Dissecting Jet Modification in the QGP with Multi-Point Energy Correlators

João M. Silva
(U. Granada/LIP - Lisbon)

Mainly based on the work by Barata, Moult, Sadofyev, JMS, 2503.13603

New Opportunities in Particle and Nuclear Physics with Energy Correlators
Wuhan, May 15th 2025

UNIVERSIDAD DE GRANADA

High Energy Theory

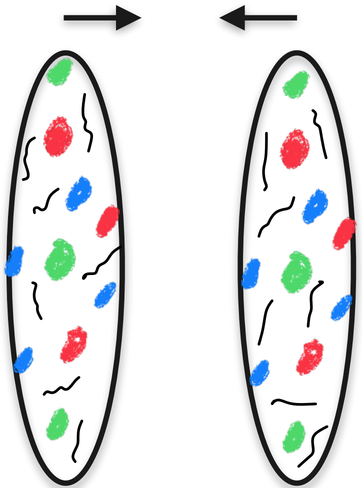
FCT Fundação para a Ciência e a Tecnologia

"ERC-PT A-Projects - Unveiling the Time Dynamics of Quantum Chromodynamics in the Quark-Gluon Plasma"

European Research Council
Established by the European Commission

Quark-gluon plasma in HICs

Initial nuclei

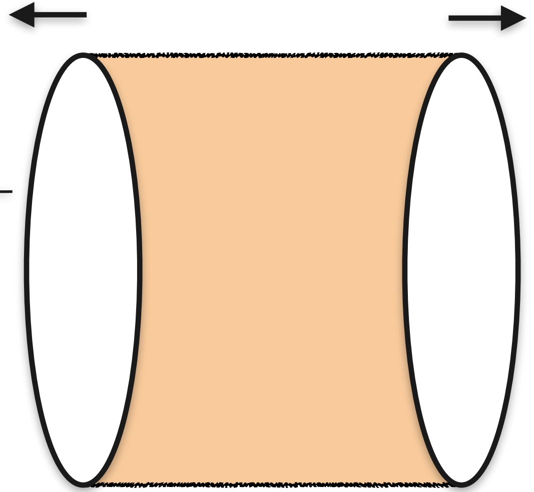


Hot and dense medium of deconfined quarks and gluons produced ~ 1 fm/c (10^{-24} s) after a HIC!

Driven to equilibrium

$\xrightarrow{\hspace{3cm}} \tau$

QGP



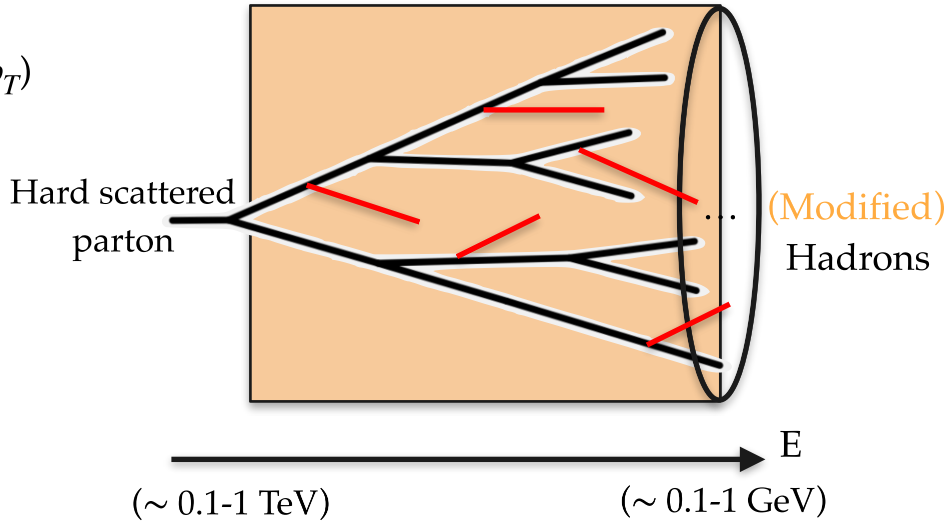
(Near) local thermal eq.

nuclear matter lifetime ~ 10 **fm** $\longrightarrow$ **use <u>hard probes</u>!**

Probing the QGP with jets

- Jets are produced **early** in the collision ($\tau \sim 1/p_T$)
- Jets are extended in time and **evolve simultaneously with the QGP.**
- Jets carry **imprints of medium interactions** (energy loss, substructure modifications, medium response, etc) - **jet quenching.**

jets - high energy, collimated QCD cascades



By **comparing heavy-ion jets** with their vacuum counterparts (**p-p jets**), dedicated observables can be used to access the **QGP's transport properties**.

Probing the QGP with jets

jet-medium **momentum exchanges**

+

induced radiation

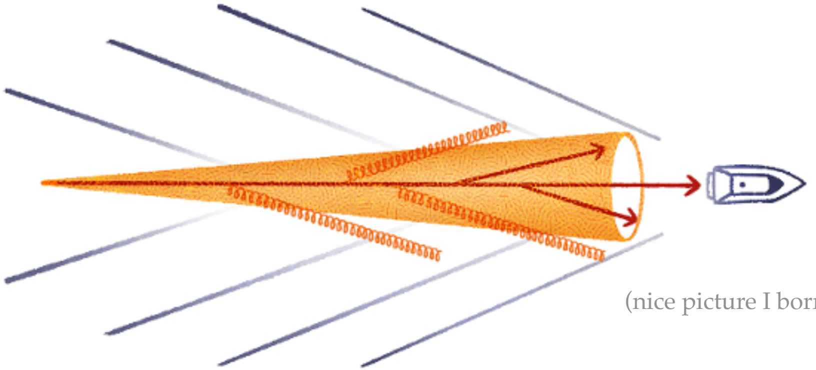
(nice picture I borrowed from Andrey)

Probing the QGP with jets

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

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

→ **medium response**



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How are these two physical effects imprinted on **energy correlators**?

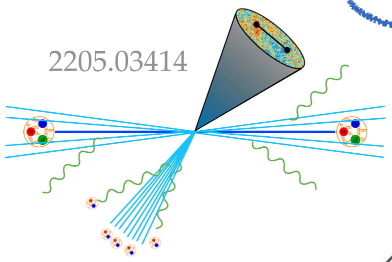
Energy correlators

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

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

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



Experimental convenience
(straightforward to calculate)

Collinear limit is particularly useful to access jet substructure.
[Dixon et al, arXiv: 1905.01310]

Organising different physics into small/large angle behaviour is helpful to **sort out QGP-induced modifications.**

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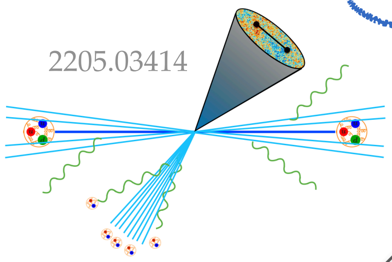

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Let us focus on the
quark PENC and E3C
(the $q \to qgg$ contribution)

Barata, Moult, Sadofyev, JMS, 2503.13603

Organising different physics into small/large angle behaviour is helpful to **sort out QGP-induced modifications.**

Energy flow operator

[Barata, Kuzmin, Milhano, Sadofyev, 2412.03616]

classical/uncorrelated energy flow
(e.g. described by hydro)

correlated energy flow
(e.g. calculated perturbatively)

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

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Includes medium response
(sourced by jet energy deposition)

Jet energy flux
(includes medium-induced modifications)

How are these two energy flows imprinted on ENCs / PENCs ?

Energy flow operator: uncorrelated part

[Barata, Kuzmin, Milhano, Sadofyev, 2412.03616]

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Energy flow operator: uncorrelated part

In 2412.03616 (Barata, Kuzmin, Milhano, Sadofyev), for E2C:

- Assume a form for the **energy deposited by the jet** on the medium.
- Use it as a source term for linearised hydrodynamics equations:

$$\partial_\mu \delta T^{\mu\nu} = J^\nu$$

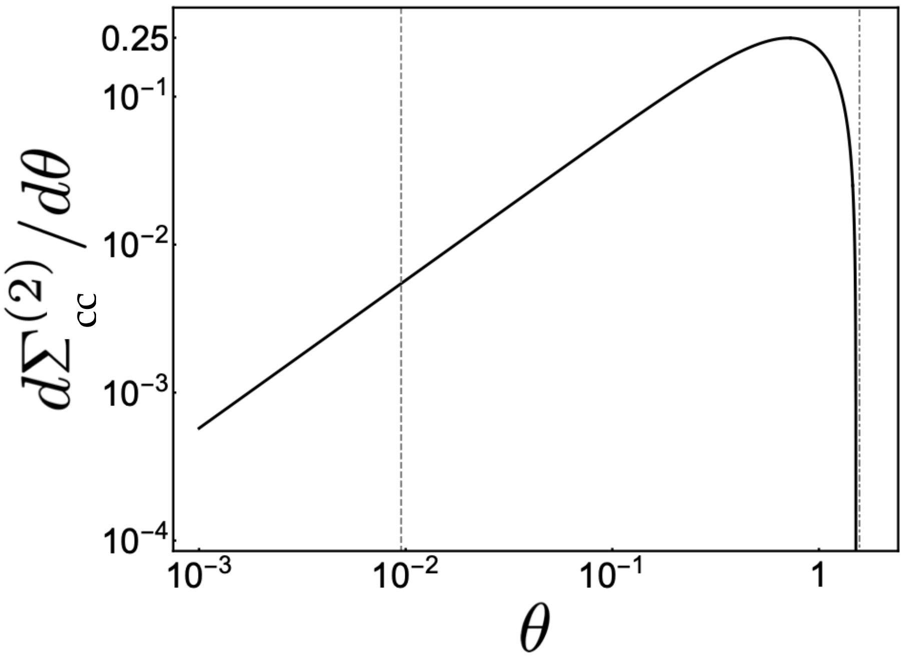
- Calculate corresponding classical energy flow from the perturbation $\delta T^{\mu\nu}$.

see Andrey's talk

Energy flow operator: uncorrelated part

[Barata, Kuzmin, Milhano, Sadofyev, 2412.03616]

$$\frac{d\Sigma^{(2)}_{cc}}{d\theta} \sim \int \frac{\langle \mathcal{E}_c(\boldsymbol{n}_1)\mathcal{E}_c(\boldsymbol{n}_2)\rangle}{p_t^2} = \int \frac{\mathcal{E}_c(\boldsymbol{n}_1)\mathcal{E}_c(\boldsymbol{n}_2)}{p_t^2}$$



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In 2503.13603 (this work, Barata, Moult, Sadofyev, JMS), for PENC and E3C:

- Directly assume the functional form for the classical energy flow as an illustration:

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

see Andrey's talk

Energy flow operator: correlated part

[Barata, Kuzmin, Milhano, Sadofyev, 2412.03616]

classical/uncorrelated energy flow
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Includes medium response
(sourced by jet energy deposition)

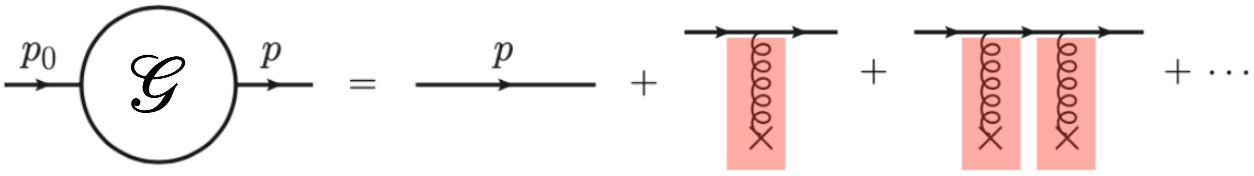
Jet energy flux
(includes medium-induced modifications)

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

$$\int \langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1)\hat{\mathcal{E}}_h(\boldsymbol{n}_2)...\hat{\mathcal{E}}_h(\boldsymbol{n}_N)\rangle \sim \int d\sigma_{1\to N} E_1 E_2 ... E_N$$

In-medium perturbative calculation

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



$$\mathcal{G}_{ij}(\boldsymbol{x_2}, t_2; \boldsymbol{x_1}, t_1) = \int_{\boldsymbol{x_1}}^{\boldsymbol{x_2}} \mathcal{D}\boldsymbol{r} \exp\left(\frac{ip^+}{2} \int_{t_1}^{t_2} dt\, \dot{\boldsymbol{r}}^2 \right) \exp\left\{ igt^a_{ij} \int_{t_1}^{t_2} dt\, \mathcal{A}^-_a(\boldsymbol{r}(t), t) \right\}$$

Diffusive motion in the transverse plane

Wilson line encoding color precession

In-medium perturbative calculation

- The medium is described by a **stochastic gauge field**, with configurations following a **gaussian white noise model**:

$$\langle \mathscr{A}_a^-(t_1, \boldsymbol{x}), \mathscr{A}_b^{*-}(t_2, \boldsymbol{y}) \rangle = \delta^{ab} n(t_1) \delta(t_2 - t_1) \gamma(\boldsymbol{x}, \boldsymbol{y})$$

matter density **collision kernel**

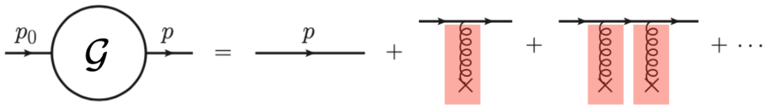
- $n(t) = n\,\Theta(t < L)$ (***static and finite length***)
- $\gamma(\boldsymbol{x}, \boldsymbol{y}) = \gamma(\boldsymbol{y} - \boldsymbol{x})$ (***homogeneous,*** i.e., translation invariant)
- $\gamma(\boldsymbol{y} - \boldsymbol{x}) = \gamma(|\boldsymbol{y} - \boldsymbol{x}|)$ (***isotropic,*** i.e., rotation invariant)

$$\boxed{g^2(\gamma(0) - \gamma(\boldsymbol{r})) \sim \hat{q} r^2} \longrightarrow \hat{q} \sim \text{accumulated } k_\perp^2 \text{ per mean free path}$$

(multiple soft scattering approximation)

In-medium perturbative calculation

Perturbative QCD + **Medium model**



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

Resummation of *single* gluon exchanges with the medium + color precession

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

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

Projected ENCs (perturbative only)

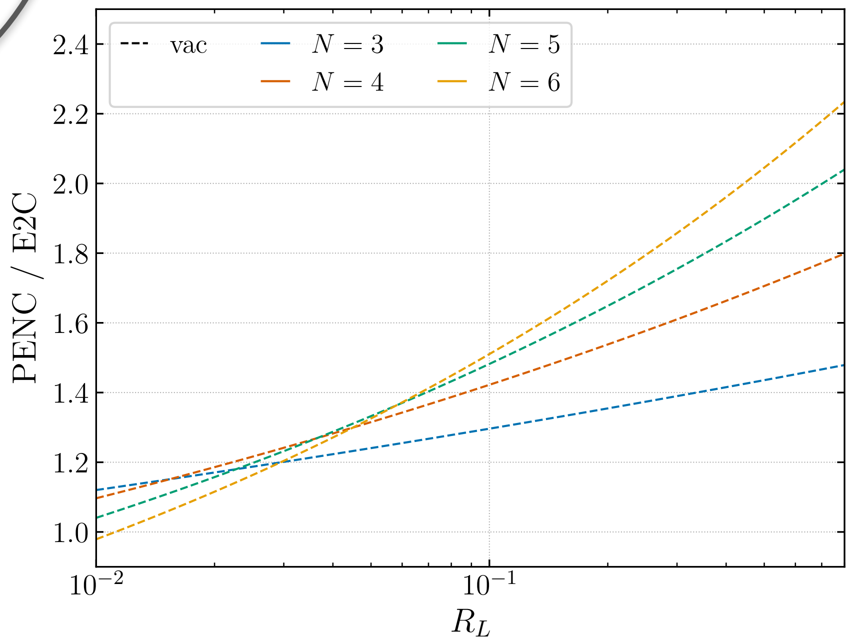
First focus on a simpler object: the **projected ENC (PENC),** i.e. only the largest angular distance (R_L) is fixed.

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

[Dixon et al, arXiv: 1905.01310]

only need the $1 \to 2$ **vacuum** splitting function for the PENC

No classical flux added yet!



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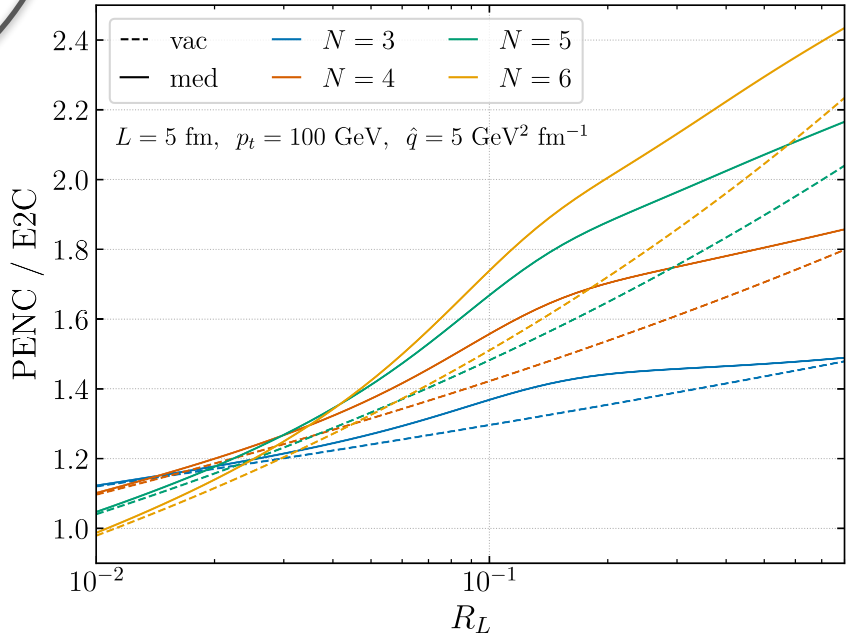
only need the 1 → 2 **medium** splitting function for the PENC

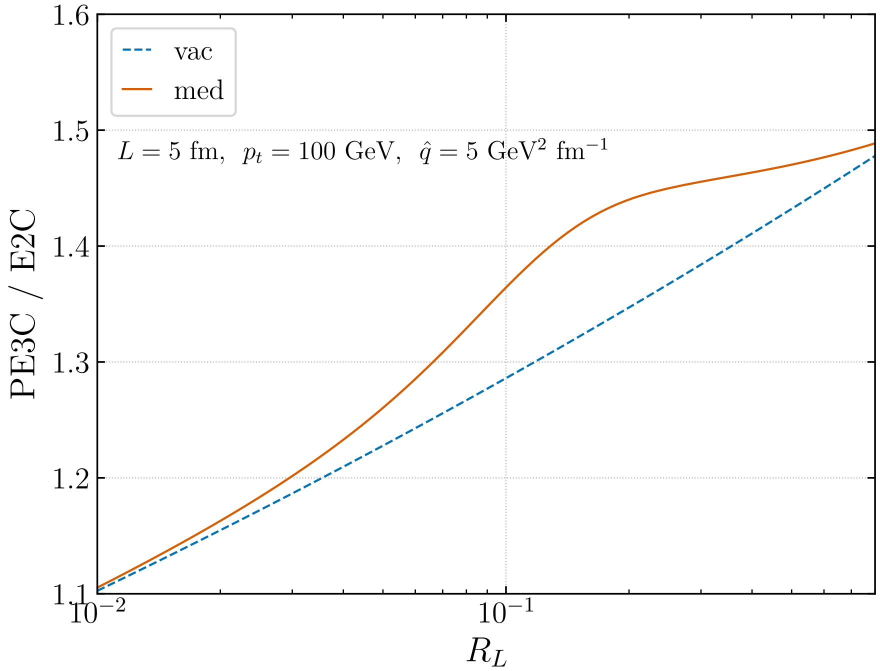
No classical flux added yet!



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

Full PE3C

Focus on the **PE3C**. What happens if we add a classical/uncorrelated energy flow?



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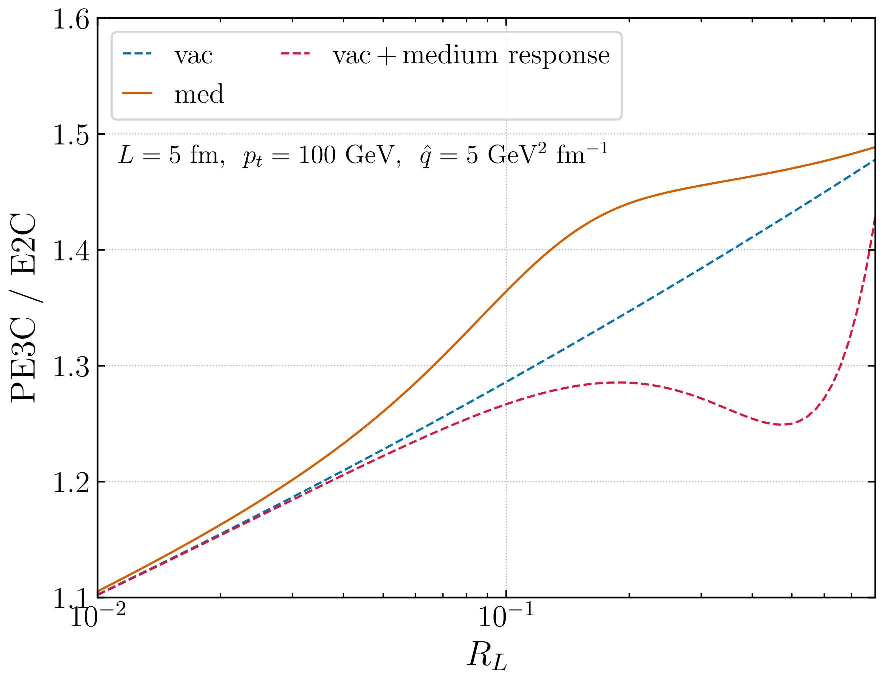

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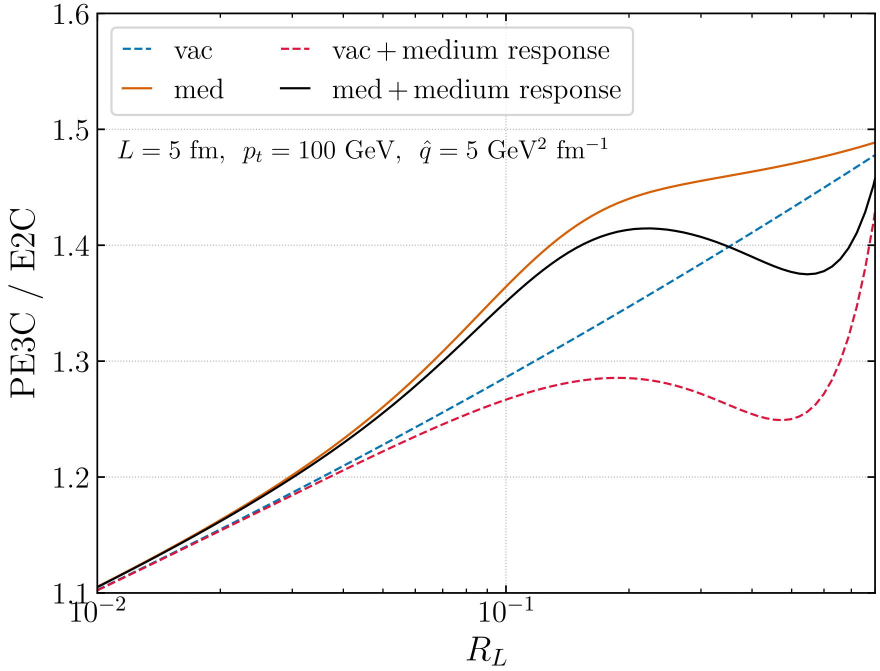
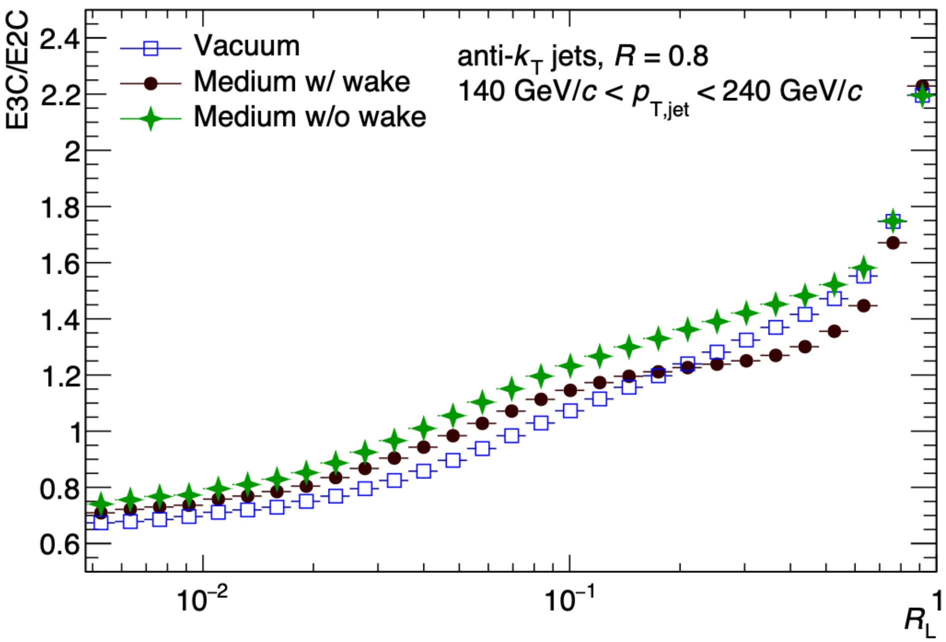
[Bossi et al., JHEP, 2024]

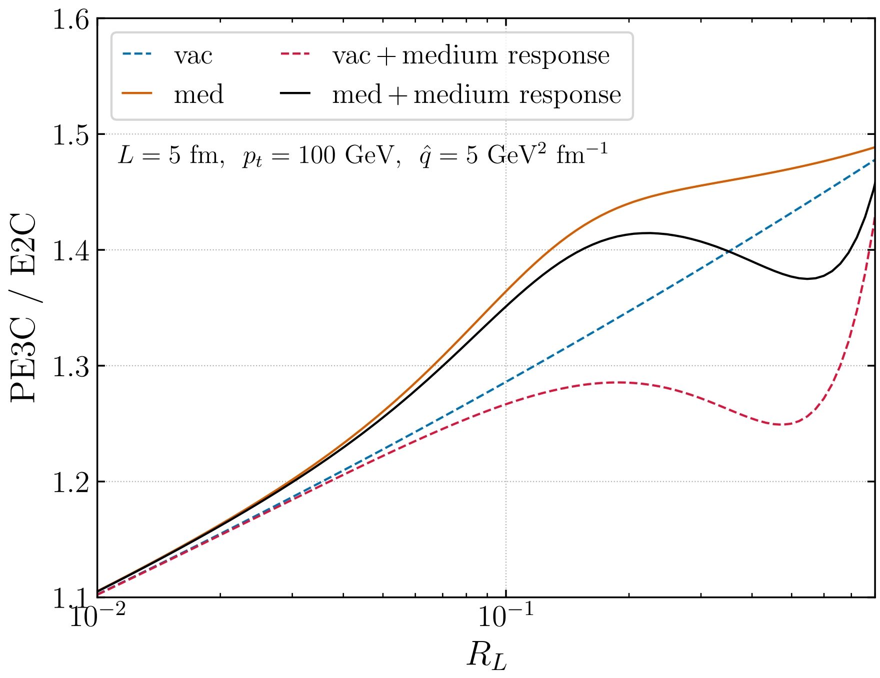




Our simple physical picture of a classical energy flow is in <u>**qualitative**</u> agreement with, e.g., the Hybrid model.

Full PE3C: collinear limit

Focus on the **PE3C**. What is the behaviour in the collinear limit?



Vacuum OPE

$$\boxed{\frac{d\Sigma^{(N)}_{\mathrm{P,vac}}}{dR_L} = \sum_{k=1} a^{\mathrm{P}(N)}_{\tau,0} R_L^{\tau-3}\Big|_{\tau=2k}}$$

Collinear limit of perturbative modification contribution

$$\boxed{\frac{d\Sigma^{(N)}_{\mathrm{P,\,med\,(no\,vac)}}}{dR_L} = \sum_{k=2} b^{\mathrm{P}(N)}_{\tau,0}(\omega_c/p_t, \theta_c) R_L^{\tau-3}\Big|_{\tau=2k}}$$

Collinear limit of classical flux contribution

$$\boxed{\frac{d\Sigma^{(N)}_{\mathrm{P,\,response}}}{dR_L} = \sum_{k=2} c^{\mathrm{P}(N)}_{\tau}\left[\mathcal{E}_c\right] R_L^{\tau-3}\Big|_{\tau=2k}}$$

Full PE3C: collinear limit

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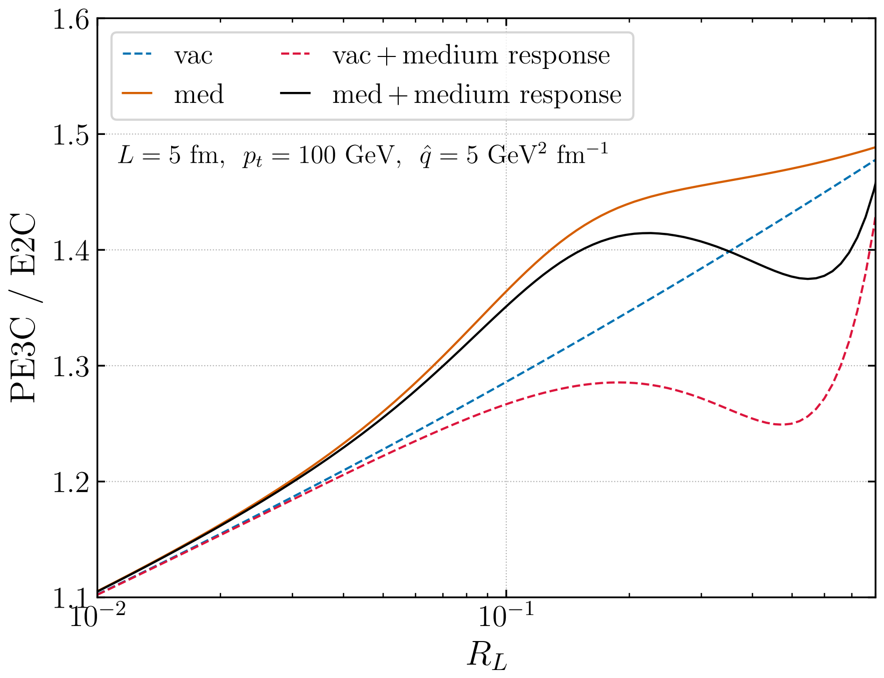


$$\frac{d\Sigma_P^{(3)}}{dR_L} = \frac{a_{2,0}^{P(3)}}{R_L} + \left(a_{4,0}^{P(3)} + b_{4,0}^{P(3)} + c_4^{P(3)}\right) R_L + \ldots$$

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**

E3C in a medium

Let us go beyond the PE3C to study the **full angular structure** of the E3C, differential in (R_L, ξ, ϕ).
We first change coordinates from the 3 angles $(R_L > R_M > R_S)$ to a more convenient set:

$$(R_L, R_M, R_S) \to (R_L, \xi, \phi) \qquad \xi = R_S/R_M \qquad \sin^2\phi = 1 - (R_L - R_M)^2/R_S^2$$

[Komiske, Moult, Thaler, Zhu, 2201.07800]

Let us focus only on the fully perturbative contribution to the E3C:

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

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

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

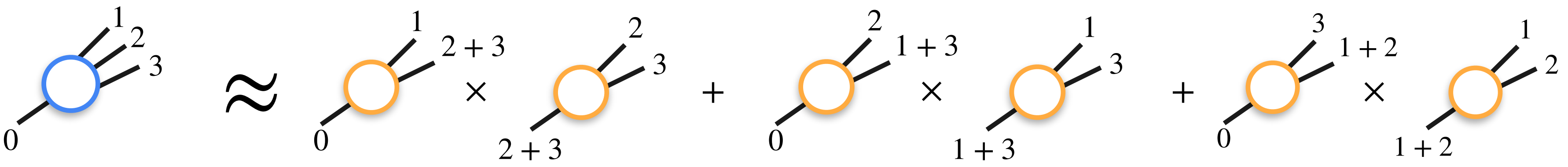
[Catani, Grazzini, hep-ph/9810389]

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:

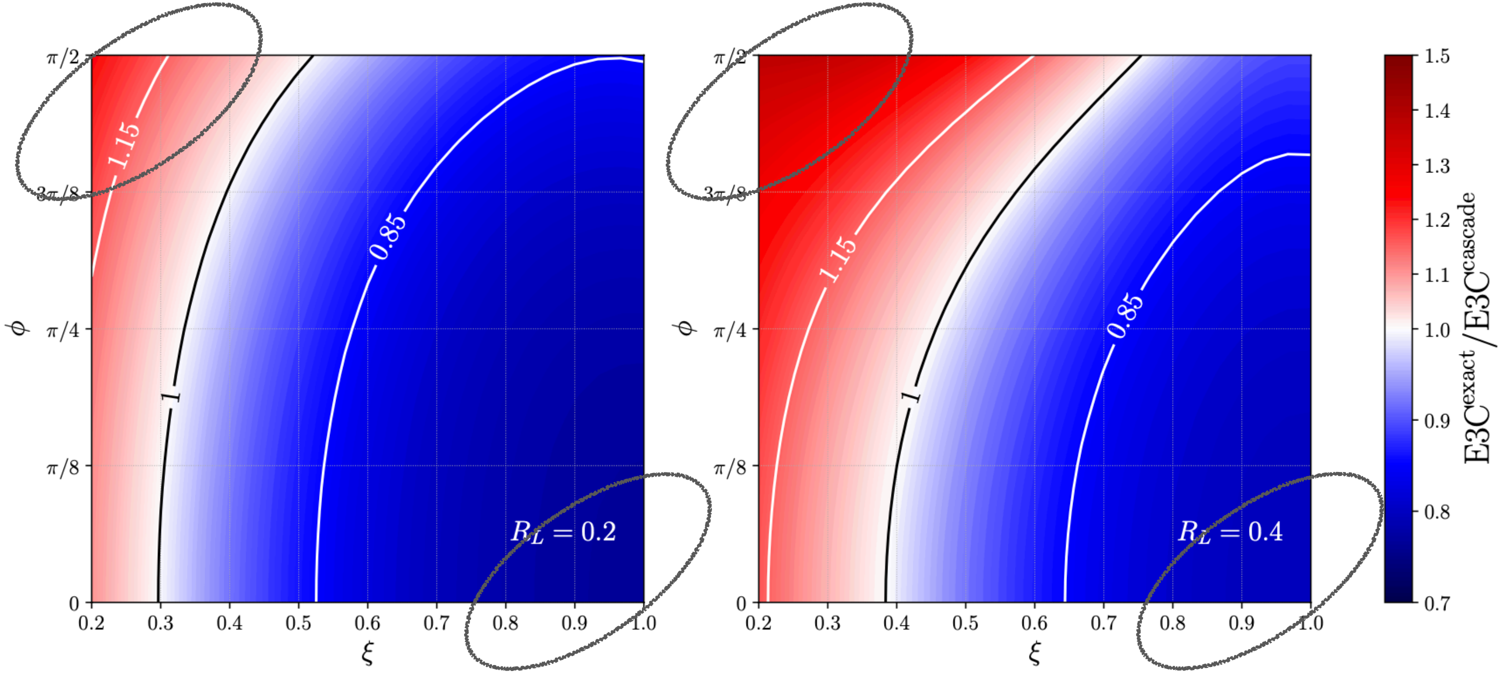


$$\frac{P_{0\to123}}{s_{123}} \approx \frac{P_{0\to1(2+3)}P_{(2+3)\to23}}{s_{1,(2+3)}} + \frac{P_{0\to2(1+3)}P_{(1+3)\to13}}{s_{2,(1+3)}} + \frac{P_{0\to3(1+2)}P_{(1+2)\to12}}{s_{3,(1+2)}}$$

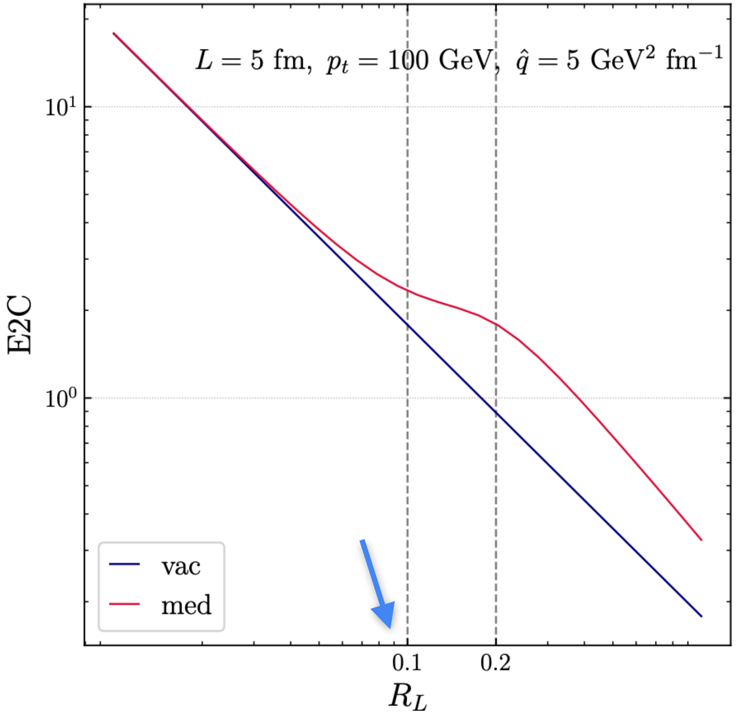
Naturally, it misses out on <u>interferences</u> which are only included in the full $1 \to 3$ splitting function.

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

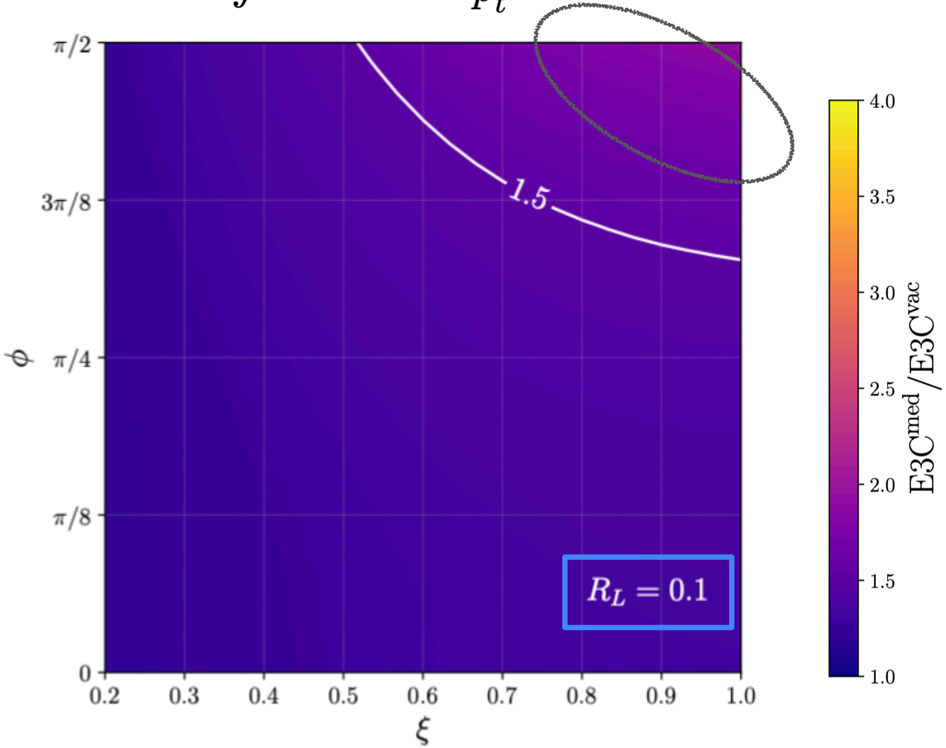
How well does the cascade approximation work in vacuum?



E3C in a medium: results for *hhh*

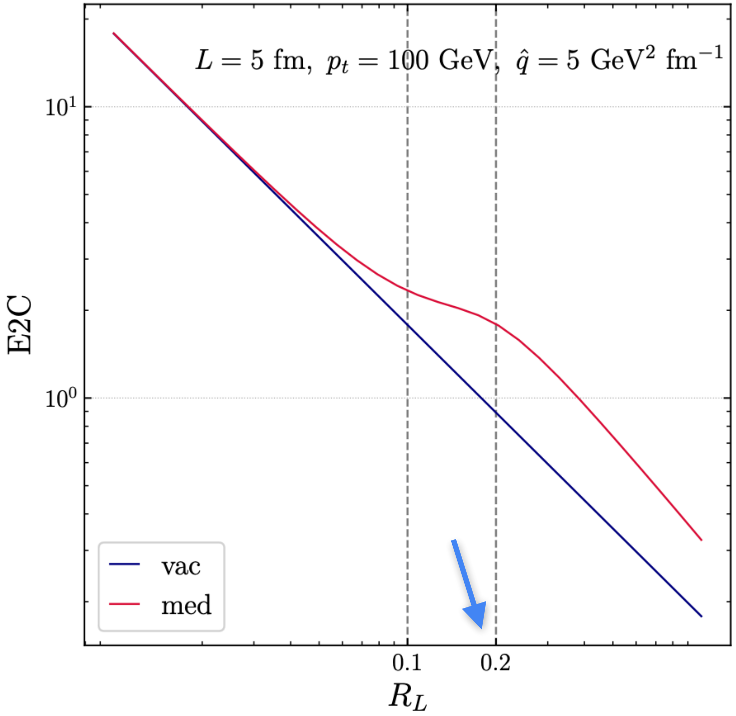


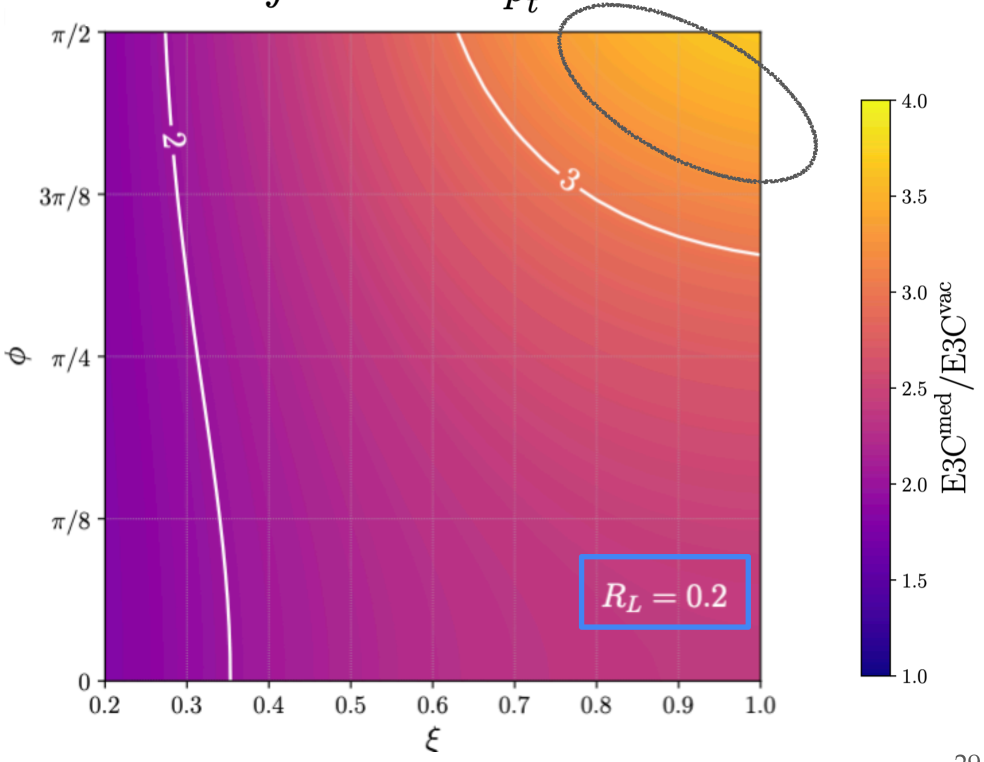
$$d\Sigma^{(3)}_{hhh} \sim \int \frac{\langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1)\hat{\mathcal{E}}_h(\boldsymbol{n}_2)\hat{\mathcal{E}}_h(\boldsymbol{n}_3)\rangle}{p_t^3}$$



E3C in a medium: results for *hhh*

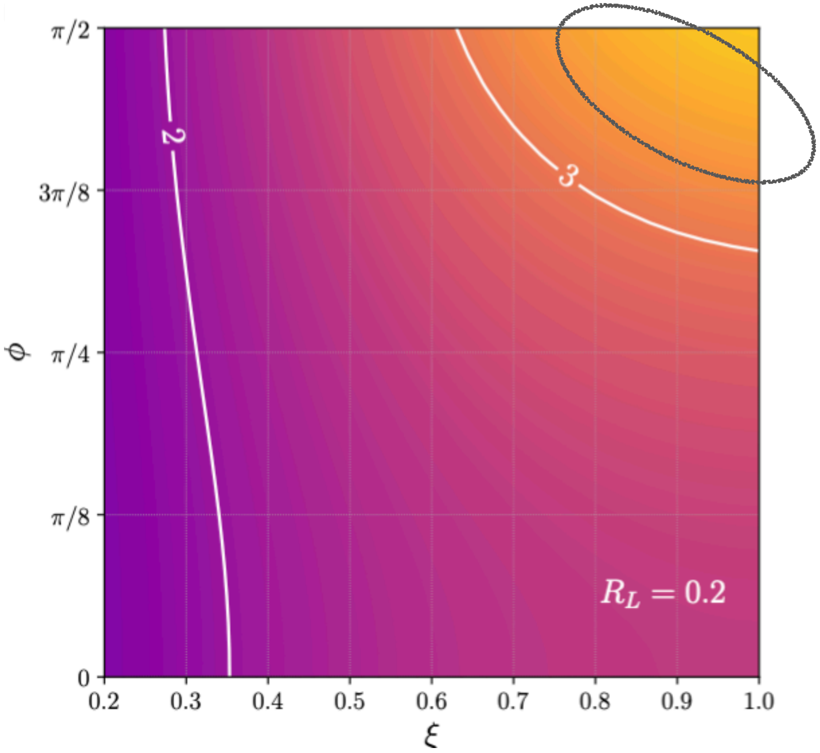
$$d\Sigma^{(3)}_{hhh} \sim \int \frac{\langle \hat{\mathcal{E}}_h(\boldsymbol{n}_1)\hat{\mathcal{E}}_h(\boldsymbol{n}_2)\hat{\mathcal{E}}_h(\boldsymbol{n}_3)\rangle}{p_t^3}$$



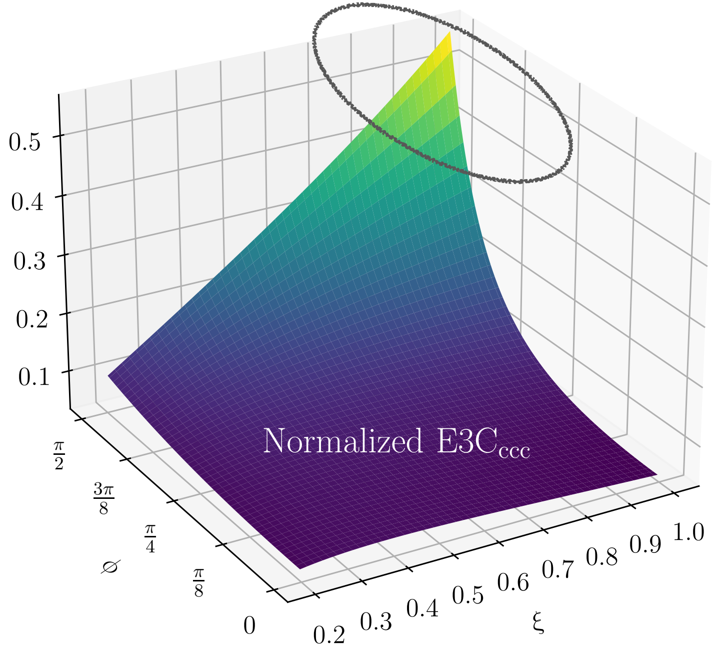


E3C in a medium: results for *hhh* and *ccc*

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



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



Directional properties $\leftrightarrow$ even powers

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

- Only **odd powers** show up in the collinear expansion.
- Perturbative contributions necessarily result in odd powers.

Directional properties ↔ even powers

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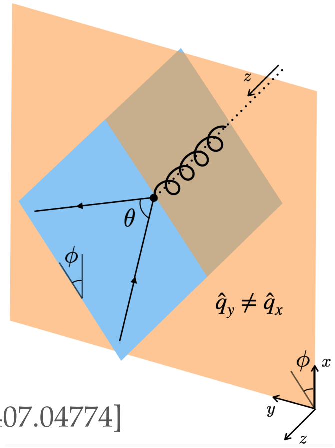
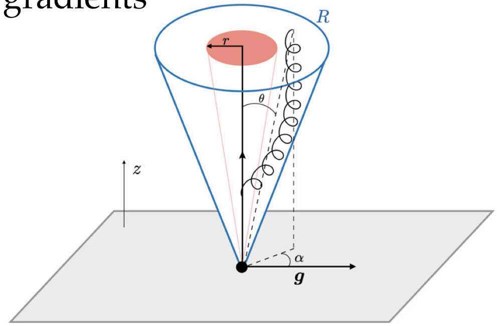
- Only **odd powers** show up in the collinear expansion.
- Perturbative contributions necessarily result in odd powers.
- Classical contribution can give rise to **even powers** for a medium with **directional effects**, e.g.:

momentum space anisotropies



[Barata, Salgado, JMS, 2407.04774]

spatial gradients



[Barata, Milhano, Sadofyev, 2308.01294]

See also e.g.
[Antiporda, Bahder, Rahman, Sievert, 2110.03590]
[Sadofyev, Sievert, 2207.07679]
[Barata, Lopez, Sadofyev, Salgado, 2304.03712]

Summary and outlook

Summary:

- Uncorrelated / classical energy fluxes leave universal imprints on energy correlators;
- These imprints are determined by **geometrical correlations** rather than by the exact functional form of the classical flux;
- **Classical (includes medium response) and perturbative contributions overlap** in both PE3C and E3C - only by accounting for both can one systematically extract information about the medium.

Outlook:

- **Even powers** of the collinear expansion of PENCs can give access to **directional properties of the medium.**

THANKS!