APS - GHP25

March 14, 2025

Recent Phenomenological Studies Of 3D Momentum-Space Hadron Structure

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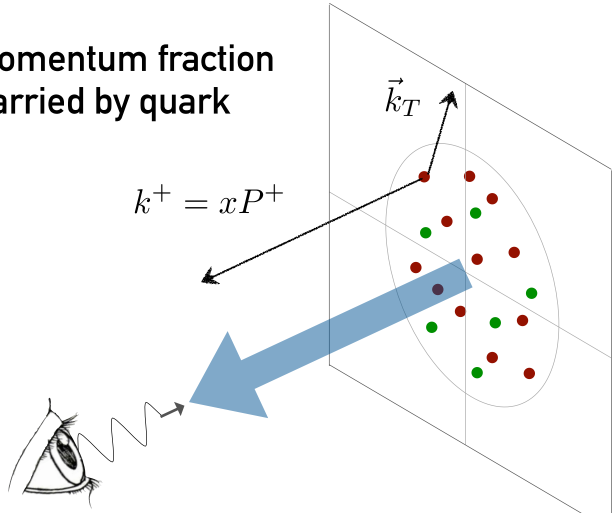
Argonne NATIONAL LABORATORY

TMDs: 3D maps

in momentum space

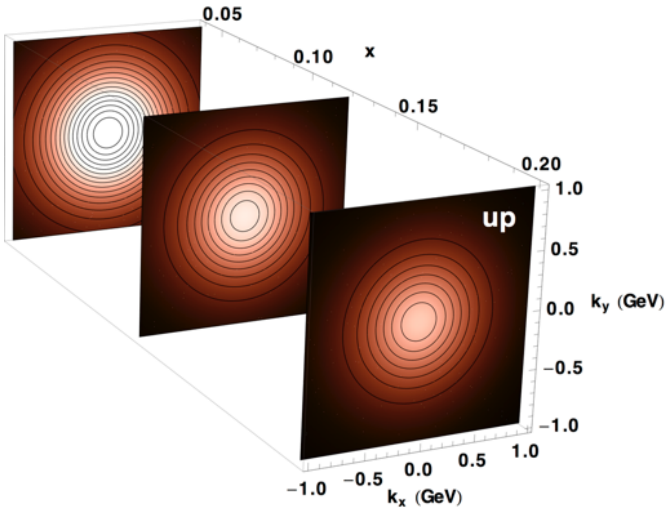
x: momentum fraction carried by quark



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)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: 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

	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: 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

What's new

some recent works about TMDs

Unpolarized TMDs

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

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

- **A Neural-Network Extraction of Unpolarized Transverse-Momentum-Dependent Distributions** — NN25
  MAP Collaboration - arXiv:2502.04166

- **Phenomenology of TMD parton distributions in Drell-Yan and Z0 boson production in a hadron structure oriented approach** — HSO
  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

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

matching to the collinear region

collinear PDFs

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

double scale dependence

perturbative evolution

non perturbative transverse content

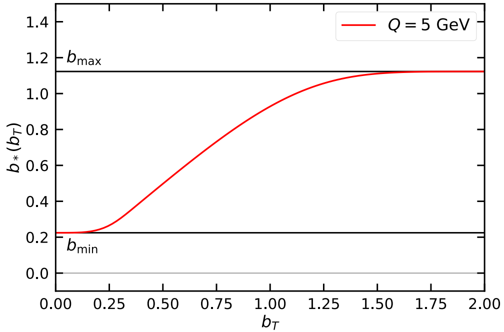
many subtleties involved in TMD analyses

b* prescription,
ζ-prescription, hadron structure oriented

parametrized and fitted to data

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

$\left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right]$ → $f_{\rm NP}(x, b, \zeta)$ fit to data

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

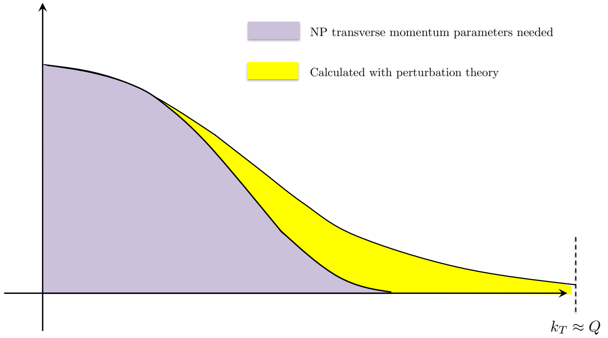
Hadron Structure Oriented approach

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

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

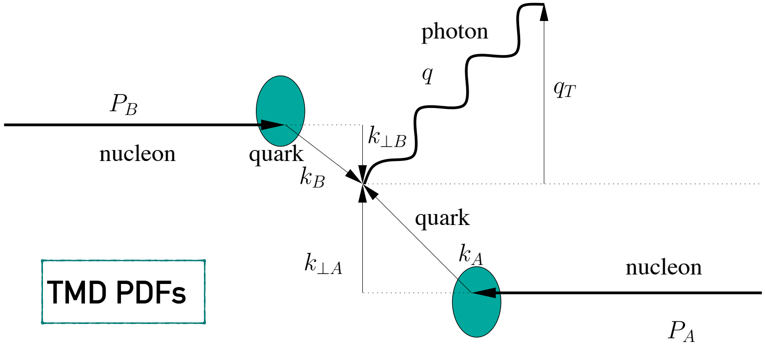
+ power suppressed.

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

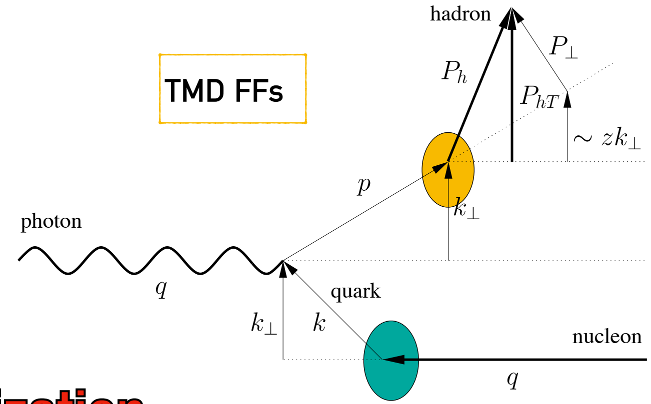
preserve the integral normalizations that
connect TMD and collinear PDFs

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

$$q_T \ll Q$$

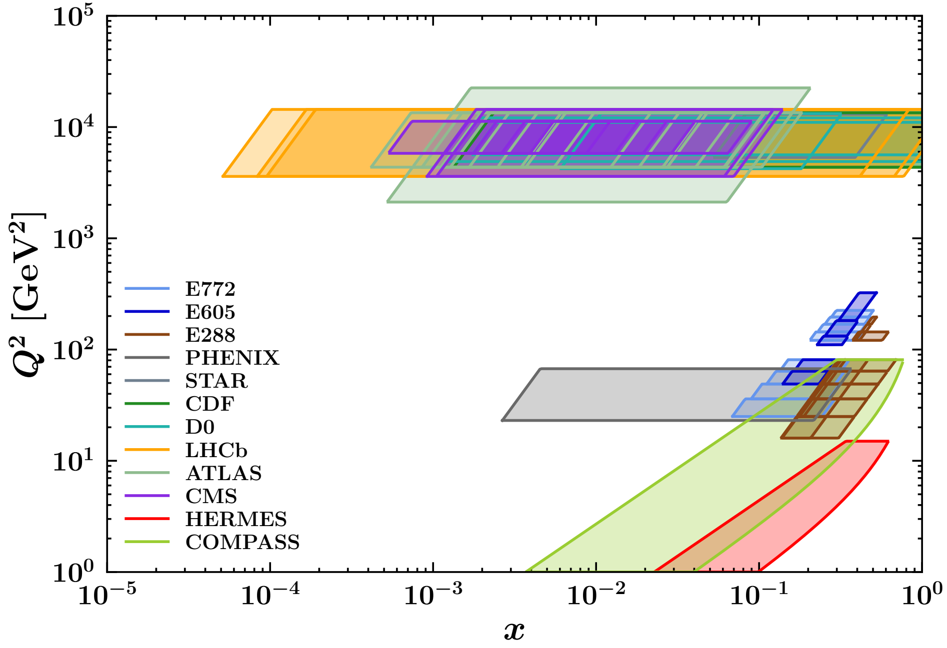
$$M^2 \ll Q^2 \qquad P_{hT}^2 \ll Q^2$$

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

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

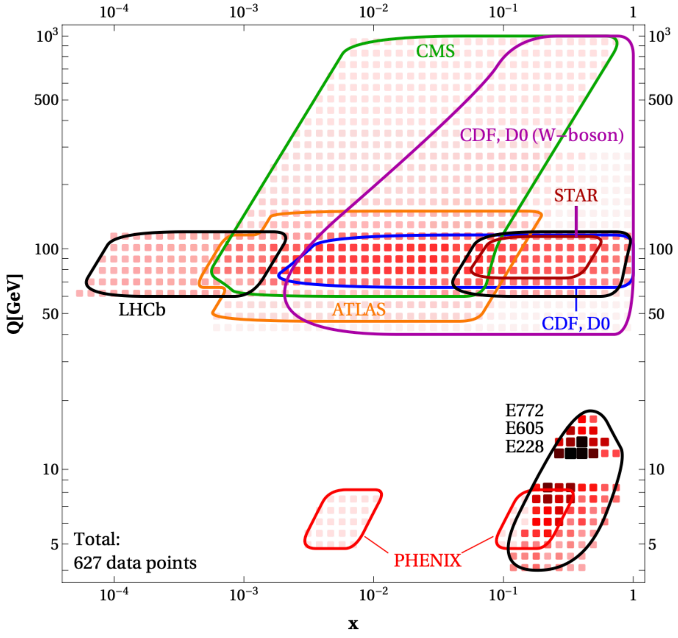
Data kinematical coverage

SIDIS & Drell-Yan



MAP Collaboration

darker color means higher density of data



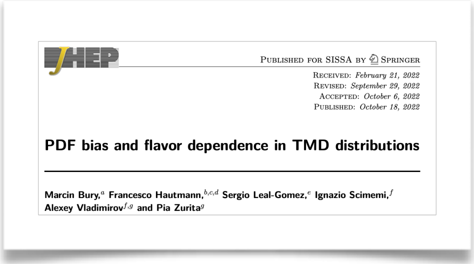
ART23 - arXiv: 2305.07473
DOI: 10.1007/JHEP05(2024)036

Extractions of unpolarized TMDs

Reference	Accuracy	HERMES	COMPASS	DY	n. of points	χ^2/n
PV 2017 [arXiv:1703.10157]	NLL	✅	✅	✅	8059	1.5
SV 2017 [arXiv:1706.01473]	NNLL′	❌	❌	✅	309	1.23
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

PDF bias

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

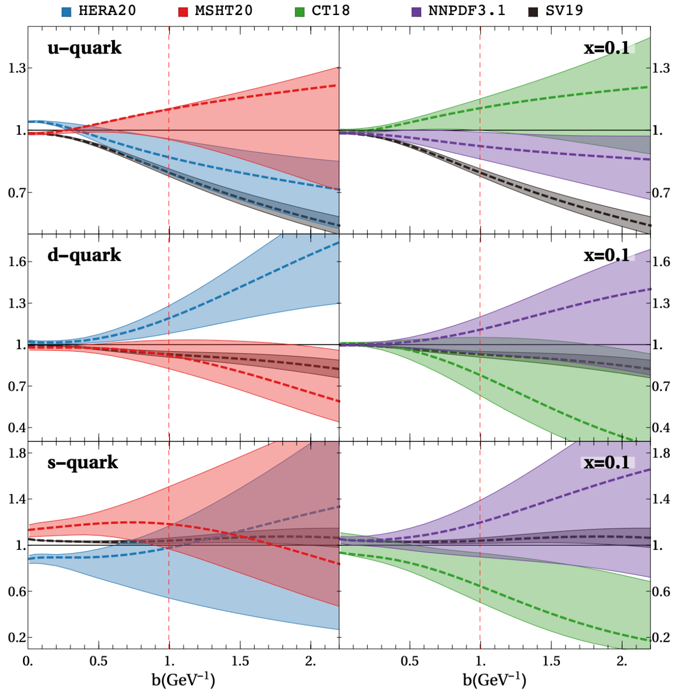

JHEP
Published for SISSA by Springer
Received: February 21, 2022
Revised: September 29, 2022
Accepted: October 6, 2022
Published: October 18, 2022
PDF bias and flavor dependence in TMD distributions
Marcin Bury,[a] Francesco Hautmann,[b,c,d] Sergio Leal-Gomez,[e] Ignazio Scimemi,[f] Alexey Vladimirov[f,g] 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

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



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

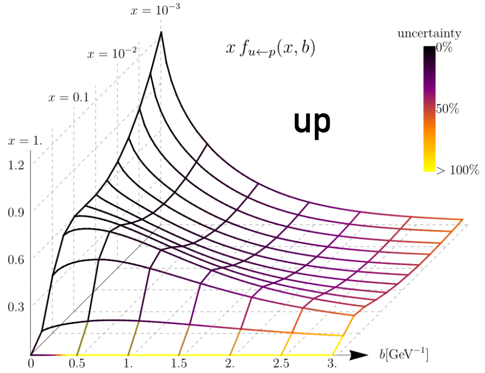
comparison of uncertainty band for unpolarized TMDPDFs extracted with different PDFs.

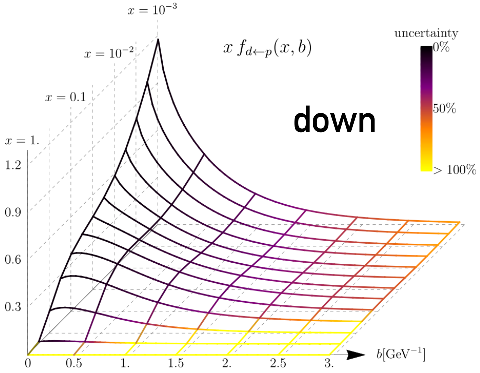
11 parameters

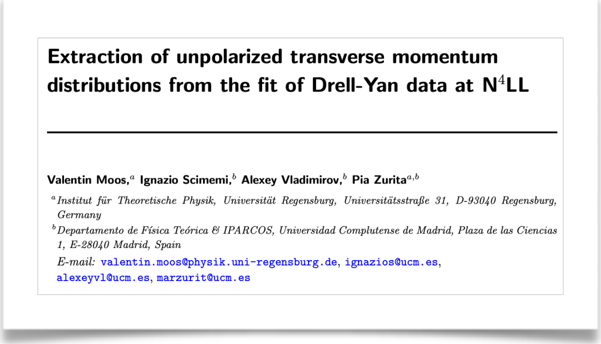
ART23

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^{4}LL

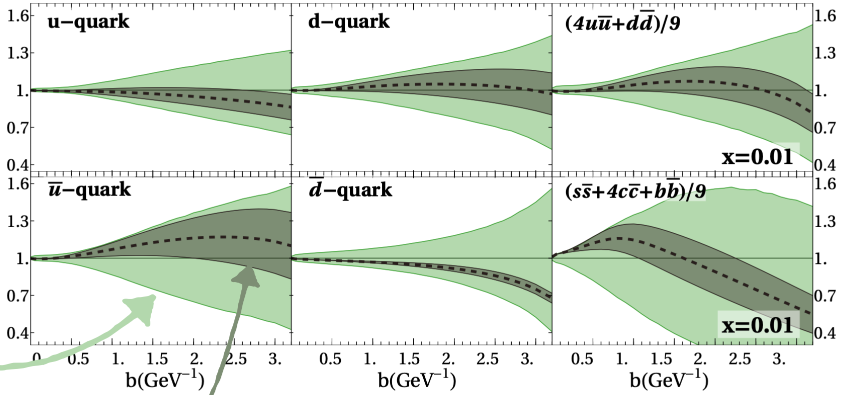
Valentin Moos,[a] Ignazio Scimemi,[b] Alexey Vladimirov,[b] Pia Zurita[a,b]
[a] Institut für Theoretische Physik, Universität Regensburg, Universitätsstraße 31, D-93040 Regensburg, Germany
[b] Departamento de Física Teórica & IPARCOS, Universidad Complutense de Madrid, Plaza de las Ciencias 1, E-28040 Madrid, Spain
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

$$f^f_{\text{NP}}(x,b) = \frac{1}{\cosh\!\Big(\big[\lambda_1^f\,(1-x)+\lambda_2^f\,x\big]\,b\Big)}$$

10 + 3 parameters



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

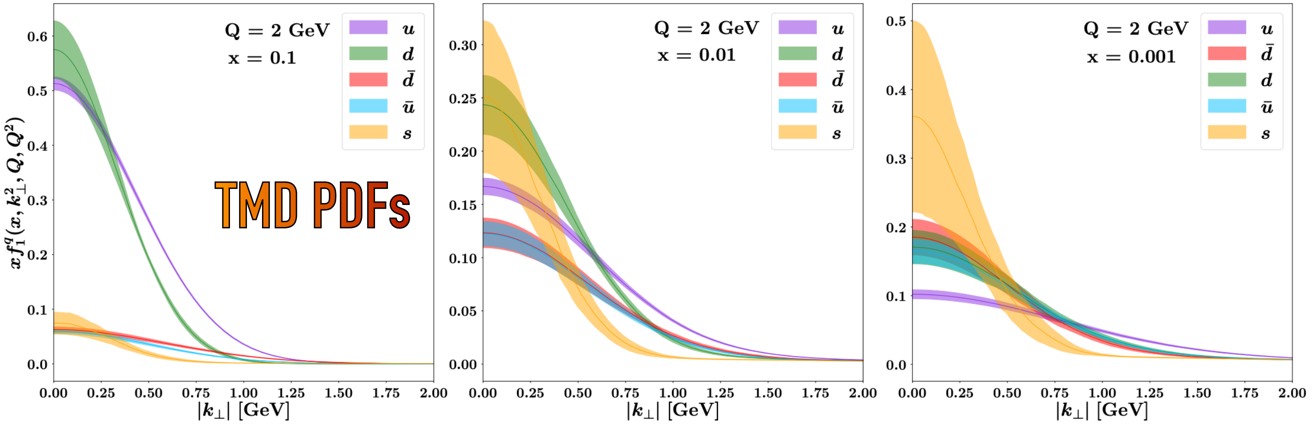
extraction minimizes the PDF bias

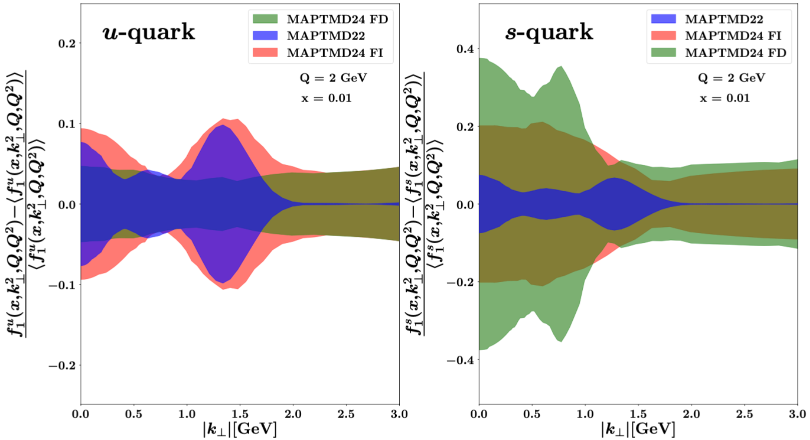
MAP24

b*-prescription

N3LL⁻

global fit: DY & SIDIS





uncertainties are larger

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

96 parameters

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

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

vs

MAP22

only central replica of collinear PDFs

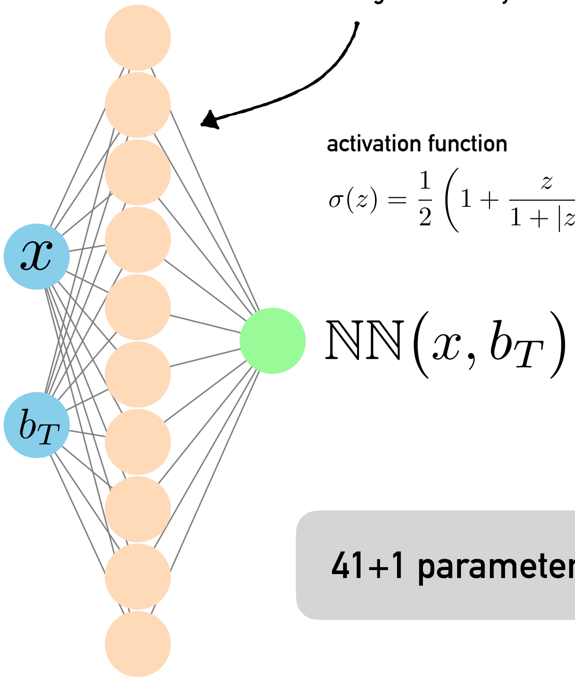
MAP Collaboration
arXiv:2502.04166

NN TMDs

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

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

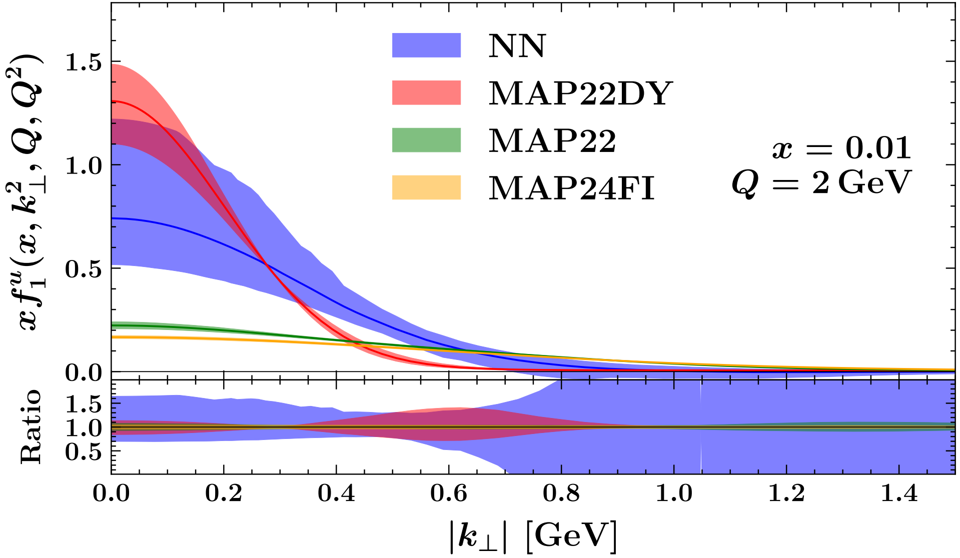
10 nodes in a single hidden layer



activation function

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

41+1 parameters

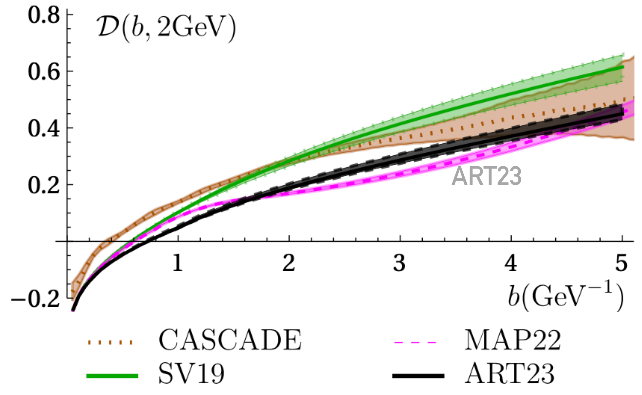


(more) reliable uncertainties

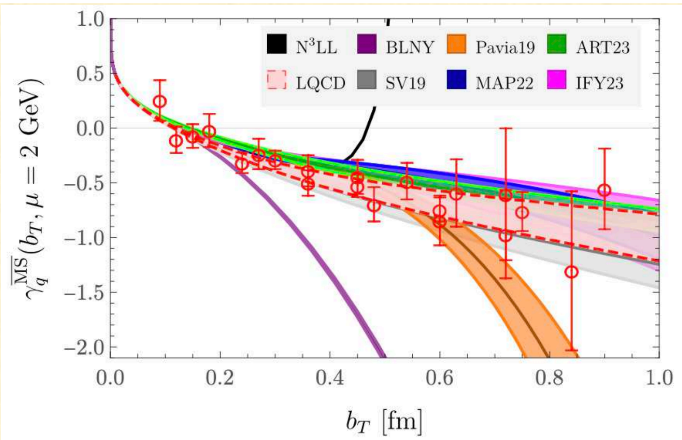
Collins-Soper kernel

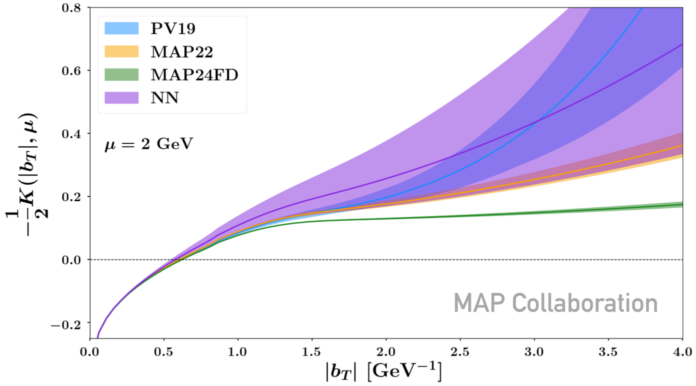
“strong” universality

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





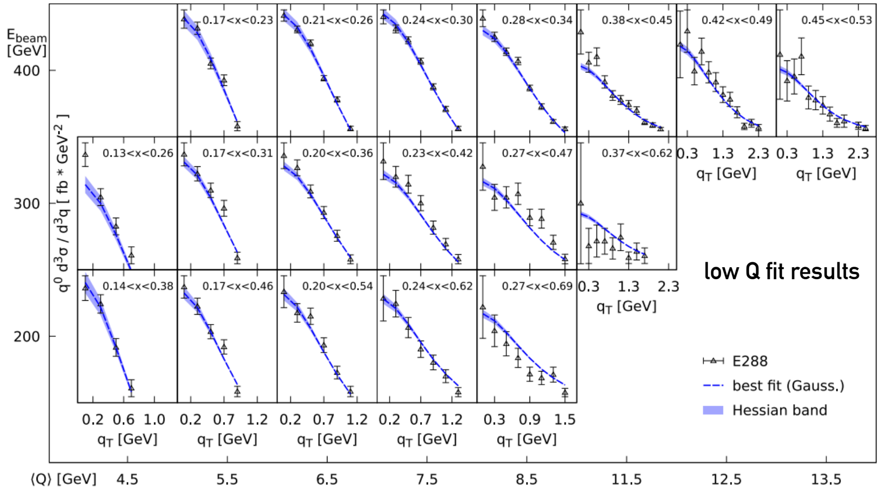
A. Avkhadiev, P. E. Shanahan,
M. L. Wagman, and Y. Zhao - arXiv: 2402.06725
DOI: 10.1103/PhysRevLett.132.231901

Hadron Structure Oriented (HSO)

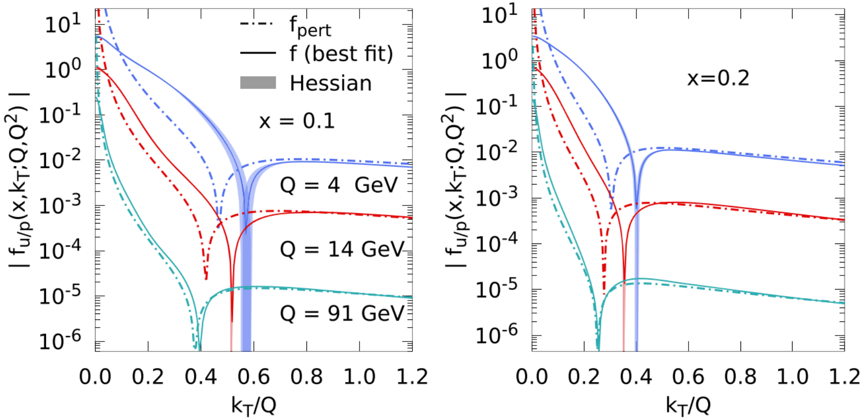
proof of principle

proposed new approach to TMD phenomenology

within 'the usual' TMD factorization



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

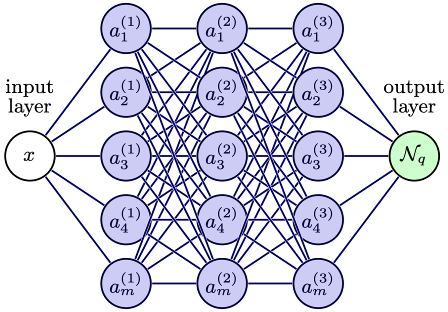
Sivers function

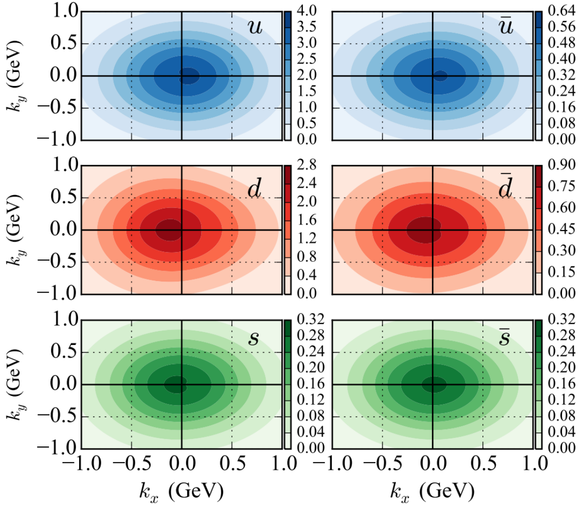
with Deep Neural Networks

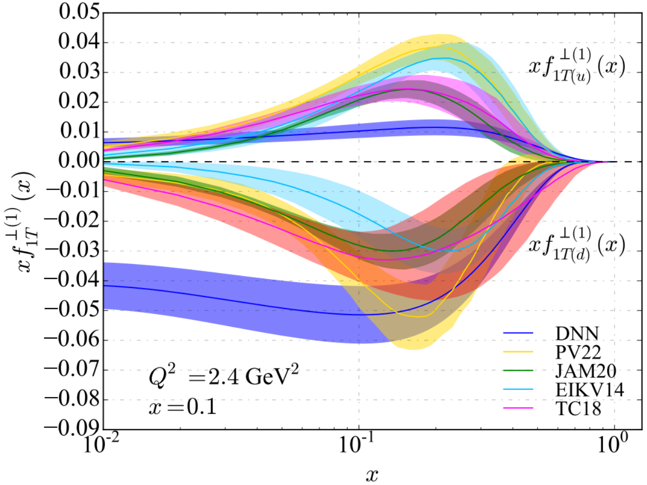
I. P. Fernando, D. Keller
DOI: 10.1103/PhysRevD.108.054007
arXiv:2304.14328

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

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

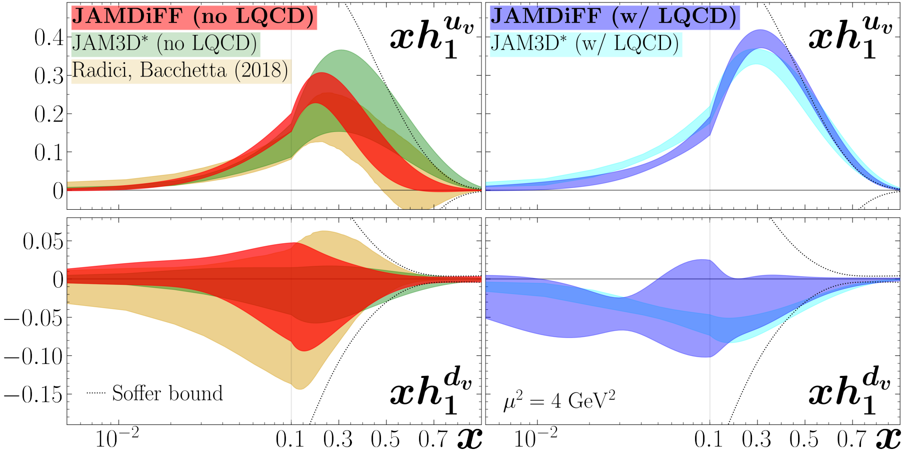
good agreement between the extractions

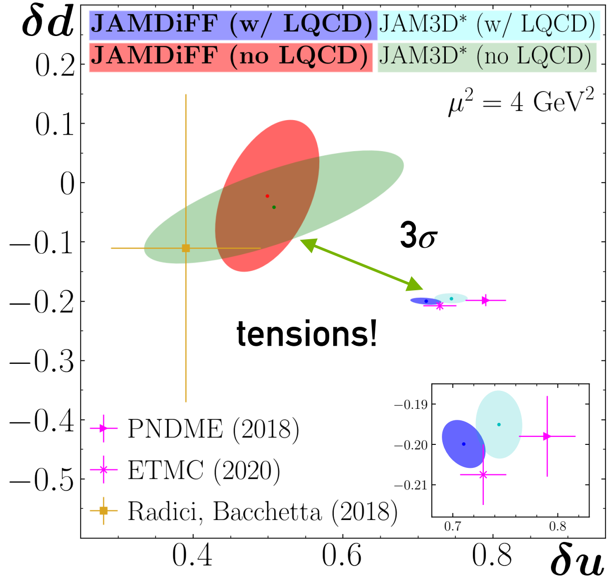
JAMDiFF

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

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Helicity

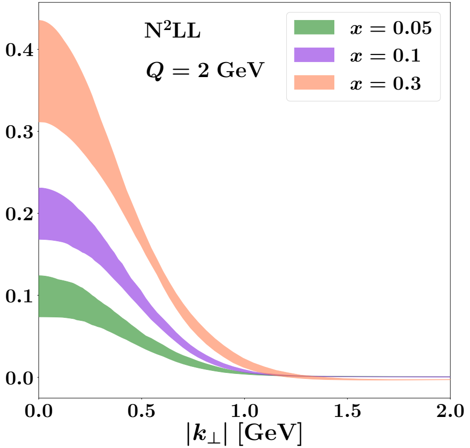
longitudinally polarized quarks

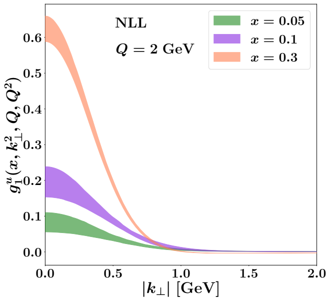
A. Bacchetta, A. Bongallino, M. Cerutti, M. Radici and L. Rossi
MAP Collaboration - arXiv:2409.18078

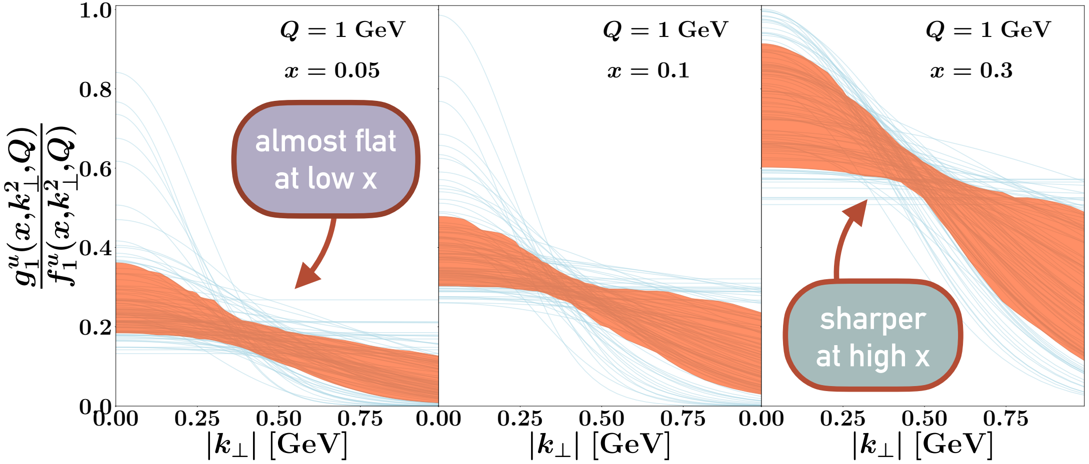
double spin asymmetry

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

SIDIS data







3 parameters

but poorly constrained due to lack of data

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

new techniques

- Neural networks fits

Polarized Quark TMDs

- great progress in extracting polarized TMDs

First Extraction of TMD Helicity Distributions
Ke Yang, Tianbo Liu, Peng Sun, Yuxiang Zhao, Bo-Qiang Ma
arXiv: 2409.08110

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

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

… and many others

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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 $\alpha_s(\mu)$

$$f_1^q(x,b;\mu,\zeta) = \sum_j \left(C_{q/j} \otimes f^j\right)(x,b_*;\mu_b)$$

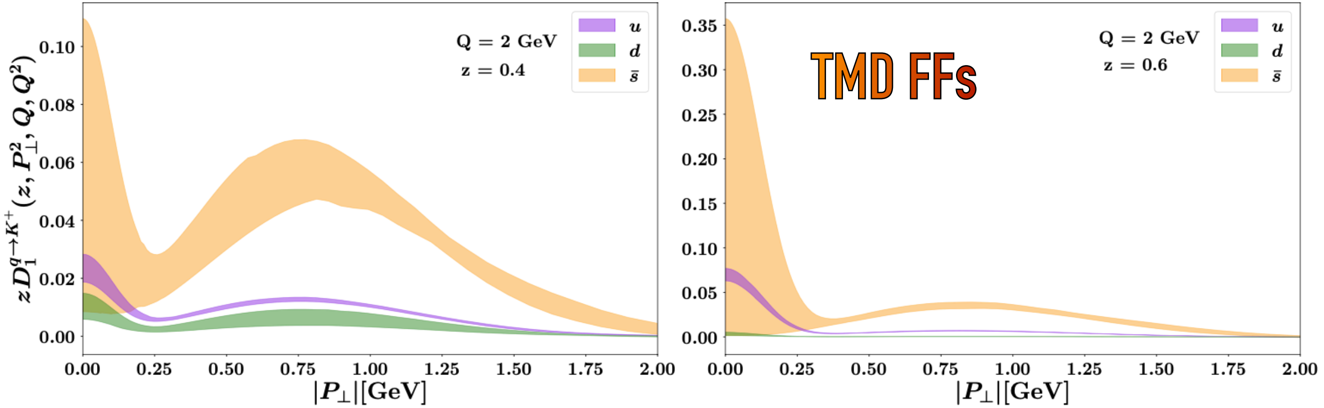
$$\times \exp\left\{K(\mu_0)\ln\frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} + \int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'}\left[\gamma_F(\alpha_s(\mu')) - \gamma_K(\alpha_s(\mu'))\ln\frac{\sqrt{\zeta}}{\mu'}\right]\right\}$$

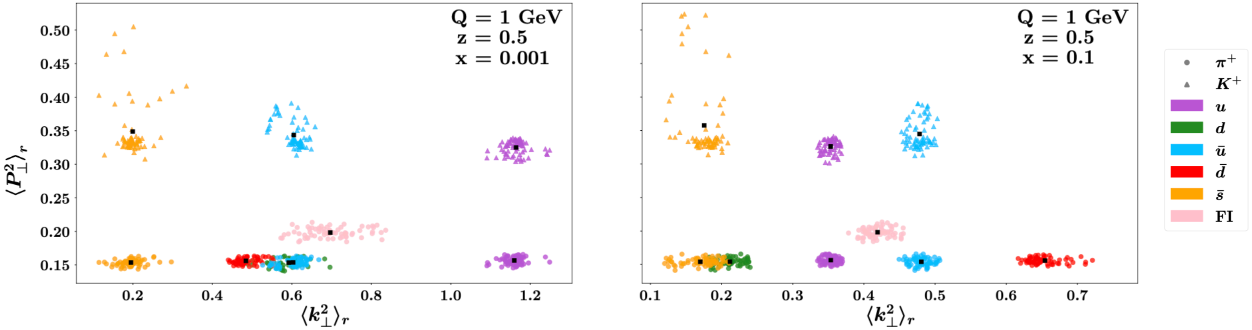
$$\times f_{\mathrm{NP}}(x,b;\zeta)$$

Accuracy	H and $C_{q/j}$	K and γ_F	γ_K	PDF and αs 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

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.

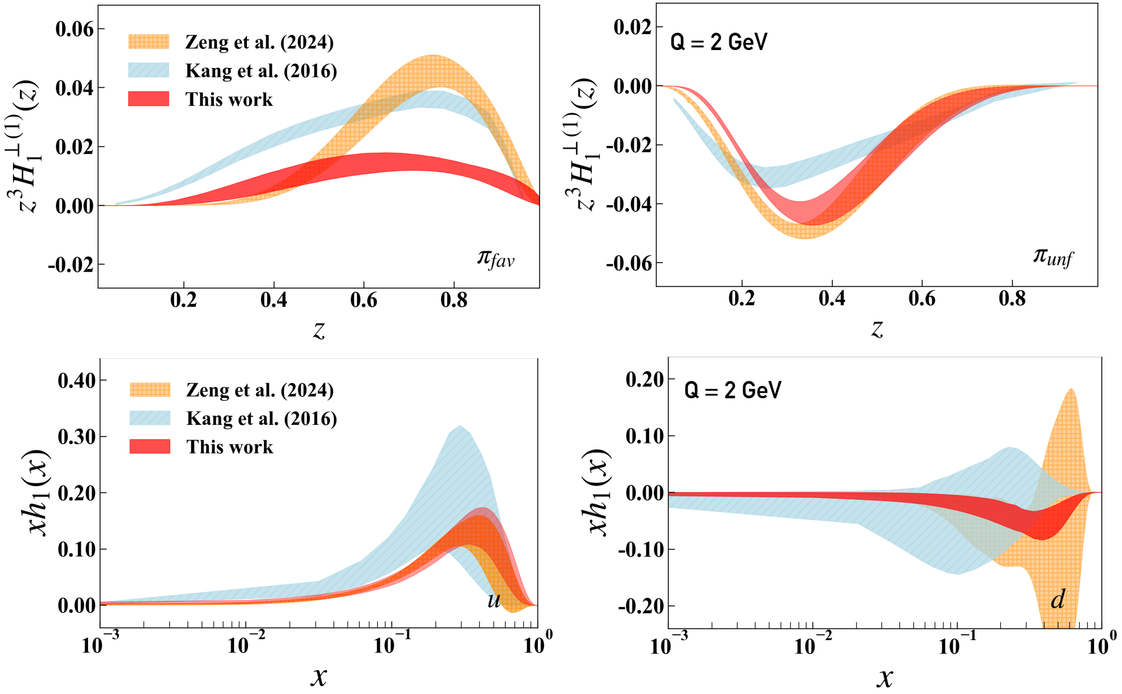
Global analysis of Sivers and Collins asymmetries

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

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

cuts because of TMD formalism

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



studies slightly different

directly extracted as collinear functions

latest COMPASS data significantly improve the determination of transversity

...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**
Phys.Rev.D 110 (2024), arXiv: 2402.01836