Accessing Nucleon Transversity via One-Point Energy Correlators
利用单点能量关联函数（OPEC）探测核子的横向性分布

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Based on: Mei-Sen Gao, Zhong-Bo Kang, Wanchen Li, Ding Yu Shao, Phys. Rev. Lett. 136, 151902 (2026), arXiv: 2509.15809.

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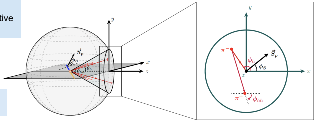
RHIC's talk on DIS2026, Bologna, Italy

- Renee Fatemi, *The 25 years RHIC legacy of QCD* on DIS 2026.

Energy-Energy Correlators in $p^{\uparrow}p$

EECs are infrared and collinear safe jet substructure observables that probe the evolution from the perturbative parton shower to non-perturbative hadronization.

$$\Sigma_{\rm EEC}(\theta_h,\phi_h) = \frac{d\left(\sum_{\rm jet}\sum_i z_{h,i}\right)}{d\theta_h\, d\phi_h}$$



The One-Point Energy Correlator is the energy weighted angular distribution of energy flux inside of a jet

$$\frac{d\Sigma}{d\theta_n\, d\phi_n\, d\eta\, dp_T} = Z_{UU} + \sin(\phi_s-\phi_n) Z_{UT}$$

Clean probe of transversity and Collins FF when $\theta_h \gg \Lambda_{QCD}/p_{T\,jet}$

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

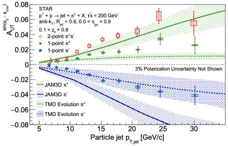
Increasing the power of the energy weight should increase the size of the asymmetry and probe higher Collins Mellin moments!

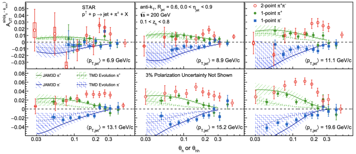
$$\Sigma_{\rm EEC}(\theta_{hh},\phi_{hh}) = \frac{d\left(\sum_{\rm jet}\sum_{i,j} z_{h,i} z_{h,j}\right)}{d\theta_{hh}\, d\phi_{hh}}$$

OPEC @ 200 GeV

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

$$A_{\rm UT} = \frac{1}{P}\frac{\Sigma^{\uparrow}_{EEC}(\phi_S-\phi)-\Sigma^{\downarrow}_{EEC}(\phi_S-\phi)}{\Sigma^{\uparrow}_{EEC}(\phi_S-\phi)+\Sigma^{\downarrow}_{EEC}(\phi_S-\phi)} =$$





Theory curves ***PRL 136, 151902 (2026)***

1. JAM3D global analysis w/o evolution effects ***Phys. Rev. D 106, 034014 (2022).***
2. Parameterization of transversity and Collins from global analysis of e⁺e⁻ and SIDIS data and implement TMD evolution as described in ***Phys. Rev. D 93, 014009 (2016).***

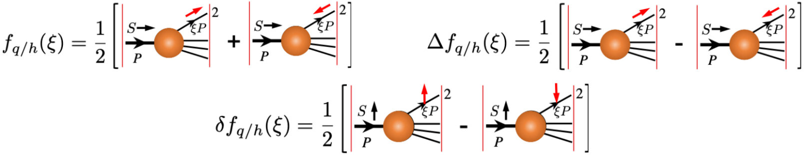
- Experiments paper: arXiv.2604.15543 from STAR collaboration.

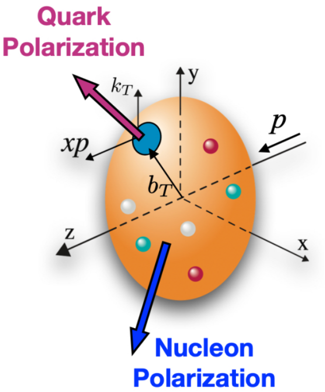
Outline

1. Transversity Distribution accessed in transversely polarized $p^\uparrow p$ Collision
   - The Transversity Distribution
   - Jet Production in Transversely Polarized $p^\uparrow p$ Collision
2. One Point Energy Correlator (OPEC)
3. Factorization with OPEC for Inclusive Jet Production
4. Phenomenology Study on Energy-Weighted $\pi^\pm$ Production in Jet
5. Conclusion: OPEC

Motivation

- Three basic parton distribution functions (PDFs) for quark q in hadron h:
  - unpolarized PDF: $f_{q/h}(x)$,
  - longitudinal polarized PDF $\Delta f_{q/h}(x)$,
  - transversity PDF $h_1^q(x)$ (or noted as $\delta f_{q/h}(x)$).





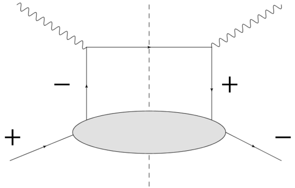
Figures from TMD handbook.

Motivation

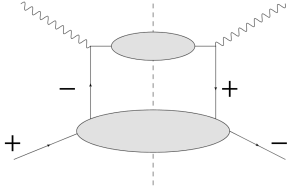
- Transversity distribution h_1^q is a fundamental, yet less known, parton distribution.
- Its chiral-odd nature prevents access via inclusive DIS.

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

- Nucleon tensor charge δq from h_1^q is essential for:
    - Nucleon spin structure,
      C. A. Aidala, S. D. Bass, D. Hasch, G. K. Mallot, 2012.
    - Lattice QCD benchmarks,
      X. Gao, A. D. Hanlon, S. Mukherjee, P. Petreczky, Q. Shi, S. Syritsyn, and Y. Zhao, 2024.
    - BSM probes, i.e. neutron β-decay.
      J. D. Jackson, S. B. Treiman, and H. W. Wyld, 1957.



Transversity forbidden in Inclusive DIS



Semi-inclusive DIS (SIDIS)

Collins function corresponds to the transverse momentum dependent (TMD) fragmentation function (FF) with transversely polarized quark that fragmented into unpolarized hadron .

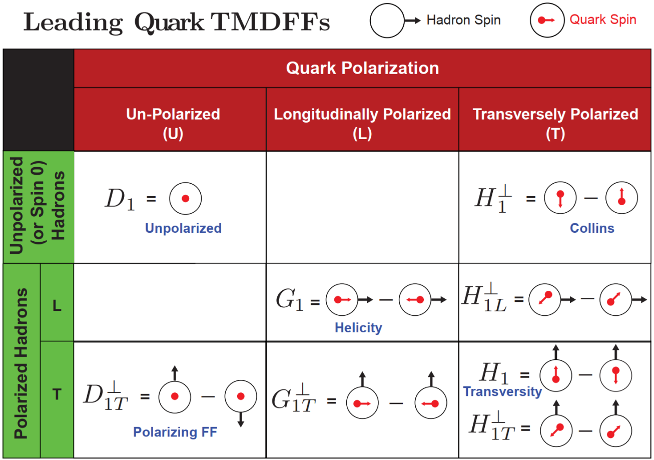
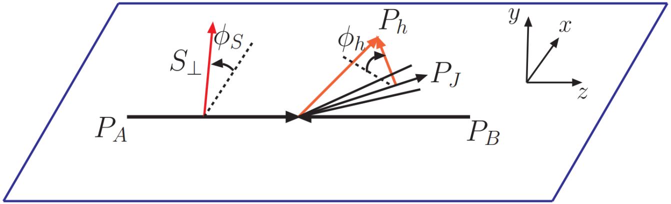


Figure from TMD handbook.

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,

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

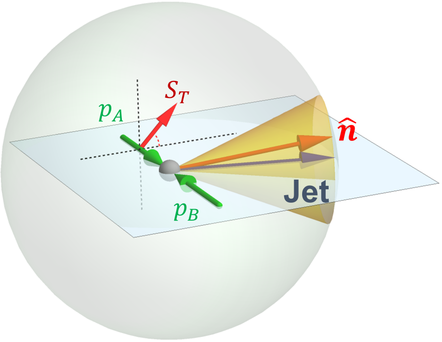
- The reaction plane is spanned by the two incoming protons and the jet axis.
  - ϕ_s: the azimuthal angle of transverse polarization vector $S_\perp$, with respect the to reaction plane.
  - ϕ_h: the azimuthal angle of hadron h in jet, with respect the to reaction plane.

One Point Energy Correlator (OPEC)

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

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

- $\hat{\boldsymbol{n}}$ 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 $|J(h_i)X\rangle$ represents the final-state unobserved particles X and observed energy flow from hadron i the jet J.



Decomposition of OPEC

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

$$\Delta_q^{[\gamma^+]} = \mathcal{J}^q,$$

$$\Delta_q^{[i\sigma^{\alpha+}\gamma_5]} = \epsilon_T^{\alpha\rho}\hat{\boldsymbol{n}}_{T,\rho}\frac{p_J^-}{2}\theta_n\mathcal{J}_{1,\perp}^q.$$

- $\mathcal{J}^q$ 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

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

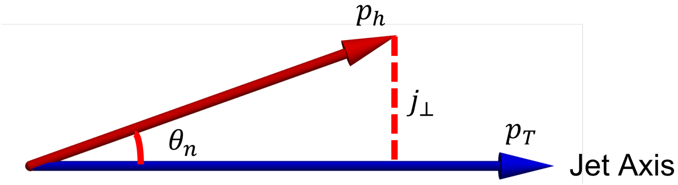
Factorization with OPEC in Inclusive Jet Production

- 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?

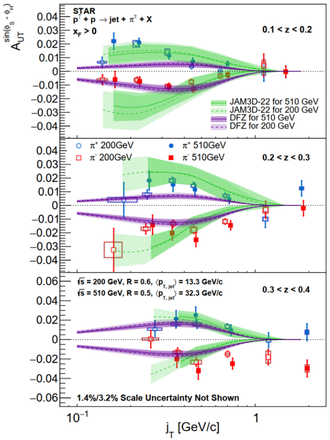
- Compared with standard non-weighted TMD analysis, we have a different overall factor

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

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

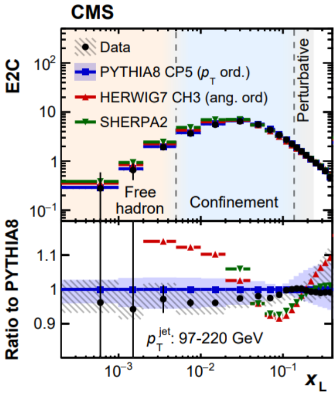
Why switch to θ_n?

- 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.

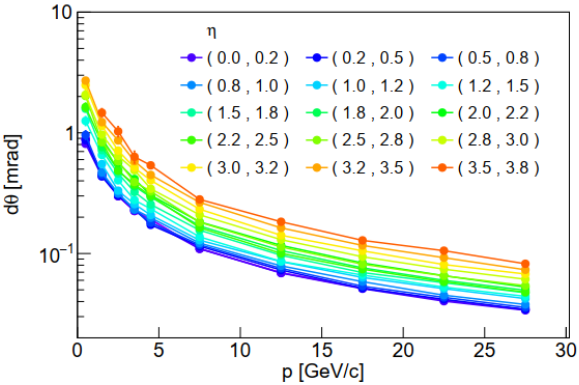


STAR collaboration arXiv.2507.16355

$j_\perp$ 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

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

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

- 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

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

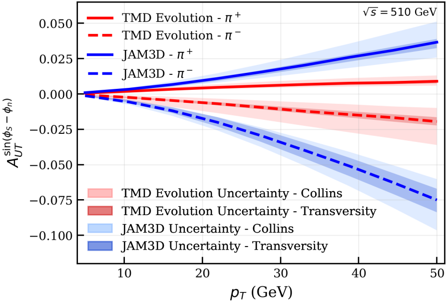
- We consider pion production in jets for two kinematic settings extensively studied by the STAR Collaboration:
  - (a) $\sqrt{s} = 510\,\text{GeV}$, $p_T = 32.3\,\text{GeV}$;
  - (b) $\sqrt{s} = 200\,\text{GeV}$, $p_T = 13.3\,\text{GeV}$.

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



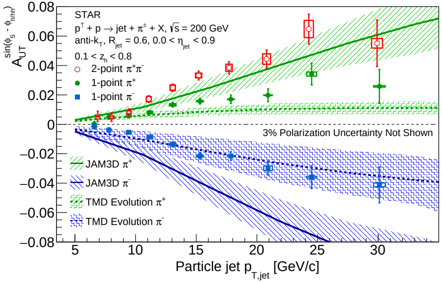
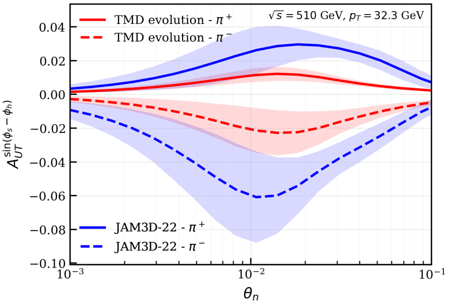


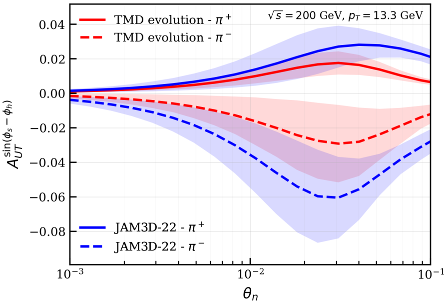
Figure from STAR Collaboration, 2604.15543.

- JAM3D analysis gives overall larger Collins asymmetry than TMD evolution results.
- 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

- STAR recent paper on OPEC Asymmetry with $\sqrt{s} = 200$ GeV.

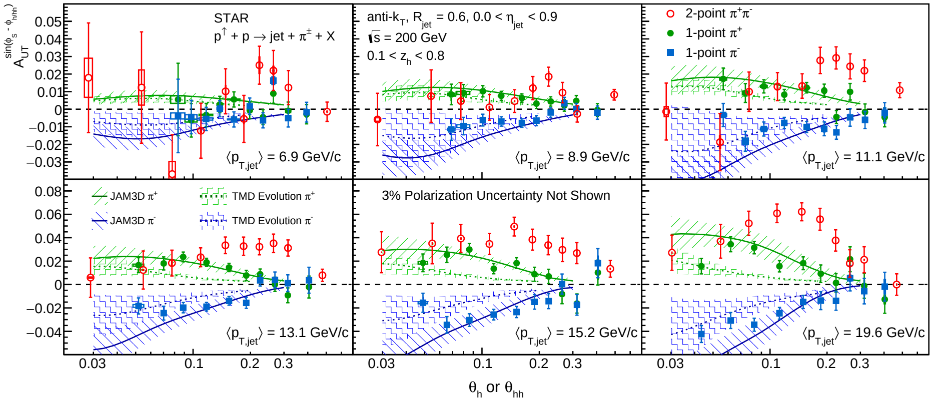
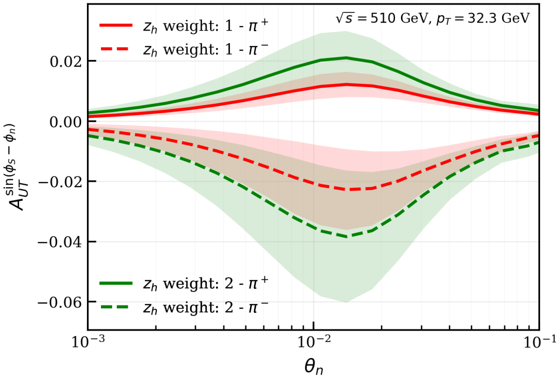


Figure from STAR Collaboration, 2604.15543.

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 with 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.
- Outlooks:
  - Two points near-side energy correlator on Collins dihadron production (see recent development: Z.B. Kang, A. Metz, D. Pitonyak, C. Zhang, arXiv:2604.28131).
  - Incorporating the twist-3 qgq correlator contributions (see recent development: D. Scantamburlo, M. Schlegel, arXiv: 2603.10628;).

OPEC FJF Factorization

- Analogously to the TMD FJFs (Z.B. Kang, X. Liu, F. Ringer, and H. Xing, 2017; Z.B. Kang, K. Lee, and F. Zhao, 2020), the OPEC FJFs admit the factorized representations in the limit $R \gg \theta_n$,

$$\begin{aligned}\mathcal{J}^c(z,\hat{\boldsymbol{n}},\omega_J R,\mu) =& \mathcal{H}_{c\to i}(z,\omega_J R,\mu)\int \mathrm{d}^2\boldsymbol{l}_\perp \mathrm{d}^2\boldsymbol{\lambda}_\perp \delta^2\left(\boldsymbol{l}_\perp + p_T\theta_n\hat{\boldsymbol{n}}_T - \boldsymbol{\lambda}_\perp\right)\\ &\times J_i^U(\boldsymbol{l}_\perp,\mu,\nu)S_i(\boldsymbol{\lambda}_\perp,\mu,\nu R)\ ,\\ p_T\theta_n\mathcal{J}^q_{1,\perp}(z,\hat{\boldsymbol{n}},\omega_J R,\mu) =& \mathcal{H}^T_{c\to i}(z,\omega_J R,\mu)\int \mathrm{d}^2\boldsymbol{l}_\perp \mathrm{d}^2\boldsymbol{\lambda}_\perp \delta^2\left(\boldsymbol{l}_\perp + p_T\theta_n\hat{\boldsymbol{n}}_T - \boldsymbol{\lambda}_\perp\right)\\ &\times p_T\theta_n J_i^T(\boldsymbol{l}_\perp,\mu,\nu)S_i(\boldsymbol{\lambda}_\perp,\mu,\nu R)\ .\end{aligned}$$

- $\mathcal{H}$ is a hard matching coefficient, encodes the contributions from radiations at the jet scale $\omega_J R$. J is the OPEC jet function.

OPEC jet function OPE

The z^{N-1} OPEC jet function can be matched on to the collinear counterparts

$$\tilde{J}_q^U(\boldsymbol{b},\mu,\nu) = C_{qq}(\boldsymbol{b},\mu,\nu)\,\tilde{D}^N_{q/q}(\mu) + C_{gq}(\boldsymbol{b},\mu,\nu)\,\tilde{D}^N_{g/q}(\mu),$$
$$\tilde{J}_g^U(\boldsymbol{b},\mu,\nu) = C_{gg}(\boldsymbol{b},\mu,\nu)\,\tilde{D}^N_{g/g}(\mu) + C_{qg}(\boldsymbol{b},\mu,\nu)\,\tilde{D}^N_{q/g}(\mu),$$
$$\tilde{J}_q^T(\boldsymbol{b},\mu,\nu) = \delta C_{qq}(\boldsymbol{b},\mu,\nu)\,\tilde{H}^{(3)N}_{q/q}(\mu),$$

with the NLO renormalized matching coefficients

$$C_{qq}(\boldsymbol{b},\mu,\nu) = 1 + \frac{\alpha_s}{2\pi}\left[C_F\left(\ln\frac{\mu^2}{\mu_b^2}\left(\frac{3}{2}+2\ln\frac{\nu}{\omega_J}\right)+\frac{1}{N(N+1)}\right)-\gamma_{qq}(N)\ln\frac{\mu^2}{\mu_b^2}-2\gamma_{qq}^{(1)}(N)\right],$$
$$C_{gq}(\boldsymbol{b},\mu,\nu) = \frac{\alpha_s}{2\pi}\left[-\gamma_{gq}(N)\ln\frac{\mu^2}{\mu_b^2}-2\gamma_{gq}^{(1)}(N)+C_F\frac{1}{N+1}\right],$$
$$C_{gg}(\boldsymbol{b},\mu,\nu) = 1 + \frac{\alpha_s}{2\pi}\left[C_A\ln\frac{\mu^2}{\mu_b^2}\left(\frac{\beta_0}{2C_A}+2\ln\frac{\nu}{\omega_J}\right)-\gamma_{gg}(N)\ln\frac{\mu^2}{\mu_b^2}-2\gamma_{gg}^{(1)}(N)\right],$$
$$C_{qg}(\boldsymbol{b},\mu,\nu) = \frac{\alpha_s}{2\pi}\left[-\gamma_{qg}(N)\ln\frac{\mu^2}{\mu_b^2}-2\gamma_{qg}^{(1)}(N)+T_F\frac{2}{(N+1)(N+2)}\right],$$
$$\delta C_{qq}(\boldsymbol{b},\mu,\nu) = 1 + \frac{\alpha_s}{2\pi}\left[C_F\ln\frac{\mu^2}{\mu_b^2}\left(\frac{3}{2}+2\ln\frac{\nu}{\omega_J}\right)-\Delta_T\gamma_{qq}(N)\ln\frac{\mu^2}{\mu_b^2}-2\Delta_T\gamma_{qq}^{(1)}(N)\right].$$

Backup: Scale uncertainties

- For the TMD evolution framework, we vary both the OPE scale μ_i and the hard scale $\mu = Q$ independently by a factor of two around their canonical values ($\mu_i = \mu_{b^*}$ and $\mu = Q = p_T$) to estimate the perturbative uncertainty.
- For the JAM3D-based approach, where only collinear DGLAP evolution is included, we vary the hard scale $\mu = Q = p_T$ in the same manner.