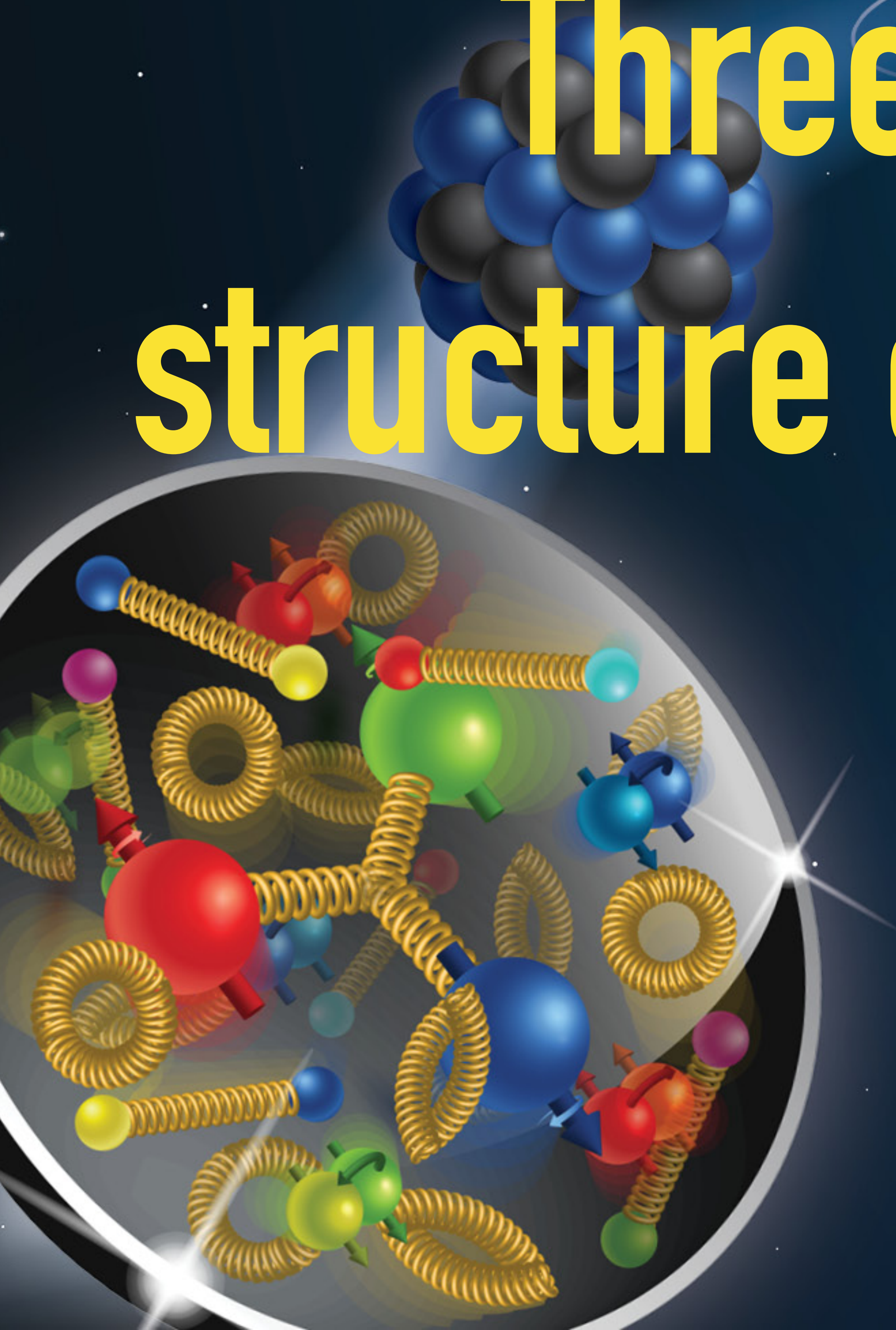
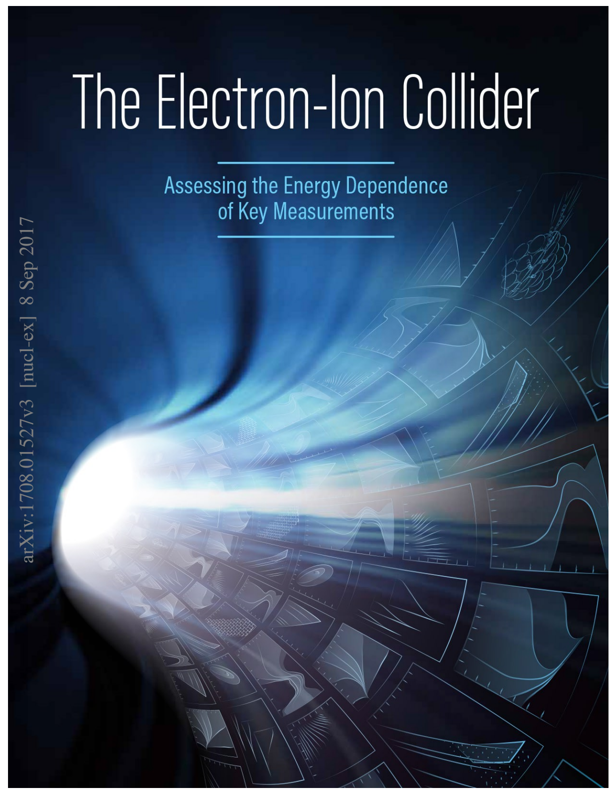
Three-dimensional structure of the nucleon and the EIC

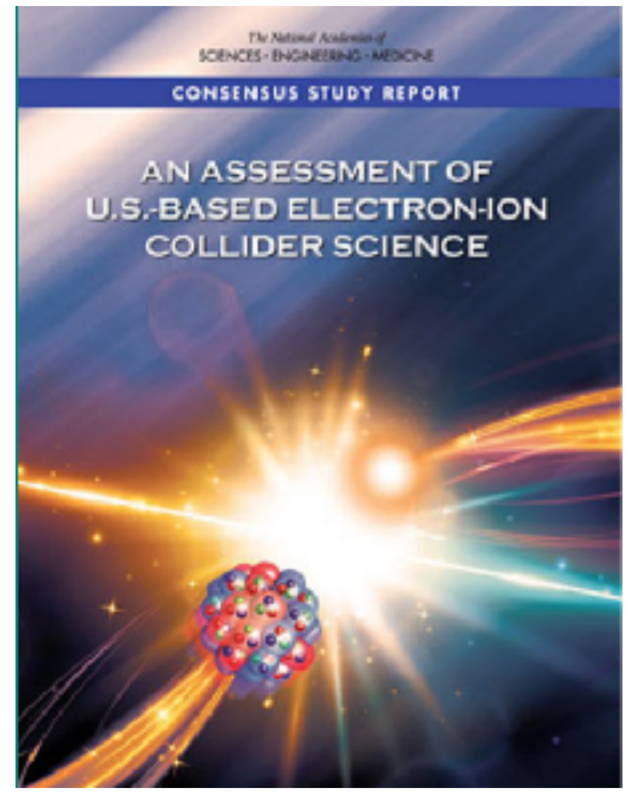


Alexei Prokudin

https://www.bnl.gov/eic/science.php

THE ELECTRON-ION COLLIDER: RELEVANT DOCUMENTS





White Paper (2012)
Accardi et al,
arXiv:1212:1701

BNL Report (2017)
Aschenauer at el,
arXiv:1708.01527

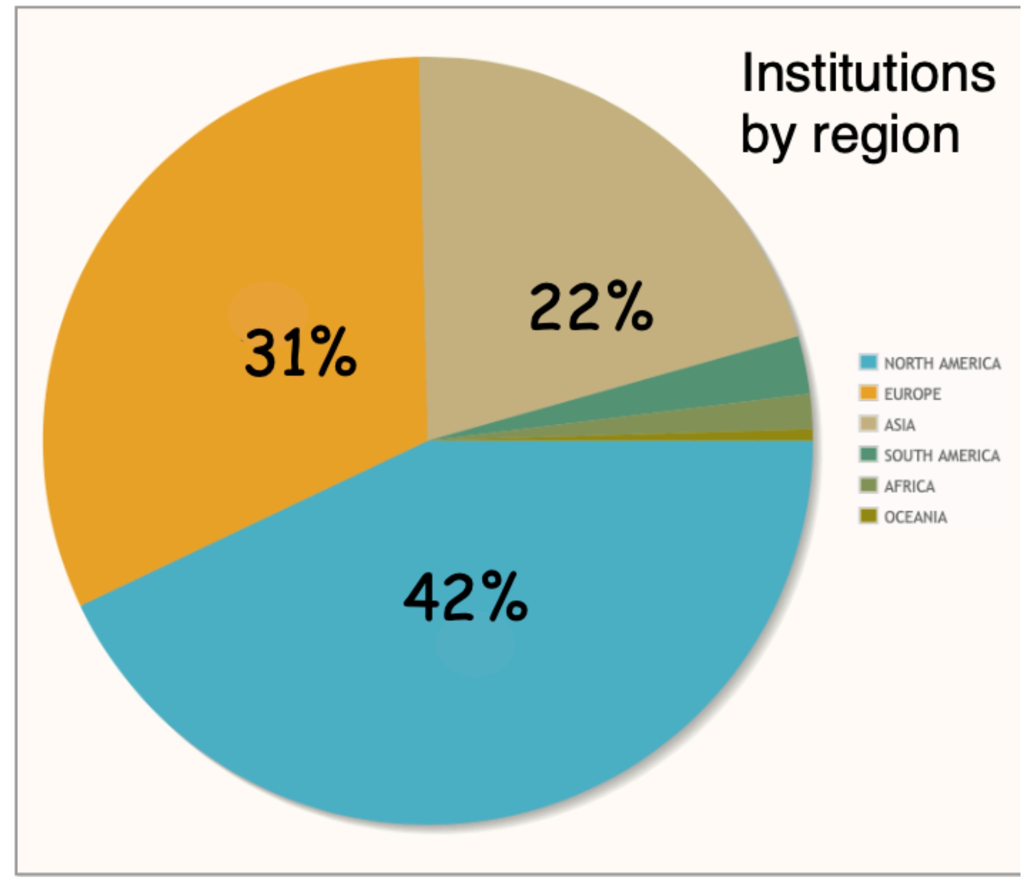
NSAC Study (2018)

EIC Yellow Report (2021)
arXiv:2103.05419

Yellow Paper (2016)
Accardi et al, Eur. Phys. J. A
(2016) 52: 268

ELECTRON-ION COLLIDER USER GROUP

- EICUG.ORG, growing community, 1200 members, 31 countries, 250 institutions



- EIC detector R&D program ~1M$/year
- EIC Accelerator R&D program ~7M$/year
- The U.S. Department of Energy has granted Critical Decision 1 (CD-1) for the Electron-Ion Collider, July 2021

THE ELECTRON-ION COLLIDER: SCIENTIFIC QUESTIONS

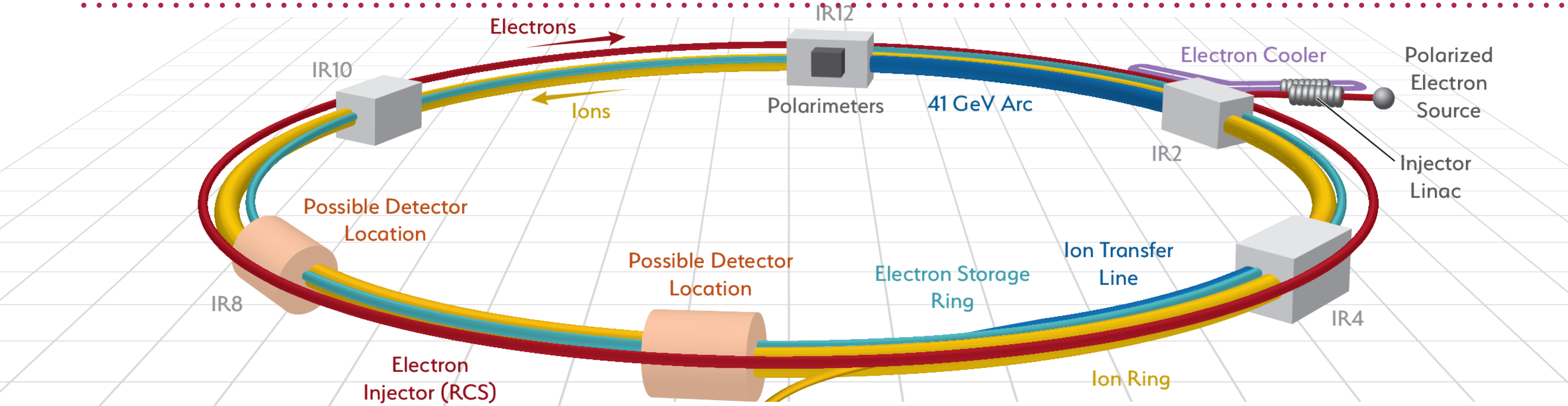
White Paper (2012)
Accardi et al, arXiv:1212:1701

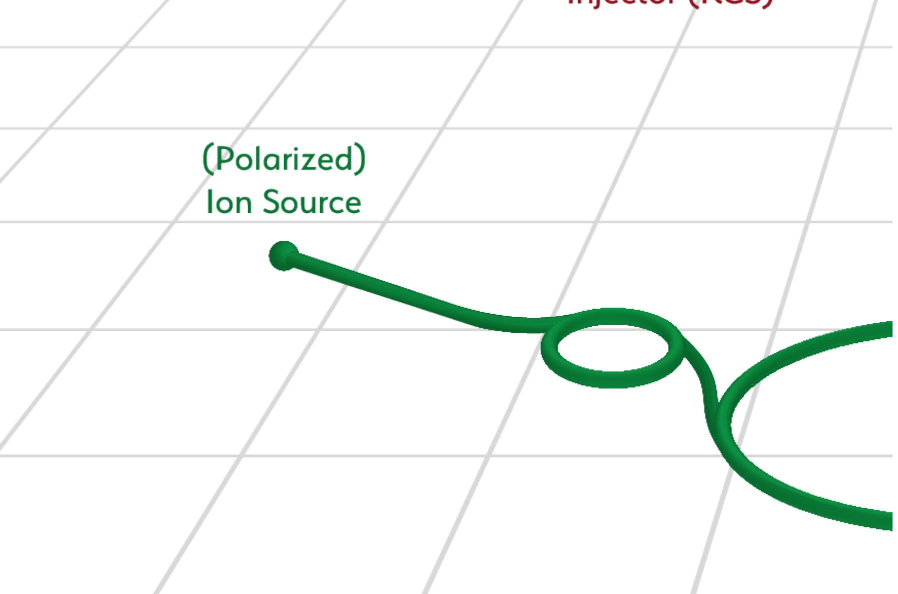
- How are the *sea quarks and gluons*, and their spins, distributed in space and momentum inside the nucleon?

- Where does the *saturation of gluon densities* set in?

- How does the *nuclear* environment affect the distribution of *quarks and gluons* and their interactions in nuclei?

THE ELECTRON-ION COLLIDER @ BNL



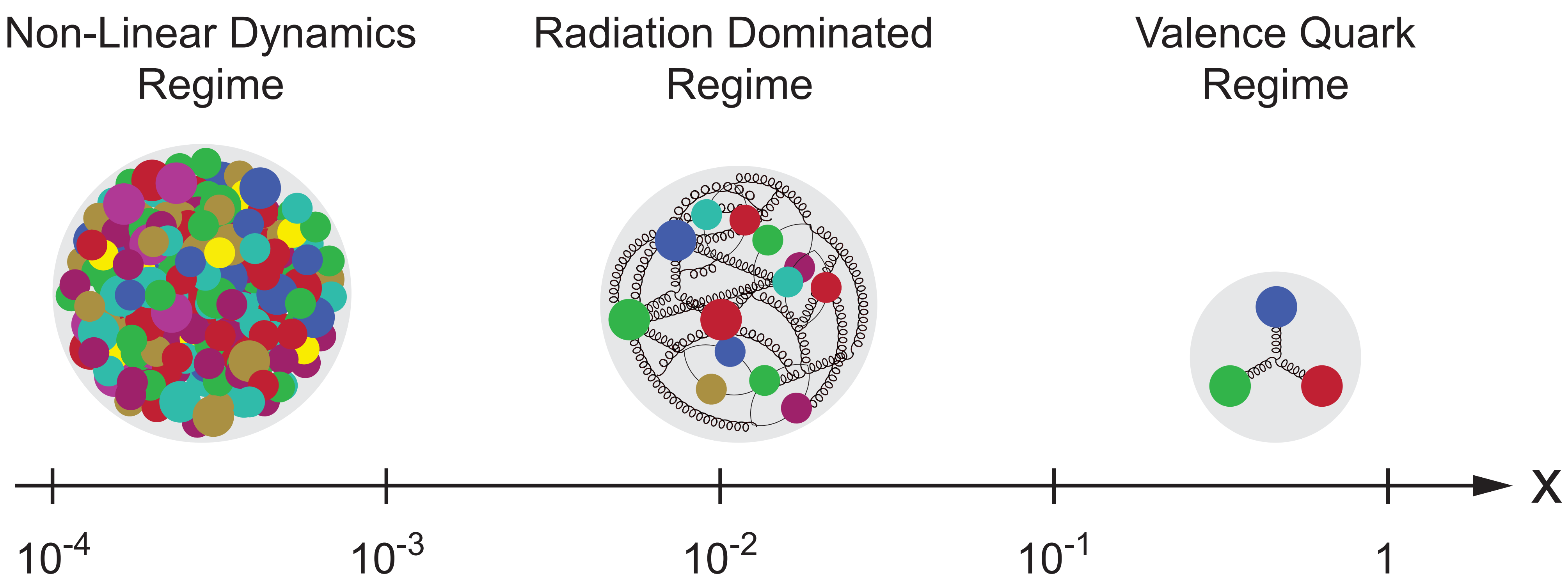


White Paper (2012)
Accardi et al, arXiv:1212:1701

- High luminosity: (~10^{34} cm^{-2} s^{-1}) (~1000 times that of HERA)
- Variable CM energy: ~20 — ~140 GeV
- Highly polarized ~70% electron and nucleon beams
- Protons and other nuclei
- Possibility of more than one interaction region (none of the major facilities operates with one detector only - important for discovery potential)

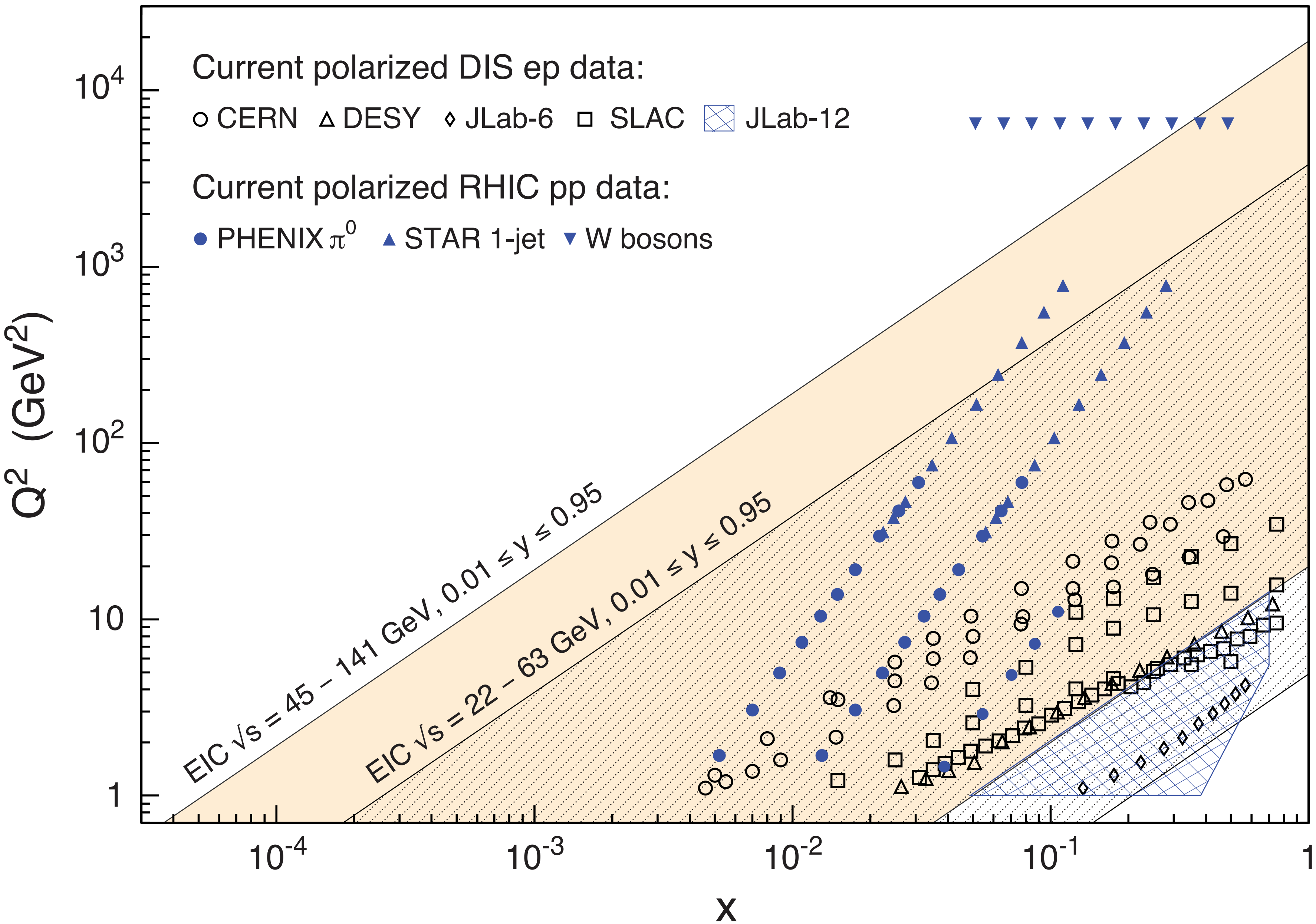
KINEMATICS

THE ELECTRON-ION COLLIDER: KINEMATICS



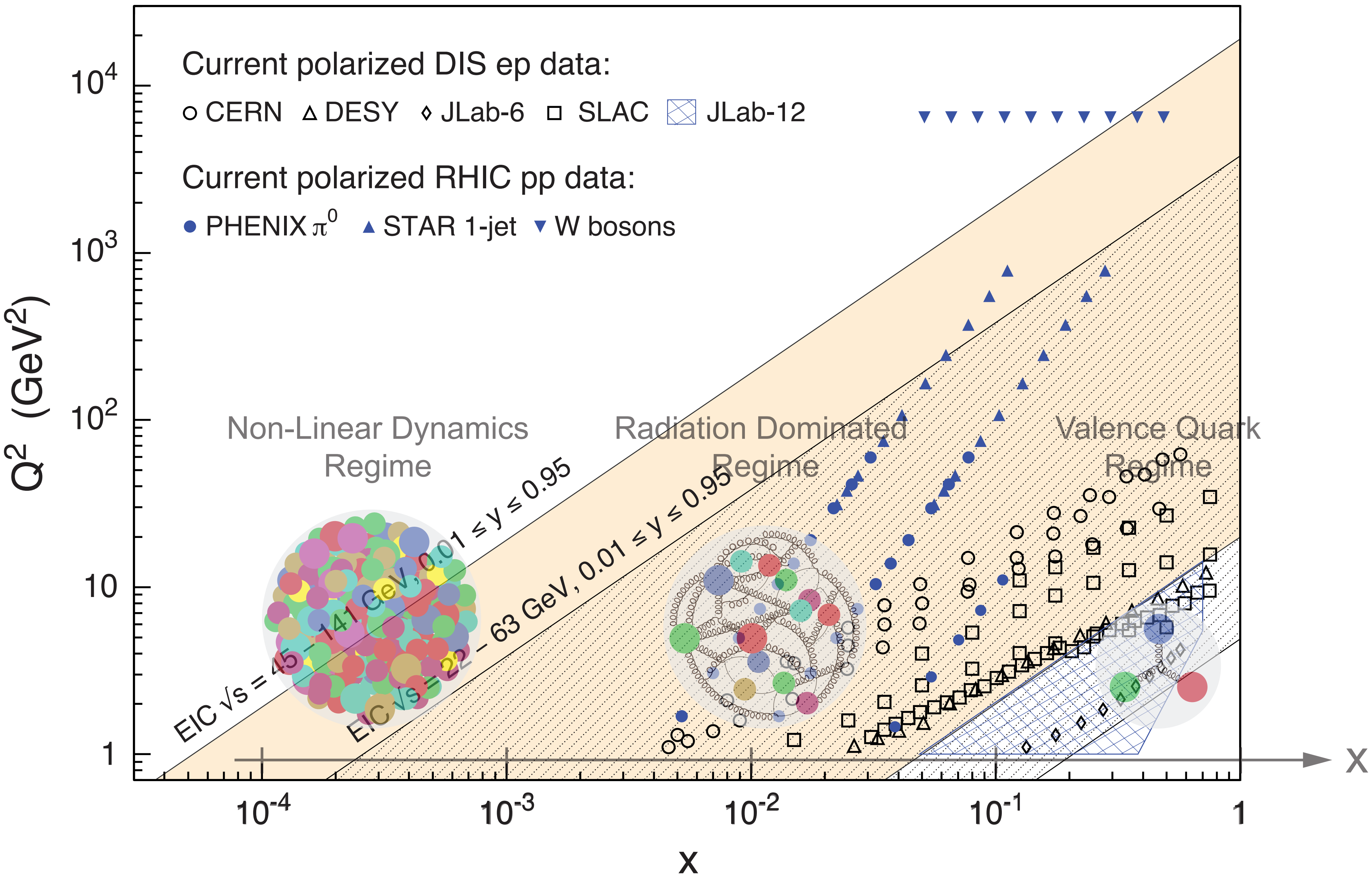
BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

THE ELECTRON-ION COLLIDER: KINEMATICS



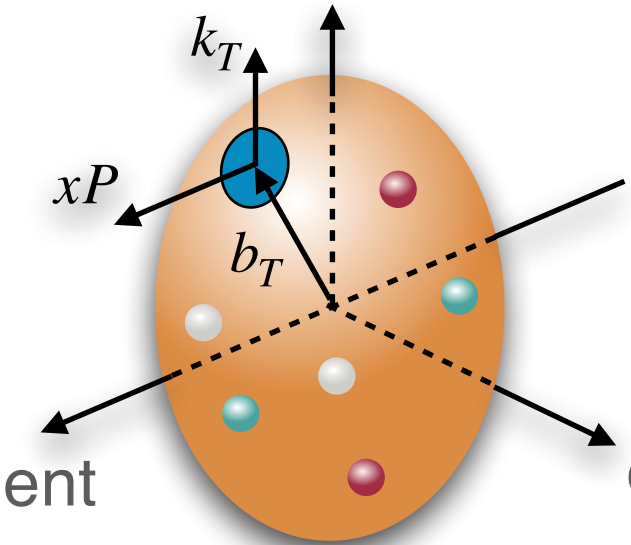
BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

THE ELECTRON-ION COLLIDER: KINEMATICS

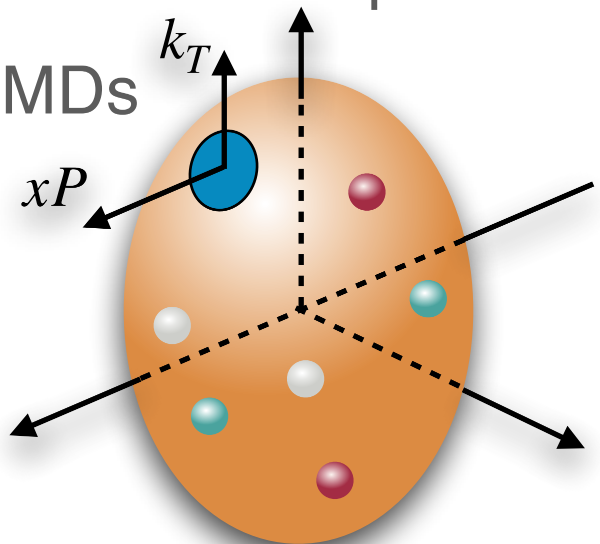


BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

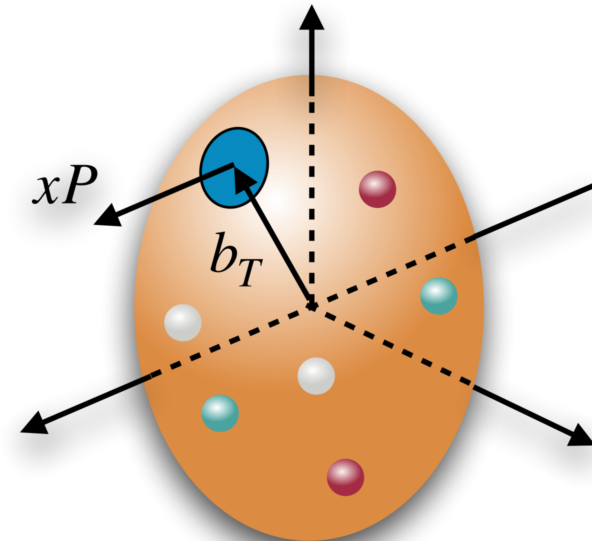
Wigner distributions
(Fourier transform of GTMDs =
Generalized Transverse
Momentum Distributions)



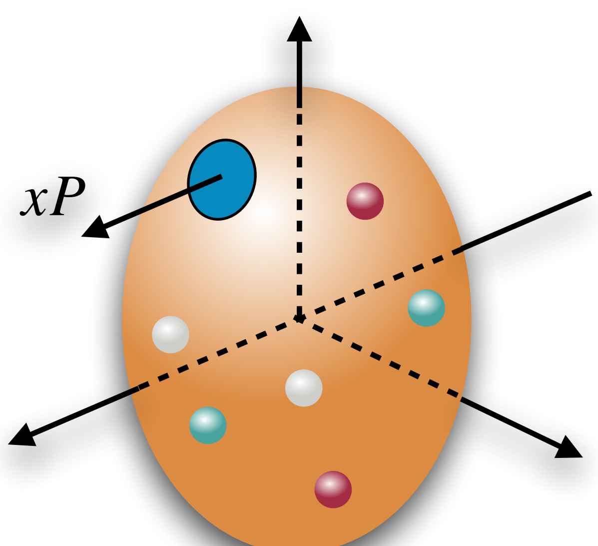
Transverse Momentum Dependent
Distributions TMDs



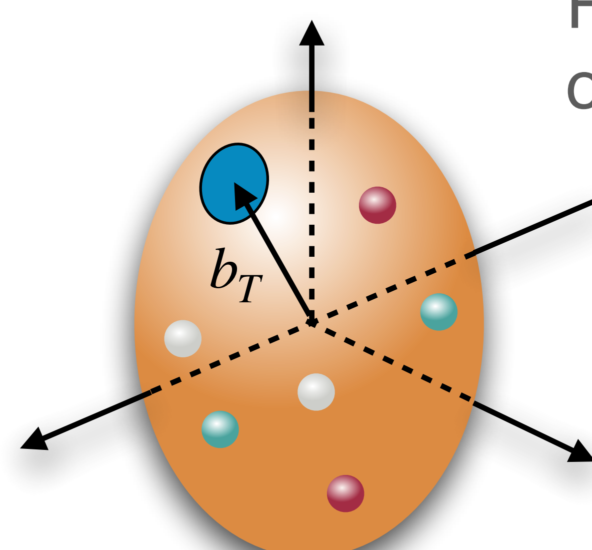
Fourier transform
of Generalized Parton Distributions
(GPDs)



PDFs



Fourier transform
of Form Factors

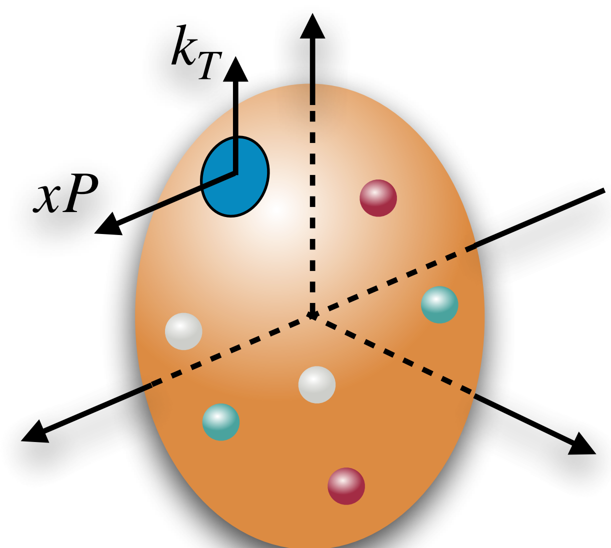


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

OVERARCHING TMD QUESTIONS

What is the 2D confined transverse motion of quarks and gluons inside a proton?

How to identify universal proton structure properties from measured k_T-dependence?

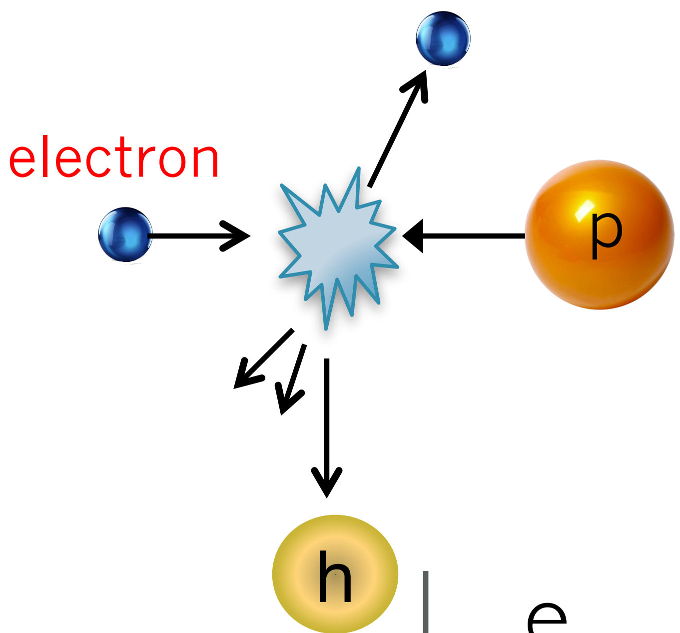


How does the confined motion change along with probing x, Q^2?

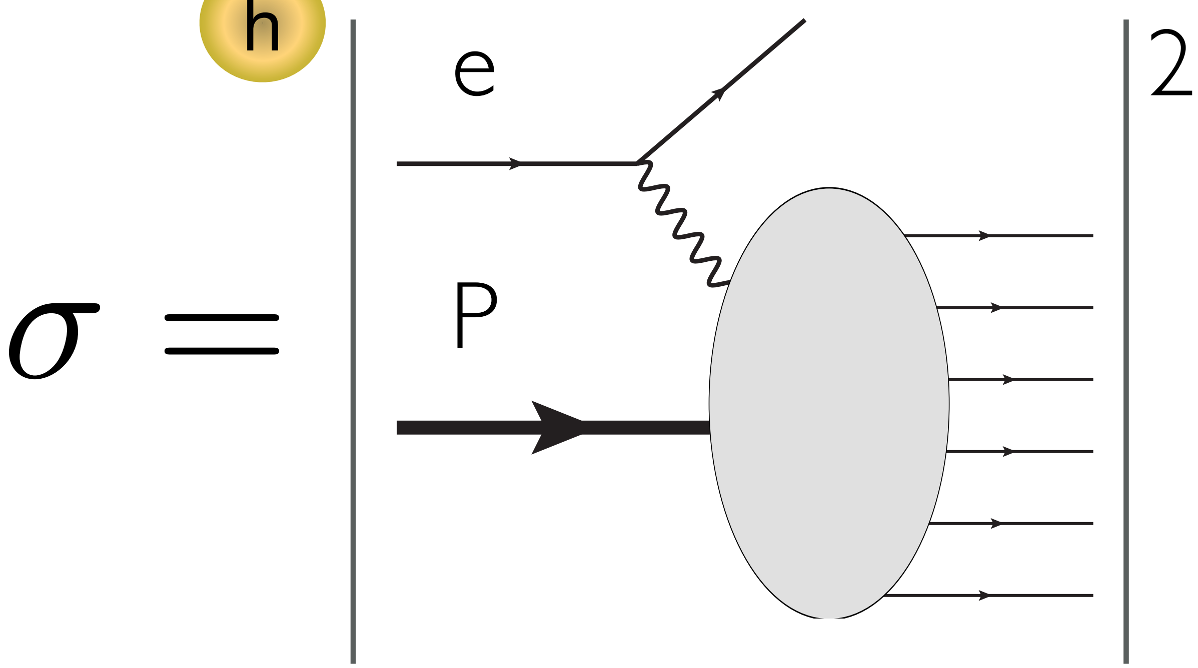
Can we extract QCD color force responsible for the confined motion?

How is the motion correlated with macroscopic proton properties, as well as microscopic parton properties, such as the spin?

QCD FACTORIZATION IS THE KEY!



We need a probe to “see” quarks and gluons



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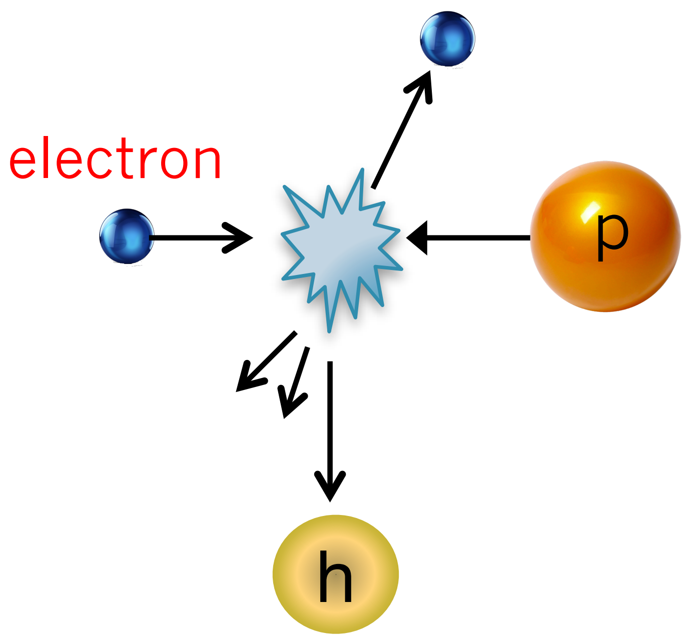
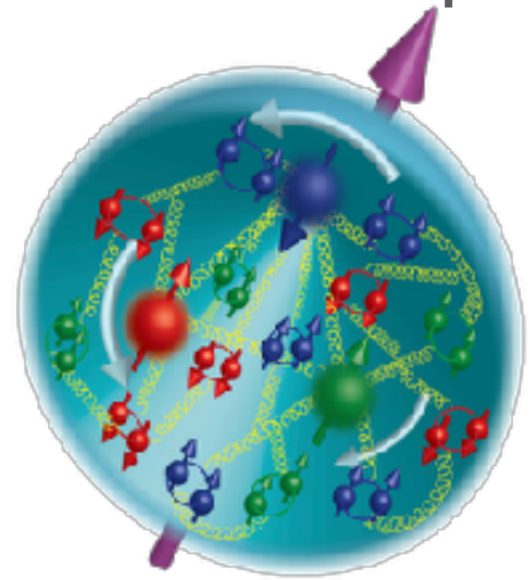
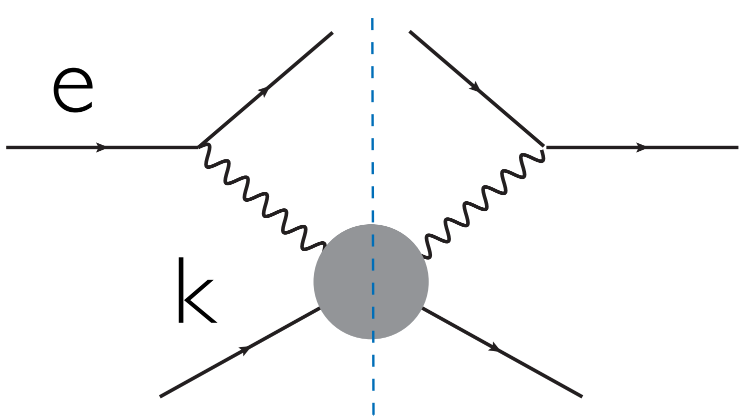
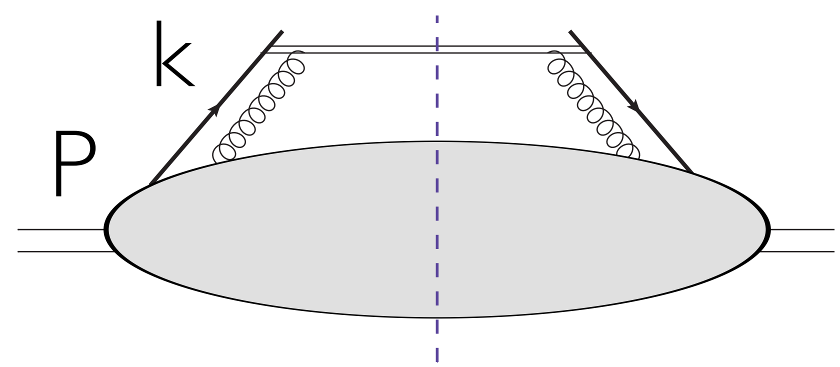




$\sigma \approx$



$\otimes$

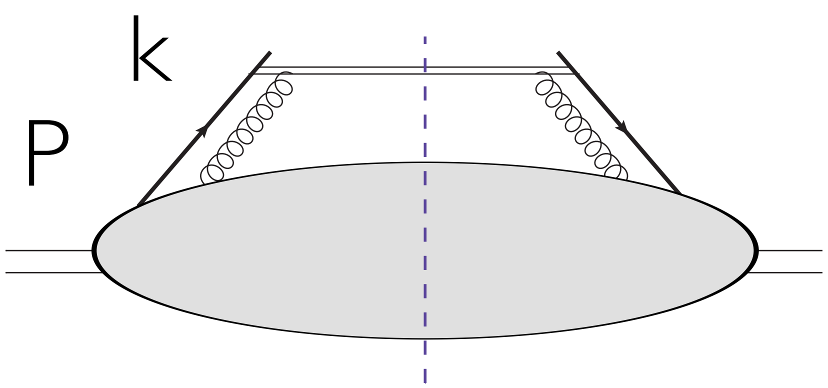


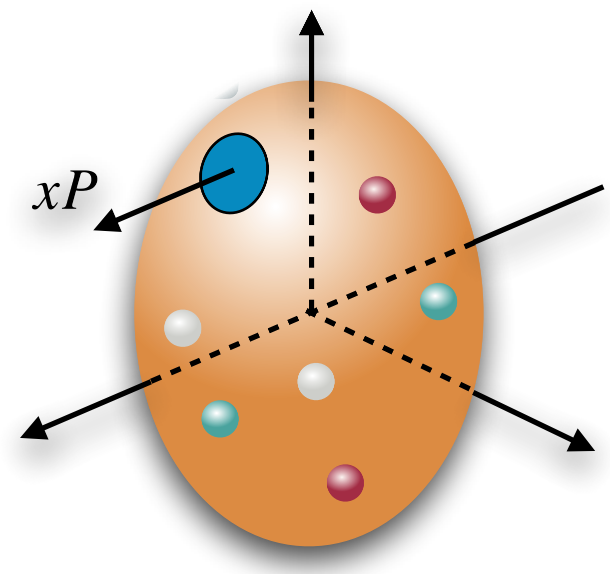
$+\mathcal{O}\left(\frac{M^2}{Q^2}\right)$

Factorization Probe Structure Power corrections

HADRON'S PARTONIC STRUCTURE

Collinear Parton Distribution Functions





$f_{q/P}(x)$

longitudinal

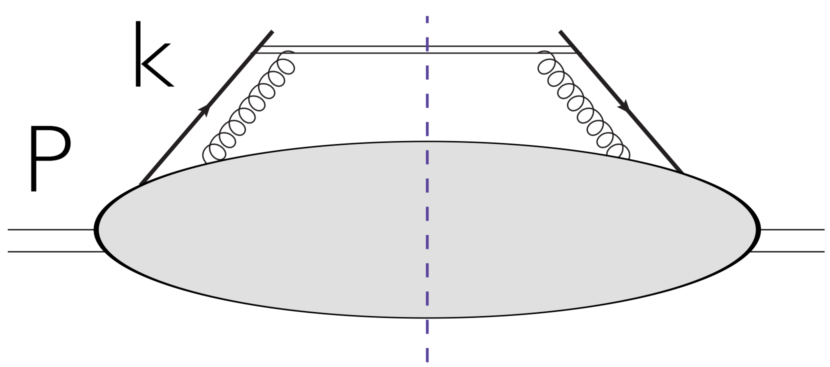
Probability density to find a quark with a momentum fraction x

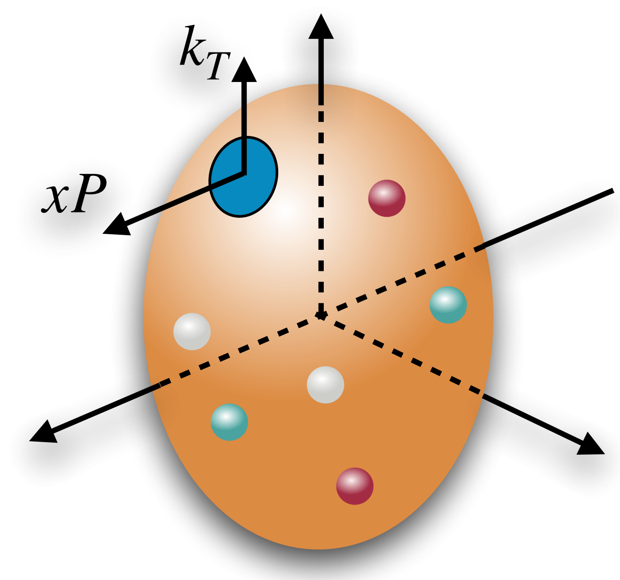
Hard probe resolves the particle nature of partons, but is not sensitive to hadron's structure at ~fm distances.

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





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

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.

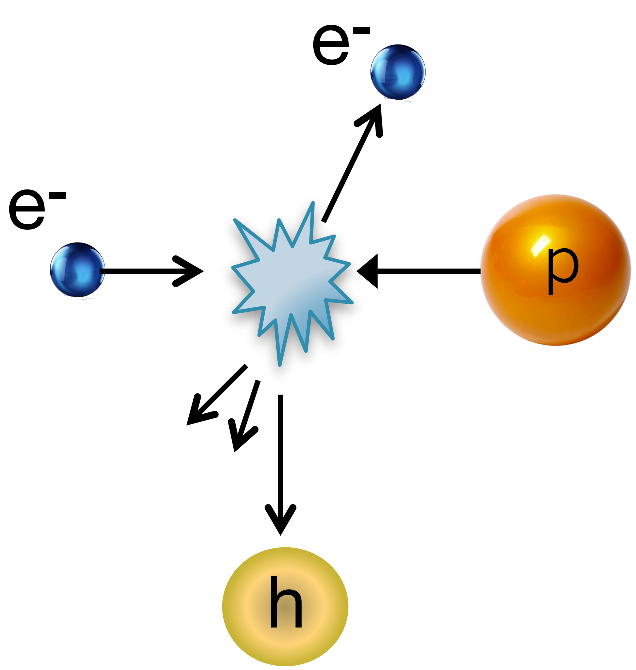
TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

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

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

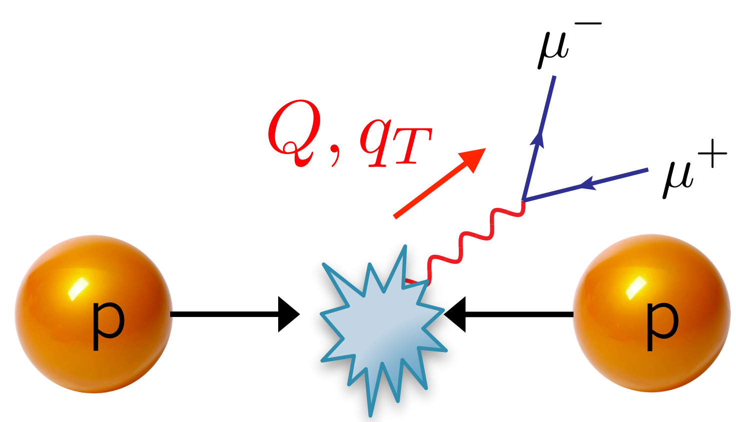
$$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(z, k_T)$$



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

Drell-Yan

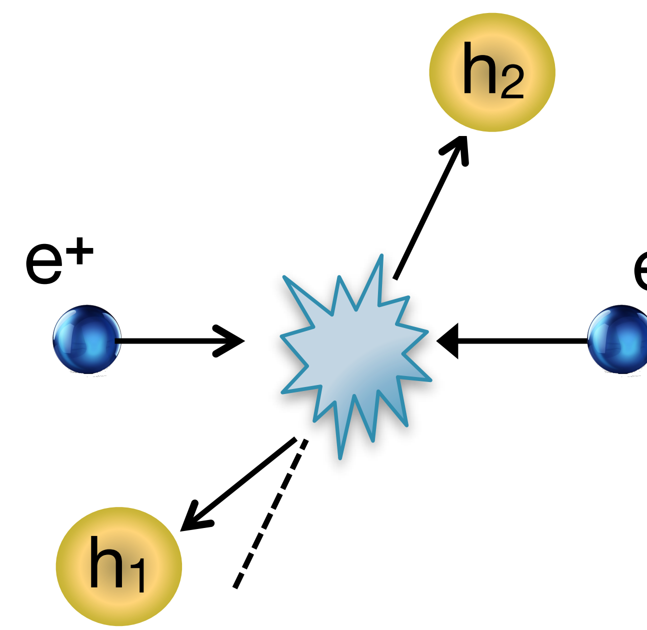
$$\sigma \sim f_{q/P}(x_1, k_T) f_{\bar{q}/P}(x_2, k_T)$$



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

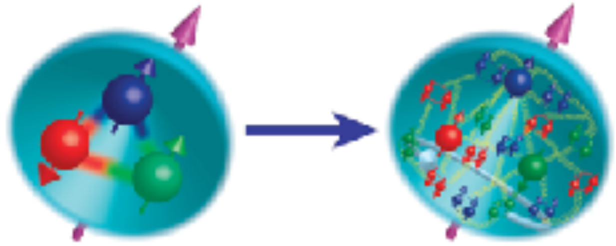
Dihadron in e^+e^-

$$\sigma \sim D_{h_1/q}(z_1, k_T) D_{h_2/\bar{q}}(z_2, k_T)$$

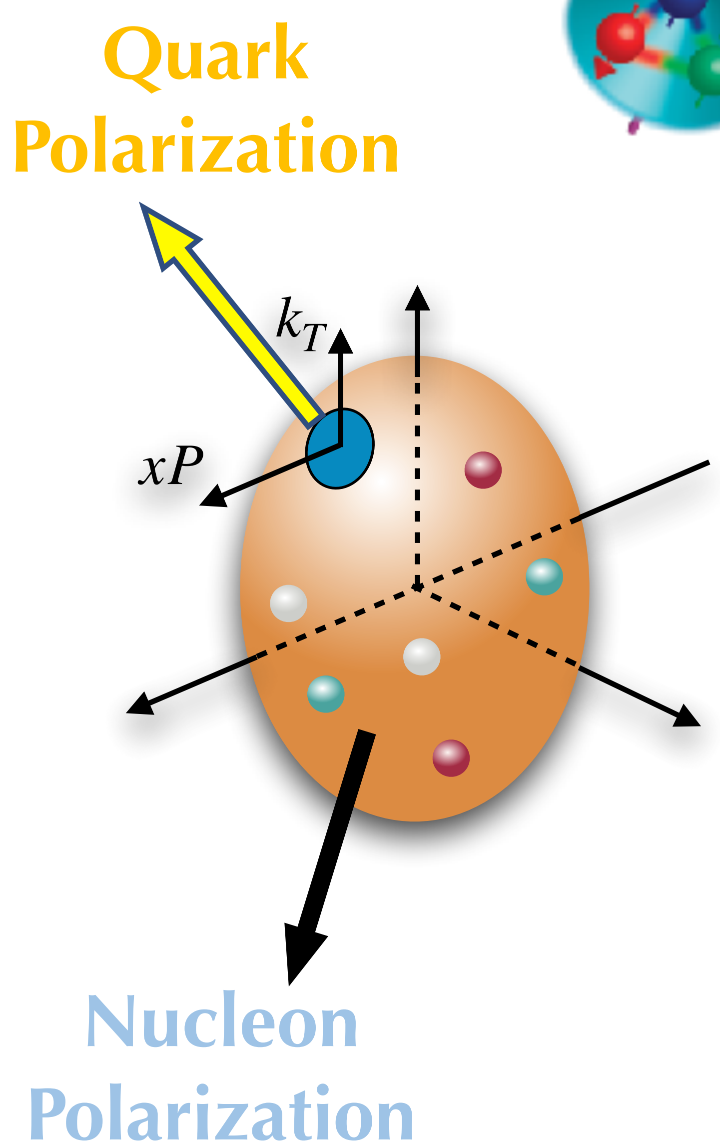


Collins, Soper (1983)
Collins (2011)

Our understanding of hadron evolves: TMDs with Polarization



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



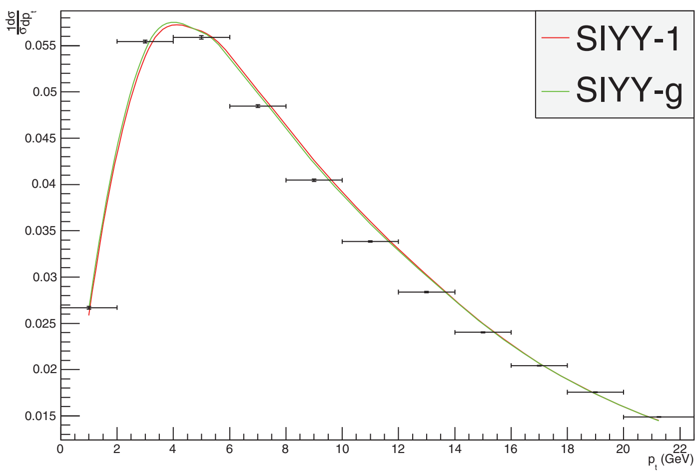
Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	$f_1(x,k_T^2)$ *Unpolarized*		$h_1^{\perp}(x,k_T^2)$ *Boer-Mulders*
L		$g_1(x,k_T^2)$ *Helicity*	$h_{1L}^{\perp}(x,k_T^2)$ *Kozinian-Mulders,"worm" 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:

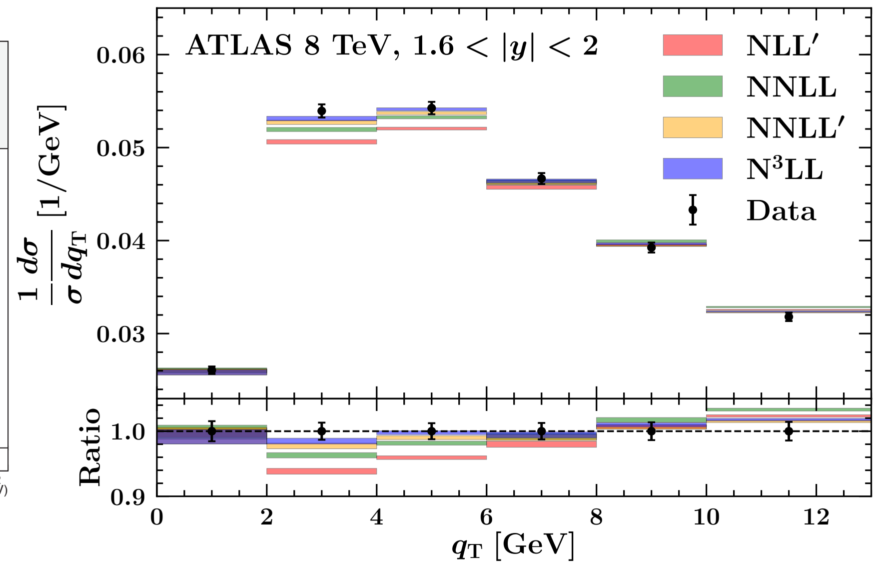
- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Nuclear targets $S \neq \frac{1}{2}$

Fast progress in TMD determinations is taking place,
but still many open questions

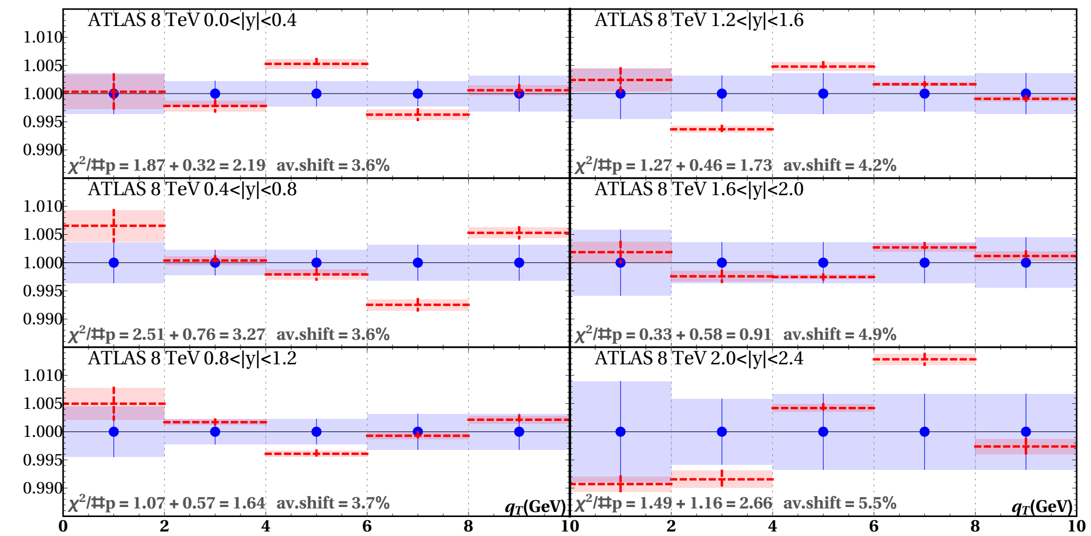
SUCCESS OF TMD FACTORIZATION PREDICTIVE POWER



Sun, Isaacson, Yuan, Yuan Int.J.Mod.Phys.A 33 (2018)



Bacchetta et al, JHEP 07 (2020) 117



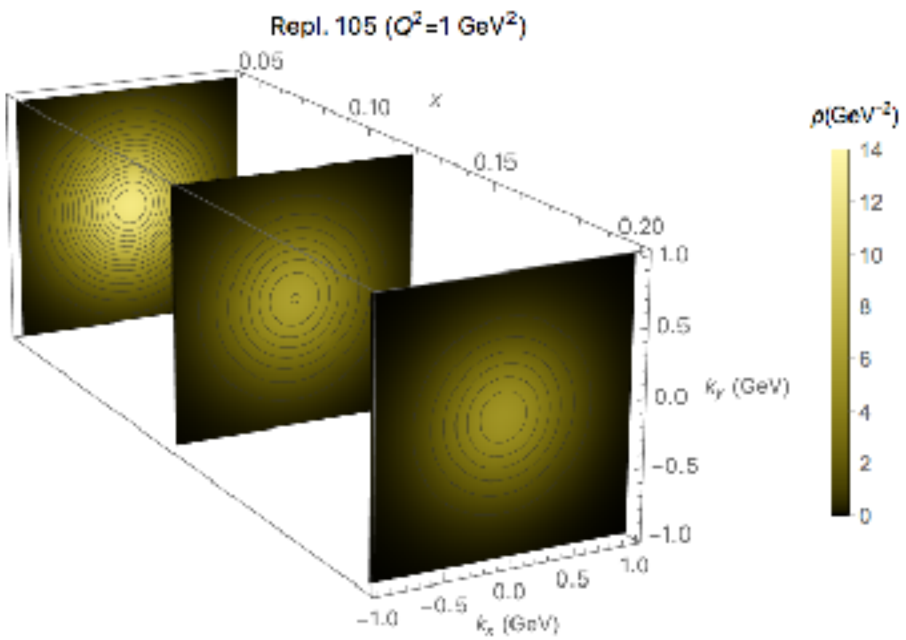
Bertone, Scimemi, Vladimirov JHEP 06 (2019) 028

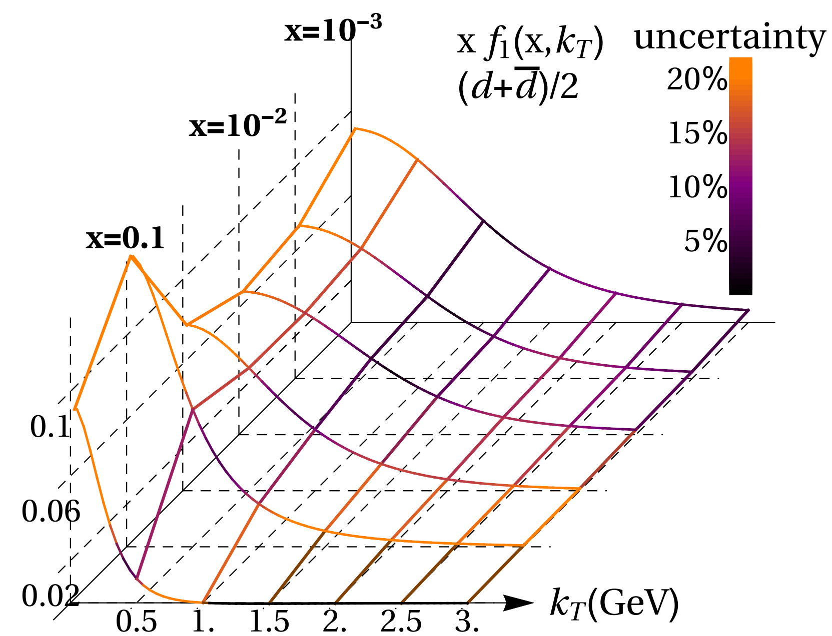
Z boson production at the LHC

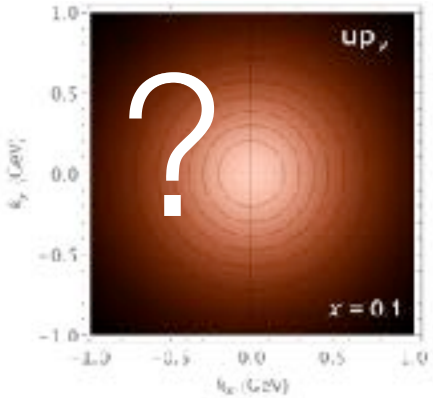
- ➤ TMD factorization (with an appropriate matching to collinear results) aims at an accurate description (and prediction) of a differential in q_T cross section in a wide range of q_T
- ➤ LHC results at 7 and 13 TeV are accurately predicted from fits of lower energies

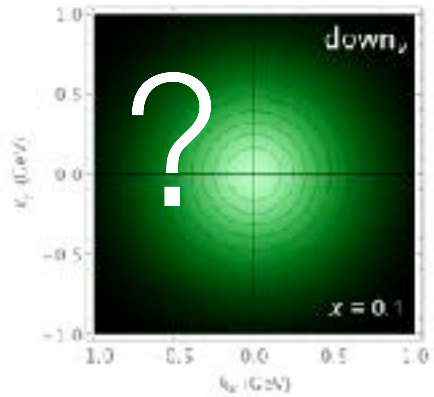
UNPOLARIZED TMD MEASUREMENTS

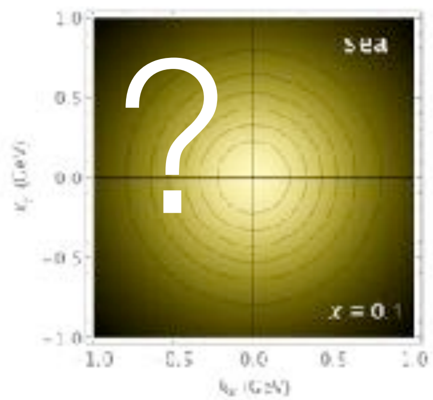
Unpolarized cross section











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

Bertone, Scimemi, Vladimirov, arXiv:1902.08474

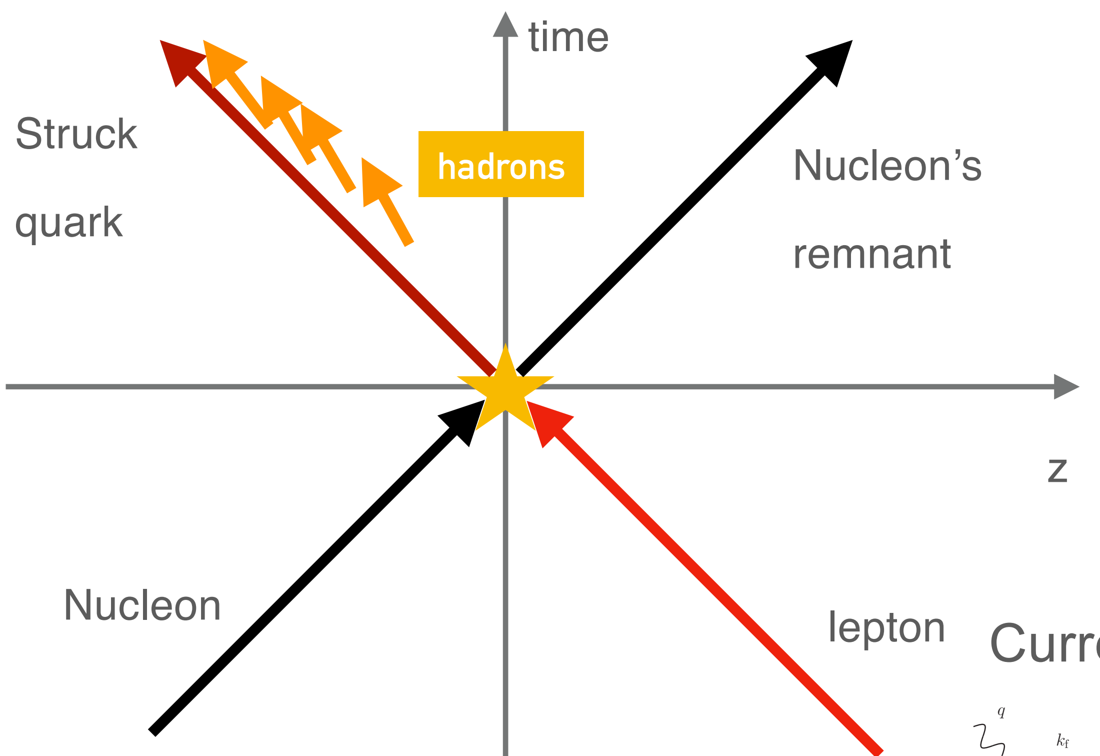
- ➤ Addresses the question of partonic confined motion
- ➤ Evolution with x and Q^2
- ➤ Flavor dependence of unpolarized TMDs
- ➤ Interplay with collinear QCD at large q_T

TMD FITS OF UNPOLARIZED DATA

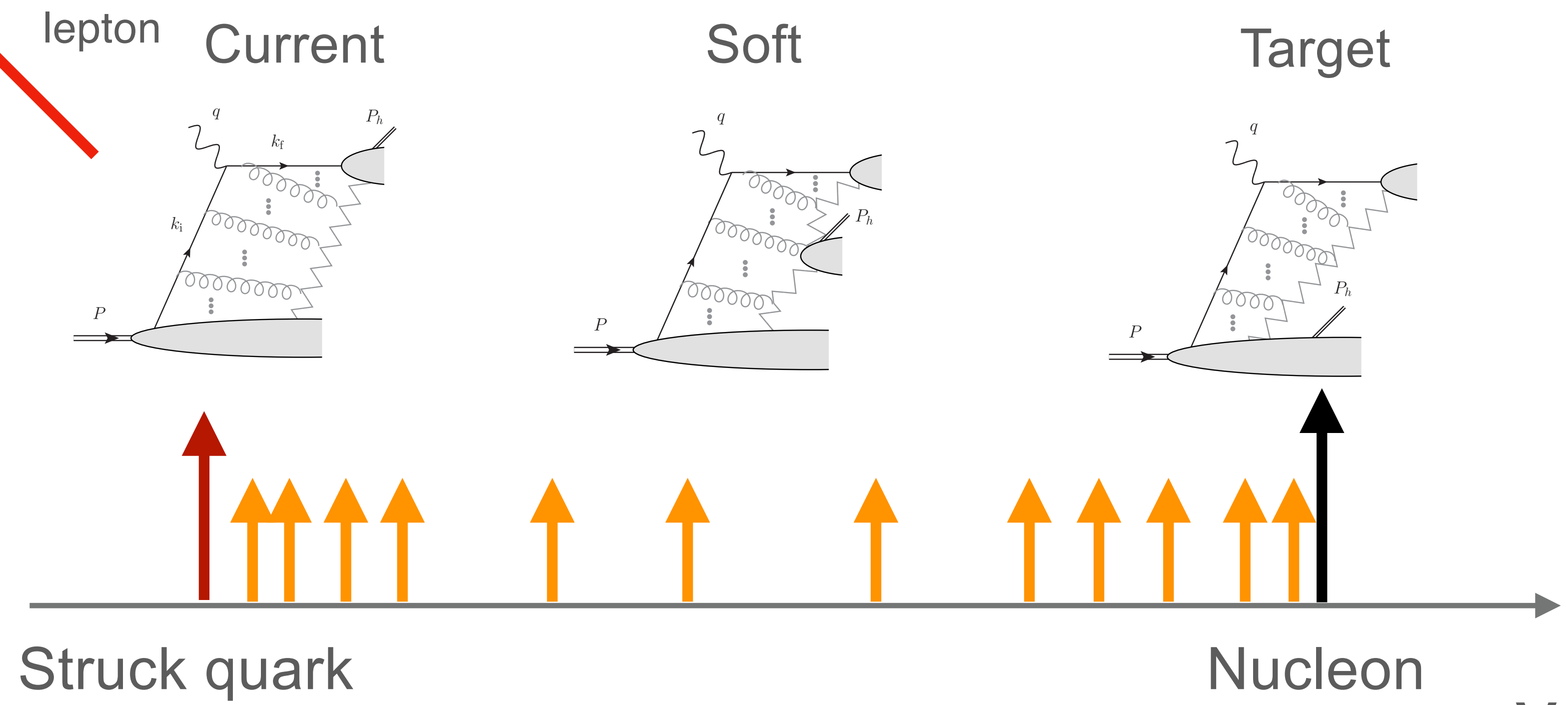
	Framework	W+Y	HERMES	COMPASS	DY	Z boson	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	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

REGIONS OF FRAGMENTATION

$$\sigma \sim \sigma_0 \, f_{q/N}(x_{Bj}) \otimes D_{q/h}(z_h)$$



- Libby-Sterman analysis (Collins 2011 Ch.5) suggests that classical trajectories dominate
- Produced hadrons are close in rapidity to the fragmenting quark



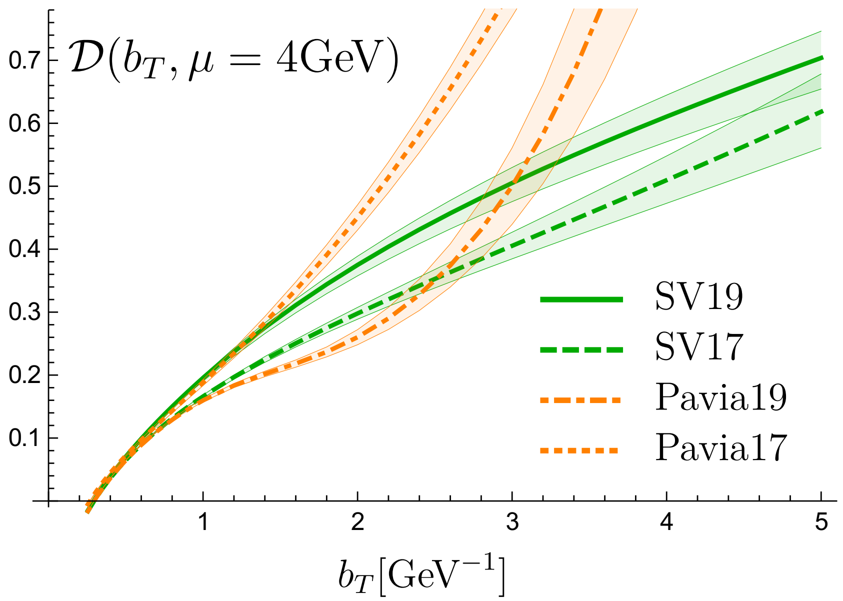
Boglione et al, 1611.10329

TMD EVOLUTION CONTAINS NON-PERTURBATIVE COMPONENT

$$F(x,b;\mu,\zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)} F(x,b)$$

Collins, Soper (1985), Scimemi, Vladimirov (18), (20), Vladimirov (20)

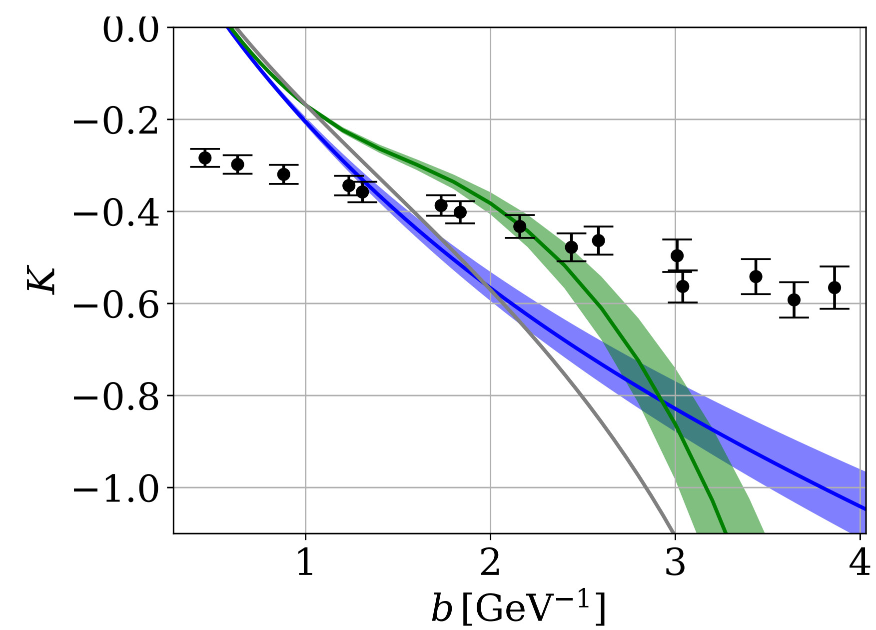
$$\mathcal{D}(b,\mu) = -K(b,\mu)/2$$



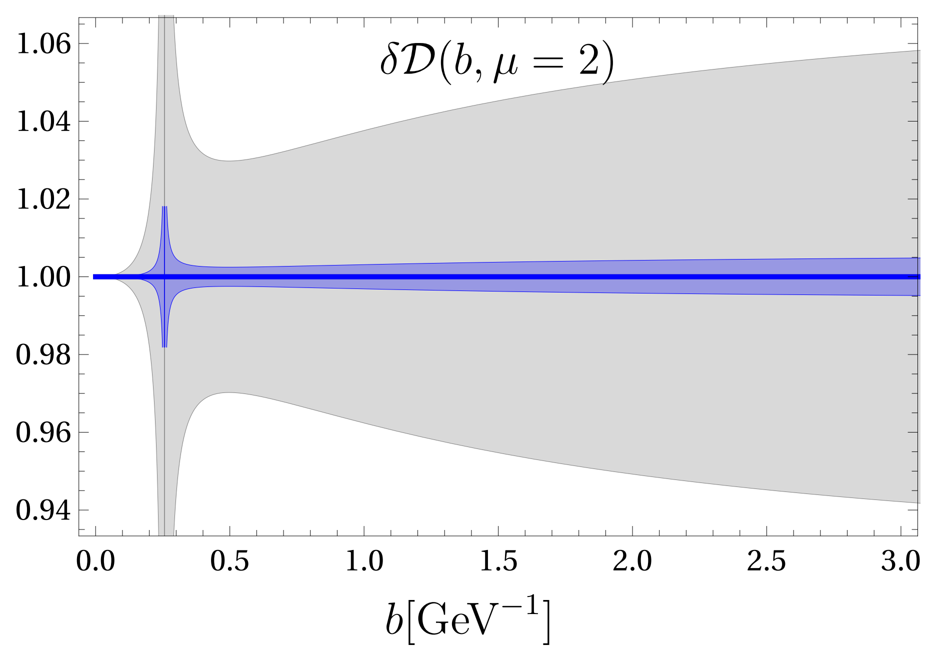
Vladimirov (20)

Colins-Soper (CS) kernel or rapidity anomalous dimension. Fundamental universal function related to the properties of QCD vacuum.

It is calculable by lattice QCD.Offers synergy of lattice, phenomenology, and models



Schlemmer et al (21)



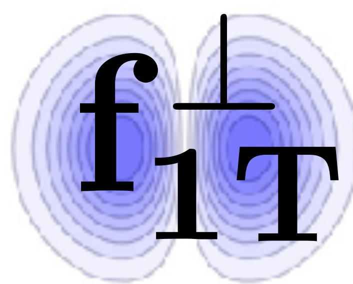
EIC Yellow report, Vladimirov (21)

EIC will make an enormous impact on the determination of the CS kernel

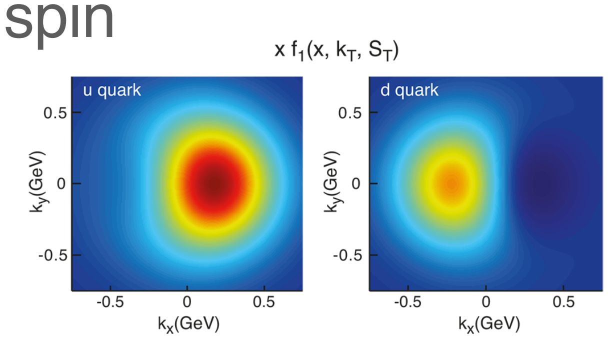
What about the 3D spin structure of the nucleon

POLARIZED TMD FUNCTIONS

Sivers function

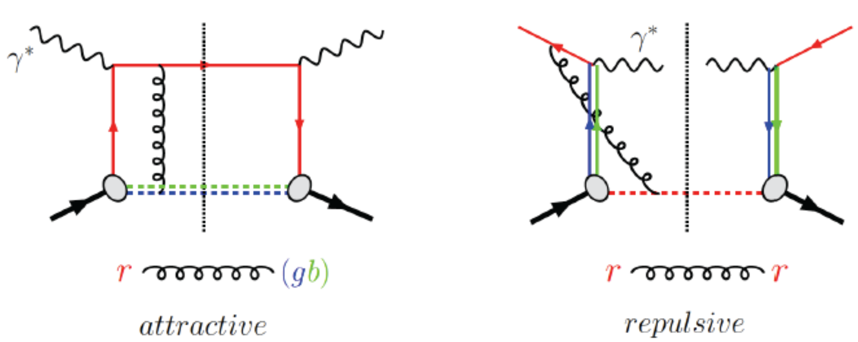


- Describes unpolarized quarks inside of transversely polarized nucleon
- Encodes the correlation of orbital motion with the spin



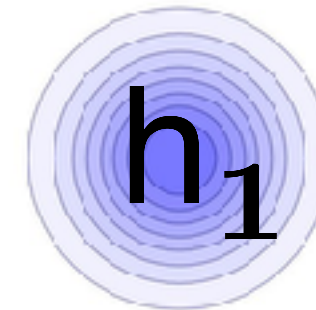
- Sign change of Sivers function is fundamental consequence of QCD

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



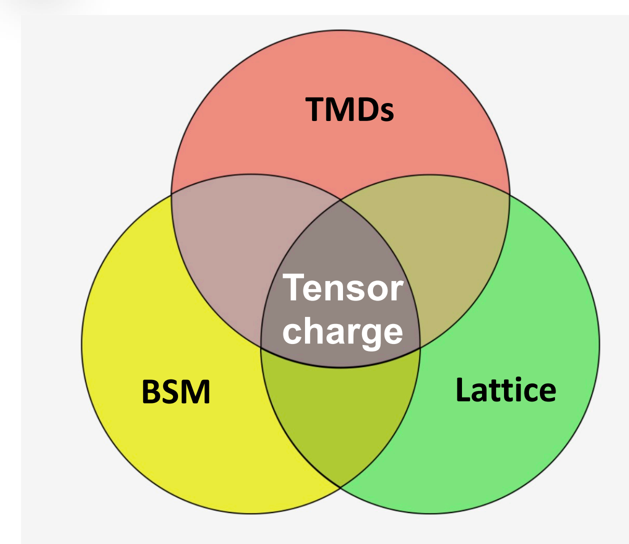
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

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

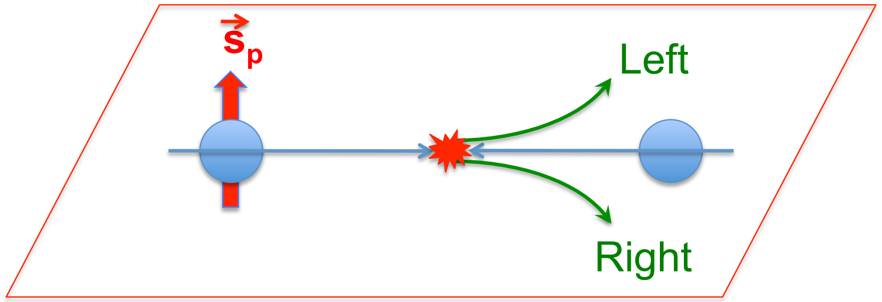
$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)\right]$$



CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

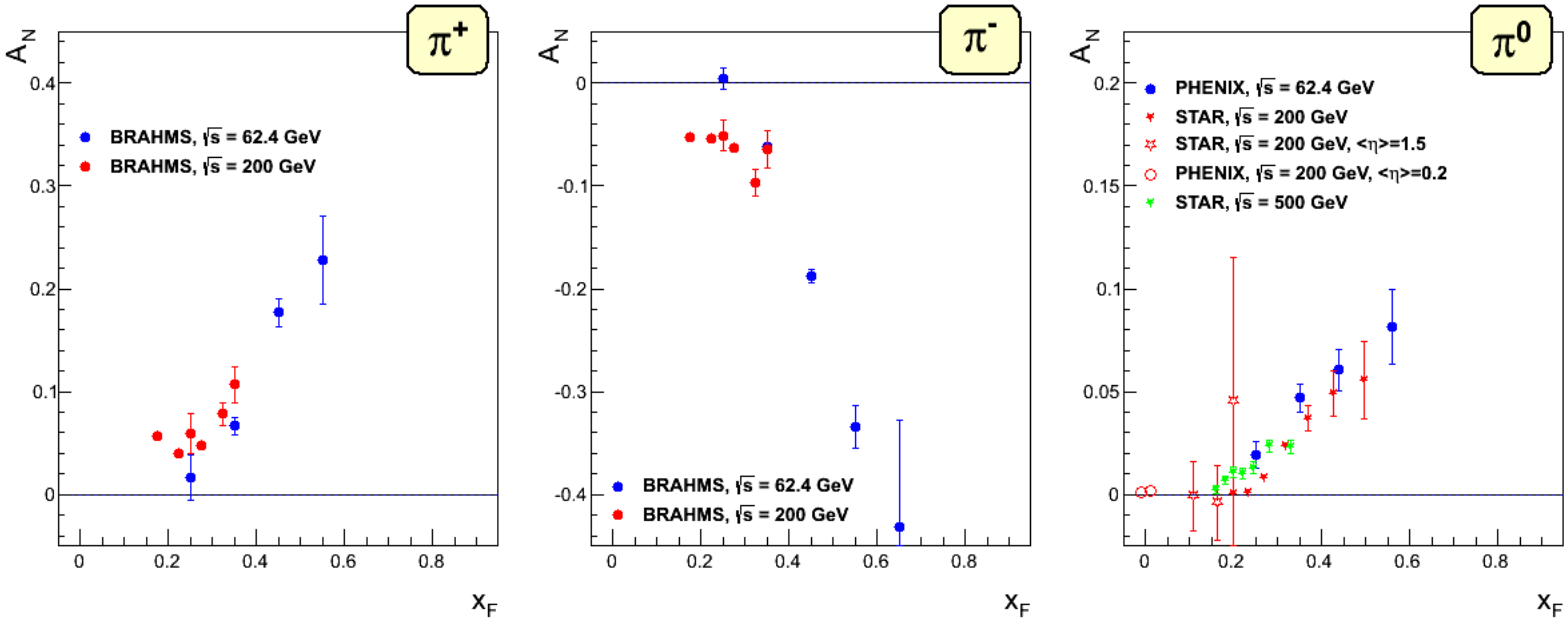
Consider polarized

hadron - hadron collisions



Asymmetry survives with growing collision energy

RHIC: STAR, BRAHMS, PHENIX



"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

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Jefferson Lab Angular Momentum Collaboration

https://www.jlab.org/theory/jam

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$
$A_{\text{SIDIS}}^{\text{Siv}}$	$e + (p,d)^{\uparrow} \to e + (\pi^+, \pi^-, \pi^0) + X$	$f_{1T}^{\perp}(x, k_T^2)$	$150.0/126 = 1.19$
$A_{\text{SIDIS}}^{\text{Col}}$	$e + (p,d)^{\uparrow} \to e + (\pi^+, \pi^-, \pi^0) + X$	$h_1(x, k_T^2), H_1^{\perp}(z, z^2 p_\perp^2)$	$111.3/126 = 0.88$
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+ \pi^- (UC, UL) + X$	$H_1^{\perp}(z, z^2 p_\perp^2)$	$154.5/176 = 0.88$
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^{\uparrow} \to \mu^+ \mu^- + X$	$f_{1T}^{\perp}(x, k_T^2)$	$5.96/12 = 0.50$
$A_{\text{DY}}^{\text{Siv}}$	$p^{\uparrow} + p \to (W^+, W^-, Z) + X$	$f_{1T}^{\perp}(x, k_T^2)$	$31.8/17 = 1.87$
A_N^h	$p^{\uparrow} + p \to (\pi^+, \pi^-, \pi^0) + X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

- JAM uses Bayesian inference in order to sample the posterior distribution of all parameters.
- Multistep strategy in the Monte Carlo framework is used.

Sato, Andres, Ethier, Melnitchouk (2019)

- Around 1000 MC samples are drawn from Bayesian posterior distributions and are analyzed.

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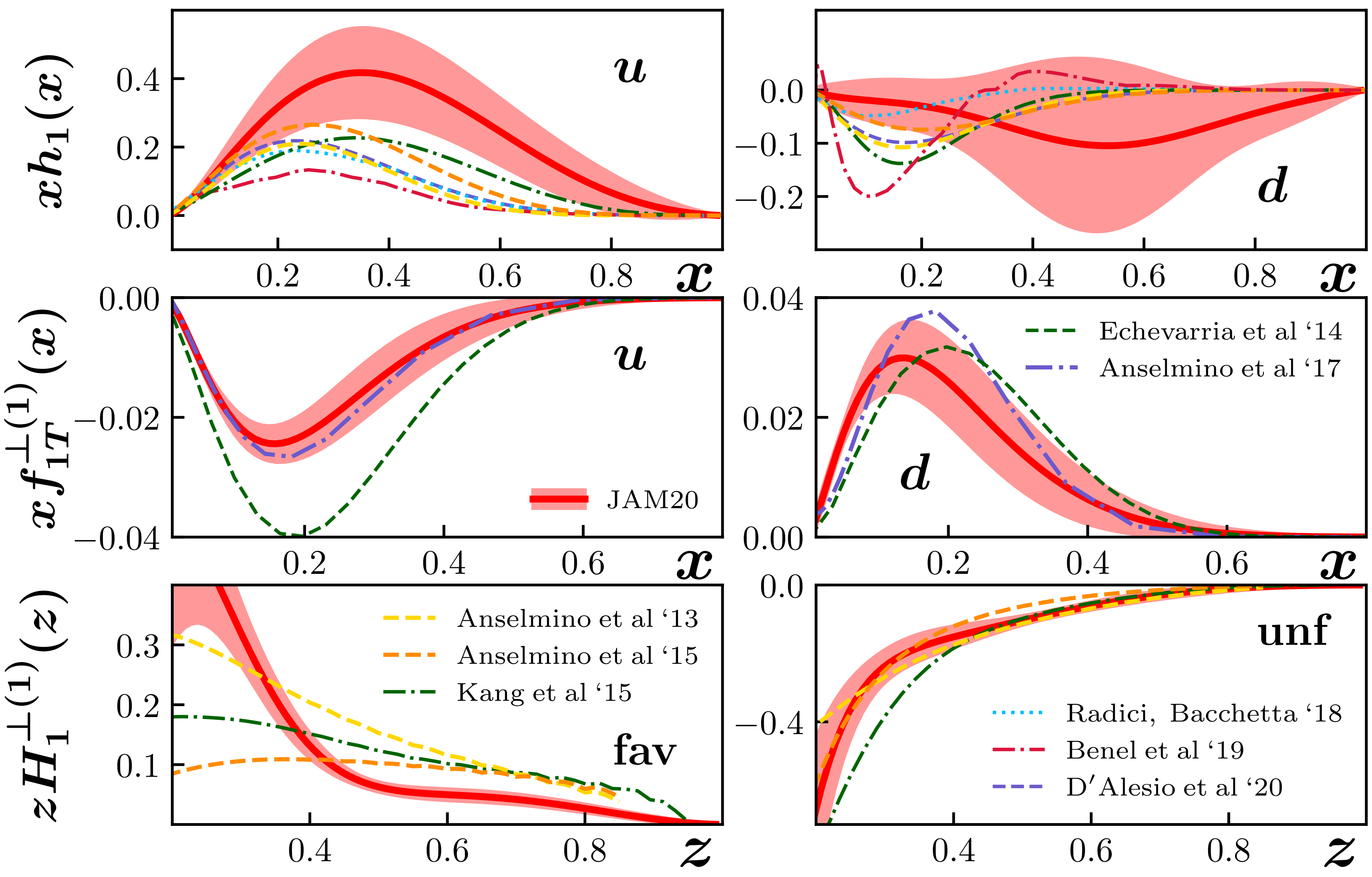
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



Transversity

$h_1(x)$

Sivers

$f_{1T}^{\perp(1)}(x)$

Collins FF

$H_1^{\perp(1)}(z)$

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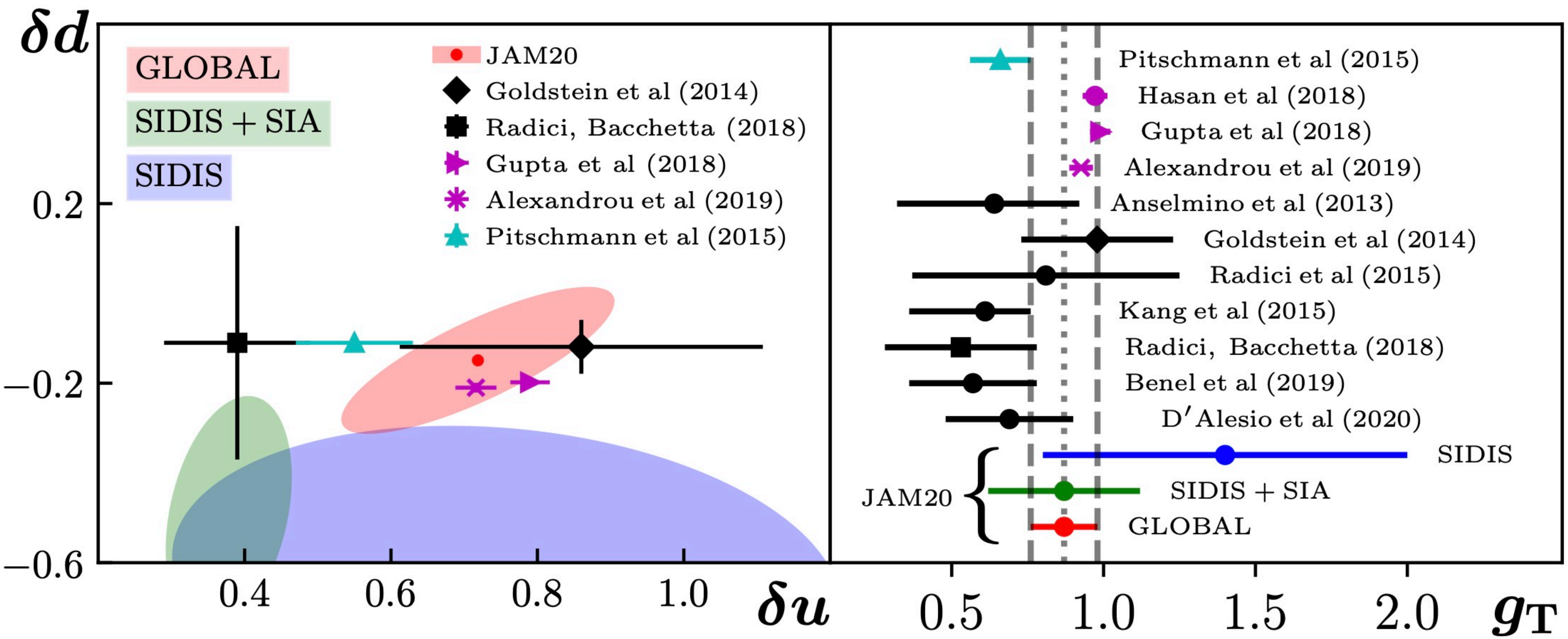
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



- Tensor charge from up and down quarks is constrained and compatible with lattice results

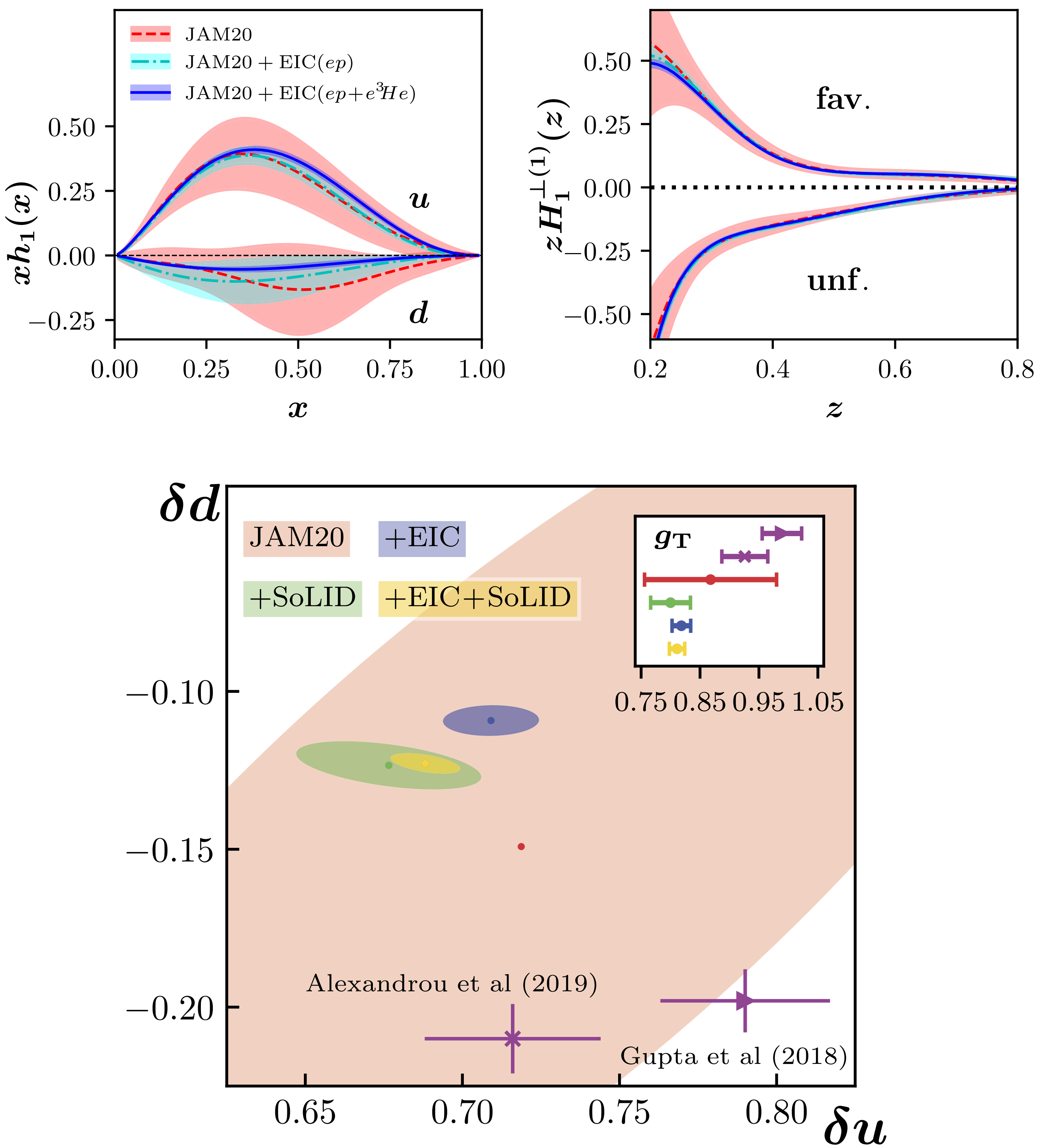
- Isovector tensor charge $g_T = \delta u - \delta d$
  $g_T = 0.89 \pm 0.12$ compatible with lattice results

<u>δu and δd Q^2=4 GeV^2</u>

δu= 0.65 $\pm$ 0.22

δd= -0.24 $\pm$ 0.2

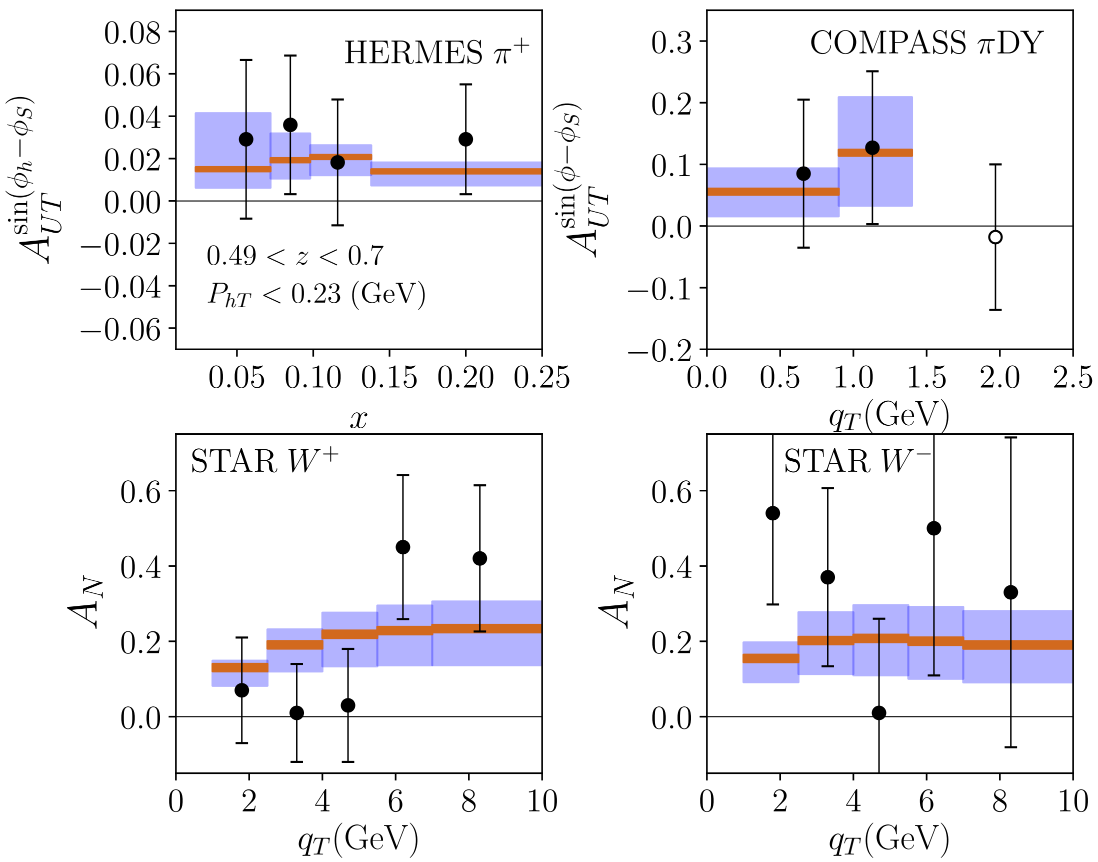
TENSOR CHARGE AND FUTURE FACILITIES



EIC data will allow to have g_T extraction at the precision at the level of lattice QCD calculations

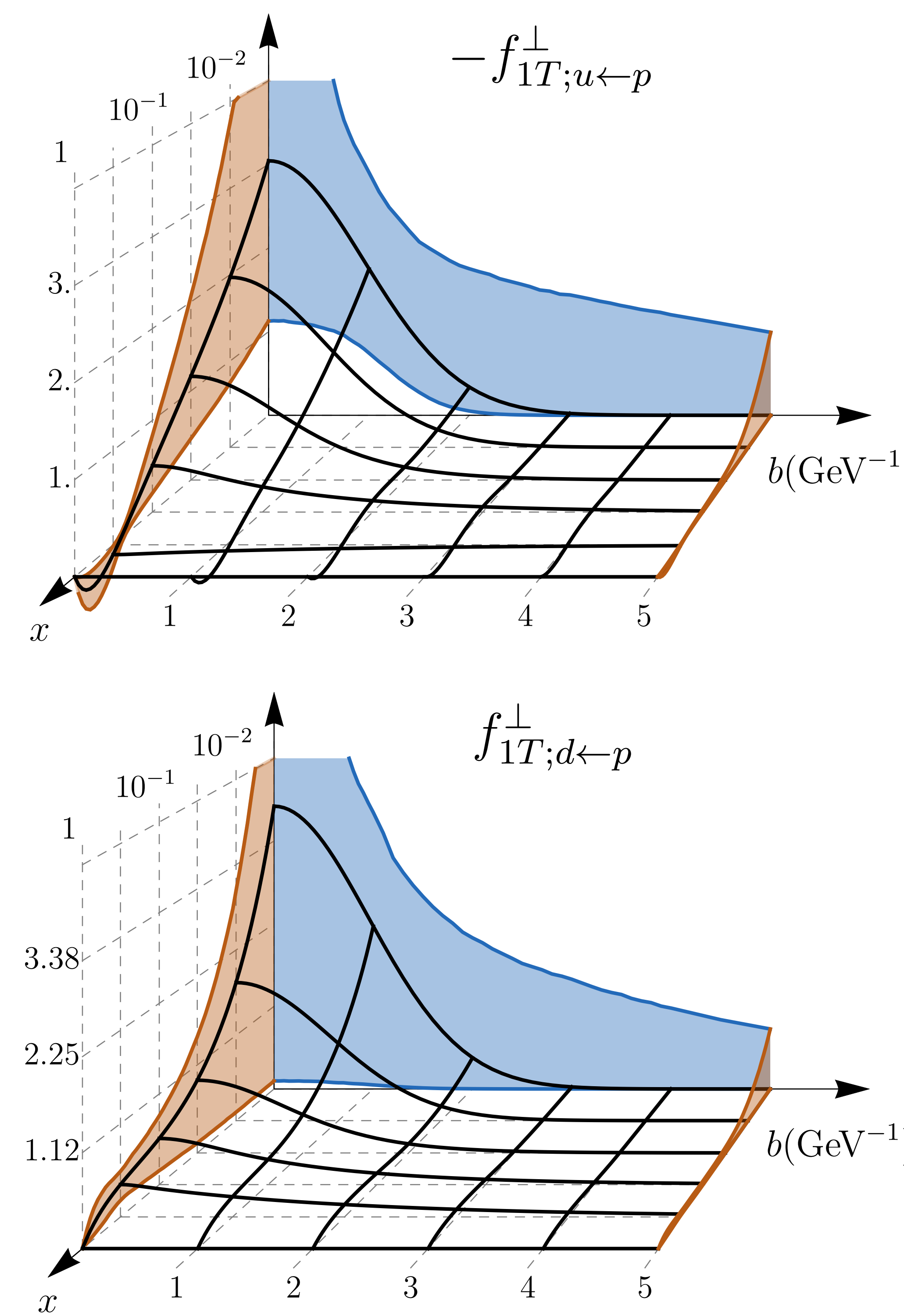
JLab 12 data will allow to have complementary information on tensor charge to test the consistency of the extraction and expand the kinematical region

N3LO EXTRACTION OF THE SIVERS FUNCTION

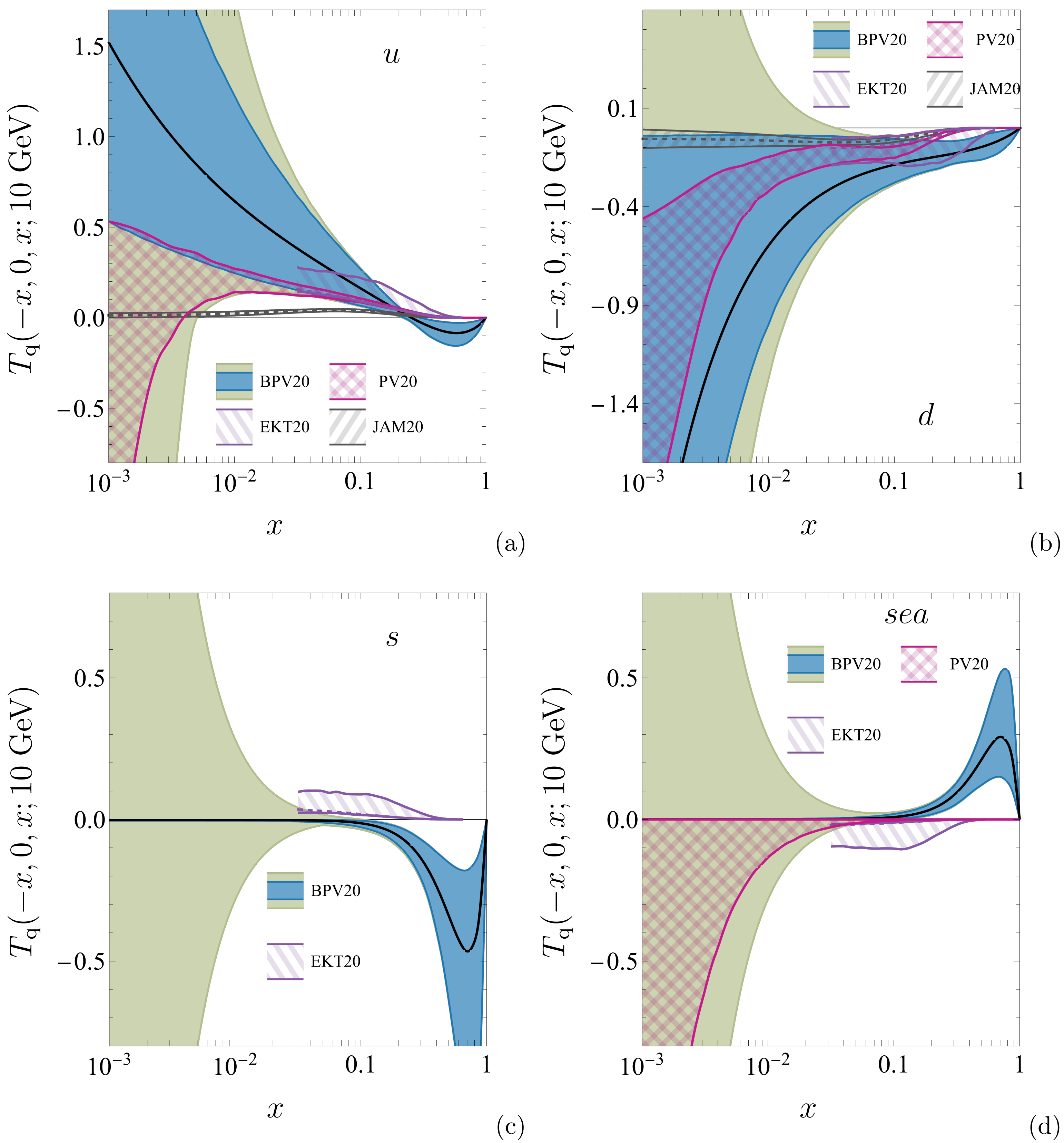


- The first next-to-next-to-next-to-leading order N3LO global QCD analysis of SIDIS, Drell-Yan and W$^{\pm}$/Z production data.
- Uses the unpolarized functions extracted at the same N3LO precision

Bury, Prokudin, Vladimirov (2020)



THE QIU-STERMAN MATRIX ELEMENT



Bury, Prokudin, Vladimirov (2020)

Compares well with JAM 20 (LO)

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

PV20 (NLL)

Bacchetta, Delcarro, Pisano, Radici (2020)

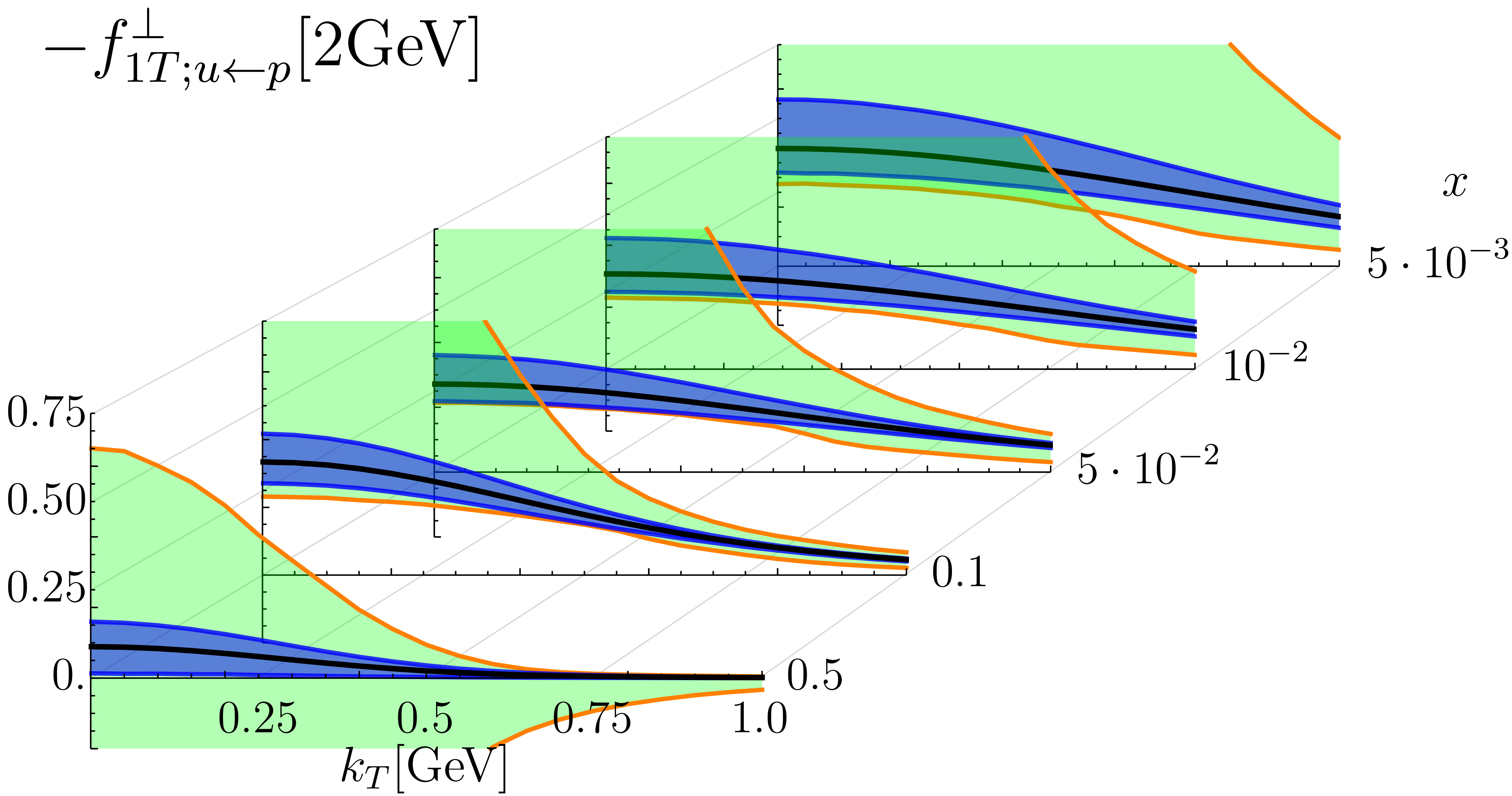
EKT20 (NNLL)

Echevarria, Kang, Terry (2020)

Sea quark functions is still a mystery to explore at the EIC

EIC AND THE SIVERS FUNCTION

Vladimirov (2021)

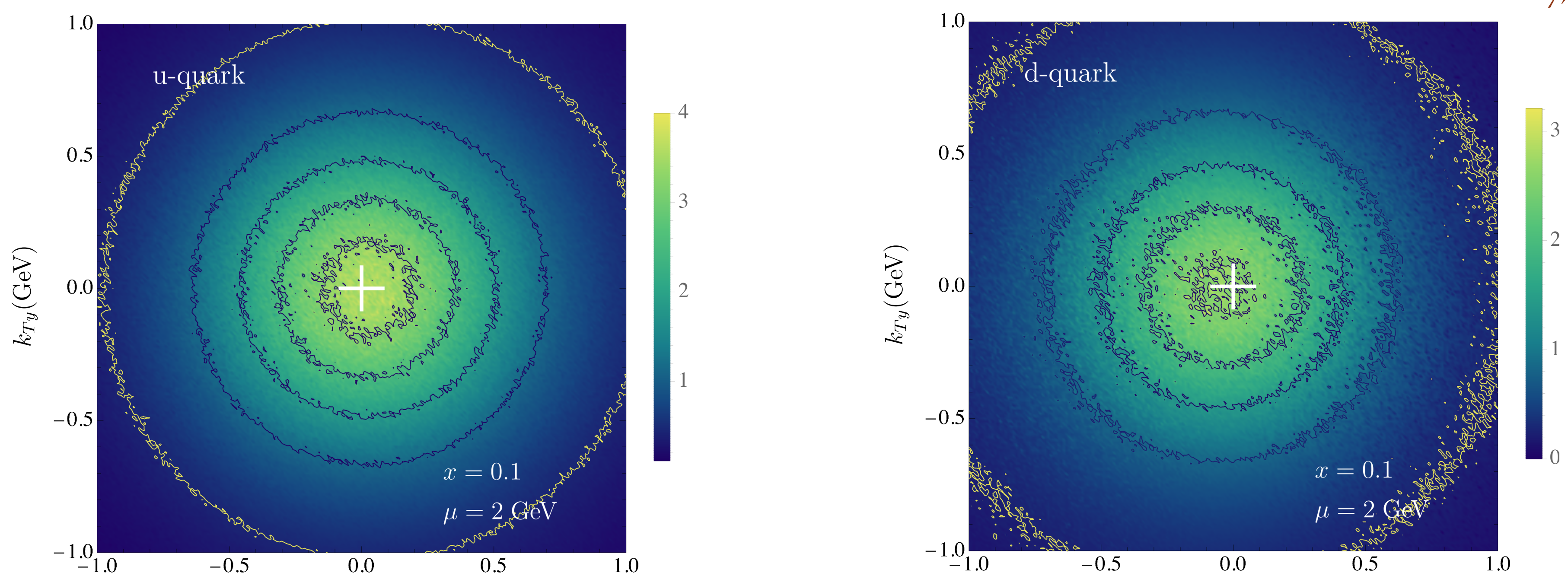


- The impact of the EIC is very substantial

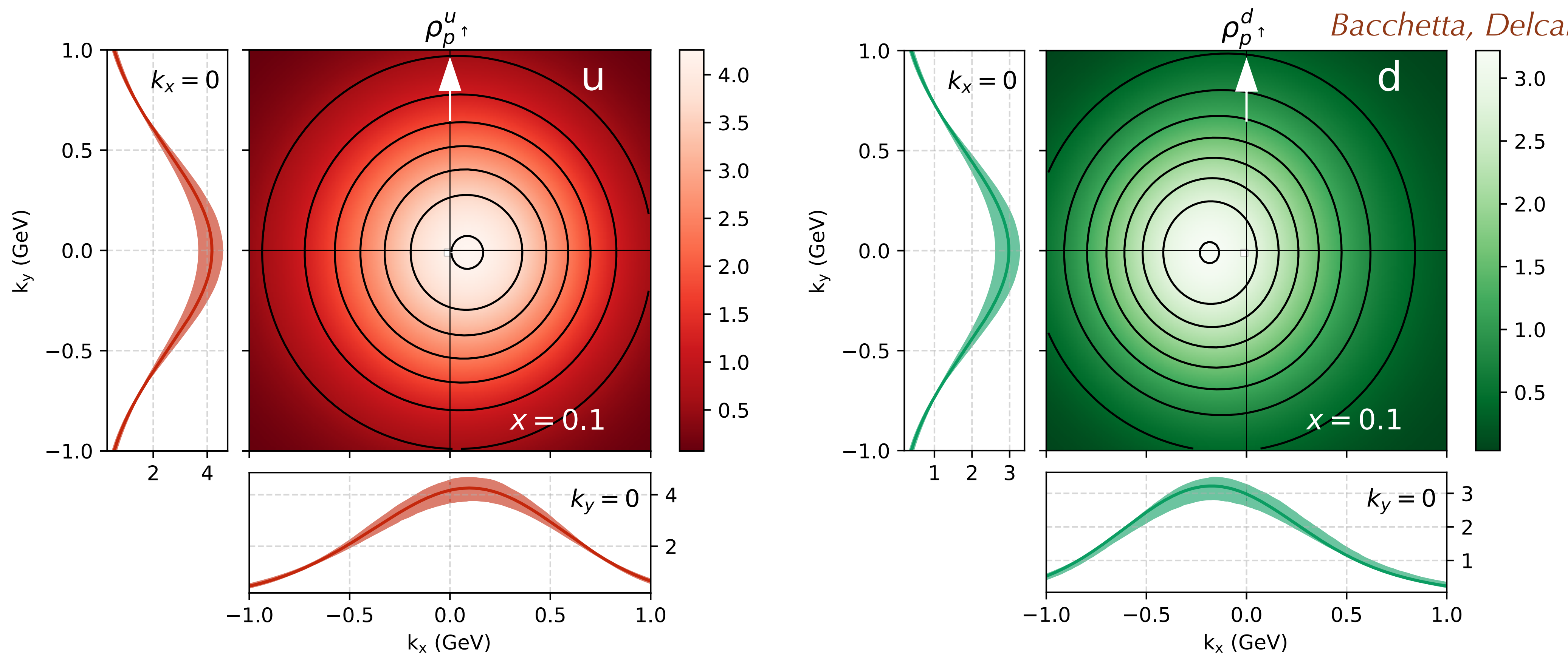
NUCLEON TOMOGRAPHY – THE FINAL GOAL

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

Bury, Prokudin, Vladimirov (2020)



Bacchetta, Delcarro, Pisano, Radici (2020)



CONCLUSIONS

- EIC physics is an exciting growing field. There will be projects for generations of nuclear physicists to come.
- TMD studies have made great progress, they are synergistic with many other areas: lattice QCD, SCET, small-x, jets, etc
- South Korea has a very good record in QCD, SCET, non perturbative methods, experimental studies. It is the time to actively join EICUG and make the difference!
- Please, send your students to the CFNS Summer School: https://indico.bnl.gov/event/7555/ next year the third edition.
- EICUG Summer Meeting August 2-6, 2021