Diffraction and Low-x

8-14 Sept. 2024
Hotel Tonnara Trabia, Palermo, Sicily

The 3D structure of the Nucleon in momentum space: TMD phenomenology

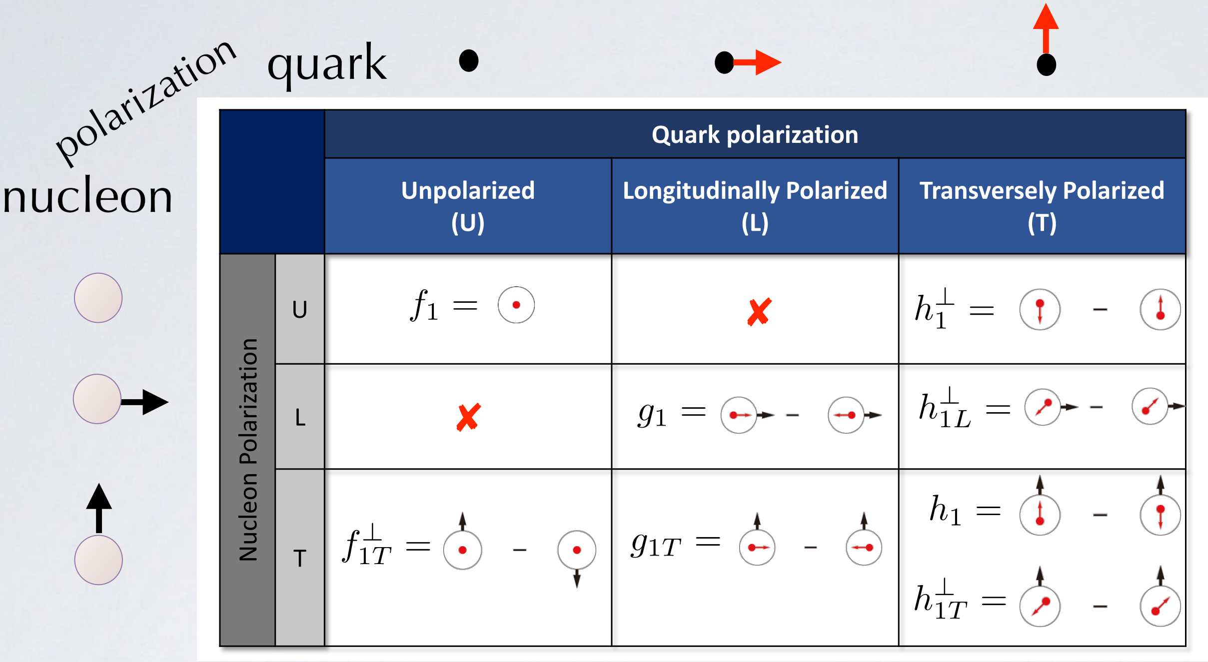
INFN
Istituto Nazionale
di Fisica Nucleare
Sezione Pavia

Marco Radici

The TMD "zoo" at leading twist for spin-1/2 hadron

(similar for gluon)

Mulders & Tangerman, N.P. **B461** (96)
Boer & Mulders, P.R. **D57** (98)



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$ ⊙	✘	$h_1^\perp =$ ⊙ - ⊙
	L	✘	$g_1 =$ ⊙ - ⊙	$h_{1L}^\perp =$ ⊙ - ⊙
	T	$f_{1T}^\perp =$ ⊙ - ⊙	$g_{1T} =$ ⊙ - ⊙	$h_1 =$ ⊙ - ⊙ $h_{1T}^\perp =$ ⊙ - ⊙

Boer-Mulders

Kotzinian-Mulders

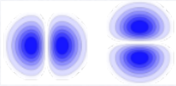
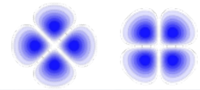
transversity

pretzelosity

Sivers worm-gear

similar table for TMDFF (z, $\mathbf{P}_\perp$; Q²) at leading twist for hadron with spin ≤ 1/2

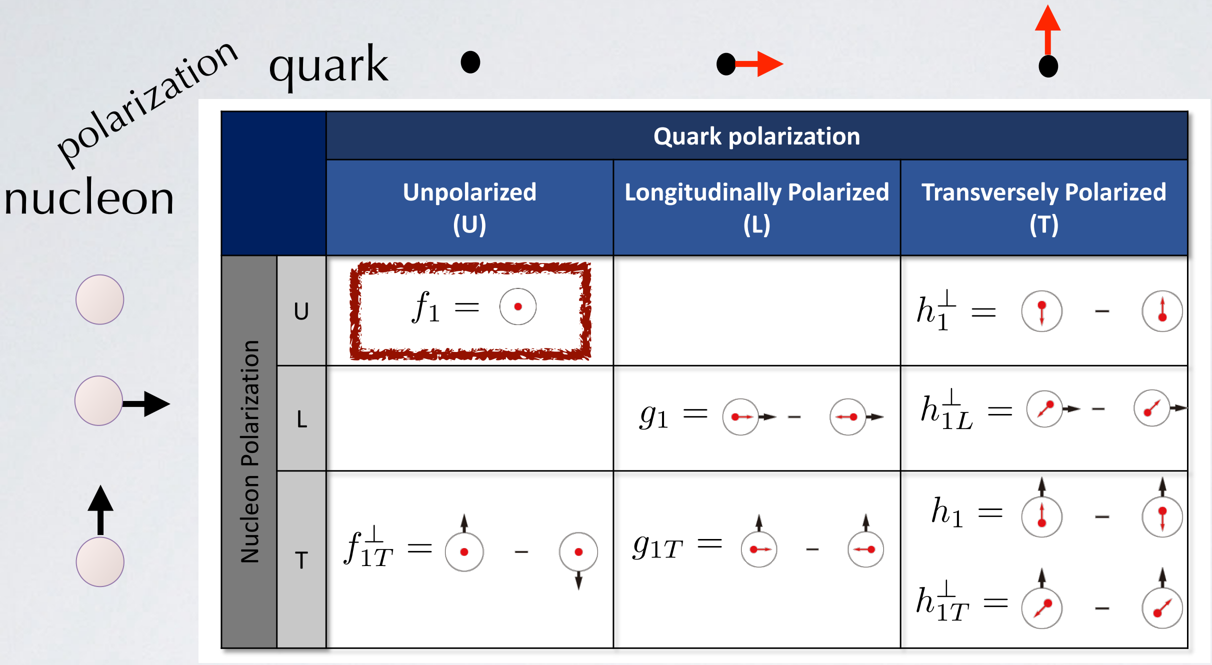
Each entry:
- has a probabilistic interpretation; ✘ = forbidden by parity invariance
- is connected to deformations induced by spin-momentum correlations

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

- **can be extracted from a specific measurable spin asymmetry**

(see next talks)

The unpolarized quark TMD



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ −
	L		$g_1 =$ −	$h_{1L}^\perp =$ −
	T	$f_{1T}^\perp =$ −	$g_{1T} =$ −	$h_1 =$ − $h_{1T}^\perp =$ −

Mulders & Tangerman, N.P. **B461** (96)
Boer & Mulders, P.R. D**57** (98)

Let's focus on the simplest unpolarized TMD PDF:

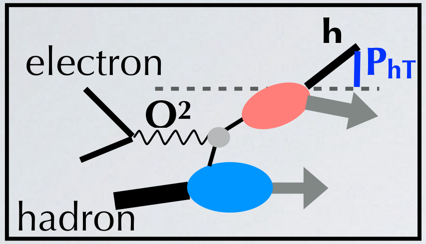
$f_1{}^q$ = probability density to find an unpolarized quark q with light-cone momentum fraction x and transverse momentum $\mathbf{k}_\perp$ in an unpolarized hadron

It enters the denominator of every spin asymmetry needed to extract the other polarized TMDs:

$$A = \frac{d\sigma(\text{pol.}) - d\sigma(-\text{pol.})}{d\sigma(\text{pol.}) + d\sigma(-\text{pol.}) \equiv d\sigma^0}$$

Phase space for processes with factorization

SIDIS



$M^2 \ll Q^2 \quad q_T^2 = \frac{P_{hT}^2}{z^2} \ll Q^2$

Fourier Transf. to b_T space:
from convolution to simple product

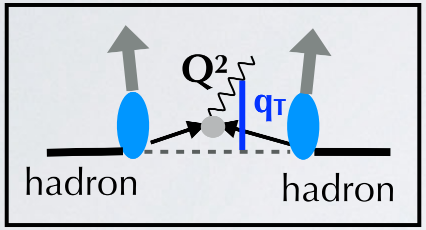
$$\frac{d\sigma}{dxdzdq_TdQ} \sim \mathscr{H}^{\text{SIDIS}}(Q^2)\, \frac{1}{2\pi}\int_0^\infty db_T\, b_T\, J_0(b_T, q_T)\;\; \tilde{f}_1^q(x, b_T^2; Q^2)\;\; \tilde{D}_1^{q\to h}(z, b_T^2; Q^2)$$

hard part

TMDPDF

TMDFF

Drell-Yan



$M^2 \ll Q^2 \quad q_T^2 \ll Q^2$

$$\frac{d\sigma}{dq_TdydQ} \sim \mathscr{H}^{\text{DY}}(Q^2)\, \frac{1}{2\pi}\int_0^\infty db_T\, b_T\; J_0(b_T, q_T)\;\; \tilde{f}_1^{\bar{q}}(x_A, b_T^2; Q^2)\;\; \tilde{f}_1^q(x_B, b_T^2; Q^2)$$

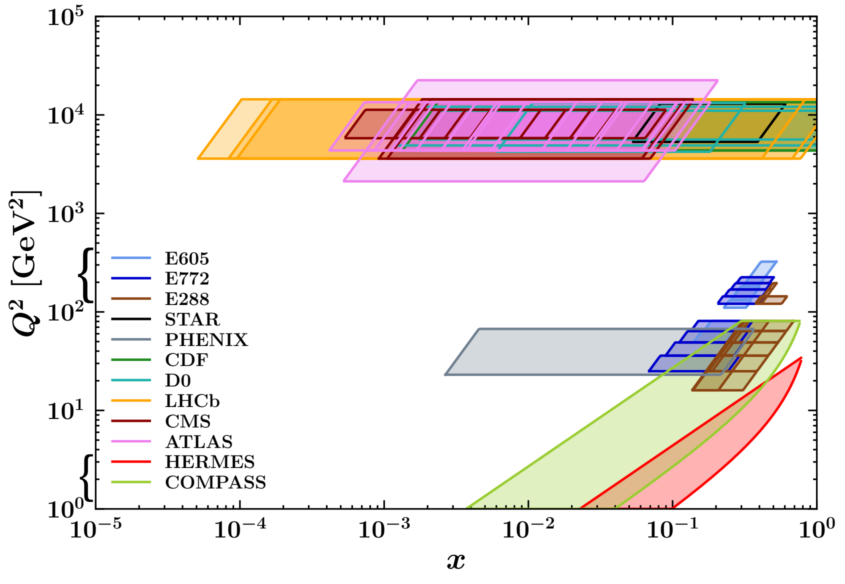
hard part

TMDPDF

TMDPDF

Drell Yan { fixed target
collider

SIDIS



Evolution of TMDs

Collins - Soper - Sterman (CSS) evolution

$$\tilde{f}_1(x, b_T^2; Q_f^2) = \quad \text{Evo}(Q_f \leftarrow Q_i) \times \tilde{f}_1(x, b_T^2; Q_i^2)$$

small b_T

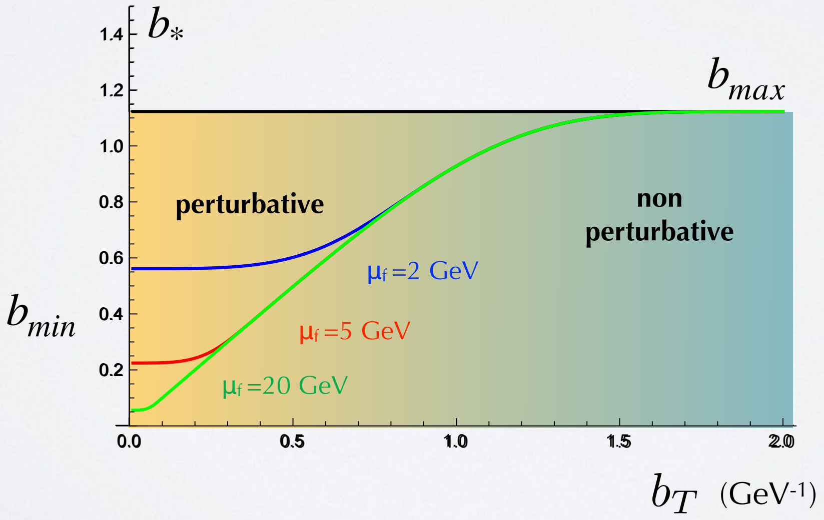
OPE

large b_T ?

$$\left[C \otimes f_1(x, Q_i^2)\right]$$

PDF

Evolution operator,
Wilson Coefficient C,
are all perturbatively
calculable



Evolution of TMDs

Collins - Soper - Sterman (CSS) evolution

$$\tilde{f}_1(x, b_T^2; Q_f^2) = \quad \text{Evo}(Q_f \leftarrow Q_i) \times \tilde{f}_1(x, b_T^2; Q_i^2) \quad \times \quad \tilde{f}_{NP}(x, b_T^2; Q_0^2)$$

small b$_T$

OPE

$$\left[C \otimes f_1(x, Q_i^2)\right]$$

PDF

large b$_T$

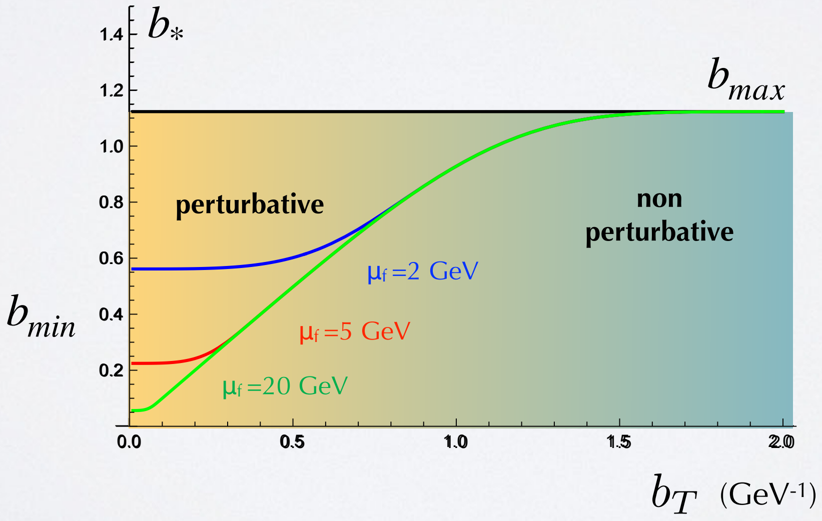
$$\lim_{b_T \to 0} \tilde{f}_{NP}(x, b_T^2; Q_0^2) = 1$$

Evolution operator,
Wilson Coefficient C,
are all perturbatively
calculable

smooth connection b*(b$_T$)

$$Q_i \propto 1 / b_*(b_T)$$

parametrized and
fitted to data



Most recent extractions of unpolarized TMD f_1

	Accuracy	SIDIS HERMES	SIDIS 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	$N^3LL(-)$	✔	✔	✔	✔	1039	1.06
PV 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.07
SV19 + flavor dep. arXiv:2201.07114	N^3LL	✘	✘	✔	✔	309	<1.08>
MAPTMD 2022 arXiv:2206.07598	$N^3LL(-)$	✔	✔	✔	✔	2031	1.06
ART23 arXiv:2305.07473	N^4LL	✘	✘	✔	✔	627	0.96
MAPTMD 2024 arXiv:2405.13833	N^3LL	✔	✔	✔	✔	2031	1.08

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increasing accuracy & precision

Most recent extractions of unpolarized TMD f_1

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only four global fits

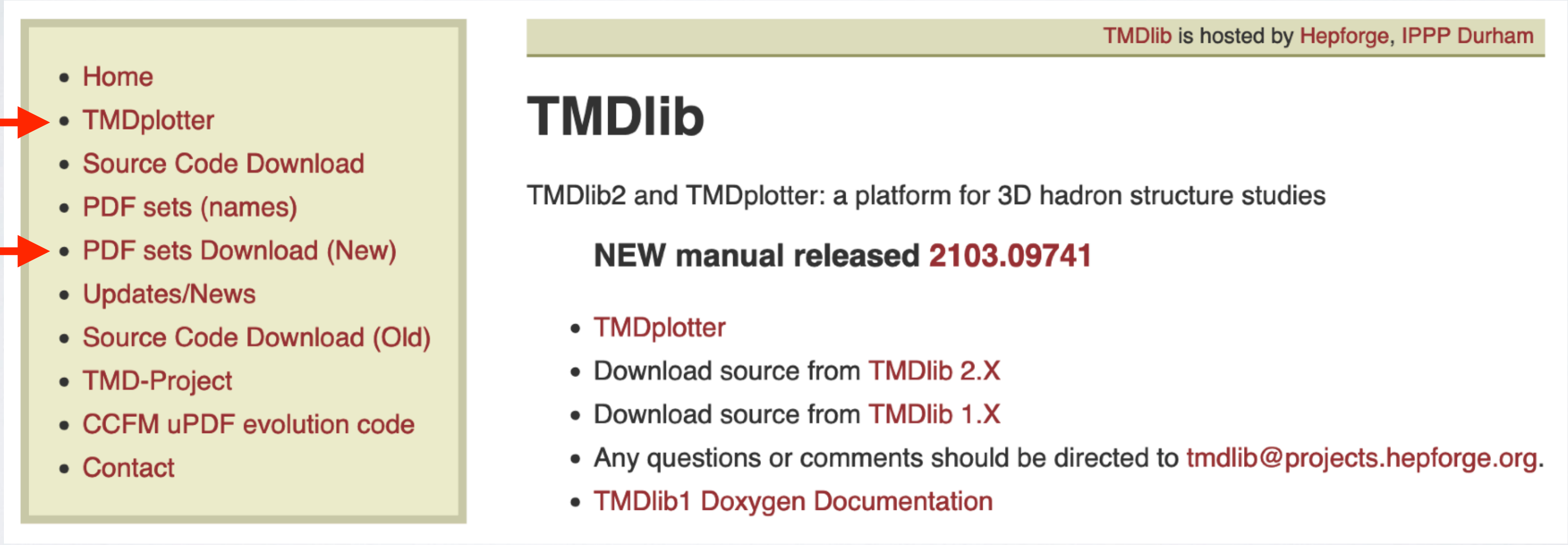
increasing accuracy & precision

The TMDlib repository

(Some) Tables of TMD grids available also at the TMDlib repository

TMD plotter

https://tmdlib.hepforge.org/



TMDlib is hosted by Hepforge, IPPP Durham

- Home
- TMDplotter
- Source Code Download
- PDF sets (names)
- PDF sets Download (New)
- Updates/News
- Source Code Download (Old)
- TMD-Project
- CCFM uPDF evolution code
- Contact

TMDlib

TMDlib2 and TMDplotter: a platform for 3D hadron structure studies

NEW manual released 2103.09741

- TMDplotter
- Download source from TMDlib 2.X
- Download source from TMDlib 1.X
- Any questions or comments should be directed to tmdlib@projects.hepforge.org.
- TMDlib1 Doxygen Documentation

Example: search for - MAP22_grids_PDF_[NLL/NNLL/N3LL].tgz

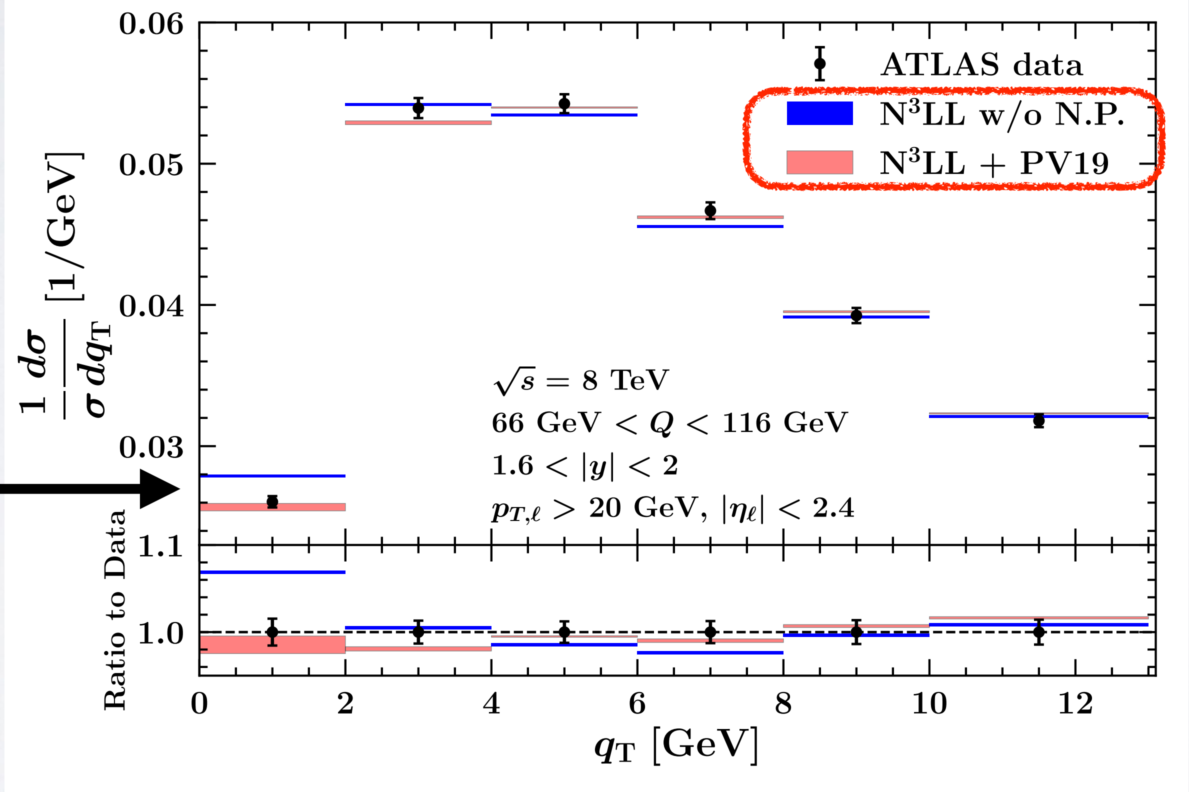
- MAP22_grids_FF_[Pip/Pim/Kp/Km]_[NLL/NNLL/N3LL].tgz

TMD precision era: impact at the LHC

G. Bozzi, I. Scimemi (eds.) et al.,
Resummed predictions of the transverse momentum distribution of Drell-Yan lepton pairs in p-p collisions at LHC
Yellow Report of CERN EW Working Group, in preparation

q_T distribution of Z in ATLAS kin.

effect of intrinsic parton $k_\perp$ from PV 2019 fit



also potential impact on W mass extraction

Bacchetta et al., P.L. **B788** (19) 542, arXiv:1807.02101

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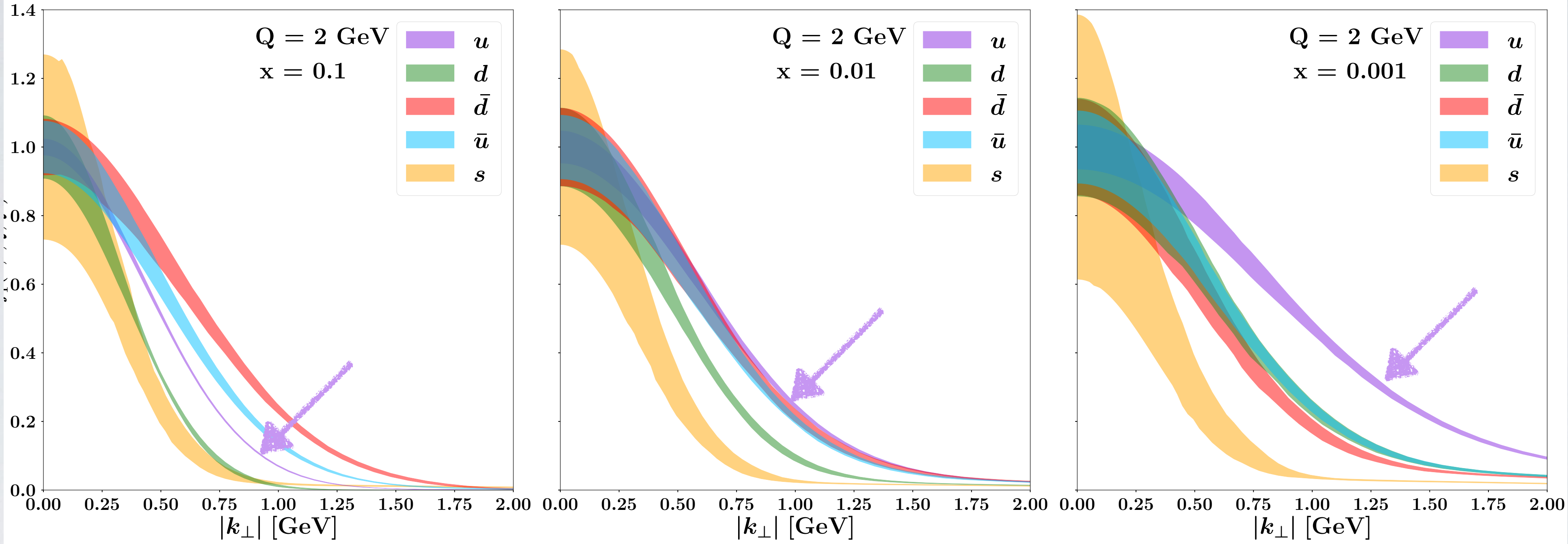
MAPTMD 2024 arXiv:2405.13833	N^3LL	✓	✓	✓	✓	2031	1.08

MAPTMD24 : introduce **flavor sensitivity of k_T-dependence**

“Normalized” MAPTMD24 TMD PDF

$$\frac{f_1(x,k_T;Q)}{f_1(x,0;Q)}$$



th. error band =
68% of all replicas

- very different k_T behavior
- it changes with x
- impact on the extraction of W mass parameter from collider data

Bacchetta et al., P.L. **B788** (19) 542, arXiv:1807.02101
Bozzi & Signori, Adv.HighEn.Phys. **2019** (19) 2526897, arXiv:1901.01162

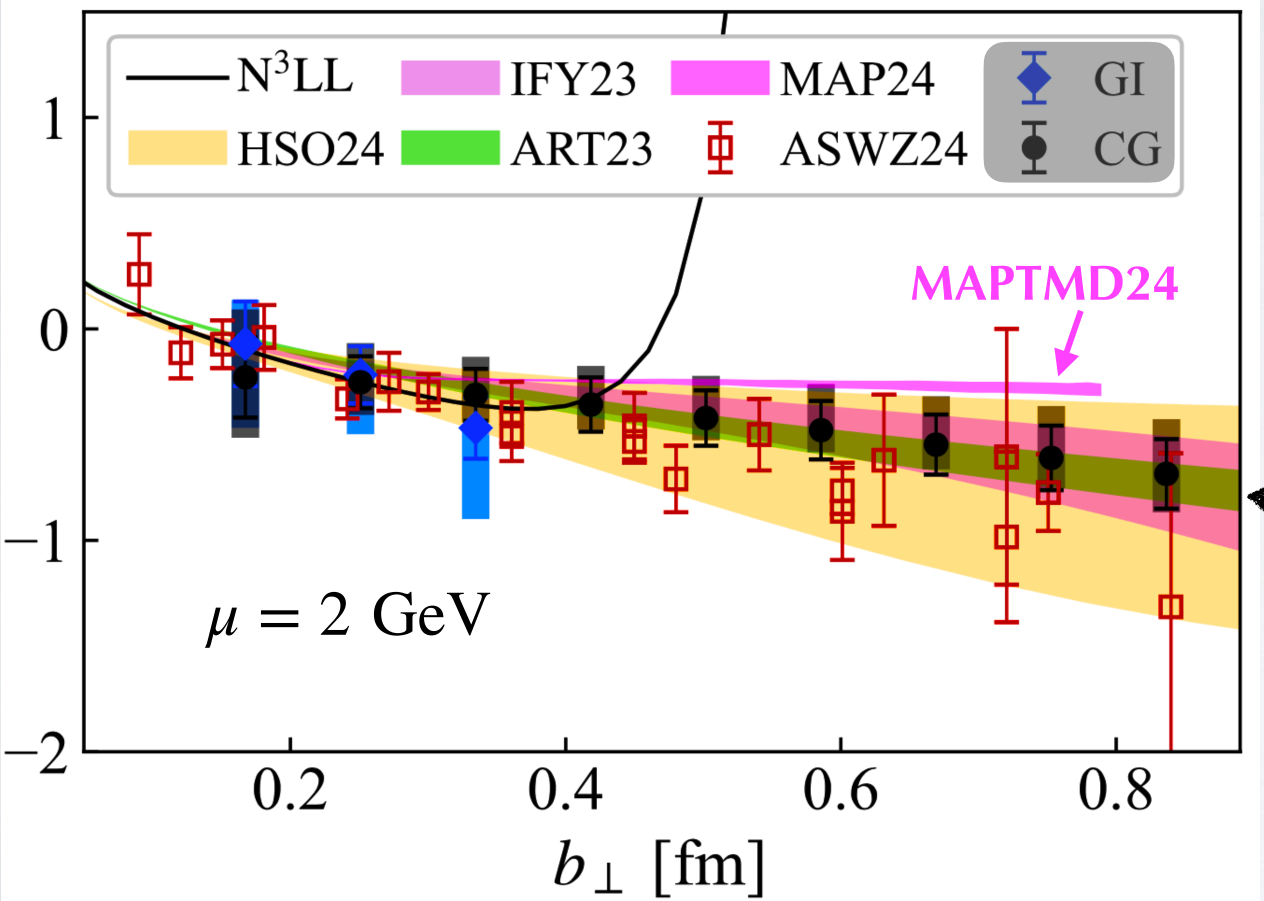
Collins-Soper evolution kernel

universal flavor-independent $K(b_T, \mu_{b_*}) = K(b_*, \mu_{b_*}) + g_K(b_T)$

drives evolution in rapidity ζ

perturbative (computed)

non-perturbative (fitted)



S. Mukherjee, QCD Evolution 2024

N^{3}LL Vladimirov, arXiv:1610.05791
Li&Zhu, arXiv:1604.01404

Pheno

HSO24 Aslan et al., arXiv:2401.14266

IFY23 Isaacson et al., arXiv:2311.09916

ART23 Moos et al., arXiv:2305.07473

MAPTMD22 ~ ART23

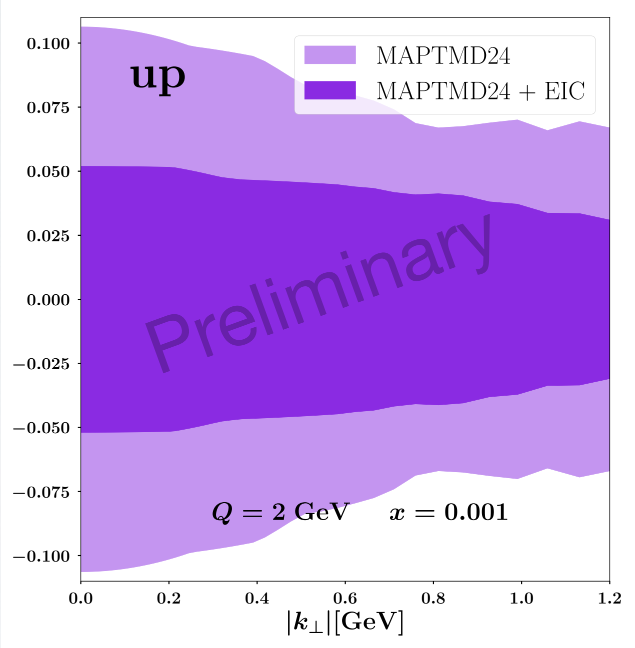
Lattice

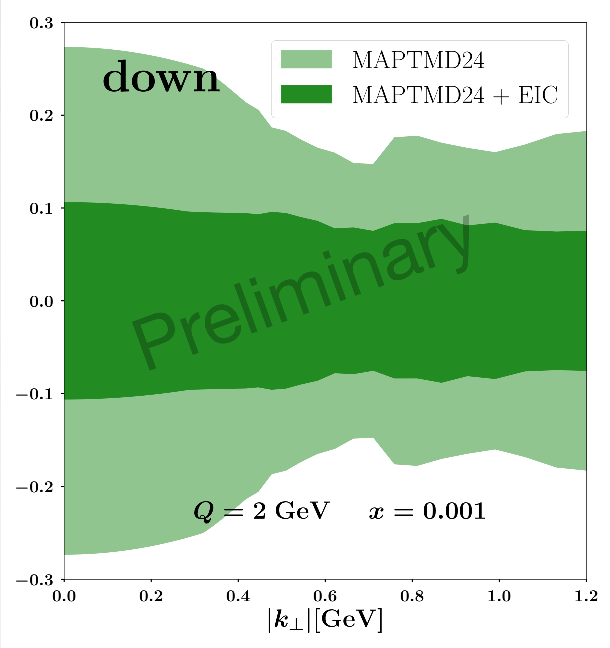
GI, CG Bollweg et al., arXiv:2403.00664

ASWZ24 Avkhadiev et al., arXiv:2402.06725

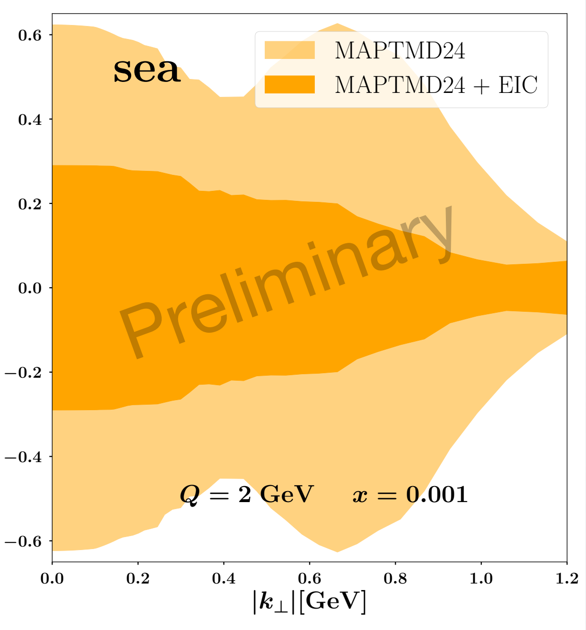
talks by Mukherjee
Cichy

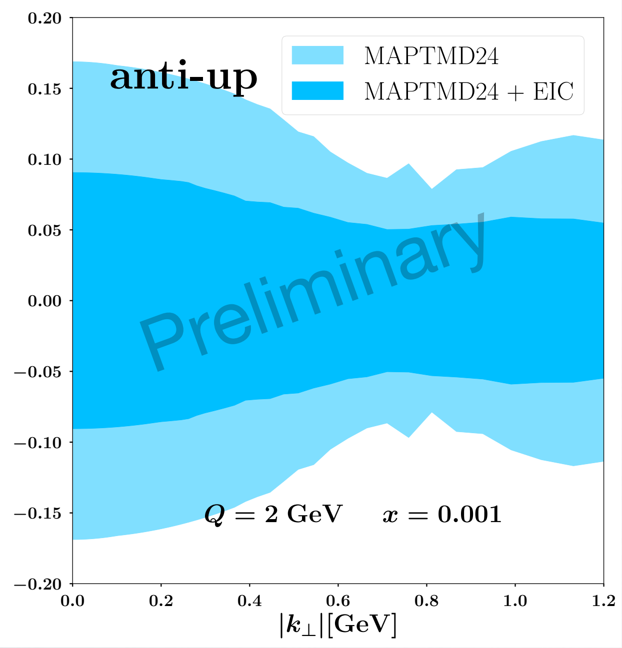
The EIC impact

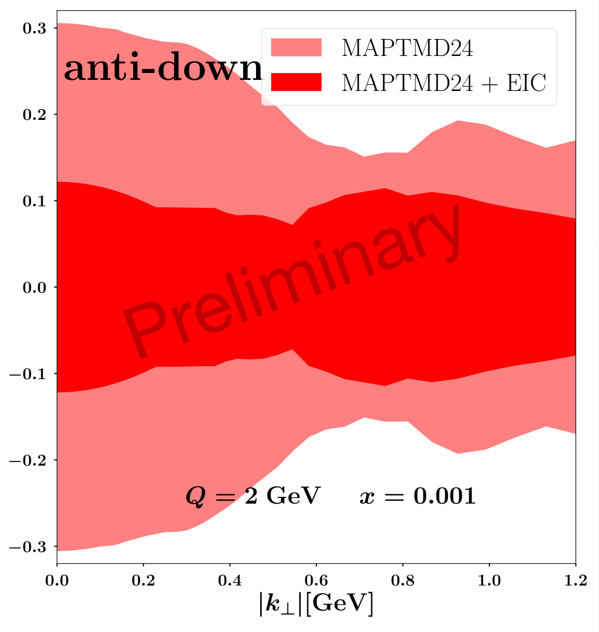




	# pts.
MAPTMD24	2031
EIC	
5x41	1273
10x100	1611
18x275	1648

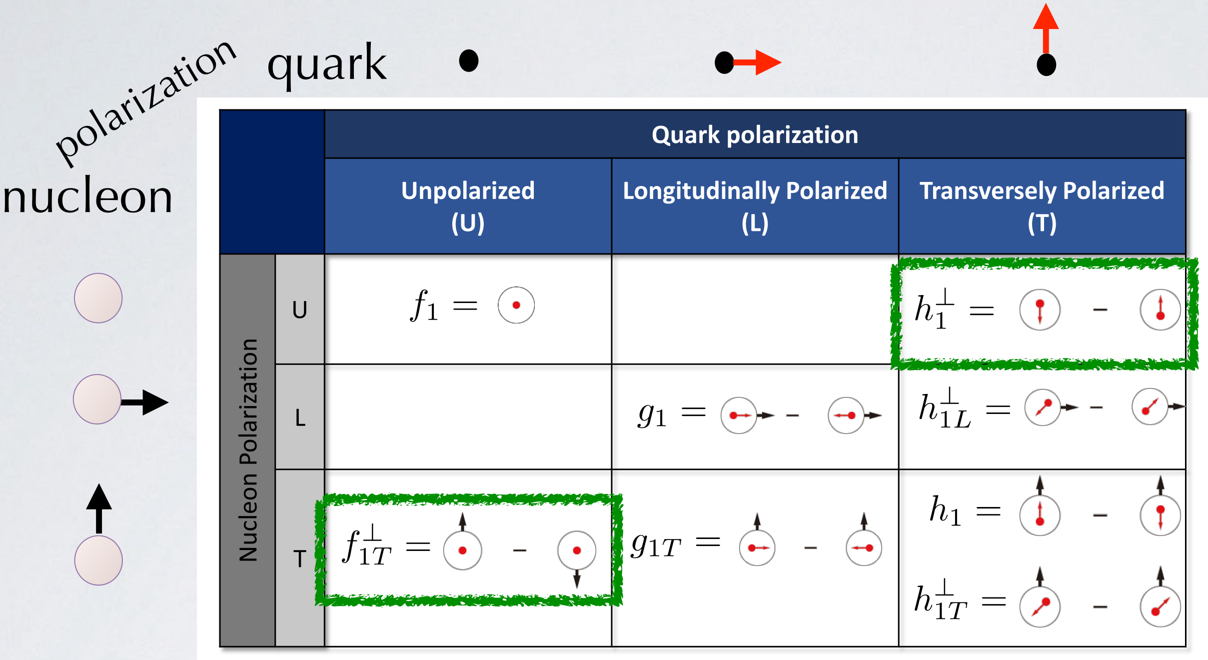






L. Rossi, Ph.D. Thesis, in preparation

The TMD “zoo” at leading twist for spin-1/2 hadron



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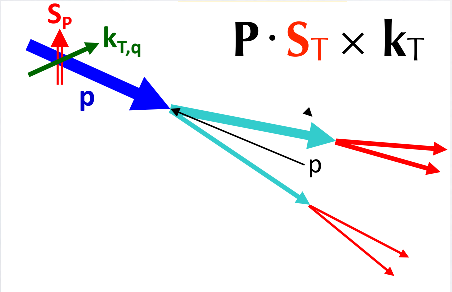
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

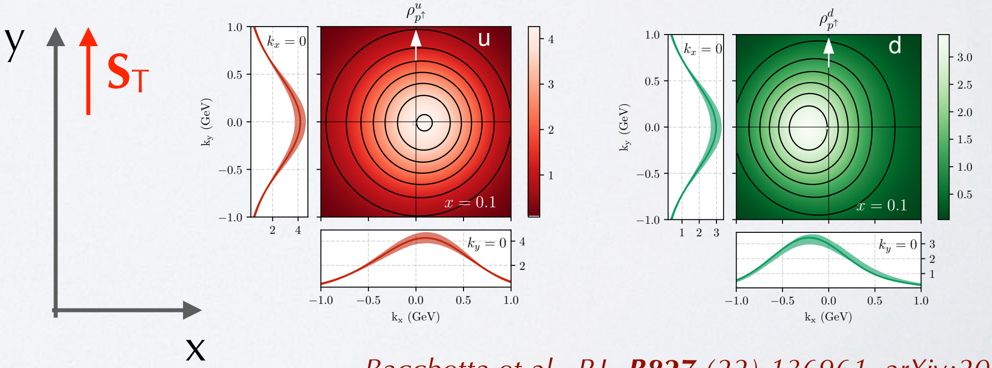
non universal, but process dependence calculable
→ exp. test of QCD

Sivers effect



$\mathbf{P}\cdot\mathbf{S}_T\times\mathbf{k}_T$

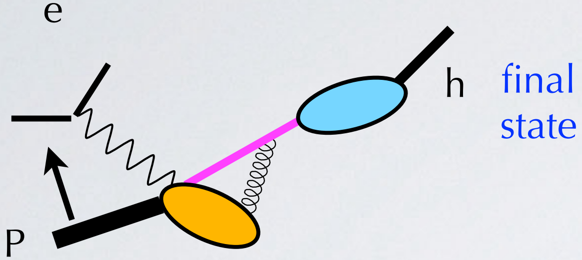
distortion of quark momentum distribution by nucleon spin



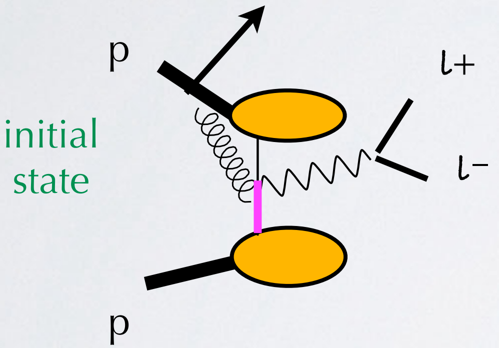
*Bacchetta et al., P.L. **B827** (22) 136961, arXiv:2004.14278*

The Sivers TMD is not universal

SIDIS



in SIDIS, the color structure describes the residual **final-state** interactions between the **struck parton** and the **residual spectators**



Drell-Yan

in Drell-Yan, the color structure describes the **initial-state** interactions between the **annihilating parton** and the **residual spectators**

Prediction of QCD based on general principles:

Sivers TMD (SIDIS) = – Sivers TMD (Drell-Yan)

The Sivers TMD is connected to the spin Odderon

spin-dependent T-odd part of dipole amplitude

spin Odderon

$$\frac{1}{N_c}\int d\mathbf{y}_T\, e^{i\,\mathbf{k}_T\cdot\mathbf{y}_T}\langle P,S_T|\,\mathrm{Tr}\left[U(\mathbf{y}_T/2)\,U^{\dagger}(-\mathbf{y}_T/2)\right]|\,P,S_T\rangle \;\propto\; \frac{\mathbf{P}\cdot\mathbf{S}_T\times\mathbf{k}_T}{M}\,O_{1T}^{\perp}(x,\mathbf{k}_T^2)$$

Wilson line $U(\mathbf{x}_T) = \mathscr{P}e^{ig\int_{-\infty}^{\infty}dx^-\,A_+(x^-,\,\mathbf{x}_T)}$

C-odd t-channel gluonic compound exchange

at small x

$$\boxed{x\,f_{1T}^{\perp}(x,\mathbf{k}_T^2)} = \frac{N_c}{8\pi^4}\int d\xi\int d\mathbf{y}_T\,\frac{\mathbf{y}_T\cdot\mathbf{k}_T}{\mathbf{k}_T^2}\boxed{O_{1T}^{\perp}(x,\mathbf{y}_T^2)}\,C(\mathbf{y}_T,\mathbf{k}_T;\xi) \searrow$$

perturbatively calculable

Sivers

spin Odderon

Dong et al., P.L. **B788** (19) 401, arXiv:1805.09479
Kovchegov & Santiago, JHEP **11** (21) 200 [E **09** (22) 186], arXiv:2108.03667

similarly for gluons Boer et al., P.R.L. **116** (16) 122001, arXiv:1511.03485

Prediction: C-odd spin Odderon $\Rightarrow$ q Sivers = $-\bar{q}$ Sivers
test existence of spin Odderon

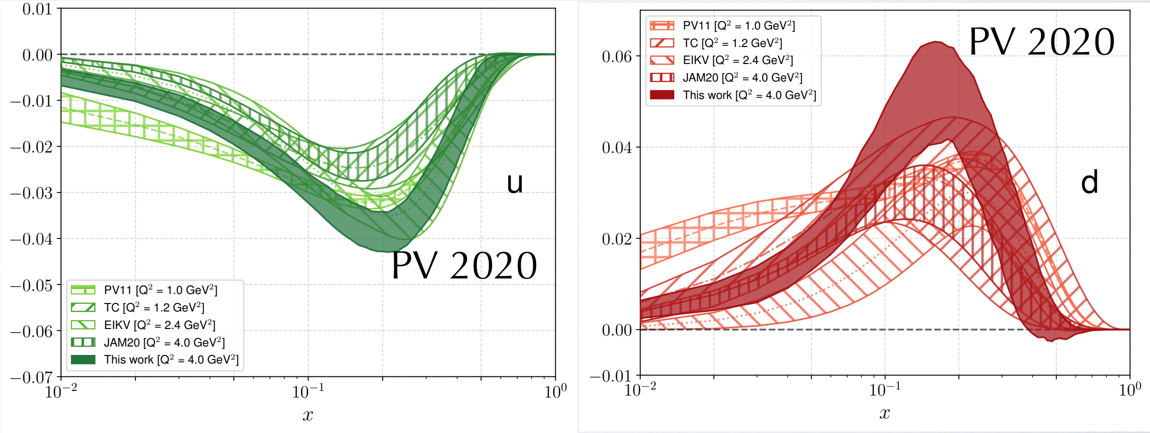
Most recent Sivers extractions

	Framework	SIDIS	DY	W/Z production	forward EM jet	e+e-	N. of points	χ^2/N	
JAM 2020 arXiv:2002.08384	generalized parton model	✔	✔	✔	✘	✔	517	1.04	
PV 2020 arXiv:2004.14278	LO+NLL	✔	✔	✔	✘	✘	125	1.08	
EKT 2020 arXiv:2009.10710	NLO+N^{2}LL	✔	✔	✔	✘	✘	226/452	0.99 /1.45	SIDIS / +STAR
BPV 2020 arXiv:2012.05135 arXiv:2103.03270	ζ prescription	✔	✔	✔	✘	✘	76	0.88	
TO-CA 2021 arXiv:2101.03955	generalized parton model	✔	✘	✘	✔	✘	238	$1.05^{+0.03}_{-0.01}$	SIDIS + reweighting

lower accuracy and less data w.r.t. unpolarized TMD

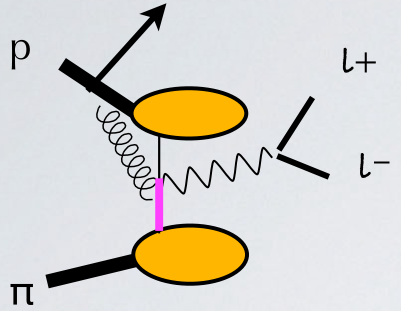
all parametrizations are in fair agreement for valence flavors

sea-quarks ~ $O(10^{-3})$ smaller



Bacchetta et al., P.L. ***B827*** *(22) 136961 arXiv:2004.14278*

Sign change puzzle



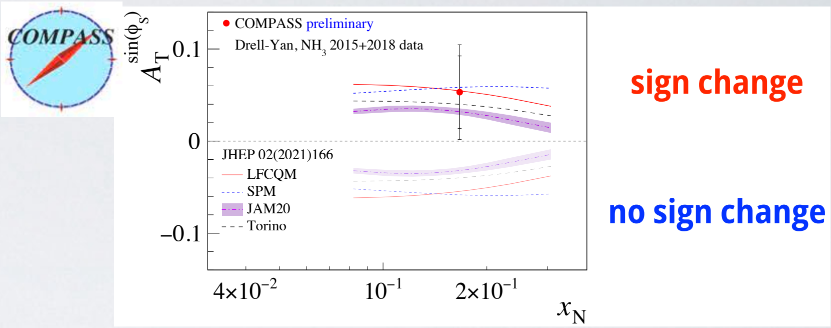
π-p↑ Drell-Yan

spin asymmetry

AT ~ $f_{1,\pi} \otimes f_{1T,p}^{\perp}$

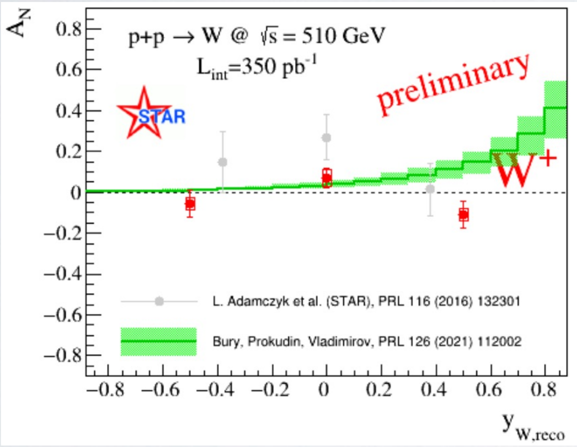
talk by Badelek

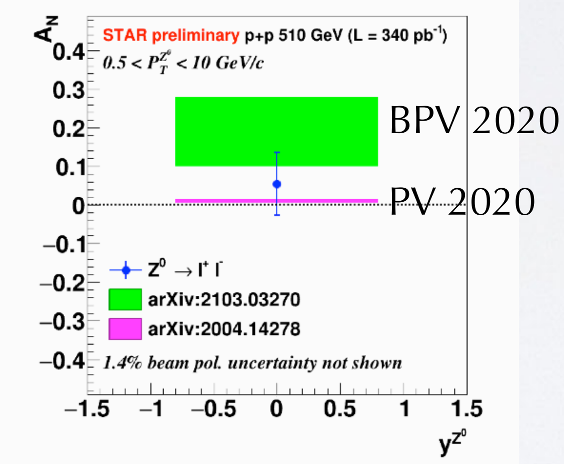
Aghasyan et al., P.R.L. ***119*** *(17) 112002*



sign change

no sign change



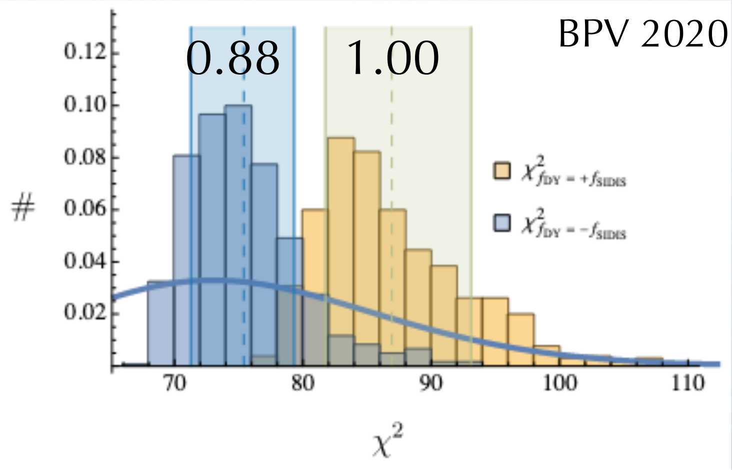


p-p↑ → W+X

AUT ~ $f_{1,p} \otimes f_{1T,p}^{\perp}$

Adamczyk et al., P.R.L. ***116*** *(16) 132301*

talk by Seidl (poster by Xiaoxuan Chu)



still not enough to confirm sign change ?

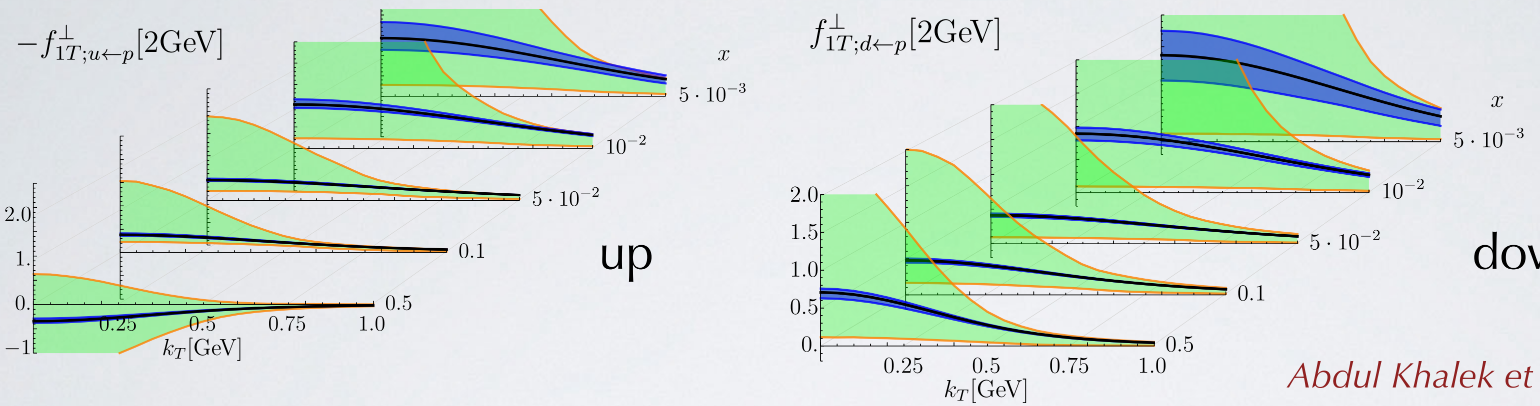
Perspective at future electron-ion colliders

impact of EIC pseudodata

$\mathcal{L}$=10 fb^{-1}

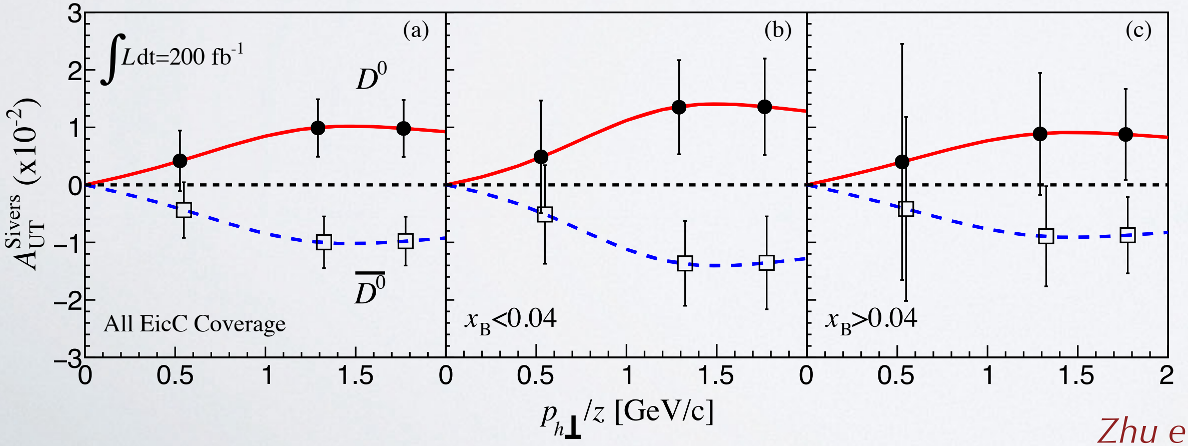
🟩 BPV 2020

🟦 + EIC 5×41 GeV
18×275



Abdul Khalek et al. (EIC Yellow Report),
N.P. ***A1026*** *(22) 122447, arXiv:2103.05419*

see talk by Nadel-Turonski
and by Santamaria for LHCspin perspectives

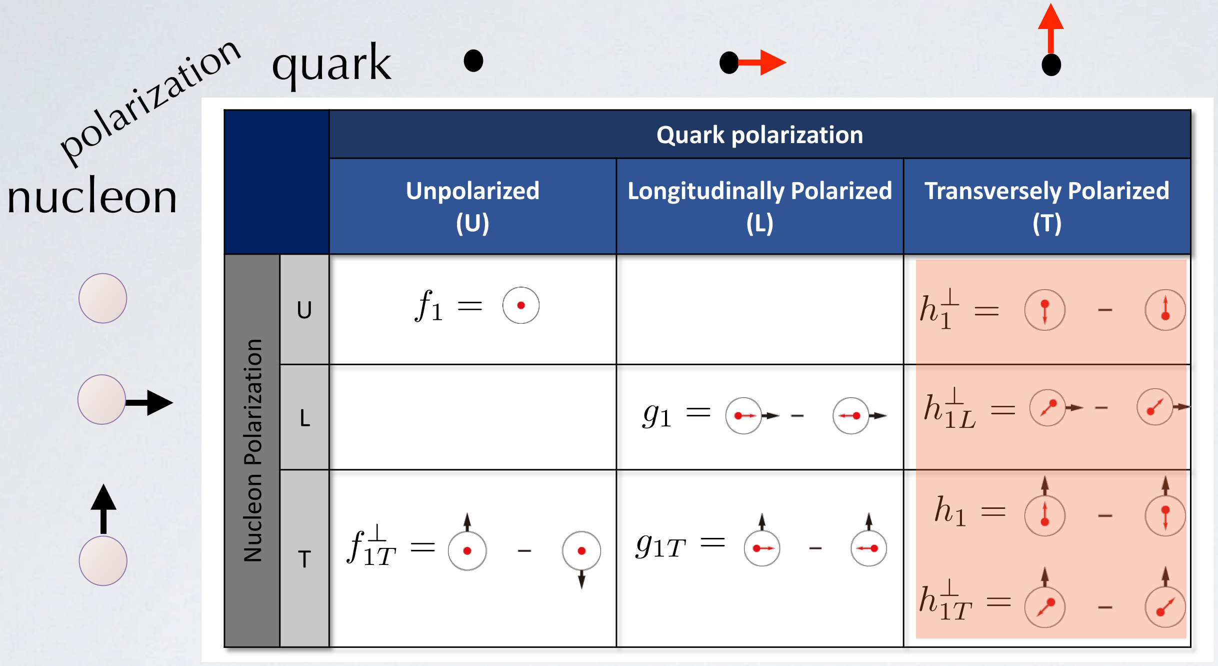


$e + p^{\uparrow} \to D^0/\bar{D}^0$
simulation at EIcC

test of
q Sivers = $-\bar{q}$ Sivers

Zhu et al., arXiv:2409.00653

The TMD “zoo” at leading twist for spin-1/2 hadron



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ -
	L		$g_1 =$ -	$h_{1L}^\perp =$ -
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

Boer-Mulders

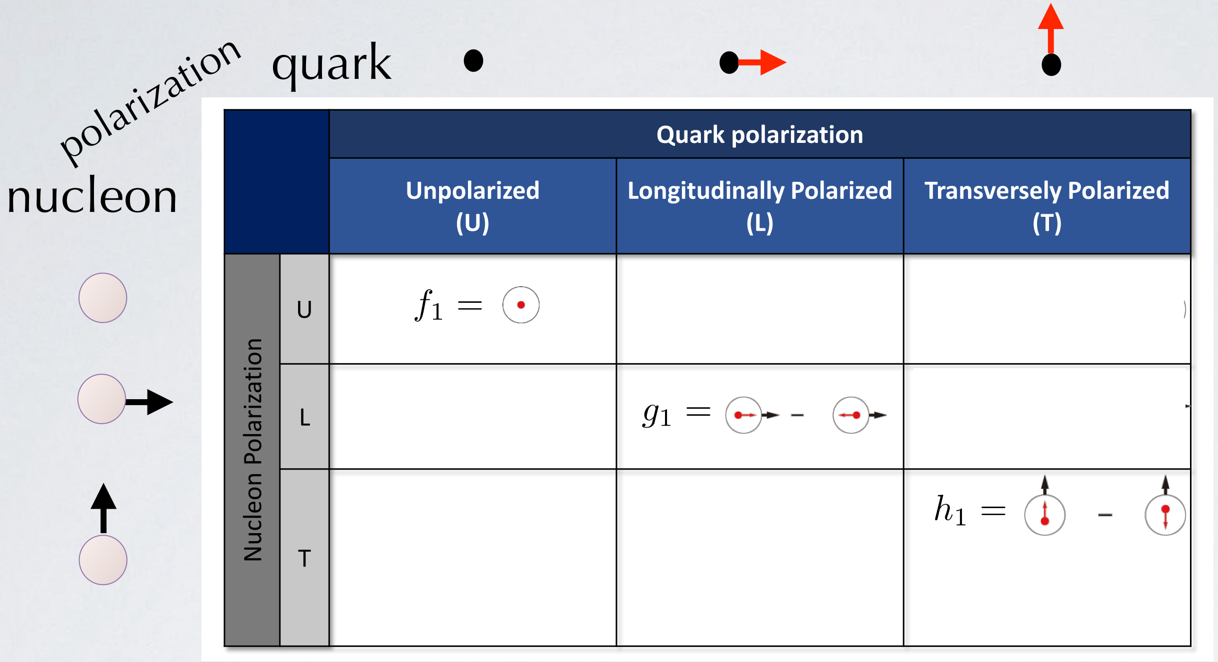
Kotzinian-Mulders

transversity

pretzelosity

- flip quark helicity → chiral-odd structures
  (need a partner in cross section)
- suppressed in pQCD as m_q / Q
- connected to tensor operators not in SM Lagrangian

Integrating $k_\perp$: collinear kinematics



polarization
quark
nucleon

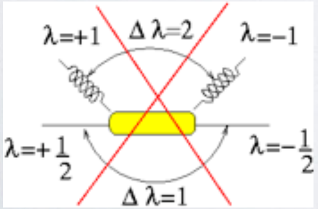
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$ ⊙		
	L		$g_1 =$ ⊙→ - ⊙→	
	T			$h_1 =$ ⊙↑ - ⊙↑

transversity

- the only chiral-odd structure that survives in collinear kinematics

- only way to determine the tensor "charge" $\delta^q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x, Q^2)$

scales!
contrary to axial charge g_A



In a spin-1/2 hadron,
no transversity of gluons

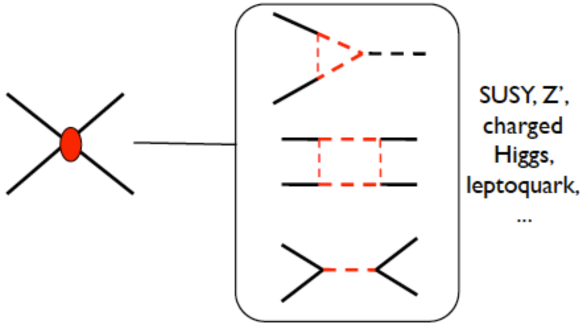
→ only non-singlet evolution

$$\boxed{h_1 \neq g_1}$$

Potential for BSM discovery ?

Tensor (and chiral-odd) structures do not appear in the Standard Model Lagrangian at tree level.

Is it a possible low-energy footprint of BSM physics at higher scale ?



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neutron β-decay

n → p e⁻ $\bar{\nu}_e$

$$\mathcal{L}_{\rm SM} \sim G_F\, V_{ud}\, \bar{e}\gamma^\mu(1-\gamma_5)\nu_e\, \bar{p}\gamma_\mu(1-\gamma_5)n$$

$$+\mathcal{L}_{\rm eff} \sim G_F\, V_{ud}\, g_T\, \varepsilon_T\, \bar{e}\sigma^{\mu\nu}\nu_e\, \bar{p}\sigma_{\mu\nu}n \quad ?$$

$$g_T = \delta u - \delta d$$

BSM coupling

$$g_T\, \overset{\swarrow}{\varepsilon_T} \approx \frac{M_W^2}{M_{\rm BSM}^2}$$

precision => BSM scale

SMEFT with strong CP violation

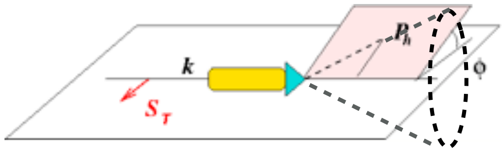
permanent Electric Dipole Mom.

$$\mathcal{L}_{\rm SMEFT} \to \sum_{f=u,d,s,c} d_f\, \bar{\psi}_f\, \sigma_{\mu\nu}\gamma_5\, \psi_f\, F^{\mu\nu} \quad ?$$

neutron EDM $d_n = \delta u\, d_u + \delta d\, d_d + \delta s\, d_s + ..$

exp. data + tensor charge => constrain amount of CP violation

Analyzers of transversity at leading twist



Collins effect

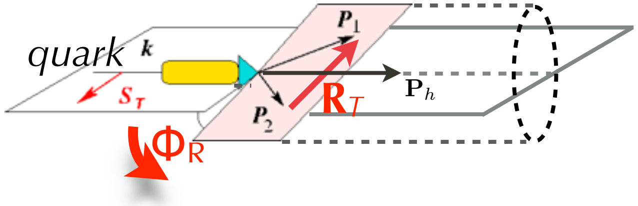
$S_T \cdot k\times P_{hT}$

Collins, N.P. **B396** (93) 161

$\propto h_1(x,k_\perp)\otimes \underline{H_1^\perp(z,P_\perp)}$

TMD framework

SIDIS



di-hadron mechanism

$S_T \cdot P_2\times P_1 = S_T \cdot P_h\times R_T$

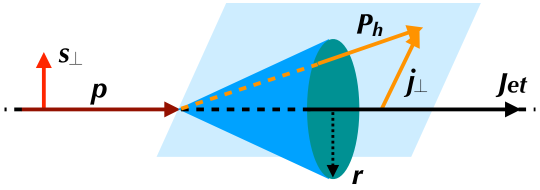
Collins et al., N.P. **B420** (94)

$\propto h_1(x)\,\underline{H_1^{\sphericalangle}(z,R_T^2 \propto M_{h_1h_2}^2)}$

collinear framework

SIDIS

p p↑



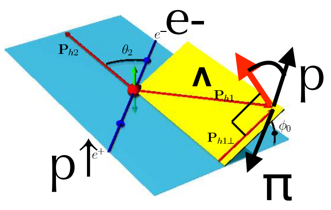
hadron-in-jet Collins effect

$j_T^2 \ll Q^2 = (P_T^{jet})^2$

Yuan, P.R.L. **100** (08)

$\propto h_1(x)\,[C(z,\mu)\otimes \underline{H_1^\perp(z_h, j_T, P_T^{\rm jet} r)}]$

hybrid framework SIDIS p p↑



Λ spin transfer

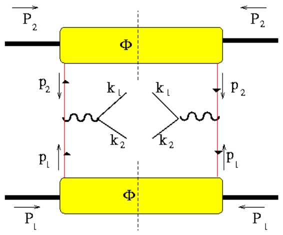
Jaffe, P.R. D**54** (96)

$\propto h_1(x)\,\underline{H_1(z)}$

collinear framework

SIDIS

p p↑



single-polarised Drell-Yan

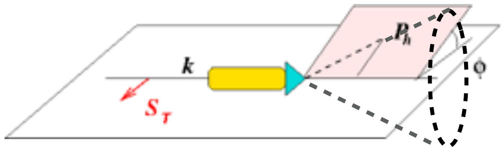
Boer, P.R. D**60** (99)

$\propto \underline{h_1^\perp(x_1,k_{\perp 1})}\otimes h_1(x_2,k_{\perp 2})$

TMD framework

π p↑

Analyzers of transversity at leading twist



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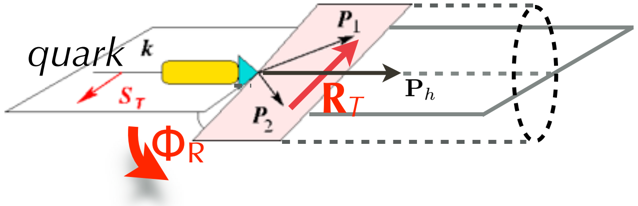
Collins, N.P. **B396** (93) 161

$\propto \; h_1(x, k_\perp) \otimes \underline{H_1^\perp(z, P_\perp)}$

TMD framework

SIDIS



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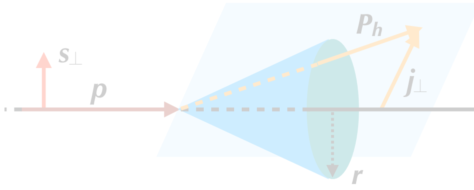
collinear framework

SIDIS

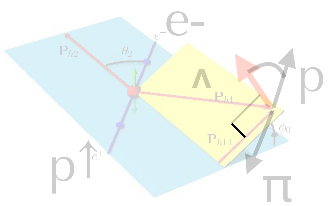
p p↑



mechanisms used so far
to extract transversity from data

$\underline{H_1^\perp(z_h, j_T, P_T^{\rm jet} r)]}$

SIDIS p p↑



Λ spin transfer

Jaffe, P.R. D**54** (96)

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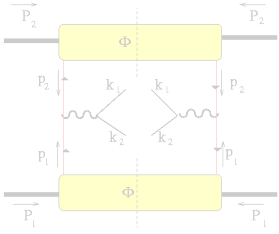
collinear framework

SIDIS

p p↑



single-polarised Drell-Yan

Boer, P.R. D**60** (99)

$\propto \; \underline{h_1^\perp(x_1, k_{\perp 1})} \otimes h_1(x_2, k_{\perp 2})$

TMD framework

π p↑

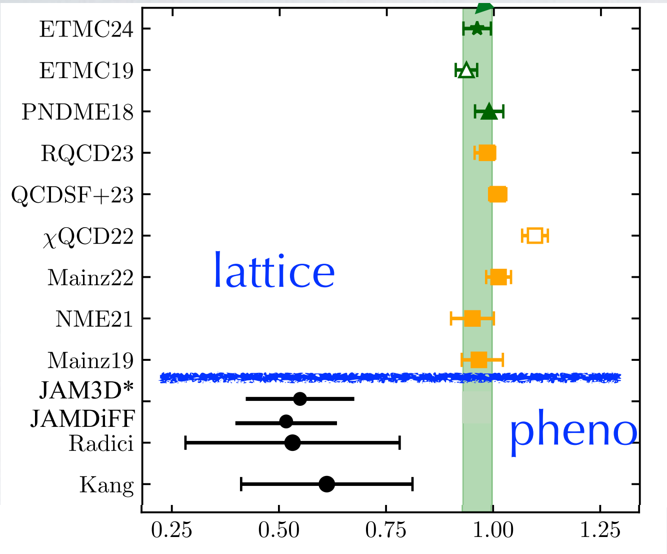
Most recent extractions

Collins effect	Framework	e+e-	SIDIS	Drell-Yan A_N	Lattice
Anselmino 2015 P.R. **D92** (15) 114023	parton model	✔	✔	✘	✘
Kang et al. 2016 P.R. **D93** (16) 014009	TMD / CSS	✔	✔	✘	✘
Lin et al. 2018 P.R.L. **120** (18) 152502	parton model	✘	✔	✘	✔ g_T
D'Alesio et al. 2020 (CA) P.L. **B803** (20) 135347	parton model	✔	✔	✘	✘
JAM3D-20 P.R. **D102** (20) 054002	parton model	✔	✔	✔	✘
JAM3D-22 P.R. **D106** (22) 034014	parton model	✔	✔	✔	✔ g_T
Boglione et al. 2024 (TO) P.L. **B854** (24) 138712	parton model	✔	✔	✔ reweighing	✘

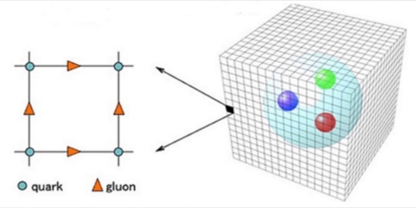
Dihadron mechanism	e+e- unpol. $d\sigma^0$	e+e- asymmetry	SIDIS	p-p collisions	Lattice
Radici & Bacchetta 2018 P.R.L. **120** (18) 192001	PYTHIA (separately)	✔ (separately)	✔	✔	✘
Benel et al. 2020 E.P.J. **C80** (20) 5	PYTHIA (separately)	✔ (separately)	✔	✘	✘
JAMDIFF 2024 P.R.L. **132** (24) 091901	✔	✔	✔	✔	✔ δu, δd

Pheno - lattice : tensor charge

$g_T = \delta u - \delta d$



adapted from C. Alexandrou, QCD Evolution 24

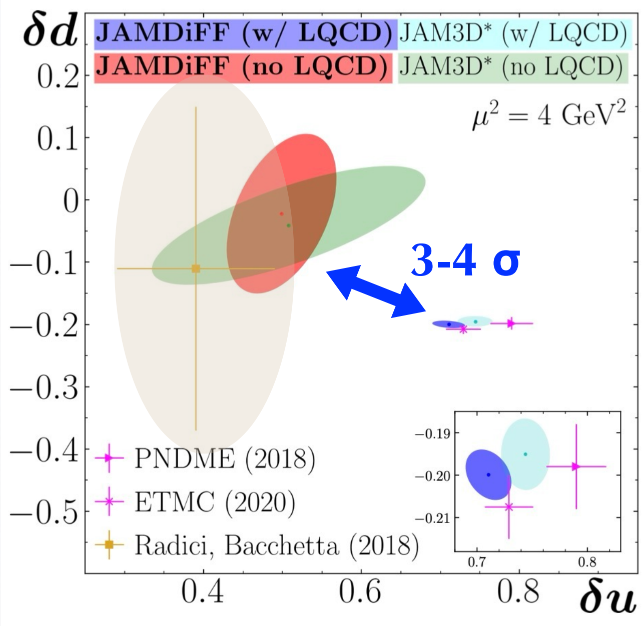


green $N_f=2+1+1$

open symbols = no continuum extrapolation

yellow $N_f=2+1$

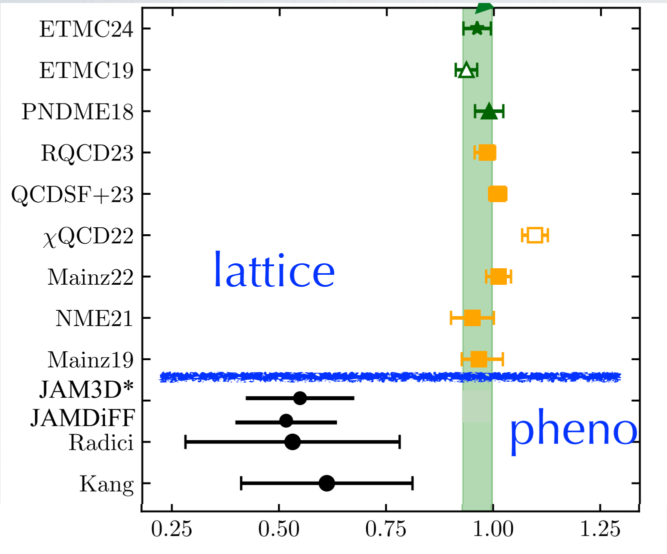
tension between pheno and lattice ?



adapted from D. Pitonyak, QCD Evolution 24

Pheno - lattice : tensor charge

$g_T = \delta u - \delta d$



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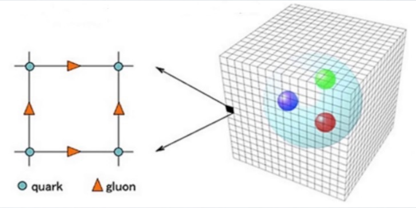


green N_f=2+1+1

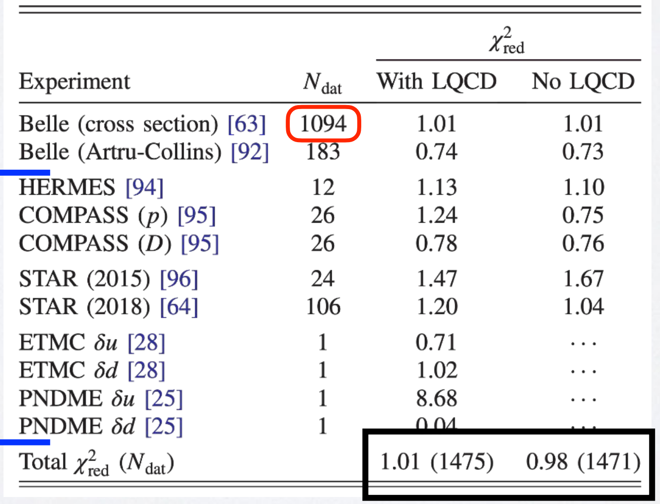
open symbols = no continuum extrapolation

yellow N_f=2+1

tension between pheno and lattice ?

Including lattice data,
JAM finds **compatibility**..

But most data insensitive
to tensor charge

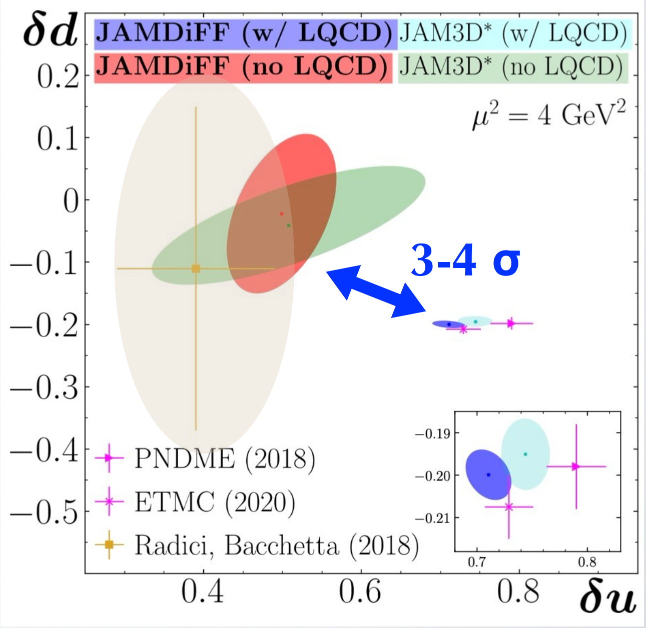


Experiment	N_{dat}	χ^2_{red} With LQCD	χ^2_{red} No LQCD
Belle (cross section) [63]	1094	1.01	1.01
Belle (Artru-Collins) [92]	183	0.74	0.73
HERMES [94]	12	1.13	1.10
COMPASS (p) [95]	26	1.24	0.75
COMPASS (D) [95]	26	0.78	0.76
STAR (2015) [96]	24	1.47	1.67
STAR (2018) [64]	106	1.20	1.04
ETMC δu [28]	1	0.71	...
ETMC δd [28]	1	1.02	...
PNDME δu [25]	1	8.68	...
PNDME δd [25]	1	0.04	...
Total χ^2_{red} (N_{dat})		1.01 (1475)	0.98 (1471)

For data sensitive to δu, δd

$\chi^2 = 203 \rightarrow 239$

$\chi^2/N_{dat} = 1.02 \rightarrow 1.21$



adapted from D. Pitonyak, QCD Evolution 24

Perspectives

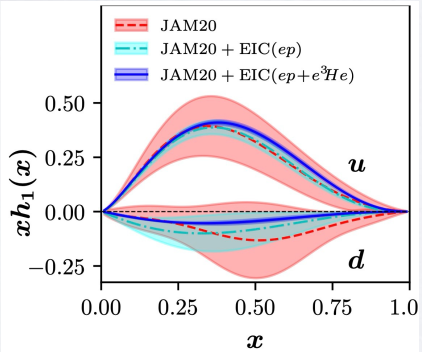
- New data on Collins effect and dihadron mechanism in SIDIS with transversely polarized deuteron target
- New data on $\pi^- - p^\uparrow$ Drell-Yan

talk by Badelek

- New data on $p^\uparrow + p \to \text{jet} + \pi^\pm + X$ hadron-in-jet Collins effect
- New data on $p^\uparrow + p \to \Lambda^\uparrow + X$ Λ spin transfer
- New data on $p^\uparrow + p \to (\pi^+\pi^-) + X$ dihadron mechanism

talk by Seidl

Future



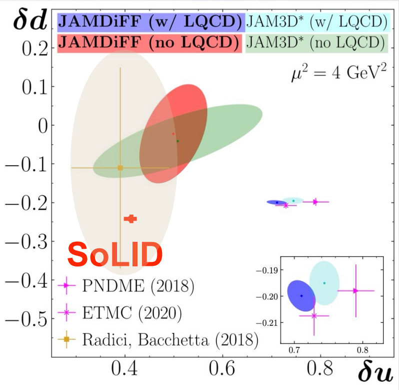
Abdul Khalek et al. (EIC Yellow Report), N.P. **A1026** (22) 122447, arXiv:2103.05419

- EIC

talk by Nadel-Turonski

- SoLID at JLab12

talk by Chen



talk by Santamaria for LHCspin

gluon TMDs

- First classification given in

  Mulders & Rodrigues,
  *P.R. D**63** (01) 094021, arXiv:hep-ph/0009343*

- Factorization, evolution & universality studied in

  *Ji et al., JHEP **07** (05) 020, arXiv:hep-ph/0503015*
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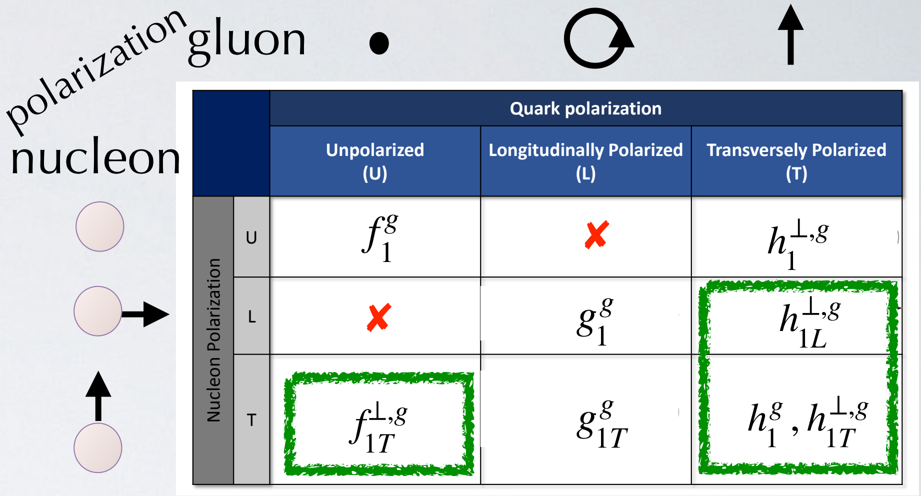
  *Boer & Van Dunnen, N.P. **B886** (14) 421, arXiv:1404.6753*
  *Echevarria et al., JHEP **07** (15) 158 [E: **05** (17) 073], arXiv:1502.05354*



	Quark polarization		
	Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1^g	✘	$h_1^{\perp,g}$
L	✘	g_1^g	$\boxed{h_{1L}^{\perp,g}}$
T	$\boxed{f_{1T}^{\perp,g}}$	g_{1T}^g	$\boxed{h_1^g\,,h_{1T}^{\perp,g}}$

T-odd TMDs

gluon TMDs

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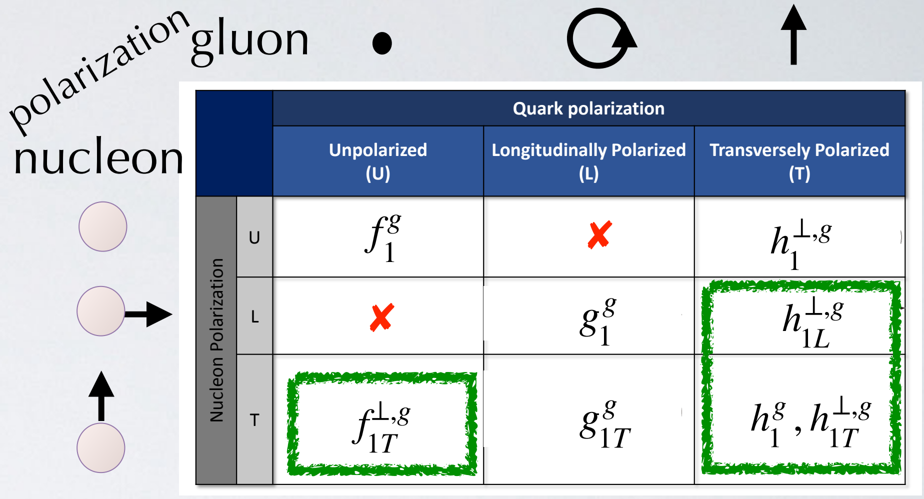

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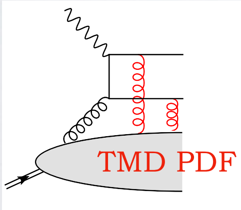
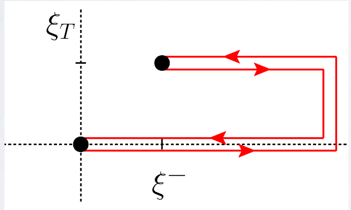
L	✘	g_1^g	$h_{1L}^{\perp,g}$
T	$f_{1T}^{\perp,g}$	g_{1T}^g	$h_1^g\,,h_{1T}^{\perp,g}$

T-odd TMDs

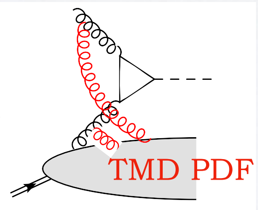
gluons carry "two color charges" → intricate non-universality



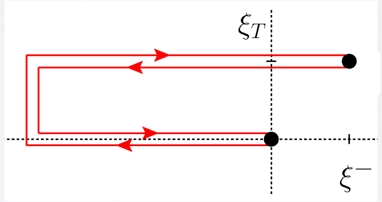
two-jets SIDIS



color structure [+,+]



gluon fusion to Higgs

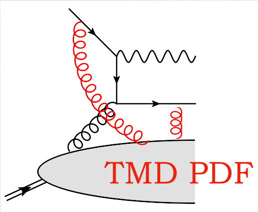


[-,-]

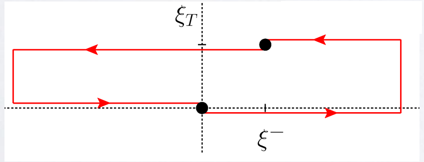
T-even: $f_1^{[+,+]} = f_1^{[-,-]}$

T-odd: $f_{1T}^{\perp\,[+,+]} = -f_{1T}^{\perp\,[-,-]}$

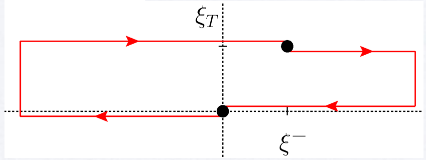
WW-type TMDs



p p → γ^*+jet



[+,-]



[-,+]

T-even: $f_1^{[+,-]} = f_1^{[-,+]}$

T-odd: $f_{1T}^{\perp\,[+,-]} = -f_{1T}^{\perp\,[-,+]}$

$\neq$

dipole-type TMDs

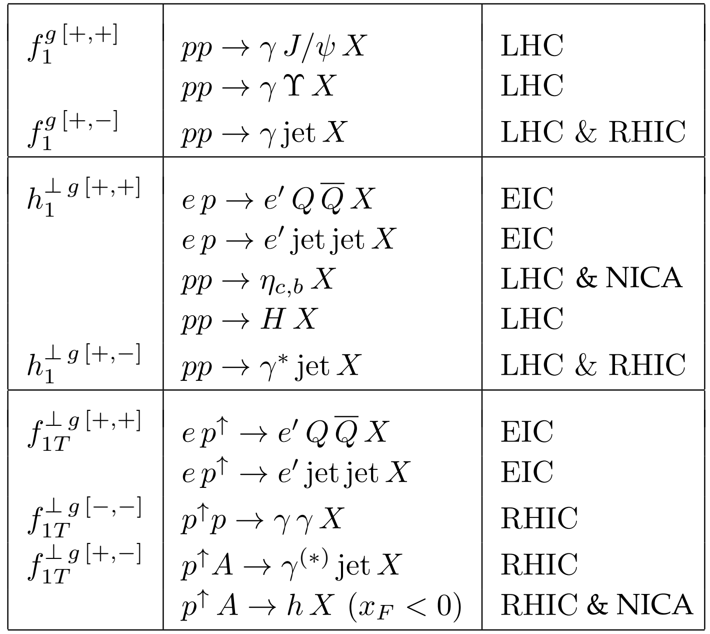
gluon TMDs

many papers exploring useful channels at colliders to extract WW and dipole gluon TMDs. Handy pocket list:

Boer, talk at IWHSS 2020

(see also recent review on quarkonium physics)

Boer et al., arXiv:2409.03691



$f_1^{g\,[+,+]}$	$pp \to \gamma\, J/\psi\, X$	LHC
	$pp \to \gamma\, \Upsilon\, X$	LHC
$f_1^{g\,[+,-]}$	$pp \to \gamma\, \text{jet}\, X$	LHC & RHIC
$h_1^{\perp\, g\,[+,+]}$	$e\,p \to e'\, Q\, \overline{Q}\, X$	EIC
	$e\,p \to e'\, \text{jet}\, \text{jet}\, X$	EIC
	$pp \to \eta_{c,b}\, X$	LHC & NICA
	$pp \to H\, X$	LHC
$h_1^{\perp\, g\,[+,-]}$	$pp \to \gamma^*\, \text{jet}\, X$	LHC & RHIC
$f_{1T}^{\perp\, g\,[+,+]}$	$e\,p^\uparrow \to e'\, Q\, \overline{Q}\, X$	EIC
	$e\,p^\uparrow \to e'\, \text{jet}\, \text{jet}\, X$	EIC
$f_{1T}^{\perp\, g\,[-,-]}$	$p^\uparrow p \to \gamma\, \gamma\, X$	RHIC
$f_{1T}^{\perp\, g\,[+,-]}$	$p^\uparrow A \to \gamma^{(*)}\, \text{jet}\, X$	RHIC
	$p^\uparrow\, A \to h\, X \;\; (x_F < 0)$	RHIC & NICA

gluon TMDs

many papers exploring useful channels at colliders to extract WW and dipole gluon TMDs. Handy pocket list:

Boer, talk at IWHSS 2020

$f_1^{g\,[+,+]}$	$pp \to \gamma\, J/\psi\, X$	LHC
	$pp \to \gamma\, \Upsilon\, X$	LHC
$f_1^{g\,[+,-]}$	$pp \to \gamma\, \text{jet}\, X$	LHC & RHIC
$h_1^{\perp\, g\,[+,+]}$	$e\, p \to e'\, Q\, \overline{Q}\, X$	EIC
	$e\, p \to e'\, \text{jet}\, \text{jet}\, X$	EIC
	$pp \to \eta_{c,b}\, X$	LHC & NICA
	$pp \to H\, X$	LHC
$h_1^{\perp\, g\,[+,-]}$	$pp \to \gamma^*\, \text{jet}\, X$	LHC & RHIC
$f_{1T}^{\perp\, g\,[+,+]}$	$e\, p^\uparrow \to e'\, Q\, \overline{Q}\, X$	EIC
	$e\, p^\uparrow \to e'\, \text{jet}\, \text{jet}\, X$	EIC
$f_{1T}^{\perp\, g\,[-,-]}$	$p^\uparrow p \to \gamma\, \gamma\, X$	RHIC
$f_{1T}^{\perp\, g\,[+,-]}$	$p^\uparrow A \to \gamma^{(*)}\, \text{jet}\, X$	RHIC
	$p^\uparrow A \to h\, X \;\; (x_F < 0)$	RHIC & NICA

(see also recent review on quarkonium physics)

Boer et al., arXiv:2409.03691

- TMD factorization $\xrightarrow{\text{small x}}$ UGD k_t factorization

WW $\;f_1^{g\,[+,+]} \longrightarrow$ # density of gluons in CGC

dipole $\;f_1^{g\,[+,-]} \longrightarrow$ Fourier Transform of color-dipole cross section in CGC

Dominguez et al., P.R.L. ***106*** *(11) 022301, arXiv:1009.2141*
*Dominguez et al., P.R. D**83** (11) 105005, arXiv:1101.0715*

- small-x limit of T-odd gluon TMDs:

WW $\quad f_{1T}^{\perp}, h_1, h_{1T}^{\perp} \;\to\; 0$

dipole $\quad xf_{1T}^{\perp} = xh_1 = xh_{1T}^{\perp} \;\to -\dfrac{k_T^2 N_c}{4\pi\alpha_s}\, O_{1T}^{\perp}(x, k_T^2)$ spin Odderon

Boer et al., P.R.L. ***116*** *(16) 122001, arXiv:1511.03485*

gluon TMDs : only models

- Available experimental information on gluon TMDs is scarce.
- Very few attempts of pheno studies:

Lansberg et al., P.L. ***B784*** *(18) 217 [E: P.L.* ***B791*** *(19) 420], arXiv:1710.01684*
*D'Alesio et al., P.R. D**96** (17) 036011, arXiv:1705.04169*
*D'Alesio et al., P.R. D**99** (19) 036013, arXiv:1811.02970*
*D'Alesio et al., P.R. D**102** (20) 094011, arXiv:2007.03353*

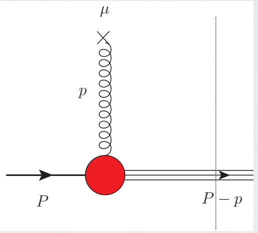
- Many models on the market (list of references too long).
  Let me advertise our one, the first providing systematically all T-even and T-odd gluon TMDs at leading twist:

Bacchetta et al., E.P.J.C ***80*** *(20) 733, arXiv:2005.02288* T-even

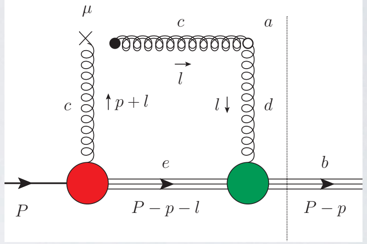
Bacchetta et al., E.P.J.C ***84*** *(24) 576, arXiv:2402.17556* T-odd

spectator model of gluon TMDs

- Nucleon = gluon + spectator on-shell spin-1/2 particle



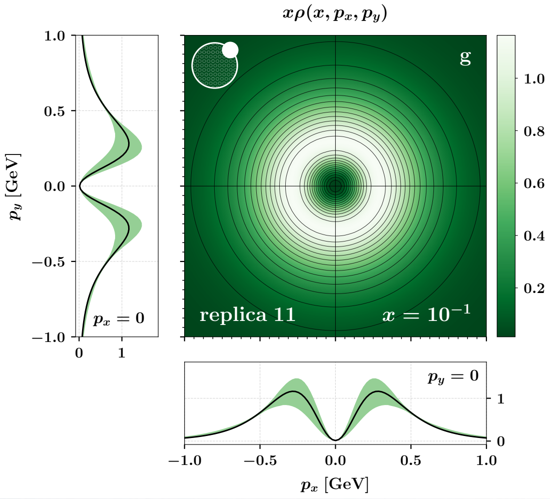
- T-odd generated by gluon-spectator FSI via 1 gluon-exchange



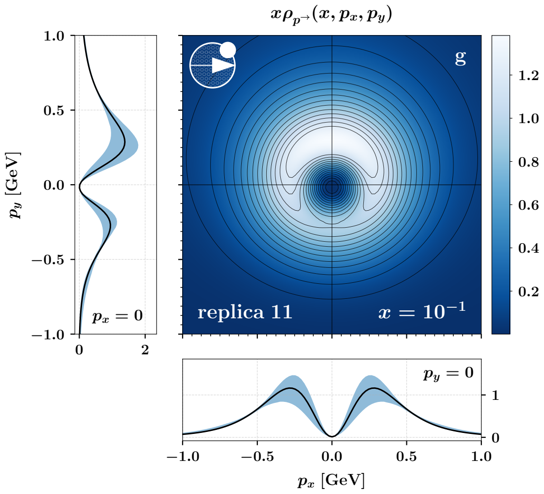
- Spectator mass takes continuous range of values through a parametric spectral function
- Parameters fixed by reproducing collinear gluon PDFs f_1 and g_1 from NNPDF3.0

Bacchetta et al., E.P.J.C ***80*** *(20) 733, arXiv:2005.02288*
Bacchetta et al., E.P.J.C ***84*** *(24) 576, arXiv:2402.17556*

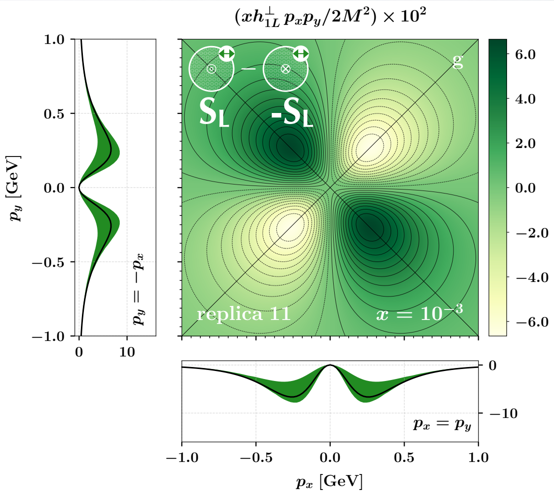
xf_1^g



$xf_1^g + (p_y/M)\, xf_{1T}^{\perp g}$



"propeller" $h_{1L}^{\perp g}$



Recap

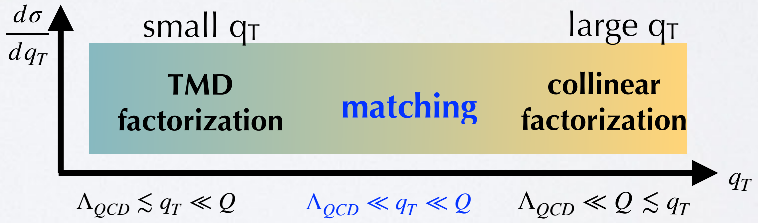
- Precision era for unpolarized TMD, comparable to PDFs: extractions from large data sets with high perturbative accuracy

➡ **Explore impact at LHC, particularly on flavor-sensitive observables like W mass**

- Polarized TMDs are a little "behind": smaller data sets and lower pert. accuracy; but newer spin asymmetry data are available for analysis

➡ **Important crosschecks (Drell-Yan - SIDIS sign change; spin Odderon) and BSM explorations (chiral-odd structures)**

- **Big open problems in Phenomenology:**
  - ➡ gluon TMDs : still rely basically only on models
  - ➡ matching with fixed-order calculations at $q_T \sim Q$



$\frac{d\sigma}{dq_T}$

small q_T

large q_T

TMD factorization

matching

collinear factorization

q_T

$\Lambda_{QCD} \lesssim q_T \ll Q$

$\Lambda_{QCD} \ll q_T \ll Q$

$\Lambda_{QCD} \ll Q \lesssim q_T$

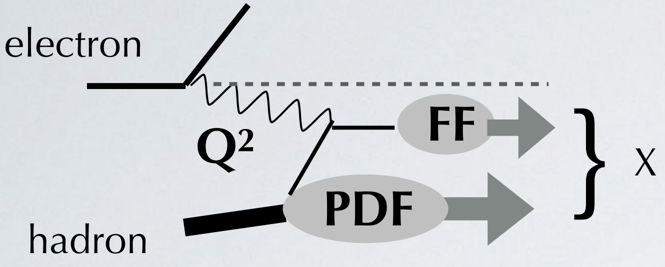
[redacted]

- **Very encouraging perspectives with future electron-ion colliders like the EIC**


THANK YOU
for your
ATTENTION!

Backup

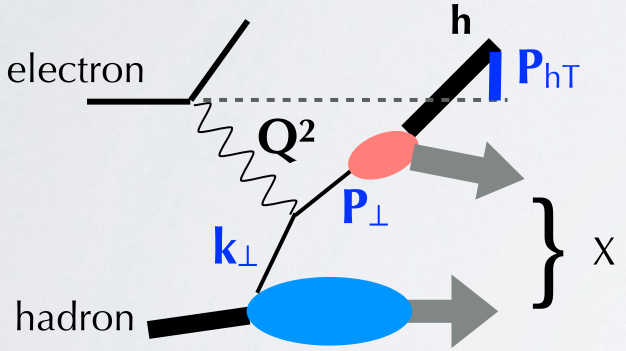
TMDs need Semi-Inclusive processes



Example: inclusive DIS

- hard scale $Q^2 = -q^2 \gg M^2$ to "see" partons through Parton Distribution Functions (PDFs)
- no further scale to probe hadron interior
- **PDFs and FFs depend on factorization scale $\mu^2 \equiv Q^2$**

Explore ⊥ momentum of quarks? Need semi-inclusive processes



Semi-inclusive DIS (SIDIS)

- hard scale $Q^2 = -q^2 \gg M^2$ to "see" partons
- hadronic system h with **soft scale** $q_T^2 = P_{hT}^2/z^2 \ll Q^2$
- sensitive to **internal motion** of partons

  $\mathbf{q}_T \approx -\mathbf{P}_{hT}/z = -\mathbf{k}_\perp - \mathbf{P}_\perp/z + \mathcal{O}(\mathbf{k}_\perp^2/Q^2)$

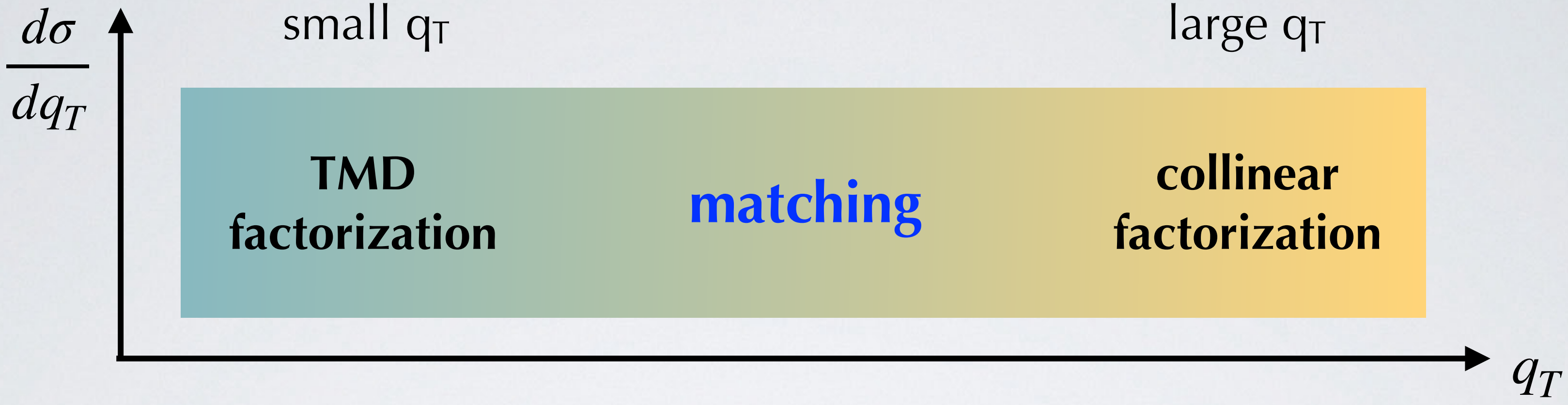
→ factorization of cross section into TMD PDFs and TMD FFs

$\mathrm{TMDPDF}^q\,(x, \mathbf{k}_\perp^2; \mu, \zeta)$ **depend on two scales:** μ = factorization scale

$\mathrm{TMDFF}^q\,(z, \mathbf{P}_\perp^2; \mu, \zeta)$ ζ = rapidity scale

(can be chosen as $\zeta = \mu^2 \equiv Q^2$)

TMD factorization



$\frac{d\sigma}{dq_T}$

small q_T

large q_T

TMD factorization

matching

collinear factorization

q_T

$\Lambda_{QCD} \lesssim q_T \ll Q$

$\Lambda_{QCD} \ll q_T \ll Q$

$\Lambda_{QCD} \ll Q \lesssim q_T$

$+ \mathcal{O}(q_T^2/Q^2)$ W-term

Y-term $Y(q_T^2, Q^2)$ such that

Fixed-Order (F.O.) $+ \mathcal{O}(M^2/q_T^2)$

$$0 \longleftarrow Y \longrightarrow \mathrm{F.O.}$$

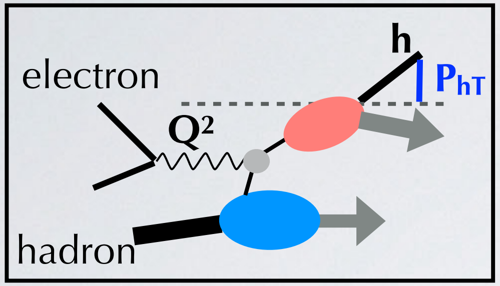
our analysis is in this regime where W-term dominates. Y-term is not included

at low Q (SIDIS), this limit does not work....

Sun *et al.*, Int.J.Mod.Phys. **A33** (18) 1841006, arXiv:1406.3073

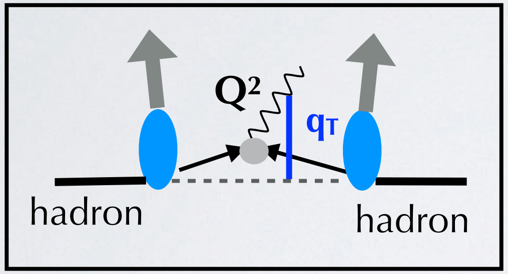
Factorization Theorems only for some processes

TMD PDF   TMD FF



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

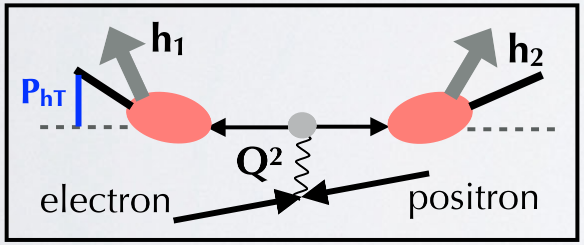
h = light-/heavy- quark hadron, jet, di-jet, di-hadron,
jet substructure (hadron-in-jet),..



hadronic collisions $q_T^2 \ll Q^2$

quarks **Q^2** carried by γ*, W, Z ; gluons by H^0, $\eta_{c,b}$

both **Q^2** carried by jet with substructure
(hybrid factorization: collinear PDF - TMD FF)



electron-positron annihilation $q_T^2 = P_{hT}^2/z^2 \ll Q^2$

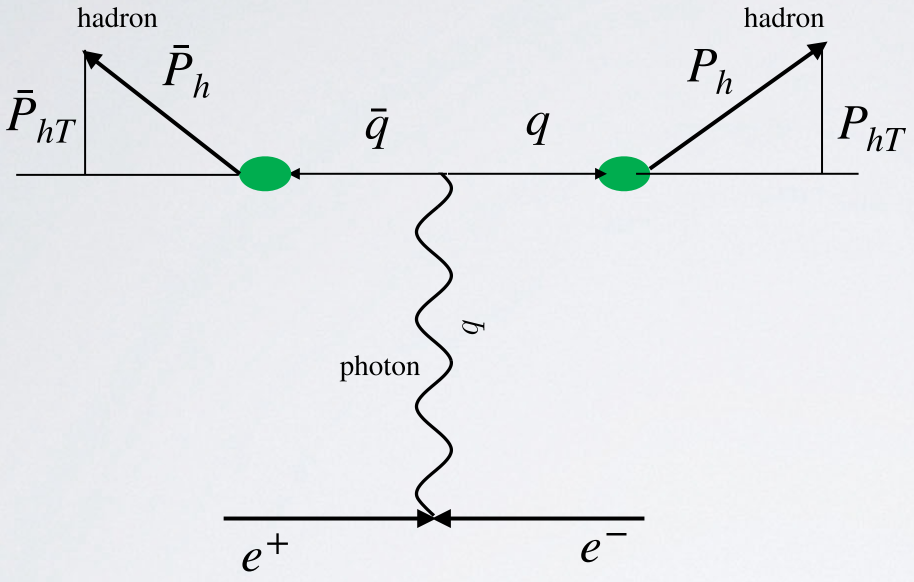
(**h_1 , h_2**) = (hadron / di-hadron , hadron / di-hadron),
(hadron / γ , jet), hadron-in-jet

TMD PDFs , TMD FFs universal
(with calculable exceptions)

Collins & Metz, P.R.L. **93** (04) 252001
Ji, Yuan, Ma, P.R. D**71** (05) 034005
Collins & Soper, N.P. B**193** (81)
Echevarria, Idilbi, Scimemi, JHEP **07** (12)

For review, see Collins, "Foundations of Perturbative QCD" (CUP, 11)

TMD factorization: e+e-



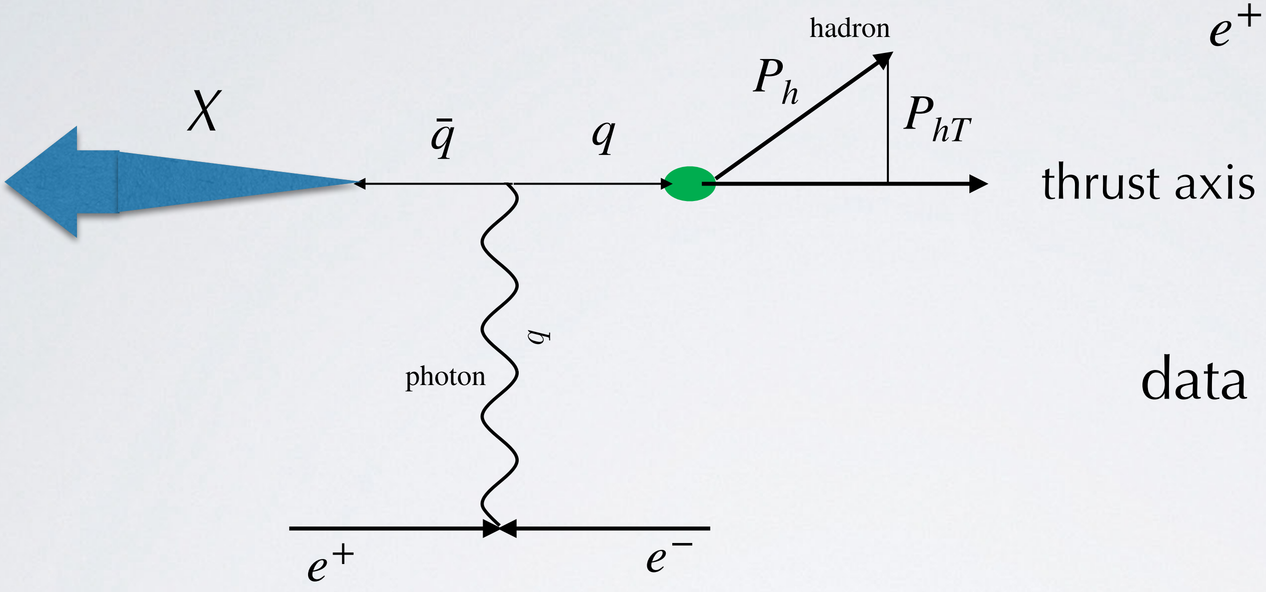
$$e^+ e^- \to h_1 + h_2 + X$$

data available only as azimuthal (spin) asymmetries

BELLE BABAR BESIII

used for polarized **TMD FF**

TMD factorization: e+e-



$$e^+ e^- \rightarrow h + X$$

data available

BELLE

arXiv:1902.01552

Complicated (and sometimes different) factorization theorems, depending on “distance” of hadron from thrust axis

Kang et al., arXiv:2007.14425
Makris et al., arXiv:2009.11871
Boglione & Simonelli, arXiv:2007.13674
arXiv:2011.07366
arXiv:2109.11497
arXiv:2306.02937

For the moment, only Drell-Yan + SIDIS

Scale dependence of TMD: the CSS scheme

$$\boxed{f_1^q(x, b_T^2; \mu_f, \zeta_f) =} \sum_i \left[C_{q\to i}(x, b_T^2; \mu_{b_*}) \otimes f_1^i(x, \mu_{b_*})\right]$$

OPE: matching collinear PDF at small b_T

$$\times \exp\left[S(\mu_f, \mu_{b_*})\right]$$

Sudakov: evolution in μ scale; contains anomalous dimensions γ_F , γ_K

$$\times \left[\frac{\zeta_f}{\mu_{b_*}^2}\right]^{K(b_*, \mu_{b_*})/2}$$

evolution in ζ scale; contains Collins-Soper kernel K

perturbative

perturbative α_S^n accuracy	$\mathscr{H}$ and C	K and γ_F	γ_K	PDF and α_S evol.	FF
LL	0	-	1	-	-
NLL	0	1	2	LO	LO
NLL'	1	1	2	NLO	NLO
NNLL	1	2	3	NLO	NLO
NNLL'	2	2	3	NNLO	NNLO
N^3LL(-)	2	3	4	NNLO	NLO
N^3LL	2	3	4	NNLO	NNLO

FF at NNLO only recently

Borsa et al.,
P.R.L. **129** (22) 012002
arXiv:2202.05060

Abdul Khalek et al.,
P.L. **B834** (22) 137456
arXiv:2204.10331

Scale dependence of TMD: the CSS scheme

$$\boxed{f_1^q(x, b_T^2; \mu_f, \zeta_f) =} \quad \sum_i \left[C_{q\to i}(x, b_T^2; \mu_{b_*}) \otimes f_1^i(x, \mu_{b_*})\right]$$

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$$\times \left[\frac{\zeta_f}{\mu_{b_*}^2}\right]^{K(b_*,\mu_{b_*})/2}$$

evolution in ζ scale; contains Collins-Soper kernel K

perturbative

$$\mu_f \geq \mu_{b_*} = \frac{2e^{-\gamma_E}}{b_*(b_T)} \geq 1$$

prescription to smoothly connect to large b_T, avoiding Landau pole. Introduces nonperturbative part

perturbative α_S^n

accuracy	$\mathscr{H}$ and C	K and γ_F	γ_K	PDF and α_S evol.	FF
LL	0	-	1	-	-
NLL	0	1	2	LO	LO
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N³LL(-)	2	3	4	NNLO	NLO
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Scale dependence of TMD: the CSS scheme

$$\boxed{f_1^q(x, b_T^2; \mu_f, \zeta_f) =} \quad \sum_i \left[C_{q\to i}(x, b_T^2; \mu_{b_*}) \otimes f_1^i(x, \mu_{b_*}) \right]$$

OPE: matching collinear PDF at small b_T

$$\times \exp\left[S(\mu_f, \mu_{b_*}) \right]$$

Sudakov: evolution in μ scale; contains anomalous dimensions γ_F , γ_K

$$\times \left[\frac{\zeta_f}{\mu_{b_*}^2} \right]^{K(b_*, \mu_{b_*})/2}$$

evolution in ζ scale; contains Collins-Soper kernel K

perturbative

$$\times \left[\frac{\zeta_f}{Q_0^2} \right]^{g_K(b_T)/2}$$

nonperturbative Collins-Soper kernel (arbitrary Q_0=1 GeV)

$$\times f_{\rm NP}(x, b_T; Q_0)$$

nonperturbative TMD at initial (arbitrary) scale Q_0

non perturbative

$$\mu_f \geq \mu_{b_*} = \frac{2e^{-\gamma_E}}{b_*(b_T)} \geq 1$$

prescription to smoothly connect to large b_T, avoiding Landau pole. Introduces nonperturbative part

perturbative	α_S^n				
accuracy	$\mathscr{H}$ and C	K and γ_F	γ_K	PDF and α_S evol.	FF
LL	0	-	1	-	-
NLL	0	1	2	LO	LO
NLL’	1	1	2	NLO	NLO
NNLL	1	2	3	NLO	NLO
NNLL’	2	2	3	NNLO	NNLO
N^{3}LL(-)	2	3	4	NNLO	NLO
N^{3}LL	2	3	4	NNLO	NNLO

FF at NNLO only recently

Borsa et al.,
P.R.L. **129** (22) 012002
arXiv:2202.05060

Abdul Khalek et al.,
P.L. **B834** (22) 137456
arXiv:2204.10331

The TMD formula

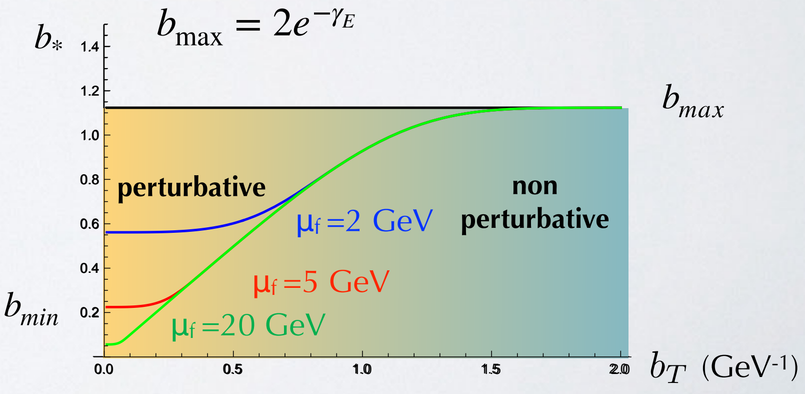
- TMDs depend on two scales: renormalization μ and rapidity ζ (rapidity divergences do not cancel)

DGLAP evolution ↓ Sudakov form factor

evolution through Collins-Soper (CS) kernel K

- for small b$_T$, TMDs at initial scale can be OPE-expanded onto PDFs through perturbative Wilson coefficients
- convenient choice for initial scale is $\mu_i = \sqrt{\zeta_i} = \mu_b = \dfrac{2e^{-\gamma_E}}{b_T}$ (cancel many large logs in resummation)
- so far, approach is perturbative; but what happens at large b$_T$? Avoid Landau pole…
- prescription $b_*(b_T)$ such that $b_{\min} \xleftarrow{\text{small } b_T} b_*(b_T) \xrightarrow{\text{large } b_T} b_{\max}$ $\quad \mu_f \geq \mu_{b_*} = \dfrac{2e^{-\gamma_E}}{b_*} \geq 1$

$$b_*(|\boldsymbol{b}_T|) = b_{\max}\left(\frac{1-e^{-|\boldsymbol{b}_T|^4/b_{\max}^4}}{1-e^{-|\boldsymbol{b}_T|^4/b_{\min}^4}}\right)^{1/4} \qquad b_{\min} = \frac{2e^{-\gamma_E}}{\mu_f}$$

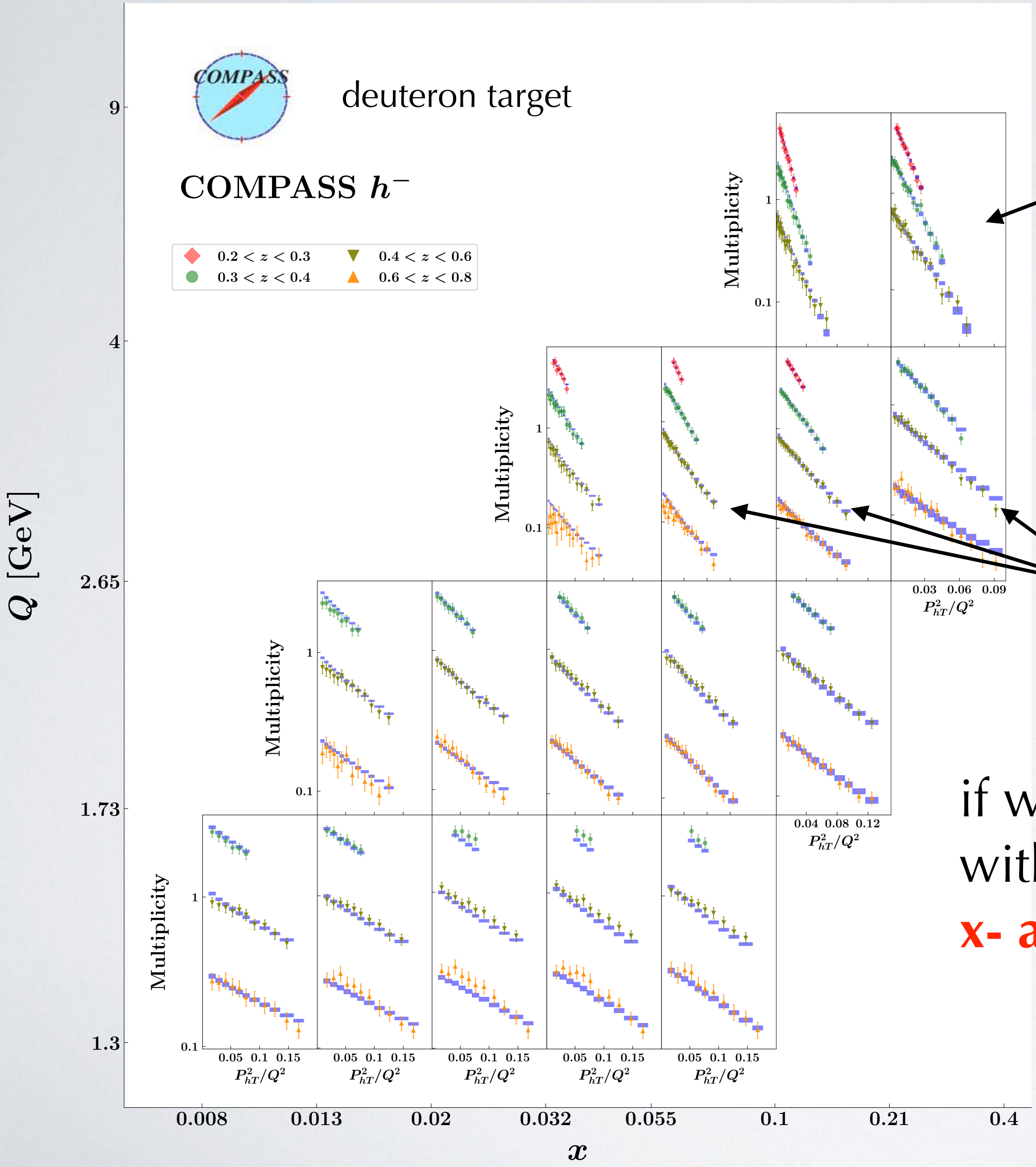


- $b_*(b_T)$ introduces a non-perturbative component

$$f_1(x,b_T,\mu,\zeta) = f_1(x,b_*(b_T),\mu,\zeta)\,\frac{f_1(x,b_T,\mu,\zeta)}{f_1(x,b_*(b_T),\mu,\zeta)}$$

$$\equiv f_1(x,b_*(b_T),\mu,\zeta)\, f_{\rm NP}(x,b_T,\zeta,Q_0)$$ arbitrary

Data-driven nonperturbative TMD



at given (x,Q²),
different slopes for different z

at given z,
different slopes for different x

if we model nonperturbative TMDs with Gaussians, we need
x- and z-dependent widths!

Parametrization of non-perturbative TMD

nonperturbative TMD PDF
Fourier Transform of sum of 3 Gaussians with x-dependent widths

$$f_{\mathrm{NP}}(x, b_T; Q_0)$$
$$= \mathrm{F.T.}\left(e^{-k_\perp^2 / g_{1A}(x)} + \lambda_B\, k_\perp^2 e^{-k_\perp^2 / g_{1B}(x)} + \lambda_C e^{-k_\perp^2 / g_{1C}(x)}\right)$$

with $$g_{1X}(x) = N_{1X} \frac{(1-x)^{\alpha_X^2}\, x^{\sigma_X}}{(1-\hat{x})^{\alpha_X^2}\, \hat{x}^{\sigma_X}} \qquad \hat{x} = 0.1$$

11 param.

suggested by models

Bacchetta, Gamberg, Goldstein, et al., PLB **659** (2008)
Bacchetta, Conti, Radici, PRD **78** (2008)
Pasquini, Cazzaniga, Boffi, PRD **78** (2008)
Matevosyan, Bentz, Cloet, Thomas, PRD **85** (2012)
Burkardt, Pasquini, EPJA (2016)
Grewal, Kang, Qiu, Signori, PRD **101** (2020)

Parametrization of non-perturbative TMD

nonperturbative TMD PDF
Fourier Transform of sum of 3 Gaussians with x-dependent widths

$$f_{\mathrm{NP}}(x, b_T; Q_0)$$

$$= \mathrm{F.T.}\left(e^{-k_\perp^2 / g_{1A}(x)} + \lambda_B\, k_\perp^2 e^{-k_\perp^2 / g_{1B}(x)} + \lambda_C e^{-k_\perp^2 / g_{1C}(x)}\right)$$

$$\text{with} \quad g_{1X}(x) = N_{1X} \frac{(1-x)^{\alpha_X^2}\, x^{\sigma_X}}{(1-\hat{x})^{\alpha_X^2}\, \hat{x}^{\sigma_X}} \qquad \hat{x} = 0.1$$

11 param.

nonperturbative TMD FF
Fourier Transform of sum of 2 Gaussians with z-dependent widths

$$D_{\mathrm{NP}}(z, b_T; Q_0)$$

$$= \mathrm{F.T.}\left(e^{-P_\perp^2 / g_{3A}(z)} + \lambda_F\, P_\perp^2 e^{-P_\perp^2 / g_{3B}(z)}\right)$$

9 param.

$$\text{with} \quad g_{3X}(z) = N_{3X} \frac{(1-z)^{\gamma_X^2}\, (z^{\beta_X} + \delta_X^2)}{(1-\hat{z})^{\gamma_X^2}\, (\hat{z}^{\beta_X} + \delta_X^2)} \qquad \hat{z} = 0.5$$

nonperturbative part of Collins-Soper kernel

$$\left[\frac{\zeta_f}{Q_0^2}\right]^{g_K(b_T)/2} \qquad g_K(b_T) = -\, g_2^2 \frac{b_T^2}{4}$$

1 param.

Total 21 param.

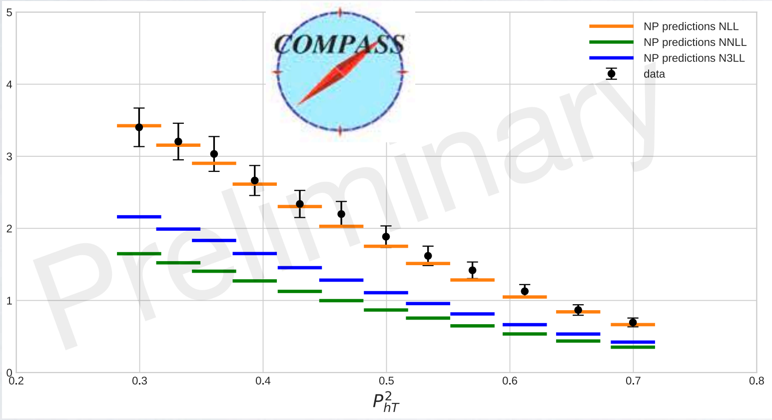
Normalization issue in SIDIS

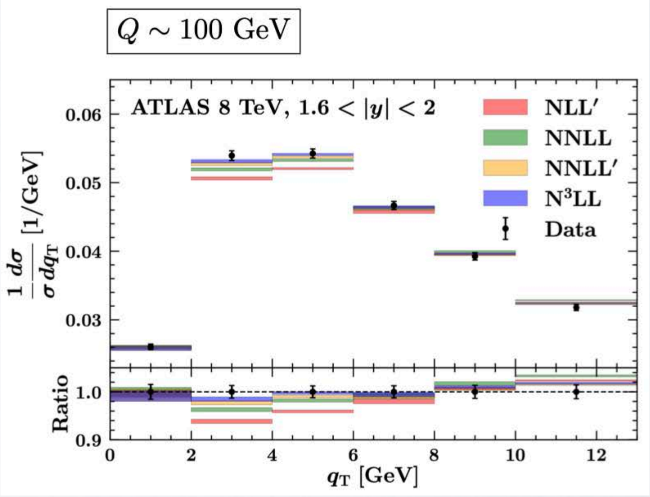
increasing perturbative accuracy

worsens agreement with SIDIS !

increases agreement with Drell-Yan

$M^h(\bar{x}, \bar{z}, \bar{Q}, q_T)$ NLL NNLL N³LL





discrepancy is P_{hT}-independent: $M_{\rm NLL}/M_{\rm NNLL} \sim 2$ $M_{\rm NLL}/M_{\rm N^3LL} \sim 1.5$

tensions observed also at larger q_T
and also in Drell-Yan at low Q
and also in e+e- annihilations

Gonzalez et al., P.R. D**98** (18) 114005
Bacchetta et al., P.R. D**100** (19) 014018
Moffat et al., P.R. D**100** (19) 094014

but not in SV 2019 fit

Scimemi & Vladimirov,
arXiv:1912.06532

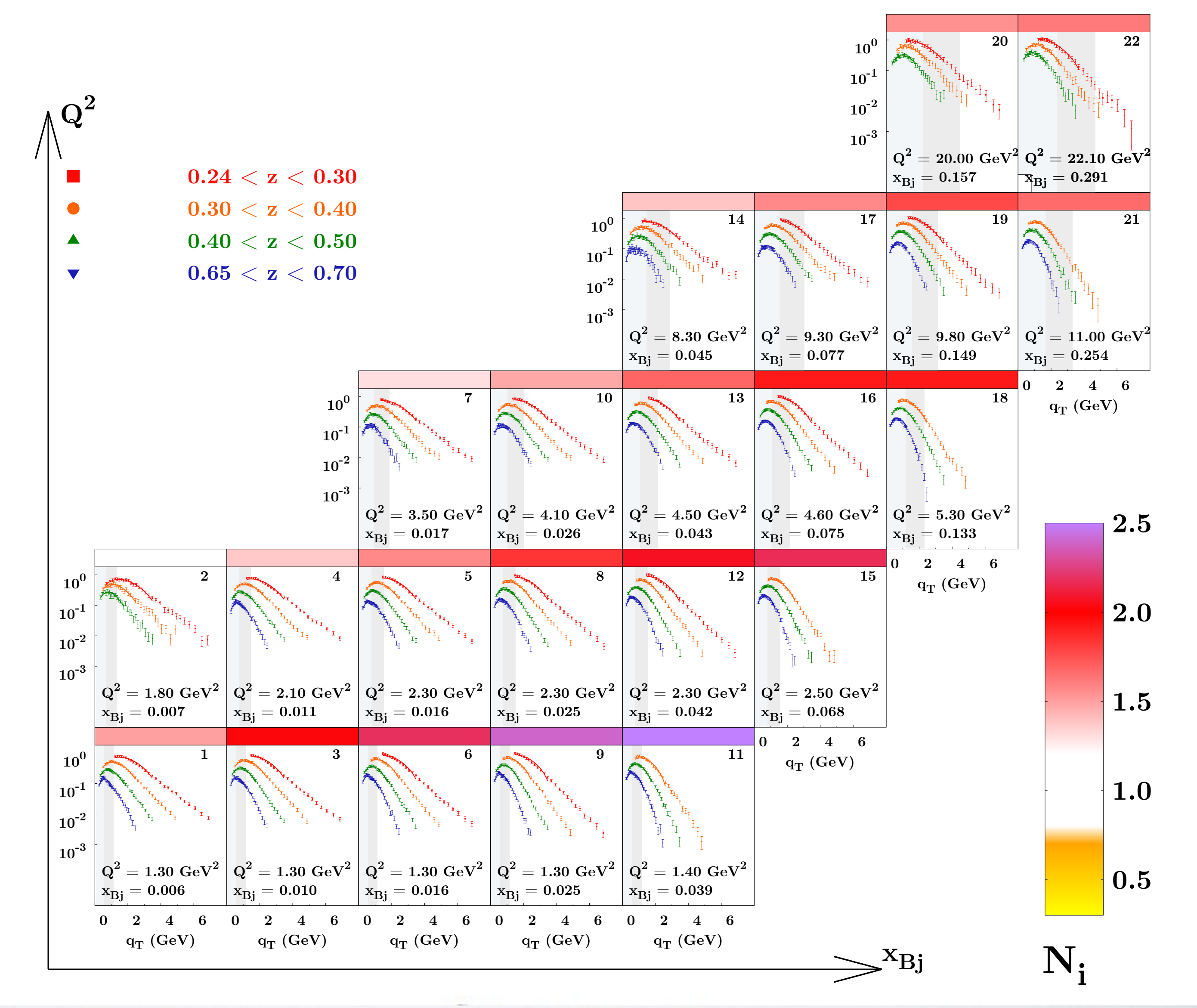
No normalization problems for
collinear SIDIS $d\sigma / dxdzdQ$:

MAPFF1.0 (Map Collaboration)
Abdul Khalek et al., arXiv:2105.08725

Normalization problem in SIDIS

Gonzalez-Hernandez,

PoS DIS2019 (2019)

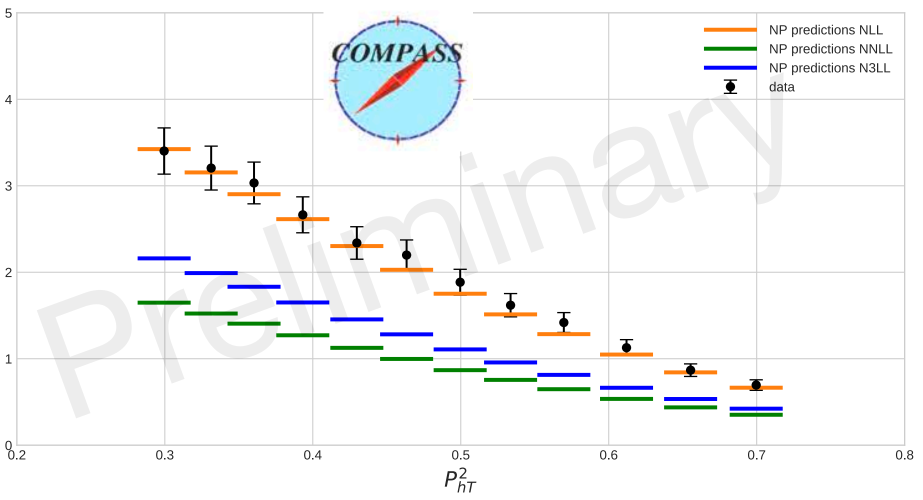


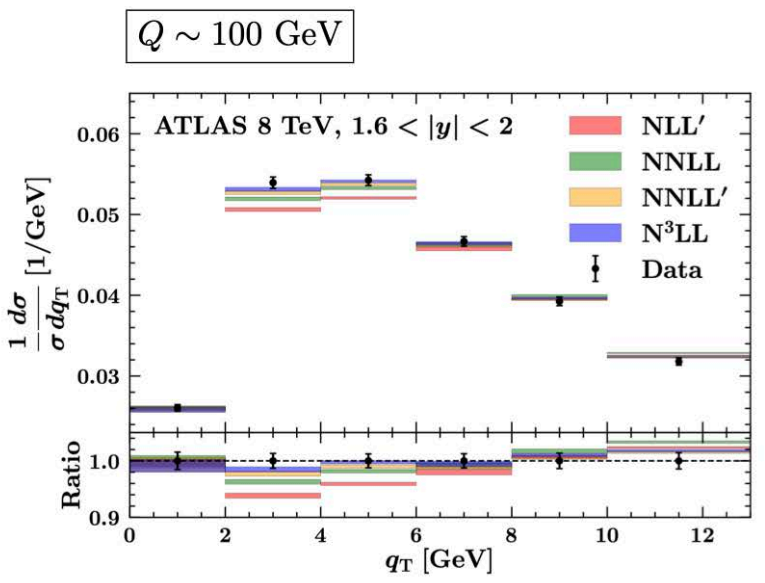
Normalization issue in SIDIS

increasing perturbative accuracy

worsens agreement with SIDIS ! increases agreement with Drell-Yan

$M^h(\bar{x}, \bar{z}, \bar{Q}, q_T)$ NLL NNLL N^{3}LL

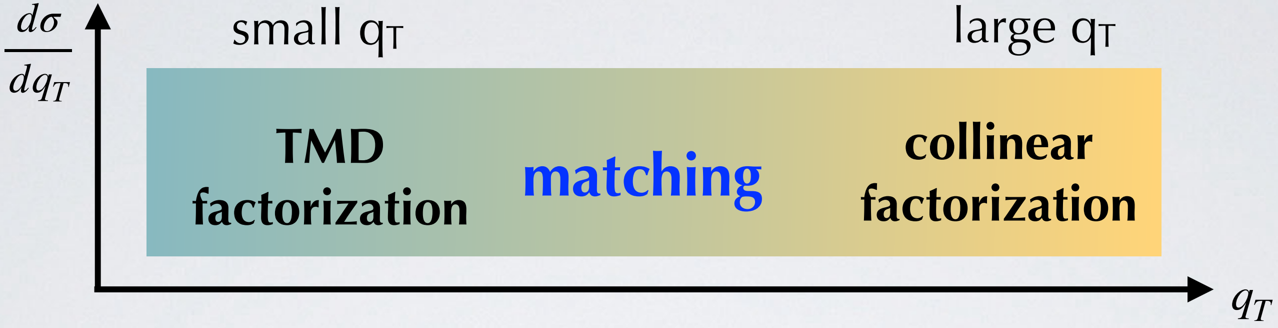




discrepancy is P$_{hT}$-independent: $M_{\text{NLL}}/M_{\text{NNLL}} \sim 2$ $M_{\text{NLL}}/M_{\text{N}^3\text{LL}} \sim 1.5$

SIDIS data as multiplicities M : $M(x, z, q_T, Q) = \dfrac{d\sigma^{\text{SIDIS}}}{dxdzdq_TdQ} \Big/ \dfrac{d\sigma^{\text{DIS}}}{dxdQ}$

Normalization issue in SIDIS



W-term   Y-term

$$\int dq_T \left[\frac{d\sigma}{dxdzdq_TdQ} = W \sim \mathscr{H} \left[\text{TMDPDF} \otimes \text{TMDFF}\right] \right] \longrightarrow \frac{d\sigma}{dxdzdQ}\Big|_{\text{LO}} \sim \text{PDF} \times \text{FF}$$

at lowest order (NLL),

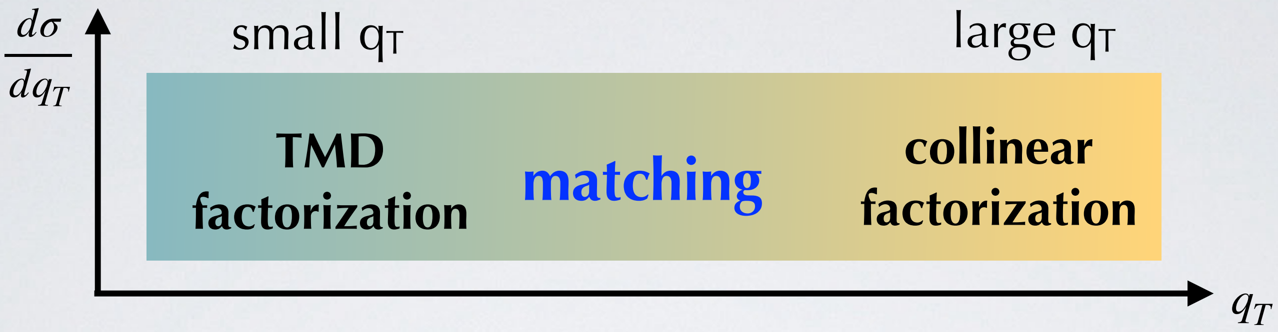
$$\mathscr{H}^{\text{SIDIS}} \approx 1$$

the integrated W-term reproduces the SIDIS collinear dσ at LO, which reasonably describes data

De Florian et al., P.R. D**75** (07) 114010

⇒ $M(x, z, q_T, Q) = \frac{d\sigma^{\text{SIDIS}}}{dxdzdq_TdQ} \Big/ \frac{d\sigma^{\text{DIS}}}{dxdQ}$ is ok

Normalization issue in SIDIS



TMD factorization

matching

collinear factorization

W-term

Y-term

$$\int dq_T \left[\frac{d\sigma}{dx\,dz\,dq_T\,dQ} = W\Big|_{\mathrm{NNLL}} \sim \mathscr{H}\,[\mathrm{TMDPDF} \otimes \mathrm{TMDFF}] \right] \neq \frac{d\sigma}{dx\,dz\,dQ}\Big|_{\mathrm{NLO}}$$

at higher order (ex.: NNLL)

$$\mathscr{H}^{\mathrm{SIDIS}} < 1$$

integrated W-term does not reproduce the SIDIS collinear dσ at NLO
Y-term contributions missing

→ $M(x, z, q_T, Q) = \frac{d\sigma^{\mathrm{SIDIS}}}{dx\,dz\,dq_T\,dQ} \Big/ \frac{d\sigma^{\mathrm{DIS}}}{dx\,dQ}$ underestimates data

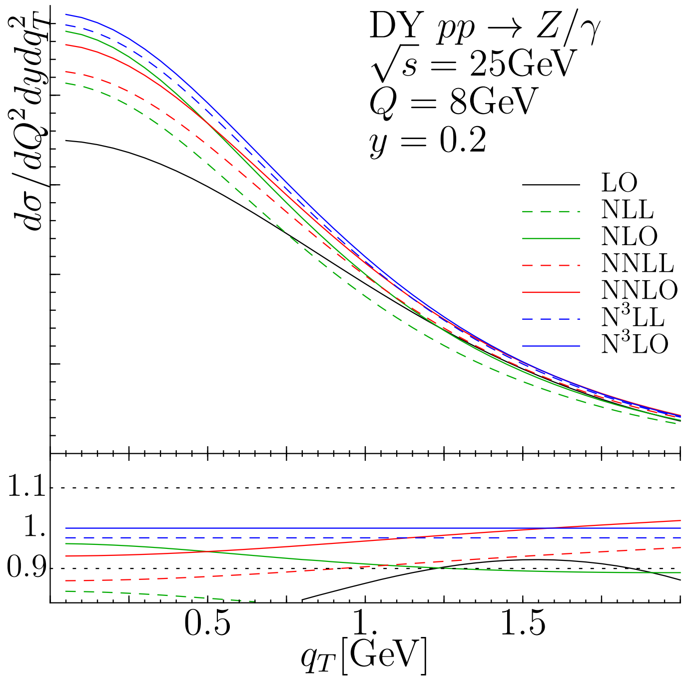
We define the normalization factor

$$\omega(x, z, Q) = \frac{d\sigma}{dx\,dz\,dQ} \Big/ \int dq_T\, W$$

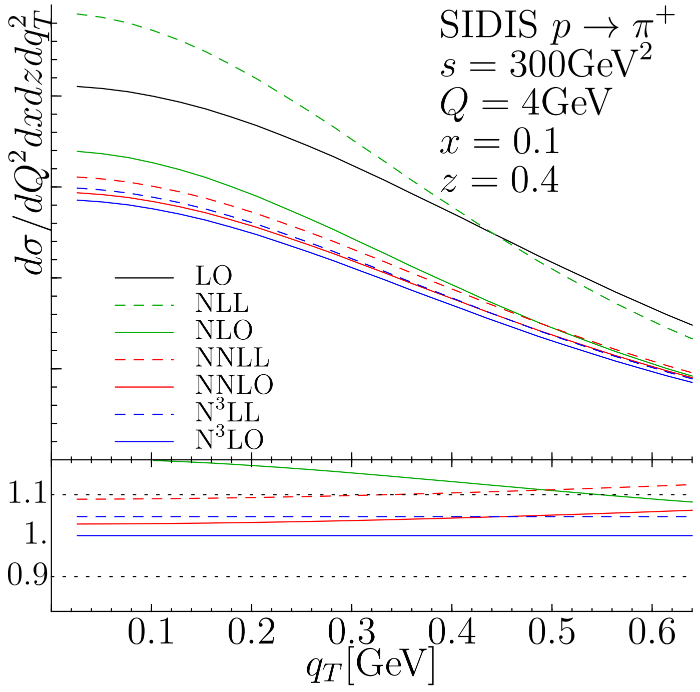
$= 1$ at NLL

Does not depend on fit parameters, precomputed

Backup: SV19 SIDIS normalization



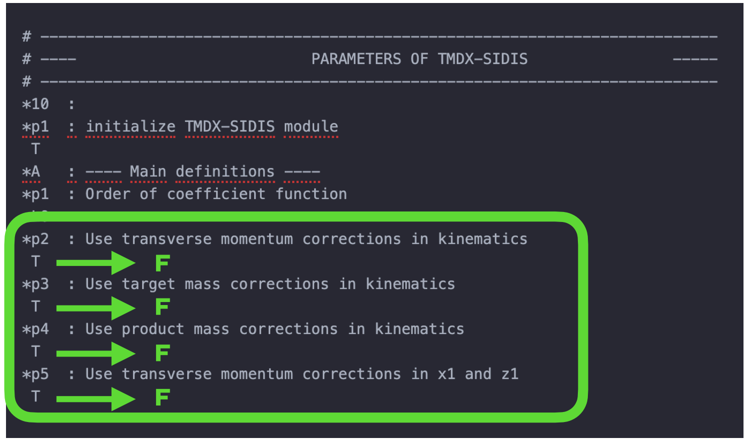
Drell-Yan



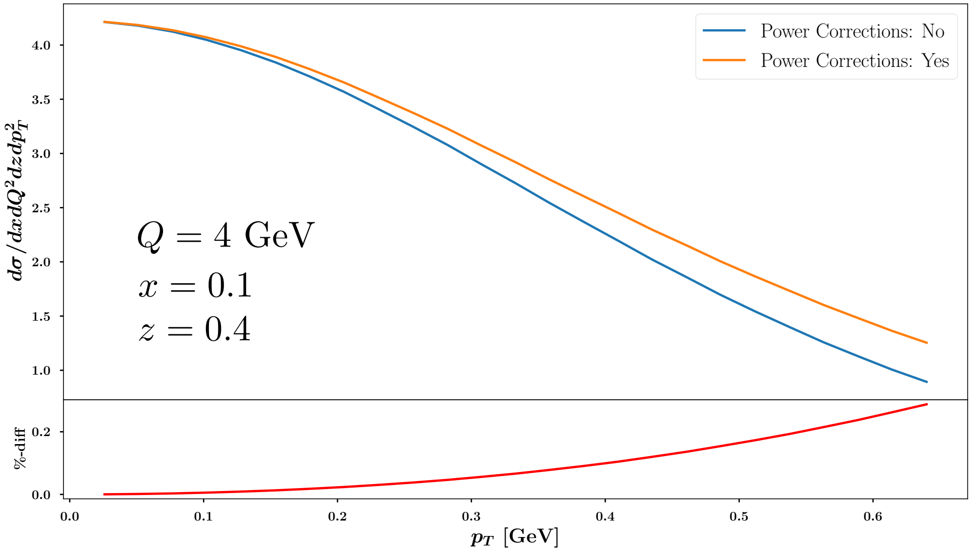
SIDIS

where are data w.r.t. NLL result?

Backup: SV19 power corrections



```
# ------------------------------------------------------------------------------
# ----                        PARAMETERS OF TMDX-SIDIS                    -----
# ------------------------------------------------------------------------------
*10  :
*p1  : initialize TMDX-SIDIS module
 T
*A   : ---- Main definitions ----
*p1  : Order of coefficient function
*p2  : Use transverse momentum corrections in kinematics
 T → F
*p3  : Use target mass corrections in kinematics
 T → F
*p4  : Use product mass corrections in kinematics
 T → F
*p5  : Use transverse momentum corrections in x1 and z1
 T → F
```



arTeMiDe includes M/Q , q_T/Q power corrections effects in the q_T tail => not a normalization effect

Drell-Yan observables

collider

Exp: normalized cross section differential in q_T in each bin

Th: for each bin [i,f]

$$\frac{1}{\sigma_{\text{fiducial}}}\frac{1}{(\Delta q_T)_{if}}\int_{q_{Ti}}^{q_{Tf}} dq_T \int_{y_i}^{y_f} dy \int_{Q_i}^{Q_f} dQ \frac{d\sigma}{dq_T dy dQ}$$

DYNNLO
with MMHT14 PDFs

---

fixed target

E288: cross section differential in average $\overline{q_T}$ and $\overline{y}$

Th: for each bin [i,f]

$$\frac{1}{2\pi\bar{q}_T}\int_{Q_i}^{Q_f} dQ \frac{d\sigma}{dq_T dy dQ}\bigg|_{y=\bar{y},\, q_T=\bar{q}_T}$$

E772: cross section differential in average $\overline{q_T}$ and $x_F = x_A - x_B$ bins

Th: for each bin [i,f]

$$\frac{1}{(\Delta x_F)_{if}}\int_{x_{Fi}}^{x_{Ff}} dx_F \int_{Q_i}^{Q_f} dQ \frac{2E}{\pi\sqrt{s}}\frac{d\sigma}{dq_T^2 dx_F dQ}\bigg|_{q_T=\bar{q}_T}$$

E605: cross section differential in average $\overline{q_T}$ and $\overline{x_F}$

Th: for each bin [i,f]

$$\int_{Q_i}^{Q_f} dQ \frac{2E}{\pi\sqrt{s}}\frac{d\sigma}{dq_T^2 dx_F dQ}\bigg|_{x_F=\bar{x}_F,\, q_T=\bar{q}_T}$$

SIDIS observable

Exp: differential SIDIS cross section divided by DIS one

$$M(x, z, P_{hT}, Q) = \frac{d\sigma^{\mathrm{SIDIS}}}{dxdzdP_{hT}dQ} \Bigg/ \frac{d\sigma^{\mathrm{DIS}}}{dxdQ}$$

Multiplicity

Th: for each bin [i,f]

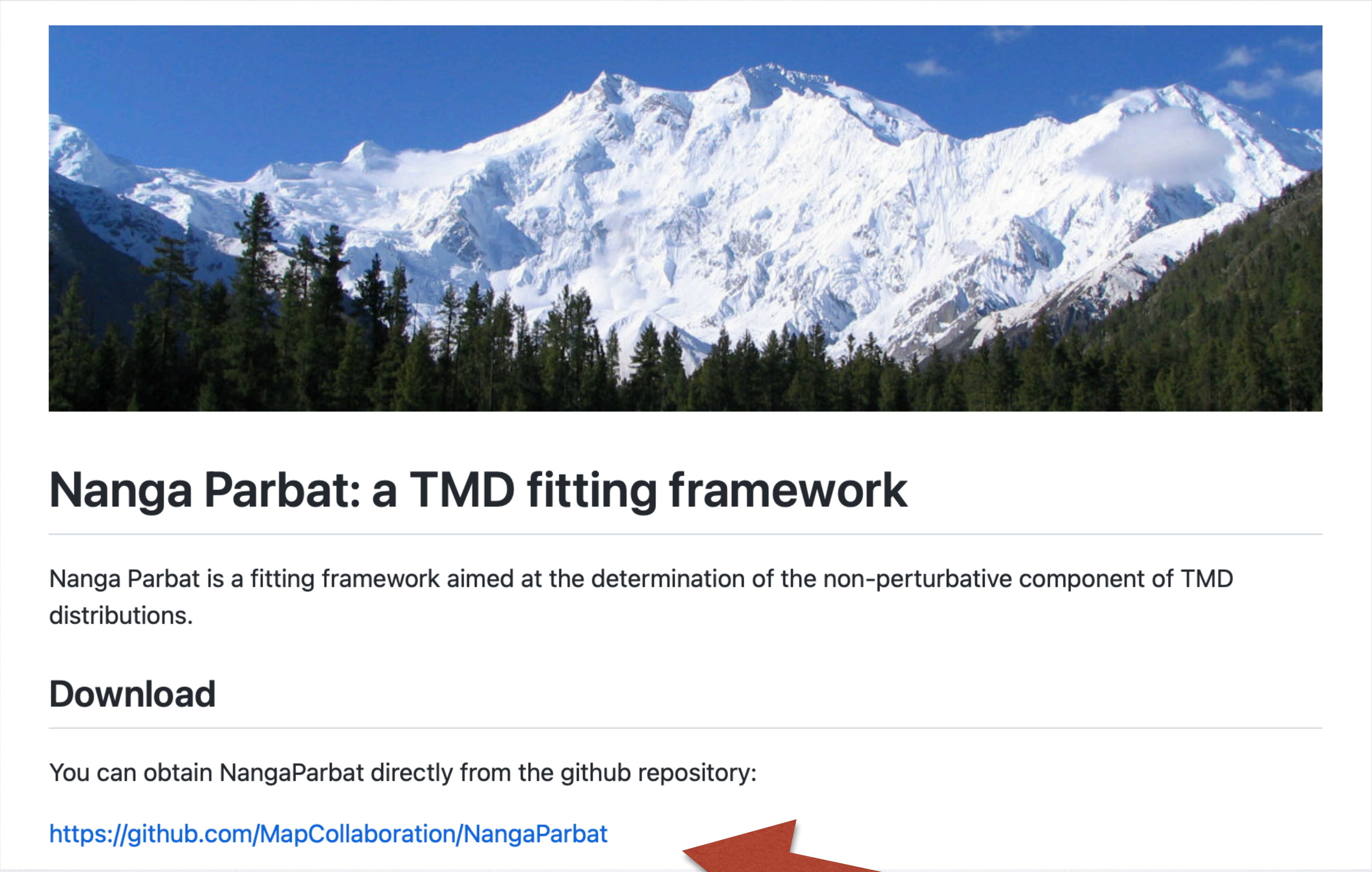
$$\mathcal{O}^{\mathrm{SIDIS}} = \frac{1}{(\Delta Q)_{if}} \int_{Q_i}^{Q_f} dQ \frac{1}{(\Delta x)_{if}} \int_{x_i}^{x_f} dx \frac{1}{(\Delta z)_{if}} \int_{z_i}^{z_f} dz \frac{1}{(\Delta P_{hT})_{if}} \int_{P_{hTi}}^{P_{hTf}} dP_{hT} \frac{d\sigma^{\mathrm{SIDIS}}}{dxdzdP_{hT}dQ}$$

$$\mathcal{O}^{\mathrm{DIS}} = \frac{1}{(\Delta Q)_{if}} \int_{Q_i}^{Q_f} dQ \frac{1}{(\Delta x)_{if}} \int_{x_i}^{x_f} dx \frac{d\sigma^{\mathrm{DIS}}}{dxdQ}$$

$$M^{\mathrm{th}}(x_{if}, z_{if}, P_{hTif}, Q_{if}) = \frac{\mathcal{O}^{\mathrm{SIDIS}}}{\mathcal{O}^{\mathrm{DIS}}}$$

The Nanga Parbat fitting framework

All material available at the Nanga Parbat GitHub site



Nanga Parbat: a TMD fitting framework

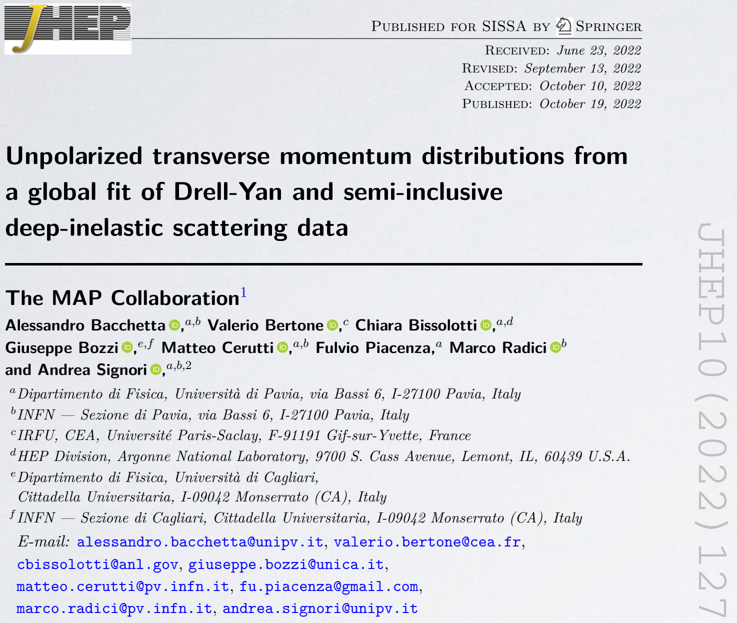
Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/MapCollaboration/NangaParbat

MAPTMD22



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Unpolarized transverse momentum distributions from a global fit of Drell-Yan and semi-inclusive deep-inelastic scattering data

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JHEP10(2022)127

MAPTMD22

arXiv:2206.07598

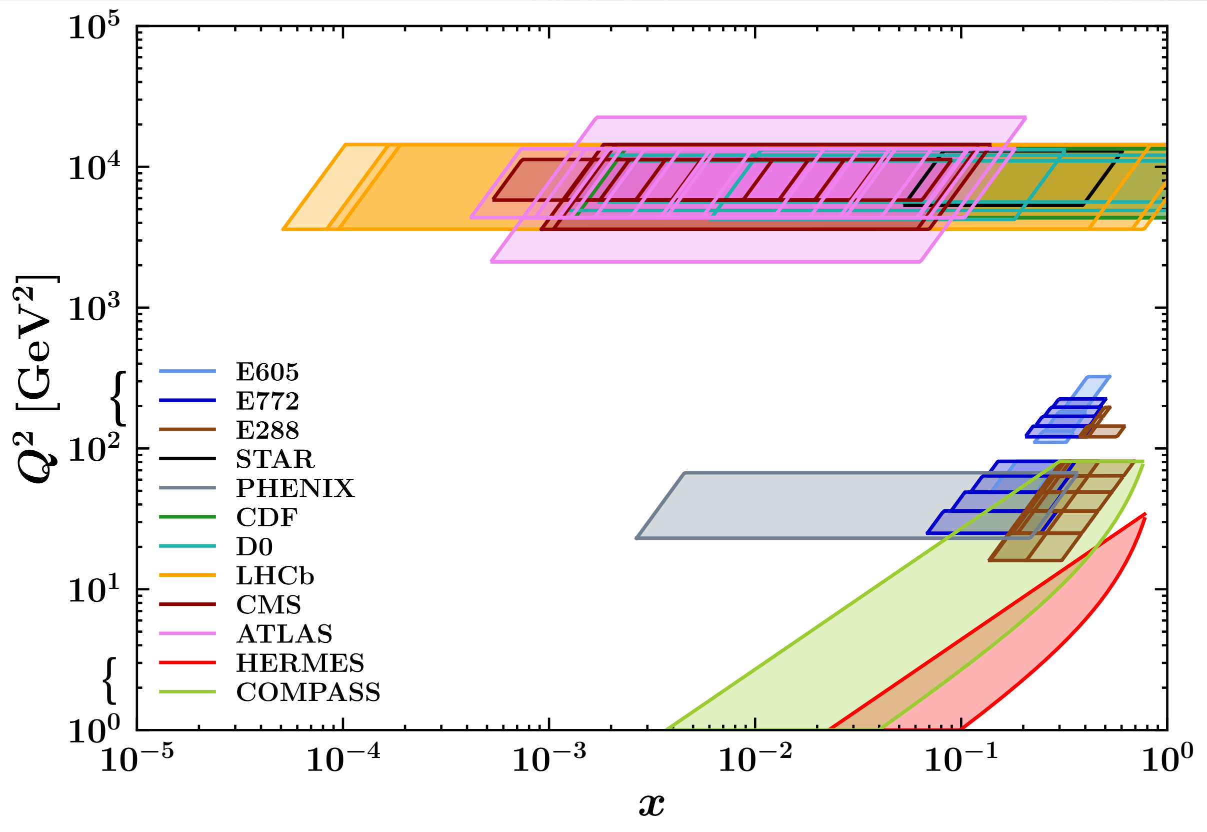
The MAPTMD22 data sets

N_{data} after cuts

Drell Yan $\left\{ \begin{array}{ll} 233 & \text{fixed target} \\ 251 & \text{collider} \end{array} \right.$

1547 SIDIS

<u>2031 data points</u>



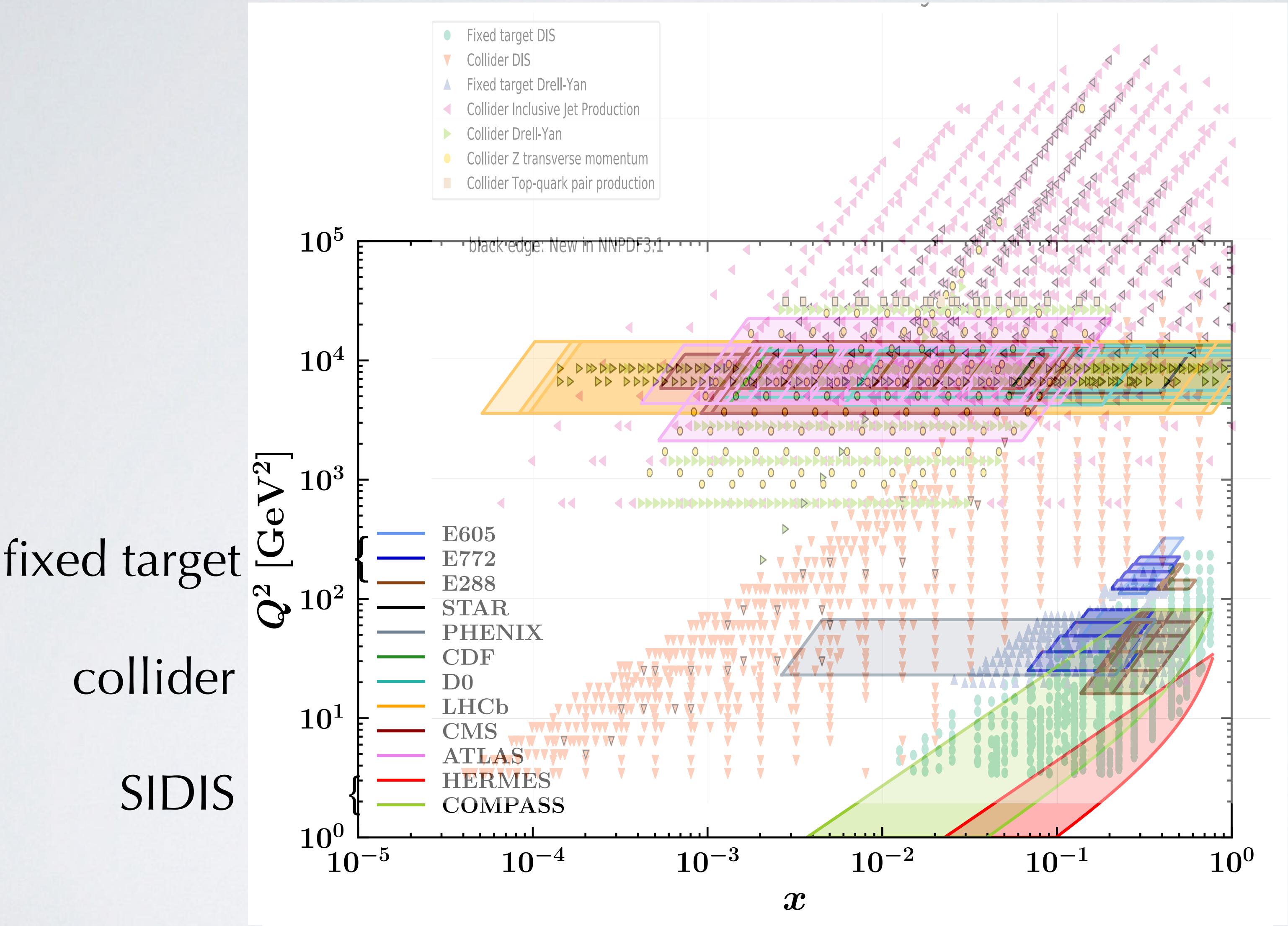
kinematic cuts

$\langle Q \rangle > 1.4$ GeV

$0.2 < z < 0.7$

Drell-Yan	$q_T < 0.2\,Q$
SIDIS	$P_{hT} < \min\Big[\min\big[0.2\,Q,\ 0.5\,Qz\big] + 0.3\,\text{GeV},\ zQ\Big]$

The (x,Q²) phase space of available data



smaller than for PDFs, but starts to be comparable…

MAPTMD22: Error treatment

bootstrap method: fitting 250 replicas of fluctuated exp. data

quality indicator: χ_0^2 of *central* replica (fitting not “ “ “)

MAPTMD22 at N³LL⁽⁻⁾ : N_{data}=**2031**, **21** parameters, $\chi_0^2/N_{\text{data}} = 1.06$

$$\chi_0^2 \sim \langle \chi^2 \rangle_{\text{replicas}}$$

(exp. / th.) errors can be uncorrelated or correlated

$$\chi^2 = \chi_D^2 + \chi_\lambda^2$$

penalty for correlated errors

$$\sum_{\text{bins}} \left(\frac{\exp - \overline{\text{th}}}{\sigma} \right)^2$$

$$\sigma^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{uncorr}}^2$$

$$\overline{\text{th}} = \text{th} + \sum_\alpha \lambda_\alpha \sigma_{\text{corr}}^{(\alpha)}$$

$$\chi_\lambda^2 = \sum_\alpha \lambda_\alpha^2$$

nuisance params.

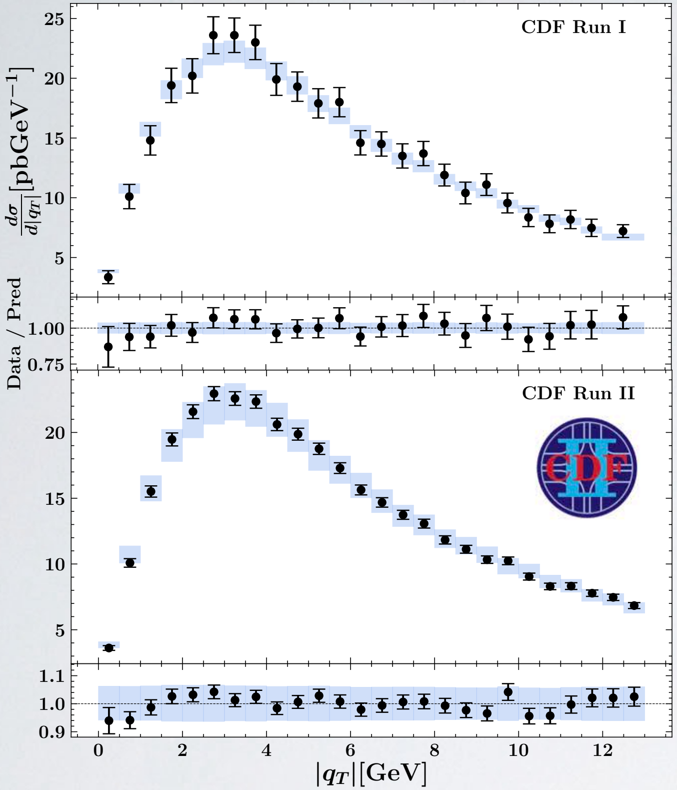
Examples of (partly) correlated errors :

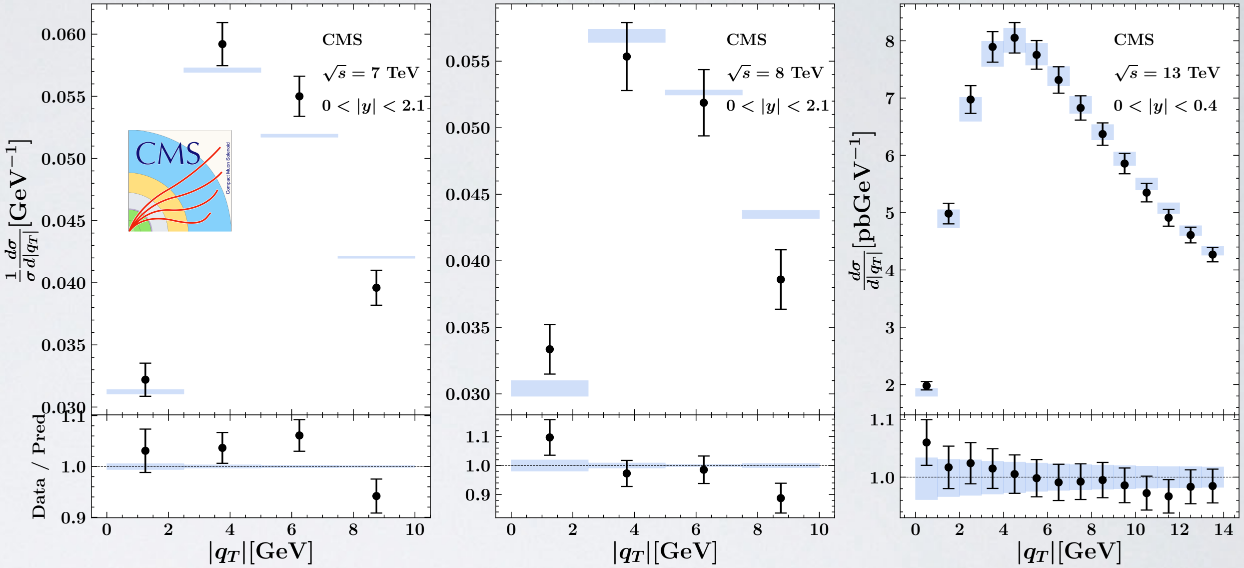
- exp.: some normalization systematic errors
- th. : uncertainties of PDFs MMHT2014

  FFs DSS14 for $\pi^\pm$

  DSS17 for $K^\pm$

MAPTMD22 N^{3}LL$^{(-)}$ global fit $\chi_0^2/N_{\text{data}} = 1.06$

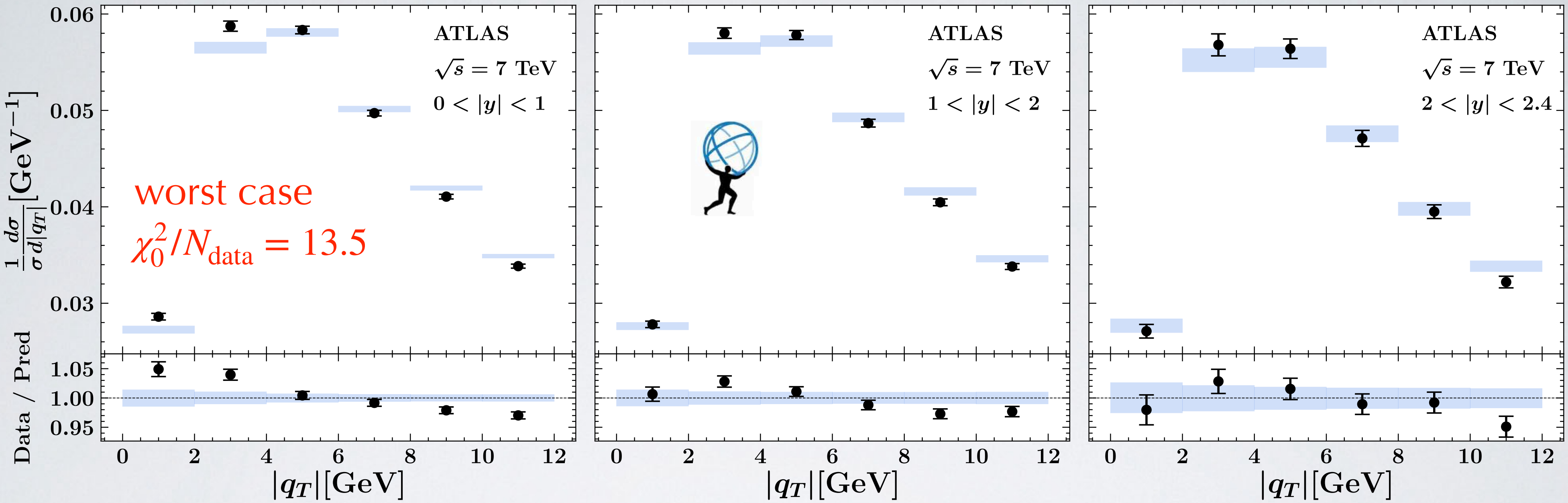




data set	N_{data}	χ_D^2	χ_λ^2	χ_0^2
Tevatron total	71	0.87	0.06	0.93
PHENIX 200	2	2.21	0.88	3.08
STAR 510	7	1.05	0.10	1.15
LHCb total	21	1.15	0.3	1.45
ATLAS total	72	4.56	0.48	5.05
CMS total	78	0.53	0.02	0.55
collider total	251	1.86	0.2	2.06
fixed target tot	233	0.85	0.4	1.24

th. error band =
68% of all replicas

MAPTMD22 N^{3}LL$^{(-)}$ global fit $\chi_0^2/N_{\text{data}} = 1.06$



worst case
$\chi_0^2/N_{\text{data}} = 13.5$

extremely small exp. errors
→ very sensitive to small th. corrections

Examples:
- numerical implementation of lepton cuts
- power corrections
- effects of matching Y term

Chen et al., arXiv:2203.01565
Camarda et al., arXiv:2111.14509
Buonocore et al., arXiv:2111.13661

data set	N_{data}	χ_D^2	χ_λ^2	χ_0^2
ATLAS 7 TeV	18	6.43	0.92	7.35
ATLAS 8 TeV	48	3.7	0.32	4.02
ATLAS 13 TeV	6	5.09	0.5	6.4
ATLAS total	72	4.56	0.48	5.05
collider total	251	1.86	0.2	2.06

Visualizing MAPTMD22 TMD PDF

TMD PDF for unpolarized up quark

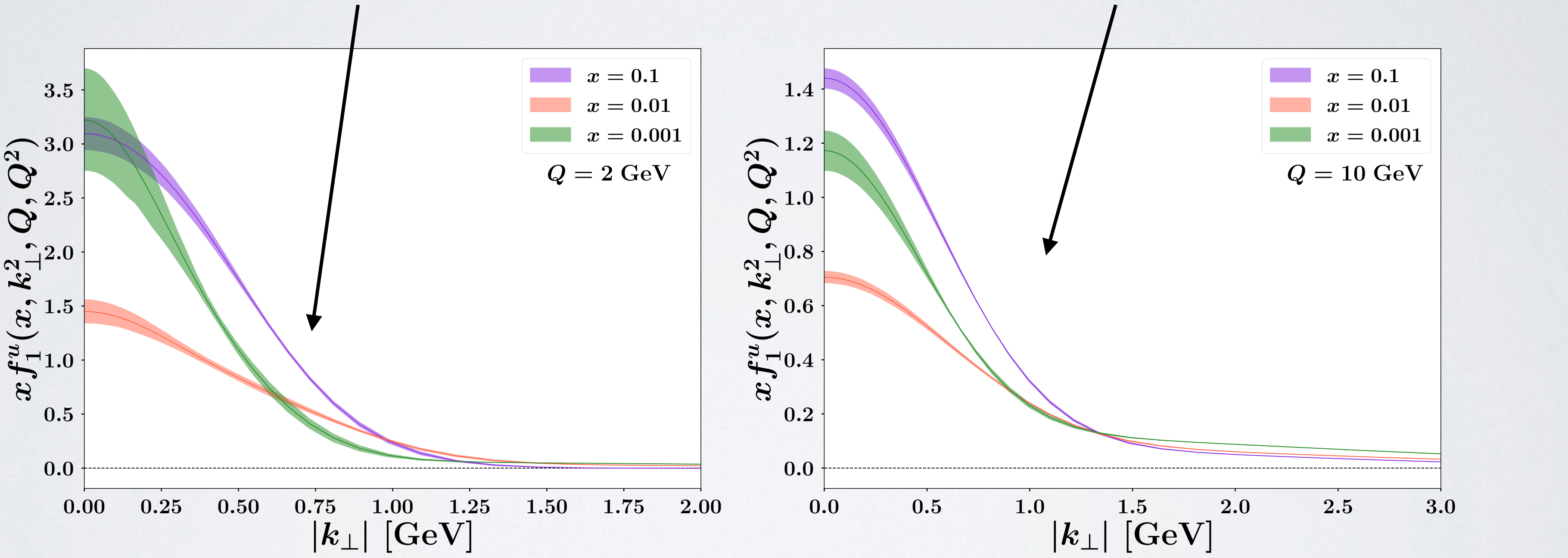
$f_{NP}(x,b_T)$

~ Gaussian + λ_B weighted Gaussian + λ_C Gaussian

non-pert. evolution $e^{-g_2^2\, b_T^2/4}$

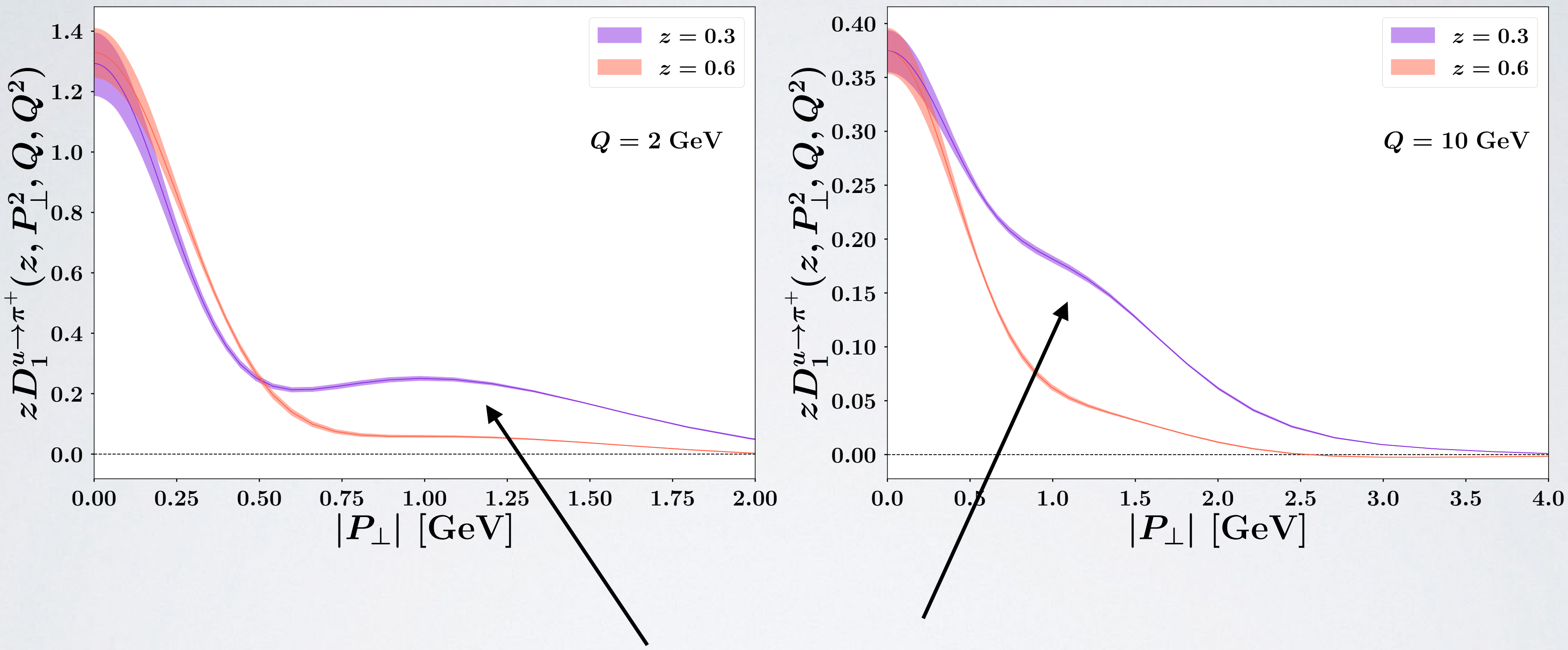
$\lambda_B = 1.82 \pm 0.29\ \mathrm{GeV}^{-1}$ $\lambda_C = 0.0215 \pm 0.0058\ \mathrm{GeV}^{-1}$

$g_2 = 0.248 \pm 0.008\ \mathrm{GeV}$



Visualizing MAPTMD22 TMD FF

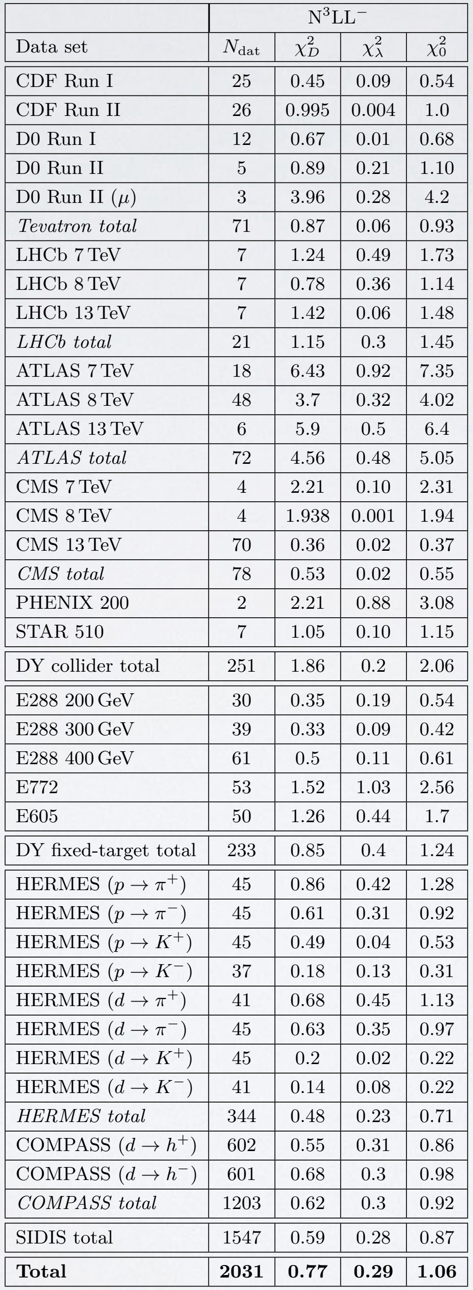
up → π^+



$D_{\mathrm{NP}}(z, P_\perp; Q_0)$ ~ Gauss + λ_{F} $P_\perp^2$ Gauss

$$\lambda_F = 0.078 \pm 0.011 \text{ GeV}^{-2}$$

MAPTMD22: χ^2 breakout



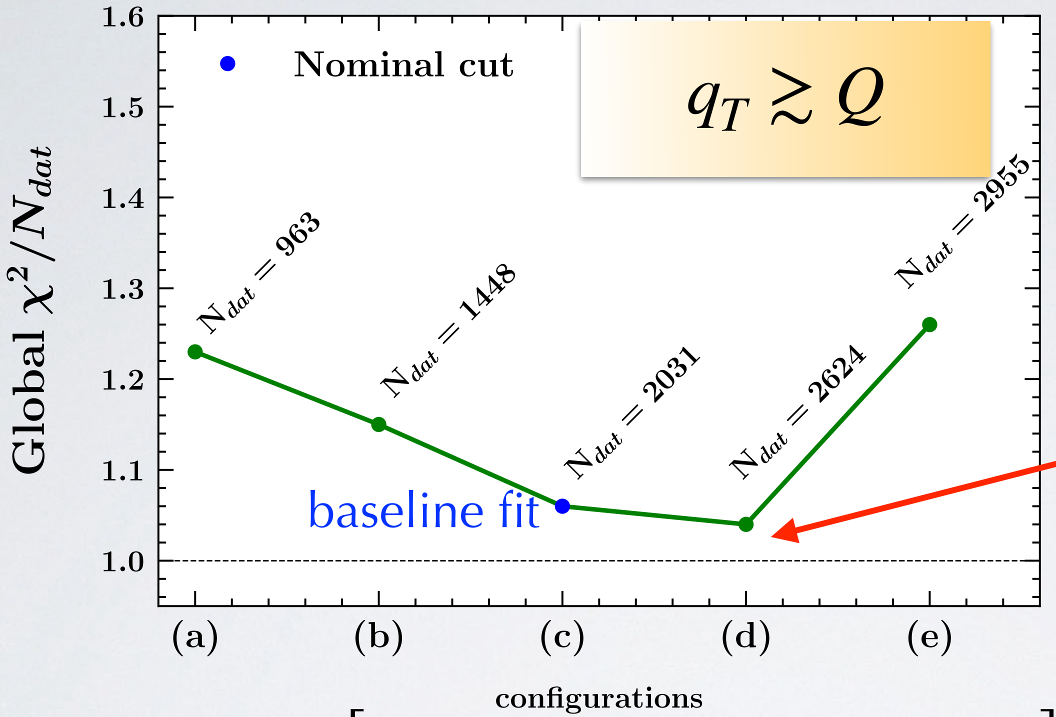
	N^3LL^-			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
CDF Run I	25	0.45	0.09	0.54
CDF Run II	26	0.995	0.004	1.0
D0 Run I	12	0.67	0.01	0.68
D0 Run II	5	0.89	0.21	1.10
D0 Run II (μ)	3	3.96	0.28	4.2
Tevatron total	71	0.87	0.06	0.93
LHCb 7 TeV	7	1.24	0.49	1.73
LHCb 8 TeV	7	0.78	0.36	1.14
LHCb 13 TeV	7	1.42	0.06	1.48
LHCb total	21	1.15	0.3	1.45
ATLAS 7 TeV	18	6.43	0.92	7.35
ATLAS 8 TeV	48	3.7	0.32	4.02
ATLAS 13 TeV	6	5.9	0.5	6.4
ATLAS total	72	4.56	0.48	5.05
CMS 7 TeV	4	2.21	0.10	2.31
CMS 8 TeV	4	1.938	0.001	1.94
CMS 13 TeV	70	0.36	0.02	0.37
CMS total	78	0.53	0.02	0.55
PHENIX 200	2	2.21	0.88	3.08
STAR 510	7	1.05	0.10	1.15
DY collider total	251	1.86	0.2	2.06
E288 200 GeV	30	0.35	0.19	0.54
E288 300 GeV	39	0.33	0.09	0.42
E288 400 GeV	61	0.5	0.11	0.61
E772	53	1.52	1.03	2.56
E605	50	1.26	0.44	1.7
DY fixed-target total	233	0.85	0.4	1.24
HERMES ($p \to \pi^+$)	45	0.86	0.42	1.28
HERMES ($p \to \pi^-$)	45	0.61	0.31	0.92
HERMES ($p \to K^+$)	45	0.49	0.04	0.53
HERMES ($p \to K^-$)	37	0.18	0.13	0.31
HERMES ($d \to \pi^+$)	41	0.68	0.45	1.13
HERMES ($d \to \pi^-$)	45	0.63	0.35	0.97
HERMES ($d \to K^+$)	45	0.2	0.02	0.22
HERMES ($d \to K^-$)	41	0.14	0.08	0.22
HERMES total	344	0.48	0.23	0.71
COMPASS ($d \to h^+$)	602	0.55	0.31	0.86
COMPASS ($d \to h^-$)	601	0.68	0.3	0.98
COMPASS total	1203	0.62	0.3	0.92
SIDIS total	1547	0.59	0.28	0.87
Total	**2031**	**0.77**	**0.29**	**1.06**

MAPTMD22: NNLL and NLL fits

	N^3LL^-		NNLL		NLL	
Data set	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$
ATLAS	72	5.01 ± 0.26	/	/	/	/
PHENIX 200	2	3.26 ± 0.31	2	0.81 ± 0.11	/	/
STAR 510	7	1.16 ± 0.04	7	0.99 ± 0.03	/	/
Other sets	170	0.83 ± 0.01	170	2.37 ± 0.11	/	/
DY collider	251	2.06 ± 0.07	179	2.3 ± 0.1	/	/
E772	53	2.48 ± 0.12	53	2.05 ± 0.22	/	/
Other sets	180	0.87 ± 0.04	180	0.71 ± 0.04	180	0.81 ± 0.04
DY fixed-target	233	1.24 ± 0.04	233	1.01 ± 0.05	180	0.81 ± 0.04
HERMES	344	0.71 ± 0.04	344	1.1 ± 0.06	344	0.51 ± 0.02
COMPASS	1203	0.95 ± 0.02	1203	0.6 ± 0.06	1203	0.41 ± 0.01
SIDIS	1547	0.89 ± 0.02	1547	0.71 ± 0.05	1547	0.43 ± 0.01
Total	2031	1.08 ± 0.01	1959	0.89 ± 0.01	1727	0.47 ± 0.01

data sets requiring higher pert. accuracy need to be excluded.
Still, these fits useful for polarized situations with less available accuracy

MAPTMD22: Kinematic cuts



better χ^2 with less conservative cuts allowing for $q_T > Q$

Where is the limit for TMD factorization??

$$P_{hT} < \min\left[\min\left[c_1\, Q,\, c_2\, Qz\right] + c_3\,\text{GeV},\, zQ\right]$$

a) $c_1 = c_2 = 0.4$, $c_3 = 0$ $q_T < 0.4\ Q$

b) $c_1 = 0.15$, $c_2 = 0.4$, $c_3 = 0.2$

c) $c_1 = 0.2$, $c_2 = 0.5$, $c_3 = 0.3$ baseline fit

d) $c_1 = 0.2$, $c_2 = 0.6$, $c_3 = 0.4$ can be $q_T > Q$

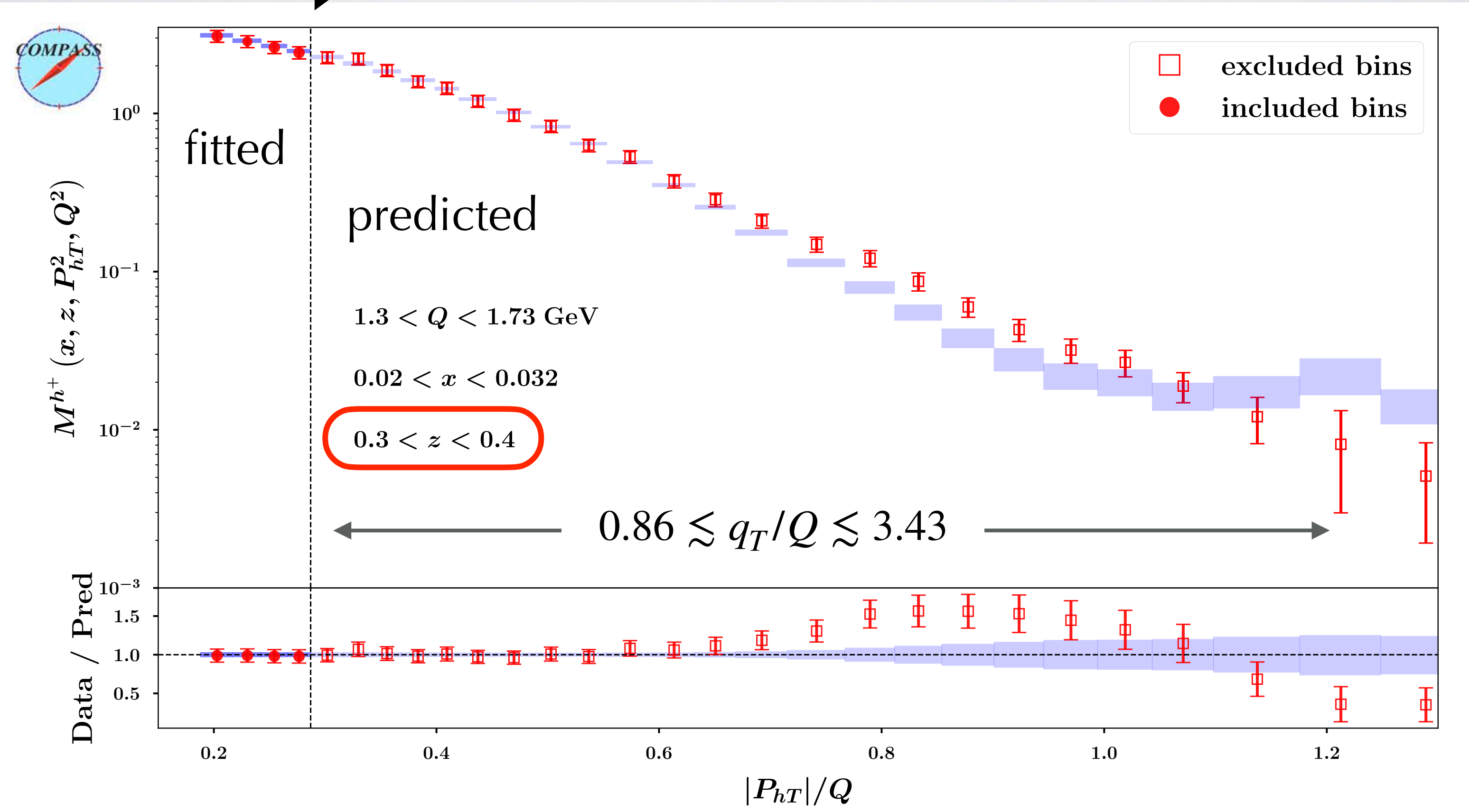
e) $c_1 = 0.2$, $c_2 = 0.7$, $c_3 = 0.5$ can be $q_T > Q$

more conservative

less conservative

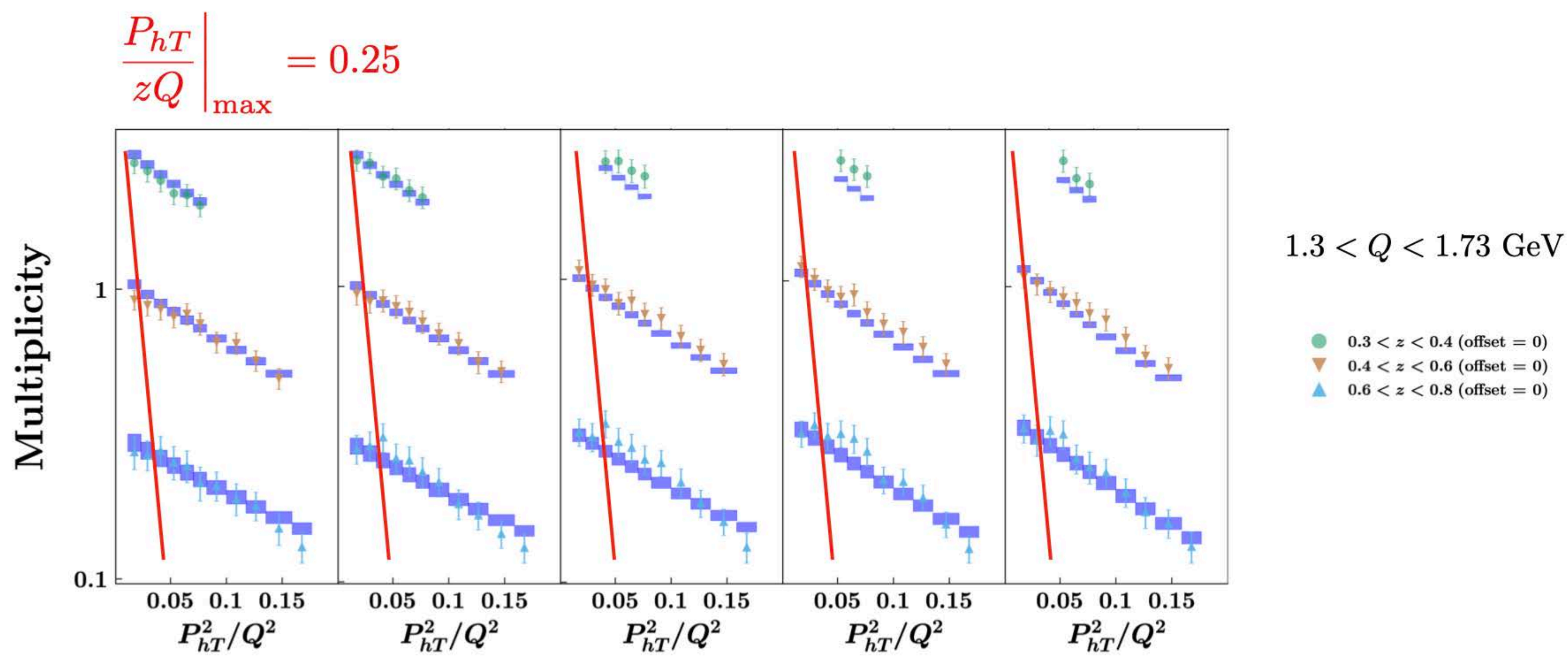
MAPTMD22: validity of TMD region?

cut of baseline fit $P_{hT} < \min\Big[\min\big[0.2\,Q,\, 0.5\,Qz\big] + 0.3\,\text{GeV},\, zQ\Big]$



validity of TMD factorization seems to extend well beyond $P_{hT}/z << Q$!

Backup: SV19 cut on COMPASS



more stringent cut => 1/3 of MAPTMD22 SIDIS data points

Visualizing the Collins-Soper evolution kernel

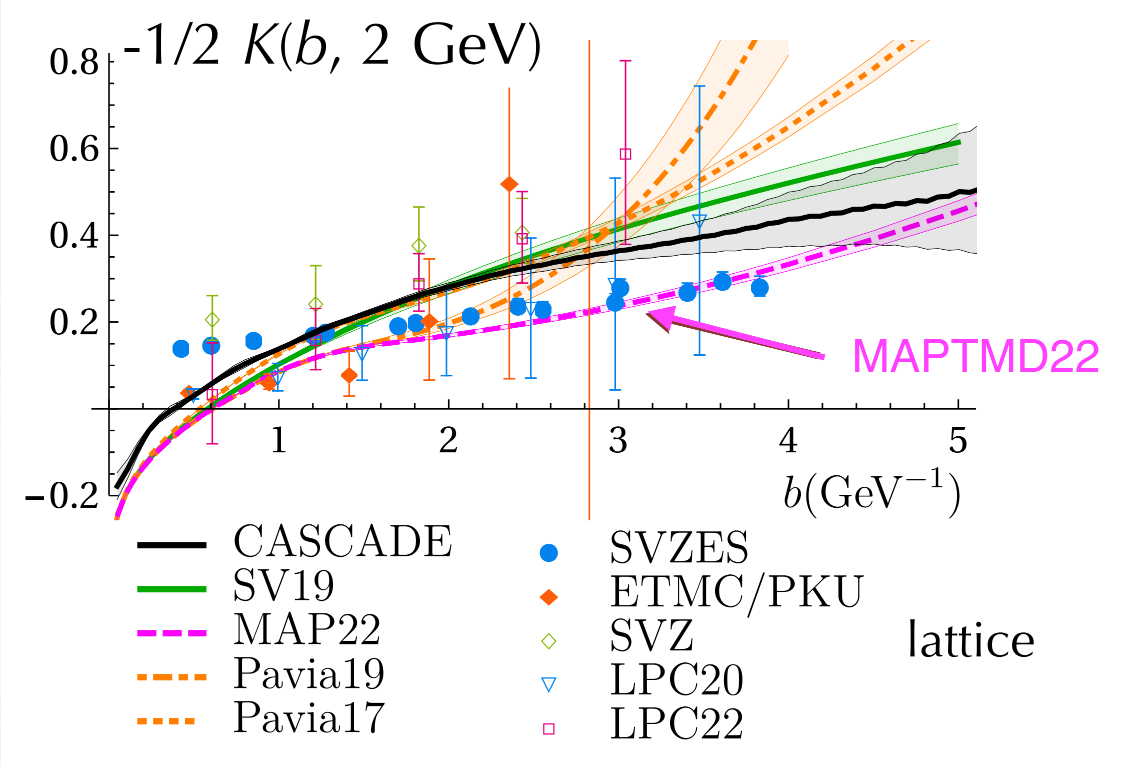
Collins-Soper kernel

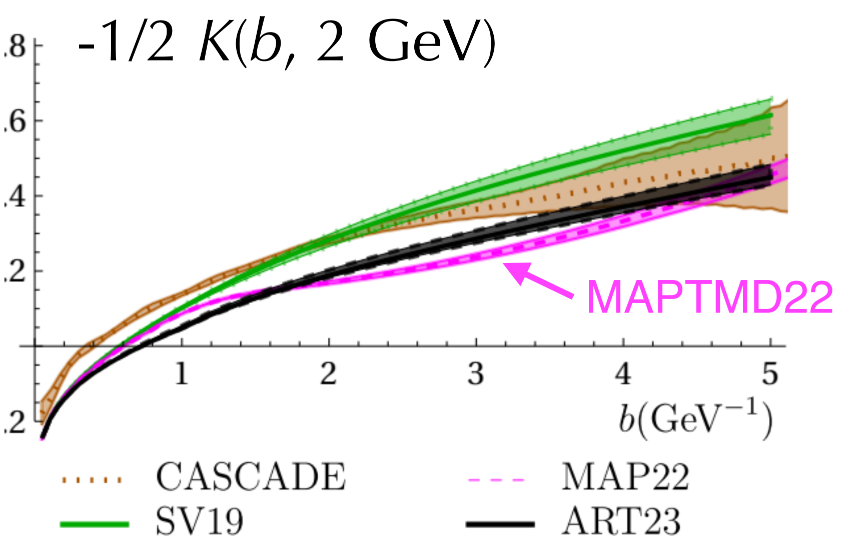
$$K(b_T, \mu_{b_*}) = K(b_*, \mu_{b_*}) \ + \ g_K(b_T)$$

drives evolution in rapidity ζ

perturbative

non-perturbative
(fitted)

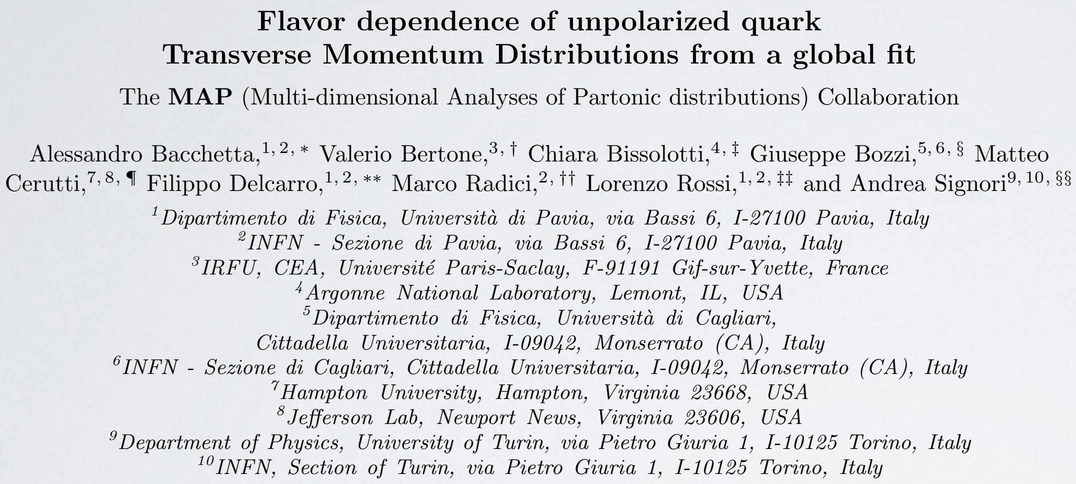




Moss et al., arXiv:2305.07473

Bermudez Martinez & Vladimirov, arXiv:2206.01105

MAPTMD24



Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit

The **MAP** (Multi-dimensional Analyses of Partonic distributions) Collaboration

Alessandro Bacchetta,[1,2,*] Valerio Bertone,[3,†] Chiara Bissolotti,[4,‡] Giuseppe Bozzi,[5,6,§] Matteo Cerutti,[7,8,¶] Filippo Delcarro,[1,2,**] Marco Radici,[2,††] Lorenzo Rossi,[1,2,‡‡] and Andrea Signori[9,10,§§]

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MAPTMD24

arXiv:2405.13833

Results with contributions from…

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Univ. Pavia

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Valerio Bertone
IRFU, CEA, Univ. Paris-Saclay

Chiara Bissolotti
ANL

Andrea Signori
Univ. Torino

Giuseppe Bozzi
Univ. Cagliari

Filippo Delcarro
postdoc Univ. Pavia

MAPTMD22 → MAPTMD24

- global fit of Drell-Yan and SIDIS data

2031 data pts. $\boxed{\rightarrow}$ same dataset =

- prescription to fix SIDIS normalization problem

pre-computed $\omega(x, z, Q)$ $\boxed{\rightarrow}$ same =

- theoretical perturbative accuracy

$N^3LL(-)$ $\boxed{\rightarrow}$ N^3LL

PDF: MMHT2014nnlo → NNPDF3.1NNLO

FF: DSS14 (π), DSS17 (K) at NLO → MAPFF1.0NNLO

New: using full Montecarlo sets

Abdul Khalek et al., arXiv:2204.10331

independence of results from choice of PDF cross-checked

- account of correlated (exp. & th.) errors including ΔPDF & ΔFF

bootstrap method → replicas of PDFs & FFs

- nonperturbative parametrisation

F.T.(combination of Gaussians) $\boxed{\rightarrow}$ same for each flavor ~

MAPTMD22 → MAPTMD24

2031 data pts. $\boxed{\rightarrow}$ same dataset

SIDIS normalization $\omega(x, z, Q)$ $\boxed{\rightarrow}$ same

N^{3}LL(-) $\boxed{\rightarrow}$ N^{3}LL

PDF: MMHT2014nnlo NNPDF3.1NNLO

FF: DSS14 (π), DSS17 (K) at NLO MAPFF1.0NNLO

correlated (exp. & th.) errors $\boxed{\rightarrow}$ same

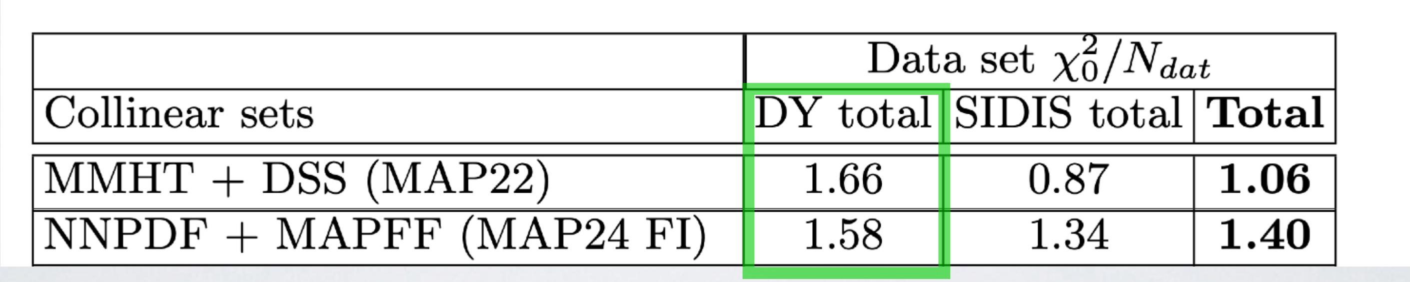
nonperturbative parametrisation $\boxed{\rightarrow}$ same flavor-independent case

21 parameters 21 parameters

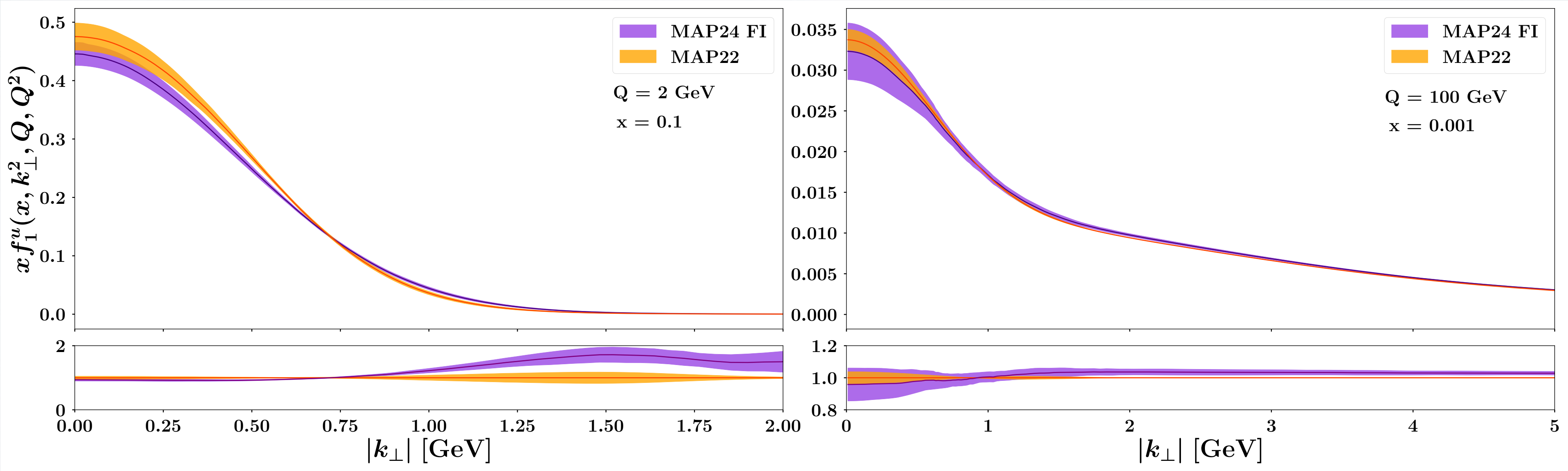
$\chi^2/N_{\text{data}} = 1.06$

$\chi^2/N_{\text{data}} = 1.40$

MAPTMD22 → MAPTMD24

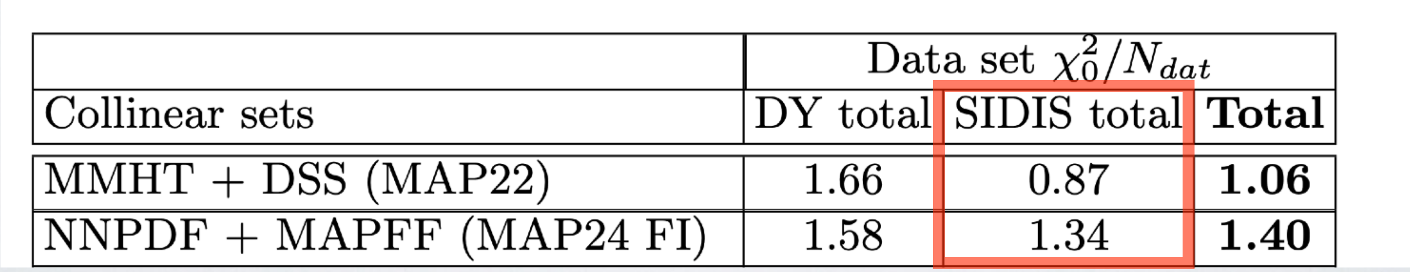


	Data set χ_0^2/N_{dat}		
Collinear sets	DY total	SIDIS total	**Total**
MMHT + DSS (MAP22)	1.66	0.87	**1.06**
NNPDF + MAPFF (MAP24 FI)	1.58	1.34	**1.40**



TMD PDFs from MAPTMD24
are compatible with MAPTMD22

MAPTMD22 → MAPTMD24



	Data set χ_0^2/N_{dat}		
Collinear sets	DY total	SIDIS total	**Total**
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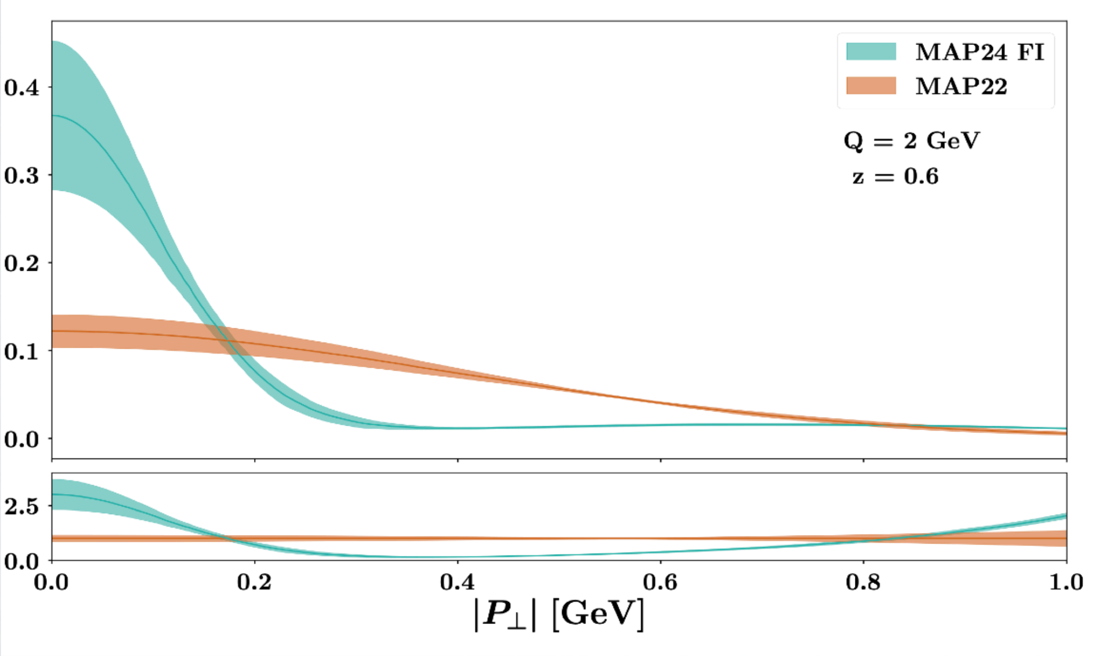
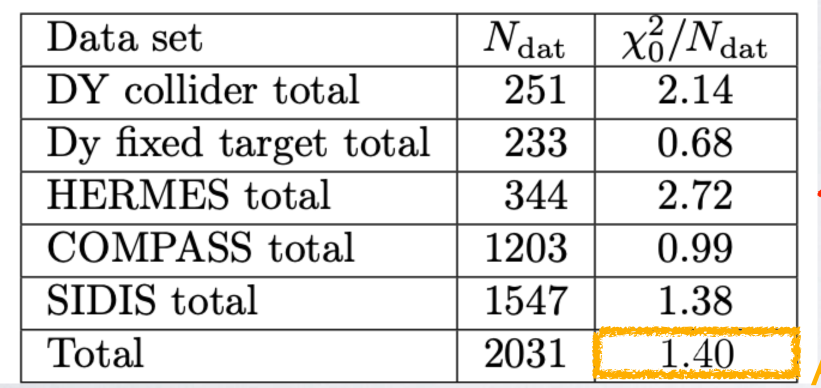


TMD FFs from MAPTMD24 are different from MAPTMD22

MAPFF1.0nnlo

- NNLO
- smaller uncertainties
- Neural Network approach

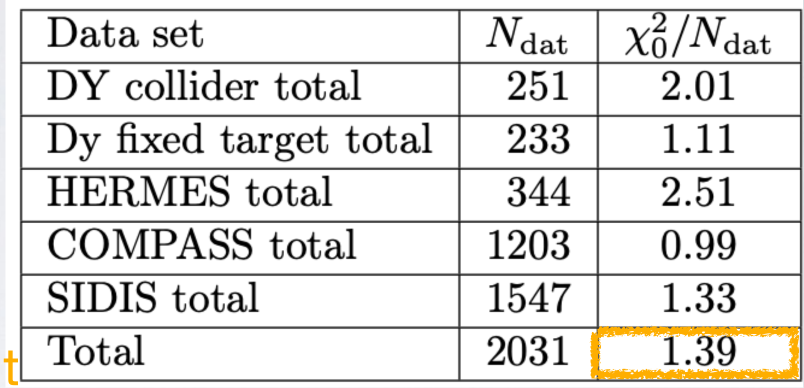
MAPTMD22 → MAPTMD24



Data set	N_{dat}	$\chi_0^2/N_{\mathrm{dat}}$
DY collider total	251	2.14
Dy fixed target total	233	0.68
HERMES total	344	2.72
COMPASS total	1203	0.99
SIDIS total	1547	1.38
Total	2031	1.40

NNPDF+MAPFF

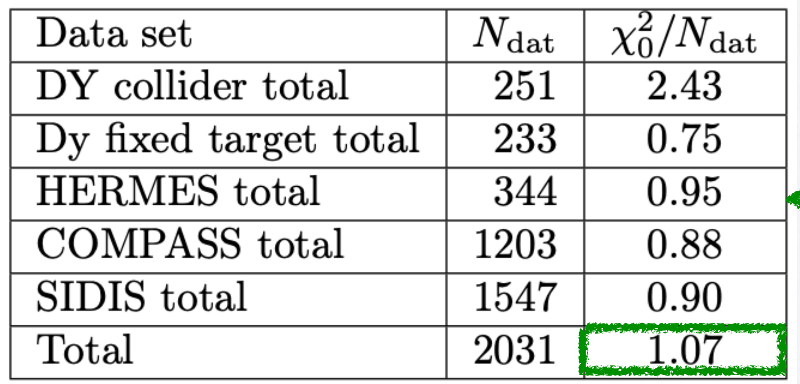
Agreement



Data set	N_{dat}	$\chi_0^2/N_{\mathrm{dat}}$
DY collider total	251	2.01
Dy fixed target total	233	1.11
HERMES total	344	2.51
COMPASS total	1203	0.99
SIDIS total	1547	1.33
Total	2031	1.39

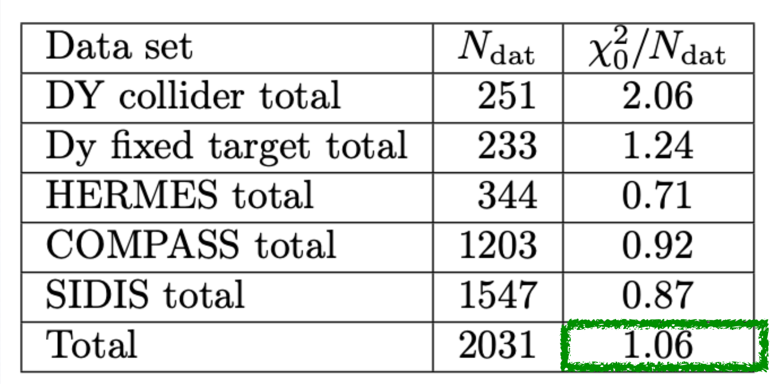
MMHT+MAPFF

Similar worsening



Data set	N_{dat}	$\chi_0^2/N_{\mathrm{dat}}$
DY collider total	251	2.43
Dy fixed target total	233	0.75
HERMES total	344	0.95
COMPASS total	1203	0.88
SIDIS total	1547	0.90
Total	2031	1.07

NNPDF+DSS



Data set	N_{dat}	$\chi_0^2/N_{\mathrm{dat}}$
DY collider total	251	2.06
Dy fixed target total	233	1.24
HERMES total	344	0.71
COMPASS total	1203	0.92
SIDIS total	1547	0.87
Total	2031	1.06

MMHT+DSS (MAPTMD22)

Good Agreement

Fit results for SIDIS

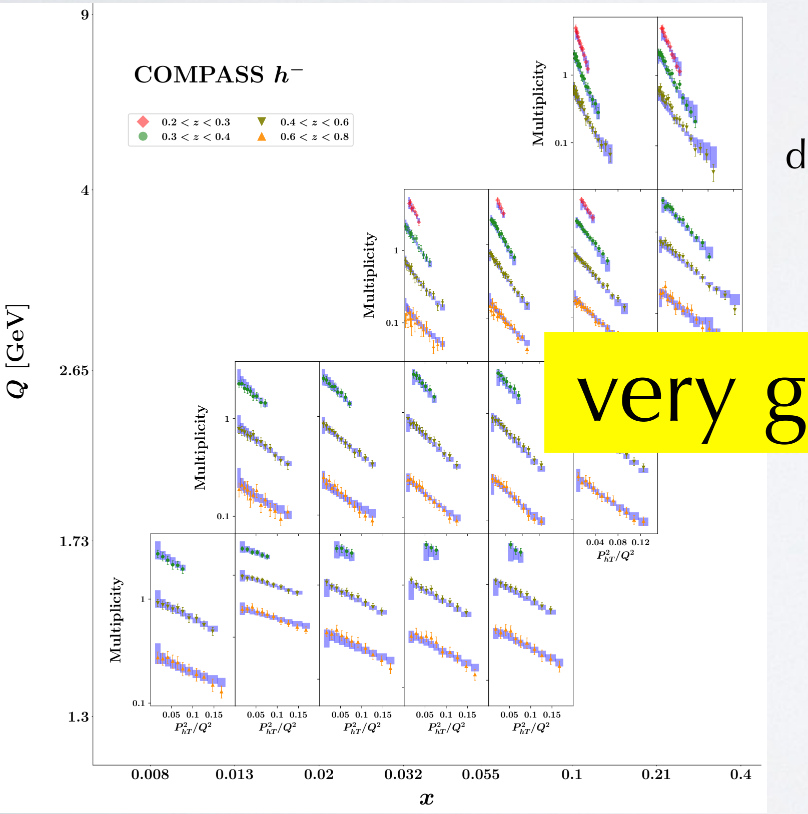
data set	N_{data}	χ^2_D	χ^2_λ	χ^2
HERMES	344	0.81	0.24	1.05
COMPASS	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
DY fixed target	233	0.63	0.31	0.94
DY collider	251	1.37	0.28	1.65
Total	**2031**	**0.81**	**0.27**	**1.08**

χ_D^2 = uncorrelated error

χ_λ^2 = correlated error

$\chi^2 = \chi_D^2 + \chi_\lambda^2$

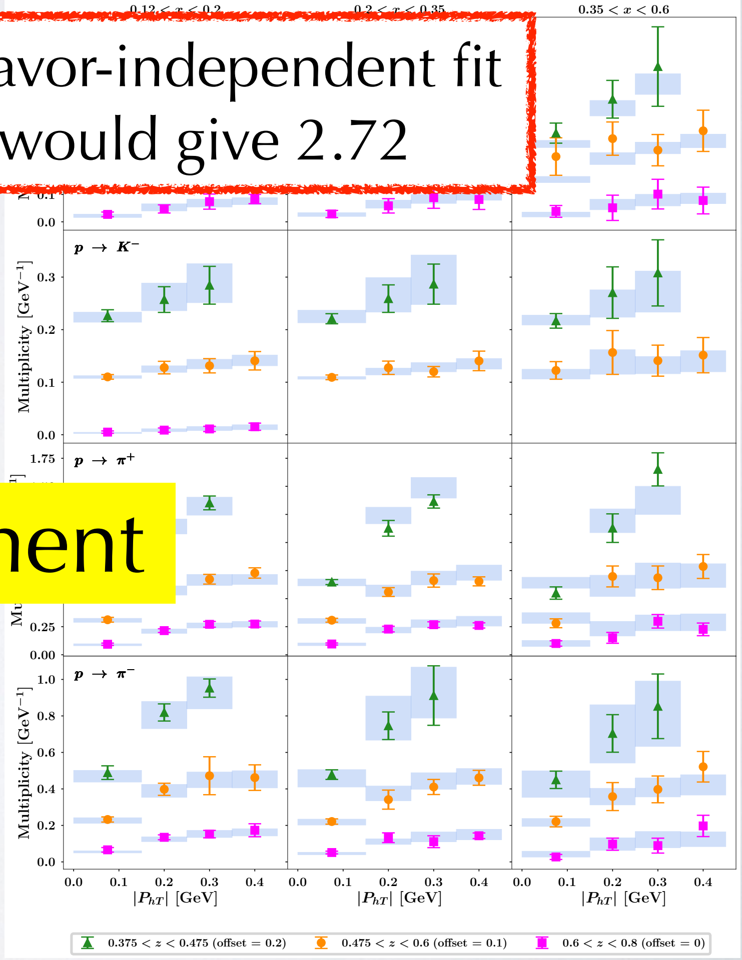
a flavor-independent fit would give 2.72



deuteron target

very good agreement

proton target



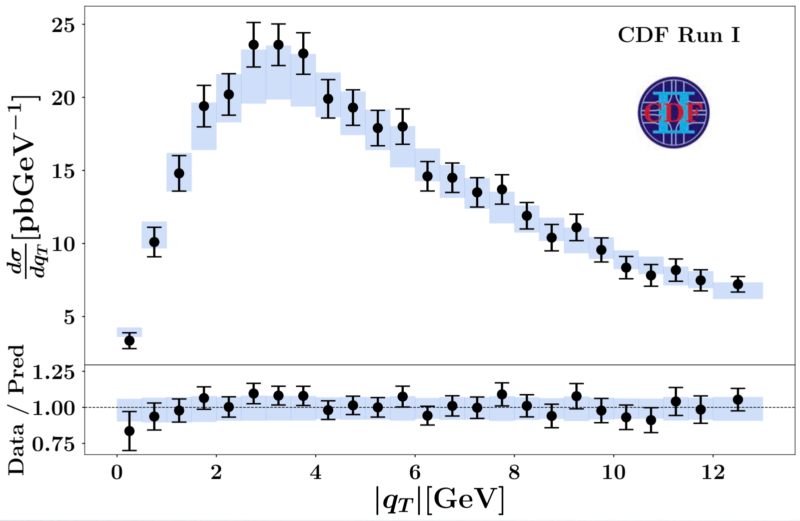
th. error band = 68% of all replicas

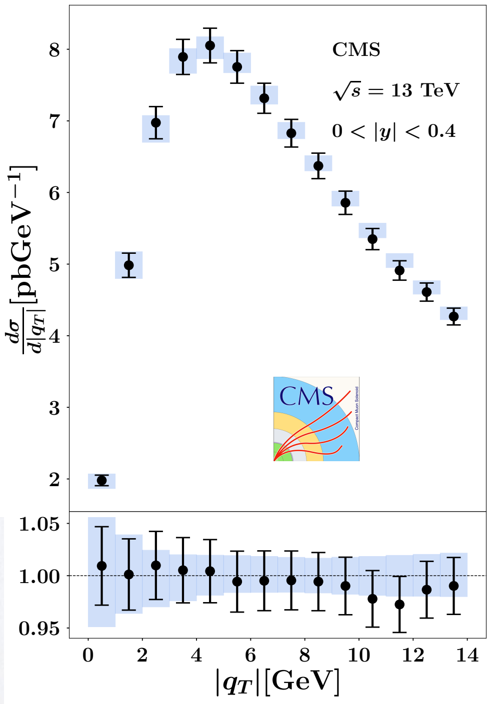
Fit results for Drell-Yan

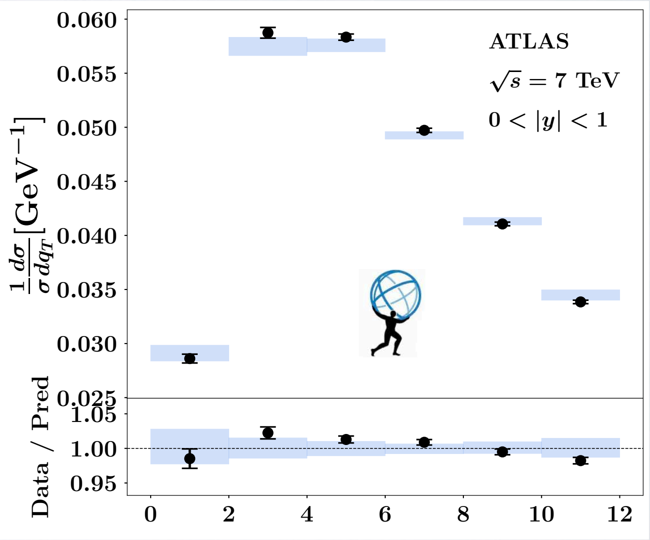
data set	N_{data}	χ^2_D	χ^2_λ	χ^2
HERMES	344	0.81	0.24	1.05
COMPASS	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
DY fixed target	233	0.63	0.31	0.94
DY collider	251	1.37	0.28	1.65
Total	**2031**	**0.81**	**0.27**	**1.08**

very good agreement

good agreement







th. error band =
68% of all replicas

Fit results for Drell-Yan

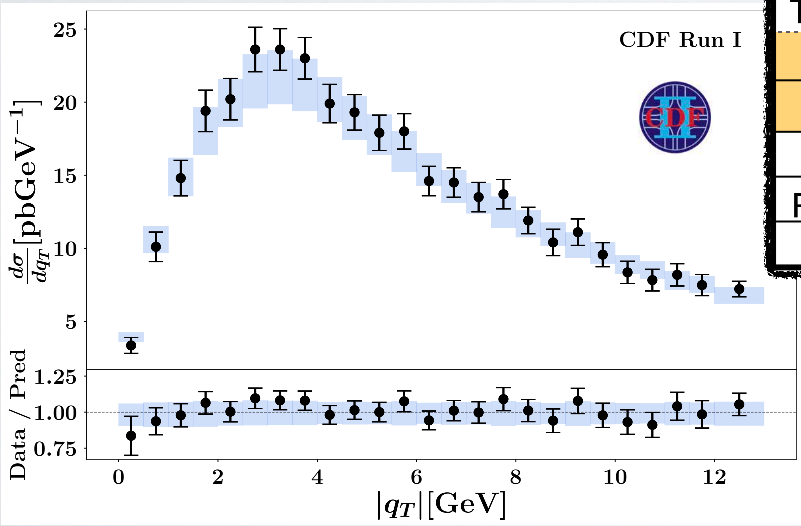
data set	N_{data}	χ^2_D	χ^2_λ	χ^2
HERMES	344	0.81	0.24	1.05
COMPASS	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
DY fixed target	233	0.63	0.31	0.94
DY collider	251	1.37	0.28	1.65
Total	**2031**	**0.81**	**0.27**	**1.08**

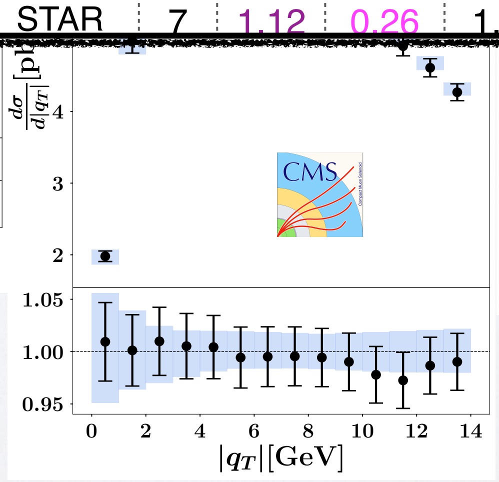
very good agreement

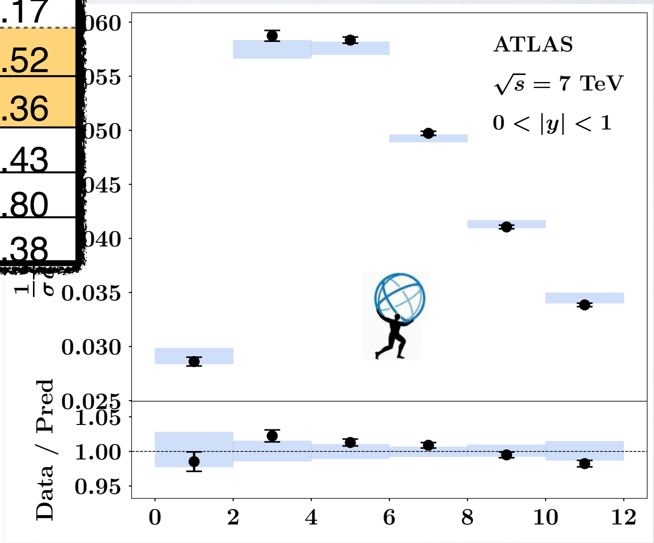
good agreement

very precise data!

data set	N_{dat}	χ^2_D	χ^2_λ	χ^2
Tevatron	71	1.10	0.07	1.17
LHCb	21	3.56	0.96	4.52
ATLAS	72	3.54	0.82	4.36
CMS	78	0.38	0.05	0.43
PHENIX	2	2.76	1.04	3.80
STAR	7	1.12	0.26	1.38







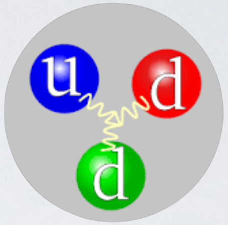
th. error band =
68% of all replicas

MAPTMD24 flavor channels

TMD PDF

$f^q_{\rm NP}(x, b_T; Q_0)$ = F.T.(combination of Gaussians)

5 channels: $q = u\,,\ \bar{u}\,,\ d\,,\ \bar{d}\,,\ sea\ (\text{“}s\text{”})$



sensitivity

Hermes

target: p, D

final: $\pi^\pm$, $K^\pm$

TMD FF

$D^q_{\rm NP}(z, b_T; Q_0)$ = F.T.(combination of Gaussians)

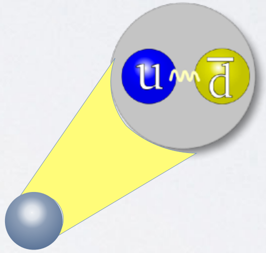
5 channels: favored pion $u \to \pi^+, \ldots$

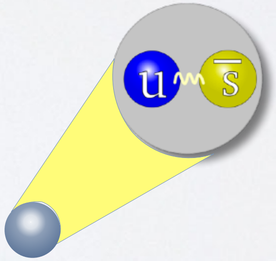
unfavored pion $d \to \pi^+, \ldots$

favored Kaon $u \to K^+, \ldots$

favored strange Kaon $\bar{s} \to K^+, \ldots$

unfavored Kaon $d, s \to K^+, \ldots$





Compass

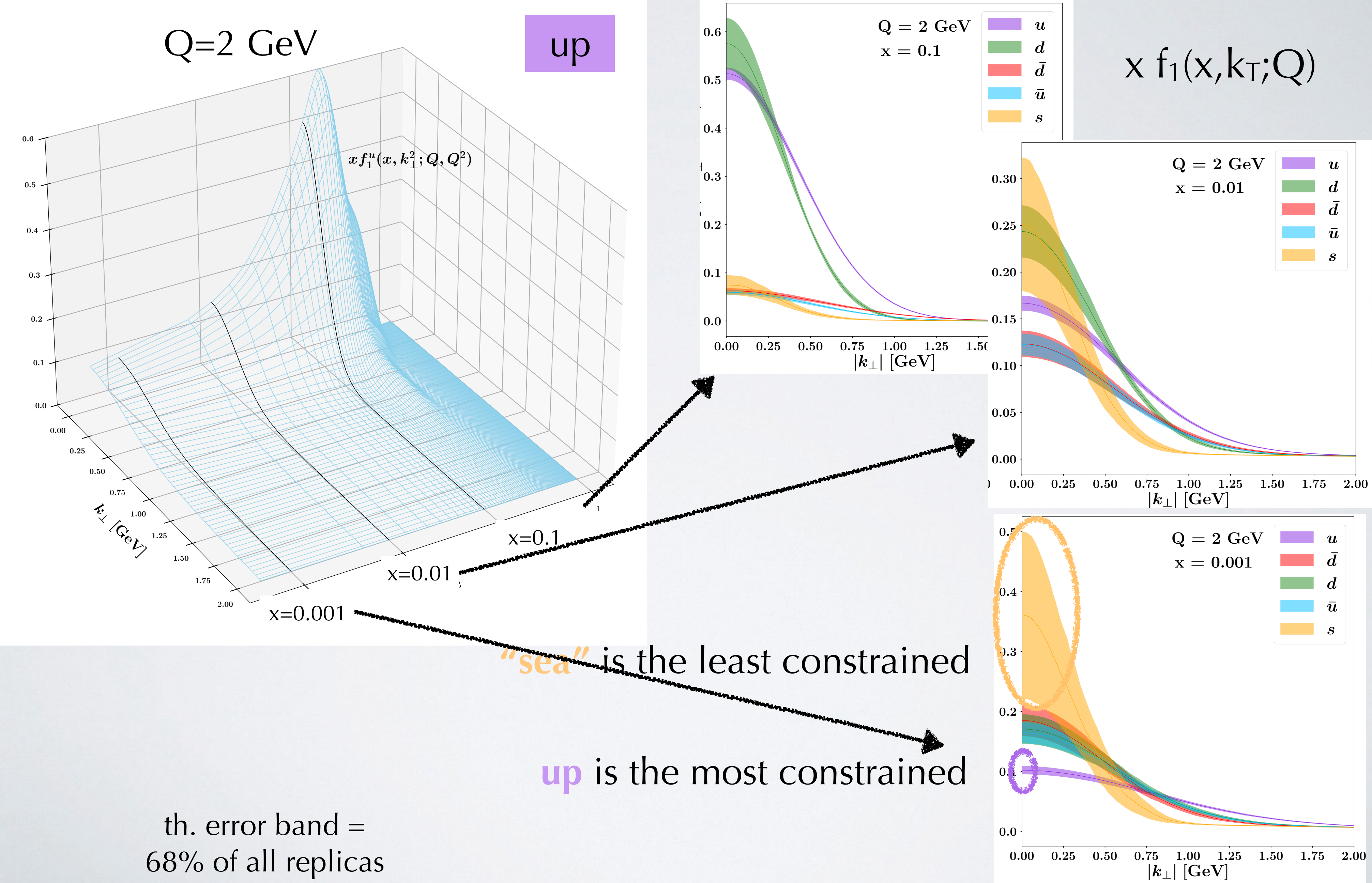
target: D

final: $h^\pm$

Drell-Yan

total of 96 parameters but with ~diagonal correlation matrix

Visualizing MAPTMD24 TMD PDF

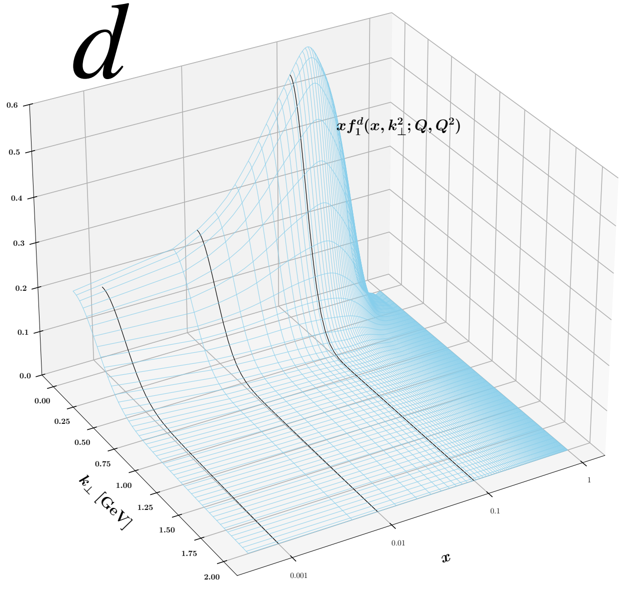


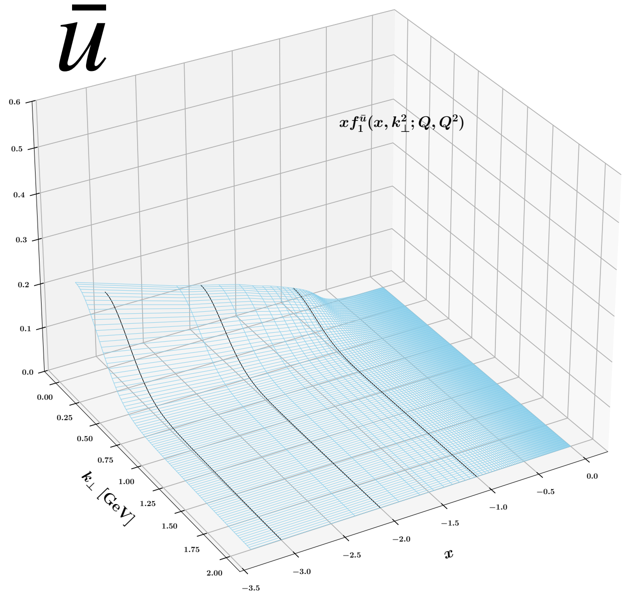
"sea" is the least constrained

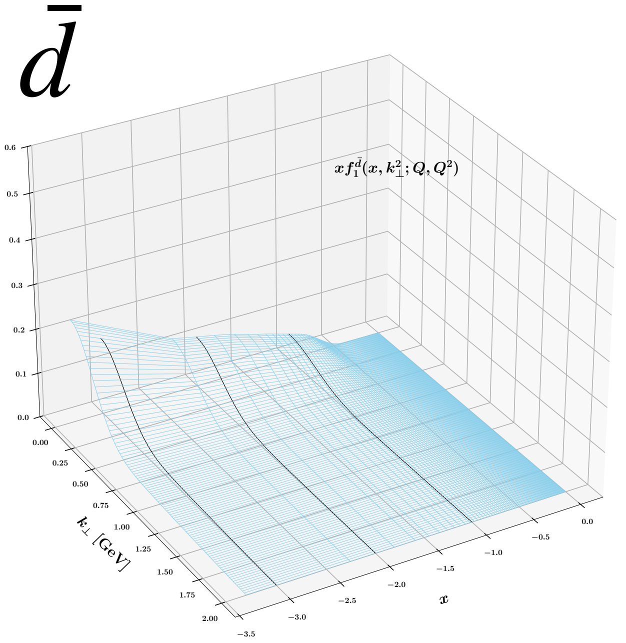
up is the most constrained

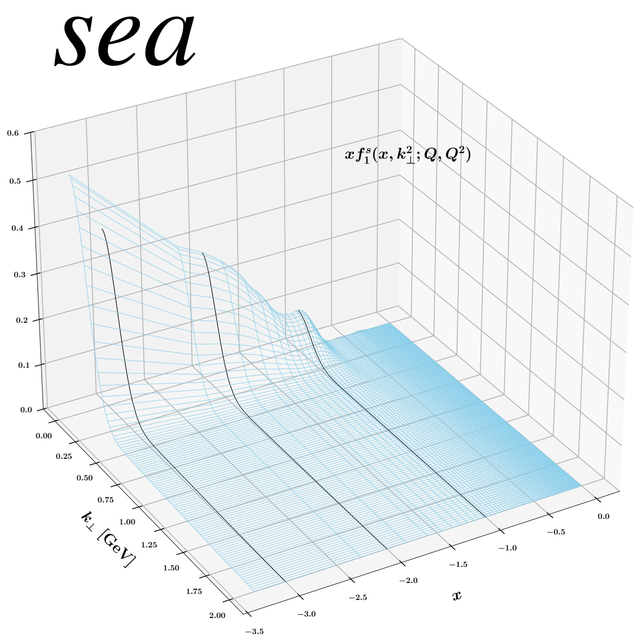
th. error band =
68% of all replicas

Visualizing MAPTMD24 TMD PDFs



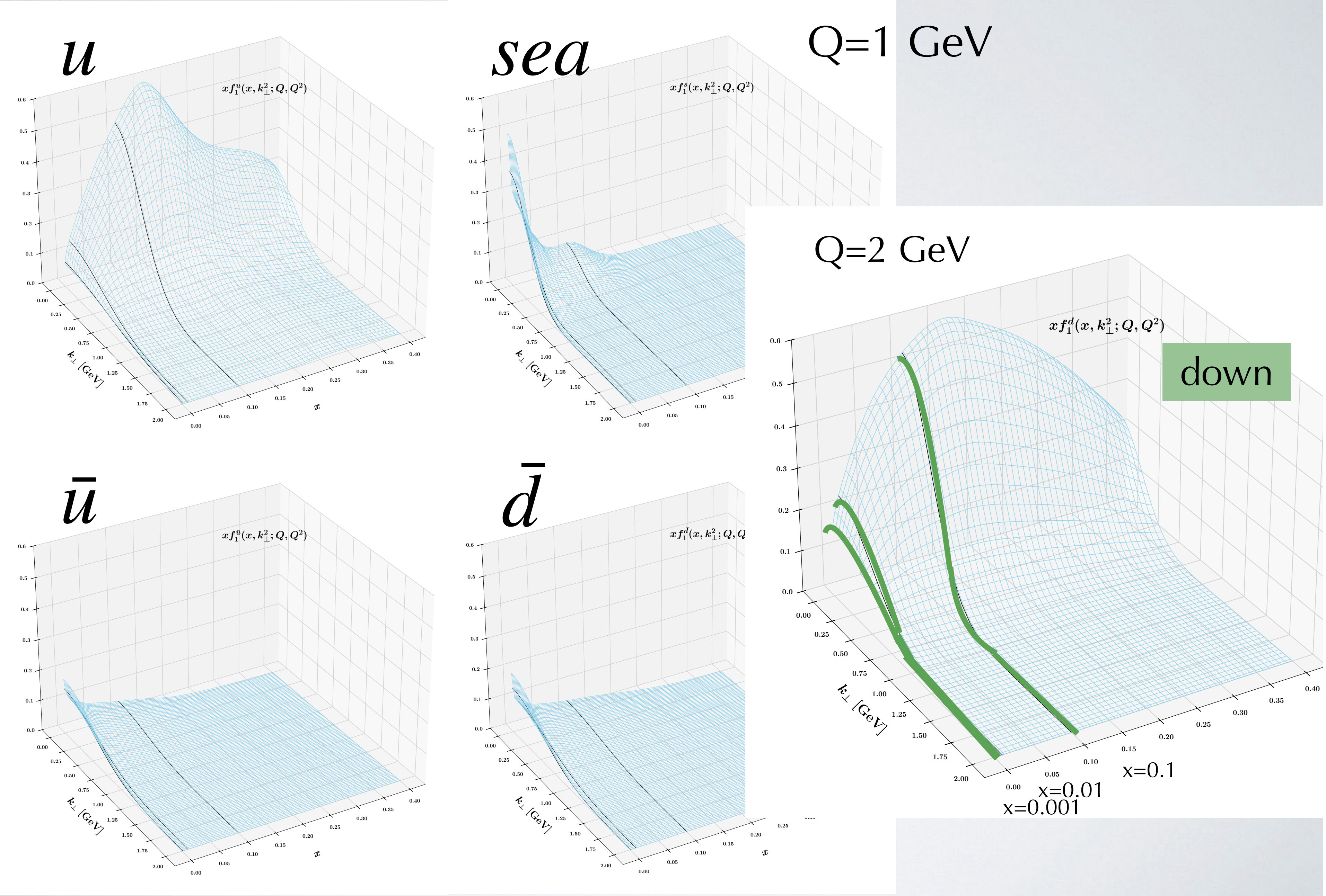






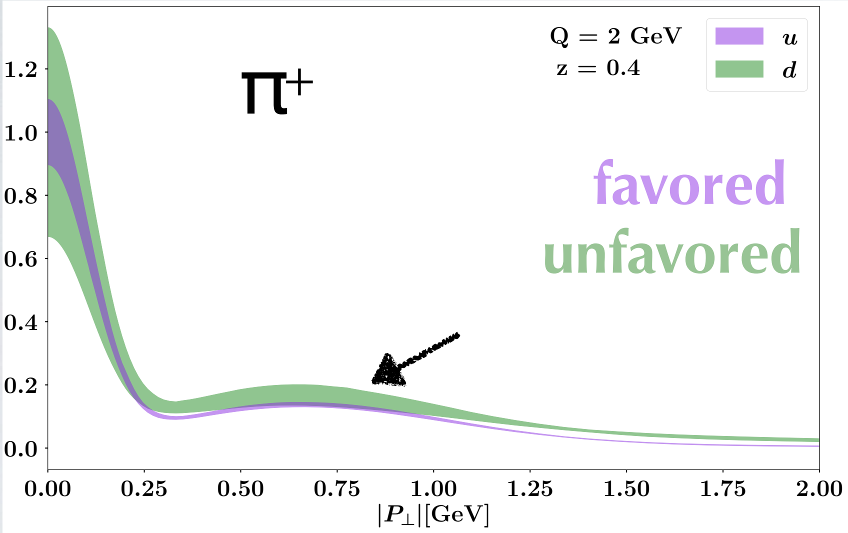
Q=2 GeV

Visualizing MAPTMD24 TMD PDFs



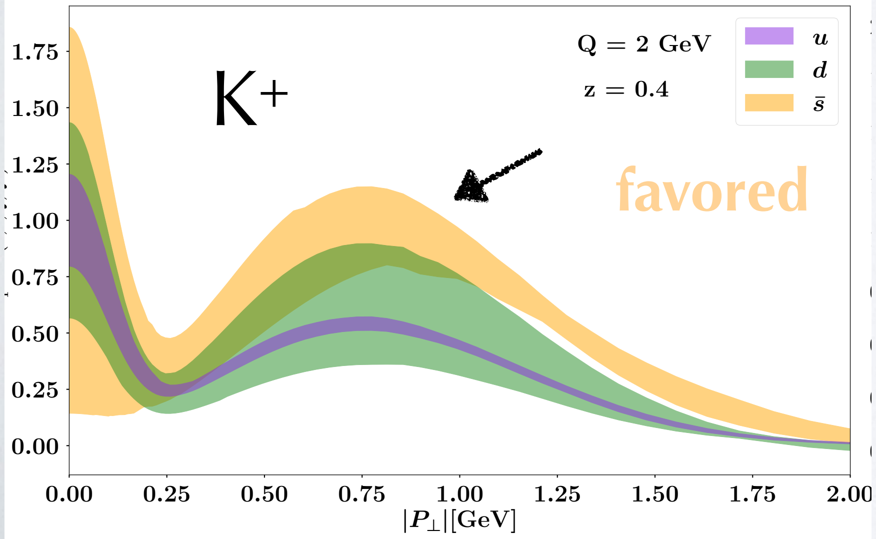
“Normalized” MAPTMD24 TMD FF

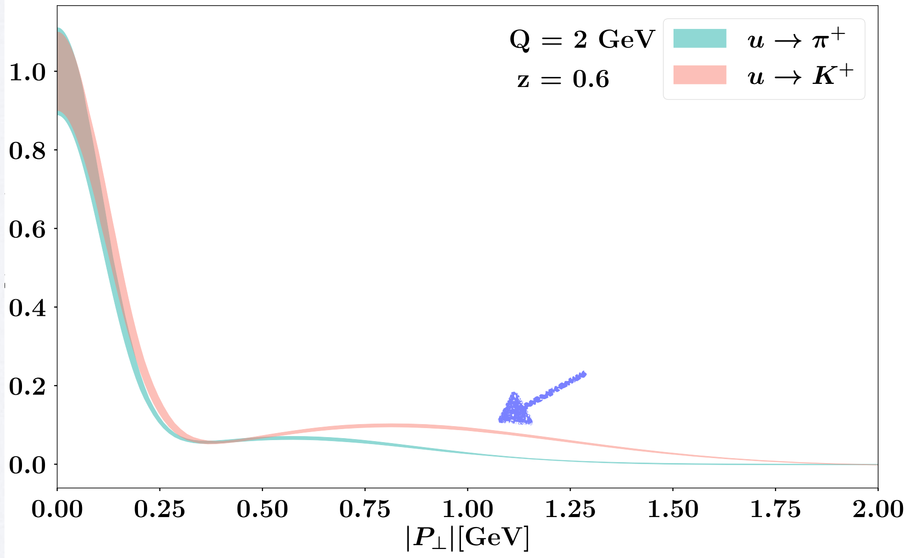
$$\frac{D_1(z,P_T;Q)}{D_1(z,0;Q)}$$



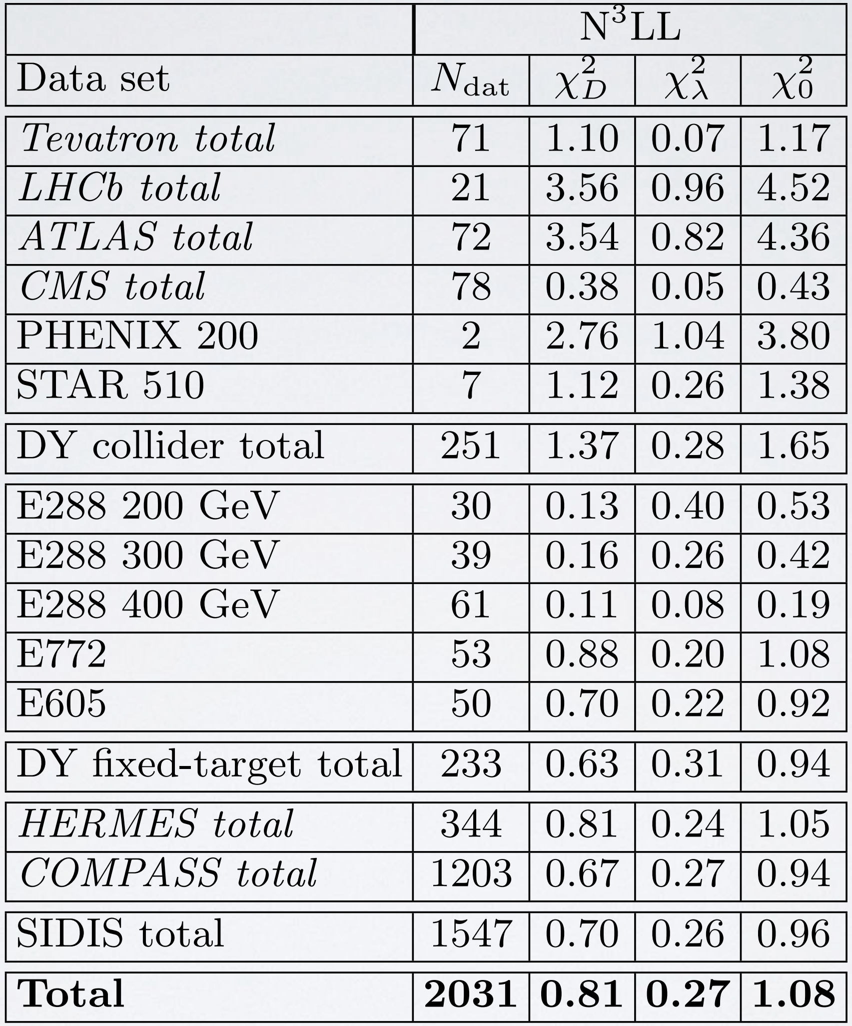
- favored better constrained than unfavored
- signs of favored ≠ unfavored
- structure from nonperturbative parametrization

- evidence of final-hadron dependence





MAPTMD24: χ^2 breakout

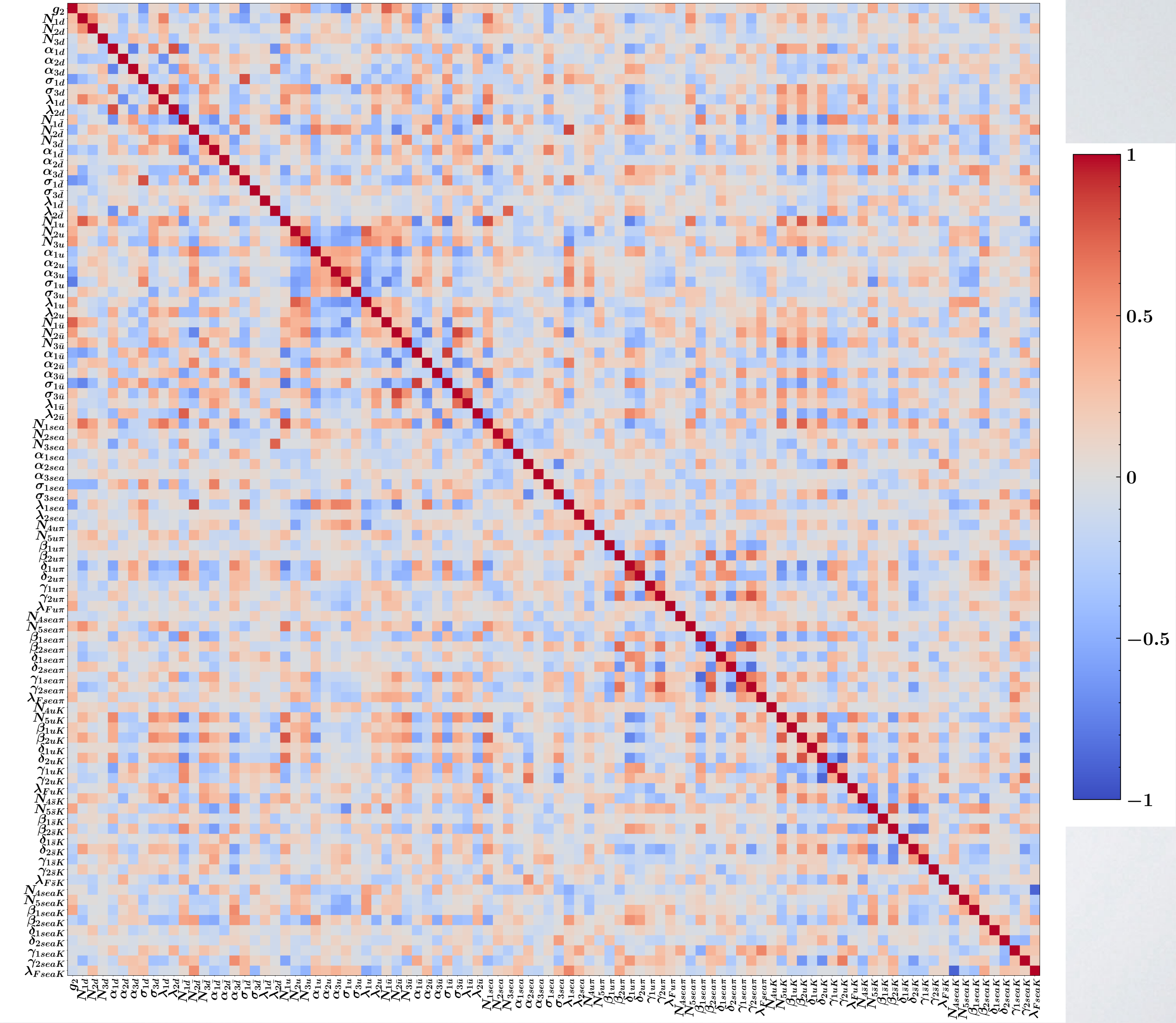


	N^{3}LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
Tevatron total	71	1.10	0.07	1.17
LHCb total	21	3.56	0.96	4.52
ATLAS total	72	3.54	0.82	4.36
CMS total	78	0.38	0.05	0.43
PHENIX 200	2	2.76	1.04	3.80
STAR 510	7	1.12	0.26	1.38
DY collider total	251	1.37	0.28	1.65
E288 200 GeV	30	0.13	0.40	0.53
E288 300 GeV	39	0.16	0.26	0.42
E288 400 GeV	61	0.11	0.08	0.19
E772	53	0.88	0.20	1.08
E605	50	0.70	0.22	0.92
DY fixed-target total	233	0.63	0.31	0.94
HERMES total	344	0.81	0.24	1.05
COMPASS total	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
Total	**2031**	**0.81**	**0.27**	**1.08**

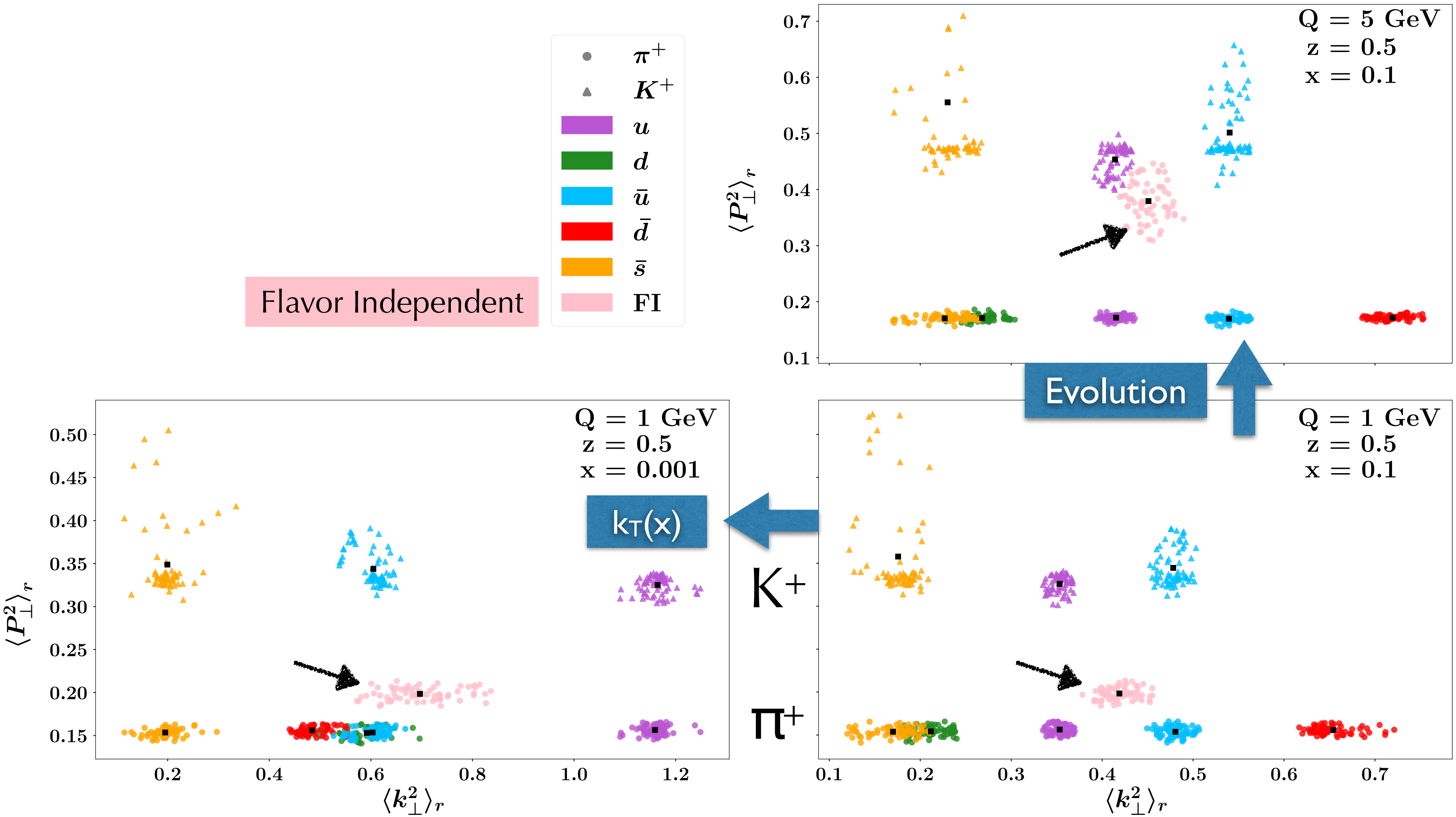
MAPTMD24: fit parameters

Parameter	Value	Parameter	Value	Parameter	Value
g_2 [GeV]	0.12 ± 0.0033				
N_{1d} [GeV^2]	0.21 ± 0.017	N_{2d} [GeV^2]	0.015 ± 0.0013	N_{3d} [GeV^2]	$(40 \pm 2.2) \times 10^{-4}$
α_{1d}	0.86 ± 0.11	α_{2d}	5.5 ± 0.041	α_{3d}	2.38 ± 0.032
σ_{1d}	-0.21 ± 0.013	$\sigma_{2d} = \sigma_{3d}$	9.91 ± 0.061		
λ_{1d} [GeV^{-1}]	0.32 ± 0.038	λ_{2d} [GeV^{-1}]	0.052 ± 0.0022		
$N_{1\bar{d}}$ [GeV^2]	0.68 ± 0.038	$N_{2\bar{d}}$ [GeV^2]	0.0037 ± 0.0037	$N_{3\bar{d}}$ [GeV^2]	$(5.9 \pm 5.8) \times 10^{-5}$
$\alpha_{1\bar{d}}$	0.64 ± 0.18	$\alpha_{2\bar{d}}$	5.69 ± 0.64	$\alpha_{3\bar{d}}$	1.57 ± 0.53
$\sigma_{1\bar{d}}$	0.075 ± 0.012	$\sigma_{2\bar{d}} = \sigma_{3\bar{d}}$	10.19 ± 0.09		
$\lambda_{1\bar{d}}$ [GeV^{-1}]	0.7 ± 0.67	$\lambda_{2\bar{d}}$ [GeV^{-1}]	0.051 ± 0.0071		
N_{1u} [GeV^2]	0.35 ± 0.0063	N_{2u} [GeV^2]	0.019 ± 0.00015	N_{3u} [GeV^2]	$(355 \pm 4.5) \times 10^{-6}$
α_{1u}	0.18 ± 0.1	α_{2u}	5.42 ± 0.0037	α_{3u}	2.14 ± 0.0068
σ_{1u}	-0.26 ± 0.0079	$\sigma_{2u} = \sigma_{3u}$	10.17 ± 0.011		
λ_{1u} [GeV^{-1}]	0.49 ± 0.0037	λ_{2u} [GeV^{-1}]	0.081 ± 0.0009		
$N_{1\bar{u}}$ [GeV^2]	0.48 ± 0.0074	$N_{2\bar{u}}$ [GeV^2]	0.022 ± 0.00037	$N_{3\bar{u}}$ [GeV^2]	$(21 \pm 1.5) \times 10^{-5}$
$\alpha_{1\bar{u}}$	0.95 ± 0.077	$\alpha_{2\bar{u}}$	5.38 ± 0.0099	$\alpha_{3\bar{u}}$	1.77 ± 0.052
$\sigma_{1\bar{u}}$	-0.026 ± 0.01	$\sigma_{2\bar{u}} = \sigma_{3\bar{u}}$	10.21 ± 0.02		
$\lambda_{1\bar{u}}$ [GeV^{-1}]	0.53 ± 0.0067	$\lambda_{2\bar{u}}$ [GeV^{-1}]	0.11 ± 0.0055		
N_{1sea} [GeV^2]	0.16 ± 0.035	N_{2sea} [GeV^2]	0.029 ± 0.0027	N_{3sea} [GeV^2]	0.0039 ± 0.002
α_{1sea}	0.65 ± 0.48	α_{2sea}	5.24 ± 0.032	α_{3sea}	1.48 ± 0.74
σ_{1sea}	-0.018 ± 0.022	$\sigma_{2sea} = \sigma_{3sea}$	10.72 ± 0.037		
λ_{1sea} [GeV^{-1}]	2.43 ± 0.97	λ_{2sea} [GeV^{-1}]	0.015 ± 0.0083		
$N_{4u\pi}$ [GeV^2]	$(82 \pm 1.8) \times 10^{-5}$	$N_{5u\pi}$ [GeV^2]	0.095 ± 0.0008	$\beta_{1u\pi}$	5.19 ± 0.066
$\beta_{2u\pi}$	2.3 ± 0.041	$\delta_{1u\pi}$	0.017 ± 0.0084	$\delta_{2u\pi}$	0.19 ± 0.0049
$\gamma_{1u\pi}$	1.46 ± 0.015	$\gamma_{2u\pi}$	0.8 ± 0.0095	$\lambda_{Fu\pi}$ [GeV^{-2}]	0.089 ± 0.003
$N_{4sea\pi}$ [GeV^2]	$(83 \pm 2.4) \times 10^{-5}$	$N_{5sea\pi}$ [GeV^2]	0.094 ± 0.0012	$\beta_{1sea\pi}$	5.38 ± 0.21
$\beta_{2sea\pi}$	2.31 ± 0.072	$\delta_{1sea\pi}$	0.022 ± 0.0064	$\delta_{2sea\pi}$	0.19 ± 0.0044
$\gamma_{1sea\pi}$	1.44 ± 0.026	$\gamma_{2sea\pi}$	0.8 ± 0.012	$\lambda_{Fsea\pi}$ [GeV^{-2}]	0.086 ± 0.004
N_{4uK} [GeV^2]	$(87 \pm 5.7) \times 10^{-5}$	N_{5uK} [GeV^2]	0.14 ± 0.0026	β_{1uK}	8.52 ± 0.081
β_{2uK}	3.86 ± 0.19	δ_{1uK}	0.0061 ± 0.0035	δ_{2uK}	0.19 ± 0.0059
γ_{1uK}	1 ± 0.041	γ_{2uK}	0.19 ± 0.054	λ_{FuK} [GeV^{-2}]	0.14 ± 0.0048
$N_{4\bar{s}K}$ [GeV^2]	$(4.5 \pm 3.7) \times 10^{-4}$	$N_{5\bar{s}K}$ [GeV^2]	0.16 ± 0.016	$\beta_{1\bar{s}K}$	7.17 ± 1.4
$\beta_{2\bar{s}K}$	5.1 ± 1.04	$\delta_{1\bar{s}K}$	1.51 ± 1.51	$\delta_{2\bar{s}K}$	0.16 ± 0.033
$\gamma_{1\bar{s}K}$	0.71 ± 0.42	$\gamma_{2\bar{s}K}$	0.36 ± 0.19	$\lambda_{F\bar{s}K}$ [GeV^{-2}]	0.34 ± 0.2
N_{4seaK} [GeV^2]	$(78 \pm 2.8) \times 10^{-5}$	N_{5seaK} [GeV^2]	0.15 ± 0.0059	β_{1seaK}	8.63 ± 0.24
β_{2seaK}	4.19 ± 0.14	δ_{1seaK}	0.0075 ± 0.0051	δ_{2seaK}	0.2 ± 0.0029
γ_{1seaK}	0.96 ± 0.036	γ_{2seaK}	0.17 ± 0.092	λ_{FseaK} [GeV^{-2}]	0.15 ± 0.0055

Correlation matrix



Average transverse momenta

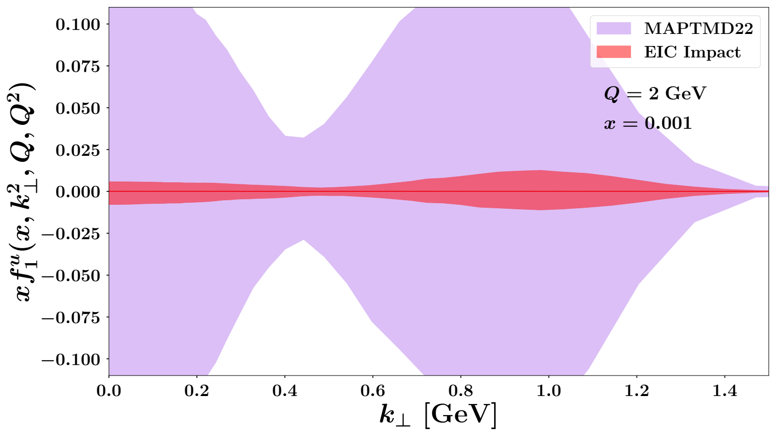


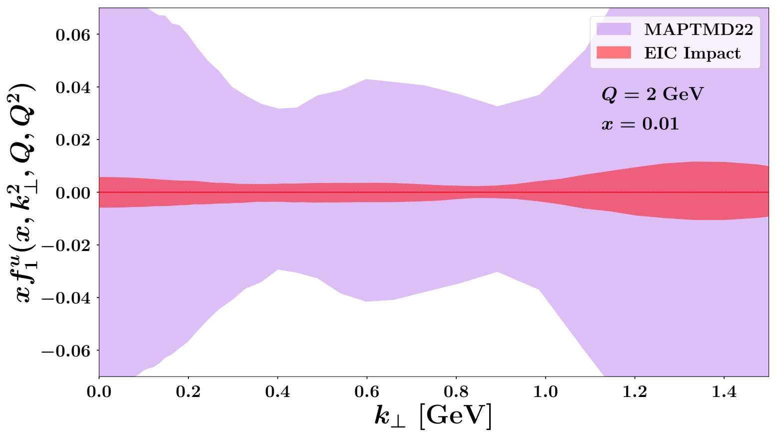
clusters = 68% of all replicas

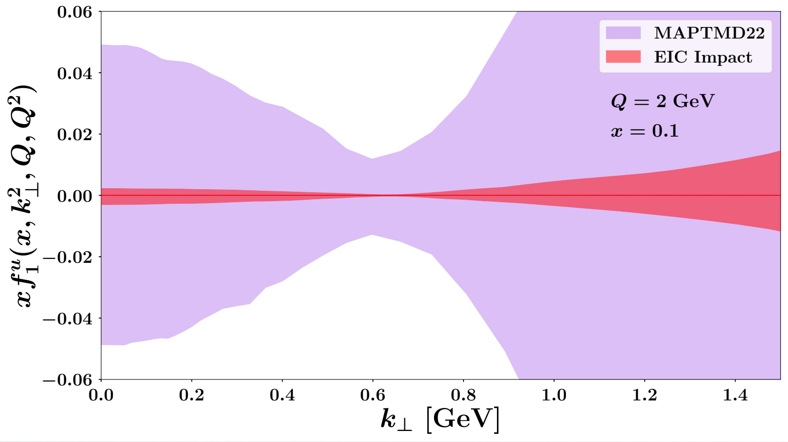
Impact studies

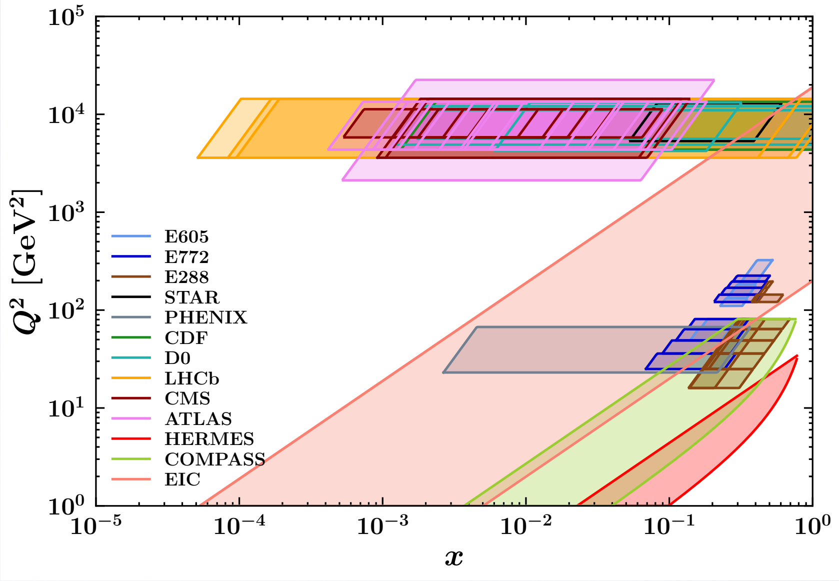
MAPTMD22 impact studies

MAPTMD22 impact on the EIC





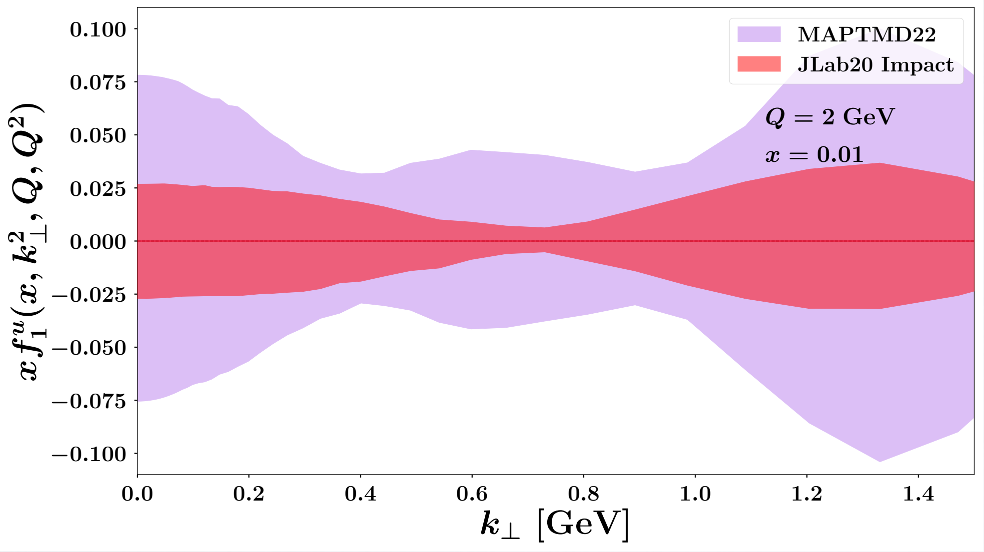


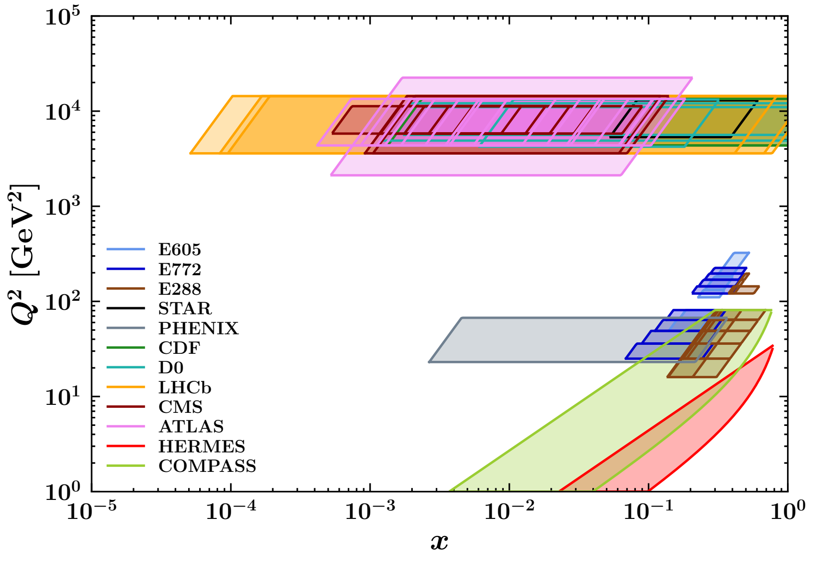


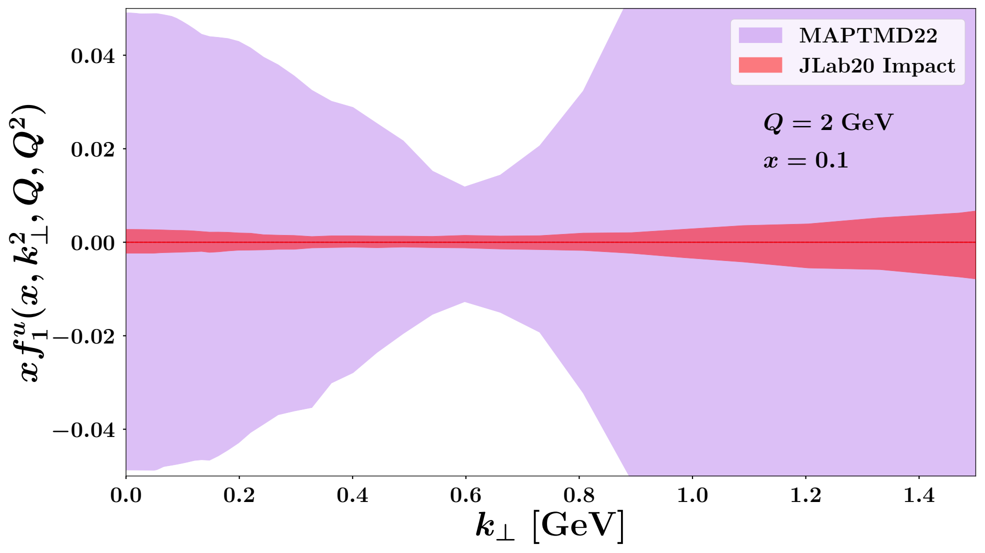
kinematics 10x100

major improvements at smaller x

MAPTMD22 impact on JLab20+





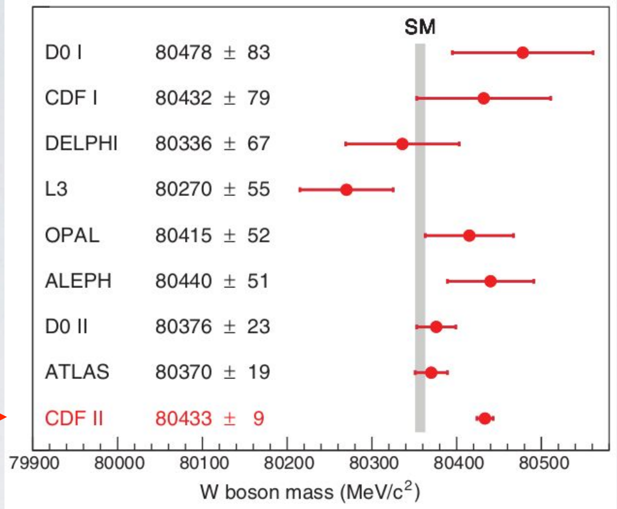


kinematics JLab20

major improvements at valence x

Potential impact on W mass

surprising CDF result

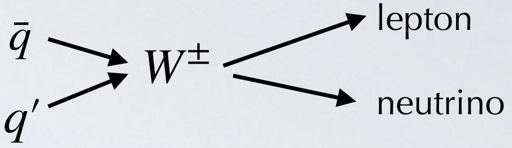


~ 7σ !

SM expectation: $M_W = 80357 \pm 6$ MeV

our work

explore sensitivity of M_W to non-perturbative flavor-dependent k⊥ distribution

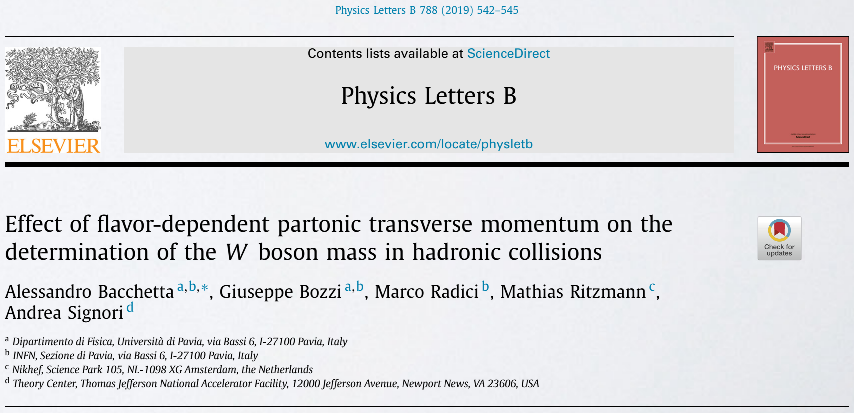


intrinsic k⊥ + resummation → $q_{TW} \to p_{T\ell}$

$u\bar{u}$, $d\bar{d}$ → Z^0 main channels

$u\bar{d}$ → W^+ main channel

but all analyses assume flavor-independent Gaussian k⊥ distribution



Physics Letters B 788 (2019) 542–545

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Effect of flavor-dependent partonic transverse momentum on the determination of the W boson mass in hadronic collisions

Alessandro Bacchetta [a,b,*], Giuseppe Bozzi [a,b], Marco Radici [b], Mathias Ritzmann [c], Andrea Signori [d]

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[c] Nikhef, Science Park 105, NL-1098 XG Amsterdam, the Netherlands
[d] Theory Center, Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, USA

P.L. **B788** (19) 542, arXiv:1807.02101

Potential impact on W mass

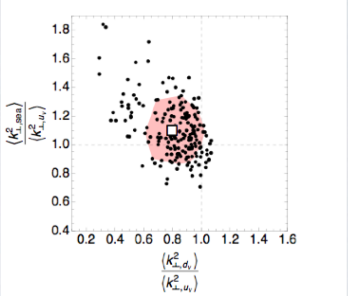
- take the DYRES code and modify the $f_{NP}\,(x,b_T)$

$$\exp\Big[-g_2\, b_T^2 \log\frac{Q^2}{Q_0^2}\Big] \longrightarrow \exp\Big[-\Big(g_2 \log\frac{Q^2}{Q_0^2}+g^q\Big)\, b_T^2\Big]$$

flavor dependent

range of variation from

Signori et al., JHEP **11** (13) 194, arXiv:1309.3507



flavor independent, ~[0.2-0.4] GeV^2

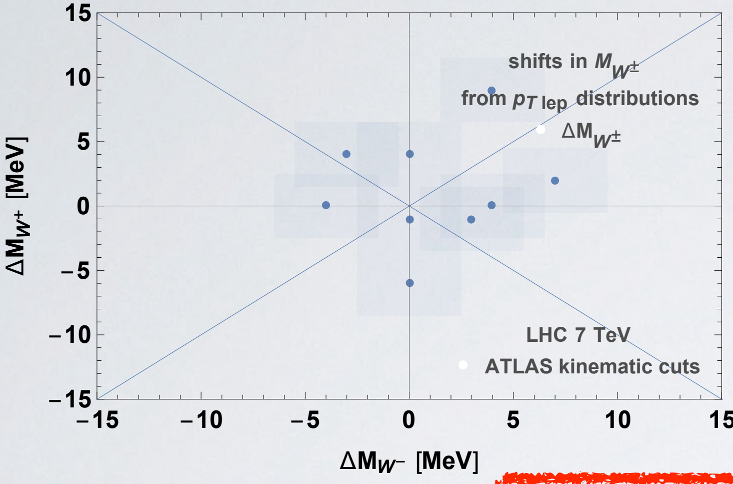
MAPTMD22 ~ 0.25 , see also

PV 2017 Bacchetta et al., JHEP **06** (17) 081, arXiv:1703.10157

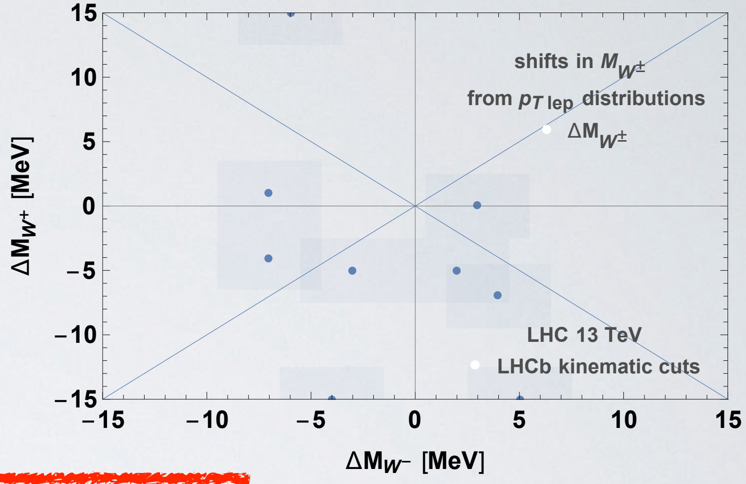
Guzzi et al., P.R. D**90** (14) 014030

- generate p_T^Z spectrum with g_2 and assigned CDF/ATLAS errors in each bin; generate sets of p_T^Z spectra with $g^q = \{g^{u_v}, g^{d_v}, g^{u_{sea}}, g^{d_{sea}}, g^s\}$ and keep those with global χ^2/d.o.f. < 1.3
- with these “Z-equivalent” sets, generate pseudodata for lepton p_T distribution at $M_W^0 = 80.370$ GeV
- with g_2, generate 30 template lepton p_T distributions with M_W in $M_W^0 \pm 0.015$ GeV
- perform template fits for each pseudodata

Potential impact on W mass



$$-6 \leq \Delta M_{W^+} \leq 9$$
$$-4 \leq \Delta M_{W^-} \leq 3$$

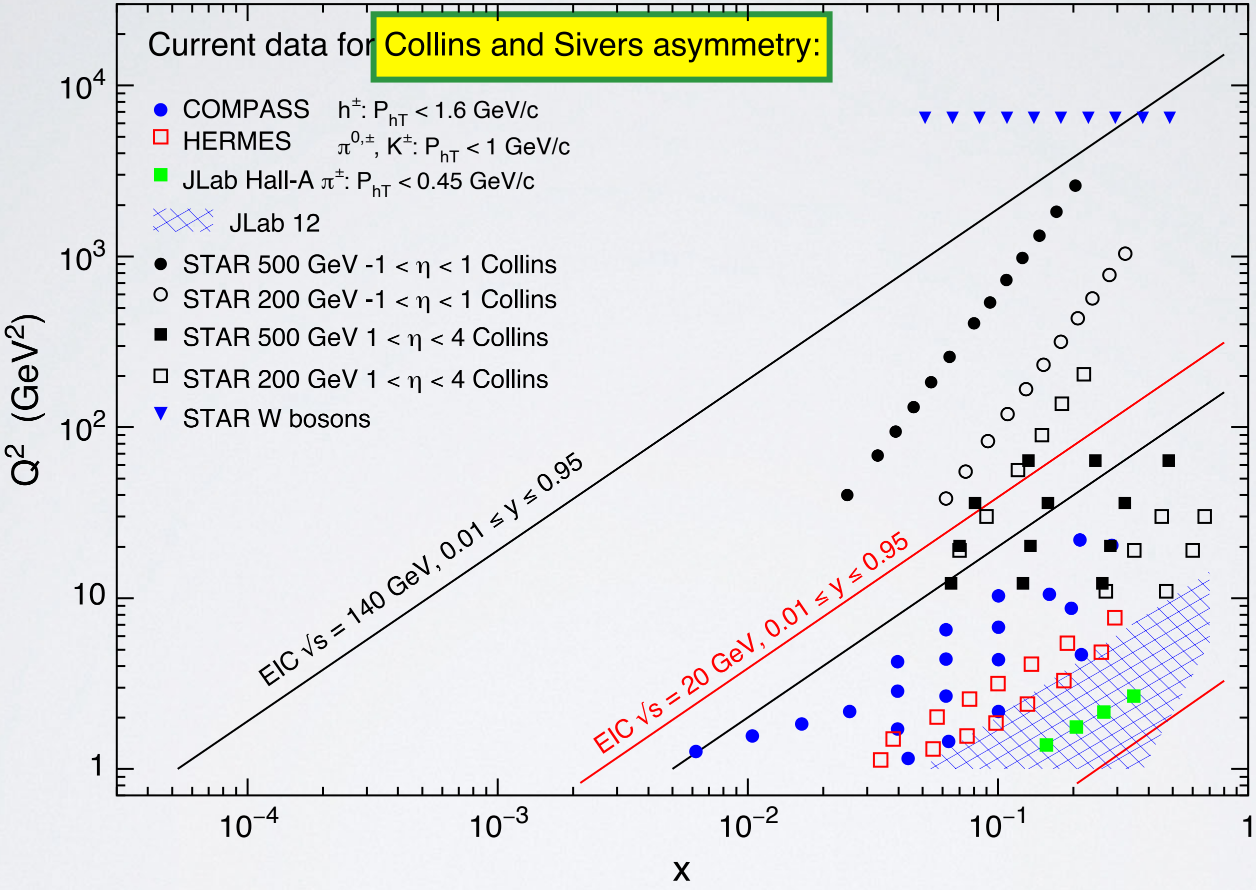


significant shifts $\Delta M_{W^+} \neq \Delta M_{W^-}$
of nonperturbative origin

- repeat impact study on extraction of W mass using MAPTMD24 flavor-dependent k_T distributions

Phase space for polarized TMDs

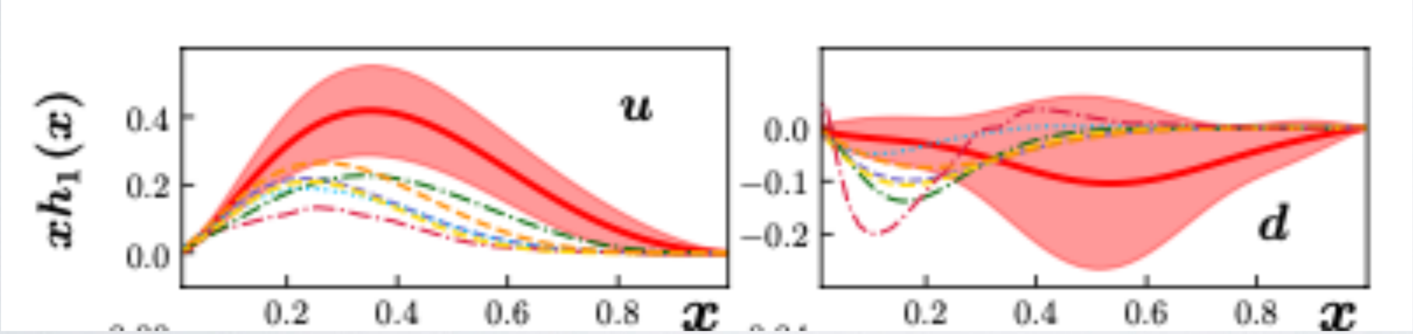
Abdul Khalek et al. (EIC Yellow Report), N.P. ***A1026*** *(22) 122447, arXiv:2103.05419*

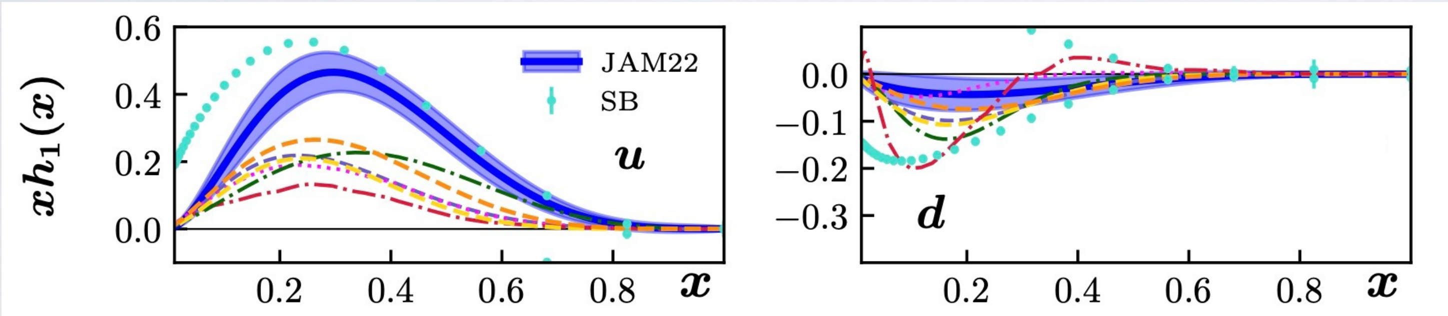


For polarized TMDs, available phase space is less than unpol. TMD, particularly at high Q^2 → more difficult to study evolution properties.

Where collider data can be most useful

Most recent extractions





JAM20

Anselmino 15

Kang 16

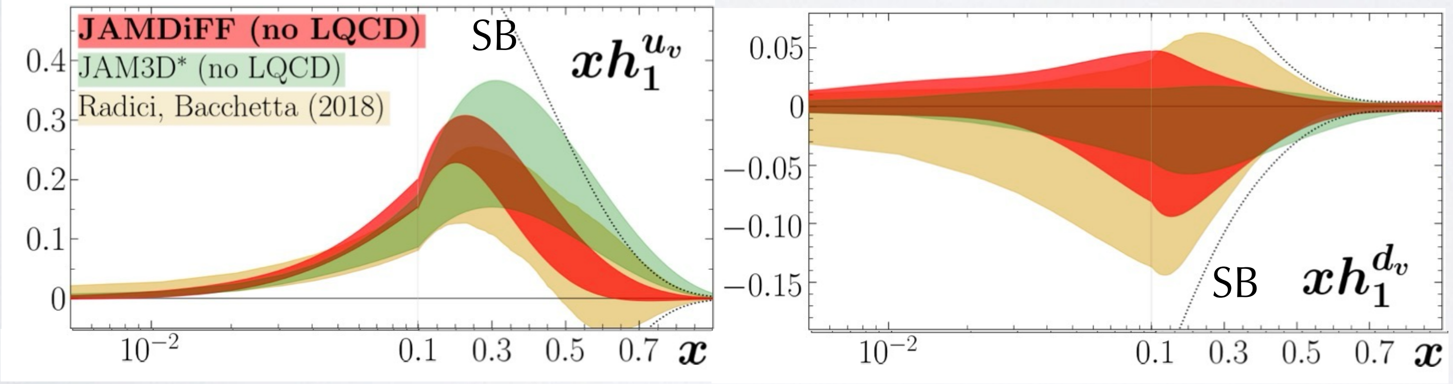
D’Alesio 20

Radici 18

Anselmino 13

Benel 19

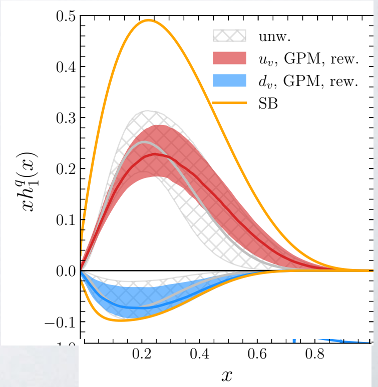
JAM22



Anselmino 15

Boglione 24

D’Alesio 20



* JAM3D includes $\bar{u} = -\bar{d}$ w.r.t. JAM22

D. Pitonyak, QCD Evolution 24

SB = Soffer Bound $h_1 \leq |f_1 + g_1|/2$