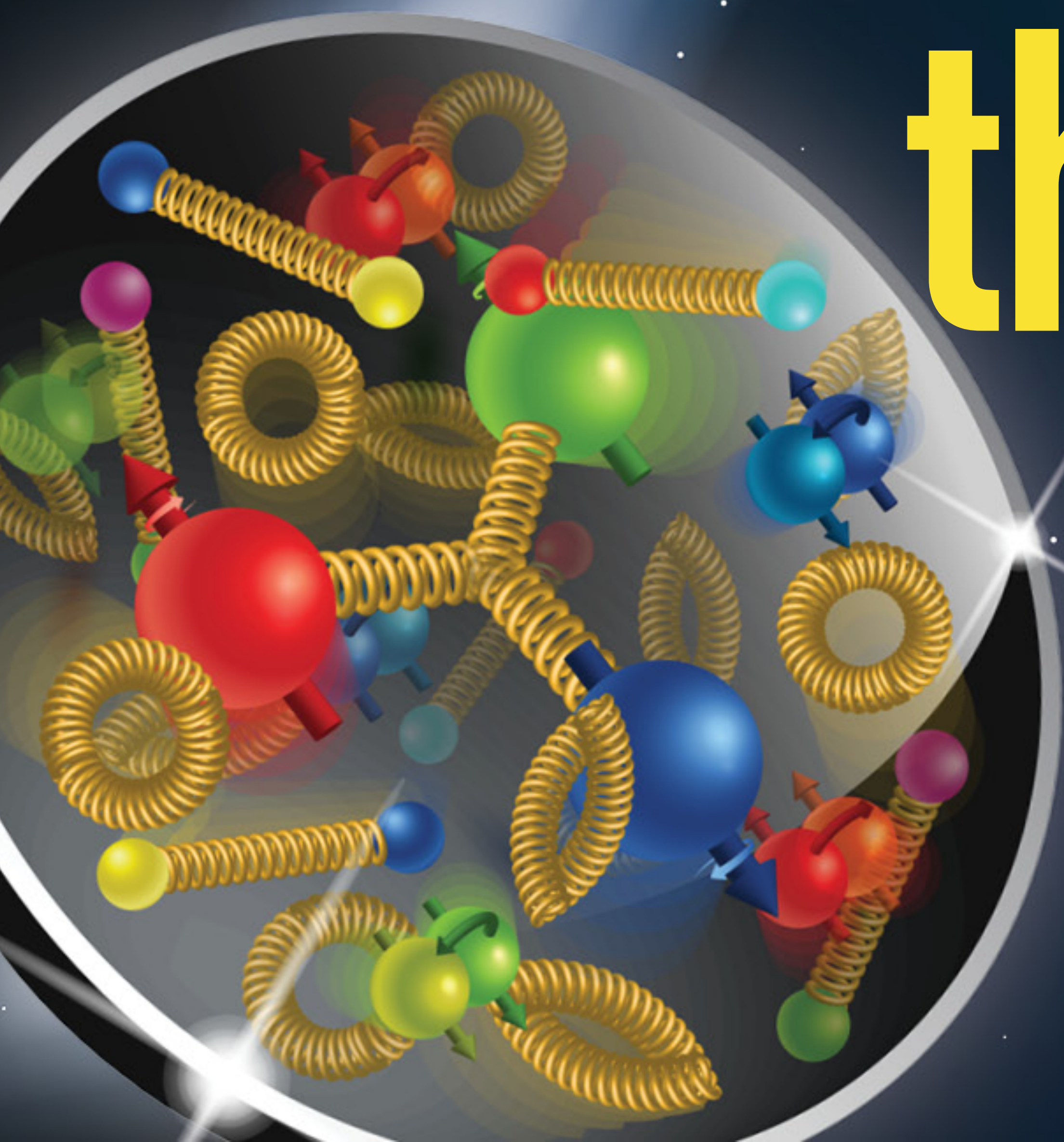
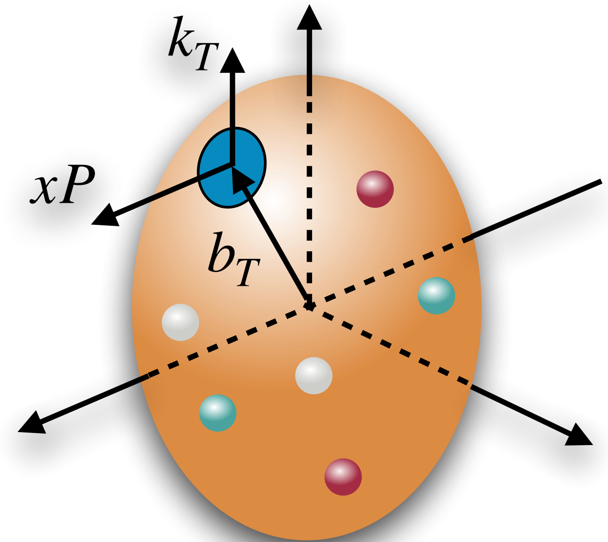
3D structure of the nucleon

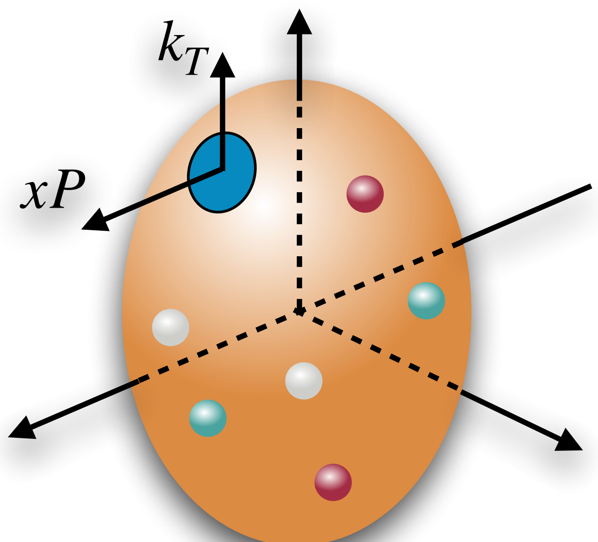


Alexei Prokudin

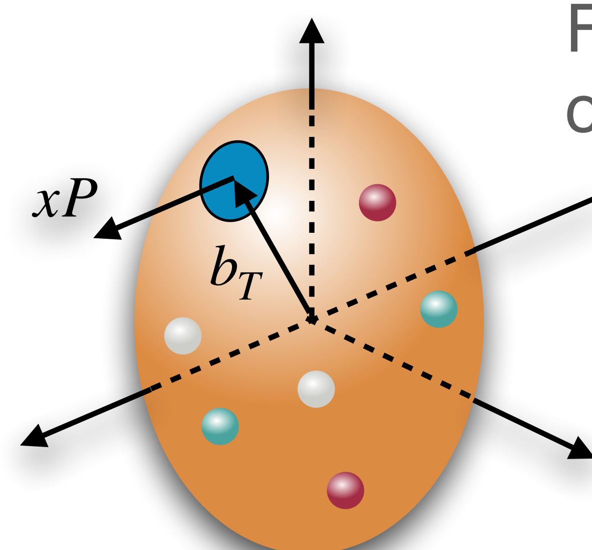
Wigner distributions
(Fourier transform of
GTMDs = Generalized
Transverse Momentum
Distributions)



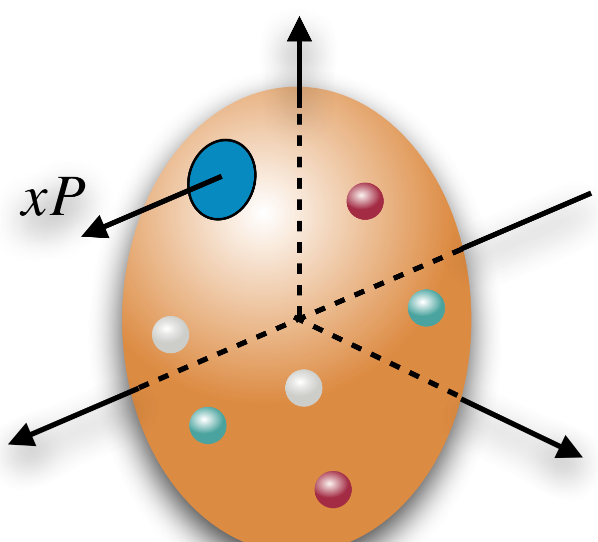
TMDs



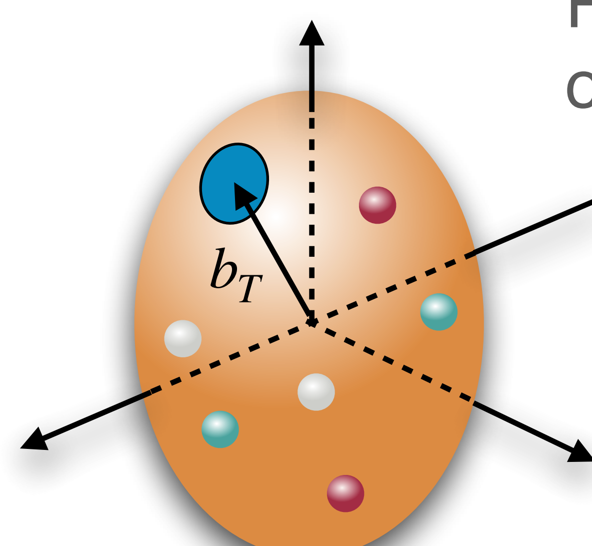
Fourier transform
of GPDs



PDFs

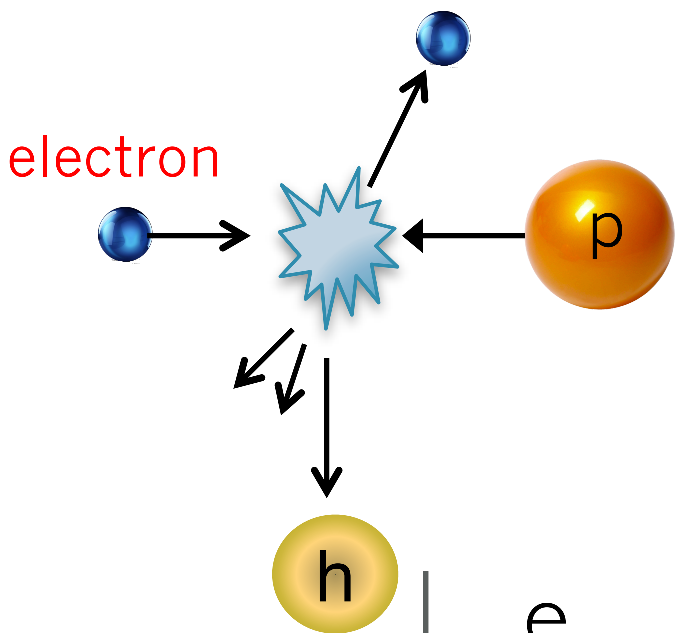


Fourier transform
of Form Factors

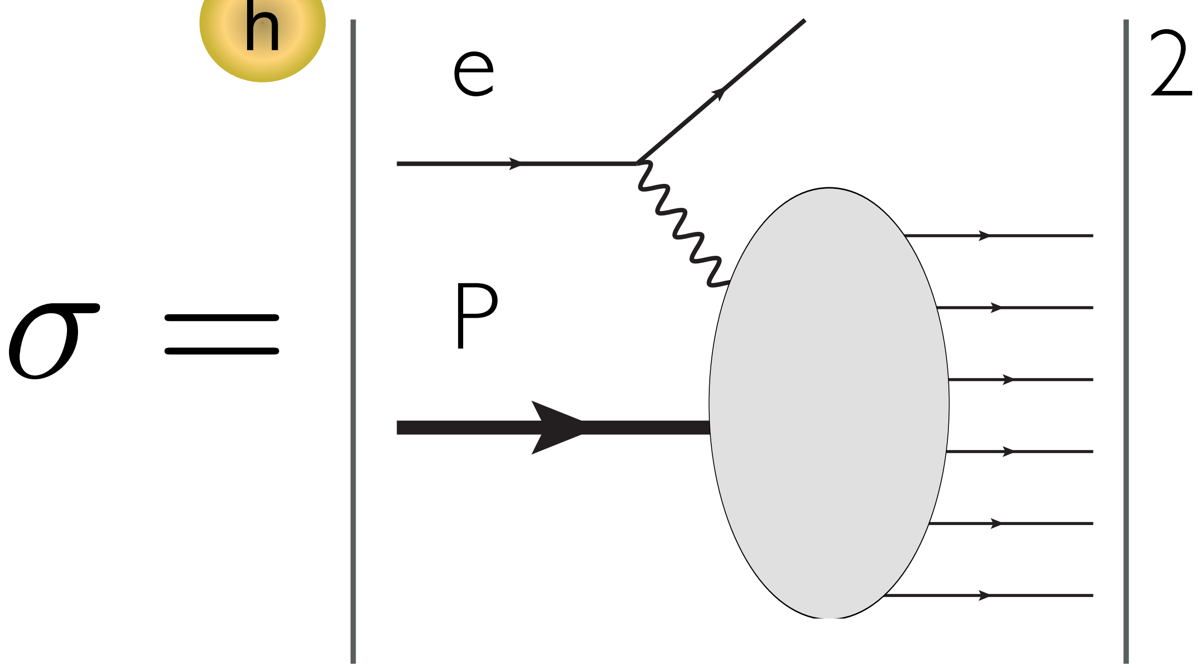


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

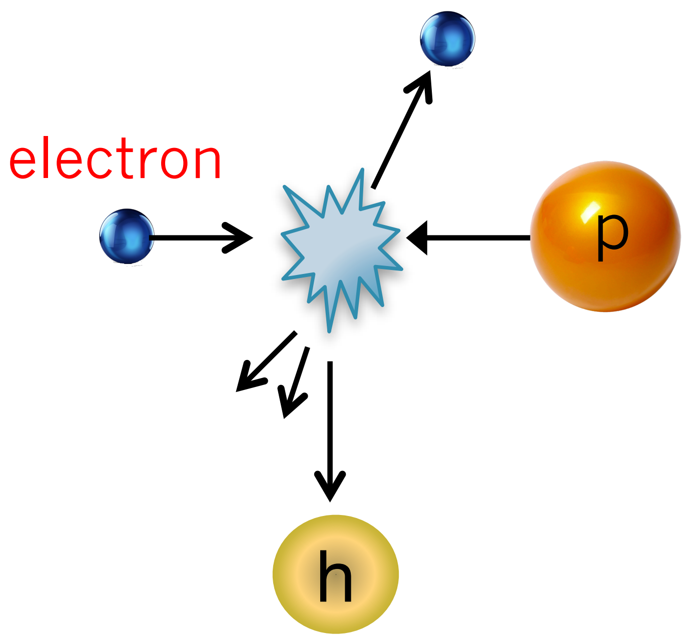
QCD FACTORIZATION IS THE KEY!



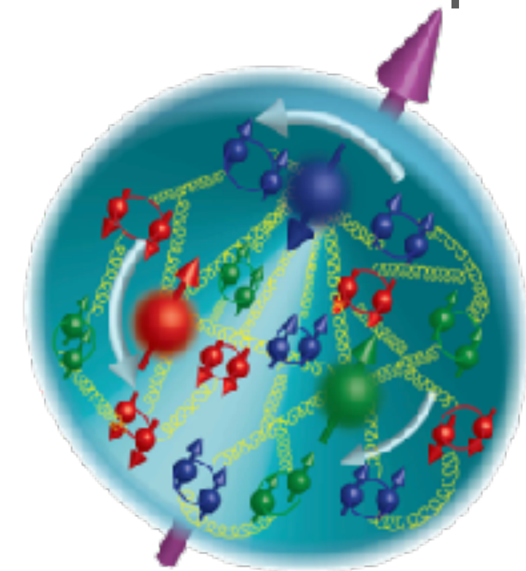
We need a probe to “see” quarks and gluons



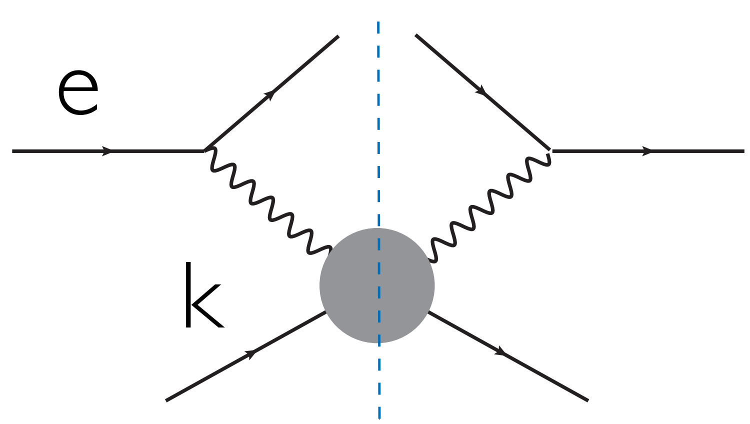
QCD FACTORIZATION IS THE KEY!



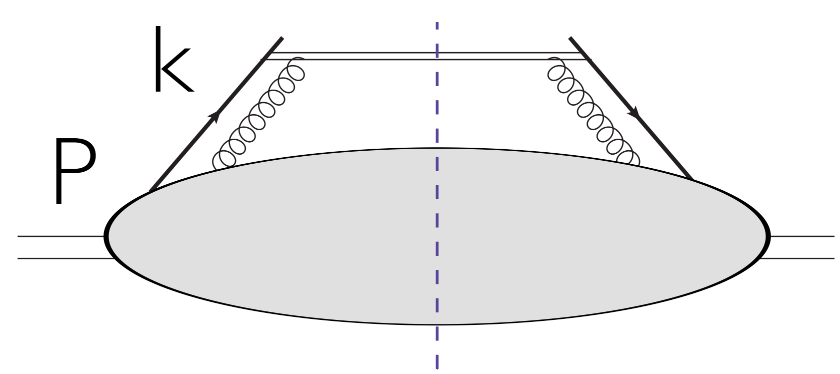
We need a probe to “see” quarks and gluons



$\sigma \approx$



$\otimes$

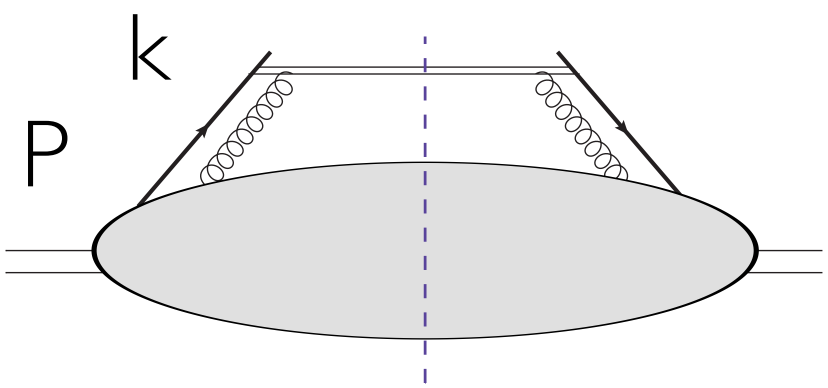


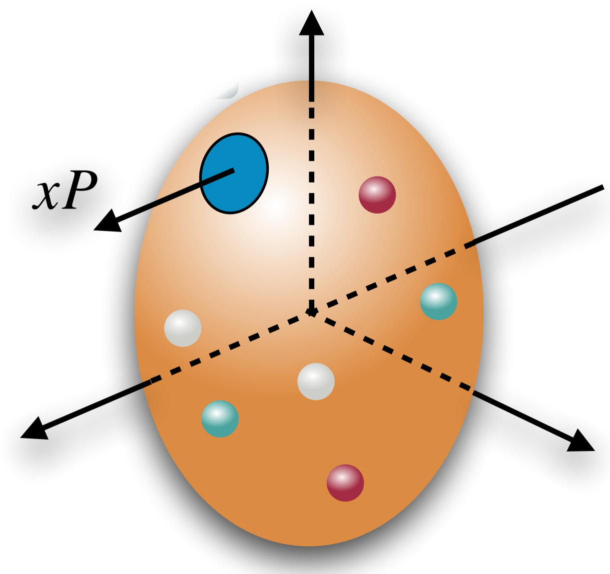
$+\mathcal{O}\left(\frac{M^2}{Q^2}\right)$

Factorization Probe Structure Power corrections

HADRON'S PARTONIC STRUCTURE

Collinear Parton Distribution Functions





$f_{q/P}(x)$

longitudinal

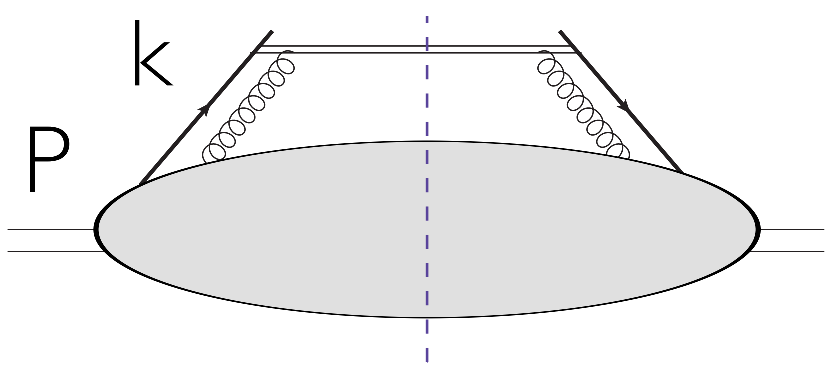
Probability density to find a quark with a momentum fraction x

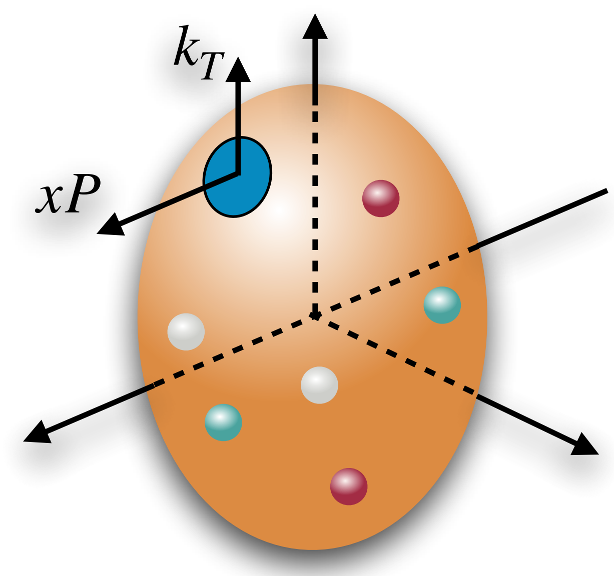
Hard probe resolves the particle nature of partons, but is not sensitive to hadron's structure at ~fm distances.

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.

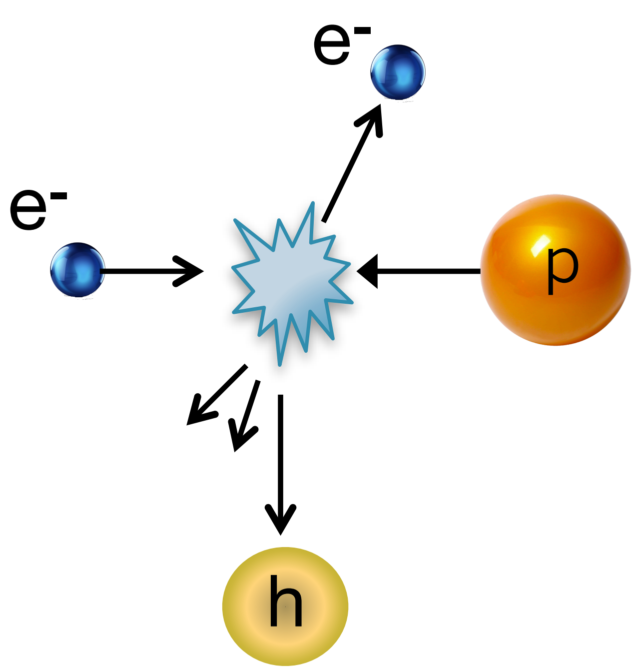
TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

Small scale $\rightarrow$ $q_T \ll Q$ $\leftarrow$ Large scale

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

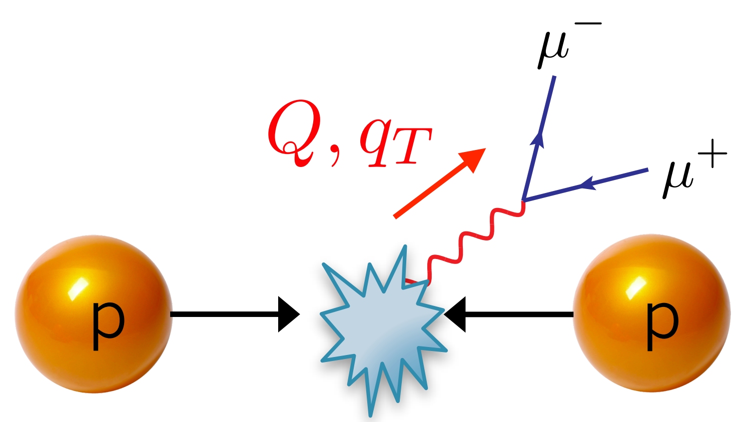
$$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(z, k_T)$$



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

Drell-Yan

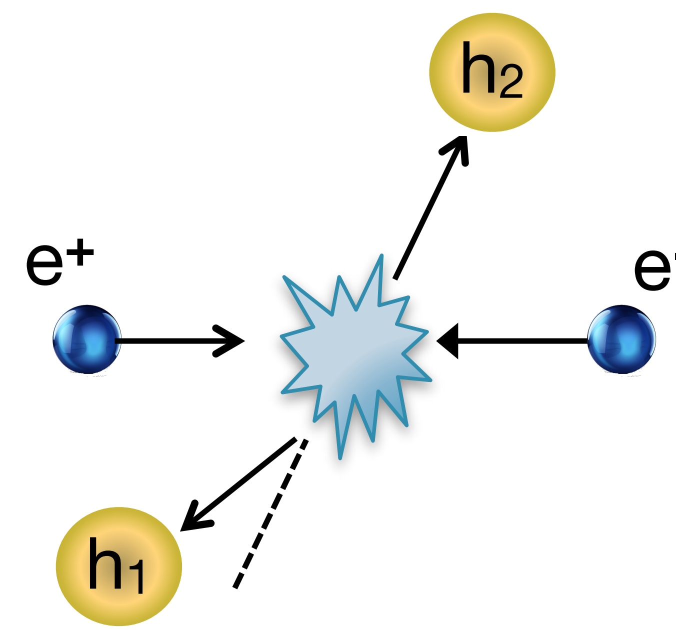
$$\sigma \sim f_{q/P}(x_1, k_T) f_{\bar{q}/P}(x_2, k_T)$$



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

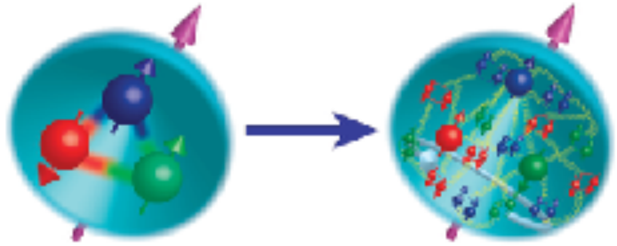
Dihadron in e+e-

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

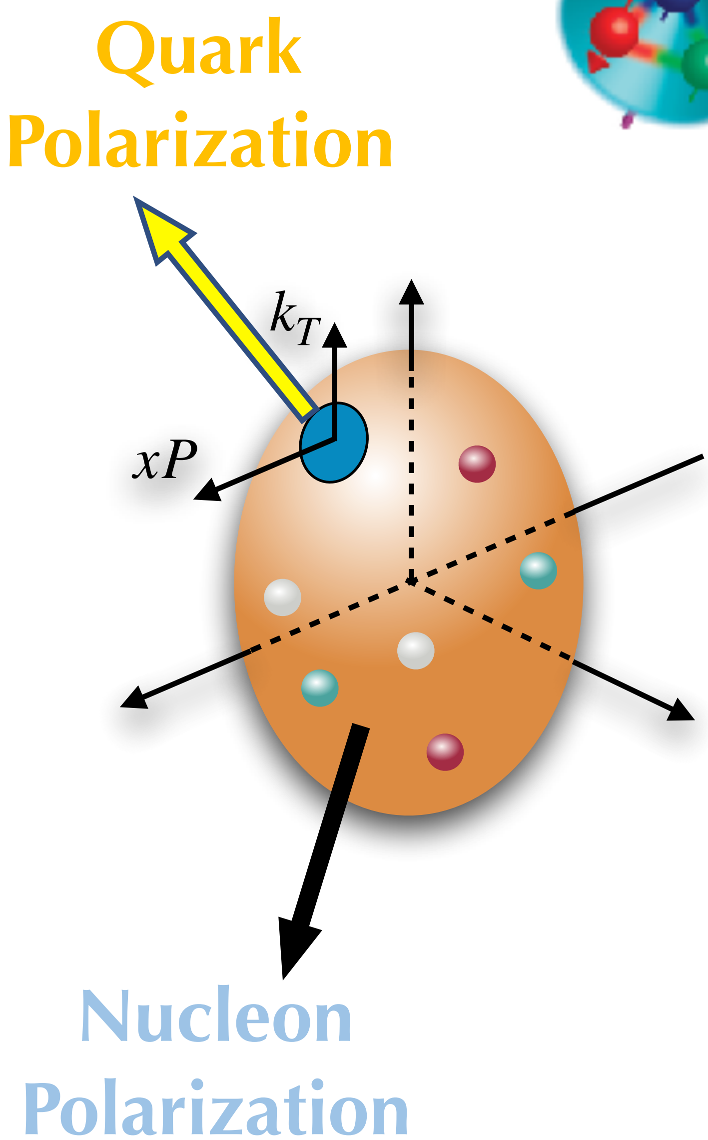


Collins, Soper (1983)
Collins (2011)

Our understanding of hadron evolves: TMDs with Polarization



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

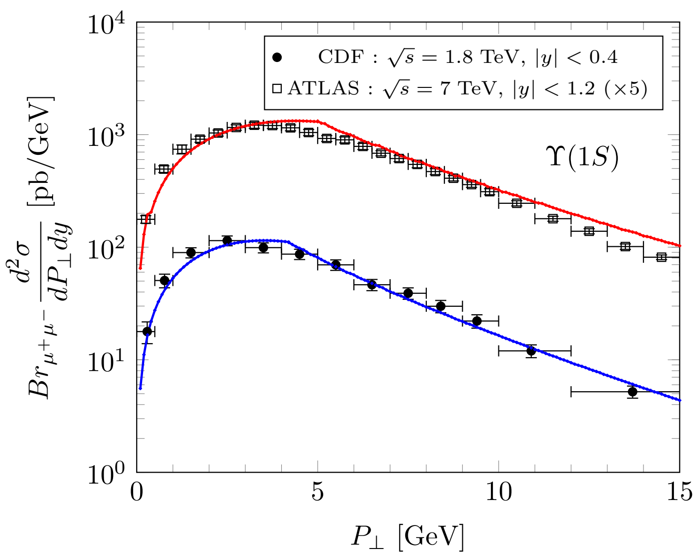


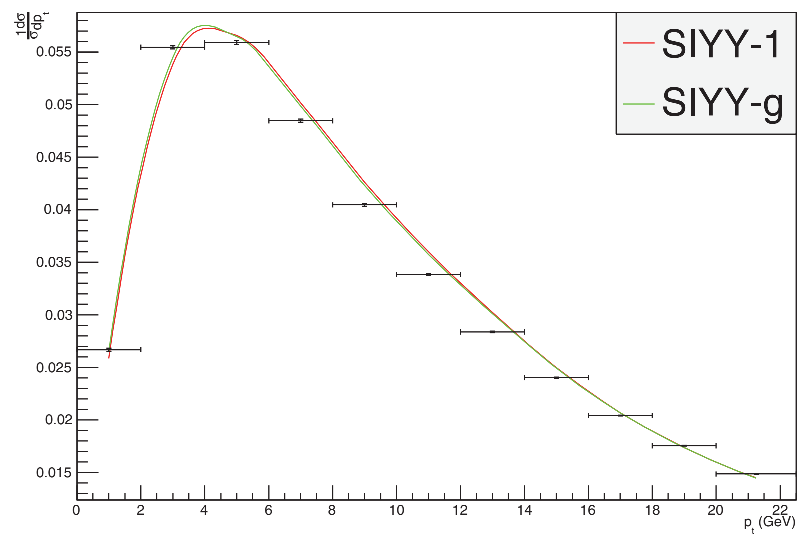
Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	$f_1(x,k_T^2)$ *Unpolarized*		$h_1^\perp(x,k_T^2)$ - *Boer-Mulders*
L		$g_1(x,k_T^2)$ - *Helicity*	$h_{1L}^\perp(x,k_T^2)$ - *Kozinian-Mulders,"worm"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

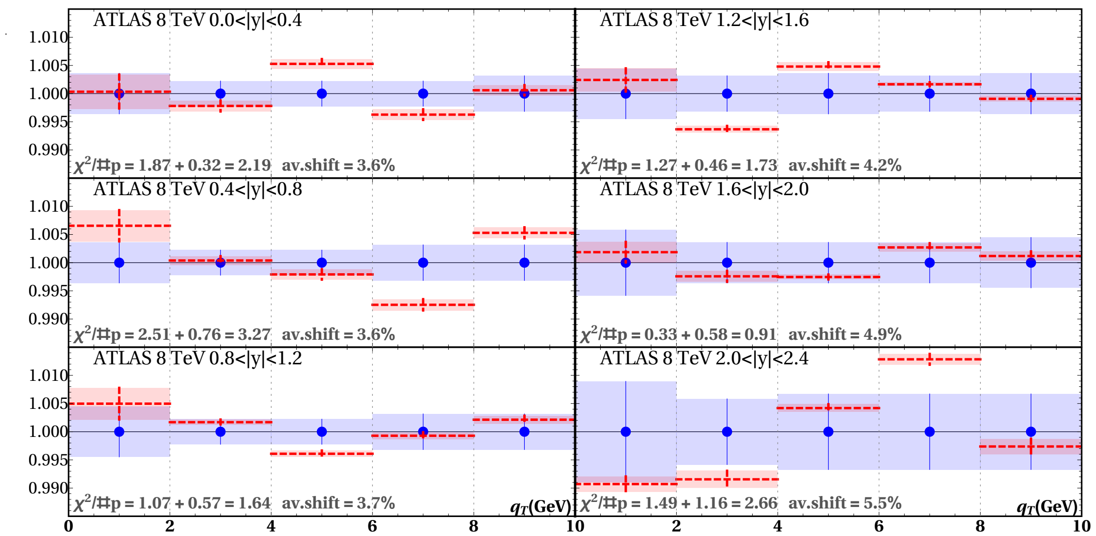
Analogous tables for:

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

SUCCESS OF TMD FACTORIZATION PREDICTIVE POWER







Qiu, Watanabe arXiv:1710.06928   *Sun, Isaacson, Yuan, Yuan arXiv:1406.3073*   *Bertone, Scimemi, Vladimirov arXiv:1902.08474*

Upsilon production   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

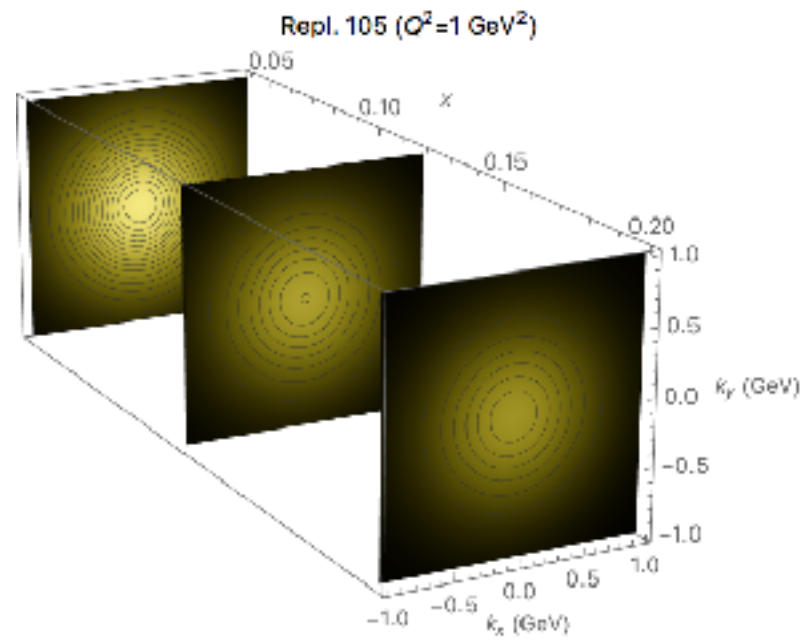
- LHC results at 7 and 13 TeV are accurately predicted from fits of lower energies

TMD FITS OF UNPOLARIZED DATA

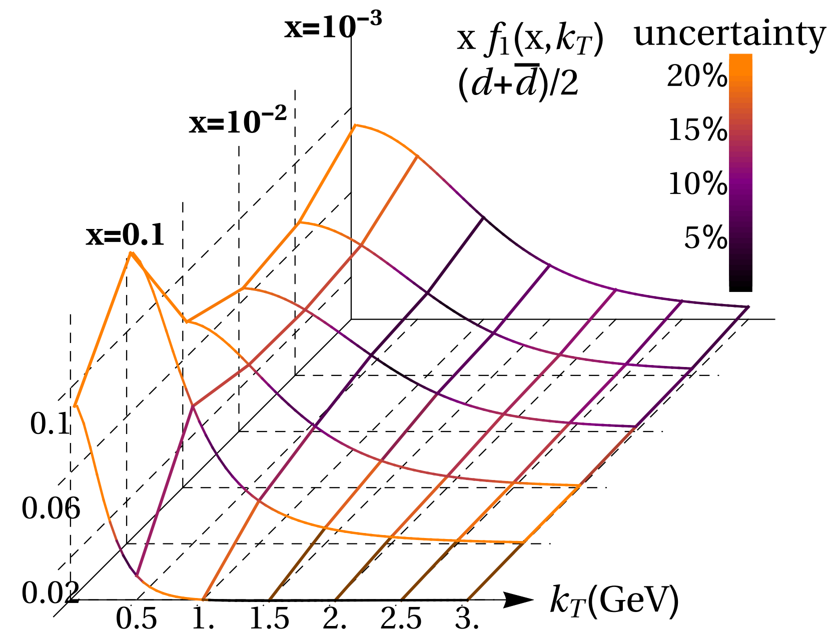
	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)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

UNPOLARIZED TMD MEASUREMENTS

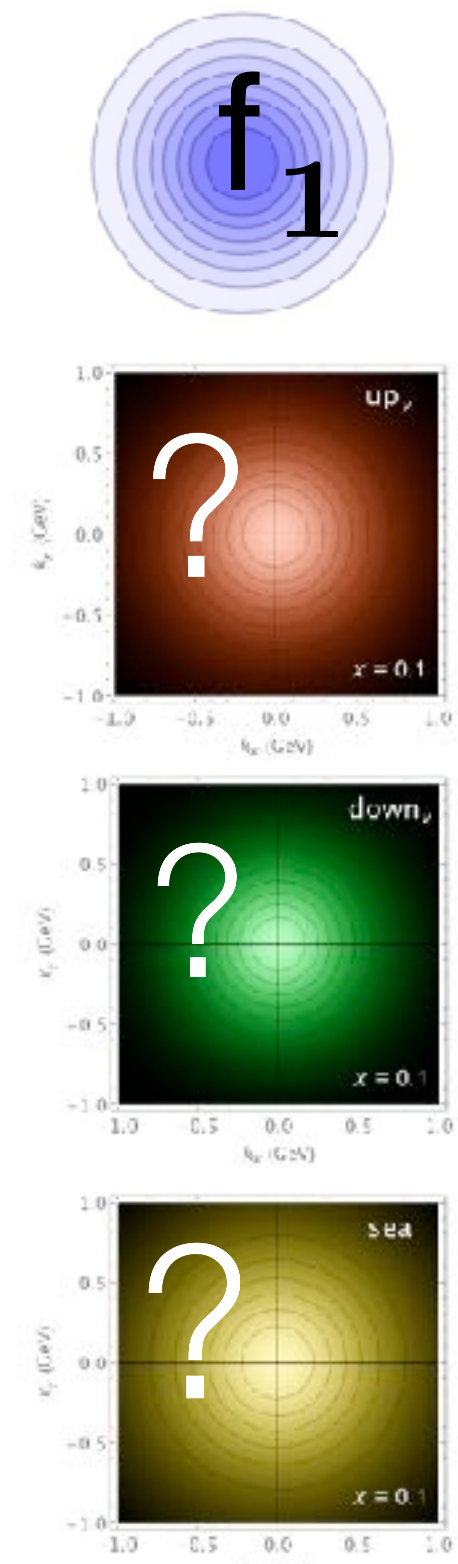
Unpolarized cross section



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

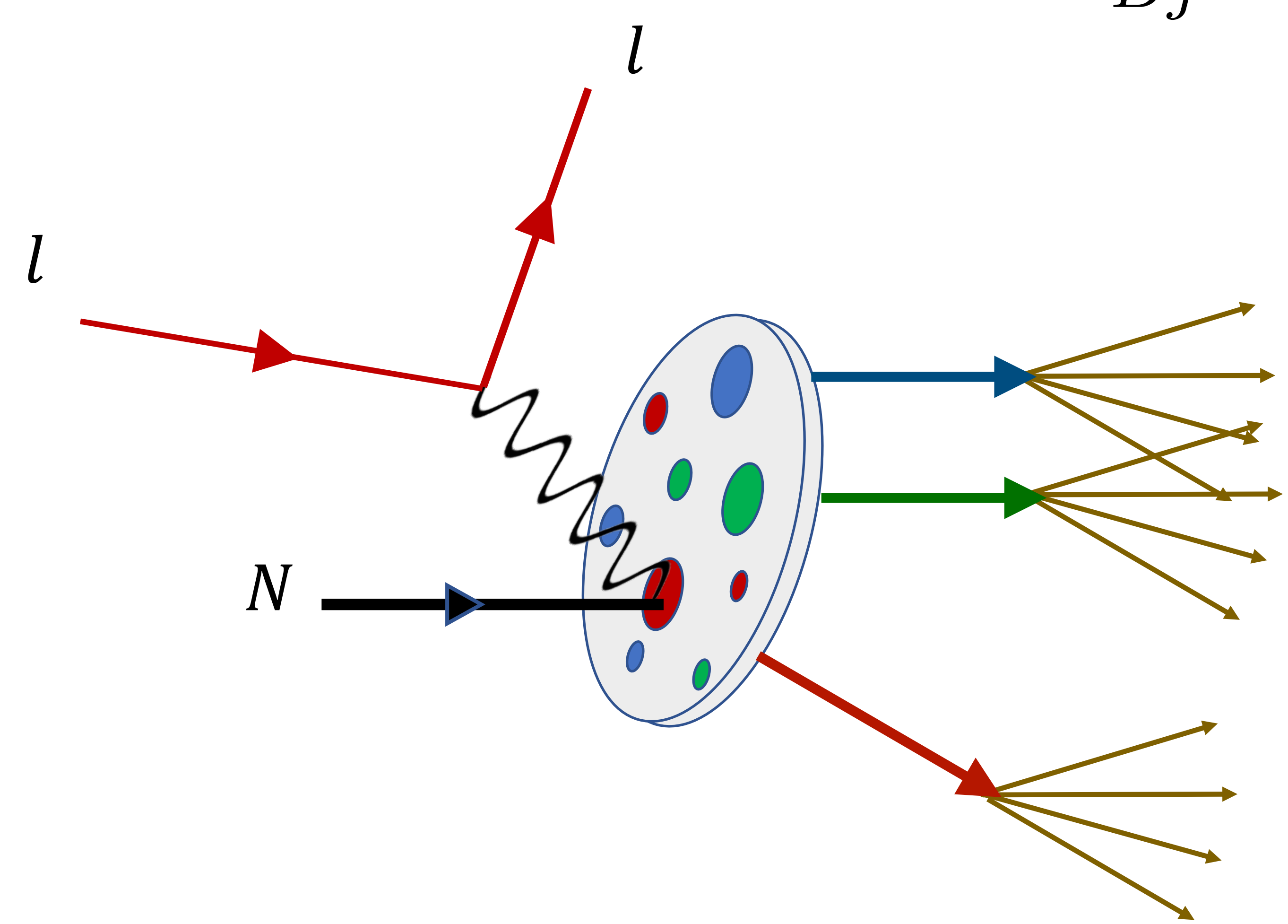
Fast progress in TMD determinations is taking place,
but still many open questions

SEMI INCLUSIVE DEEP INELASTIC SCATTERING

Consider electron - hadron collisions in DIS regime

$$Q^2 \to \infty$$

$$x_{Bj} = \frac{Q^2}{2P \cdot q} = const$$

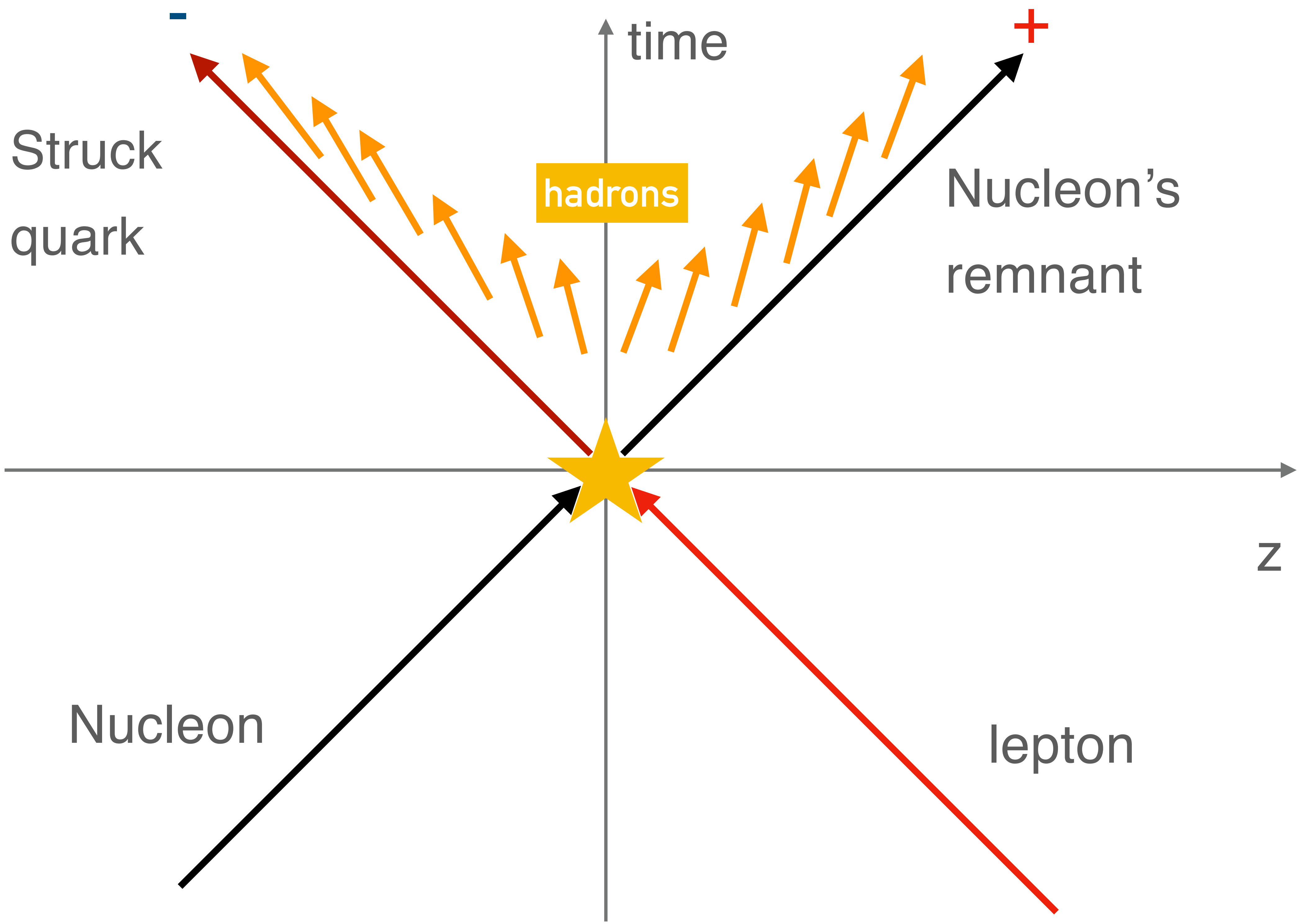


Target fragmentation region

Current fragmentation region

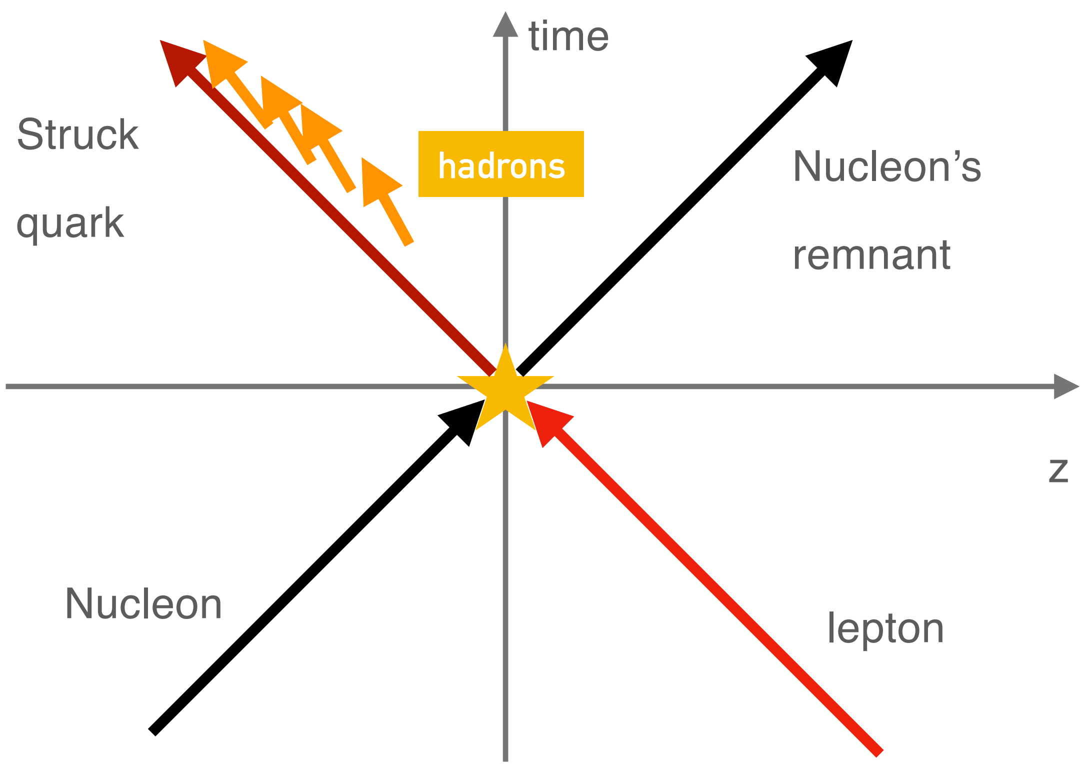
Detect a pion in the final state

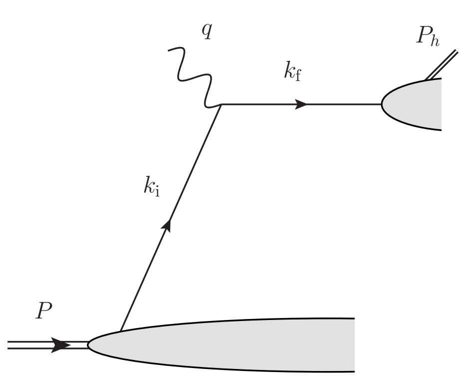
SPACE-TIME PICTURE OF THE COLLISION



CURRENT REGION FACTORIZATION

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





Boglione et al, 1611.10329

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

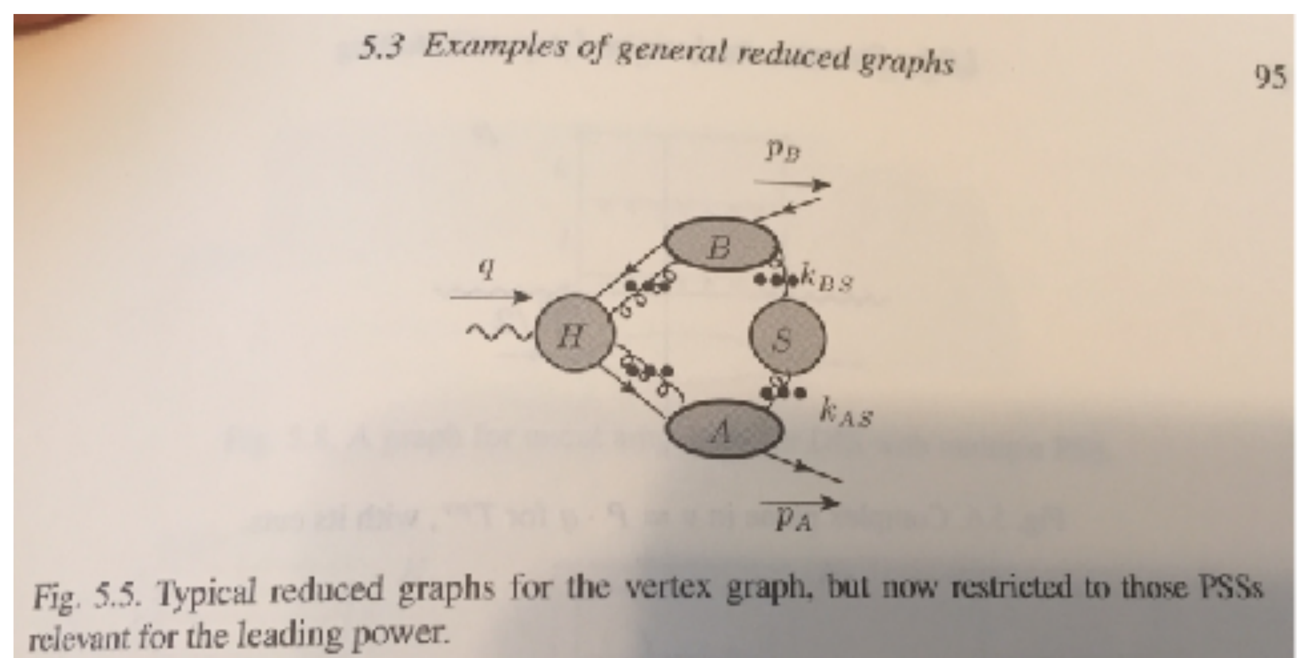

5.3 Examples of general reduced graphs 95

Fig. 5.5. Typical reduced graphs for the vertex graph, but now restricted to those PSSs relevant for the leading power.

Example of pinch-singular surfaces for e+e-

Boglione et al, 1611.10329

CURRENT REGION FACTORIZATION

Berger "back of the envelope" criterium is a popular choice

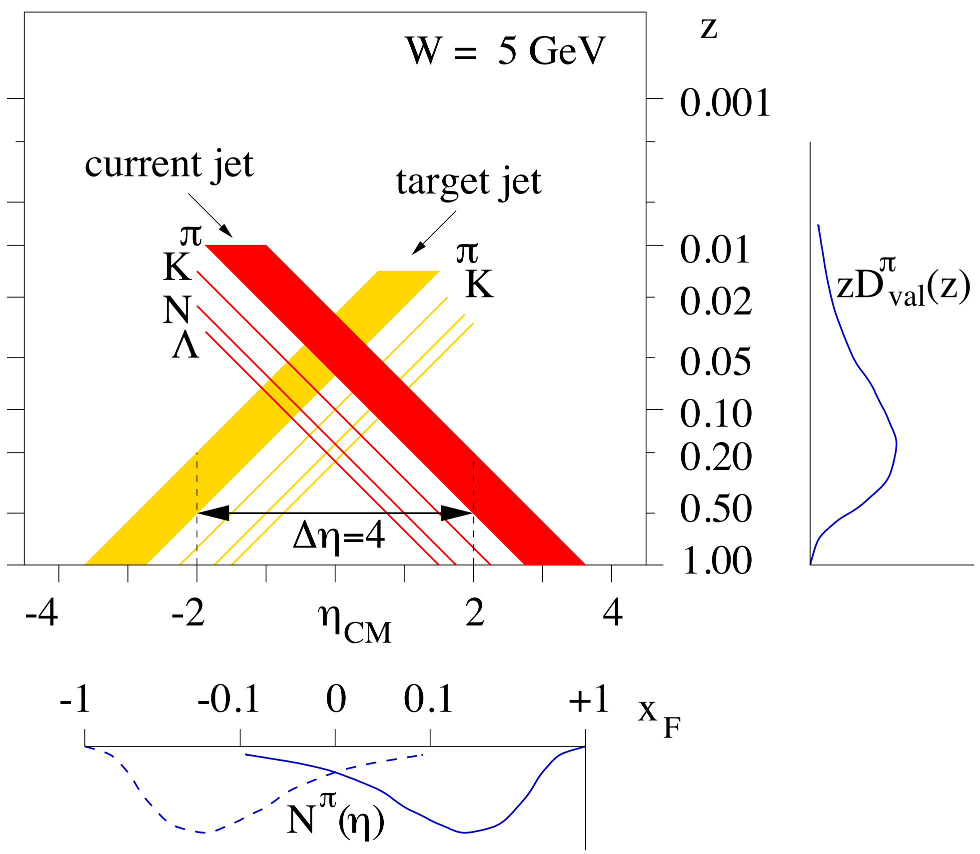
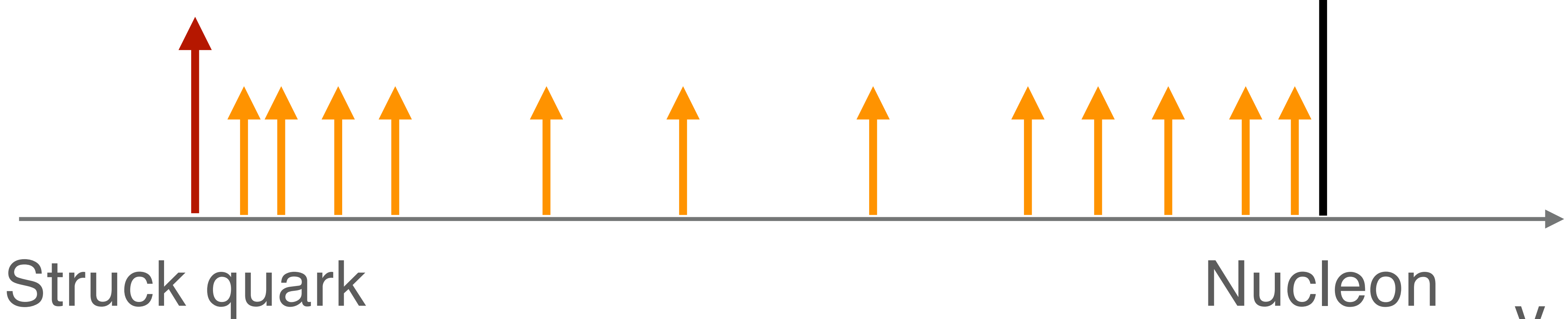


FIGURE 2. Relation between $z - values$ in fragmentation and CM rapidity for $W = 5$ GeV.

Berger, '87, Mulders, 001.0199

- Keep rapidity separation
- Keep z_h large enough



Boglione et al, 1611.10329

CURRENT REGION FACTORIZATION

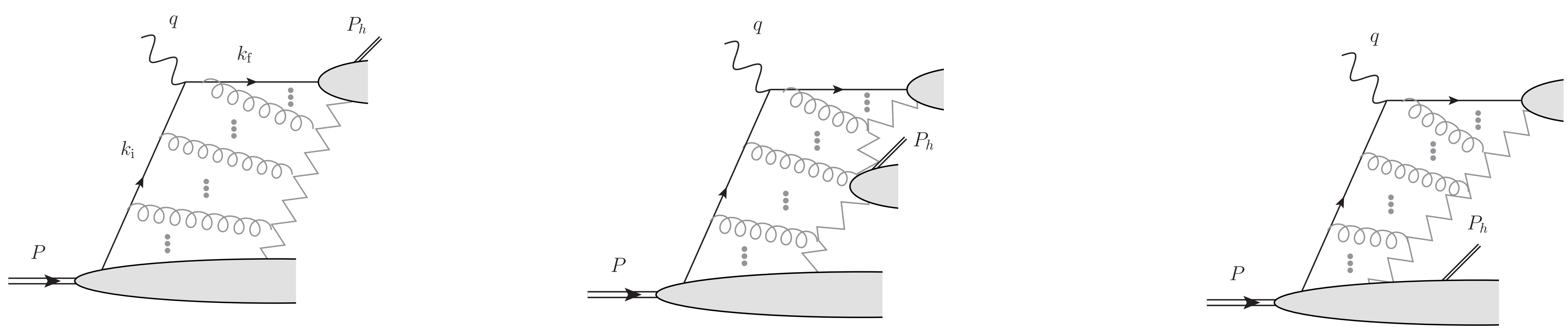
Fresh look:

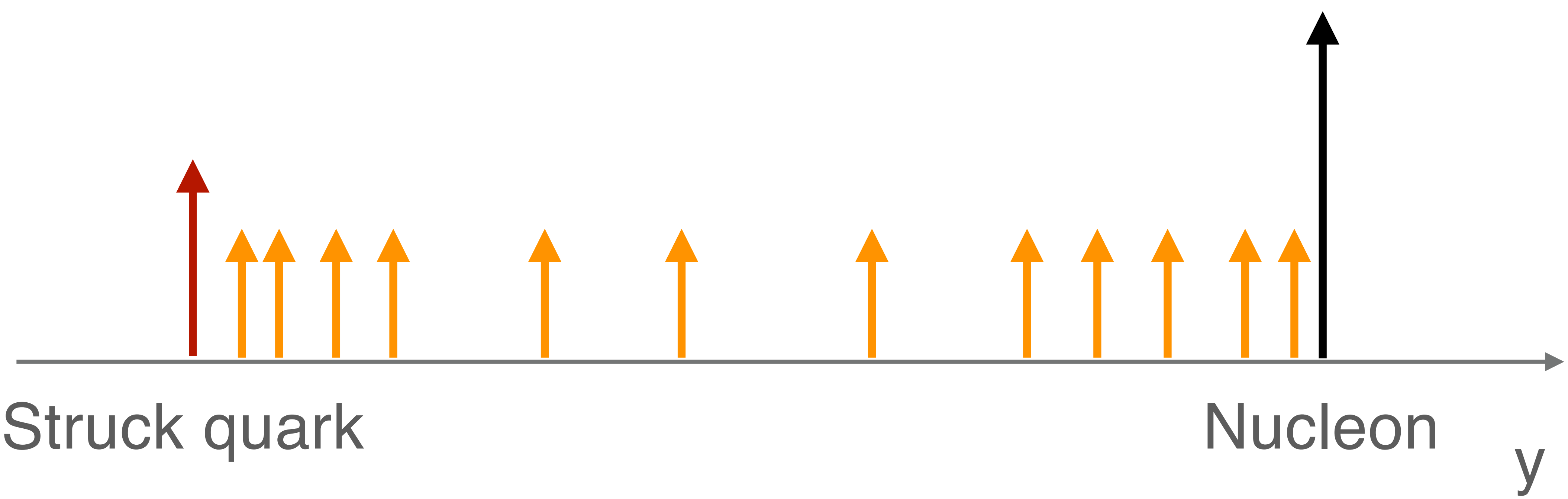
Define ratios of kinematical variables and identify regions

Current

Soft

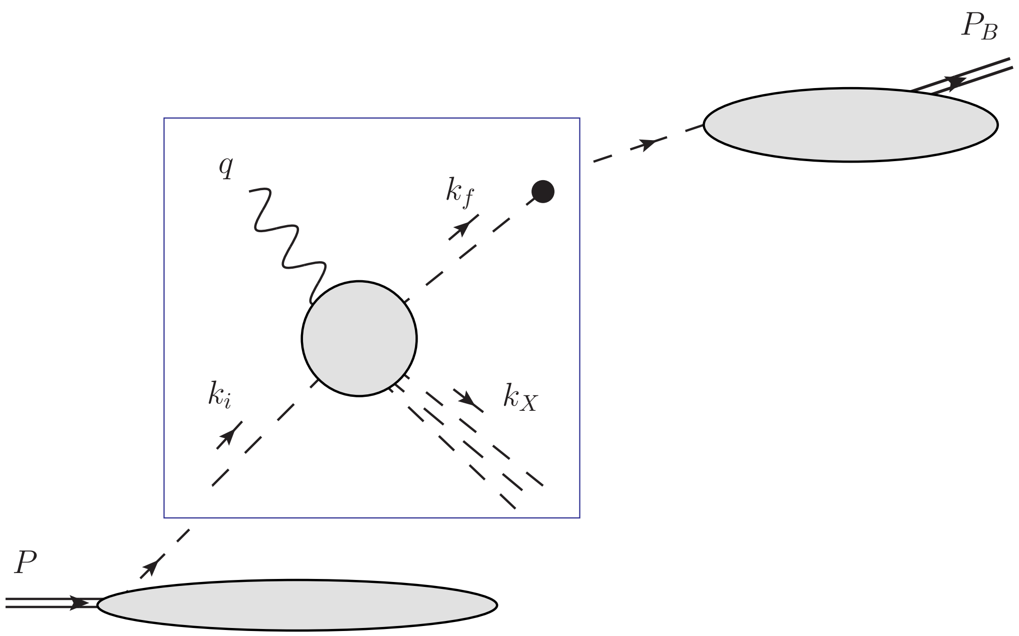
Target





REGIONS IN SIDIS AND RATIOS

Boglione et al, 1611.10329
Boglione et al, 1904.12882



- Define ratios, R_0, R_1, R_2, R_3 that depend on parton's kinematics
- Identify regions

	R_0	R_1	R_2	R_3
TMD Current region	small	small	small	X
Hard region	small	small	large	small (low order pQCD)
	small	small	large	large (high order pQCD)
Target region	small	large	X	X
Soft region	small	large	small	X

Table 1: Examples for sizes of ratios corresponding to particular regions of SIDIS. The "X" means "irrelevant or ill-defined." This ranking should be viewed as schematic since "small" and "large" need to be defined quantitatively and can in general be scale-dependent.

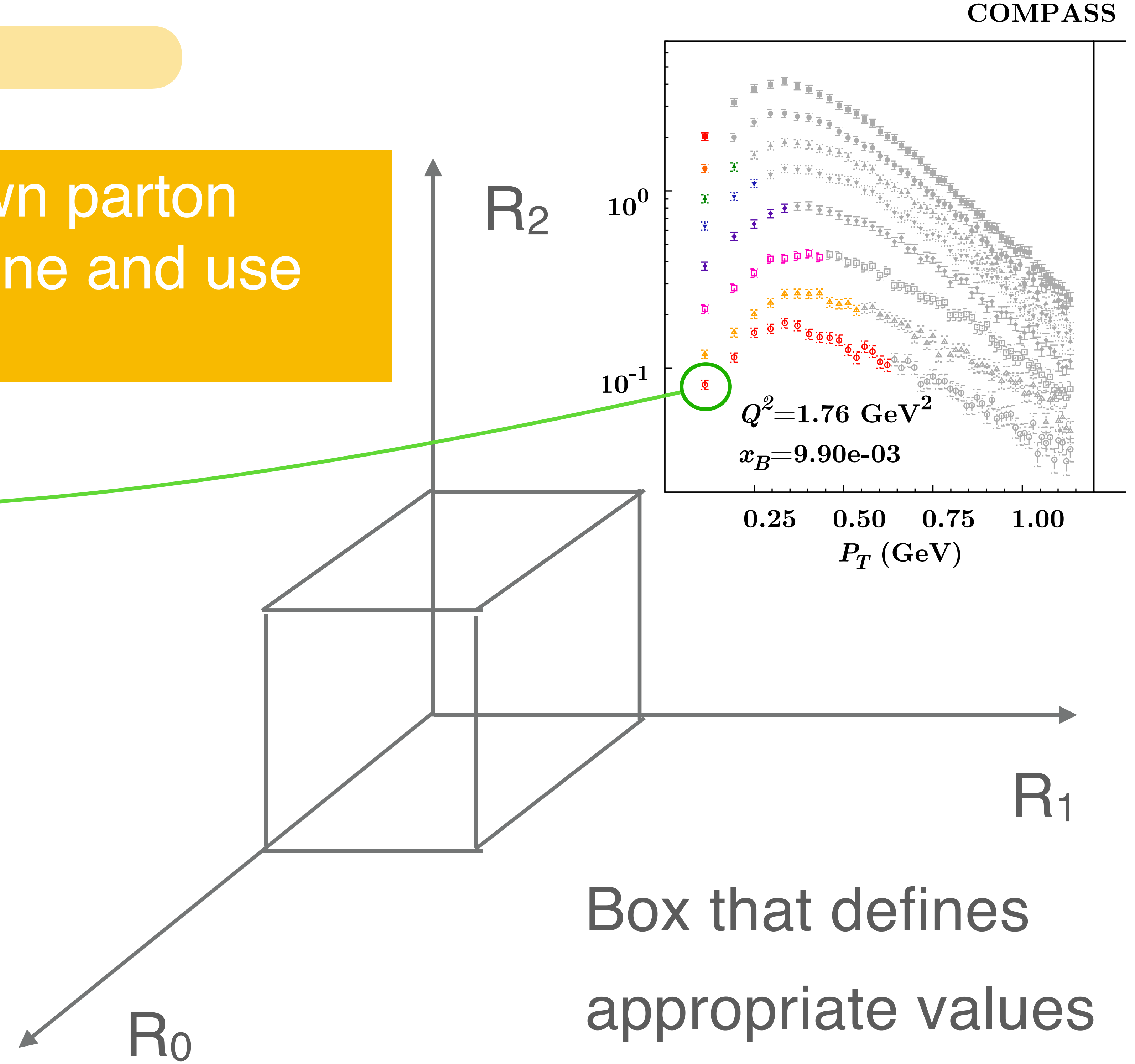
REGIONS IN SIDIS AND RATIOS

Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

- Define ratios

Ratios depend on unknown parton momenta. Ho can we define and use them?

Where does this bin belong?



- Use a Monte Carlo* with parton momenta
- Sample experimental bins for ratios

Box that defines appropriate values

* by saying Monte Carlo we do not intend Pythia!

REGIONS IN SIDIS AND RATIOS

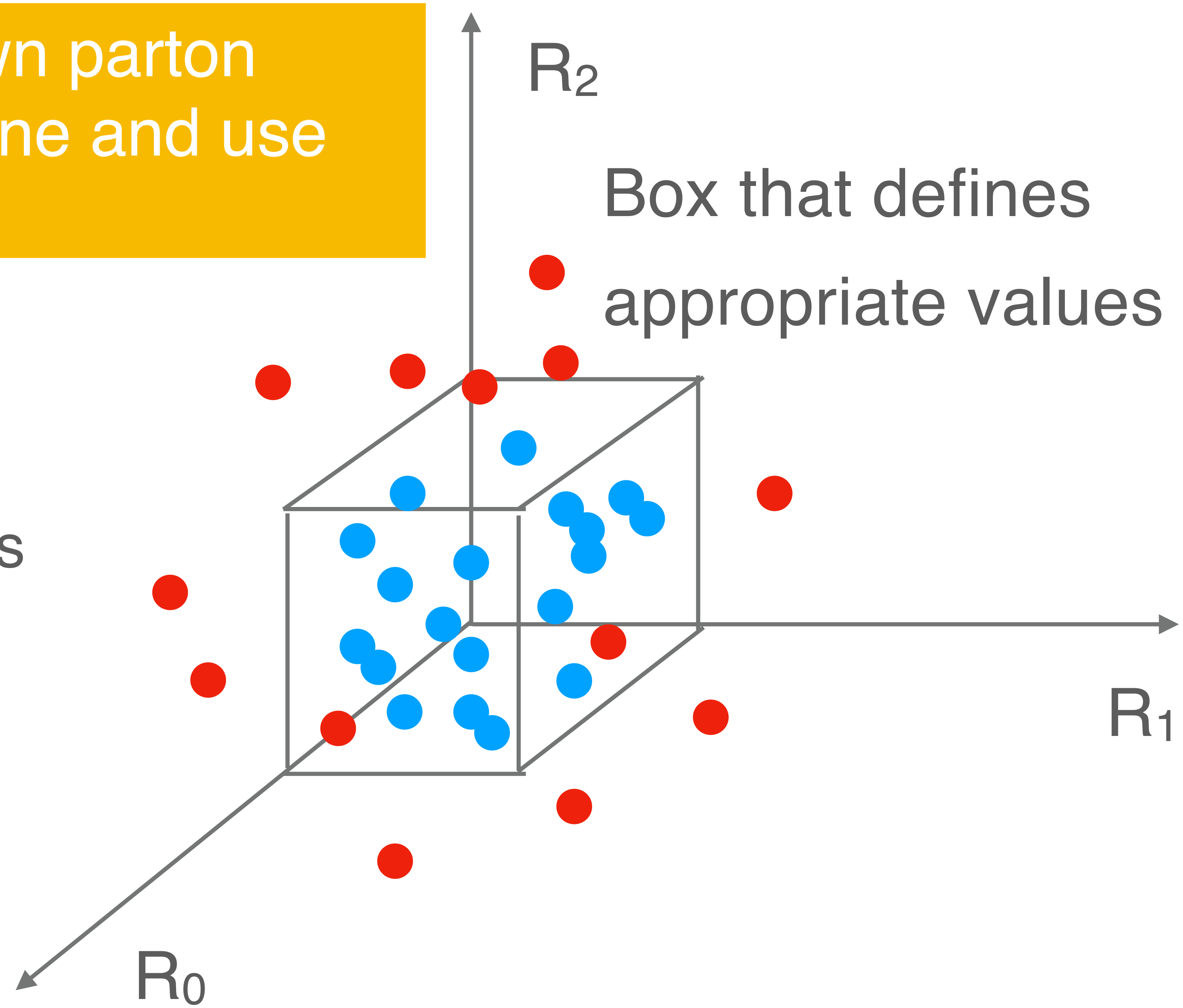
Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

➤ Define ratios

Ratios depend on unknown parton momenta. Ho can we define and use them?

➤ Use a Monte Carlo* with parton momenta

➤ Sample experimental bins for ratios



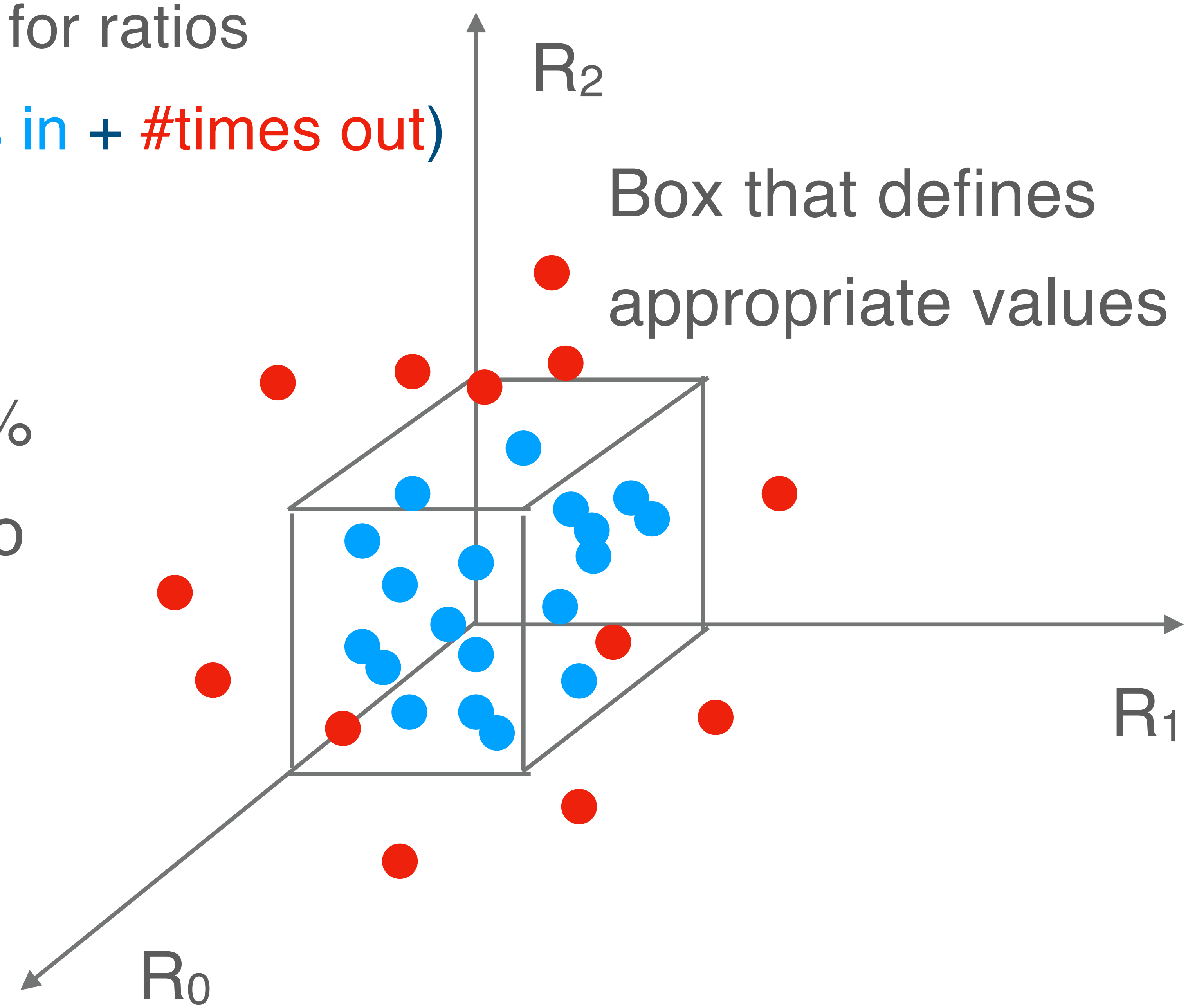
* by saying Monte Carlo we do not intend Pythia!

AFFINITY

Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

- Use a Monte Carlo* with parton momenta
- Sample experimental bins for ratios
- Affinity = #times in/(#times in + #times out)

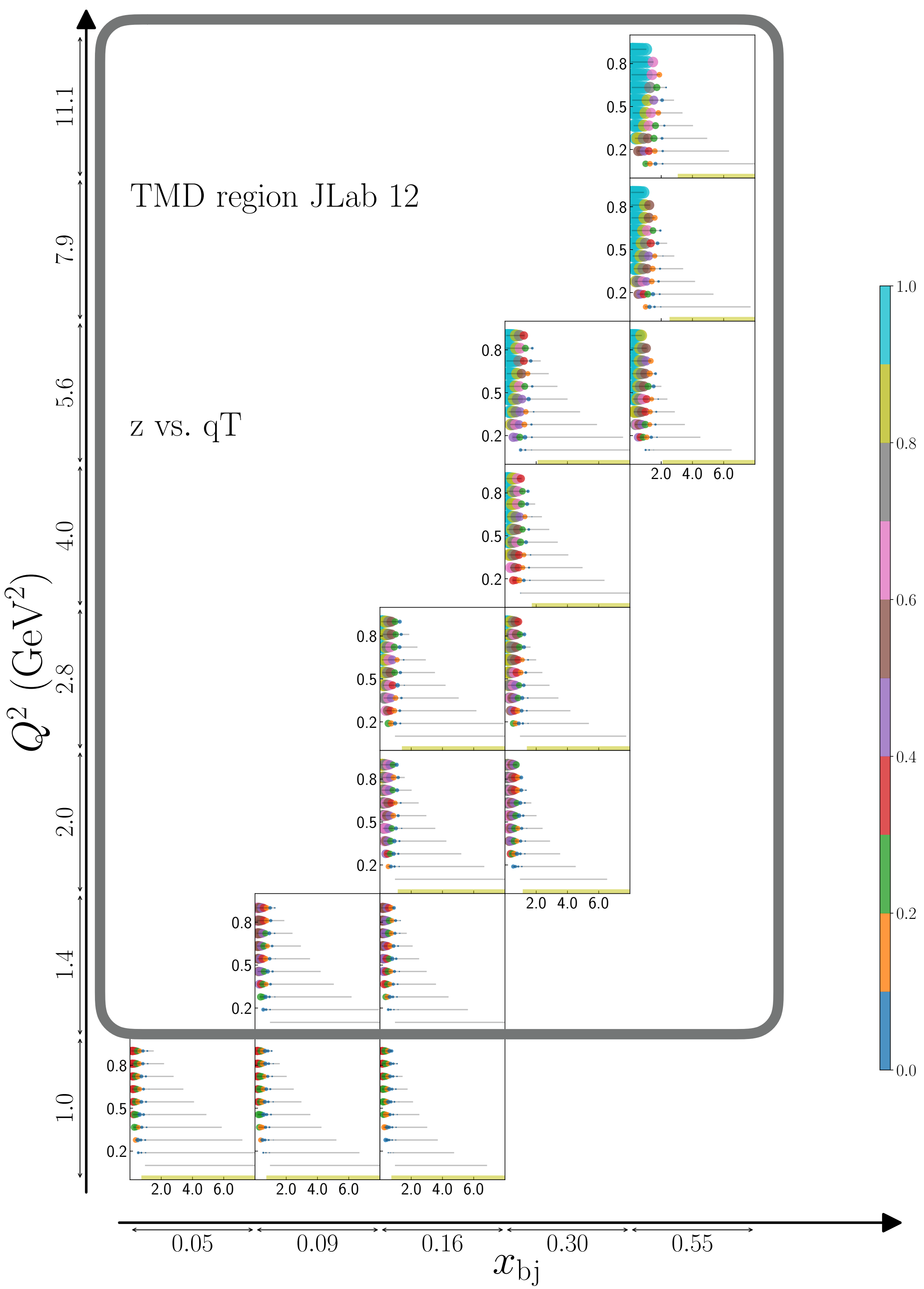
Affinity is from 0% to 100% indicates affinity of a bin to a particular region

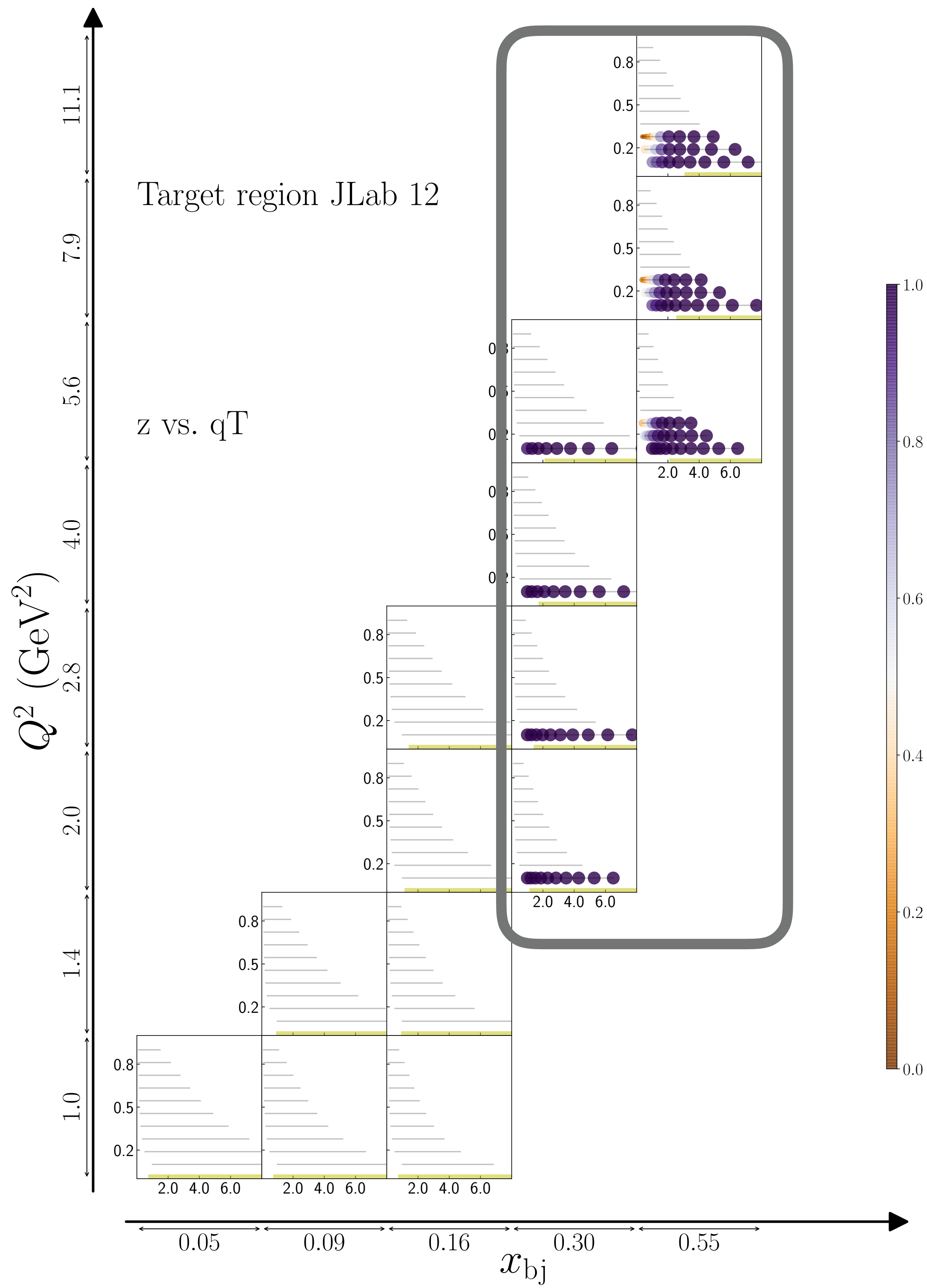


* by saying Monte Carlo we do not intend Pythia!

JEFFERSON LAB 12

Current study

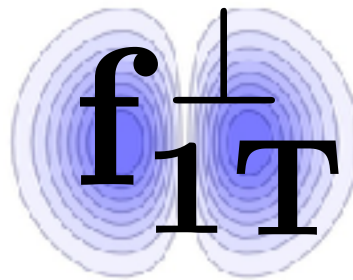




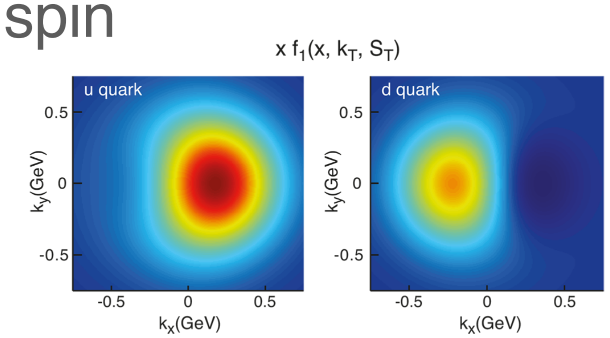
What about the 3D spin structure of the nucleon

POLARIZED TMD FUNCTIONS

Sivers function

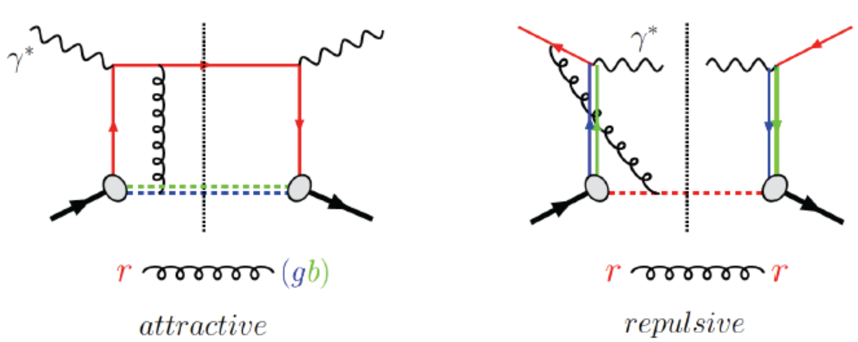


- Describes unpolarized quarks inside of transversely polarized nucleon
- Encodes the correlation of orbital motion with the spin



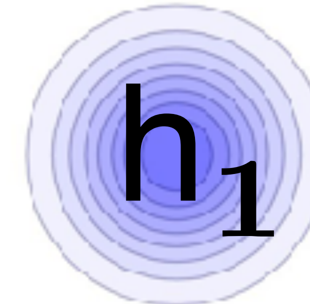
- Sign change of Sievers function is fundamental consequence of QCD

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



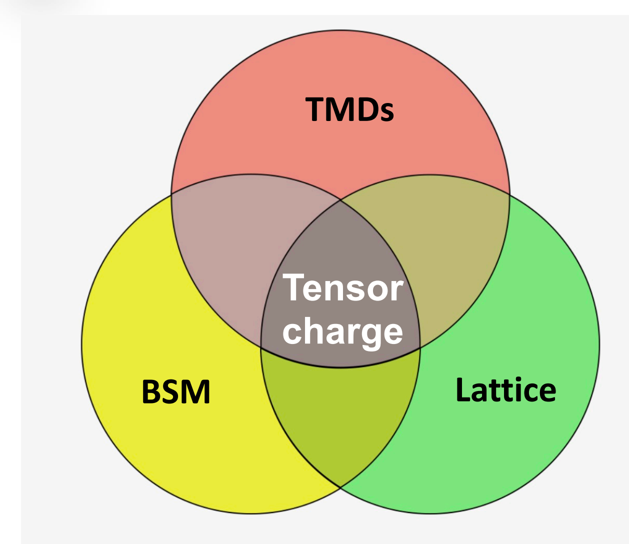
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

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

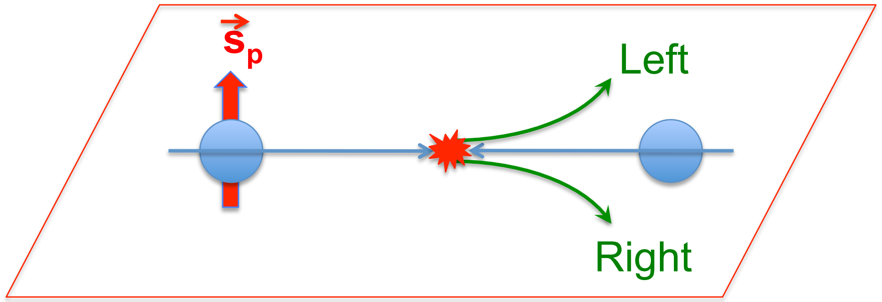
$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)\right]$$



CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

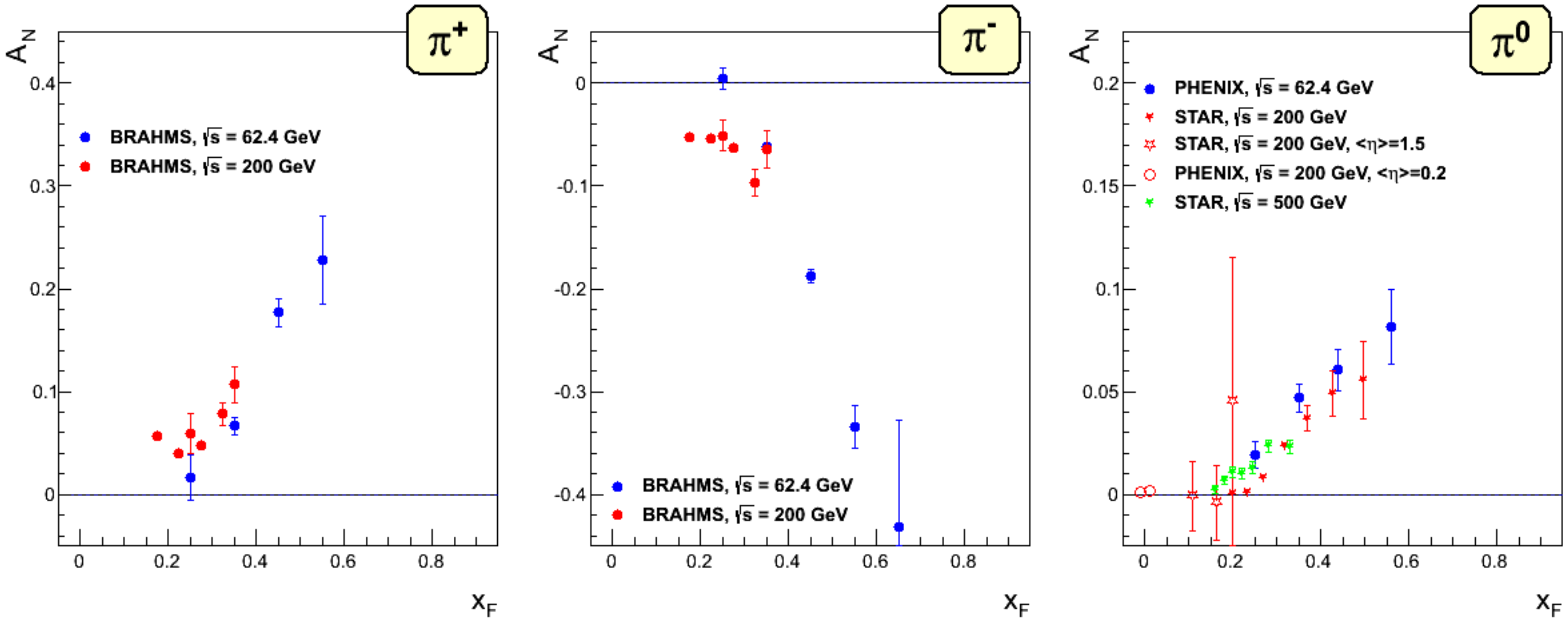
Consider polarized

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)

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

UNIVERSAL GLOBAL FIT 2020

Jefferson Lab Angular Momentum Collaboration

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

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

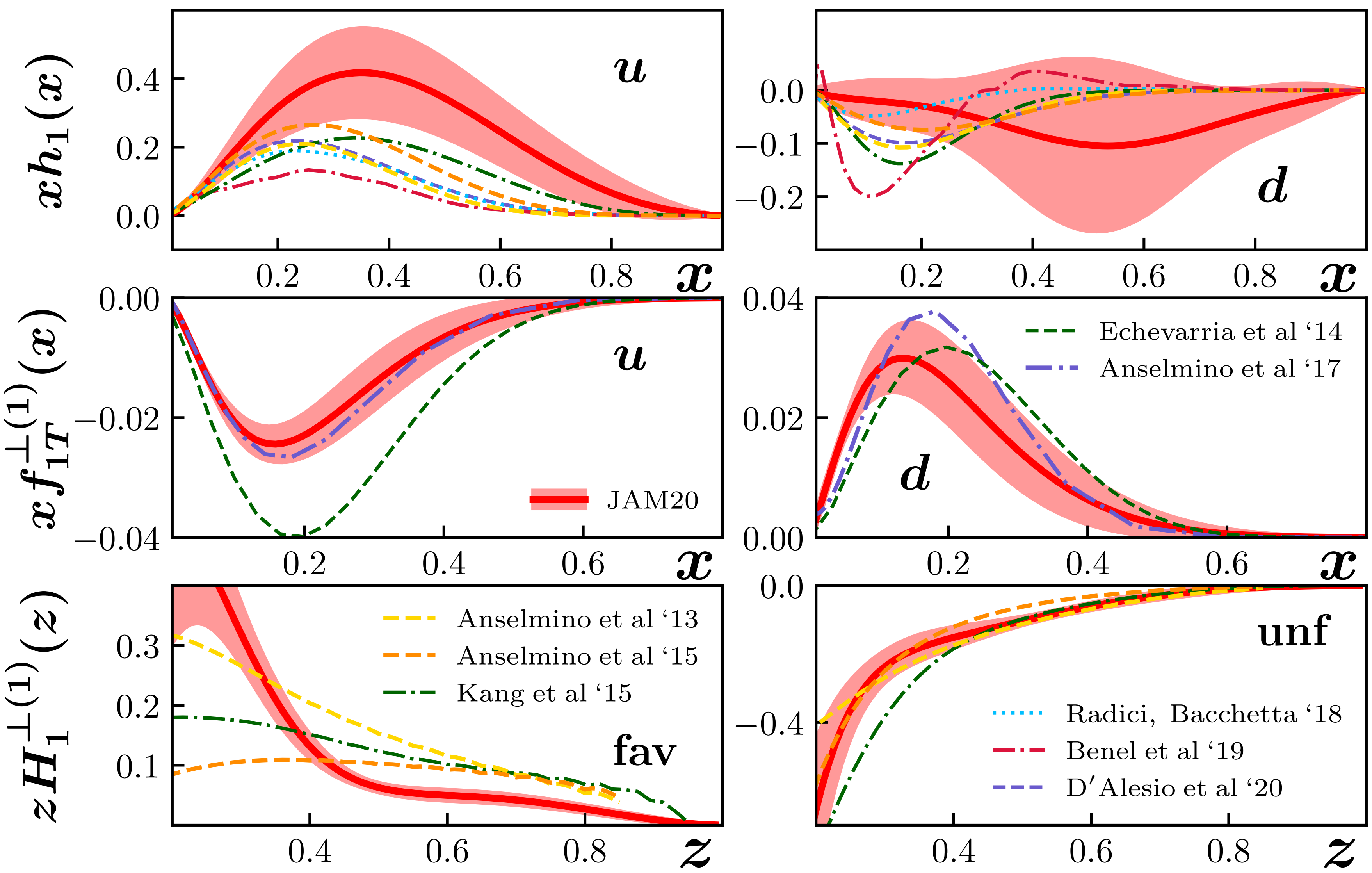
- JAM uses Bayesian inference in order to sample the posterior distribution of all parameters.
- Multistep strategy in the Monte Carlo framework is used.

Sato, Andres, Ethier, Melnitchouk (2019)

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

UNIVERSAL GLOBAL FIT 2020

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



Transversity

$h_1(x)$

Sivers

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

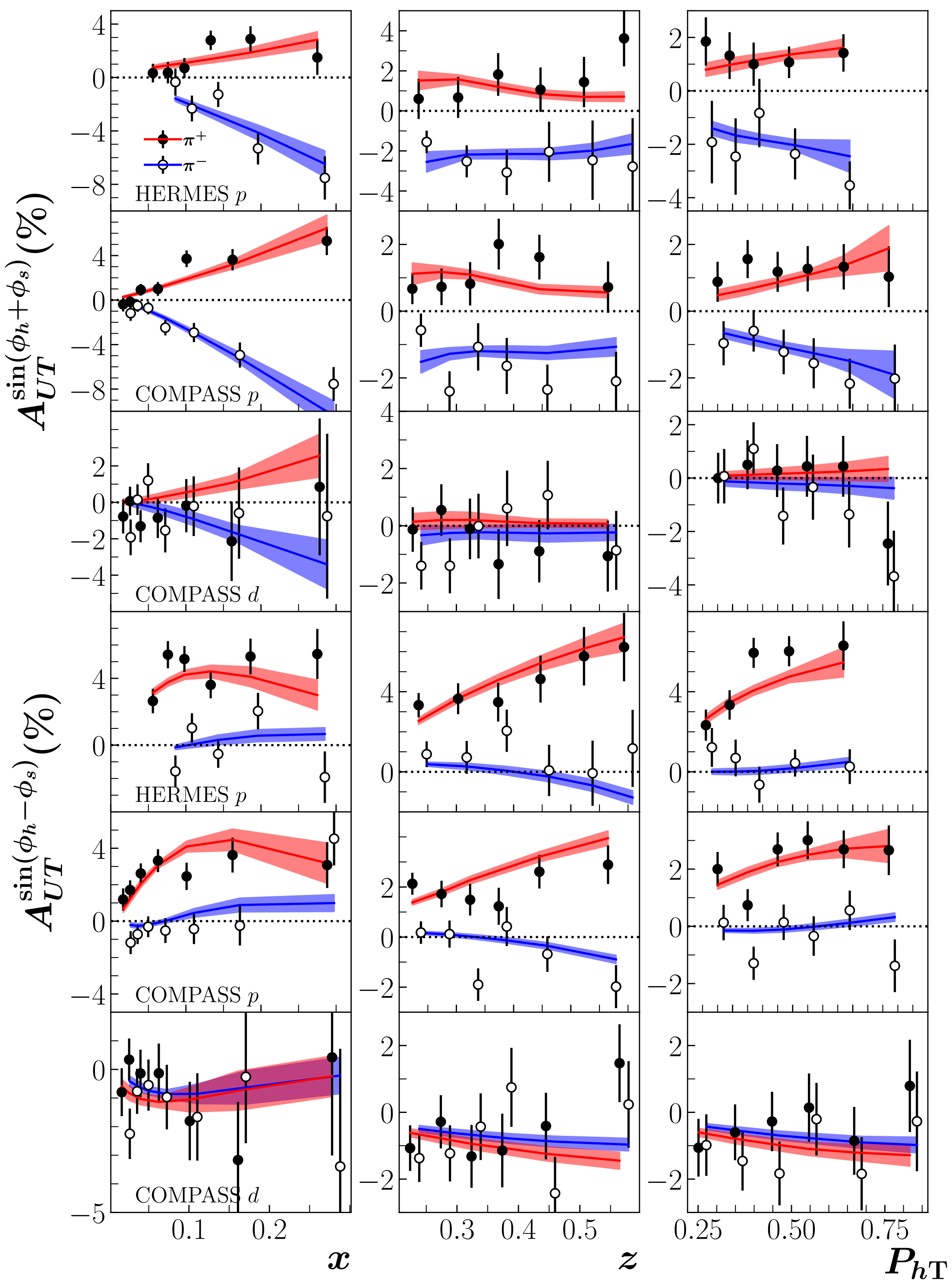
Collins FF

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

UNIVERSAL GLOBAL FIT 2020

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

SIDIS



Collins asymmetry

$$\frac{\chi^2}{npoints} = \frac{107.1}{126} = 0.85$$

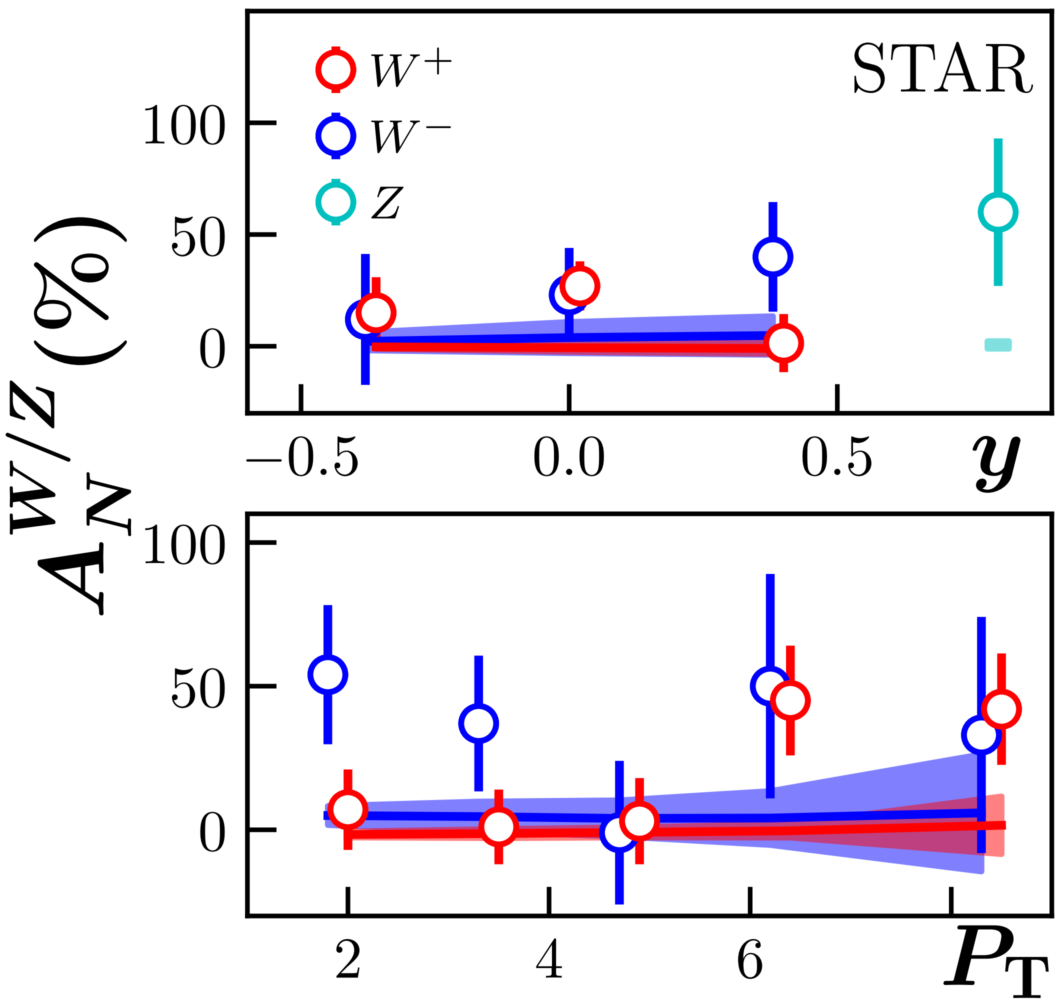
Sivers asymmetry

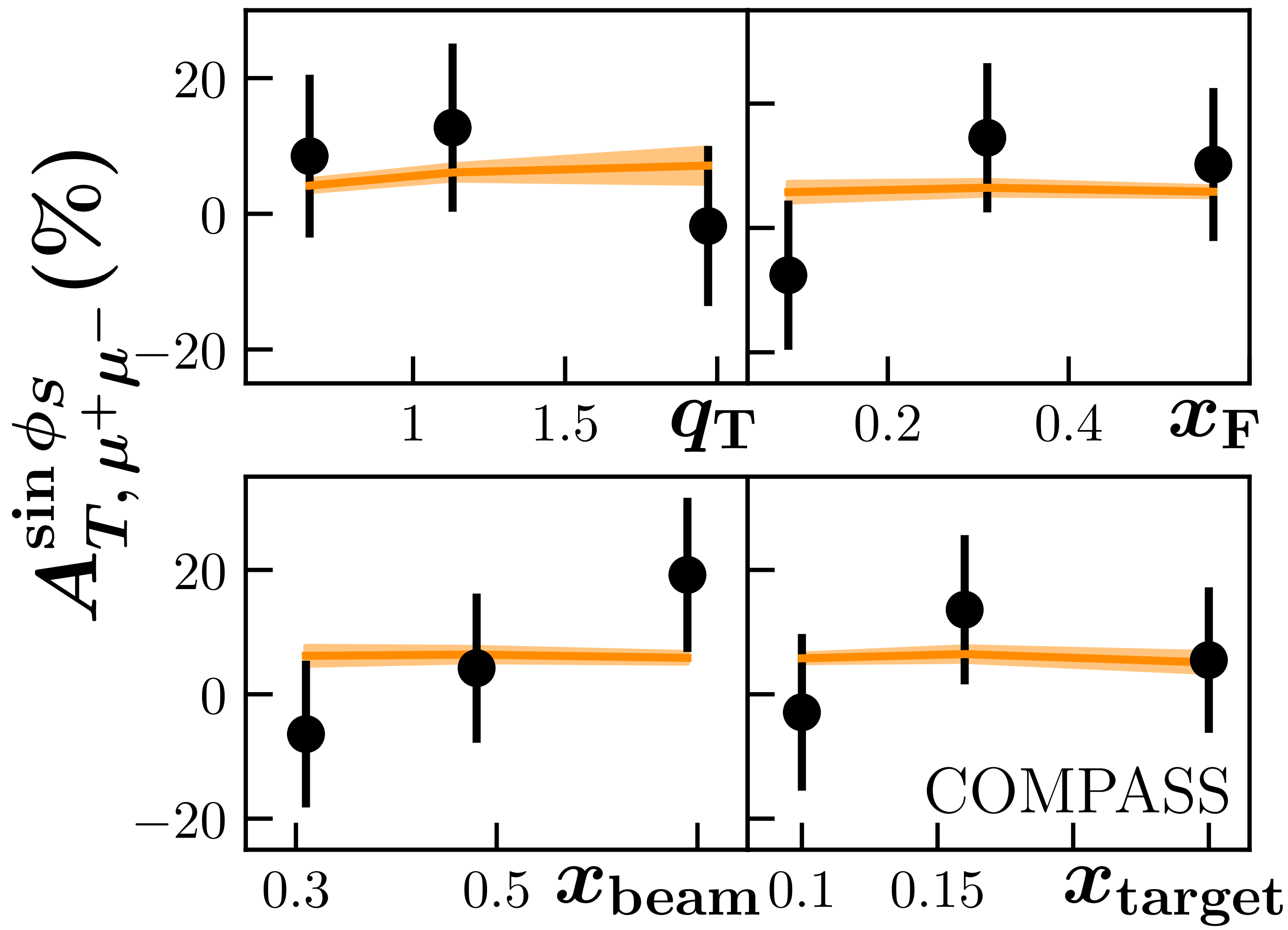
$$\frac{\chi^2}{npoints} = \frac{85.4}{88} = 0.97$$

UNIVERSAL GLOBAL FIT 2020

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

Drell-Yan





$$\frac{\chi^2}{npoints} = \frac{29.8}{17} = 1.75$$

$$\frac{\chi^2}{npoints} = \frac{7.6}{12} = 0.63$$

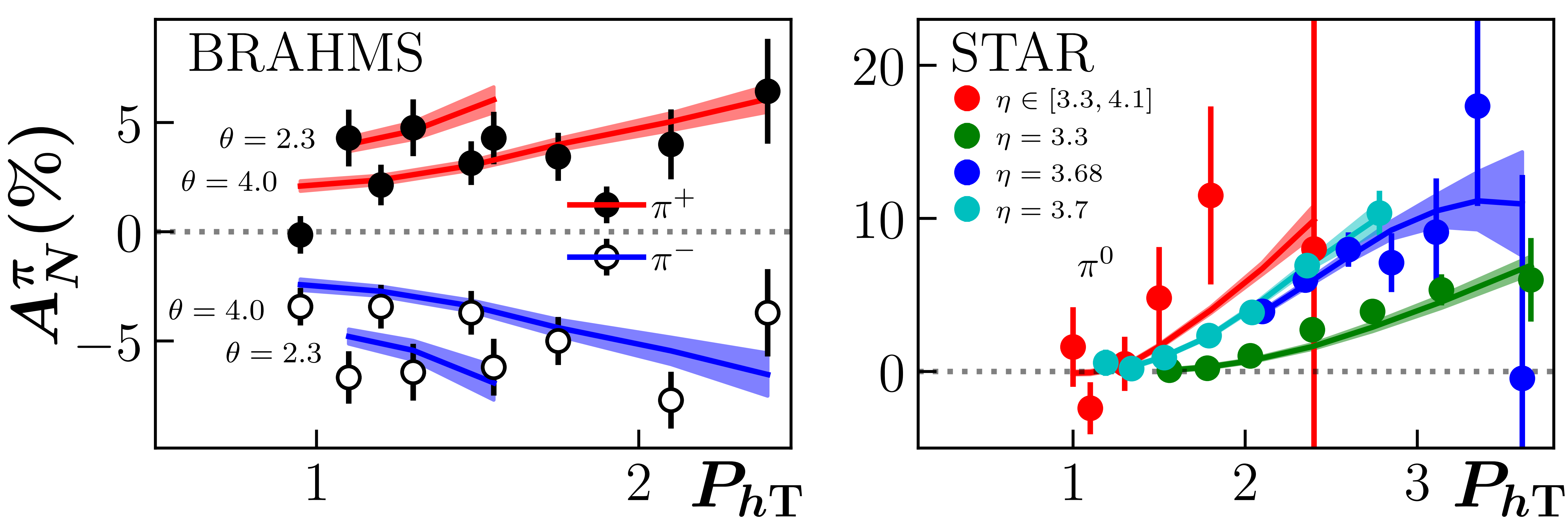
STAR

COMPASS DY

UNIVERSAL GLOBAL FIT 2020

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

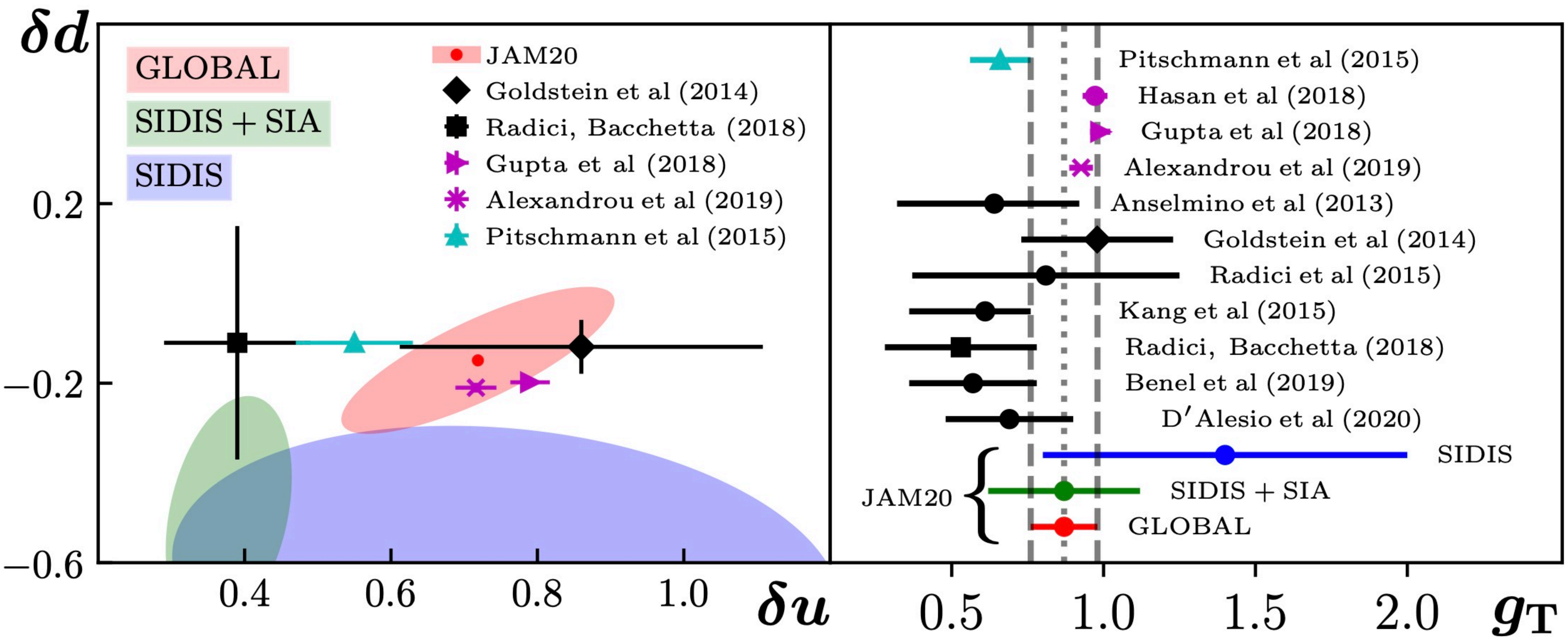
proton-proton A_N



$$\frac{\chi^2}{npoints} = \frac{72.0}{60} = 1.2$$

UNIVERSAL GLOBAL FIT 2020

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



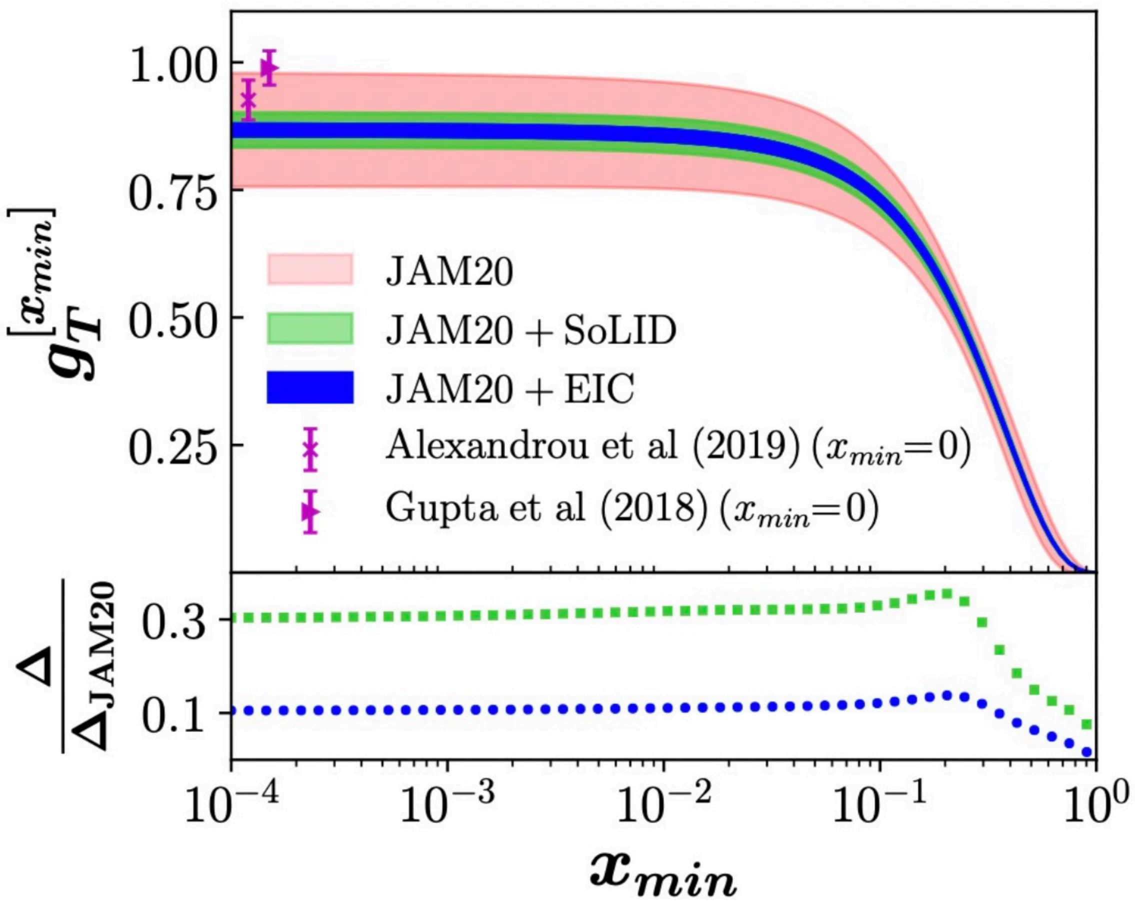
- Tensor charge from up and down quarks is constrained and compatible with lattice results
- Isovector tensor charge $g_T = \delta u - \delta d$
  $g_T = 0.89 \pm 0.12$ compatible with lattice results

<u>δu and δd Q^2=4 GeV^2</u>

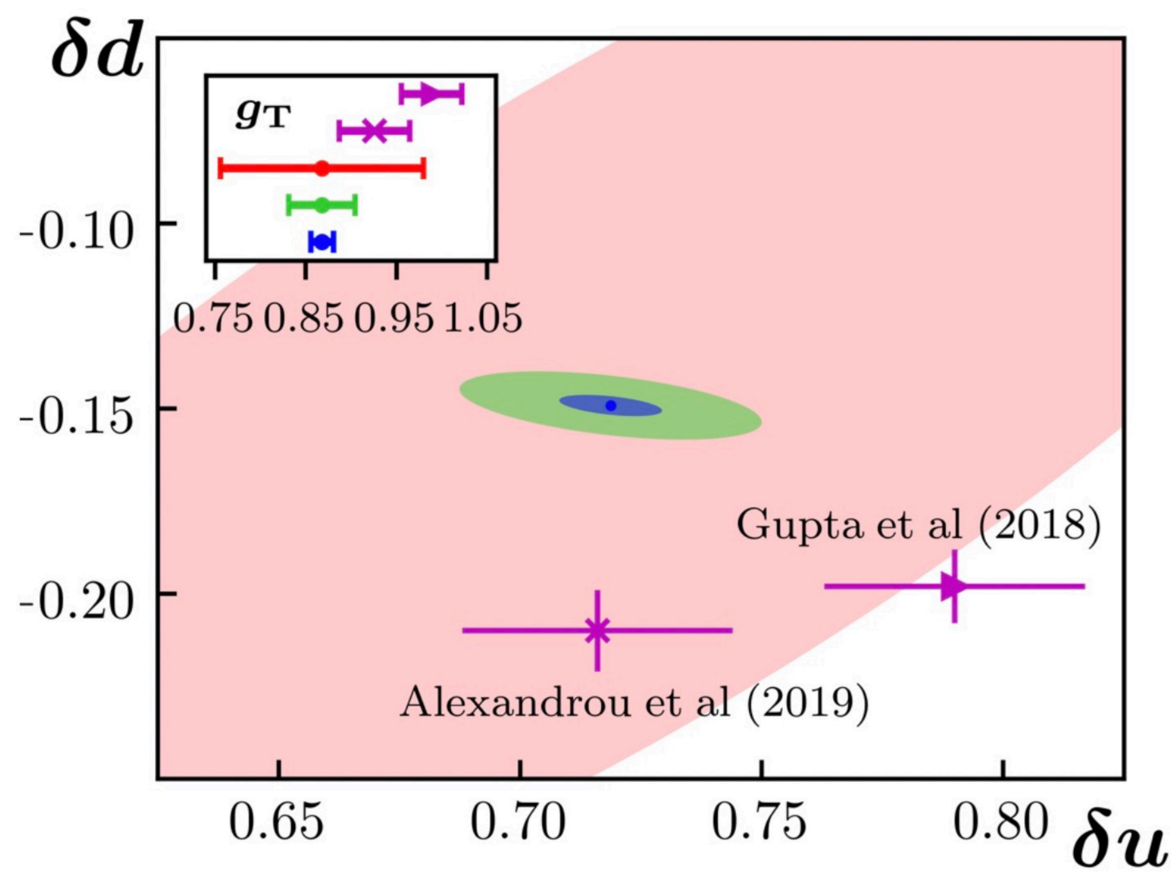
δu= 0.65 ± 0.22

δd= -0.24 ± 0.2

TENSOR CHARGE AND FUTURE FACILITIES



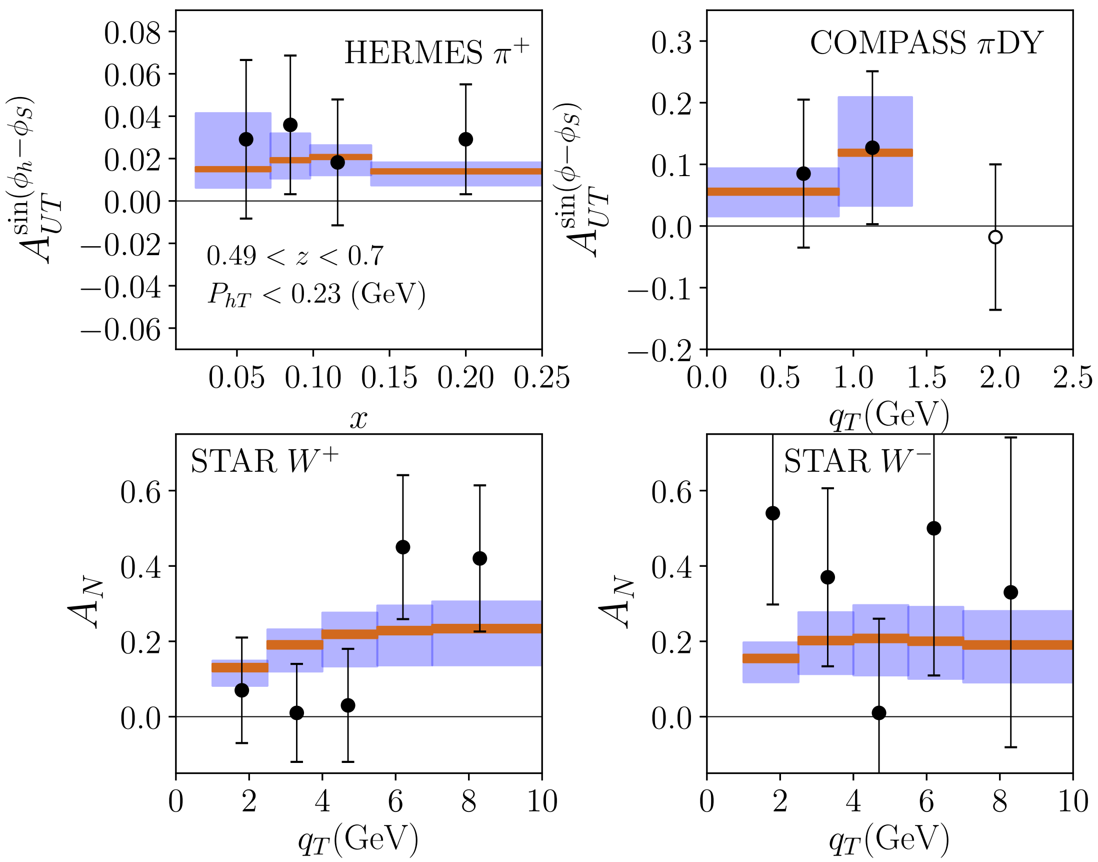
Gamberg, Kang, Pitonyak, Prokudin, Sato, Seidl (2021)



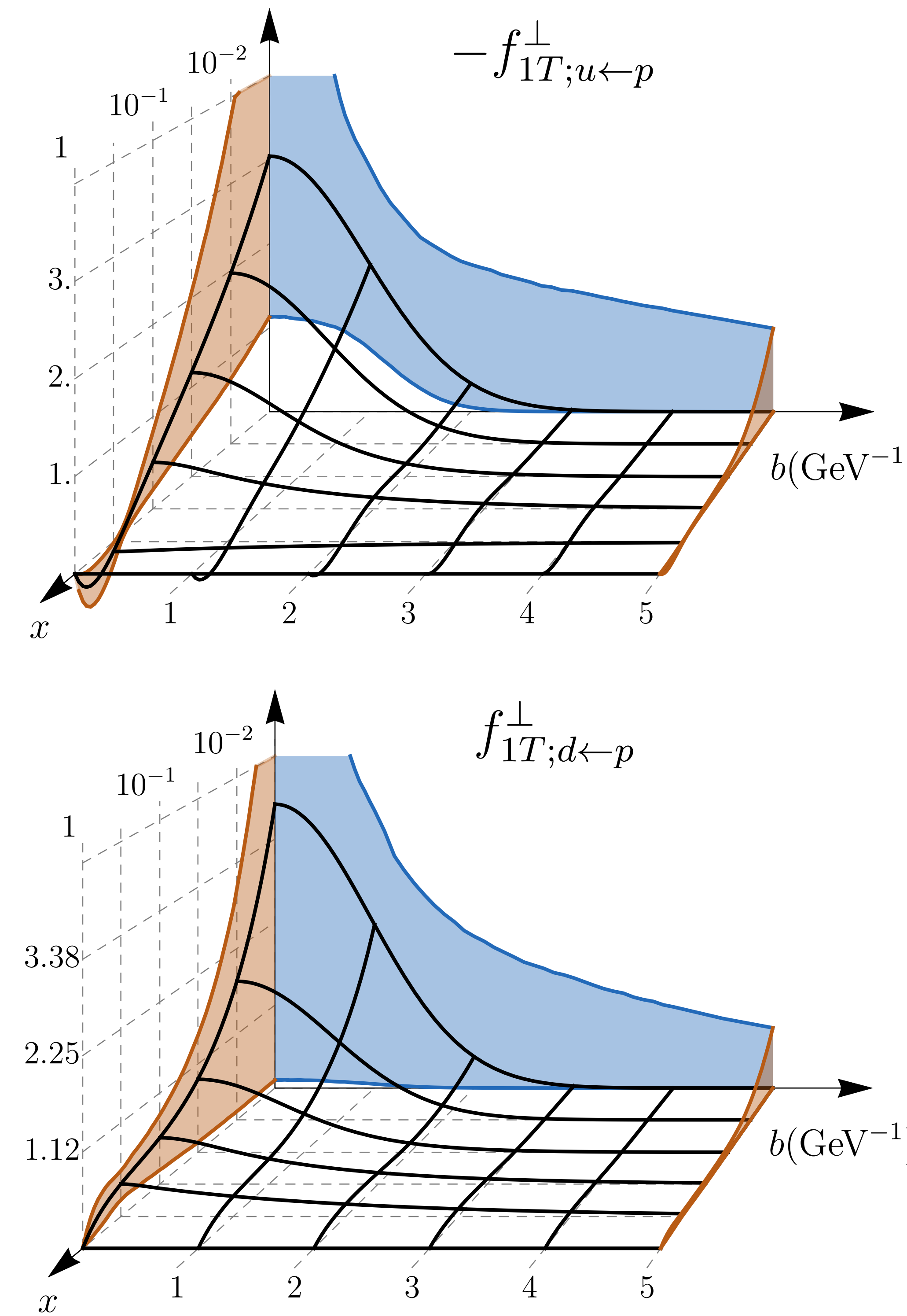
EIC data will allow to have g_T extraction at the precision at the level of lattice QCD calculations

Lab 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



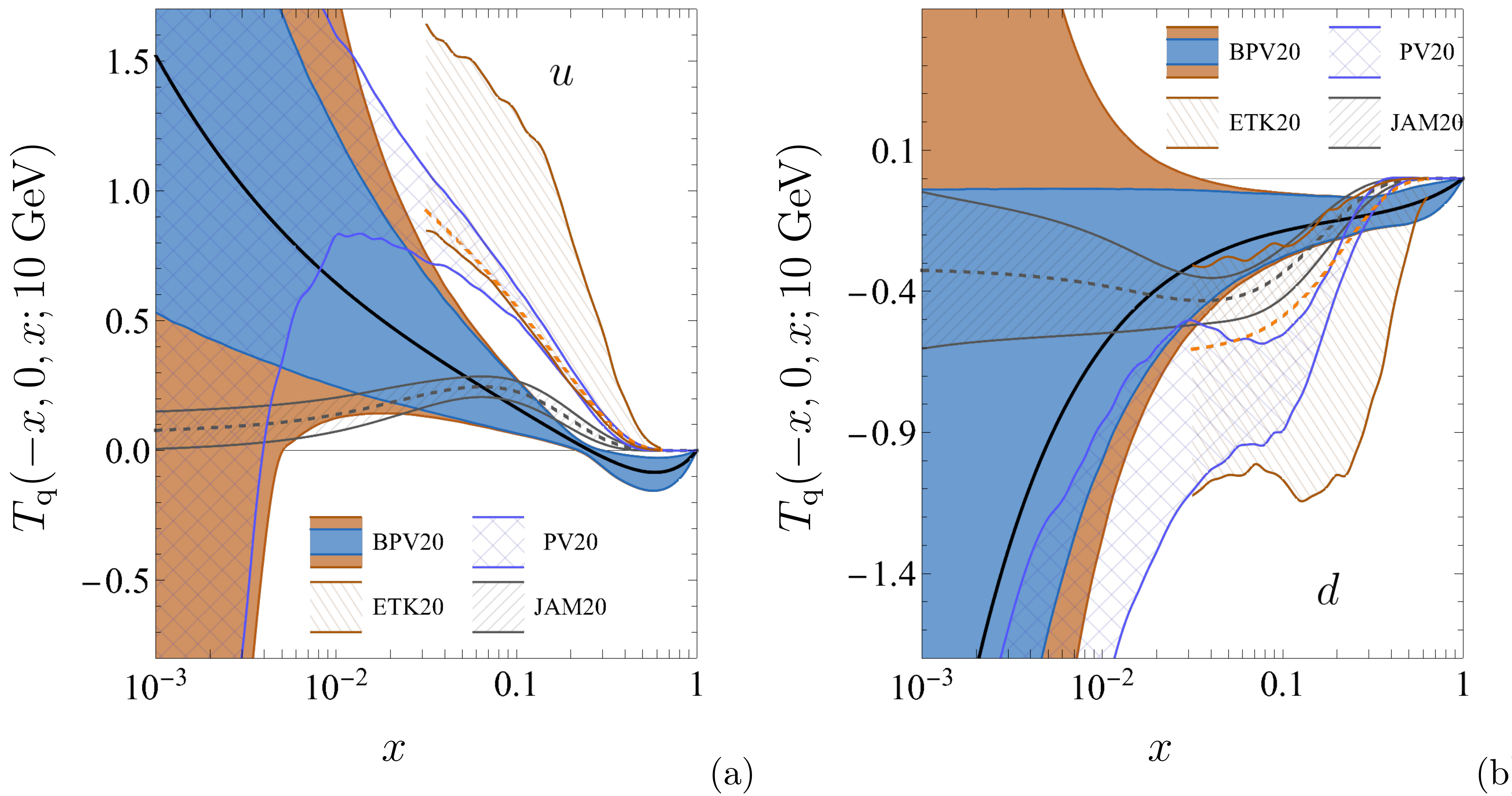
Bury, Prokudin, Vladimirov (2020)



- 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

N3LO EXTRACTION OF THE SIVERS FUNCTION

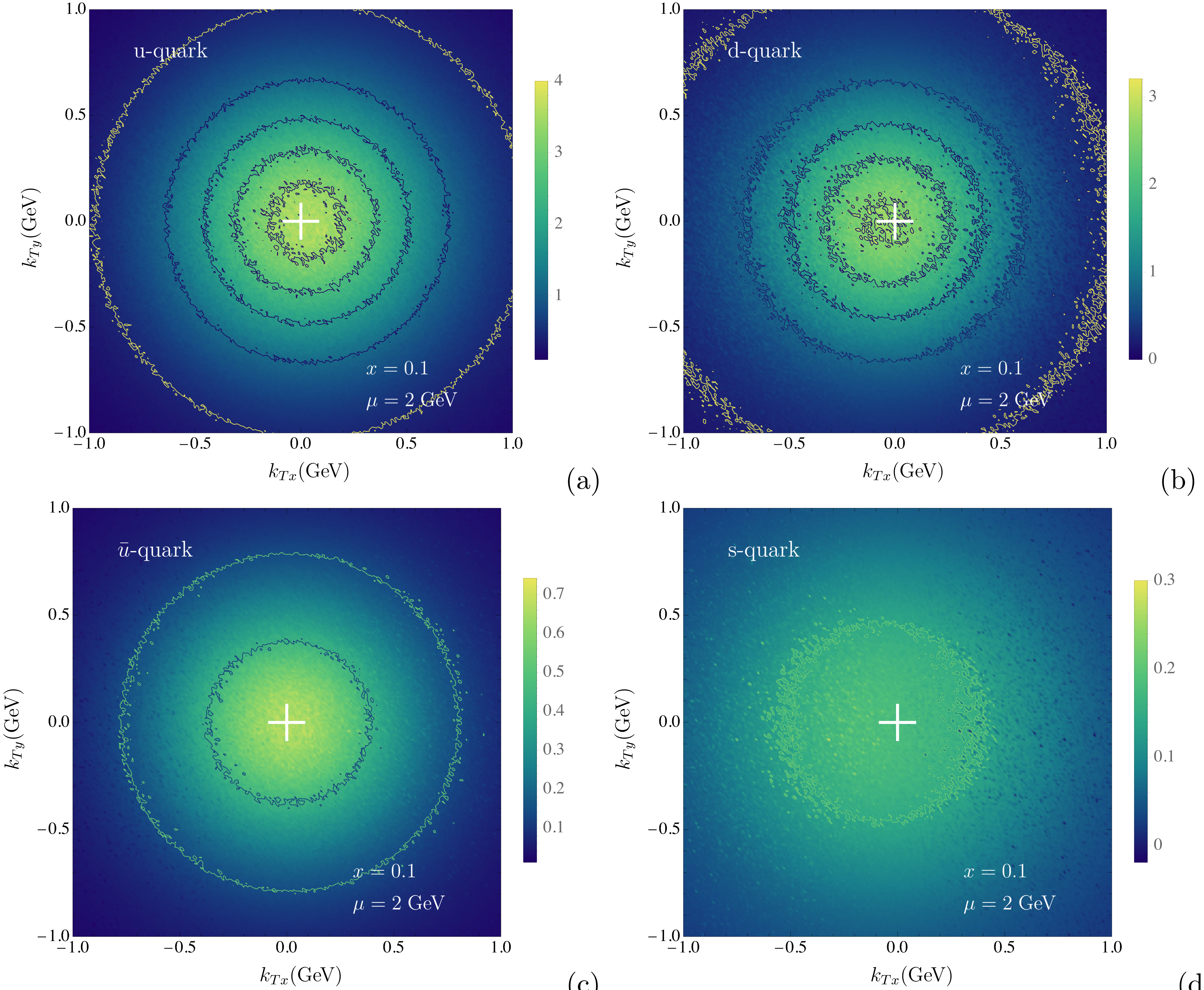
Bury, Prokudin, Vladimirov (2020)



- Consistency of the formalism and new benchmark for future studies

NUCLEON TOMOGRAPHY

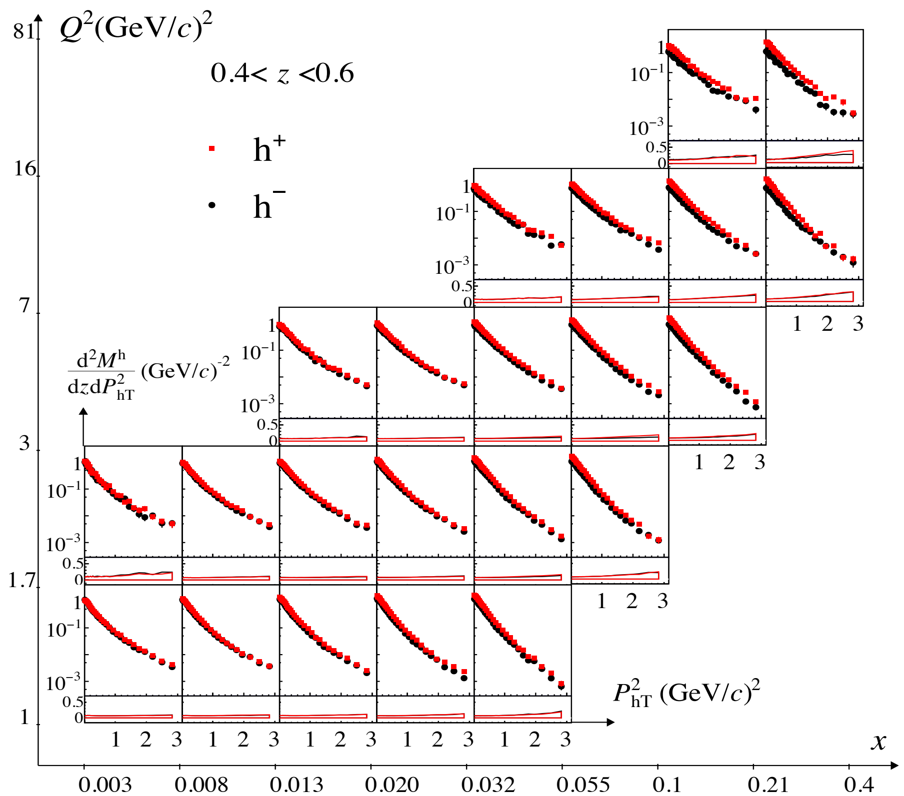
Bury, Prokudin, Vladimirov (2021)



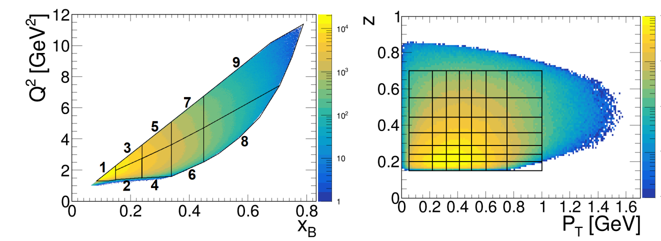
THE FUTURE

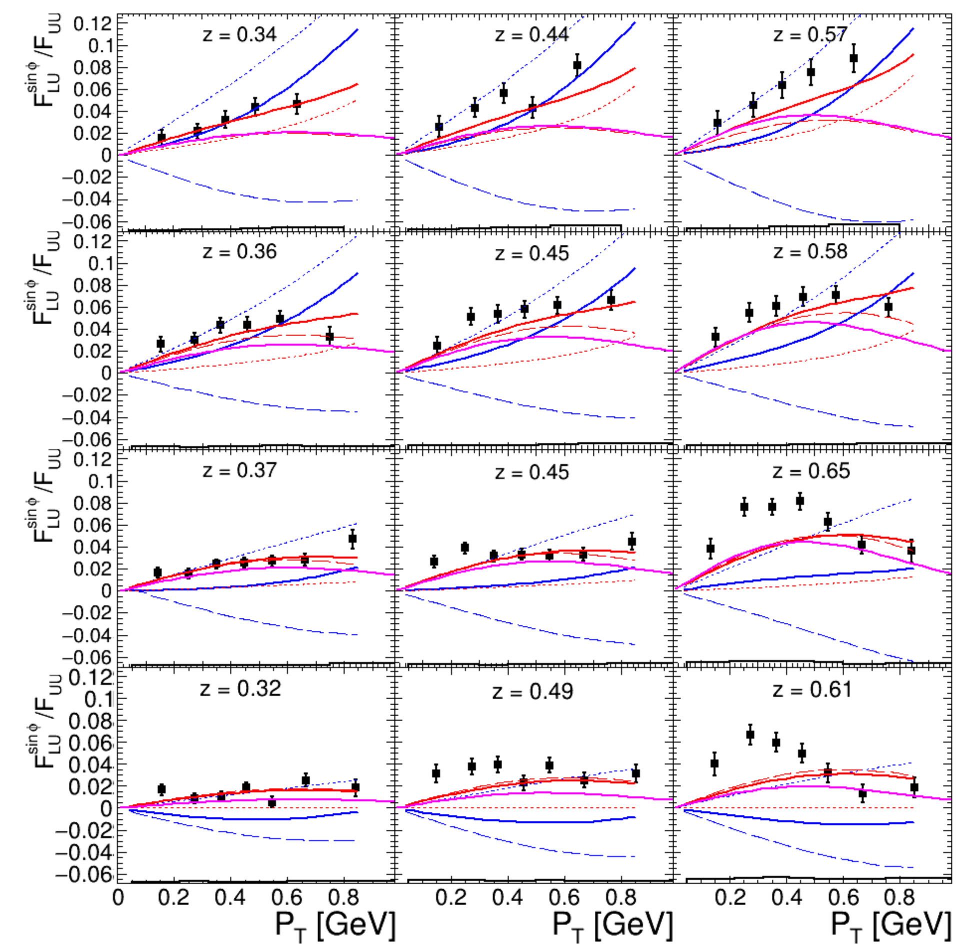
NEW DATA FROM COMPASS AND JLAB

Multidimensional binning



COMPASS Collab., arXiv:1709.07374

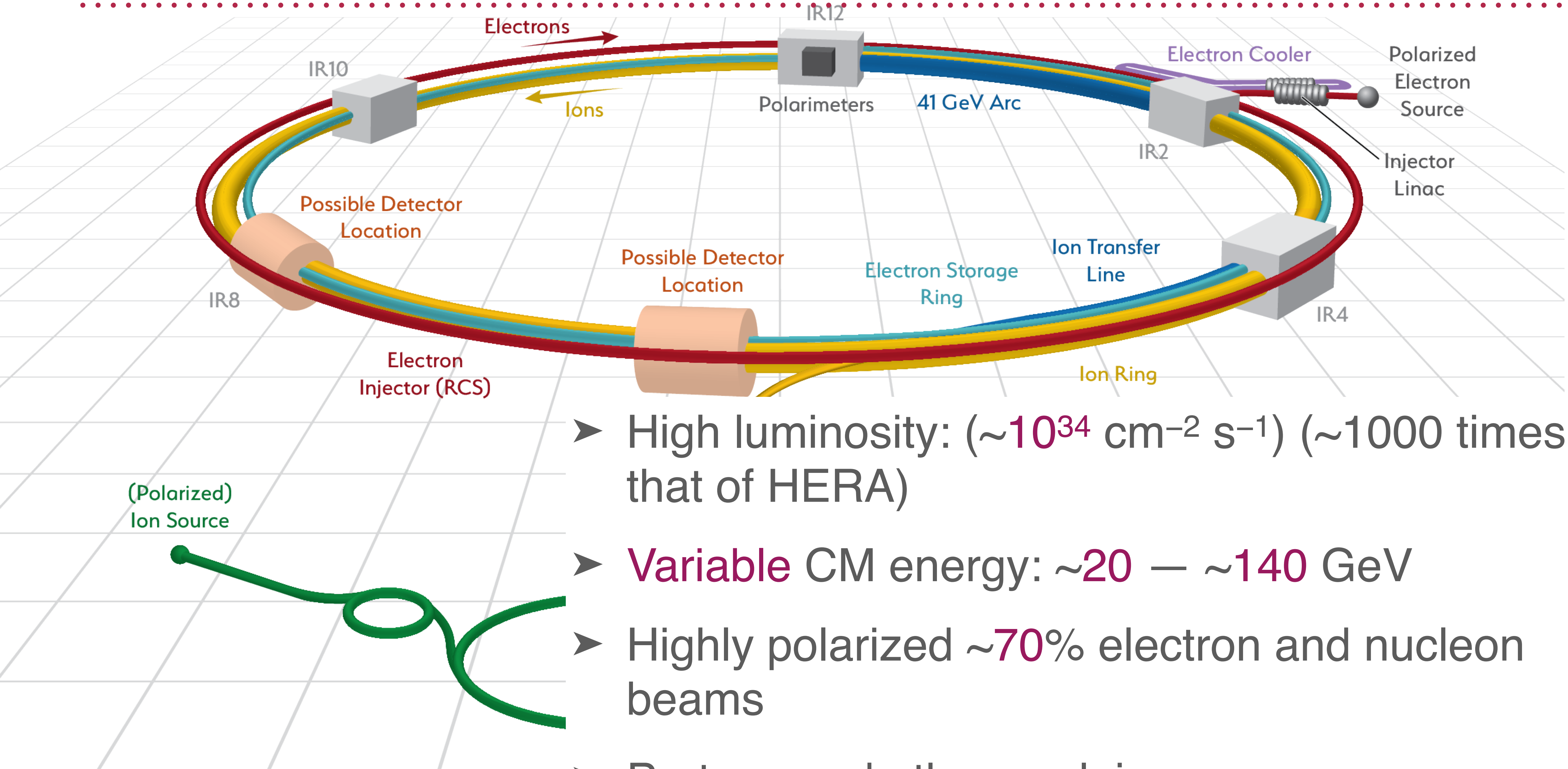




CLAS Collab., ArXiv:2101.03544

COMPASS is in “full swing” mode. JLAB 12 data are following.

THE ELECTRON-ION COLLIDER @ BNL

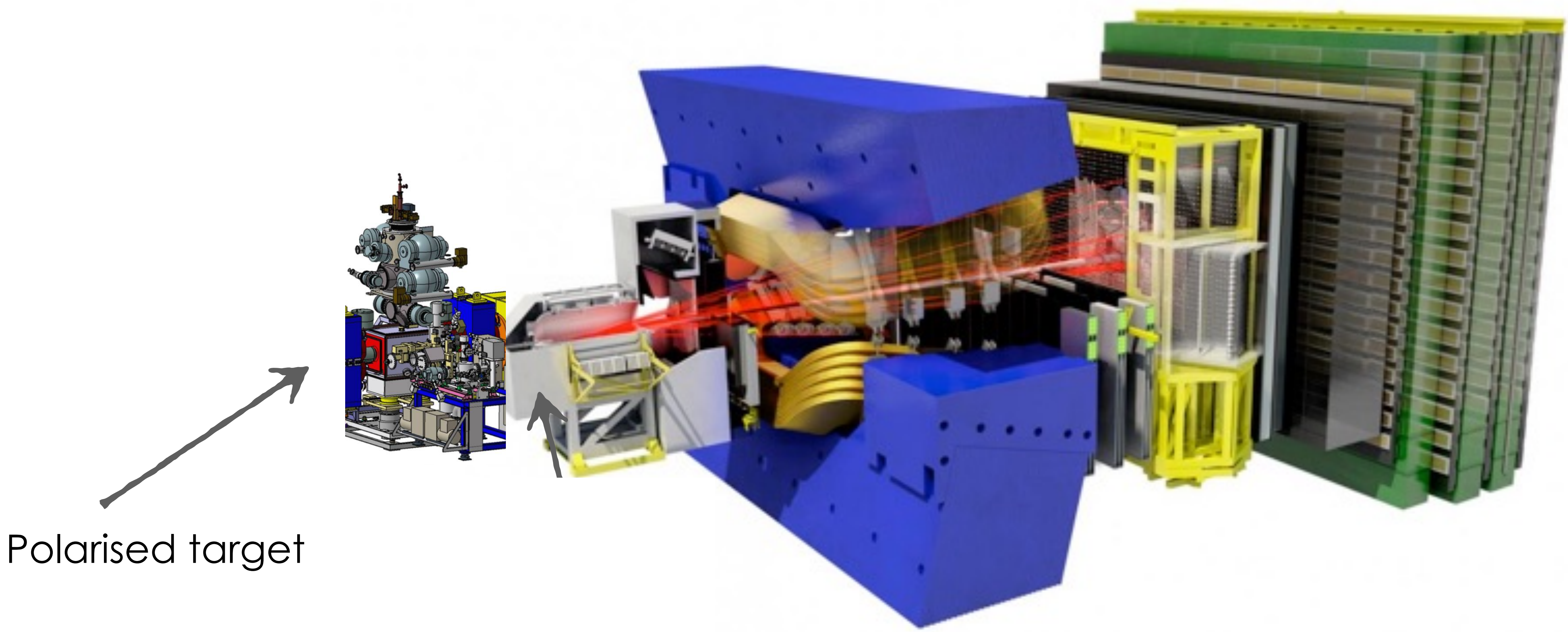


White Paper (2012)
Accardi et al, arXiv:1212:1701

- 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)

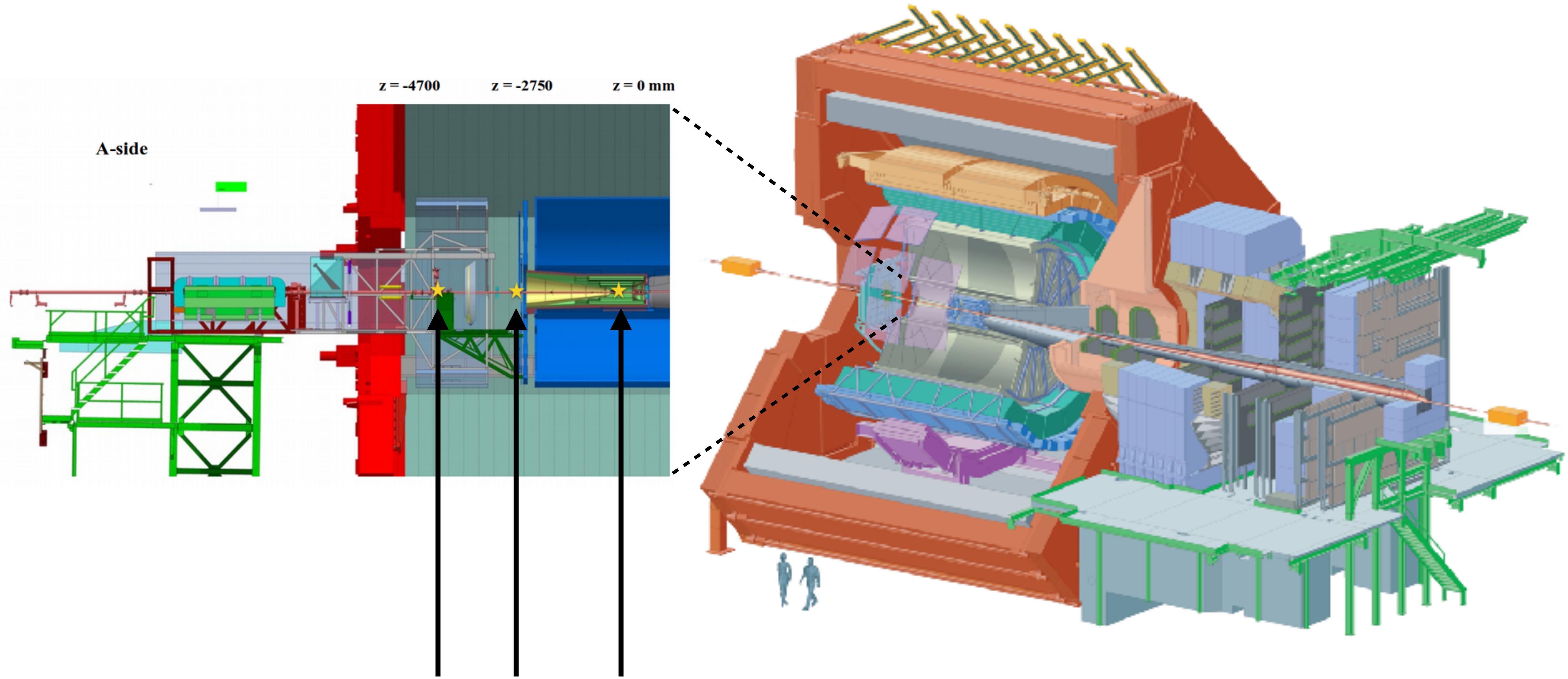
LHCb FIXED TARGET, INCLUDING POLARIZATION

https://indico.cern.ch/event/755856/



ALICE FIXED TARGET

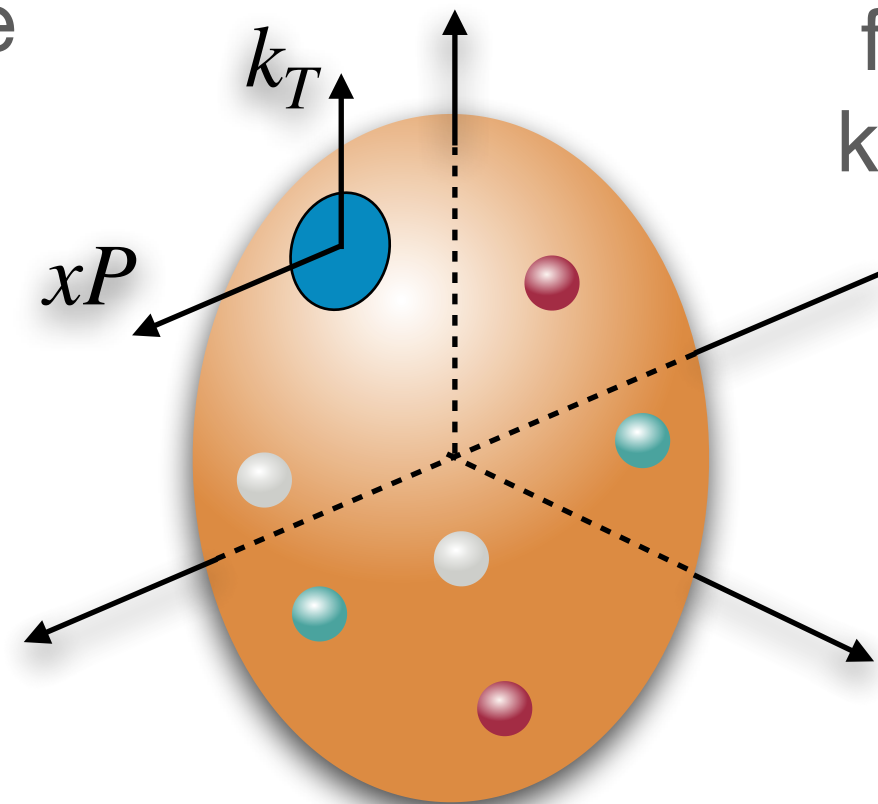
https://indico.cern.ch/event/755856/



Possible fixed-target positioning

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?