EMMI Workshop: Probing the early stages with jets

Understanding the origin of collective phenomena in jets

Xiaoyu Liu
Rice University

Based on: PRL 133 (2024) 142301, CMS-PAS-HIN-24-024, and recent model studies (to be submitted soon)

U.S. DEPARTMENT OF ENERGY Office of Science

Elliptic Anisotropy from Quantum Diffraction

Erik Carrió

with Daniel Pablos arXiv:2603.12346, Phys.Rev.D 114 (2026) 1, 014015
and Xoán Mayo López WIP

EMMI Workshop: Probing the early stages with jets
13th. July 2026

Universidad de Oviedo

Flow Effects on Jet Substructure in Monte Carlo Approach

EMMI: Probing the Initial Stages with Jets

Jo Bahder (CCNU)
& Matthew Sievert (NMSU)

GSI – Darmstadt, Germany
13th July, 2026

Deriving a parton shower for jet thermalization in QCD plasmas

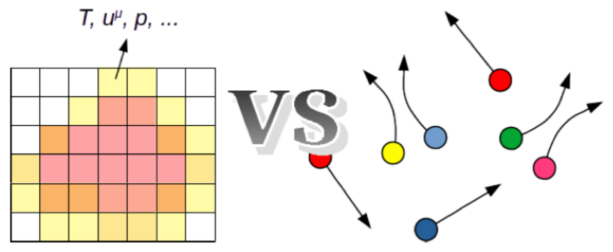
[I. Soudi, AT 2510.25837, 2607.xxxx]

Adam Takacs
CERN TH,
University of Bergen

EMMI Workshop: Probing the early stages with jet quenching (July 13-17), Darmstadt 2026

Non-equilibrium evolution of the soft sector in hadronic collisions from kinetic theory

Clemens Werthmann
Ghent University



GHENT UNIVERSITY
Funded by the European Union
erc European Research Council

Azimuthal momentum isotropization in the early stages

Sergio Barrera Cabodevila
in collaboration with
Xiaojian Du, Carlos A. Salgado and Bin Wu

based on

(July 2026). SBC, Du, Salgado, and Wu [arXiv:2607.07796]

Emmy Noether-Programm DFG

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

In-medium QCD splittings

Beyond the soft, large N_c and harmonic-oscillator approximations all at once

Marco Leitão
IPhT (Saclay) & LIP

In collaboration with: G. Milhano (LIP/IST) and A. Soto-Ontoso (U. Granada)

EMMI Workshop: Probing early stages with jets

GSI, Darmstadt
13th July 2026

Based on: arXiv:2606.26039

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MIT CENTER FOR THEORETICAL PHYSICS – A LEINWEBER INSTITUTE

FWF Österreichischer Wissenschaftsfonds

How the nonequilibrium initial stages influence medium-induced radiation

Mainly based on
Phys.Rev.D 113 (2026) 11, 114009 [Barata, Boguslavski, FL, Sadofyev]

Florian Lindenbauer (MIT Center for Theoretical Physics – a Leinweber Institute)

July 13, 2026, EMMI Workshop “Probing the early stages with jets”, GSI, Darmstadt

Jet substructure correlation to matter structure

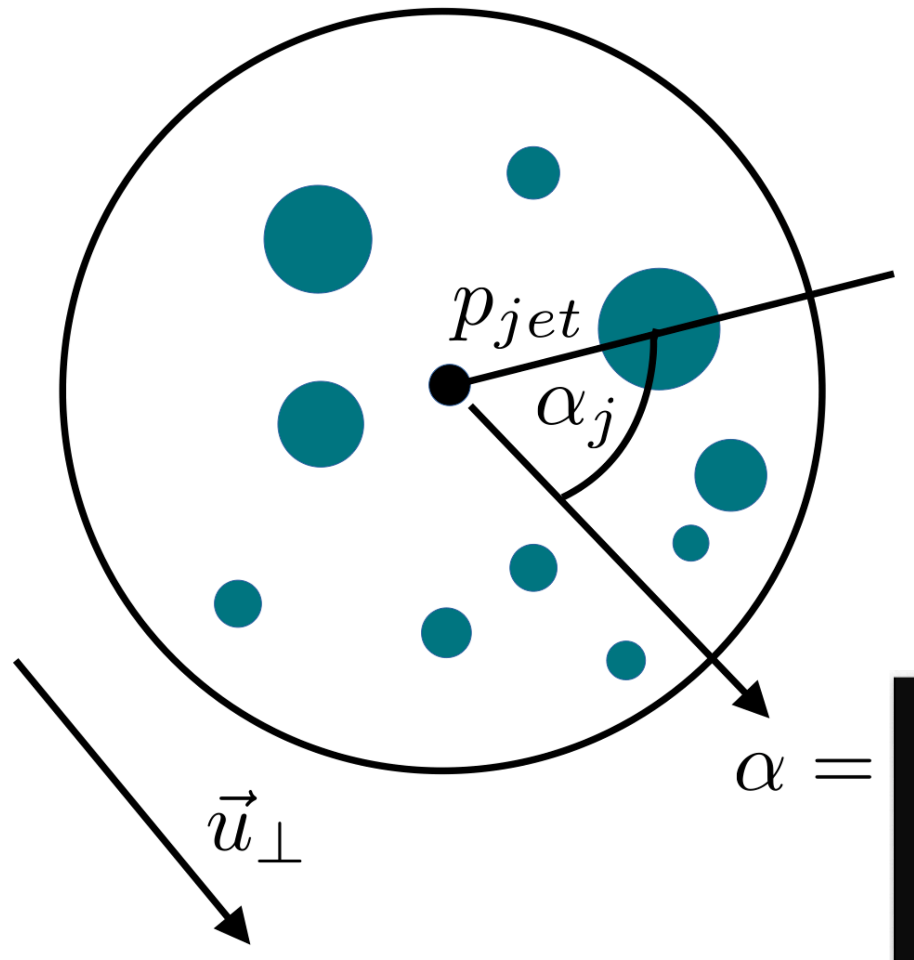
Jet Substructure Harmonics

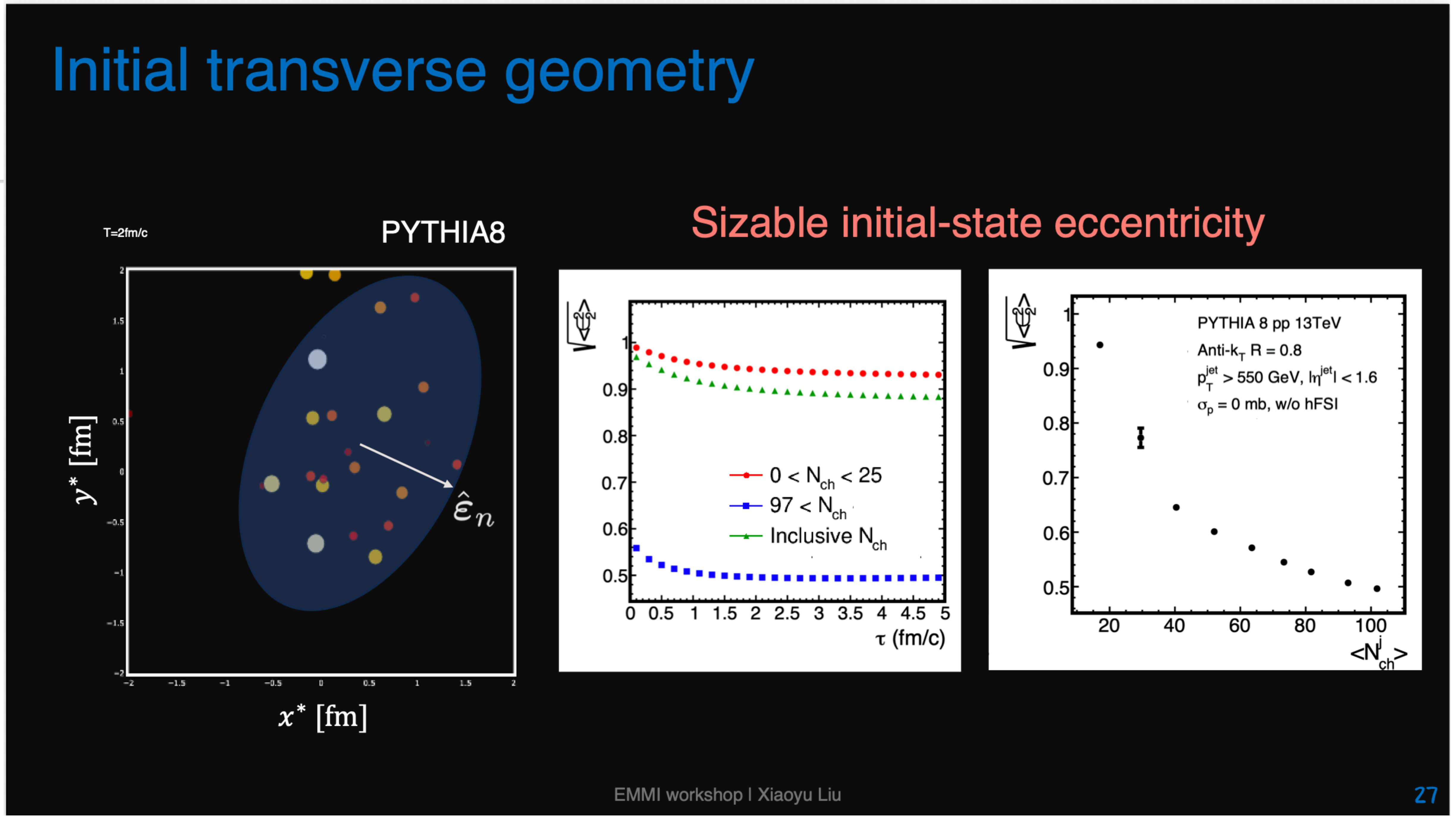
- Phase alignment with flow coupling direction
- Measures azimuthal distortion towards flow
- Highly dependent on your jet algorithm
  - E.g. anti-kT, enforces a circular jet on $y\phi$ cylinder
- We'll focus on this one for the moment...

$$v_n(E) = \left\langle \frac{\sum_j \cos(n\alpha_j)}{\sum_j} \right\rangle_{events}$$

To eliminate contribution from pp dist. in small sample:

$$\Delta v_n(E) = v_n^{AA}(E) - v_n^{pp}(E)$$



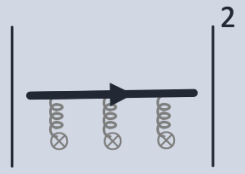


Jet quenching description developments in early stages

Example: jets in large medium

[Blaizot, Dominguez, Iancu, Mehtar-Tani]
[Casalderrey-Solana, Mehtar-Tani, Tywoniuk, Salgado]
[Caucal, Iancu, Mueller, Soyez]

- Broadening: (in vacuum straight line $\delta_{ij}\delta(p-p')$)



$$\left|\ \cdots\ \right|^2 \approx \mathcal{G}_{ij}(p',p,L)$$

changing color and momentum

- Evolution equation for mom. distr:

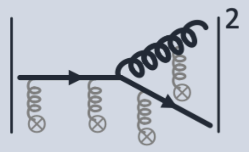
$$\partial_t \mathcal{P}(\boldsymbol{p},t) = \int_{\boldsymbol{q}_\perp} \left[C(\boldsymbol{q}_\perp)\mathcal{P}(\boldsymbol{p}-\boldsymbol{q}_\perp,t) - C(\boldsymbol{q}_\perp)\mathcal{P}(\boldsymbol{p},t)\right]$$

"time" mom. distribution scattering rate virtual term

$$\approx \hat{q}\,\partial_p^2\mathcal{P}(p,t)$$

diffusion approx. $q \ll p$

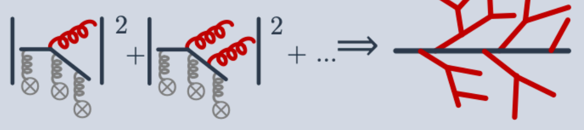
- Radiation: medium-induced (+ vacuum)



$$\Longrightarrow \frac{d\sigma}{dz\,d\vartheta} \approx 2\bar{\alpha}_s\sqrt{\frac{Q_{med}}{z^3E}}\,B(\vartheta)$$

Medium ($k_t \sim Q_{med}, z \ll Q_{med}/E$): soft & ~~collin.~~ pole

- Wide-angle medium-induced cascade:



(+ mixing with jet evolution!)

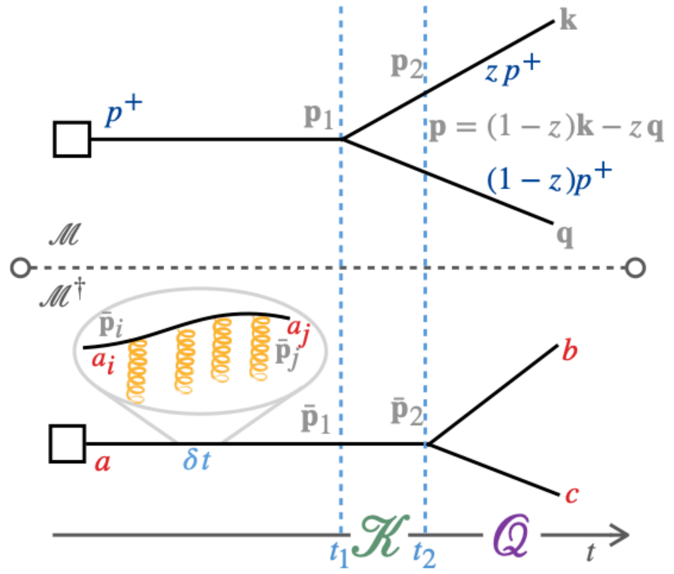
- Cascade evolution:

$$\partial_t D(x,t) = \int dz\left[\Gamma(z,\tfrac{x}{z})D(\tfrac{x}{z},t) - \tfrac{1}{2}\Gamma(z,p)D(x,t)\right]$$

"time" FF BDMPS-Z splitting rate virtual term

In-medium spectrum

Integration of matrix element squared in the light-cone time, with **distinct time variables** for the **amplitude (t_1)** and the **conjugate amplitude (t_2).**



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$$\frac{dI}{dz\,d^2\boldsymbol{p}} = \frac{\alpha_s P_{ba}(z)}{4\pi^2\omega^2}\Re\left[\int_{\boldsymbol{p}_1,\boldsymbol{p}_2,\bar{\boldsymbol{p}}_2,\bar{\boldsymbol{p}}}\int_0^\infty dt_1\int_{t_1}^\infty dt_2\,\delta^{(2)}_{\bar{\boldsymbol{p}}+\boldsymbol{p}} \times (\boldsymbol{p}_1\cdot\bar{\boldsymbol{p}}_2)\,\underbrace{\mathcal{K}(\boldsymbol{p}_2,\boldsymbol{p}_1|t_2,t_1)}_{\text{Kernel (3-pt)}}\,\underbrace{\mathcal{Q}(\boldsymbol{p},\bar{\boldsymbol{p}},\boldsymbol{p}_2,-\bar{\boldsymbol{p}}_2|t_\infty,t_2)}_{\text{Quadrupole (4-pt)}}\right],$$

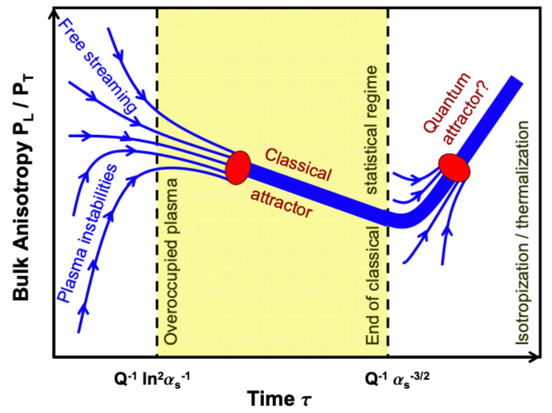
$$\mathcal{K}(t_2,t_1|\boldsymbol{u}_2,\boldsymbol{u}_1) = \int\mathcal{D}\boldsymbol{u}\,e^{i\int_{t_1}^{t_2}ds\,\frac{\omega}{2}\dot{\boldsymbol{u}}^2}\,\mathbb{C}^{(3)}(t_2,t_1|\boldsymbol{u})$$

$$\mathcal{Q}(L,t_2|\boldsymbol{u},\bar{\boldsymbol{u}},\boldsymbol{u}_2,\bar{\boldsymbol{u}}_2) = \int_{\boldsymbol{u}_2}^{\boldsymbol{u}}\mathcal{D}\boldsymbol{u}'\int_{\bar{\boldsymbol{u}}_2}^{\bar{\boldsymbol{u}}}\mathcal{D}\bar{\boldsymbol{u}}'\,e^{i\int_{t_1}^{t_2}ds\,\frac{\omega}{2}(\dot{\boldsymbol{u}}'^2-\dot{\bar{\boldsymbol{u}}}'^2)}\,\mathbb{C}^{(4)}(L,t_2|\boldsymbol{u}',\bar{\boldsymbol{u}}')$$

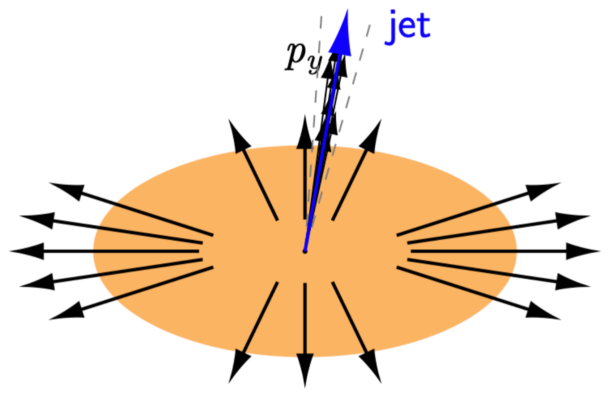
$$\mathbb{C}^{(3)} \sim \langle U_{R,b}U_{R,c}U^\dagger_{R,\bar{a}}\rangle \text{ and } \mathbb{C}^{(4)} \sim \langle U_{R,b}U_{R,c}U^\dagger_{R,\bar{c}}U^\dagger_{R,\bar{b}}\rangle$$

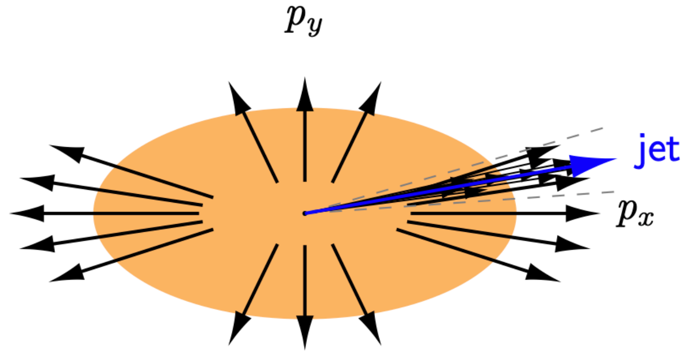
What happens to initial state anisotropies?

- We expect initial anisotropies to be washed out at hydrodynamization time in HIC
- Some questions arise:
  - Do initial azimuthal anisotropies disappear before hydrodynamization in small systems?
  - How do final-state interactions relax these anisotropies?
  - Can a hard probe (such as a jet) be sensitive to these initial anisotropies?



Phys. Rev. D 89.7 (2014). Berges, Boguslavski, Schlichting, and Venugopalan





Jet shape

Phys.Rev.D 113 (2026) 11 [Barata, Boguslavski, FL, Sadofyev]

- Energy deposited in *annulus* with radii r and R

$$\frac{d\rho(r,R)}{d\omega} = \int_{r\omega}^{R\omega} d^2\mathbf{k}\,\omega\frac{dI}{d\omega\,d^2\mathbf{k}}$$

- Qualitatively same behavior as spectra maximum