Resolving QCD matter with Multipoint Energy Correlators

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Mainly based on 2503.13603, 2604.21971
in collaboration with Barata, Kuzmin, Moult, Sadofyev, JMS

EMMI

EMMI Workshop: Probing the early stages with jets
Darmstadt, July 16th 2026

TÉCNICO LISBOA

FCT Fundação para a Ciência e a Tecnologia

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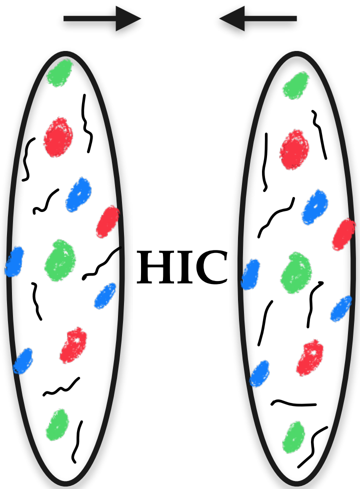
QCD matter in HICs

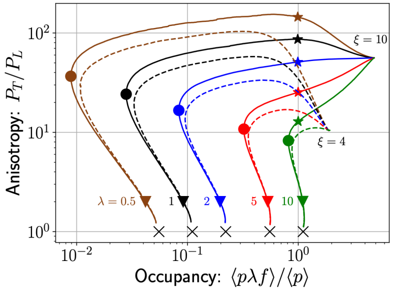
Initial nuclei



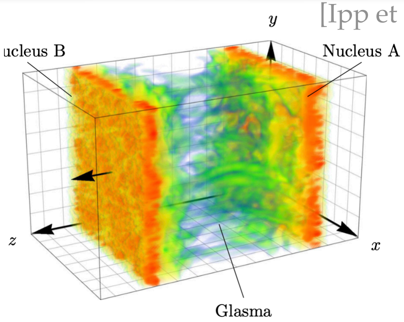
Gluon saturation
(~ CGC)

Coherent longitudinal fields

[Boguslavski et al., 2303.12595]



[Ipp et al., 2009.02044]

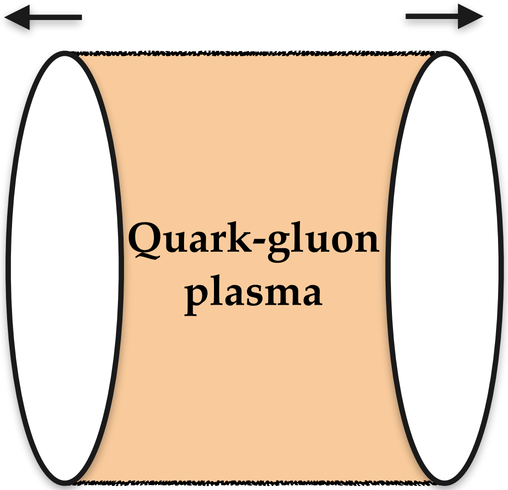


Large pressure anisotropy

Hydro. onset

τ

Nuclear matter lifetime $\sim$ **10 fm**



(Near) local thermal eq.
(~ (viscous) hydrodynamics)

What properties can **final-state energy correlations** resolve from this multi-stage evolution?

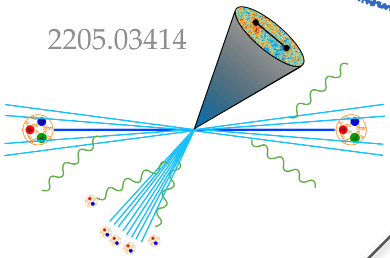
Energy-correlators

$$\hat{\mathcal{E}}(\boldsymbol{n}) = r^2 \lim_{r\to\infty} \int_0^{+\infty} dt\, n^i T^{0i}(t, r\boldsymbol{n})$$

asymptotic energy flow operator along $\boldsymbol{n}$

$$\textbf{Energy correlators} \sim \int \langle \hat{\mathcal{E}}(\boldsymbol{n}_1)\hat{\mathcal{E}}(\boldsymbol{n}_2)...\hat{\mathcal{E}}(\boldsymbol{n}_N)\rangle$$

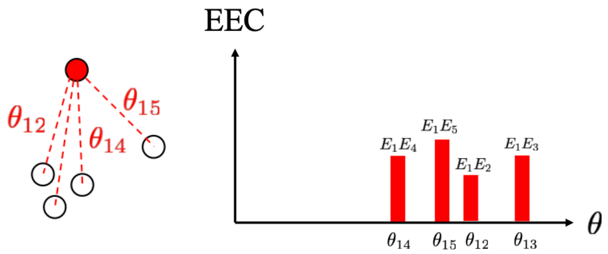
2205.03414



Collinear limit accesses jet substructure.

[Dixon et al, arXiv: 1905.01310]

Experimental convenience (straightforward to calculate).



see ENCs in QGP, e.g.
[Andres et al., 2307.15110]
[Barata et al., 2308.01294]
[Yang et al., 2310.01500]
[Bossi et al., 2407.13818]

Different angular resolutions can access different remnants of the dynamical evolution of the medium.

see [Moult, Zhu, 2506.09119] for an extensive review

Energy flow operator

[Barata, Kuzmin, Milhano, Sadofyev, 2412.03616]

classical / uncorrelated energy flow

$$\langle \hat{\mathcal{E}}(\boldsymbol{n}) \rangle = \mathcal{E}_c(\boldsymbol{n})$$

correlated energy flow

$$\langle \delta\hat{\mathcal{E}}(\boldsymbol{n}) \rangle = 0$$

$$\hat{\mathcal{E}}(\boldsymbol{n}) = \mathcal{E}_c(\boldsymbol{n}) + \delta\hat{\mathcal{E}}(\boldsymbol{n})$$

e.g.
mean bulk flow,
medium backreaction sourced by a jet, …

e.g.
fluctuations around mean flow,
perturbative **jet radiation, …**

Different angular scales probe different contributions to the final state energy flow.

Energy-correlators in bulk matter

$$\hat{\mathcal{E}}(\boldsymbol{n}) = \boxed{\mathcal{E}_c(\boldsymbol{n})} + \boxed{\delta\hat{\mathcal{E}}(\boldsymbol{n})}$$

mean flow **fluctuations**

Disconnected vs connected

The simplest object: the 2-point function $\langle \hat{\mathcal{E}}(\boldsymbol{n}_1)\hat{\mathcal{E}}(\boldsymbol{n}_2)\rangle$

Disconnected contributions

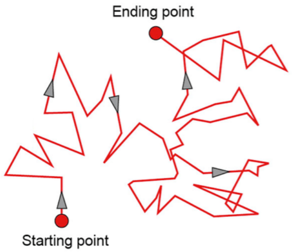
$$\mathcal{E}_c(\boldsymbol{n}_1)\mathcal{E}_c(\boldsymbol{n}_2)$$

Pure geometric correlations from mean flow

dominates when the two directions probe two widely separated flow elements (scales as $\sim \chi$)

[Barata, Kuzmin, Milhano, Sadofyev, 2412.03616]

Connected contributions



$$\langle \delta\hat{\mathcal{E}}(\boldsymbol{n}_1)\delta\hat{\mathcal{E}}(\boldsymbol{n}_2)\rangle$$

Correlations of fluctuations around a mean flow

expected to become increasingly important as the angular separation gets smaller

Disconnected contributions to EEC

[Barata, Kuzmin, Moult, Sadofyev, **JMS**, 2604.21971]

$$\left[\ \mathcal{E}_c(\boldsymbol{n}) = \langle \mathcal{E}(\boldsymbol{n}) \rangle\ \right]$$

$$\mathcal{E}_c(\boldsymbol{n}) = r^2 \lim_{r\to\infty} \int_0^\infty dt\, n^i\, \underline{T^{0i}_{\text{had.}}}(t, r\boldsymbol{n})$$

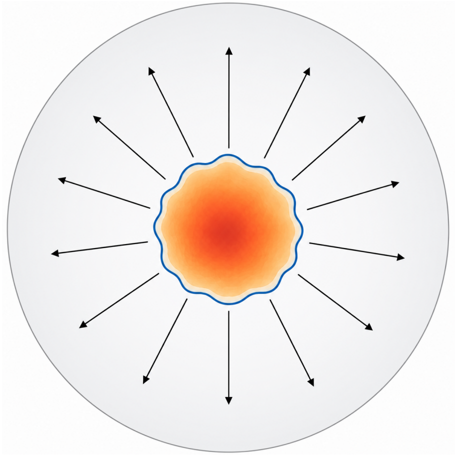
EMT of final state hadrons

=

EMT of **fluid** at the **freeze-out surface**

+

hadrons **free-streaming** to the detector



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EMT of final state hadrons

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EMT of **fluid** at the **freeze-out surface**

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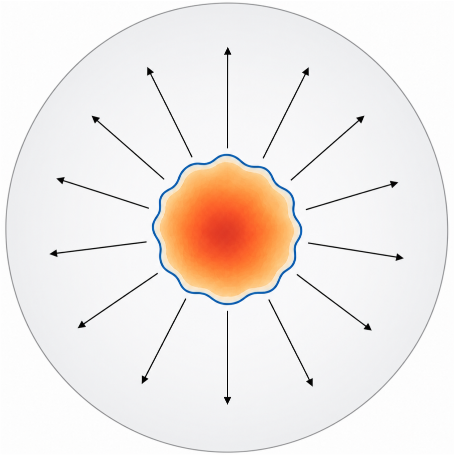
hadrons **free-streaming** to the detector

boost invariant fluid

w/ small azimuthal deformation

$$\mathcal{E}_c(\theta, \phi) = \frac{\mathcal{F}(\phi)}{\sin^3\theta}$$



ϕ - azimuthal angle in plane transverse to beam axis

$\mathcal{F}(\phi)$ determined by the freeze-out EMT of fluid

θ dependence characteristic of boost invariant system

Disconnected contributions to EEC

[Barata, Kuzmin, Moult, Sadofyev, **JMS**, 2604.21971]

For an (azimuthally) **unperturbed** fluid:

fluid properties

geometry (boost invariance)

$$\frac{d\Sigma}{d\chi} = \int_{\boldsymbol{n}_1,\boldsymbol{n}_2} \mathcal{E}_c(\boldsymbol{n}_1)\mathcal{E}_c(\boldsymbol{n}_2)\delta(\cos\chi - \boldsymbol{n}_1\cdot\boldsymbol{n}_2) \sim (\mathcal{F}_0)^2 f_0(\chi)$$

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[Barata, Kuzmin, Moult, Sadofyev, **JMS**, 2604.21971]

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More interesting: azimuthally differential EEC for a **perturbed** fluid with, e.g.,

$$\mathcal{F} = \mathcal{F}_0 + \sum_{n=1}^{\infty} \varepsilon_n \mathcal{F}_n^c \cos n\phi$$

$$\frac{d\Sigma}{d\chi d\psi} = v_0^{\text{EEC}} + \sum_{n=1}^{\infty} v_n^{\text{EEC}} \cos n\psi$$

fluid properties geometry

$$\frac{1}{\varepsilon_n}\frac{v_n^{\text{EEC}}(\chi)}{v_0^{\text{EEC}}(\chi)} = \frac{\mathcal{F}_n^c\, f_n(\chi)}{\mathcal{F}_0\, f_0(\chi)} = \frac{\mathcal{F}_n^c}{\mathcal{F}_0} + \mathcal{O}(\chi^2)$$

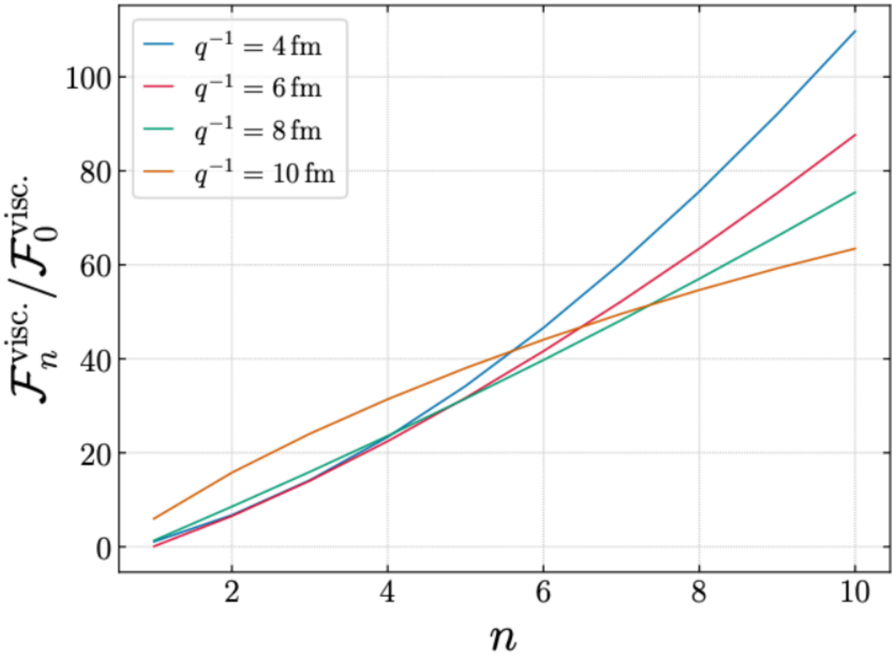
$\boxed{\text{azimuthal asymmetry of EEC directly calculable from perturbations to the hydro. solution}}$

ψ : azimuthal orientation of $\boldsymbol{n}_1 + \boldsymbol{n}_2$ in plane transverse to beam axis

Disconnected contributions to EEC

[Barata, Kuzmin, Moult, Sadofyev, **JMS**, 2604.21971]

q^{-1} sets the finite transverse size of the fluid



Example:
azimuthally perturbed, viscous Gubser flow

$$\frac{1}{\varepsilon_n} \frac{v_n^{\mathrm{EEC}}(\chi)}{v_0^{\mathrm{EEC}}(\chi)} = \frac{\mathcal{F}_n^c}{\mathcal{F}_0} + \mathcal{O}(\chi^2)$$

azimuthal asymmetry of EEC directly calculable from perturbations to the hydro solution

Connected EECs from thermal fluctuations

[Barata, Kuzmin, Moult, Sadofyev, **JMS**, 2604.21971]

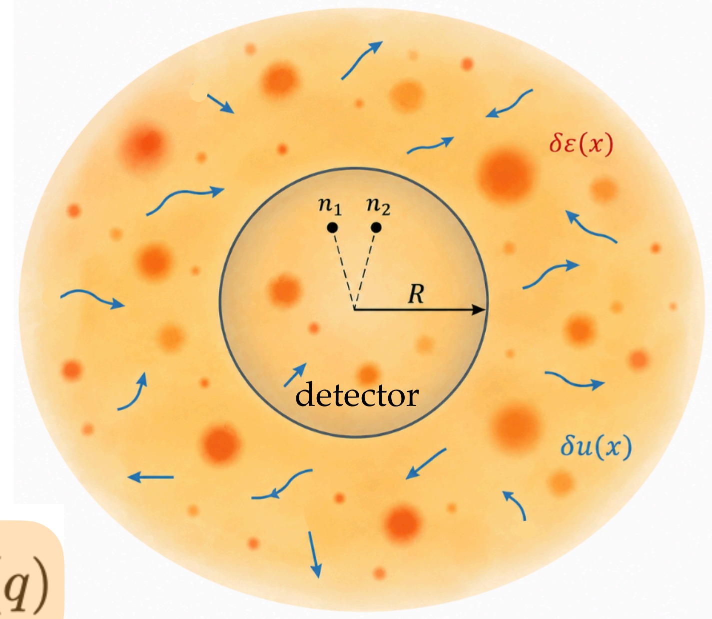
Consider the following model:

- Large static, homogeneous fluid → **no mean flow**

$$\langle \hat{\mathcal{E}}(\boldsymbol{n}_1)\hat{\mathcal{E}}(\boldsymbol{n}_2)\rangle = \langle \delta\hat{\mathcal{E}}(\boldsymbol{n}_1)\delta\hat{\mathcal{E}}(\boldsymbol{n}_2)\rangle$$

- Close to **local thermal equilibrium**

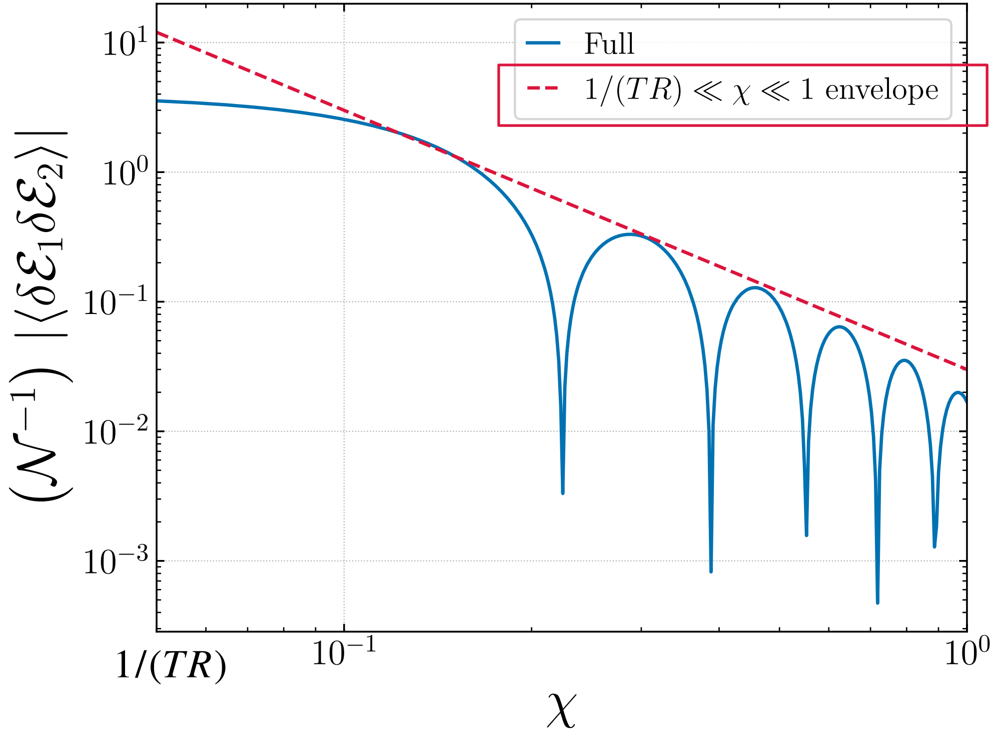
$$\langle \delta\hat{\mathcal{E}}(\boldsymbol{n}_1)\delta\hat{\mathcal{E}}(\boldsymbol{n}_2)\rangle \sim \int d^4q\, e^{iq\cdot(x_1-x_2)}\, G^{>}_{T^{0i}T^{0j}}(q)$$



thermal EMT Wightman function

Connected EECs from thermal fluctuations

Consider only the long-wavelength contribution to the thermal correlator ($\omega, |\vec{q}| \ll T$) governed by hydrodynamic modes.



$$\langle \delta\hat{\mathcal{E}}(\boldsymbol{n}_1)\delta\hat{\mathcal{E}}(\boldsymbol{n}_2)\rangle \simeq -\frac{R^2 w \tau^2}{2\pi^2\chi^2}\cos(TR\chi)$$

χ^{-2} envelope scaling

oscillations are an artifact from hard UV cutoff

Hydro fluctuations become increasingly important at smaller angles.

[Barata, Kuzmin, Moult, Sadofyev, **JMS**, 2604.21971]

Multipoint energy correlators inside jets

$$\hat{\mathcal{E}}(\boldsymbol{n}) = \boxed{\mathcal{E}_c(\boldsymbol{n})} + \boxed{\delta\hat{\mathcal{E}}(\boldsymbol{n})}$$

medium backreaction

jet energy flux

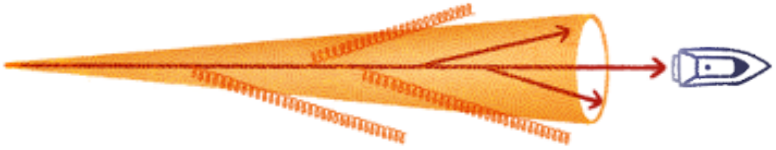
Matter modifications to jets

Jets are **extended objects** and evolve simultaneously with the matter, **carrying imprints** of their interaction.

jet-medium **momentum exchanges**

+

induced radiation



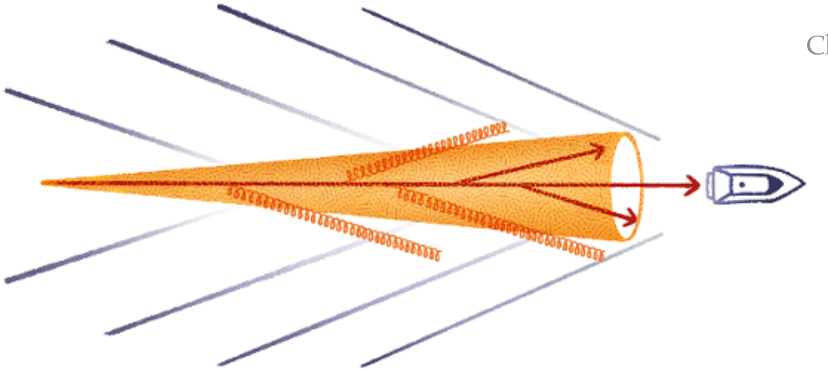
Matter modifications to jets

Jets are **extended objects** and evolve simultaneously with the matter, **carrying imprints** of their interaction.

jet-medium **momentum exchanges**
+
induced radiation

→ **medium response**

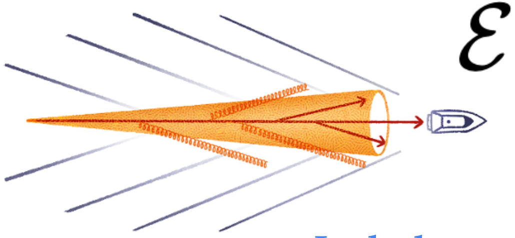
see, e.g.,
He, Luo, Wang, Zhu, PRC, 2015
Tachibana, Chang, Qin, PRC, 2017
Casalderrey-Solana et al, JHEP, 2021
Chen, Yang, He, Ke, Pang, Wang, PRL, 2021
Yang, Luo, Chen, Pang, Wang, PRL, 2023



How are these two physical effects imprinted on energy correlators?

Energy flow operator: medium response

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]



$$\hat{\mathcal{E}}(\boldsymbol{n}) = \mathcal{E}_c(\boldsymbol{n}) + \hat{\mathcal{E}}_h(\boldsymbol{n})$$

Includes medium response
(sourced by jet energy deposition)

Jet energy flux
(includes medium-induced modifications)

see e.g. Andres et al., 2307.15110, Barata et al., 2308.01294

can be computed from simulation; here assume a simple form:

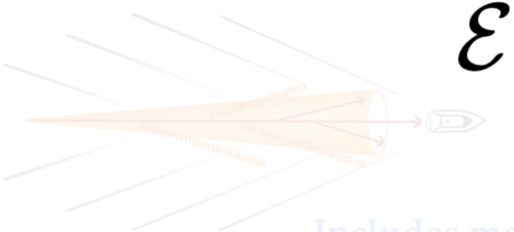
$$\int \langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1) \cdots \hat{\mathcal{E}}_h(\boldsymbol{n}_N) \rangle \sim \int d\sigma_{1\to N} E_1 \cdots E_N$$

$$\mathcal{E}_c(\boldsymbol{n}) = \frac{\Delta}{\pi\theta_0} e^{-\theta^2/\theta_0^2}$$

Energy flow operator: perturbative radiation

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]

$$\hat{\mathcal{E}}(\boldsymbol{n}) = \mathcal{E}_c(\boldsymbol{n}) + \hat{\mathcal{E}}_h(\boldsymbol{n})$$



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see e.g. Andres et al., 2307.15110, Barata et al., 2308.01294

can be computed from simulation; here assume a simple form:

$$\mathcal{E}_c(\boldsymbol{n}) = \frac{\Delta}{\pi\theta_0} e^{-\theta^2/\theta_0^2}$$

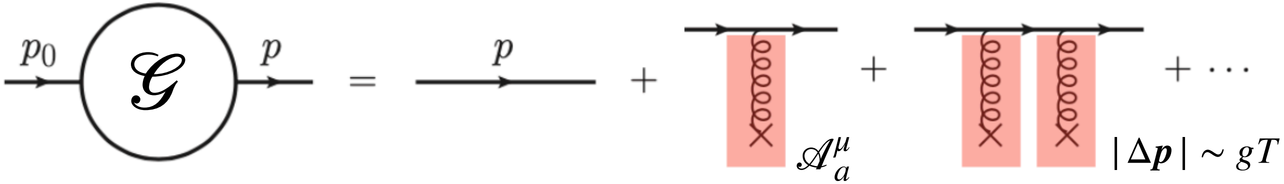
$$\int \langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1) \cdots \hat{\mathcal{E}}_h(\boldsymbol{n}_N) \rangle \sim \int d\sigma_{1\to N} E_1 \cdots E_N$$

BDMPS-Z formalism

Resummation of *single* gluon exchanges with the medium (***BDMPS-Z***) ($p^+ \gg |\boldsymbol{p}|, |\Delta\boldsymbol{p}| \sim gT$)

LC gauge ($n \cdot \mathscr{A} = \mathscr{A}^+ = 0$)

($p_0^+ = p^+$)



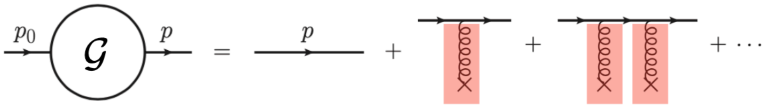
Dressed propagator

$$\mathscr{G}_{ij}(\boldsymbol{x_2}, t_2; \boldsymbol{x_1}, t_1) = \underbrace{\int_{\boldsymbol{x_1}}^{\boldsymbol{x_2}} \mathscr{D}\boldsymbol{r} \exp\left(\frac{ip^+}{2} \int_{t_1}^{t_2} dt\, \dot{\boldsymbol{r}}^2 \right)}_{\text{Diffusive motion in the transverse plane}} \underbrace{\exp\left\{ igT^a_{ij} \int_{t_1}^{t_2} dt\, \mathscr{A}_a^-(\boldsymbol{r}(t), t) \right\}}_{\text{Wilson line encoding color precession}}$$

see talks by Marco, Matvei, Xoán

BDMPS-Z formalism

Perturbative QCD + **Medium model**



$$\boxed{\langle \mathscr{A}_a^-(x^+, \boldsymbol{x}), \mathscr{A}_b^{*-}(y^+, \boldsymbol{y})\rangle}$$

Resummation of *single* gluon exchanges with the medium, assuming large p^+ + vacuum QCD vertices

Stochastic gauge field in light-cone gauge
Gaussian white noise model

Boils down to: $$\frac{d\sigma_{1\to N}}{d\Omega_N}(\hat{q}, L, \ldots) = \langle \mathscr{M}\mathscr{M}^\dagger \rangle_{\mathscr{A}} \sim \int \mathscr{D}\boldsymbol{r}_1 \ldots \langle \mathscr{U}_1 \mathscr{U}_2^\dagger \ldots \rangle_{\mathscr{A}}$$

Projected ENCs (perturbative only)

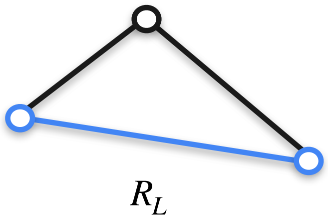
First focus on a simpler object: the **projected ENC (PENC),** i.e. only the largest angular distance (R_L) is kept.

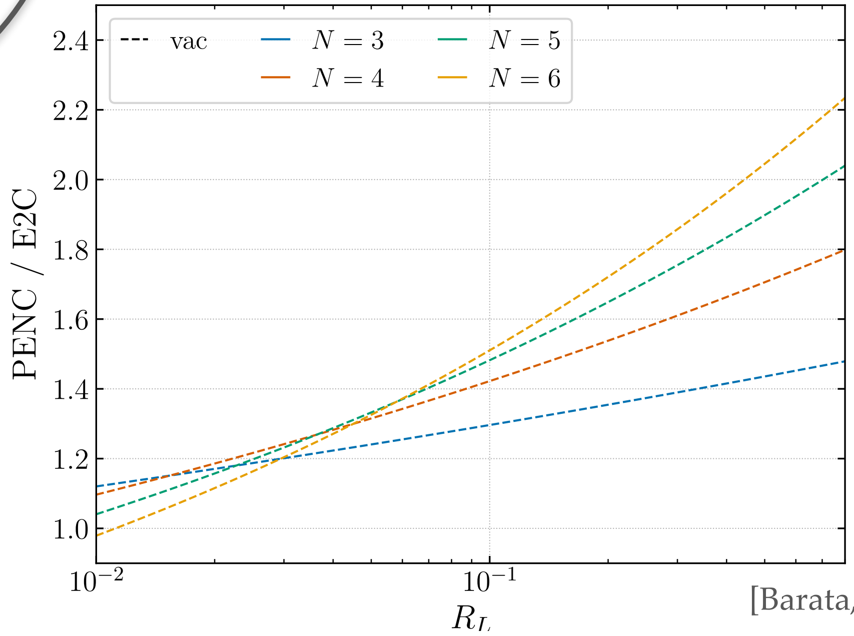
[Dixon et al, arXiv: 1905.01310]

$$\frac{d\Sigma_{\mathrm{P}}^{(N)}}{dR_L} = \frac{\alpha_s R_L^{\frac{\alpha_s}{\pi}\gamma(N+1)}}{\pi R_L} \int_0^1 dz\,(1 - z^N - (1-z)^N) P_{gq}$$

only need the $q \to qg$ **vacuum** splitting function for the quark PENC

No classical flux added yet!





[Barata, Moult, Sadofyev, **JMS**, 2503.13603]

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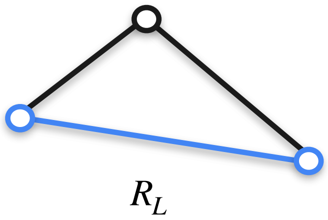
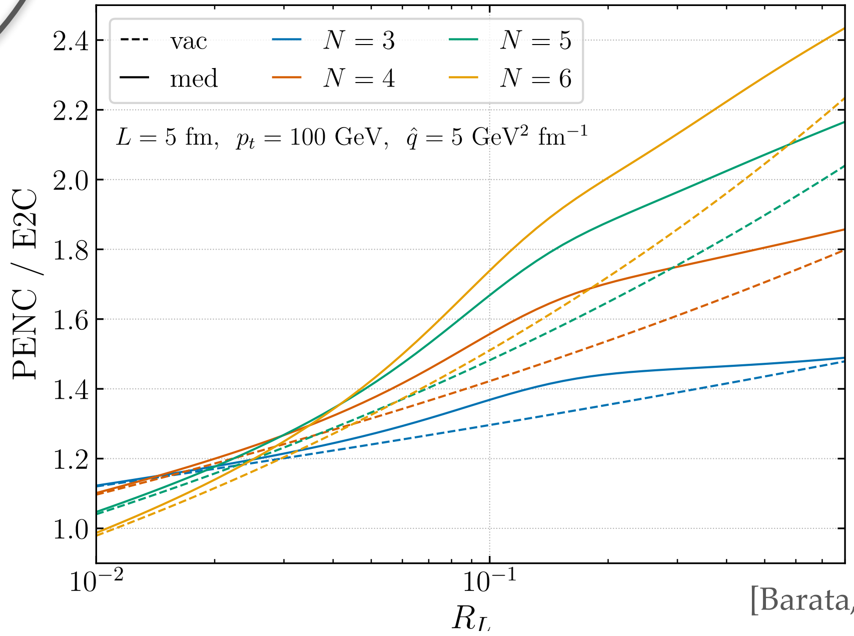
only need the $q \to qg$ **medium** splitting function for the quark PENC

No classical flux added yet!





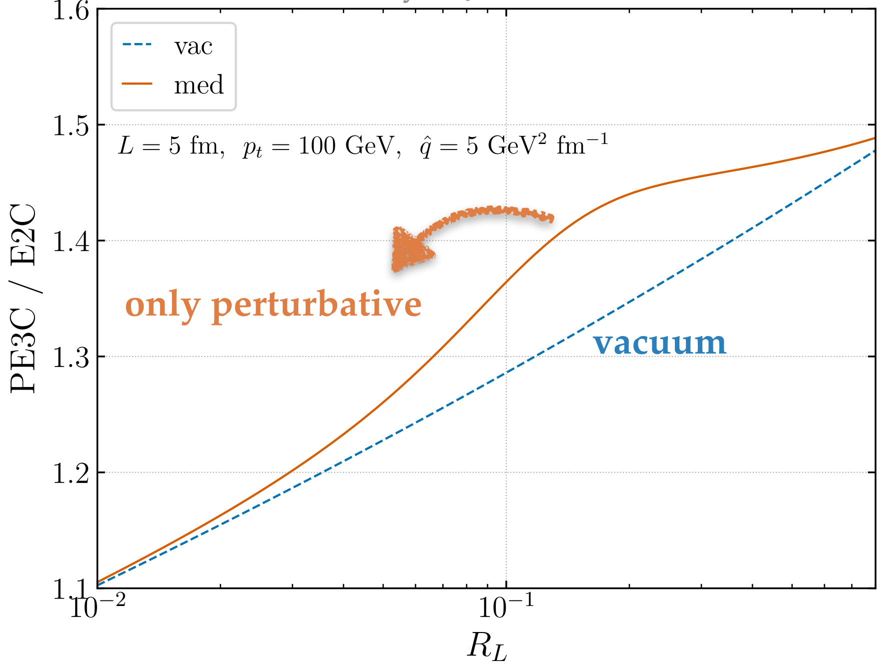
increasing N increases the medium-induced effect on the PENC/E2C ratio

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]

Full PE3C

Fix **N = 3**. What happens if we add a classical/uncorrelated energy flow to the **PE3C**?

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]



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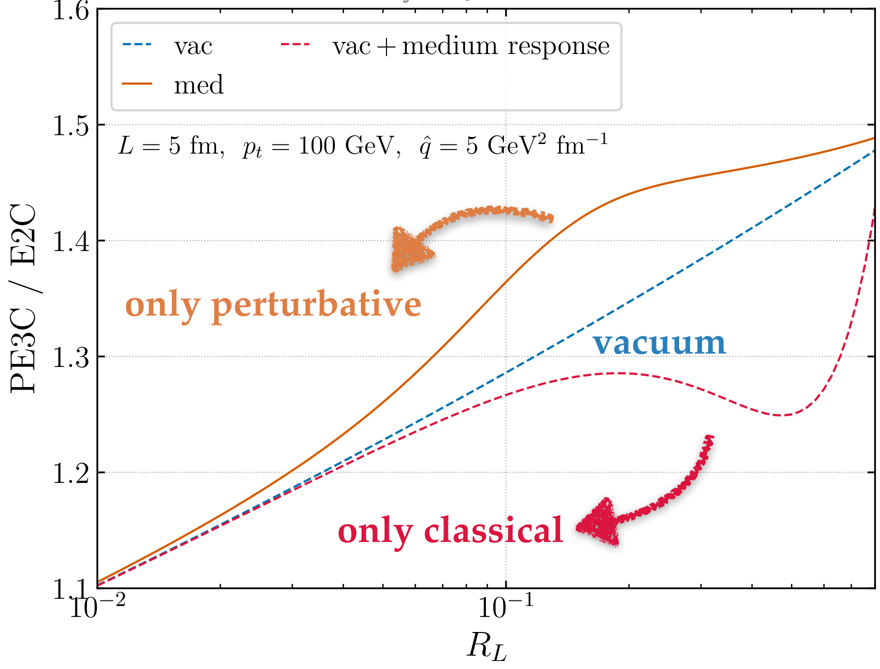

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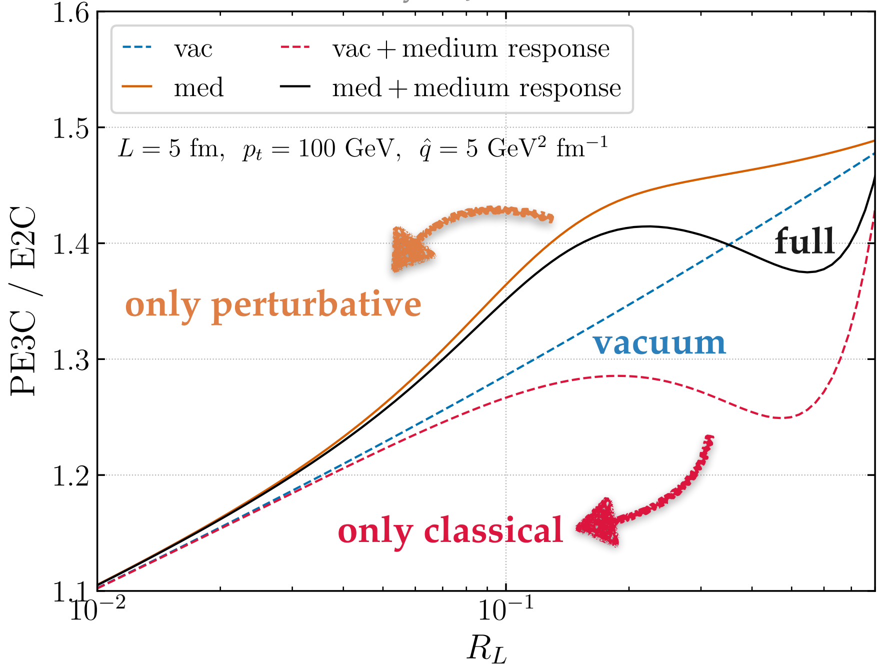
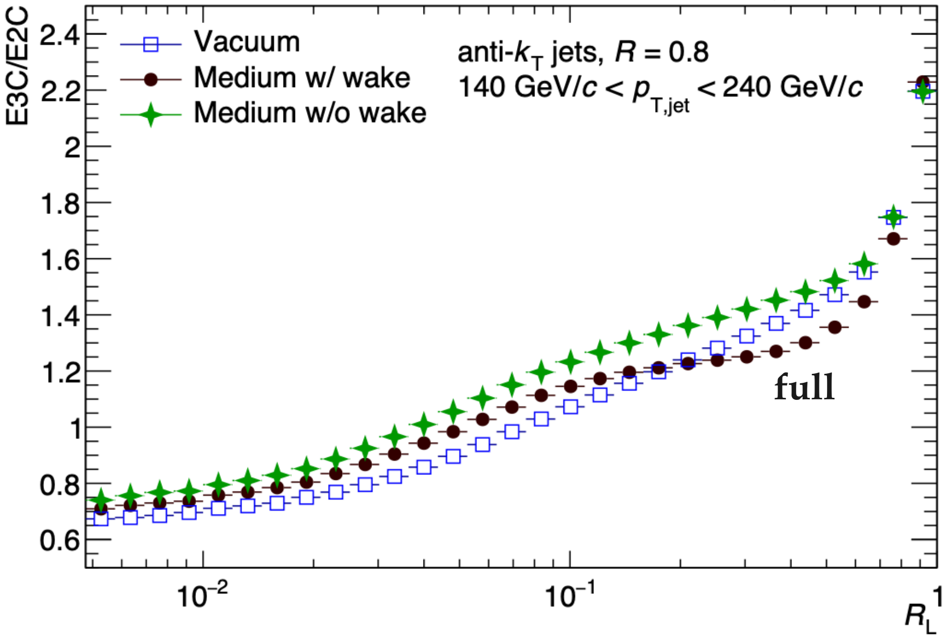


[Bossi et al., JHEP, 2024]

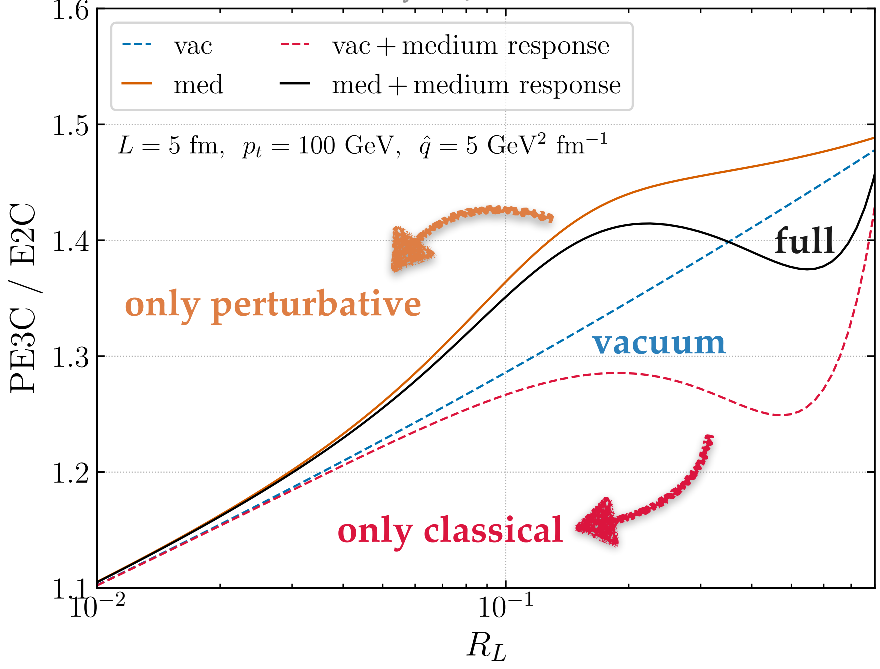


In **qualitative** agreement with, e.g., the Hybrid model.

Full PE3C: collinear limit

What is the behaviour in the collinear limit?

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]



$$\frac{d\Sigma_P^{(3)}}{dR_L} = \frac{a_{2,0}^{P(3)}}{R_L} + \left(a_{4,0}^{P(3)} + b_{4,0}^{P(3)} + c_4^{P(3)} \right) R_L + \ldots$$

Perturbative and **classical** contributions:

1. start at order R_L
2. are entangled with each other, i.e., an extraction of the series coefficients **mixes** information about **perturbative** jet modifications and **classical energy flow**

Shape dependent E3C

Let us go beyond the PE3C to study the **full angular structure** of the E3C.

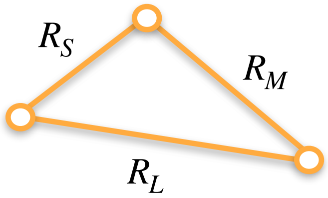
We first change coordinates from the 3 angles ($R_L > R_M > R_S$) to a more convenient set:

$$(R_L, R_M, R_S) \to (R_L, \xi, \phi)$$

[Komiske, Moult, Thaler, Zhu, 2201.07800]

$$\xi = R_S / R_M$$

$$\sin^2 \phi = 1 - (R_L - R_M)^2 / R_S^2$$



Let us focus only on the fully perturbative contribution to the E3C, i.e.,

$$d\Sigma^{(3)}_{hhh} \sim \int d\Phi_3 \frac{g^4}{2 s_{123}^2} \underline{P_{q\to qgg}} z_1 z_2 z_3$$

we need the $1 \to 3$ **splitting function!**

$$P^{\text{vac}}_{q\to qgg} \quad ✓ \qquad\qquad P^{\text{med}}_{q\to qgg} \quad ?$$

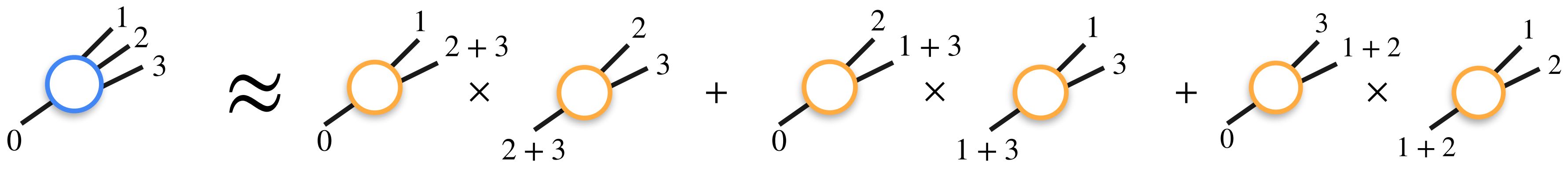
[Catani, Grazzini, hep-ph/9810389]

Cascade approximation for the $q \to qgg$ splitting function

We approximate the $1 \to 3$ splitting function by a succession of $1 \to 2$ branchings $\to$ **cascade approximation.**

[Fickinger, Ovanesyan, Vitev, arXiv:1304.3497]

Schematically:



$$\frac{P_{0\to123}}{s_{123}} \approx \frac{P_{0\to1(2+3)}P_{(2+3)\to23}}{s_{1,(2+3)}} + \frac{P_{0\to2(1+3)}P_{(1+3)\to13}}{s_{2,(1+3)}} + \frac{P_{0\to3(1+2)}P_{(1+2)\to12}}{s_{3,(1+2)}}$$

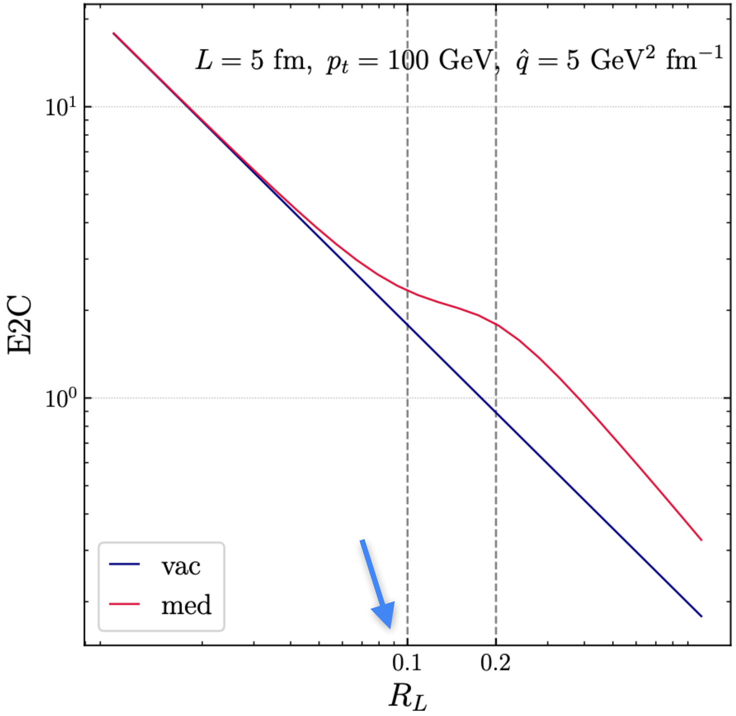
Naturally, it misses out on <u>interferences</u> which are only included in the full $1 \to 3$ splitting function.

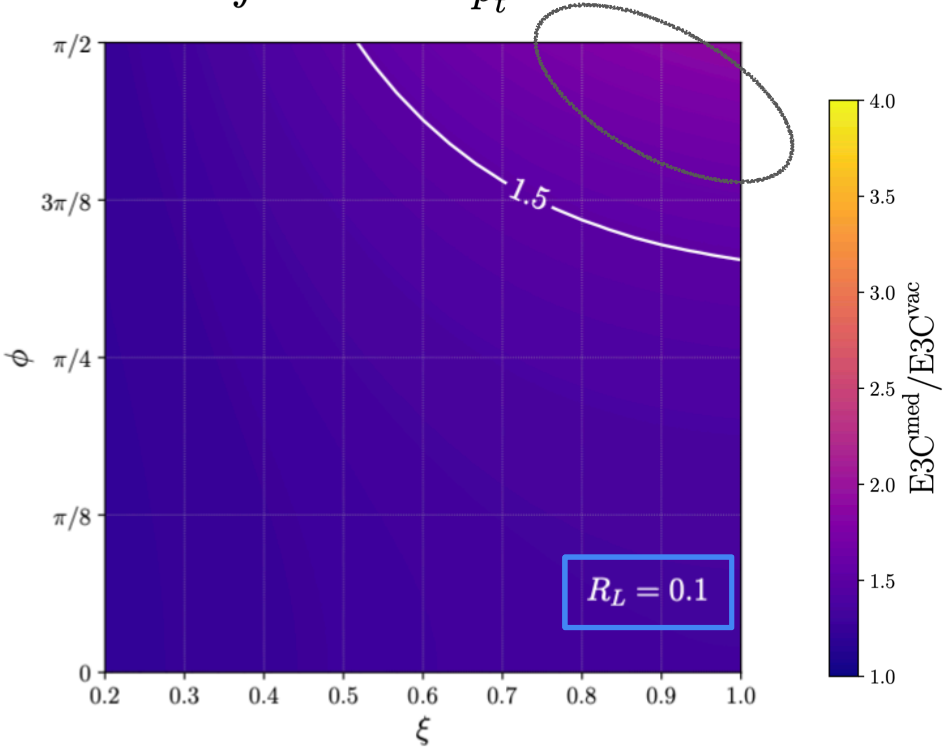
[see 1304.3497 for a full calculation in opacity expansion]

E3C in a medium: results for *hhh*

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]

$$d\Sigma^{(3)}_{hhh} \sim \int \frac{\langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1)\hat{\mathcal{E}}_h(\boldsymbol{n}_2)\hat{\mathcal{E}}_h(\boldsymbol{n}_3)\rangle}{p_t^3}$$

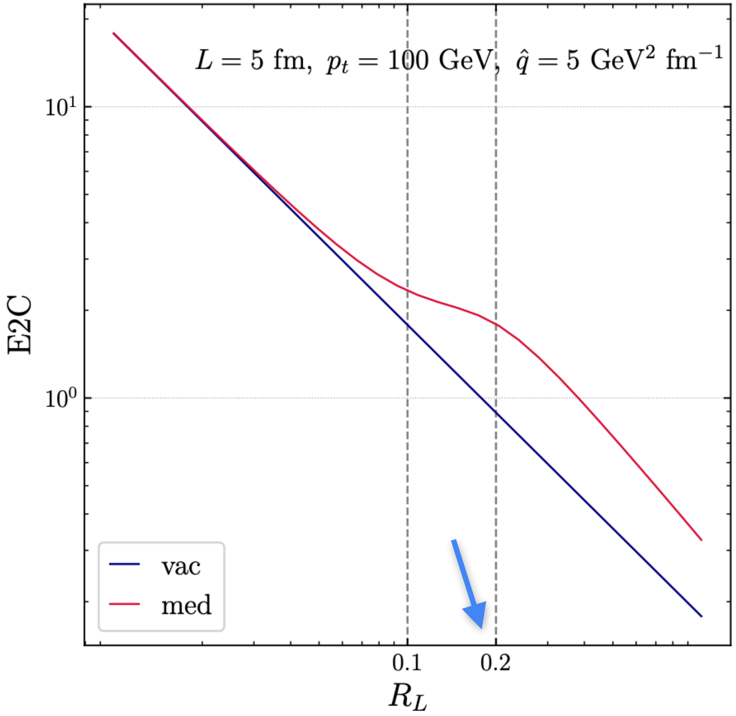


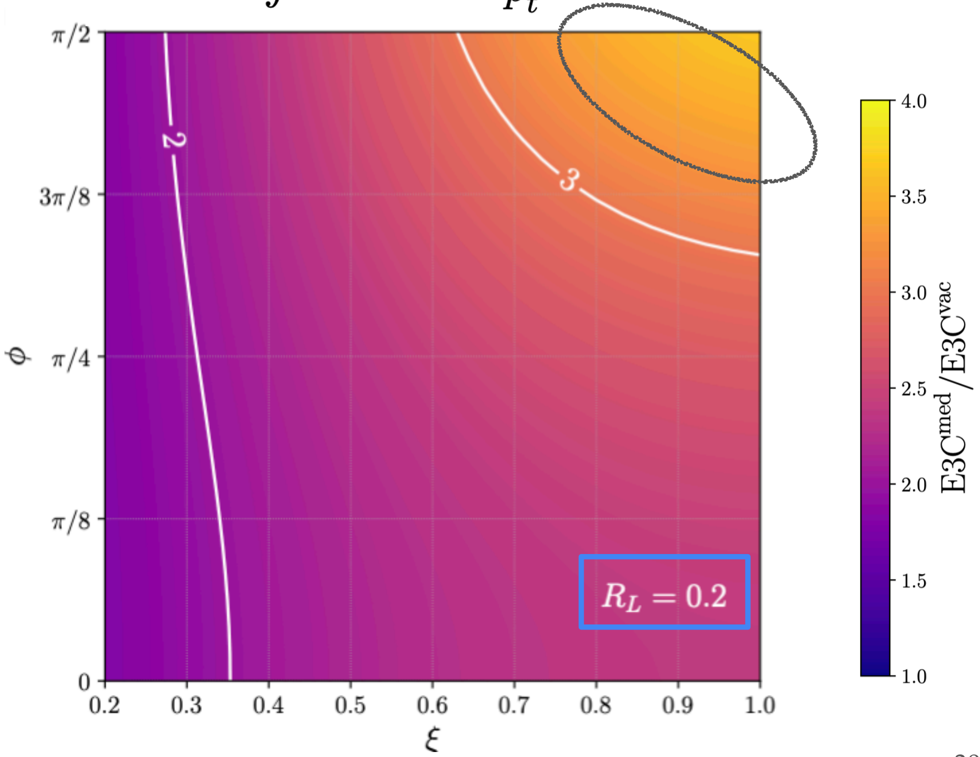


E3C in a medium: results for *hhh*

[Barata, Moult, Sadofyev, **JMS**, 2503.13603]

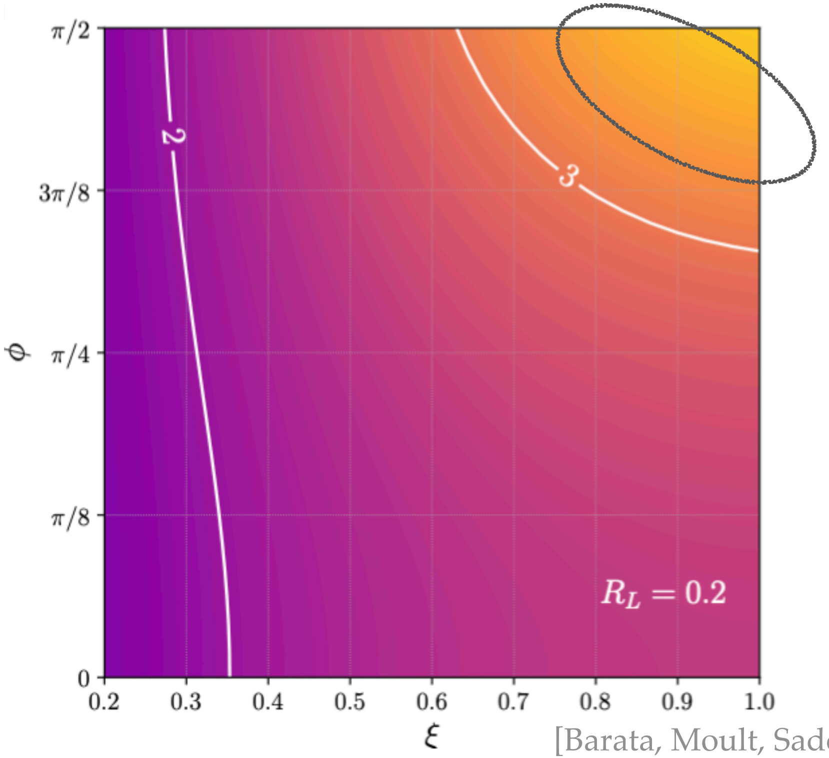
$$d\Sigma^{(3)}_{hhh} \sim \int \frac{\langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1)\hat{\mathcal{E}}_h(\boldsymbol{n}_2)\hat{\mathcal{E}}_h(\boldsymbol{n}_3)\rangle}{p_t^3}$$



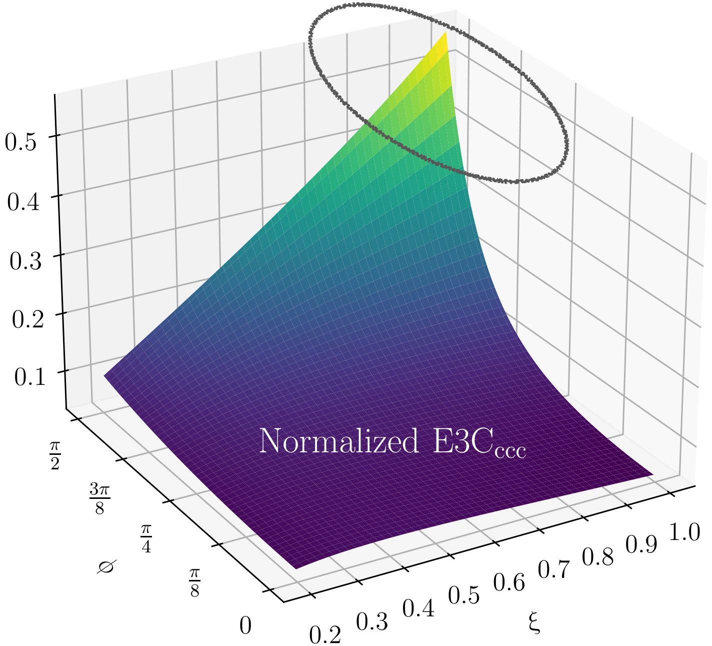


E3C in a medium: results for *hhh* and *ccc*

$$\langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1)\hat{\mathcal{E}}_h(\boldsymbol{n}_2)\hat{\mathcal{E}}_h(\boldsymbol{n}_3)\rangle$$



$$\langle \mathcal{E}_c(\mathbf{n}_1)\mathcal{E}_c(\mathbf{n}_2)\mathcal{E}_c(\mathbf{n}_3)\rangle = \mathcal{E}_c(\mathbf{n}_1)\mathcal{E}_c(\mathbf{n}_2)\mathcal{E}_c(\mathbf{n}_3)$$



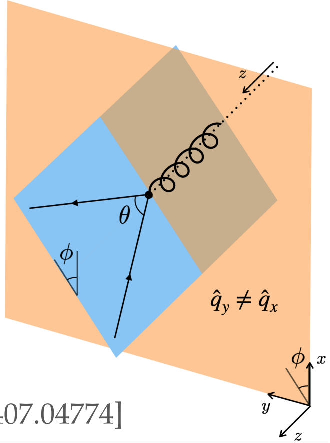
[Barata, Moult, Sadofyev, **JMS**, 2503.13603]

Outlook: directional effects in in-jet ECs

$$\frac{d\Sigma_P^{(3)}}{dR_L} = \frac{a_{2,0}^{P(3)}}{R_L} + \left(a_{4,0}^{P(3)} + b_{4,0}^{P(3)} + c_4^{P(3)}\right) R_L + (\ldots)R_L^2 + (\ldots)R_L^3 + \ldots$$

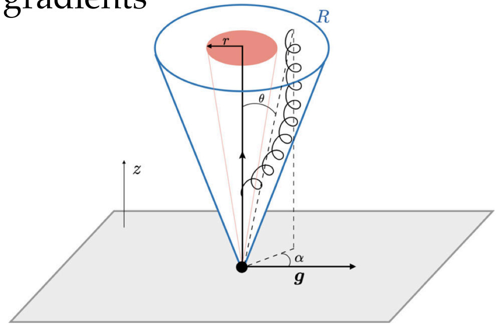
- Only **odd powers** show up in the collinear expansion.
- Perturbative contributions necessarily result in odd powers.
- Classical contribution can give rise to **even powers** for a medium with **directional effects**, e.g.:

momentum space anisotropies



[Barata, Salgado, **JMS**, 2407.04774]

spatial gradients



[Barata, Milhano, Sadofyev, 2308.01294]

See also e.g.
[Sadofyev, Sievert, Vitev, 2104.09513]
[Antiporda, Bahder, Rahman, Sievert, 2110.03590]
[Barata, López, Sadofyev, Salgado, 2304.03712]
[Kuzmin, López, Reiten, Sadofyev, 2309.00683]
…

Outlook: directional effects in in-jet ECs

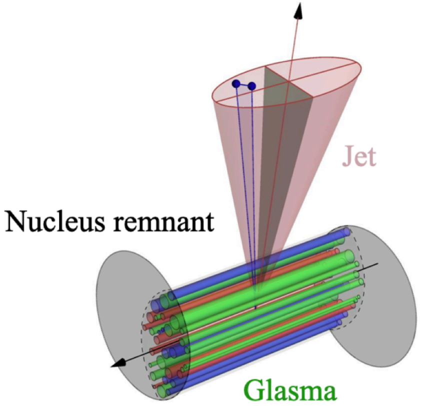
[Barata, Milhano, Sadofyev, **JMS**, 2512.17009]

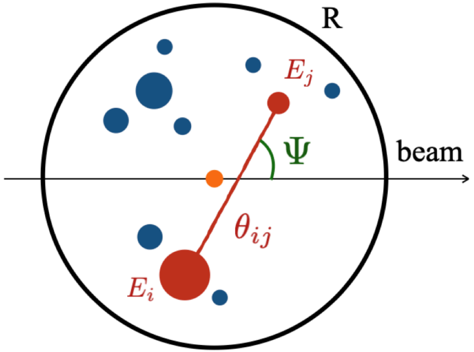
Azimuthally differential in-jet EEC

$$\frac{d\Sigma^{\text{jet}}}{d\chi d\psi} = v_0^{\text{EEC}} + \sum_{n=1}^{\infty} v_n^{\text{EEC}} \cos n\psi$$

ψ defined relative to beam axis

see Andrey's talk today!





Summary

- Energy correlators are a natural observable to distinguish mean flow from genuine fluctuating flow contributions, both in the bulk and inside jets;
- For bulk EECs, **mean flow** imprints are determined by geometrical correlations and become dominant at **larger angles**, while **fluctuating contributions** are expected to become important for **smaller angles**;
- For in-jet ENCs, **mean flow (medium response)** and **perturbative contributions overlap** - only by accounting for both and analysing how they scale can one systematically extract information about the medium.

THANKS!