Center for Frontiers in Nuclear Science

Light Cone 2026: Applications at EIC era

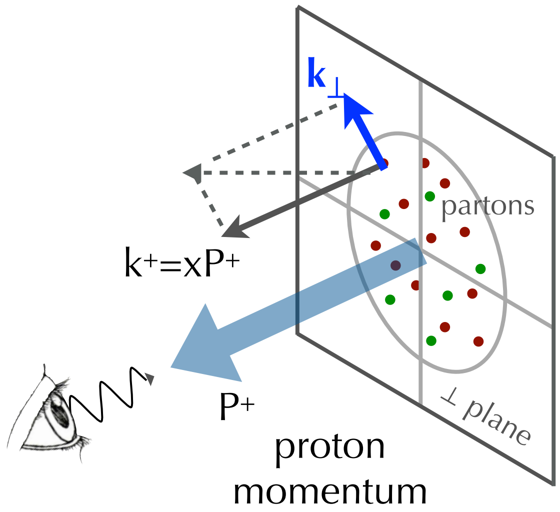
EIC impact on TMD phenomenology

INFN Istituto Nazionale di Fisica Nucleare Sezione Pavia

Marco Radici

ePIC

TMDs: Transverse Momentum Dependent PDFs (and FFs)



from 1D to 3D mapping
in momentum space

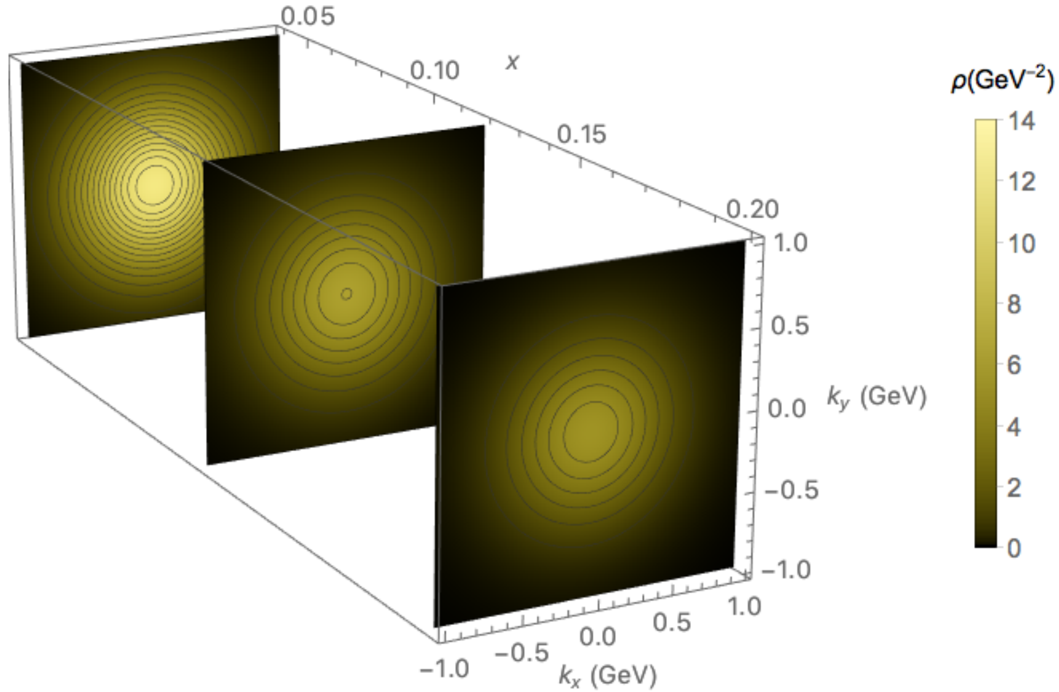
How do partons move and orbit inside hadrons?

How wide is the distribution ?

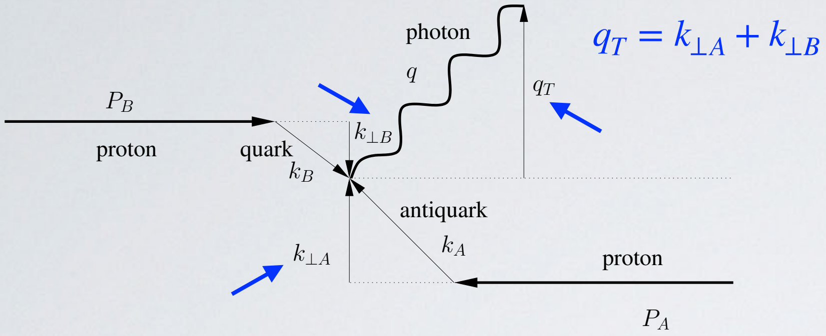
How does it change with x ?

How does it change with flavor ?

What if the hadron is polarized ?



Where TMDs ?



Drell-Yan

factorization conditions

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

hard part — TMDPDF — TMDPDF

$$\frac{d\sigma}{dq_T dy dQ} \sim \mathscr{H}^{\mathrm{DY}}(Q^2)\, \frac{1}{2\pi} \int_0^\infty db_T\, b_T\, J_0(b_T, q_T)\ \tilde{f}_1^{\bar{q}}(x_A, b_T^2; Q^2)\ \tilde{f}_1^{q}(x_B, b_T^2; Q^2)\ + \mathscr{O}(q_T^2/Q^2, M^2/Q^2)$$

Collins, Soper, Sterman, N.P. B**250** (85) 199
Echevarria, Idilbi, Scimemi, JHEP **07** (12)

$\tilde{f}$ = Fourier Transf. to b_T space: from convolution to simple product

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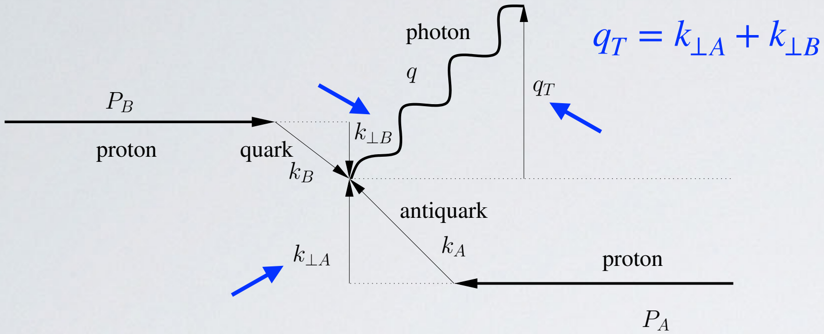

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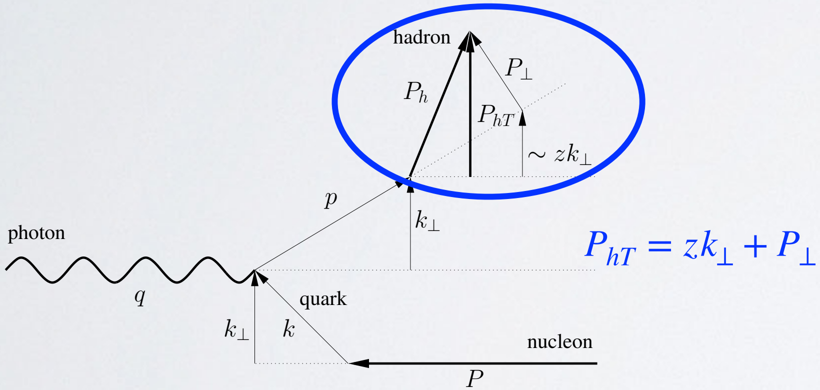

SIDIS

factorization conditions

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

integating on hadron angles $\int d\phi_h$

hard part — TMDPDF — TMDFF

$$\frac{d\sigma}{dx dz dq_T dQ} \sim \mathscr{H}^{\mathrm{SIDIS}}(Q^2)\, \frac{1}{2\pi}\int_0^\infty db_T\, b_T\; J_0(b_T, q_T)\;\; \tilde{f}_1^{q}(x, b_T^2; Q^2)\;\; \tilde{D}_1^{q\to h}(z, b_T^2; Q^2)\;\; + \mathcal{O}(q_T^2/Q^2, M^2/Q^2)$$

Ji, Ma, Yuan, P.R. D**71** (05); Rogers & Aybat, P.R. D**83** (11)
Collins & Metz, P.R.L. **93** (04) 252001

$\tilde{f}$ = Fourier Transf. to b_T space: from convolution to simple product

small k_T ← matching → large k_T

TMD factorization $\quad q_T^2 \ll Q^2$

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hard part $\qquad$ TMDPDF $\qquad$ TMDPDF

$k_\perp$ ←——— - - - - - - - ———→ b_T

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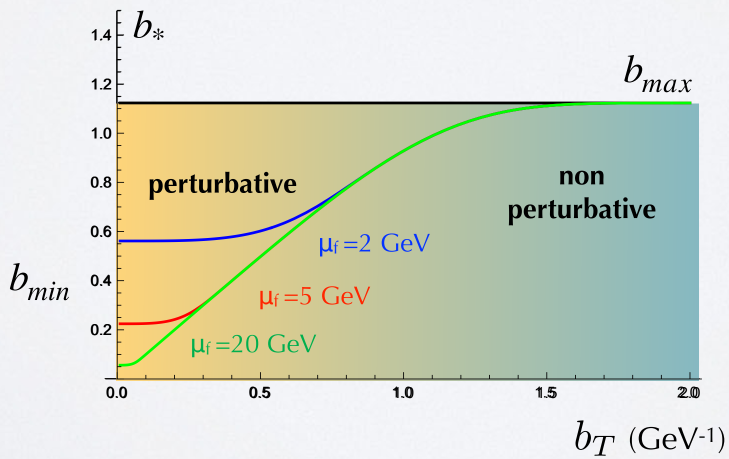
hard part   TMDPDF   TMDPDF

$k_\perp$ ←-------------------------------→ b_T

small b_T (large parton $k_\perp$)
perturbative
OPE expansion on PDF
calculable

← matching prescription (arbitrary) →

large b_T (small parton $k_\perp$)
non perturbative
parametrized
and **fitted to data**



$$Q \geq \mu_{b_*} = \frac{2e^{-\gamma_E}}{b_*} \geq 1$$

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hard part | TMDPDF | TMDPDF

$k_\perp$ ⟵ - - - - - ⟶ b_T

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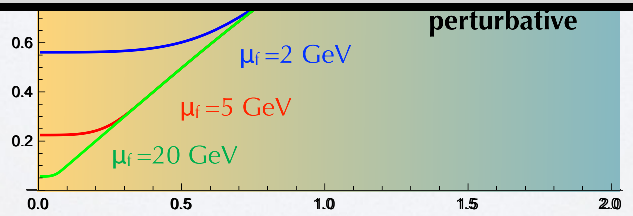
and **fitted to data**

Quality of TMD extraction:
- perturbative accuracy
- size of data set and best χ^2



b_{min}

b_T (GeV-1)

$$Q \geq \mu_{b_*} = \frac{2e^{-\gamma_E}}{b_*} \geq 1$$

Most recent global fits of quark TMDs in Nucleon

	Accuracy	SIDIS	Drell-Yan	N of points	χ^2/N_{points}	Flavor dep.
PV 2017 arXiv:1703.10157	NLL	✔	✔	8059	1.5	✘
SV 2019 arXiv:1912.06532	$N^3LL(-)$	✔	✔ (LHC)	1039	1.06	✘
MAPTMD 2022 arXiv:2206.07598	$N^3LL(-)$	✔	✔ (LHC)	2031	1.06	✘
MAPTMD 2024 arXiv:2405.13833	N^3LL	✔	✔ (LHC)	2031	1.08	✔
ART25 arXiv:2503.11201	$N^4LL(-)$	✔	✔ (LHC)	1209	1.05	✔
MAPNN 2025 arXiv:2502.13833	N^3LL	✘	✔ (LHC)	482	0.97	✘
$JAM25_{PDF+TMD}$ arXiv:2510.13771	NNLL	✘	✔ (LHC)	436 (+4279 DIS)	1.10	✔

Increasing level of perturbative accuracy and quality of fit

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Increasing level of perturbative accuracy and quality of fit

MAPTMD 2024: first global fit with **flavor sensitivity** of intrinsic quark $k_\perp$

5 channels: $q = u\,,\,\bar{u}\,,\,d\,,\,\bar{d}\,,\,sea$ + (un)favored $\to \pi, K$

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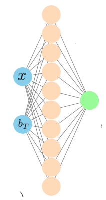
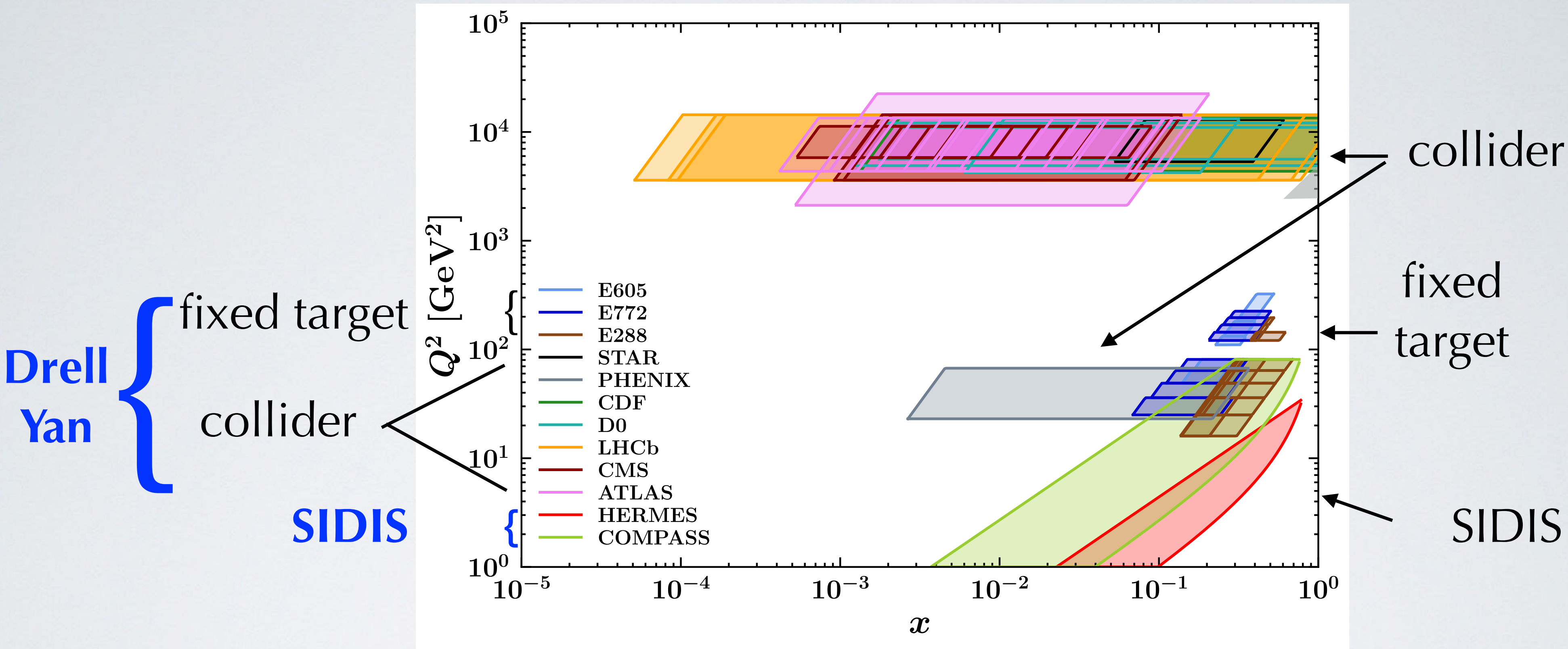
MAPNN 2025: not a global fit but first based on **Neural Network**



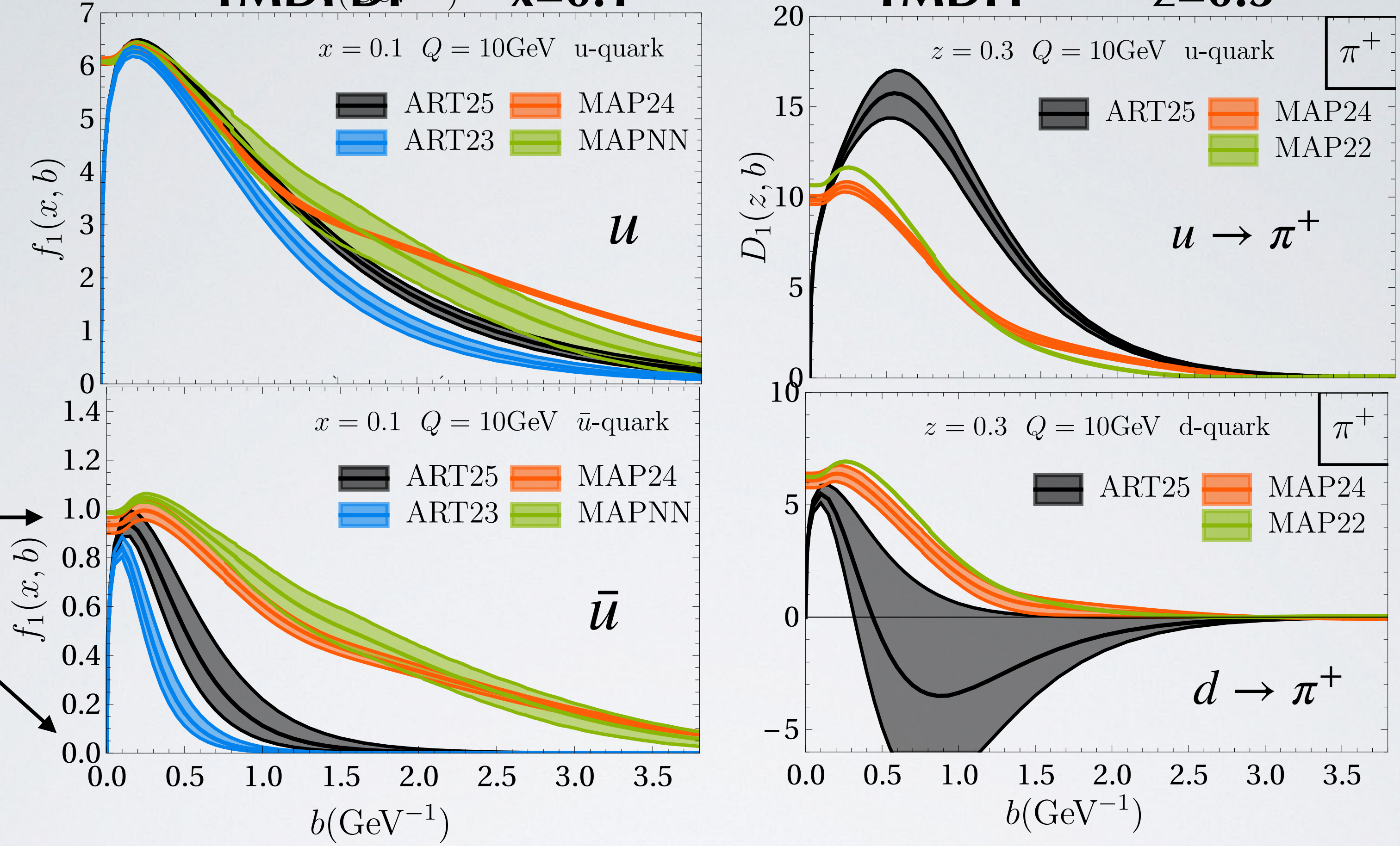
$JAM25_{PDF+TMD}$: not a global fit but first combining PDF & TMD

Typical phase space coverage



Moss et al. , JHEP **11** (25), 2503.11201

TMDPDF x=0.1 **TMDFF z=0.3**



- significant differences in nonperturbative models at large b

- different approach to collinear limit b→0

freezing parameter

b_{max}

Λ_{QCD}

$b(b_T)$

$\mu \sim \frac{1}{b_*(b_T)}$

prescription b_{min}

Q

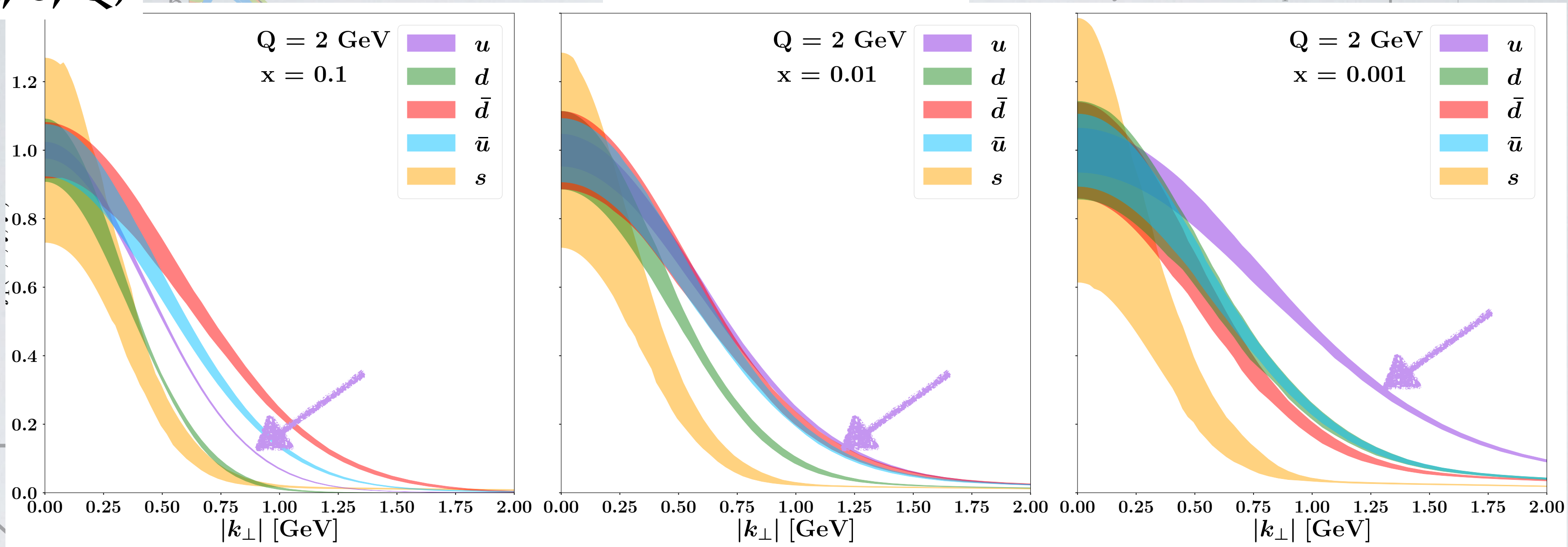
vs. cutoff

$$\mathrm{PDF}(x,\mu) = \int_0^{\mu} dk_T \mathrm{TMD}(x,k_T)$$

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

MAPTMD 2024

Bacchetta et al. (MAP), JHEP **08** (24), 2405.13833



better appreciate the very different k_T behavior that changes with x

- significant differences in nonperturbative models at large b

- different approach to collinear limit b→0

freezing parameter b_{max}

Λ_{QCD}

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prescription vs. cutoff b_{min}

Q

$$\mathrm{PDF}(x,\mu) = \int_0^{\mu} dk_T \, \mathrm{TMD}(x, k_T)$$

TMD evolution: the Collins-Soper kernel

In general, $\tilde{f}_1^q(x, b_T^2; \mu^2, \zeta)$

RGE evolution in factorization scale μ

evolution in rapidity scale ζ → CS kernel K

must be $\zeta\mu^2 = Q^4$

std choice $\zeta=\mu^2 = Q^2$

***K* universal**: same for TMDPDF and TMDFF, it does not depend on process, hadron type , x , and flavor !

$$K(b_T) \; + \; g_K(b_T)$$

perturbative, calculable

fitted to data; calculable on lattice

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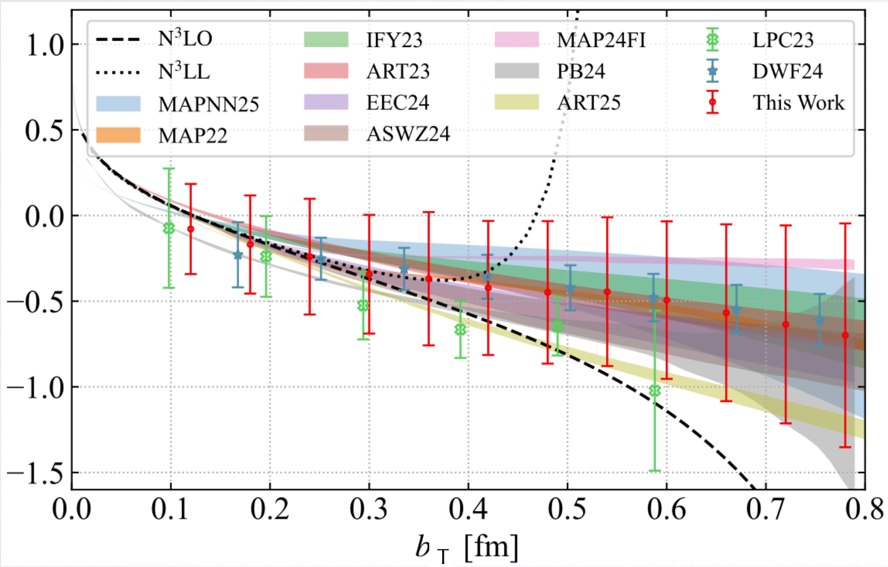


pQCD

N³LL Vladimirov, arXiv:1610.05791

N³LO Li&Zhu, arXiv:1604.01404

Lattice

DWF24 Bollweg et al., arXiv:2403.00664

LPC23 Chu et al. (LPC), arXiv:2306.06488

ASWZ24 Avkhadiev et al., arXiv:2402.06725

"This work" Bollweg et al., arXiv:2504.04625

Pheno

IFY23 (ResBos) Isaacson et al., arXiv:2311.09916

EEC24 Kang et al., arXiv:2410.21435

PB24 Martinez et al., arXiv:2412.21116

MAP Collaboration

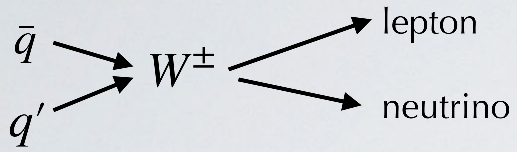
MAP-22 arXiv:2206.07598 -24 arXiv:2405.13833

-NN arXiv:2502.04166

Artemide Collaboration

ART-23 arXiv:2305.07473 -25 arXiv:2503.11201

Potential impact on W mass



intrinsic $k_\perp$ + resummation $\rightarrow q_{TW} \rightarrow p_{T\ell}$

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

$u\bar{d} \ \rightarrow\ W^+$ main channel

but all analyses assume flavor-independent intrinsic $k_\perp$ distribution

Procedure

- **template fit** with varying M_W on pseudodata based on sets of flavor-dep. non-perturb. parameters of TMDs that reproduce same q_T-distribution of Z^0

Finding:

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

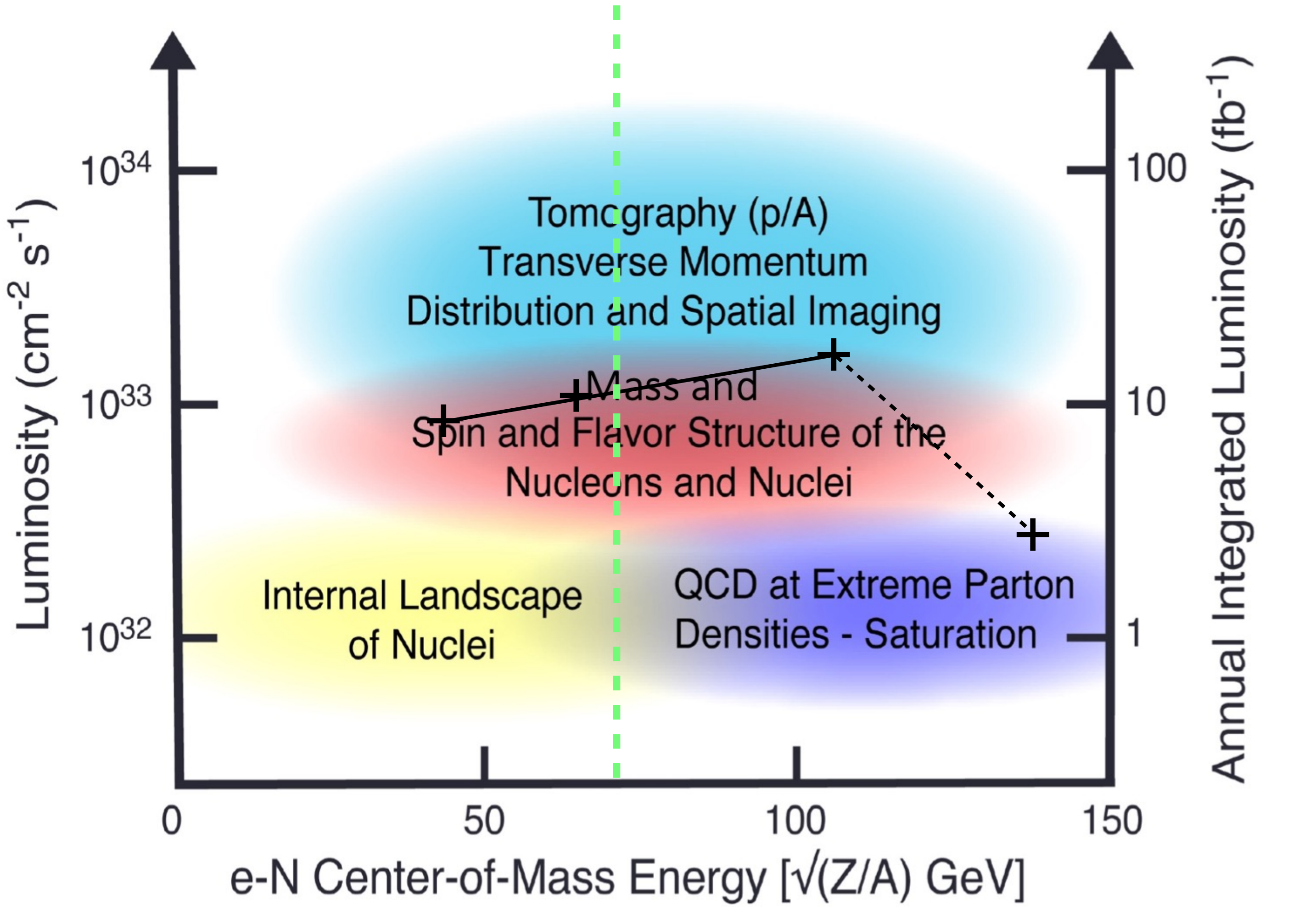
MeV and $\Delta M_{W^+} \neq \Delta M_{W^-}$

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

In progress: repeat the analysis with MAPTMD24 at N^3LL

EIC Luminosity curve

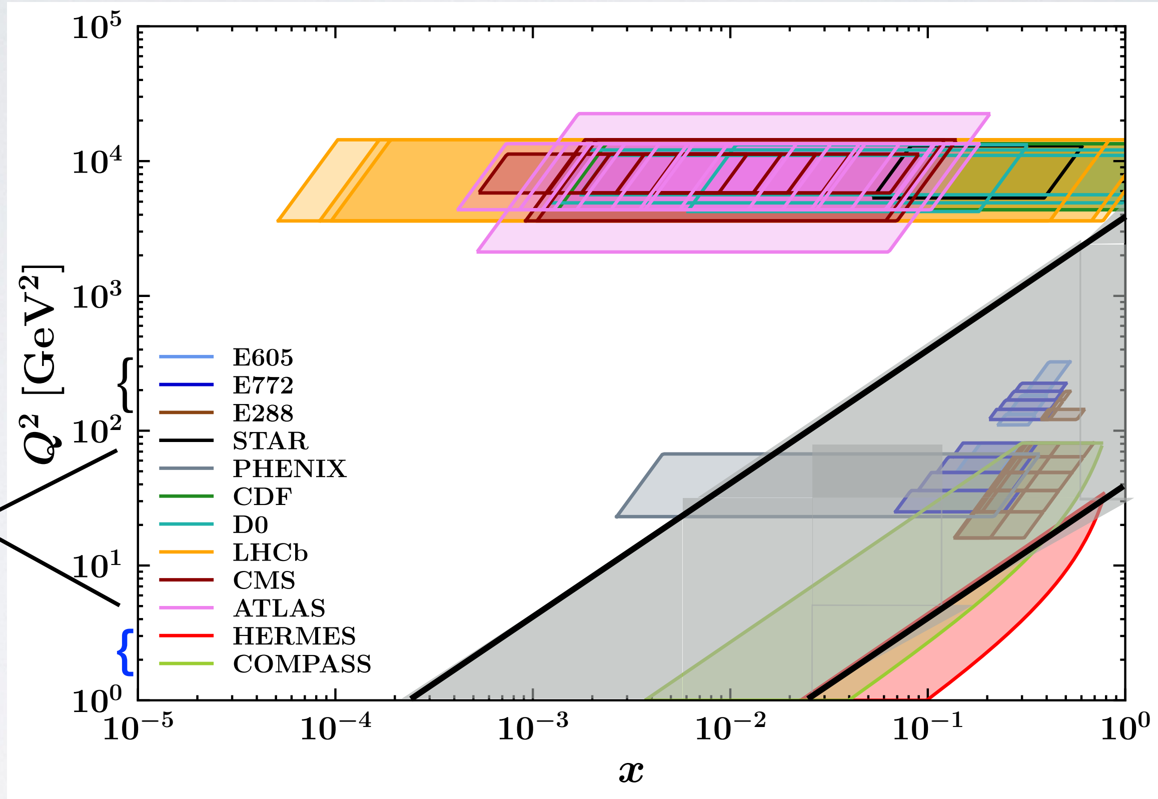
$\sqrt{s} \sim 72$ GeV $\rightarrow$ 10 (e-) x 130 (p) GeV



Phase space of EIC @10x130

Drell Yan { fixed target / collider

SIDIS

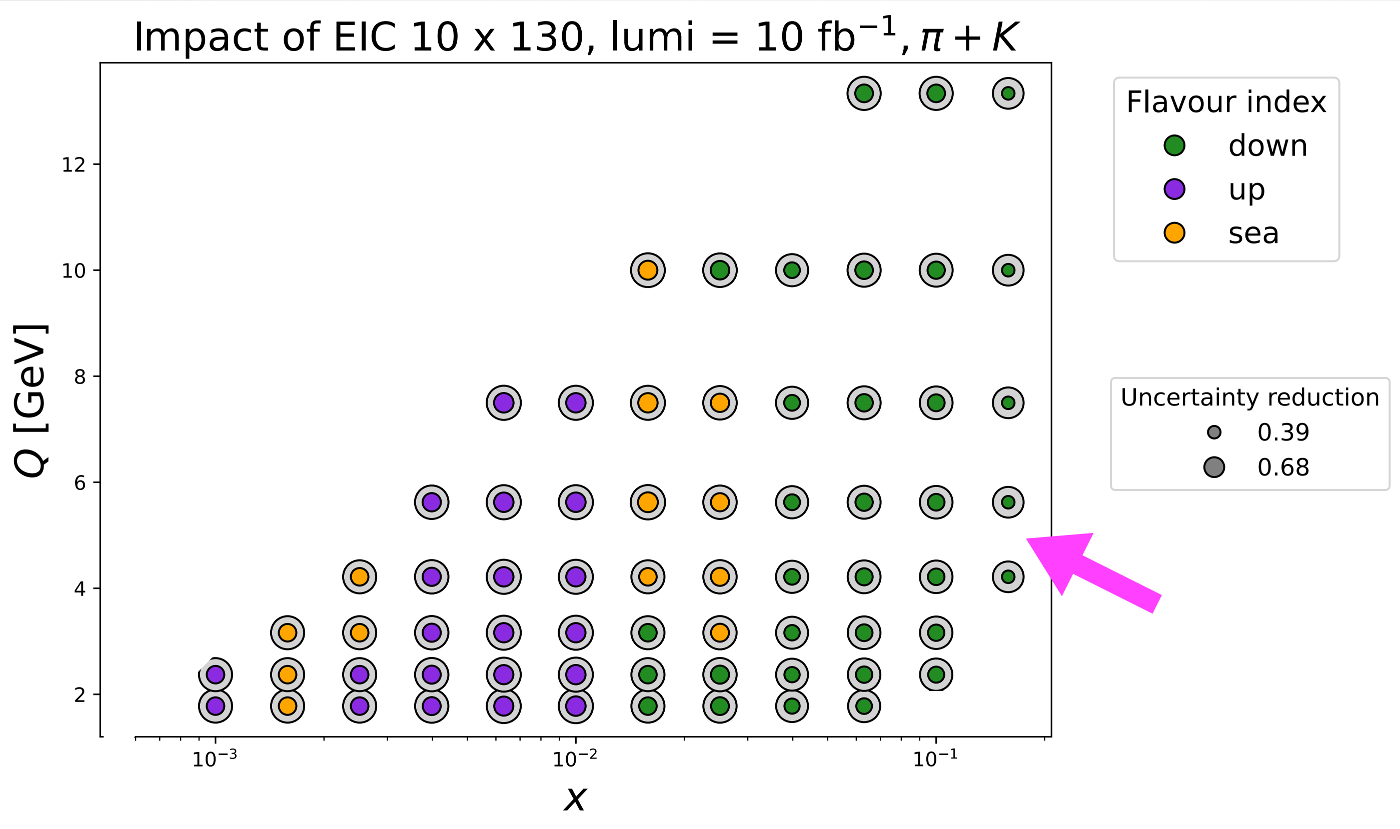


EIC

including EIC pseudodata in the fit:

MAPTMD24
2031 pts
→
+ **EIC**
+ ~1700 pts per kin. π
+ ~3400 pts per kin. π+K

lumi = 10 fb^{-1} , proton target, SIDIS π + K



For each (x,Q²) bin:

from MAPTMD24, max. uncertainty of $f_1^q(x, k_T^2; Q)$ over all k_T and all flavors q

u d sea

including EIC pseudodata, color code indicates the flavor with max. reduction in uncertainty over all k_T

increased reduction ~60% for **down** at large x and several Q^2

EIC impact: 10x130 lumi=10 fb^{-1}

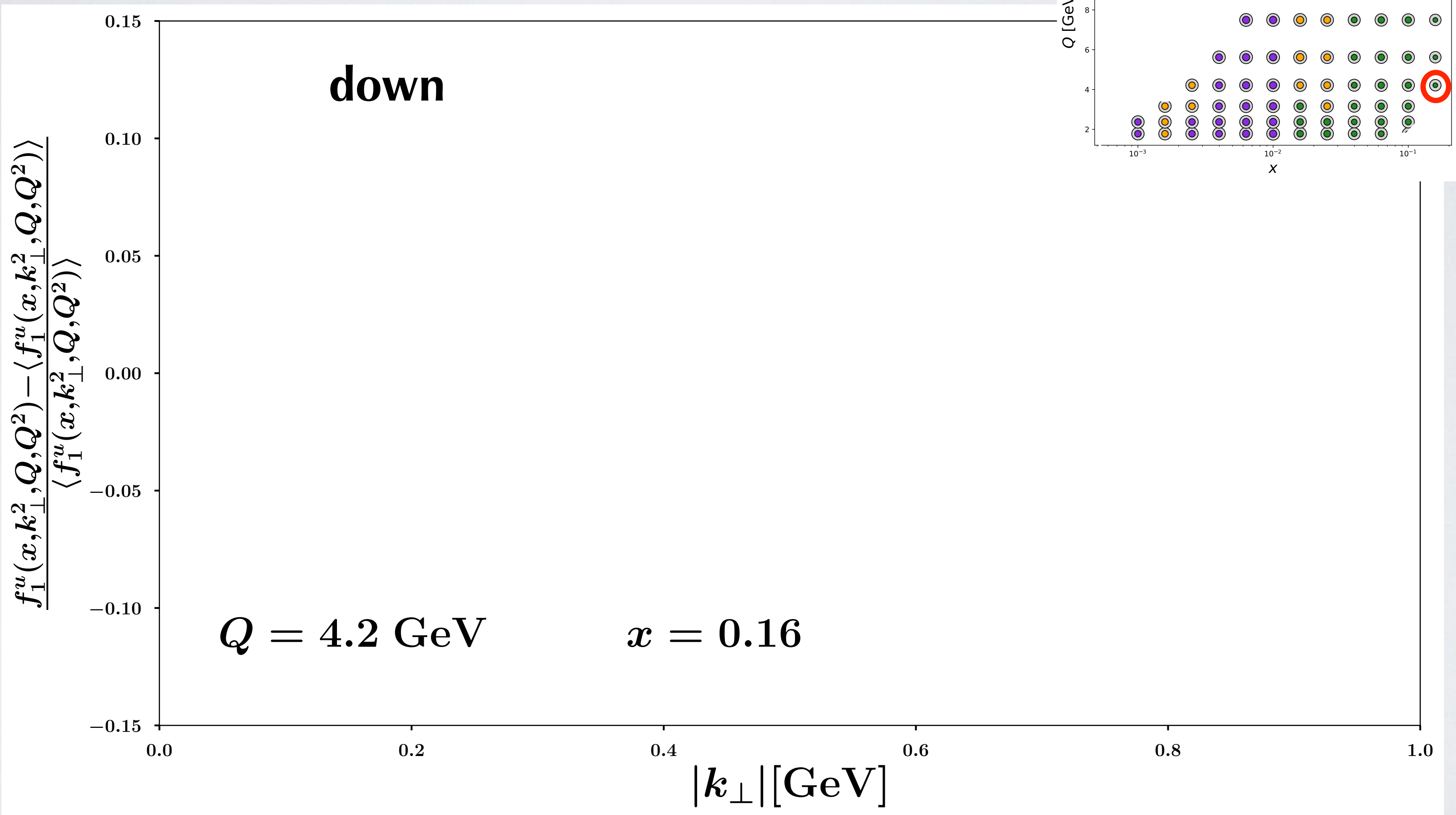
MAPTMD24 2031

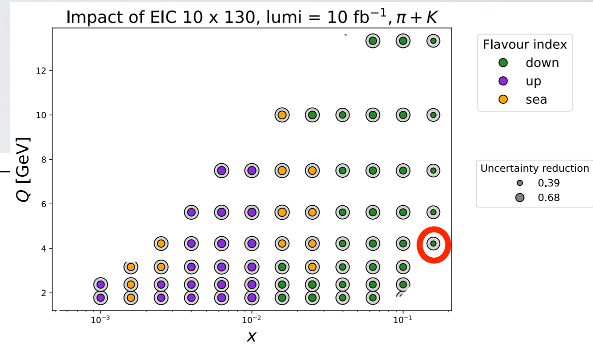
EIC	**# pts.**	**lumi [fb^{-1}]**
10x130	~1700	**10**

(early Science conditions, **all π + K production**)

$$\frac{\text{TMD}^q - \langle \text{TMD}^q \rangle}{\langle \text{TMD}^q \rangle}$$

x=0.16, Q=4.2 GeV





~60% reduction at medium Q^2

courtesy L. Rossi

EIC impact: 10x130 lumi=10 fb^{-1}

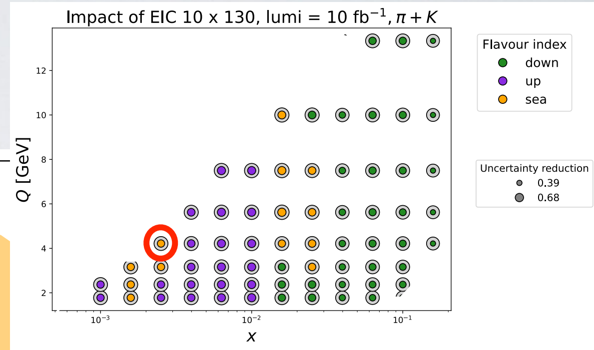
MAPTMD24   2031

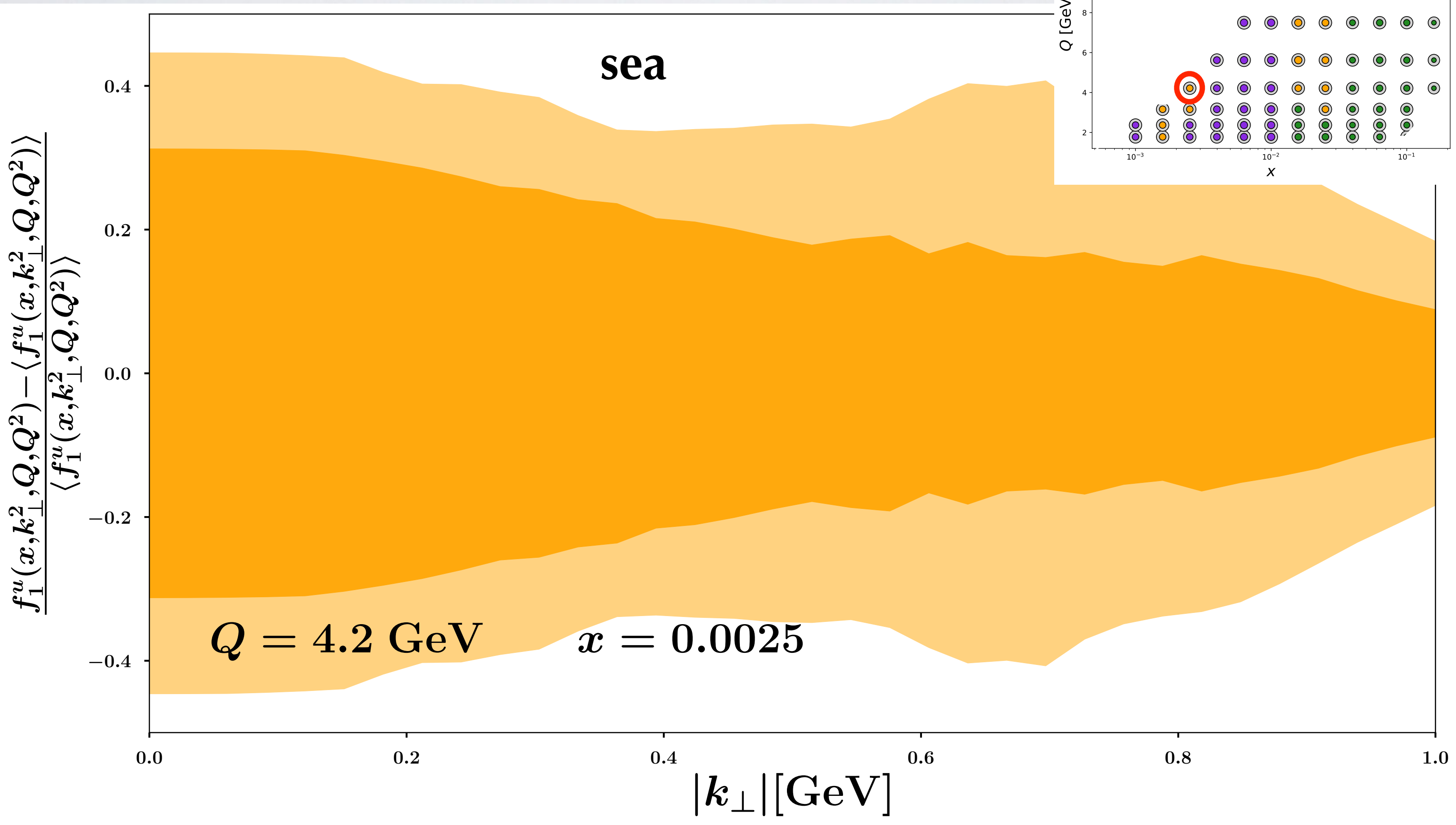
EIC	**# pts.**	**lumi [fb^{-1}]**
10x130	~1700	**10**

(early Science conditions, **all π + K production**)

$$\frac{\text{TMD}^q - \langle\text{TMD}^q\rangle}{\langle\text{TMD}^q\rangle}$$

x=0.0025, Q=4.2 GeV

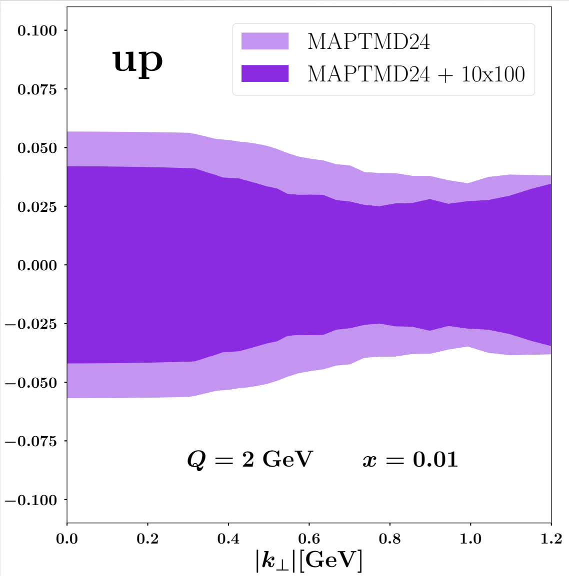


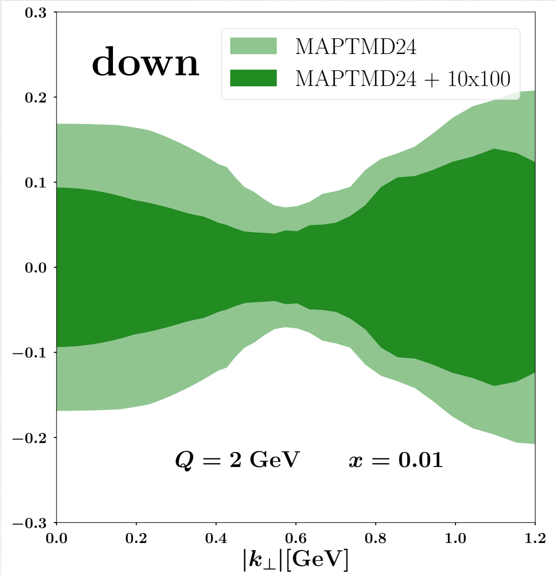


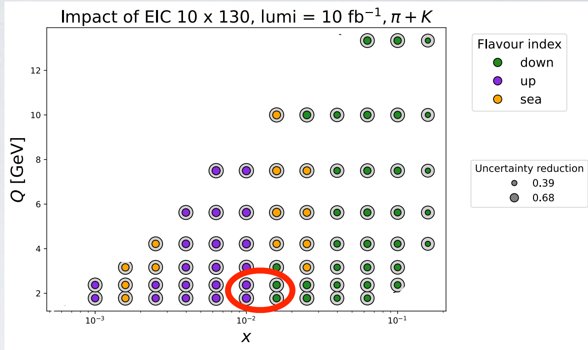
slightly more than ~30% reduction at medium-large Q^2

courtesy L. Rossi

EIC impact: 10x100 lumi~50 fb^{-1} (5 years)



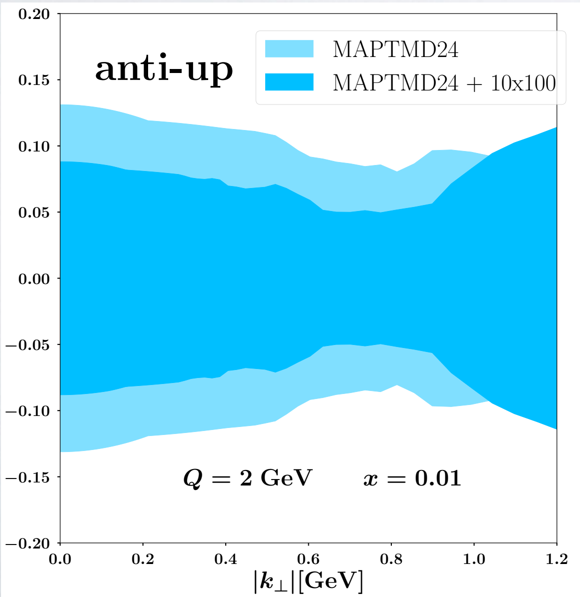


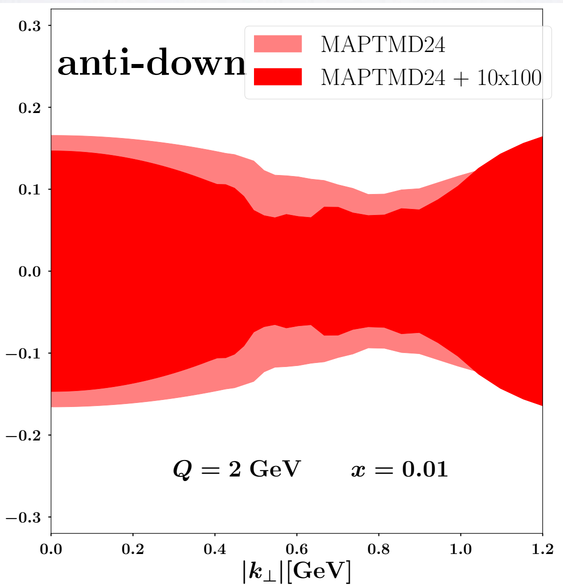


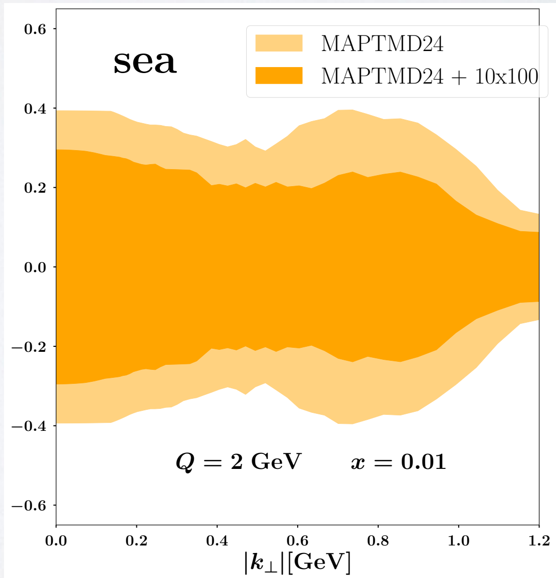
MAPTMD24	2031	
EIC	**# pts.**	**lumi [fb^{-1}]**
10x100	1611	51.3

(simulation campaign of May 2024)

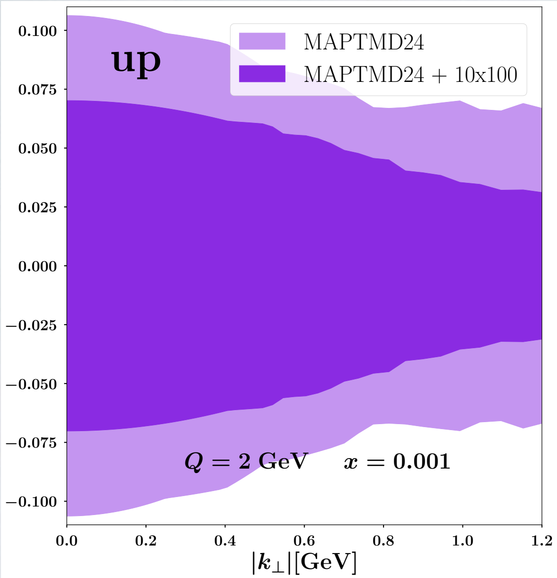
L. Rossi, Ph.D. Thesis

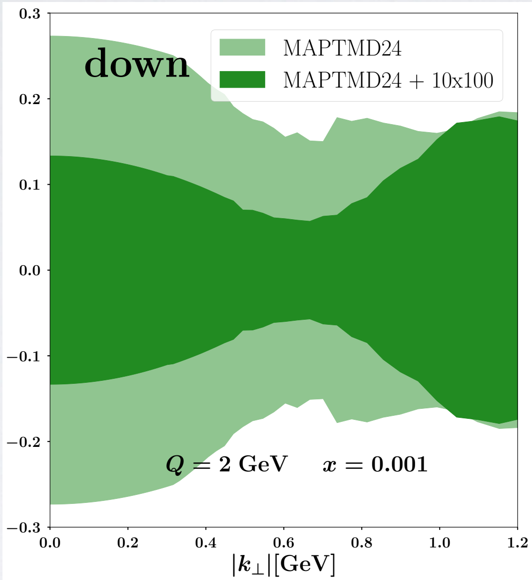


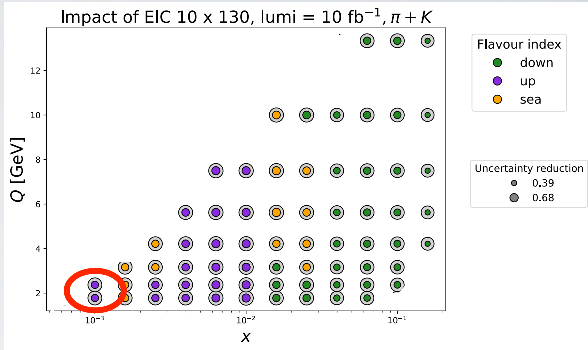




EIC impact: 10x100 lumi~50 fb^{-1} (5 years)







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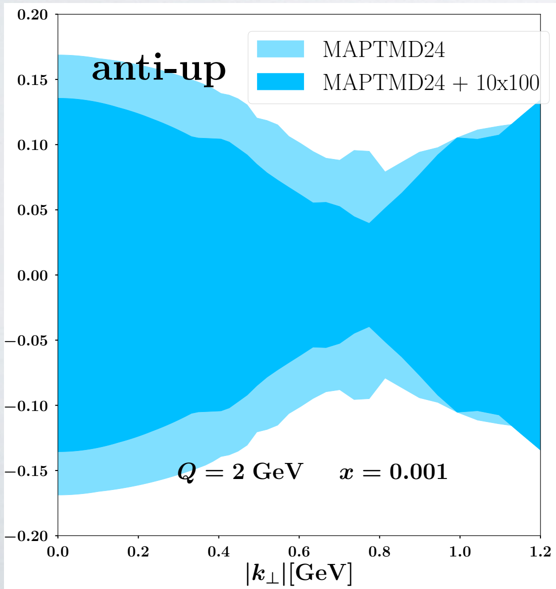
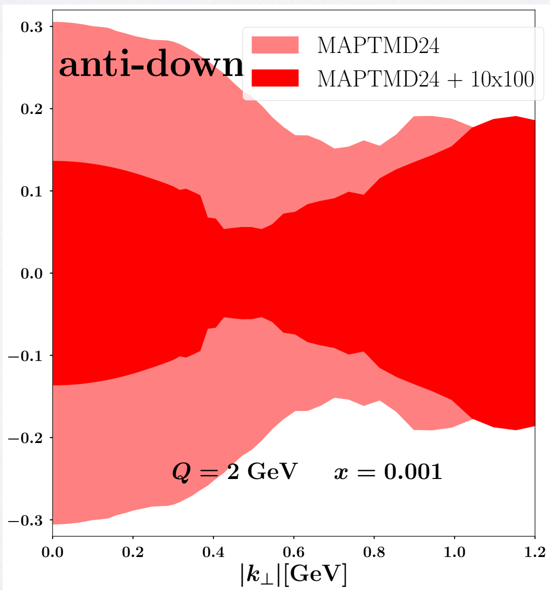
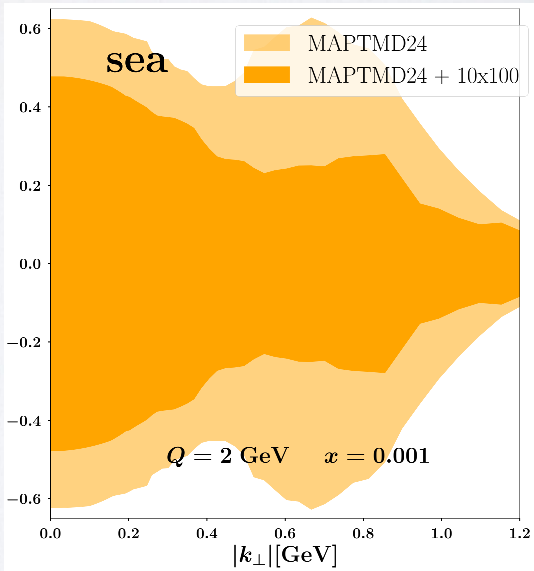


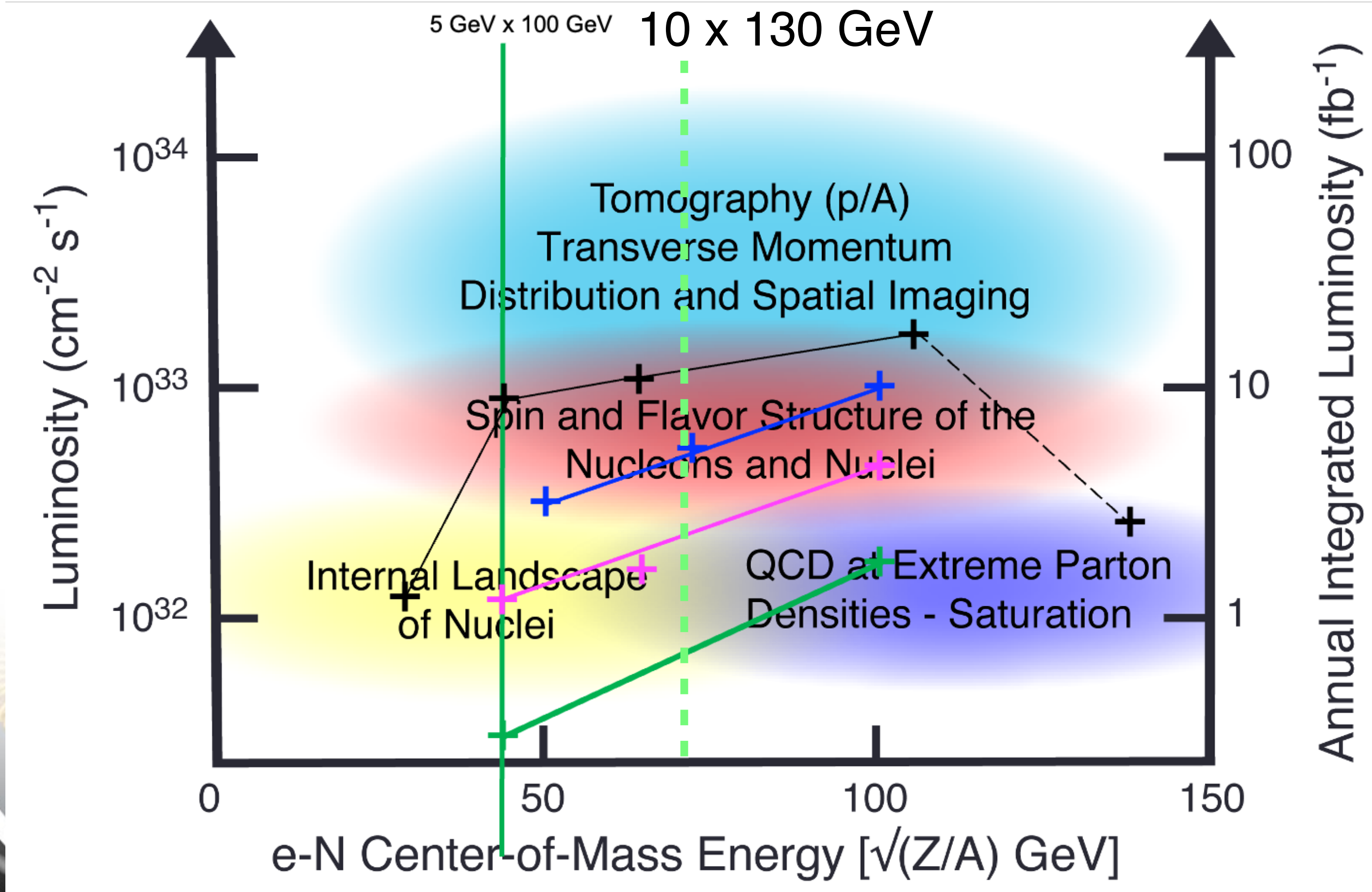




Actions to meet the $ 3B cap

reduce costs and scope by deferring ultimate performance capabilities:

- Electron Storage Ring: reduce to 2 SRF systems, 10nC/bunch E= 9 GeV
- Defer IR Crab system   - Defer low-energy cooling (reduce lumi by 2x to 3x)
- Hadron Storage Ring: defer bypass line at 41 GeV (increase min s = (45 GeV)^2)



From the March 27th GM:
https://indico.bnl.gov/event/31936/

talk by A. Deshpande
on Friday

Early Science Conditions

New matrix:

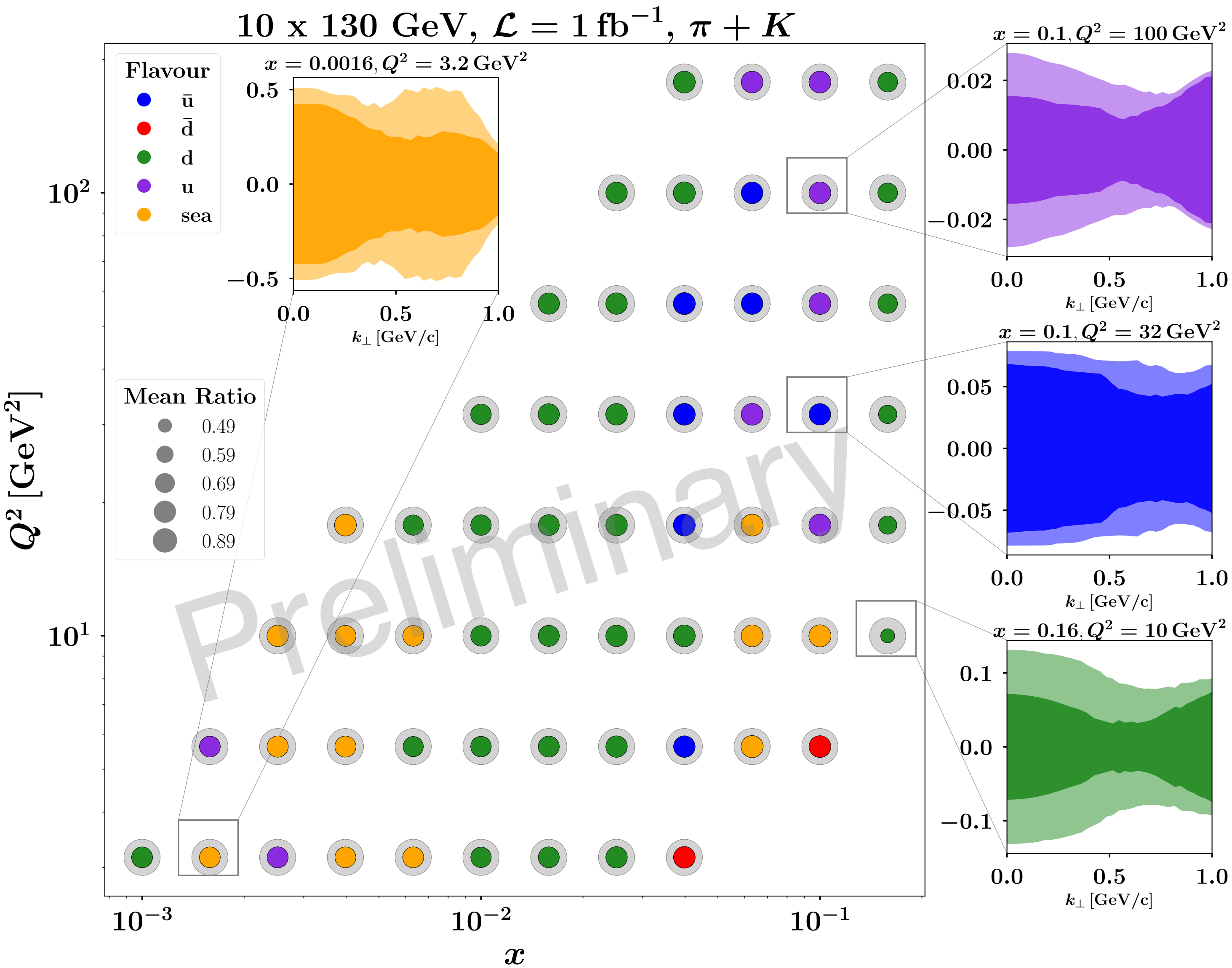
Species	Beam energy (GeV)	Integrated luminosity	Electron-beam polarization	Hadron-beam polarization
e+Ag	9×115	1.0 fb^{-1}	NO	N/A
e+D	9×130	1.5 fb^{-1}	LONG	NO
$e+p$	9×130	1.0 fb^{-1}	LONG	TRANS and/or LONG
$e+p$	9×275	2.5 fb^{-1}	LONG	TRANS and/or LONG
e+Au	9×100	1.0 fb^{-1}	LONG	N/A
$e+{}^3$He	9×166	1.5 fb^{-1}	LONG	TRANS and/or LONG

Table 1: EIC Early Science Matrix. The eA luminosity is per nucleon.

BNL & JLab Associate Lab Directors charged ePIC to summarize the science achievable with early data according to above matrix, before full machine capabilities

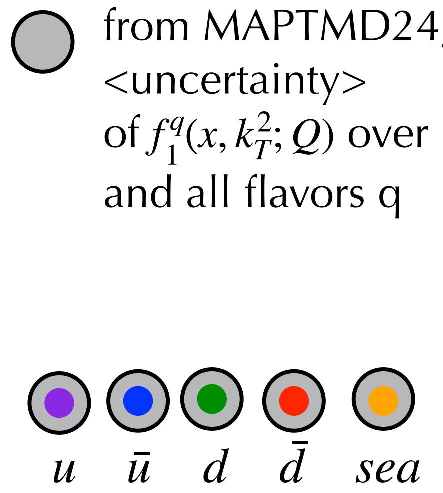
Early Science Report (ESR) due by July 1st; v2 document circulated to community

EIC impact: 10x130 lumi=1 fb^{-1}



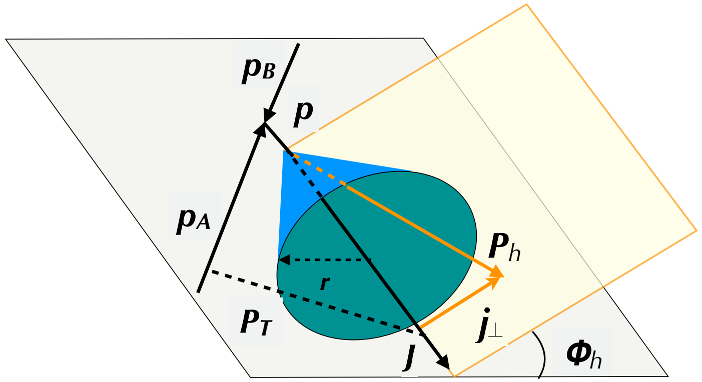
For each (x,Q^2) bin:

from MAPTMD24, <uncertainty> of $f_1^q(x, k_T^2; Q)$ over k_T and all flavors q



including EIC pseudodata, color code indicates the flavor with max. reduction of <uncertainty> over all k_T

New opportunity: hadron-in-jet



$$z_J = \frac{J^-}{p^-} \qquad z_h = \frac{P_h^-}{J^-}$$

1

- **hard collision** of proton $\mathbf{p_A}$ and proton $\mathbf{p_B}$
- a parton **p** fragments into the **jet J** with radius **r**
- **hard scale** = $\mathbf{P_T}$ of jet J w.r.t. collision axis
- hadron $\mathbf{P_h}$ **inside jet** J with $j_\perp$ w.r.t. jet axis

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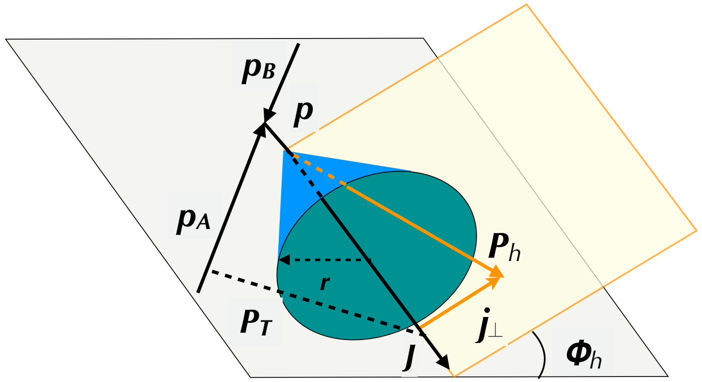

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$$z_J = \frac{J^-}{p^-} \qquad z_h = \frac{P_h^-}{J^-} \qquad \Lambda^2_{\mathrm{QCD}} \simeq j_\perp^2 \ll (P_T r)^2$$

hybrid factorization theorem

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

collinear

$$\frac{d\sigma}{d\eta\, d|\mathbf{P}_T|\, dz_h\, d\mathbf{j}_\perp} = \frac{2\pi|\mathbf{P}_T|}{s} \sum_{a,b,c,d} \int \frac{dx_A dx_B dz_J}{x_A x_B} \delta(z_J - \bar{z}_J)\; f_1^a(x_A) f_1^b(x_B)\, H_{ab\to cd} \times \mathscr{D}_c^h(z_J, z_h, \mathbf{j}_\perp; |\mathbf{P}_T|, |\mathbf{P}_T| r)$$

TMD

$$\bar{z}_J = \frac{|\mathbf{P}_T|}{\sqrt{s}} \frac{x_A e^{-\eta} + x_B e^{\eta}}{x_A x_B}$$

JTMDFF

$$\mathscr{D}_q^h(z_J, z_h, \mathbf{j}_\perp; |\mathbf{P}_T|, |\mathbf{P}_T| r) = \sum_i C_{q\,i}(z_J, |\mathbf{P}_T|, |\mathbf{P}_T| r) \int \frac{d\mathbf{b}_T}{(2\pi)^2} e^{i\mathbf{j}_\perp\cdot\mathbf{b}_T/z_h} \tilde{D}_1^{i\to h}(z_h, \mathbf{b}_T; |\mathbf{P}_T| r)$$

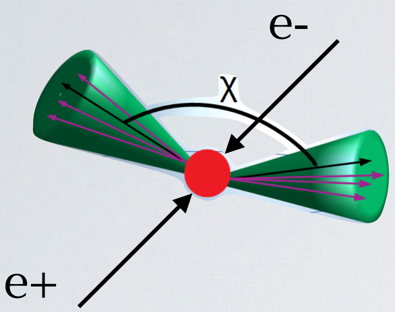
access to TMD FF

$$\overset{\mathrm{LO}}{=} \sum_i \delta(1 - z_J)\, \delta_{qi}\, D_1^i(z_h, \mathbf{j}_\perp^2; |\mathbf{P}_T|)$$

Kang et al., JHEP **11** (2017)
arXiv:1705.08443

Similarly for hadron-in-jet SIDIS at the EIC

New opportunity: Energy-Energy Correlator in e+e-



$$\mathrm{EEC}(\zeta) = \frac{d\sigma^{e+e-}}{d\zeta} = \sum_{ij} \int d\sigma_{e+e-\to ij+X} \frac{E_i E_j}{Q^2} \delta\left(\zeta - \frac{1-\cos\chi_{ij}}{2}\right)$$

energy-weighted e+e- cross section
measures correlation of two energy flows along specific directions
IR-safe, well measured, known up to NNLO

for $\zeta \to 1$ ($\chi \to \pi$)
factorized formula:

$$\frac{d\sigma}{d\zeta} = \underbrace{\frac{\sigma_0}{8}}_{\text{Born}} \sum_{q\bar{q}} \underbrace{H_{q\bar{q}}}_{\text{Hard}} \int db_T\, J_0(b_T Q\sqrt{1-\zeta})\ \mathrm{Jet}^q(b_T)\ \mathrm{Jet}^{\bar{q}}(b_T)$$

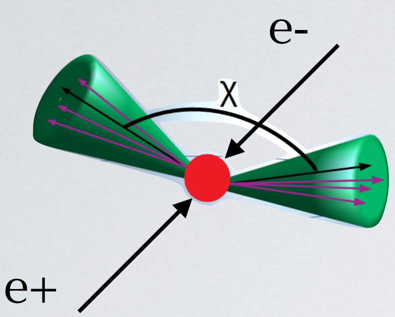
$$\mathrm{Jet}^q(b_T) = \sum_{\text{hadrons}} \int_0^1 dz\, z^3\, \mathrm{TMDFF}^{q\to h}(z, b_T) = \mathrm{Jet}^q_{\text{pert}} + \mathrm{Jet}^q_{NP}$$

$\longleftarrow$ fitted to data

→ **sensitivity only to CS kernel**

Kang et al., arXiv:2410.21435
Bris et al., arXiv:2507.17478
Ferrera et al., arXiv:2603.19162

New opportunity: Energy-Energy Correlator in e+e-



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for ζ→1 (χ→π)

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$$\frac{d\sigma}{d\zeta} = \overset{\text{Born}}{\frac{\sigma_0}{8}} \sum_{q\bar{q}} \overset{\text{Hard}}{H_{q\bar{q}}} \int db_T\, J_0(b_T Q\sqrt{1-\zeta})\ \ \text{Jet}^q(b_T)\ \ \text{Jet}^{\bar{q}}(b_T)$$

$$\text{Jet}^q(b_T) = \sum_{\text{hadrons}} \int_0^1 dz\, z^3\, \text{TMDFF}^{q\to h}(z, b_T) = \text{Jet}^q_{\text{pert}} + \text{Jet}^q_{NP}$$ ⟵ fitted to data

sensitivity only to CS kernel

use OPAL, DELPHI, L3, SLD, ALEPH, TOPAZ, TASSO,… data to constrain CS kernel

agreement with latest pheno results for CS kernel

Kang et al., arXiv:2410.21435

Bris et al., arXiv:2507.17478

Ferrera et al., arXiv:2603.19162

quark TMDs in Pion

	Accuracy	Drell-Yan	N of points	χ^2/N_{points}	Flavor dep.
Wang et al., 2017 JHEP **08** (17) 137	NLL	✔	96	1.61	✘
Vladimirov 2019 JHEP **10** (19) 090	NNLL′	✔	80	1.44	✘
MAPTMDPion22 PRD **107** (23)	N^3LL(-)	✔	138	1.55	✘
JAM23 PRD **108** (23)	NNLL	✔	93	1.37	✘
MAPTMDPion25 2509.25098	N^3LL	✔	101	1.22	✔

← simultaneous extraction of pion PDF & TMD proton TMD

MAPTMDPion25 First fit sensitive to **flavor dep. of k_T distributions**: valence - sea, 6 parameters

data set: E615, E537 π^--N Drell-Yan, Nucleon TMDs from MAPTMD24 with same CS kernel

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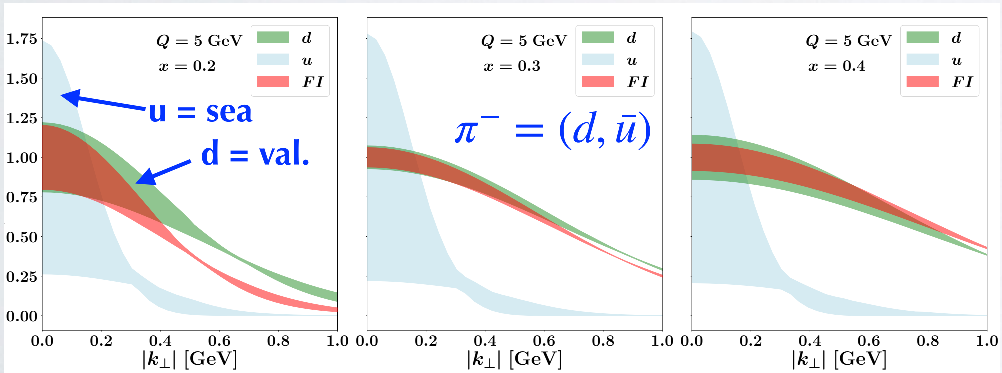
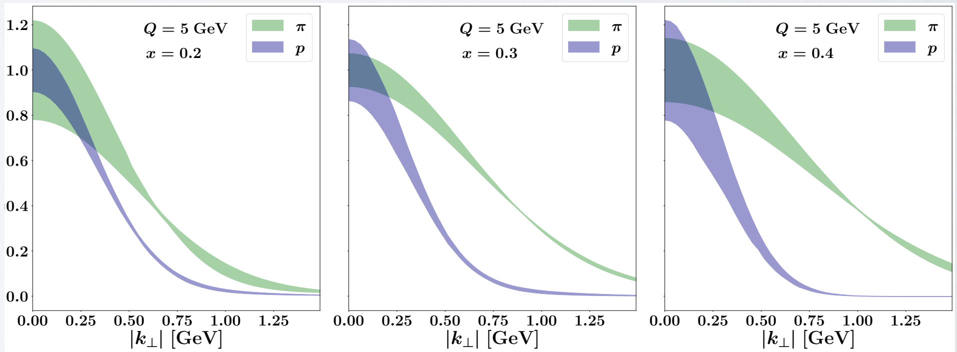




valence and sea have different k_T distributions

FI = flavor-independent
~intermediate between valence & sea

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

down quark in pion vs. proton

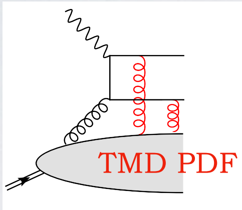
in k_T space, proton is narrower than pion

same finding in JAM23, lattice, and chiral QCD

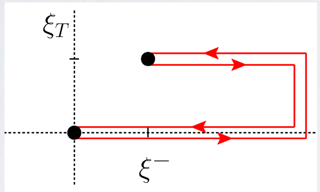
gluon TMDs

two types depending on complicated color structure of Wilson lines:

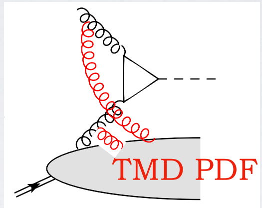
WW-type



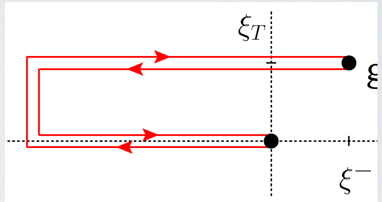
2-jet SIDIS



[+,+]

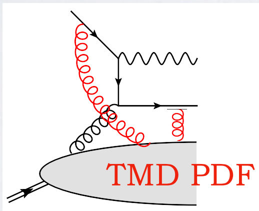


gluon fusion to Higgs

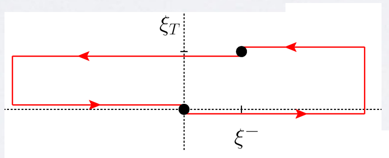


[-,-]

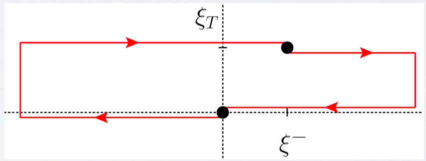
dipole-type



p p $\rightarrow$ γ^*+jet



[+,-]



[-,+]

WW $\neq$ dipole: different mechanisms, different processes..

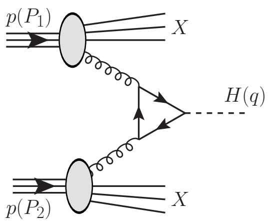
(Warning: factorization under investigation for most processes)

often use models as guidance

spectator model for all
- T-even *Bacchetta et al., arXiv:2005.02288*
- T-odd *Bacchetta et al., arXiv:2402.17556*

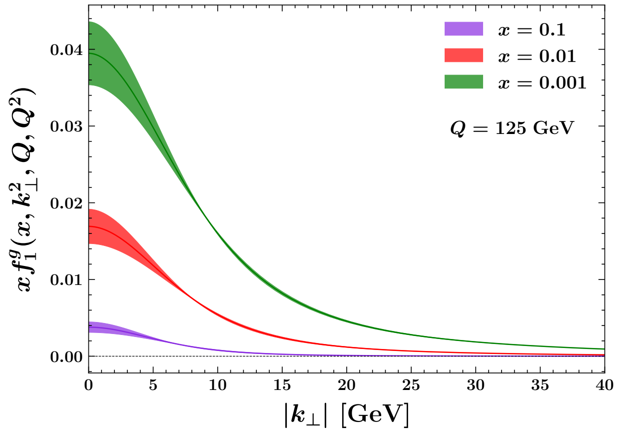
first extraction of gluon TMD in proton

	Accuracy	Drell-Yan	N of points	χ^2/N$_{points}$	Flavor dep.
Anedda et al. (MAP), arXiv:2605.28216	N^{3}LL	✔ (LHC)	30	1.49	✘

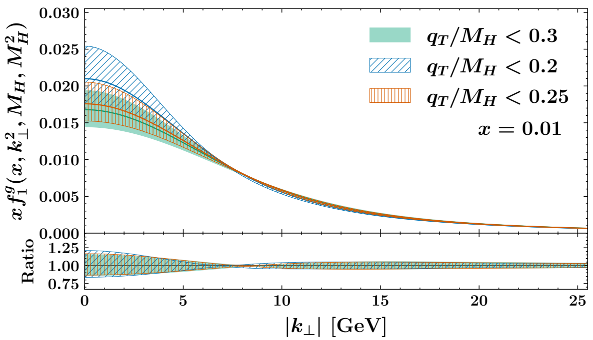


process: gluon-gluon fusion to Higgs → WW-type gluon TMD

data set: CMS Run I,II ; ATLAS Run I,II   channel: $pp \to H \to \gamma\gamma$ or 4ℓ



TMD factorization cut: $q_T / M_H < 0.3$



effect of cut → tensions from large q_T data

Cut	N_{dat}	χ^2/N_{dat}
$q_T/M_H < 0.2$	20	1.08
$q_T/M_H < 0.25$	28	1.35
$q_T/M_H < 0.3$	**30**	**1.49**

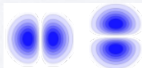
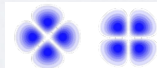
quark TMD PDFs at leading twist

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

quark polarization / nucleon

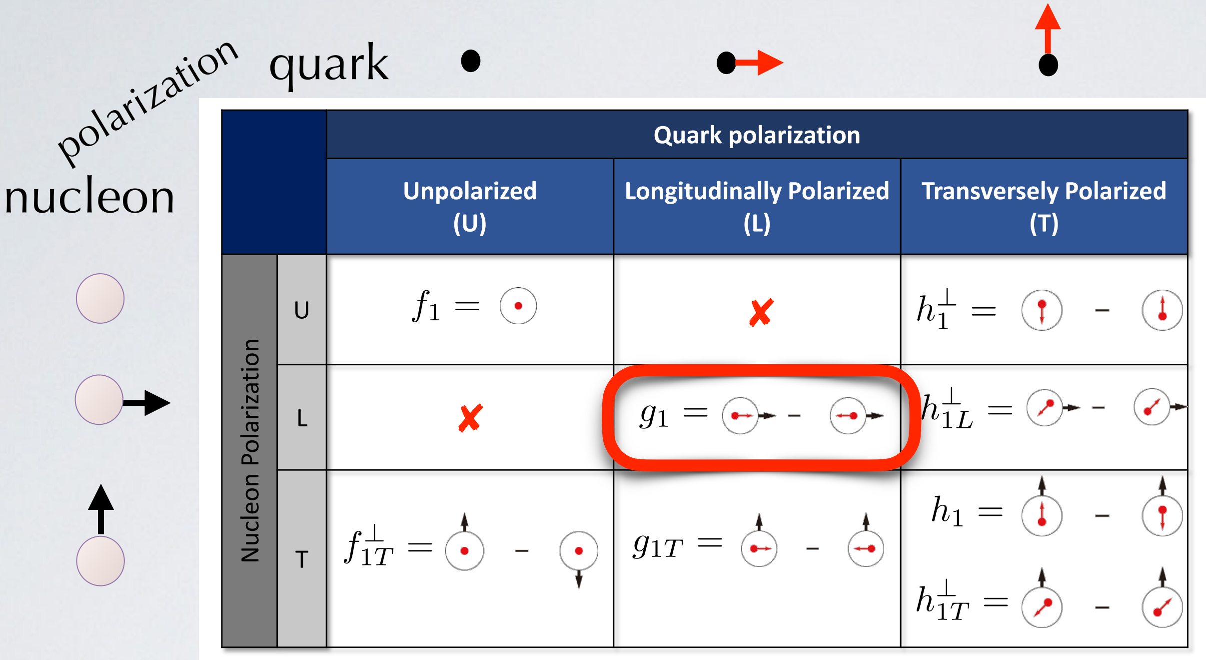
Nucleon Polarization		Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)	
	U	$f_1 =$	✘	$h_1^\perp =$ −	Boer-Mulders
	L	✘	$g_1 =$ −	$h_{1L}^\perp =$ −	Kotzinian-Mulders
	T	$f_{1T}^\perp =$ −	$g_{1T} =$ −	$h_1 =$ −	transversity
				$h_{1T}^\perp =$ −	pretzelosity
		Sivers	worm-gear		

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

quark TMD PDFs at leading twist



Mulders & Tangerman, N.P. **B461** (96)
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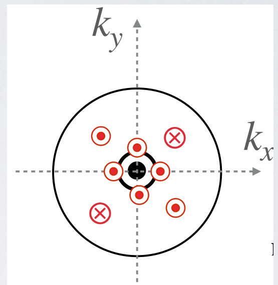
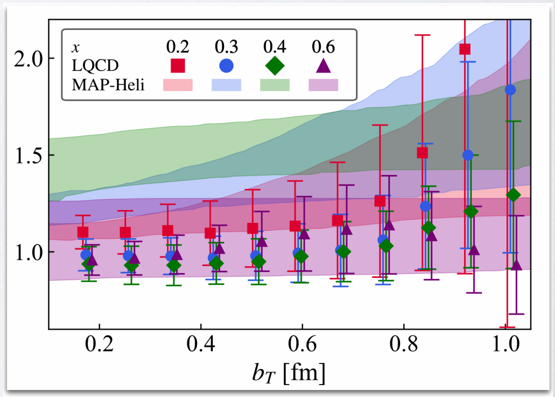
Helicity TMD



Do quarks with spin || proton spin have larger / smaller k_T than those with spin anti-ll ?

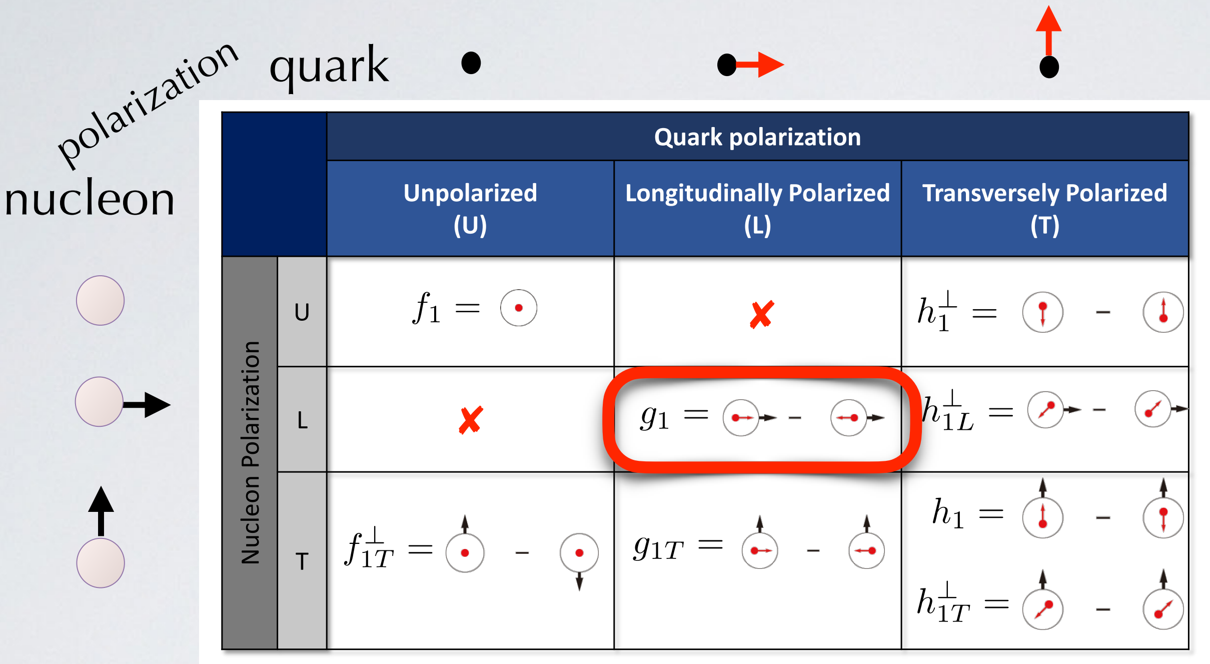
$$g_{1L}^{\Delta u_+ - \Delta d_+}(x, b_T; 1.62) \Big/ g_A\, f_1^{u_v - d_v}(x, b_T; 1.62)$$

	Accuracy	SIDIS	Drell-Yan	N of points	χ^2/N	Flavor dep.
MAPTMD22pol Bacchetta et al. (MAP) P.R.L. **134** (25)	NNLL	✔	✘	291	1.09	✘
YLSZM Yang et al. (TNT) P.R.L. **134** (25)	NNLL	✔	✘	253	0.74	✘



Bollweg et al., arXiv:2505.18430

quark TMD PDFs at leading twist



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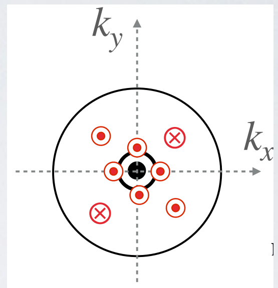

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$$g_{1L}^{\Delta u_+ - \Delta d_+}(x, b_T; 1.62) \big/ g_A\, f_1^{u_v - d_v}(x, b_T; 1.62) \quad > 0$$

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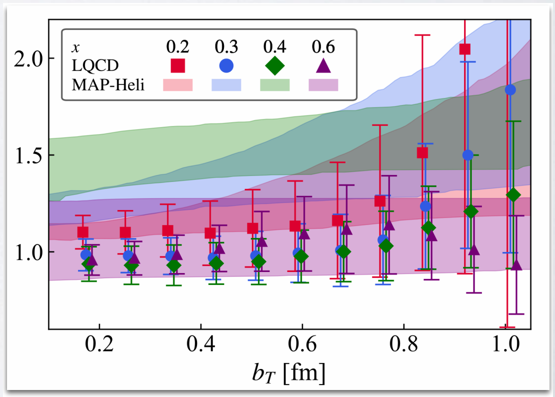

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Mulders & Tangerman, N.P. **B461** (96)
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polarization
quark
nucleon

		Quark polarization		
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Nucleon Polarization	U	$f_1 =$	✘	$h_1^\perp =$ -
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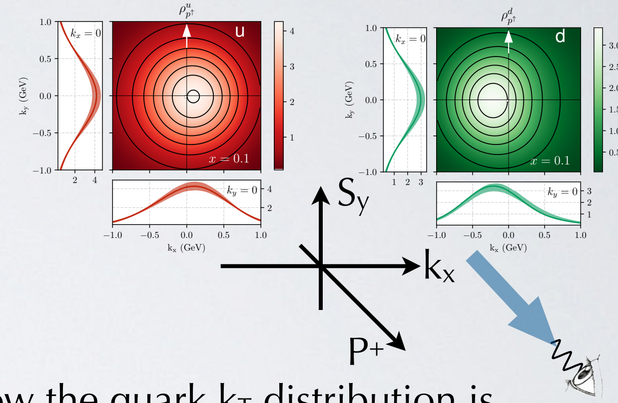
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

naïve T-odd: non universal, but in a predictable way..

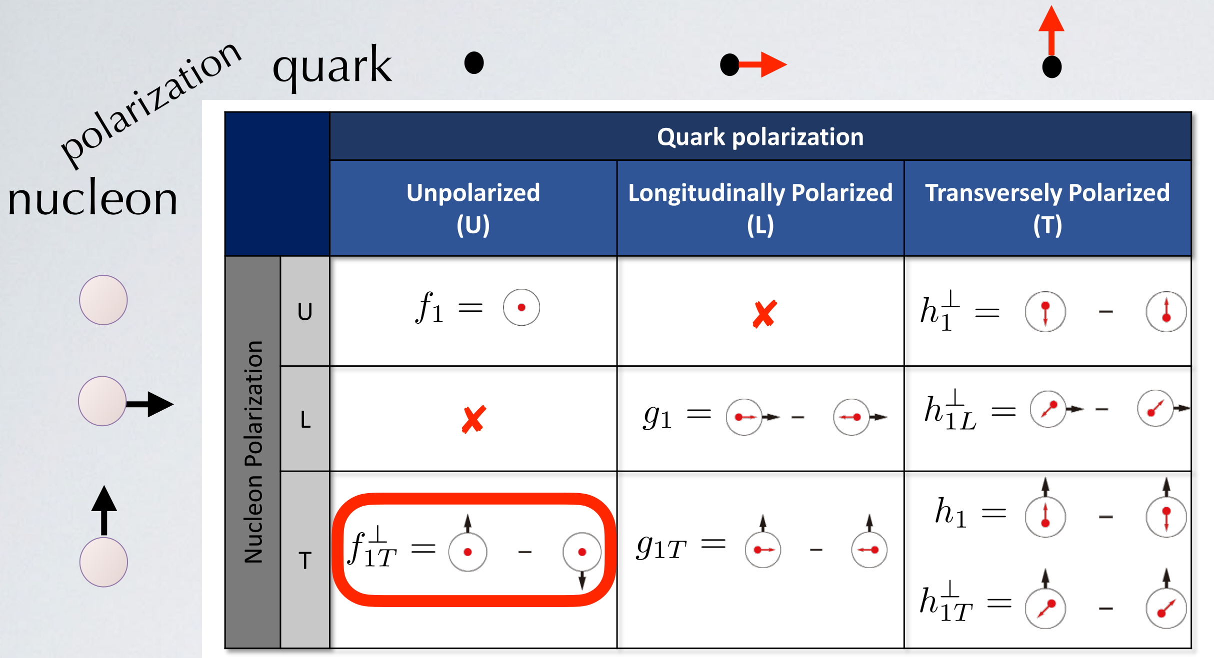
Sivers TMD



how the quark k_T distribution is distorted by the nucleon T polarization

quark TMD PDFs at leading twist

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



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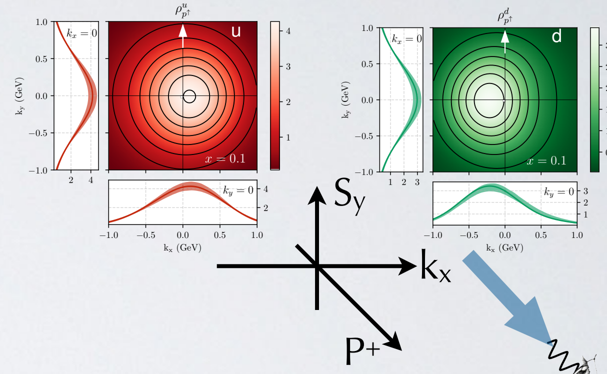

how the quark k_T distribution is distorted by the nucleon T polarization

<u>Many extractions:</u>

TMD framework	PV 2020 arXiv:2004.14278	EKT 2020 arXiv:2009.10710	BPV 2020 arXiv:2012.05135 arXiv:2103.03270	TNT 2024 arXiv:2412.18324
generalized Parton Model	JAM 2020 arXiv:2002.08384	TO-CA 2021 arXiv:2101.03955	JAM 2022 arXiv:2205.00999	Fernando-Keller arXiv:2304.14328

all parametrizations are in fair agreement for x-dep. of $f_{1T}^{\perp(1)}(x)$ for valence flavors
k_T-dependence is still much unconstrained

quark TMD PDFs at leading twist

Mulders & Tangerman, N.P. **B461** (96)
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polarization: quark / nucleon

Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)	
	U	$f_1 =$	✘	$h_1^\perp =$ -	Boer-Mulders
	L	✘	$g_1 =$ -	$h_{1L}^\perp =$ -	Kotzinian-Mulders
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ -	transversity
	T			$h_{1T}^\perp =$ -	pretzelosity
		Sivers	worm-gear		

collinear PDFs surviving integration in k_T

quark TMD PDFs at leading twist

polarization: quark / nucleon

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

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

transversity

tensor *charge* $\delta^q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x, Q^2)$

potential doorway to new Phys.?

the only chiral-odd structure that survives in collinear kinematics
→ 2 different mechanisms

quark TMD PDFs at leading twist

polarization quark

nucleon

		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)

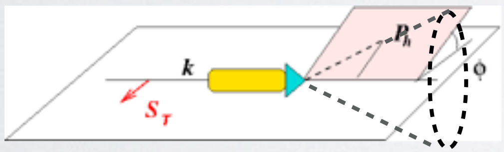
transversity

tensor charge $\delta^q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x, Q^2)$

potential doorway to new Phys.?

the only chiral-odd structure that survives in collinear kinematics

→ 2 different mechanisms



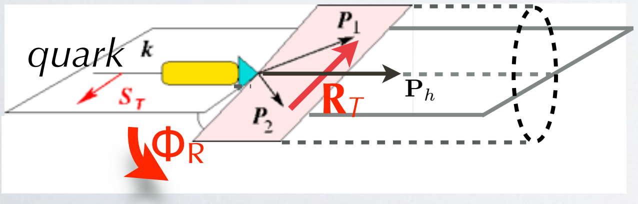
Collins effect

$S_T \cdot \mathbf{k} \times \mathbf{P}_{hT}$

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

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

TMD framework



di-hadron mechanism

$S_T \cdot \mathbf{P}_2 \times \mathbf{P}_1 = S_T \cdot \mathbf{P}_h \times \mathbf{R}_T$

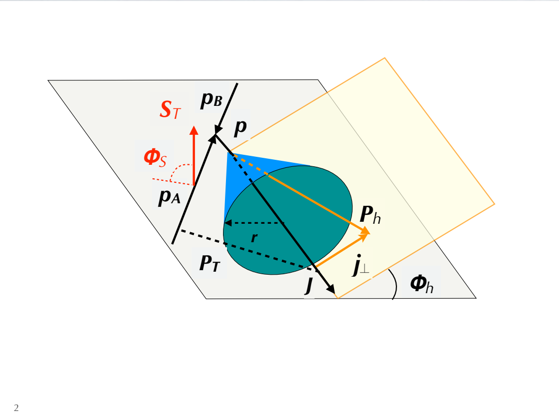
Collins et al., N.P. **B420** (94)

$\propto h_1(x)\, H_1^{\sphericalangle}(z, R_T^2 \propto M_{h_1 h_2}^2)$ SIDIS

collinear framework p p↑

talk by A. Metz today

hadron-in-jet Collins effect



$$\frac{d\sigma}{d\eta\, d|\mathbf{P}_T|\, dz_h\, d\mathbf{j}_\perp d\phi_S} = S_T \sin(\phi_S - \phi_h) \frac{|\mathbf{P}_T|}{s} \sum_{a,b,c,d} \int \frac{dx_A dx_B dz_J}{x_A x_B}\, \delta(z_J - \bar{z}_J)$$

hybrid

collinear $\times\, h_1^a(x_A) f_1^b(x_B)\, H^{\rm Collins}_{ab^\uparrow \to c^\uparrow d}$

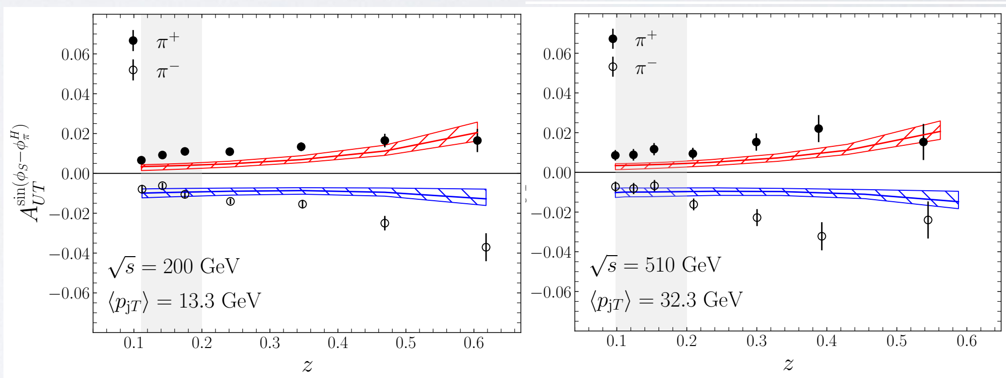
Jet-Collins $\times\, \mathscr{H}_c^{\perp h}(z_J, z_h, \mathbf{j}_\perp; |\mathbf{P}_T|, |\mathbf{P}_T| r)$

RHIC

$$p^\uparrow p \to (\pi)_{\rm jet} X$$

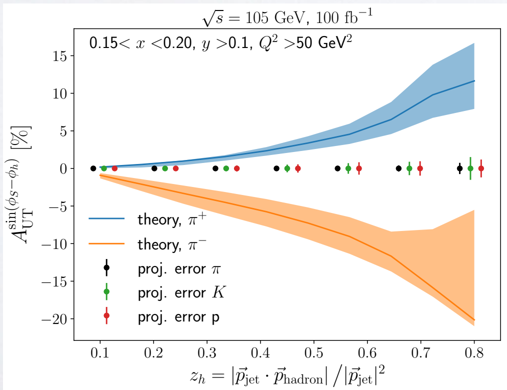
Predictions for STAR data integrated in forward η

*D'Alesio et al. P.L. **B871** (2025)*
arXiv:2506.21959



EIC

Abdul Khalek et al.
(EIC Yellow Report),
arXiv:2103.05419



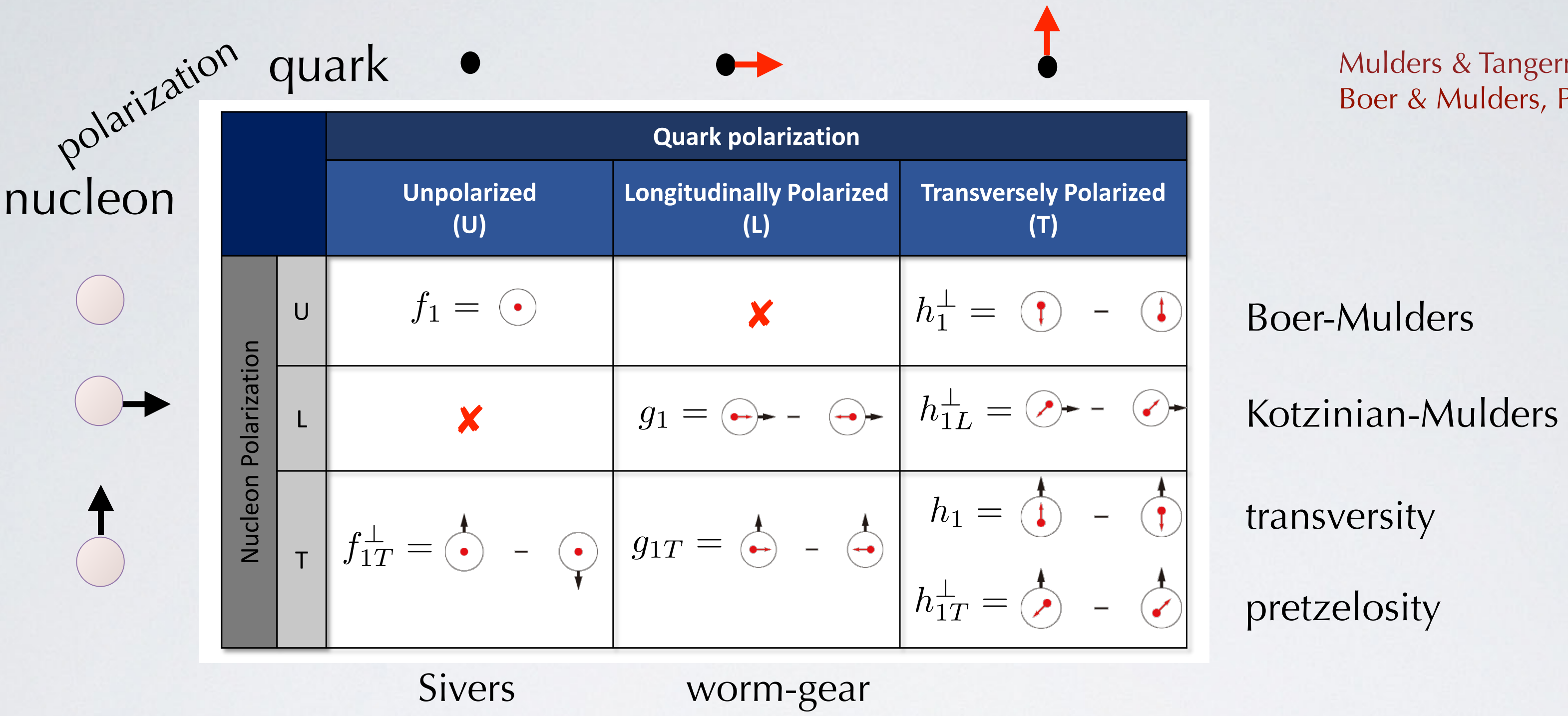
projected errors at the EIC
see also

*Arratia et al. P.R. D**102** (2020)*

D'Alesio et al. arXiv:2605.02890

quark TMD PDFs at leading twist

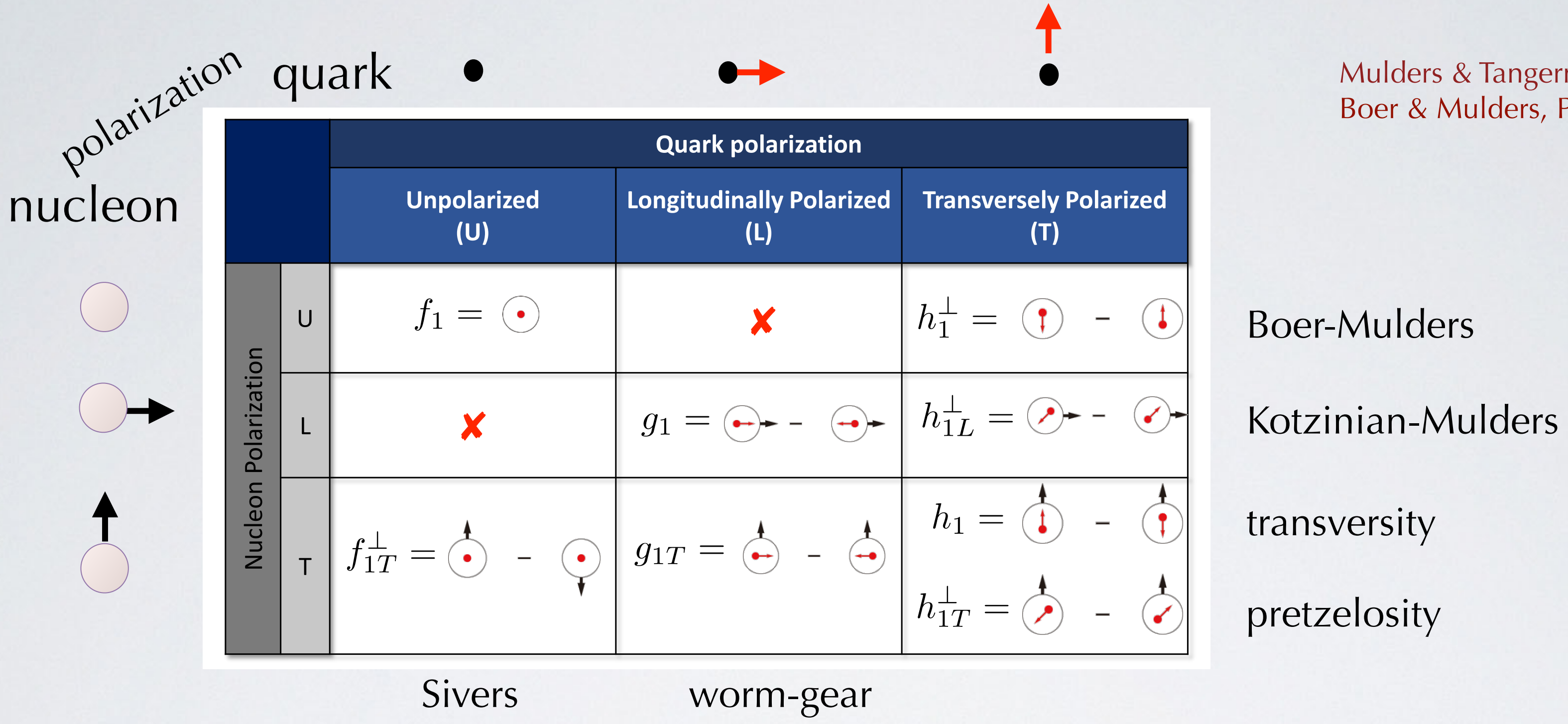
Mulders & Tangerman, N.P. **B461** (96)
Boer & Mulders, P.R. D**57** (98)



Boer-Mulders	arXiv:2004.02117, arXiv:2407.06277
Worm-gear g1T	arXiv:2110.10253, arXiv:2210.07268
(Kotzinian-Mulders) Worm-gear h1L	
Pretzelosity	arXiv:1411.0580

not mentioned TMD fragmentation functions, nuclear TMDs

Summary for quark TMD PDFs



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

Good knowledge of the x-dependence of f_1 and g_1

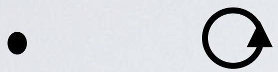
Good knowledge of the k_T-dependence of f_1 (also for pions)

Fair knowledge of $f_{1T}^\perp$ and h_1 (mainly, x-dependence)

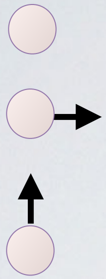
Some hints about the others

Summary for gluon TMD PDFs

polarization gluon



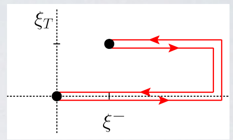
nucleon



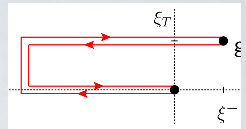
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1^g	✘	$h_1^{\perp,g}$
	L	✘	g_1^g	$h_{1L}^{\perp,g}$
	T	$f_{1T}^{\perp,g}$	g_{1T}^g	$h_1^g\,,h_{1T}^{\perp,g}$

for each entry:

WW-type

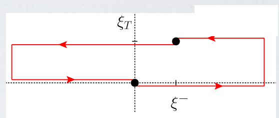


[+,+]

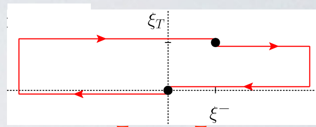


[-,-]

dipole-type



[+,-]



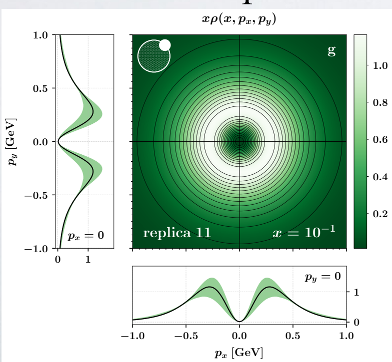
[-,+]

first extraction of $f_1^g(x,k_T)$

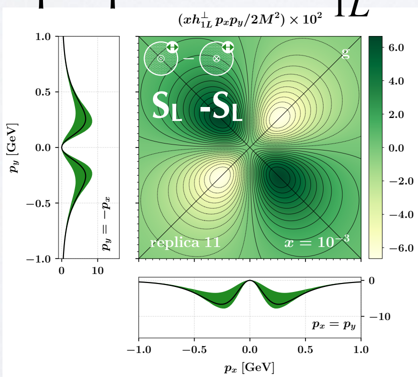
Boer, talk at IWHSS 2020
Boer et al., arXiv:2409.03691

use model guidance
spectator model for all { T-even *Bacchetta et al., arXiv:2005.02288*
T-odd *Bacchetta et al., arXiv:2402.17556*

xf_1^g



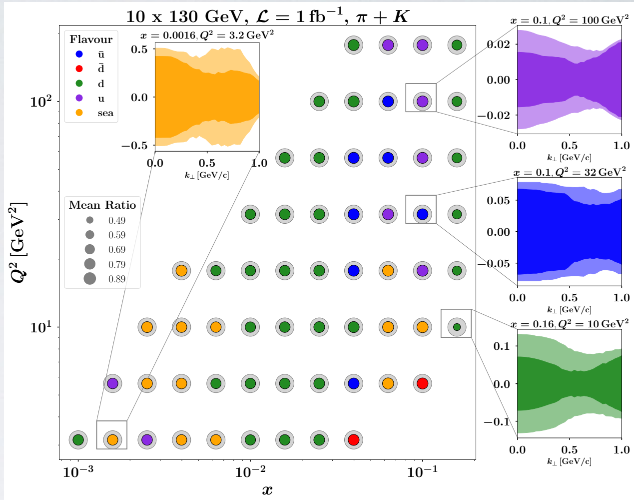
"propeller" $xh_{1L}^{\perp g}$



Complementarity of various colliders

$f_1^{g\,[+,+]}$	$pp \to \gamma\, J/\psi\, X$	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

Conclusions



quark TMD in the proton

significant impact of EIC, already in early years, for both spin-averaged and transversely polarized observables

quark TMD in pion & gluon TMD

phenomenology just started

interesting new opportunities from new collider observables (hadron-in-jet, EEC)

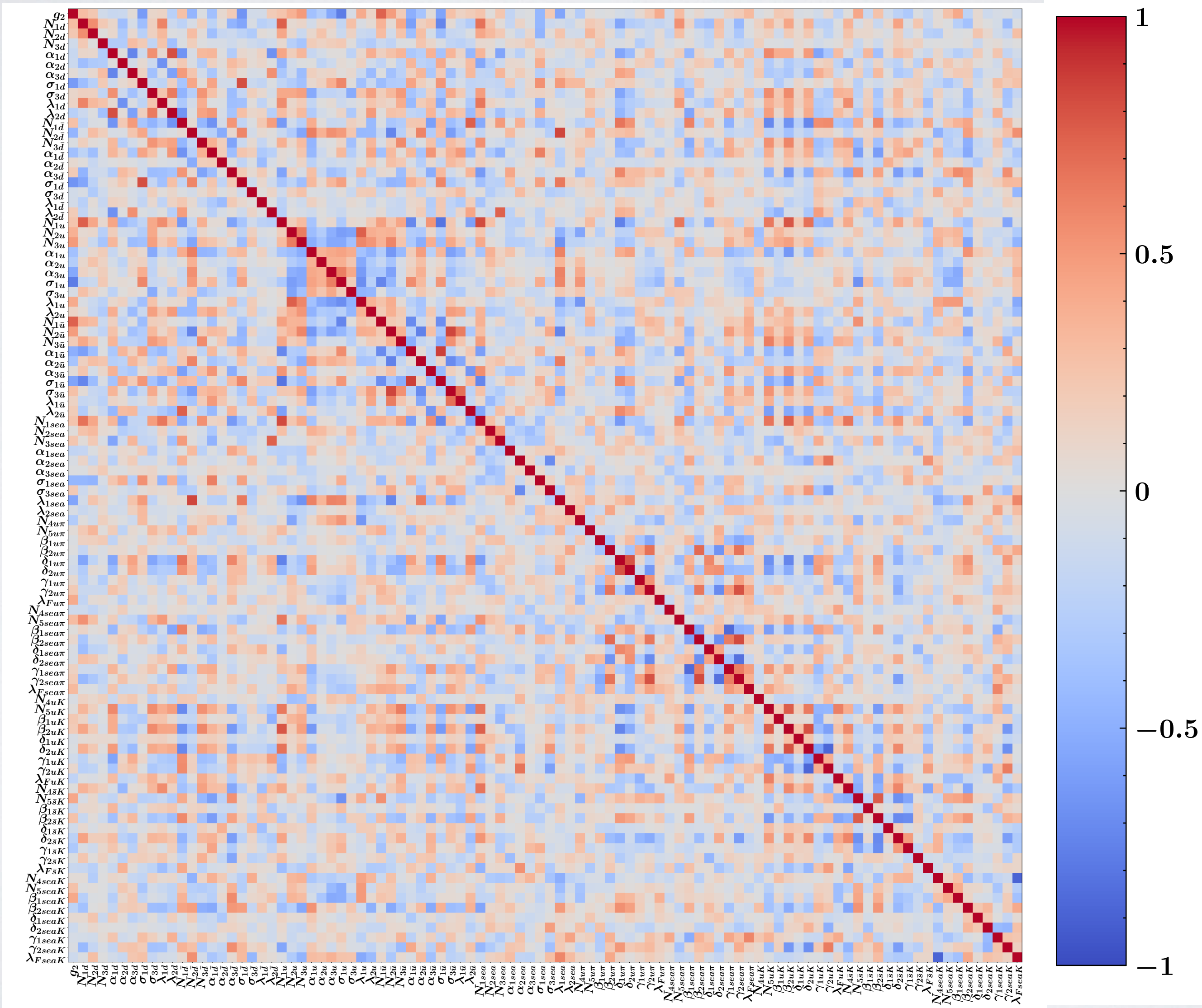
guidance from models where phenomenology is missing (particularly, for gluons)

Backup

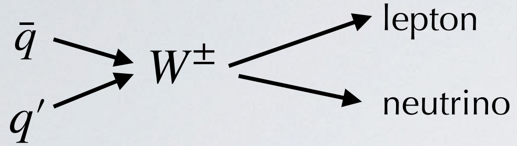
correlation matrix

Bacchetta et al. (MAP), JHEP **08** (24) 232, arXiv:2405.13833

MAPTMD24 total of 96 parameters



Potential impact on W mass



intrinsic $k_\perp$ + resummation $\rightarrow q_{TW} \rightarrow p_{T\ell}$

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

$u\bar{d}$ $\rightarrow$ W^+ main channel

but all analyses assume flavor-independent intrinsic $k_\perp$ distribution

Procedure

- take the DYTURBO code, **introduce sets of flavor dep. parameters** in nonpert. part and generate **p_T^Z spectra** compatible with exp. spectrum including ATLAS and CMS errors (χ^2/d.o.f. < 1.3)
- with these **"Z-equivalent" sets**, generate **pseudodata** for lepton p_T distribution at **M_W^0**
- with **flavor-indep. nonpert. part**, generate **30 template** lepton p_T distributions with M_W in **M_W^0 ± 0.015** GeV
- perform **template fits** for each pseudodata

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

Finding: $-6 \leq \Delta M_{W^+} \leq 9 \quad -4 \leq \Delta M_{W^-} \leq 3$ MeV and $\Delta M_{W^+} \neq \Delta M_{W^-}$

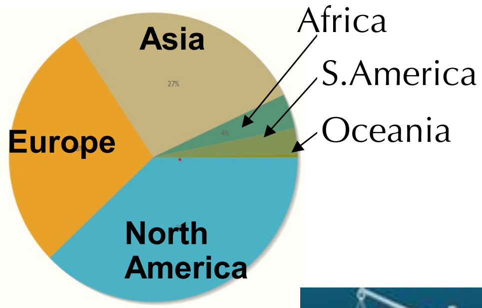
In progress: repeat the analysis with MAPTMD24 at N³LL

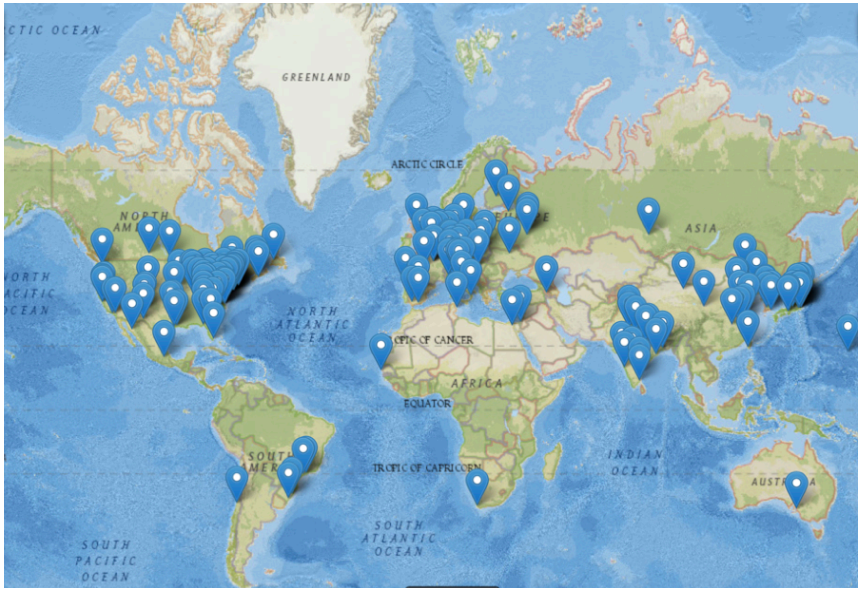
Snapshot of the EIC and ePIC

EIC Users Group

41 countries
310 Institutions
1557 members

as of June 1st, 2026

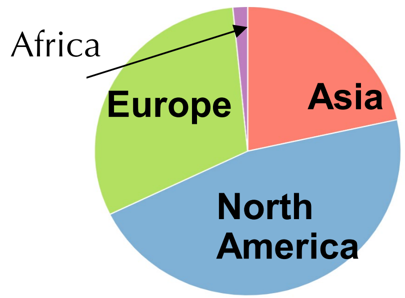




ePIC Collaboration

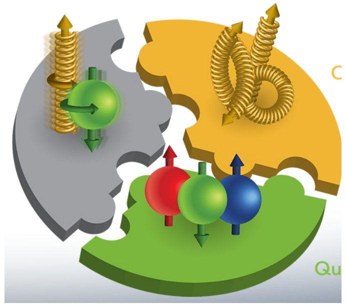
25 countries
183 Institutions
1158 members

as of June 1st, 2026



The NAS Science Pillars

origin of N mass

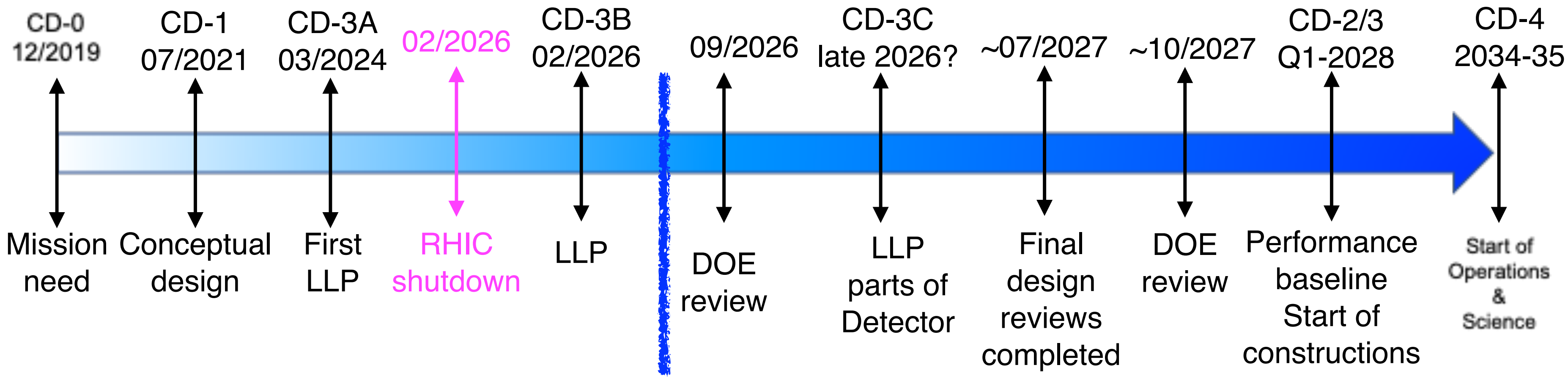


origin of N spin

dense gluonic matter saturation?

Electron-Ion Collider

The current EIC Project timeline



Current design maturity > 75%

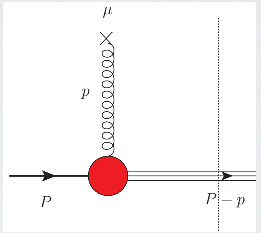
9-12 Mar 2026: EIC Project Director's Review (summary):

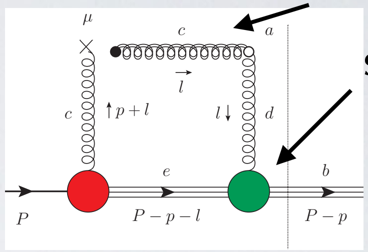
- The EIC Project has made strong technical progress and demonstrates the capability to deliver the facility.
- The primary challenge is no longer technical feasibility, but:
- Establishing a credible, fully integrated baseline and aligning scope, cost, schedule, and risk management to meet the $3B cap while preserving mission need.
- Current estimates exceed the $3B cap; systematic cost reductions tied to a defensible baseline are required.

Electron-Ion Collider

spectator model of gluon TMDs

- Nucleon = gluon + spectator on-shell spin-1/2 particle; vertex contains a Gordon-like propagator with parametric dipolar couplings





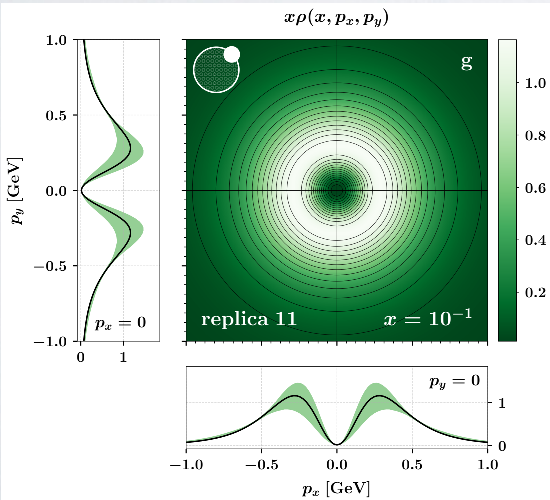
eikonal approx.

same structure as 🔴 but with f-type and d-type color structures

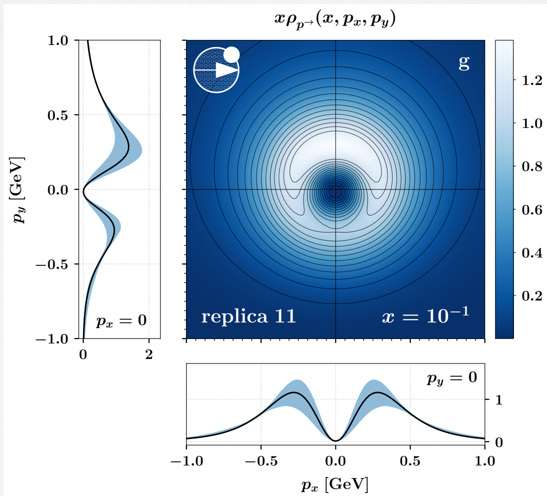
- T-odd generated by gluon-spectator FSI via 1 gluon-exchange; WW-type $\rightarrow f^{bde}$, dipole $\rightarrow d^{bde}$
- Spectator mass takes continuous range of values through a parametric spectral function
- Parameters (9) fixed by reproducing collinear gluon PDFs f_1 and g_1 from NNPDF3.0

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*

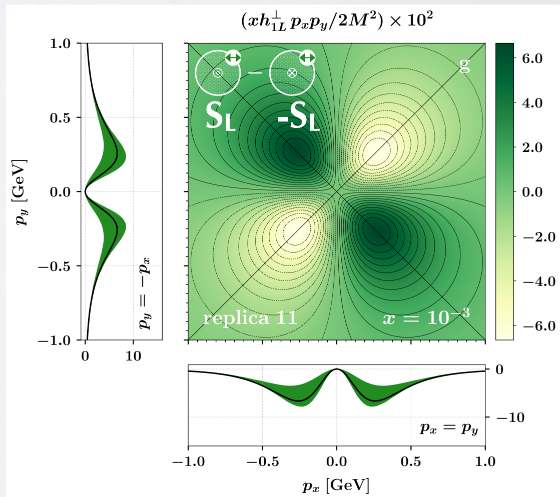
xf_1^g



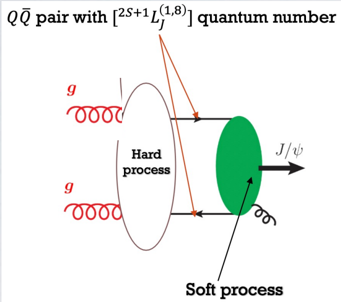
$xf_1^g + (p_y/M)\, xf_{1T}^{\perp g}$



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



gluon TMDs



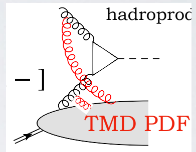
g-g fusion

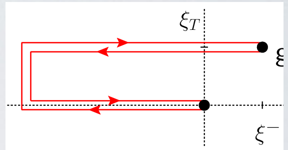
J/ψ, Υ production $\quad q_T^{Q\bar{Q}} \ll M_{Q\bar{Q}}$ TMD factorization

$$d\sigma \sim \sum_n (\alpha_s)^n H^n \; [\text{gTMD} \otimes \text{gTMD} \otimes \text{TMDShF}]$$

hard $ab \to c\bar{c}[n]$

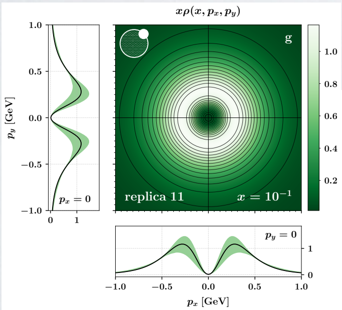
WW-type
gluon TMD



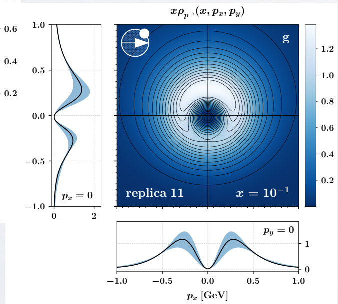


fit data (~100 pts, mostly RHIC) with some parametrization,
maybe inspired by model calculations

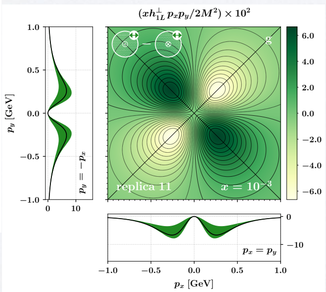
xf_1^g



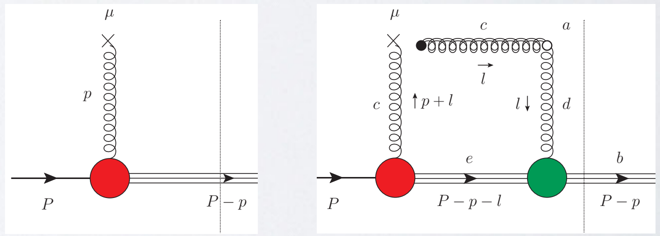
$xf_1^g + (p_y/M)\, xf_{1T}^{\perp g}$



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



spectator model predictions



- generate T-odd with 1gluon - exchange
- spectral mass function for spectator
- parameters fixed to collinear gluon PDF

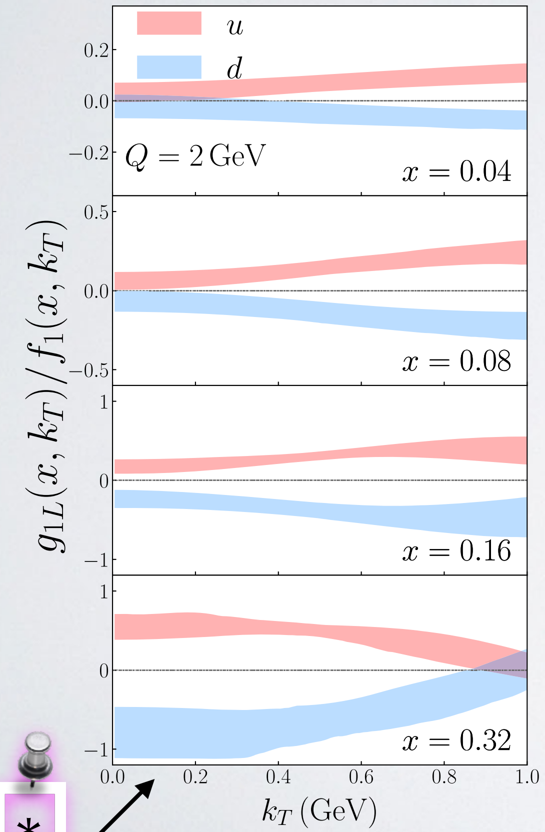
*Bacchetta et al., E.P.J.C **80** (20) 733, arXiv:2005.02288*
*E.P.J.C **84** (24) 576, arXiv:2402.17556*

	Accuracy	SIDIS	Drell-Yan	N of points	χ²/N	Flavor dep.
MAPTMD22pol Bacchetta et al. (MAP) P.R.L. **134** (25) 121901	NNLL	✔	✘	291	1.09	✘
YLSZM Yang et al. (TNT) P.R.L. **134** (25) 121902	NNLL	✔	✘	253	0.74	✘

← enforced $|g_1| \leq f_1$ *

accuracy limited by gluon Wilson coeffs.

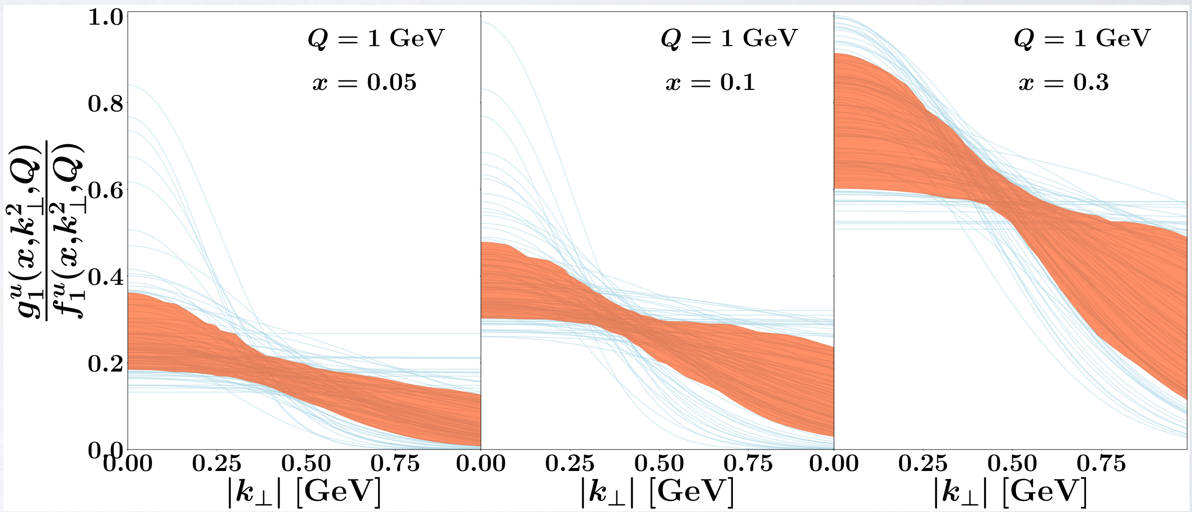
data from SIDIS DSA A_1



*

YLSZM

Yang et al.,
P.R.L. **134** (25) 121902

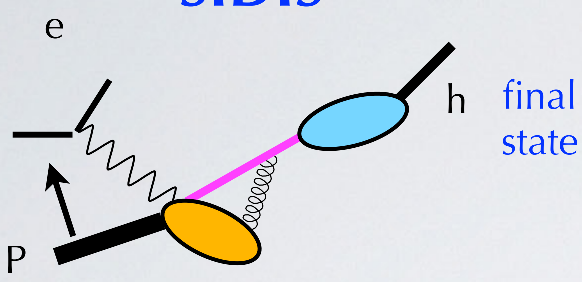


MAPTMD22pol

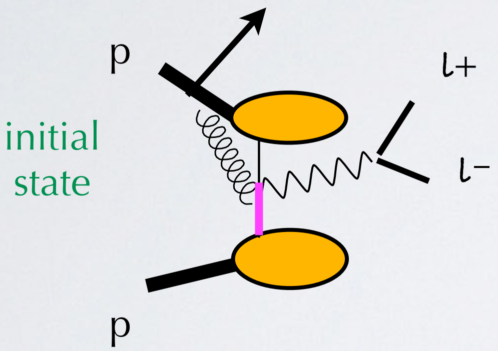
Bacchetta et al. (MAP),
P.R.L. **134** (25) 121901

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**

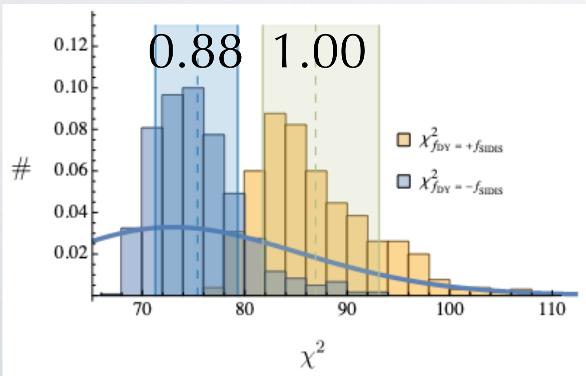


Drell-Yan

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:

$$f_{1T}^{\perp}|_{\text{SIDIS}} = - f_{1T}^{\perp}|_{\text{Drell-Yan}}$$



Bury et al.,
arXiv:2012.05135
2103.03270

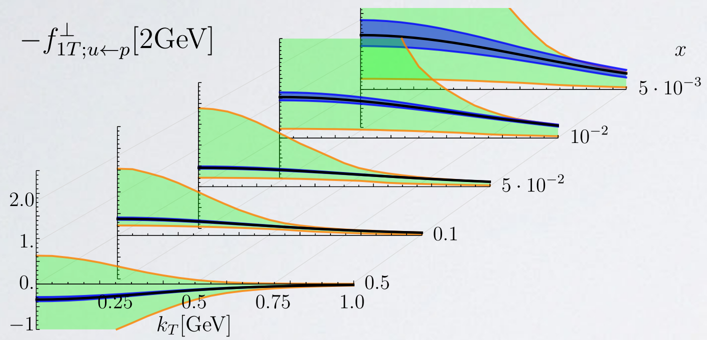
current statistical precision of exp. data is not enough to confirm the sign change

Sivers effect at the EIC

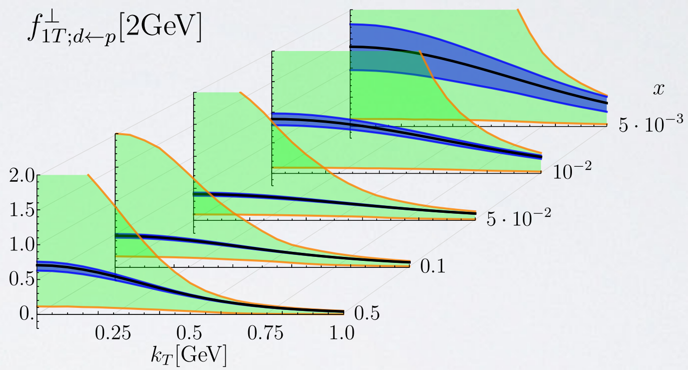
Abdul Khalek *et al.* (EIC Yellow Report),
N.P. **A1026** (22) 122447, arXiv:2103.05419

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

- up



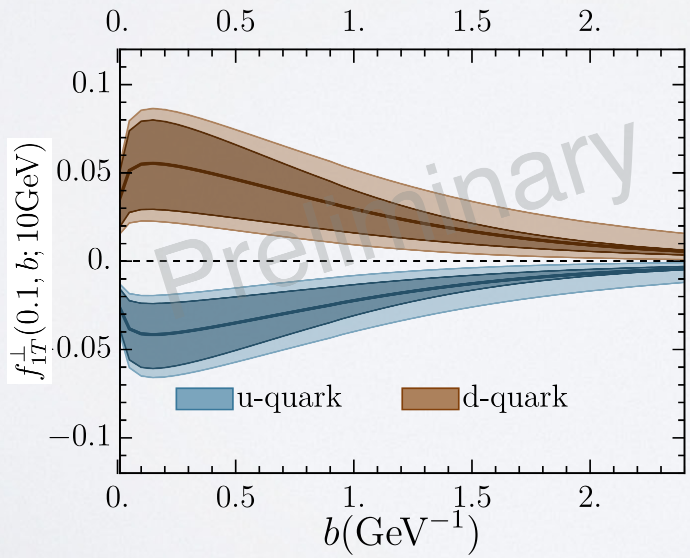
down



BPV 2020

+ EIC
5×41 GeV
18×275

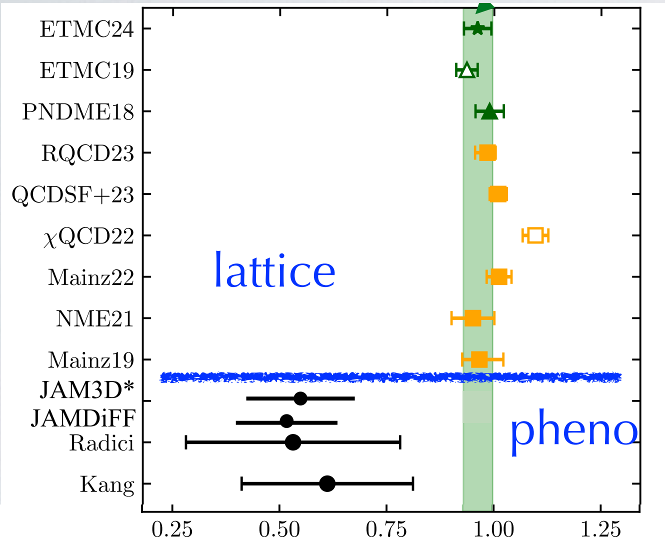
$\mathcal{L}$=1 fb^{-1}



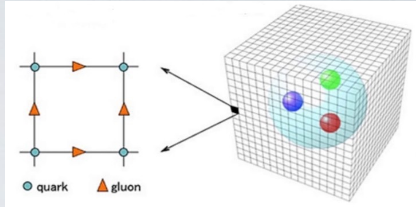
x=0.1

Pheno - lattice : tensor charge

$g_T = \delta u - \delta d$



adapted from C. Alexandrou, QCD Evolution 24



green N_f=2+1+1

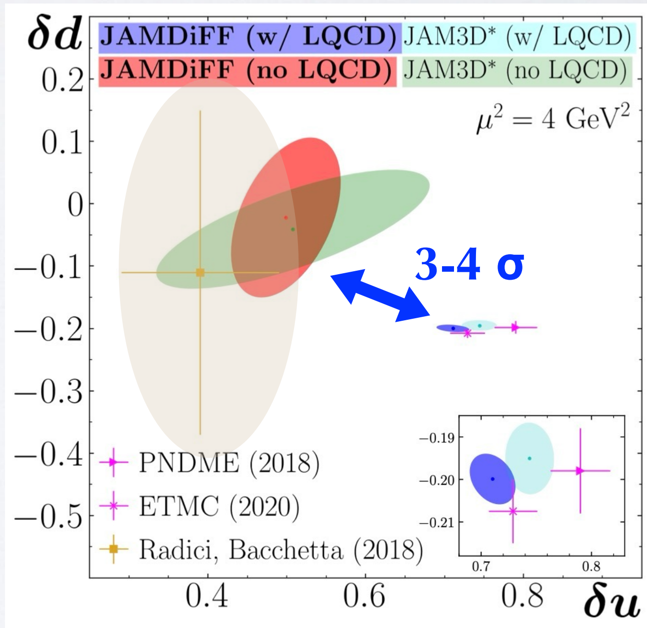
open symbols = no continuum extrapolation

yellow N_f=2+1

tension between pheno and lattice ?

JAM claim:
including lattice points,
restore compatibility

but still under discussion…



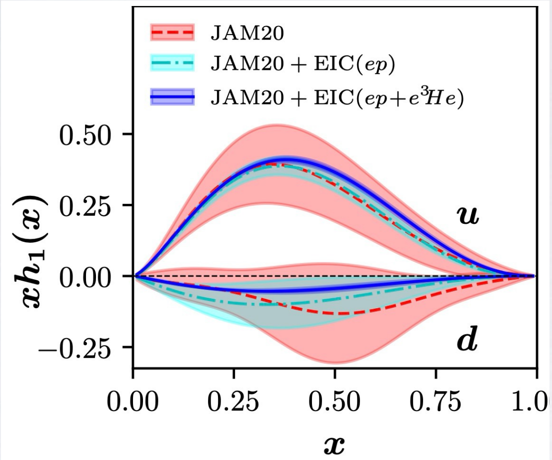
adapted from D. Pitonyak, QCD Evolution 24

Transversity at the EIC

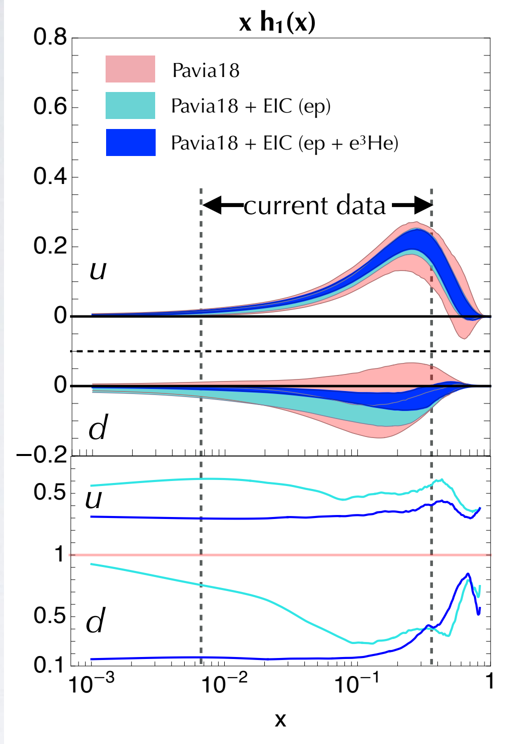
EIC

Abdul Khalek et al. (EIC Yellow Report), arXiv:2103.05419

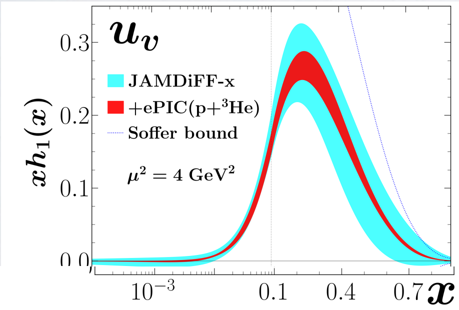
Collins effect

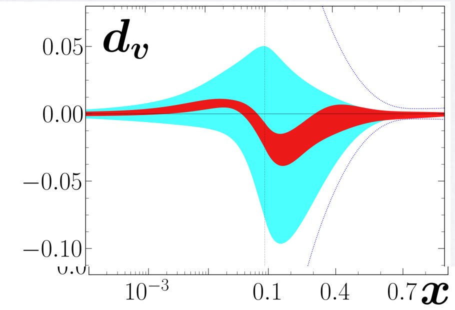


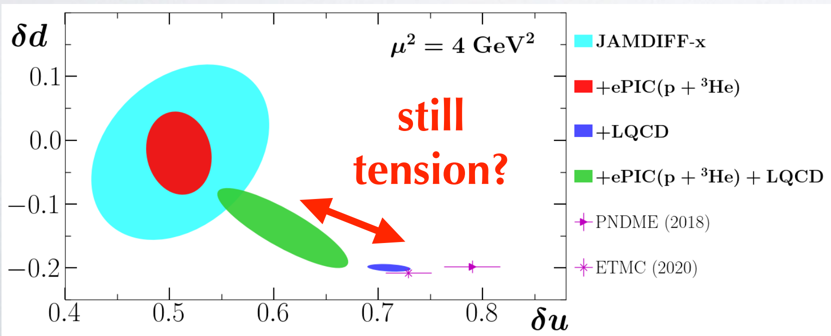
dihadron mechanism



dihadron mechanism ePIC 10x100 GeV 10 fb^{-1}





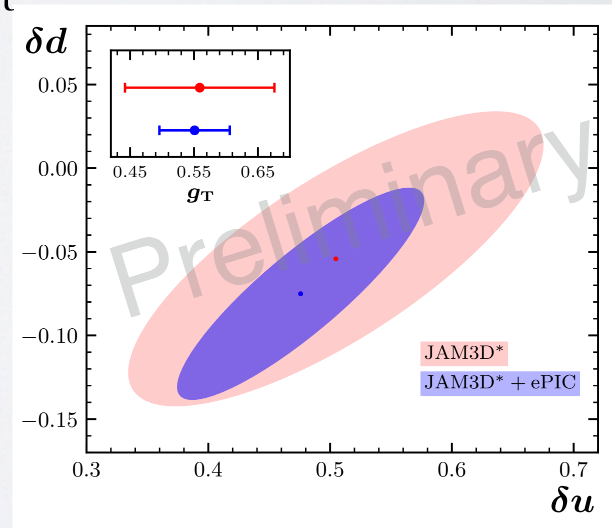


JAMDiFF, arXiv:2606.00362

Collins effect

e-p
10x130 GeV
1.25 fb^{-1}

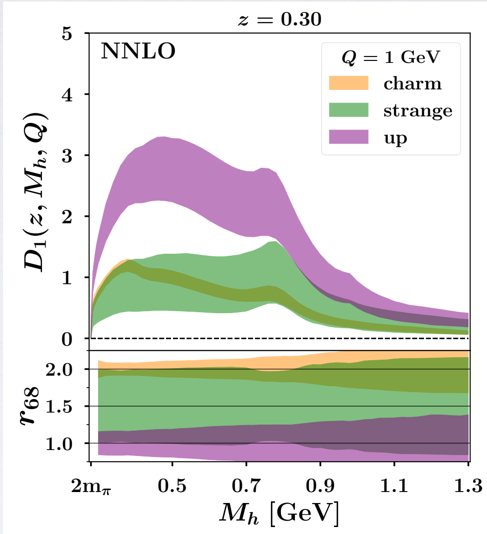
e-^{3}He
10x166 GeV
0.75 fb^{-1}

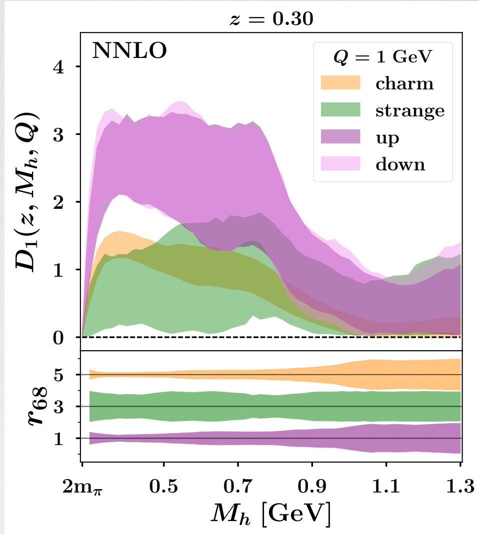


polarized DiFFs

<u>PVDiFF25:</u>
extract unpol. quark DiFF D_1 up to NNLO from Belle data + PYTHIA flavor-tagged e+e- cross section

*Mahaut et al. (MAP), JHEP**02** (26) 051 arXiv:2509.11855*





fixed parametrization

Neural Network

Work in progress to extend to polarized quark DiFF $H_1^{\sphericalangle}$

Problem with gluon DiFF D_1 basically unconstrained

Need di-hadron multiplicities from hadron collisions (RHIC) and SIDIS