Energy–energy correlators for jet production in *pp* and *pA* collisions

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Based on 2411.11782

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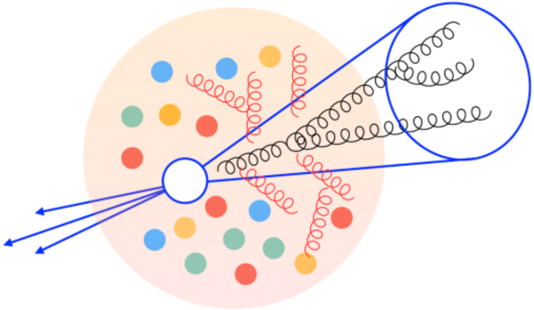
SURGE collaboration

2025 California EIC Consortium Collaboration Meeting

Jets as a tool to study high-energy collisions



Jets: Collimated sprays of hadrons

- Useful probes in studying precision QCD
- Get modified in the nuclear medium
  - Multiple scatterings
  - Quark–gluon plasma

Jets substructure:

- Information from the radiation pattern inside the jet
- Can be measured using e.g. **energy–energy correlators**
  - Recent measurements: CMS (2402.13864) ALICE (2409.12687)

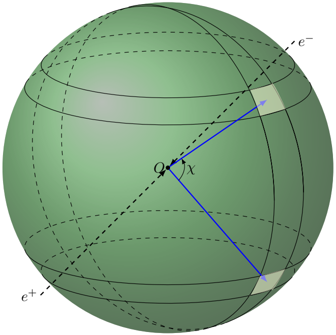
Energy–energy correlators (EEC)

- Two-point energy correlator
- Particles weighted by their energy

  $\Rightarrow$ Less sensitive to the nonperturbative IR region

  - One of the first infrared-safe event shapes in QCD

    Basham, Brown, Ellis, Love (Phys.Rev.Lett. 41 (1978) 1585, Phys.Lett.B 85 (1979) 297-299)



Moult, Zhu (1801.02627)

- $e^+ + e^- \to X$:

$$\frac{\mathrm{d}\Sigma_{e^+e^-}}{\mathrm{d}\cos\chi} = \sum_{i,j} \int \mathrm{d}\sigma \, \frac{E_i E_j}{Q^2} \delta(\cos\theta_{ij} - \cos\chi)$$

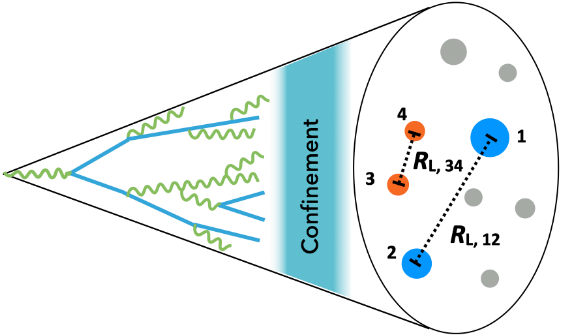
where $Q^2 = (\sum_i E_i)^2$

EEC inside jets

- Measure angular distance R_L between pairs of particles:

$$R_{L,ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2} \approx \Delta\theta_{ij} \cosh\eta$$

  - ϕ = tranverse angle
  - η = pseudorapidity
  - θ = 3D angle

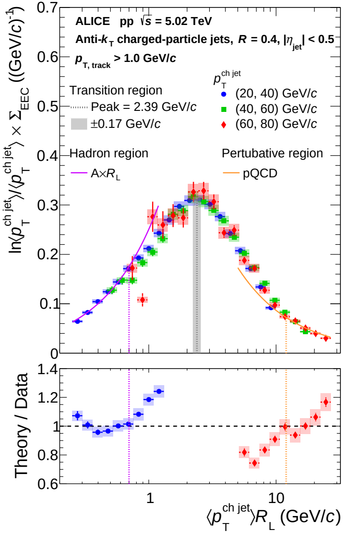


ALICE (2409.12687)

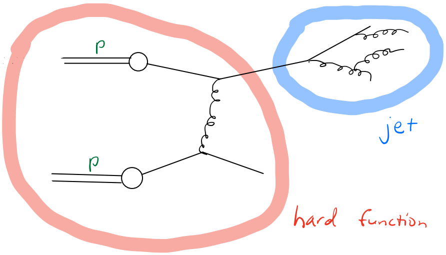
EEC inside jets

- Relative transverse momentum between the pair:
  $k_T \sim p_T R_L$
  - p_T = jet transverse momentum
- Different regions:
  - $k_T \gg \Lambda_{\mathrm{QCD}}$: perturbative
    - Probes jet formation
  - $k_T \sim \Lambda_{\mathrm{QCD}}$: nonperturbative
    - Effects from confinement and hadronization

ALICE (2409.12687)



Collinear factorization



Collinear limit: Factorization into hard and jet functions

$$\frac{\mathrm{d}\Sigma^{pp}}{\mathrm{d}p_T\,\mathrm{d}y\,\mathrm{d}R_L} = \int_0^1 \mathrm{d}x\, x^2 \frac{\mathrm{d}J(x, p_T, R_L)}{\mathrm{d}R_L} \cdot H(x, y, p_T)$$

where the hard function is defined as the normalized cross section

$$H = \left(\frac{1}{\sigma_q} \frac{\mathrm{d}\sigma_q}{\mathrm{d}p_T\ \mathrm{d}y}, \frac{1}{\sigma_g} \frac{\mathrm{d}\sigma_g}{\mathrm{d}p_T\ \mathrm{d}y} \right)$$

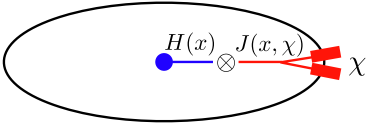
$$\frac{\mathrm{d}\sigma_c}{\mathrm{d}p_T\ \mathrm{d}y} = \sum_{a,b} f_{a/p}(x_a, \mu) \otimes f_{b/p}(x_b, \mu) \otimes \hat{\sigma}_{a+b\to c}$$

Independence of the renormalization scale μ

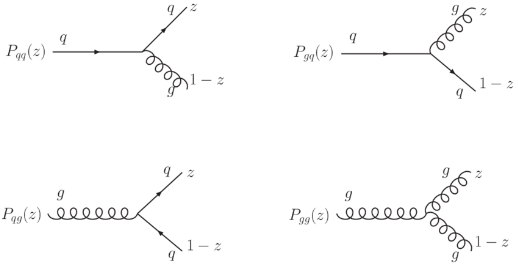
$\Rightarrow$ Evolution equation for the jet function

$$\frac{\mathrm{d}J(\mu)}{\mathrm{d}\log\mu^2} = -\frac{\alpha_s(\mu)}{4\pi} J(\mu)\cdot\gamma(3)$$

- $\gamma(n) = -\int_0^1 \mathrm{d}z\, z^{n-1}\hat{P}(z)$ is the anomalous dimension
- $\hat{P}$ = renormalized splitting function (matrix)



Dixon, Moult, Zhu (1905.01310)



Nonperturbative contribution

- Low momentum region:

  Sensitive to extra momentum kick from hadronization

- TMD ansatz: described by the nonperturbative Sudakov term

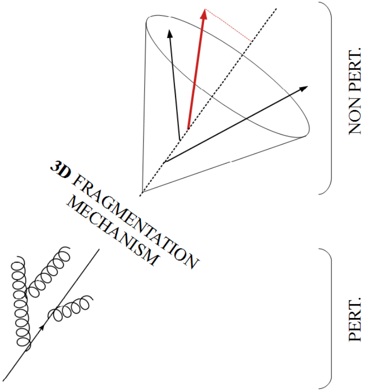
- Convenient to compute in the coordinate space ($R_L p_T \Leftrightarrow b$)

$$\frac{\mathrm{d}\Sigma^{pp}}{\mathrm{d}p_T\,\mathrm{d}y\,\mathrm{d}R_L} = R_L p_T^2 \int_0^\infty \mathrm{d}b\, b\, J_0(R_L p_T b)\, j_{\mathrm{np}}(b)\, \widetilde{\Sigma}(b)$$

$$j_{\mathrm{np}}(b) \equiv \exp(-a_0 b)$$

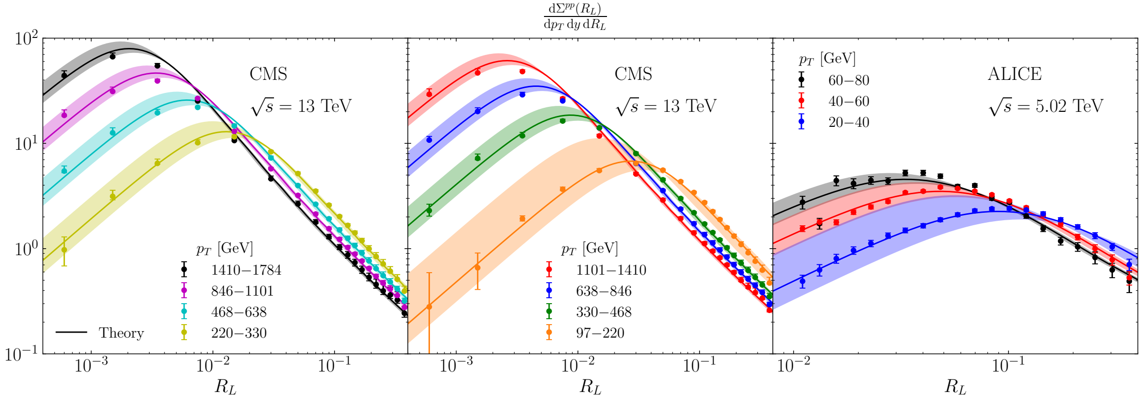
$$\widetilde{\Sigma}(b) = (1,1) \cdot \left(\frac{\alpha_s(Rp_T)}{\alpha_s(\mu_{b_*})}\right)^{\frac{\gamma(3)}{\beta_0}} \cdot H(p_T)$$

where $R = 0.4$ is the jet radius



Boglione and Simonelli (2007.13674)

pp results



- a_0 fitted to data: CMS: $a_0 = 3.8\,\text{GeV}$, ALICE: $a_0 = 2.5\,\text{GeV}$
  - Difference in measurements: CMS inclusive jets, ALICE charged jets
- Can describe both the perturbative and nonperturbative region across a vast range of p_T!

pA collisions: modifications from the nuclear medium

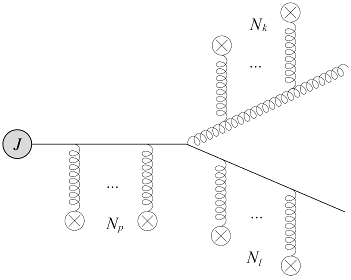
1. Nonperturbative part:

   Modification from multiple scatterings

$$j_{\mathrm{np}}(b) = \exp(-a_0 b) \Rightarrow j_{\mathrm{np}}(b) = \exp\left(-a_0 b - a_1 b^2\right)$$

2. Perturbative part: modification to the splitting function

$$\frac{\mathrm{d}J^{\mathrm{med}}}{\mathrm{d}R_L} = \frac{\alpha_s(R_L p_T)}{\pi R_L} \int_0^1 \mathrm{d}x\, x(1-x) P^{\mathrm{vac}}(x) F_{\mathrm{med}}(p_T, R_L, x)$$



Barata et al. (2304.03712)

- F_{med}: can be written in terms of Wilson lines
- Described by two parameters:
  1. Jet quenching parameter $\hat{q} \approx 0.02\,\mathrm{GeV}^2/\mathrm{fm}$ Ru et al. (1907.11808)
  2. Medium length $L \approx 3\,\mathrm{fm}$

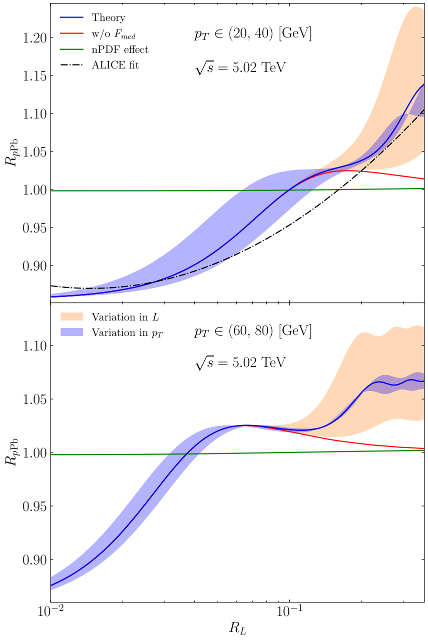
Study medium effects with the ratio:

$$R_{p\mathrm{Pb}} = \frac{\mathrm{d}\Sigma^{p\mathrm{Pb}}}{\mathrm{d}y\,\mathrm{d}p_T\,\mathrm{d}R_L} \Big/ \frac{\mathrm{d}\Sigma^{pp}}{\mathrm{d}y\,\mathrm{d}p_T\,\mathrm{d}R_L}$$

- Effect of nPDF vanishes in the ratio
- We fix $a_1 = 0.25\,\mathrm{GeV}^2$

  $\Rightarrow$ Matches data fit in the NP region
- Including also F_{med}:

  $\Rightarrow$ Describes the trend in the data for all R_L
- Both nonperturbative and perturbative medium corrections important!



Summary

- Energy–energy correlators are promising observables for studying precision QCD
  - Energy weight: reduces the sensitivity on nonperturbative fragmentation
- EEC inside jets: potential to study medium effects
- Nonperturbative physics in the collinear region:

  Need to take transverse momentum in hadronization into account
- pA collisions: medium effects for EEC important