Accessing Nucleon Transversity via Energy Correlators:
Theory vs. Data

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May 21th, 2026

Reference

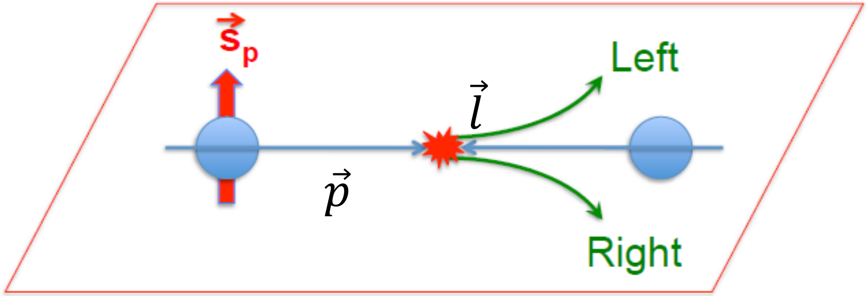
- Theory
  https://journals.aps.org/prl/abstract/10.1103/1lz2-3fm9
  https://arxiv.org/abs/2509.15809
  https://agenda.infn.it/event/47074/contributions/289127/attachments/149530/228704/WanchenLi_OPEC.pdf
- Experiment (STAR)
  https://arxiv.org/abs/2511.00149
  https://journals.aps.org/prl/abstract/10.1103/wv2t-dkgn
- TMDs global analysis
  - https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.192001
  - https://journals.aps.org/prd/abstract/10.1103/PhysRevD.106.034014
  - https://journals.aps.org/prd/abstract/10.1103/PhysRevD.102.054002
  - https://journals.aps.org/prd/abstract/10.1103/PhysRevD.93.014009

Outline

- Transverse spin asymmetry – TMDs
- Global analysis of “Transversity” (h1)
- One point energy correlator (OPEC) within jets
- OPEC in the polarized p+p at sqrt(s)=200 GeV
- Predictions vs. measurements
- Summary & EIC outlooks

SINGLE SPIN ASYMMETRIES

Consider polarized hadron - hadron collisions



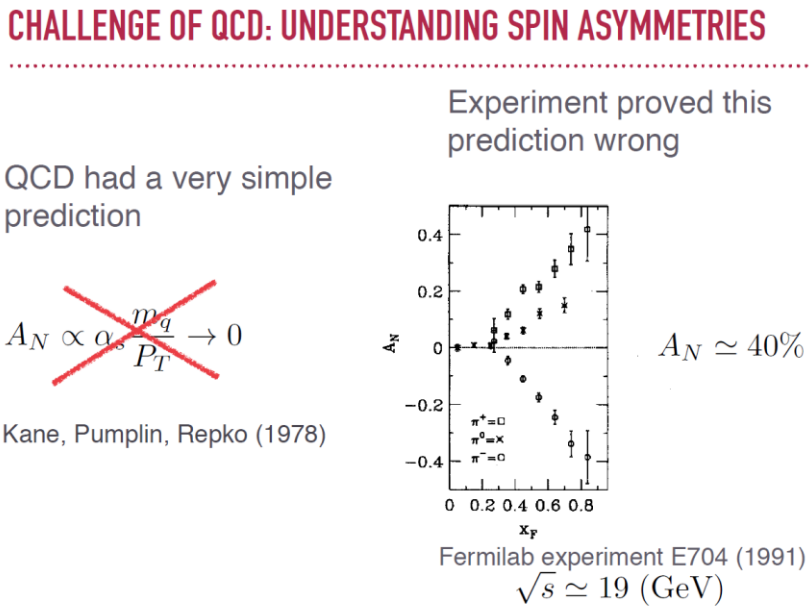
$$A_N(l, \vec{s}_\perp) \propto \vec{s}_\perp \cdot (\vec{p} \times \vec{l})$$

Count pions going to the right or to the left with respect to the spin direction

$$A_N \equiv \frac{\sigma(\vec{s}_P) - \sigma(-\vec{s}_P)}{\sigma(\vec{s}_P) + \sigma(-\vec{s}_P)}$$

Prehistory of Transverse Spin Effect

- 1966 Christ and Lee: transverse single-spin asymmetry (SSA or A_N), a T-odd quantity, is prohibited by time-reversal invariance in DIS.
- 1975 Large SSA in p↑p→πX
- 1976 Large transverse polarization of Λ in pp→ΛX
- 1978 Kane, Pumplin and Repko: SSAs shall vanish in the massless limit.



CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

QCD had a very simple prediction

$$A_N \propto \cancel{\alpha_s \frac{m_q}{P_T}} \to 0$$

Kane, Pumplin, Repko (1978)

Experiment proved this prediction wrong

$A_N \simeq 40\%$

Fermilab experiment E704 (1991)

$\sqrt{s} \simeq 19\ (\mathrm{GeV})$

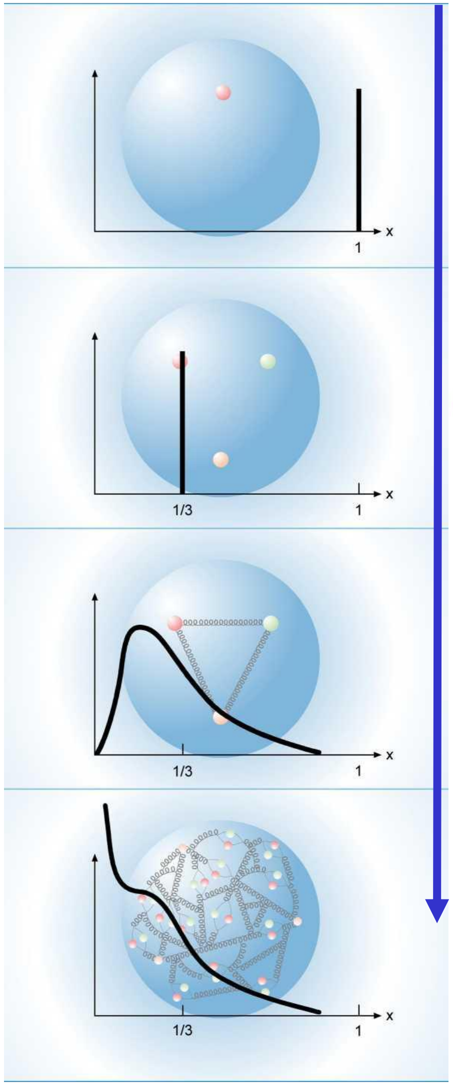
History of Transverse Spin Effect

- 1990 Sivers: SSAs originating from the intrinsic k_T motion of quarks in a transversely polarized hadron.
- 1993 Collins: a spin asymmetry in the fragmentation of transversely polarized quarks, correlating with k_T, into an unpolarized hadron, which enables the measurement of SSAs in SIDIS.

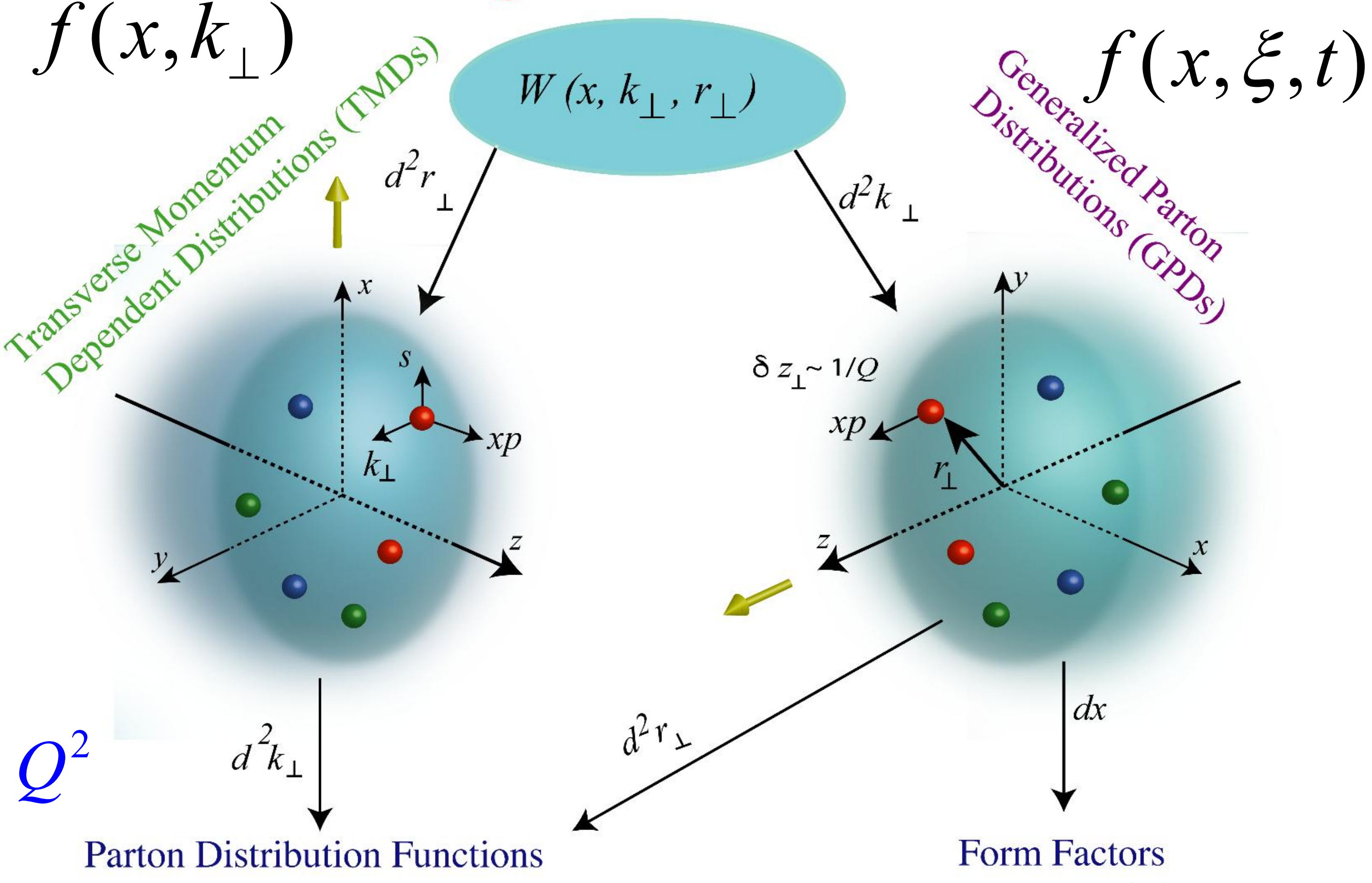
History of Transverse Spin Effect

- 1993 Collins: Sivers function should vanish due to parity and time reversal invariance.
- 2002 Brodsky, Hwang and Schmidt: SSAs in SIDIS might be finite taking account of orbital motion of quarks and multiple gluon scattering.
- 2002 Collins: *Sivers function could be non-zero due to the gauge link. The Sivers functions in SIDIS and Drell-Yan processes are of opposite sign.*

Multi-dimensional Partonic Structures



Q^2



Wigner Distributions

$W(x, k_\perp, r_\perp)$

$f(x,k_\perp)$

Transverse Momentum Dependent Distributions (TMDs)

Generalized Parton Distributions (GPDs)

$f(x,\xi,t)$

Parton Distribution Functions

$f(x)$

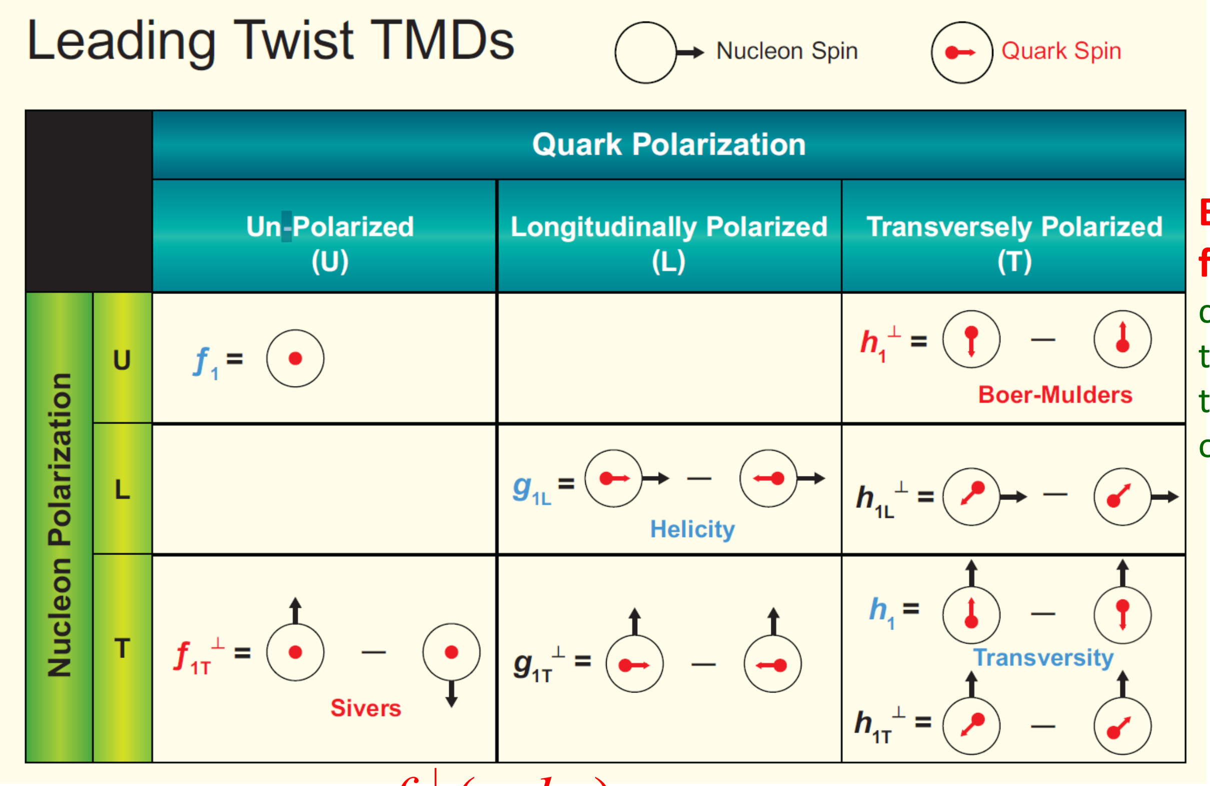
Form Factors

$F_{1,2}(t)$

$$\int_{-1}^{+1} \mathrm{d}x\, H^{\mathrm{q}}(x,\xi,t) = F_1^{\mathrm{q}}(t), \quad \int_{-1}^{+1} \mathrm{d}x\, E^{\mathrm{q}}(x,\xi,t) = F_2^{\mathrm{q}}(t),$$

$$\int_{-1}^{+1} \mathrm{d}x\, \tilde{H}^{\mathrm{q}}(x,\xi,t) = G_A^{\mathrm{q}}(t), \quad \int_{-1}^{+1} \mathrm{d}x\, \tilde{E}^{\mathrm{q}}(x,\xi,t) = G_P^{\mathrm{q}}(t).$$

Transverse momentum dependent (TMD) PDFs



Boer-Mulders function $h_1^\perp(x,k_T)$

correlation between the transverse spin and the transverse momentum of the quark in unpolarized nucleons

Sivers function $f_{1T}^\perp(x,k_T)$

correlation between the transverse spin of the nucleon and the transverse momentum of the quark.

sensitive to orbital angular momentum

TMD FF

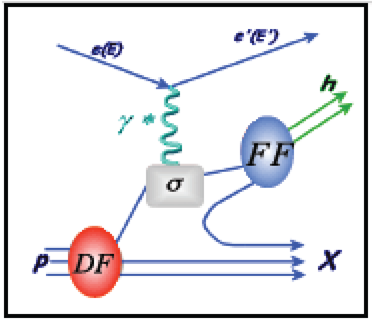
quark pol.

hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1, $H_{1T}^\perp$

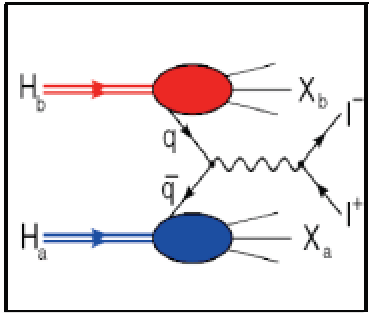
arXiv:1212.1701

Accessing TMDs



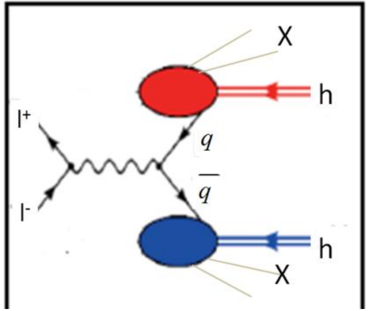
SIDIS: ep → ehX

$$\sigma^{ep\to ehX} = \sum_q \text{DF} \otimes \sigma^{eq\to eq} \otimes \text{FF}$$



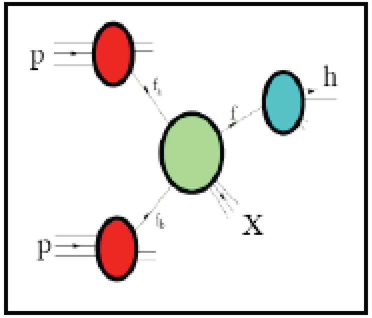
Drell-Yan: pp → e^+e^-X

$$\sigma^{pp\to eeX} = \sum_q \text{DF} \otimes \text{DF} \otimes \sigma^{qq\to ee}$$



Dihadron in e+e-: e^+e^- →h_1 h_2 X

$$\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes \text{FF} \otimes \text{FF}$$



Hadron production in pp: pp → hX

$$\sigma^{pp\to hX} = \sum_q \text{DF} \otimes \text{DF} \otimes \sigma^{qq\to qq} \otimes \text{FF}$$

hermes

COMPASS

Jefferson Lab

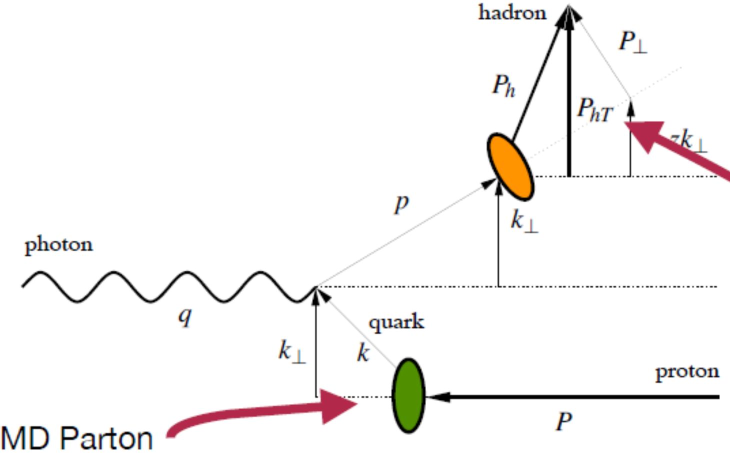
Fermilab

CERN

BELLE

BROOKHAVEN
NATIONAL LABORATORY

TMDS IN SEMI-INCLUSIVE DIS



TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$
\begin{aligned}
&F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)\\
&= x\sum_q \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp \boxed{f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)}\boxed{D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)}\delta(z\boldsymbol{k}_\perp-\boldsymbol{P}_{hT}+\boldsymbol{P}_\perp)\\
&= x\sum_a \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|)\hat{f}_1^q(x,z^2b_\perp^2;\mu^2)\,\hat{D}_1^{a\to h}(z,b_\perp^2;\mu^2)
\end{aligned}
$$

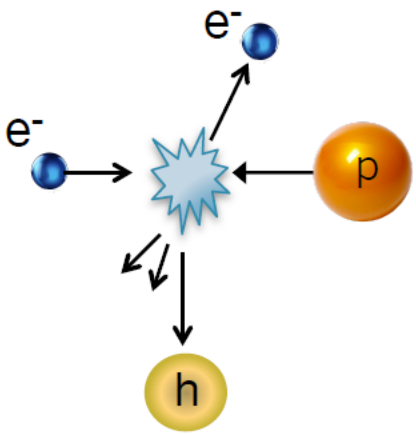
hard factor

TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

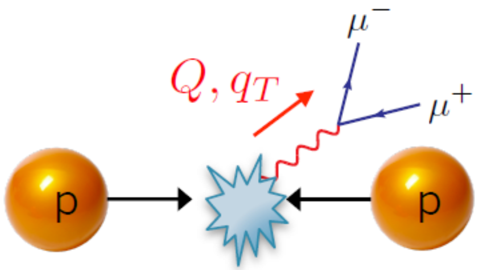
$$\sigma \sim f_{q/P}(x,k_T)D_{h/q}(x,k_T)$$



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

Drell-Yan

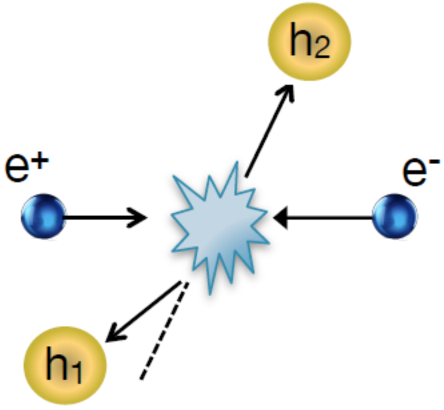
$$\sigma \sim f_{q/P}(x,k_T)f_{q/P}(x,k_T)$$



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

Dihadron in e^+e^-

$$\sigma \sim D_{h_1/q}(x,k_T)D_{h_2/q}(x,k_T)$$



Collins, Soper (1983)
Collins (2011)

Small scale → $q_T \ll Q$ ← Large scale

TMDs & CT3

For the unpolarized and transversity TMDs we have

$$f^q(x,k_T^2) = f^q(x)\ \mathcal{G}_f^q(k_T^2)\,, \qquad (3)$$

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

$$\mathcal{G}_f^q(k_T^2) = \frac{1}{\pi\langle k_T^2\rangle_f^q}\exp\left[-\frac{k_T^2}{\langle k_T^2\rangle_f^q}\right]. \qquad (4)$$

Transversity

Sivers

Collins

Observable	Reactions	Non-Perturbative Function(s)
$A_{\rm SIDIS}^{\rm Siv}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,k_T^2)$
$A_{\rm SIDIS}^{\rm Col}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2),\, H_1^\perp(z,z^2p_\perp^2)$
$A_{\rm SIA}^{\rm Col}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2p_\perp^2)$
$A_{\rm DY}^{\rm Siv}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,k_T^2)$
$A_{\rm DY}^{\rm Siv}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,k_T^2)$
A_N^h	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x),\, F_{FT}(x,x) = \frac{1}{\pi}f_{1T}^{\perp(1)}(x),\, H_1^{\perp(1)}(z)$

$$H_1^{\perp(1)}(z) \equiv z^2\int d^2\vec{p}_\perp \frac{p_\perp^2}{2M_h^2}H_1^\perp(z,z^2p_\perp^2)$$

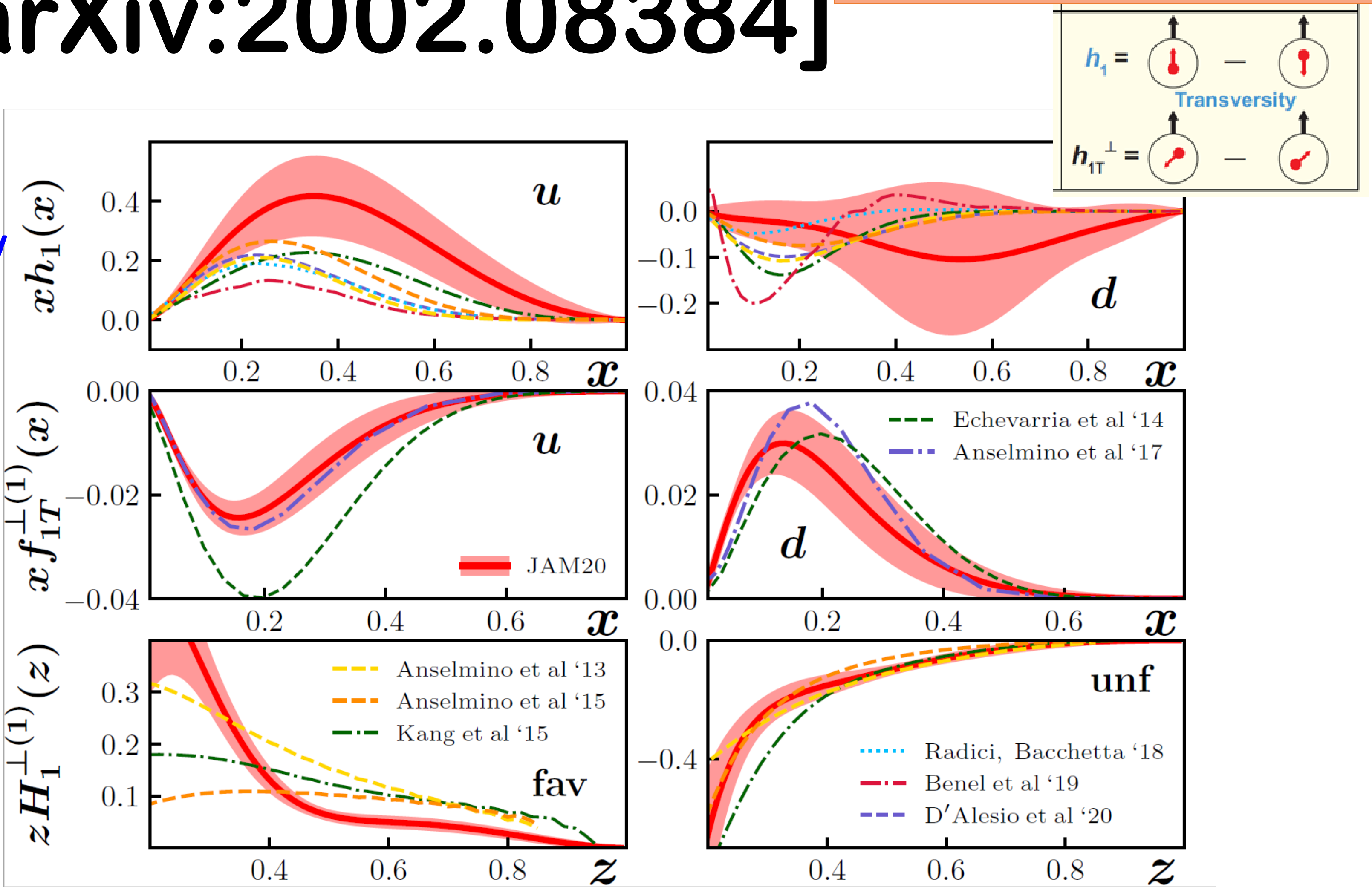
Collinear (twist-2) transversity

Qiu-Sterman function

$$\pi F_{FT}(x,x) = \int d^2\vec{k}_T\,\frac{k_T^2}{2M^2}f_{1T}^\perp(x,k_T^2) \equiv f_{1T}^{\perp(1)}(x)$$

Extracted TMDs [arXiv:2002.08384]

Current extractions from experimental data are limited by their reliance on nonperturbative fragmentation functions (FFs), which carry significant modeling uncertainties.



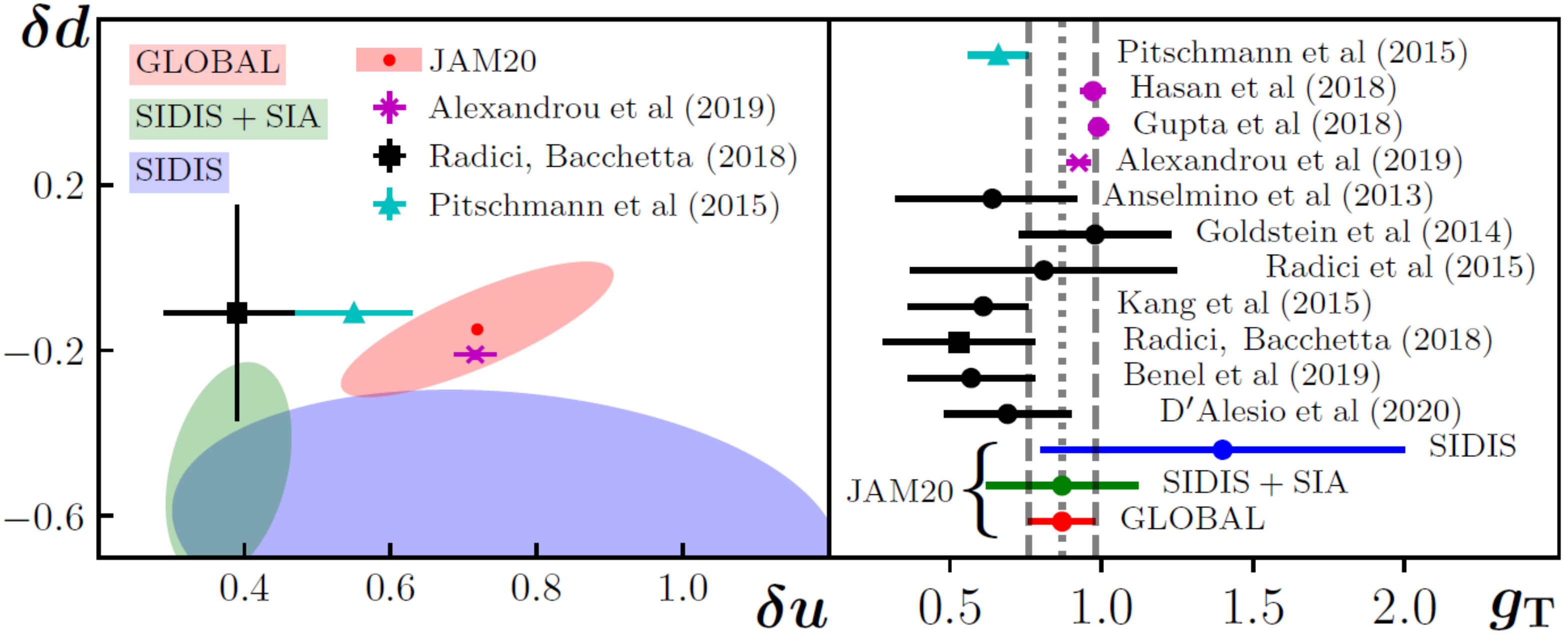
Transversity

Sivers

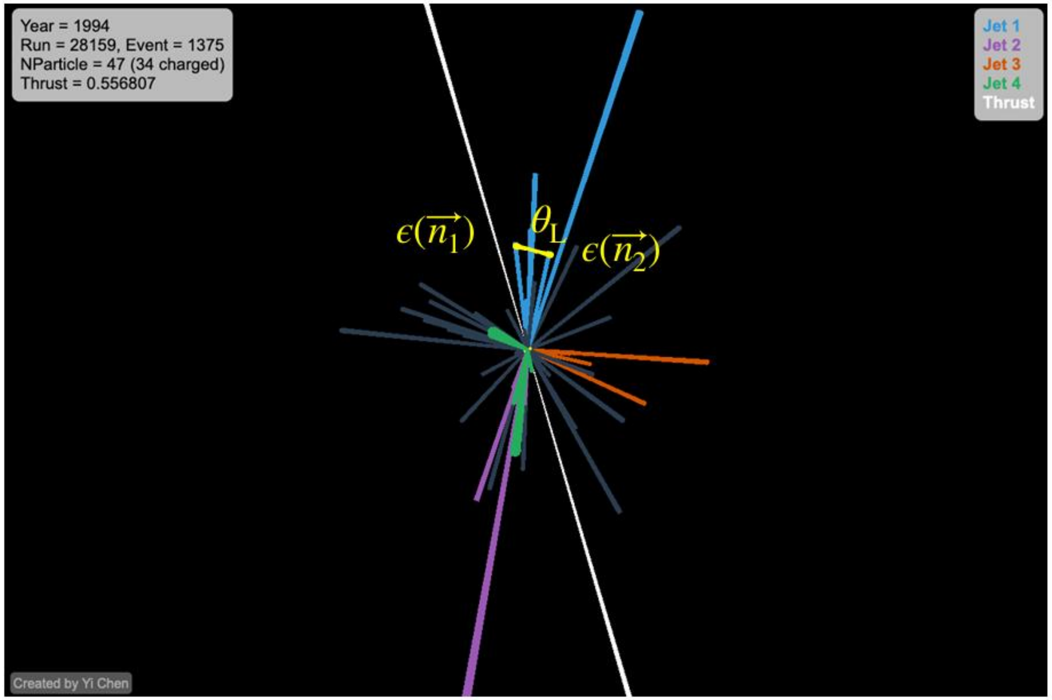
Collins FF

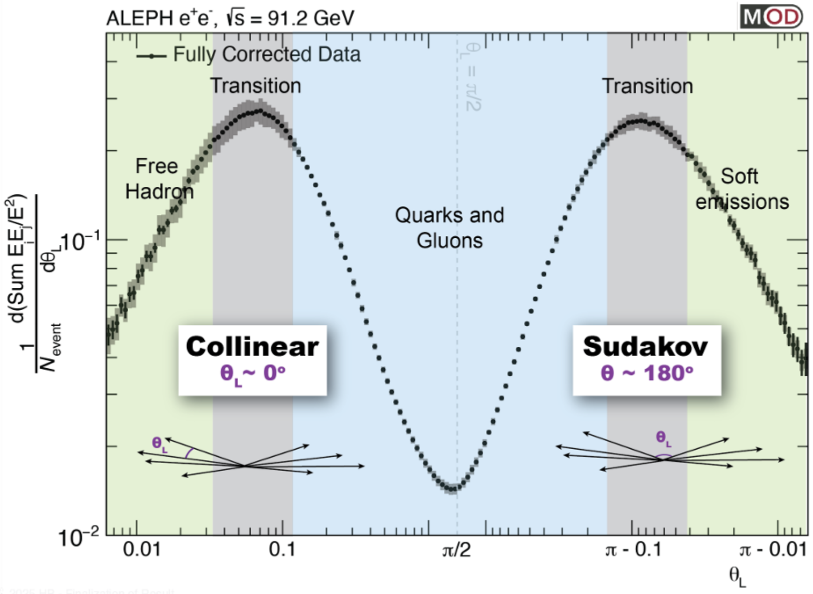
Extracted Tensor Charges [arXiv:2002.08384]

$$\delta q \equiv \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x) \right] dx \qquad g_T \equiv \delta u - \delta d$$



Energy-energy correlator in collisions



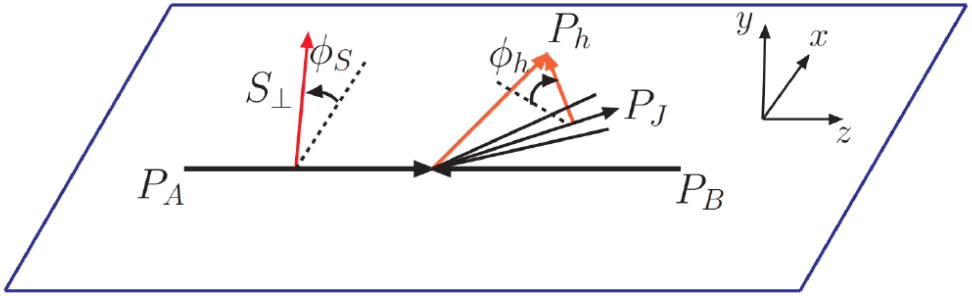


https://arxiv.org/abs/2505.11828

Energy-energy correlators (EECs)

- EECs are infrared- and collinear-safe jet substructure observables that quantify the angular correlation of energy flow within a jet.
- By directly measuring energy flow rather than individual hadrons, they provide a unique probe of the transition from the perturbative parton shower to nonperturbative hadronization, bridging the regimes of asymptotic freedom and color confinement.

Jet Production in Transversely Polarized $p^{\uparrow}p$ Collision



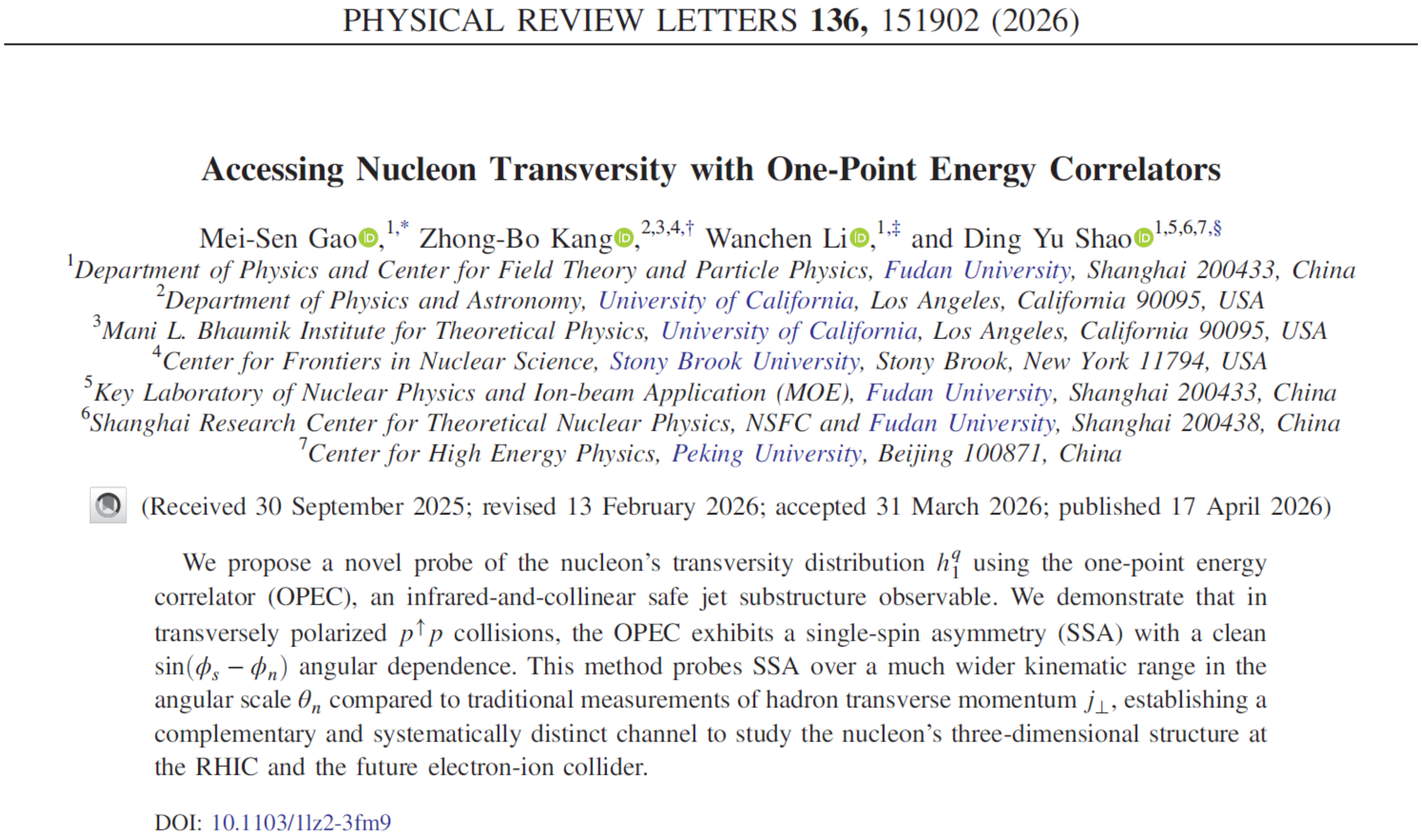
- Proposed by F. Yuan, Phys.Rev.Lett. 100, 032003 (2008), the differential cross section comes with an azimuthal modualtion,

Asymmetric Azimuthal Distribution of Hadrons inside a Jet

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{PS}} = F_{UU} + \sin\left(\phi_s - \phi_h\right) F_{UT}.$$

- The reaction plane is spanned by the two incoming protons and the jet axis.
  - ϕ_s: the azimuthal angle of transverse polarization vector $S_\perp$, with respect the to reaction plane.
  - ϕ_h: the azimuthal angle of hadron h in jet, with respect the to reaction plane.

2509.15809



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Accessing Nucleon Transversity with One-Point Energy Correlators

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We propose a novel probe of the nucleon's transversity distribution h_1^q using the one-point energy correlator (OPEC), an infrared-and-collinear safe jet substructure observable. We demonstrate that in transversely polarized $p^\uparrow p$ collisions, the OPEC exhibits a single-spin asymmetry (SSA) with a clean $\sin(\phi_s - \phi_n)$ angular dependence. This method probes SSA over a much wider kinematic range in the angular scale θ_n compared to traditional measurements of hadron transverse momentum $j_\perp$, establishing a complementary and systematically distinct channel to study the nucleon's three-dimensional structure at the RHIC and the future electron-ion collider.

DOI: 10.1103/1lz2-3fm9

$$A_{UT}^{\sin(\phi_s-\phi_n)}(p_T^{jet},\eta^{jet},\theta_n)=\frac{Z_{UT}}{Z_{UU}}$$

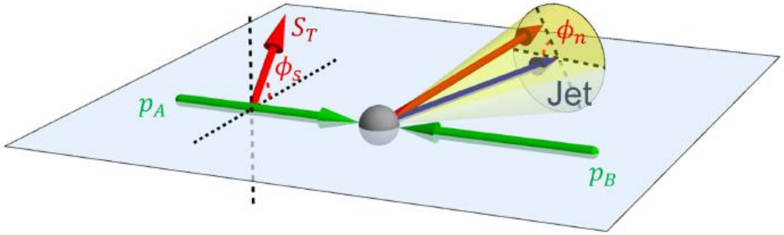


FIG. 1. Kinematics of hadron production inside a jet in transversely polarized $p^{\uparrow}p$ collisions. The reaction plane is defined by the incoming proton momenta p_A, p_B, and the jet axis. The azimuthal angles ϕ_s and ϕ_n specify the orientations of the proton transverse spin vector S_T and the energy detector with respect to this plane.

Factorization

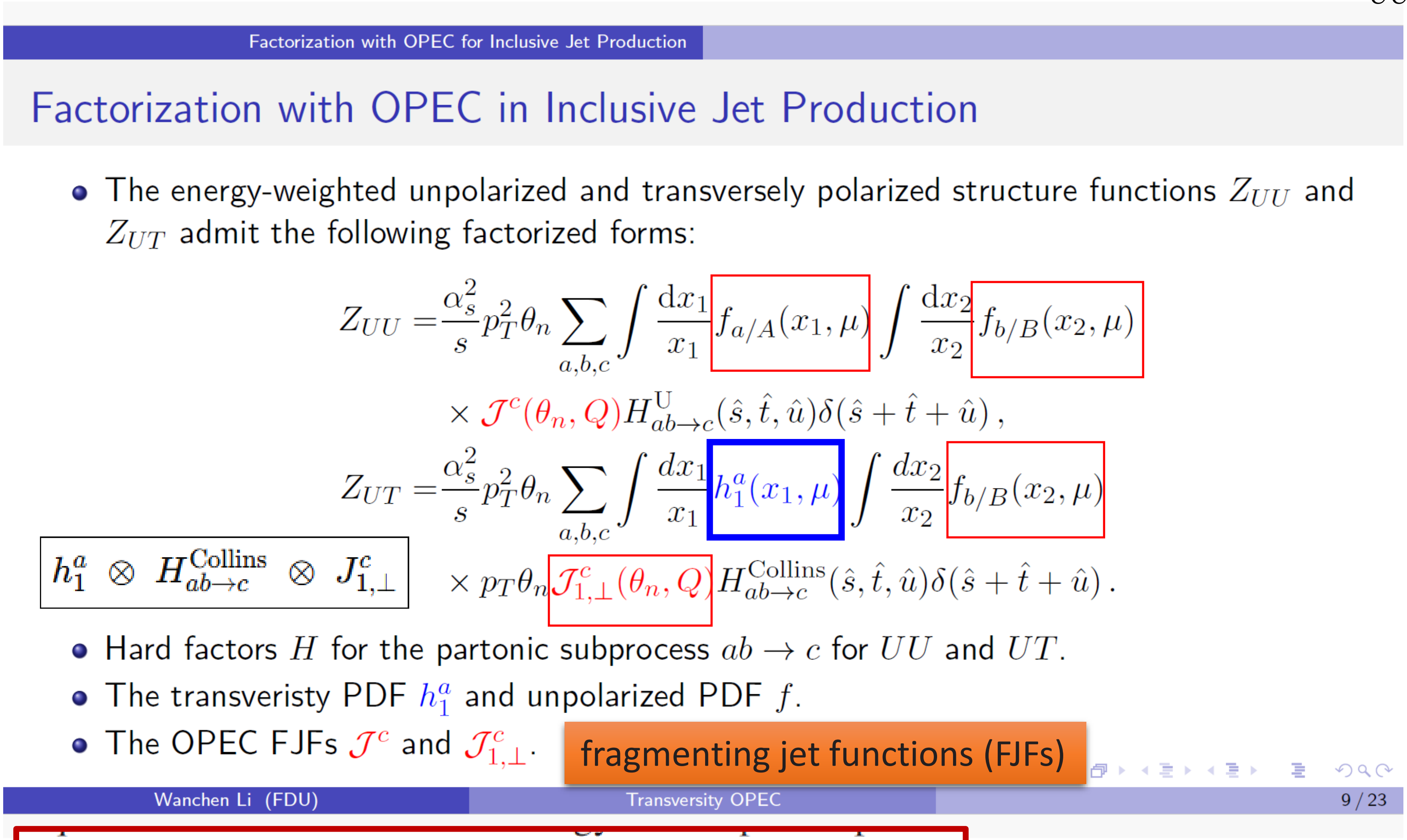
- We consider the OPEC in inclusive jet production in $p^{\uparrow}+p\to J+X$

$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\theta_n\mathrm{d}\phi_n\mathrm{d}\eta\,\mathrm{d}p_T}=\boxed{\sum_{h\in J}}\int_0^1\mathrm{d}z_h\int\mathrm{d}^2\Omega_{\boldsymbol{h}}\,\delta\left(\phi_n-\phi_h\right)$$
$$\times\,\delta\left(\theta_n-\theta_h\right)\boxed{z_h}\boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}z_h\,\mathrm{d}^2\Omega_h\mathrm{d}\eta\,\mathrm{d}p_T}}$$

- z_h is the weight factor.
- Integral on z_h converts the final-state z_h distribution into a number!
- The jet is characterized by the rapidity η and transverse momentum p_T.
- The azimuthal dependent OPEC inclusive jet production can be described by

$$\boxed{\frac{\mathrm{d}\Sigma}{\mathrm{d}\theta_n\mathrm{d}\phi_n\mathrm{d}\eta\,\mathrm{d}p_T}=Z_{UU}+\sin\left(\phi_s-\phi_n\right)Z_{UT}.}$$

$$A_{UT}^{\sin(\phi_s-\phi_n)}(p_T^{jet},\eta^{jet},\theta_n)=\frac{Z_{UT}}{Z_{UU}}$$



Factorization with OPEC for Inclusive Jet Production

Factorization with OPEC in Inclusive Jet Production

- The energy-weighted unpolarized and transversely polarized structure functions Z_{UU} and Z_{UT} admit the following factorized forms:

$$Z_{UU}=\frac{\alpha_s^2}{s}p_T^2\theta_n\sum_{a,b,c}\int\frac{\mathrm{d}x_1}{x_1}\boxed{f_{a/A}(x_1,\mu)}\int\frac{\mathrm{d}x_2}{x_2}\boxed{f_{b/B}(x_2,\mu)}\times\mathcal{J}^c(\theta_n,Q)H^{\mathrm{U}}_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u})\,,$$

$$Z_{UT}=\frac{\alpha_s^2}{s}p_T^2\theta_n\sum_{a,b,c}\int\frac{dx_1}{x_1}\boxed{h_1^a(x_1,\mu)}\int\frac{dx_2}{x_2}\boxed{f_{b/B}(x_2,\mu)}\times p_T\theta_n\boxed{\mathcal{J}^c_{1,\perp}(\theta_n,Q)}H^{\mathrm{Collins}}_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u})\,.$$

$$\boxed{h_1^a\otimes H^{\mathrm{Collins}}_{ab\to c}\otimes J^c_{1,\perp}}$$

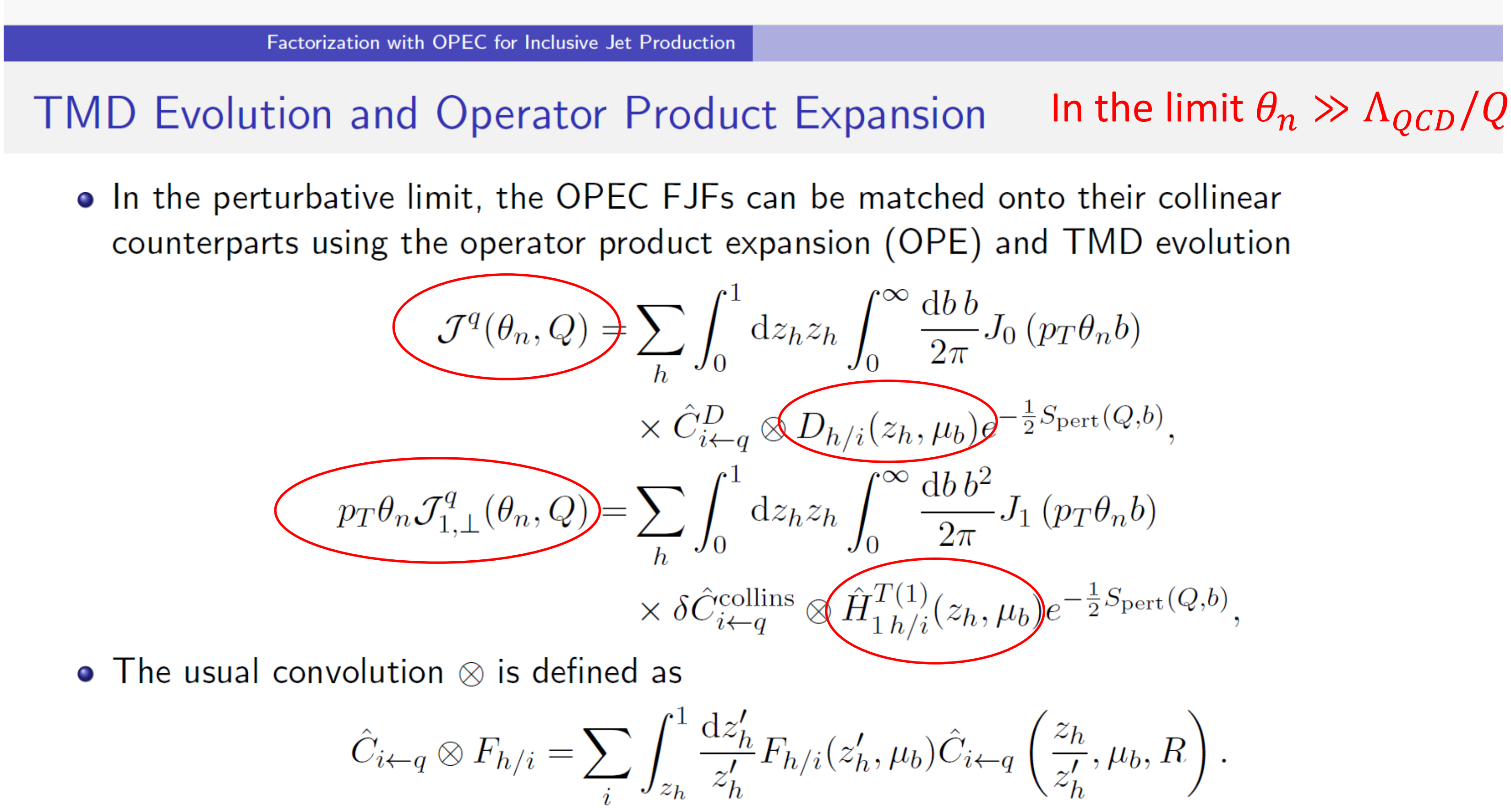
- Hard factors H for the partonic subprocess $ab\to c$ for UU and UT.
- The transveristy PDF h_1^a and unpolarized PDF f.
- The OPEC FJFs $\mathcal{J}^c$ and $\mathcal{J}^c_{1,\perp}$.

fragmenting jet functions (FJFs)

Wanchen Li (FDU) Transversity OPEC 9 / 23

system. The hard functions $H^{\mathrm{U}}_{ab\to c}$ and $H^{\mathrm{Collins}}_{ab\to c}$ represent the unpolarized and spin-dependent partonic matrix elements, respectively, for the subprocess $ab\to c$ [65,68,83,84]. The

Matching to the TMDs



TMD Evolution and Operator Product Expansion

In the limit $\theta_n \gg \Lambda_{QCD}/Q$

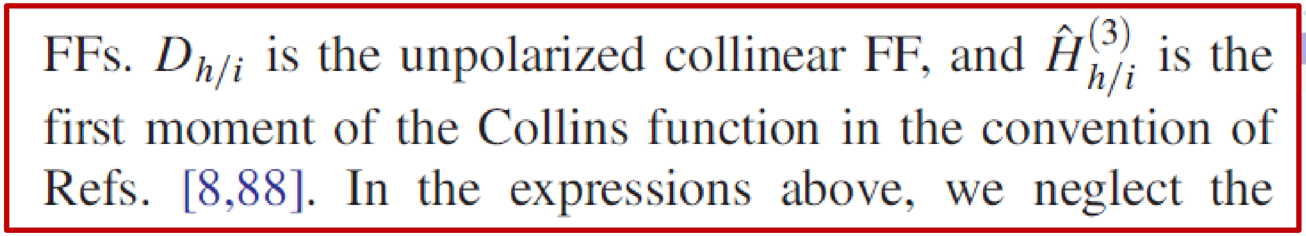
- In the perturbative limit, the OPEC FJFs can be matched onto their collinear counterparts using the operator product expansion (OPE) and TMD evolution

$$\mathcal{J}^q(\theta_n, Q) = \sum_h \int_0^1 \mathrm{d}z_h z_h \int_0^\infty \frac{\mathrm{d}b\, b}{2\pi} J_0\left(p_T \theta_n b\right) \times \hat{C}^D_{i\leftarrow q} \otimes D_{h/i}(z_h, \mu_b) e^{-\frac{1}{2}S_{\mathrm{pert}}(Q,b)},$$

$$p_T \theta_n \mathcal{J}^q_{1,\perp}(\theta_n, Q) = \sum_h \int_0^1 \mathrm{d}z_h z_h \int_0^\infty \frac{\mathrm{d}b\, b^2}{2\pi} J_1\left(p_T \theta_n b\right) \times \delta\hat{C}^{\mathrm{collins}}_{i\leftarrow q} \otimes \hat{H}^{T(1)}_{1\, h/i}(z_h, \mu_b) e^{-\frac{1}{2}S_{\mathrm{pert}}(Q,b)},$$

- The usual convolution $\otimes$ is defined as

$$\hat{C}_{i\leftarrow q} \otimes F_{h/i} = \sum_i \int_{z_h}^1 \frac{\mathrm{d}z_h'}{z_h'} F_{h/i}(z_h', \mu_b) \hat{C}_{i\leftarrow q}\left(\frac{z_h}{z_h'}, \mu_b, R\right).$$



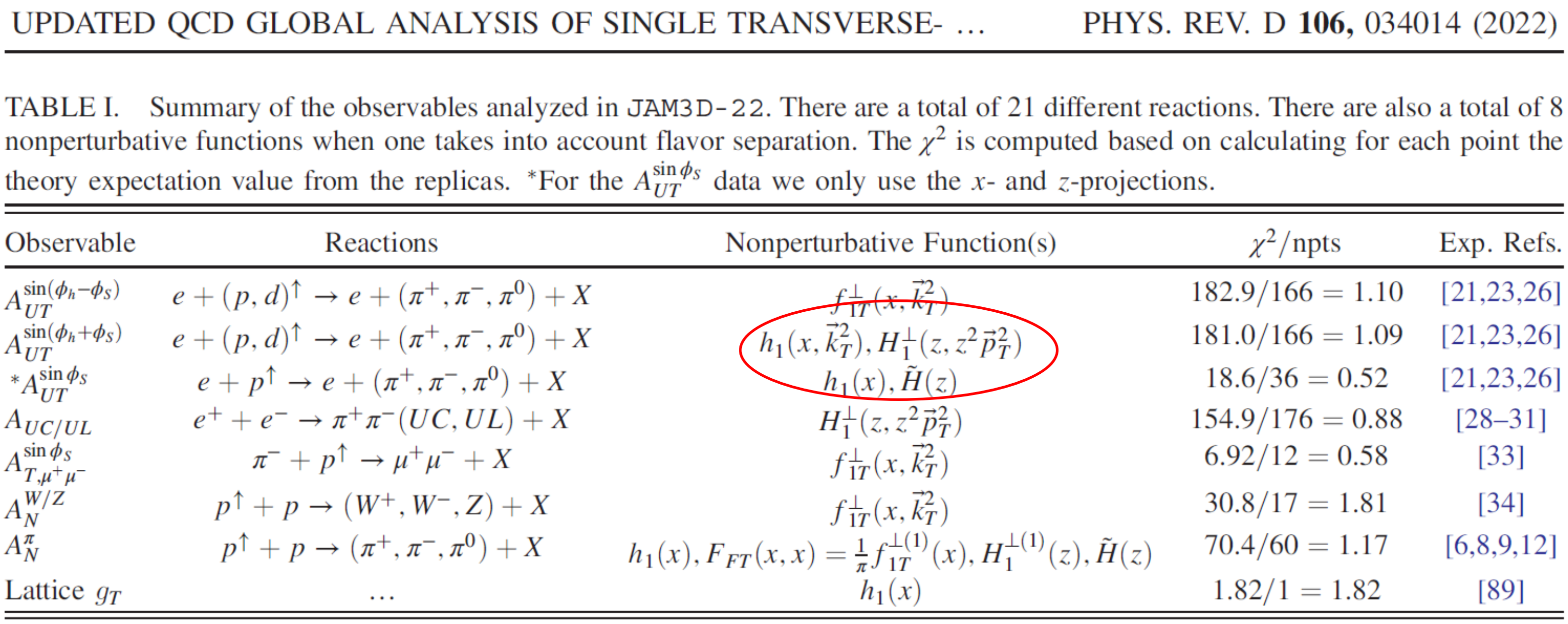
FFs. $D_{h/i}$ is the unpolarized collinear FF, and $\hat{H}^{(3)}_{h/i}$ is the first moment of the Collins function in the convention of Refs. [8,88]. In the expressions above, we neglect the

Evaluation Frameworks

We present evaluation in two approaches:

- A full TMD evolution framework
  - Parametrization of the transversity PDF, Collins functions, and non-perturbative Sudakov factor from Kang, Prokudin, Sun, Yuan (2016) ,
  - The extraction is done for SIDIS and e^+e^- annhilation,
  - The application on $p^{\uparrow}p$ collision can be a complementary test of the TMD universality.
- The JAM3D-22 global QCD analysis: JAM (2022)
  - The TMD functions are modeled by Gaussian ansätze,
  - The corresponding collinear components evolve with only DGLAP.

JAM3D-22

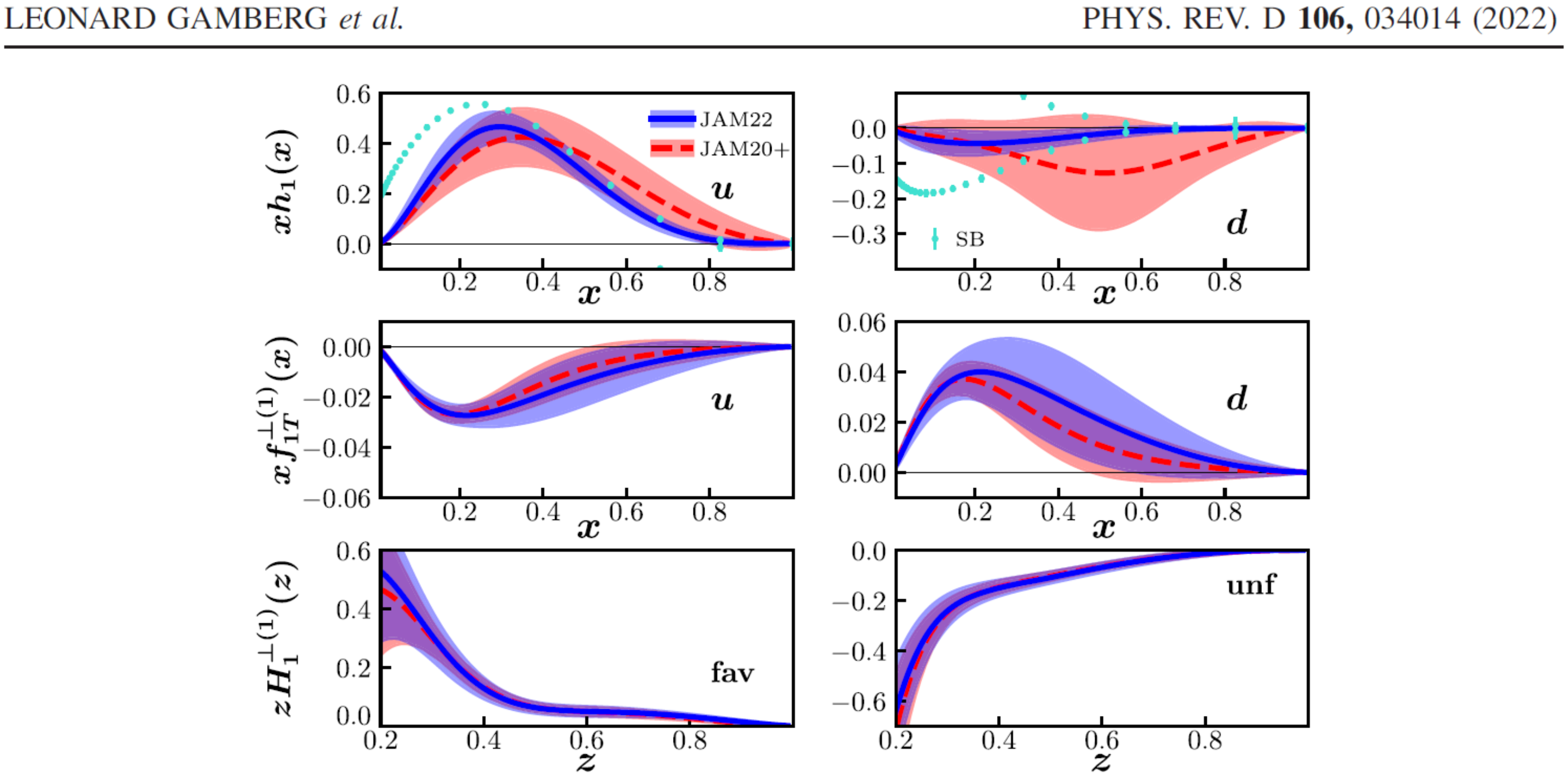


UPDATED QCD GLOBAL ANALYSIS OF SINGLE TRANSVERSE- … PHYS. REV. D **106,** 034014 (2022)

TABLE I. Summary of the observables analyzed in `JAM3D-22`. There are a total of 21 different reactions. There are also a total of 8 nonperturbative functions when one takes into account flavor separation. The χ^2 is computed based on calculating for each point the theory expectation value from the replicas. *For the $A_{UT}^{\sin\phi_S}$ data we only use the x- and z-projections.

Observable	Reactions	Nonperturbative Function(s)	χ^2/npts	Exp. Refs.
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$182.9/166 = 1.10$	[21,23,26]
$A_{UT}^{\sin(\phi_h+\phi_S)}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,\vec{k}_T^2), H_1^\perp(z,z^2\vec{p}_T^2)$	$181.0/166 = 1.09$	[21,23,26]
${}^*A_{UT}^{\sin\phi_S}$	$e+p^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x), \tilde{H}(z)$	$18.6/36 = 0.52$	[21,23,26]
$A_{UC/UL}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2\vec{p}_T^2)$	$154.9/176 = 0.88$	[28–31]
$A_{T,\mu^+\mu^-}^{\sin\phi_S}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$6.92/12 = 0.58$	[33]
$A_N^{W/Z}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,\vec{k}_T^2)$	$30.8/17 = 1.81$	[34]
A_N^π	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z), \tilde{H}(z)$	$70.4/60 = 1.17$	[6,8,9,12]
Lattice g_T	…	$h_1(x)$	$1.82/1 = 1.82$	[89]

JAM3D-22



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Theory Predictions

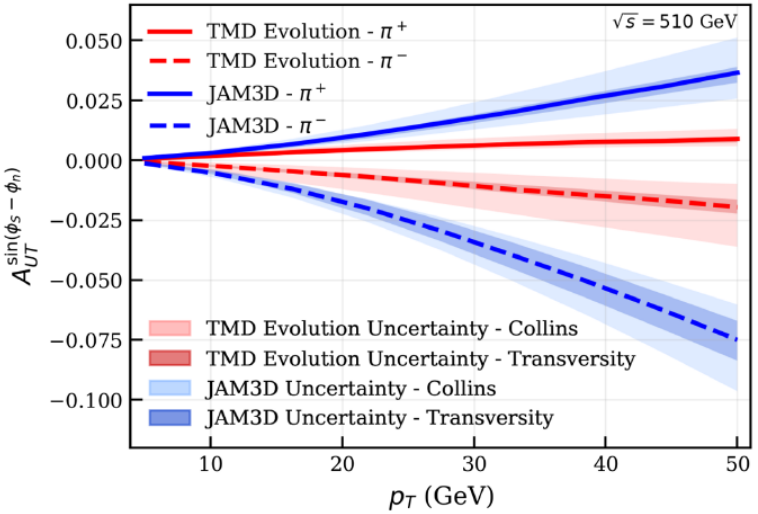
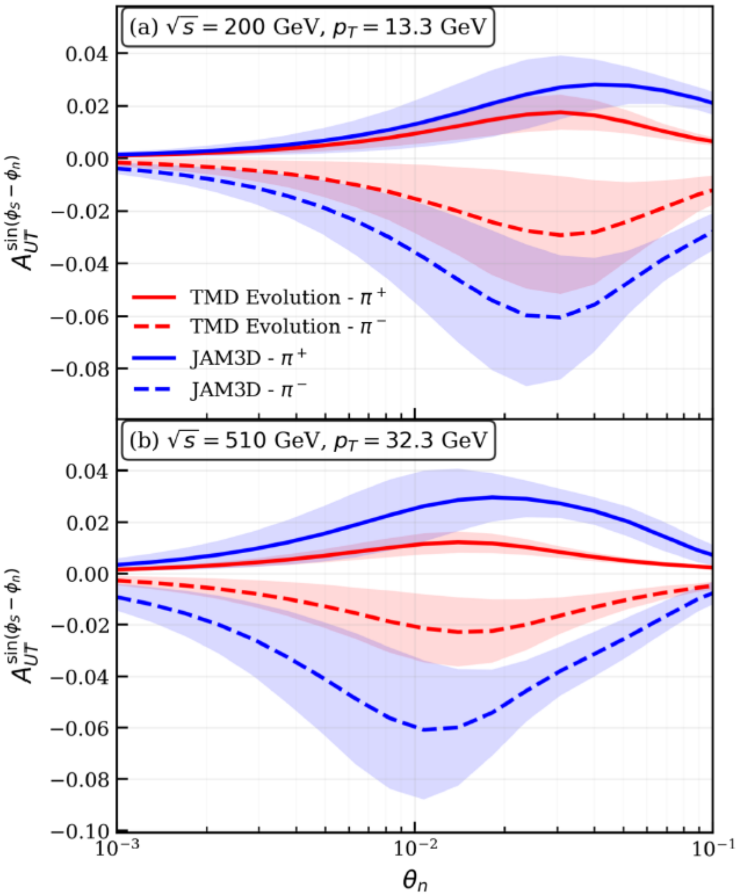


FIG. 2. SSA $A_{UT}^{\sin(\phi_s-\phi_n)}$ as a function of jet transverse momentum p_T for $\pi^{\pm}$ at $\sqrt{s} = 510$ GeV, evaluated using two approaches: the JAM3D-22 and the TMD evolution framework. Error bands represent uncertainties from the transversity PDF and the Collins FF parametrizations, respectively. The p_T distribution is obtained by integrating over $\theta_n \in [0, 0.1]$.



$$A_{UT}^{\sin(\phi_s-\phi_n)}(p_T^{jet},\eta^{jet},\theta_n)=\frac{Z_{UT}}{Z_{UU}}$$

Measurements by STAR [2604.15543]

$$\Sigma_{\mathrm{EC}}(\theta_h, \phi_h) = \frac{d\left(\sum_{\mathrm{jet}} \sum_{i\in \mathrm{jet}} z_{h,i}\right)}{d\theta_h d\phi_h}$$

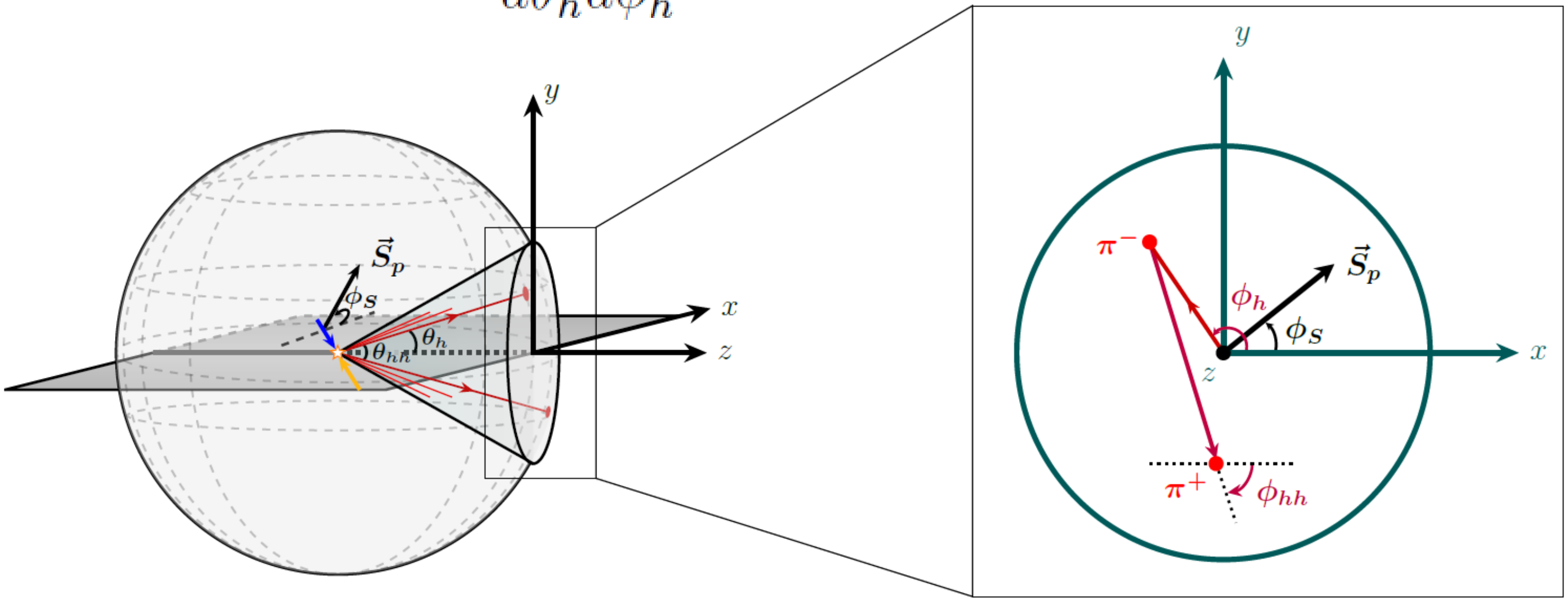
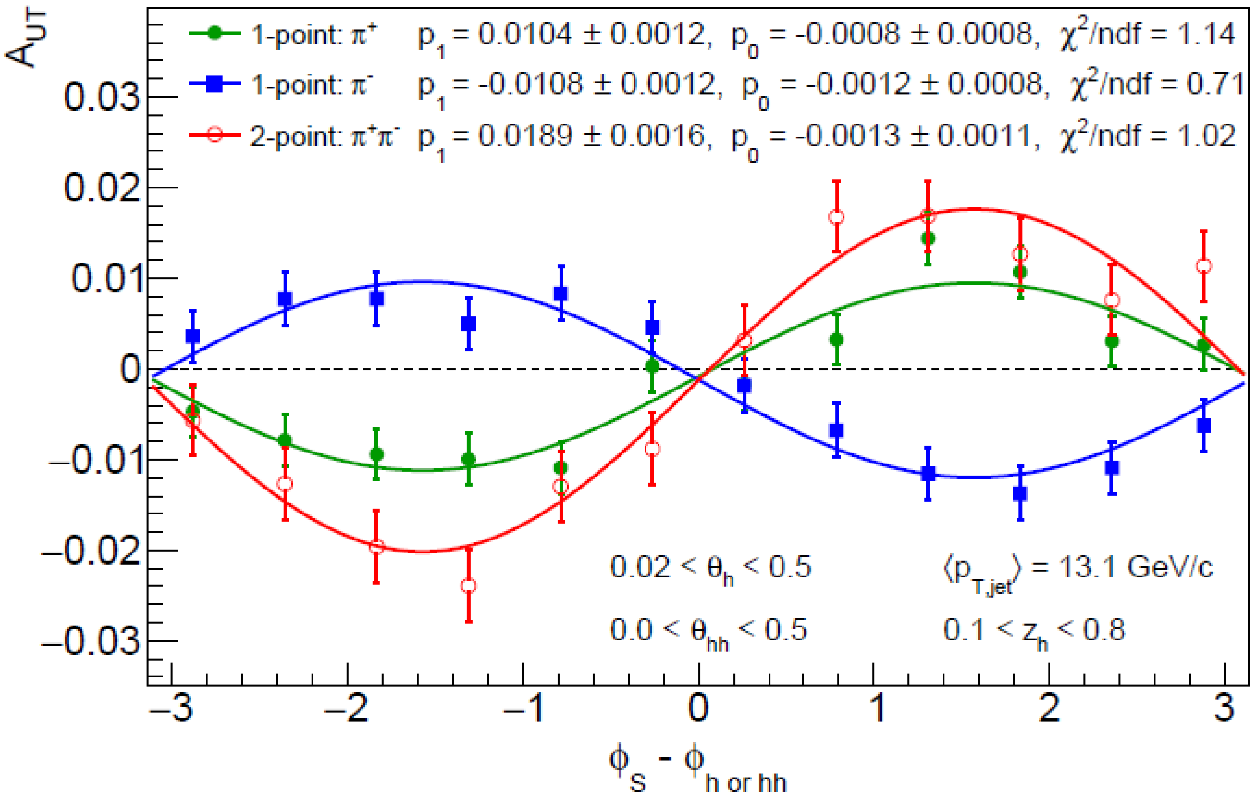


FIG. 1. Representation of the jet scattering plane and the angular distance θ_h, θ_{hh} and azimuthal angles ϕ_S, ϕ_h, and ϕ_{hh}. ϕ_{hh} is defined by the pair vector pointing from the negatively charged hadron to the positively charged one. The blue and yellow arrows indicate the incoming proton beam directions. The jet axis points along the z direction and the polarized proton beam lies in the jet scattering plane (x-z plane).

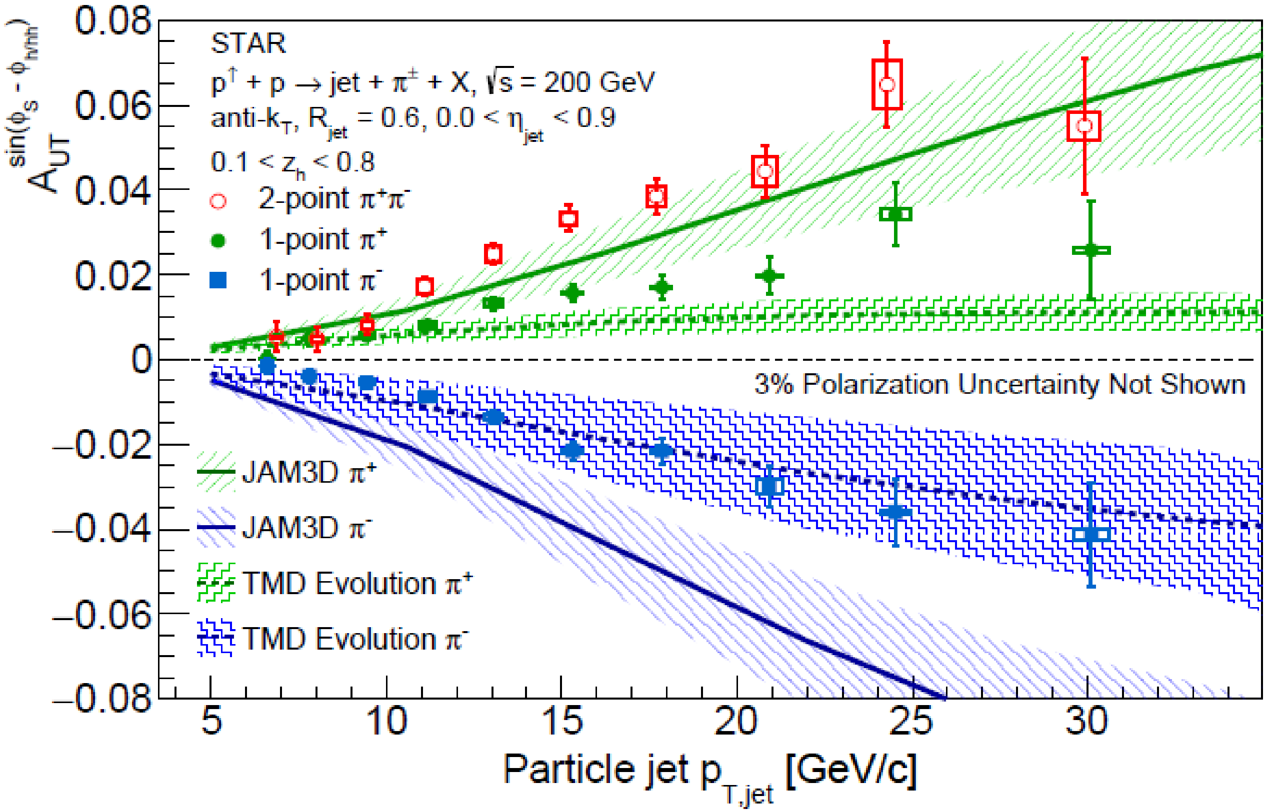
Cross-ratio method



$$A_{\mathrm{UT}}^{\sin(\phi_S-\phi_h)}\sin(\phi_S-\phi_h) = \frac{1}{P}\frac{\sqrt{\Sigma^{\uparrow}_{EC}[\phi_S-\phi_h]\Sigma^{\downarrow}_{EC}[(\phi_S+\pi)-\phi_h]}-\sqrt{\Sigma^{\downarrow}_{EC}[\phi_S-\phi_h]\Sigma^{\uparrow}_{EC}[(\phi_S+\pi)-\phi_h]}}{\sqrt{\Sigma^{\uparrow}_{EC}[\phi_S-\phi_h]\Sigma^{\downarrow}_{EC}[(\phi_S+\pi)-\phi_h]}+\sqrt{\Sigma^{\downarrow}_{EC}[\phi_S-\phi_h]\Sigma^{\uparrow}_{EC}[(\phi_S+\pi)-\phi_h]}}$$

Theory vs. Data

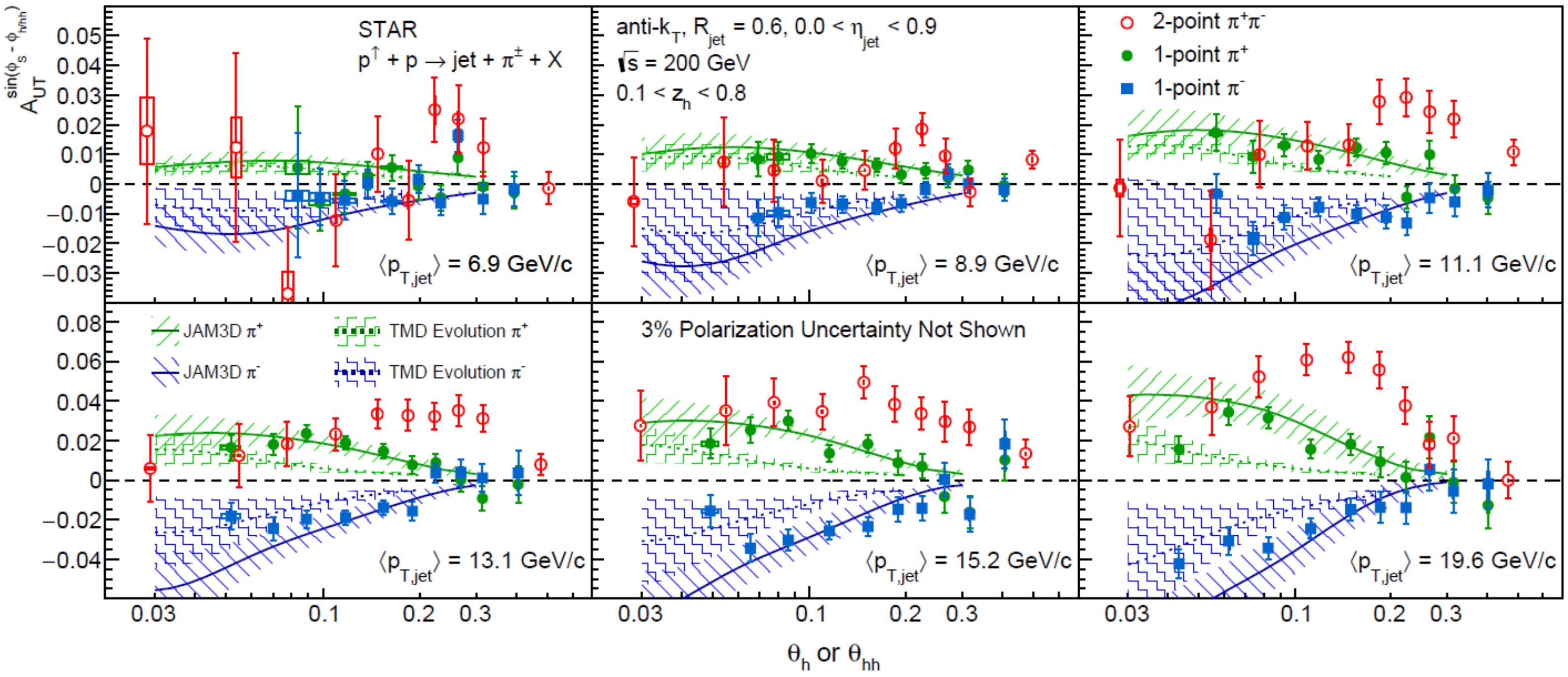
Data qualitatively align better with the TMD evolution trends.



$$A_{UT}^{\sin(\phi_s-\phi_n)}(p_T^{jet},\eta^{jet},\theta_n)=\frac{Z_{UT}}{Z_{UU}}$$

Theory vs. Data

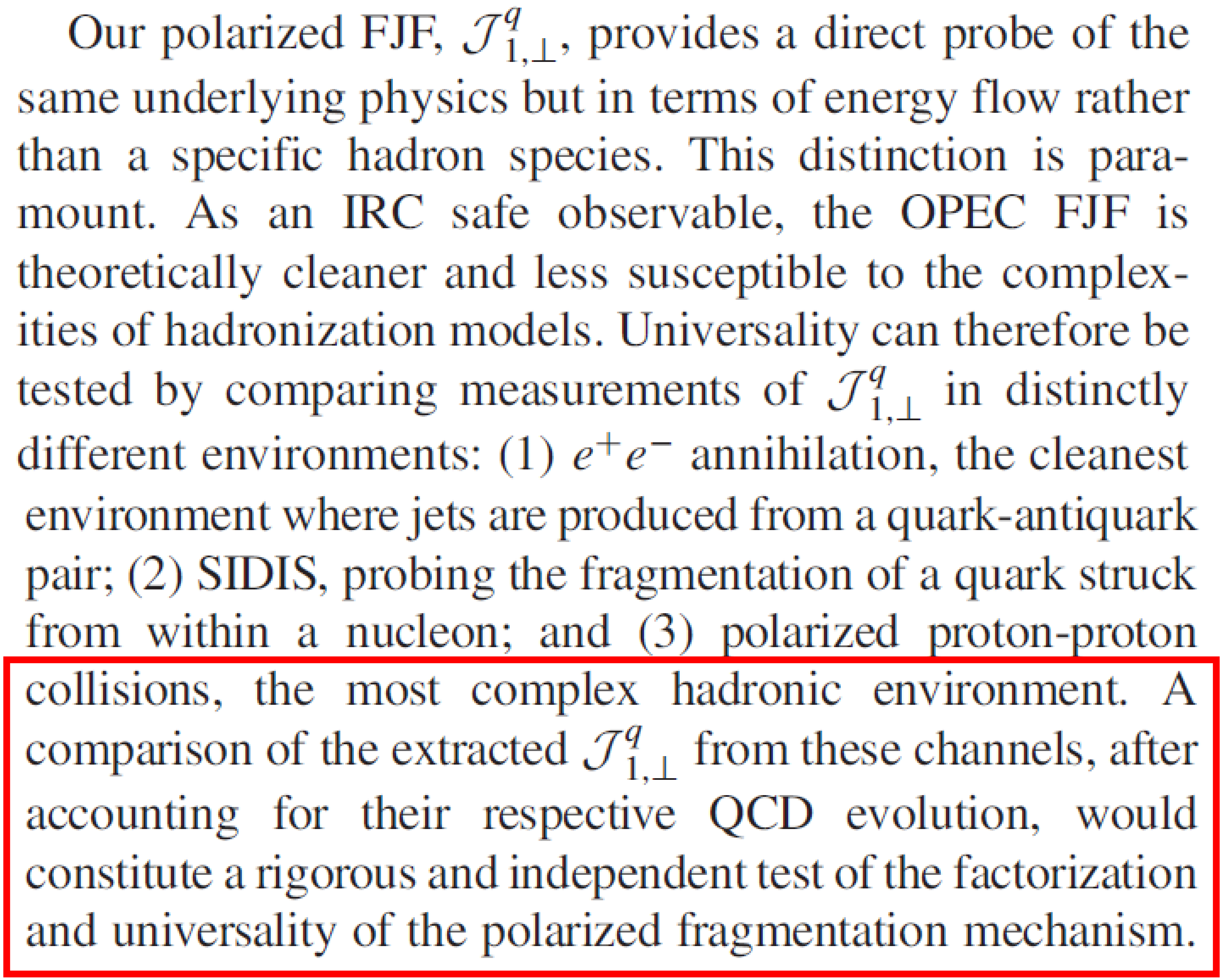
Data favor the TMD Evolution model at low $p_{T,jet}$ and small θ_h, while the JAM3D framework provides a better description at higher values of θ_h



$$A_{UT}^{\sin(\phi_s-\phi_n)}(p_T^{jet},\eta^{jet},\theta_n)=\frac{Z_{UT}}{Z_{UU}}$$

Factorization and Universality

2509.15809



Our polarized FJF, $\mathcal{J}^q_{1,\perp}$, provides a direct probe of the same underlying physics but in terms of energy flow rather than a specific hadron species. This distinction is paramount. As an IRC safe observable, the OPEC FJF is theoretically cleaner and less susceptible to the complexities of hadronization models. Universality can therefore be tested by comparing measurements of $\mathcal{J}^q_{1,\perp}$ in distinctly different environments: (1) e^+e^- annihilation, the cleanest environment where jets are produced from a quark-antiquark pair; (2) SIDIS, probing the fragmentation of a quark struck from within a nucleon; and (3) polarized proton-proton collisions, the most complex hadronic environment. A comparison of the extracted $\mathcal{J}^q_{1,\perp}$ from these channels, after accounting for their respective QCD evolution, would constitute a rigorous and independent test of the factorization and universality of the polarized fragmentation mechanism.

Summary

- Conventionally the nucleon transversity (h1) is determined by the azimuthal asymmetries in SIDIS or p+p collisions with transversely-polarized beams/targets.
- Accessing the nucleon transversity has been recently extended from the studying of particle azimuthal asymmetries within a jet to the associated energy correlator.
- Agreement of theory predictions with the measurements from STAR suggests that the energy correlators could work as a promising tool to explore nucleon spin structures.
- A rigorous test of the factorization and university of the involved polarized fragmentation jet function (FJFs, similar to Collins FFs in TMDs) from various processes is required for validating this theoretical approach.

Outlooks for EIC

- Simplified approach to extracting nucleon transversity in collinear factorization using near-side energy-energy correlators https://arxiv.org/abs/2604.28131
- Nucleon Energy Correlators as a Probe of Light-Quark Dipole Operators at the Electron-Ion Collider https://arxiv.org/abs/2508.08516
- Sivers Tomography from Charge and Angle Only https://arxiv.org/abs/2605.15280