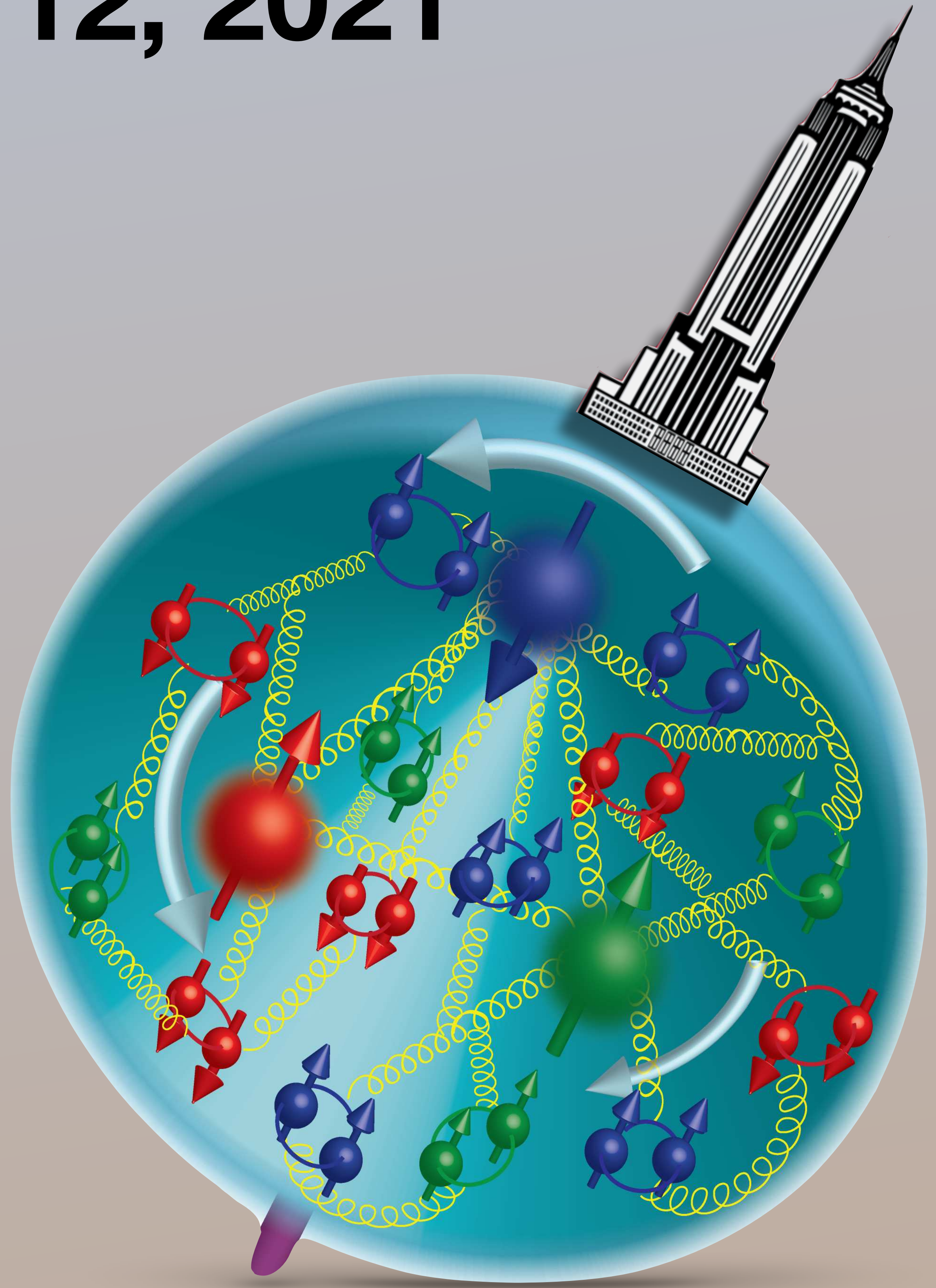
Recent Highlights from Spin-Physics Experiments

April 12, 2021



Caroline Riedl (UIUC)

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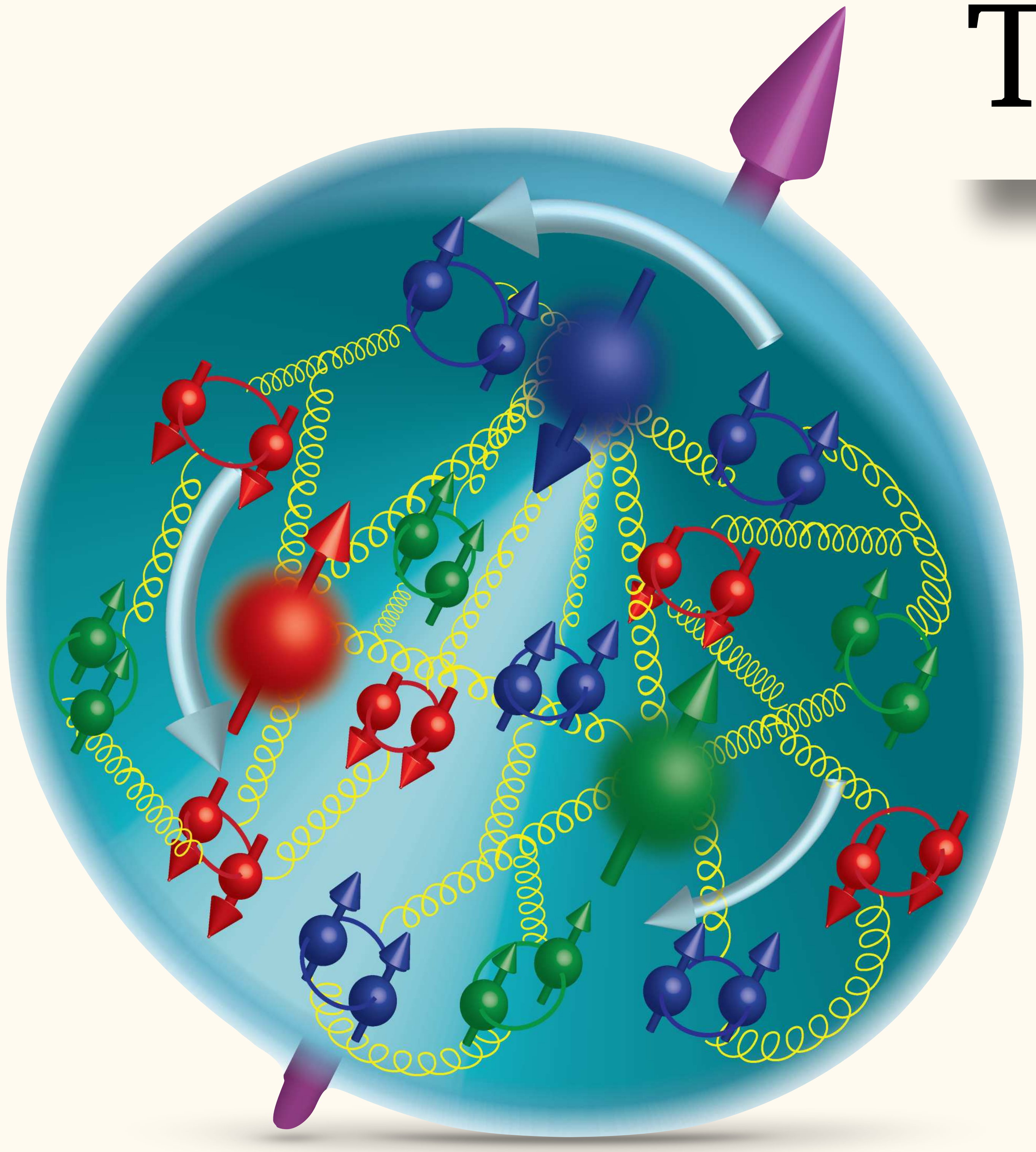


	nucleon polarization				
	U	L	T	TMD	GPD
Sea quark distributions	❋				
Multiplicities	❋			❋	
Quark helicities		❋		(❋)	
Gluon helicity		❋			
Sivers TMD			❋	❋	
Twist-3 correlation functions			❋	❋	
Transversity TMD & Collins FF			❋	❋	
Higher twist in SIDIS	❋			❋	
DVCS	❋	❋	❋		❋
Hard exclusive mesons	❋	❋			❋
Selected near future	❋		❋	❋	❋

For details, refer to parallel sessions

Hall A

Hall C

The physics questions

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

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

Spin puzzle

quark spin $\Delta\Sigma \approx \tfrac{1}{3}$

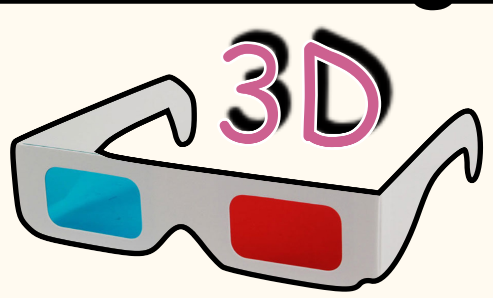
quark orbital angular momentum

gluon spin & orbital angular momentum

* 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?

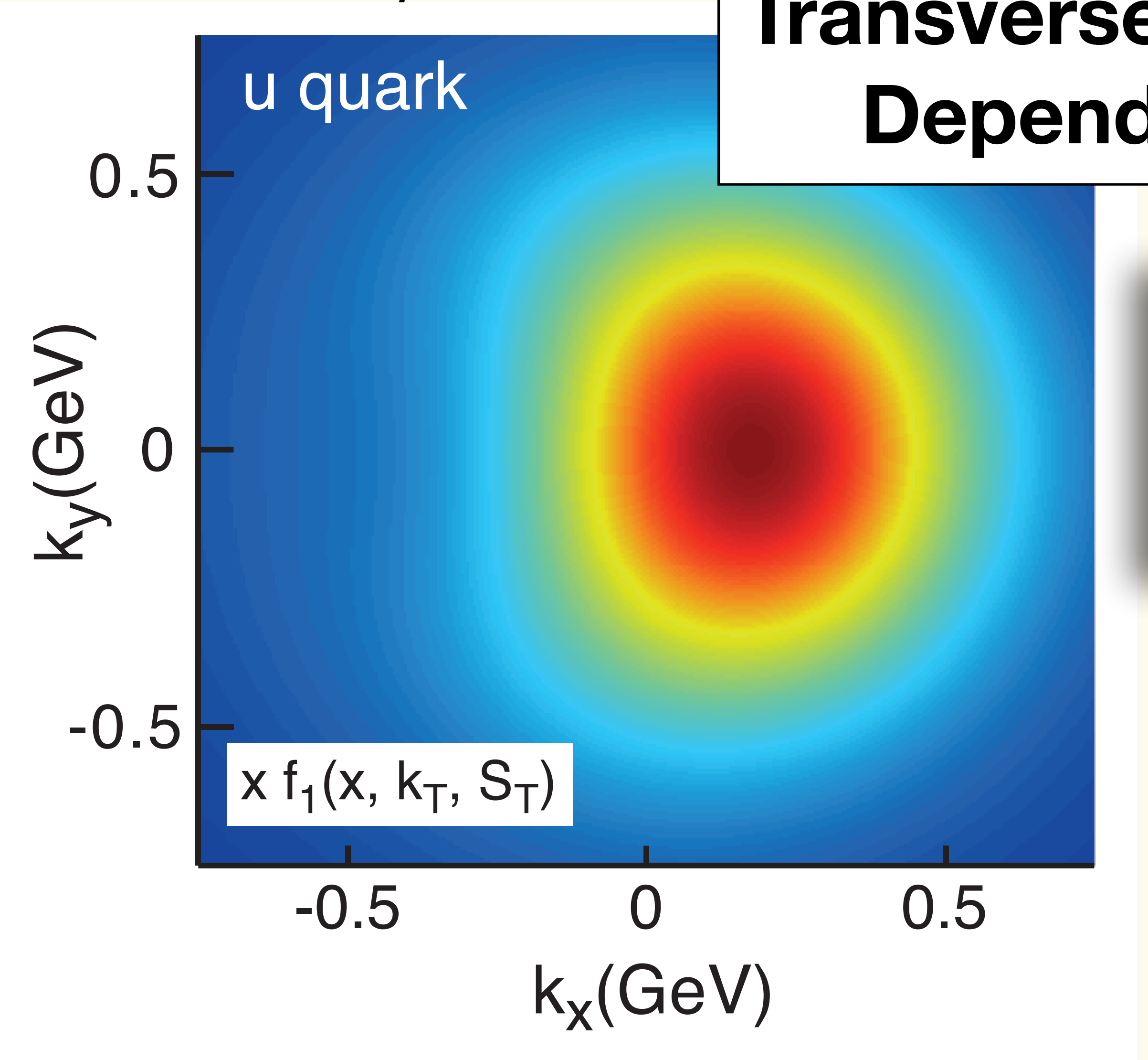
Nucleon tomography



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 $f(x,k_T)$

k_T-integration

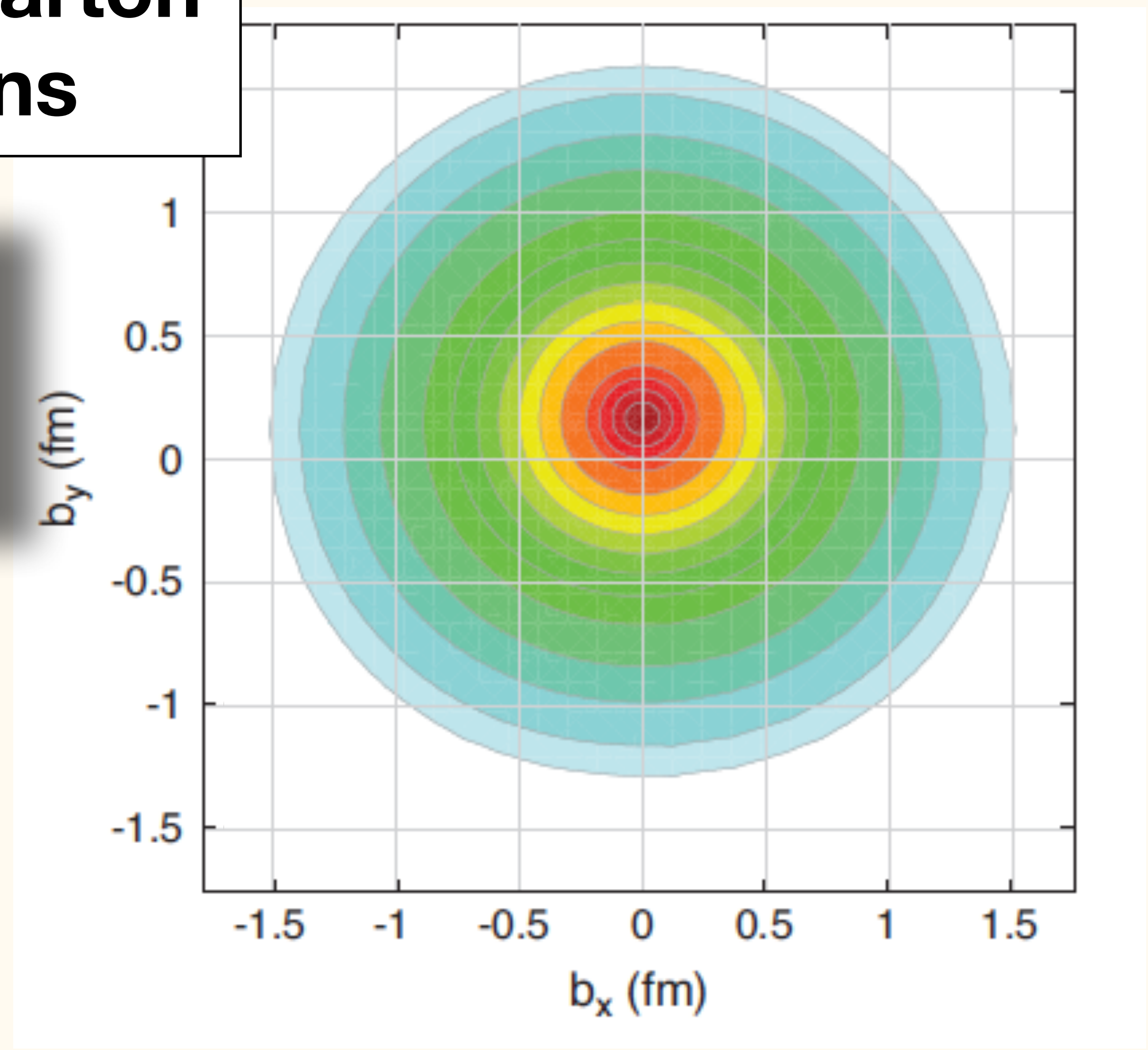
Generalized Parton Distributions

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

ξ=0, t=0

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

Deformation of parton's spatial distribution when hadron is polarized



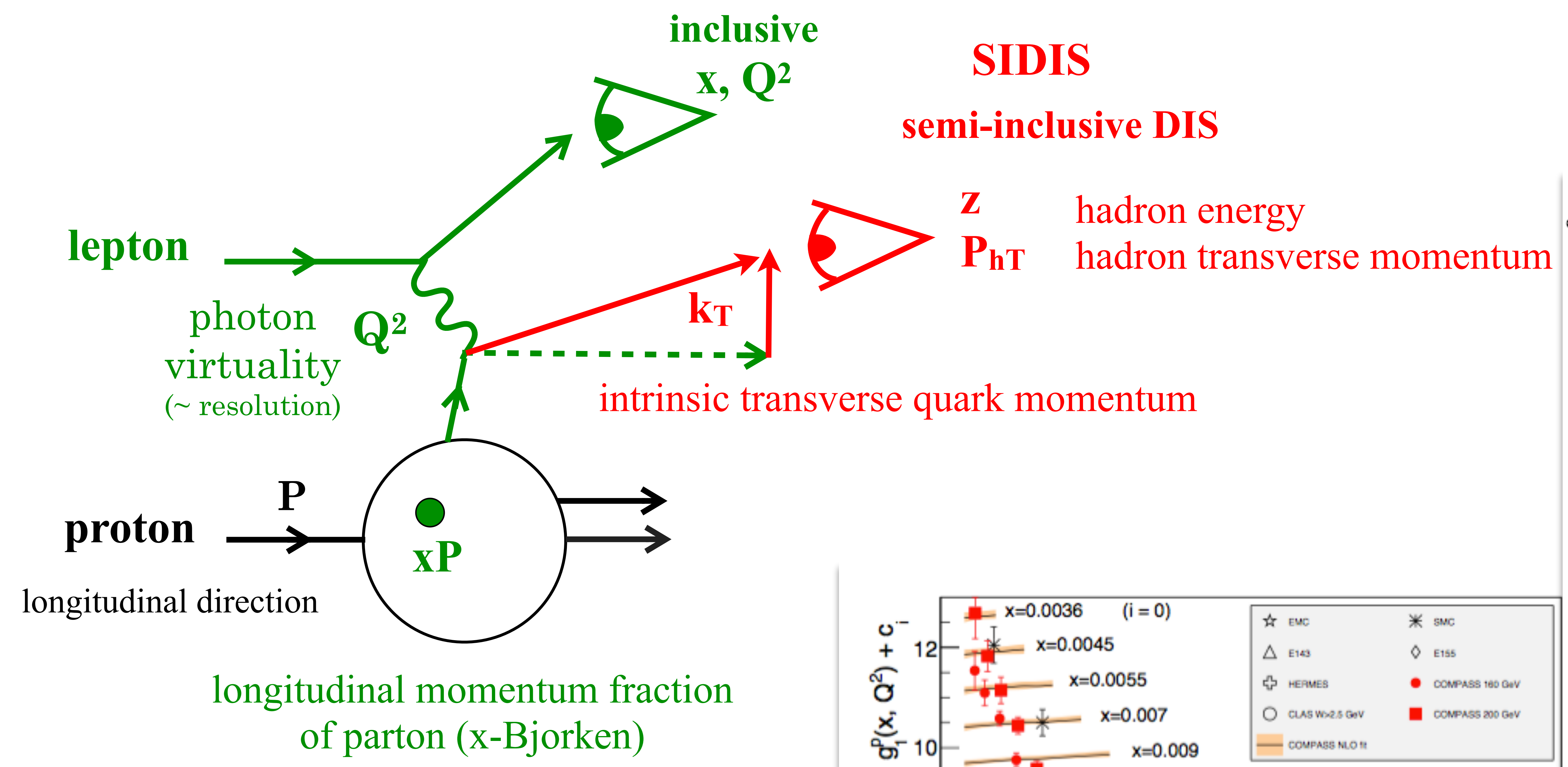
position space

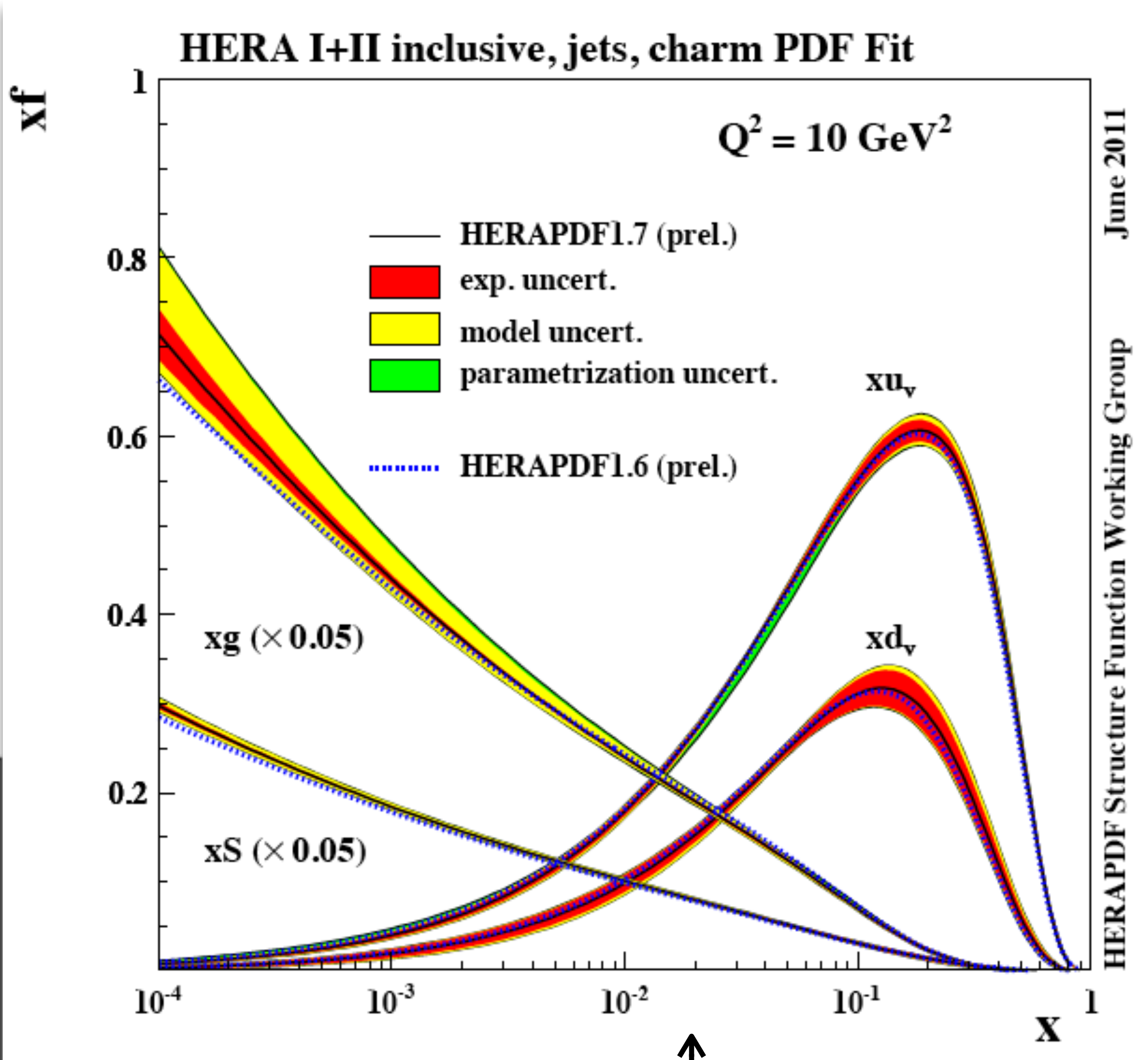
A. Bacchetta, U. D'Alesio, M. Diehl, and C. A. Miller, Phys. Rev. D70, 117504 (2004)

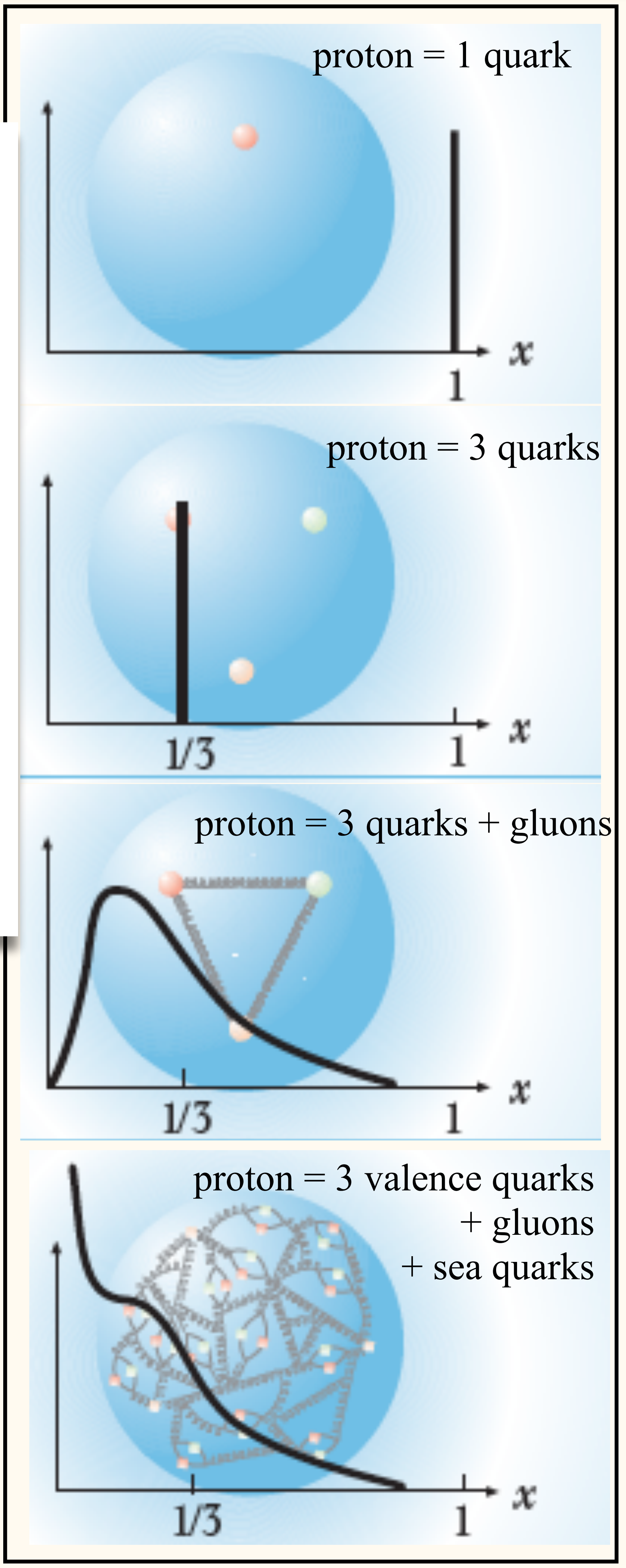
see next talk by B. Pasquini for a theory overview

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.

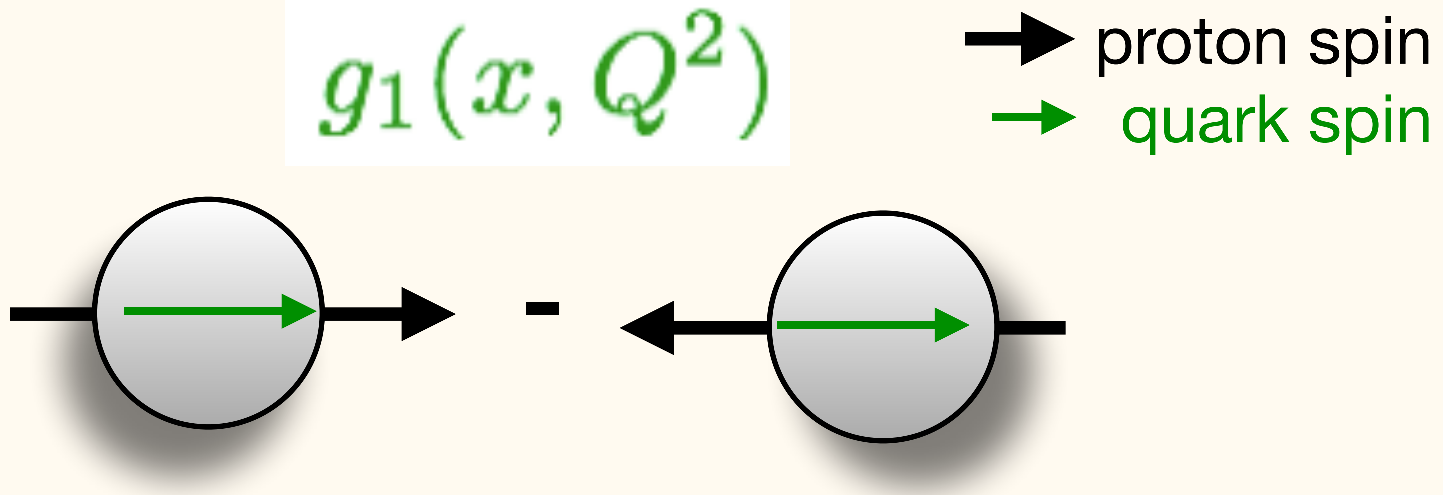


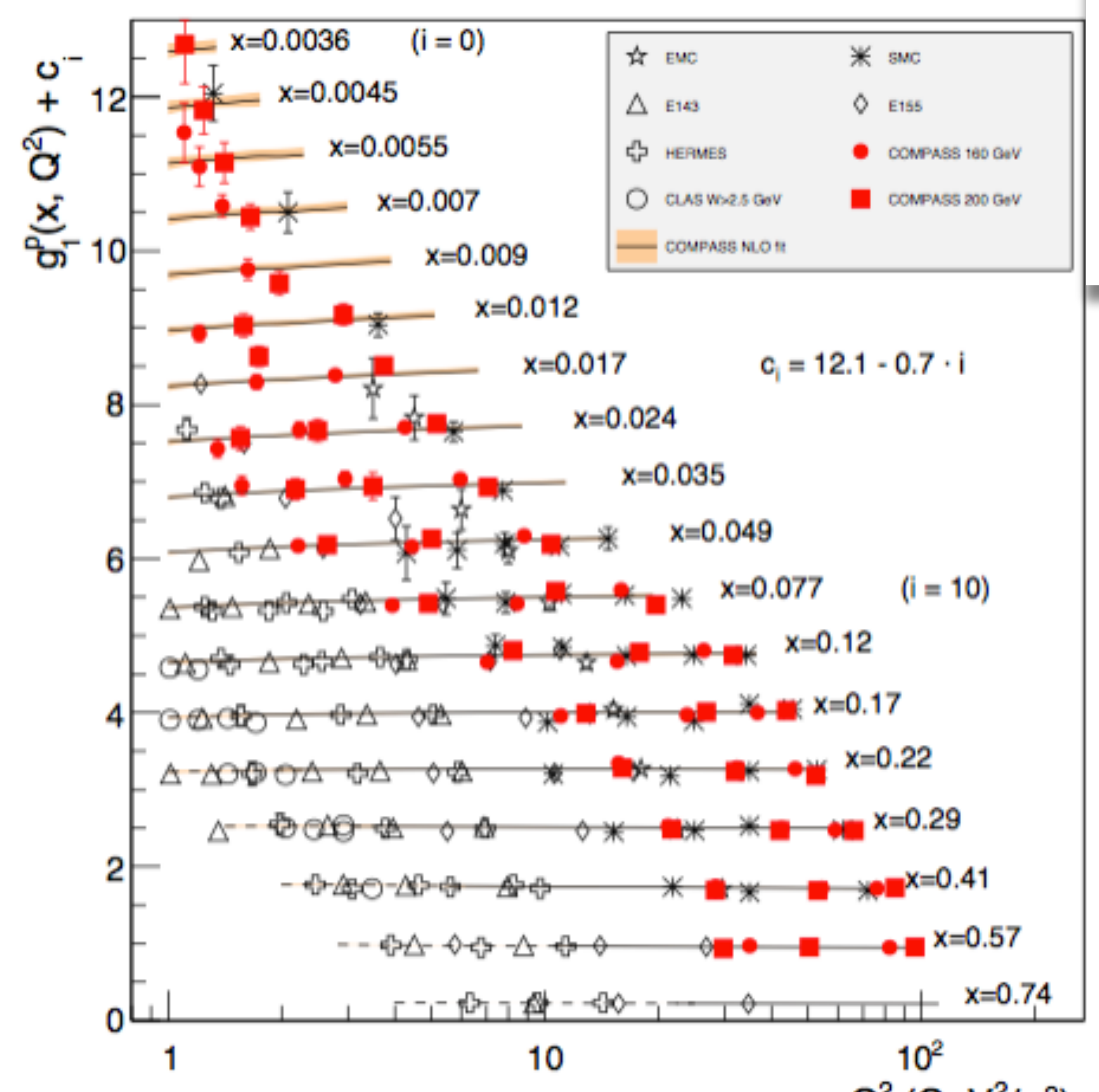




add spin… for example, inclusive DIS:
“spin structure” or “helicity” function
of the proton

$g_1(x, Q^2)$





[COMPASS PLB 753 (2016) 18]

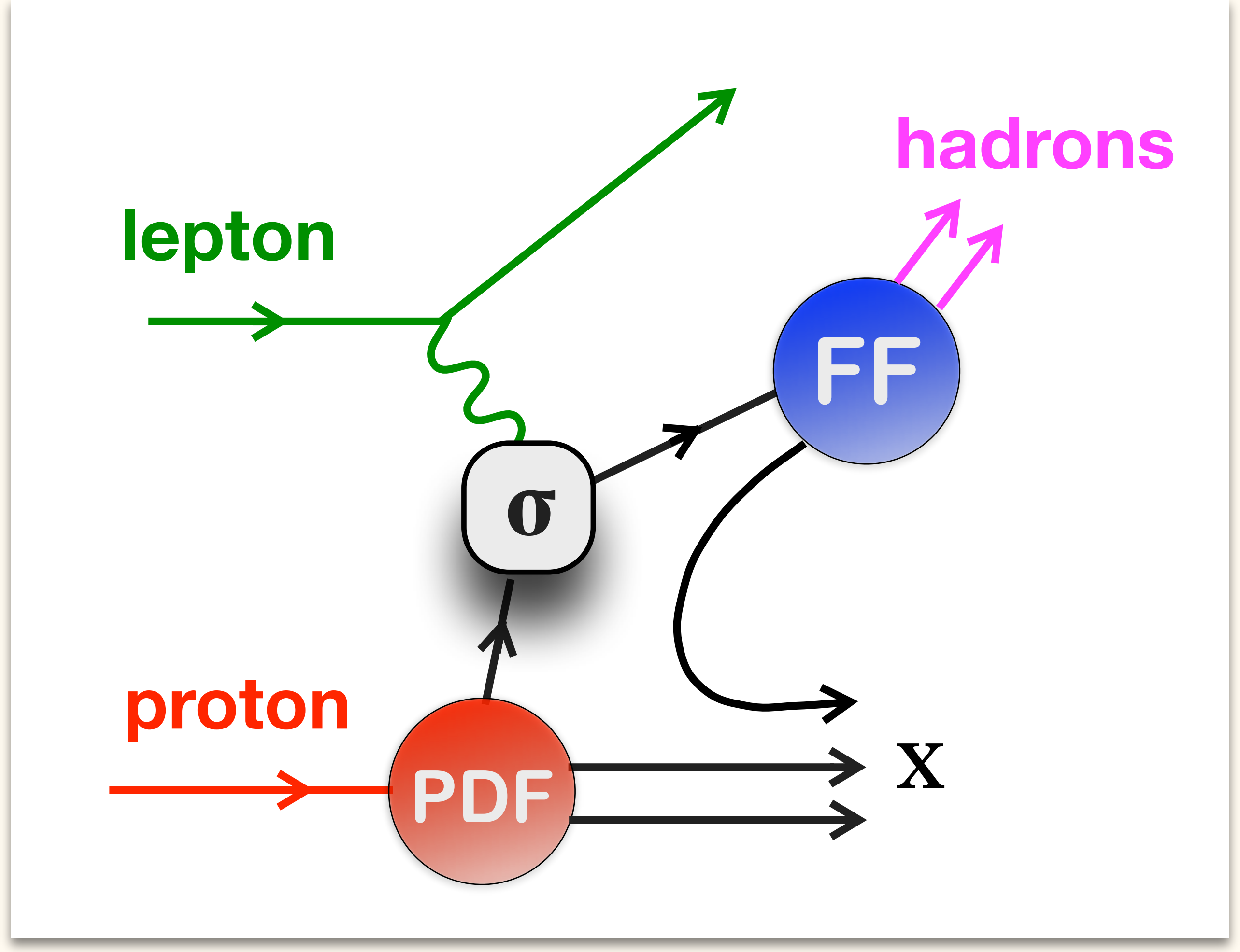
spin-independent from DESY (H1, ZEUS)

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



Cahn-effect + BM ⊗ Collins

Worm-gear (Kotzinian-Mulders) ⊗ Collins

BM ⊗ Collins

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

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

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

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

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

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

Sivers ⊗ D1

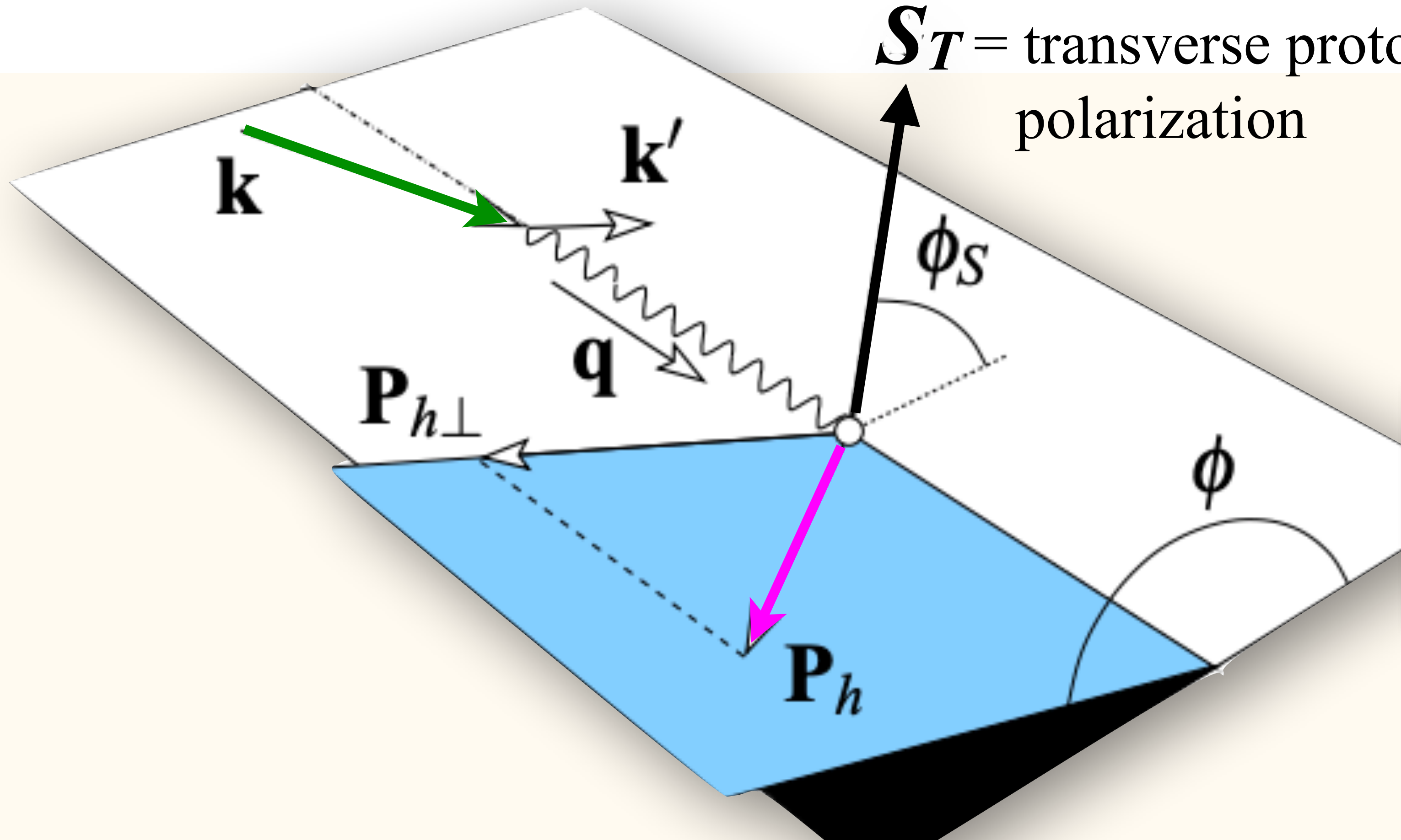
Worm-gear ⊗ D1

Transversity ⊗ Collins

Pretzelosity ⊗ Collins

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

S_T = transverse proton polarization



- $F_{XY[Z]}$ = 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

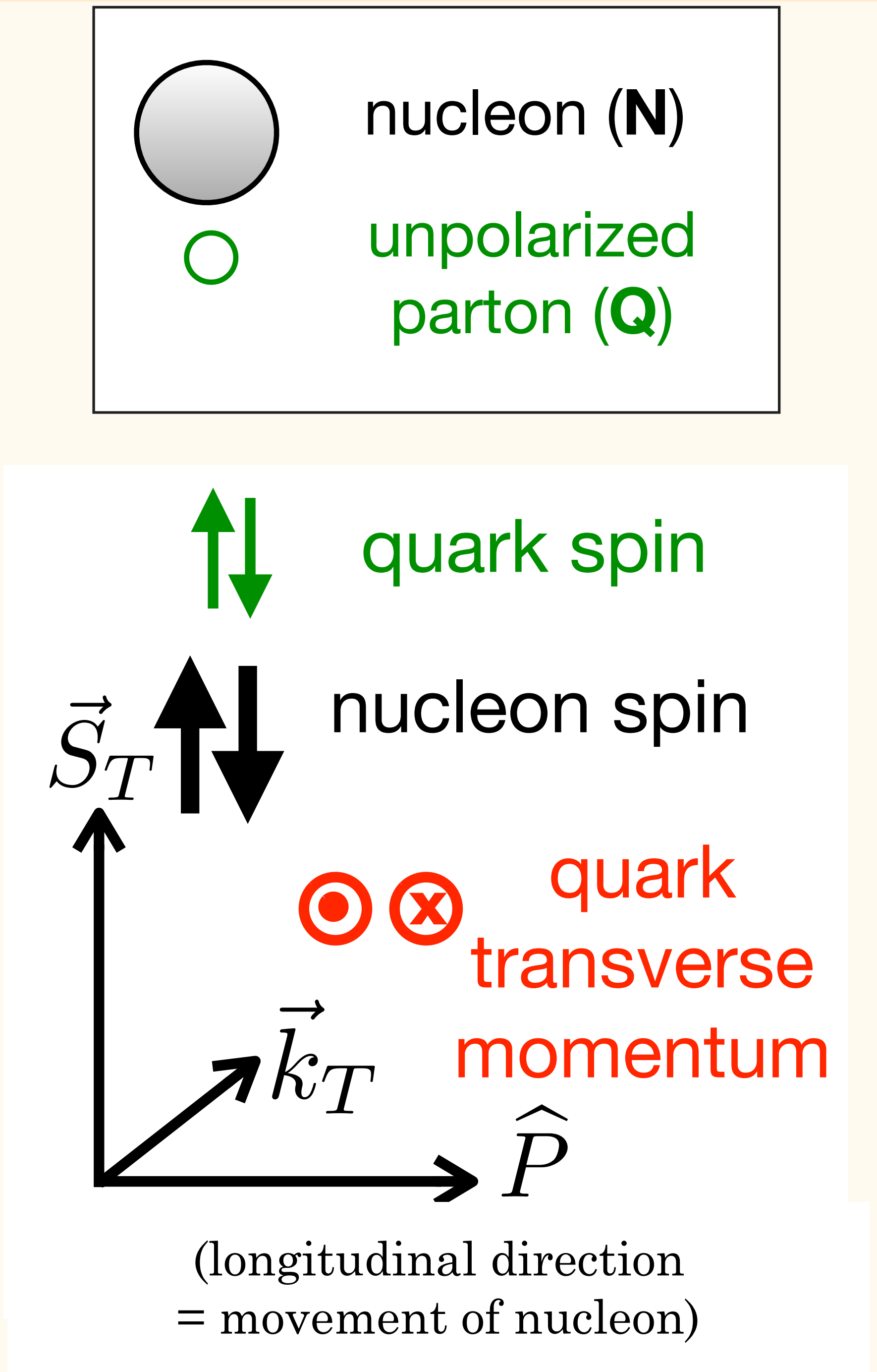
Unpolarized
Longitudinally
Transversely

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)

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} worm-gear	h_1 transversity	$h_{1T}^\perp$ pretzelosity

TMDs surviving integration over k_T. "Collinear analysis"

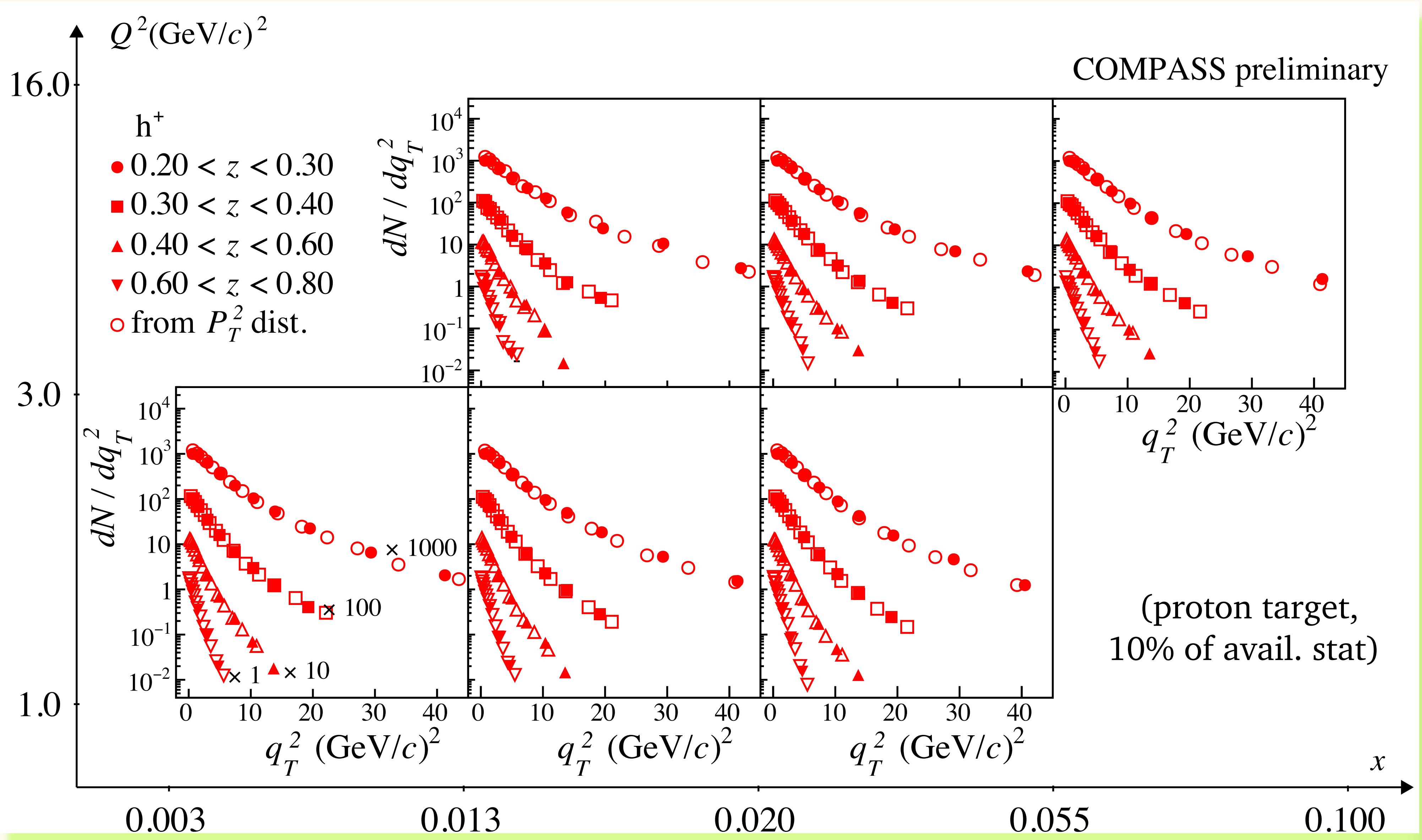
Naive time-reversal odd TMDs describing strength of **spin-orbit correlations.**

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

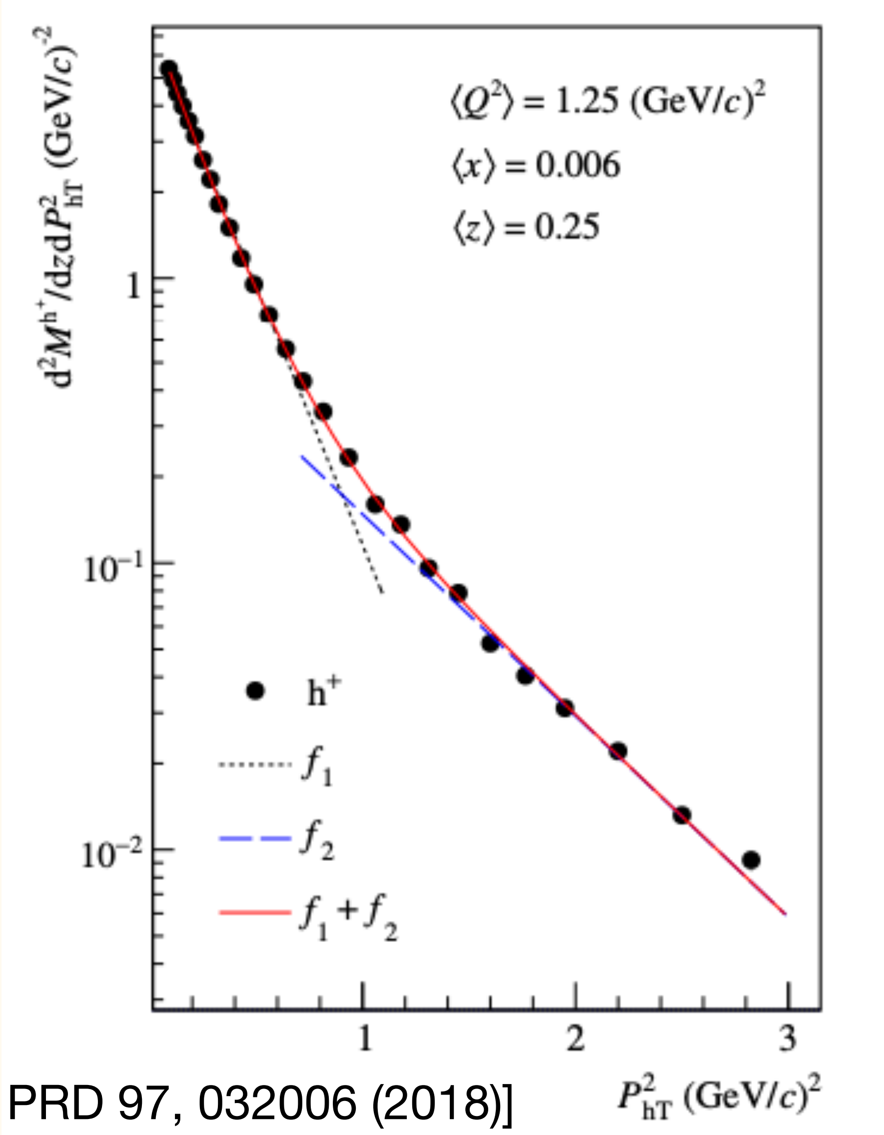
TMD effects in unpolarized SIDIS

New prelim COMPASS p_T dependences & azimuthal asymmetries



see talk by A. Moretti, Thursday, 12:35

✦ p_T distributions provide complementary information to $\cos(\phi)$ Boer-Mulders & Cahn and $\cos(2\phi)$ 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)

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

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

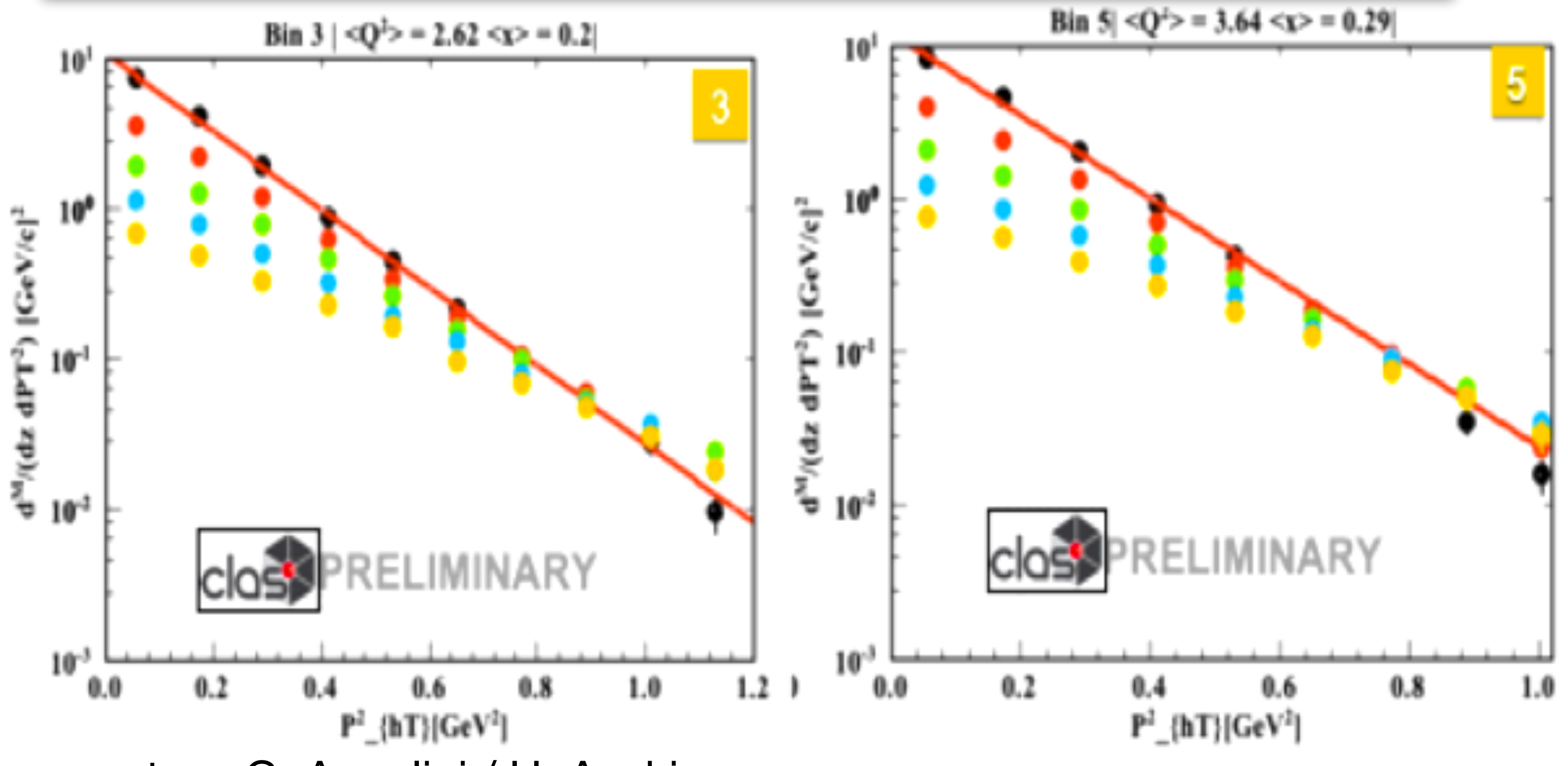
Towards a more complete mapping of the SIDIS landscape - current vs. target fragmentation

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

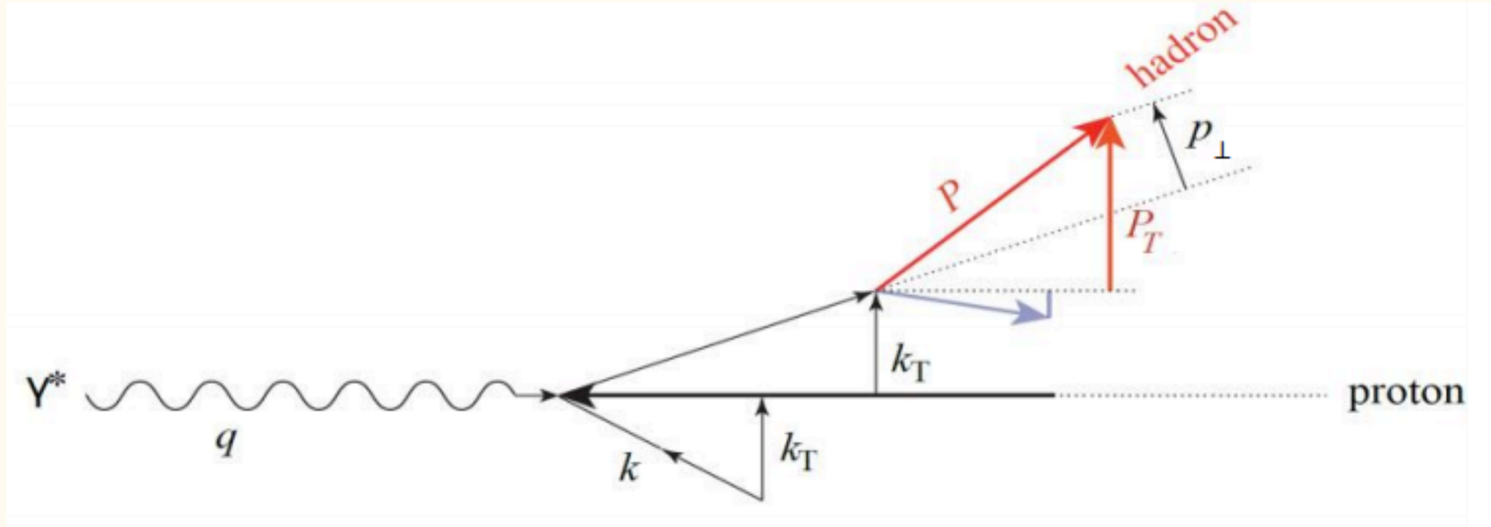
π^+ multiplicities in example (x, Q^2) bins, for various z

0.2<z<0.3
0.3<z<0.4
0.4<z<0.5
0.5<z<0.6
0.6<z<0.7

quark-to-hadron FF

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

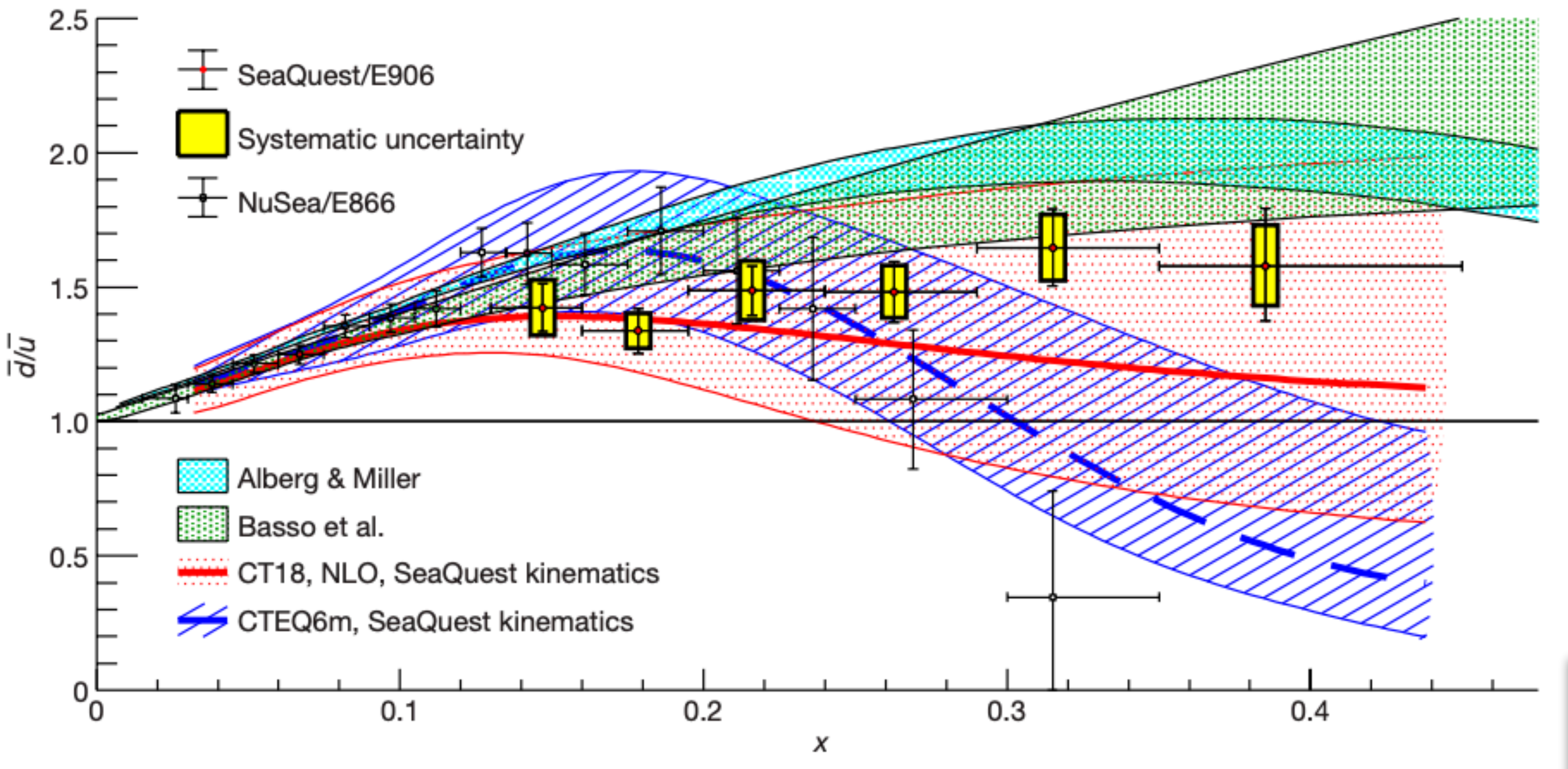
quark PDF



Flavor composition of the sea

New SeaQuest Drell-Yan **dbar / ubar**

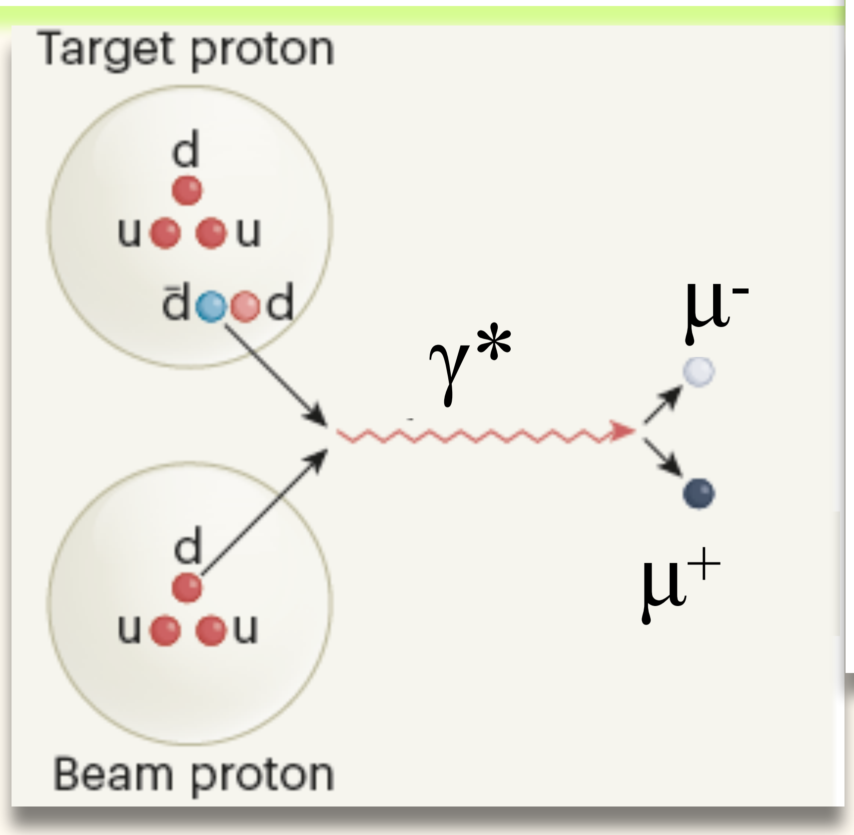
- ✦ More anti-down than anti-up quarks in the proton from Drell-Yan with 120 GeV proton beam on liquid hydrogen and deuterium targets. The finding is in agreement with meson-cloud and statistical models.



[SeaQuest Nature 590, 561–565 (2021)]

see talk by K. Nagai, Thursday, 9:12

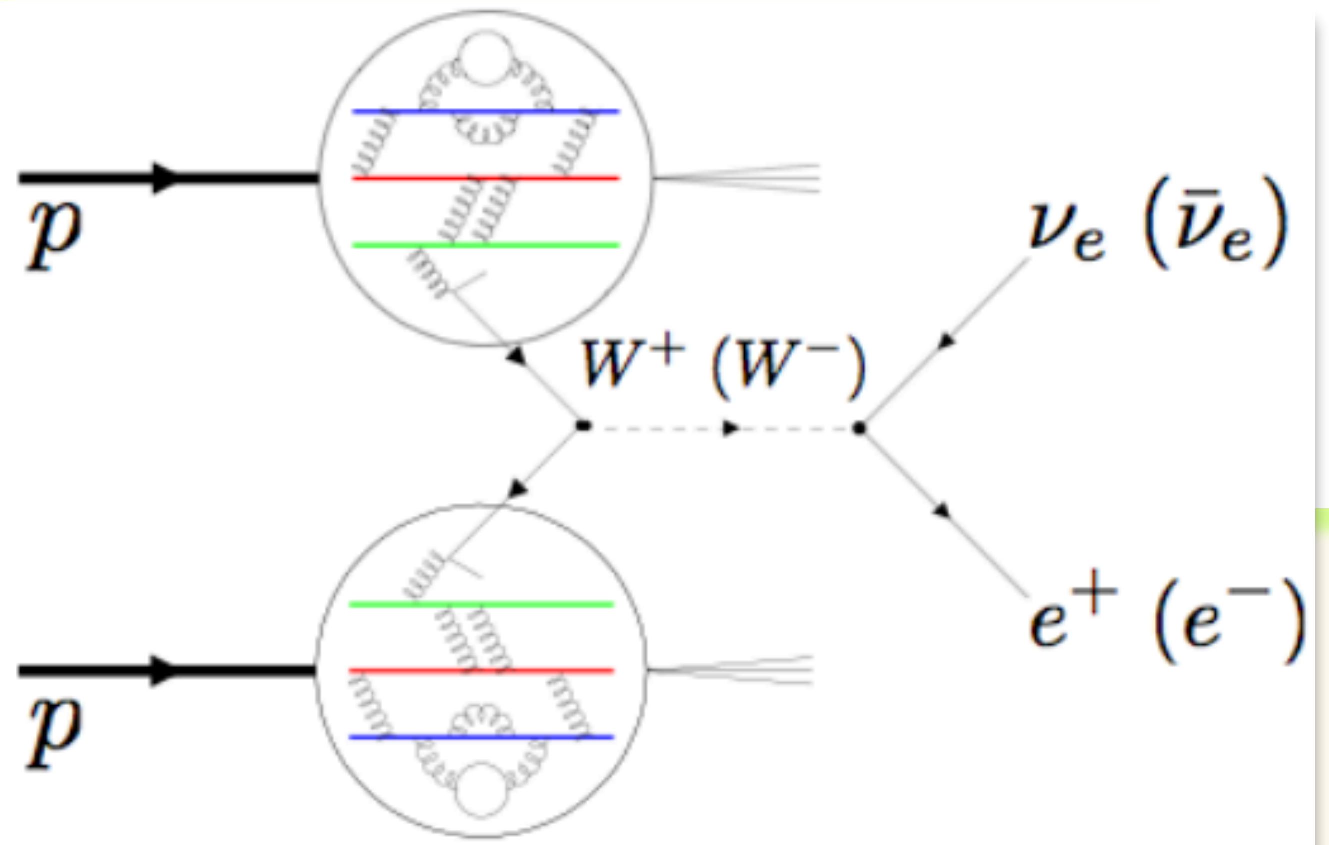
$$\sigma_D/\sigma_H \approx (\sigma_p + \sigma_n)/\sigma_p \approx 1 + [\bar{d}_p(x_t)/\bar{u}_p(x_t)]$$



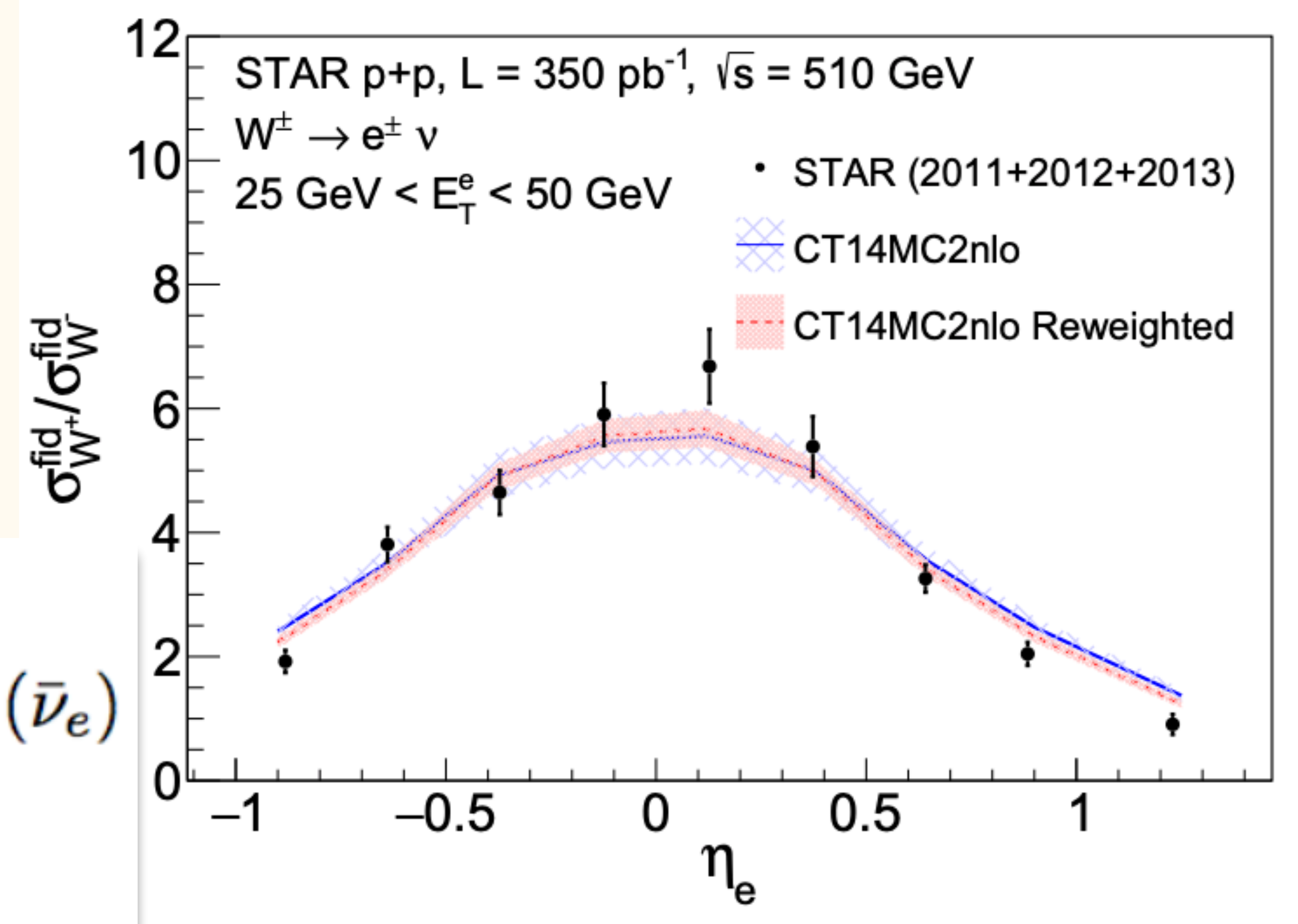
New STAR weak boson **dbar / ubar**

- ✦ Cross section ratio W^+/W^- (dbar-u / ubar-d fusion) in proton-proton collisions at $\sqrt{s}$=500 GeV
- ✦ Complementary to the SeaQuest result, at large momentum scale $Q^2 = M_W^2$ & complementary (@higher x) also to LHC results

Flavor asymmetric sea dbar(x) > ubar(x)



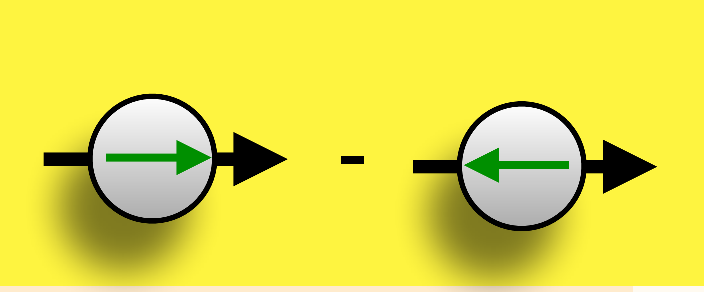
$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{d(x_1)\bar{u}(x_2) + d(x_2)\bar{u}(x_1)}$$



[STAR PRD 103 (2021) 012001]

see talk by S. Fazio and talk by J. Nam, Thursday, 9:30 including new preliminary results

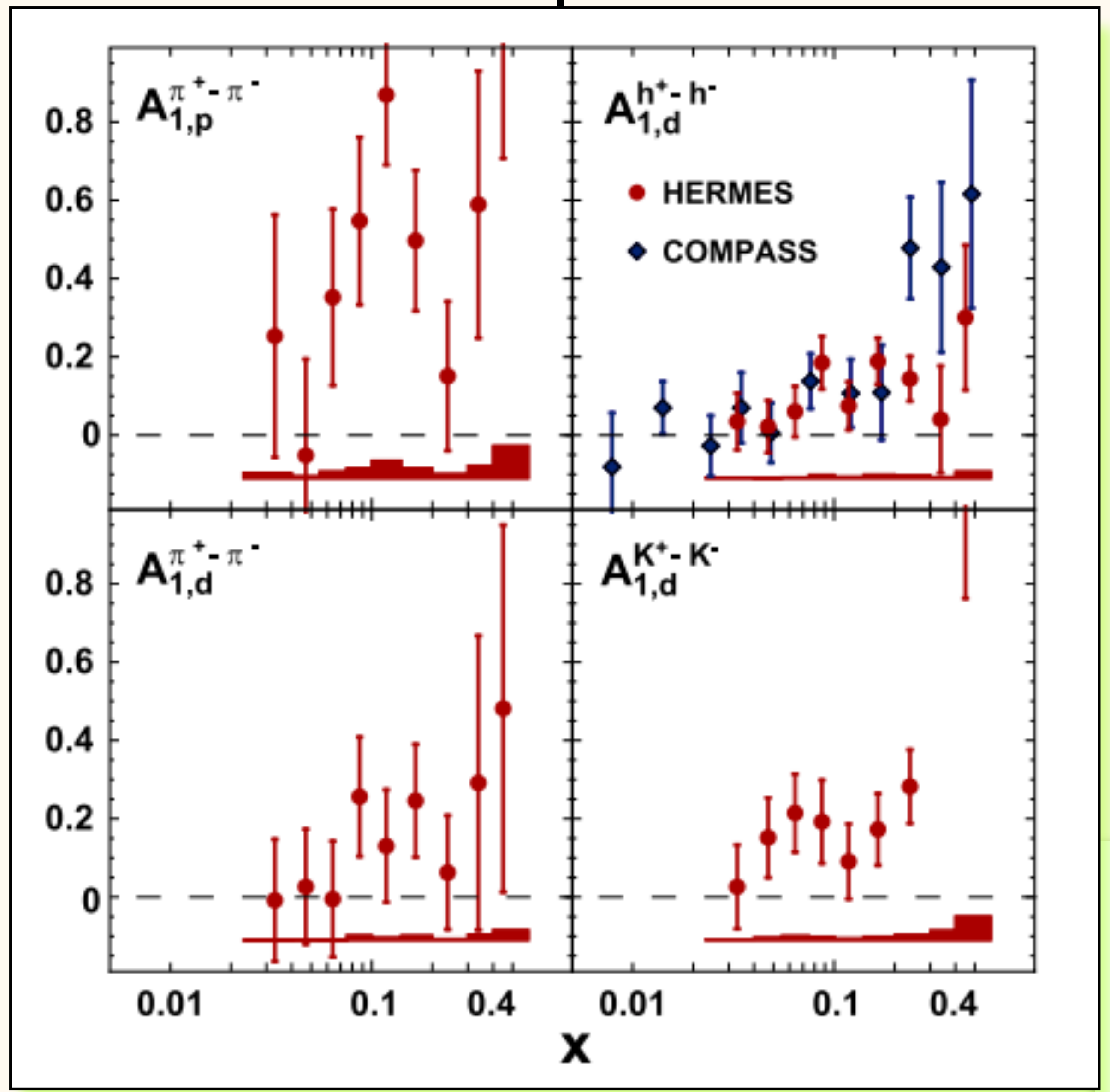
Quark helicities from longitudinally polarized protons



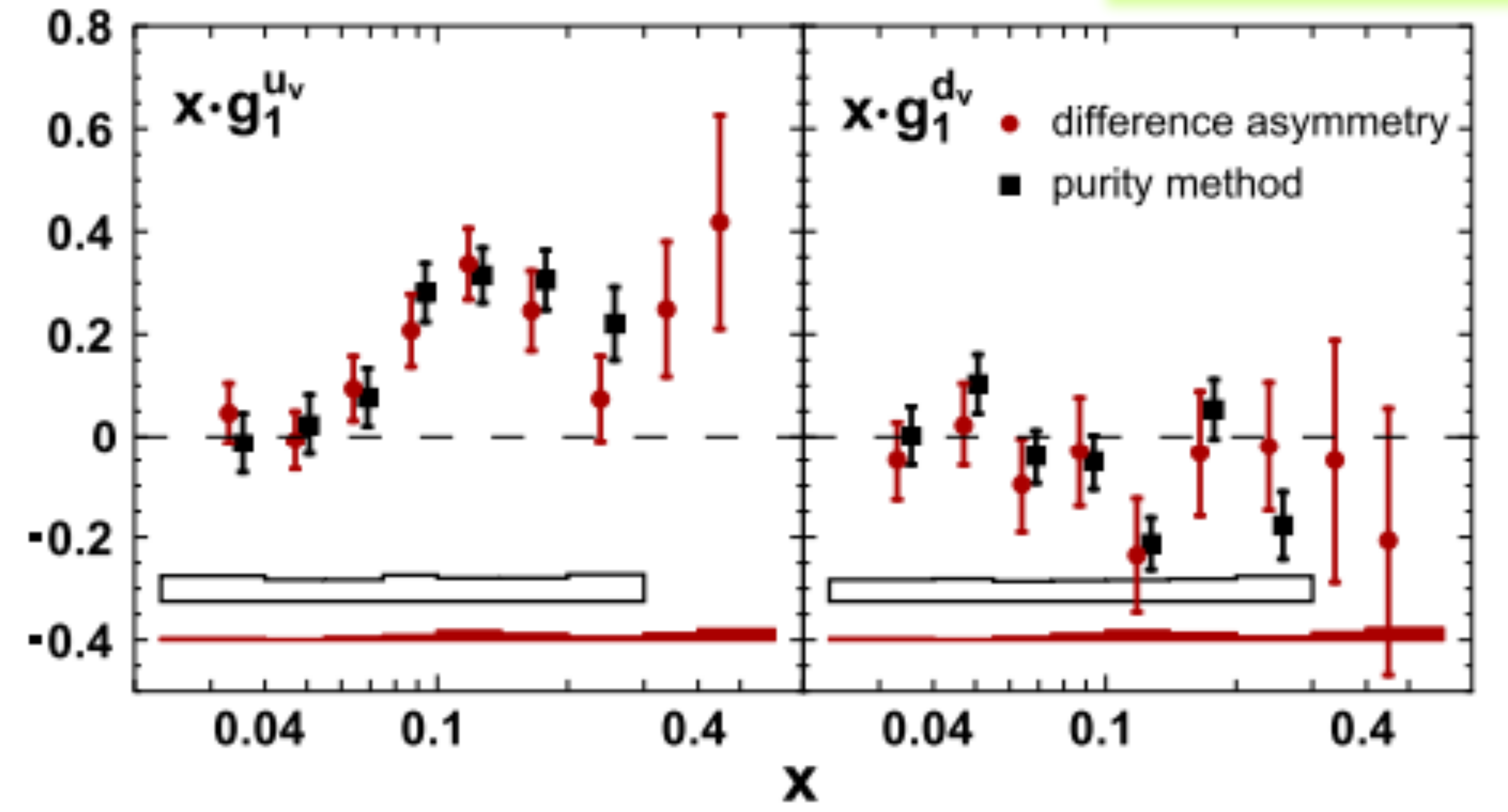
Final HERMES **SIDIS valence quark helicities**

- Hadron charge-difference double-spin asymmetry A_{LL} provides direct extraction of valence-quark helicities
  under isospin symmetry assumptions of fragmentation functions.

  P_T dependence found to be weak and consistent with findings by COMPASS & CLAS (not shown here)



[HERMES PRD 99, 112001 (2019)]

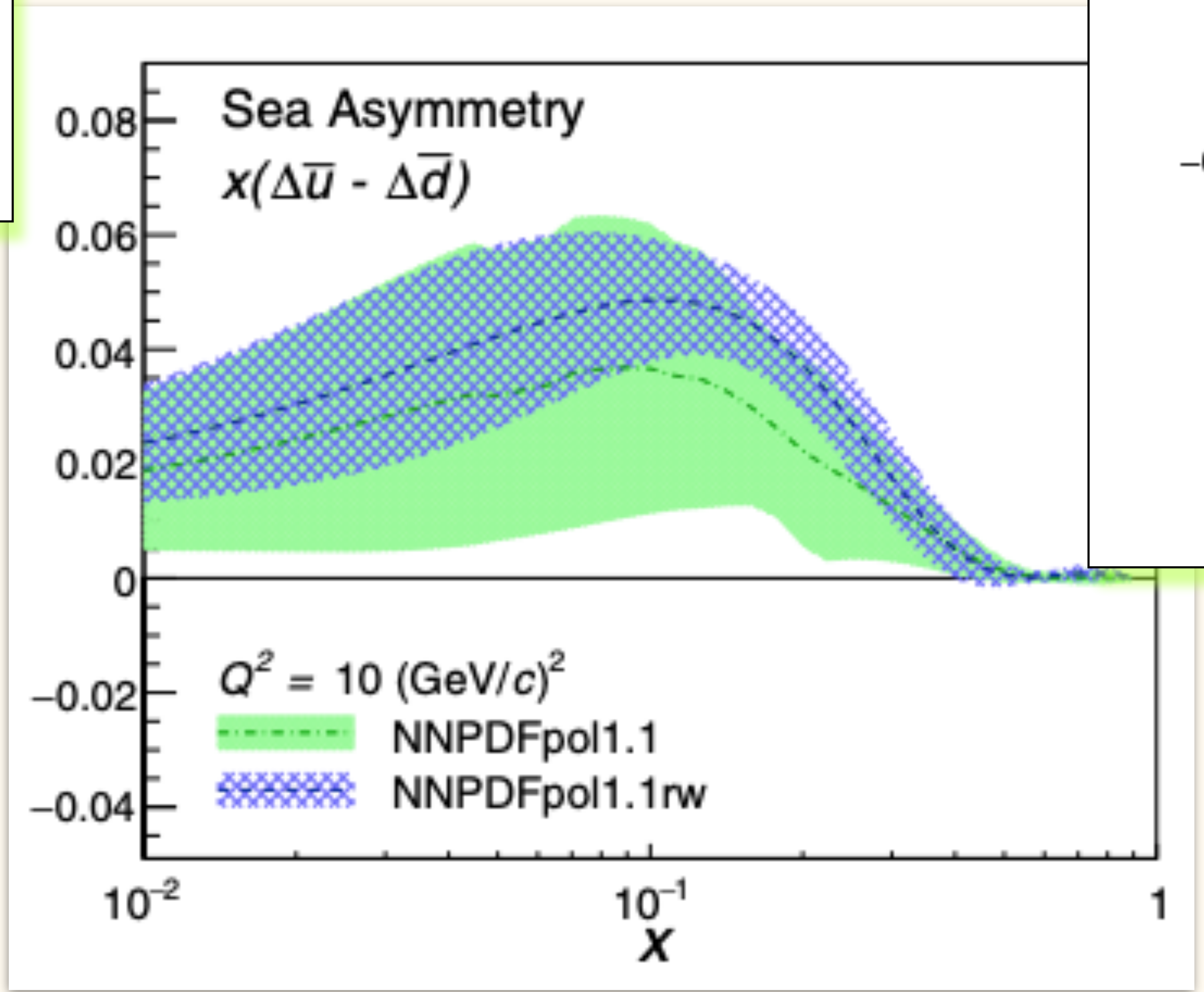


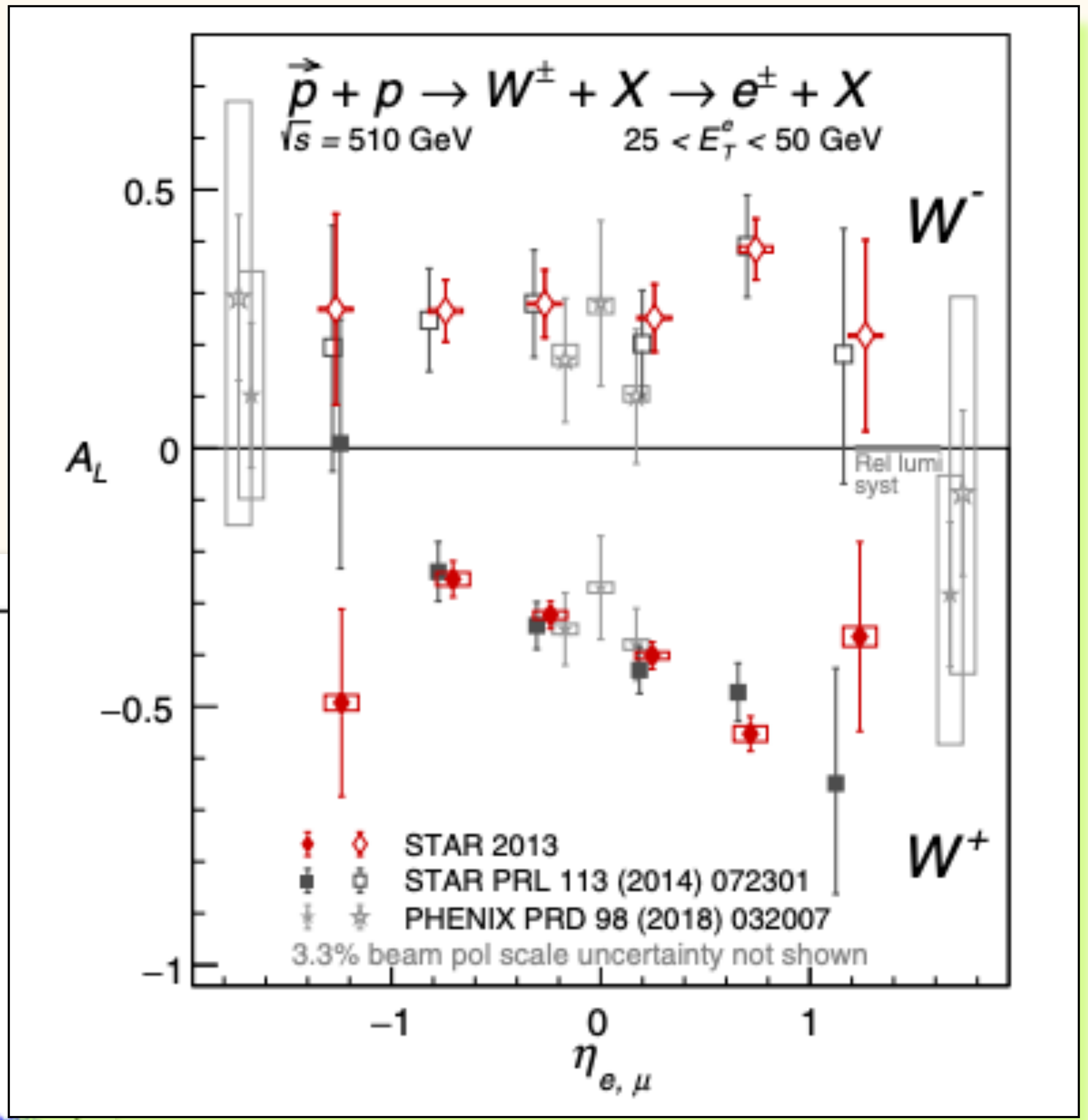
see talk by D. Veretennikov, Thursday, 12:15

STAR & PHENIX **W^+/W^- sea quark helicities**

- Longitudinal spin asymmetry in weak-boson production
- Recent data allow improvement of NNPDF fits.

Strong evidence for flavor-symmetry breaking in the polarized sector
Opposite to unpolarized sector!
$\Delta\bar{u}(x,Q^2) > \Delta\bar{d}(x,Q^2)$



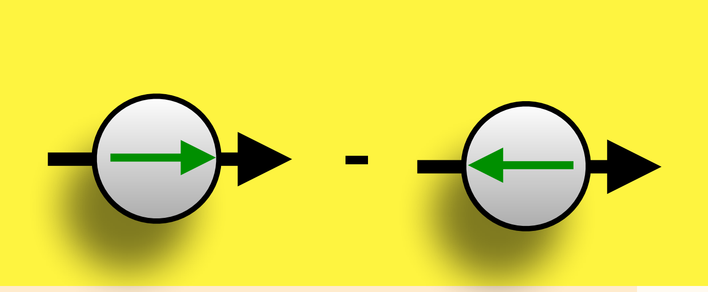


[STAR PRD 99 (2019) 051102]

with [PHENIX PRD 98 (2018) 032007]

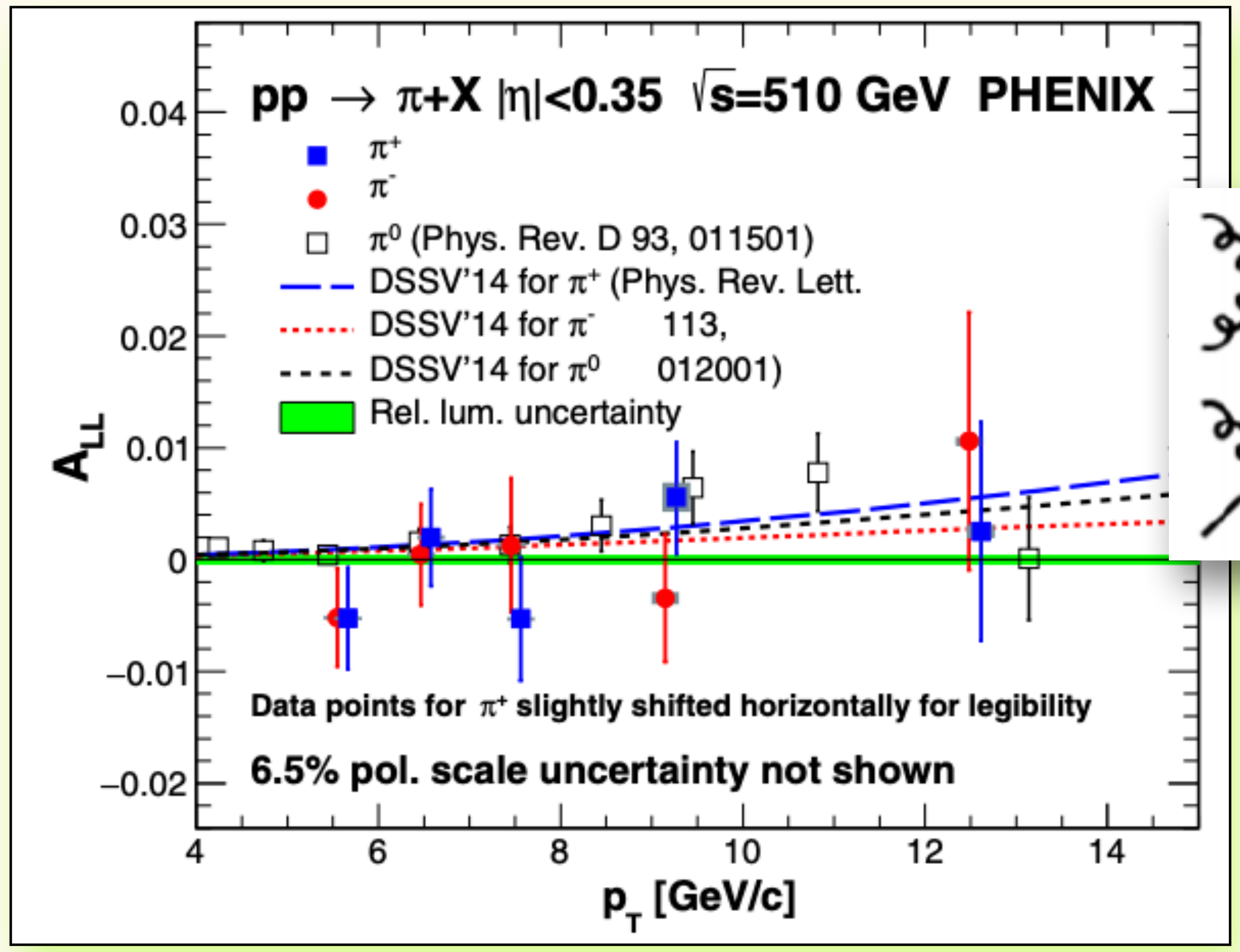
[NNPDF Collaboration Nucl. Phys. B887, 276 (2014)]

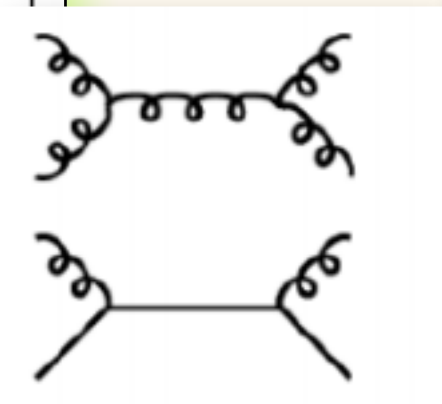
Gluon helicity from longitudinally polarized protons



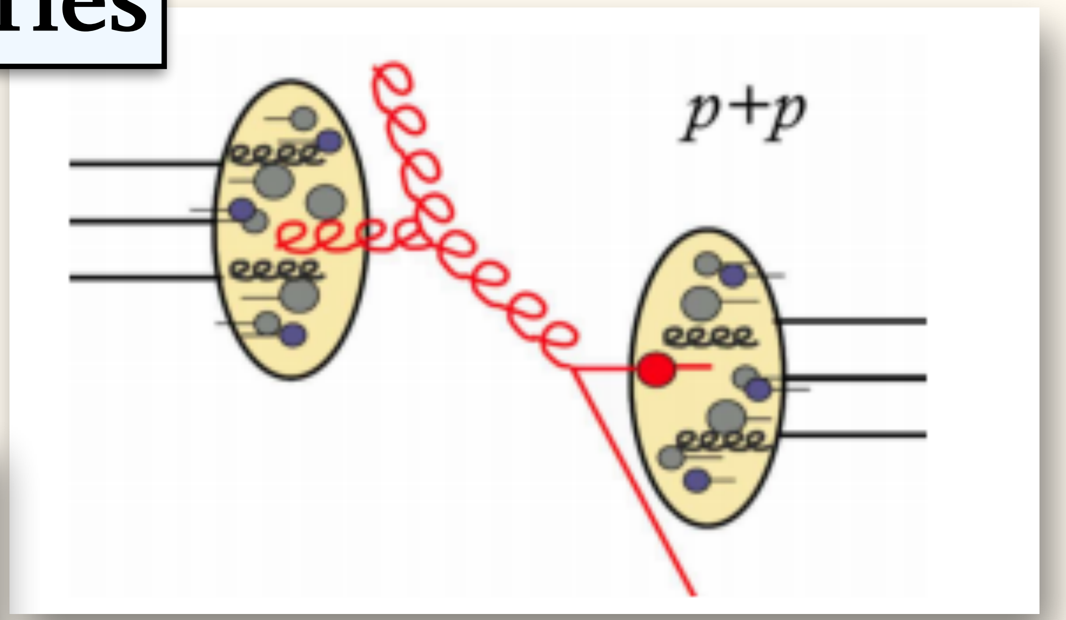
RHIC longitudinal double-spin asymmetries

✦ PHENIX charged-pion A_{LL}



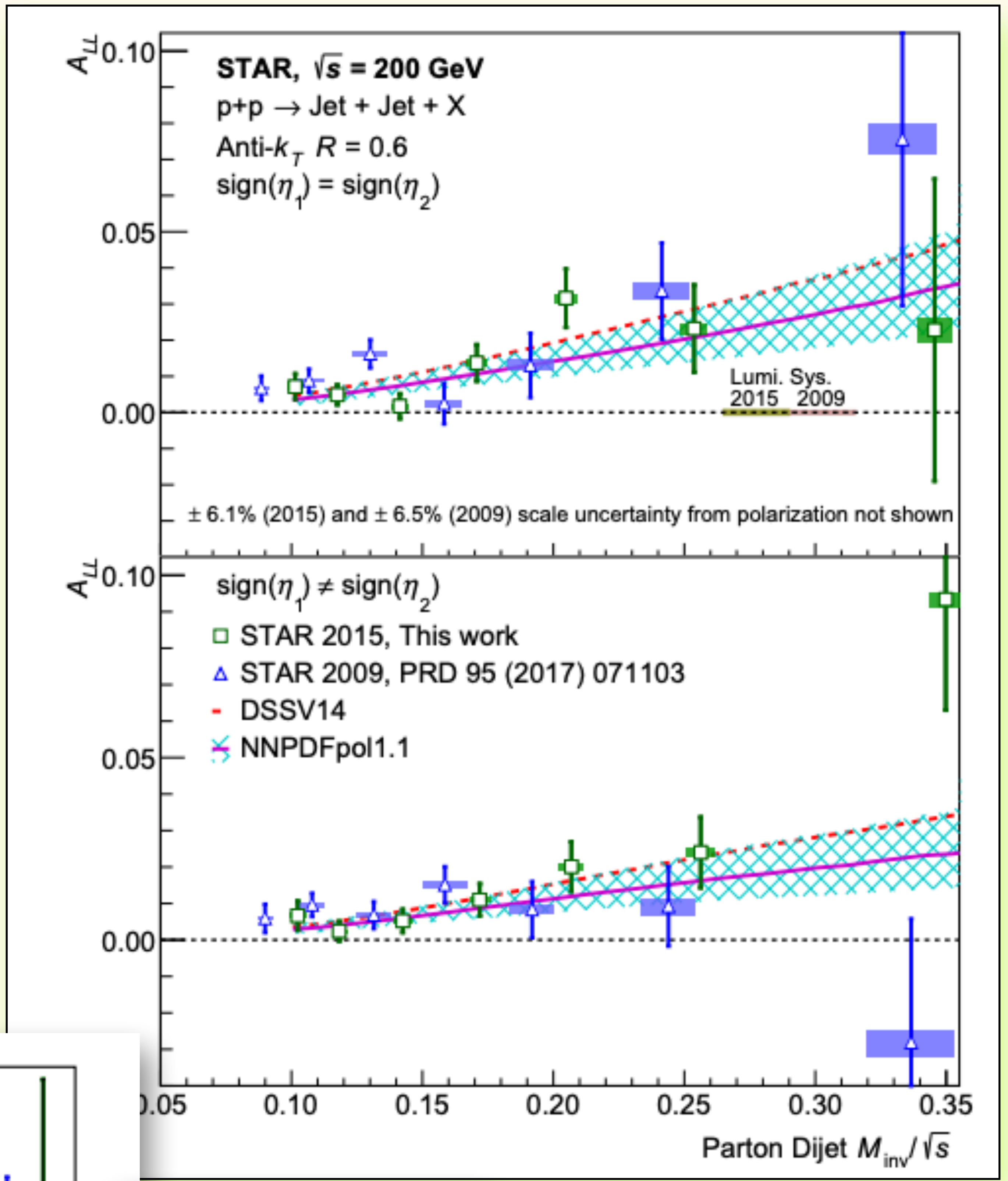


[PHENIX PRD 102 (2020) 3, 032001]



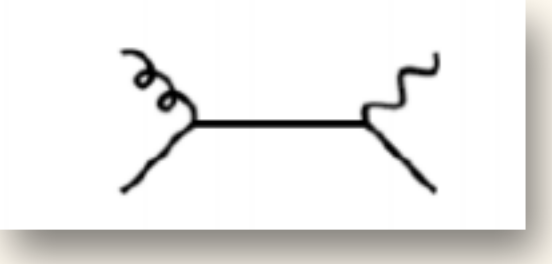
Direct access to gluon helicity via proton-proton collisions (indirect in DIS). At RHIC, qg & gg dominate.

✦ STAR: A_{LL} in di-jet and inclusive jet production

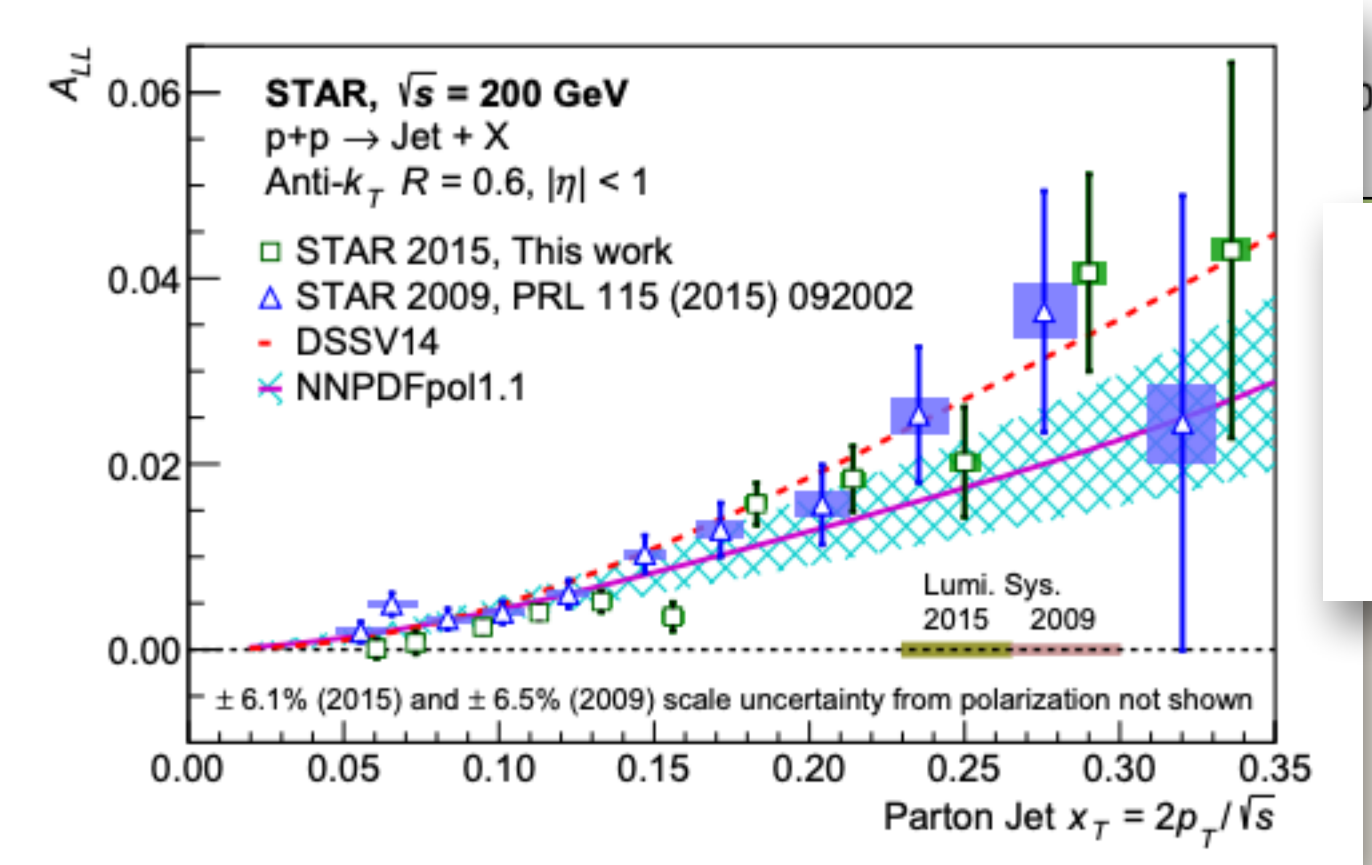


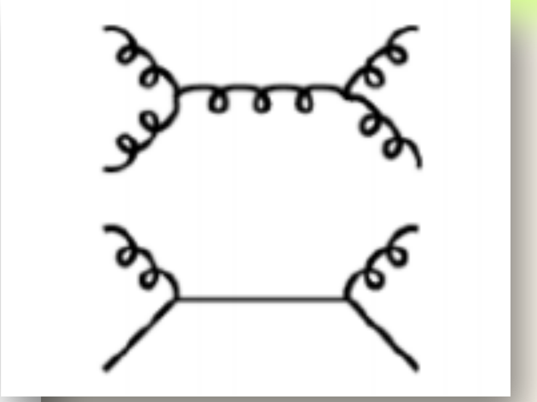
Recent high-precision mid-rapidity data consistent with global QCD fits that indicate **non-zero positive and large (60%) gluon-spin contribution to the proton spin in the region 0.05 < x < 0.2**.

✦ PHENIX A_{LL} in isolated direct-photon cleanest probe, hard interaction ~ qg



see talk by Z. Ji, Wednesday, 12:51





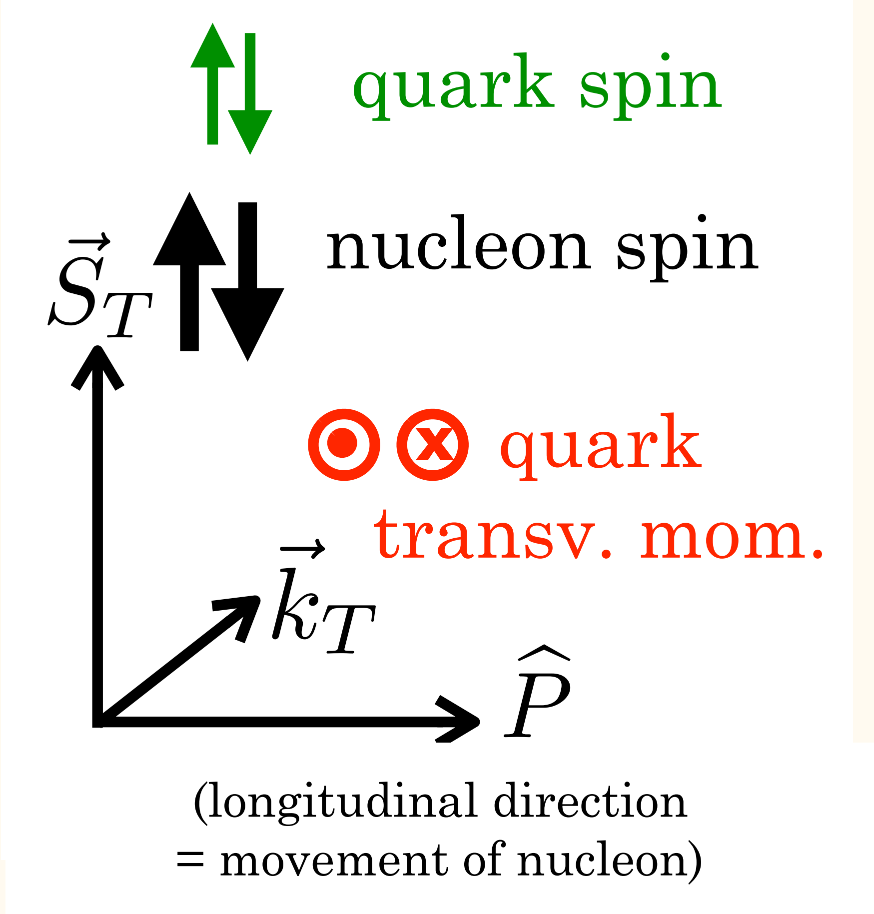
[STAR arXiv:2103.05571]

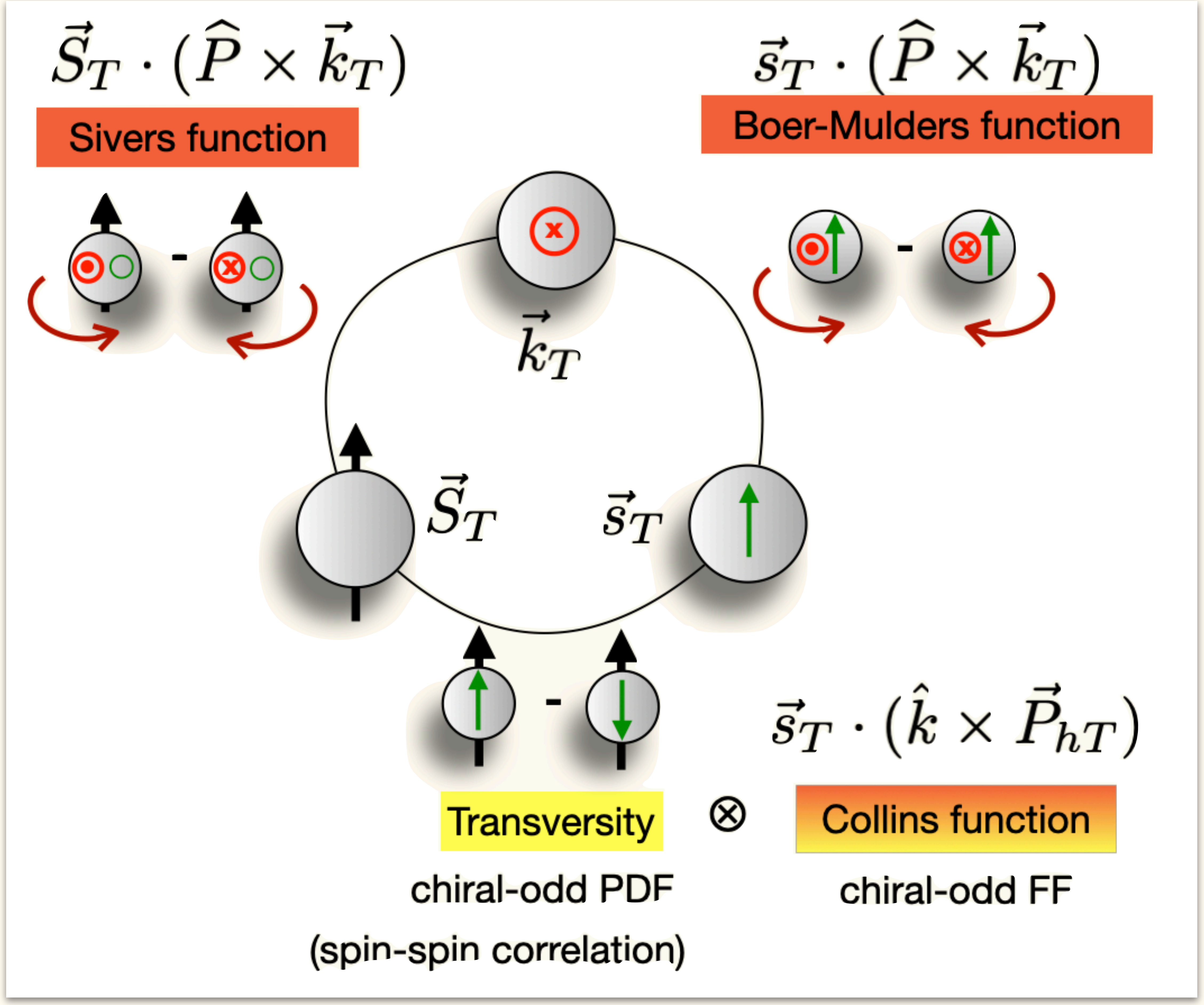
see talk by M. Zurek, Wednesday, 12:33

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.

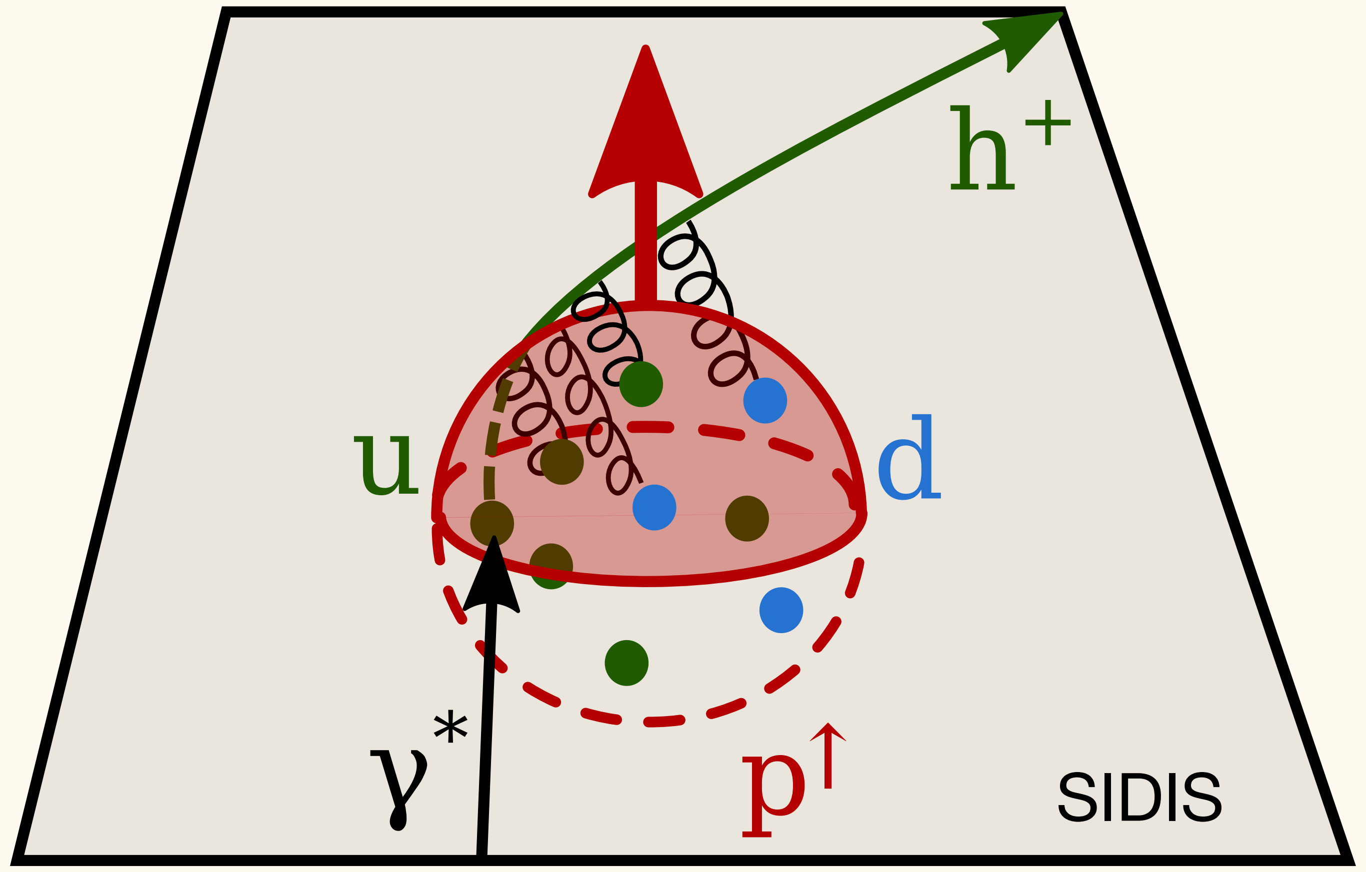




"Collinear analysis"

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



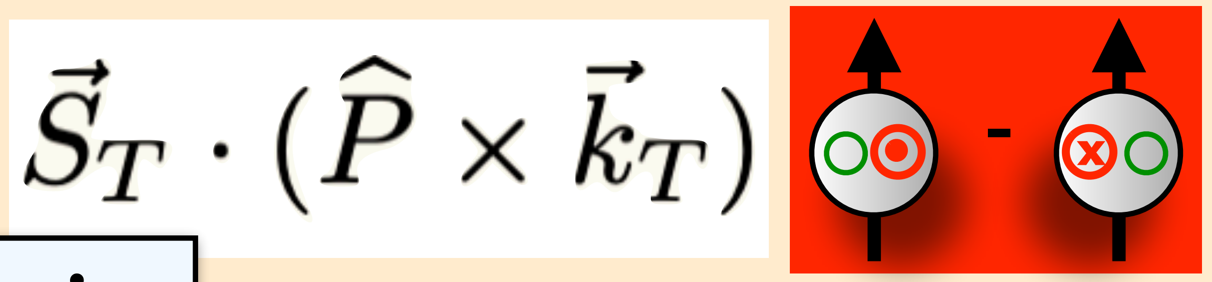
The Sivers function was originally thought to vanish (*).

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

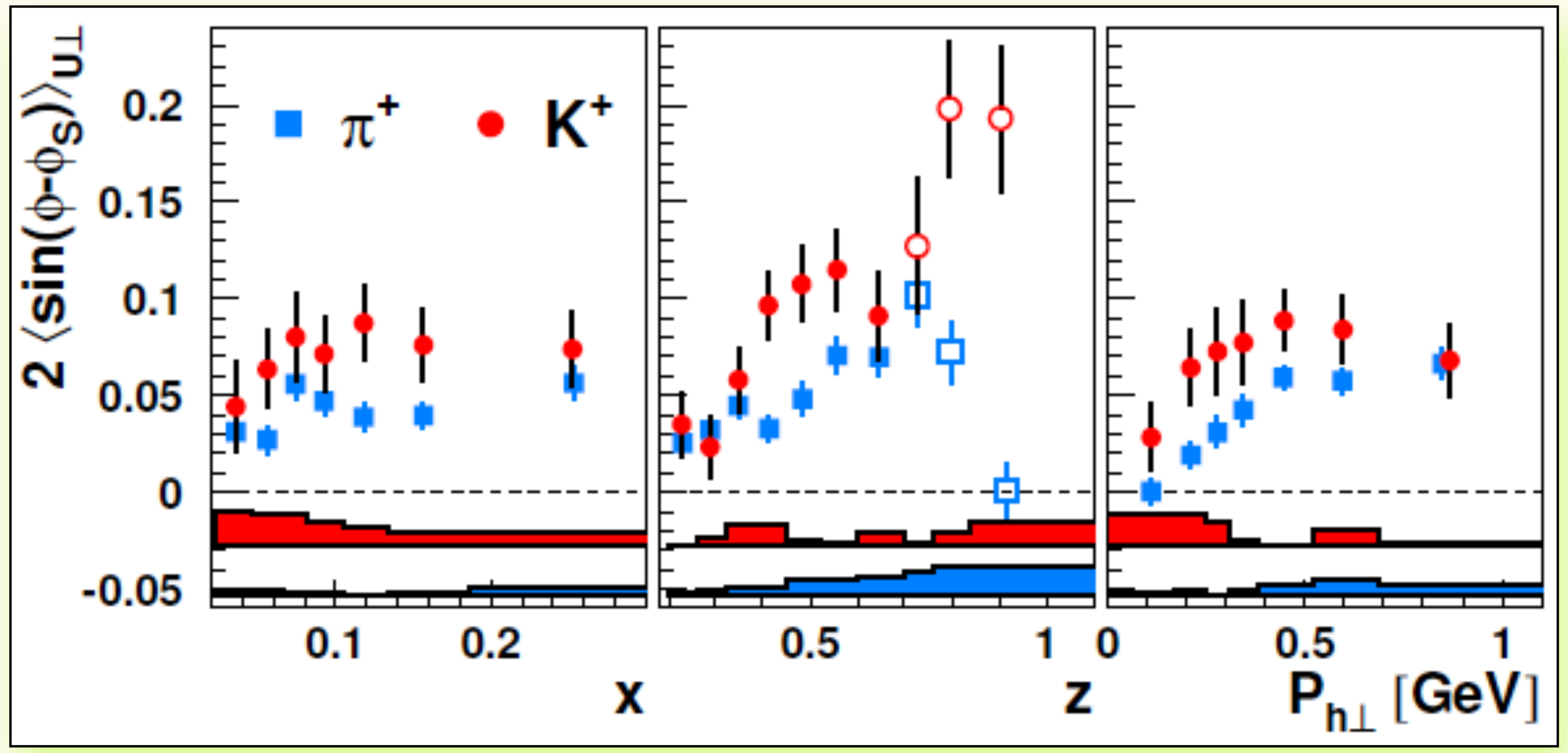
Sivers TMD in SIDIS



Final HERMES **Sivers asymmetries**

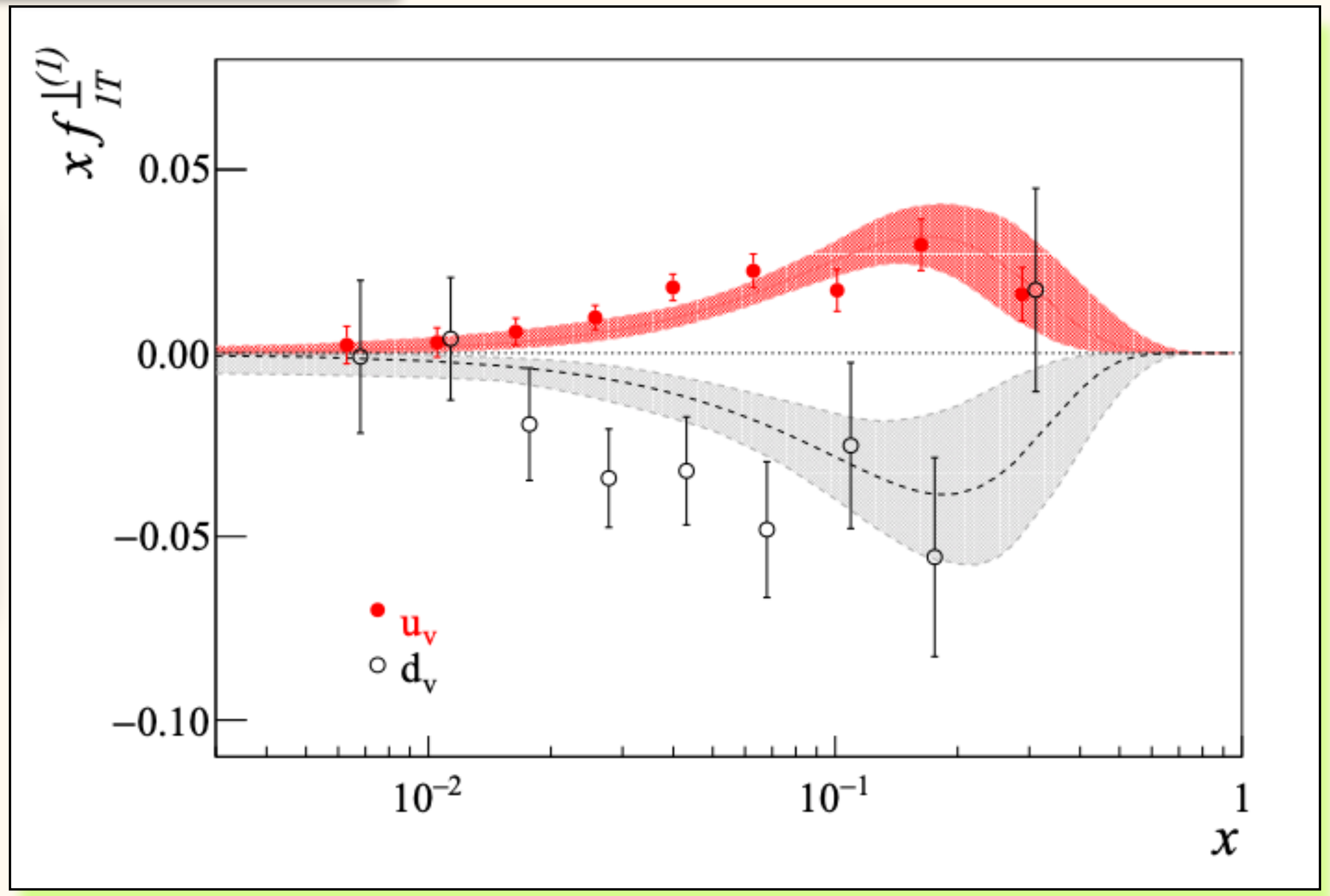
COMPASS **Sivers asymmetries**

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



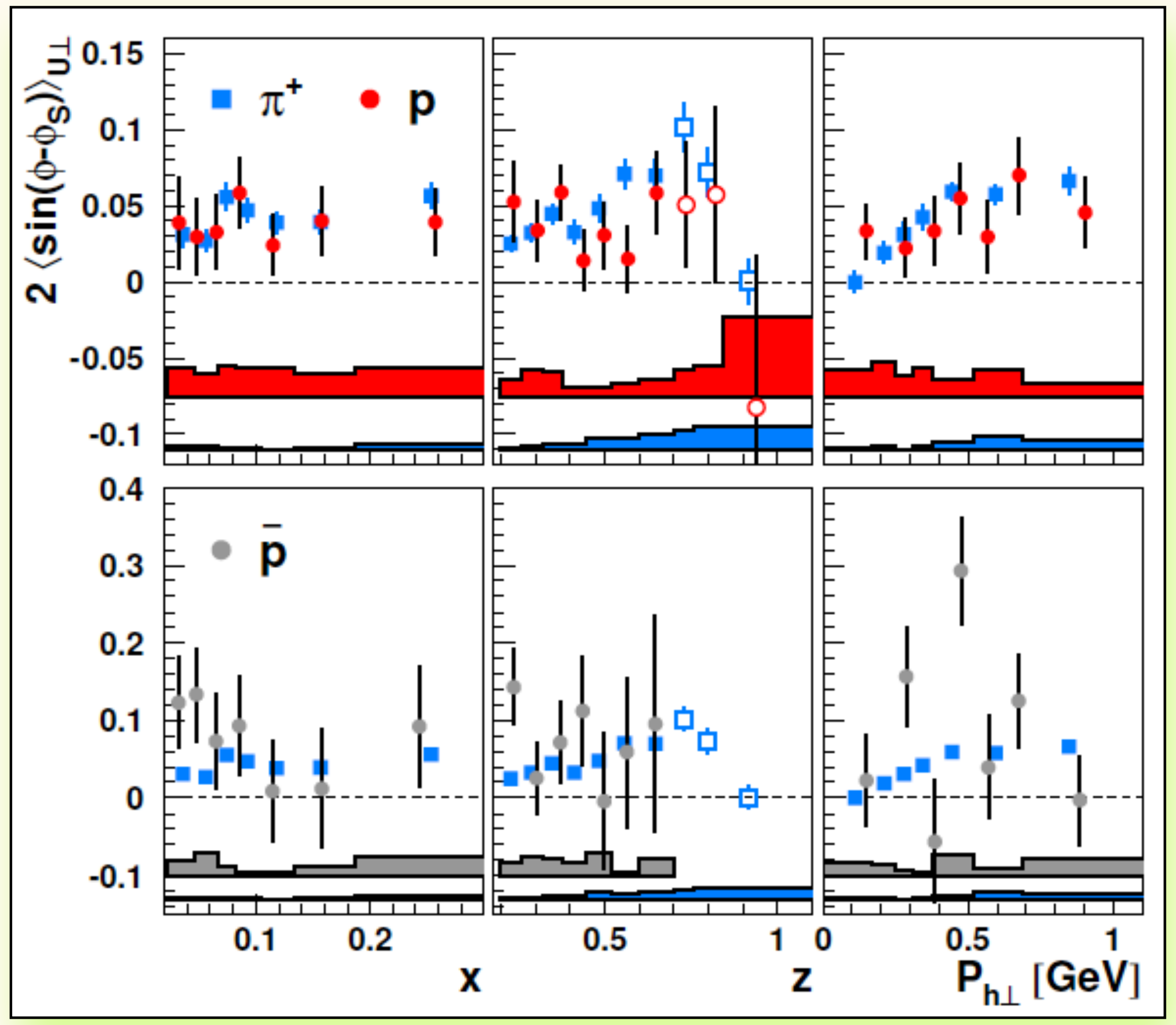
Kaon amplitudes larger than pion
~Unexpected if u-quark scattering dominates. Role of sea quarks?

u- and d-quark Sivers functions have different signs



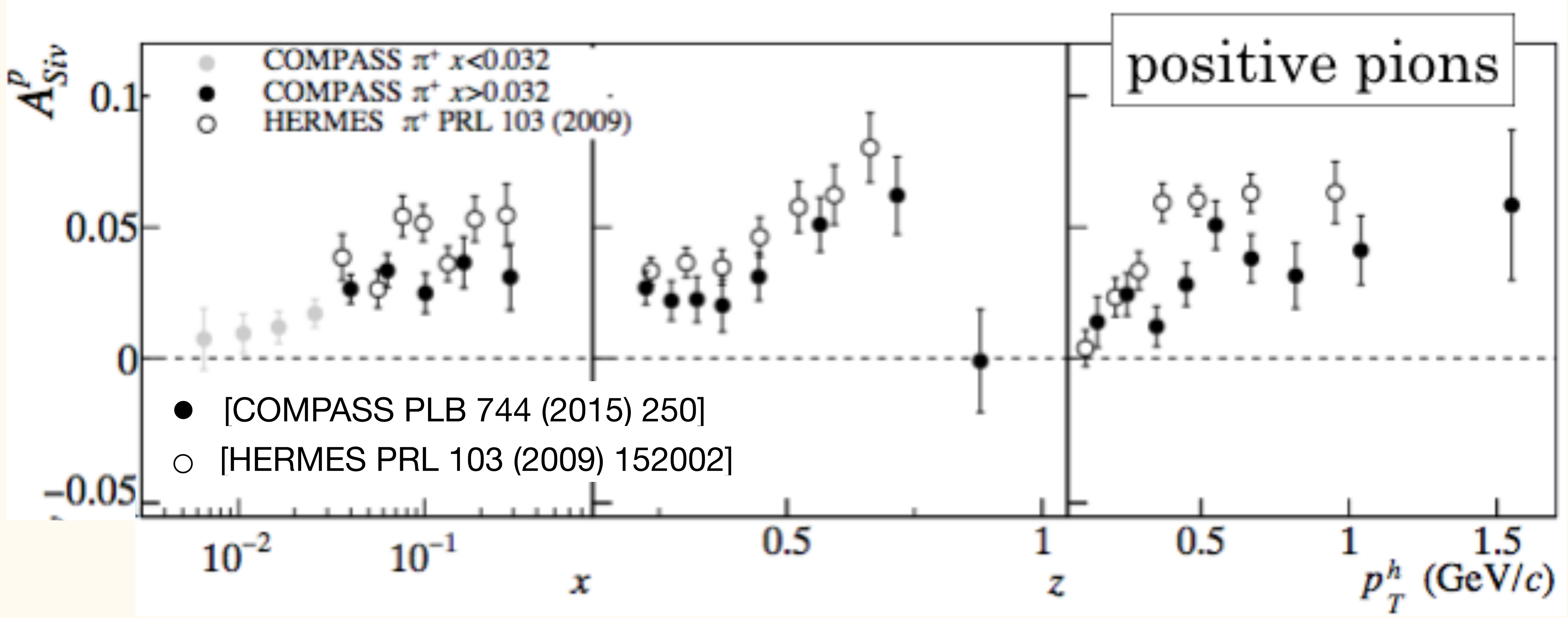
[COMPASS NPB 940 (2019) 34]
[Anselmino *et al.*, Phys.Rev. D86 (2012) 014028]

see talk by L. Pappalardo, Tuesday, 12:00



- ✦ 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

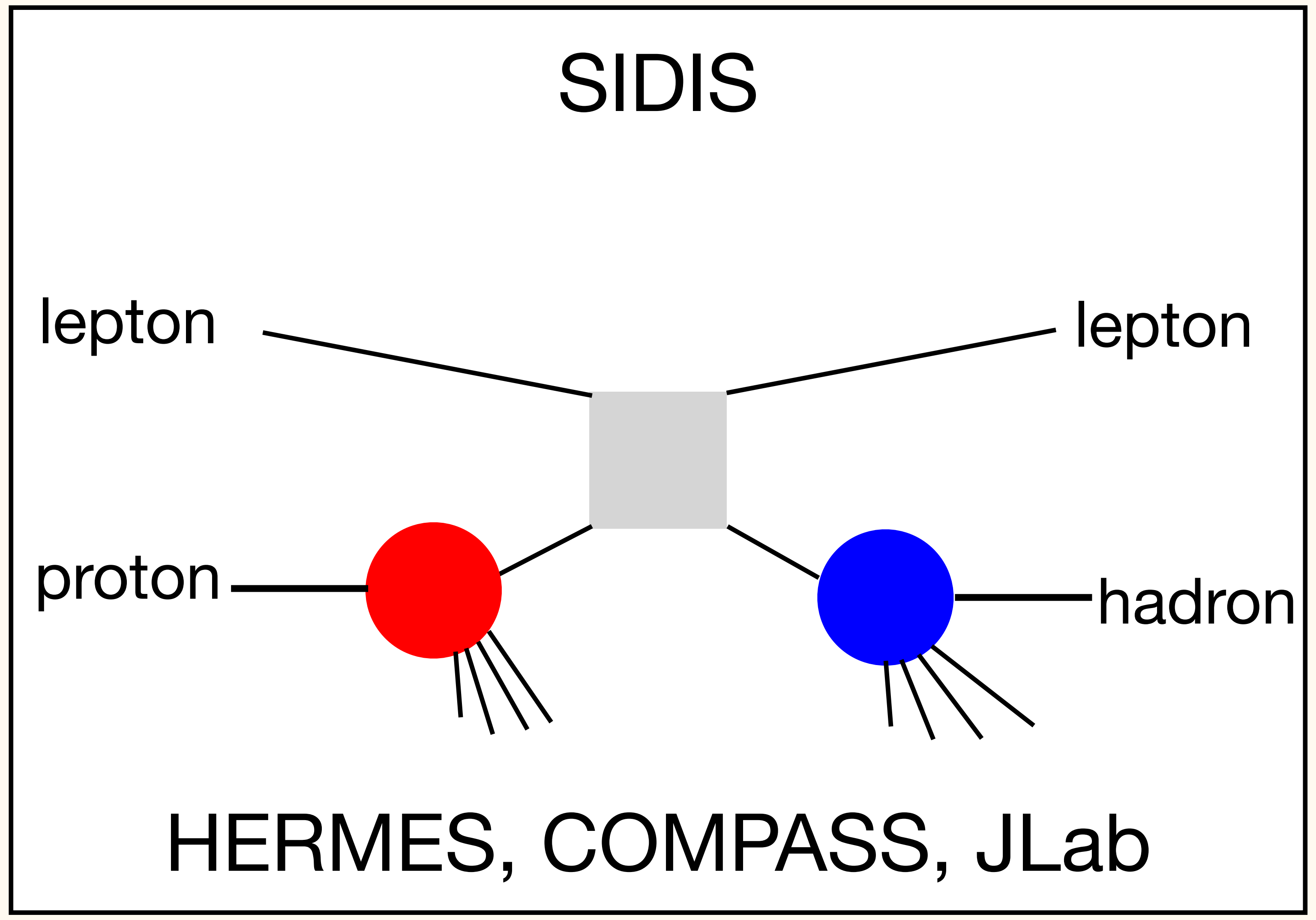
Sivers signal smaller at COMPASS than at HERMES. TMD evolution…?

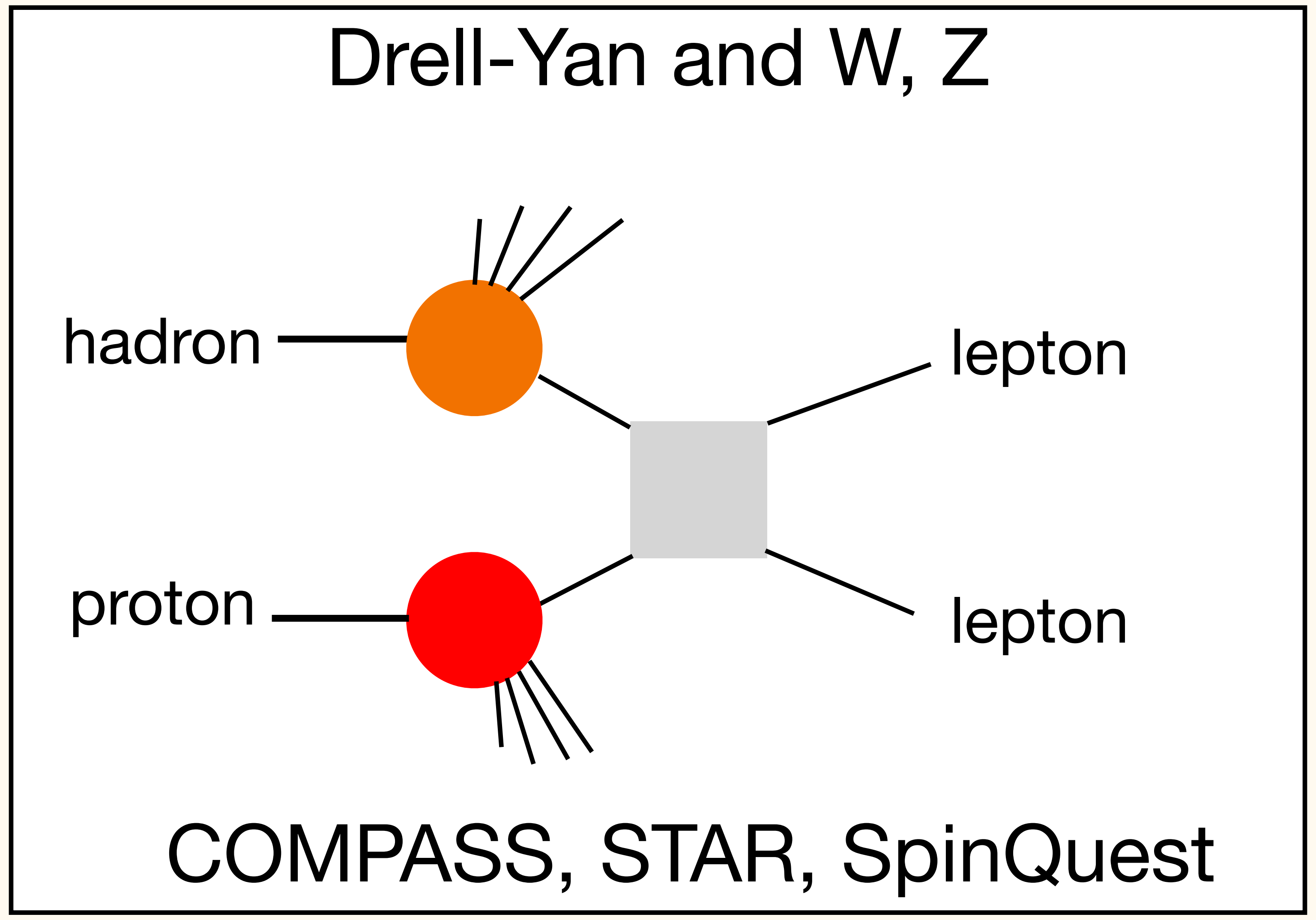


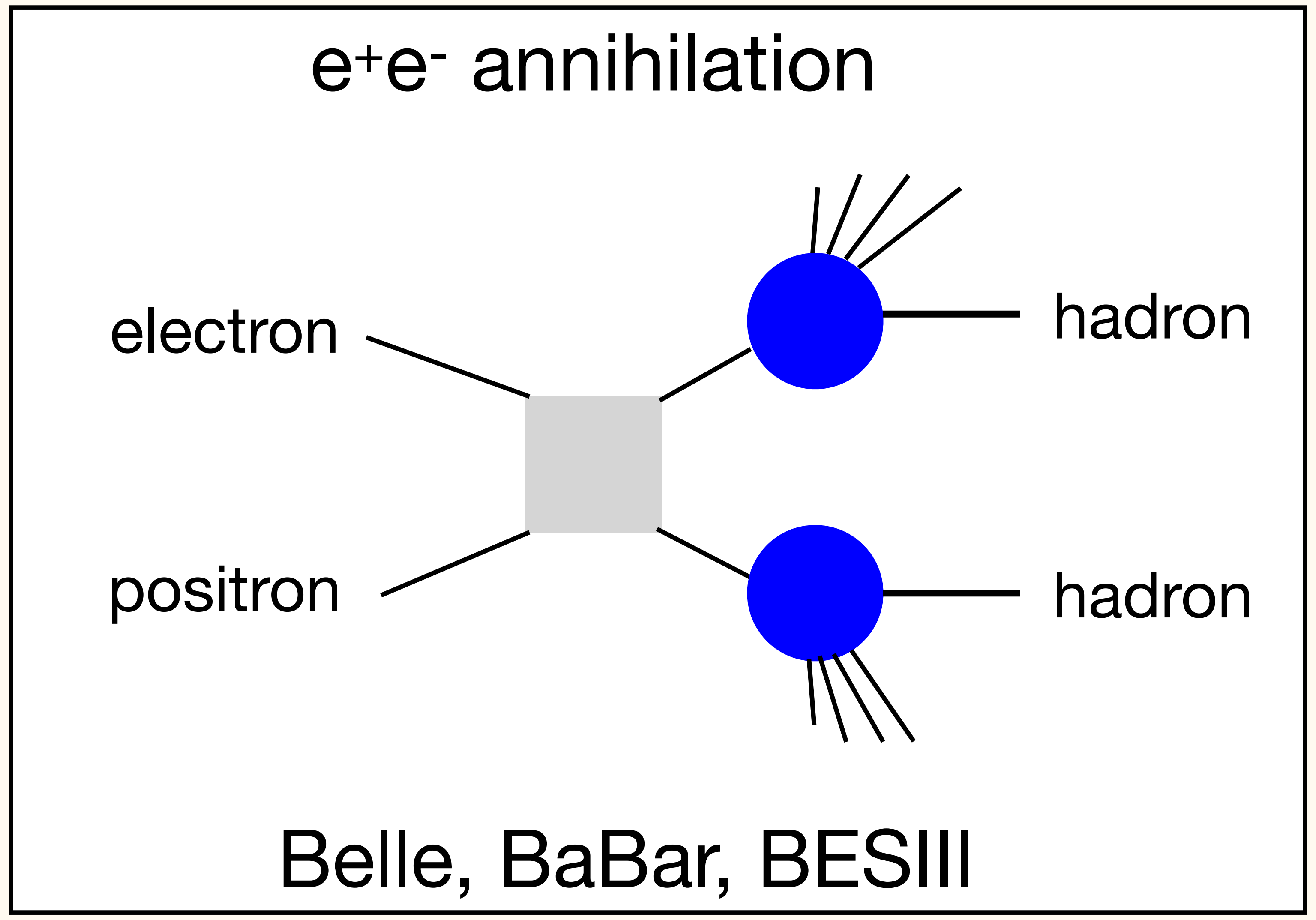
● [COMPASS PLB 744 (2015) 250]
○ [HERMES PRL 103 (2009) 152002]

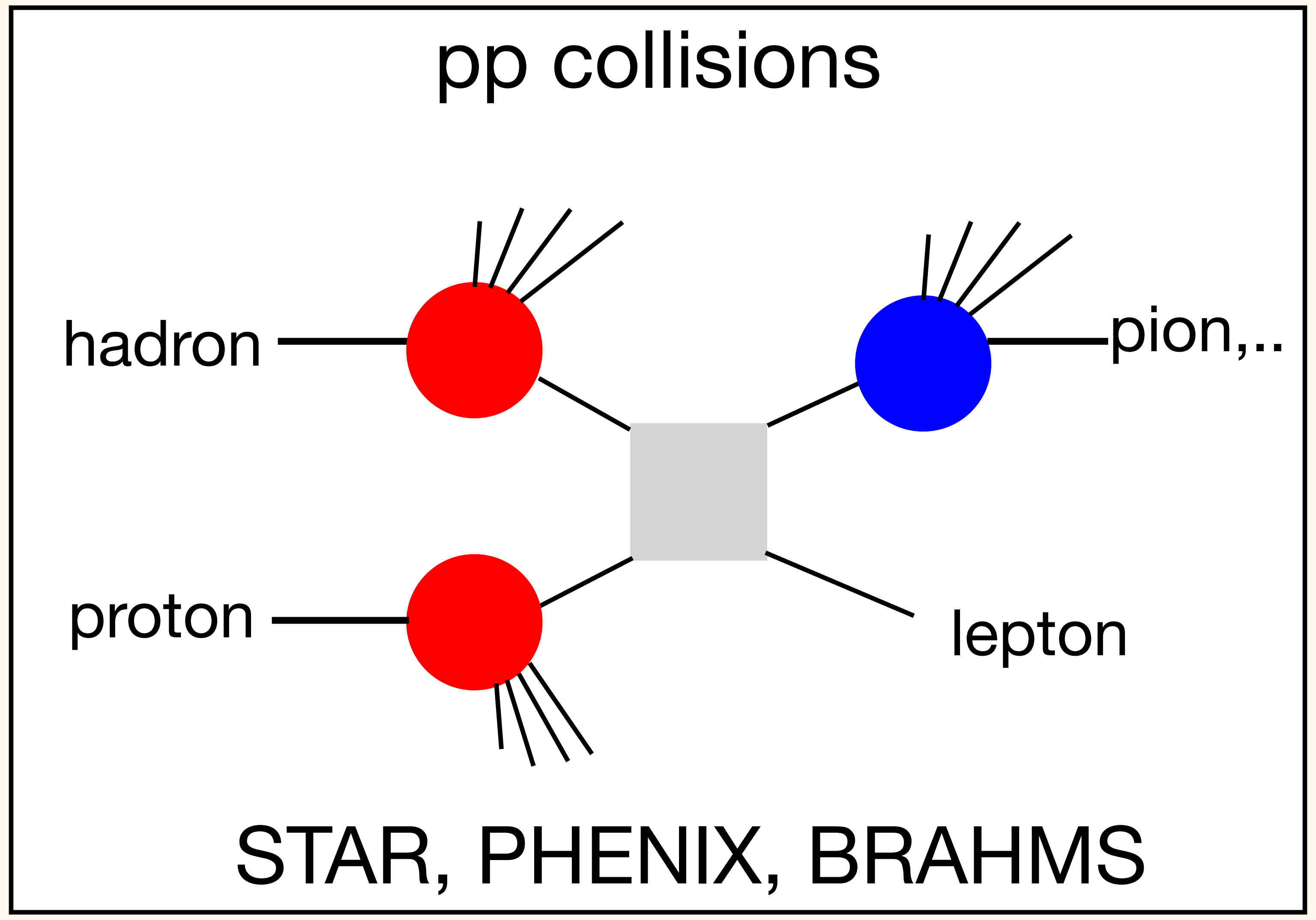
- ✦ Higher lepton-beam energy than at HERMES (160 GeV vs. 27.6 GeV)

Experimental TMD probes TMD FF



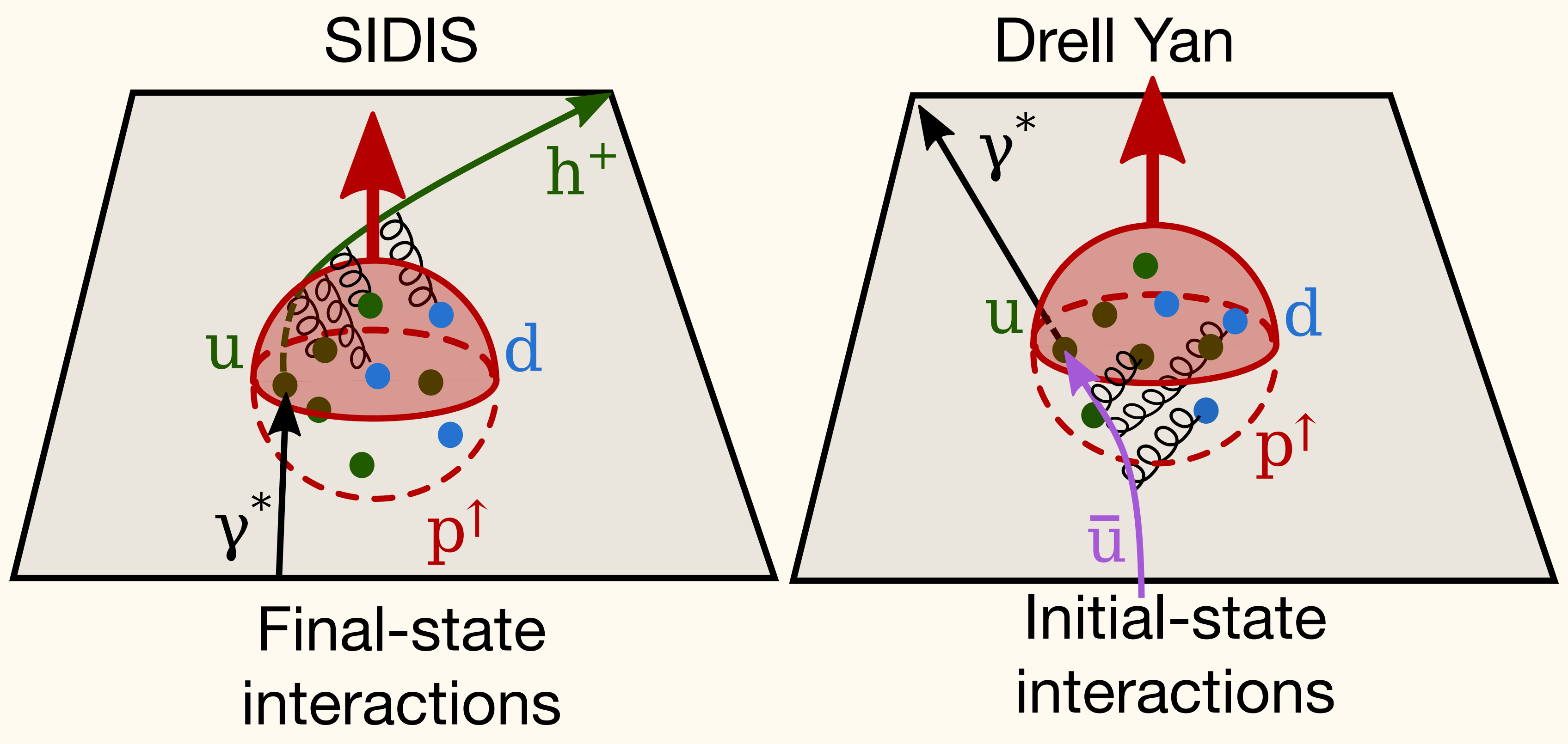






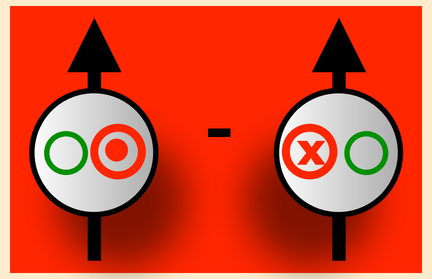
adapted from A. Prokudin *et al.*

- ✦ 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.

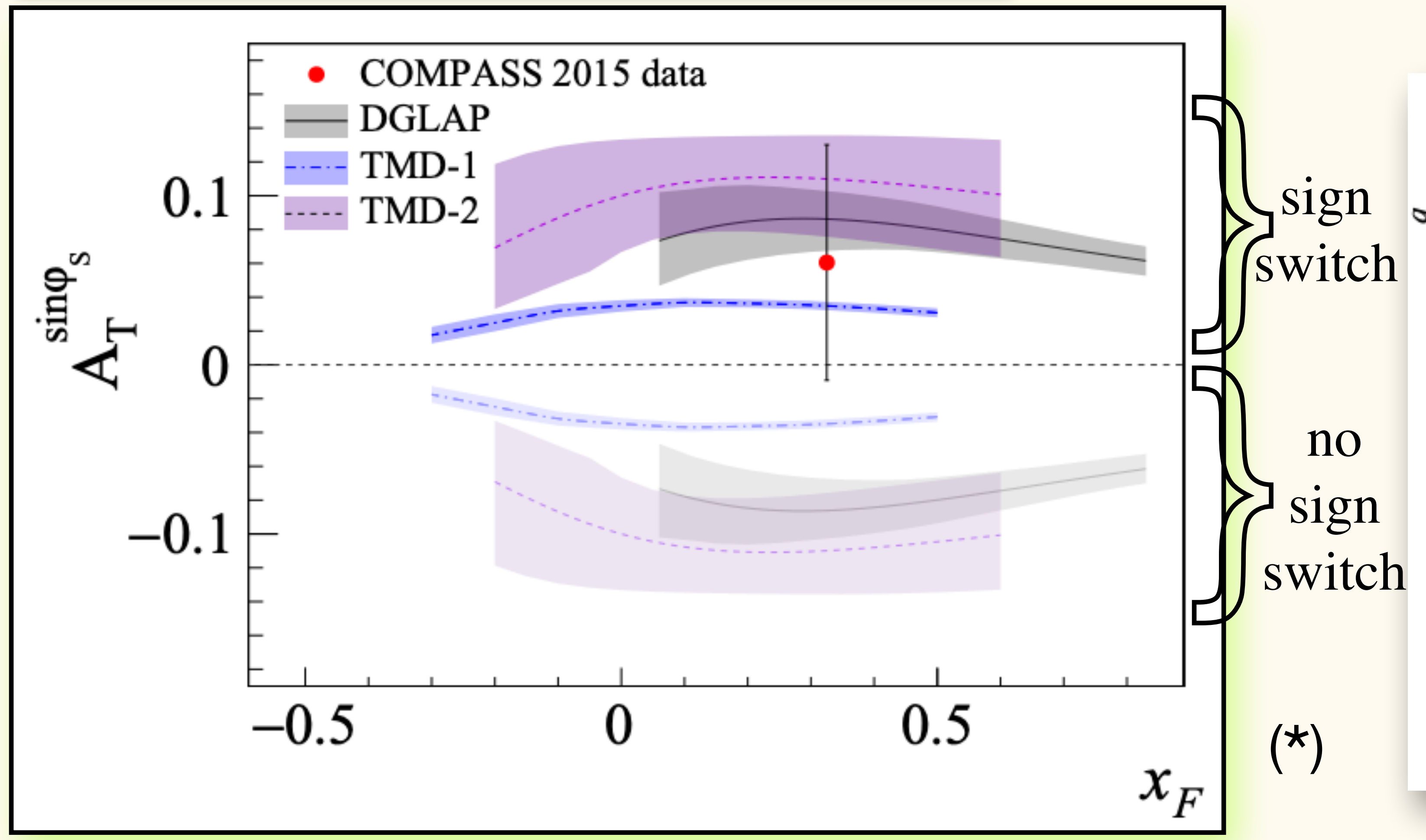


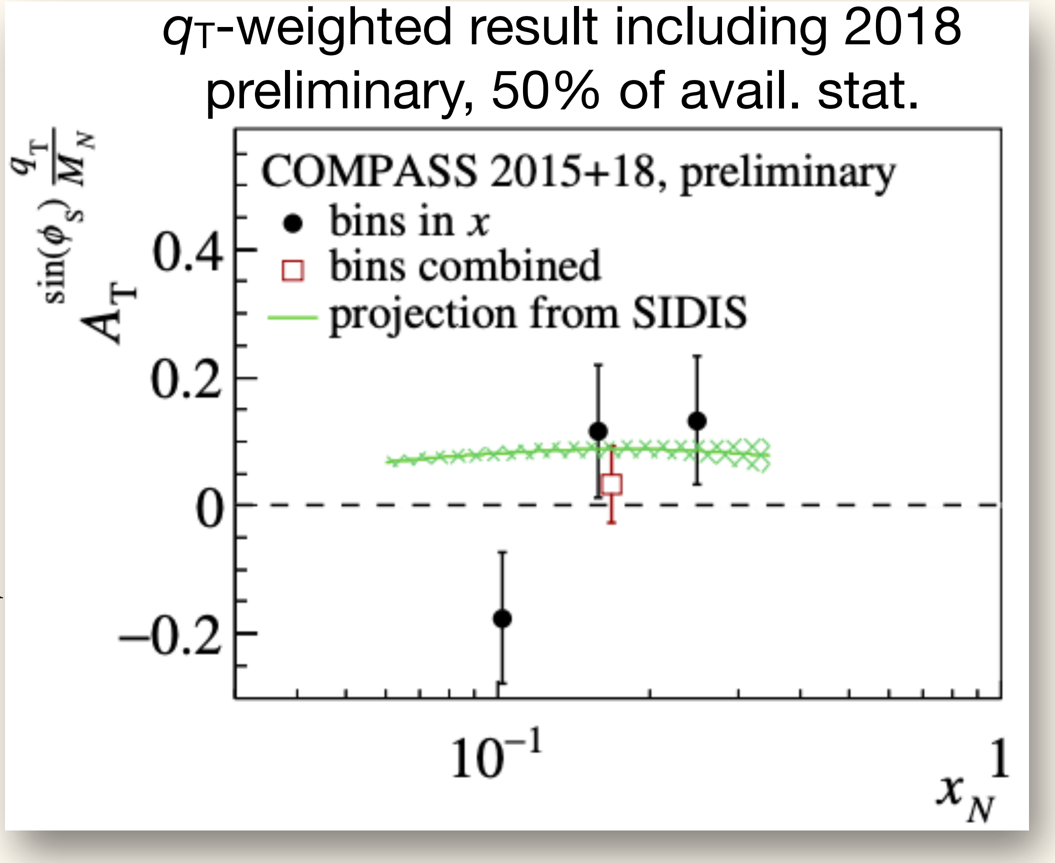
sketches courtesy Jan Matoušek / COMPASS

The Sivers sign switch

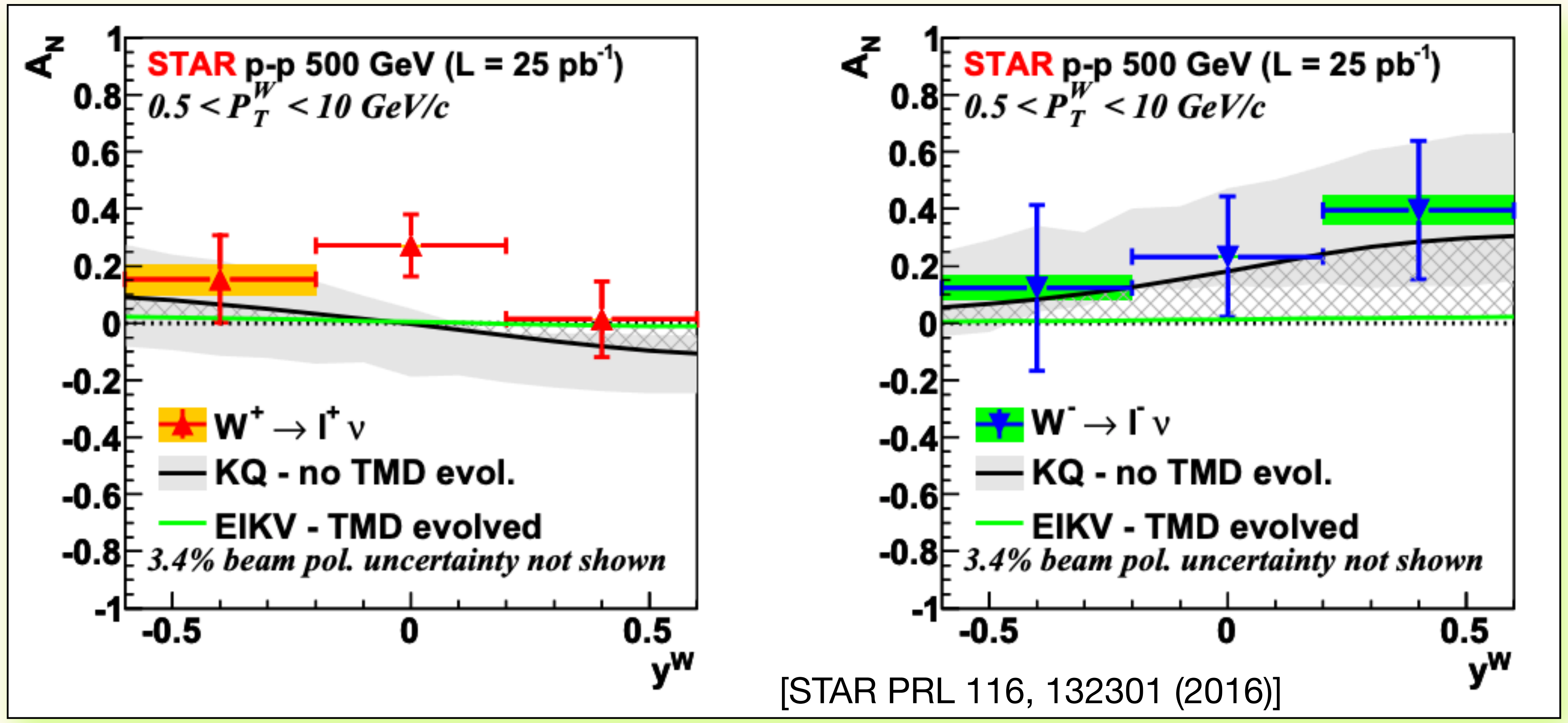


COMPASS Drell-Yan Sivers





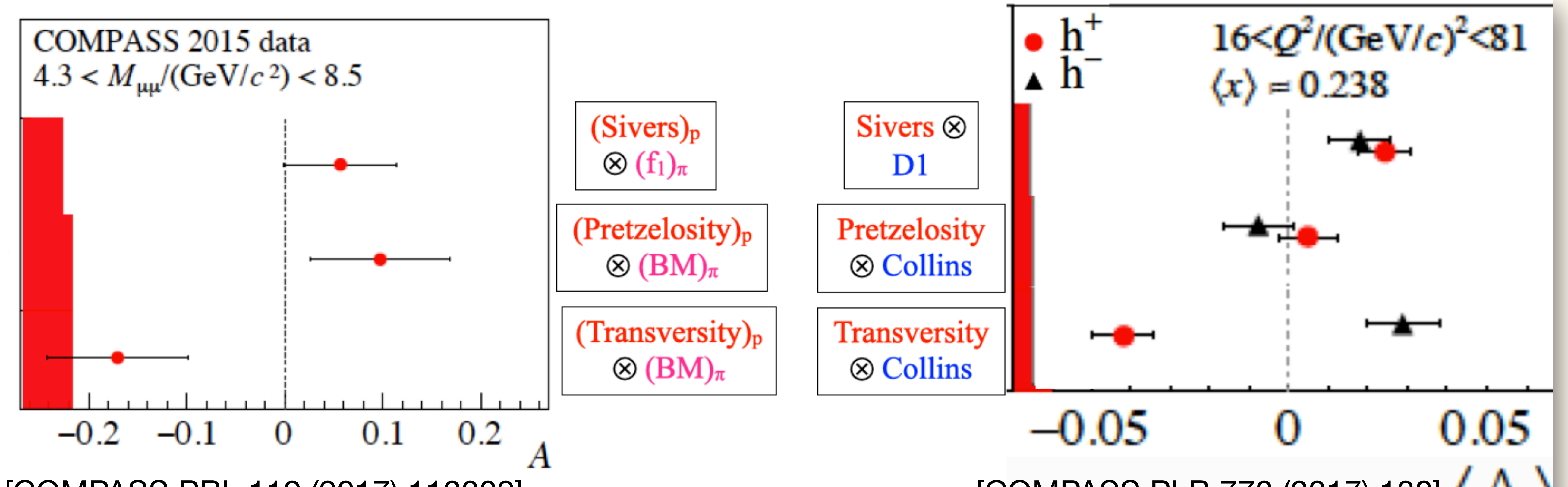
STAR W±/Z A_N



- 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 Y-S. Lien Tuesday, 12:20

Drell-Yan (DY) 2015 data

SIDIS *in the DY kinematic range*



[COMPASS PRL 119 (2017) 112002]

[COMPASS PLB 770 (2017) 138]

- STAR: A_N in $p^\uparrow p \to W^\pm \to e^\pm + \nu$
  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]

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

(*) **"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).

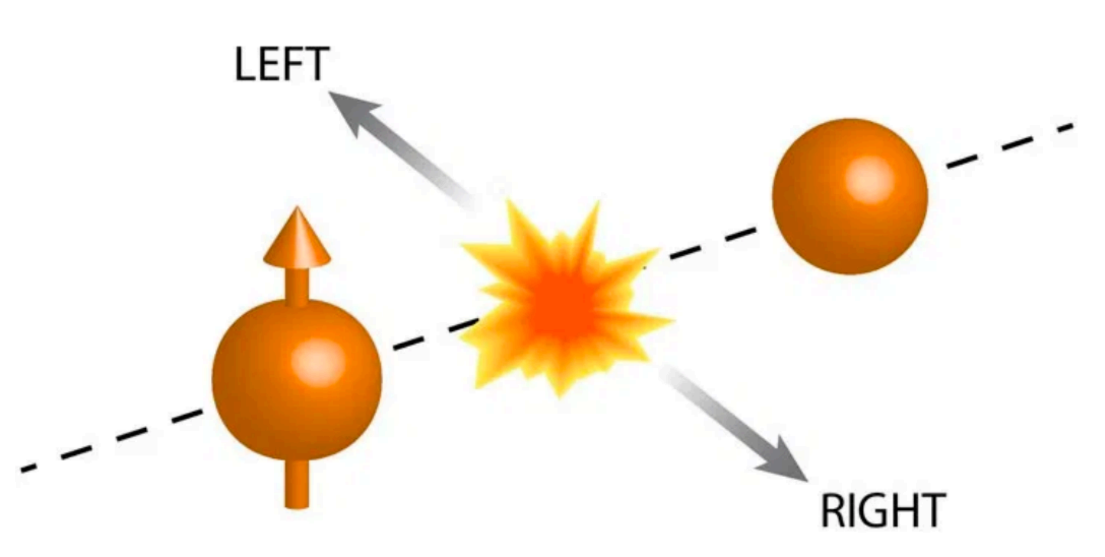
Left-right asymmetries

- 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.

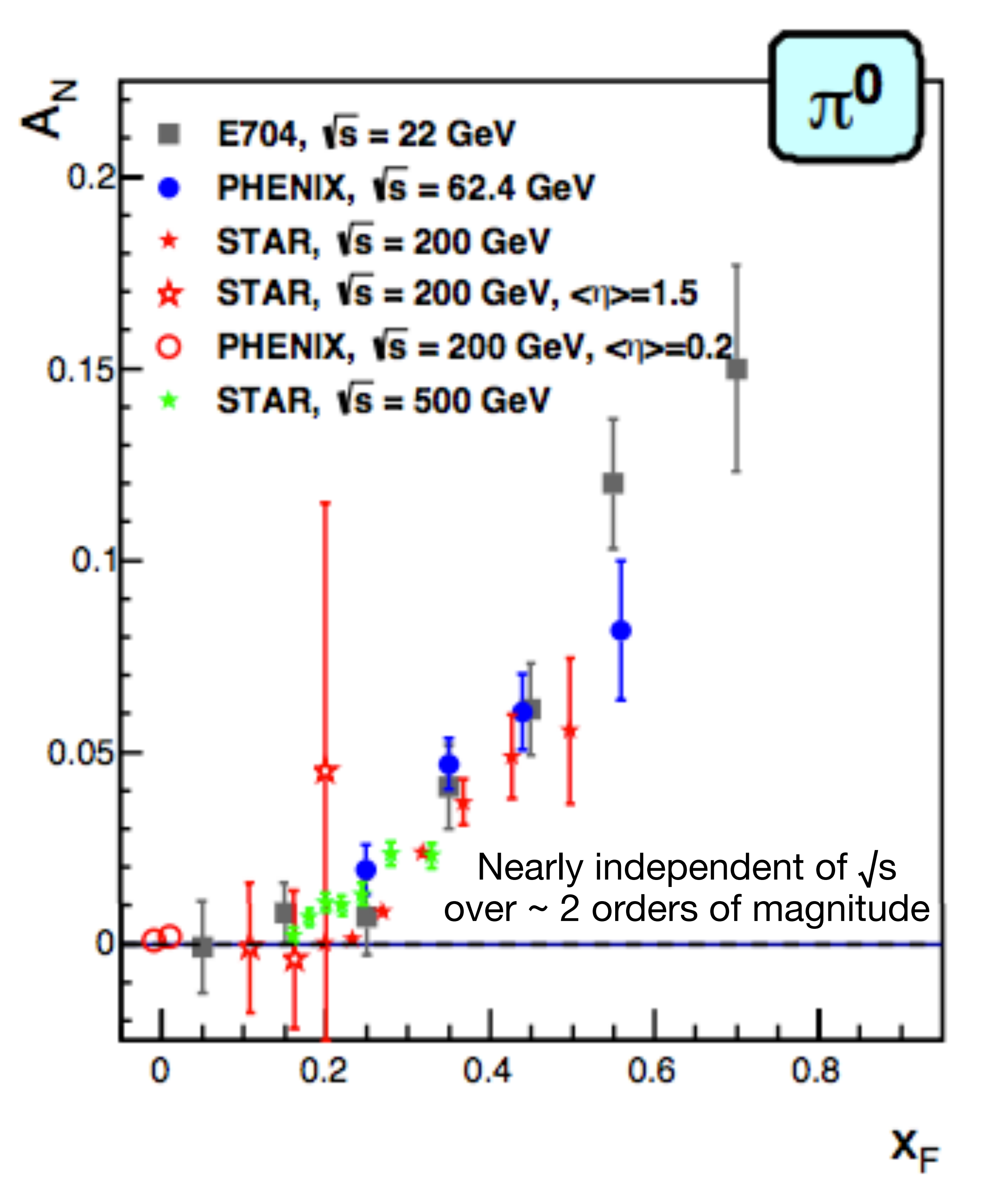
e.g. [Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (JAM Collaboration), PRD 102, 054002 (2020)]

- **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.

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



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

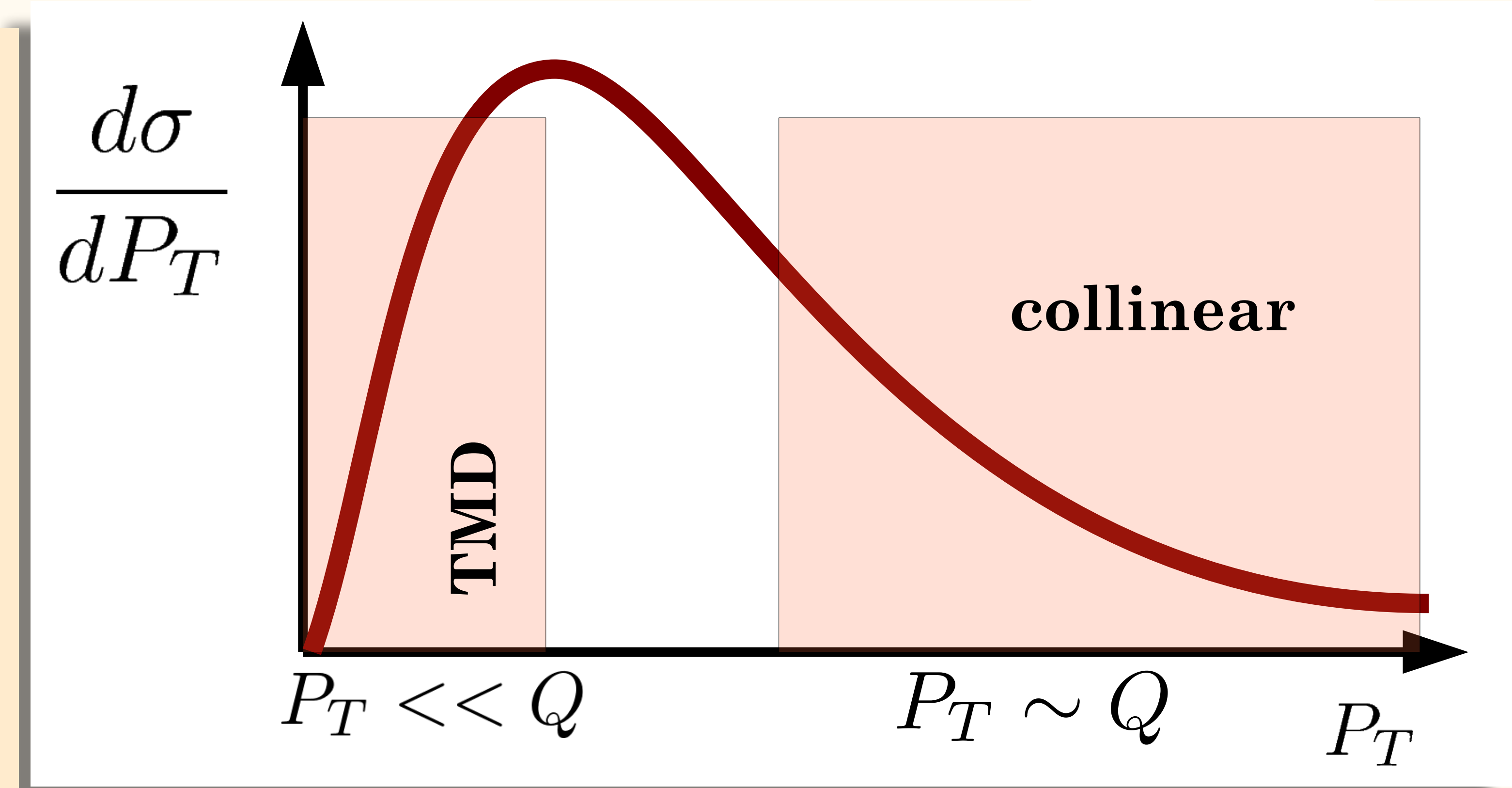


[The RHIC spin program - achievements and future opportunities, E. Aschenauer et al. arXiv:1304.0079]

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)**

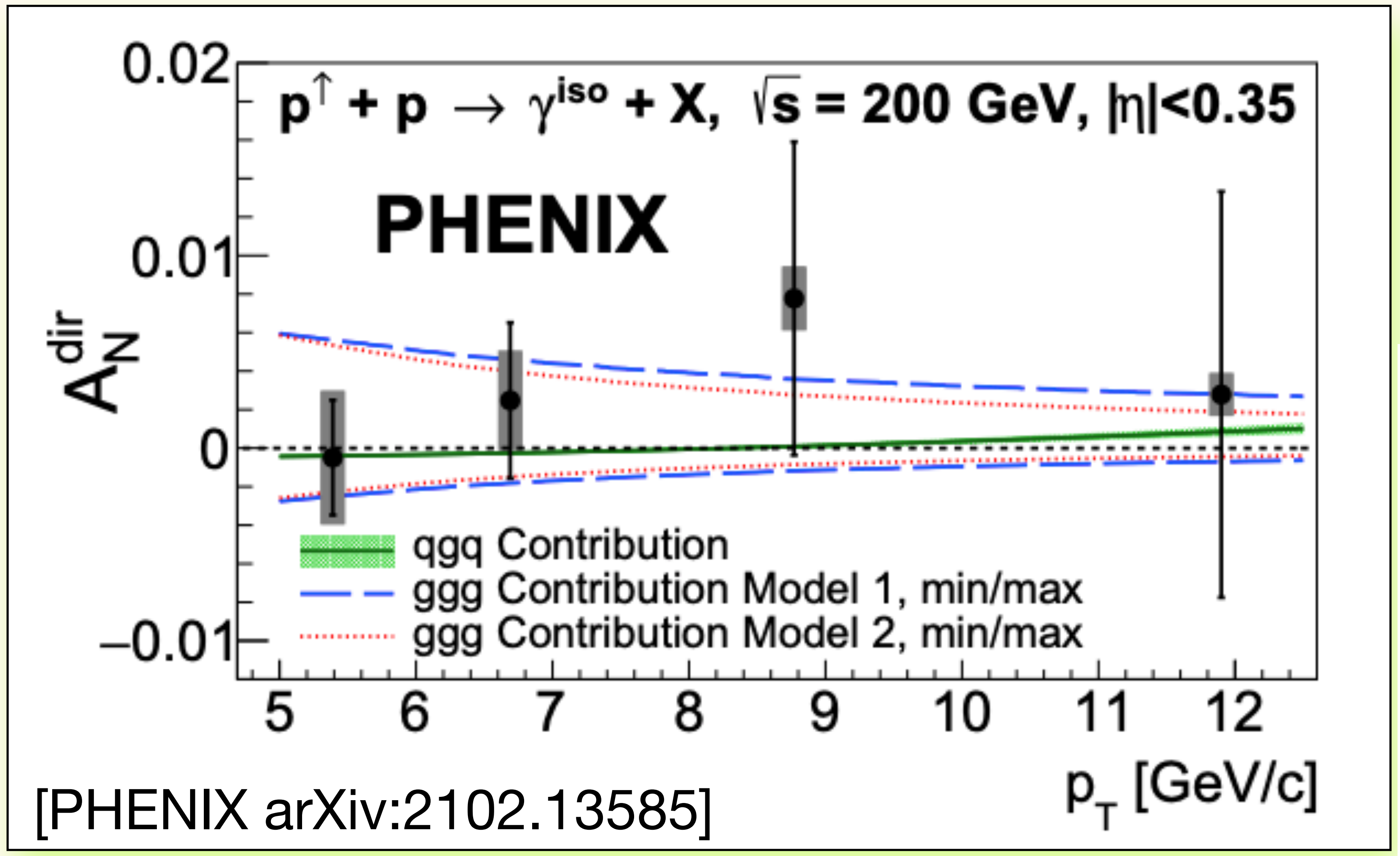
single inclusive particle production in pp (particle or jet p_T)

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



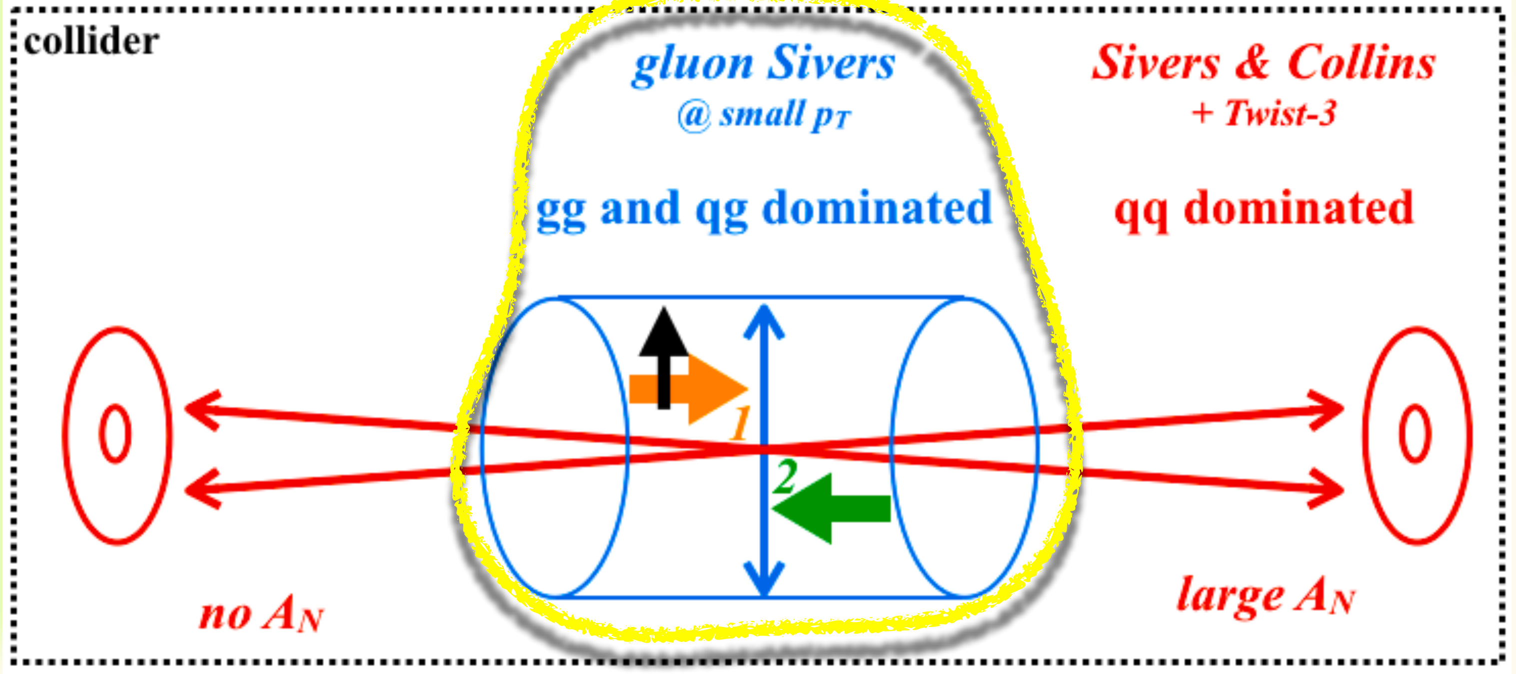
[PHENIX arXiv:2102.13585]

see talk by N. Lewis, Tuesday, 9:43

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

gluon Sivers TMD

no signals, at high precision



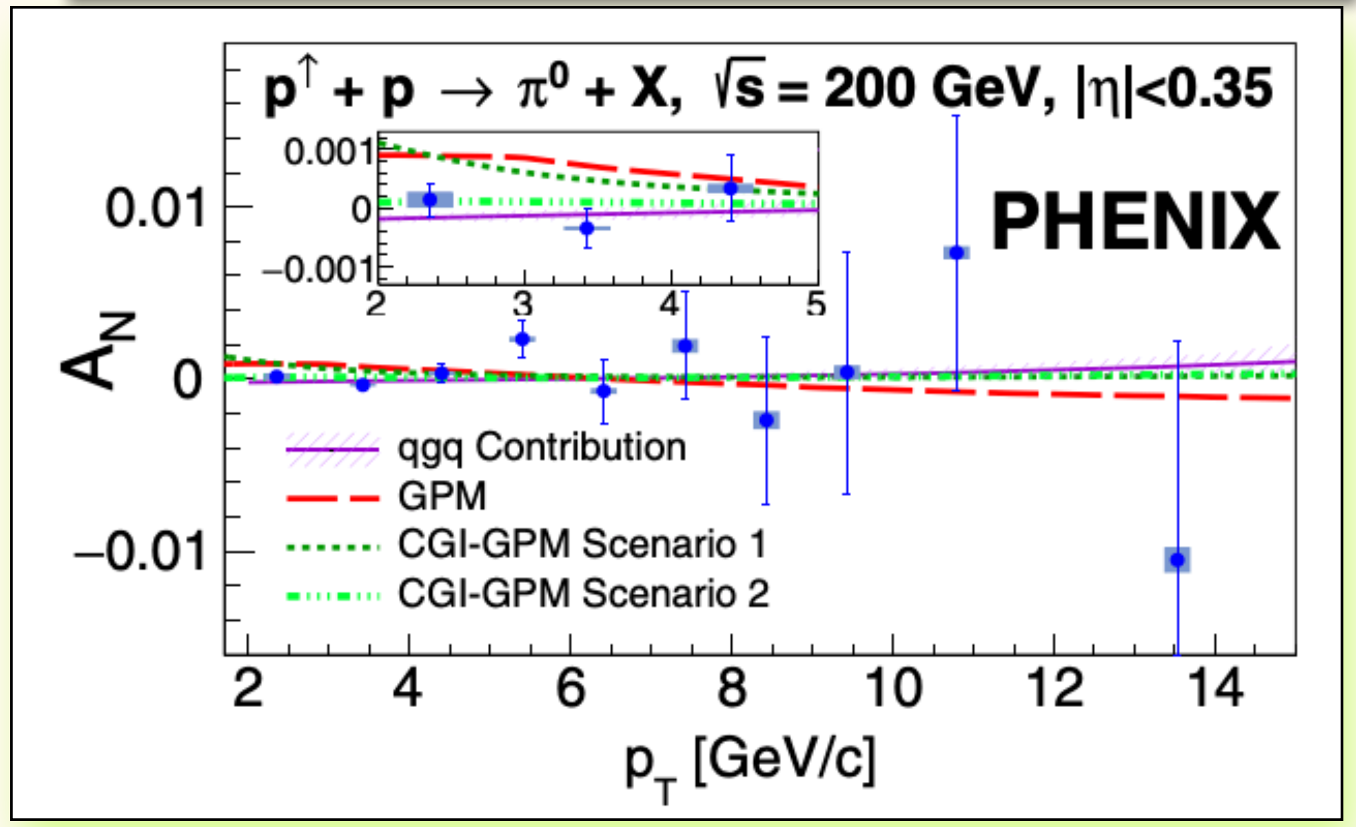
- ✦ How do these results relate to the non-zero SIDIS results from COMPASS?
  - Photon-gluon fusion with signature of 2 high-p_T hadrons, p+d: A_{Siv} = -0.23 ± 0.08(stat) ± 0.05(sys), PLB 772 (2017) 854
  - Exclusive J/Psi production in SIDIS on p: A_{Siv} = −0.28 ± 0.18, preliminary

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

- ✦ Yet another gluon probe: PHENIX heavy-flavor A_N to be released at DIS 21

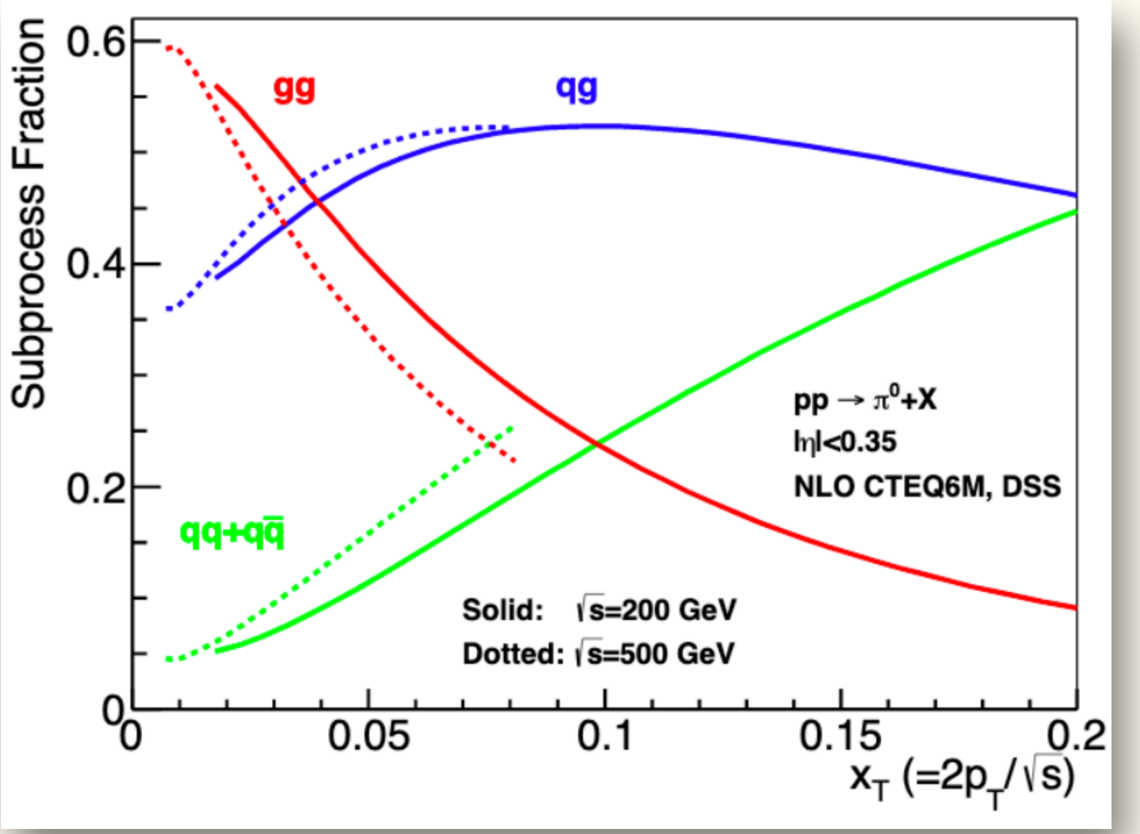
heavy flavor A_N: see talk by D. Fitzgerald, Tuesday, 10:01

New PHENIX **pion and eta A_N**

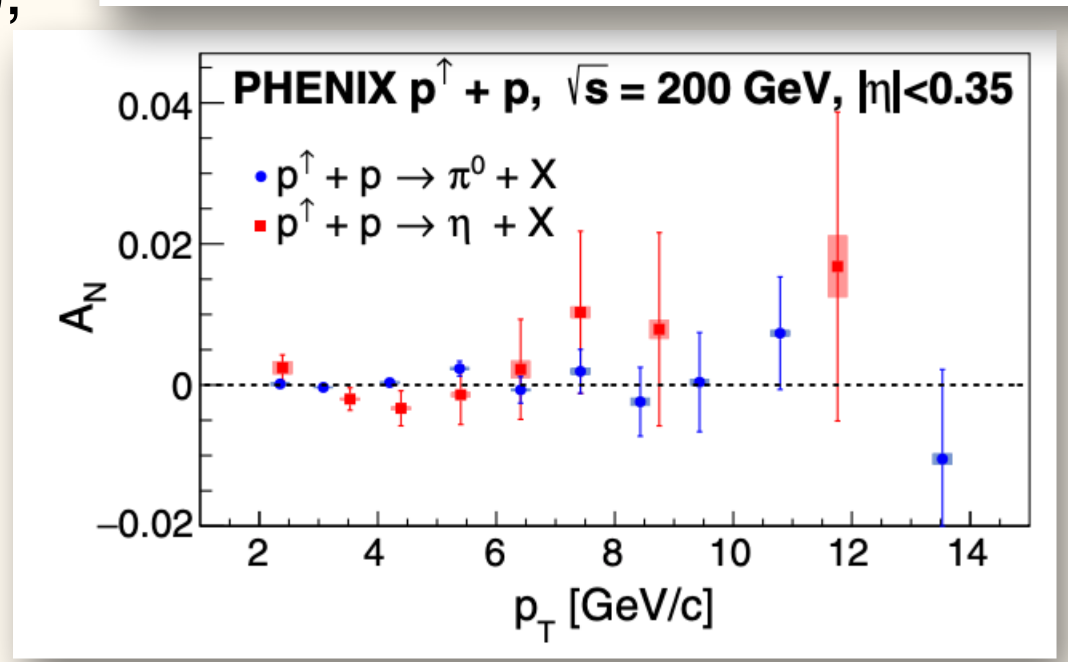


GPM scenarios: [D'Alesio, Flore, Murgia, Pisano, Taels, PRD 99, 036013 (2019)]

[PHENIX PRD 103 (2021) 5, 052009]

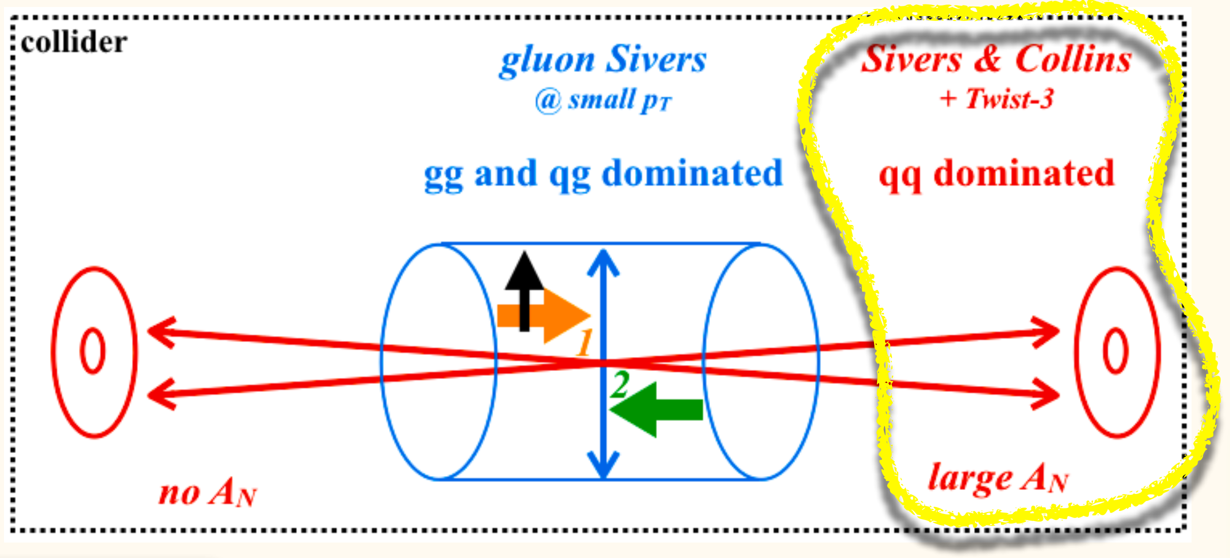


Subprocess fractions at RHIC energies for gg, qg, qq+qqbar



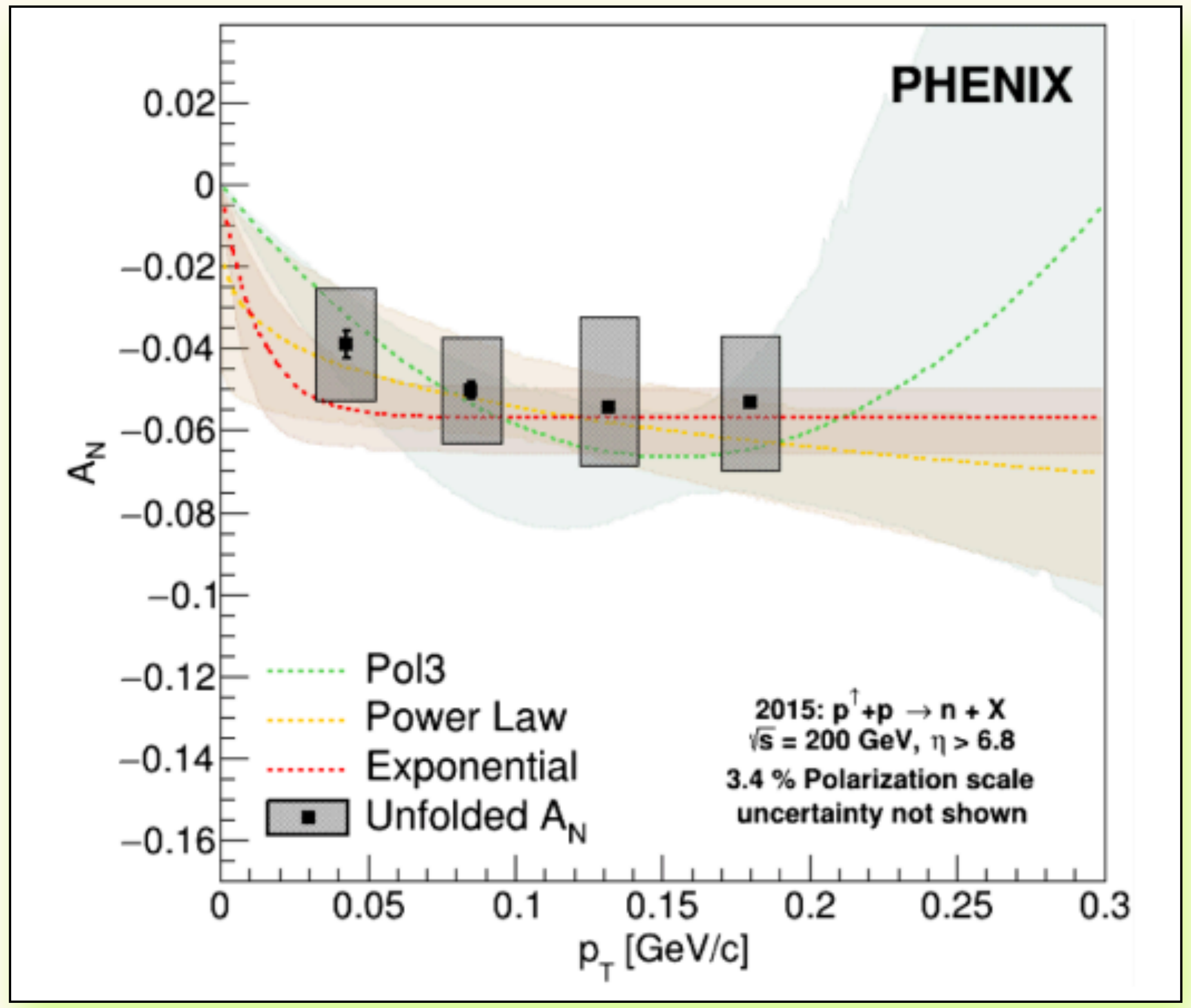
ΔA_N π^0 vs. η: disentangle possible effects of strangeness, isospin, or mass. Improvement by factor of 3 in stat. uncertainty

A_N in the very forward



PHENIX

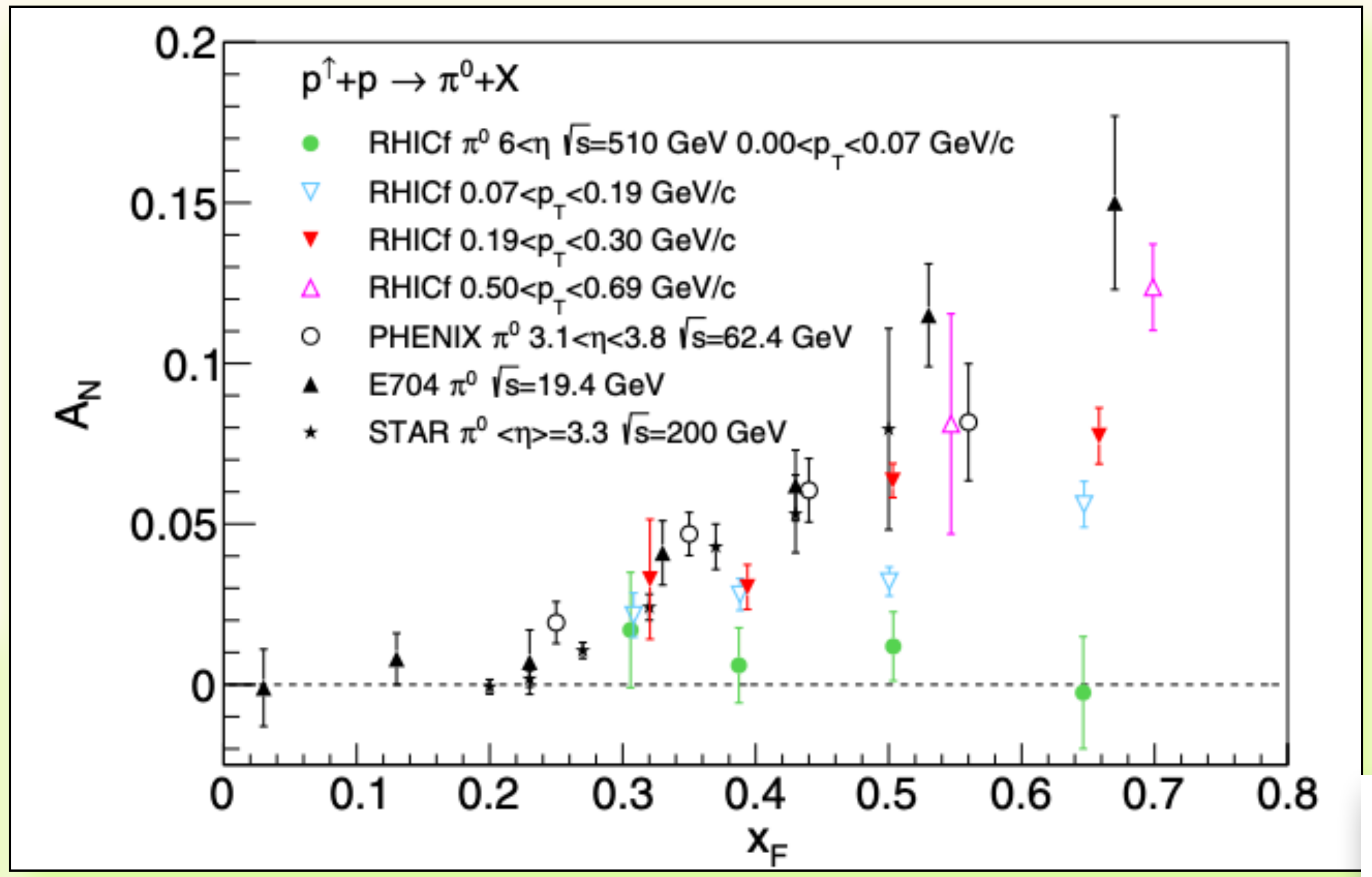
✦ Detection of very forward neutrons using a zero-degree calorimeter (ZDC) ~20m from PHENIX IP



[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)]

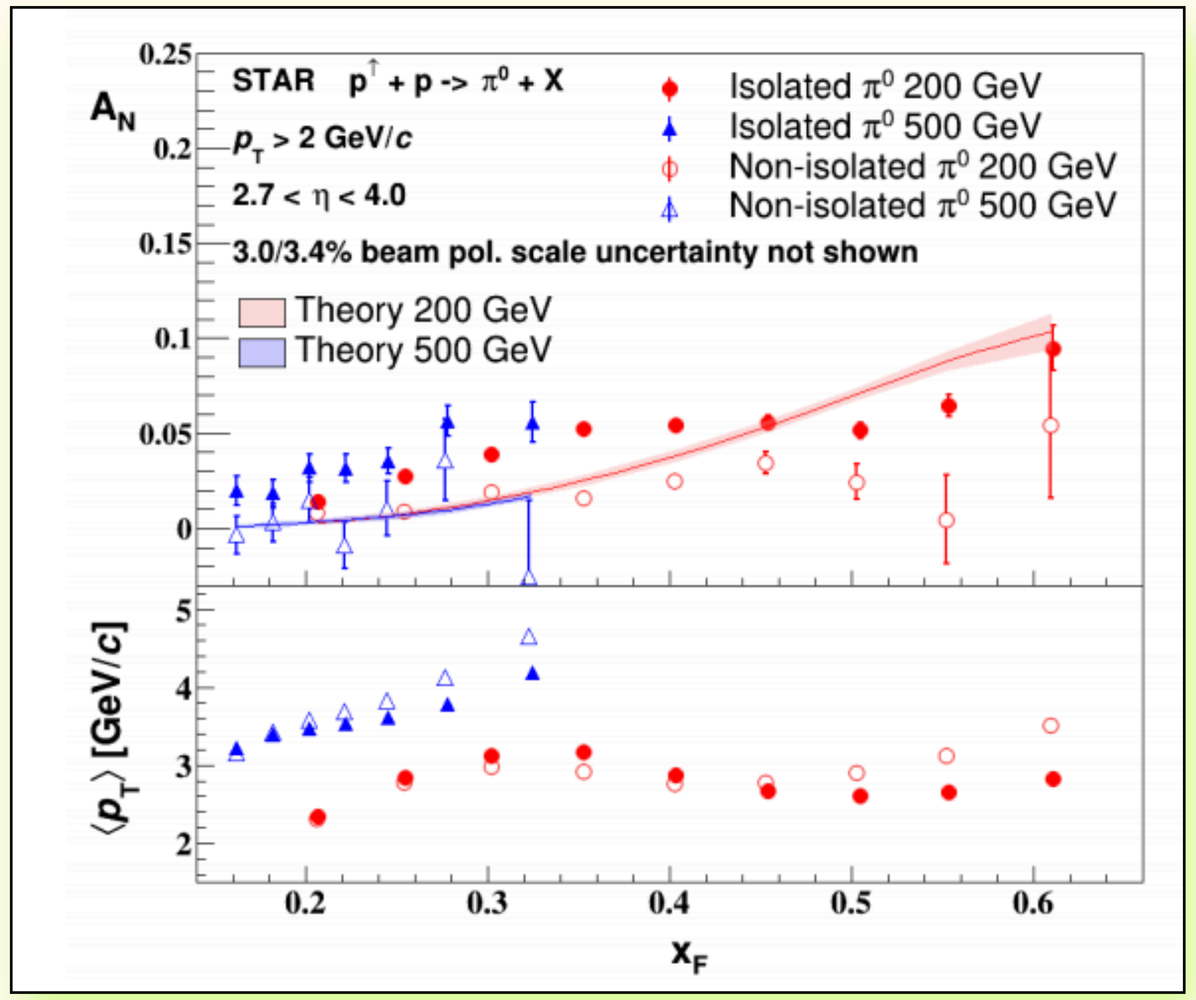
see talk by M. Kim, Wednesday, 10:00

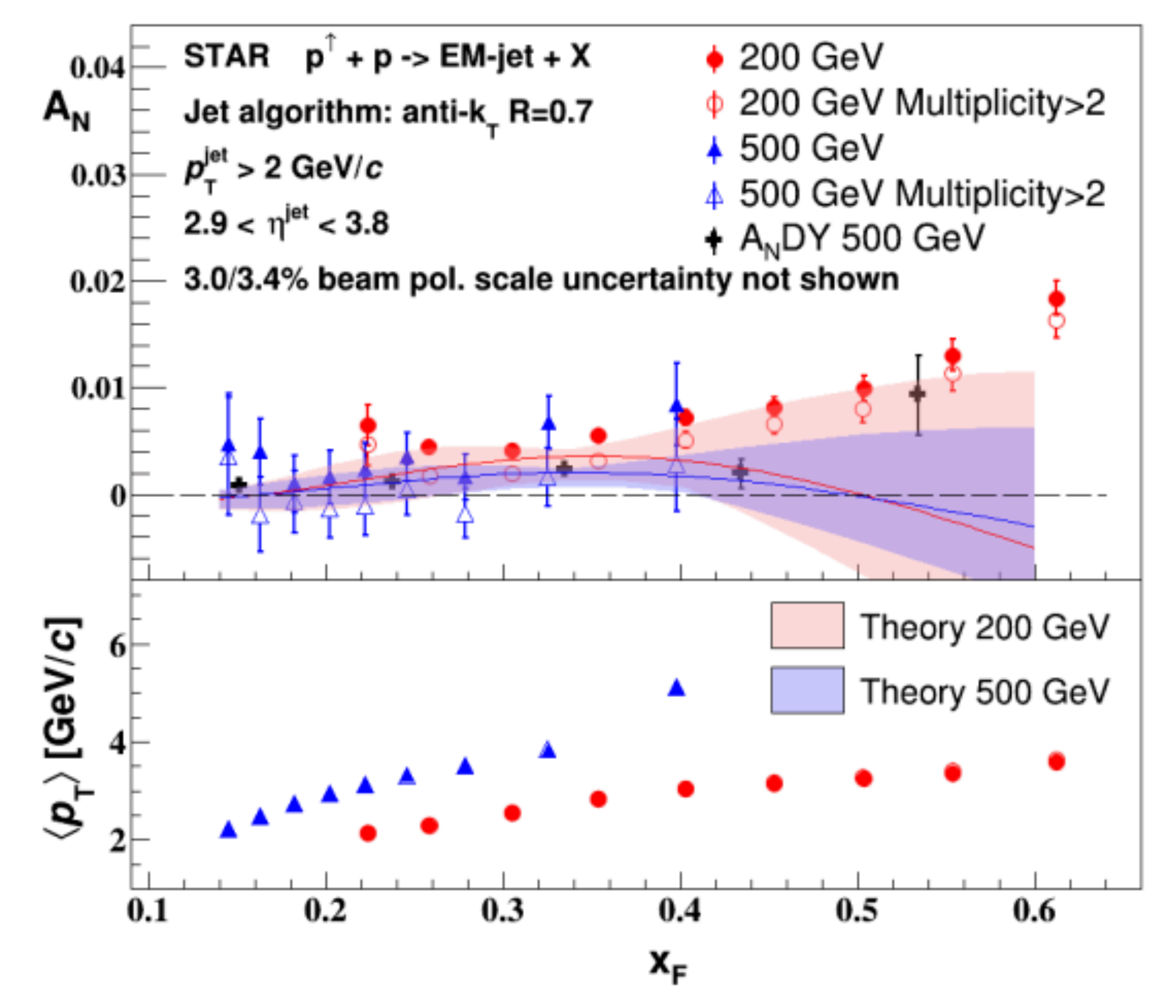
A_N increases with p_T & forwardness & π^0 isolation (STAR) & γ multiplicity (STAR)

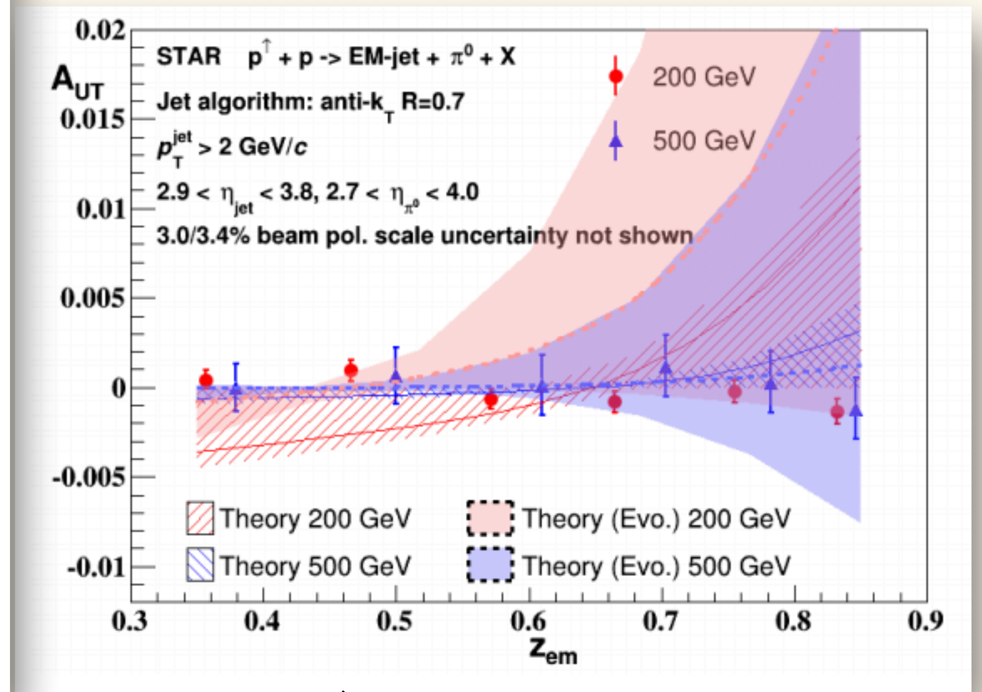
A_N from soft processes such as diffractive scattering?

STAR

✦ π^0 and electromagnetic jets using Forward Meson Spectrometer





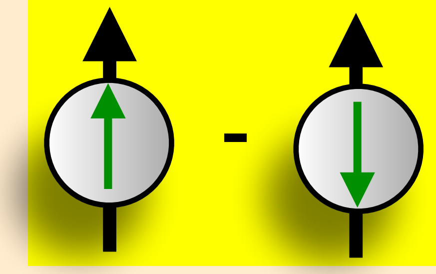


[STAR arXiv:2012.11428]

Collins asymmetries small…

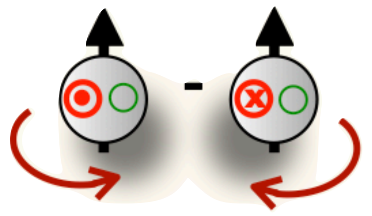
see talk by Z. Zhu, Tuesday, 9:25

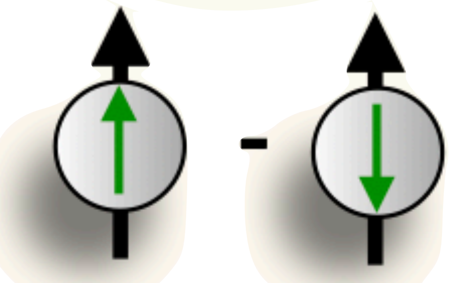
Collins asymmetries



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

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

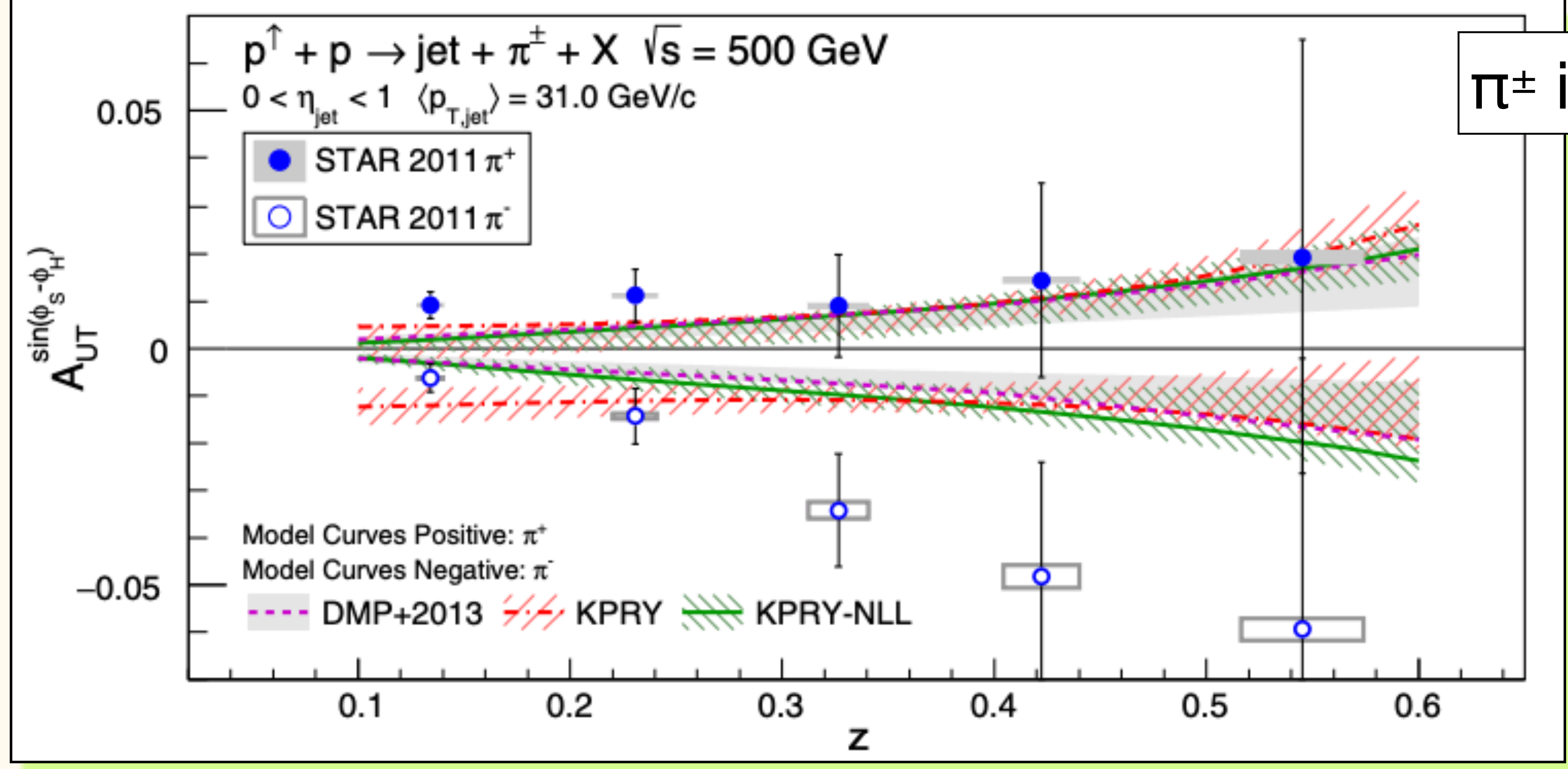
Collins effect: spin-dependent fragmentation of a transversely polarized parton into a final-state hadron — **"quark polarimeter"**

STAR **hadrons in jets** (midrapidity)

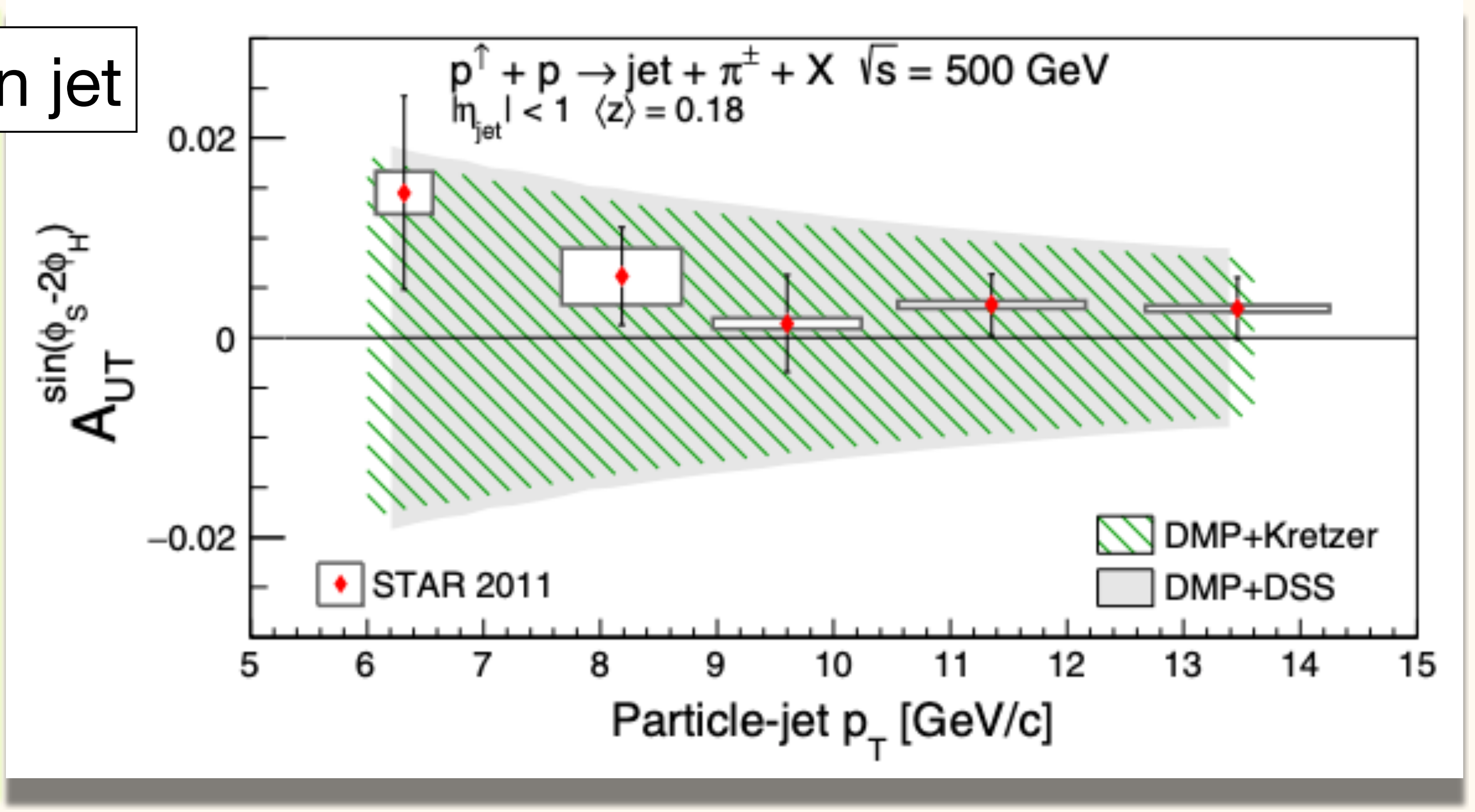
[STAR PRD 97 (2018) 032004]

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

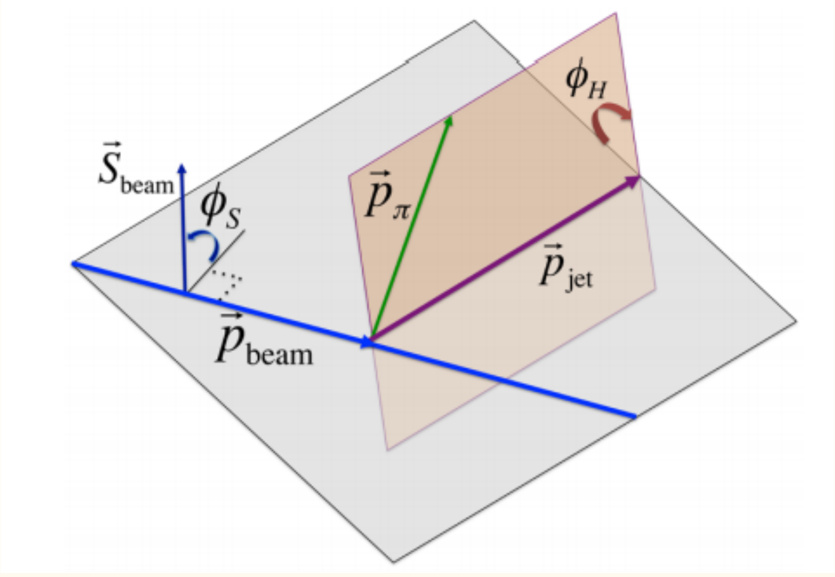
π± in jet

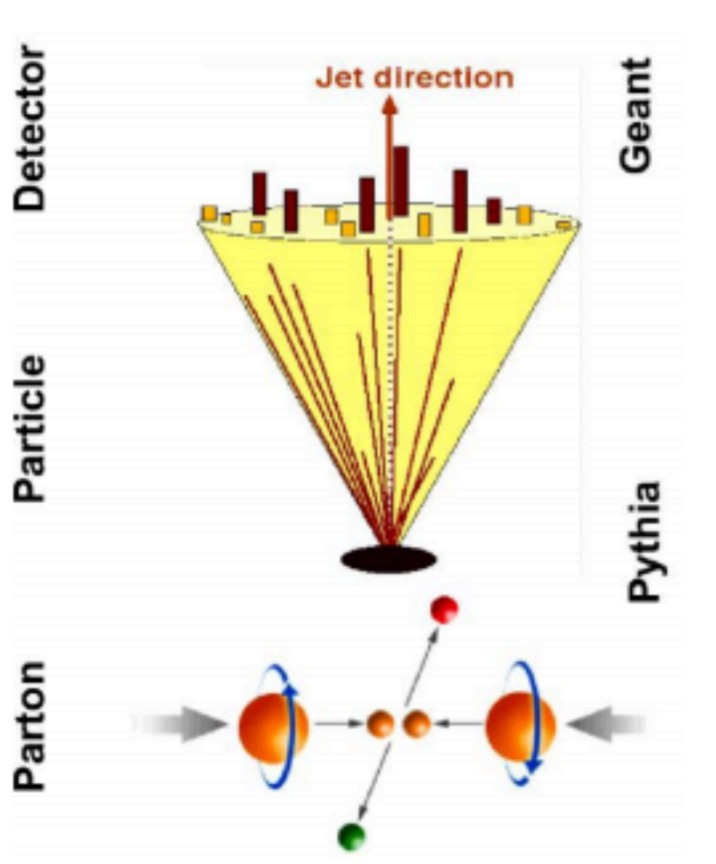


First experimental constraint on Collins-like asymmetry, sensitive to linear gluon polarization (gluon analog to quark FF)



- ✦ 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



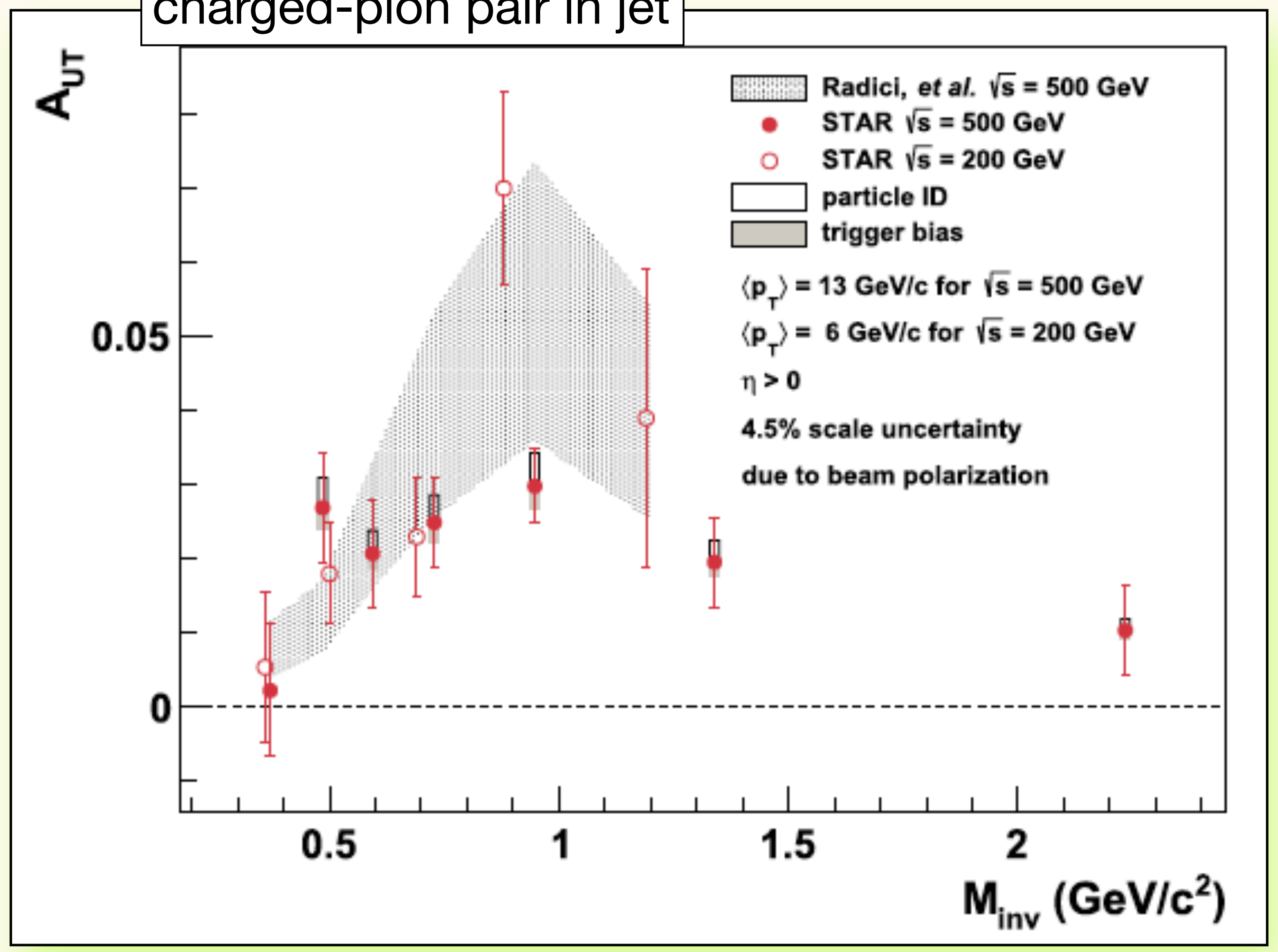


RHIC results enable tests of TMD universality and factorization breaking (expected for hadronic interactions)

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



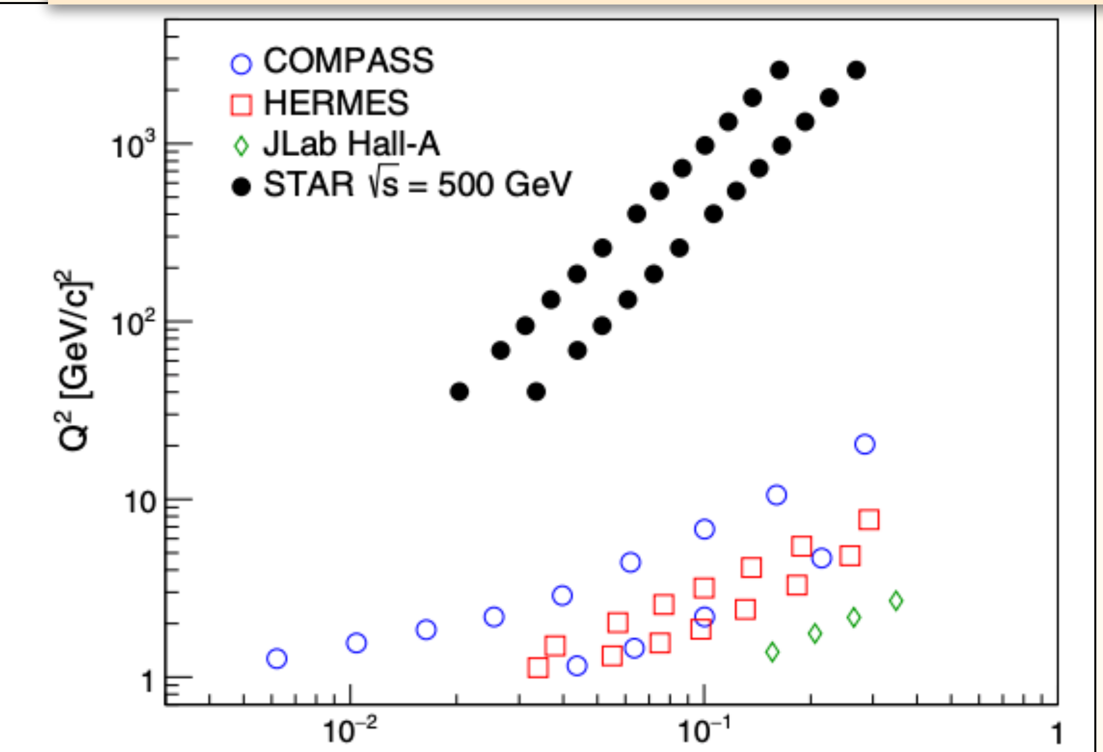
Not shown today: FFs measured in e^+e^- at Belle, Barbar, BESIII

Belle back-to-back pairs of charged and neutral mesons: see talk by A. Vossen, Thursday, 11:12

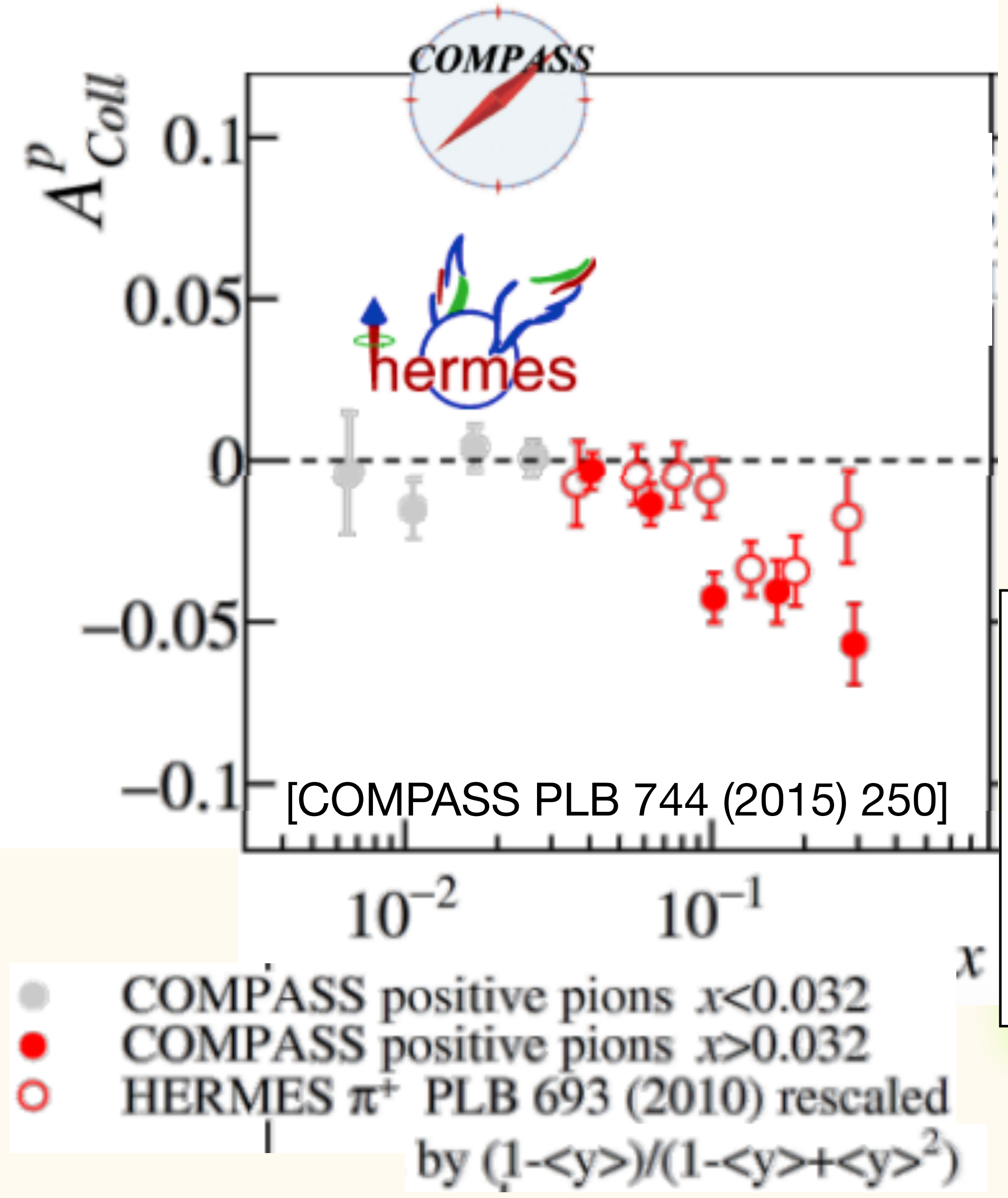
- ✦ More STAR data analyzed in multi-dimensional binning & kaons / protons: see talk by B. Pokhrel, Wednesday, 8:18

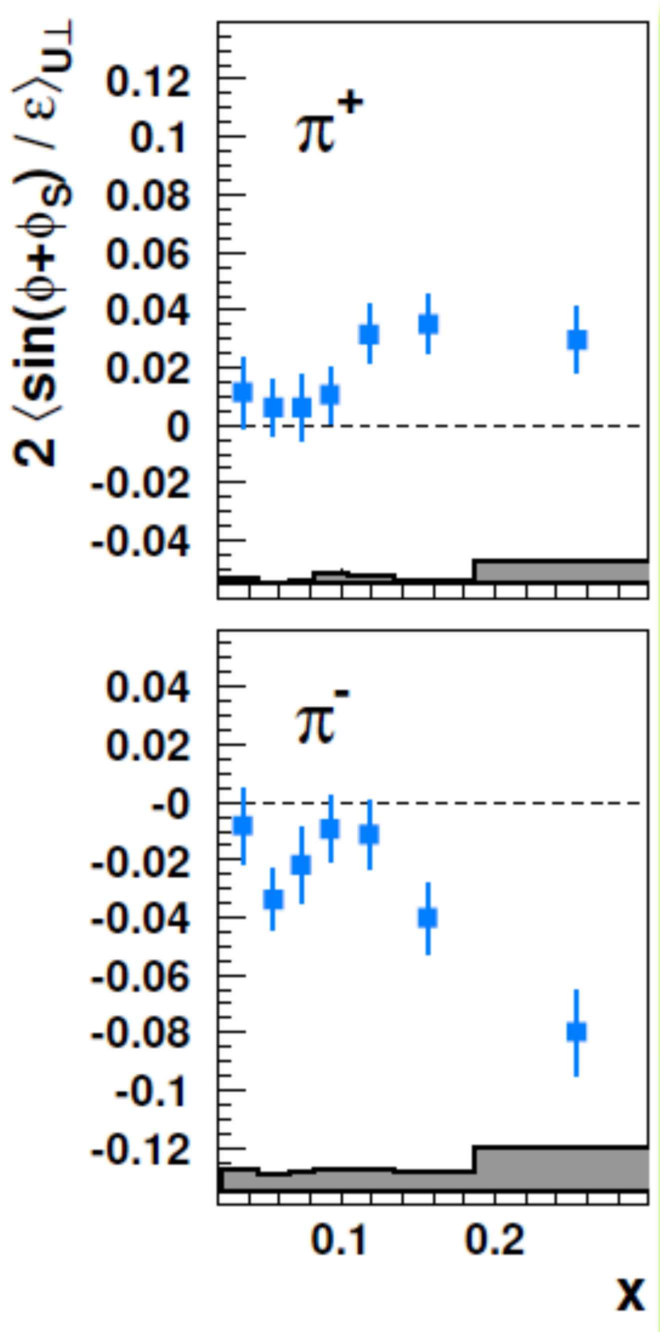
Collins asymmetries in SIDIS $\ell N^{\uparrow} \rightarrow \ell h(h) X$

HERMES & COMPASS **Collins asymmetries**



[STAR PRD 97, 032004 (2018)] x



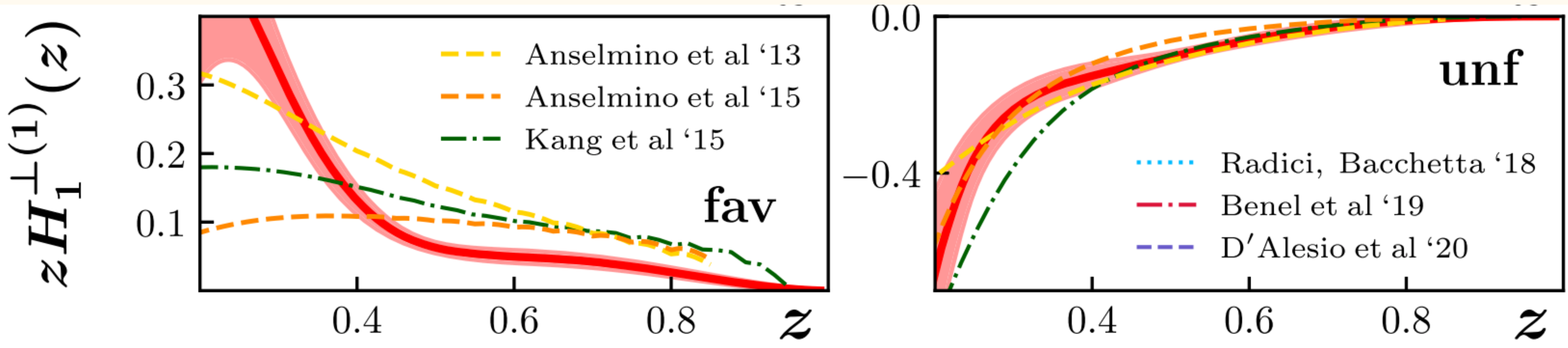


[HERMES JHEP 12 (2020) 010]

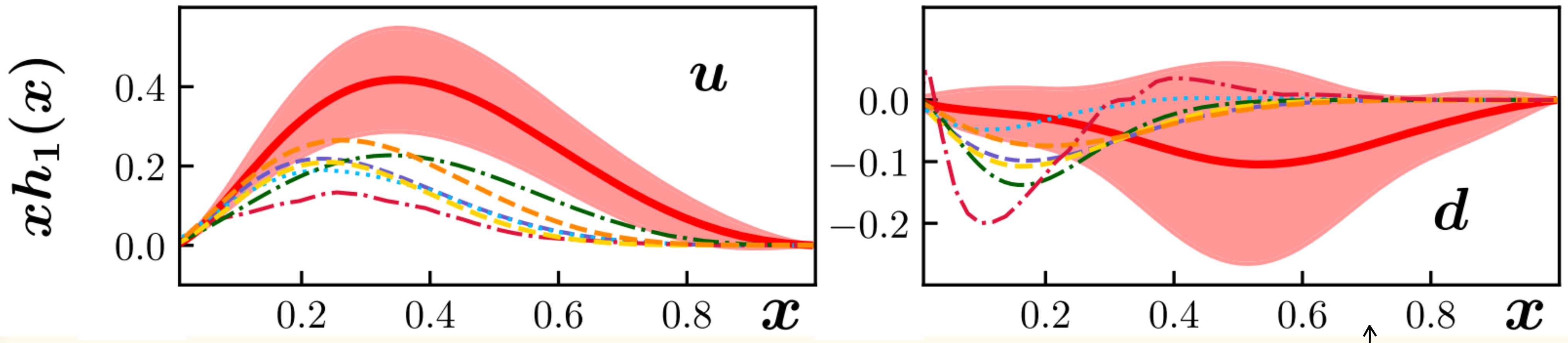
Mirror symmetry for π⁺ & π⁻: ***u-*** (δ_u) and ***d*-quark transversity** (δ_d) have ~ **equal magnitude** & **opposite signs** for favored and unfavored Collins FFs.

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

Global extractions - <u>Collins function:</u>



\- <u>transversity</u>:



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

✦ <u>*d*-quark transversity</u> 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
- <u>COMPASS</u>: SIDIS on trans.pol protons, to be submitted to PLB
- <u>STAR</u>: see talk by Y. Xu, Thursday, 10:00

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 will be shown

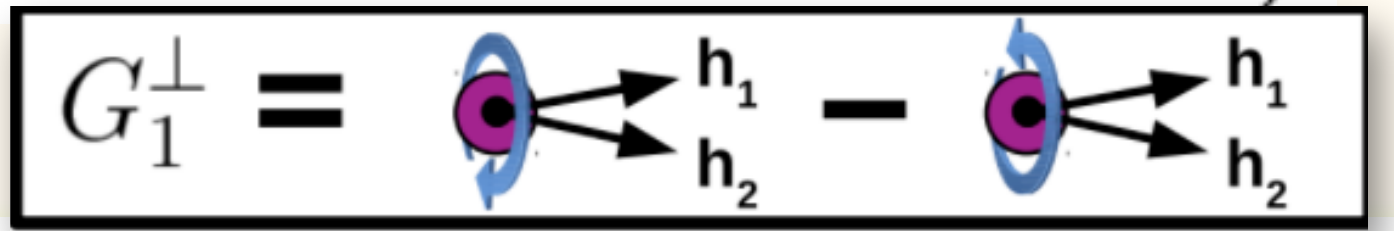
see talk by A. Kerbizi, Thursday, 12:51

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

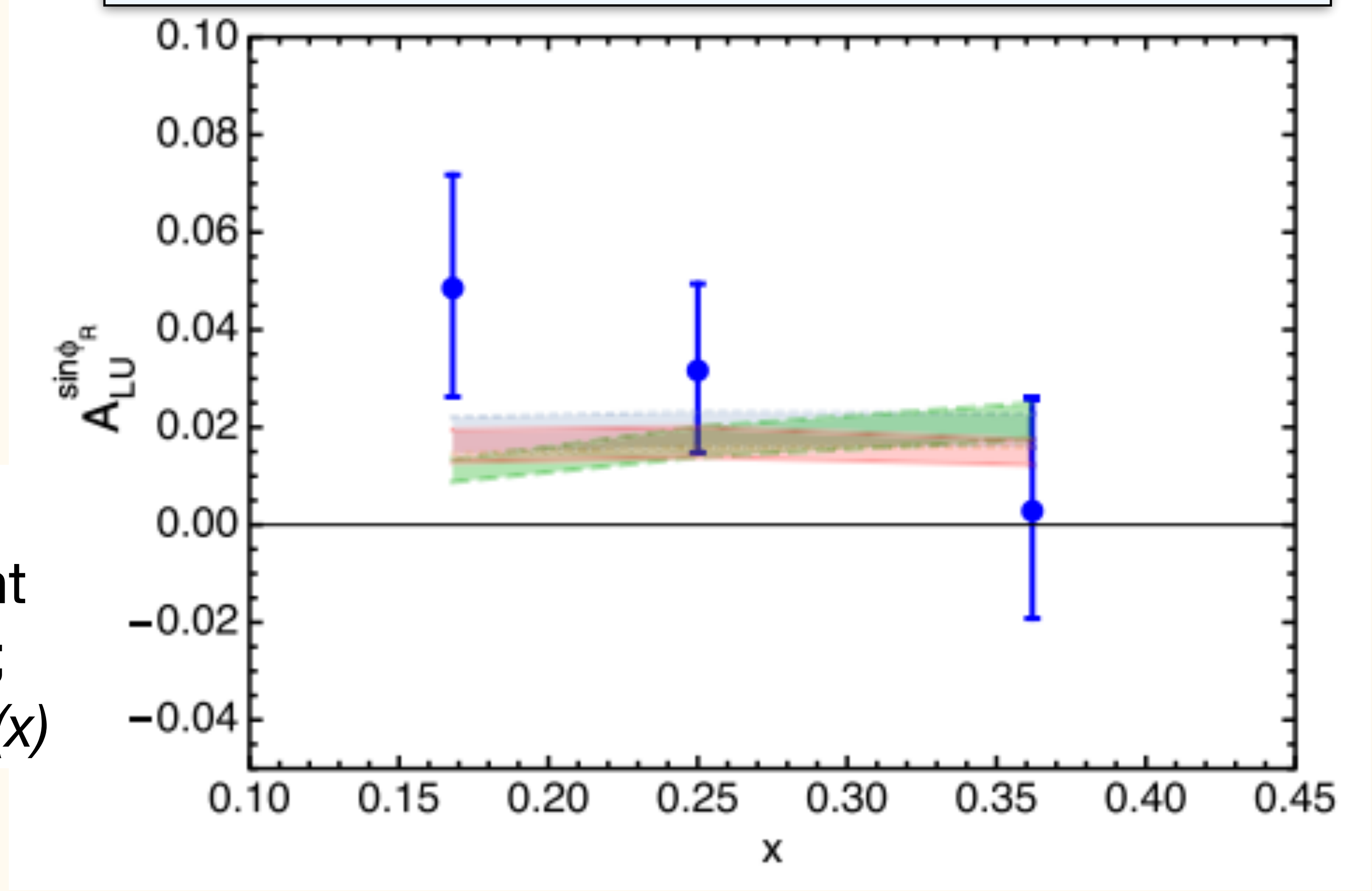
  In the ρ-mass region, can be used to test predictions by the Artru model about the relative size of Collins asymmetries of vector and scalar mesons
  - Data also allow for a point-by-point extraction of the **collinear-twist-3 PDF $e(x)$**

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

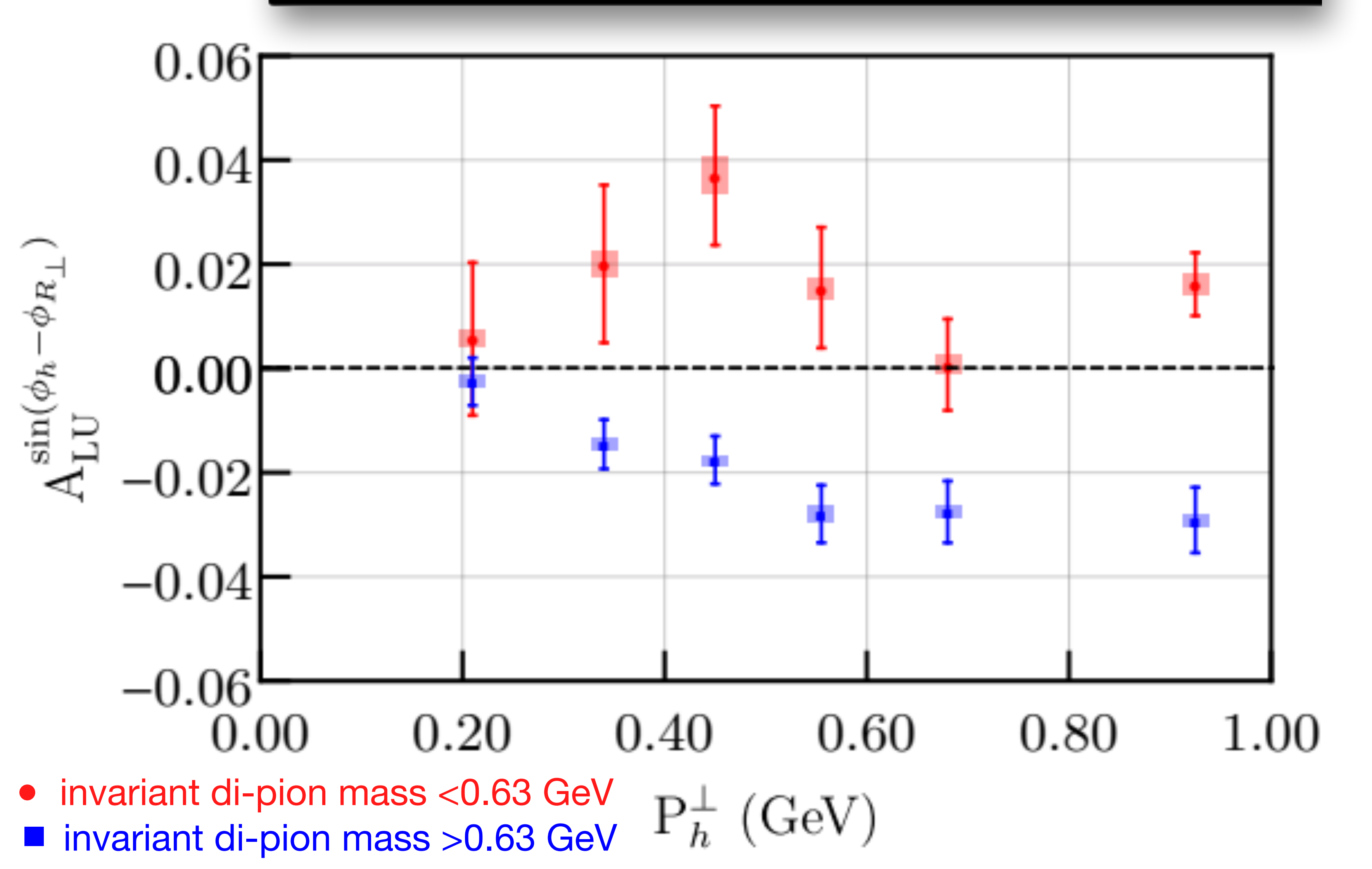


New CLAS **higher-twist di-hadron beam-spin asymmetry**

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



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

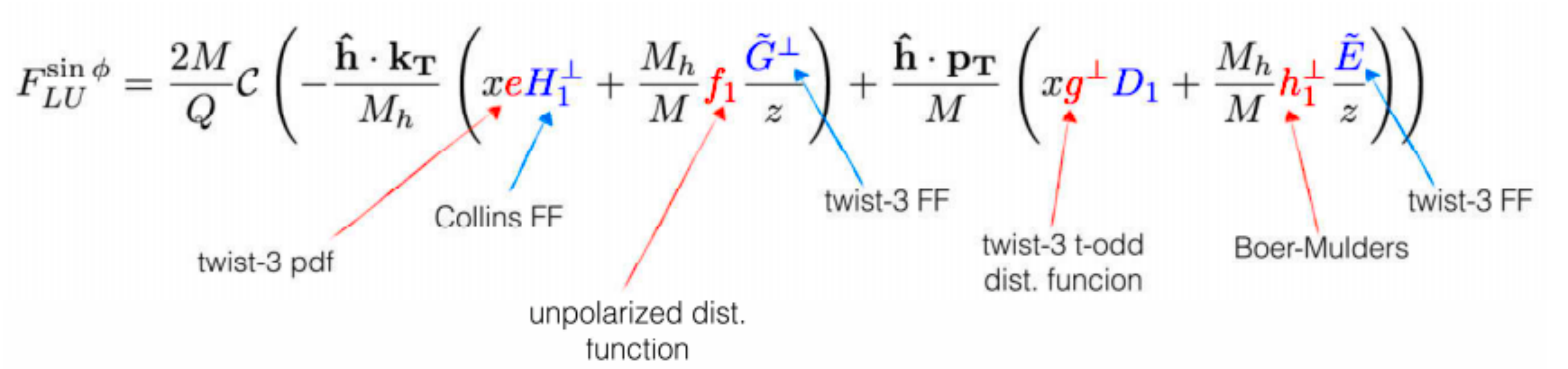


[CLAS12 / T. Hayward arxiv:2101.04842]

see talk by C. Dilks, Thursday, 13:27

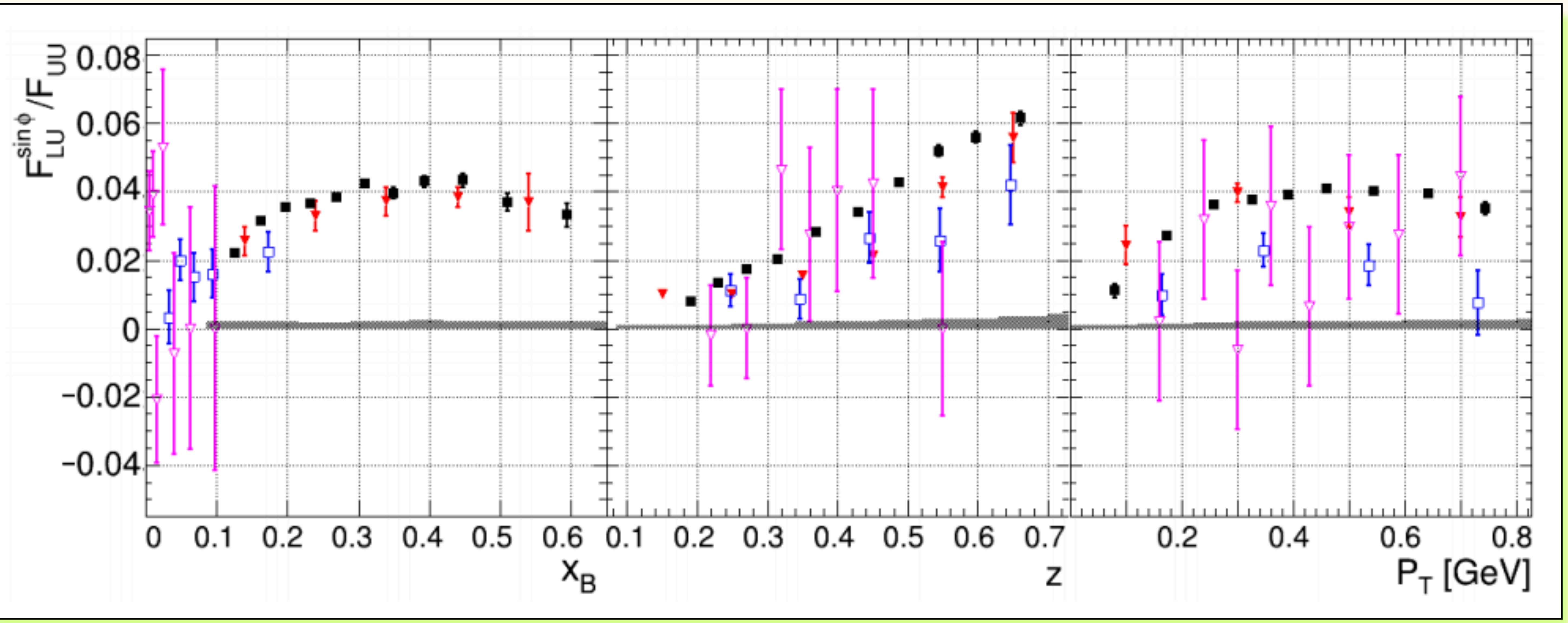
More higher twist in single-hadron SIDIS

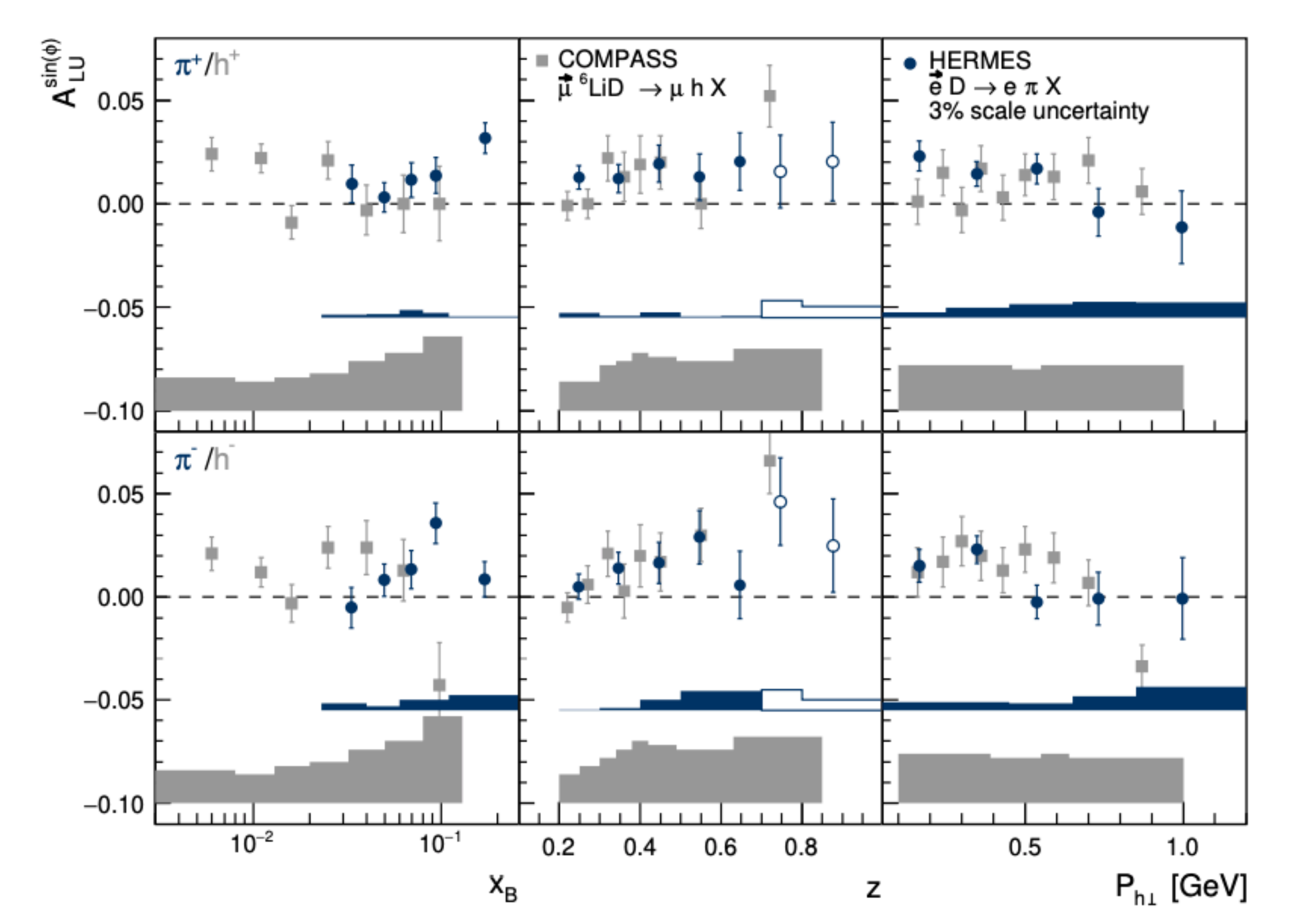
New CLAS12 and HERMES **SIDIS beam-spin asymmetries**



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

- ✦ 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]

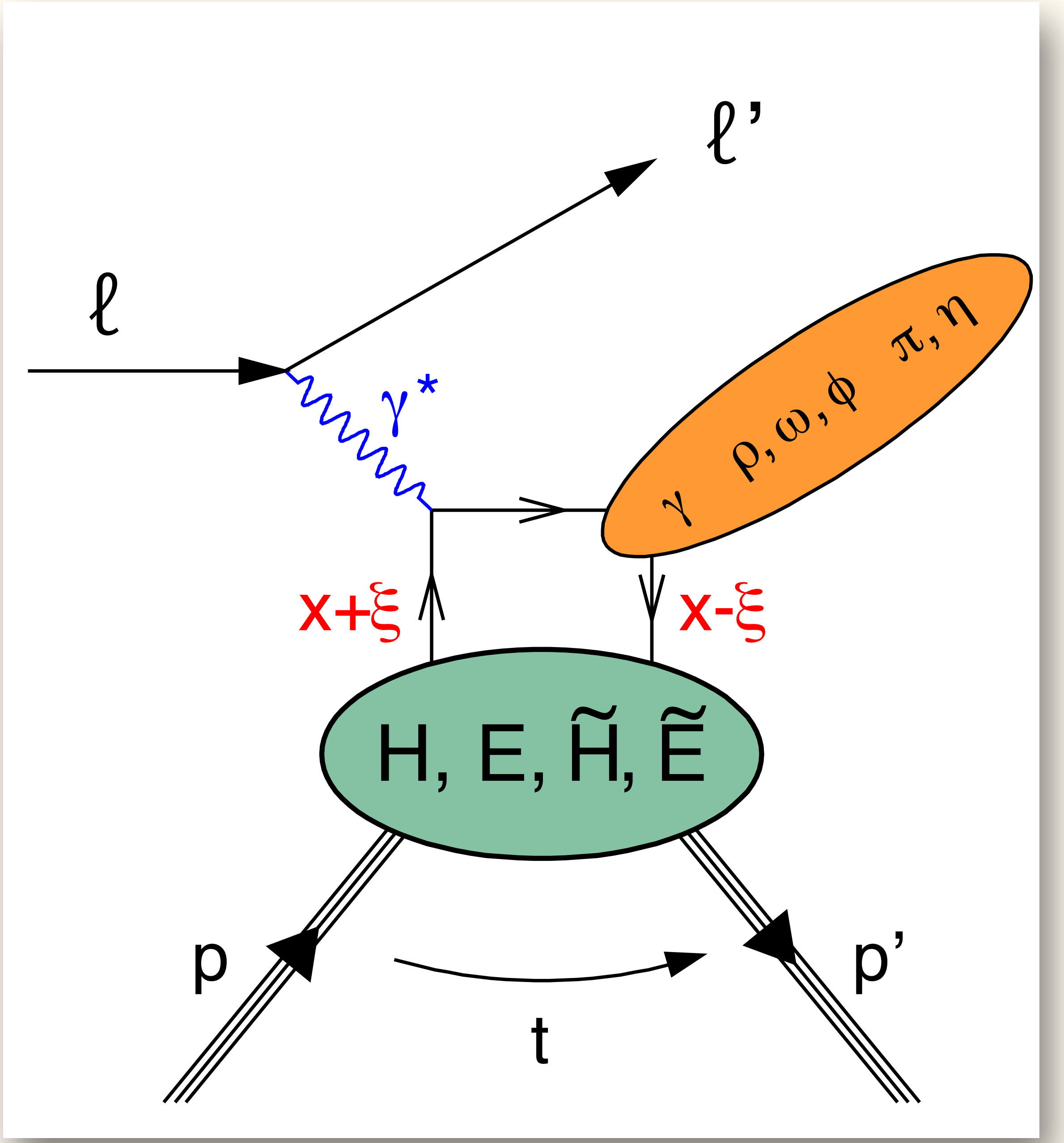
- ■ **[CLAS12 / S. Diehl arXiv:2101.03544]**
- ❐ [HERMES PLB 797 (2019) 134886]
- ▼ [CLAS Phys. Rev. D 89, 072011 (2014)]
- ▽ [COMPASS Nucl. Phys. B 886, 1046 (2014)]

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

see talk by S. Diehl, Thursday, 13:09

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

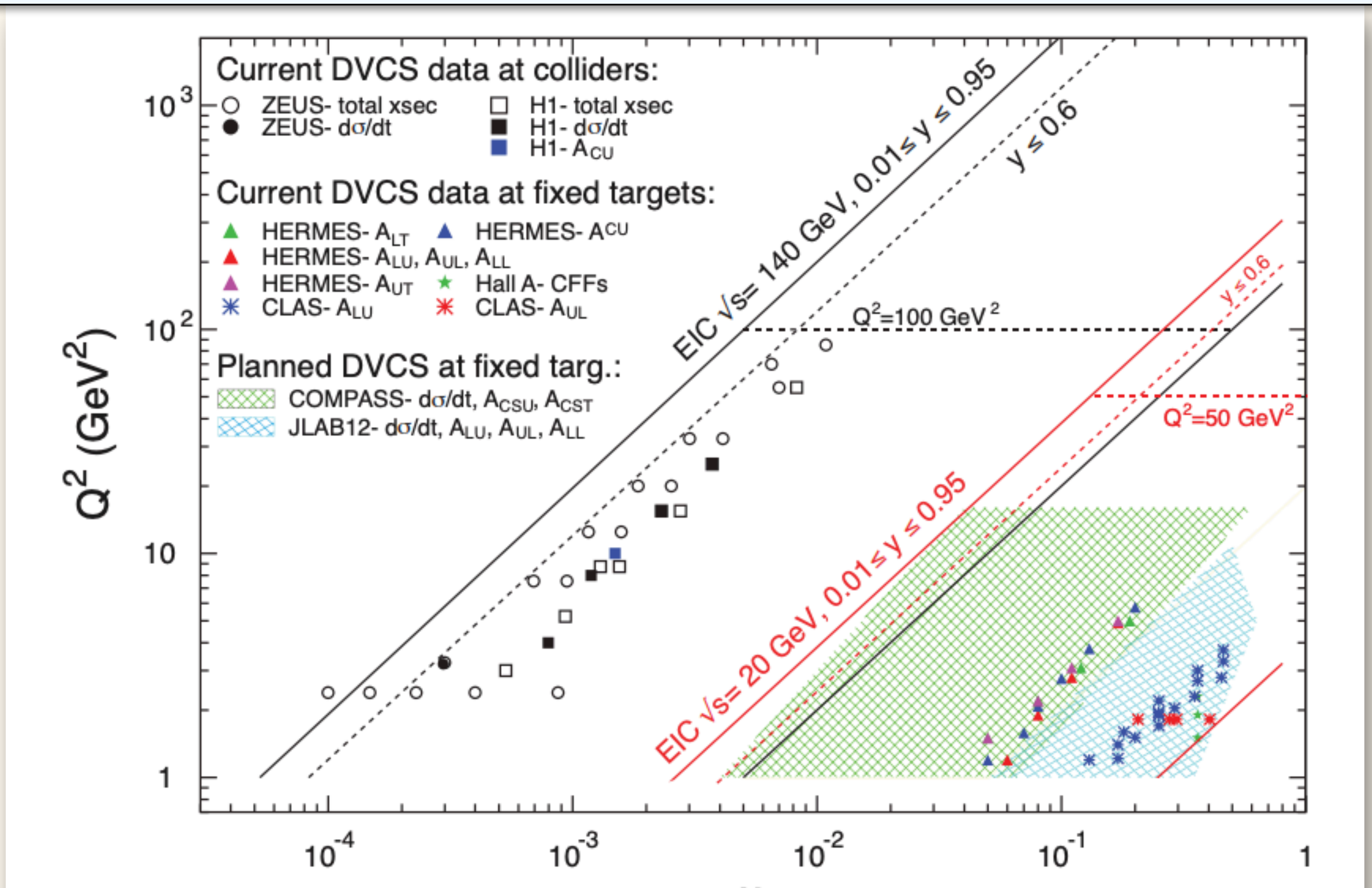
t: squared 4-momentum transfer to target

$\ell p \to \ell p \gamma$ — 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	Ẽ	H̃

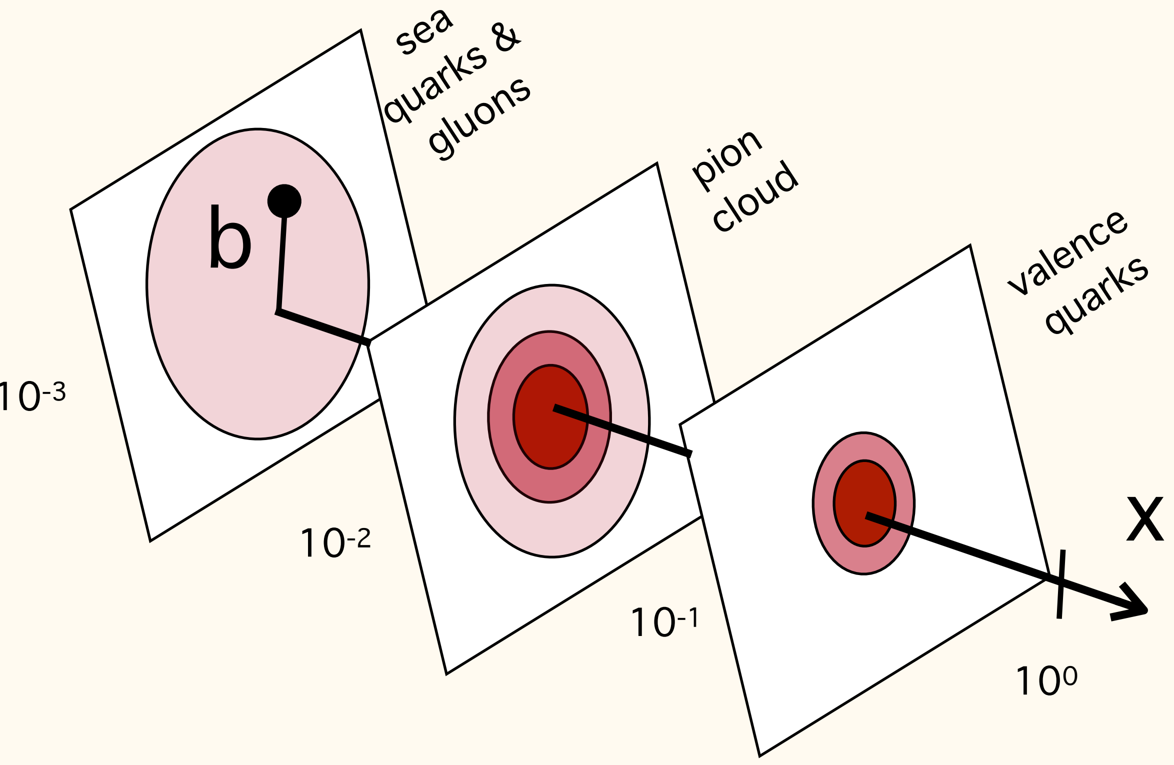
4 chiral-even quark GPDs
@leading twist for a spin-½ target

H → *q(x)*; H̃ → $\triangle q(x)$ (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; $(2\tilde{H}_T + E_T)$ ↔ Boer-Mulders; $\tilde{E}_T$

Transverse imaging of the nucleon



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

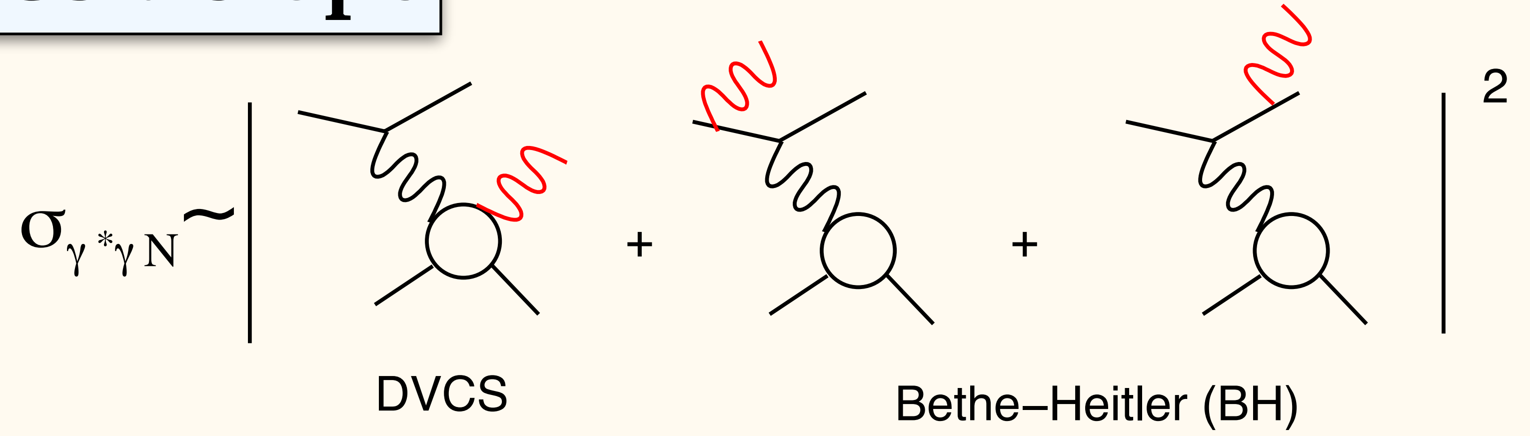
b = "t-slope" = average impact parameter

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**



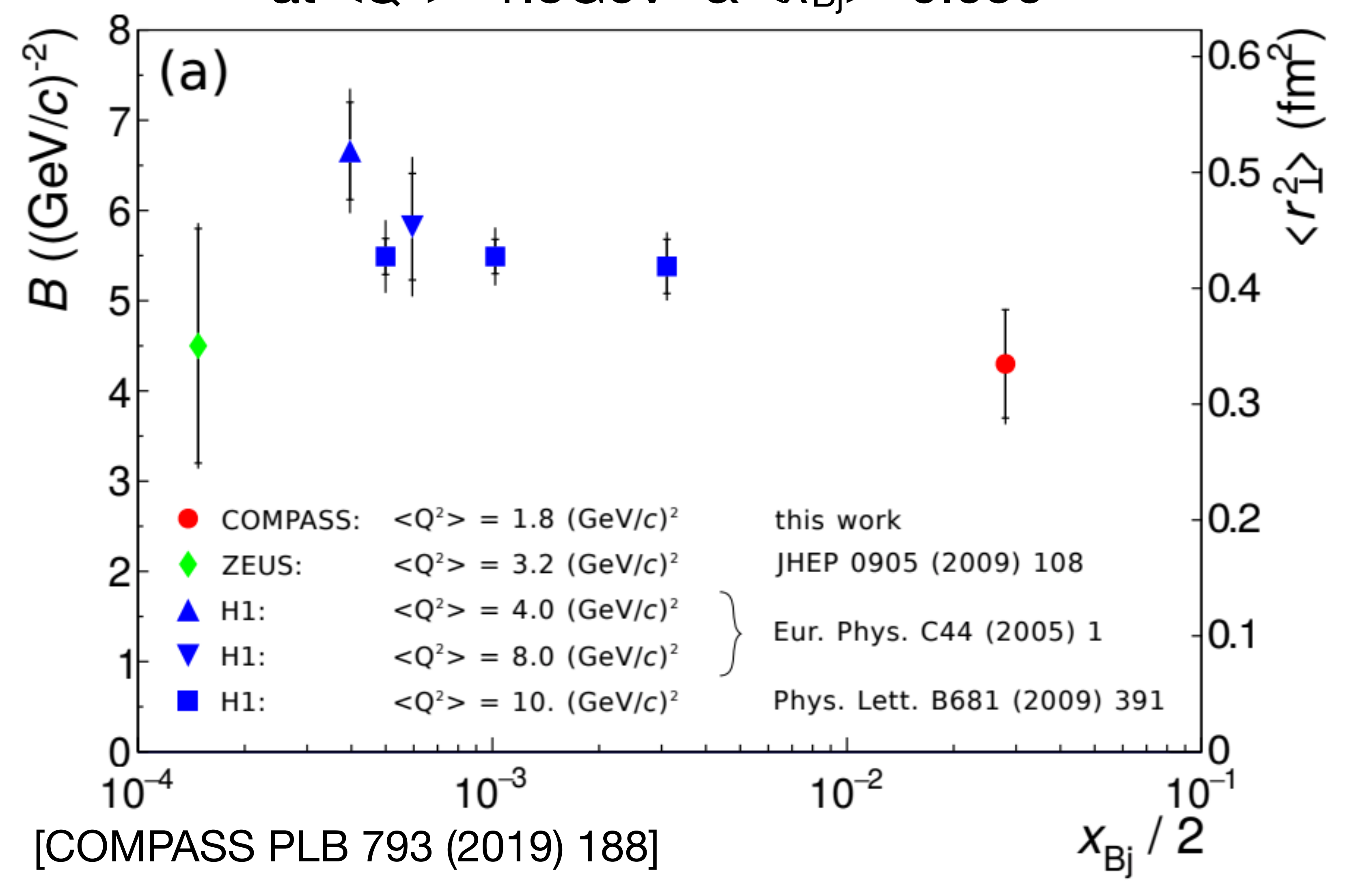
$$= |\mathcal{T}_{\mathrm{BH}}|^2 + (\mathcal{T}_{\mathrm{DVCS}}\mathcal{T}^*_{\mathrm{BH}} + \mathcal{T}^*_{\mathrm{DVCS}}\mathcal{T}_{\mathrm{BH}}) + |\mathcal{T}_{\mathrm{DVCS}}|^2$$

BH reference yield — **DVCS amplitude:** ϕ-modulations in cross section — **Transverse imaging:** ϕ-integrated cross section

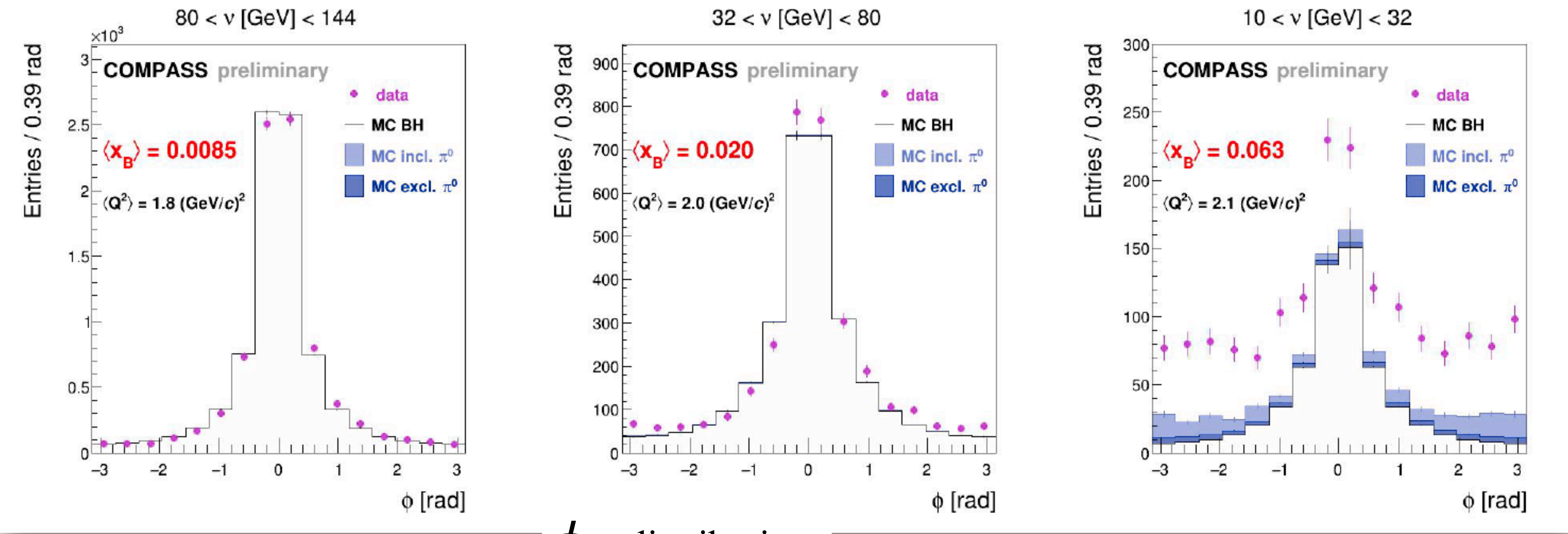
✦ Determination of transverse extension of partons
- in the Bjorken-x domain of COMPASS between valence quarks and gluon
- 2012 DVCS data on LH_2 target (10% of 2016/17) with recoil-proton detector CAMERA

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

at $\langle Q^2 \rangle$=1.8GeV² & $\langle x_{Bj} \rangle$=0.056

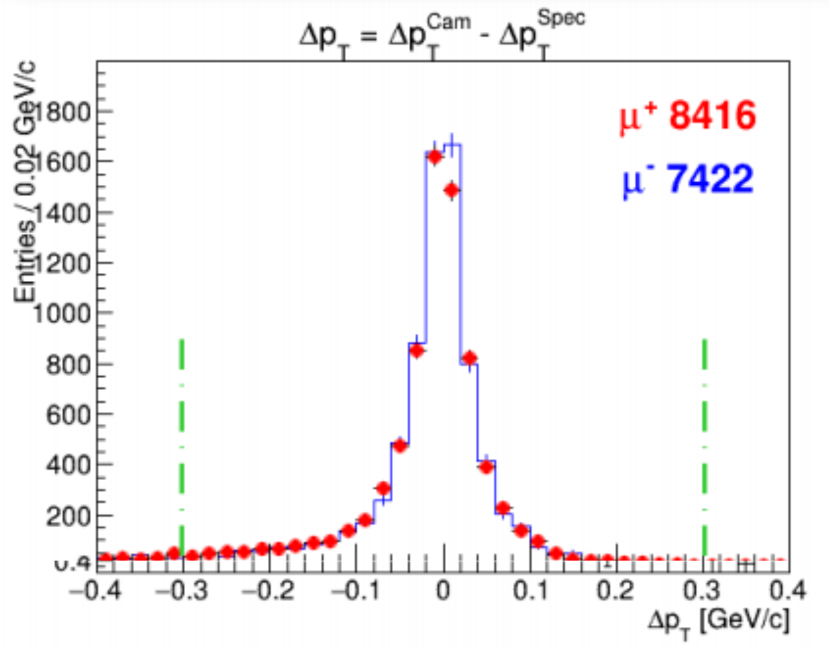


[COMPASS PLB 793 (2019) 188]



$\phi_{\gamma\gamma}$ distributions

BH + measured & simulated π^0 subtracted

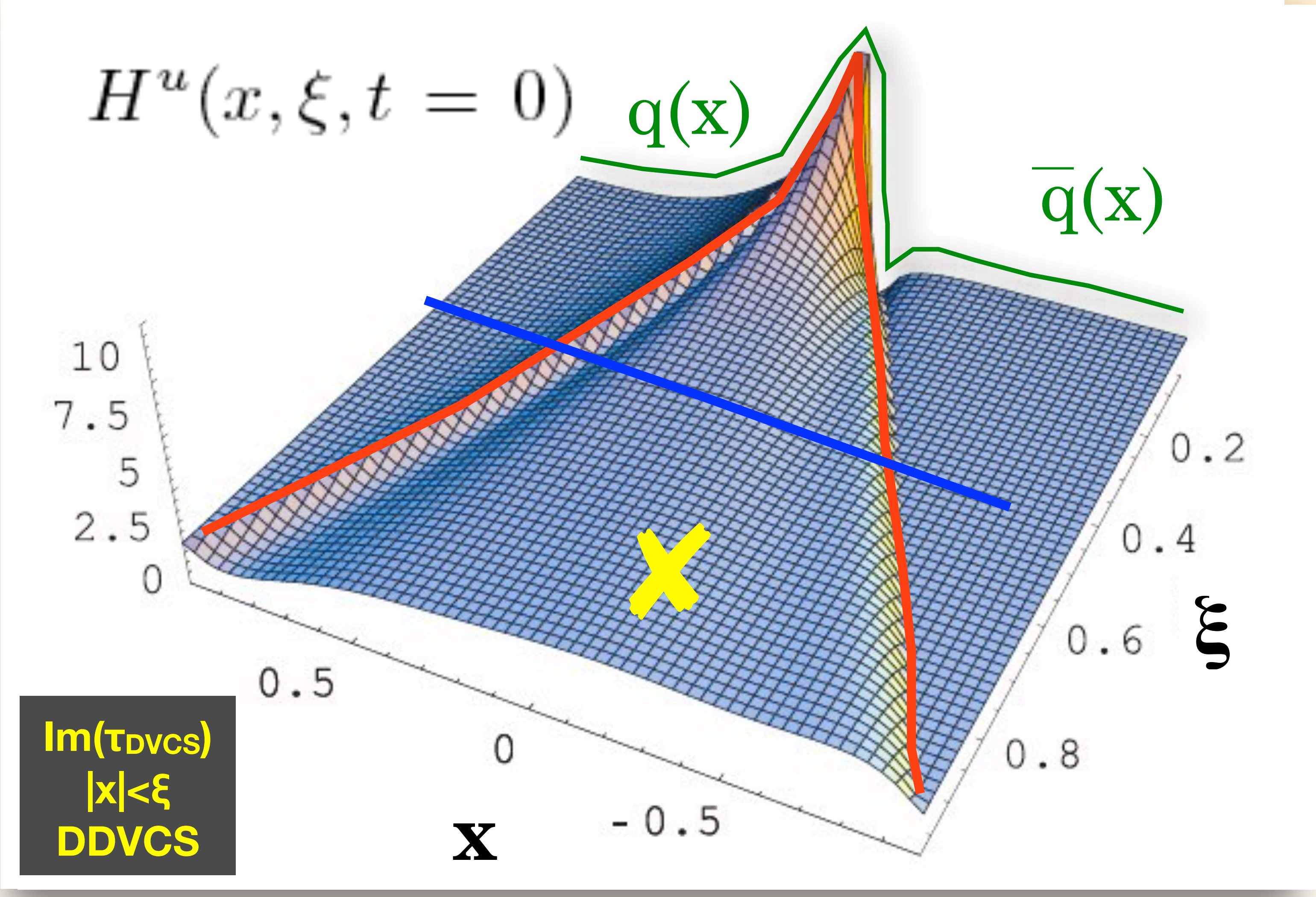


new: 2016/17 DVCS data (~25% of available data, 2 times more than 2012 data) on LH_2 target with recoil-proton detector CAMERA

see talk by B. Ventura (N. D'Hose), Thursday, 8:54

exclusivity ensured by recoil-proton detector

Exploring Compton Form Factors



possibility at JLab Halls B&C investigated

- ✦ **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

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

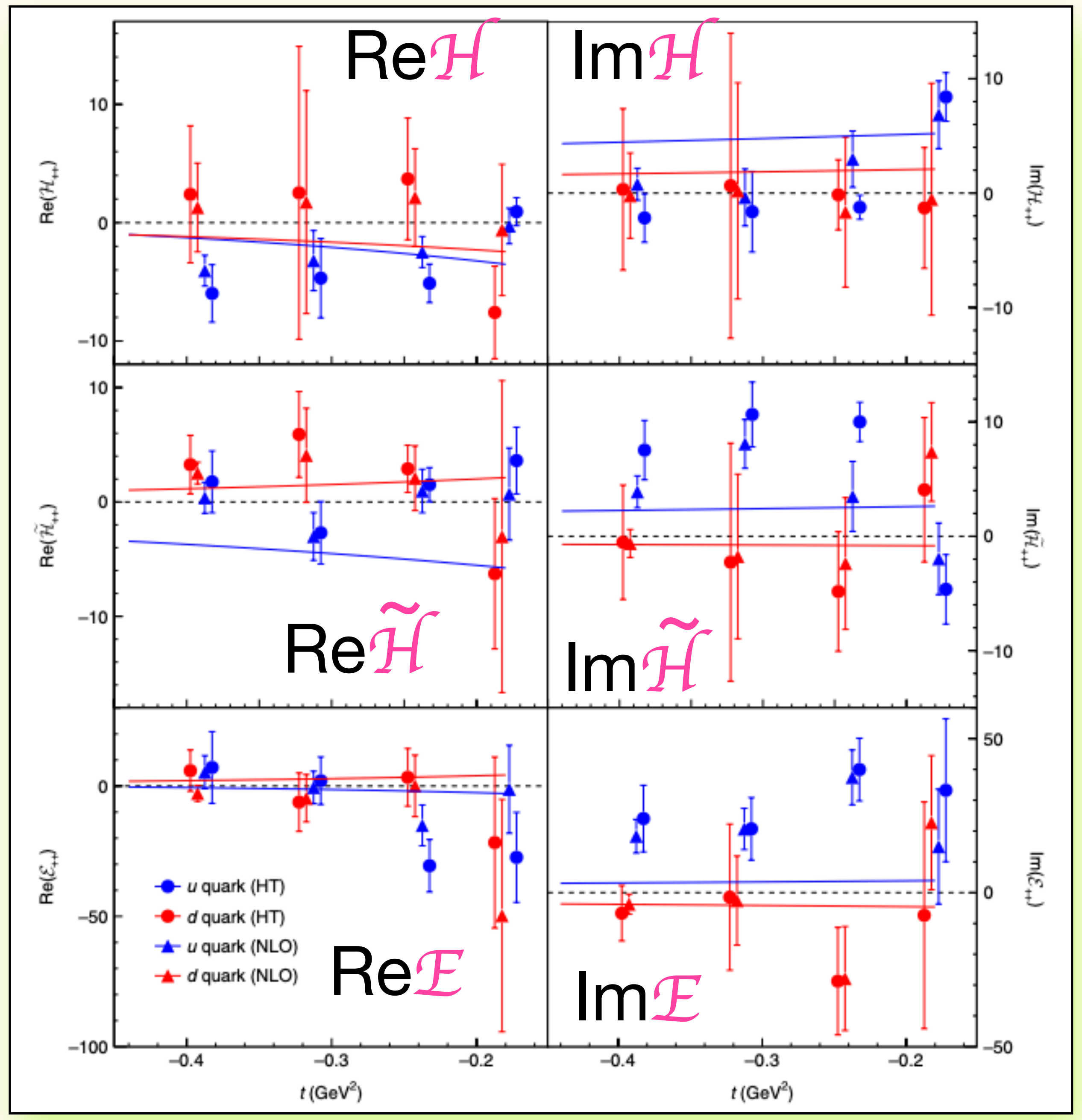
example: access via COMPASS beam-spin&-charge asymmetries	$d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$	$d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$
	Re(τDVCS) **integral over x**	**Im(τDVCS)** **x=ξ**

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.)

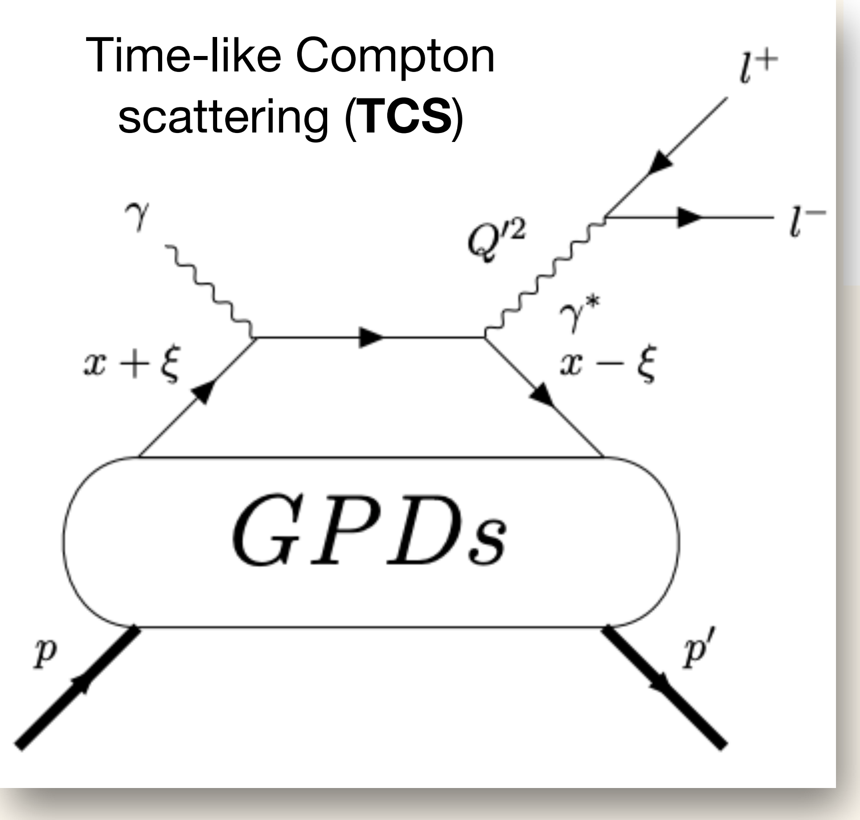
- ✦ **Dispersion relation with D-term** *D(t)*: related to shear forces and radial distribution of pressure inside the nucleon

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

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

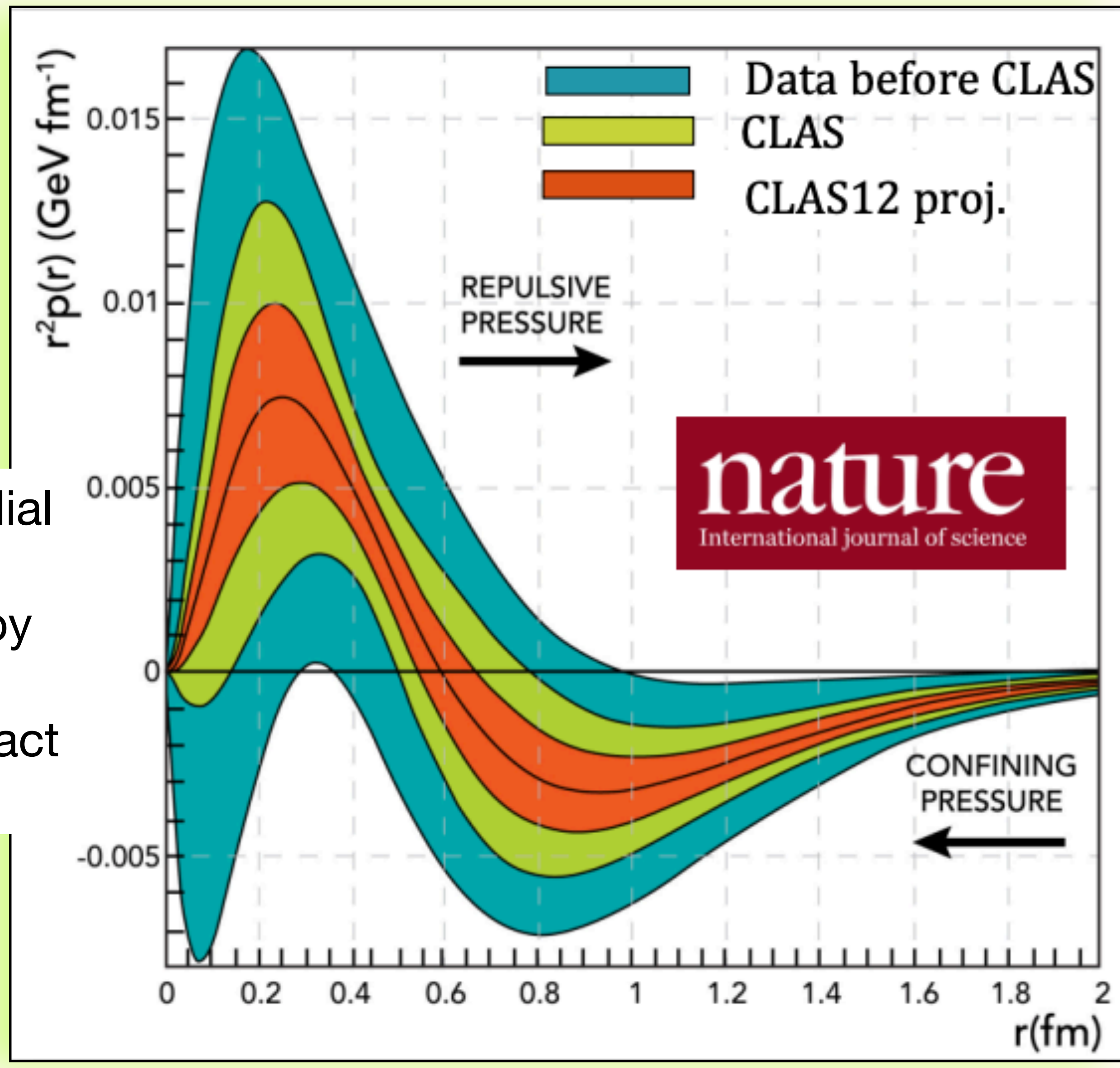
CLAS12 **TCS**

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]

GPD *E* linked to orbital angular momentum

GPD *E*

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

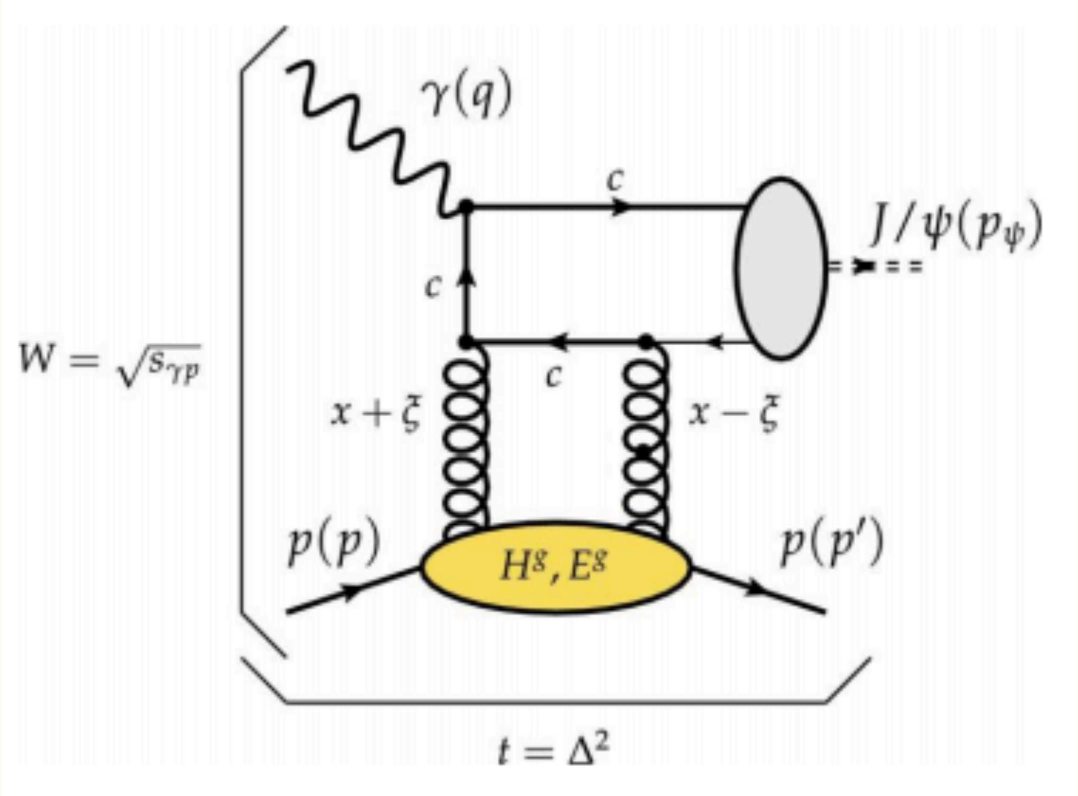
$$J_{\mathrm{q}} = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \left[H^{\mathrm{q}}(x,\xi,t) + E^{\mathrm{q}}(x,\xi,t) \right]$$

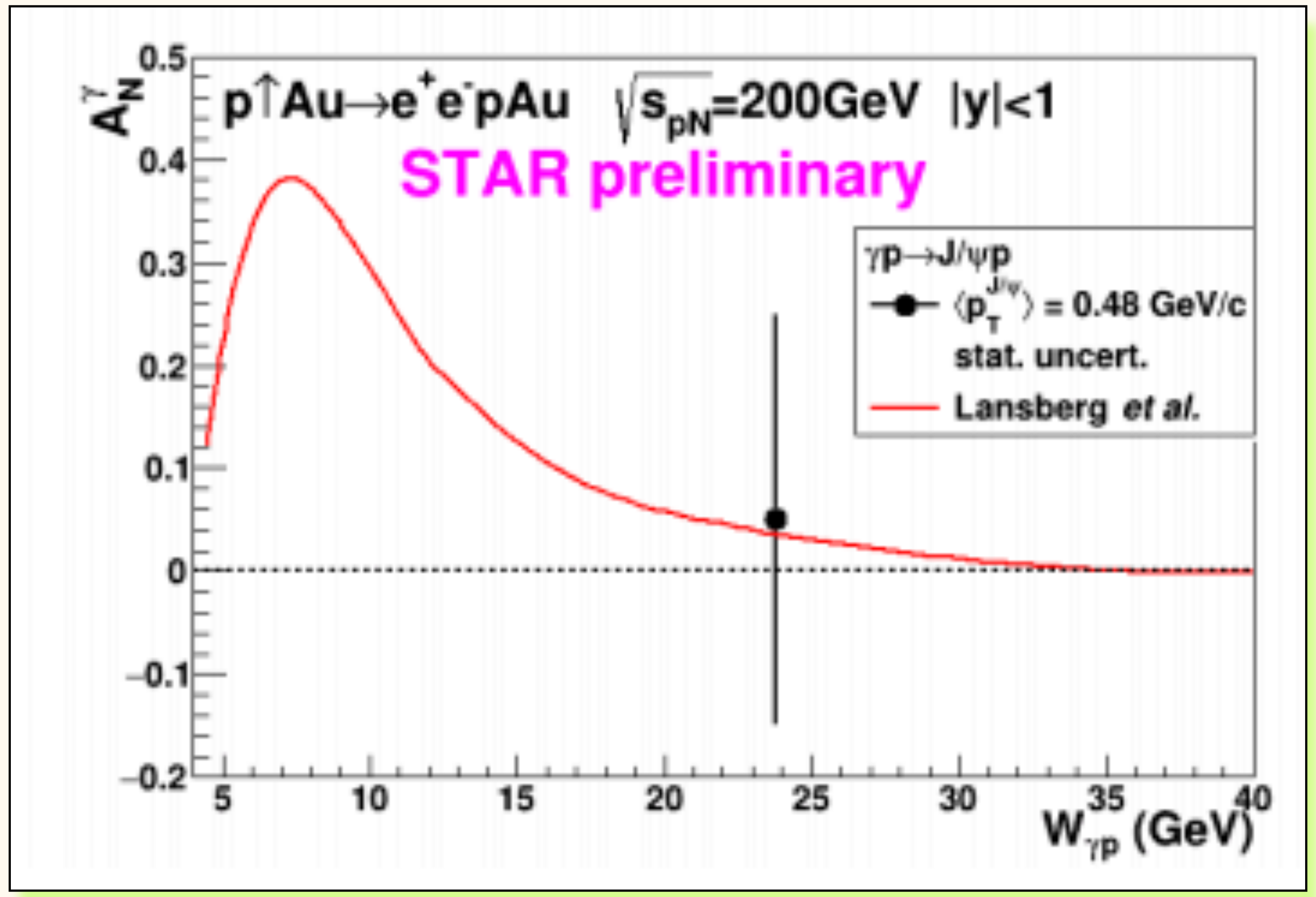
CLAS12 DVCS **beam-spin asymmetries** on the deuteron (neutron)

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

$e\,p \rightarrow e\,\pi^0\,p$

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

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

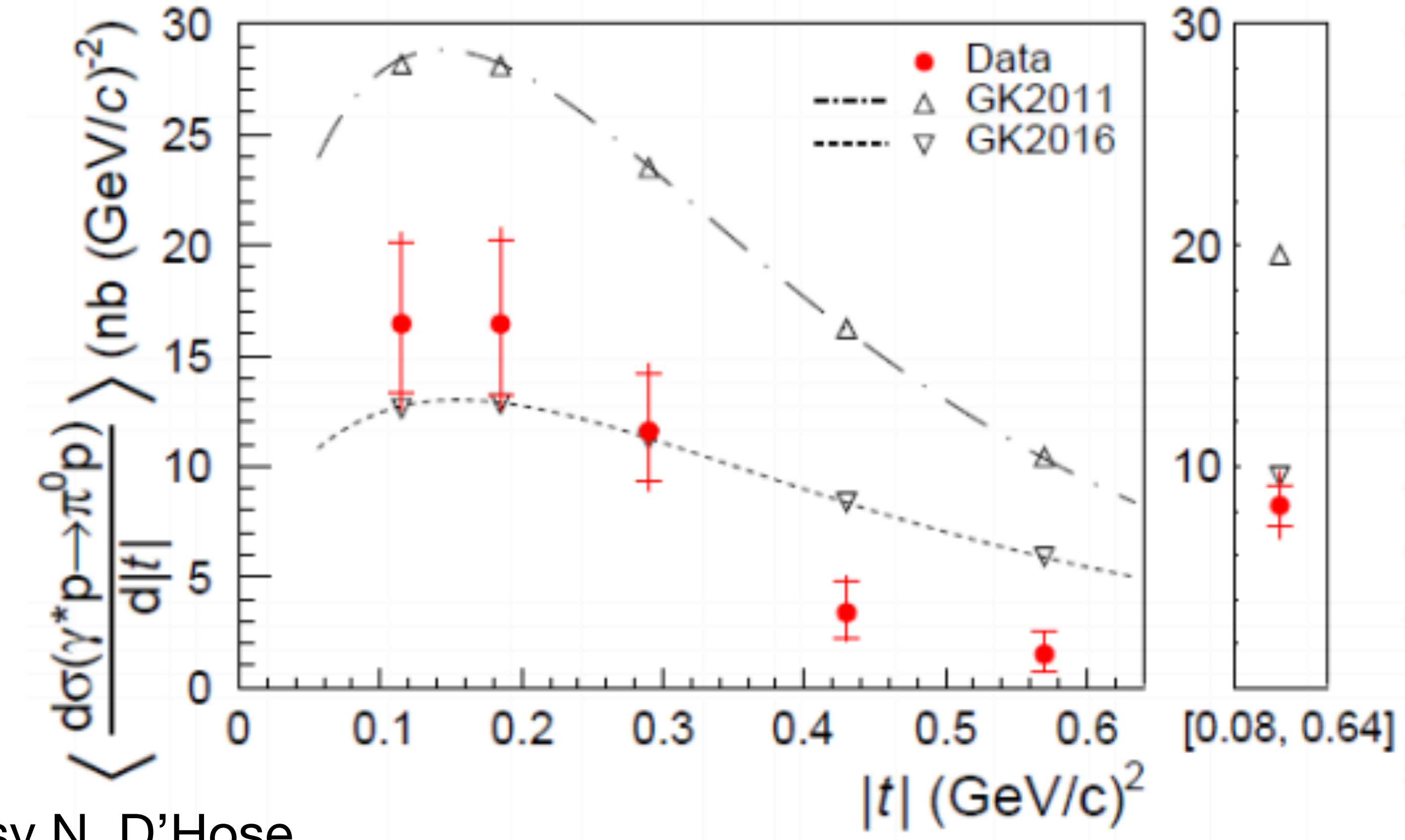
$$\left\langle\frac{d\sigma_T}{d|t|} + \epsilon\frac{d\sigma_L}{d|t|}\right\rangle = (8.2 \pm 0.9_{\text{stat}}\,{}^{+1.2}_{-1.2}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

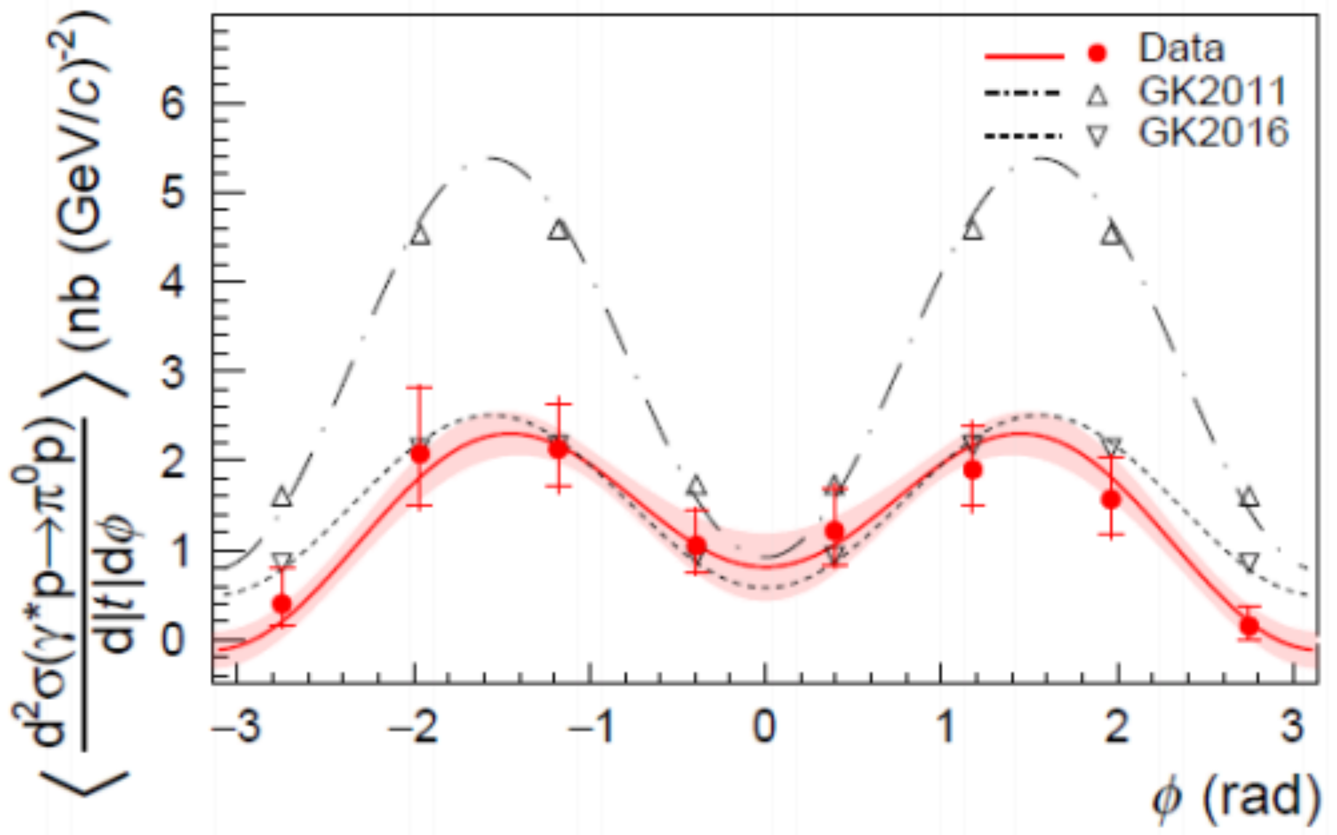
$$\left\langle\frac{d\sigma_{TT}}{d|t|}\right\rangle = (-6.1 \pm 1.3_{\text{stat}}\,{}^{+0.7}_{-0.7}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

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

σ_{TT} large (impact of $\bar{E}_T$)

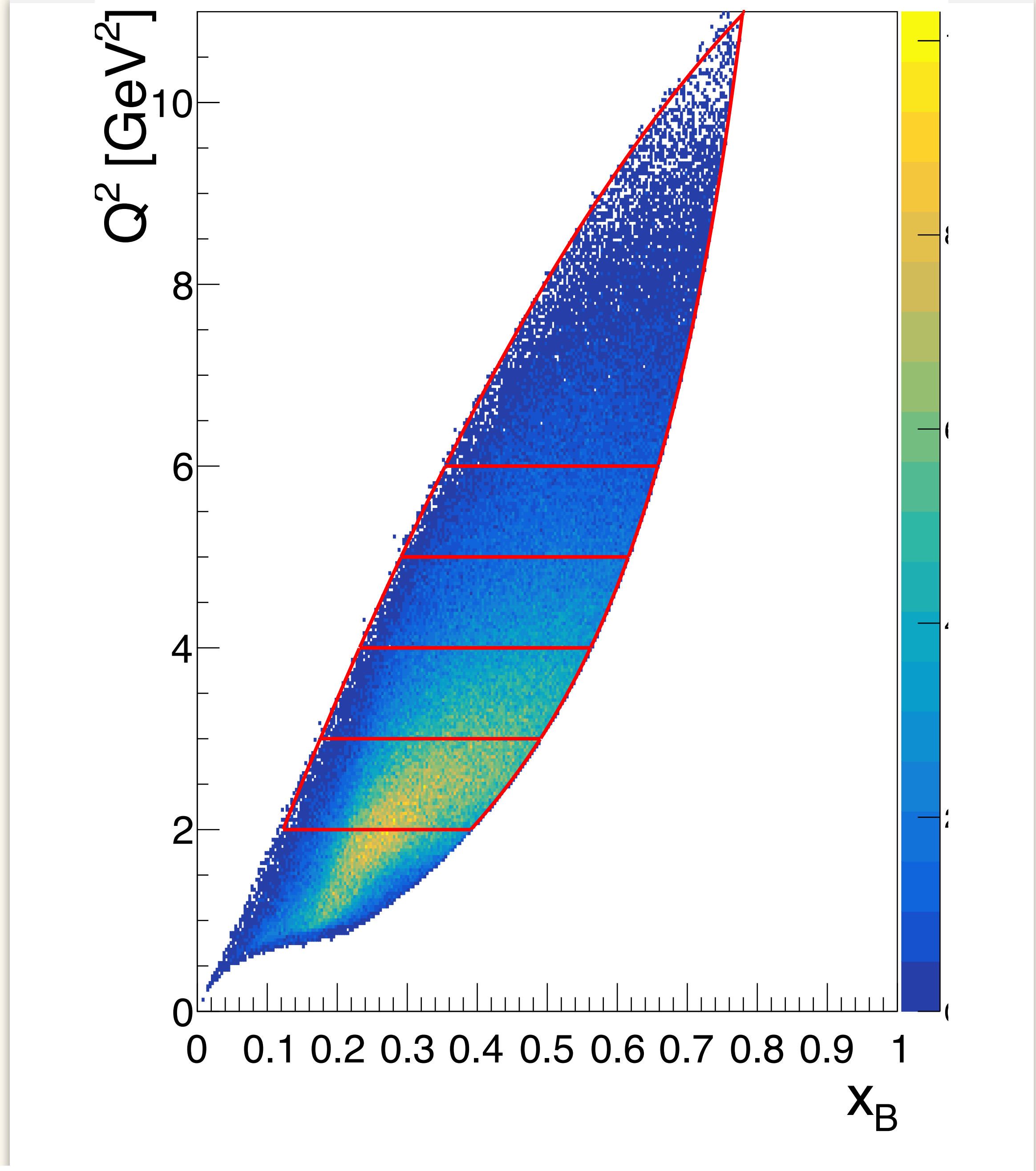
σ_{LT} smaller but significantly positive as at CLAS





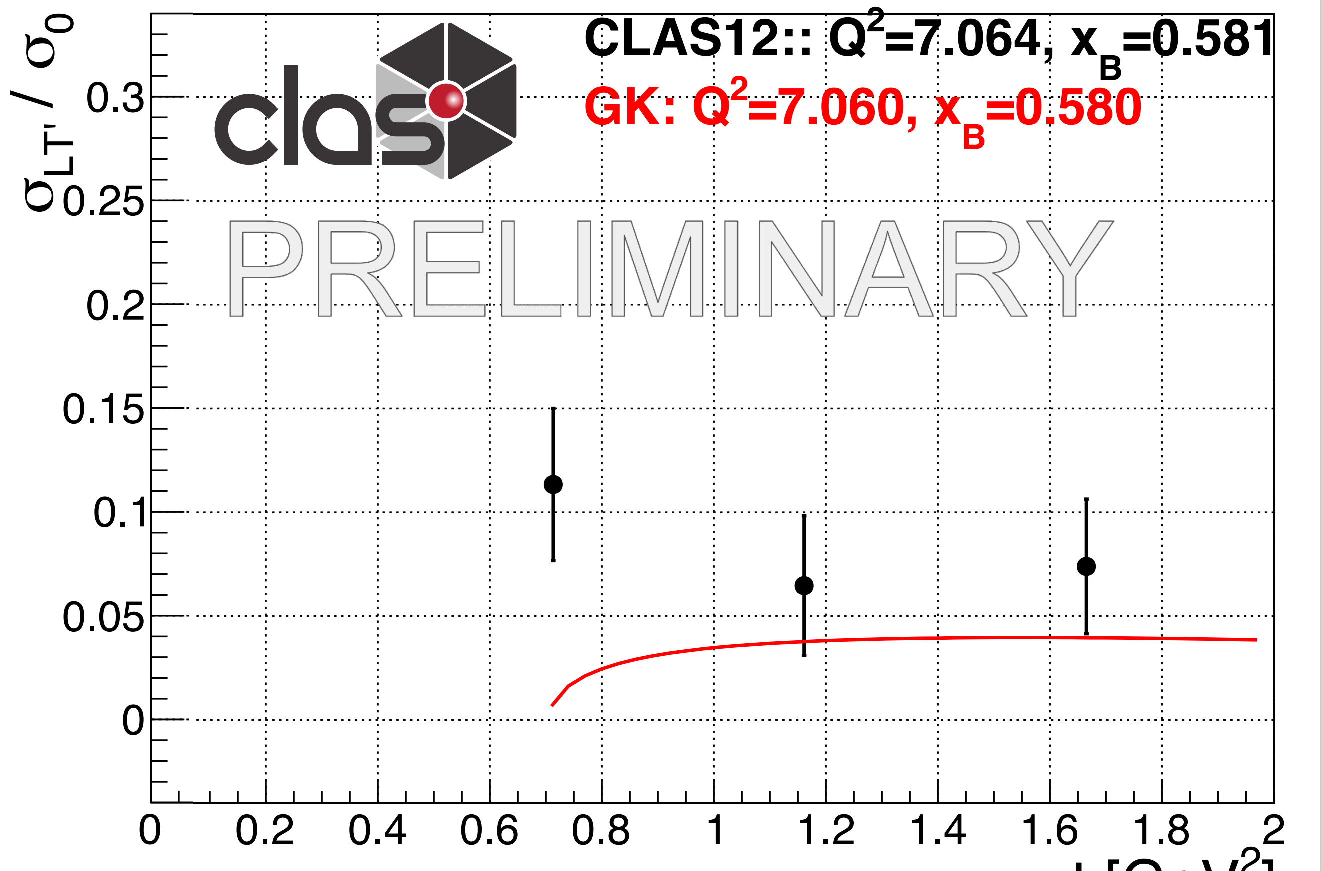
courtesy N. D'Hose

[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

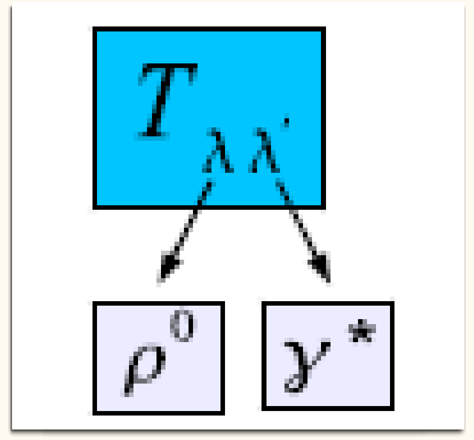
Spin density matrix elements in ℓp→ℓpVM

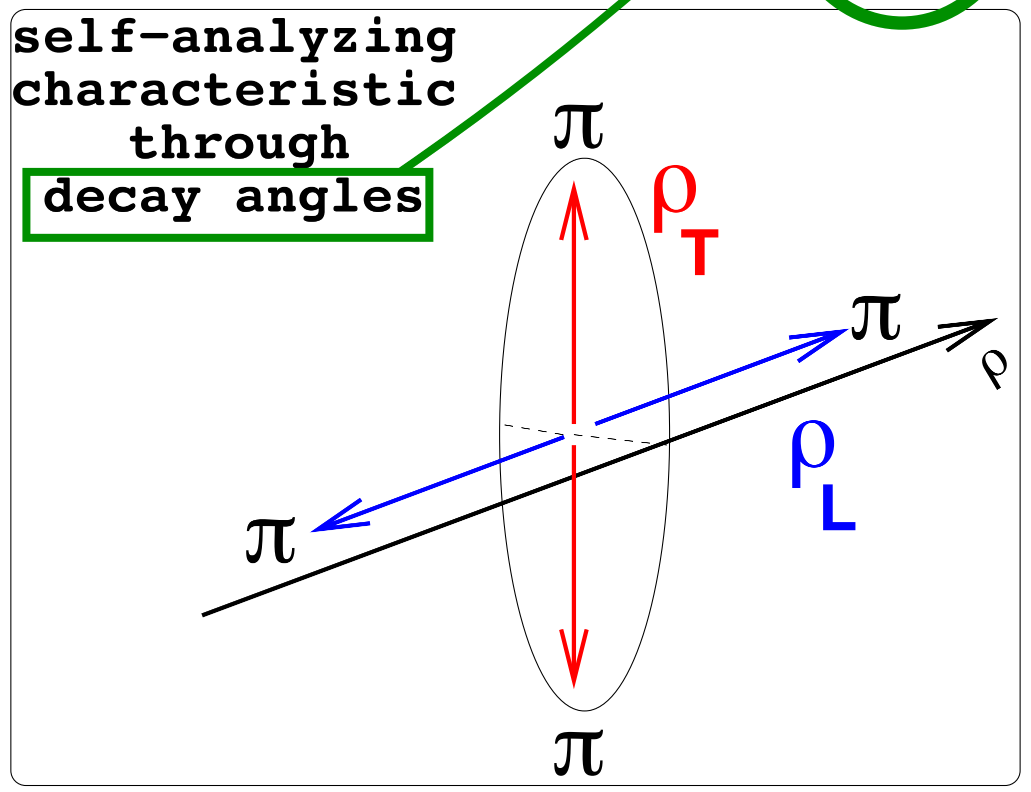
GPDs H_T & E_T

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

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

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



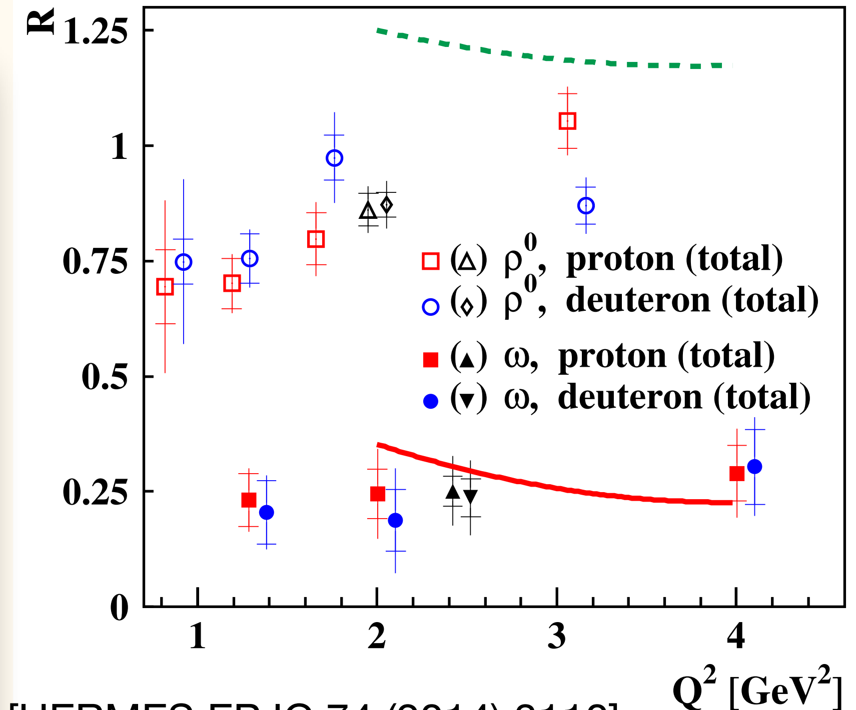


if SCHC ($\lambda_{\gamma^*}=\lambda_{VM}$) measured

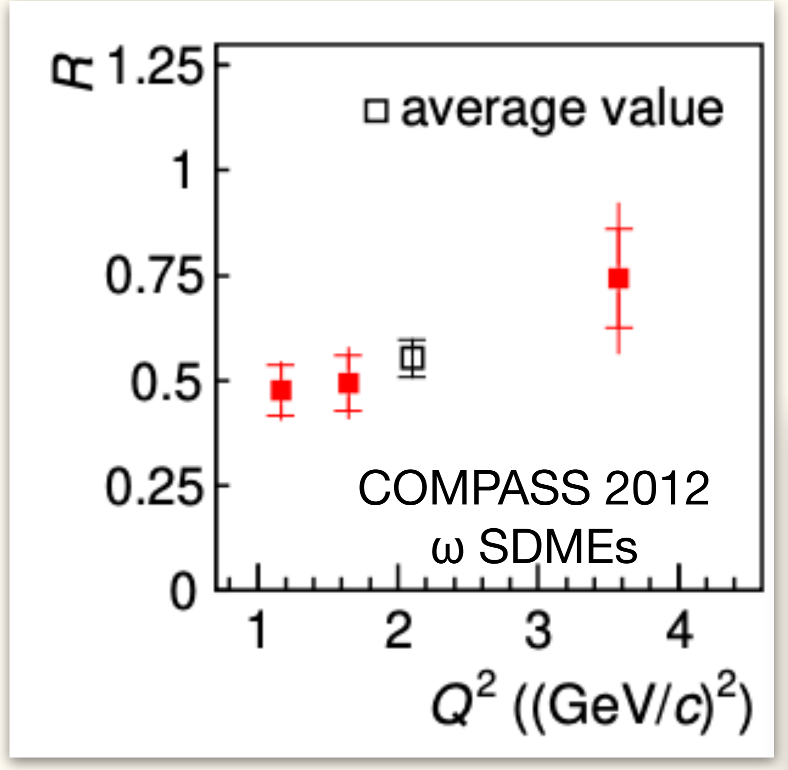
$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0$	✓	$-0.010 \pm 0.032 \pm 0.047$
$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0$		$0.014 \pm 0.011 \pm 0.013$
$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0$		$-0.088 \pm 0.110 \pm 0.196$

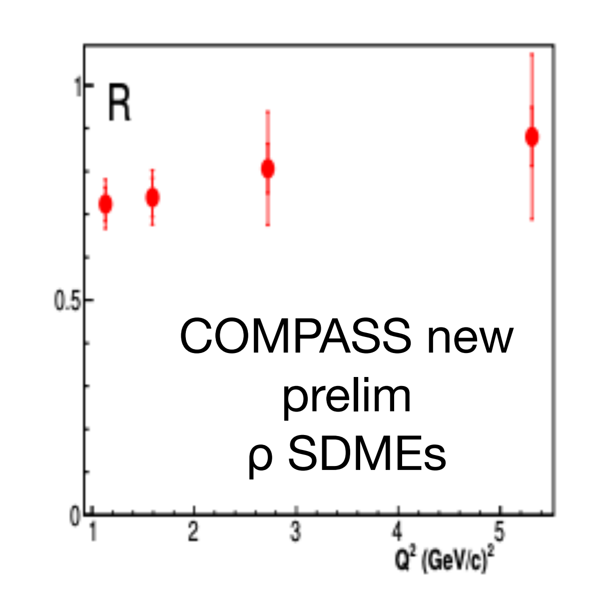
- ✦ Considerable ~~SCHC~~ in $\gamma^*_T \to \omega_L$ (class C), with interesting kinematic dep. Transitions sensitive to chiral-odd GPDs H_T and E_T
- ✦ Cross-section ratio *R* of longitudinal to transverse vector mesons comparison to HERMES

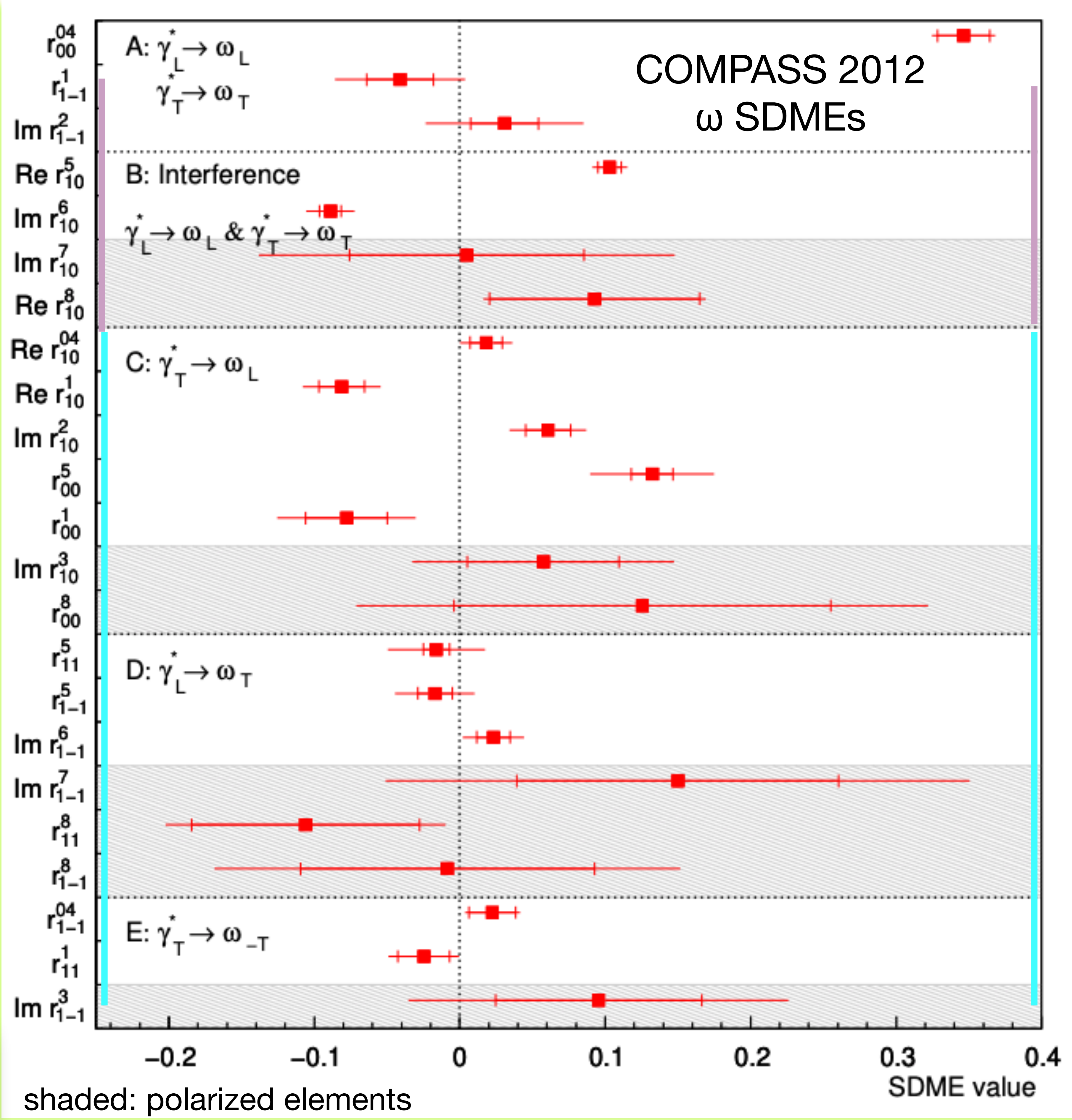
Spin density matrix elements describe how the spin components of the virtual photon are transferred to the created vector meson



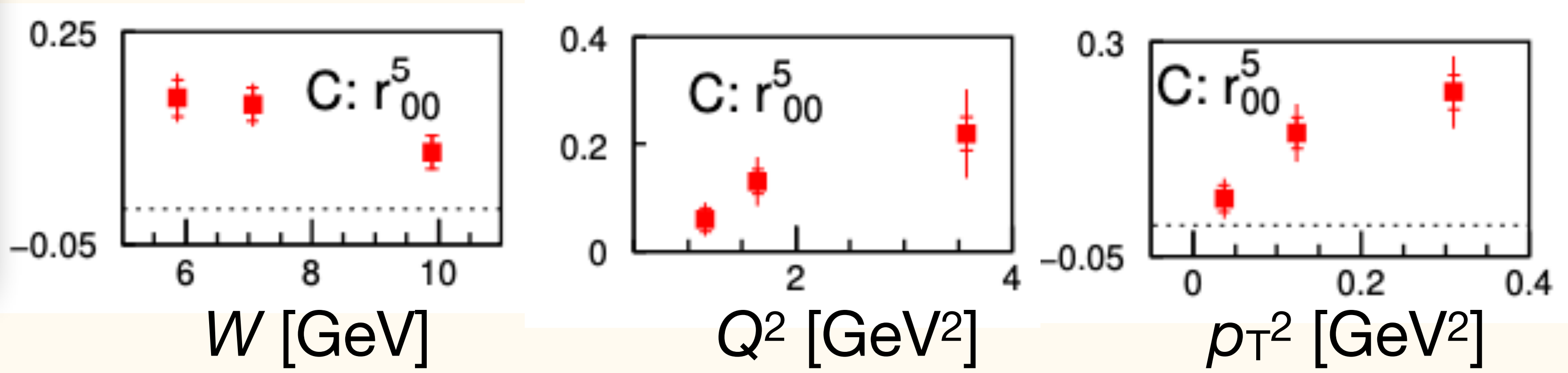
[HERMES EPJC 74 (2014) 3110]
[Goloskokov, Kroll EPJ A (50 2014) 146]







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]



- 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.

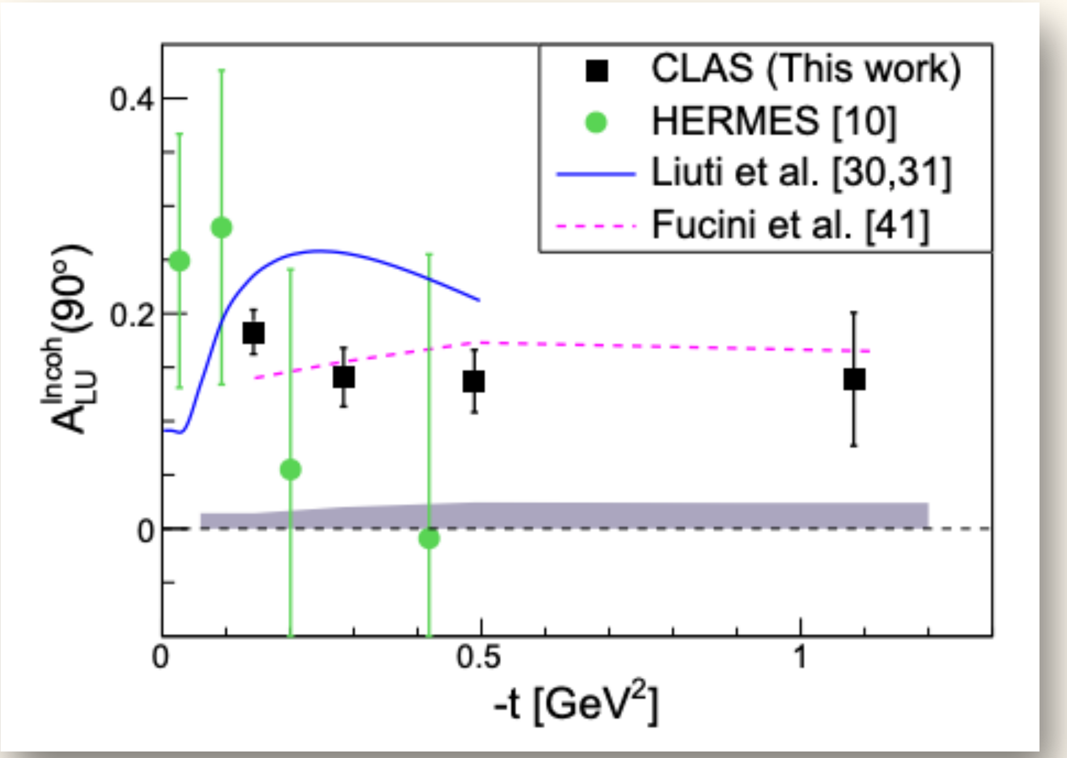
COMPASS rho SDMEs: see talk by W. Augustyniak, Wednesday, 10:54

More exclusive measurements

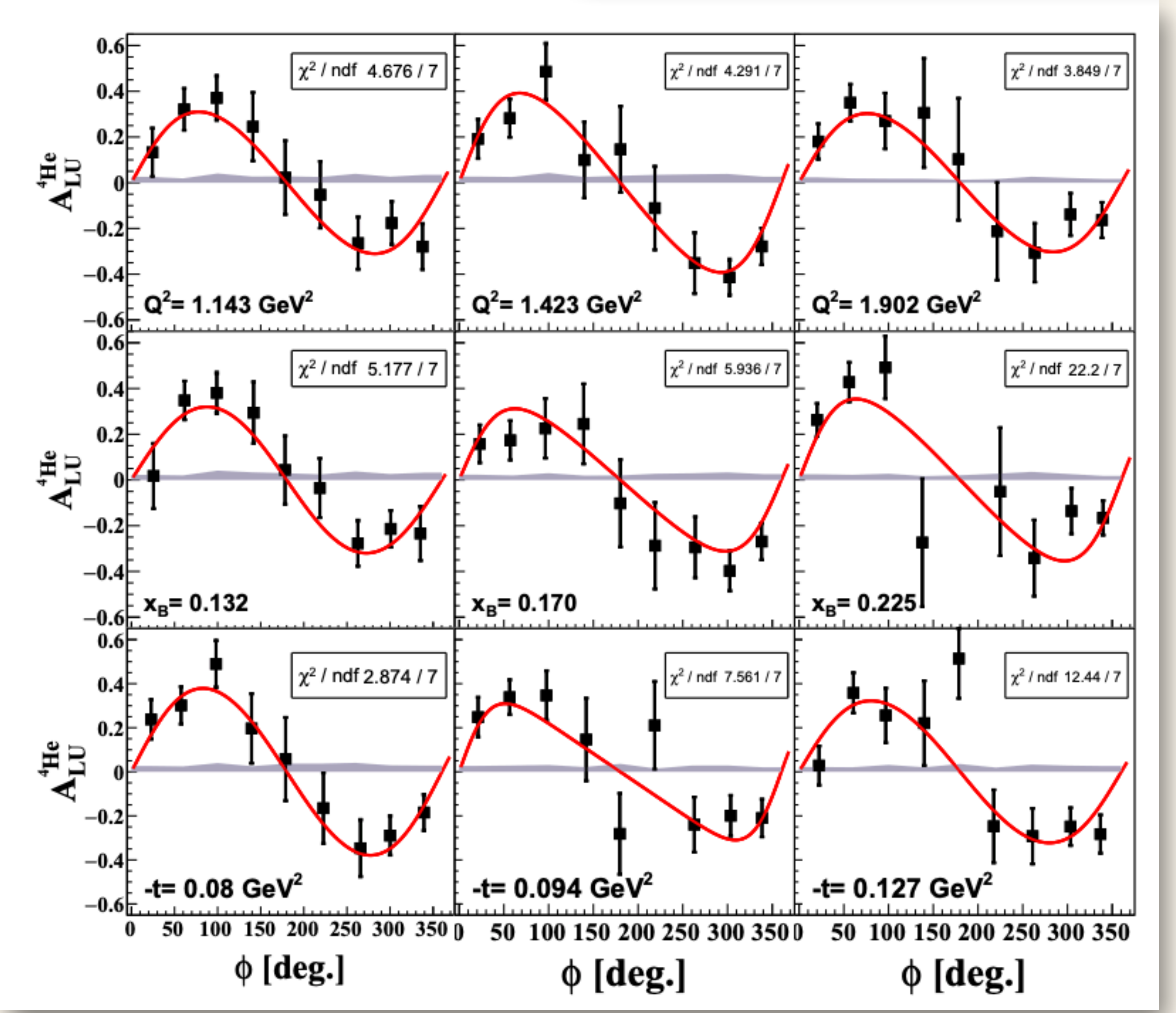
New CLAS **coherent DVCS**

✦ 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

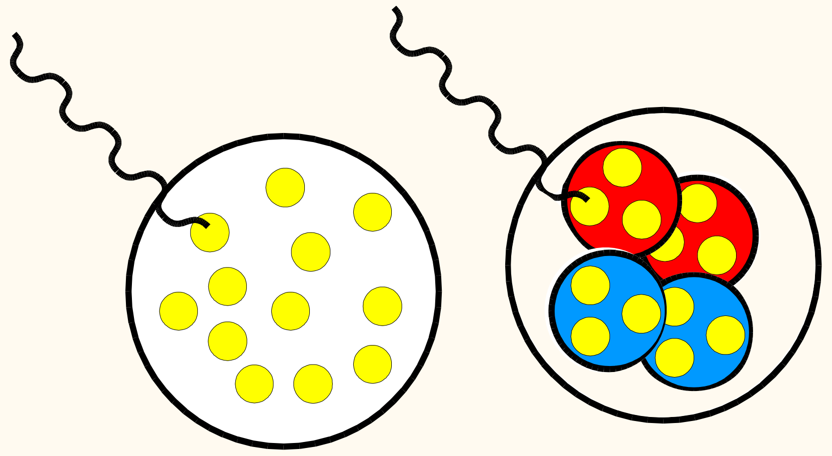
Coherent DVCS allows to study if the DVCS amplitude rises with *A* and if there is a 'generalized EMC effect'



[CLAS / R. Dupre arxiv:2102.07419]



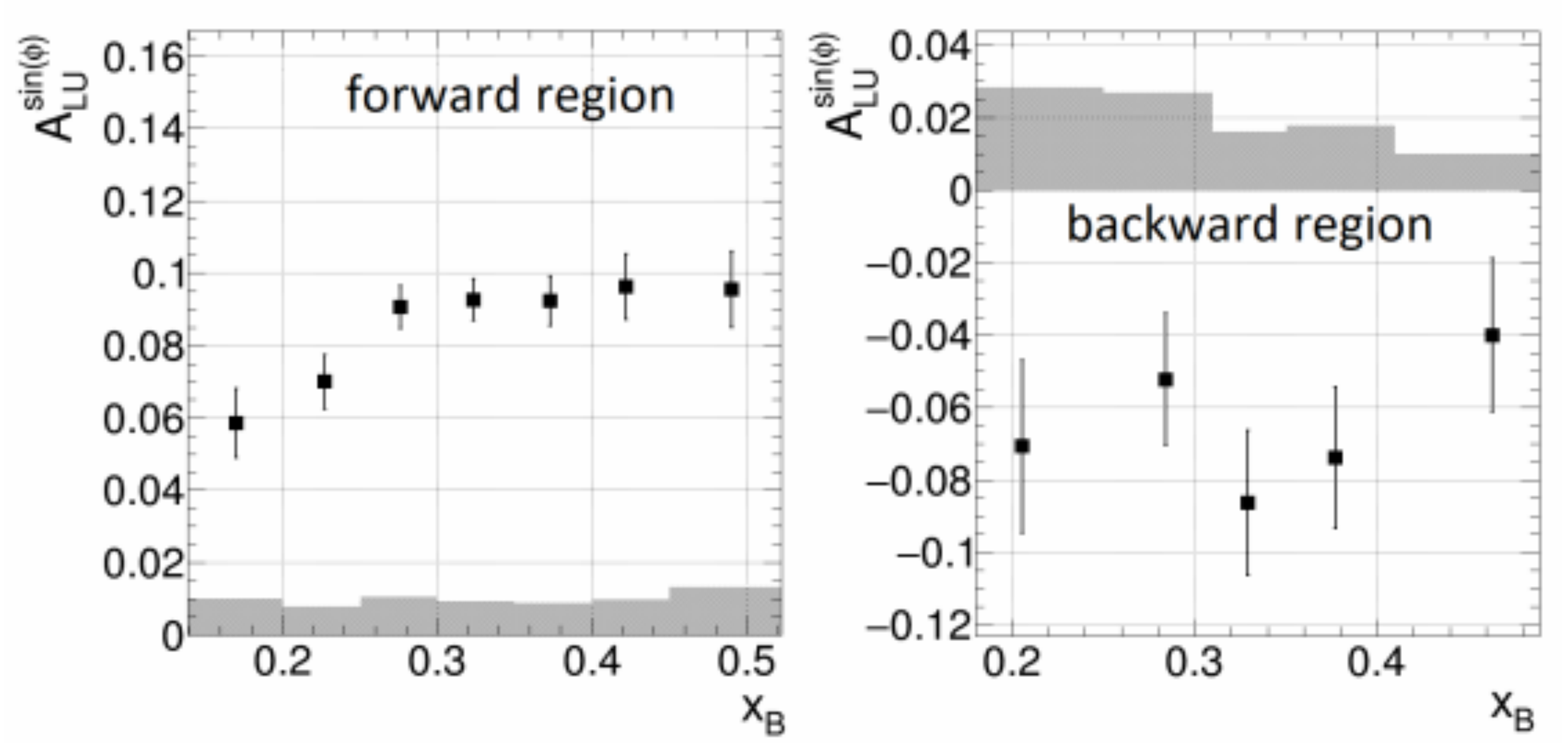
DVCS on ^{4}He

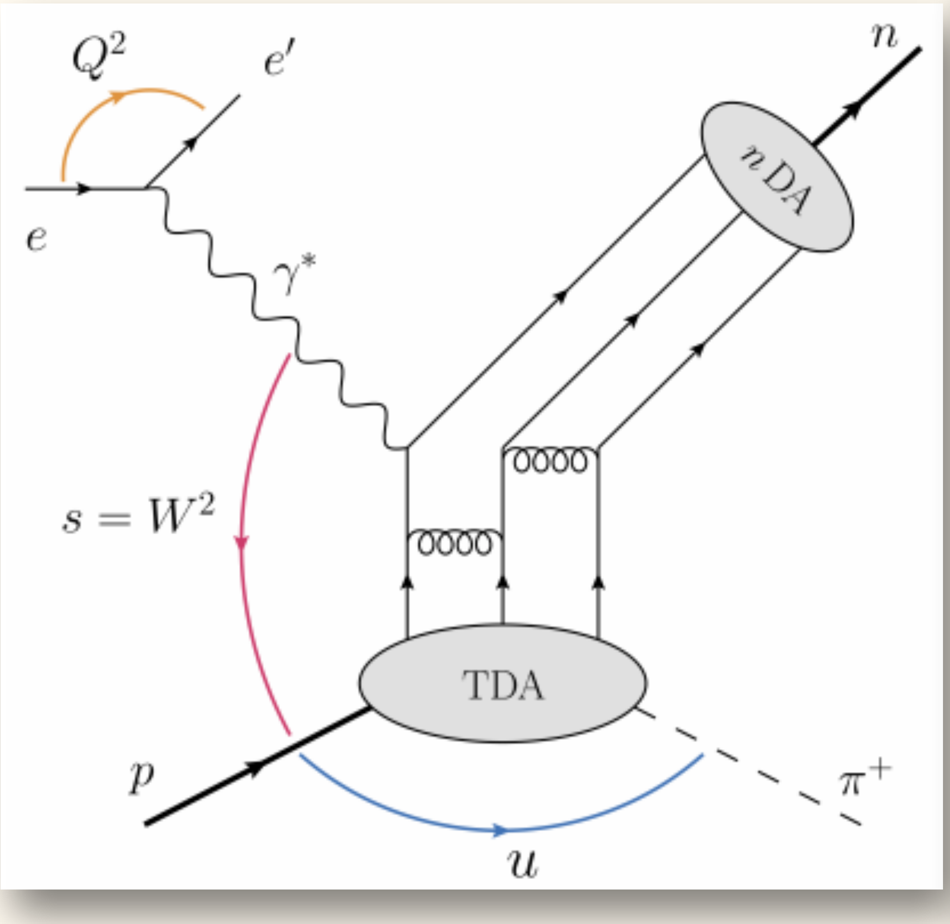


coherent **incoherent**

✦ More measurements planned at CLAS12

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]

see talk by S. Diehl, Wednesday, 10:18

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.*

CLAS12: see talk by M. Battaglieri, Wednesday, 8:00
SoLID: see talk by JP. Chen, Wednesday, 8:25

- **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

see talk by O. Tsai, Tuesday, 12:25

- **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 A. Bazilevsky, recorded flash talk

- **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 M.Yurov, Wednesday, 9:26

- **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 the COMPASS d-quark transversity run, 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

see talk by D. Banerjee, Thursday, 12:40

- **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

see talk by M. Santimaria, Wednesday, 8:50

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

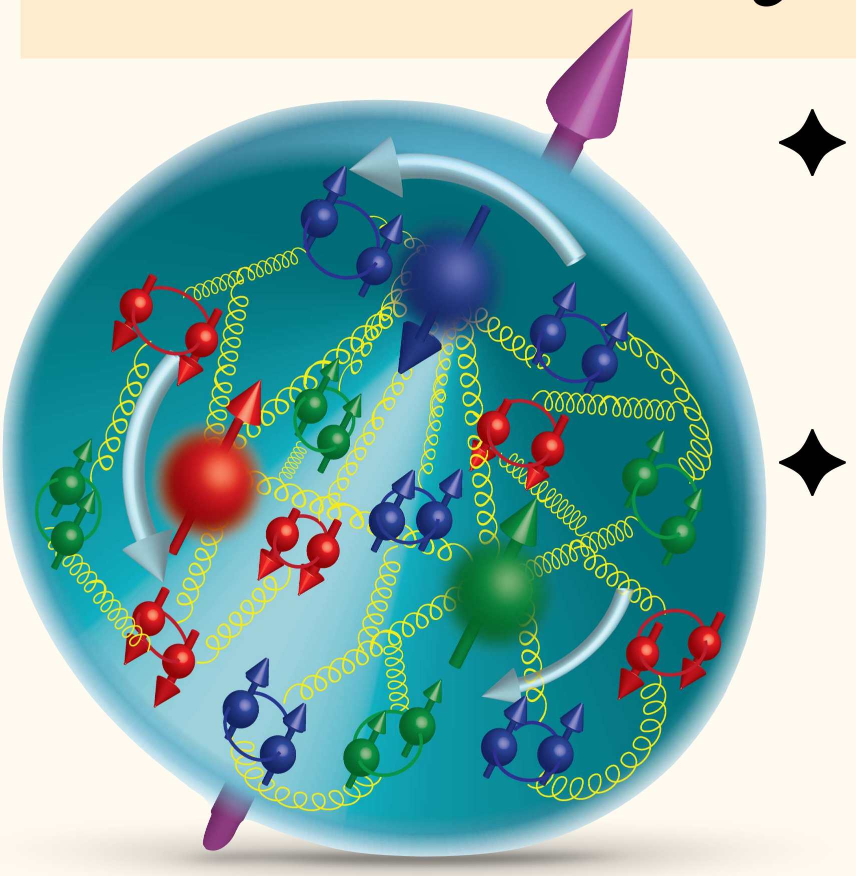
- **SPD at NICA,** JINR: collider experiment with polarized proton and deuteron beams, >2025, http://spd.jinr.ru/

see talk by A. Korzenev, Tuesday, 10:51

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

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

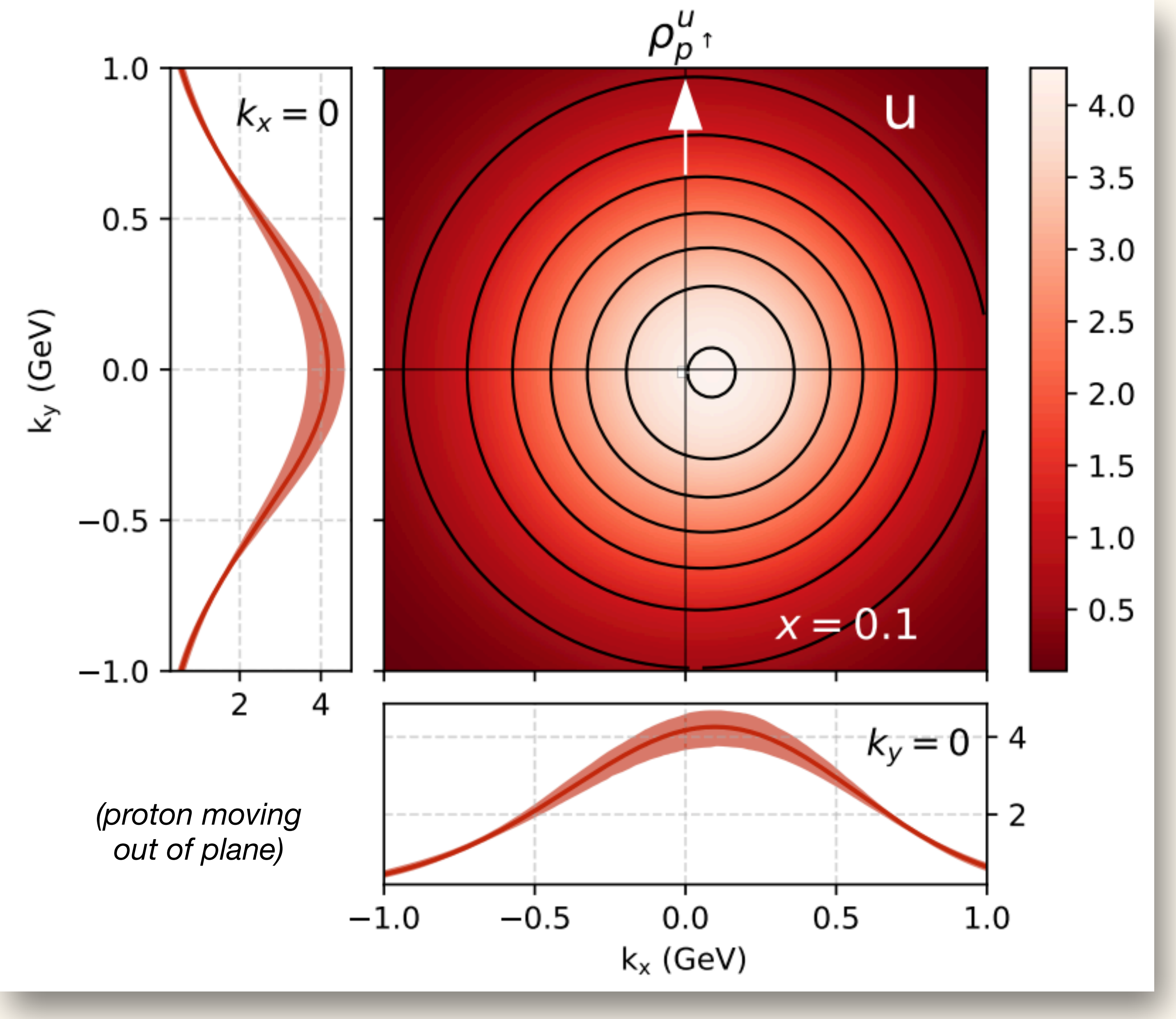
Summary and outlook



- ✦ 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.

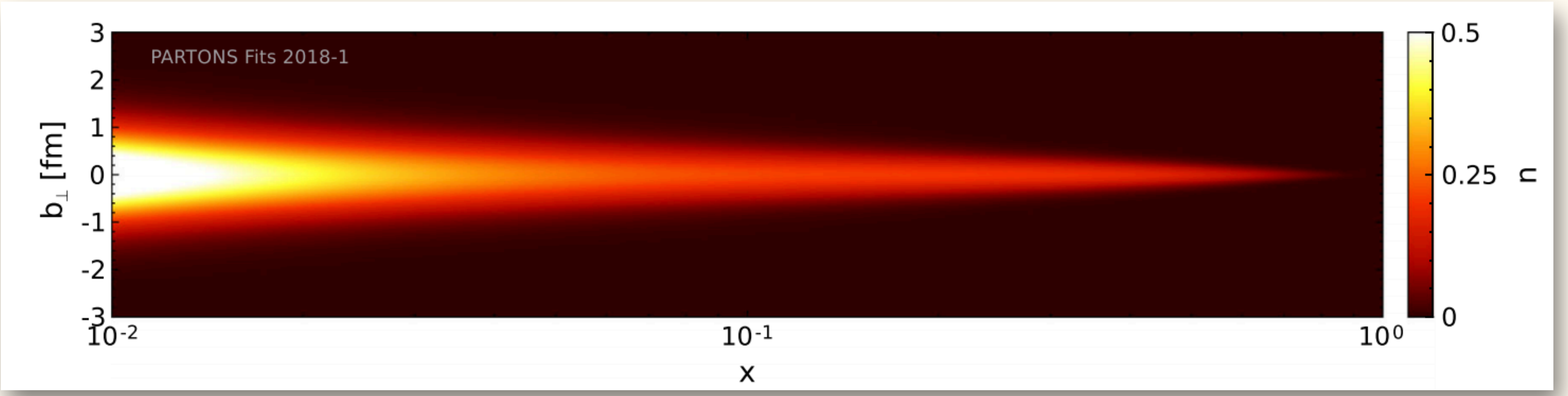
In transverse-momentum space (k_x, k_y):
density distribution of unpolarized u-quark in transversely polarized proton at x=0.1 and Q^2=4 GeV^2



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