Towards understanding in-medium energy correlators

12th July 2024, MITP

João Barata, BNL

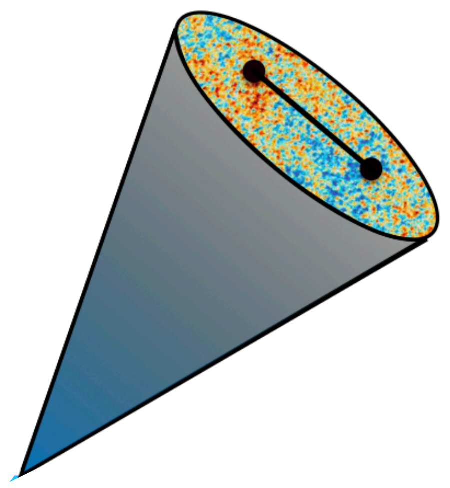
Mainly based on: 2312.12527, 24xx.xxxx, with P. Caucal, P. Monni, A. Soto-Ontoso, R. Szafron [in-medium EEC and Lund EEC]

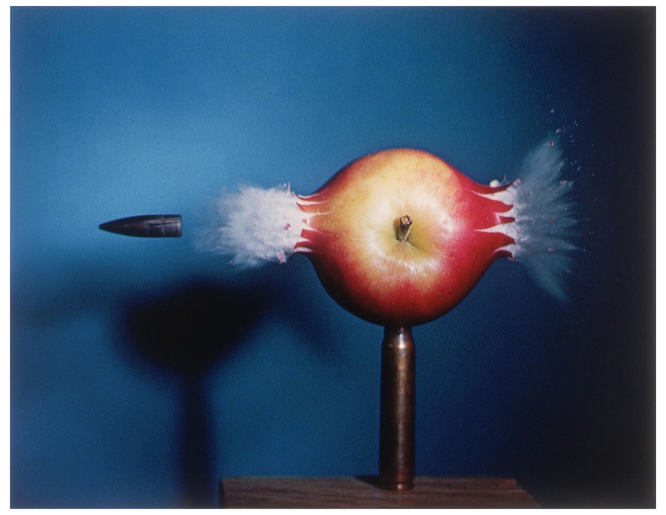
2401.04164, ongoing, with R. Szafron [in-medium track functions]

2308.01294, with J. G. Milhano, A. V. Sadofyev [anisotropic ENCs]

Outline

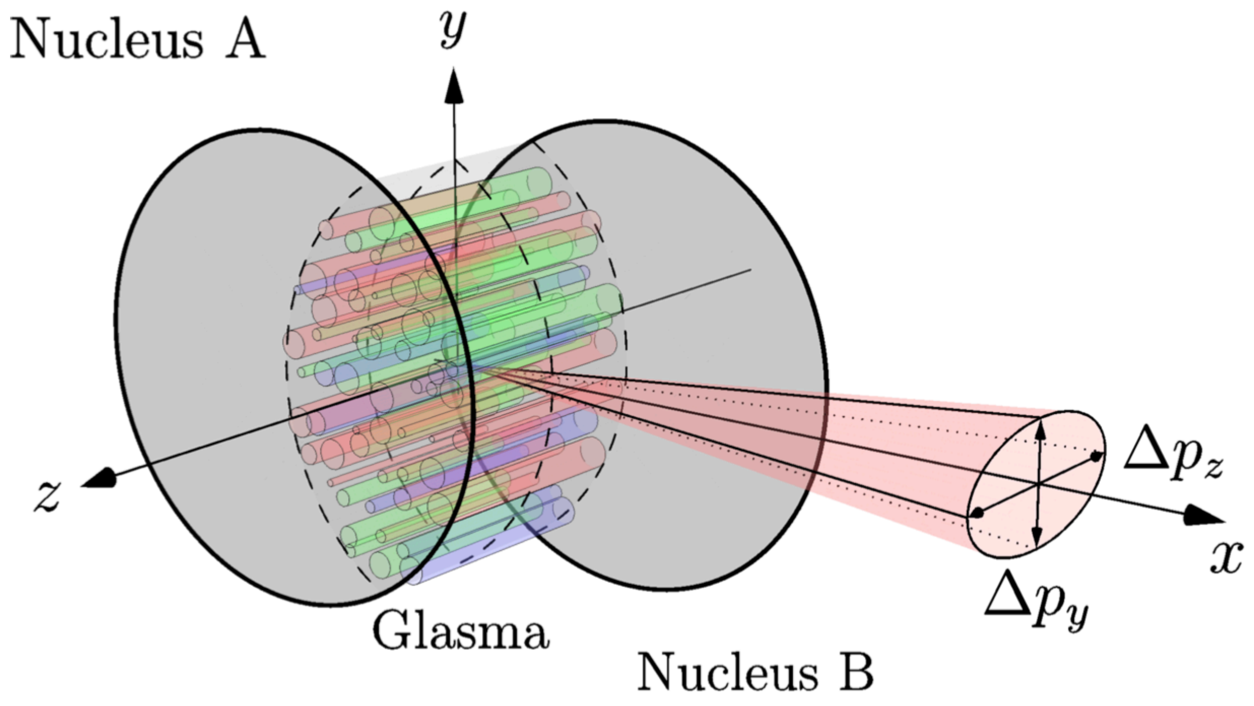
1





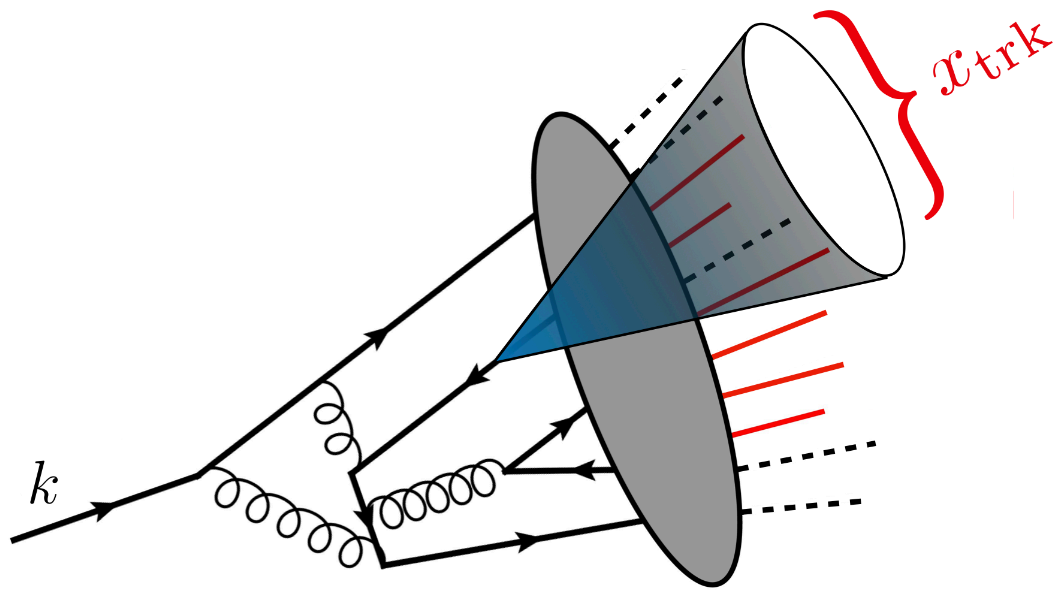
Jet EEC in heavy ion collisions

3



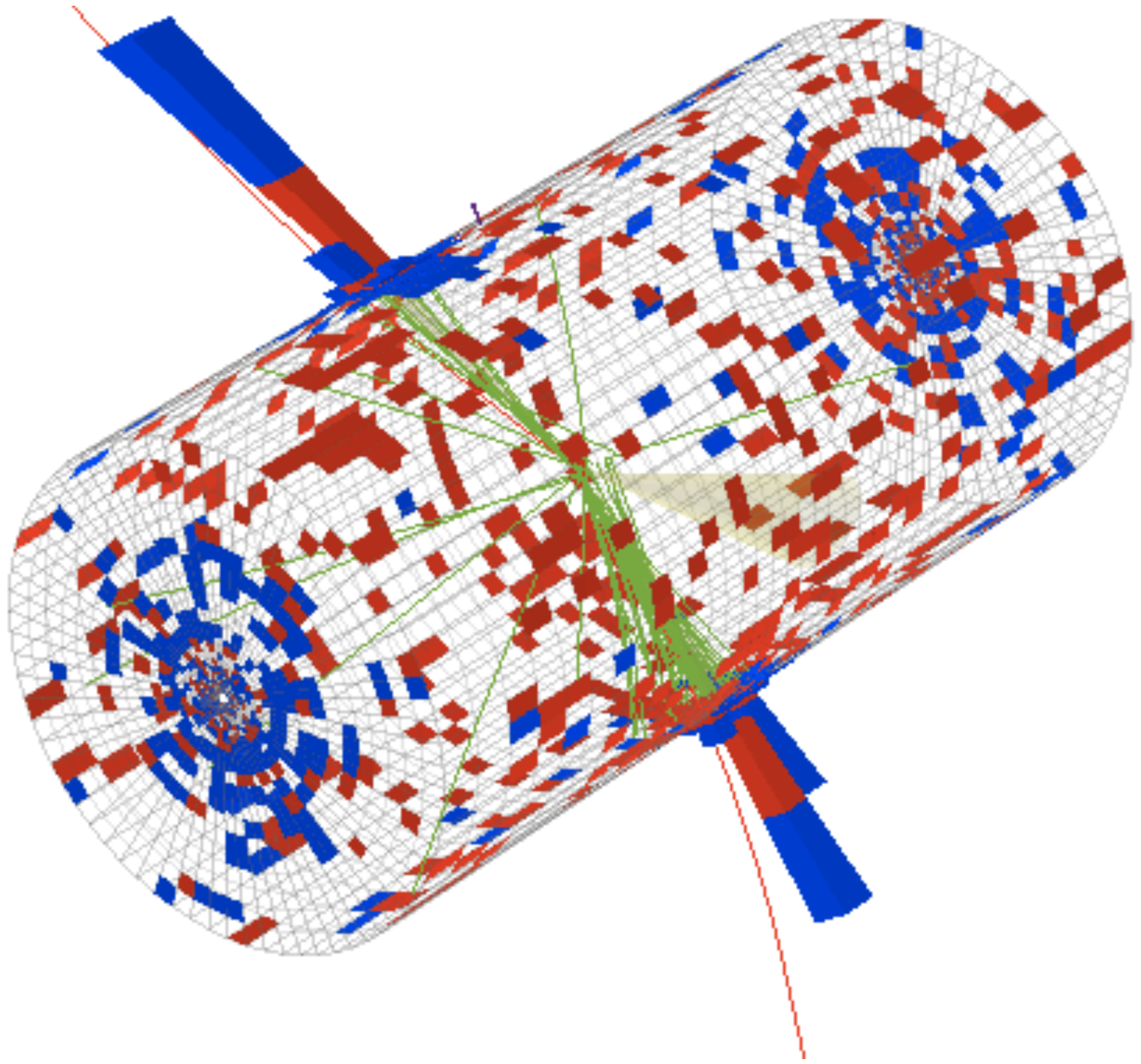
EECs in anisotropic matter

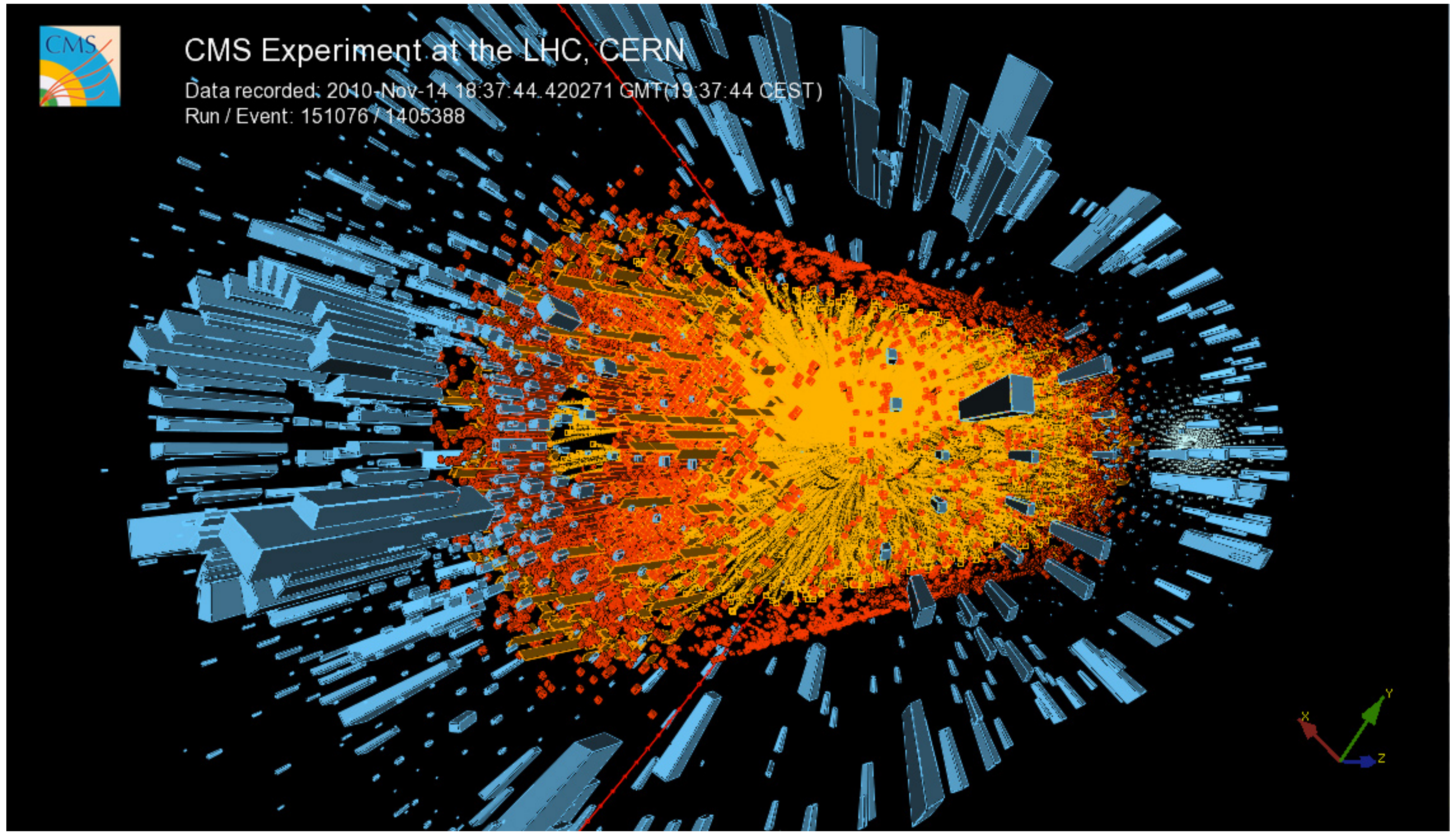
2



Higher weight EECs

From pp to AA





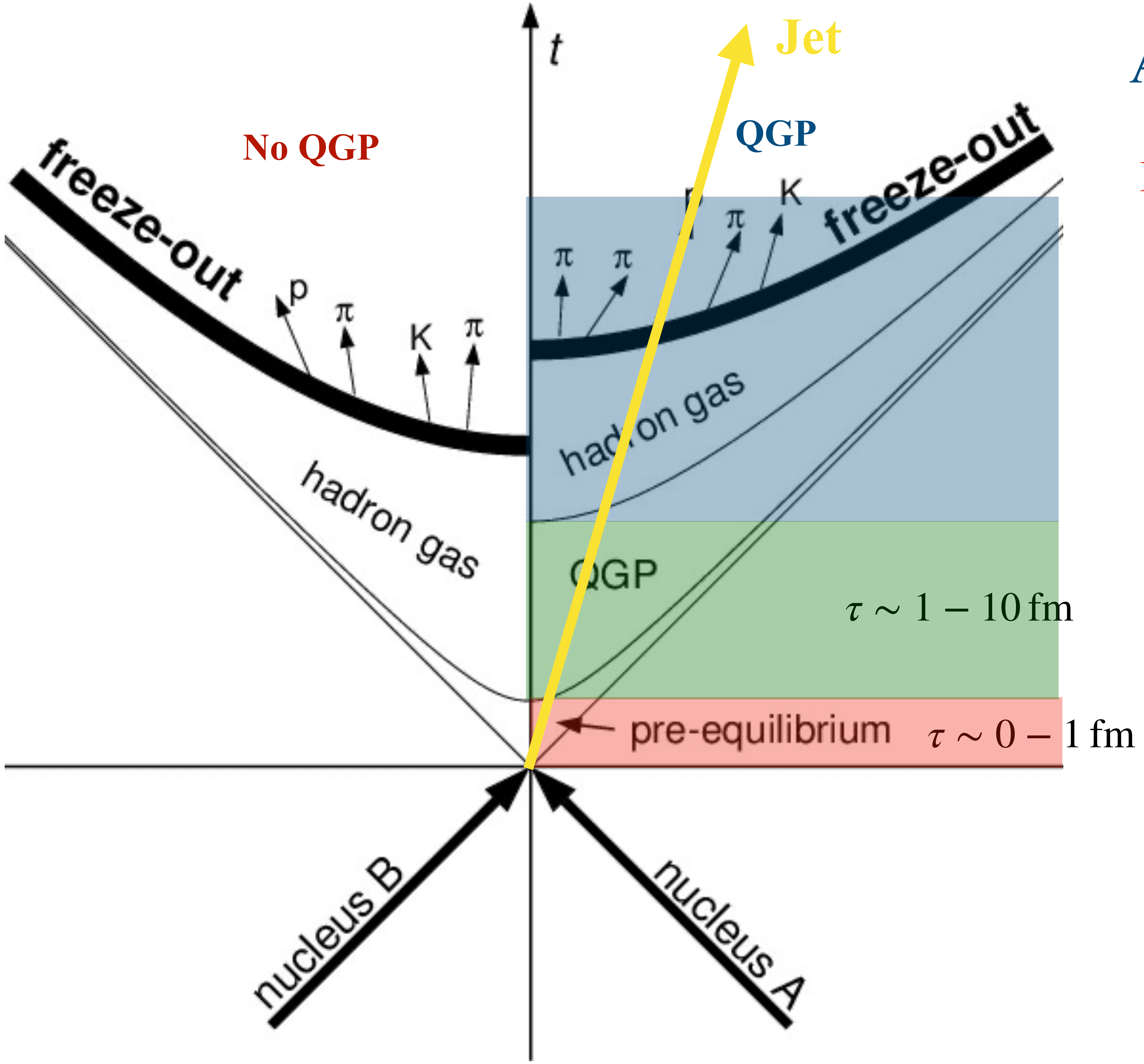
pp collision: a few particles are detected

Allows for precision tests of QCD

AA collision: thousands of detected particles

Emergent many-body properties of QCD

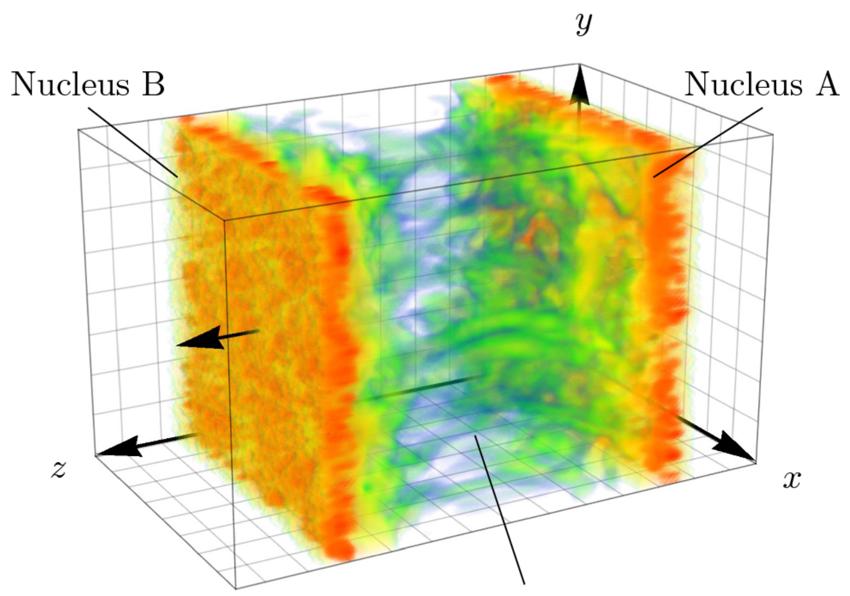
The spacetime picture of HICs

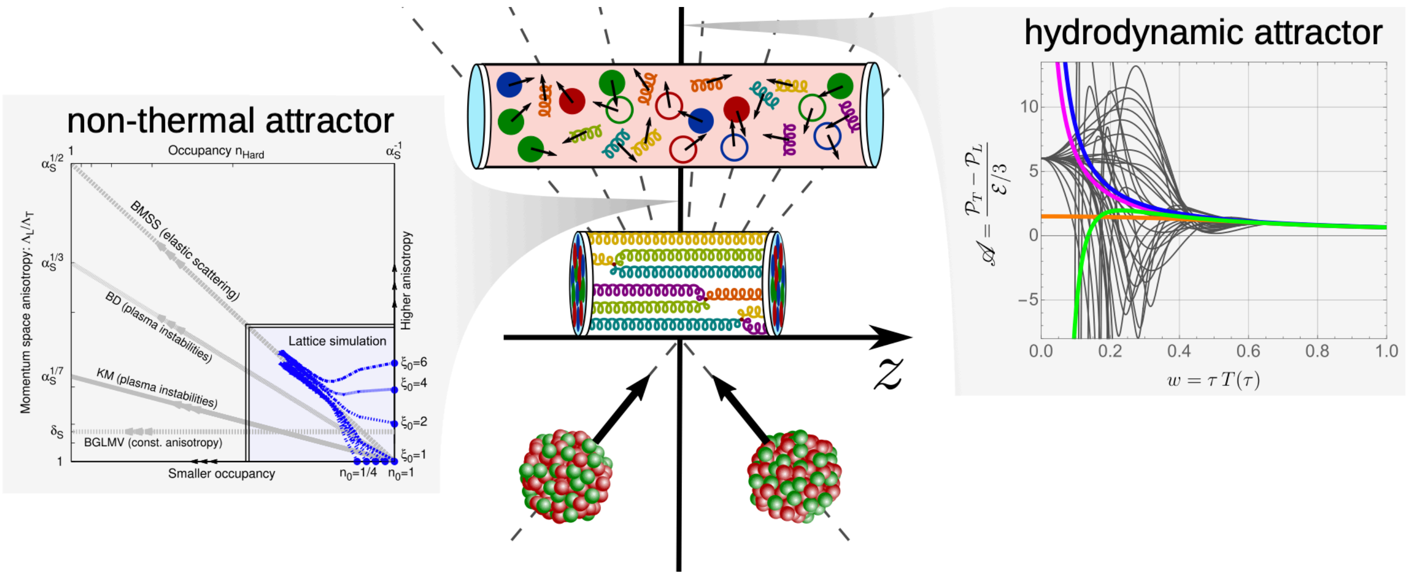


$1\,\mathrm{fm} \sim 10^{-24}\,\mathrm{s}$

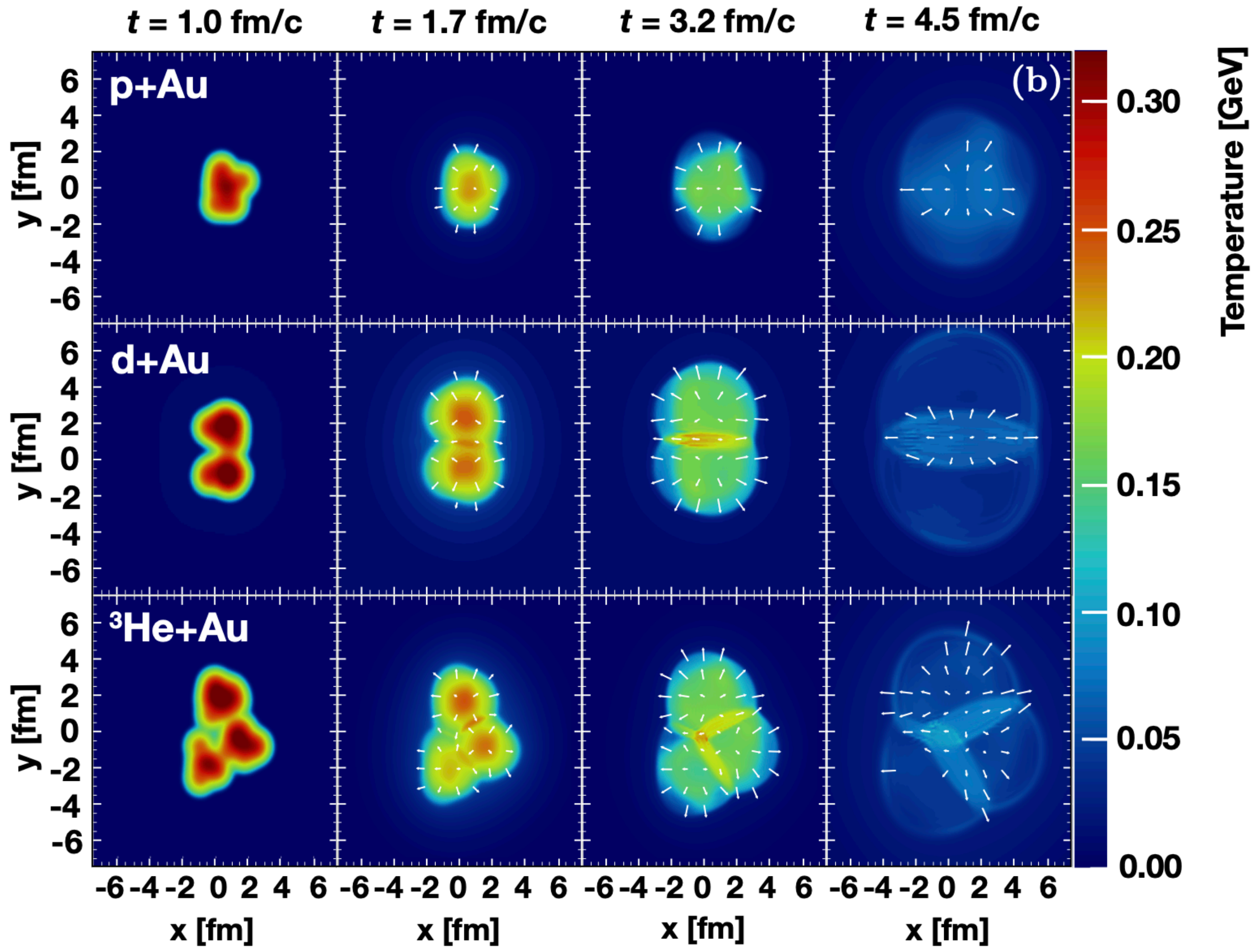
A brief summary of the different epochs in HICs

Early times:

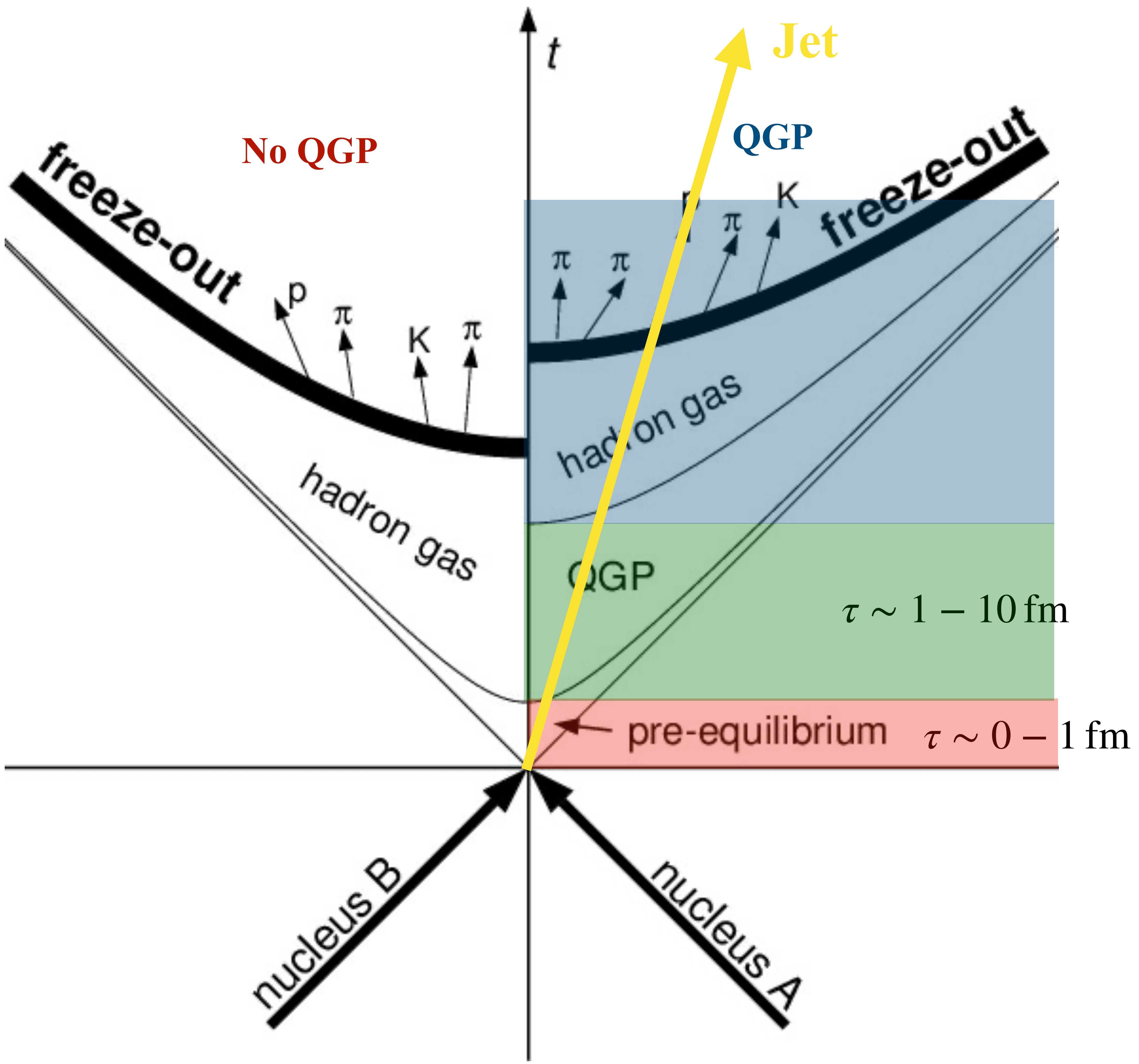




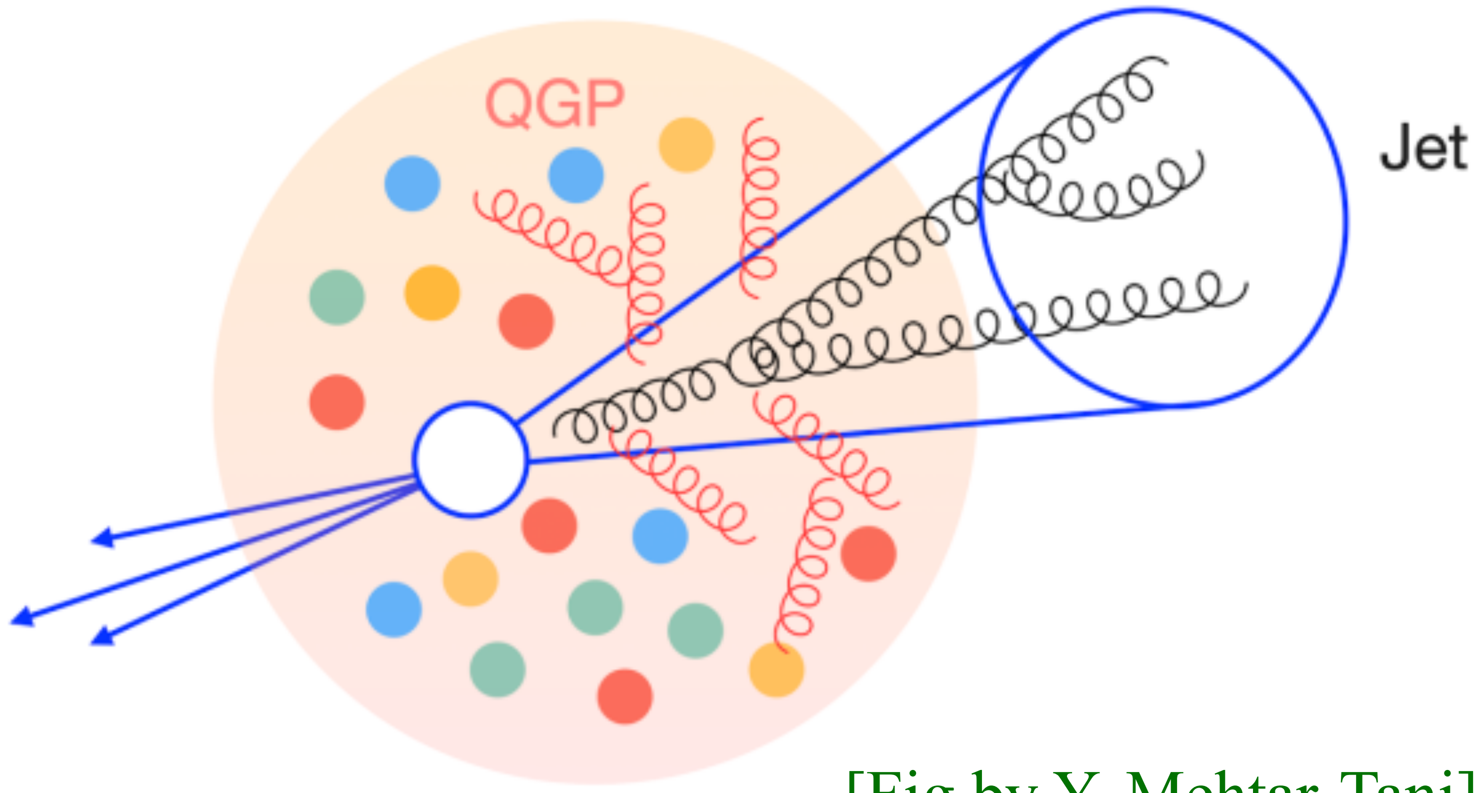
Intermediate times:



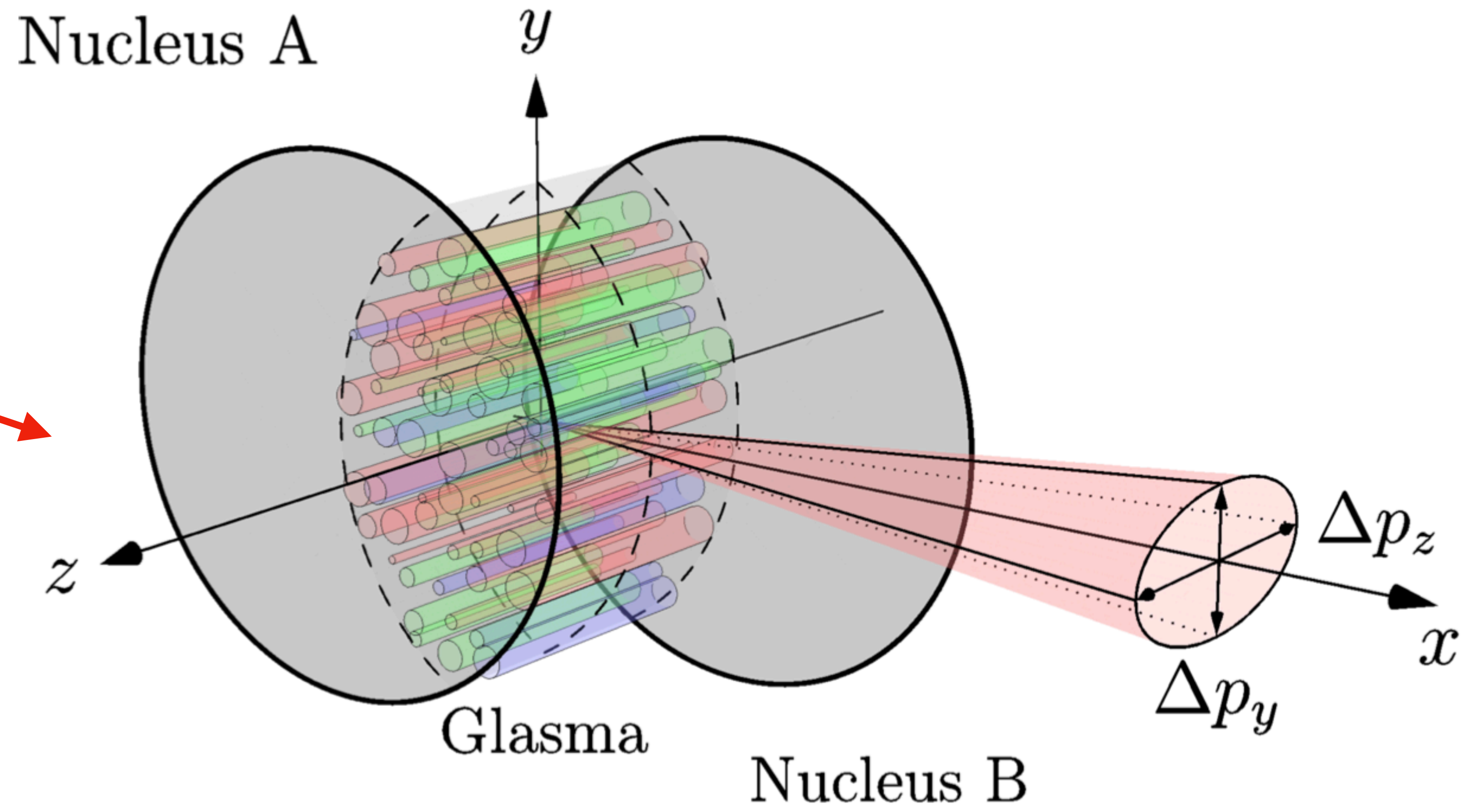
The spacetime picture of HICs



An ideal probe: QCD jets



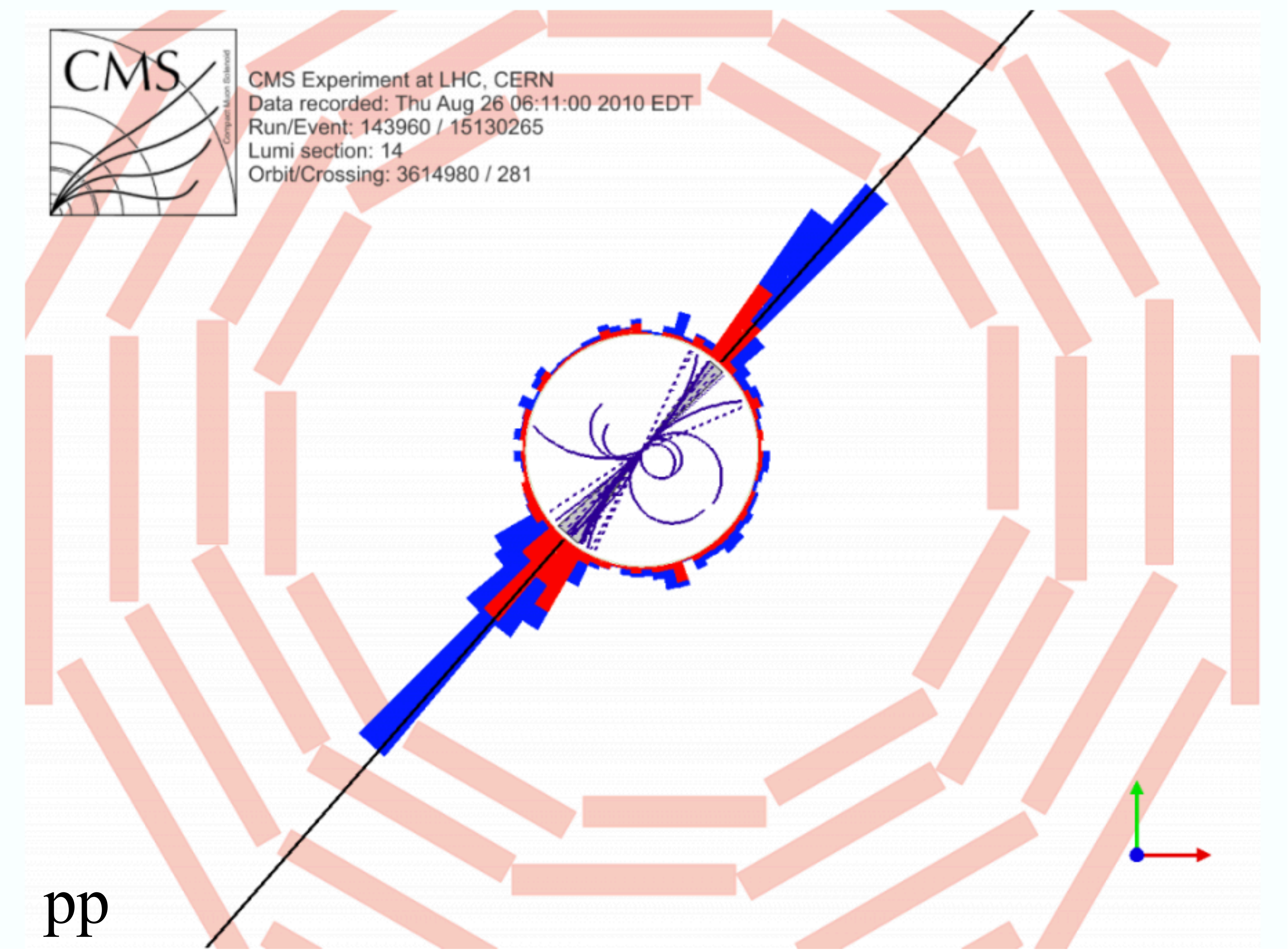
[Fig by Y. Mehtar-Tani]

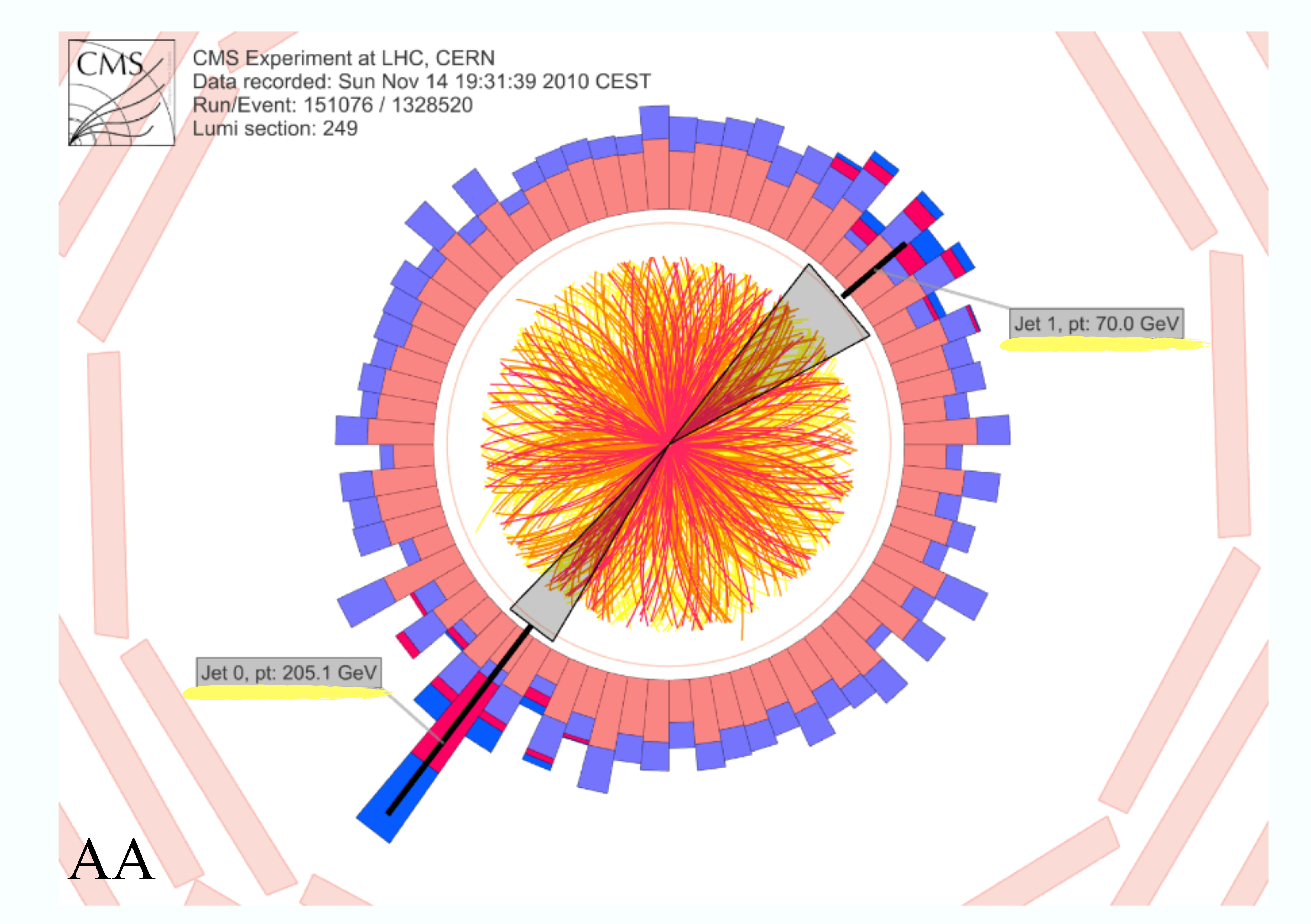


[A. App, D. I. Muller, D. Schuh, 2009.14206]

Jets in AA

What happens to jets in HICs ?





The modification of jets due to the propagation in the QGP is generally referred to as **jet quenching**

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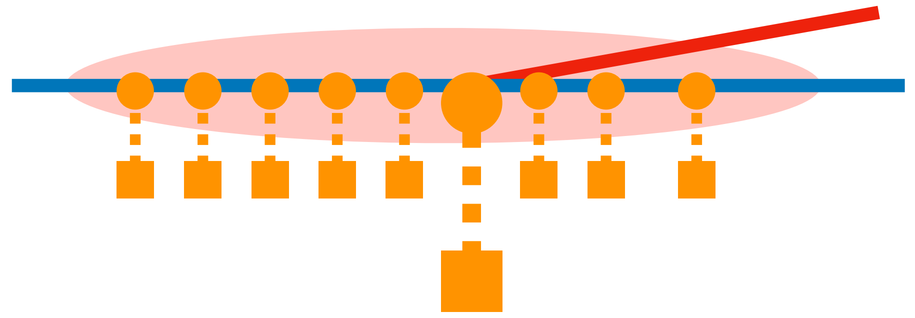
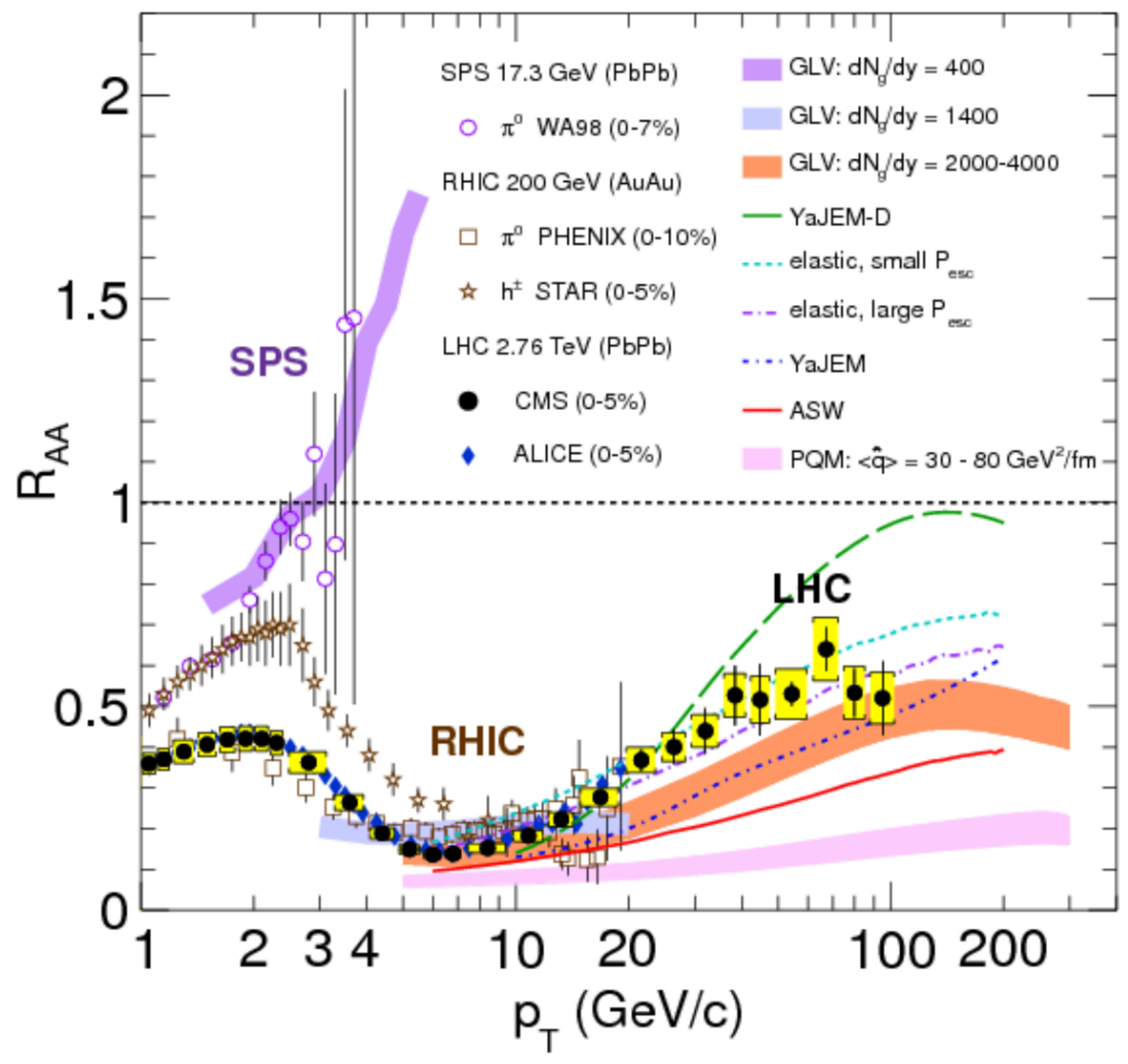
Energy loss and stimulated radiation



$$\sim \langle \mathcal{T} \prod \{\mathcal{G}, \Gamma\} \rangle_{\text{matter}}$$

$$d\sigma = d\sigma^{\text{vac}} + d\sigma^{\text{med}}$$

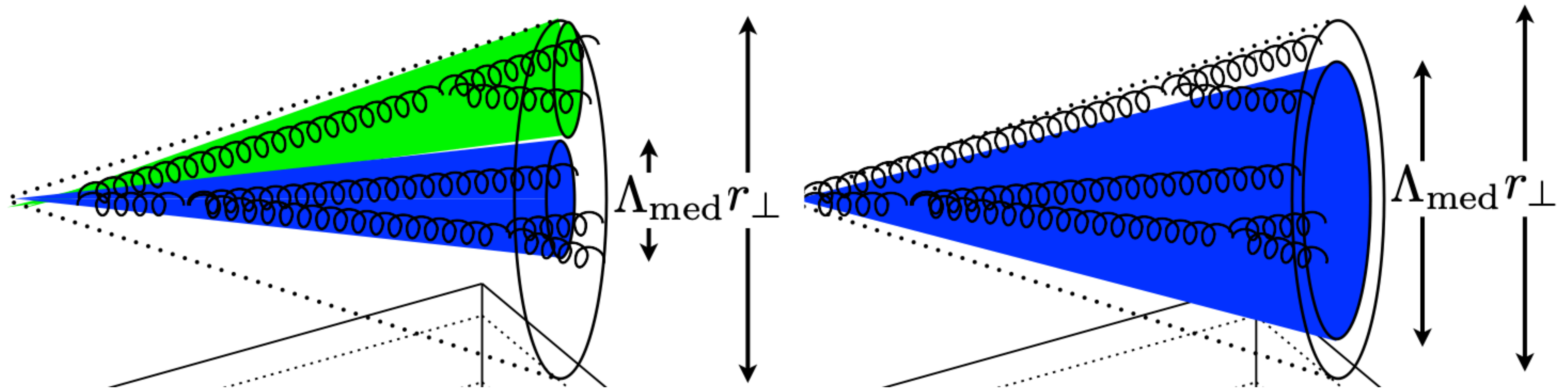
$0 < Q_q < 1$

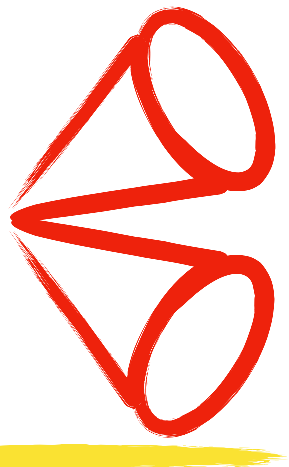


$$\frac{d\sigma_q^{\text{med}}}{dp_t d\theta} \approx \frac{d\sigma_q^{\text{vac}}}{dp_t d\theta} \int_0^\infty d\varepsilon\, D_q(\varepsilon) e^{-\frac{n\varepsilon}{p_t}} \equiv Q_q(p_t) \frac{d\sigma_q^{\text{vac}}}{dp_t d\theta}$$

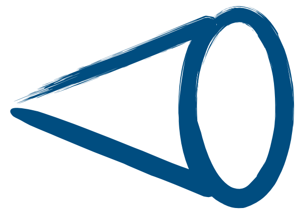
[R. Baier, Y. Dokshitzer, A. H. Mueller, hep-ph/0106347]

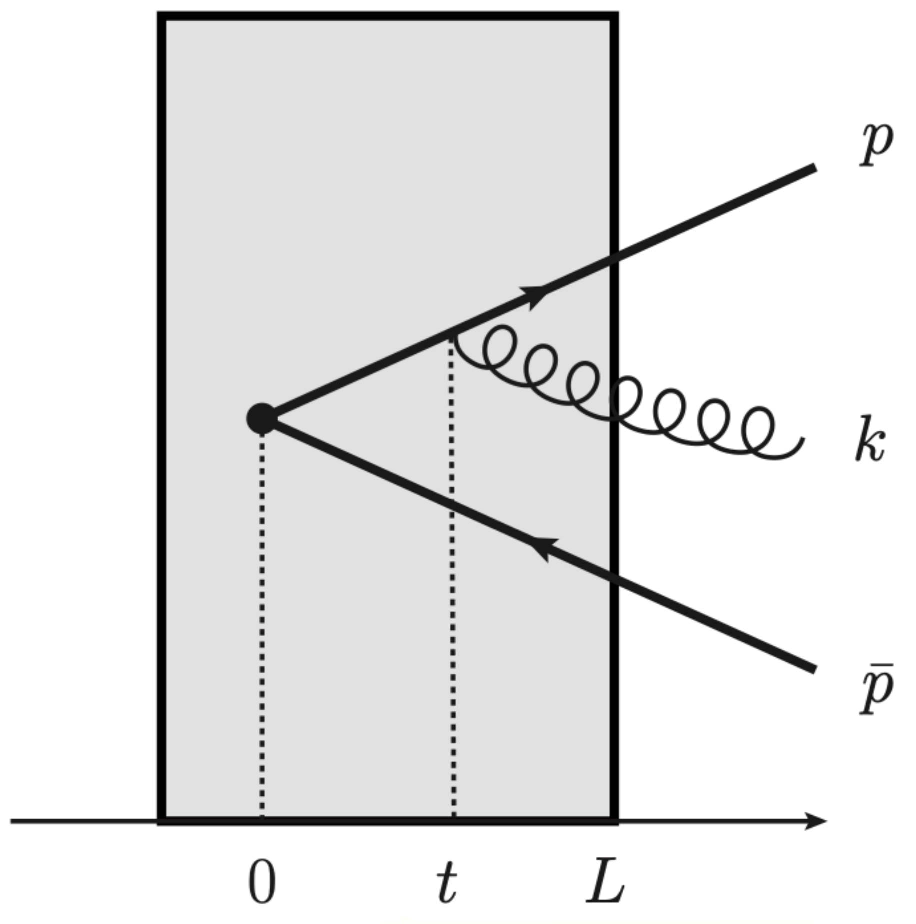
Color coherence and jet substructure





QCD vertices





vacuum → angular ordering

medium → "anti-angular" ordering

[Salgado, Tywoniuk, Mehtar-Tani; Iancu, Casalderrey-Solana, early 2010s]

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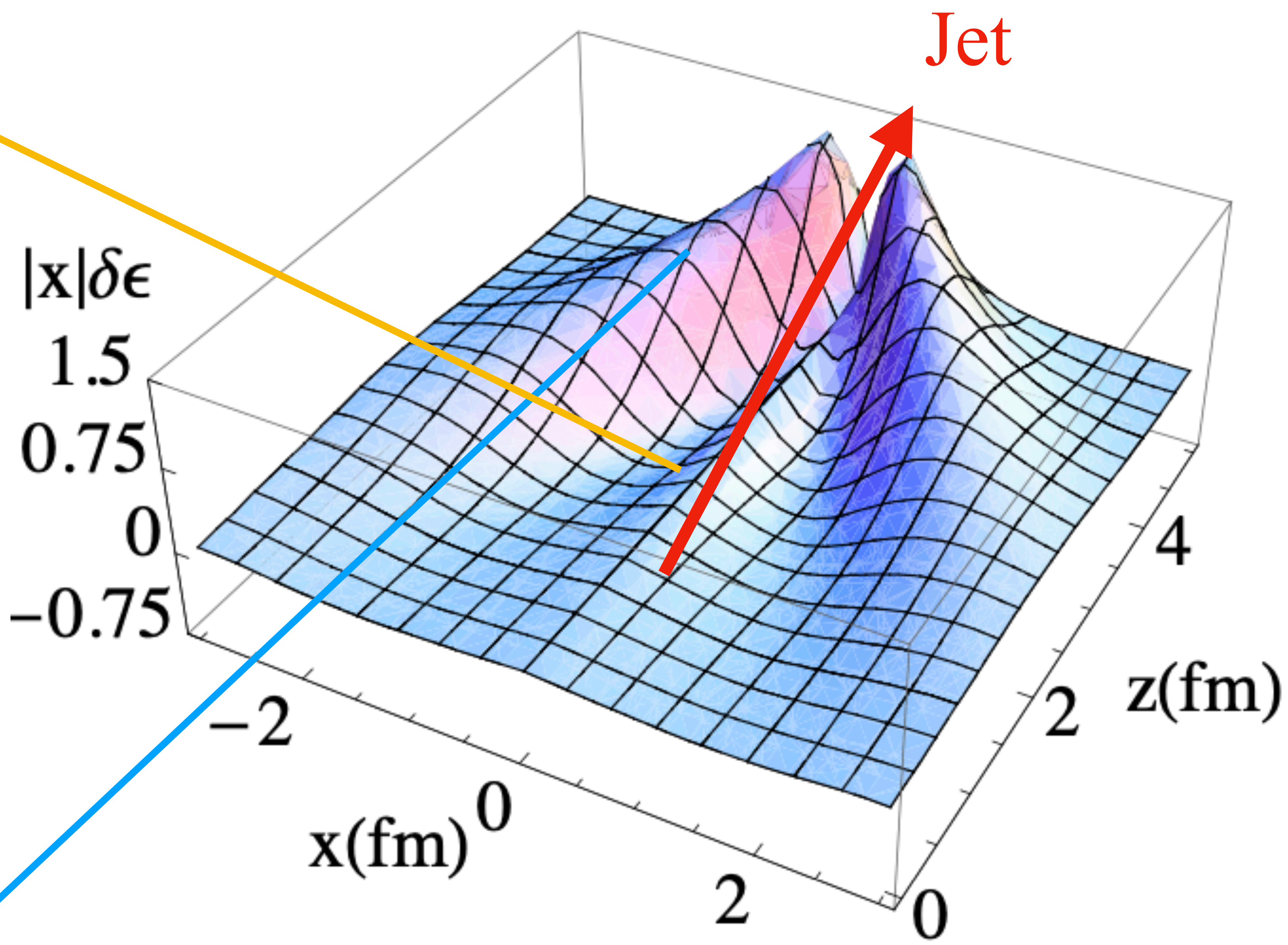
Back-reaction: Jet induced wake on the plasma

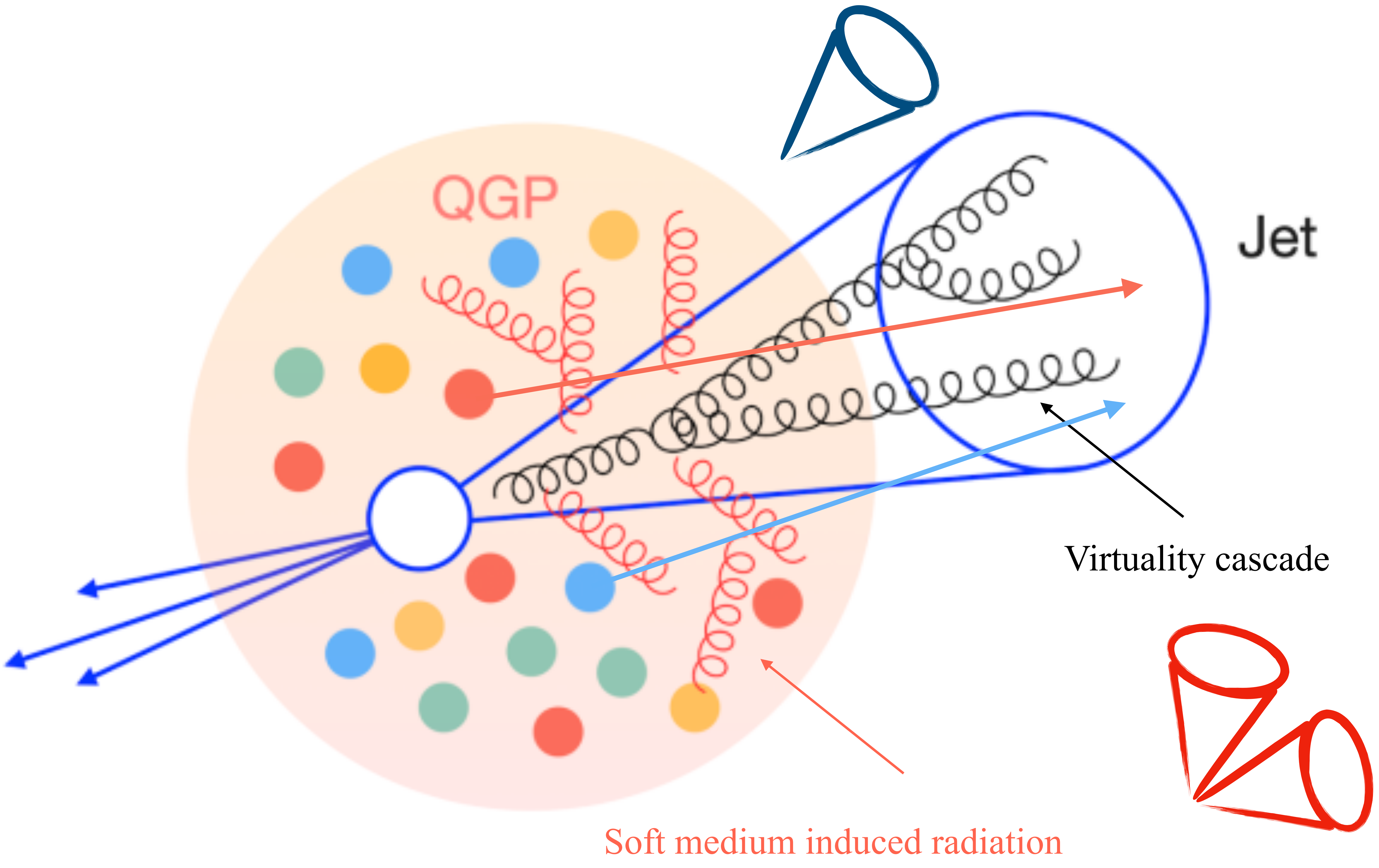
Depletion of energy

[G.-Y. Qin, A. Majumder, H. Song, U. Heinz, 0903.22255]

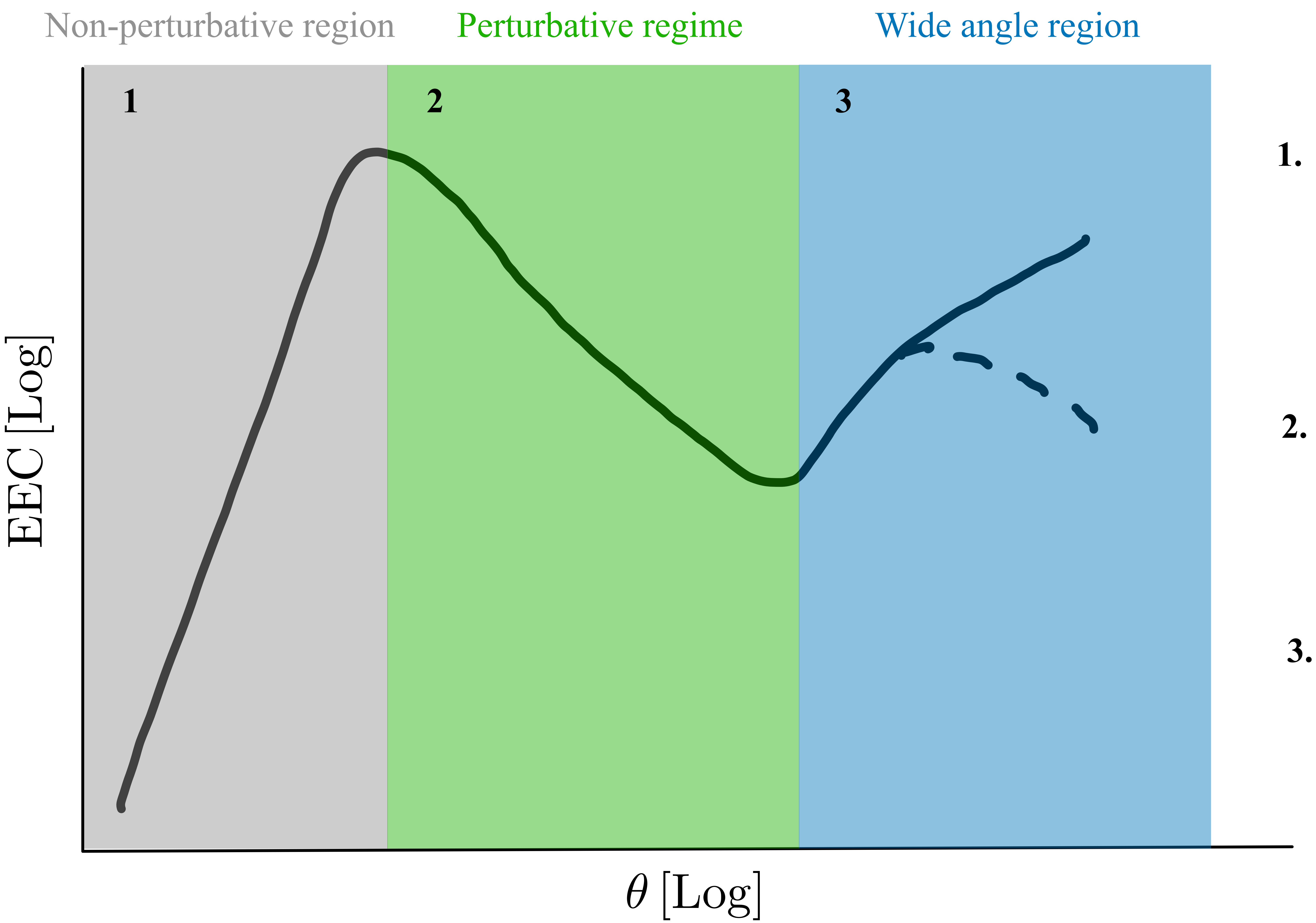


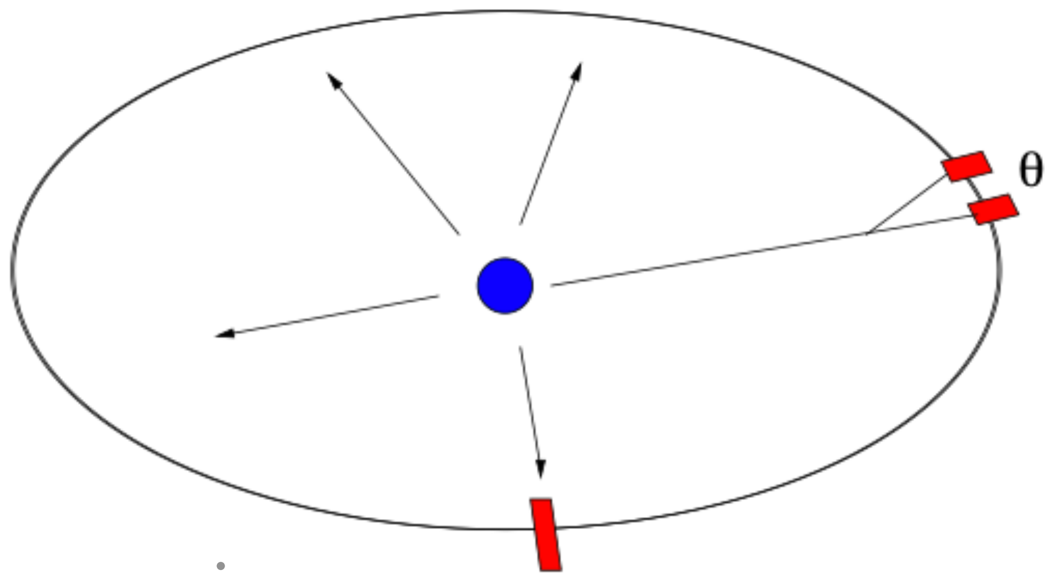
Excess of soft particles

These results form the basis for jet quenching phenomenology



Energy correlators inside jets in heavy ions





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

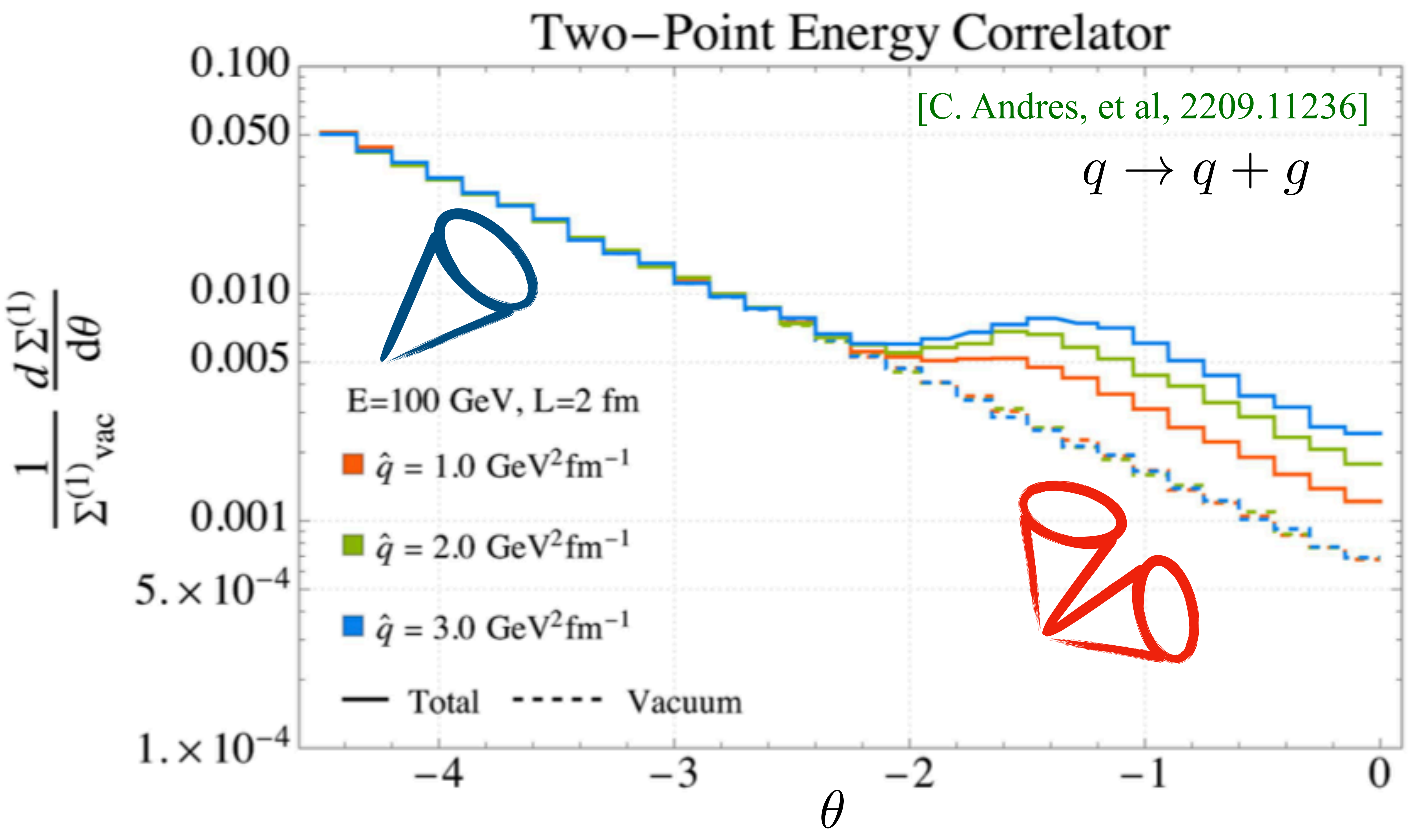
3. Wide angle region:

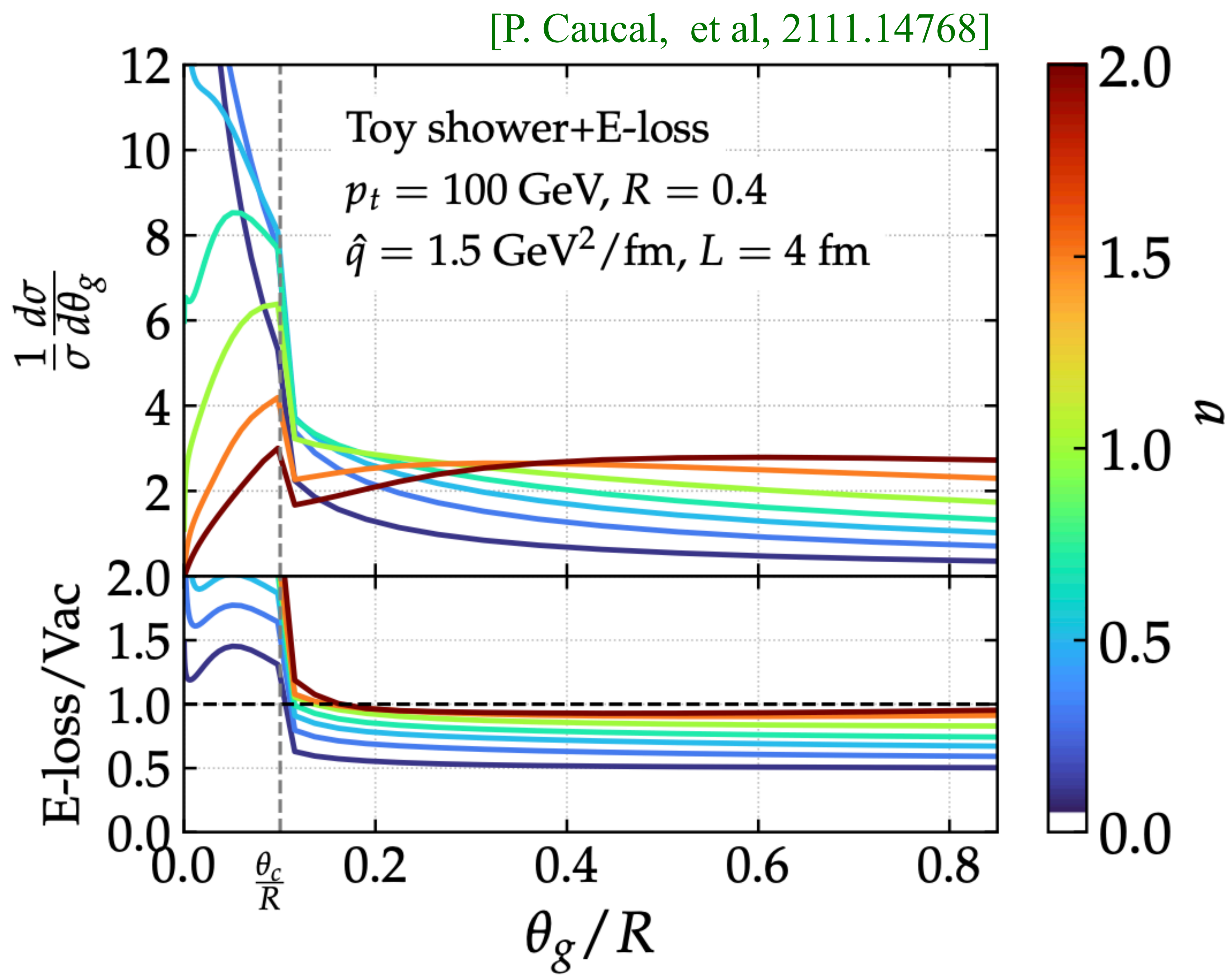
   Vacuum: no modification with respect to **2.**

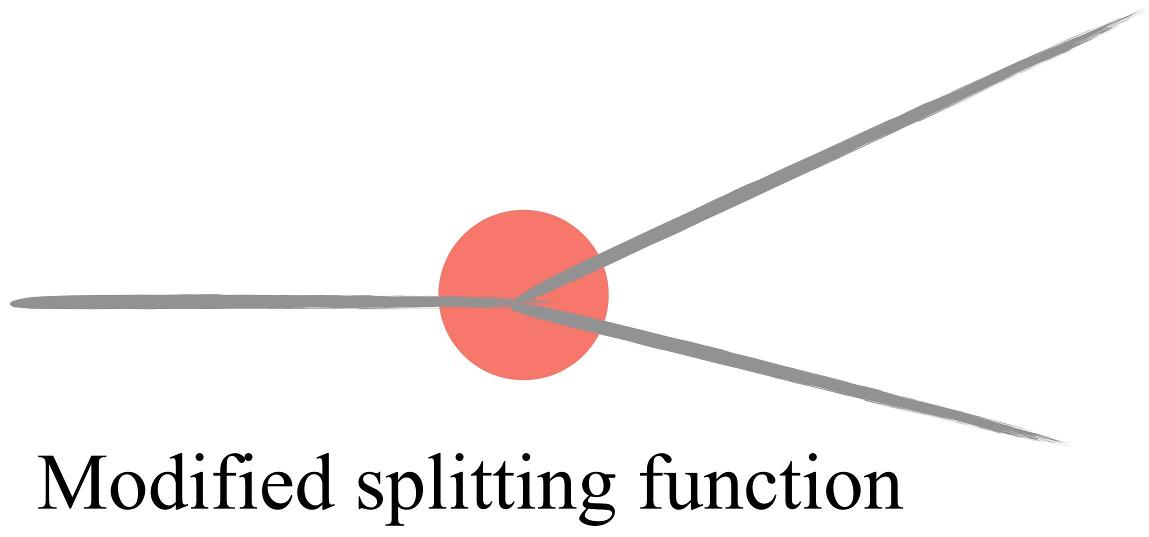
   In-medium: wake (?), perturbative medium modifications (?)

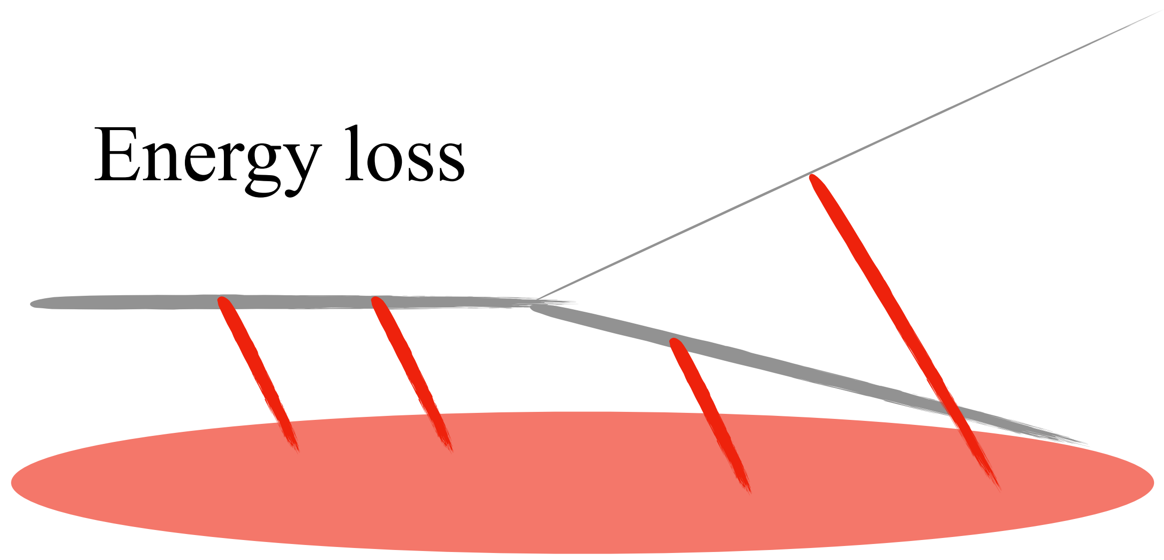
Critical step: make sense of **perturbative baseline** to access all regions

Energy correlators inside jets in heavy ions

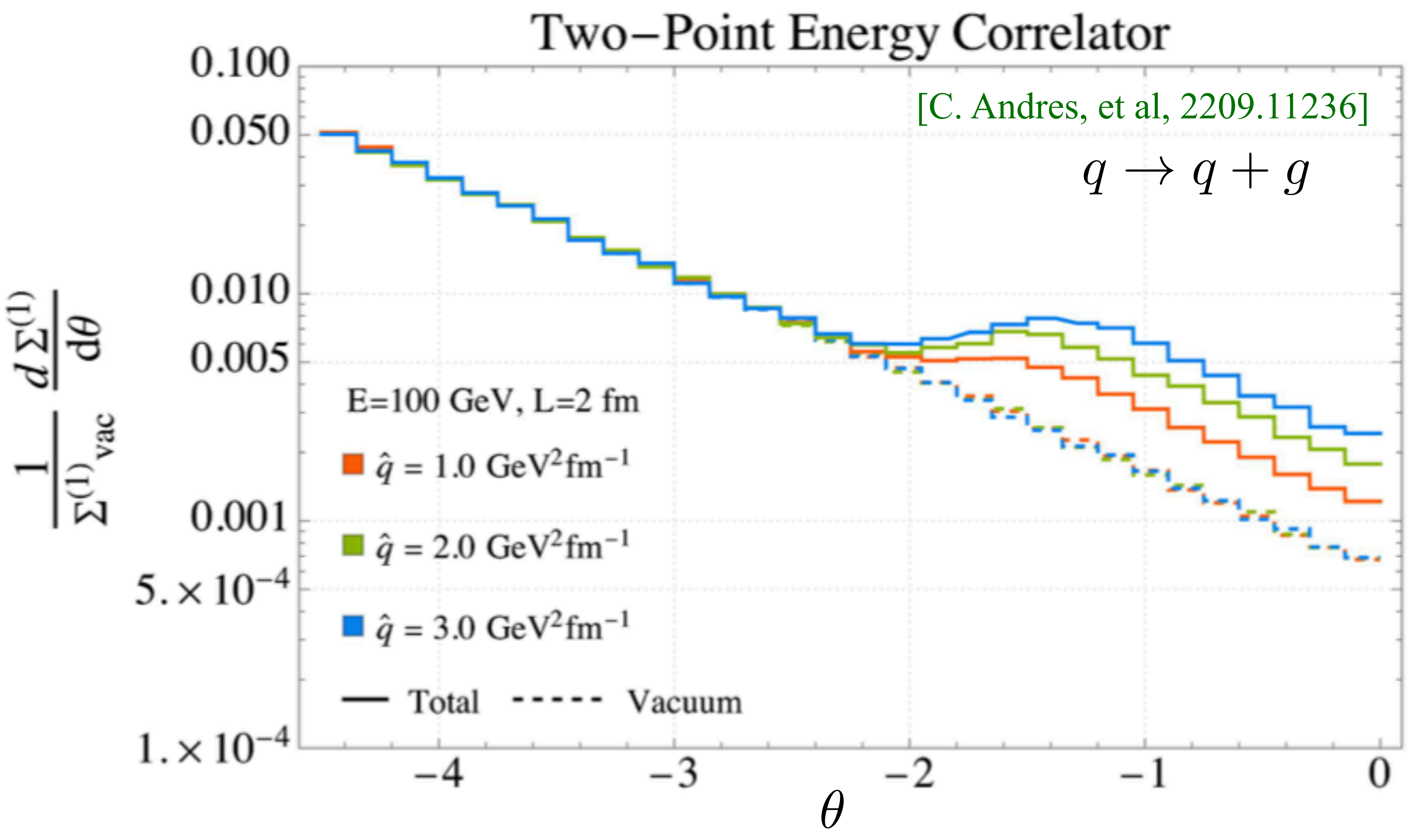






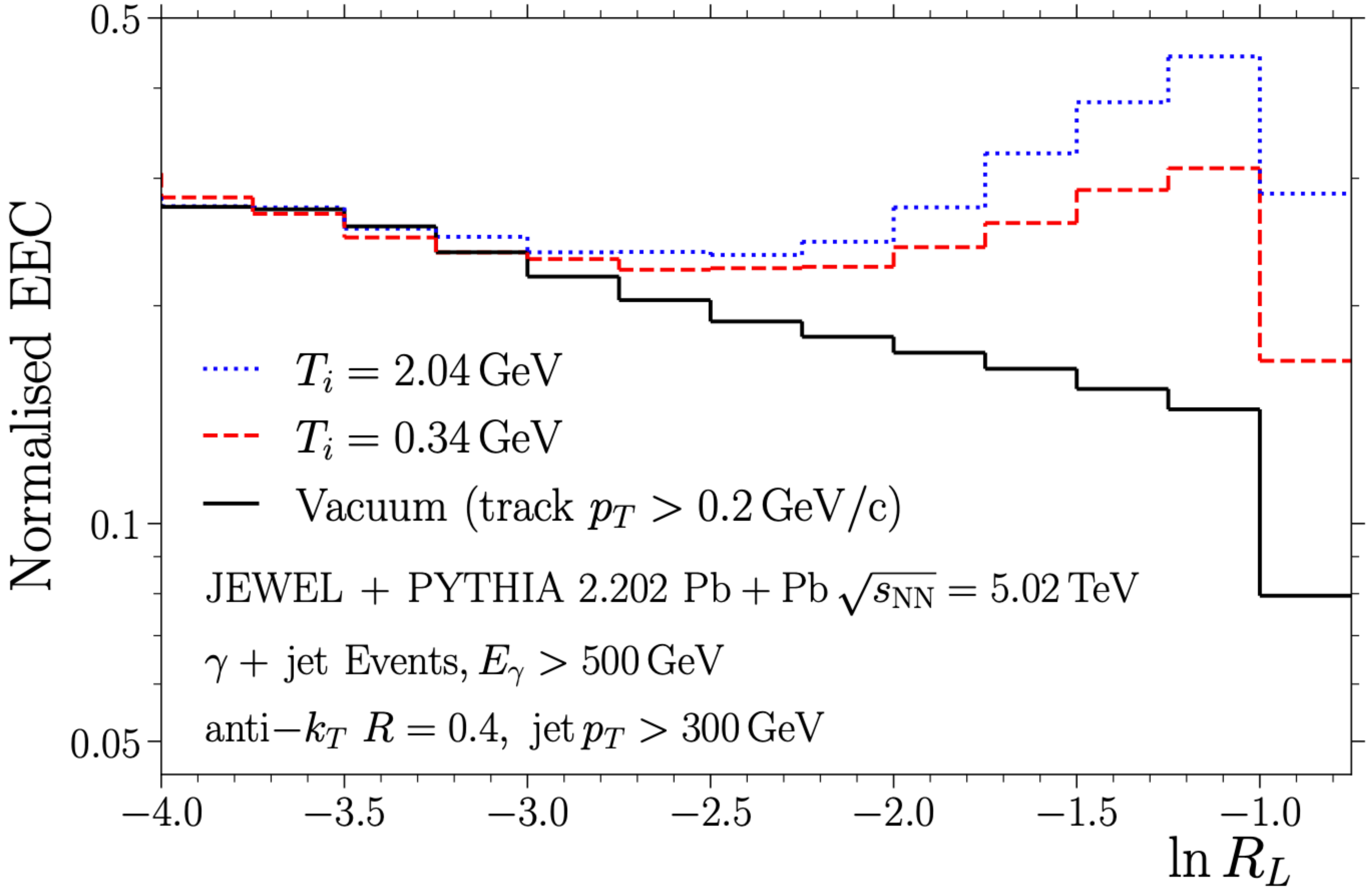


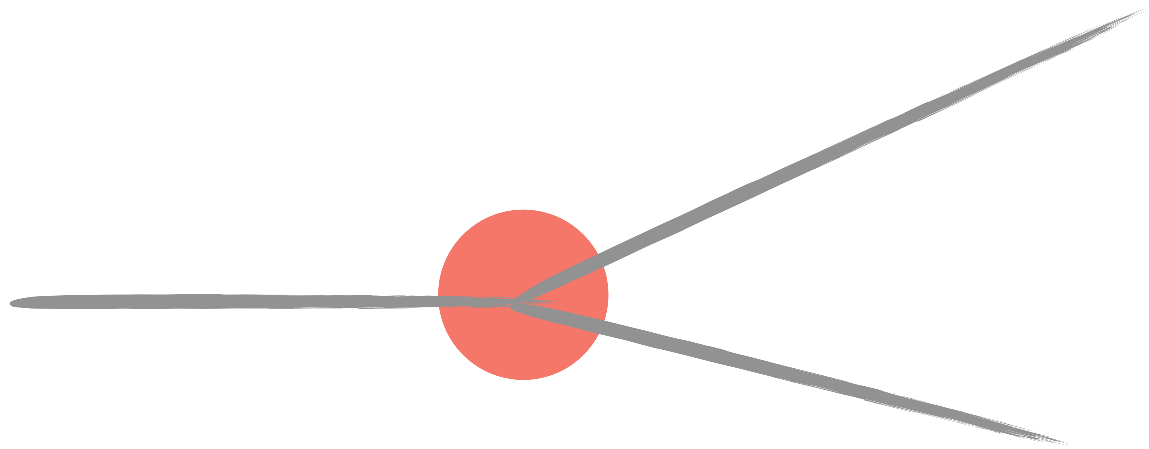
Energy correlators inside jets in heavy ions



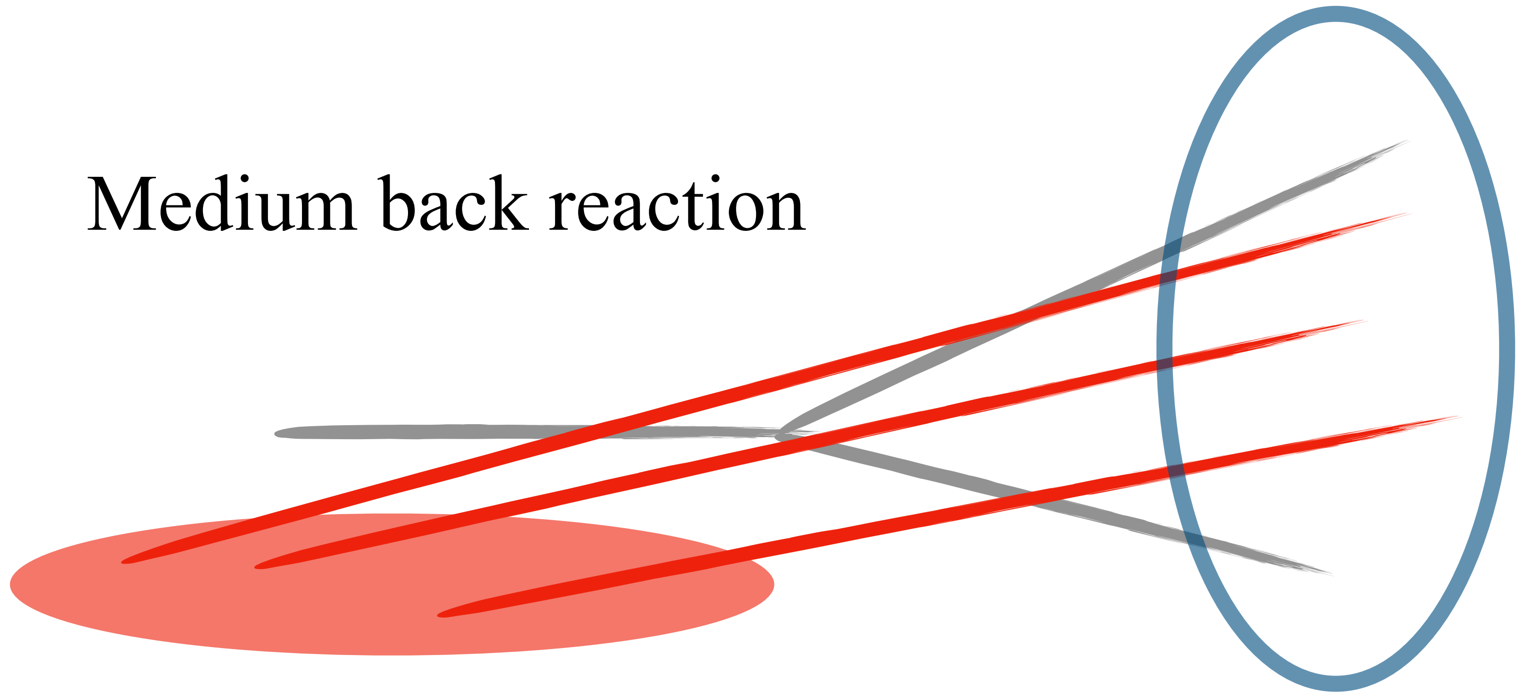
[C. Andres, et al, 2209.11236]

also [Z. Yang, et al, 2310.01500]





Modified splitting function



Medium back reaction

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron

At LL accuracy the in-medium EEC can be written as (in Abelian channel)

$$\frac{\mathrm{d}\Sigma^{q\to qg}}{\mathrm{d}\chi} \approx \frac{2\bar{\alpha}}{\chi}\int_0^1 \mathrm{d}z\, z(1-z)P_{gq}(z)\left(\frac{(1-\Theta_{\rm veto})^{gq}}{\chi^{-\bar{\alpha}\gamma_{gq}^{\rm med}(3,\chi)}} + F_{\rm med}^{gq}(\chi,z)\right)Q_{qg}(p_t,\chi,z)$$

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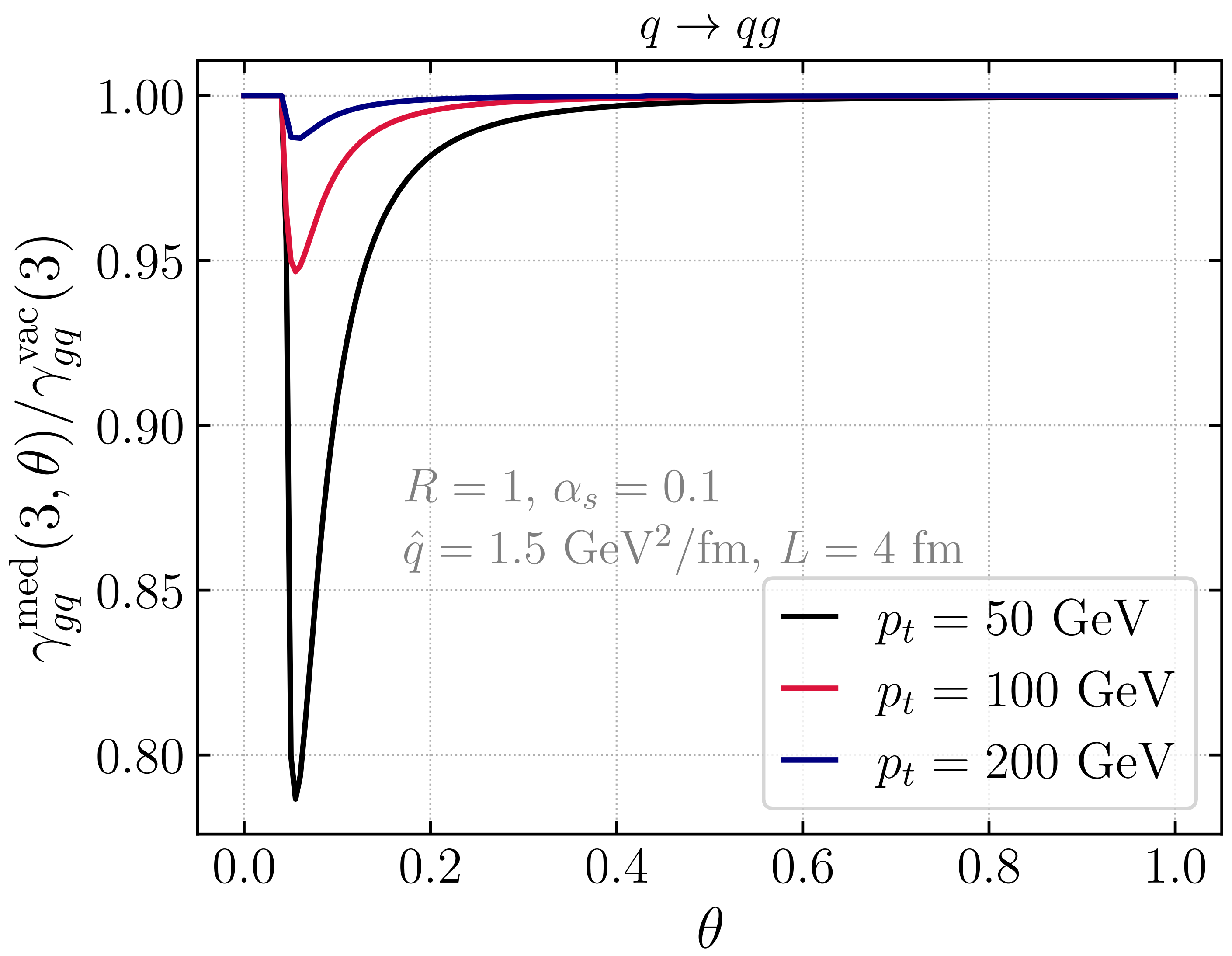
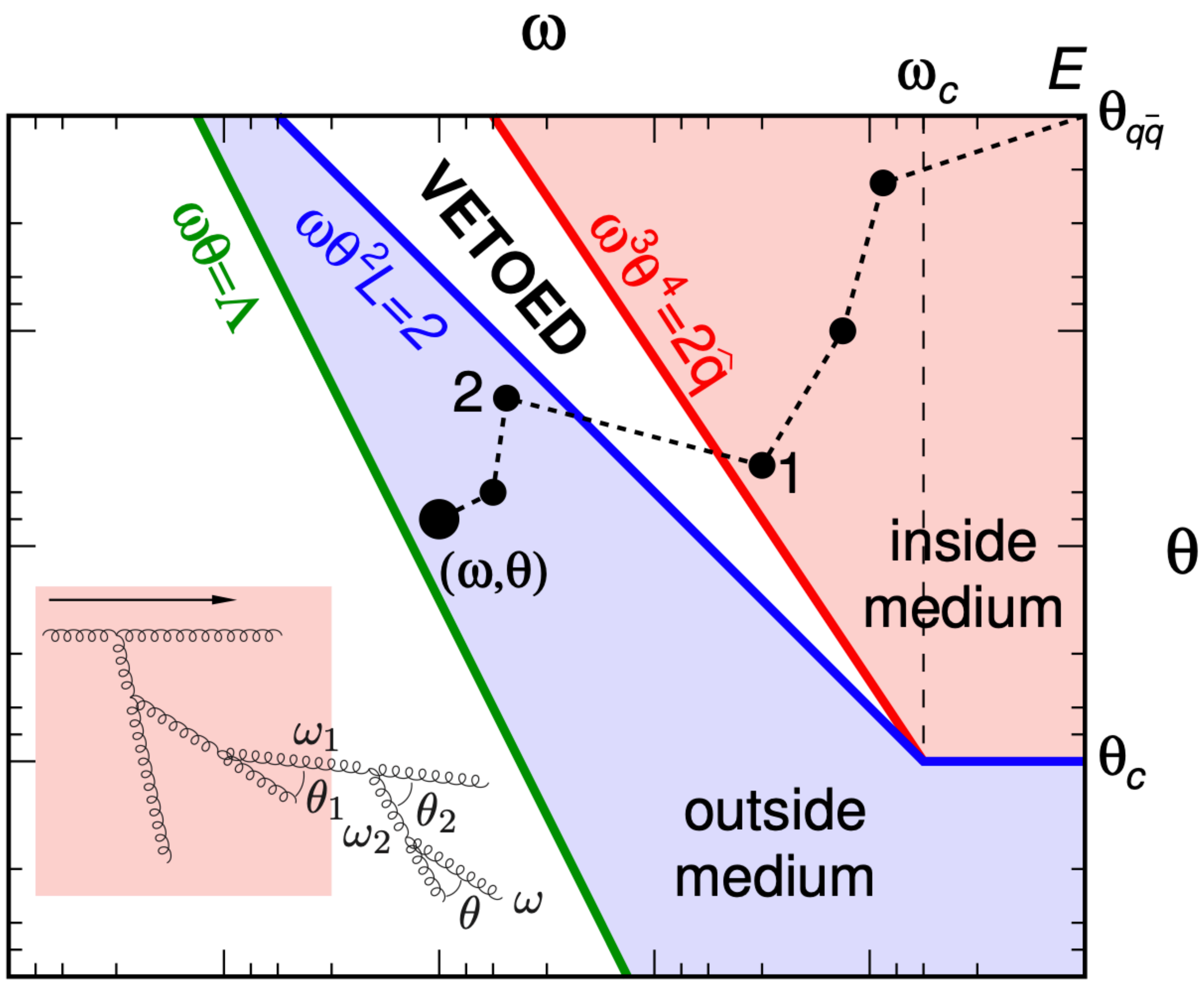
What are the modifications induced by the medium?

1) Phase space reduction for virtuality cascade

$$\Theta_{\rm veto} = \Theta(t_f - t_f^{\rm med})\Theta(L-t_f)$$





[P. Caucal, E. Iancu, G. Soyez, 2018-now]

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron

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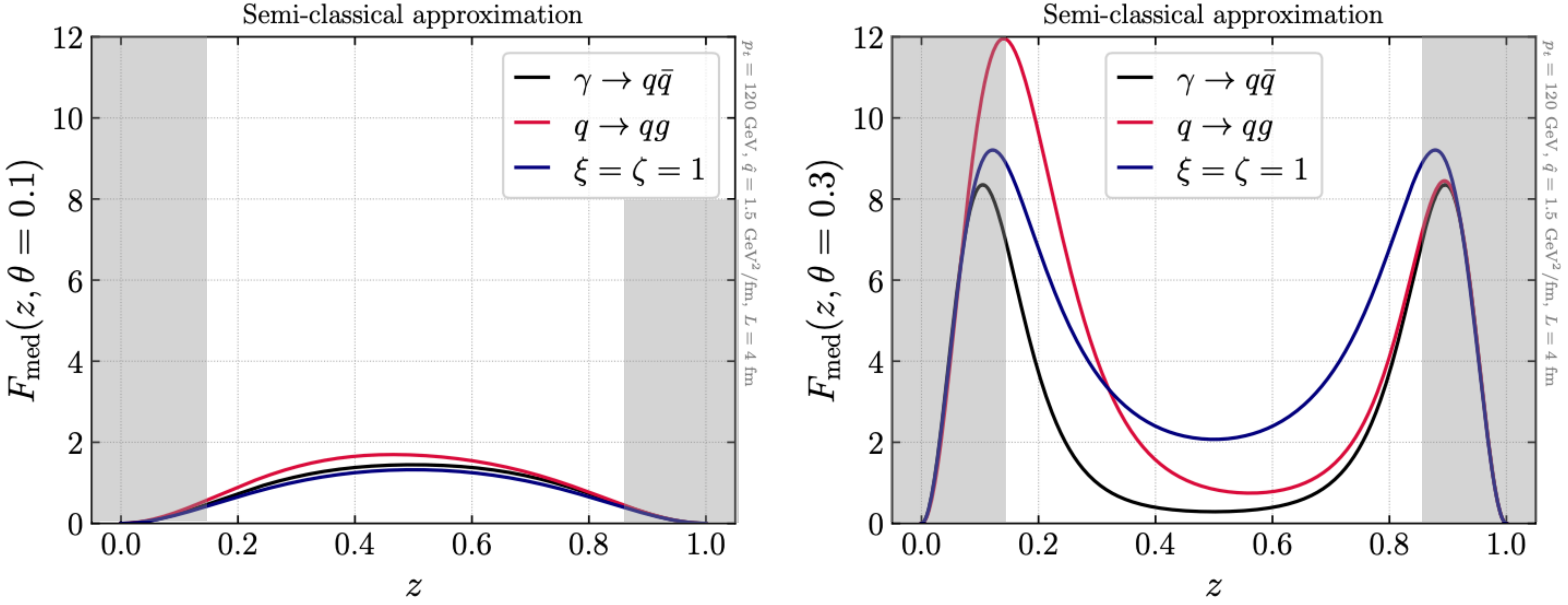
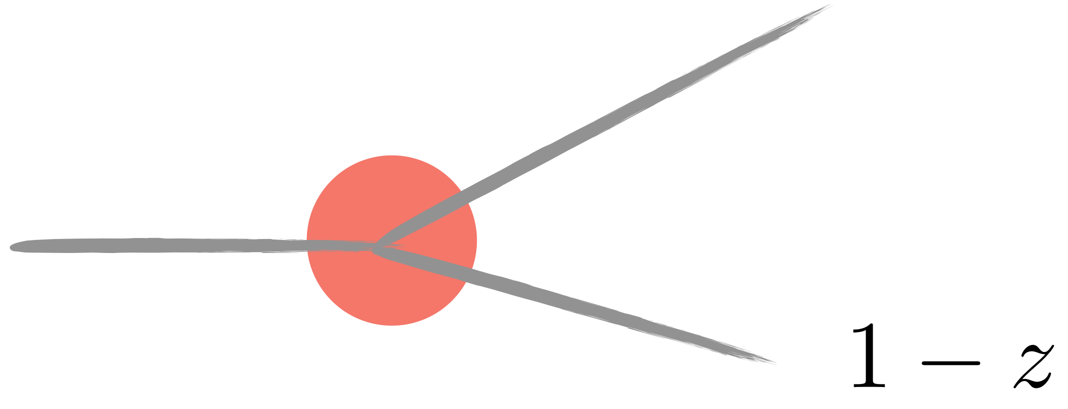
What are the modifications induced by the medium?

2) Modification of the "splitting function"





Only known in certain limits, e.g.

→ $z \ll 1$, BDMPS-Z limit

→ $z \sim 1/2$, semiclassical expansion of path integrals

see e.g. [T. Altinoluk, et al, 1404.2219]

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron

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What are the modifications induced by the medium?

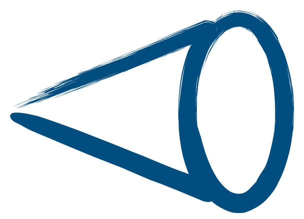
3) Energy loss and substructure

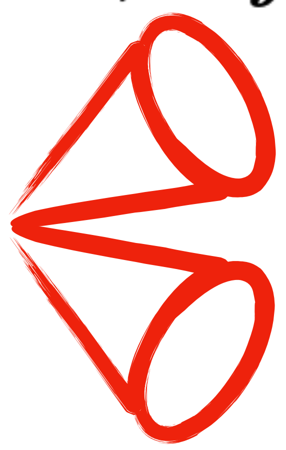
$$\frac{\mathrm{d}\sigma_q^{\text{med}}}{\mathrm{d}p_t\mathrm{d}\theta} \approx \frac{\mathrm{d}\sigma_q^{\text{vac}}}{\mathrm{d}p_t\mathrm{d}\theta}\int_0^\infty \mathrm{d}\varepsilon\, D_q(\varepsilon)e^{-\frac{n\varepsilon}{p_t}} \equiv Q_q(p_t)\frac{\mathrm{d}\sigma_q^{\text{vac}}}{\mathrm{d}p_t\mathrm{d}\theta}$$

$\longrightarrow$ $$Q_i = \exp\left\{-\int_T^{\omega_s}\mathrm{d}\omega\int \mathrm{d}^2\boldsymbol{k}\frac{\mathrm{d}\mathcal{P}_i^{\text{med}}}{\mathrm{d}\omega\mathrm{d}^2\boldsymbol{k}}\left(1-e^{-\frac{n\omega}{p_t}}\right) + \int_{\omega_s}^\infty \mathrm{d}\omega\int \mathrm{d}^2\boldsymbol{k}\frac{\mathrm{d}\mathcal{P}_i^{\text{med}}}{\mathrm{d}\omega\mathrm{d}^2\boldsymbol{k}}\left(1-e^{-\frac{n\omega}{p_t}}\right)\right\}$$

$$\omega_s \equiv \left(\frac{\alpha_s^{\text{med}}N_c}{\pi}\right)^2\omega_c$$

$\longrightarrow$ $$Q_{ij}(p_t,\theta,z) = Q_i(p_t,R)(1-\Theta_{\text{res}}) + Q_i(p_t,R)Q_j(p_t,R)\Theta_{\text{res}}$$

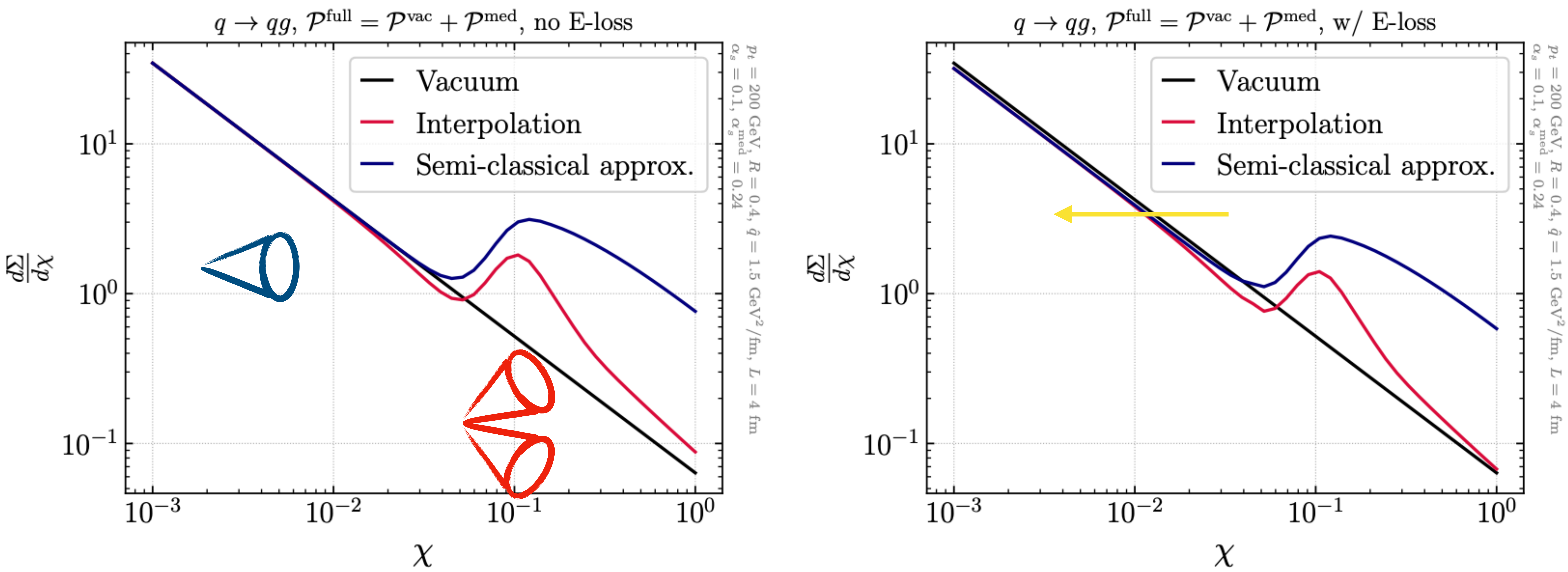




$F_{\text{med}}^{gq}(\chi,z)$

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron

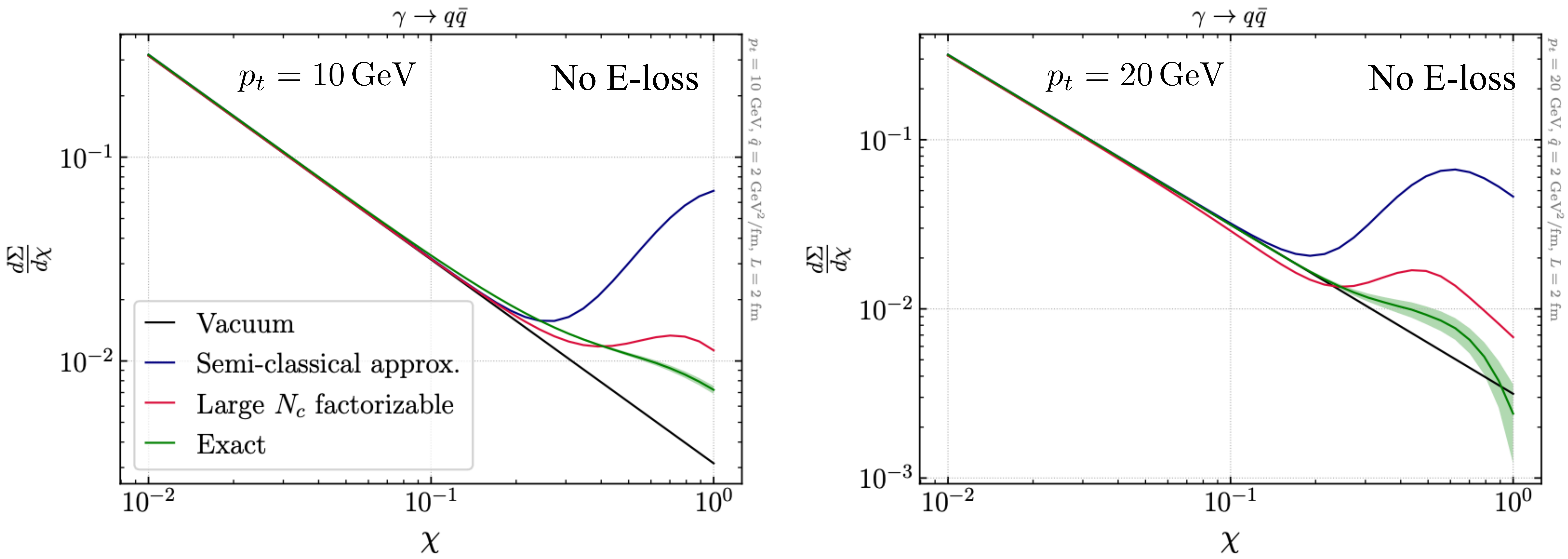


- Interpolation: remove soft branchings from the medium modified splitting function
- Suppression at large angles due to an overestimation from semi-classical approximation
- Energy loss leads to overall shift and competes against LO medium enhancement

already seen in JB, Mehtar-Tani 2022; Z. Yang et al 2023

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron



→ Exact: numerical evaluation of the medium modified "splitting function"

→ Large Nc: analytical result at large Nc **without** semiclassical expansion

"Improved" descriptions lead to a significant reduction compared to simpler analytical estimates

Energy correlators inside jets in heavy ions

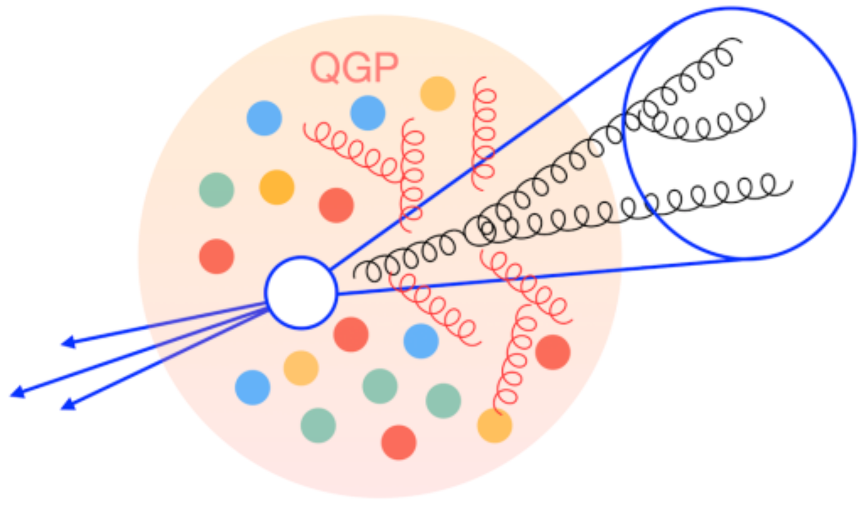
2312.12527, B, Caucal, Soto-Ontoso, Szafron

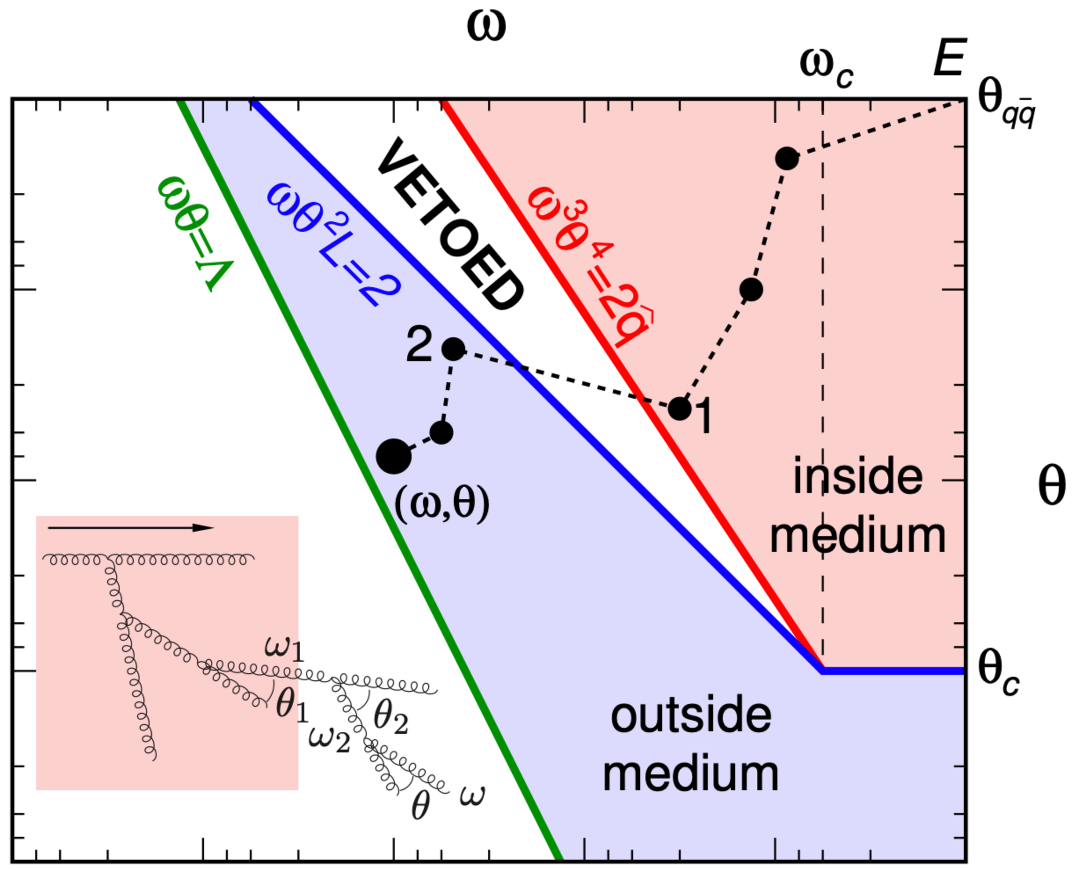
To complete this study we perform a study using the JetMed MC generator. This includes:

→ Energy loss beyond quenching weight approximation

→ Color coherence effect and anti-angular ordering

→ Medium induced and virtuality cascades in parallel





→ LO medium modified hard branching kernel is introduced; we have the following cases:

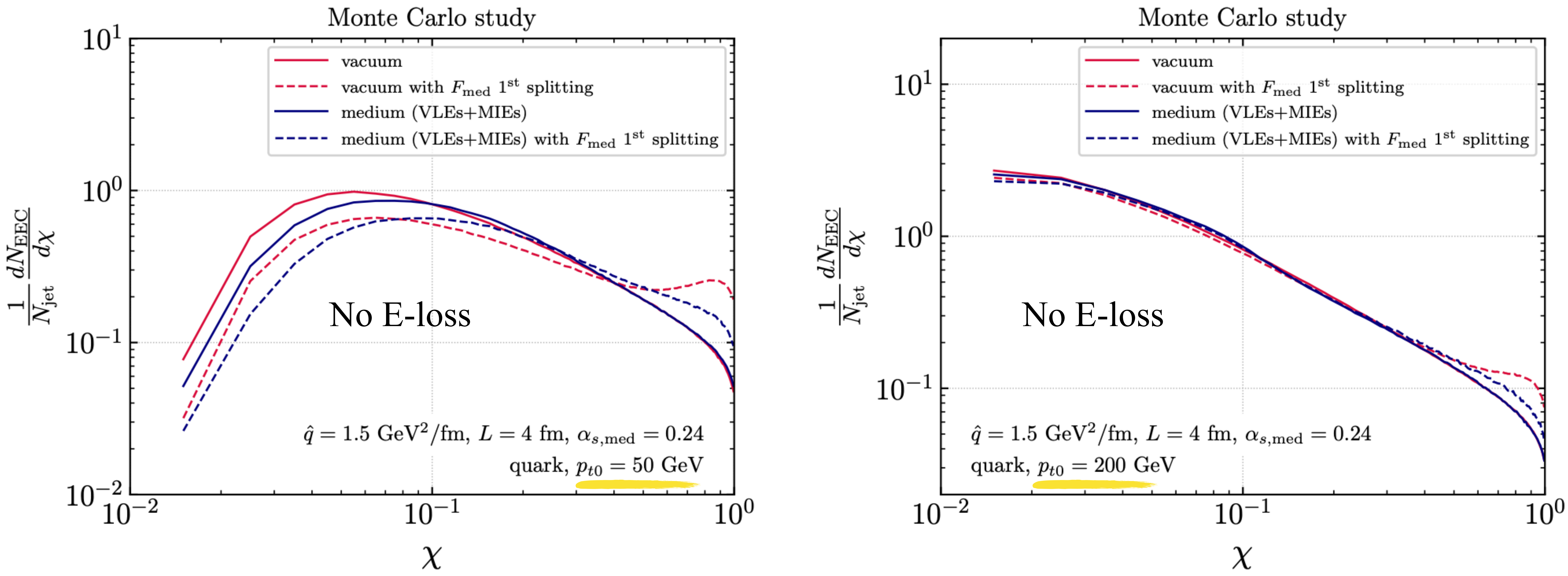
Default JetMed: no hard splitting, just soft induced radiation and virtuality cascade

Vacuum + hard induced splitting: comparable to analytical model with no energy loss

JetMed + hard induced splitting: most complete version

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron

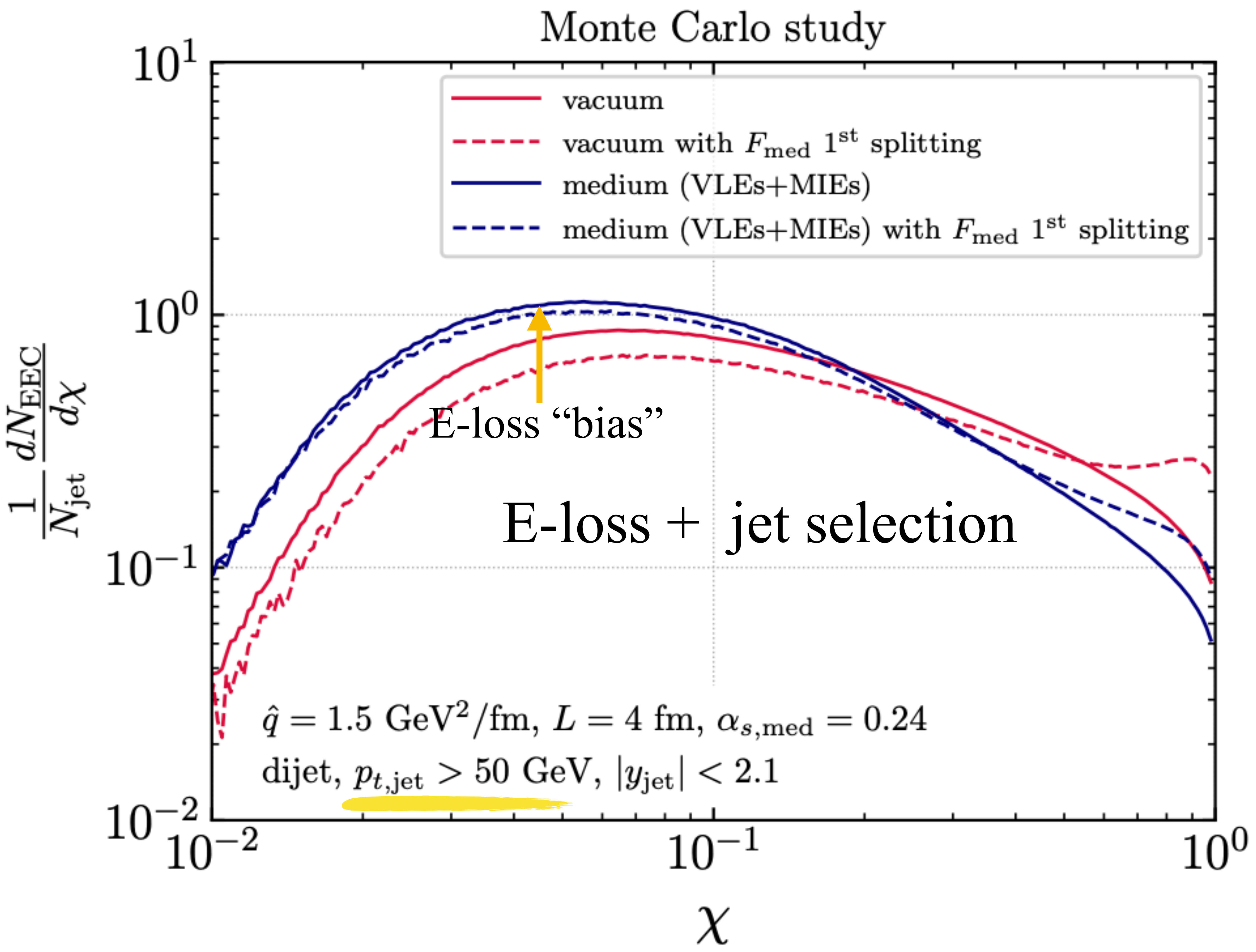


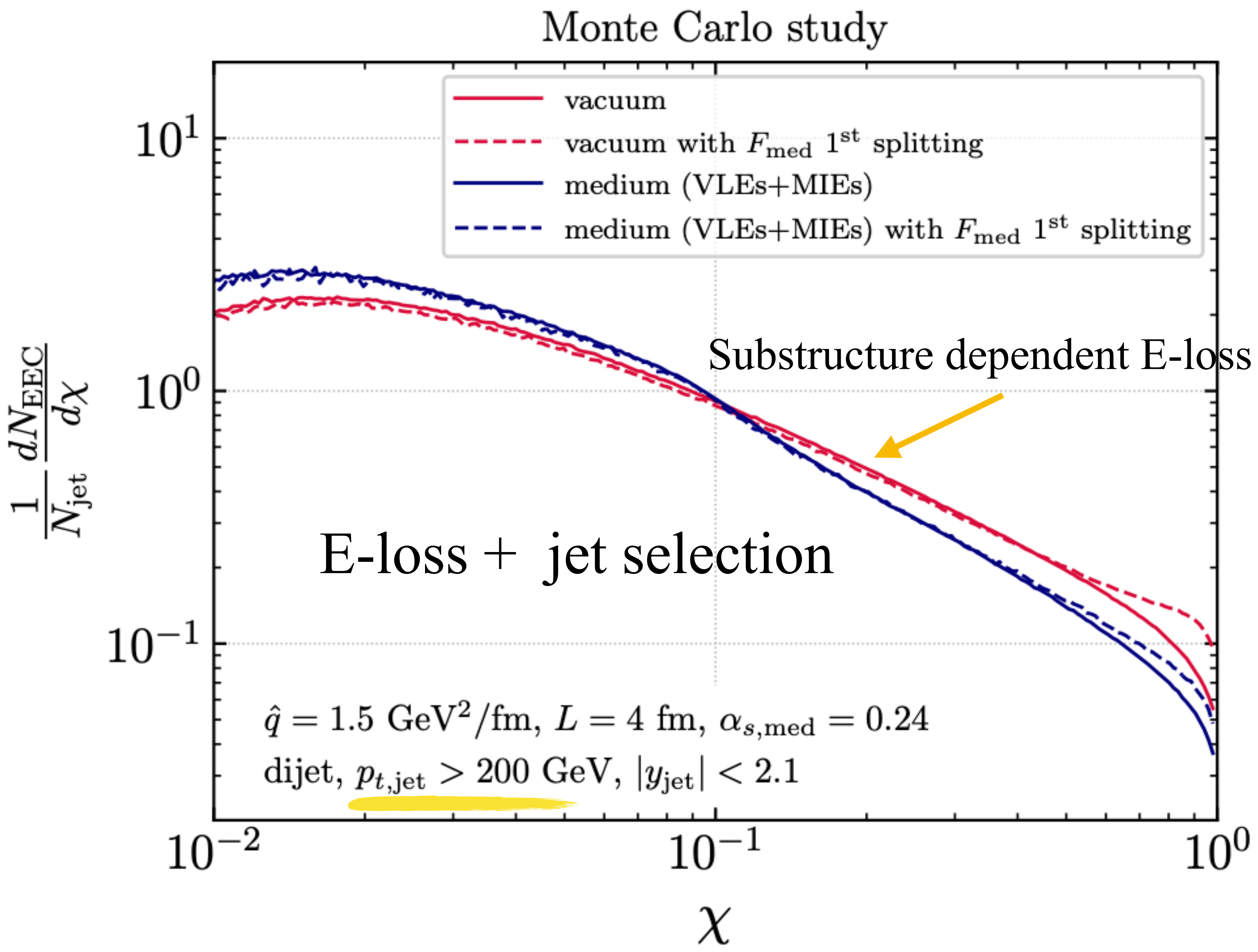
→ Turn-over set by shower cut-off; no hadronization effects

→ Large angle enhancement only present when semi-hard emissions are included

Energy correlators inside jets in heavy ions

2312.12527, B, Caucal, Soto-Ontoso, Szafron



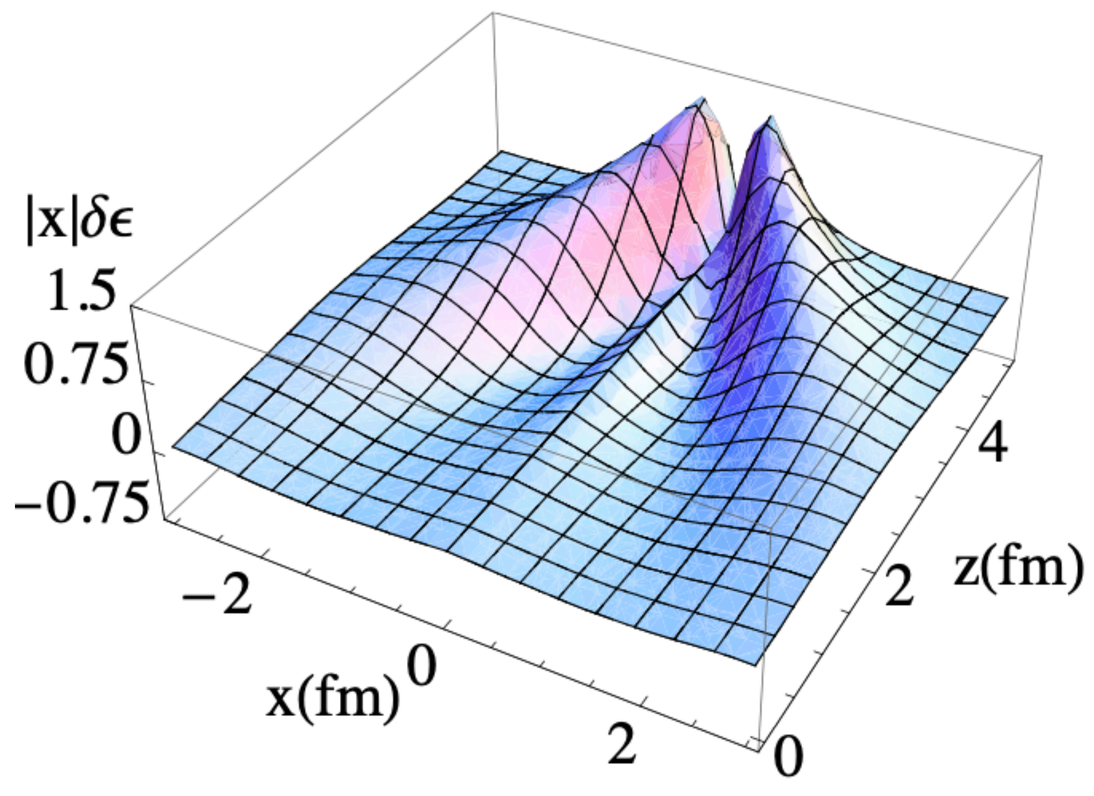


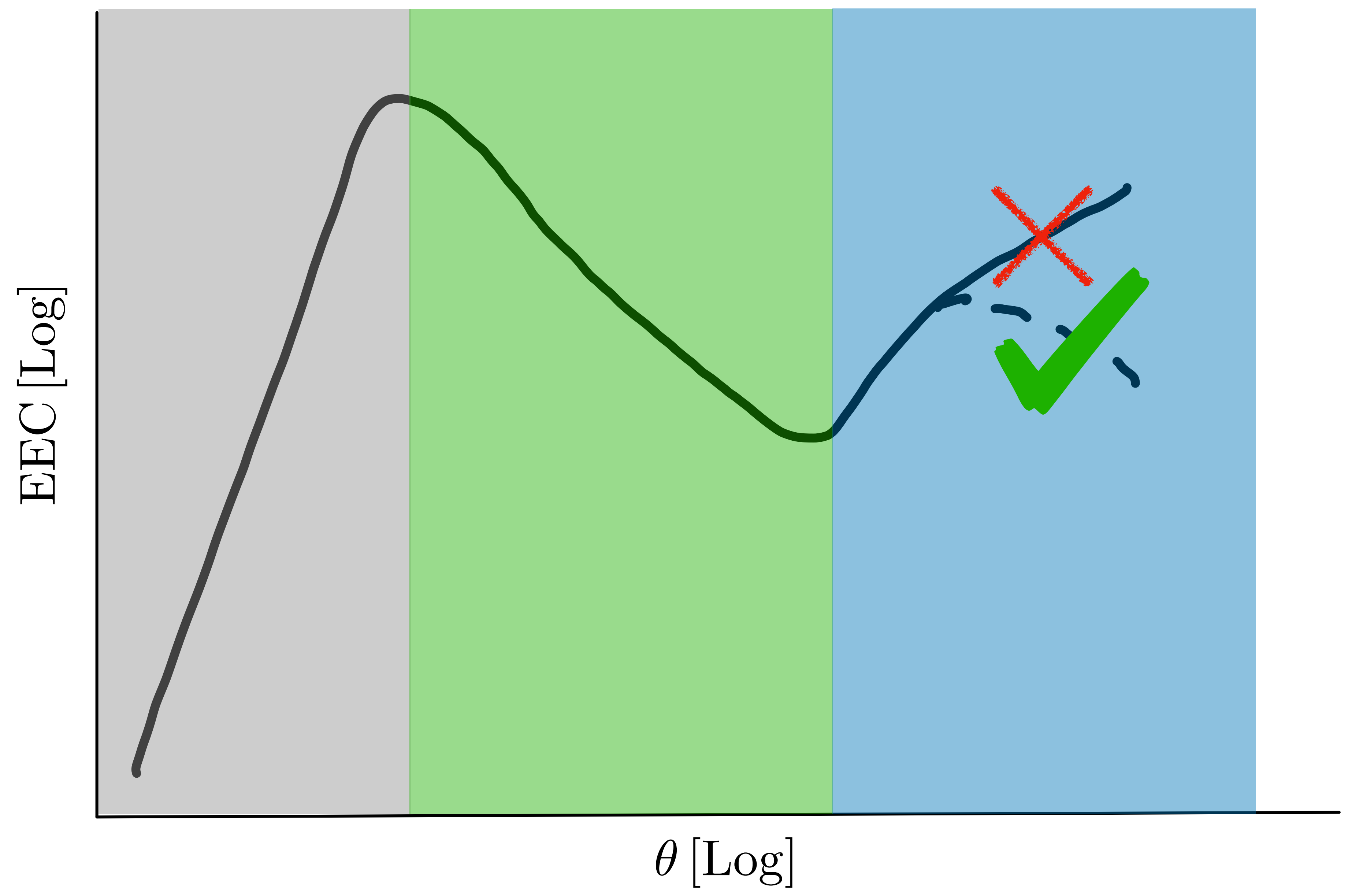
→ Energy loss leads to suppression at large angles and enhancement at small ones (solid lines)

→ Adding F_{med} introduces slight enhancement at large angles, which competes with E-loss

Higher weight energy correlators

To make sense of **perturbative baseline** one needs to clean soft uncorrelated radiation





Two possible ways to go:

1. EECs on subjets inside a jet:

$$\frac{d\Sigma}{d\theta}_{\text{subjets}} = \int_{\vec{n}_1,\vec{n}_2} \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{p_t^2}\delta(\vec{n}_1\cdot\vec{n}_2 - \cos\theta)$$

2. Higher power EEC + track functions:

$$\frac{d\Sigma^{(n)}}{d\theta}\Big|_{\text{trks}} = \int_{\vec{n}_1,\vec{n}_2} \frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{p_t^{2n}}\delta(\vec{n}_1\cdot\vec{n}_2 - \cos\theta)$$

Lund/subjet based EEC

2312.12527 + 24xx, B, Caucal, Monni, Soto-Ontoso, Szafron

Brookhaven National Laboratory

Idea: compute EEC on IRC safe objects

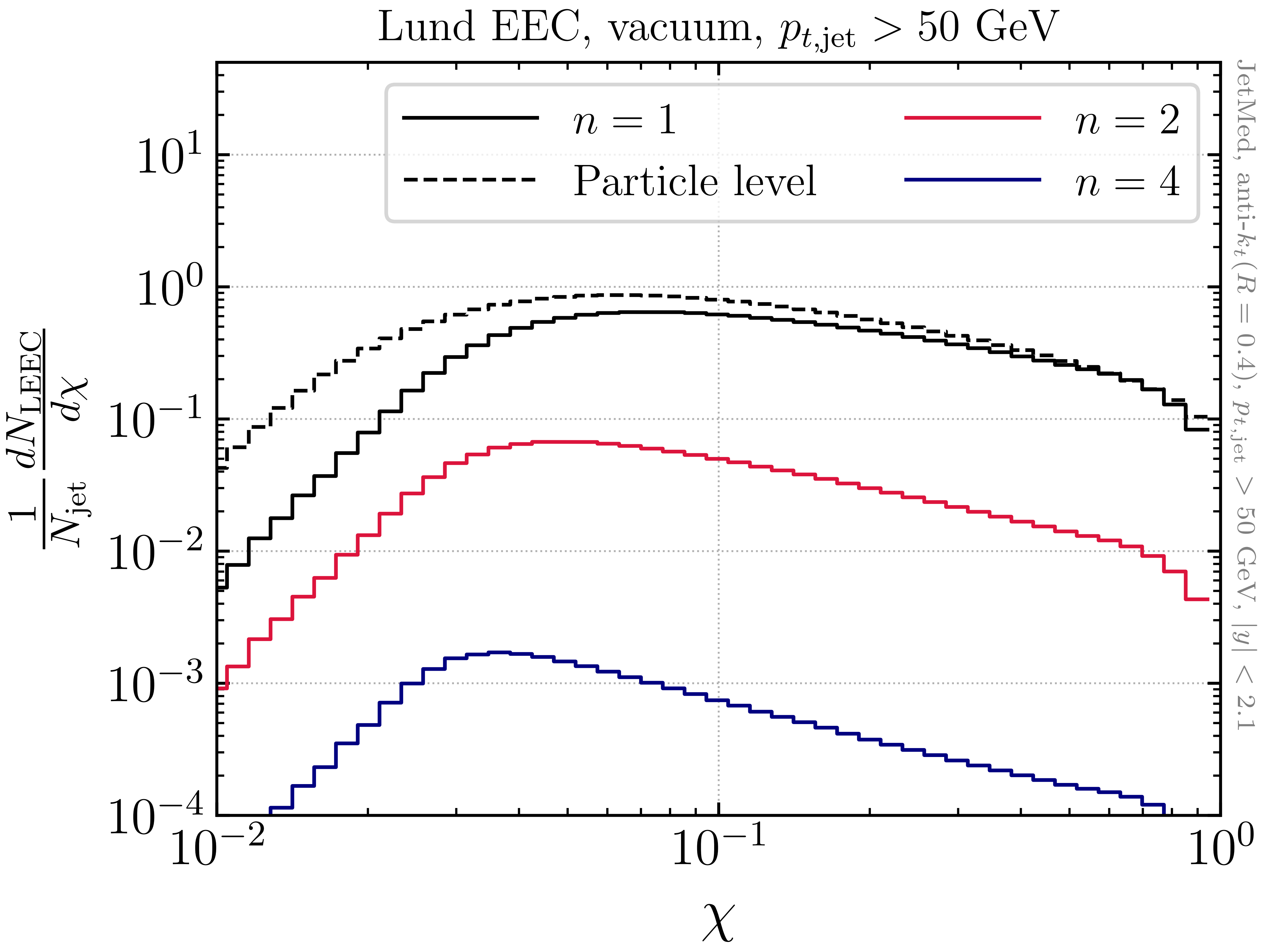
[F. A. Dreyer, G. P. Salam, G. Soyez, 1807.04758]

- Undo the last-clustering step to generate two subjets, j_1 and j_2.
- Calculate their relative k_t defined as $k_t = \min(x_1, x_2)\Delta R_{12}$, where the concrete definitions of x (an energy-like variable) and ΔR_{12} (an angular-like variable) depend on the collision system. For e^+e^-, $x_i = E_i$ and $\Delta = \theta_{ij}$, while in pp in $x_i = p_{ti}$ and $\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$.
- Only when $k_t > k_{t,\mathrm{cut}}$, record the softest branch, so-called primary Lund declustering.
- Repeat from step 1 following only the hardest subjet, i.e., the primary branch.
- Once there is nothing left to decluster, calculate the EEC as

$$\frac{d\Sigma^{(n)}}{d\chi} = \frac{1}{\sigma} \sum_{\{i,j\}\in \text{declust.}} \int_0^1 dz \frac{d\sigma}{d\theta_{ij} dz} z^n (1-z)^n \delta\left(\chi - \frac{\theta_{ij}}{R}\right) \Theta(k_t > k_{t,\mathrm{cut}}), \quad (5.1)$$

where the sum runs over all primary Lund declusterings.

pp $\quad k_{t,cut} = 0.25$ GeV

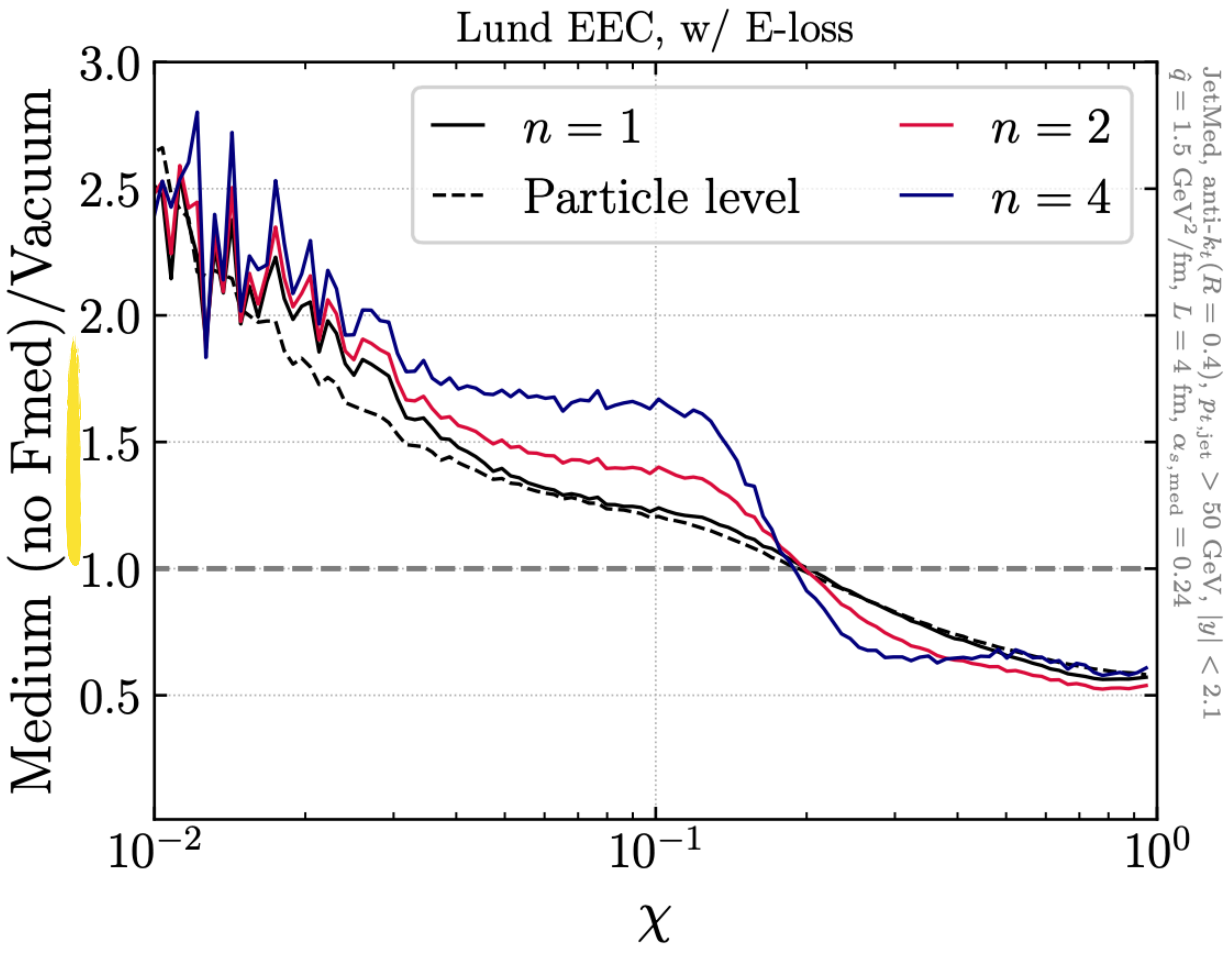


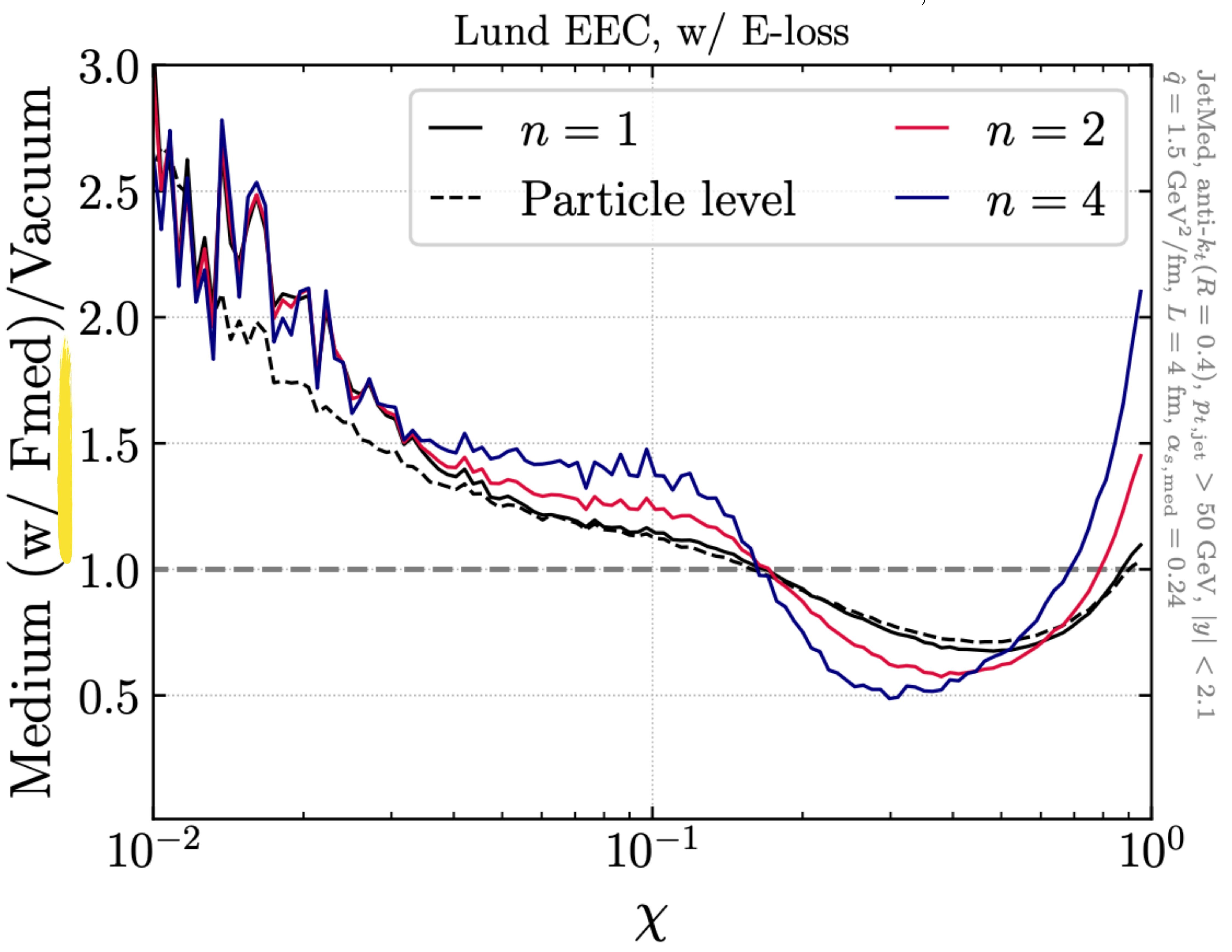
→ Exact definition of subjets is not critical, it will only determine calculability from analytical side

Lund/subjet based EEC

2312.12527 + 24xx, B, Caucal, Monni, Soto-Ontoso, Szafron

$k_{t,cut} = 0.25\,\text{GeV}$





→ Lund and particle level show similar behavior for standard EEC

→ Higher power results in narrowing due to dominance of harder branchings, similar to θ_g distribution

→ Medium enhanced splitting function leads to peak at the edge of the jet

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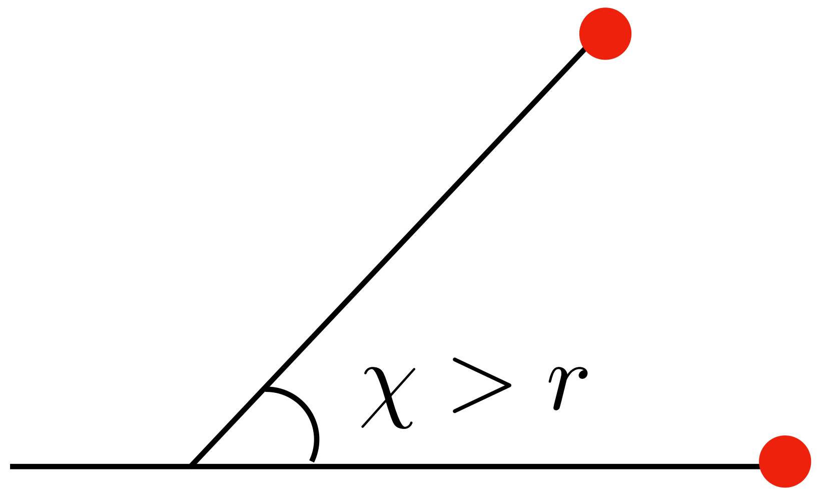
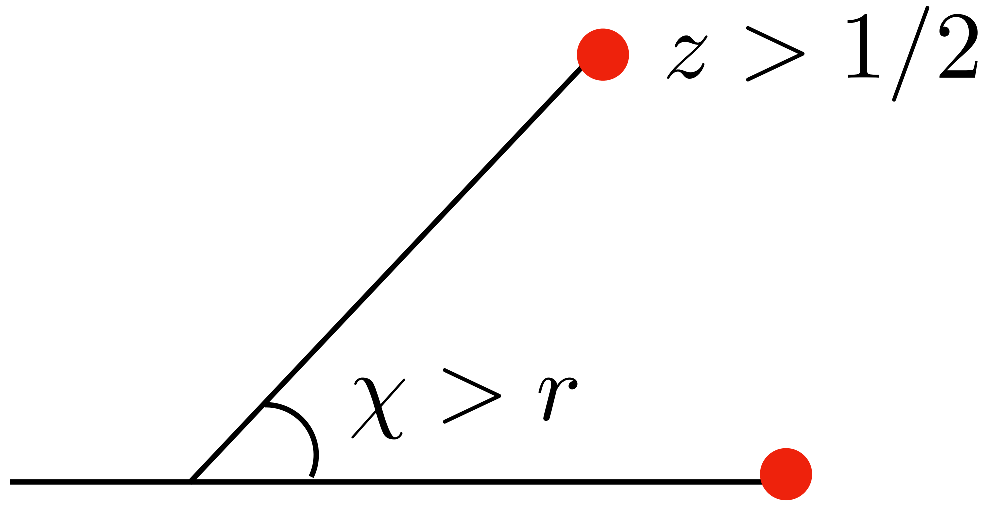
It is worth studying the LL resummation of the EEC for subjets:

→ We consider first when only splittings above r contribute $n \geq 1$



$$\hat{\gamma}(3) \to \hat{\gamma}(2n+1)\,, r \sim \chi \ll 1$$

→ The same calculation can be performed for Lund declusterings



$$\hat{\gamma}(3) \to \hat{\gamma}^{+}(2n+1) + \hat{\gamma}^{-}(2n+1)\,, r \sim \chi \ll 1$$

→ The leading power correction scaling changes as

$$\frac{A_1}{\chi^3 Q} \to \frac{A_1'}{\chi^{2n+1} Q^n}$$

EEC on tracks in-medium

2401.04164, B, Szafron

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Track functions were proposed a decade ago to have theory analog of measurements made on charged particles

2013, Chang, Procura, Thaler, Waalewijn

e.g. quark track function for quantum number R

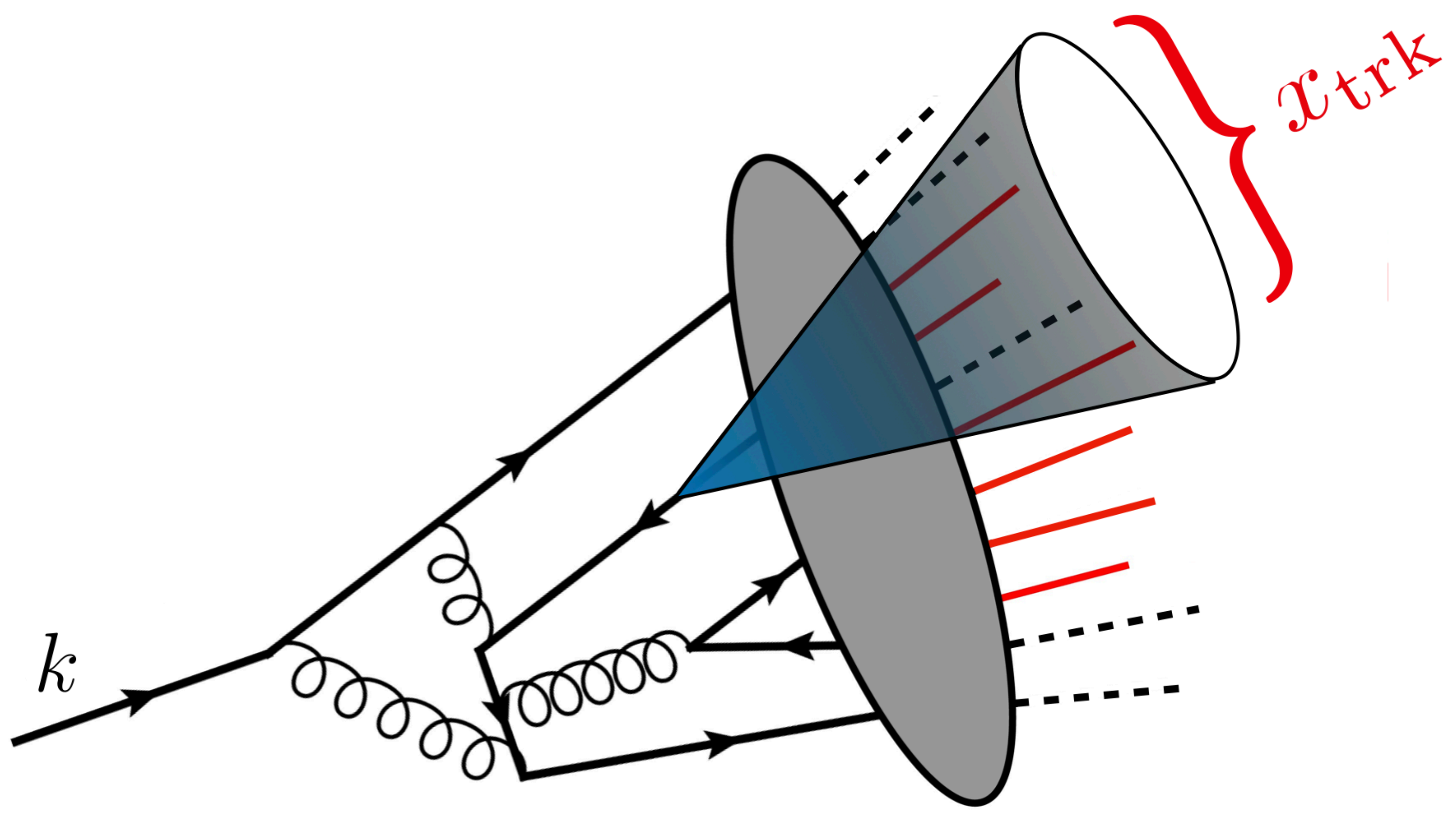
$$T_q(x) = \int \mathrm{d}y^+ \mathrm{d}^{d-2} y_\perp e^{ik^- y^+/2} \sum_X \delta\left(x - \frac{P_R^-}{k^-}\right) \frac{1}{2N_c} \mathrm{tr}\left[\frac{\gamma^-}{2} \langle 0|\psi(y^+, 0, y_\perp)|X\rangle\langle X|\bar{\psi}(0)|0\rangle\right]$$

For EECs moments of track functions enter as the natural matching coefficients to hadronic observable

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

Moments satisfy a non-linear RG evolution, here for Yang-Mills at LO:

$$\mu \frac{dT^{[N]}}{d\mu} = \frac{\alpha_s}{2\pi} \int_0^1 dz P(z) \int_{x_1,x_2} T(x_1,\mu) T(x_2,\mu) (z x_1 + (1-z) x_2)^N$$



For HICs we need to understand RG evolution of these objects

EEC on tracks in-medium

2401.04164, B, Szafron

Vacuum RGE: $$\mu \frac{dT^{[N]}}{d\mu} = \frac{\alpha_s}{2\pi} \int_0^1 dz P(z) \int_{x_1, x_2} T(x_1, \mu) T(x_2, \mu) (z x_1 + (1-z) x_2)^N$$

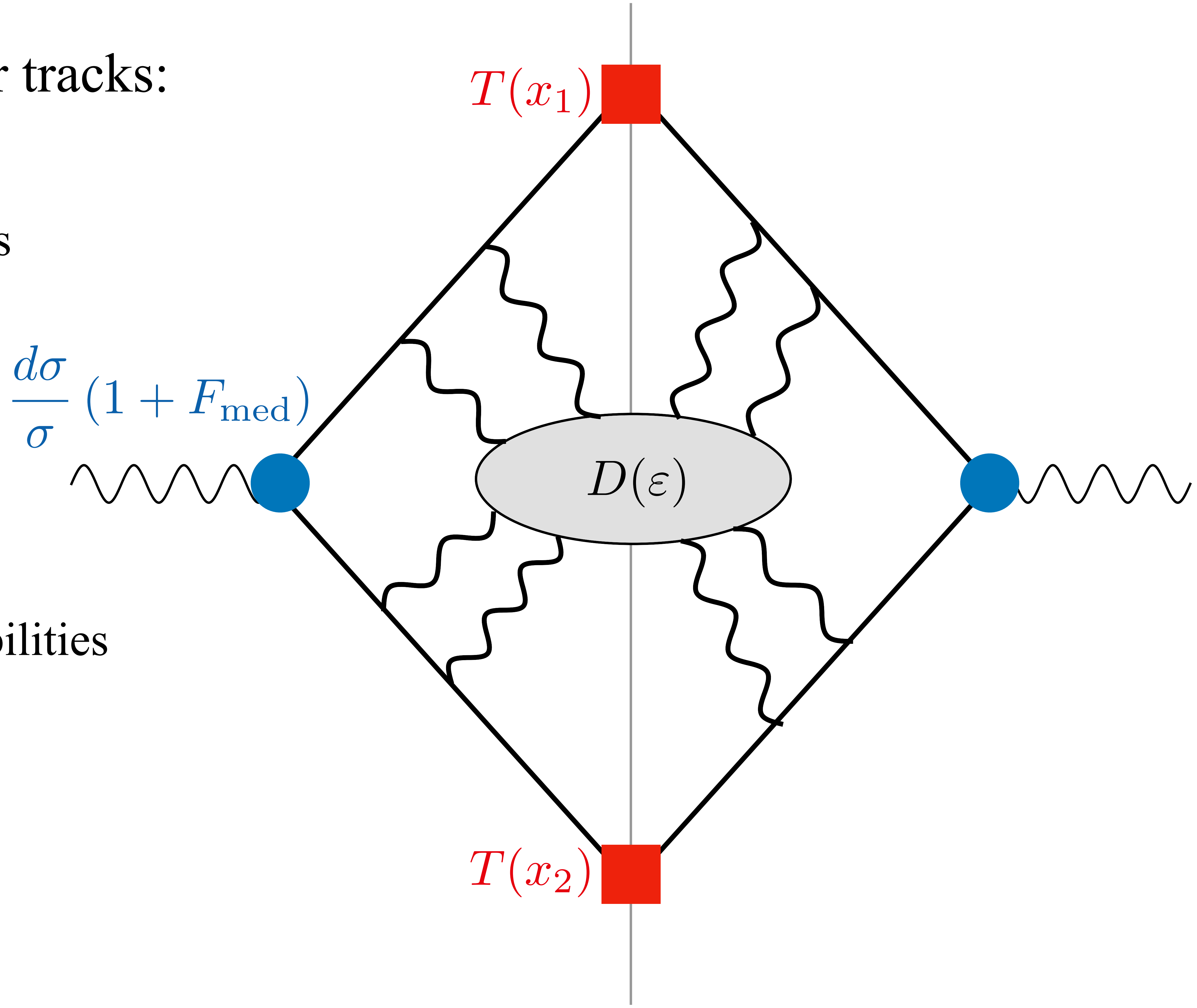
We introduce the medium modifications discussed before for tracks:

Modified phase space: same RG but with “new” anomalous dimensions

$$\gamma(j, \mu) = -\int_0^1 dz\, P(z) \Theta_{\mathrm{PS}}(\mu, z) z^{j-1}$$

Energy loss: modified evolution, in convolution with energy loss probabilities

$$\mu \frac{dT}{d\mu} = \frac{\alpha_s}{2\pi} \int_{\varepsilon_1, \varepsilon_2} D(\varepsilon_1) D(\varepsilon_2) \int_0^1 dz P\left(z + \frac{\varepsilon_1}{p_t} + \frac{\varepsilon_2}{p_t}\right)$$
$$\times \int_{x_1, x_2} T(x_1, \mu) T(x_2, \mu)\, \delta(x - z x_1 - (1-z) x_2)$$

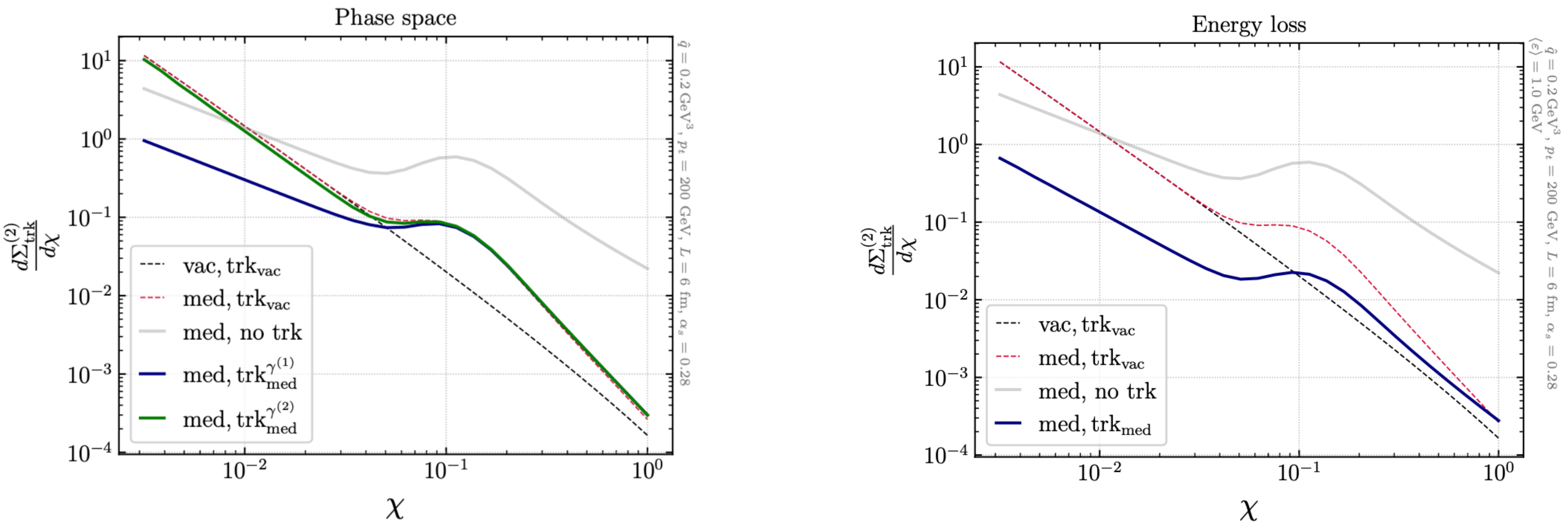


similar to 2016, Mehtar-Tani, Tywoniuk

EEC on tracks in-medium

2401.04164, B, Szafron

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

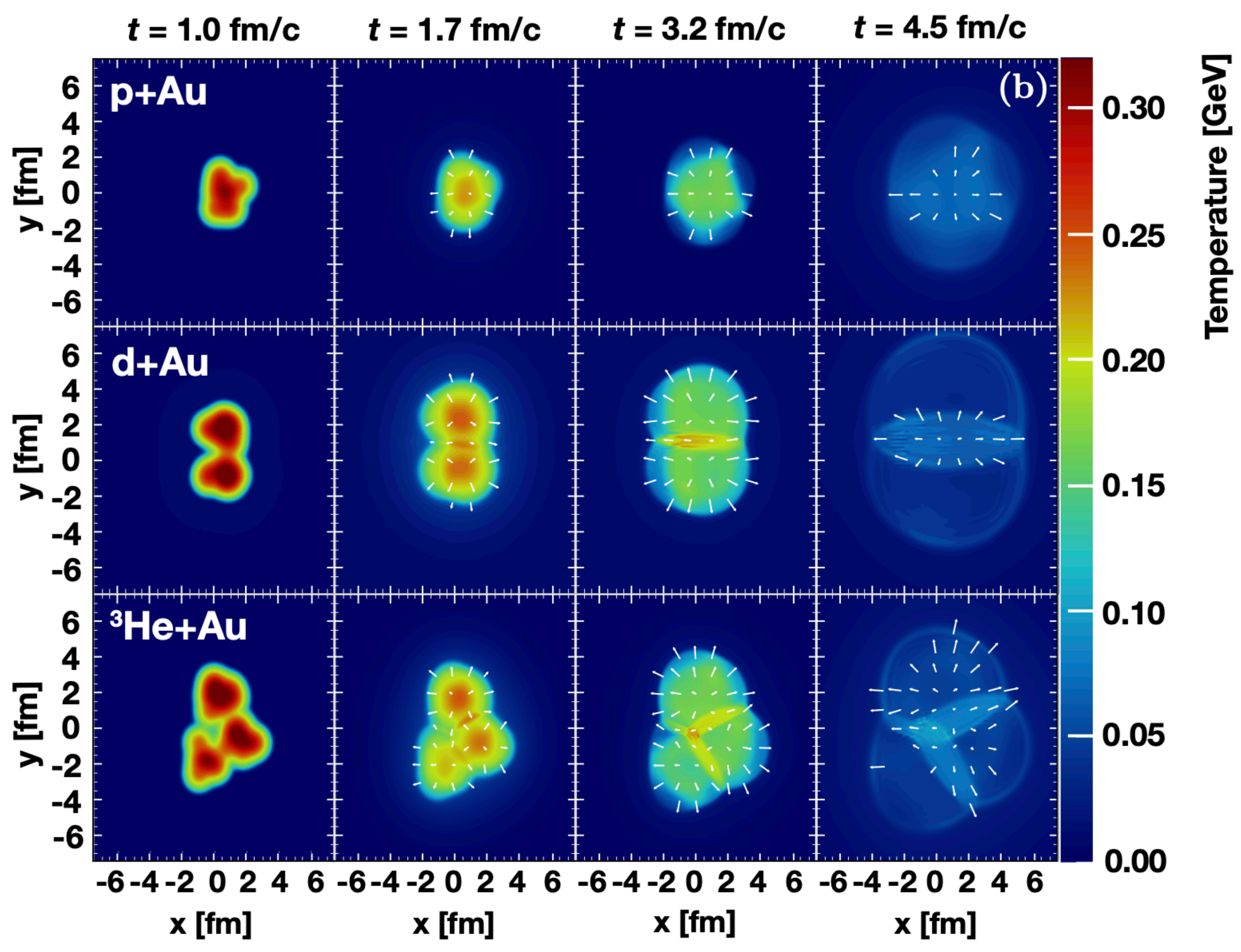


In the HIC context **track functions can be used to have a better treatment of energy loss effects**;
Energy loss distributions and tracks satisfy the same RG

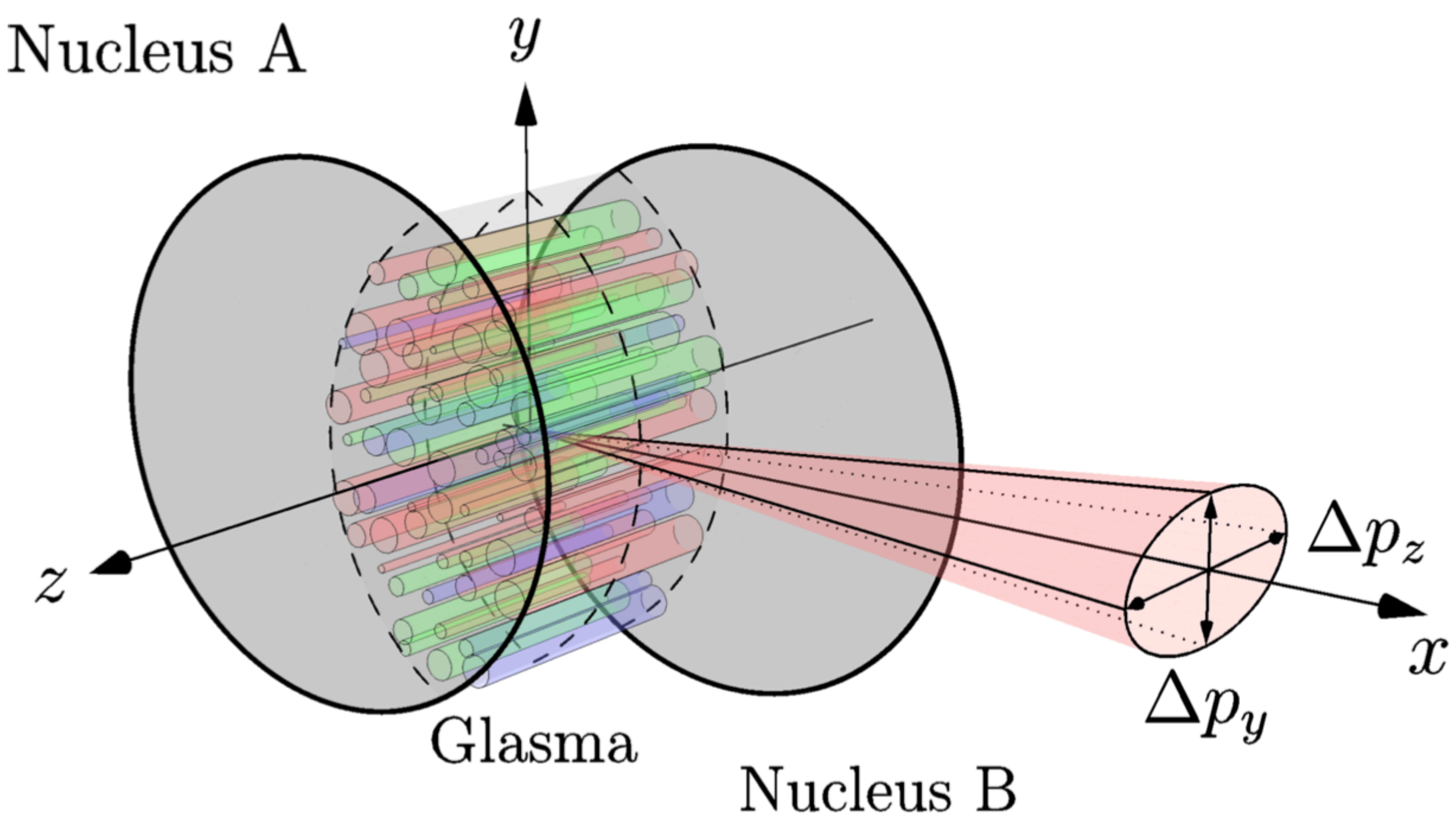
Energy correlators in anisotropic matter

2308.01294, B, Milhano, Sadofyev

Jet evolution in expanding plasma



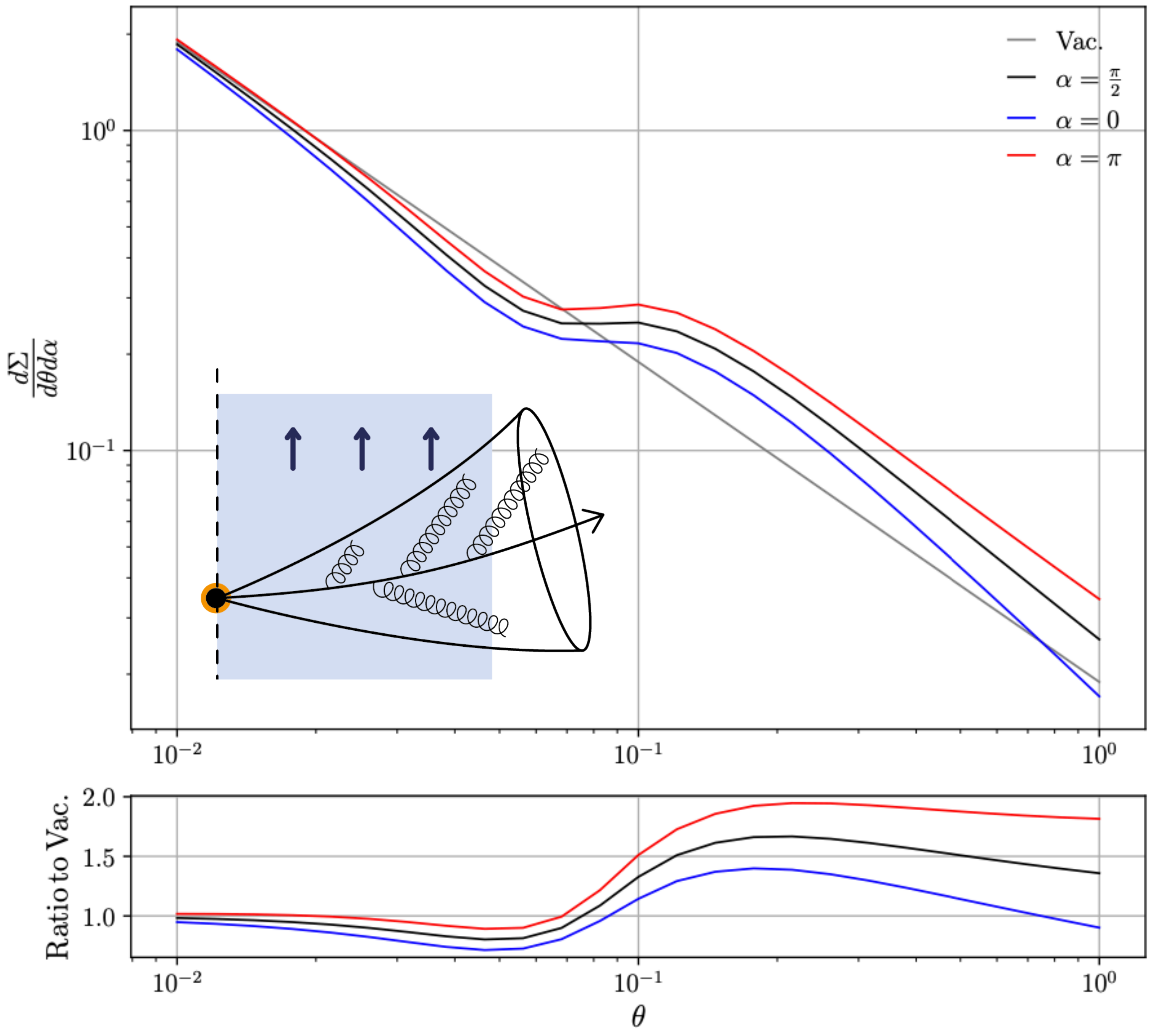
Jet evolution in Glasma phase



Energy correlators in anisotropic matter

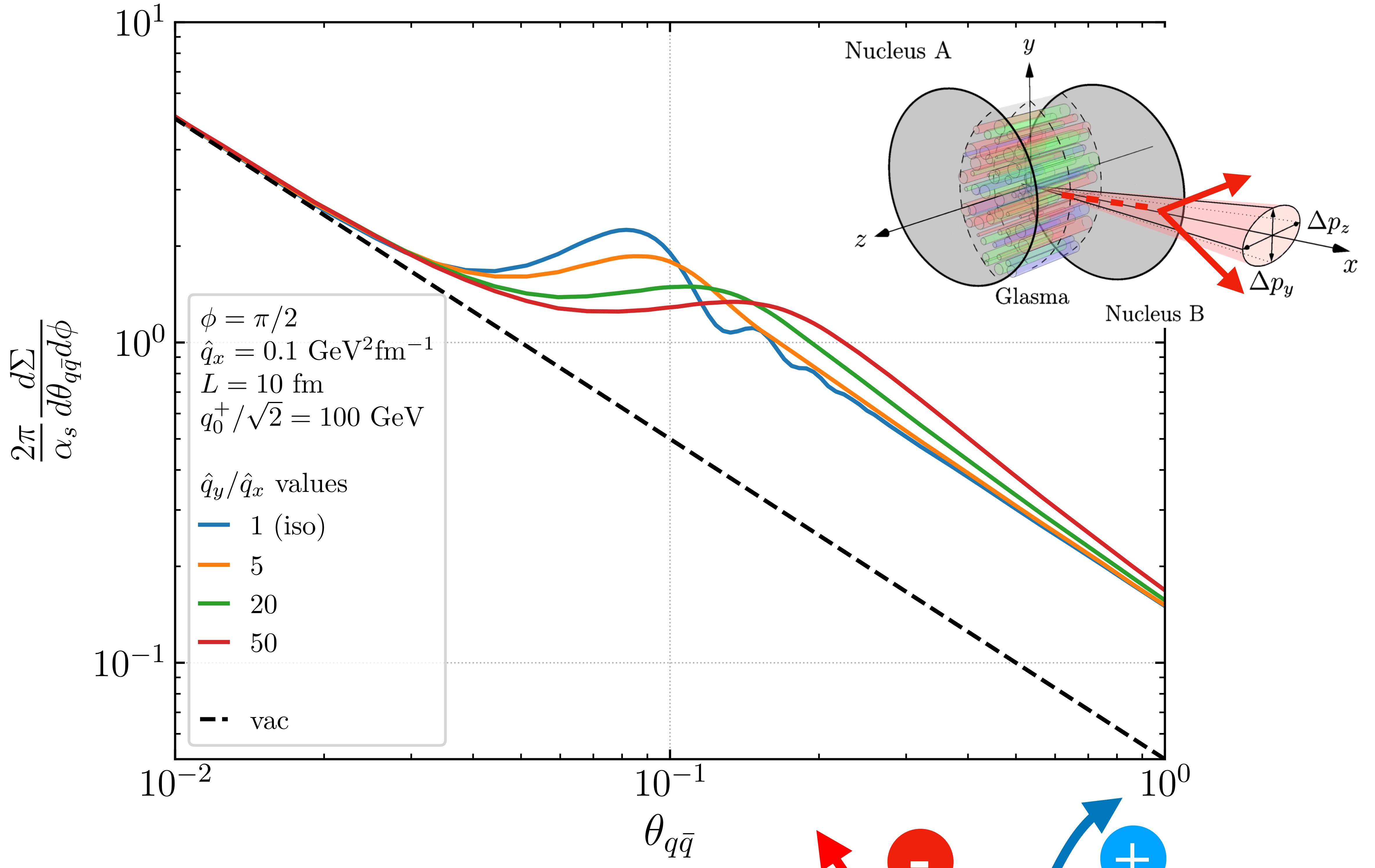
2308.01294, B, Milhano, Sadofyev
2407.04774, B, Silva, Salgado

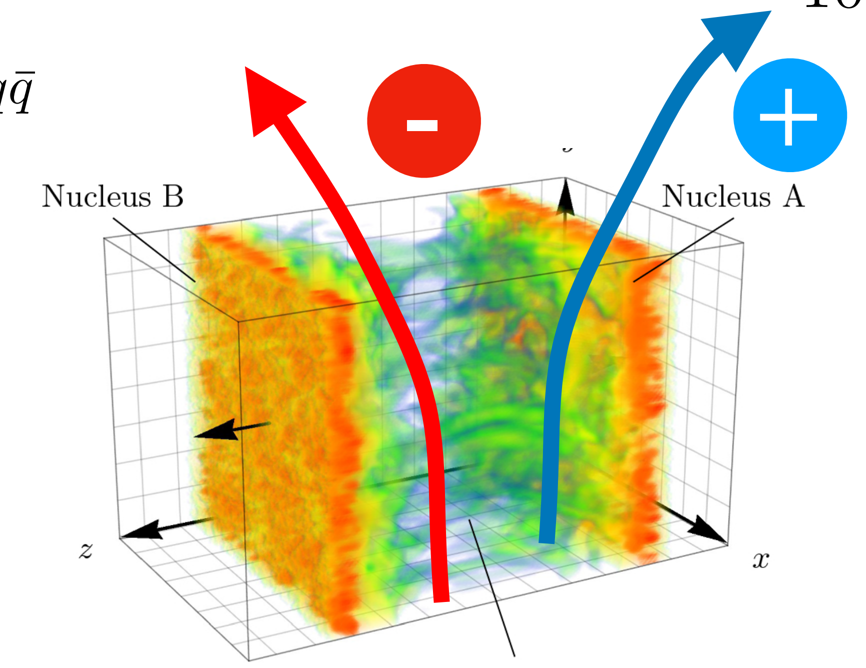
Jet evolution in expanding plasma



Jet evolution in Glasma phase

$$\frac{2\pi}{dN^h/dz}\frac{dN^h}{dzd\phi} = 1 + \sum_{n=1}^{\infty} v_n^{(h)}\cos(n\phi) + \sum_{n=1}^{\infty} w_n^{(h)}\sin(n\phi)$$





→ This is the simplest EC sensitive to (transverse) matter structure

→ Structure of matter can be further probed by looking at other currents

Summary and Outlook

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EEC in heavy ions

Great motivation for higher order calculations in jet quenching

Can be used to map structure of matter in the different evolution stages

Many of the tools developed in the EC context (e.g. tracks) can provide new ways to better describe jets in matter

Some future directions

Study charged correlators to understand how matter "filters" different parts of the jet

Back-to-back dijet production vs standard acoplanarity studies