

Recent results on polarized nucleon structure: global fit of Sivers function

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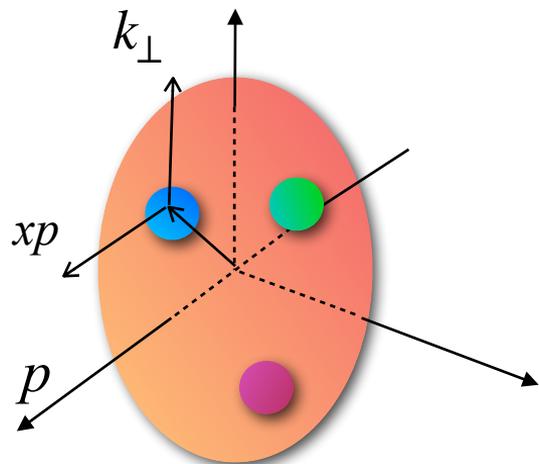


Center for Frontiers
in Nuclear Science

CFNS Postdoc meeting
23 October 2025

Transverse Momentum Distributions: TMD PDF

quark pol.



nucleon pol.

	U	L	T
U	f_1		h_1^\perp
L		g_{1L}	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}	h_1, h_{1T}^\perp

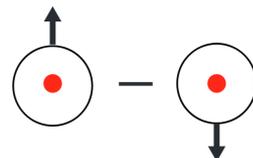
Sivers function

dependence on:

longitudinal momentum fraction x

transverse momentum k_\perp

energy scale



Spin and quark motion correlation

Open issues

spin budget of hadrons

missing contributions from elementary constituents
not yet quantified

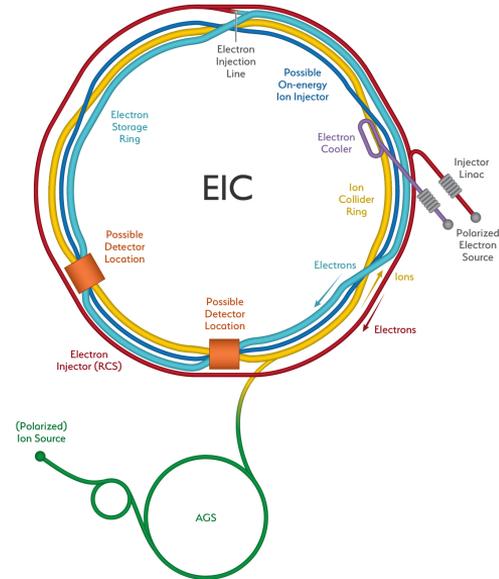
SSAs in hadron reactions

- not vanishing as expected with increasing energy
- correlation with parton dynamics

Effect of polarization on nucleon internal structure density

polarized TMDs and anomalous magnetic moment

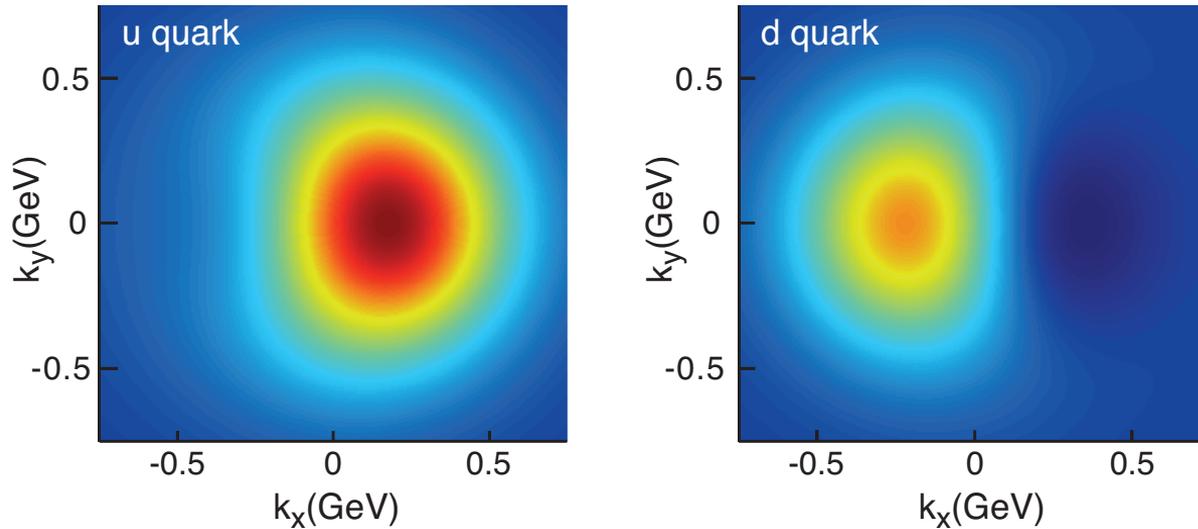
purpose-built
playground



Phenomenology of polarized TMDs

⇒ presence of a non-zero Sivers function f_{1T}^\perp induces a dipole deformation of f_1

$x f_1(x, k_T, S_T)$

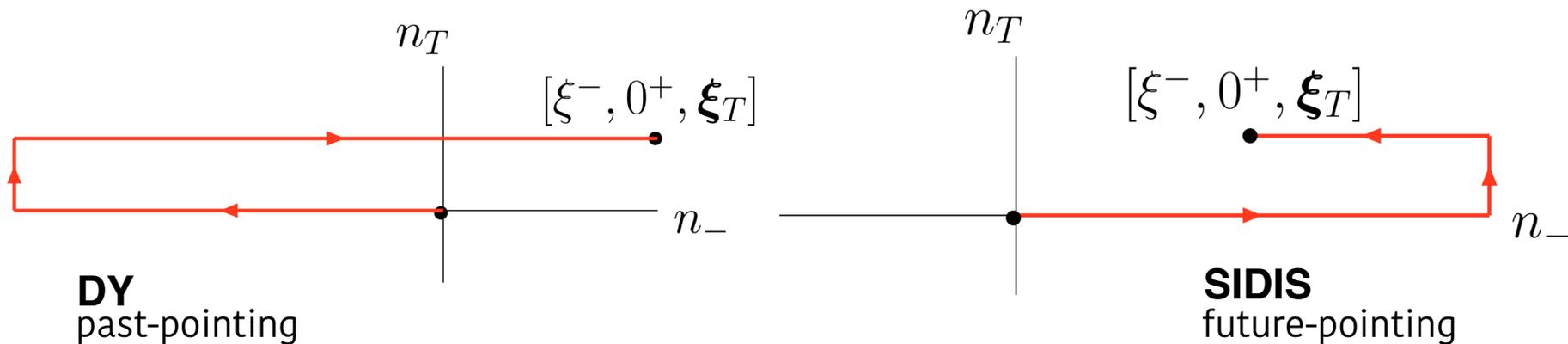


[EIC White Paper]

Sivers function sign change

vanishing Sivers function? \longrightarrow

Final state interactions and
g.i. Wilson lines to consider

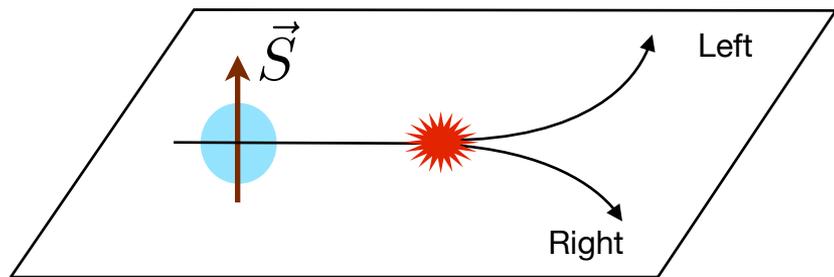


Sign change in Sivers function

$$f_{1T,DIS}^\perp = -f_{1T,DY}^\perp$$

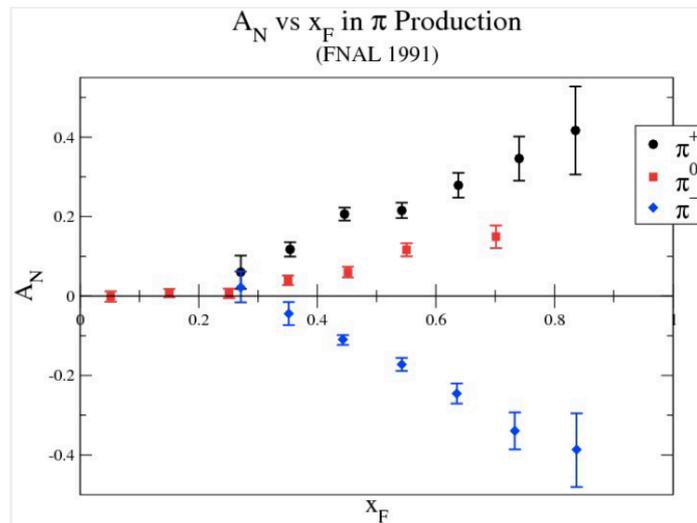
Single-spin asymmetry (SSA)

scattering of transversely polarized proton off an unpolarized proton or electron



positive A_N means that for upward polarization, the pions tend to go to the left.

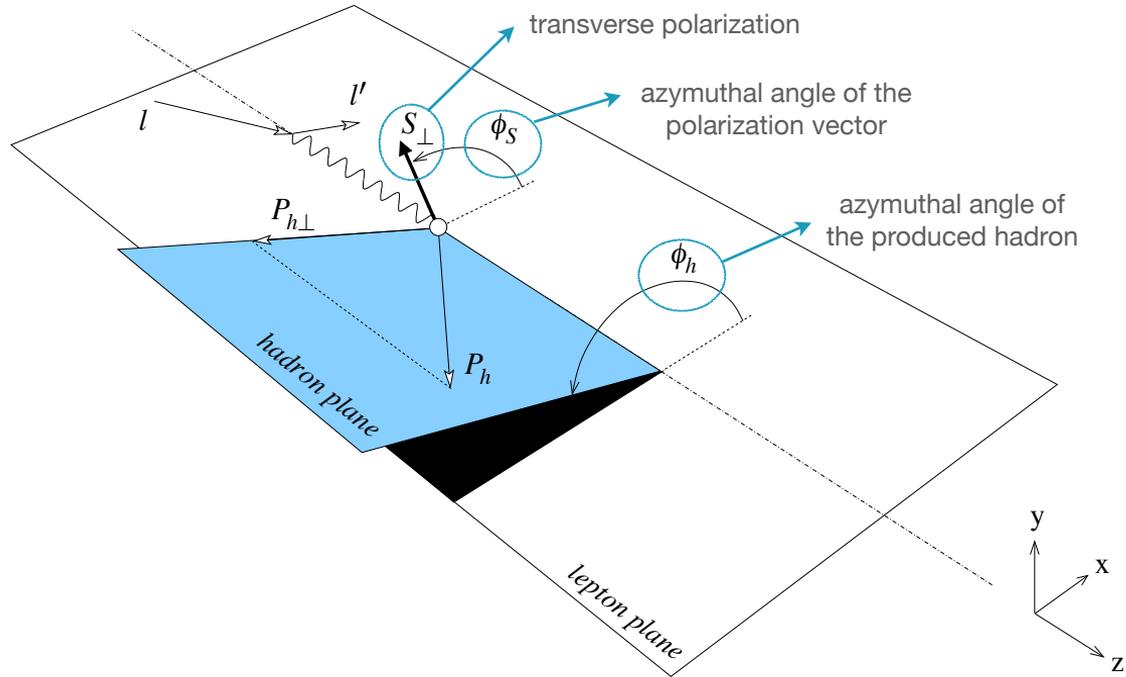
$$A_N(x_F, k_\perp) \equiv \frac{L - R}{L + R} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$



Such large asymmetries cannot be explained in terms of collinear leading twist pdfs, pol. TMDs are necessary

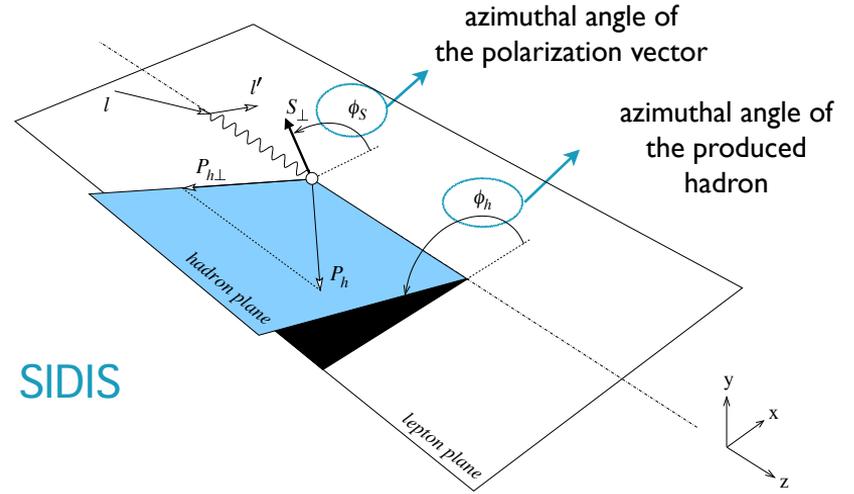
Extraction of Sivers Function

Determined through its contributions to the cross section of
polarized SIDIS



Extraction of Sivers Function

Determined through its contributions to the cross section of **polarized SIDIS**



LO - NLL

$$A_{UT}^{\sin(\phi_h - \phi_S)} \equiv \langle \sin(\phi_h - \phi_S) \rangle \sim \frac{f_{1T}^\perp \otimes D_1^{a \rightarrow h}}{f_1^a \otimes D_1^{a \rightarrow h}}$$

universality

Parametrization of Sivers function

Sivers function parametrized in terms of its first moment

$$f_{1T}^\perp(x, k_\perp^2) = \underbrace{f_{1T}^{\perp(1)}(x)} \underbrace{f_{1TNP}^\perp(x, k_\perp^2)}$$

Its nonperturbative part is arbitrary, but constrained by the positivity bound.

$$\underbrace{f_{1TNP}^\perp(x, k_\perp^2)} = \frac{1}{\pi K_f} \frac{1}{F_{max}} \frac{(1 + \lambda_S k_\perp^2)}{(M_1^2 + \lambda_S M_1^4)} e^{-k_\perp^2/M_1^2} \underbrace{f_{1NP}(x, k_\perp^2)}$$

following the definition to the nonperturbative part of the unpolarized TMD distribution

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

from MAP22 TMD extraction

Free parameters λ_S, M_1

Parametrization of Sivers function

$$f_{1T}^{\perp(1)}(x) = \frac{N_{Siv}^a}{G_{max}^a} x^{\alpha_a} (1-x)^{\beta_a} (1 + A_a T_1(x) + B_a T_2(x)) f_1(x, Q^2)$$

normalization
(abs. value < 1)

maximum value
of the function

$T_n(x)$ Chebyshev polynomials

Free parameters $N_{Siv}^a, \alpha_a, \beta_a, A_a, B_a$

Flavor dependent: distinct for up, down, sea

Evolution of Siverson function first moment

evolved Siverson function first moment

$$\begin{aligned}
 \tilde{f}_{1T}^{\perp(1)a}(x, b_T^2; Q^2) &= \\
 &= \sum_i (\tilde{C}_{ali} \otimes f_1^i)(x, \bar{b}_*; \mu_b) e^{\tilde{S}(\bar{b}_*; \mu_b, \mu)} e^{g_K(b_T) \ln(\mu/\mu_0)} \hat{f}_{1TNP}^{\perp(1)a}(x, b_T)
 \end{aligned}$$

nonperturbative part of TMD

collinear PDF → \tilde{C}_{ali}

pQCD → f_1^i

(Wilson Coefficient) → \tilde{C}_{ali}

(Sudakov form factor) → $e^{\tilde{S}(\bar{b}_*; \mu_b, \mu)}$

nonperturbative part of evolution → $e^{g_K(b_T) \ln(\mu/\mu_0)}$

$\hat{f}_{1TNP}^{\perp(1)a}(x, b_T)$

Free parameters g_2

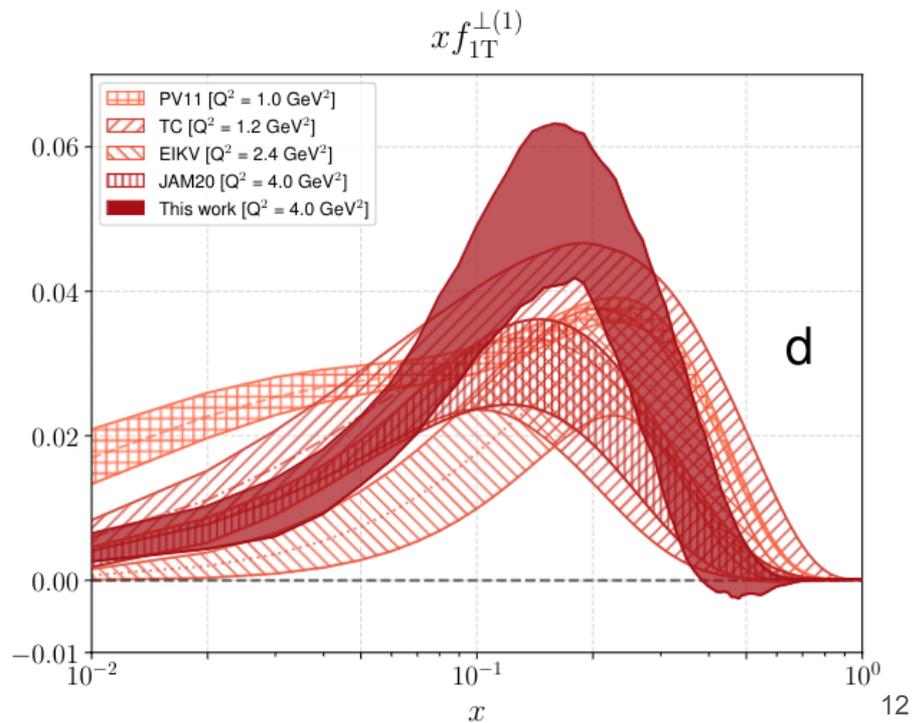
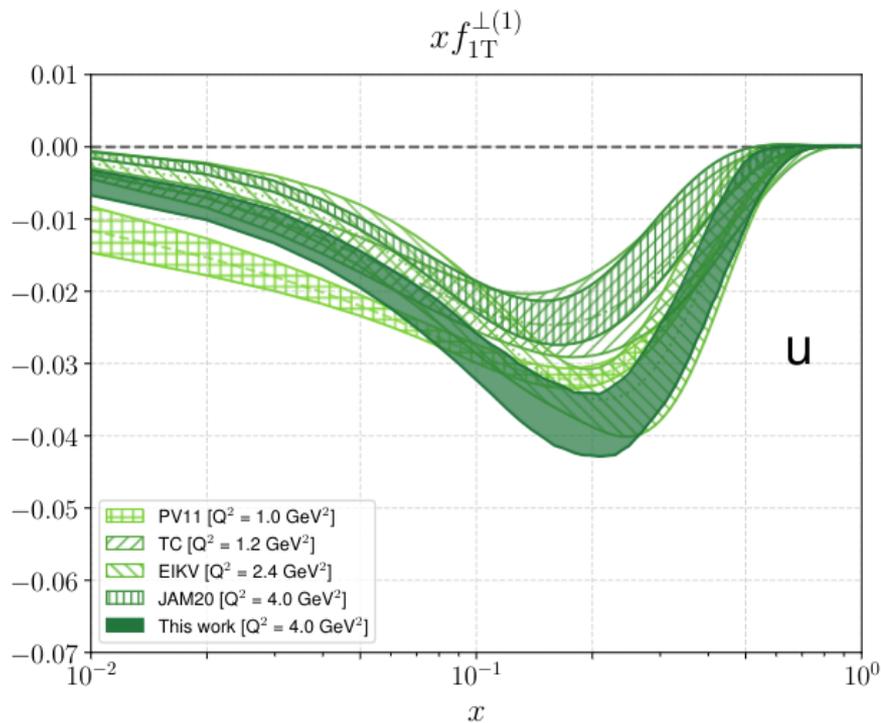
Fourier transform: b_T space

PV20Sivers: Polarized TMDs

$$\chi^2 = 1.12$$

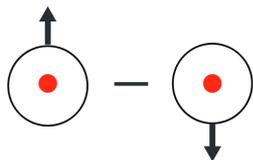
125 data points from SIDIS, DY

LO-NLL



TMDs

PV20Sivers



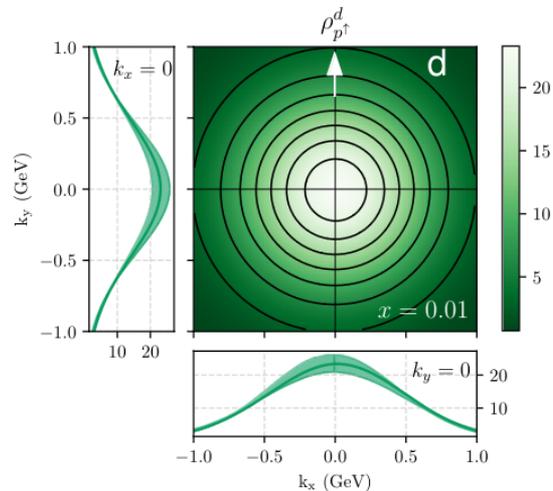
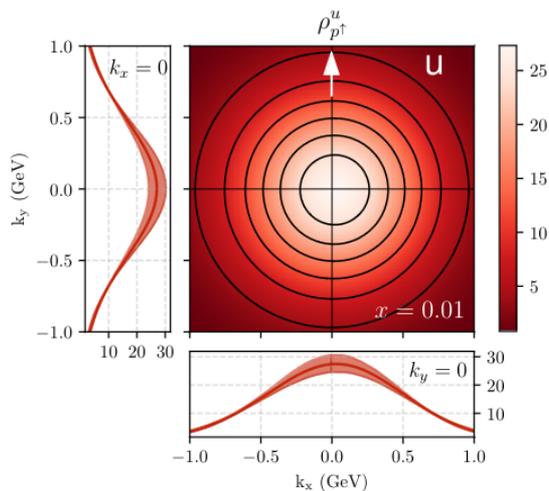
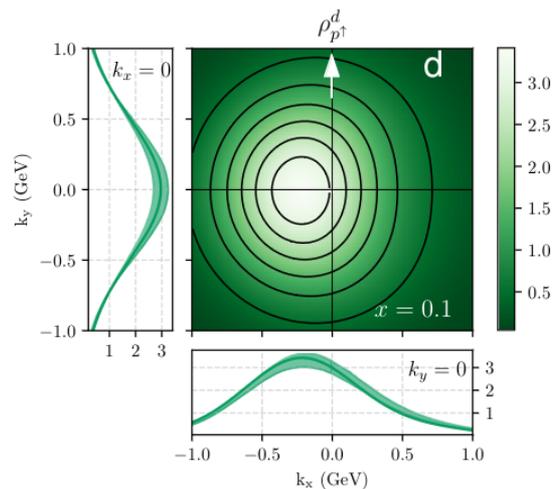
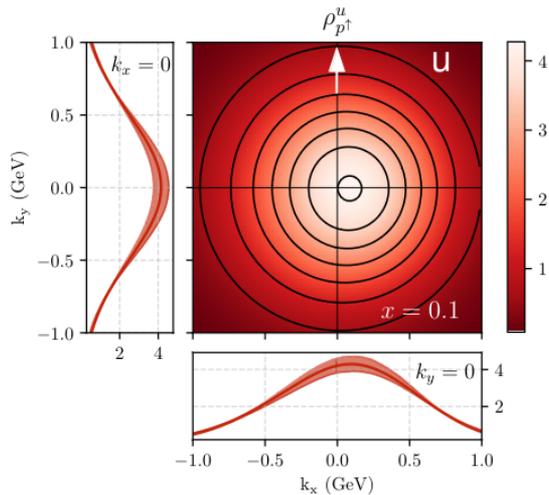
polarized

$$f_1(x, k_\perp; Q^2) - f_{1T}^\perp(x, k_\perp; Q^2)$$

PV17



unpolarized



Updated Sivvers extraction

Additional data

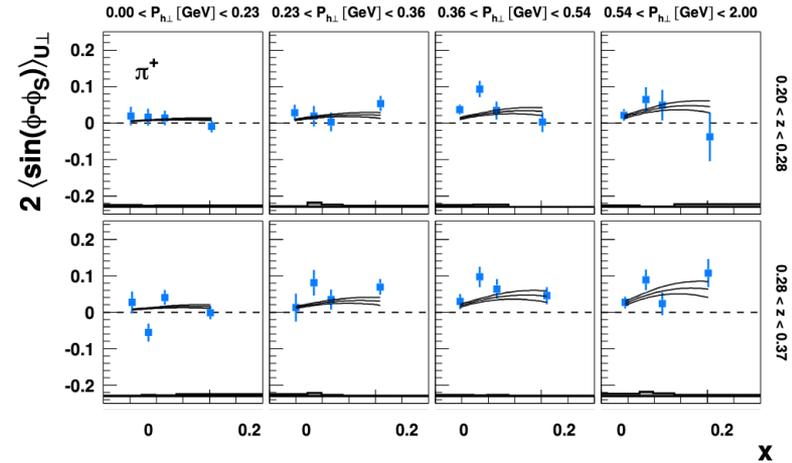


2020

[JHEP12(2020)010]

SIDIS

Multidimensional
 x, P_{hT}, z



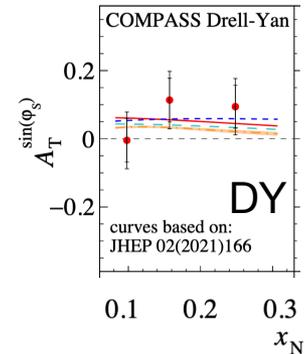
2022

2015-2018

SIDIS

pion-induced
DY

projected in x

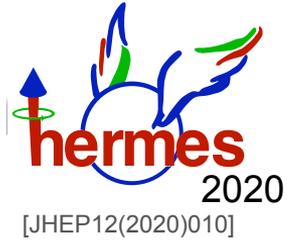


[PRL133]

Updated Sivvers extraction

included datasets

SIDIS



target: proton [H]

final state hadron
 π^+, π^-, K^+, K^-

250 data points

[PRL107,072003(2011)]



t: neutron [^3He]
6 data points



[PLB673,127(2009)]
[PLB770,138(2017)]
[PRL133]

2009 t: deuteron [^6LiD]

2017 t: Proton [NH_3]

2022 t: deuteron [^6LiD]

f.s.h

h^+, h^-

98 data points

DY

W-Z production
2016



[PRL116,132301(2016)]

7 data points

2015-2018

pion-induced DY
t: Proton [NH_3]

3 data points



[PRL133]

Total number of data

364

Updated Sivvers extraction

Additional data



2020
[JHEP12(2020)010]



2022
2015-2018

[PRL133]

More accurate unpolarized TMDs
for a self-consistent global extraction

MAPTMD22

[JHEP10(2022)127]

pionMAPTMD

[PRD.107.014014]

Updated Sivvers extraction

Additional data



2022

2015-2018

[PRL133]

Accurate unpolarized TMDs

MAPTMD22

[JHEP10(2022)127]

pionMAPTMD

[PRD.107.014014]

Revised fitting framework

NangaParbat

Nanga Parbat: MAP framework

Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

You can obtain NangaParbat directly from the github repository:

<https://github.com/MapCollaboration/NangaParbat>



updated MAP Sivers Fit results

Total number of data

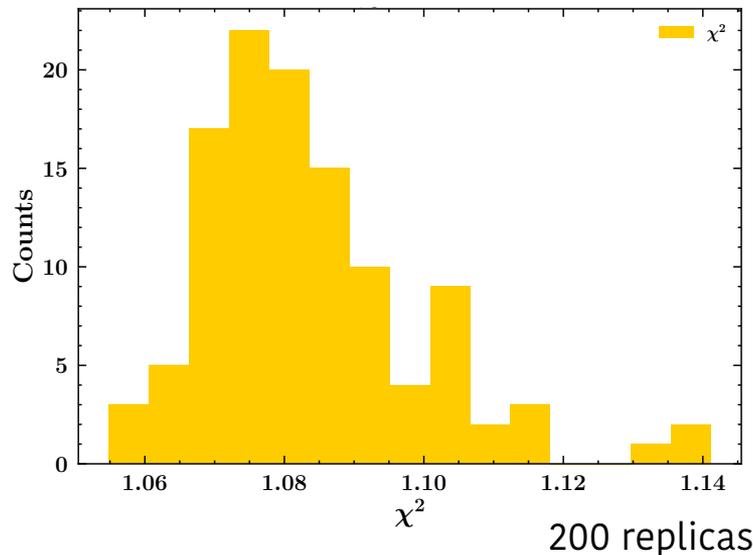
364

global fit from

- semi-inclusive DIS,
- pion-induced Drell-Yan,
- W-Z boson production

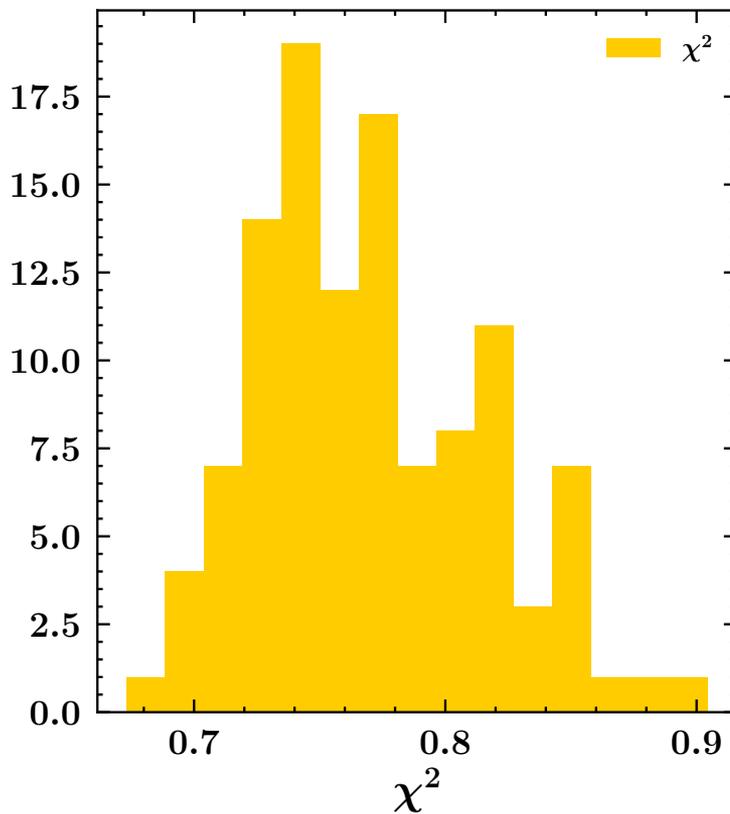
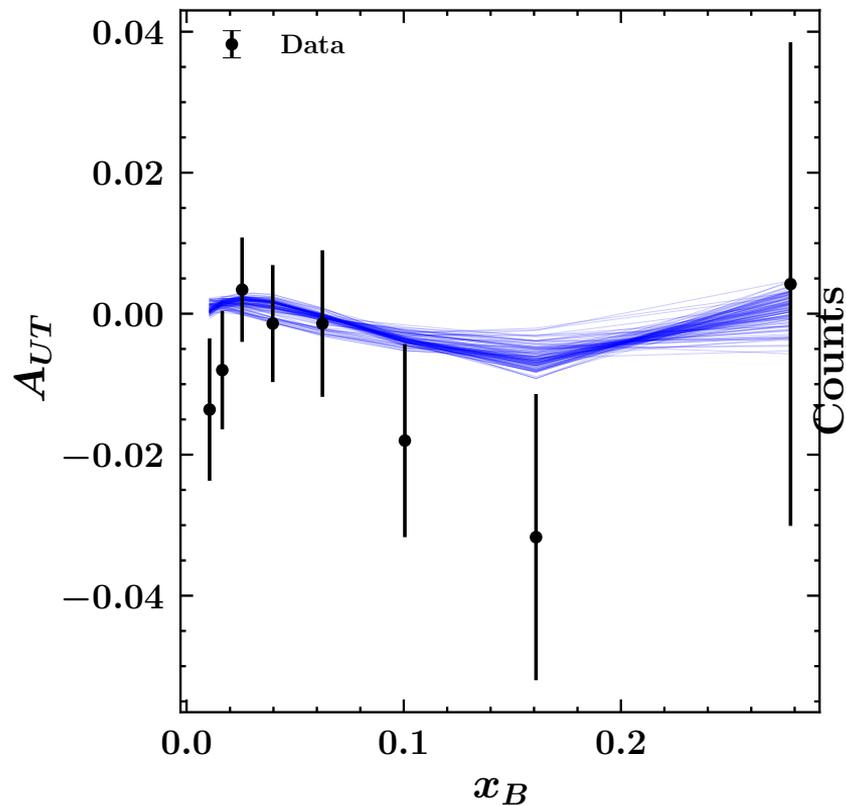
Accuracy: NLL-LO

$$\chi^2 = 1.08$$



Selected results: Compass 2009

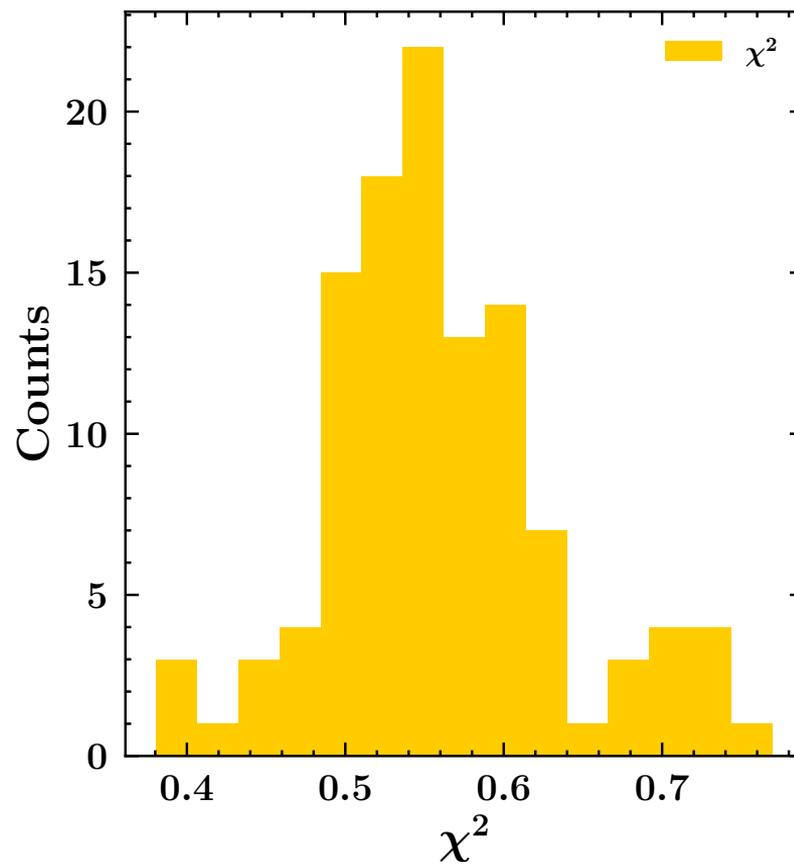
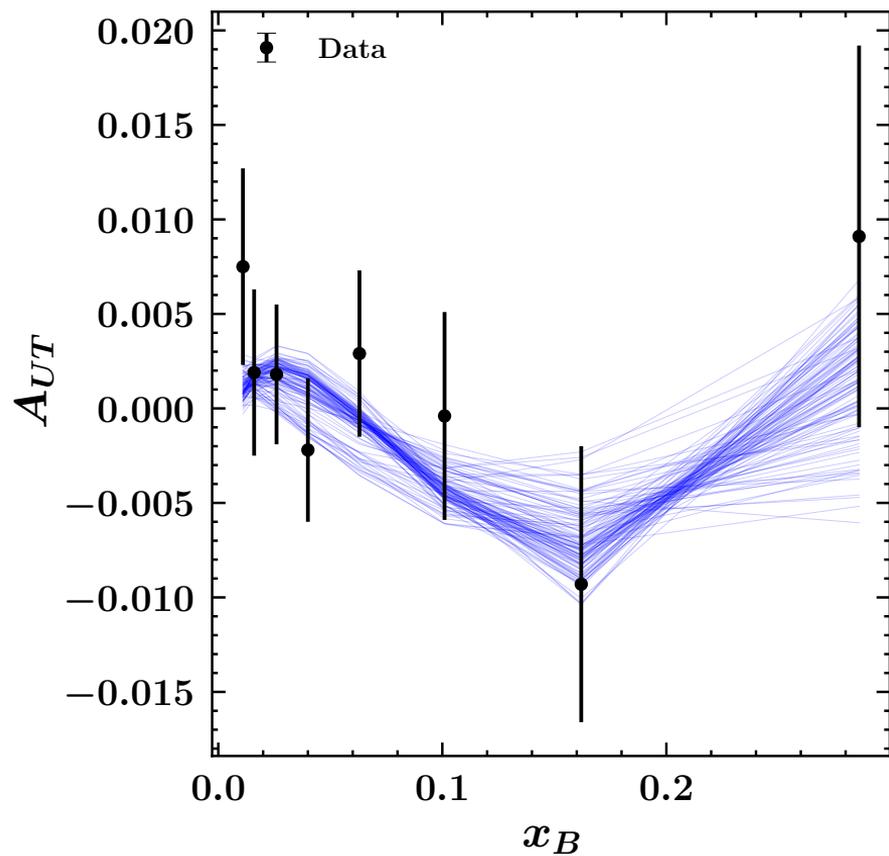
SIDIS $D - \pi^+$



Selected results: COMPASS 2022

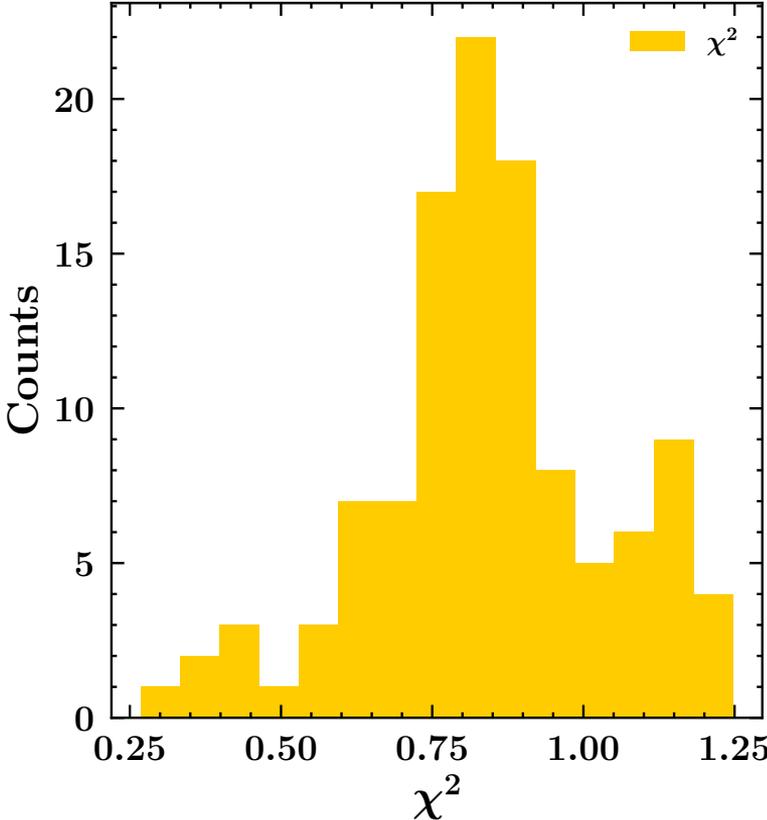
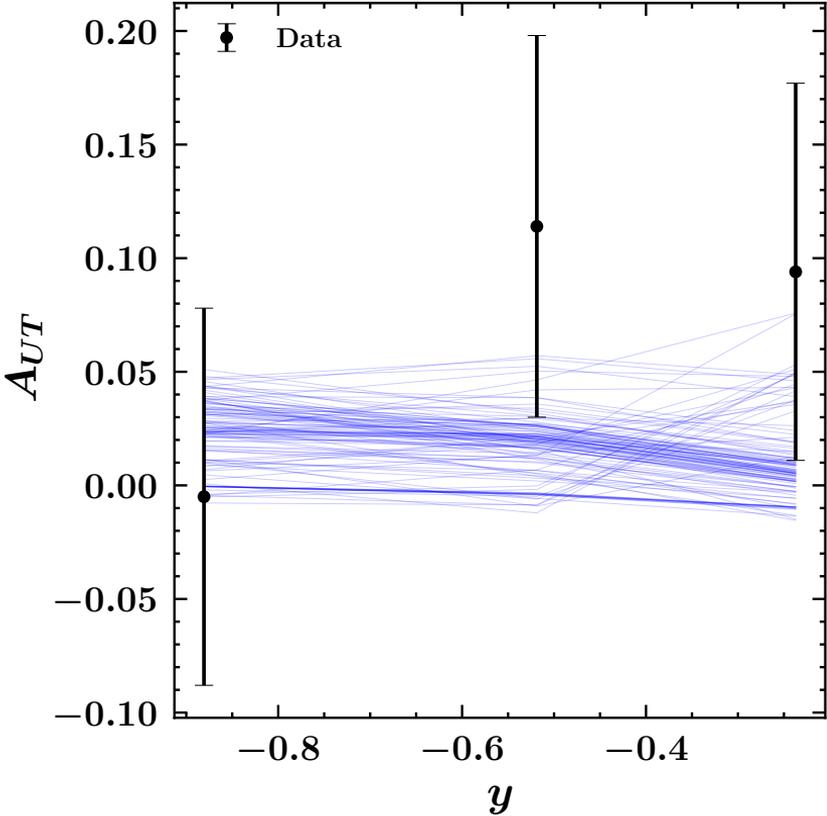
SIDIS $D - h^+$

μ beam



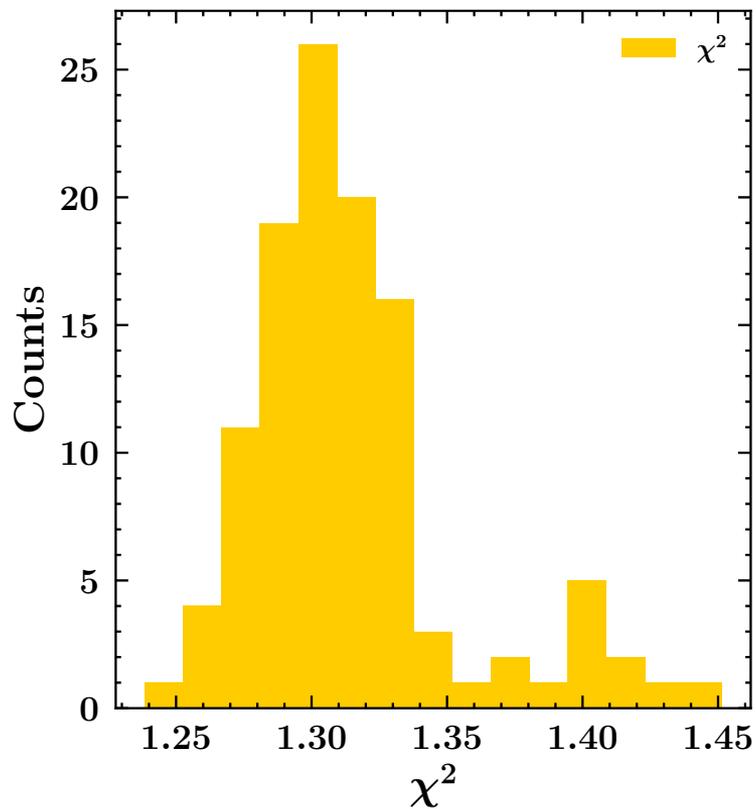
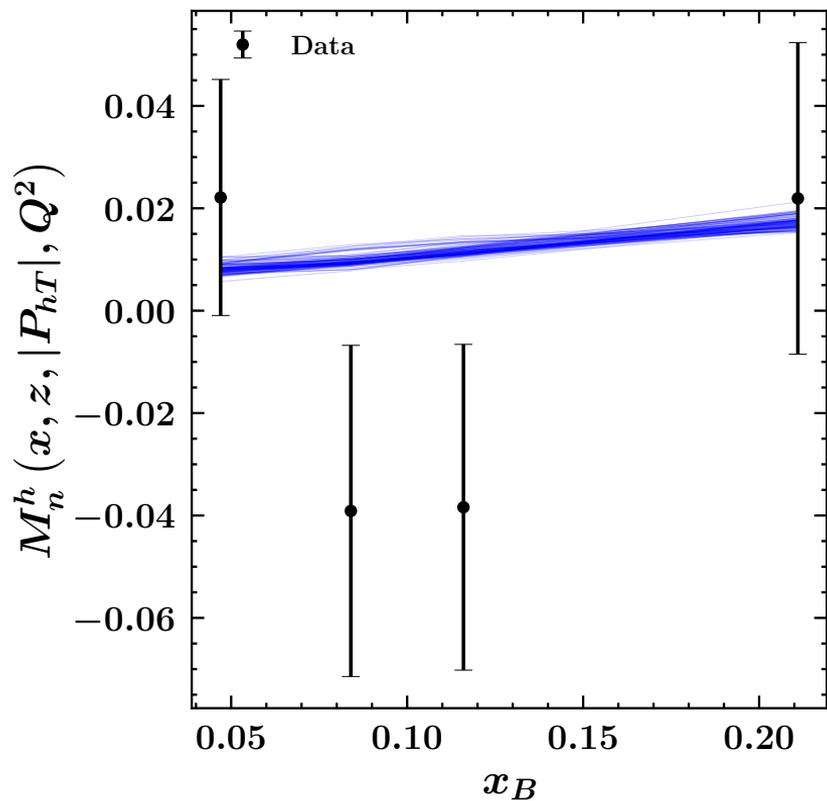
Selected results: COMPASS DY 2015

pion DY



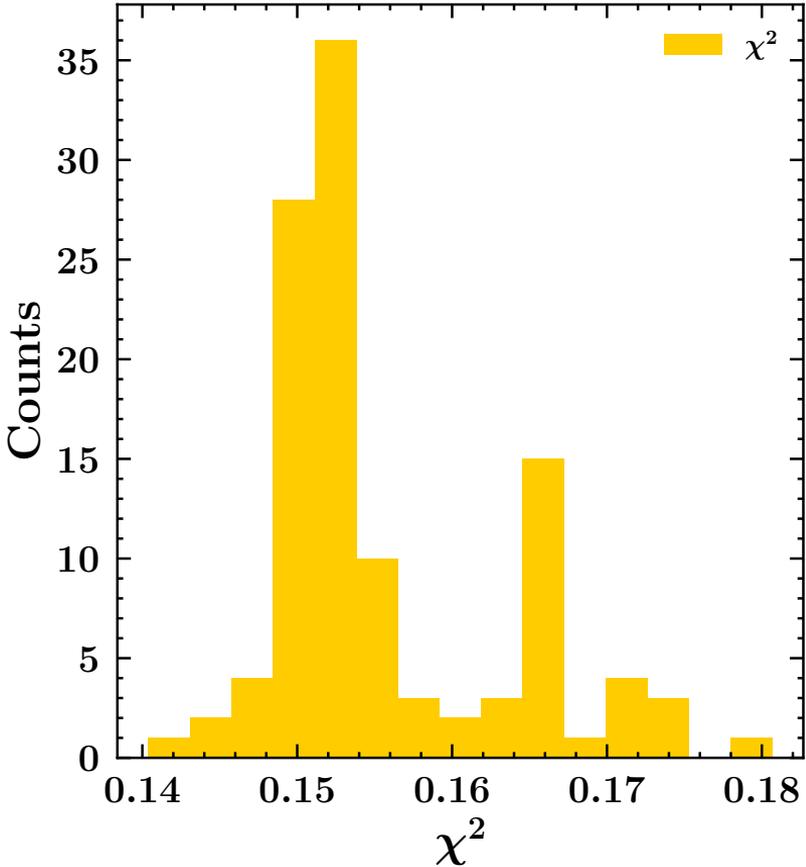
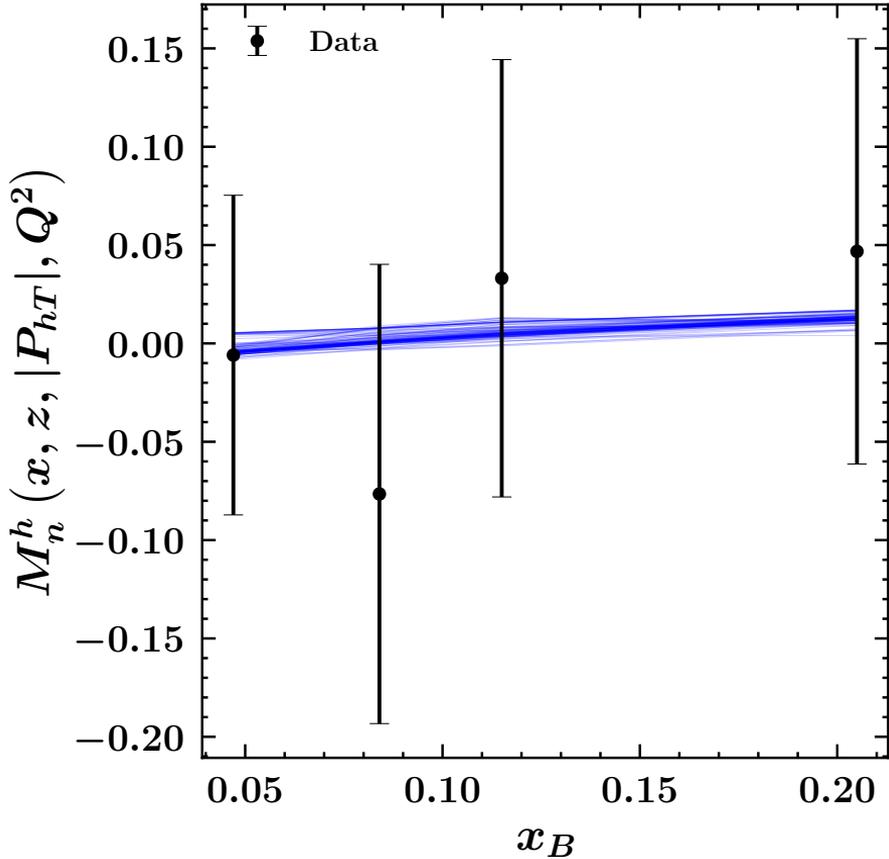
Selected results: HERMES 2020

HERMES $p - \pi^-$ $0.36 < P_{hT} < 0.54$, $0.28 < z < 0.37$



Selected results: HERMES 2020

HERMES $p - K^-$ $0.36 < P_{hT} < 0.54$, $0.28 < z < 0.37$

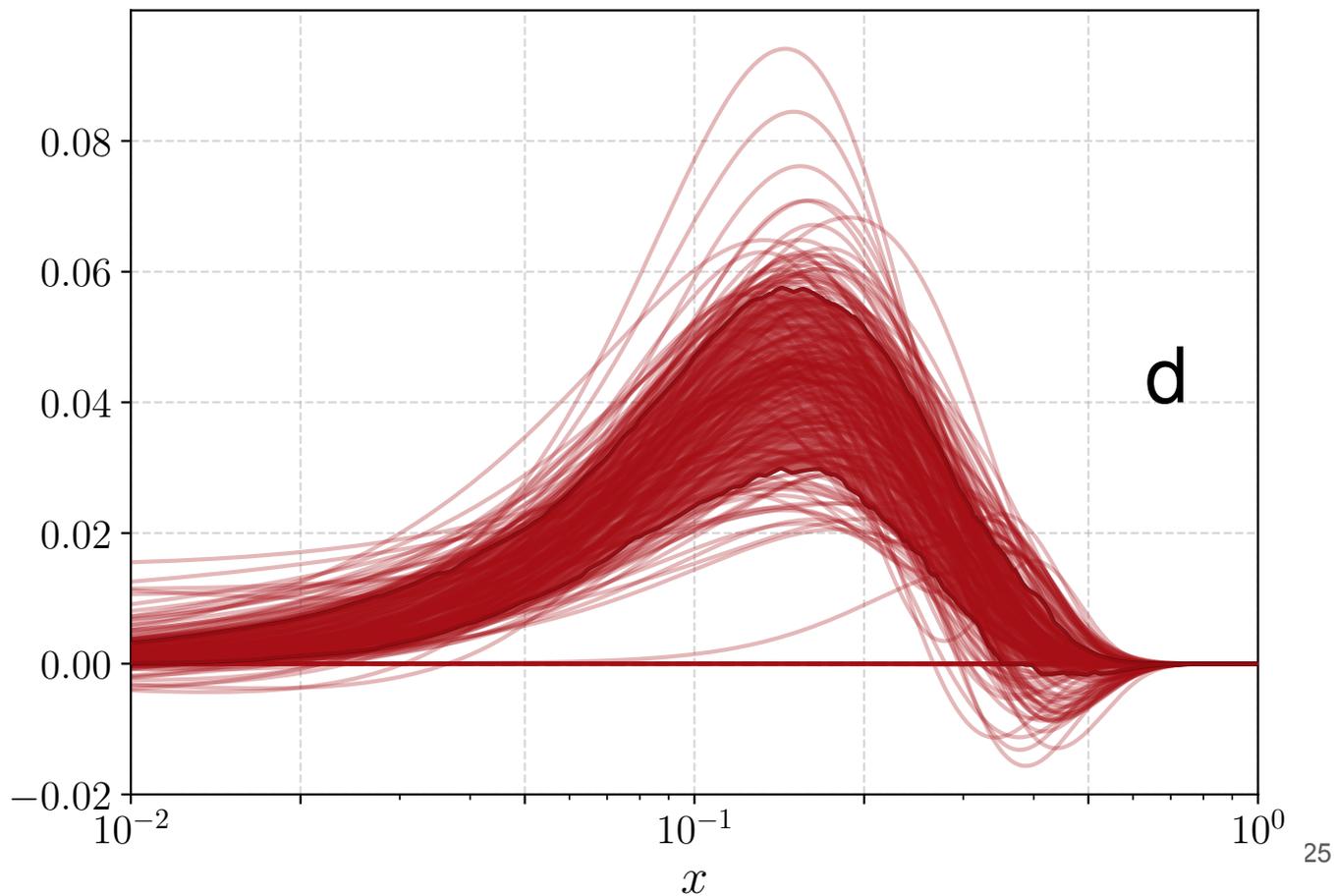


Sivers TMD

down quark

$$xf_{1T}^{\perp(1)}(x; Q^2)$$

$$Q^2 = 4 \text{ GeV}^2$$

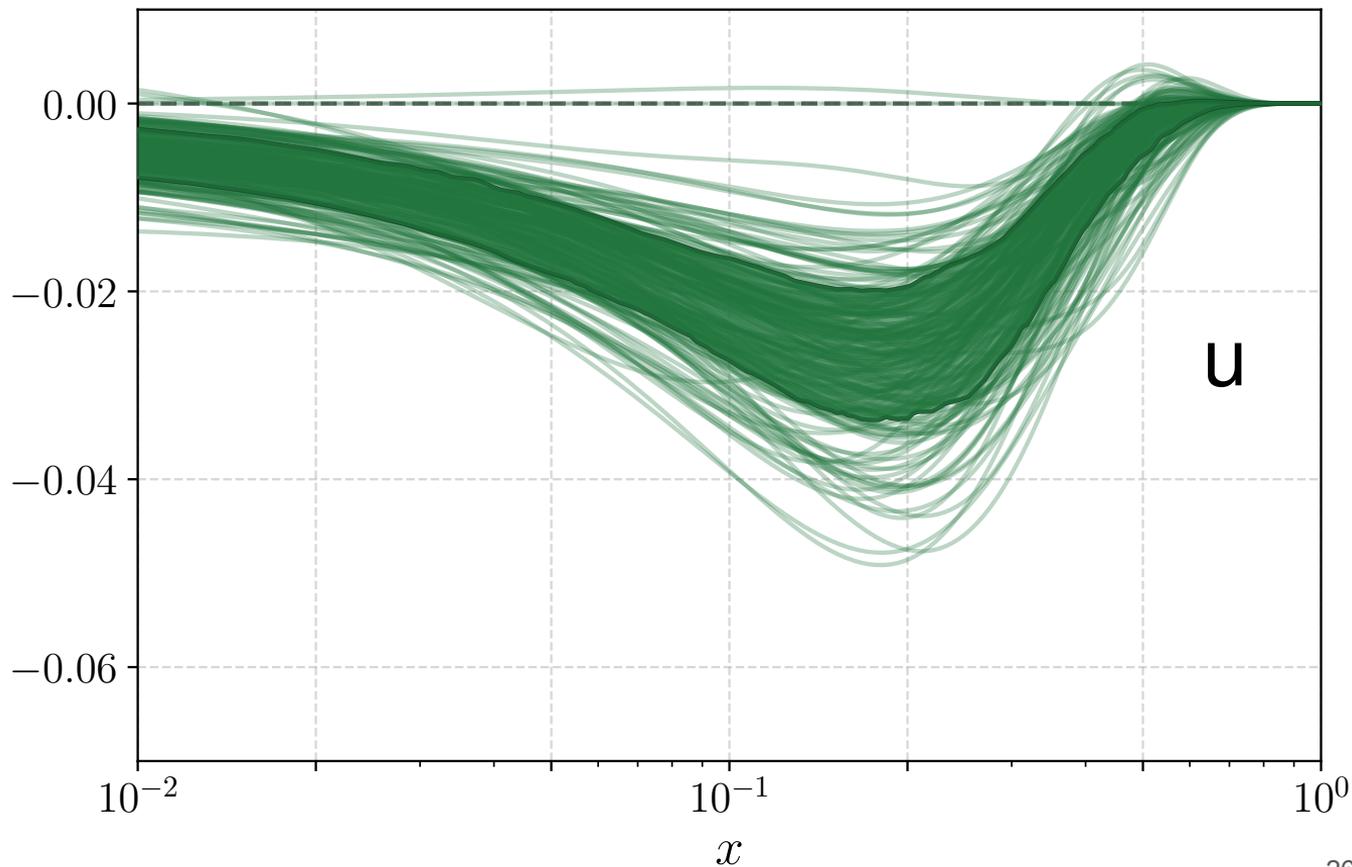


Sivers TMD

up quark

$$xf_{1T}^{\perp(1)}(x; Q^2)$$

$$Q^2 = 4 \text{ GeV}^2$$



Conclusions

- Updated MAP global extraction of Sivers function with a fully consistent TMD framework
- New data from COMPASS, Hermes, STAR help explore new phenomenological aspects of polarized TMDs (multi dim., DY)
- New datasets confirm previous works, allowing more flexibility

To Do

- Implement flavor dependent unpolarized TMD (MAP24)
- NN parametrization of nonperturbative part
- Impact studies with updated Sivers