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

CFNS TMD Workshop
June 21, 2023

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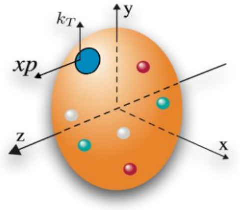
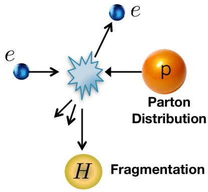
Goal

Construct an angular EIC observable that optimally resolves how spin and transverse momentum are distributed within the nucleon, and transferred during hadronization.



SIDIS and transverse momentum reconstruction



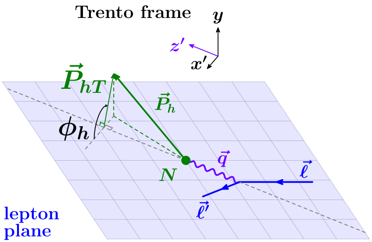
Semi-inclusive Deep-Inelastic Scattering:

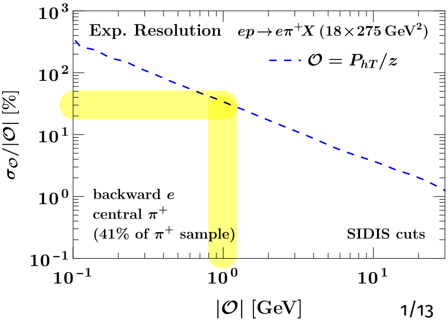
- Workhorse process at the EIC to unveil structure of the nucleon
- Cross section for $\vec{P}_{hT} \sim \Lambda_{\text{QCD}} \ll Q$ factorizes into

  Transverse-**M**omentum **D**ependent { **P**arton **D**istribution **F**unctions / **F**ragmentation **F**unctions }

- Experimental challenge: Reconstructing small $\vec{P}_{hT}$ from large $\vec{\ell}' \sim Q$

  e.g. Typical exp. resolution $|\vec{\ell}'| = (20 \pm 0.5)\,\text{GeV} \Rightarrow |\vec{P}_{hT}| = (1 \pm 0.5)\,\text{GeV}$





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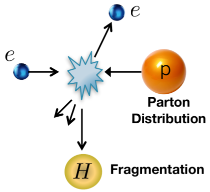

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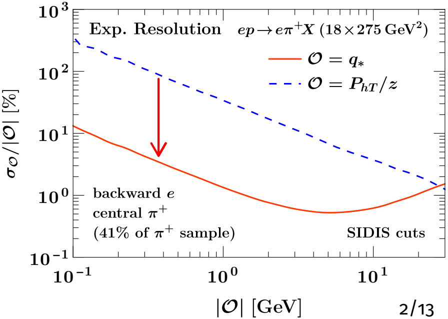
New observable to deliver *order of magnitude* improvement in resolution.

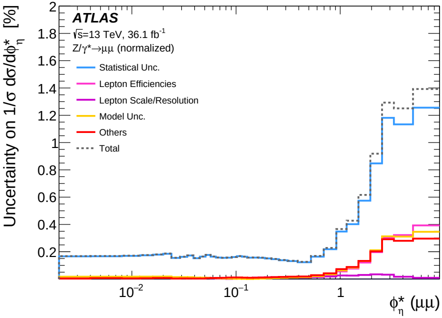


Idea

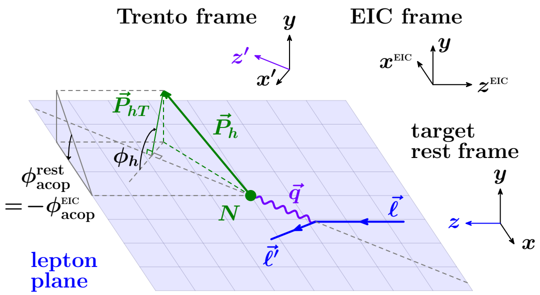
Charged-particle track angles are much easier to measure than momenta.

- Construct a TMD observable 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]



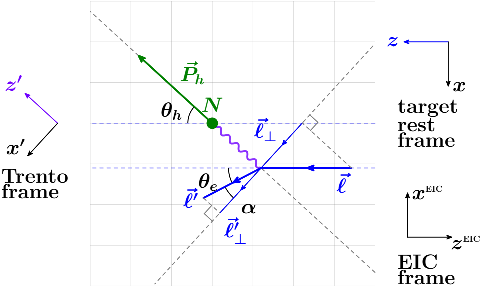
[ATLAS, EPJC 80 (2020) 7, 616, 1912.02844]



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

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

$$q^\mu = \ell^\mu - \ell'^\mu \qquad z = P \cdot P_h / P \cdot q$$
$$Q^2 = -q^2 \qquad y = P \cdot q / P \cdot \ell$$

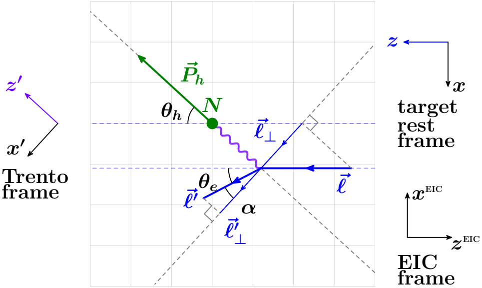


$$\tan \phi_{\text{acop}}^{\text{rest}} = \frac{\sin \phi_h \, P_{hT}}{zQ\sqrt{1-y}} + \mathcal{O}(\lambda^2) \Rightarrow$$ get rid of prefactors?

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

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

  - Same form as HERA "double-angle formula" using a tree-level "struck quark"
    [S. Bentvelsen, J. Engelen, and P. Kooijman, in Workshop on Physics at HERA (1992).]
  - By contrast, this is valid to all orders in α_s and controlled by TMD limit

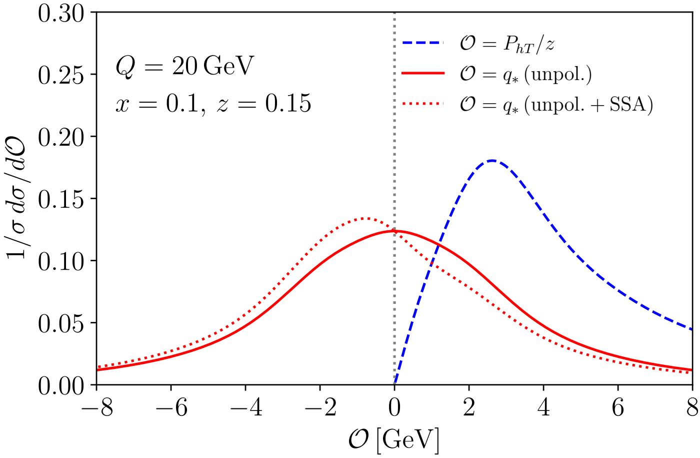


- Convert to EIC lab-frame pseudorapidites and take $M \ll Q$ (for brevity):

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

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

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



- Key property: $\boldsymbol{q_* \propto \tan\phi^{\mathrm{EIC}}_{\mathrm{acop}} \propto -\sin\phi_h}$ is a signed observable
- Spectrum is even and peaked at $\boldsymbol{q_* = 0}$ for unpolarized nucleons
- Single-Spin Asymmetries (SSAs) induce odd contributions!
  [See Liu, Ringer, Vogelsang, Yuan '18 for odd (Sivers) effect in DIS jet production]

- Start from simple leading-power form of $q_* = -\sin\phi_h \dfrac{P_{hT}}{z}$
- Insert into standard leading-power SIDIS TMD factorization for $\vec{P}_{hT}$

e.g. $$W_{UU}^{\cos(2\phi_h)}(x,z,P_{hT}) \propto \int_0^\infty \frac{\mathrm{d}b_T\, b_T}{2\pi}\, \mathcal{H}\, \tilde{h}_1^{\perp(1)}(x,b_T)\, \tilde{H}_1^{\perp(1)}(z,b_T)\, J_2\!\left(b_T \frac{P_{hT}}{z}\right)$$

[Bessel integral: Boer, Gamberg, Musch, Prokudin, '11]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}q_*} \supset \int_0^\infty \mathrm{d}P_{hT}\, P_{hT} \int_0^{2\pi} \mathrm{d}\phi_h\, \delta\!\left(q_* + \sin\phi_h \frac{P_{hT}}{z}\right) \cos(2\phi_h)\, W_{UU}^{\cos(2\phi_h)}$$

$$= -\frac{2z^3}{\pi} \int \mathrm{d}b_T\, \mathcal{H}\, \tilde{h}_1^{\perp(1)}\, \tilde{H}_1^{\perp(1)}$$

$$\times \int_0^{2\pi} \frac{\mathrm{d}\phi_H}{\sin^2\phi_h}\, \Theta\!\left(-\frac{q_*}{\sin\phi_h}\right) \cos(2\phi_h)\, \frac{b_T |q_*|}{2}\, J_2\!\left(\frac{b_T q_*}{\sin\phi_h}\right)$$

$$= -\frac{2z^3}{\pi} \int \mathrm{d}b_T\, \mathcal{H}\, \tilde{h}_1^{\perp(1)}\, \tilde{H}_1^{\perp(1)}\, \cos(q_* b_T)$$

- Start from simple leading-power form of $q_* = -\sin\phi_h \, \frac{P_{hT}}{z}$
- Insert into standard leading-power SIDIS TMD factorization for $\vec{P}_{hT}$

▸ Spectrum factorizes in terms of *standard* TMD PDFs and FFs:

$$\frac{d\sigma}{dx\,dy\,dz\,dq_*} = \mathcal{H}\int_0^\infty db_T \Big\{ \cos(q_* b_T)\Big(\tilde{f}_1\,\tilde{D}_1 - \epsilon\,\tilde{h}_1^{\perp(1)}\tilde{H}_1^{\perp(1)} + \lambda_e\,S_L\sqrt{1-\epsilon^2}\,\tilde{g}_{1L}\,\tilde{D}_1\Big)$$

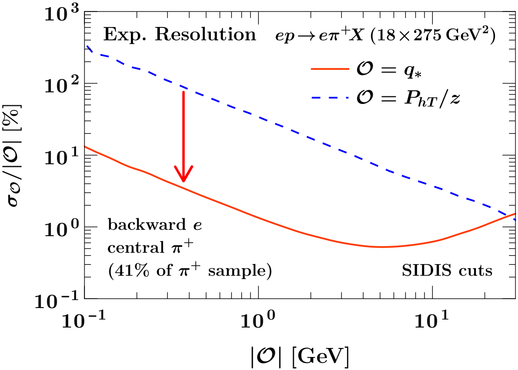
$$+ \cos\phi_S\,\sin(q_* b_T)\,S_T\Big(\tilde{f}_{1T}^{\perp(1)}\,\tilde{D}_1 + \epsilon\,\tilde{h}_1\,\tilde{H}_1^{\perp(1)} + \frac{\epsilon}{4}\,\tilde{h}_{1T}^{\perp(2)}\,\tilde{H}_1^{\perp(1)}\Big)$$

$$- \sin\phi_S\,\sin(q_* b_T)\,\lambda_e\,S_T\sqrt{1-\epsilon^2}\,\tilde{g}_{1T}^{\perp(1)}\,\tilde{D}_1\Big\} \qquad \epsilon = \frac{1-y}{1-y+y^2}$$

- Can disentangle (almost all) contributions by forming asymmetries, e.g.:

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

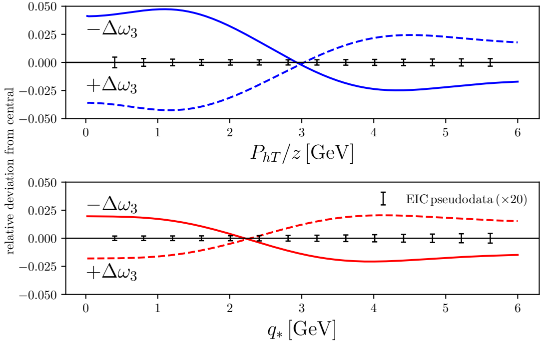
Experimental properties: Expected detector resolution



- Simulate SIDIS events in `Pythia` with Gaussian smearing as detector response
- Use momentum resolution $\sigma_p/p = (0.05 - 1)\%\, p \oplus (0.5 - 2)\%$
  [EIC Yellow Report Design Requirements, 2103.05419]
- Assume fixed angular resolution $\sigma_{\theta,\phi} = 0.001$

As promised ...

- q_* is expected to outperform P_{hT}/z by a factor of 10 in resolution.



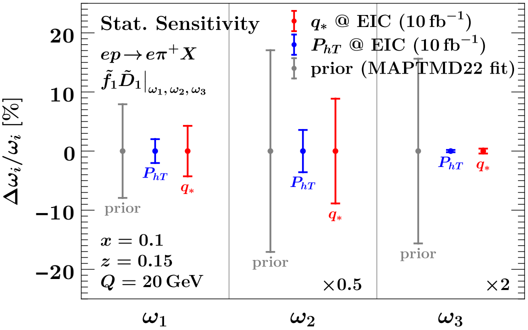
- Generate normalized pseudodata from a simple TMD PDF/FF model at fixed x, z:

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

- Populate Gaussian priors for free parameters ω_i from MAPTMD22 global fit
  [Bacchetta et al., 2206.07598; see Chiara's talk this morning!]

- Bayesian reweighting to pseudodata assuming $10\,\mathrm{fb}^{-1}$, $N_{\pi^+} = 4.18 \times 10^8$

⇒ Statistical sensitivity of q_* to underlying TMD physics compares well to P_{hT}



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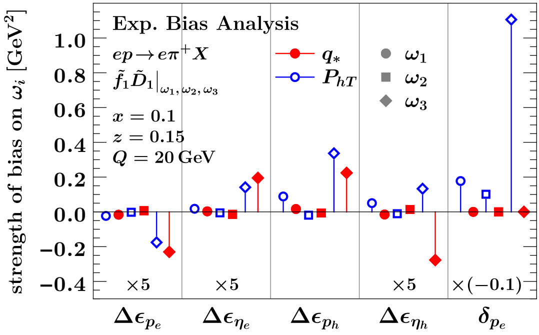


Can also inject ansatz for systematic detector bias into Bayesian reweighting:

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

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

⇒ Similar impact on extracted model parameters using either q_* or P_{hT}

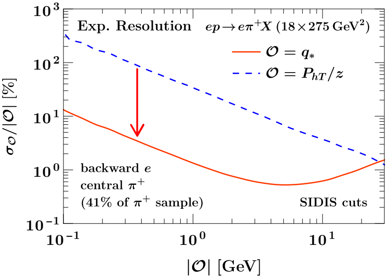
2. Electron momentum scale/calibration uncertainty: $p_e \to (1 + \delta_{p_e})\, p_e$

⇒ q_* perfectly robust, large bias when using P_{hT}

Proposed a new SIDIS TMD observable q_* for the EIC:

- Defined purely in terms of electron and hadron angles in the lab frame:

$$q_* \equiv 2E_N \frac{e^{\eta_h}}{1 + e^{\Delta\eta}} \tan \phi_{\mathrm{acop}}^{\mathrm{EIC}}$$



- Factorizes in terms of standard TMD PDFs and FFs, retaining sensitivity to spin.
- Superior resolution expected compared to P_{hT}.
- Independent of momentum calibration by construction.

▶ Bright prospects for mapping the 3D structure of hadronization and confinement!

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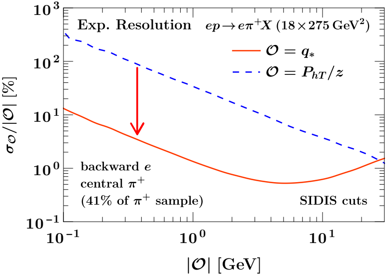

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Thank you for your attention!

Backup

Distinguish three sources of $\mathcal{O}(\lambda)$ corrections in $\lambda \sim q_*/Q$:

1. Power corrections to the observable itself
   - Straightforward to compute & retain (see also supplemental material):

$$q_* = -\sin\phi_h \frac{P_{hT}}{z}\left[1 - \frac{\cos\phi_h}{2}\sqrt{\frac{1}{1-y}}\,\frac{P_{hT}}{zQ} + \mathcal{O}(\lambda^2)\right]$$

2. Power corrections from region $|\phi_h| \leq \mathcal{O}(\lambda)$ at $P_{hT} \sim Q$
   - Include through standard Y term computed in collinear factorization
3. Power corrections from $\mathcal{O}(\lambda)$ hadronic structure functions
   - Cahn effect $W_{\cos\phi}$ drops out due to symmetries of q_*
   - Others, in particular spin-dependent ones,
     are genuinely interesting in their own right!
     [See also talk by Anjie!]