Accessing Nucleon Transversity via One-Point Energy Correlators

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Outline

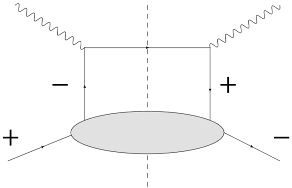
Motivation

- Transversity distribution h_1^q is a fundamental, yet less known, parton distribution.
- Its chiral-odd nature prevents access via inclusive DIS.
- Nucleon tensor charge δq from h_1^q

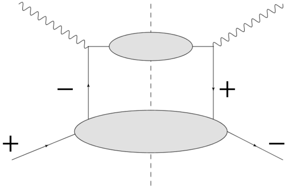
$$\delta q \equiv \int_0^1 dx\,[h_1^q(x) - h_1^{\bar{q}}(x)]$$

is essential for:

  - Nucleon spin structure,
  - Lattice QCD benchmarks,
  - BSM probes, i.e. neutron β-decay.

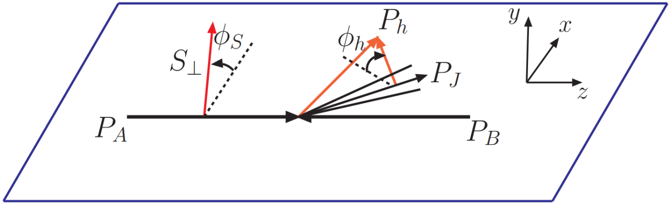


Transversity forbidden in Inclusive DIS



Semi-inclusive DIS (SIDIS)

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,

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

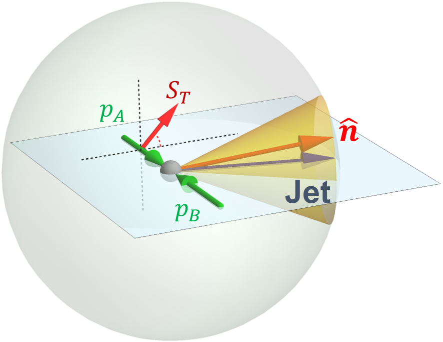
- The reaction plane is spanned by the two incoming protons and the jet axis.
  - ϕ_s: the azimuthal angle of transverse polarization vector $S_\perp$, with respect the to reaction plane.
  - ϕ_h: the azimuthal angle of hadron h in jet, with respect the to reaction plane.

One Point Energy Correlator (OPEC)

- We define the infrared-collinear (IRC) safe one-point energy correlator (OPEC) as

$$\Delta^q(z,\hat{\boldsymbol{n}}) = \sum_X \sum_{i\in J} \langle \Omega | \bar{\chi}_n \delta_{Q,\mathcal{P}_n} \delta^{(2)}(\hat{\boldsymbol{n}} - \hat{\boldsymbol{n}}_i) | JX \rangle \, \frac{E_i}{E_J} \, \langle JX | \chi | \Omega \rangle .$$

- $\hat{\boldsymbol{n}}$ is the direction of the energy flow.
- The energy fraction of the jet carried by the hadron i is $z_i = \frac{E_i}{E_J}$.
- χ is the gauge-invarinat quark field.
- The state $|JX\rangle$ represents the final-state unobserved particles X and the jet J.



Decomposition of OPEC

- Ignoring irrelevant helicity and transverse components, we decompose OPEC into two parts:

$$\Delta^q = \frac{\not{\bar{n}}}{2}\mathcal{J}^q + \frac{\epsilon_T^{ij}\hat{\boldsymbol{n}}_{T,j}\theta_n p_J^-}{2}\frac{i\bar{n}_\mu\sigma^{i\mu}\gamma_5}{2}\mathcal{J}_{1,\perp}^q.$$

- $\mathcal{J}^q$ is the unpolarized OPEC fragmenting jet function (FJF).
- $\mathcal{J}_{1,\perp}^q$ is the transversely polarized OPEC FJF.
- θ_n is the energy flow polar angle.

Factorization

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

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

- 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

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

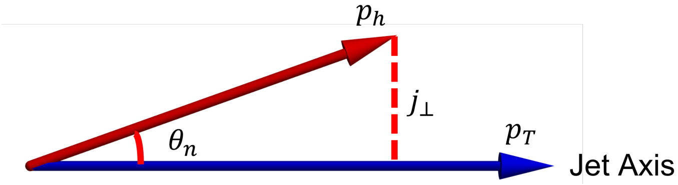
Factorization with OPEC in Inclusive Jet Production

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

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

- 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 $\mathcal{J}^c_{1,\perp}$.

Kinematics of OPEC Hadron in Jet



- The geometry yields

$$p_h^z = |\boldsymbol{p}_J| z_h = |\boldsymbol{p}_h| \cos\theta_n ,$$

- In the collinear limit, we further see:

$$\theta_n \approx \sin\theta_n = \frac{j_\perp}{p_h^z} = \frac{j_\perp}{p_T z_h},$$

- Note in the centra rapidity, jet $|\boldsymbol{p}_J| = p_T$.

$j_\perp$ or θ_n?

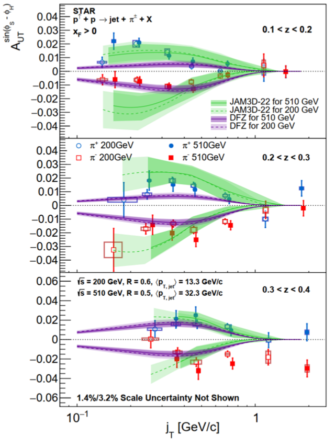
- Compared with standard non-weighted TMD analysis, we have a different overall factor

$$z_h \, \mathrm{d}j_\perp^2 = p_T^2 \, z_h^3 \, \mathrm{d}\theta_n^2,$$

due to $j_\perp \simeq p_T z_h \theta_n$ in the collinear limit.

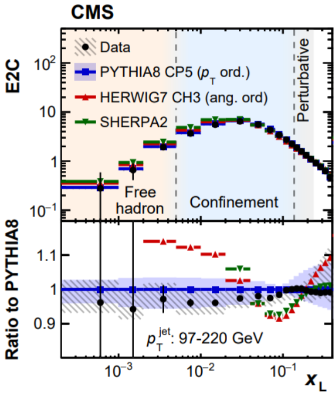
Why switch to θ_n?

- In one STAR configuration,
  - $\sqrt{s} = 510\,\mathrm{GeV}$, $p_T = 32.3\,\mathrm{GeV}$,
  - at lower cut $z = 0.1$,
  - $j_\perp$ can be measured in about (0.1, 1) GeV.
- $j_\perp$ only corresponds to θ_n about $(0.03, 0.3)$ rad.

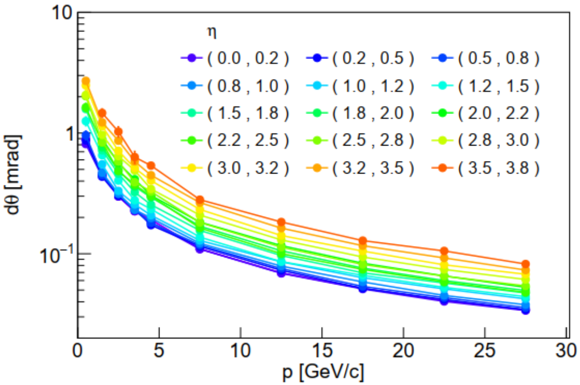


STAR collaboration arXiv.2507.16355

$j_\perp$ or θ_n?



CMS (2024)



J. Arrington et al., EIC (2021)

- However, modern colliders could achieve angular resolution at 1 mrad!

TMD Evolution and Operator Product Expansion

- 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

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

Phenomenology Study on Energy-Weighted $\pi^{\pm}$ Production in Jet

- The OPEC Collins azimuthal asymmetry is defined as

$$A_{UT}^{\sin(\phi_s-\phi_n)} = \frac{Z_{UT}}{Z_{UU}}.$$

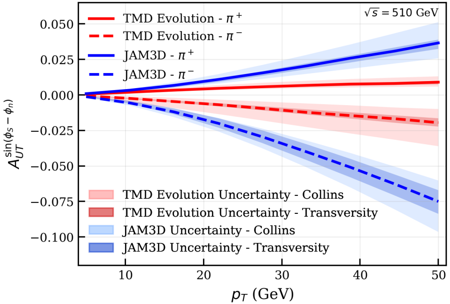
- We consider pion production in jets for two kinematic settings extensively studied by the STAR Collaboration:
  - (a) $\sqrt{s} = 510\,\text{GeV}$, $p_T = 32.3\,\text{GeV}$;
  - (b) $\sqrt{s} = 200\,\text{GeV}$, $p_T = 13.3\,\text{GeV}$.

Evaluation Frameworks

We present evaluation in two approaches:

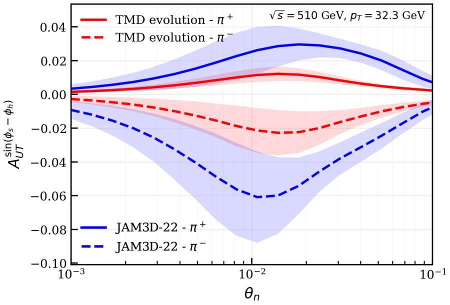
- A full TMD evolution framework
    - Parametrization of the transversity PDF, Collins functions, and non-perturbative Sudakov factor from Kang, Prokudin, Sun, Yuan (2016) ,
    - The extraction is done for SIDIS and $e^{+}e^{-}$ annhilation,
    - The application on $p^{\uparrow}p$ collision can be 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.

p_T Distribution of the OPEC Collins Asymmetry

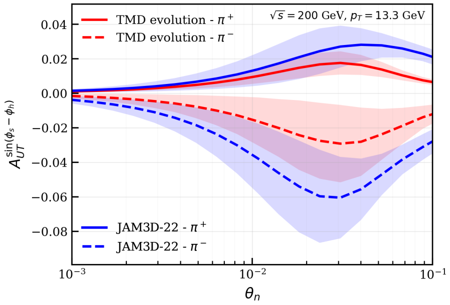


- JAM3D analysis gives overall larger Collins asymmetry than the TMD evolution framework.
- The error propagated from the parametrization of the Collins function is larger than from the transversity PDF.
- θ_n is integrated on (0, 0.1).

θ_n Distribution of the OPEC Collins Asymmetry



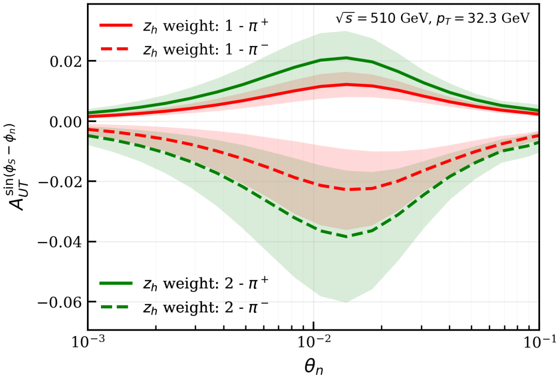
(a) $\sqrt{s} = 510$ GeV, $p_T = 32.3$ GeV



(b) $\sqrt{s} = 200$ GeV, $p_T = 13.3$ GeV

- Error is estimated from transversity PDF and Collins function combined.
- Two scenarios differ on the positions of their peak in θ_n.
- Current parametrizations do not yet allow us to resolve the effects of TMD evolution.

θ_n Distribution of the OPEC Collins Asymmetry for Different Weights



- Consistently enhancement of the Collins asymmetry for a higher power of the weight z_h (i.e. higher Mellin moment).

Conclusion

- We propose the one-point energy correlator (OPEC) for inclusive jet production in transversely polarized $p^\uparrow p$ collisions, sensitive to the transverse polarization effect through a $\sin(\phi_s - \phi_n)$ modulation.
- Compared with standard TMD studies, OPEC has two major benefits on determination of the transversity distribution:
  - The model dependency on final state fragmentation is reduced by taking the Mellin moment of the FJF.
  - OPEC estimates the Collins asymmetry by energy flow polar angle θ_n, accessing a much broader kinematic range of the jet substructure.
- We present a phenomenology study on $\pi^\pm$ production in jet.