The origin of single transverse-spin asymmetries in high-energy collisions

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In this letter, we present, for the first time, a phenomenological analysis that demonstrates single transverse-spin asymmetries in high-energy collisions have a common origin. We perform the first global fit of data from semi-inclusive deep inelastic scattering, Drell-Yan, e^+e^- annihilation into hadron pairs, and proton-proton collisions. Consequently, we are able to extract a universal set of non-perturbative functions that describes the observed asymmetries in these reactions. Furthermore, we achieve the first phenomenological agreement with lattice on the up and down quark tensor charges of the nucleon.

Introduction. For about fifty years, the spin and momentum structure of hadrons has been investigated in terms of their partonic (quark and gluon) content within the theory of Quantum Chromodynamics (QCD). Single transverse-spin asymmetries (SSAs) have played a central role in these studies and continue to pose a number of challenges and puzzles. Early predictions from QCD that SSAs in single-inclusive hadron production should be exceedingly small [1] were in stark contrast with measurements showing large asymmetries [2, 3] that persist in recent experiments [4–18].

A better understanding of SSAs has emerged with the aid of QCD factorization theorems [19–23]. They separate cross sections into short distance, perturbatively calculable scattering contributions and long distance, non-perturbative physics that are encoded in parton distribution functions (PDFs) and fragmentation functions (FFs). QCD factorization theorems constrain the definitions of PDFs and FFs, and they ultimately lead to equations governing how those functions evolve with the energy scale.

For processes with one large measured scale, $Q \gg \Lambda_{\rm QCD}$, where $\Lambda_{\rm QCD}$ is a typical hadronic mass scale, experiments are sensitive to the collinear motion of partons. For example, in $p^\uparrow p \to h\,X$, the hard scale is set by the hadron transverse momentum P_{hT}. In this case, collinear twist-3 (CT3) factorization [19, 20] is valid, and spin asymmetries arise due to the quantum mechanical interference from multi-parton states, such as quark-gluon-quark or tri-gluon [19, 20, 24–32].

For reactions with two well-separated scales $Q_2 \gg Q_1 \sim \Lambda_{\rm QCD}$, experiments probe not only collinear but also intrinsic parton motion that is transverse to the parent hadron's momentum. For example, in semi-inclusive deep inelastic scattering (SIDIS), one has $\Lambda_{\rm QCD} \sim P_{hT} \ll Q$, where $-Q^2$ is the photon virtuality. For such processes, transverse momentum dependent (TMD) factorization [21–23, 33, 34] is valid, and the mechanism responsible for spin asymmetries is encoded in TMD PDFs and FFs (collectively called TMDs) [35–40].

There is theoretical evidence that CT3 and TMD factorization theorems yield a unified picture of spin asymmetries in hard processes [41–46]. This is one of the cornerstones for studying the 3-dimensional structure of hadrons at existing [47–51] and future facilities, including the Electron-Ion Collider [52, 53]. However, it has never been shown that one can simultaneously fit a universal set of non-perturbative functions to SSAs in both types of reactions [54–57]. In this letter, we provide, for the first time, a phenomenological demonstration that SSAs have a common origin. We perform the first simultaneous global analysis of the available data in SIDIS, Drell-Yan (DY), semi-inclusive e^+e^- annihilation (SIA), and proton-proton collisions. Furthermore, we find, for the first time, very good agreement with lattice for the up and down quark tensor charges.

Theoretical Background. The key observation that makes our analysis possible is that in both the CT3 and TMD formalisms, collinear multi-parton correlations play an important role. For example, a generic TMD PDF $F(x,k_T)$ depends on x, the longitudinal momentum fraction of the nucleon's momentum carried by the parton, and $k_T \equiv |\vec{k}_T|$, the parton's transverse momentum. The Fourier conjugated position (b_T) space TMD is $\tilde{F}(x,b_T)$ [34, 58–60]. When b_T (in units of GeV^{-1}) becomes very small, it sets a dynamical scale $\sim 1/b_T$ that can be used for the Operator Product Expansion (OPE) of TMDs. In the case of TMDs relevant for SSAs, the OPE is expressed in terms of CT3 multi-parton correlation functions [60–63].

Another way to establish the connection is to use parton model identities that result in relations between CT3 functions and TMDs. One such relation is $\pi F_{FT}(x,x) = \int d^2\vec{k}_T\,(k_T^2/(2M^2)) f_{1T}^{\perp}(x,k_T^2) \equiv f_{1T}^{\perp(1)}(x)$ [64], where $F_{FT}(x,x)$ is the Qiu-Sterman CT3 matrix element, and $f_{1T}^{\perp(1)}(x)$ is the first moment of the TMD Sivers function $f_{1T}^{\perp}(x,k_T^2)$ [65, 66]. The dependence of this relation on the energy scale is under further investigation since TMDs and CT3 functions have different divergences that make their evolution principally different. Here we use the leading order identities and do not address their validity beyond this order [60–63]. We also parameterize the transverse momentum dependence of all TMDs with a Gaussian shape. This assumes that most of the transverse momentum dependence is nonperturbative and is thus related to intrinsic properties of the colliding hadrons rather than to hard gluon radiation.

A central focus of TMD asymmetries is on the Sivers and Collins SSAs in SIDIS, $A_{\rm SIDIS}^{\rm Siv}$ [67–69] and $A_{\rm SIDIS}^{\rm Col}$ [68–70]; Sivers SSA in DY, $A_{\rm DY}^{\rm Siv}$ [71, 72]; and Collins SSA in SIA, $A_{\rm SIA}^{\rm Col}$ [73–76]. The relevant TMDs probed by these processes [35–40] are the transversity TMD $h_1(x,k_T^2)$ [77], the Sivers function $f_{1T}^{\perp}(x,k_T^2)$ [65, 66], and Collins function $H_1^{\perp}(z,z^2p_\perp^2)$ [78]. Each of them can be written in terms of a collinear counterpart via the OPE. The function $h_1(x,k_T^2)$ is related to the collinear (twist-2) transversity function $h_1(x)$ [79]; $f_{1T}^{\perp}(x,k_T^2)$ to the Qiu-Sterman function $F_{FT}(x,x)$ [60]; and $H_1^{\perp}(z,z^2p_\perp^2)$ to its first $p_\perp$-moment $H_1^{\perp(1)}(z) \equiv z^2\int d^2\vec{p}_\perp\,(p_\perp^2/(2M_h^2)) H_1^{\perp}(z,z^2p_\perp^2)$ [80], where M_h is the hadron mass and $p_\perp$ the parton transverse momentum.

The same set of functions, $h_1(x)$, $F_{FT}(x,x)$, $H_1^{\perp(1)}(z)$, that arise in the OPE of TMDs are also the non-perturbative objects that drive collinear SSAs like A_N^h in $p^\uparrow p \to h\,X$ [26, 28, 30–32]. In fact, in the CT3 framework, the main cause of A_N^h can be explained by the coupling of $h_1(x)$ to $H_1^{\perp(1)}(z)$ and another multi-parton correlator $\tilde{H}(z)$ [56, 57]. The latter generates the P_{hT}-integrated SIDIS $A_{UT}^{\sin\phi_S}$ asymmetry by coupling with $h_1(x)$ [38].

One can therefore argue that SSAs have a common origin, namely, multi-parton correlations. We present the first phenomenological verification of this claim by simultaneously fitting $A_{\rm SIDIS}^{\rm Siv}$, $A_{\rm SIDIS}^{\rm Col}$, $A_{\rm DY}^{\rm Siv}$, $A_{\rm SIA}^{\rm Col}$, and A_N^h, and extracting the non-perturbative functions $h_1(x)$, $F_{FT}(x,x)$, and $H_1^{\perp(1)}(z)$, along with their relevant transverse-momentum widths. (Ultimately, $\tilde{H}(z)$ was set to zero in our analysis, as explained in the Methodology section.)

We further argue that such an analysis exhibits universal properties for the underlying partonic functions and therefore operates as a consistency test on the validity of the theoretical framework. In particular, a set of necessary conditions for a universality test is as follows. 1) The system must be over-constrained. That is, the number of equations relating partonic functions to observables must be larger than the total number of partonic functions. 2) Each function must appear at least twice in such equations. 3) There must be reasonable kinematical coverage between observables.

This is satisfied in the present analysis, as summarized in Table I. There is also considerable kinematical overlap in x, z, and Q^2 between the observables. SIDIS (after data cuts) covers a region $x \lesssim 0.3$, $0.2 \lesssim z \lesssim 0.6$, and $2 \lesssim Q^2 \lesssim 40\,\mathrm{GeV}^2$. SIA data has $0.2 \lesssim z \lesssim 0.8$ and $Q^2 \approx 13\,\mathrm{GeV}^2$ or $110\,\mathrm{GeV}^2$. For DY data, $0.1 \lesssim x \lesssim 0.35$ and $Q^2 \approx 30\,\mathrm{GeV}^2$ or $(80\,\mathrm{GeV})^2$. Lastly, A_N^h integrates from x_{min} to 1 and z_{min} to 1, where $0.2 \lesssim (x_{min}, z_{min}) \lesssim 0.7$, with $1 \lesssim Q^2 \lesssim 13\,\mathrm{GeV}^2$.

Methodology. In order to perform our global analysis, we must postulate a functional form for the non-perturbative functions. Since we use the leading order relations between CT3 and TMD functions, for the TMDs we will employ a simple Gaussian parametrization for the transverse momentum dependence. This is a standard approach within the literature – see, e.g., Refs. [81–83]. The dependence of the TMDs on the parton longitudinal momentum fraction is constructed from the collinear functions that arise in the OPE.

The type of parameterization outlined above does not have the complete features of TMD evolution, in particular the broadening of the transverse momentum widths. However, it was shown that analyses [84, 85] utilizing this parameterization are compatible with results using full TMD evolution [80, 86–88]. In addition, asymmetries are ratios of cross sections where the effects of evolution may cancel out [88].

For the unpolarized and transversity TMDs we have

$$f^q(x,k_T^2) = f^q(x)\;\mathcal{G}_f^q(k_T^2)\,, \tag{1}$$

where the generic function $f^q = f_1^q$ or h_1^q, and

$$\mathcal{G}_f^q(k_T^2) = \frac{1}{\pi\langle k_T^2\rangle_f^q}\,\exp\left[-\frac{k_T^2}{\langle k_T^2\rangle_f^q}\right]. \tag{2}$$

Using the relation that $\pi F_{FT}(x,x) = f_{1T}^{\perp(1)}(x)$ [64], the Sivers function reads

$$f_{1T}^{\perp\,q}(x,k_T^2) = \frac{2M^2}{\langle k_T^2\rangle_{f_{1T}^\perp}^q}\,\pi F_{FT}(x,x)\;\mathcal{G}_{f_{1T}^\perp}^q(k_T^2)\,. \tag{3}$$

The transverse momentum widths $\langle k_T^2\rangle_f^q$ are in general flavor dependent, and can be functions of x, although here we assume there is no x dependence.

For the TMD FFs, the unpolarized function is parameterized as

$$D_1^{h/q}(z,z^2p_\perp^2) = D_1^{h/q}(z)\;\mathcal{G}_{D_1}^{h/q}(z^2p_\perp^2)\,, \tag{4}$$

while the Collins FF reads

$$H_1^{\perp\,h/q}(z,z^2p_\perp^2) = \frac{2z^2M_h^2}{\langle p_\perp^2\rangle_{H_1^\perp}^{h/q}}\,H_{1\,h/q}^{\perp(1)}(z)\;\mathcal{G}_{H_1^\perp}^{h/q}(z^2p_\perp^2)\,, \tag{5}$$

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$	Exp. Refs.
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,k_T^2)$	$150.0/126=1.19$	[67–69]
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^\perp(z,z^2p_\perp^2)$	$111.3/126=0.88$	[68–70]
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2p_\perp^2)$	$154.5/176=0.88$	[73–76]
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,k_T^2)$	$5.96/12=0.50$	[71]
$A_{\text{DY}}^{\text{Siv}}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,k_T^2)$	$31.8/17=1.87$	[72]
A_N^h	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x)=\frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60=1.11$	[7, 9, 10, 13]

TABLE I. Summary of the SSAs analyzed in our global fit. There are a total of 18 observables when one accounts for the various initial and final states. This includes the "unlike-charged" (UC) and "unlike-like" (UL) combinations for $A_{\text{SIA}}^{\text{Col}}$. For $f_{1T}^\perp, h_1$ we have up and down quarks, while for $H_1^\perp$ we have favored and unfavored fragmentation. This gives a total of 6 non-perturbative functions. We also include $\chi^2/N_{\text{pts.}}$ for each observable in our fit, where $N_{\text{pts.}}$ is the number of data points.

where we have explicitly written its z dependence in terms of its first moment $H_{1\,h/q}^{\perp(1)}(z)$ [80]. For $f_1^q(x)$ and $D_1^q(z)$ we use the leading order CJ15 [89] and DSS [90] functions. The pion PDFs are taken from Ref. [91].

Note Eqs. (1), (3), (5) make fully manifest that the underlying non-perturbative functions, $h_1(x)$, $F_{FT}(x,x)$, $H_1^{\perp(1)}(z)$, that drive the (TMD) SSAs $A_{\text{SIDIS}}^{\text{Siv}}$, $A_{\text{SIDIS}}^{\text{Col}}$, $A_{\text{DY}}^{\text{Siv}}$, and $A_{\text{SIA}}^{\text{Col}}$, are the same collinear functions that enter the SSA A_N^h (along with $\tilde{H}(z)$). We generically parameterize these collinear functions as

$$F^q(x) = \frac{N_q\, x^{a_q}(1-x)^{b_q}(1+\gamma_q\, x^{\alpha_q}(1-x)^{\beta_q})}{\mathrm{B}[a_q+2,b_q+1]+\gamma_q \mathrm{B}[a_q+\alpha_q+2,b_q+\beta_q+1]}\,, \tag{6}$$

where $F^q = h_1^q, \pi F_{FT}^q$, $H_{1\,h/q}^{\perp(1)}$ (with $x \to z$ for the Collins function). In the course of our analysis, we found that $\tilde{H}(z)$ was consistent with zero within error bands. Moreover, if one considers the relative error of the moment $F^{(1)} \equiv \int_0^1 dx\, xF(x)$ of the various functions in our fit, $h_1(x)$, $\pi F_{FT}(x,x)$, and $H_1^{\perp(1)}(z)$ all have $\delta F^{(1)}/F^{(1)} \lesssim 1.5$, whereas for $\tilde{H}(z)$, $\delta F^{(1)}/F^{(1)} \gg 1.5$. This indicates that there is no discernible signal for $\tilde{H}(z)$ from A_N^h data alone, and the function simply emerges as noise in our fit. Therefore, data on the aforementioned (P_{hT}-integrated) $A_{UT}^{\sin\phi_S}$ asymmetry in SIDIS is needed to properly constrain $\tilde{H}(z)$. For now, we set $\tilde{H}(z)$ to zero, which is consistent with preliminary data from HERMES and COMPASS showing a very small $A_{UT}^{\sin\phi_S}$.

For the collinear PDFs $h_1^q(x)$ and $\pi F_{FT}^q(x,x)$, we only allow $q = u, d$ and set anti-quark functions to zero. For both functions we also set $b_u = b_d$. For the collinear FF $H_{1\,h/q}^{\perp(1)}(z)$, we allow for favored (fav) and unfavored (unf) parameters. We also found that the set of parameters $\{\gamma,\alpha,\beta\}$ is needed only for $H_{1\,h/q}^{\perp(1)}(z)$, due to the fact that the data for $A_{\text{SIA}}^{\text{Col}}$ has a different shape at smaller versus larger z. Since those data (and the ones for $A_{\text{SIDIS}}^{\text{Col}}$) are at $z \gtrsim 0.2$, we set $\alpha_{fav} = \alpha_{unf} = 0$, similar to what has been done in fits of unpolarized collinear FFs [90]. This gives us a total of 20 parameters for the collinear functions. There are also 4 parameters for the transverse momentum widths associated with h_1, $f_{1T}^\perp$, and $H_1^\perp$: $\langle k_T^2\rangle_{f_{1T}^\perp}^u = \langle k_T^2\rangle_{f_{1T}^\perp}^d \equiv \langle k_T^2\rangle_{f_{1T}^\perp}$; $\langle k_T^2\rangle_{h_1}^u = \langle k_T^2\rangle_{h_1}^d \equiv \langle k_T^2\rangle_{h_1}$; $\langle p_\perp^2\rangle_{H_1^\perp}^{fav}$ and $\langle p_\perp^2\rangle_{H_1^\perp}^{unf}$.

We simultaneously extract unpolarized TMD widths by including HERMES pion and kaon multiplicity data [92] in our fit, which involves 6 more parameters associated with the valence and sea unpolarized PDF widths, and favored and unfavored unpolarized FF widths for pions and for kaons: $\langle k_T^2\rangle_{f_1}^{val}$, $\langle k_T^2\rangle_{f_1}^{sea}$, $\langle p_\perp^2\rangle_{D_1^{\{\pi,K\}}}^{fav}$, $\langle p_\perp^2\rangle_{D_1^{\{\pi,K\}}}^{unf}$. The pion PDFs widths are taken to be the same as those for the proton. The overall normalization of the data is fit with 77 "nuisance" parameters, one for each data set. We also implement a DGLAP-type evolution of the collinear functions analogous to Ref. [93], where a double-logarithmic Q^2-dependent term is explicitly added to the parameters. Note that the transverse momentum widths do not vary with Q^2. We leave a more rigorous treatment of the complete TMD and CT3 evolution for future work.

Phenomenological Results. Using the above methodology, we fit SSA data from HERMES [67, 70], COMPASS [68, 69, 71], Belle [73], BaBar [74, 75], BESIII [76], BRAHMS [9], and STAR [7, 10, 13, 72] using the Monte Carlo analysis outlined in Ref. [94]. For $A_{\text{SIDIS}}^{\text{Siv}}$, $A_{\text{SIDIS}}^{\text{Col}}$, $A_{\text{SIA}}^{\text{Col}}$, and A_N^h, we focus on pion production data, while for $A_{\text{DY}}^{\text{Siv}}$ we use both the $\mu^+\mu^-$ pair production data from COMPASS and the weak gauge boson production data from STAR. For $A_{\text{SIA}}^{\text{Col}}$ we have only included the so-called A_0 asymmetry since this analysis respects TMD factorization. A_N^π data with $P_{hT} < 1\,\text{GeV}$ has also been excluded in order to stay within the perturbative regime. Likewise, we do not include low-energy SSA data from JLab due to concerns about the pion production mechanism [95–97] at relatively low energies. The standard cuts [98] of $0.2 < z < 0.6$, $Q^2 > 1.63\,\text{GeV}^2$, and $0.2 < P_{hT} < 0.9\,\text{GeV}$ have been applied to all SIDIS data sets. This gives us a total of 517 SSA data points in the fit along with 807 HERMES multiplicity [92] data points.

The extracted functions and their comparison to other groups are shown in Fig. 1. A repository with a code that generates these functions can be found at Ref. [99]. The overall agreement between the experimental data and theoretical curves is very good – see Figs. 2–4. We obtained $(\chi^2/N_{\text{pts.}})_{\text{SSA}} = 520.1/517 = 1.01$ for SSA

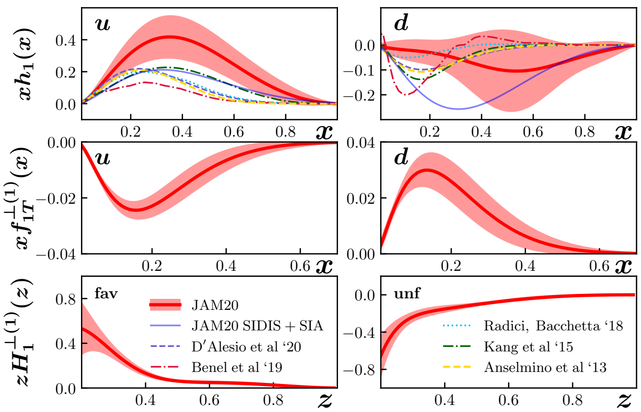

FIG. 1. Functions $h_1(x)$, $f_{1T}^{\perp(1)}(x) = \pi F_{FT}(x,x)$, and $H_1^{\perp(1)}(z)$ at $Q^2 = 4$ GeV^2 compared to other extractions.

data alone, and $\chi^2/N_{\rm pts.} = 1373/1324 = 1.04$ for all data (both SSAs and HERMES multiplicities). Figure 2 presents results for SIA data from Belle [73], BaBar [74, 75], and BESIII [76]. Charged pion data from HERMES [67, 70] and COMPASS [68, 69] for SIDIS with proton and deuterium targets are shown in Fig. 3. We

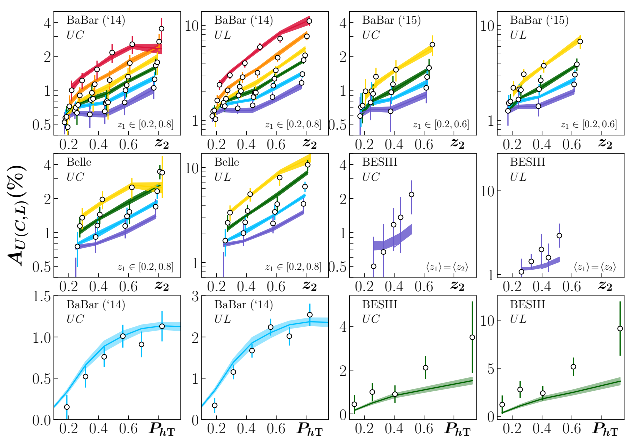

FIG. 2. Theory compared to experiment for $A_{\rm SIA}^{\rm Col}$ [73–76].

note that data from HERMES for π^0 were also included in the fit but are not shown. Figure 4 shows proton-proton A_N^π data for $\pi^\pm$ from BRAHMS [9] and π^0 from STAR [7, 10, 13]. Drell-Yan data for $W^\pm/Z$ production from STAR [72] and for $\mu^+\mu^-$ production from COMPASS [71] are also featured.

Figure 5 gives our extracted tensor charges of the nucleon. The individual flavor charges $\delta q \equiv \int_0^1 dx\,[h_1^q(x) - h_1^{\bar q}(x)]$ are shown along with the isovector combination $g_T \equiv \delta u - \delta d$. We compare our results to those from lattice computations at the physical point [100–102], other phenomenological extractions [80, 83, 103–107], and a calculation using Dyson-Schwinger equations [108]. One clearly notices the impact when more SSA data sets are included in our fit. If only SIDIS data is used then the tensor charge is basically unconstrained. The extraction becomes more precise when both SIDIS and SIA data sets are included. Once the global fit is performed

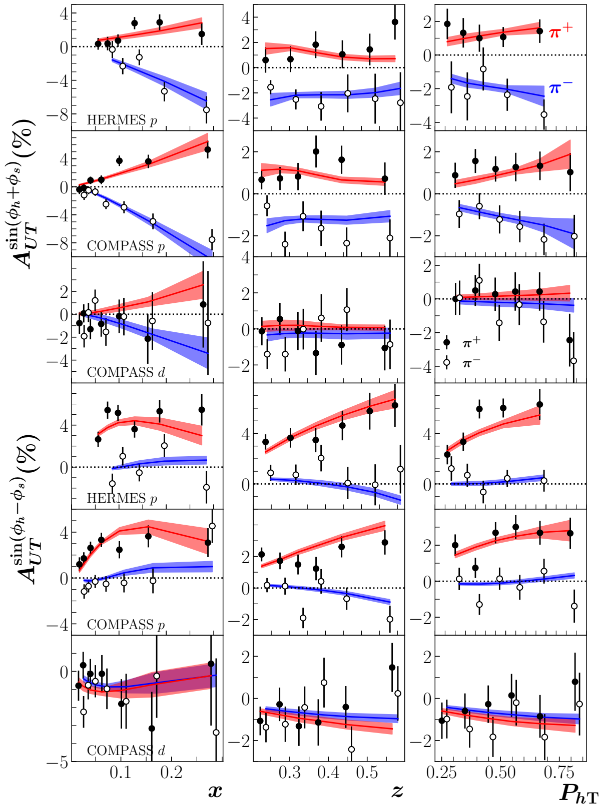

FIG. 3. Theory compared to experiment for $A_{\rm SIDIS}^{\rm Col} \equiv A_{UT}^{\sin(\phi_h+\phi_S)}$ [68–70] and $A_{\rm SIDIS}^{\rm Siv} \equiv A_{UT}^{\sin(\phi_h-\phi_S)}$ [67–69].

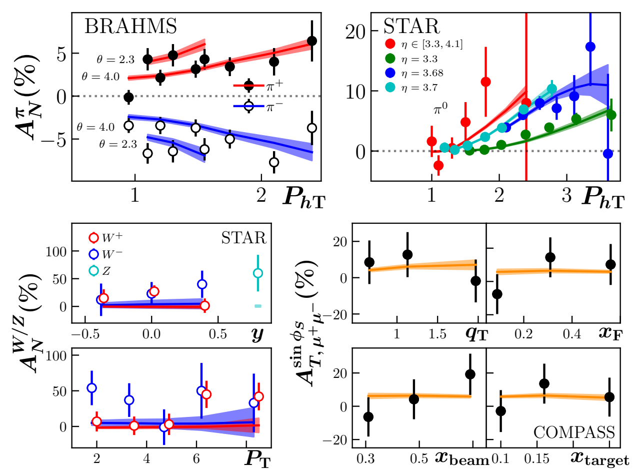

FIG. 4. Theory compared to experiment for A_N^π [7, 9, 10, 13] and for $A_{\rm DY}^{\rm Siv}$ in $W^\pm/Z$ production $\equiv A_N^{W/Z}$ [72], and in $\mu^+\mu^-$ production $\equiv A_{T,\mu^+\mu^-}^{\sin\phi_S}$ [71].

(which, in particular, means A_N^π data is included), we obtain the most accurate value for g_T. In going from SIDIS $\to$ (SIDIS + SIA) $\to$ GLOBAL, we find $g_T = 1.4(6) \to 0.87(25) \to 0.87(11)$. This is the most precise phenomenological determination of g_T to date. All of the tensor charges (δu, δd, and g_T) are also in very good agreement with lattice. Note that the inclusion of A_N^π data is crucial in order to achieve this agreement between our results $\delta u = 0.72(19)$, $\delta d = -0.15(16)$ and those of lattice.

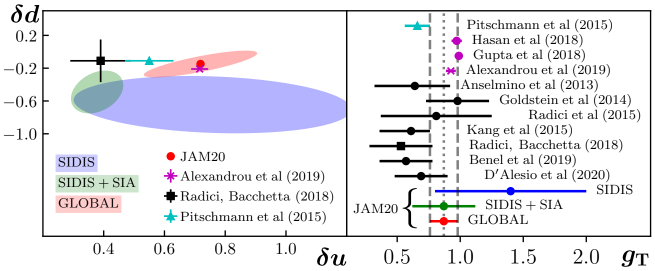

FIG. 5. The 1-σ CL tensor charges δu, δd, and g_T at $Q^2 = 4$ GeV^2 from phenomenology (black), lattice (purple), and Dyson-Schwinger (cyan).

Conclusions. In this paper we have performed the first global analysis of the available SSA data in SIDIS, DY, e^+e^- annihilation, and proton-proton collisions. The predictive power exhibited by the combined analysis suggests a common physical origin of SSAs. Namely, they are due to the intrinsic quantum-mechanical interference from multi-parton states. The success achieved with Gaussian shapes for the transverse momentum dependence further implies that the effects are dominantly nonperturbative and intrinsic to hadronic wavefunctions. We also observe that the extracted up and down quark tensor charges are in very good agreement with lattice.

The final experimental data from COMPASS and HERMES on the $A_{UT}^{\sin\phi_S}$ observable in SIDIS will give us stronger and more direct constraints on the function $\tilde{H}(z)$. Moreover, the future data coming from Jefferson Lab 12 GeV, COMPASS, an upgraded RHIC, Belle II, and the Electron-Ion Collider will help to reduce the uncertainties of the extracted functions and ultimately lead to a better understanding of hadronic structure.

Acknowledgments. This work has been supported by the NSF under Grants No. PHY-1623454 (A.P.), No. PHY-1720486 (Z.K.), the DOE Contracts No. DE-AC05-06OR23177 (L.G.), No. DE-AC05-06OR23177 (A.P., N.S., T.R.) under which JSA, LLC operates JLab, a LVC Arnold Student-Faculty Research Grant (J.A.M. and D.P.), and within the framework of the TMD Topical Collaboration.

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