# Jets at the EIC

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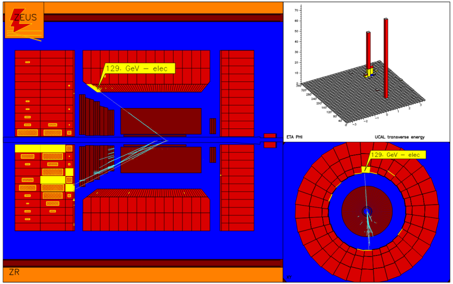
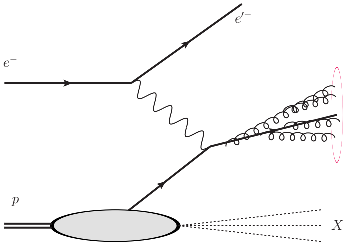
# Outline of this presentation

- Jet definitions in DIS.
- Physics opportunities with jets at the EIC (selected topics).

# Jets in DIS




- Jets result from successive collinear/soft emissions from a virtual parton. $\mathcal{O}(10)$ particles/jet with $p_t > 250$ MeV in average for $10 - 40$ GeV jets. Page, Chu, Aschenauer, 1911.00657
- Clean environment in DIS. Ex: precise $\alpha_s$ extraction at HERA.
- In practice, one needs an IRC safe jet definition, to be used both in experimental measurements and in theory calculations.

# Jet sequential recombination algorithms

- Popular jet definitions nowadays use sequential recombination algorithms.
  (Unlike cone-based jet definitions)
- Example with jets in $e^+e^-$: JADE, $k_t$ algorithms,...
  JADE, Z.Phys.C 33 (1986), Catani, Dokshitzer, Olsson, Turnock, Webber, PLB 269, 432 (1991)
- Distance measure $d_{ij}$ between particles $i$, $j$.
  Ex: $d_{ij} = M_{ij}^2/Q^2$ for JADE def.
- Sequential clustering of particles.
  - $\rightarrow$ For each pair of particles $(i, j)$, work out the distance $d_{ik}$.
  - $\rightarrow$ Find the minimum of all $d_{ij}$.
  - $\rightarrow$ If the min is $< d_{\mathrm{cut}}$, recombine $i$ and $j$ and repeat from step 1.
    Otherwise, terminate the iteration.

# Jet algorithms in hadronic collisions

- Problem: initial state soft/collinear radiations. Need to distinguish between the beam remnant and high $p_t$ jets.
- Idea: introduce particle-beam distance, $d_{iB}$, in addition to $d_{ij}$.

  Catani, Dokshitzer, Webber, PLB 285, 291 (1992)

- Sequential recombination algorithms widely used at the LHC: "generalized-$k_t$" algorithms.

$$d_{ij} = \min(p_{t,i}^{2k}, p_{t,j}^{2k}) \frac{\Delta R_{ij}^2}{R^2} , \quad d_{iB} = p_{t,i}^{2k}$$

  Catani, Dokshitzer, M.H. Seymour, Webber, NPB, 406 (1993), Cacciari, Salam, Soyez, JHEP 0804:063,2008

- The distance measure is longitudinally invariant $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta \phi_{ij}^2$.
- Same algorithm, but it stops when $d_{iB}$ is the minimum among all $d_{ij}, d_{iB}$.

# What about DIS?

- Jet definitions designed to ensure factorisation of inclusive jet cross sections in terms of universal pdf.
- Lorentz-invariant definition by Webber, J. Phys. G 19, 1567 (1993) similar to JADE.

$$d_{ij} = \frac{M_{ij}^2}{Q^2 R^2}\,, \qquad d_{iB} = 2x_{\mathrm{Bj}}\frac{k_i \cdot P}{Q^2}$$

- $e^+e^-$ spherically invariant jet definitions in the Breit frame.

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

- Many jet analysis at HERA chose longitudinally invariant $k_t$ algorithm in the Breit frame. Ex: $\alpha_s$ determination from jet cross-sections with ZEUS, PLB 547 (2002), H1 PLB 653, 134 (2007), ...

# Issues with previous options

- JADE-like algorithms have undesirable features.
  Soft particles get recombined in the early stage, even if widely separated in angles.

- Spherically invariant jet definitions in the Breit frame are not boost invariant.
  $\Rightarrow$ Hard to distinguish beam remnant from forward jets.

- Longitudinally invariant jet definitions in Breit frame fail to cluster hadrons in the backward region.

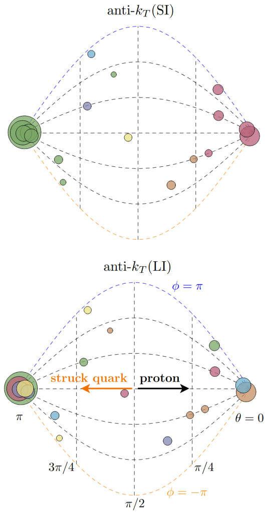



Fig. from Arratia, Makris, Neill, Ringer, Sato, 2006.10751

# Recent developments: asymmetric jet clustering

- Centauro algorithm Arratia, Makris, Neill, Ringer, Sato, 2006.10751.

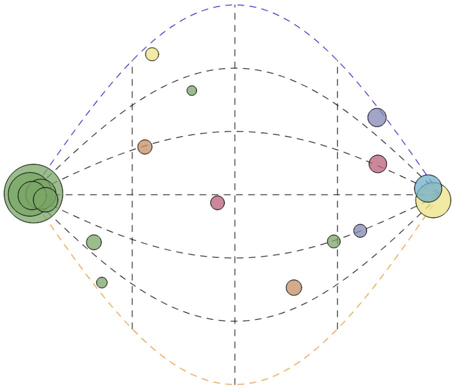
$$d_{ij} = (\Delta\bar{\eta}_{ij}^2 + 2\bar{\eta}_i\bar{\eta}_j(1 - \cos(\Delta\phi_{ij})))/R^2, \quad d_{iB} = 1$$

with $\bar{\eta}_i = -\frac{2Q}{\bar{n}\cdot q}\frac{p_{\perp,i}}{n\cdot p_i}$.

- Recent proposal from PC, Iancu, Mueller, Yuan 2408.03129,

$$d_{ij} = \frac{M_{ij}^2}{z_i z_j Q^2 R^2}, \quad d_{iB} = 1, \quad z_i = \frac{p_i \cdot P}{P \cdot q}$$

- Boost invariant and properly cluster the forward region.
- Most importantly, they ensure TMD factorisation for SIDIS with jets in the limit $P_\perp \ll Q$. 2408.03129



# Single inclusive jet production in DIS

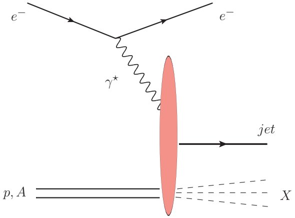
⇒ Measure **jets** in DIS events and bin in terms of $P_\perp$ measured in Breit of dipole frame:

$$\frac{\mathrm{d}\sigma^{e+A\to \mathrm{e'}+\mathrm{jet}+X}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2\mathrm{d}P_\perp}$$

Related studies with TMD jet functions: Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi, PRL 121, 162001 (2018)

⇒ In the case of a hadron measurement, TMD factorisation theorem for $Q^2 \gg P_{\perp,h}^2$. Accesses the quark TMD, see Valerio's talk on Wednesday.

- What about jets, in particular for $x_{\mathrm{Bj}} \ll 1$ ? [PC, Iancu, Mueller, Yuan, 2408.03129]



# Jet definition and Sudakov logarithms

- NLO Sudakov logs $L = \ln(Q^2/\boldsymbol{P}_\perp^2)$ depend on the jet definition!

For LI generalised $k_t$ alg.,

$$\left.\frac{\mathrm{d}\sigma^{\gamma_\mathrm{T}^*+A\to j+X}}{\mathrm{d}^2\boldsymbol{P}_\perp}\right|_{\mathrm{NLO}} = \left.\frac{\mathrm{d}\sigma^{\gamma_\mathrm{T}^*+A\to j+X}}{\mathrm{d}^2\boldsymbol{P}_\perp}\right|_{\mathrm{LO}} \times \frac{\alpha_s C_F}{\pi}\left[-\frac{3}{4}L^2 + \left(\frac{3}{4} - \ln(R)\right)L + \mathcal{O}(1)\right]$$

while for SI generalised $k_t$ alg. $(\beta = 2)$ or asymmetric jet definition $(\beta = 0)$

$$\left.\frac{\mathrm{d}\sigma^{\gamma_\mathrm{T}^*+A\to j(B)+X}}{\mathrm{d}^2\boldsymbol{P}_\perp}\right|_{\mathrm{NLO}} = \left.\frac{\mathrm{d}\sigma^{\gamma_\mathrm{T}^*+A\to j+X}}{\mathrm{d}^2\boldsymbol{P}_\perp}\right|_{\mathrm{LO}} \times \frac{\alpha_s C_F}{\pi}\left[-\frac{1}{4}L^2 + \left(\frac{3(1-\beta/2)}{4} + \ln(R)\right)L + \mathcal{O}(1)\right]$$

- From CSS evolution of the quark TMD alone, we expect the log structure

$$\frac{\alpha_s C_F}{\pi}\left[-\frac{1}{4}L^2 + \frac{3}{4}L\right]$$

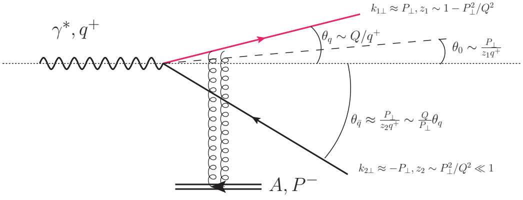
$\Rightarrow$ TMD factorisation implies $\beta = 0$.
New LI jet definition in DIS suitable for TMD factorisation with jets.

# Physical interpretation in the dipole frame

- Angle of the jet set by its virtuality rather by its transverse momentum. (Naively, $\theta_{\text{jet}} \sim \frac{P_\perp}{zq^+}$.)

- Soft gluons contributing to Sudakov must have $\theta_g \gg \theta_{\text{jet}}$.
  $\Rightarrow$ stronger constraint than $\theta_g \gg \frac{P_\perp}{zq^+}$!

- Jet from the antiquark is forward in the Breit frame. Must be distinguished from the beam remnant.




$\Uparrow$

*Aligned jet configuration in dipole frame.*

# Lepton-jet correlation: probe of quark TMD

[Liu, Ringer, Vogelsang, Yuan, PRL 122 (2019)]

- Back to the lab frame. Measure the imbalance between outgoing lepton and jet.
- Probes quark TMD. No need for fragmentation function (less model dependence).
- Sensitivity to cold nuclear matter transport coefficient.
- Sensitivity to **Sivers effect** for polarized nucleon.

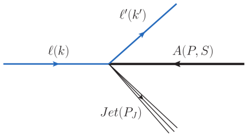
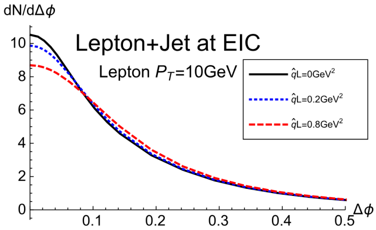
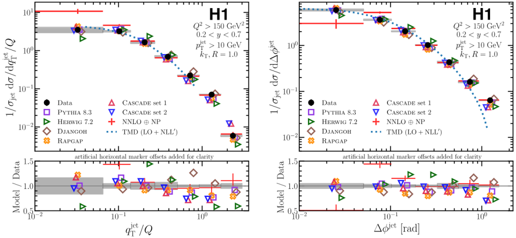



FIG. 1. The lepton-jet correlation in deep-inelastic scattering with a nucleon or nucleus at the EIC or HERA.

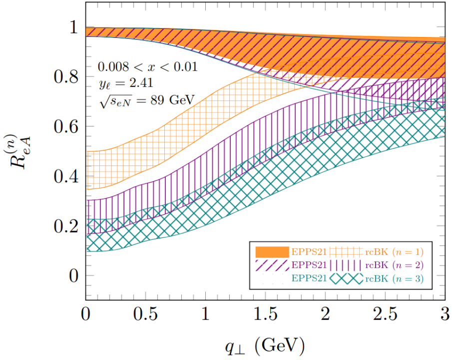



H1, PRL 128 (2022)

# Lepton-jet correlation for saturation physics

- In particular, at small $x$, sensitivity to sea quarks and saturation scale.
- New opportunities with large nuclei! Plot below for gold nucleus.
- Harmonic coefficient as a function of the lepton-jet transverse momentum imbalance.

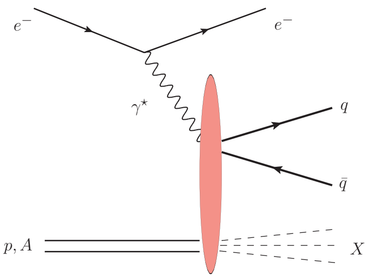


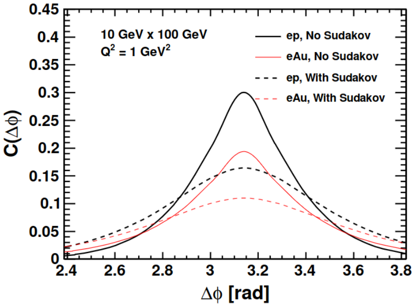

[Tong, Xiao, Zhang, PRL 130 (2023)]

# Back-to-back di-jets in DIS

⇒ probe of the saturated regime of QCD

⇒ access to the Weizsäcker-Williams gluon TMD in the back-to-back limit.

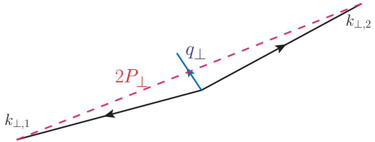



Zheng, Aschenauer, Lee, Xiao, 1403.2413

# LO: common language between small-$x$ and TMD communities

- Def: $|\boldsymbol{P}_\perp| = |z_2 \boldsymbol{k}_{\perp,1} - z_1 \boldsymbol{k}_{\perp,2}| \gg |\boldsymbol{q}_\perp| = |\boldsymbol{k}_{\perp,1} + \boldsymbol{k}_{\perp,2}|$




- LO in photon-gluon fusion channel: TMD factorization Dominguez, Marquet, Xiao, Yuan, 1101.0715

$$\left.\frac{\mathrm{d}\sigma^{\gamma^\star \to q\bar{q}+X}}{\mathrm{d}^2\boldsymbol{P}_\perp \mathrm{d}^2\boldsymbol{q}_\perp}\right|_{\mathrm{LO}} \propto \mathcal{H}^{ij}(\boldsymbol{P}_\perp) G^{ij}_Y(\boldsymbol{q}_\perp) + \mathcal{O}\left(\frac{q_\perp}{P_\perp}\right) + \mathcal{O}\left(\frac{Q_s}{P_\perp}\right)$$

See also del Castillo, Echevarria, Makris, Scimemi, 2008.07531

- $G_Y(\boldsymbol{q}_\perp)$ : WW gluon TMD

$$G^{ij}_{Y=\ln(1/x)}(\boldsymbol{q}_\perp) = 2\int \frac{\mathrm{d}\xi^- \mathrm{d}^2\boldsymbol{\xi}_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - iq_\perp \xi_\perp} \left\langle P \left| F^{+i}(\xi^-, \boldsymbol{\xi}_\perp) U^{[+]\dagger}_\xi F^{+j}(0) U^{[+]}_\xi \right| P \right\rangle \quad \text{TMD}$$

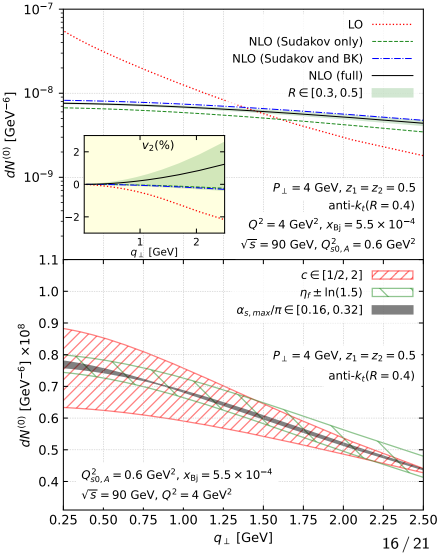
$$= \frac{-2}{\alpha_s}\int \frac{\mathrm{d}^2\boldsymbol{b}_\perp \mathrm{d}^2\boldsymbol{b}'_\perp}{(2\pi)^4} e^{-iq_\perp\cdot r_{bb'}} \left\langle \mathrm{Tr}\left[\partial^i V^\dagger(\boldsymbol{b}_\perp) V(\boldsymbol{b}'_\perp) \partial^j V^\dagger(\boldsymbol{b}'_\perp) V(\boldsymbol{b}_\perp)\right]\right\rangle_Y \quad \text{CGC}$$

# NLO results at small $x$

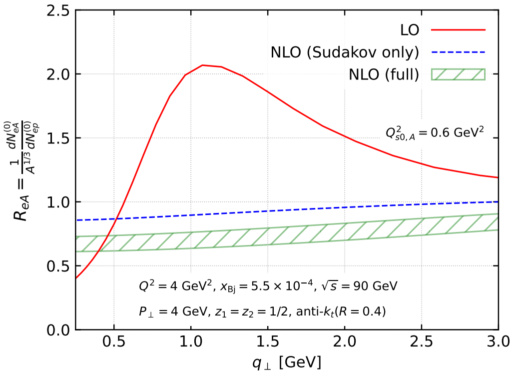
[PC, Salazar, Schenke, Stebel, Venugopalan, PRL 132 (8), 081902]

$$\langle \mathrm{d}\sigma^{\lambda}_{\mathrm{NLO}} \rangle_{x_f} = \mathcal{H}^{\lambda,ii}_{\mathrm{LO}} \int \frac{\mathrm{d}^2 \boldsymbol{r}_{bb'}}{(2\pi)^4} e^{-i\boldsymbol{q}_\perp \cdot \boldsymbol{r}_{bb'}} \hat{G}^0(x_f, \boldsymbol{r}_{bb'})$$
$$\times \left\{ 1 + \frac{\alpha_s(\mu_R)}{\pi} \left[ -\frac{N_c}{4} \ln^2\left(\frac{\boldsymbol{P}_\perp^2 \boldsymbol{r}_{bb'}^2}{c_0^2}\right) - s_L \ln\left(\frac{\boldsymbol{P}_\perp^2 \boldsymbol{r}_{bb'}^2}{c_0^2}\right) \right.\right.$$
$$\left.\left. + \beta_0 \ln\left(\frac{\mu_R^2 \boldsymbol{r}_{bb'}^2}{c_0^2}\right) + \mathcal{C}^\lambda(Q/M_{q\bar{q}}, z_1, R, x_f/x_g) \right] \right\}$$

- $x_f$ dependence of the gluon TMD obtained from high energy evolution with collinear improvement.
  See also Taels, Altinoluk, Beuf, Marquet, JHEP 10 (2022) 184
- First line is exponentiated à la CSS to resum large double and single Sudakov logs.
- $s_L = -C_F \ln(z_1 z_2) + N_c \ln(1 + Q^2/M_{q\bar{q}}^2) - C_F \ln(R^2)$
  $\Rightarrow$ agreement with [Hatta, Xiao, Yuan, Zhou, PRD 104 (2021) 5]



# Nuclear modification factor probes non-linear evolution effects




- In $R_{eA}$ ratio, "vacuum" physics largely cancels.
- High energy resummation gives a strong suppression.
- These results depends on the initial condition: need to fit the WW TMD at small $x$.

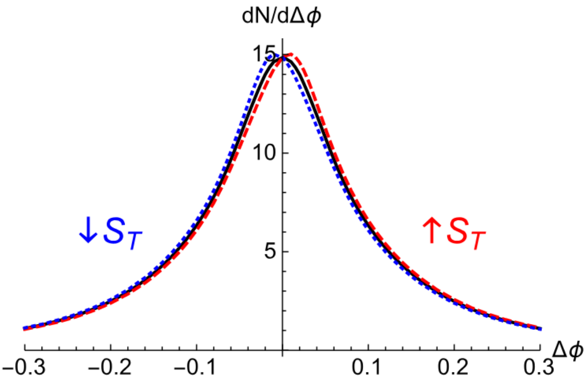
# Conclusion

- Importance of the choice of jet definitions in DIS, depending on the goal of the measurement (ex: $\alpha_s$, pdf or TMD extraction).
- In the case of TMD measurement with jet final states, additional studies should be performed to design optimal jet reconstruction algorithms.
- Selected jet observables that will benefit from the EIC capabilities: lepton-jet and dijet correlations.
- Many things that I have not covered, in particular recent progresses in the Monte-Carlo simulation of jets in DIS,
  van Beekveld, Ferrario Ravasio, JHEP 02 (2024) 001, PanScales NLL accurate parton showers, etc
- or jets in diffractive processes probing diffractive TMDs,
  Iancu, Mueller, Triantafyllopoulos, PRL 128 (2022), Hatta, Xiao, Yuan, PRD 106 (2022)
- ...

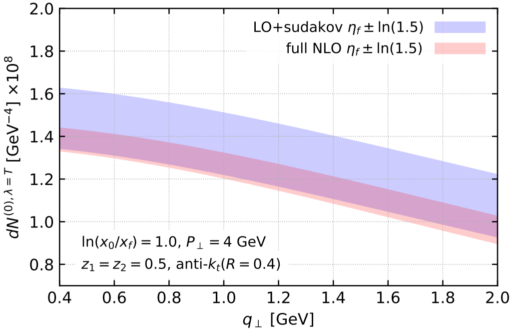
THANKS!

# Back-up slides

# Sivers effect in lepton-jet correlation



# Rapidity factorization scale dependence at EIC kinematics




- $x_f$ variation around a central value to gauge the sensitivity to missing N$^2$LO corrections.
- Scale variations shrink from LO to NLO.
- One expects thinner NLO bands when $\alpha_s \ln(x_0/x_f) = \mathcal{O}(1)$.