15th Conference on the Intersections of Particle and Nuclear Physics - (CIPANP25)

Latest Advancements in TMD Phenomenology & Update From the MAP Collaboration

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June 12, 2025
Madison, WI

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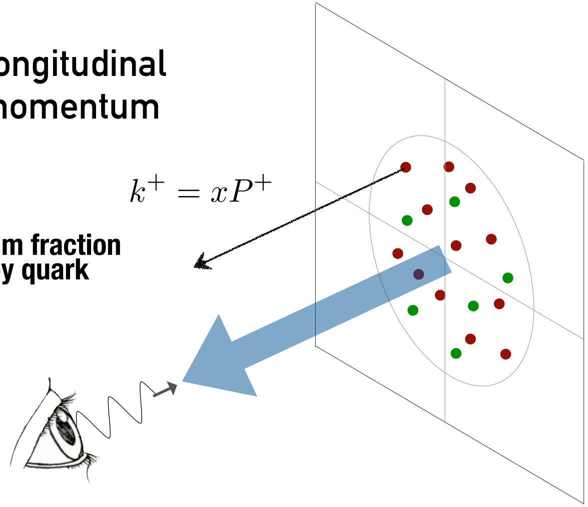
Parton distributions

Longitudinal momentum

$k^+ = xP^+$

x: momentum fraction carried by quark



momentum

position

$$\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$$

$$\int d^2\mathbf{b}_T$$

Transverse Momentum Distributions

TMDs

$$\int d^2\mathbf{k}_T$$

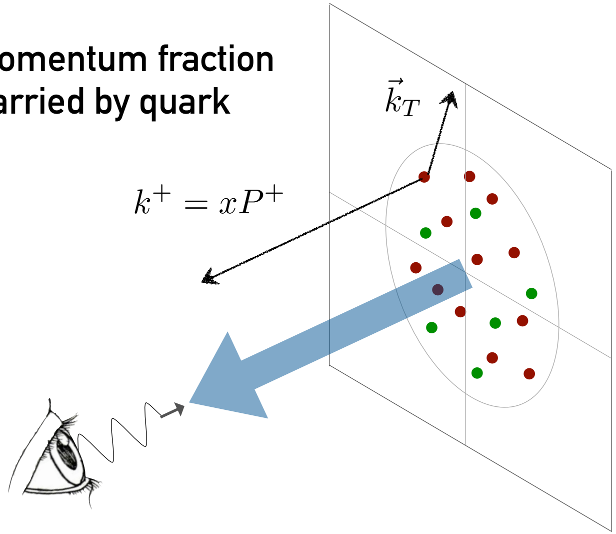
Parton Distribution Functions

PDFs

TMDs: 3D maps

in momentum space

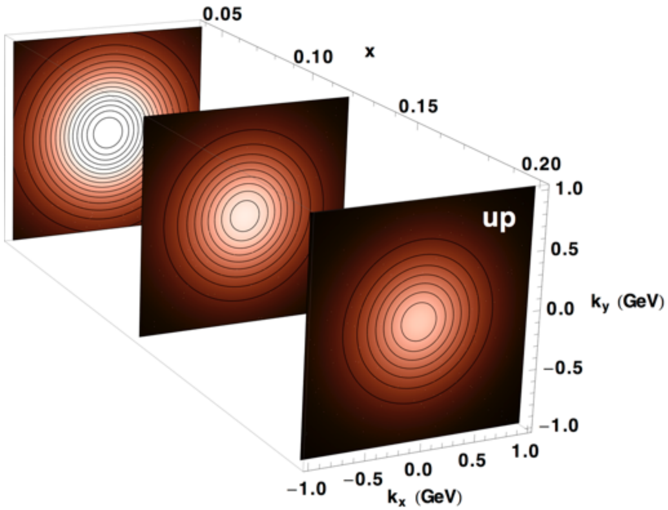
x: momentum fraction carried by quark



Transverse Momentum Distributions

TMDs

$$f^q(x, \mathbf{k_T})$$



Leading quark TMDs

the distribution of quarks sharply depends on the orientation of their spins

Leading Quark TMDPDFs

Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity $h_{1T}^\perp$ = Pretzelosity

Leading Quark TMDFFs

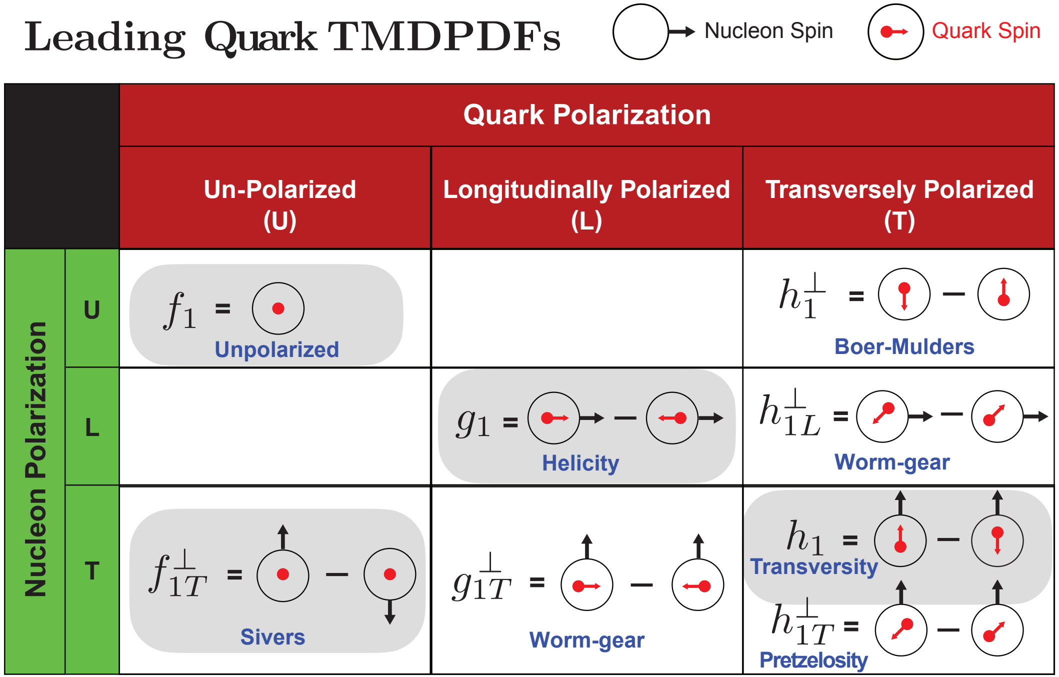
Hadron Spin — Quark Spin

	Hadron	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^\perp$ =
Polarized Hadrons	T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$ =	H_1 = Transversity $H_{1T}^\perp$ =

from the TMD handbook, arXiv:2304.03302

Transverse Momentum Distributions

the distribution of quarks sharply depends on the orientation of their spins



from the TMD handbook, arXiv:2304.03302

What's new

some recent works about TMDs

very active field!

Unpolarized TMDs

ART25
- Determination of unpolarized TMD distributions from the fit of Drell-Yan and SIDIS data at N^4LL
  Valentin Moos, Ignazio Scimemi, Alexey Vladimirov, Pia Zurita – arXiv:2503.11201v1

MAP24
- Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit
  MAP Collaboration – DOI: 10.1007/JHEP08(2024)232 - arXiv:2405.13833

ART23
- Extraction of unpolarized transverse momentum distributions from fit of Drell–Yan data at N^4LL
  Valentin Moos, Ignazio Scimemi, Alexey Vladimirov, Pia Zurita – DOI: 10.1007/JHEP05(2024)036 - arXiv:2305.07473

MAPNN25
- A Neural-Network Extraction of Unpolarized Transverse-Momentum-Dependent Distributions
  MAP Collaboration - arXiv:2502.04166

HSO
- Phenomenology of TMD parton distributions in Drell-Yan and Z0 boson production in a hadron structure oriented approach
  F. Aslan, M. Boglione, J. O. Gonzalez-Hernandez, T. Rainaldi, T. Rogers and A. Simonelli
  arXiv: 2401.14266 - DOI: 10.1103/PhysRevD.110.074016

What's new

some recent works about TMDs

... about the polarized TMDs

Helicity & Transversity

- First simultaneous global QCD analysis of dihadron fragmentation functions and transversity parton distribution functions
  JAM Collaboration - DOI: 10.1103/PhysRevD.109.034024 - arXiv: 2308.14857

- Exploring the three-dimensional momentum distribution of longitudinally polarized quarks in the proton
  MAP Collaboration
  A. Bacchetta, A. Bongallino, M. Cerutti, M. Radici and L. Rossi - arXiv:2409.18078.

Sivers

- Extraction of the Sivers function with deep neural networks
  I. P. Fernando, D. Keller – DOI: 10.1103/PhysRevD.108.054007 - arXiv:2304.14328

- Global analysis of Sivers and Collins asymmetries within the TMD factorization
  Chunhua Zeng, Hongxin Dong, Tianbo Liu, Peng Sun, Yuxiang Zhao – arXiv:2412.18324

TMD PDFs

every TMD has the same general structure

perturbative terms

matching to the collinear region

collinear PDFs

non-perturbative but used as input here, not fitted

$$f_1^q(x,b;\mu,\zeta) = \sum_j (C_j \otimes f^j)(x,b_*;\mu_b) e^{R(b_*;\mu_b,\mu)} f_{\rm NP}(x,b)$$

double scale dependence

perturbative evolution

non perturbative transverse content

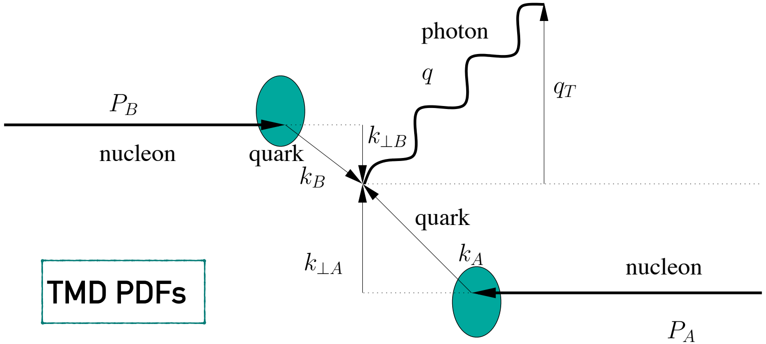
many subtleties involved in TMD analyses

b* prescription,
ζ-prescription, hadron structure oriented

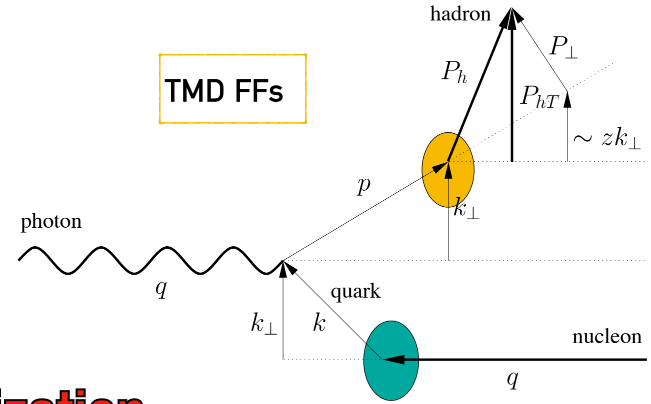
parametrized and fitted to data

Drell-Yan and SIDIS

$$N(P_A) + N(P_B) \to \gamma^*/Z \to l^+ l^-$$



$$\ell(l) + N(p) \to \ell(l') + h(P_h) + X$$



TMD factorization

$$q_T \ll Q$$

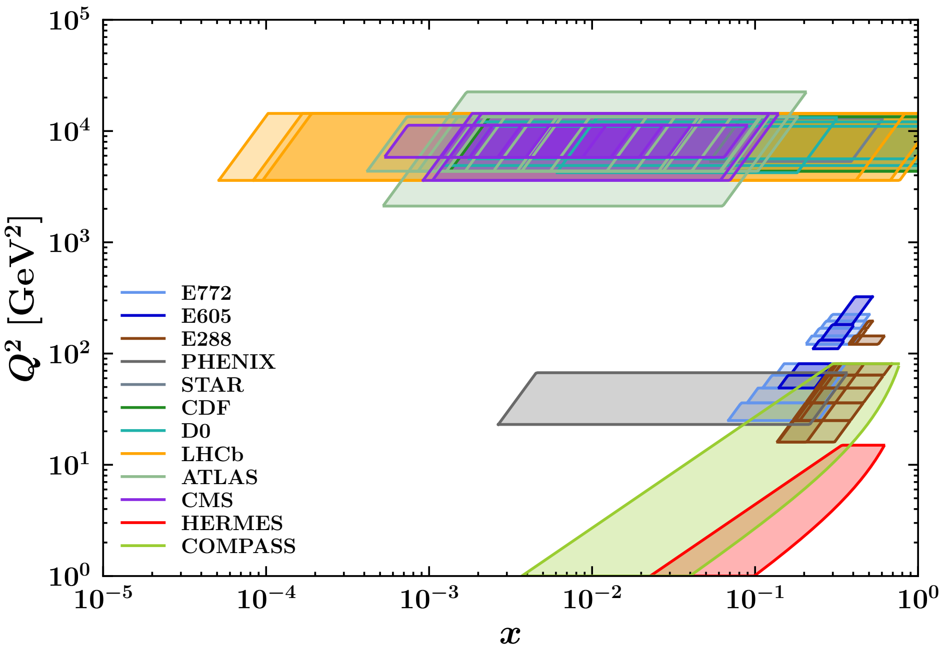
$$M^2 \ll Q^2 \qquad P_{hT}^2 \ll Q^2$$

$$\left(\frac{d\sigma}{dq_T}\right) \propto \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} x_1 f_1^q(x_1, \mathbf{b}) x_2 f_1^{\bar{q}}(x_2, \mathbf{b})$$

$$\left(\frac{d\sigma}{dq_T}\right) \propto \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} f_1^q(x, \mathbf{b}) D_1^{q\to h}(z, \mathbf{b})$$

Data kinematical coverage

SIDIS & Drell-Yan



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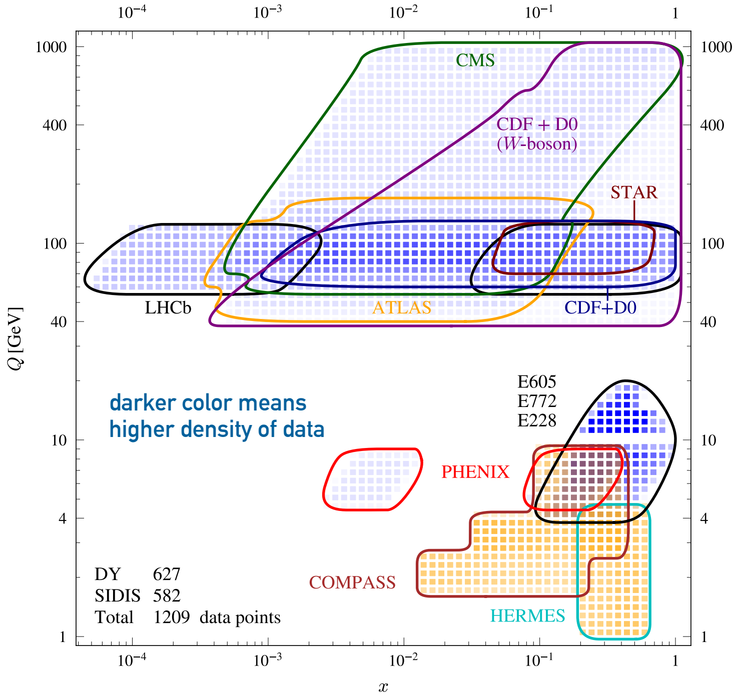


ART25 - arXiv:2503.11201v1

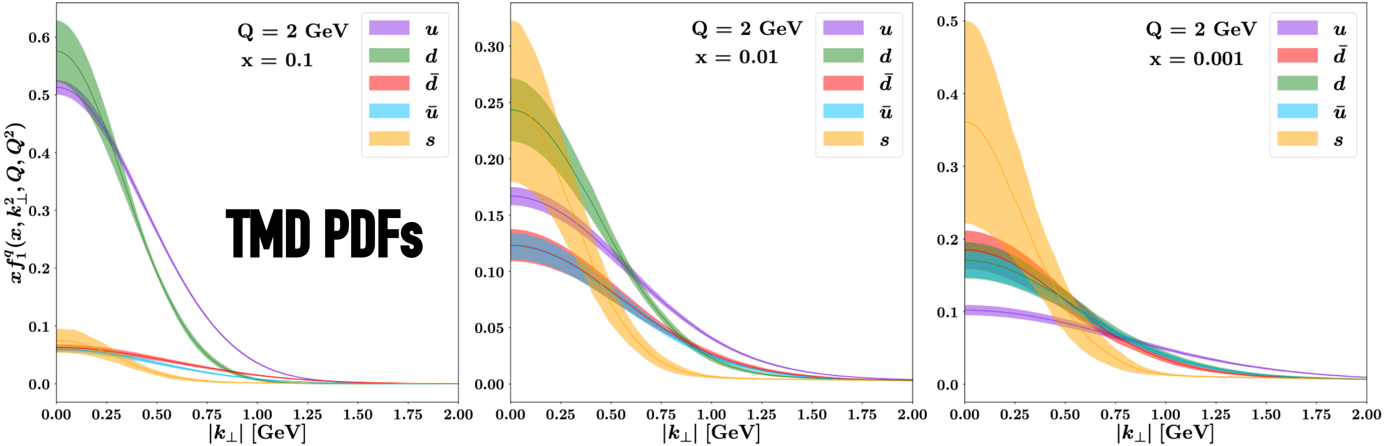
Extractions of unpolarized TMDs

Reference	Accuracy	HERMES	COMPASS	DY	n. of points	χ^2/n
PV 2017 [arXiv:1703.10157]	NLL	✅	✅	✅	8059	1.5
SV19 [arXiv:1912.06532]	$N^3LL(-)$	✅	✅	✅	1039	1.06
PV19 [arXiv:1912.07550]	N^3LL	❌	❌	✅	353	1.07
SV19 + flavor dep. [arXiv:2201.07114]	N^3LL	❌	❌	✅	309	<1.08>
MAP22 [arXiv:2206.07598]	$N^3LL(-)$	✅	✅	✅	2031	1.06
ART23 [arXiv:2305.07473]	N^4LL	❌	❌	✅	627	0.96
MAP24 [arXiv:2405.13833]	N^3LL	✅	✅	✅	2031	1.08
ART25 [arXiv:2503.11201v1]	N^4LL	✅	✅	✅	1209	1.05

MAP24

@N3LL$^-$

global fit: DY & SIDIS



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NP Evol. : $$g_K(b_T^2) = -g_2^2 \frac{b_T^2}{4}$$

TMD PDFs : $$f_{1\mathrm{NP}}(x, b_T^2) \propto \mathrm{F.T.\ of} \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right)$$

TMD FFs : $$D_{1\mathrm{NP}}(z, b_T^2) \propto \mathrm{F.T.\,of} \left(e^{-\frac{P_\perp^2}{g_{3A}}} + \lambda_{FB}\, k_\perp^2\, e^{-\frac{P_\perp^2}{g_{3B}}} \right)$$

f_{NP} same as in MAP22

96 parameters

1 + (5 flavors × 10 parameters) for TMD PDFs, and 45 (5 channels × 9 parameters) for TMD FFs.

$$g_1(x) = N_1 \frac{(1-x)^\alpha \, x^\sigma}{(1-\hat{x})^\alpha \, \hat{x}^\sigma} \qquad g_3(z) = N_3 \frac{(z^\beta + \delta)\,(1-z)^\gamma}{(\hat{z}^\beta + \delta)\,(1-\hat{z})^\gamma}$$

MAP24

flavor dependent global fit

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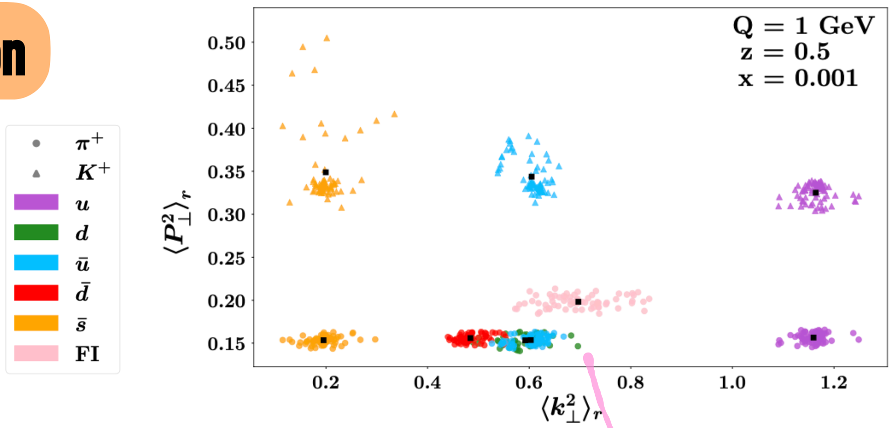
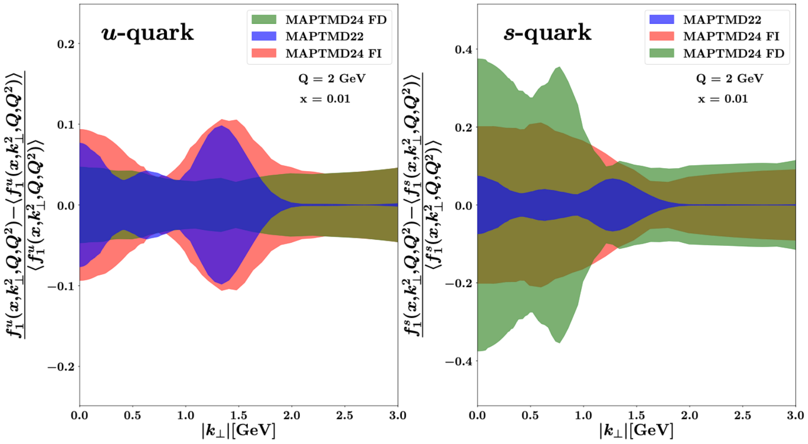
Evidence of different behaviors for
different flavors
and for different measured hadrons



nice check:
flavor independent fit
is ~ average of all flavors



uncertainties
are larger

each TMD replica is matched onto a
different replica of the collinear PDFs

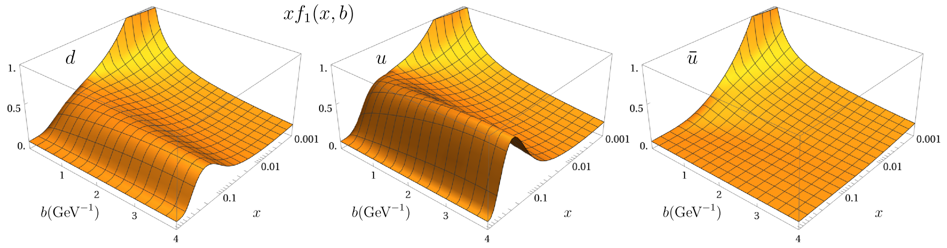
vs **MAP22** only central replica
of collinear PDFs

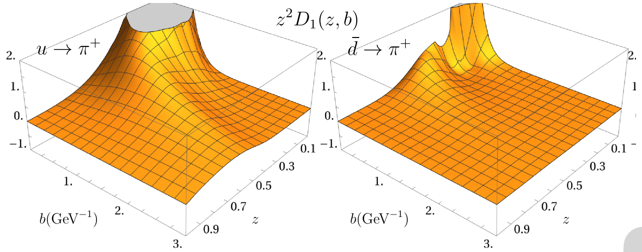
ART25

V. Moos, I. Scimemi, A. Vladimirov, P. Zurita
arXiv:2503.11201v1

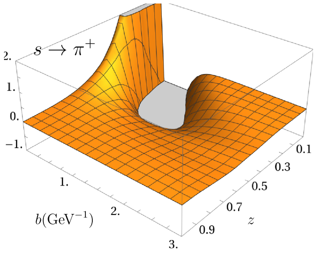
explicit flavor and hadron dependence

TMD PDFs





TMD FFs



distinguish {u, d, ubar, dbar}
and sea = {s, sbar, c, cbar, bbar, b}

10 + 10 + 2 = 22 parameters

TMD PDFs : $$F^f_{\mathrm{NP}}(x,b) = \frac{1}{\cosh\left[\left(\lambda_1^f (1-x)^{\lambda_3^f} + \lambda_2^f\, x\right) b\right]}$$

TMD FFs : $$D^{f/h}_{\mathrm{NP}}(z,b) = \frac{1 + \eta_1^{h,f}\,\dfrac{b^2}{z^2}}{\cosh\left(\eta_0^h\,\dfrac{b}{z}\right)}$$

NP Evol. : $$\mathcal{D}_{\mathrm{NP}}(b) = b\, b^* \left[c_0 + c_1 \ln\left(\frac{b^*}{B_{\mathrm{NP}}}\right)\right]$$

NN TMDs

MAP Collaboration

Neural Network

extraction of $f_1(x, k_T)$ from DY data

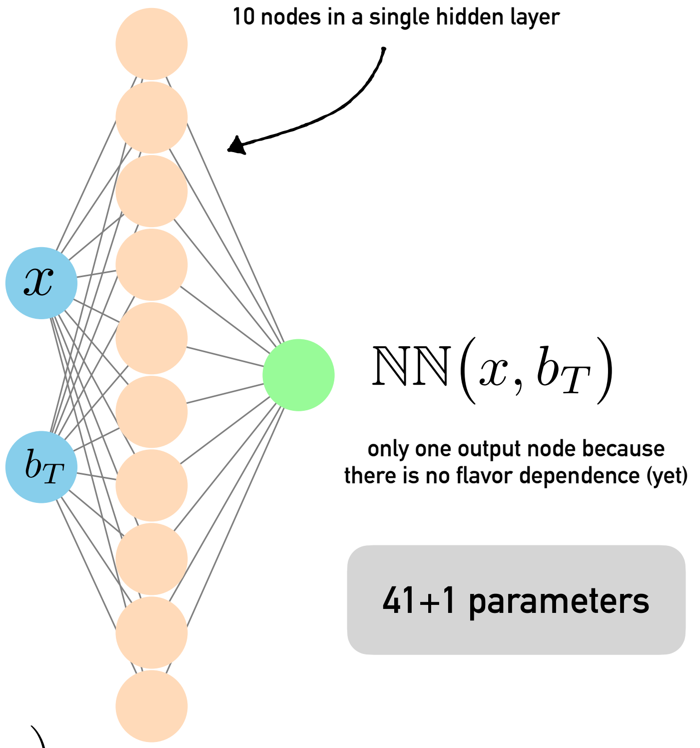
MAP Collaboration
arXiv:2502.04166

chosen parametrization
of the non-perturbative part of $f_1(x, k_T)$

$$f_{\mathrm{NP}}(x, b_T; \zeta) = \frac{\mathrm{NN}(x, b_T, \{p_i\})}{\mathrm{NN}(x, 0, \{p_i\})} \exp\left[- g_2^2\, b_T^2\, \ln\left(\frac{\zeta}{Q_0^2} \right) \right]$$

- physically required constraints

$f_{\mathrm{NP}} \to 1$ **for** $b_T \to 0$



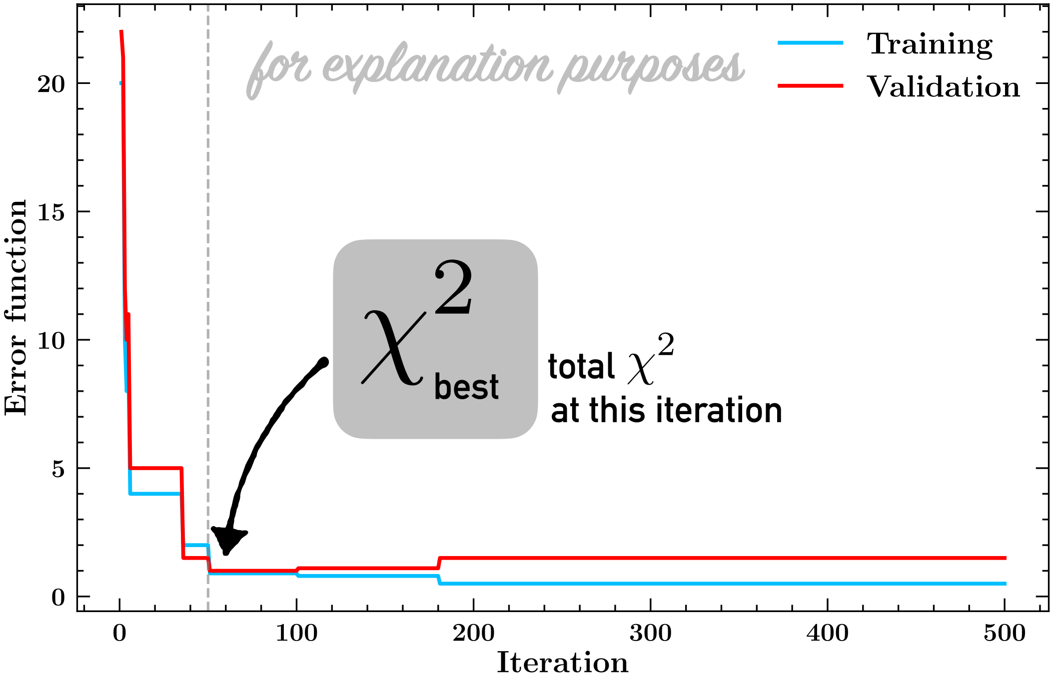
41+1 parameters

with activation function

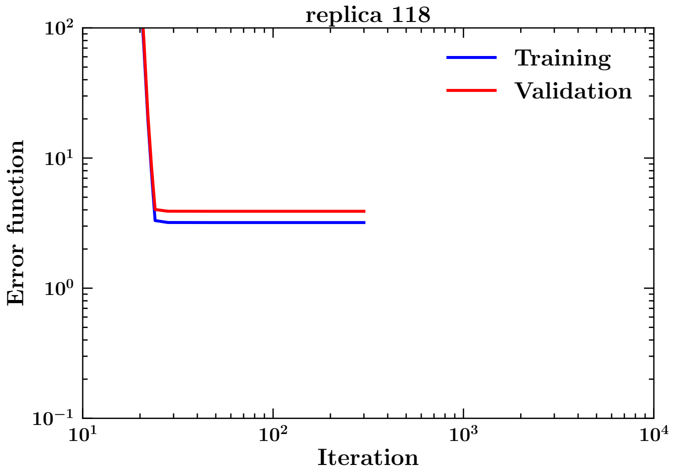
$$\sigma(z) = \frac{1}{2}\left(1 + \frac{z}{1+|z|}\right)$$

avoid overfitting

split data into training and validation set



total χ^2 at this iteration



random splitting

50% - 50%

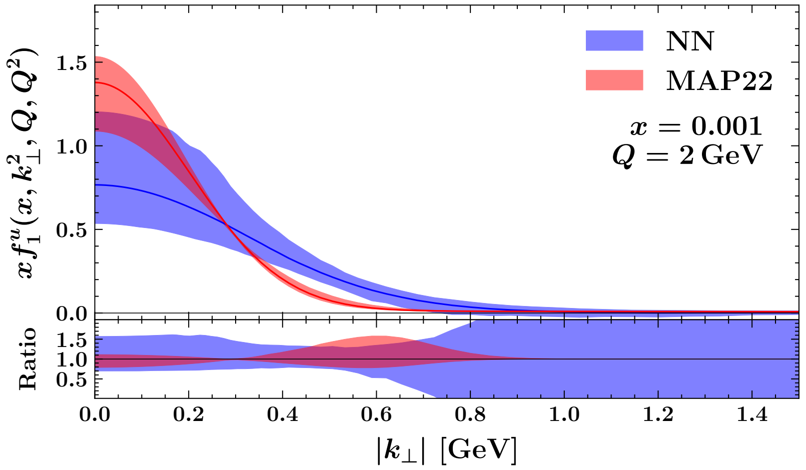
dataset by dataset

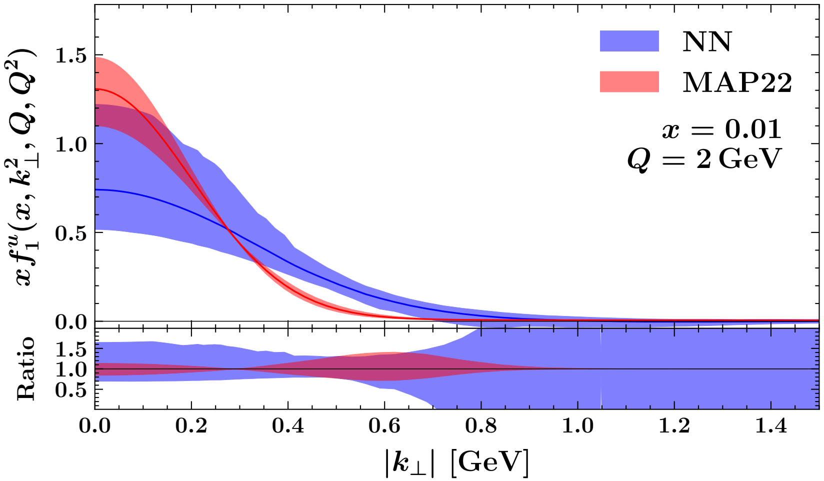
NN TMDs

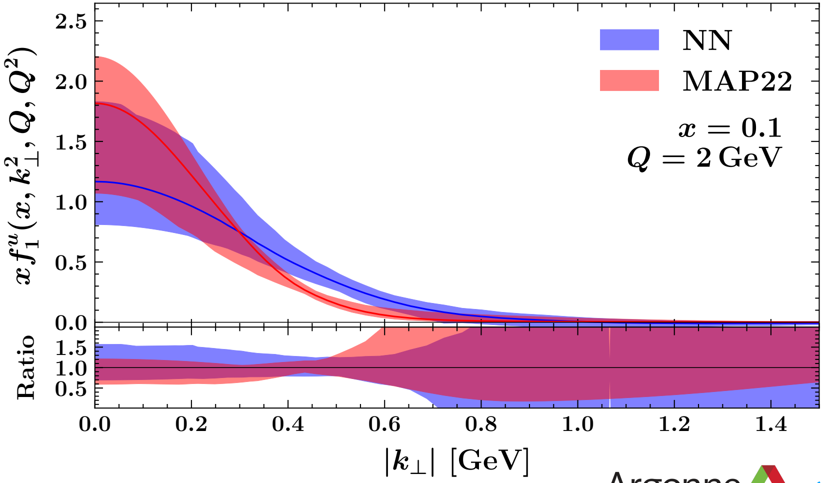
MAP Collaboration

extraction of $f_1(x, k_T)$ from DY data

MAP Collaboration
arXiv:2502.04166







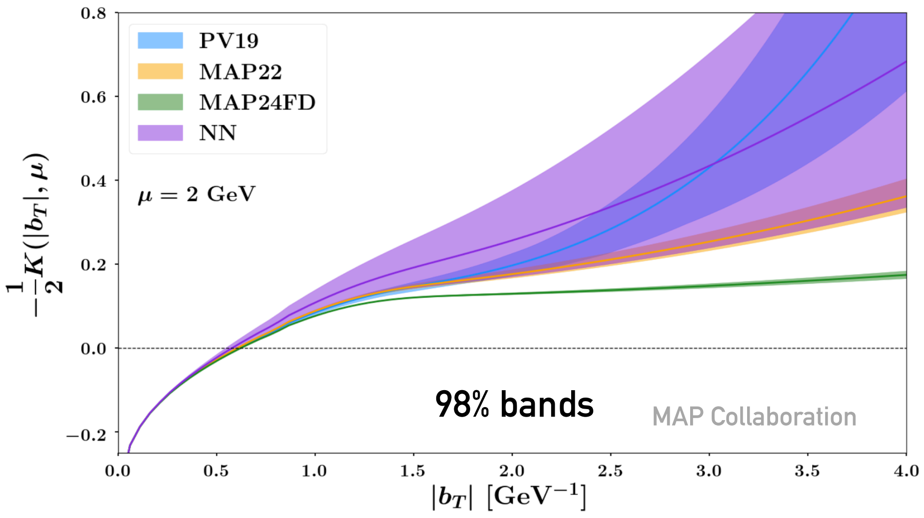
NN fit has larger bands

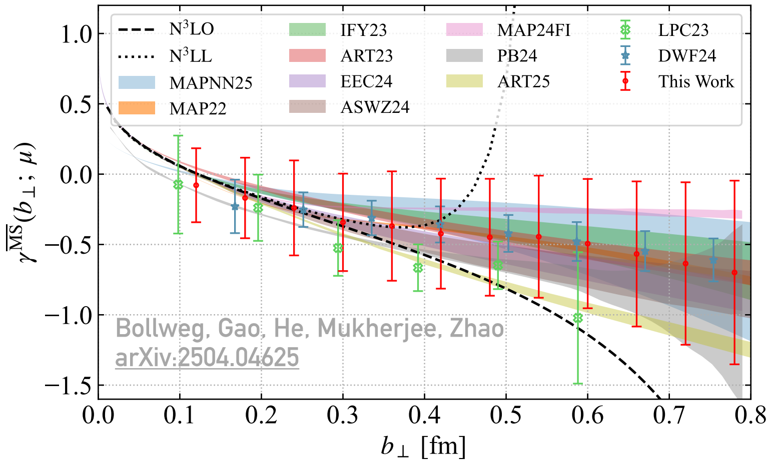
more reliable estimation uncertainties

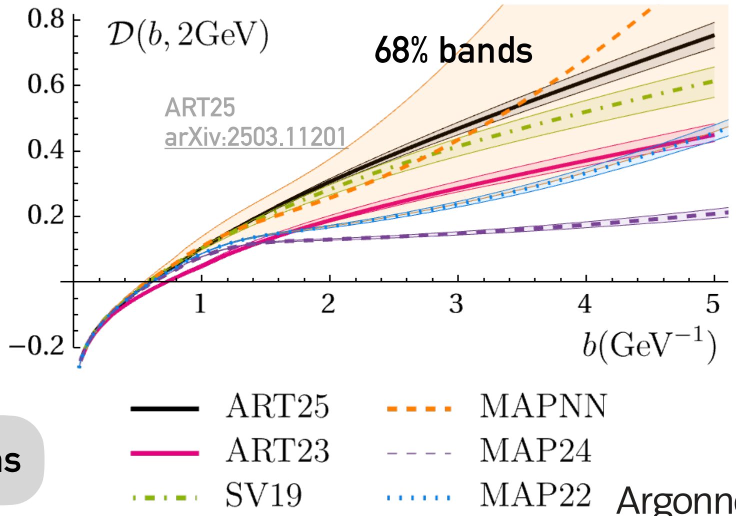
Collins-Soper kernel

“strong” universality

process independent,
insensitive to the types of external hadrons involved,
not dependent on polarization, on the flavors of the quarks, and on the scale Q





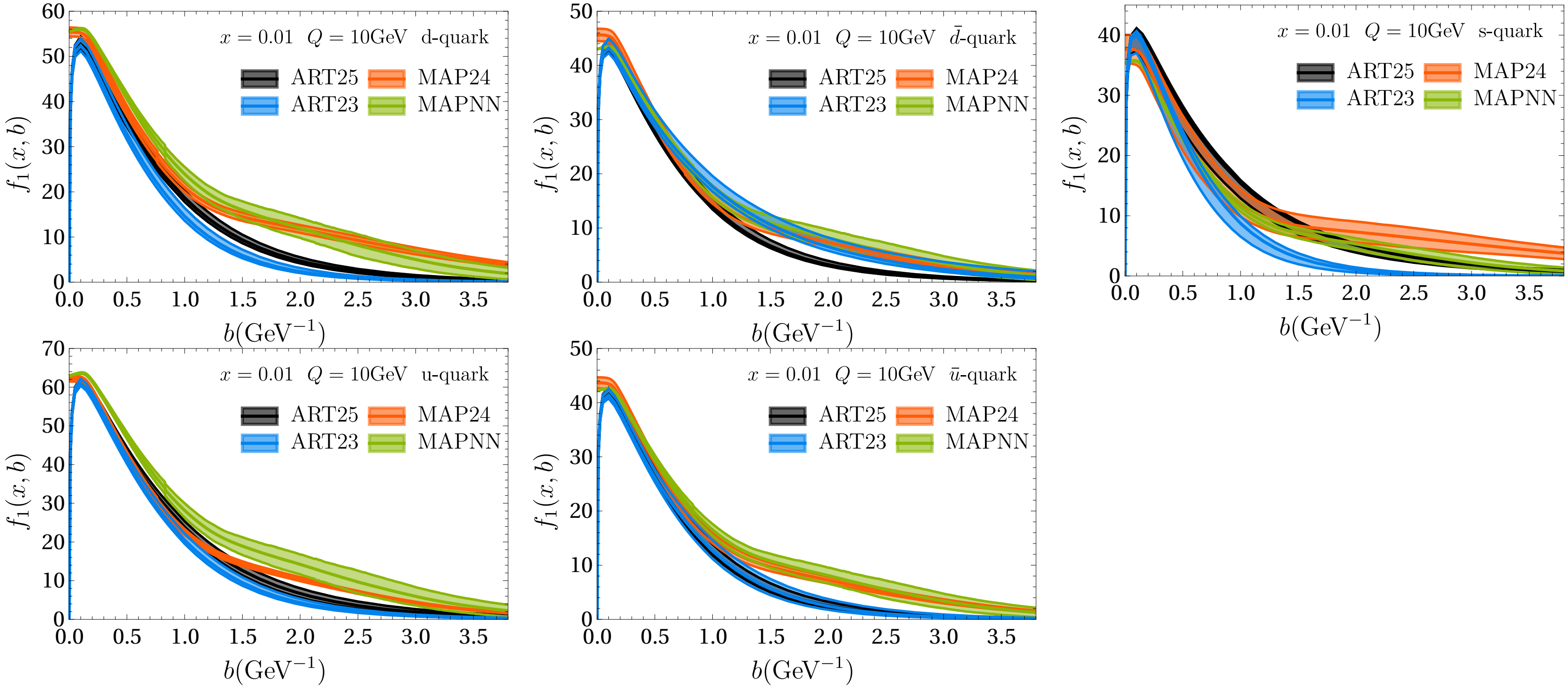


good agreement between the extractions

TMD PDFs comparison

from ART25

two latest extraction of
unpolarized quark TMD PDF
from the ART and the MAP Collaborations



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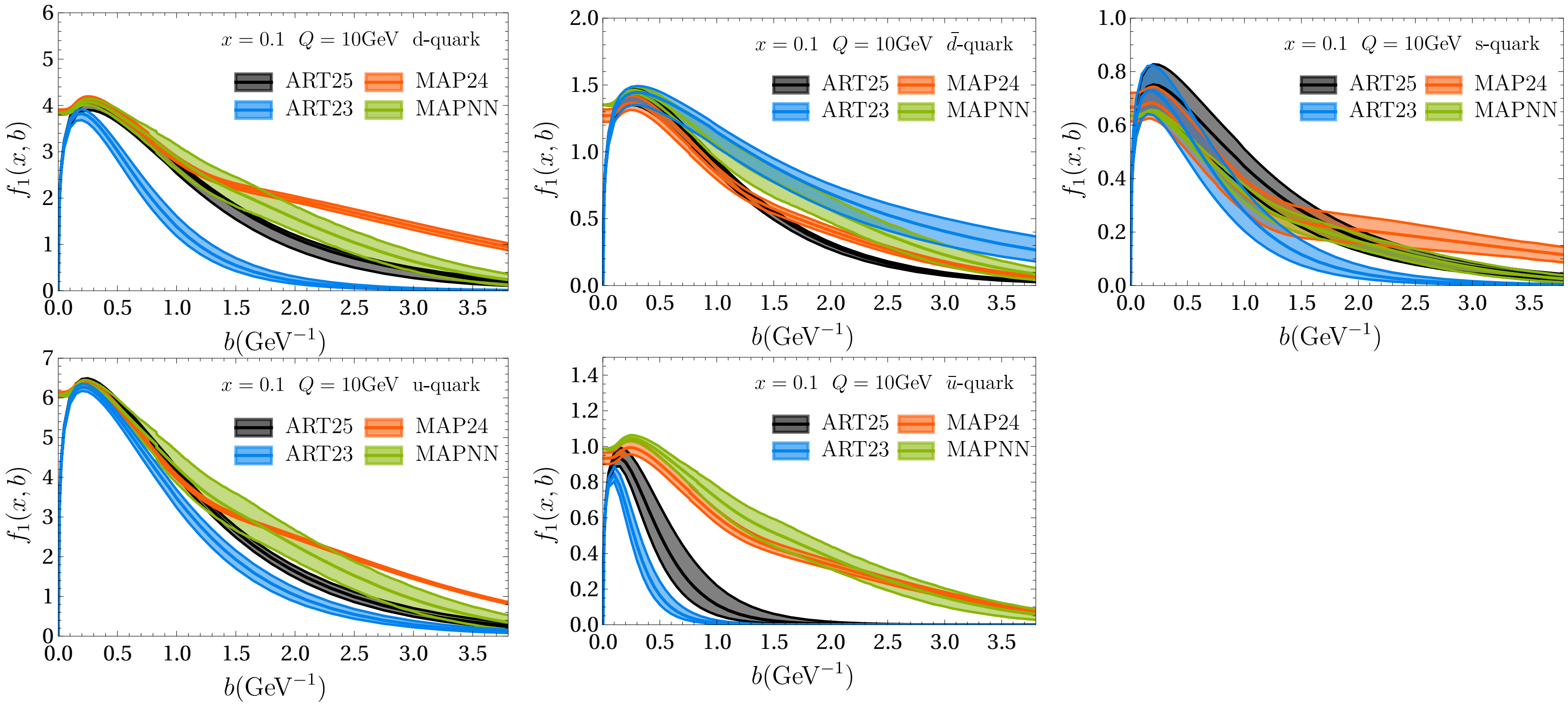
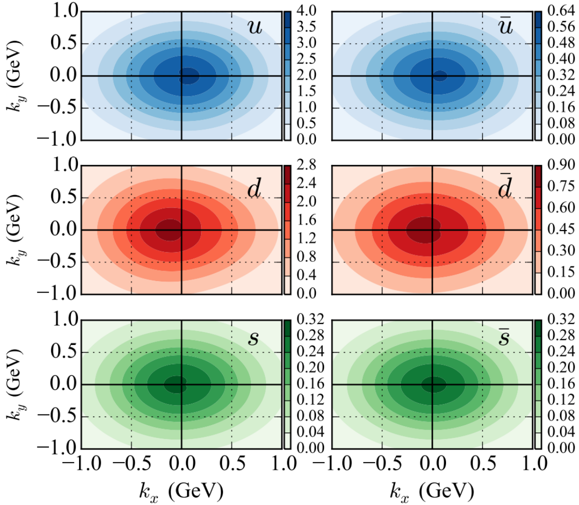


Sivers function

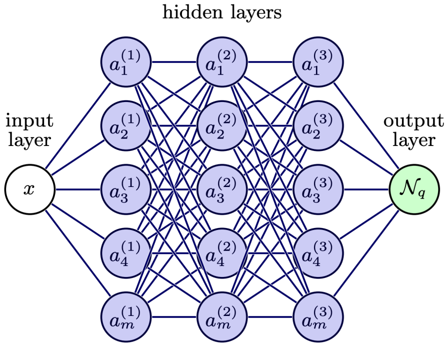
with Deep Neural Networks

I. P. Fernando, D. Keller
DOI: 10.1103/PhysRevD.108.054007
arXiv:2304.14328



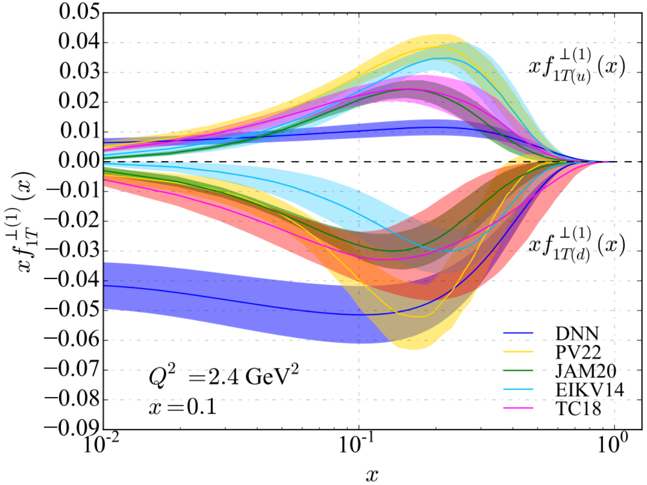
$$\rho_N^q(x, k_x, k_y; Q^2) = f_1^q(x, k_T^2, Q^2) - \frac{k_x}{M} f_{1T}^{\perp q}(x, k_T^2, Q^2)$$

in a nucleon polarized in the +y direction,
the distribution of quarks can be distorted in the x direction



exploratory analysis

using HERMES and COMPASS data



good agreement between the extractions

Sivers function

Q = 2 GeV

$$\rho_N^q(x, k_x, k_y; Q^2) = f_1^q(x, k_T^2, Q^2) - \frac{k_x}{M} f_{1T}^{\perp q}(x, k_T^2, Q^2)$$

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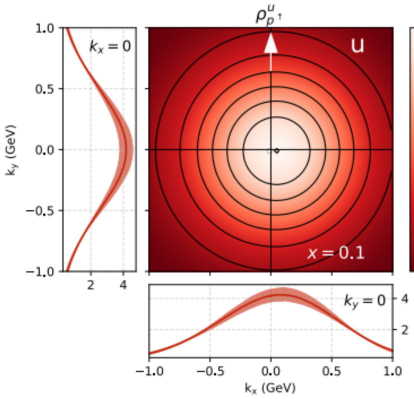
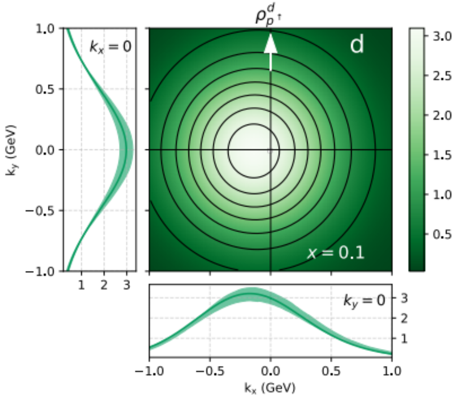
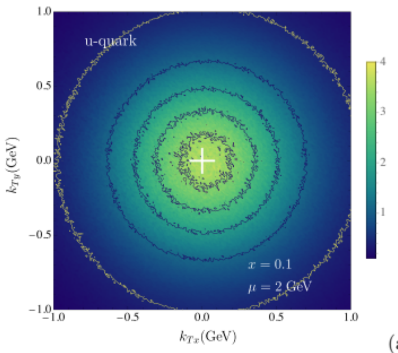


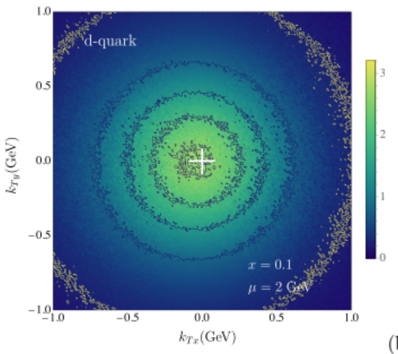


MAP Collaboration

A.Bacchetta, F. Delcarro, C. Pisano, M.Radici
arXiv: 2004.14278



(a)



(b)

M. Bury, A. Prokudin, A. Vladimirov
arXiv: 2103.03270

Helicity

longitudinally polarized quarks

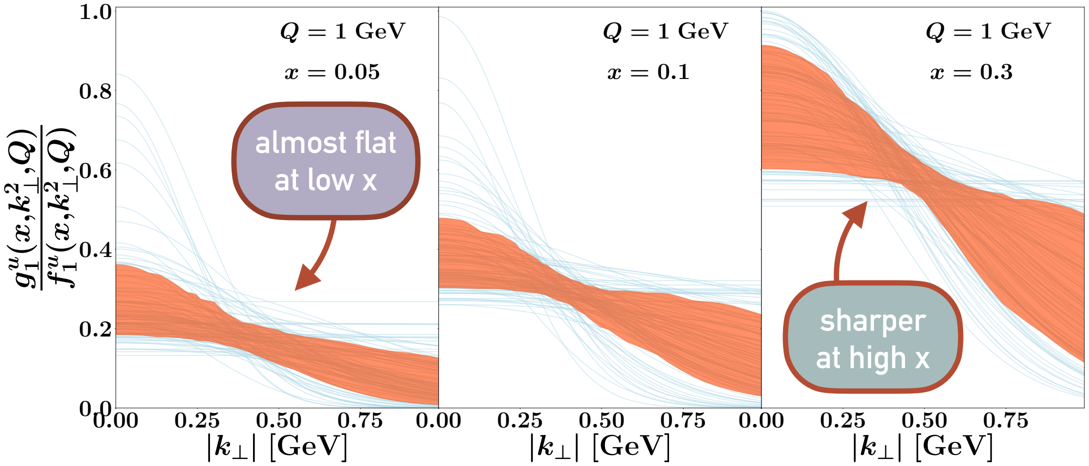
A. Bacchetta, A. Bongallino, M. Cerutti, M. Radici and L. Rossi
MAP Collaboration - arXiv:2409.18078

SIDIS data ~300

MAP Collaboration

double spin asymmetry

$$A_1(x, z, Q, |\boldsymbol{P}_{hT}|) = \frac{\sum_{a=q,\bar{q}} e_a^2 \int_0^{+\infty} d|\boldsymbol{b}_T|^2 J_0\left(\frac{|\boldsymbol{b}_T||\boldsymbol{P}_{hT}|}{z}\right) \hat{g}_1^a(x, |\boldsymbol{b}_T|^2, Q) \hat{D}_1^{a\to h}(z, |\boldsymbol{b}_T|^2, Q)}{\sum_{a=q,\bar{q}} e_a^2 \int_0^{+\infty} d|\boldsymbol{b}_T|^2 J_0\left(\frac{|\boldsymbol{b}_T||\boldsymbol{P}_{hT}|}{z}\right) \hat{f}_1^a(x, |\boldsymbol{b}_T|^2, Q) \hat{D}_1^{a\to h}(z, |\boldsymbol{b}_T|^2, Q)}$$



Parameters	N_{1g}	α_{1g}	σ_{1g}
NLL	0.70 ± 0.54	27.81 ± 27.70	0.42 ± 0.86
NNLL	0.87 ± 0.72	6.73 ± 6.58	3.04 ± 3.09

3 parameters

but poorly constrained due to lack of data

TMD phenomenology

Status and Future Directions

Unpolarized Quark TMDs

- we are entering the **precision era**

  TMDs extracted from fits of large datasets with high perturbative accuracy.

- flavor dependence, reduction of PDF bias

Polarized Quark TMDs

- great progress in extracting polarized TMDs

exploration of

- Sivers function
- Helicity,
- Transversity…

New techniques

- Neural Networks fits

more reliable estimation uncertainties

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unpolarized quark TMD

factorizes as hard
and longitudinal non-perturbative

matching to the
collinear region

$b_T \ll 1/\Lambda_{QCD}$

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b)$$

$$\times \exp\left\{K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'}\right]\right\}$$

$$\times \exp\left\{g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}\right\}$$

CS and RGE
evolution

non perturbative
transverse content

parametrized
and **fitted to data**

Logarithmic accuracy

$$\left(\frac{d\sigma}{dq_T}\right) \propto H(Q,\mu) \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} x_1 f_1^q(x_1,\mathbf{b};\mu,\zeta_1) x_2 f_1^{\bar{q}}(x_2,\mathbf{b};\mu,\zeta_2)$$

perturbative expansion in $\alpha_s(\mu)$

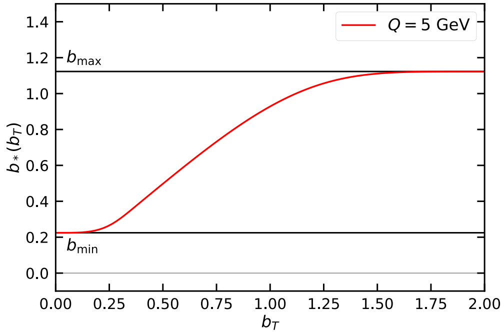
$$f_1^q(x,b;\mu,\zeta) = \sum_j \left(C_{q/j} \otimes f^j\right)(x,b_*;\mu_b)$$
$$\times \exp\left\{K(\mu_0)\ln\frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} + \int_{\mu_0}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F(\alpha_s(\mu')) - \gamma_K(\alpha_s(\mu'))\ln\frac{\sqrt{\zeta}}{\mu'}\right]\right\}$$
$$\times f_{\rm NP}(x,b;\zeta)$$

Accuracy	H and $C_{q/j}$	K and γ_F	γ_K	PDF and α_s evol.
LL	0	-	1	-
NLL	0	1	2	LO
NLL'	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL'	2	2	3	NNLO
N^3LL	2	3	4	NNLO
N^3LL'	3	3	4	N^3LO

b* prescription

$$b_T \to \infty \qquad \alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$$

→ invalidates perturbative calculations $\Rightarrow b_{\max}$



$$F(x,b;\mu,\zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x,b_*(b);\mu,\zeta)$$

$F(x,b_*(b);\mu,\zeta)$ → perturbative

$f_{\rm NP}(x,b,\zeta)$ fit to data

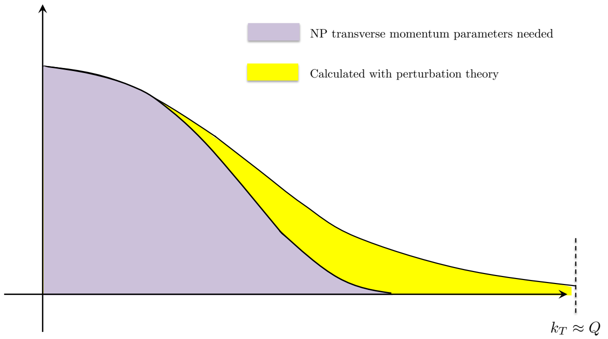
important

f_{NP} not directly comparable between fits, it depends on the choice of b* prescription

Hadron Structure Oriented approach

TMD PDF HSO parametrization at input scale

F. Aslan, M. Boglione, J. O. Gonzalez-Hernandez, T. Rainaldi, T. Rogers and A. Simonelli
DOI: 10.1103/PhysRevD.110.074016



$$f_{\mathrm{inpt},i/p}(x, \mathbf{k_T}; \mu_{Q_0}, Q_0^2) = \text{pQCD and collinear factorization} + C^f_{i/p}\ \text{NP model}$$

coefficient such that the integral relations/OPE expansion is satisfied

the relative contributions cannot be adjusted independently from one another

$$f_{j/h}(x,\mu) = \pi \int_0^{\mu^2} dk_T^2\, f_{j/h}(x, k_T; \mu, \mu^2) + \Delta(f(x), \alpha_s(\mu))$$

+ power suppressed.

no need to divide space into two parts with b_{max}

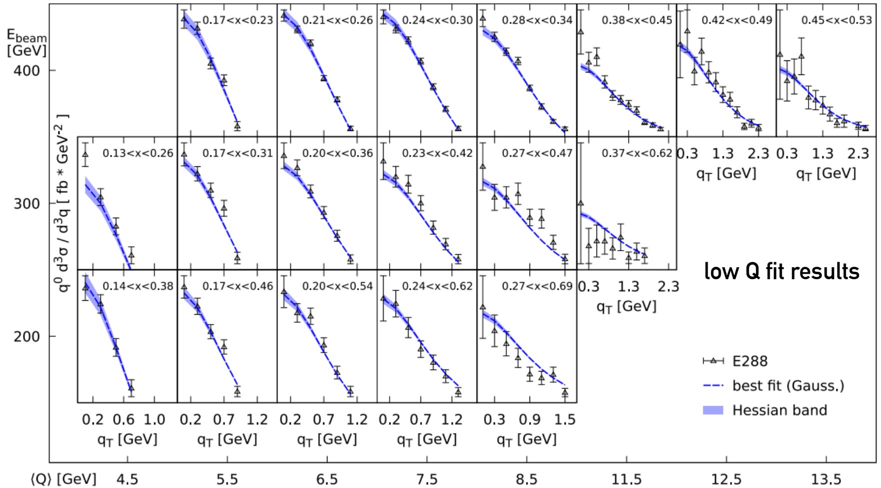
preserve the integral normalizations that connect TMD and collinear PDFs

Hadron Structure Oriented (HSO)

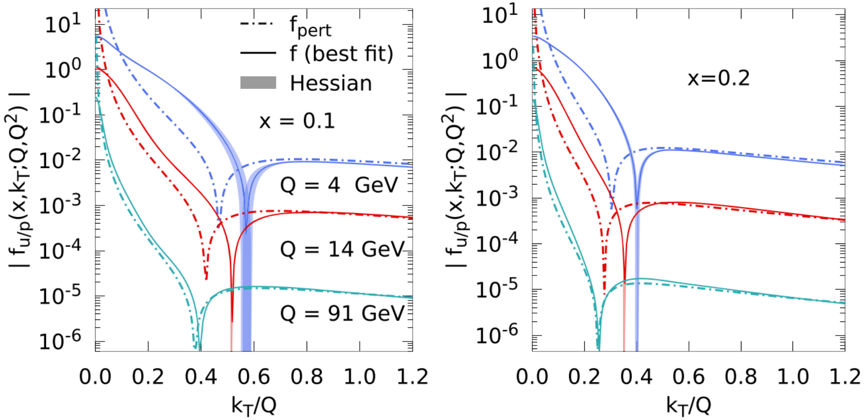
proof of principle

proposed new approach to TMD phenomenology

within 'the usual' TMD factorization



	E288 (130 pts)	E605 (52 pts)
$\chi^2_{d.o.f.}$	1.04	1.68



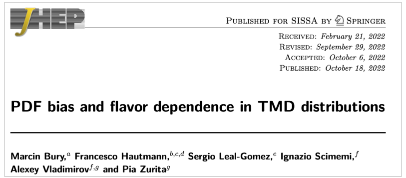
HSO approach guarantees that the TMD pdf asymptotes to the perturbative tail

4 parameters

F. Aslan, M. Boglione, J. O. Gonzalez-Hernandez, T. Rainaldi, T. Rogers and A. Simonelli
DOI: 10.1103/PhysRevD.110.074016

PDF bias

M. Bury, F. Hautmann, S. Leal-Gomez, I. Scimemi, A. Vladimirov, P. Zurita - arXiv: 2201.0714 - DOI: 10.1007/JHEP10(2022)118


JHEP — Published for SISSA by Springer
Received: February 21, 2022
Revised: September 29, 2022
Accepted: October 6, 2022
Published: October 18, 2022

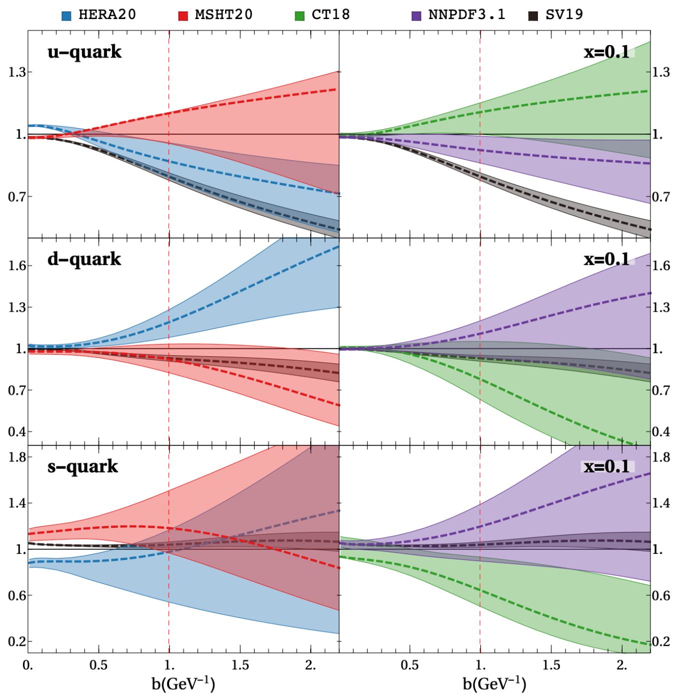
PDF bias and flavor dependence in TMD distributions

Marcin Bury,[a] Francesco Hautmann,[b,c,d] Sergio Leal-Gomez,[e] Ignazio Scimemi,[f] Alexey Vladimirov[f,g] and Pia Zurita[g]

ζ-prescription

N3LL

H	$C_{f\leftarrow f'}$	Γ_{cusp}	γ_V	$\mathcal{D}_{\text{resum}}$	α_s running & PDF evolution
α_s^2	α_s^2	α_s^3	α_s^2	α_s^2	NNLO



$$f_{NP}^{f}(x,b) = \exp\left[-\frac{\left[(1-x)\,\lambda_1^f + x\,\lambda_2^f\right] b^2}{\sqrt{1+\lambda_0^f\,x^2\,b^2}}\right]$$

distinguish {u, d, ubar, dbar}
and sea = {s, sbar, c, cbar, bbar, b}

comparison of uncertainty band for unpolarized TMDPDFs extracted with different PDFs.

11 parameters

ART23

V. Moos, I. Scimemi, A. Vladimirov, P. Zurita
DOI: 10.1007/JHEP05(2024)036 - arXiv: 2305.07473

explicit flavor dependence

Extraction of unpolarized transverse momentum distributions from the fit of Drell-Yan data at N^4LL

Valentin Moos,[a] Ignazio Scimemi,[b] Alexey Vladimirov,[b] Pia Zurita[a,b]

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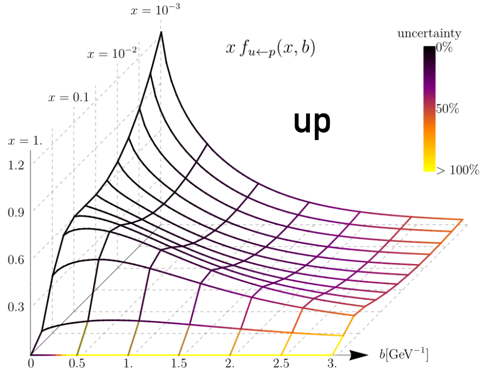
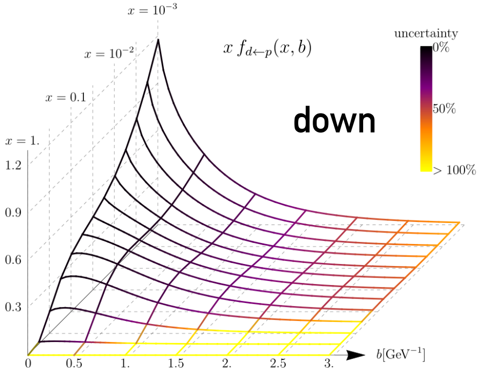
E-mail: valentin.moos@physik.uni-regensburg.de, ignazios@ucm.es, alexeyvl@ucm.es, marzurit@ucm.es





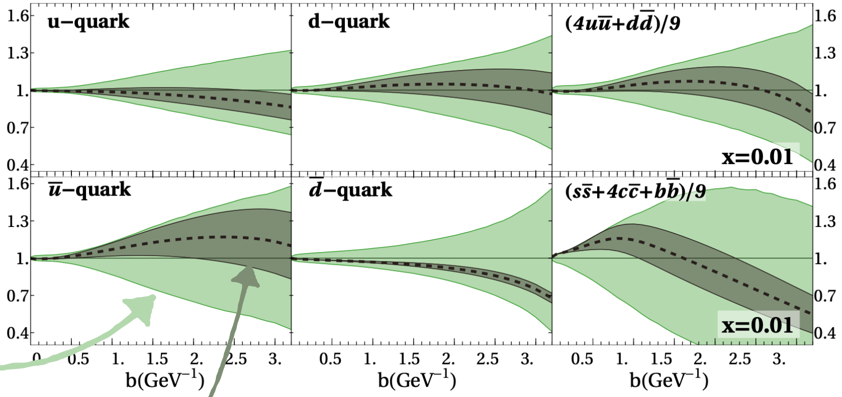
N4LL

Γ_{cusp}	γ_V	$\mathcal{D}_{\text{small-b}}$	$C_{f\leftarrow f'}$	C_V	PDF
$a_s^5\ (\Gamma_4)$	$a_s^4\ (\gamma_4)$	$a_s^4\ (d^{(4,0)})$	$a_s^3\ (C^{[3]}_{f\leftarrow f'})$	a_s^4	NNLO

$$f_{\mathrm{NP}}^{f}(x,b) = \frac{1}{\cosh\left(\left[\lambda_1^f\,(1-x) + \lambda_2^f\,x\right]b\right)}$$

10 + 3 parameters

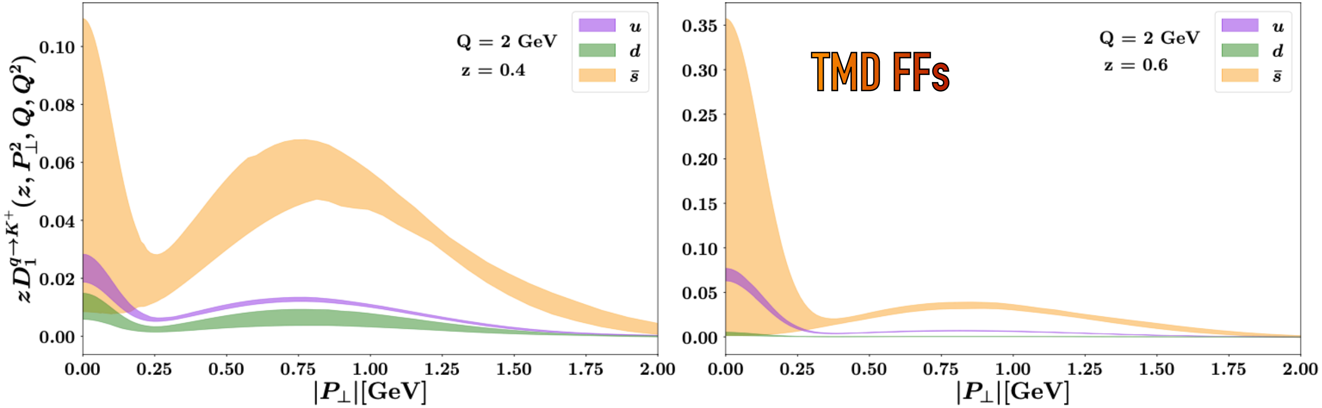
extraction minimizes the PDF bias

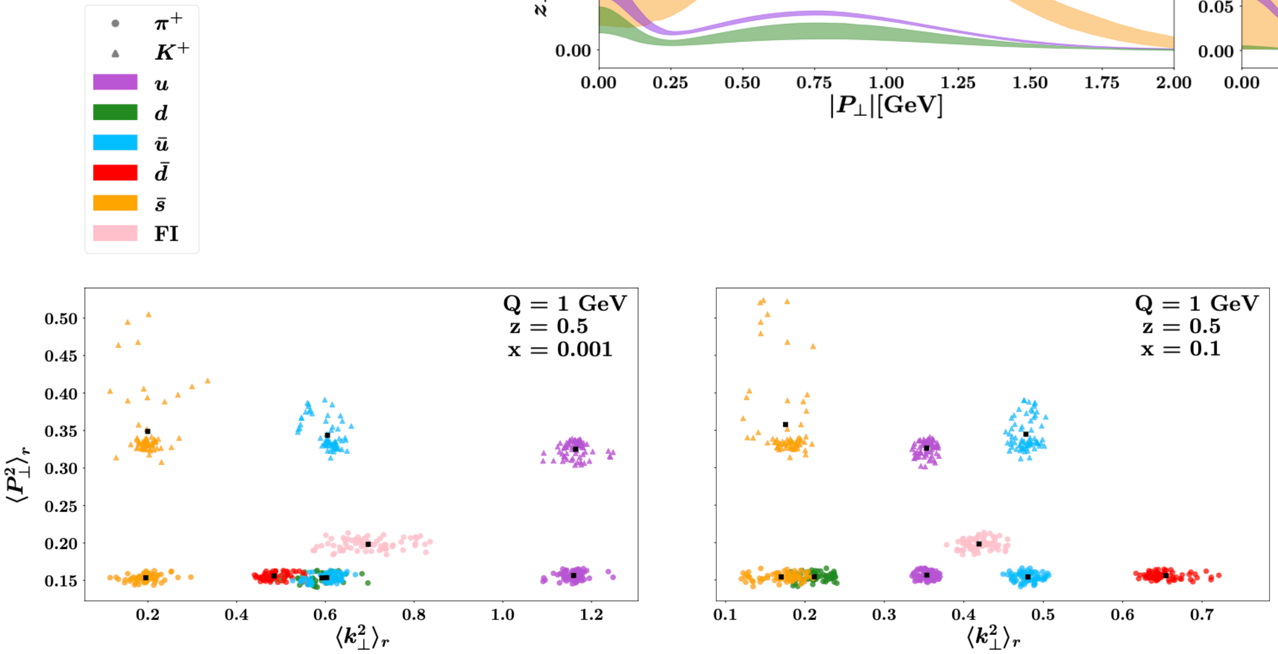


full uncertainty bands
in comparison to
the extraction at the central PDF replica

MAP24

b*-prescription with b_min





global fit: DY & SIDIS

$f_{\rm NP}$ same as in MAP22

96 parameters

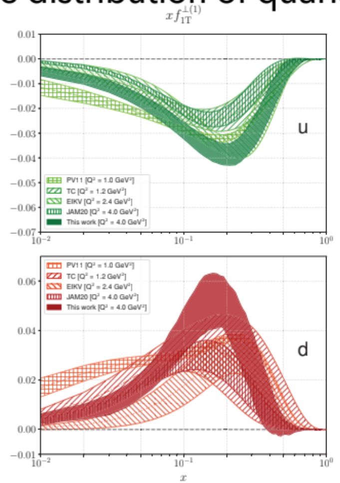
1 + (5 flavors × 10 parameters) for TMD PDFs, and
45 (5 channels × 9 parameters) for TMD FFs.

Sivers Function

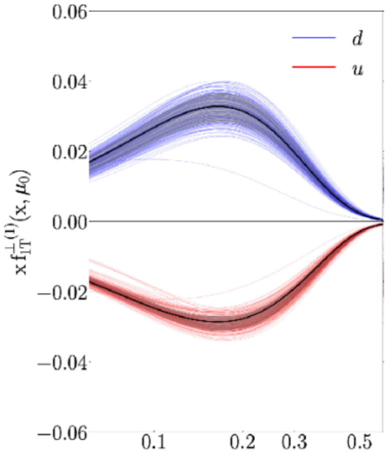
comparison between extractions

$$\rho^{q}_{N\uparrow}(x, k_x, k_y; Q^2) = f_1^q(x, k_T^2; Q^2) - \frac{k_x}{M} f_{1T}^{\perp q}(x, k_T^2; Q^2)$$

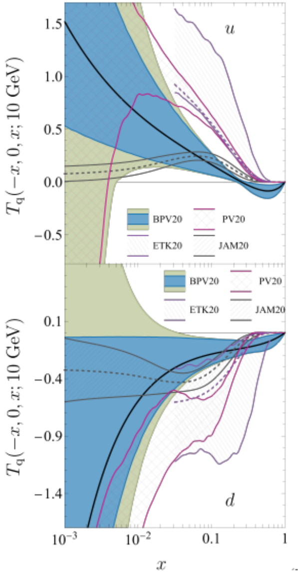
In a nucleon polarized in the +y direction,
the distribution of quarks can be distorted in the x direction



Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278



Echevarria, Kang, Terry, arXiv:2009.10710



Bury, Prokudin, Vladimirov, arXiv:2103.03270

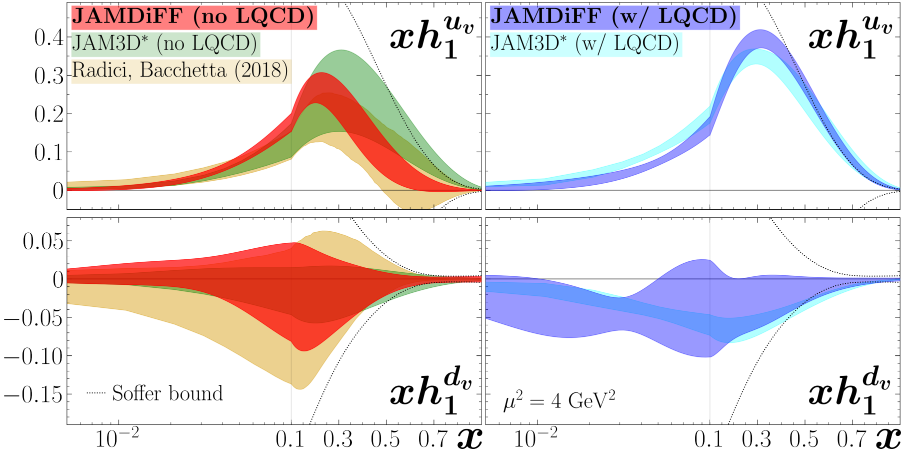
slide adapted from A. Bacchetta

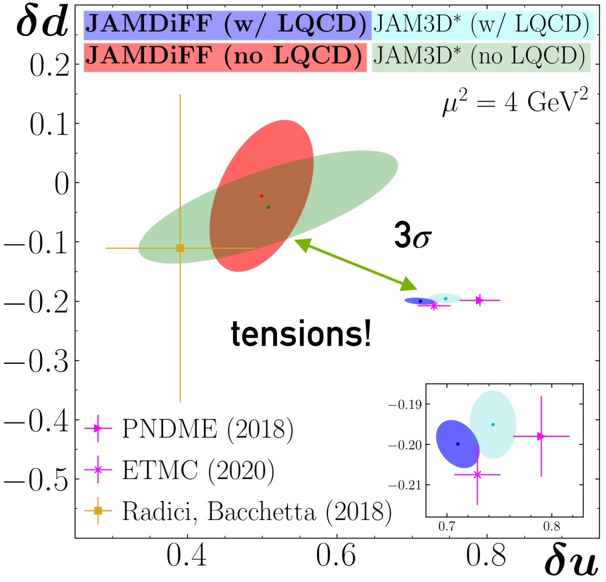
JAMDiFF

JAM Collaboration - arXiv: 2308.14857
DOI: 10.1103/PhysRevD.109.034024

first simultaneous global analysis of the $\pi^+\pi^-$ DiFFs and transversity PDFs

h_1 quantifies the degree of transverse polarization of quarks within a transversely polarized nucleon.





Phys. Rev. Lett. 132, 091901 (2024)
arXiv: 2306.12998

inclusion of LQCD data on tensor charges in the fit

$$\delta u = \int_0^1 \mathrm{d}x \; h_1^{u_v}(x;\mu)\,, \qquad \delta d = \int_0^1 \mathrm{d}x \; h_1^{d_v}(x;\mu)$$

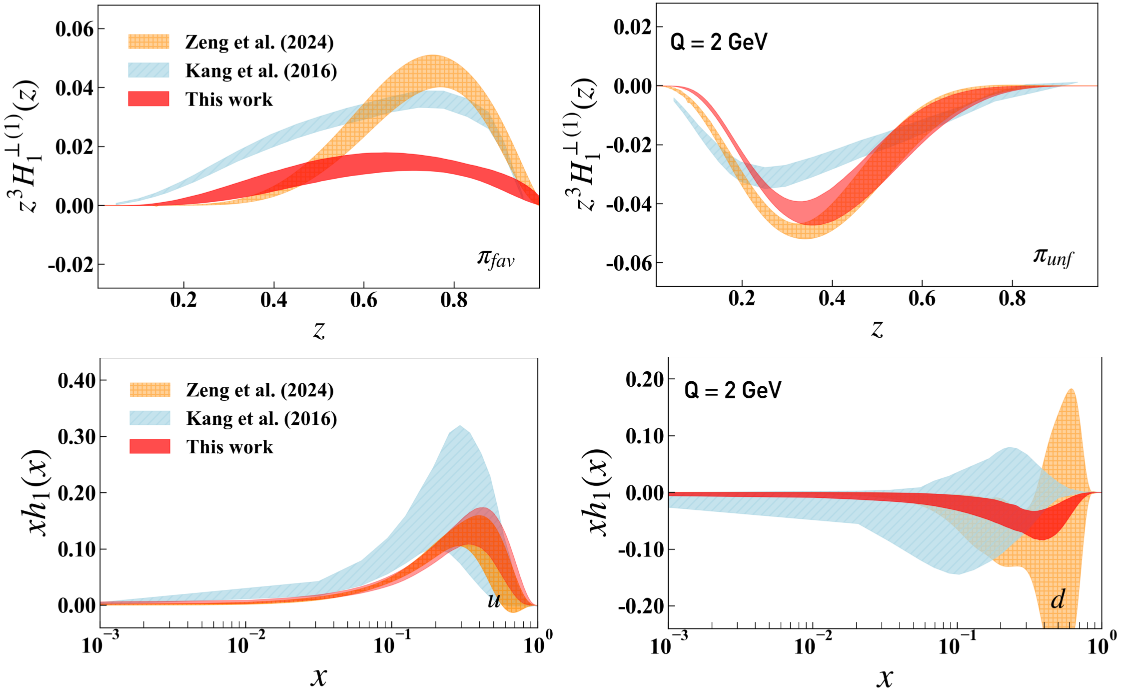
tensor charges

e^+e^-, SIDIS, and pp data

LQCD data reduces uncertainties in the large-x region

Global analysis of Sivers and Collins asymmetries

Chunhua Zeng, Hongxin Dong, Tianbo Liu, Peng Sun, Yuxiang Zhao
(Transverse Nucleon Tomography Collaboration)
arXiv:2412.18324



$$H_1^{\perp(1)}(z) = \int_0^{p_T^{\rm cut}} d^2\boldsymbol{p}_T \frac{p_T^2}{2z^2M_h^2} H_1^\perp(z, p_T),$$

cuts because of TMD formalism

$$h_1(x) = \int_0^{k_T^{\rm cut}} d^2\boldsymbol{k}_T h_1(x, k_T).$$

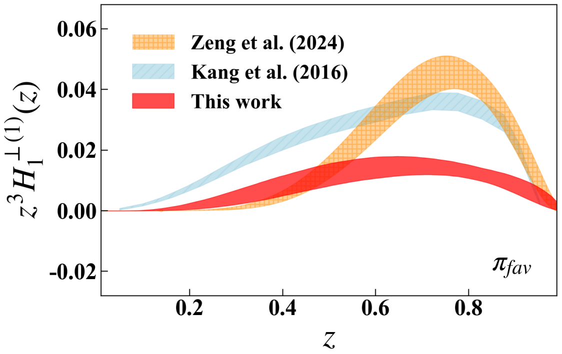
🍎🍏 studies slightly different

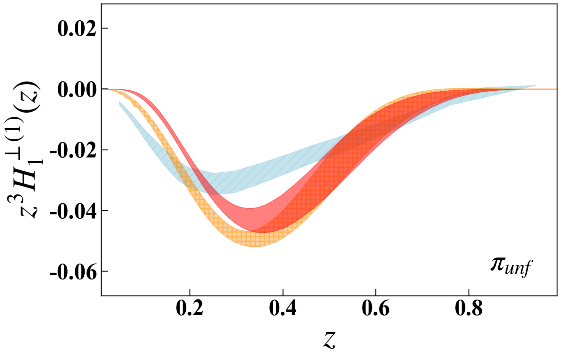
directly extracted as collinear functions

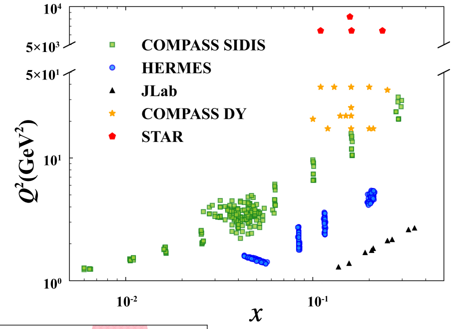
latest COMPASS data significantly improve the determination of transversity

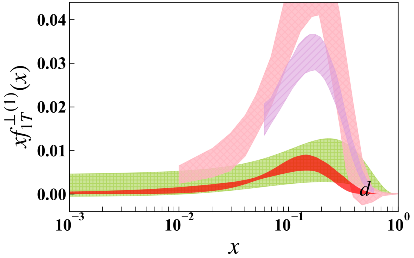
Global analysis of Sivers and Collins asymmetries

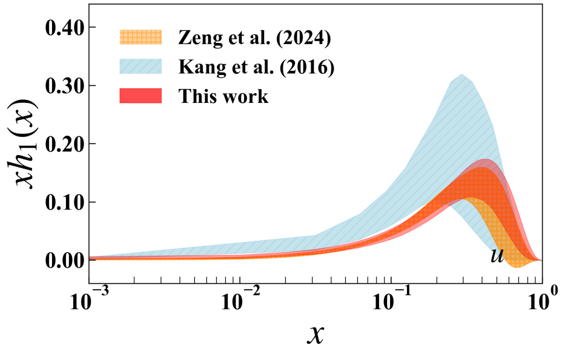
Chunhua Zeng, Hongxin Dong, Tianbo Liu, Peng Sun, Yuxiang Zhao
(Transverse Nucleon Tomography Collaboration)
arXiv:2412.18324

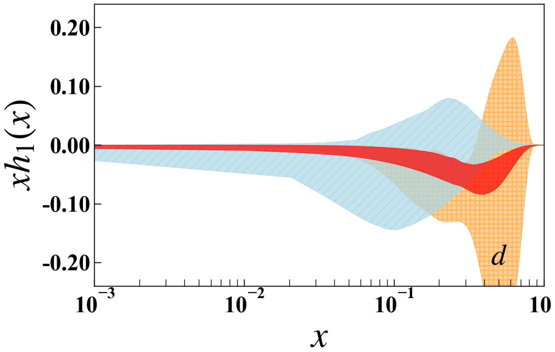


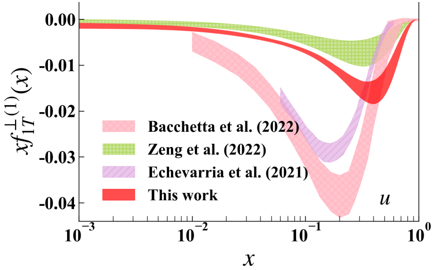












Helicity

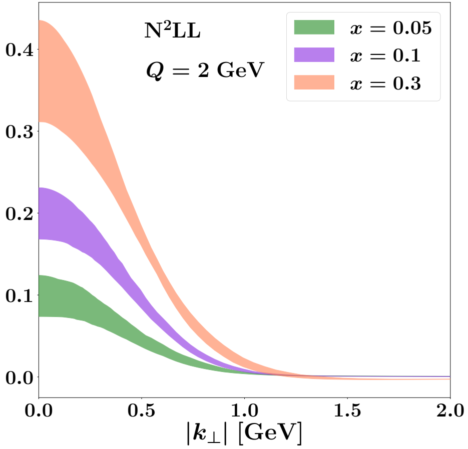
longitudinally polarized quarks

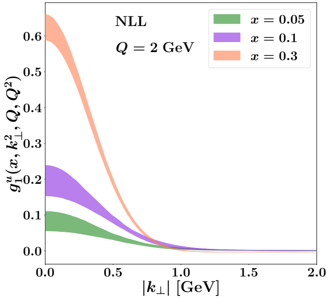
A. Bacchetta, A. Bongallino, M. Cerutti, M. Radici and L. Rossi
MAP Collaboration - arXiv:2409.18078

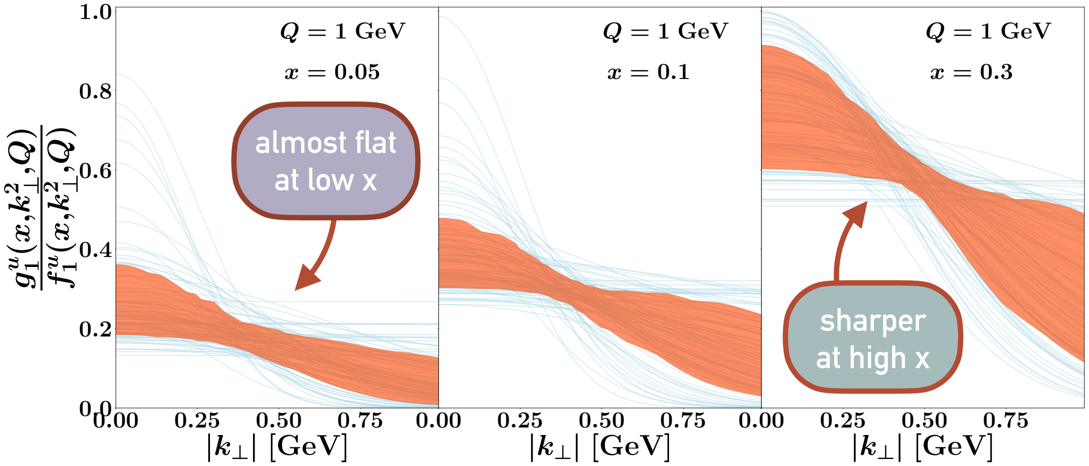
double spin asymmetry

$$A_1(x,z,Q,|\boldsymbol{P}_{hT}|) = \frac{\sum_{a=q,\bar{q}} e_a^2 \int_0^{+\infty} d|\boldsymbol{b}_T|^2 J_0\left(\frac{|\boldsymbol{b}_T||\boldsymbol{P}_{hT}|}{z}\right) \hat{g}_1^a(x,|\boldsymbol{b}_T|^2,Q)\, \hat{D}_1^{a\to h}(z,|\boldsymbol{b}_T|^2,Q)}{\sum_{a=q,\bar{q}} e_a^2 \int_0^{+\infty} d|\boldsymbol{b}_T|^2 J_0\left(\frac{|\boldsymbol{b}_T||\boldsymbol{P}_{hT}|}{z}\right) \hat{f}_1^a(x,|\boldsymbol{b}_T|^2,Q)\, \hat{D}_1^{a\to h}(z,|\boldsymbol{b}_T|^2,Q)}$$

SIDIS data







3 parameters

but poorly constrained due to lack of data

MAP Collaboration

...a selection of some more works

on 3D hadron structure

- Extraction of the Sivers function from SIDIS, Drell-Yan, and W / Z boson production data with TMD evolution
  M. Bury, A. Prokudin, A. Vladimirov –
  DOI: 10.1007/JHEP05(2021)151, arXiv:2103.03270

- Global analysis of polarized DIS and SIDIS data with improved small-x helicity evolution
  D. Adamiak, N. Baldonado, Y. V. Kovchegov, W. Melnitchouk, D. Pitonyak, N. Sato, M. D. Sievert, A. Tarasov, Y. Tawabutr (JAM Collaboration)
  Phys. Rev. D 108, 114007 (2023) - arXiv: 2308.07461

- Tomography of pions and protons via TMD distributions
  P. C. Barry, L. Gamberg, W. Melnitchouk, E. Moffat, D. Pitonyak, A. Prokudin, N. Sato (JAM Collaboration) - Phys. Rev. D 108, L091504 (2023) - arXiv: 2302.01192

- Transversity distributions and tensor charges of the nucleon: extraction from dihadron production and their universal nature
  C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl
  Phys. Rev. Lett. 132, 091901 (2024), arXiv:2306.12998

- Transverse momentum distributions at large x
  O. del Rio, A. Prokudin, I. Scimemi, A. Vladimirov - arXiv: 2501.17274

&

- Transverse Momentum Moments
  C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl
  Phys.Rev.D 110 (2024), arXiv: 2402.01836

TMD phenomenology

Status and Future Directions

Unpolarized Quark TMDs

- Precision era: extracted from fits of large datasets with high perturbative accuracy. Flavor dependence.

Polarized Quark TMDs

- great progress in extracting polarized
- TMDs (Sivers, Helicity, Transversity)

NN fits

Gluon TMDs

- Complete leading twist classification with process dependence and evolution properties
- Few phenomenological studies exist due to scarce experimental information.
- Progress expected with more experimental data (EIC)