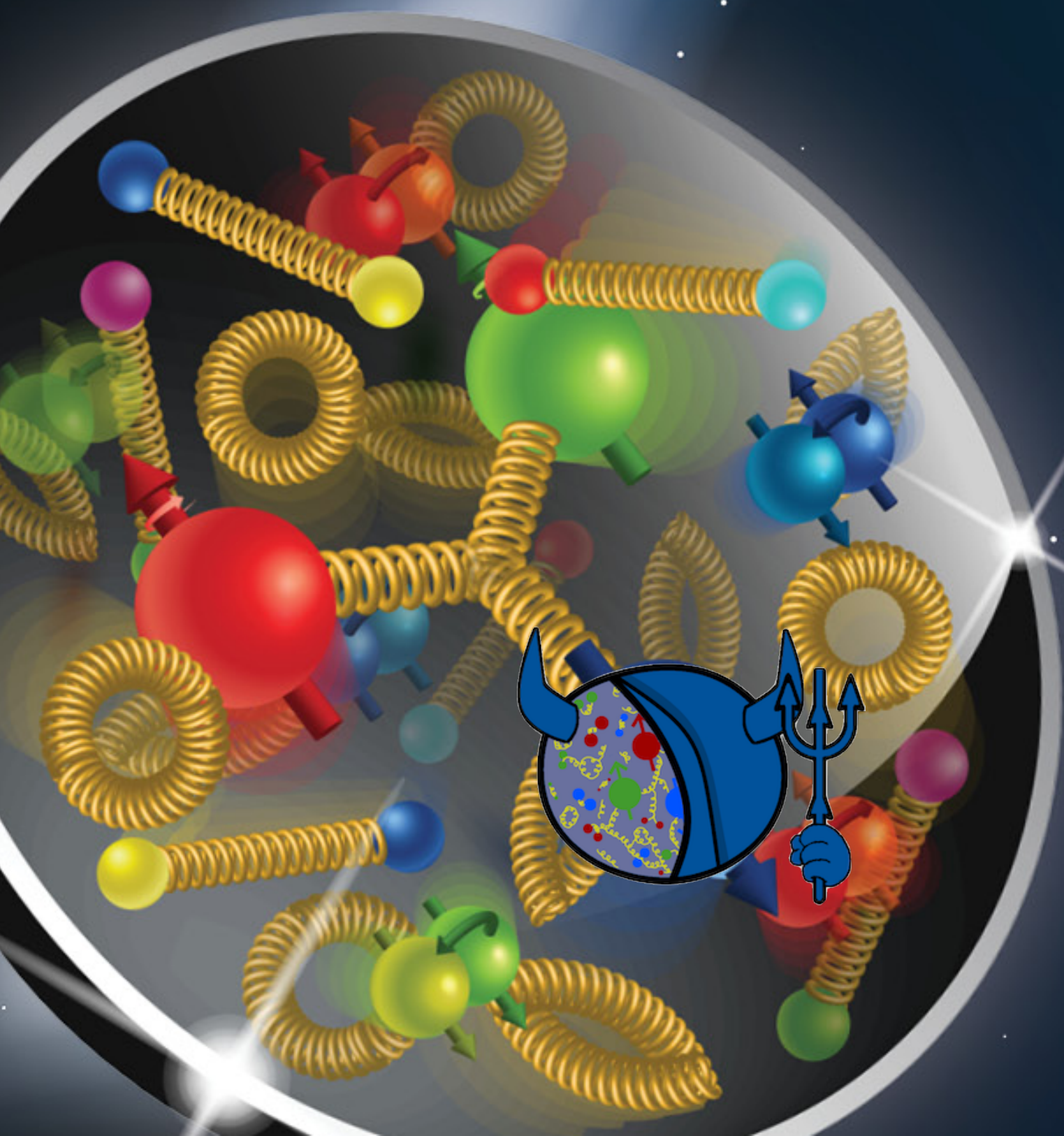
THREE-DIMENSIONAL NUCLEON STRUCTURE

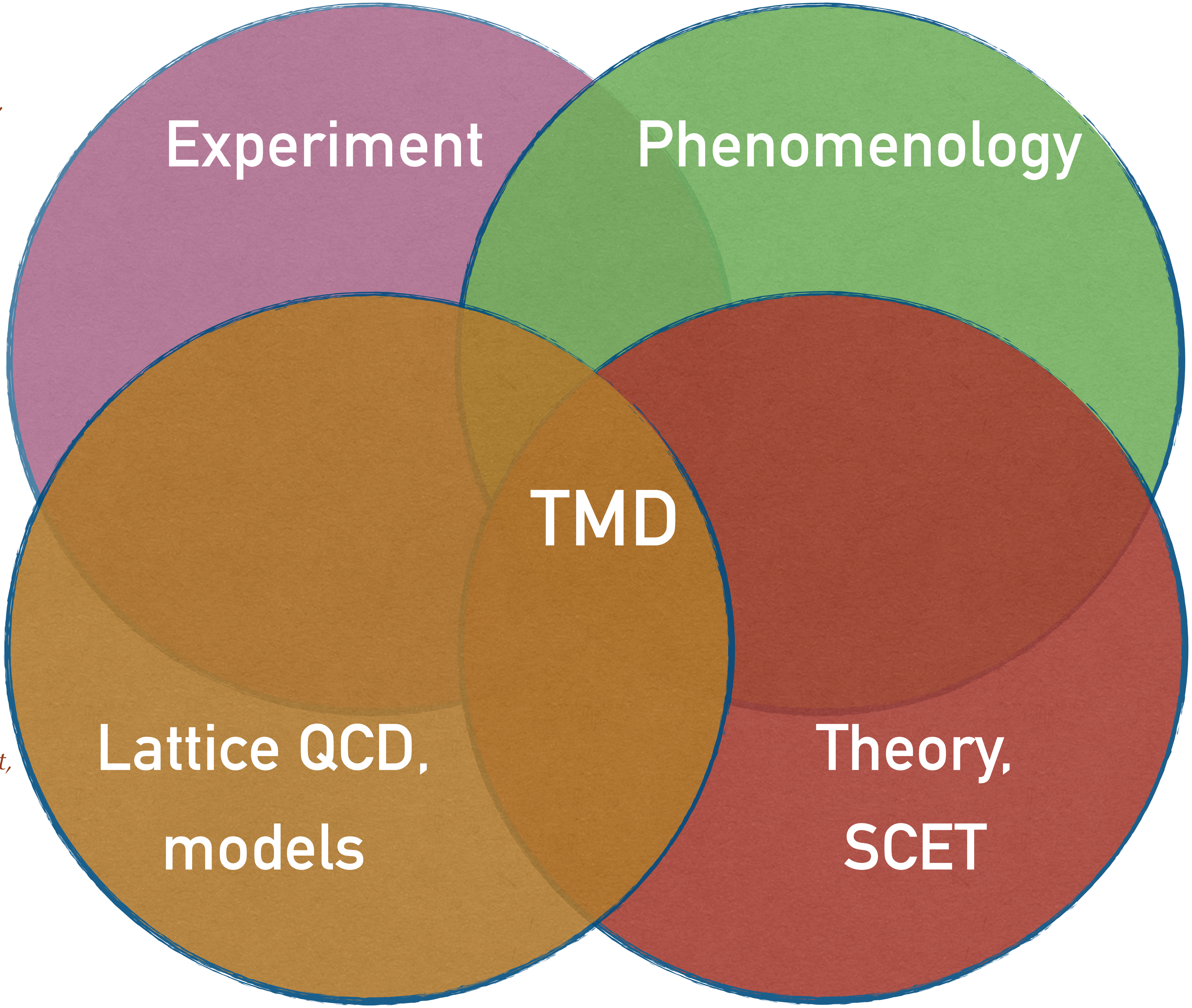


Alexei Prokudin

PSU Berks and JLab

TMD PHYSICS

Talks by:
B. Parsamyan,
H. Avakyan,
M.Scott,
T. Hayward,
A. Martin,
Z. Ji,
Y. Deng,
V. Andrieux,
C. Aidala,
etc



Talks by:
A. Bacchetta,
P. Barry,
F. Celiberto,
A. Kerbizi,
F. Zhao,
I. Fernando,
A. Conover,
M. Alrashed,
etc

Talks by:
M. Engelhardt,
D. Sivers,
Y. Zhao,
etc

Talks by:
J. Terry,
L. Gamberg,
T. Rainaldi,
I. Moult,
etc

TMD Handbook

April 6, 2023

A modern introduction to the physics of
Transverse Momentum Dependent distributions

TMD Collaboration

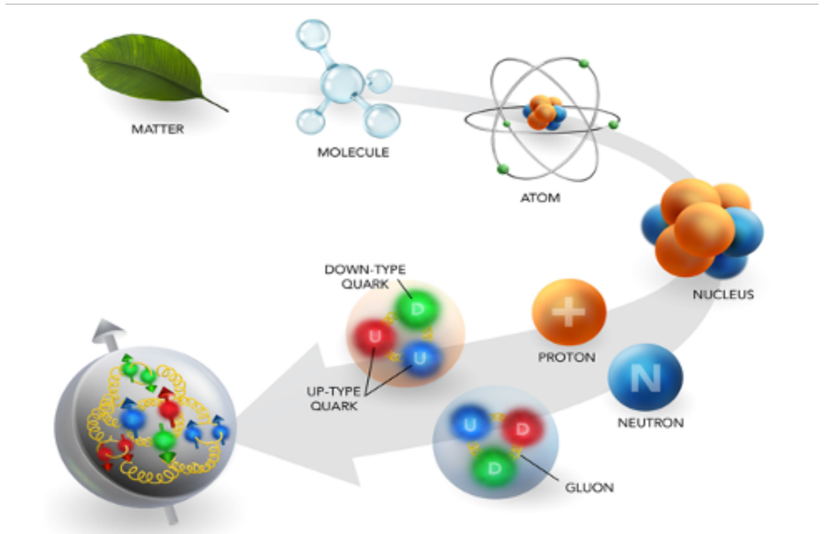
Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

* - Editors

Almost everything I will talk about can be found in the TMD Handbook
[2304.03302]

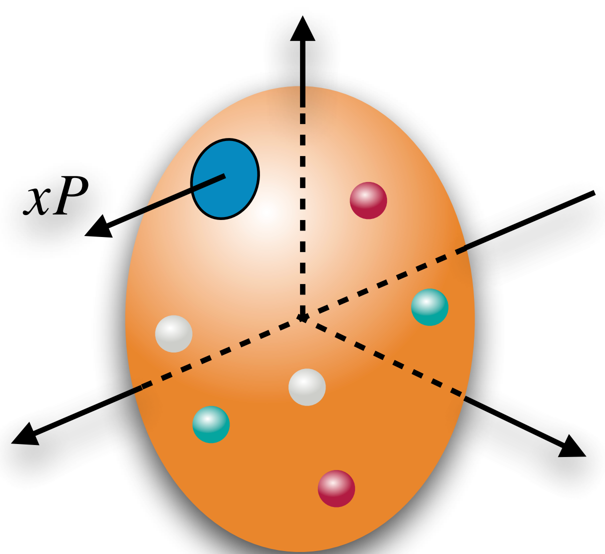
- TMD Topical Collaboration
- 12 chapters
- 471 pages

UNRAVELLING THE MYSTERIES OF RELATIVISTIC HADRONIC BOUND STATES



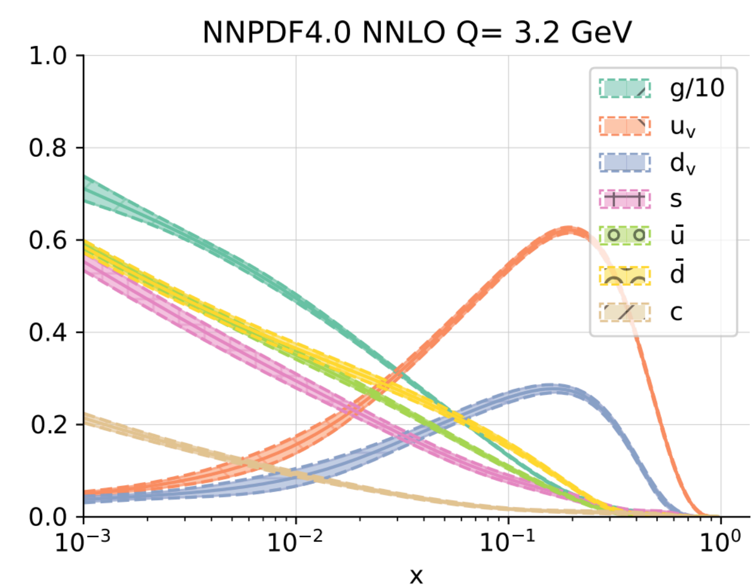
- Nucleons provide 98% of the mass of the visible universe
- One of the goals of the modern nuclear physics is to study details of the structure of the nucleon

Parton Distribution Functions provide fundamental description



$f_{q/P}(x)$

longitudinal

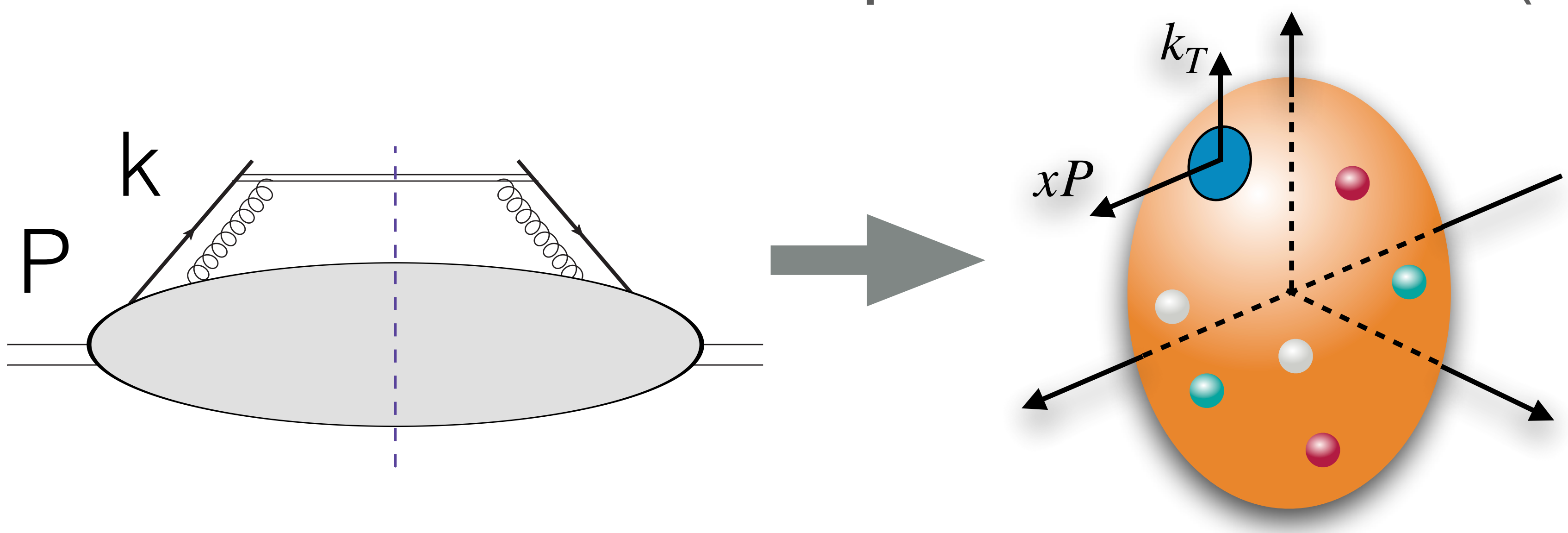


- Probability density to find a quark with a momentum fraction x
- 1D snapshot of fundamental constituents
- Study of confined quarks and gluons

HADRON'S PARTONIC STRUCTURE

To study the physics of *confined motion of quarks and gluons* inside of the proton one needs a new type "hard probe" with two scales.

Transverse Momentum Dependent functions (TMDs)

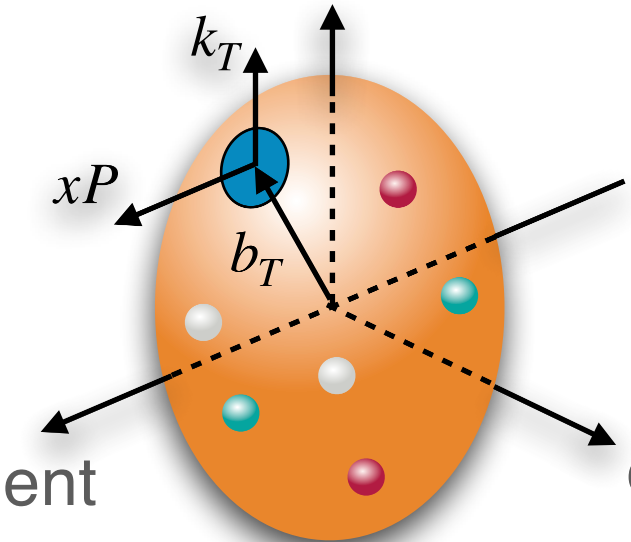


$$f_{q/P}(x, k_T)$$

longitudinal & transverse

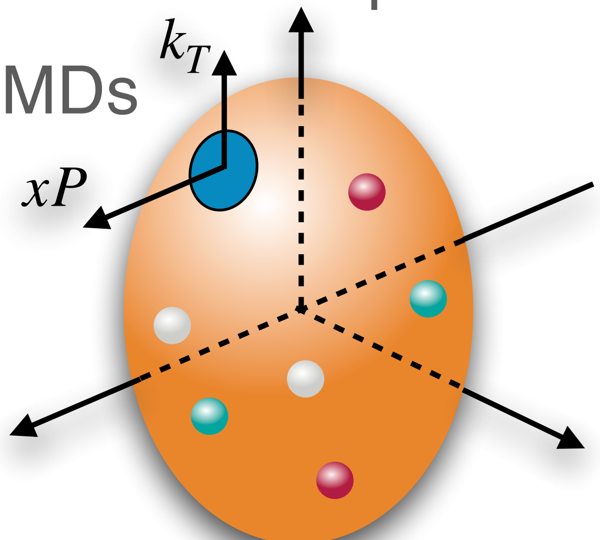
- One large scale (Q) sensitive to particle nature of quark and gluons
- One small scale (k_T) *sensitive to how QCD bounds partons* and to the detailed structure at ~fm distances.
- TMDs provide detailed information on the spin structure
- TMDs contain new probes, e.g. qgq operators rather that just qq or gg and thus include correlations
- TMDs encode 3D structure in the momentum space (complementary to GPDs)

Wigner distributions
(Fourier transform of GTMDs =
Generalized Transverse
Momentum Distributions)



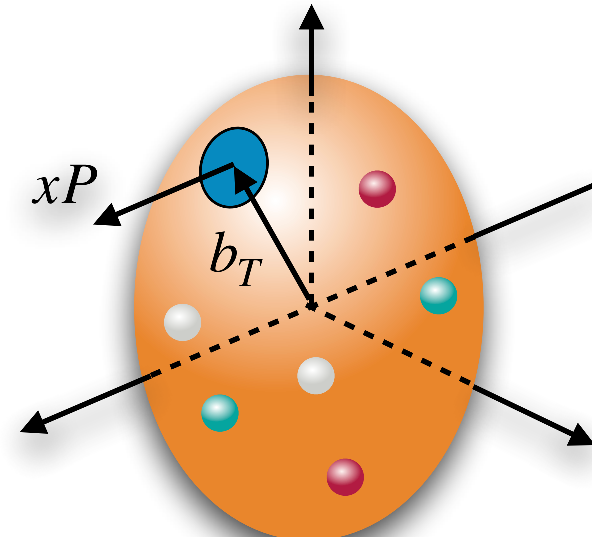
Transverse Momentum Dependent

Distributions TMDs

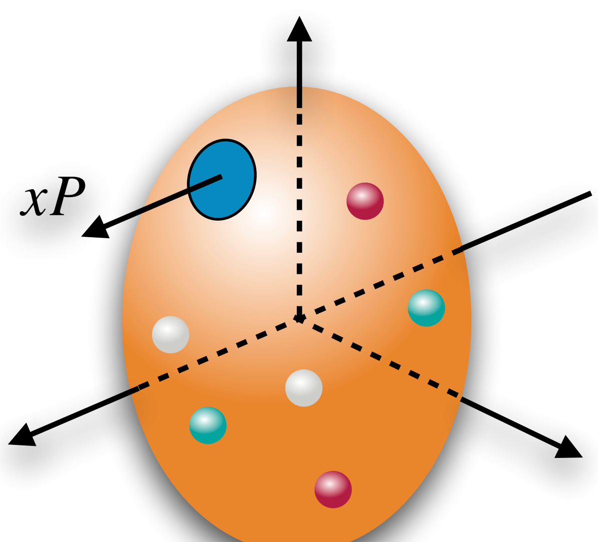


Fourier transform
of Generalized Parton Distributions

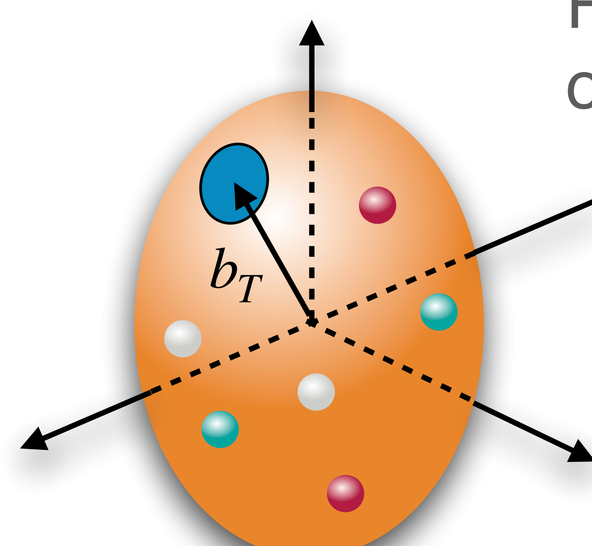
(GPDs)



PDFs



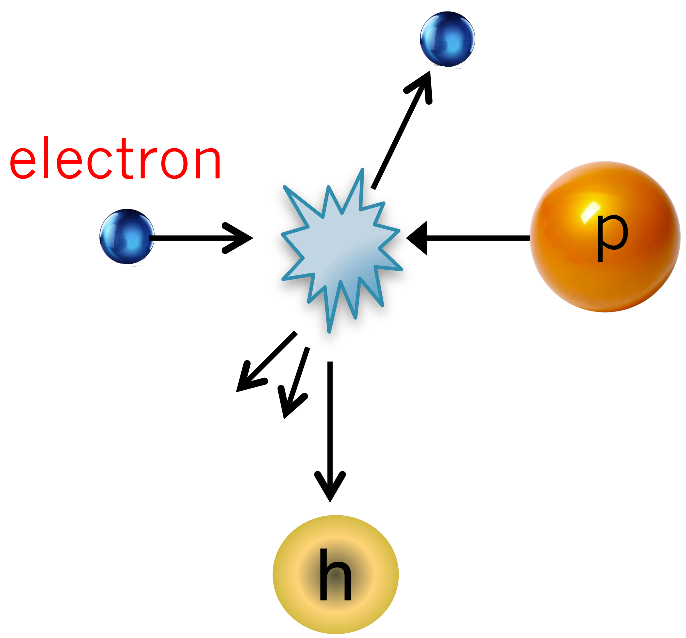
Fourier transform
of Form Factors

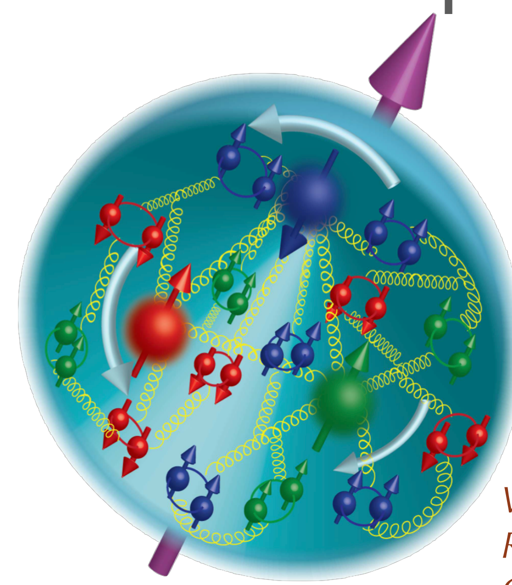


SEE, E.G., C. LORCÉ, B. PASQUINI, M. VANDERHAEGHEN, JHEP 1105 (11)

QCD FACTORIZATION IS THE KEY!

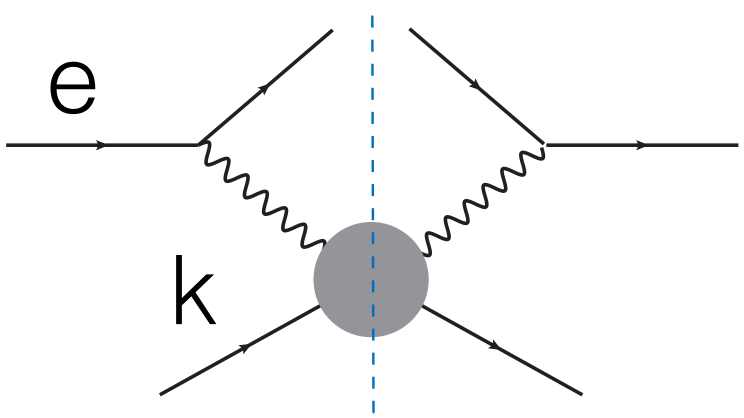
We need a probe to “see” quarks and gluons



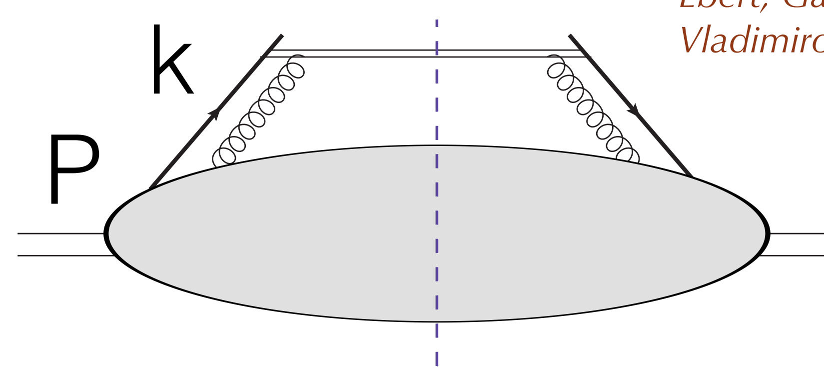


Vladimirov, arXiv:2307.1305
Rodini, Vladimirov, arXiv:2306.09495
Gamberg et al, arXiv:2211.13209
Ebert, Gao, Stewart, arXiv:2112.07680
Vladimirov, Moos, Scimemi, arXiv:2109.09771

$\sigma \approx$



$\otimes$



$$+\mathcal{O}\left(\frac{M^2}{Q^2}\right)$$

Factorization Probe Structure Power corrections

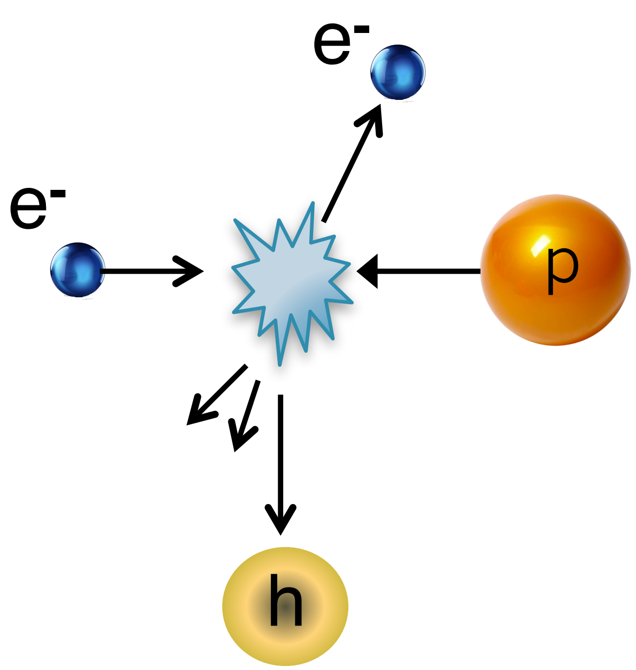
TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

Small scale → $q_T \ll Q$ ← Large scale

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

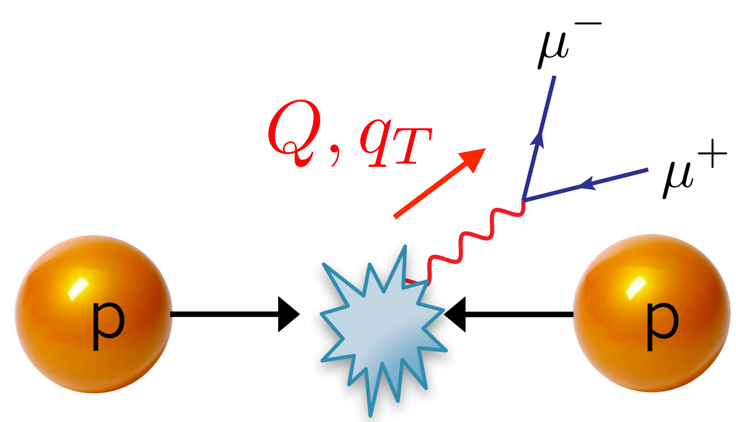
$$\sigma \sim f_{q/P}(x,k_T) D_{h/q}(z,k_T)$$



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)

Drell-Yan

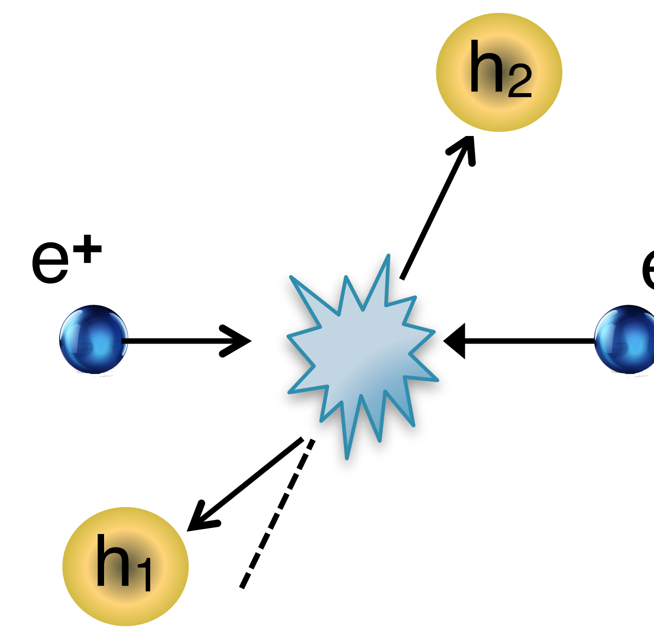
$$\sigma \sim f_{q/P}(x,k_T) f_{q/P}(x,k_T)$$



Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

Dihadron in e+e-

$$\sigma \sim D_{h_1/P}(z,k_T) D_{h_2/q}(z,k_T)$$



Collins, Soper (1983)
Collins (2011)

COLLINS-SOPER EVOLUTION EQUATIONS

$$\frac{d\ln \tilde{F}(x, b_T, \mu, \zeta)}{d\ln \mu} = \gamma_F(\mu)$$

μ = renormalization scale

- Anomalous dimension of the TMD, can be expanded in perturbative series

Known up to 4 loops

R.N. Lee, A. von Manteuffel, R.M. Schabinger, A.V. Smirnov, V.A. Smirnov and M. Steinhauser, Phys. Rev. Lett. 128 (2022) 212002

$$\frac{\partial \ln \tilde{F}(x, b_T, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T, \mu)$$

ζ = Collins-Soper parameter

- Collins-Soper kernel, can be expanded in perturbative series at small b_T

Known up to 4 loops

C. Duhr, B. Mistlberger and G. Vita, Phys. Rev. Lett. 129 (2022) 162001
I. Moult, H.X. Zhu and Y.J. Zhu, JHEP 08 (2022) 280

$$\frac{d\tilde{K}(b_T, \mu)}{d\ln \mu} = -\gamma_K(\mu)$$

- Cusp anomalous dimension, can be expanded in perturbative series

Known up to 5 loops

F. Herzog, S. Moch, B. Ruijl, T. Ueda, J.A.M. Vermaseren, A. Vogt, Phys. Lett. B 790 (2019)

COLLINS-SOPER EVOLUTION EQUATIONS

Solutions of evolution equations contain large logarithms $\alpha_s \log(Q/q_T) \sim \alpha_s \log(Qb_T) \sim 1$ and this logs can spoil perturbative convergence

$$\begin{aligned}\widetilde{\sigma}^W(\boldsymbol{b}_T) = f_q(x_1) f_{\bar{q}}(x_2) C[\alpha_s] \exp\Bigg\{ &\frac{\alpha_s}{4\pi} \left(d_{12} L_b^2 + d_{11} L_b \right) \\ &+ \left(\frac{\alpha_s}{4\pi}\right)^2 \left(d_{23} L_b^3 + d_{22} L_b^2 + d_{21} L_b \right) \\ &+ \left(\frac{\alpha_s}{4\pi}\right)^3 \left(d_{34} L_b^4 + d_{33} L_b^3 + d_{32} L_b^2 + d_{31} L_b \right) \Bigg\} + \ldots \\ &\quad \text{LL} \quad \text{NLL} \quad \text{NNLL} \quad \text{N}^3\text{LL}\end{aligned}$$

Towers of these logs are resummed to all orders and therefore the precision is defined as logarithmic precision: (LL) Leading Log, (NLL) Next-to-Leading Log, etc

The highest precision achieved so far in TMD phenomenology is N4LL

TMDS AT SMALL b_T

Operator Product Expansion is used to connect TMD to collinear PDFs (or other collinear functions for polarized TMDs)

Known up to N3LO

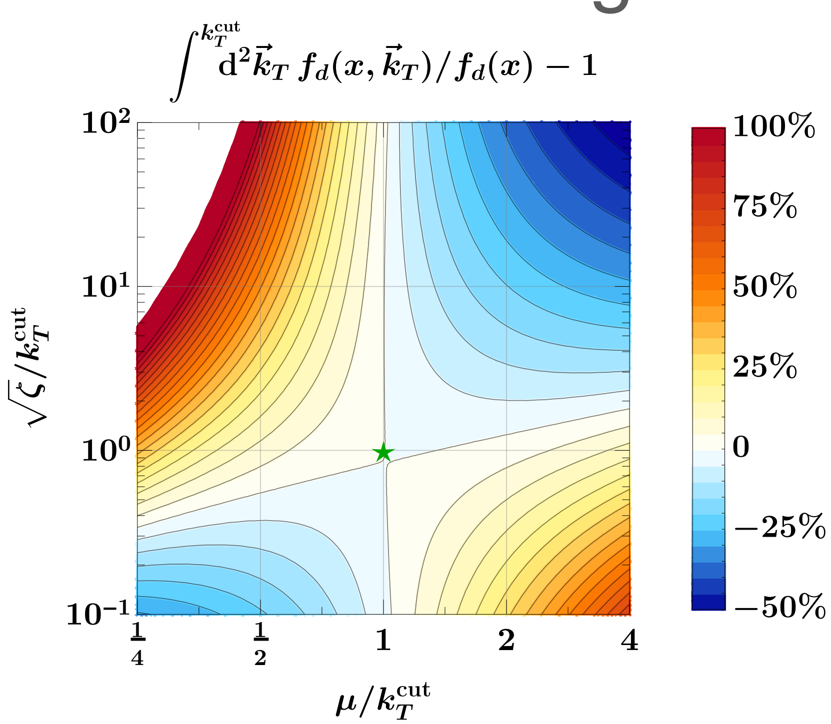
M.A. Ebert, B. Mistlberger and G. Vita, JHEP 09 (2020) 146
M.-x. Luo, T.-Z. Yang, H.X. Zhu and Y.J. Zhu, JHEP 06 (2021) 115

$$\tilde{f}_1^q(x, b_T; \mu, \zeta) = \sum_k \int_{x-}^{1+} \frac{d\hat{x}}{\hat{x}} \tilde{C}^{\rm PDF}_{q/k}\left(\frac{x}{\hat{x}}, b_T; \zeta, \mu, \alpha_s(\mu)\right) f_1^k(\hat{x}; \mu) \;+\; O\left[(m b_T)^p\right]$$

- New studies to extend OPE to other TMDs

Felix Rein, Simone Rodini, Andreas Schäfer, Alexey Vladimirov, e-Print: 2209.00962
Daniel Gutierrez-Reyes , Ignazio Scimemi, Alexey Vladimirov JHEP 07 (2018) 172
Ignazio Scimemi, Alexey Vladimirov Eur.Phys.J.C 78 (2018) 10, 802

- Are there integral relations?

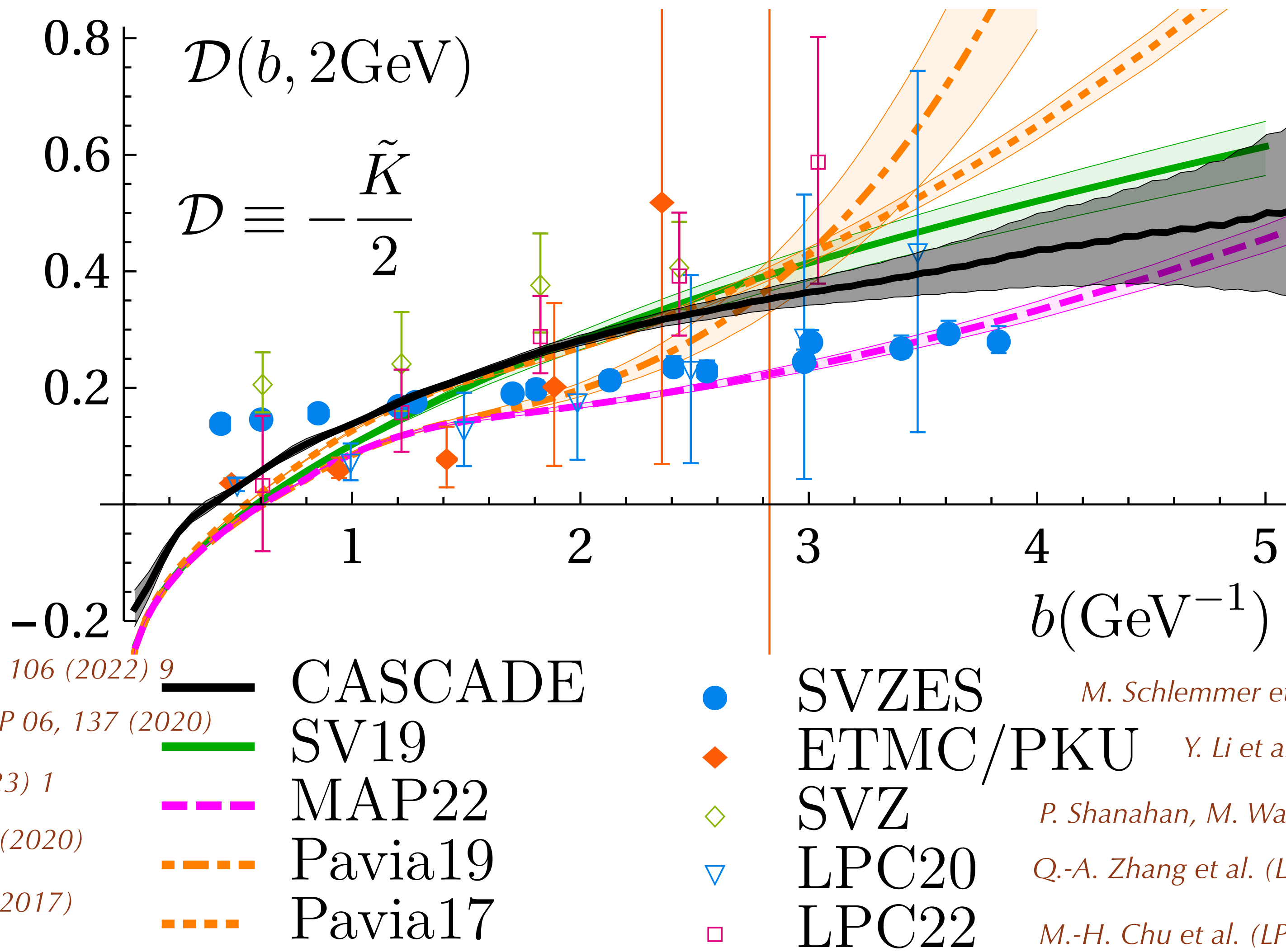


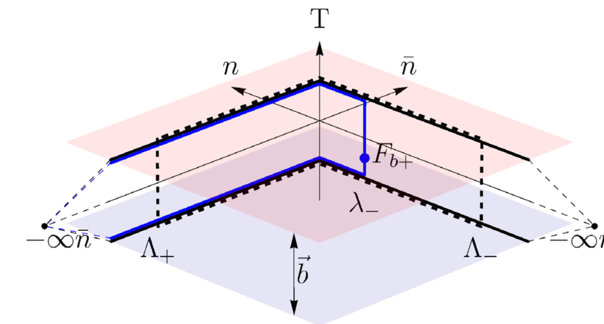
$$\int_{k_T \le k_T^{\rm cut}} {\rm d}^2\mathbf{k}_T\, f_{i/p}\left(x, \mathbf{k}_T, \mu = k_T^{\rm cut}, \sqrt{\zeta} = k_T^{\rm cut}\right) \simeq f_i(x, \mu = k_T^{\rm cut})$$

M. A. Ebert, J. K. L. Michel, I. W. Stewart and Z. Sun, JHEP 07 (2022) 129
Gonzalez-Hernandez, T. Rainaldi, T.C. Rogers Phys.Rev.D 107 (2023) 9, 094029
A. Bacchetta, A. Prokudin, Nucl.Phys.B 875 (2013) 536-551

COLLINS-SOPER KERNEL

Martinez and Vladimirov, Phys.Rev.D 106 (2022) 9





Martinez, Vladimirov, Phys.Rev.D 106 (2022) 9

I. Scimemi and A. Vladimirov, JHEP 06, 137 (2020)

Cerurri et al, Phys.Rev.D 107 (2023) 1

A. Bacchetta et al , JHEP 07, 117 (2020)

A. Bacchetta et al, JHEP 06, 081 (2017)

M. Schlemmer et al, JHEP 08, 004 (2021)

Y. Li et al., Phys. Rev. Lett. 128, 062002 (2022)

P. Shanahan, M. Wagman, and Y. Zhao, Phys. Rev. D104, 114502 (2021)

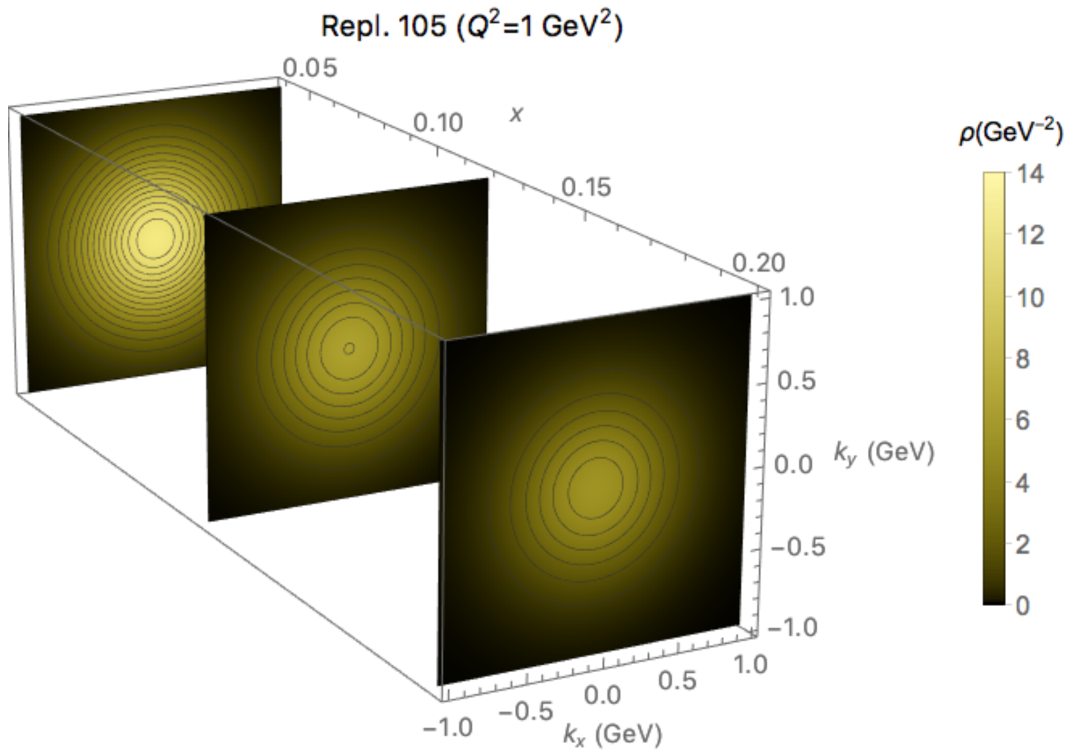
Q.-A. Zhang et al. (Lattice Parton), Phys. Rev. Lett. 125, 192001 (2020)

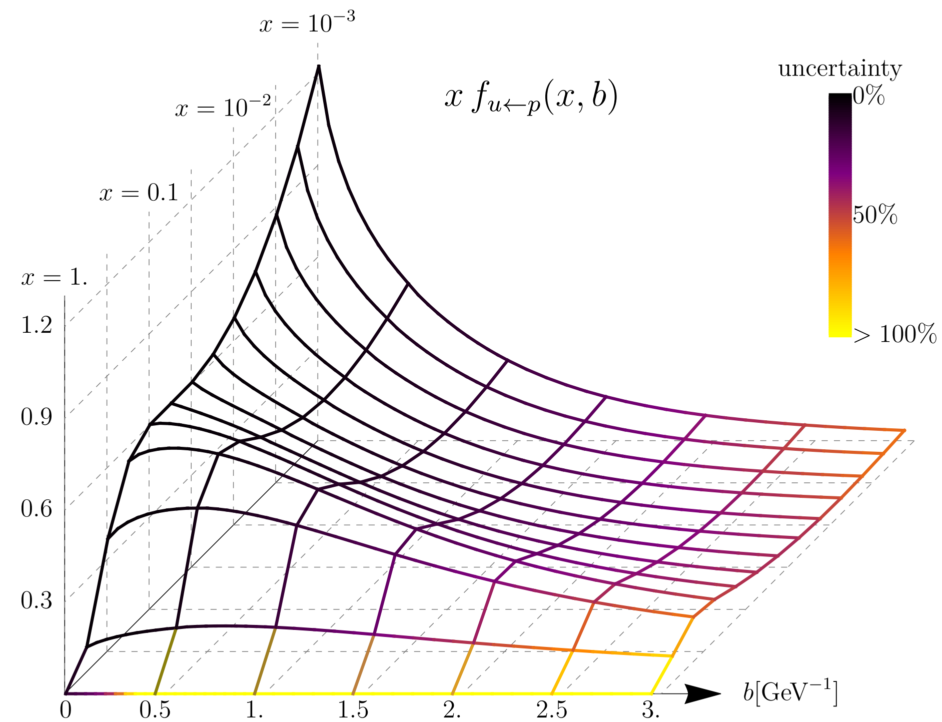
M.-H. Chu et al. (LPC), Phys.Rev.D 106 (2022) 3

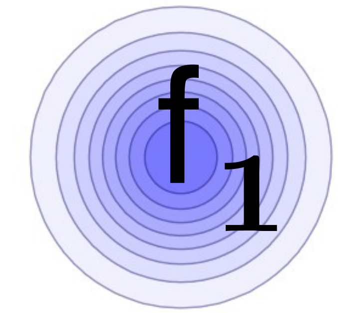
- Collins-Soper kernel is related to properties of QCD vacuum
- It can be extracted from the data *Alexey Vladimirov, Phys.Rev.Lett. 125 (2020) 19, 192002*
- It can be computed on lattice QCD

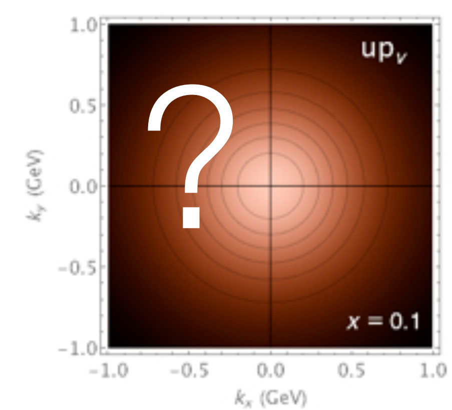
UNPOLARIZED STRUCTURE OF THE NUCLEON

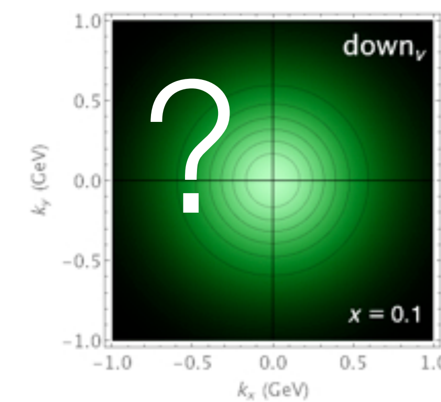
UNPOLARIZED TMD MEASUREMENTS

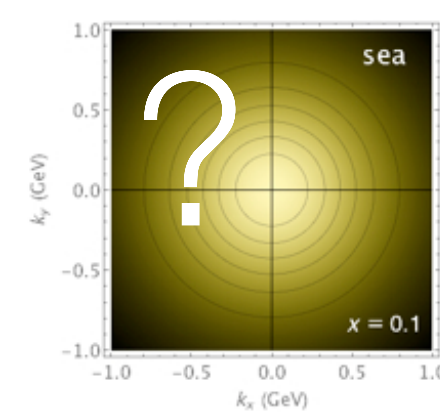












Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

V. Moos, I. Scimemi, A. Vladimirov, P. Zurita arXiv:2305.07473

- Addresses the question of partonic confined motion
- Evolution with x and Q^2
- Flavor dependence of unpolarized TMDs
- Interplay with collinear QCD at large q_T

TMD FITS OF UNPOLARIZED DATA

	Framework	W+Y	HERMES	COMPASS	DY	Z boson	W boson	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	✘	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	✘	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	✘	>100 (?)
Pavia 2013 arXiv:1309.3507	LO-PM	W	✔	✘	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO-PM	W	✔ (separately)	✔ (separately)	✘	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	✘	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	✘	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	✘	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	✘	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	✘	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	✘	457
Pavia 2019 arXiv:1912.07550	NNLO-N3LL	W	✘	✘	✔	✔	✘	353
SV 2019 arXiv:1912.06532	NNLO-N3LL	W	✔	✔	✔	✔	✘	1039
MAP pion 2022 arXiv:2210.01733	NLO-N3LL	W	✘	✘	✔	✘	✘	138
MAP 2022 arXiv:2206.07598	NNLO-N3LL-	W	✔	✔	✔	✔	✘	2031
JAM 2023 arXiv: 2302.01192	NLO-NNLL	W	✘	✘	✔	✘	✘	608
ART 2023 arXiv:2305.07473	N3LO-N4LL	W	✘	✘	✔	✔	✔	627

TMD ANALYSES

- Usually implement the data cut $q_T/Q < 0.2 \div 0.25$ to minimize power corrections (aka W term only)

- High perturbative accuracy and matching to collinear PDFs. Good perturbative convergence

- Neglecting small higher twist contributions (i.e. Boer-Mulders)

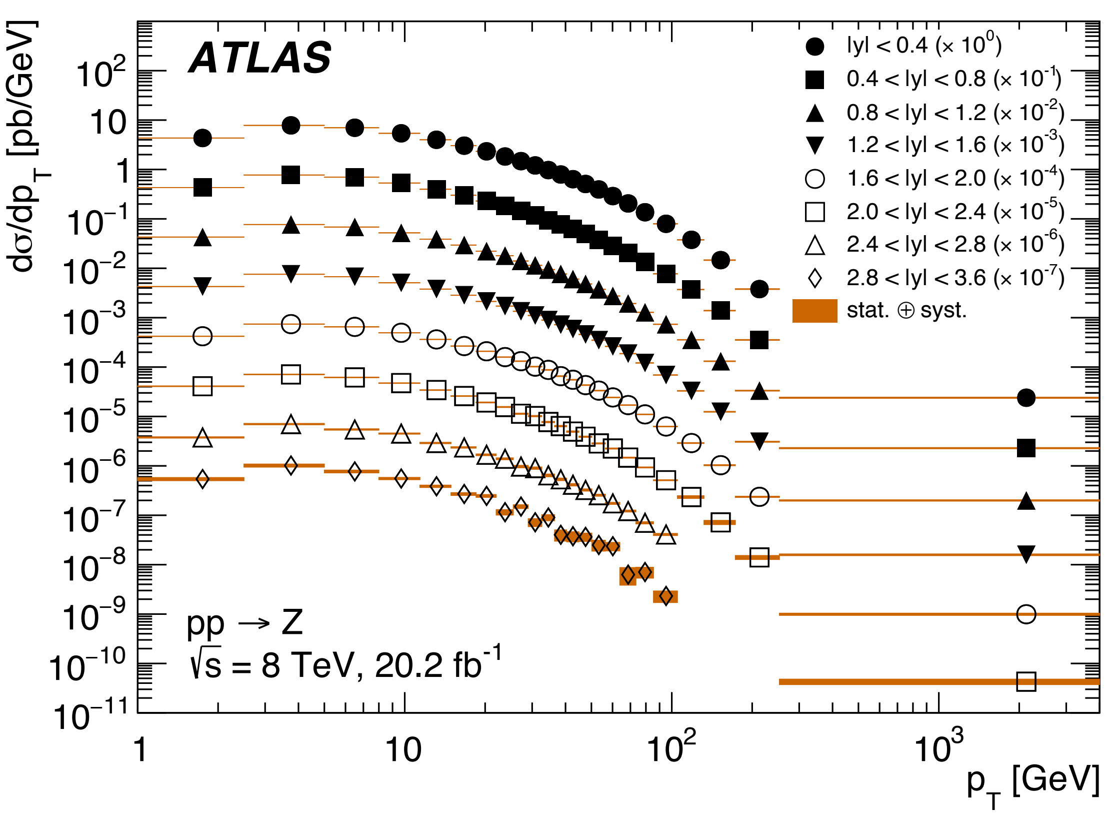
- Non perturbative TMD behavior in b_T and x - dependent, either flavor dependent or not

- Some differences in solutions of evolution equations and separation of perturbative and non perturbative contributions

UNPOLARIZED TMD MEASUREMENTS

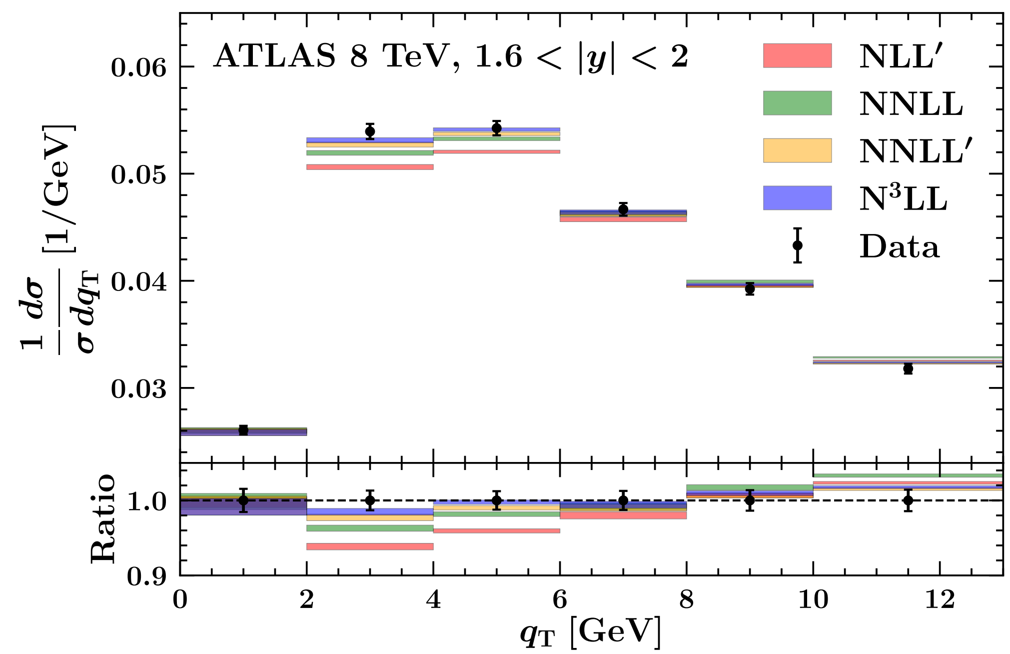
LHC provides DY data dominated by statistical sub % errors

The ATLAS Collaboration, arXiv:2309.09318

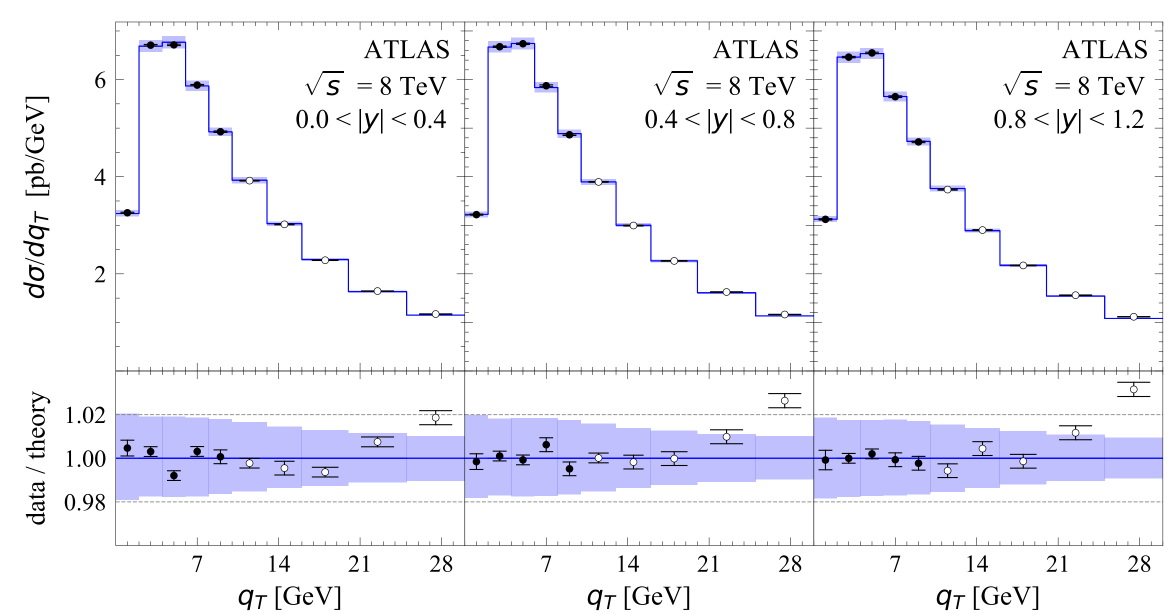


To be compared with precise TMD calculations

Bacchetta et al, JHEP 07 (2020) 117



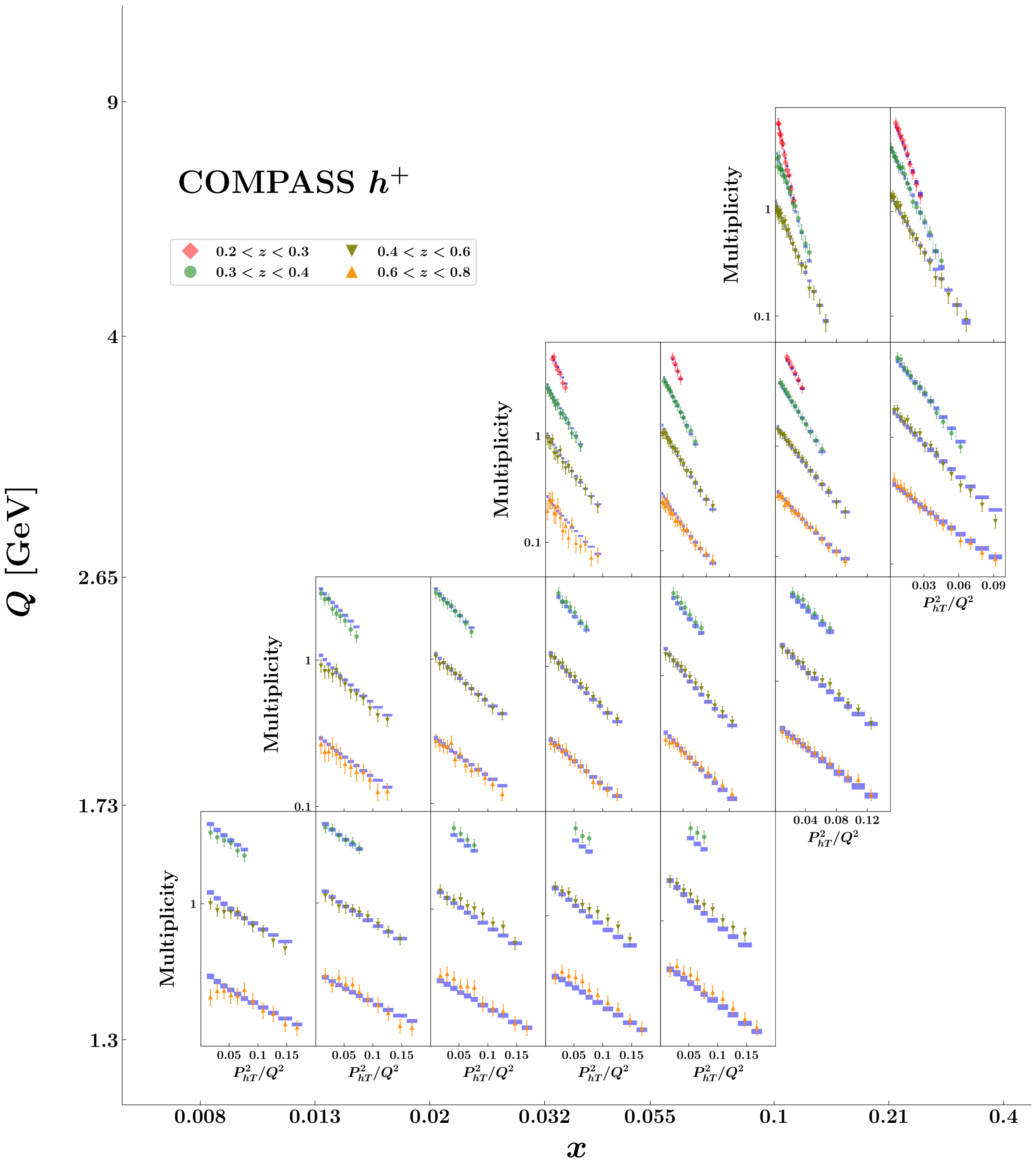
V. Moos, I. Scimemi, A. Vladimirov, P. Zurita arXiv:2305.07473



UNPOLARIZED SIDIS TMD MEASUREMENTS

f_1

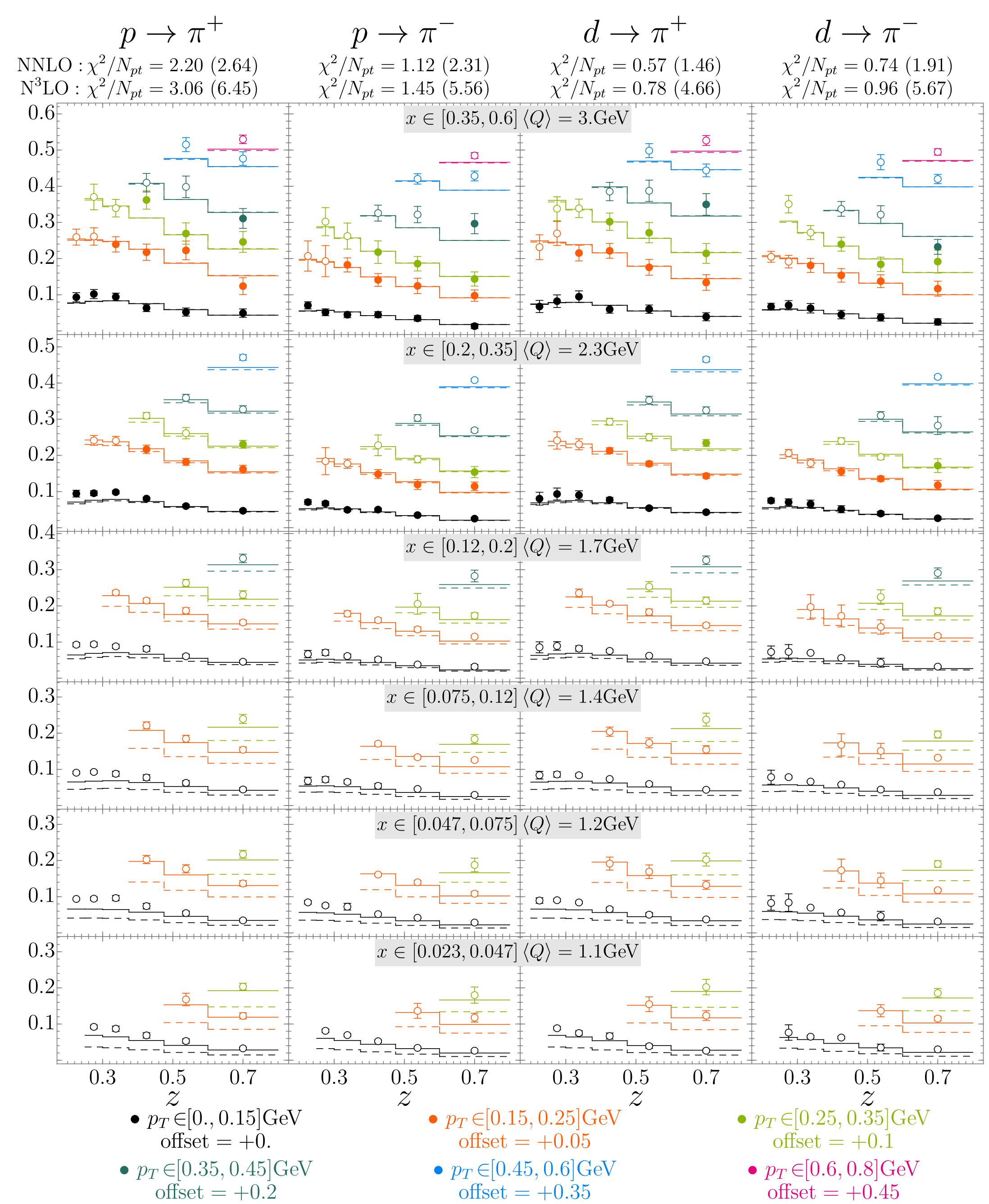
Combination of various processes is important for the tests of universality



MAP22:Bacchetta et al, JHEP 10 (2022) 127

$$\frac{d\sigma_{\omega}^{\rm SIDIS}}{dx\,dz\,d|\boldsymbol{q}_T|\,dQ} = \omega(x,z,Q)\,\frac{d\sigma^{\rm SIDIS}}{dx\,dz\,d|\boldsymbol{q}_T|\,dQ}.$$

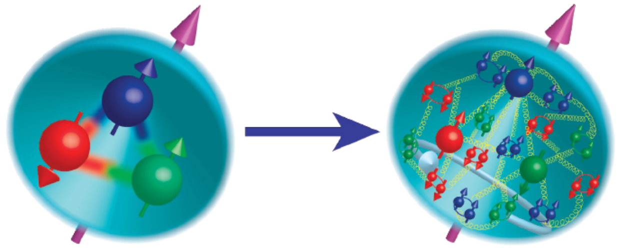
HERMES



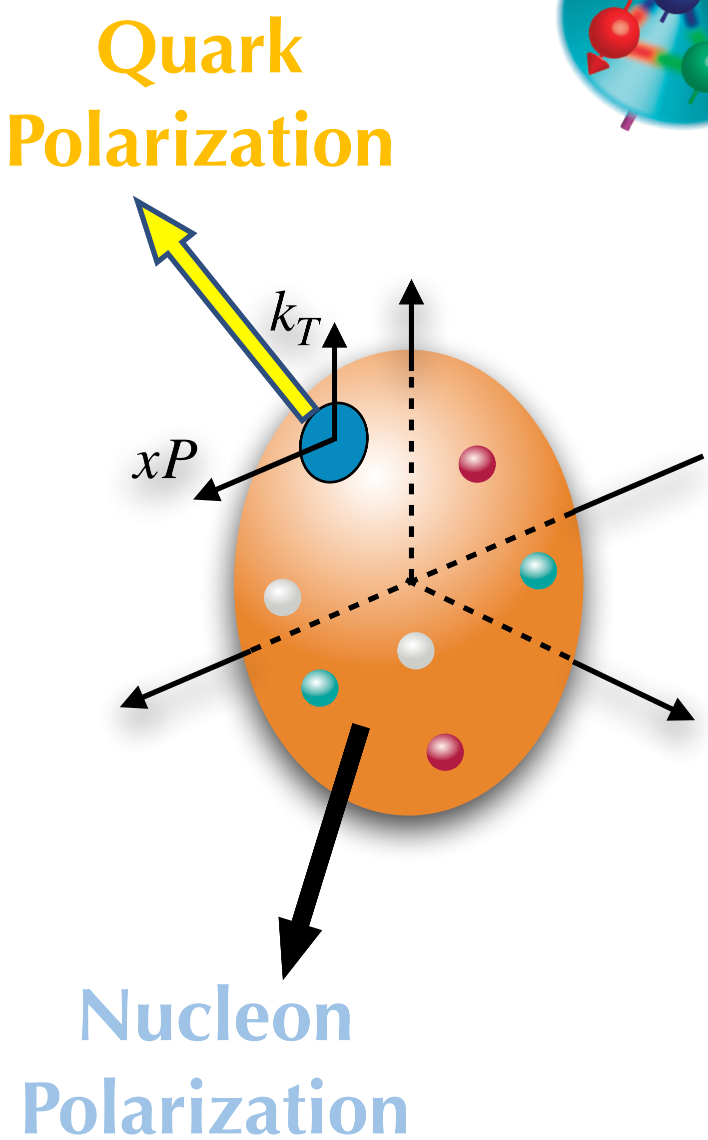
Ignazio Scimemi, Alexey Vladimirov JHEP 06 (2020) 137

SPIN STRUCTURE OF THE NUCLEON

Our understanding of hadron evolves: TMDs with Polarization



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons



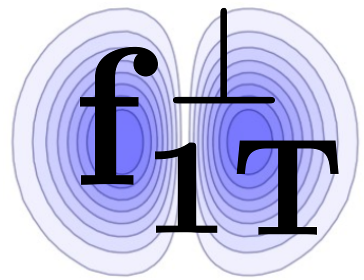
Nucleon Polarization		Quark Polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	U	$f_1(x,k_T^2)$ *Unpolarized*		$h_1^\perp(x,k_T^2)$ *Boer-Mulders*
	L		$g_1(x,k_T^2)$ *Helicity*	$h_{1L}^\perp(x,k_T^2)$ *Kozinian-Mulders,“worm” gear*
	T	$f_{1T}^\perp(x,k_T^2)$ *Sivers*	$g_{1T}(x,k_T^2)$ *Kozinian-Mulders, “worm” gear*	$h_1(x,k_T^2)$ *Transversity* $h_{1T}^\perp(x,k_T^2)$ *Pretzelosity*

Analogous tables for:

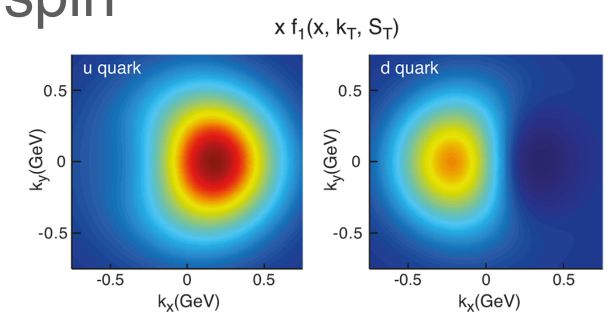
- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Nuclear targets $S \neq \frac{1}{2}$

POLARIZED TMD FUNCTIONS

Sivers function

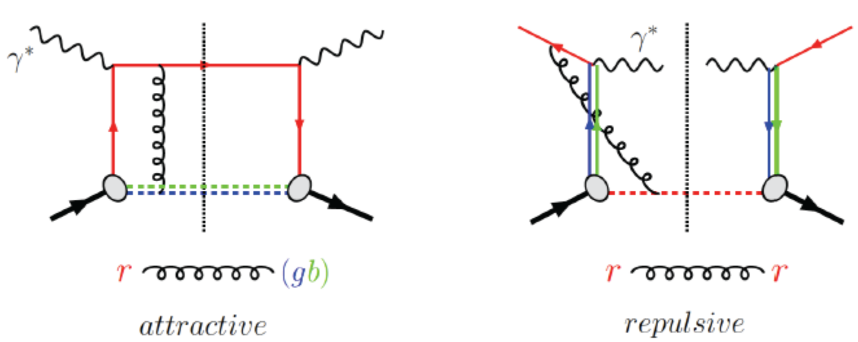


- Describes unpolarized quarks inside of transversely polarized nucleon
- Encodes the correlation of orbital motion with the spin



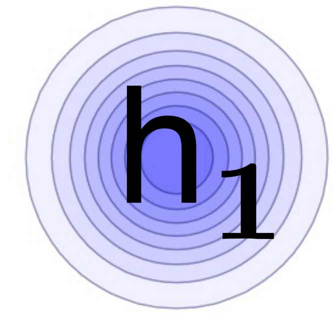
- Sign change of Sivers function is fundamental consequence of QCD

Brodsky, Hwang, Schmidt (2002), Collins (2002)



$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

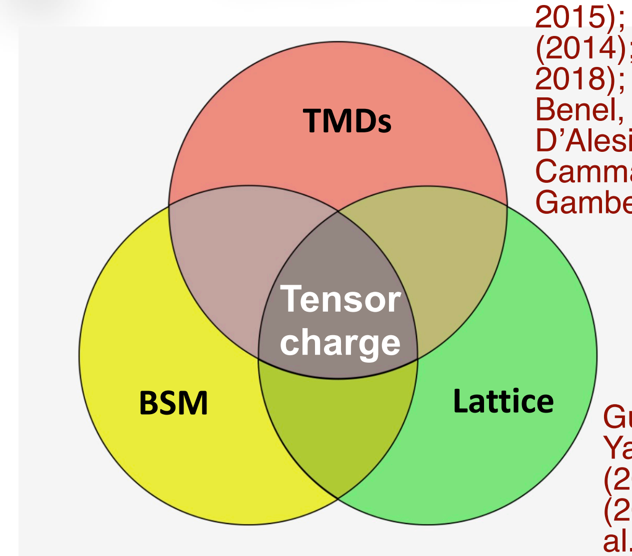
Transversity



- The only source of information on tensor charge of the nucleon
- Couples to Collins fragmentation function or di-hadron interference fragmentation functions in SIDIS

$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$

Anselmino, et al. (2013, 2015); Goldstein, et al. (2014); Radici, et al. (2013, 2018); Kang, et al. (2016); Benel, et al. (2019); D'Alesio, et al. (2020); Cammarota, et al. (2020) Gamberg et al (2022), etc



Courtoy, et al. (2015); Yamanaka, et al. (2017); Liu, et al. (2018); Gonzalez-Alonso, et al. (2019), etc

Gupta, et al. (2018); Yamanaka, et al. (2018); Hasan, et al. (2019); Alexandrou, et al. (2019, etc

TMD FITS OF POLARIZED DATA

	Framework	e+e-	SIDIS	DY	W,Z boson	A_N pp	lattice	Extracted
Anselmino et al 2015 arXiv:1510.05389	parton model	✔	✔	-	-	-	✘	Transversity, Collins FF
Lefky, Prokudin 2015 arXiv:1411.0580	parton model	-	✔	-	-	-	-	$h_{1T}^{\perp}$
Kang et al 2016 arXiv:1505.05589	NLO-NLL	✔	✔	-	-	-	✘	Transversity, Collins FF
Anselmino et al 2017 arXiv:1612.06413	parton model	-	✔	✔	-	-	-	Sivers
Lin et al 2018 arXiv:1710.09858	parton model	✔	✔	-	-	-	✔	Transversity, Collins FF
D'Alesio et al 2020 arXiv:2001.01573	parton model	✔	✔	✘	-	✘	✘	Transversity, Collins FF
Cammarora et al 2020 (JAM3D20) arXiv:2002.08384	parton model	✔	✔	✔	✔	✔	✘	Transversity, Sivers, Collins
Bachetta et al 2020 arXiv:2004.14278	NLO-NNLL	-	✔	✔	✔	✘	-	Sivers
Echevarria et al 2021 arXiv:2009.10710	NLO-NNLL	-	✔	✔	✔	✘	-	Sivers
Bhattacharya et al 2021 arXiv:2110.10253	parton model	-	✔	-	-	-	-	g_{1T}
Bury, Prokudin, Valdimirov 2021 arXiv:2103.03270	NLO-N3LL	-	✔	✔	✔	✘	-	Sivers
Gamberg et al 2022 (JAM3D22) arXiv:2205.00999	parton model	✔	✔	✔	✔	✔	✔	Transversity, Sivers, Collins
Horstmann et al 2022 arXiv:2210.07268	NLO-N3LL	-	✔	-	-	-	-	g_{1T}
Fernando et al 2023 arXiv:2304.14328	parton model	-	✔	✔	✘	✘	-	Sivers

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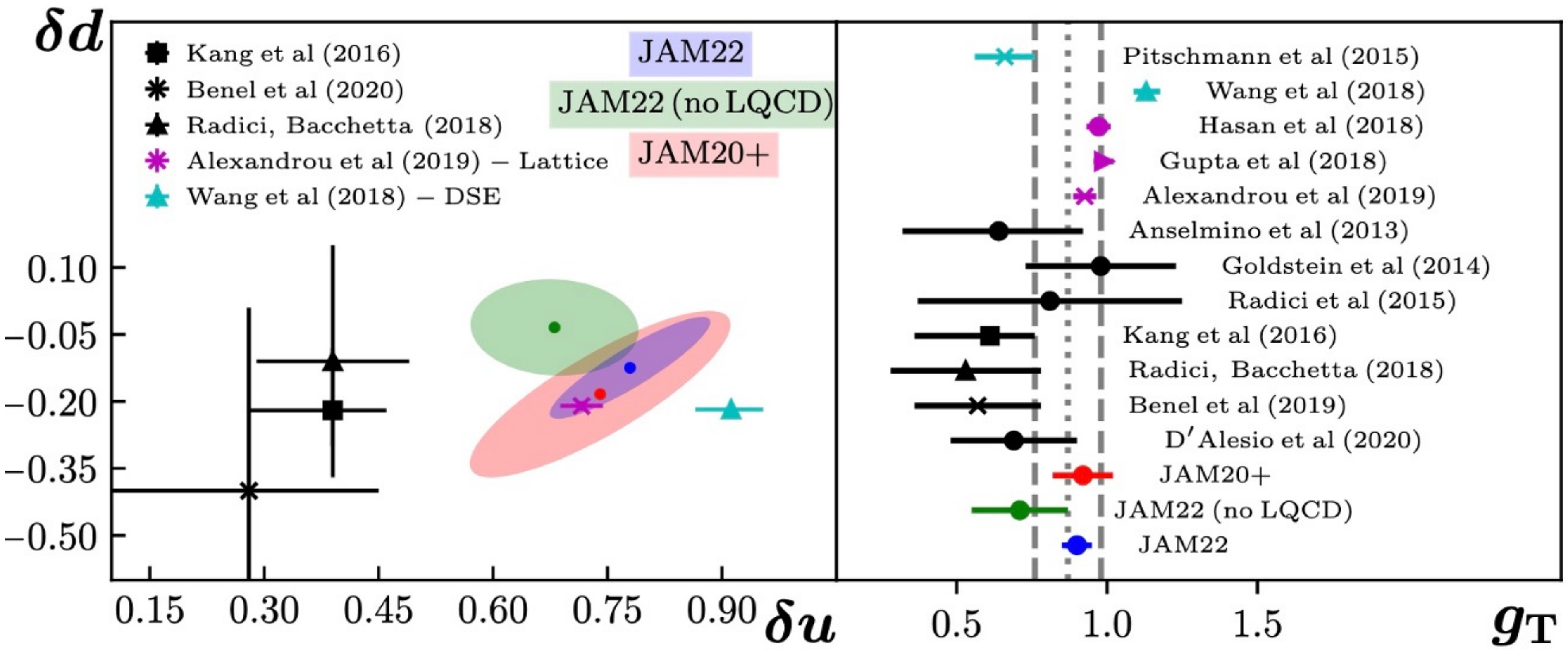
JAM22: Gamberg, Malda, Miller, Pitonyak, Prokudin, Sato, Phys.Rev.D 106 (2022) 3, 034014



- Tensor charge from up and down quarks and $g_T = \delta u - \delta d$ are well constrained and compatible with both lattice results and the Soffer bound

δu and δd Q^2=4 GeV^2

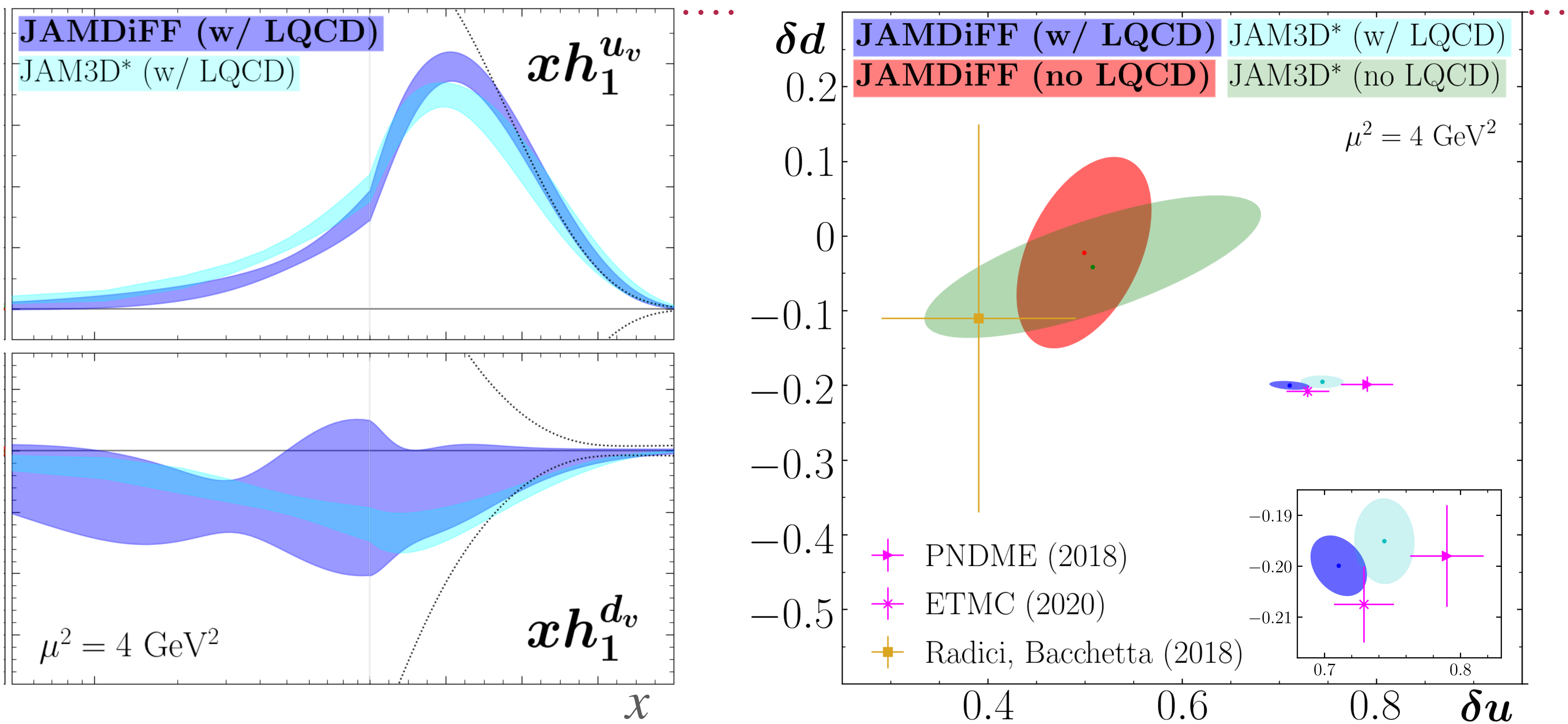
δu= 0.74 $\pm$ 0.11

δd= -0.15 $\pm$ 0.12

g_T= 0.89 $\pm$ 0.06

- Once the the lattice g_T data point is included, we find the non-perturbative functions can accommodate it and still describe the experimental data well

TENSOR CHARGE

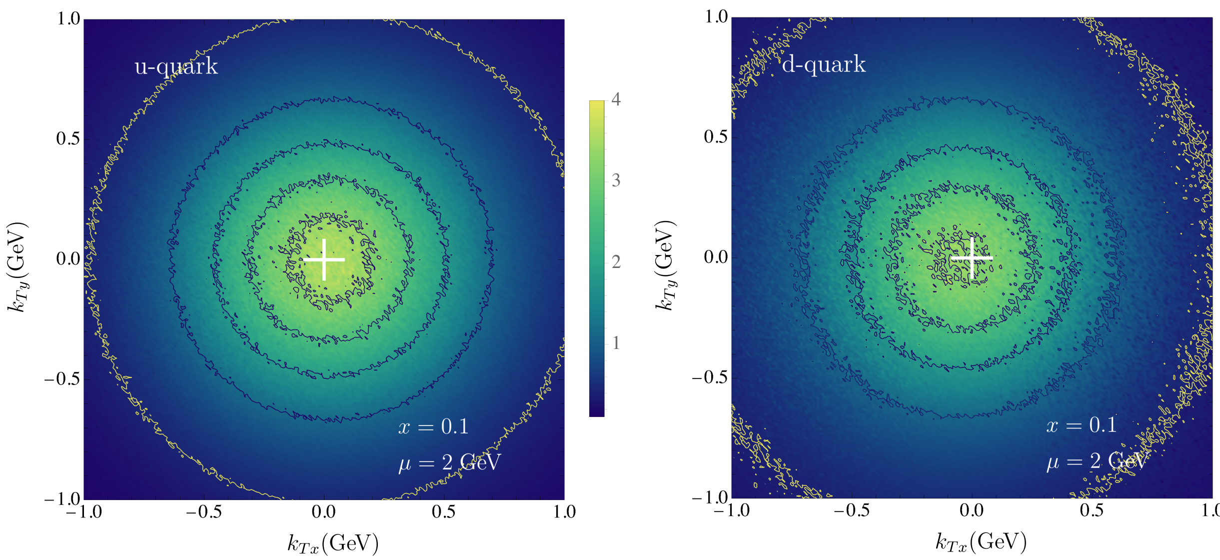


- The experimental measurements are sensitive to the x-dependence of the transversity PDFs, not the full moment like the lattice data (EIC and JLab are needed)
- JAM3D* and JAMDiFF agree on the x-dependence of transversity (nontrivial since the lattice data only constrains the full moment of the transversity PDFs)
- JAM3D* and JAMDiFF can successfully include lattice QCD data on the tensor charges in the analyses, thus showing for the first time the universal nature of all available information on transversity and the tensor charges of the nucleon

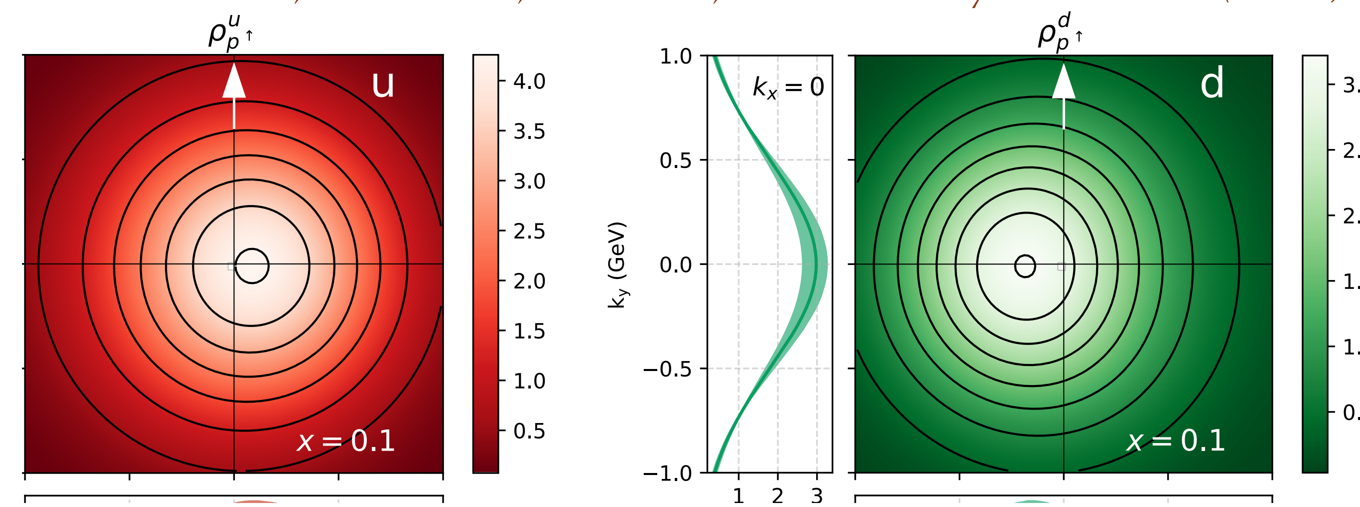
NUCLEON TOMOGRAPHY

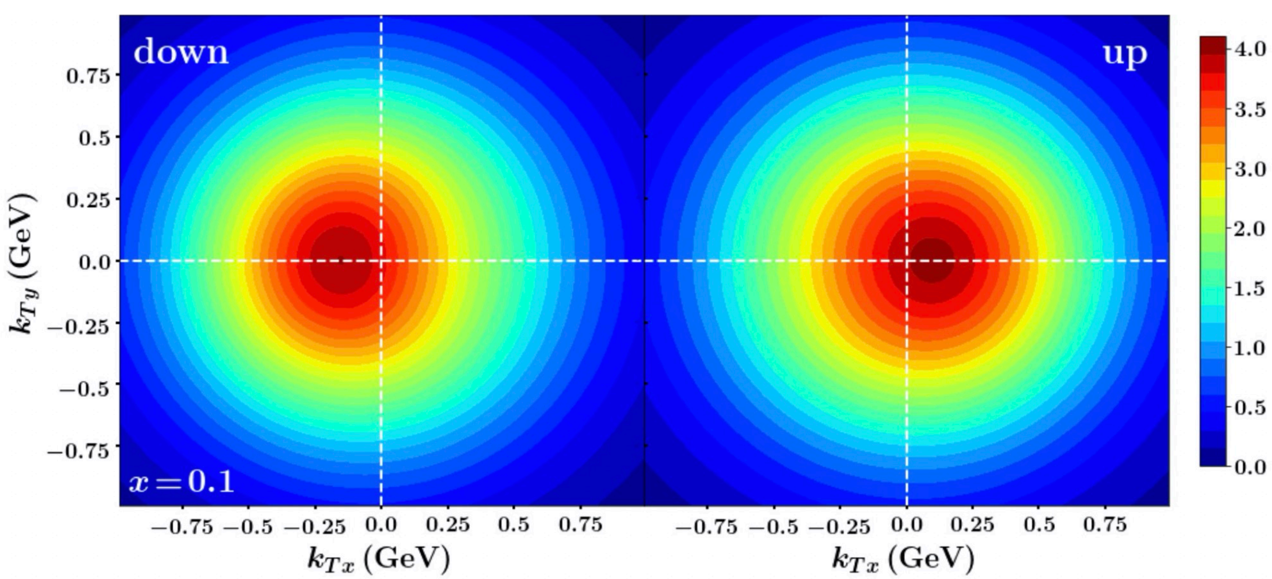
$$\rho_{1;q\leftarrow h^{\uparrow}}(x,\boldsymbol{k}_T,\boldsymbol{S}_T,\mu) = f_{1;q\leftarrow h}(x,k_T;\mu,\mu^2) - \frac{k_{Tx}}{M} f_{1T;q\leftarrow h}^{\perp}(x,k_T;\mu,\mu^2)$$

M. Bury, A. Prokudin, A. Vladimirov, Phys.Rev.Lett. 126 (2021)

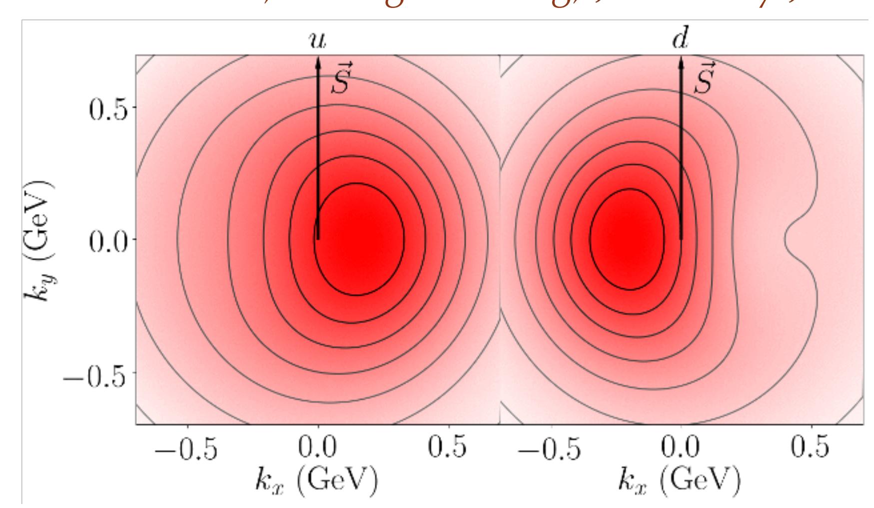


A. Bacchetta, F. Delcarro, C. Pisano, M. Radici Phys.Lett.B 827 (2020)





Miguel G. Echevarria, Zhong-Bo Kang, John Terry JHEP 01 (2021) 126



JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)

- The shift in the transverse plane is generated by the Sivers function
- The opposite signs of the shift are consistent with lattice QCD findings on the opposite signs of the OAM for u and d quarks

CONCLUSIONS

- TMD studies have made great progress, they are synergistic with many other areas: lattice QCD, SCET, small-x, jets, etc
- Current: HERMES, COMPASS, JLab 12, BELLE, RHIC spin, and LHC provide great experimental measurements for TMD physics
- Future: EIC, together with other experiments such as SoLID at JLab 12 and BELLE II, will make significant contributions to TMD studies