Energy Correlators in pp and AA

3rd June 2024, LHCP24

João Barata, BNL

Disclaimer

1) I will focus on the recent progresses in AA

2) I will focus on the collinear limit of Energy Correlators

Some other developments:

See Ian Moult's talk this evening for more details

Strong coupling extraction: [1804.09146, 2201.07800]

Deadcone effect: [2210.09311, 2307.15110]

Higher precision calculation: [2210.09311,2312.16408, 2011.02492]

Nuclear EC: [2102.05669, 2209.02080]

Track functions: [2210.10058, 2308.00746]

Spin correlations: [2011.02492, 2103.16526]

TEEC: [2006.02437, 2312.16408,2311.17142]

Top mass: [2011.02492, 2103.16526]

Power corrections: [hep-ph/9902341, 2305.19311]

… and many more works

See also:

Talks by Holguin, Andres

Posters by Bossi, Rai

Next talk by Simon on exp results

A brief history of ECs

Brookhaven National Laboratory

70's, QCD

Energy Correlations in Electron-Positron Annihilation: Testing Quantum Chromodynamics

C. Louis Basham, Lowell S. Brown, Stephen D. Ellis, and Sherwin T. Love
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 August 1978)

1-point correlator

$$\frac{d\Sigma}{d\Omega}=\sum_{N=2}^{\infty}\int\sum_{a=1}E_a^{-1}d^3p_a\,\frac{d^N\sigma}{E_1^{-1}d^3p_1\cdots E_N^{-1}d^3p_N}S_N\left[\sum_{b=1}^{N}\frac{E_b}{W}\delta(\Omega_b-\Omega)\right]$$

2-point correlator

$$\frac{d^2\Sigma}{d\Omega\,d\Omega'}=\sum_{N=2}^{\infty}\int\prod_{a=1}^{N}E_a^{-1}d^3p_a\,\frac{d^N\sigma}{E_1^{-1}d^3p_1\cdots E_N^{-1}d^3p_N}S_N\left[\sum_{b,c=1}^{N}\frac{E_bE_c}{W^2}\delta(\Omega_b-\Omega)\delta(\Omega_c-\Omega')\right]$$

- N-particle cross-section
- Energy weighting
- Restricted angular region
- Form pairs out of N partons

It should be emphasized that the measurement of the energy cross section, Eq. (1), *does not require any detailed event-by-event analysis* as is the case for tests which specify a quantity involving the definition of a jet axis in each event.[5]

A brief history of ECs

90's to today, formal QFT/CFT

Jets and Quantum Field Theory

N.A.Sveshnikov [a] and F.V.Tkachov [b]

Conformal collider physics: Energy and charge correlations

Diego M. Hofman[a] and Juan Maldacena[b]

Many more works from formal QFT: Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, Kravchuk, Simmons-Duffin, Kologlu, Dixon, Luo, Sterman, …

at high energies. We argue that from the point of view of general quantum field theory, all information about the multijet structure is contained in the values of a family of multiparticle quantum correlators that can be expressed in terms of the energy–momentum tensor.

In summary: *The small angle behavior of the energy correlation functions is determined by the spin $j = 3$ non-local operators that appear in the OPE*

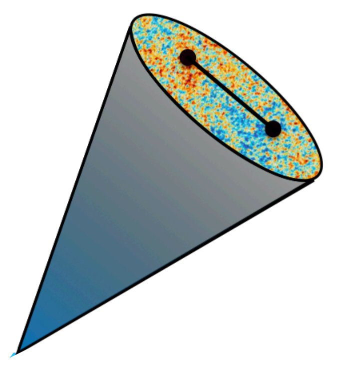
$$\langle \mathcal{E}(\theta_1)\mathcal{E}(\theta_2)\cdots\rangle \sim \sum |\theta_{12}|^{\tau_n - 4} \langle \mathcal{U}_{3-1,n}(\theta_2)\cdots\rangle \qquad (2.19)$$

The prototypical example: the EEC

Brookhaven National Laboratory

ECs boil down to measuring correlation functions of the **energy flow operator** $\mathcal{E}(\vec{n})$

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} \int dt\, r^2 n^i T^{0i}(t, r\,\vec{n}) \longrightarrow \langle 0|\bar{\psi}(x)\mathcal{E}(\vec{n_1})\mathcal{E}(\vec{n_2})\psi(0)|0\rangle$$



In the simplest case, we can consider the one dimensional projection

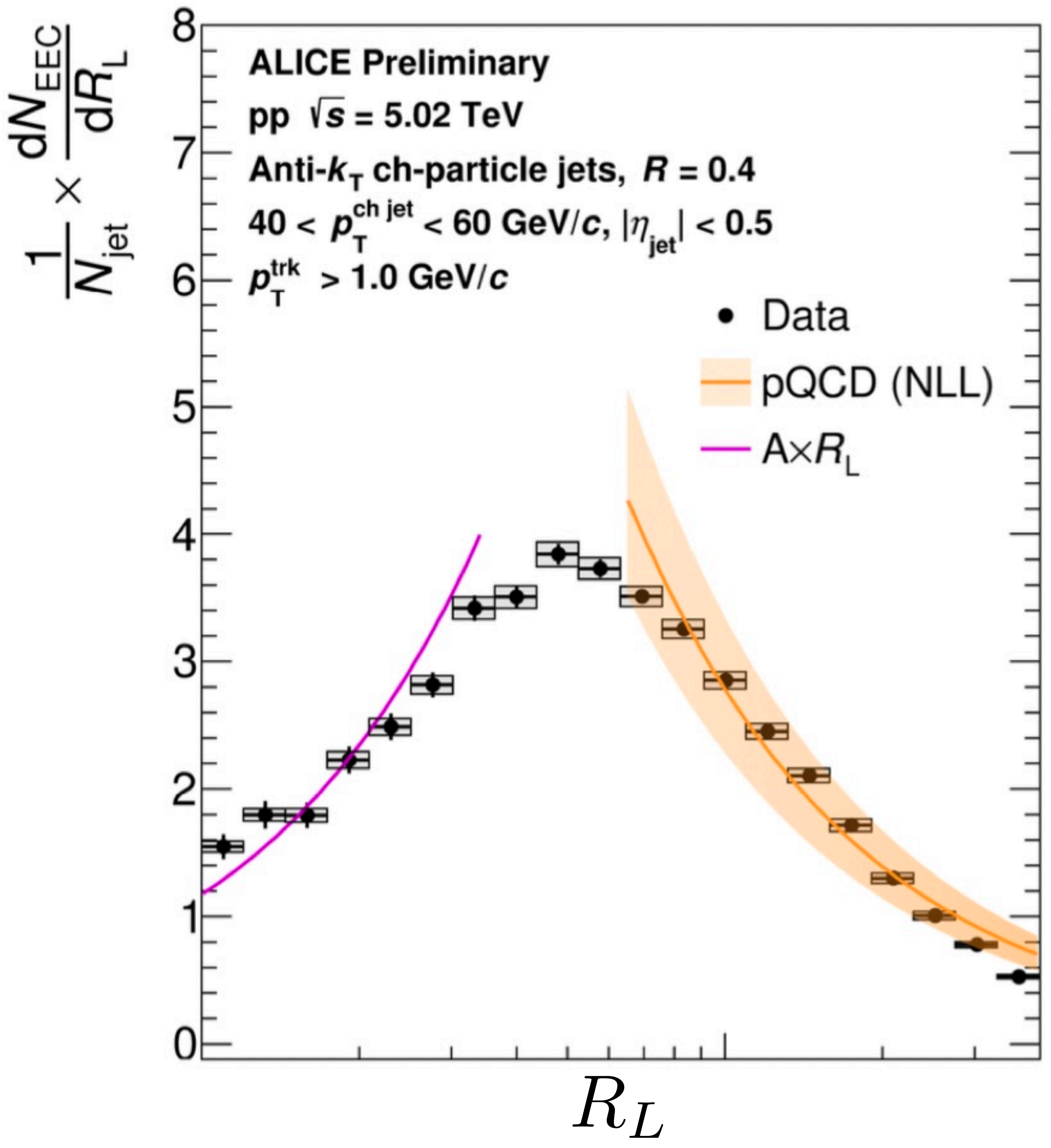
$$\frac{d\Sigma}{d\theta} = \int_{\vec{n}_1,\vec{n}_2} \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{p_t^2}\delta(\vec{n}_1\cdot\vec{n}_2 - \cos\theta) \longrightarrow \frac{d\Sigma}{d\theta} = \int_z \frac{d\sigma}{\sigma d\theta dz} z(1-z)$$

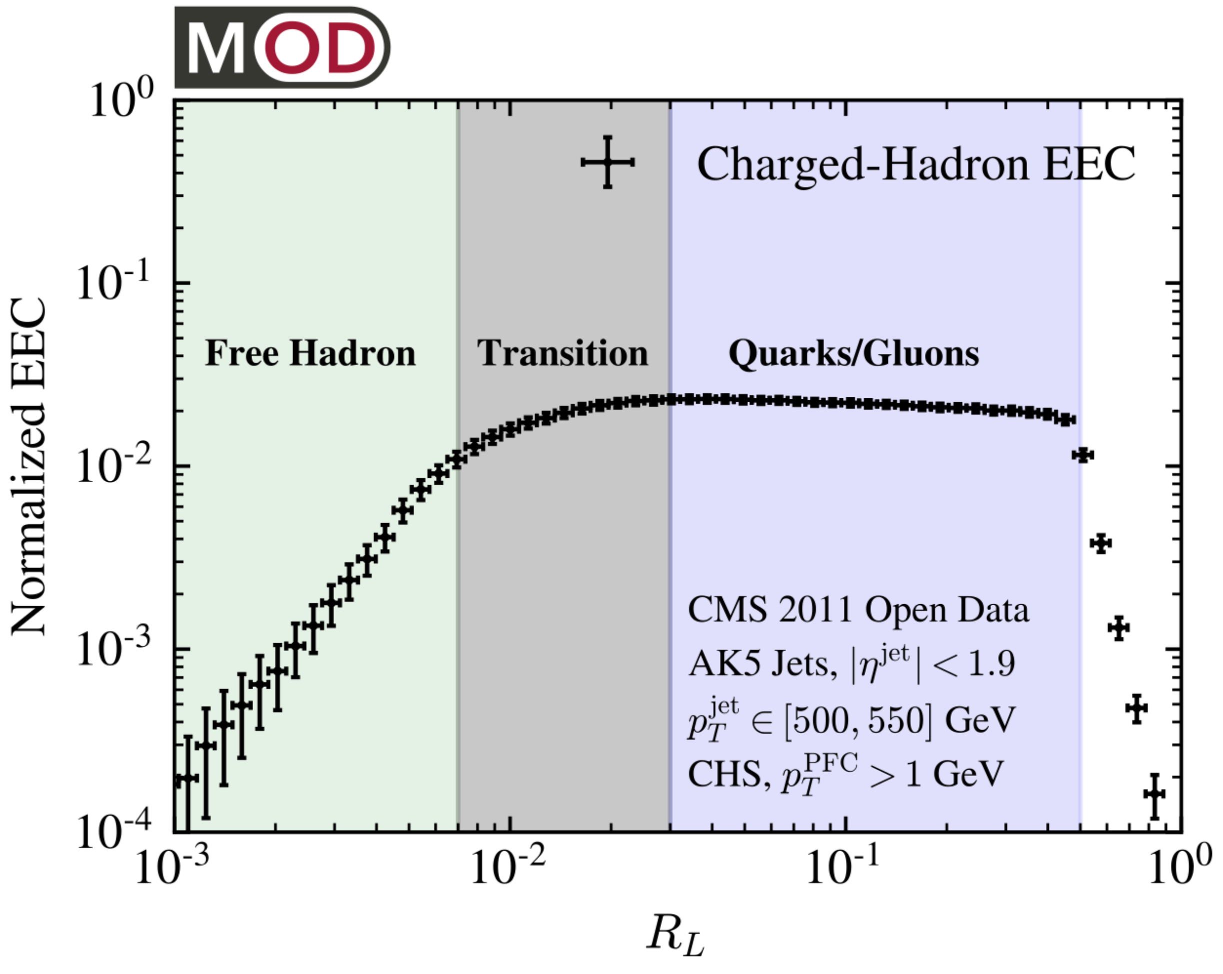
IR safe

$$\frac{d\sigma}{\sigma d\theta dz} \sim \frac{1}{\theta^\alpha}$$

at LO : $\alpha = 1$, deviations controlled by quantum theory

ECs in vacuum in the collinear limit



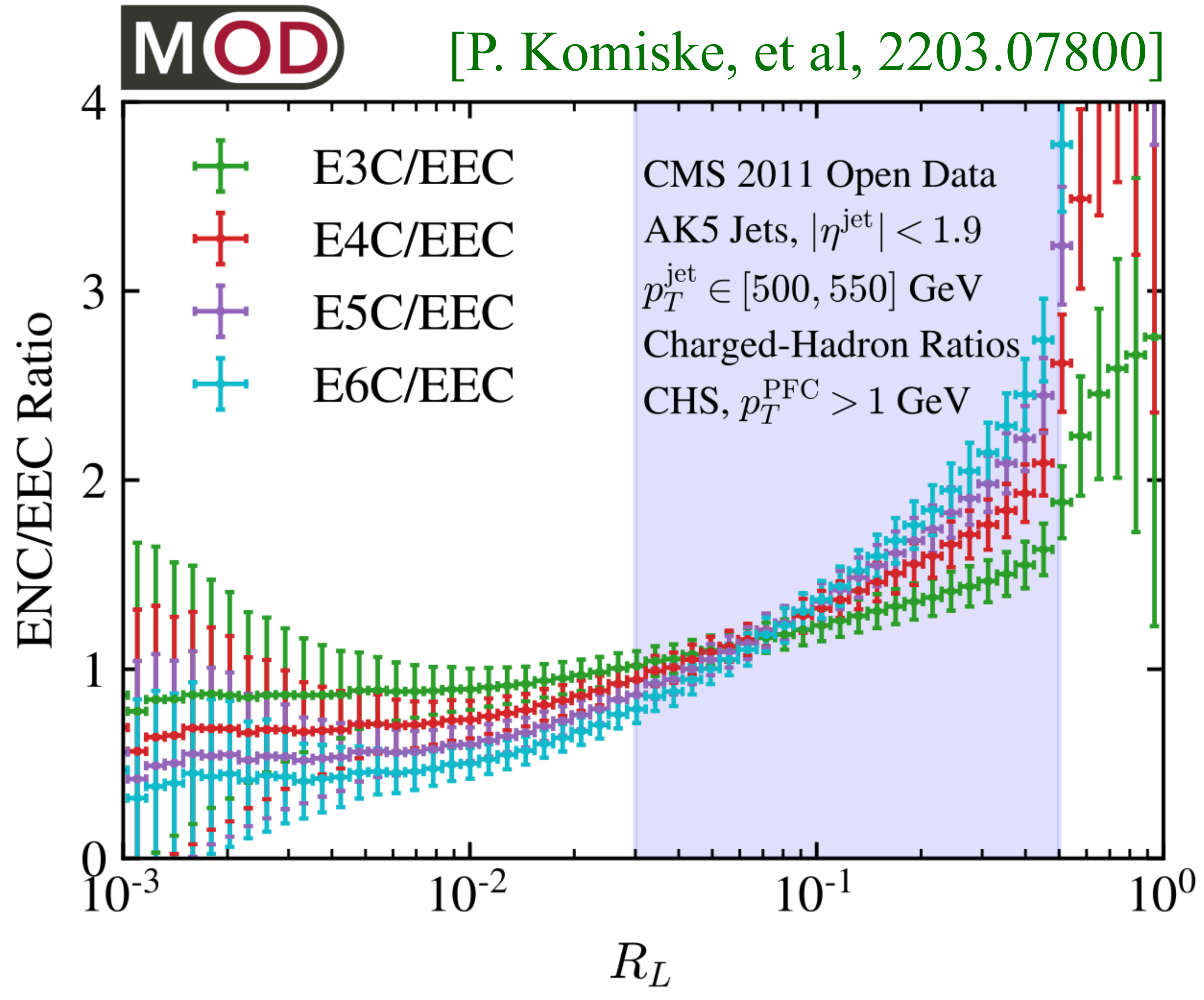


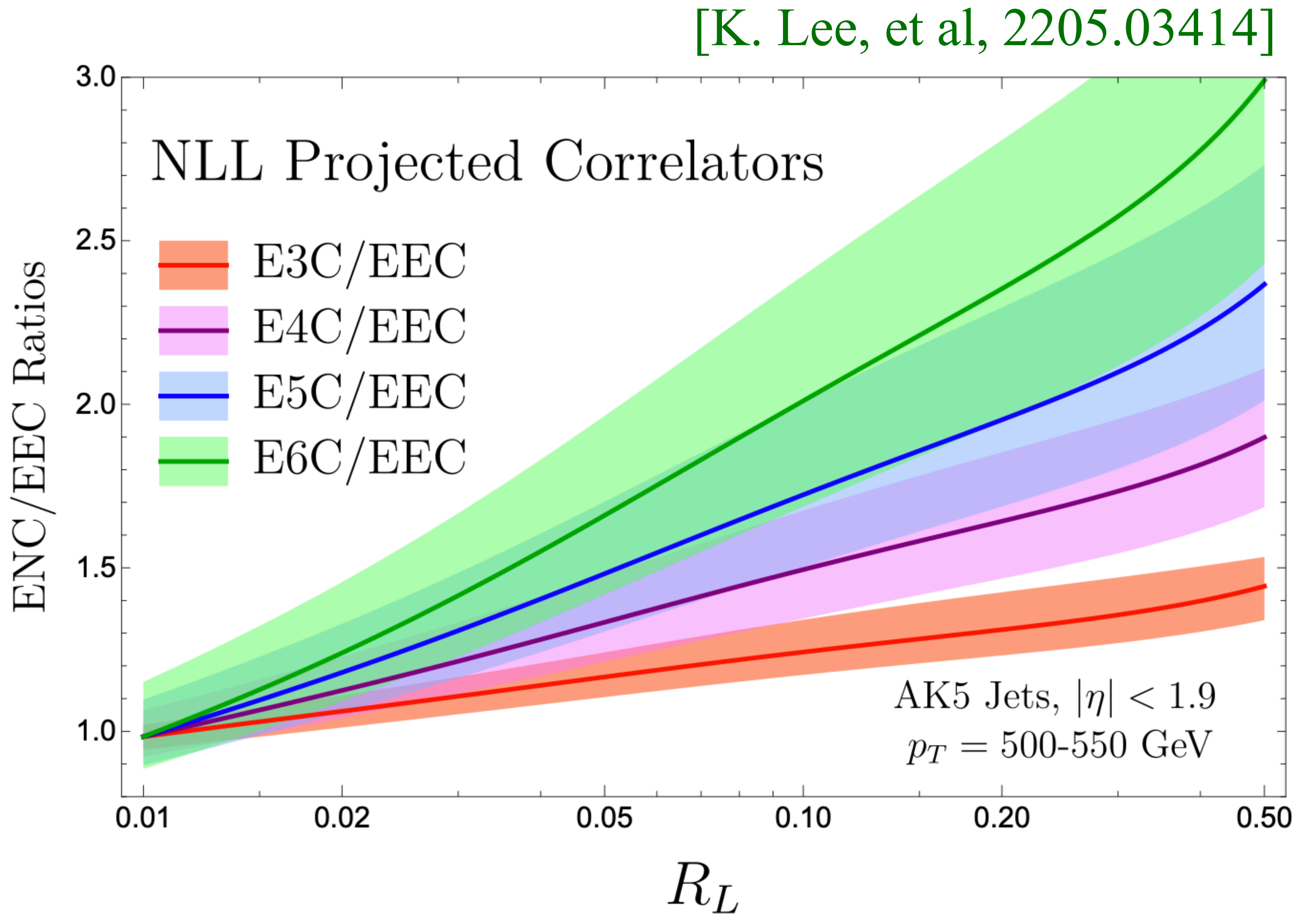
Clear visualization of hadronization transition

Allows for precision study of anomalous scaling in QCD

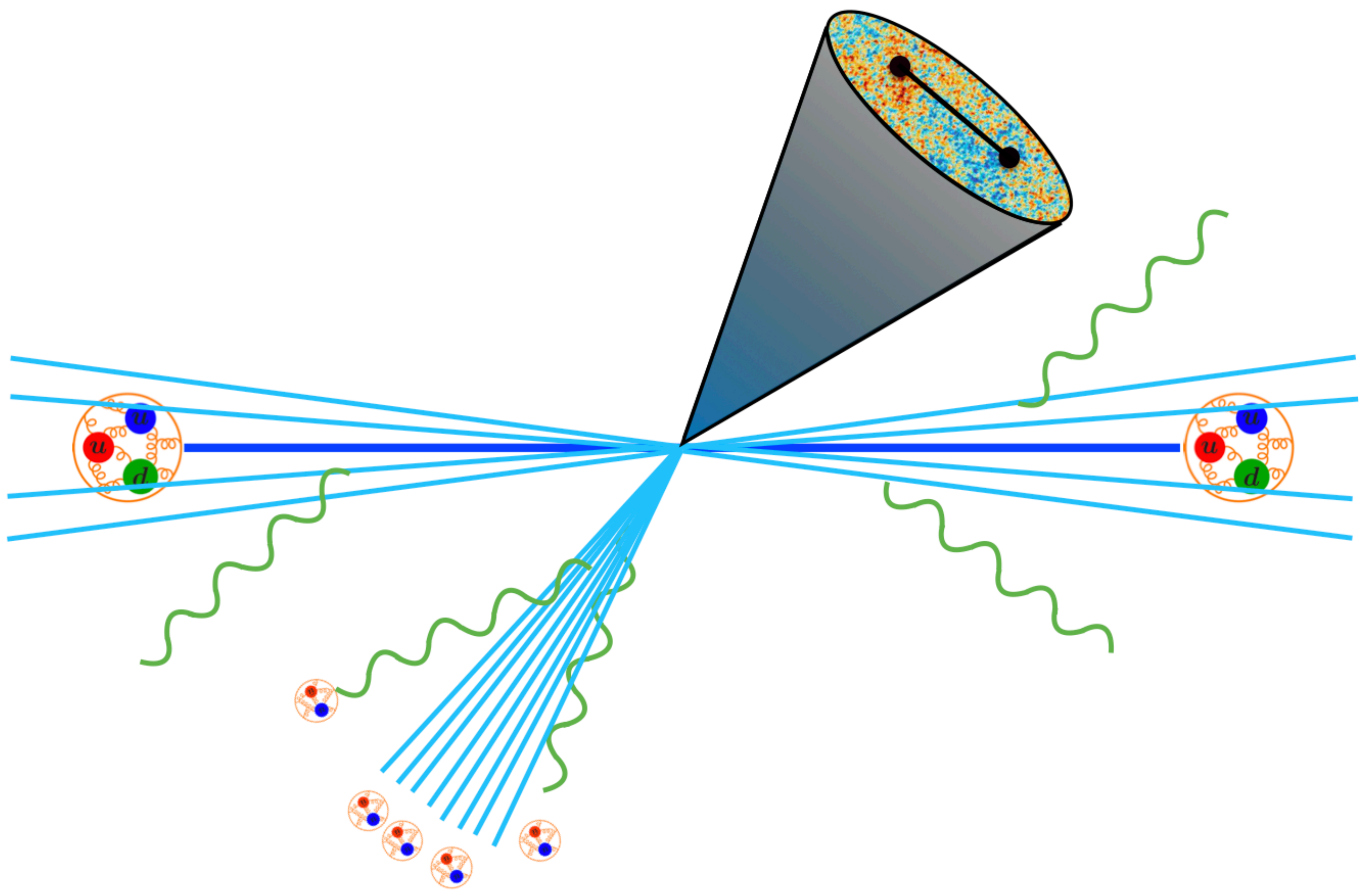
$$\frac{\text{ENC}}{\text{EEC}} \propto R_L^{\gamma(3+N)-\gamma(3)}$$

Scaling exponents have been computed in QCD to high precision !

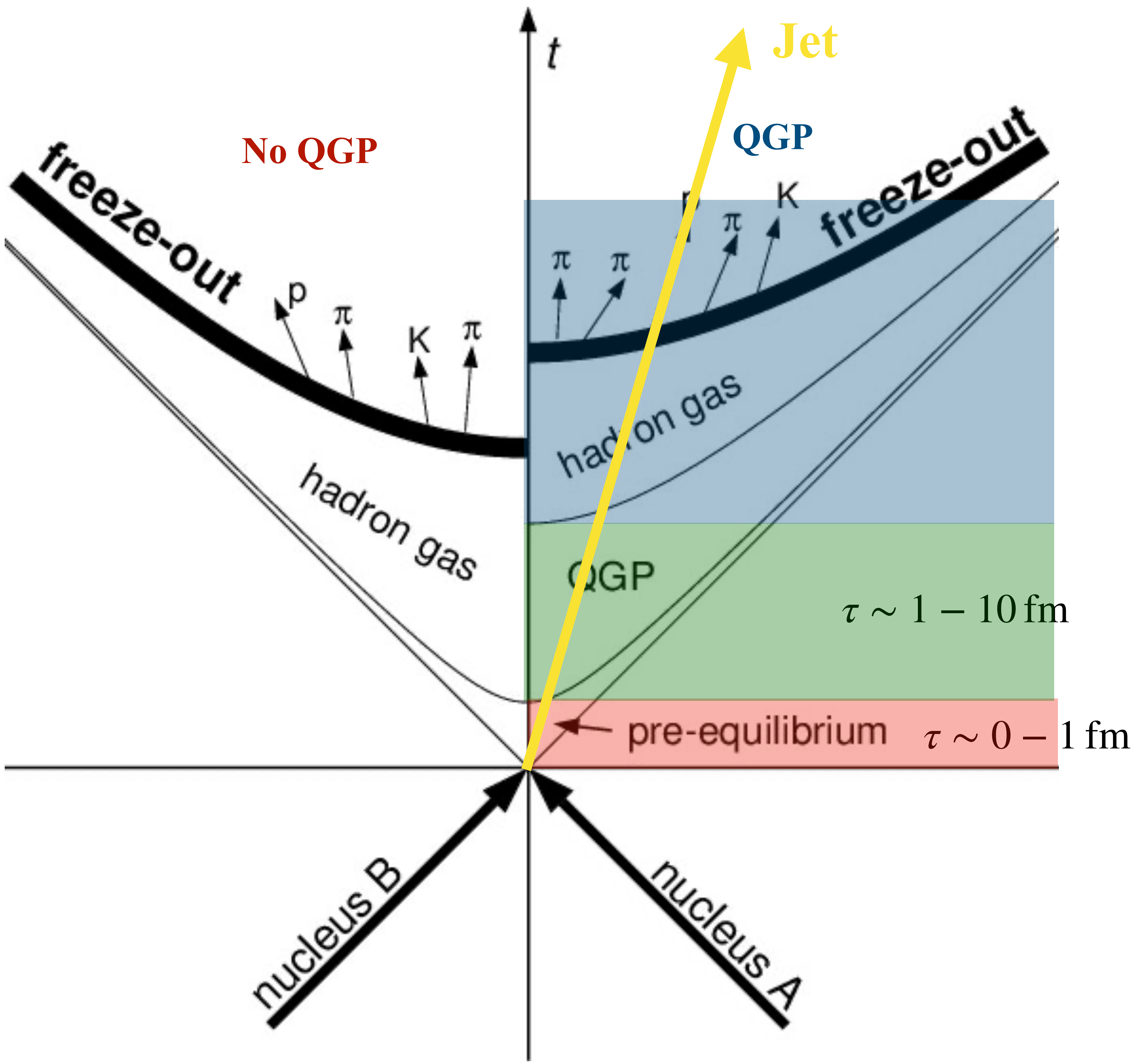




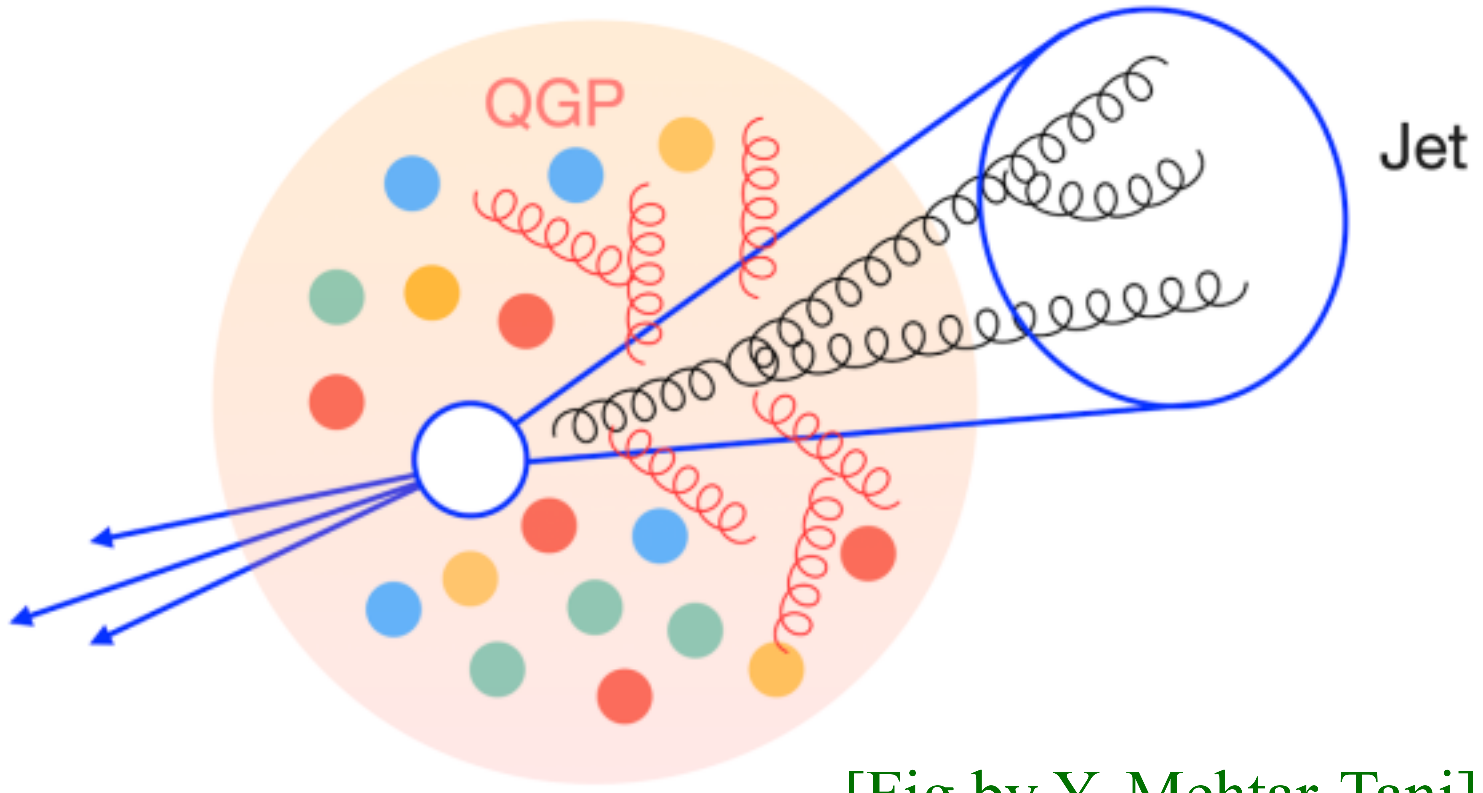
Energy correlators inside jets in heavy ions



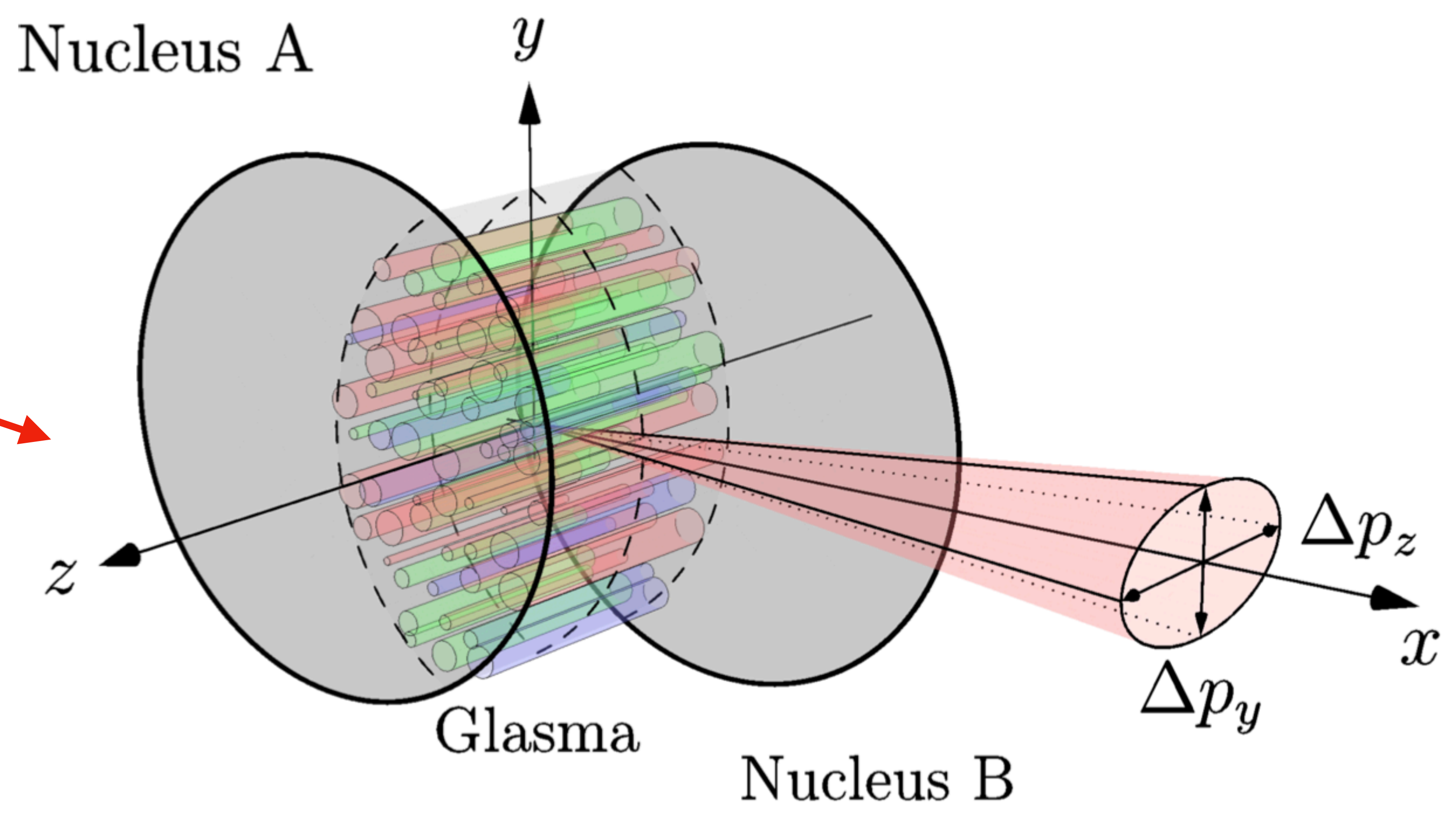
Jets in heavy ion collisions



An ideal probe: QCD jets



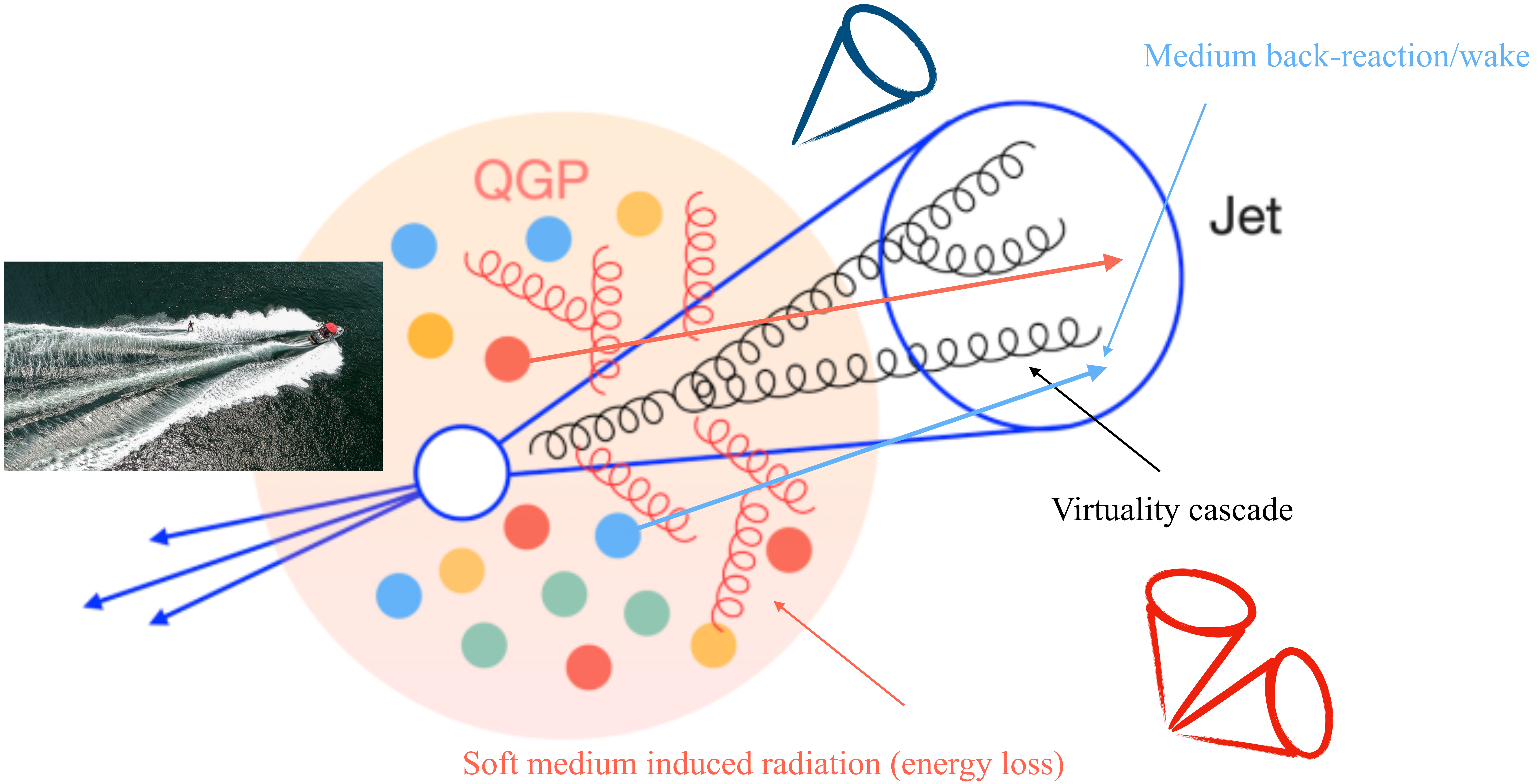
[Fig by Y. Mehtar-Tani]



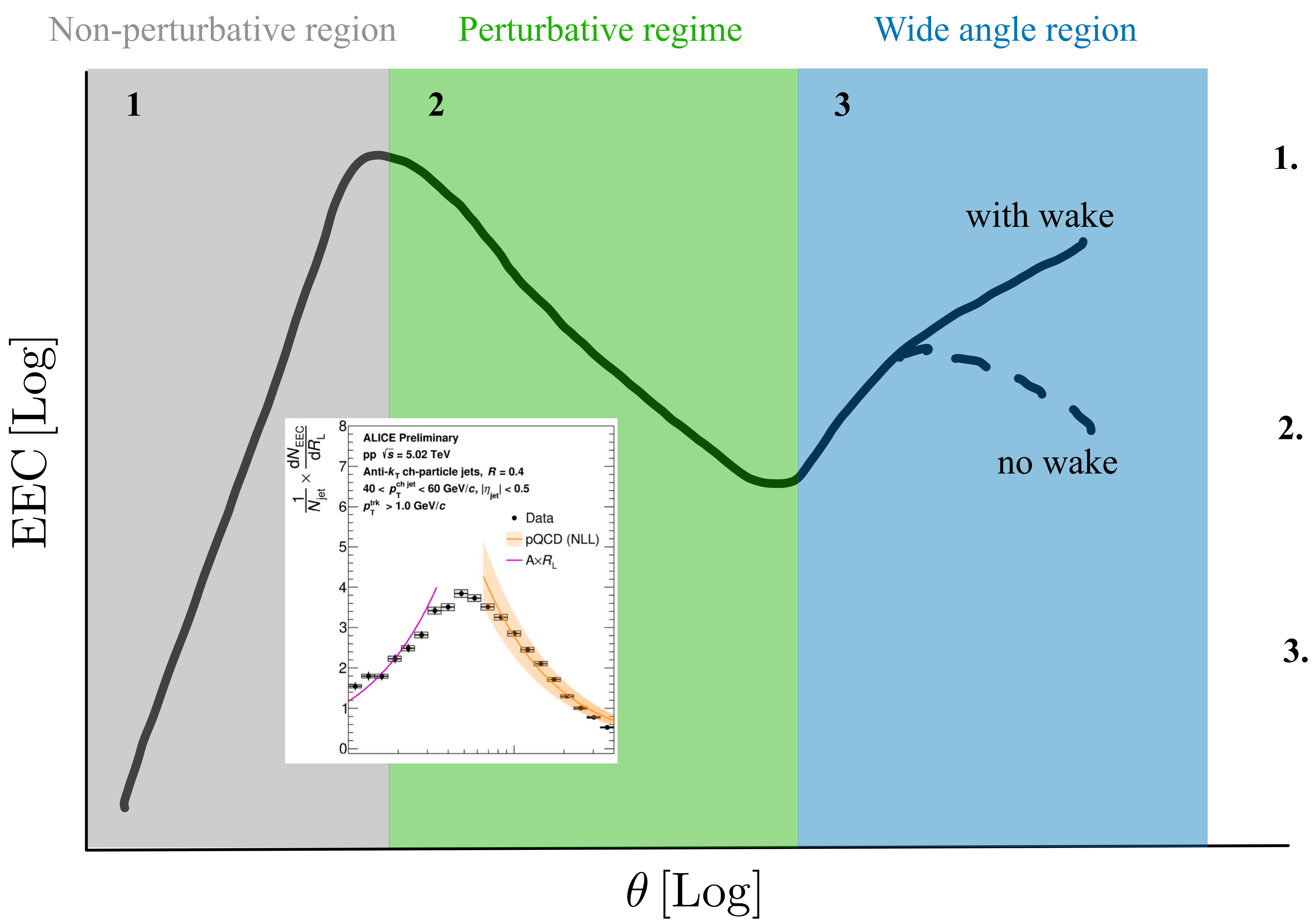
[2009.14206]

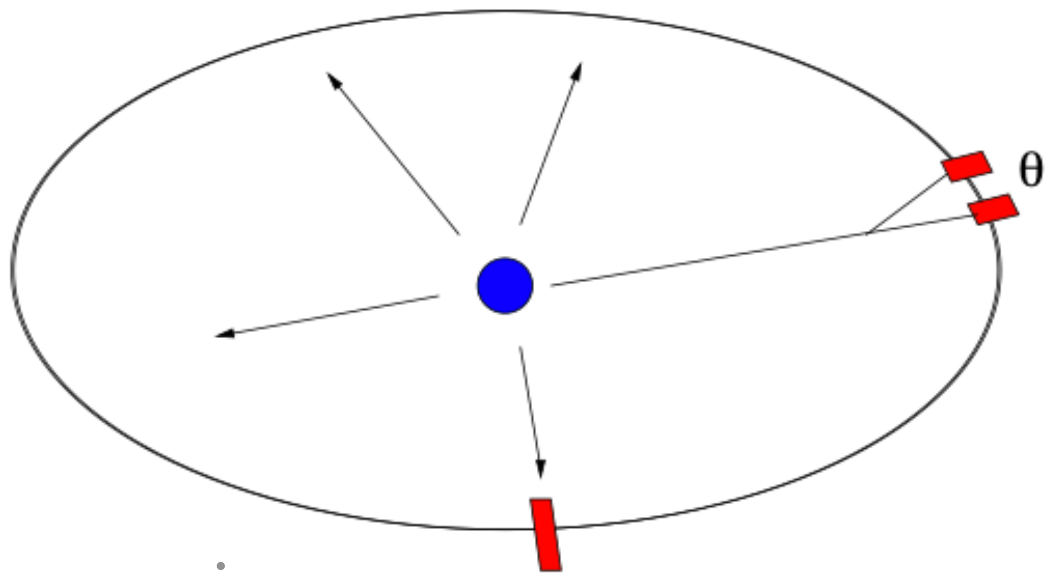
In-medium jet modifications

[See talk by Adam]



Energy correlators inside jets in heavy ions: what to expect





1. Non-perturbative region:

   Vacuum: sensitive to confinement transition

   In-medium: modifications to hadronization pattern, connection to QCD phase diagram (?), energy loss

2. Perturbative region:

   Vacuum: Described by γ_{ij} of the relevant spin-3 operators

   In-medium: pQCD computable jet modifications (?)

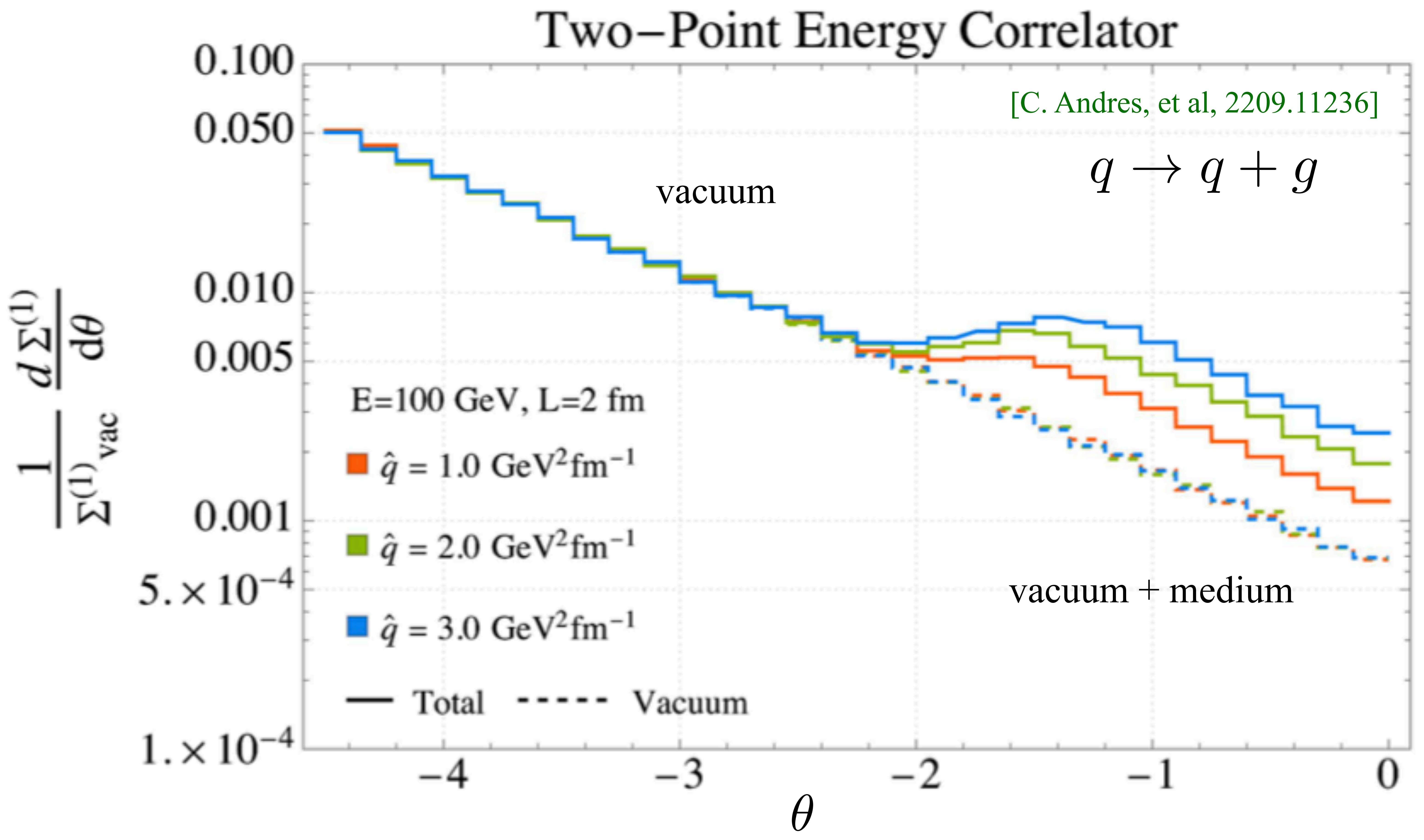
3. Wide angle region:

   Vacuum: no modification with respect to **2.**

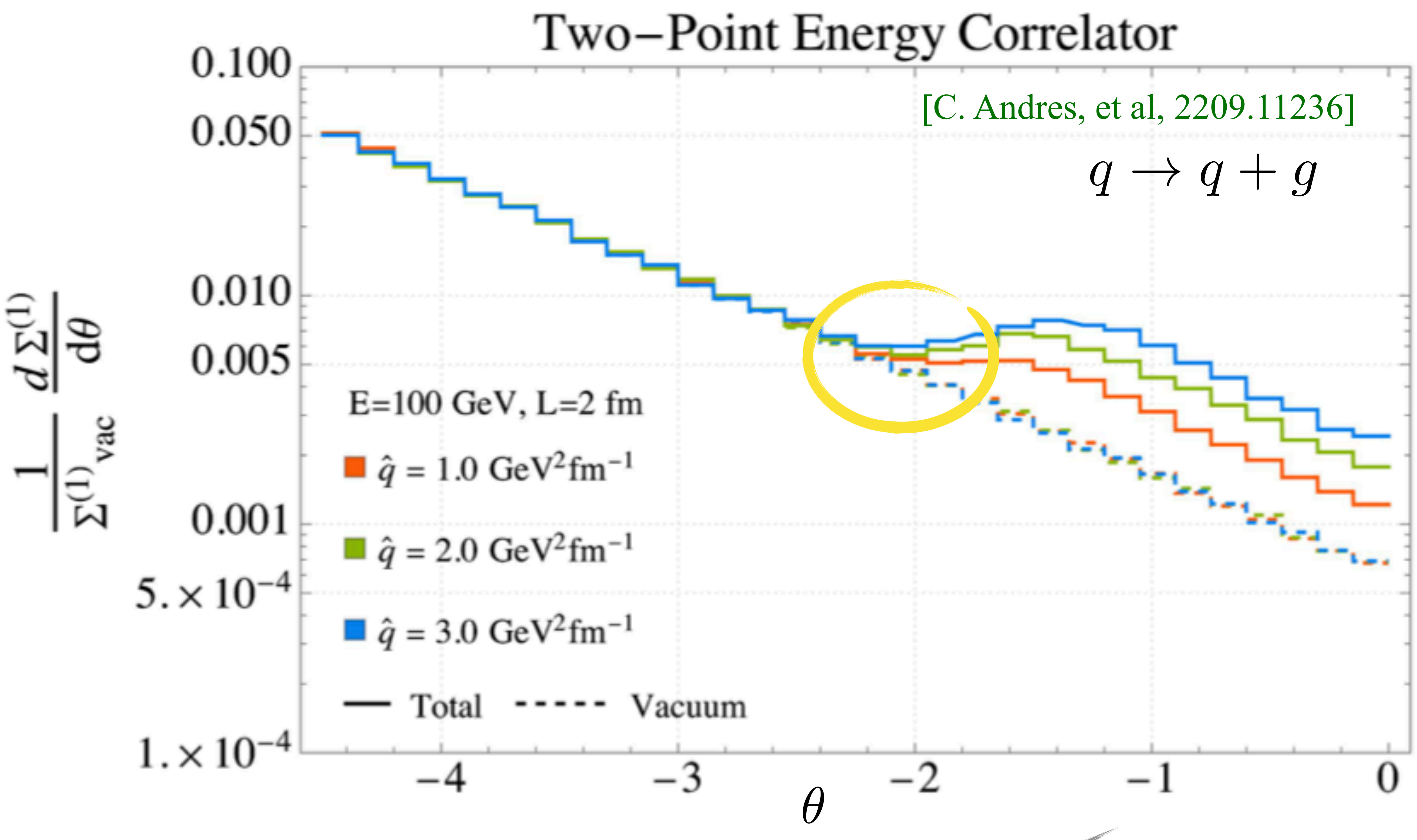
   In-medium: wake (?), non-perturbative soft-physics (?), perturbative medium modifications (?)

Critical step: make sense of **perturbative baseline** to access all regions

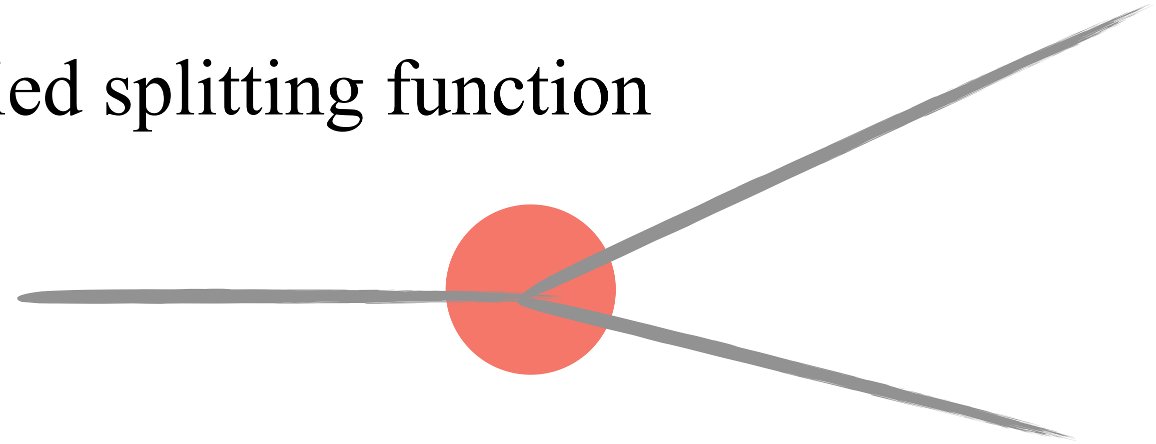
Energy correlators inside jets in heavy ions



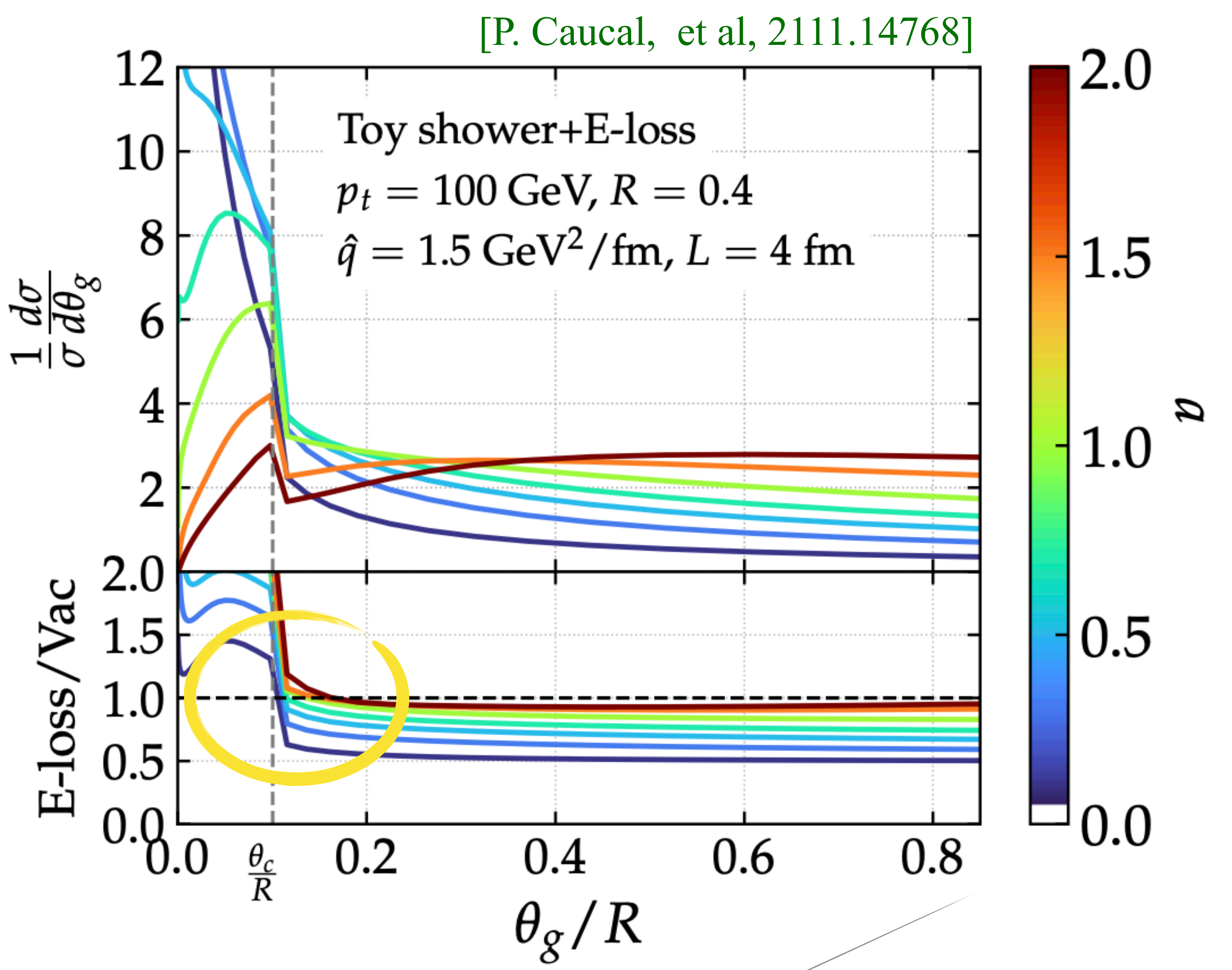
Energy correlators inside jets in heavy ions: some puzzles

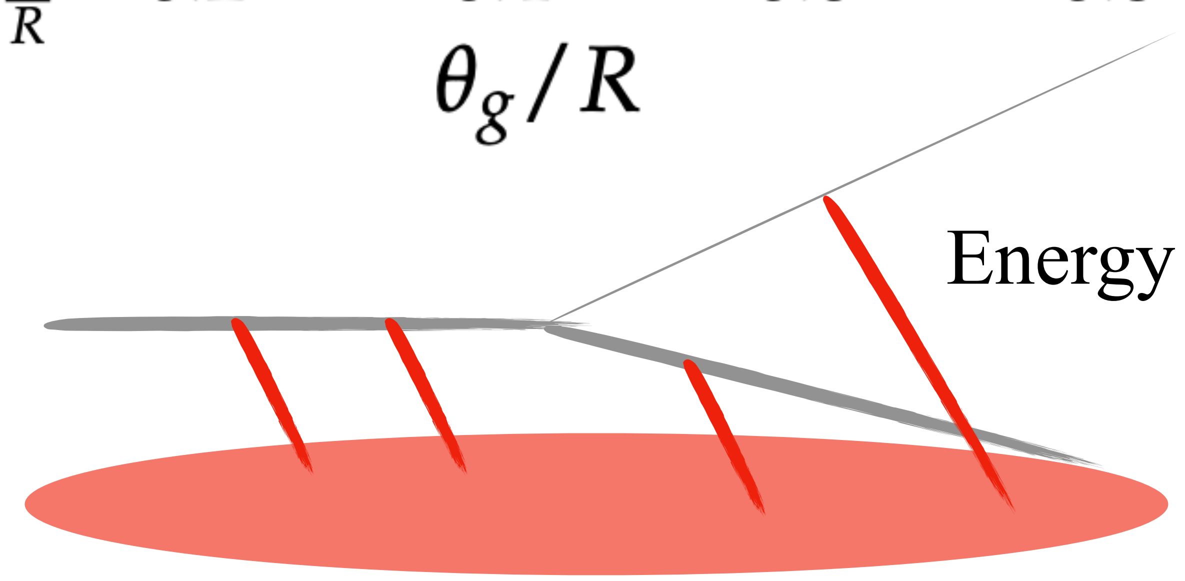


Modified splitting function



an example:

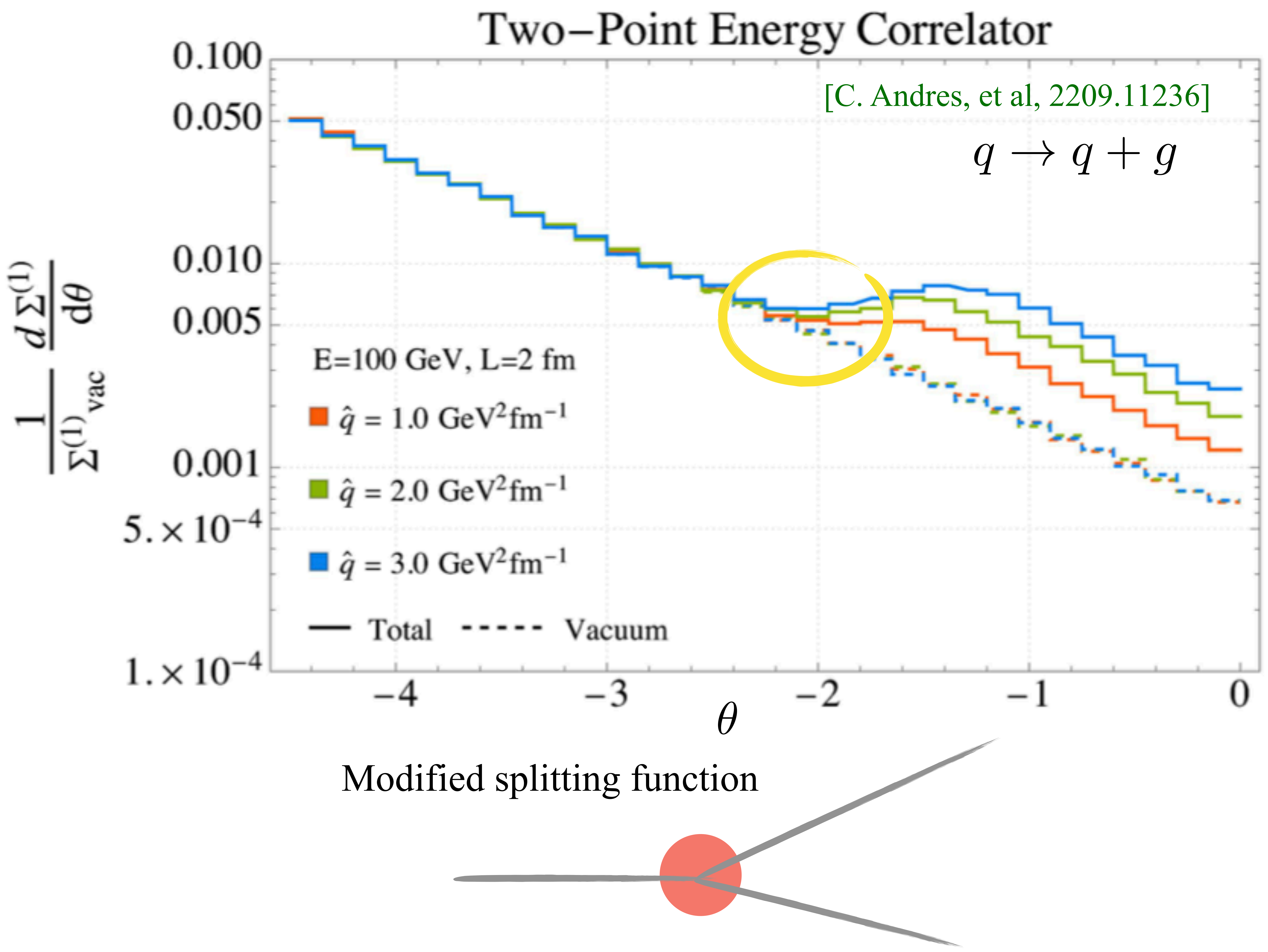


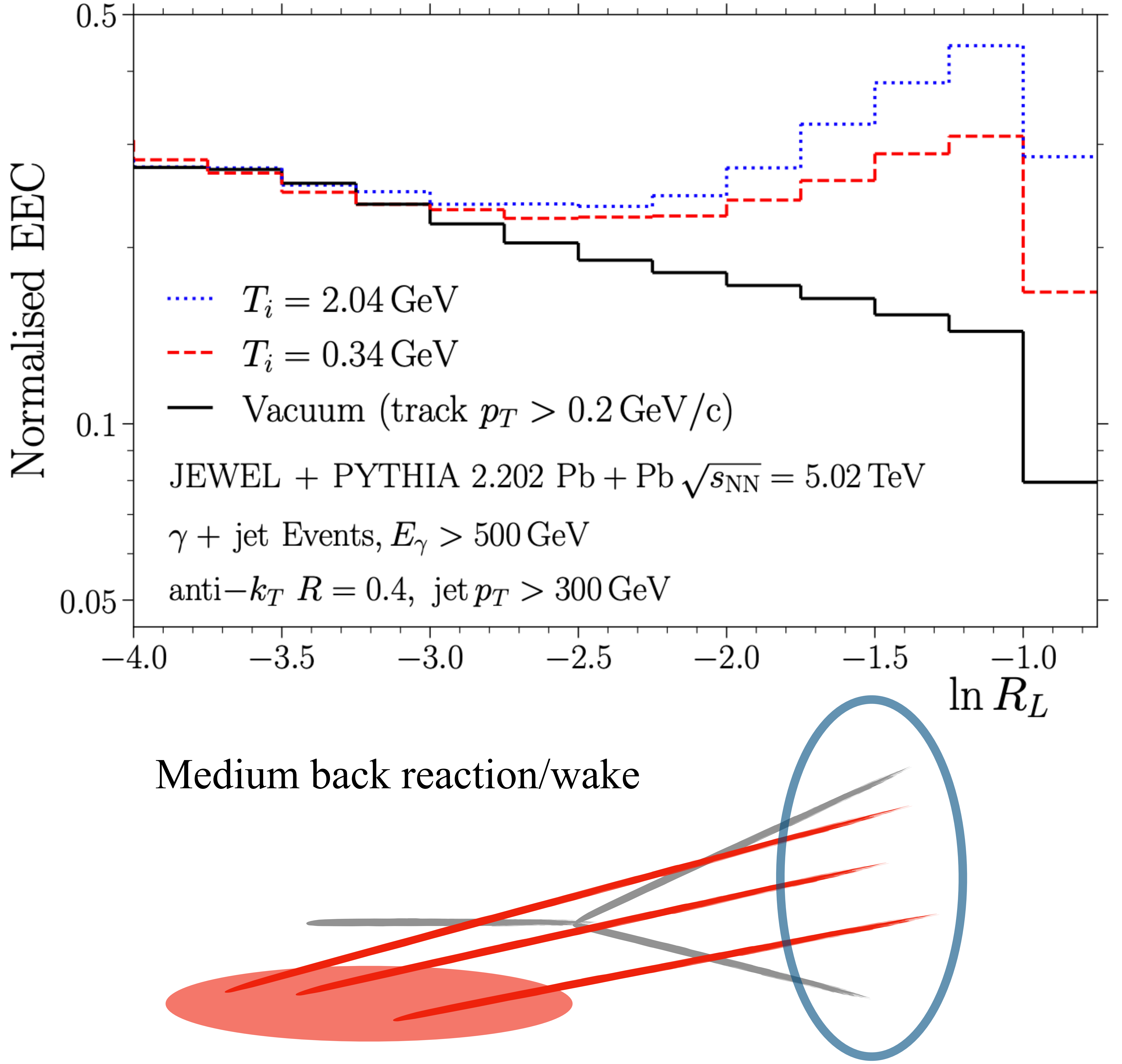


Different physics, similar qualitative features

Energy correlators inside jets in heavy ions: some puzzles

[C. Andres, et al, 2209.11236]
also [Z. Yang, et al, 2310.01500]





Different physics, similar qualitative features

Energy correlators inside jets in heavy ions: some puzzles

There are several open questions which ideally should be understood to make sense of data

1) How well do we capture the leading “perturbative” contributions to the EEC ?

Now: models with several shortcomings; tools to achieve this goal are available !

2) In simplified models, can we get a consistent picture between other observables and the EEC ?

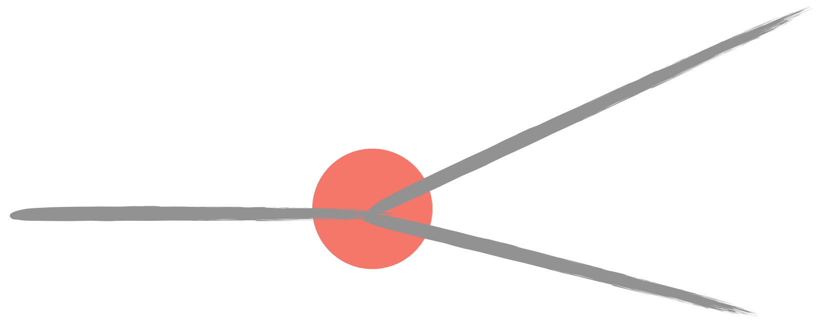
Now (theory): several missing pieces but doable in the near future

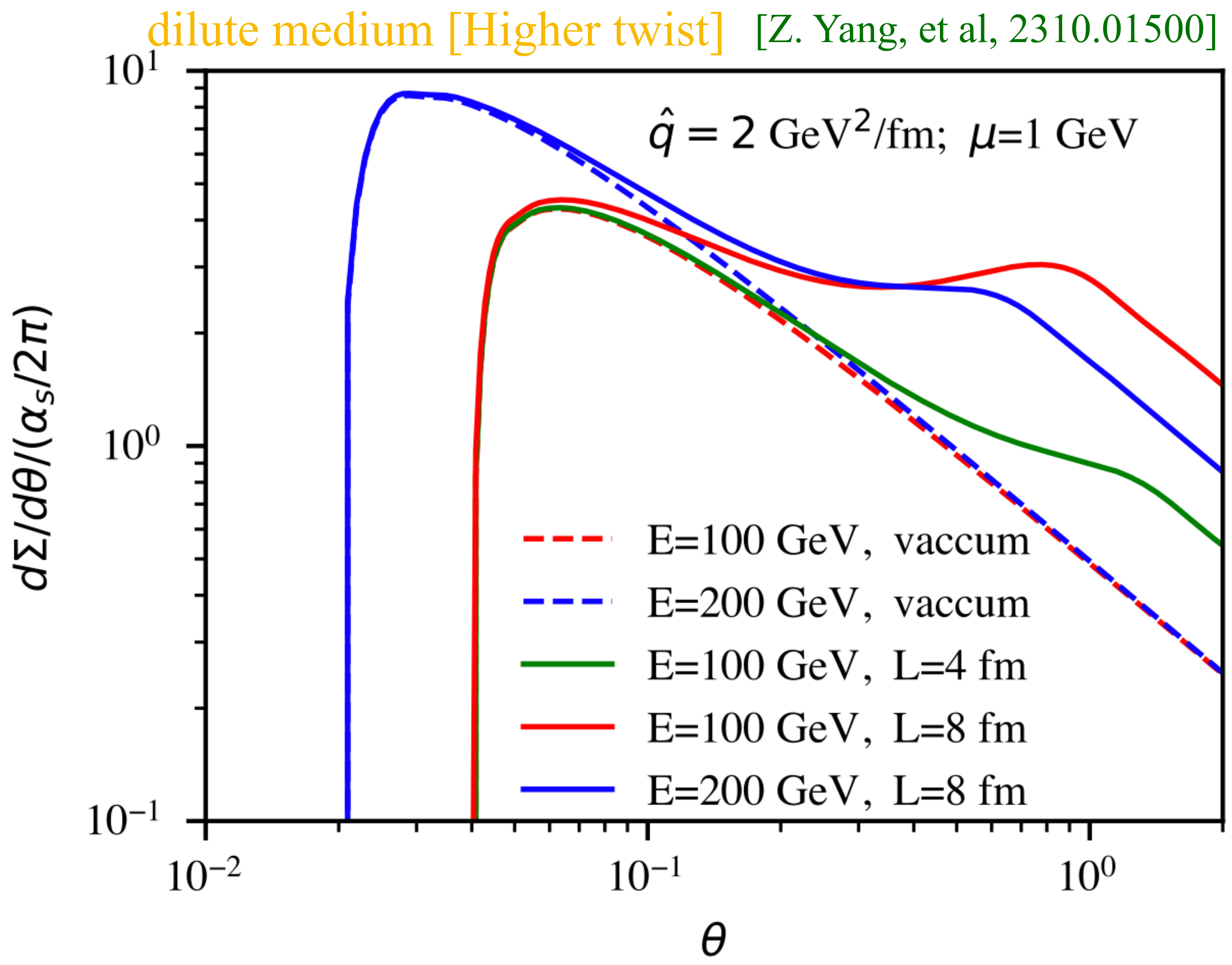
3) Can perturbative features be mimicked by other effects ?

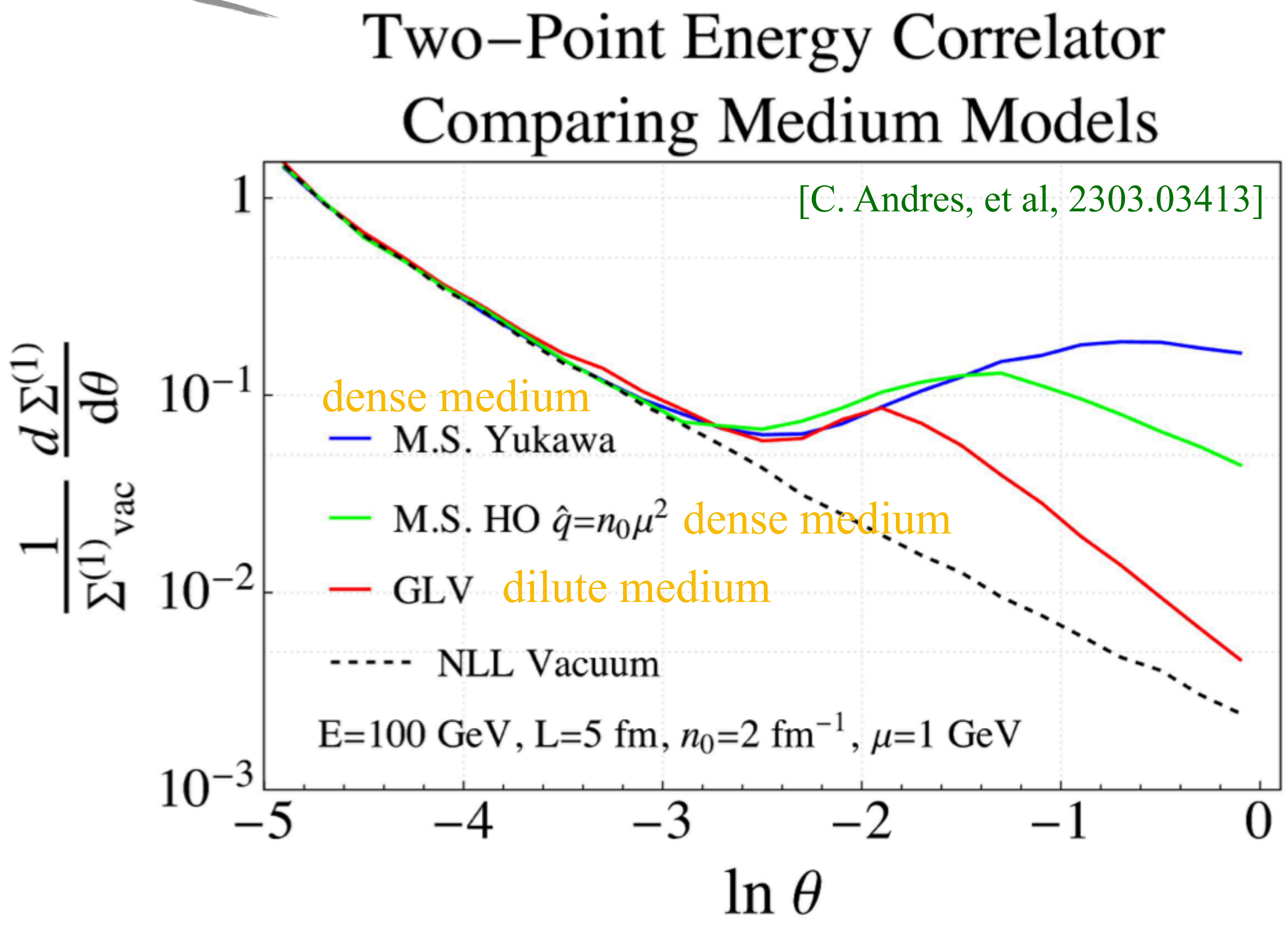
Now: potentially yes, but missing a good understanding of several elements

In what follows, I will summarize the state of the art of the EEC computation in HIC

Perturbative contribution







→ Dilute medium limit reproduces qualitative features seen for dense matter

→ Still detailed qualitative behavior differs between medium models

Perturbative contribution

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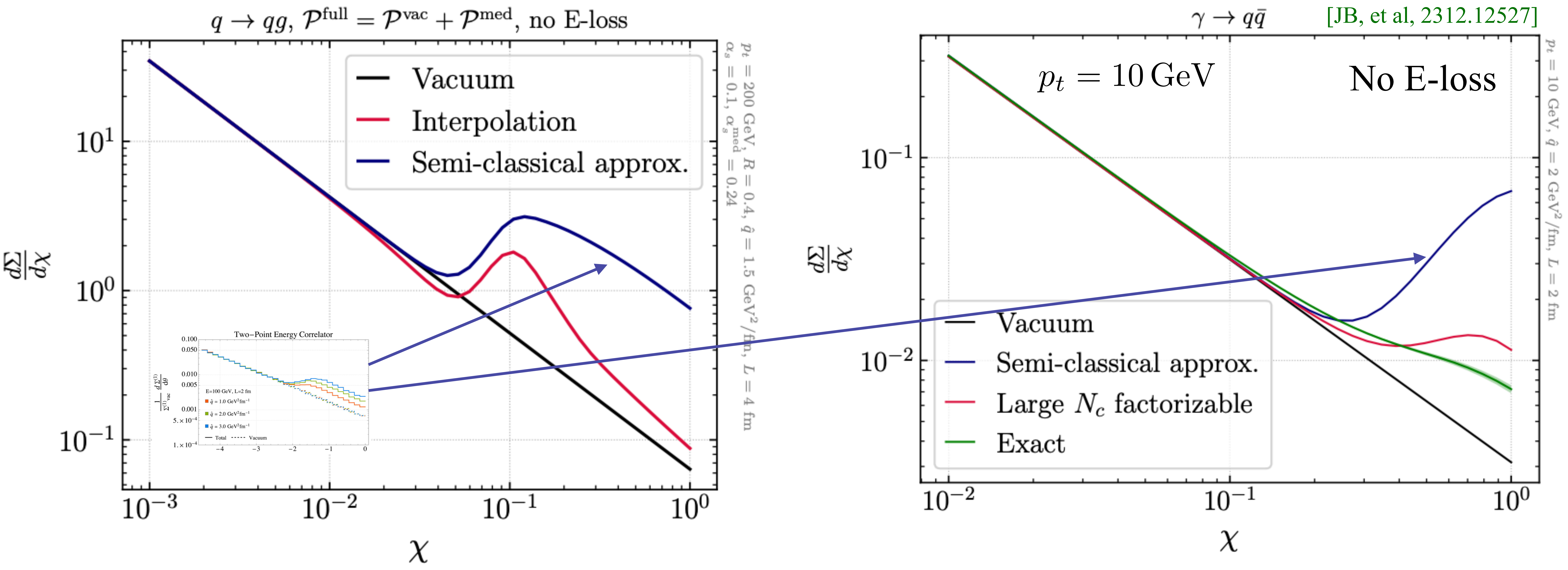
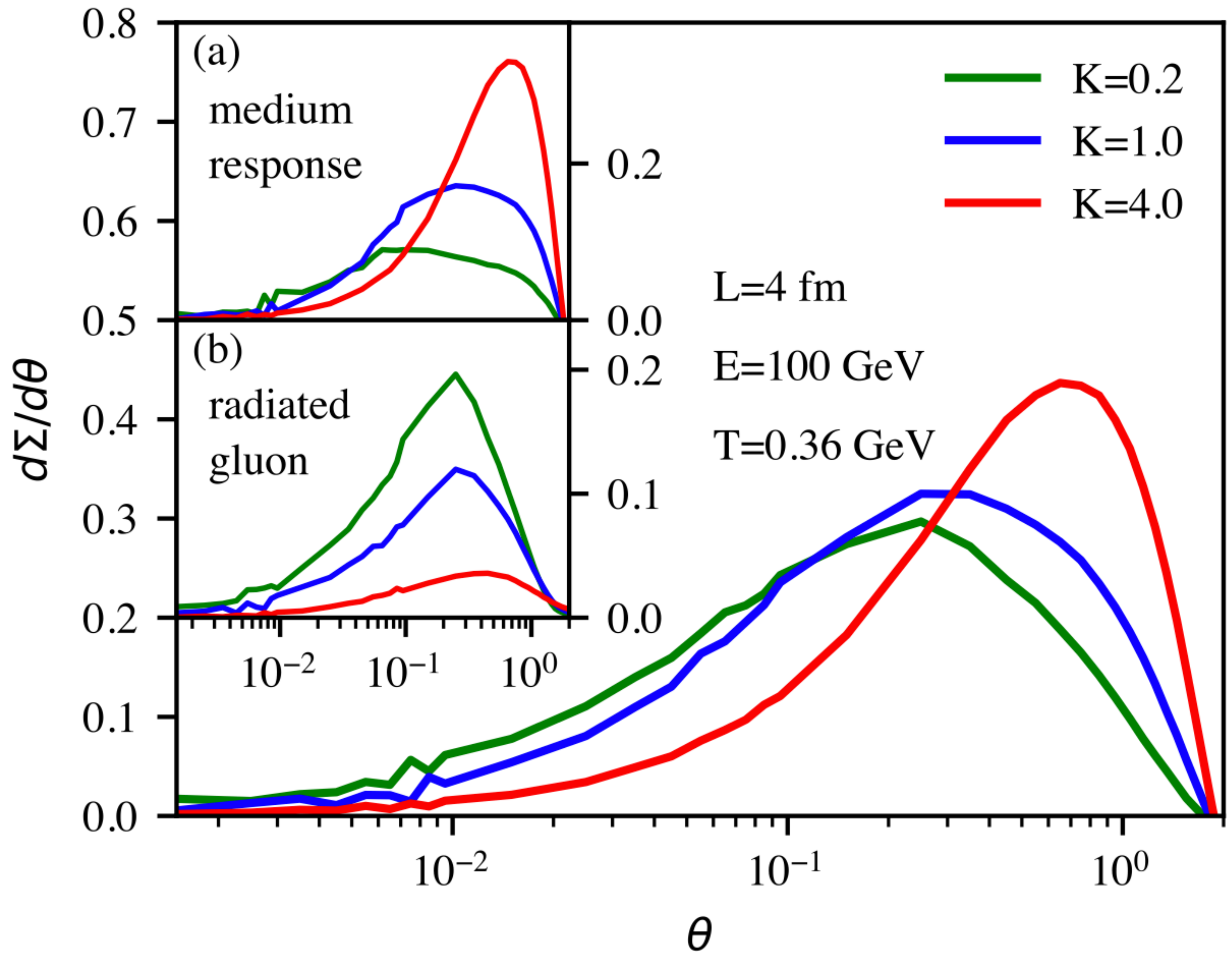


- Modified "splitting function" in dense regime at full kinematics is still not under control
- Numerical tools are available to go beyond this, but need further implementation efforts

Gluon emissions vs wake contributions

[Z. Yang, et al, 2310.01500]



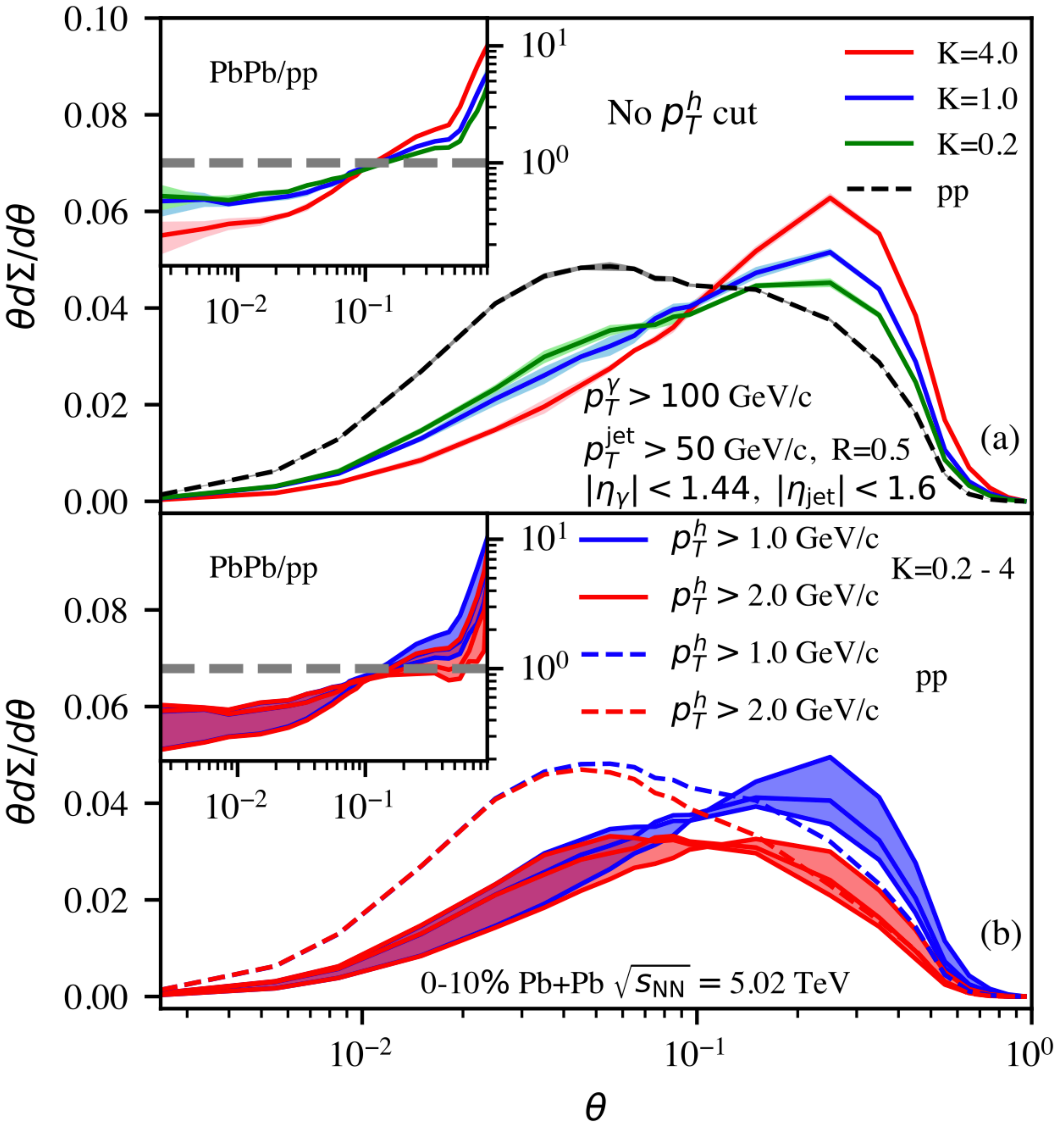
Larger K = Larger Debye mass

→ Including back reaction, there is an (expected) competition effect with splitting function

→ These contributions scale differently with medium parameters, so maybe they can be distinguished

EEC from LBT

[Z. Yang, et al, 2310.01500]



Qualitatively close to perturbative calculations

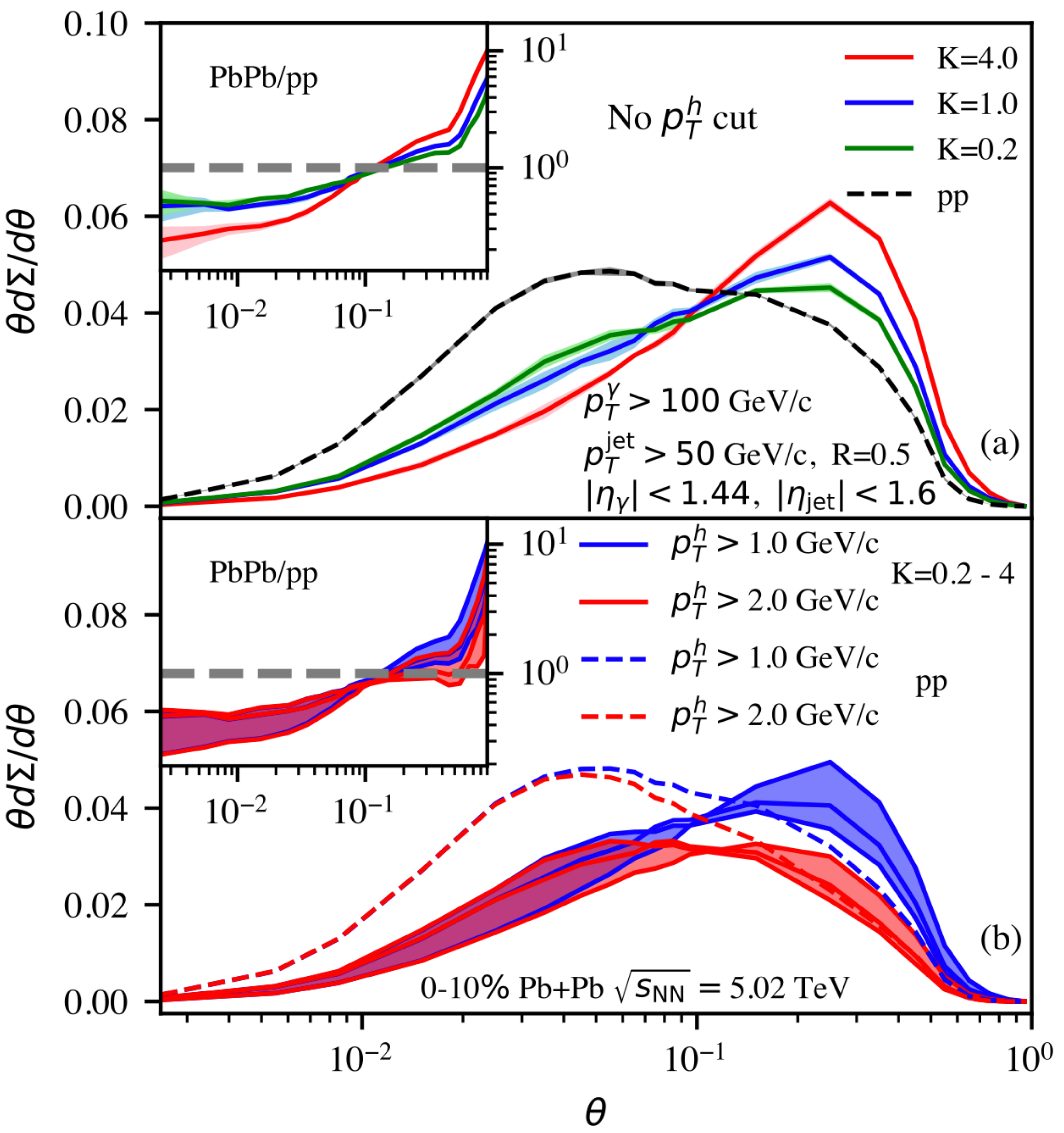
Enhancement increases with Debye mass (K)

This suggests dominance of medium response

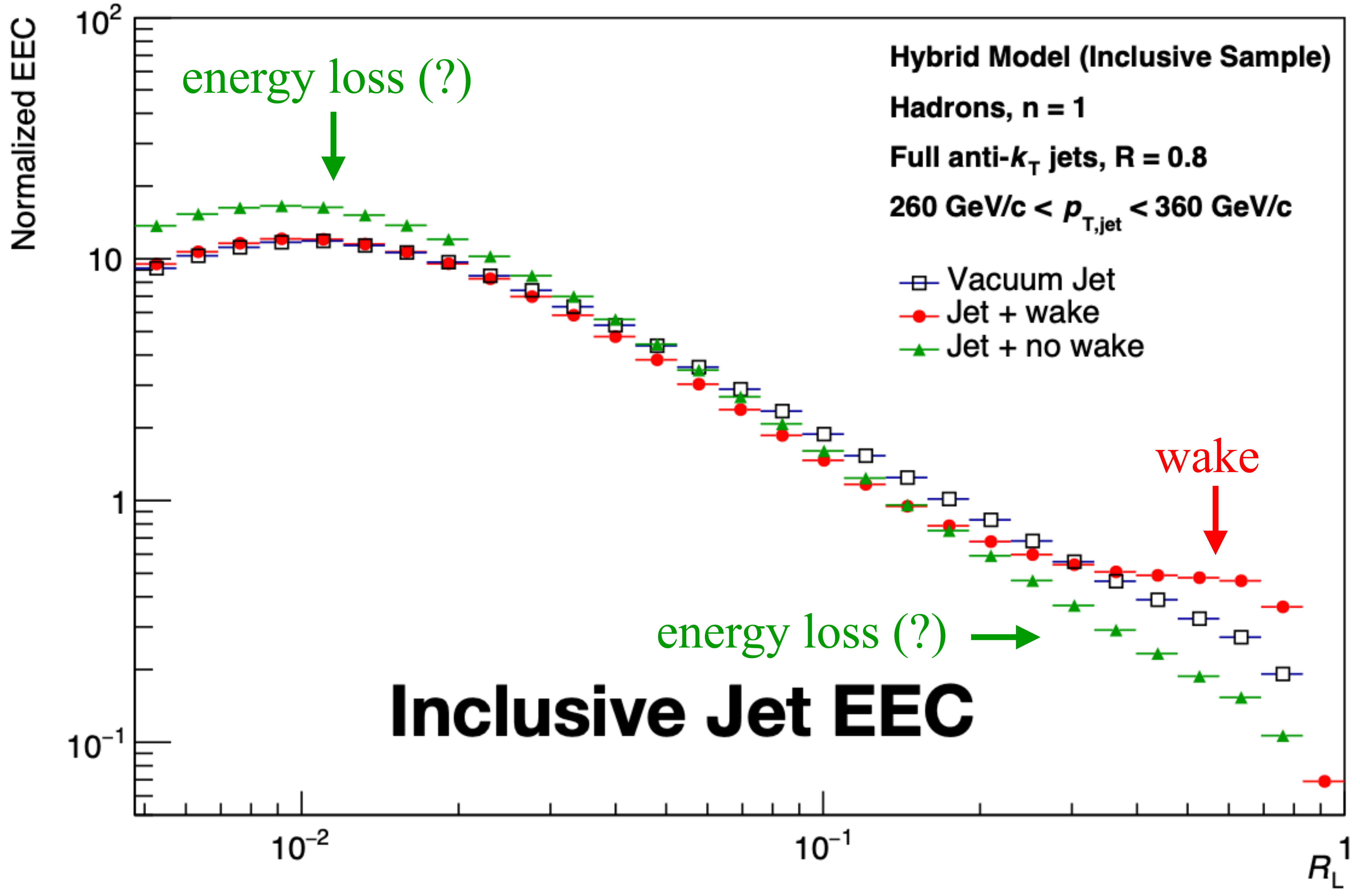
Introducing large enough p_T cut collapses result to vacuum

EEC from LBT

[Z. Yang, et al, 2310.01500]



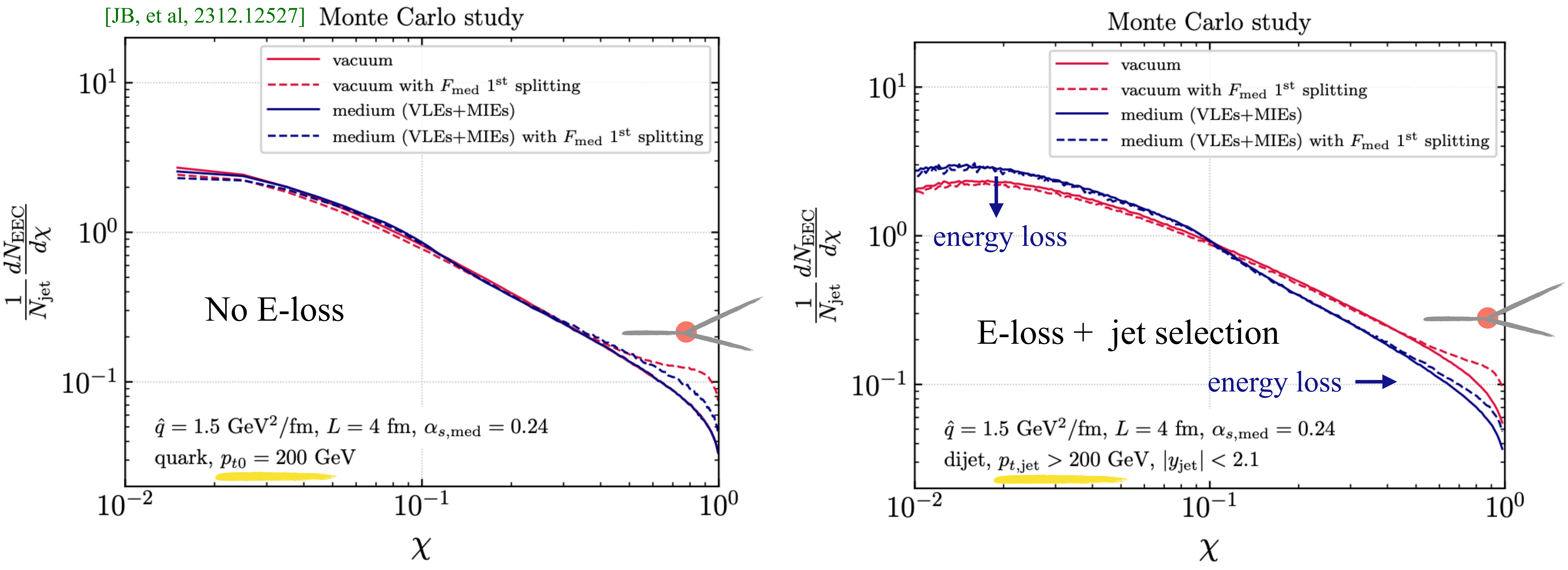
[H. Bossi, Trento 2024]



Need detailed results from other models to further understand role of wake

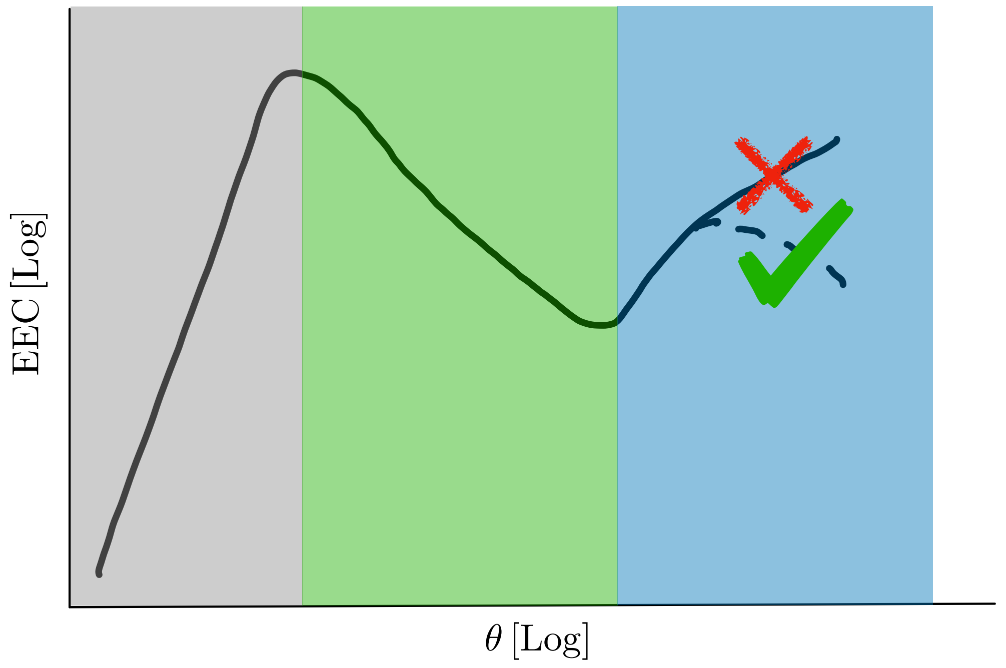
EEC from modified JetMed

[JB, et al, 2312.12527]



- To match perturbative calculations requires introducing balanced splittings in-medium
- Energy loss effect competes with perturbative results, and can become dominant

Higher weight Energy correlators



If we want to understand the jet evolution, we need to remove the wake

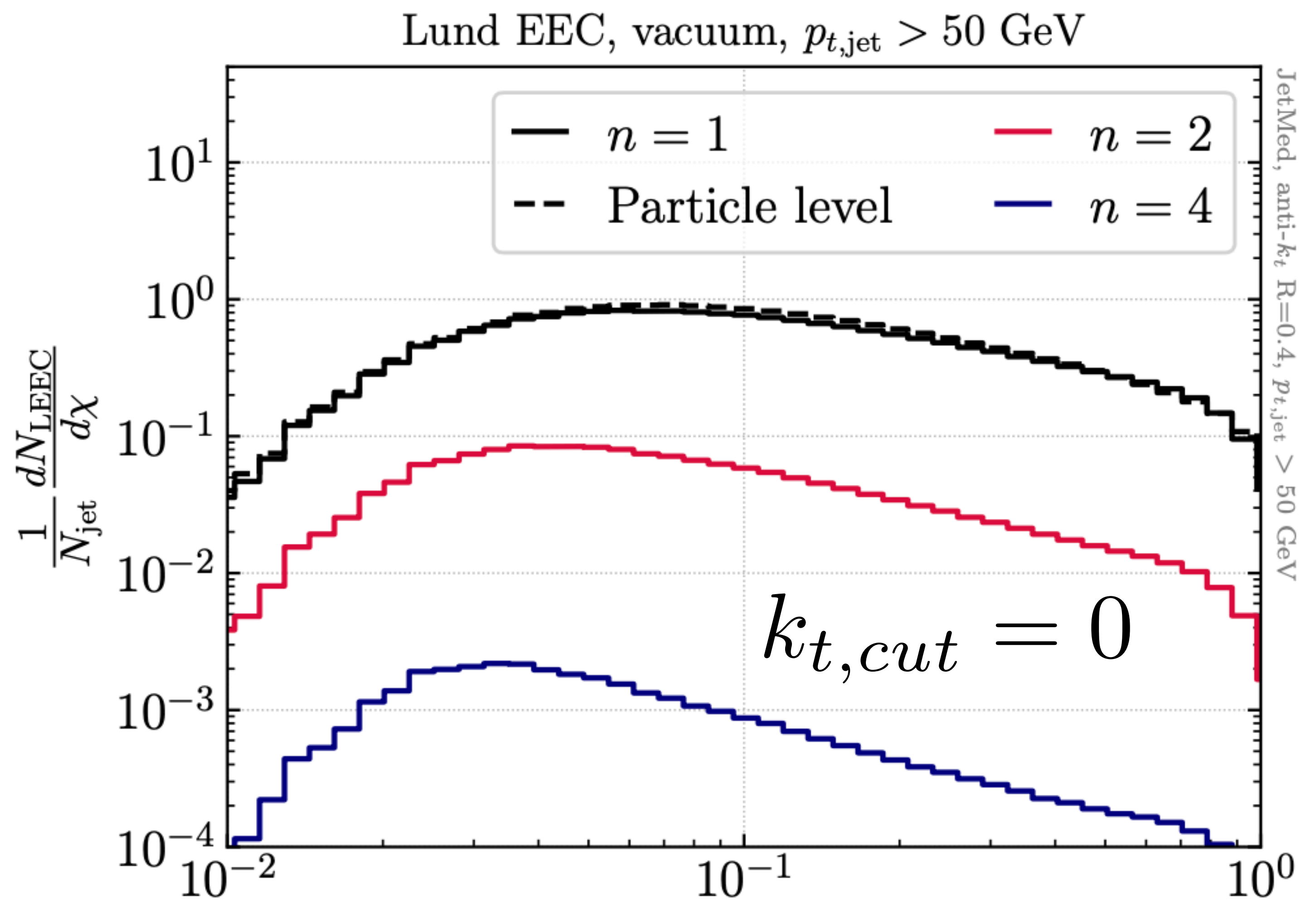
Several options to do this, here two examples:

1. EECs on subjets inside a jet:

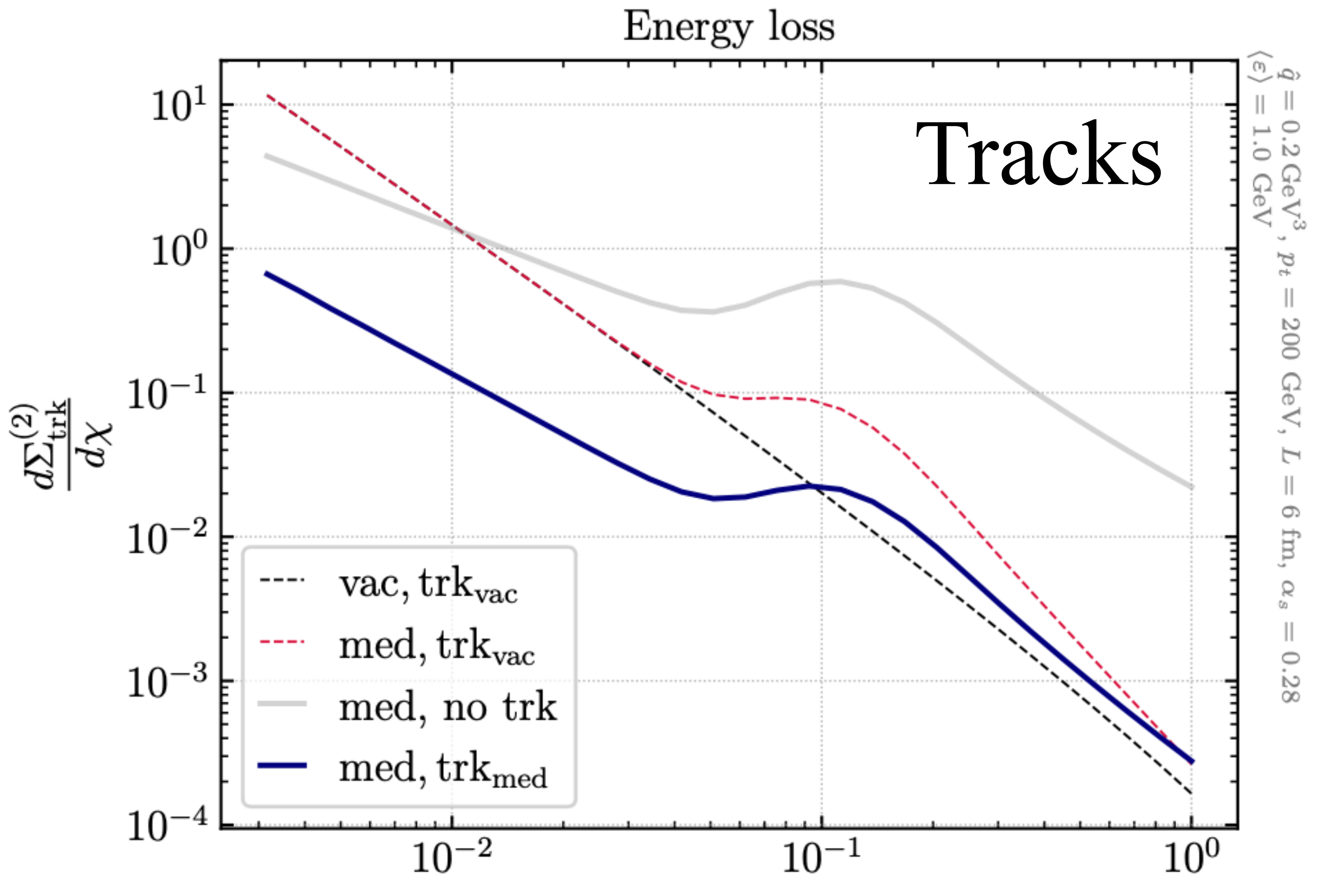
$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\chi} = \frac{1}{\sigma} \sum_{\{i,j\}\in\text{declust.}} \int_0^1 \mathrm{d}z \frac{\mathrm{d}\sigma}{\mathrm{d}\theta_{ij}\mathrm{d}z} z^n(1-z)^n \delta\left(\chi - \frac{\theta_{ij}}{R}\right) \Theta(k_t > k_{t,\text{cut}})$$

2. Higher power EEC + track functions:

$$\left.\frac{d\Sigma^{(n)}}{d\theta}\right|_{\text{tracks}} = \int_{E_1,E_2} \int_{x_1,x_2} x_1^n T(x_1) x_2^n T(x_2) \frac{E_1^n E_2^n}{Q^{2n}} \frac{d\sigma}{\sigma dz d\theta} = \int_0^1 dz T_a^{[n]}(\theta p_t) T_b^{[n]}(\theta p_t) z^n (1-z)^n \frac{d\sigma}{\sigma dz d\theta}$$



[JB, et al, 2312.12527]



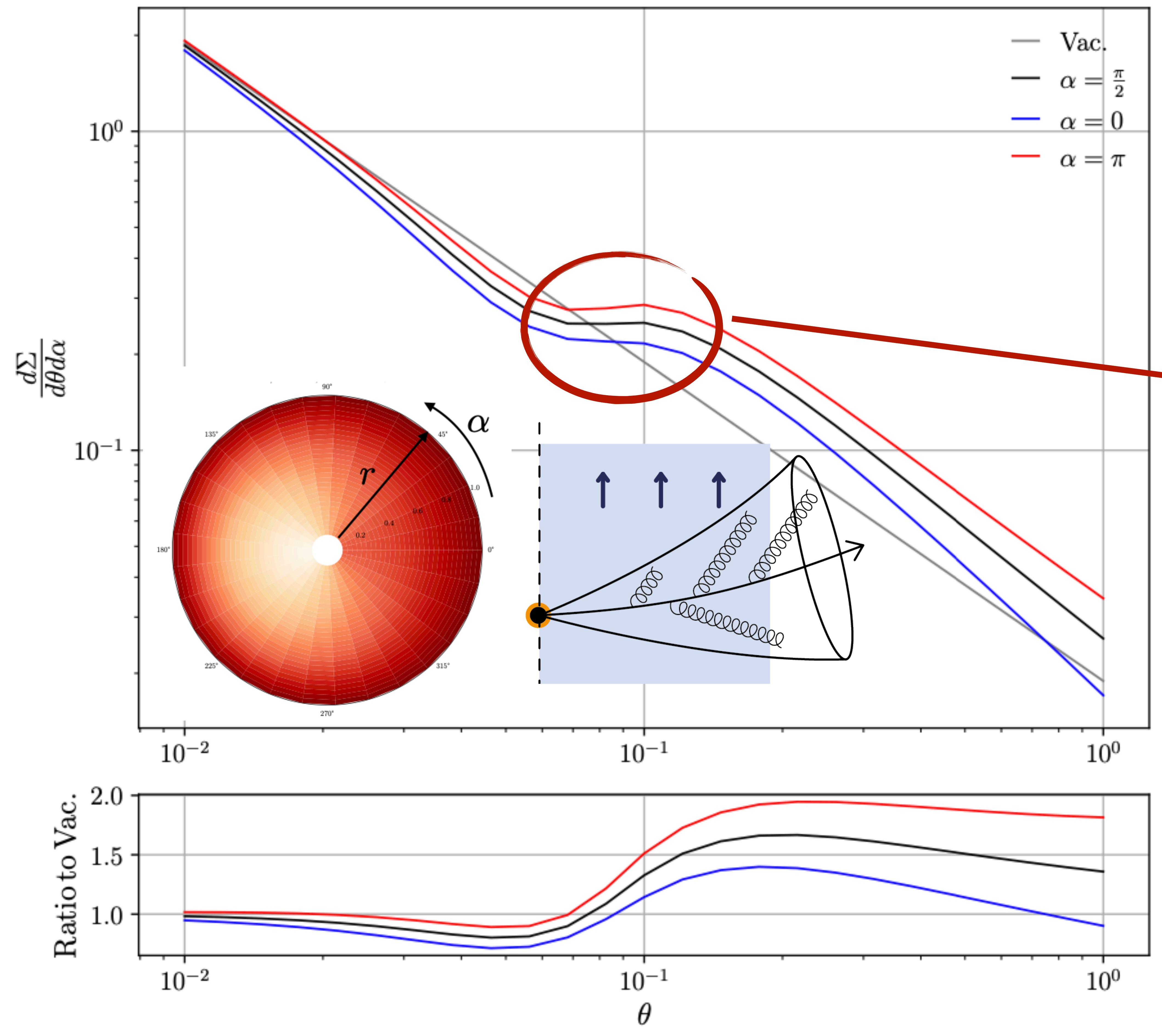
[JB, et al, 2401.04164]

Energy correlators for tomographic imaging

Brookhaven National Laboratory

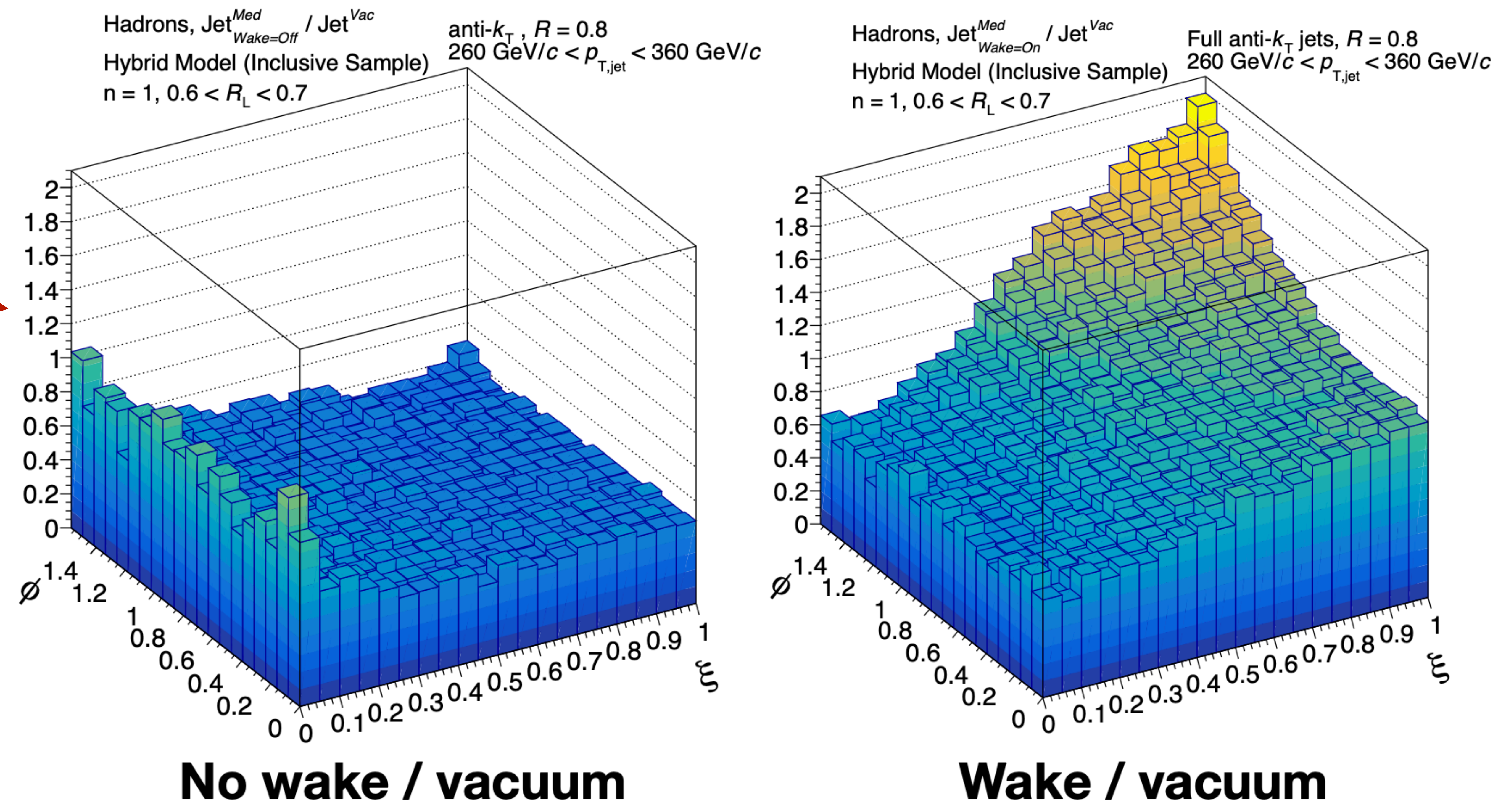
→ Simplest EEC gives info on scales, but ECs can be used in more powerful ways

[JB, et al, 2308.01294]



$\frac{d\Sigma}{d\theta d\phi}$: can see medium anisotropies !

[H. Bossi, Trento 2024]



E3C as a way to probe the wake

Summary and Outlook

→ **EEC in heavy ions: why it is interesting for theory**

Great motivation for higher order calculations in jet quenching

Higher point correlators will give information about *shape* of particle distribution

So far focused on collinear limit, but many more opportunities in other kinematical limits

→ **EEC in heavy ions: where to go**

Several competing effects entering the observable: need for controlled LO theory result

Need further definitions which allow to better control wake contribution

Standard EEC gives access to scales, but ECs can be used as full tomographic tools