Polarization and TMDs: recent results on Sivers function extraction

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IFJ seminars
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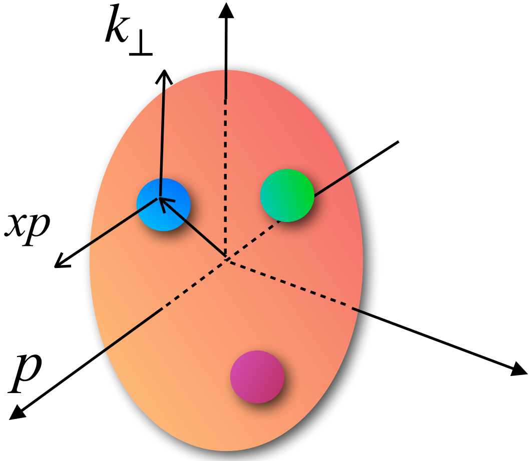
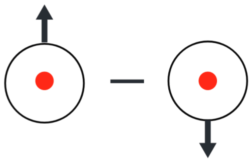
Transverse Momentum Distributions: TMD PDF



quark pol. (columns) / nucleon pol. (rows)

	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

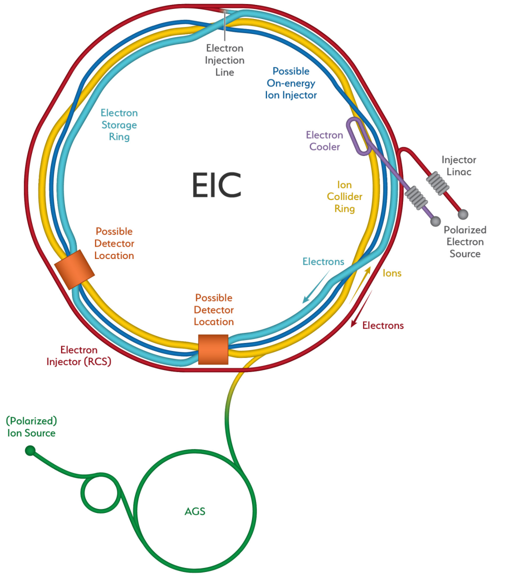
Effect of polarization on nucleon

internal structure density

polarized TMDs and anomalous magnetic moment

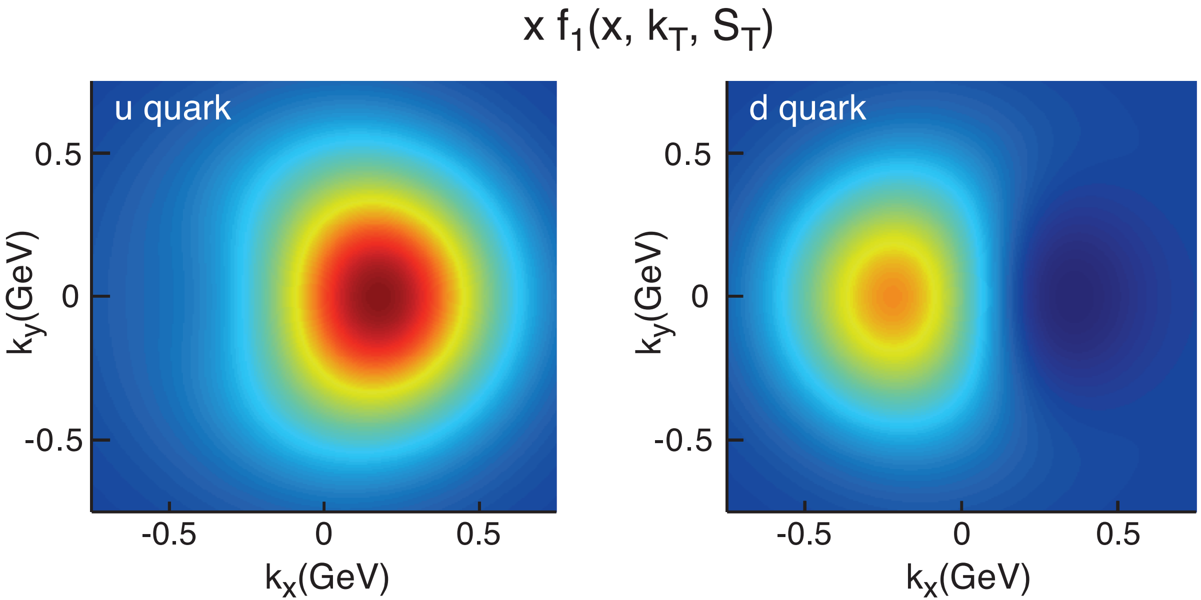
purpose-built

playground



Phenomenology of polarized TMDs

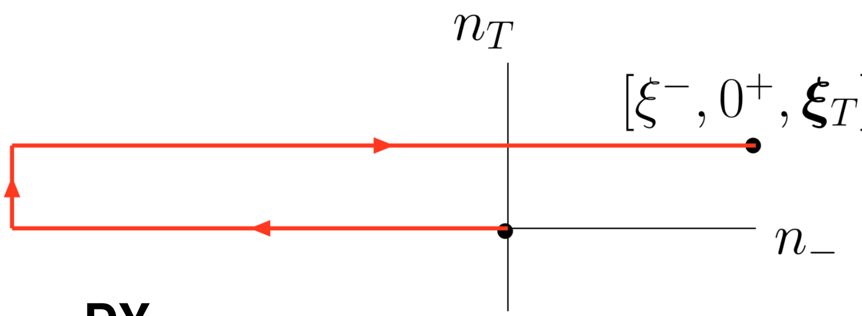
⇒ presence of a non-zero Sivers function $f_{1T}^{\perp}$ induces a dipole deformation of f_1



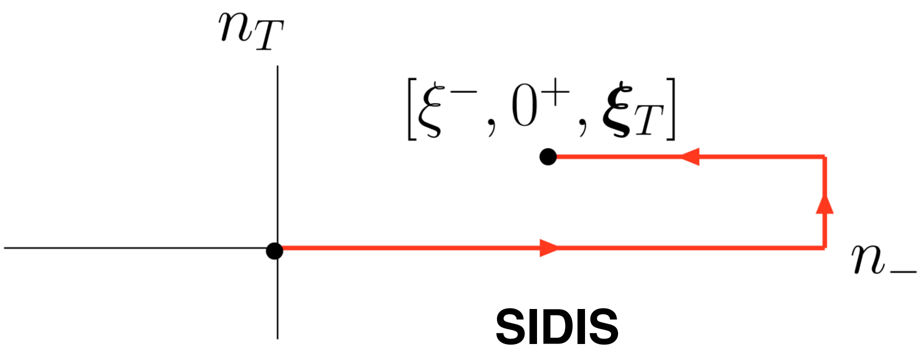
[EIC White Paper]

Sivers function sign change

vanishing Sivers function? $\longrightarrow$ Final state interactions and g.i. Wilson lines to consider



DY
past-pointing



SIDIS
future-pointing

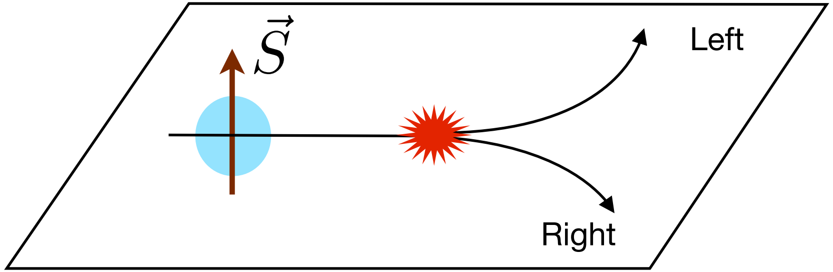
Sign change in Sivers function

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

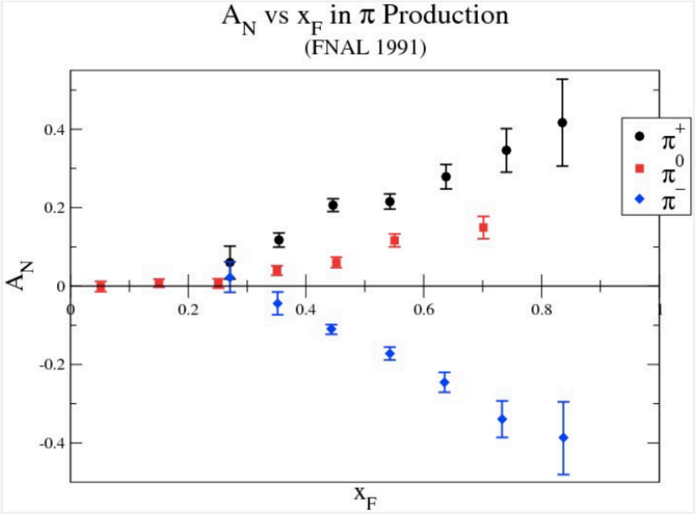
Single-spin asymmetry (SSA)

scattering of transversely polarized proton off an unpolarized proton or electron

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



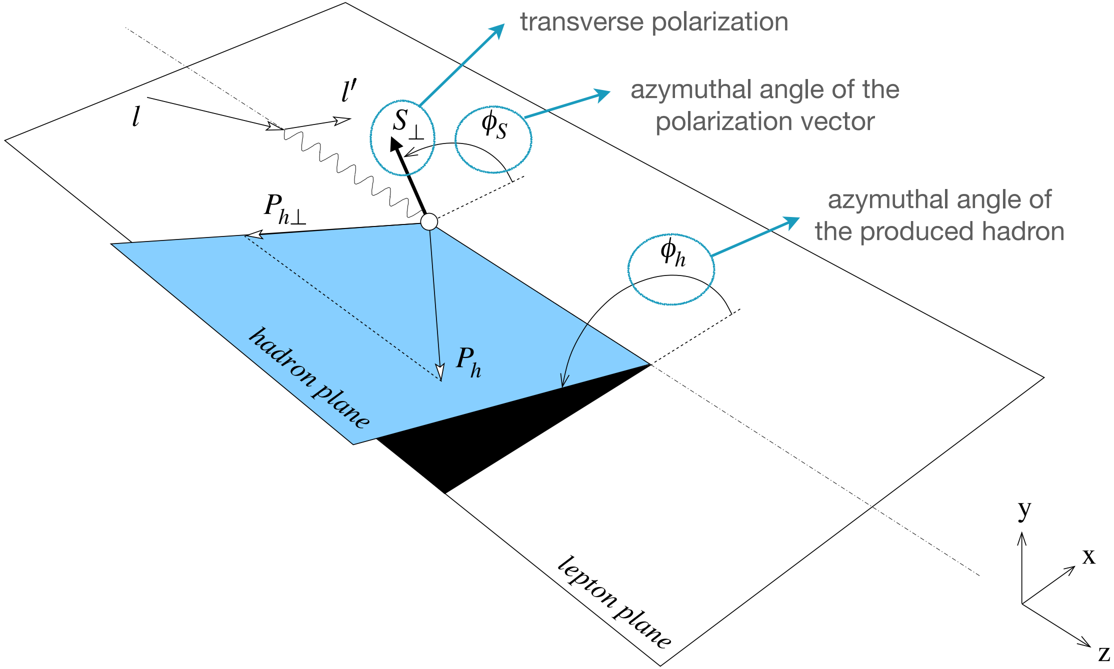
positive A_N means that for upward polarization, the pions tend to go to the left.



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

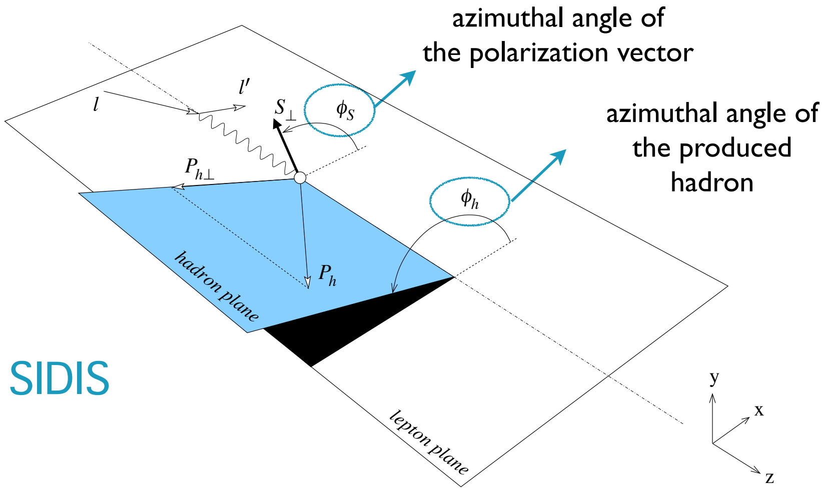
Extraction of Sivers Function

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



SIDIS

LO - NLL

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

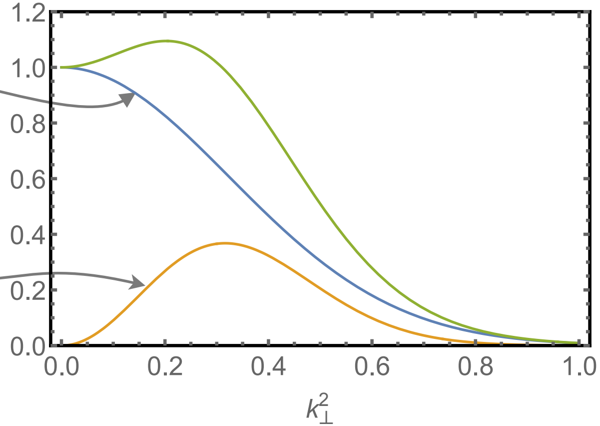
universality

Model: non perturbative elements

input TMD PDF @ Q^2=1GeV^2

$$\tilde{f}^a_{NP} = \mathcal{F}.\mathcal{T}.\text{ of}$$

$$\left(\exp\left(\frac{-k_\perp^2}{g_1}\right) + \lambda k_\perp \exp\left(\frac{-k_\perp^2}{g_1}\right) \right)$$



sum of two different gaussians
dependent on transverse momenta

$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

where

$$N_1 \equiv g_1(\hat{x})$$
$$\hat{x} = 0.1$$

for the FF we use two different variances: $g_3(z), g_4(z)$

Parametrization of Sivers function

Sivers function parametrized in terms of its first moment

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

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

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

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

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

from MAP22 TMD extraction

Free parameters $\lambda_S\,, M_1$

Parametrization of Sivers function

normalization
(abs.value <1)

$T_n(x)$ Chebyshev polynomials

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

maximum value
of the function

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

Flavor dependent: distinct for up, down, sea

Evolution of Sivers function first moment

evolved Sivers function first moment

$$\tilde{f}_{1T}^{\perp(1)a}(x, b_T^2; Q^2) =$$

nonperturbative part of TMD

$$= \sum_i \left(\tilde{C}_{a/i} \otimes f_1^i\right)\left(x, \overline{b}_*; \mu_b\right) e^{\tilde{S}\left(\overline{b}_*; \mu_b, \mu\right)} e^{g_K(b_T)\ln(\mu/\mu_0)} \hat{f}_{1TNP}^{\perp(1)a}\left(x, b_T\right)$$

(Wilson Coefficient)

(Sudakov form factor)

collinear PDF

pQCD

nonperturbative part of evolution

Free parameters g_2

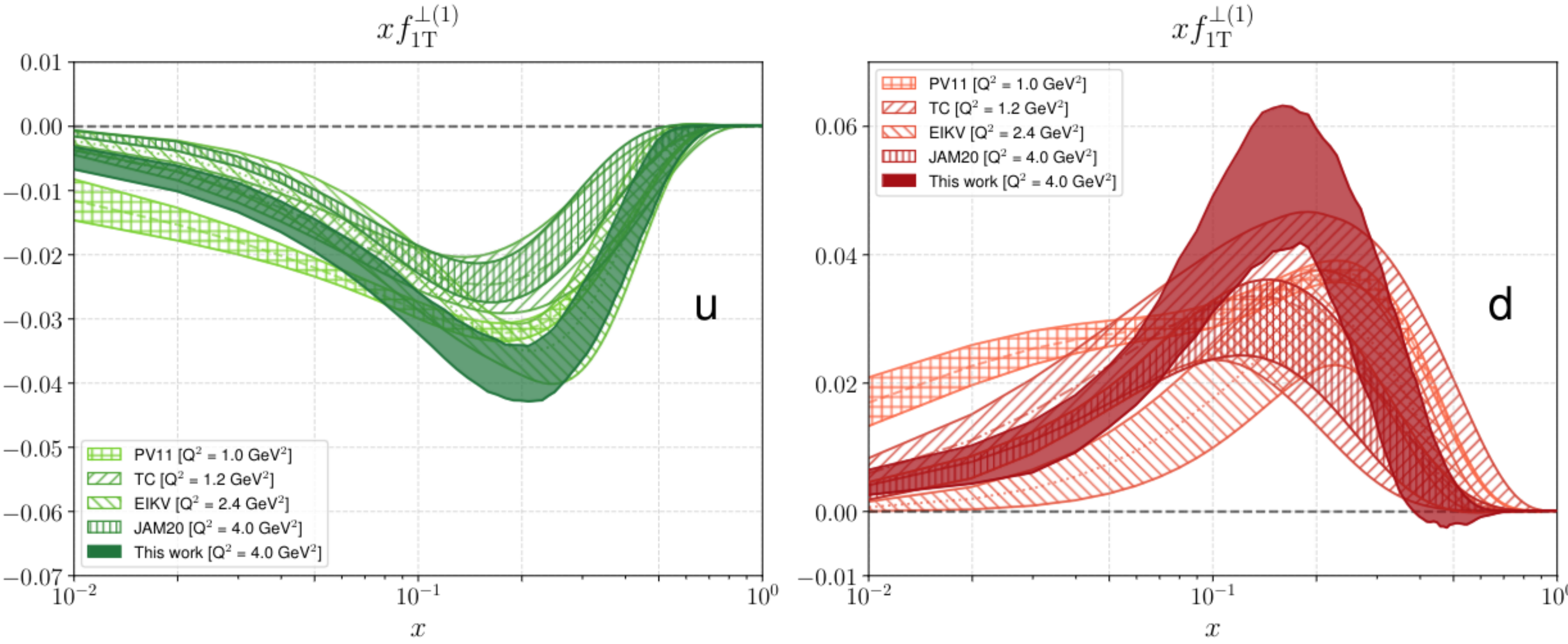
Fourier transform: b_T space

PV20Sivers: Polarized TMDs

$$\chi^2 = 1.12$$

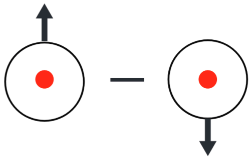
125 data points from SIDIS, DY

LO-NLL



TMDs

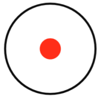
PV20Sivers



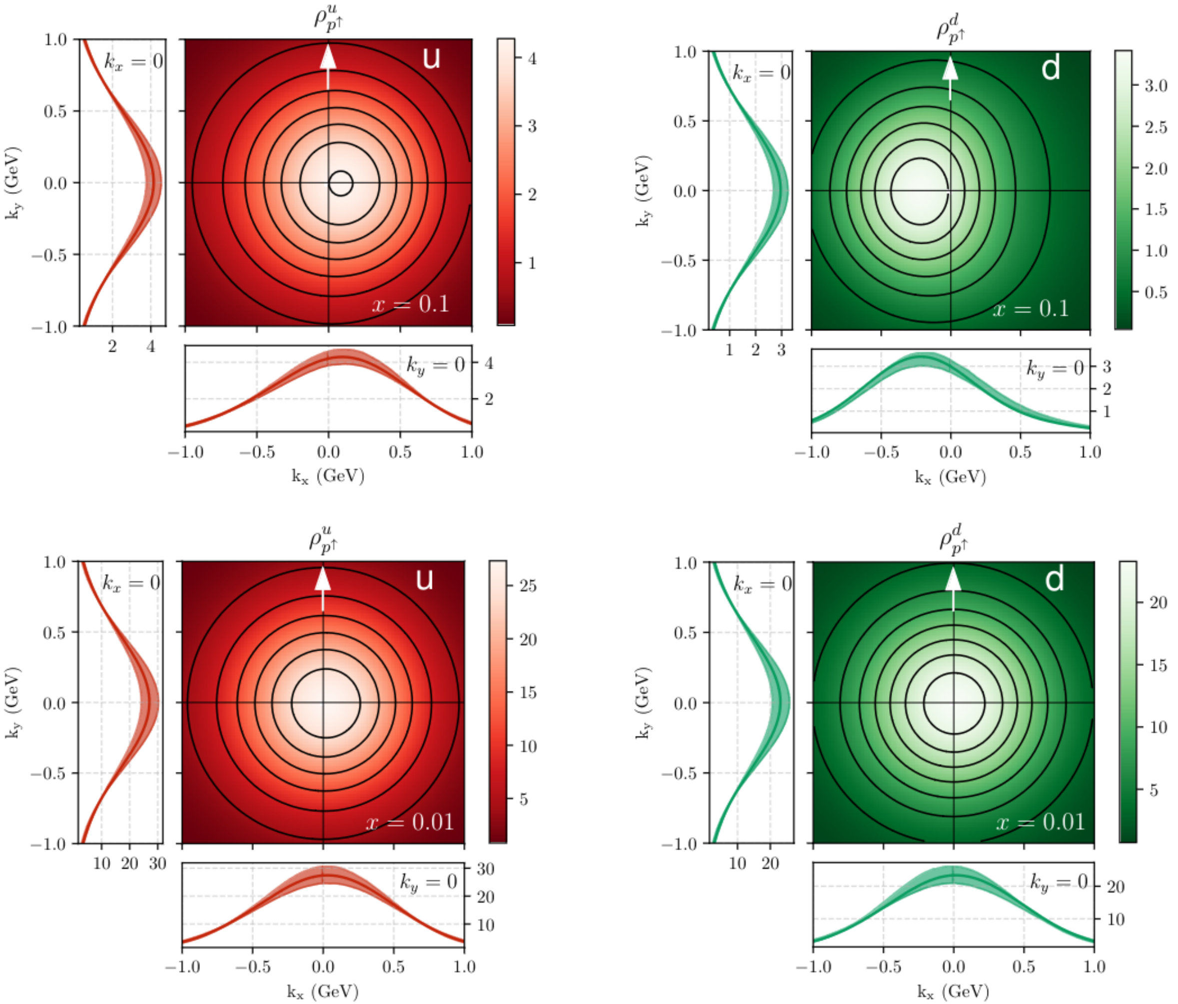
polarized

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

PV17



unpolarized



Updated Sivers extraction

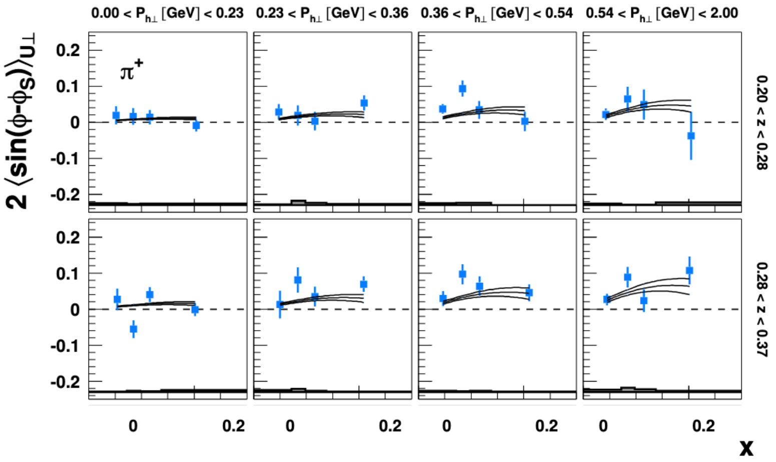
Additional data

[JHEP12(2020)010]

2020

SIDIS

Multidimensional
x, P_{hT}, z



[PRL133]

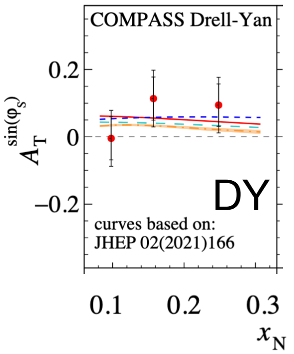
2022

SIDIS

2015-2018

pion-induced
DY

projected in *x*



Updated Sivers extraction

included datasets

SIDIS

hermes 2020

[JHEP12(2020)010]

target: proton [H]

final state hadron

π^+, π^-, K^+, K^-

250 data points

[PRL107,072003(2011)]

Jefferson Lab

t: neutron [^3He]

6 data points

COMPASS

2009 t: deuteron [^6LiD]

2017 t: Proton [NH_3]

2022 t: deuteron [^6LiD]

[PLB673,127(2009)]

[PLB770,138(2017)]

[PRL133]

f.s.h

h^+, h^-

98 data points

DY

W-Z production 2016

STAR

[PRL116,132301(2016)]

7 data points

2015-2018

COMPASS

pion-induced DY

t: Proton [NH_3]

3 data points

[PRL133]

Total number of data

364

Updated Sivers extraction

Additional data

hermes 2020
[JHEP12(2020)010]

COMPASS 2022
2015-2018
[PRL133]

More accurate unpolarized TMDs

for a self-consistent global extraction

MAPTMD22 [JHEP10(2022)127]

pionMAPTMD [PRD.107.014014]

Updated Sivers extraction

Additional data

2020

[JHEP12(2020)010]

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

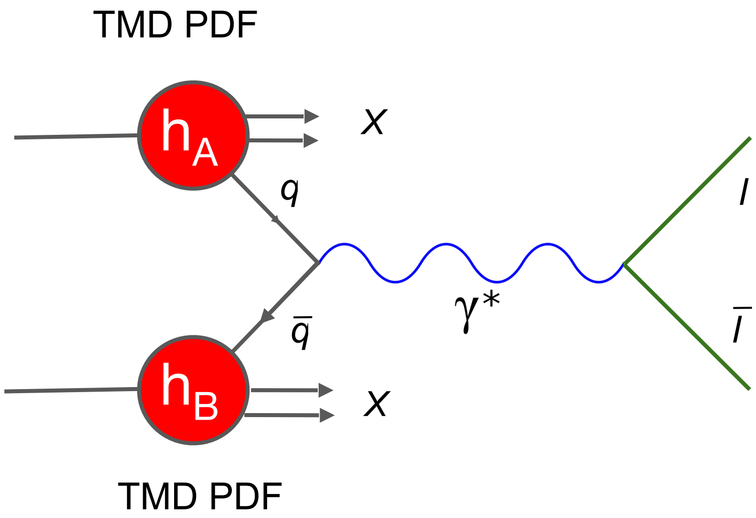
Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

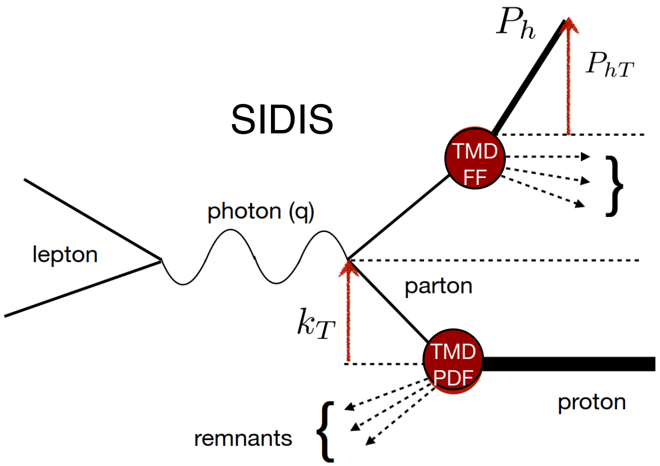
You can obtain NangaParbat directly from the github repository:

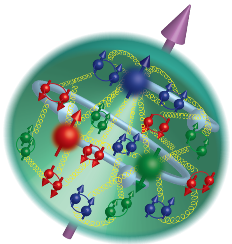
https://github.com/MapCollaboration/NangaParbat

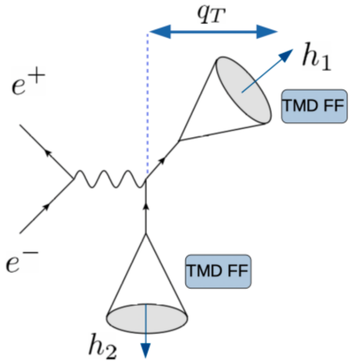
Nucleon TMDs and Pion TMDs



Drell-Yan

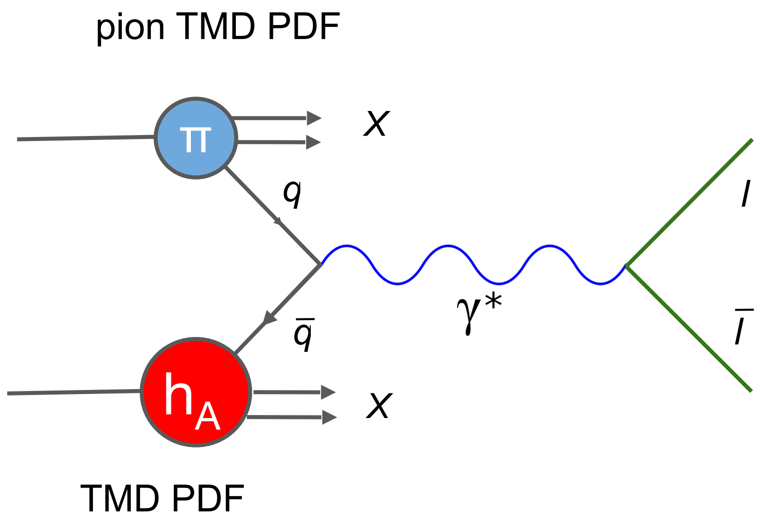


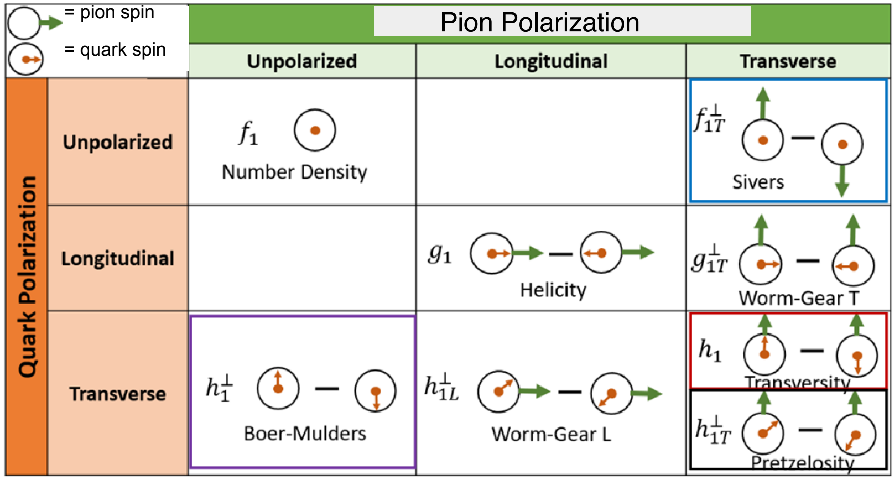




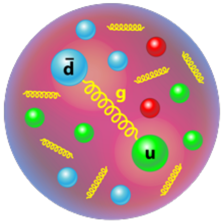
e^+e^- annihilation

Pion TMDs

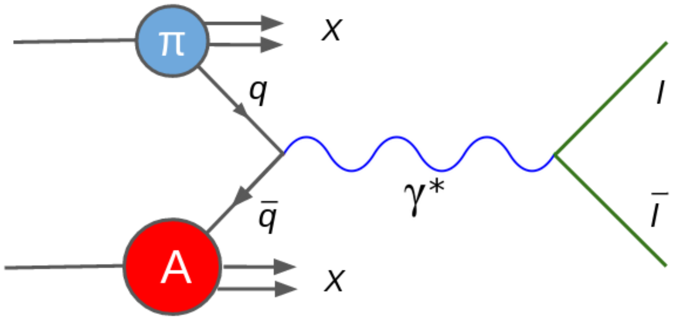




Drell-Yan



Pion TMD extraction: MAP22Pion



<u>accuracy</u>

N3LL

[PRD 107 (2023) 1, 014014]

$$\frac{d\sigma^{DY}}{d|\boldsymbol{q}_T|dydQ} \propto \int d|\boldsymbol{b}_T||\boldsymbol{b}_T|J_0(|\boldsymbol{q}_T||\boldsymbol{b}_T|)\boxed{\hat{f}^{\,a}_{1\pi}(x_A, \boldsymbol{b}_T^2; \mu, \zeta_A)}\boxed{\hat{f}^{\,\bar{a}}_{1p}(x_B, \boldsymbol{b}_T^2; \mu, \zeta_B)}$$

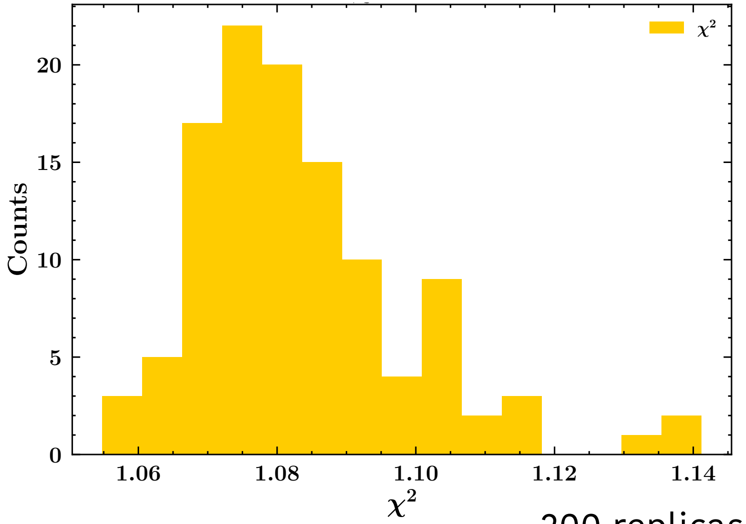
updated MAP Sivers Fit results

Accuracy: NLL-LO

Total number of data

364

$$\chi^2 = 1.08$$

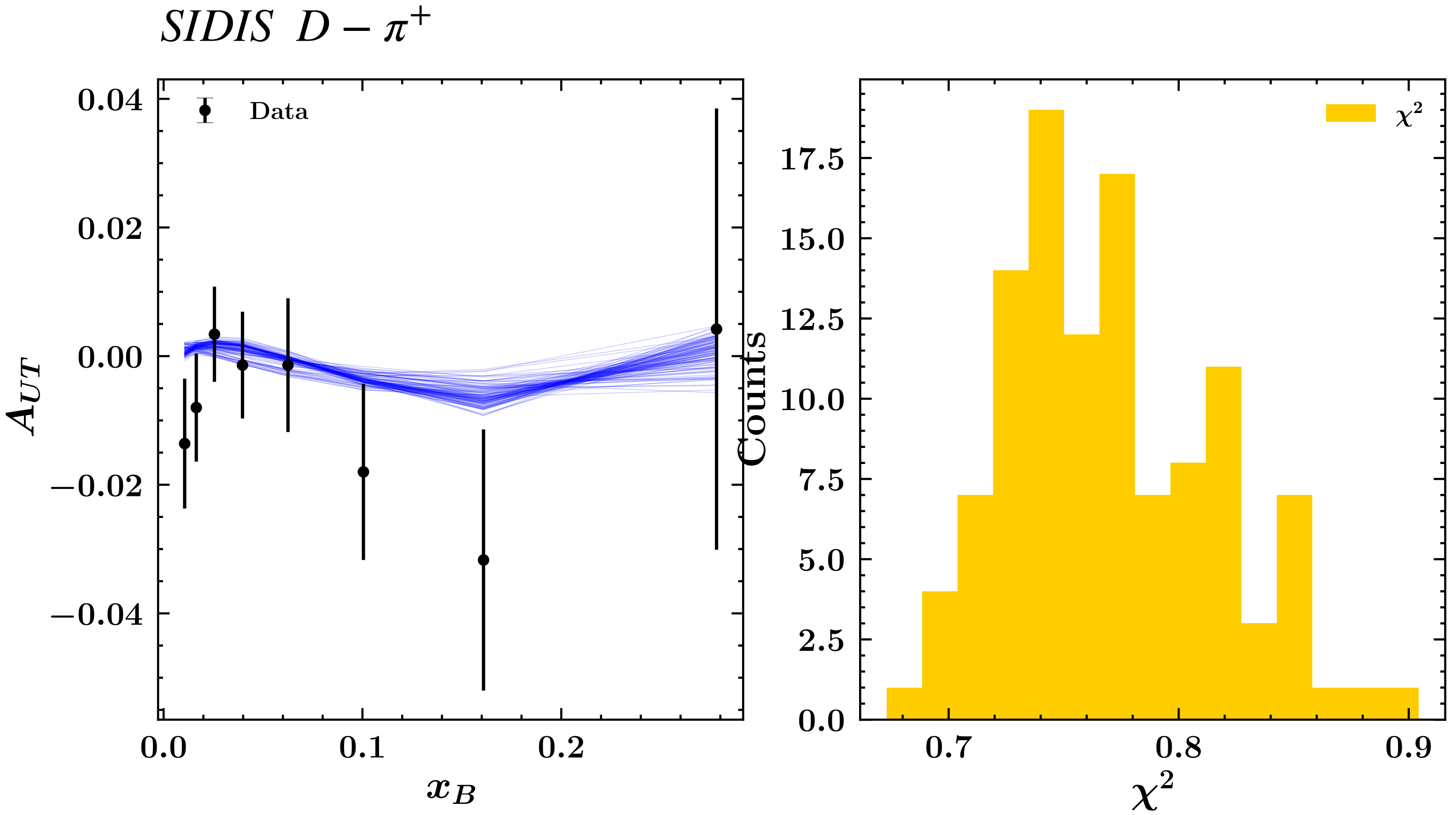


200 replicas

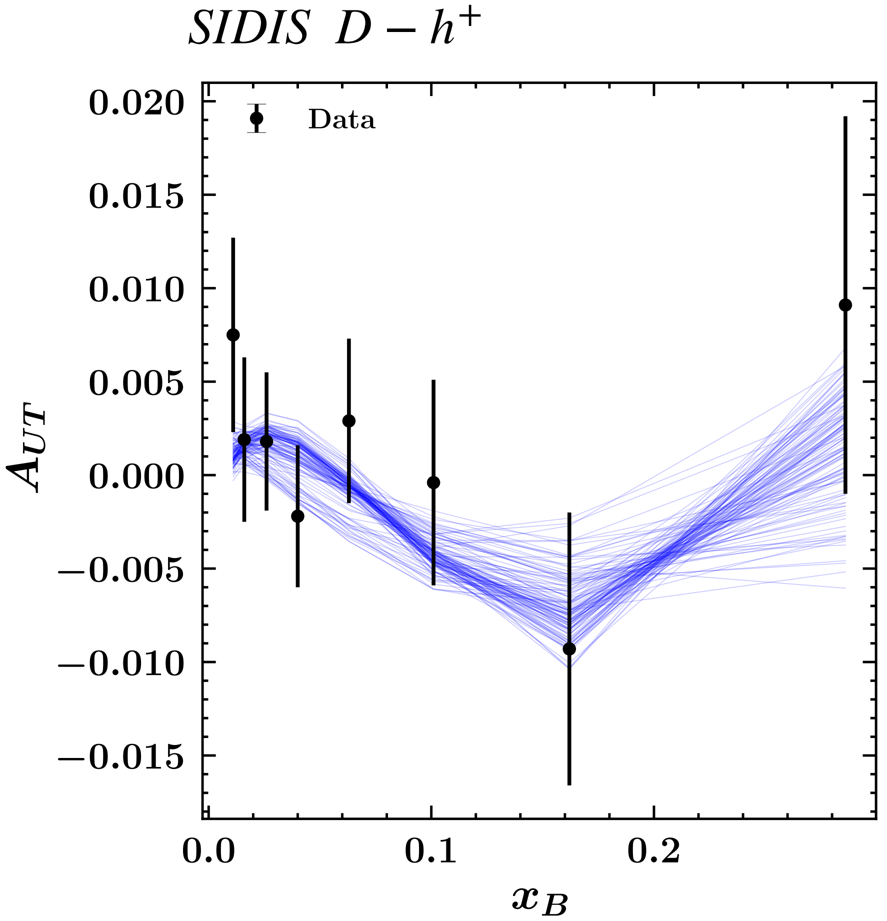
global fit from

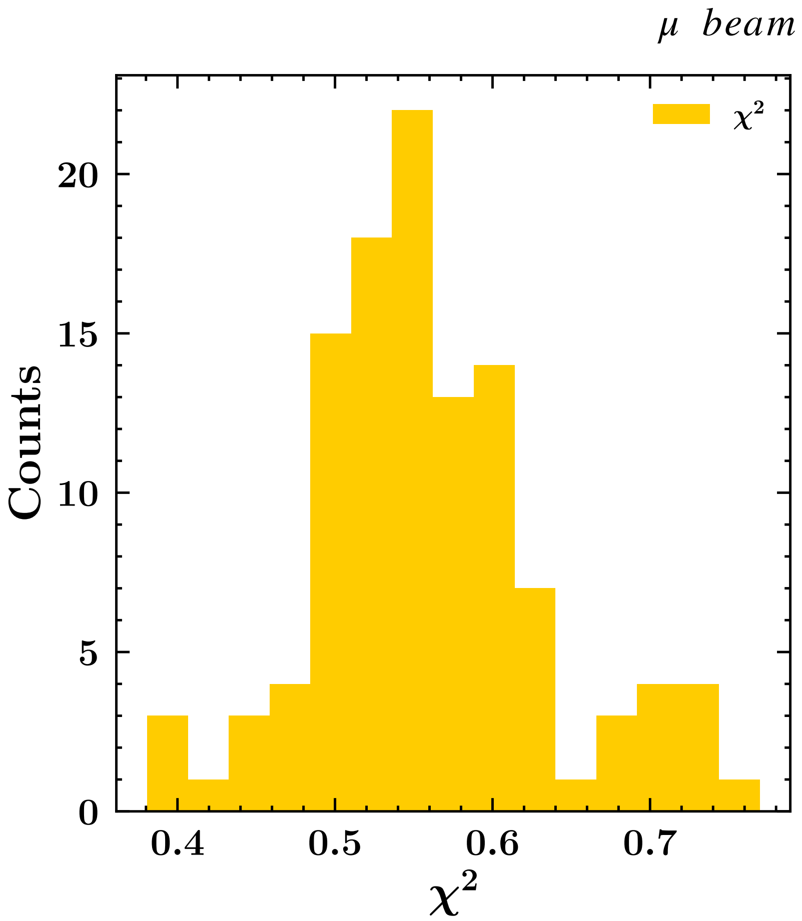
- semi-inclusive DIS,
- pion-induced Drell-Yan,
- W-Z boson production

Selected results: Compass 2009



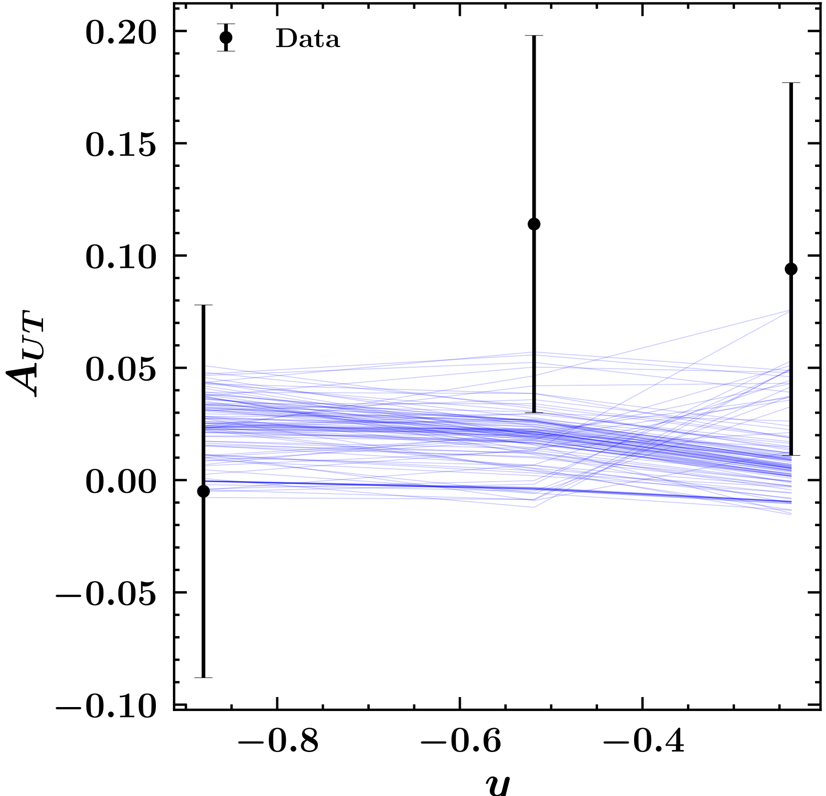
Selected results: COMPASS 2022

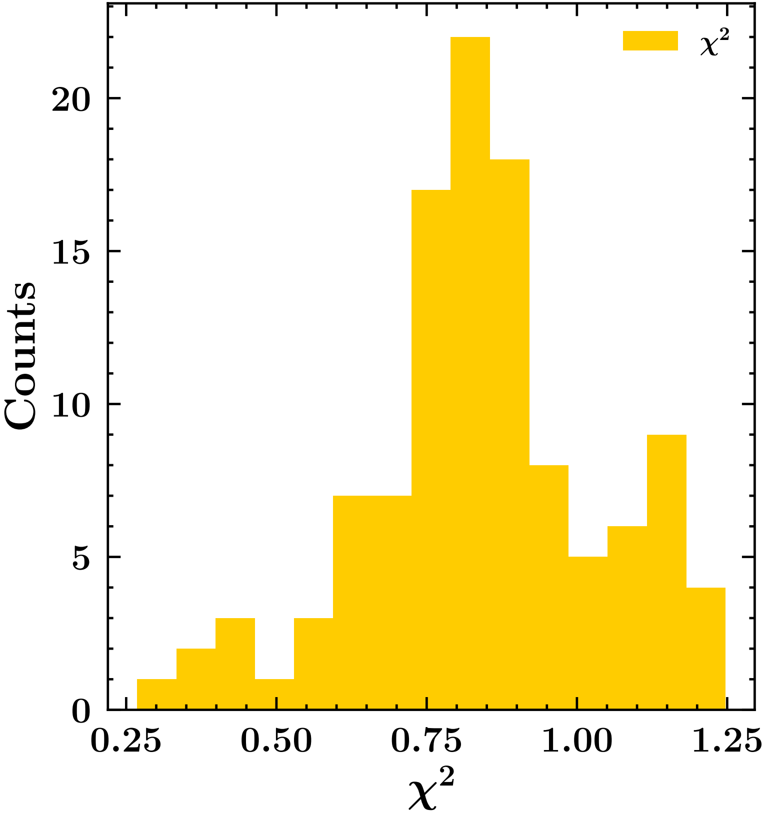




Selected results: COMPASS DY 2015

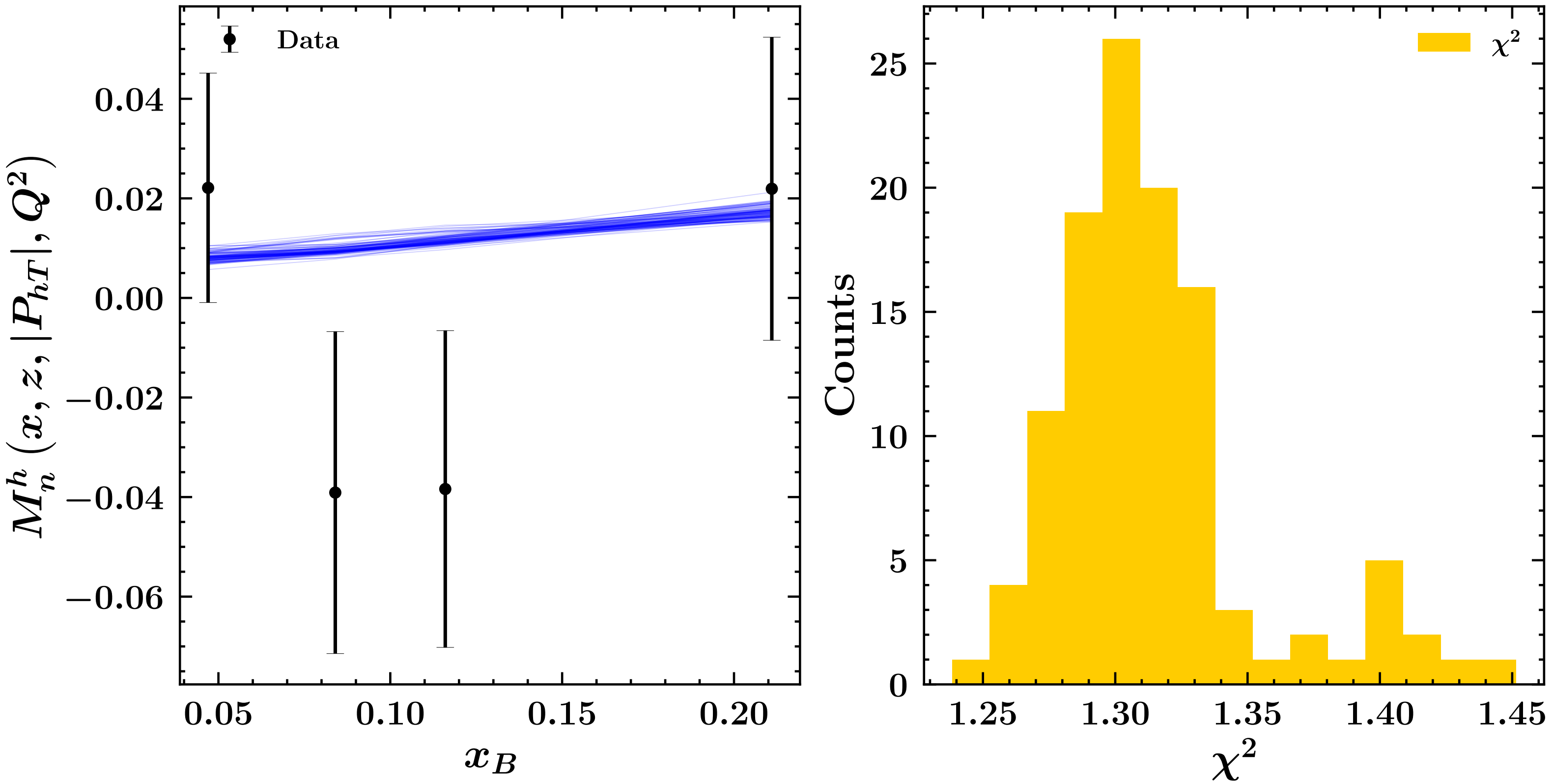
pion DY





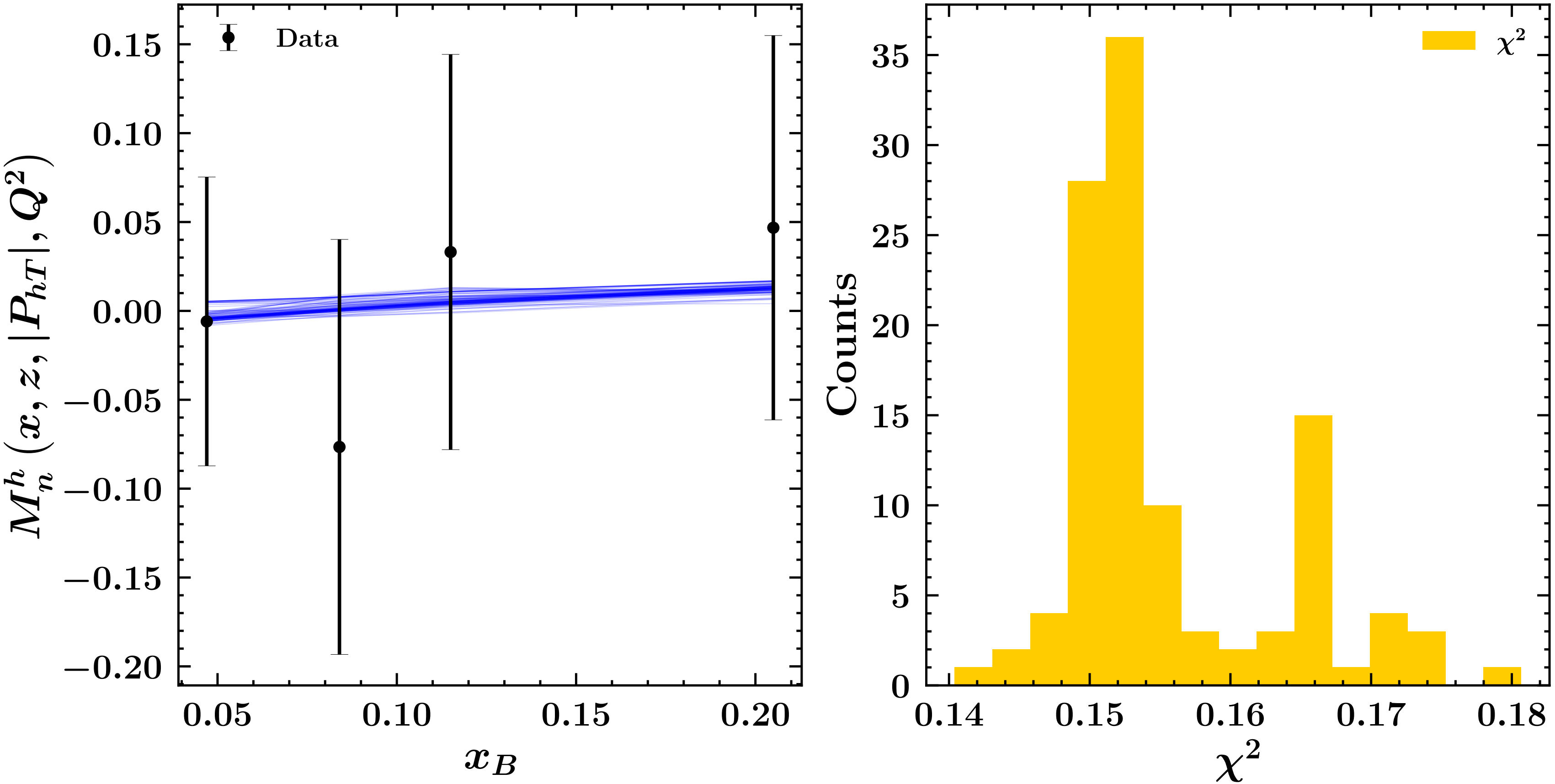
Selected results: HERMES 2020

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



Selected results: HERMES 2020

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

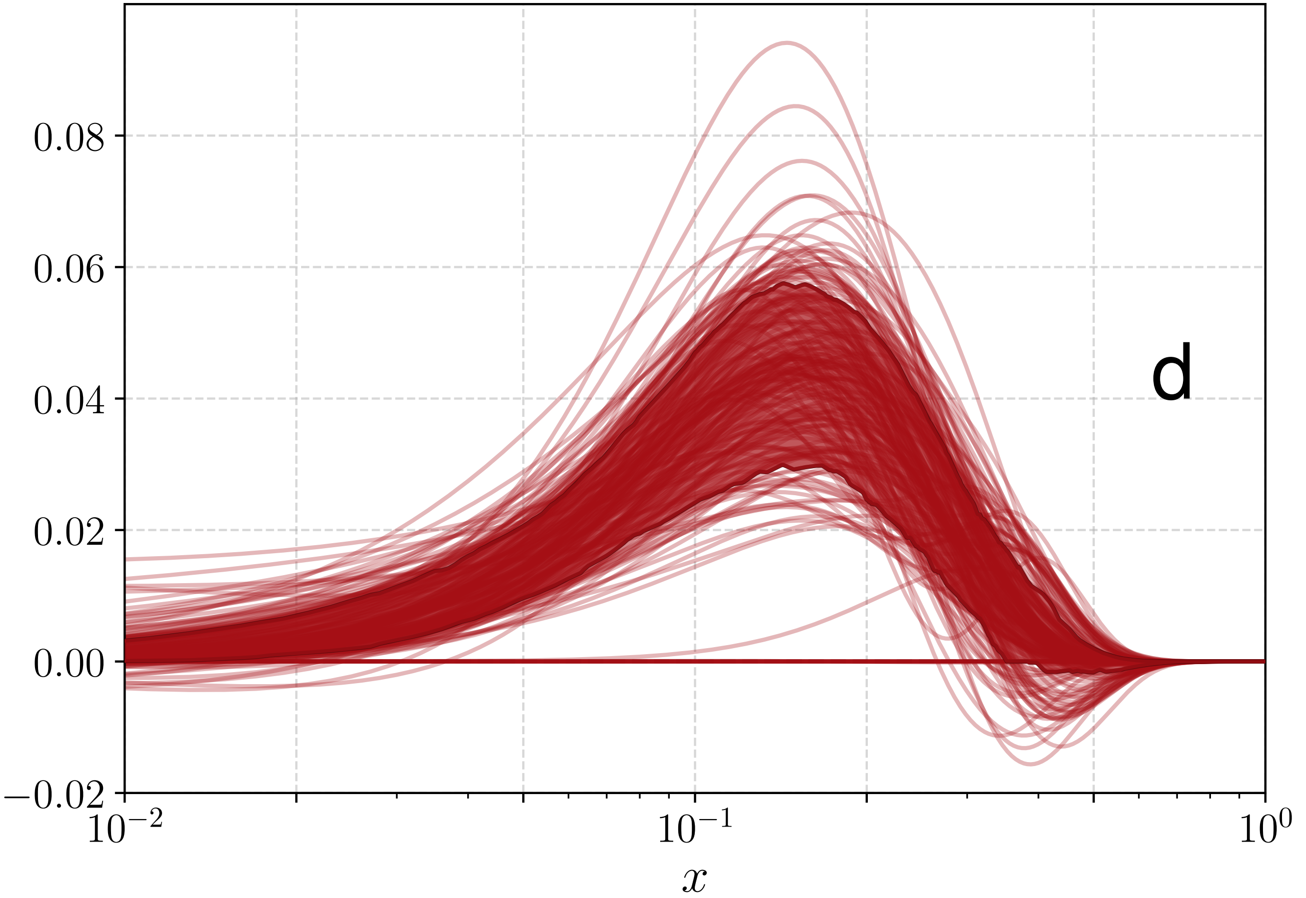


Sivers TMD

down quark

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

$Q^2 = 4\, GeV^2$

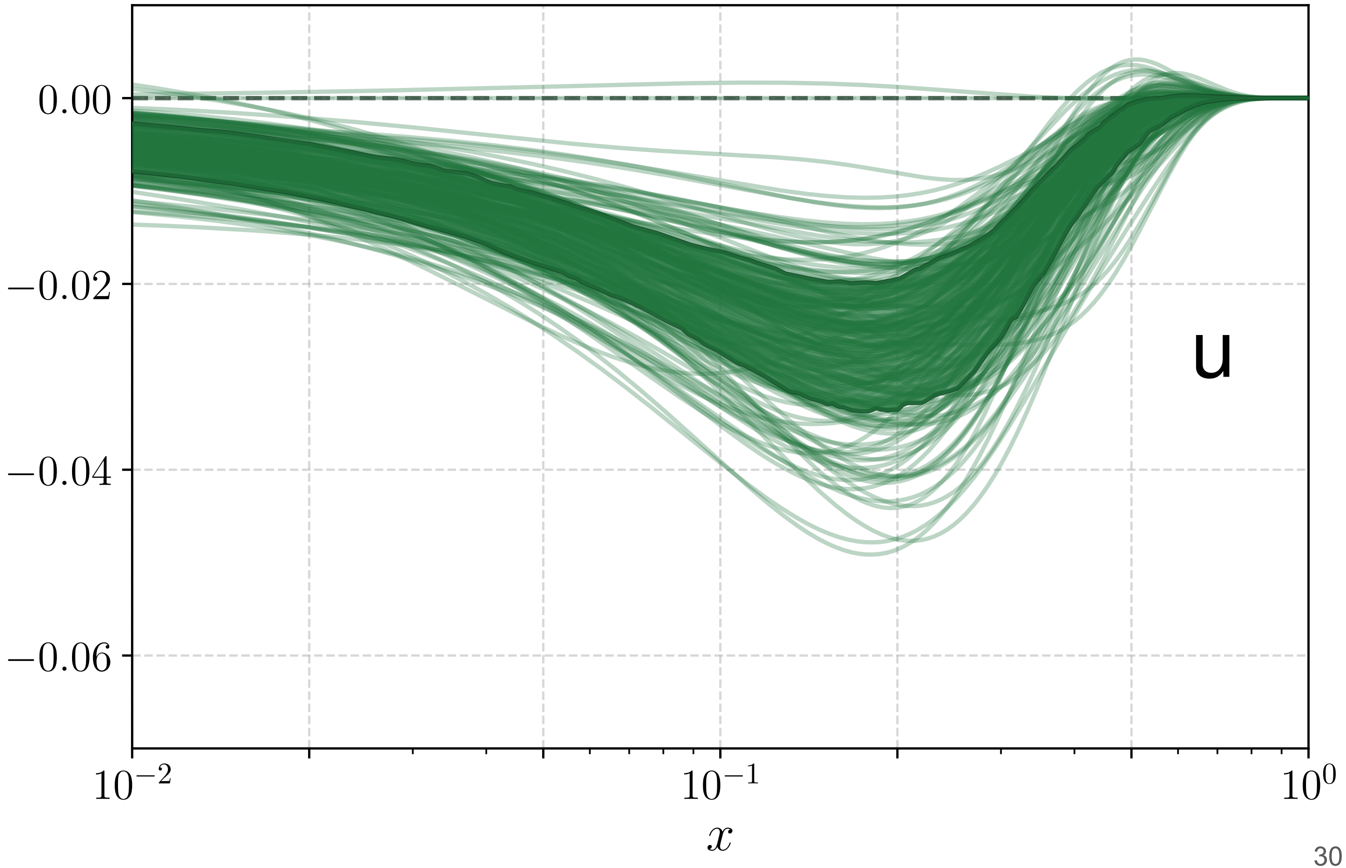


Sivers TMD

up quark

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

$Q^2 = 4\, GeV^2$



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