Probing inner-jet correlations in hot QCD

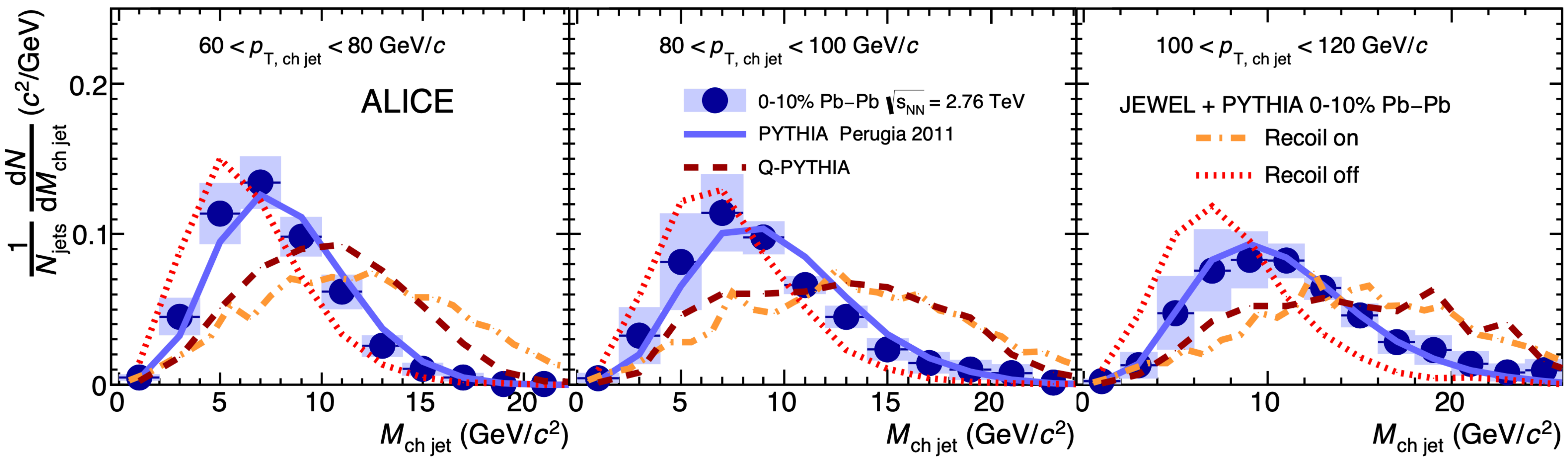
17th October 2023, INT

João Barata, BNL

Mainly based on: 2305.10476, xxxx.xxxx, with J.-P. Blaizot, Y. Mehtar-Tani
2307.08943, with Y. Mehtar-Tani
xxxx.xxxx, with P. Caucal, A. Soto-Ontoso, R. Szafron
xxxx.xxxx, with R. Szafron

Entropy and Energy correlators to understand jets

Most jet quenching observables compute projections of the final particle distribution inside jets (e.g. mass)



These capture particular aspects of the distribution, but not the most natural ones from the QFT perspective

Can we directly target the intrinsic correlations inside jets? Is this fundamentally different?

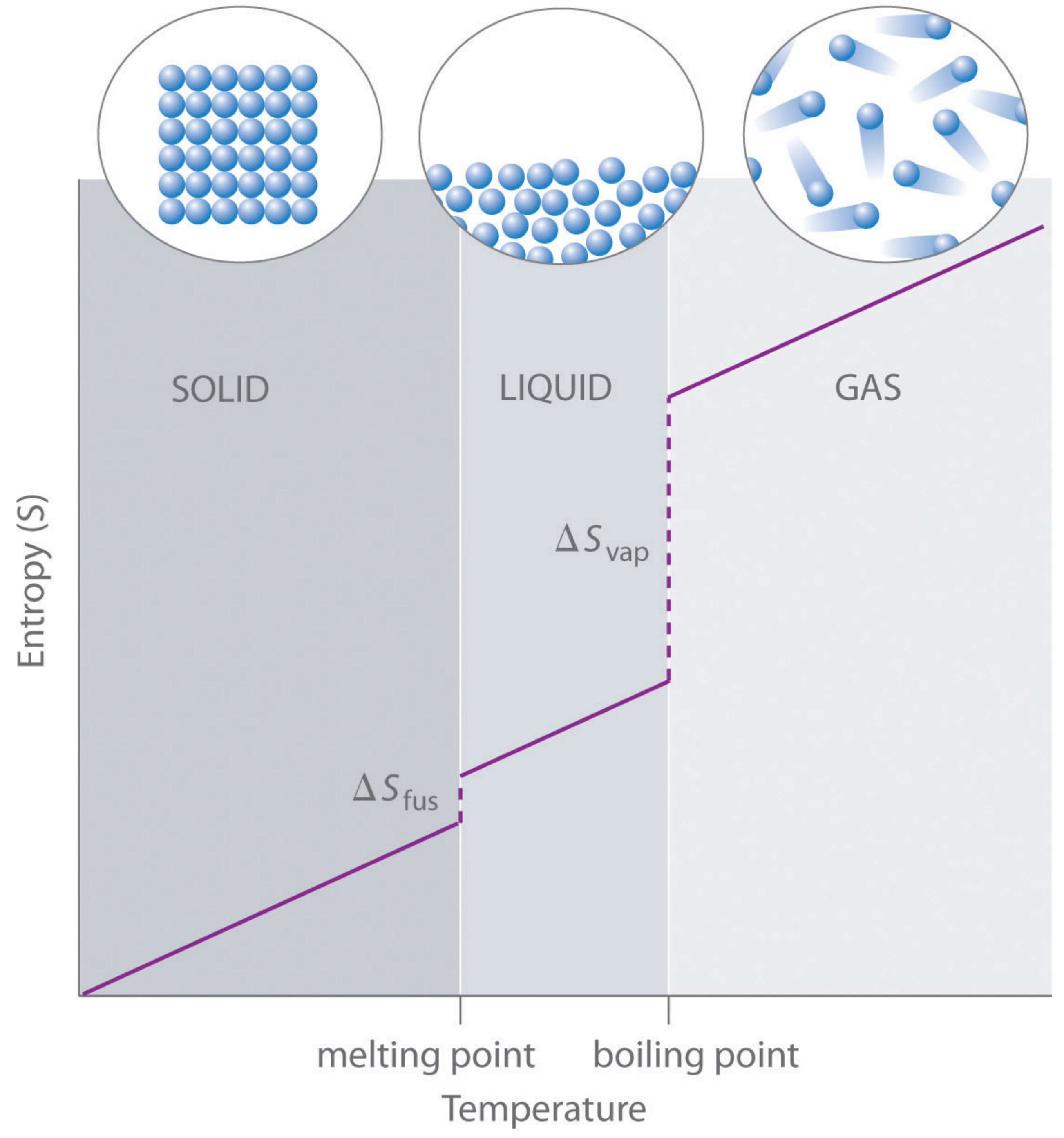
(in a calculable and measurable way)

Entropy and Energy correlators to understand jets

Brookhaven National Laboratory

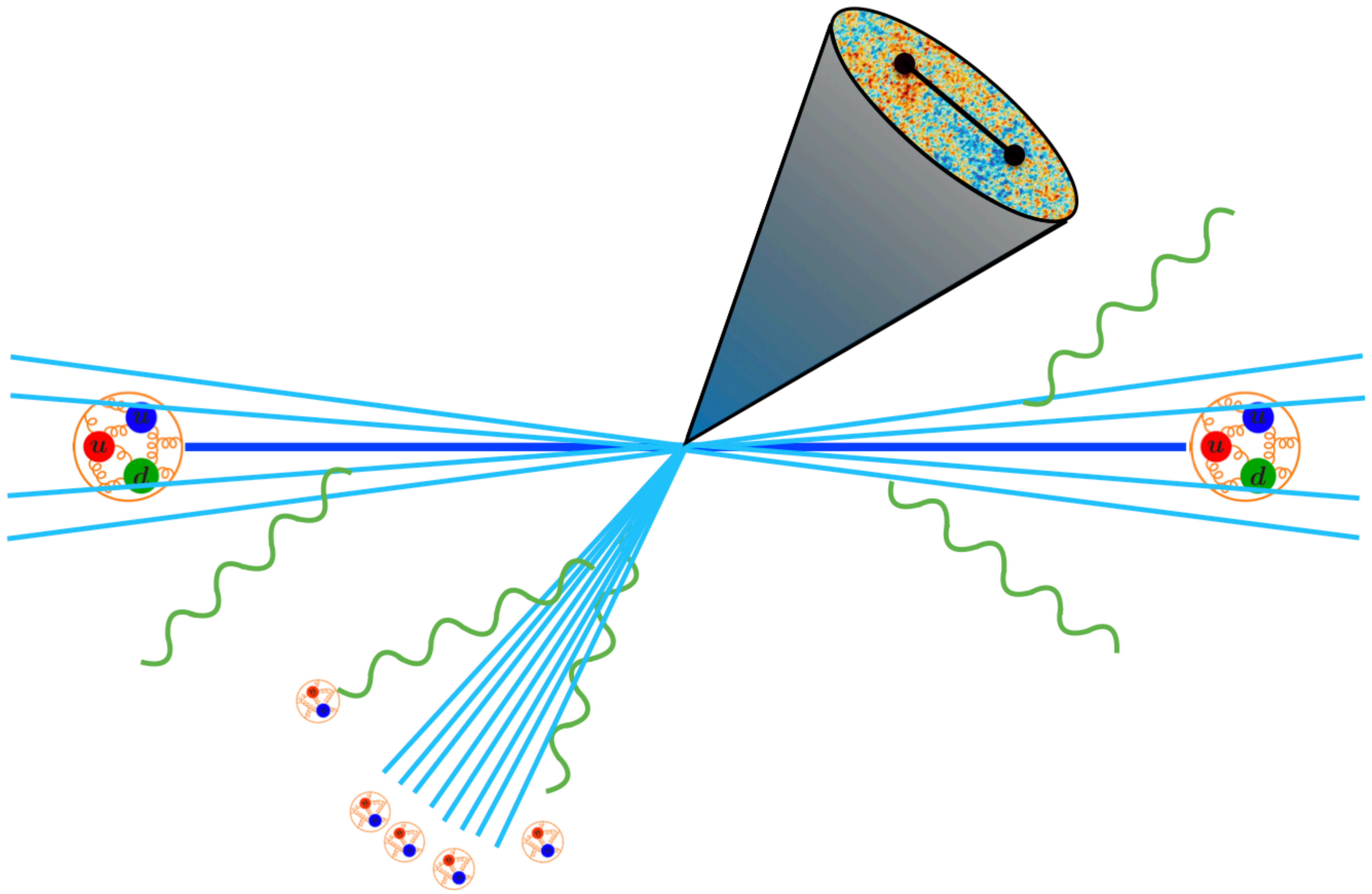
Today I will talk about two possible ways to go forward in this direction inherited from HET:

Jet entropy



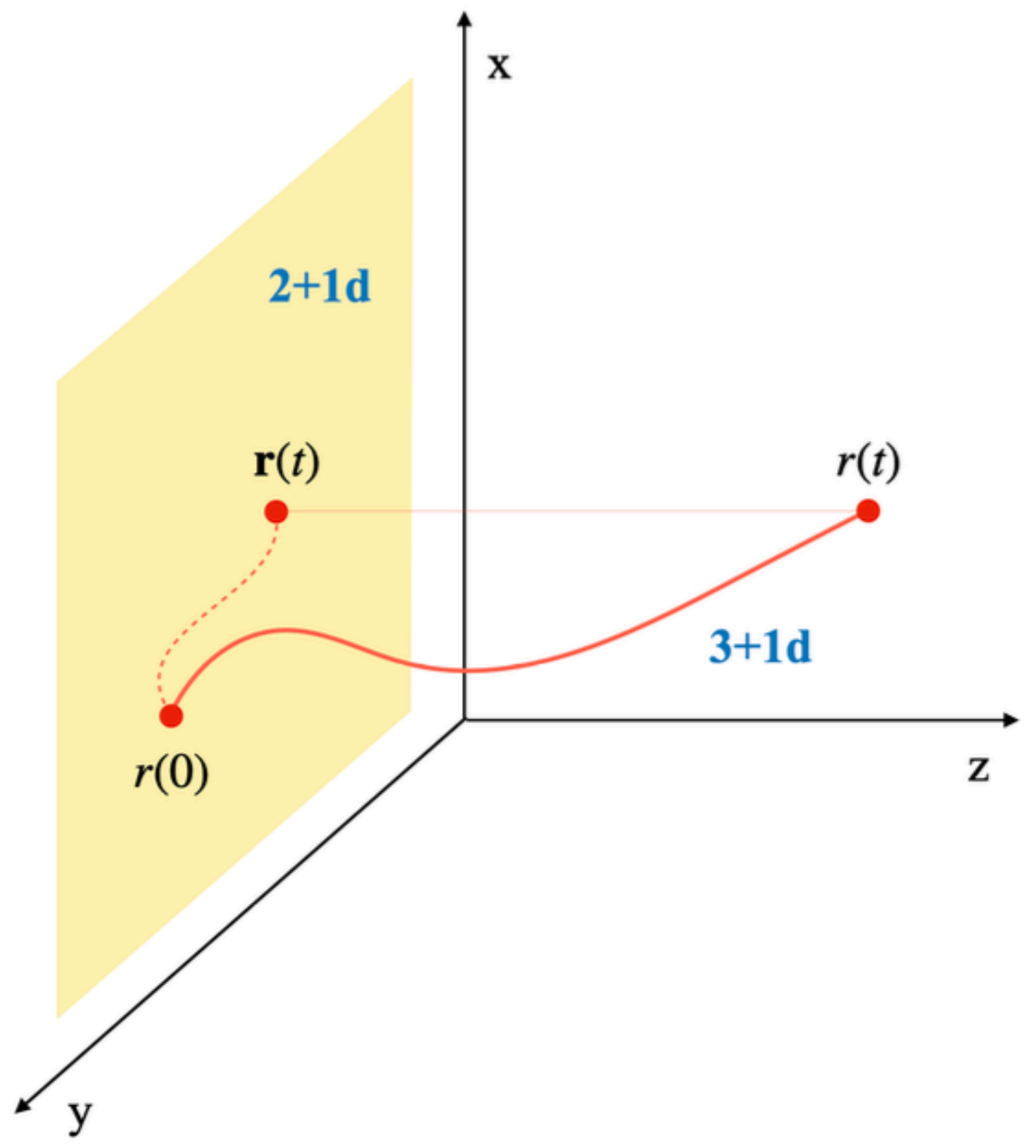
Encapsulates multipoint correlators and can be generalized for mixed states

Energy Correlators (inside jets)



Measures correlations within final particle distribution, similar to CMB physics

Outline



In-medium jet density matrix and its entropy

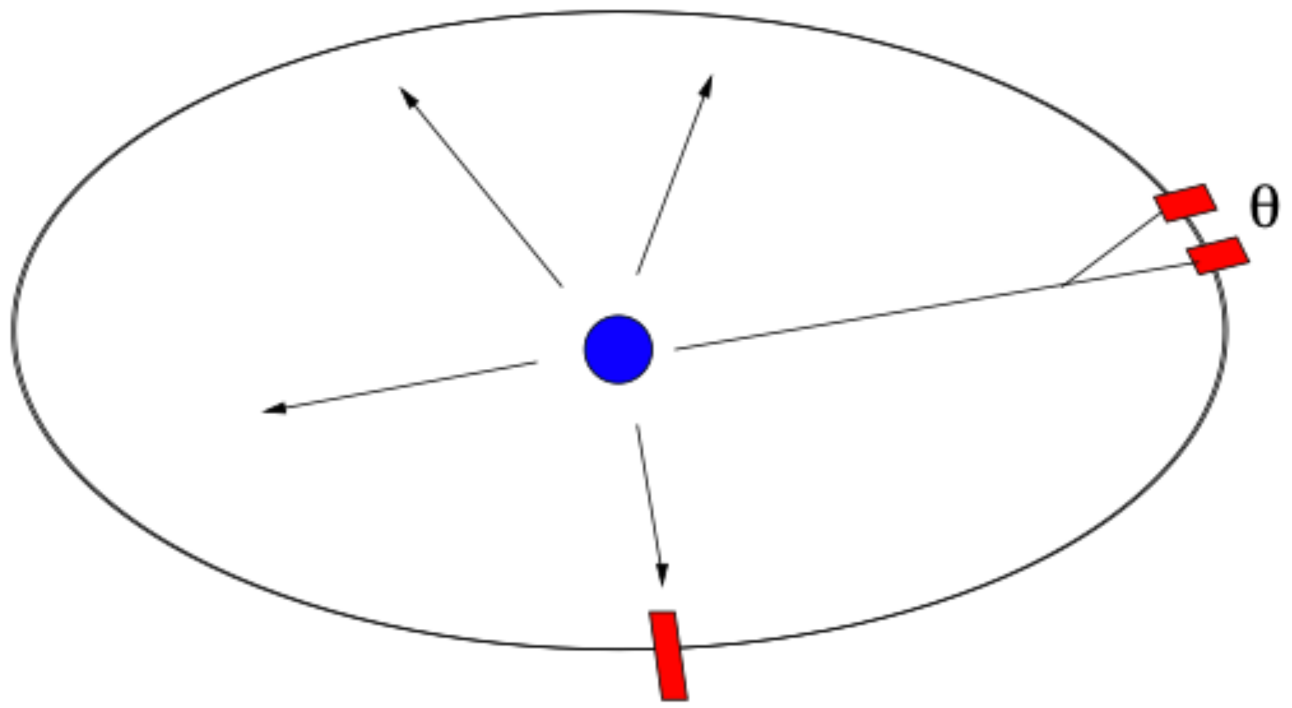
with J.-P. Blaizot, Y. Mehtar-Tani

Is the jet entropy sensitive to the in-medium jet evolution ?

Can it resolve the structure of the jet? How?

Towards understanding jet Energy Correlators in heavy ions

with Y. Mehtar-Tani; P. Caucal, A. Soto-Ontoso, R. Szafron; R. Szafron



How do jet Energy Correlators (ENCs) behave in HI?

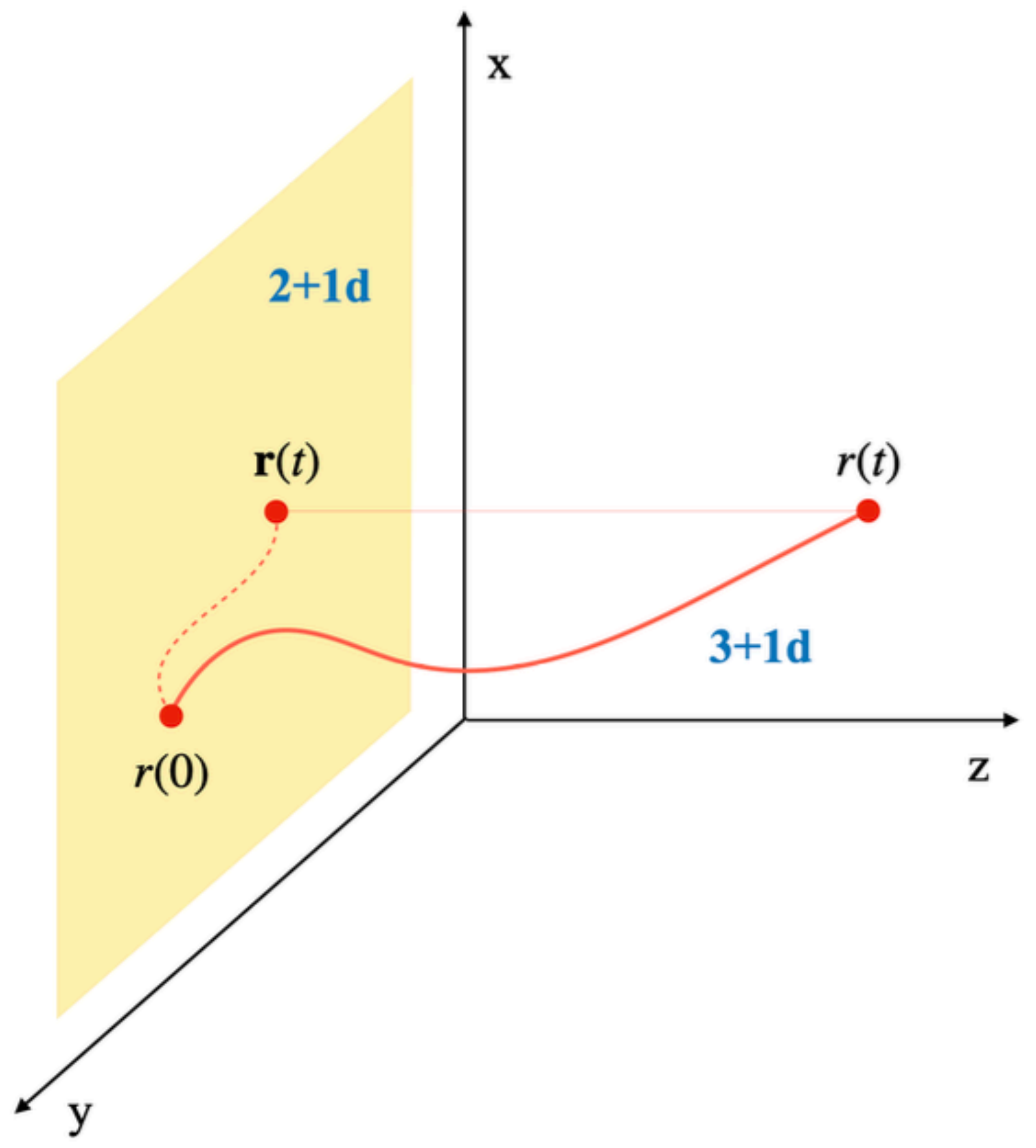
Do we understand their evolution from the theory side?

How can we learn about the perturbative sector?

Outline

In-medium jet density matrix and its entropy

with J.-P. Blaizot, Y. Mehtar-Tani



Towards understanding jet Energy Correlators in heavy ions

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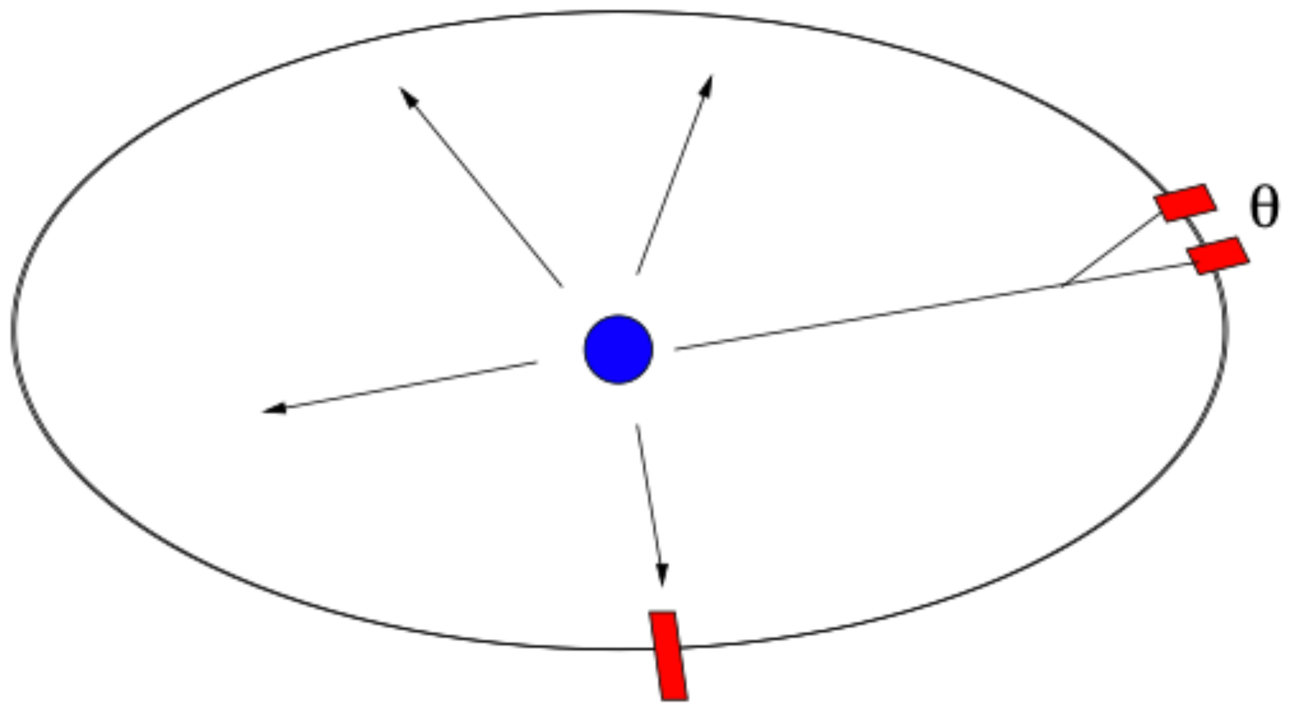
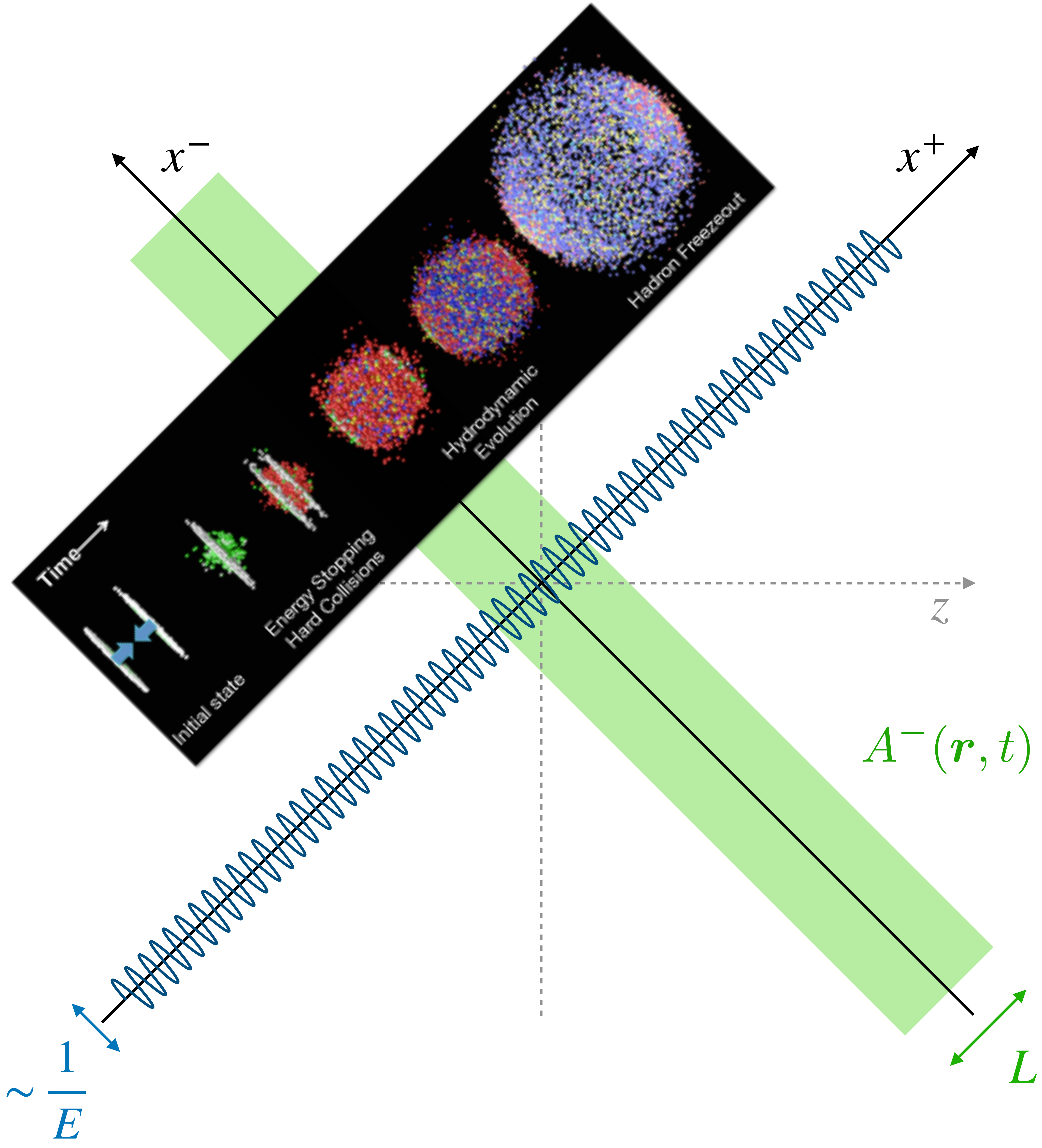


Quark reduced density matrix in matter
2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani



The single parton wave function satisfies

Coupling to matter background

$$\left[i\partial_t + \frac{\partial_\perp^2}{2E} + gA(\boldsymbol{r}, t) \right] \psi(\boldsymbol{r}, t) = 0$$

Light-front kinetic energy

The reduced density matrix can be defined as

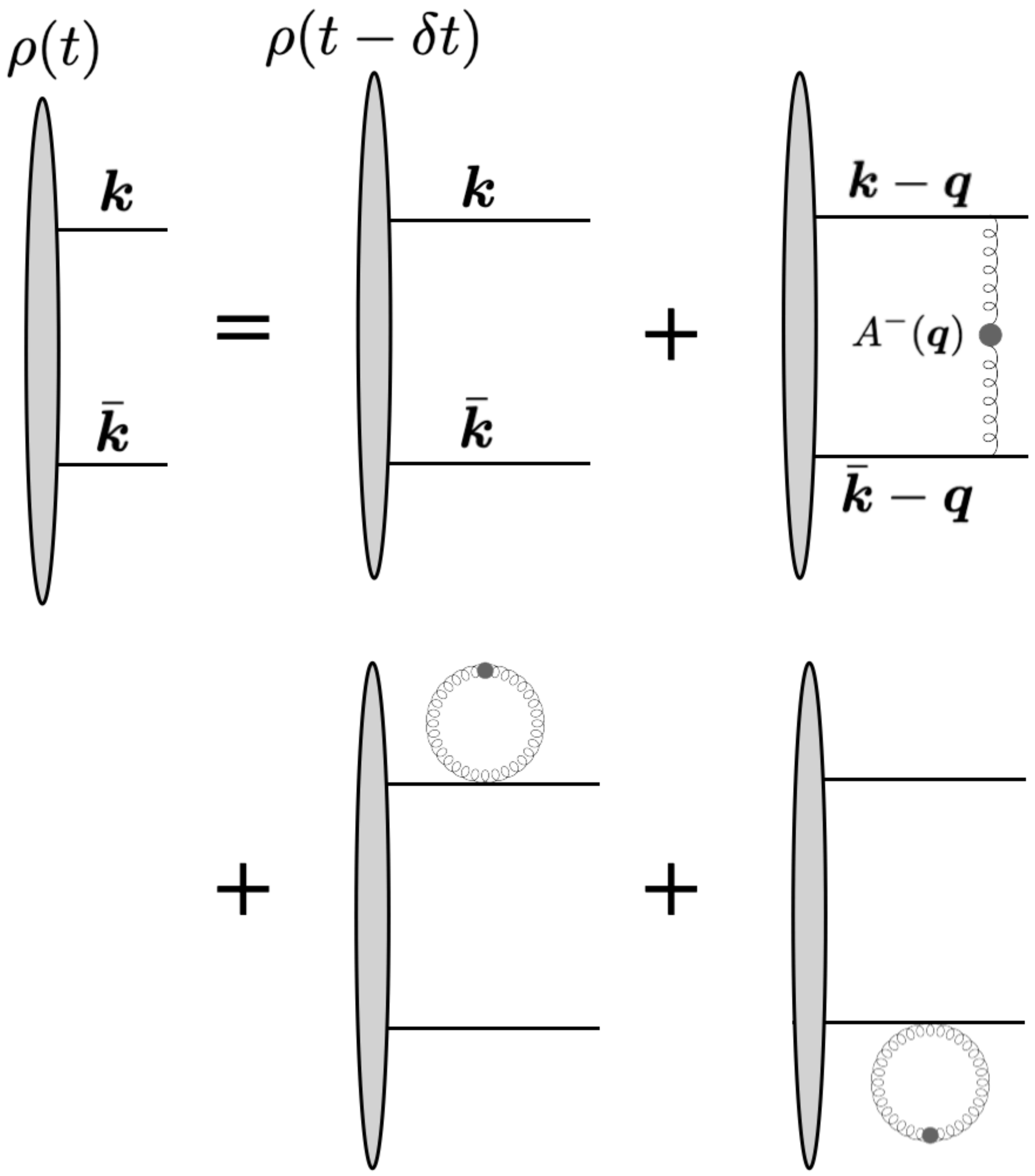
$$\rho \equiv \mathrm{tr}_A(\rho[A]) = \Big\langle |\psi_A(t)\rangle\langle\psi_A(t)| \Big\rangle_A$$

We use Gaussian approximation for the background field

$$g^2 \Big\langle A^a(\boldsymbol{q}, t) A^{\dagger b}(\boldsymbol{q}', t') \Big\rangle_A = \delta^{ab}\delta(t - t')(2\pi)^2\delta^{(2)}(\boldsymbol{q} - \boldsymbol{q}')\,\gamma(\boldsymbol{q})$$

Constructing the evolution equations

2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani



$$b \equiv \frac{\boldsymbol{r}+\bar{\boldsymbol{r}}}{2}, \quad \boldsymbol{x} \equiv \boldsymbol{r}-\bar{\boldsymbol{r}} \qquad \boldsymbol{K} = \frac{\boldsymbol{k}+\bar{\boldsymbol{k}}}{2}, \quad \boldsymbol{\ell} = \boldsymbol{k}-\bar{\boldsymbol{k}}$$

$$3 \otimes \bar{3} = 1 \oplus 8$$

$$\rho(t) \equiv \rho_{\rm s} + t^a \rho_{\rm o}^a = \frac{1}{N_c}{\rm Tr}_c(\rho) + 2\, t^a {\rm Tr}_c(t^a \rho)$$

For color singlet:

$$\langle \boldsymbol{k}|\rho_{\rm s}(t)|\bar{\boldsymbol{k}}\rangle = C_F \int_{\boldsymbol{q}} \int_0^t dt'\, e^{i\frac{(\boldsymbol{k}^2-\bar{\boldsymbol{k}}^2)}{2E}(t-t')} \times \gamma(\boldsymbol{q}) \left[\langle \boldsymbol{k}-\boldsymbol{q}|\rho_{\rm s}(t')|\bar{\boldsymbol{k}}-\boldsymbol{q}\rangle - \langle \boldsymbol{k}|\rho_{\rm s}(t')|\bar{\boldsymbol{k}}\rangle\right]$$

For color octet:

$$\langle \boldsymbol{k}|\rho_{\rm o}(t)|\bar{\boldsymbol{k}}\rangle = C_F \int_{\boldsymbol{q}} \int_0^t dt'\, e^{i\frac{(\boldsymbol{k}^2-\bar{\boldsymbol{k}}^2)}{2E}(t-t')} \times \gamma(\boldsymbol{q}) \left[\langle \boldsymbol{k}-\boldsymbol{q}|\rho_{\rm o}(t')|\bar{\boldsymbol{k}}-\boldsymbol{q}\rangle + \frac{1}{2N_cC_F}\langle \boldsymbol{k}|\rho_{\rm o}(t')|\bar{\boldsymbol{k}}\rangle\right]$$

Time evolution of the single component 2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani

Brookhaven National Laboratory

There are 3 important timescales in this problem:

$$t_2^3 = t_1 t_0^2 \qquad \theta_\mu^2 = \frac{\mu^2}{E^2}\,, \quad \theta_c^2(t) = \frac{1}{\hat{q}t^3}\,, \quad \theta_{\rm br}^2(t) = \frac{\hat{q}t}{E^2}$$

The natural spreading time for the initial wavepacket

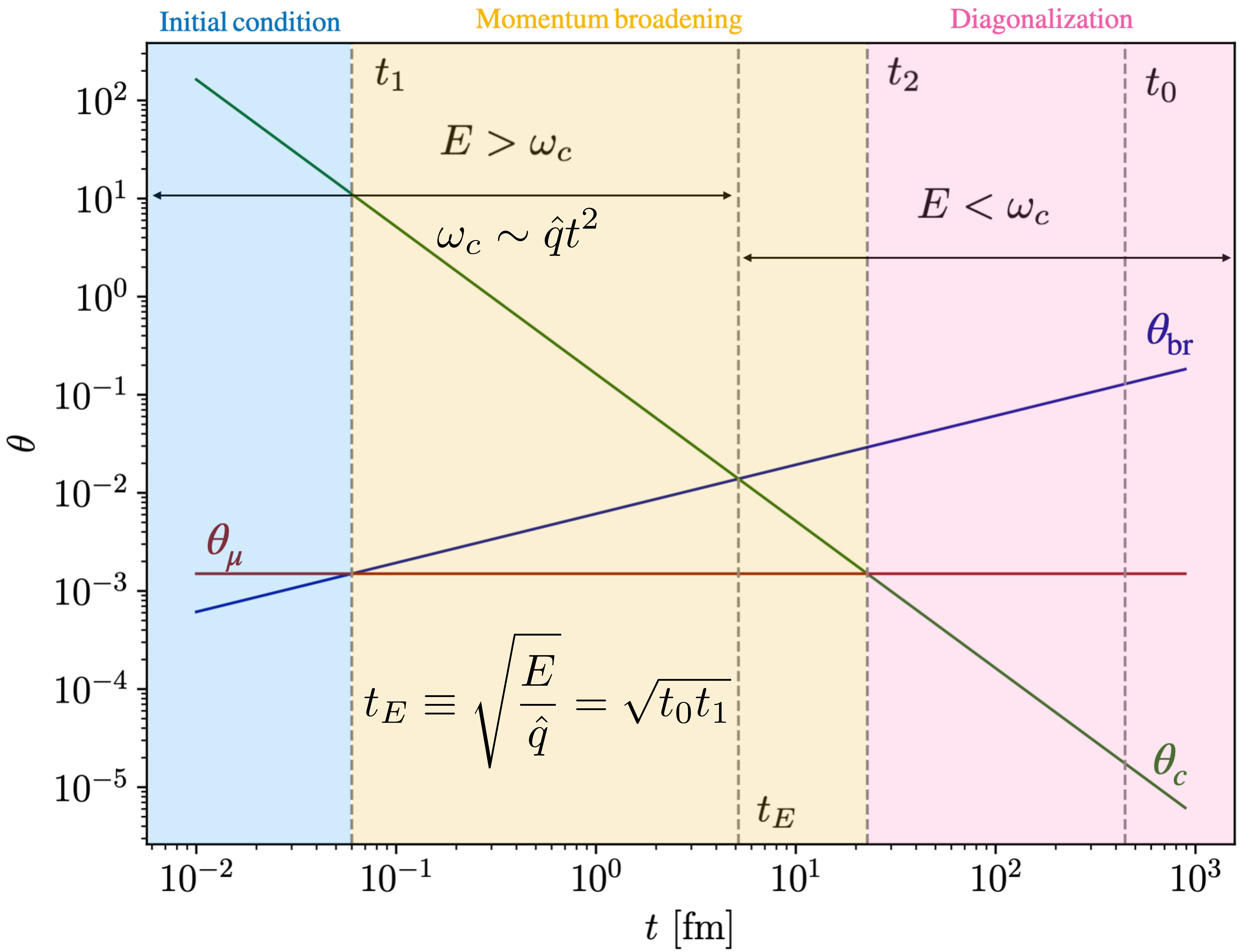
$$t_0 = \frac{E}{\mu^2}$$

The timescale for interactions to become *noticeable*

$$t_1 = \frac{\mu^2}{\hat{q}}$$

The timescale for spatial displacement

$$t_2^3 = \frac{E^2}{\hat{q}\mu^2}$$



Time evolution of the single component 2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani

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$$t_2^3 = t_1 t_0^2$$

$$t_0 > t_2 > t_1$$

Medium-parton interactions dominate evolution

vs

$$t_0 < t_2 < t_1$$

Natural wave packet spreading determines evolution

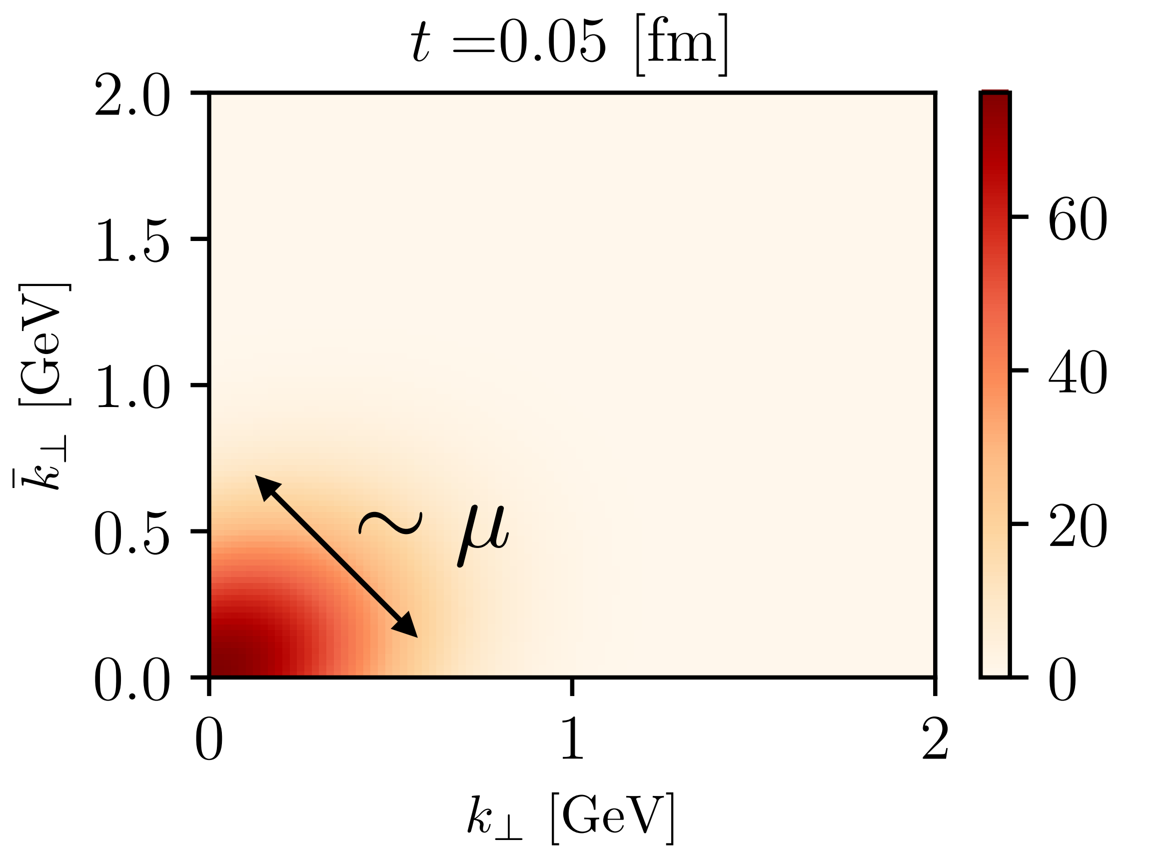
$\hat{q} = 0.3\,\mathrm{GeV}^3$, $\mu = 0.3$ GeV, and $E = 200\,\mathrm{GeV}$

$t_1 \simeq 0.06$ fm $\quad t_2 \simeq 22.80$ fm, $\quad t_0 \simeq 444.44$ fm,

Time evolution of the single component

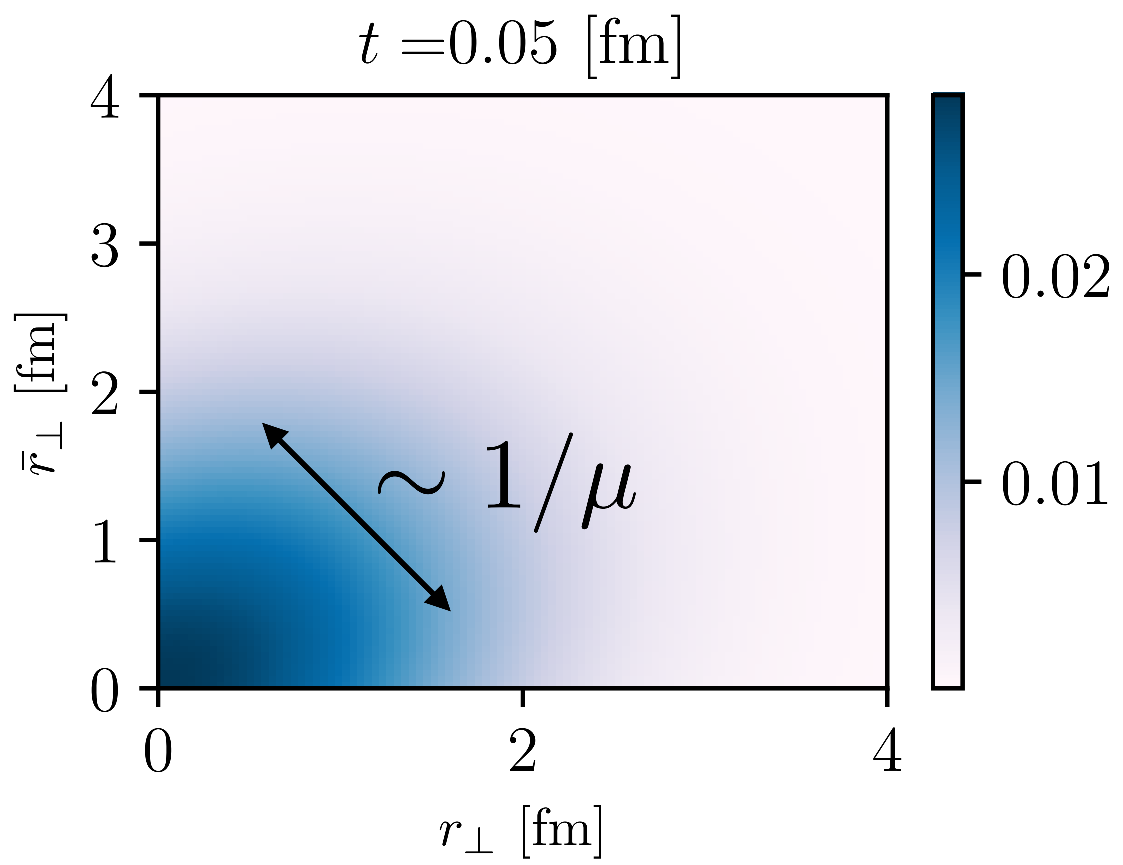
2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani

$$t_1 \simeq 0.06 \text{ fm} \qquad t_2 \simeq 22.80 \text{ fm} \qquad t_0 \simeq 444.44 \text{ fm}$$



Momentum space

time



Position space

Time evolution of the single component
2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani

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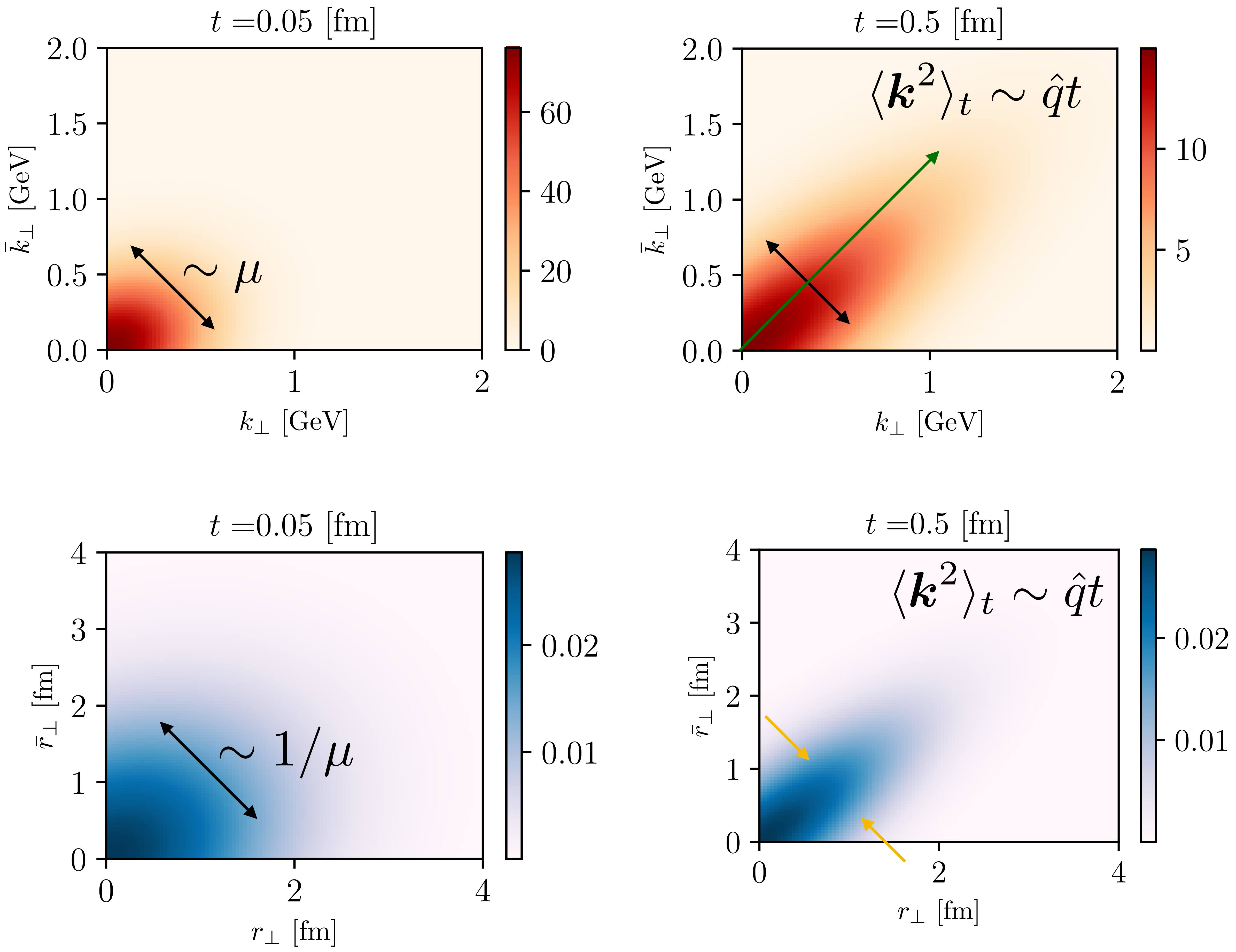

Time evolution of the single component 2305.10476, with J.-P. Blaizot, Y. Mehtar-Tani

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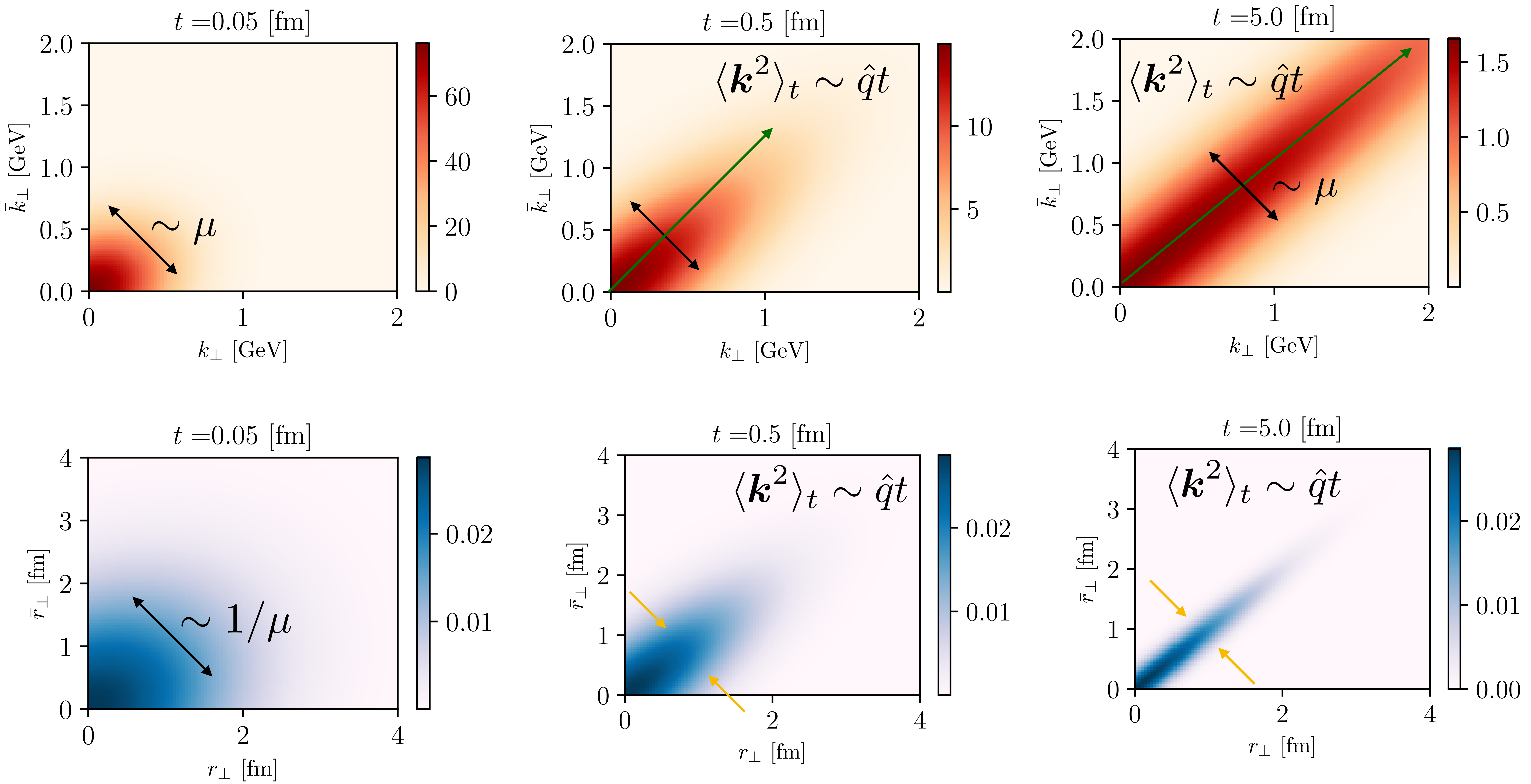

Time evolution of the single component

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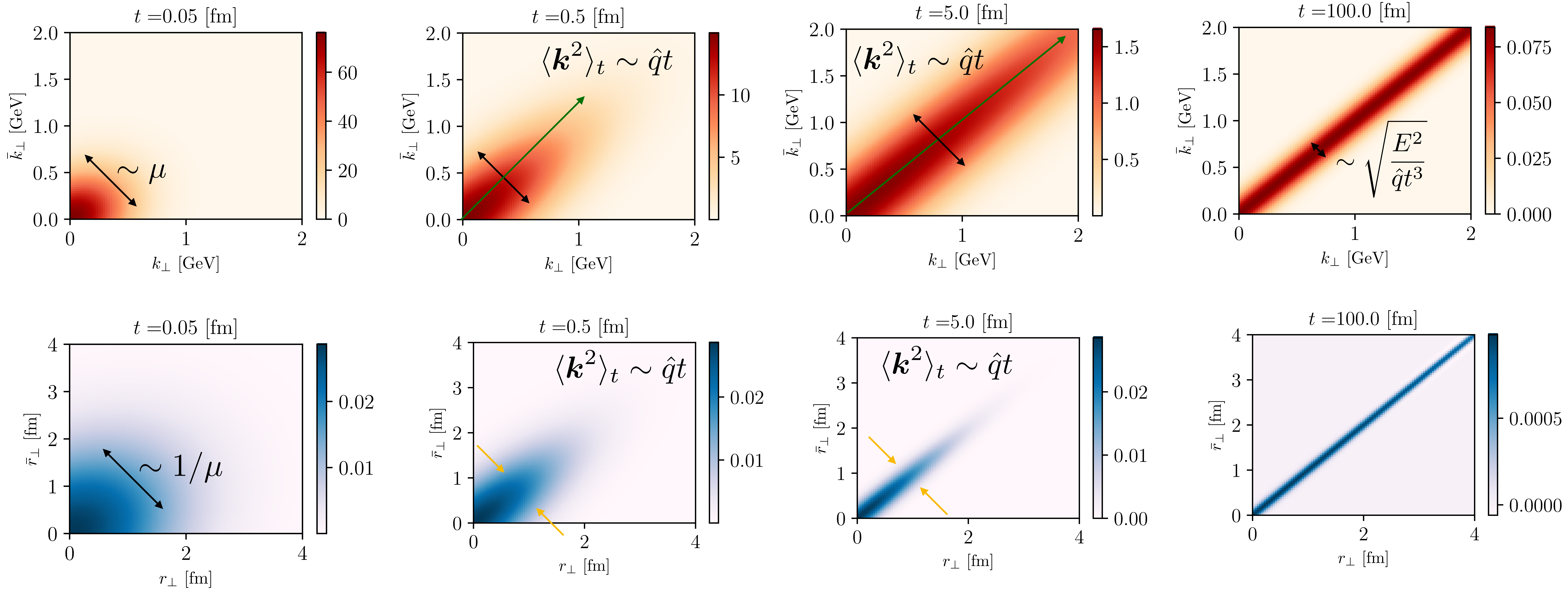
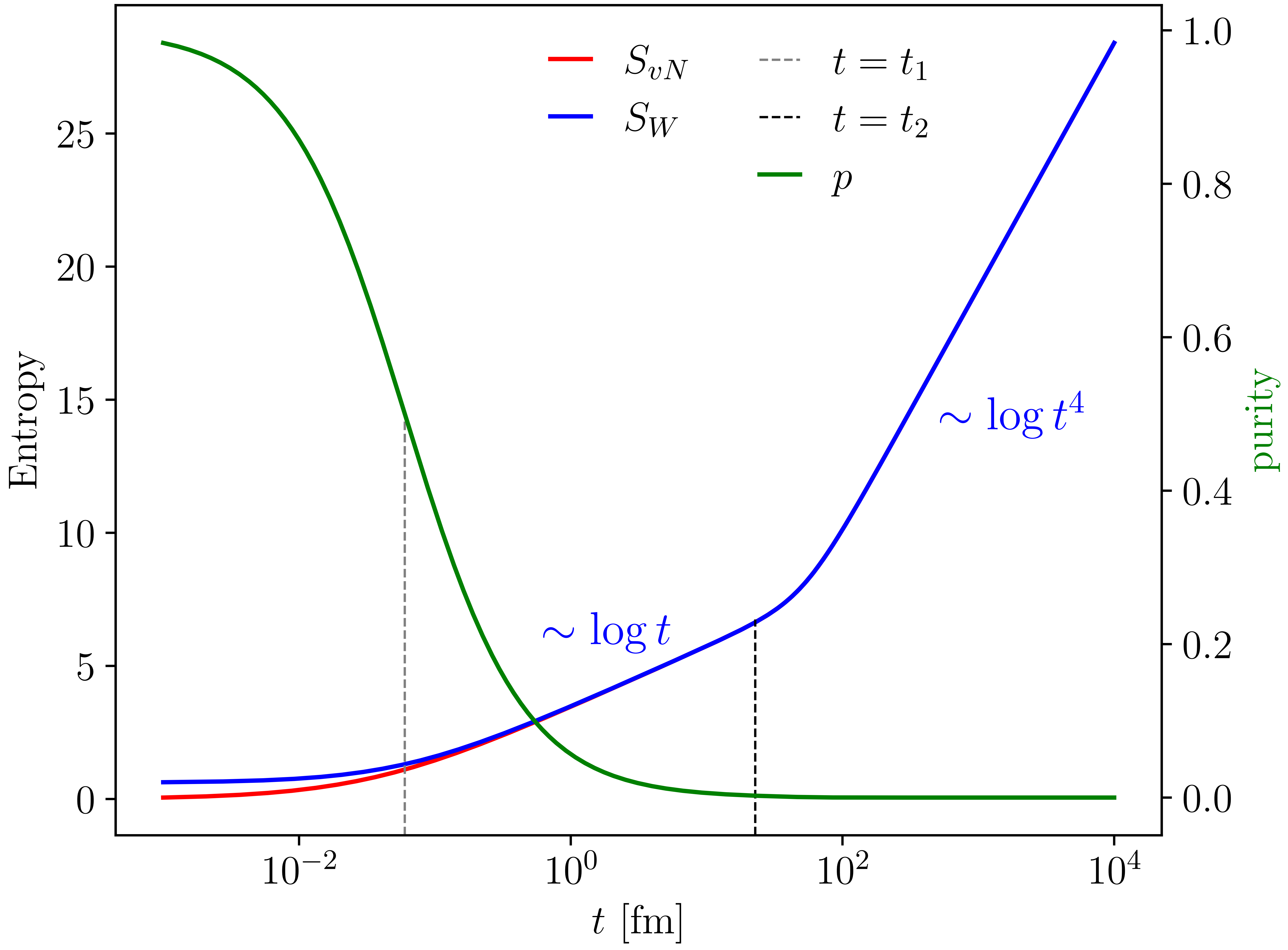


Entropy as a measure of quantum to classical transition

$t_1 \simeq 0.06$ fm $\quad t_2 \simeq 22.80$ fm $\quad t_0 \simeq 444.44$ fm $\quad t_{\rm rel} \simeq 66.7$ fm



von-Neumann entropy

$$S_{\rm vN}[\rho] = -{\rm Tr}\rho \ln \rho$$

Wigner entropy

$$S_{\rm w} \equiv -\int_{\boldsymbol{K},\boldsymbol{b}} \rho_{\rm w}(\boldsymbol{b},\boldsymbol{K}) \log \rho_{\rm w}(\boldsymbol{b},\boldsymbol{K})$$

Asymptotically, one has that

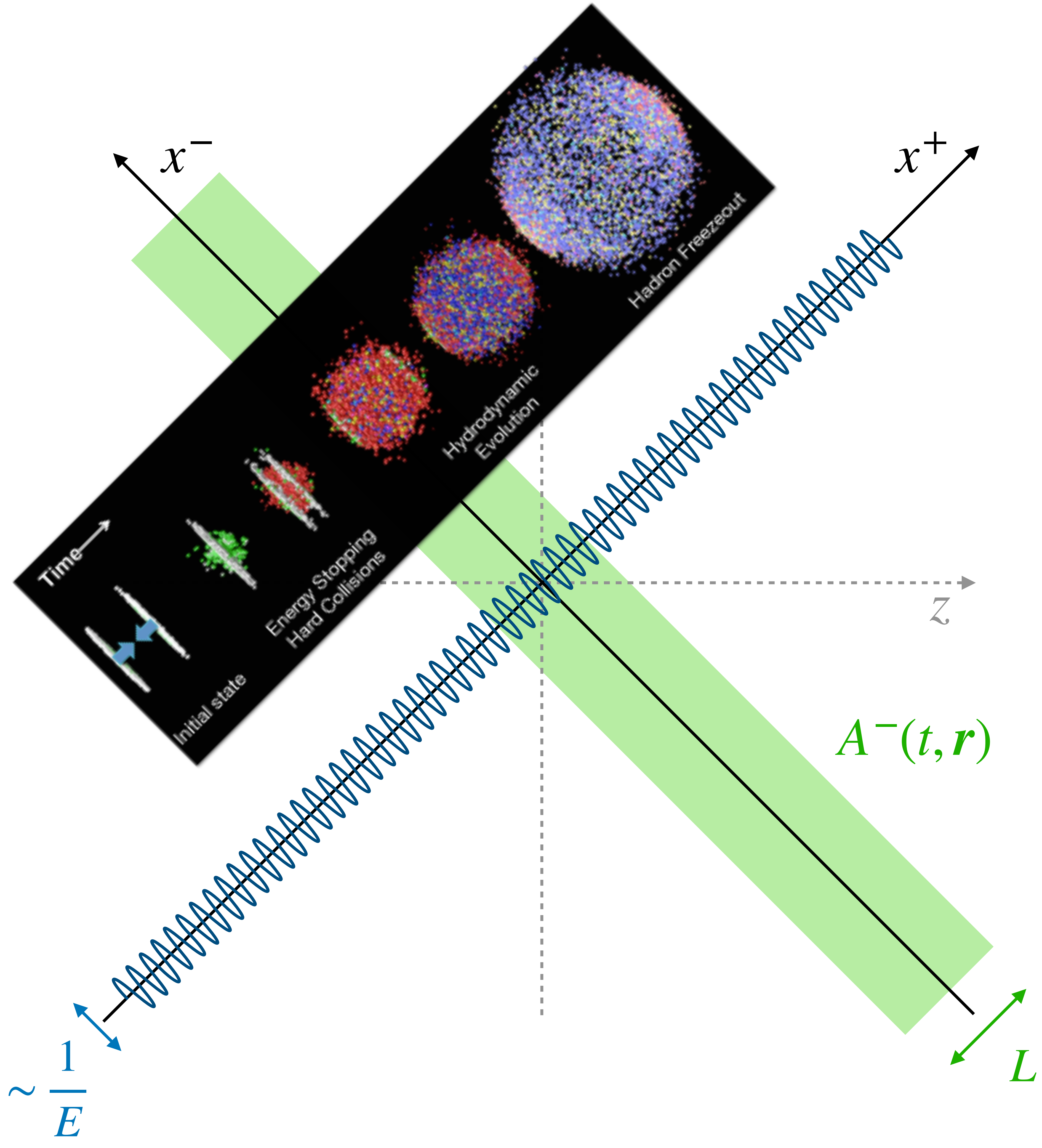
$$S_{\rm vN} \simeq \ln\langle \boldsymbol{k}^2\rangle_t \langle \boldsymbol{b}^2\rangle_t$$

thus, the **entropy content of the density matrix coincides with that of a classical distribution**

Jet entropy and gluon radiation

2307.01792, with X. Du, M. Li, W. Qian, C. Salgado

also 2208.06750, 2104.04661, and previous works by M. Li et al

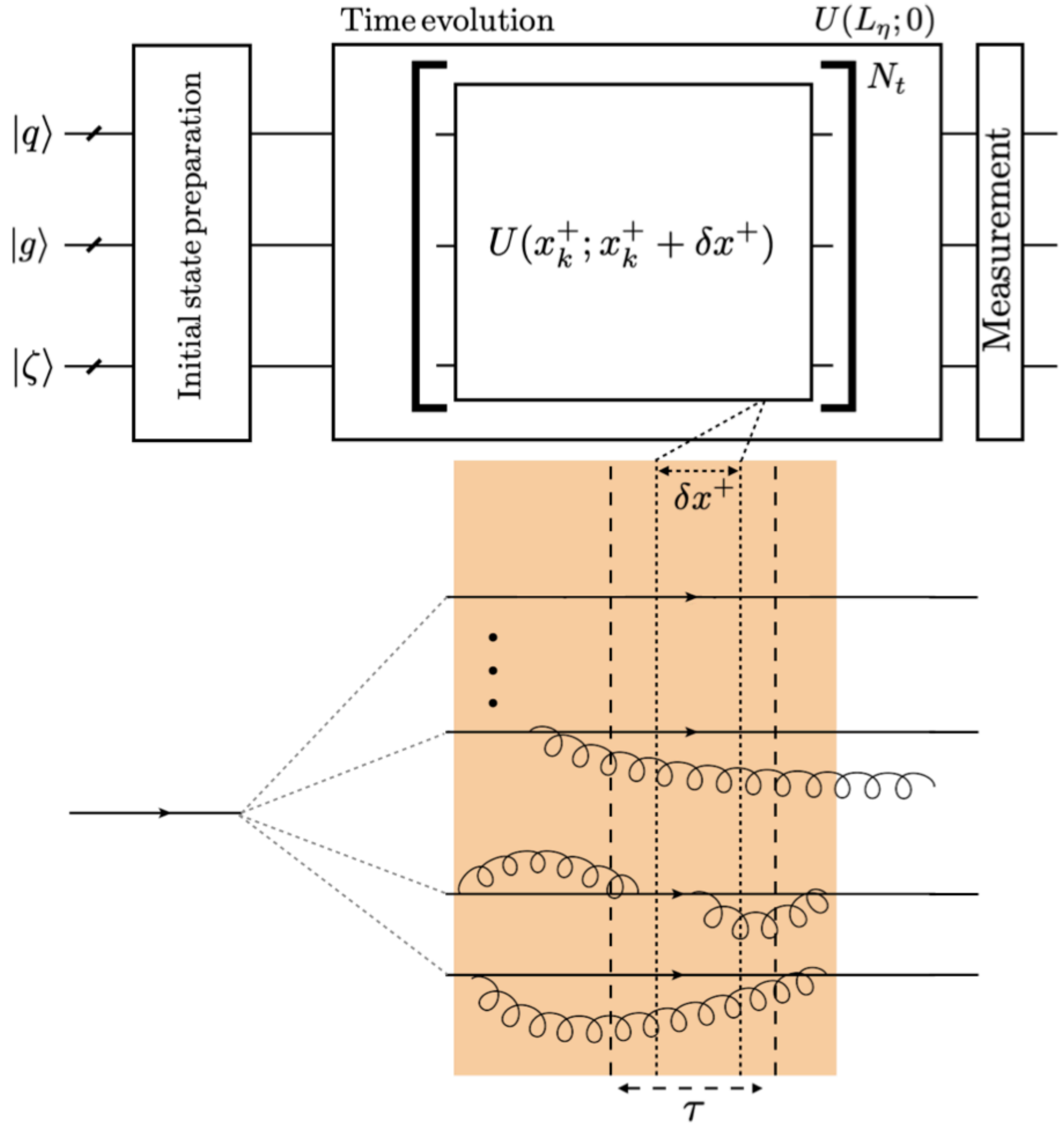


$$|\psi\rangle = e^{-iHt}\,|\psi_0\rangle$$

Jet evolution can be formulated in Hamiltonian formalism

↔

Using new techniques from QIS, this allows to explore real time dynamics



$$+\mathcal{O}(\alpha_s^2)$$

Jet entropy and gluon radiation

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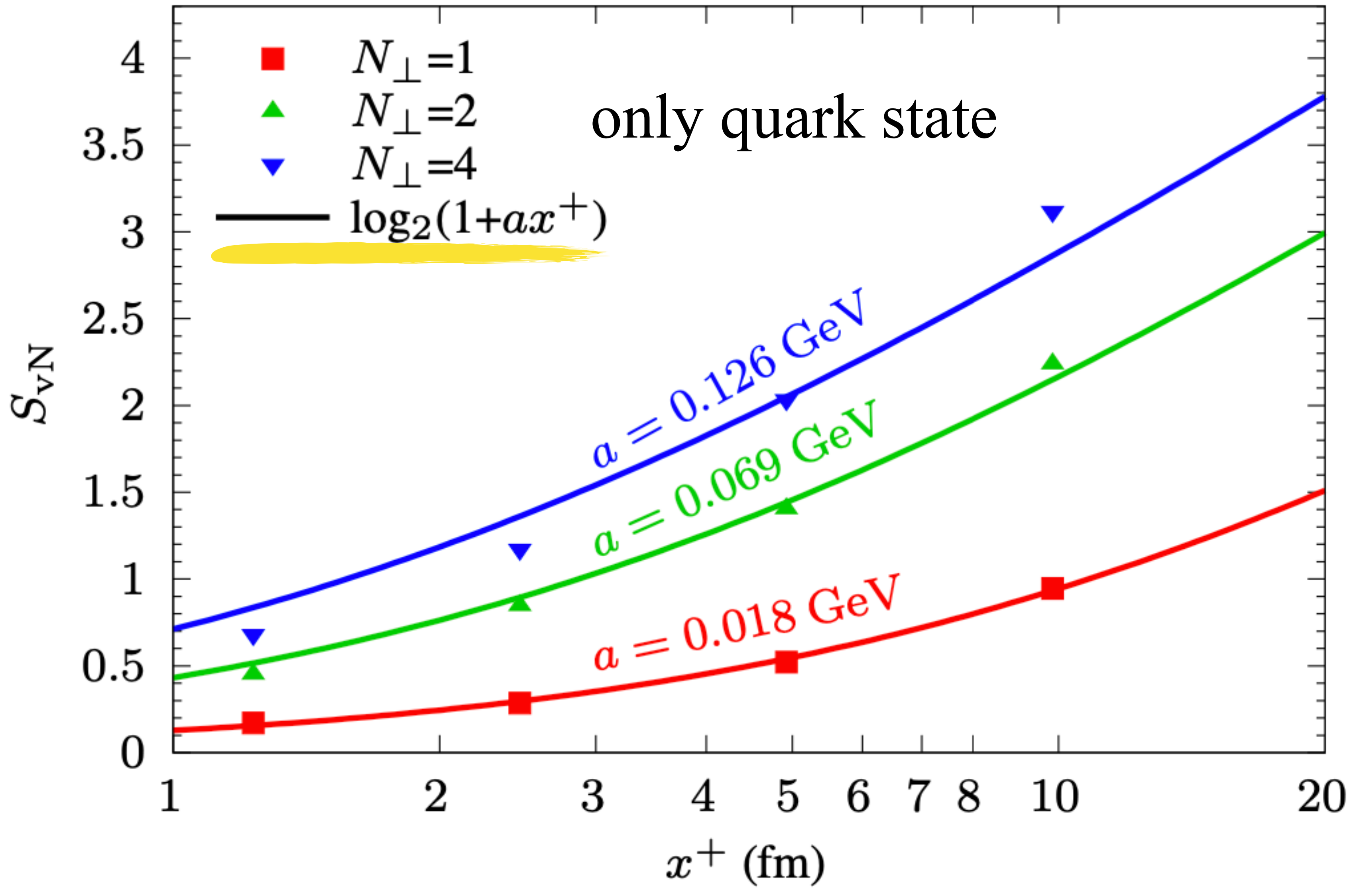
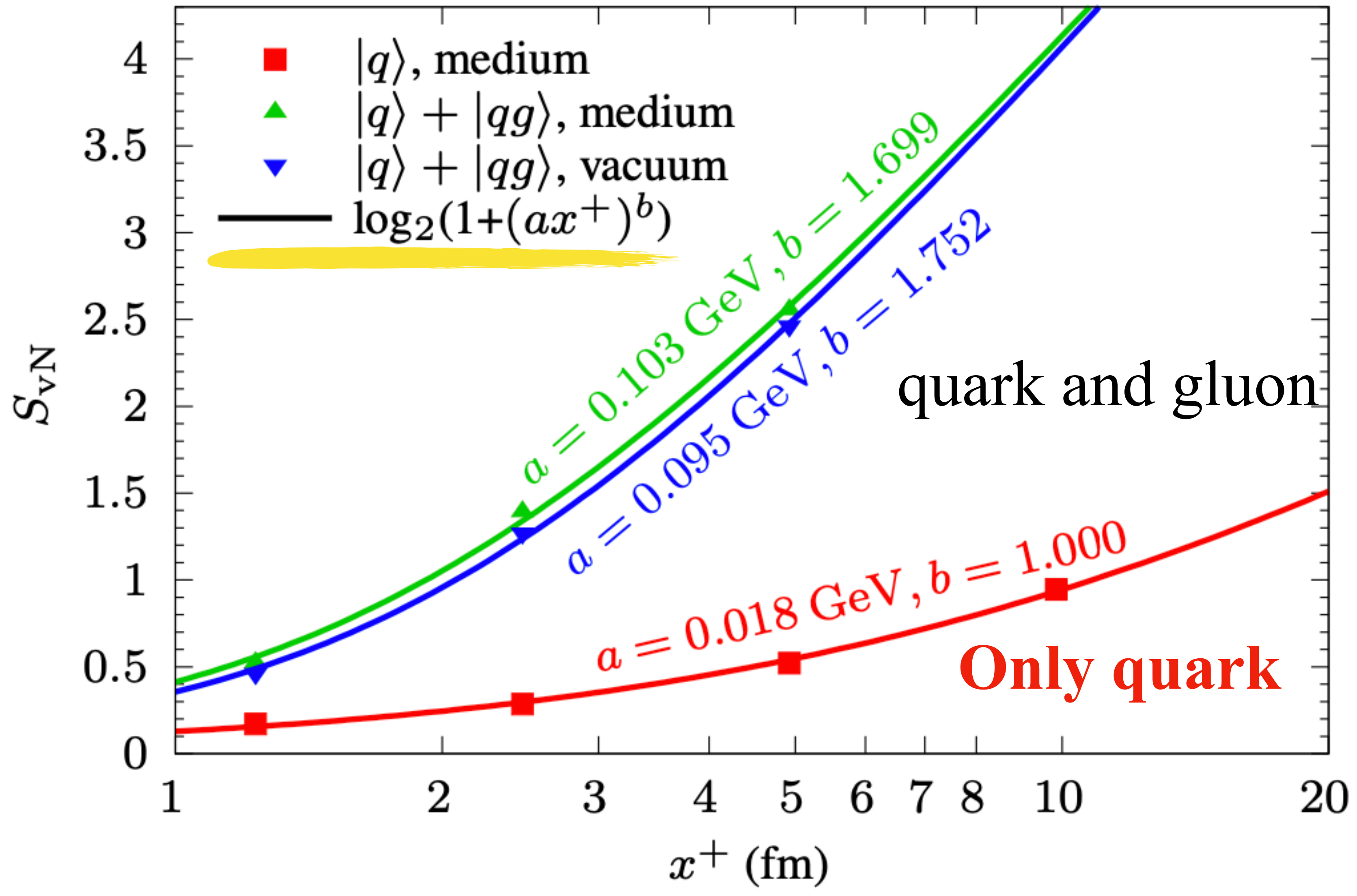
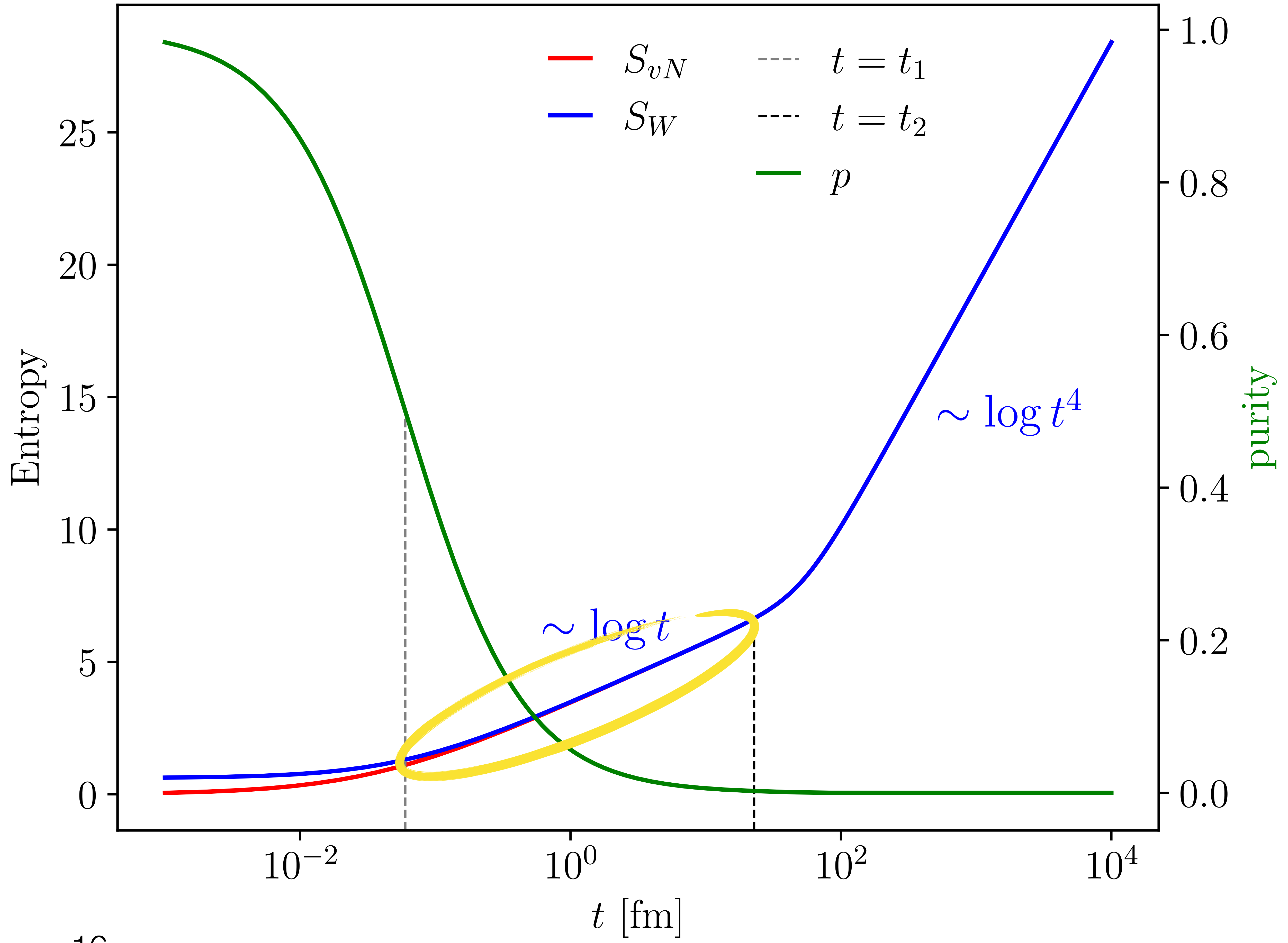


quark + gluon (med) quark + gluon (vac)



Largest contribution to entropy is due to gluon production



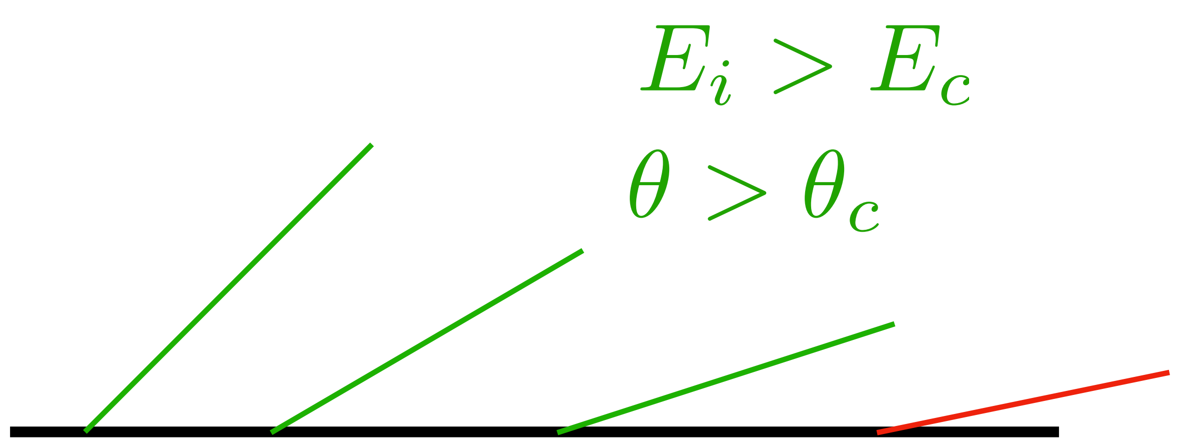
Jet entropy and gluon radiation

in preparation, JB, J.-P. Blaizot, Y. Mehtar-Tani

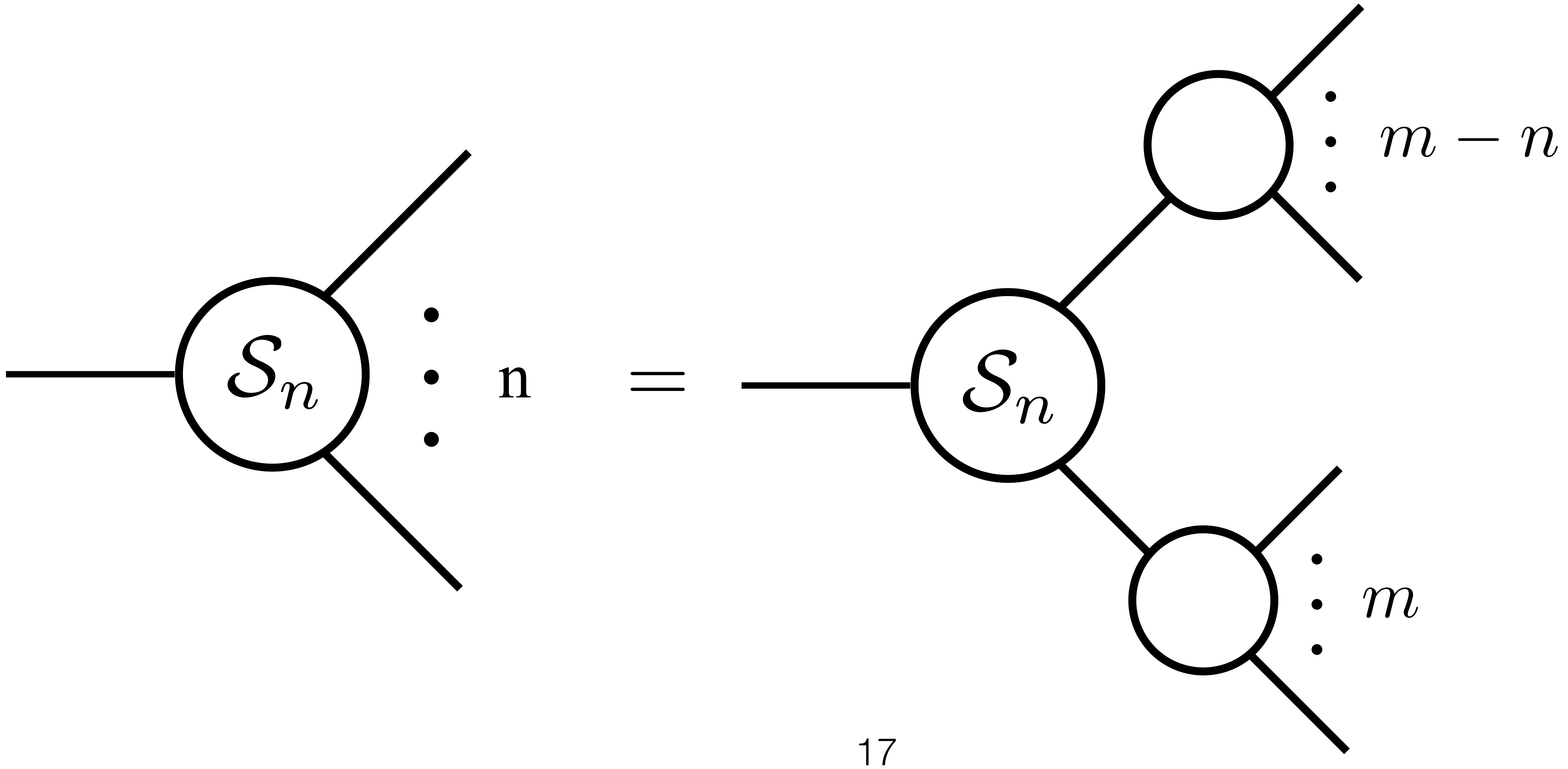
Going beyond: assuming the decoherence mechanism in the QGP works at late times, we can write the entropy for the hardest subjets in a jet

$$\mathcal{S} = -\sum_n \int d\Pi_n \frac{dP}{d\Pi_n} \log \frac{dP}{d\Pi_n} = \sum_n \mathcal{S}_n$$

2019, Neill, Waalewijn



At leading logarithmic accuracy and using a physical gauge, we can then write

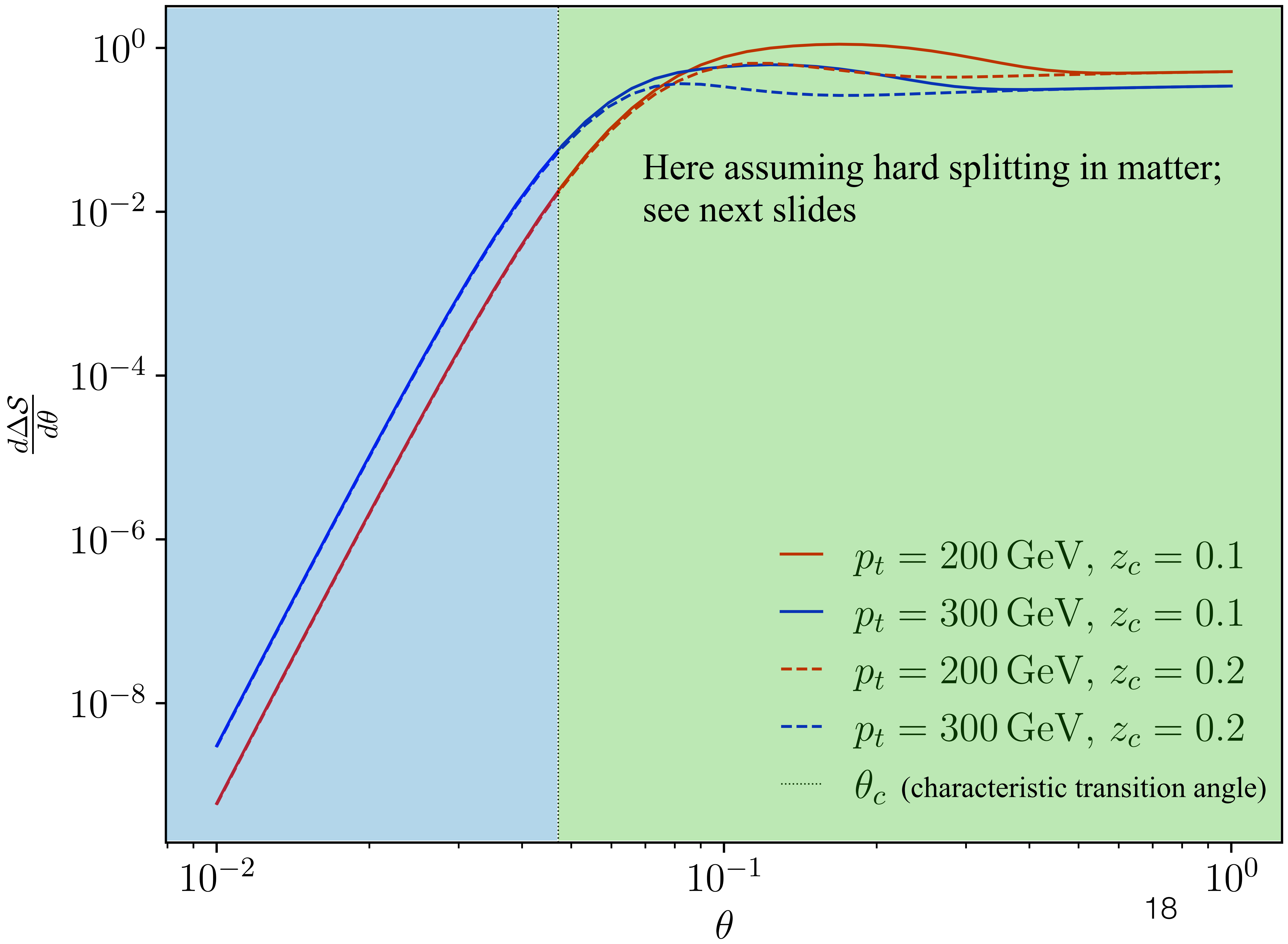


Example: modified splitting kernel

in preparation, JB, J.-P. Blaizot, Y. Mehtar-Tani

Medium induced radiation: at LO the modified splitting function can always be written as $\frac{d\sigma}{\sigma}(1+F_{\rm med})$

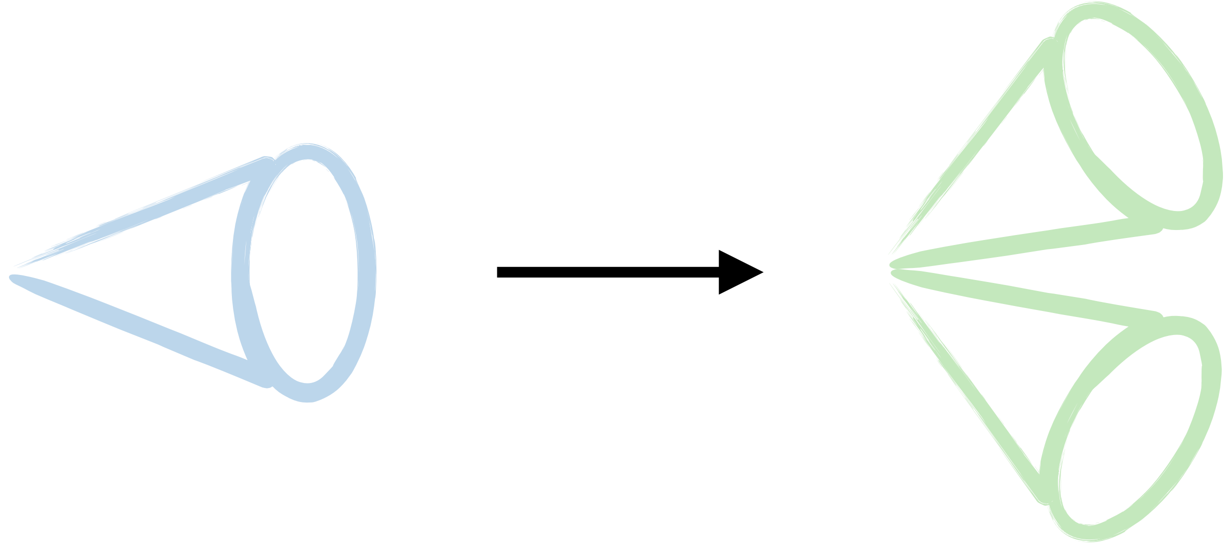
The **entropy variation with respect to the vacuum** then reads



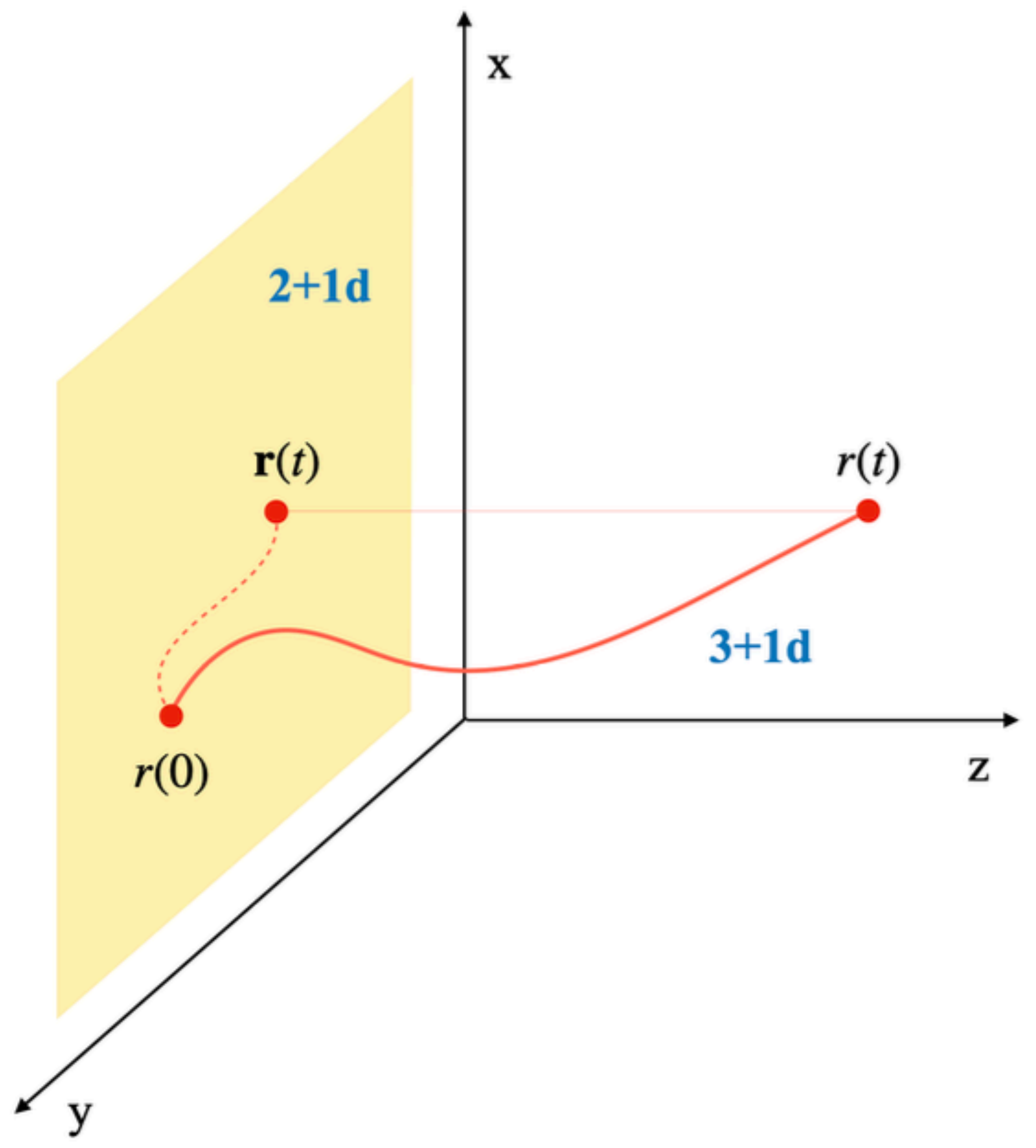
$$\frac{d[\Delta\mathcal{S}](p_t)}{d\theta} \approx \frac{2\alpha_s}{\pi\theta}\left\{\int_{z_c}^{1}\frac{dz}{z}\log\left[\frac{e^{F_{\rm med}(\theta,z)}}{1+F_{\rm med}(\theta,z)}\right]\right\}$$

which exhibits a sharp transition between the coherent and decoherent regimes

This offers another way to understand the structure of jets



Outline



In-medium jet density matrix and its entropy

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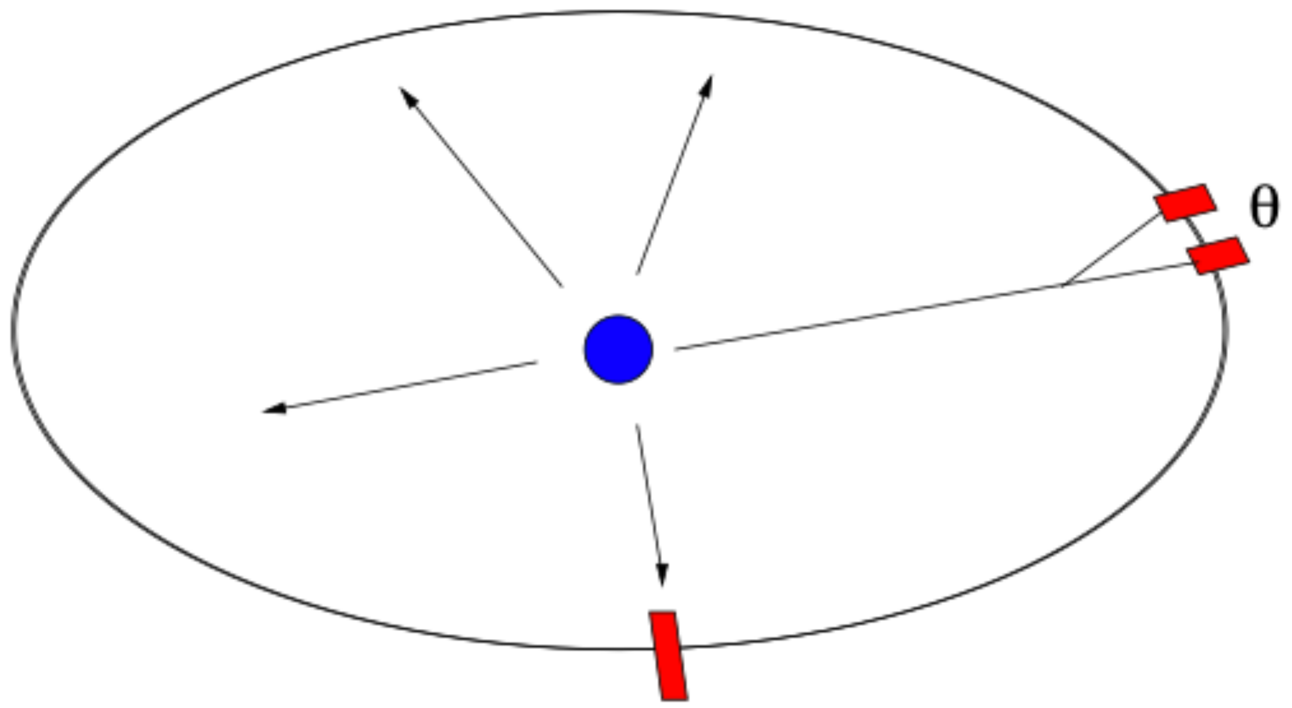
Towards understanding jet Energy Correlators in heavy ions

with Y. Mehtar-Tani; P. Caucal, A. Soto-Ontoso, R. Szafron; R. Szafron



A practical overview of ENCs

ENCs boil down to measuring projections of correlations functions of the **flow/light-ray operator**

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

For the two point functions one can show

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

EECs at LO in heavy ions

in preparation, with P. Caucal, A. Soto-Ontoso, R. Szafron

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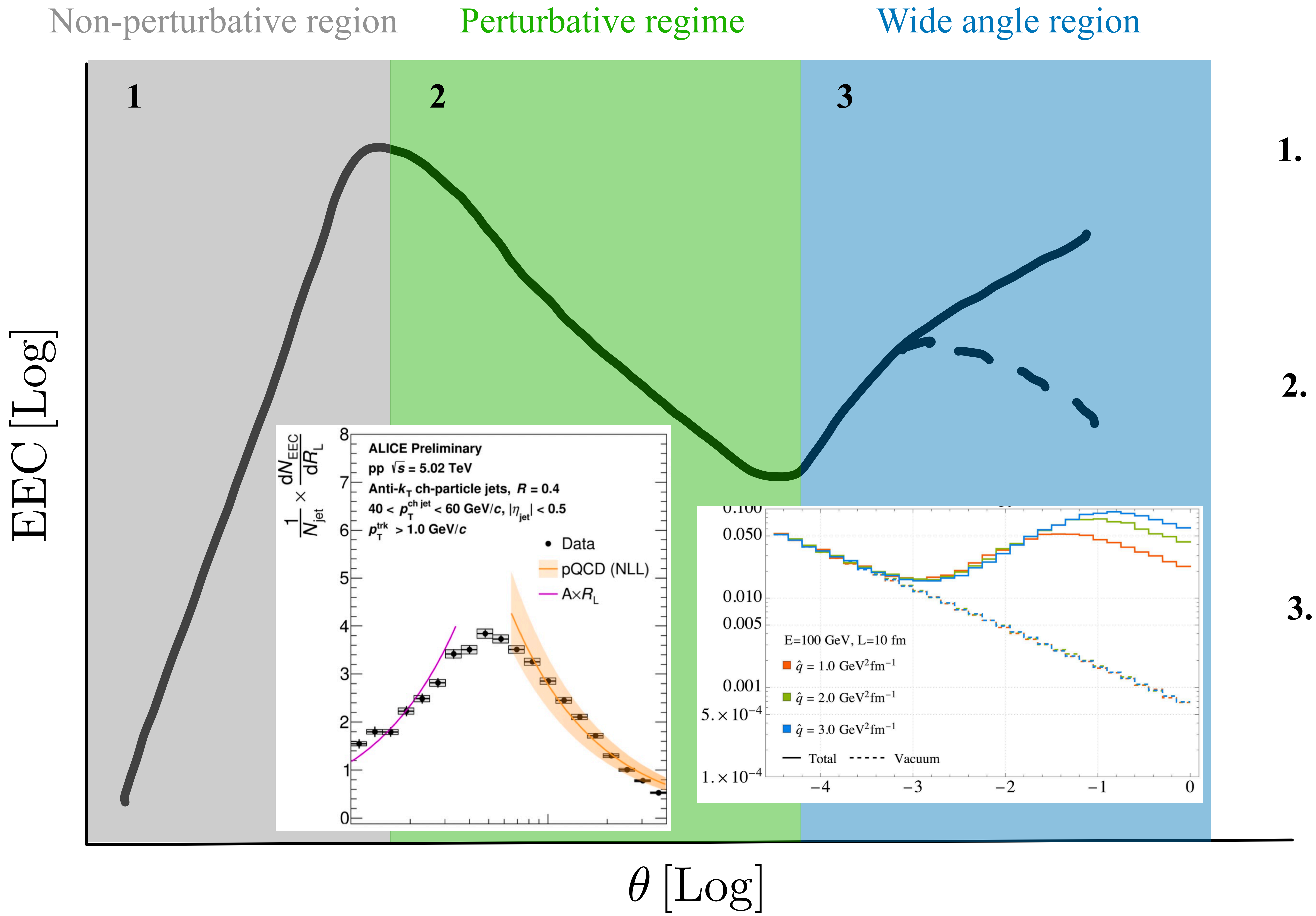
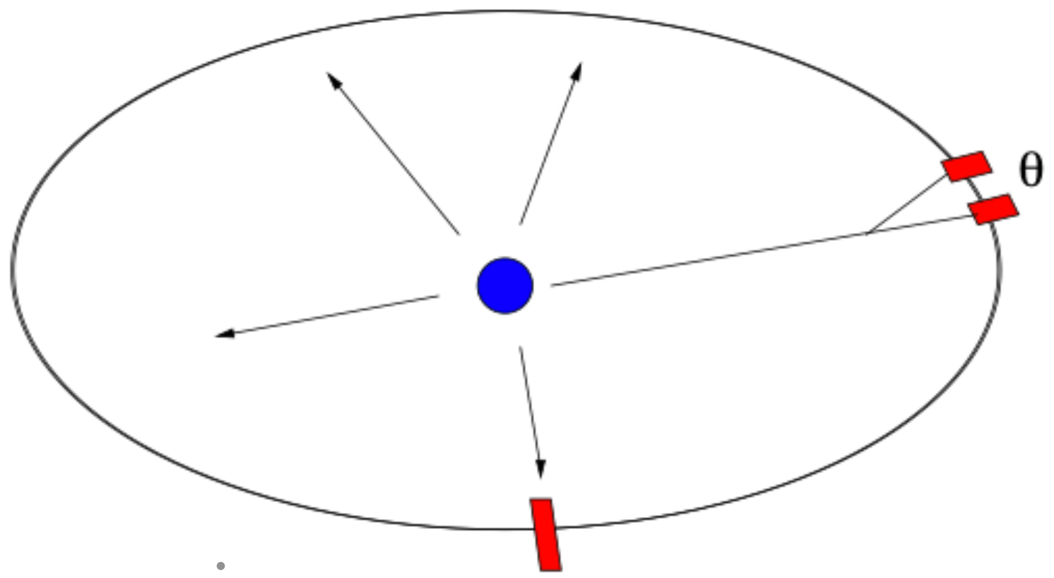




1. Non-perturbative region:

   Vacuum: sensitive to confinement scale

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

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.**

   Pablos QM23

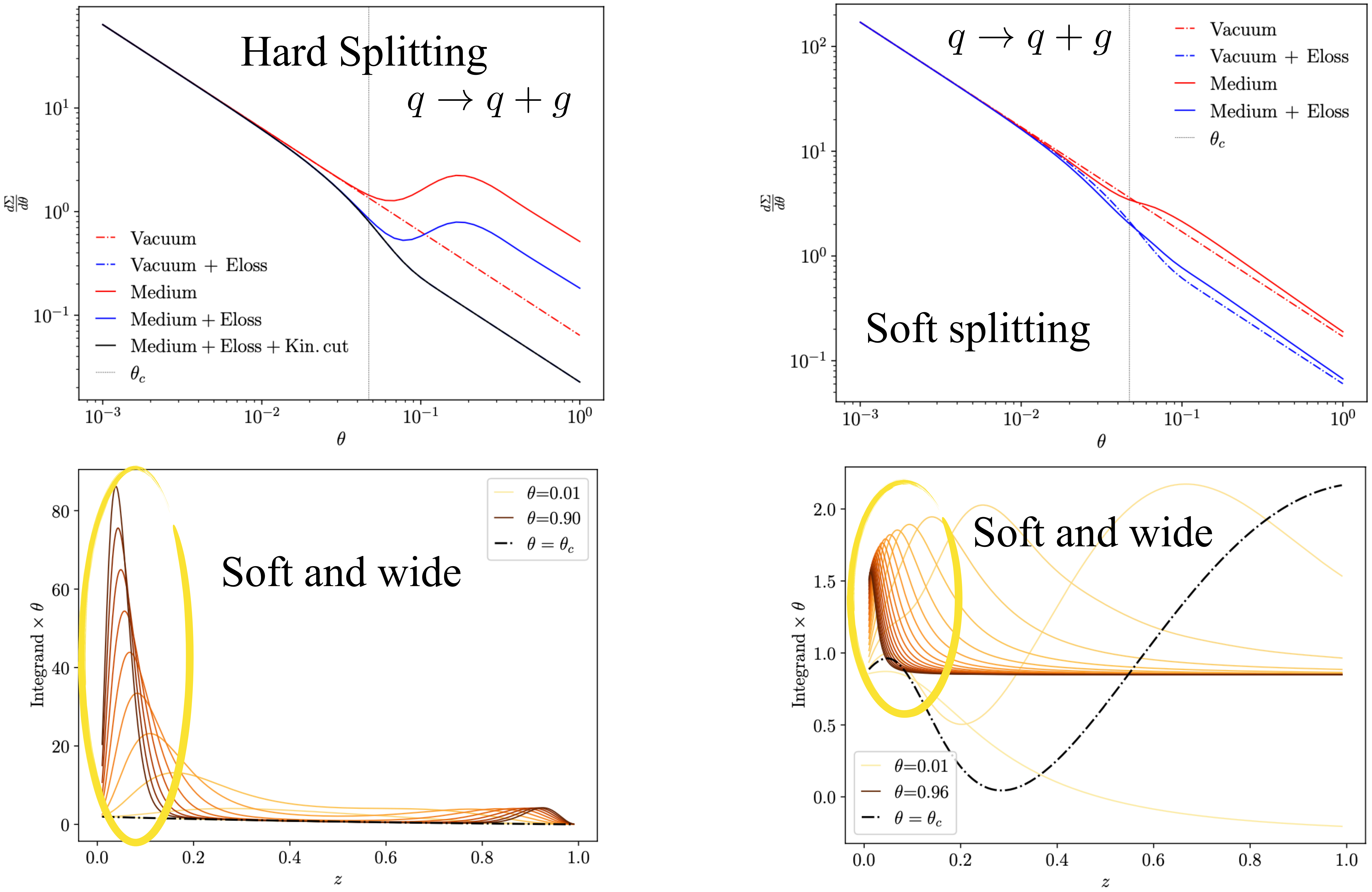
   In-medium: wake (?), non-perturbative soft-physics (?), perturbative medium modifications (?)

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

EECs at LO in heavy ions

2307.08943, with Y. Mehtar-Tani

1 Simple exercise: include energy loss and understand types of splittings at each angle



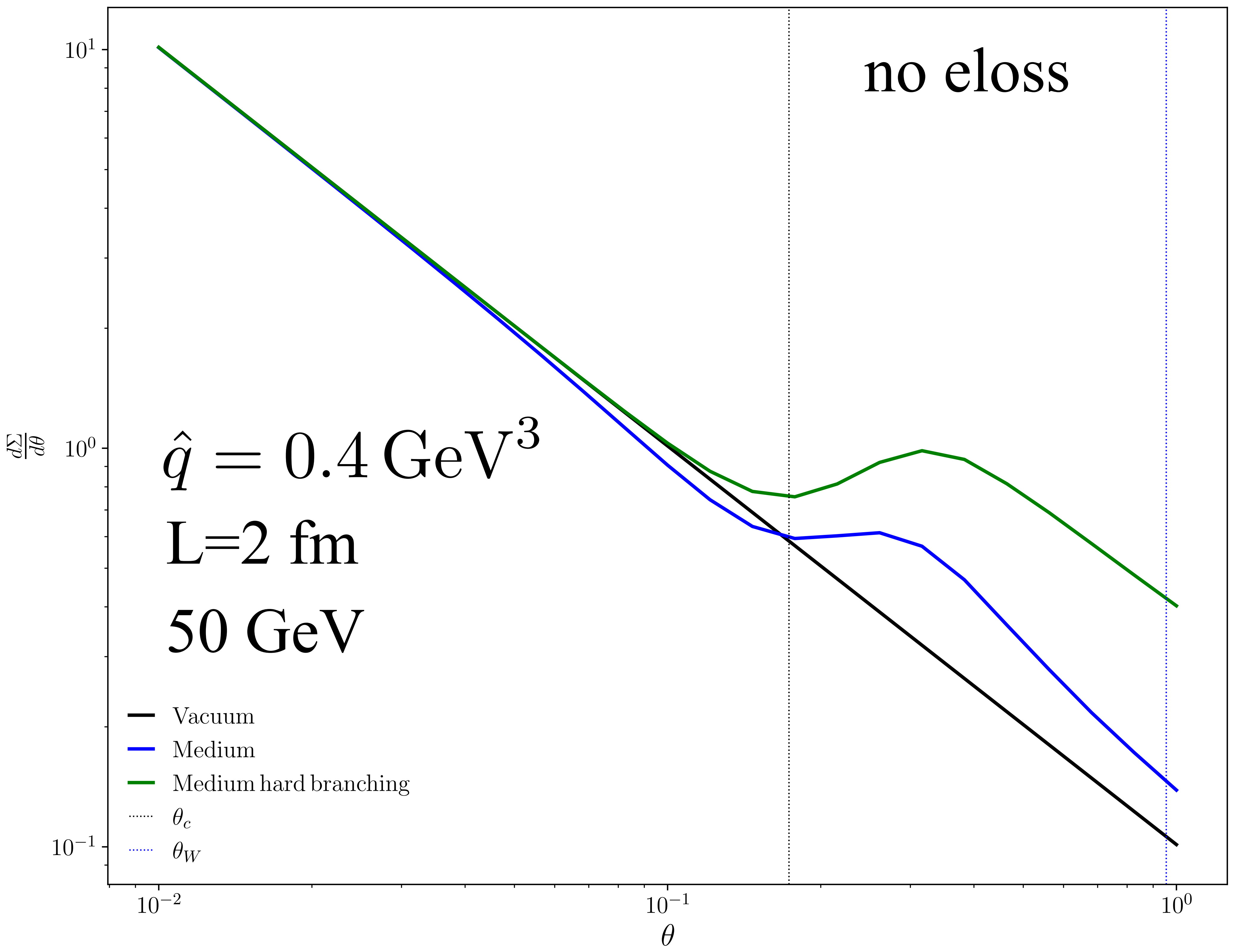
EECs at LO in heavy ions

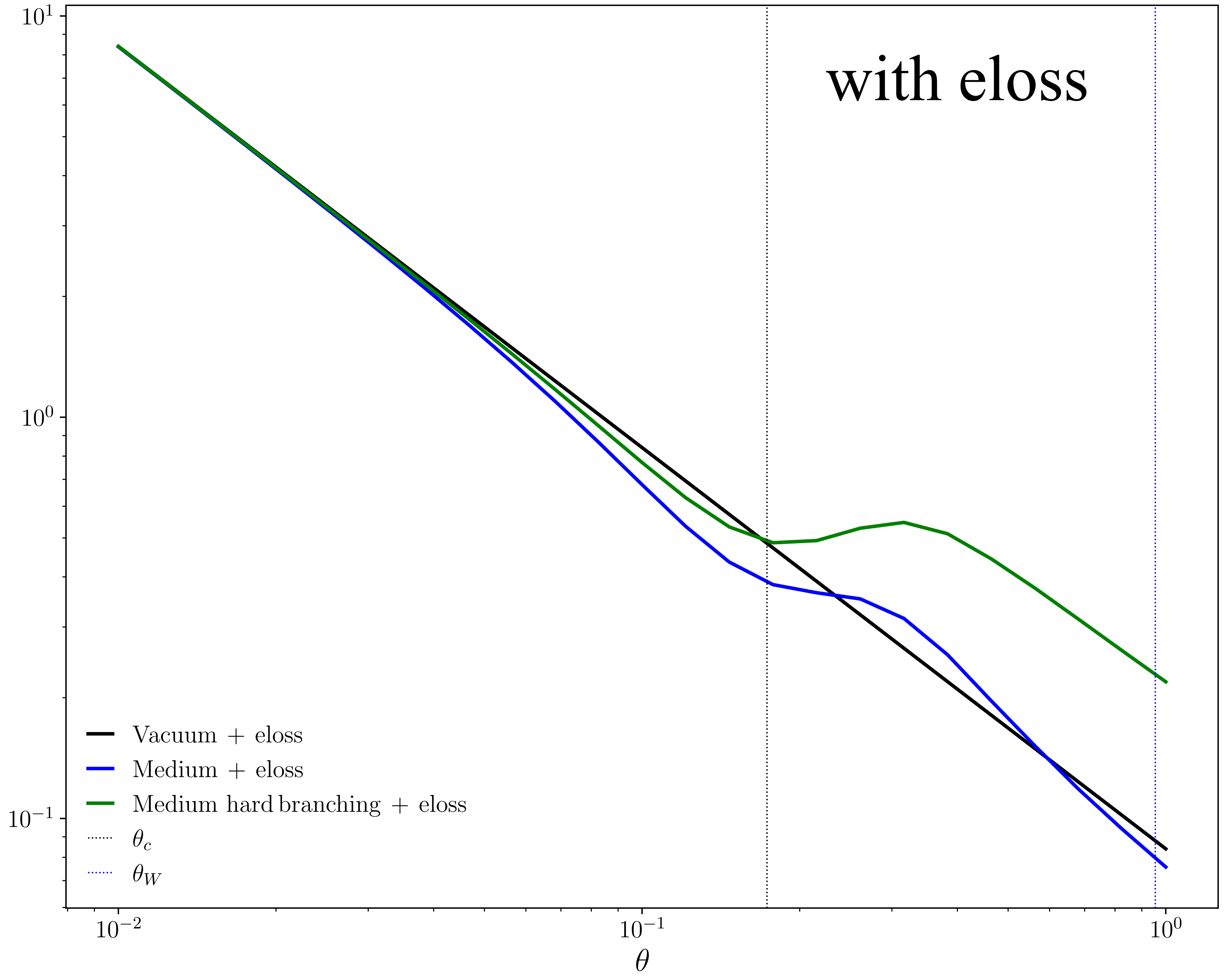
in preparation, with P. Caucal, A. Soto-Ontoso, R. Szafron

2 Interpolate between hard collinear and soft wide splittings

$\omega_c = \hat{q}L^2$

$$dI^{\text{med}} = dI^{h.c.}\Theta(\min(z,1-z)p_t > \omega_c) + dI^{\text{s.w.}}_{z\to 0}\Theta(zp_t < \omega_c) + dI^{\text{s.w.}}_{(1-z)p_t\to 0}\Theta((1-z)p_t < \omega_c)$$





Behavior largely depends on modeling and interplay between splitting function enhancement and energy loss suppression

EECs at LO in heavy ions

in preparation, with P. Caucal, A. Soto-Ontoso, R. Szafron

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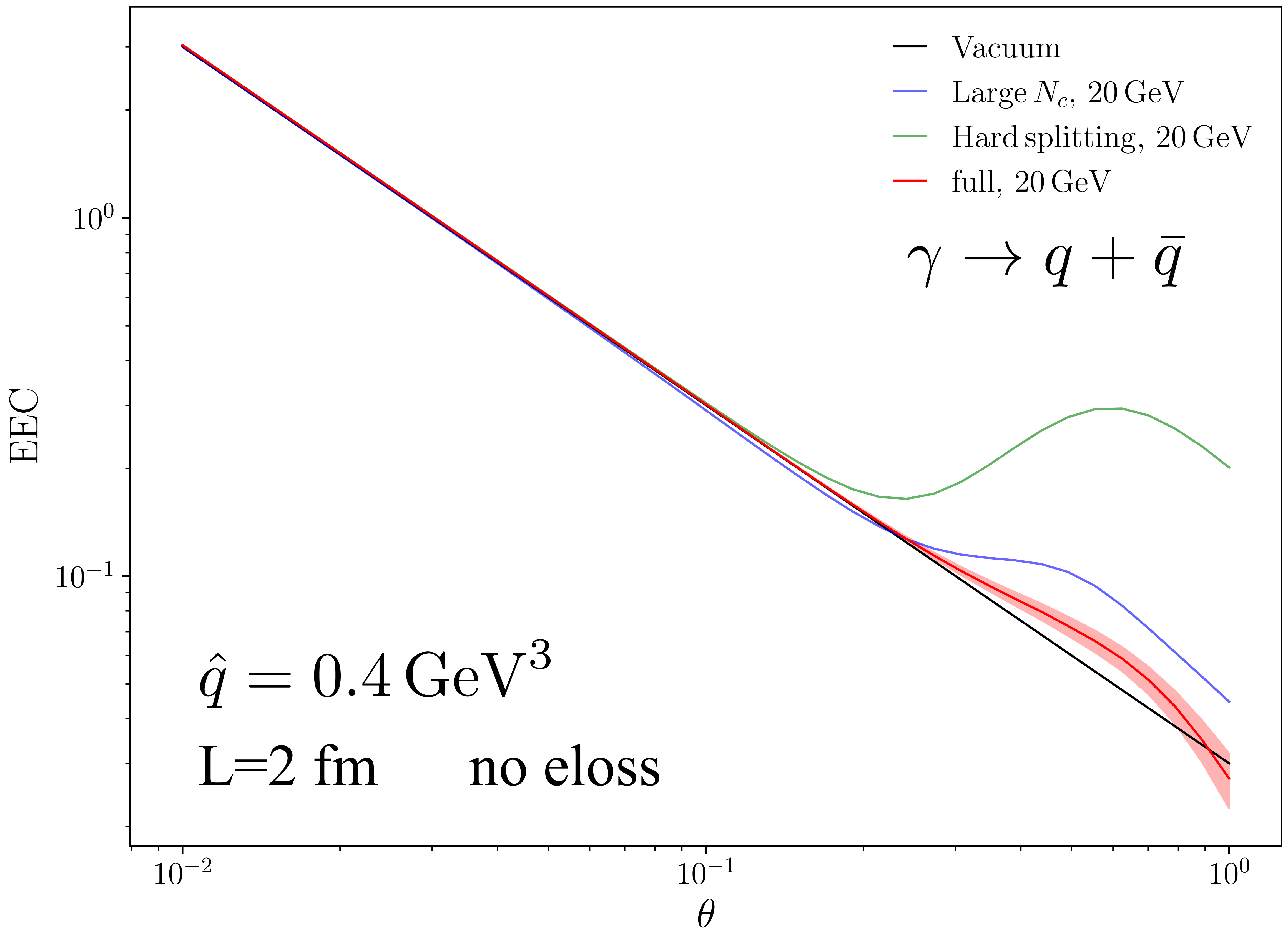
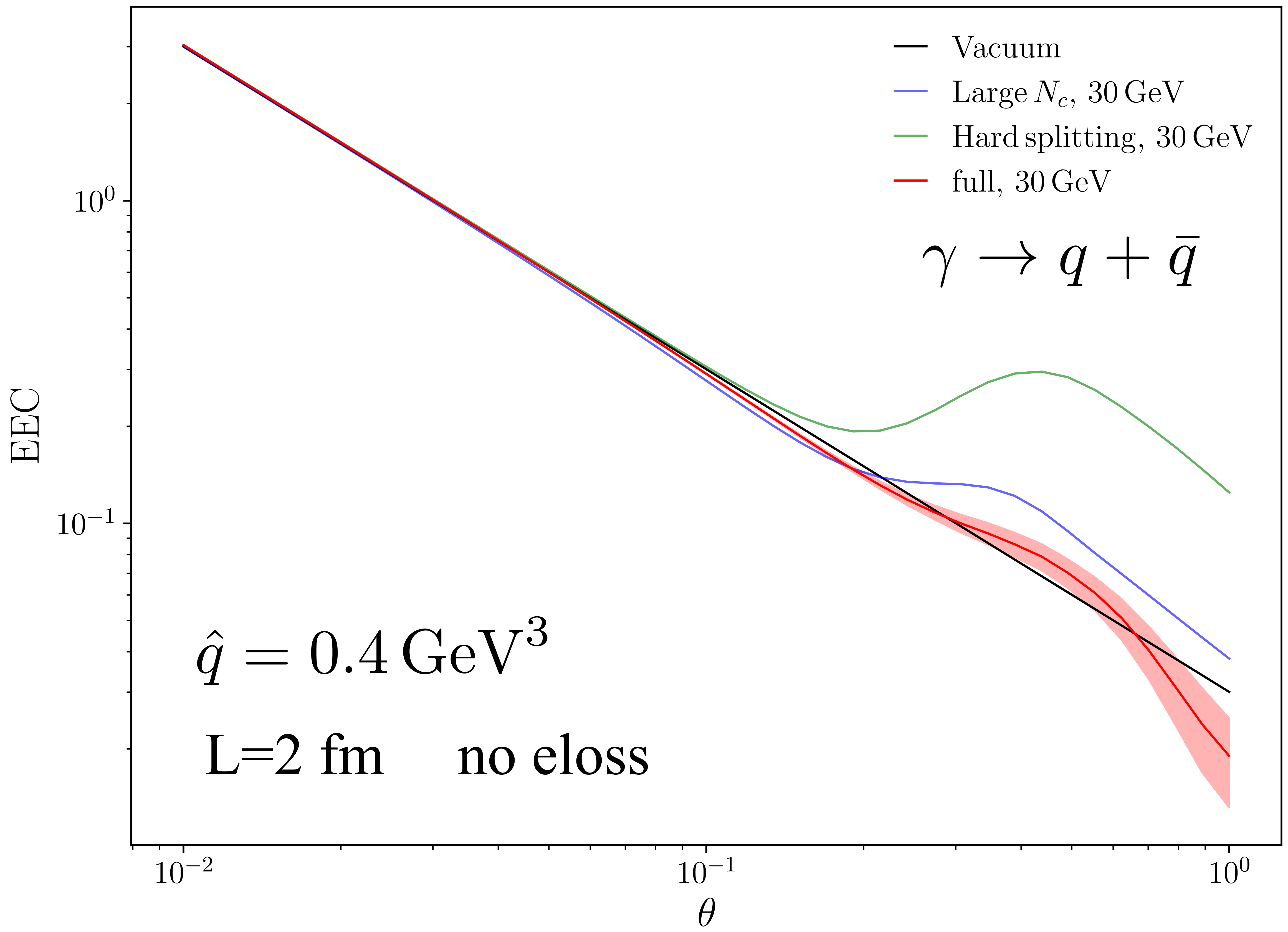
3 Exact LO EEC in the harmonic approximation 2023, Isaksen, Tywoniuk





Behavior qualitatively distinct from hard splitting approximation

Suppressing soft particle contamination

in preparation, with P. Caucal, A. Soto-Ontoso, R. Szafron

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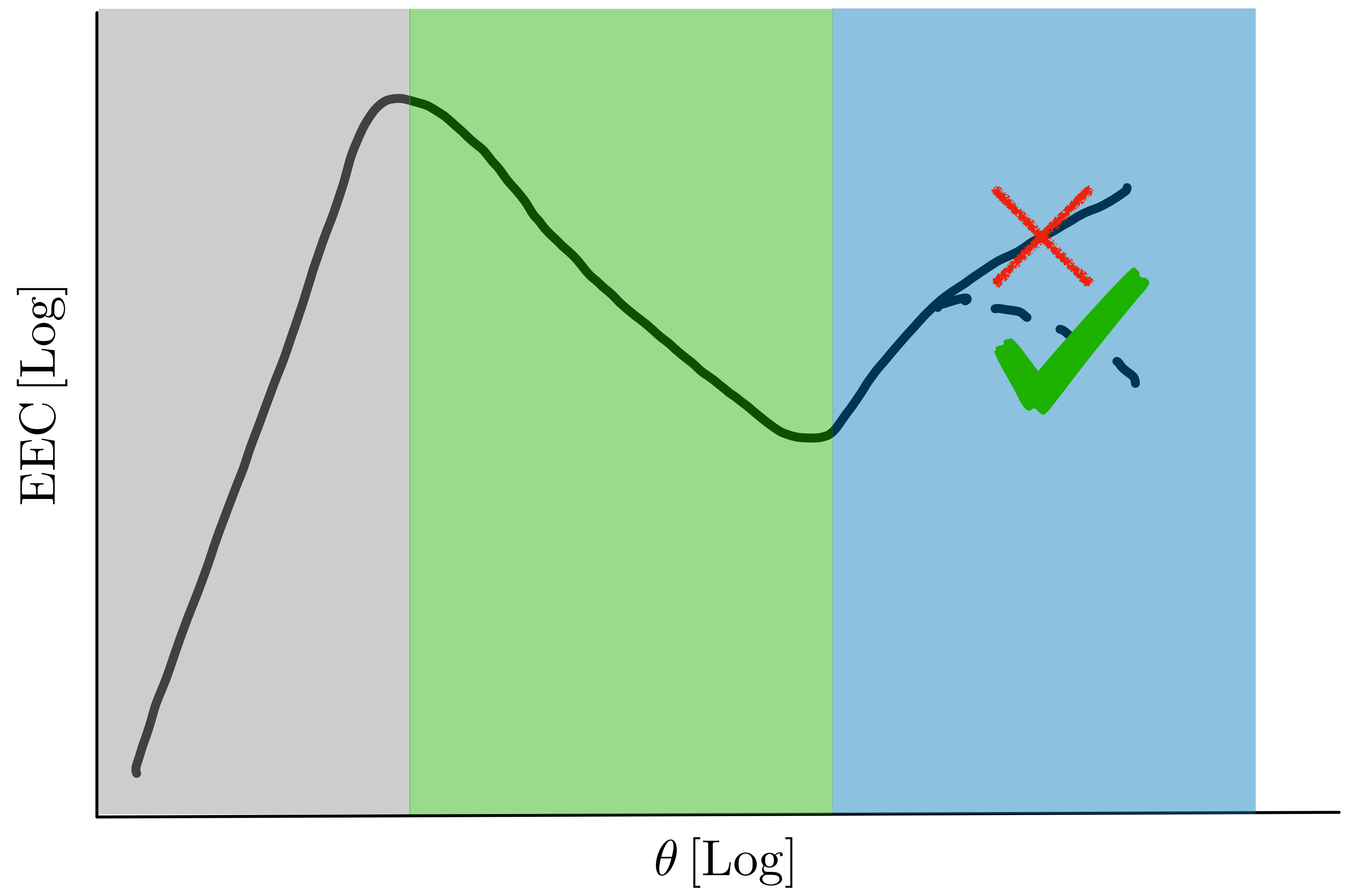

To make sense of **perturbative baseline** one needs to clean soft uncorrelated radiation

Two methods:

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:

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

Suppressing soft particle contamination: subjets

in preparation, with P. Caucal, A. Soto-Ontoso, R. Szafron

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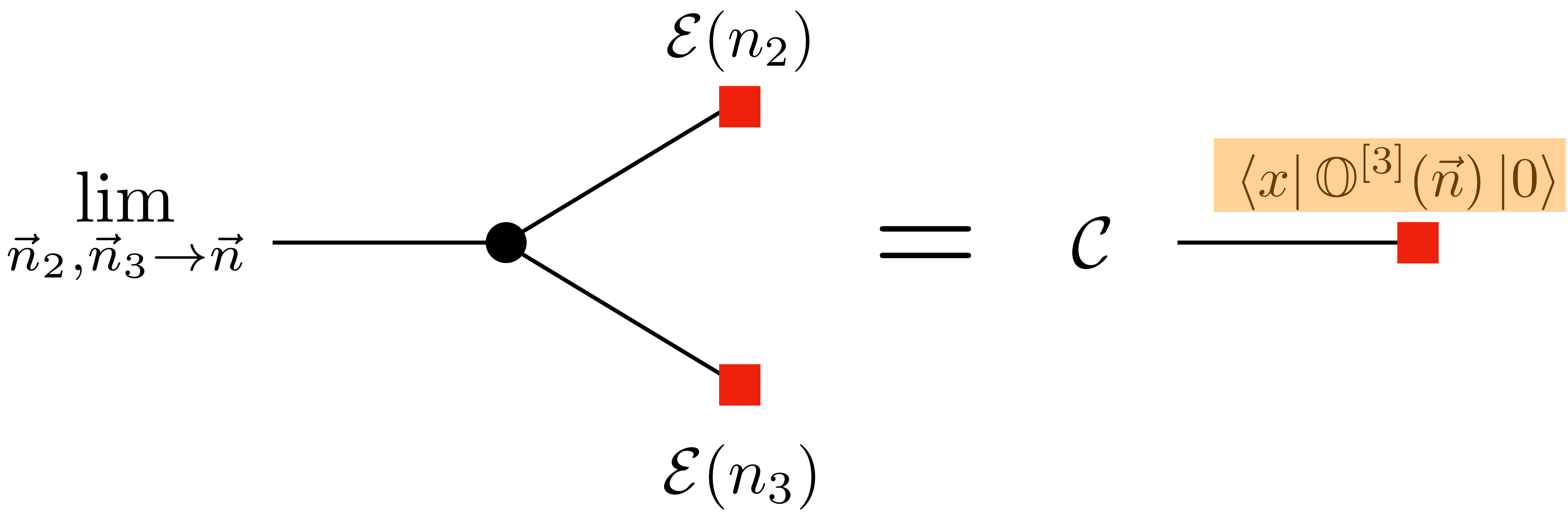
Matching at LO:



Particles:

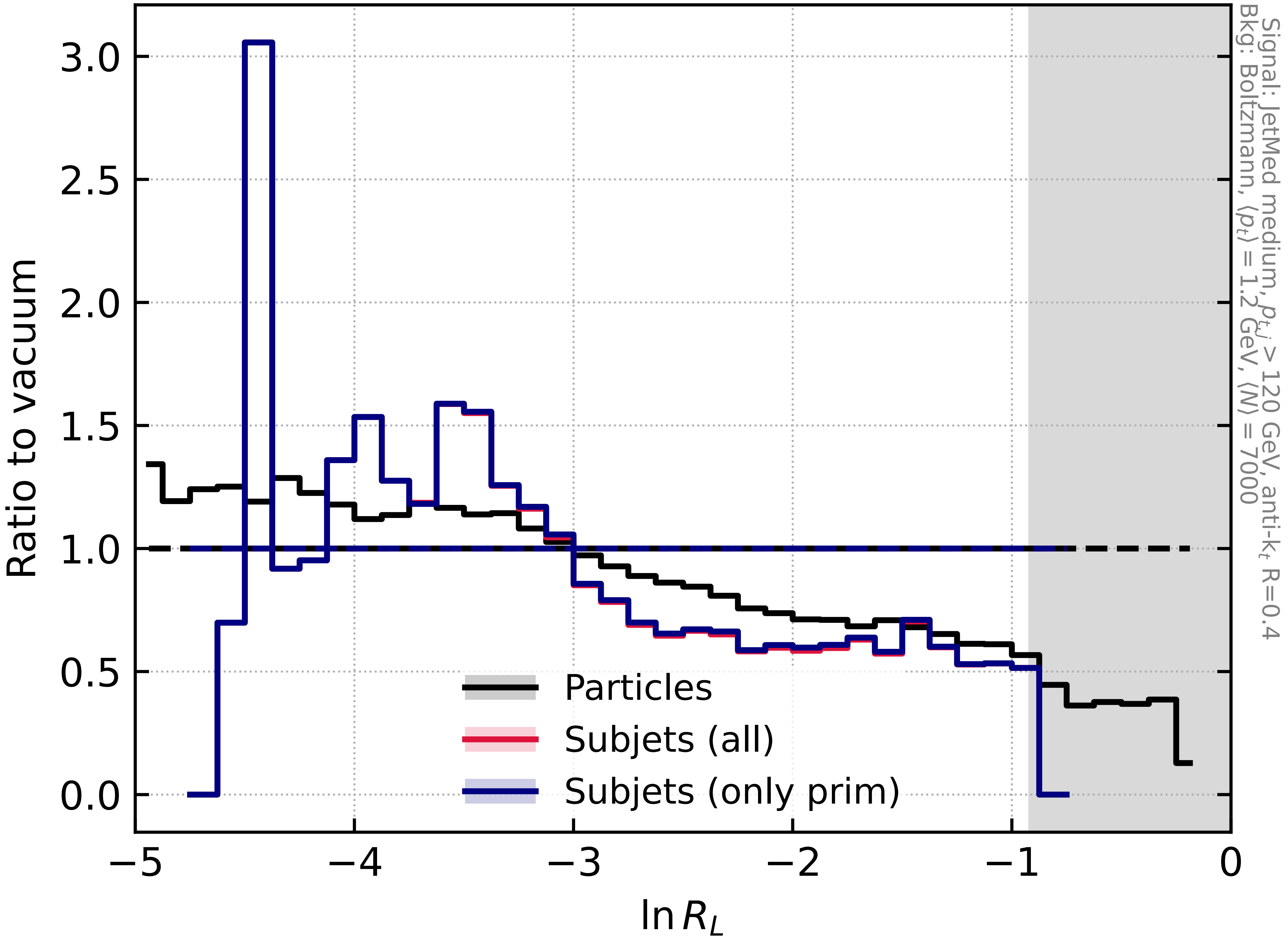
$$\frac{1}{N_c}\mathrm{Tr}_c\,\langle x|\,\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\,|0\rangle = \frac{2g^2C_F}{2\theta^2(2\pi)^3}\int_0^1 dz\, z(1-z)P(z)\int\frac{dE E^2}{(2\pi)^3 2E}E^3\not{n}e^{-ix\cdot nE}$$

Subjets:

$$\frac{1}{N_c}\mathrm{Tr}_c\,\langle x|\,\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\,|0\rangle = \frac{2g^2C_F}{2\theta^2(2\pi)^3}\int_0^1 dz\, z(1-z)P(z)\int\frac{dE E^2}{(2\pi)^3 2E}E^3\not{n}e^{-ix\cdot nE}\Theta\left(p_2\cdot p_3 > \frac{k_{\mathrm{cut}}^2}{2z(1-z)}\right)$$

$$= \frac{2g^2C_F}{2\theta^2(2\pi)^3}\int_{z^-}^{z^+} dz\, z(1-z)P(z)\int\frac{dE E^2}{(2\pi)^3 2E}E^3\not{n}e^{-ix\cdot nE}\Theta\left(E > \frac{4k_{\mathrm{cut}}}{\theta}\right)$$

Numerics/MC:



Ongoing: understanding resummation for subjets

Suppressing soft particle contamination: track functions

in preparation, with R. Szafron

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

2013, Chang, Procura, Thaler, Waalewijn

$T_i(x,\mu)$: describes the fraction of energy from parton i going into e.g. charged particles

They allow for higher angular resolution but are non-perturbative like FFs

Ideal for ENCs since only moments are necessary:

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

For HICs we need to understand RG evolution for these objects

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Vacuum RGE: $$R\frac{\partial T_i(x,R)}{\partial R} = \frac{\alpha_s}{2\pi}\sum_{jk}\int_0^1 dz \hat{P}_{i\to jk}(z)\int_{x_1,x_2} T_j(x_1,R)T_k(x_2,R)\delta(x = zx_1 + (1-z)x_2)$$

In-medium we have several pieces:

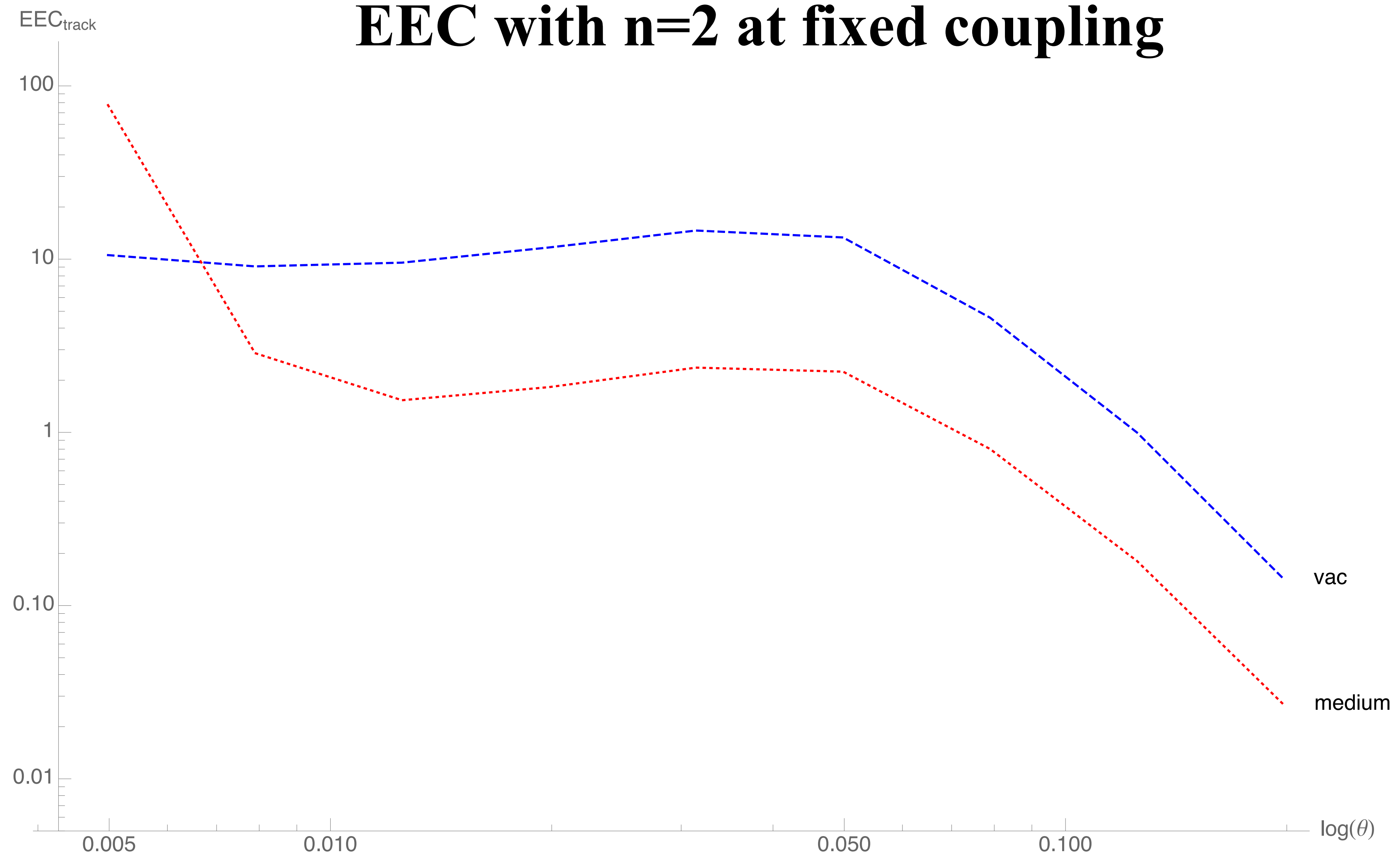
Modified splitting function: same RG but with new anomalous dimensions

$$\gamma_{c\to ab}(j) = -\int_0^1 dz\,(P_{c\to ab}(z) + P^{\rm med}_{c\to ab}(z,\theta))z^{j-1}$$

In a very simple case using BDMPS motivated kernel, we find

$$\gamma_{med}(j) = -\int_0^1 \left\{P(z) + \sqrt{\frac{\omega_c}{2p_t}}(2N_c)2z\mathcal{K}(z) + c_{med}\delta(1-z)\right\} z^{j-1}$$

EEC with n=2 at fixed coupling



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In-medium we have several pieces:

Modified phase space: same RG but with new anomalous dimensions

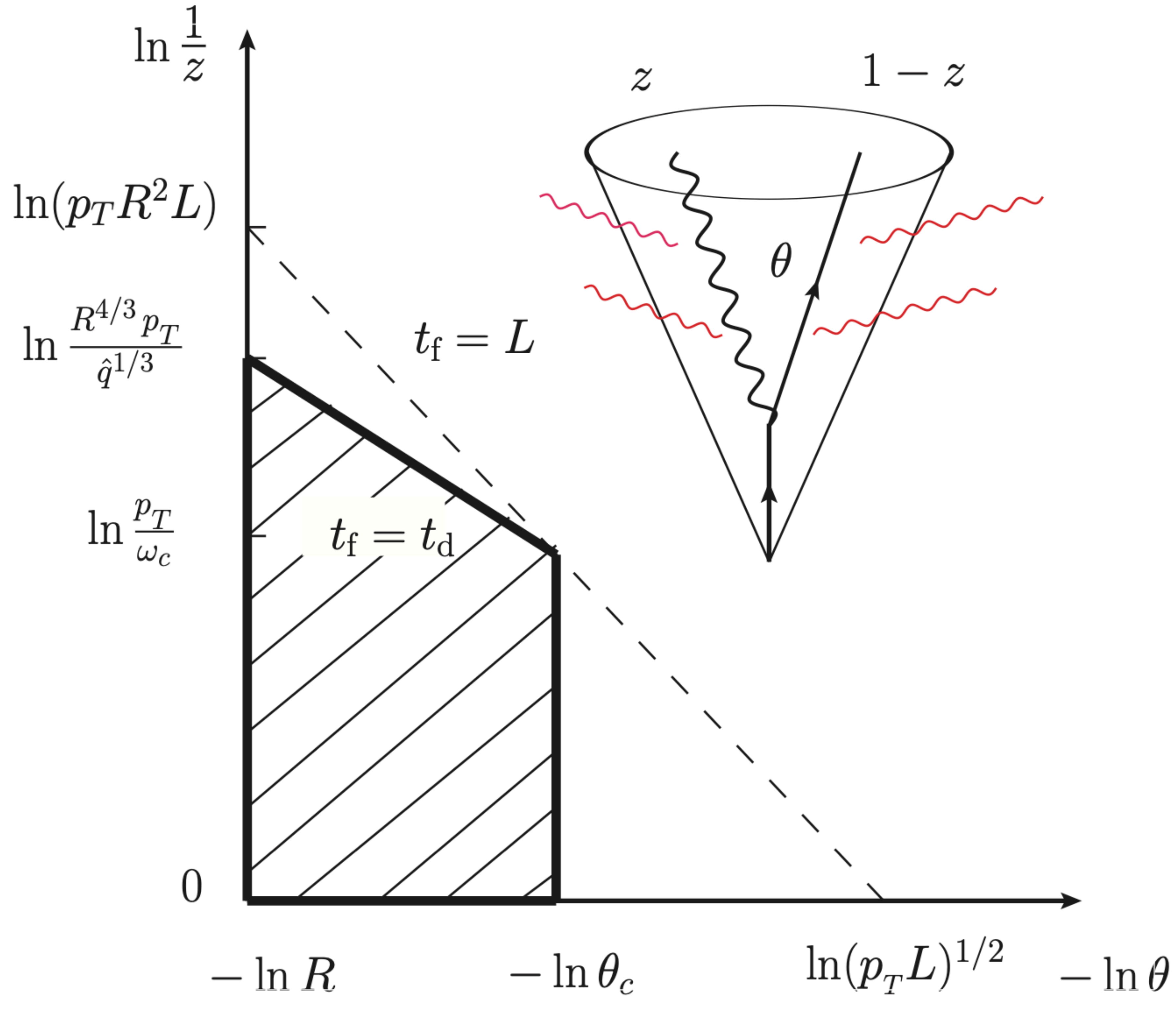
$$\gamma(j,\theta) = -\int_0^1 dz\, P(z)\Theta_{P.S.}(\theta,z)z^{j-1}$$

In DLA limit we obtain the limiting form

$$\gamma(j,\mu) = \gamma_{\rm vac}(j,\mu)\left(1-\left(\frac{2\hat{q}p_t}{\mu^4}\right)^{\frac{j-1}{3}}\right)$$

and extra constraints which modify the boundary of the RG evolution

1706.06047, Y. Mehtar-Tani, K. Tywoniuk



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Brookhaven National Laboratory

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In-medium we have several pieces:

Energy loss: more evolved RG and new anomalous dimensions; for the PDF we obtain

similar to 2016, Mehtar-Tani, Tywoniuk

$$\frac{\partial q(x)}{\partial \log \mu^2} \approx \int_{x_1}\int_0^{(z-zx_1)p_t} d\varepsilon\, D(\varepsilon)\int_0^1 dz\, P\left(z+\frac{\varepsilon}{p_t}\right) q(x_1)\delta(x = x_1 z)$$

For the track functions we have double convolution of the same type, leading to the anomalous dimension

$$\gamma[j] = -\int_0^1\int_{\varepsilon_1,\varepsilon_2} D(\varepsilon_1)D(\varepsilon_2)P\left(z+\frac{\varepsilon_1+\varepsilon_2}{p_t}\right) z^{j-1}$$

This breaks energy conservation which can be imposed via

$$c_{med} = \int_0^1\int_{\varepsilon_1,\varepsilon_2} D(\varepsilon_1)D(\varepsilon_2)P\left(z+\frac{\varepsilon_1+\varepsilon_2}{p_t}\right) z$$

Outlook

Jet entropy:

Sensitive to transition between coherent and decoherent evolution inside the jet

Can be easily computed in pQCD at LL accuracy

Simplest in a family of QIS entanglement measures: mutual information, Qdiscord …

EECs:

Need to understand leading calculations to make sense of any future data

Great motivation to go towards higher order calculations in jet quenching

Higher point correlators will give information about *shape* of correlations

[JB, Moult, Sadofyev, xxxx.xxxx]