



16th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei

Pre Conference Workshops: 26 & 27 October 2025
Conference: 27 October – 1 November 2025

Theoretical Perspectives on Electromagnetic Hadronic Physics



Marco Radici

Congratulations for
the 30th anniversary
of EINN



I was there in the early editions (Santorini 1995, 1997; 2003)
and in the 7th (2009) in Milos...

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Adamas (Milos)



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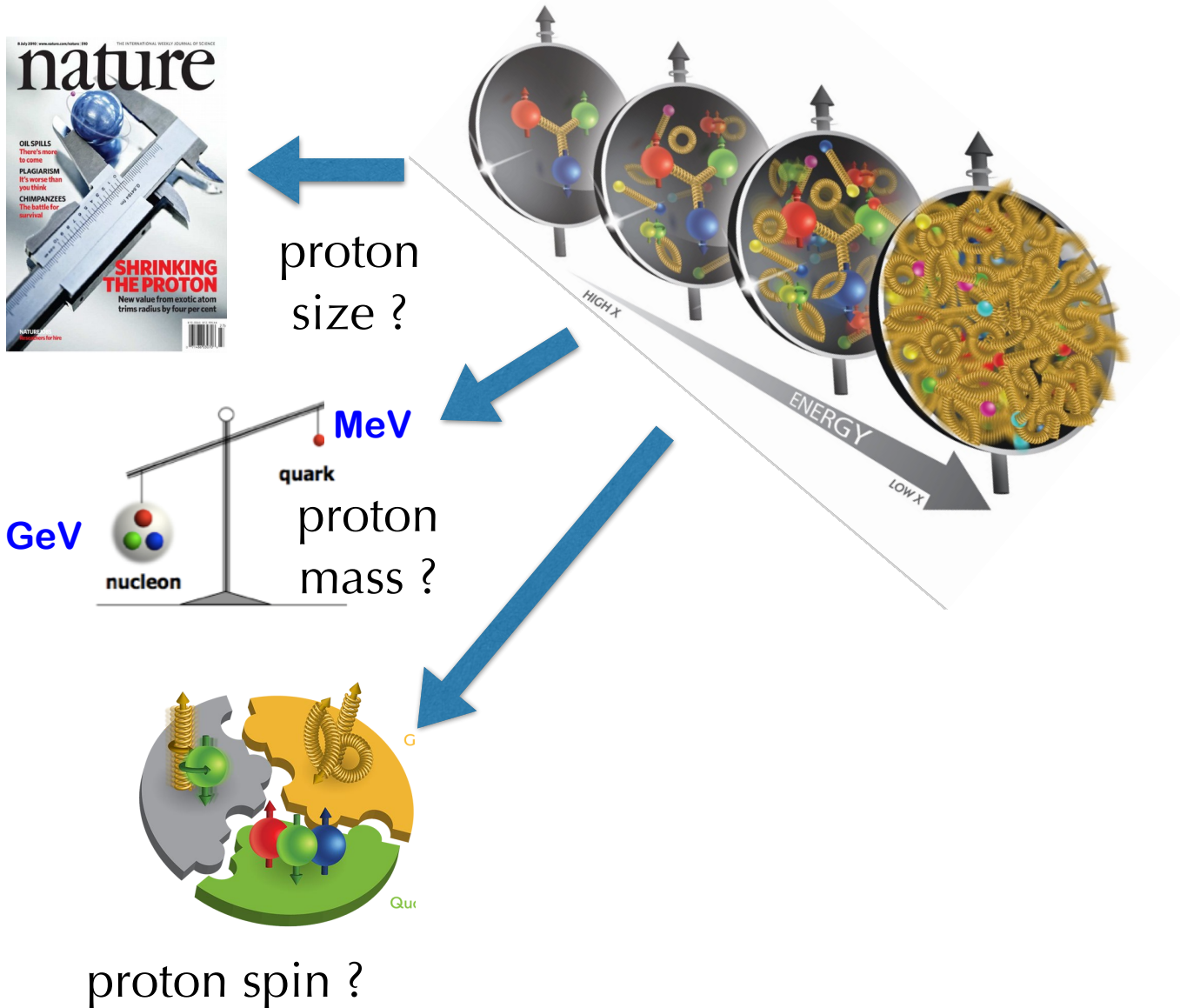


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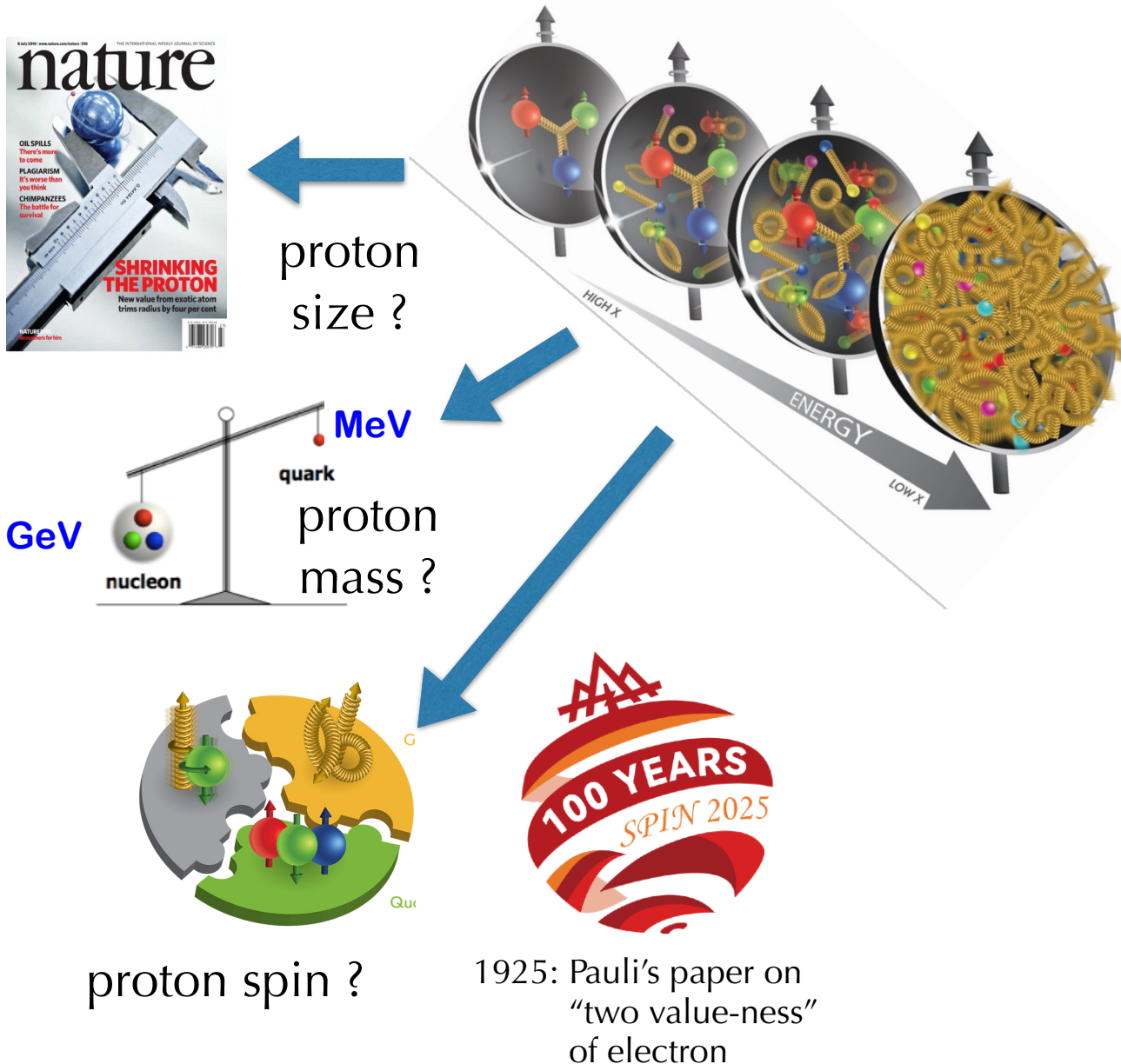
Adamas (Milos)



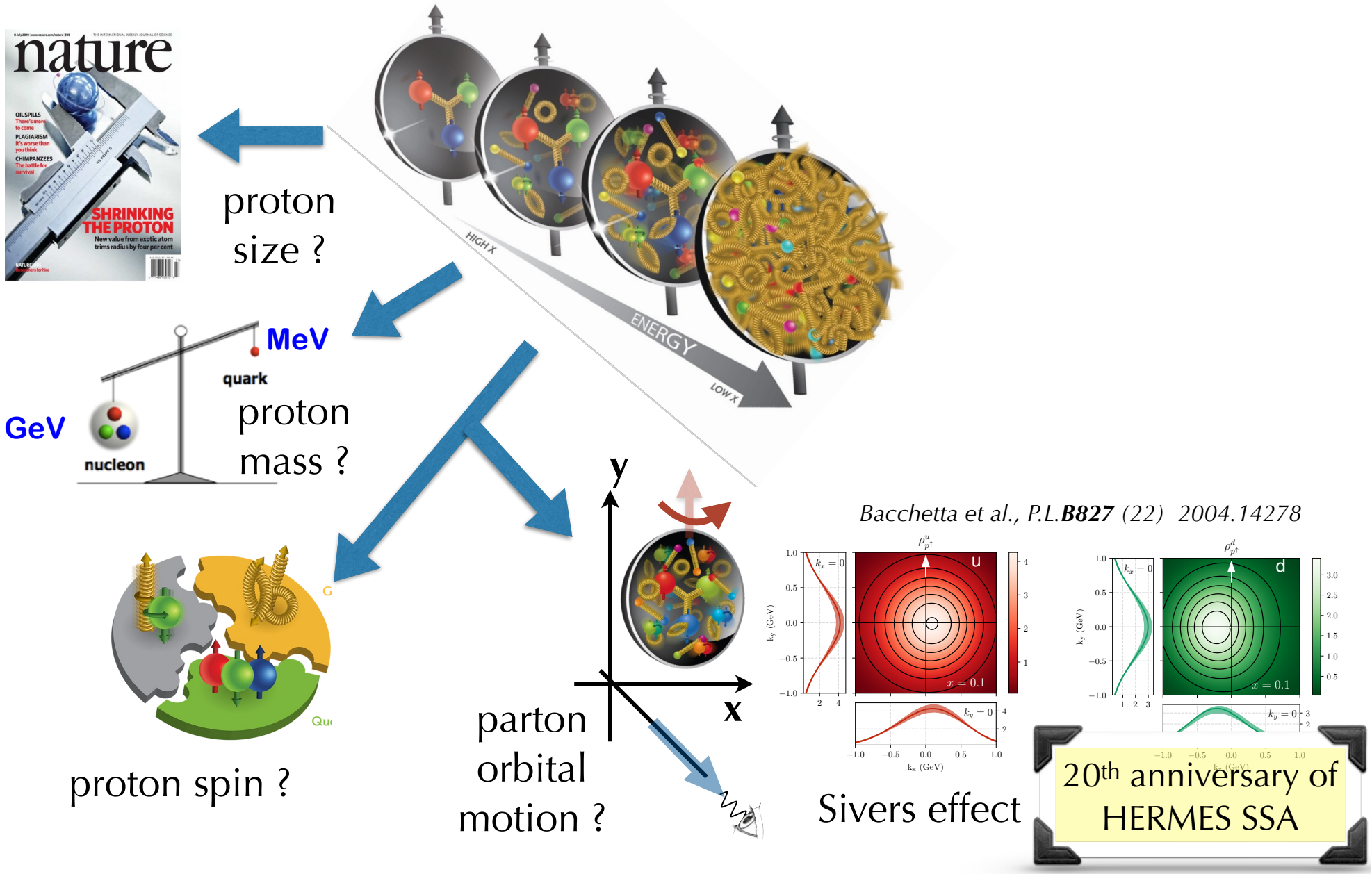
Proton: the proto(n)-type of all nuclei the simplest one, still many (important) open questions



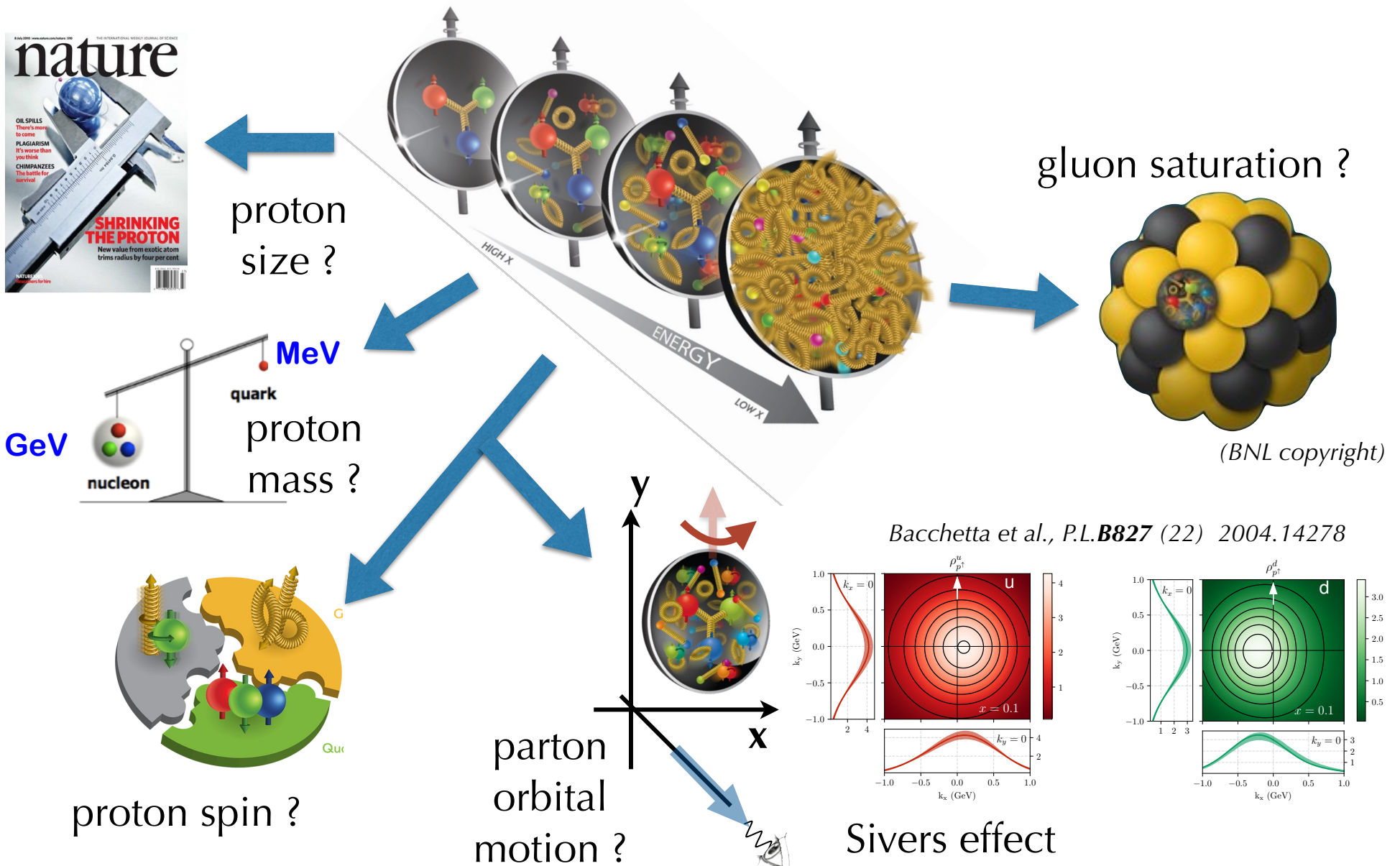
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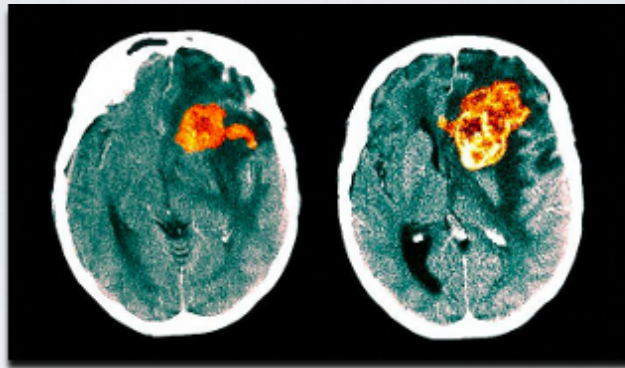


Seeing is believing - the power of imaging

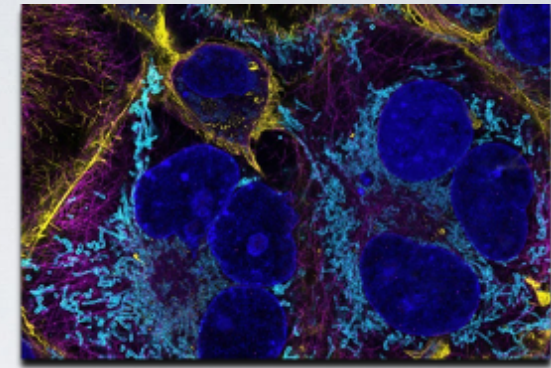
courtesy Kong Tu (BNL)



black hole
(Event Horizon telescope)



CT scan sequence of brain
with glioblastoma



3D image of myelin
(coating of nerve fibres)

10^{12} m

10^{-2} m

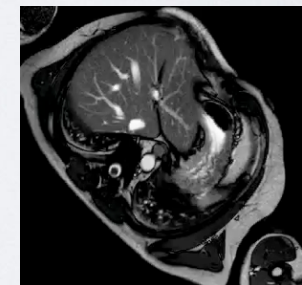
10^{-9} m

**Imaging: a powerful scientific method to understand Nature from
astronomical to microscopic scale**

**Muldi-dim. imaging:
fundamental to enhance
this power !**



1D ECG



3D cardio MR

(incomplete) list of EINN25 topics

muon g-2

dispersion relations

chiral EFT and nuclear structure

spectroscopy: hybrids, glueballs,
charmonium-like states..

GlueX

e.m. and weak N form factors

BESIII

low-energy dark sector

JLab

proton (charge) radius

MESA

TMD

GPD

BSM

EIC (and ePIC)

Cold & Hot QCD

strange sector and EoS of neutron stars

N e.m. polarizabilities

2N- & 3N-correlations



lattice

(incomplete) list of EINN25 topics

muon $g-2$

dispersion relations



No time to touch all theory topics of the conference.
Apologies for those that will not be mentioned.

In this talk, main focus on tools for imaging:
“(femto-)tomography” of the Nucleon
(with specific reference to very recent results,
typically $> 2024..$)

TMD

GPD

EIC (and ePIC)

BSM

Cold & Hot QCD

strange sector and EoS of neutron stars

N e.m. polarizabilities

2N- & 3N-correlations

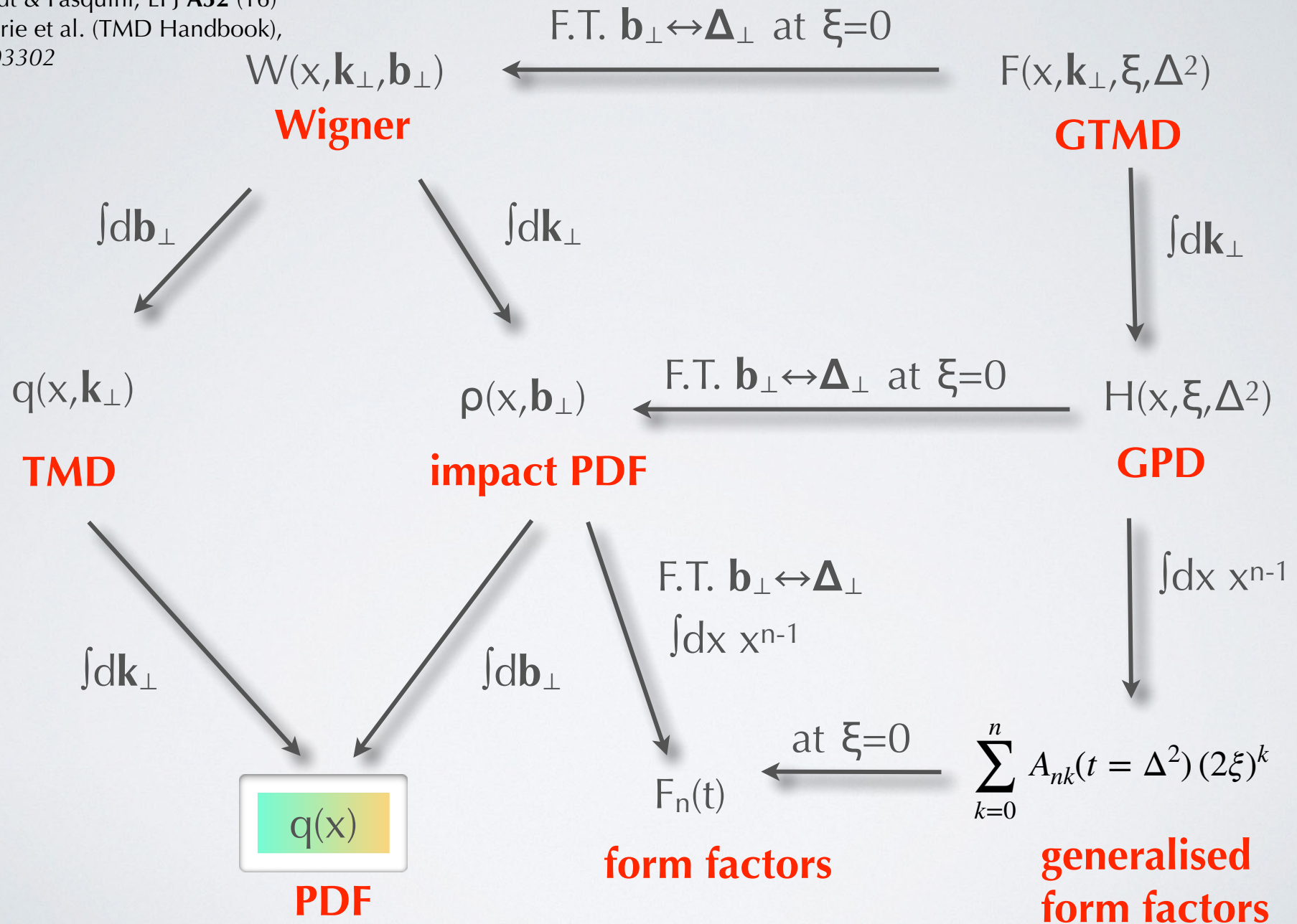
Nucleon “femtography”

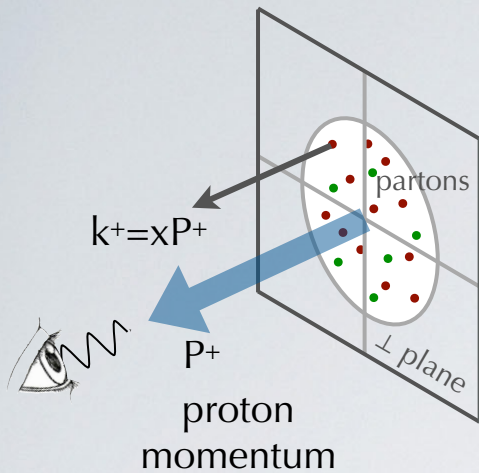
Multi-dim. maps of Nucleon structure

Lorcé et al., JHEP **05** (11)

Burkardt & Pasquini, EPJ **A52** (16)

Boussarie et al. (TMD Handbook),
2304.03302

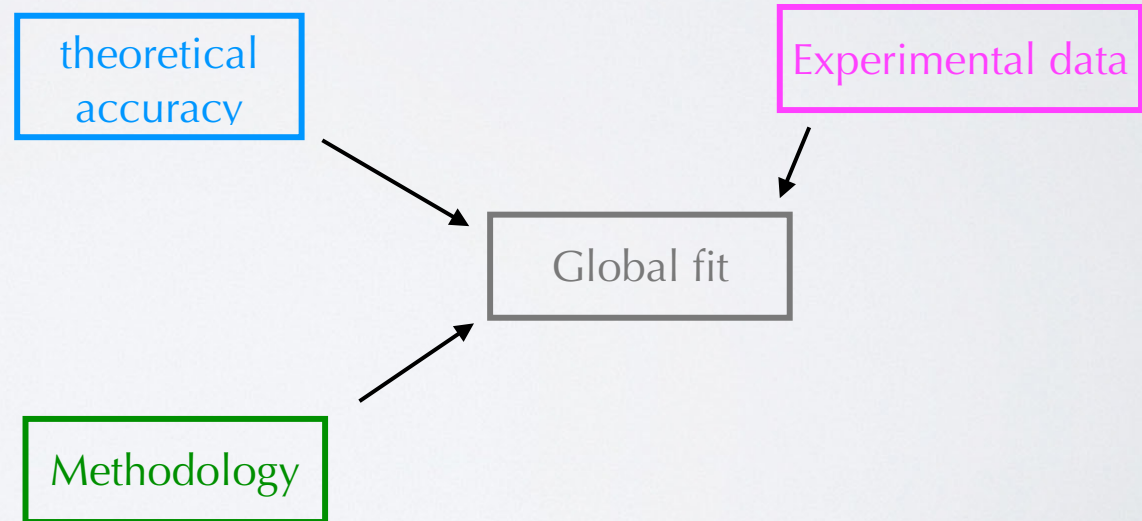




PDF: Parton Distribution Functions (1D mapping)

Ongoing major effort in **increasing precision** and **estimate uncertainties**, demanded by reproducing new data (primarily, LHC)

reducing the uncertainty
depends on the accuracy of
all ingredients entering a
global fit

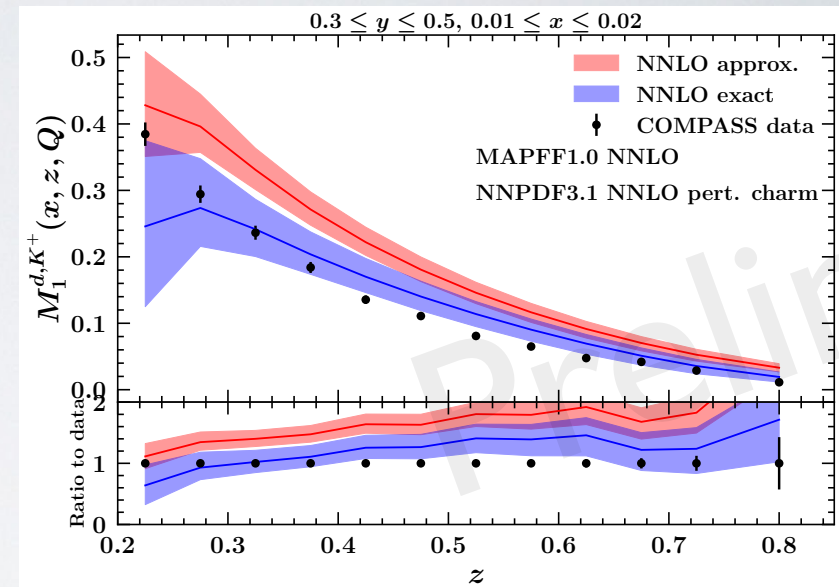


theoretical
accuracy

Exact NNLO corrections for
unpolarized SIDIS
long. polarized SIDIS
NC-, CC-unpolarized SIDIS

Significant impact on NNLO FFs

Goyal et al., 2312.17711; Bonino et al., 2401.16281
Bonino et al., 2404.08597; Goyal et al., 2404.09959
Bonino et al., 2506.19926



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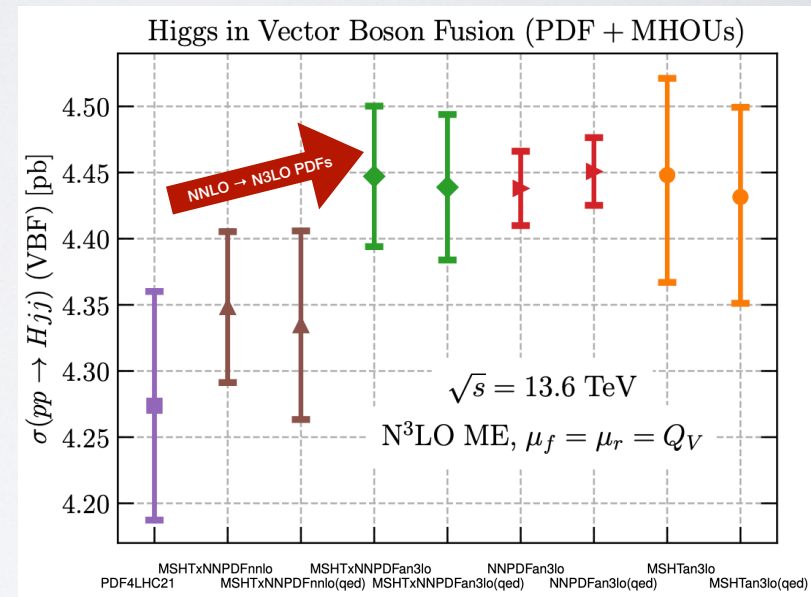
Goyal et al., 2312.17711; Bonino et al., 2401.16281
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Significant impact on NNLO FFs

approximate N³LO (aN³LO) PDF sets for unpolarized PDFs in inclusive processes

MSHT 2207.04739 NNPDF 2402.18635

NNLO → aN³LO
unexpected significant shift



Cridge et al., 2411.05373

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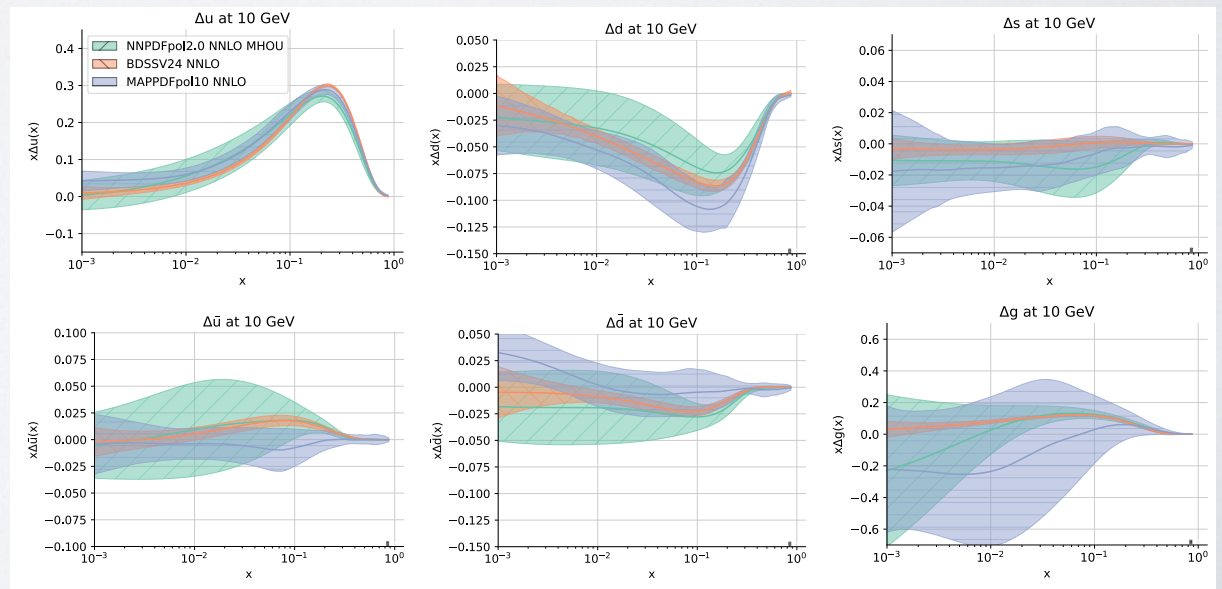
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Polarized PDFs at NNLO: good agreement among different groups

Nocera @SPIN 2025



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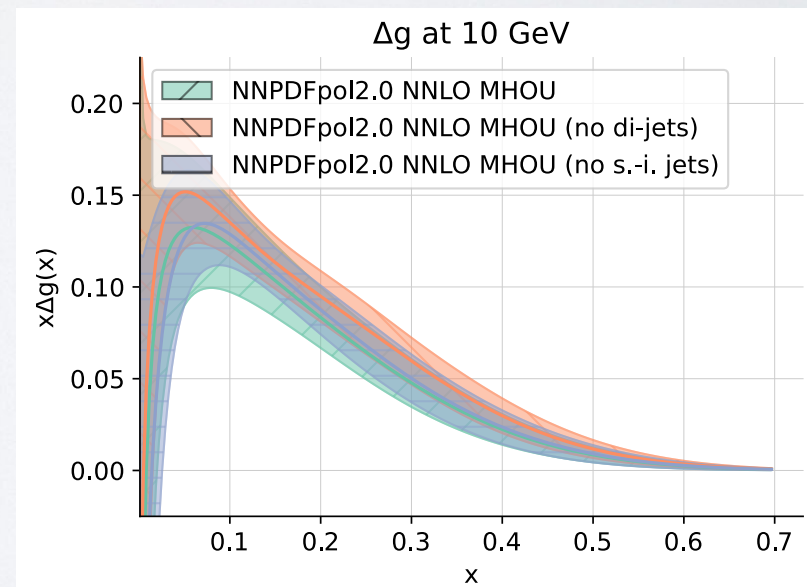
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Polarized PDFs at NNLO: good agreement among different groups

Hight-pT jet data confirm $\Delta g > 0$ in the proton

Nocera @SPIN 2025



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Hight-pT jet data confirm $\Delta g > 0$ in the proton

See also recent extraction at NLO from polarized DIS+SIDIS+pp

Cocuzza et al. (JAM), 2506.13616

Methodology

Parametrization: reduce th. bias by replacing standard Mellin-transformable expressions with **Neural Networks** (NN)

NN can have $O(\sim 100)$ parameters $\rightarrow$ need M.L.-inspired techniques to find minimum χ^2

NN flexibility $\rightarrow$ risk of overfitting $\rightarrow$ **cross-validation tests**

Closure tests: statistical validation of methodology and PDF faithfulness
(generate pseudodata from known model and try to fit it)

Generalization tests: how well do PDF sets describe new data not included in the fit?

need exact NNLO predictions
(PineAPPLE, NNLOJET,..)

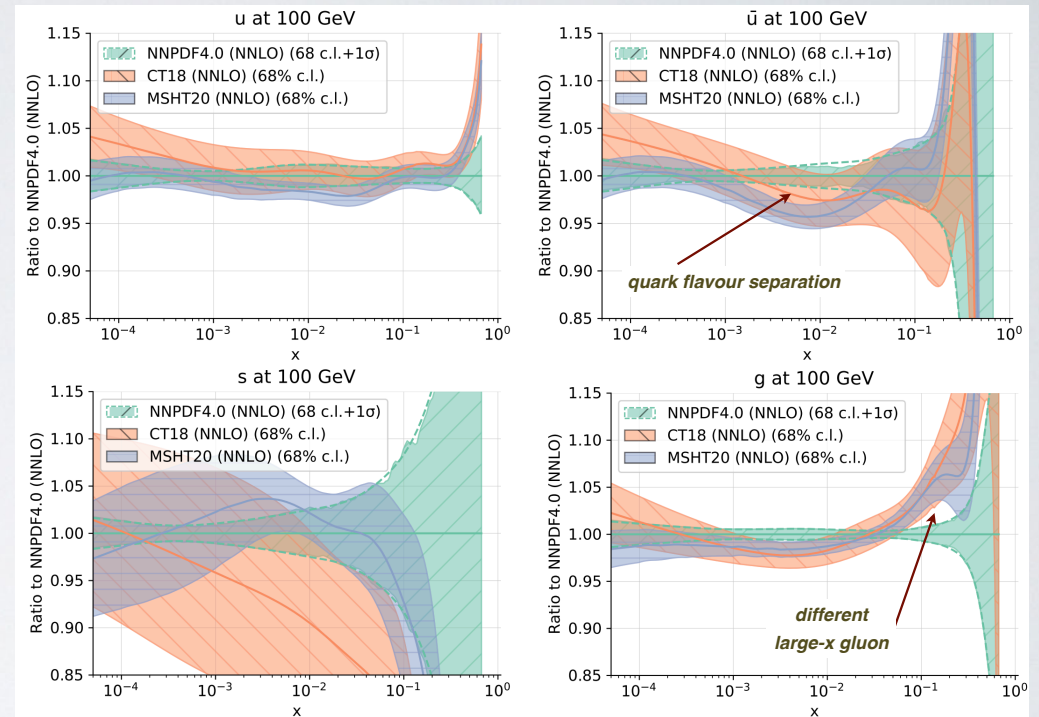
need to include in χ^2 all exp. and th. uncertainties:

bin-by-bin correlations, MHO, α_s , PDF, QED corrections,..

Open Issues with PDF

Uncertainties at large x in unpolarized PDFs (for strangeness, over all x 's..)

impacts BSM searches at LHC $x \sim \frac{M_X}{\sqrt{s}}$

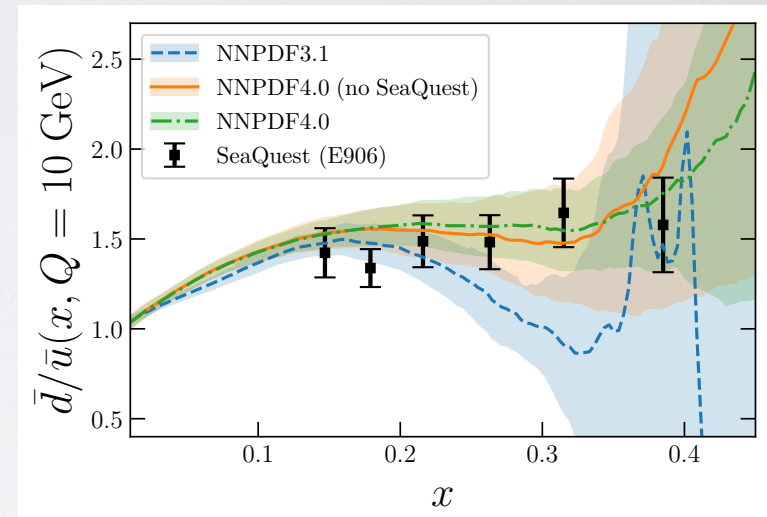


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impacts antimatter asymmetry explorations (SeaQuest) $\bar{d}(x)/\bar{u}(x) \xrightarrow{x \rightarrow 1} ?$



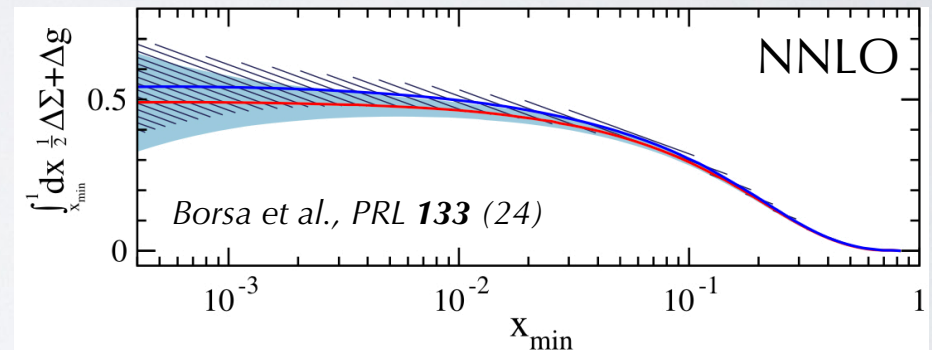
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polarized PDFs: small- x singlet helicity $\Delta\Sigma$ and Δg , is there room for OAM?



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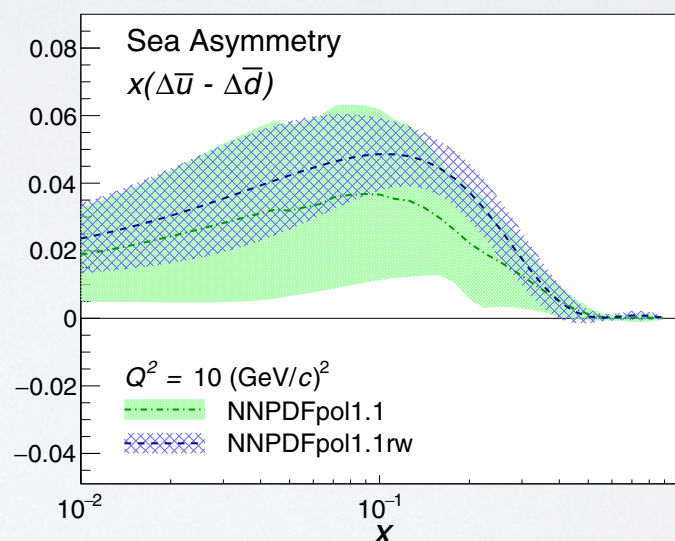
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polarized PDFs: small- x singlet helicity $\Delta\Sigma$ and Δg , is there room for OAM?

antimatter helicity asymmetry ?



Nocera, 1702.05077

Open Issues with PDF

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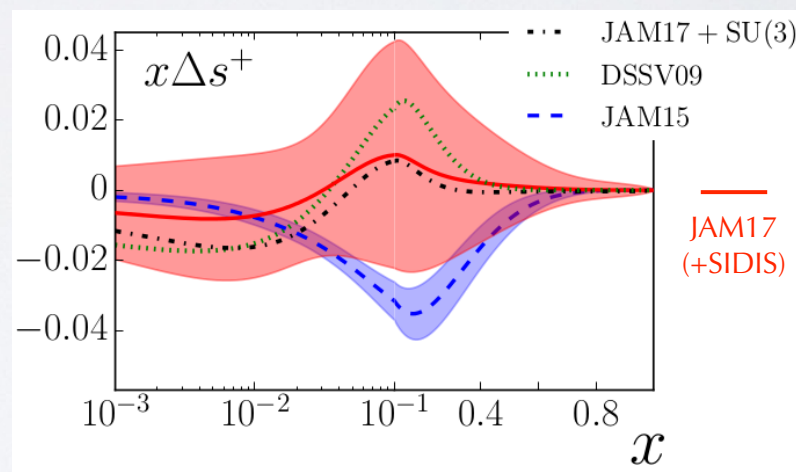
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strange helicity?



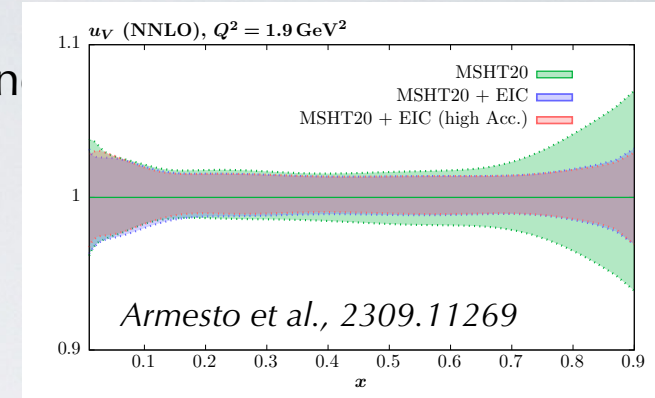
JAM, 1705.05889

Expected impact of the EIC

Uncertainties at large x in unpolarized PDFs (for strangeness)

impacts BSM searches at LHC $x \sim \frac{M_X}{\sqrt{s}}$

impacts antimatter asymmetry explorations (SeaQuest)

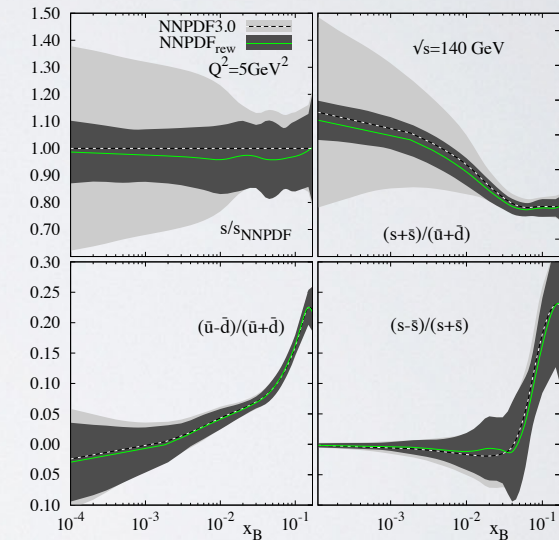


polarized PDFs: small- x singlet helicity $\Delta\Sigma$ and Δg , is there room for OAM?

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strange helicity?

large impact on strange
and sea-quark ratio R_s



EIC Yellow Report, 2103.05419

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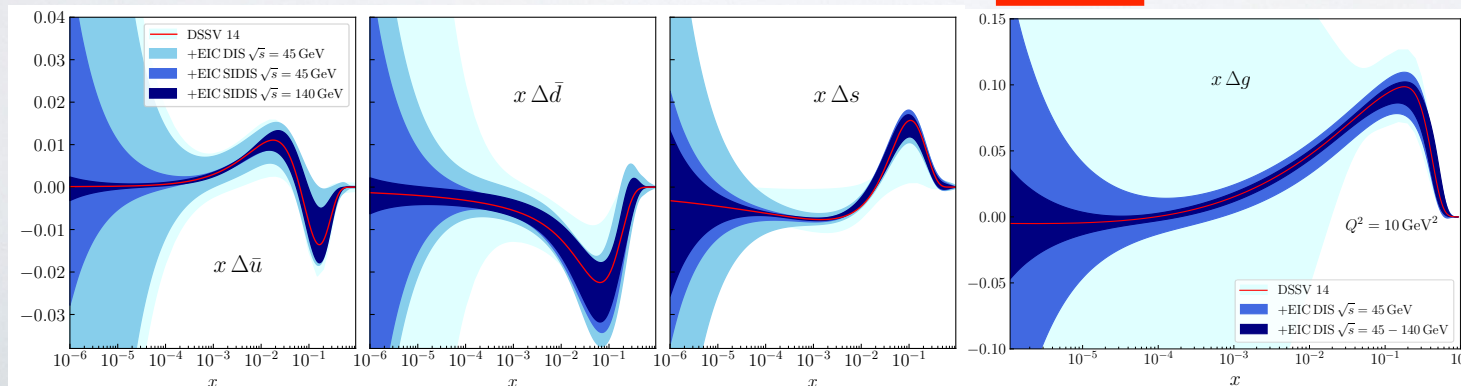
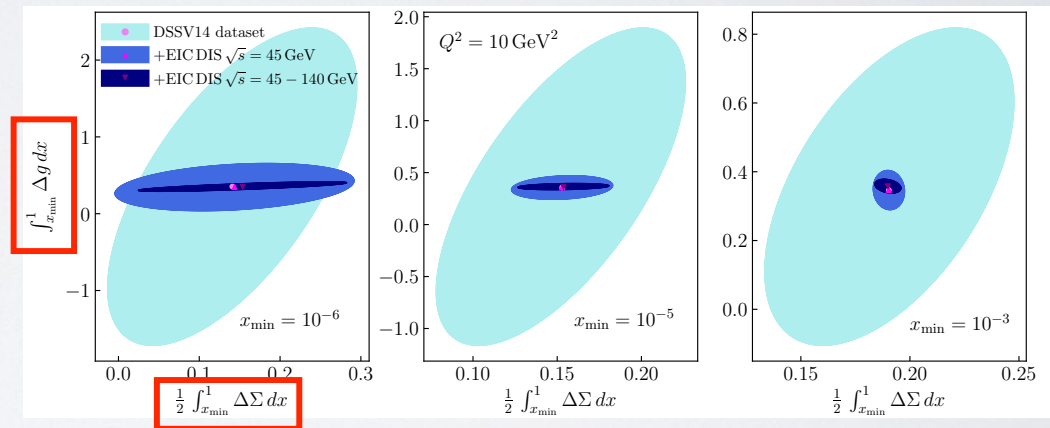
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polarized PDFs: small- x singlet helicity $\Delta\Sigma$ and Δg , is there room for OAM?

impact on helicity contribution
to spin sum rule



Borsa et al., 2007.08300

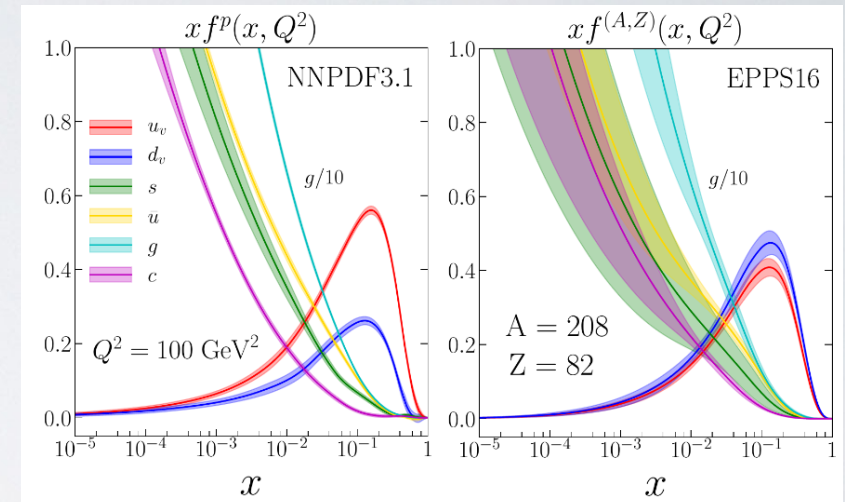
Nuclear PDFs (nPDFs)

data sets: LHC (Z, W, HQs, dijets, ALICE), RHIC, ν and NC DIS, pA and π A Drell-Yan

nPDF sets: KSAG20	NLO+NNLO	PRD 104 (21)
TUJU21	" "	PRD 105 (22)
EPPS21	NLO	EPJ C82 (22)
nNNPDF3.0	"	EPJ C82 (22)
nCTEQ15HQ	"	PRD 105 (22)

differ in datasets and fitting methodology

PDFs vs. nPDFs



Nocera @DIS 2025

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differ in datasets and
fitting methodology

$$R_q^A(x, Q^2) = f_{p/A}^q(x, Q^2) / f_p^q(x, Q^2)$$

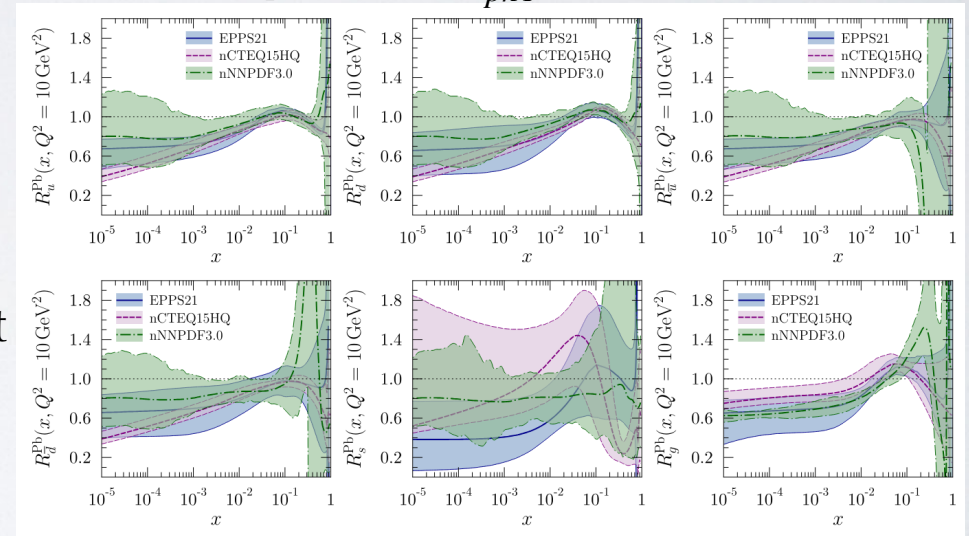
evidence of (anti-)shadowing in all partons

good agreement except strange EPPS21

impact of dijet data, particularly on gluon

potential impact of target mass corrections at
large x and small Q *Prog.Part.Nucl.Phys.* **136** (24)

impact of NNLO on gluon at x > 0.03



ongoing work on integrated QCD fit of PDFs and nPDFs

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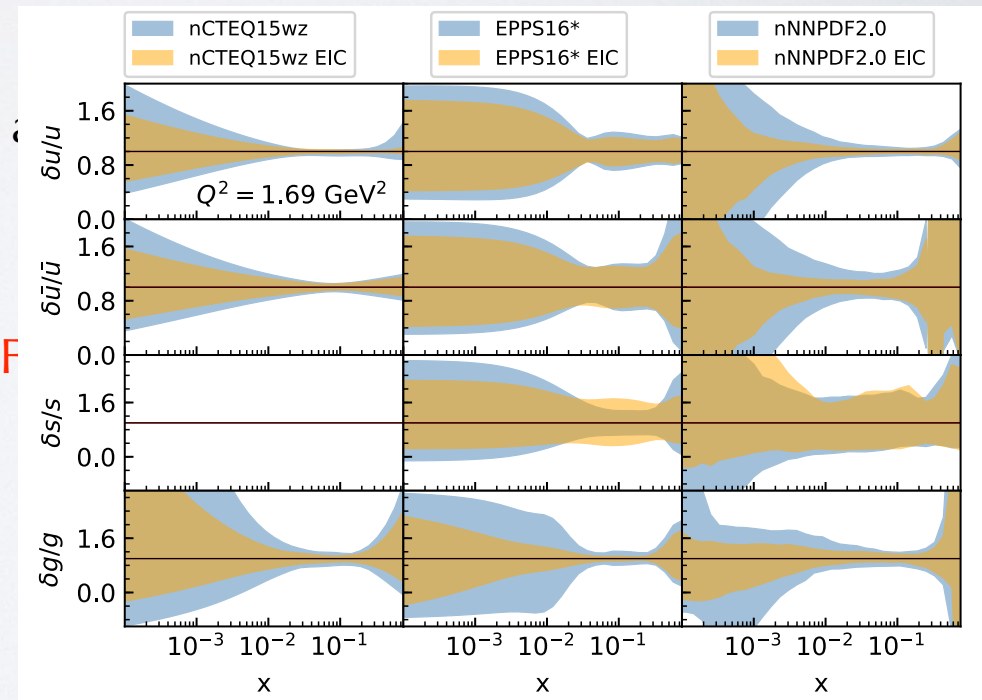
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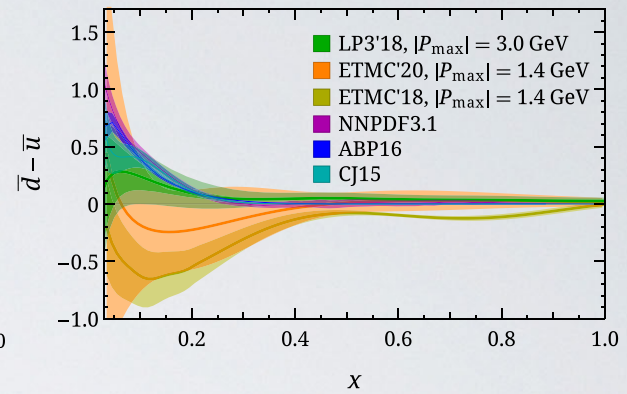
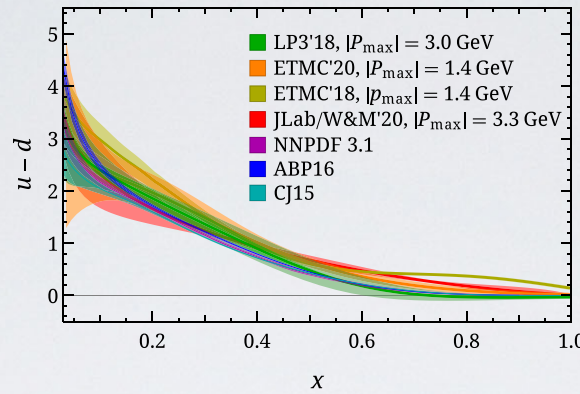
expected EIC impact

EIC Yellow Report, 2103.05419

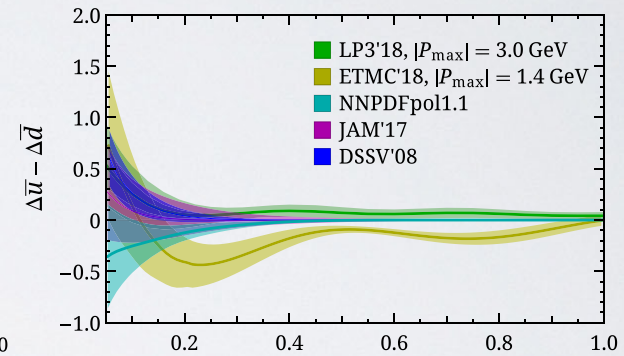
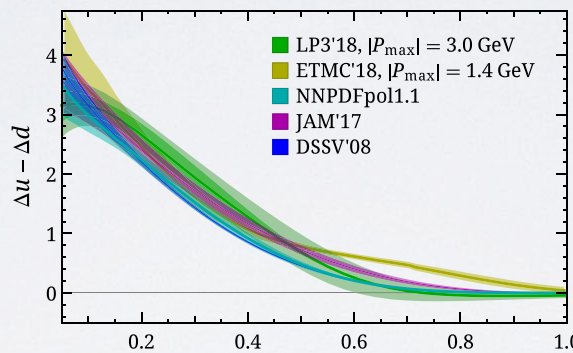


Comparison with lattice

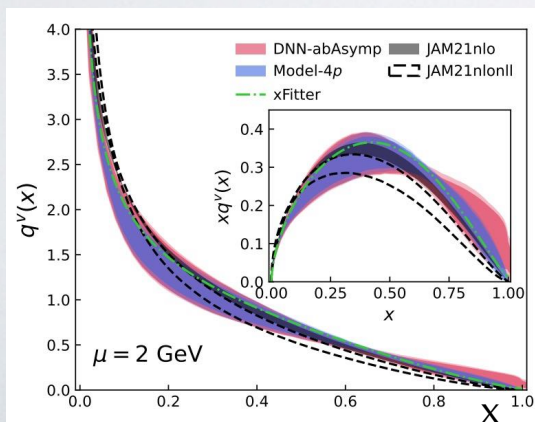
isovector unpolarized PDFs



isovector helicity PDFs



pion valence PDF

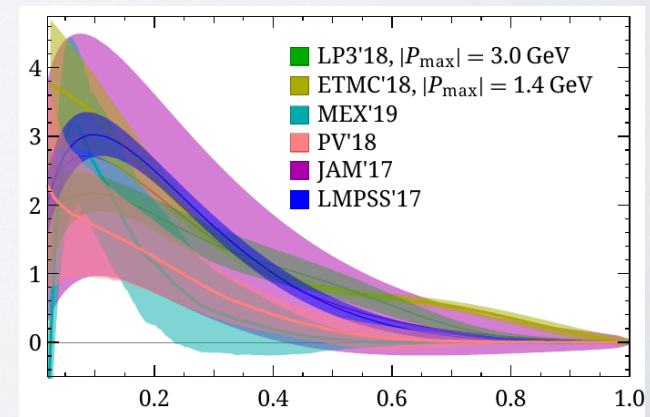


LPC, PRD **106** (22)

x PDF Lattice studies, Prog.Part.Nucl.Phys. **121** (21)

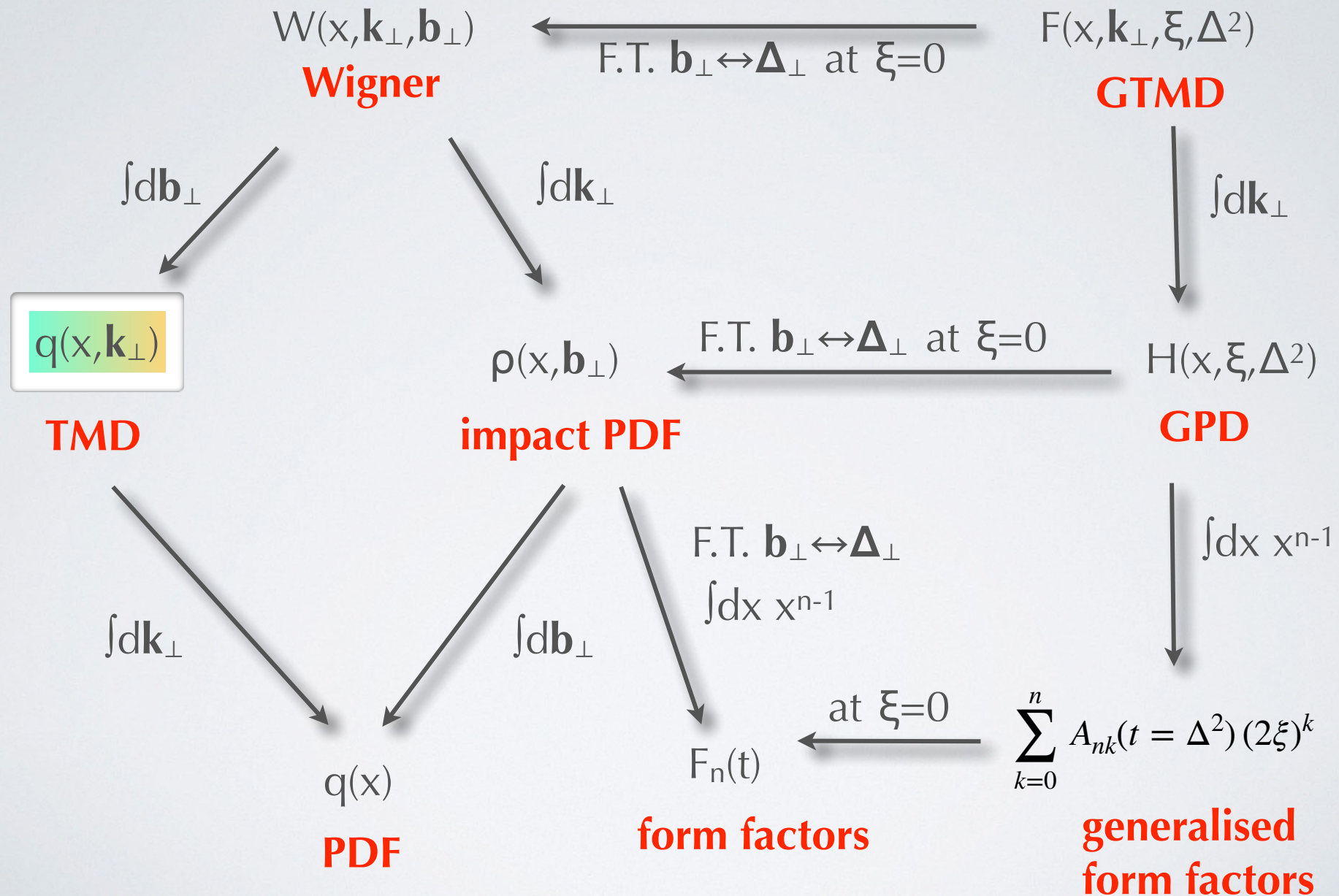
isovector transversity PDFs

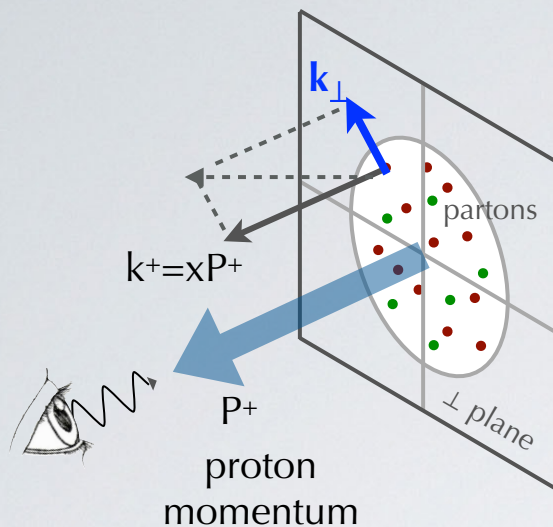
talk by
Delmar, Wednesday
(Workshop 1)



Nucleon “femtography”

Multi-dim. maps of Nucleon structure





TMDs: Transverse Momentum Dependent PDFs (and FFs) from 1D to 3D mapping

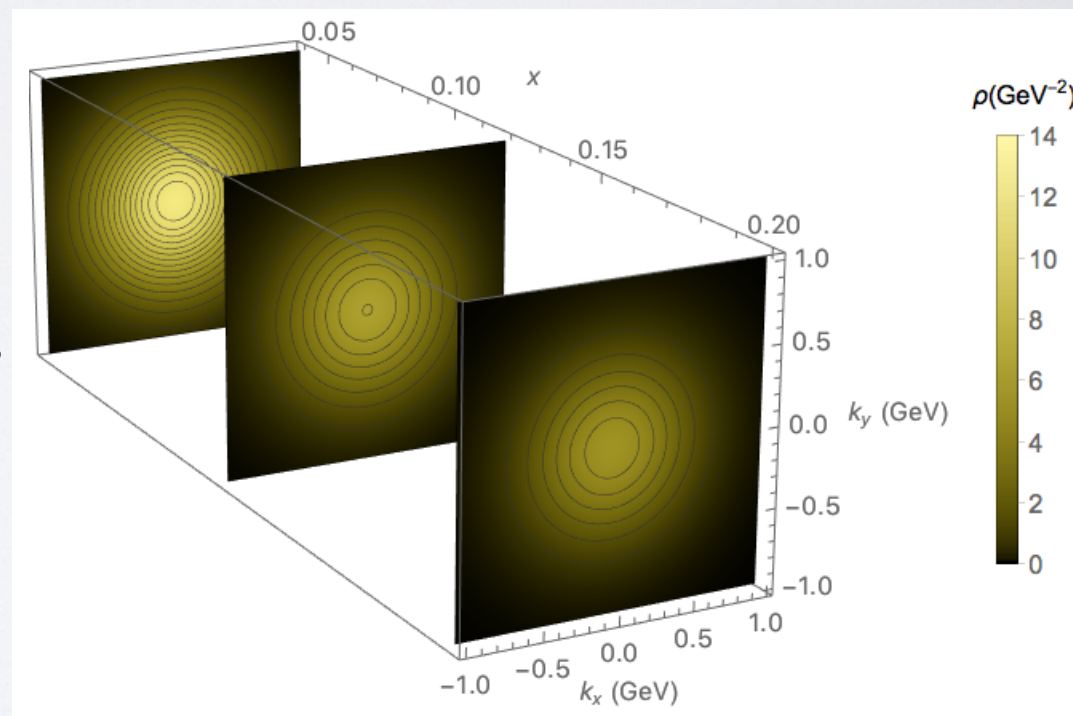
How do partons move and orbit inside hadrons?

How wide is the distribution ?

How does it change with x ?

How does it change with flavor ?

What if the hadron is polarized ?



quark TMD PDFs at leading twist

polarization

quark

nucleon

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$	$\times$	$h_1^\perp = \uparrow - \downarrow$
	L	$\times$	$g_1 = \rightarrow - \leftarrow$	$h_{1L}^\perp = \nearrow - \searrow$
	T	$f_{1T}^\perp = \uparrow - \downarrow$	$g_{1T} = \rightarrow - \leftarrow$	$h_1 = \uparrow - \downarrow$ $h_{1T}^\perp = \nearrow - \searrow$

Sivers worm-gear

Mulders & Tangeman, N.P. **B461** (96)

Boer & Mulders, P.R. **D57** (98)

Boer-Mulders

Kotzinian-Mulders

transversity

pretzelosity

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

$$f_1 \quad \text{[circular blob]} \quad \longrightarrow \quad h_1^\perp, f_{1T}^\perp \quad \text{[dumbbell blobs]} \quad g_{1T}, h_{1L}^\perp, h_{1T}^\perp \quad \text{[four-lobed blobs]}$$

- can be extracted from a specific measurable spin asymmetry
- f_1 enters the denominator of each asymmetry $\rightarrow$ influences all others

quark TMD PDFs at leading twist

polarization

quark

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

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Boer-Mulders

Kotzinian-Mulders

transversity

pretzelosity

collinear PDFs surviving integration in k_T

chiral-odd: need a chiral-odd partner in the cross section

naïve T-odd: vanishing without residual color final-state interactions
→ non universal, but in a predictable way..

quark TMD PDFs at leading twist

polarization

quark

nucleon

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Boer-Mulders

Kotzinian-Mulders

transversity

pretzelosity

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

quark TMD PDFs at leading twist

polarization quark

nucleon

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similar table for **TMD FFs**; and also for **gluon TMD PDFs**, but with **some differences**

Gluons carry "two color charges" → intricate T-oddness: WW-type and dipole-type

Different color structures → different mechanisms → different processes to extract them

WW-type: heavy quarkonia, di-jets dipole-type: photon-jet factorization under investigation

Complementary role of colliders: RHIC, LHC, EIC, NICA

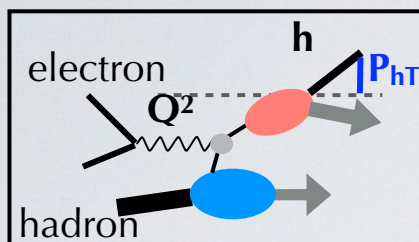
similar classification for **subleading-twist TMD PDFs**

talk by
Scimemi, Wednesday

Where TMDs ?

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

SIDIS



factorization conditions

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

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

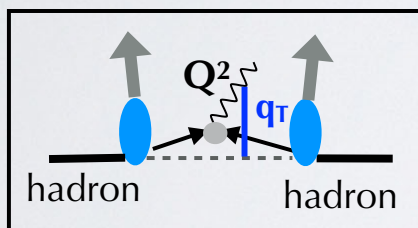
TMDPDF

TMDFF

Ji, Ma, Yuan, P.R. **D71** (05); Rogers & Aybat, P.R. **D83** (11)

Collins & Metz, P.R.L. **93** (04) 252001

Drell-Yan



factorization conditions

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

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

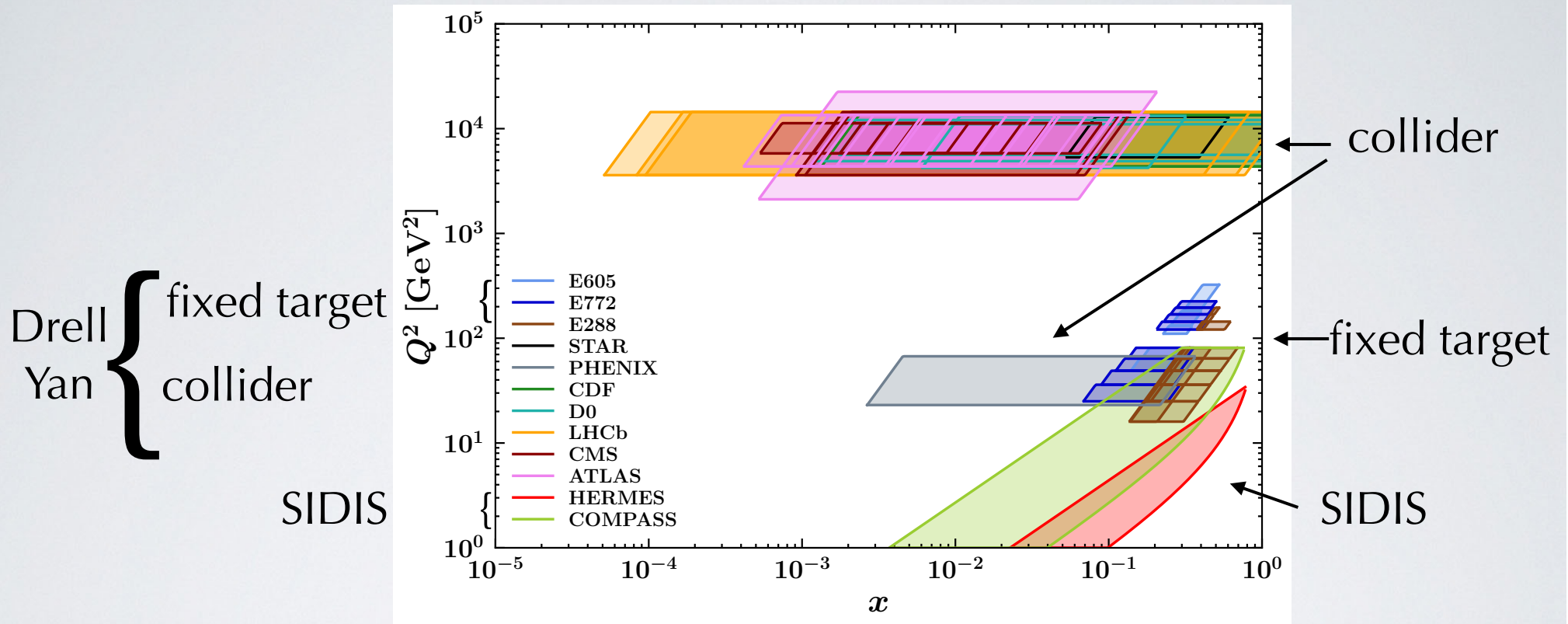
TMDPDF

TMDPDF

Collins, Soper, Sterman, N.P. **B250** (85)
199

Echevarria, Idilbi, Scimemi, JHEP **07** (12)

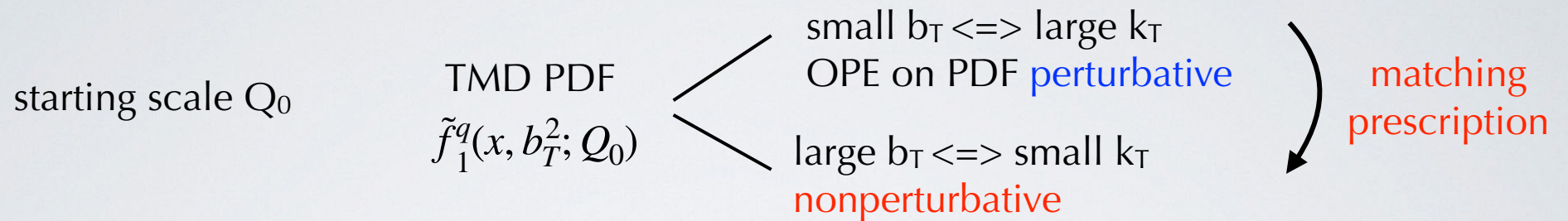
Kinematic coverage of exp. data



Complementarity between SIDIS and Drell-Yan
For unpolarized TMDs $O(\lesssim 2000)$ points,
smaller but comparable with unpolarized PDFs [$O(5000)$]

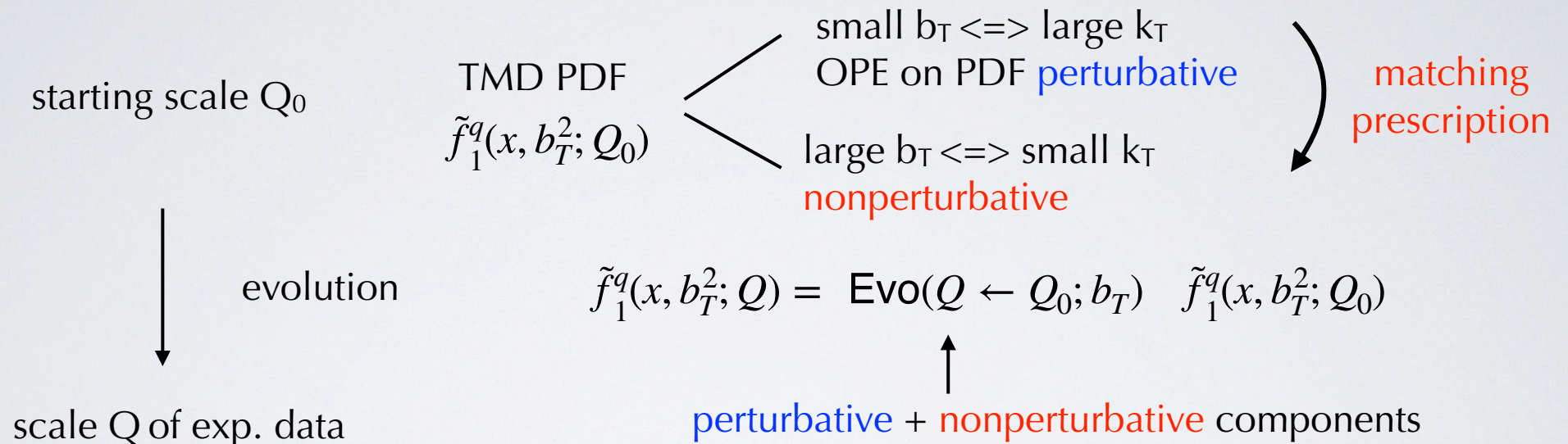
Evolution of TMDs

very different from PDFs: no cross talk between different x ; no quark $\leftrightarrow$ gluon transition
two scales, μ (virtuality cutoff) and ζ (rapidity cutoff), usually
taken $\mu^2 = \zeta = Q^2$



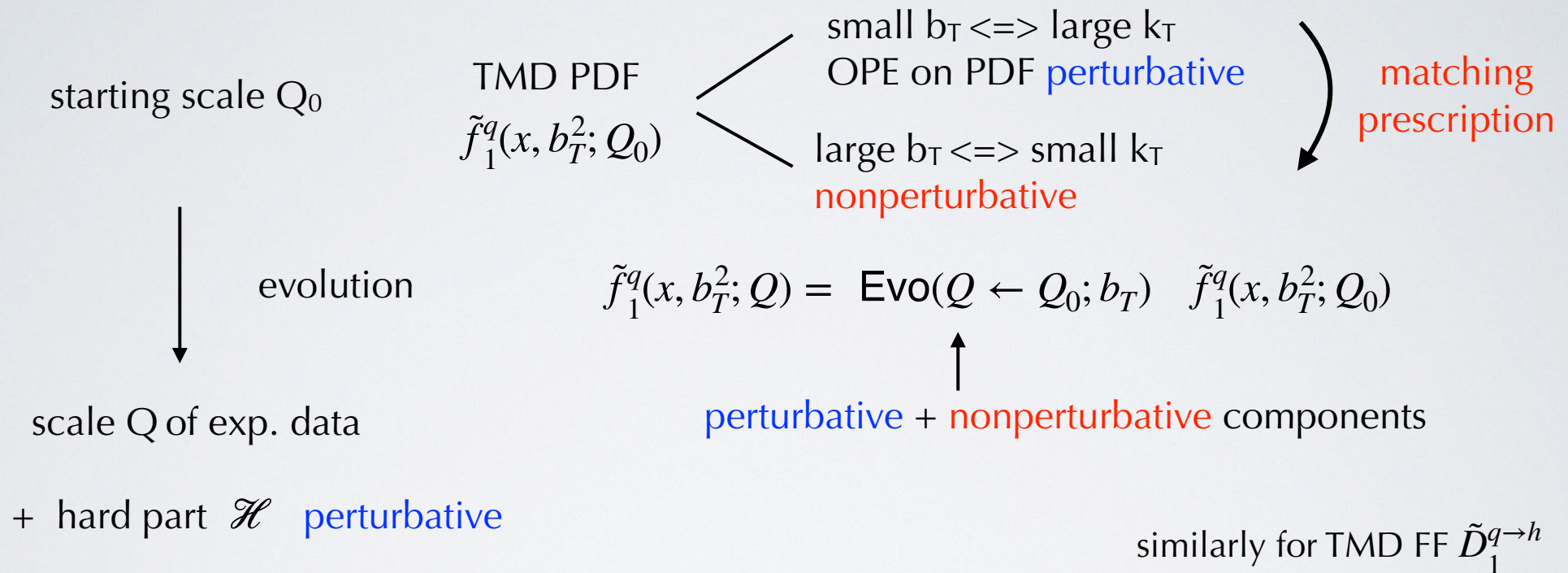
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Evolution of TMDs

very different from PDFs: no cross talk between different x ; no quark $\leftrightarrow$ gluon transition
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every component **in red** is arbitrary $\Rightarrow$ depends on **parameters** to be fitted to data

Quality of TMD extraction:

- **perturbative accuracy**
- **size of data set and best χ^2**

quark TMD PDFs at leading twist

polarization quark

nucleon

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$	✗	$h_1^\perp = \uparrow - \downarrow$
	L	✗	$g_1 = \rightarrow - \leftarrow$	$h_{1L}^\perp = \nearrow - \nwarrow$
	T	$f_{1T}^\perp = \uparrow - \downarrow$	$g_{1T} = \rightarrow - \leftarrow$	$h_1 = \uparrow - \downarrow$ $h_{1T}^\perp = \nearrow - \nwarrow$

Sivers worm-gear

Mulders & Tangeman, N.P. **B461** (96)

Boer & Mulders, P.R. **D57** (98)

Boer-Mulders

Kotzinian-Mulders

transversity

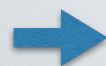
pretzelosity

Just quick flash about very recent (~2024-25) results on unpolarized TMD PDF (f_1) and helicity TMD PDF (g_1)

overview talk by
Pitonyak, Thursday

Most recent extractions of Nucleon TMD f_1

	Accuracy	SIDIS	Drell-Yan	N of points	χ^2/N_{points}	Flavor dep.
PV 2017 arXiv:1703.10157	NLL	✓	✓	8059	1.5	✗
SV 2017 arXiv:1706.01473	N ³ LL	✗	✓ (LHC)	309	1.23	✗
BSV 2019 arXiv:1902.08474	N ³ LL	✗	✓ (LHC)	457	1.17	✗
SV 2019 arXiv:1912.06532	N ³ LL(-)	✓	✓ (LHC)	1039	1.06	✗
PV 2019 arXiv:1912.07550	N ³ LL	✗	✓ (LHC)	353	1.07	✗
MAPTMD 2022 arXiv:2206.07598	N ³ LL(-)	✓	✓ (LHC)	2031	1.06	✗
ART23 arXiv:2305.07473	N ⁴ LL(-)	✗	✓ (LHC)	627	0.96	✓
MAPTMD 2024 arXiv:2405.13833	N ³ LL	✓	✓ (LHC)	2031	1.08	✓
MAPNN 2025 arXiv:2502.04166	N ³ LL	✗	✓ (LHC)	482	0.97	✗
ART25 arXiv:2503.11201	N ⁴ LL(-)	✓	✓ (LHC)	1209	1.05	✓



Also, first simultaneous extraction of PDF & TMD f_1 from DIS + Drell-Yan data

JAM, 2510.13771

Most recent extractions of Nucleon TMD f_1

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PV 2017 arXiv:1703.10157	NLL	✓	✓	8059	1.5	✗
Global fits now able to discriminate between k_T distributions of different flavors						
BSV 2019 arXiv:1902.08474	N ³ LL	✗	✓ (LHC)	457	1.17	✗
SV 2019 arXiv:1912.06532	N ³ LL(-)	✓	✓ (LHC)	1039	1.06	✗
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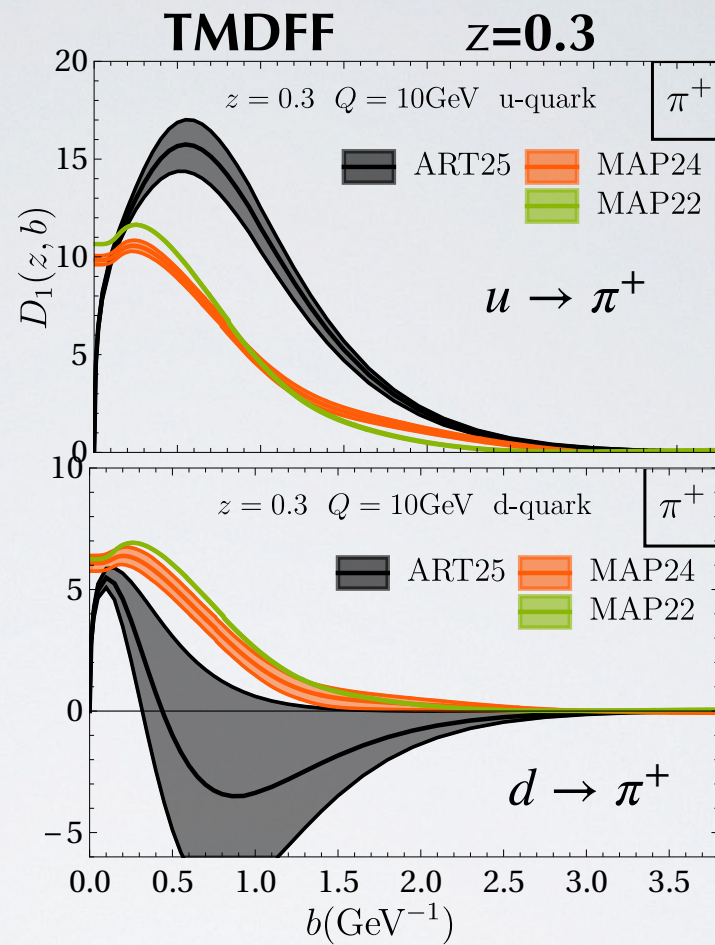
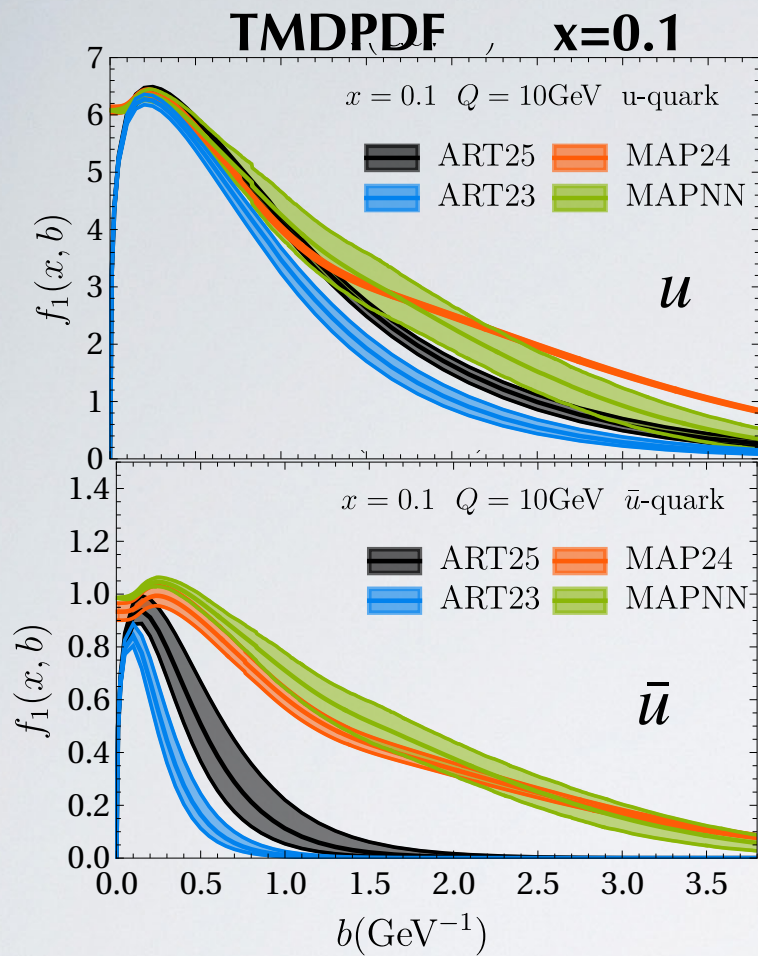
➡ Also, first simultaneous extraction of PDF & TMD f_1 from DIS + Drell-Yan data *JAM*, 2510.13771

Most recent extractions of Nucleon TMD f_1

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ART25 arXiv:2503.11201	N ⁴ LL(-)	✓	✓ (LHC)	1209	1.05	✓

First extraction of TMDs using Neural Networks

→ Also, first simultaneous extraction of PDF & TMD f_1 from DIS + Drell-Yan data *JAM*, 2510.13771

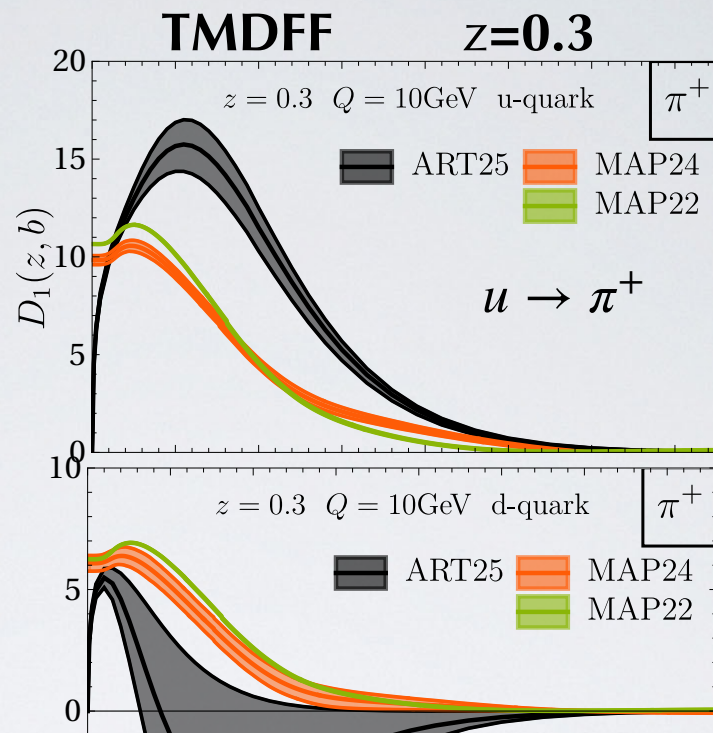
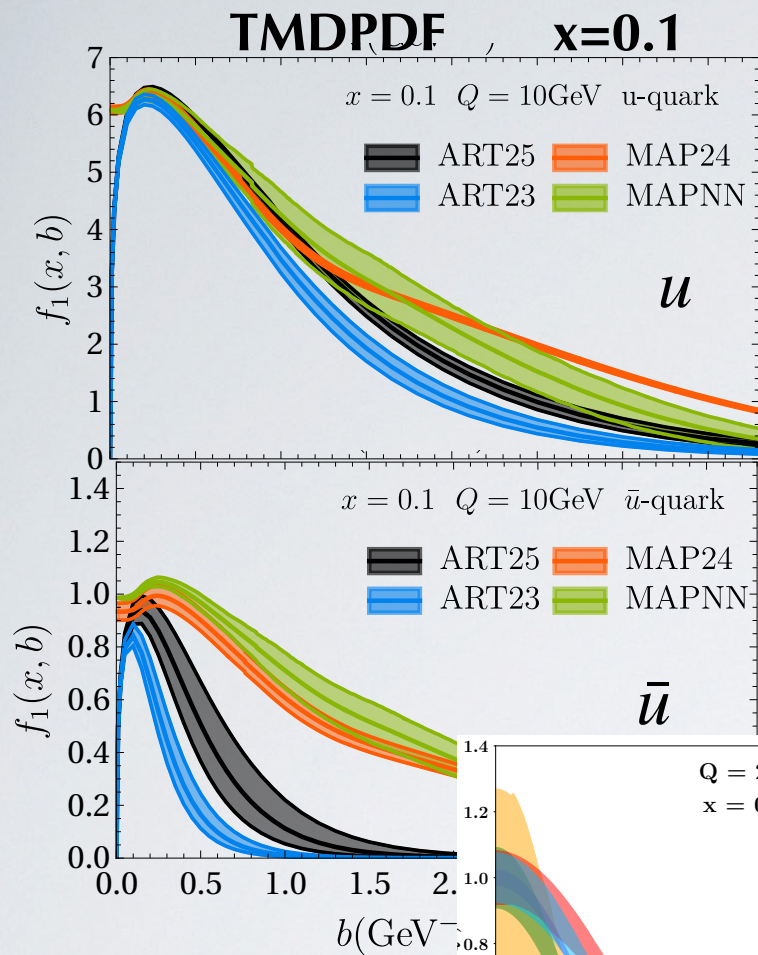


significant differences
in nonpert. model

different approach to
collinear limit $b \rightarrow 0$

more realistic
description of
uncertainties with
MAPNN

**overview talk by
Pitonyak, Thursday**

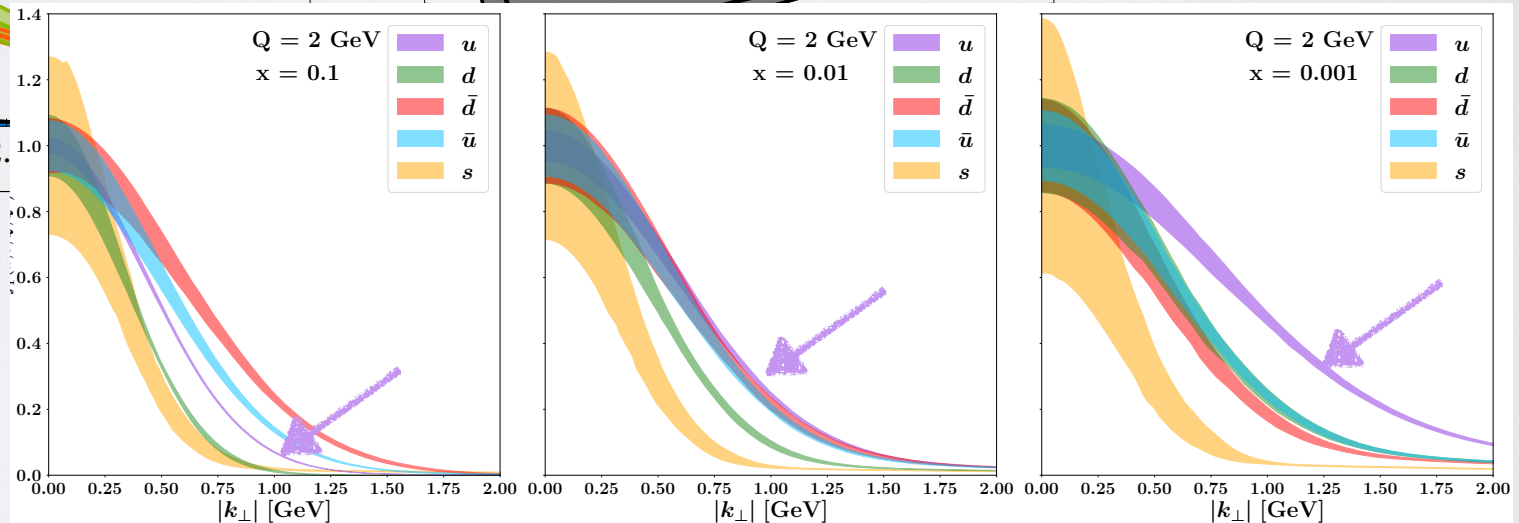


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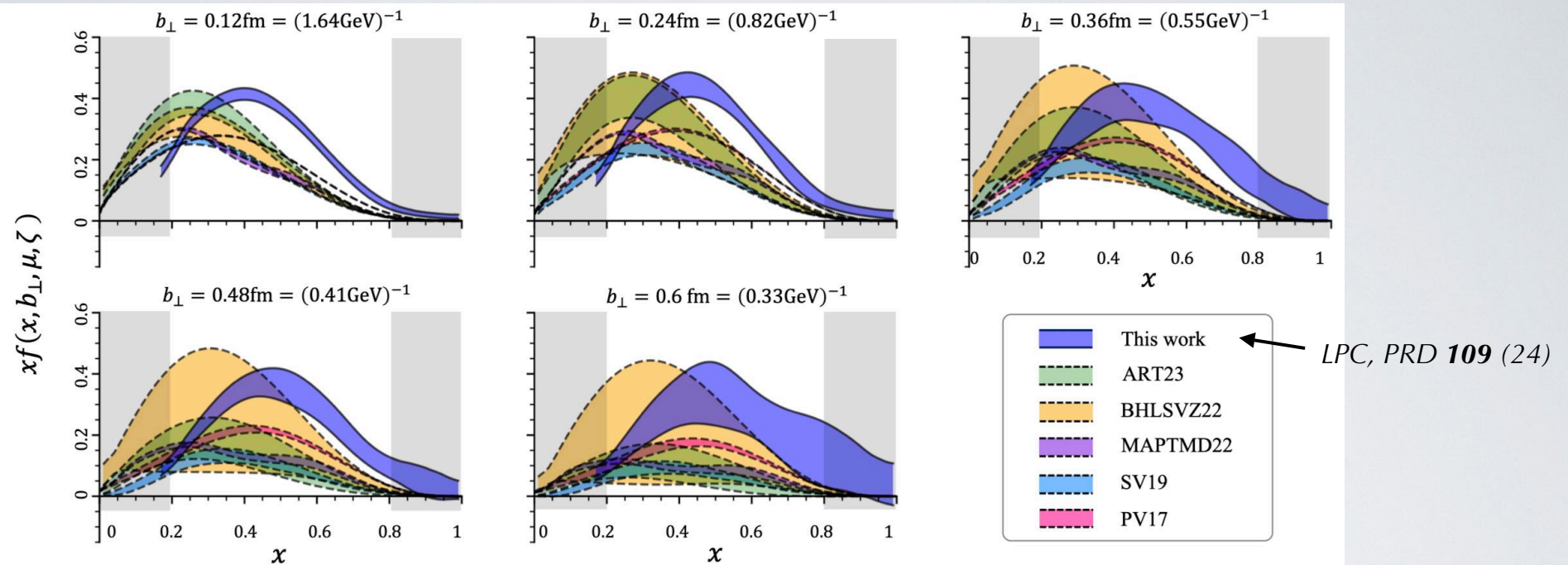
more realistic
description of
uncertainties with
MAPNN

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

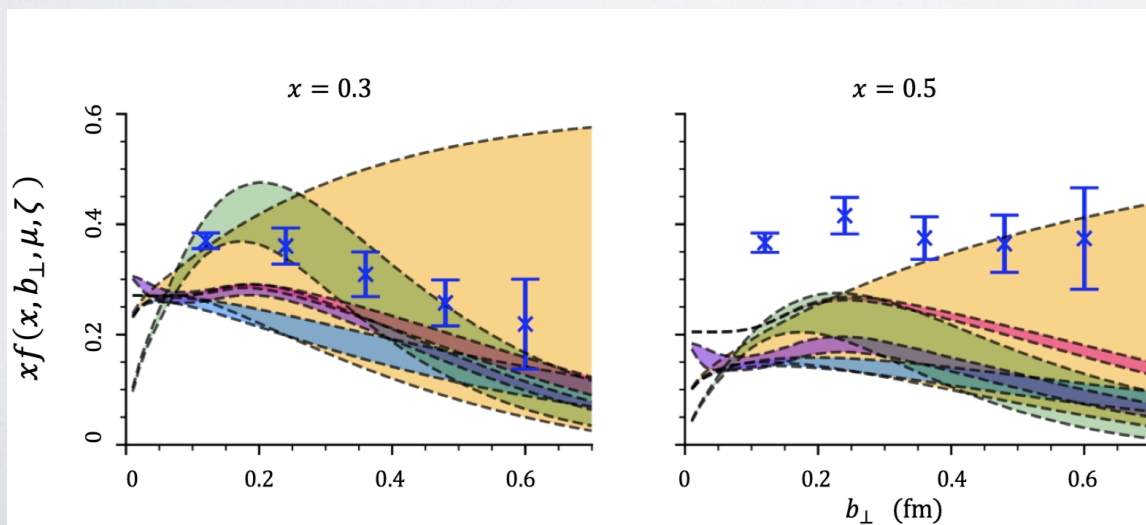


better appreciate the very different k_T behavior
that changes with x

Comparison with lattice: TMDs in b_T space



x -dependence

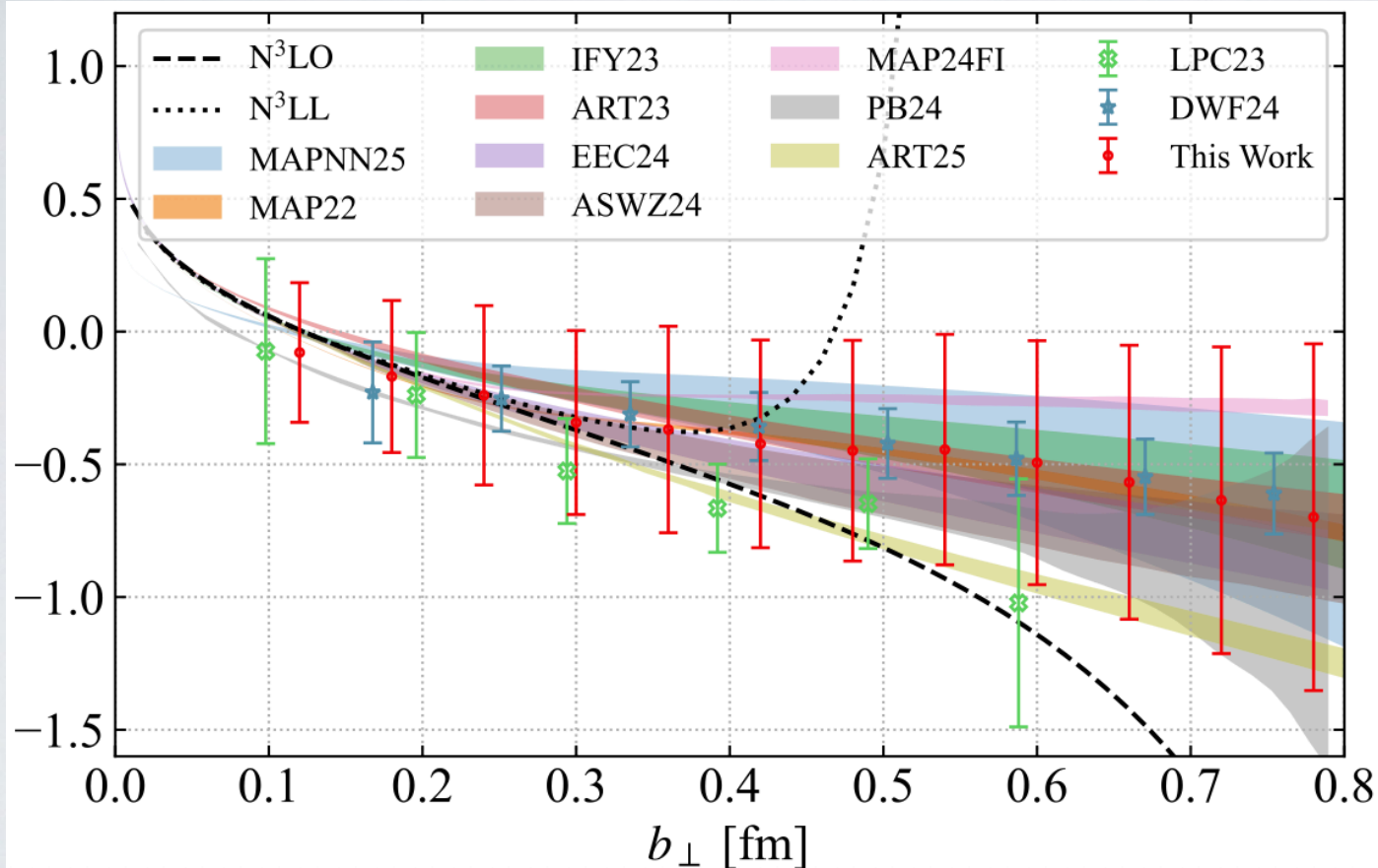


b_T -dependence

overview talk by
Zhang, Thursday

Comparison with lattice: Collins-Soper kernel

universal flavor-independent drives evolution in rapidity ζ
 perturbative + nonperturbative



Bollweg et al., arXiv:2504.04625

remarkable agreement with pheno $\leftrightarrow$ lattice

Lattice

DWF24 Bollweg et al., arXiv:2403.00664
 LPC23 Chu et al. (LPC), arXiv:2306.06488
 ASWZ24 Avkhadiev et al., arXiv:2402.06725

Pheno

IFY23 (ResBos) Isaacson et al., arXiv:2311.09916
 EEC24 Kang et al., arXiv:2410.21435
 PB24 Martinez et al., arXiv:2412.21116

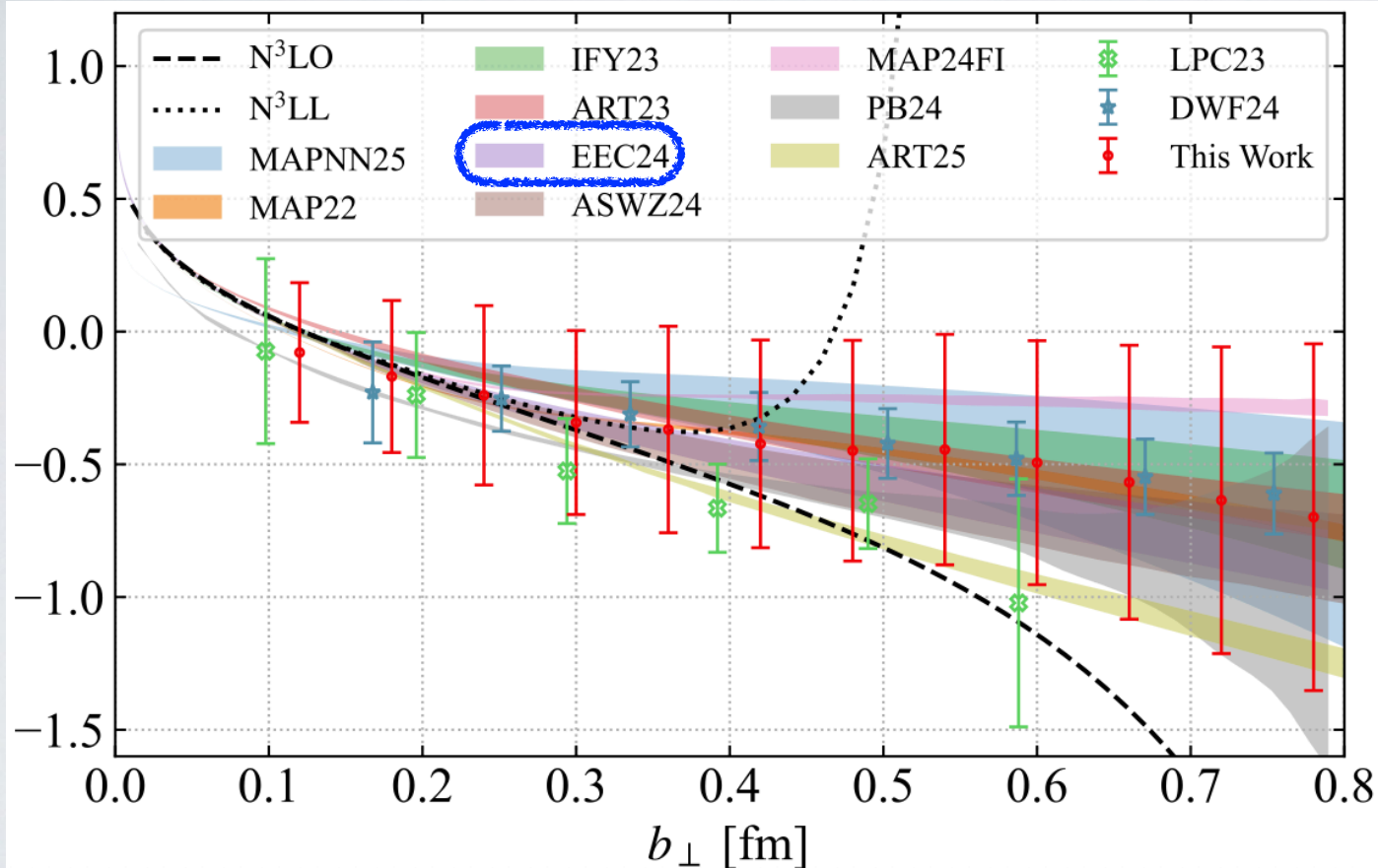
+ MAPTMD-22, -24, -NN
 + ART-23, -25

pQCD

N³LL Vladimirov, arXiv:1610.05791
 N³LO Li&Zhu, arXiv:1604.01404

Comparison with lattice: Collins-Soper kernel

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Lattice

DWF24 Bollweg et al., arXiv:2403.00664
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 ASWZ24 Avkhadiev et al., arXiv:2402.06725

Pheno

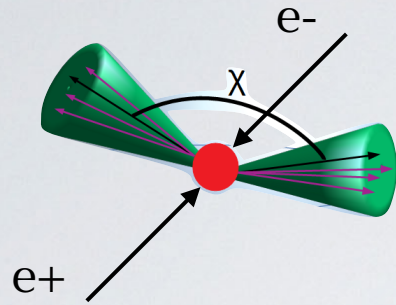
IFY23 (ResBos) Isaacson et al., arXiv:2311.09916
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+ MAPTMD-22, -24, -NN
 + ART-23, -25

pQCD

N³LL Vladimirov, arXiv:1610.05791
 N³LO Li&Zhu, arXiv:1604.01404

Additional info: Energy-Energy Correlator in e+e-



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

energy-weighted e+e- cross section

measures correlation of two energy flows along specific directions

for $\zeta \rightarrow 1$ ($\chi \rightarrow \pi$)

factorized formula:

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

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

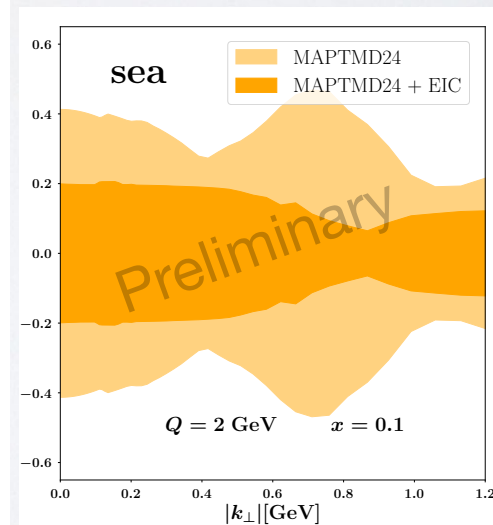
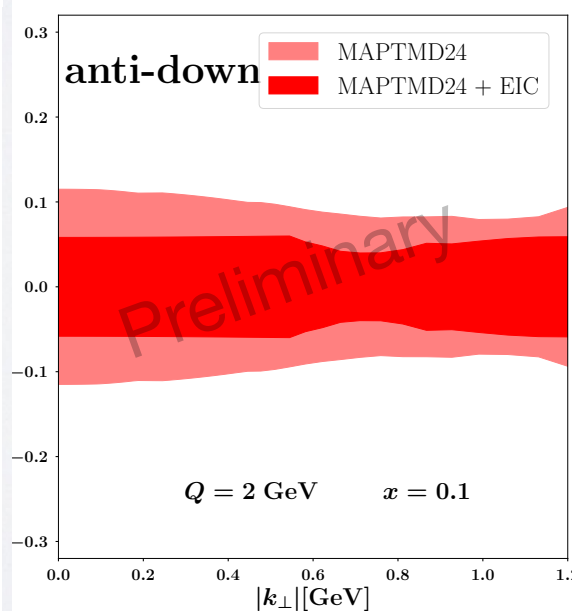
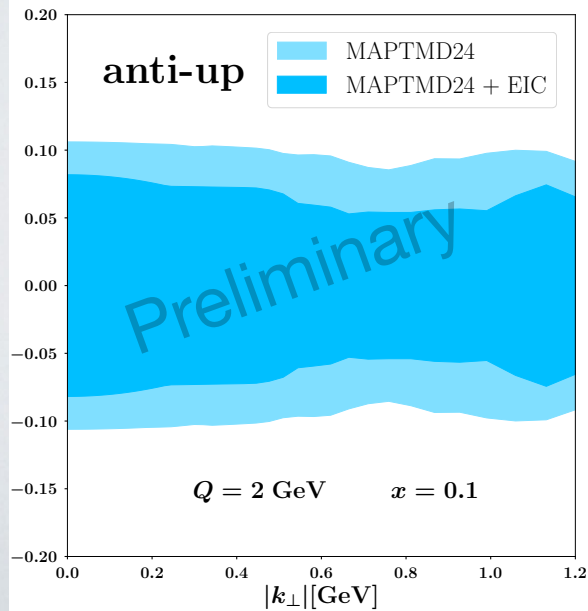
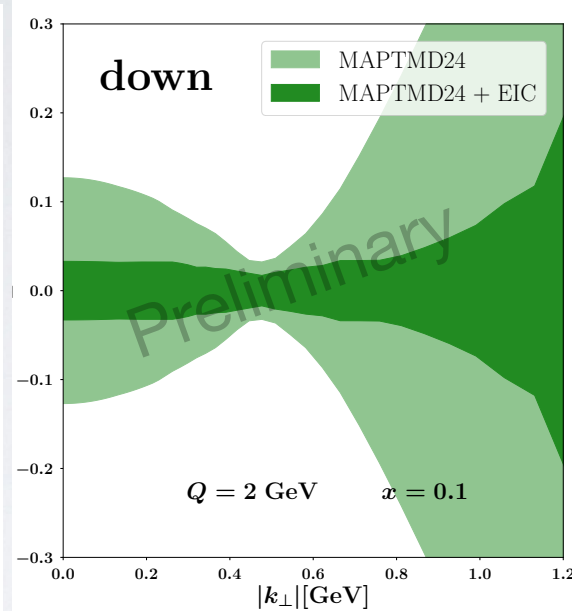
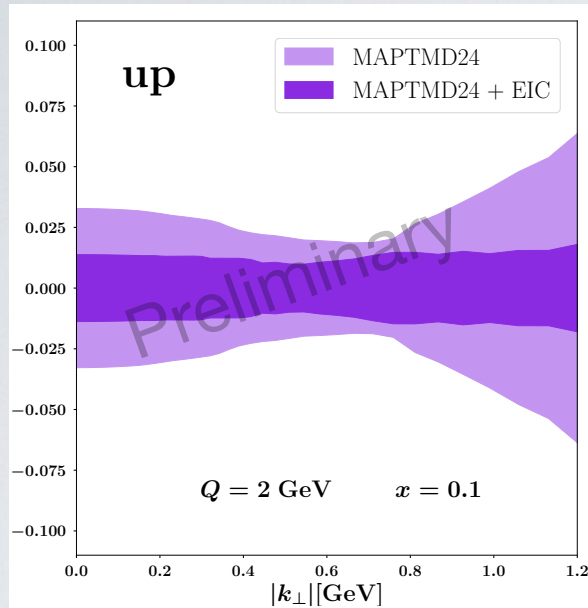
sensitivity only to Collins-Soper kernel

use OPAL, SLD, TOPAZ, TASSO, DELPHI,... data to constrain CS kernel

Kang et al., arXiv:2410.21435

Bris et al., arXiv:2507.17478

The EIC impact at $x=0.1$, $Q=2$ GeV



MAPTMD24 2031

EIC # pts. lumi [fb⁻¹]

5x41 1273 2.85

10x100 1611 51.3

18x275 1648 10

(simulation campaign May '24,
only π^+ production)

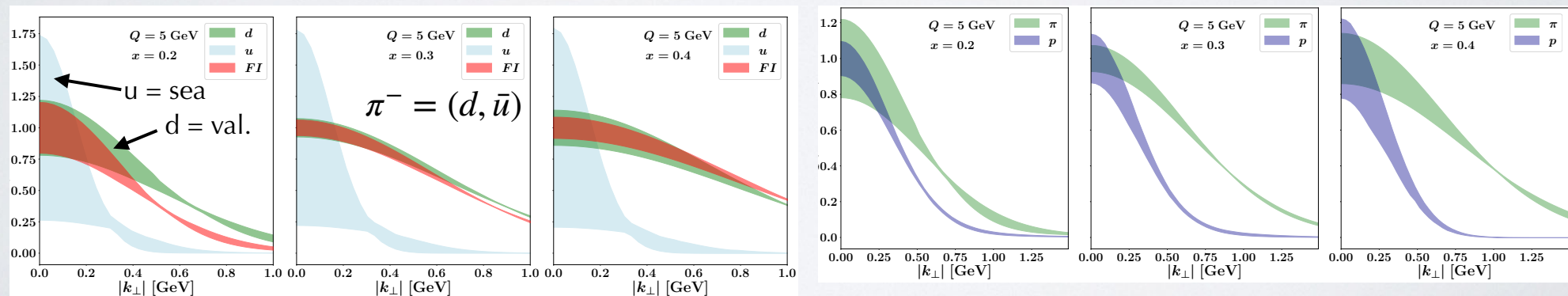
L. Rossi, Ph.D. Thesis
and in preparation

Extractions of **Pion** TMD f_1

	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 ³ LL(-)	✓	138	1.55	✗
JAM23 PRD 108 (23)	NNLL	✓	93	1.37	✗
MAPTMDPion25 2509.25098	N ³ LL	✓	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
E615, E537 π^- -N Drell-Yan, N TMDs from MAPTMD24 with same CS kernel



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

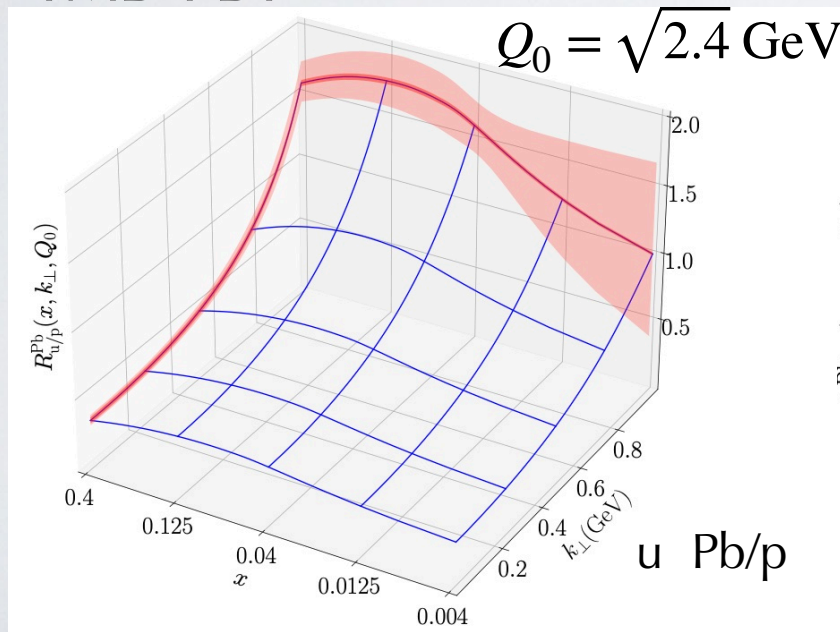
Nuclear TMD f_1^A

Global fit using TMD factorization

Alrashed et al., *PRL* **129** (22)

Alrashed et al., *arXiv:2312.09226*

TMD PDF

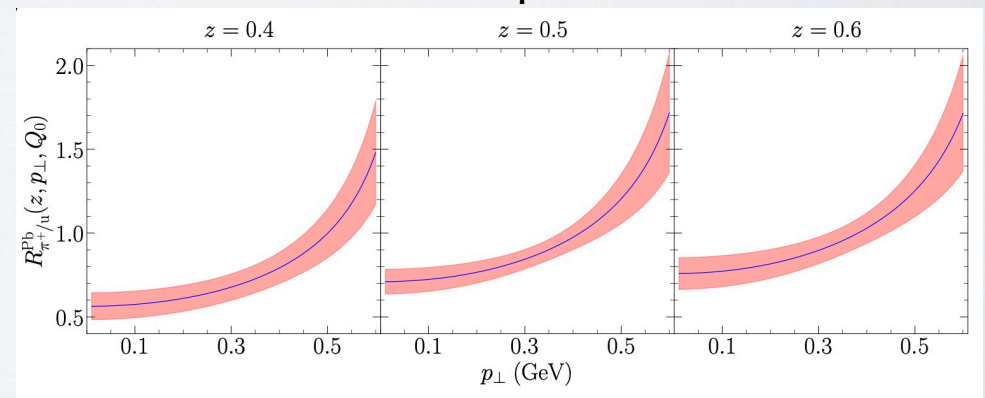


(anti-)shadowing visible

Collaboration	Process	Baseline	Nuclei	N_{data}	χ^2
JLAB [49]	SIDIS(π)	D	C, Fe, Pb	36	41.7
HERMES [40]	SIDIS(π)	D	Ne, Kr, Xe	18	10.2
RHIC [43]	DY	p	Au	4	1.3
E772 [41]	DY	D	C, Fe, W	16	40.2
E866 [42]	DY	Be	Fe, W	28	20.6
CMS [63]	γ^*/Z	N/A	Pb	8	10.4
ATLAS [83]	γ^*/Z	N/A	Pb	7	13.3
Total				117	137.8

$$\chi^2/N_{\text{data}} = 1.275$$

TMD FF $u \rightarrow \pi^+ \text{ Pb/p}$



k_T broadening

Helicity TMD PDF

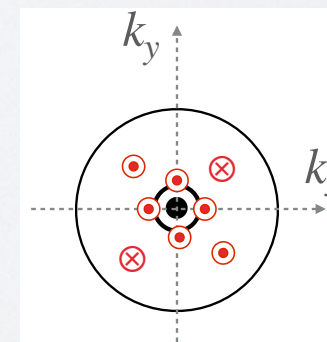
polarizations

quark • → ↑

nucleon

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

- How does polarization of quarks distort their k_T ?
- Do quarks with spin parallel to proton spin have larger / smaller k_T than those with spin antiparallel ?

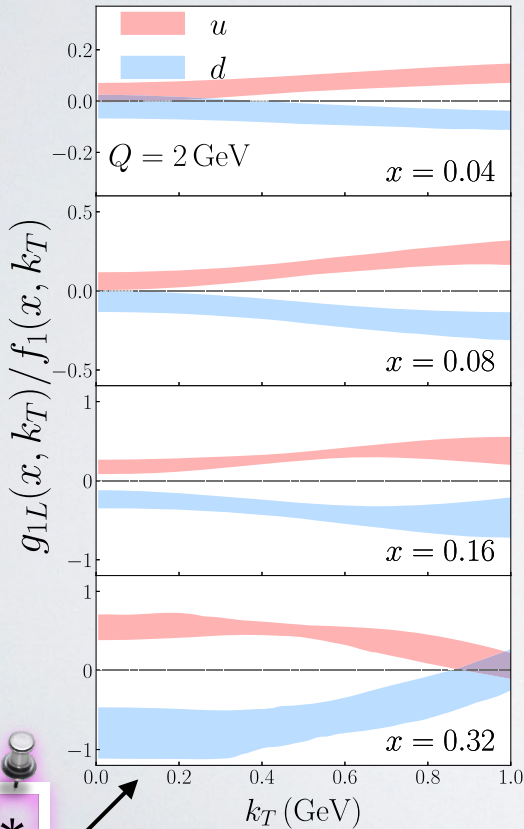


	Accuracy	SIDIS	Drell-Yan	N of points	χ^2/N	Flavor dep.
MAPTMD22pol Bacchetta et al. (MAP) P.R.L. 134 (25) 121901	NNLL	✓	✗	291	1.09	✗
YLSZM Yang et al. (TNT) P.R.L. 134 (25) 121902	NNLL	✓	✗	253	0.74	✗

← enforced $|g_1| \leq f_1$

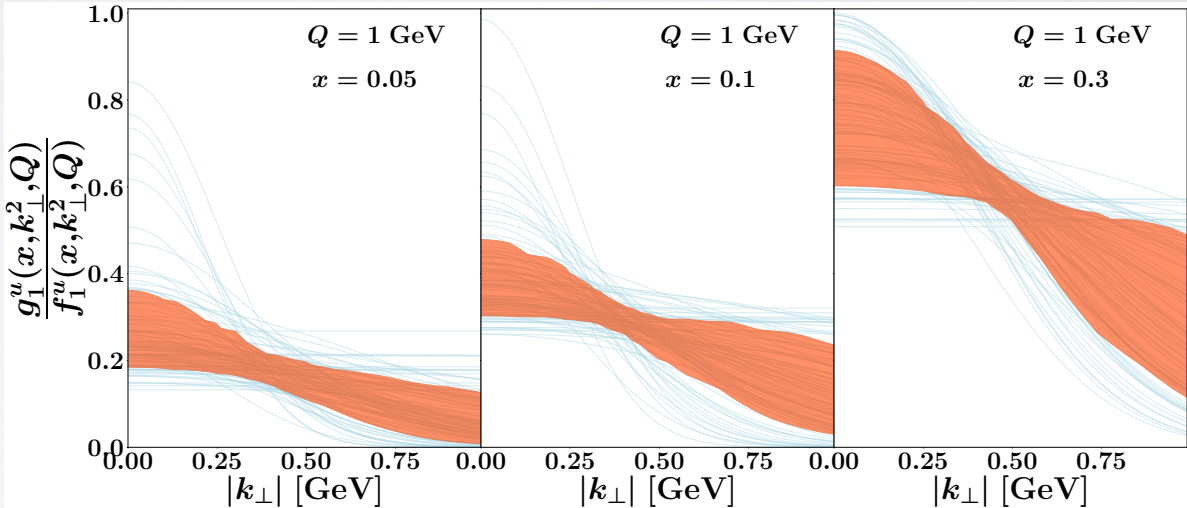
accuracy limited by gluon
Wilson coeffs.

data from SIDIS DSA A₁



YLSZM

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



MAPTMD22pol

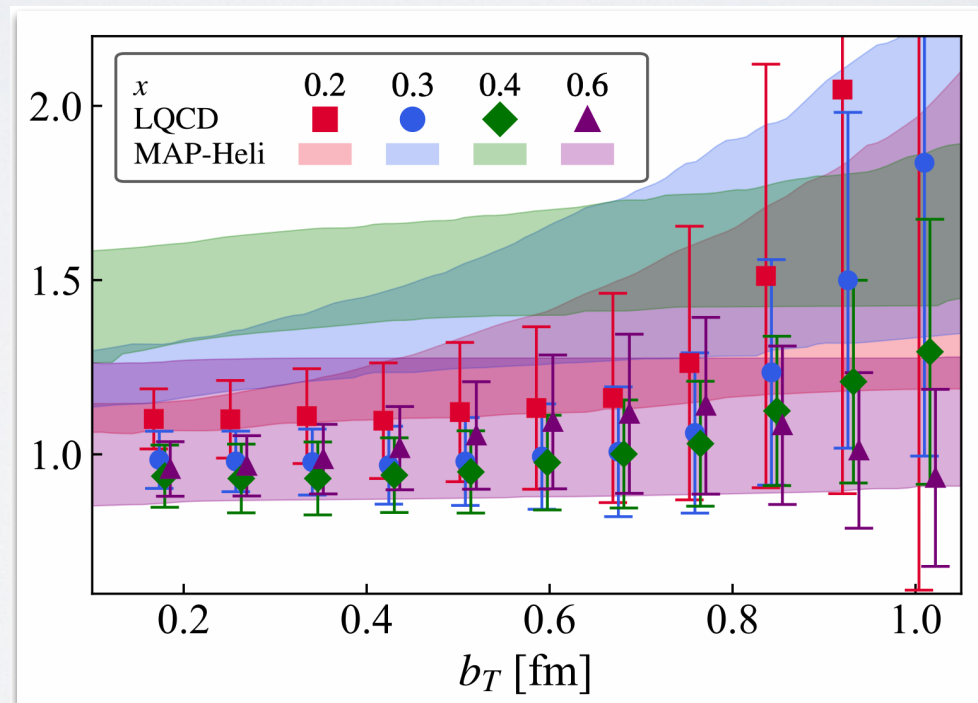
Bacchetta et al. (MAP),
P.R.L. **134** (25) 121901

Comparison with lattice: isovector g_1/f_1 ratio

input from lattice

$$\frac{g_{1L}^{\Delta u_+ - \Delta d_+}(x, b_T; \mu, \zeta)}{g_A f_1^{u_v - d_v}(x, b_T; \mu, \zeta)} \quad \mu = \sqrt{\zeta} = 1.62 \text{ GeV}$$

Bollweg et al., arXiv:2505.18430

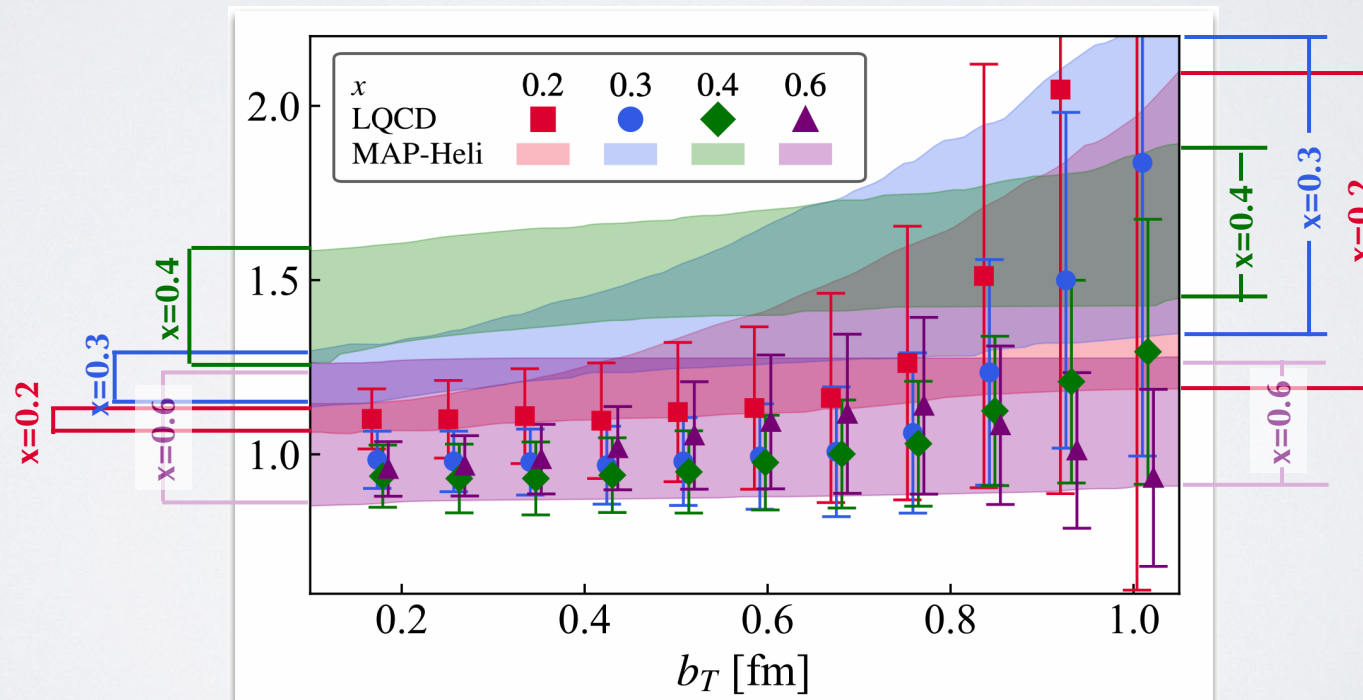


Comparison with lattice: isovector g_1/f_1 ratio

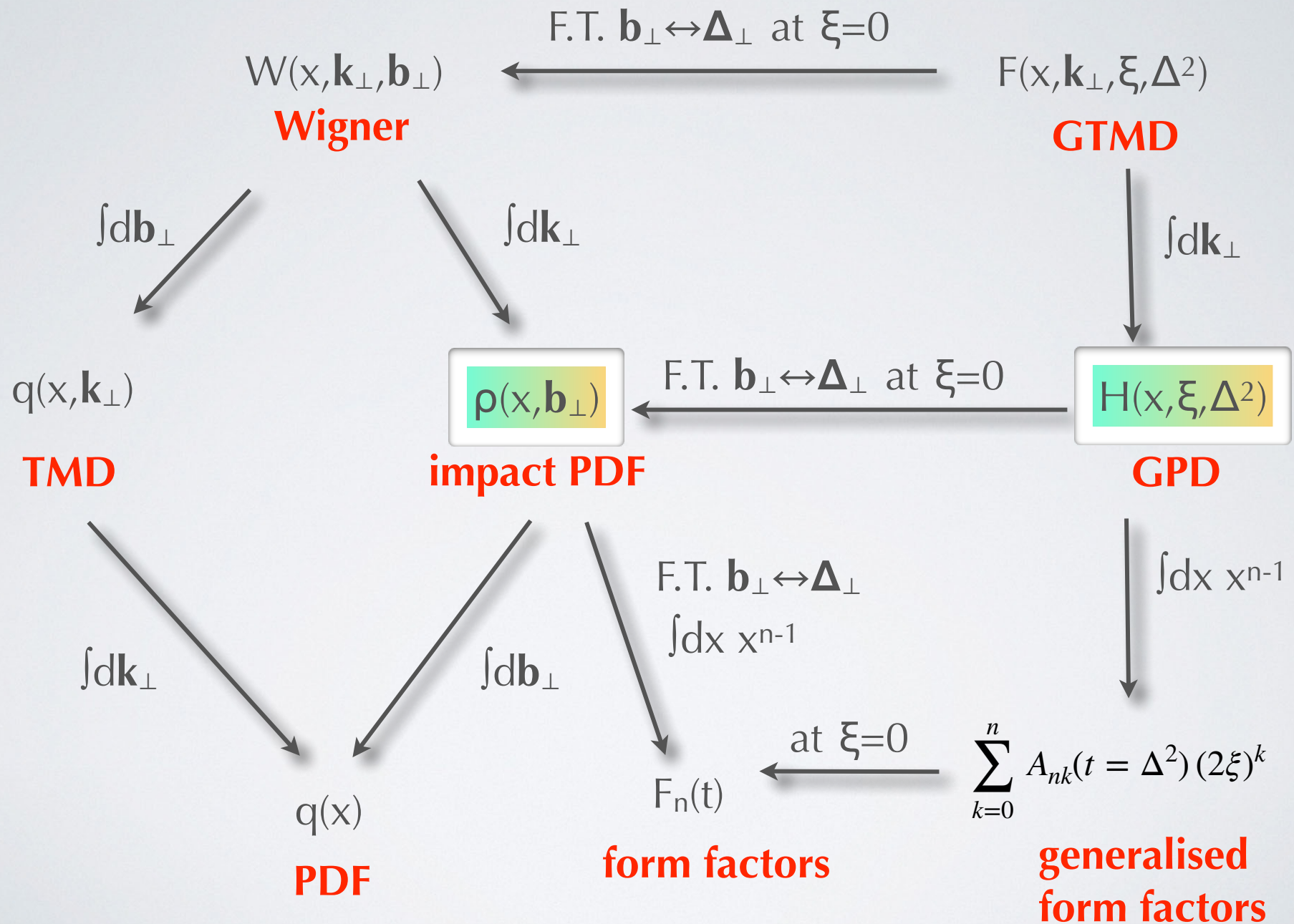
input from lattice $\frac{g_{1L}^{\Delta u_+ - \Delta d_+}(x, b_T; \mu, \zeta)}{g_A f_1^{u_v - d_v}(x, b_T; \mu, \zeta)} \quad \mu = \sqrt{\zeta} = 1.62 \text{ GeV}$

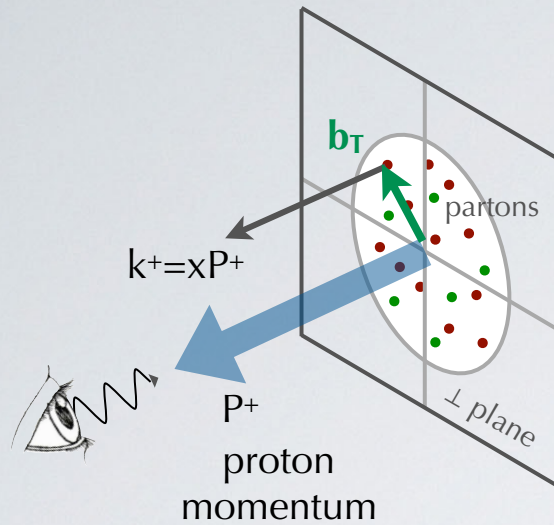
compatibility for $x=0.2, 0.6$
 partial " for $x=0.3, 0.4$

Bollweg et al., arXiv:2505.18430



Multi-dim. maps of Nucleon structure



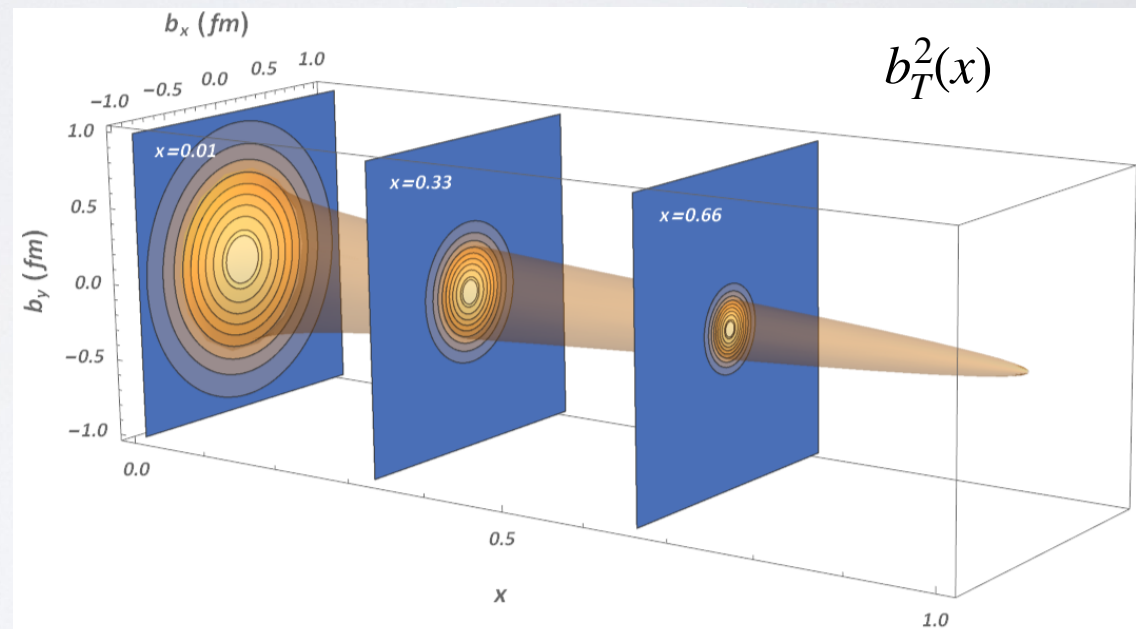


GPDs: access to 1D (momentum) x 2D spatial distribution of partons inside hadrons

Where are partons at a given momentum x ?

2D spatial density at given
momentum x

Hadron tomography

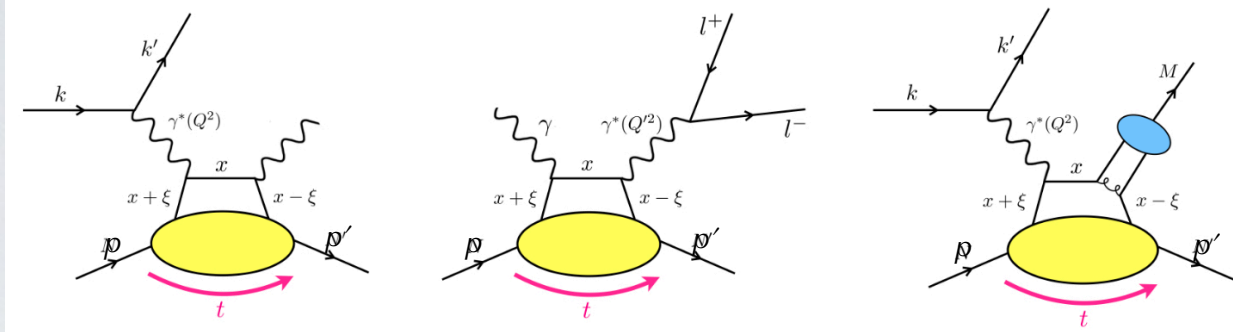


for $x \rightarrow 1$, active parton carries the whole momentum
and represents the center of momentum;
low- x sea quarks populate the periphery

Lorcé et al. (*Encyclopedia Part. Phys.*), 2507.12664

Dupré et al., *PRD* **95** (17)

Where GPDs ?



Deeply Virtual
Compton Scattering
(DVCS)

Time-like
Compton Scattering
(TCS)

Deeply Virtual
Meson Production
(DVMP)

**Th overview by
Sznajder, Thursday**

**exp. talks by
Niccolai, Wednesday
Van Hulse, Thursday**

Factorization for $|t| \ll Q^2, s$

Universality of GPDs in different processes

exclusive processes $\rightarrow$ GPDs are scattering amplitudes, depending on $\text{GPD}(x, \xi, t)$

$$x = \frac{(k + k')^+}{(p + p')^+} = \frac{\bar{k}^+}{P^+}$$

average longitudinal
momentum of partons

$$\xi = \frac{(p - p')^+}{(p + p')^+} = -\frac{\Delta^+}{2P^+}$$

skewness: fraction of
longitudinal momentum
transfer

$$t = (p - p')^2 = \Delta^2$$

momentum transfer
squared (t-channel)

quark GPDs at leading twist

polarization quark • •→ •↑

nucleon

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H	$\times$	ε_T
	L	$\times$	$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	H_T $\tilde{H}_T$

similar table for gluons

GPDs in blue in the collinear limit reduce to PDFs: $H^q(x,0,0) \rightarrow f_1^q(x)$, $\tilde{H}^q \rightarrow g_1^q$, $H_T^q \rightarrow h_1^q$

Chiral-odd GPDs not accessible in DVCS

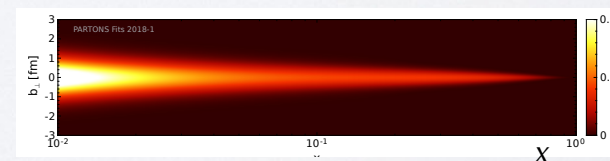
At $\xi=0$, Fourier Transf. $\Delta_\perp \leftrightarrow \mathbf{b}_\perp$ gives a probability density: the impact parameter PDF

no data in this limit, extrapolation needed
→ model dependence

$$\rho(x, \mathbf{b}_\perp) = \int \frac{d\Delta_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \Delta_\perp} H^q(x, 0, \Delta^2)$$

Burkardt, PRD **62** (00)

$$\langle b_T^2(x) \rangle$$



Polynomiality of GPDs and spin sum rule

$$\int_{-1}^1 dx x^m H(x, \xi, t) = \sum_{j=0}^{\lfloor \frac{m}{2} \rfloor} \xi^{2j} A_{2j}(t) + \text{mod}(m, 2) \xi^{m+1} C_{m+1}(t)$$

$$\int_{-1}^1 dx x^m E(x, \xi, t) = \sum_{j=0}^{\lfloor \frac{m}{2} \rfloor} \xi^{2j} B_{2j}(t) - \text{mod}(m, 2) \xi^{m+1} C_{m+1}(t)$$

very general principle
(Lorentz covariance)

Ji, J.Phys.G **24** (98) 1181

Radyushkin, P.L. **B449** (99)
81

m=0 → **connection to elastic form factors**
(only for chiral-even GPDs)

$$\int_{-1}^1 dx H^q(x, \xi, t) = F_1^q(t) \quad \int_{-1}^1 dx E^q(x, \xi, t) = F_2^q(t)$$

similarly, $\tilde{H} \leftrightarrow g_A(t)$, $\tilde{E} \leftrightarrow g_P(t)$

Polynomiality of GPDs and spin sum rule

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Ji, J.Phys.G **24** (98) 1181
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81

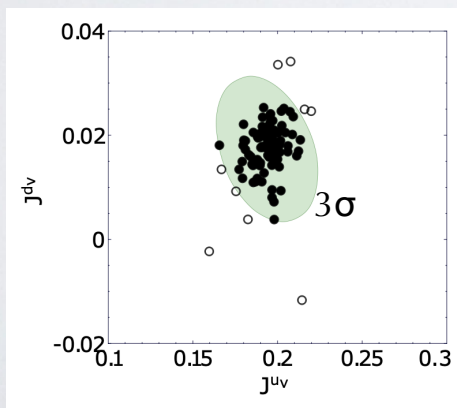
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similarly, $\tilde{H} \leftrightarrow g_A(t)$, $\tilde{E} \leftrightarrow g_P(t)$

m=1 → Ji spin sum rule $J^q = \frac{1}{2} \int_{-1}^1 dx x [H^q(x, \xi, 0) + E^q(x, \xi, 0)] = A^q(0) + B^q(0)$

Ji, P.R.L. **78** (97) 610



recent result fitting elastic FF
and lattice data
compatible with

Diehl-Kroll GPD model
(fitted to elastic data)

Bacchetta & M.R.
(fitting SIDIS data + Burkardt's
lensing function $\text{Sivers} \leftrightarrow \text{GPD E}$)

$$J^{u_v} = 0.195 \pm 0.010$$

$$J^{d_v} = 0.0173 \pm 0.0046$$

Cichy et al., PRD **110**
(24)

$$J^{u_v} = 0.230^{+0.009}_{-0.024}$$

$$J^{d_v} = -0.004^{+0.010}_{-0.016}$$

EPJ **C73** (13)

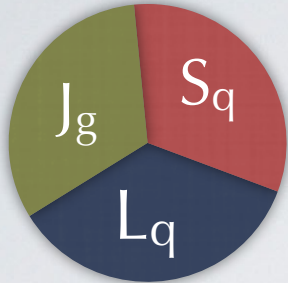
$$J^u = 0.229 \pm 0.002^{+0.008}_{-0.012}, J^{\bar{u}} = 0.015 \pm 0.003^{+0.001}_{-0.000}$$

$$J^d = -0.007 \pm 0.003^{+0.020}_{-0.005}, J^{\bar{d}} = 0.022 \pm 0.005^{+0.001}_{-0.000}$$

Bacchetta & M.R., PRL **107** (11)

pizza “Tre Stagioni”

© M. Burkardt



PRL **78** (97) 610

Ji sum rule

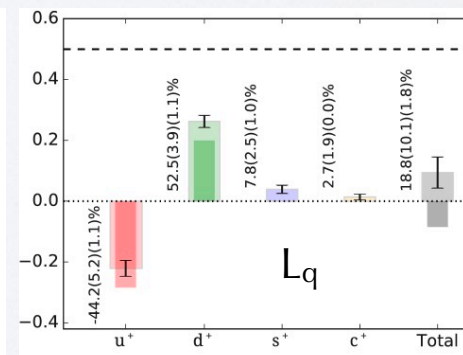
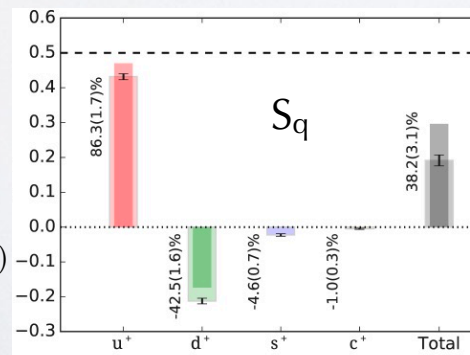
$$1/2 = \underbrace{L_q + S_q}_{J_q} + J_g$$

- manifestly gauge invariant
- “ready” for lattice (J_q , J_g from moments of GPD)
- * L_q does not satisfy canonical relations

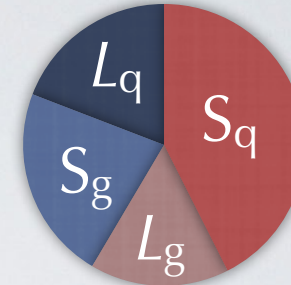
intuitive $L_q - L_g$ difference:
color Lorentz force acting on active quark and
producing a torque along its trajectory Burkardt, PRD **88** (13)

Lattice calculations
of S_q and $L_q = (J_q - S_q)$

Alexandrou et al., PRD **101** (20)



pizza “Quattro Stagioni”



NPB **337** (90) 509

Jaffe-Manohar

$$1/2 = L_q + S_q + L_g + S_g$$

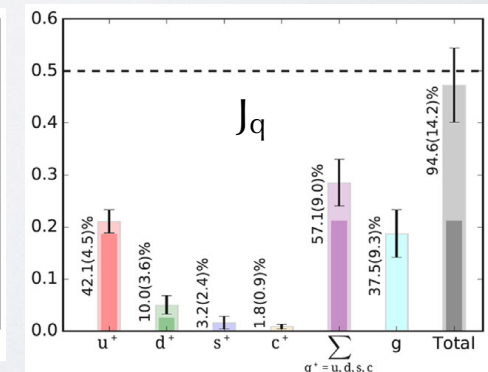
- L_q and L_g satisfy canonical relations
- * each term gauge dependent (but measurable)
- L_q and L_g can be computed from Wigner distributions, or from twist-3 GPDs

Lorcé & Pasquini, PRD **84** (11)

also, exploratory calculations on lattice

Engelhardt, PRD **95** (17); **102** (20)

dark bars: connected diagrams



QCD Energy-Momentum Tensor (EMT)

	Energy Density		Momentum Density	
$T^{\mu\nu} =$	T^{00}	T^{01}	T^{02}	T^{03}
	T^{10}	T^{11}	T^{12}	T^{13}
	T^{20}	T^{21}	T^{22}	T^{23}
	T^{30}	T^{31}	T^{32}	T^{33}
	Energy Flux		Momentum Flux	
				— shear forces
				— pressure

$$\langle P' | T_{\mu\nu}^{q,g} | P \rangle = \bar{u}(P') \left[A^{q,g}(t) \frac{P_\mu P_\nu}{M_N} + J^{q,g}(t) \frac{i(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho}) \Delta^\rho}{2M_N} + D^{q,g}(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{5M_N} + \bar{c}_{q,g}(t) g_{\mu\nu} \right] u(P)$$

Charges

$A^{q,g}(0)$ = mass and momentum of partons

$J^{q,g}(0)$ = angular momentum of partons

$D^{q,g}(0)$ = “D-term” related to internal stability

$\bar{c}^{q,g}$ = “anomalous” contribution to mass (trace T^μ_μ)

Connection to GPDs

$$\int dx x H(x, \xi, t) = A(t) + \frac{4}{5} D(t) \xi^2$$

$$\int dx x E(x, \xi, t) = 2J(t) - A(t) - \frac{4}{5} D(t) \xi^2$$

Mechanical properties of the Nucleon

Fourier Transf. of EMT in Breit frame

$$T_{ij}(\mathbf{r}) = \underset{\substack{\uparrow \\ \text{shear force}}}{s(r)} \left(\frac{r_i r_j}{r^2} - \frac{1}{3} \delta_{ij} \right) + \underset{\substack{\uparrow \\ \text{isotopic pressure}}}{p(r)} \delta_{ij}$$

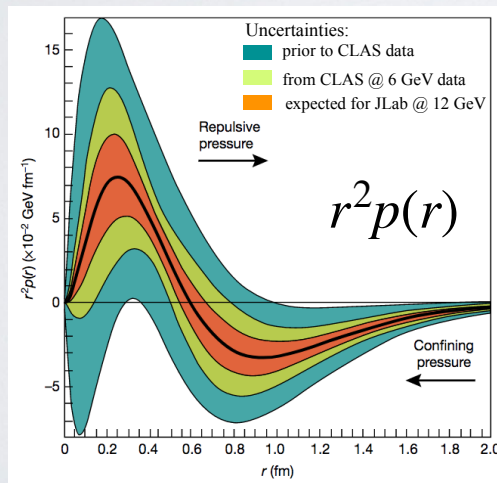
Lorcé et al, P.L. **B776** (18) 38

Lorcé et al., E.P.J. **C79** (19) 1

Polyakov, P.L. **B555** (03) 57

$$s(r) = -\frac{1}{2M} r \frac{d}{dr} \frac{1}{r} \frac{d}{dr} [\text{F.T. of } D(t)]$$

$$p(r) = \frac{1}{6M} \frac{1}{r^2} \frac{d}{dr} r^2 \frac{d}{dr} [\text{F.T. of } D(t)]$$



Girod et al., Nature **557** (18)
7705

Mechanical properties of the Nucleon

Fourier Transf. of EMT in Breit frame

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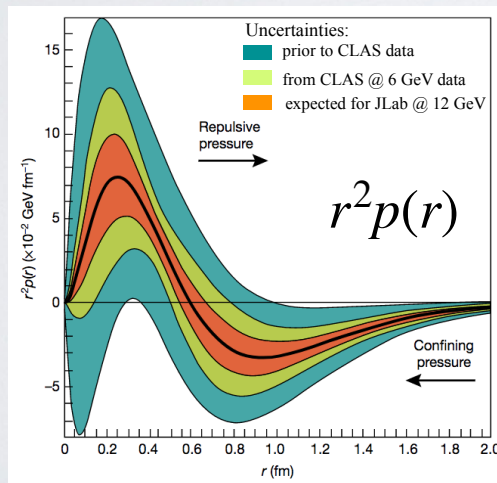
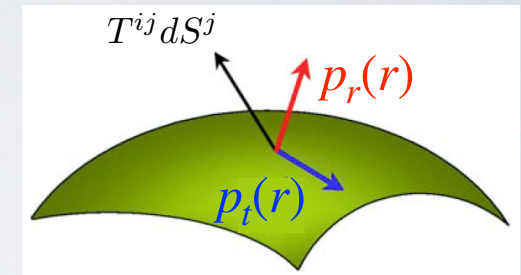
Lorcé et al, P.L. **B776** (18) 38
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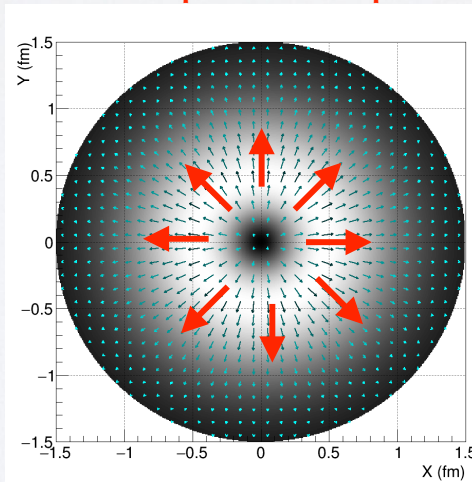
$$p_r(r) = p(r) + \frac{2}{3}s(r)$$

$$p_t(r) = p(r) - \frac{1}{3}s(r)$$

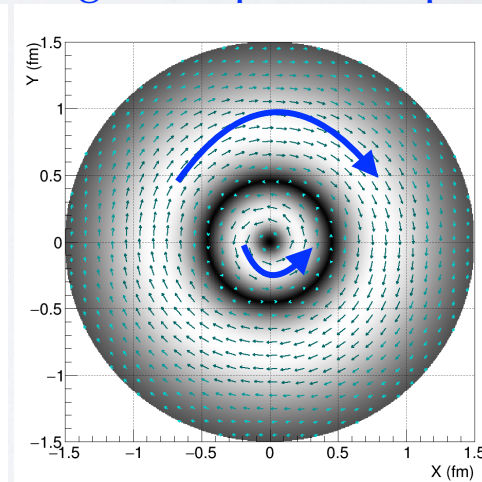


Girod et al., Nature **557** (18) 7705

radial pressure $p_r(r)$



tangential pressure $p_t(r)$

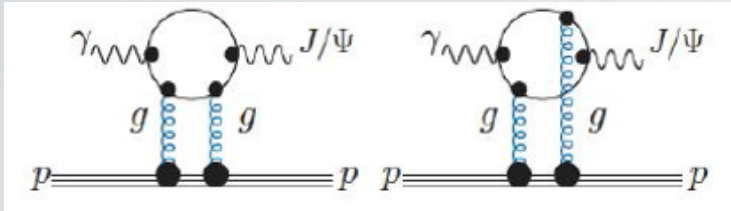


node at
 $r \sim 0.45$ fm
then
changes sign

always positive, fades away with r

Burkardt et al, Prog.Part.Nucl.Phys. **131** (23)

Gluonic EMT form factors



J/ψ DVMP suggested to address the gluon EMT

$$\frac{d\sigma}{dt} \sim |\mathcal{M}_{\gamma p \rightarrow J/\psi}(t)|^2 \sim |\langle P' | T_{\mu}^{\mu g} | P \rangle|^2 \xrightarrow{t \rightarrow 0} \begin{cases} A^g(0) \\ D^g(0) \\ \bar{c}^g(0) \end{cases}$$

$$D^g(0) \rightarrow \text{gluon contribution to} \begin{cases} \text{mechanical radius} & r_p = \sqrt{\frac{\int d\mathbf{r} r^2 p_r(r)}{\int d\mathbf{r} p_r(r)}} \\ \text{mass radius} & r_m = \sqrt{\frac{\int d\mathbf{r} r^2 T^{00}(r)}{\int d\mathbf{r} T^{00}(r)}} \end{cases}$$

lattice / pheno / model analyses → **mechanical and mass radii < charge radius**

gluon contribution extends proton size w.r.t. quark

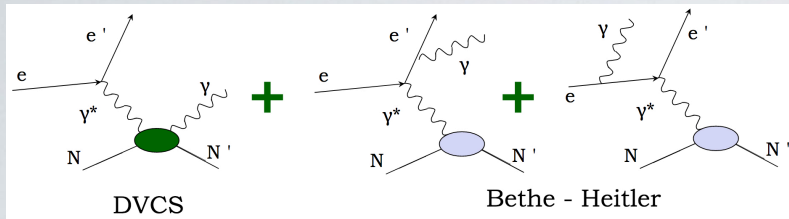
Hackett et al, PRL **132** (24)

$\bar{c}^g(0) \rightarrow$ gluon contribution to proton mass from trace anomaly

talk by
Castelli, Wednesday

Problems: - factorization th. holds only for V= J/ψ, Y production at threshold
- lowest-order approximation in M_N / M_V and α_s

Deconvolution problem



GPDs from interference amplitude
DVCS - Bethe-Heitler

interference cross section contains convolutions of
perturbative kernels and Compton Form Factors (CFF)

$$\text{CFF}(\xi, t) = \underbrace{\text{PV} \int_{-1}^1 dx \frac{\text{GPD}(x, \xi, t)}{x - \xi}}_{\text{Re(CFF)}} - \underbrace{i\pi \text{GPD}(x = \pm \xi, \xi, t)}_{\text{Im(CFF)}} + o\left(\frac{1}{Q^2}\right)$$

How to deconvolute
GPDs from CFFs ?

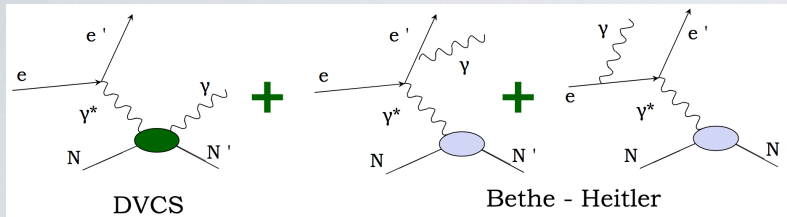
problem of shadow GPDs

Bertone et al, PRD **103**

(21)

Cichy et al, PRD **110** (24)

Deconvolution problem

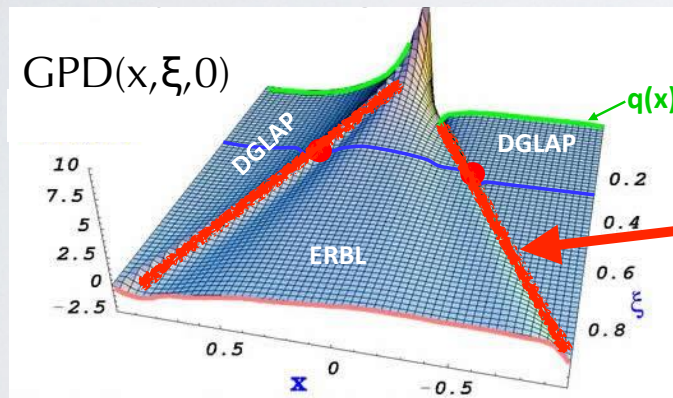


GPDs from interference amplitude
DVCS - Bethe-Heitler

interference cross section contains convolutions of
perturbative kernels and Compton Form Factors (CFF)

$$\text{CFF}(\xi, t) = \underbrace{\text{PV} \int_{-1}^1 dx \frac{\text{GPD}(x, \xi, t)}{x - \xi}}_{\text{Re(CFF)}} - \underbrace{i\pi \text{GPD}(x = \pm \xi, \xi, t)}_{\text{Im(CFF)}} + o\left(\frac{1}{Q^2}\right)$$

How to deconvolute
GPDs from CFFs ?



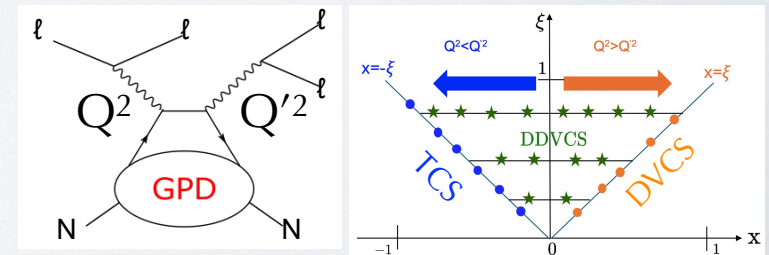
$$\text{GPD}(x, 0, 0) = \text{PDF}(x)$$

Access only to the
 $(x = \pm \xi, \xi, t)$ dependence

problem of shadow GPDs
Bertone et al, PRD **103**
(21)
Cichy et al, PRD **110** (24)

Alternatives: - access $x \neq \pm \xi$ dependence with **DDVCS**
(proposal approved (C1) by JLab PAC53)

- use **lattice**

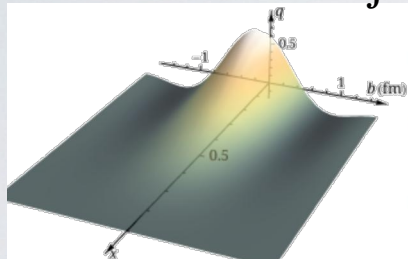


Deja et al, PRD **107** (23) (25) Alvarado et al., PRC **111**

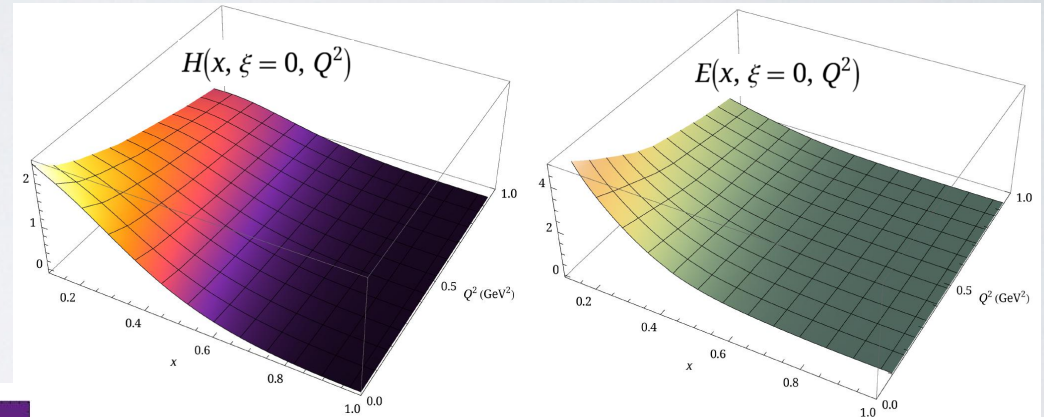
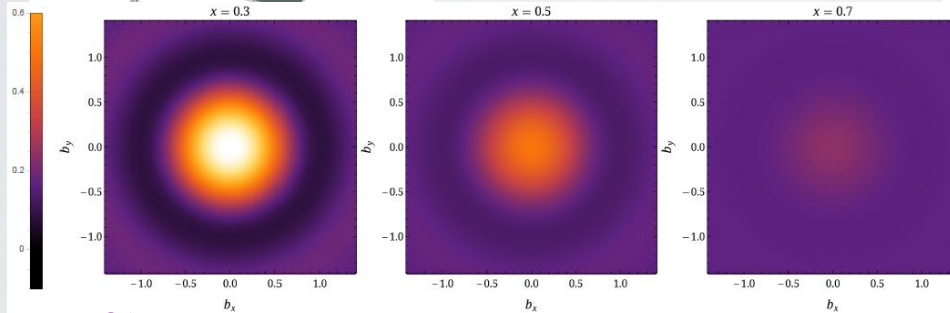
Lattice calculations of GPDs

Access x-dependence of GPDs using LaMET theory, matching parton correlators in Euclidean space to Light-cone ones with perturbative coefficients and for large hadron momenta $P_z \gg M$

$$q(x, \mathbf{b}) = \int d\Delta_\perp e^{-i\mathbf{b} \cdot \Delta_\perp} H^q(x, 0, t = -\Delta_\perp^2)$$



Lin, PRL **127** (21)



Also for $\tilde{H}$ and for pion H

Lin (MSULatt), PLB **824** (22); **846** (23)

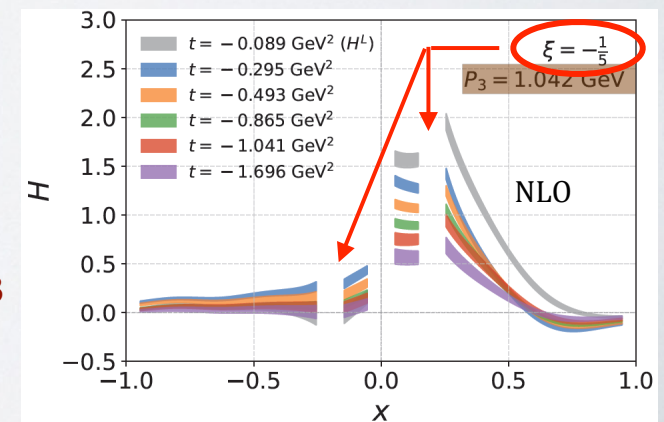
talks by

Lin, Miller, Wednesday

Cichy, Zhang overview, Thursday

new: at $\xi \neq 0$ using
asymmetric frame

ETMC, arXiv:2508.17998



Conclusions

Significant progresses in many areas

Complementarity between experiments, phenomenology, theory, and lattice

New theory developments: precision (higher-order correction), novel processes..

New robust methodologies and data science tools for reliable phenomenological information

Significant contributions from lattice, guiding both theory and experiments in “intricate” regions

Future more precise data, particularly from EIC, can turn the field to a higher level

Enjoy the rest of the workshop !

