SQUHADRON

M. Radici - A. Signori

University of Pavia & INFN

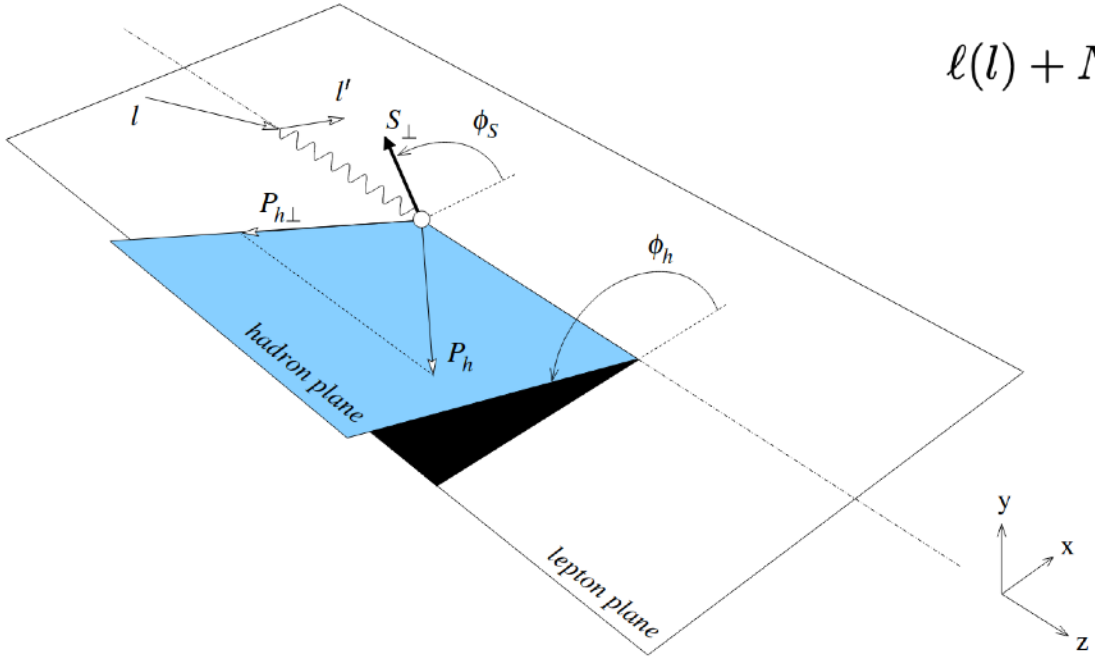
Theory status, predictions & perspectives

SIDIS WG kickoff meeting

April 27, 2022

Outline

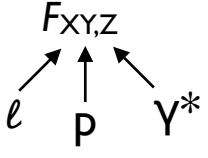
1. **Unpolarized TMD**
2. **Sivers TMD**
3. **Transversity**



$$\ell(l) + N(P) \rightarrow \ell(l') + h(P_h) + X,$$

hep-ph/0611265

$$F_{\ldots}(x_B, z_h, P_{hT}^2, Q^2)$$

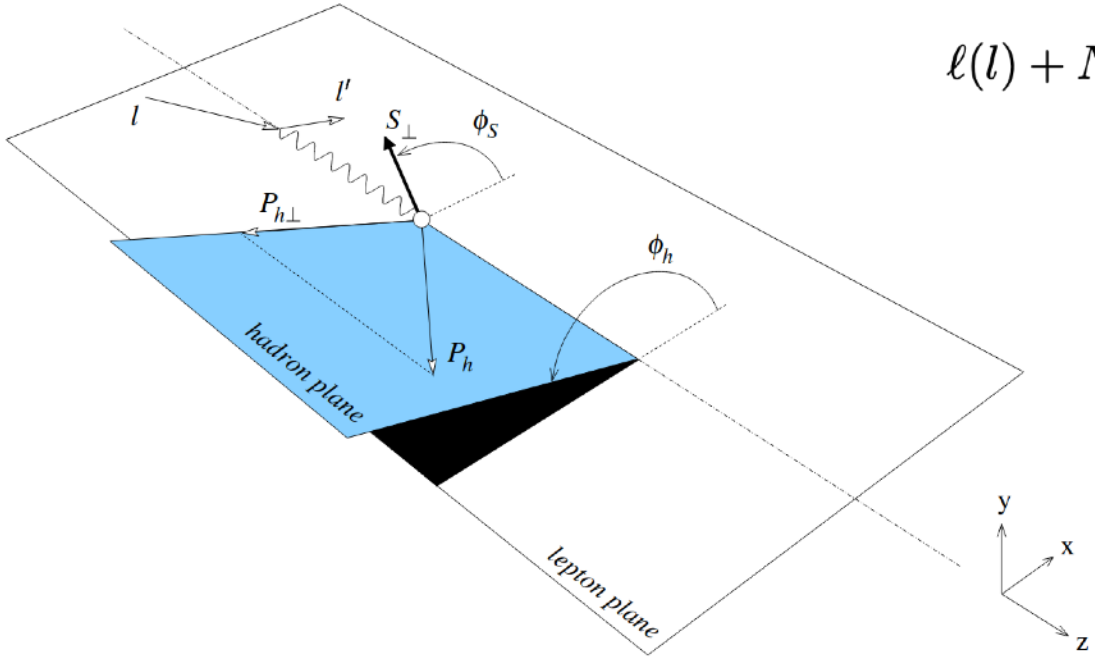


$$\frac{d\sigma}{dx_B dy d\phi_S dz_h d\phi_h dP_{hT}^2} = \frac{\alpha^2}{x_B y Q^2}\Big[A(y)\,F_{UU,T} + B(y)\,\cos 2\phi_h\,F_{UU}^{\cos 2\phi_h} + S_L\,\sin 2\phi_h\,F_{UL}^{\sin 2\phi_h} + \lambda_e\,S_L\,C(y)\,F_{LL}$$

$$+ S_T\Big[A(y)\,\sin(\phi_h - \phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)} + B(y)\,\sin(\phi_h + \phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ B(y)\,\sin(3\phi_h - \phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

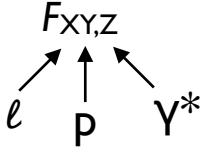
$$+ \lambda_e\,S_T\,C(y)\,\cos(\phi_h - \phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big] \quad + \mathcal{O}\left(\frac{M}{Q}\right)$$



$$\ell(l) + N(P) \rightarrow \ell(l') + h(P_h) + X,$$

hep-ph/0611265

$$F_{\ldots}(x_B, z_h, P_{hT}^2, Q^2)$$



$$\frac{d\sigma}{dx_B dy d\phi_S dz_h d\phi_h dP_{hT}^2} = \frac{\alpha^2}{x_B y Q^2}\Big[A(y)\,F_{UU,T} + B(y)\,\cos 2\phi_h\,F_{UU}^{\cos 2\phi_h} + S_L\,\sin 2\phi_h\,F_{UL}^{\sin 2\phi_h} + \lambda_e\,S_L\,C(y)\,F_{LL}$$

$$+ S_T\Big[A(y)\,\sin(\phi_h - \phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)} + B(y)\,\sin(\phi_h + \phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ B(y)\,\sin(3\phi_h - \phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

$$+ \lambda_e\,S_T\,C(y)\,\cos(\phi_h - \phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big] \quad + \mathcal{O}\left(\frac{M}{Q}\right)$$

Recent fits for unpolarized TMD $F_{UU,T} \sim f_1 \otimes D_1$

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.02

Recent fits for unpolarized TMD $F_{UU,T} \sim f_1 \otimes D_1$

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^{3}LL	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^{3}LL	✘	✘	✔	✔	353	1.02

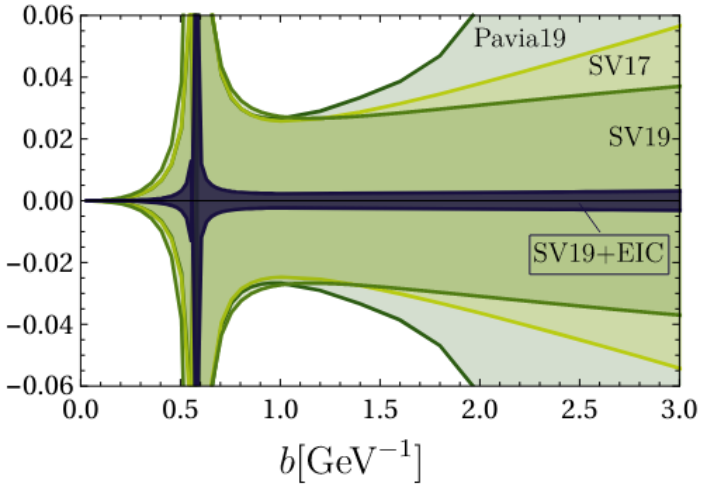
TMD impact studies: SV19

See EIC Yellow Report arXiv:2103.05419

$$\left(\frac{\zeta}{\zeta_0}\right)^{-D(b_T\mu_0,\alpha_s(\mu_0))} + g_K(b_T;\lambda)$$

→ evolution in ζ

nonperturbative corrections (large b_T)



Typically a function of b_T^2 with one or two parameters (with variations of course)

Huge impact of EIC SIDIS program on **non-perturbative TMD evolution**

TMD impact studies: SV19

See EIC Yellow Report arXiv:2103.05419

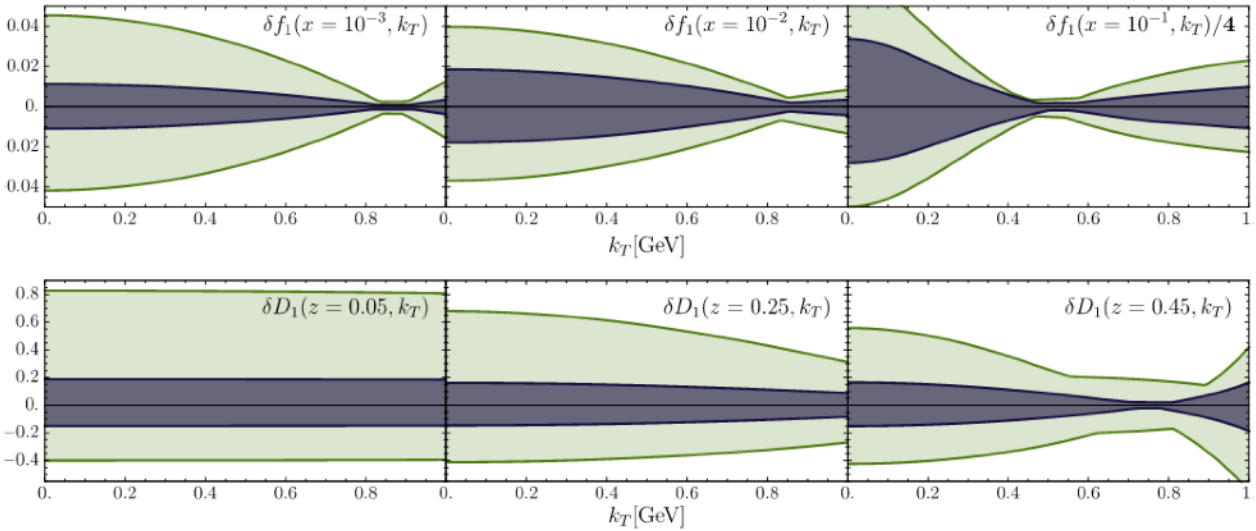


Figure 7.52: Comparison of relative uncertainty bands (i.e. uncertainties normalized by central value) for up-quark unpolarized TMD PDFs (upper panel) and $u \to \pi^+$ pion TMD FFs (lower panel), at different values of x and z as a function of k_T, for $\mu = 2$ GeV. Lighter band is the SV19 extraction, darker is SV19 with EIC pseudodata.

up in proton
TMD PDF

up to π^+
TMD FF

Fit with EIC pseudo-data

Recent fits for unpolarized TMD $F_{UU,T} \sim f_1 \otimes D_1$

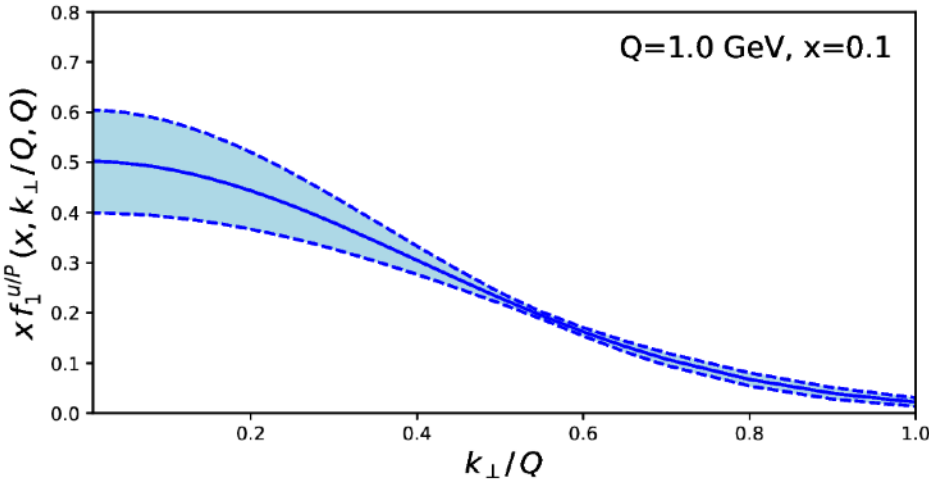
	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.02

Unpolarized TMDs - PV17

see arXiv:1703.10157

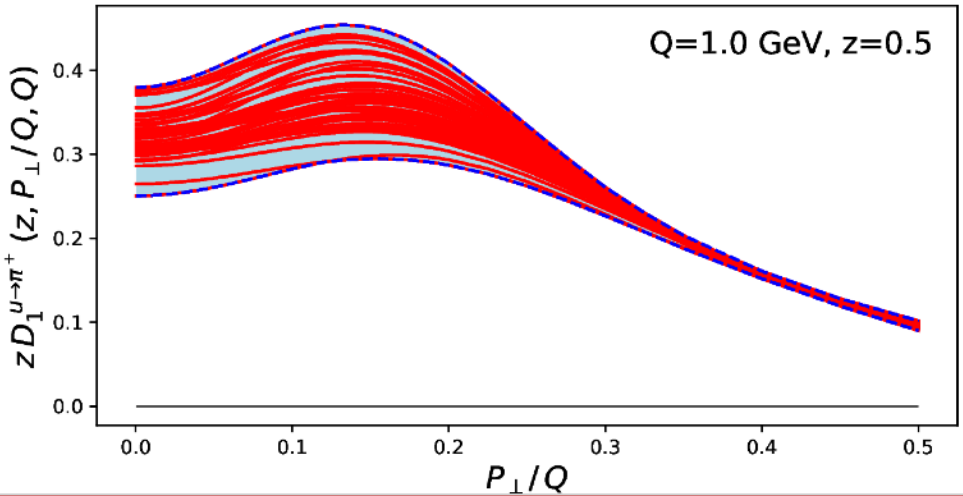
Imaging from **SIDIS** data (Hermes and Compass)
and **Drell-Yan** data (fixed-target & Z production @ Fermilab)

$$F_{UU,T} \sim f_1 \otimes D_1$$



Unpolarized TMD PDF

Unpolarized TMD FF



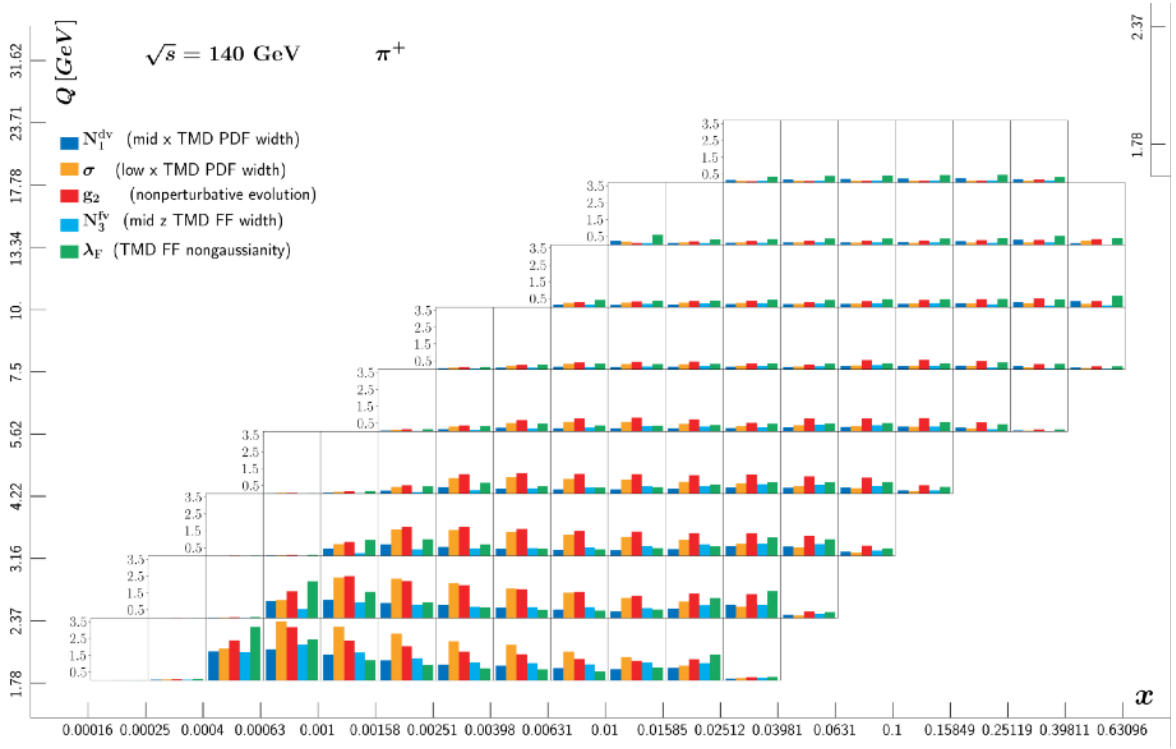
Combining SIDIS and Drell-Yan:
Possibility to disentangle
hadron structure and formation

TMD impact studies: PV17

See EIC Yellow Report arXiv:2103.05419
and also Bissolotti's talk at DIS 2021

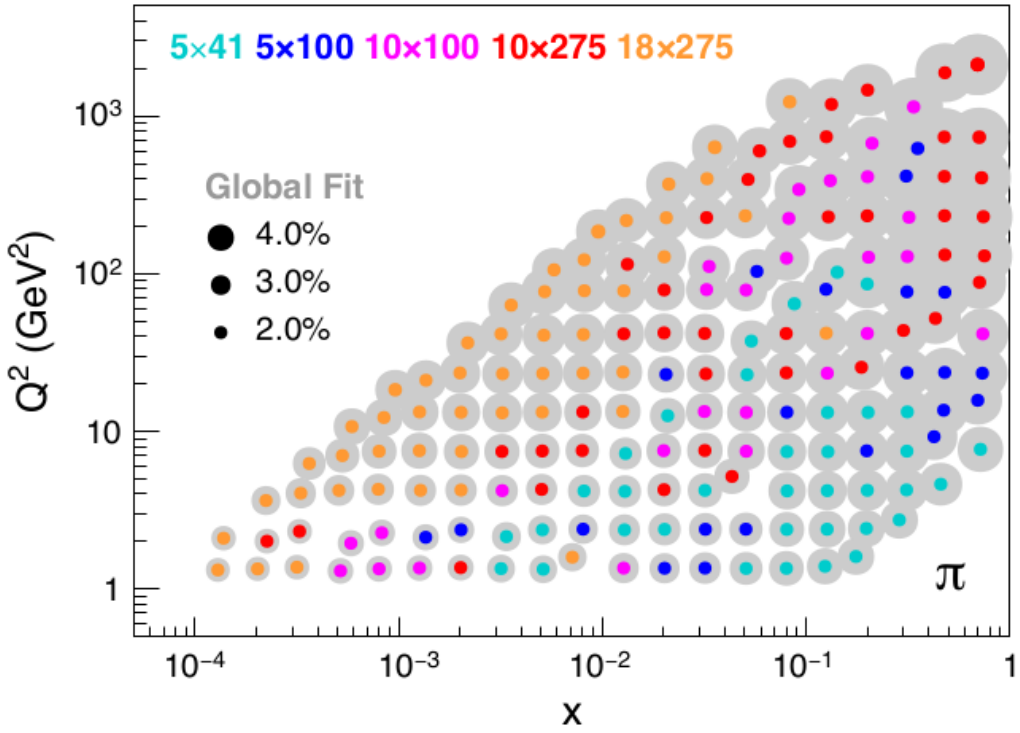
$$S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\delta \mathcal{O} \Delta f_i}$$

O: e.g. a SIDIS structure function
f_i : the non-perturbative TMD parameters



$$\sqrt{s} = 140 \text{ GeV}$$

ATHENA - unpolarized cross section uncertainties

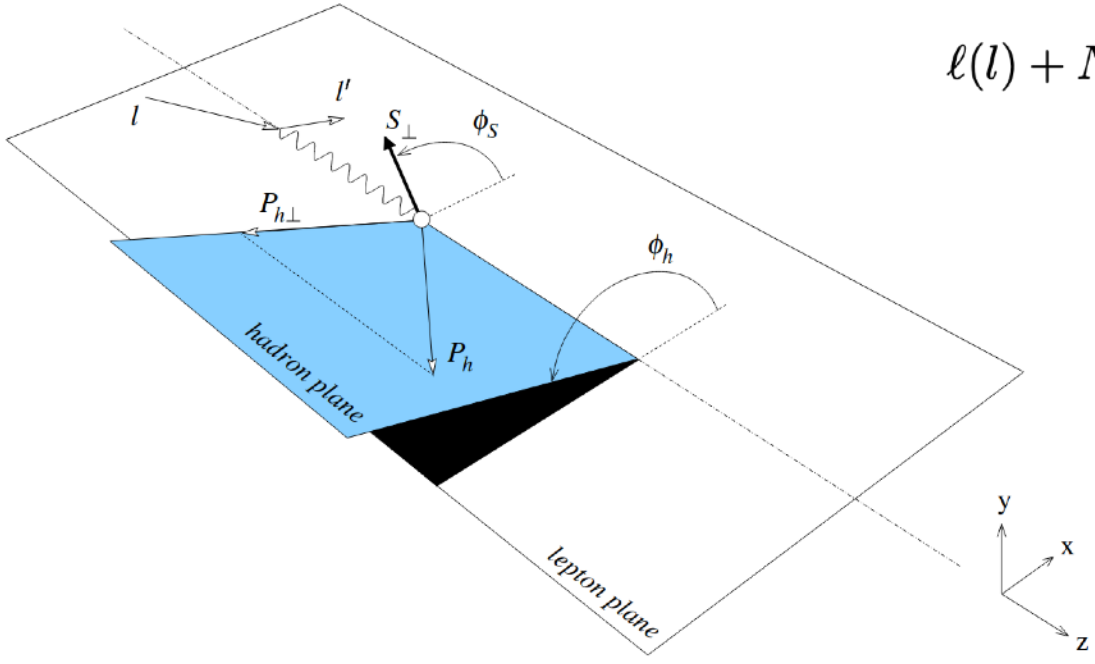


grey blobs = uncertainties from **PV17**

colored blobs = projected uncertainties at various **ATHENA** configurations (including 3% systematic error)

at each (Q^2,x) bin, configuration with largest impact is shown

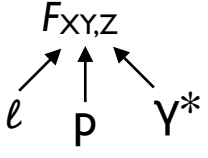
Adam et al. (ATHENA), ATHENA Detector proposal (2021)



$$\ell(l) + N(P) \rightarrow \ell(l') + h(P_h) + X,$$

hep-ph/0611265

$$F_{\ldots}(x_B, z_h, P_{hT}^2, Q^2)$$



$$\frac{d\sigma}{dx_B dy d\phi_S dz_h d\phi_h dP_{hT}^2} = \frac{\alpha^2}{x_B y Q^2}\Big[A(y)\,F_{UU,T} + B(y)\,\cos 2\phi_h\,F_{UU}^{\cos 2\phi_h} + S_L\,\sin 2\phi_h\,F_{UL}^{\sin 2\phi_h} + \lambda_e\,S_L\,C(y)\,F_{LL}$$

$$+ S_T\Big[A(y)\,\sin(\phi_h - \phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)} + B(y)\,\sin(\phi_h + \phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ B(y)\,\sin(3\phi_h - \phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

$$+ \lambda_e\,S_T\,C(y)\,\cos(\phi_h - \phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big] \quad + \mathcal{O}\left(\frac{M}{Q}\right)$$

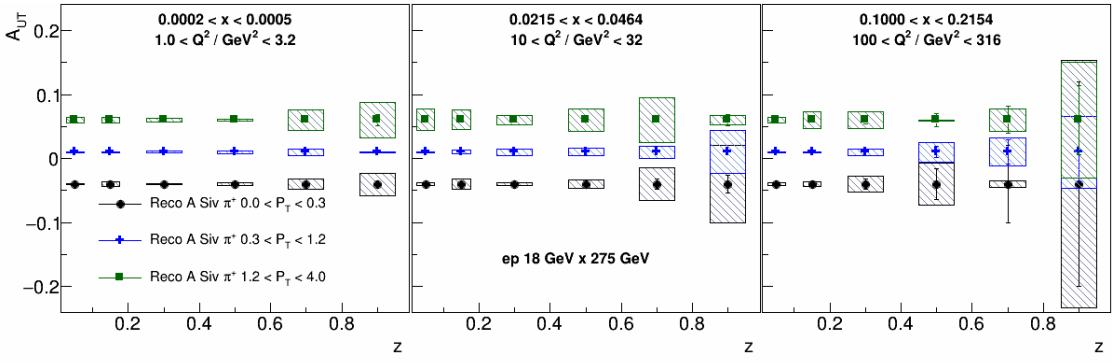
Recent fits for Sivers TMD

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto \frac{F_{UT,T}^{\sin(\phi_h-\phi_S)}}{F_{UU,T}} \sim \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

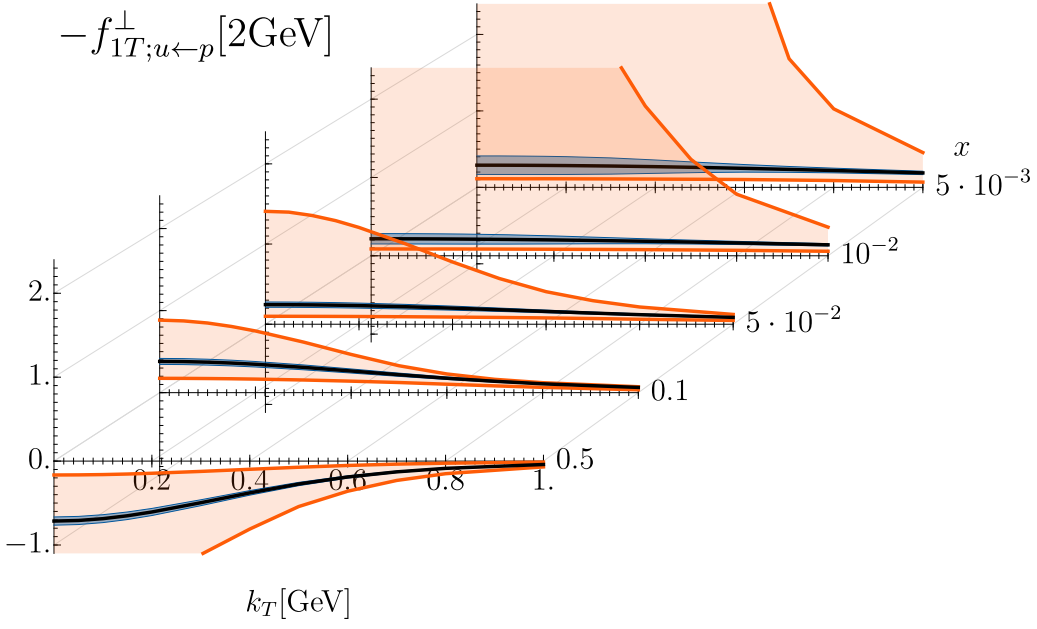
	Framework	SIDIS	A_N - DY	A_N - W/Z production	A_N - forward EM jet	N. pts	χ^2/N.pts
JAM 20 arXiv:2002.08384	extended parton model	✔	✔	✔	✘	517	1.04
PV 20 arXiv:2004.14278	NLL	✔	✔	✔	✘	125	1.08
EKT 20 arXiv:2009.10710	NNLL	✔	✔	✔	✘	226 (452)	0.989 (1.446)
BPV 20 arXiv:2012.05135	no CSS formalism	✔	✔	✔	✘	76	0.88
TO-CA reweighing arXiv:2101.03955	extended parton model	✔	✘	✘	✔	238	$1.05^{+0.03}_{-0.01}$

only SIDIS
+ STAR x 13

Expected uncertainties for Sivers asymmetry in selected bins



Sivers impact studies: BPV 20



ECCE Detector proposal (2021)

Recent fits for Sivers TMD

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto \frac{F_{UT,T}^{\sin(\phi_h-\phi_S)}}{F_{UU,T}} \sim \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

	Framework	SIDIS	A_N - DY	A_N - W/Z production	A_N - forward EM jet	N. pts	χ^2/N.pts	
JAM 20 arXiv:2002.08384	extended parton model	✔	✔	✔	✘	517	1.04	
PV 20 arXiv:2004.14278	NLL	✔	✔	✔	✘	125	1.08	
EKT 20 arXiv:2009.10710	NNLL	✔	✔	✔	✘	226 (452)	0.989 (1.446)	only SIDIS + STAR x 13
BPV 20 arXiv:2012.05135	no CSS formalism	✔	✔	✔	✘	76	0.88	
TO-CA reweighing arXiv:2101.03955	extended parton model	✔	✘	✘	✔	238	$1.05^{+0.03}_{-0.01}$	

Sivers TMD - PV20

see arXiv:2004.14278

JLAB-THY-20-3186

The three-dimensional distribution of quarks in momentum space

Alessandro Bacchetta,[1,2,*] Filippo Delcarro,[3,†] Cristian Pisano,[4,5,‡] and Marco Radici[2,§]

[1] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia*
[2] *INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy*
[3] *Jefferson Lab, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*
[4] *Dipartimento di Fisica, Università di Cagliari, Cittadella Universitaria, I-09042 Monserrato (CA), Italy*
[5] *INFN Sezione di Cagliari, Cittadella Universitaria, I-09042 Monserrato (CA), Italy*

We present the distribution of unpolarized quarks in a transversely polarized proton in three-dimensional momentum space. Our results are based on consistent extractions of the unpolarized and Sivers transverse momentum dependent parton distributions (TMDs).

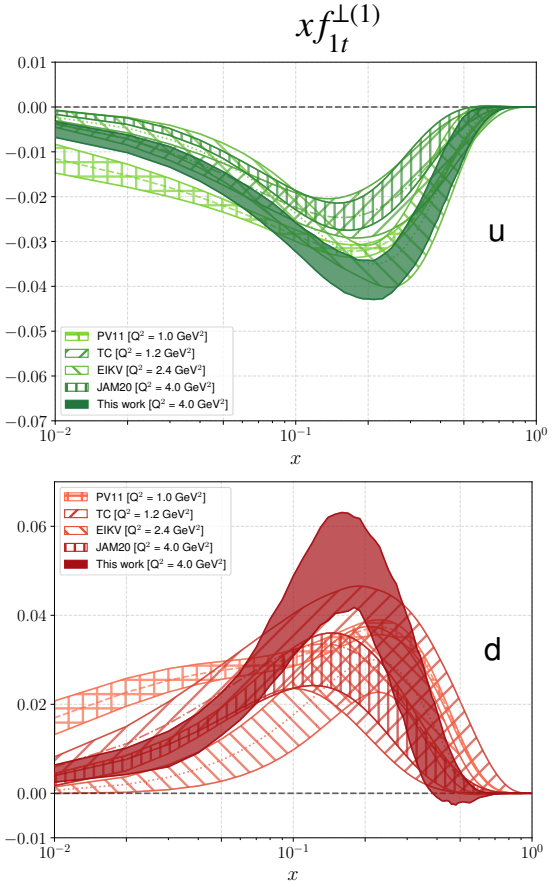
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto \frac{F_{UT,T}^{\sin(\phi_h-\phi_S)}}{F_{UU,T}} \sim \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

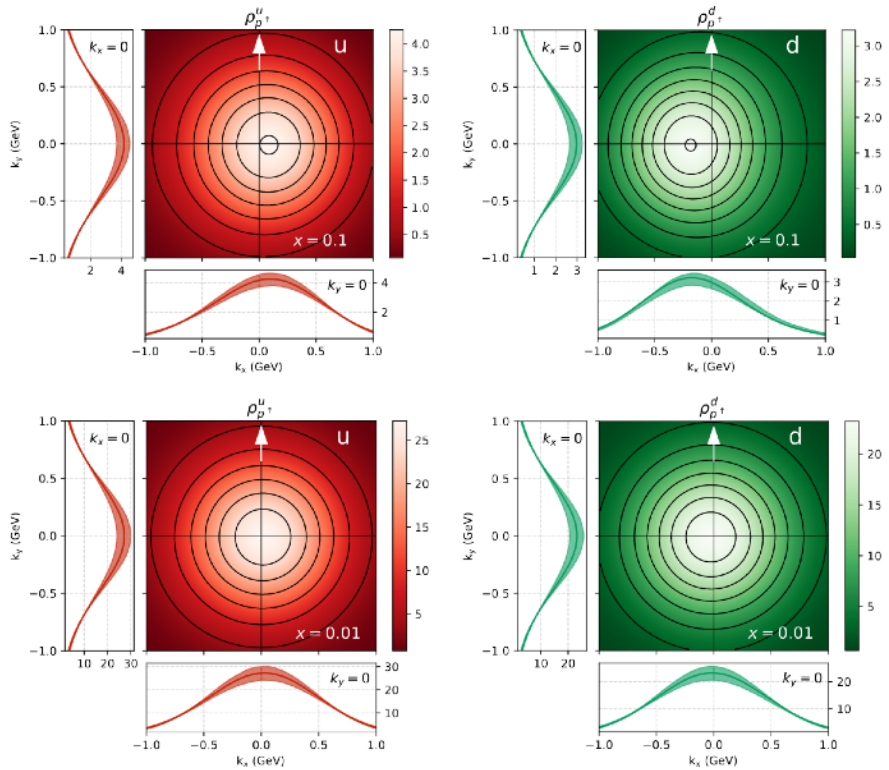
CSS formalism: f_1 and $f_{1T}^{\perp}$ must have same non-perturbative evolution (g_K)
Sivers effect depends on extraction of unpolarized TMD

PV20 first in implementing this
Relies on PV17 extraction of unpolarized TMD

Sivers TMD - PV20

see arXiv:2004.14278





Grids for $F_{UU,T}(x, Q^2, z, q_T/Q)$ $F_{UT,T}(x, Q^2, z, q_T/Q)$

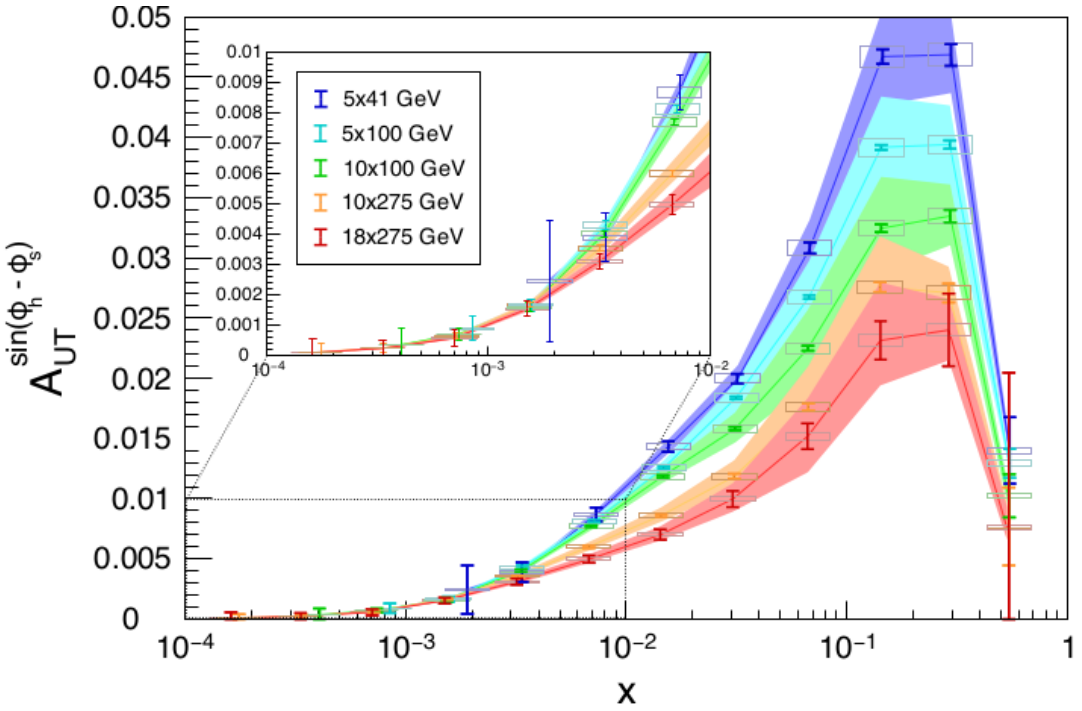
$$q_T = P_{hT}/z$$

Standard “table format” : ~ 80 MB (1 replica, proton / pi - plus)

200 Monte Carlo replicas x 4 target / hadron configurations

Total size ~ 60 GB (15 GB each target / hadron configuration)

ATHENA - Sivers asymmetry



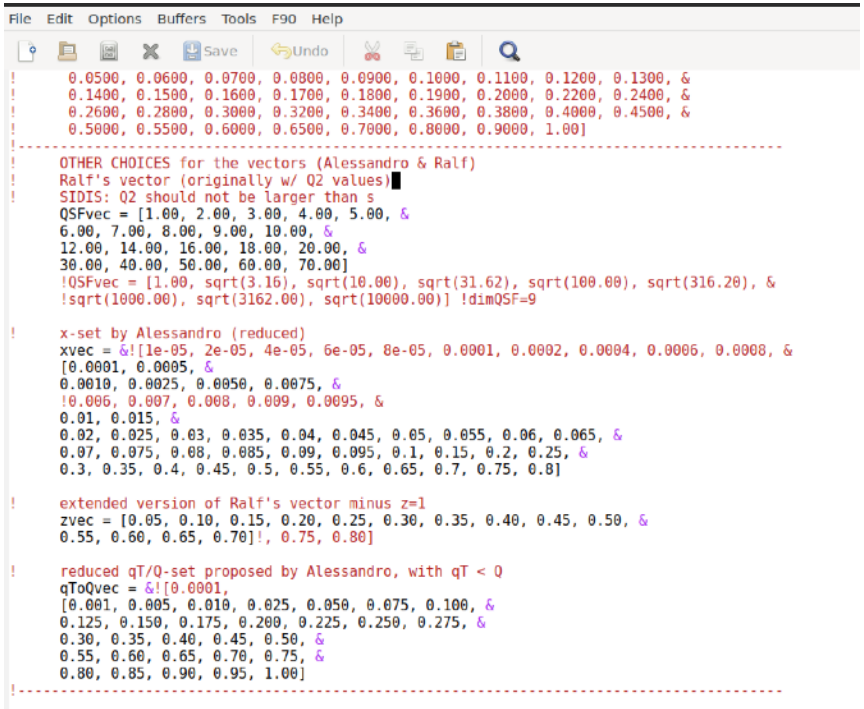
projected uncertainties using **PV 20**

kin. cuts: $Q^2 > 1$ GeV^2 , $0.2 < z < 0.7$, $y > 0.05$

assuming equal data taking times, all uncertainties scaled to **L=10 fb^{-1}** at **10x275 GeV**

Adam et al. (ATHENA), ATHENA Detector proposal (2021)

Short-term goal #1



Repeat the assessment of projected uncertainties for Sivers asymmetry by re-building grids for structure function with:

1- finer Q binning

2- push minimum x to lower values

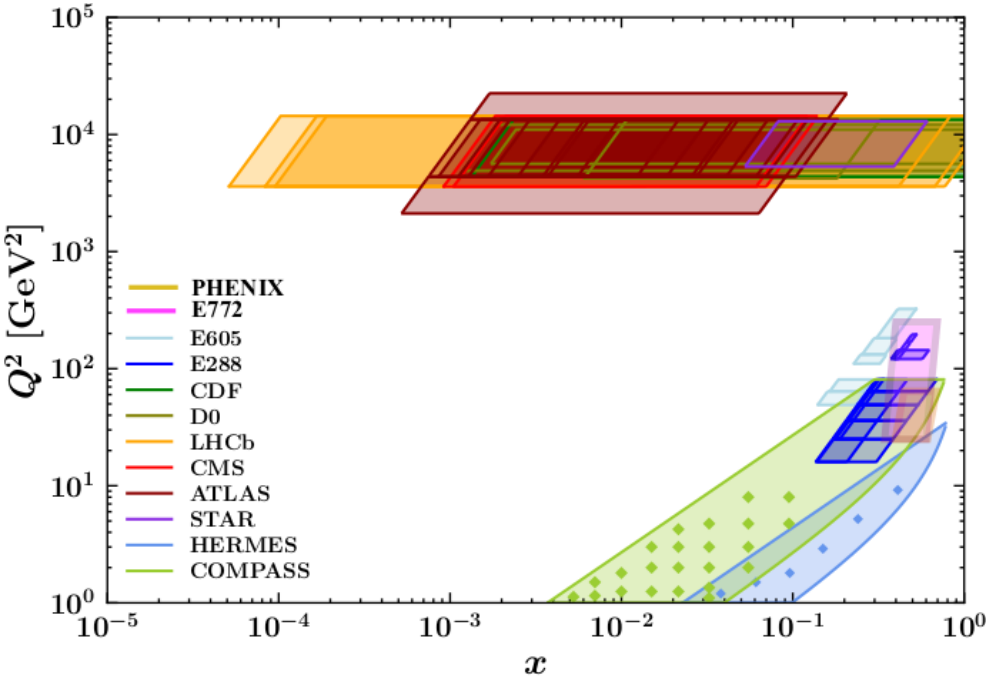
q_T/Q and z vectors should be ok

New unpolarized MAPTMD22 fit

$$F_{UU,T} \sim f_1 \otimes D_1$$

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
PV 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.5
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL’	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^{3}LL	✔	✔	✔	✔	1039	1.06
PV 2019 arXiv:1912.07550	N^{3}LL	✘	✘	✔	✔	353	1.02
MAP 2022 in preparation	N^{3}LL	✔	✔	✔	✔	2031	0.99

New unpolarized MAPTMD22 fit: kinematics



"***Global***" fit of ***unpolarized TMDs*** at ***N3LL*** accuracy

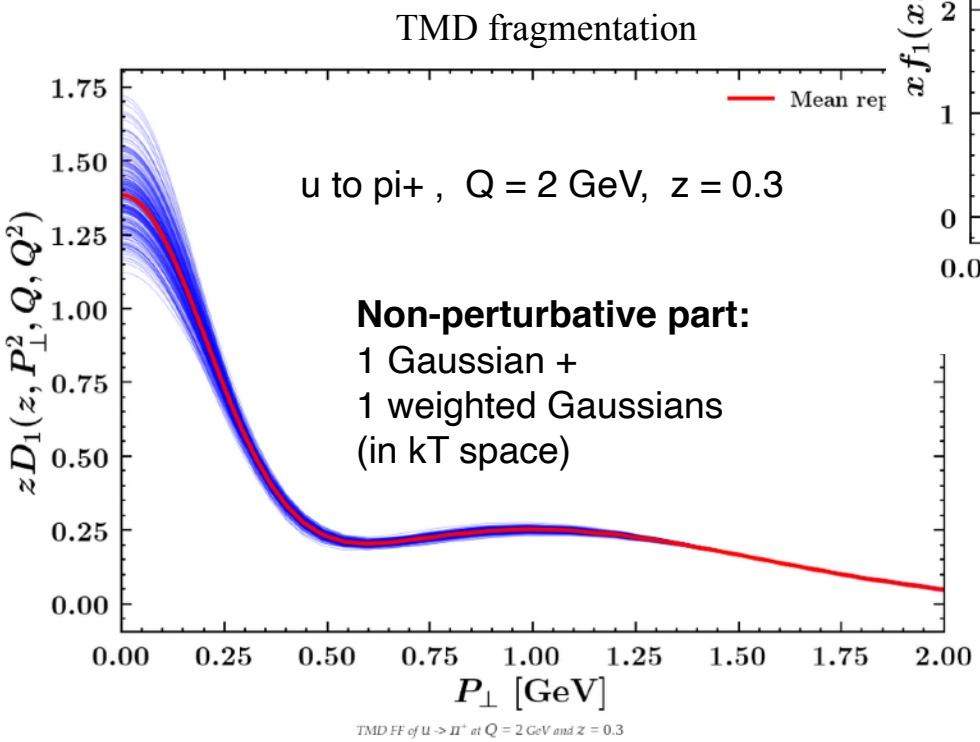
Drell-Yan / Z and **SIDIS** data

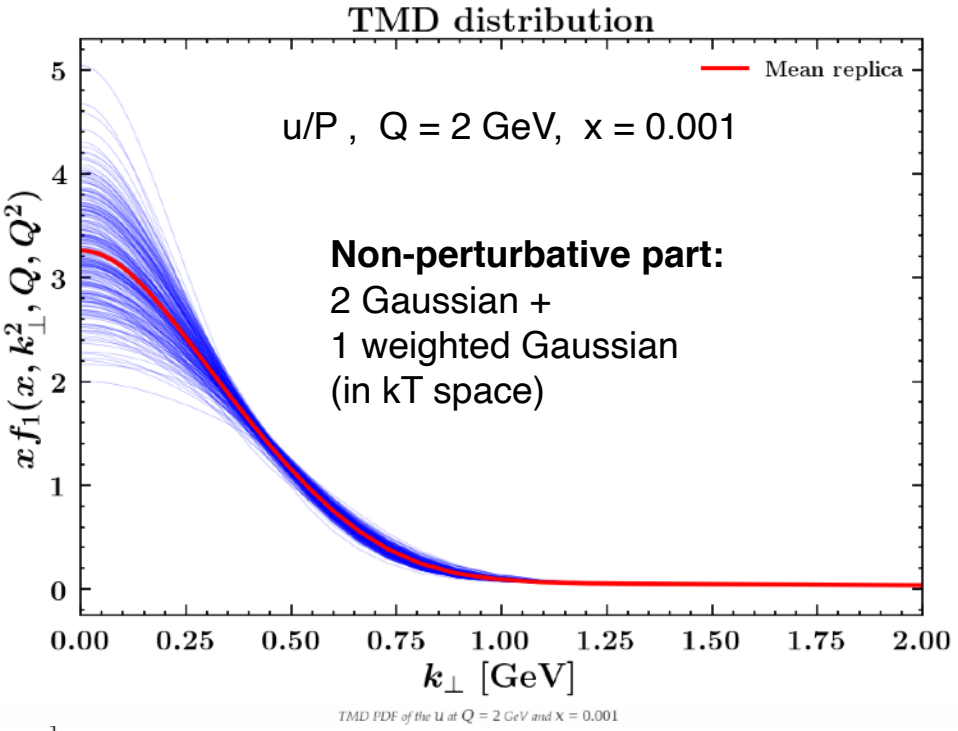
2031 data
21 parameters

In preparation

MAPTMD22 : TMDs

In preparation



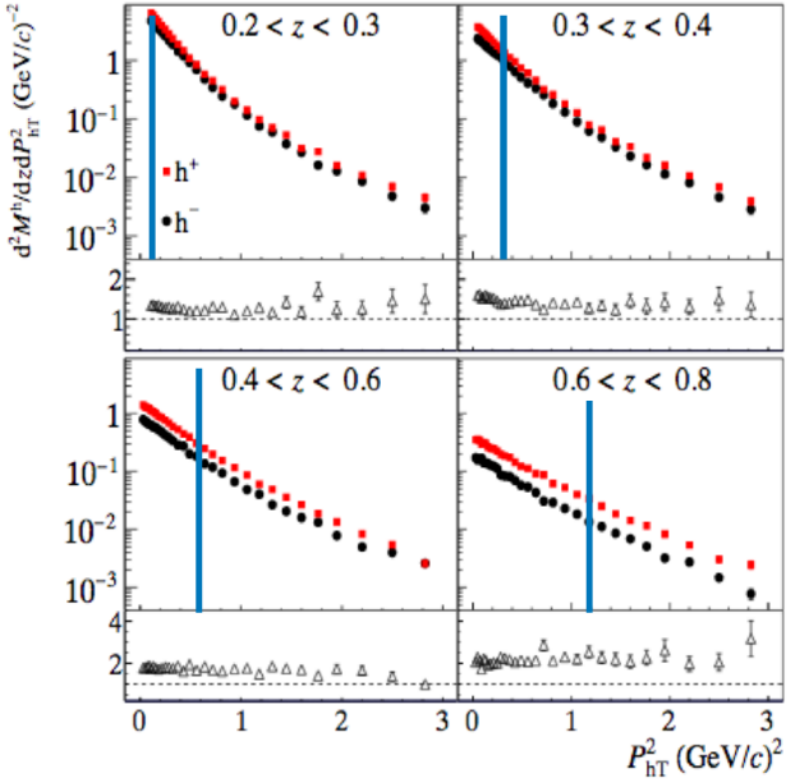


No TMD flavor dependence yet

(computationally much more demanding)

TMD region: low transverse momentum

$q_T \ll Q$



SIDIS - TMD region

$P_{hT}^2/z^2 \ll Q^2$

Let's highlight

$P_{hT}^2/z^2 \sim 0.25\ Q^2$

One of the bins with highest Q:

$\langle Q^2 \rangle = 9.78\ \mathrm{GeV}^2$

$\langle x \rangle = 0.149$

COMPASS unpolarized SIDIS multiplicities - arxiv 1709.07374

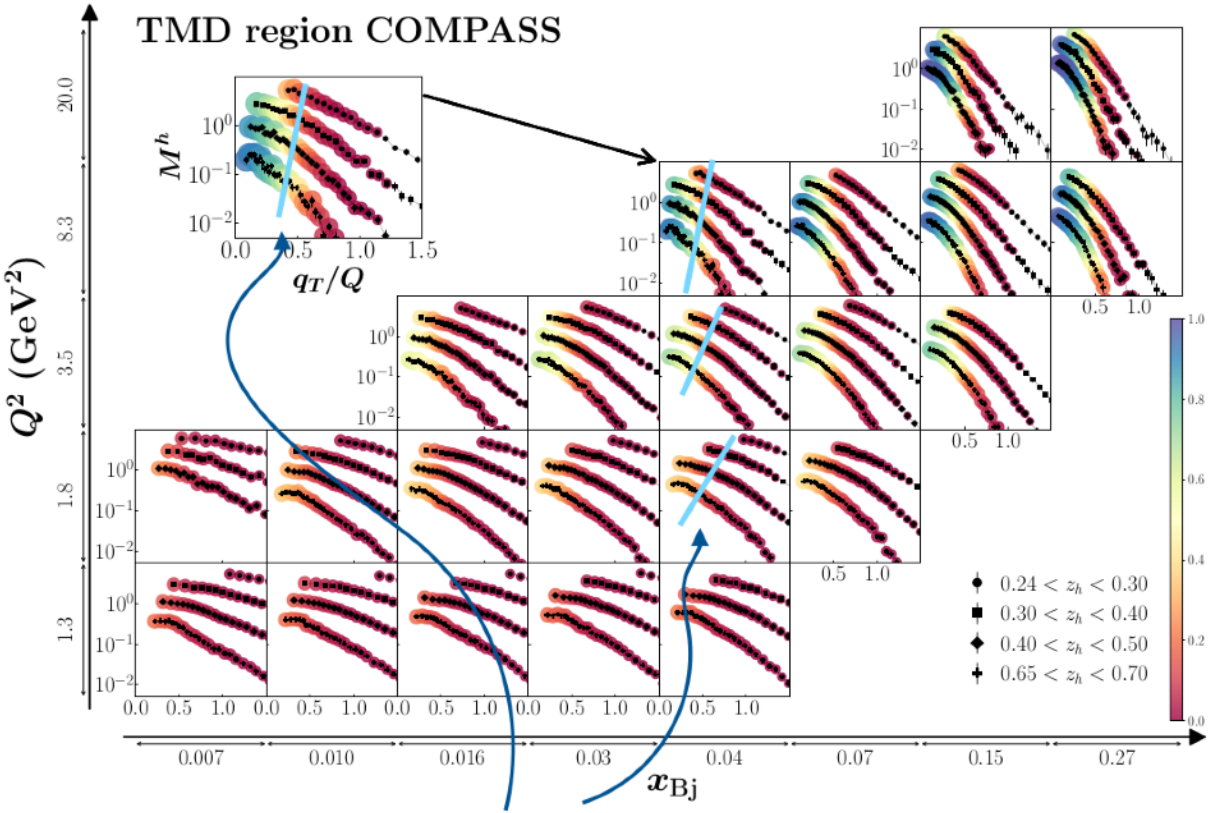
MAPTMD22 : TMD region

arXiv:2201.12197

see A. Bacchetta, recent "CLAS collaboration meeting"

MAPTMD22 implementation of TMD region for SIDIS:

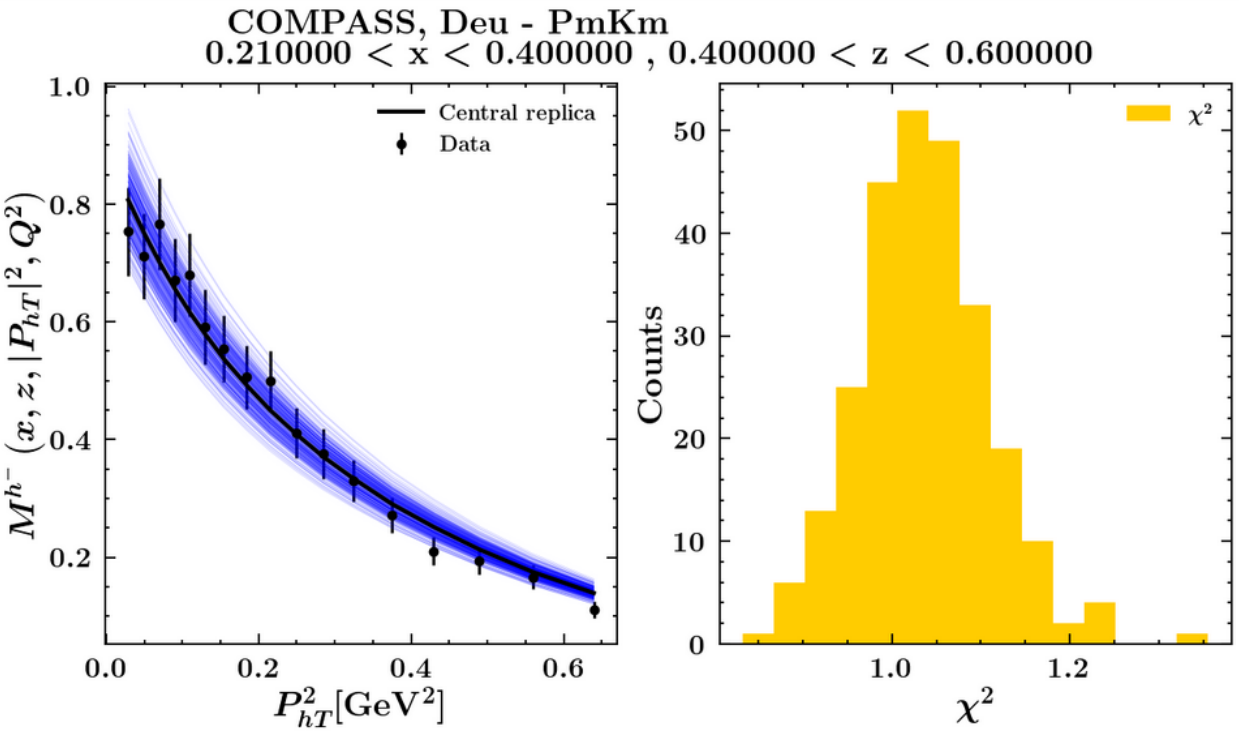
$q_T \leq Q$ ***at most***



Approximate region included in MAP22 fit

MAPTMD22 : comparison with data

In preparation



300 Monte Carlo replicas (bootstrap)

SIDIS data: overall satisfactory

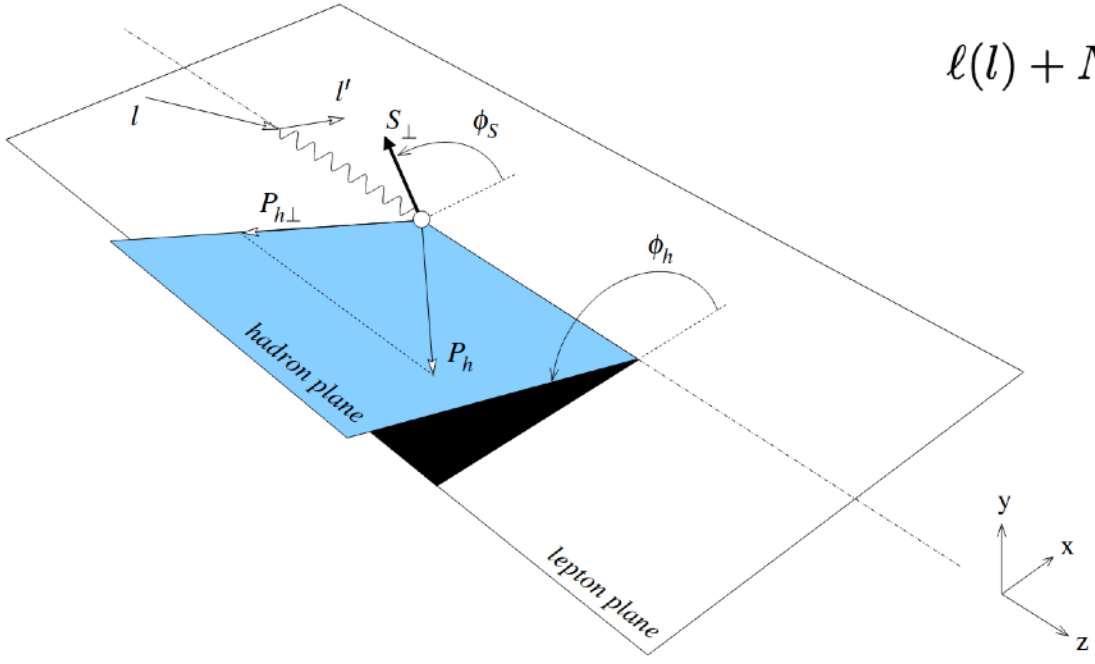
Drell-Yan data: *major problems with ATLAS data*

Short-term goal #2

Repeat the assessment of the theoretical vs experimental uncertainties for unpolarized SIDIS based on this new global analysis of unpolarized TMD

Longer-term goal #1

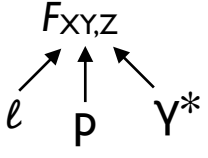
Repeat the assessment of the theoretical vs experimental uncertainties for Sivers effect based on this new global analysis of unpolarized TMD



$$\ell(l) + N(P) \rightarrow \ell(l') + h(P_h) + X,$$

hep-ph/0611265

$$F_{\dots}(x_B, z_h, P_{hT}^2, Q^2)$$



$$\frac{d\sigma}{dx_B dy d\phi_S dz_h d\phi_h dP_{hT}^2} = \frac{\alpha^2}{x_B y Q^2}\Big[A(y)\,F_{UU,T} + B(y)\,\cos 2\phi_h\,F_{UU}^{\cos 2\phi_h} + S_L\,\sin 2\phi_h\,F_{UL}^{\sin 2\phi_h} + \lambda_e\,S_L\,C(y)\,F_{LL}$$

$$+ S_T\Big[A(y)\,\sin(\phi_h - \phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)} + B(y)\,\sin(\phi_h + \phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ B(y)\,\sin(3\phi_h - \phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

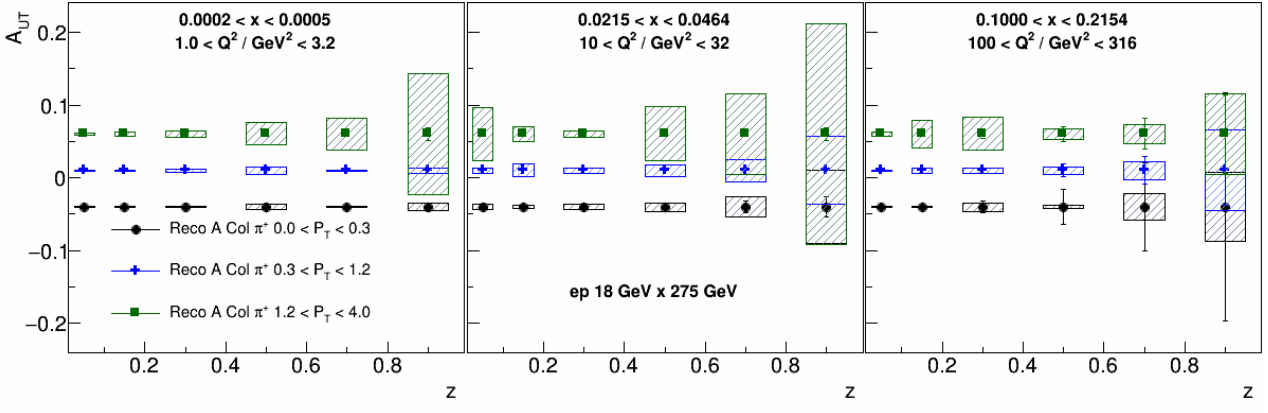
$$+ \lambda_e\,S_T\,C(y)\,\cos(\phi_h - \phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big] \quad + \mathcal{O}\left(\frac{M}{Q}\right)$$

Recent fits for transversity

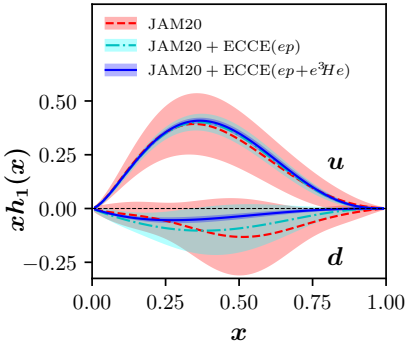
$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto \frac{F_{UT}^{\sin(\phi_h+\phi_S)}}{F_{UU}} \sim \frac{h_1 \otimes H_1^{\perp}}{f_1 \otimes D_1}$$

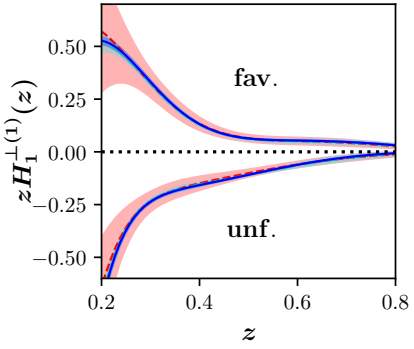
	Mechanism	Framework	SIDIS	e+e-	p-p collisions	N pts
PV 2018 arXiv:1802.05212	collinear DiFF	LO	✔	✔	✔	78
JAM 2020 arXiv:2002.08384	TMD Collins effect	generalized parton model	✔	✔	✔	517
MEX 2019 arXiv:1912.03289	collinear DiFF	LO	✔	✔	✘	68
CA 2020 arXiv:2001.01573	TMD Collins effect	generalized parton model	✔	✔	✘	76

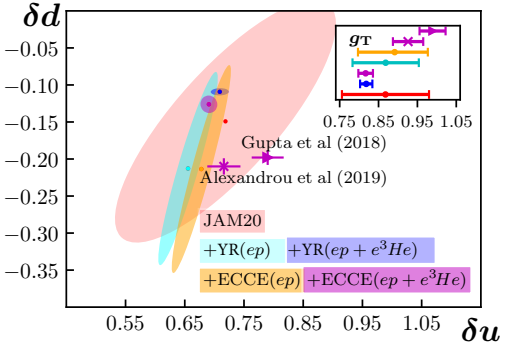
Expected uncertainties for Collins effect in selected bins



transversity impact studies: JAM 20







ECCE Detector proposal (2021)

Recent fits for transversity

$$A_{UT}^{\sin(\phi_R+\phi_S)} \propto \frac{h_1 H_1^{\sphericalangle}}{f_1 D_1}$$

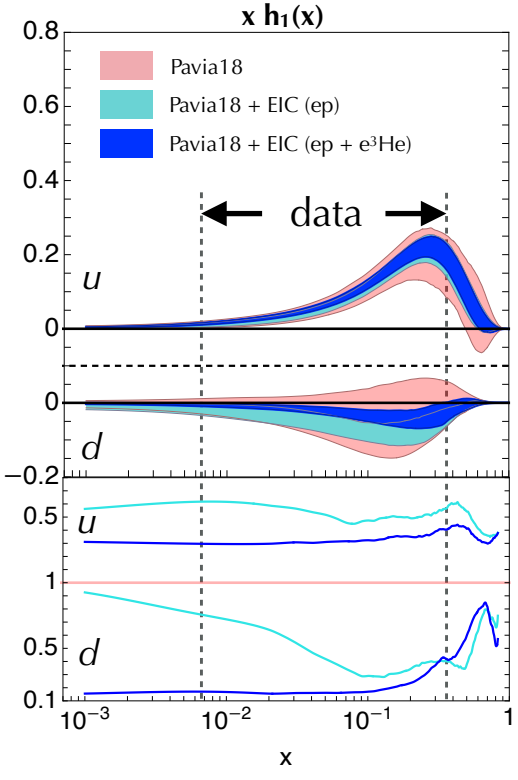
DiFFs

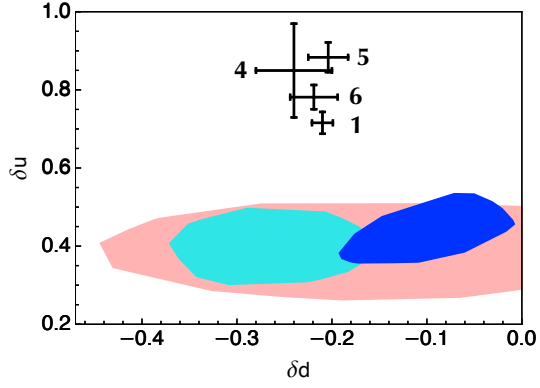
collinear framework

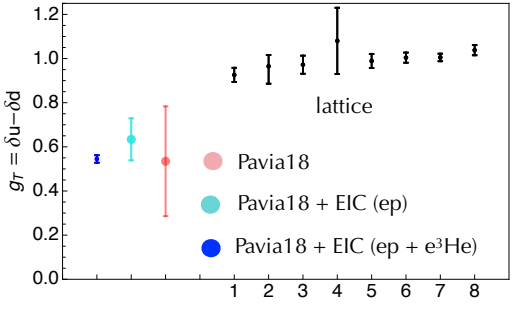
	Mechanism	Framework	SIDIS	e+e-	p-p collisions	N pts
PV 2018 arXiv:1802.05212	collinear DiFF	LO	✔	✔	✔	78
JAM 2020 arXiv:2002.08384	TMD Collins effect	generalized parton model	✔	✔	✔	517
MEX 2019 arXiv:1912.03289	collinear DiFF	LO	✔	✔	✘	68
CA 2020 arXiv:2001.01573	TMD Collins effect	generalized parton model	✔	✔	✘	76

transversity impact studies: PV 18

EIC Yellow Report arXiv:2103.05419







$\mathcal{L}$=10 fb^{-1} , 3852 data pts,
proton&^{3}He [GeV]: 10x100

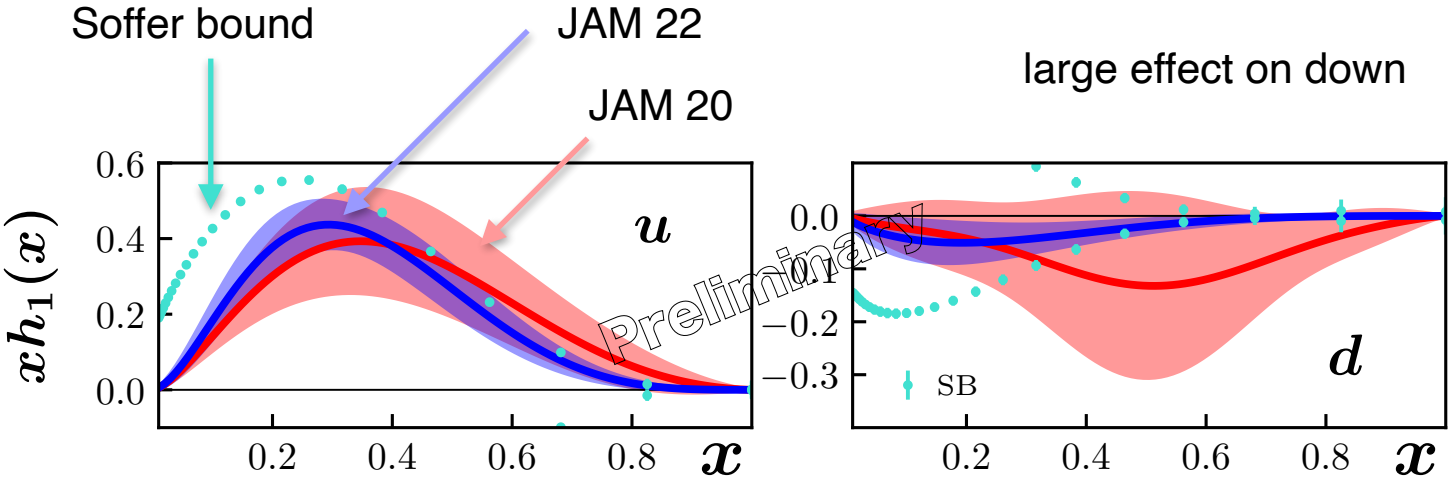
Lattice results

1)	**ETMC '19**	*Alexandrou et al., arXiv:1909.00485*
2)	**Mainz '19**	*Harris et al., P.R. D**100** (19) 034513*
3)	**LHPC '19**	*Hasan et al., P.R. D**99** (19) 114505*
4)	**JLQCD '18**	*Yamanaka et al., P.R. D**98** (18) 054516*
5)	**PNDME '18**	*Gupta et al., P.R. D**98** (18) 034503*
6)	**ETMC '17**	*Alexandrou et al., P.R. D**95** (17) 114514; (E) P.R. D**96** (17) 099906*
7)	**RQCD '14**	*Bali et al., P.R. D**91** (15) 054501*
8)	**LHPC '12**	*Green et al., P.R. D**86** (12) 114509*

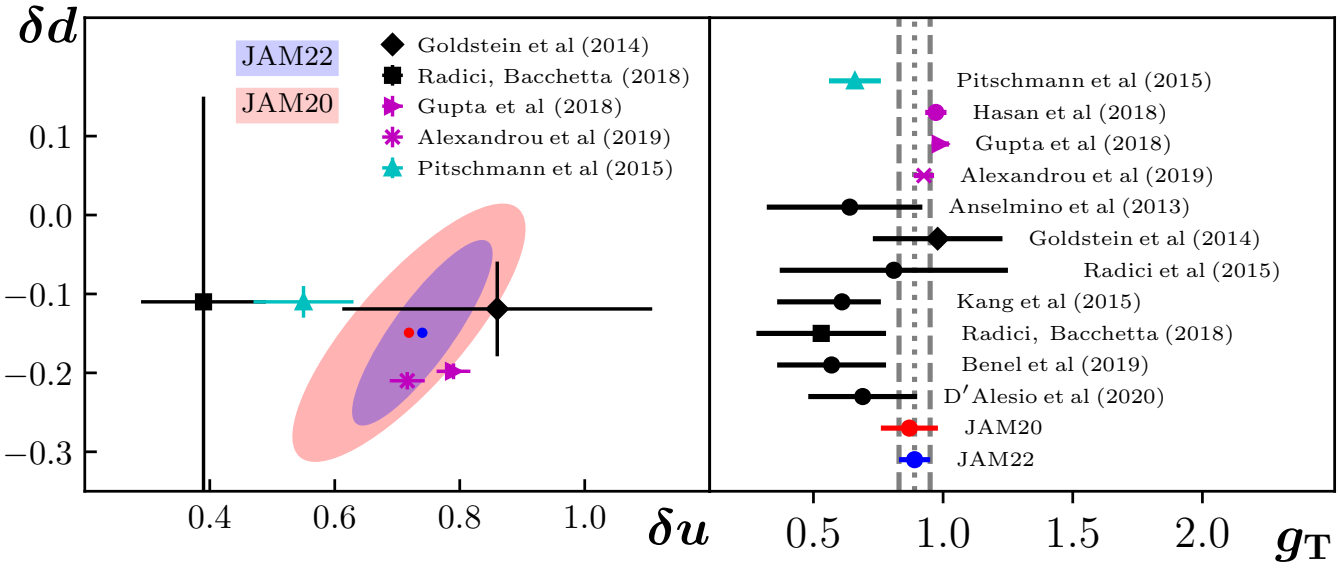
New analysis: JAM 22

In preparation

- compatible with **Soffer bound**
- fit constrained by **lattice** results for **tensor charges**



Tensor charge



- results compatible with Soffer bound
- **compatibility with lattice by construction**
- **tension** with **DiFF** extraction more pronounced

Longer-term goal

Update the assessment of the theoretical vs experimental uncertainties for transversity extraction with both Collins and DiFF methods