A Better Angle on Hadron TMDs at the EIC

Anjie Gao, Johannes K. L. Michel, Iain W. Stewart, and Zhiquan Sun
MIT Center for Theoretical Physics

EPIC SIDIS Working Group Meeting
Remote Locations, October 18, 2022

[2209.11211]



jklmich@mit.edu

Outline

1. Construction of the New q_* TMD Observable
2. Theoretical and Experimental Properties
3. A Theorist's Perspective on Reconstructing (Q^2, x, y) in SIDIS

Outline

1. Construction of the New q_* TMD Observable
2. Theoretical and Experimental Properties
3. A Theorist's Perspective on Reconstructing (Q^2, x, y) in SIDIS

Constructing the observable: Key idea

$$e^-(\ell) + N(P) \to e^-(\ell') + h(P_h) + X$$

- Want to precisely measure P_{hT} in the TMD region $P_{hT} \sim \Lambda_{\mathrm{QCD}} \ll Q$

$\Rightarrow$ TMD factorization theorems in terms of universal TMD PDFs and FFs

- Challenge: P_{hT} is defined w/r/t photon direction reconstructed from $\vec{\ell}'$

$\Rightarrow$ Typical exp. resolution $|\vec{\ell}'| = (20 \pm 0.5)\,\mathrm{GeV} \Rightarrow P_{hT} = (1 \pm 0.5)\,\mathrm{GeV}$

Idea

Construct TMD-sensitive observable q_* purely in terms of *lab-frame angles*.

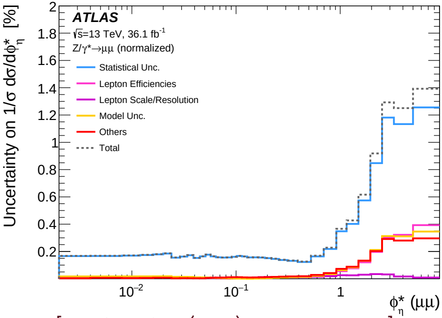
- Bypasses the need to reconstruct photon momentum q^μ altogether

I.e., for the TMD part $= \vec{P}_{hT}$. Still need Q, x (and z) to get 4D distribution $\longrightarrow$ later.

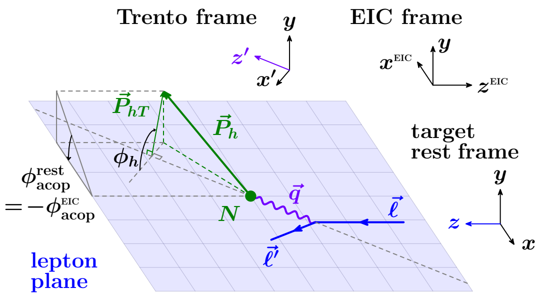
Idea

Construct TMD-sensitive observable q_* purely in terms of *lab-frame angles*.

- Inspired by (but with key differences to) ϕ^*_η observable in unpol'ed Drell-Yan:
  [Banfi et al., EPJC 71, 1600 (2011), arXiv:1009.1580]



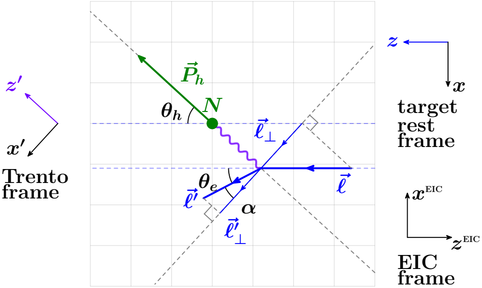
[ATLAS, EPJC 80 (2020) 7, 616, 1912.02844]



- Look at target rest frame with incoming electron along z axis
  - Boost along z direction & reverse direction of z to get to EIC lab frame
  - Azimuthal angles change sign, rapidities (polar angles) easy to relate
- Need (small) nonzero P_{hT} for $e^- N \to e^- h$ scatter to be (a little bit) nonplanar
- Work out acoplanarity angle for small $\lambda \sim P_{hT}/Q \ll 1$:

$$\tan \phi^{\text{rest}}_{\text{acop}} = \frac{\sin \phi_h \, P_{hT}}{zQ\sqrt{1-y}} + \mathcal{O}(\lambda^2)$$

Constructing the observable: Double Angle method revisited

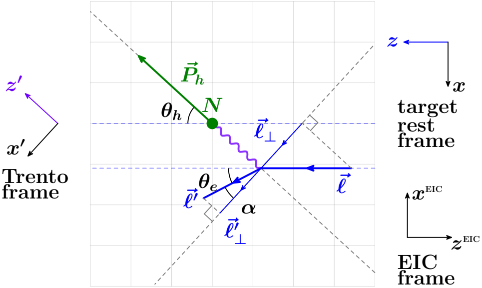


- Acoplanarity angle guarantees $\propto P_{hT}$:

$$\tan\phi_{\text{acop}}^{\text{rest}} = \frac{\sin\phi_h\, P_{hT}}{zQ\sqrt{1-y}} + \mathcal{O}(\lambda^2)$$

- For $P_{hT} \sim \lambda Q \ll Q$, can get Q, y (and x) from hadron & electron angles:

$$Q^2 = (\ell^0_{\text{rest}})^2\left[\frac{\sin^2\theta_e}{\cos^2\alpha} - \left(1 - \frac{\sin\theta_h}{\cos\alpha}\right)^2\right] + \mathcal{O}(\lambda) \qquad y = 1 - \frac{\sin\theta_h}{\cos\alpha} + \mathcal{O}(\lambda^2)$$



- Convert to EIC lab-frame pseudorapidites and take $M \ll Q$ (for brevity):

$$Q^2 = (2P^0_{\text{EIC}})^2 \frac{e^{\eta_e+\eta_h}}{1+e^{\Delta\eta}} + \mathcal{O}(\lambda) \qquad y = \frac{1}{1+e^{\Delta\eta}} + \mathcal{O}(\lambda^2)$$

- Combine with ϕ_{acop} to construct a purely angular SIDIS TMD observable:

$$\boxed{q_* \equiv 2P^0_{\text{EIC}} \frac{e^{\eta_h}}{1+e^{\Delta\eta}} \tan \phi^{\text{EIC}}_{\text{acop}} = -\sin \phi_h \frac{P_{hT}}{z} \left[1 + \mathcal{O}(\lambda)\right]}$$

Outline

Theory: All-order TMD factorization for q_*

- Start from simple form of q_* at $q_* \ll Q$:

$$q_* = -\sin\phi_h \frac{P_{hT}}{z}\left[1 + \mathcal{O}(\lambda)\right]$$

- Insert into standard SIDIS TMD factorization, get:

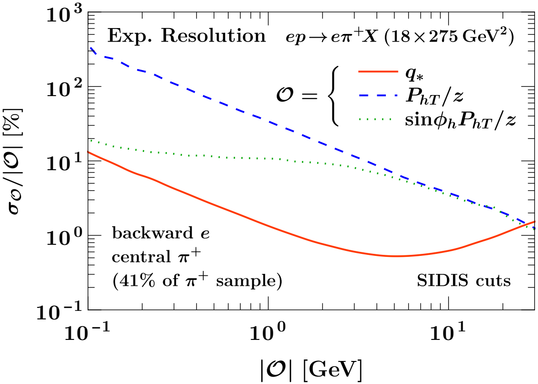
$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}q_*} = \frac{2z^3}{\pi}\sigma_0 \int_0^\infty \mathrm{d}b_T \Big\{ &\cos(q_* b_T)\Big(\mathcal{I}\big[\mathcal{H}\,\tilde{f}_1\,\tilde{D}_1\big] \\ &- \epsilon\,\mathcal{I}\big[\mathcal{H}\,\tilde{h}_1^{\perp(1)}\tilde{H}_1^{\perp(1)}\big] + \lambda_e S_L\sqrt{1-\epsilon^2}\,\mathcal{I}\big[\mathcal{H}\,\tilde{g}_{1L}\,\tilde{D}_1\big]\Big) \\ &+ \cos\phi_S\sin(q_* b_T)\,S_T\Big(\mathcal{I}\big[\mathcal{H}\,\tilde{f}_{1T}^{\perp(1)}\,\tilde{D}_1\big] + \epsilon\,\mathcal{I}\big[\mathcal{H}\,\tilde{h}_1\,\tilde{H}_1^{\perp(1)}\big] \\ &+ \frac{\epsilon}{4}\,\mathcal{I}\big[\mathcal{H}\,\tilde{h}_{1T}^{\perp(2)}\,\tilde{H}_1^{\perp(1)}\big]\Big) \\ &- \sin\phi_S\sin(q_* b_T)\,\lambda_e S_T\sqrt{1-\epsilon^2}\,\mathcal{I}\big[\mathcal{H}\,\tilde{g}_{1T}^{\perp(1)}\,\tilde{D}_1\big]\Big\}\end{aligned}$$

- Factorizes in terms of *standard* TMD PDFs and FFs
- Can disentangle (almost) all contributions by forming asymmetries, e.g.

double asymmetry$(\pm q_*, \pm\lambda_e)$ $\propto$ Worm-gear T function $\tilde{g}_{1T}^{(1)}$

[cf. Horstmann, Schäfer, Vladimirov, 2210.07268, for current challenges in extracting $\tilde{g}_{1T}^{(1)}$]

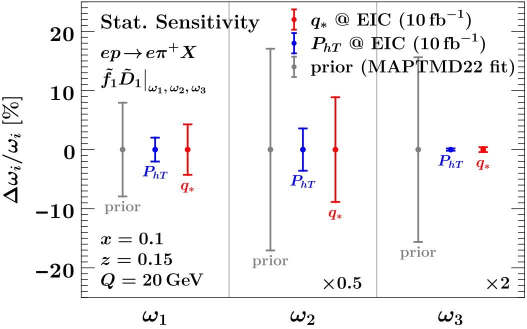
Expected detector resolution



- Consider 18×275 EIC, $h = \pi^+$, $|\eta_h| < 1$, $-3.5\eta_e < -1$,
  $x > 0.001\,,\ 0.01 < y < 0.95\,,\ z > 0.05\,,\ Q^2 > 16\,\mathrm{GeV}^2\,,\ W^2 > 100\,\mathrm{GeV}^2$
- Apply Gaussian smearing according to Handbook Detector (tracker only):
  $\sigma_p/p = 0.05\%\,p \oplus 0.5\%$ $(0.05\%\,p \oplus 1\%$, $0.1\%\,p \oplus 2\%)$
  for $|\eta| < 1$ $(1 < |\eta| < 2.5$, $2.5 < |\eta| < 3.5)$
- Assume angular resolution $\sigma_{\theta,\phi} = 0.001$

$\Rightarrow$ q_* expected to outperform $q_T = P_{hT}/z$ by a factor of 10 in resolution

Statistical Sensitivity



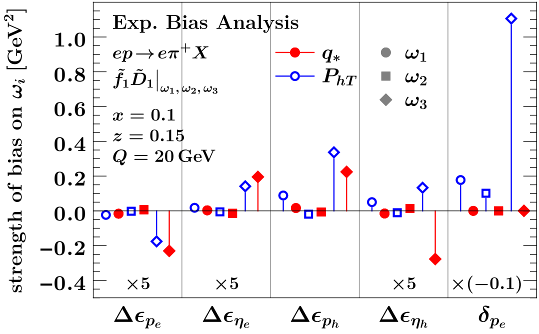
- Generate normalized pseudodata from a simple TMD PDF/FF model at fixed x, z:

$$\tilde{f}_1^{\mathrm{NP}}(b_T) = e^{-\omega_1 b_T^2} \qquad \tilde{D}_1^{\mathrm{NP}}(b_T) = \alpha\, e^{-\omega_2 b_T^2} + (1-\alpha)(1-\omega_3 b_T^2)\, e^{-\omega_3 b_T^2}$$

- Bayesian reweighting assuming $10\,\mathrm{fb}^{-1}$, $N_{\pi^+} = 4.18 \times 10^8$ across 1000 bins
- Populate Gaussian priors for free parameters ω_i from MAPTMD22 fit [Bacchetta et al., 2206.07598]

$\Rightarrow$ Statistical sensitivity of q_* to underlying TMD physics is similar to P_{hT}

Robustness against systematic bias



Can also inject a broad ansatz for systematic bias into Bayesian reweighting:

1. Nonuniform detector response $\epsilon(X)$ with $X = \{p_e, p_h, \eta_e, \eta_h\}$, e.g. efficiency:

$$\epsilon(X) = 1 + \Delta\epsilon_X \big(X - \langle X \rangle\big)/\Delta X$$

$\Rightarrow$ Similar impact on extracted model parameters using either q_* or P_{hT}

2. Electron momentum scale/calibration uncertainty: $p_e \to (1 + \delta_{p_e})\, p_e$

$\Rightarrow$ q_* perfectly robust, large bias when using P_{hT}

Summary of observable construction & properties

Proposed a new SIDIS TMD observable $q_* = 2P^0_{\mathrm{EIC}} \dfrac{e^{\eta_h}}{1+e^{\Delta\eta}} \tan\phi^{\mathrm{EIC}}_{\mathrm{acop}}$:

- Defined purely in terms of electron and hadron angles in the lab frame.
  - Eliminates need to reconstruct q^μ for most fickle part of measurement.
  - Superior resolution expected compared to P_{hT}.
  - Independent of momentum calibration by construction.
- Comparable statistical sensitivity & robustness against non-uniform response.

Two kinds of reconstruction error (one of which is actually a theory error)

Issue: Kinematic reconstruction methods $(Q^2, x, y)^{\rm had}$ using the hadronic final state fundamentally measure a different observable and *will not* in general yield the actual truth value $(Q^2, x, y)_{\rm truth} \neq (Q^2, x, y)^{\rm had}_{\rm truth}$ even at truth level.

- Instead, will in general have (same for x, y):

$$
\begin{aligned}
Q^{\rm had}_{\rm det} &= Q_{\rm truth} + \left[Q^{\rm had}_{\rm truth} - Q_{\rm truth}\right] + \left[Q^{\rm had}_{\rm det} - Q^{\rm had}_{\rm truth}\right] \\
&\equiv Q_{\rm truth} + \Delta_{\rm obs} + \Delta_{\rm det}
\end{aligned}
$$

- Typically, $\Delta_{\rm obs} = \mathcal{O}(\alpha_s)$ or $\Delta_{\rm obs} = \mathcal{O}(\lambda) = \mathcal{O}(P_{hT}/Q)$ for TMD SIDIS.

$\Rightarrow$ Effect can be missed during design if generator uses tree-level hard scattering or does not include power corrections to TMD factorization/soft and collinear limits.

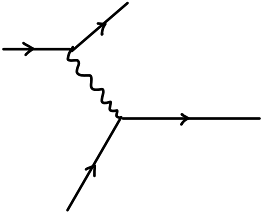
…and all of this is okay, but …

Key question

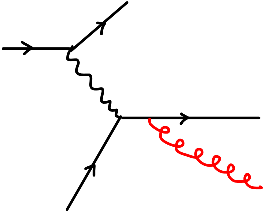
(from theory perspective, but also analysis sustainability, …)

How hard will it be to compute and correct for $\Delta_{\rm obs}$ during (re)interpretation?

- Unfold to a quantity only defined within the generator/at tree level
  e.g. “struck quark angle”
- Cannot be corrected to higher orders/powers without “inverting” the generator

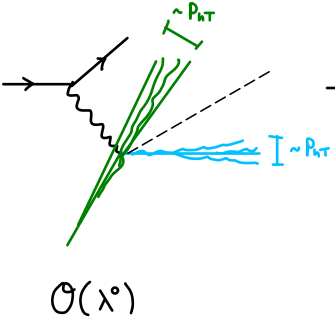


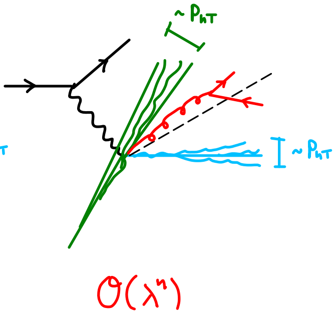
$\mathcal{O}(\alpha_s^0)$



$\mathcal{O}(\alpha_s)$

- Use total momentum/angle of all hadronic radiation inside fixed acceptance cuts
- Easy to reinterpret at strict leading power in $\lambda \sim P_{hT}/Q$ in the TMD limit
  - Hadronic final state and beam remnant are collimated, well separated
- Much harder to reinterpret for general P_{hT}, where the observable becomes sensitive to details of splitting/hadronization near boundary (IRC unsafe)





- Using IRC safe or simple hadron-level information about the hadronic final state yields a reconstruction that is interpretable for any P_{hT}.

  e.g. find axis by recursive jet algorithm (anti-k_T, Centauro, ...), by minimizing a DIS event shape, ...

- Also very promising: white-box (or white-boxeable ...) ML frameworks
  [See e.g. Pecar, Vossen, 2209.14489, using PFNs introduced in Komiske, Metodiev, Thaler, 1810.05165]

- Our personal favorite for SIDIS, used to cancel factors in q_*:
  Use the angle of the ID'ed hadron *itself*.

  - Ensures reinterpretability in terms of $\dfrac{\mathrm{d}\sigma_\mathrm{SIDIS}}{\mathrm{d}^3\vec{P}_h\,\mathrm{d}^3\vec{\ell}'}$
    $=$ TMD factorization at leading + first subleading power
    + matching to collinear factorization

- All of these are guaranteed to approach the true (Q, x, y) to all orders in α_s as $P_{hT}/Q \to 0$ by power counting
  (as long as beam remnant is vetoed efficiently)

- But in all cases, should disentangle Δ_obs and Δ_det!

Summary

Proposed a new SIDIS TMD observable $q_* = 2P^0_{\rm EIC}\frac{e^{\eta_h}}{1+e^{\Delta\eta}}\tan\phi^{\rm EIC}_{\rm acop}$:

- Defined purely in terms of electron and hadron angles in the lab frame.
  - Eliminates need to reconstruct q^μ for most fickle part of measurement.
  - Superior resolution expected compared to P_{hT}.
  - Independent of momentum calibration by construction.
- Comparable statistical sensitivity & robustness against non-uniform response.

Discussed SIDIS hadronic q^μ reconstruction with an eye towards (re)interpretability:

- Hadronic methods for reconstructing q^μ are a great tool, and remain needed for other three directions of 4D measurements also when using q_*.
- Great opportunities for productive experiment/theory dialogue to ensure reinterpretability at the precision level.

Summary

Proposed a new SIDIS TMD observable $q_* = 2P^0_{\mathrm{EIC}} \dfrac{e^{\eta_h}}{1+e^{\Delta\eta}} \tan\phi^{\mathrm{EIC}}_{\mathrm{acop}}$:

- Defined purely in terms of electron and hadron angles in the lab frame.
  - Eliminates need to reconstruct q^μ for most fickle part of measurement.
  - Superior resolution expected compared to P_{hT}.
  - Independent of momentum calibration by construction.
- Comparable statistical sensitivity & robustness against non-uniform response.

Discussed SIDIS hadronic q^μ reconstruction with an eye towards (re)interpretability:

- Hadronic methods for reconstructing q^μ are a great tool, and remain needed for other three directions of 4D measurements also when using q_*.
- Great opportunities for productive experiment/theory dialogue to ensure reinterpretability at the precision level.

Thank you for your attention!