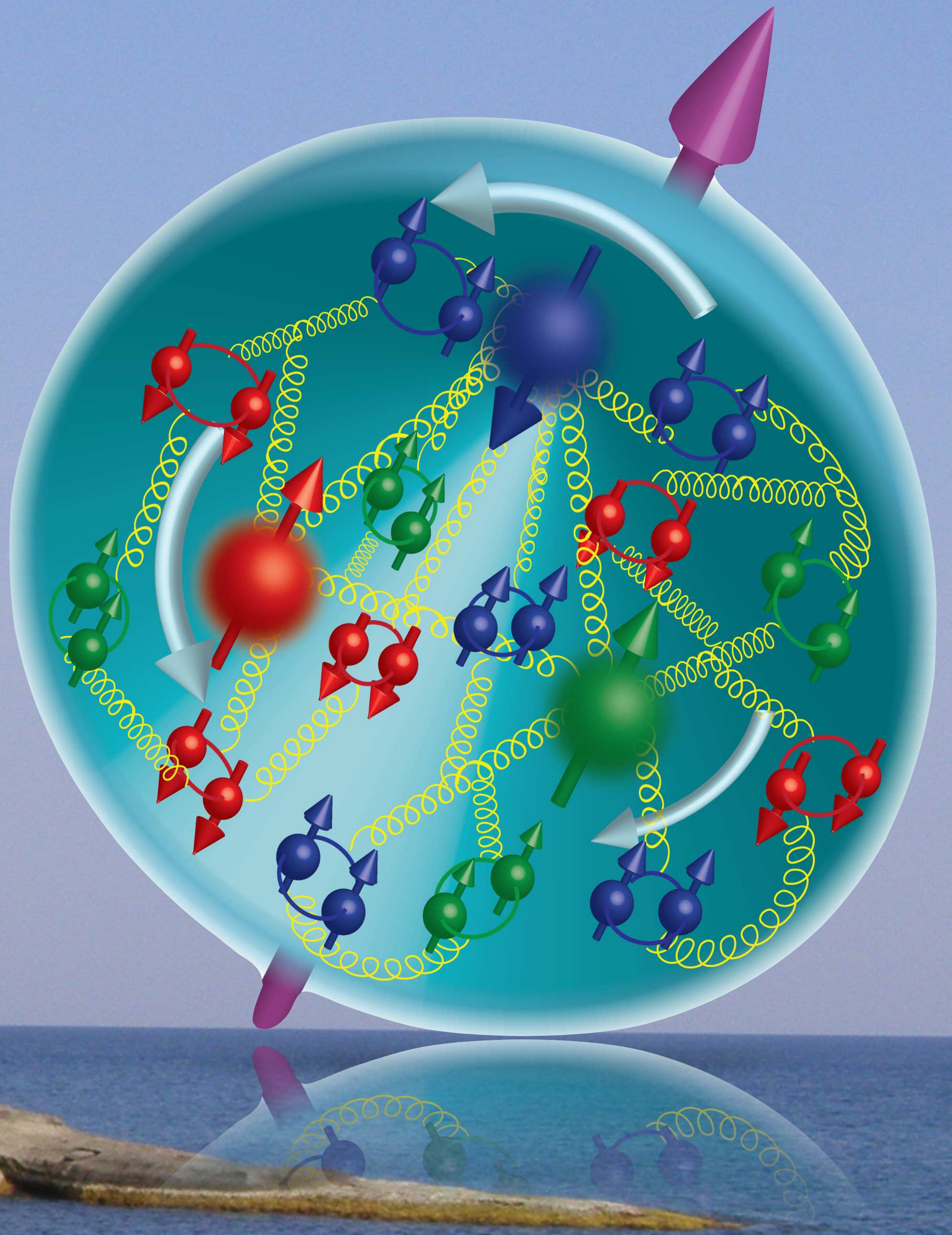


Probing nucleon spin structure

Recent advances in spin-physics measurements

Caroline Riedl

15th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei (**EINN2023**)
October 31 – November 4, 2023
Paphos, Cyprus

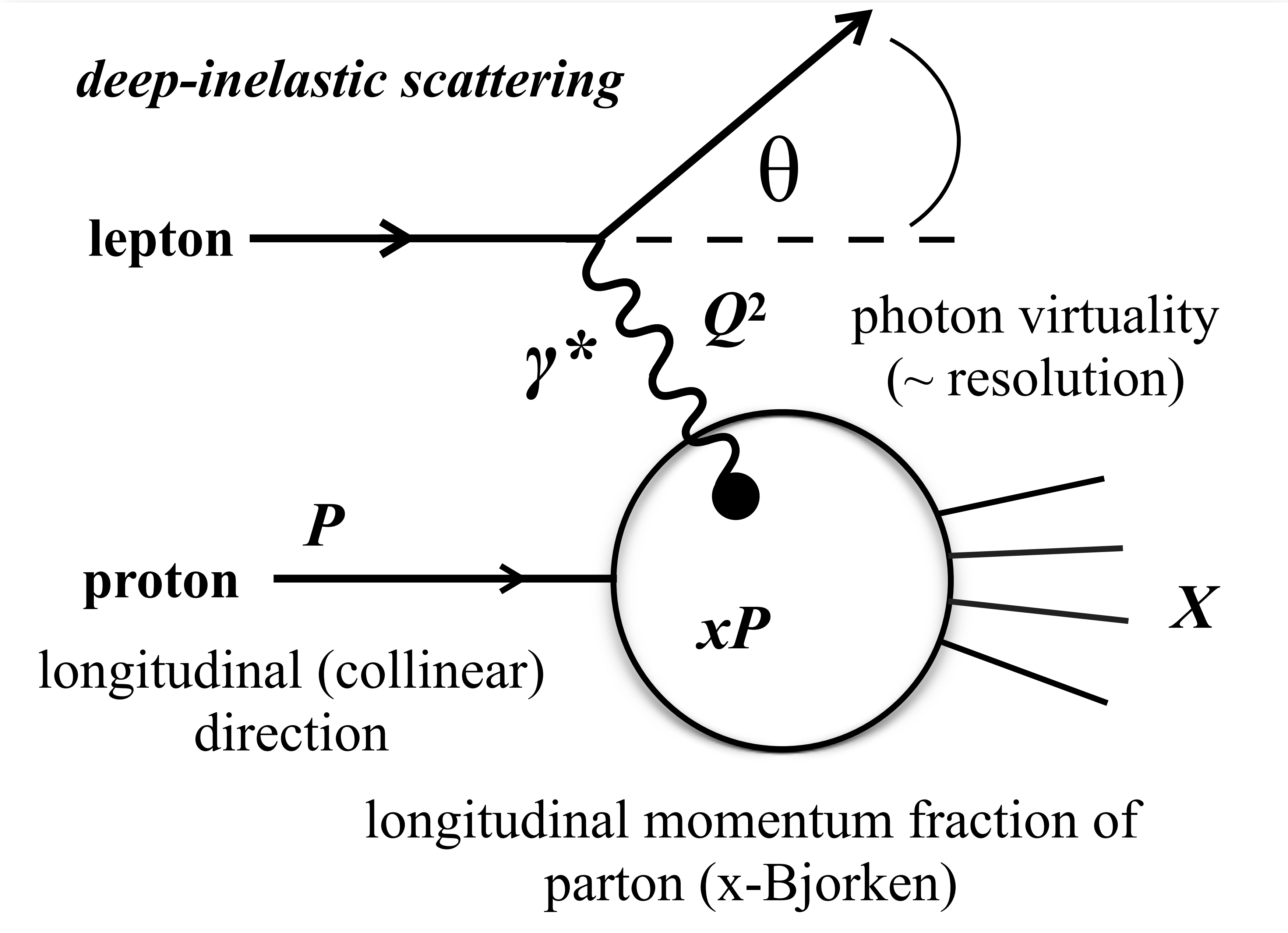
Probing nucleon spin structure

"**Deeper questions about QCD and hadron physics**" from the 2023 US Long Range Plan

- How does QCD generate the spectrum and structure of conventional and exotic hadrons?
- How do the mass and spin of the nucleon emerge from the quarks and gluons inside and their dynamics?
- How are the pressure and shear forces distributed inside the nucleon?
- How does the quark–gluon structure of the nucleon change when bound in a nucleus?
- How are hadrons formed from quarks and gluons produced in high-energy collisions?

Disclaimer: the references and results in this talk are not exhaustive. Sorry if I overlooked your recent result, represented it wrongly, or did not cite you. Please reach out, criedl AT illinois DOT edu

Lessons from the first DIS experiments (SLAC-MIT late 1960's)

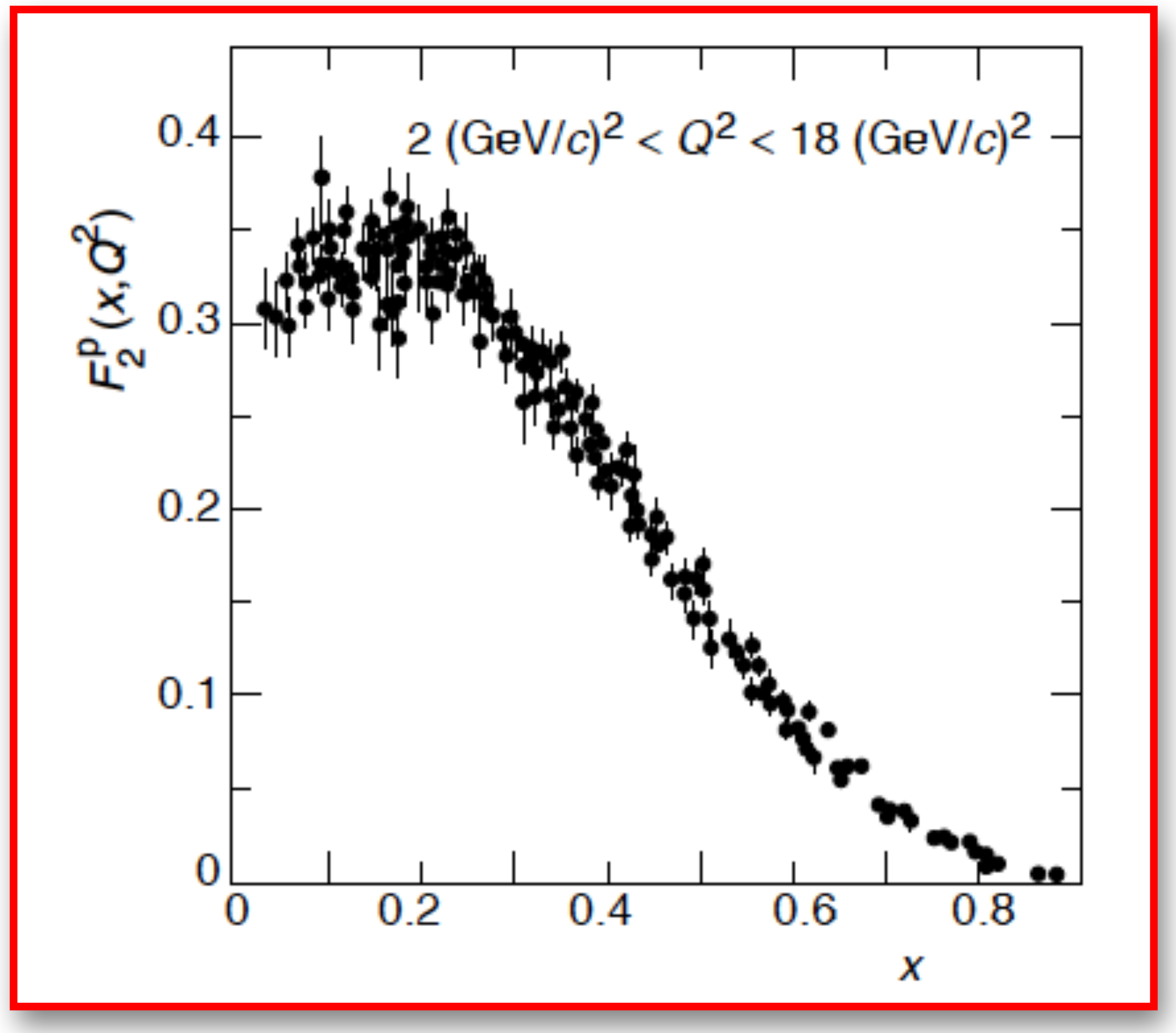


- There are two **structure functions** (F_1, F_2) parameterizing the "QCD non-perturbative structure" of the unpolarized spin-1/2 nucleon.

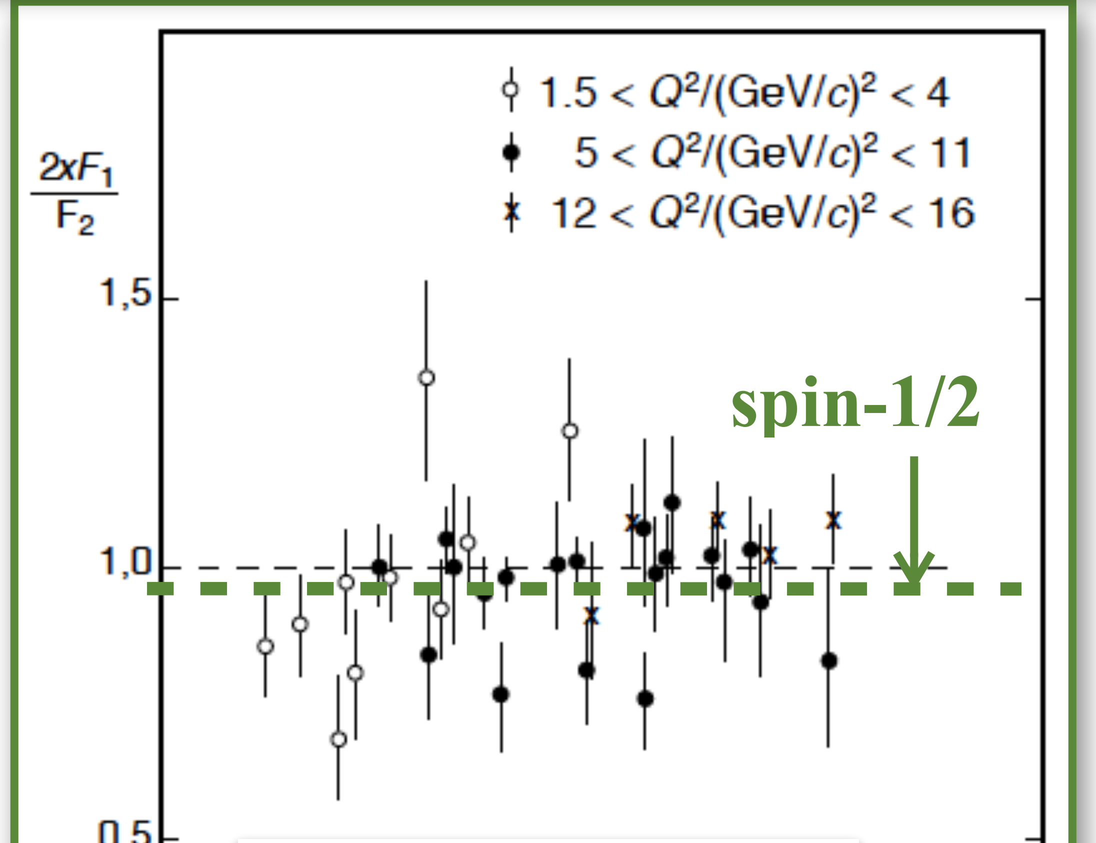
$$\frac{d^2\sigma}{d\Omega dE'} = \underbrace{\underbrace{\frac{Z^2\alpha^2}{4E^2}\cdot\frac{1}{\sin^4(\frac{\theta}{2})}}_{\text{Rutherford}}\cdot\cos^2(\frac{\theta}{2})}_{\text{Mott}}\left[\frac{1}{\nu}\underbrace{F_2(\nu,Q^2)}_{\text{electric effects}}+\underbrace{\frac{2}{M}\tan^2(\frac{\theta}{2})\cdot F_1(\nu,Q^2)}_{\text{magnetic effects}}\right]$$

- The structure functions can be expressed in terms of quark **longitudinal-momentum probability distributions** $q(x)$.
$\Rightarrow$ parton distribution functions (**PDFs**)

$$F_2(x) = x\cdot\sum_{q,\bar{q}} e_q^2\,(q(x)+\bar{q}(x))$$



- $F_2(x, Q^2)$ is in first order independent of Q^2 (**scaling**) $\Rightarrow$ nucleons have a substructure of **point-like constituents**.
- The point-like constituents of the proton have **spin-1/2** (**quarks**).



$$2xF_1(x) = F_2(x)$$

Callan-Gross relation expected for spin-1/2 Dirac particles

Experiments with nuclear and/or lepton polarization

- HERMES at DESY (1995-2007)
  - Self-polarized 27.6 GeV electrons and positrons in HERA storage ring
  - Pure L- and T-polarized gas targets

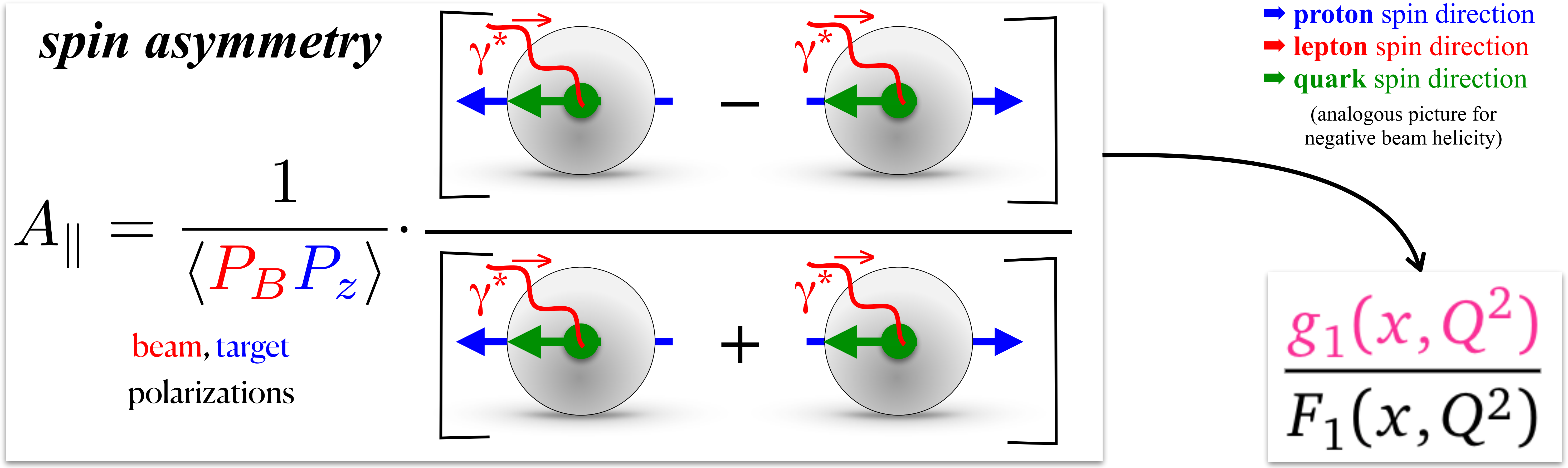
- COMPASS at CERN (2002-2022)
  - Secondary and tertiary beams (M2 SPS beam line).
    160 /200 GeV muons polarized via pion decay
  - Solid-state L- and T-polarized targets (ammonia and deuterated lithium)

- sPHENIX (2023-2025), STAR (2000-2025), PHENIX (2000-2015) at RHIC / BNL
  - Collisions of L- and T-polarized proton beams (pp & pA)
    $\sqrt{s}$ = 200, 500/510 GeV
  - Optically pumped ion source (OPPIS)

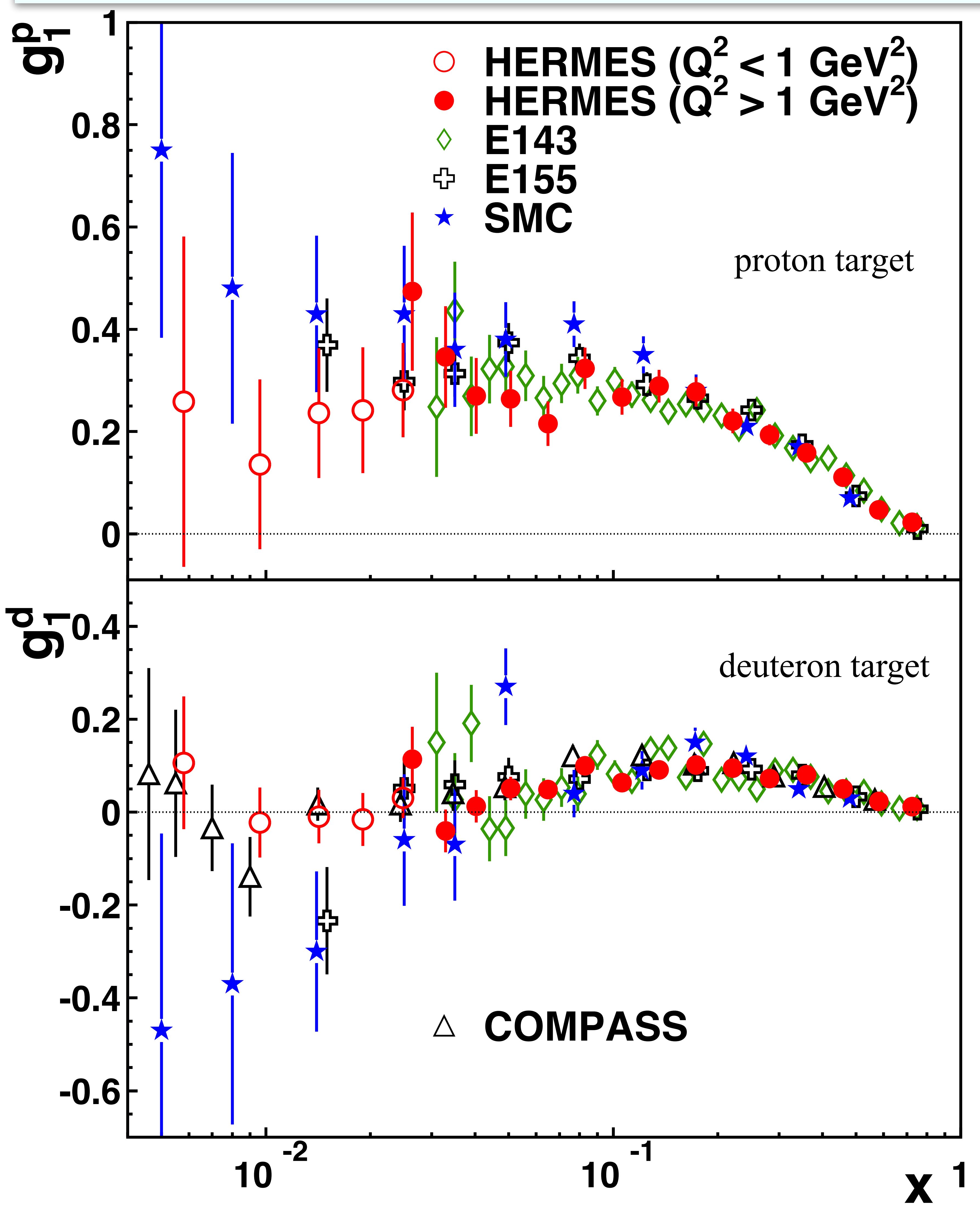
And many more: the polarized electron beams at JLab-CEBAF, the polarized targets at JLab, Fermilab, LHC-spin at CERN…

Quark spin contribution to the nucleon spin

- Measurements with longitudinal nucleon polarization at DESY, CERN and SLAC
- Need additional structure functions if targets and/or beams are polarized. Measurement of a **spin asymmetry** allows accessing information about the spin-dependent structure function.



Global spin structure function measurements



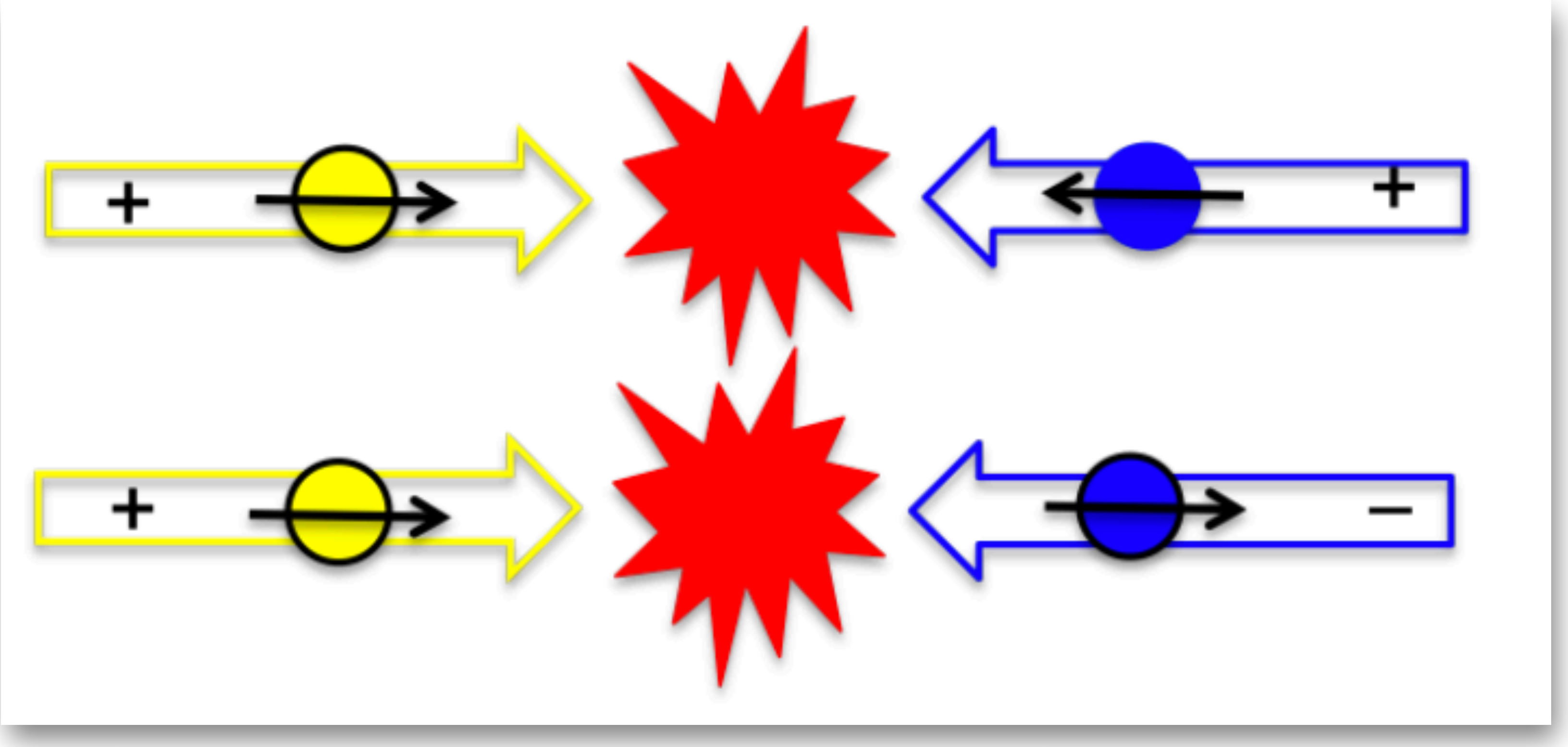
[HERMES Phys. Rev. D 75 (2007) 012007]

- From measurements related to the **spin structure function** $g_1(x,Q^2)$ at fixed-target experiments at DESY, CERN and SLAC, and a full QCD analysis, the quark spin contribution to the spin of the proton was determined to be **$\Delta\Sigma \approx 1/4 \ldots 1/3$**.

Gluon spin contribution to the nucleon spin

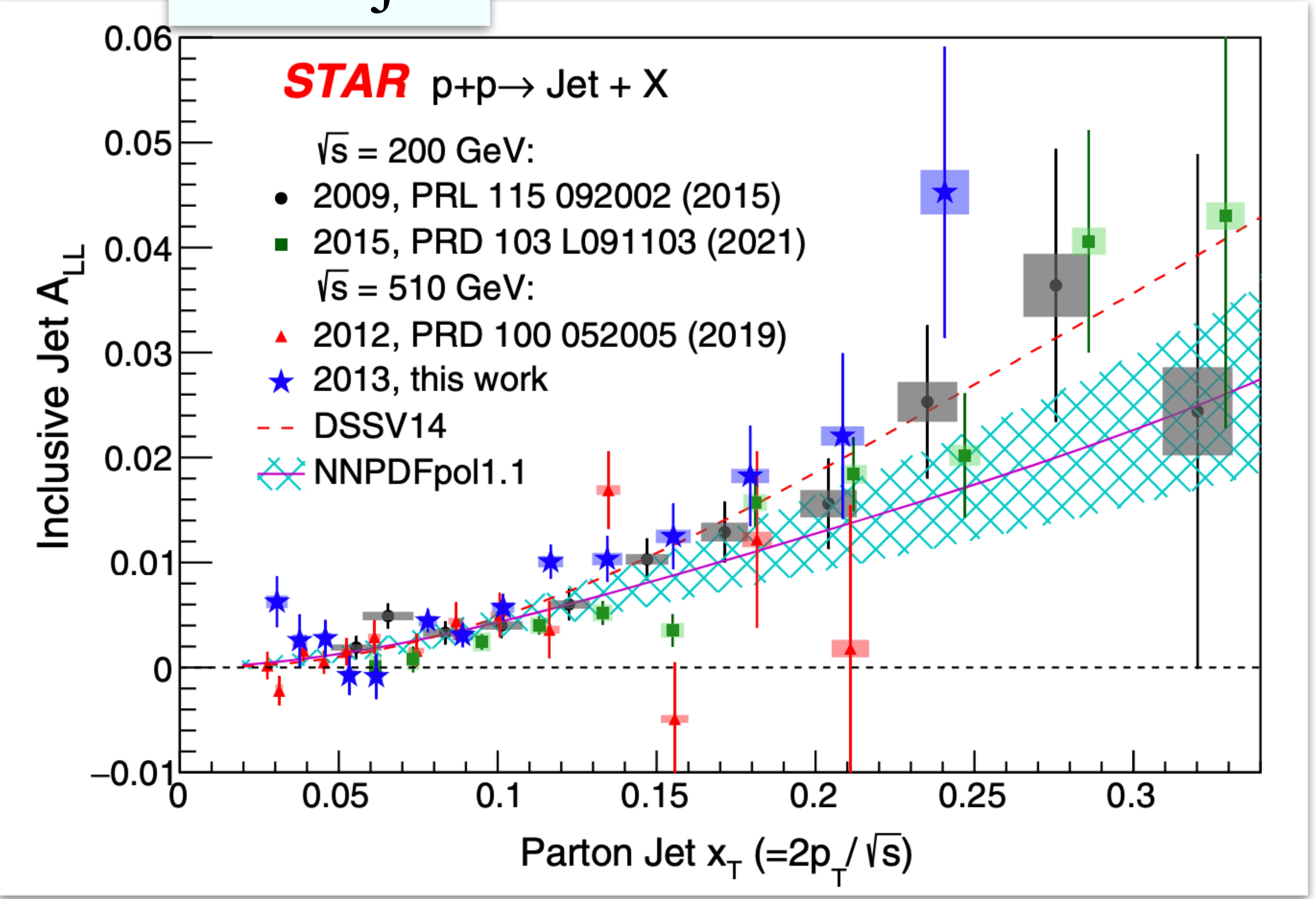
- Measurements with longitudinal polarization at RHIC - pp accesses directly gluonic subprocesses at leading order.
- Last LL RHIC data collected 2013 & 2015.

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$



Possible production channels:
- Charged and neutral pions
- Isolated direct photon
- Inclusive jet
- Dijets

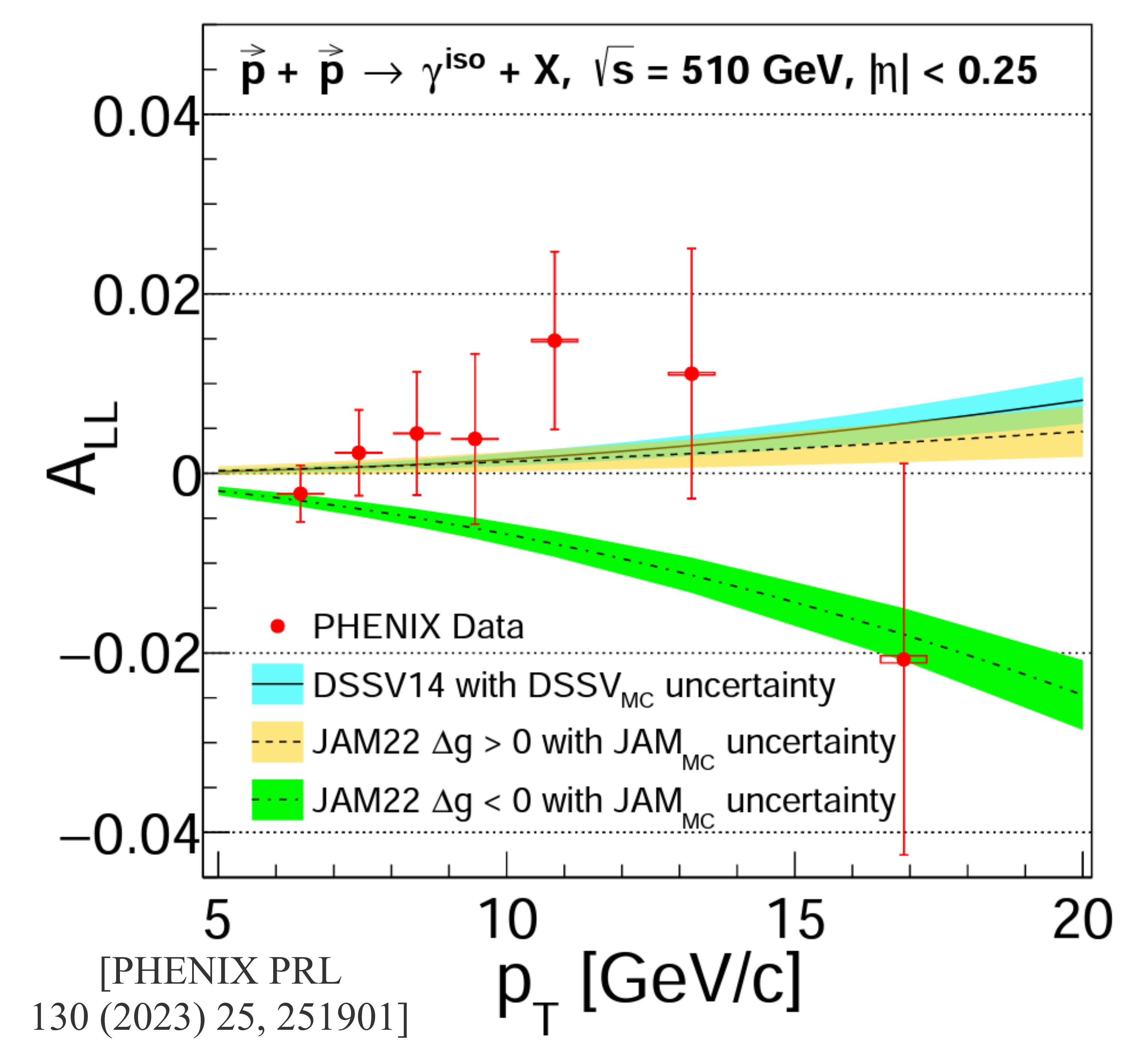
STAR jets



[STAR PRD 105, 092011 (2022)]

gluon momentum range: 0.015<x<0.25
agree with NLO global analyses & input for better constraint on Δg shape

PHENIX direct photon



[PHENIX PRL 130 (2023) 25, 251901]

gluon momentum range: 0.02<x<0.08
favors positive gluon-spin contributions

- From global analysis of **longitudinal double-spin asymmetries: $\Delta G \approx 20\%$** (& indication there is more at lower *x*)

$$\int_{0.05}^{1} dx \Delta g = 0.22 \pm 0.03$$

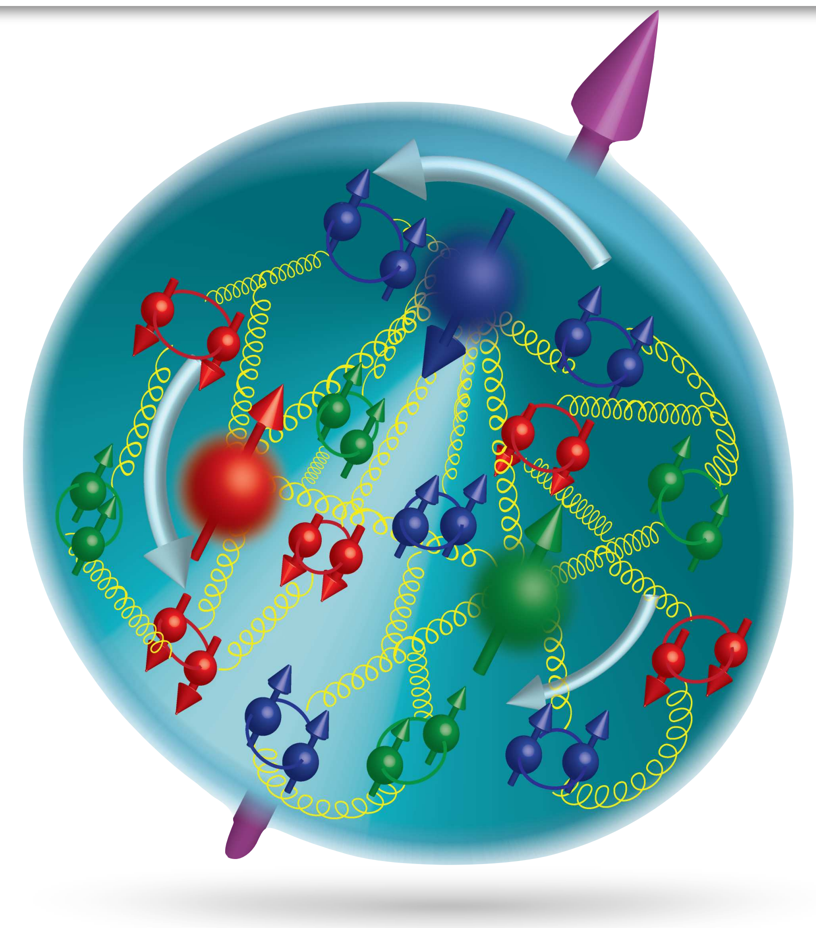
DSSV (2019), PRD 100 114027
White paper of the RHIC cold QCD program

STAR endcap dijets preliminary [STAR, DIS 2023]

STAR π± tagged jet preliminary [STAR, 2023]

Proton spin puzzle & nucleon tomography

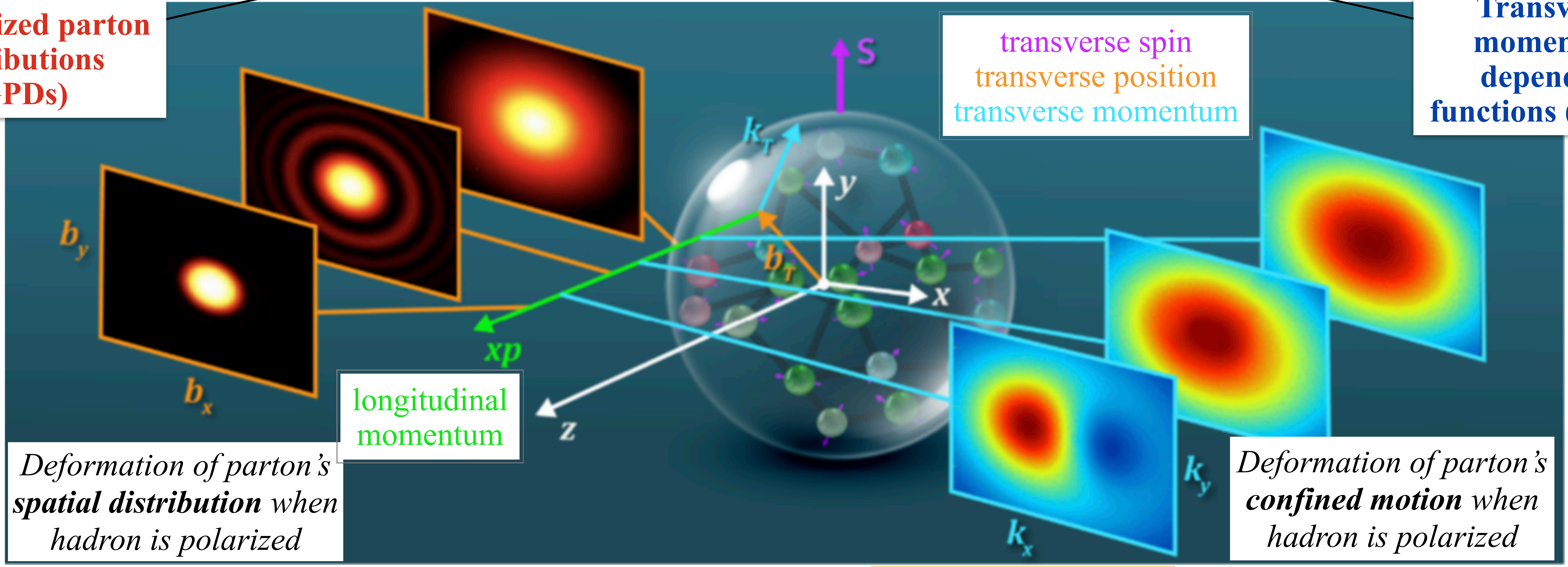
- Spin decomposition of the proton: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}$
- Experimental results from DIS and pp experiments & global QCD analysis:
  - The quark spins contribute 1/4 to 1/3 to the spin of the proton.
  - The gluon spins contribute some positive amount in the currently covered experimental range.
- Where is the remaining proton spin coming from? Parton orbital angular momentum?



GTMDs

Generalized parton distributions (GPDs)

Transverse momentum dependent functions (TMDs)



*Deformation of parton's **spatial distribution** when hadron is polarized*

*Deformation of parton's **confined motion** when hadron is polarized*

image from https://arxiv.org/abs/2303.02579

see talk by A. Metz, Thu am

Outline - Probing nucleon spin structure

☑ Introduction

- ☑ Longitudinal DIS, structure functions, & PDFs
- ☑ Spin-polarized experiments
- ☑ Proton spin puzzle & hadron tomography

☐ TMDs

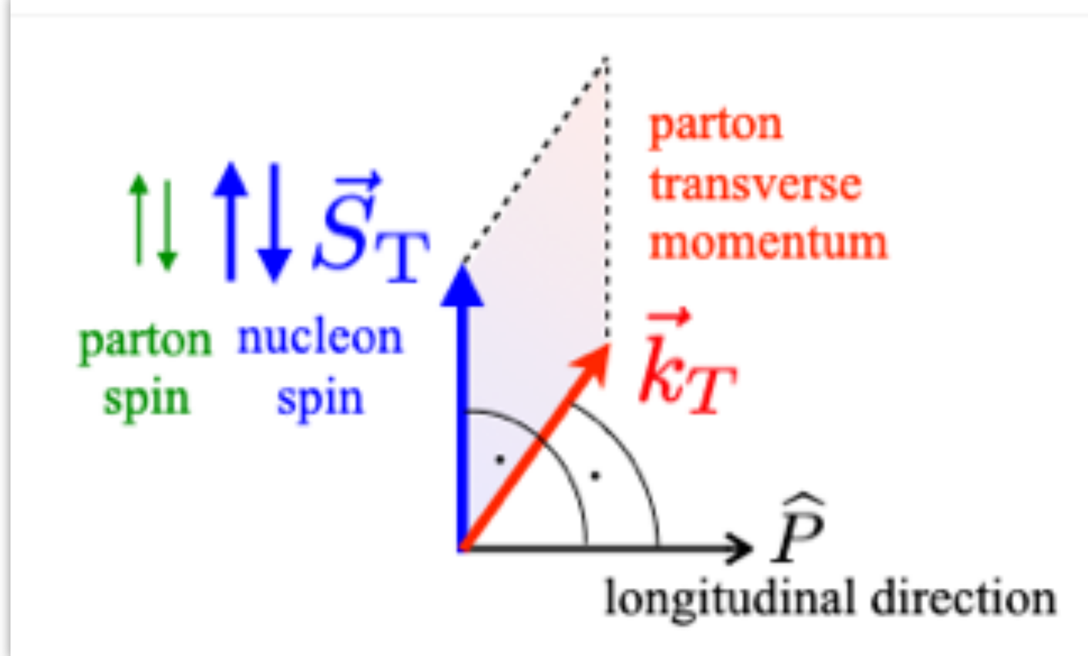
- ☐ Nucleon TMD structure and spin-orbit correlations
- ☐ TMD universal description
- ☐ Sivers TMD PDF in SIDIS and modified universality
- ☐ Gluon correlators & Sivers TMD PDF
- ☐ Sivers effect in di-jet production
- ☐ Collins FF in ee and Collins asymmetry in pp & SIDIS
- ☐ Di-hadron fragmentation function in pp and SIDIS
- ☐ Other spin-dependent fragmentation functions in SIDIS

☐ GPDs

- ☐ Hard exclusive reactions
- ☐ Chiral-even GPDs & DVCS asymmetries
- ☐ Exploring Compton form factors
- ☐ Parton orbital angular momentum & gluon GPDs
- ☐ Chiral-odd GPDs & vector mesons
- ☐ Transition DAs & transition GPDs

☐ Outlook & summary

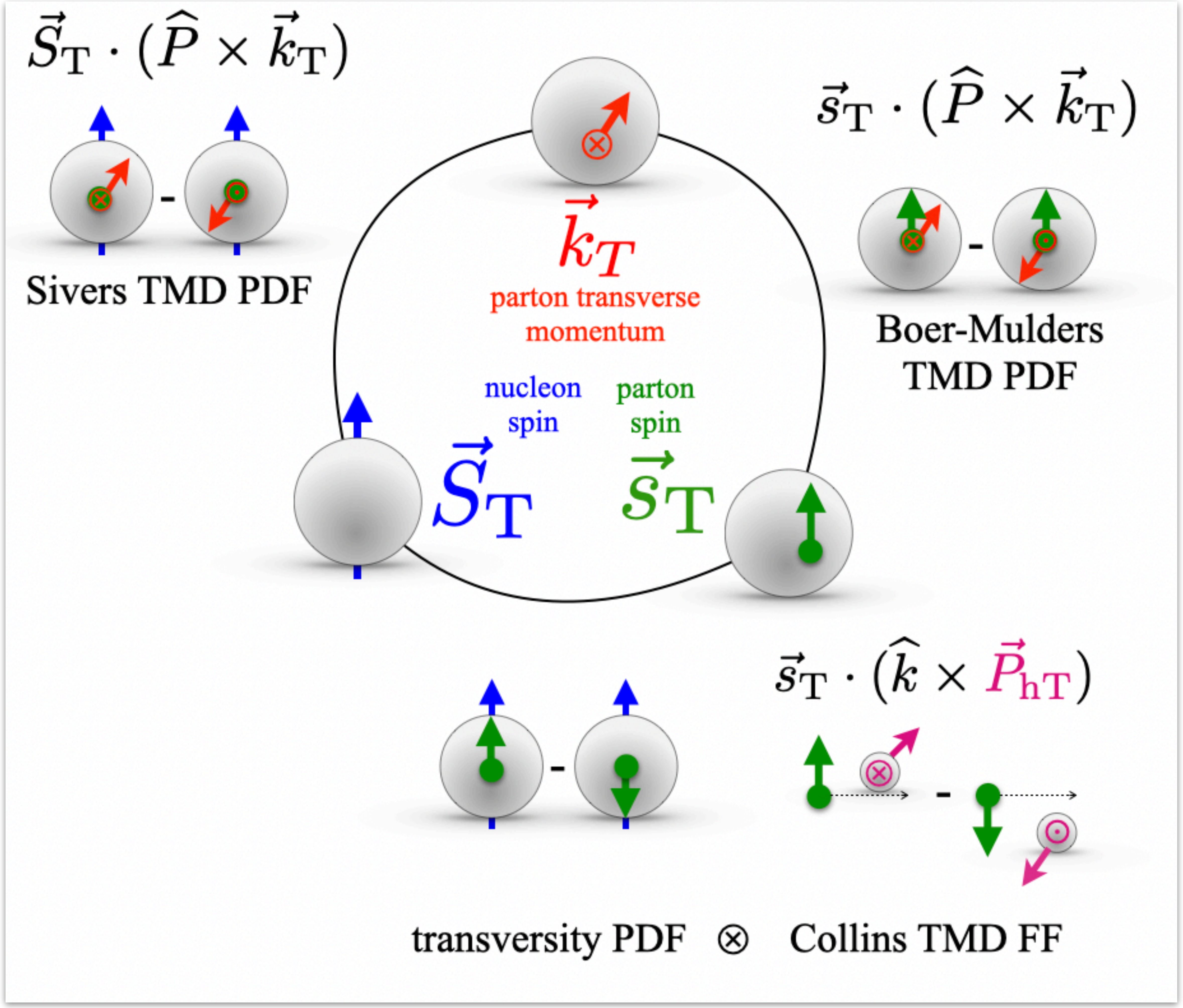
TMD structure of the nucleon



Taking into account parton intrinsic transverse momentum, 8 **TMD PDFs** are needed for a full description of nucleon structure (@leading order), some of which encode **spin-orbit correlations.**

N \ q	U	L	T	
U	number density		Boer-Mulders	
L		helicity	worm-gear-L	
T	Sivers	Kotzinian-Mulders (worm-gear-T)	transversity	pretzelosity

CKR-20231014



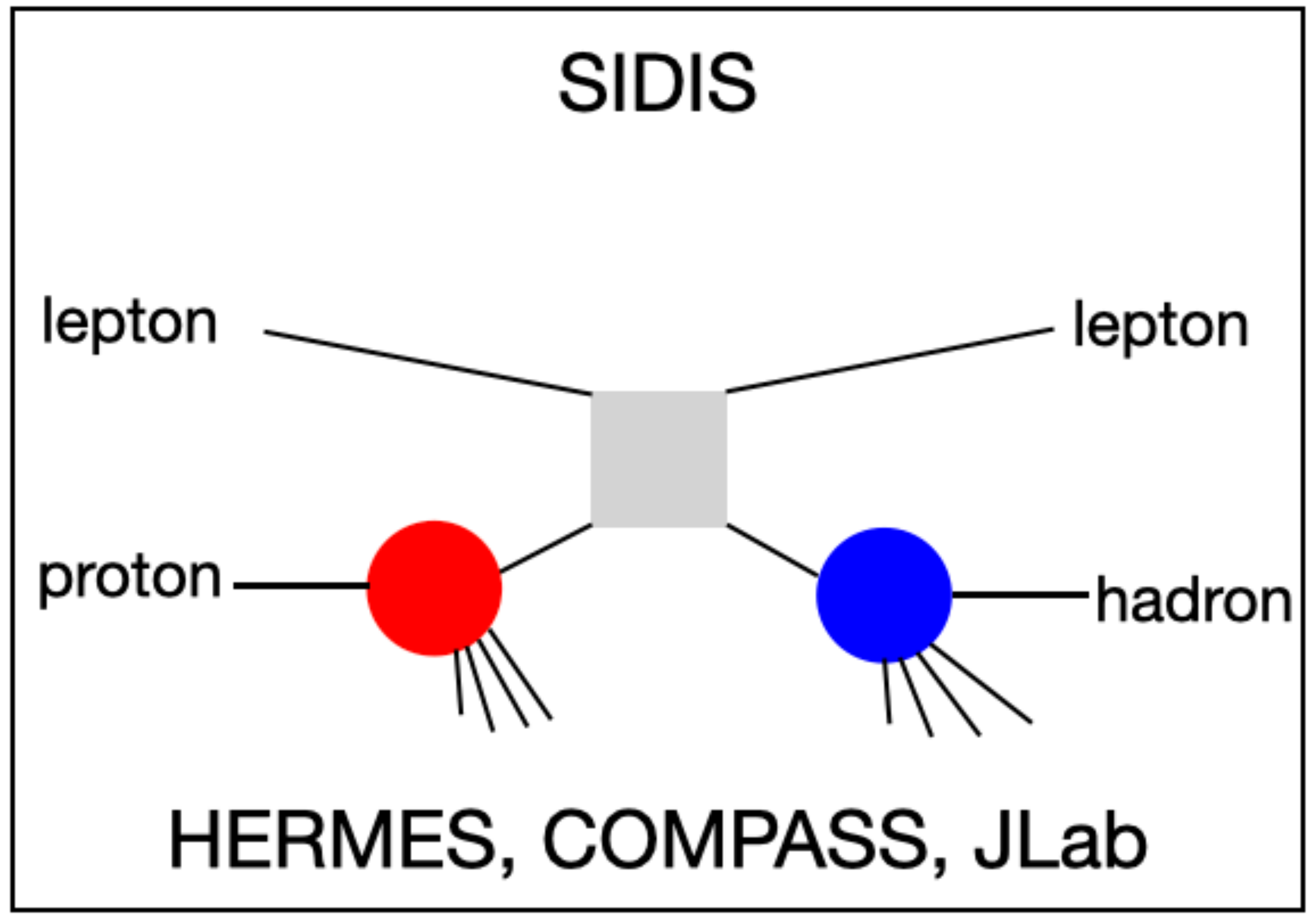
collinear

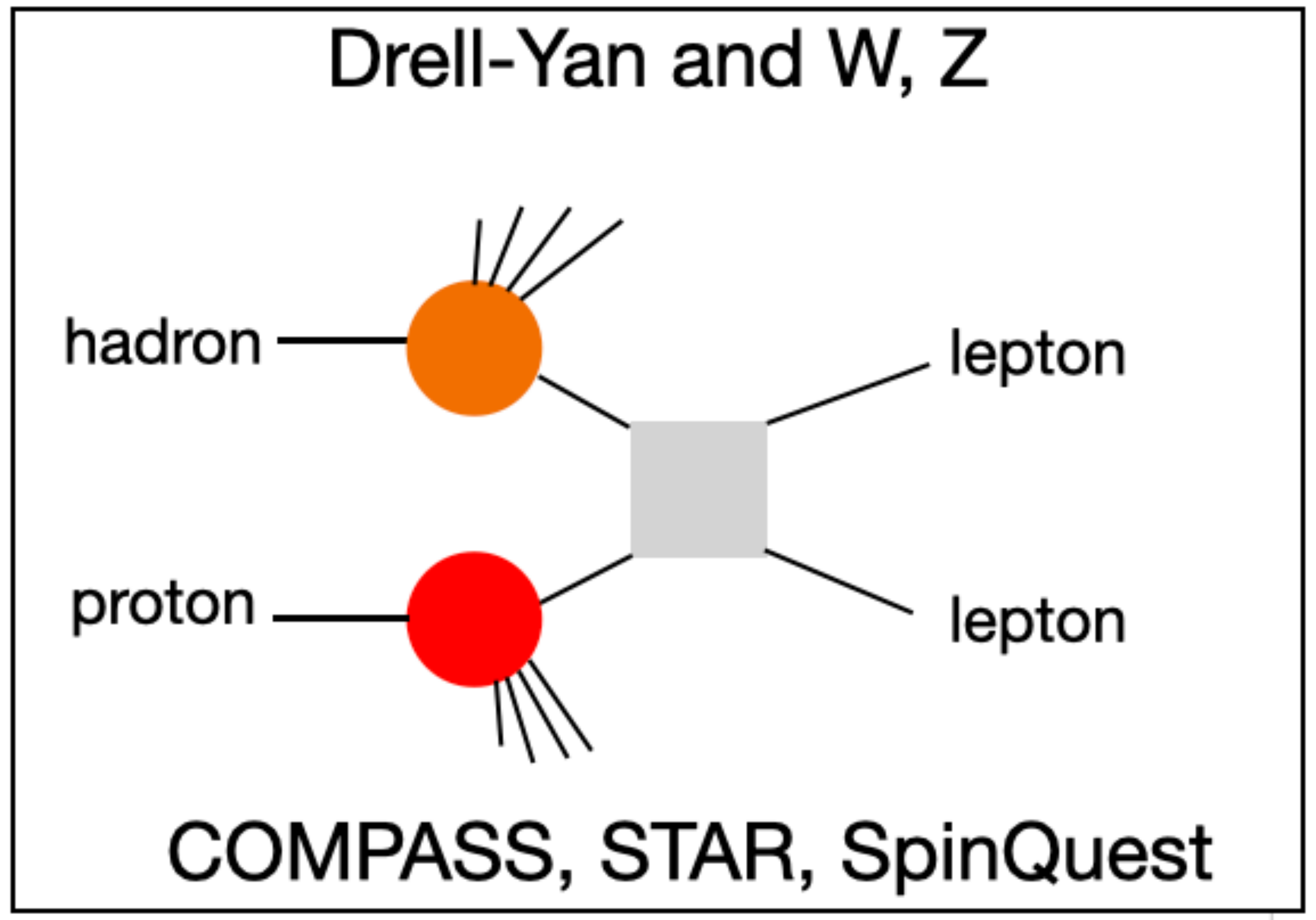
chiral-odd

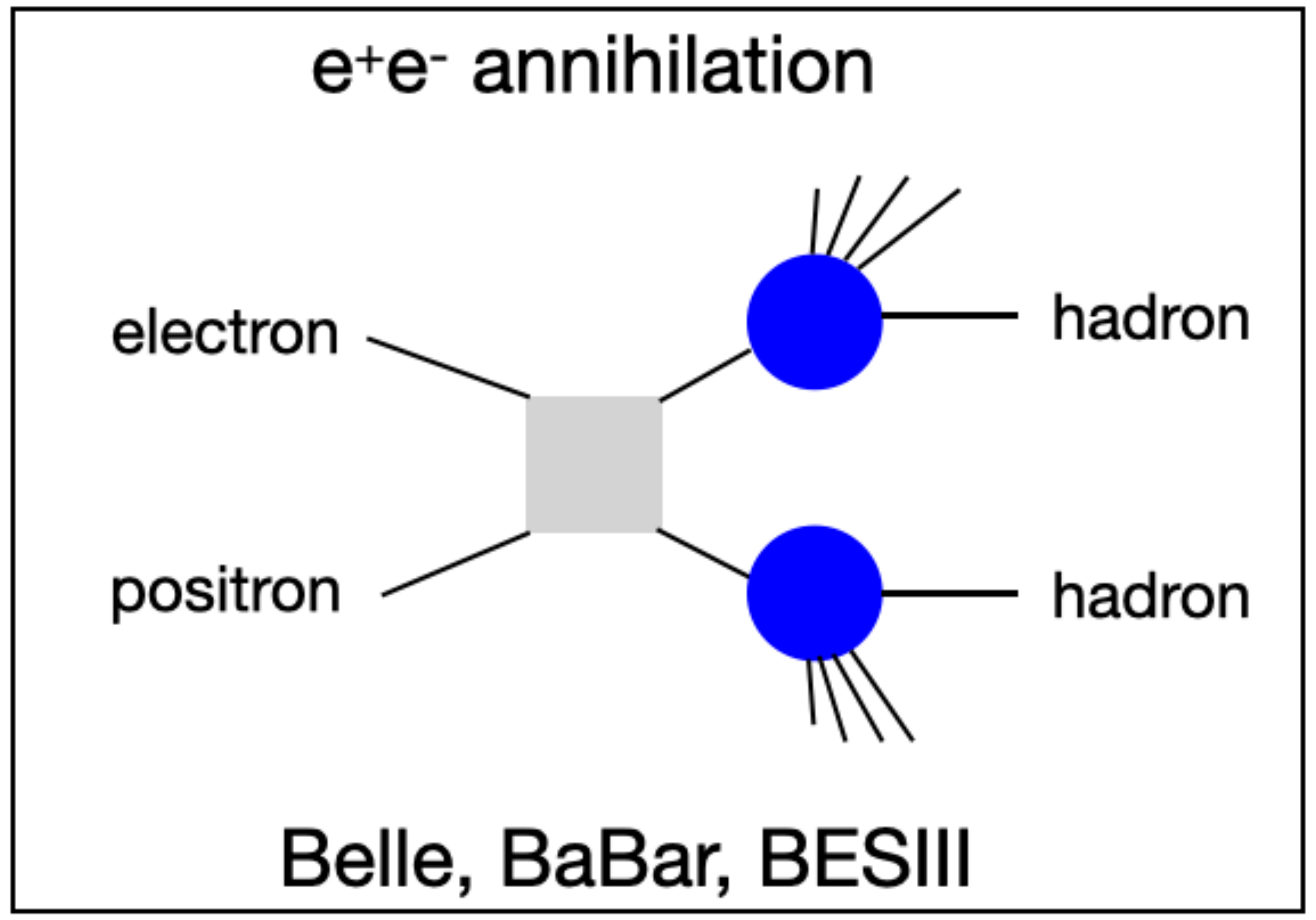
naive time-reversal odd

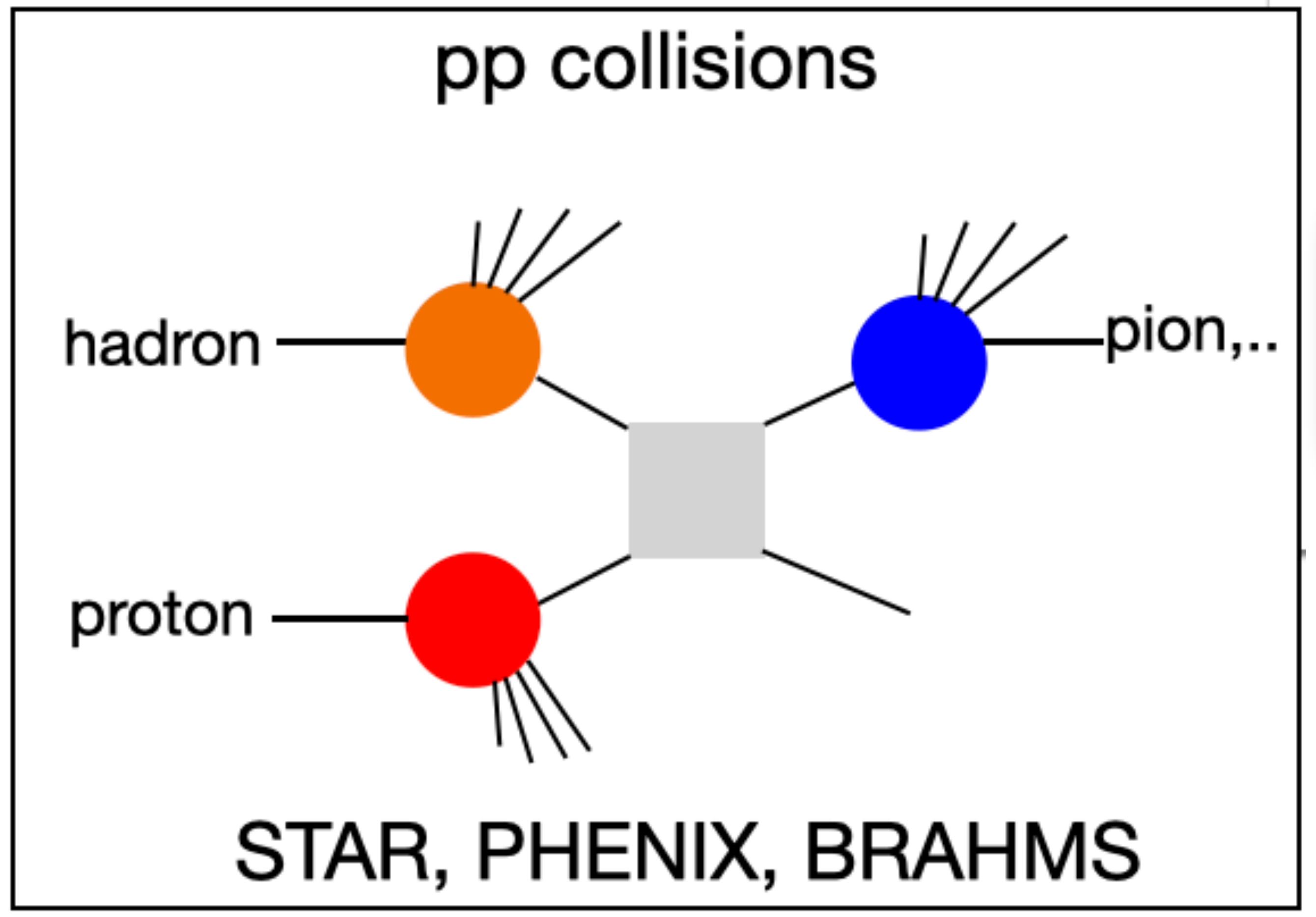
Observables to probe TMD universality

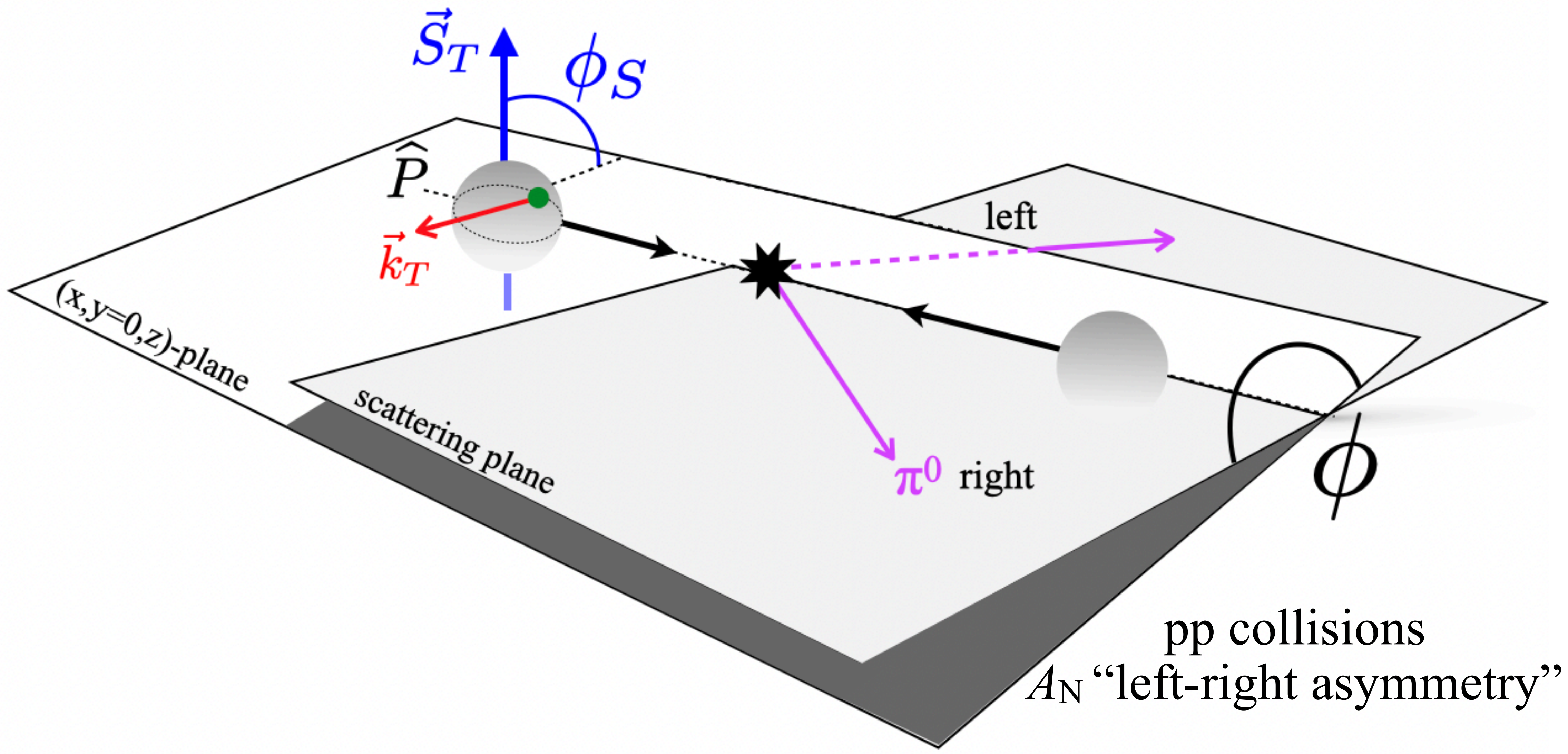
parton distribution function PDF FF **fragmentation function**











Transverse spin asymmetries have **common origin** - simultaneous description across different collision species possible.

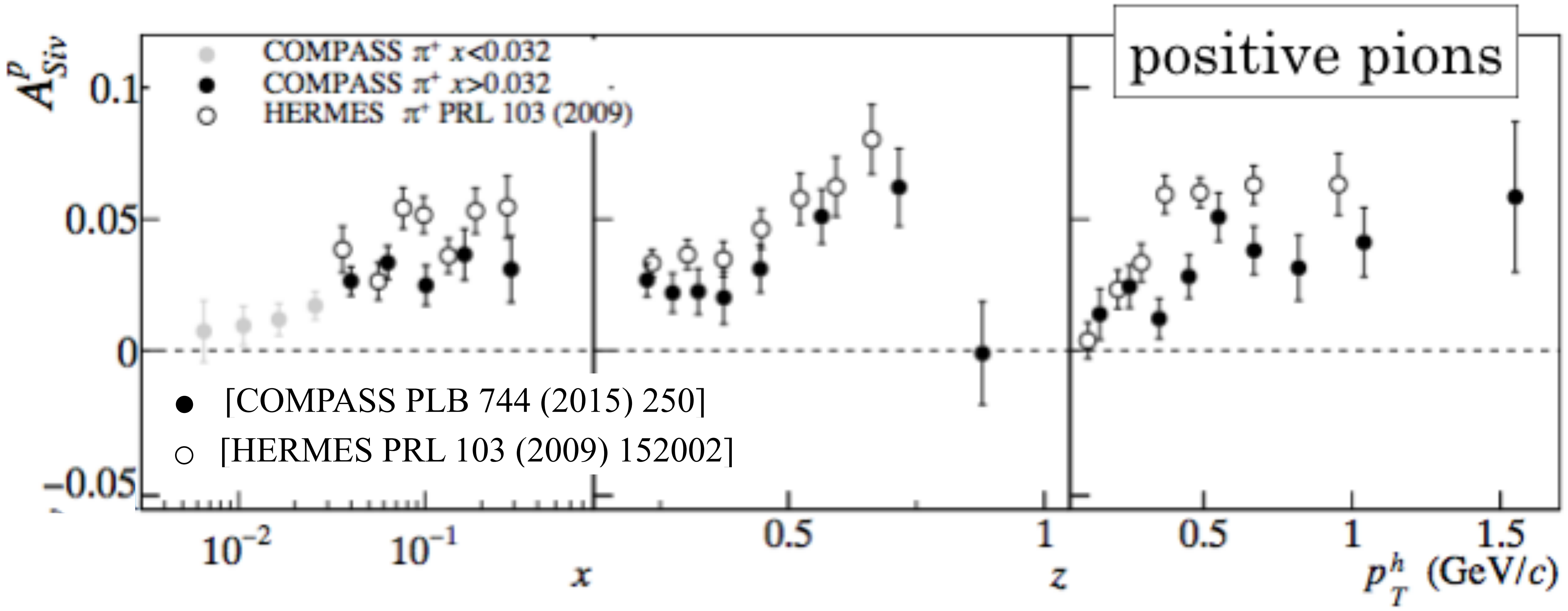
e.g. [Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (JAM Collaboration), PRD 102, 054002 (2020)]

Two complementary but related **theoretical descriptions**, depending on **what is reconstructed experimentally**

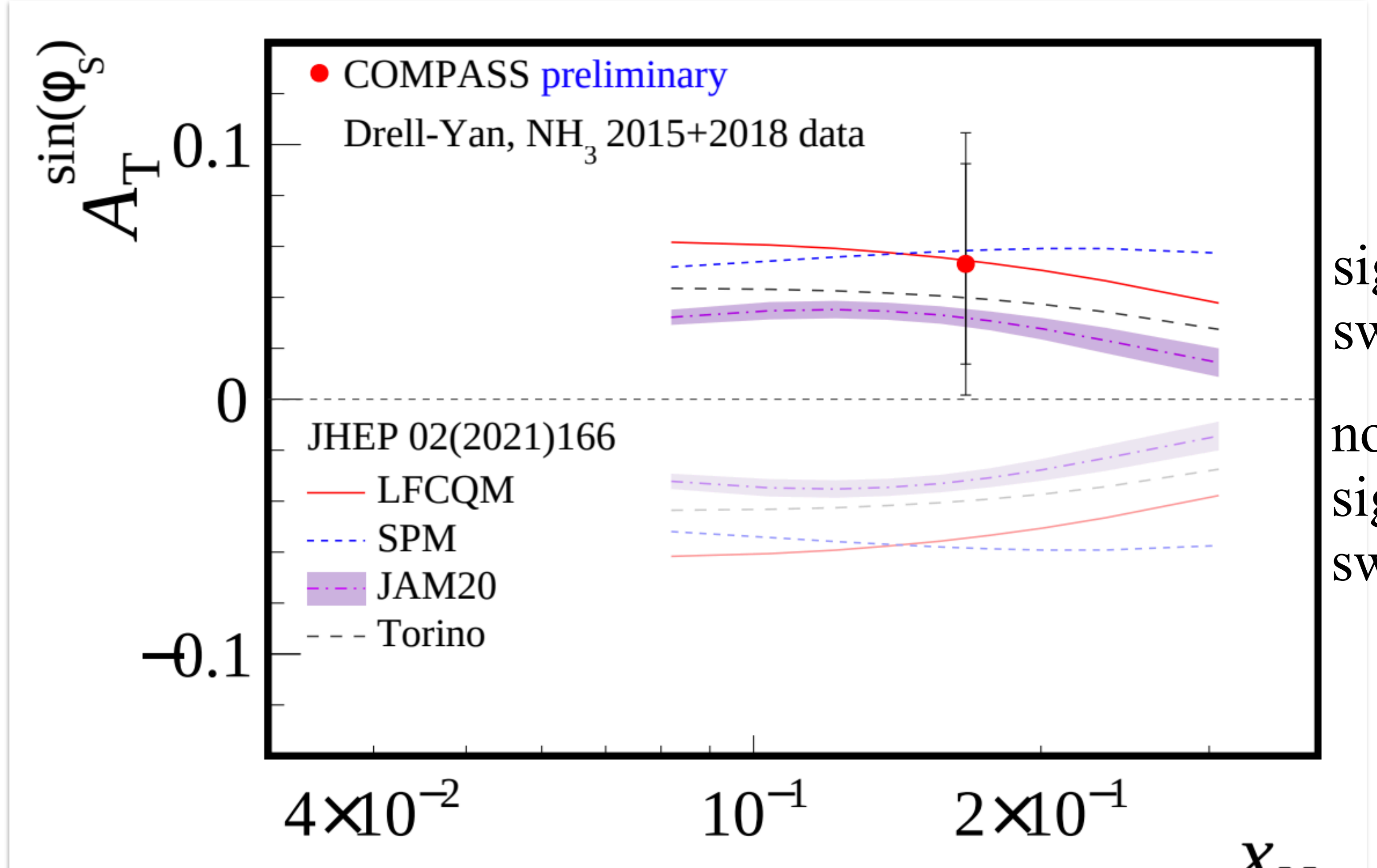
- **TMD framework -** measure 2 scales with $p_T \ll Q$; SIDIS, DY, W/Z, dijets, hadrons in jets
- **Collinear higher-twist (HT) framework -** measure 1 scale with $p_T \approx Q$; single inclusive particle production in pp (particle or jet p_T); spin asymmetries from quantum mechanical interference of multi-parton states (→ qgq and ggg correlators)

The Sivers sign switch – modified TMD universality

HERMES vs. COMPASS Sivers amplitude in SIDIS



COMPASS Sivers amplitude in π−p↑→μμX



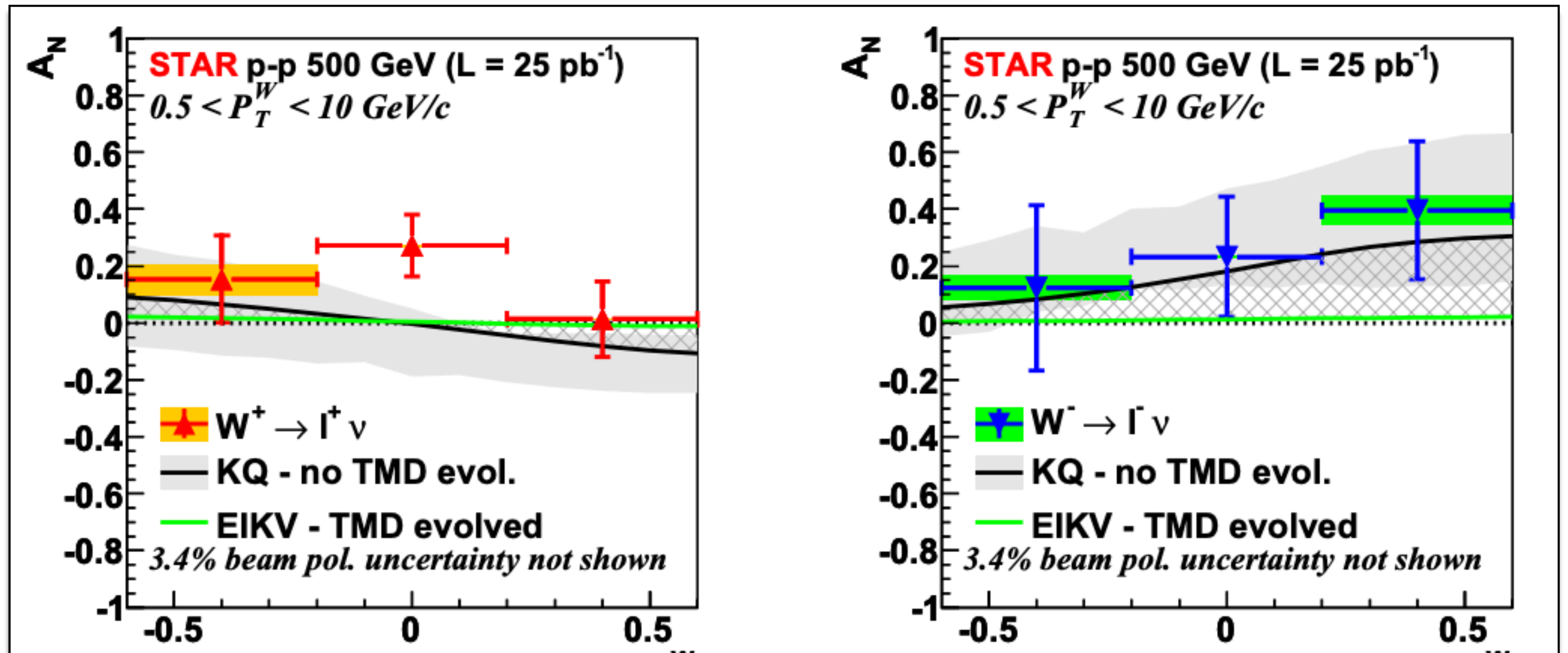
[COMPASS PRL 119 (2017) 112002 + preliminary.]

Final publication in preparation

Modified universality concept of Sivers & Boer-Mulders TMDs. The experimental data tend to support the Sivers sign switch, albeit still within large experimental uncertainties.

Important test of TMD-QCD framework, predicted due to the gauge invariance of QCD.

STAR: A_N in p↑p→W±→e±+ν

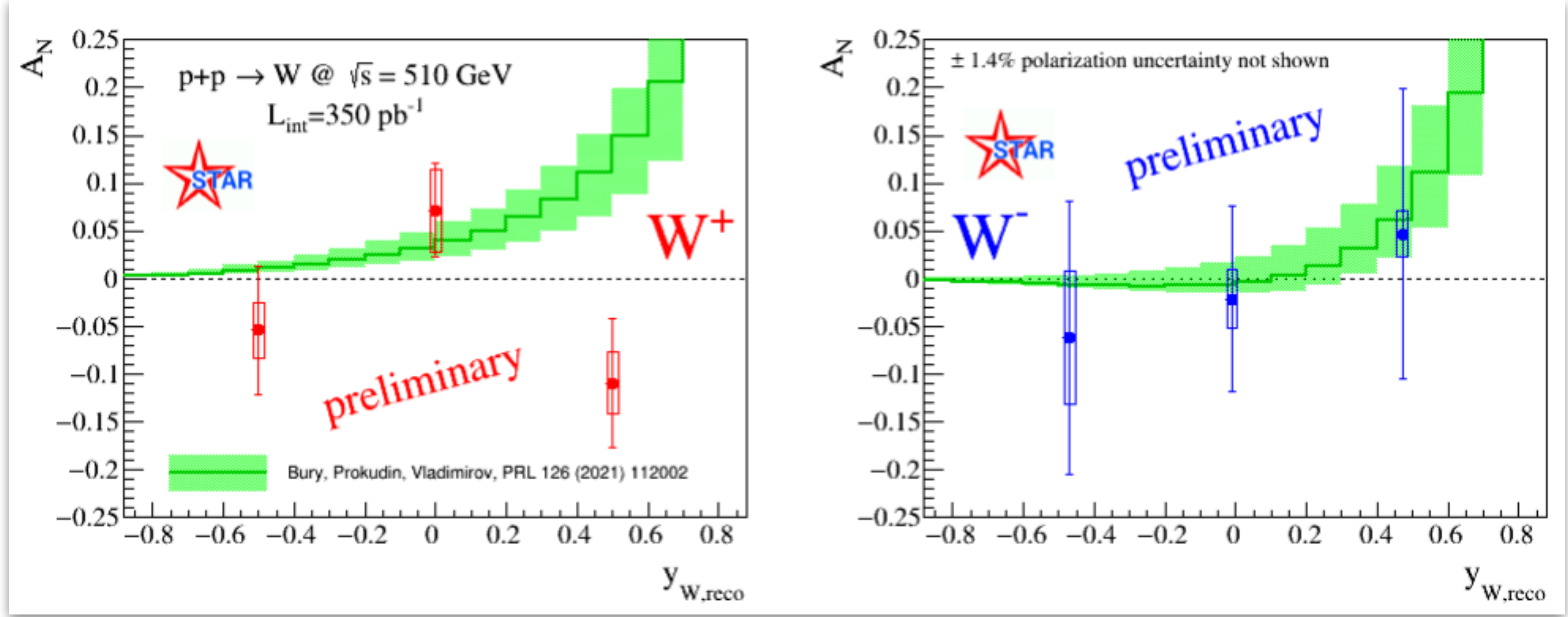


[STAR PRL 116, 132301 (2016)]

Curves with sign-switch assumption.

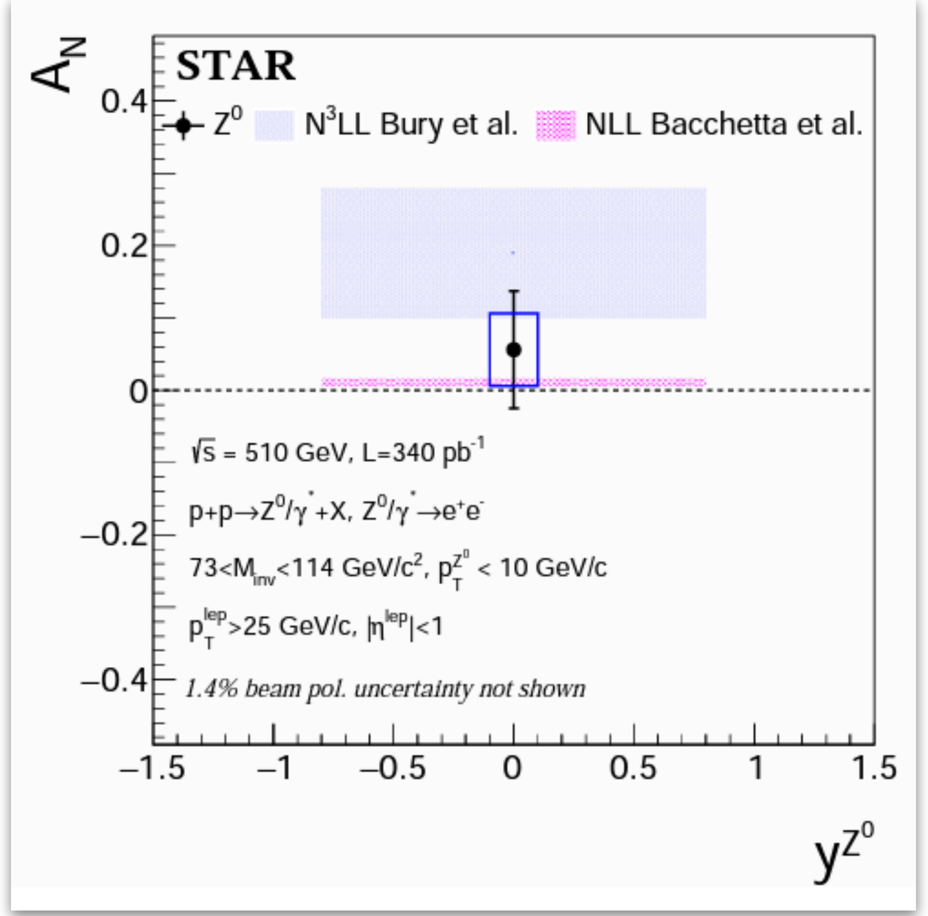
STAR new 2017 data

[STAR, AUM2021]



With N3LO theory prediction [PRL 126 (2021) 112002] based on global fit [JAM collab, PRD 102 (2020) 054002]

[STAR arXiv:2308.15496]



Tri-gluon HT correlations at RHIC midrapidity

PHENIX isolated direct-photon

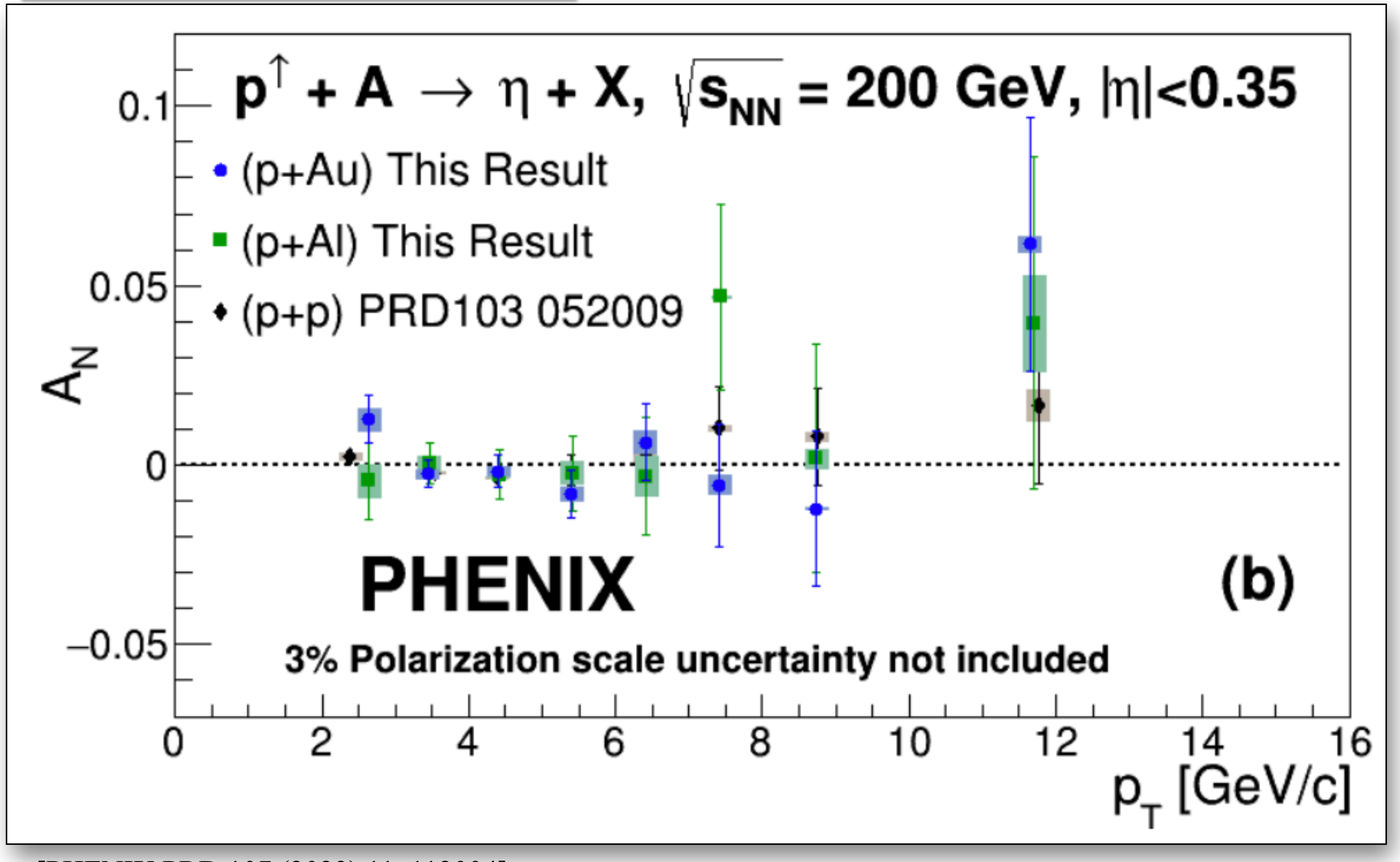
[PHENIX PRL 127, 162001 (2021)]

PHENIX pion

[PHENIX PRD 103 (2021) 5, 052009]

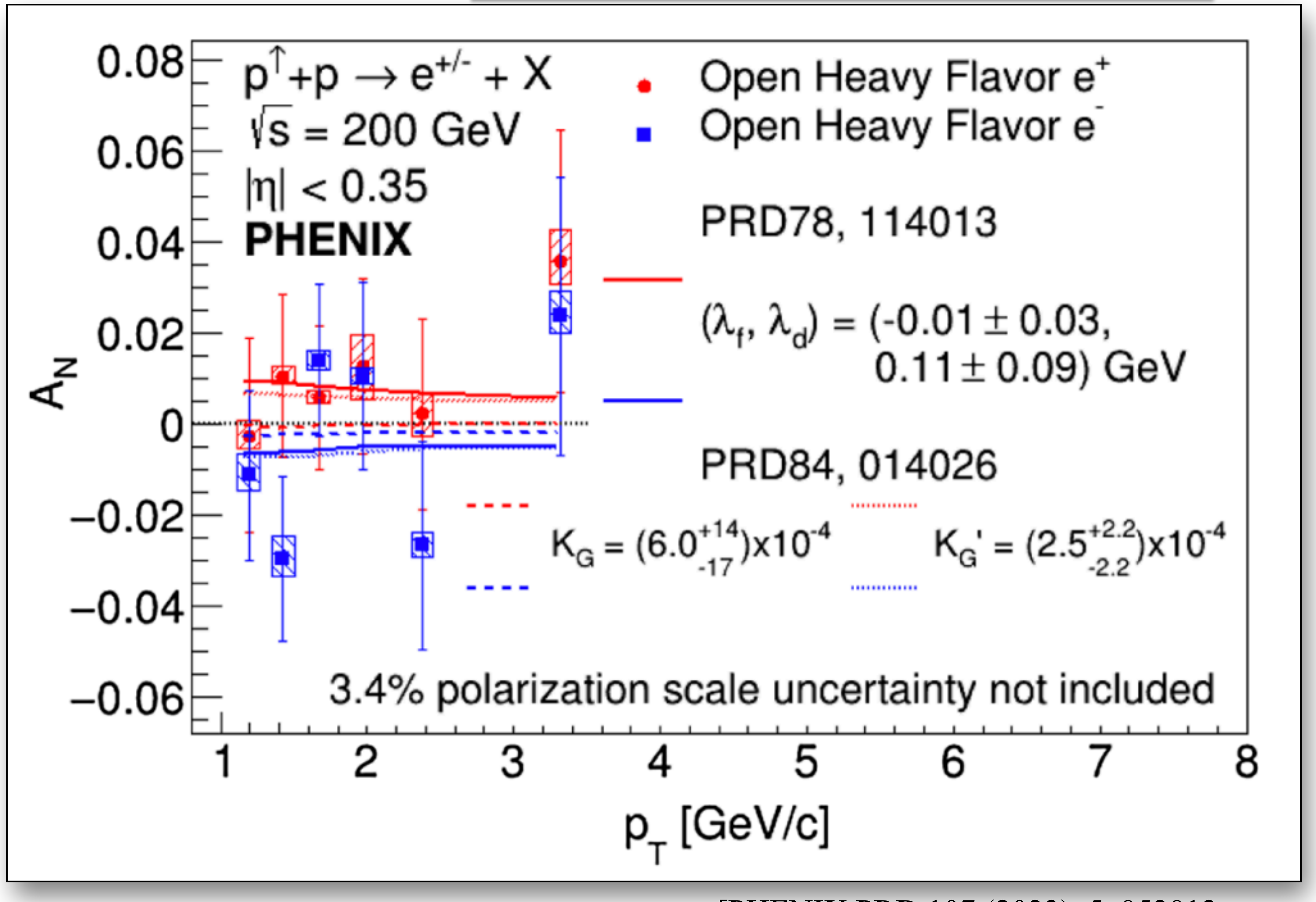
RHIC midrapidity measurements sensitive to tri-gluon higher-twist correlation functions ↔ gluon Sivers TMD
no signals, at high precision

PHENIX eta & nuclear



[PHENIX PRD 107 (2023) 11, 112004]

PHENIX open heavy flavor



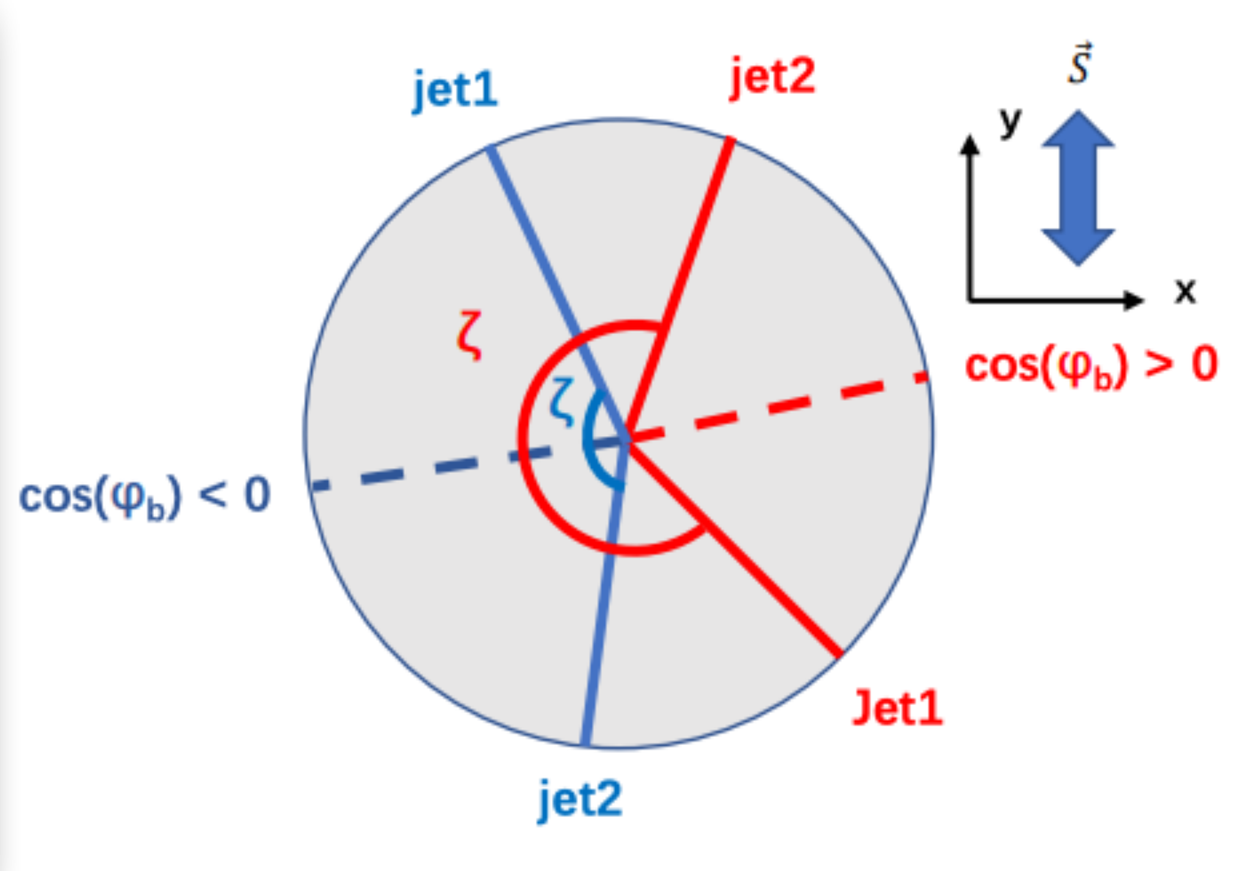
[PHENIX PRD 107 (2023), 5, 052012]

Consistent with expectation from Burkardt sum rule over parton transverse momenta, which leaves little room for gluon k_T

[M. Burkardt, arXiv:0408009 [hep-ph]]

First observation of the Sivers effect in di-jet production

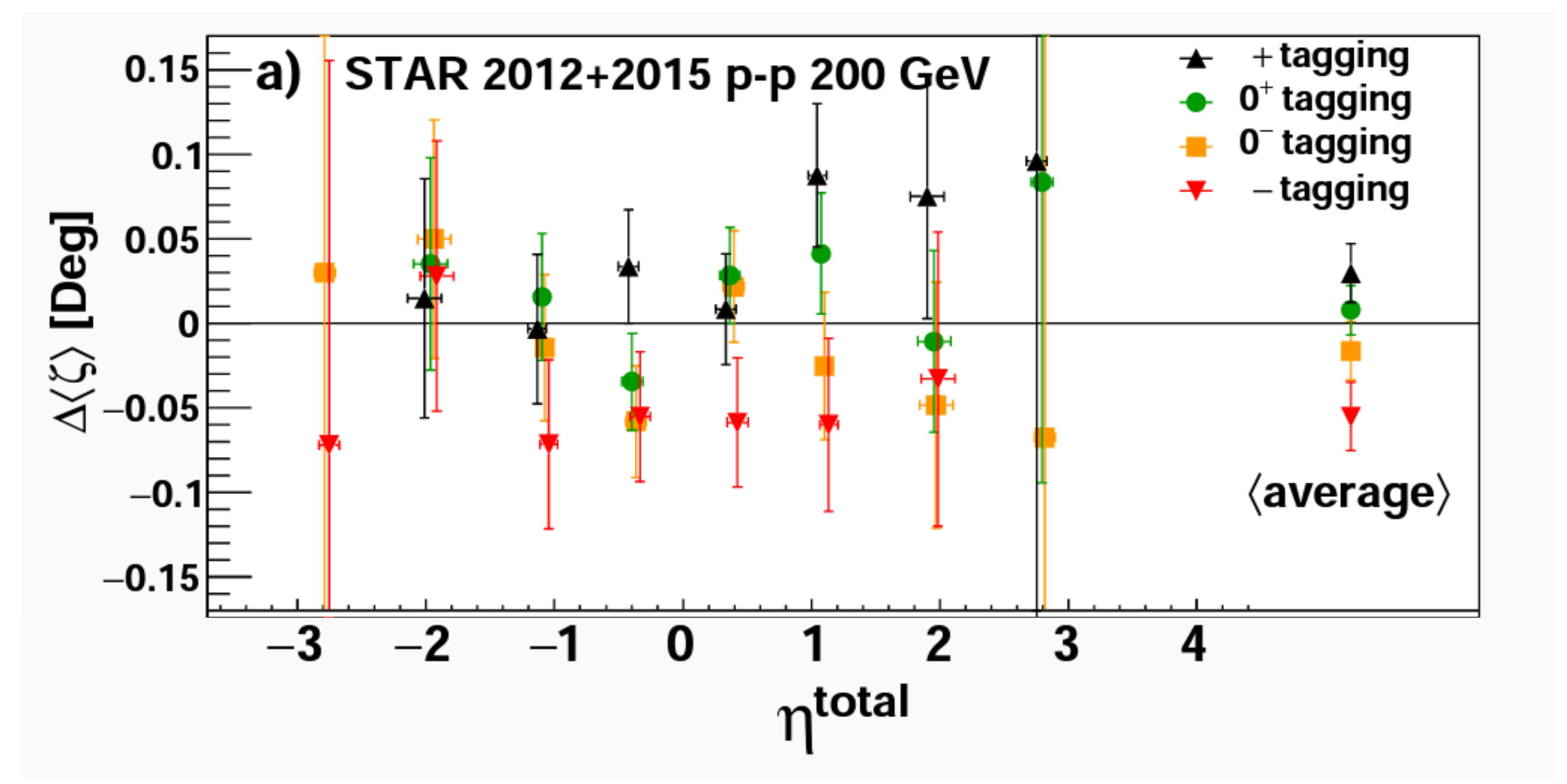
Di-jet production in pp↑ directly probes **average intrinsic quark and gluon transverse momenta, <k_T>,** via the asymmetry of the spin-dependent **tilt** of di-jet opening angle, closely tied to transv. mom. imbalance



$$\langle \vec{S}_T \cdot (\hat{P} \times \vec{k}_T) \rangle \neq 0$$

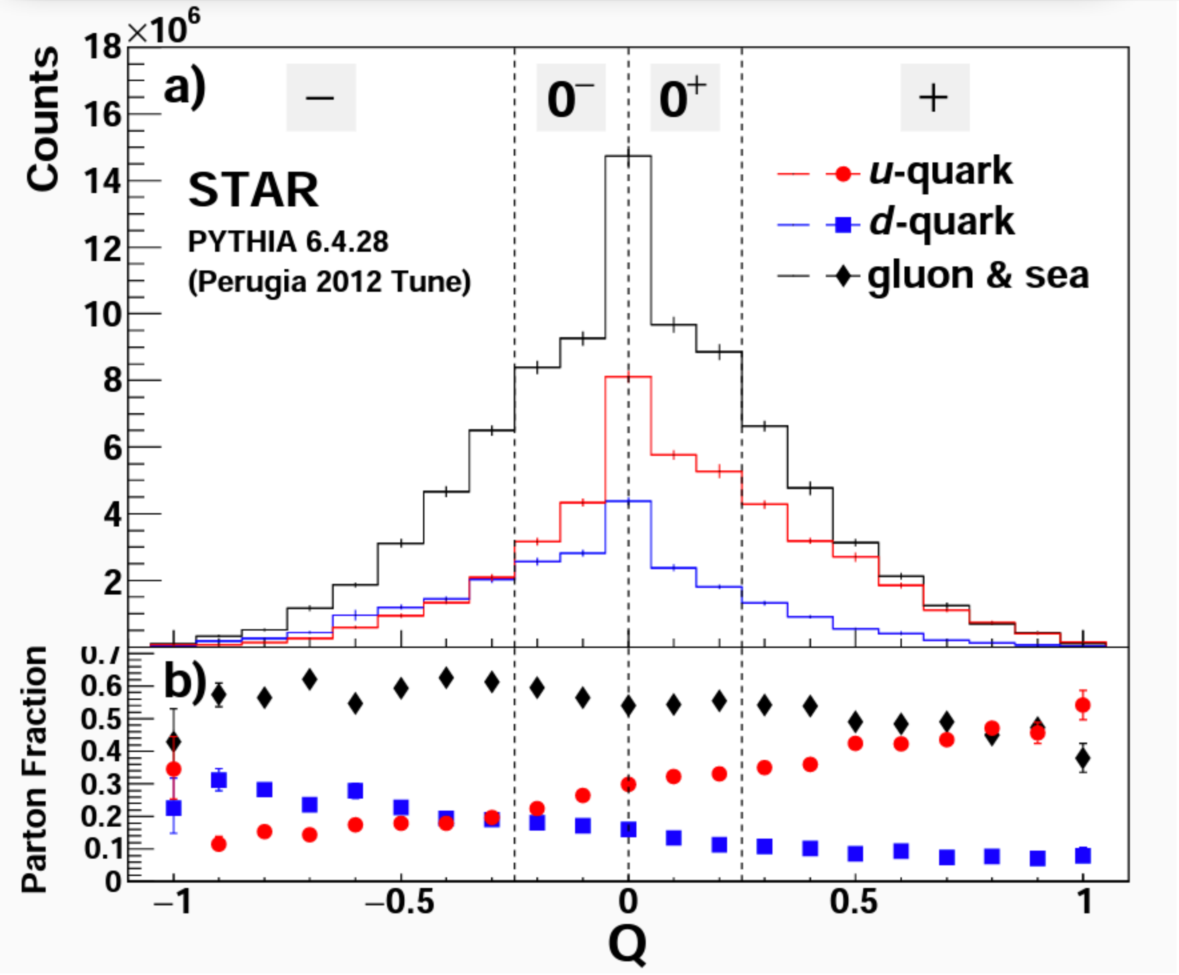
$$\Delta\langle\zeta\rangle = \frac{\langle\zeta\rangle^+ - \langle\zeta\rangle^-}{P}$$

STAR pp↑→j1j2 X, 2012 & 2015 data



unfolding

Jet charge tagging to create **u- and d-quark enhanced** categories



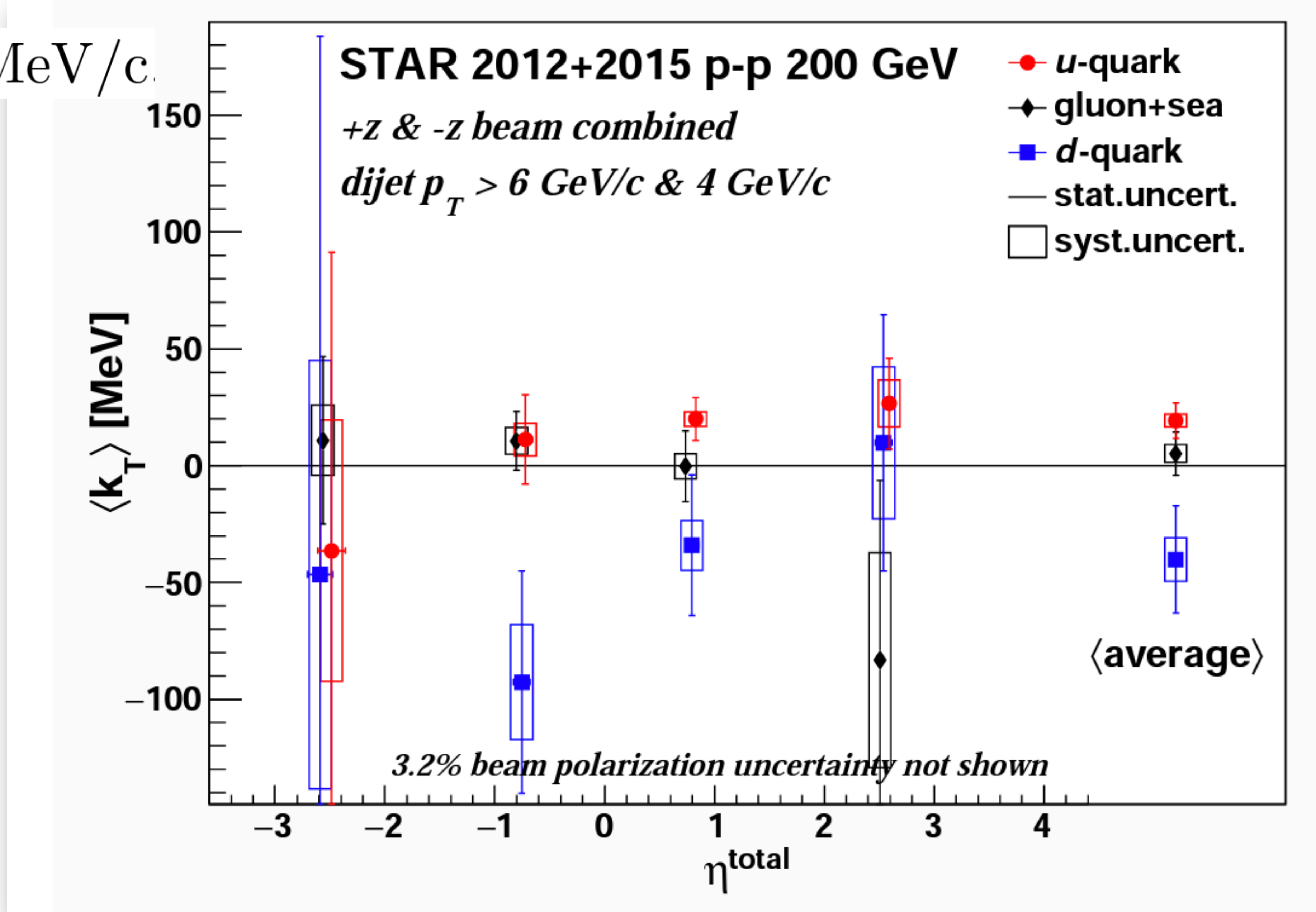
$$\langle k_T^u \rangle \sim +19.3 \pm 7.6 \text{ (stat.)} \pm 2.6 \text{ (syst.) MeV/c}$$

$$\langle k_T^d \rangle \sim -40.2 \pm 23.0 \pm 9.3 \text{ MeV/c}$$

Sivers partonic <k_T> values for **u- and d-quarks of opposite sign & similar magnitude**, for sea quarks and gluons (combined) ~ zero. ↔ SIDIS

$$Q = \sum_{|p^{track}|>0.8\ GeV/c} \frac{|p^{track}|}{|p^{jet}|} \cdot q^{track}$$

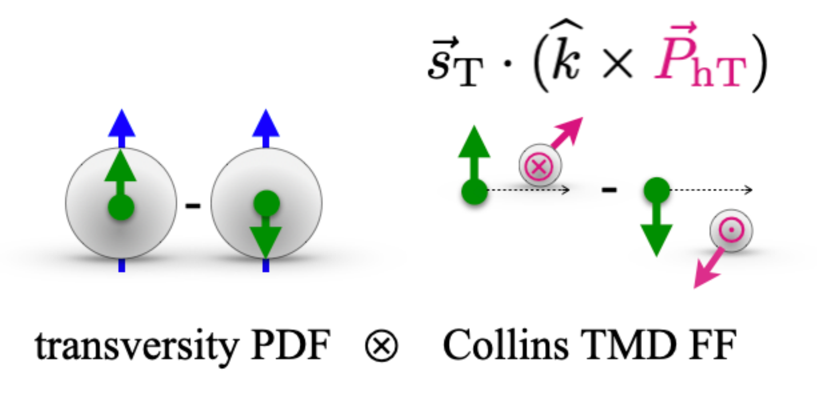
More data being analyzed incl. forward upgrade



[STAR arXiv:2305.10359 (sub PRL)]

Collins fragmentation function in e+e- & Collins asymmetry in pp

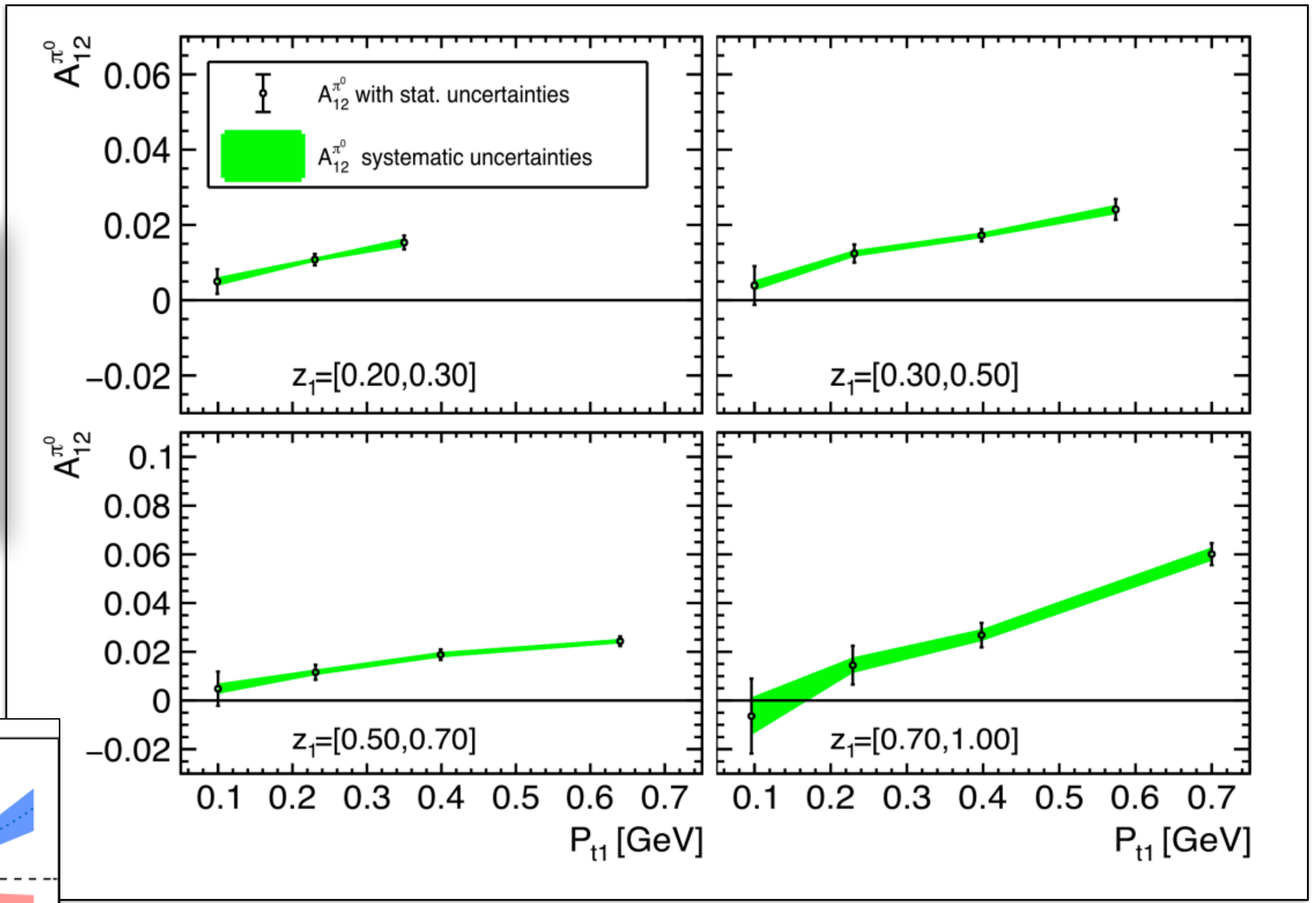
- **Collins effect:** spin-dependent fragmentation of a transversely polarized parton into a final-state hadron → **azimuthal modulations** of hadron yields (thrust or jet axis)
- In pp & SIDIS generated by the coupling of the **Collins FF** to the **transversity PDF**



e+e- annihilation provides cleanest environment to access to Collins FF

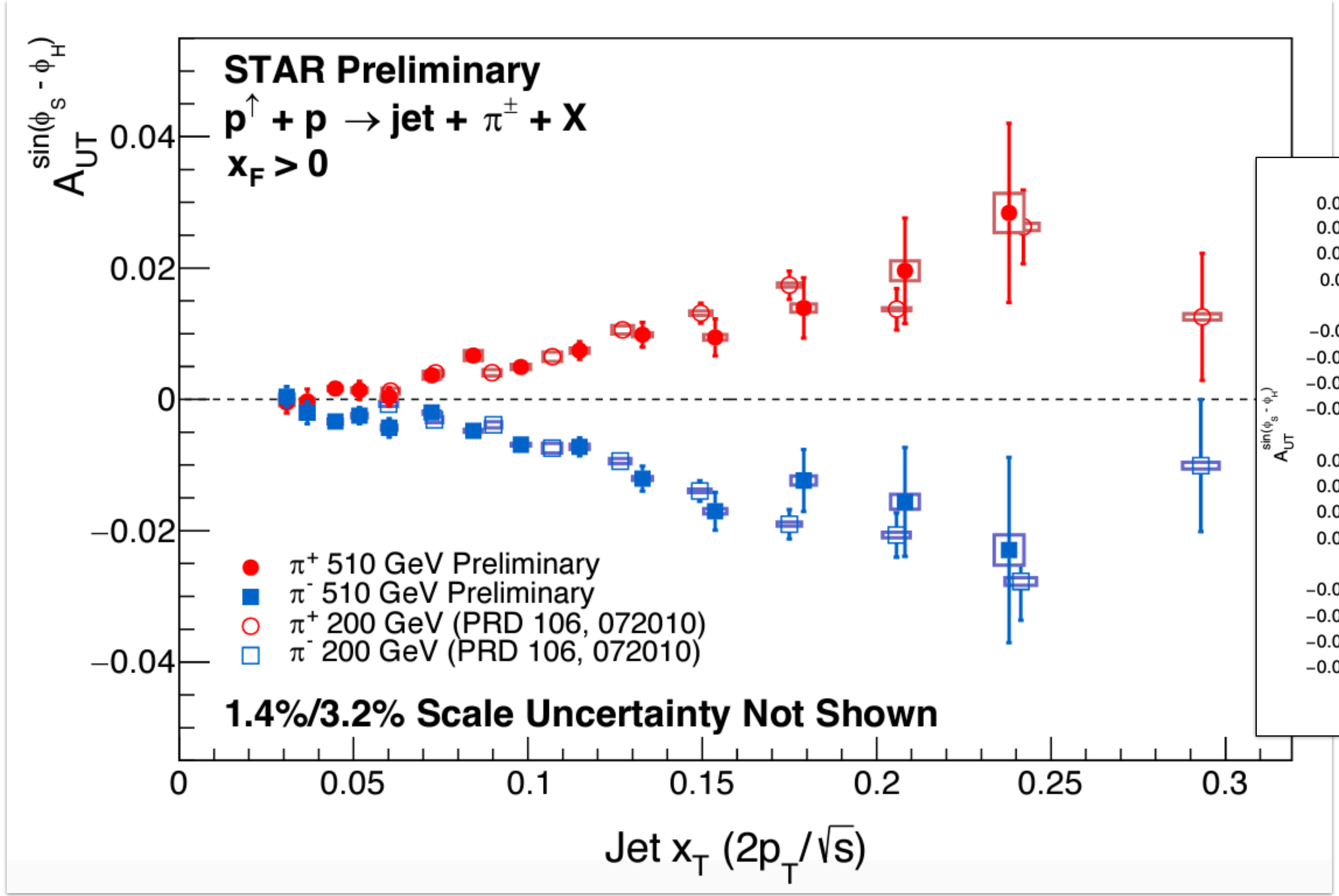
see talk by R. Seidl, Thu am

Belle $e^+e^- \to h_1h_2|_{\text{back-to-back}}X$

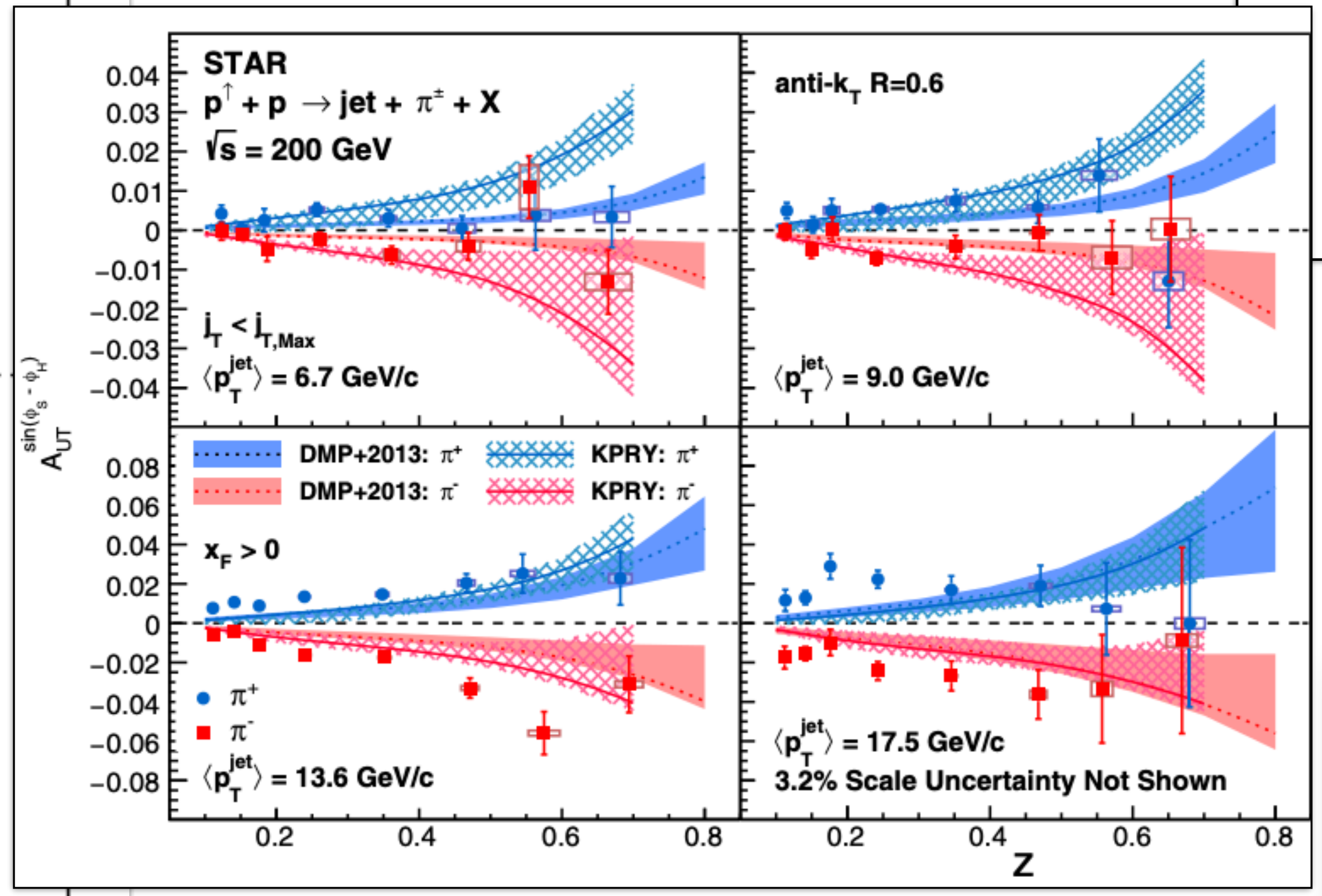


[Belle (H. Li, A. Vossen et al.) PRD 100, 092008 (2019)]

new STAR pp↑→jet h±X (500 GeV midrapidity)



also 500 GeV - [STAR PRD 97, 032004 (2018)]



200 GeV [STAR PRD 106, 072010 (2022)]

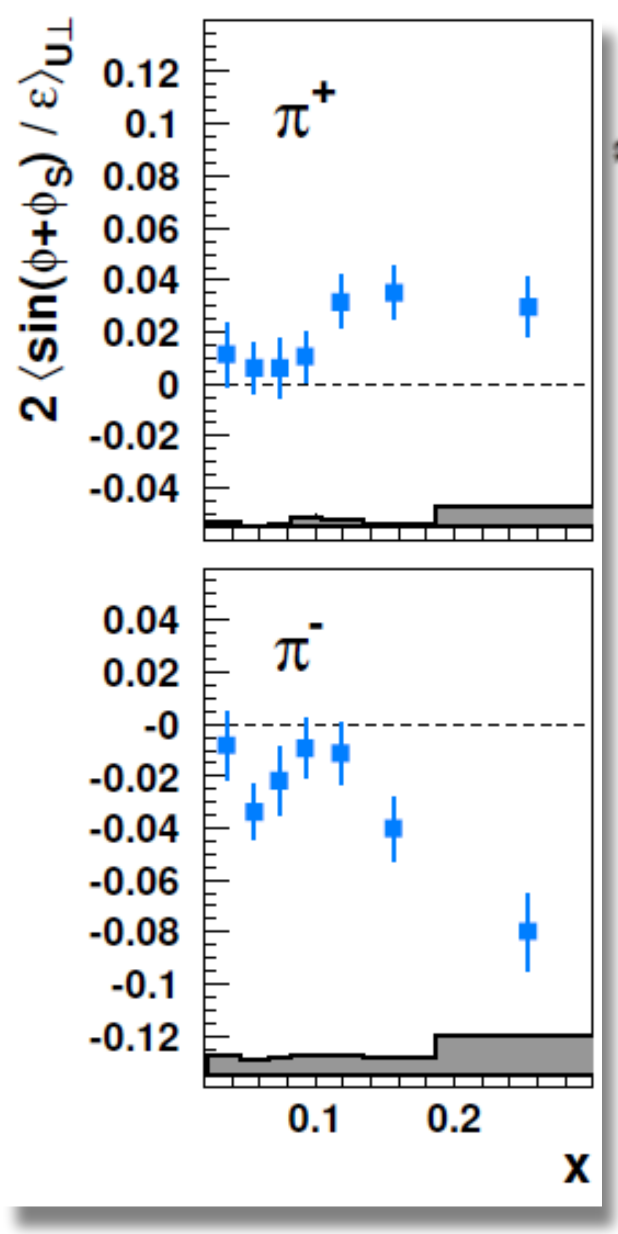
Also kaons and protons

Tests of TMD universality, factorization breaking (texpected for hadronic interactions) and evolution

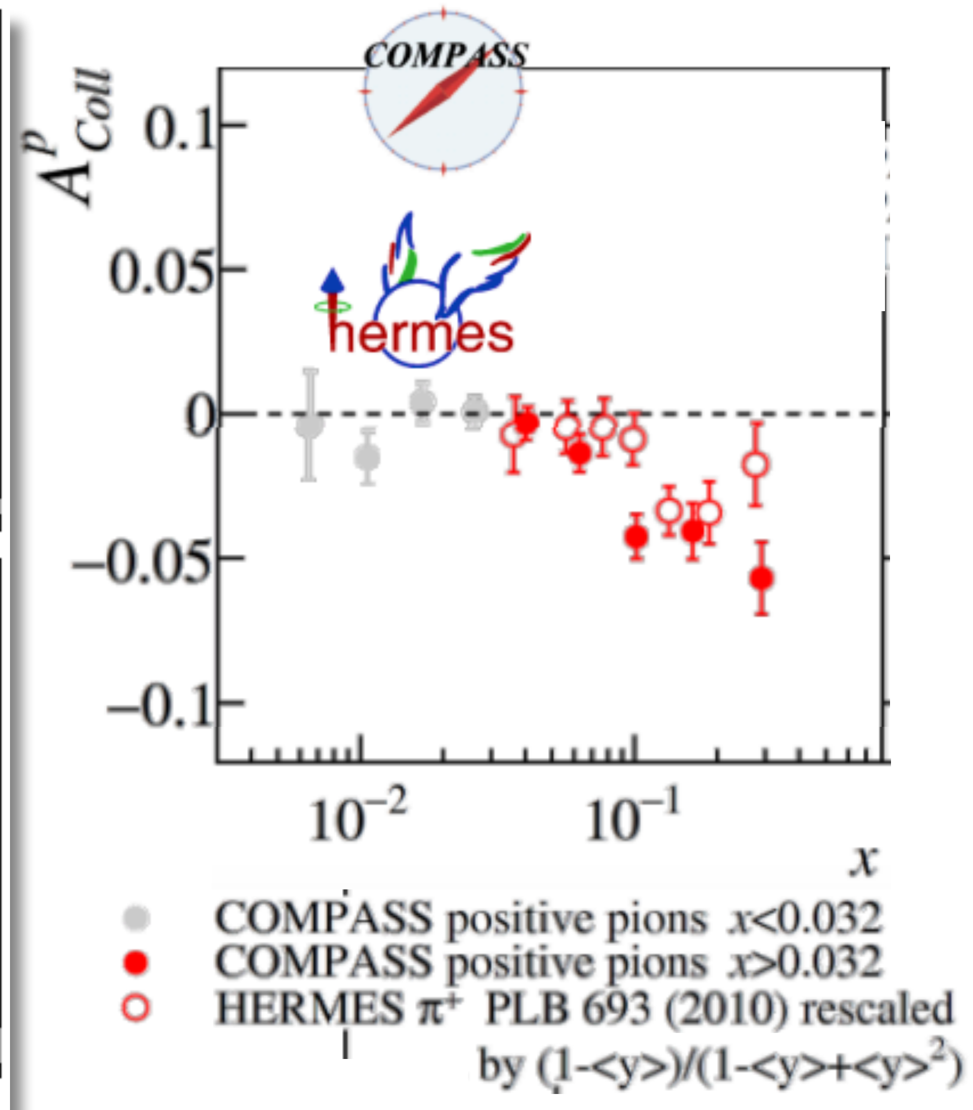
Model curves based on SIDIS & e+e- data assuming Collins factorization & universality
[KPRY, PLB 774, 635 (2017)]
[DMP, PLB 773, 300 (2017)]

Collins asymmetry and transversity TMD PDF in SIDIS

HERMES & COMPASS Collins asymmetries in ℓN↑→ℓh±X



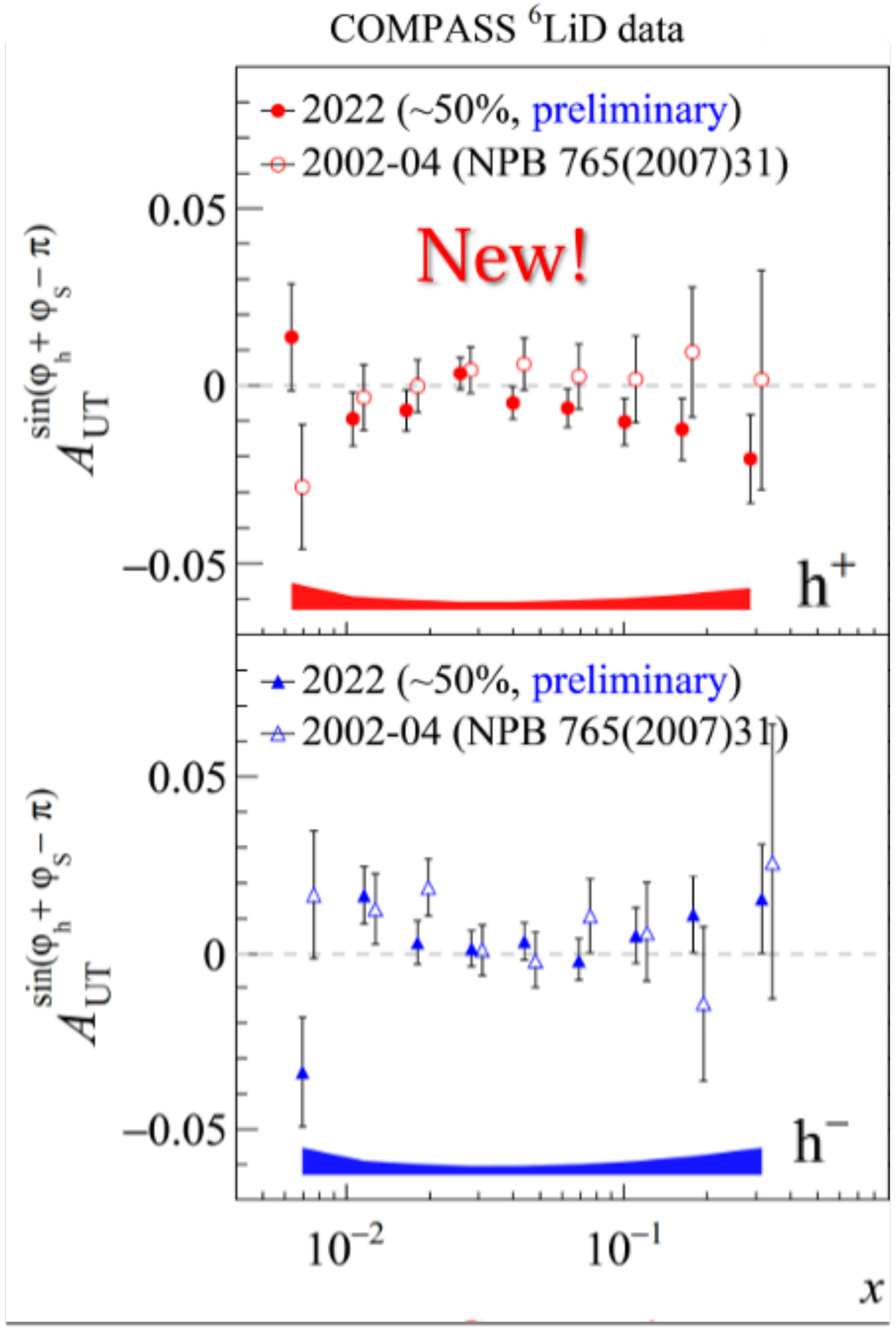
[HERMES JHEP 12 (2020) 010]



[COMPASS PLB 744 (2015) 250]

Mirror symmetry for π^+ & π^- : *u*- and *d*-quark transversity have ~ equal magnitude & opposite signs.

- ***d*-quark transversity PDF less constrained** given the *u*-quark dominance of many of the processes used in the global fits.
  - **Recent COMPASS 2022 transversity run on the deuteron** will improve the experimental precision on the proton's tensor charge, $g_T = \delta_u - \delta_d$, by a factor of ~2.
  - Further prior-to-EIC measurements of Collins asymmetries: STAR with forward upgrade, sPHENIX, SpinQuest, JLab12/SoLID, …
- Alternative method to access transversity: **measure hyperon transverse polarization**, which may have been transferred from struck quark
  - COMPASS and STAR. Hyperon polarization also measured in unpolarized and longitudinally polarized settings at LHCb and CLAS12, resp.



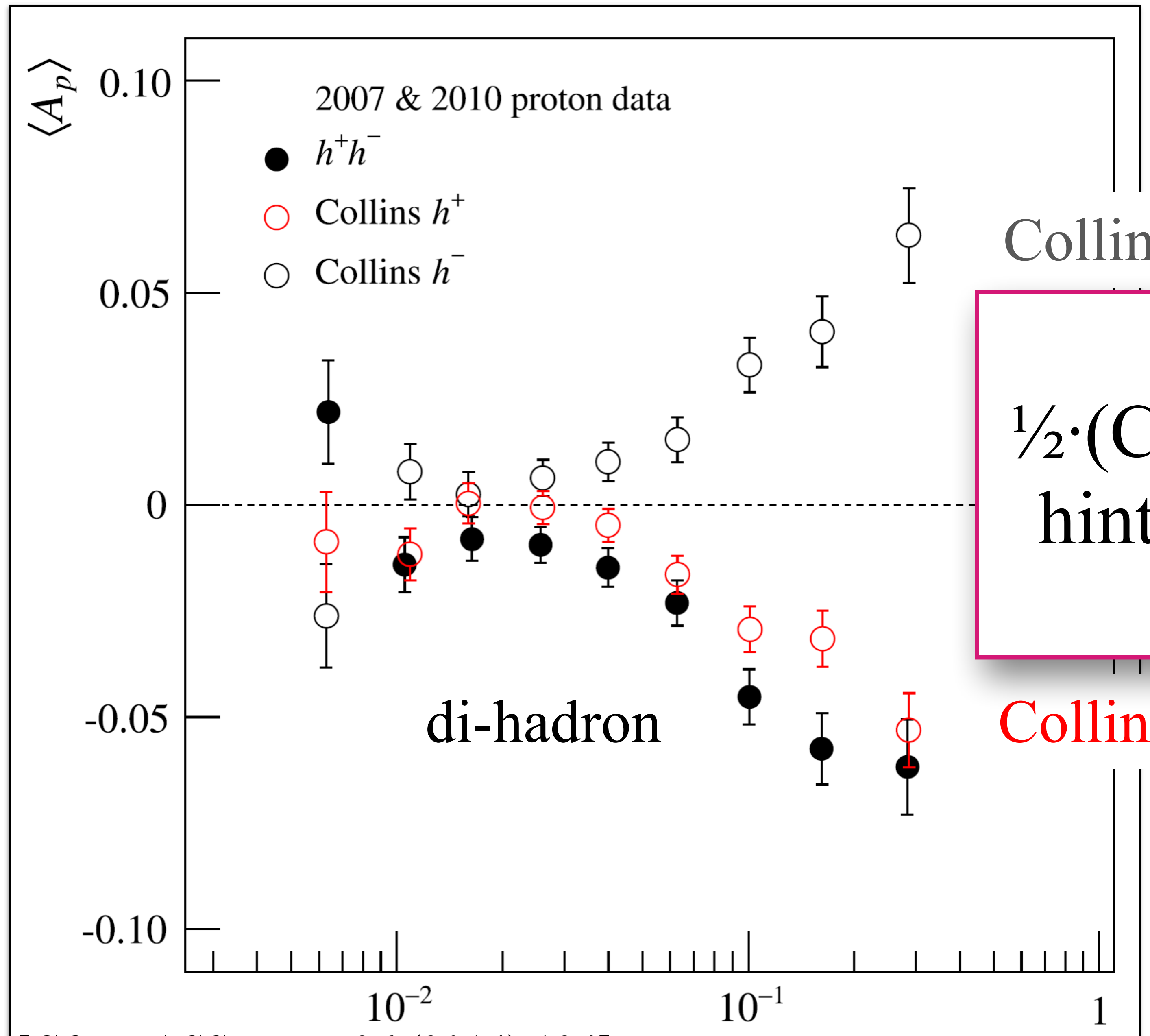
first shown at SPIN 2023 (talk A. Martin for COMPASS)

Di-hadron fragmentation function (h+h-) in pp and SIDIS

Transversity PDF coupled to **interference**, or **di-hadron, fragmentation function** (collinear) in SIDIS & pp as **complementary probe** of **transversity PDF**

& **independent measurement to e+e-**

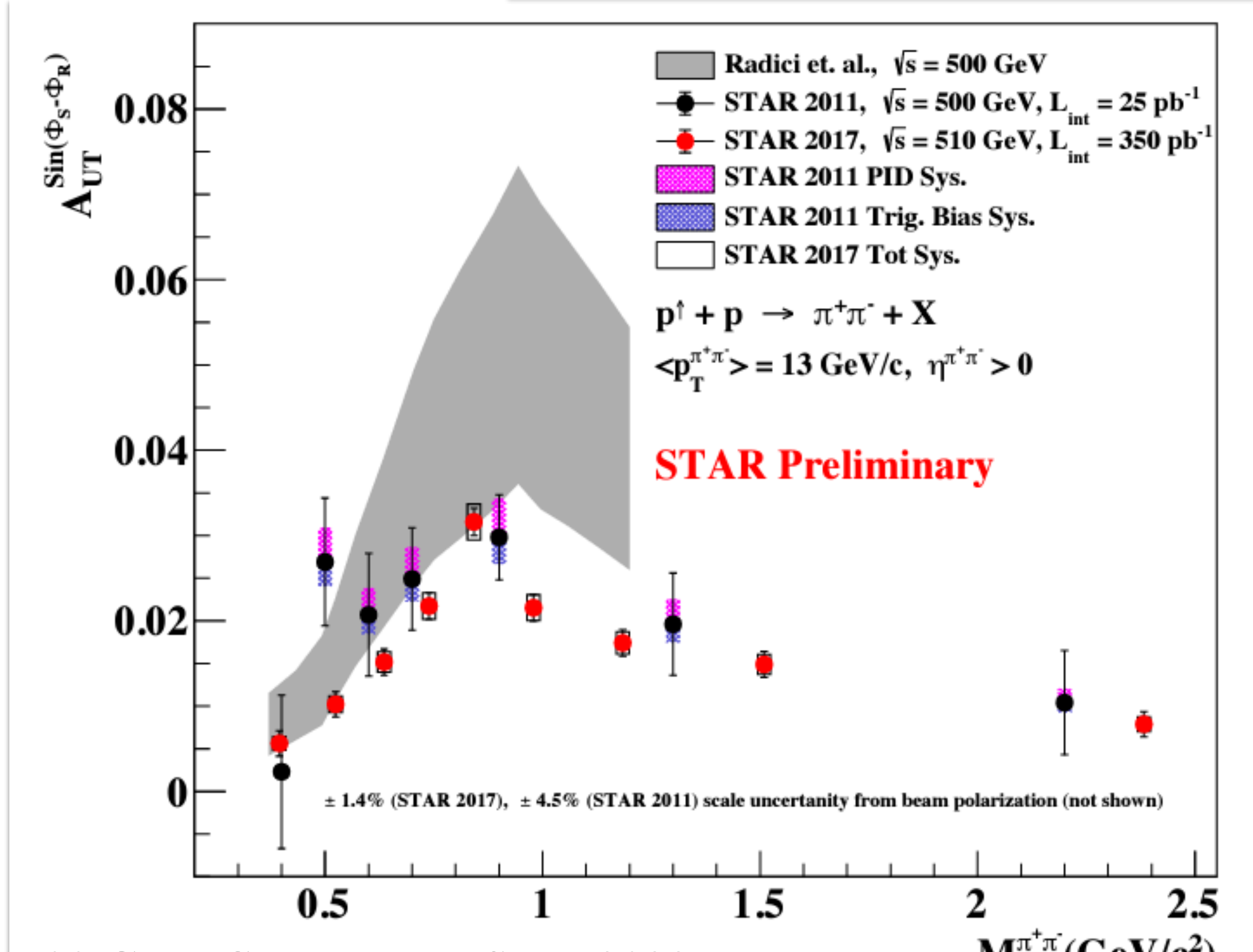
COMPASS di-hadron asymmetry in SIDIS



[COMPASS PLB 736 (2014) 124]

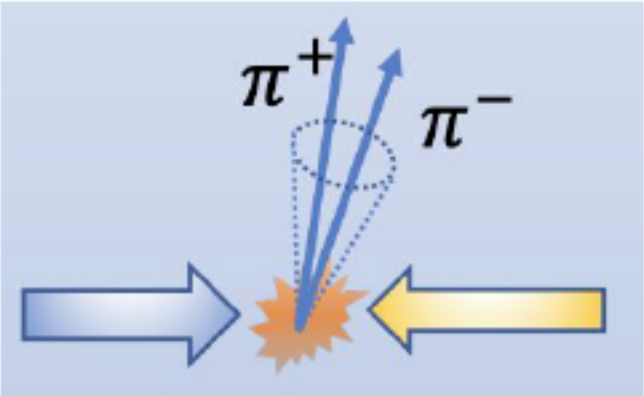
Interference FF ≈ ½·(Collins[h+] + (-1)·Collins[h−]) hints to common physical origin for Collins & IFF

STAR di-hadron asymmetry in pp

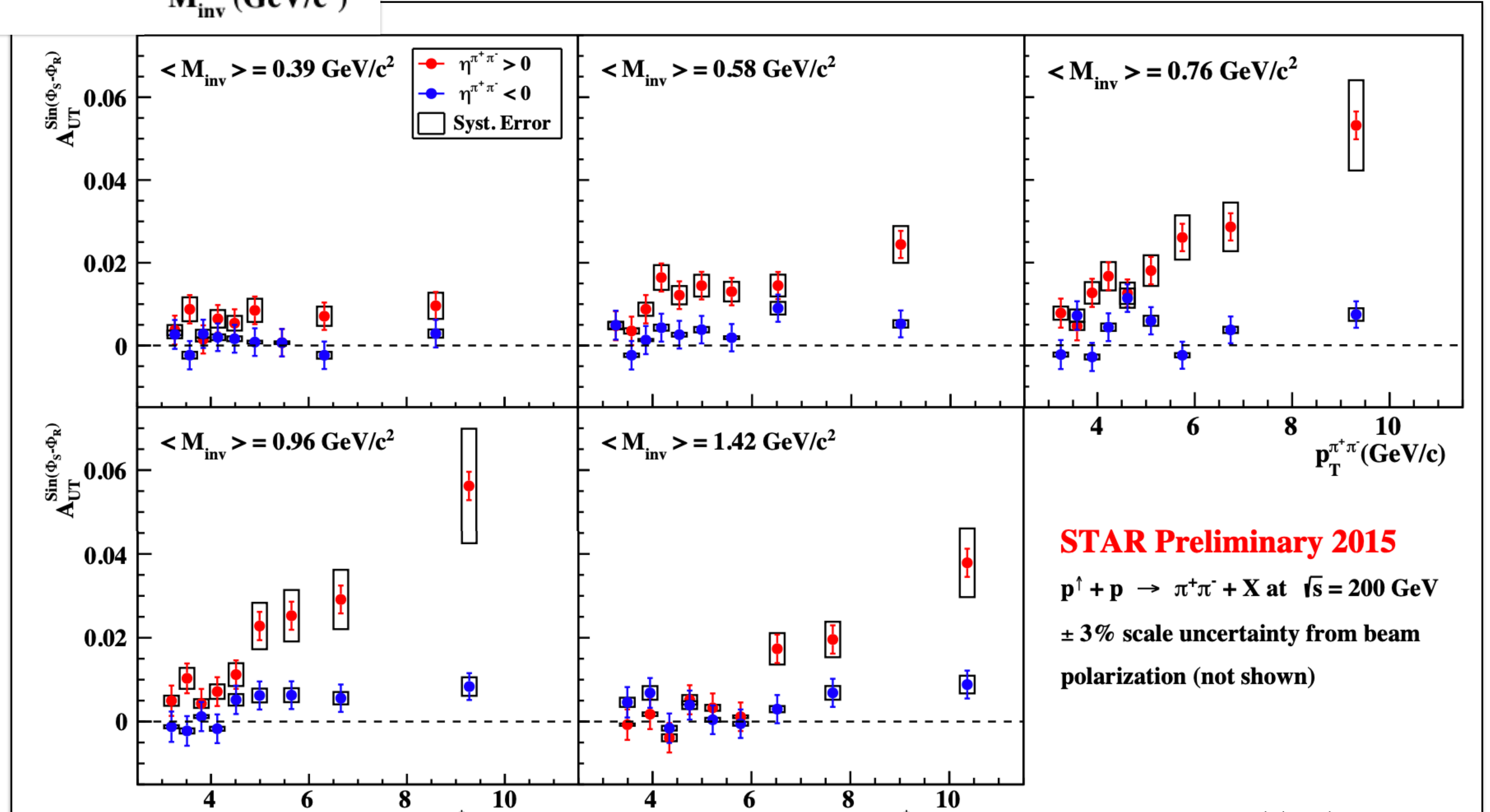


500 GeV: G. Navagyan SPIN 2023

see talk by B. Surrow, Wed pm



- **New** 500 GeV (2017 data) & 200 GeV (2015 data) high-precision results
- Large signal increasing linearly with pT in the forward, small in the backward
- Enhancement of signal around δ mass
- Crucial role in constraining transversity in global fits
- More data on tape & to be taken; kaons → strange quark transversity



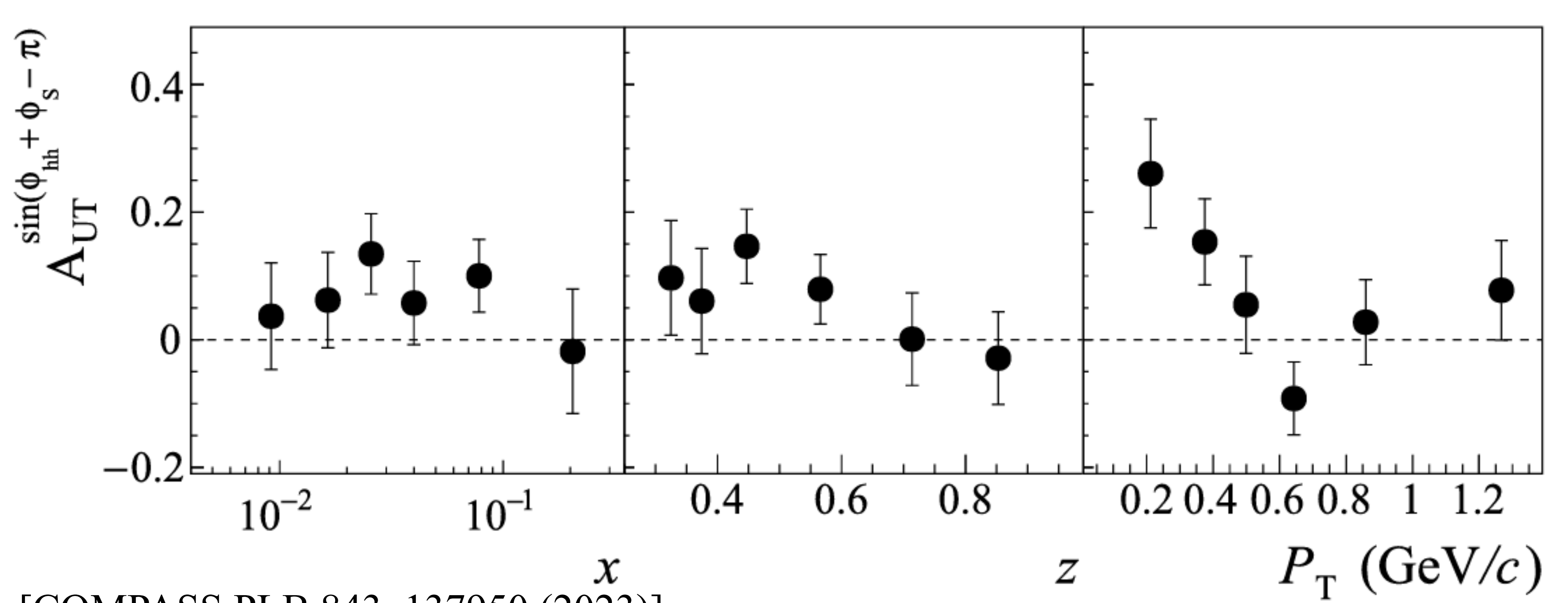
2011 data [STAR PLB 780 (2018) 332]
2006 data [STAR, PRL 115, 242501 (2015)]

200 GeV: B. Pokhrel DIS 2023

Other spin-dependent fragmentation functions in SIDIS

COMPASS Collins asym. in ρ^0 production on p↑

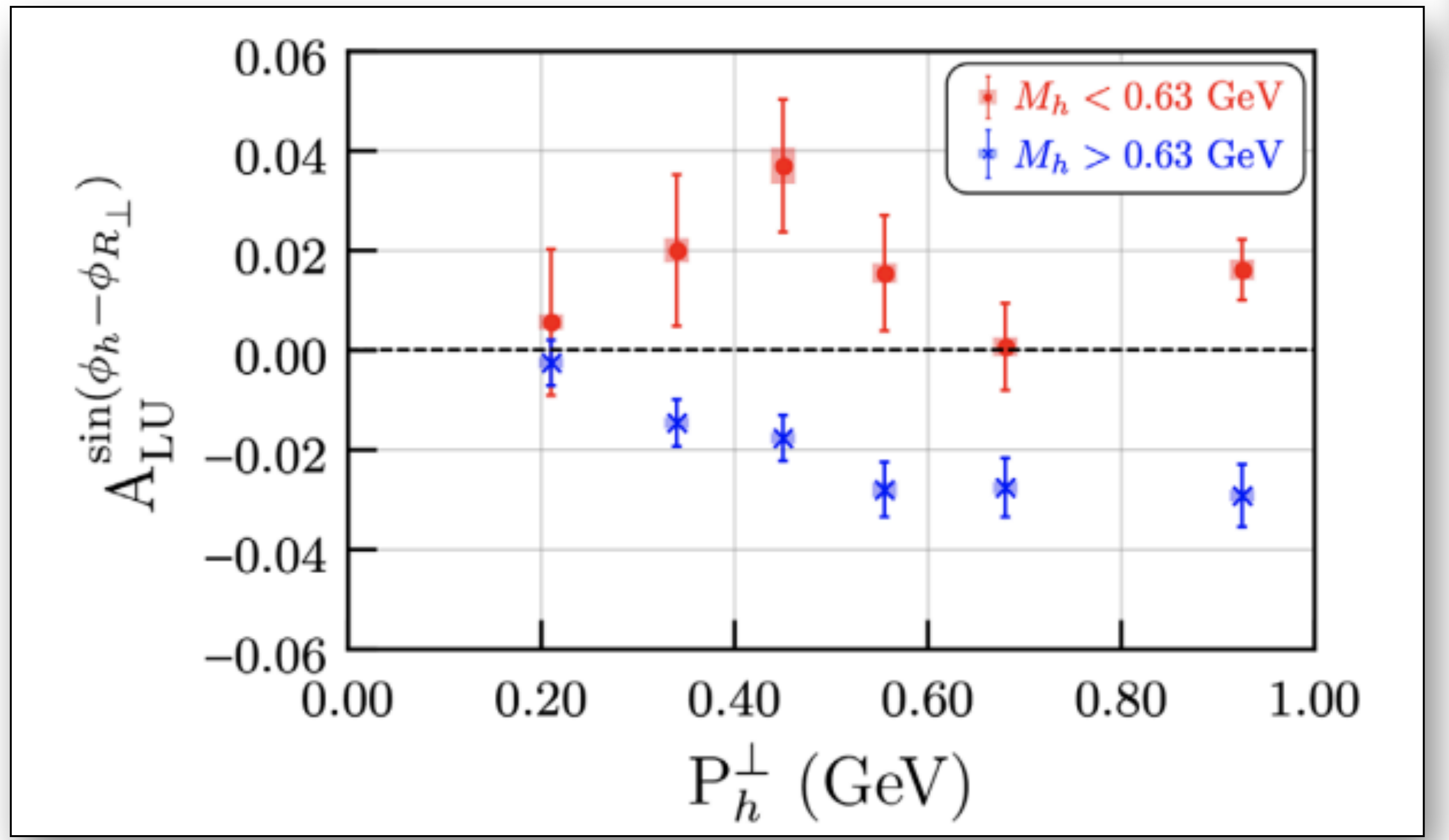
Fragmentation function H_{1LL} describing fragmentation of quarks in vector mesons. Investigate the different Collins mechanisms of spin-1 vector mesons vs. pseudoscalar mesons (ordinary Collins FF).

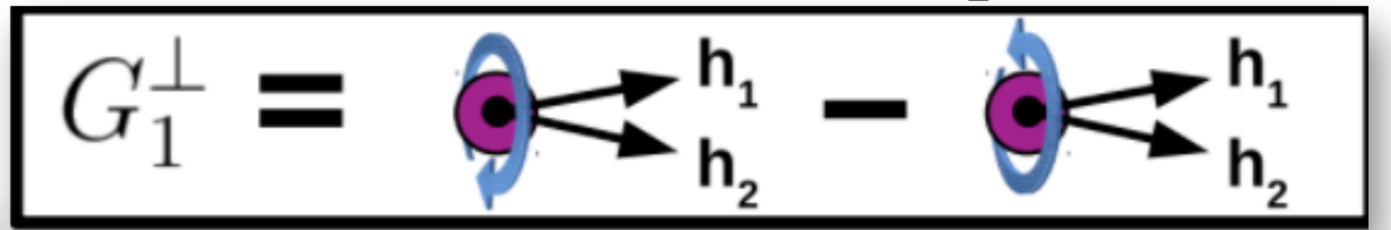


[COMPASS PLB 843, 137950 (2023)]

CLAS & CLAS12 higher-twist di-hadron BSA

First empirical evidence of a nonzero **parton helicity-dependent di-pion fragmentation function** $G^{\perp}_1$: equivalent to the Collins FF for two pions. Coupled to sub-leading twist PDF *e(x)*



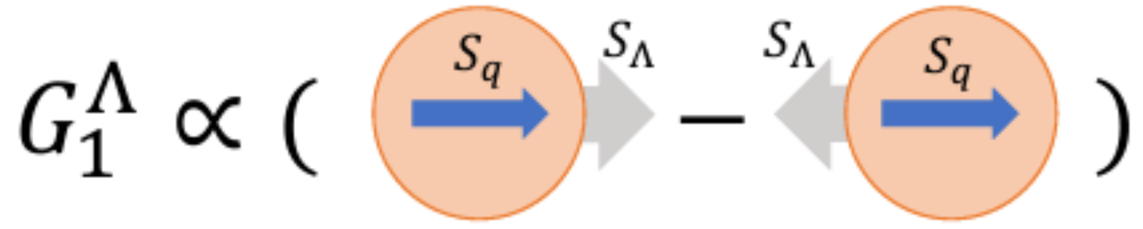


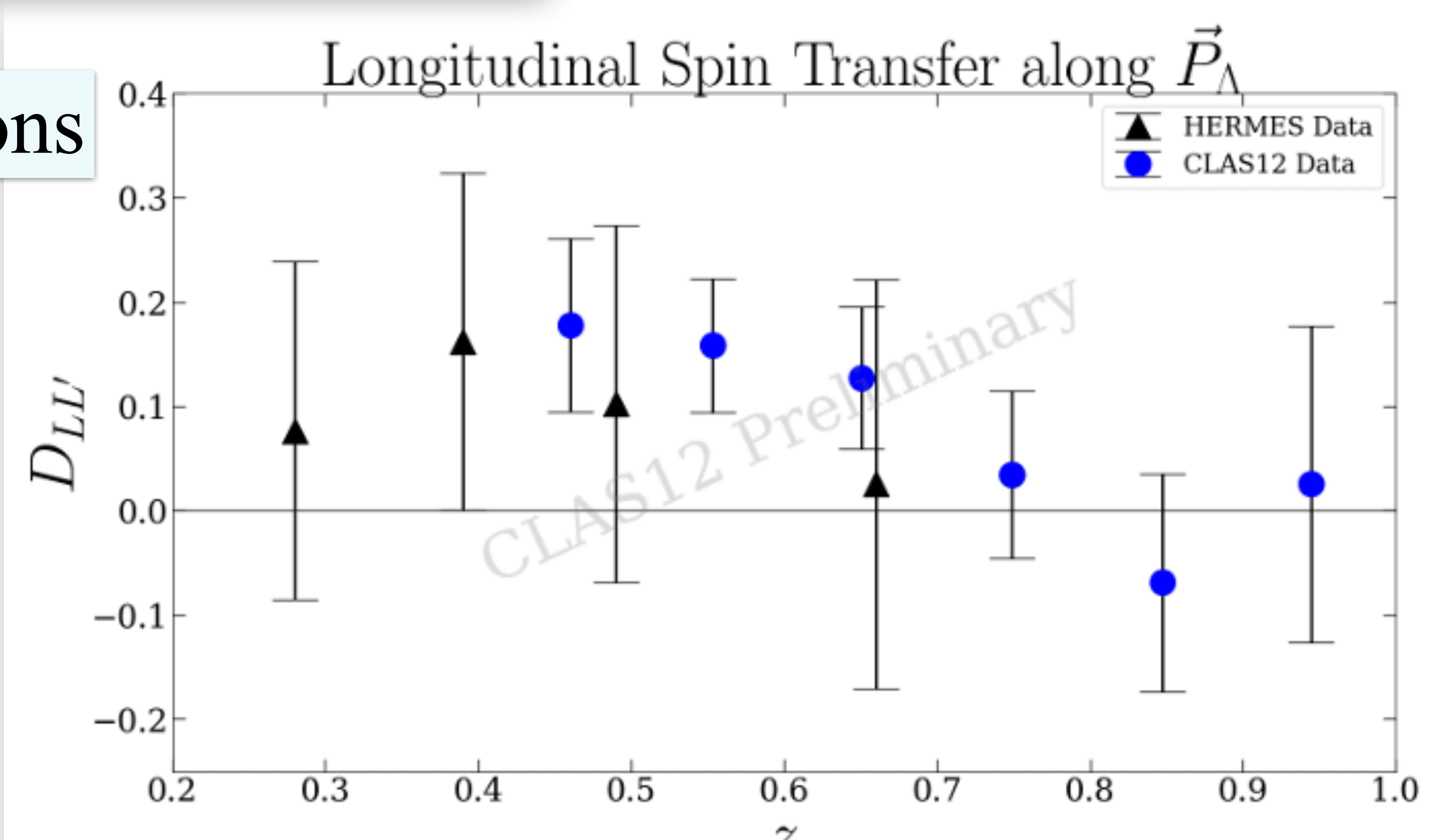
[CLAS12 / T. Hayward PRL 126, 152501 (2021)]

also: [CLAS / M. Mirazita PRL 126, 062002 (2021)]

CLAS12 spin transfer to Λ hyperons

Helicity fragmentation function of the Λ





One analysis example with (planned) application of graph neural networks [M. McEneaney, A. Vossen 2023 JINST 18 P06002]

[CLAS12 / M. McEneaney at SPIN 2023]

More higher twist… & fracture functions at JLab

CLAS(12), HERMES and COMPASS **HT single-hadron SIDIS beam-spin asymmetries** - sizeable recent asymmetries from unpolarized target and longitudinally polarized lepton beam [backup].

Fracture functions ↔ target fragmentation region: final-state hadrons also form from the left-over target remnant, the partonic structure of which is defined by fracture functions. Complementary approach to understand SIDIS production [T. Hayward, H. Avakian at SPIN 2023].

Outline - Probing nucleon spin structure

☑ Introduction

- ☑ Longitudinal DIS, structure functions, & PDFs
- ☑ Spin-polarized experiments
- ☑ Proton spin puzzle & hadron tomography

☑ TMDs

- ☑ Nucleon TMD structure and spin-orbit correlations
- ☑ TMD universal description
- ☑ Sivers TMD PDF in SIDIS and modified universality
- ☑ Gluon correlators & Sivers TMD PDF
- ☑ Sivers effect in di-jet production
- ☑ Collins FF in ee and Collins asymmetry in pp & SIDIS
- ☑ Di-hadron fragmentation function in pp and SIDIS
- ☑ Other spin-dependent fragmentation functions in SIDIS

☐ GPDs

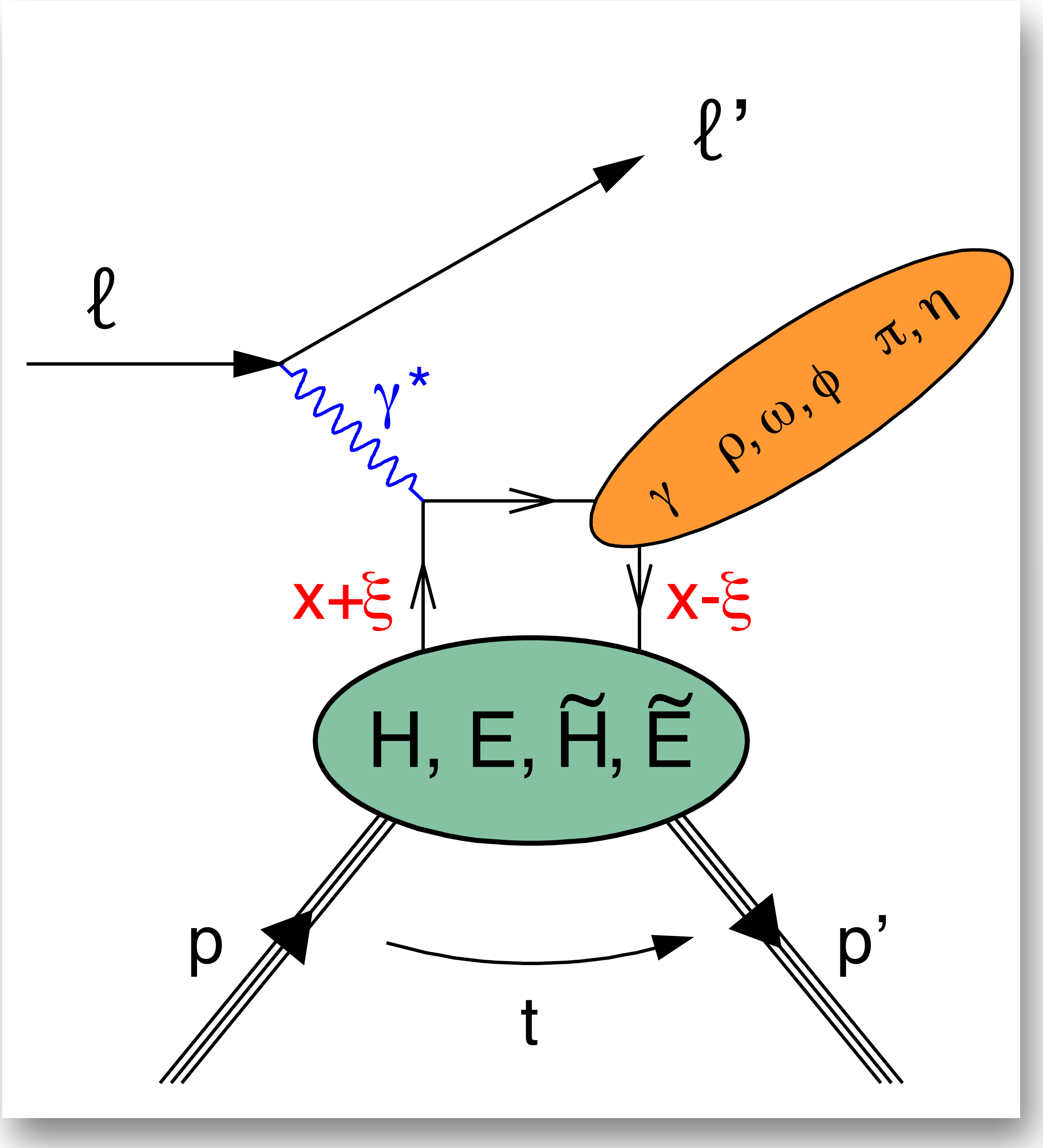
- ☐ Hard exclusive reactions
- ☐ Chiral-even GPDs & DVCS asymmetries
- ☐ Exploring Compton form factors
- ☐ Parton orbital angular momentum & gluon GPDs
- ☐ Chiral-odd GPDs & vector mesons
- ☐ Transition DAs & transition GPDs

☐ Outlook & summary

Hard exclusive reactions

From HERMES & JLab-6 & HERA to COMPASS & JLab12 & RHIC to the EIC

exclusive measurement = detection of entire final state (or assumed to be known)



$\ell p \to \ell p \gamma$

Deeply Virtual Compton Scattering (DVCS)

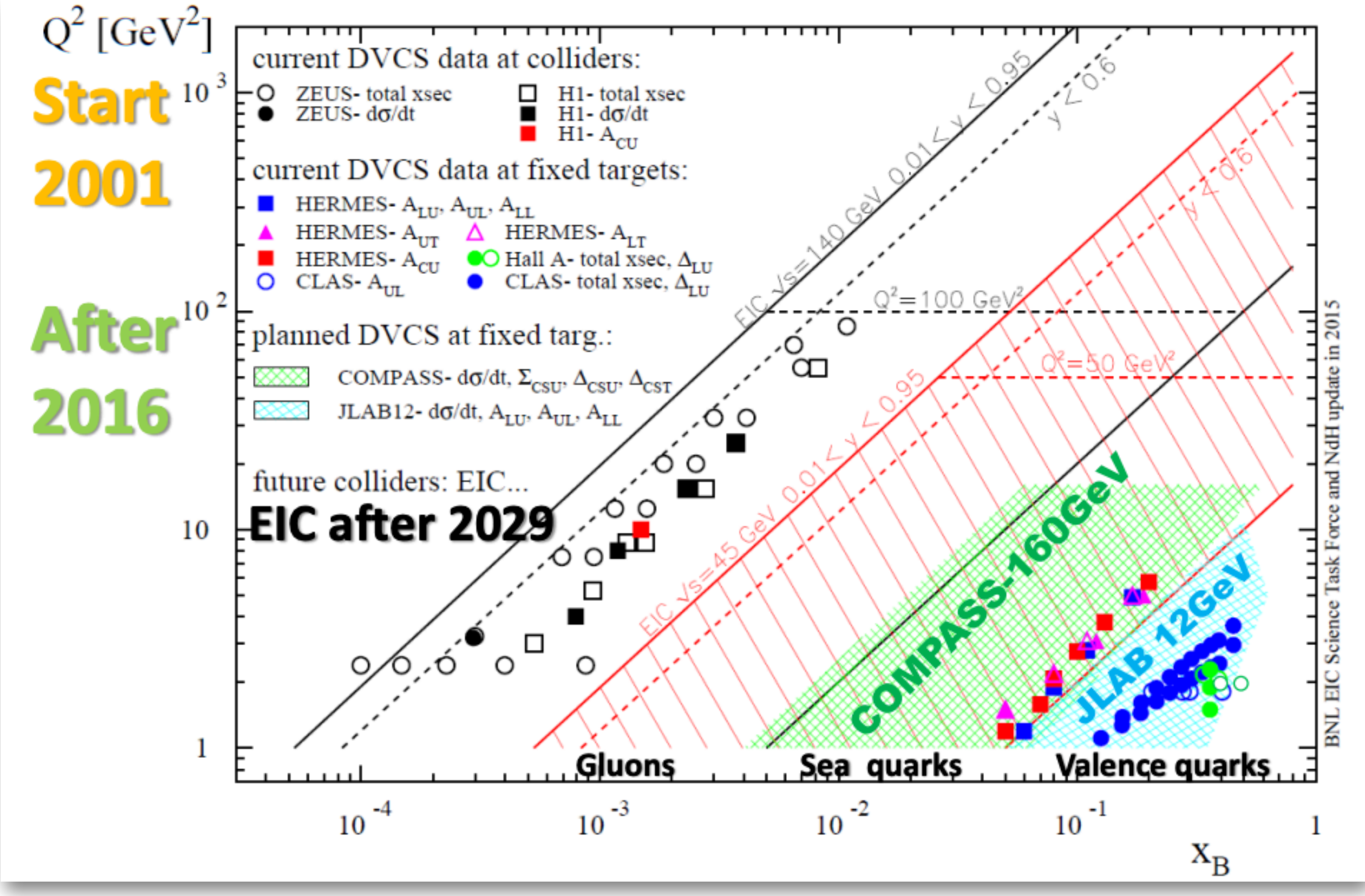
$\ell p \to \ell p M$

Deeply Virtual Meson Production (DVMP)

Standard channels to access generalized parton distributions

Different exclusive final-state particles allow probing different GPDs

4 chiral-even (conserve quark helicity)
4 chiral-odd GPDs (flip quark helicity)
→ connection with chiral-odd TMDs



x, ξ: longitudinal momentum fractions of probed quark
- **skewness $\xi \simeq x_B / (2-x_B)$** in Bjorken limit (Q^2 large & x_B, t fixed)
- **average mom. x: mute variable**, not accessible in DVCS & DVMP (is not x-Bjorken)

t: squared 4-momentum transfer to target

@leading twist for a spin-½ target

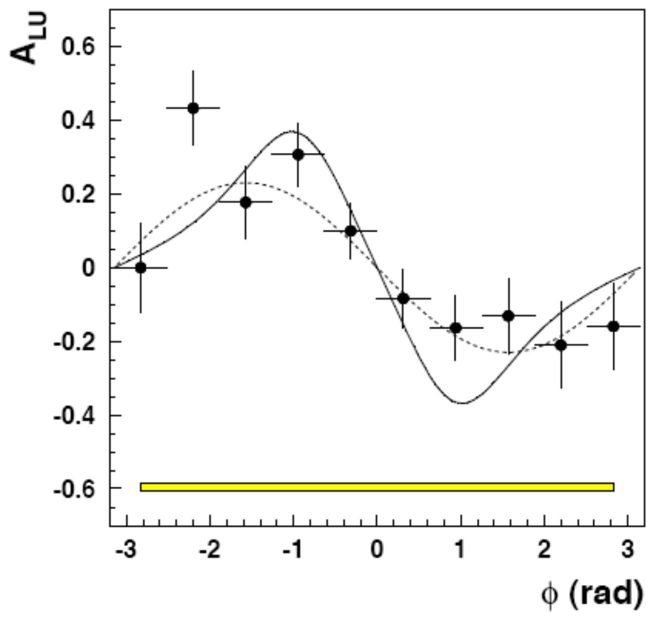
GPD	flips nucleon helicity	conserves nucleon helicity	forward limit $\xi \to 0$, $t \to 0$		
does not depend on quark helicity	**E**	**H**	→ $F_1(x)$	$J^P=1^-$ vector mesons	$J^P=1^-$ photon (DVCS)
depends on quark helicity	**Ẽ**	**H̃**	→ $g_1(x)$	$J^P=0^-$ pseudoscalar mesons	

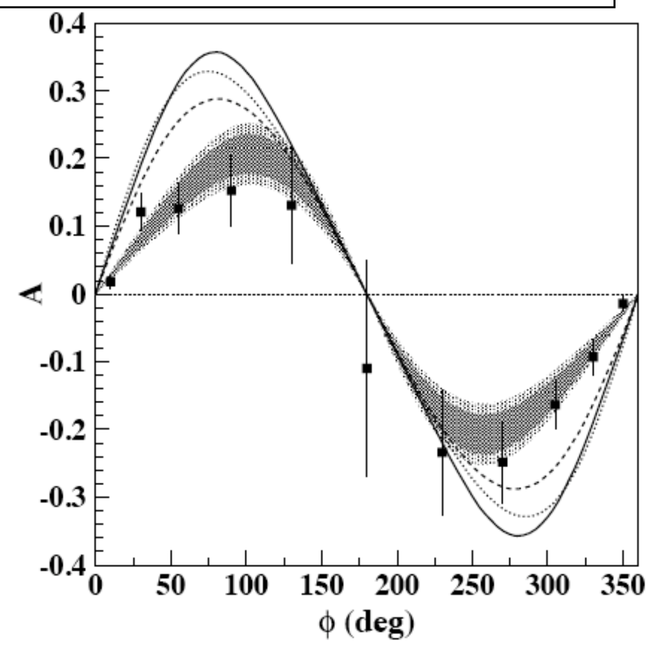
Chiral-even GPDs from deeply virtual Compton scattering (DVCS)

GPDs at JLab - E. Voutier, Thu am | DVCS at CLAS12 - A. Hobart, Wed pm

How it started…

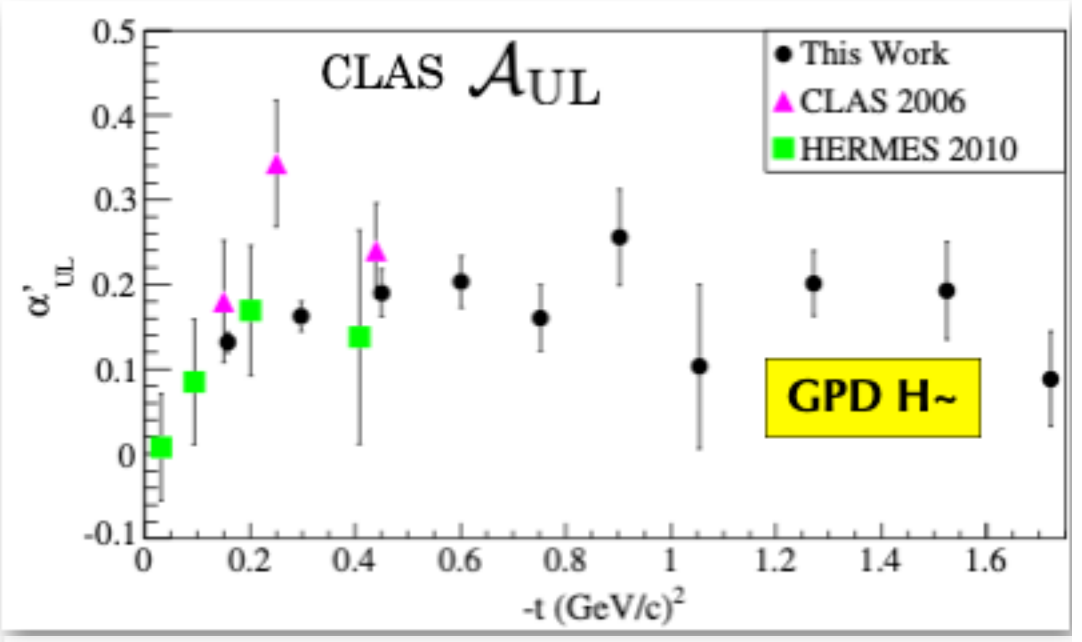
First beam spin asymmetries in 2001 at HERMES and CLAS

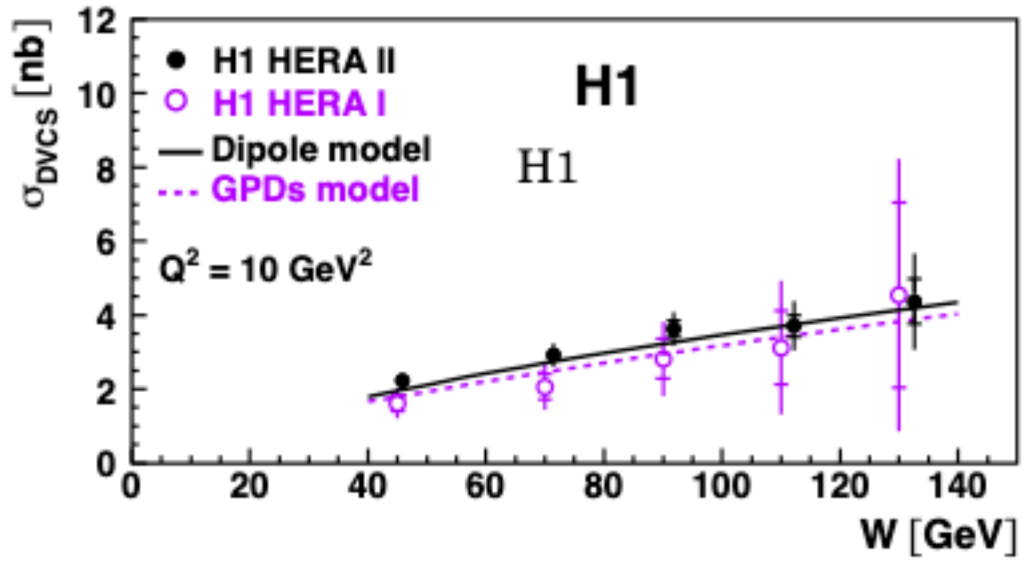


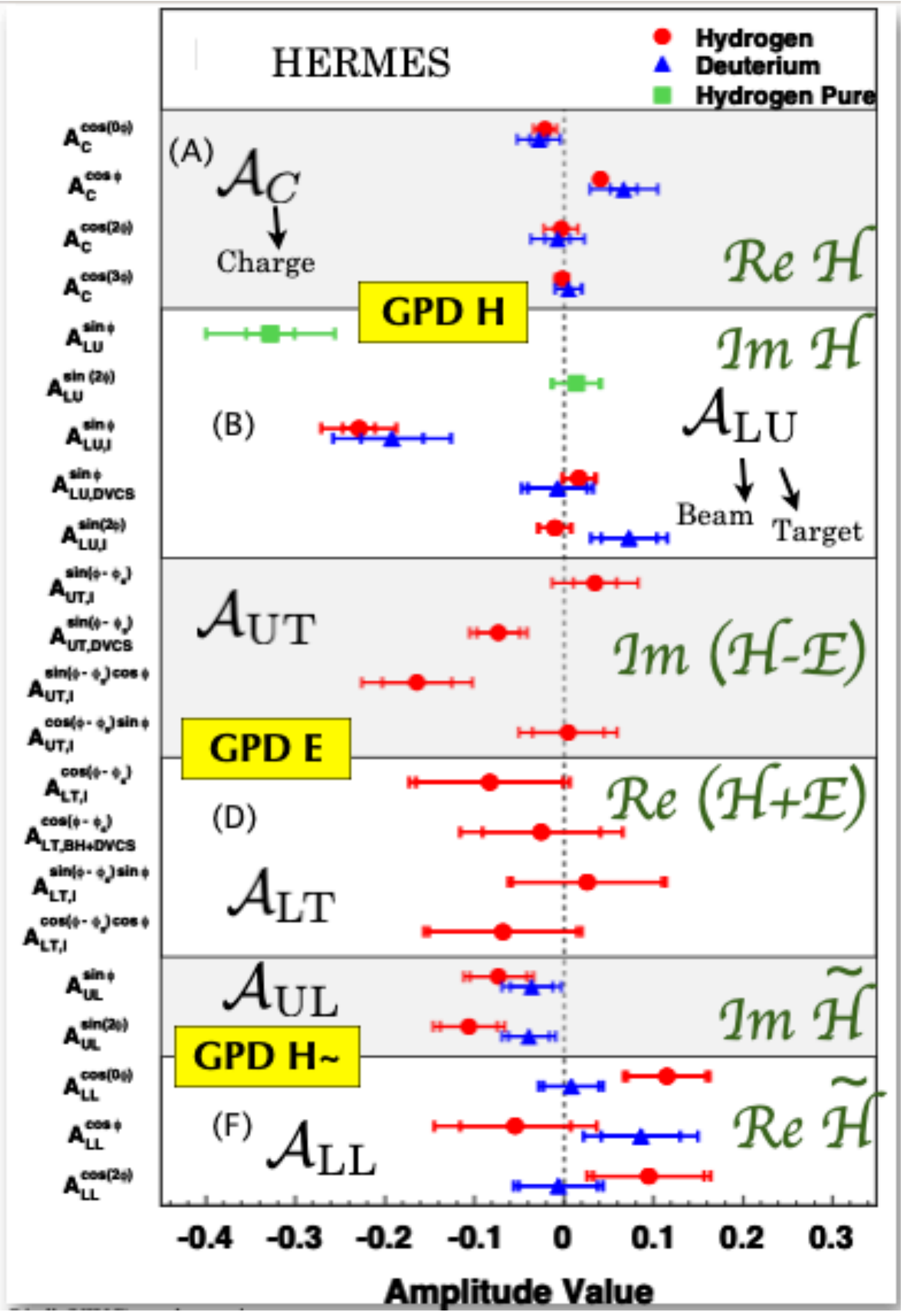


…how it evolved…

Azimuthal asymmetry amplitudes with respect to beam spin or beam charge or target spin, and cross sections

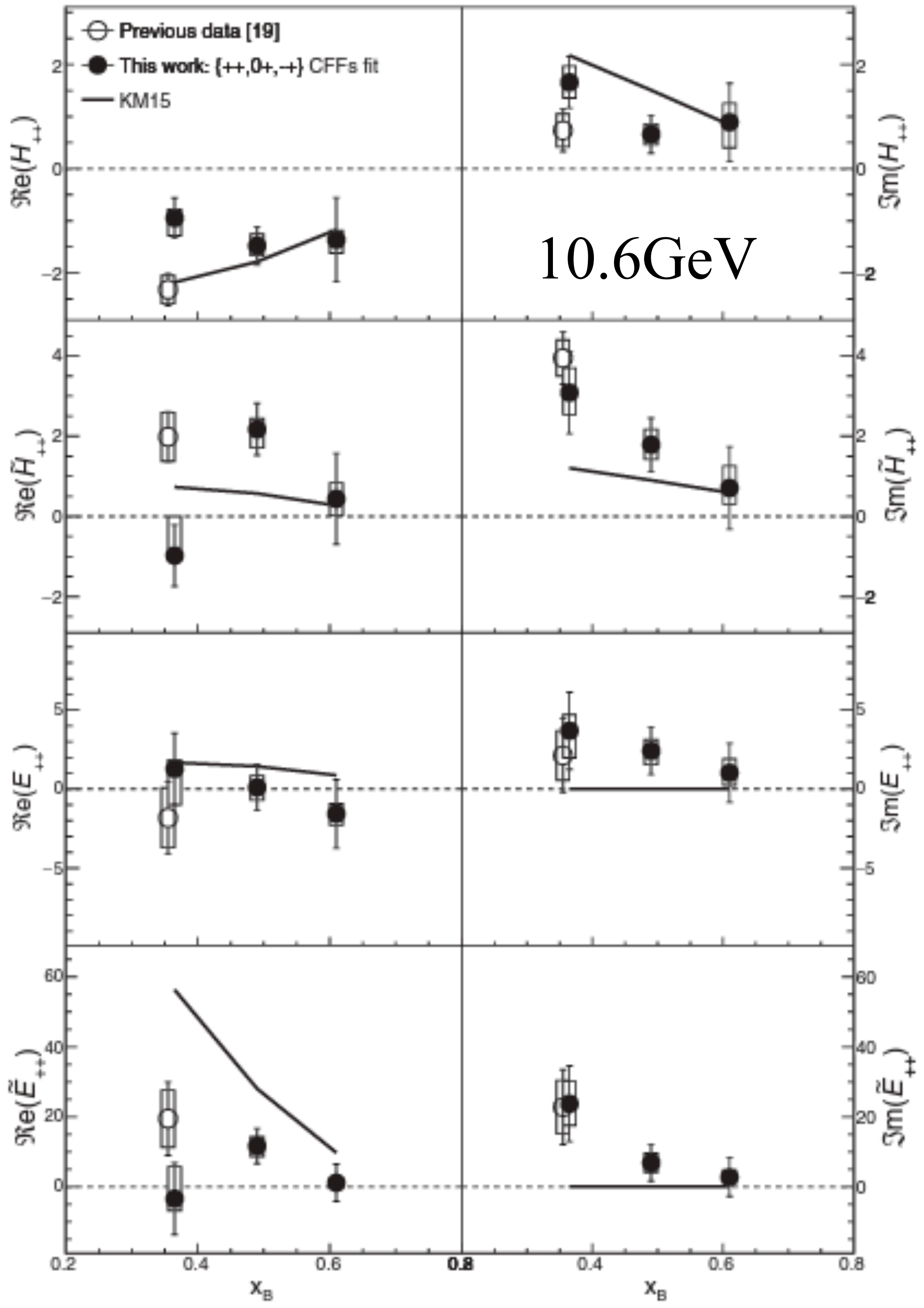






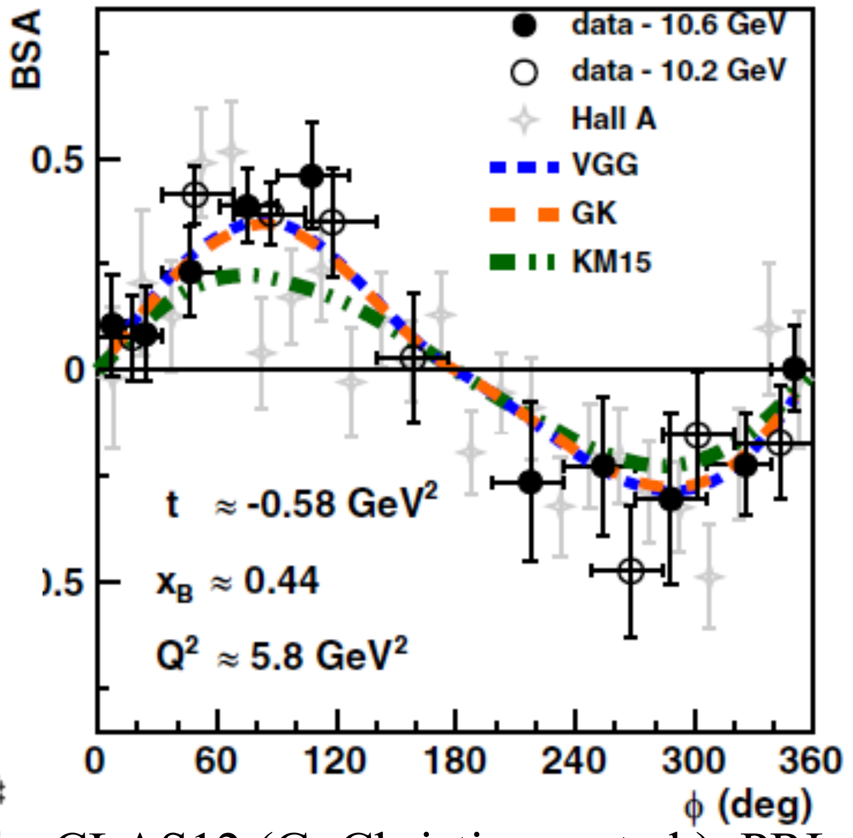
… and how it is going nowadays

Hall A high-precision extraction of Compton form factors from cross sections



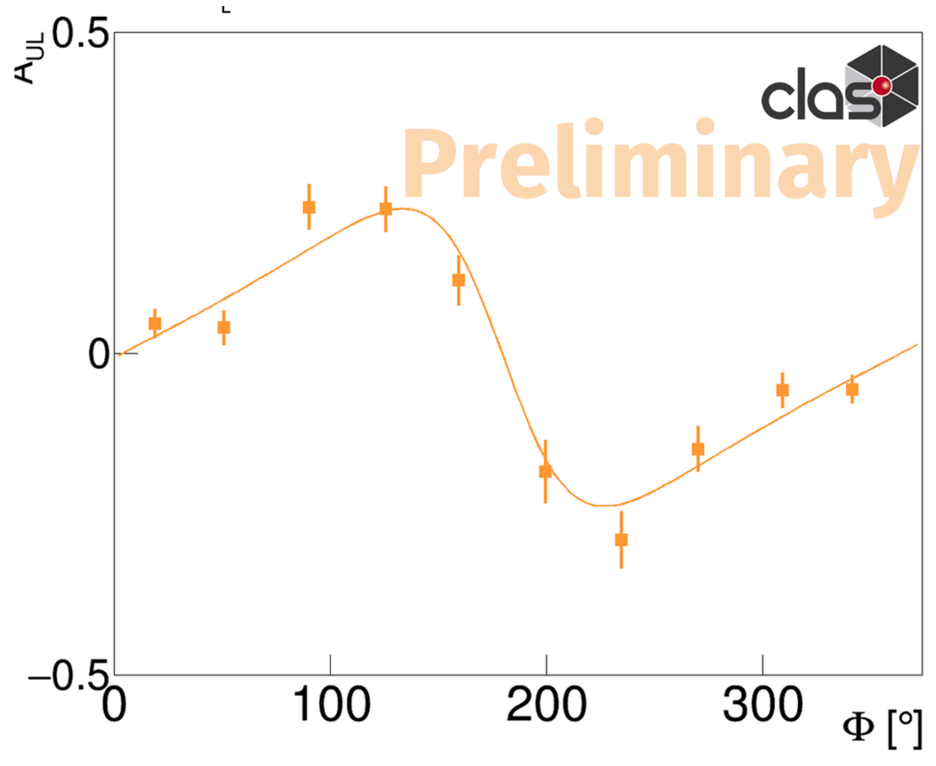
Hall A Collaboration (F. Georges et al.), PRL **128**, 252002 (2022)

CLAS 12 beam-spin asymmetry in the extended valence region

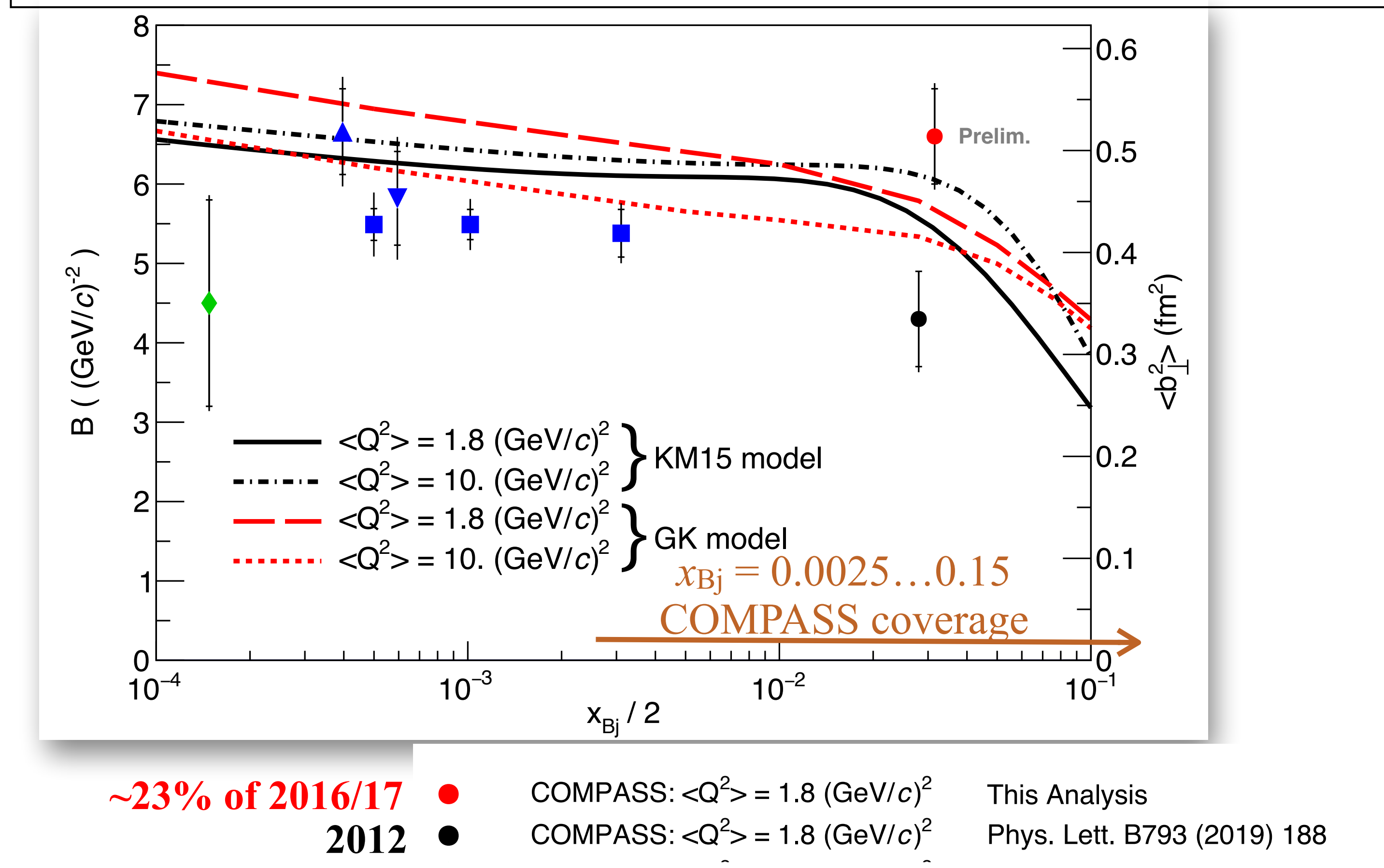


CLAS12 (G. Christiaens et al.), PRL **130**, 211902 (2023)

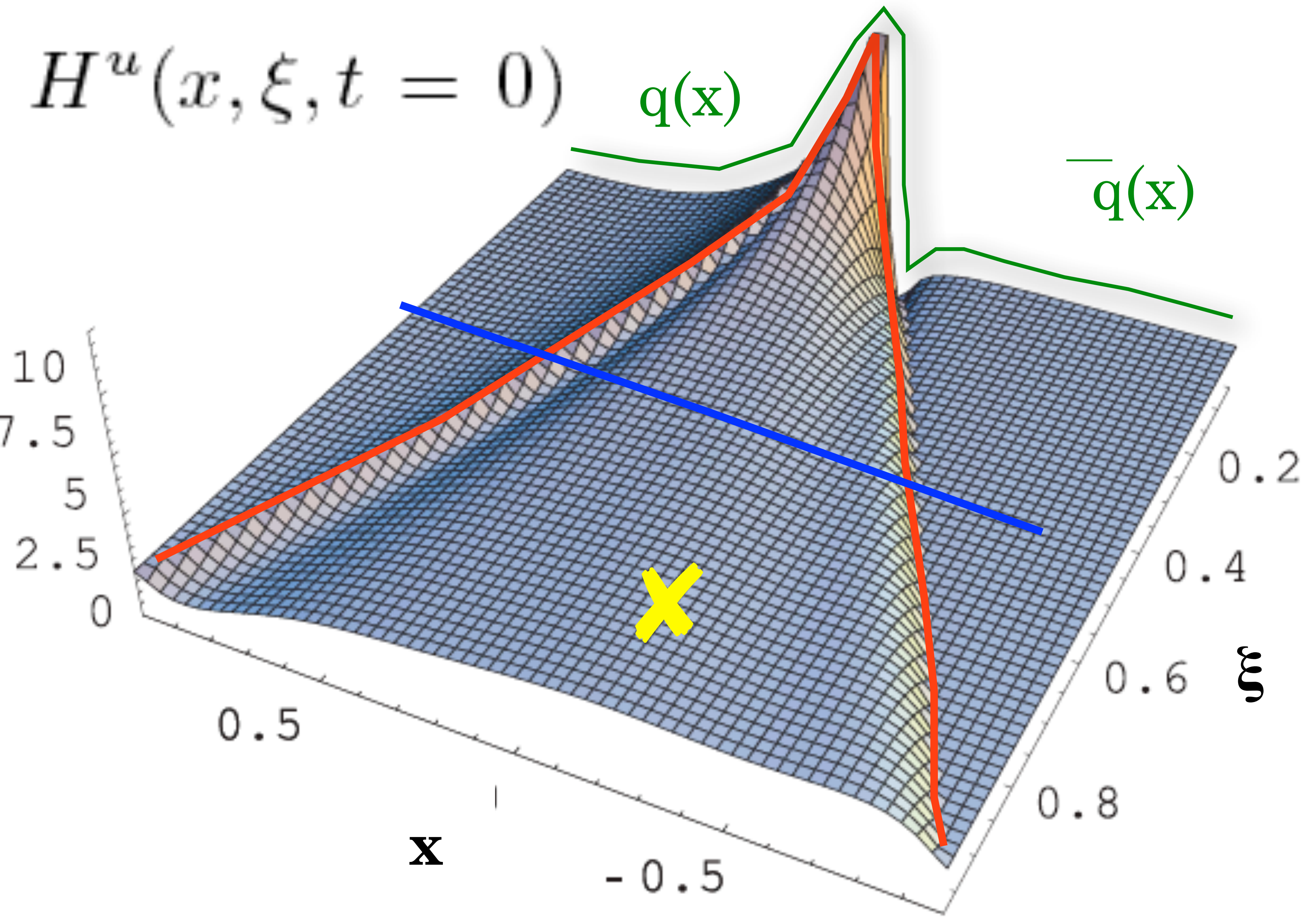
CLAS12 new longitudinal target spin asymmetry



COMPASS t-differential cross section & t-slope to probe transverse extension of partons



DVCS: Compton form factors ↔ GPDs



Im(τ$_{\text{DVCS}}$)
x*=*ξ

Re(τ$_{\text{DVCS}}$)
integral over *x*

Im(τ$_{\text{DVCS}}$)
|*x*|<*ξ*
DDVCS

In DVCS, the experimentally accessed quantity is a complex **Compton Form Factor:**

$$\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x\, \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t)$$

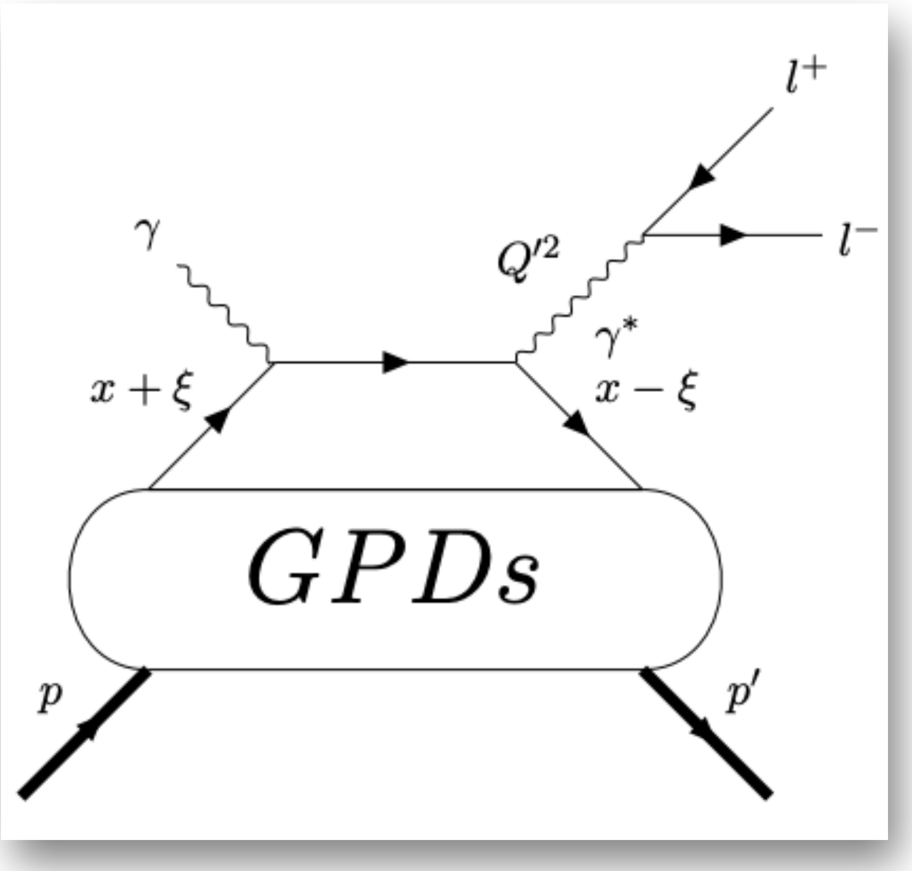
COMPASS DVCS asymmetries

$\mathrm{d}\sigma^{\overset{+}{\leftarrow}} - \mathrm{d}\sigma^{\overset{-}{\rightarrow}}$ $\quad$ $\mathrm{d}\sigma^{\overset{+}{\leftarrow}} + \mathrm{d}\sigma^{\overset{-}{\rightarrow}}$ (analysis in progress)

CLAS12 TCS 1st ever measurement

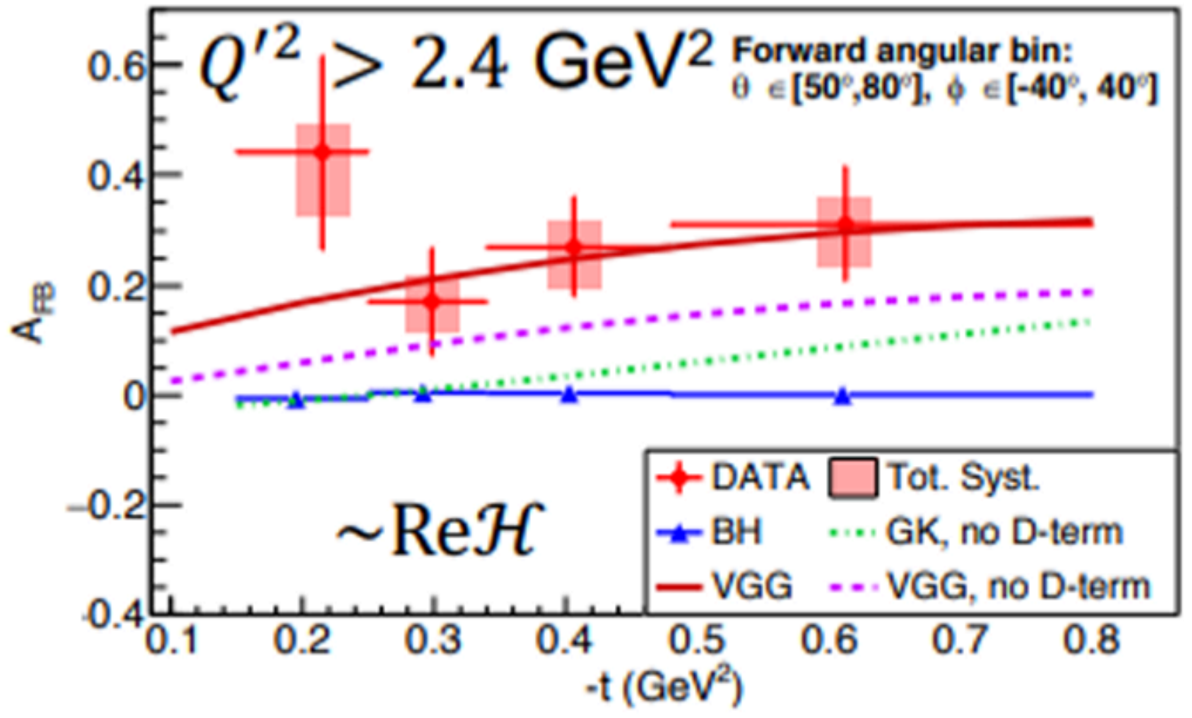
forward-backward asymmetry

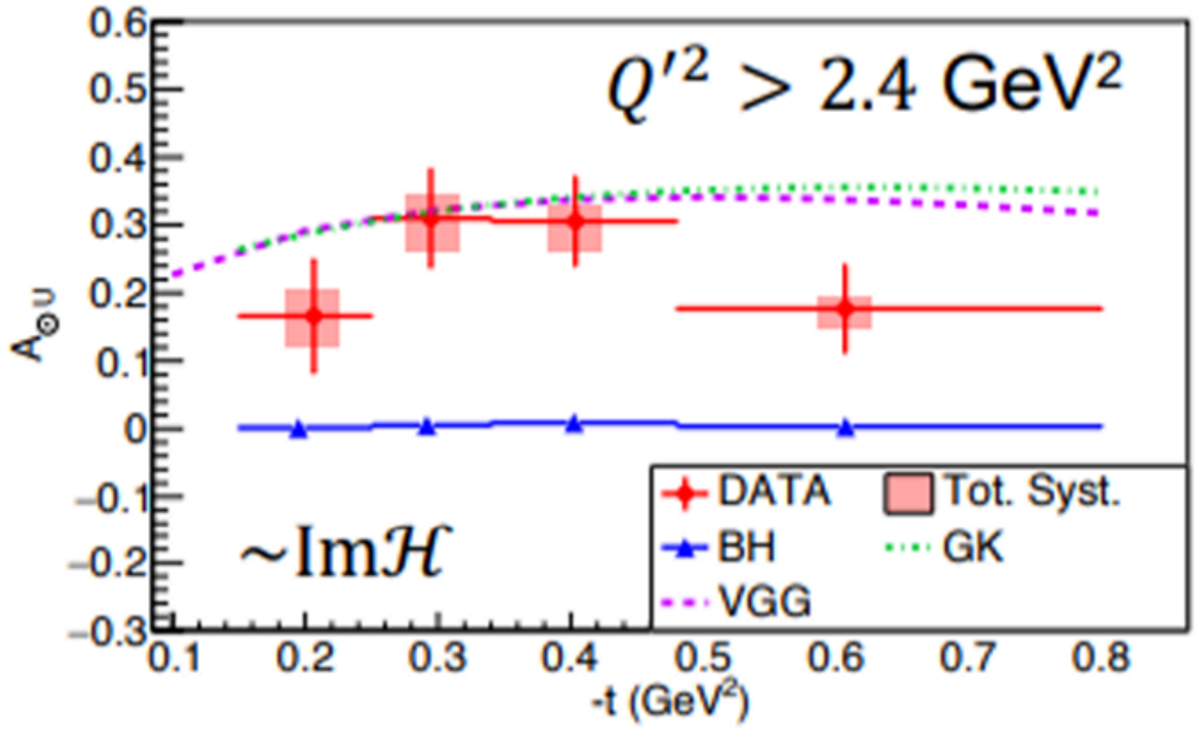
photon circular polarization asymmetry



time-like Compton scattering, **TCS** = time-reversal symmetric process of DVCS.

CLAS12 (P. Chatagnon et al.), PRL **127**, 262501 (2021)





Exploring Compton FFs & gravitational FFs

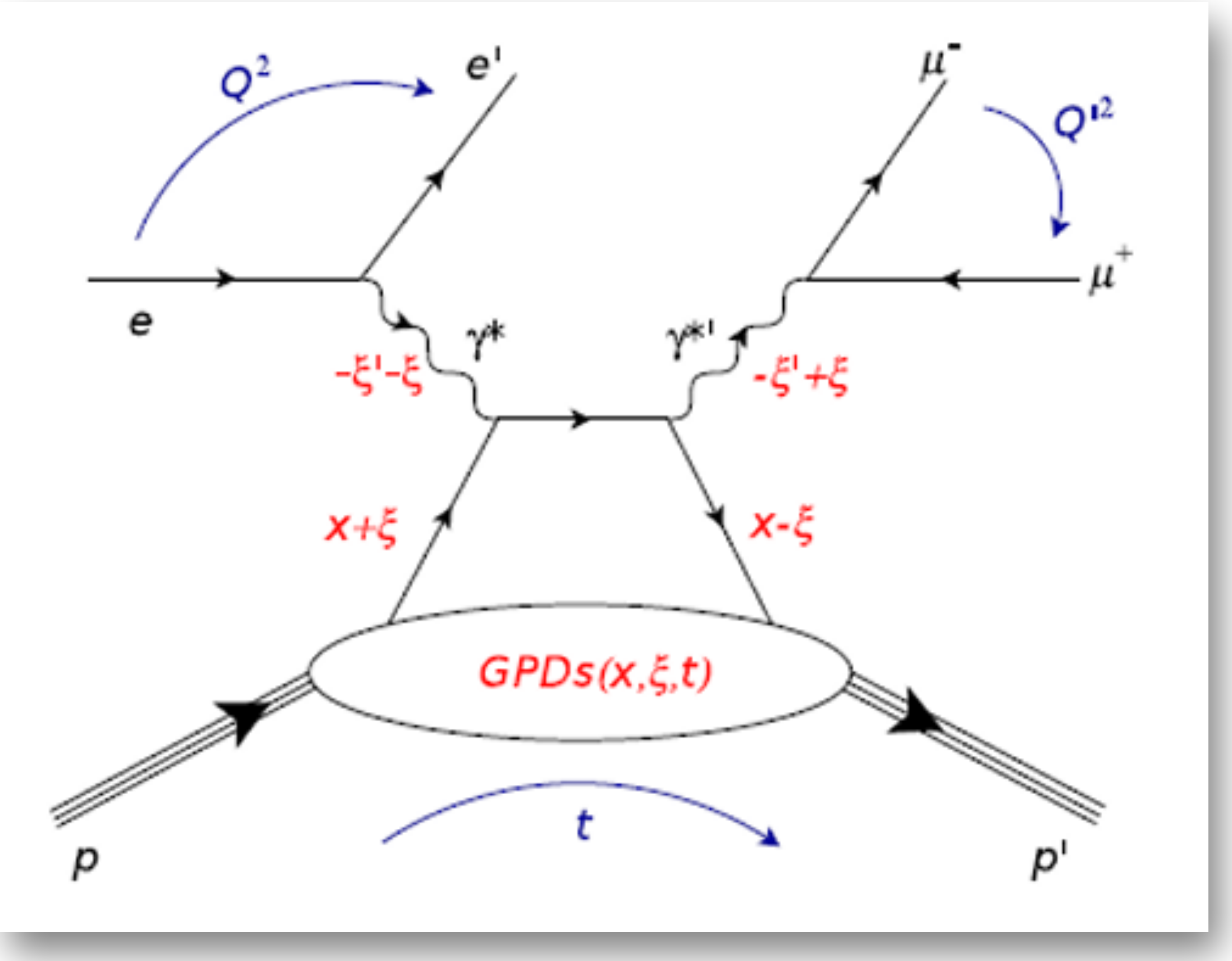
✦ **Unmuting *x* (x≠ ±ξ line)** via Single Diffractive Hard Exclusive Processes (SDHEP), e.g.,

- double DVCS. Small x-section & requires muon ID. LOIs: CLAS12 upgrade, SOLID@ Hall A
- exclusive photoproduction - possibility @Hall D

[J.-W. Qiu, Z. Yu, arXiv.org:2305.15397]

[Pedrak, Pire, Szymanowski, Wagner, PRD 96 (2017) 7, 074008]

JLab DDVCS



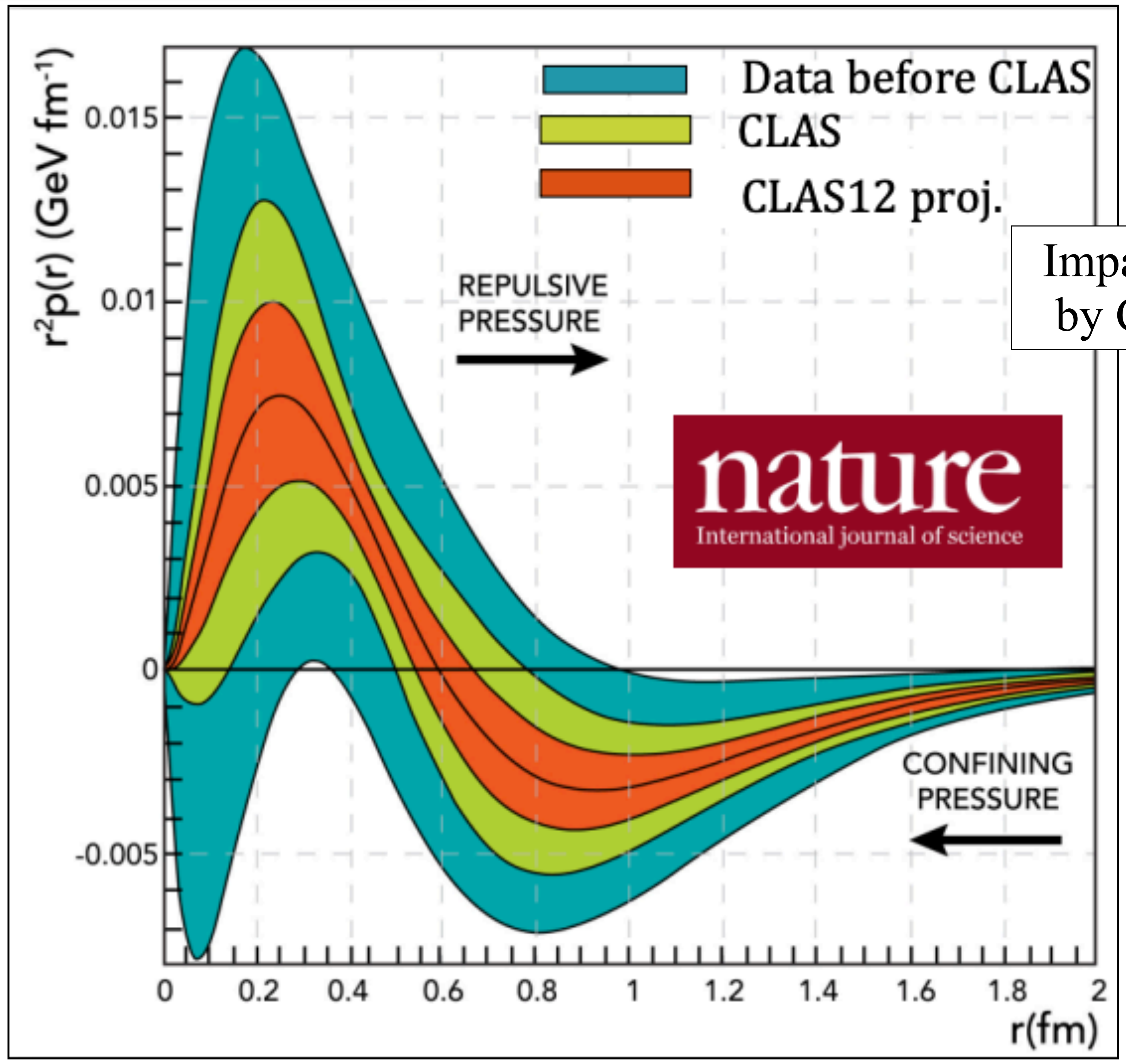
✦ **D-term** *D(t)*: related to shear forces and radial distribution of pressure inside the nucleon

$$\mathcal{R}e\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathcal{I}m\mathcal{H}(x,t)}{x-\xi} + D(t)$$

gravitational form factors (**GFFs**) of the proton
- matrix elements of QCD energy-momentum tensor (**EMT**)
- related to mass; angular momentum; shear force & pressure
- Linked to GPDs via *x*-moment

[Lorcé, Metz, Pasquini, Rodini, JHEP 2021, 121 (2021)]

CLAS DVCS



Impact on radial **quark** pressure distribution by CLAS and expected impact by CLAS12

[Burkert, Elouadrhiri, Girod, Nature 557, 396–399 (2018)]

[Polyakov, Schweitzer, Int.J.Mod.Phys. A33 (2018) 1830025]

Related: **gluonic** gravitational form factor of the nucleon from threshold J/ψ photoproduction

see talk by S. Joosten, Tue am

Hall C J/ψ-007

[Duran, Meziani, Joosten, et al., Nature 615, 813–816 (2023)]

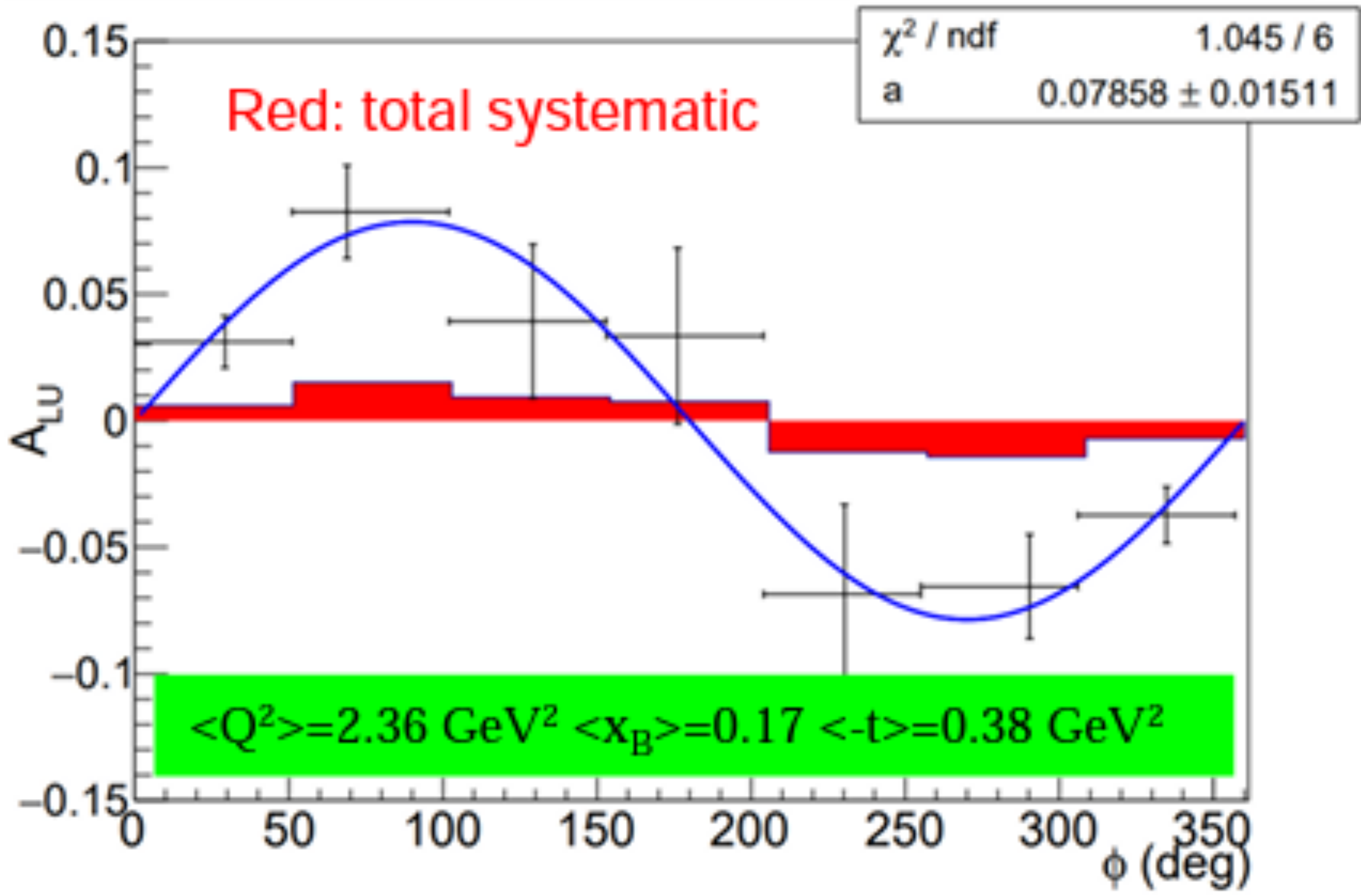
GPD E and parton orbital angular momentum

Ji sum rule links GPD E to **parton orbital angular momentum** (see next slide - connection with Sivers TMD PDF & spin-orbit correlations)

$$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \; x \left[H^q(x,\xi,t) + E^q(x,\xi,t) \right]$$

[Ji, PRL 78 (1997) 610]

CLAS12 DVCS beam-spin asymmetries on the deuteron (neutron)

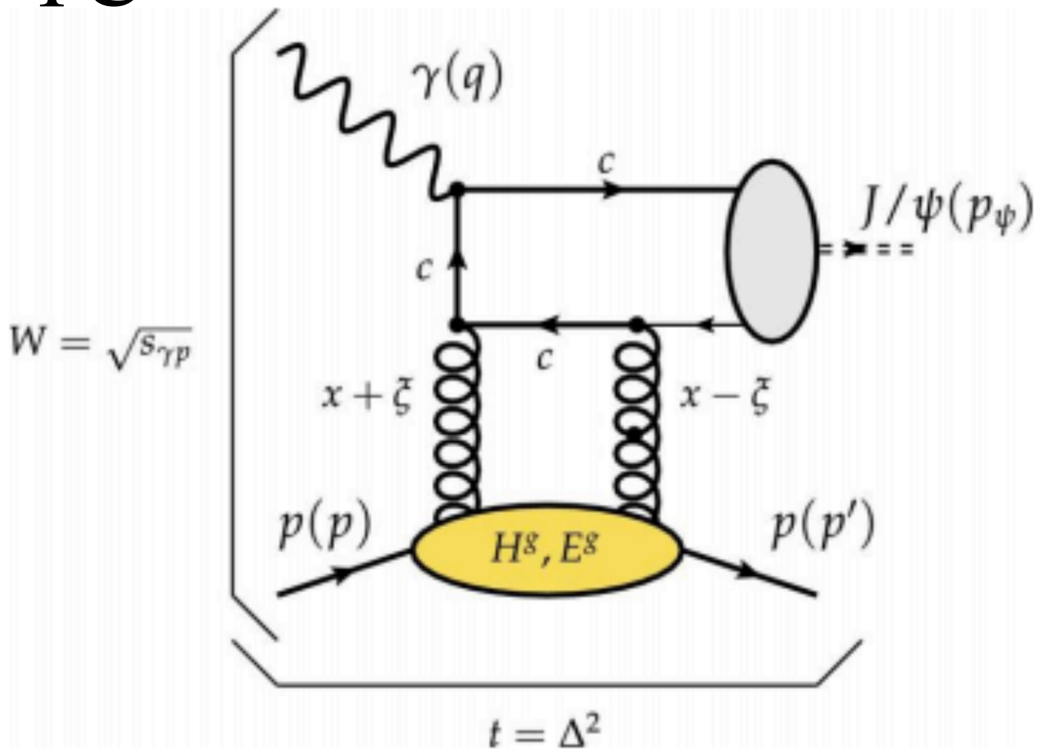


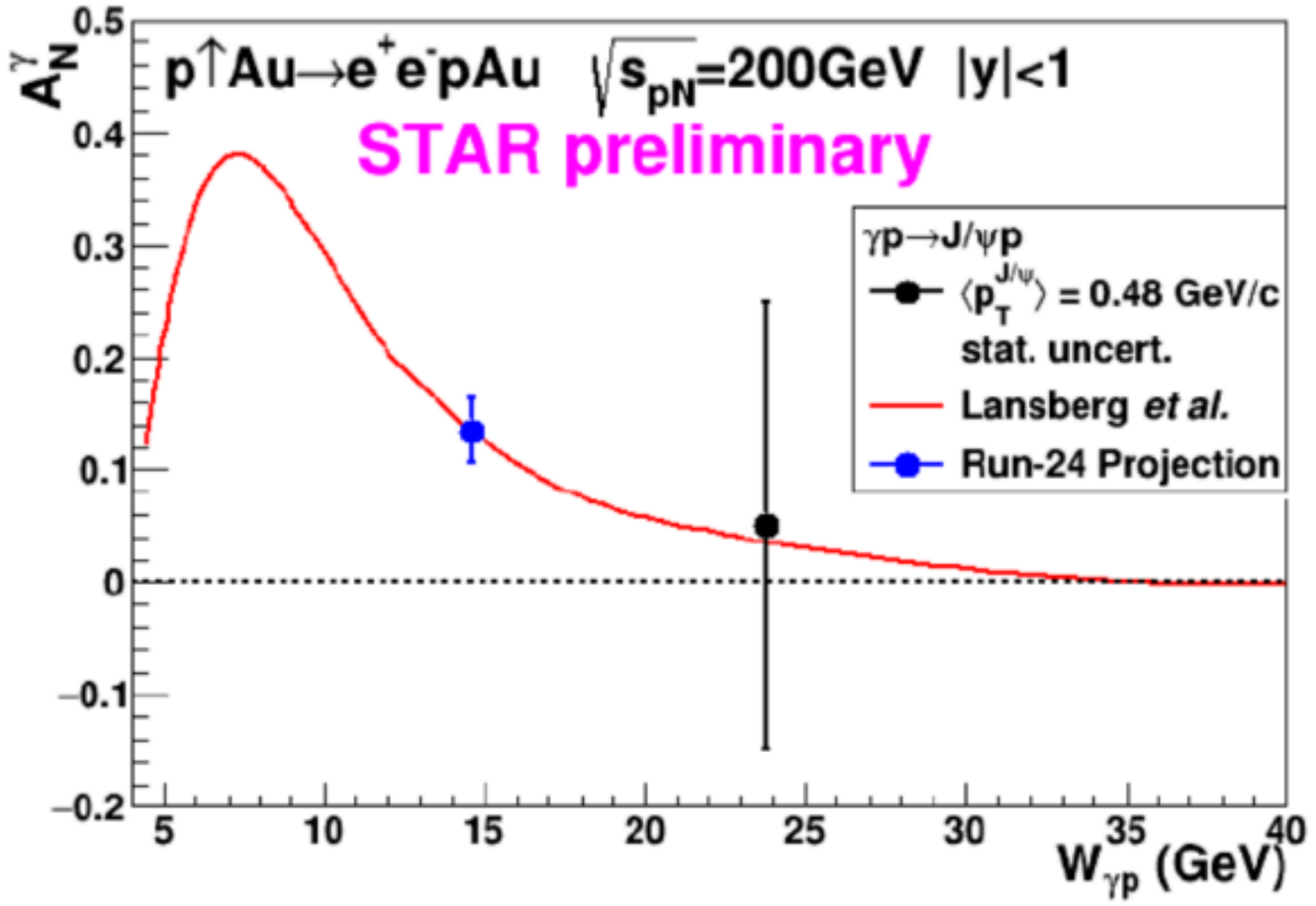
- CLAS12: DVCS on the neutron (LD_2 target with detection of active neutron), preliminary results (A. Hobart)
- CLAS12: on the transversely polarized proton, data to be taken (so far available data are from HERMES)

- All so-far discussed GPDs were **quark** GPDs

STAR excl. J/Psi A_N in UPC, **gluon** GPD E

- STAR: exclusive J/Psi production in ultra-peripheral collisions (UPC) → **gluon** GPD *E*. Future new data with forward upgrade





Deeply virtual meson production

N \ q	U	L	T
U	H		$\bar{E}_T$ → BM
L		$\tilde{H}$	$\tilde{E}_T$
T	E → Sivers	$\tilde{E}$	H_T → transversity, $\tilde{H}_T$

CKR-20231017

collinear
chiral-odd
naive time-reversal odd

Deeply virtual meson production allows access to higher-twist **chiral-odd GPDs**, which are related to TMD PDFs (e.g., tranversity). Mesons act as quark **flavor filter** & provide different sensitivity to **gluon GPDs**.

[Goloskokov, Kroll, EPJC 74, 2725 (2014)]

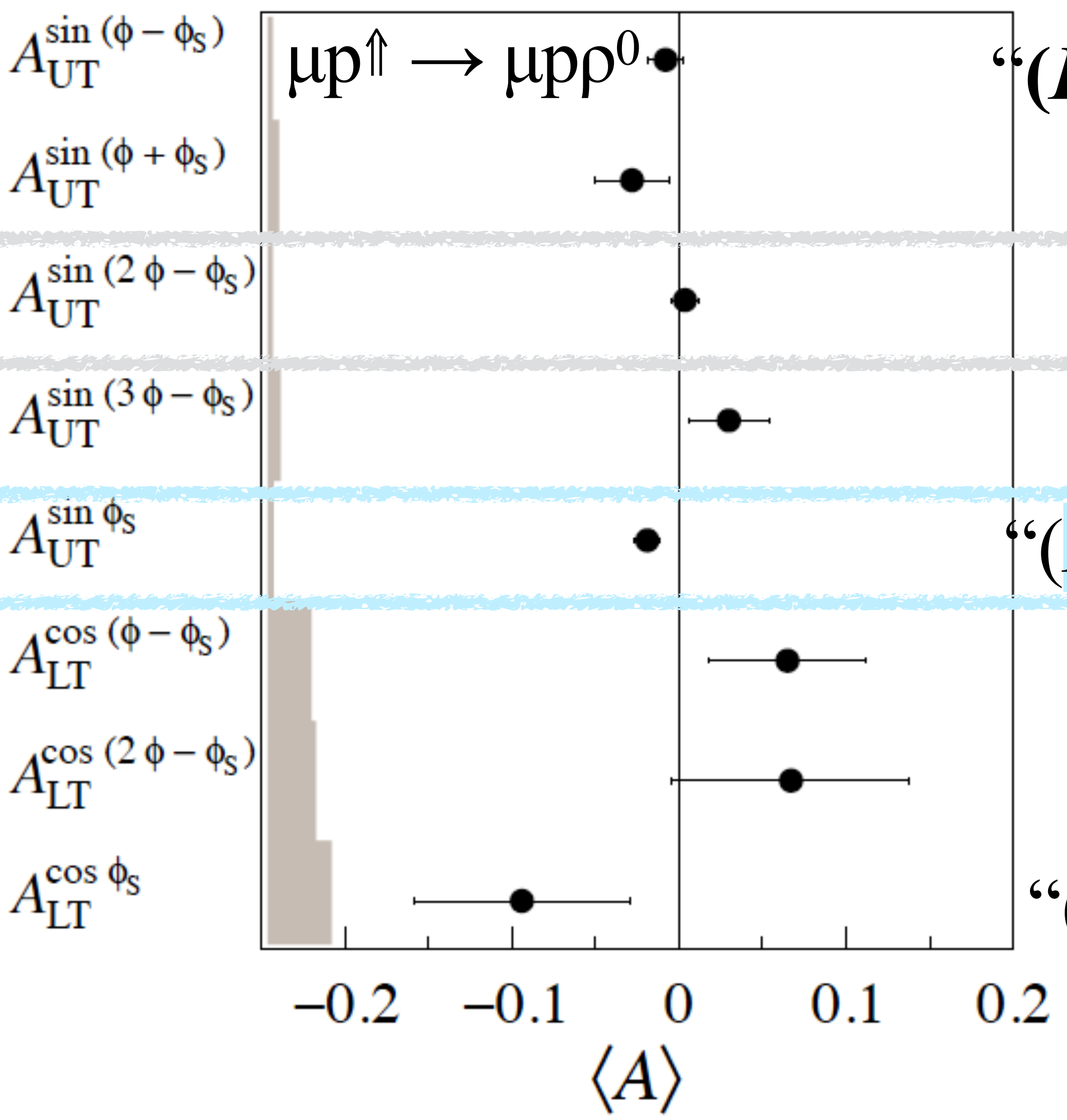
CLAS12 exclusive vector meson beam-spin asymmetries

preliminary results for ρ, ω (N. Trotta) and ϕ (B. Clary), gluon GPDs

COMPASS exclusive vector meson transverse target-spin asymmetries

$$E^{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}\frac{E^g}{x}\right)$$
$$E^{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{3}{4}\frac{E^g}{x}\right)$$
$$E^{\phi} = -\frac{1}{3}E^s + \frac{1}{8}\frac{E^g}{x}.$$

[M. Diehl, Vinnikov, Phys. Lett. B 609 (2005) 286]



[COMPASS PLB B731 (2014) 19]

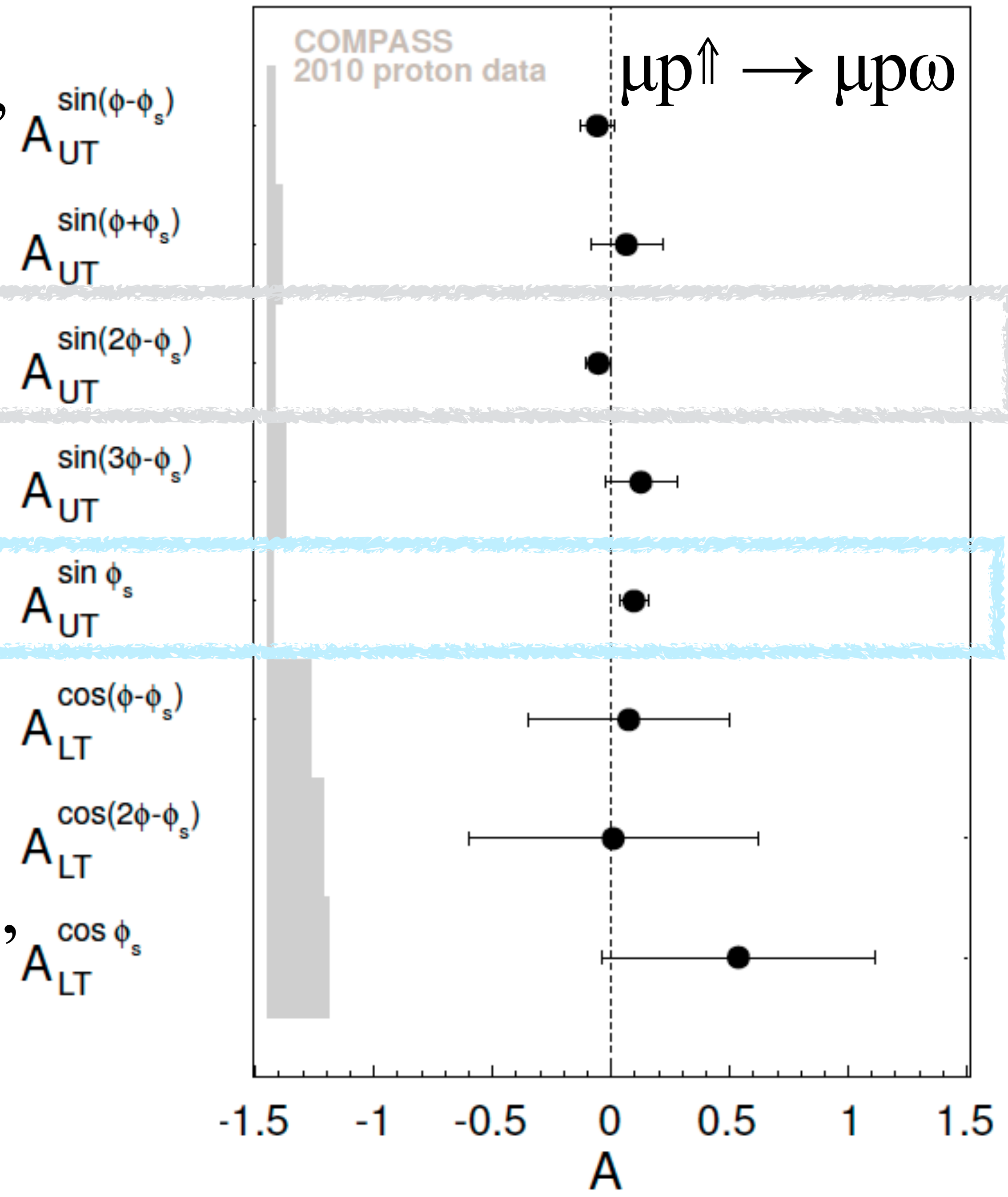
"(E,H) + $(\bar{E}_T,H_T)$"

"$(\bar{E}_T,E)$"

"(H_T,H) - $(\bar{E}_T,E)$"

"(H_T,H) - $(\bar{E}_T,E)$"

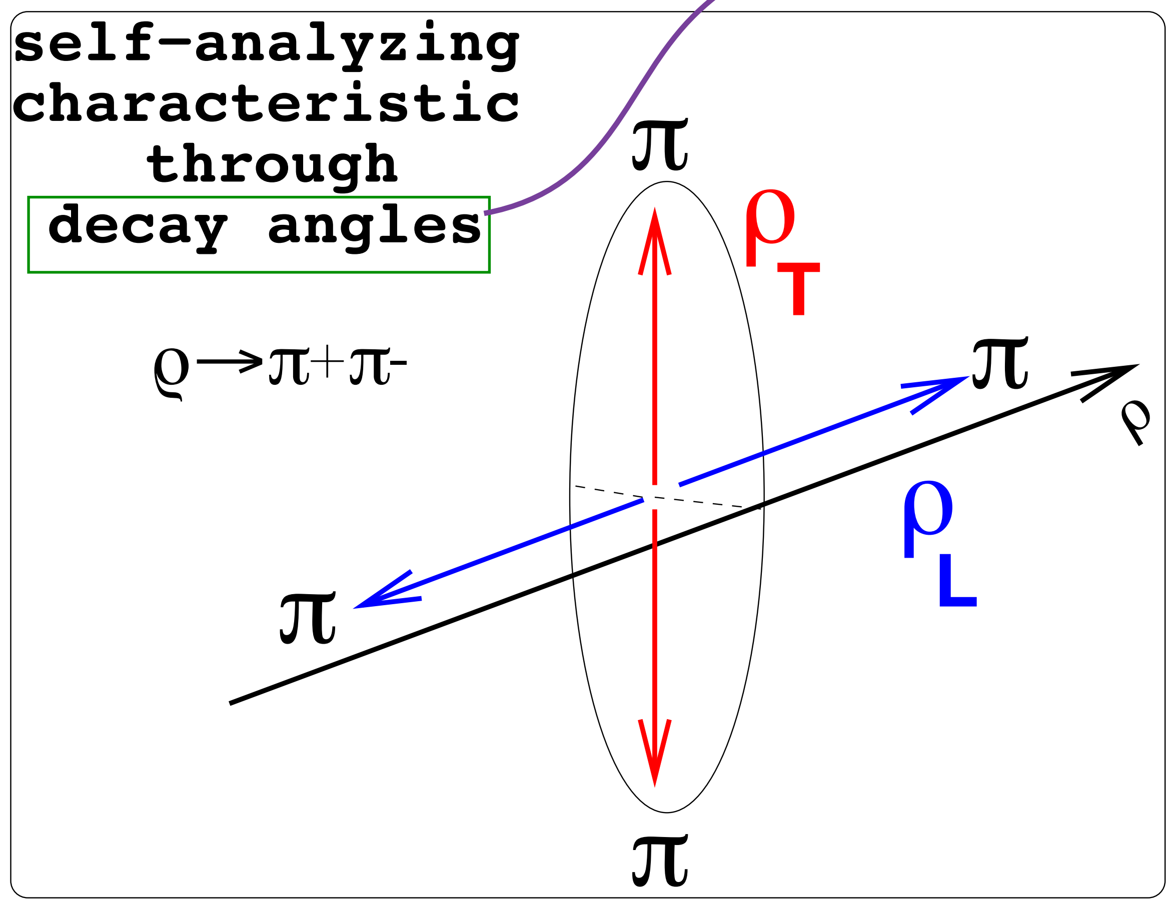
Different contributions from pion pole



[COMPASS NPB 915 (2017) 454]

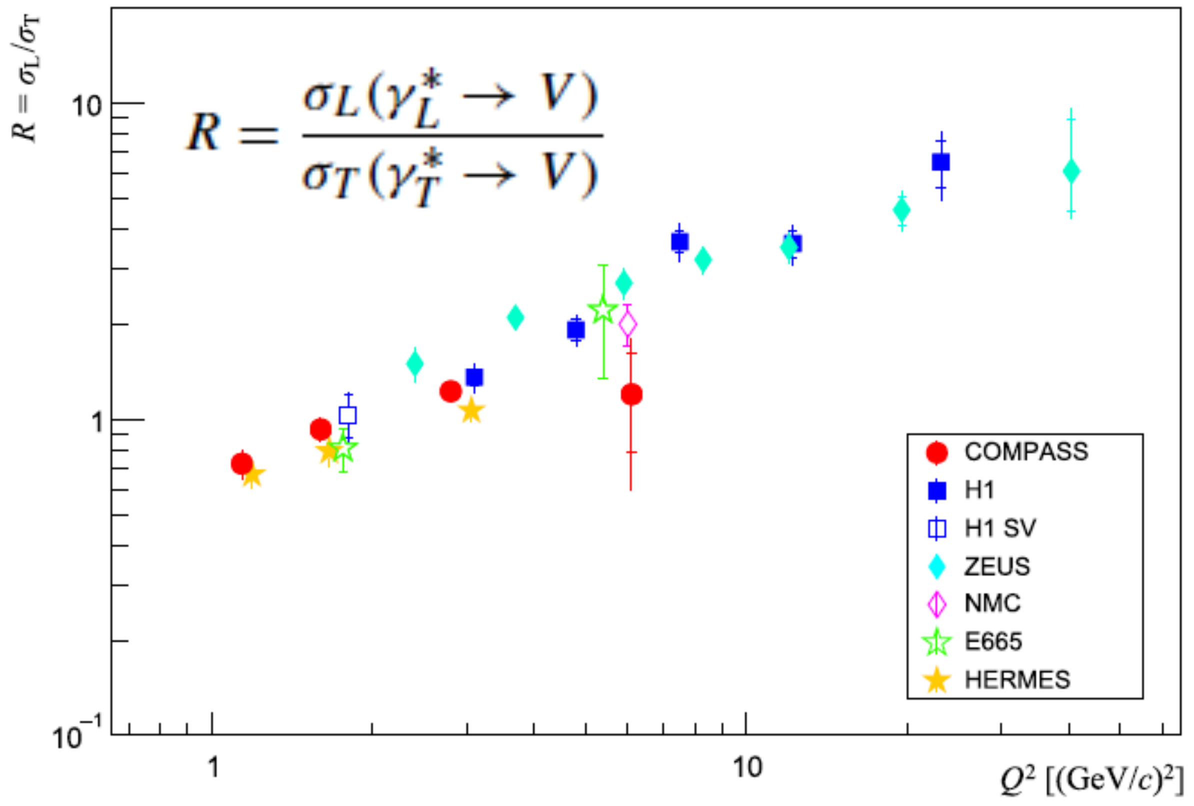
Spin density matrix elements

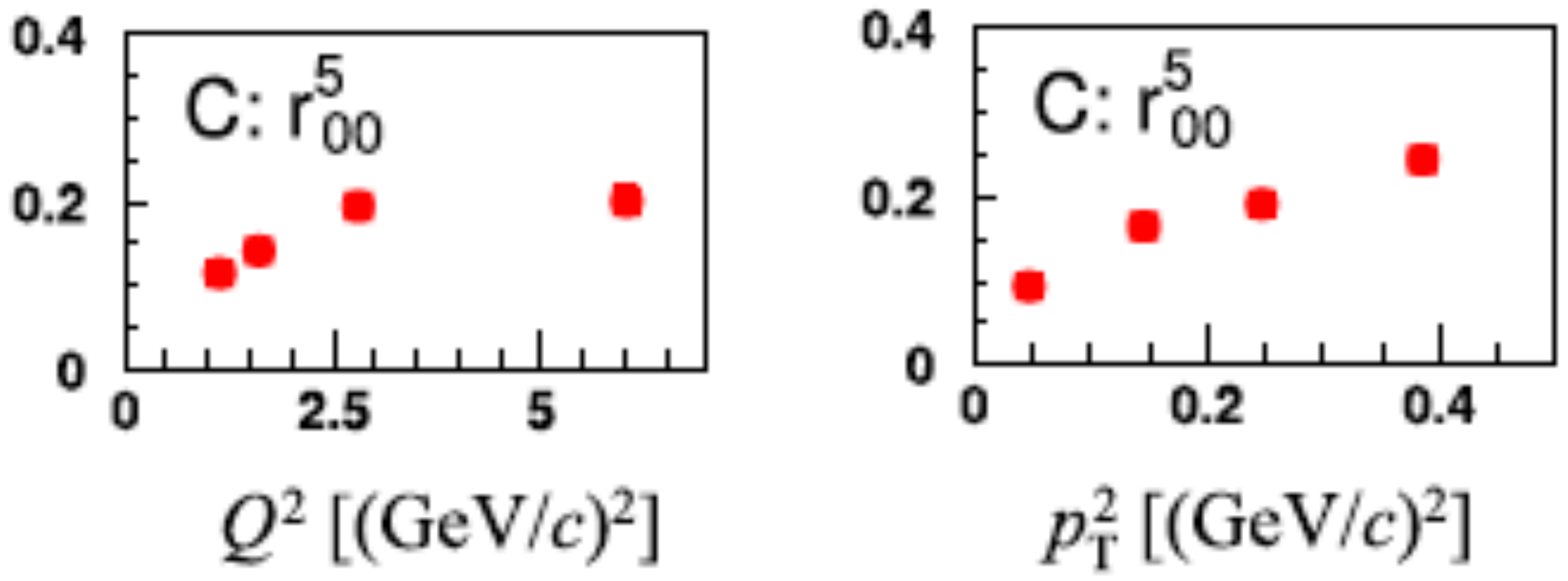
$$\frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)$$



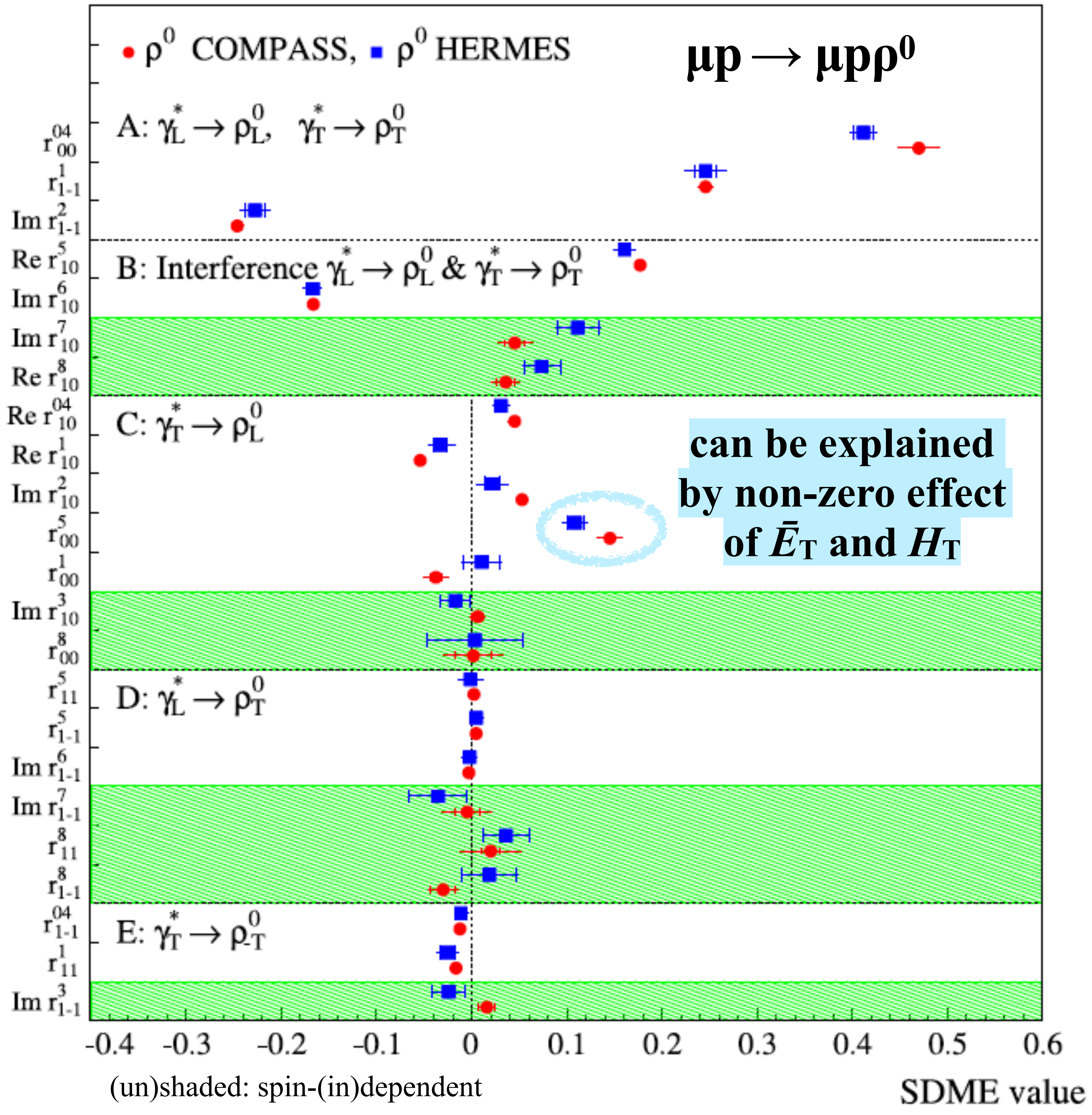
Spin density matrix elements describe how the spin components of the virtual photon are transferred to the created vector meson, and provide sensitivity to the chiral-odd GPDs H_T and $\bar{E}_T$.

- Provide further constraints on GPD parameterizations beyond cross-section and spin-asymmetry measurements
- Test of s-channel helicity conservation (SCHC), $\lambda_{\gamma^*}=\lambda_{VM}$, : only SDMEs of classes A&B are not restricted to =0 if SCHC. Observed: considerable ~~SCHC~~ in $\gamma^*_T \rightarrow \omega_L$ (class C)





COMPASS & HERMES SDMEs



[ρ⁰ COMPASS EPJC (2023) 83, 924]

[ρ⁰ HERMES EPJC (2009) 62, 659]

[ω COMPASS EPJC (2021) 81, 126] (not shown)

Exclusive pion leptoproduction

$$\frac{\mathrm{d}^2\sigma_{\gamma^* p}}{\mathrm{d}t\mathrm{d}\phi} = \frac{1}{2\pi}\left[\frac{\mathrm{d}\sigma_T}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}t} + \epsilon\cos(2\phi)\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}\right.$$

$\ell p \to \ell p \pi$

$$\left.\mp |P_l|\sqrt{2\epsilon(1-\epsilon)}\sin\phi\frac{\mathrm{d}\sigma'_{LT}}{\mathrm{d}t}\right]$$

$\frac{\mathrm{d}\sigma_T}{\mathrm{d}t}$: $\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2\right]$

$\frac{\mathrm{d}\sigma_L}{\mathrm{d}t}$: $\left[(1-\xi^2)|\langle\tilde{H}\rangle|^2 - 2\xi^2 Re\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4M^2}\xi^2|\langle\tilde{E}\rangle|^2\right]$

sensitivity to chiral-odd GPDs

$\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}t}$: $t'|\langle\bar{E}_T\rangle|^2$

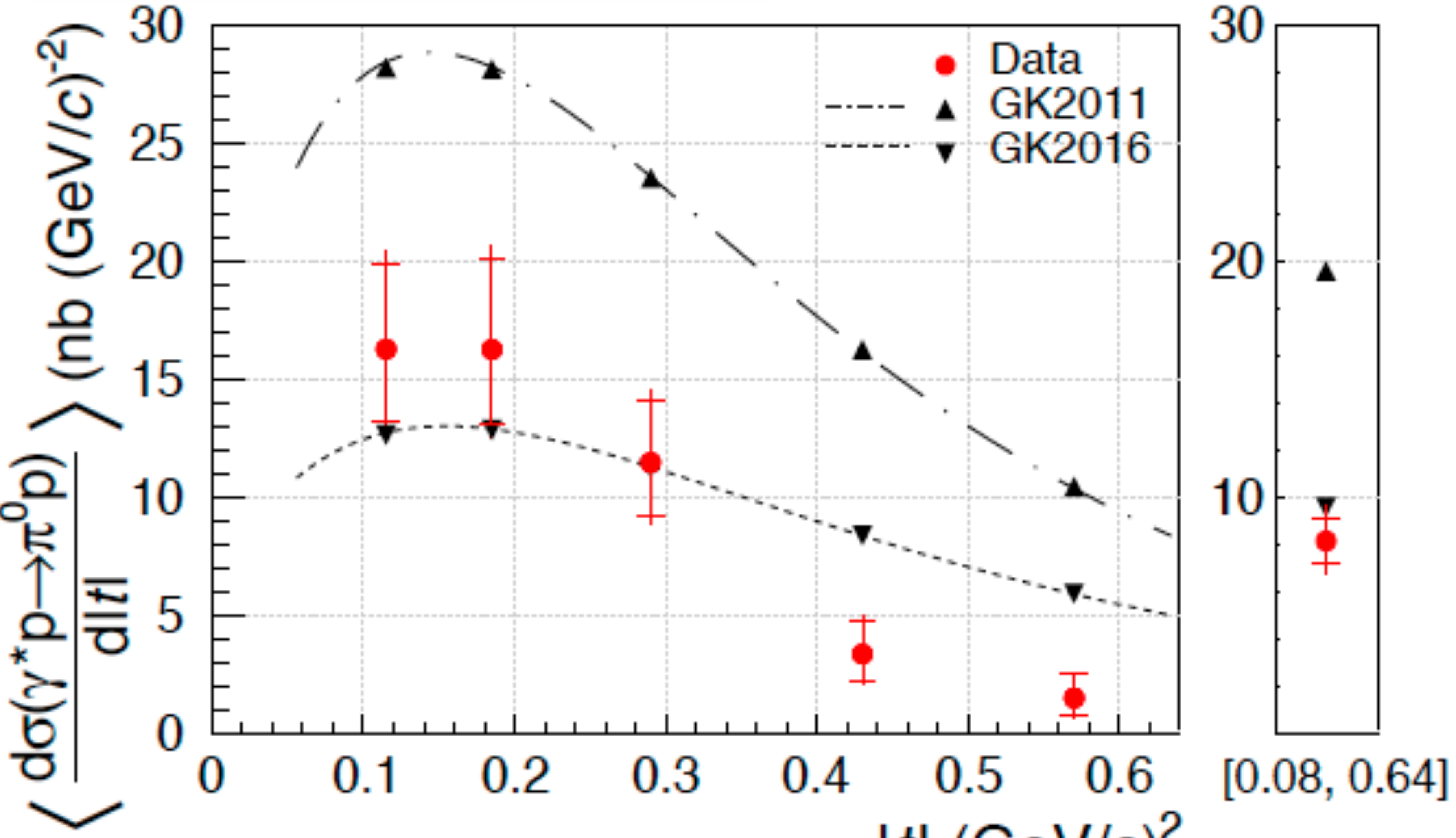
$\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}t}$: $\xi\sqrt{1-\xi^2}\sqrt{-t'}Re\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$

$\frac{\mathrm{d}\sigma'_{LT}}{\mathrm{d}t}$: $\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}Im\left[\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle + \langle H_T\rangle^*\langle\tilde{E}\rangle\right]$

L, T indices indicate polarization of virtual photon. Double index = interference

Effects of **chiral-odd GPDs $\bar{E}_T$, H_T** in exclusive π^0, π^+ production

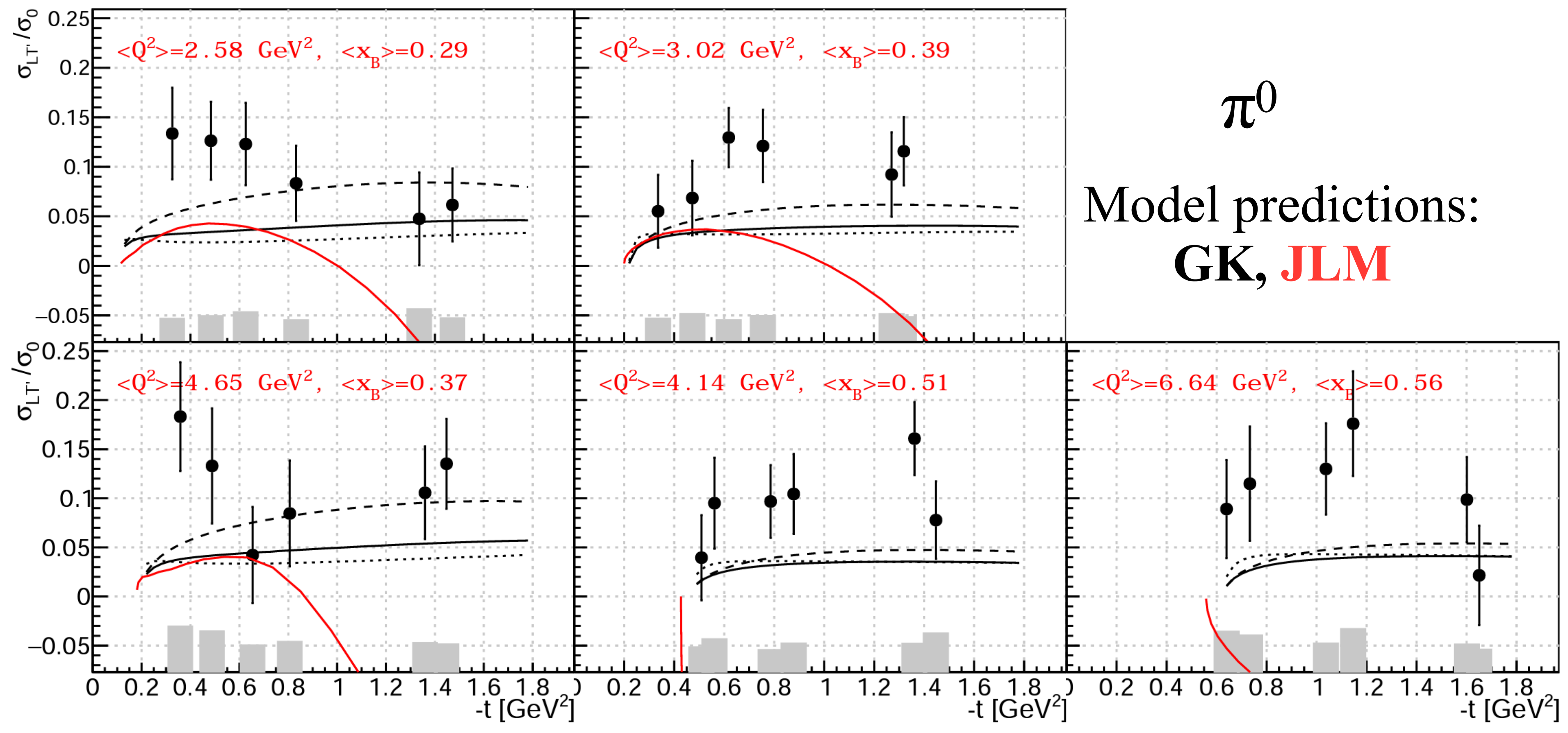
COMPASS π^0 x-section



[COMPASS, PLB 805 (2020) 135454]

Dip at small $|t|$ indicative of large effect by chiral-odd GPD $\bar{E}_T$

CLAS12 π^0 & π^+ beam-spin asymmetry



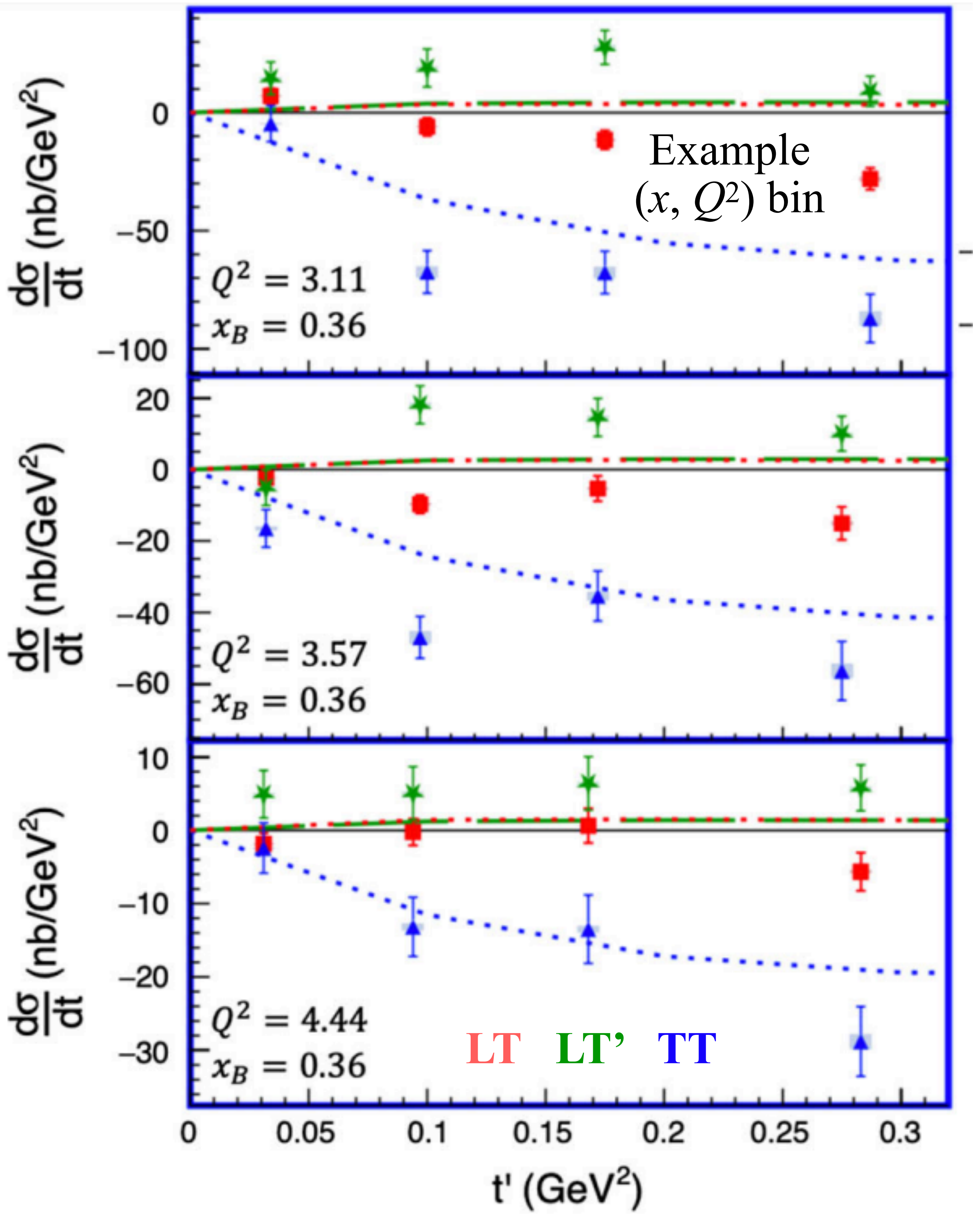
π^0

Model predictions: **GK**, **JLM**

[π^0 CLAS12 (A. Kim et al), arXiv:2307.07874, submitted to PLB]

[π^+ CLAS (S. Diehl et al), PLB 839, 137761 (2023)]

JLab12 Hall A π^0 x-section

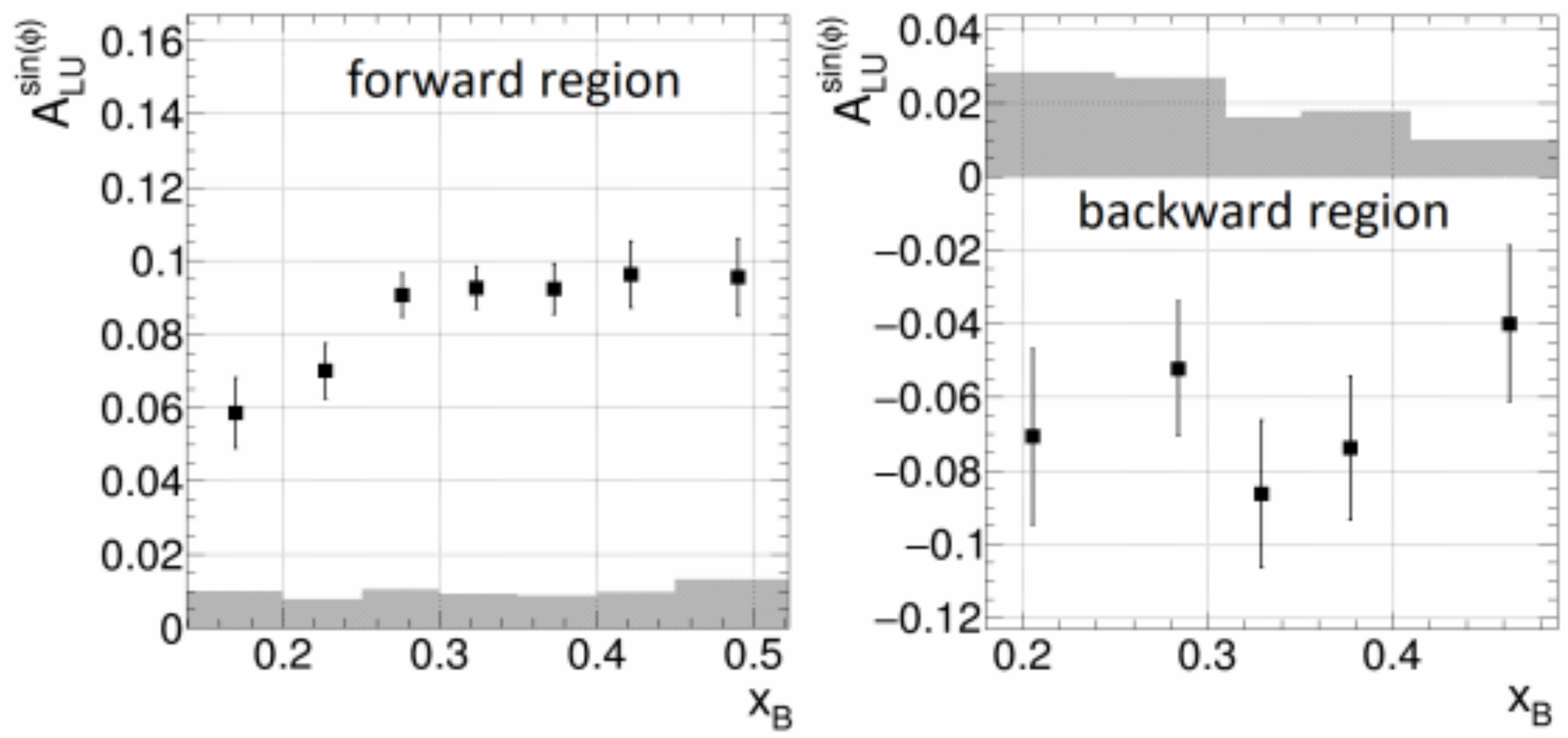


[Hall A collaboration (M. Dlamini et al.), PRL 127, 152301 (2021)]

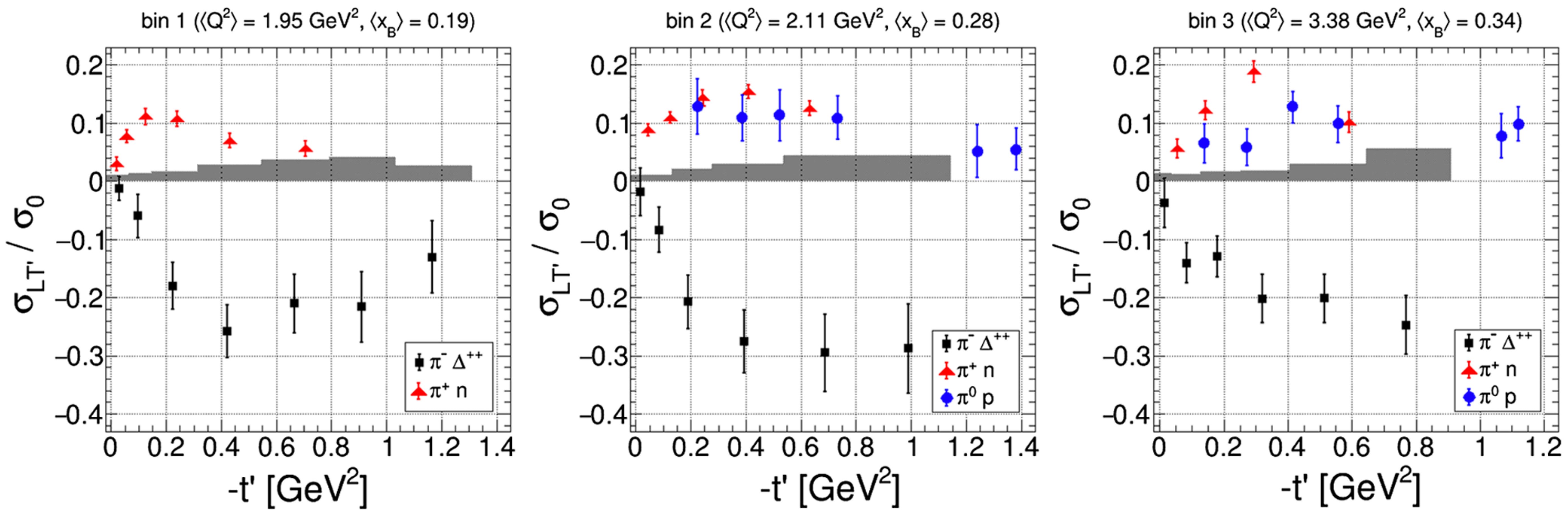
Large TT contribution $\rightarrow$ **significant role of transversely polarized photons** in excl. π^0 production

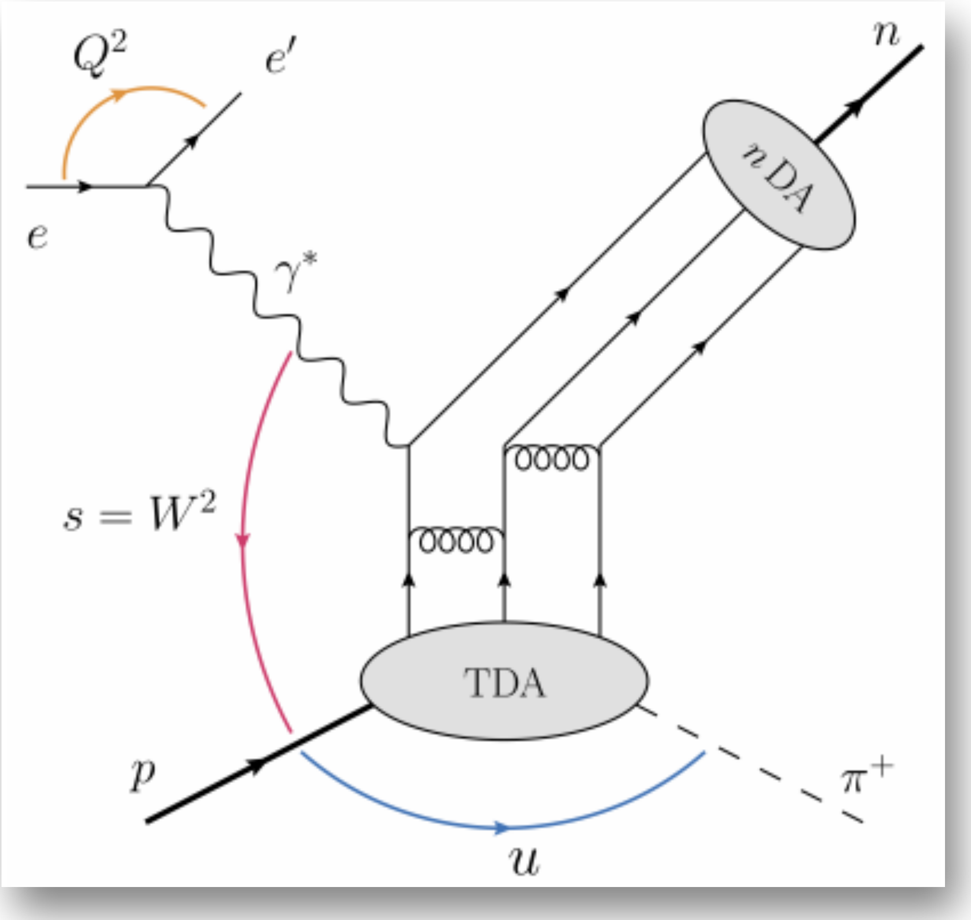
Transition DAs and transition GPDs

CLAS excl. π^+ beam-spin asymmetries in the backward



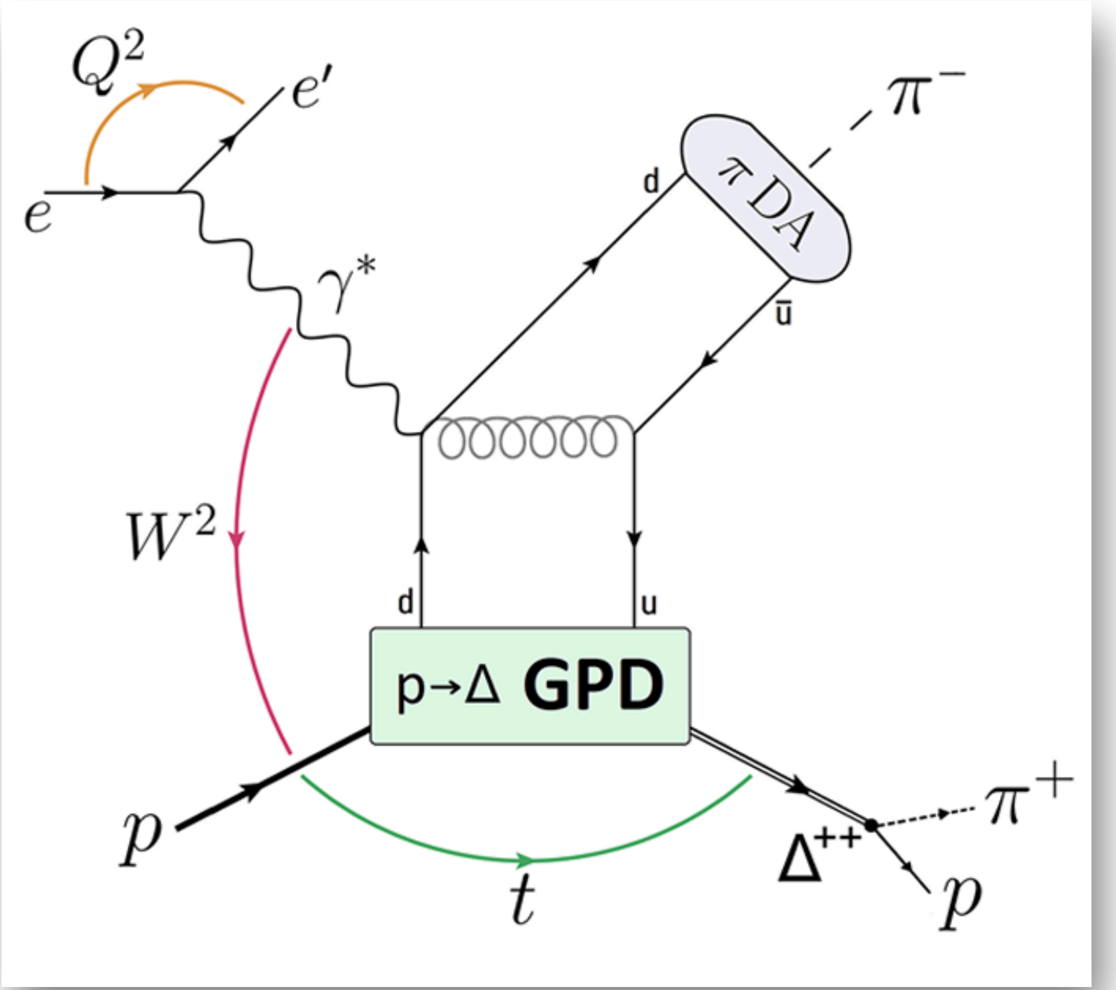
CLAS12 excl. $\pi^-\Delta^{++}$ beam-spin asymmetries, first ever data





Exclusive pion production **in the backward** allows to study nucleon-to-pion baryonic **transition distribution amplitudes (TDAs)**, a further generalization of the GPD concept

How does **nucleon resonant excitation** affect its 3D structure? Information encoded in **transition GPDs** (8 chiral-even and 8 chiral-odd).



very forward kinematics ($-t/Q^2 \ll 1$)

[CLAS (S. Diehl et al., PRL125, 182001]

[CLAS12 (S. Diehl et al.), PRL131, 021901 (2023)]

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- ☑ Sivers effect in di-jet production
- ☑ Collins FF in ee and Collins asymmetry in pp & SIDIS
- ☑ Di-hadron fragmentation function in pp and SIDIS
- ☑ Other spin-dependent fragmentation functions in SIDIS

☑ GPDs

- ☑ Hard exclusive reactions
- ☑ Chiral-even GPDs & DVCS asymmetries
- ☑ Exploring Compton form factors
- ☑ Parton orbital angular momentum & gluon GPDs
- ☑ Chiral-odd GPDs & vector mesons
- ☑ Transition DAs & transition GPDs

☐ Outlook & summary

Selected near future - before the EIC

- **JLab 12 GeV high-luminosity facility**:
  - Has started experimental program
  - New generation of precision data for valence quarks to come from CLAS12, SoLID, et al.

- **SpinQuest / E1039 at FNAL** (2024++):
  - Transversely polarized NH3/ND3 target with E906 spectrometer
  - First polarized DY experiment with proton beam
  - Sivers & transversity TMDs of sea quarks.

- **LHCspin at CERN**, fixed trans.polarized H2 & D2 targets with LHCb as forward spectrometer, >2025, https://inspirehep.net/literature/1821190

EIC - see Mo - Thu pm parallel talks

- **STAR cold QCD with forward upgrade at RHIC**:
  - Tracking system of silicon & small TGC
  - Forward electromagnetic & hadronic calorimetry, $2.5<\eta<4$
  - midrapidity: improve statistics of Sivers via dijet & W/Z, Collins via hadrons in jets, GPD E via J/Psi UPC
  - forward rapidity: TMDs at high-x & GPD E

RHIC cold QCD program with 2024 pp↑ $\sqrt{s_{NN}}$=200 GeV run

[Aschenauer, Barish, Bazilevsky, et al.,arXiv:2302.00605]

- **sPHENIX cold QCD at RHIC**:
  - Optimized for jets, heavy-flavor measurements and displaced vertices with MAPS-based vertex tracker
  - Gluon Sivers TMD PDF via A_N in single-photon & heavy flavor
  - Di-hadron IFF / Collins asymmetry & transversity PDF via hadron-charge tagging & hadron-in-jet

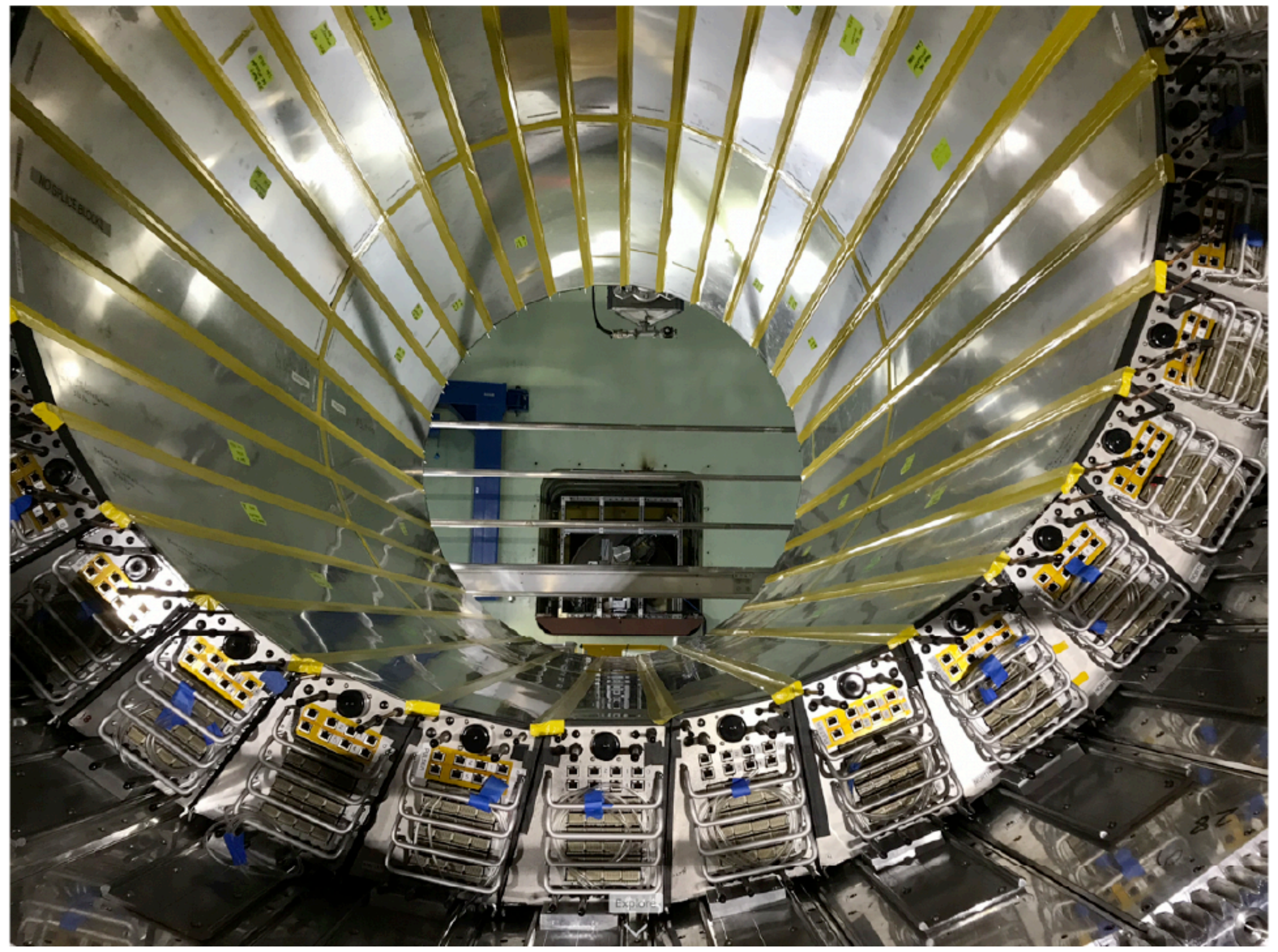
- **AMBER:**
  - Emergence of hadron mass, pion and kaon PDFs, proton and meson radius

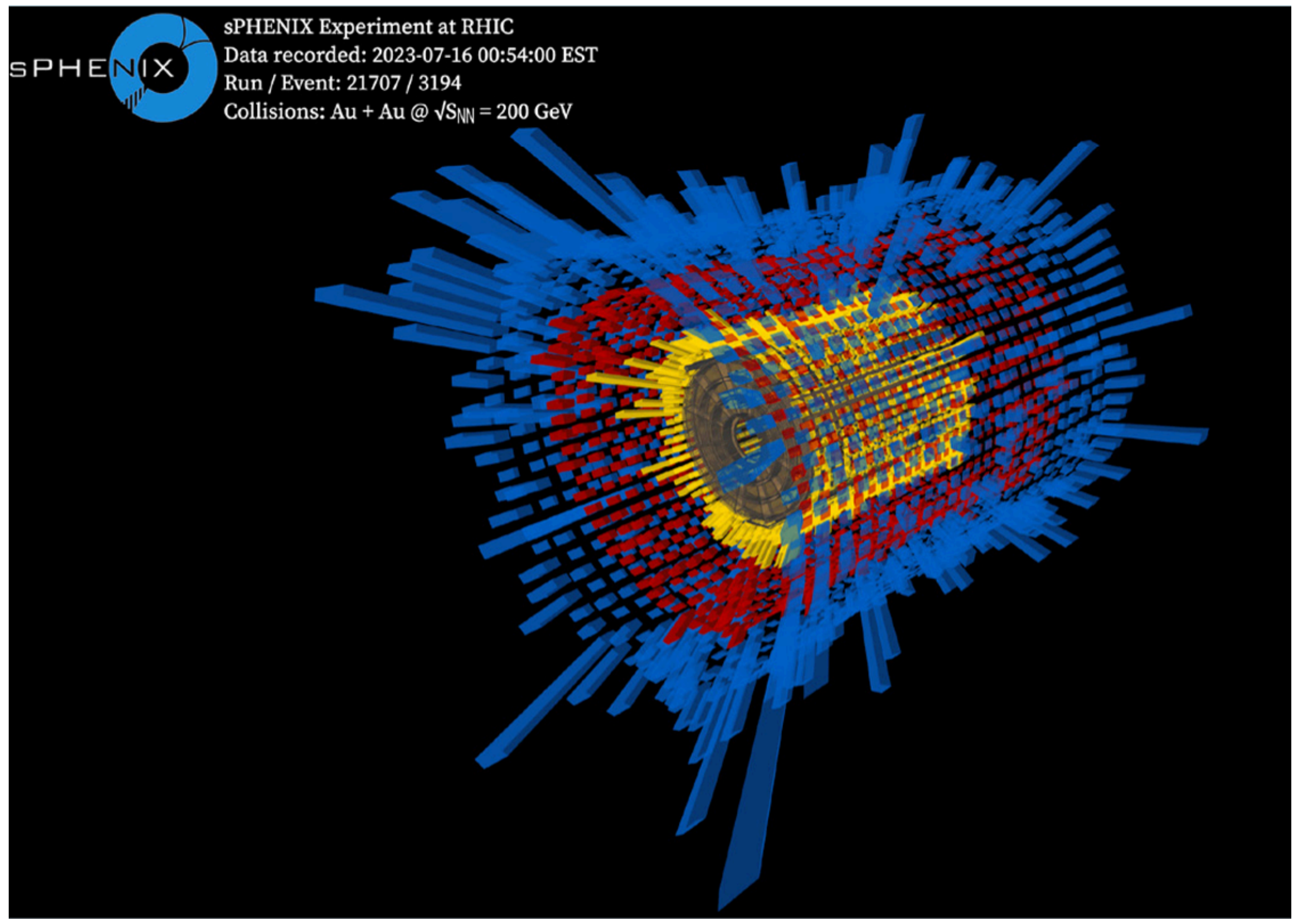
AMBER - see talk by C. Quintans, Thu am

sPHENIX - preparing for transversely polarized pp in 2024

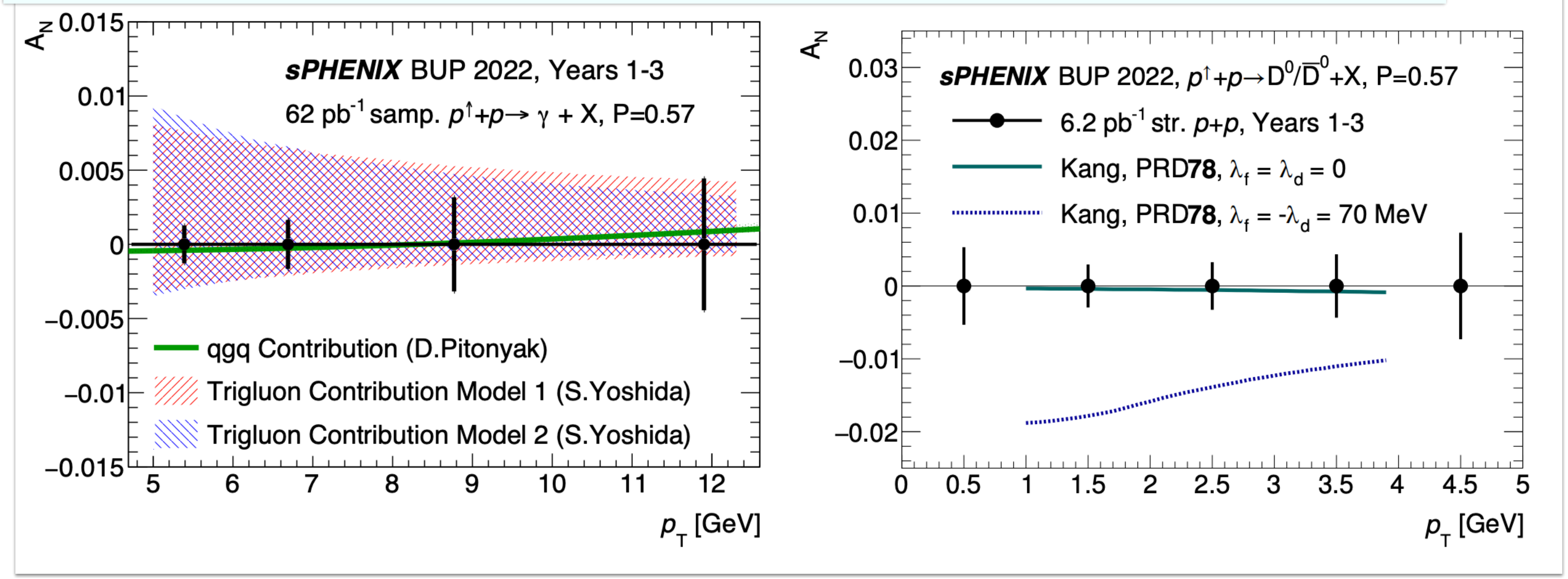
- Commissioning 2023 with brand new experiment at RHIC IP 8
- Optimized for jets, heavy-flavor measurements & displaced vertices with MAPS-based vertex tracker
- Gluon Sivers TMD PDF via A_N in single-photon & heavy flavor production
- Di-hadron IFF / Collins asymmetry & transversity PDF via hadron-charge tagging & hadrons-in-jets

Fully installed EMCal & calorimeter event display

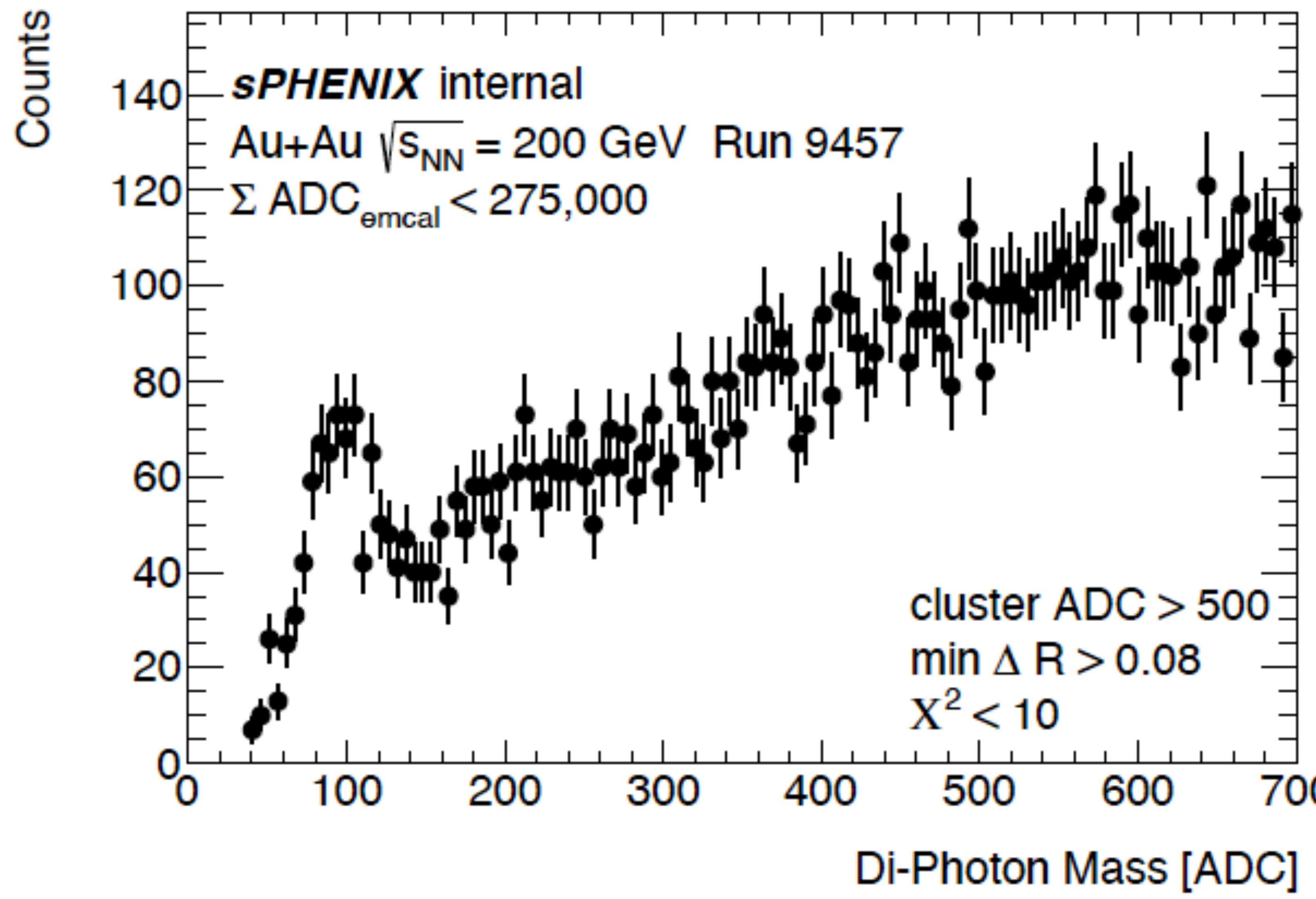




Expected stat uncertainties for isolated photon & heavy-flavor production



First pi0s in the EMCal



Expect factor of ~2 less stat in 2024 than shown here

Summary - Probing nucleon spin structure

Experiments at **BNL**, **JLab**, **CERN**, **DESY**, **RIKEN**, **Fermilab**, *et al.* unravel proton and nucleus structure

The **spins of quarks and gluons** contribute to the **proton's spin** and there is indication they also possess **orbital angular momentum**. The nucleon is explored via **tomographic images** in transverse-momentum- and position-space using data from various types of scattering experiments.

Probes for **TMD** factorization, evolution & universality

OAM as pre-requisite for Sivers effect… and linked to GPDs

GPDs beyond chiral even; nucleon ground state; away from the x= ±ξ line; extremely high precision in the valence region & bridging the region between gluons and valence

Experimental (and in some cases lattice) data serve as **input to global fits**

The **Electron Ion Collider** will be the ultimate tool to precisely map the rich spin- and multi-dimensional structure of nucleons and nuclei from low- to high x_{Bjorken}.

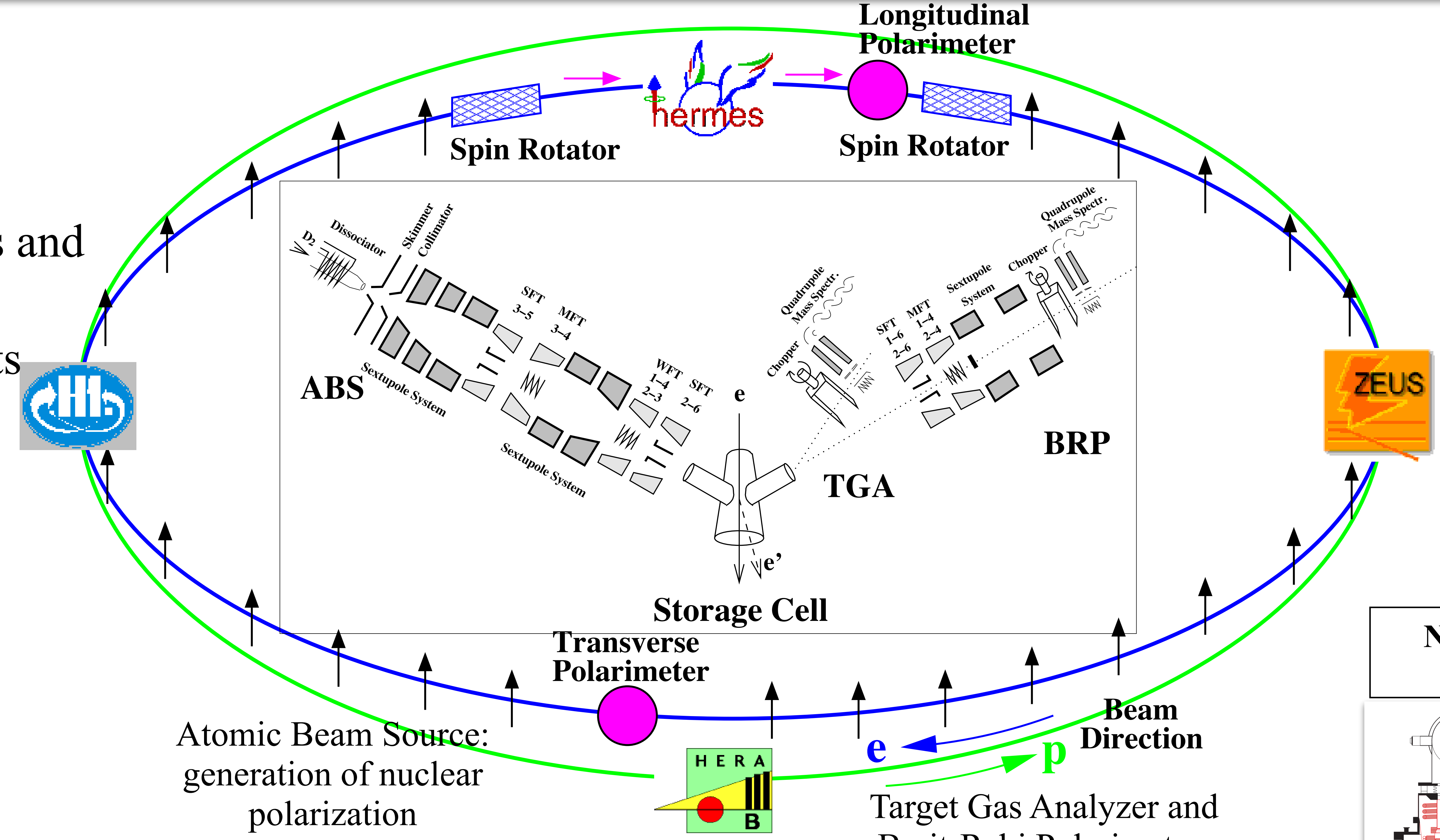
- Skipped probably many results - e.g., unpolarized Boer-Mulders TMD
  - Some of it covered in backup

- TMD Handbook, R. Boussarie *et al*. for the TMD Collaboration, arXiv:2304.03302
- The RHIC Cold QCD Program (White Paper) - Contribution to the NSAC Long-Range Planning process, E.C. Aschenauer *et al*. (RHIC SPIN collaboration), arXiv:2302.00605
- The US Long Range Plan for Nuclear Science released in October 2023 https://nuclearsciencefuture.org/
- CR's 2022 arXiv https://arxiv.org/abs/2204.03684

Extra slides

Going polarized at fixed-targets experiments

- HERMES at (1995-2007)
  - Self-polarized 27.6 GeV electrons and positrons in HERA storage ring
  - Pure L- and T-polarized gas targets



Atomic Beam Source: generation of nuclear polarization
- microwave system

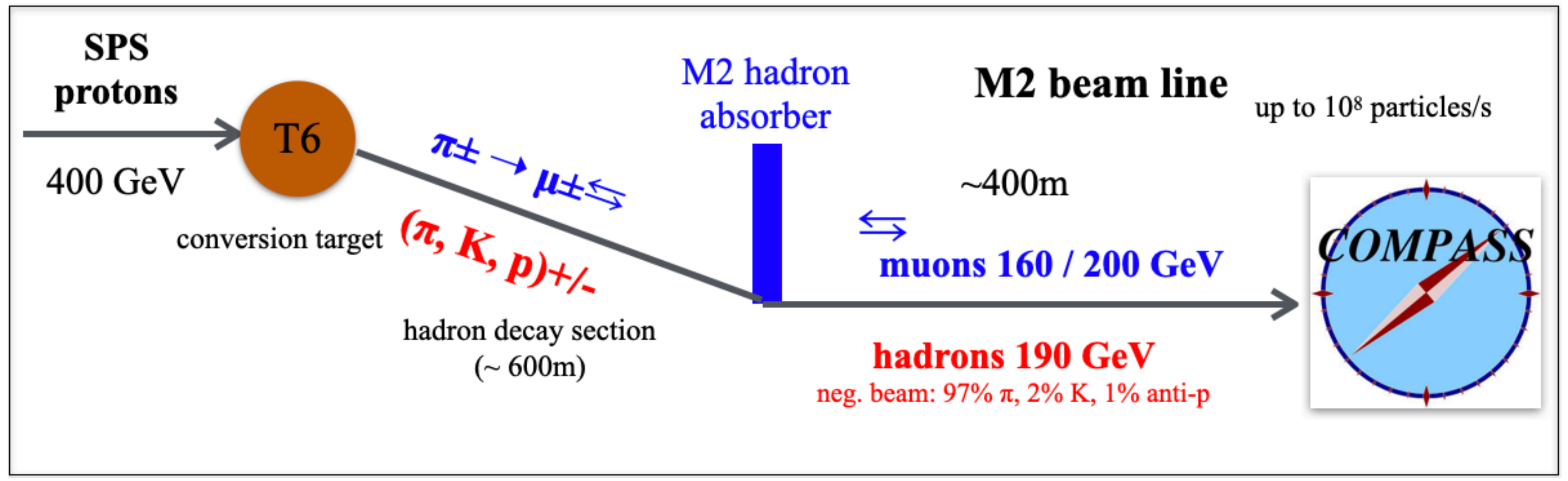
Target Gas Analyzer and Breit-Rabi Polarimeter: monitoring systems

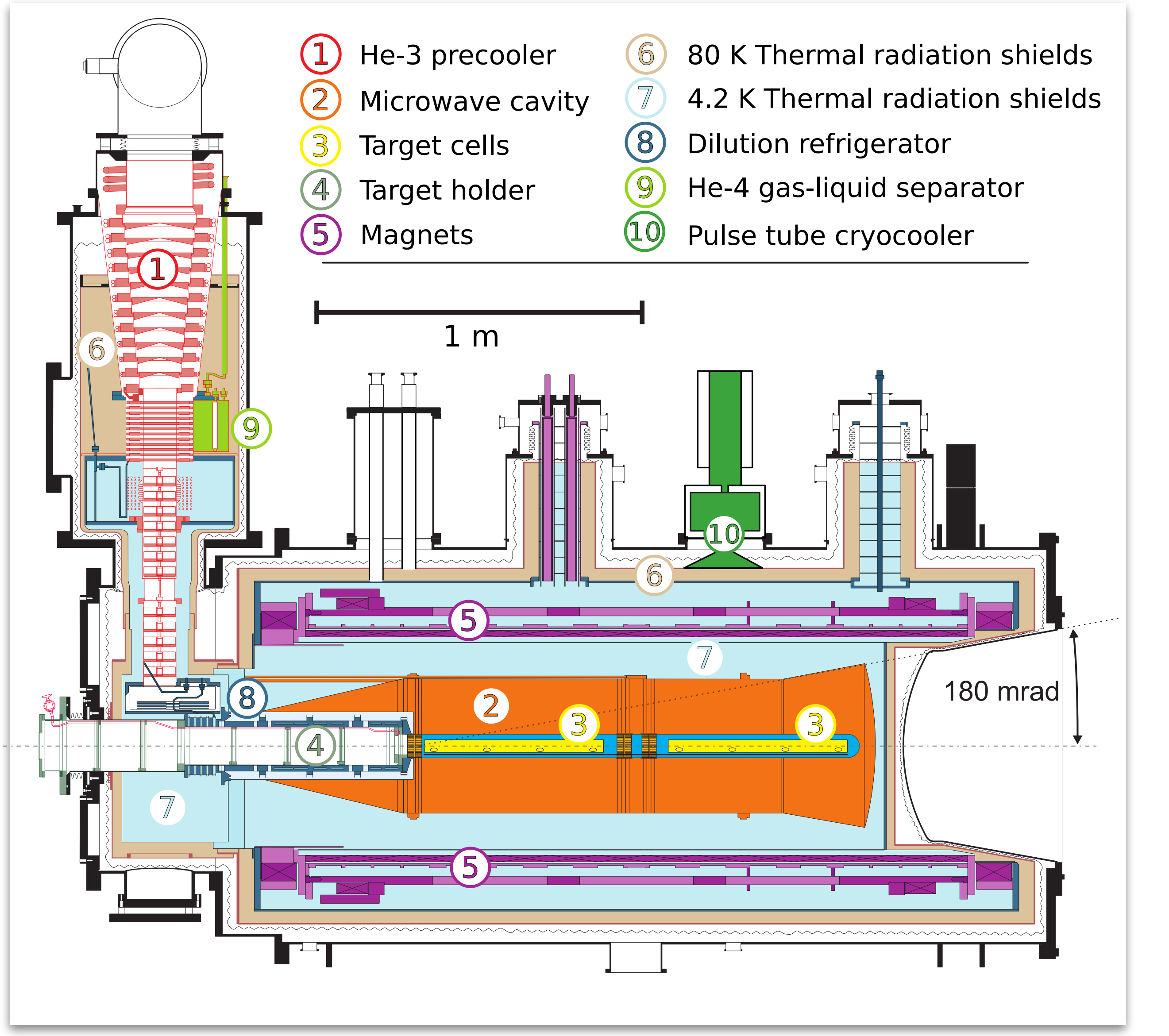
Polarization achieved by **Dynamic Nuclear Polarization (DNP)**
- dilution refrigerator: ~60mK
- dipole magnet (transverse): 0.5T
- solenoid (longitudinal): 2.5T
- microwave system

Polarization determined with **Nuclear Magnetic Resonance (NMR)**

- COMPASS at (2002-2022)
  - Secondary and tertiary beams (M2 SPS beam line). Muons polarized via pion decay
  - Solid-state L- and T-polarized targets

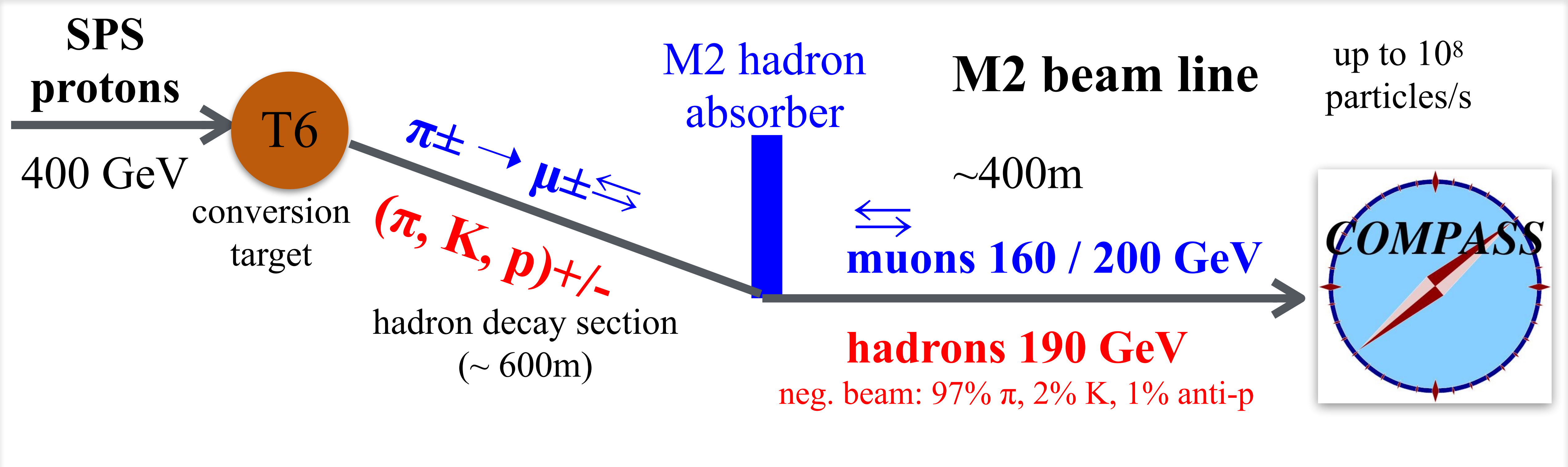
NH_3: ammonia beads, **^{6}LiD:** deuterated lithium dilution factor ~ 0.22 (NH3), 0.5 (LiD)





And many more: the polarized electron beams at JLab-CEBAF, the polarized targets at JLab, Fermilab, LHC-spin…

COMPASS experimental setup and future



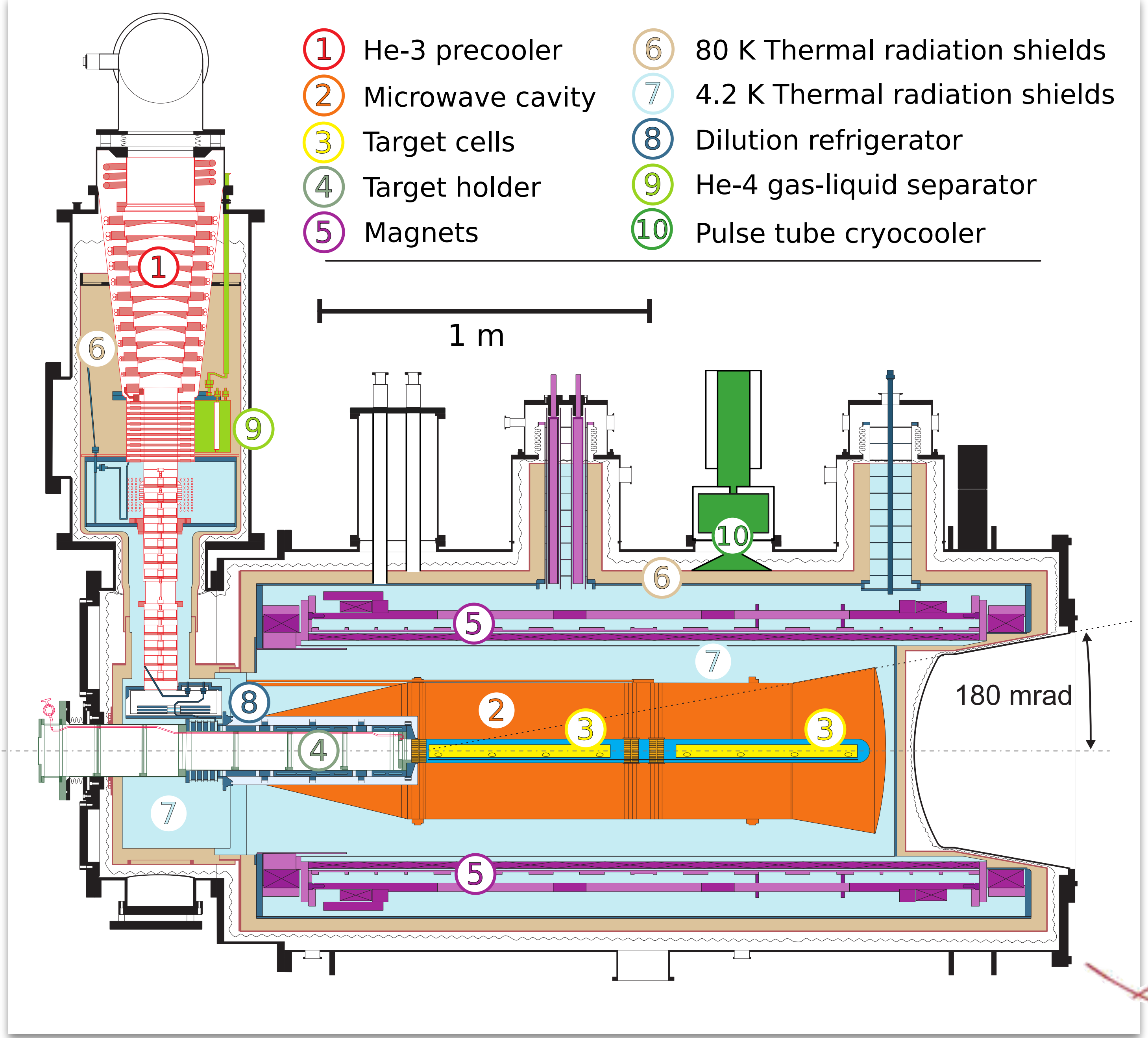
The 2022 data-taking campaign was the last run of the COMPASS experiment, and the last of the exploratory study of the nucleon structure

COMPASS changed from "data taking" to "data analysis" and will continue for several years

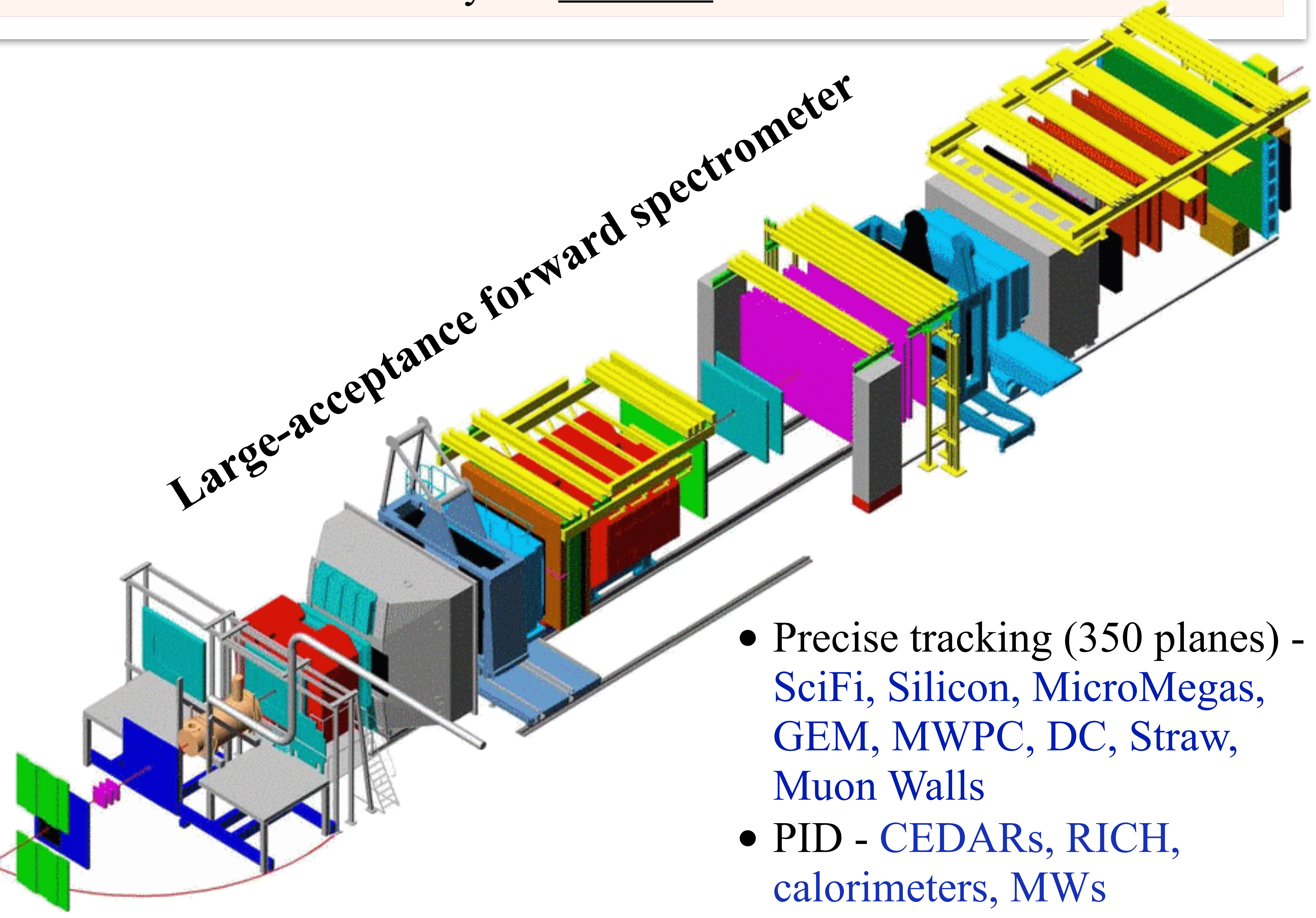
The spectrometer will stay in the experimental hall and is being upgraded and run by the AMBER Collaboration

COMPASS polarized solid-state target

- Polarization achieved by **Dynamic Nuclear Polarization (DNP)**
  - dilution refrigerator: ~60mK
  - dipole magnet (transverse): 0.5T
  - solenoid (longitudinal): 2.5T
  - microwave system
- Polarization determined with **Nuclear Magnetic Resonance (NMR)**



NH_3: ammonia beads, **^{6}LiD:** deuterated lithium
dilution factor ~ 0.22 (NH3), 0.5 (LiD)

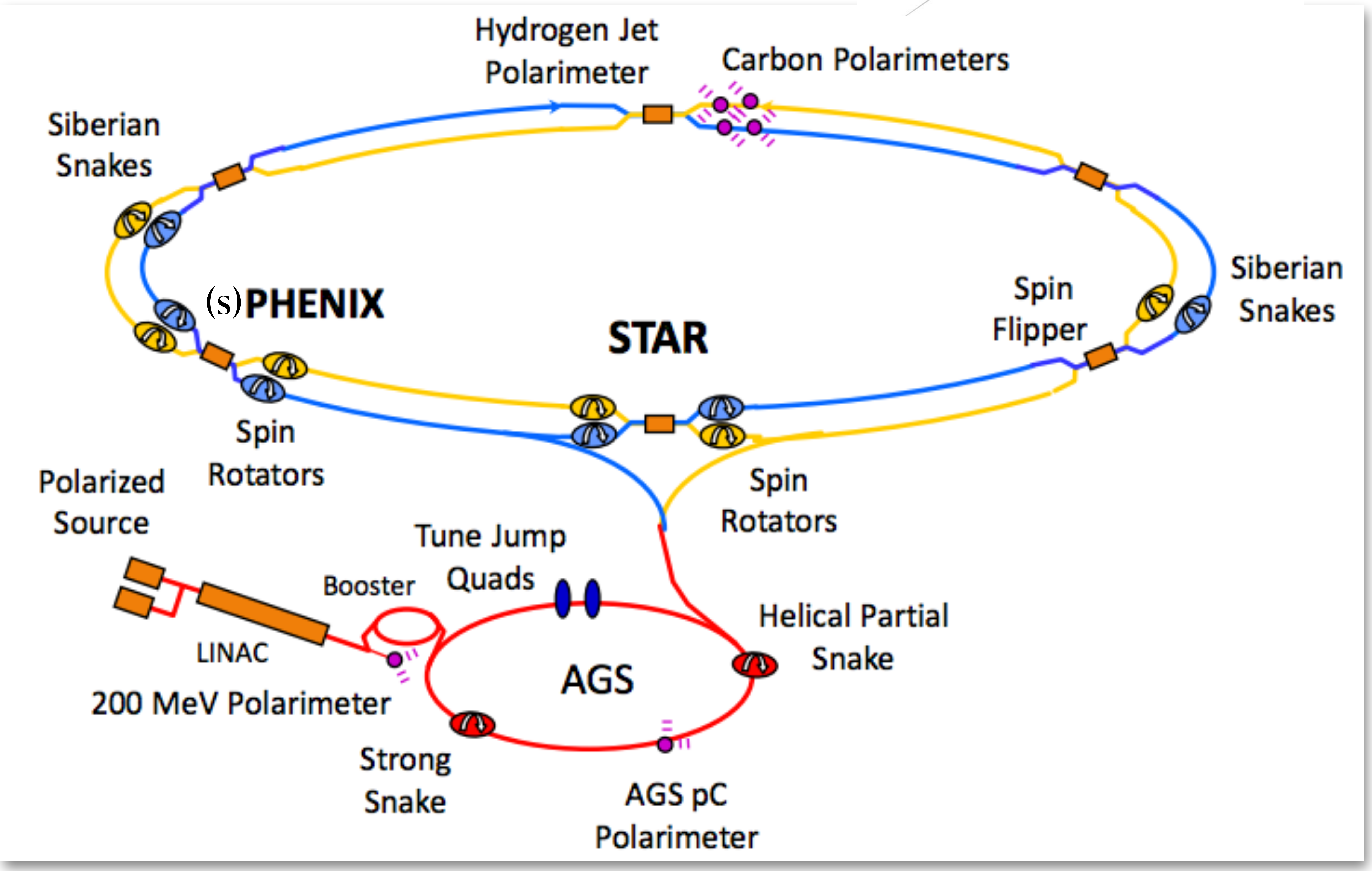


- Precise tracking (350 planes) - SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon Walls
- PID - CEDARs, RICH, calorimeters, MWs

Collisions with polarized protons at RHIC

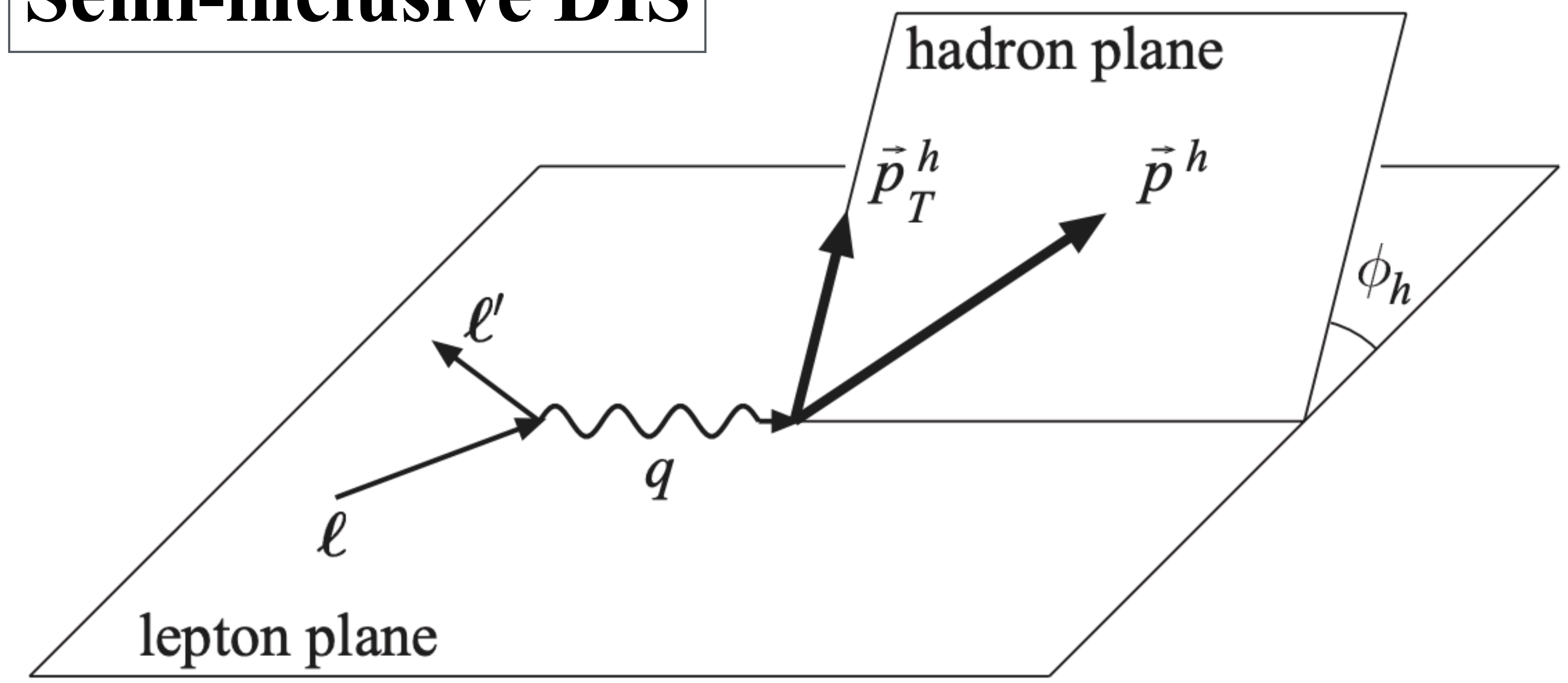
- Relativistic heavy ion collider - RHIC
- Collisions of L- and T-polarized protons, $\sqrt{s}$ = 200, 500/510 GeV
- Optically pumped ion source (OPPIS) that transfers electron polarization to protons. Siberian Snakes to overcome the effects of depolarizing resonances.

BROOKHAVEN NATIONAL LABORATORY



Accessing intrinsic transverse parton momenta in SIDIS

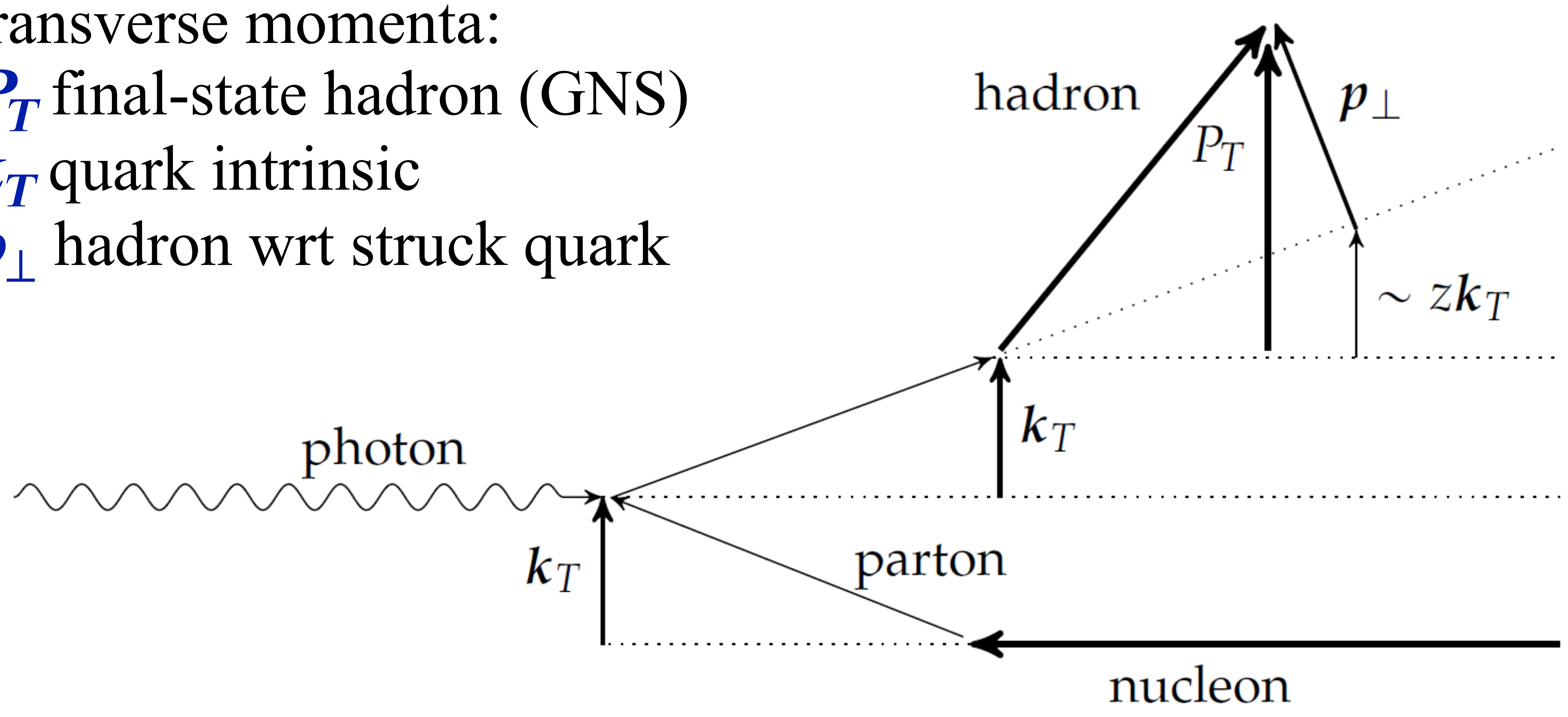
Semi-inclusive DIS



detect in addition to scattered lepton also hadron with **energy z** and **transverse momentum P_T**

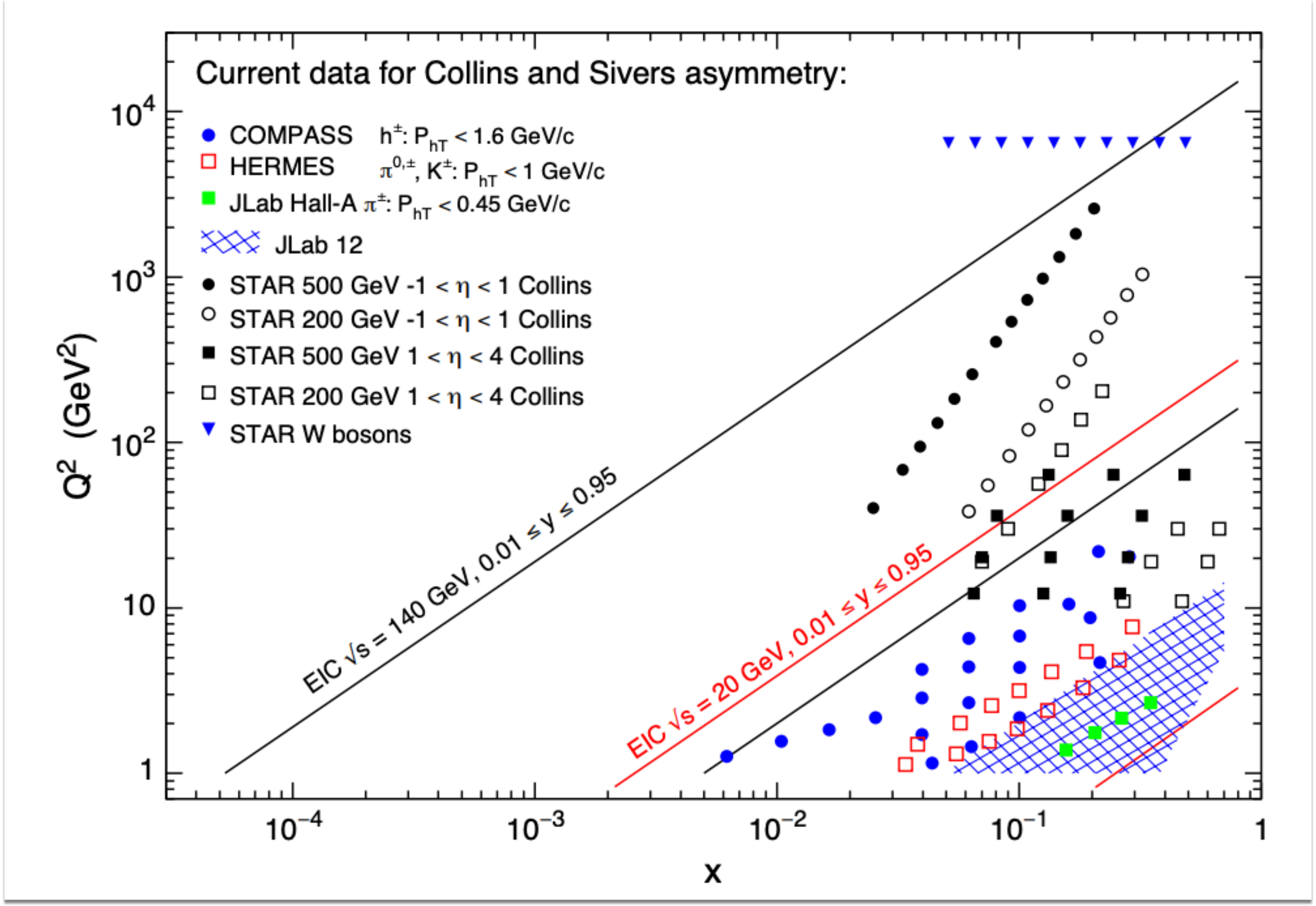
k_T intrinsic transverse quark momentum

transverse momenta:
P_T final-state hadron (GNS)
k_T quark intrinsic
$p_\perp$ hadron wrt struck quark



TMD backup

TMD measurements - a huge experimental effort

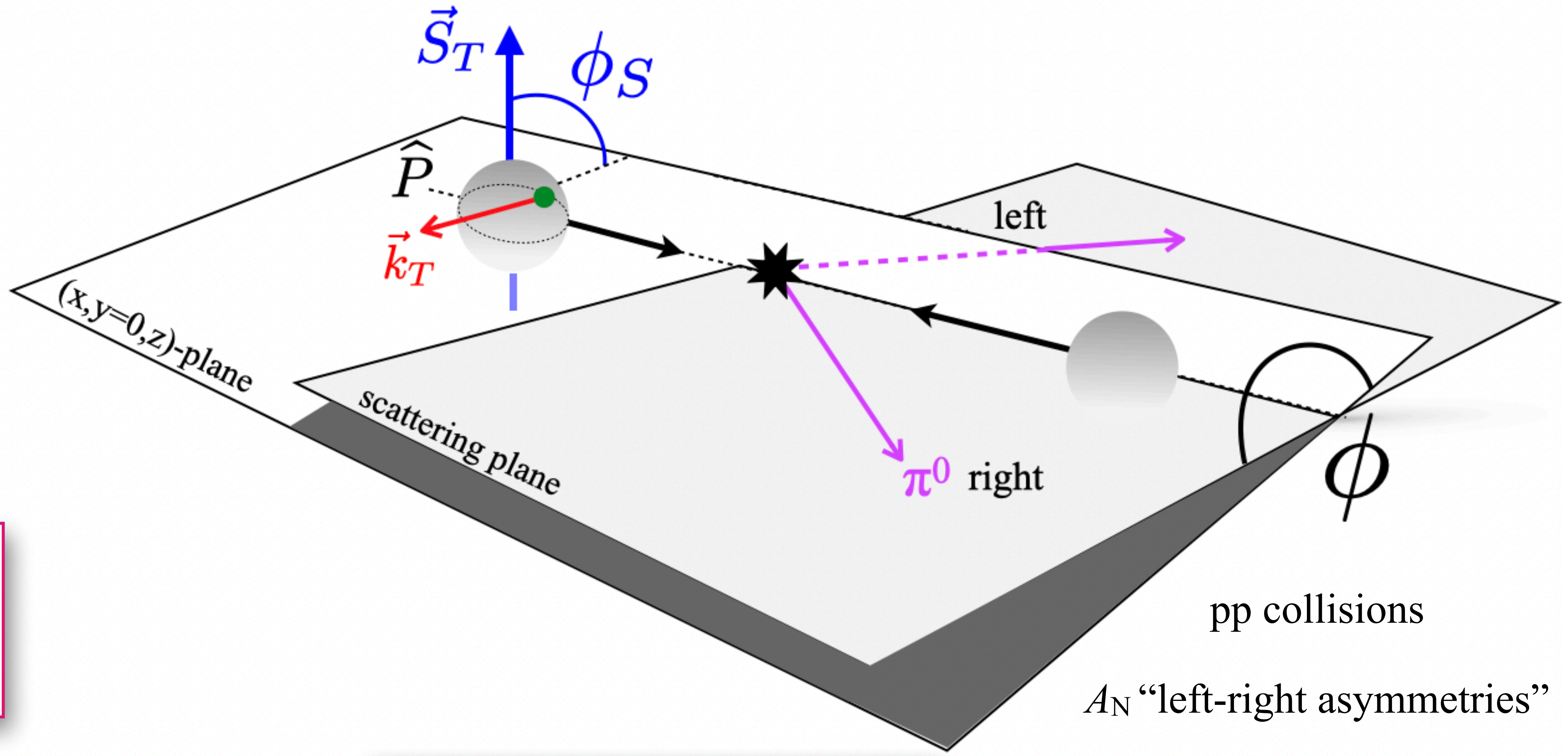


[EIC yellow report, arXiv:2103.05419]

Transverse single-spin asymmetries

Transverse spin asymmetries have **common origin** - simultaneous description across different collision species possible.

e.g. [Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (JAM Collaboration), PRD 102, 054002 (2020)]



pp collisions

A_N "left-right asymmetries"

Two complementary but related **theoretical descriptions**, depending on **what is measured** (reconstructed experimentally)

Probing with two scales (not only here) - hard resolves particle nature of partons, soft reveals emergent phenomena

- **TMD framework** when transverse momentum is probed
  - measure 2 scales with $p_T \ll Q$; SIDIS, DY, W/Z, dijets, hadrons in jets
- **Collinear higher-twist (HT) framework**
  - Measure 1-scale with $p_T \approx Q$; single inclusive particle production in pp (particle or jet p_T)
  - spin asymmetries from quantum mechanical interference of multi-parton states (→ qgq and ggg correlators)

Spin-orbit correlations in the proton $\vec{S} \cdot (\vec{p_1} \times \vec{p_2})$

- If TMDs describing strength of **spin-orbit correlations** are non-zero: may in certain models be connected to parton **orbital angular momentum (OAM)**.
  - No quantitative relation between TMDs & OAM identified yet.
- **Sivers effect:** correlation between the nucleon transverse spin & parton transverse momentum in the transversely polarized nucleon
- The Sivers function was originally thought to vanish (*). A nonzero Sivers function was then shown to be allowed due to **QCD final state interactions** (soft gluon exchange) in SIDIS between the outgoing quark and the target remnant (**).
- **“Chromodynamic lensing”** [M. Burkardt, Nucl.Phys.A735:185-199,2004]

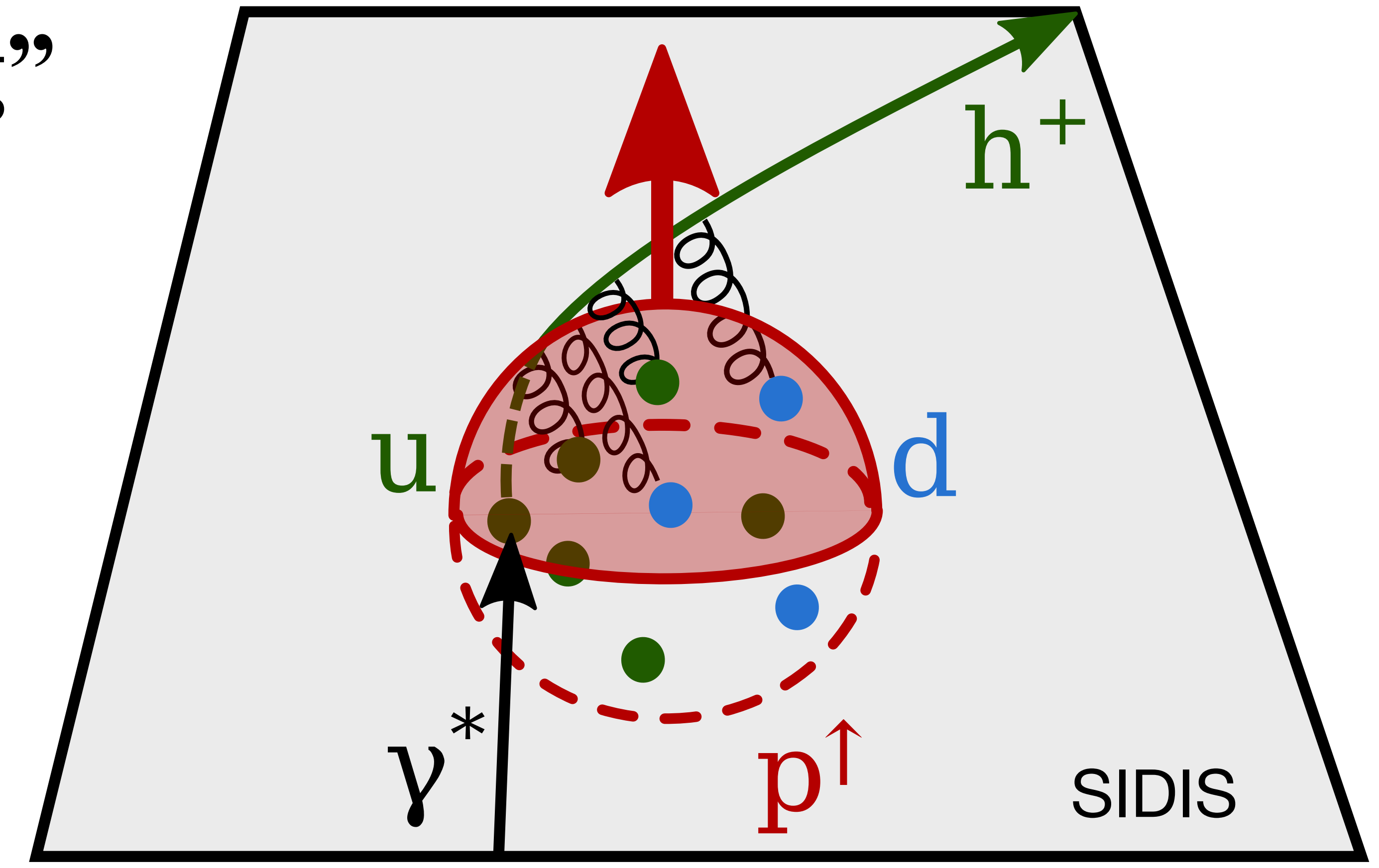
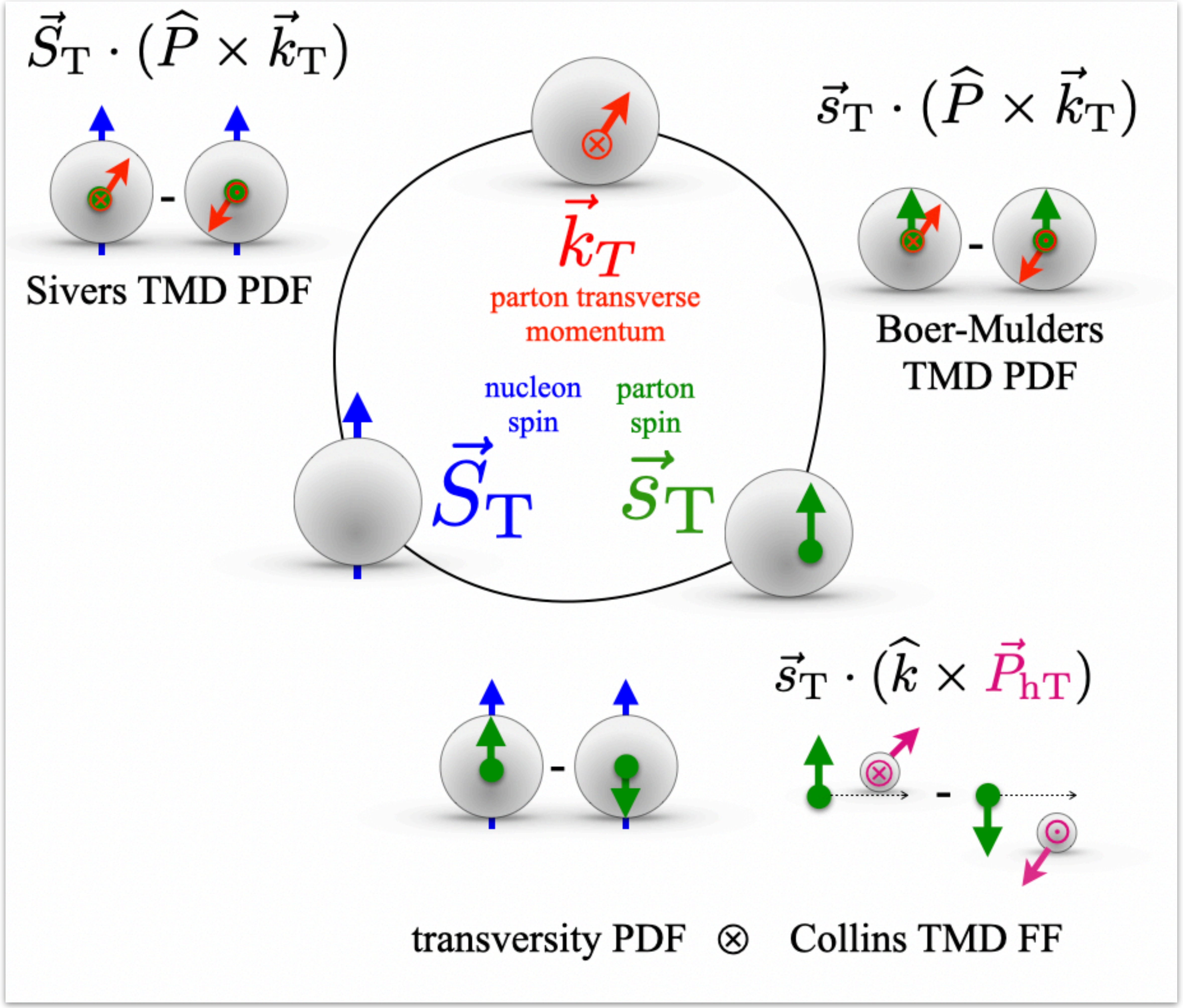


Image courtesy Jan Matoušek



- **Collins effect:** fragmentation of a transversely polarized parton into a final-state hadron (spin-spin correlation)

(*) [J. C. Collins, Nucl. Phys. B396, 161 (1993)]
(**) [S. J. Brodsky et al., Phys. Lett. B530, 99 (2002)]

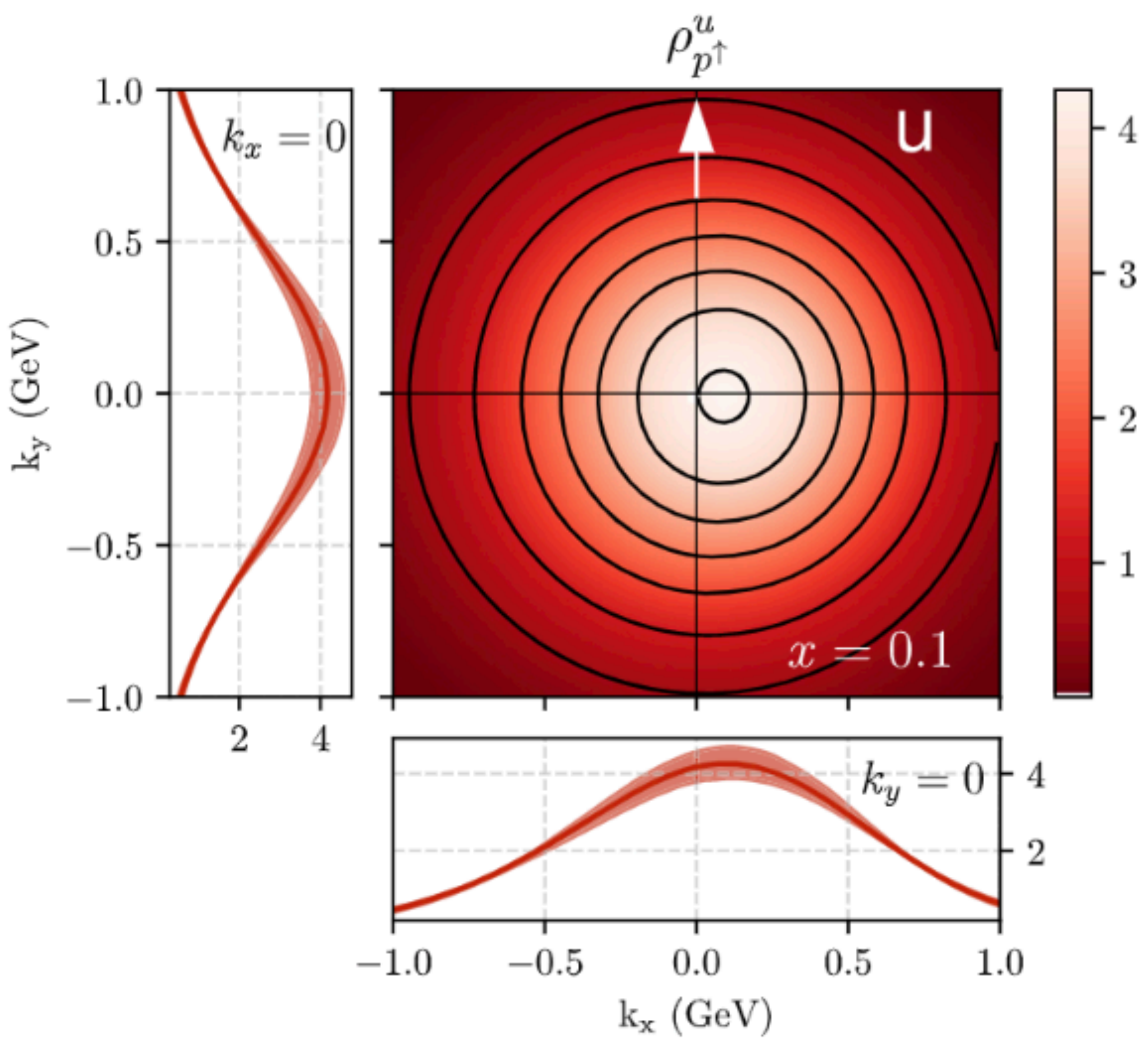
The strength of distortion in transverse-momentum space is proportional to

$\vec{S}_T \cdot (\widehat{P} \times \vec{k}_T)$

and is called the Sivers amplitude

$f_{1T}^{\perp q}$

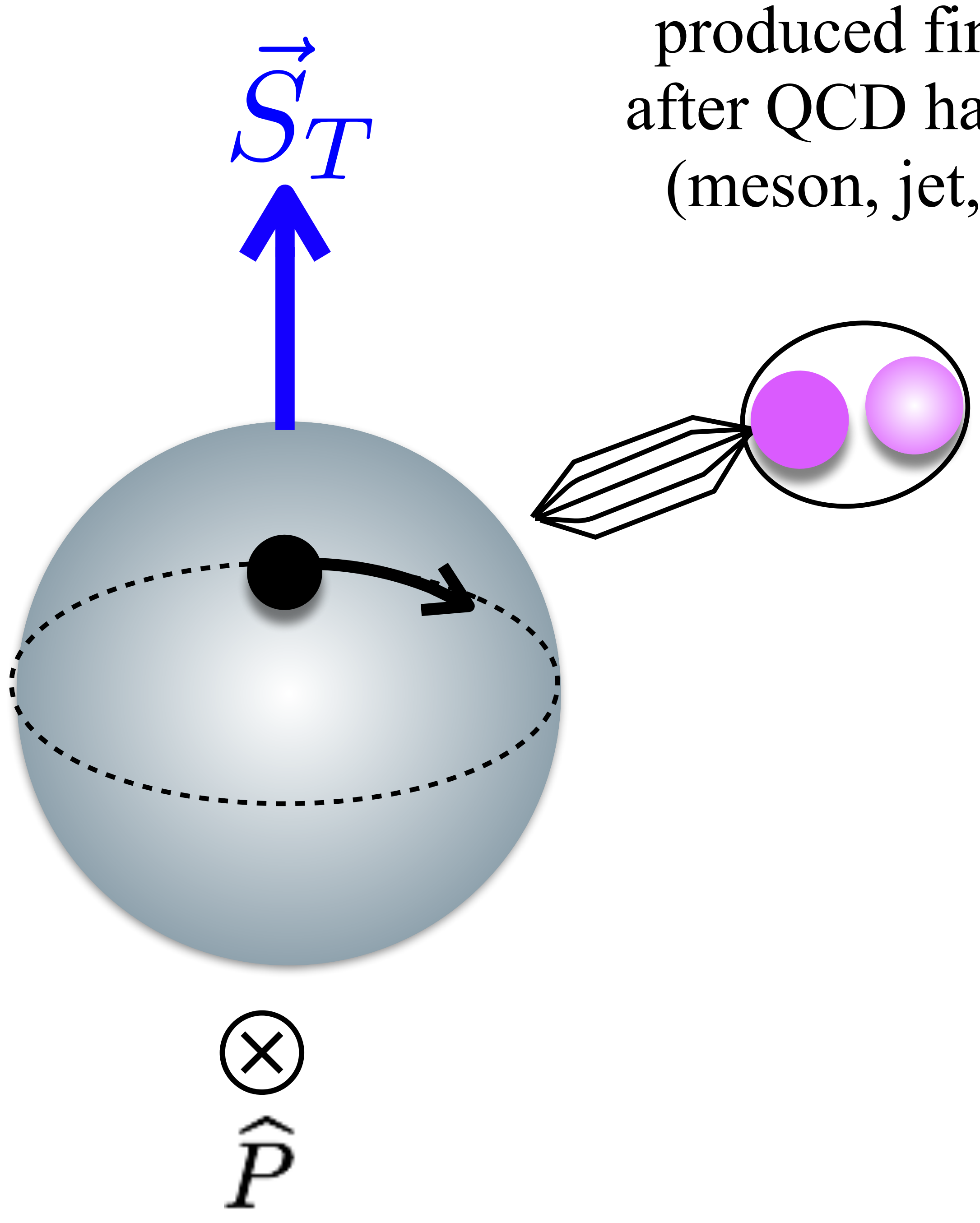
$$f_{q/p^\uparrow}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T^2) - f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)\, \boldsymbol{S} \cdot \left(\frac{\hat{\boldsymbol{P}}}{M} \times \boldsymbol{k}_T \right)$$



PV19 fit using SIDIS data from HERMES, COMPASS and Hall A

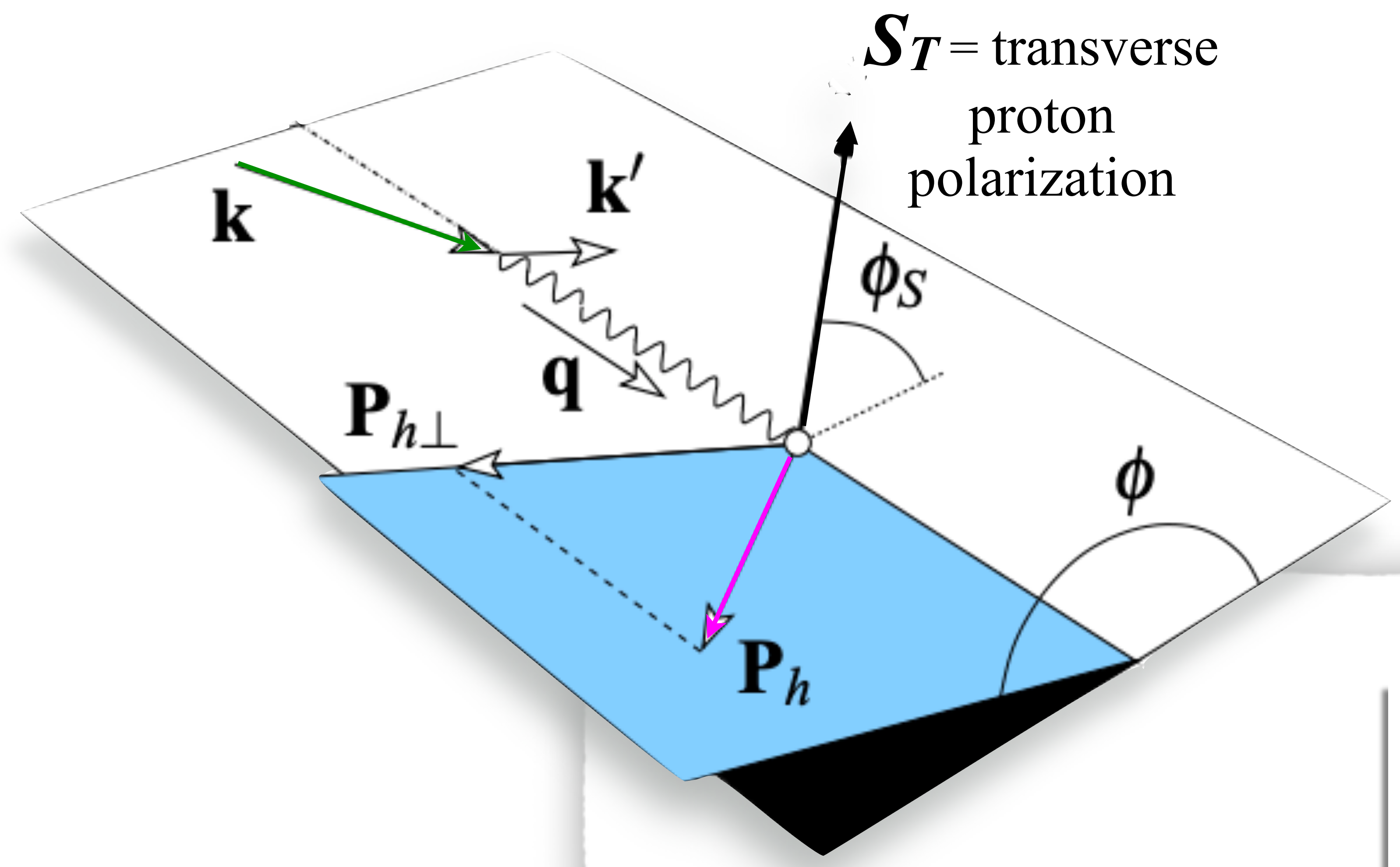
$\vec{S}_T \cdot (\widehat{P} \times \vec{k}_T)$

[Bacchetta, Delcarro, Pisano, Radici, PLB 827, 136961 (2022)]



produced final state well after QCD hard interaction (meson, jet, photon, …)

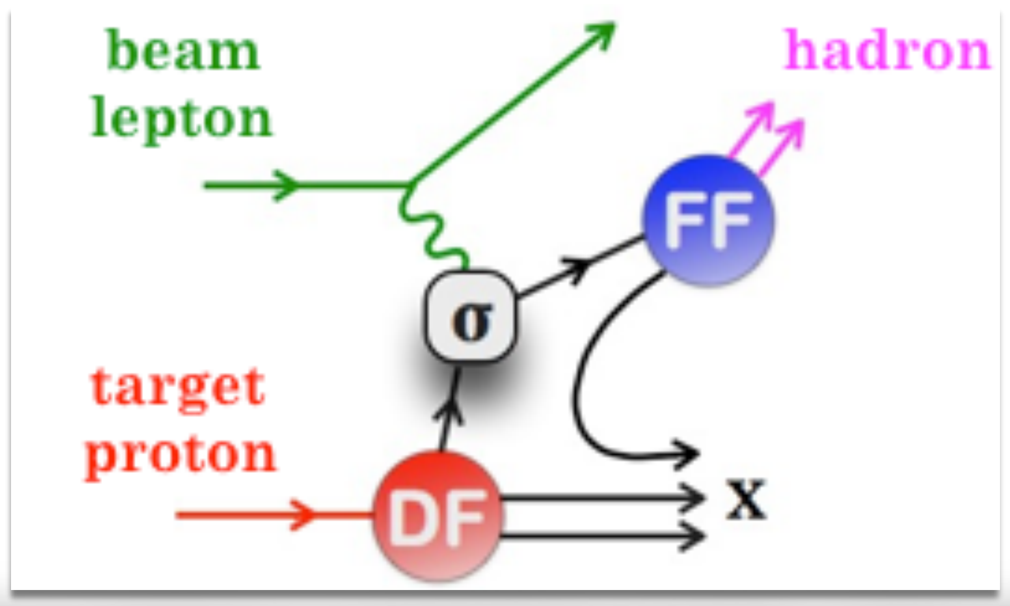
Semi-inclusive deep-inelastic scattering cross section



"~ harmonic(ϕ, ϕ_S) · PDF ⊗ FF"

measured observable:

$$A_{UT}(\phi) = \frac{1}{f S_T} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$



fragmentation function (FF)

parton distribution function (PDF)

$$\sigma(\phi,\phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi\, F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi\, F_{LU}^{\sin\phi}\right] +$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\,\sin\phi\, F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right] + S_L\lambda_e\left[\sqrt{1-\epsilon^2}\, F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi\, F_{LL}^{\cos\phi}\right]$$

$$+|S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\,\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+|S_T|\lambda_e\Big[\sqrt{1-\epsilon^2}\,\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\,\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}.$$

no proton polarization

longitudinal proton polarization

transverse proton polarization

Cahn-effect + BM ⊗ Collins

worm-gear-L ⊗ Collins

BM ⊗ Collins

Sivers ⊗ D1

KM (worm-gear-T) ⊗ D1

transversity ⊗ Collins

pretzelosity ⊗ Collins

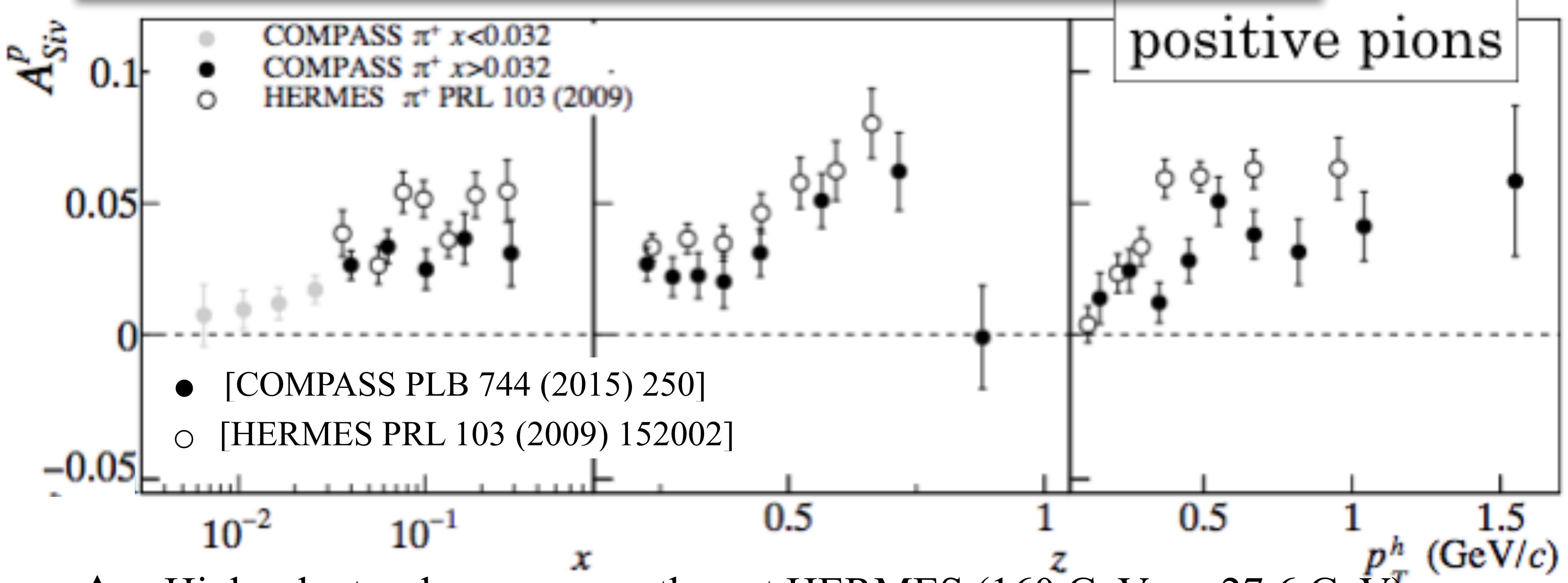
$F_{XY[Z]}$ = structure function. X=beam, Y= target polarization, [Z= virtual-photon polarization]. X, Y ∈ {U, L, T}. λ_e = helicity of lepton beam. S_L and S_T = longitudinal and transverse target polarization. ϵ = ratio of longitudinal / transverse photon fluxes

[Bacchetta, Diehl, Klaus Goeke, Metz, Mulders, Schlegel, JHEP 02 (2007) 093]

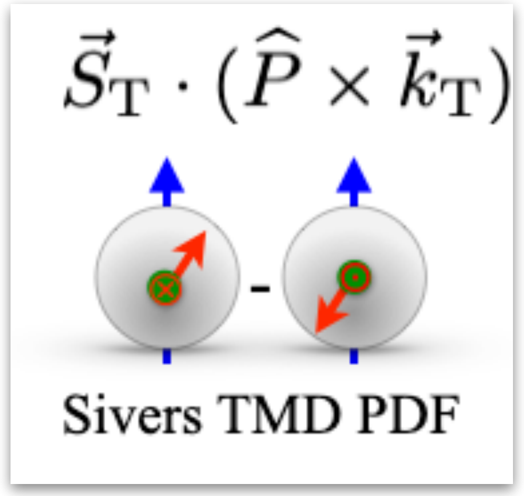
Sivers TMD PDF from SIDIS

HERMES vs. COMPASS Sivers asymmetries

positive pions



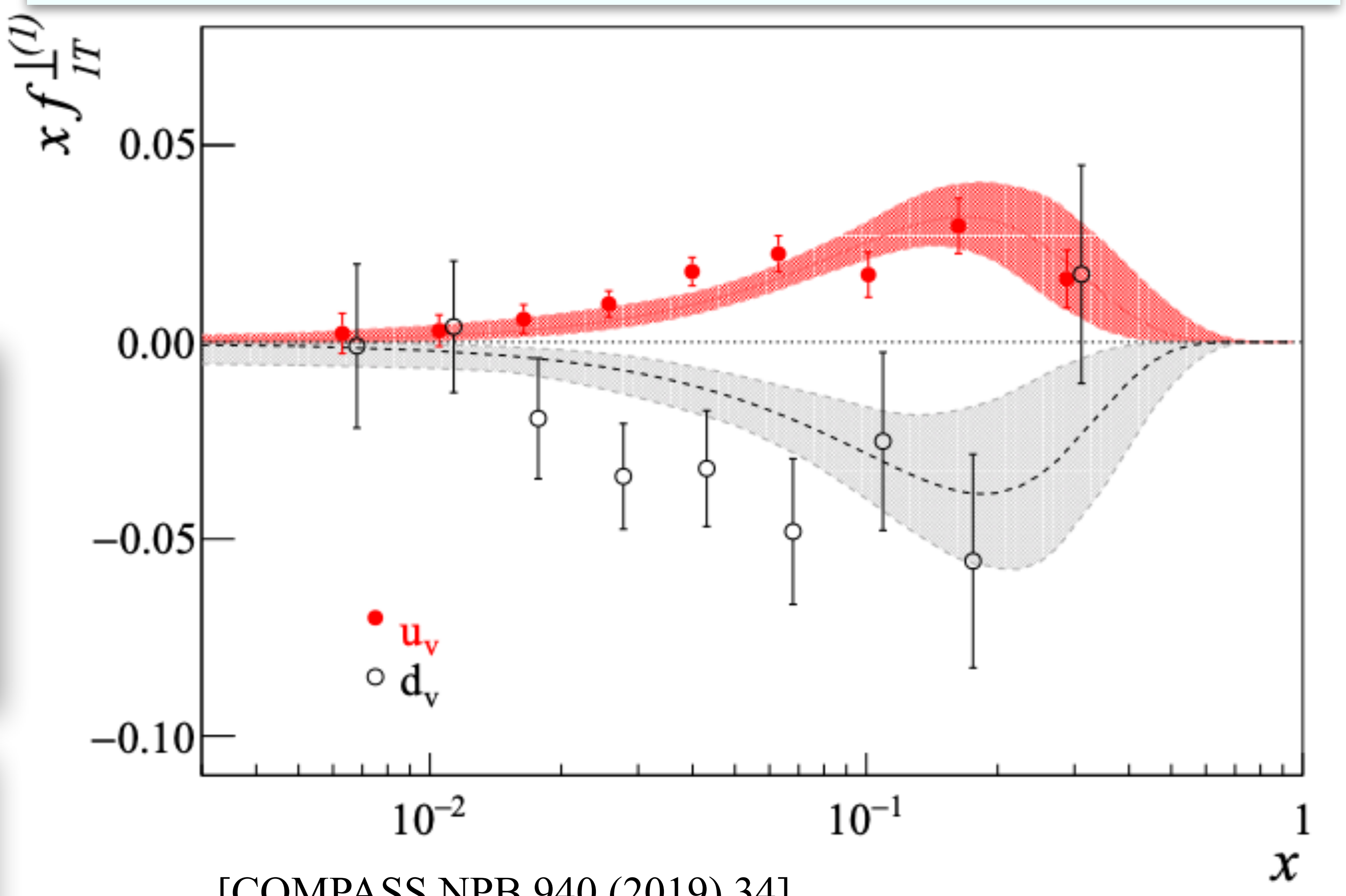
✦ Higher lepton-beam energy than at HERMES (160 GeV vs. 27.6 GeV)



Sivers signal smaller at COMPASS than at HERMES.
TMD evolution…?

u- and d-quark Sivers functions have opposite signs

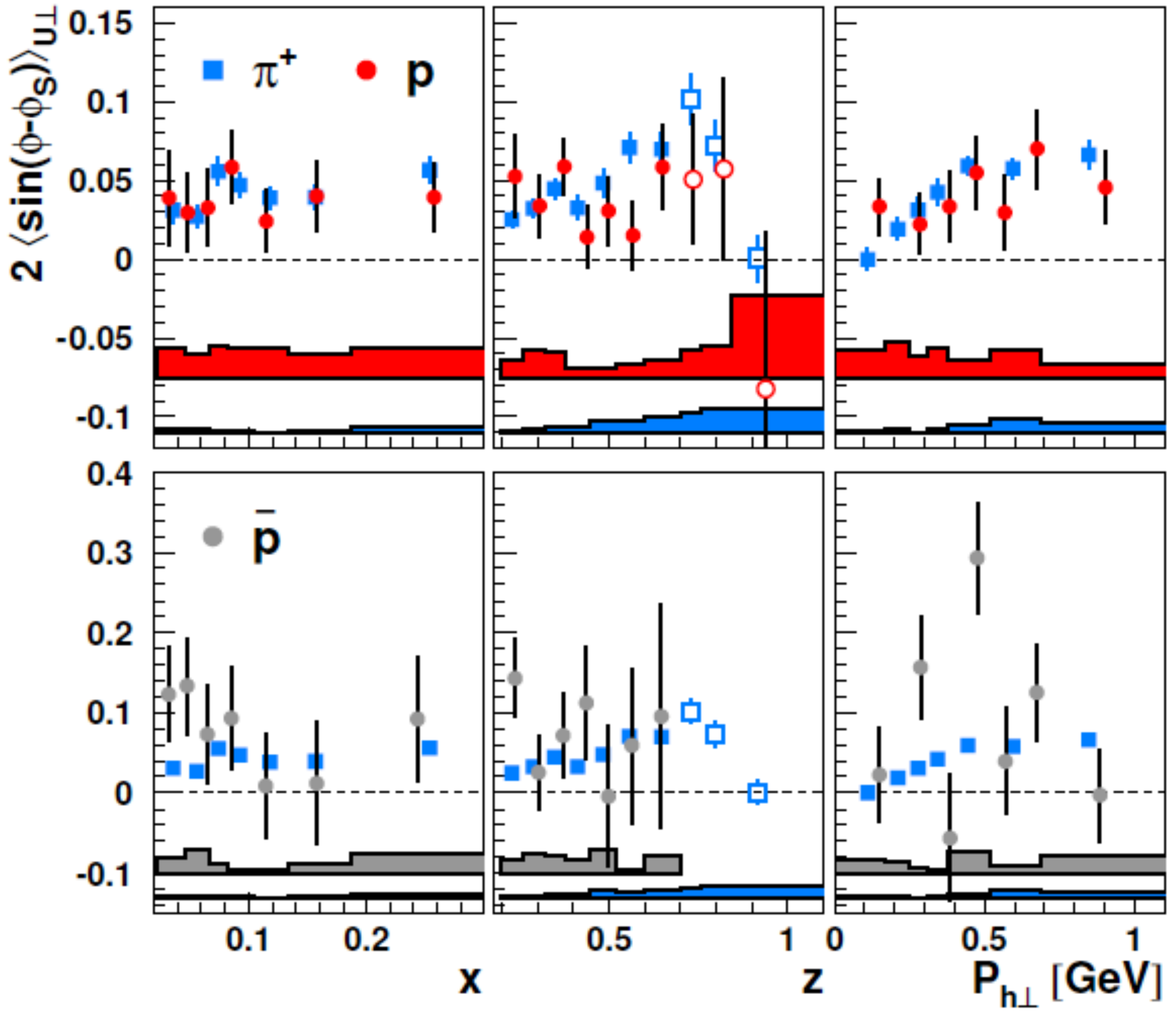
Sivers function from COMPASS asym.

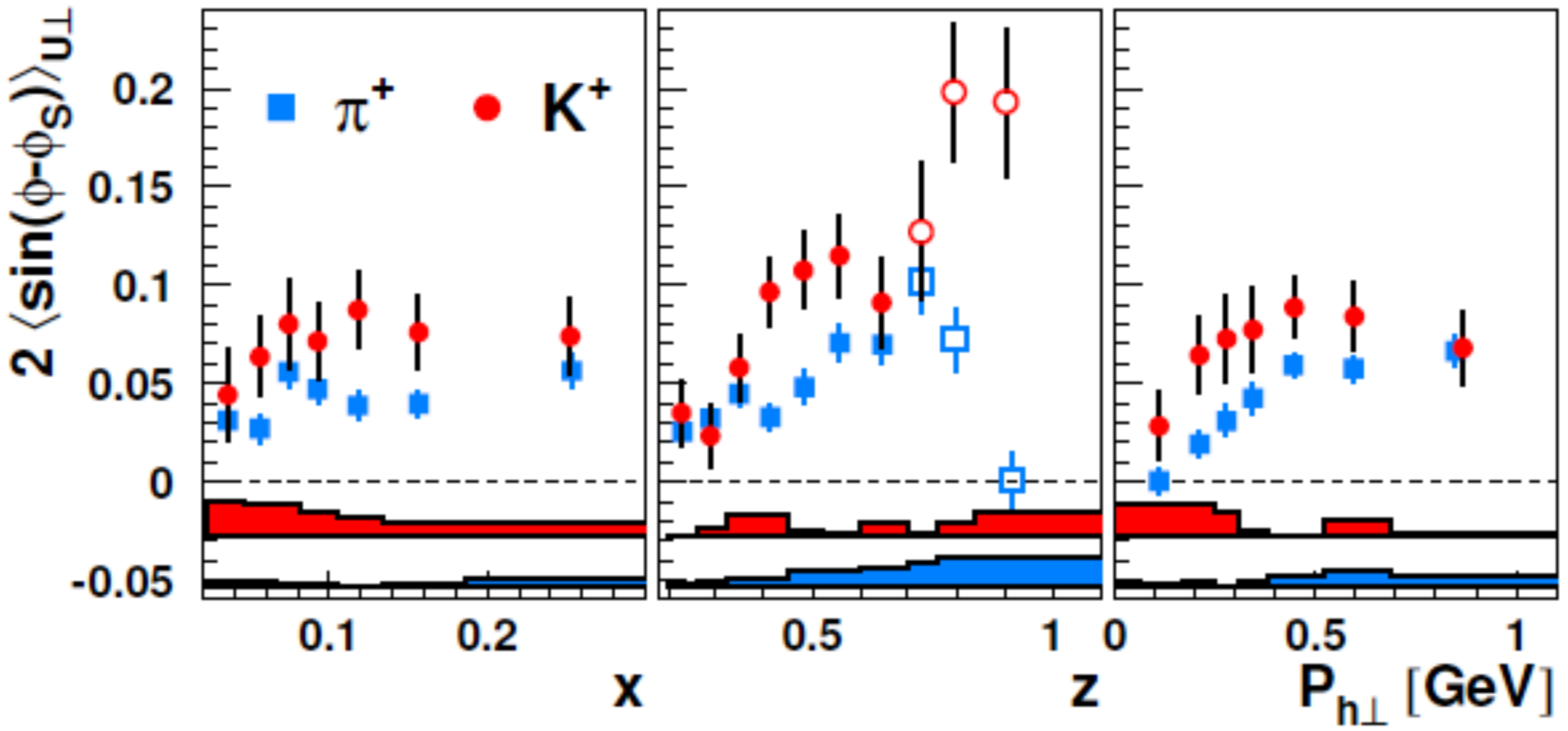


[COMPASS NPB 940 (2019) 34]
[Anselmino *et al.*, Phys.Rev. D86 (2012) 014028]

✦ p_T-weighted asymmetries: direct measurement of TMD k_T^2 moments that avoids assumptions on shape of k_T. Products instead of convolutions of TMDs

HERMES TMD final compendium



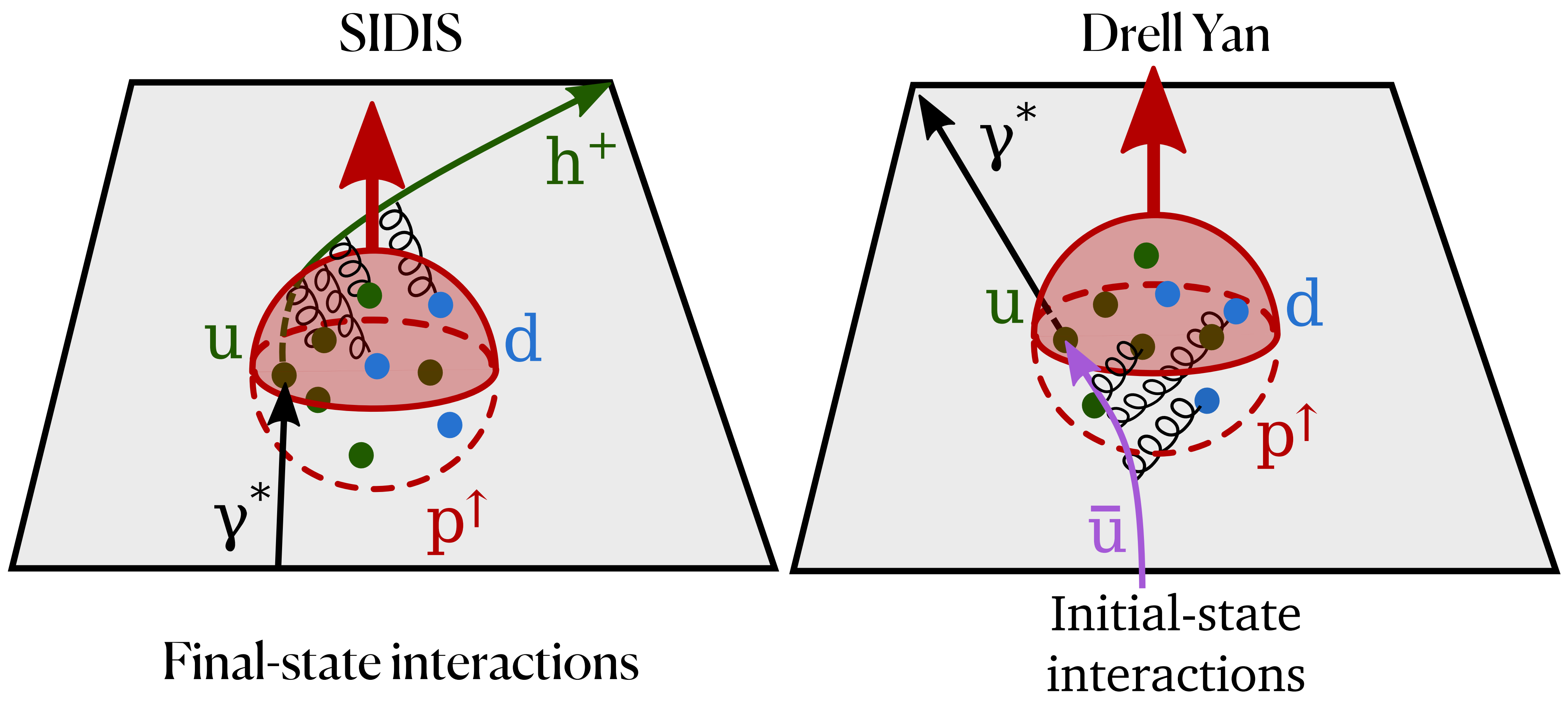


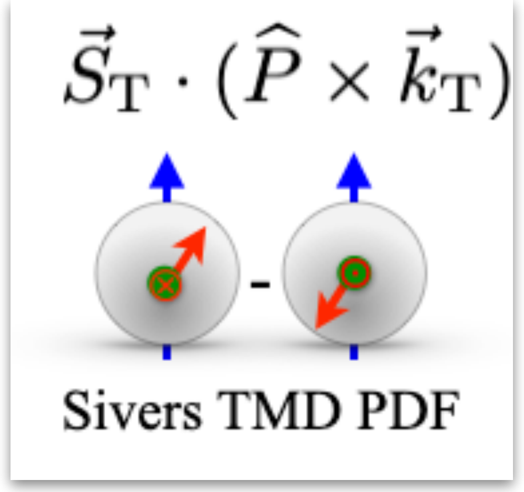
[HERMES JHEP 12 (2020) 010]

Kaon amplitudes larger than pion
~Unexpected if u-quark scattering dominates.
Role of sea quarks?

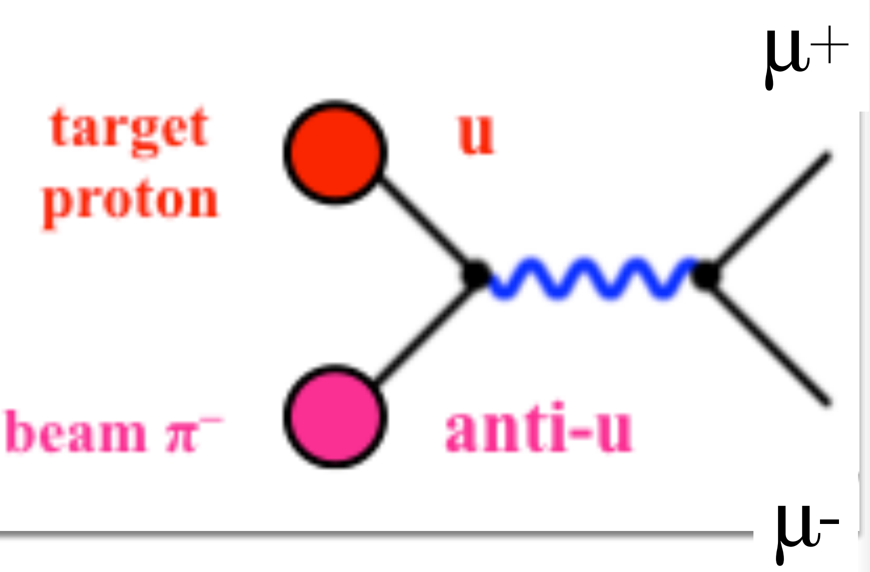
Sivers-TMD sign switch

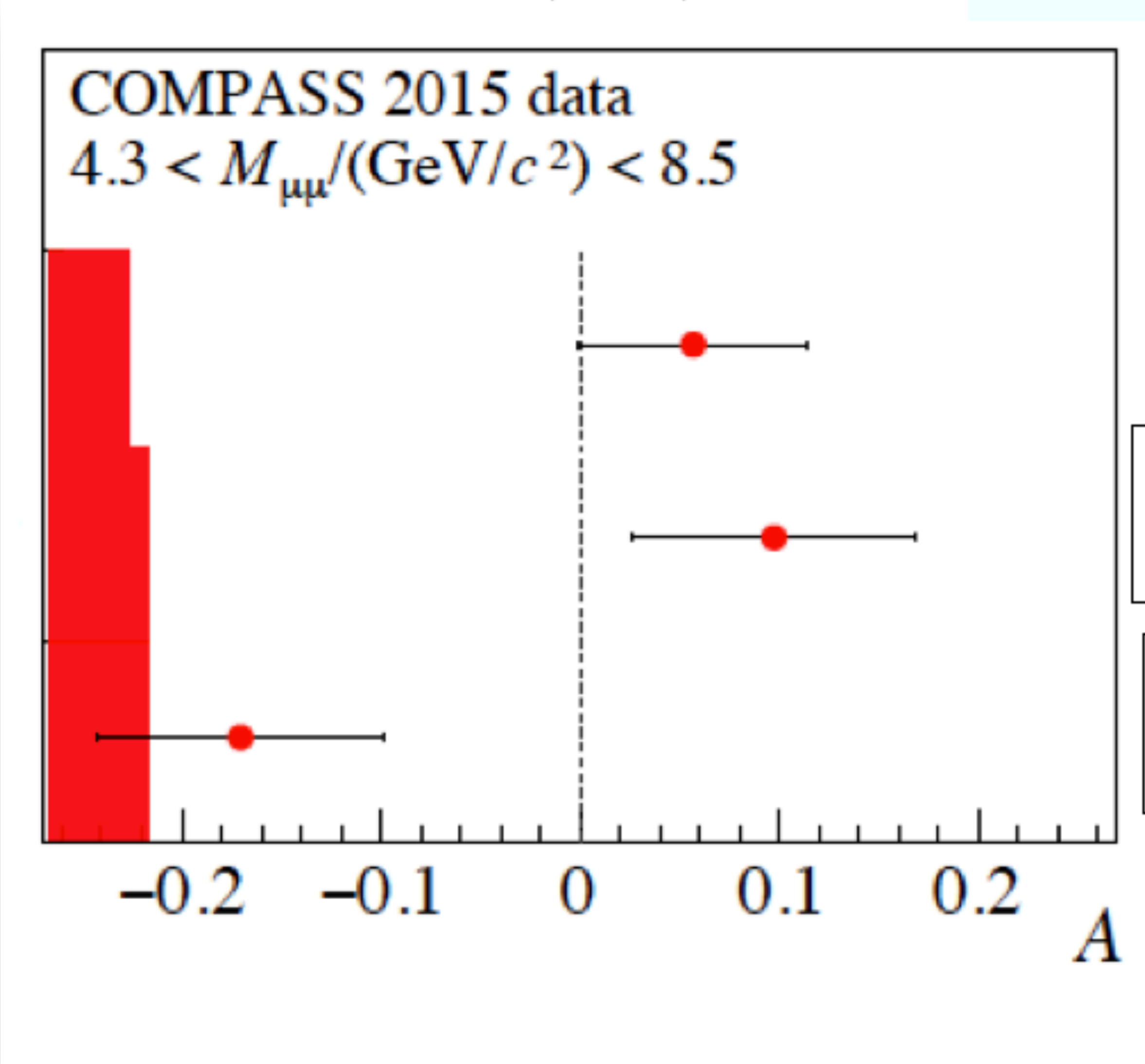
The experimental test of the **Sivers TMD PDF** (and other naive time-reversal odd TMDs) **sign-switch** prediction is an important test of TMD-QCD framework.





Drell-Yan COMPASS Sivers asymmetry **SIDIS**





(Sivers)p ⊗ (f1)π

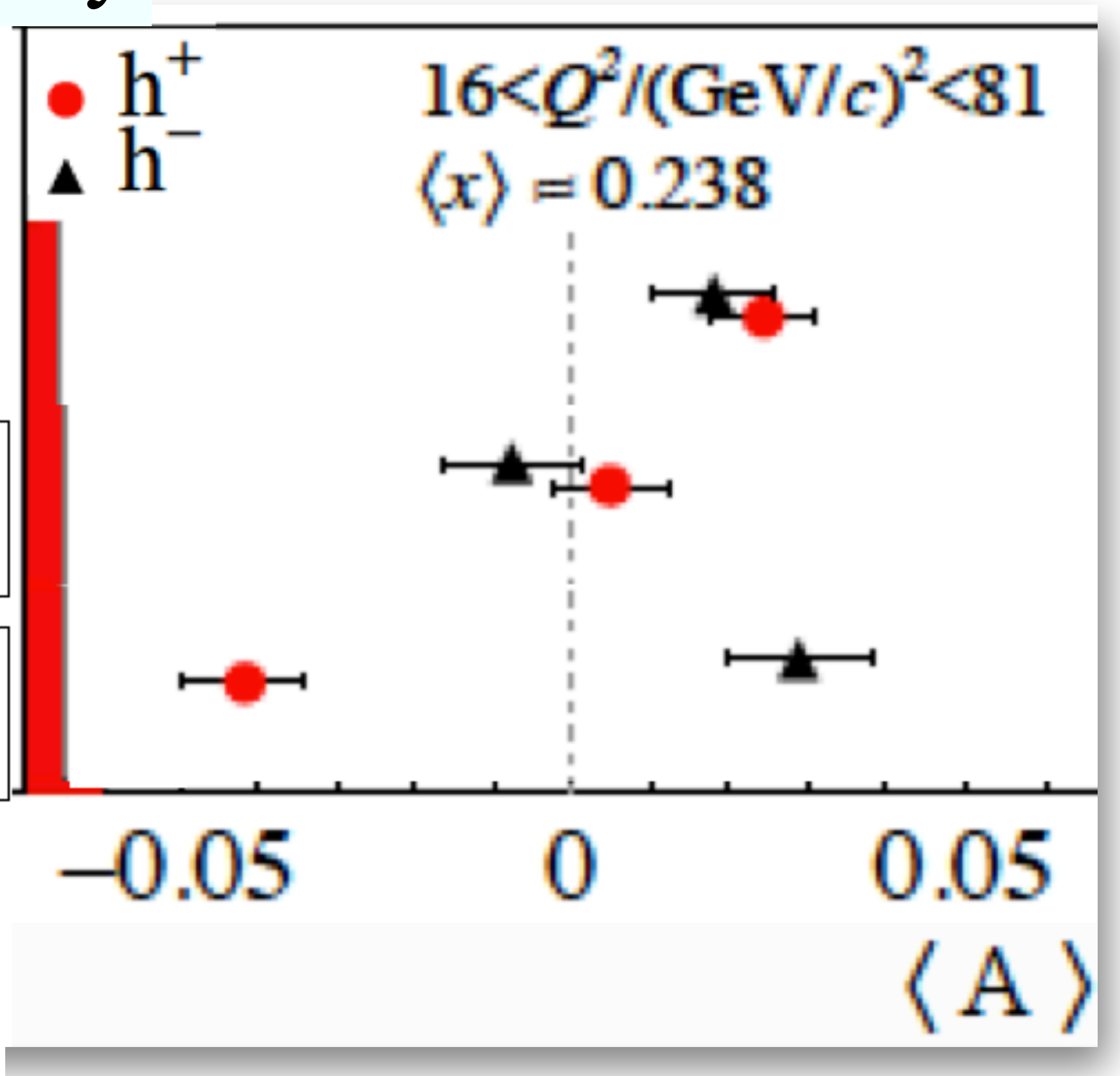
(Pretzelosity)p ⊗ (BM)π

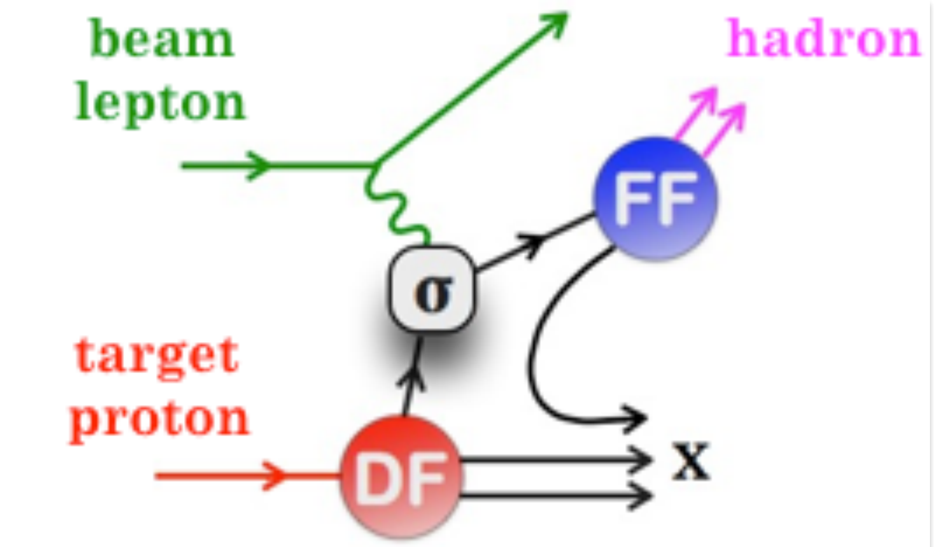
(Transversity)p ⊗ (BM)π

Sivers ⊗ D1

Pretzelosity ⊗ Collins

Transversity ⊗ Collins





[COMPASS PRL 119 (2017) 112002]

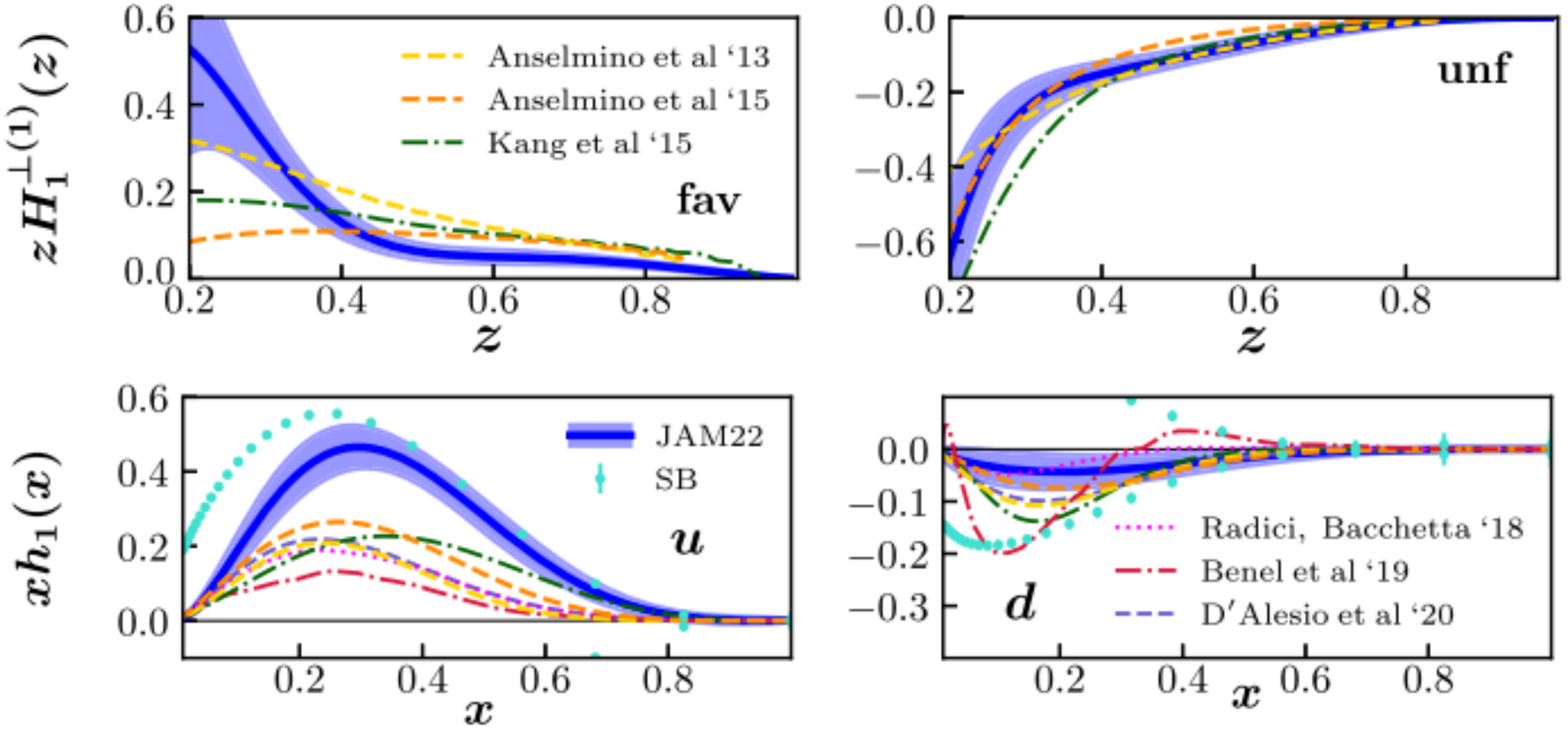
Drell-Yan (DY) 2015 data

COMPASS measurement of Sivers SIDIS & DY asymmetries with ~same apparatus & in overlapping kinematics.

[COMPASS PLB 770 (2017) 138]

SIDIS *in the DY kinematic range*

Global TMD analysis - Collins FF, di-hadron FF, transversity TMD PDF

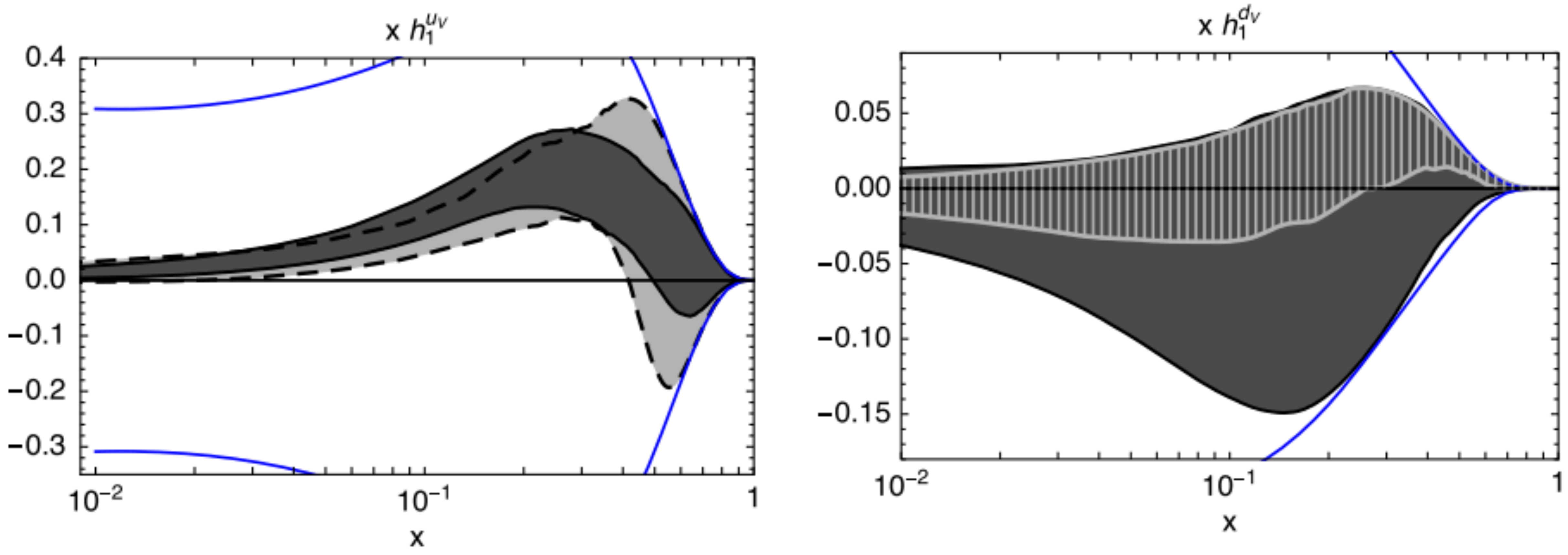


[JAM Collaboration - JAM3D-22, PRDD 106, 034014 (2022)]

- ***d*-quark transversity less constrained** given the *u*-quark dominance of many of the processes used in the global fits.
  - JAM-22 reduced uncertainties wrt JAM20 due to inclusion of lattice QCD data and Soffer bound.
  - COMPASS 22 transversity run on the deuteron will improve the experimental precision on the proton's tensor charge, $g_T = \delta_u - \delta_d$, by a factor of ~2.
  - Further prior-to-EIC measurements of Collins asymmetries include STAR with forward upgrade, sPHENIX, JLab12/SoLID, SpinQuest.

Global extraction of <u>transversity from di-hadron data:</u>

pion-pair multiplicities in pp needed

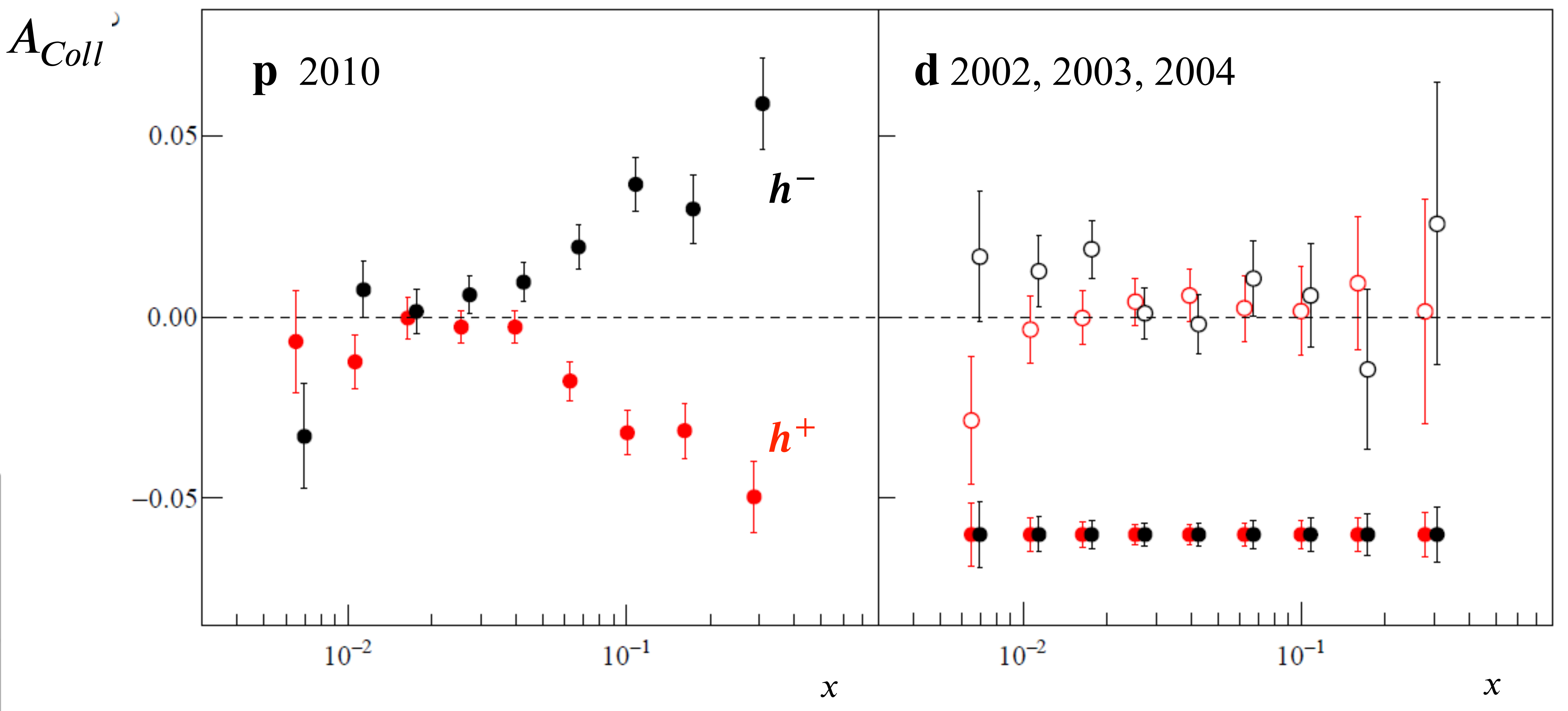


[Radici, Bacchetta, PRL 120, 192001 (2018)]

- Transversity TMD PDF coupled to **interference**, or **di-hadron, fragmentation function**
  - 2 collinear observables (DGLAP evolution, not TMD) - **complementary probe of transversity TMD**
  - interference of different channels of the fragmentation process into the two-hadron system (interference of S and P states)

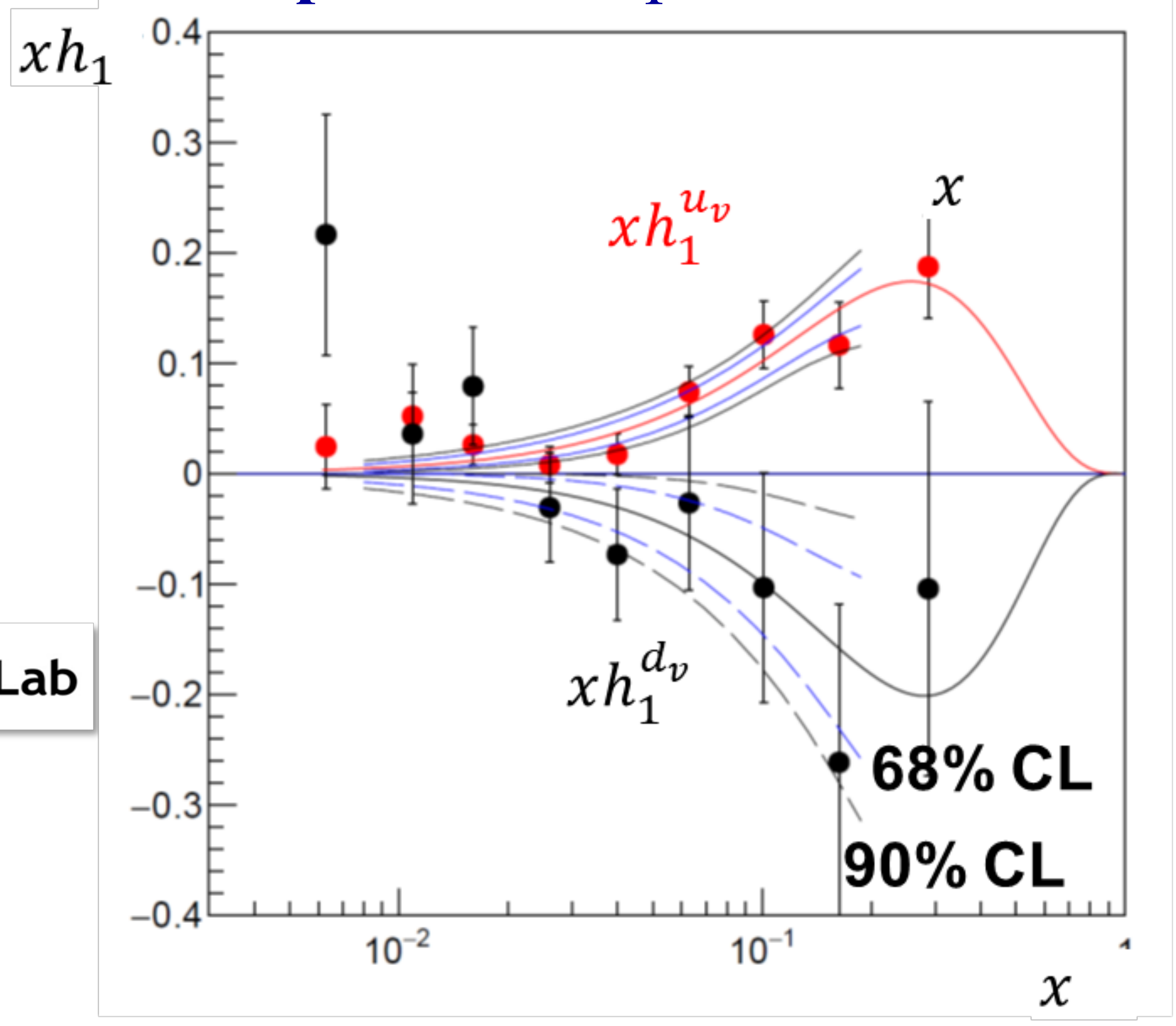
The 2022 COMPASS run: $\mu d^{\uparrow} \rightarrow hX$

- June - November 2022 with transversely polarized deuteron (^{6}LiD) target with almost the same conditions as 2010 proton run.
- Impact on the deuteron **SIDIS Collins asymmetry** - the 2022 uncertainties are expected to be a factor 2 to 5 smaller.
- Impact on **transversity TMD PDF** and on **tensor charge**

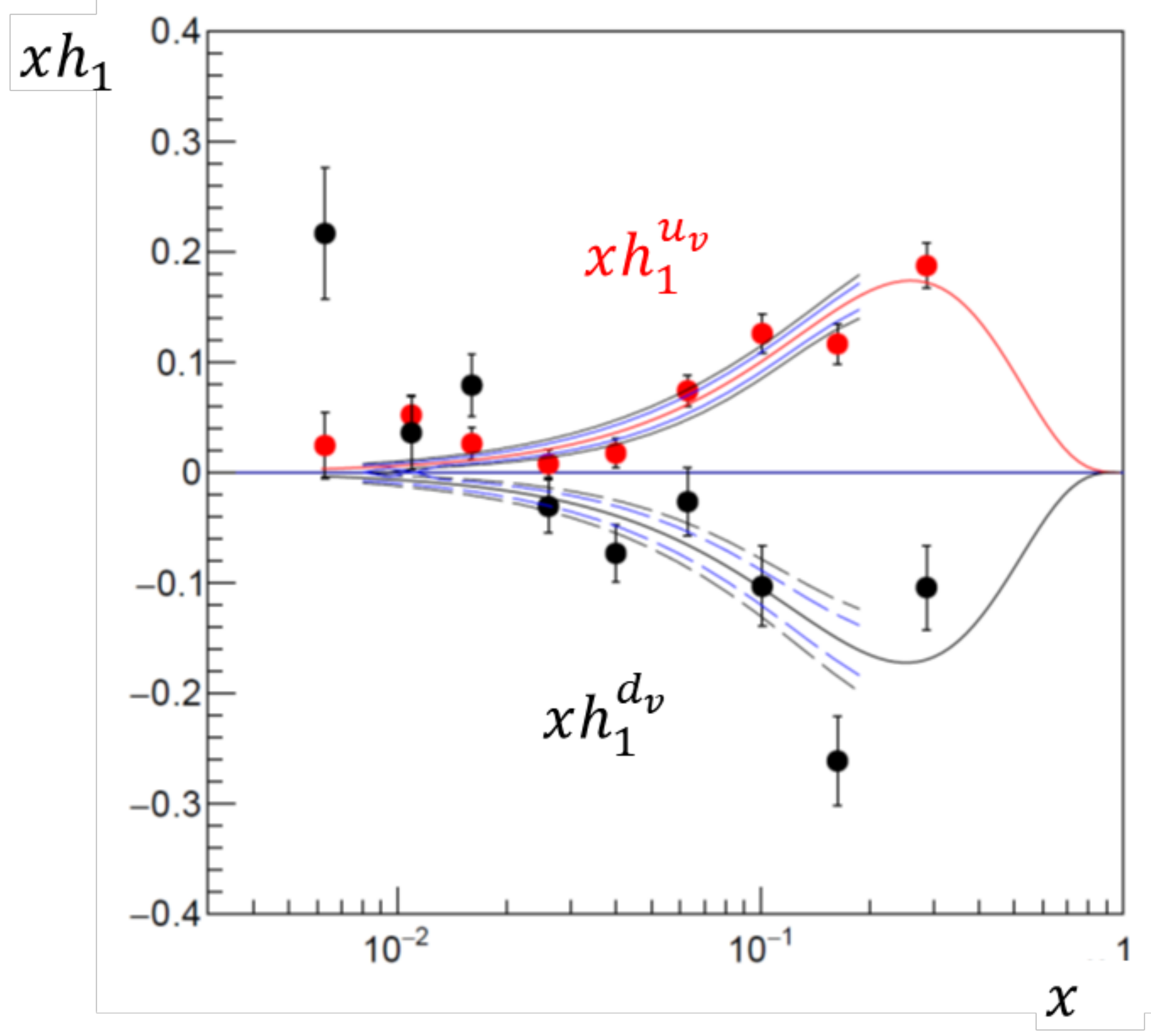


Ω_x: 0.008 ÷ 0.210	$\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{d}(x)$	$g_T = \delta_u - \delta_d$
present	$0.201 \pm \mathbf{0.032}$	$-0.189 \pm \mathbf{0.108}$	$0.390 \pm \mathbf{0.087}$
projected	$0.201 \pm \mathbf{0.019}$	$-0.189 \pm \mathbf{0.040}$	$0.390 \pm \mathbf{0.044}$

present: all p and d data

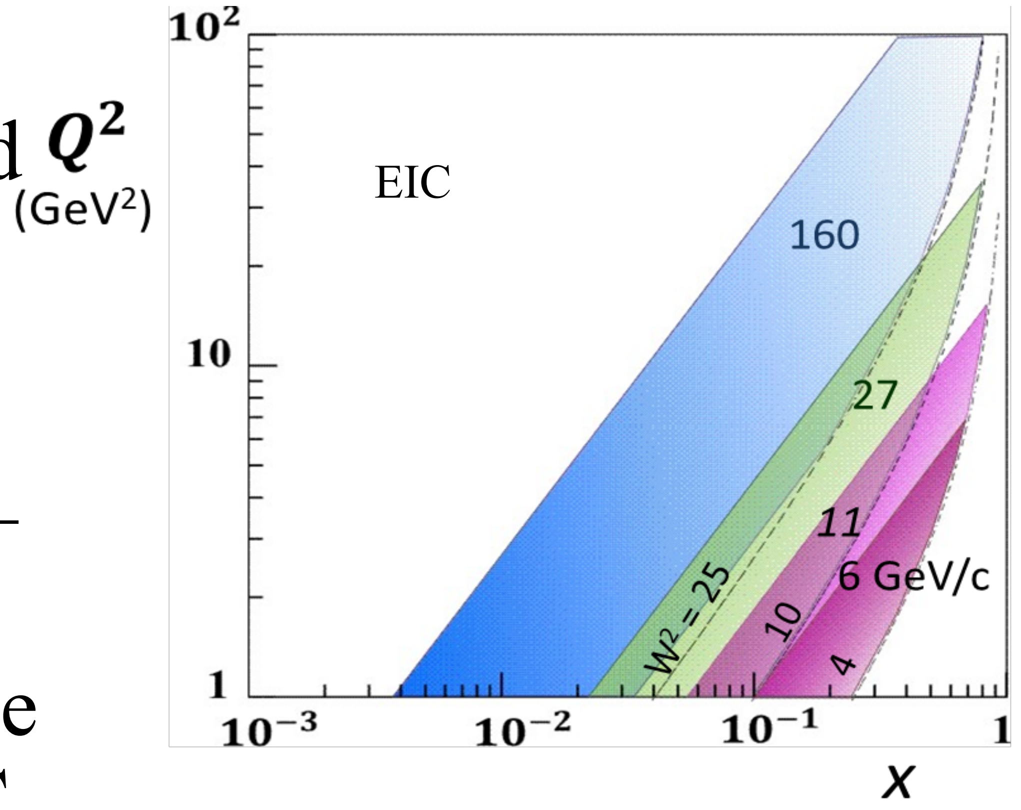


projected: all p and 2022 d data



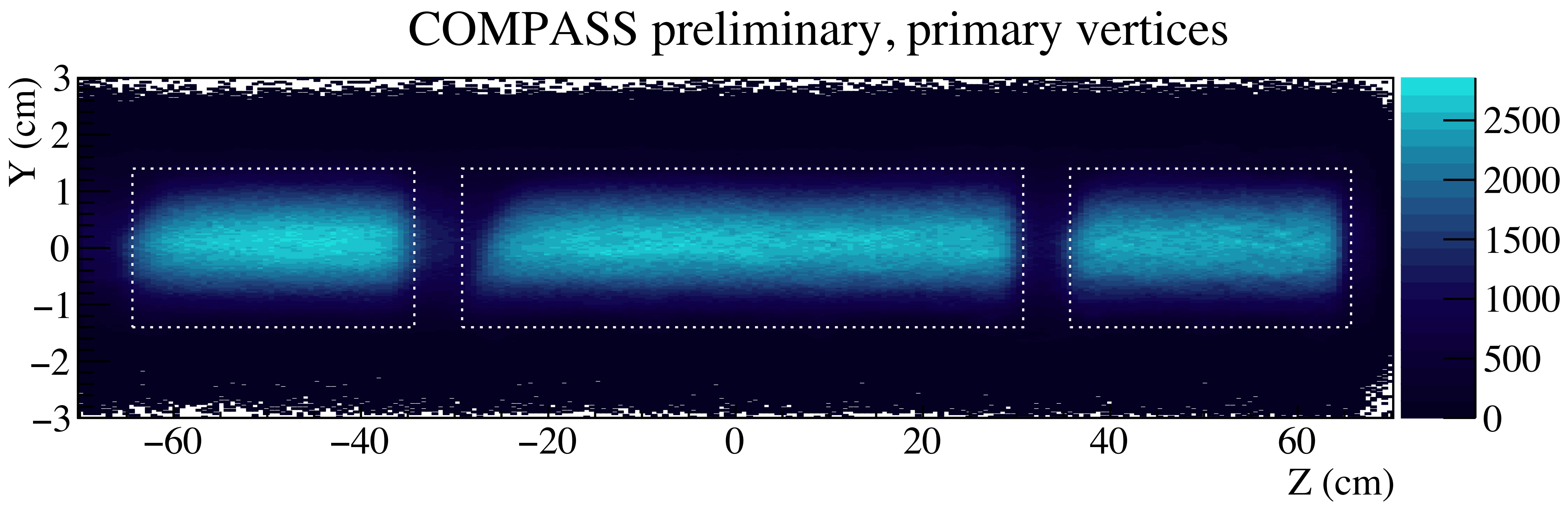
The work will not be over with the COMPASS measurements - precise measurements are needed asap, in particular at larger x.

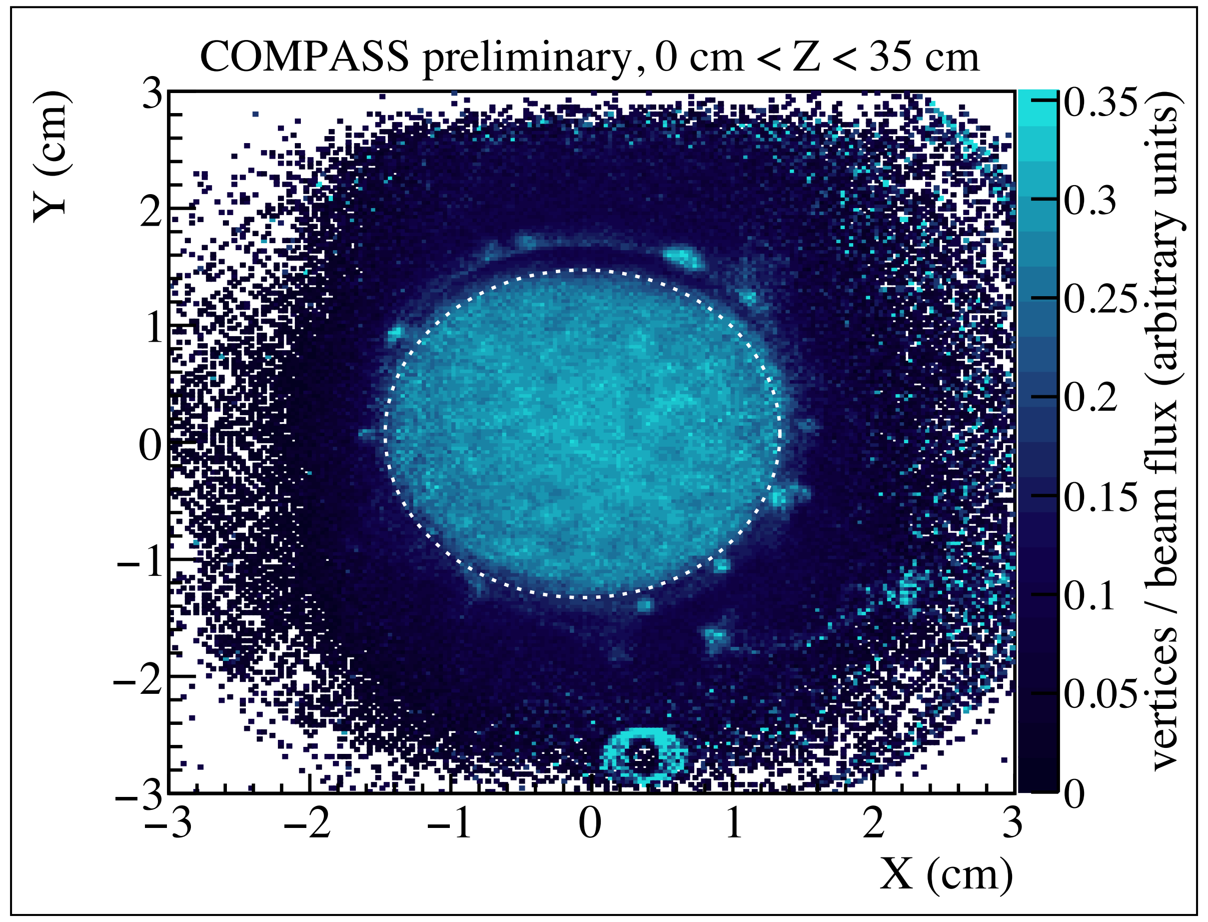
The complementary measurements at Jlab 12 and 20+ will allow for a more precise measurement of the tensor charge and, in the farther future, the EIC.

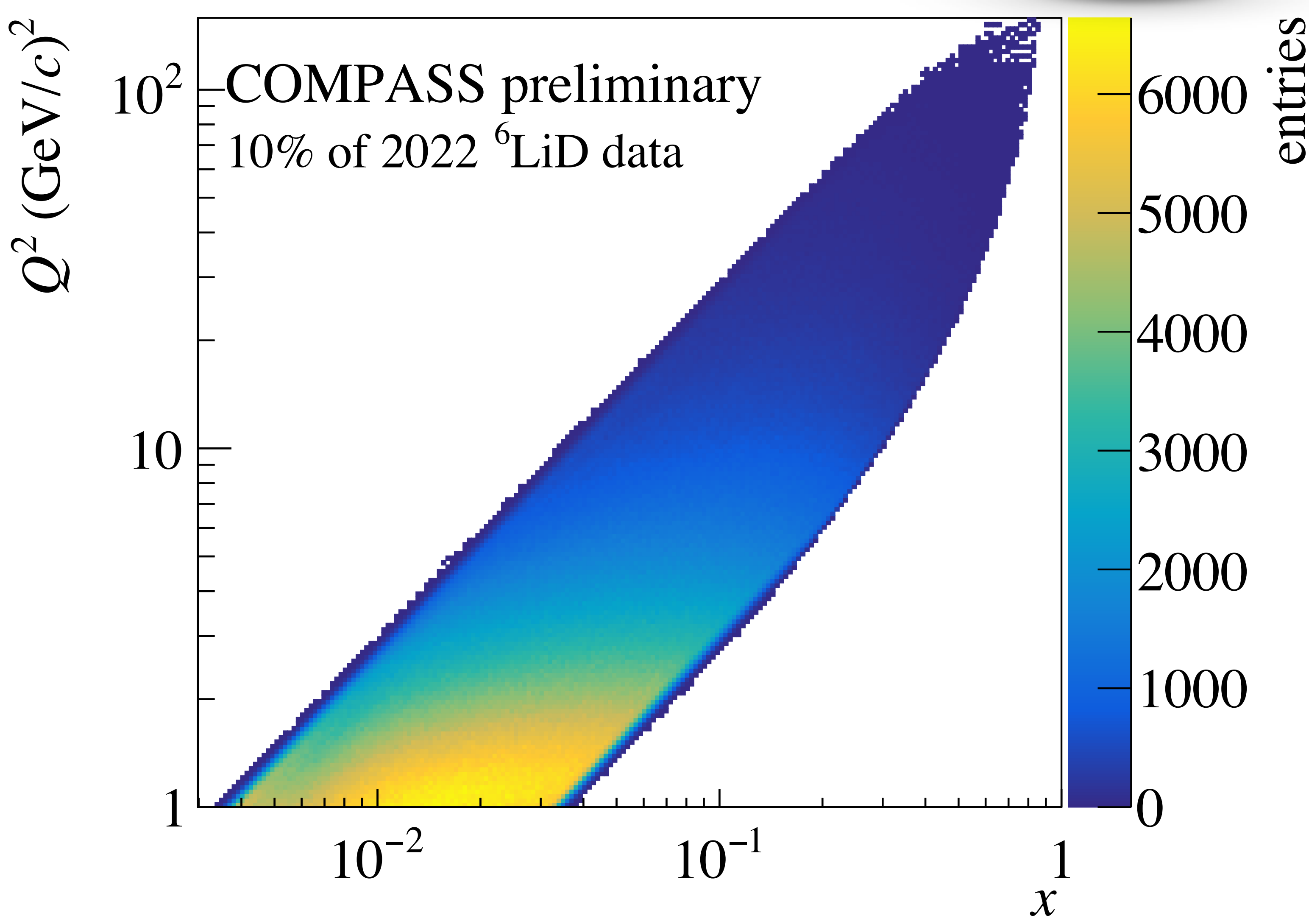


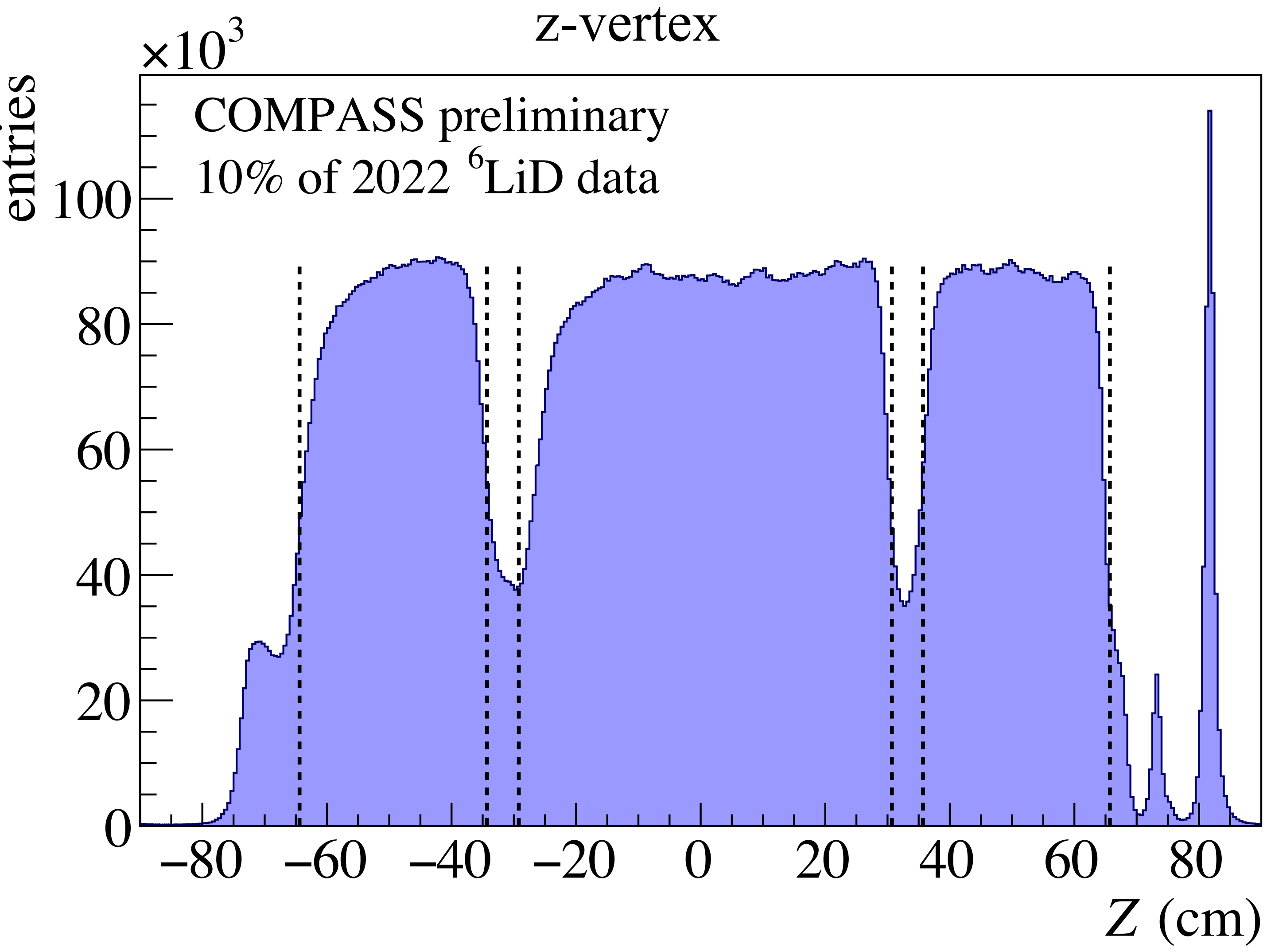
COMPASS
hermes
Jefferson Lab

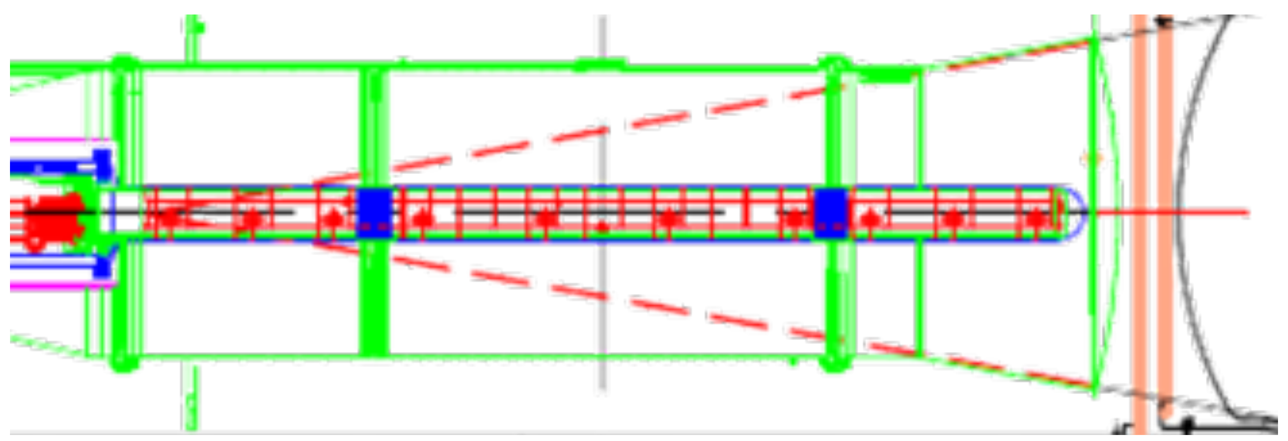
First look at the COMPASS 2022 data (about 10%)

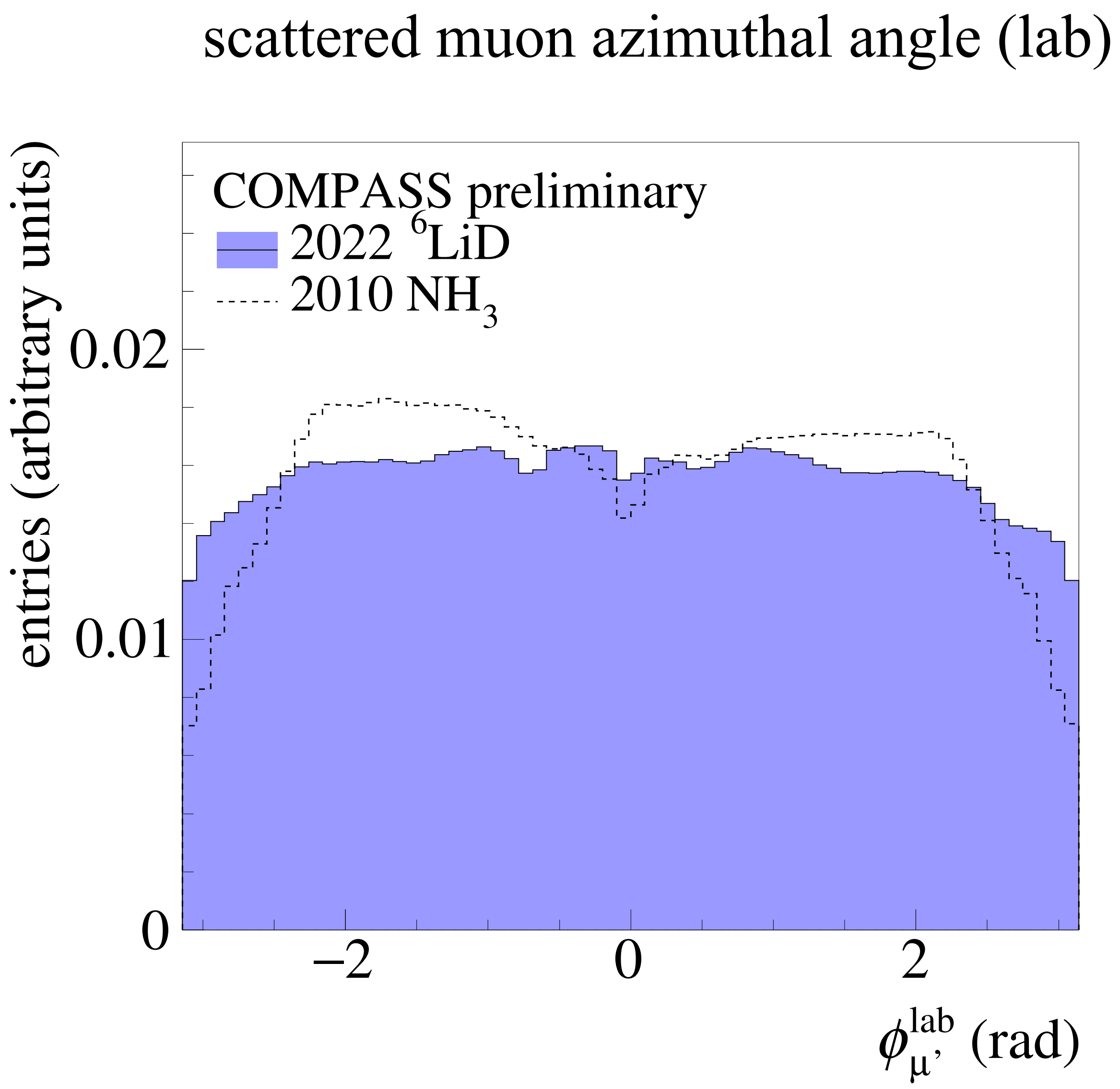


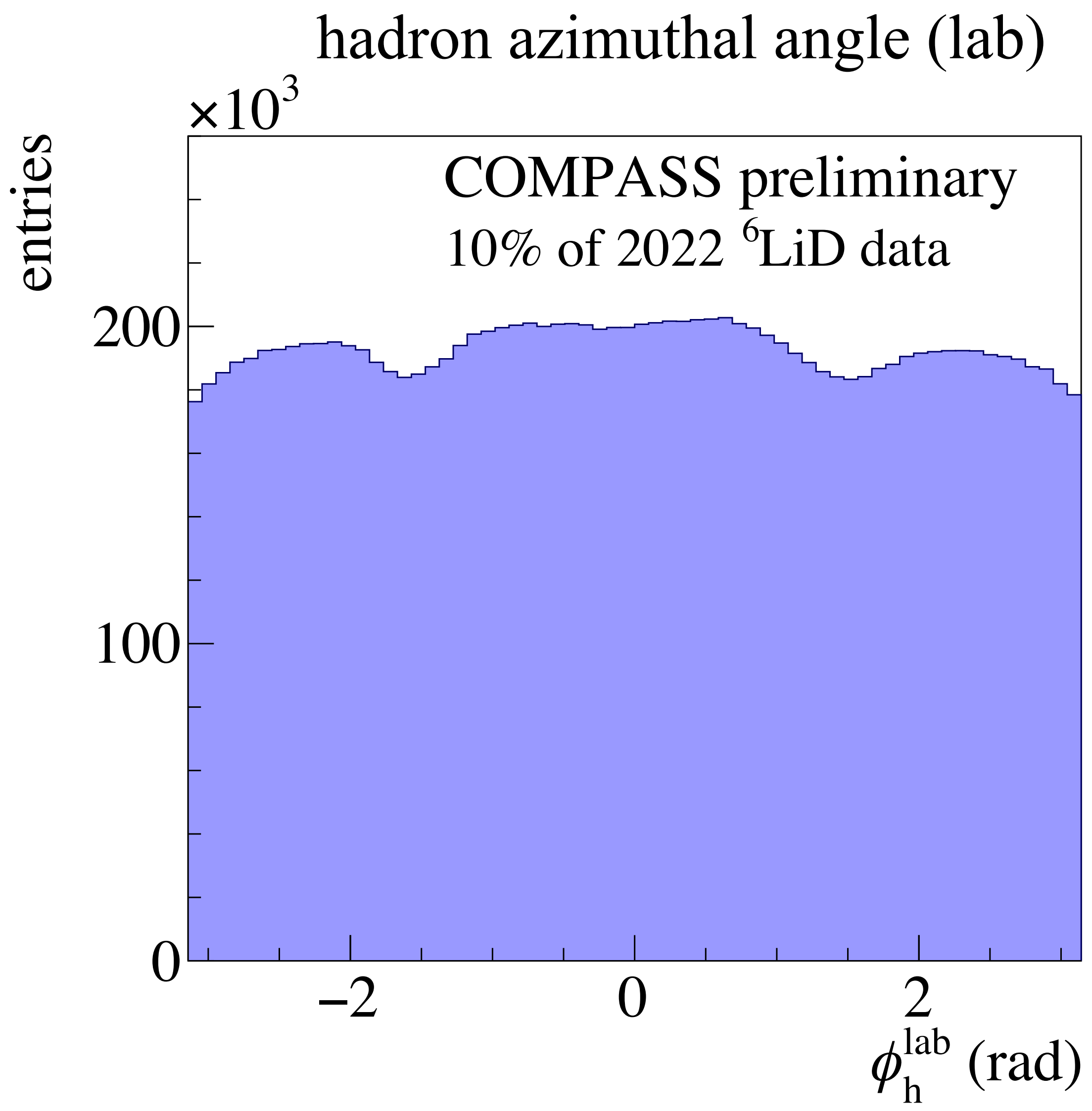




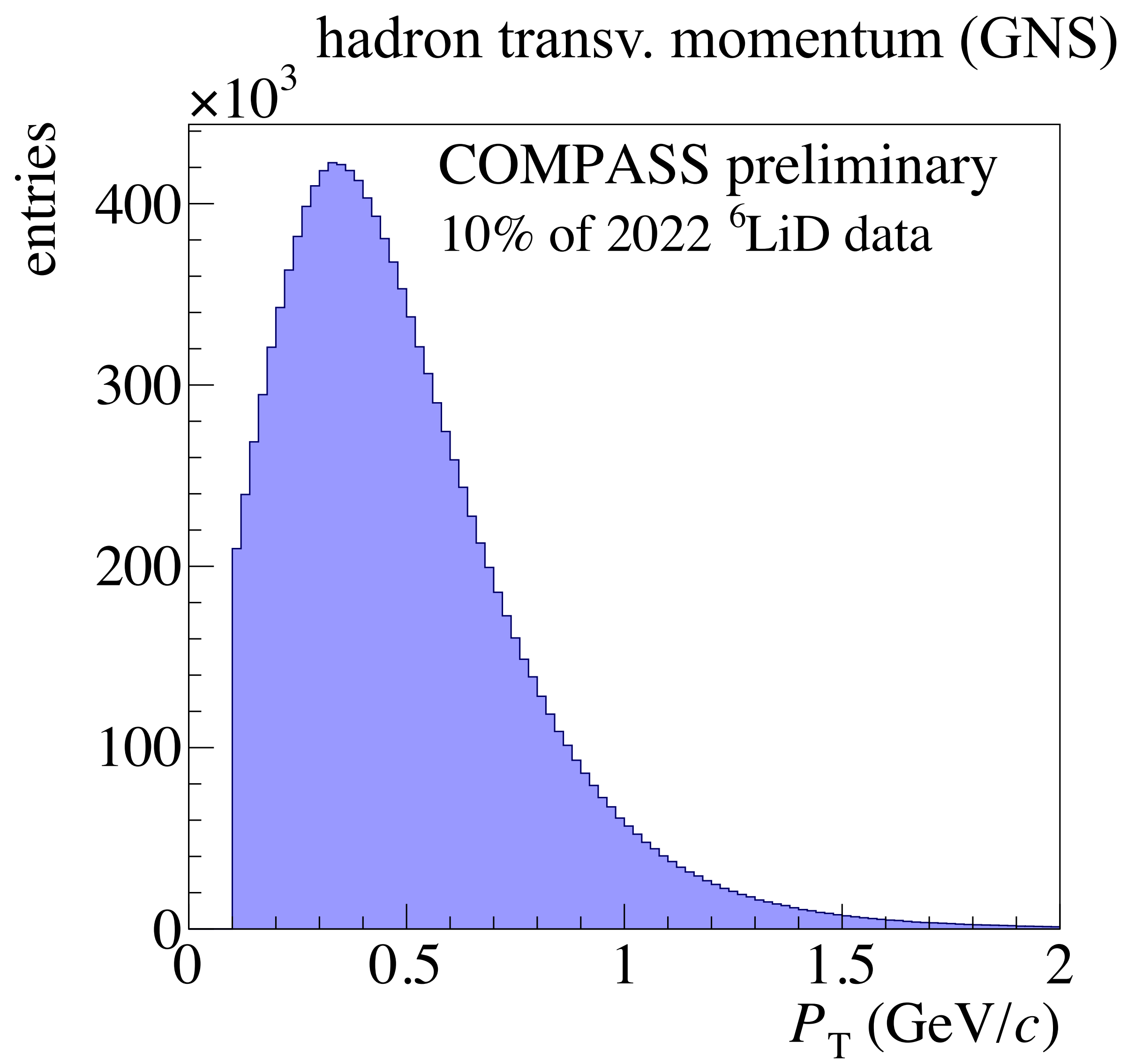






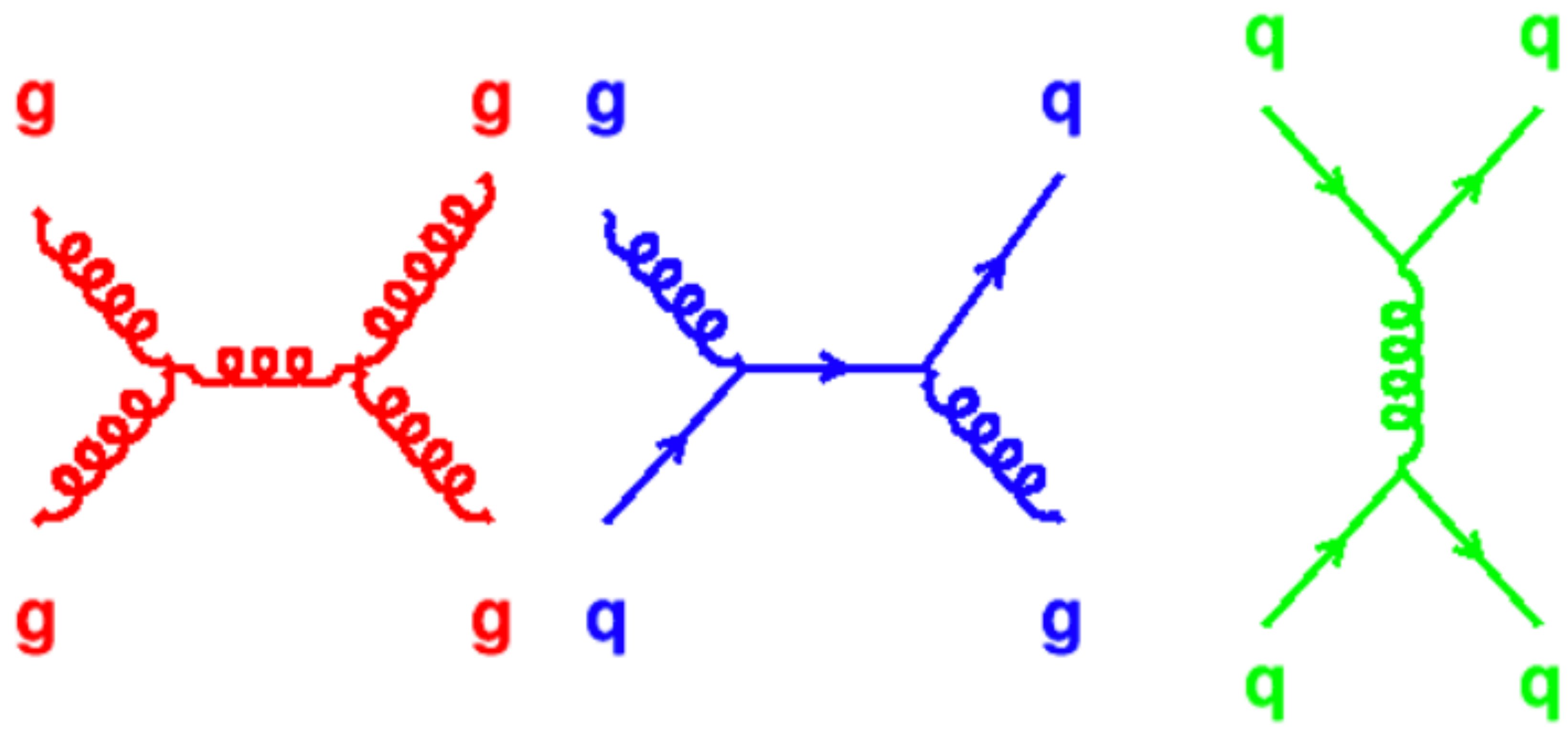


DIS events

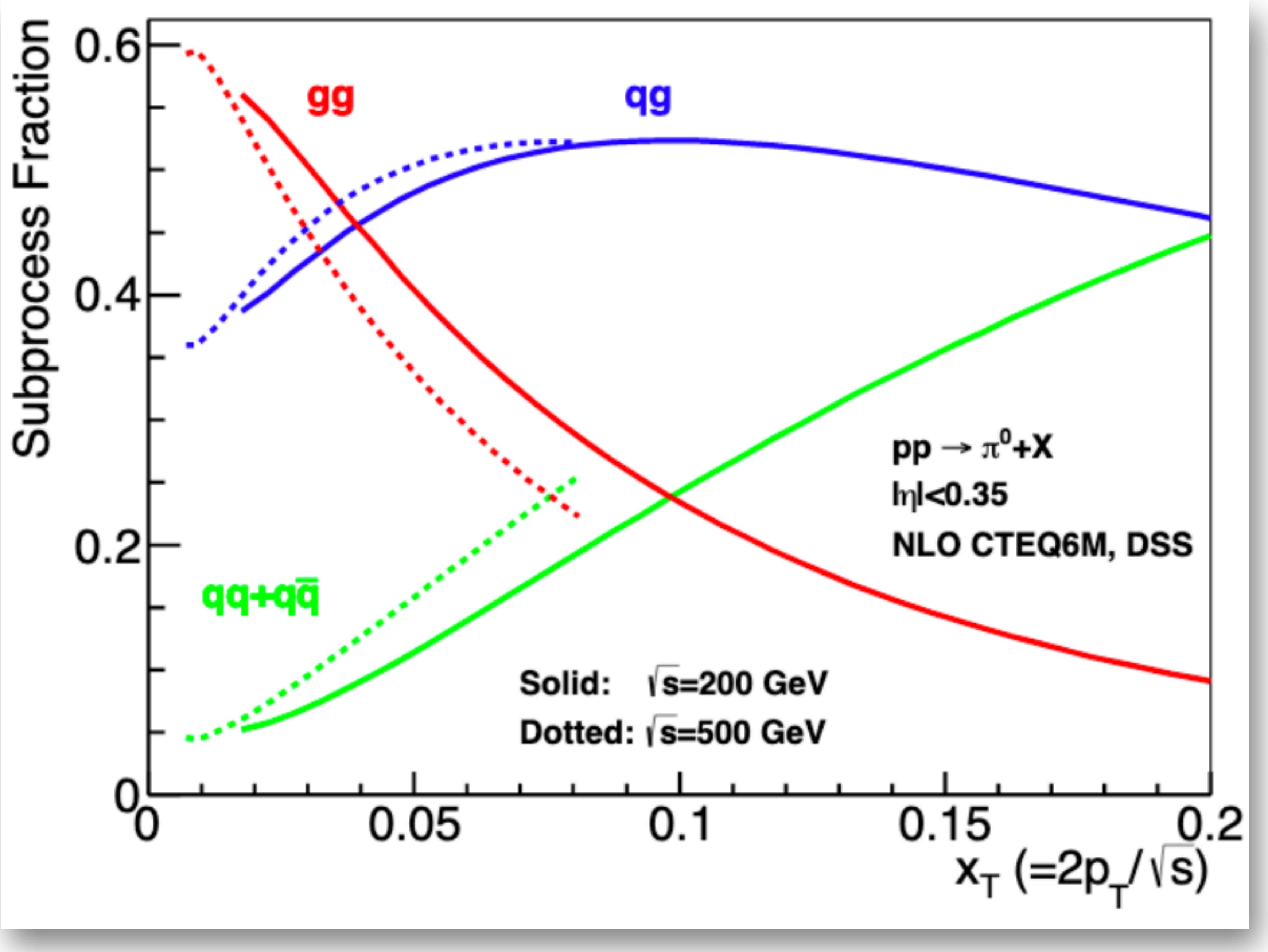


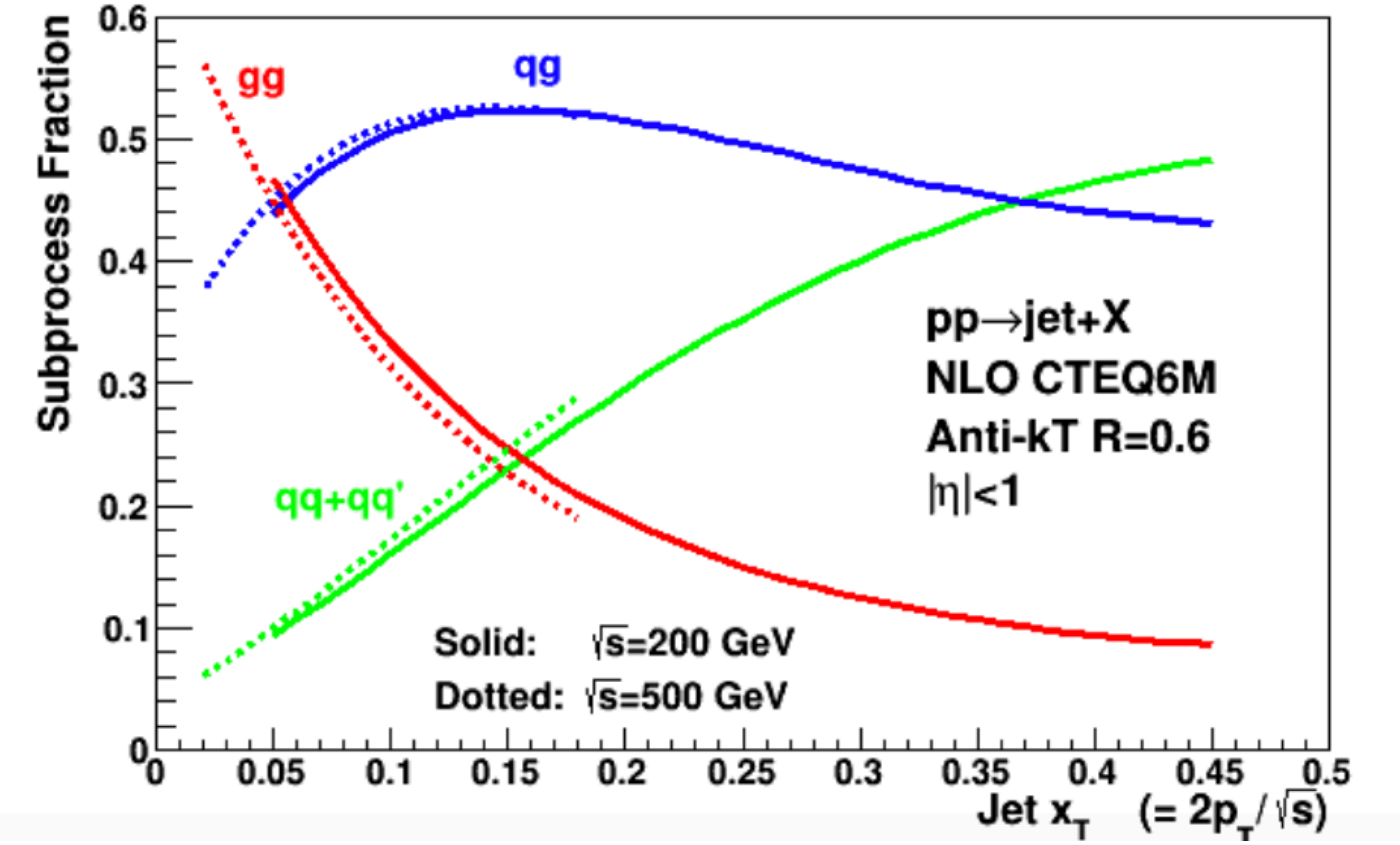
Twist-3 tri-gluon correlations - sensitivity & subprocesses

Subprocess fractions at RHIC energies
for gg, qg, qq+qqbar
(leading order hard QCD processes)



A. Mukherjee *et al.*, PRD86,094009

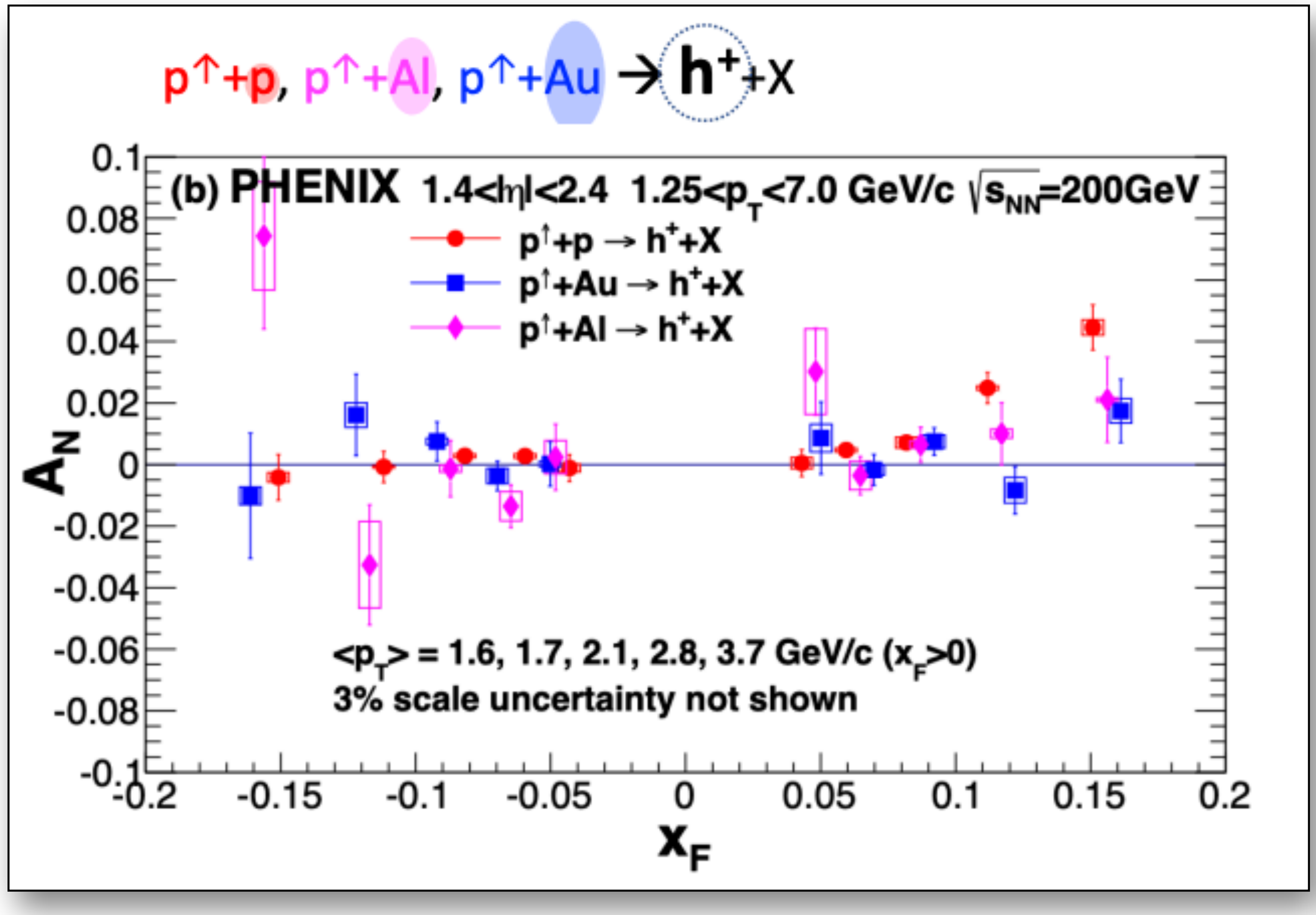




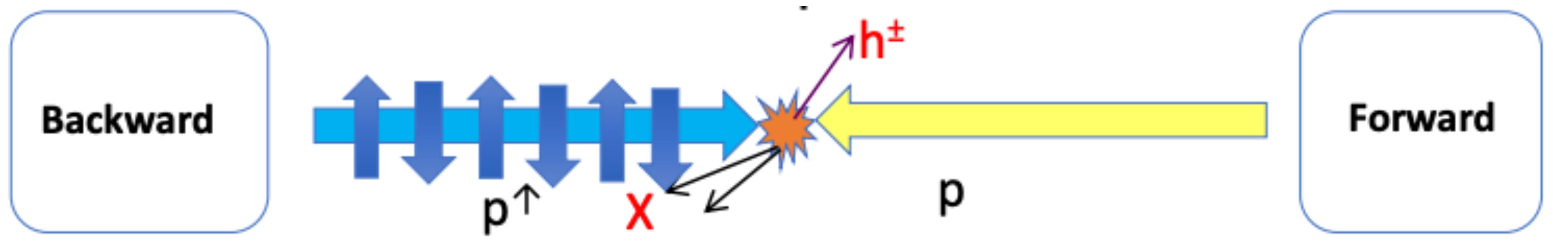
courtesy Z. Chang

A_N in the very forward

PHENIX charged hadrons



[PHENIX arXiv:2303.07191]

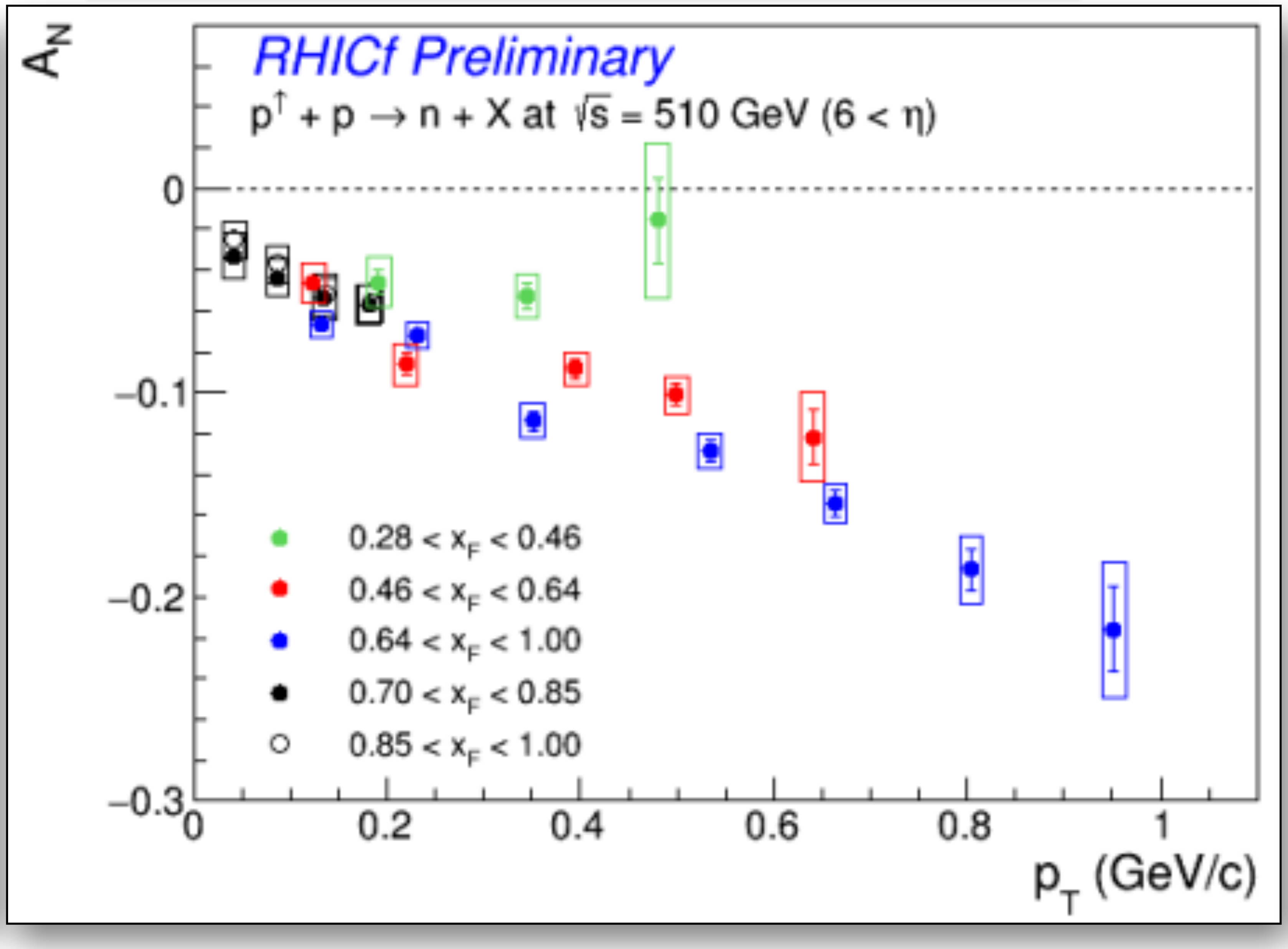


Smaller A_N for h+ at $0.1 < x_F < 0.2$ in pA

A_N(h⁻) small to zero at $x_F>0$: opposite sign of A_N for h⁻ canceled partially

also - forward neutron: [PHENIX PRD 103 (2021) 3, 032007]

RHICf very forward neutrons ($\eta<6$)

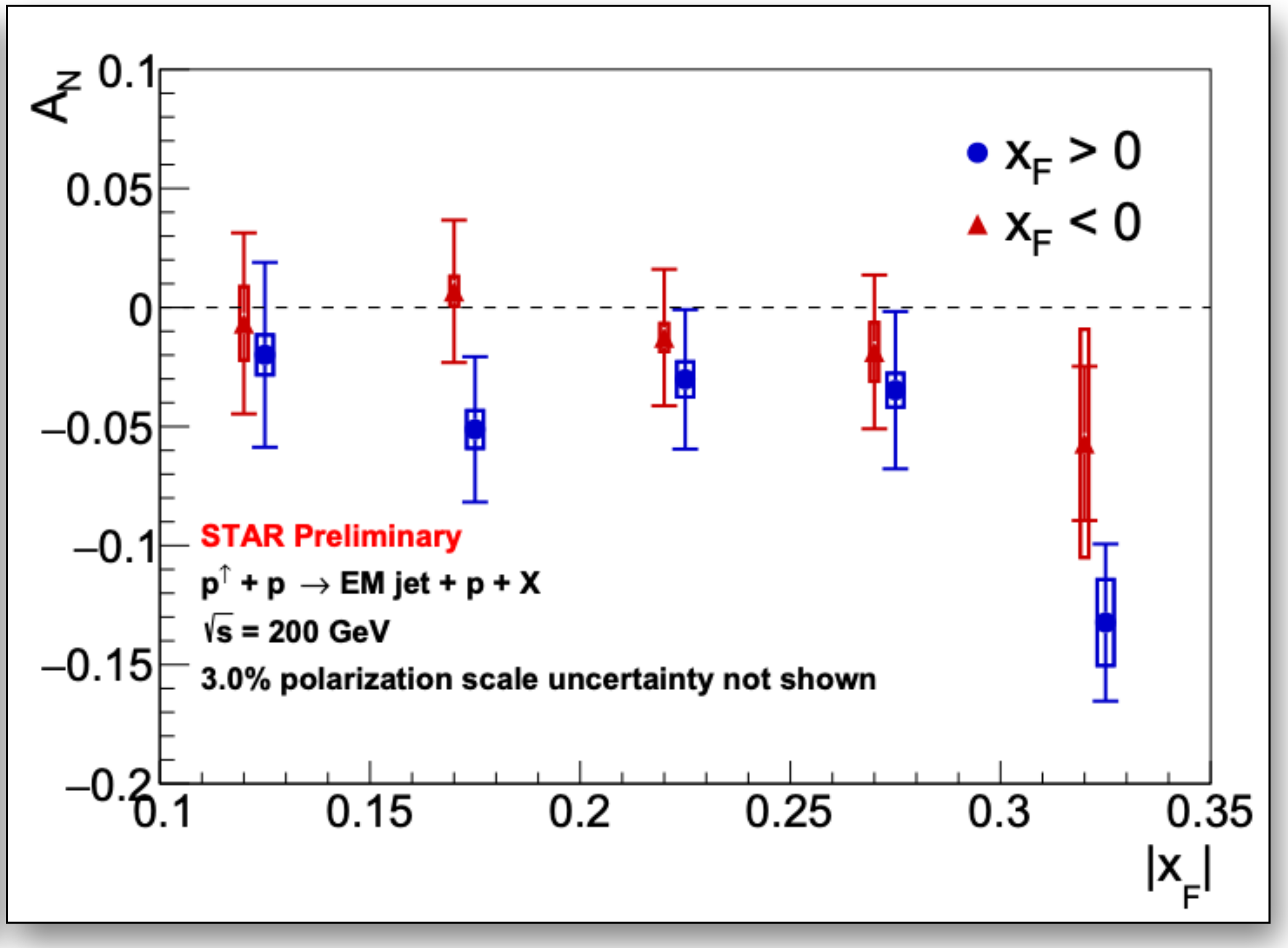


Publication with improved background estimation in preparation.

Increase in p_T: interference between spin flip and spin non-flip amplitudes (π / a_1 exchange model [PRD 84 (2011) 114012]

also - neutral pion: [RHICf PRL 124, 252501 (2020)]

STAR electromagnetic jets



Analysis for 510 GeV ongoing.

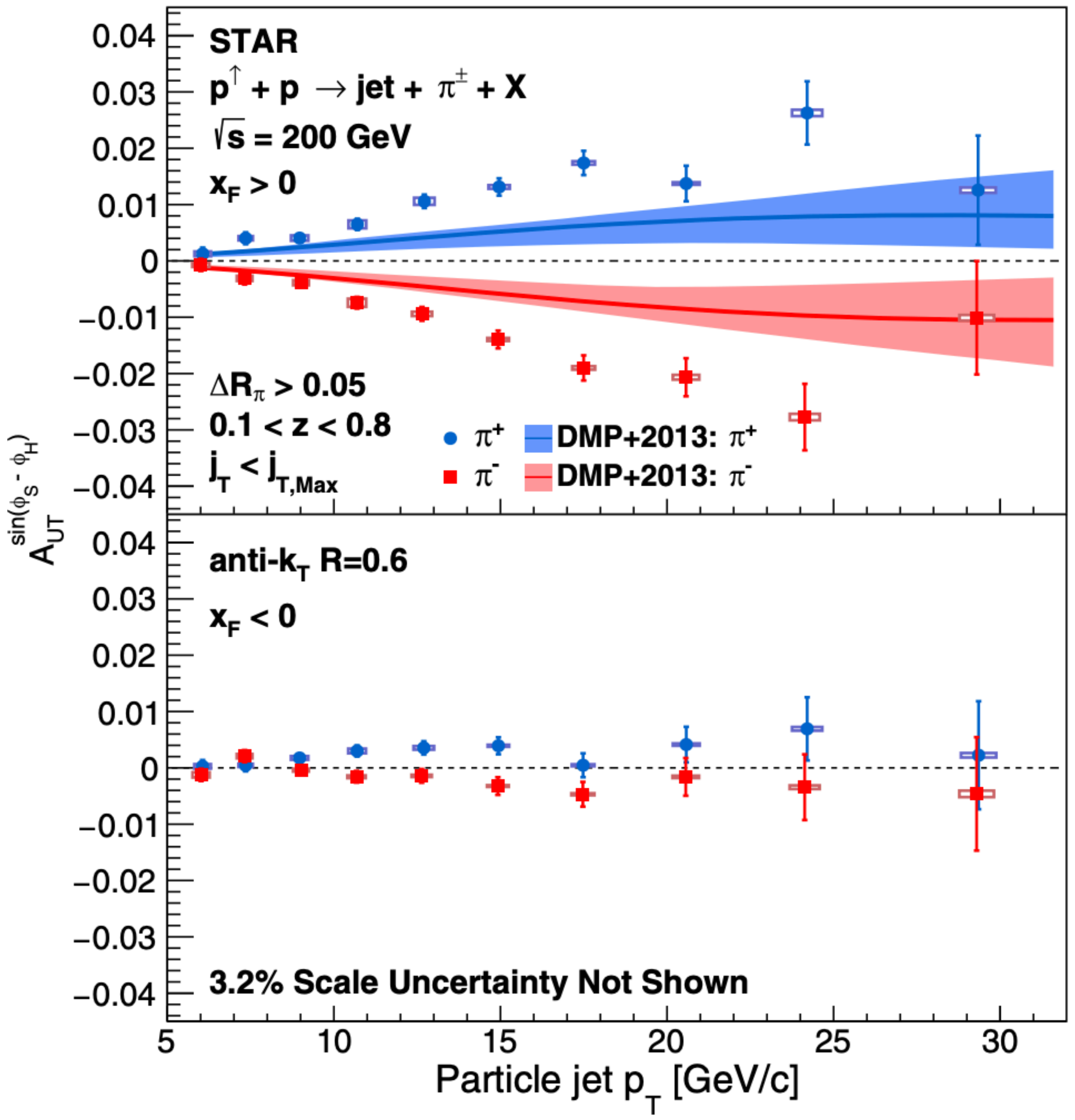
(π^0 not shown) also - [STAR PRD 103, 092009 (2021)]

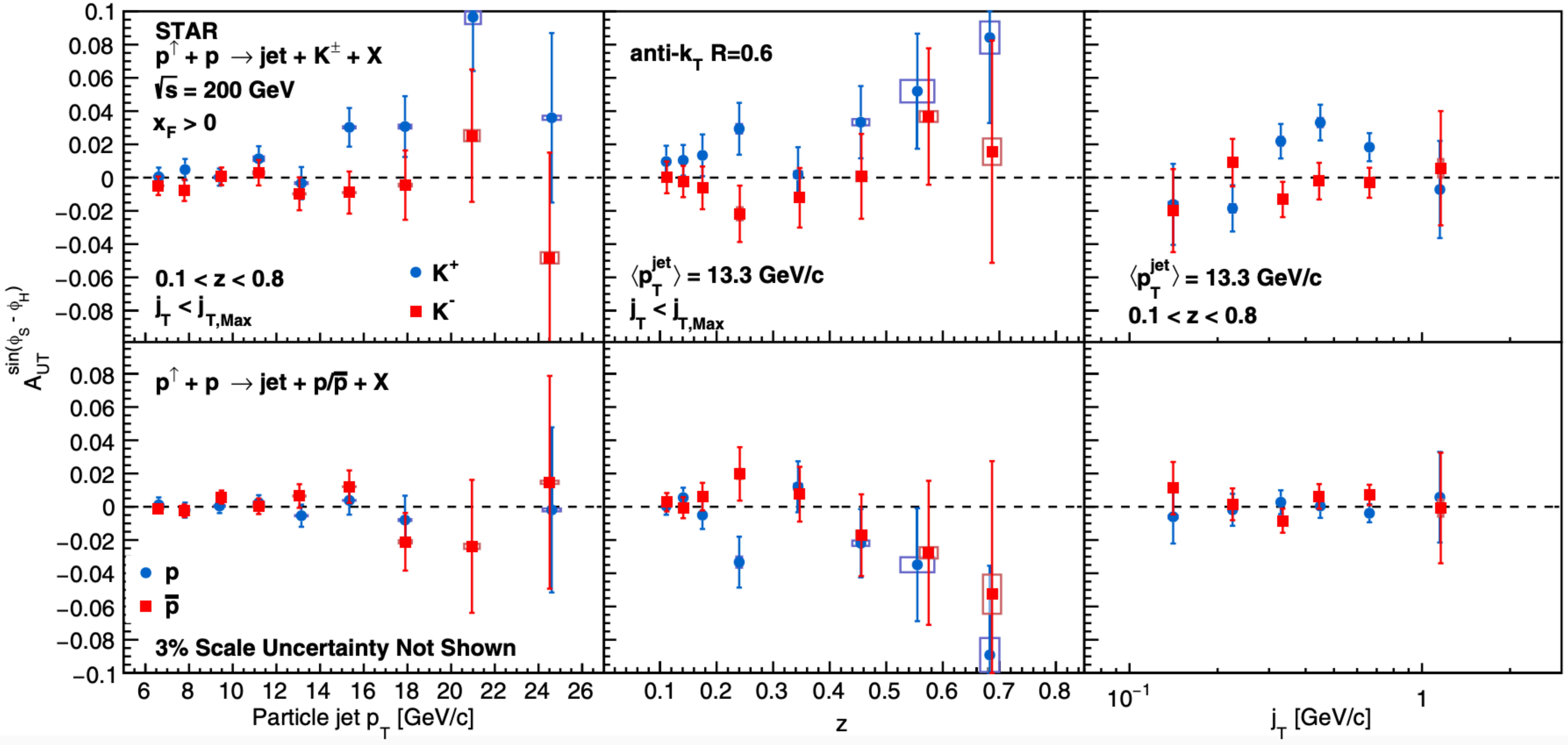
A_N increases with p_T (for $x_F > 0.46$ - RHICf) & forwardness & π^0 isolation (STAR) & lower γ multiplicity (STAR)

A_N from soft processes such as diffractive scattering?

TMD fragmentation function (Collins) from $pp^{\uparrow} \rightarrow$ jet $h^{\pm}X$ - kaons and protons

STAR hadrons in jets (midrapidity)





[STAR PRD 106, 072010 (2022)]

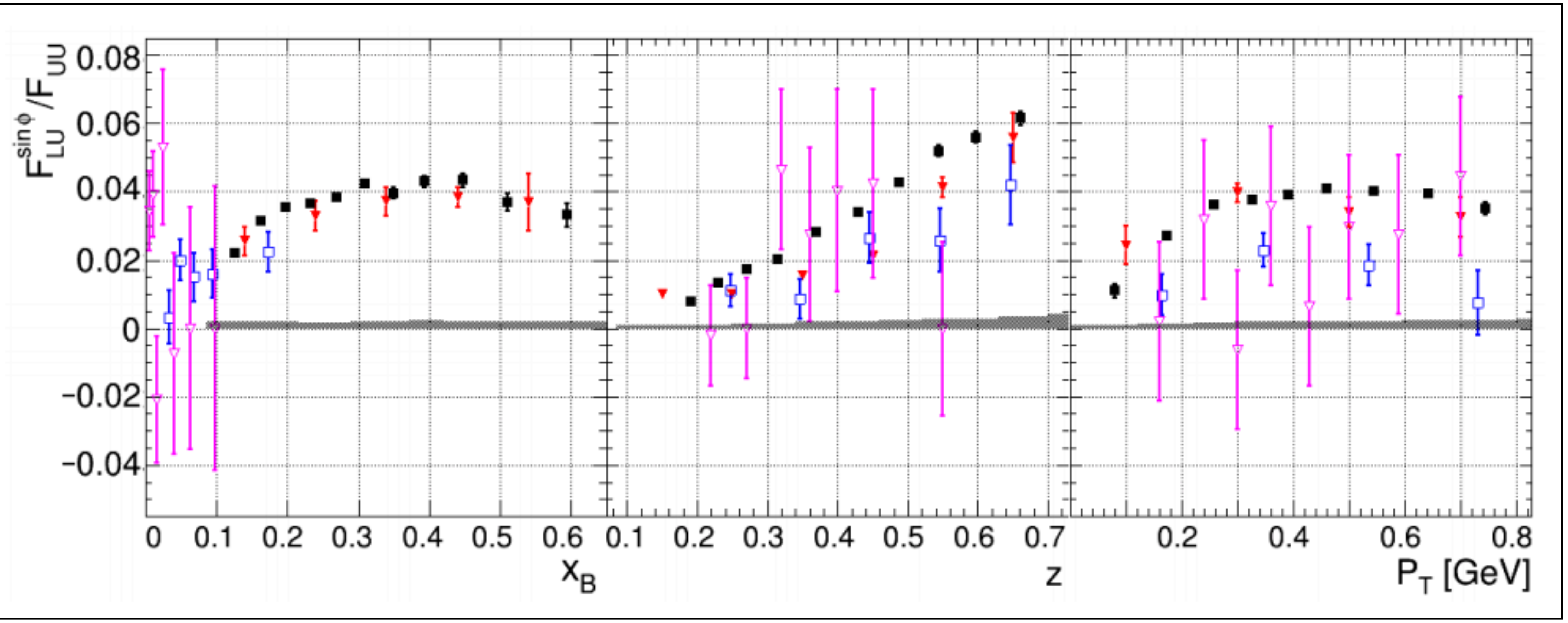
More higher twist in single-hadron SIDIS

CLAS(12), HERMES and COMPASS SIDIS beam-spin asymmetries

- Sizeable recent asymmetries from unpolarized target and longitudinally polarized lepton beam. Expected to be suppressed by $\mathcal{O}(M/Q)$
- Provides access to so-far poorly known subleading twist-3 TMD PDFs & fragmentation functions containing information about **quark-gluon correlations in the proton and in the hadronization process**

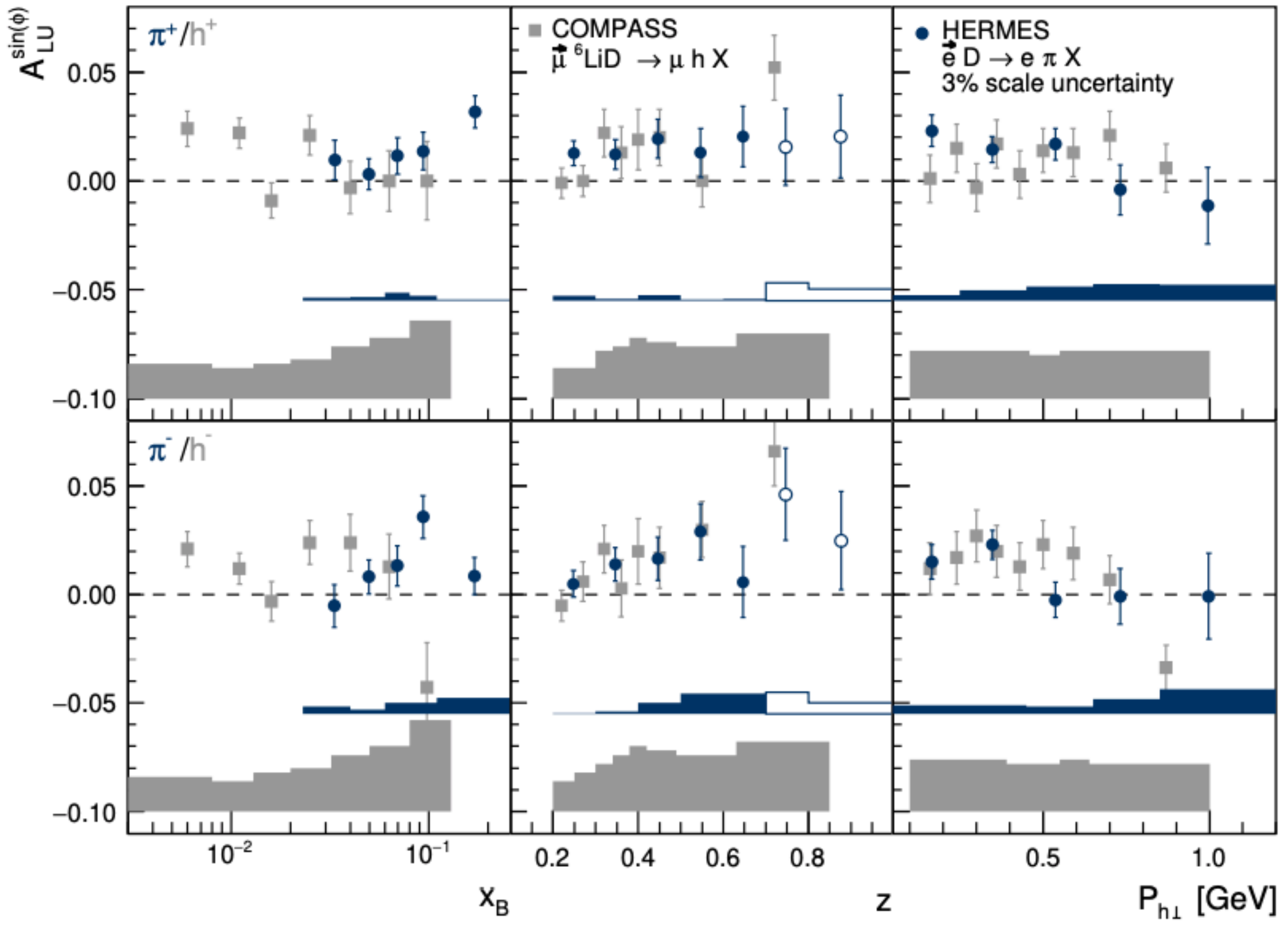
$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf; Collins FF; unpolarized dist. function; twist-3 FF; twist-3 t-odd dist. funcion; Boer-Mulders; twist-3 FF



■ **[CLAS12 / S. Diehl arXiv:2101.03544]**
❐ [HERMES PLB 797 (2019) 134886]
▼ [CLAS Phys. Rev. D 89, 072011 (2014)]
▽ [COMPASS Nucl. Phys. B 886, 1046 (2014)]

$$A_{LU}^{\sin\phi} = \frac{\sqrt{2\epsilon(1-\epsilon)}\;F_{LU}^{\sin\phi}}{F_{UU,T} + \epsilon F_{UU,L}}$$



[HERMES PLB 797 (2019) 134886]

SIDIS off longitudinally polarized targets

- COMPASS collected a large amount of L-SIDIS data with unprecedented precision for some amplitudes

$A_{UL}^{\sin\phi_h}$

- Q-suppression, higher-twist subleading effects
- Sizable TSA-mixing
- Significant h+ asymmetry, clear z-dependence
- h– compatible with zero

$A_{UL}^{\sin2\phi_h}$

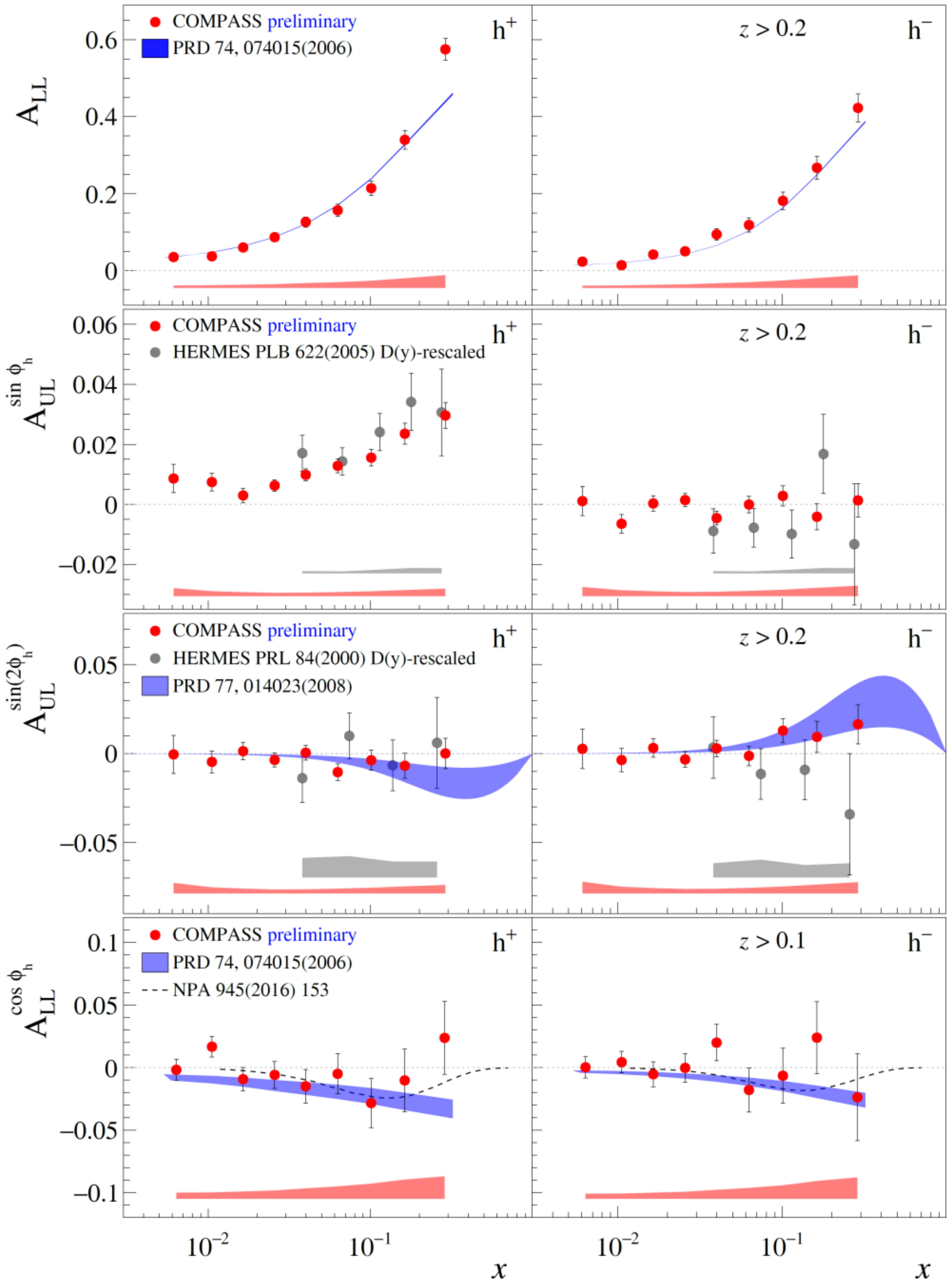
- Only "twist-2" ingredients
- Additional P_T-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

$A_{LL}^{\cos\phi_h}$

- Q-suppression, higher-twist subleading effects
- Compatible with zero, in agreement with models

- Di-hadron asymmetries (not shown)

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



Accessing intrinsic transverse parton momenta in SIDIS

Azimuthal modulation of hadron yield

⟷ complementary

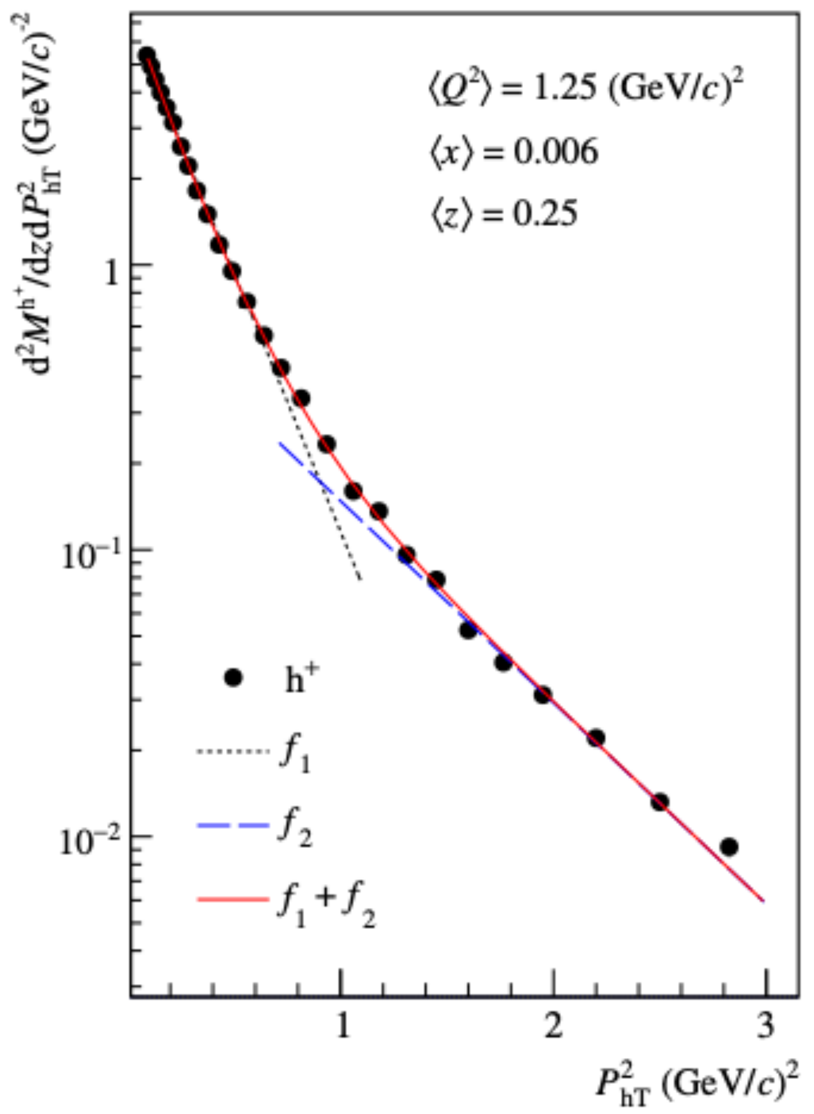
Transverse-momentum dependent hadron multiplicities

- **Cahn effect** - $\cos\phi_h$ modulation purely due to the presence of intrinsic transverse momenta of unpolarized quarks in the unpolarized nucleon.
  - No such modulation in the collinear case. Next-to-leading-order effect.

$$\langle k_T^2\rangle_{eff} = -\frac{Q\langle P_T^2\rangle A_{UU}^{\cos\phi_h}}{2zP_T}$$

$$\frac{d^2N^h(x, Q^2; z, P_T^2)}{dz\, dP_T^2} \propto \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right)$$

$$\langle P_T^2\rangle = z^2\langle k_T^2\rangle + \langle p_\perp^2\rangle$$

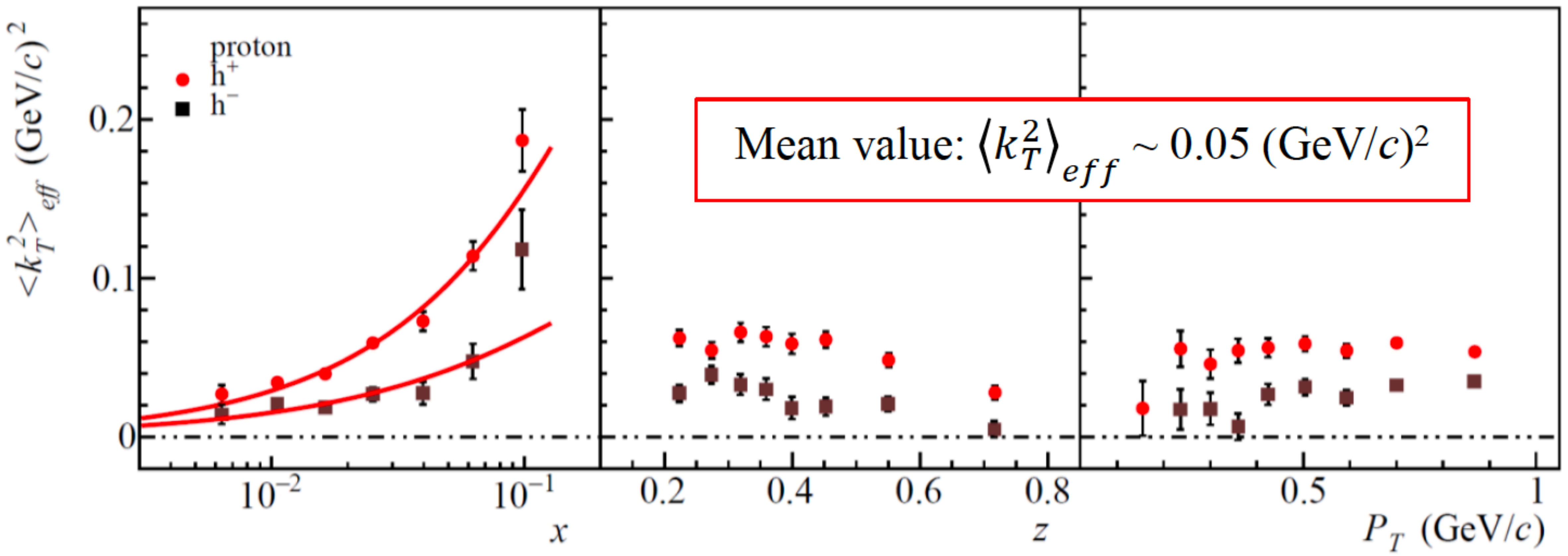


[COMPASS PRD 97, 032006 (2018)]

- Double-Gauss structure in P_T spectrum separated at ~ 1 GeV/c

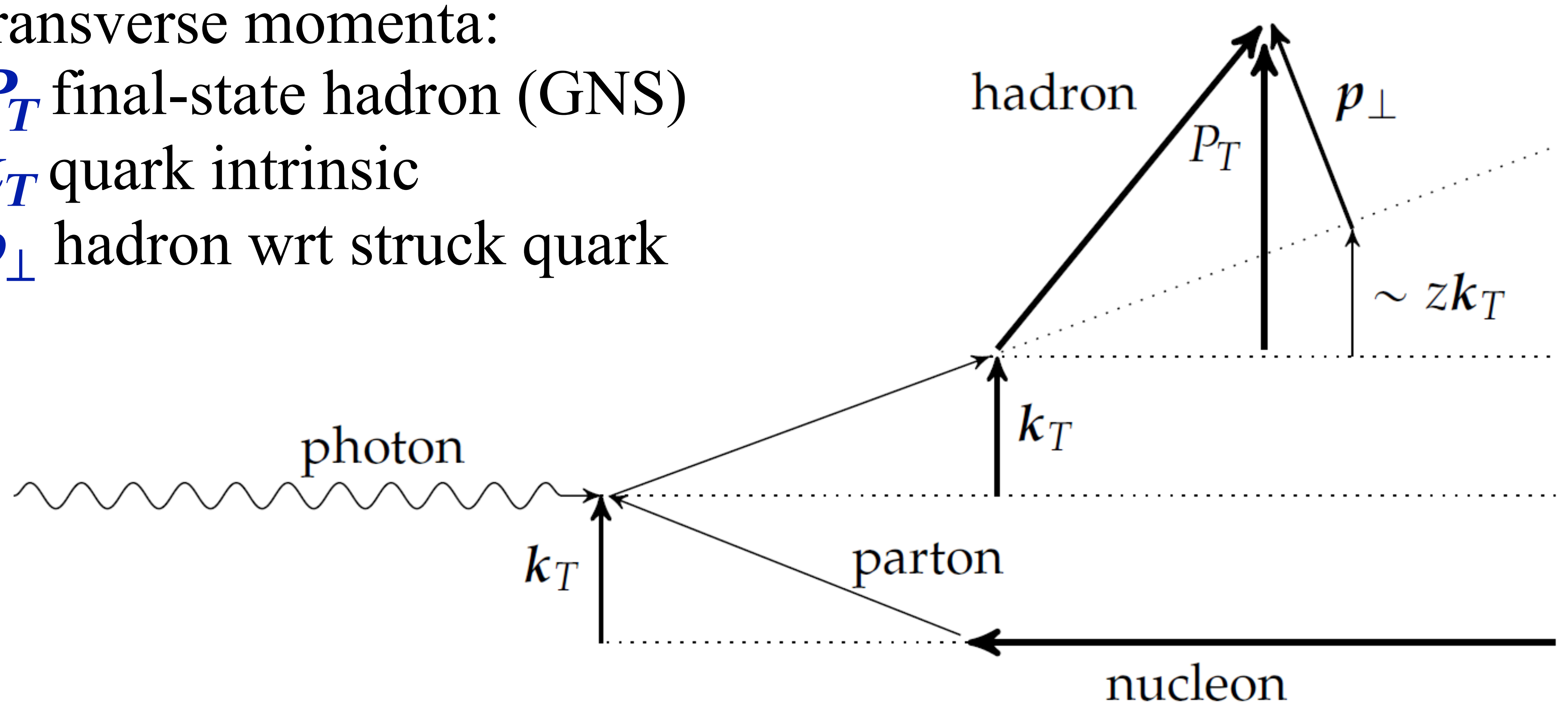
e.g. Gonzales-Hernandez et al., *Phys.Rev.D* 98 (2018) 11, 114005

COMPASS preliminary



courtesy A. Moretti

transverse momenta:
P_T final-state hadron (GNS)
k_T quark intrinsic
$p_\perp$ hadron wrt struck quark



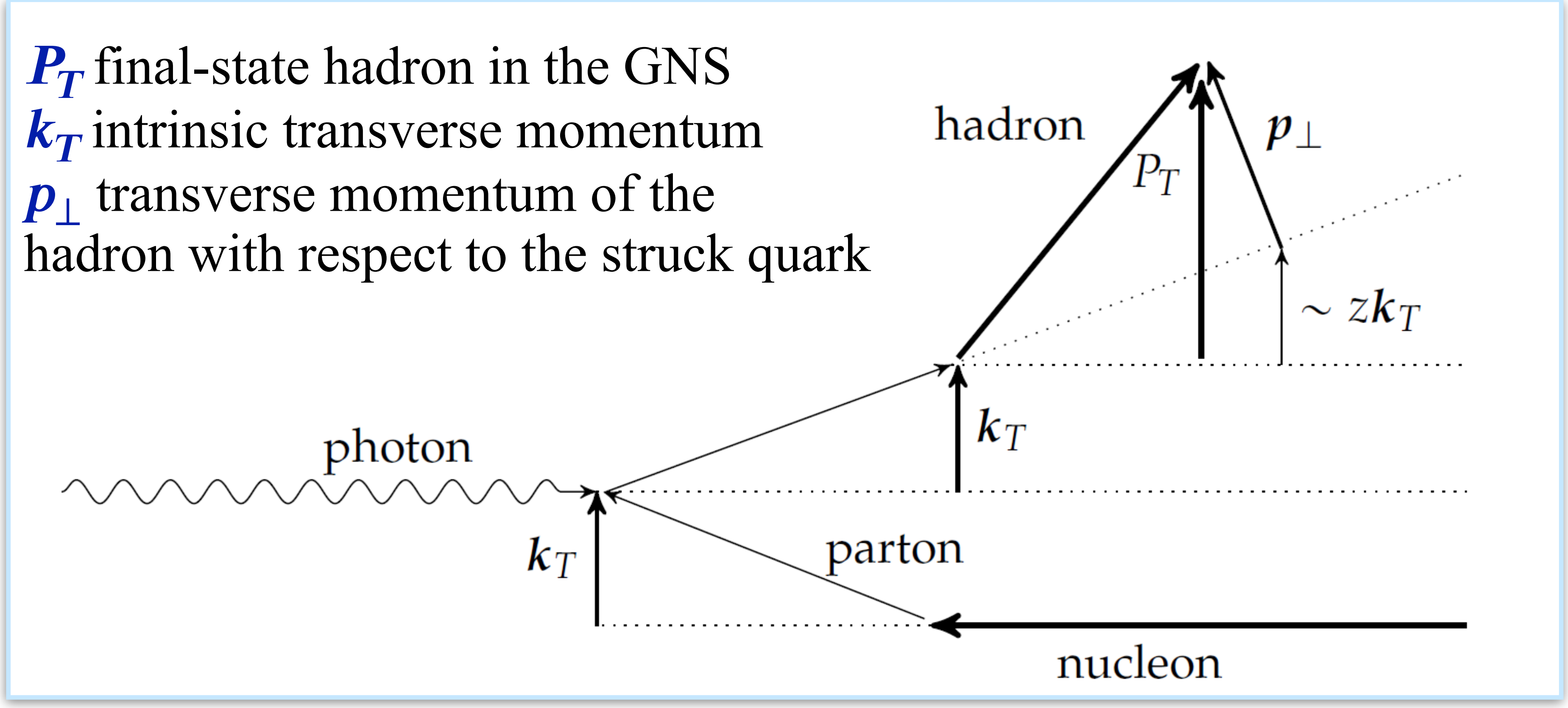
Transverse-momentum distributions

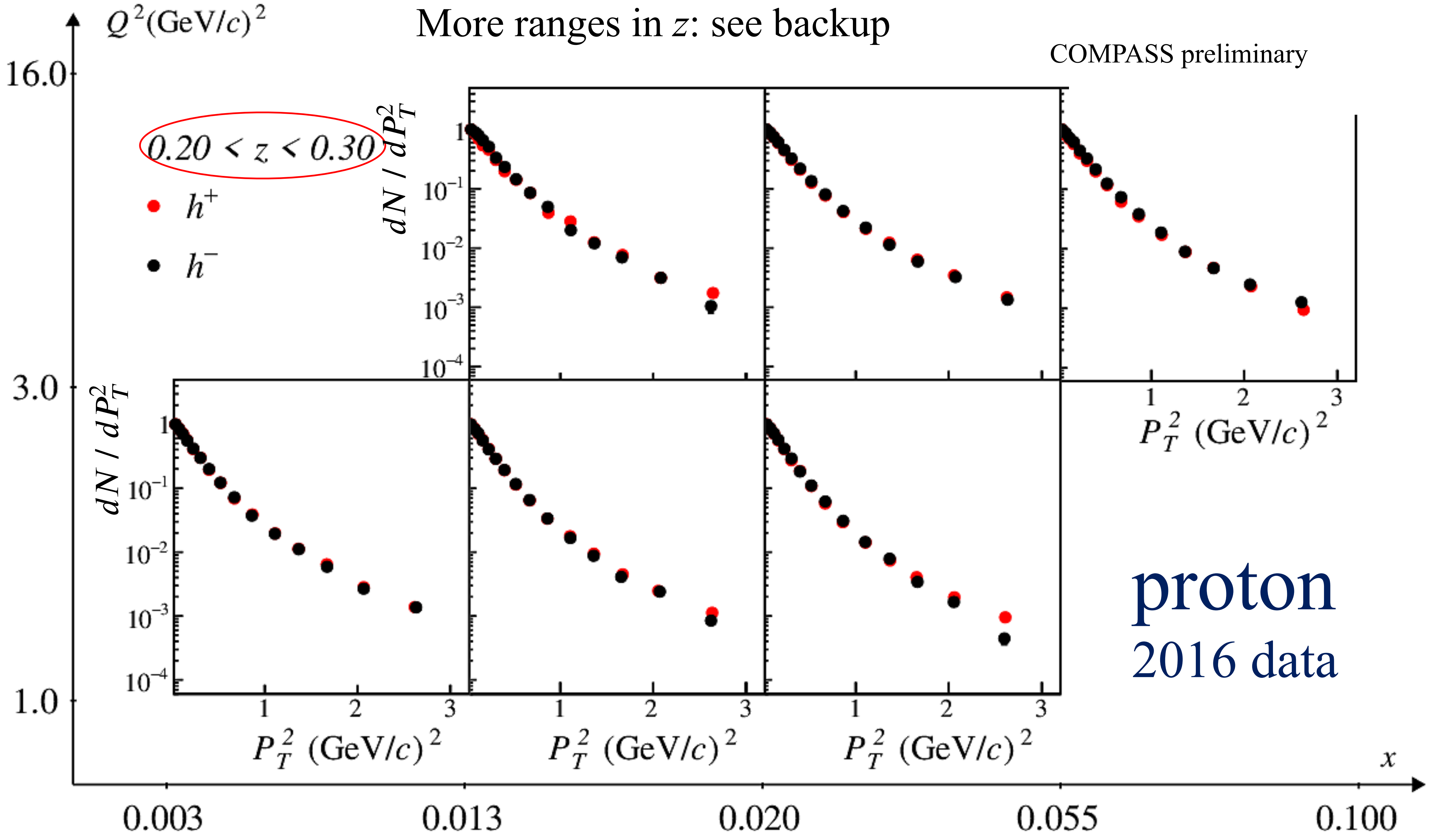
- Allow to gain information about **intrinsic quark momentum** k_T by measuring transverse momentum P_T of the produced hadron.
- Important for **TMD evolution studies & comparison between experiments.** Intense theoretical work ongoing to reproduce the experimental distributions over a wide energy range.
- In Gaussian approximation, at small values of P_T, the number of hadrons is expected to follow:

$$\frac{d^2N^h(x,Q^2;z,\ P_T^2)}{dz\,dP_T^2} \propto \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right)$$

$$\langle P_T^2\rangle = z^2\langle k_T^2\rangle + \langle p_\perp^2\rangle$$

- Double Gauss structure in P_T spectrum separated at 1 GeV/c → 2 different slopes
  - Perturbative effects expected to contribute more at high P_T
  - Likely not sufficient to explain the high-P_T trend
    e.g. Gonzales-Hernandez et al., *Phys.Rev.D* 98 (2018) 11, 114005
- Hadron multiplicities (not shown)
  - p-/p+ and K-/K+ at high z PLB 807 (2020) 135600, K-/K+ at high z PLB 786 (2018) 390
  - h PRD 97 (2018) 032006, K isoscalar PLB 767 (2017) 133, π± and h± PLB 764 (2017) 001





- Normalization: first P_T^2 bin.
- Different normalization for each bin and charge
- Error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.3\,\sigma_{stat}$

Boer-Mulders function and Cahn effect in SIDIS

- The **Boer-Mulders function** describes the strength of the spin-orbit correlation between quark spin s_T and intrinsic transverse momentum k_T:

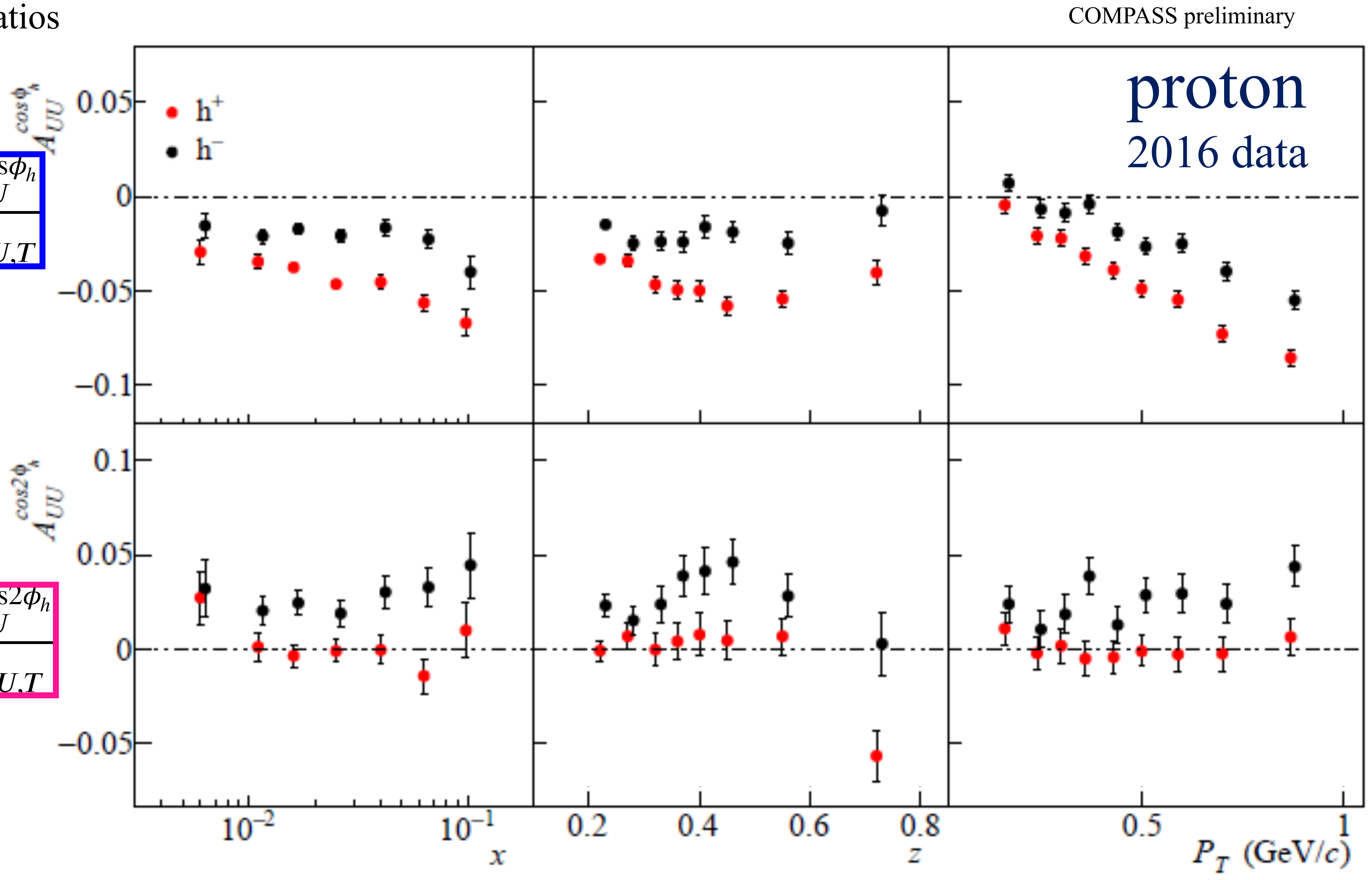
$$\vec{s}_T \cdot (\hat{P} \times \vec{k}_T)$$

  - Contributes to **$\cos\phi_h$** and **$\cos(2\phi_h)$**
  - Strong kinematic dependences & interesting differences between positive and negative hadrons, as observed in previous measurements by COMPASS on deuteron and by HERMES (u-quark dominance, opposite signs of Collins FF into h+ and h-)
- **Cahn effect**
  - Contributes to **$\cos\phi_h$** only → next slide
- Higher-twist beam-spin asymmetry $A_{LU}^{\sin\phi_h} = \frac{F_{LU}^{\sin\phi_h}}{F_{UU,T}}$ (backup)
- Azimuthal asymmetries for **hadron pairs** on the unpolarized proton (backup)
  - Collins FF for 2 hadrons & interference fragmentation function

Azimuthal asymmetries defined as the ratios

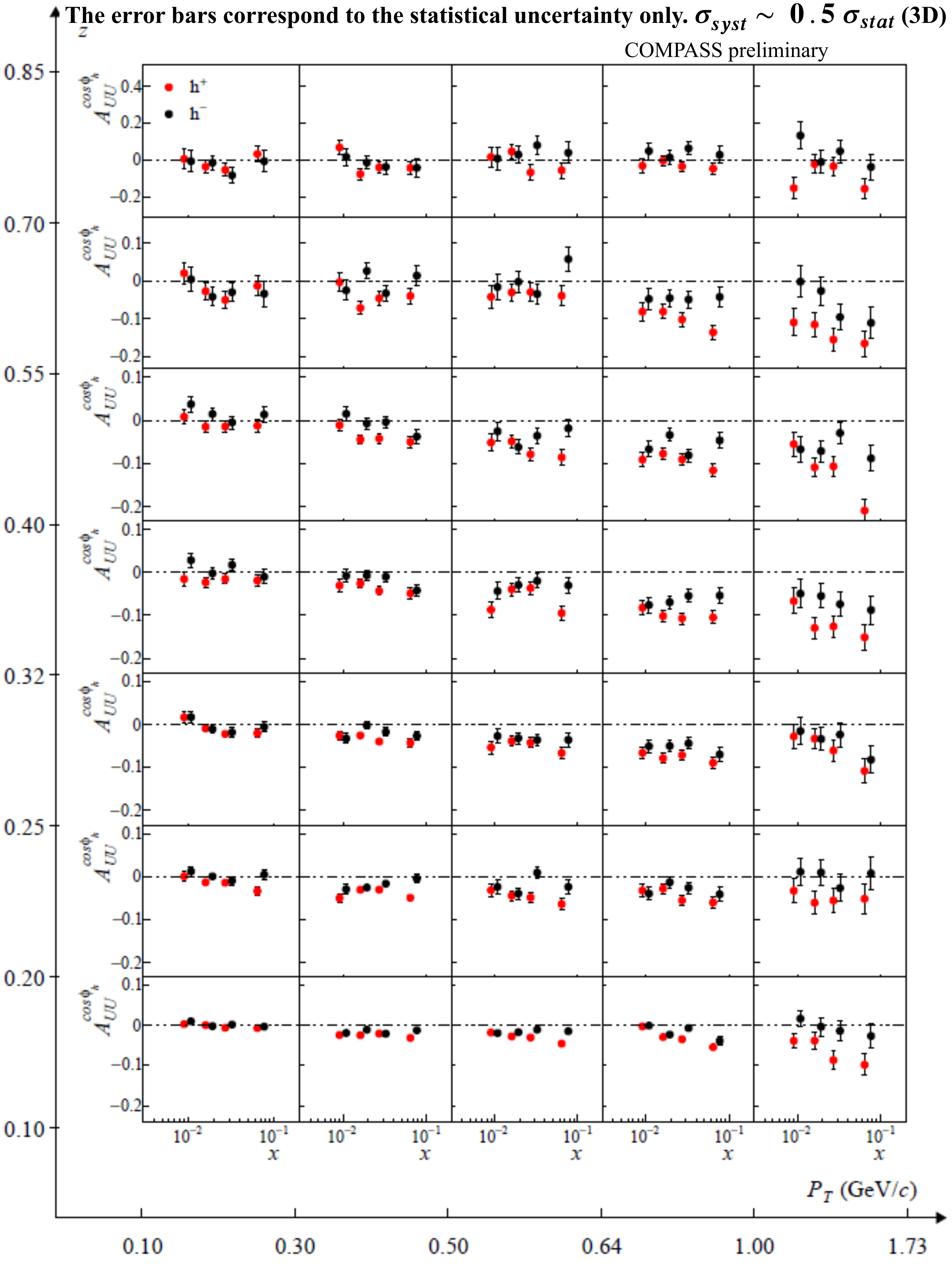
$$A_{UU}^{\cos\phi_h} = \frac{F_{UU}^{\cos\phi_h}}{F_{UU,T}}$$

$$A_{UU}^{\cos 2\phi_h} = \frac{F_{UU}^{\cos 2\phi_h}}{F_{UU,T}}$$



The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim \sigma_{stat}$ (1D)

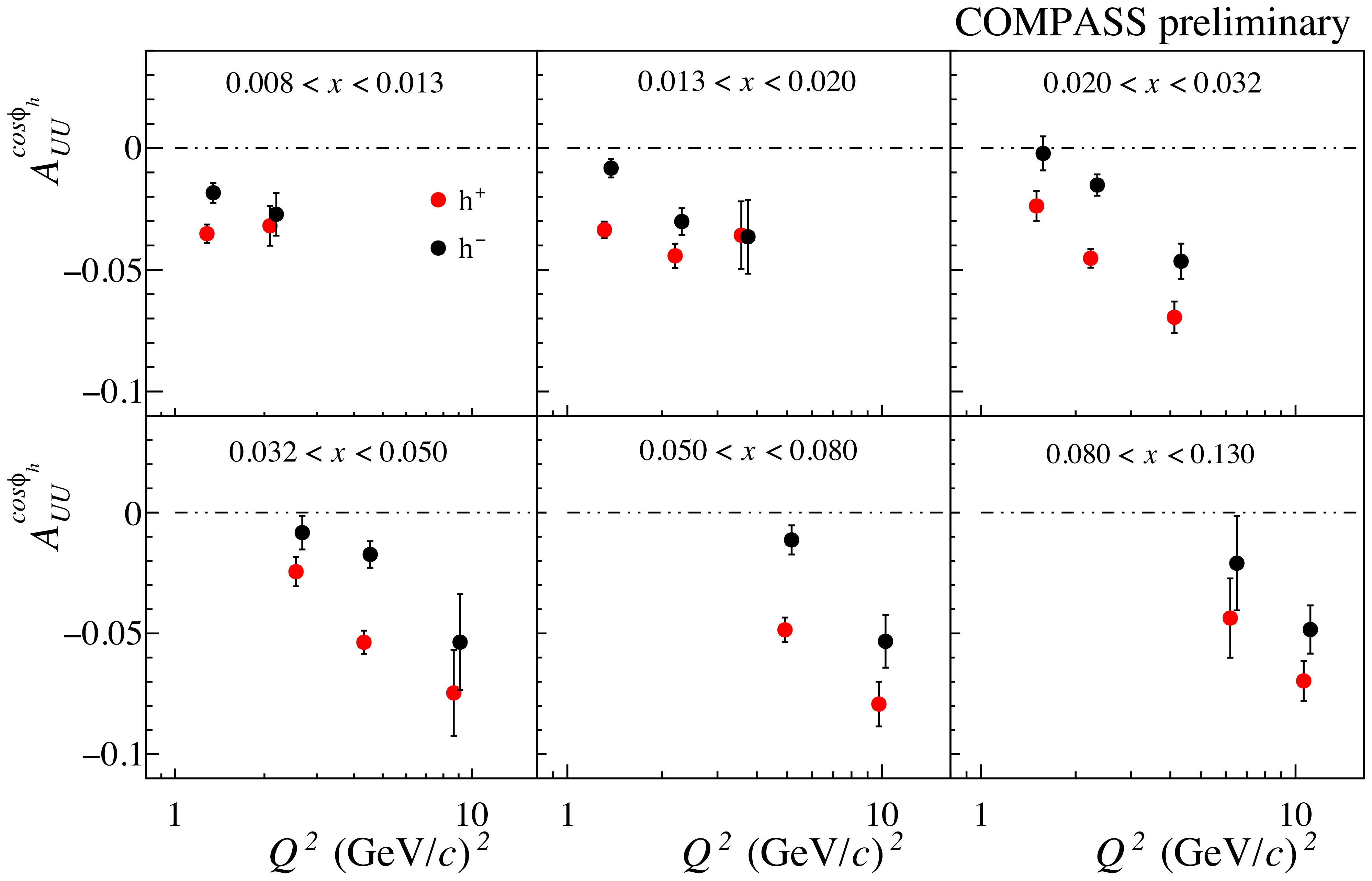
Cahn effect and quark intrinsic momentum from SIDIS



- **Cahn effect** - additional (to BM) $\cos\phi_h$ modulation purely due to the presence of intrinsic transverse momenta of unpolarized quarks in the unpolarized nucleon. No such modulation in the collinear case. Next-to-leading-order effect.
  - Clear signal, strong dependence on P_T.
    Compatible with zero at high z. In agreement with COMPASS deuteron results.
- Naive expectation

$$A_{UU|Cahn}^{\cos\phi_h} = -\frac{2zP_T\langle k_T^2\rangle}{Q\,\langle P_T^2\rangle}$$

  - observed trend is however opposite (increase with Q^2)

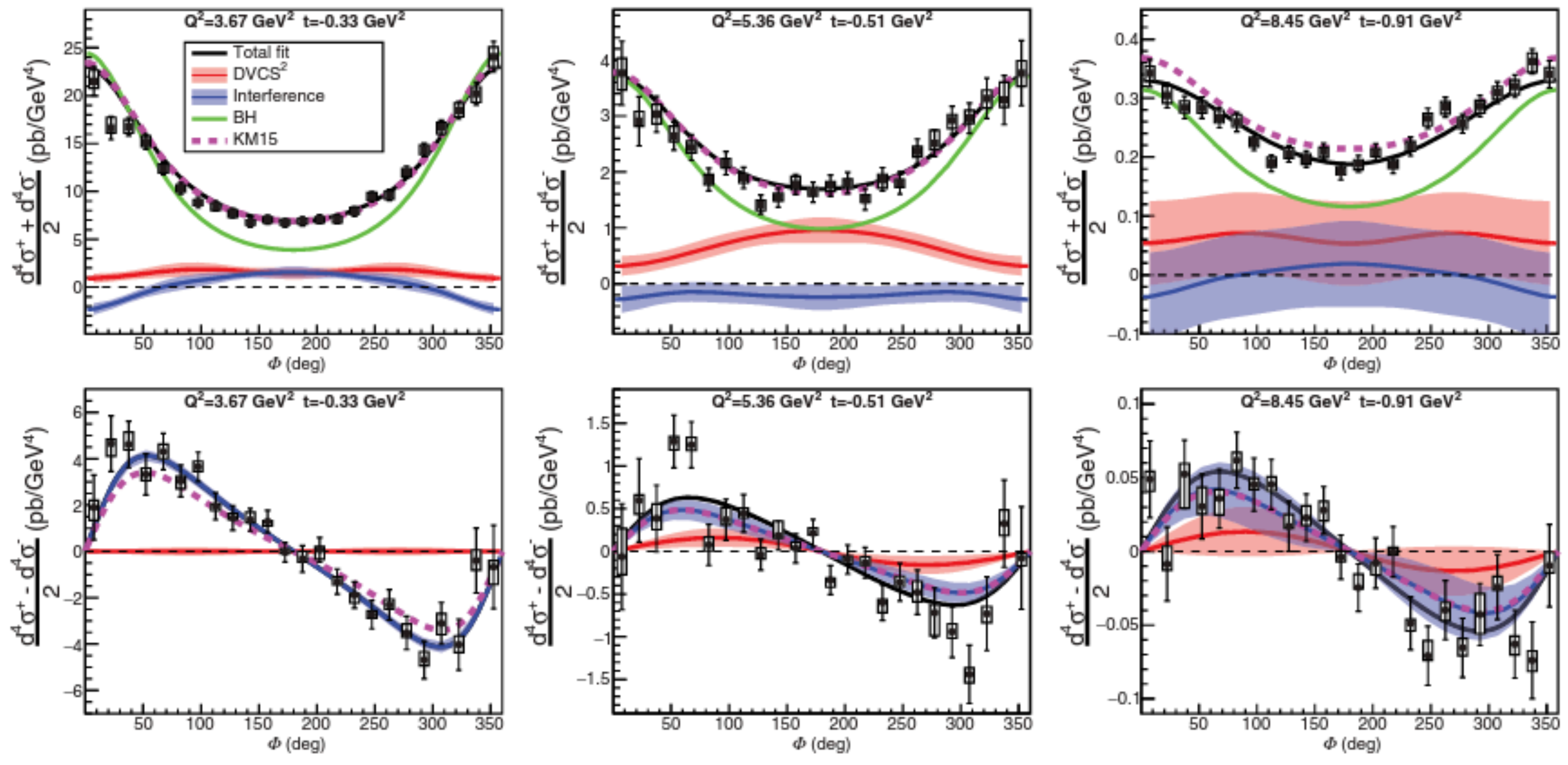


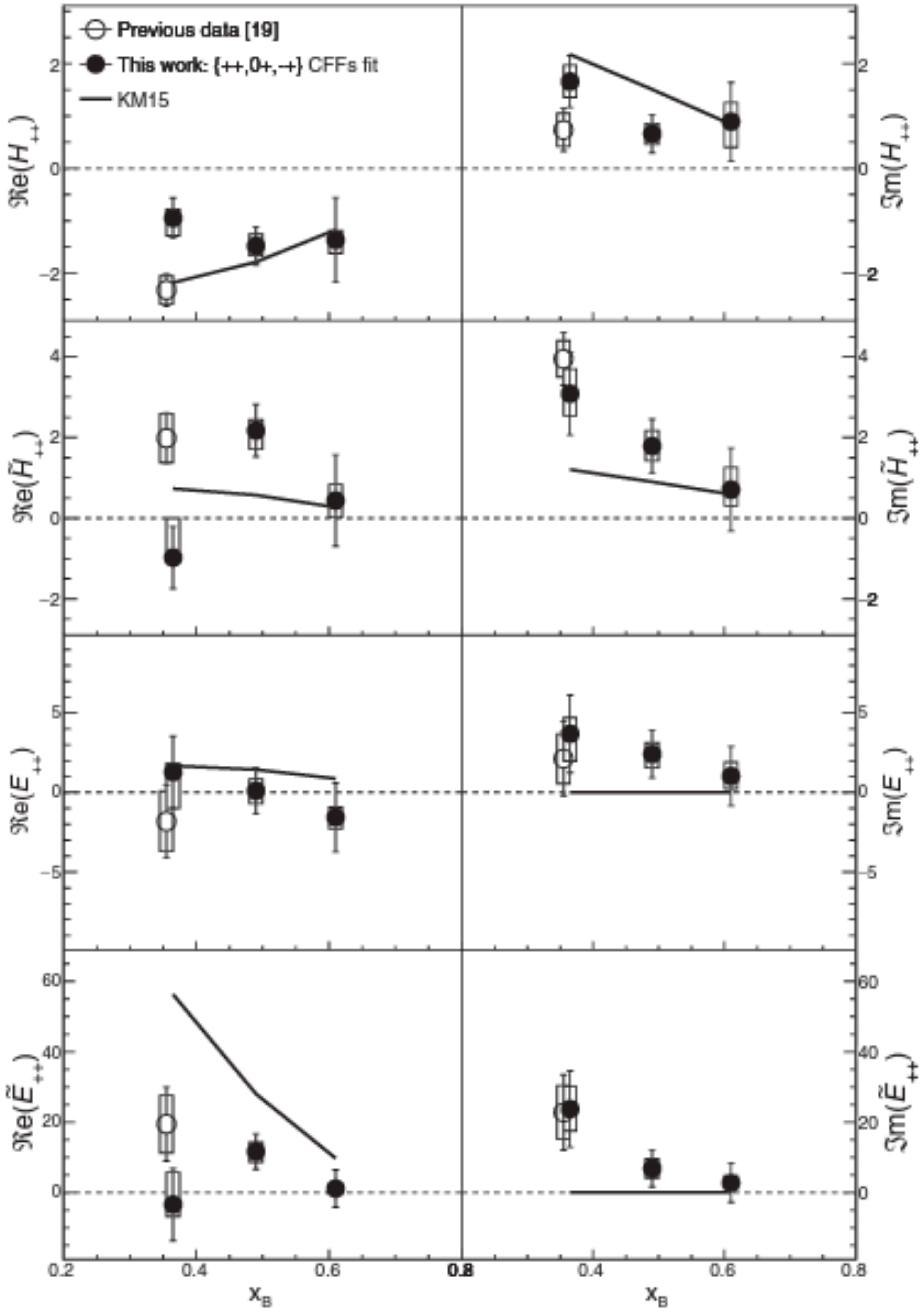
- Complementary access to **quark intrinsic transverse momentum** + other PDFs & FFs contributions

proton
2016 data

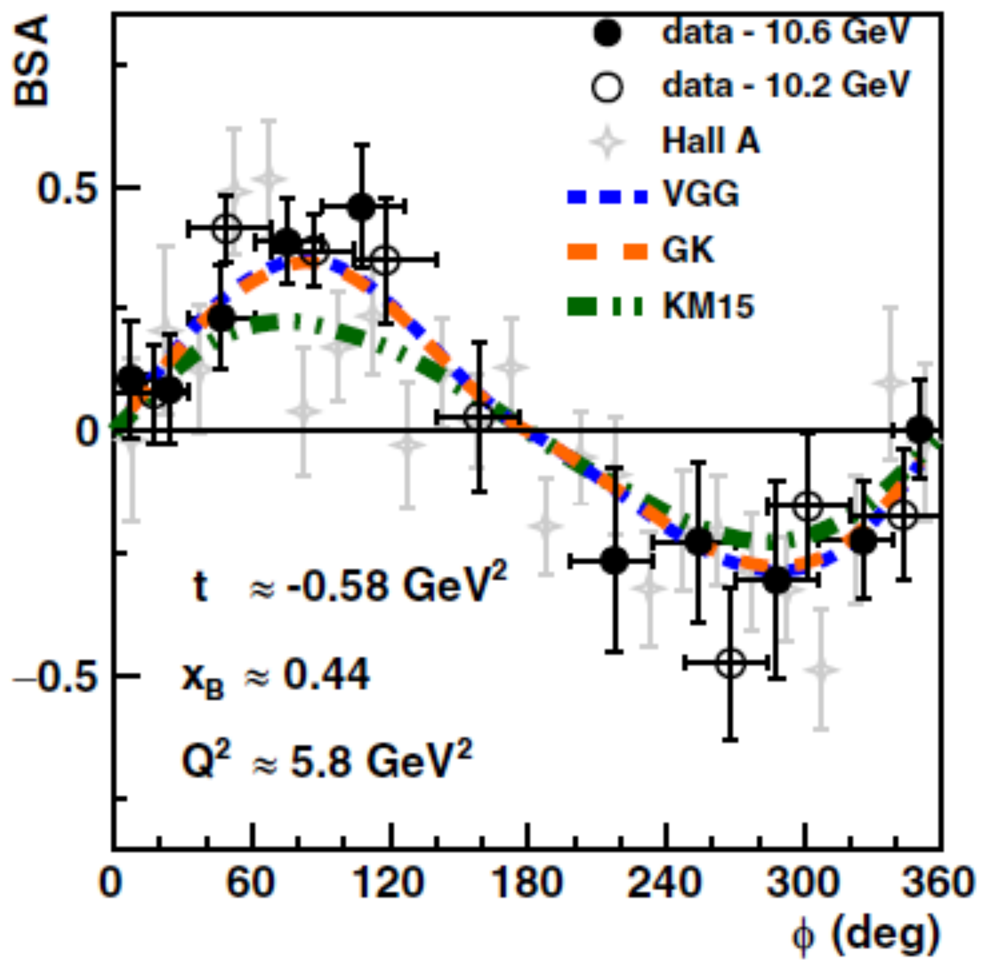
GPD backup

2 most recent JLab DVCS publications - my cheat sheet

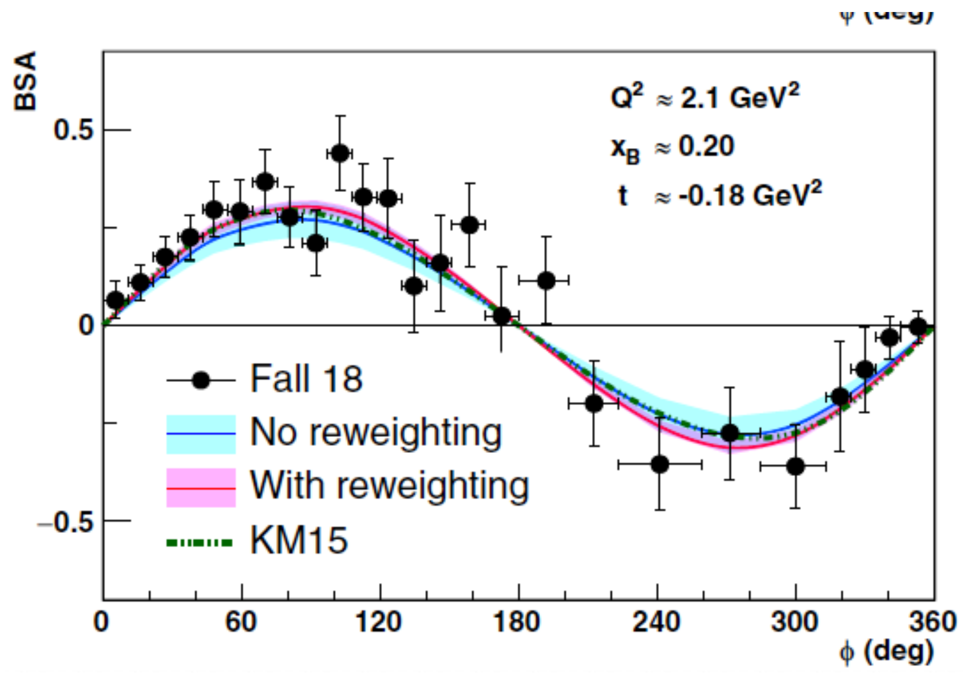




Hall A Collaboration (F. Georges et al.), Phys. Rev. Lett. 128 (2022)



left: one of 64 bins accessible only with ~10 GeV beam. Tension in KM15. right: "weighted" and "unweighted" is PARTON ANN. Only part of data set taken is published, already now compatible with JLab 6-Gev

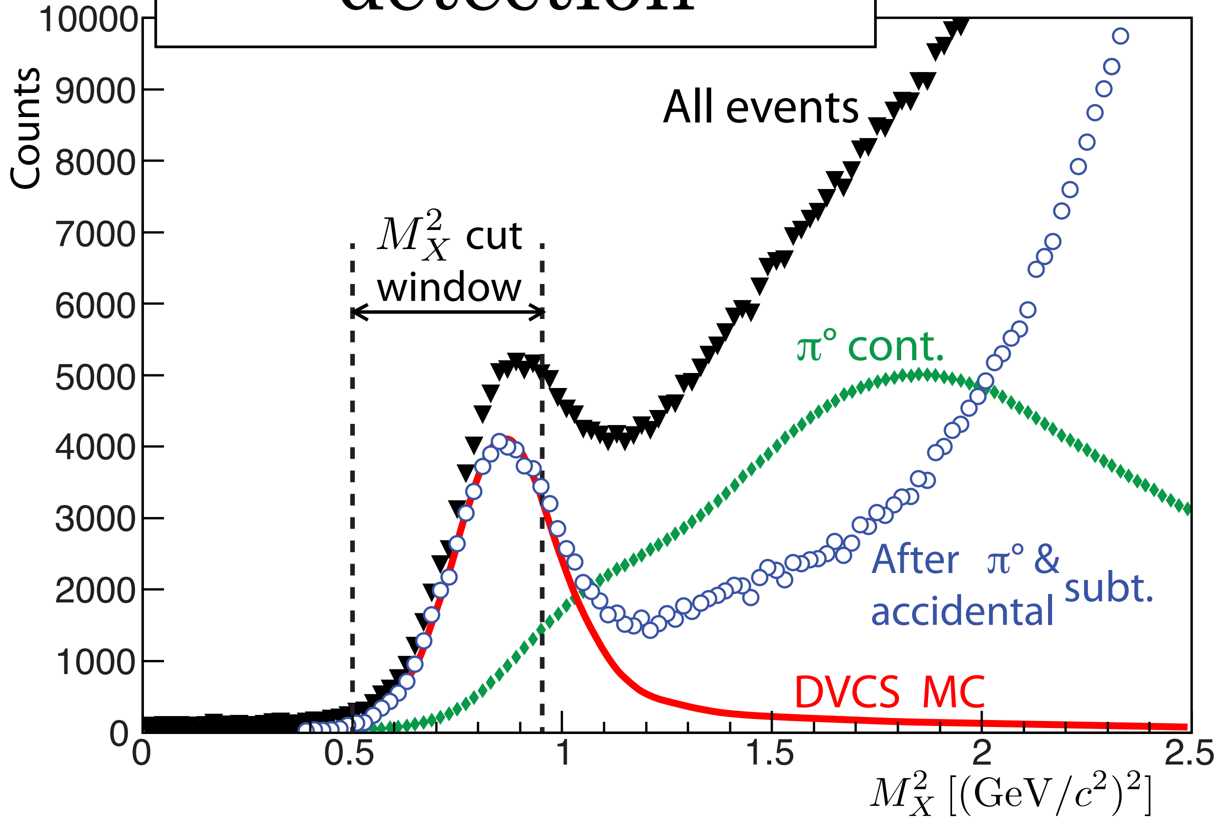


CLAS12 (G. Christiaens et al.), PRL **130**, 211902 (2023)

Selection of exclusive data sample

Hall-A DVCS: eγ detection

6 GeV

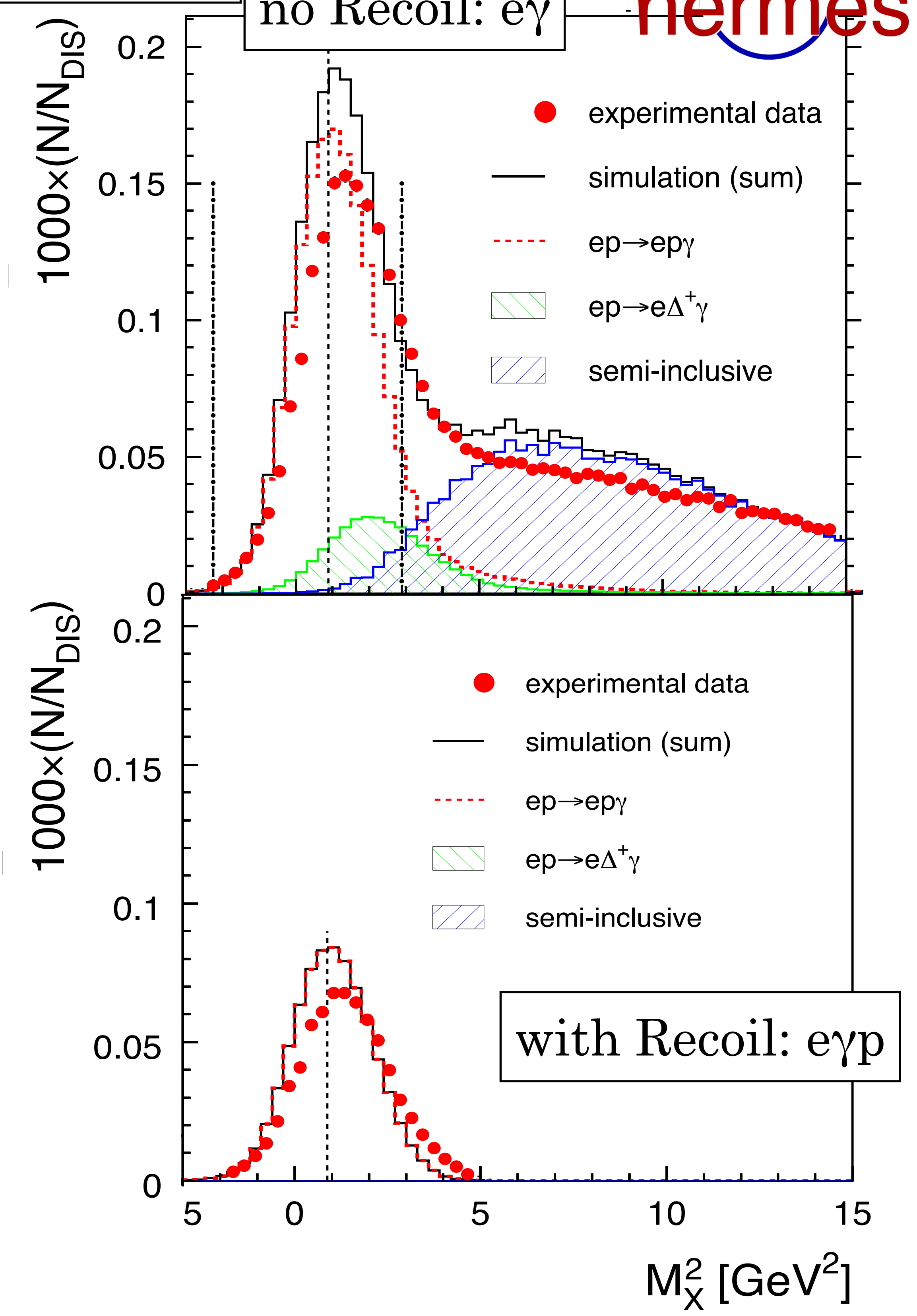


HERMES DVCS:

27.6 GeV

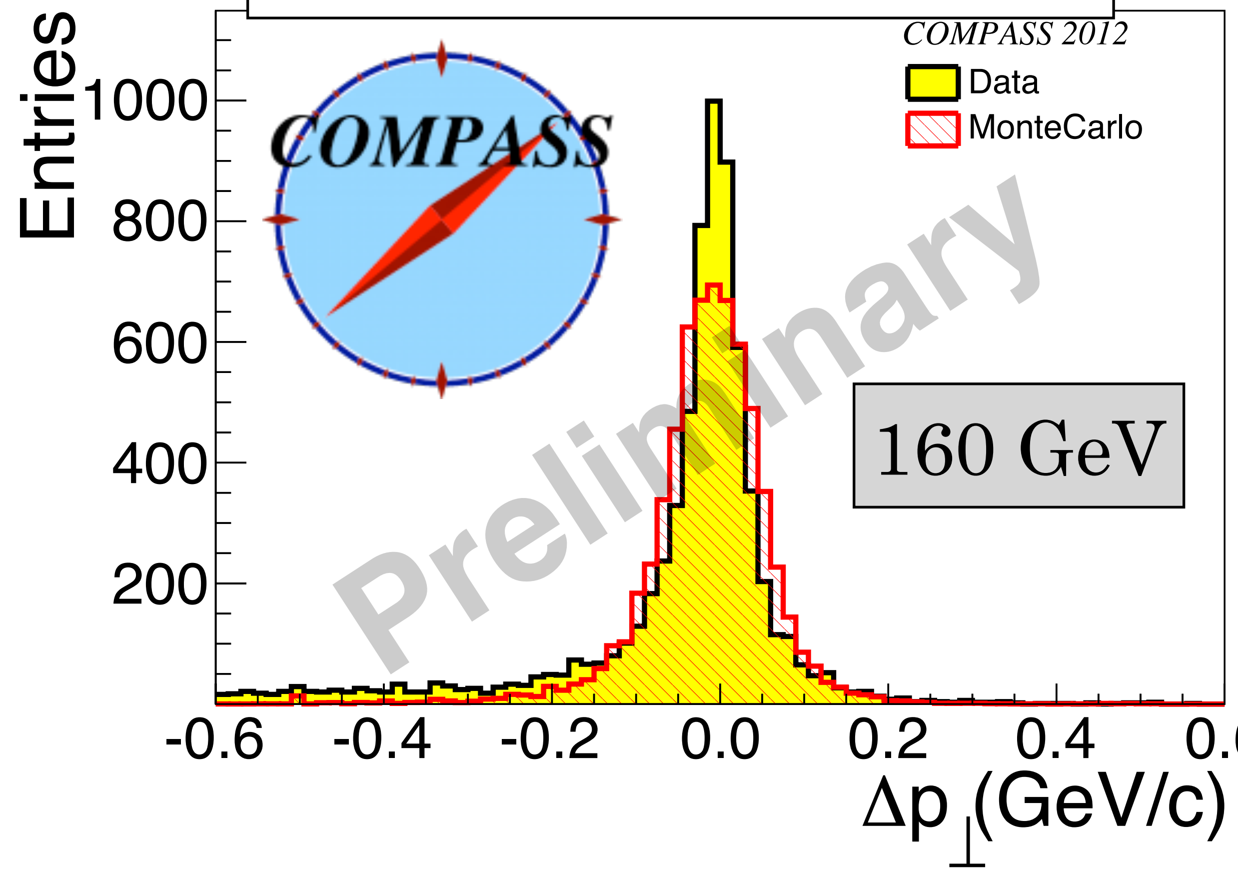
no Recoil: eγ

with Recoil: eγp

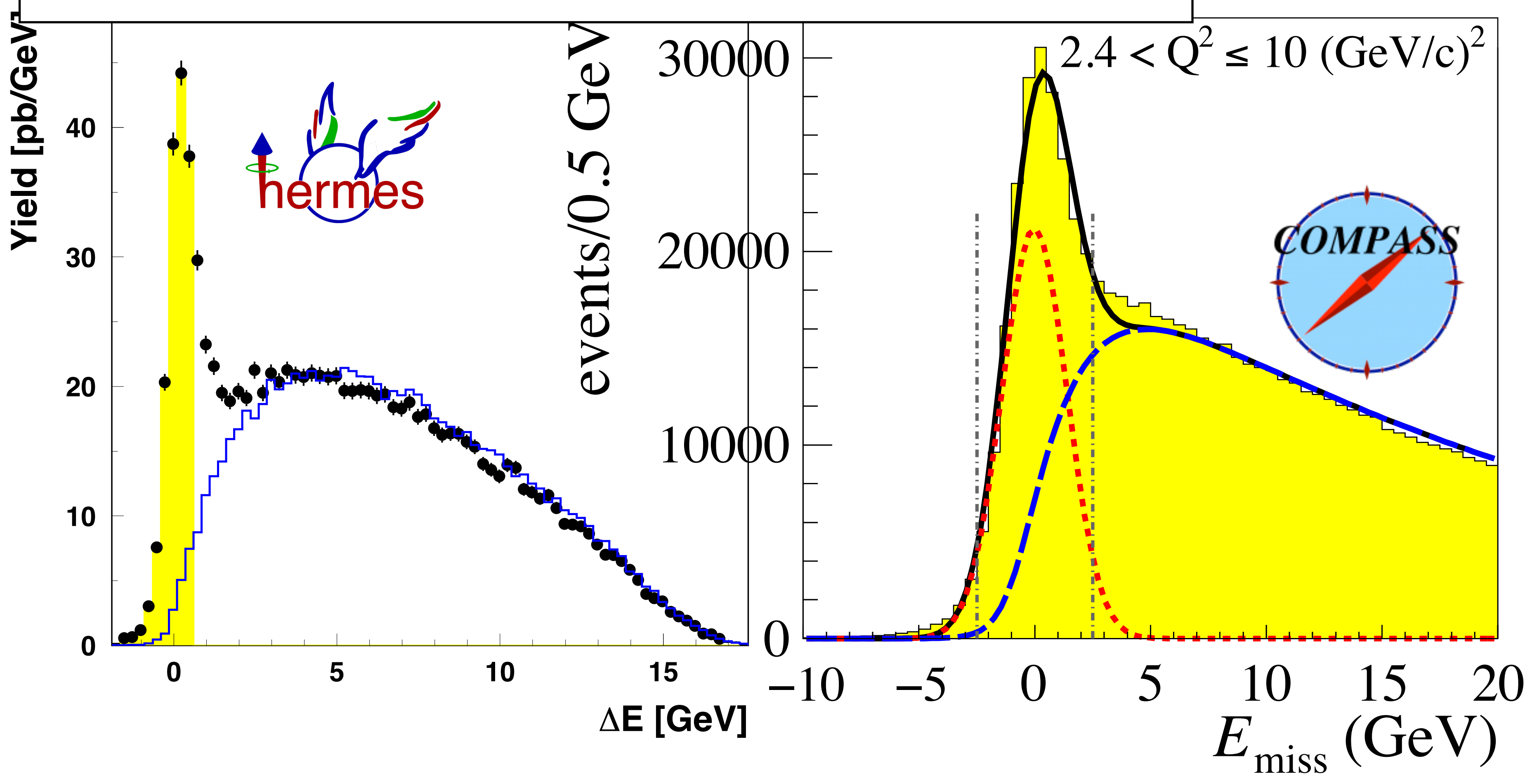


COMPASS DVCS: μγp detection

160 GeV



HERMES & COMPASS excl. ρ: ℓπ-π+ detection



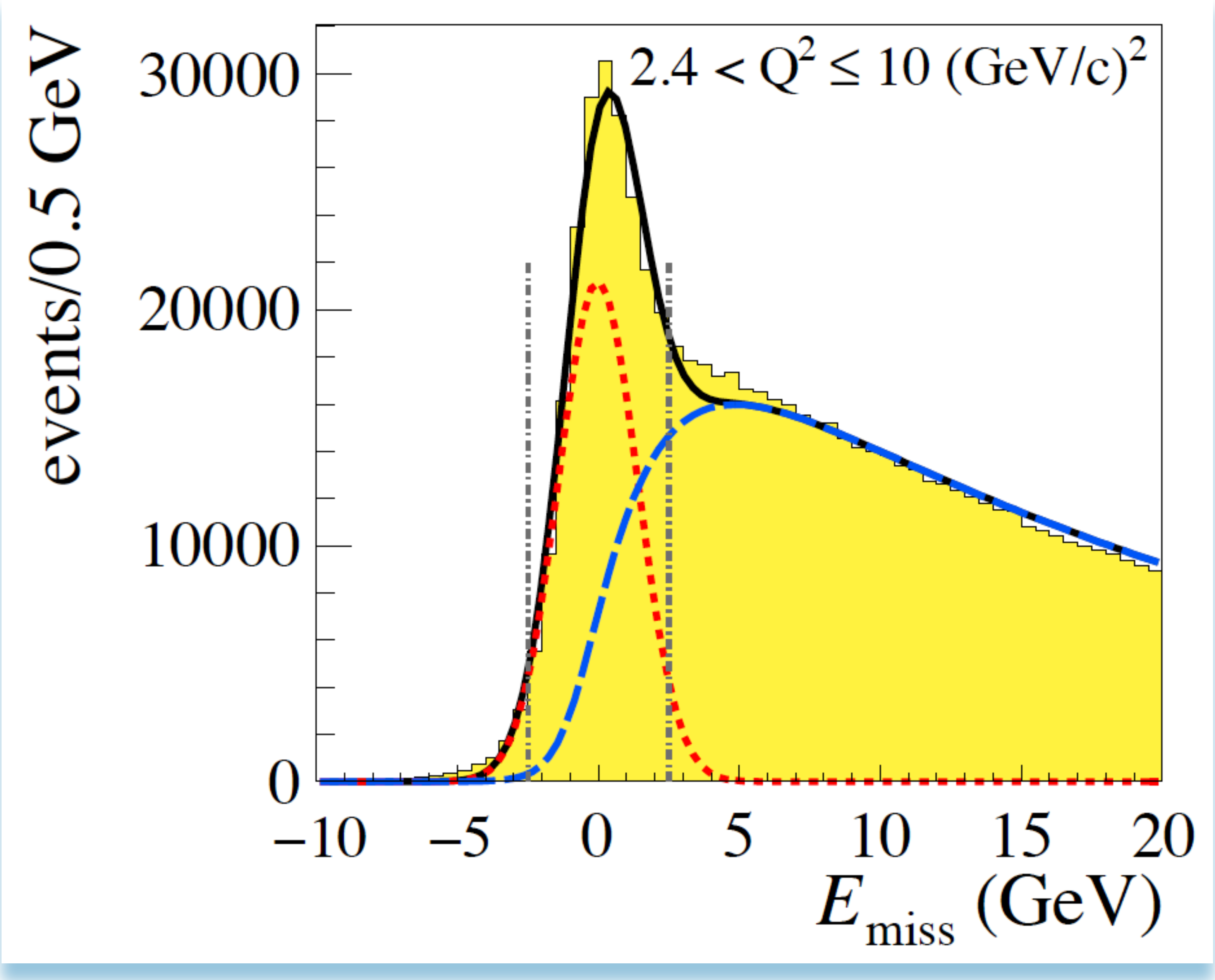
CLAS DVCS:
no Inner Calo: ep or epγ
with Inner Calo: epγ

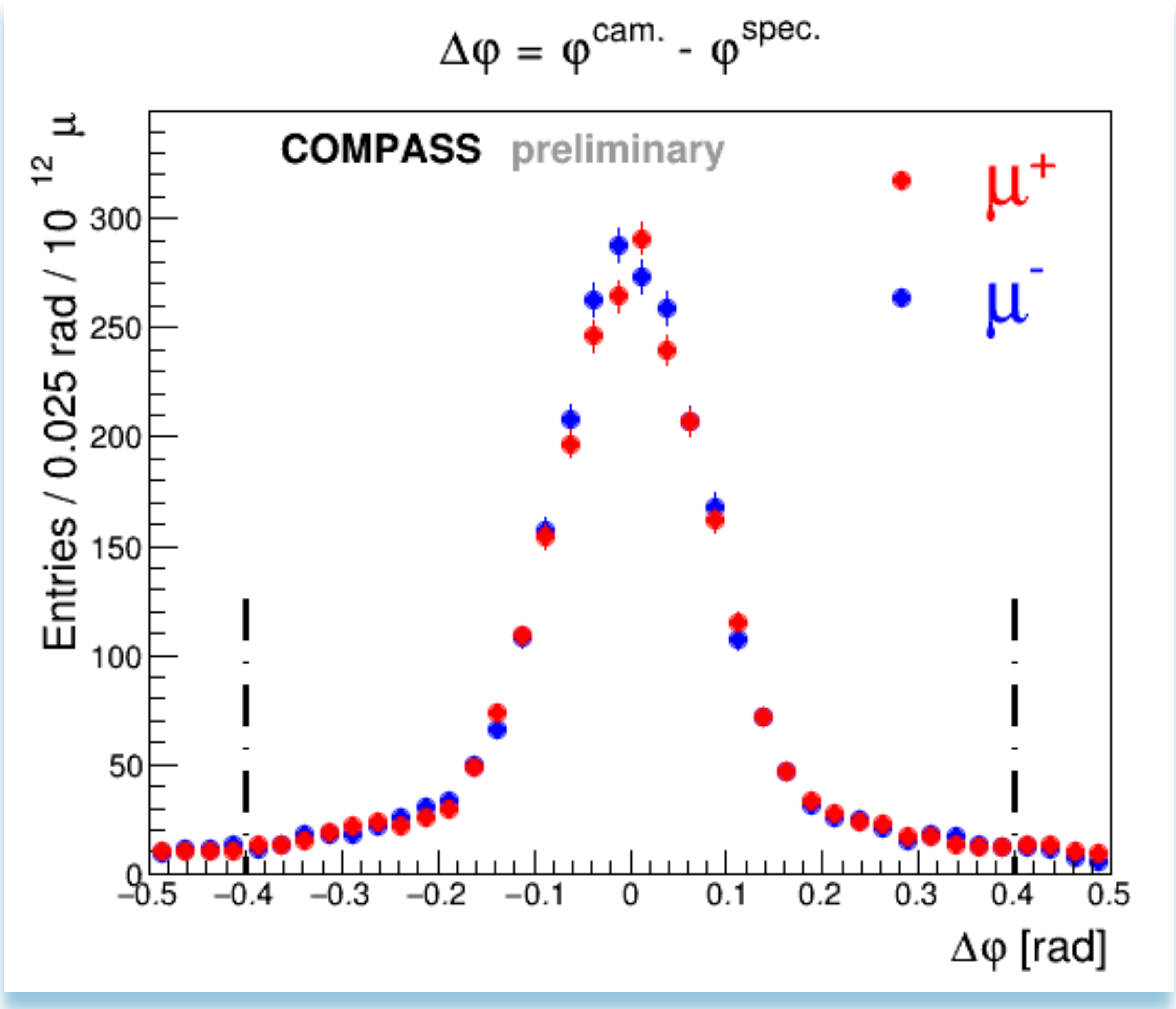
H1/ZEUS DVCS:
eγ + forward veto
ZEUS subsample: epγ

DVMP without recoil-proton detection:
missing energy technique assuming proton mass

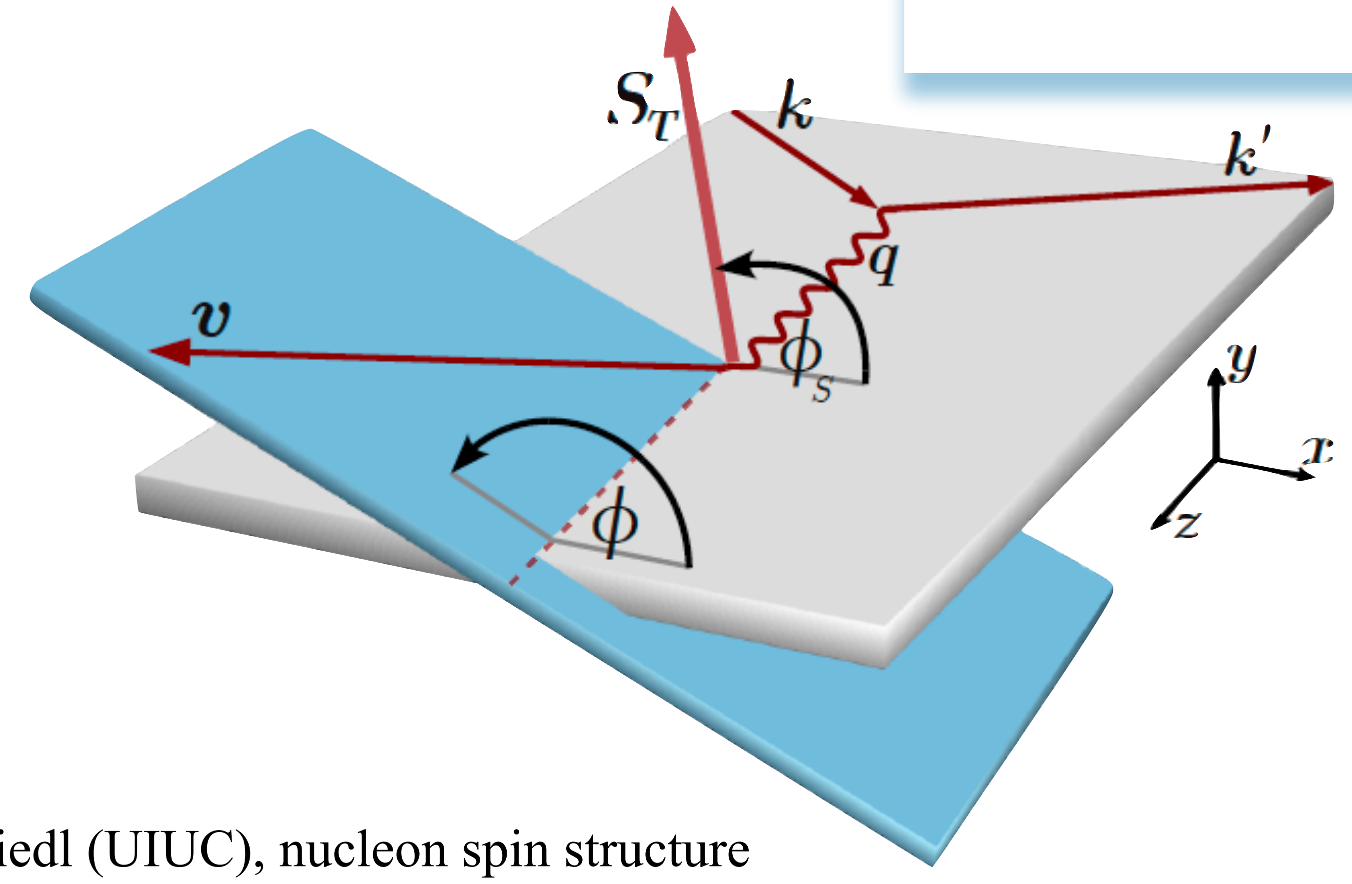
DVCS with recoil-proton detector (RPD):
comparison of proton kinematics measured in RPD vs. expected in spectrometer (from μγ)

Exclusive ρ^0 production
$\mu p^{(\uparrow)} \rightarrow \mu p \rho^0$
with simulated exclusive signal & SIDIS background





DVCS
$\mu^{\pm} p \rightarrow \mu^{\pm} p \gamma$

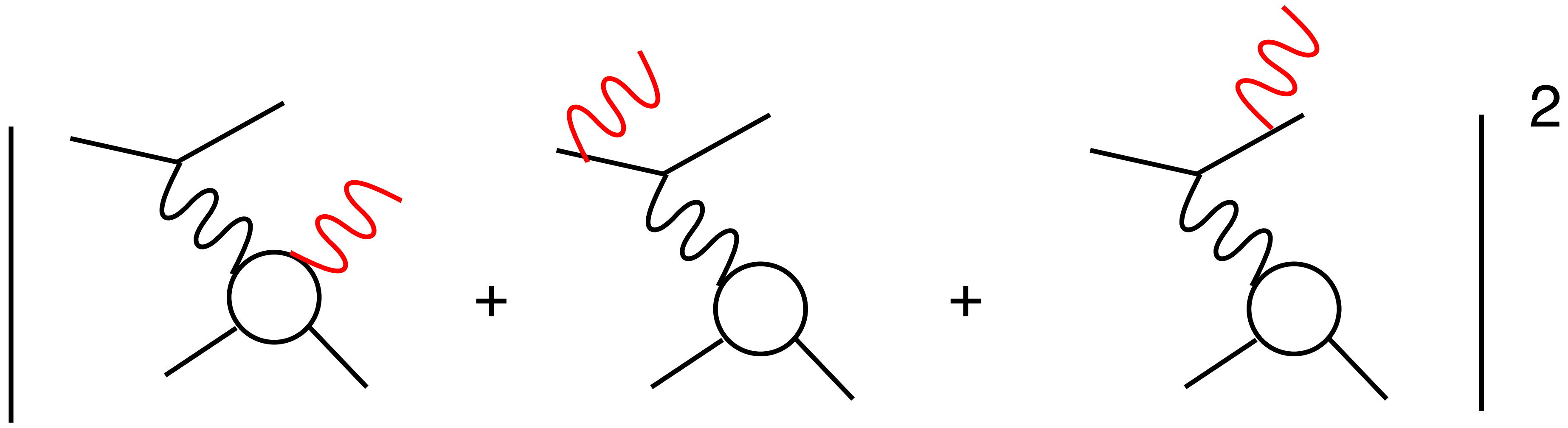


In case of transverse target polarization: additional **azimuthal angle** φ_S defined by direction of transverse target-polarization vector

+ kinematically complete event reconstruction via kinematic event fitting

Access to CFFs at COMPASS

DVCS $\sigma_{\gamma^*\gamma N} \sim$



$$= |\mathcal{T}_{BH}|^2 + \left(\mathcal{T}_{DVCS}\mathcal{T}^*_{BH} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH}\right) + |\mathcal{T}_{DVCS}|^2$$

Analysis of azimuthal modulations (HERMES- and JLab-type) on DVCS on the unpolarized proton in progress

dominant at small x_B
(remainder ~ 5% from KM / GK model)

$$\mathrm{Im}\left(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

$$\mathrm{Re}\left(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

at leading twist (twist 2) on the proton

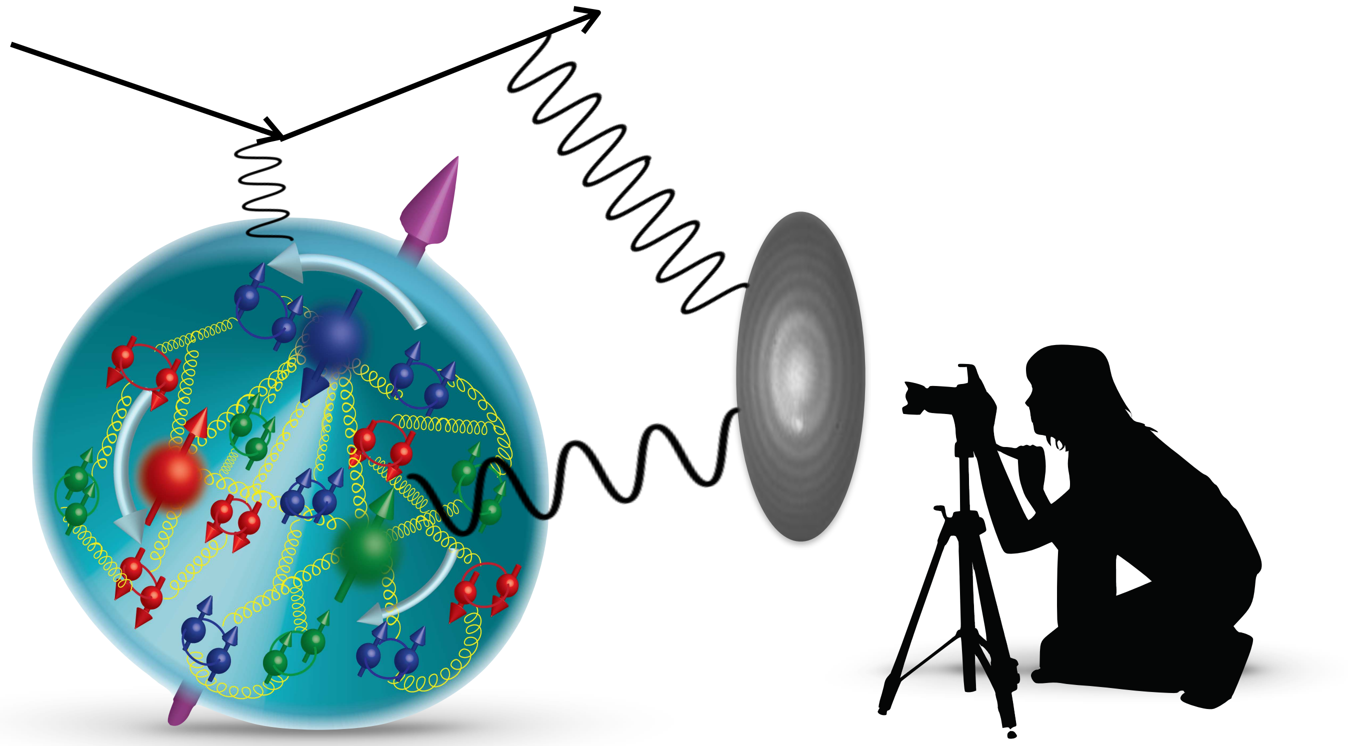
The DVCS / Bethe-Heitler interference term allows to disentangle
Re(τ_{DVCS}) and **Im(τ_{DVCS})**
magnitude and **phase**
of DVCS amplitude τ_{DVCS}

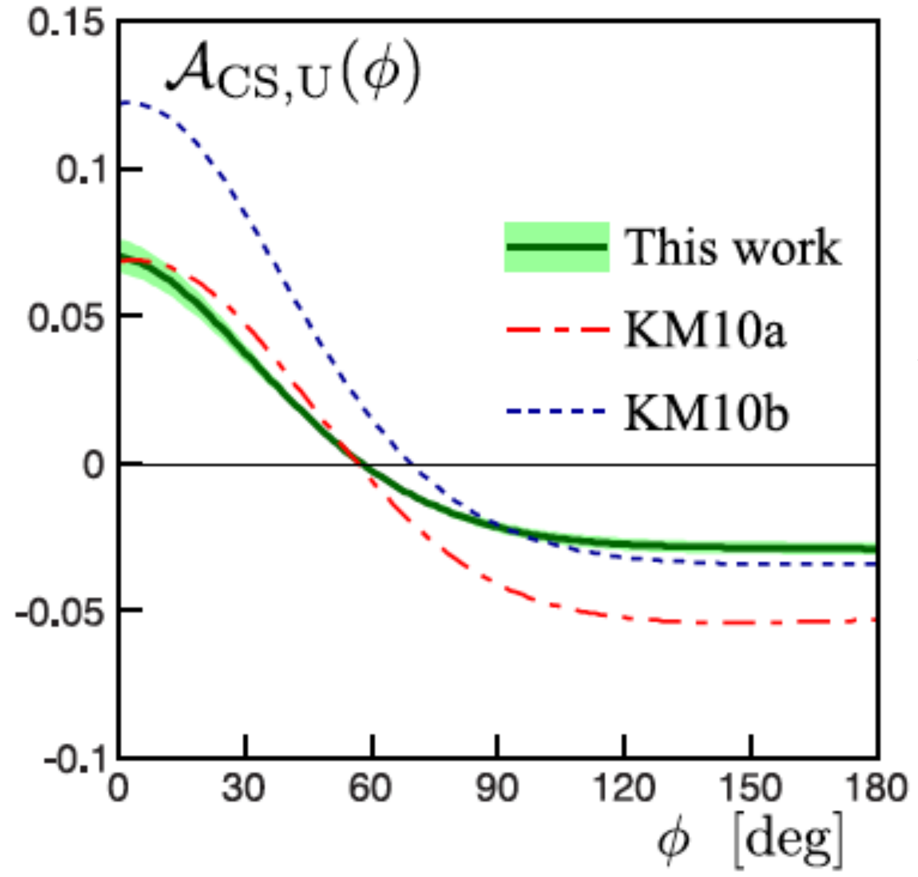
$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$$

$$\mathcal{A}_{CS,U} \equiv \frac{d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}}{d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}$$

Spin-independent DVCS cross section ∝
$$4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$





Sign & magnitude of cosφ amplitude for beam-charge asymmetry? (changes sign between HERMES and HERA)

Kroll, Moutarde, Sabatié, Eur. Phys. J. C (2013) 73:2278
Test of GPD universality: use DVMP data to constrain GPD parameters

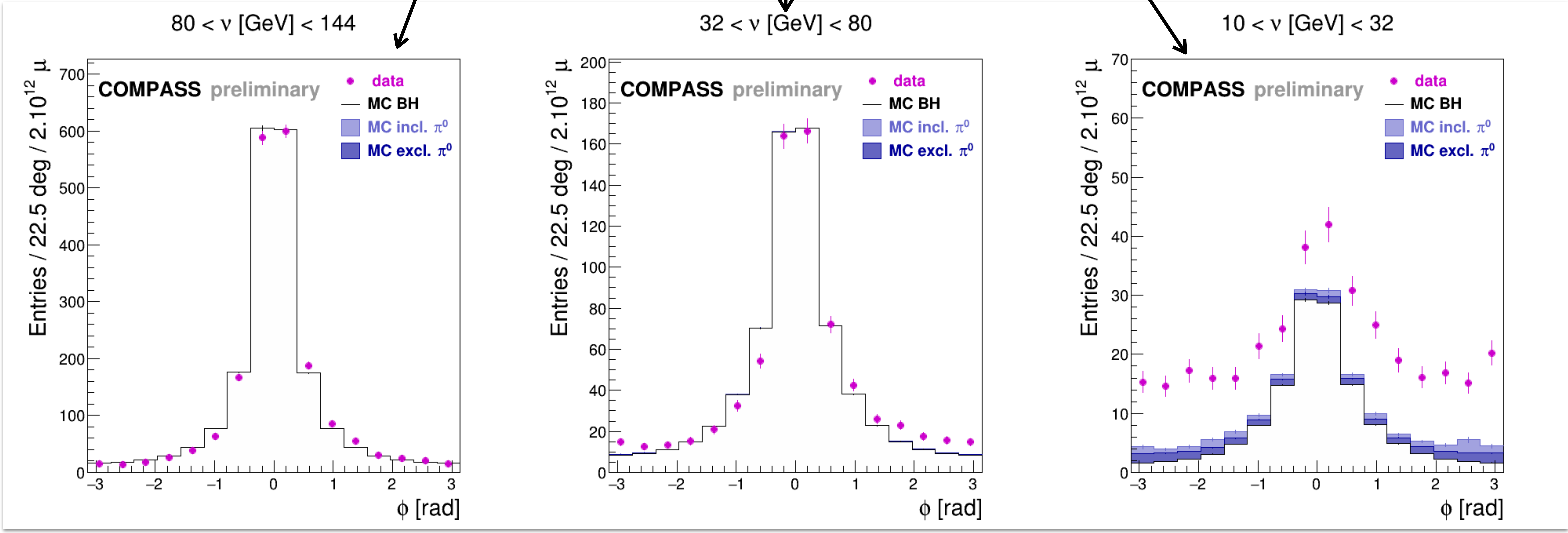
Extraction of pure DVCS yield at COMPASS

$$|\mathcal{T}_{\mathrm{BH}}|^2 + (\mathcal{T}_{\mathrm{DVCS}}\mathcal{T}^*_{\mathrm{BH}} + \mathcal{T}^*_{\mathrm{DVCS}}\mathcal{T}_{\mathrm{BH}}) + |\mathcal{T}_{\mathrm{DVCS}}|^2$$

BH reference yield:
at small $\langle x_B \rangle$=0.0085

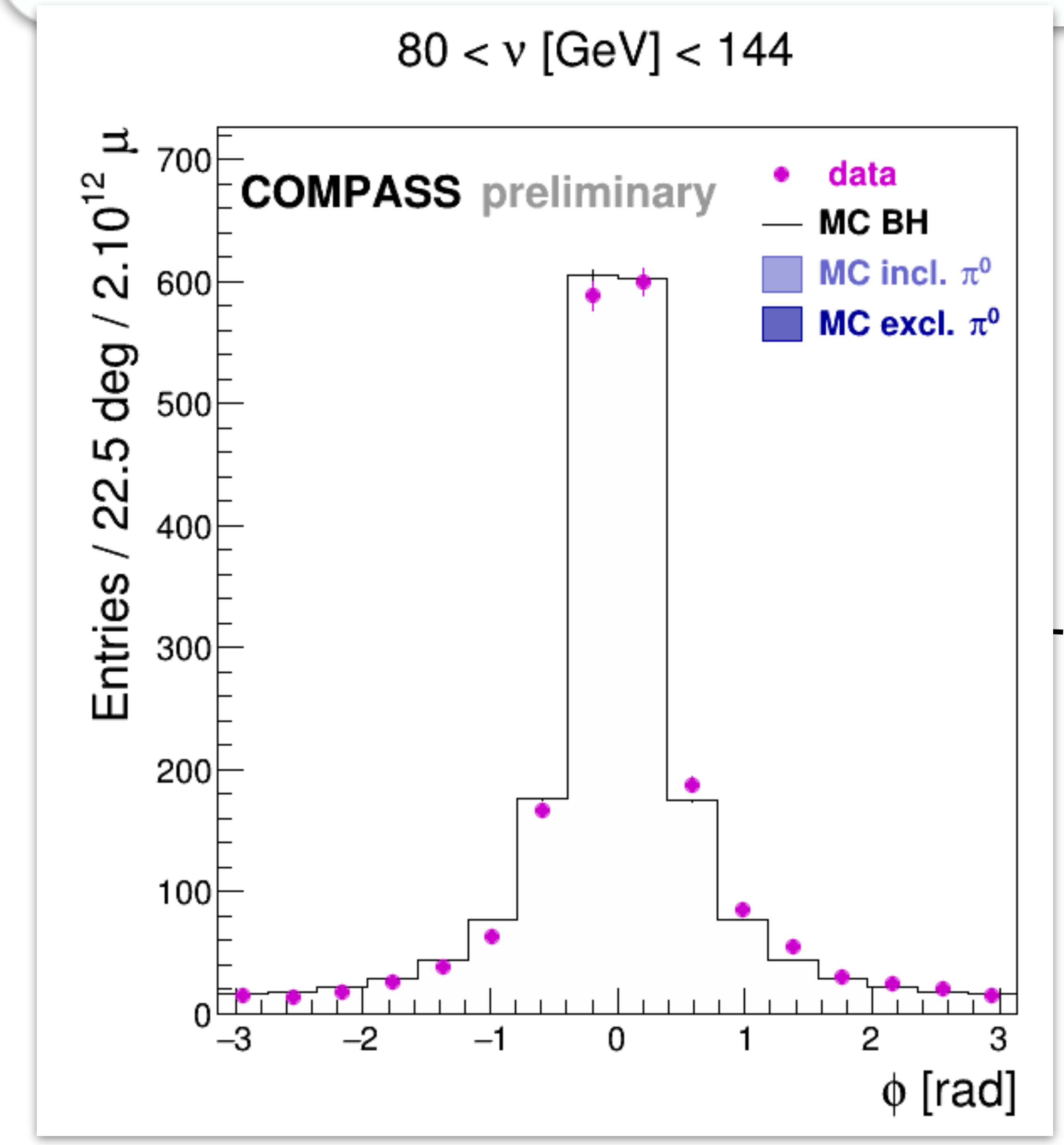
DVCS amplitude:
ϕ-modulations in cross section
at medium $\langle x_B \rangle$=0.0200

Transverse imaging:
ϕ-integrated cross section
at medium $\langle x_B \rangle$=0.0630



portion of the 2016 data = 2x 2012 data

Extraction of pure DVCS yield at COMPASS



DVCS / BH: μp→μpγ

π⁰ production: μp→μp π⁰→μpγ(γ)(X) exclusive or SIDIS

γγ: “visible π⁰”, γ: invisible π⁰ background

↓

Determine BH reference yield at low-x_B ⇔ high-ν: tune MC to data

↓

Subtract BH yield in high-x_B ⇔ low-ν bin

↓

Subtract measured visible π⁰ yield in high-x_B ⇔ low-ν bin

↓

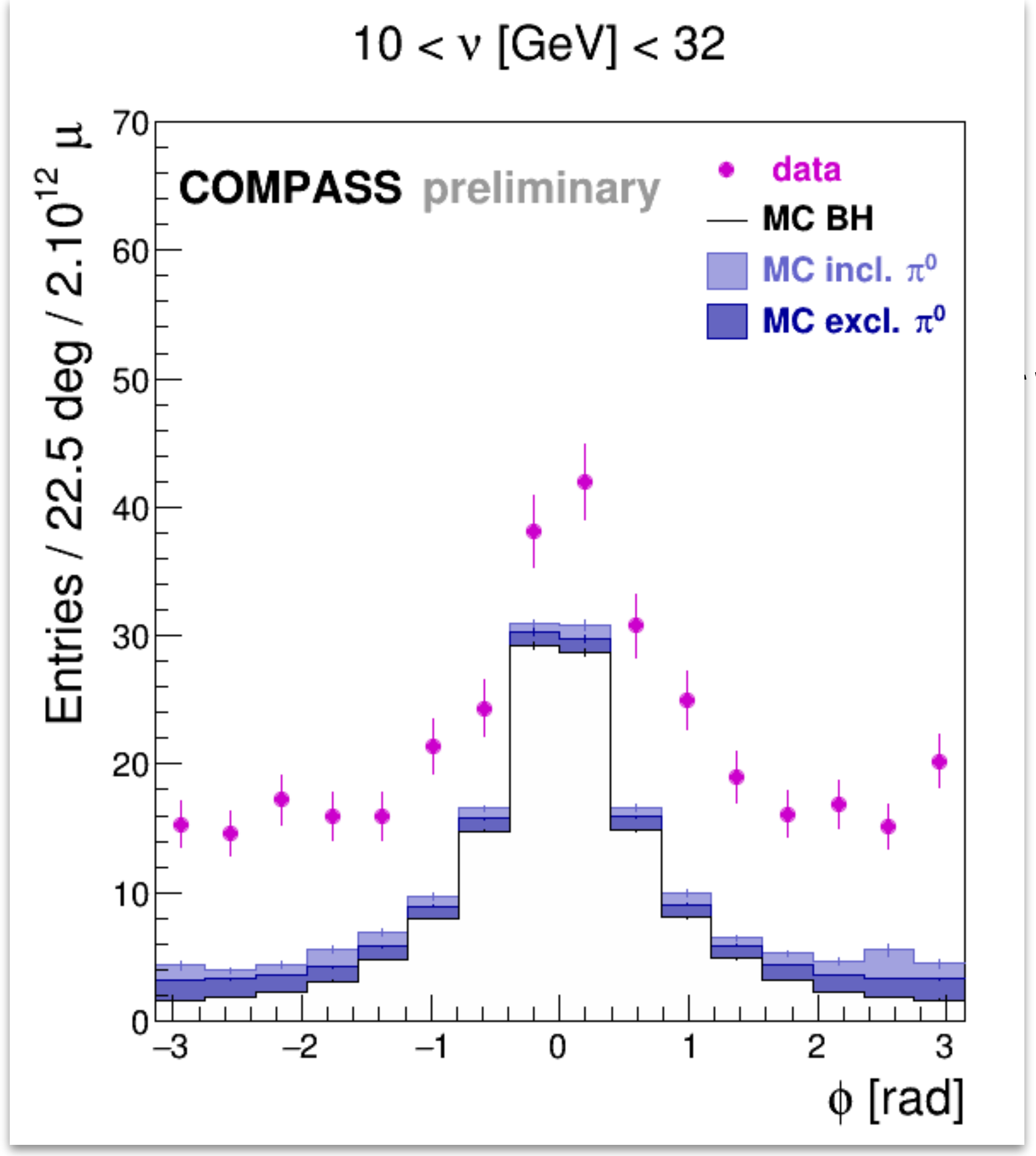
Estimate π⁰ invisible background from MC:
SIDIS 40% (LEPTO) + exclusive 60% (HEPGEN with GK model)
with 10% uncertainty each

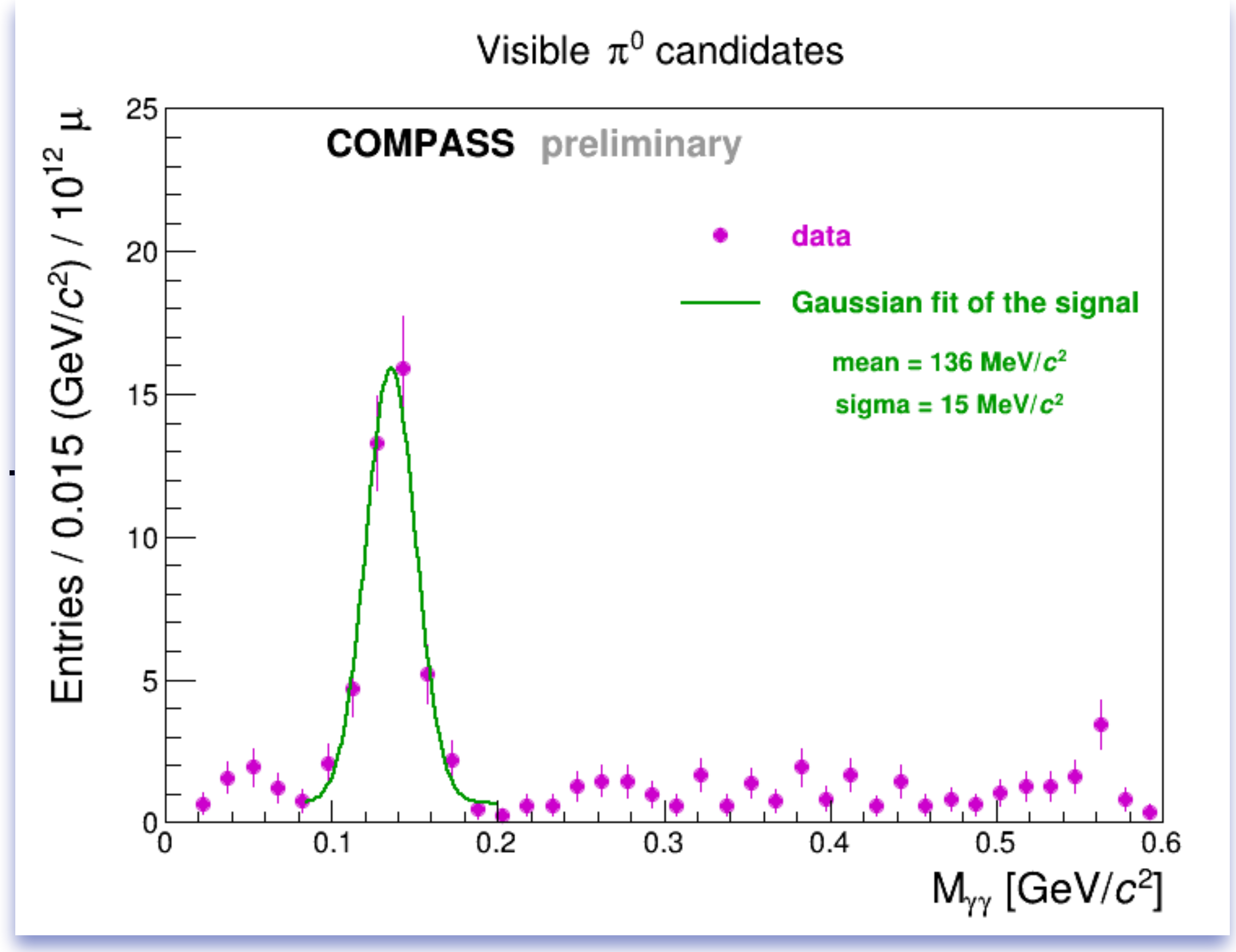
↓

Remove invisible π⁰ yield (invisible normalized to visible yield)

↓

Pure DVCS yield





portion of the 2016 data = 2x 2012 data

Transverse imaging of the nucleon

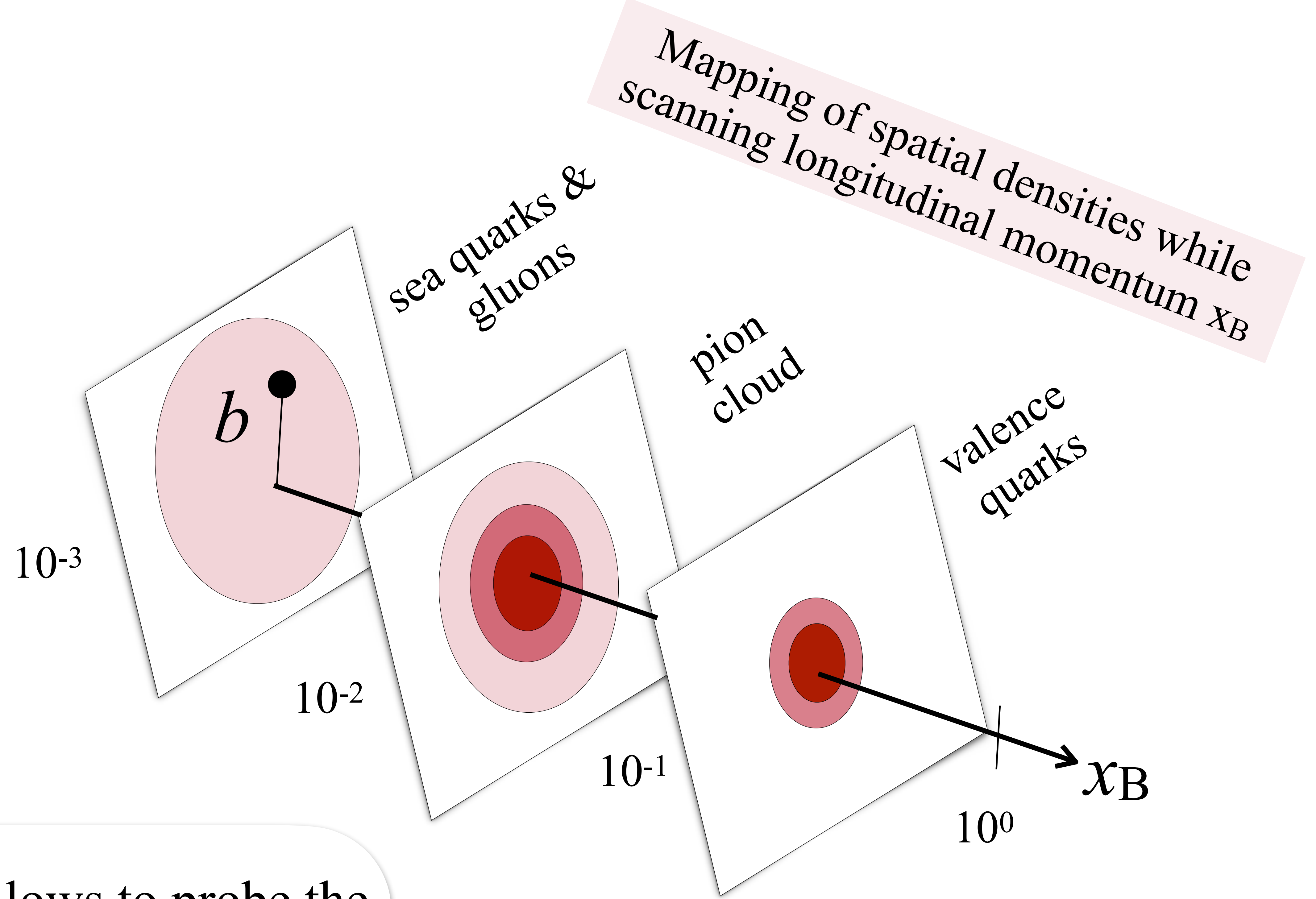
Impact-parameter representation of parton distribution function:

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

[Burkardt, Int. J. Mod. Phys. A18 (2003) 173]

"spatial parton density = Fourier transform of GPD"

$\boldsymbol{b}_\perp$ is the impact parameter,
$\boldsymbol{\Delta}_\perp$ is the difference of initial and final transverse momenta,
$\boldsymbol{\Delta}_\perp^2$ is related to the Mandelstam-t



3-dim "tomographic images" of the nucleon in longitudinal momentum and transverse position

The differential DVCS cross section allows to probe the **transverse extension of partons** in the nucleon:

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-b|t|}$$

b = "t-slope" = average impact parameter

Transverse imaging of the nucleon

PDF impact-parameter representation:

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

[Burkardt, Int. J. Mod. Phys. A18 (2003) 173]

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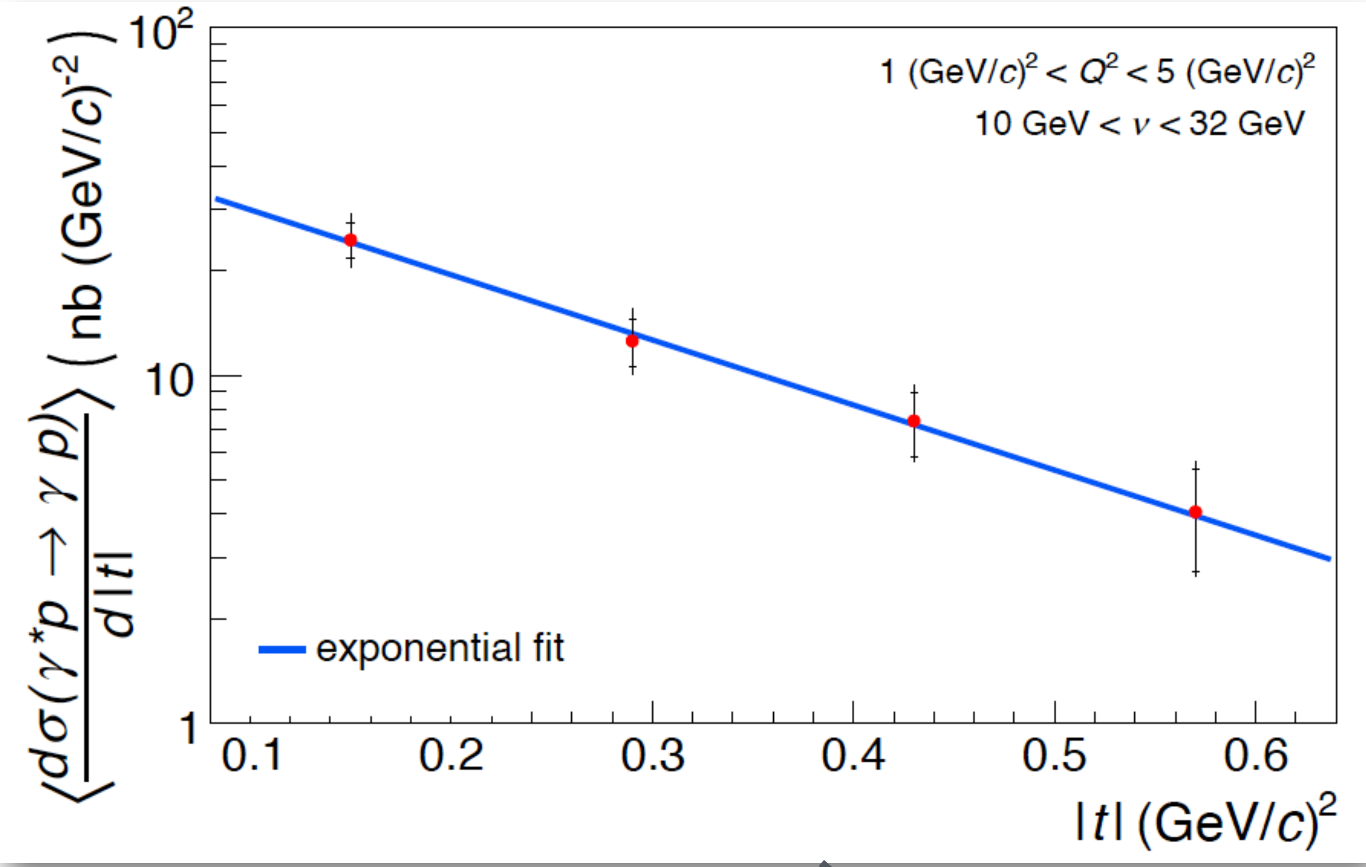
$\boldsymbol{\Delta}_\perp^2$ is related to the Mandelstam-t

Differential DVCS cross section with "t-slope" = average impact parameter

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-B|t|}$$

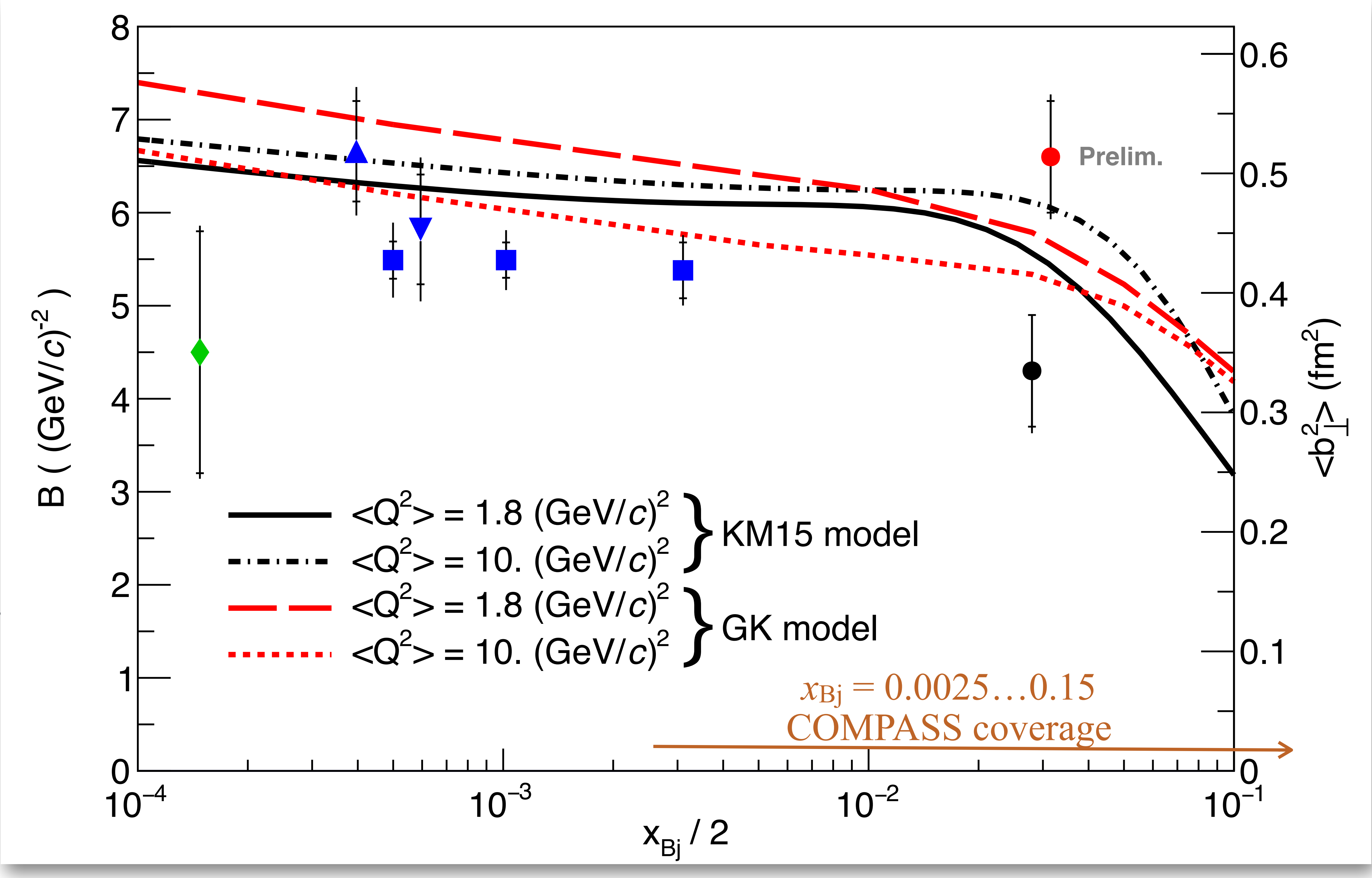


COMPASS DVCS t-slope

- Sea-quark domain between gluons and valence-quarks
- Transverse extension of partons and t-slope B:

$$\langle r_\perp^2(x_{\mathrm{Bj}})\rangle \approx 2\langle B(x_{\mathrm{Bj}})\rangle \hbar^2$$

$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\mathrm{stat}} {}^{+0.01}_{-0.02}|_{\mathrm{sys}} \pm 0.04_{\mathrm{model}})\ \mathrm{fm}$$



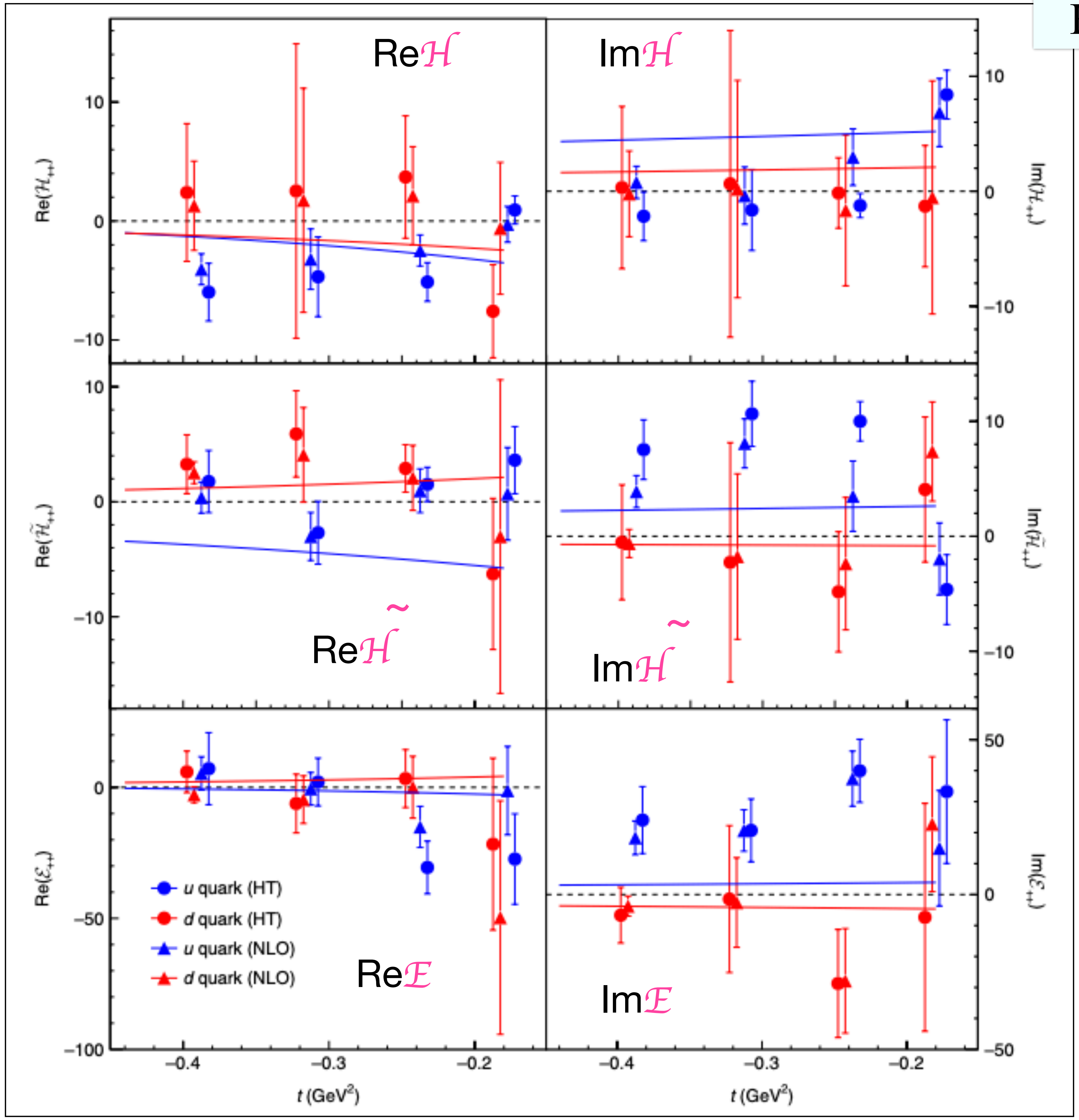
~23% of 2016/17	●	COMPASS:	$\langle Q^2\rangle$ = 1.8 $(\mathrm{GeV}/c)^2$	This Analysis
2012	●	COMPASS:	$\langle Q^2\rangle$ = 1.8 $(\mathrm{GeV}/c)^2$	Phys. Lett. B793 (2019) 188
	♦	ZEUS:	$\langle Q^2\rangle$ = 3.2 $(\mathrm{GeV}/c)^2$	JHEP 0905 (2009) 108
	▲	H1:	$\langle Q^2\rangle$ = 4.0 $(\mathrm{GeV}/c)^2$	Eur. Phys. C44 (2005) 1
	▼	H1:	$\langle Q^2\rangle$ = 8.0 $(\mathrm{GeV}/c)^2$	Eur. Phys. C44 (2005) 1
	■	H1:	$\langle Q^2\rangle$ = 10. $(\mathrm{GeV}/c)^2$	Phys. Lett. B681 (2009) 391

Flavor separation of CFFs

- **Flavor separation of CFFs:** **u-quark**, **d-quark**

[Benali, Desnault, Mazouz, *et al.*, Nature Physics 16 (2020) 191–198]

with reggeized diquark model (Goldstein, Liuti, et al.)



Hall A neutron DVCS

JLab 6&12
p & n DVCS

Preliminary global fits of CFF using NN & dispersion relation

[Marija Čuić et al, arxiv2007.00029]