Unveiling Nucleon 3D Chiral-Odd Structure with Jet Axes

Wai Kin Lai

University of California, Los Angeles South China Normal University

WKL, Xiaohui Liu, Manman Wang, Hongxi Xing, arXiv:2205.04570 [hep-ph]

Sept 7, 2022

The 9th International Conference on Quarks and Nuclear Physics QNP 2022

MOTIVATION

- 3D structures of proton were studied typically using
 - semi-inclusive DIS/Drell-Yan [Mulders, Tangerman (1996), Brodsky, Hwang, Schmidt (2002), Bacchetta *et al.*(2007), Bacchetta *et al.*, MAP Collaboration (2022)]
 - jet production/hadron in jet [Kang, Metz, Qiu, Zhou (2011), Liu, Ringer, Vodelsang, Yuan (2019), Kang, Lee, Shao, Zhao (2021)]

Motivation

- 3D structures of proton were studied typically using
 - semi-inclusive DIS/Drell-Yan [Mulders, Tangerman (1996), Brodsky, Hwang, Schmidt (2002), Bacchetta *et al.*(2007), Bacchetta *et al.*, MAP Collaboration (2022)]
 - jet production/hadron in jet [Kang, Metz, Qiu, Zhou (2011), Liu, Ringer, Vodelsang, Yuan (2019), Kang, Lee, Shao, Zhao (2021)]
- Jet was thought to be able to probe only a subset of TMD PDFs (4 out of 8 at leading twist).

MOTIVATION

- 3D structures of proton were studied typically using
 - semi-inclusive DIS/Drell-Yan [Mulders, Tangerman (1996), Brodsky, Hwang, Schmidt (2002), Bacchetta *et al.*(2007), Bacchetta *et al.*, MAP Collaboration (2022)]
 - jet production/hadron in jet [Kang, Metz, Qiu, Zhou (2011), Liu, Ringer, Vodelsang, Yuan (2019), Kang, Lee, Shao, Zhao (2021)]
- Jet was thought to be able to probe only a subset of TMD PDFs (4 out of 8 at leading twist).
- We will demonstrate how all TMD PDFs at leading twist can be accessed by jets by including the T-odd jet function. [WKL, Liu, Xing, Wang, arXiv:2205.04570 [hep-ph]]

T-odd jet function was introduced by [X. Liu and H. Xing (2021)]

ROLE OF JET ALGORITHM

Consider $l + p(P, S) \rightarrow l' + J(P_J) + X$ at EIC

• A lot of statistics at small p_T in the forward region.



- Focus on the region $\Lambda_{QCD} \sim p_T \ll Q$. This is unlike LHC, for which only jets with $p_T \gg \Lambda_{QCD}$ are of interest.
- Still get jets if we use jet algorithms that involve energy (e.g. spherically-invariant jet algorithm [Cacciari, Salam, Soyez (2012)]) instead of k_T. Low p_T (~ Λ_{QCD}) and low Q² (~ 5 − 100 GeV²) is not a problem.

Role of jet axis definition

- Probes of TMD PDFs amount to measuring q_T of the virtual photon w.r.t. two pre-defined axes:
 - Drell-Yan: Two nucleon beams define two axes.
 - SIDIS: Nucleon beam and momentum of tagged hadron define two axes.
- In DIS, with a specific recombination scheme, a jet axis can be defined for a given jet. Once the axis is defined, we can forget about the fact that it's a jet. We thus get a nucleon beam axis and a jet axis, w.r.t. which q_T of the virtual photon can be defined. Therefore, jet probes of nucleon structure in DIS are as differential as SIDIS or Drell-Yan.





FACTORIZATION

Factorization frame:



For $Q \gg |\boldsymbol{q}_T|$ and $Q \gg \Lambda_{\rm QCD}$, factorization from SCET:

 $\sigma = H \otimes \Phi \otimes \mathcal{J}$

H: hard function, Φ : TMD PDFs, \mathcal{J} : TMD jet functions (JFs) [Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi (2018)]

$$\begin{split} \Phi^{ij}(x,p_T) &= \int \frac{dy^- d^2 \boldsymbol{y}_T}{(2\pi)^3} e^{ip \cdot y} \langle P | \bar{\chi}^j_n(0) \chi^i_n(y) | P \rangle |_{y^+=0} \\ \mathcal{J}^{ij}(z,k_T) &= \frac{1}{2z} \sum_X \int \frac{dy^+ d^2 \boldsymbol{y}_T}{(2\pi)^3} e^{ik \cdot y} \langle 0 | \chi^i_{\bar{n}}(y) | JX \rangle \langle JX | \bar{\chi}^j_{\bar{n}}(0) | 0 \rangle |_{y^-=0} \end{split}$$

GNS frame: $(P_{J\perp} = -zq_T)$



AZIMUTHAL ASYMMETRIES

TMD PDFs and TMD JFs encoded in azimuthal asymmetries (leading power in 1/Q):

$$\begin{split} \frac{d\sigma}{dxdydzd\psi d\phi_J dP_{J\perp}^2} &= \frac{\alpha^2}{xyQ^2} \left\{ \left(1 - y + \frac{y^2}{2} \right) F_{UU,T} + (1 - y)\cos(2\phi_J) F_{UU}^{\cos(2\phi_J)} \\ &+ S_{\parallel}(1 - y)\sin(2\phi_J) F_{UL}^{\sin(2\phi_J)} + S_{\parallel}\lambda_e y \left(1 - \frac{y}{2} \right) F_{LL} \\ &+ |S_{\perp}| \left[\left(1 - y + \frac{y^2}{2} \right) \sin(\phi_J - \phi_S) F_{UT,T}^{\sin(\phi_J - \phi_S)} + (1 - y)\sin(\phi_J + \phi_S) F_{UT}^{\sin(\phi_J + \phi_S)} \\ &+ (1 - y)\sin(3\phi_J - \phi_S) F_{UT}^{\sin(3\phi_J - \phi_S)} \right] + |S_{\perp}|\lambda_e y \left(1 - \frac{y}{2} \right) \cos(\phi_J - \phi_S) F_{LT}^{\cos(\phi_J - \phi_S)} \Big\} \end{split}$$

 $F\sp{is:}$ convolutions of TMD PDFs and TMD JFs.

F's: accessible by traditional jet function F's: inaccessible by traditional jet function



$\Phi = \frac{1}{2} \left\{ f_1 \not\!\!/ - f_{1T}^{\perp} \frac{\epsilon_{\alpha\beta} p_T^{\alpha} S_T^{\beta}}{M} \not\!\!/ + \left(S_L g_{1L} - \frac{p_T \cdot S_T}{M} g_{1T} \right) \gamma_5 \not\!\!/ \right\}$			
$+ \frac{h_{1T}}{2} \frac{[S_T', \not\!\!\!/] \gamma_5}{2} + \left(S_L h_{1L}^{\perp} - \frac{p_T \cdot S_T}{M} h_{1T}^{\perp} \right) \frac{[p_T', \not\!\!\!/] \gamma_5}{2M} + i h_1^{\perp} \frac{[p_T', \not\!\!\!/]}{2M} \bigg\}$			
quark hadron	unpolarized	longitudinal	transverse
U	f_1		h_1^\perp (Boer-Mulders)
L		g_{1L}	h_{1L}^{\perp}
Т	f_{1T}^{\perp} (Sivers)	g_{1T}	h_{1T}, h_{1T}^{\perp} (transversity)
[Appeles Martinez et al (2015)]			

Angeles-IviarLinez et al. (2013)

- 8 TMD PDFs at leading twist, functions of x and p_T^2
- 3 functions f_1, g_{1L}, h_{1T} survive after p_T integration giving collinear PDFs
- T-even: $f_1, g_{1L}, g_{1T}, h_{1T}, h_{1L}^{\perp}, h_{1T}^{\perp}$ T-odd: $f_{1T}^{\perp}, h_1^{\perp}$
- Chiral-even (accessible by traditional jet function): $f_1, f_{1T}^{\perp}, g_{1L}, g_{1T}$ Chiral-odd (inaccessible by traditional jet function): $h_{1}^{\perp}, h_{1L}^{\perp}, h_{1T}, h_{1T}^{\perp}$

T-ODD JET FUNCTION

- Traditionally, only jets with high p_T ($\gg \Lambda_{\rm QCD}$) were of interest. Production of high- p_T jets is perturbative. Since massless perturbative QCD is chiral-symmetric, only chiral-even (and T-even) jet functions appear.
- At low p_T ($\sim \Lambda_{QCD}$), the jet is sensitive to nonperturbative physics. In particular, spontaneous chiral symmetry breaking leads to a nonzero chiral-odd (and T-odd) jet function when the jet axis is different from the direction of the fragmenting parton. (This is similar to Collins effect in fragmentation functions of hadrons [Collins (2002)].) [Liu and Xing (2021)]

$$\mathcal{J}(z,k_T) = \mathcal{J}_1(z,k_T)\frac{\not\!\!\!/}{2} + i\mathcal{J}_T(z,k_T)\frac{\not\!\!\!/}{2}$$

- \mathcal{J}_1 : chiral-even, T-even, traditional jet function
- \mathcal{J}_T : chiral-odd, T-odd, encodes correlations of quark transverse spin with quark transverse momentum (analogue of Collins function)



Advantages of T-odd jet function

• Universality

Like the T-even \mathcal{J}_1 , T-odd \mathcal{J}_T is process independent.

• Flexibility

Flexibility of choosing jet recombination scheme and hence the jet axis

- \Rightarrow Adjust sensitivity to different nonperturbative contributions
- \Rightarrow Provide opportunity to "film" the QCD nonperturbative dynamics, if one continuously change the axis from one to another.

High predictive power

• Perturbative predictability. Since a jet contains many hadrons, the jet function has more perturbatively calculable degrees of freedom than the fragmentation function. For instance, in the WTA scheme, for $R \sim \mathcal{O}(1) \gg |\mathbf{q}_T|/E_J$, the z-dependence in the jet function is completely determined:

$$\mathcal{J}(z,k_T,R) = \delta(1-z)J(k_T) + \mathcal{O}\left(\frac{k_T^2}{E_J^2 R^2}\right)$$

[Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi (2018)]

• Nonperturbative predictability. Similar to the study in [Becher and Bell (2014)], \mathcal{J}_T can be factorized into a product of a perturbative coefficient and a nonperturbative factor. The nonperturbative factor has an operator definition [Vladimirov (2020)], and as a vacuum matrix element can be calculated on the lattice. This is unlike the TMD fragmentation function, which is an operator element of $|h + X\rangle$.

$$A^{\sin(\phi_J + \phi_S)}(|\mathbf{P}_{J\perp}|) = \frac{2}{|\mathbf{S}_{\perp}| \int d\sigma\epsilon} \int d\sigma \sin(\phi_J + \phi_S) = \frac{\langle \epsilon F_{UT}^{\sin(\phi_J + \phi_S)}}{\bar{\epsilon} \langle F_{UU,T} \rangle}$$

•
$$F_{UT}^{\sin(\phi_J+\phi_S)}\sim h_1\otimes J_T$$
, probes transversity $h_1\equiv h_{1T}+rac{p_T^2}{2M^2}h_{1T}^{\perp}$

We simulate using PYTHIA 8.2+STRINGSPINNER [Kerbizi, Loennblad (2021)], with jet charge [Kang, Liu, Mantry, Shao (2020)] measured to enhance flavor separation (not mandatory), with EIC kinematics.

Use the spherically-invariant jet algorithm [Cacciari, Salam, Soyez (2012)]:

$$d_{ij} = min(E_i^{-2}, E_j^{-2}) \frac{1 - \cos \theta_{ij}}{1 - \cos R}, \quad d_{iB} = E_i^{-2}$$





$$A^{\sin(\phi_J + \phi_S)}(|\mathbf{P}_{J\perp}|) = \frac{2}{|\mathbf{S}_{\perp}| \int d\sigma\epsilon} \int d\sigma \sin(\phi_J + \phi_S) = \frac{\langle \epsilon F_{UT}^{\sin(\phi_J + \phi_S)} \rangle}{\bar{\epsilon} \langle F_{UU,T} \rangle}$$

•
$$F_{UT}^{\sin(\phi_J+\phi_S)}\sim h_1\otimes J_T$$
, probes transversity $h_1\equiv h_{1T}+rac{p_T^2}{2M^2}h_{1T}^{\perp}$

We simulate using PYTHIA 8.2+STRINGSPINNER [Kerbizi, Loennblad (2021)], with jet charge [Kang, Liu, Mantry, Shao (2020)] measured to enhance flavor separation (not mandatory), with EIC kinematics.

Use the spherically-invariant jet algorithm [Cacciari, Salam, Soyez (2012)]:

$$d_{ij} = \min(E_i^{-2}, E_j^{-2}) \frac{1 - \cos \theta_{ij}}{1 - \cos R}, \quad d_{iB} = E_i^{-2}$$

(Conventional anti- k_T algorithms using k_T instead of E not good for low- p_T jets)

• Change the jet axis from one to another (WTA \rightarrow E-scheme), "film" nonperturbative physics. E-scheme: $e+p\rightarrow e+J_{E-scheme}+X$ (EIC)



 $k_r = k_1 + k_2$





• Data points: from PYTHIA simulations Lines: from factorization formula (including evolution via Sudakov factors, normalization of J₁ fixed by jet charge bins, k_T-dependence of J₁ and J_T from pion FFs, ratio of normalization of J_T to that of J₁ set equal to that for pions)

 \bullet Asymmetries at lower \sqrt{s} are generally larger, owing to the perturbative Sudakov factor.

$$A^{\cos(2\phi_J)}(|\mathbf{P}_{J\perp}|) = \frac{2}{\int d\sigma\epsilon} \int d\sigma \cos(2\phi_J) = \frac{\langle \epsilon F_{UU}^{\cos(2\phi_J)} \rangle}{\bar{\epsilon} \langle F_{UU,T} \rangle}$$

 $F_{UU}^{\cos(2\phi_J)}\sim h_1^\perp\otimes J_T$, probes Boer-Mulders function

Predictions from factorization formula:



COMPARISON WITH HERMES SIDIS DATA



e^+e^- ANNIHILATION

We give prediction on azimuthal asymmetry in $e^+e^- \rightarrow J + X$ at $\sqrt{s} = \sqrt{110}$ GeV (Belle, BaBar), 91.2, 165, 240 GeV (CEPC) with WTA scheme:

$$A = 2 \int d\cos\theta \, \frac{d\phi_1}{\pi} \cos(2\phi_1) A^{J_1 J_2}$$
$$A^{J_1 J_2} = 1 + \cos(2\phi_1) \frac{\sin^2\theta}{1 + \cos^2\theta} \frac{F_T}{F_U}$$
$$F_T \sim J_T \otimes J_T$$



SUMMARY AND OUTLOOK

- With spherically-invariant jet algorithms, we can study jets at low p_T ($\sim \Lambda_{\rm QCD}$), e.g. at EIC.
- Specification of a jet axis makes jet probes of TMD PDFs in DIS as differential as SIDIS or Drell-Yan.
- Using the T-odd jet function, together with the traditional T-even one, we can probe all 8 TMD PDFs at leading twist using jets.
- T-odd jet function has the advantages of universality, flexibility, and high predictive power.
- We have shown that the T-odd jet function gives rise to sizable azimuthal asymmetries at EIC, which help probe the chiral-odd TMD PDFs, such as the quark transversity and the Boer-Mulders function, which the traditional jet function is unable to access.
- T-odd jet function provides new input to the global analysis of nonperturbative proton structure.

Thank you.

Backup slides

TMD PDFs and TMD JFs encoded in azimuthal asymmetries:

$$\frac{d\sigma}{dxdydzd\psi d\phi_J dP_{J\perp}^2} = \frac{\alpha^2}{xyQ^2} \left\{ \left(1 - y + \frac{y^2}{2} \right) F_{UU,T} + (1 - y)\cos(2\phi_J) F_{UU}^{\cos(2\phi_J)} \right. \\ \left. + S_{\parallel}(1 - y)\sin(2\phi_J) F_{UL}^{\sin(2\phi_J)} + S_{\parallel}\lambda_e y \left(1 - \frac{y}{2} \right) F_{LL} \right. \\ \left. + \left| \boldsymbol{S}_{\perp} \right| \left[\left(1 - y + \frac{y^2}{2} \right) \sin(\phi_J - \phi_S) F_{UT,T}^{\sin(\phi_J - \phi_S)} + (1 - y)\sin(\phi_J + \phi_S) F_{UT}^{\sin(\phi_J + \phi_S)} \right. \\ \left. + (1 - y)\sin(3\phi_J - \phi_S) F_{UT}^{\sin(3\phi_J - \phi_S)} \right] + \left| \boldsymbol{S}_{\perp} \right| \lambda_e y \left(1 - \frac{y}{2} \right) \cos(\phi_J - \phi_S) F_{LT}^{\cos(\phi_J - \phi_S)}$$

The *F*'s are convolutions of TMD PDFs and TMD JFs:

$$\mathcal{C}[wfJ] \equiv x \sum_{a} e_q^2 \int d^2 \mathbf{p}_T \int d^2 \mathbf{k}_T \delta^{(2)} \left(\mathbf{p}_T + \mathbf{q}_T - \mathbf{k}_T\right) w(\mathbf{p}_T, \mathbf{k}_T) f(x, p_T^2) J(z, k_T^2)$$

$$\begin{split} F_{UU,T} &= \mathcal{C}[f_{1}\mathcal{J}_{1}], \quad F_{LL} = \mathcal{C}[g_{1L}\mathcal{J}_{1}] \\ F_{UT,T}^{\sin(\phi_{J}-\phi_{S})} &= \mathcal{C}\left[-\frac{\hat{h}\cdot p_{T}}{M}f_{1T}^{\perp}\mathcal{J}_{1}\right], \quad F_{LT}^{\cos(\phi_{J}-\phi_{S})} = \mathcal{C}\left[\frac{\hat{h}\cdot p_{T}}{M}g_{1T}\mathcal{J}_{1}\right], \\ F_{UU}^{\cos(2\phi_{J})} &= \mathcal{C}\left[-\frac{(2(\hat{h}\cdot k_{T})(\hat{h}\cdot p_{T}) - k_{T}\cdot p_{T})}{M}h_{1}^{\perp}\mathcal{J}_{T}\right] \\ F_{UL}^{\sin(2\phi_{J})} &= \mathcal{C}\left[-\frac{(2(\hat{h}\cdot k_{T})(\hat{h}\cdot p_{T}) - k_{T}\cdot p_{T})}{M}h_{1L}^{\perp}\mathcal{J}_{T}\right] \\ F_{UT}^{\sin(\phi_{J}+\phi_{S})} &= \mathcal{C}\left[-\hat{h}\cdot k_{T}h_{1}\mathcal{J}_{T}\right] \\ F_{UT}^{\sin(3\phi_{J}-\phi_{S})} &= \mathcal{C}\left[\frac{2(\hat{h}\cdot p_{T})(p_{T}\cdot k_{T}) + p_{T}^{2}(\hat{h}\cdot k_{T}) - 4(\hat{h}\cdot p_{T})^{2}(\hat{h}\cdot k_{T})}{2M^{2}}h_{1T}^{\perp}\mathcal{J}_{T}\right] \end{split}$$

where $\hat{h}\equiv P_{J\perp}/|P_{J\perp}|$ and $h_1\equiv h_{1T}+rac{p_T^2}{2M^2}h_{1T}^{\perp}$