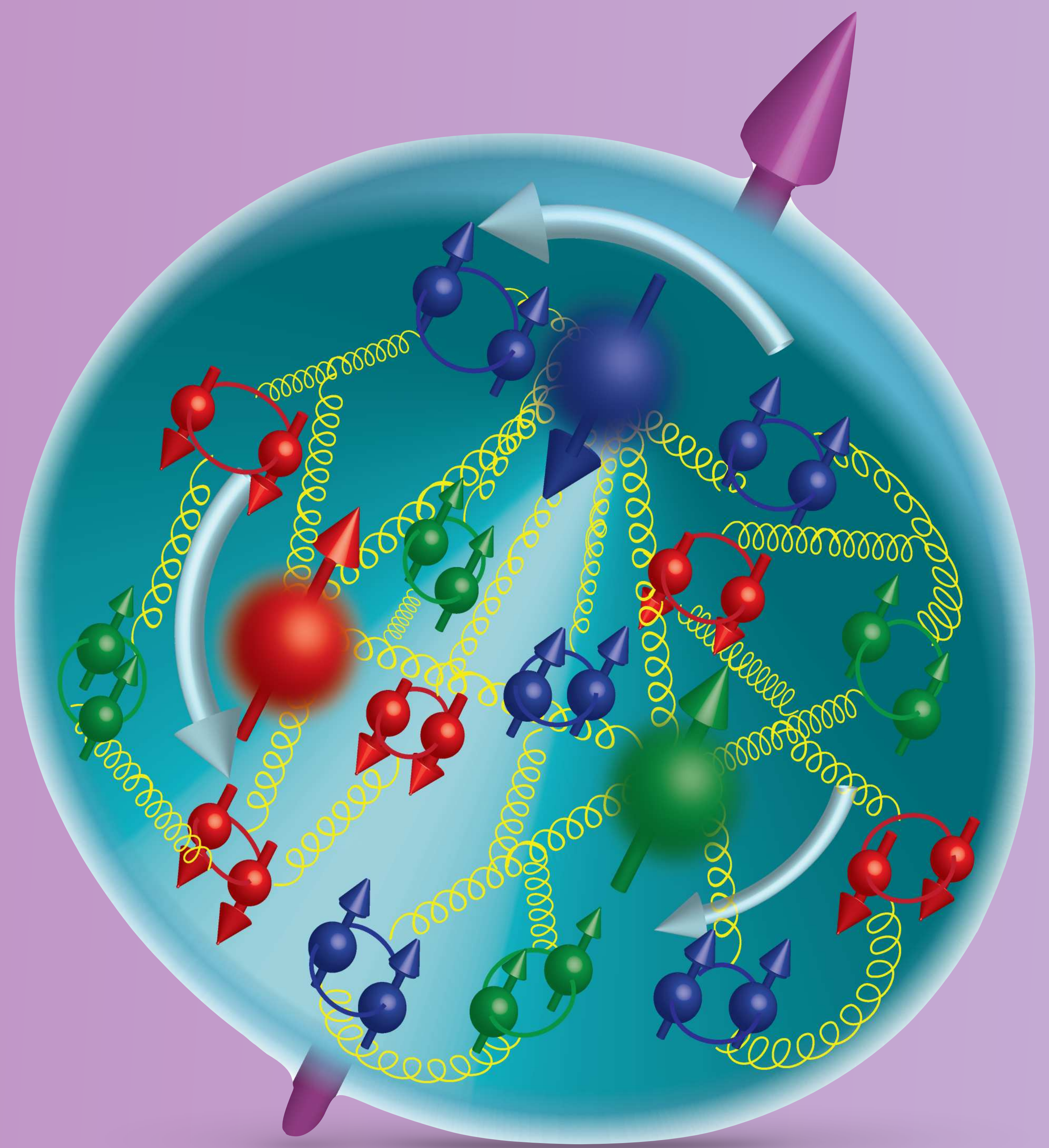
Highlights from the spin-polarized experiments: mapping the nucleon

April 14, 2021



9th workshop of the APS Topical Group on Hadronic Physics (GHP)

Caroline Riedl (UIUC)

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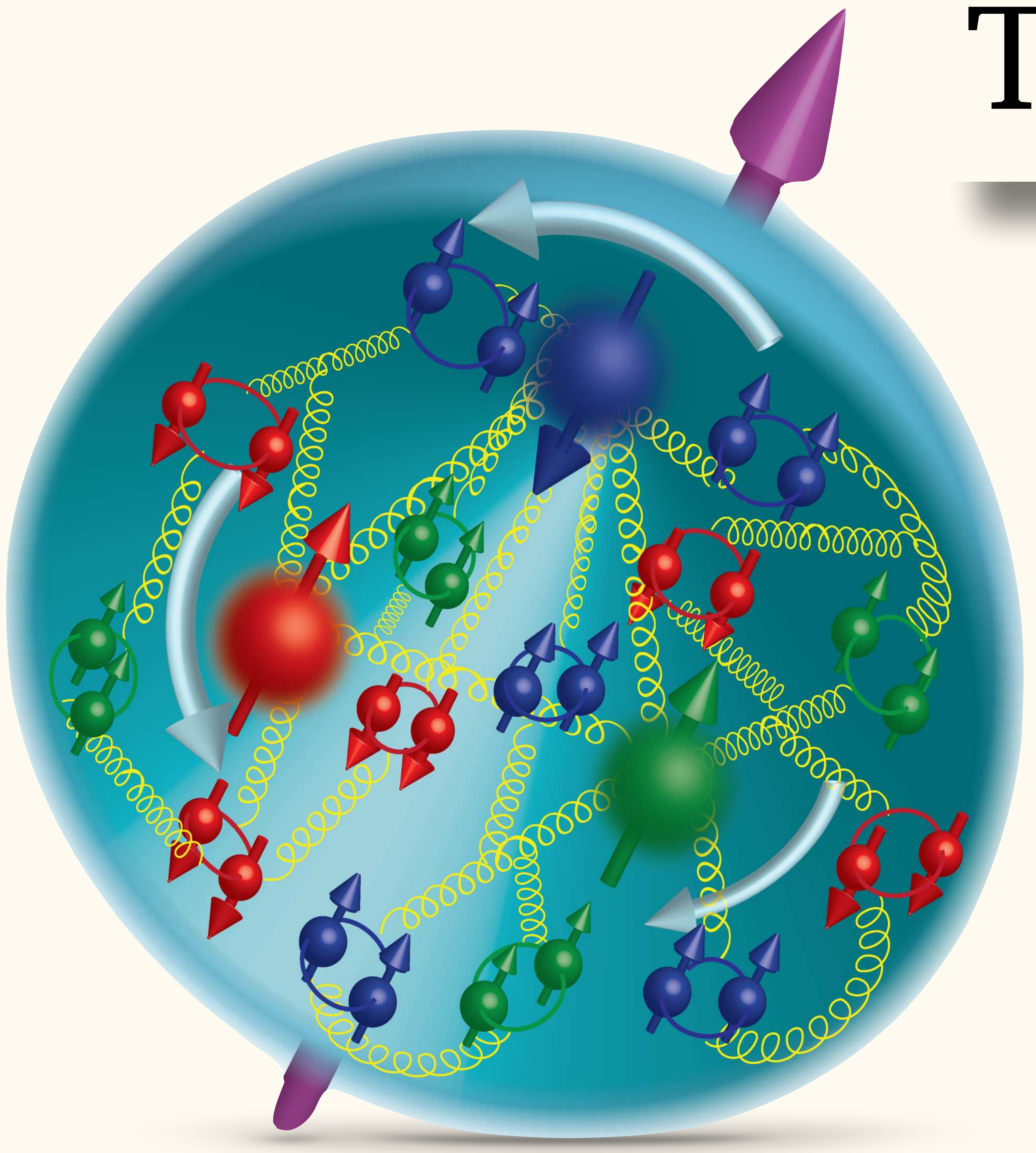


nucleon polarization

	U	L	T	TMD	GPD
Multiplicities	❋			❋	
Sivers TMD			❋	❋	
Twist-3 correlation functions			❋	❋	
Transversity TMD & Collins FF			❋	❋	
Higher twist in SIDIS	❋			❋	
DVCS	❋	❋	❋		❋
Hard exclusive mesons	❋	❋			❋
Selected near future	❋		❋	❋	❋

For details, refer to parallel sessions

JLab dedicated talk: see talk by Dipangkar Dutta 11:00

RHIC-spin dedicated talk by Matt Posik Friday 16:00

Theory talks, e.g., by Daniël Boer and Barbara Pasquini Friday morning

Hall A

Hall C

The physics questions

How do quarks & gluons, and their dynamics, make up proton spin?

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + L_q + J_g$$ *

Spin puzzle

quark spin

$\Delta\Sigma \approx 1/3$

quark orbital angular momentum

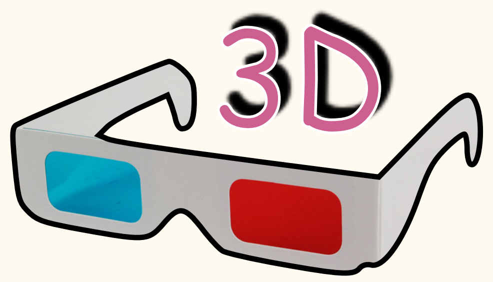
gluon spin & orbital angular momentum

from recent global fits to RHIC data: non-zero positive and large (60%) gluon-spin contribution to the proton spin in the region 0.05 < x < 0.2

* so-called Ji decomposition. There is also the Jaffe & Manohar decomposition, $\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_g$, but translations are not straight forward - see e.g. Matthias Burkardt arXiv:1011.2466

How is the proton spin correlated with the motion of quarks/gluons?

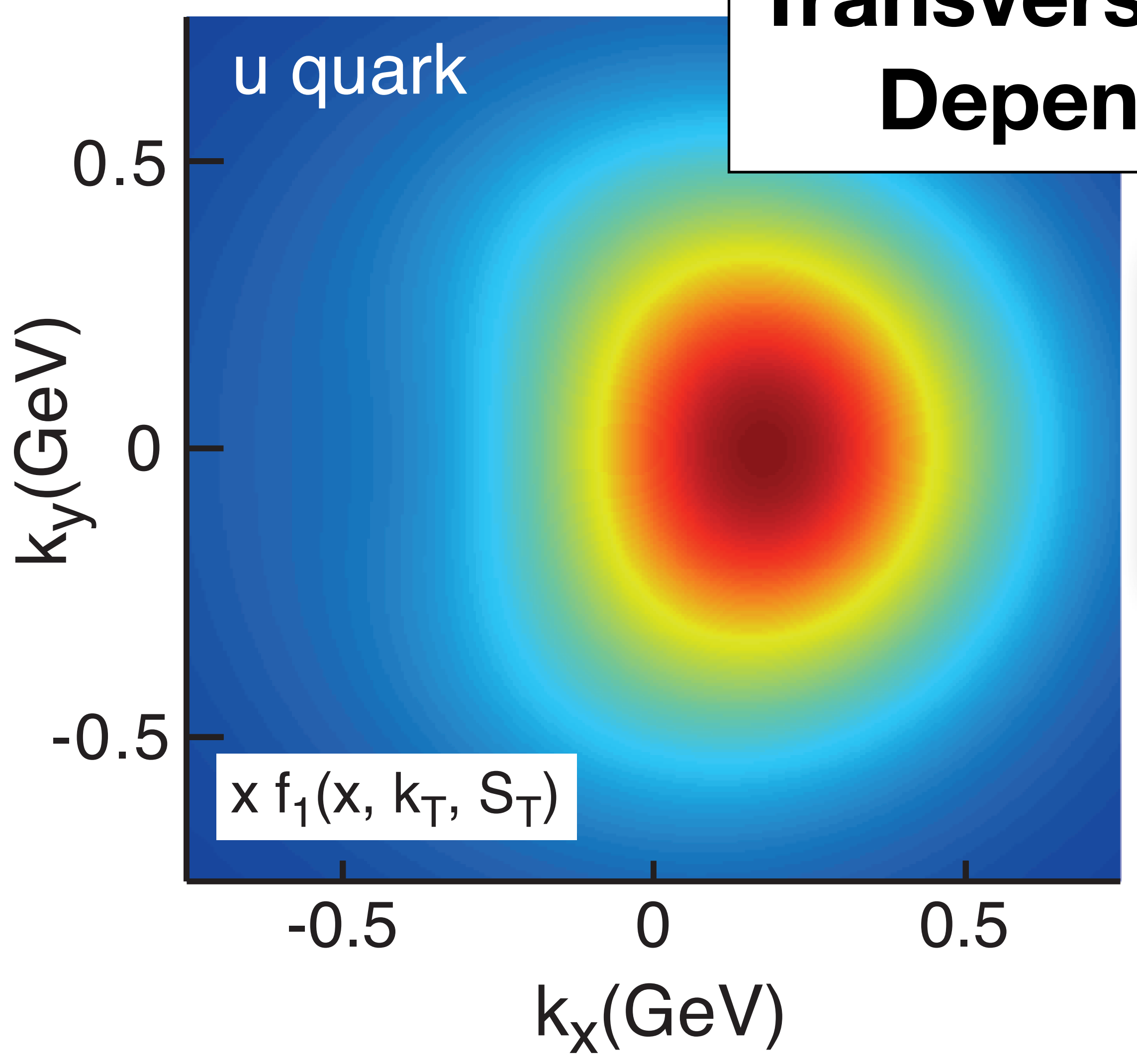
Nucleon tomography



How does the proton spin influence the spatial distribution of partons?

Deformation of parton's confined motion when hadron is polarized

momentum space



EIC "White Paper" arXiv:1212.1701, based on M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011)

Transverse Momentum Dependent PDFs

TMDs
$f(x,k_T)$

Generalized Parton Distributions

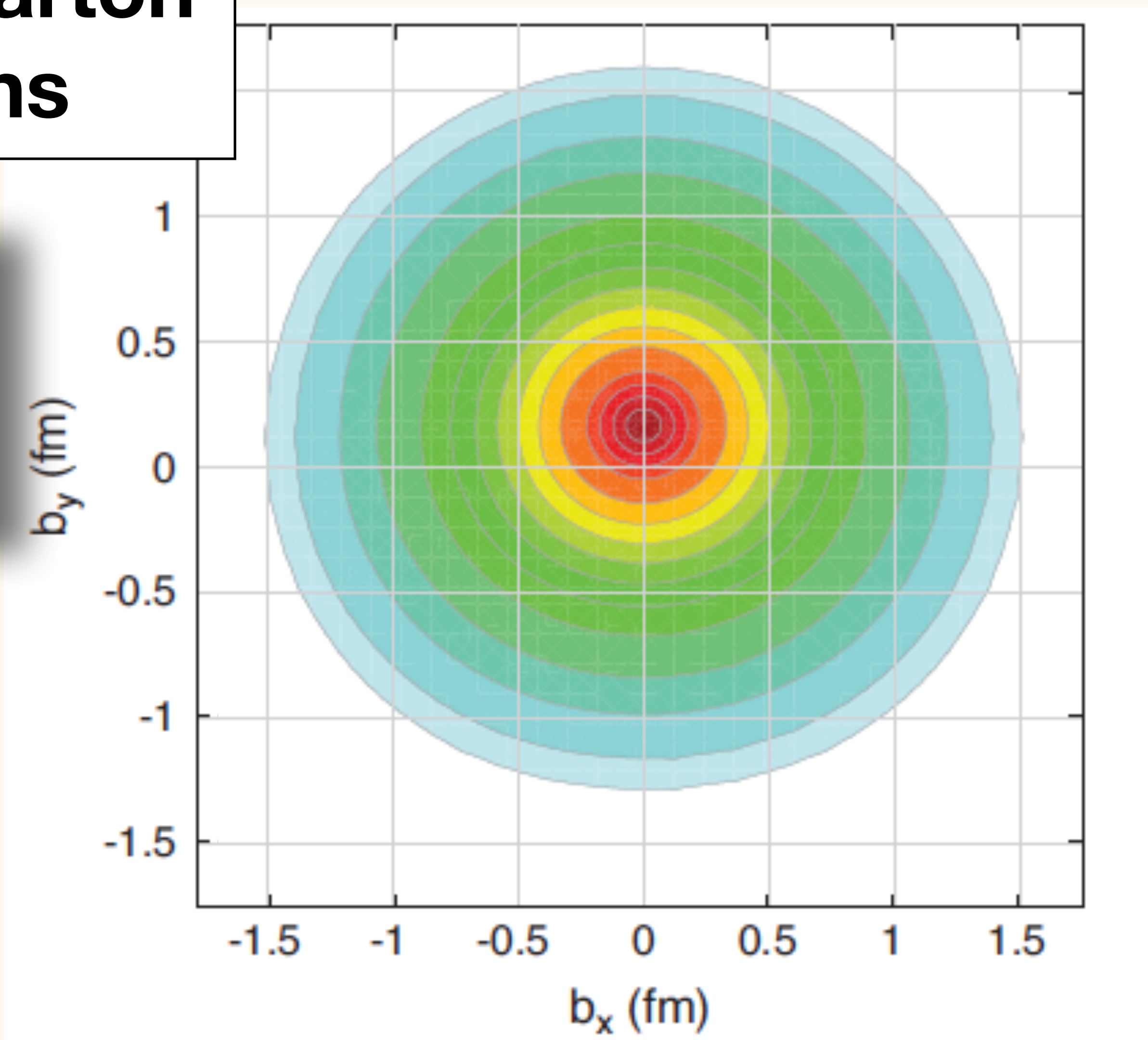
GPDs
$H(x,\xi,t)$

k_T-integration

$\xi=0,\ t=0$

(collinear) PDFs $q(x)$, 1D

Deformation of parton's spatial distribution when hadron is polarized

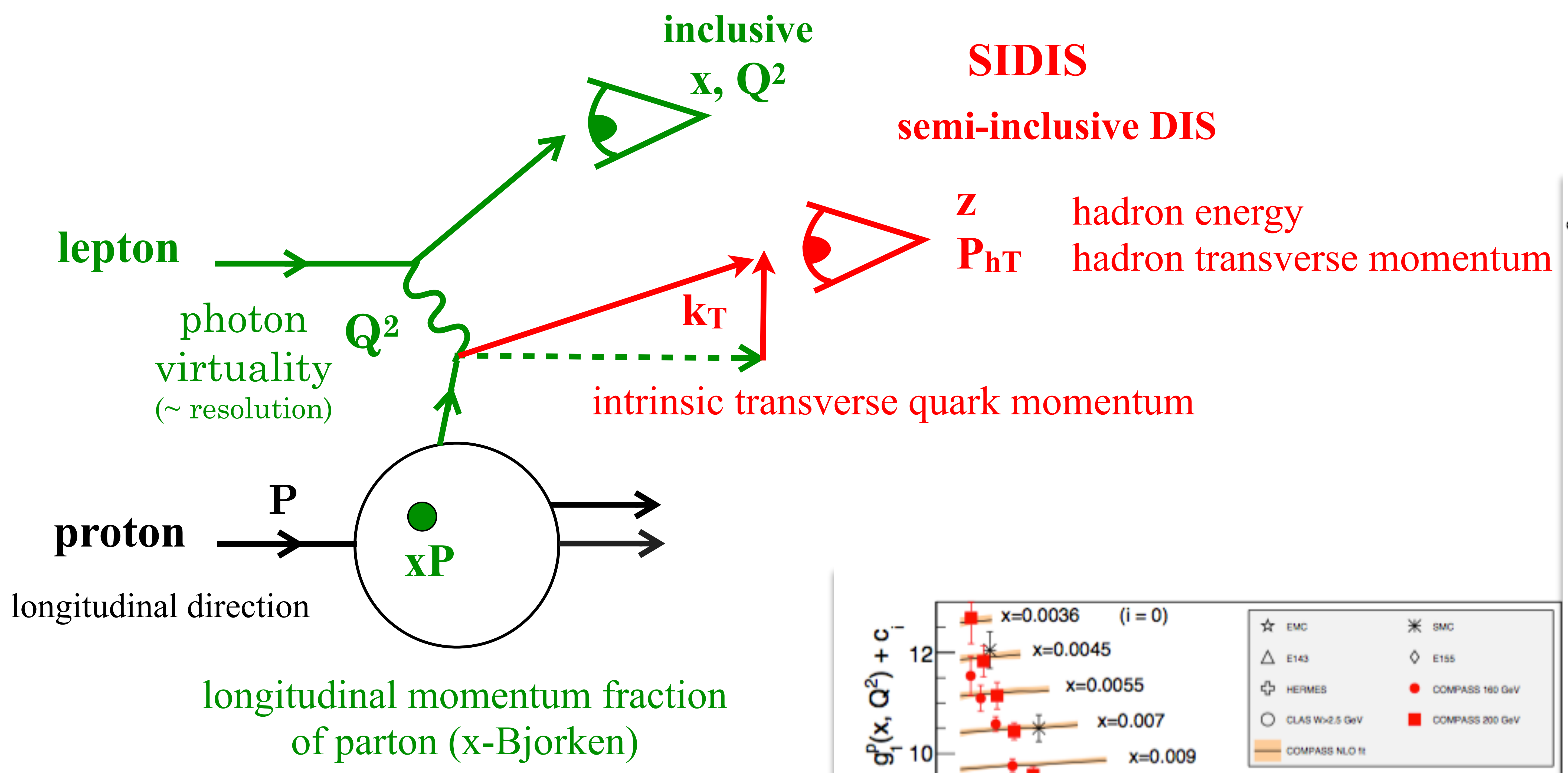


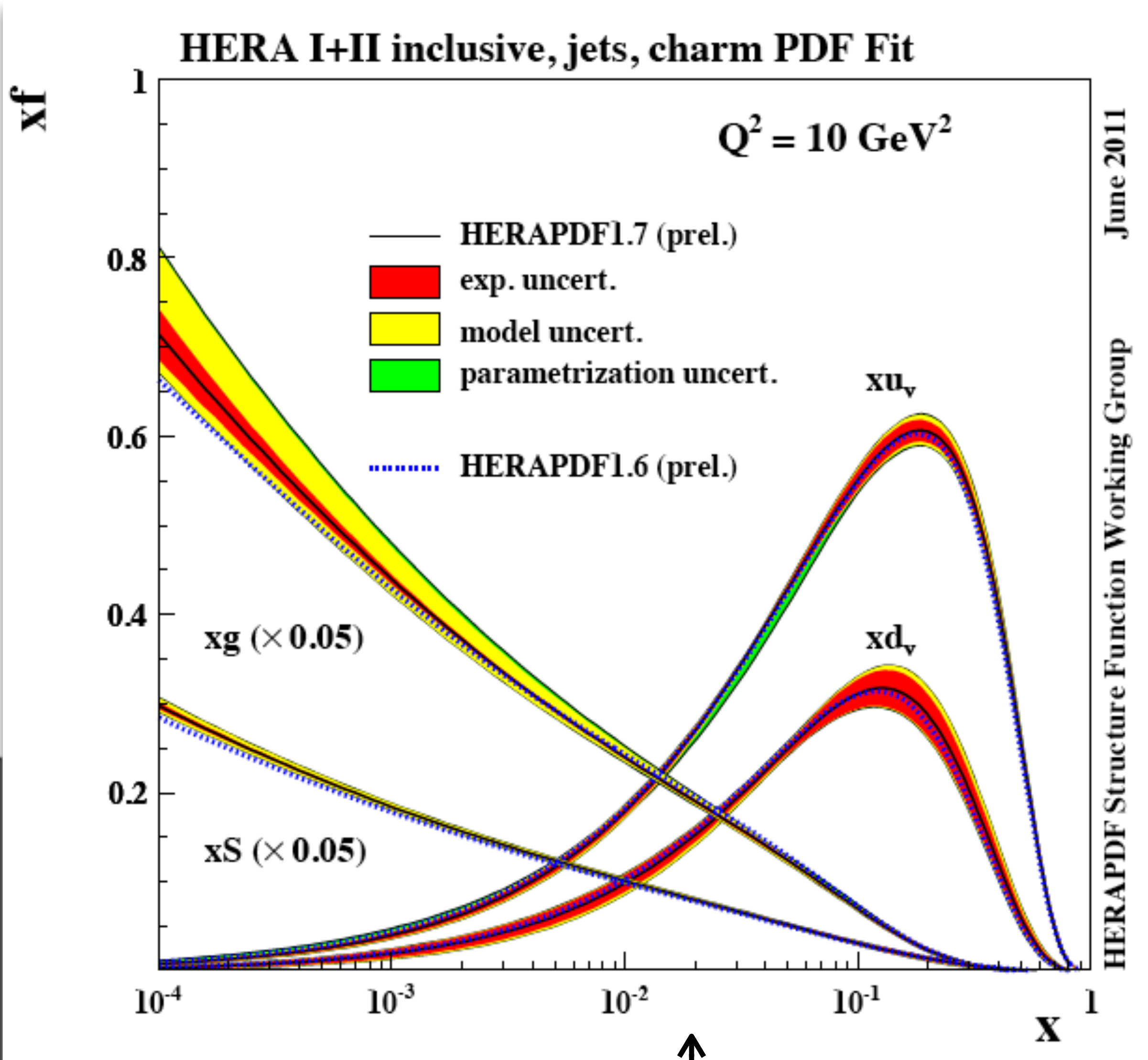
position space

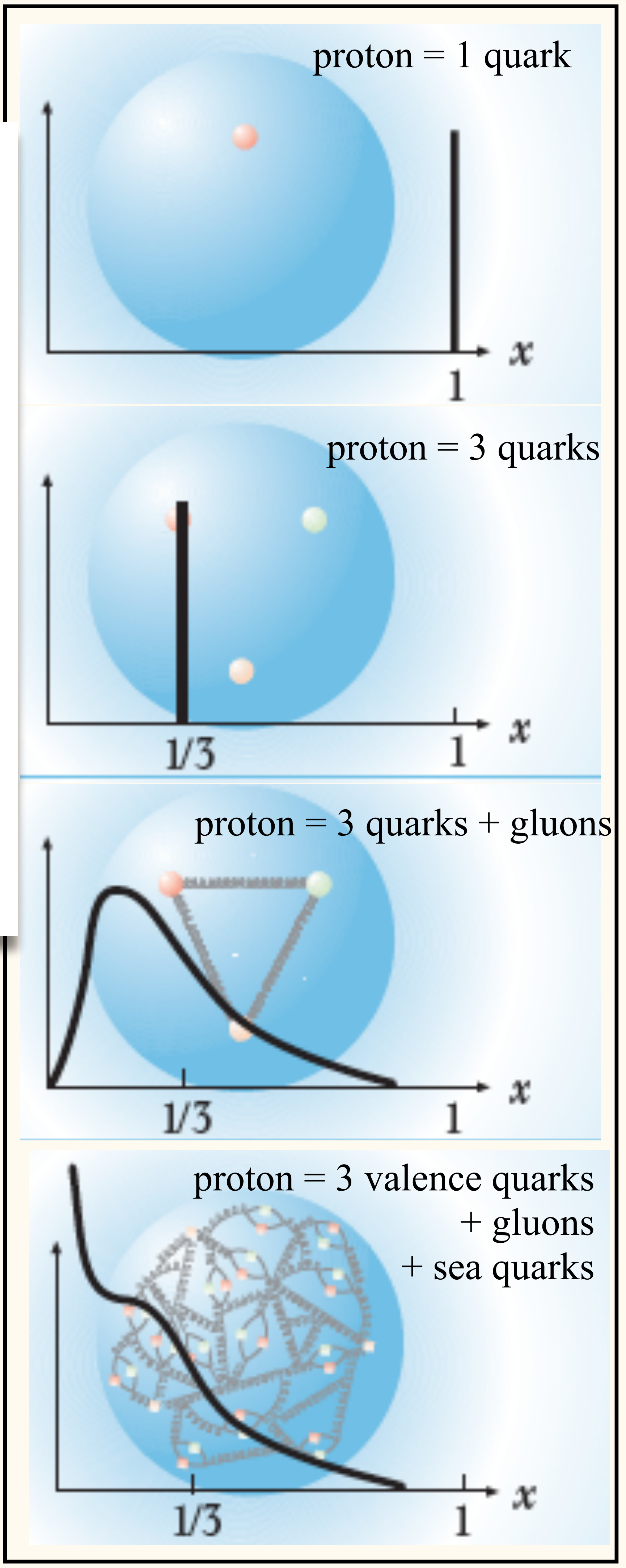
A. Bacchetta, U. D'Alesio, M. Diehl, and C. A. Miller, Phys. Rev. D70, 117504 (2004)

Deep Inelastic Scattering: ℓN→ℓ(h)X

The DIS cross section contains non-perturbative, non-calculable objects: **Parton Distribution Functions (PDFs)** encoding information about the momentum-dependent distribution of quarks inside the proton.





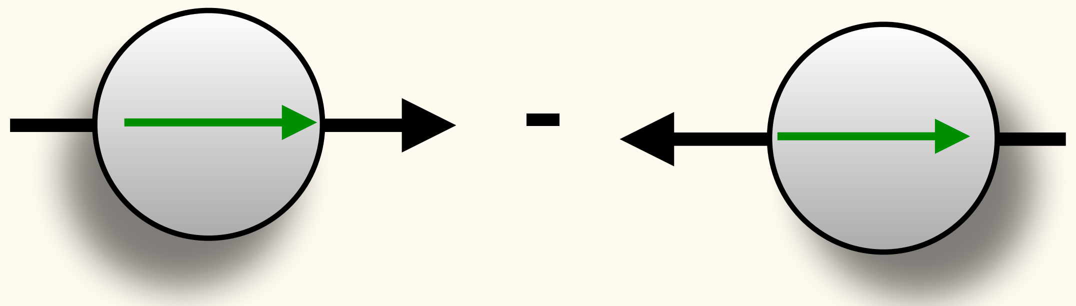


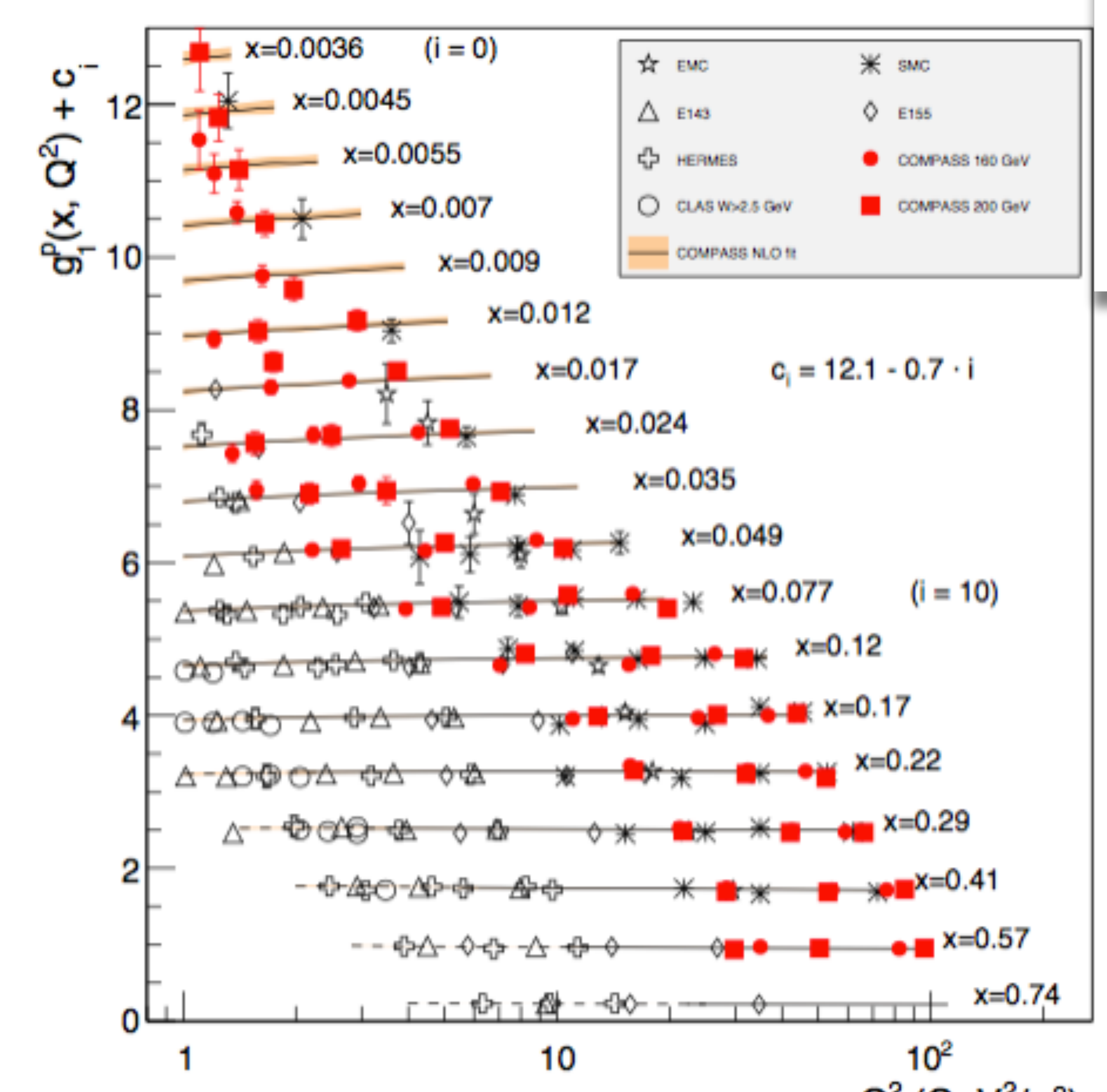
spin-independent from DESY (H1, ZEUS)

add spin… for example, inclusive DIS:
“spin structure” or “helicity” function of the proton

$$g_1(x, Q^2)$$

→ proton spin
→ quark spin





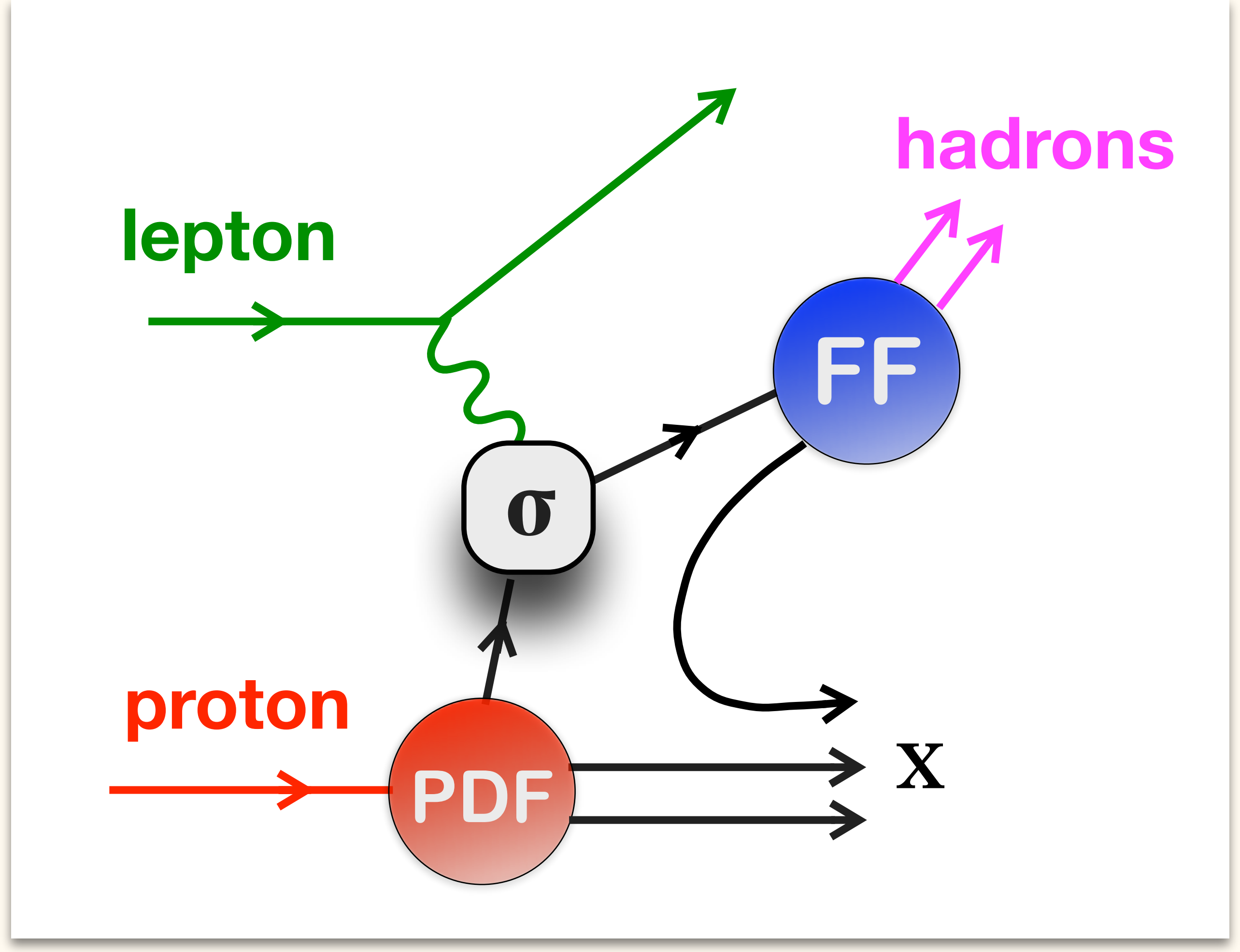
[COMPASS PLB 753 (2016) 18]

spin-dependent from SLAC, CERN, DESY (HERMES), JLab

SIDIS cross section parameterized by structure functions

"~ harmonic(ϕ, ϕ_S) · PDF ⊗ FF"

fragmentation function FF
hard scattering cross section σ
distribution function PDF



Worm-gear (Kotzinian-Mulders) ⊗ Collins

Cahn-effect + BM ⊗ Collins

BM ⊗ Collins

$$\sigma(\phi,\phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$
$$\Big\{F_{UU,T} + \epsilon F_{UU,L} + \boxed{\sqrt{2\epsilon(1+\epsilon)}\,\cos\phi\, F_{UU}^{\cos\phi}} + \boxed{\epsilon\cos(2\phi)\,F_{UU}^{\cos(2\phi)}} + \lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi\,F_{LU}^{\sin\phi}\right] +$$
$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\,\sin\phi\,F_{UL}^{\sin\phi} + \boxed{\epsilon\sin(2\phi)\,F_{UL}^{\sin(2\phi)}}\right] + S_L\lambda_e\left[\sqrt{1-\epsilon^2}\,F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi\,F_{LL}^{\cos\phi}\right]$$
$$+|S_T|\Big[\boxed{\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)} + \boxed{\epsilon\sin(\phi+\phi_S)\,F_{UT}^{\sin(\phi+\phi_S)}} + \boxed{\epsilon\sin(3\phi-\phi_S)\,F_{UT}^{\sin(3\phi-\phi_S)}}$$
$$+\sqrt{2\epsilon(1+\epsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\,\sin(2\phi-\phi_S)\,F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$
$$+|S_T|\lambda_e\Big[\boxed{\sqrt{1-\epsilon^2}\,\cos(\phi-\phi_S)\,F_{LT}^{\cos(\phi-\phi_S)}} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\,\cos(2\phi-\phi_S)\,F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\},$$

Sivers ⊗ D1

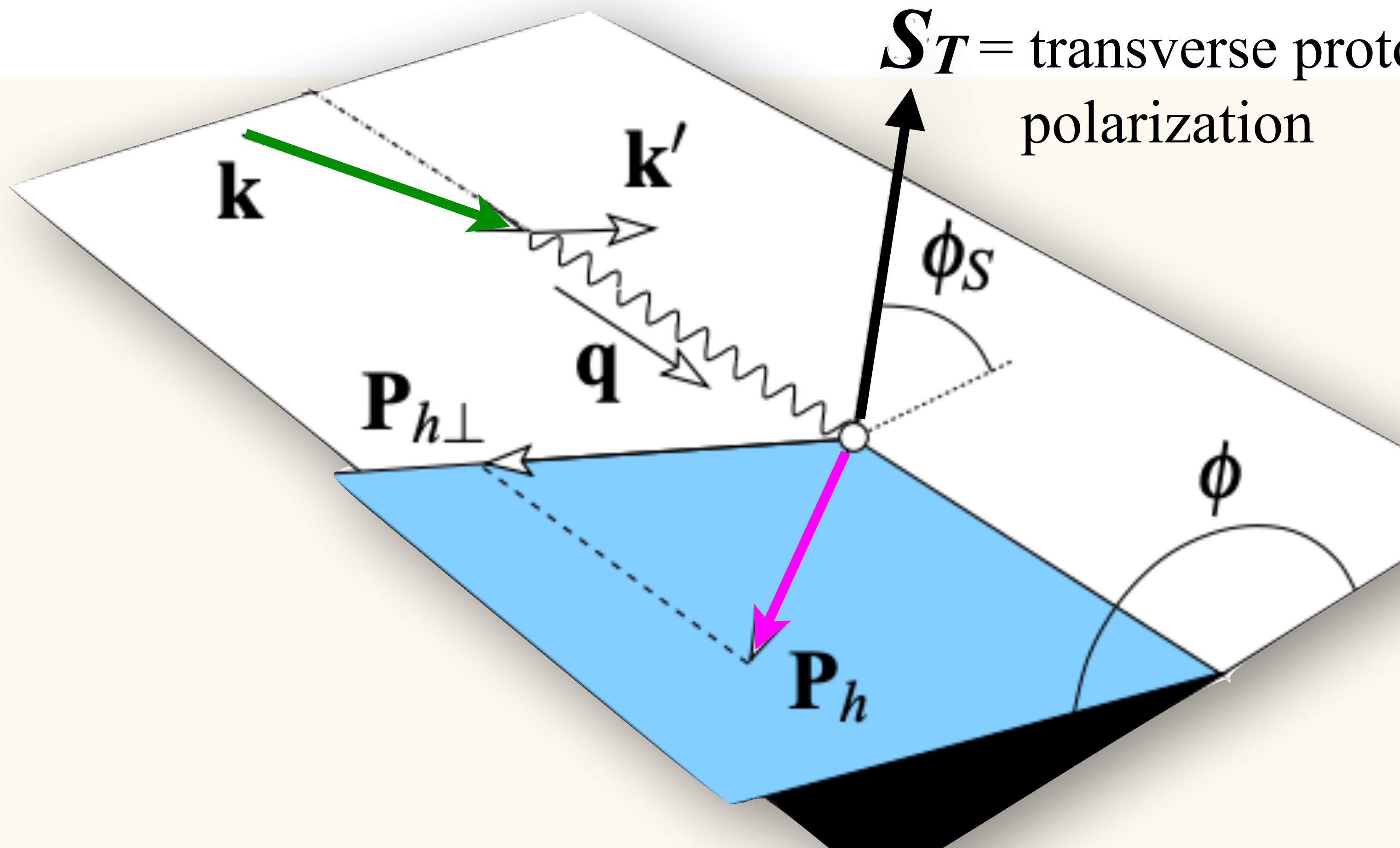
Worm-gear ⊗ D1

Transversity ⊗ Collins

Pretzelosity ⊗ Collins

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

S_T = transverse proton polarization



type of experimental observable:

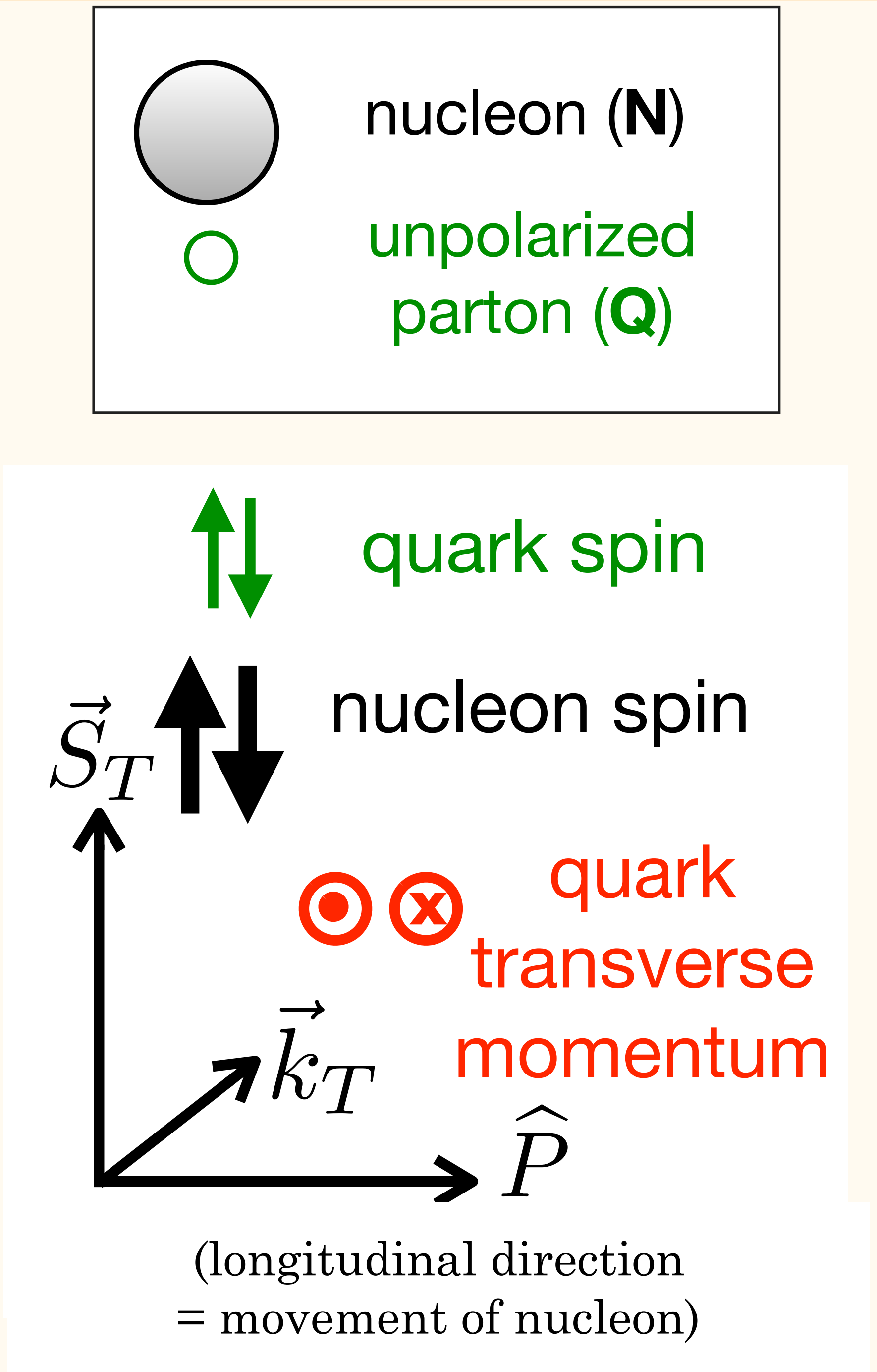
$$A_{UT}(\phi) = \frac{1}{fS_T}\frac{N^{\uparrow}(\phi)-N^{\downarrow}(\phi)}{N^{\uparrow}(\phi)+N^{\downarrow}(\phi)}$$

(more complicated in reality)

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

Unpolarized
Longitudinally
Transversely

Transverse momentum dependent (TMD) PDFs



N \ Q	U	L	T
U	f_1 number density		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity / $h_{1T}^\perp$ pretzelosity

TMDs surviving integration over k_T. "Collinear analysis"

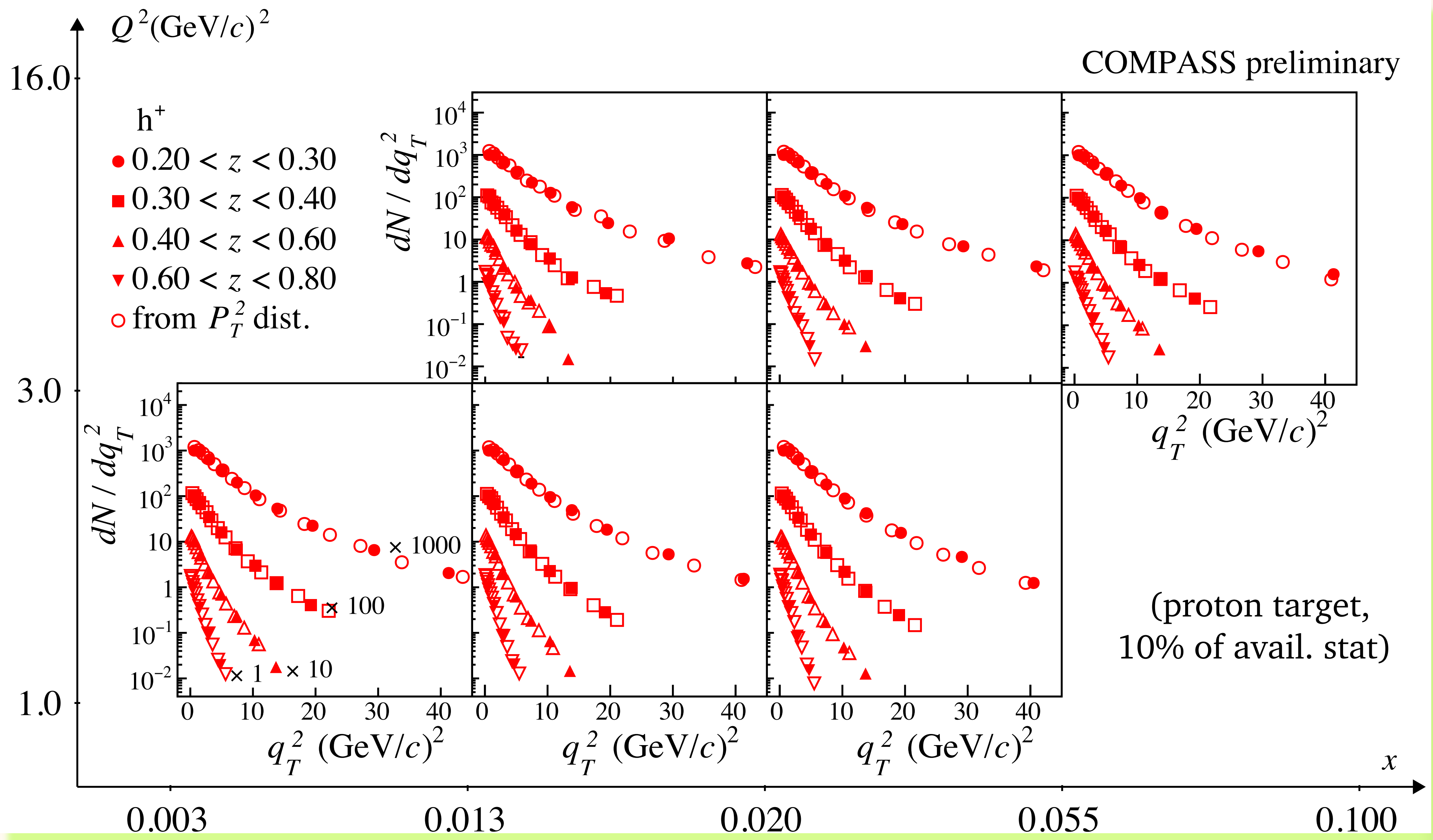
Naive time-reversal odd TMDs describing strength of **spin-orbit correlations.**

chiral odd TMDs
Exist because of **chiral symmetry breaking** of the QCD nucleon wave function

- 8 TMD (PDFs) needed at leading-twist description.
- Analog table for fragmentation functions (capital letters except for UU=D_1)
- Flavor indices and kinematic dependences skipped for simplicity

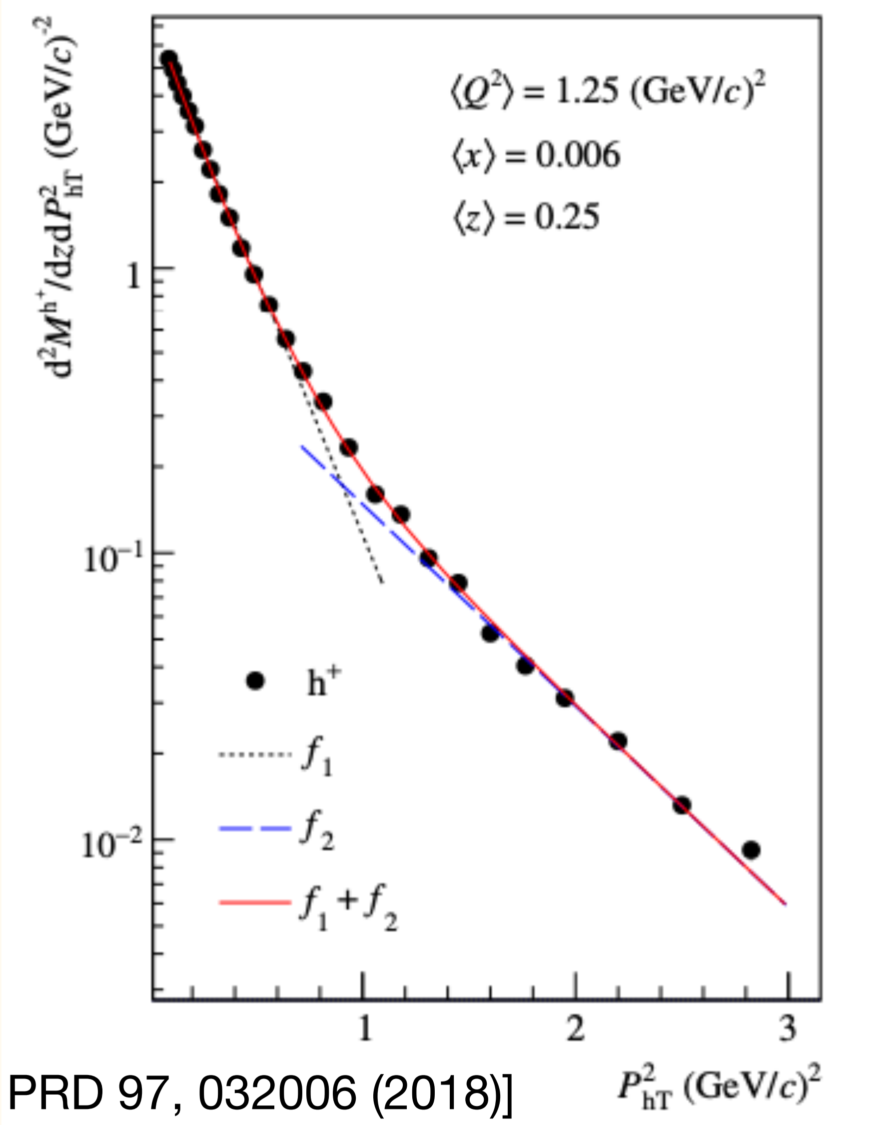
TMD effects in unpolarized SIDIS

New prelim COMPASS p_T dependences & azimuthal asymmetries



see A. Moretti, DIS21

✦ p_T distributions provide complementary information to cos(ϕ) Boer-Mulders & Cahn and cos(2ϕ) Boer-Mulders azimuthal asymmetries (not shown)



[COMPASS PRD 97, 032006 (2018)]

Modern multi-dimensional binnings in p_T, Q^2, x, z, W allow for TMD evolution studies & comparison between experiments

New data will help to clarify the double-Gauss structures in p_T

- Real $\langle k_T^2\rangle$ underestimated
- Importance of vector-meson decays (CLAS12)

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

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

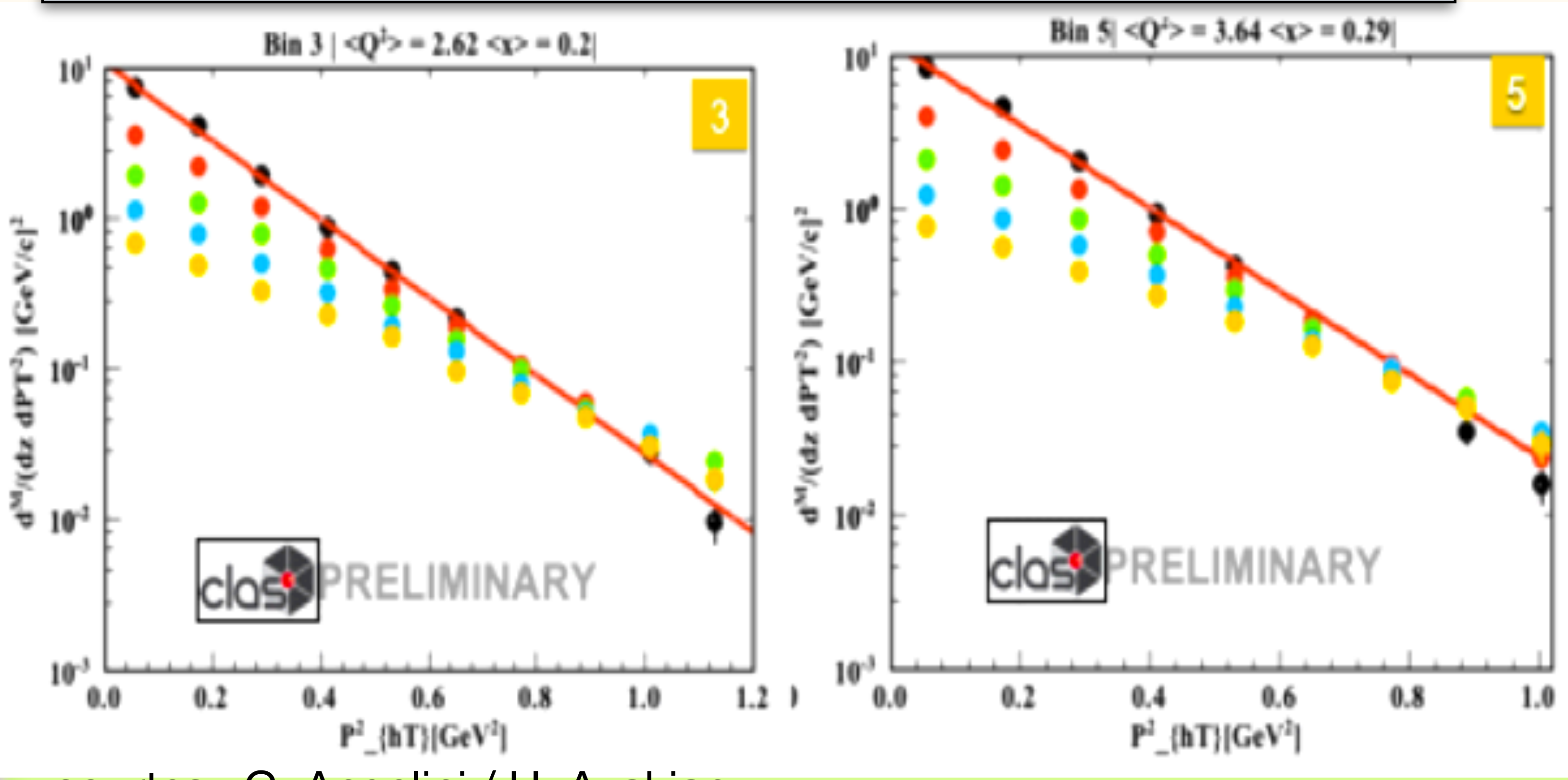
Towards a more complete mapping of the SIDIS landscape - current vs. target fragmentation

Phenomenological approximation for q_T works well for new COMPASS data.

$q_T = P_T/z$ to validate region of TMD formalism

[Boglione *et al.*, JHEP10 (2019) 122]

Prelim CLAS12 pion multiplicities



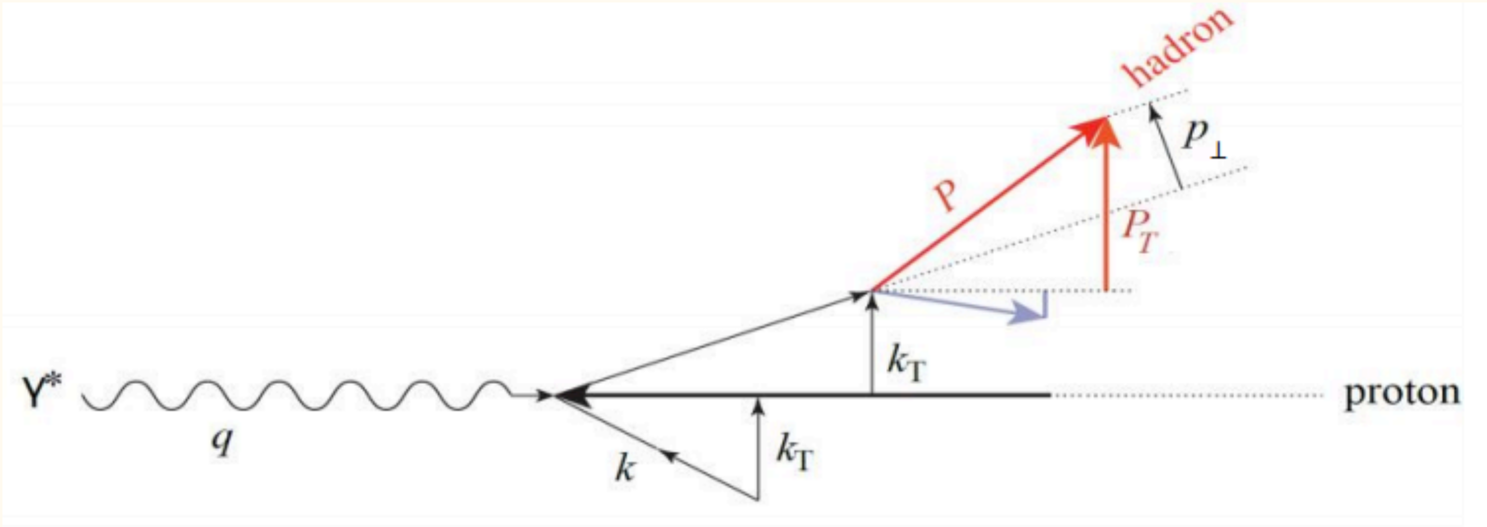
courtesy G. Angelini / H. Avakian

π+ multiplicities in example (x, Q^2) bins, for various z

$$\frac{dM^h(x,Q^2,z)}{dz} = \frac{\sum_a e_a^2 \boxed{f_a(x,Q^2)}\,\boxed{D_a^h(z,Q^2)}}{\sum_a e_a^2 \boxed{f_a(x,Q^2)}}$$

quark-to-hadron FF

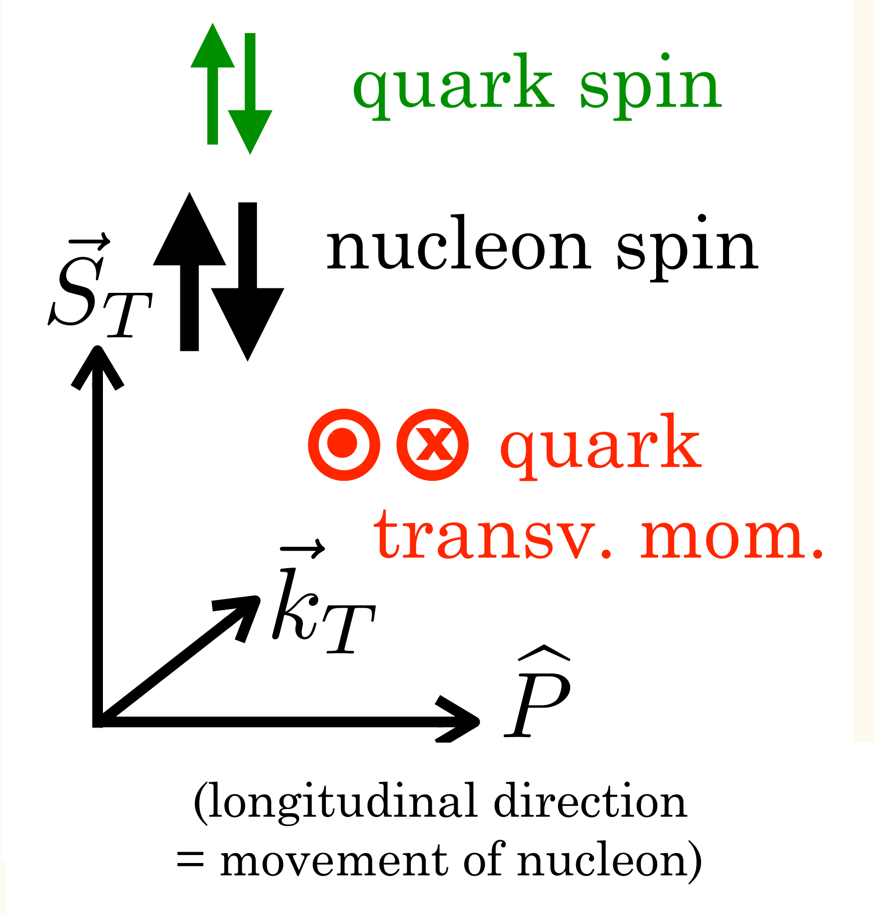
quark PDF

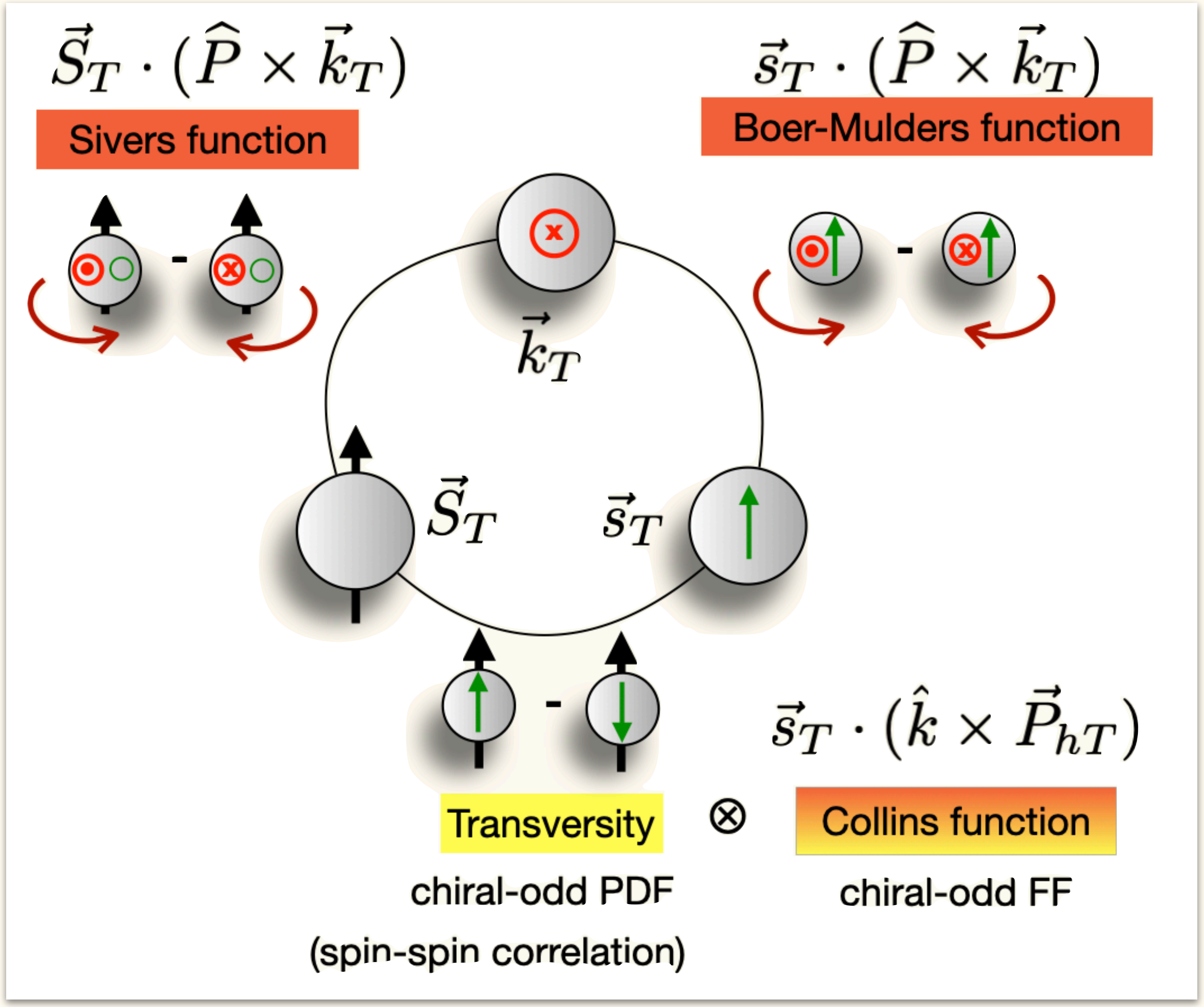


Spin-orbit correlations in the proton

If TMDs describing strength of **spin-orbit correlations** are non-zero: indicates parton orbital angular momentum (OAM).

No quantitative relation between TMDs & OAM identified yet.

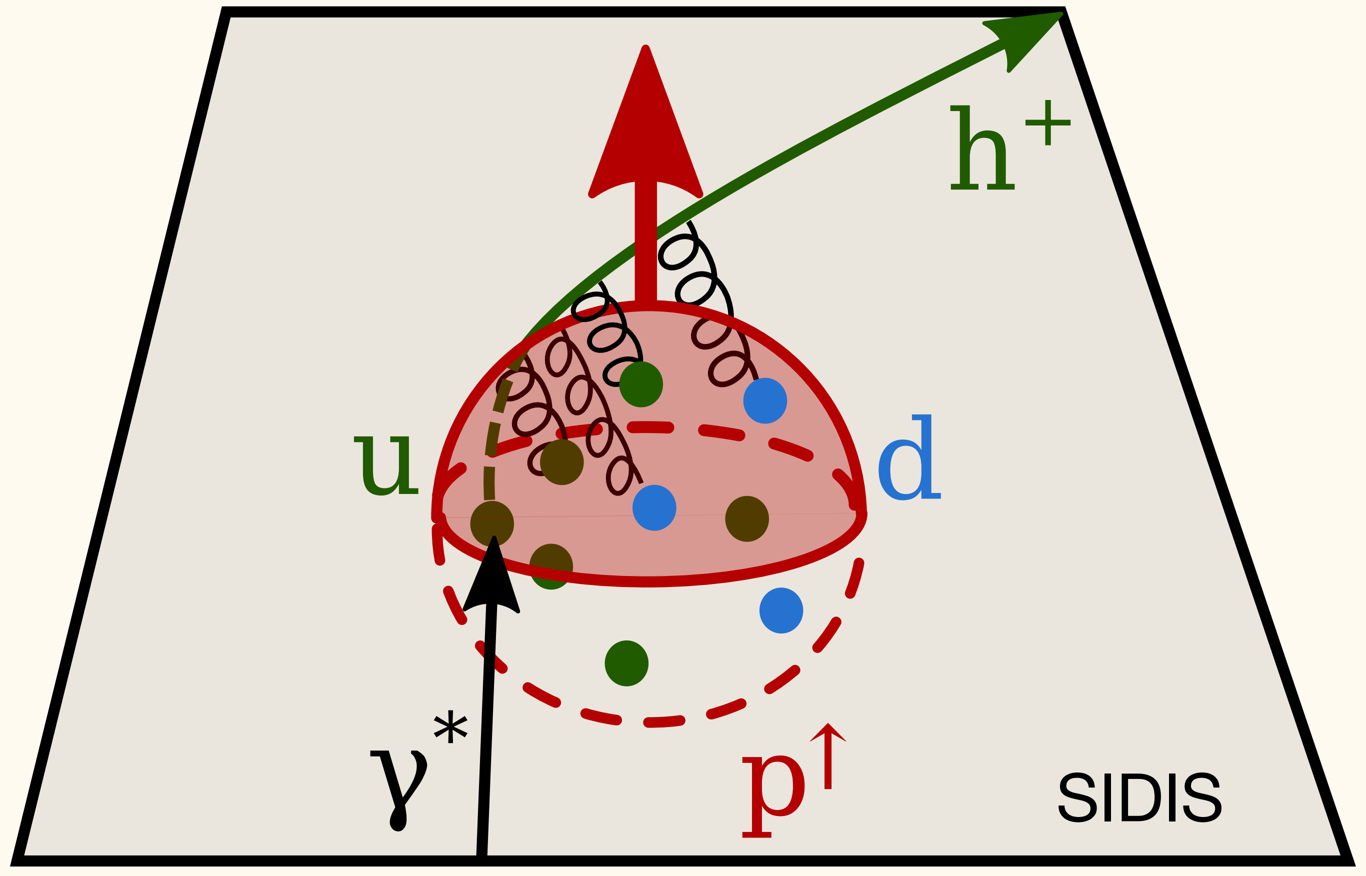




"Collinear analysis"

Collins effect: fragmentation of a transversely polarized parton into a final-state hadron

Sivers effect: correlations between the nucleon transverse spin direction & parton transverse momentum in the polarized nucleon



The Sivers function was originally thought to vanish (*).

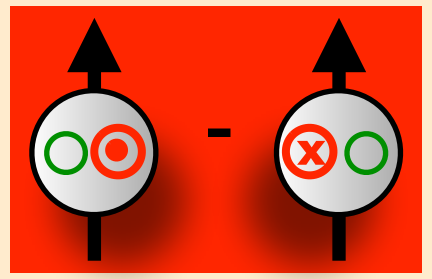
A nonzero Sivers function was then shown to be allowed due to **QCD final state interactions** (soft gluon exchange) in SIDIS between the outgoing quark and the target remnant (**).

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

sketch courtesy Jan Matoušek / COMPASS

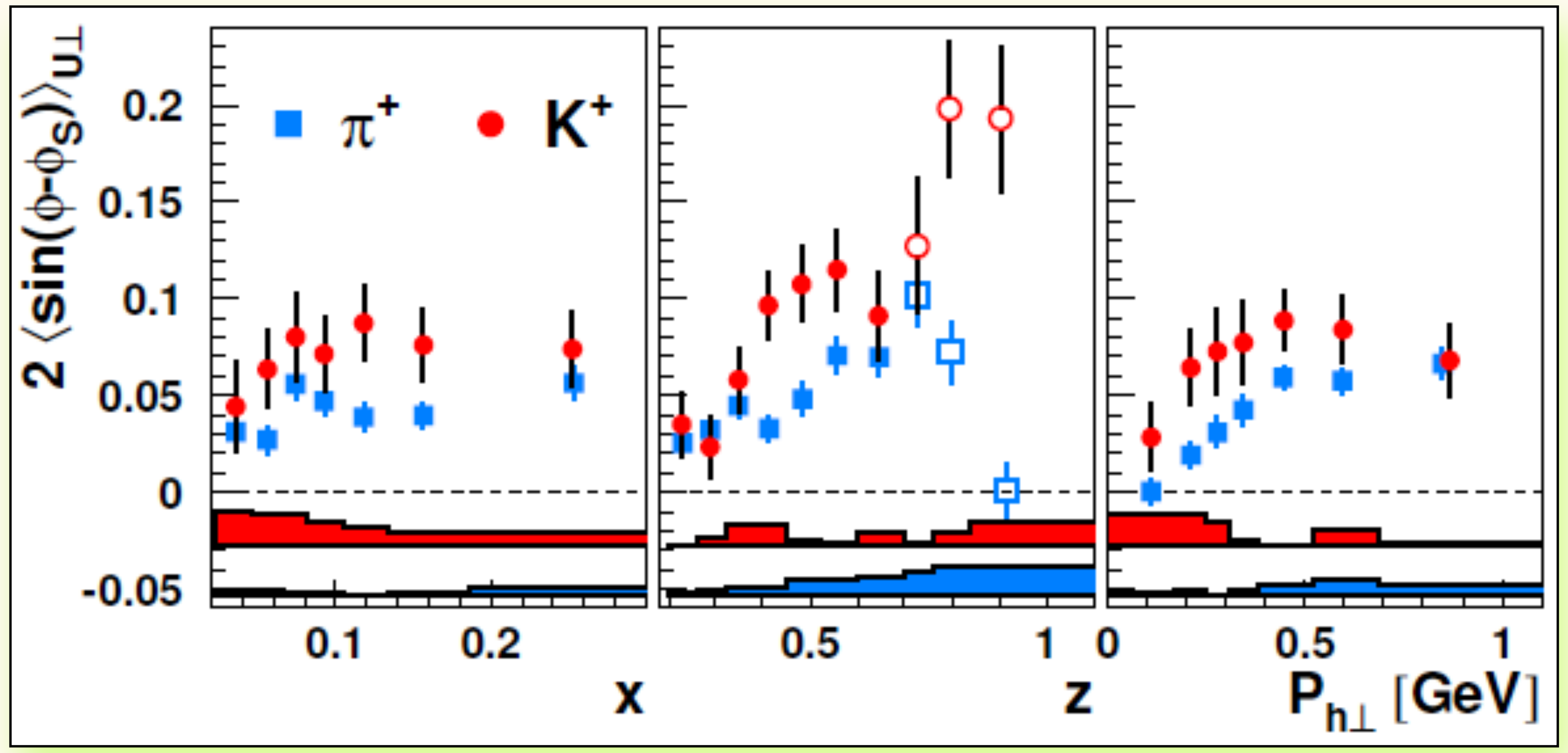
Sivers TMD in SIDIS

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



Final HERMES **Sivers asymmetries**

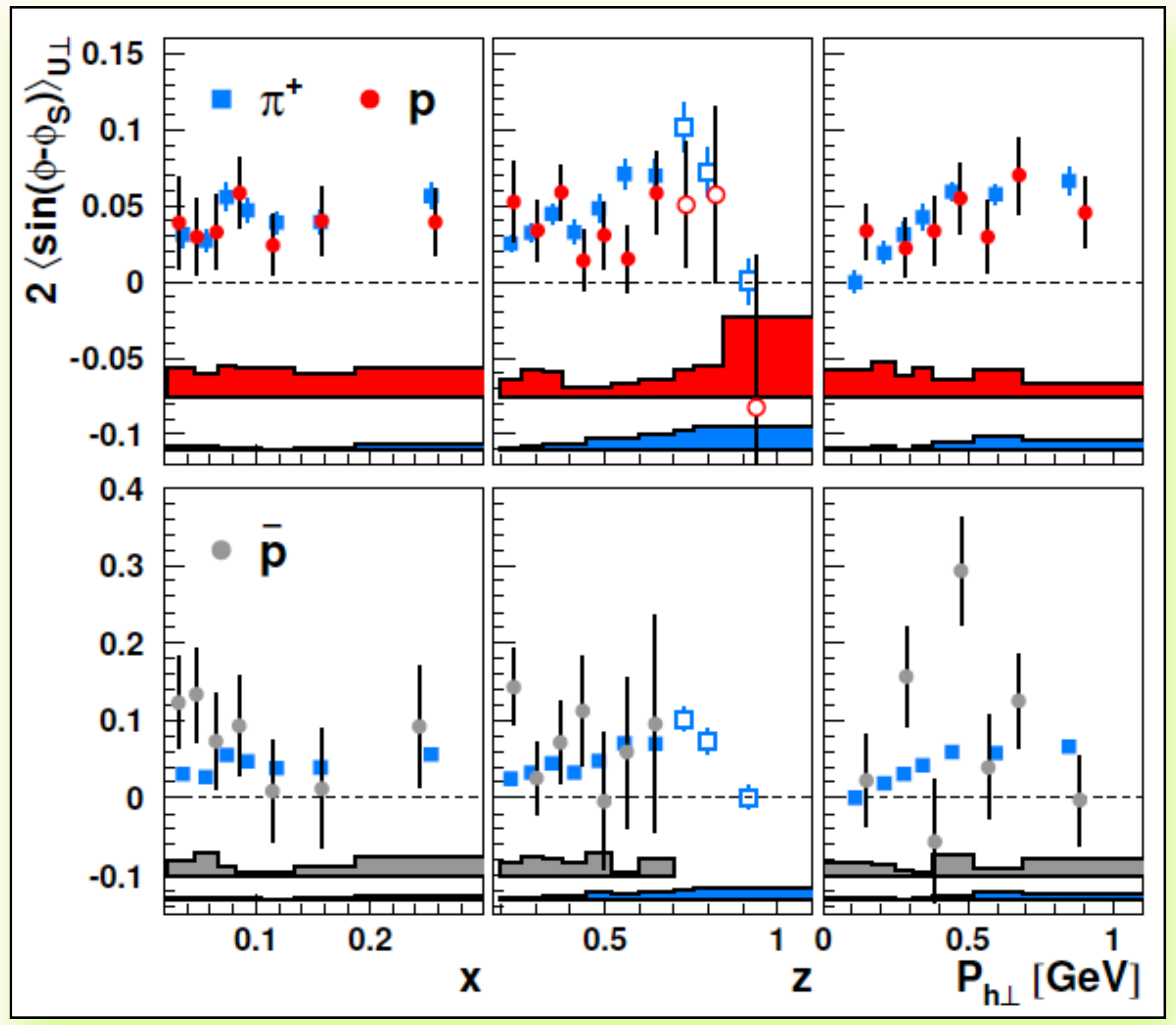
✦ Final compendium of HERMES TMD results. Refined analysis, multi-dimensional binnings, first (anti-)proton measurements. [HERMES JHEP 12 (2020) 010]



Kaon amplitudes larger than pion

~Unexpected if u-quark scattering dominates. Role of sea quarks?

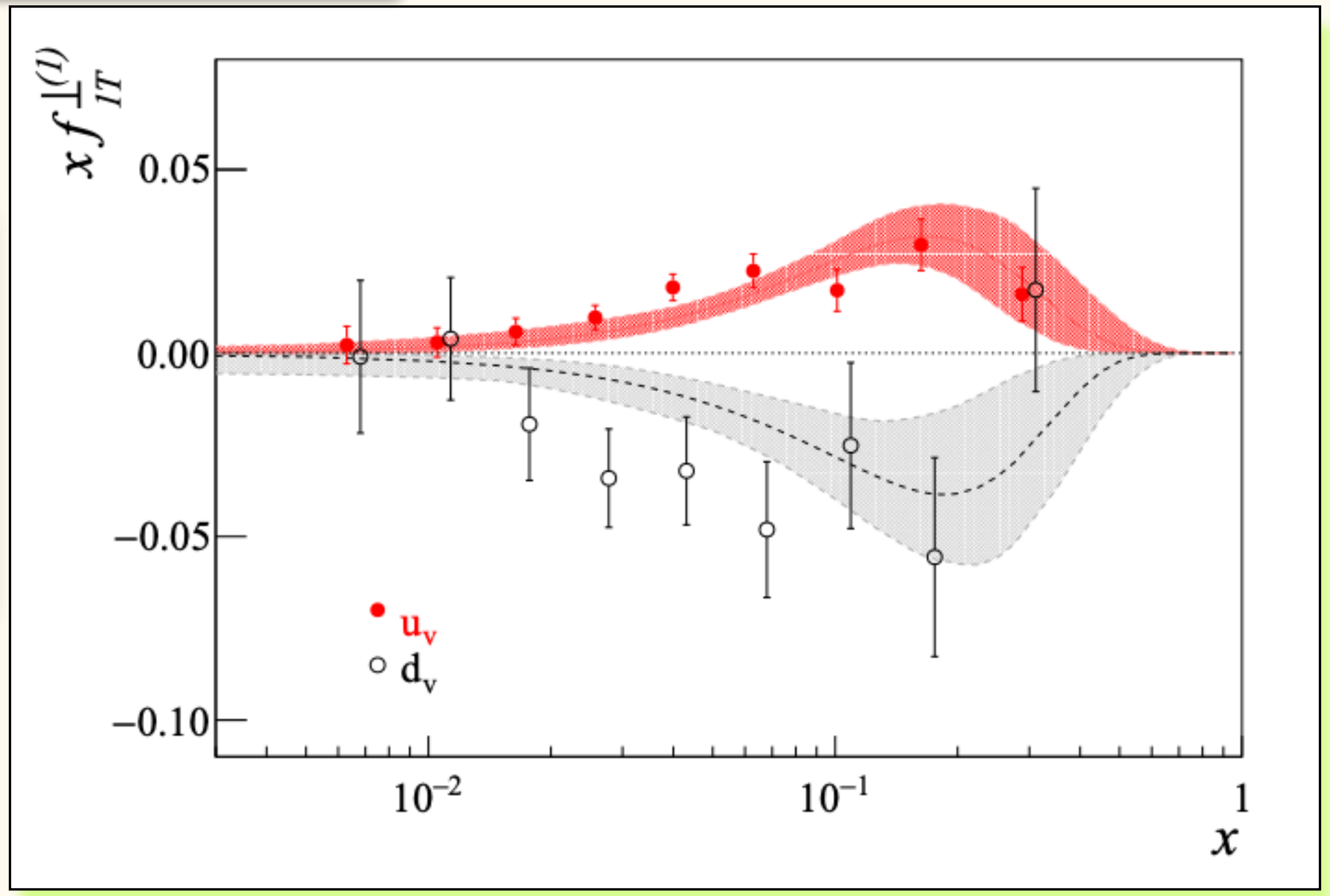
see talk by M. Diefenthaler, Wednesday 14:50



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

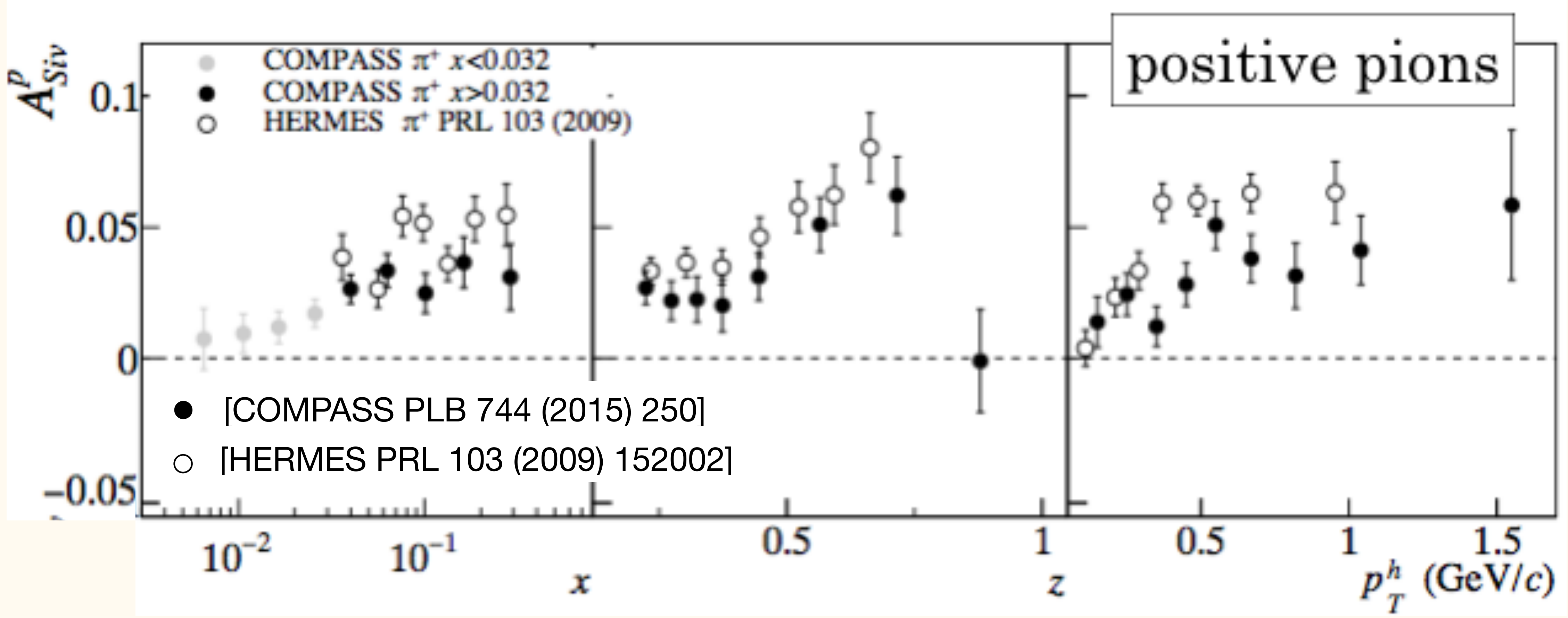
COMPASS **Sivers asymmetries**

u- and d-quark Sivers functions have different signs



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

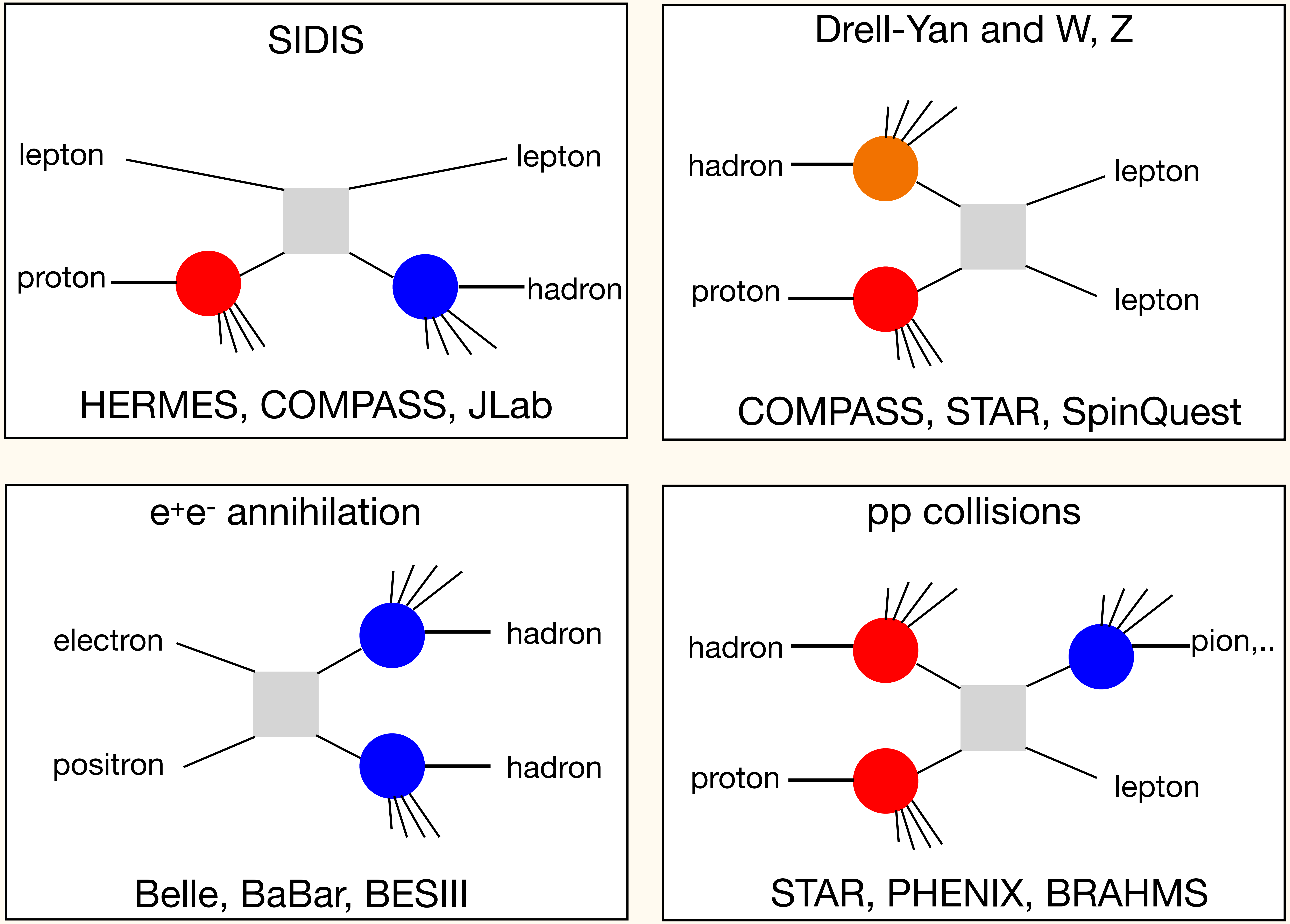
✦ p_T-weighted asymmetries: direct measurement of TMD k_T^2 moments that avoids assumptions on shape of k_T. Products instead of convolutions of TMDs



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

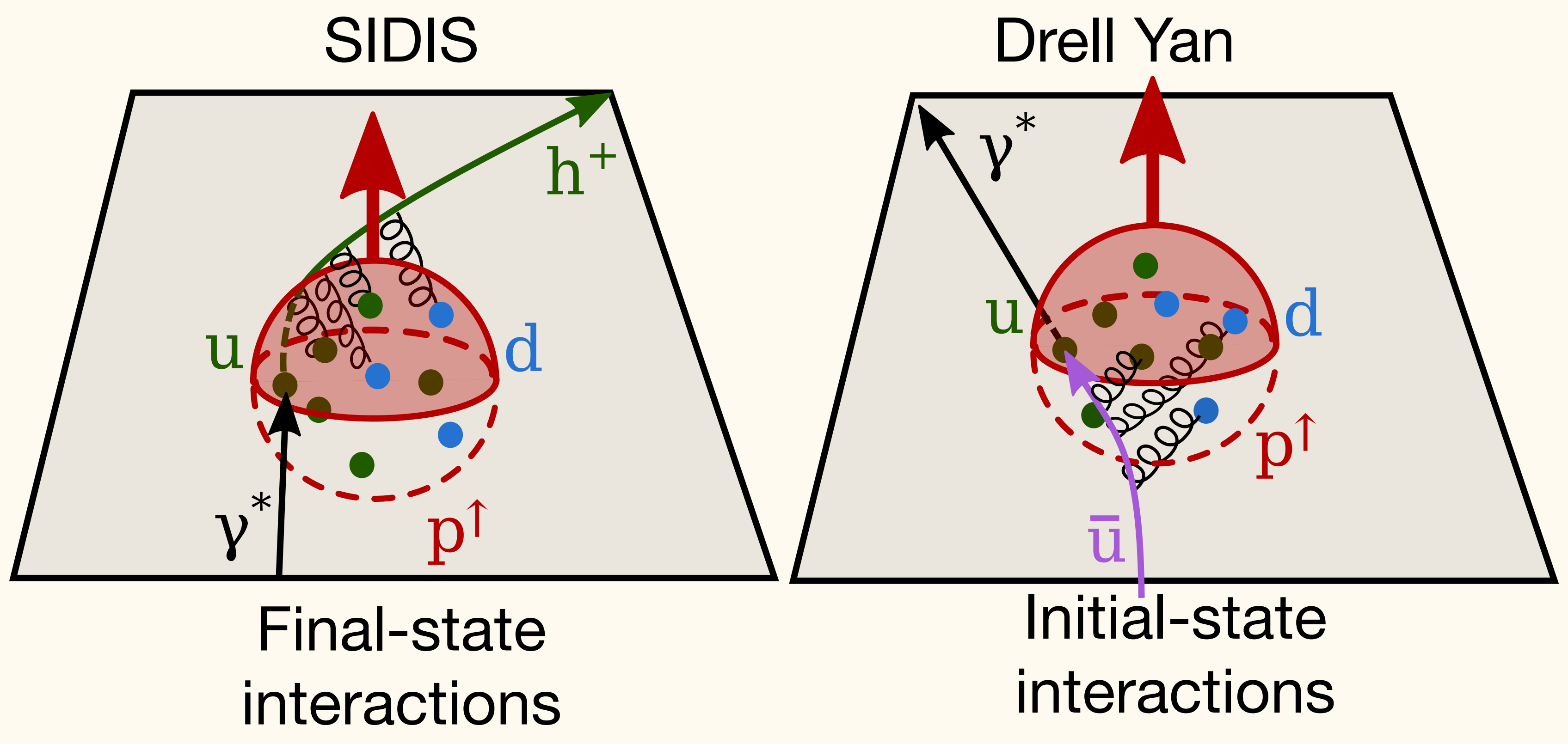
Experimental TMD probes

TMD FF



adapted from A. Prokudin *et al.*

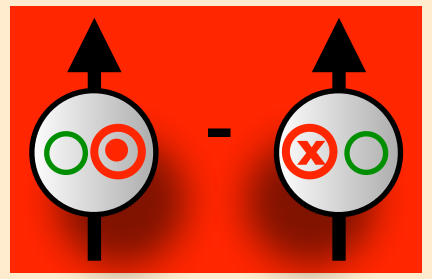
- ✦ Measuring TMD observables in different scattering processes allows to probe TMD universality.
- ✦ The naive time-reversal odd TMD PDFs - Sivers and the Boer-Mulders - are expected to switch sign when measured in SIDIS vs. Drell Yan. The experimental test of this prediction is an important test of TMD-QCD framework.



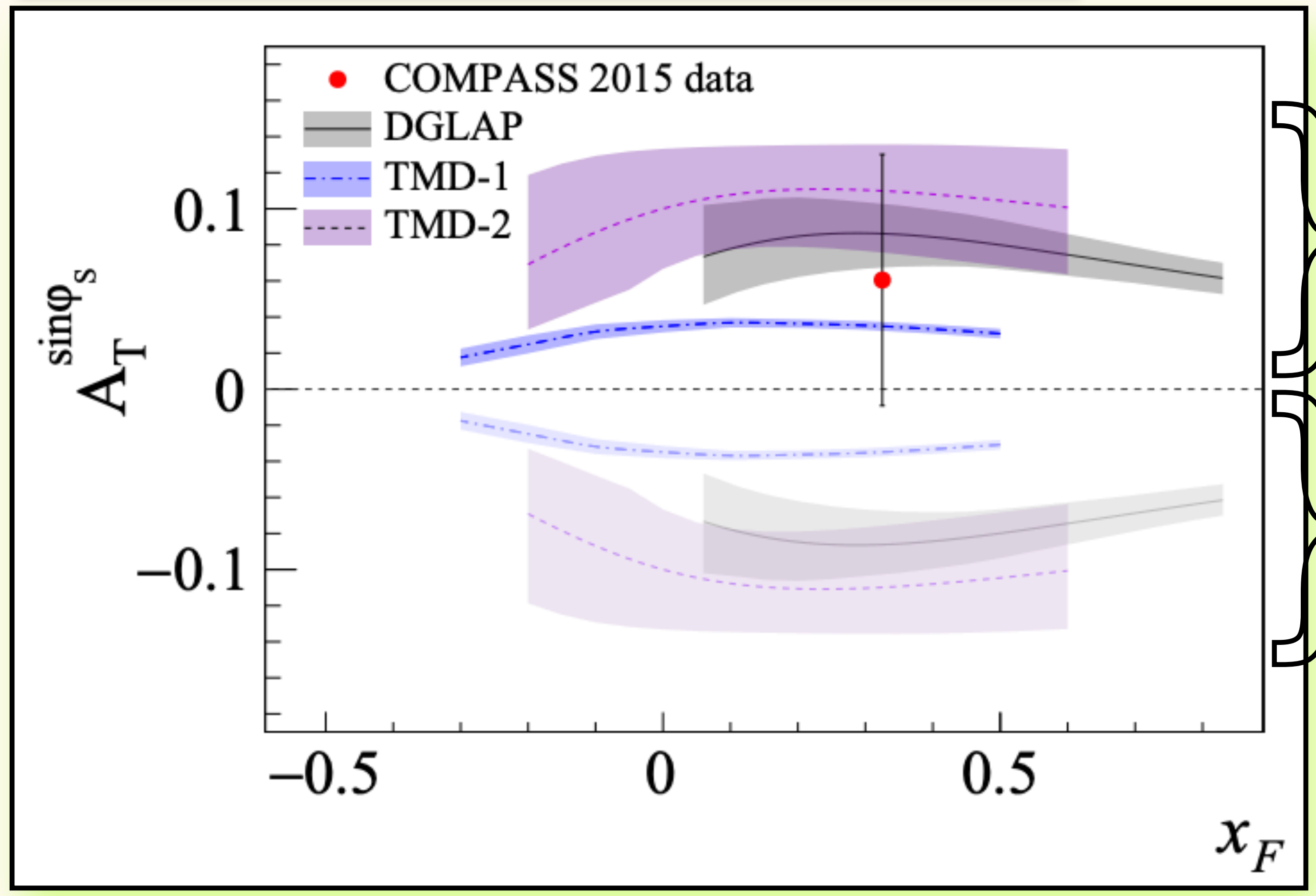
global extraction of Sivers function: see talk by A. Prokudin, Wednesday, 16:50

sketches courtesy Jan Matoušek / COMPASS

The Sivers sign switch



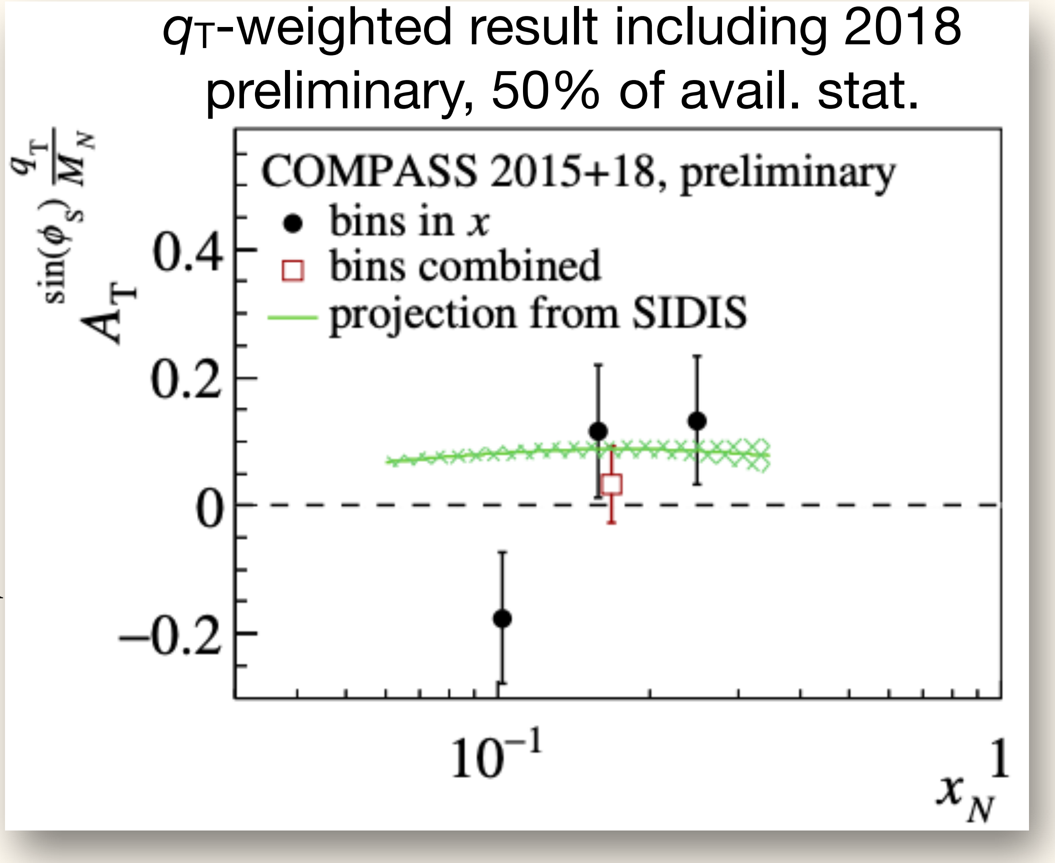
COMPASS **Drell-Yan Sivers**



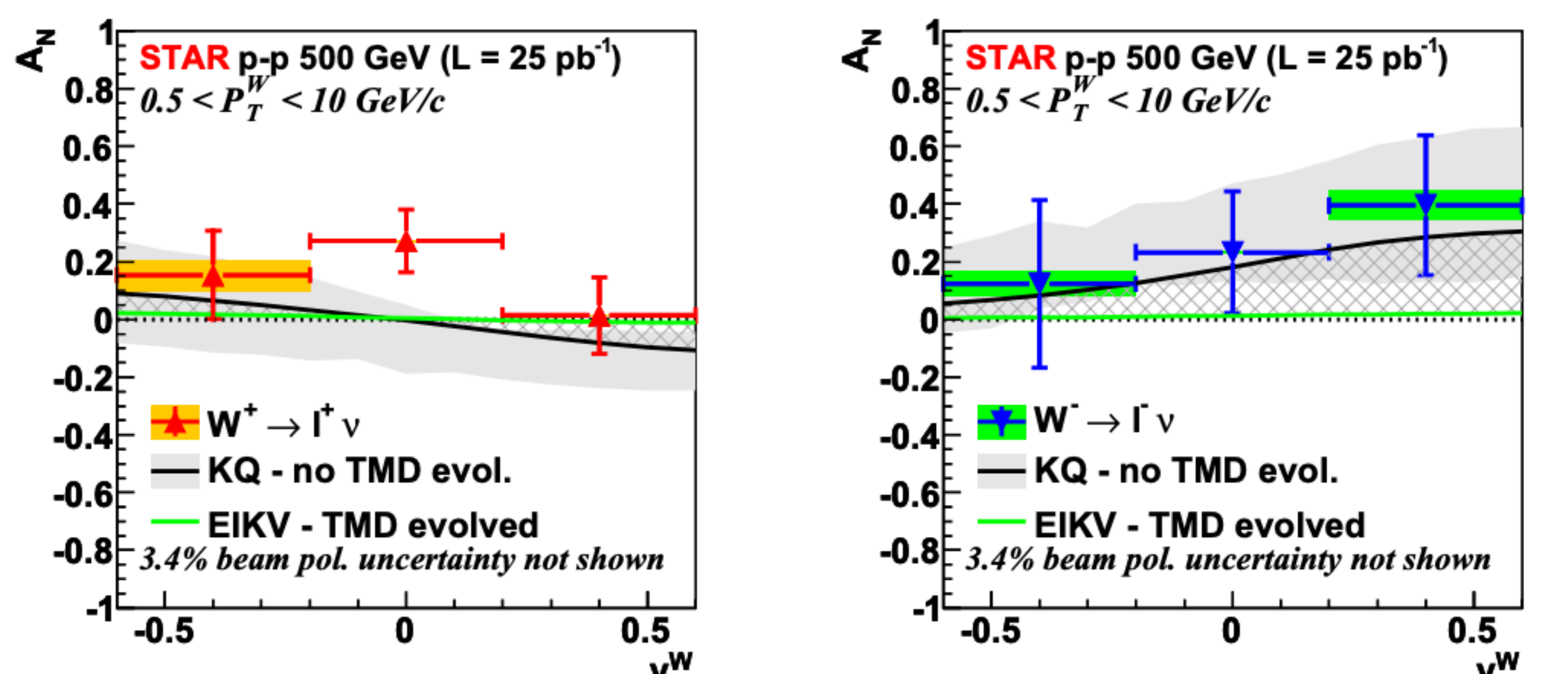
sign switch

no sign switch

(*)



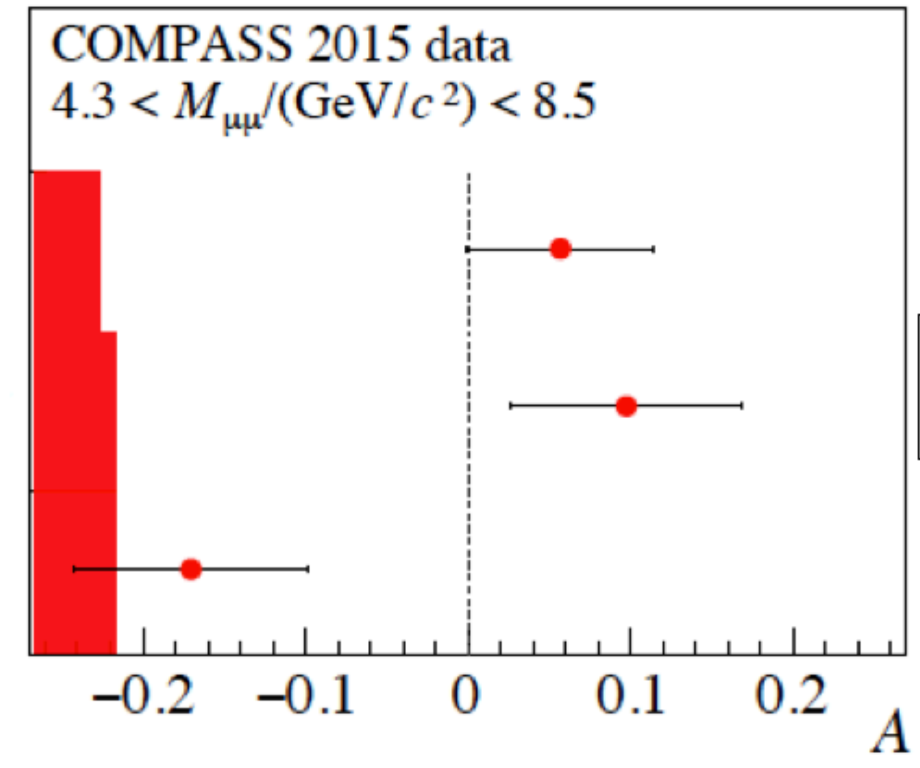
STAR $W^\pm/Z$ A_N



[STAR PRL 116, 132301 (2016)]

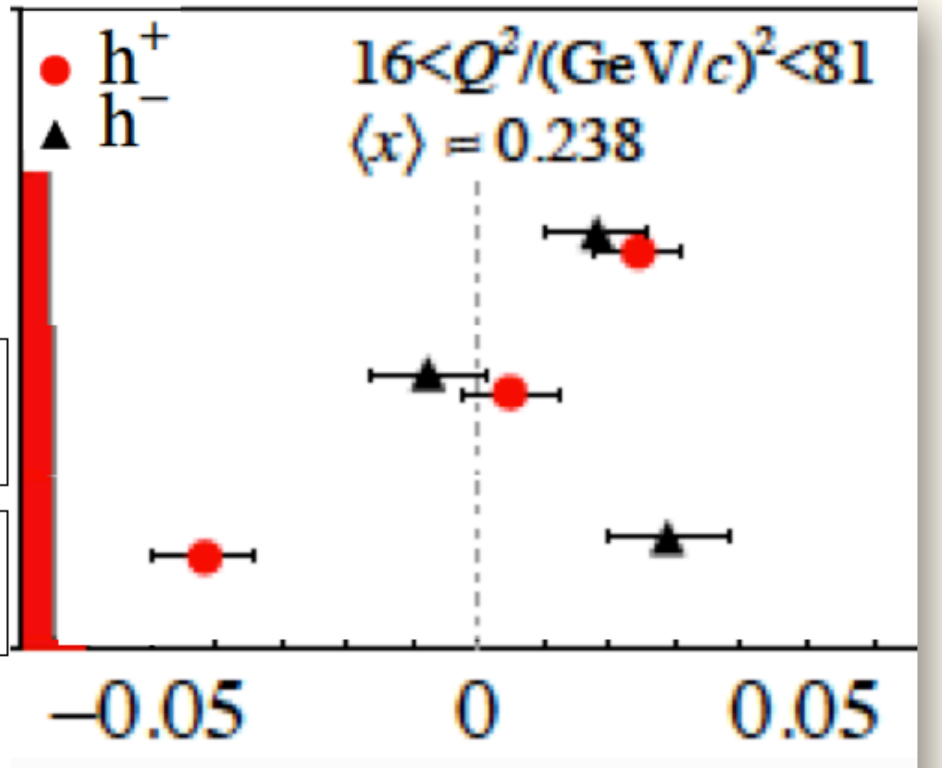
- ✦ COMPASS measurement of Sivers SIDIS & DY asymmetries with ~same apparatus & in overlapping kinematics.
- ✦ Also other TMDs measured in DY, including Boer-Mulders and Lam-Tung relation on tungsten. see talk by A. Townsend, Wednesday, 16:10

Drell-Yan (DY) 2015 data



$(\text{Sivers})_p \otimes (f_1)_\pi$	Sivers ⊗ D1
$(\text{Pretzelosity})_p \otimes (\text{BM})_\pi$	Pretzelosity ⊗ Collins
$(\text{Transversity})_p \otimes (\text{BM})_\pi$	Transversity ⊗ Collins

SIDIS *in the DY kinematic range*



[COMPASS PRL 119 (2017) 112002]

[COMPASS PLB 770 (2017) 138] ⟨ A ⟩

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

- ✦ STAR: A_N in $p^\uparrow p \rightarrow W^\pm \rightarrow e^\pm + \nu$
  Curves with sign-change assumption.
- ✦ Both collaborations currently working on the **analysis of more data** for the same channels.
- ✦ STAR measured first flavor-tagged di-jet Sivers asymmetries in polarized pp that flip with charge sign. Connection between di-jet opening angle and k_T. [see DNP2019]

(*) **"DGLAP"** M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia, & A. Prokudin, JHEP 04 (2017) 046.
"TMD 1" M. G. Echevarria, A. Idilbi, Z.-B. Kang, and I. Vitev, PRD 89, 074013 (2014).
"TMD 2" P. Sun and F. Yuan, PRD 88, 114012 (2013).

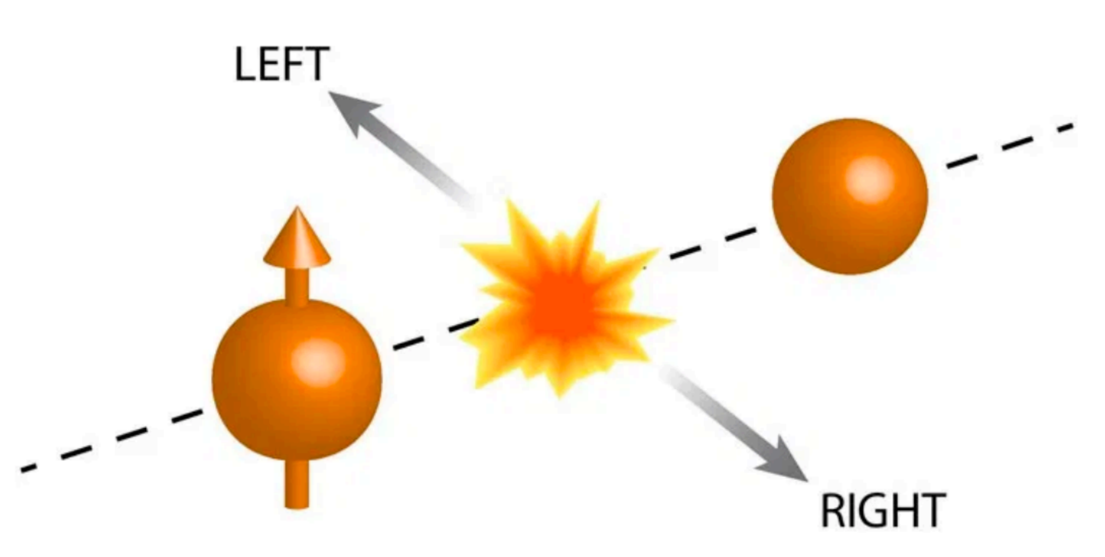
Left-right asymmetries

- The simultaneous description of left-right asymmetries A_N across multiple collision species indicates that **all A_N have a common origin** that is related to multi-parton correlations.

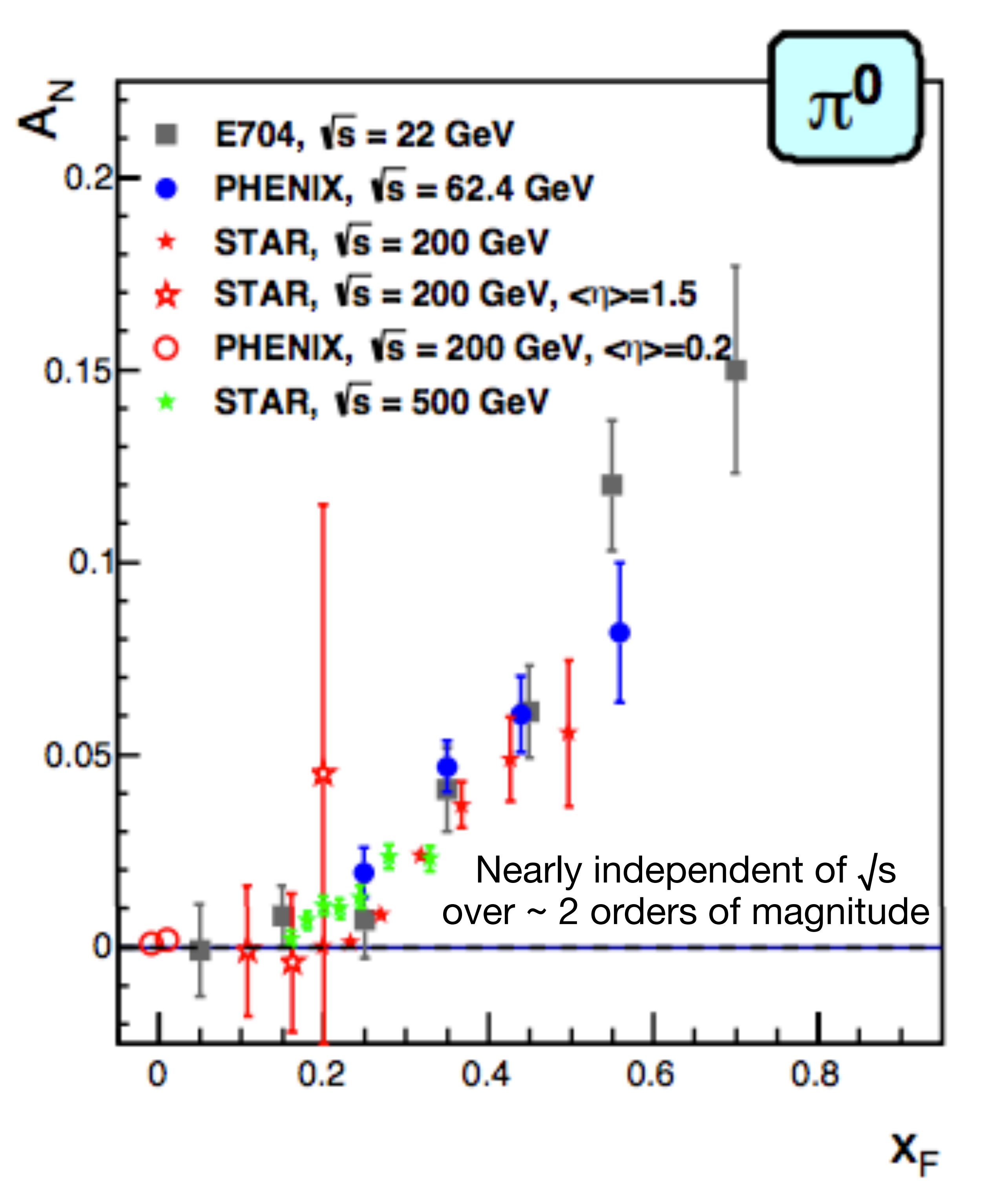
e.g. [Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (JAM Collaboration), PRD 102, 054002 (2020)]

- **TMD factorization vs. collinear twist-3 factorization**
Example: the k_T moment of the Sivers TMD is related to the twist-3 Efremov-Teryaev-Qiu-Sterman (ETQS) function.

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp,q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$



$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

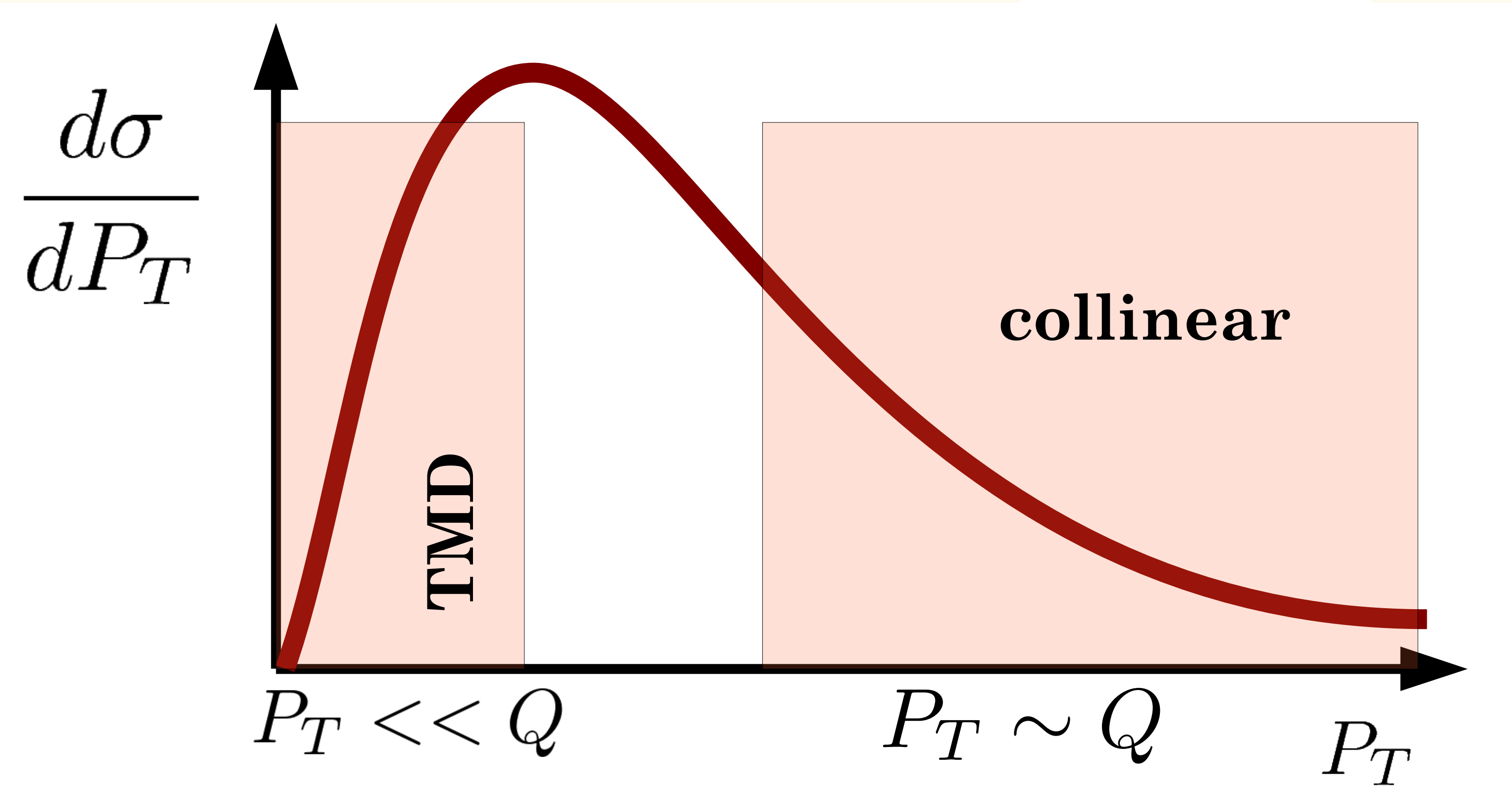


[The RHIC spin program - achievements and future opportunities, E. Aschenauer et al. arXiv:1304.0079]

A_N from TMD mechanism.

TMD factorization
2-scale problem
***f*(*x*, k_T; Q^2)**

SIDIS, DY, W/Z, dijets, hadrons in jets



The 2 factorization schemes are related and equivalent in the overlapping kinematics.

[Ji, J. Qiu, Vogelsang, Yuan, PRL 97, 082002 (2006)]

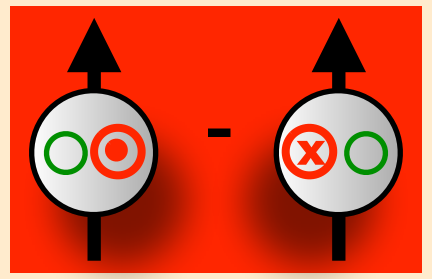
A_N from spin-momentum correlations (qgq or ggg)

Collinear twist-3 factorization
1-scale problem
***f*(*x*; Q^2)**

single inclusive particle production in pp (particle or jet p_T)

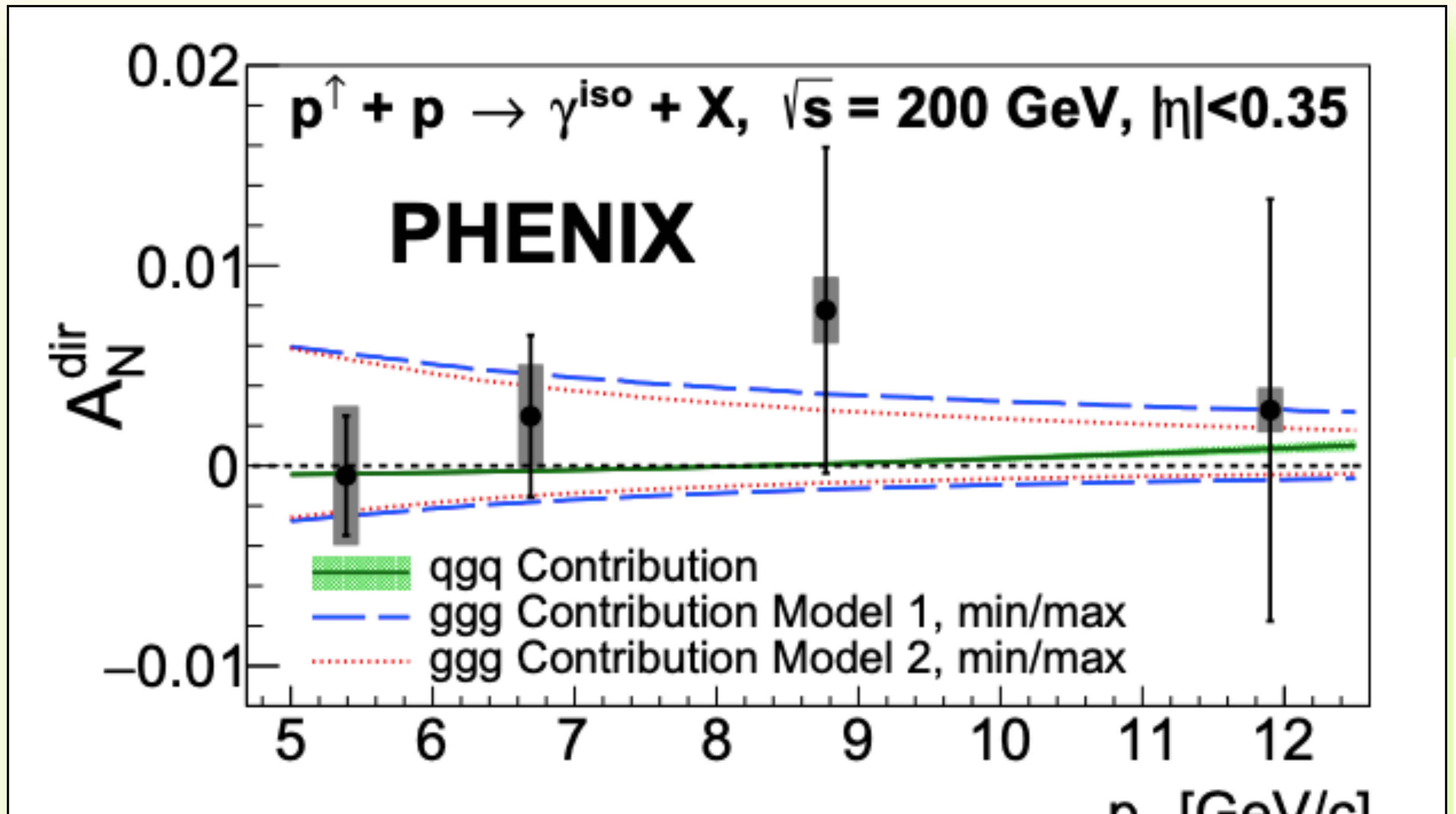
Continuation of measurements is important to further the understanding of the physical origin of A_N

Twist-3 tri-gluon correlations & gluon Sivers



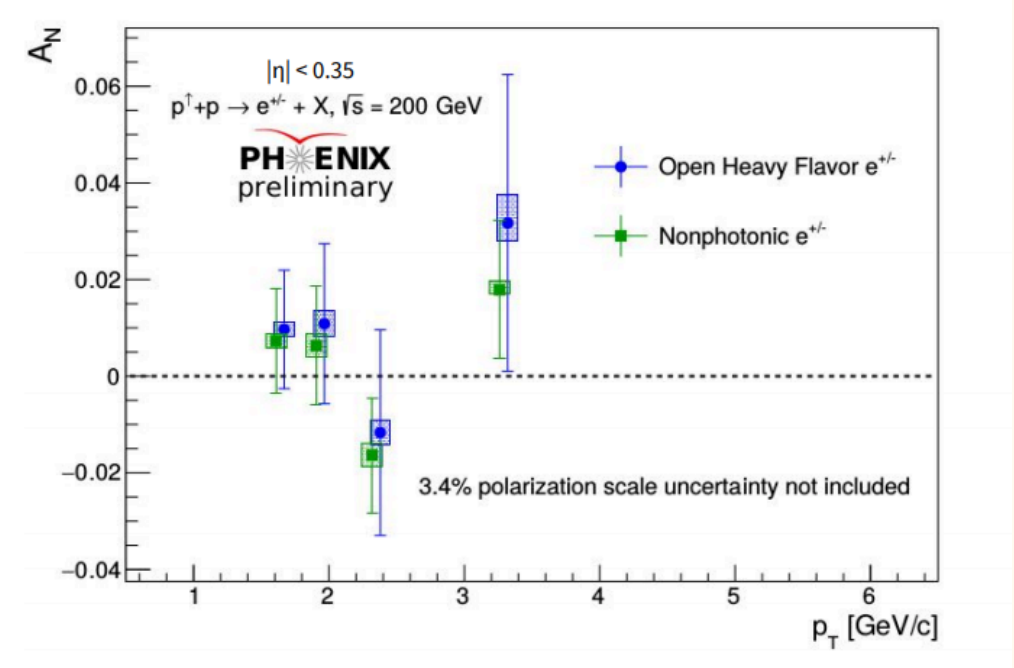
New PHENIX **isolated direct-photon A_N**

- ✦ Direct photons as clean probe
  - first measurement in ~ 30 years, with higher p_T reach and ~50x better uncertainty



[PHENIX arXiv:2102.13585]

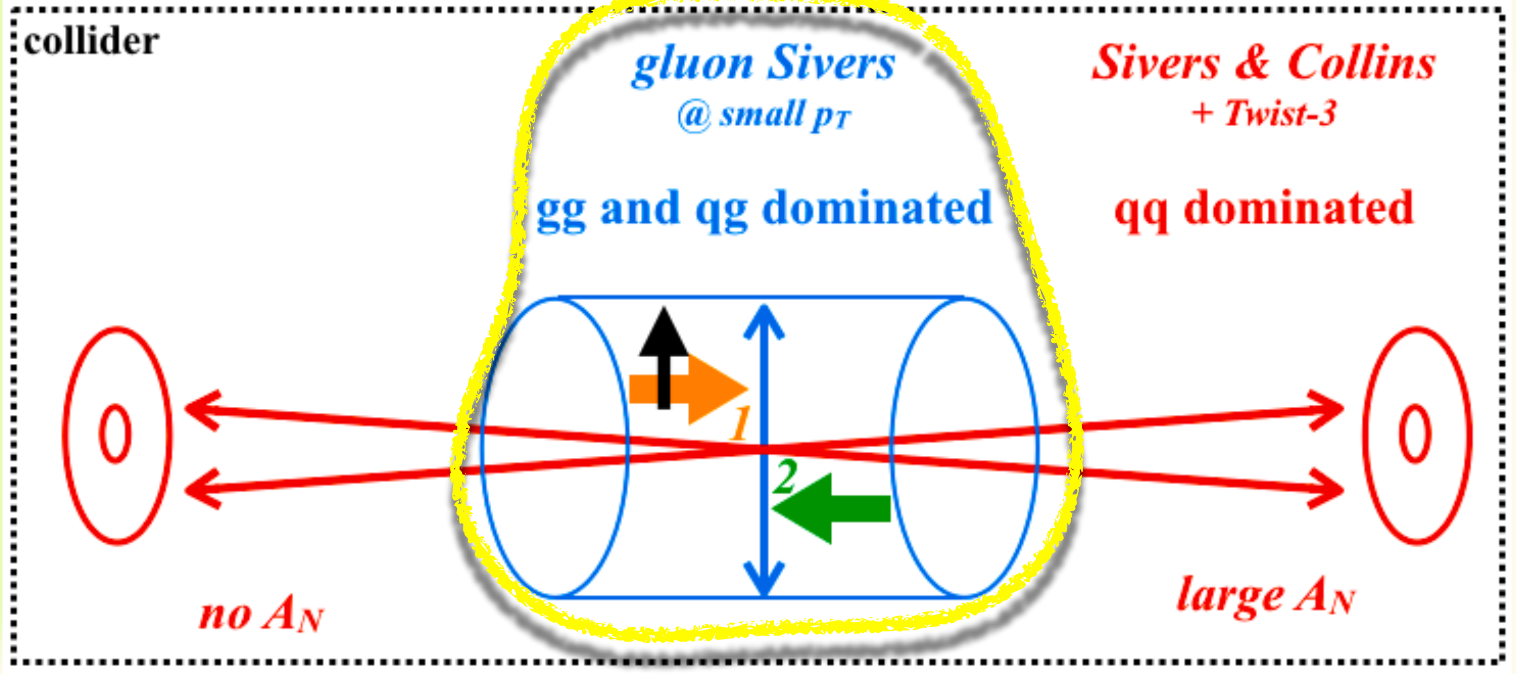
- ✦ Open heavy flavor A_N at PHENIX, new at DIS21 (D. Fitzgerald)



RHIC midrapidity measurements sensitive to tri-gluon twist-3 correlation functions ↔

gluon Sivers TMD

no signals, at high precision

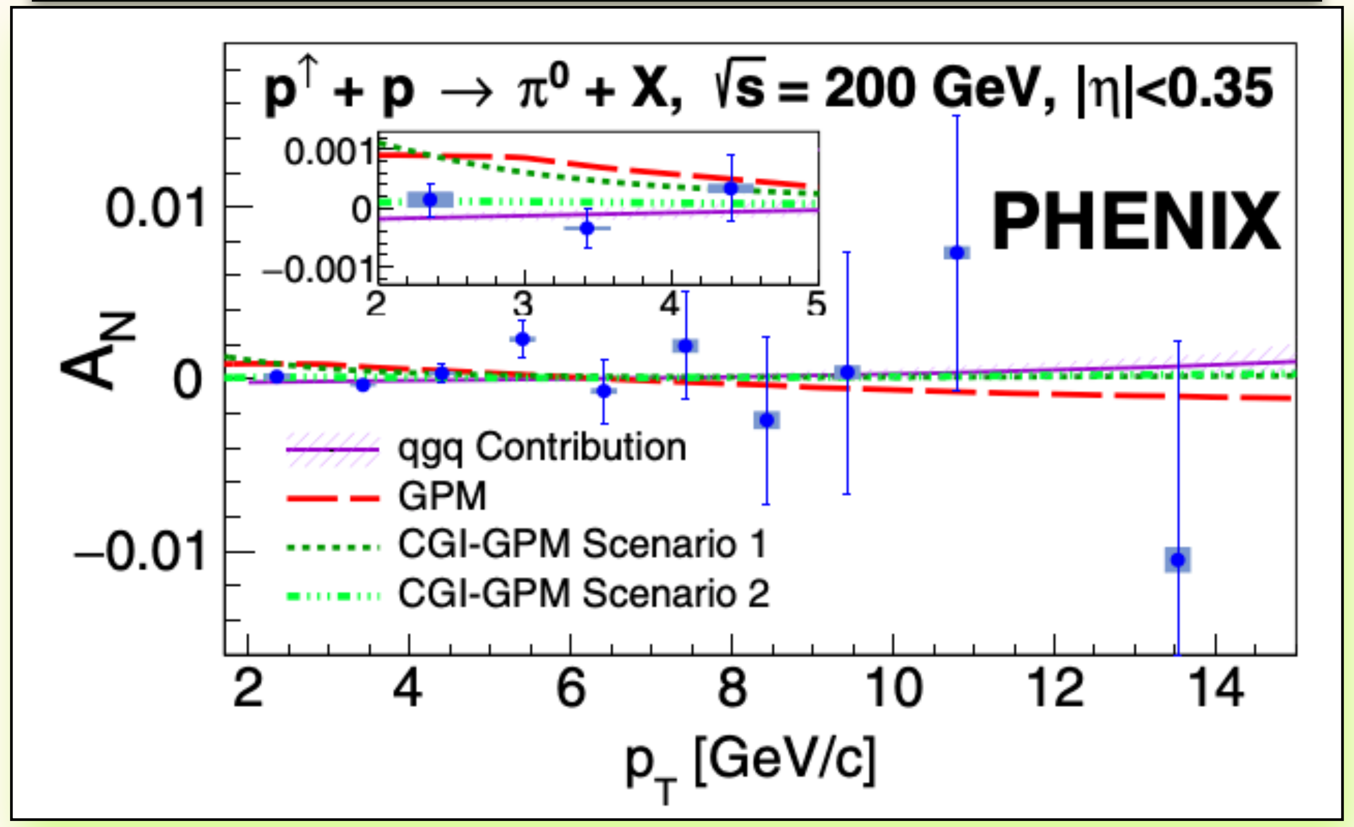


- ✦ How do these results relate to the non-zero SIDIS result from COMPASS?

- Photon-gluon fusion
with signature of 2 high-p_T hadrons,
p+d: A_{Siv} = -0.23 ± 0.08(stat) ± 0.05(sys),
PLB 772 (2017) 854

-Sivers asymmetry in J/Psi production in pion-proton collisions at COMPASS.
Analysis in progress.

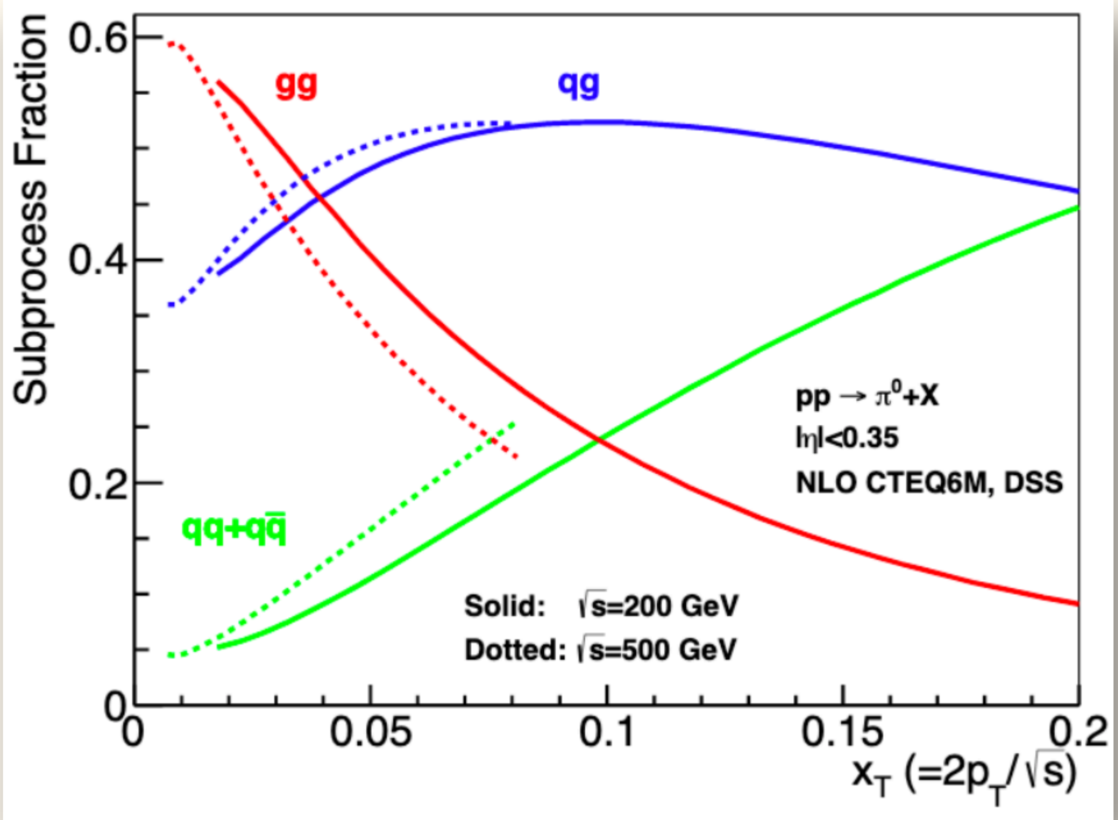
New PHENIX **pion and eta A_N**



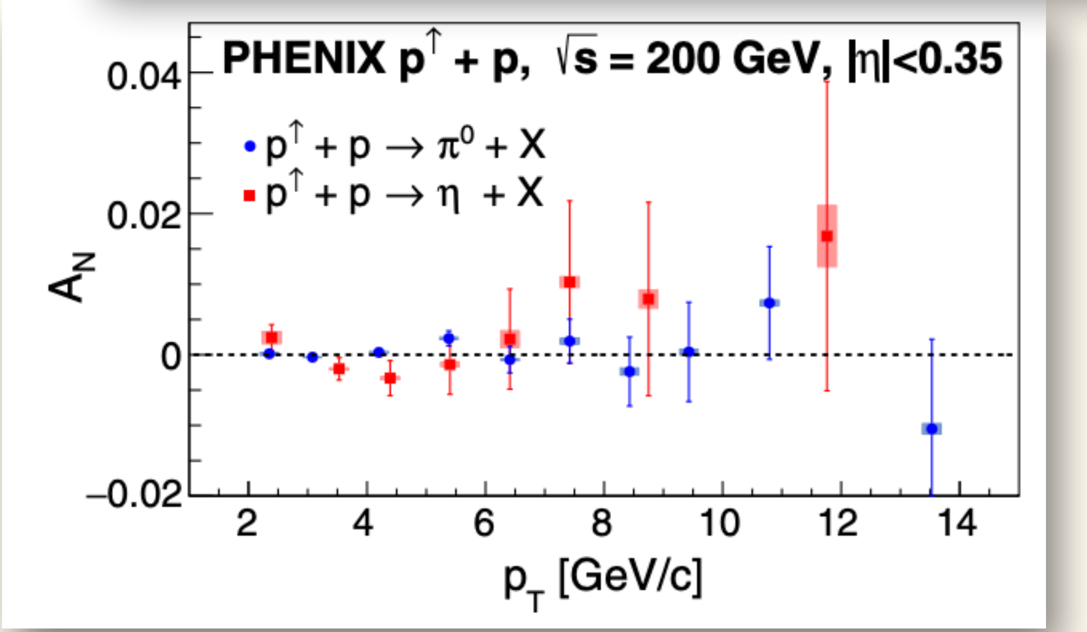
GPM scenarios: [D'Alesio, Flore, Murgia, Pisano, Taels, PRD 99, 036013 (2019)]

see talk by J. Yoo, Wednesday 14:50

[PHENIX PRD 103 (2021) 5, 052009]

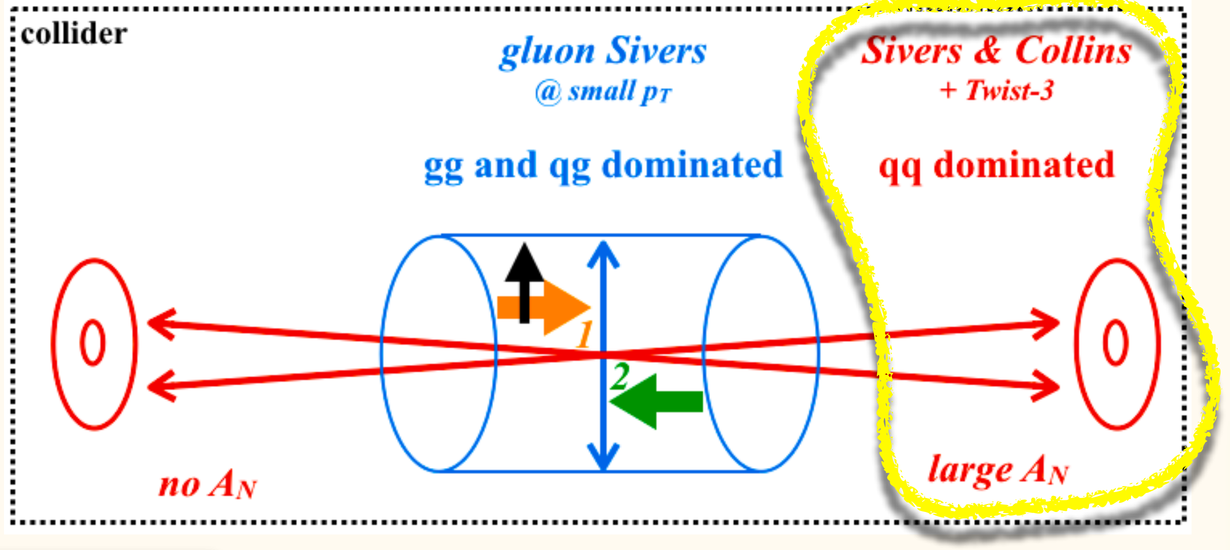


Subprocess fractions at RHIC energies for gg, qg, qq+qqbar



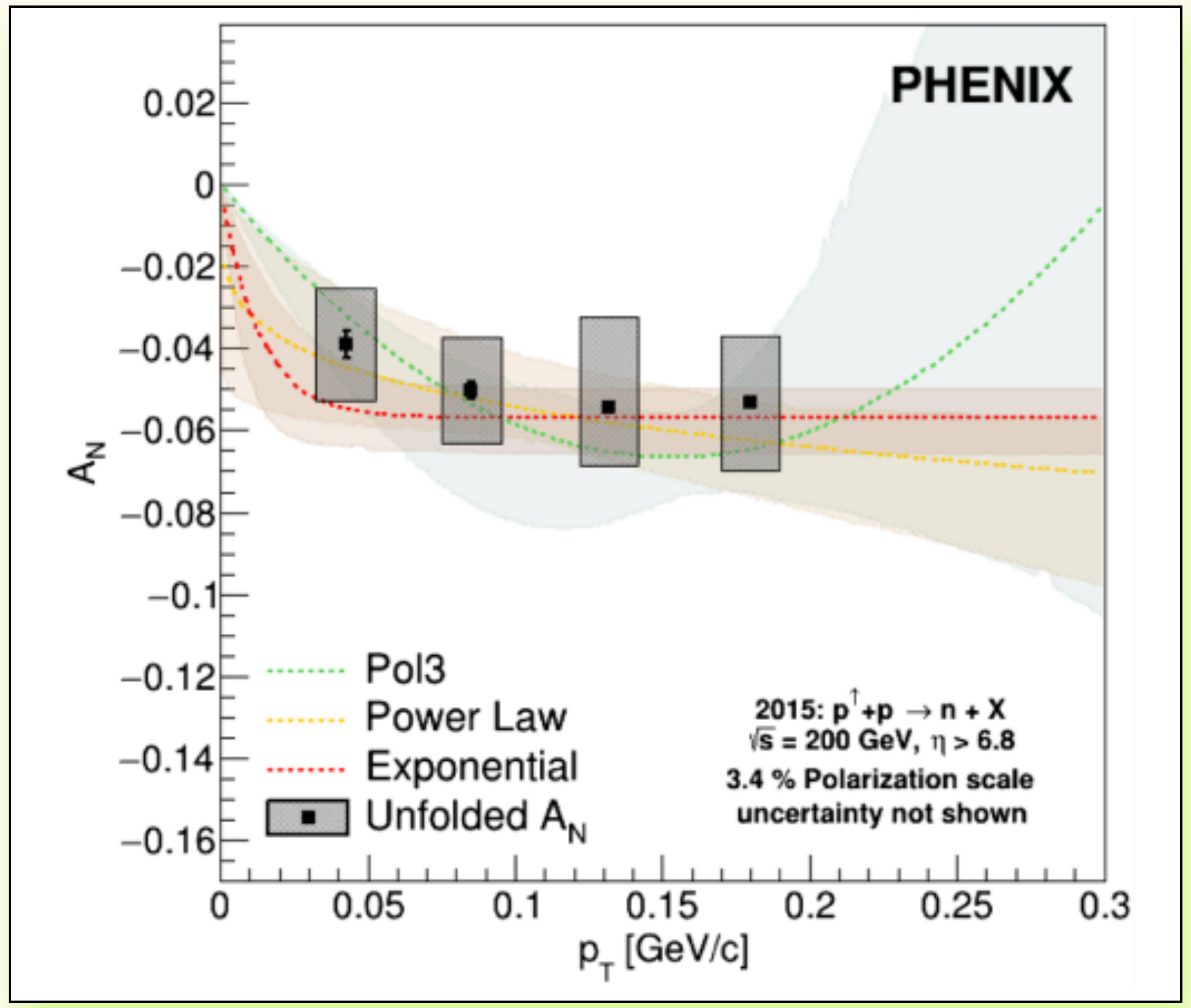
ΔA_N π^0 vs. η: disentangle possible effects of strangeness, isospin, or mass. Improvement by factor of 3 in stat. uncertainty

A_N in the very forward



PHENIX

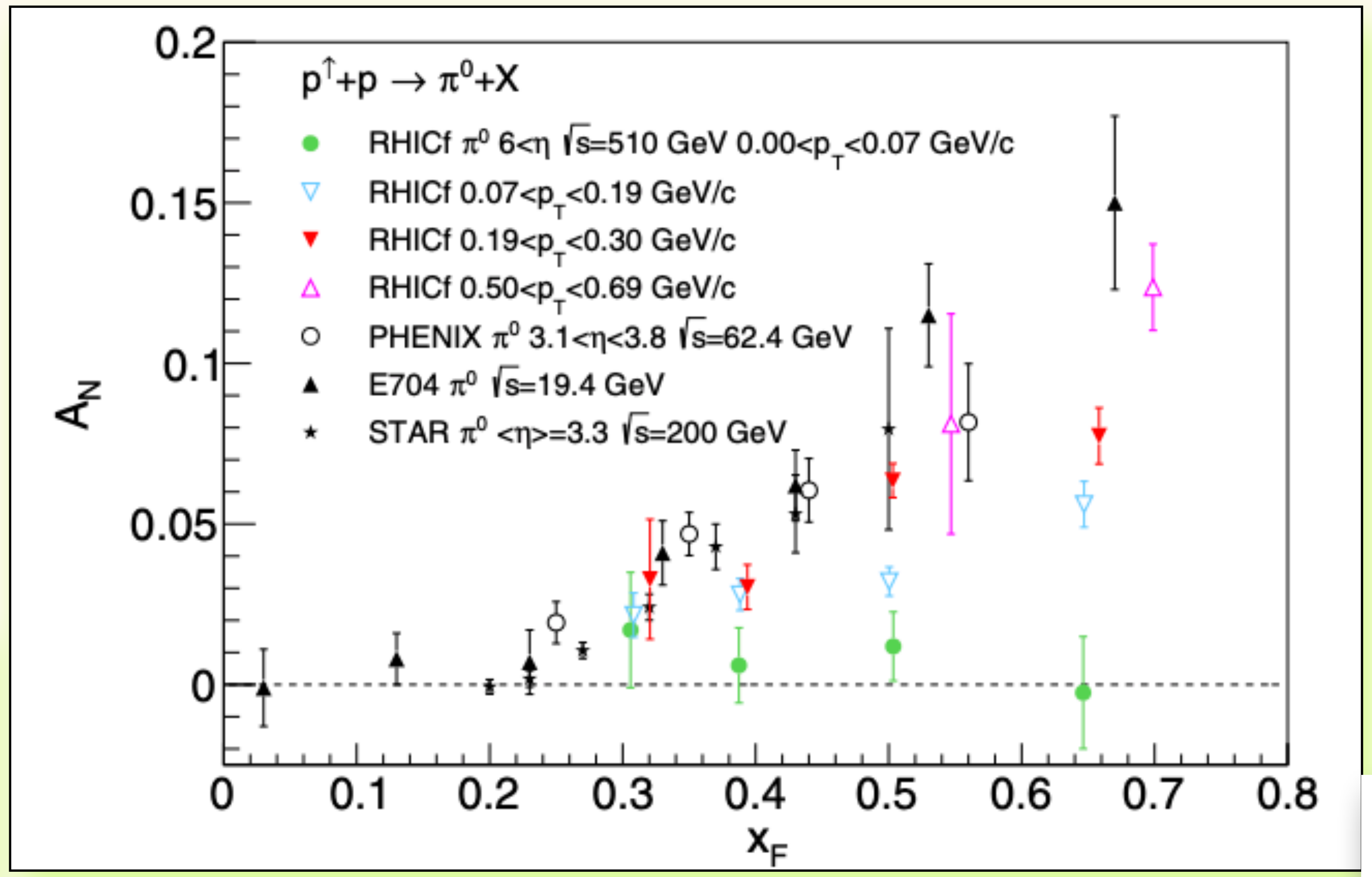
- ✦ Detection of very forward neutrons using a zero-degree calorimeter (ZDC) ~20m from PHENIX IP



[PHENIX PRD 103 (2021) 3, 032007]

RHICf

- ✦ RHICf(orward) calorimeter 18m from STAR IP
  π^0 in elmag jet, $2.8 < \eta < 4.0$



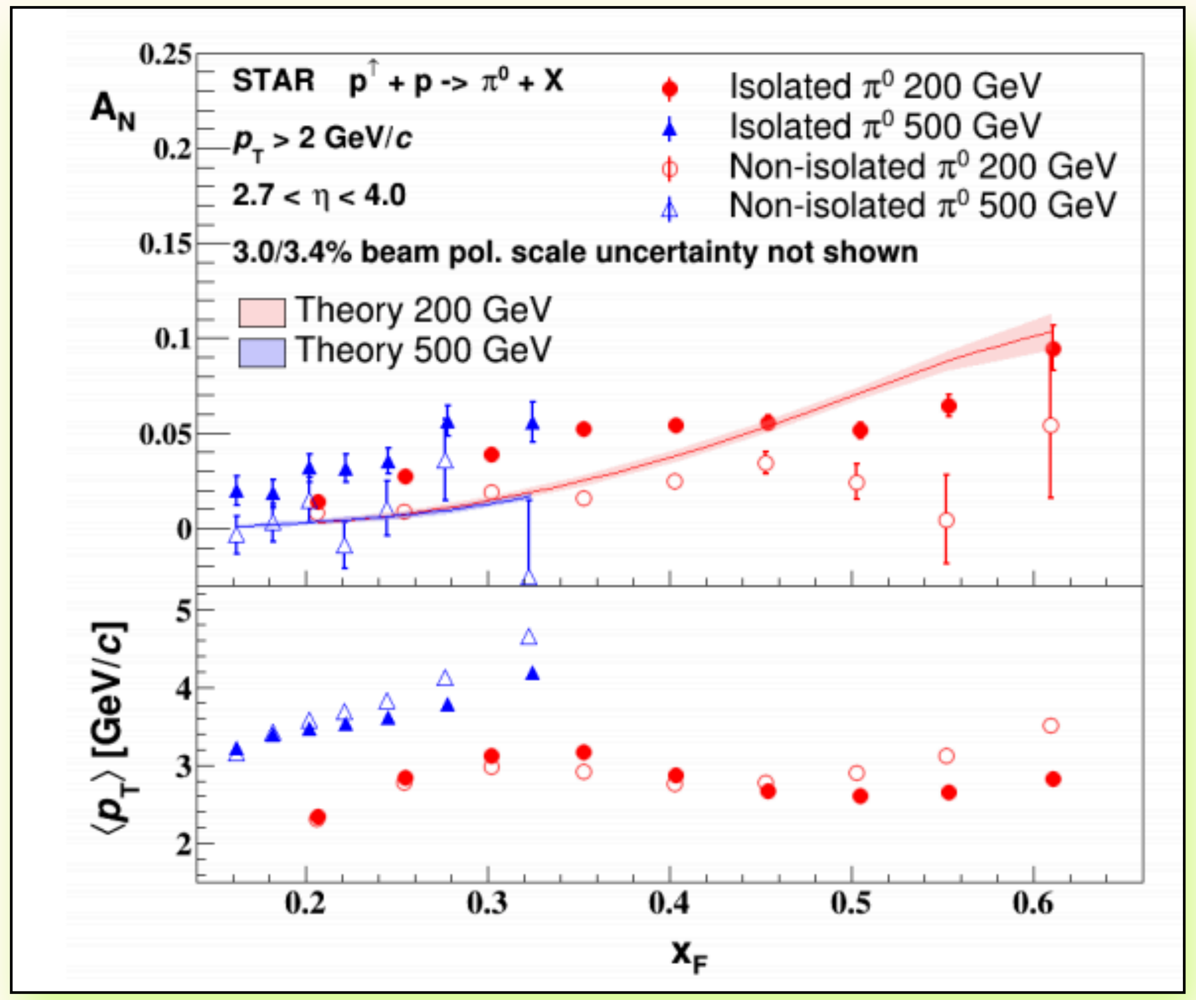
[RHICf PRL 124, 252501 (2020)]

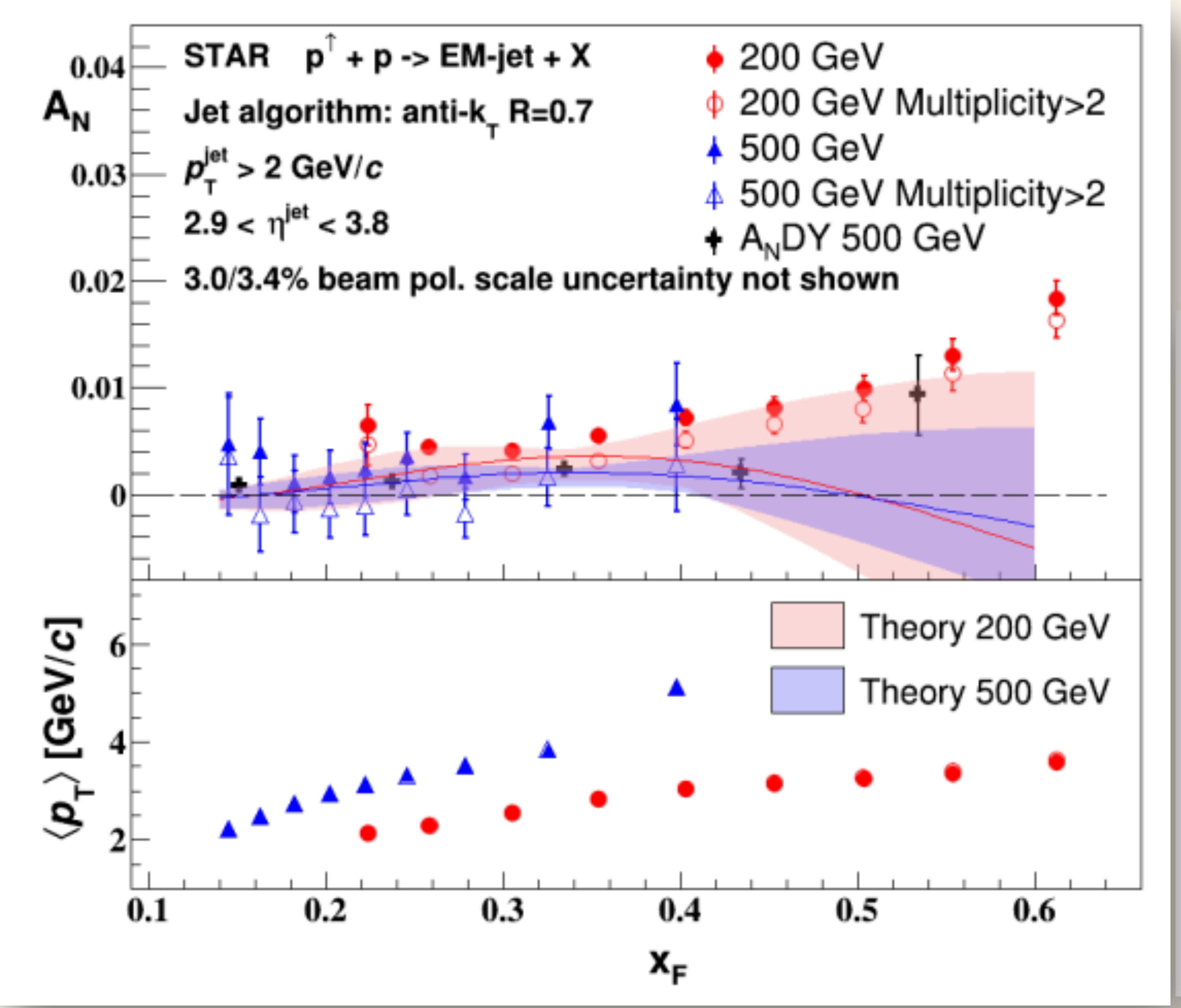
A_N increases with p_T & forwardness & π^0 isolation (STAR) & γ multiplicity (STAR)

A_N from soft processes such as diffractive scattering?

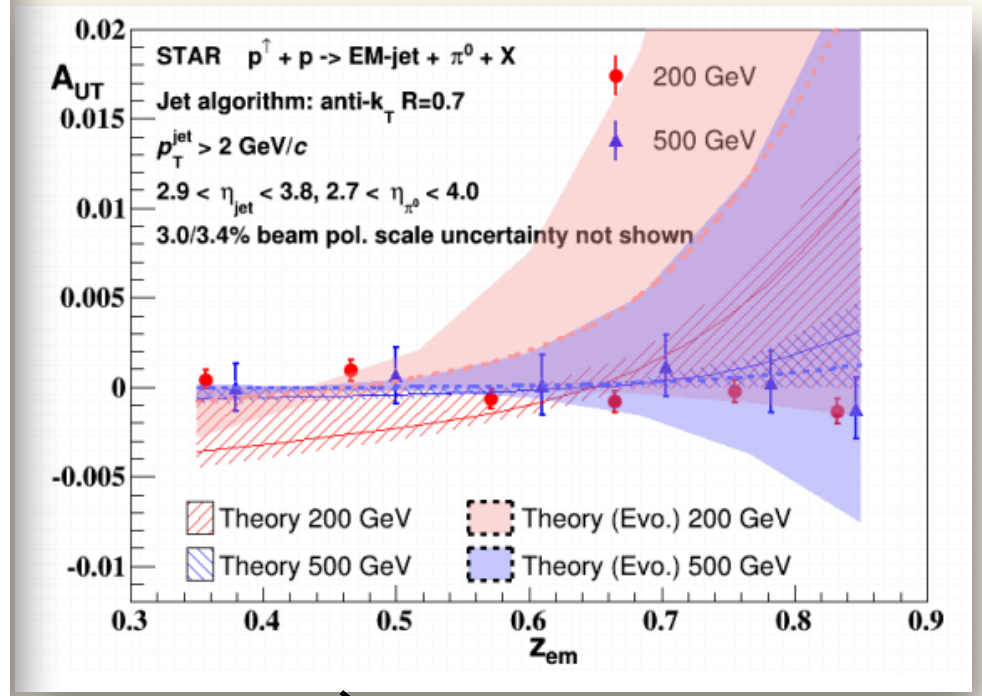
STAR

- ✦ π^0 and electromagnetic jets using Forward Meson Spectrometer





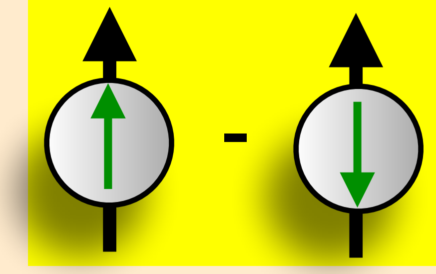
see talk by L. Kabir, Wednesday, 13:50



[STAR arXiv:2012.11428]

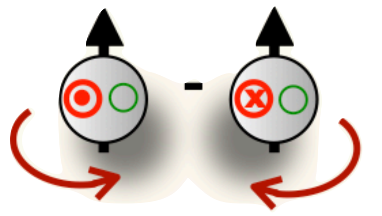
Collins asymmetries small…

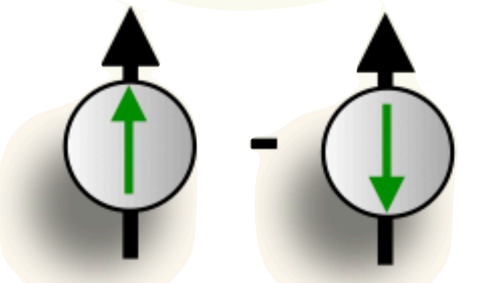
Collins asymmetries



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

Sivers function





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

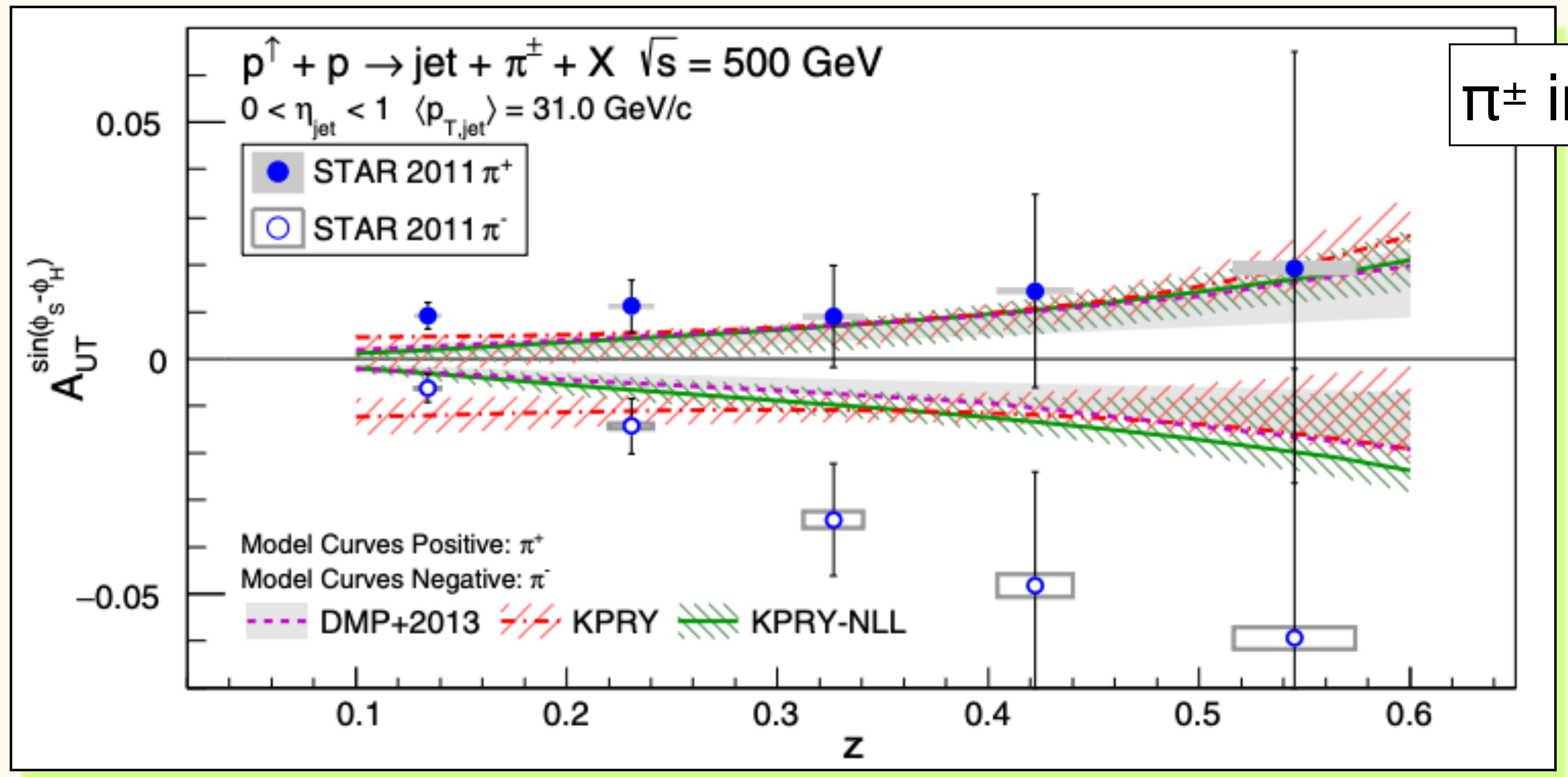
Transversity	⊗	Collins function
chiral-odd PDF		chiral-odd FF
	⊗	di-hadron interference FF

Collins effect: spin-dependent fragmentation of a transversely polarized parton into a final-state hadron — **"quark polarimeter"**

STAR **hadrons in jets** (midrapidity)

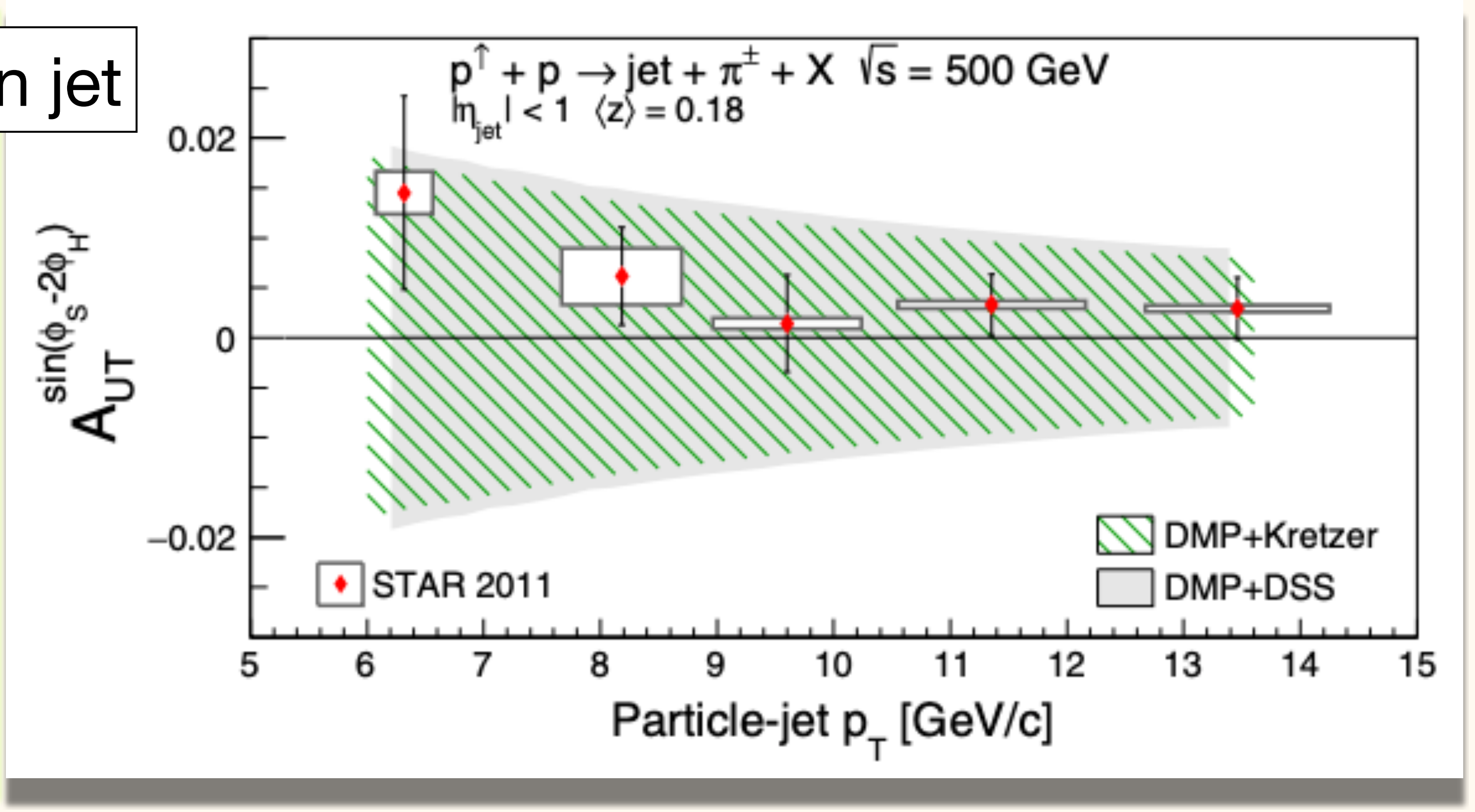
[STAR PRD 97 (2018) 032004]

Collins asymmetry Calculations based on SIDIS & e+e- data assuming Collins factorization & universality [PLB 773 (2017) 300]

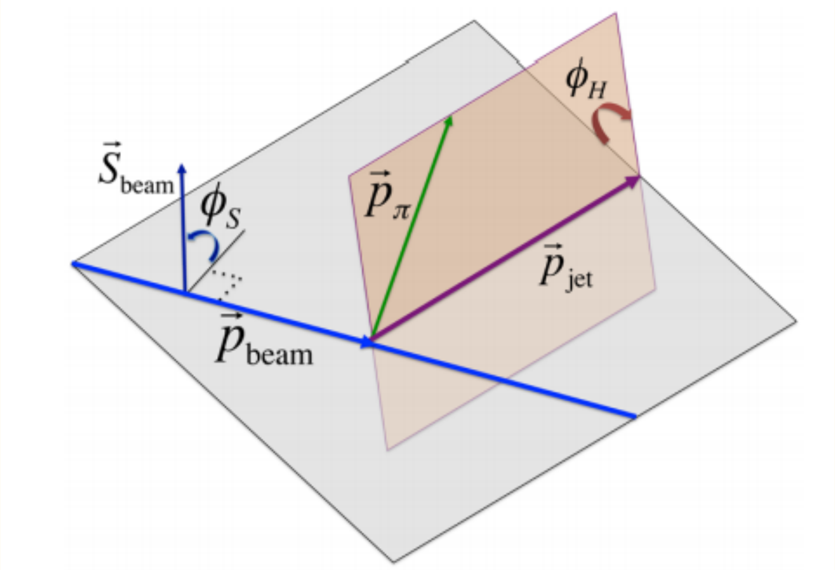


π± in jet

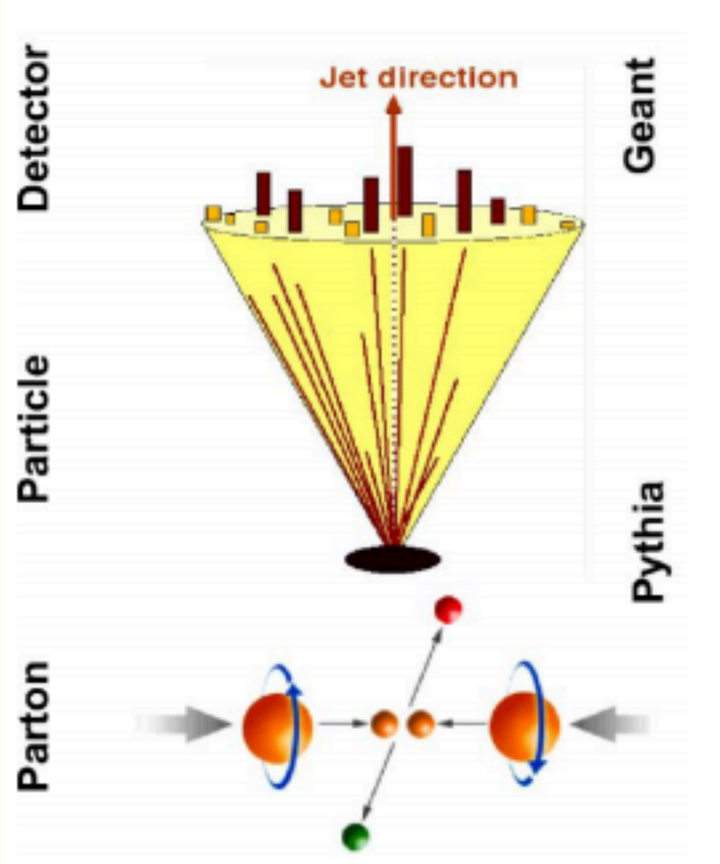
First experimental constraint on Collins-like asymmetry, sensitive to linear gluon polarization (gluon analog to quark FF)



- Coupling of Collins to transversity TMD leads to azimuthal modulations of charged-hadron yields around the jet axis



- Two hard scales allow for TMD interpretation:
  p_T of jet
  j_T of hadron in jet

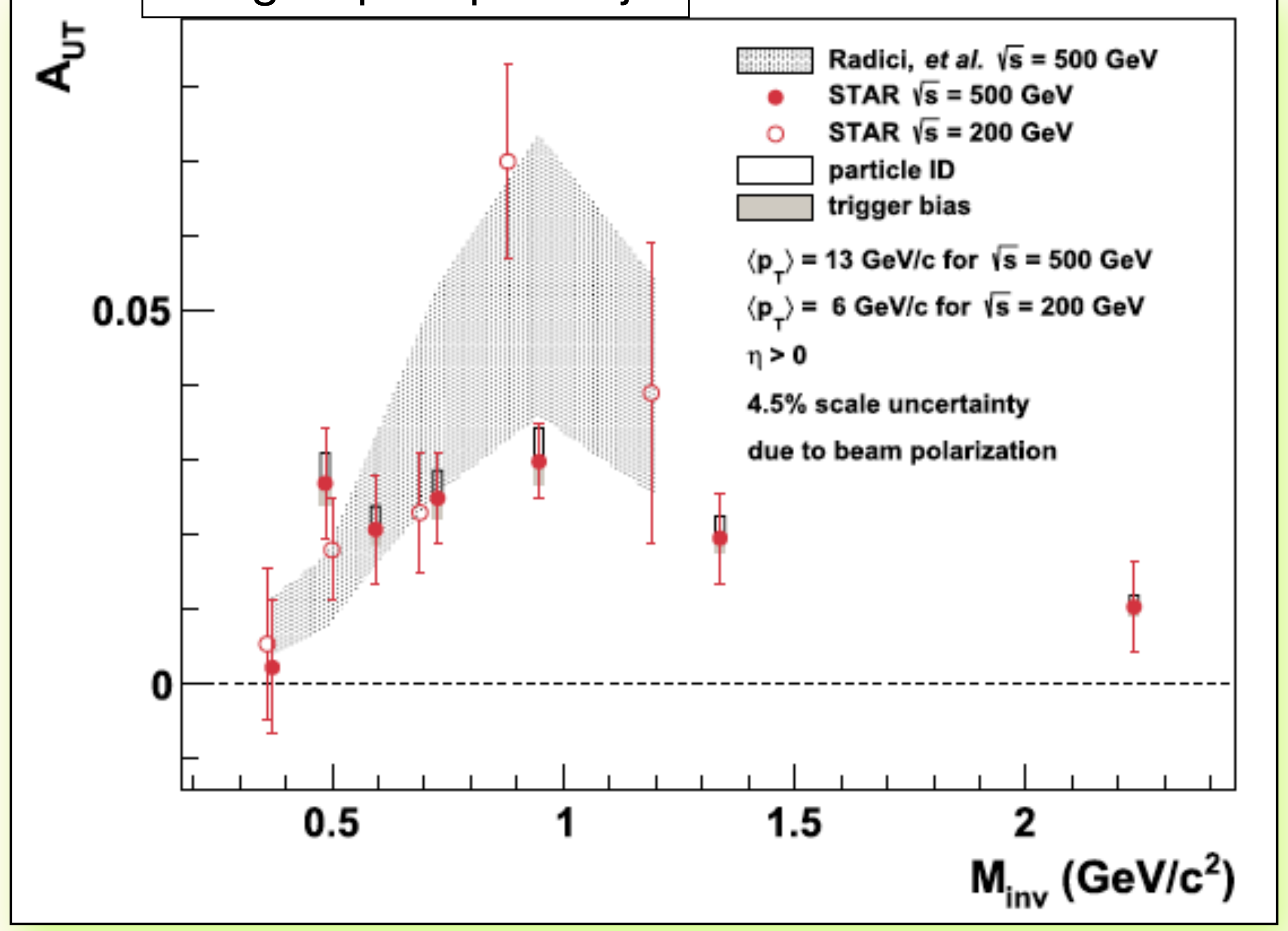


RHIC results enable tests of TMD universality and factorization breaking
(expected for hadronic interactions)

Collins-dihadron-interference-fragmentation asymmetry vs. di-pion invariant mass in highest p_T bin.

[STAR PLB 780 (2018) 332]

charged-pion pair in jet

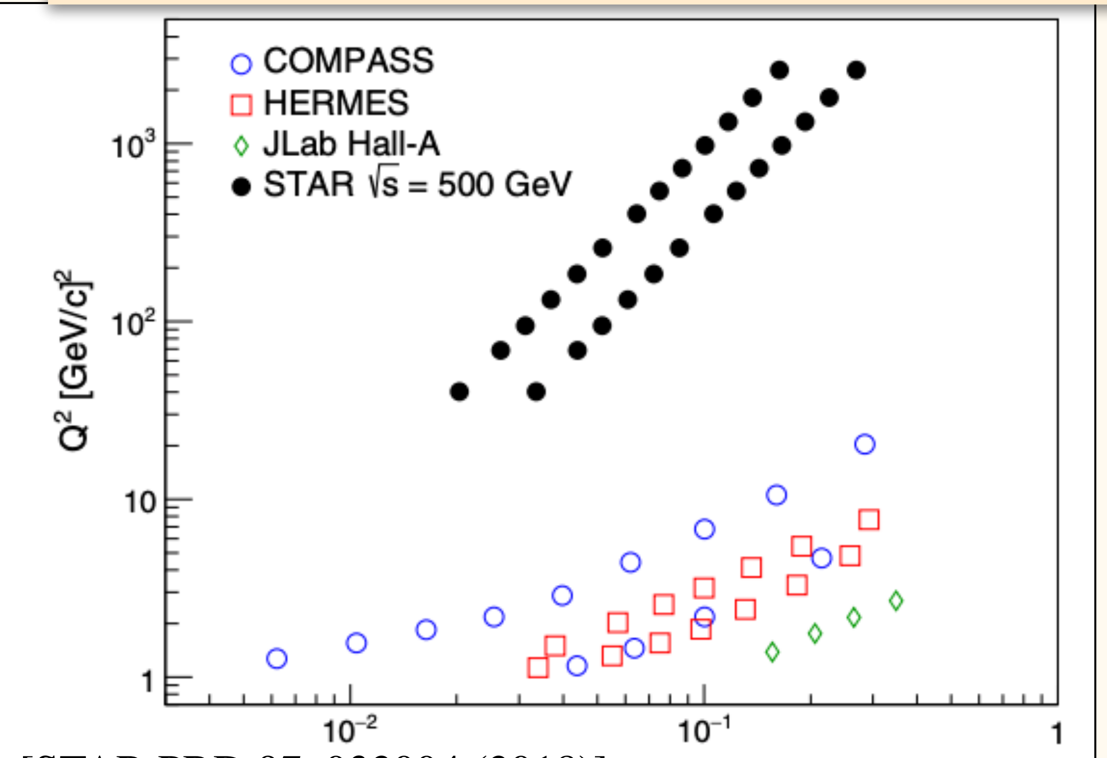


Not shown today: FFs measured in e^+e^- at Belle, Barbar, BESIII

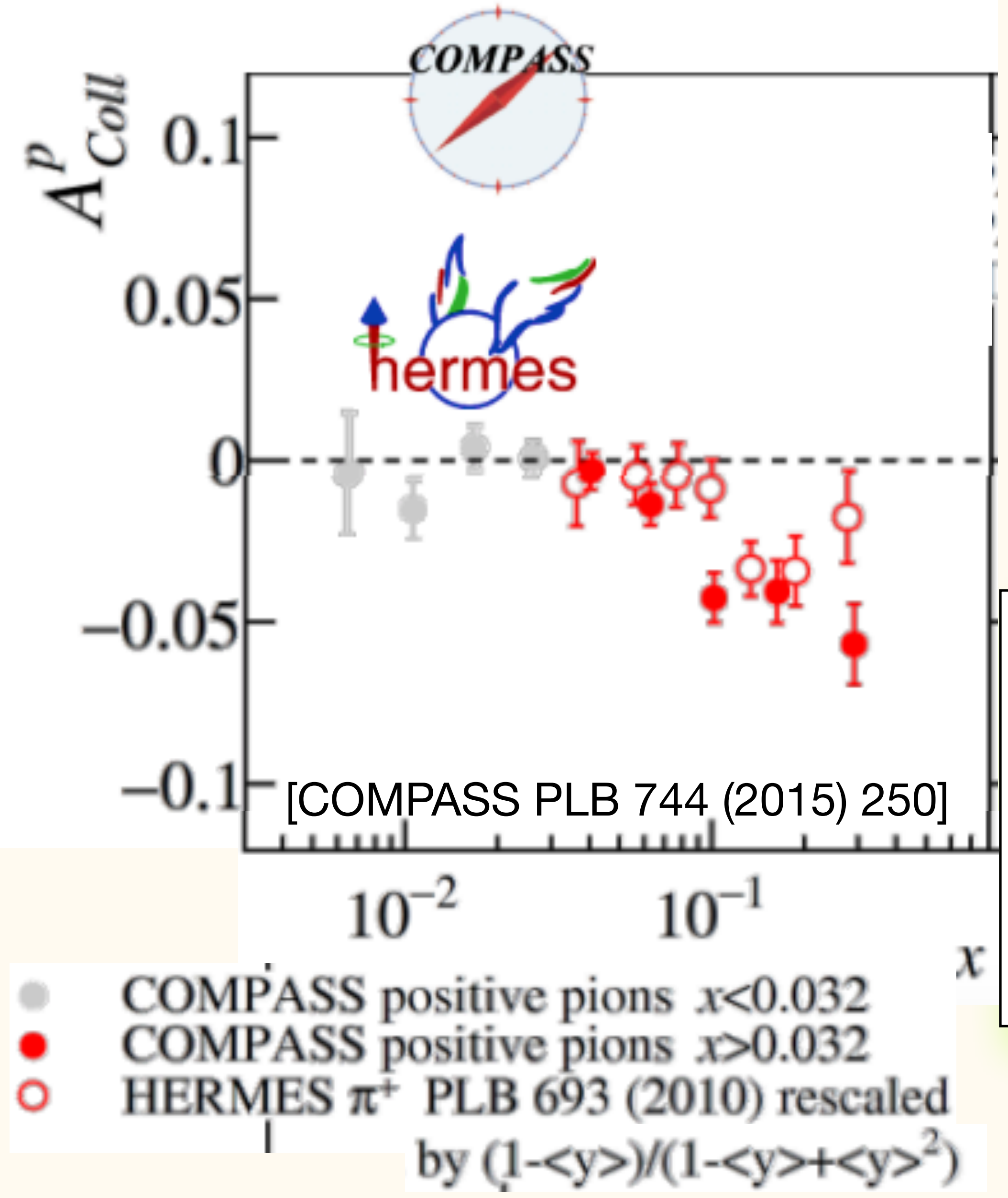
- More STAR data analyzed in multi-dimensional binning & kaons / protons: new at DIS21 (B. Pokhrel)

Collins asymmetries in SIDIS $\ell N^{\uparrow} \rightarrow \ell h(h) X$

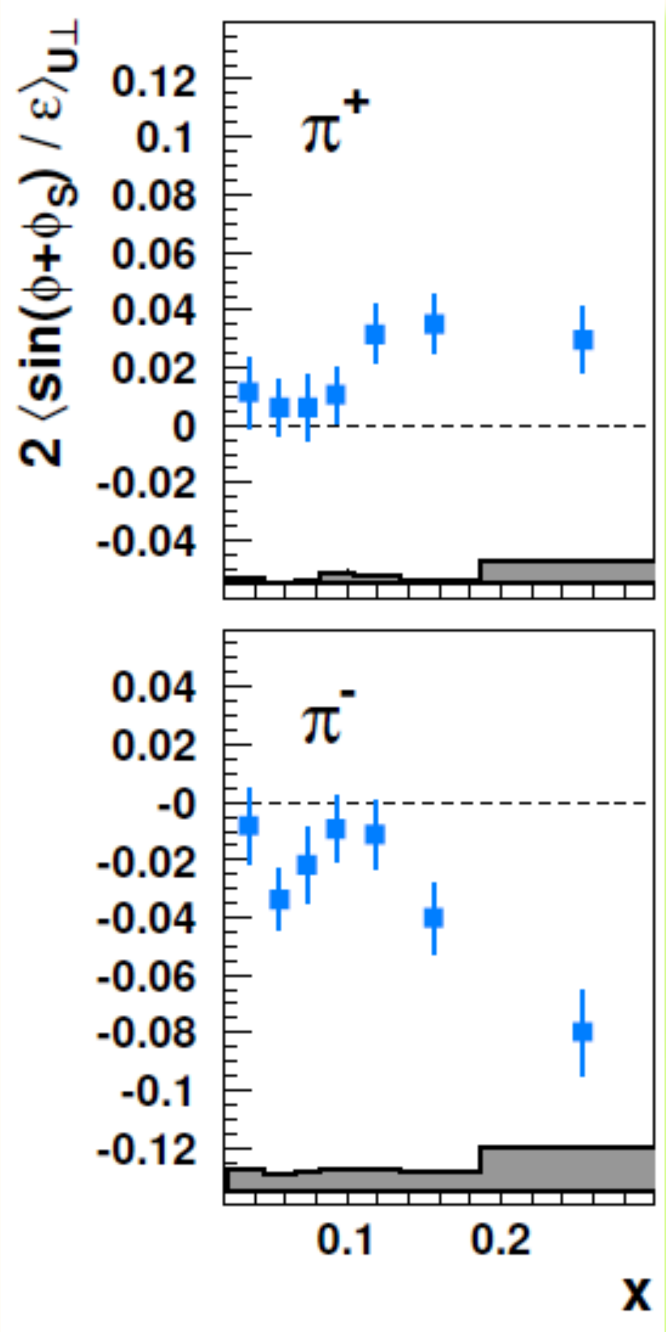
HERMES & COMPASS **Collins asymmetries**



[STAR PRD 97, 032004 (2018)] x



[COMPASS PLB 744 (2015) 250]

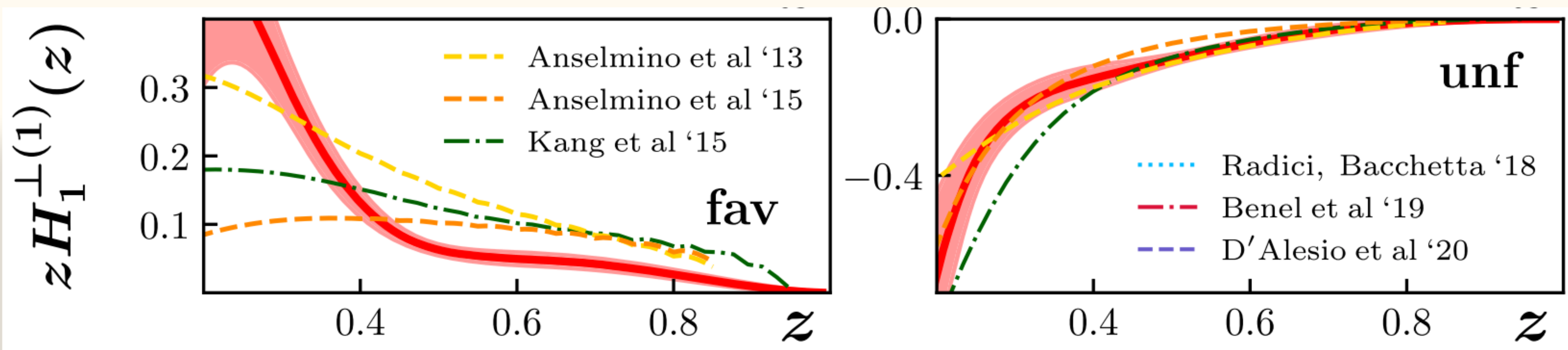


[HERMES JHEP 12 (2020) 010]

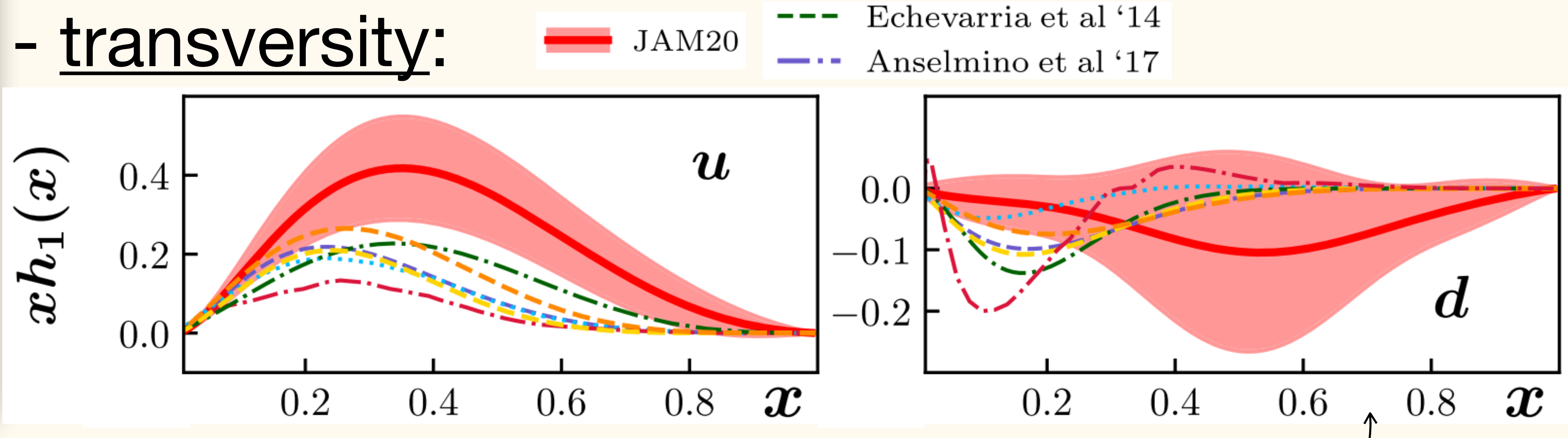
Mirror symmetry for π⁺ & π⁻: ***u***- (δ_u) and ***d*-quark transversity** (δ_d) have ~ **equal magnitude** & **opposite signs** for favored and unfavored Collins FFs.

Transversity = valence-quark effect (increase with *x*).

Global extractions - Collins function:



- transversity:



[JAM Collaboration, PRD 102, 054002 (2020)]

- ✦ *d*-quark transversity less constrained given the *u*-quark dominance of many of the processes used in the global fits. **COMPASS 2021 transversity run** on the deuteron will **double** the experimental precision on the proton's **tensor charge $g_T = \delta_u - \delta_d$** [CERN–SPSC–2017–034]
  - Further prior-to-EIC measurements of Collins asymmetries: STAR with forward upgrade, sPHENIX, JLab12/SoLID, SpinQuest
- ✦ Check of **TMD universality:** COMPASS Collins asymmetries SIDIS vs. Drell-Yan.
- ✦ Alternative methods to access transversity: measure hyperon transverse polarization, which may have been transferred from struck quark
  - COMPASS: SIDIS on trans.pol protons, to be submitted to PLB
  - STAR:

Novel spin-dependent fragmentation functions

New COMPASS **Collins asymmetry in ρ^0 production**

- **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). Czyzewski model, Artru, string+3P0 model
- Collins (and also Sivers) asymmetry for ρ^0 production on transversely polarized proton target, new at DIS21 (A. Kerbizi)

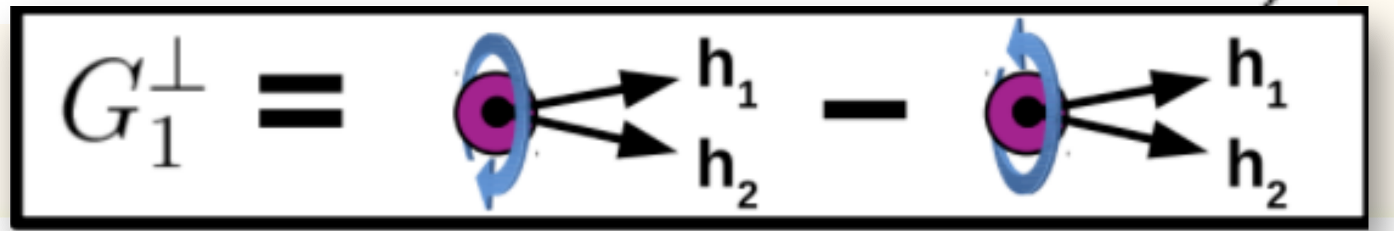
New CLAS12 **higher-twist di-hadron beam-spin asymmetry**

- First empirical evidence of a nonzero **parton helicity-dependent di-pion fragmentation function $G_{\perp 1}$**
  - Encodes spin-momentum correlations in hadronization
  - Equivalent to the Collins FF for two pions

  In the ρ-mass region, can be used to test predictions by the Artru model about the relative size of Collins asymmetries of vector and scalar mesons
  - Data also allow for a point-by-point extraction of the **collinear-twist-3 PDF $e(x)$**

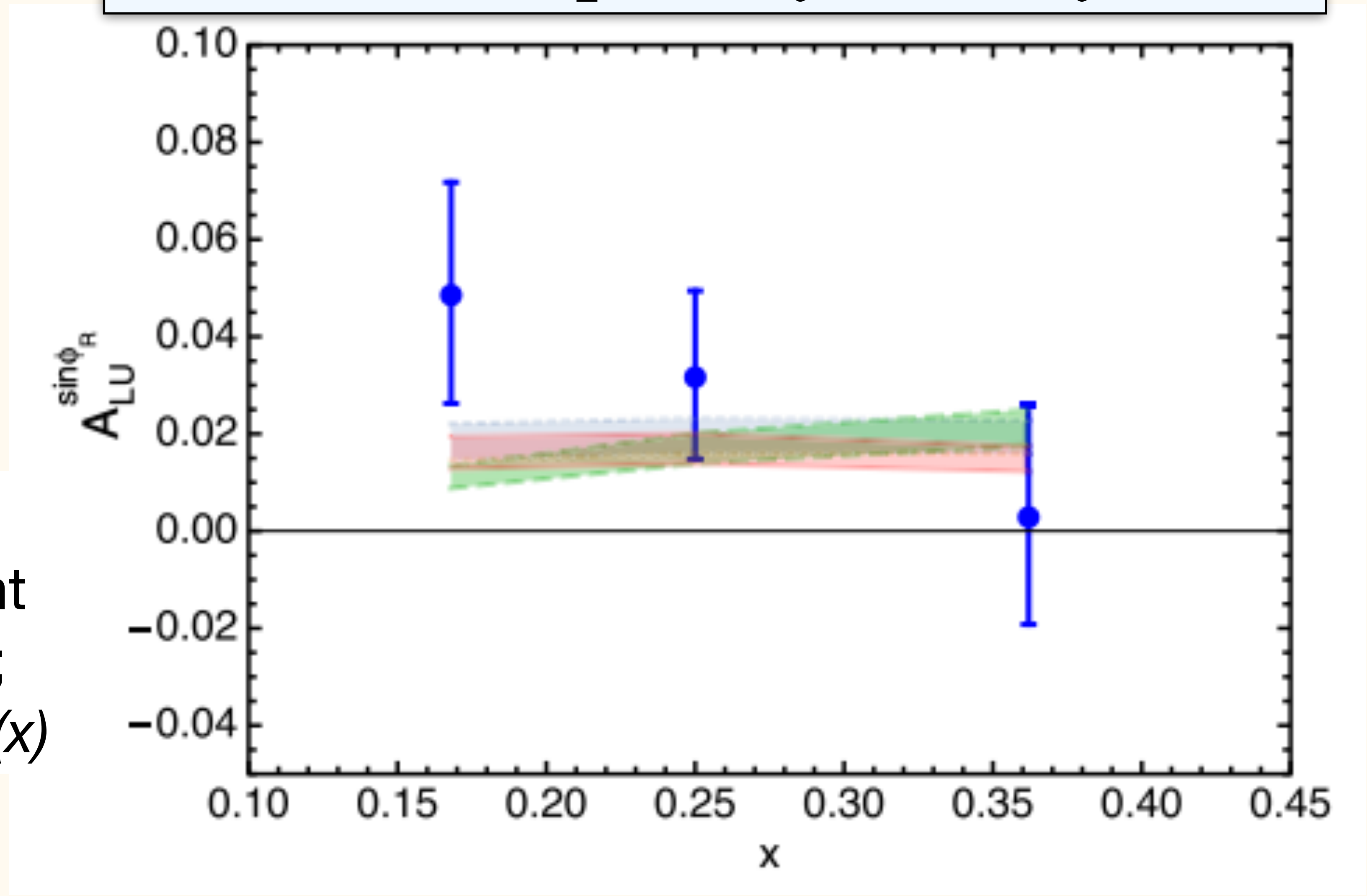
$$d\sigma_{LU} \propto \quad W\lambda_e \sin(\phi_{R_\perp}) \left(xe(x)H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f(x)\tilde{G}^{\sphericalangle}(z, M_h) \right)$$

see talk by C. Dilks, Wednesday 15:30

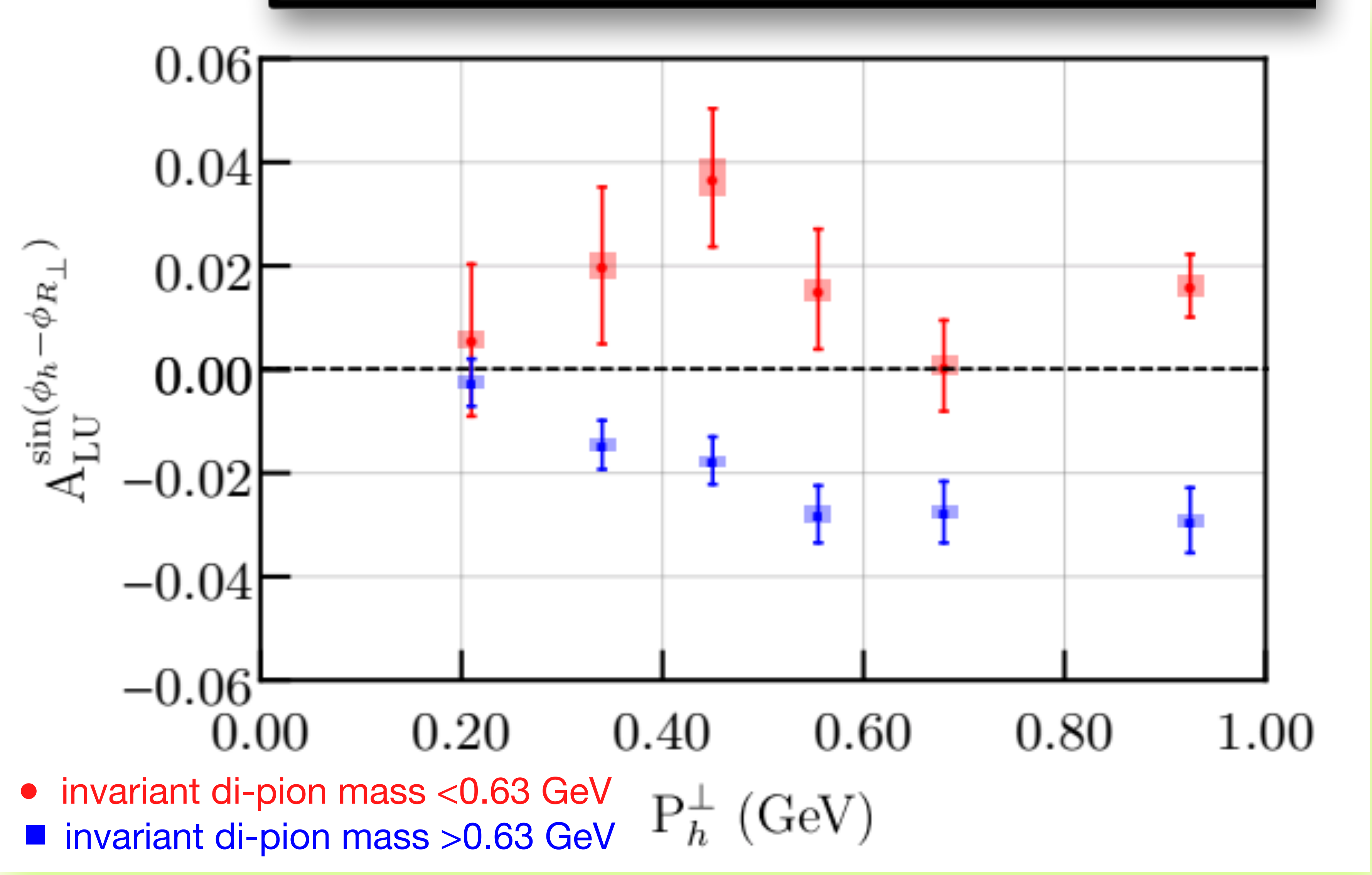


New CLAS **higher-twist di-hadron beam-spin asymmetry**

First measurement of that BSA; sensitive to *e(x)*



[CLAS / M. Mirazita PRL 126, 062002 (2021) & arXiv:2010.09544]



[CLAS12 / T. Hayward arxiv:2101.04842]

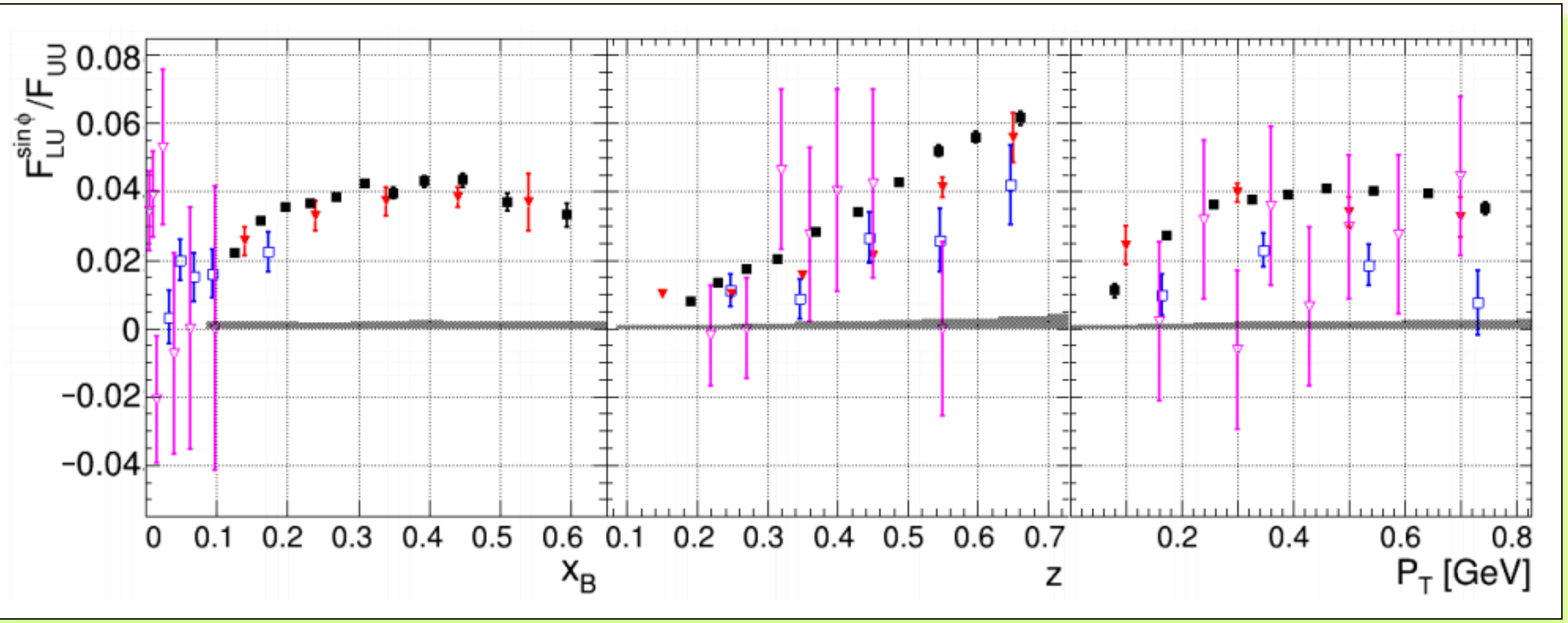
More higher twist in single-hadron SIDIS

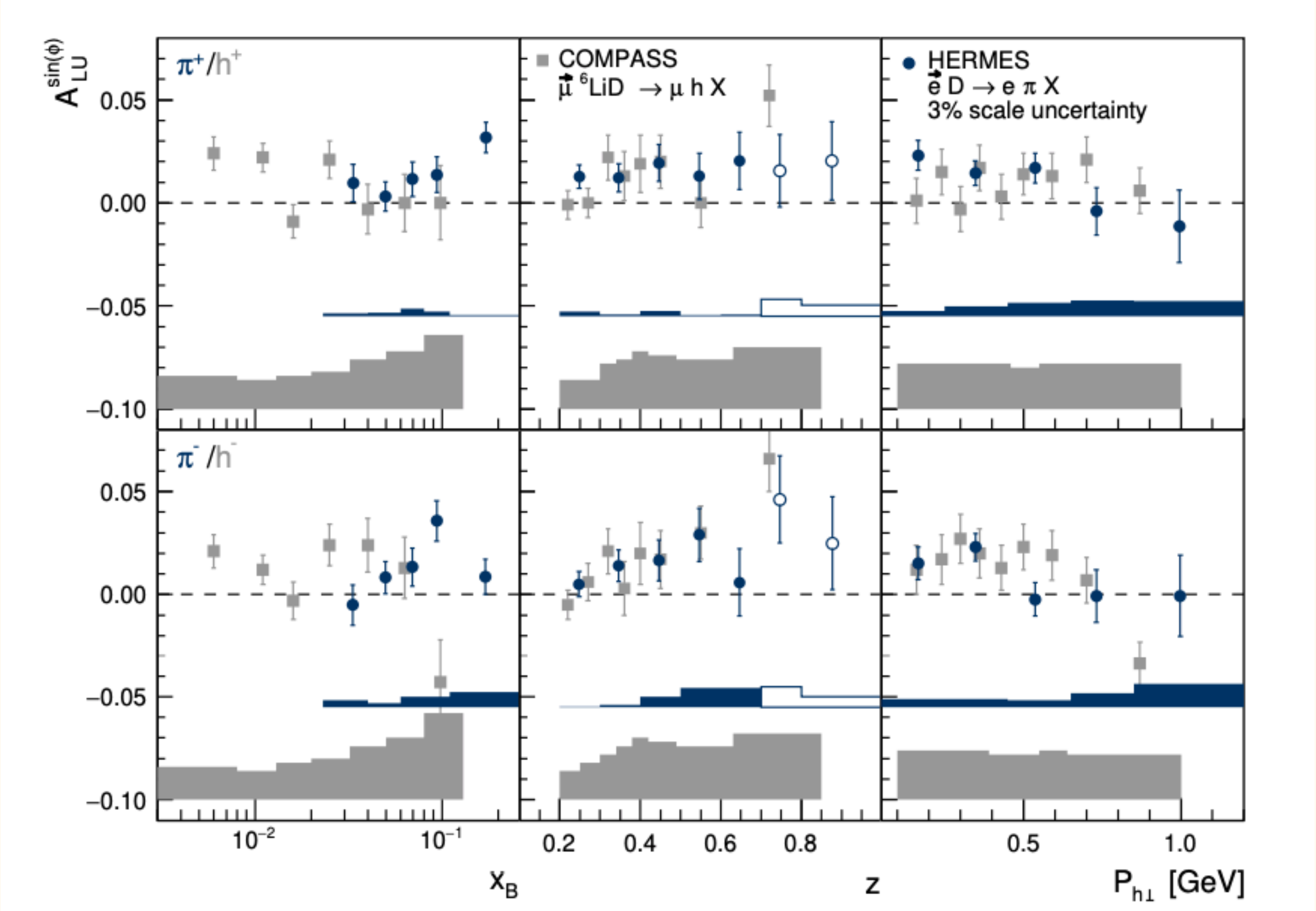
New CLAS12 and HERMES **SIDIS beam-spin asymmetries**

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

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

- ✦ 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**





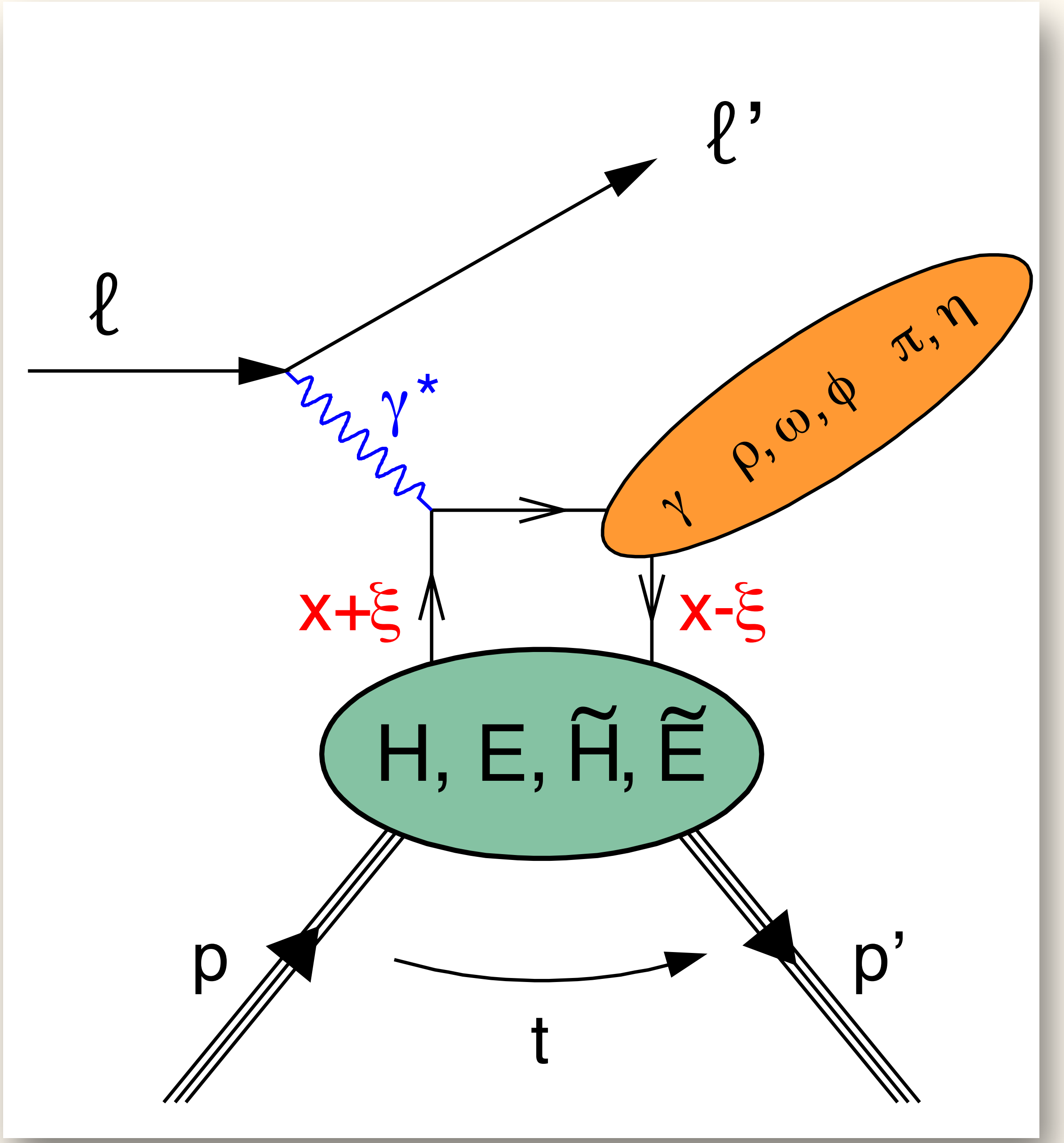
[HERMES PLB 797 (2019) 134886]

- ■ **[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)]

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

Hard exclusive processes

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



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

t: squared 4-momentum transfer to target

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

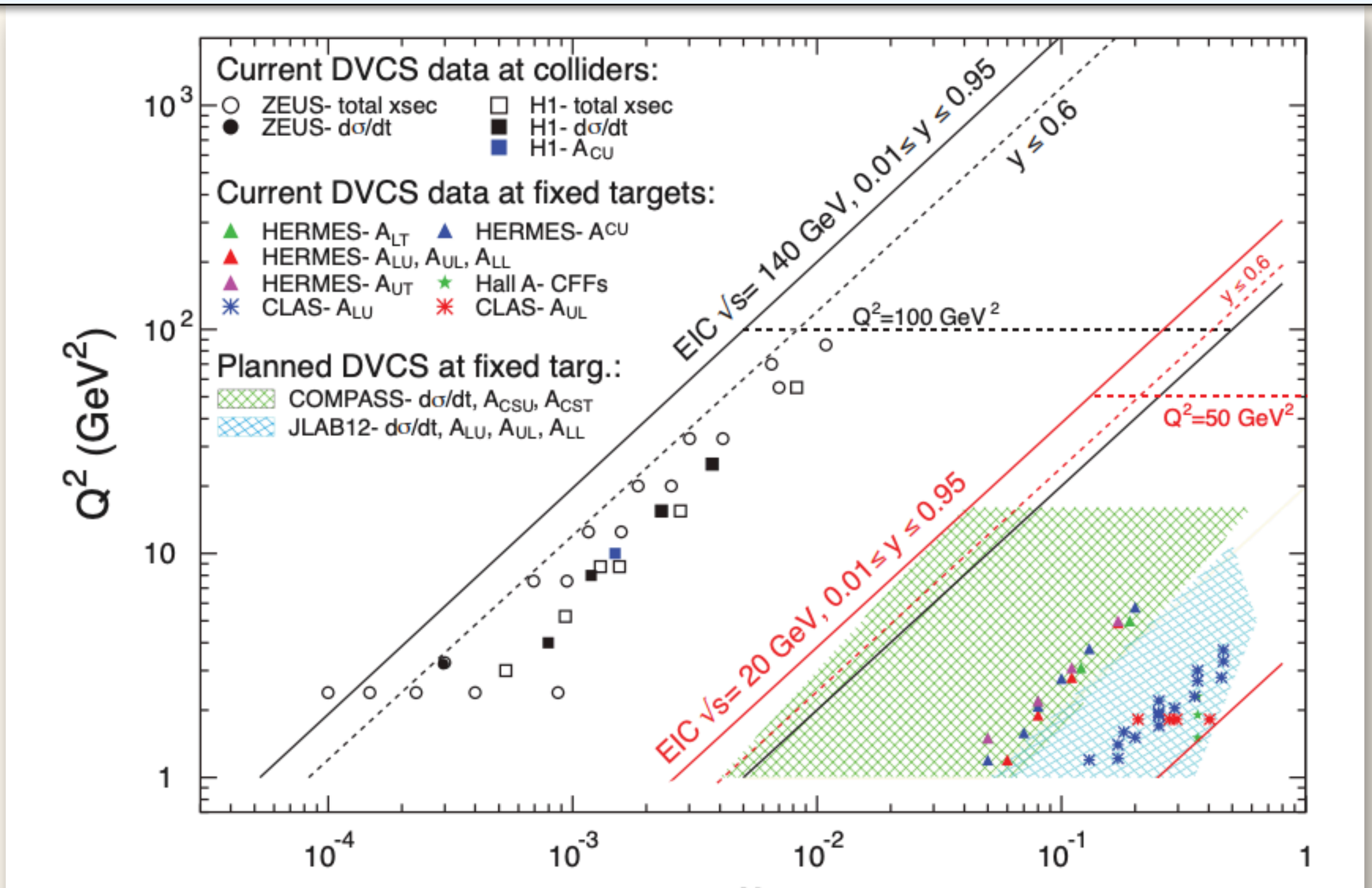
Deeply Virtual Compton Scattering (DVCS)

$\ell p \to \ell p M$

Deeply Virtual Meson Production (DVMP)

Standard channels to access generalized parton distributions are DVCS & DVMP

4 chiral-even &
4 chiral-odd GPDs



[JHEP 1309 093 (2013)]

GPDs	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	E	H
depends on quark helicity	$\tilde{E}$	$\tilde{H}$

4 chiral-even quark GPDs
@leading twist for a spin-½ target

H → ***q(x)***
$\tilde{H}$ → **△*q(x)***

forward limit
$\xi \to 0$, $t \to 0$

$J^P=1^-$ vector mesons	$J^P=1^-$ photon (DVCS)
$J^P=0^-$ pseudoscalar mesons	

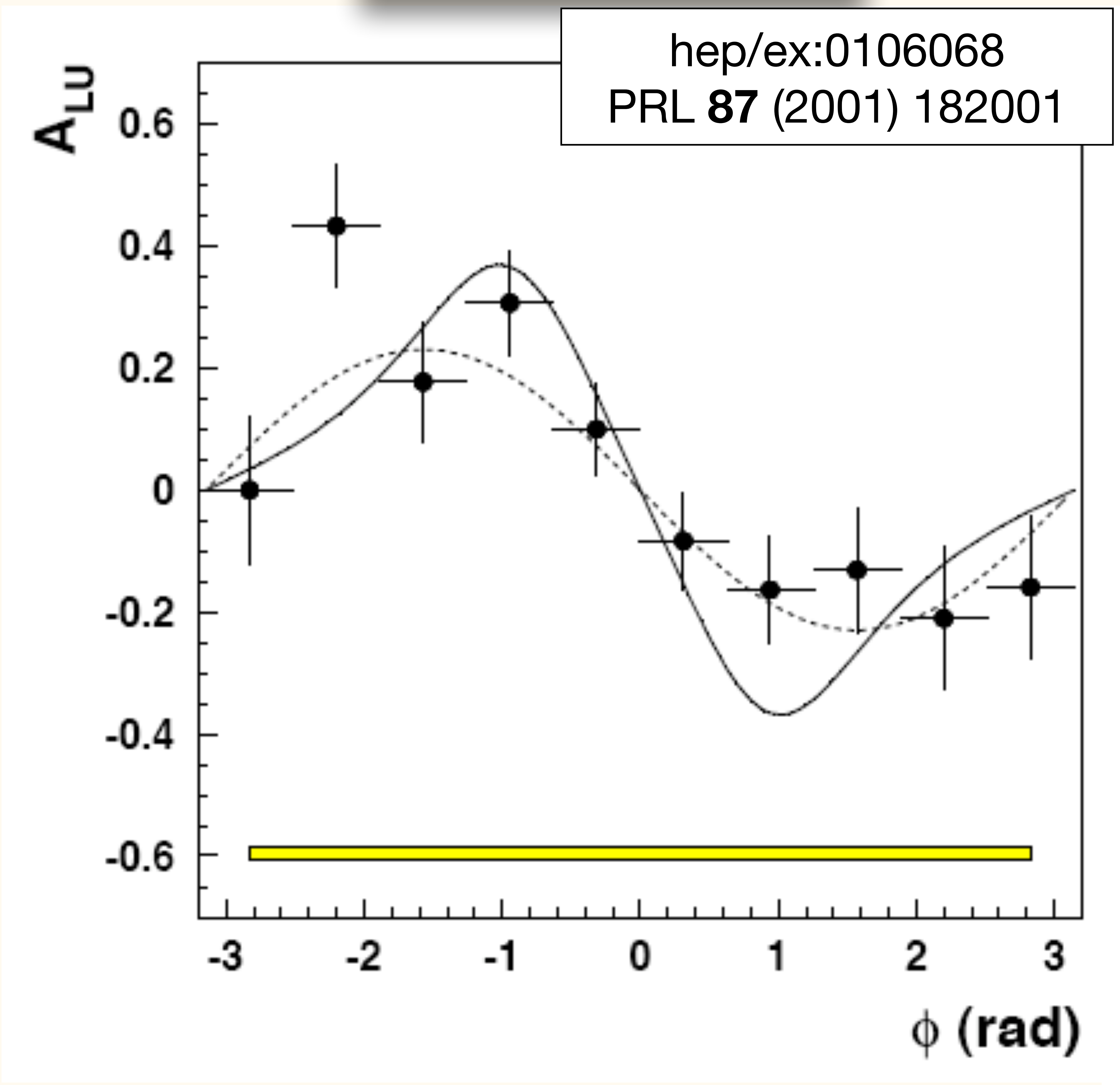
+ 4 chiral-odd GPDs: $\tilde{H}_T$ ↔ transversity TMD; $(2H_T + E_T)$ ↔ Boer-Mulders; $\tilde{E}_T$

2001: first observation of azimuthal modulation in DVCS spin asymmetry

20 years

HERMES @ DESY

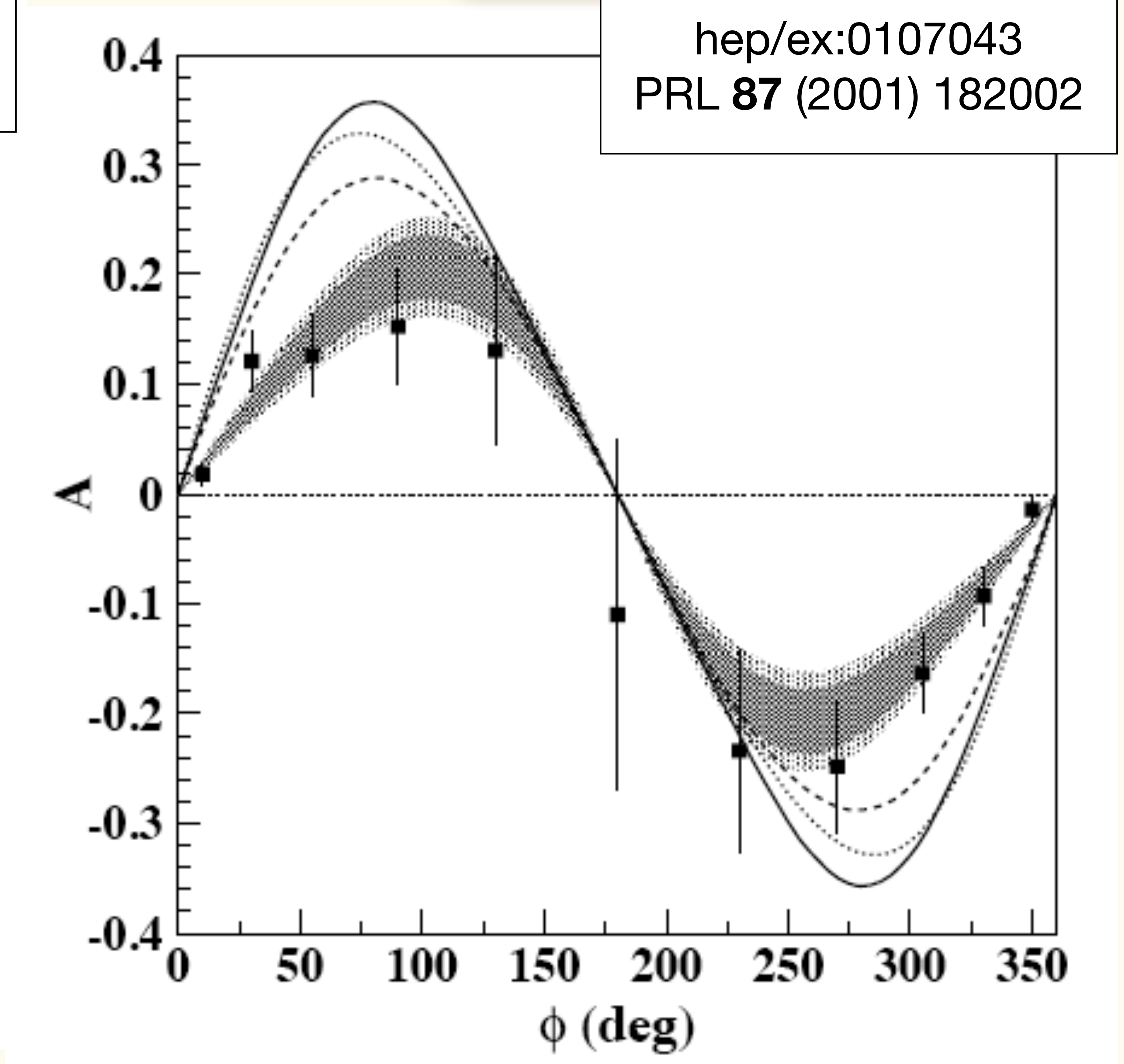
hep/ex:0106068
PRL **87** (2001) 182001



(positrons on proton target)

CLAS @ JLab

hep/ex:0107043
PRL **87** (2001) 182002

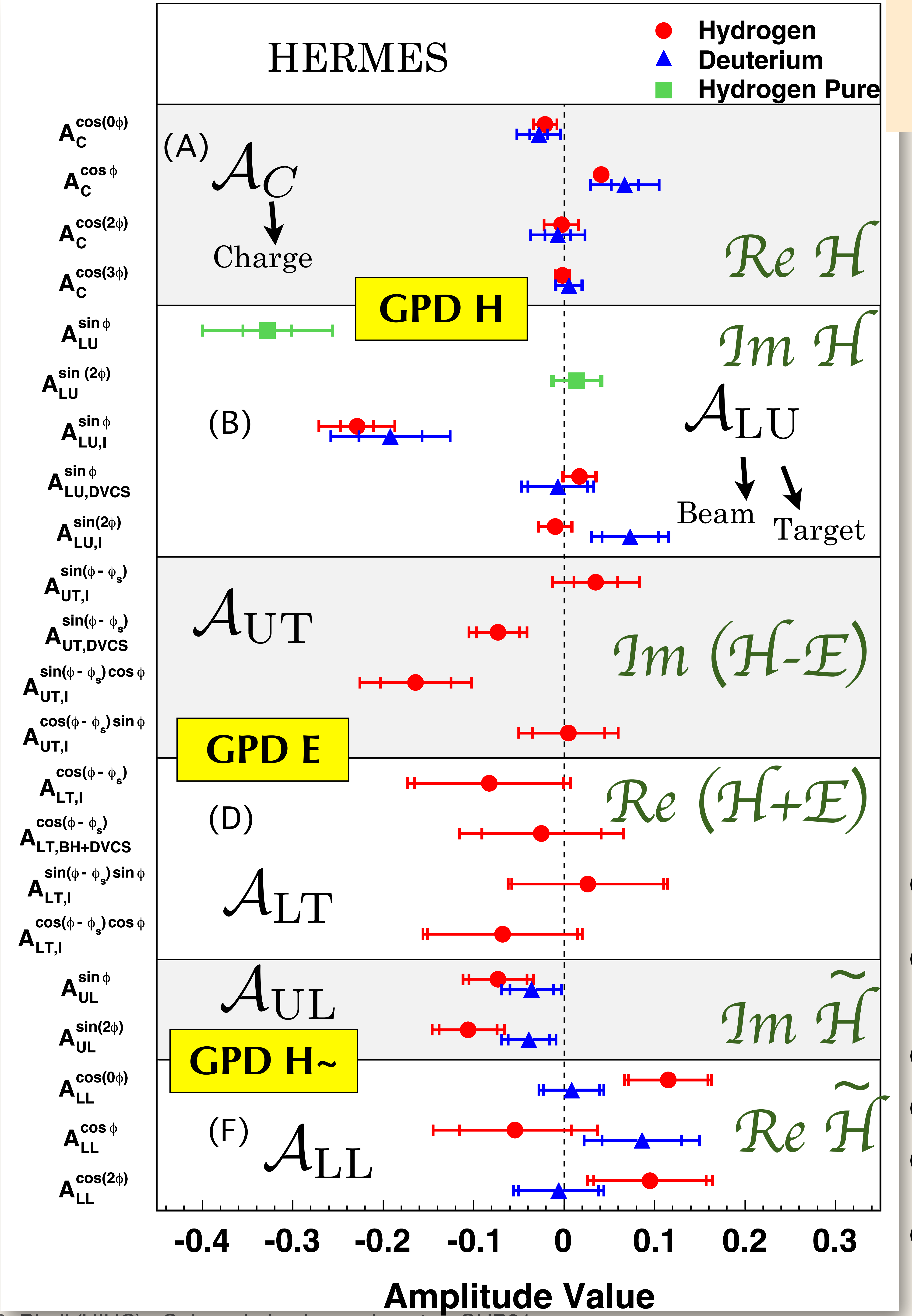


(electrons on proton target)

$$A_{\mathrm{LU}}(\phi) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

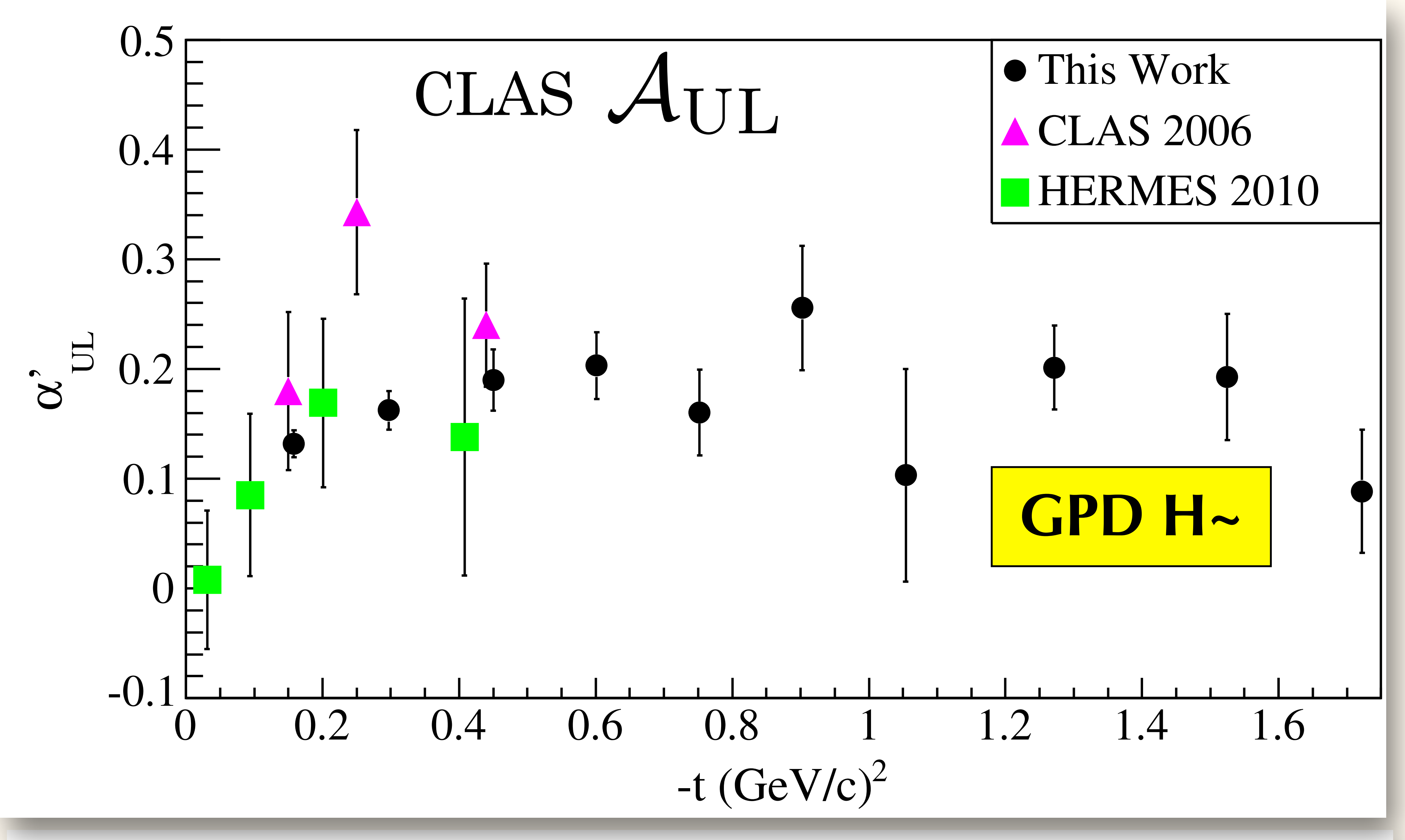
Beam-spin asymmetry

DVCS highlights



← azimuthal asymmetry amplitudes

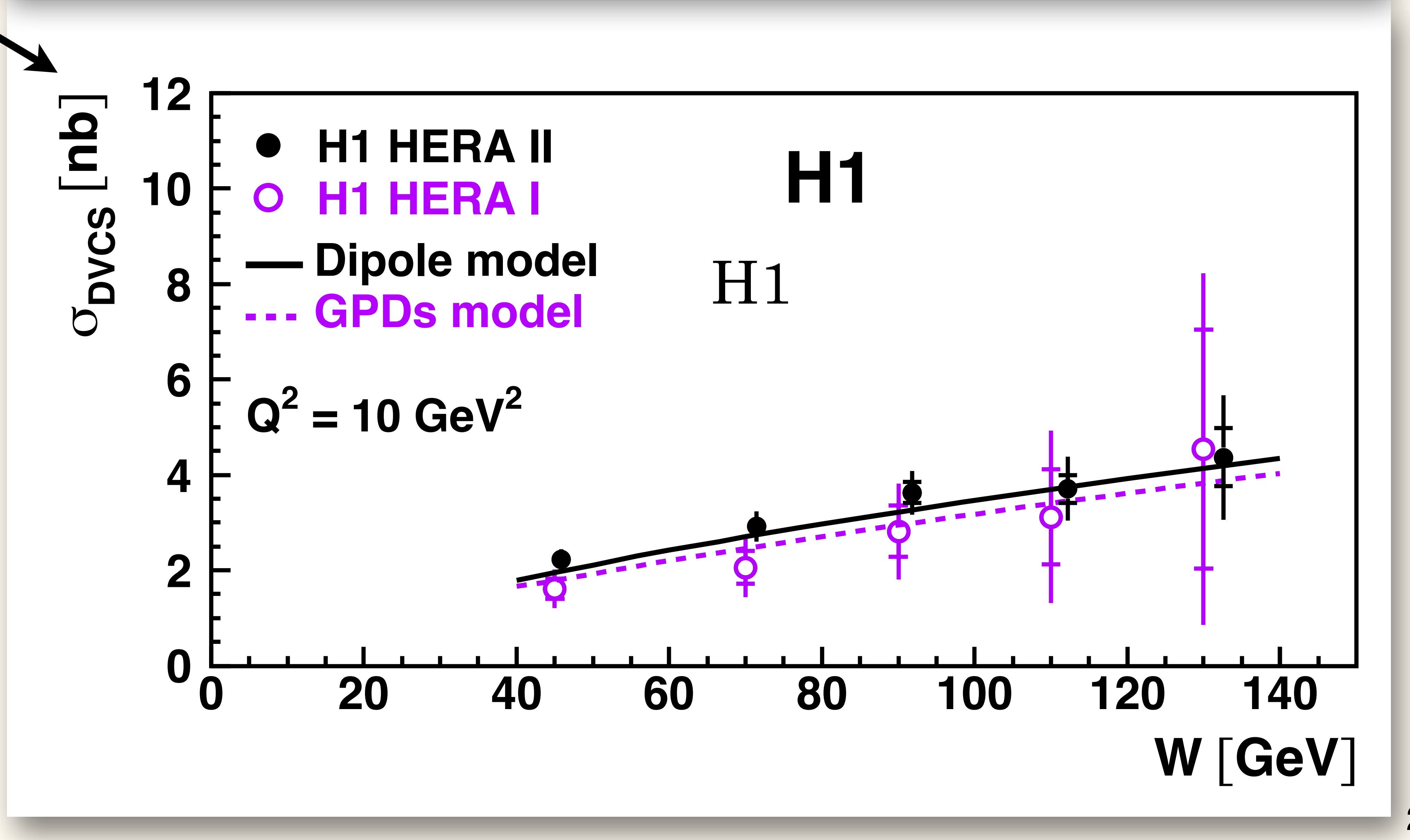
with respect to beam spin or beam charge or target spin



CLAS (S. Pisano et al.), PRD 91, 052014 (2015)
CLAS (Seder et al.), PRL 114, 032001 (2015)

H1: PLB 681 (2009) 391

cross sections



HERMES:

(A) [JHEP 07 (2012) 032 - Nucl. Phys. B 829 (2010) 1-27]

(B) [JHEP 07 (2012) 032 - Nucl. Phys. B 829 (2010) 1-27 - JHEP10 (2012) 042]

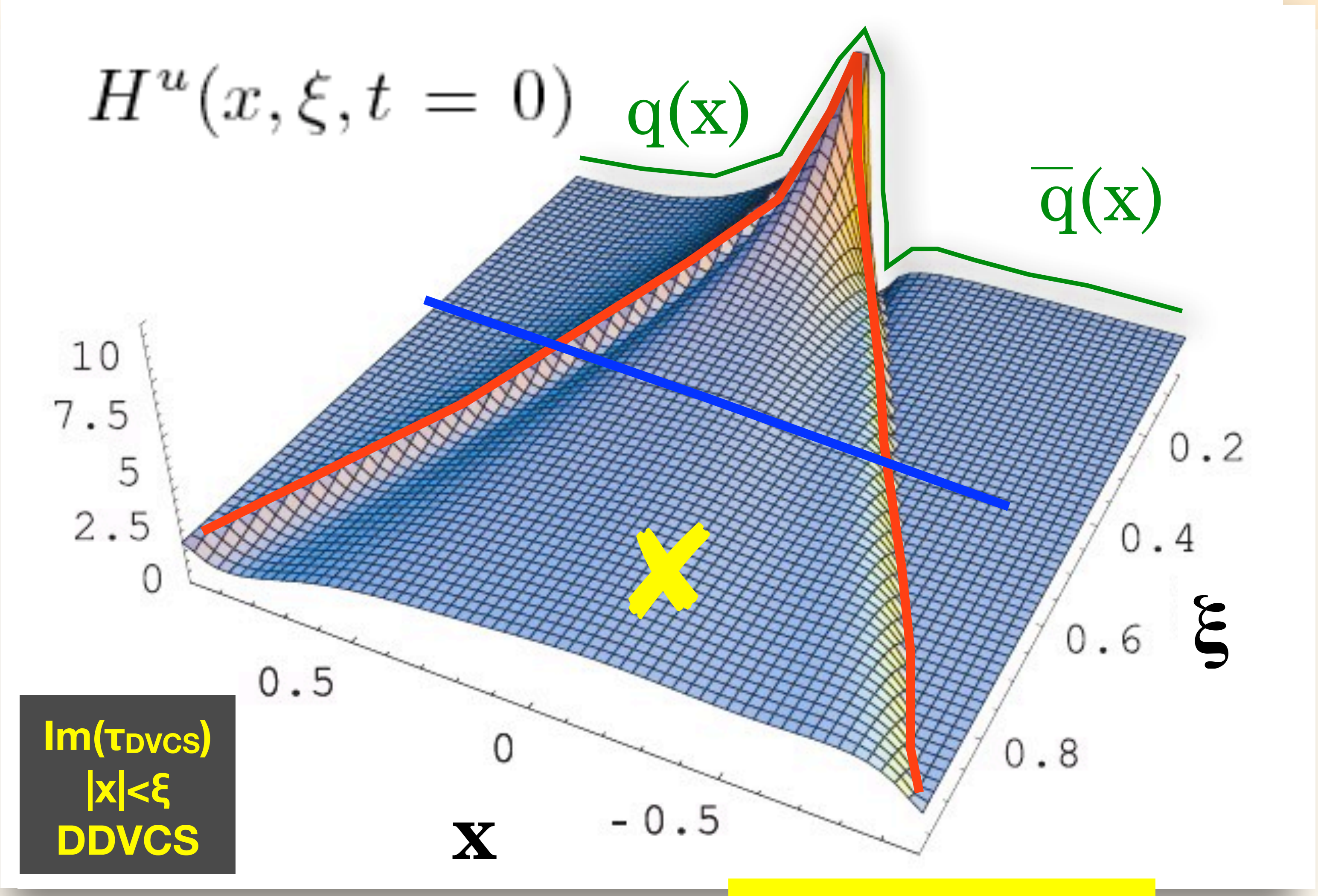
(C) [JHEP 06 (2008) 066]

(D) [Phys. Lett. B 704 (2011) 15-23]

(E) [JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

(F) [JHEP 06 (2010) 019 - Nucl. Phys. B 842 (2011) 265-298]

Exploring Compton Form Factors



possibility at JLab Halls B&C investigated see talk by M. Boer

- **Experimental access to GPDs** via CFFs.
Access to different (parts of) CFFs via different experimental configurations:
(target polarization, beam polarization, beam charge, and their combinations.

CFF

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

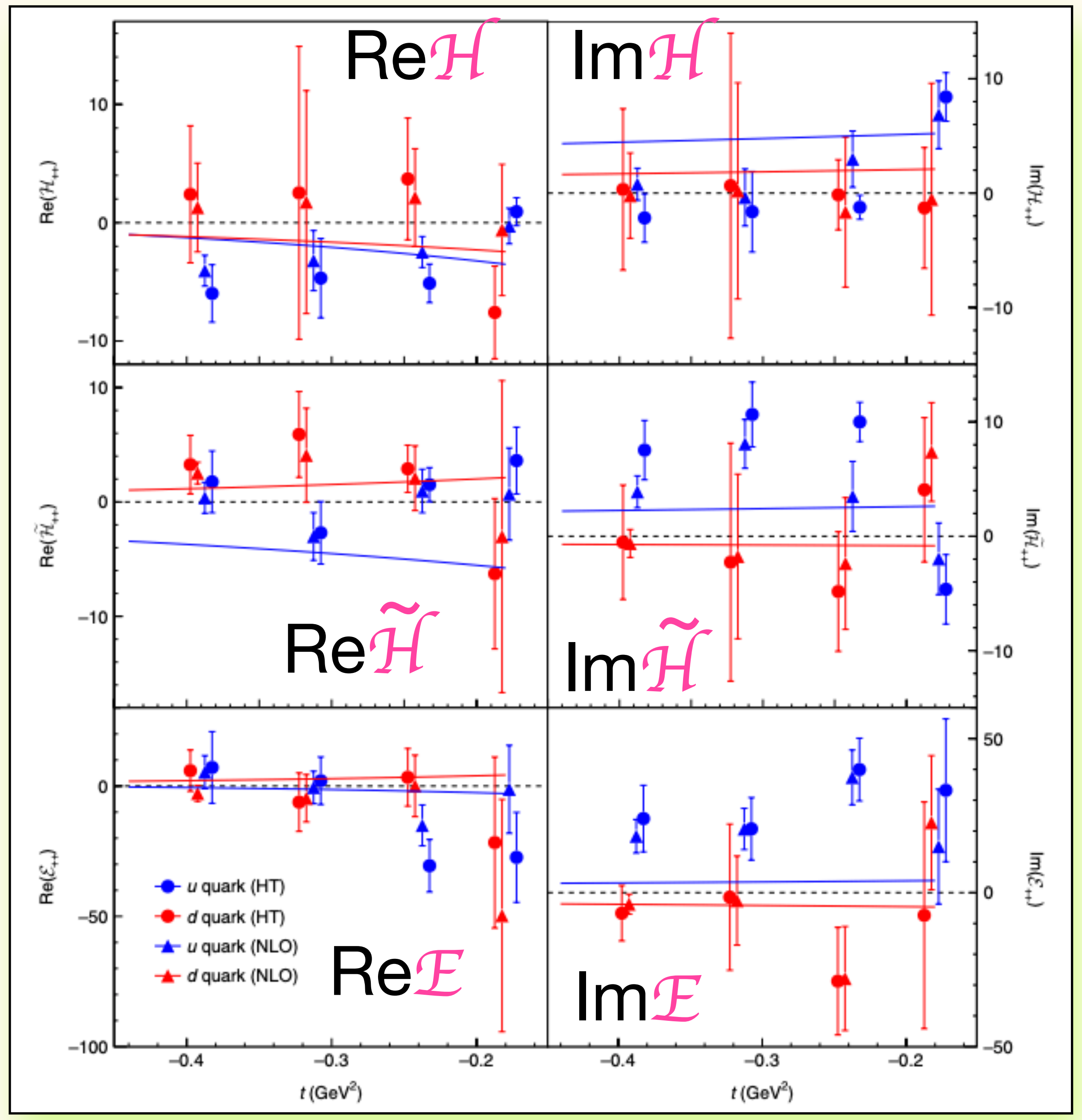
example: access via COMPASS beam-spin&-charge asymmetries	$d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$	$d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$
	Re(τDVCS) integral over x	**Im(τDVCS) x=ξ**

COMPASS **DVCS asymmetries**
(results to come)

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

Hall A **neutron DVCS**

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



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

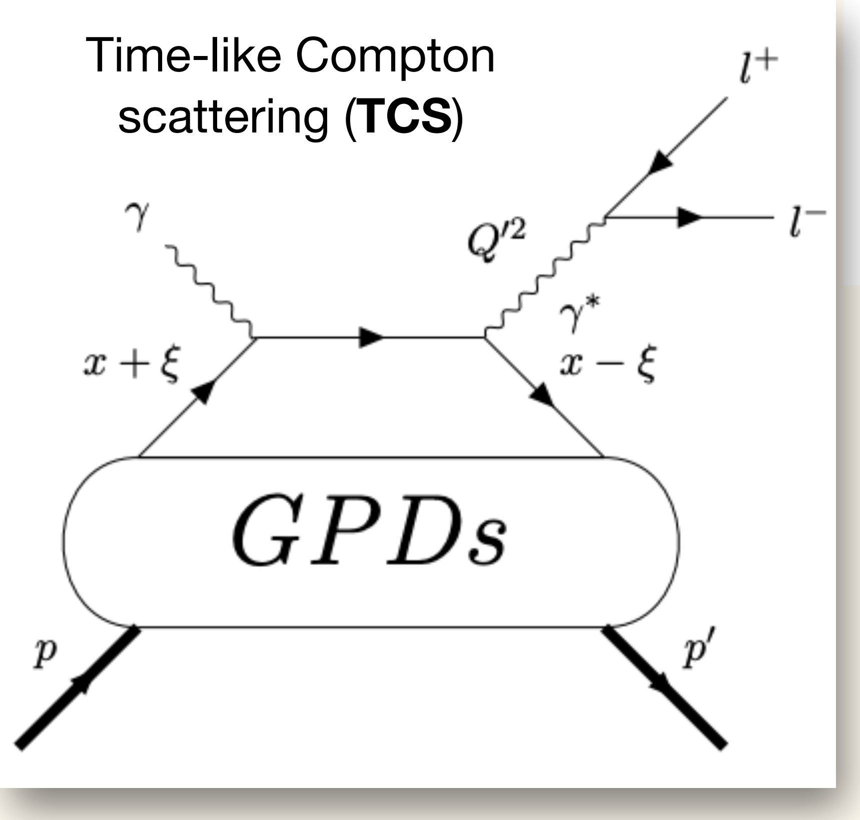
- **Dispersion relation with D-term** *D(t)*: related to shear forces and radial distribution of pressure inside the nucleon

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

access at CLAS12 e.g. via **TCS** = time-reversal symmetric process of DVCS. First results from fall 2018 data expected very soon.

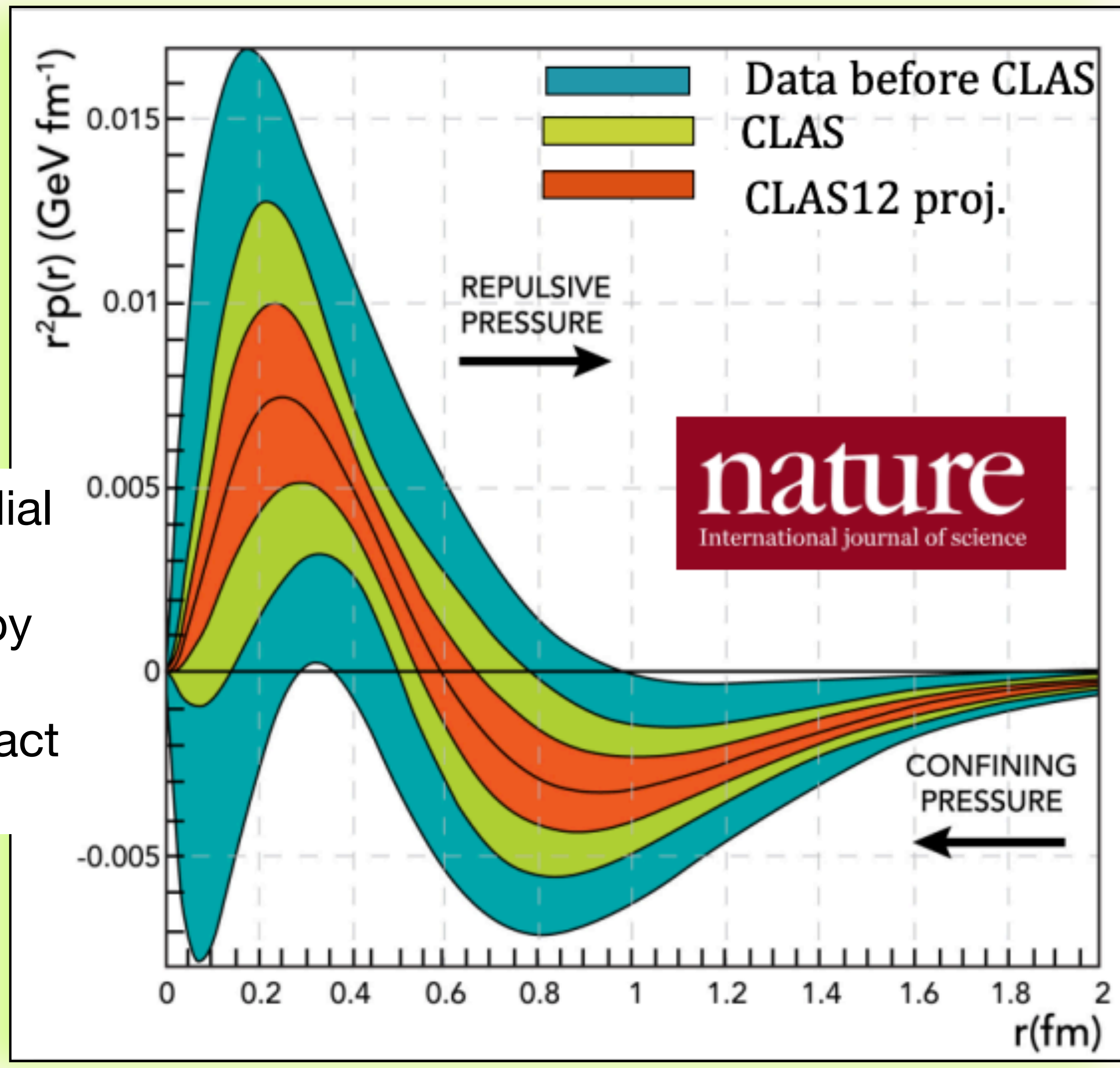
CLAS12 **TCS**

CLAS12 **proton DVCS**
analysis in progress, GPD *H*



[P. Chatagnon / CLAS 2020 J. Phys.: Conf. Ser. 1643 012185]

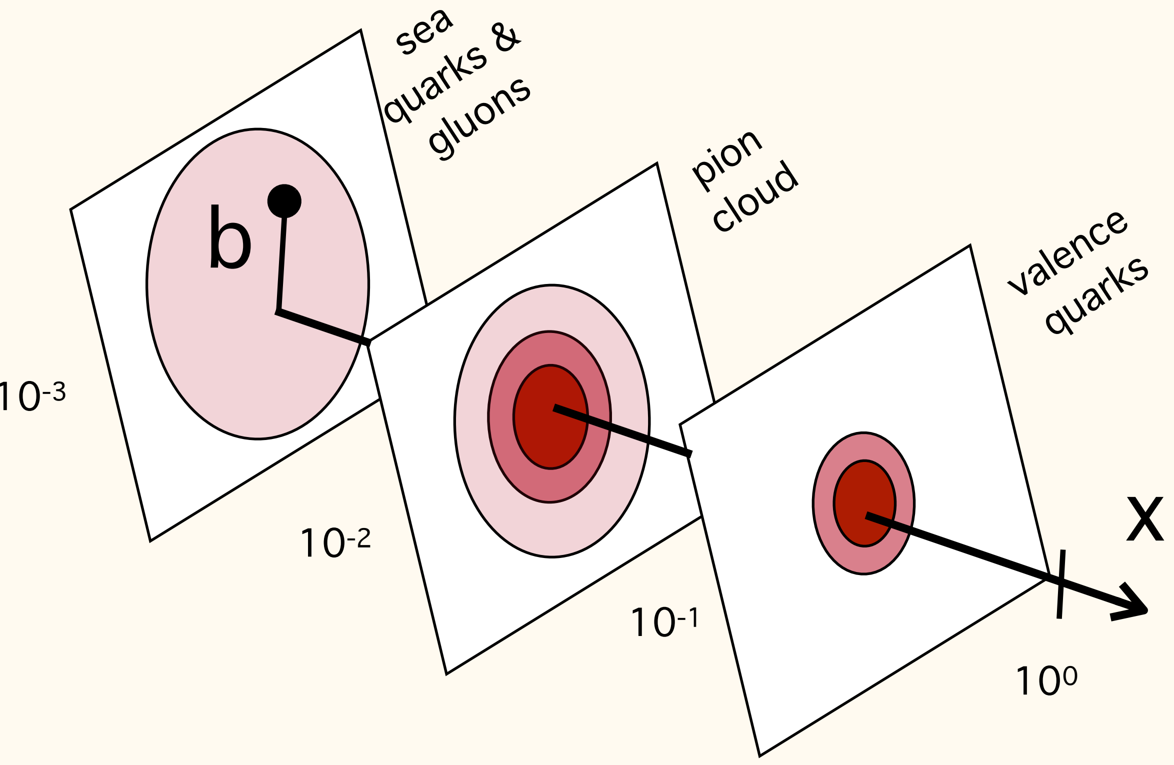
Impact on radial pressure distribution by CLAS and expected impact by CLAS12



[V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396–399 (2018)]

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

Transverse imaging of the nucleon



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

b = “t-slope” = average impact parameter

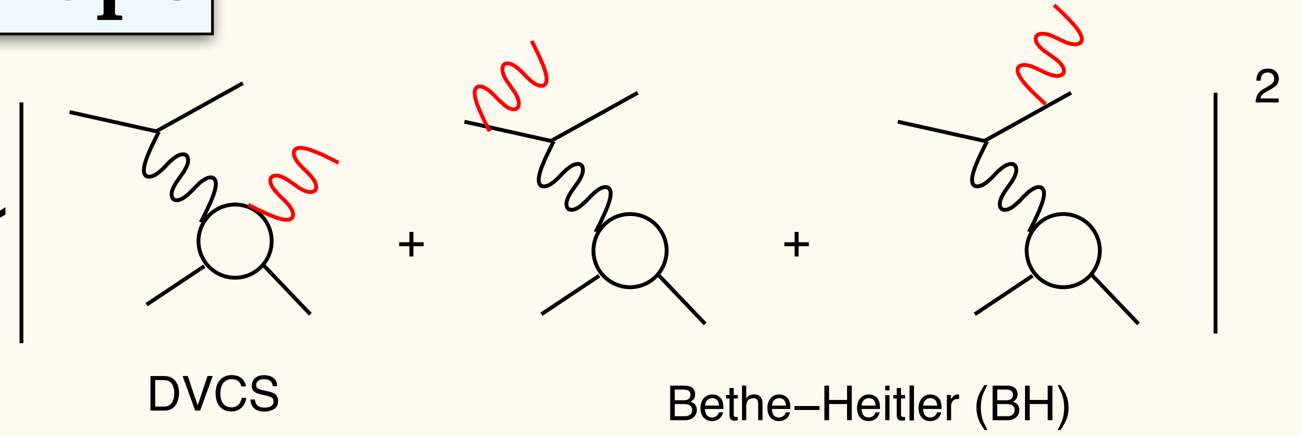
Impact-parameter representation:

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

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

COMPASS **DVCS *t*-slope**

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



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

BH reference yield

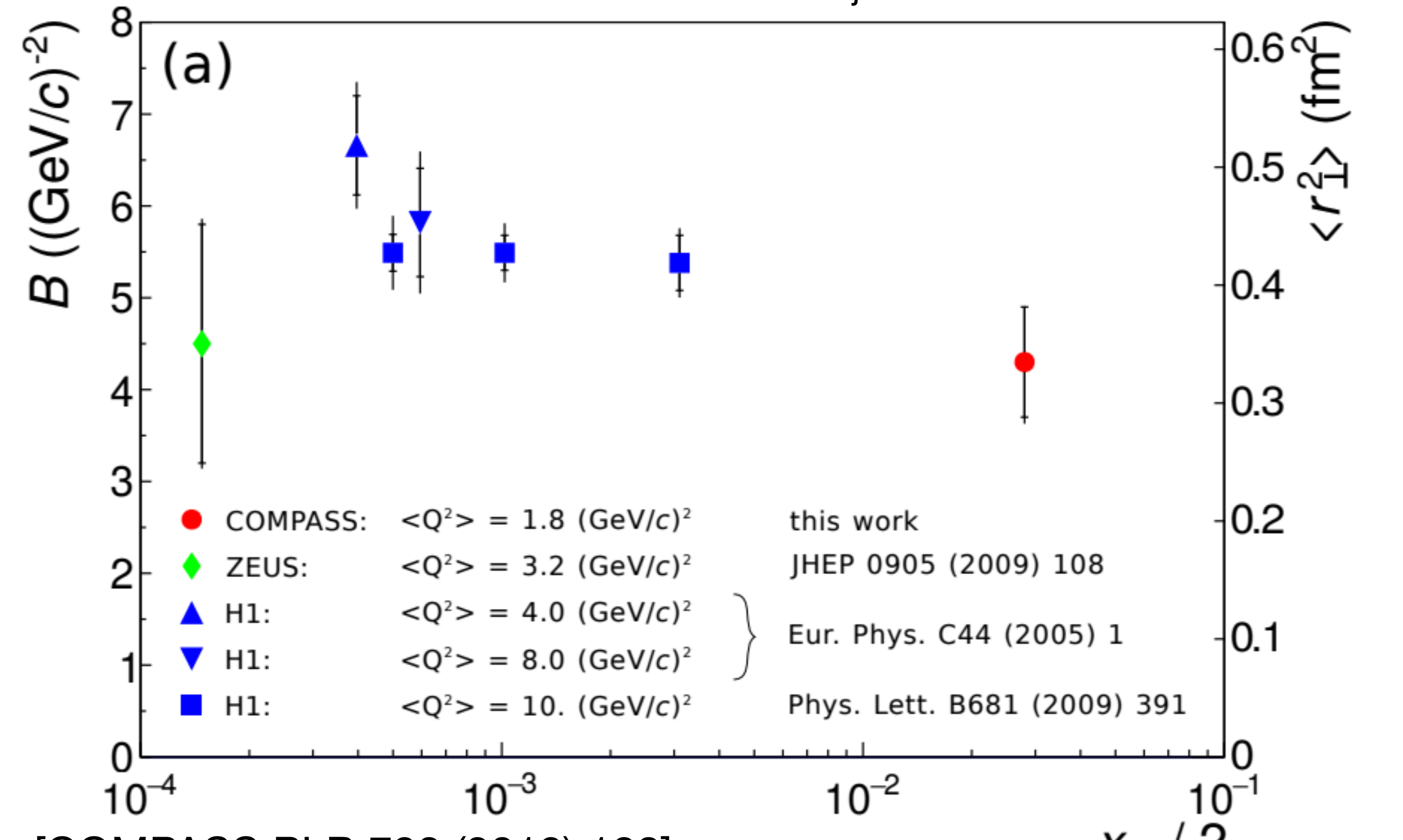
DVCS amplitude: ϕ-modulations in cross section

Transverse imaging: ϕ-integrated cross section

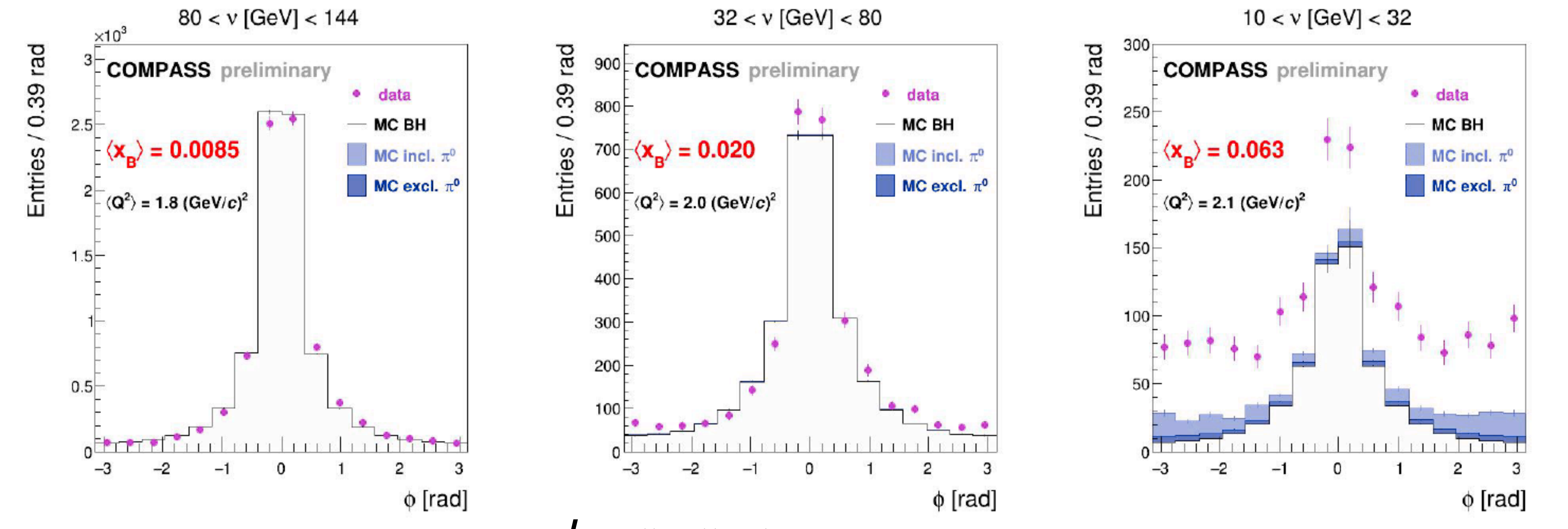
- ✦ Determination of transverse extension of partons
  - in the Bjorken-x domain of COMPASS between valence quarks and gluon
  - 2012 DVCS data on LH_2 target (10% of 2016/17) with recoil-proton detector CAMERA

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

at $\langle Q^2 \rangle$=1.8GeV^2 & $\langle x_{Bj} \rangle$=0.056

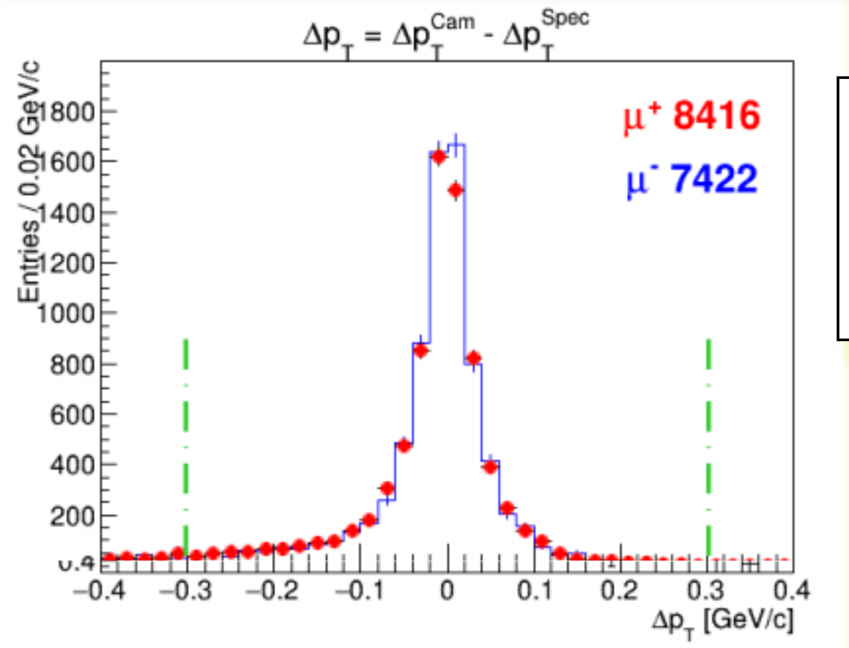


[COMPASS PLB 793 (2019) 188]



$\phi_{\gamma\gamma}$ distributions

BH + measured & simulated π^0 subtracted



exclusivity ensured by recoil-proton detector

new: 2016/17 DVCS data (~25% of available data, 2 times more than 2012 data) on LH_2 target with recoil-proton detector CAMERA

New at DIS21 (B. Ventura)

GPD E linked to orbital angular momentum

GPD E

Ji sum rule for the nucleon: [Ji, PRL 78 (1997) 610]

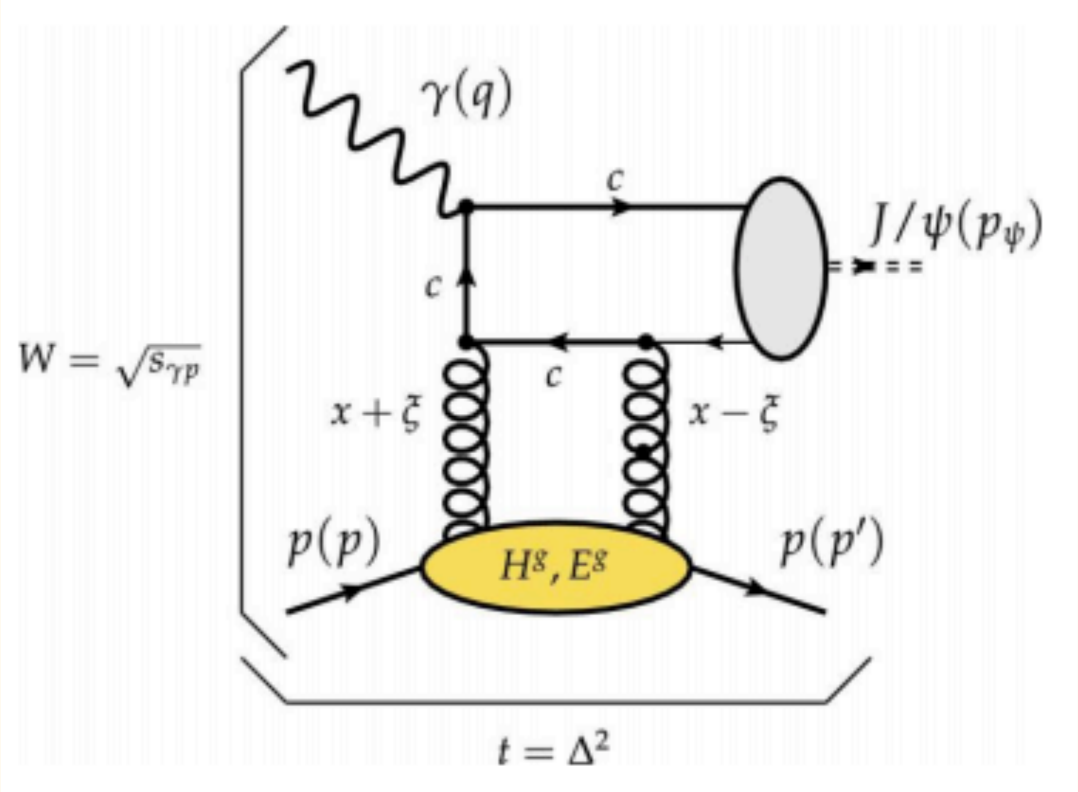
$$J_{\mathrm{q}} = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \left[H^{\mathrm{q}}(x, \xi, t) + E^{\mathrm{q}}(x, \xi, t) \right]$$

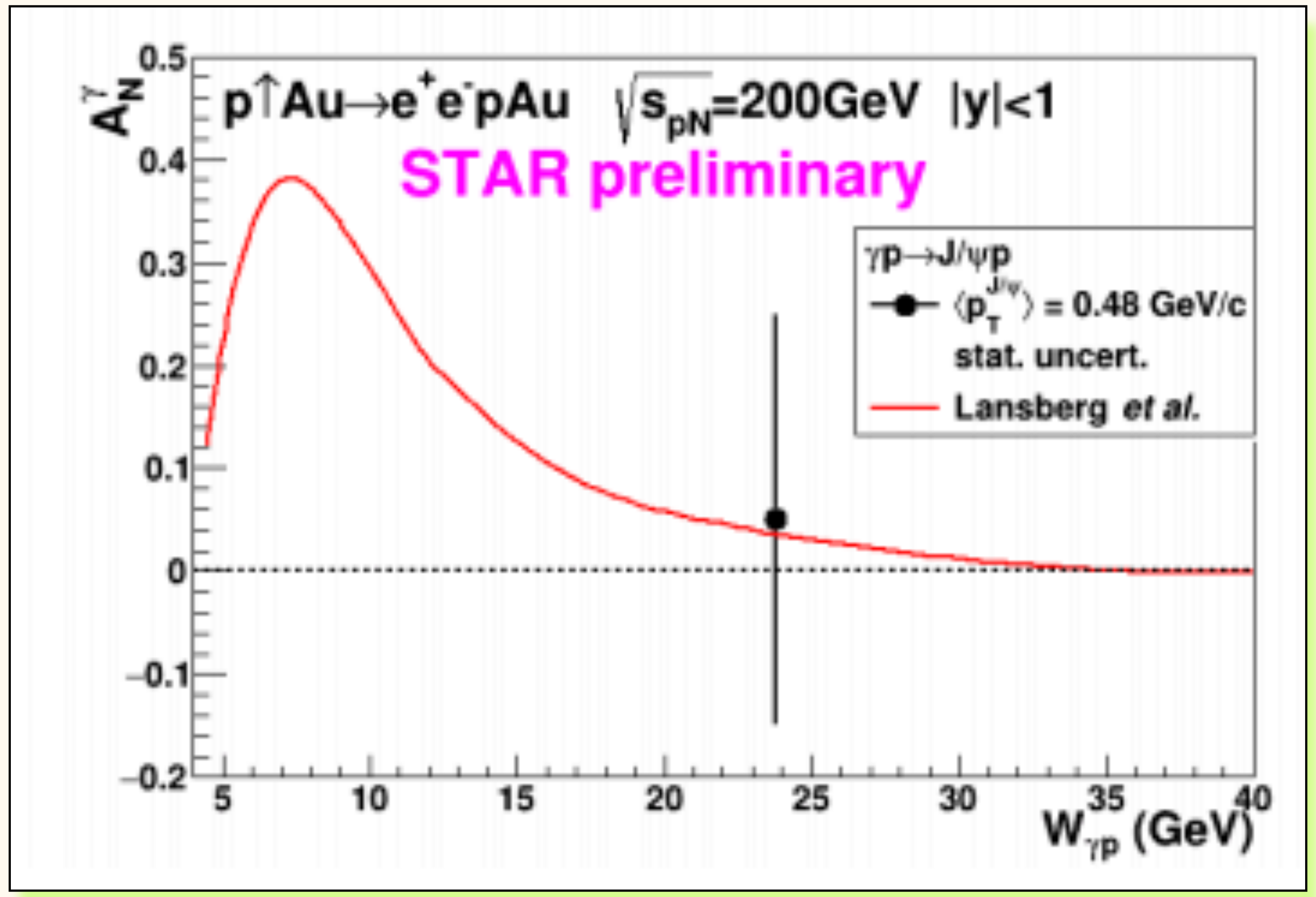
CLAS12 DVCS **beam-spin asymmetries** on the deuteron (neutron)

CLAS12 DVCS **target-spin asymmetries** on the transversely polarized proton

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

- ✦ CLAS12: DVCS on the neutron (LD_2 target with neutron detector), analysis in progress
- ✦ CLAS12: on the transversely polarized proton, data to be taken
- ✦ All so-far discussed GPDs were **quark** GPDs
- ✦ STAR: exclusive J/Psi production in ultra-peripheral collisions (UPC) → **gluon** GPD *E*
  Significant improvement of precision expected with the upgrades (iTPC & forward), more data will be taken





- ✦ RHIC with UPC and COMPASS with high-energy muon beams at CERN will provide first results of sea quarks and gluons at small x_B.

Exclusive π^0 & $\pi^\pm$ production

GPDs H_T & E_T

COMPASS **excl. π^0 cross section**

e p → e π^0 p

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\epsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}\right)+\epsilon\cos 2\phi_\pi\frac{d\sigma_{TT}}{dt}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi\frac{d\sigma_{LT}}{dt}\right]$$

$$\left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2 \qquad \left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2 \qquad \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2 \qquad \frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

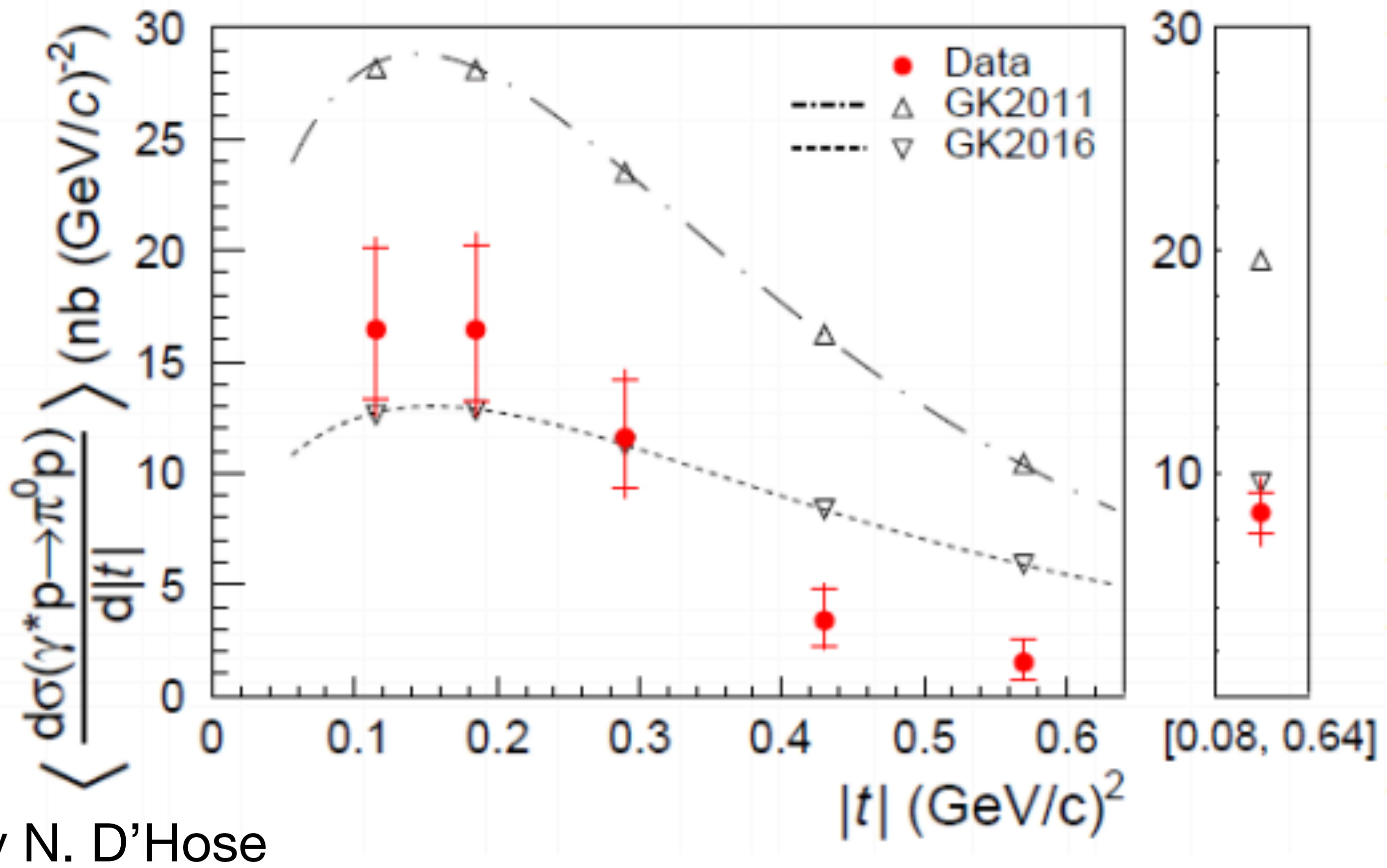
$$\left\langle\frac{d\sigma_T}{d|t|}+\epsilon\frac{d\sigma_L}{d|t|}\right\rangle = (8.2 \pm 0.9_{\text{stat}}\,{}^{+\,1.2}_{-\,1.2}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

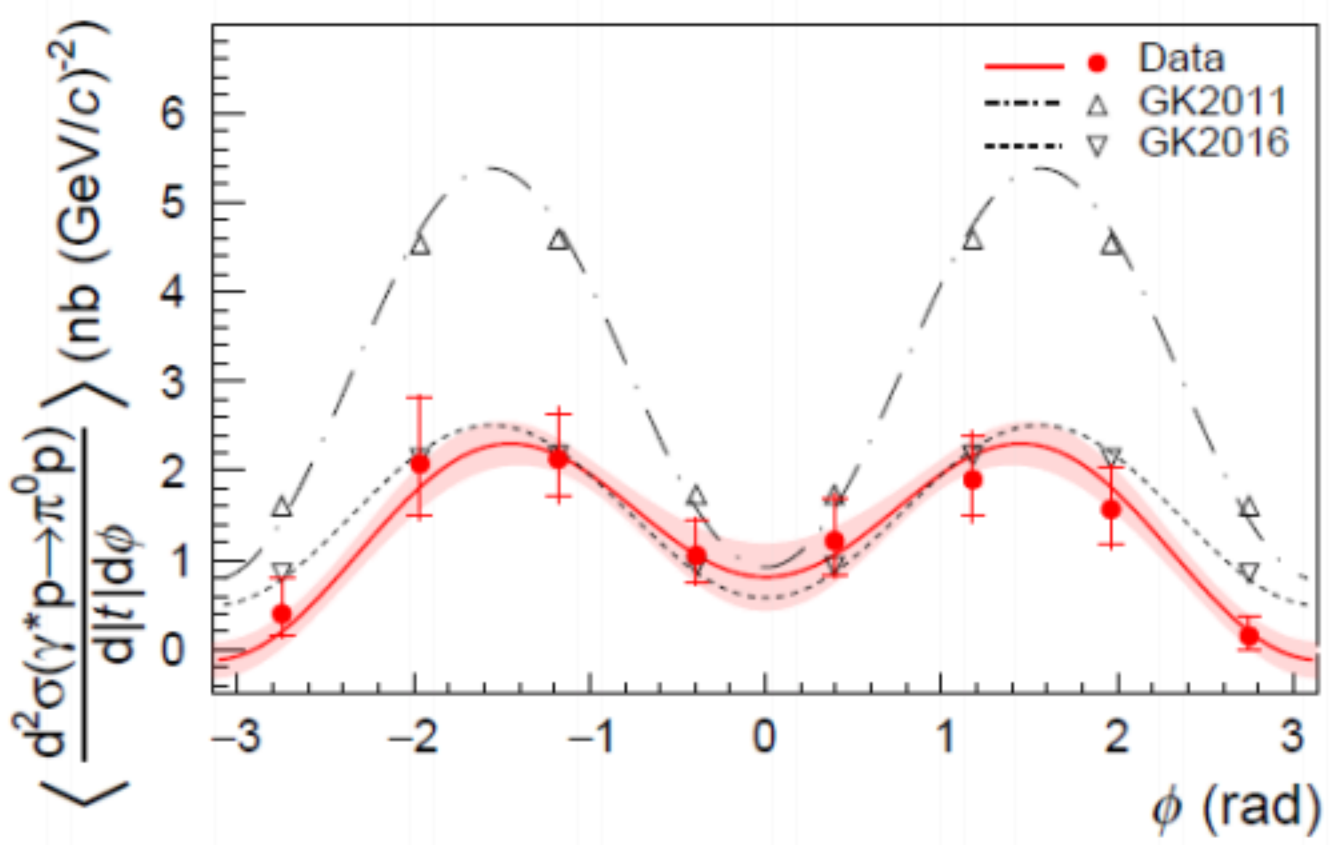
$$\left\langle\frac{d\sigma_{TT}}{d|t|}\right\rangle = (-6.1 \pm 1.3_{\text{stat}}\,{}^{+\,0.7}_{-\,0.7}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

σ_{TT} large (impact of $\bar{E}_T$)

$$\left\langle\frac{d\sigma_{LT}}{d|t|}\right\rangle = (1.5 \pm 0.5_{\text{stat}}\,{}^{+\,0.3}_{-\,0.2}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

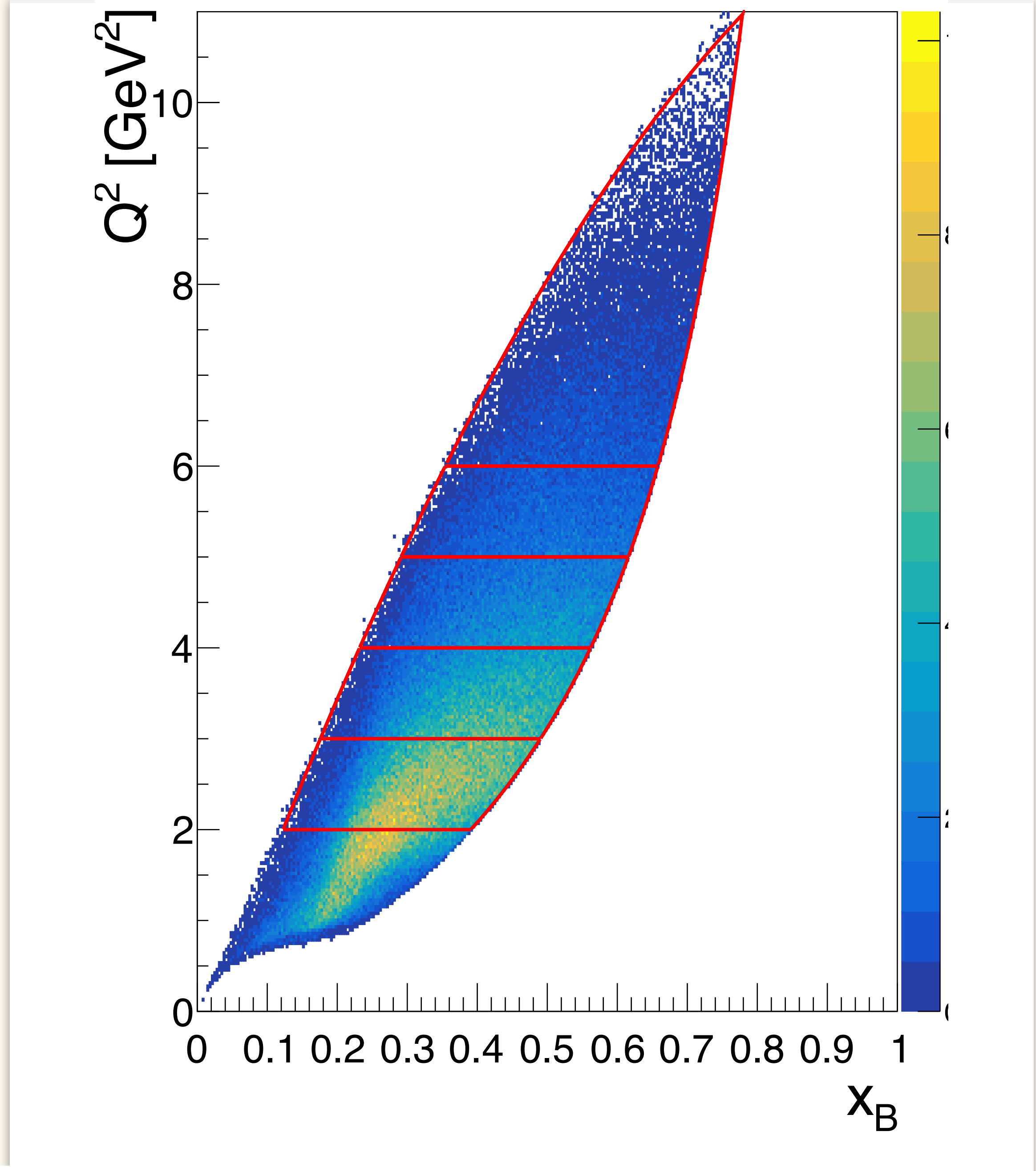
σ_{LT} smaller but significantly positive as at CLAS





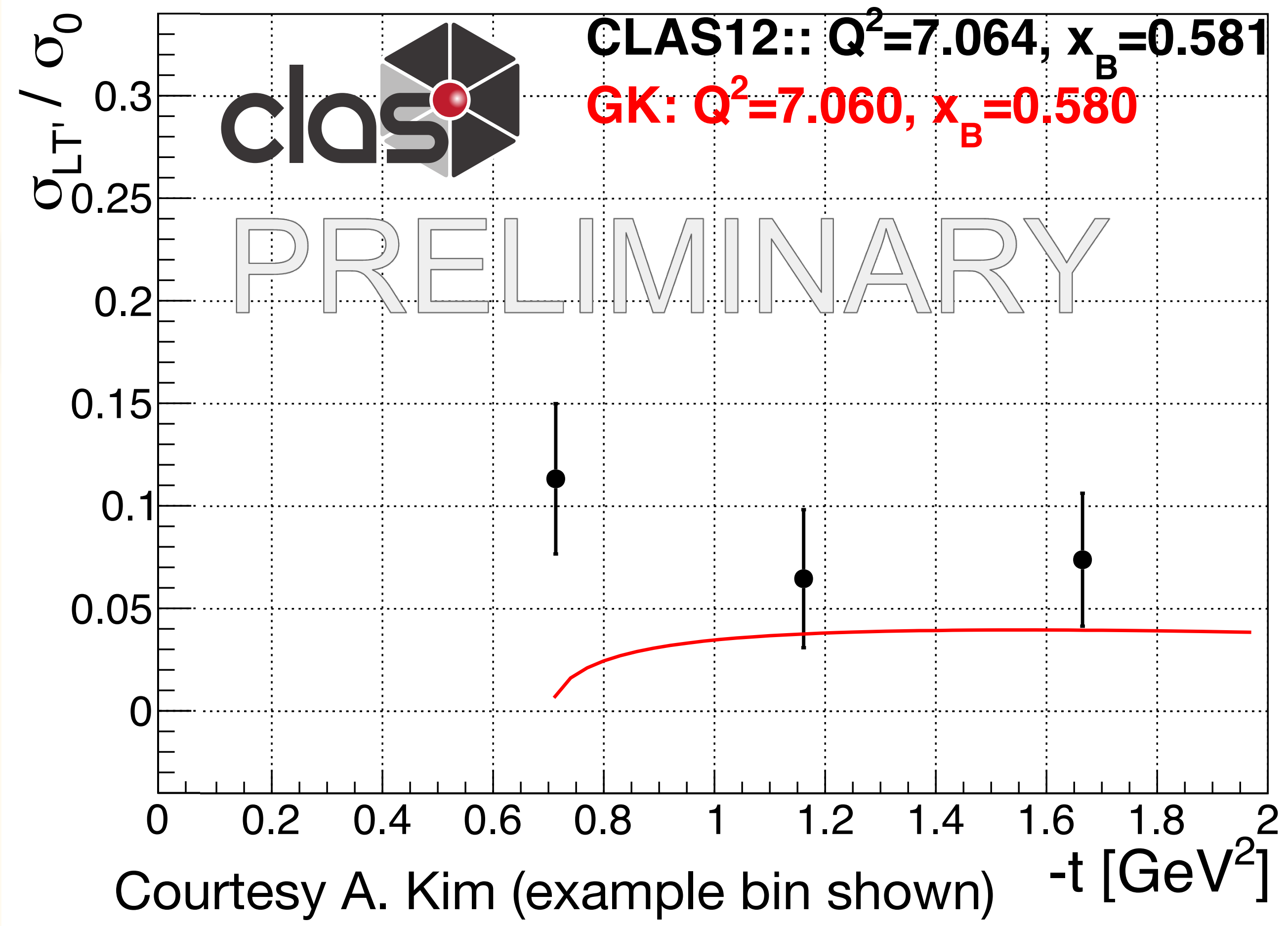
courtesy N. D'Hose

[COMPASS PLB 805 (2020)]



CLAS12 **excl. π^0 beam-spin asymmetry**

Analysis in progress, to be released very soon.



Courtesy A. Kim (example bin shown)

CLAS12 **excl. π^+ beam-spin asymmetry** to improve the extraction on H_T

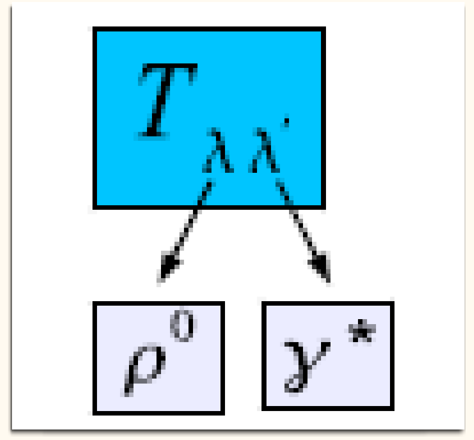
Analysis in progress

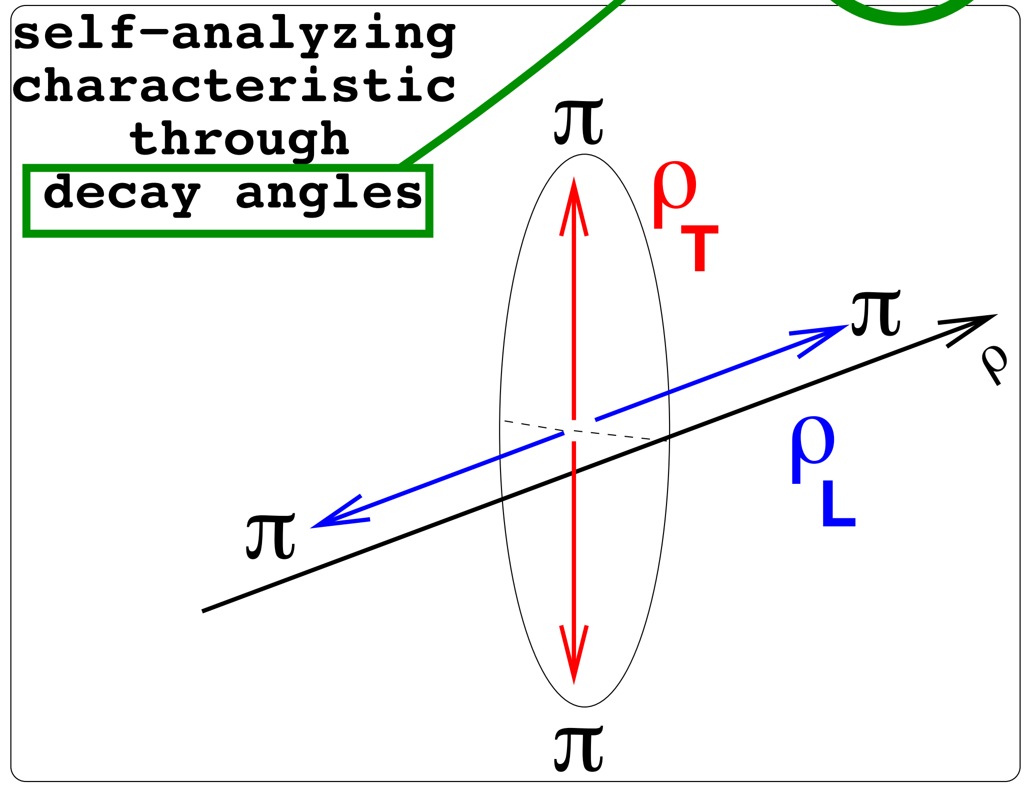
Spin density matrix elements in $\ell p \rightarrow \ell p VM$

GPDs H_T & E_T

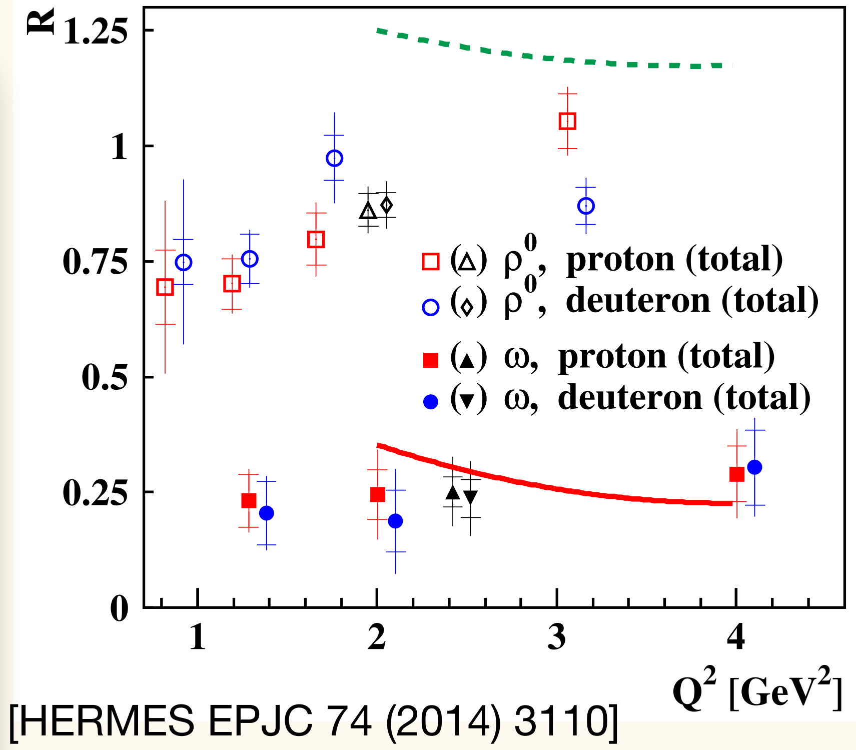
$$\frac{d\sigma}{dx_B\, dQ^2\, dt}\, W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)$$

W(…) parametrized by Spin Density Matrix Elements (SDMEs)





Spin density matrix elements describe how the spin components of the virtual photon are transferred to the created vector meson



[HERMES EPJC 74 (2014) 3110]
[Goloskokov, Kroll EPJ A (50 2014) 146]

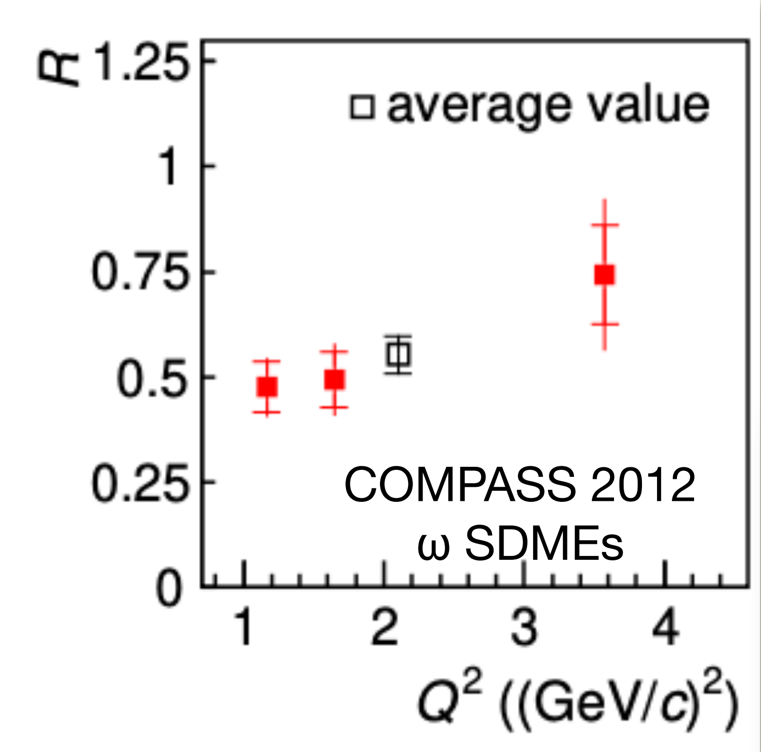
- Test of hierarchy of helicity amplitudes
- Test of hypothesis of s-channel helicity conservation (SCHC)
- Evaluation of unnatural-parity-exchange transitions
- Determination of phase differences between helicity amplitudes & longitudinal-to-transverse cross-section ratio.
- Constraints on GPD parameterizations beyond cross section and spin-asymmetry measurements.

New COMPASS **ω and ρ SDMEs** (unpol. proton target)

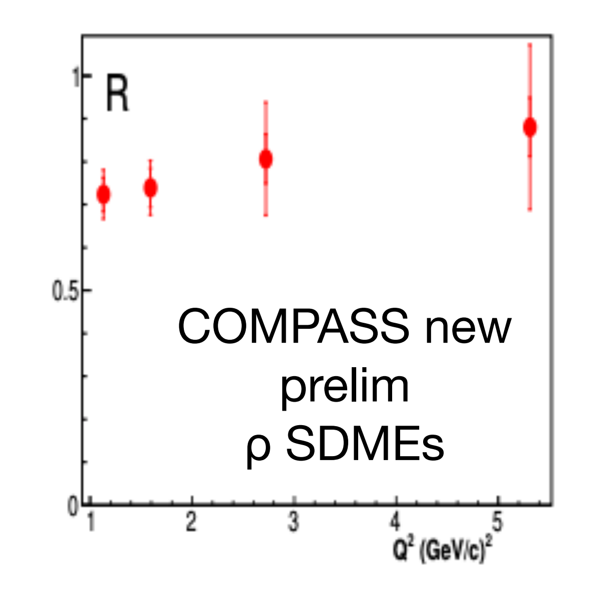
if SCHC ($\lambda_{\gamma^*}=\lambda_{VM}$)		measured
$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\}$	$= 0$	$-0.010 \pm 0.032 \pm 0.047$
$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\}$	$= 0$ ✓	$0.014 \pm 0.011 \pm 0.013$
$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\}$	$= 0$	$-0.088 \pm 0.110 \pm 0.196$

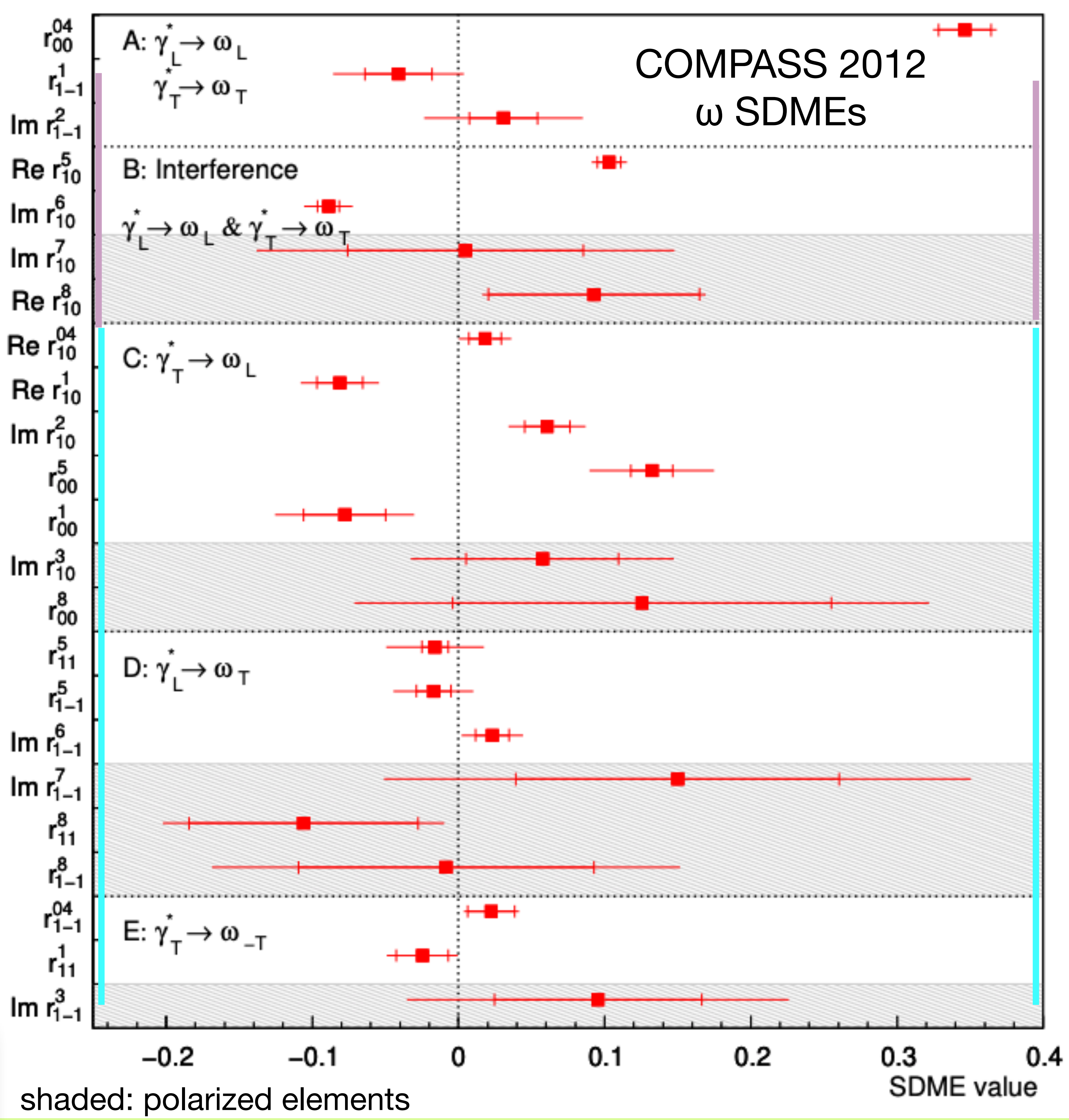
✦ Considerable ~~SCHC~~ in $\gamma^*_T \rightarrow \omega_L$ (class C), with interesting kinematic dep. Transitions sensitive to chiral-odd GPDs H_T and E_T

✦ Cross-section ratio *R* of longitudinal to transverse vector mesons comparison to HERMES



see W. Augustyniak, DIS21

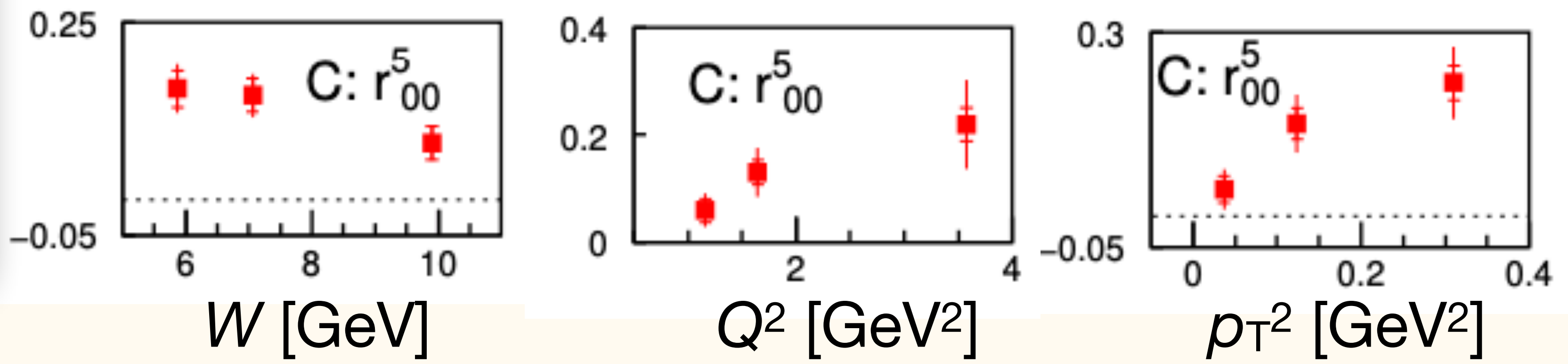




shaded: polarized elements

$\langle Q^2 \rangle = 2.1$ (GeV/c)^2 , $\langle W \rangle = 7.6$ GeV/c^2, $\langle p_T^2 \rangle = 0.16$ (GeV/c)^2

[COMPASS EPJC (2021) 81 126]

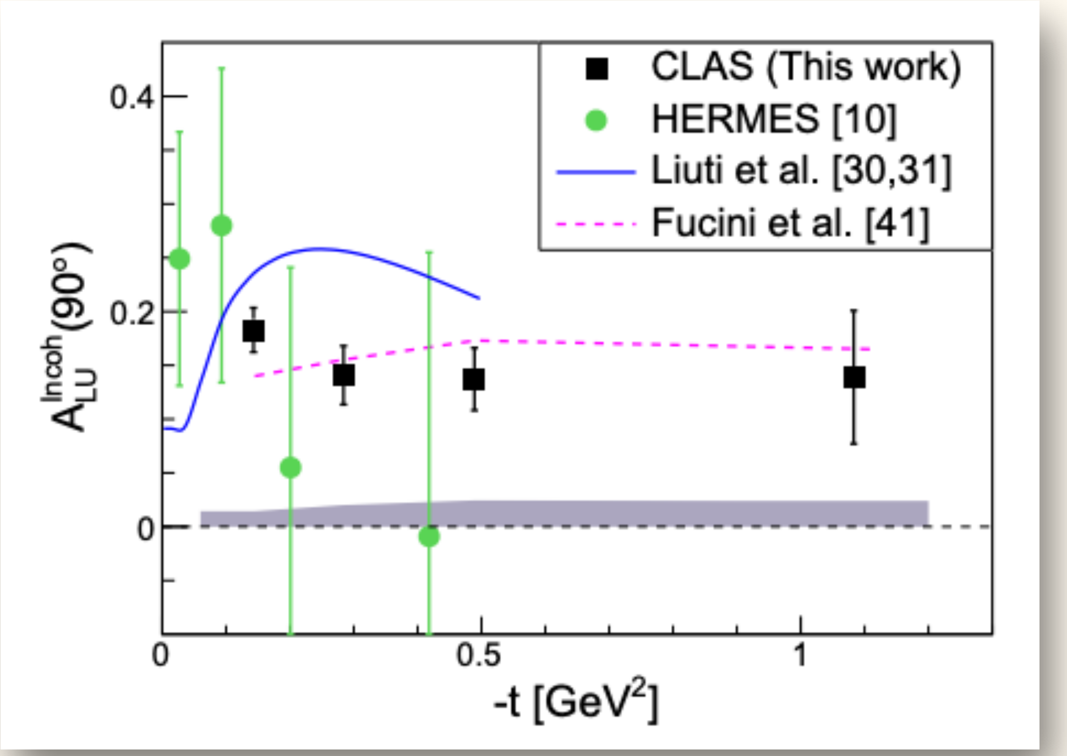


More exclusive measurements

New CLAS **coherent DVCS**

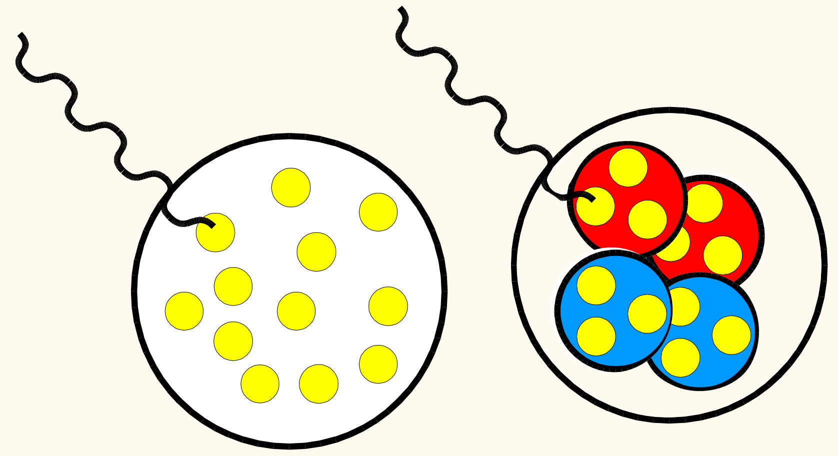
- ✦ For the first time, DVCS beam-spin asymmetry in the coherent channel measured to be larger than the in incoherent proton channel, thanks to measuring the helium recoils using a radial TPC.
Recoil in nuclear DVCS at HERMES was not detected

see talk by R. Dupré, Wednesday 13:30

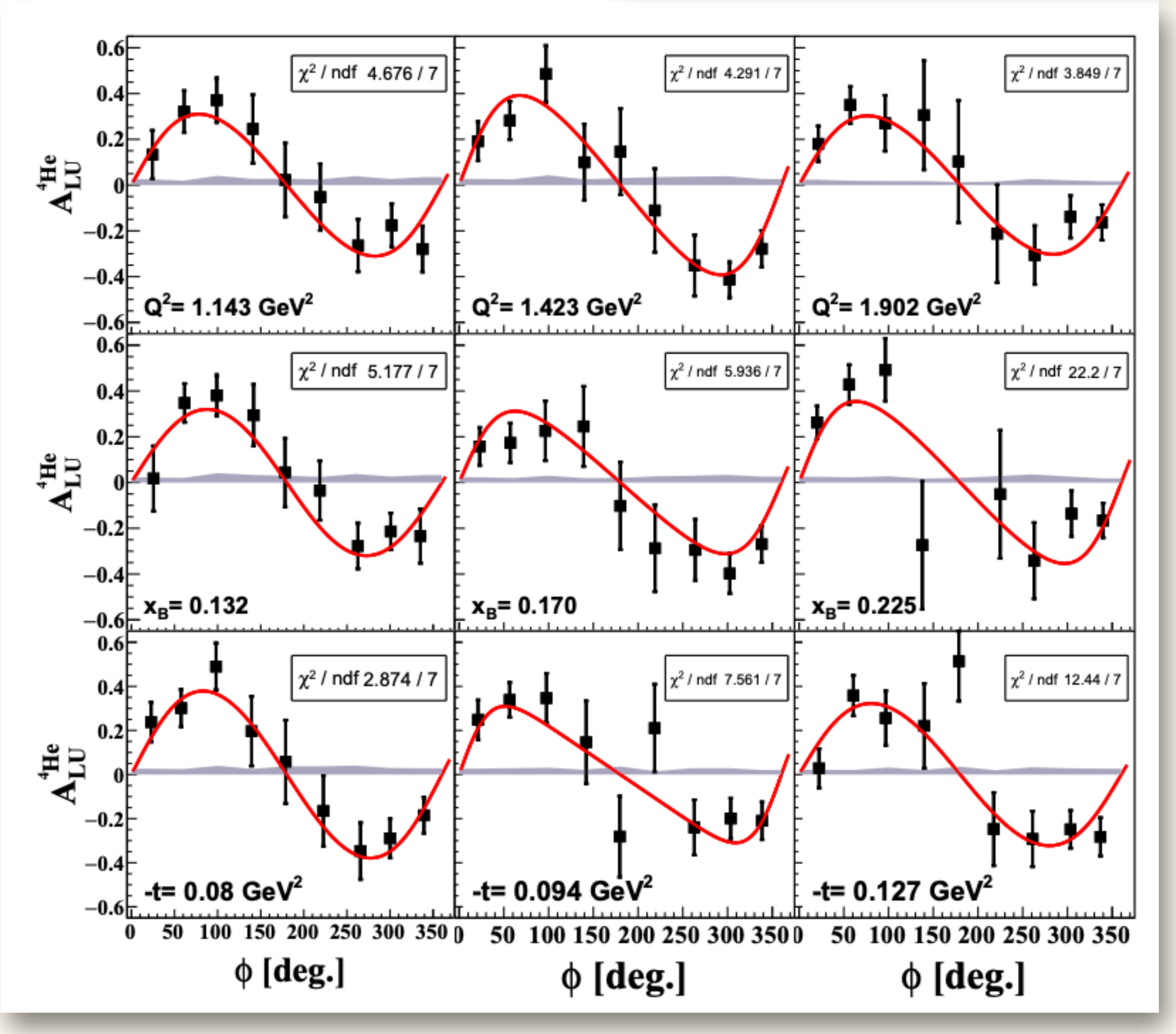


[CLAS / R. Dupre arxiv:2102.07419]

DVCS on ^{4}He

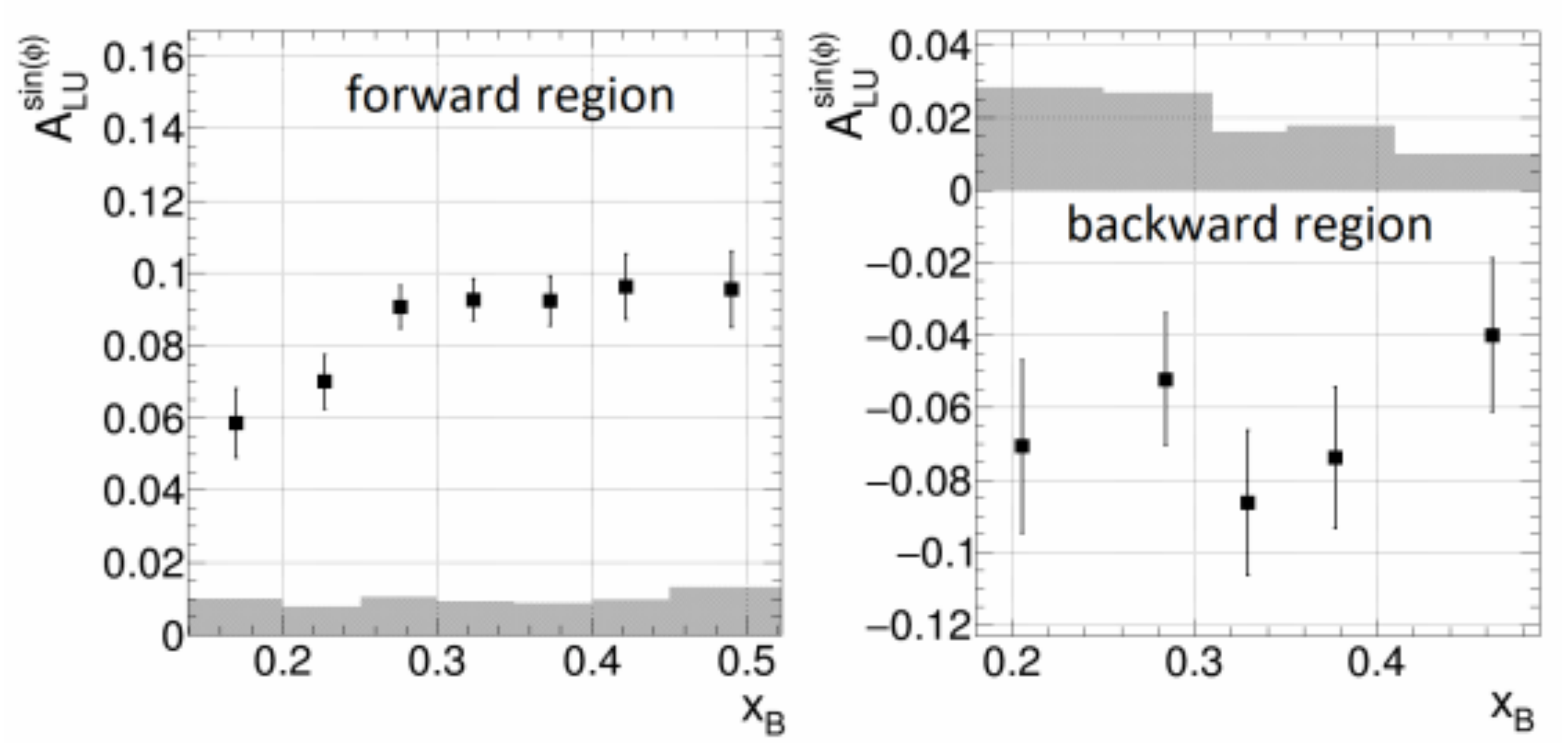


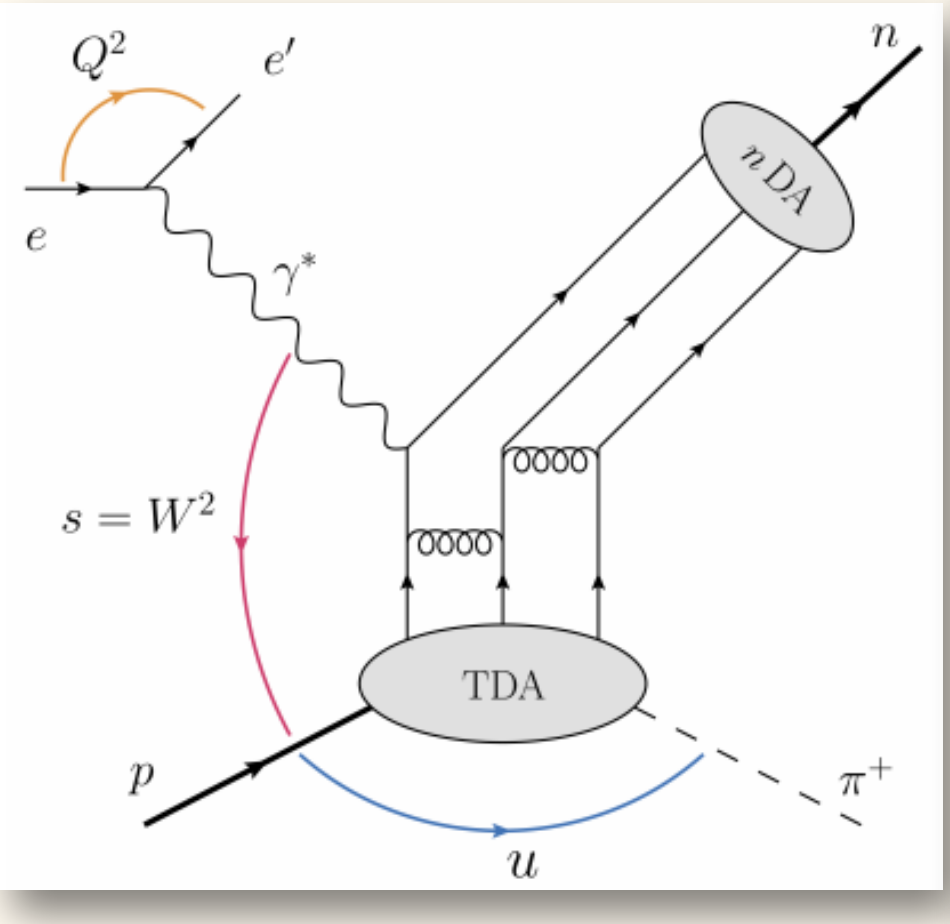
coherent **incoherent**



Coherent DVCS allows to study if the DVCS amplitude rises with *A* and if there is a 'generalized EMC effect'

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





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

[CLAS / S. Diehl PRL125, 182001]

- ✦ More measurements planned at CLAS12!

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.*

  see talk by D. Dutta, Wednesday 11:00

- **STAR** cold QCD with forward upgrade at RHIC:
  - 2022/24, $p^\uparrow p^\uparrow$ & $p^\uparrow A$, $\sqrt{s_{NN}}$=200 & 500 GeV
  - 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*
  - and more, https://drupal.star.bnl.gov/STAR/files/ForwardUpgrade.v20.pdf

- **sPHENIX** cold QCD program at RHIC:
  - 2024, $p^\uparrow p^\uparrow$ & $p^\uparrow A$, $\sqrt{s_{NN}}$=200 GeV, $\eta=\pm1.1$
  - Design optimized for heavy-flavor measurements with jets and displaced vertices with MAPS-based vertex tracker
  - Gluon Sivers TMD via A_N in single-photon & heavy flavor
  - Di-hadron IFF / Collins asymmetry & transversity TMD via hadron-charge tagging & hadron-in-jet
  - and more, sPHENIX-note sPH-cQCD-2017-002

  see talk by J. Frantz, Wednesday 15:50

- **SpinQuest / E1039** at FNAL (2021++):
  - Transversely polarized NH_3/ND_3 target with E906 spectrometer
  - First polarized DY experiment with proton beam
  - Sivers & transversity TMDs of sea quarks.

  see talk by C. Ayuso, Wednesday 16:30

- **COMPASS transversity run 2021**
  - transversely polarized ^{6}LiD target for d-quark transversity *et al.*

- **AMBER / NA66** at the CERN M2 beamline:
  - Beam time approved for phase 1 after 2021 after the end of COMPASS, no time window yet.
  - Pion structure in phase I with pion beams
  - Kaon structure in phase II with kaon beams
  - TMDs with π, K, anti-proton beams
  - and more (e.g., proton radius in elastic μp scattering), https://nqf-m2.web.cern.ch

- **J-PARC,** meson & anti-proton beams, https://j-parc.jp/Hadron/en/index.html

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

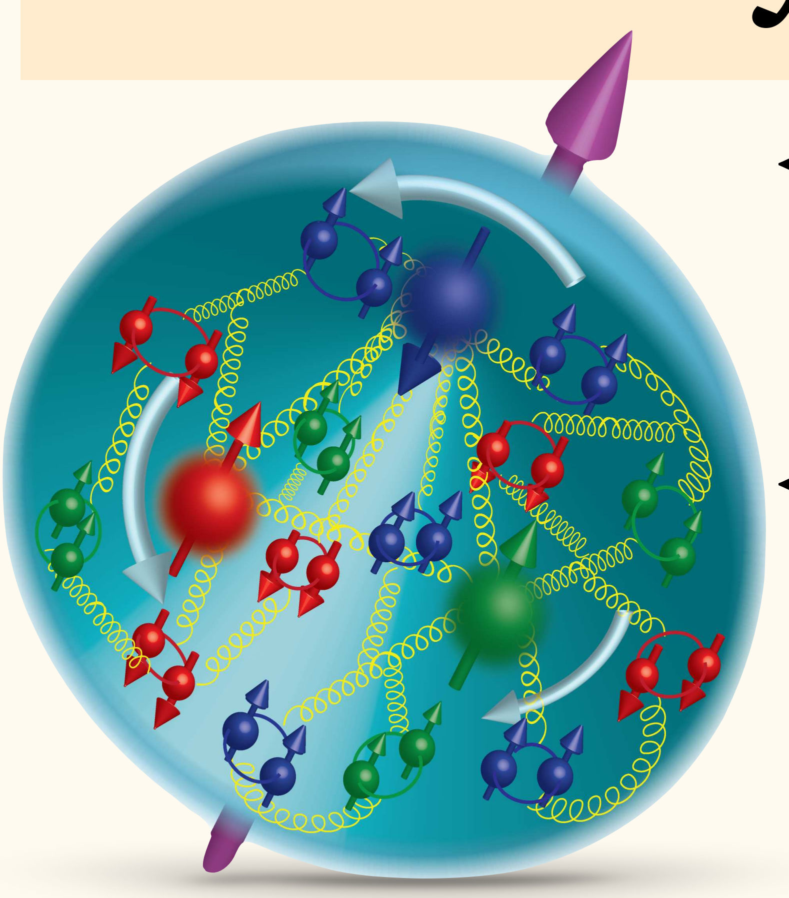
- **AFTER @LHC, CERN** fixed target, >2025, https://doi.org/10.1016/j.physrep.2021.01.002

- **SPD at NICA,** JINR: collider experiment with polarized proton and deuteron beams, >2025, http://spd.jinr.ru/

- **PANDA at FAIR**, fixed target with anti-proton beams, https://panda.gsi.de/article/panda-physics

- **EicC (China) at HIAF**, > 2025, arXiv:2102.09222

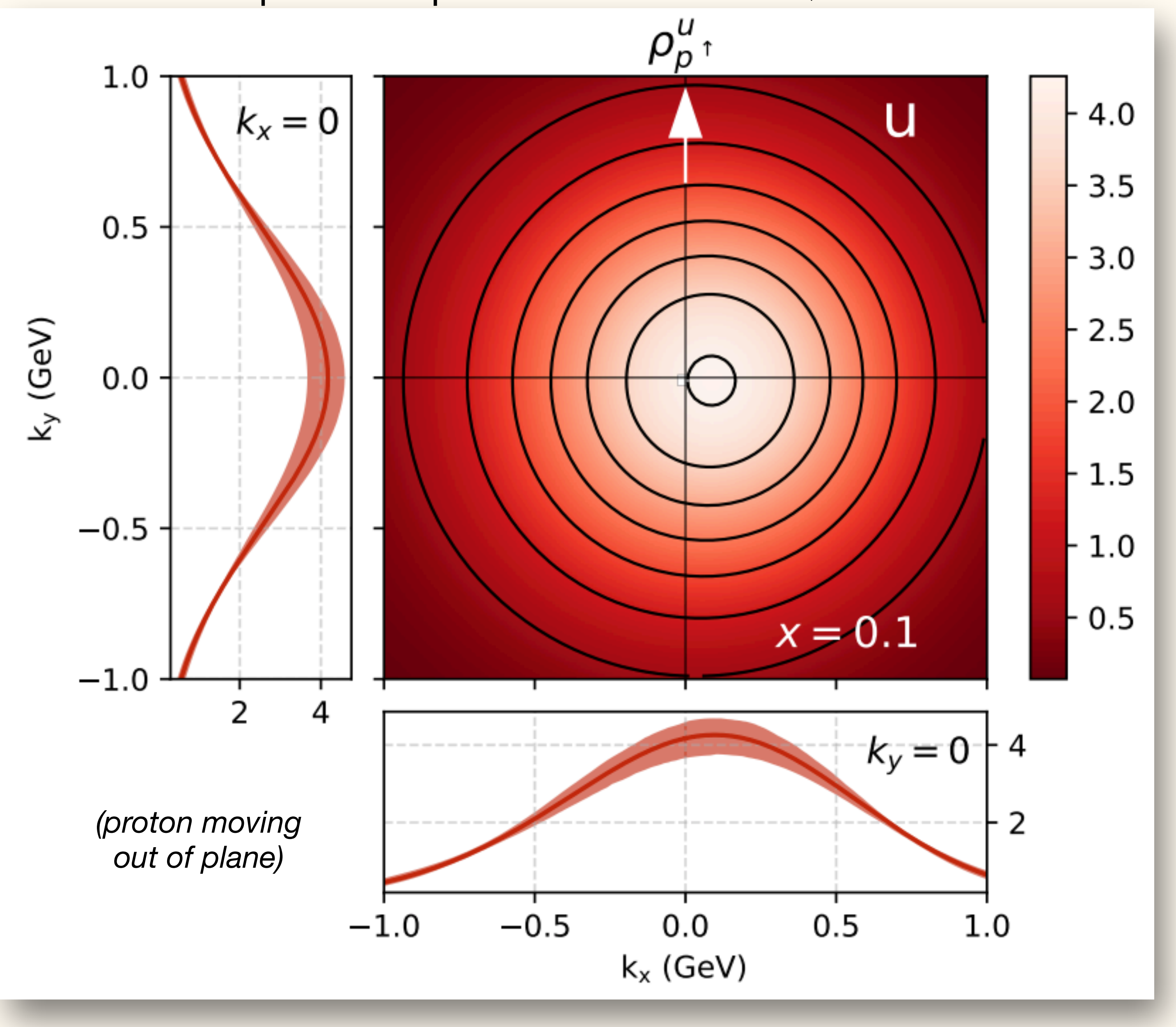
Summary and outlook



- ✦ Experiments at BNL, JLab, FNAL, CERN, DESY, RIKEN, JPARC, *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.

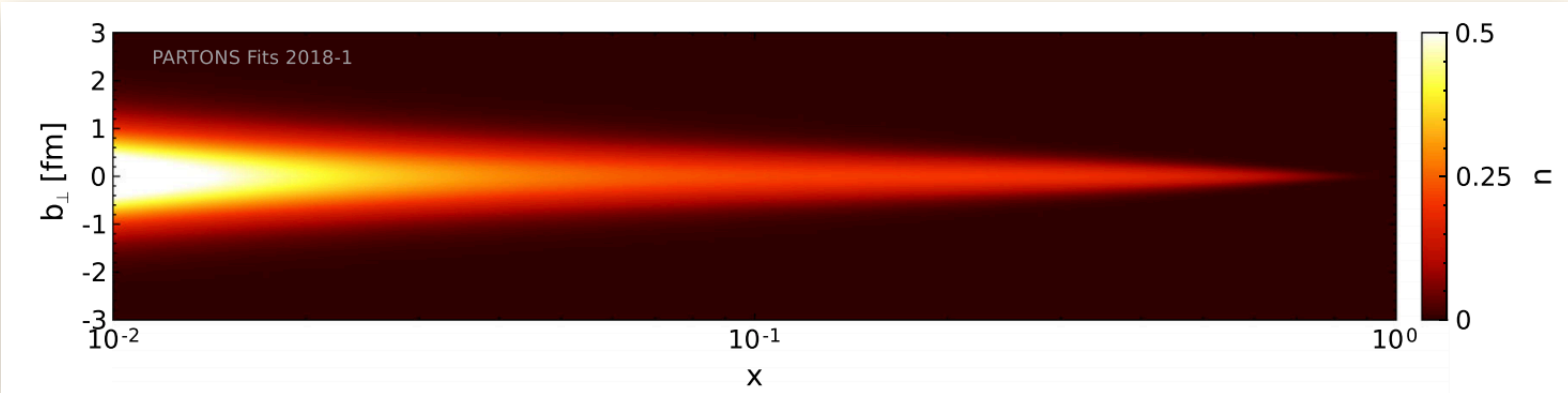
In transverse-momentum space (k_x, k_y):
density distribution of unpolarized u-quark in transversely polarized proton at x=0.1 and Q^2=4 GeV^2



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

[Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278]

In impact-parameter space ($b_\perp$,x):
position of up quarks in an unpolarized proton at t = –0.3 GeV^2 and Q^2 = 2 GeV^2



PARTONS fits 2018-1 using world data of elastic form factors and DVCS proton data from HERMES, CLAS, Hall A and COMPASS

[Moutarde, Sznajder, Wagner, EPJ C78, 890 (2018)]

- ✦ 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}.

Thank you: Vincent Andrieux, Harut Avakian, Marco Battaglieri, Alexander Bazilevsky, Pierre Chatagnon, Nicole D'Hose, Markus Diefenthaler, Pasquale Di Nezza, Oleg Eyser, Renee Fatemi, Matthias Grosse Perdekamp, Alexey Guskov, Andrey Kim, Minho Kim, Riccardo Longo, Nick Lukow, Anna Martin, Jan Matousek, Luciano Pappalardo, Bakur Parsamyan, Milap Patel, Jen-Chieh Peng, Matt Posik, Alexei Prokudin, Gunar Schnell, Ralf Seidl, April Townsend