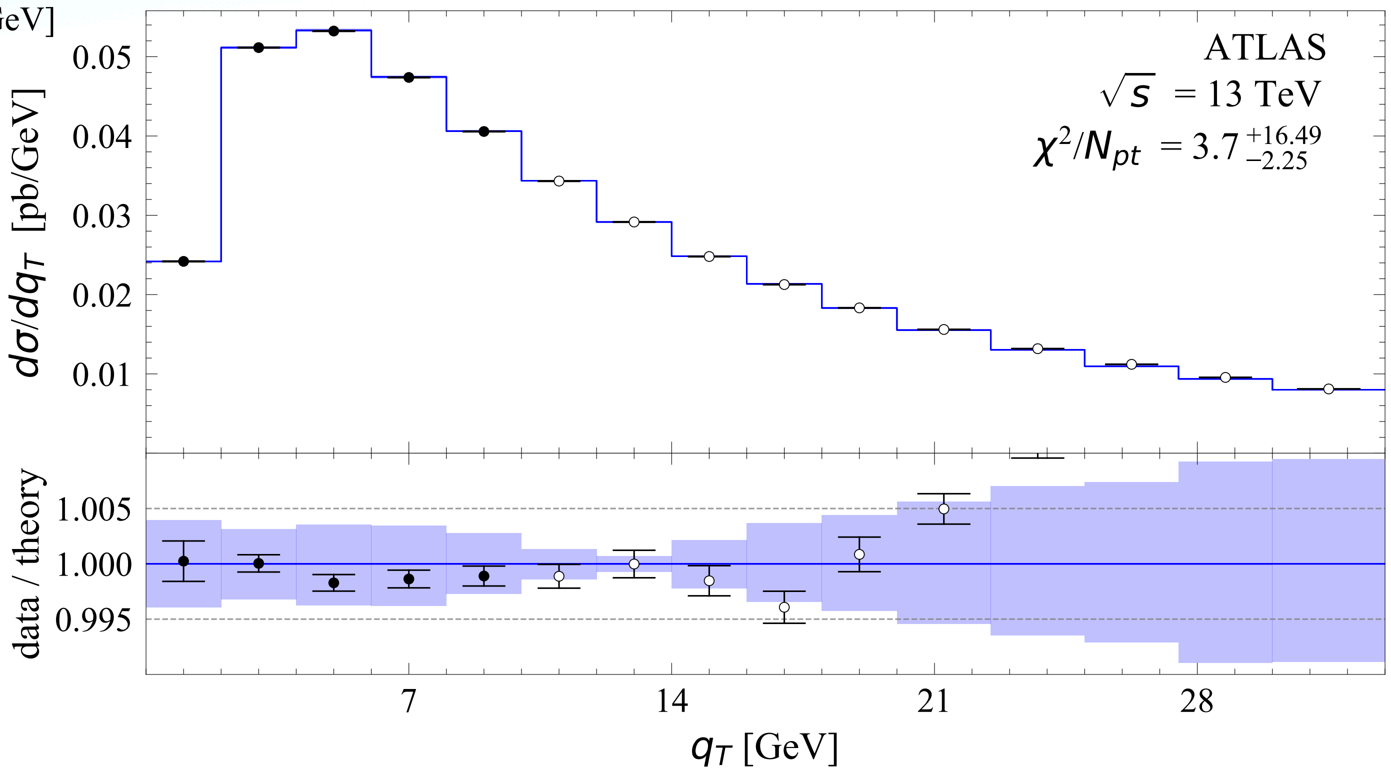
Γ_{cusp}	γ_V	β	$\mathcal{D}_{\text{small-b}}$	$C_{f\leftarrow f'}$	C_V	PDF
a_s^5 (Γ_4)	a_s^4 (γ_4)	a_s^6 (β_4)	a_s^4 $(d^{(4,0)})$	a_s^3 $(C^{[3]}_{f\leftarrow f'})$	a_s^4	NNLO

ART23: results

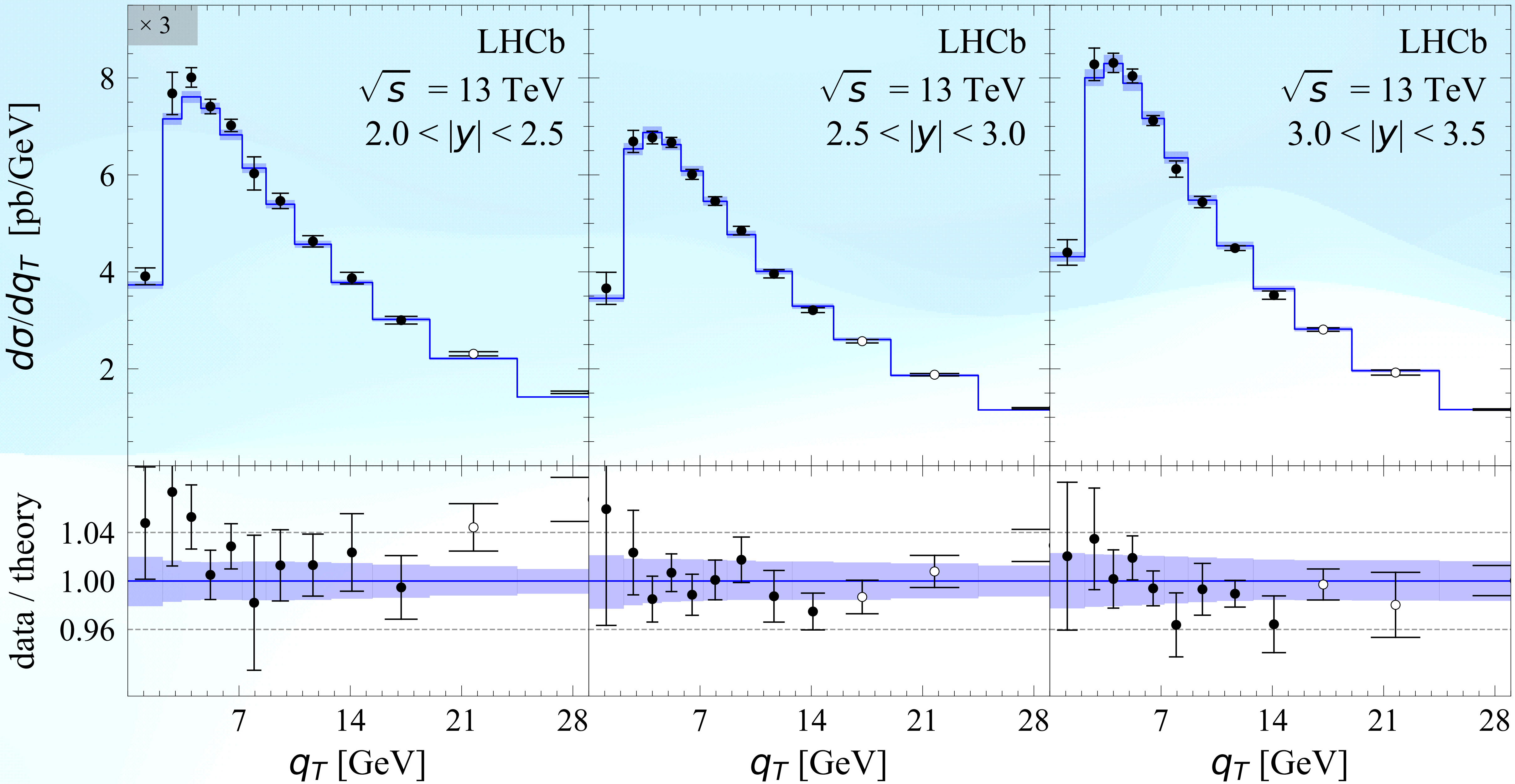


ART23: results

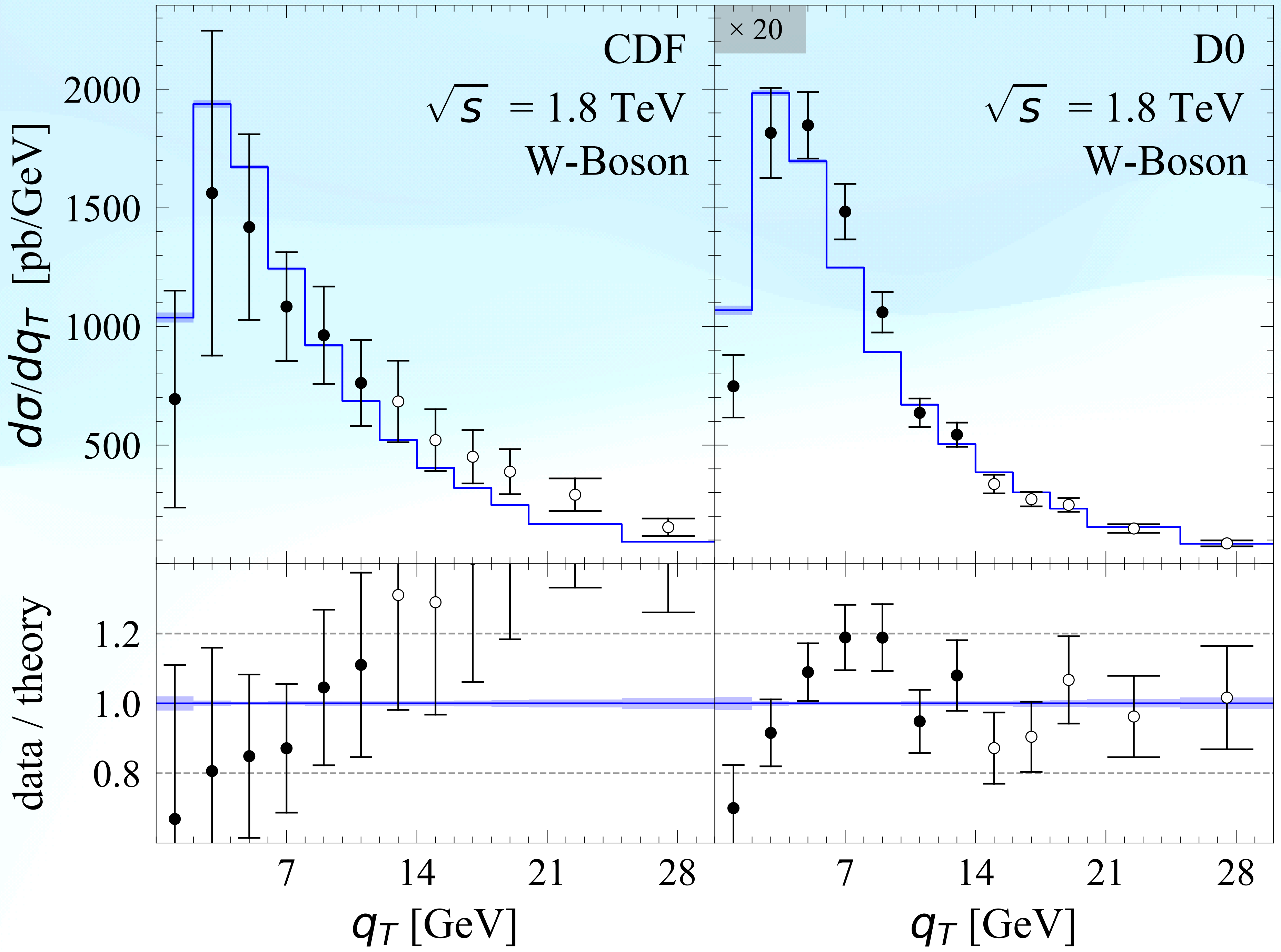




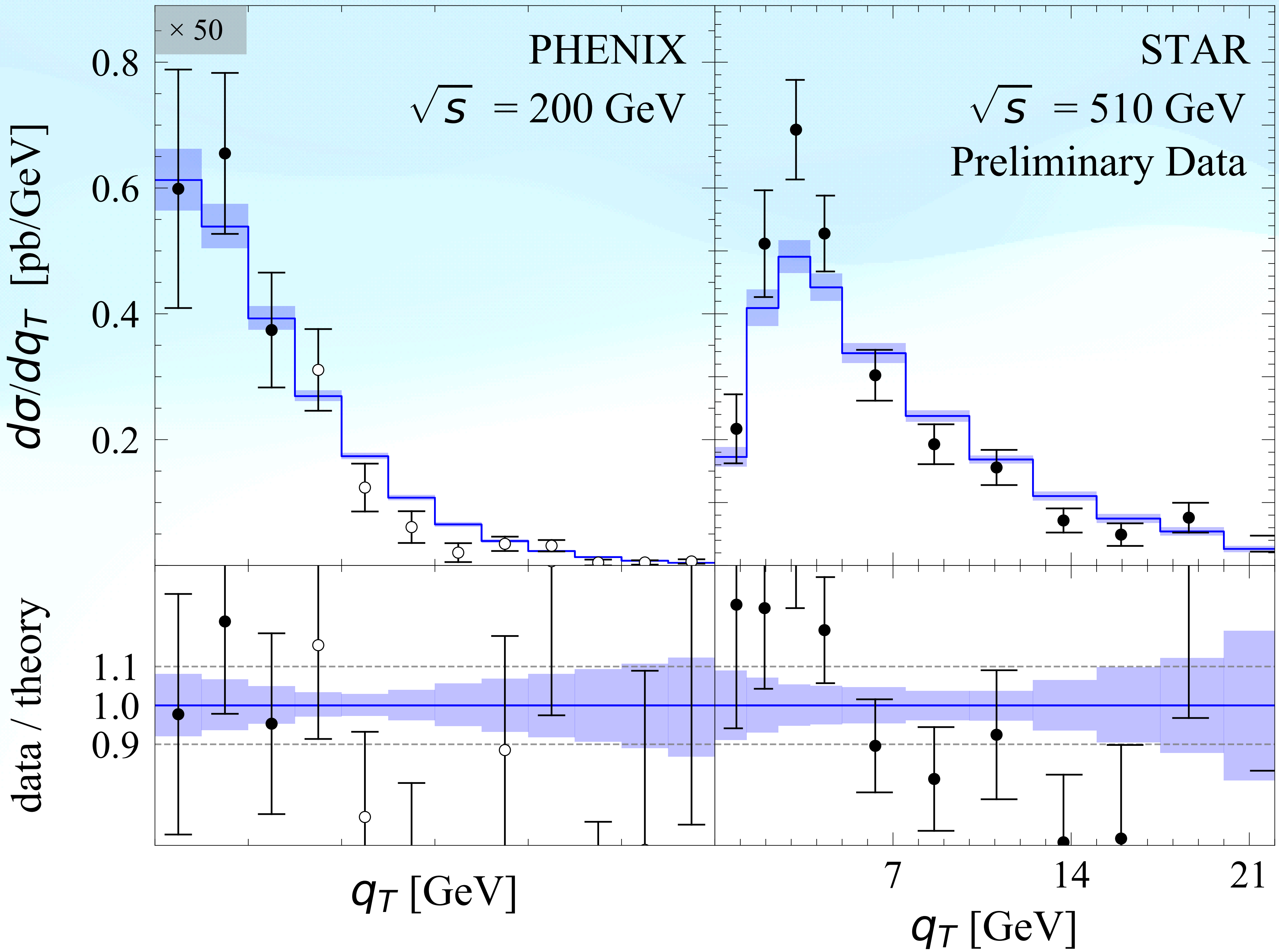
ART23: results



ART23: results

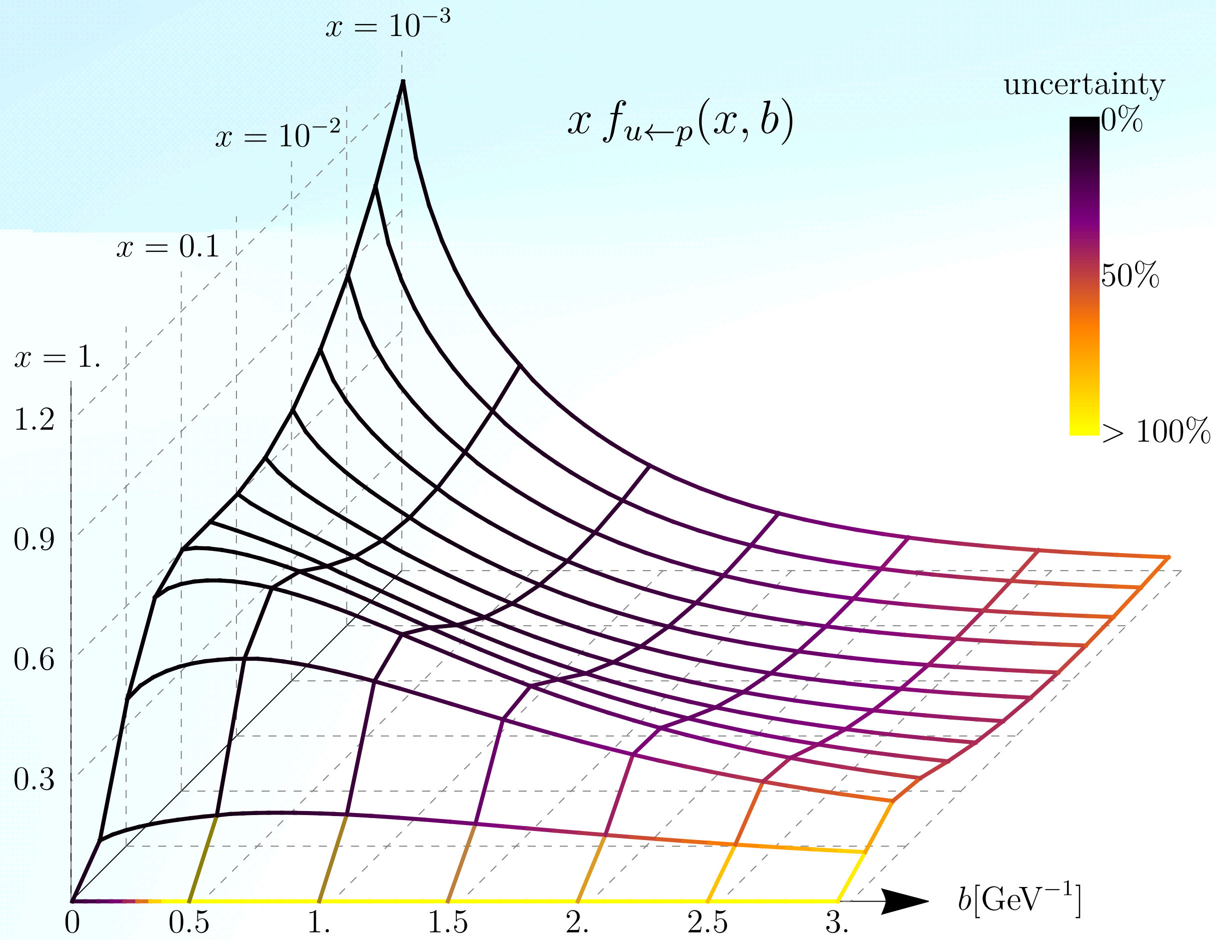


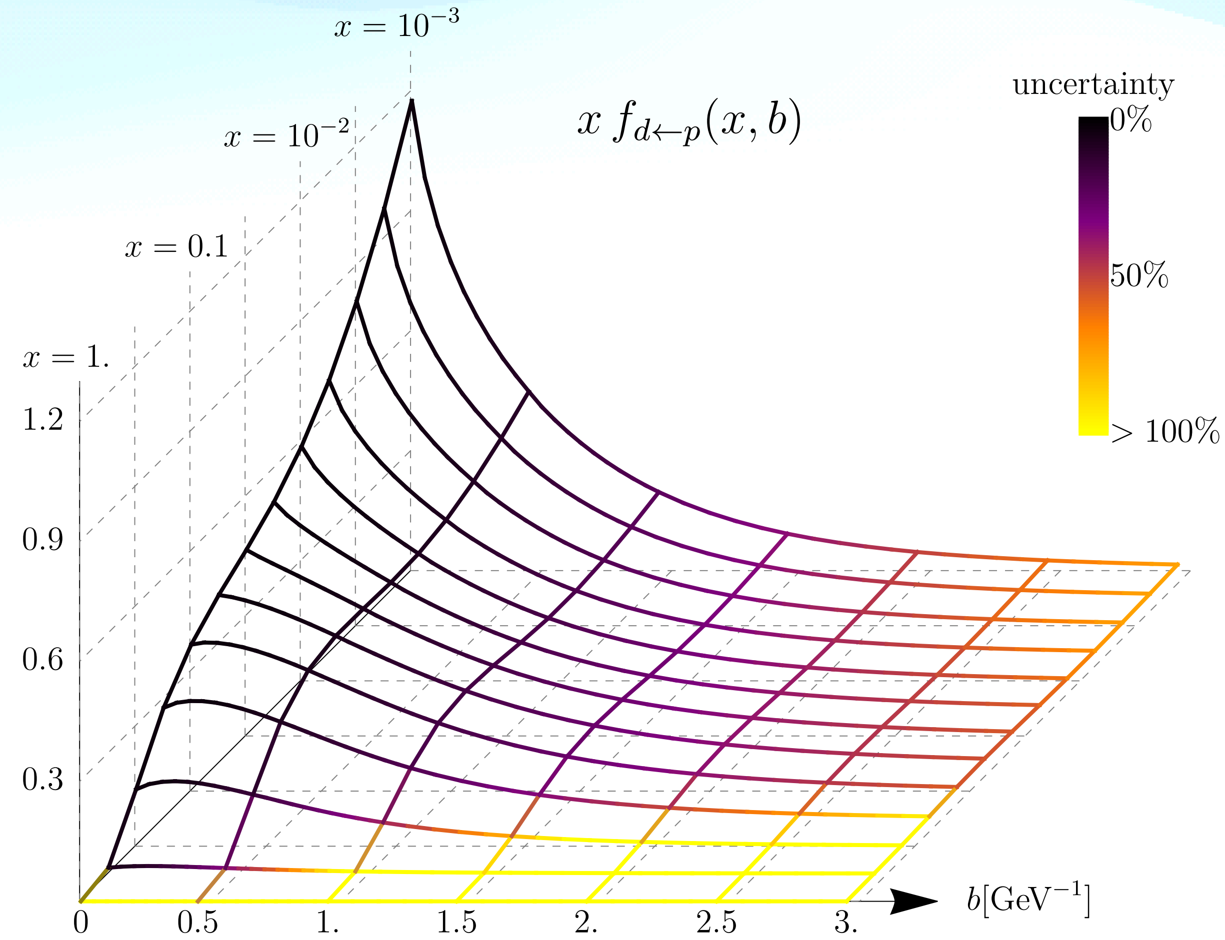
ART23: results



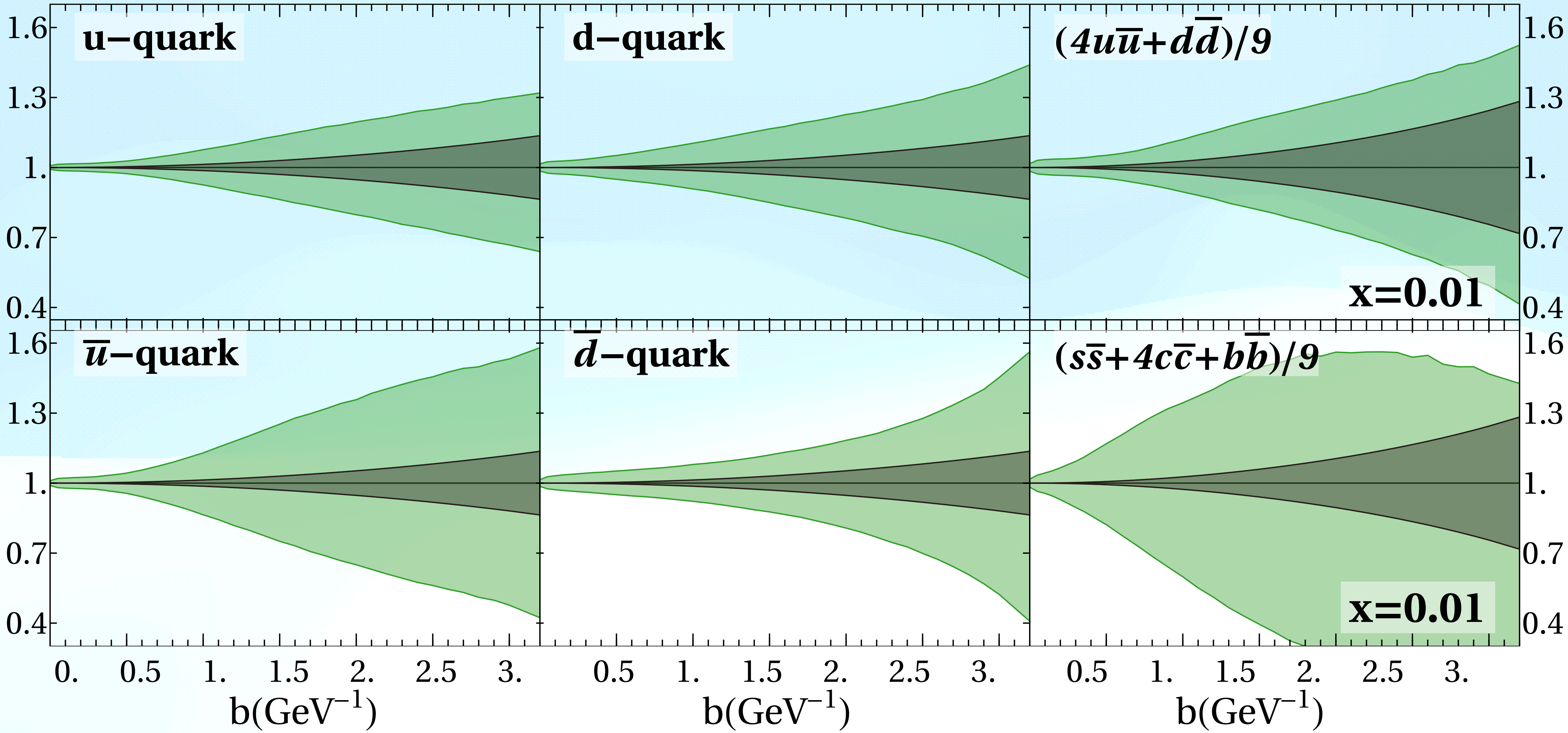
ART23: results

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





ART23: results



Light green: ART23
Dark green: SV19

Summary

The factorization of transverse momentum distributions has a long story, but recent understanding make it spectacular (and more to come!)!

- **TMDPDF are now extracted at N4LL (No other distribution uses the number of perturbative QCD orders)**

- 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

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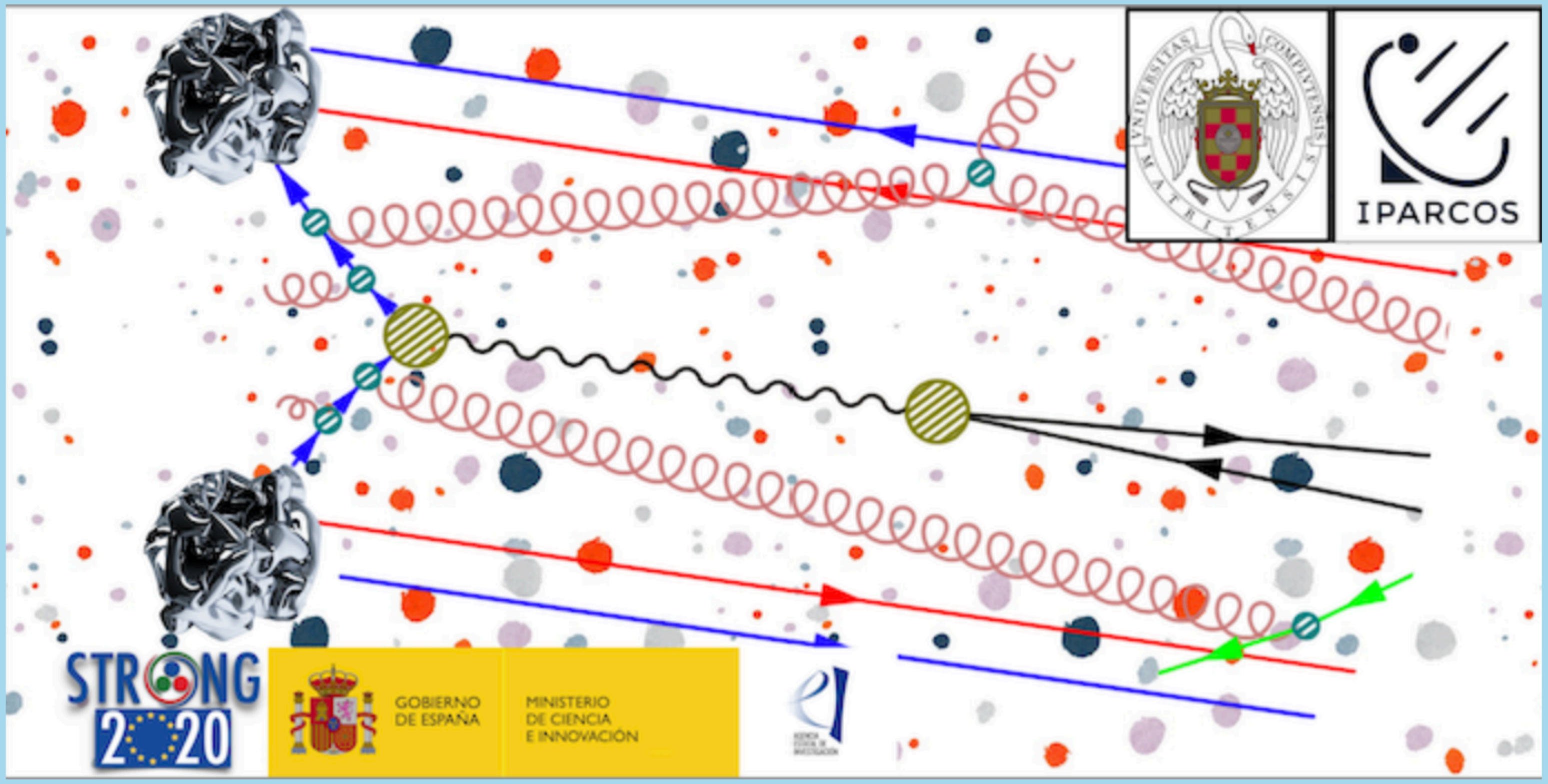

Resummation, Evolution, Factorization 2023 (REF2023)

23-27 octubre 2023
Facultad de Físicas
Europe/Madrid timezone

https://indico.fis.ucm.es/event/19/

Back-up

SCET 2024
Salamanca (Spain)
April15-18, 2024
Organizers:
Vicent Mateu
Teresa F. Caramés
German Sborlini
Ignazio Scimemi
Alexey Vladimirov
Student support:
Miguel Angel Benítez, Alberto Martín
VNiVERSiDAD D SALAMANCA
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NNPDF3.1: COMPARISON