Time-reversal odd side of a jet

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based on
X. Liu and H. Xing, arXiv:2104.03328 [hep-ph], and work in progress

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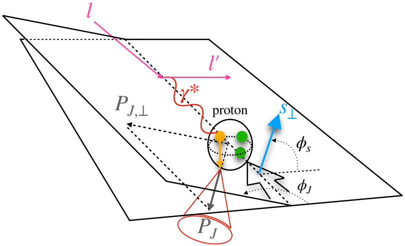
Motivation

- 3D structures of proton were studied typically using
  - semi-inclusive hadron production
    [Mulders, Tangerman (1996), Brodsky, Hwang, Schmidt (2002), Bacchetta *et al.*(2007)]
  - 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).
- This work: Investigate possibility of probing all TMD PDFs with jet.

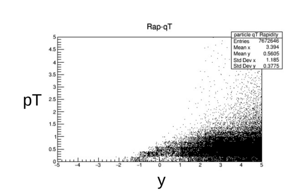
Consider $l + p(P,S) \to l' + J(P_J) + X$



This is like SIDIS, but replace a hadron by a jet.
[Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi (2018)]

Jets at EIC

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



- Focus on the region $\Lambda_{\rm QCD} \sim |\boldsymbol{P}_{J\perp}| \ll Q$.
This is unlike LHC, for which only jets with $|\boldsymbol{P}_{J\perp}| \gg \Lambda_{\rm QCD}$ are of interest.
- Still get jets if we use jet algorithms that involve energy (i.e. spherically-invariant jet algorithm [Cacciari, Salam, Soyez (2012)]) instead of k_T. Low p_T ($\sim \Lambda_{\rm QCD}$) and low Q^2 ($\sim 10 - 100~{\rm GeV}^2$) is not a problem.

Factorization

- 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)]

$$\Phi^{ij}(x, p_T) = \int \frac{dy^- d^2\boldsymbol{y}_T}{(2\pi)^3} e^{ip\cdot y} \langle P | \bar{\chi}_n^j(0) \chi_n^i(y) | P \rangle |_{y^+=0}$$

$$\mathcal{J}^{ij}(z, k_T) = \frac{1}{2z} \sum_X \int \frac{dy^+ d^2\boldsymbol{y}_T}{(2\pi)^3} e^{ik\cdot y} \langle 0 | \chi_{\bar{n}}^i(y) | JX \rangle \langle JX | \bar{\chi}_{\bar{n}}^j(0) | 0 \rangle |_{y^-=0}$$

- TMD PDFs and TMD JFs encoded in azimuthal asymmetries:

$$\begin{aligned}
\frac{d\sigma}{dx\,dy\,dz\,d\psi\,d\phi_J\,dP_J^2} = \frac{\alpha^2}{xyQ^2} \Bigg\{ & \left(1 - y + \frac{y^2}{2}\right) F_{UU,T} + (1-y)\cos(2\phi_J) F_{UU}^{\cos(2\phi_J)} \\
& + S_\parallel (1-y)\sin(2\phi_J) F_{UL}^{\sin(2\phi_J)} + S_\parallel \lambda_e y \left(1 - \frac{y}{2}\right) F_{LL} \\
& + |\boldsymbol{S}_\perp| \left[\left(1 - y + \frac{y^2}{2}\right) \sin(\phi_J - \phi_S) F_{UT,T}^{\sin(\phi_J - \phi_S)} + (1-y)\sin(\phi_J + \phi_S) F_{UT}^{\sin(\phi_J + \phi_S)} \right. \\
& \left. + (1-y)\sin(3\phi_J - \phi_S) F_{UT}^{\sin(3\phi_J - \phi_S)} \right] + |\boldsymbol{S}_\perp| \lambda_e y \left(1 - \frac{y}{2}\right) \cos(\phi_J - \phi_S) F_{LT}^{\cos(\phi_J - \phi_S)} \Bigg\}
\end{aligned}$$

F's: convolutions of TMD PDFs and TMD JFs.
F's: accessible by traditional jet function
F's: inaccessible by traditional jet function

TMD PDFs at leading twist

$$\Phi = \frac{1}{2}\left\{ f_1 \not{n} - f_{1T}^{\perp} \frac{\epsilon_{\alpha\beta} p_T^{\alpha} S_T^{\beta}}{M} \not{n} + \left(S_L g_{1L} - \frac{p_T \cdot S_T}{M} g_{1T} \right) \gamma_5 \not{n} \right.$$
$$\left. + h_{1T} \frac{[\not{S}_T, \not{n}]\gamma_5}{2} + \left(S_L h_{1L}^{\perp} - \frac{p_T \cdot S_T}{M} h_{1T}^{\perp} \right) \frac{[\not{p}_T, \not{n}]\gamma_5}{2M} + i h_1^{\perp} \frac{[\not{p}_T, \not{n}]}{2M} \right\}$$

hadron \ quark	unpolarized	chiral	transverse
U	f_1		$h_1^{\perp}$ (Boer-Mulders)
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$ (Sivers)	g_{1T}	$h_{1T}, h_{1T}^{\perp}$ (transversity)

[Angeles-Martinez, Bacchetta, Balitsky, Boer, Boglione, Boussarie, Ceccopieri, Cherednikov, Connor *et al.*(2015)]

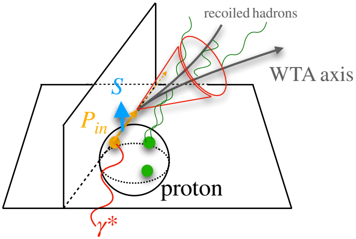
- 8 TMD PDFs at leading twist, functions of x and p_T^2
- T-even: $f_1, g_{1L}, g_{1T}, h_{1T}, h_{1L}^{\perp}, h_{1T}^{\perp}$
  T-odd: $f_{1T}^{\perp}, h_1^{\perp}$
- 3 functions f_1, g_{1L}, h_{1T} survive after p_T integration giving collinear PDF
- Chiral-even TMD PDFs accessible by traditional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

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 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 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)].)

$$\mathcal{J}(z,k_T) = \mathcal{J}_1(z,k_T)\frac{\not{\bar{n}}}{2} + i\mathcal{J}_T(z,k_T)\frac{\not{k}_T\not{\bar{n}}}{2}$$

- $\mathcal{J}_1$: T-even, traditional jet function
- $\mathcal{J}_T$: 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, the z-dependence in the jet function is completely determined:

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

    [Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi (2018)]
  - *Nonperturbative predictability*. Similar to the study in [Becher, 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 $|h + X\rangle$.

AZIMUTHAL ASYMMETRY

$\sin(\phi_J + \phi_s)$ azimuthal asymmetry:

$$A_{UT}^{\sin(\phi_J+\phi_s)} = \frac{F_{UT}^{\sin(\phi_J+\phi_s)}}{F_{UU}}$$

- $F_{UT}^{\sin(\phi_J+\phi_s)} \sim h_1 \otimes J_T$, probes transversity
- 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)]

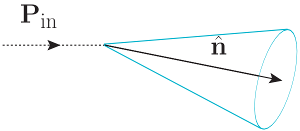
$$d_{ij} = min(E_i^{-2}, E_j^{-2})\frac{1-\cos\theta_{ij}}{1-\cos R}\ , \quad d_{iB} = E_i^{-2}$$

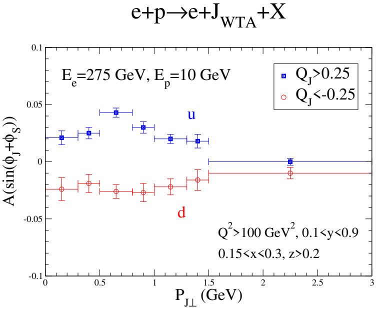
(Conventional anti-k_T algorithms using k_T instead of E not good for low p_T jets)

- **Change the jet axis from one to another (WTA $\to$ E-scheme), "film" nonperturbative physics.**

WTA scheme:

$$\hat{\boldsymbol{n}}_r = \begin{cases} \hat{\boldsymbol{n}}_1\ , & \text{if } E_1 > E_2 \\ \hat{\boldsymbol{n}}_2\ , & \text{if } E_2 > E_1 \end{cases}$$





$\sin(\phi_J + \phi_s)$ azimuthal asymmetry:

$$A_{UT}^{\sin(\phi_J+\phi_s)} = \frac{F_{UT}^{\sin(\phi_J+\phi_s)}}{F_{UU}}$$

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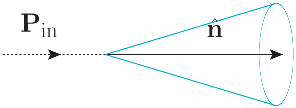
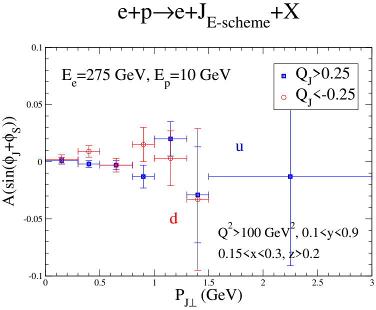
(Conventional anti-k_T algorithms using k_T instead of E not good for low p_T jets)

- **Change the jet axis from one to another (WTA → E-scheme), "film" nonperturbative physics.**

E-scheme:

$$k_r = k_1 + k_2$$



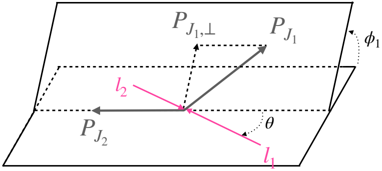


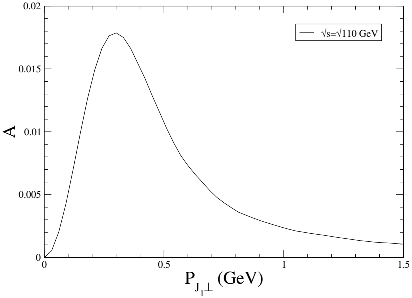
e^+e^- ANNIHILATION

We demonstrate prediction on azimuthal asymmetry in back-to-back dijet production in e^+e^- annihilation at $\sqrt{s} = \sqrt{110}$ GeV, with WTA scheme and parametrized nonperturbative Sudakov for J_T:

$$A^{J_1 J_2} = 1 + \cos(2\phi_1)\frac{\sin^2\theta}{1+\cos^2\theta}\frac{F_T(q_T)}{F_U(q_T)}$$

$$A = 2\int d\cos\theta\,\frac{d\phi_1}{\pi}\cos(2\phi_1)A^{J_1 J_2}$$





Summary and outlook

- We introduce the T-odd jet function, which is relevant for low p_T jets, i.e. jets at EIC.
- Using 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.
- T-odd jet functions provide new input to the global analysis of nonperturbative proton structure.

Thank you.

Backup slides

Azimuthal asymmetry at leading twist

TMD PDFs and TMD JFs encoded in azimuthal asymmetries:

$$\frac{d\sigma}{dx\,dy\,dz\,d\psi\,d\phi_J\,dP_J^2} = \frac{\alpha^2}{xyQ^2}\Bigg\{\left(1-y+\frac{y^2}{2}\right)F_{UU,T} + (1-y)\cos(2\phi_J)F_{UU}^{\cos(2\phi_J)}$$

$$+ S_\parallel(1-y)\sin(2\phi_J)F_{UL}^{\sin(2\phi_J)} + S_\parallel\lambda_e y\left(1-\frac{y}{2}\right)F_{LL}$$

$$+|\boldsymbol{S}_\perp|\left[\left(1-y+\frac{y^2}{2}\right)\sin(\phi_J-\phi_S)F_{UT,T}^{\sin(\phi_J-\phi_S)} + (1-y)\sin(\phi_J+\phi_S)F_{UT}^{\sin(\phi_J+\phi_S)}\right.$$

$$\left.+(1-y)\sin(3\phi_J-\phi_S)F_{UT}^{\sin(3\phi_J-\phi_S)}\right] + |\boldsymbol{S}_\perp|\lambda_e y\left(1-\frac{y}{2}\right)\cos(\phi_J-\phi_S)F_{LT}^{\cos(\phi_J-\phi_S)}\Bigg\}$$

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

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

$$F_{UU,T} = \mathcal{C}[f_1 \mathcal{J}_1], \quad F_{LL} = \mathcal{C}[g_{1L} \mathcal{J}_1]$$

$$F_{UT,T}^{\sin(\phi_J-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_{1T}^{\perp} \mathcal{J}_1\right], \quad F_{UT,T}^{\cos(\phi_J-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} \mathcal{J}_1\right],$$

$$F_{UU}^{\cos(2\phi_J)} = \mathcal{C}\left[-\frac{(2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T)}{M} h_1^{\perp} \mathcal{J}_T\right]$$

$$F_{UL}^{\sin(2\phi_J)} = \mathcal{C}\left[-\frac{(2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T)}{M} h_{1L}^{\perp} \mathcal{J}_T\right]$$

$$F_{UT}^{\sin(\phi_J+\phi_S)} = \mathcal{C}\left[-\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T h_1 \mathcal{J}_T\right]$$

$$F_{UT}^{\sin(3\phi_J-\phi_S)} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)(\boldsymbol{p}_T\cdot\boldsymbol{k}_T) + \boldsymbol{p}_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T) - 4(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)}{2M^2} h_{1T}^{\perp} \mathcal{J}_T\right]$$

where $\hat{\boldsymbol{h}} \equiv \boldsymbol{P}_{J\perp}/|\boldsymbol{P}_{J\perp}|$ and $h_1 \equiv h_{1T} + \frac{\boldsymbol{p}_T^2}{2M^2} h_{1T}^{\perp}$