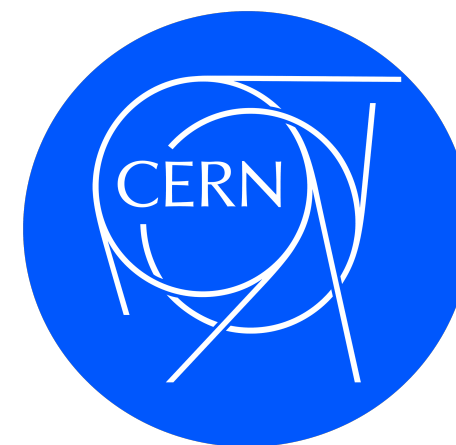


Energy Correlators in High Energy Nuclear Physics

REF-Milan, 13th October 2025

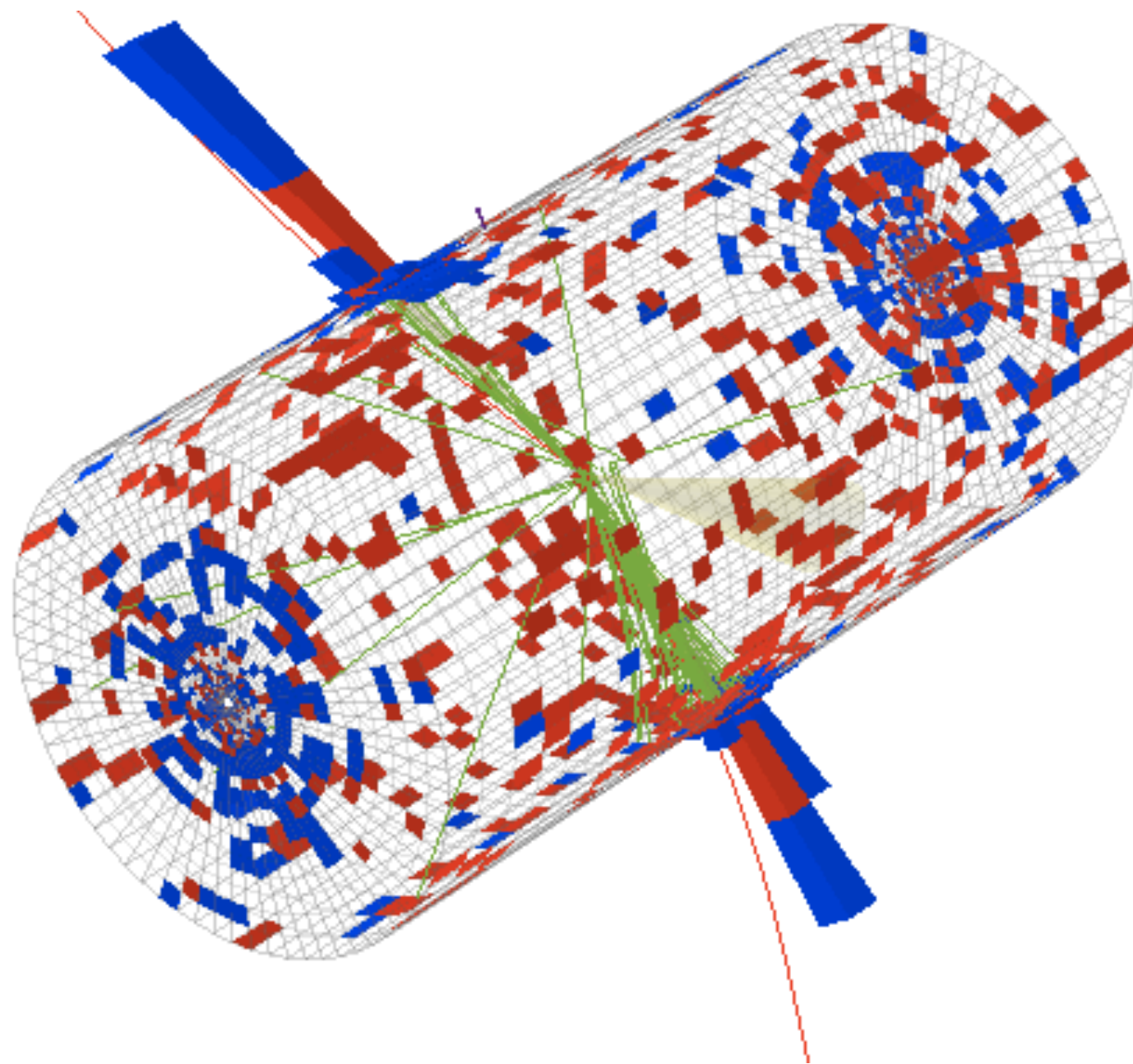


Mainly based on: 2412.03616, 2503.13603 and ongoing work

with G. Milhano, I. Moulton, M. Kuzmin, A. Sadofyev, J. Silva

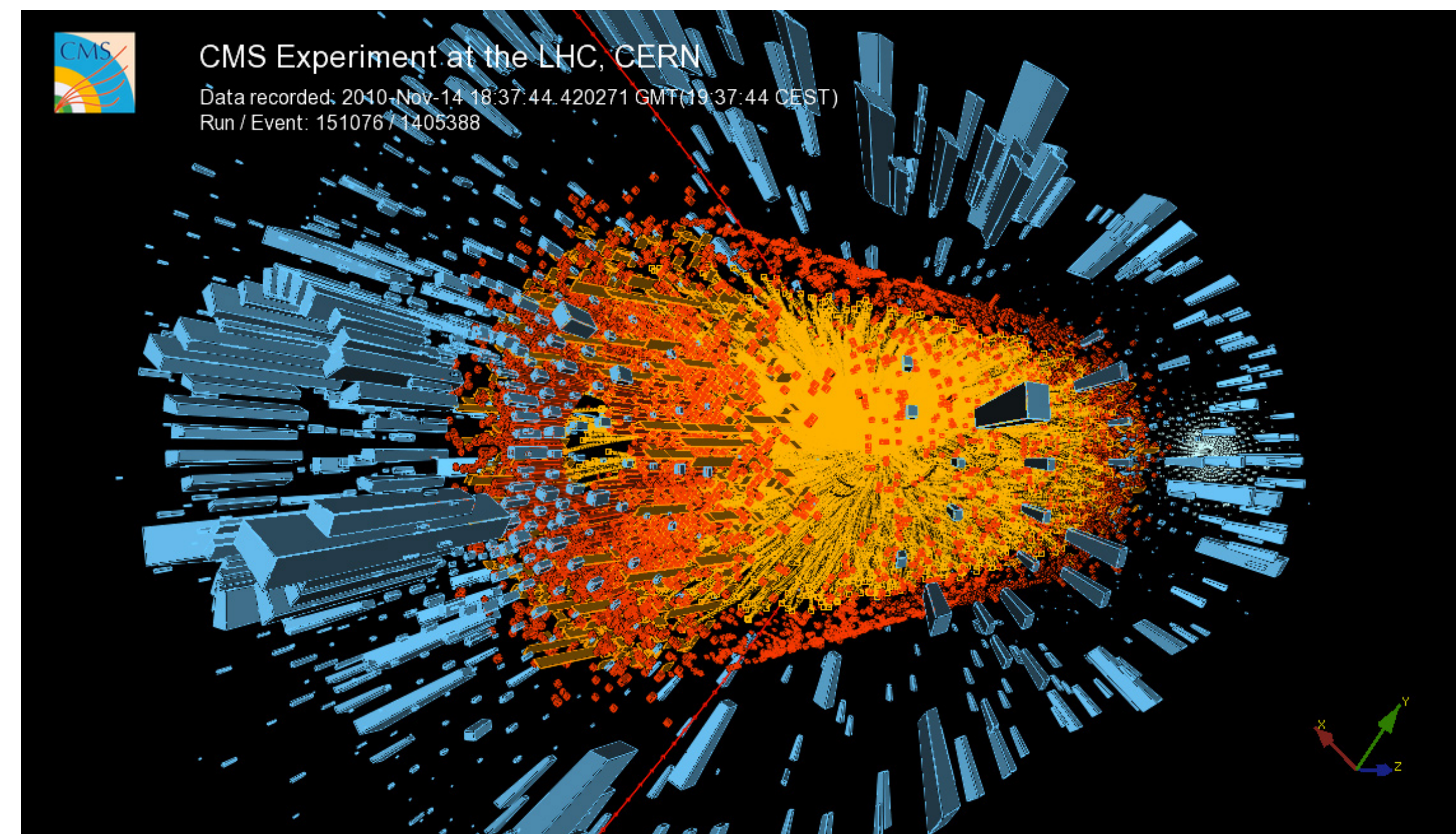
João Barata, CERN-TH

Why Heavy Ion collisions (HICs) ?



pp collision: a few particles are detected

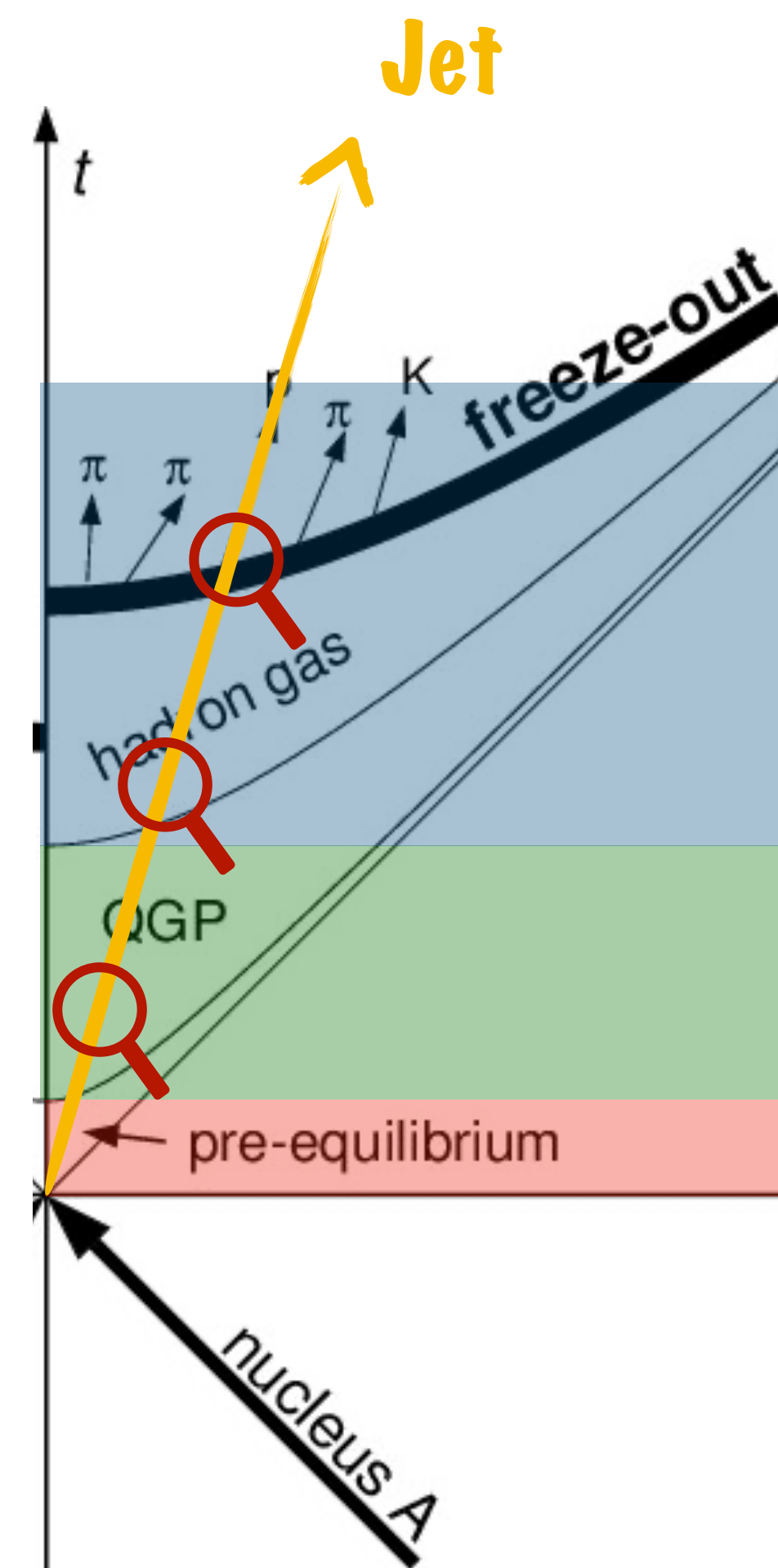
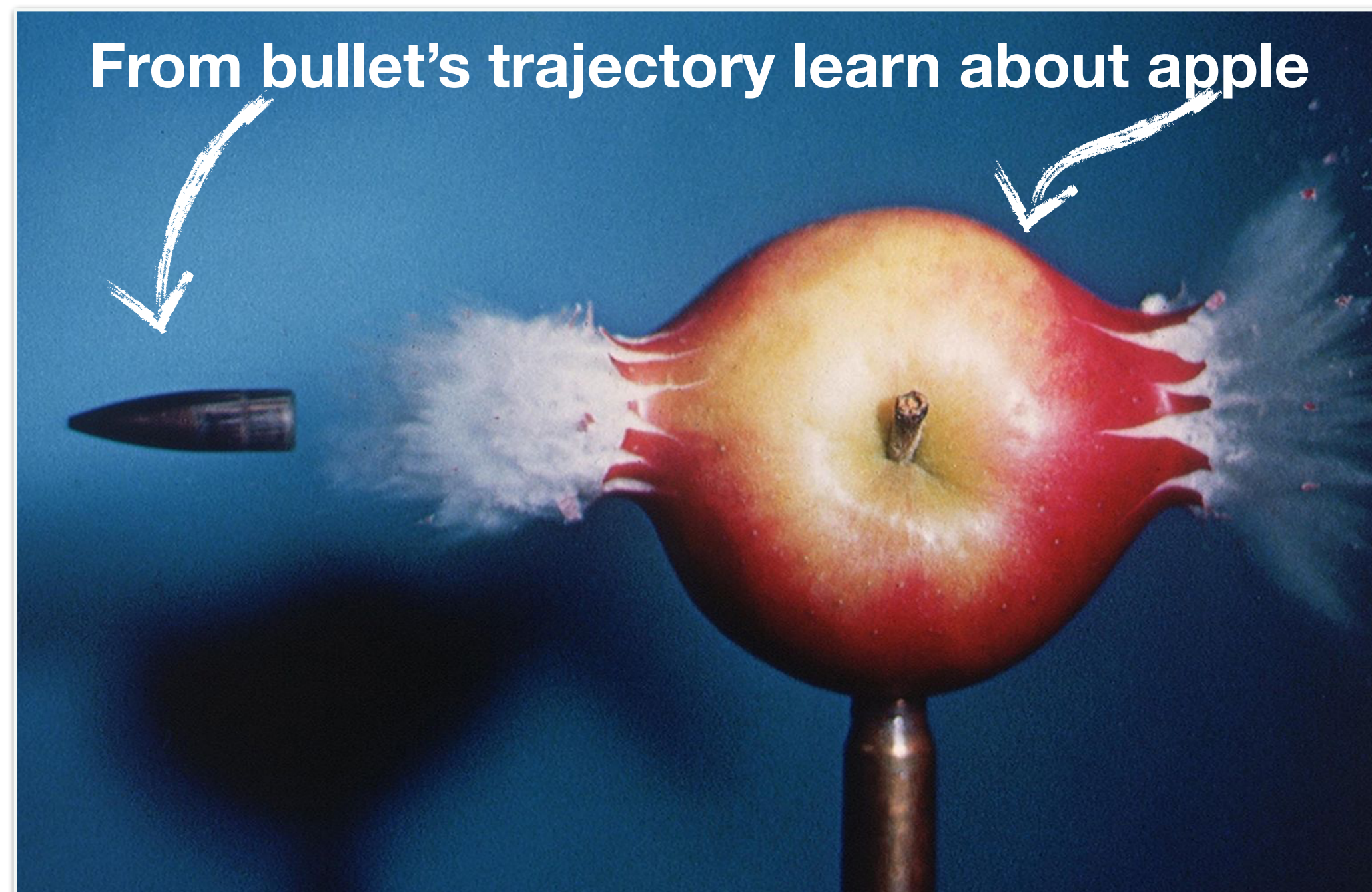
Precision tests of QCD



AA collision: thousands of detected particles

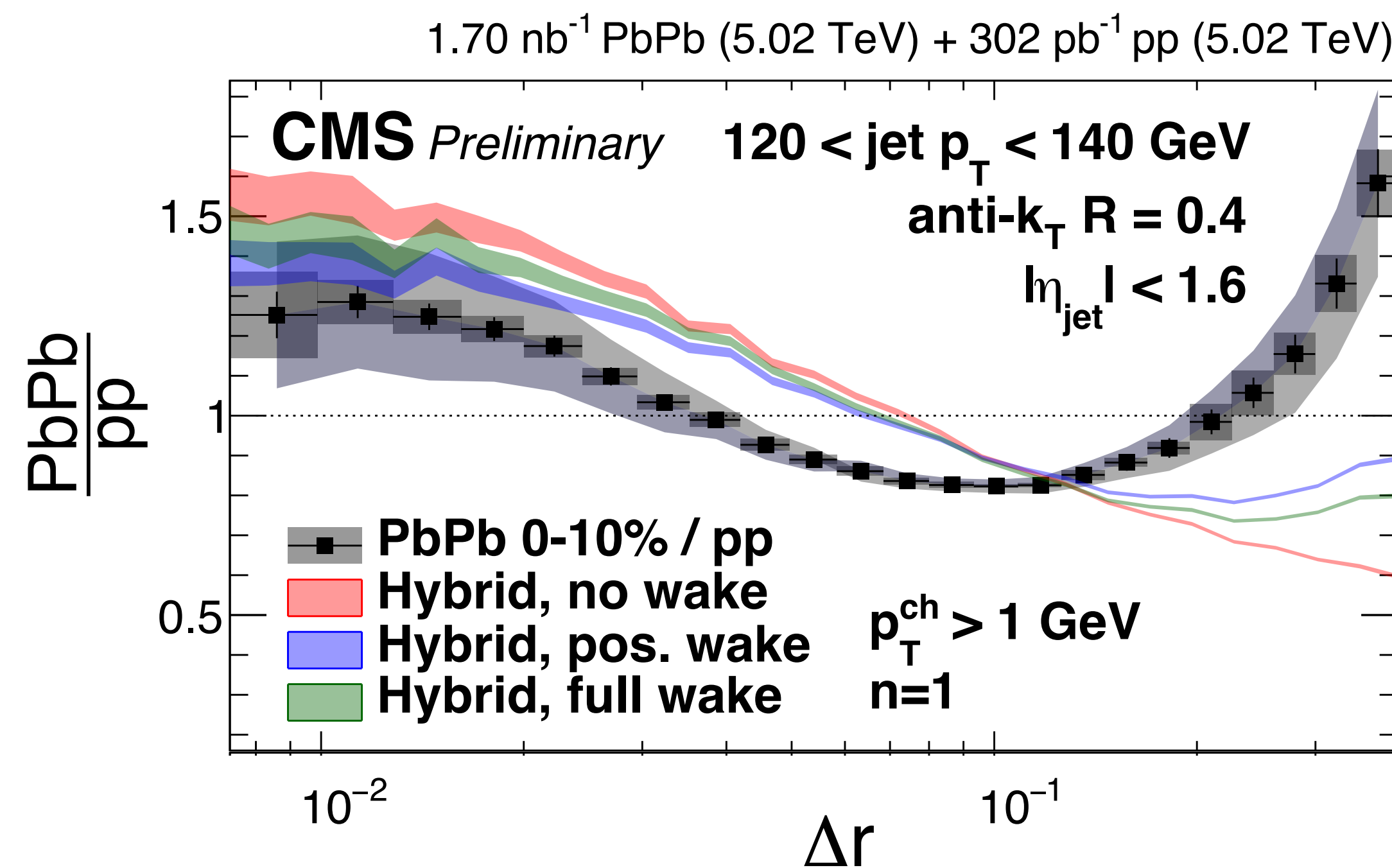
Emergent many-body properties of QCD

Why **jets in** Heavy Ion collisions ?



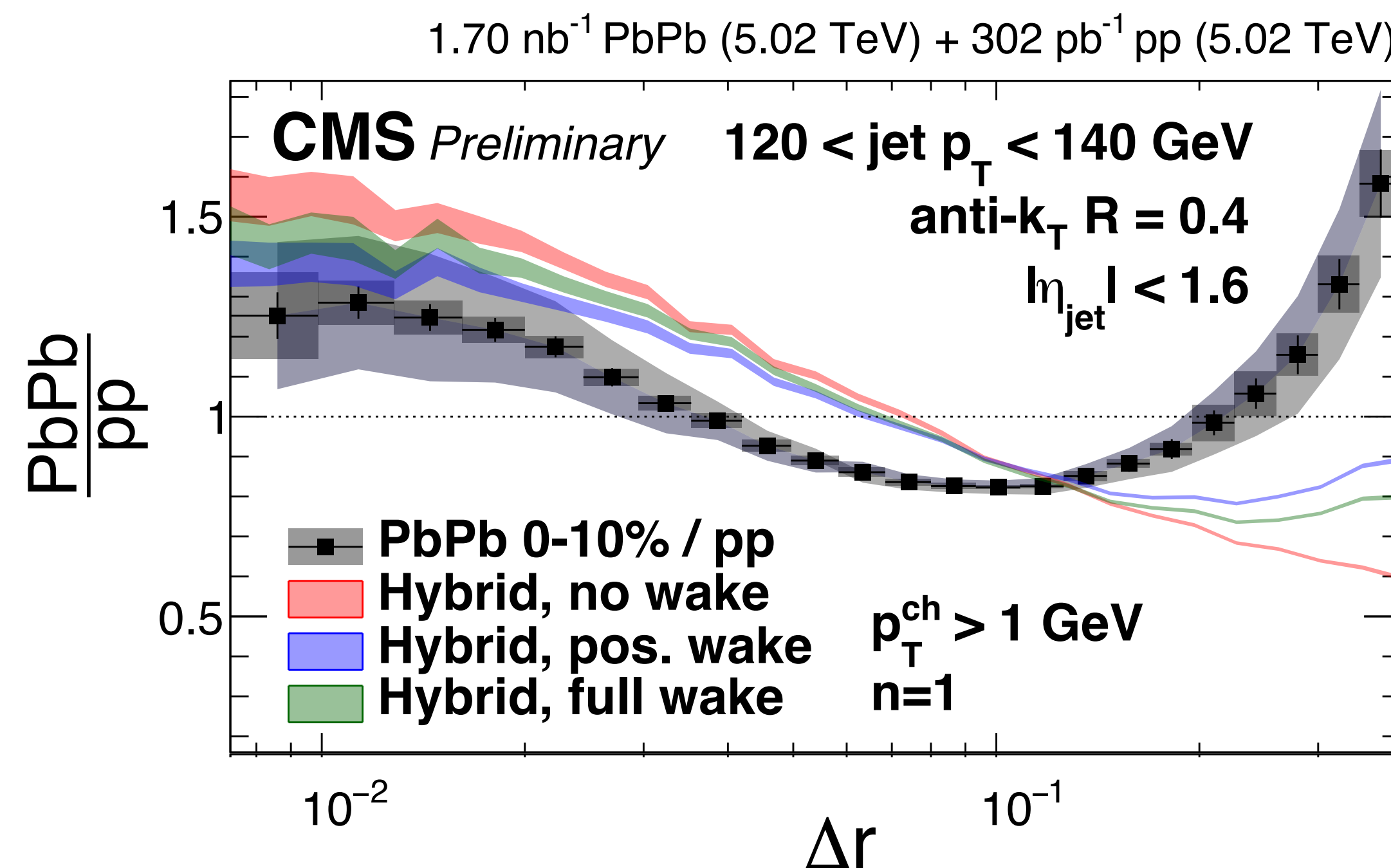
Jets offer a way to characterize bulk matter as probes with perturbative control

What can we learn from **jet based ENC**s in HICs ?



*The OPE limit of
ENCs in HICs*

What can we learn from **jet based ENC**s in HICs ?



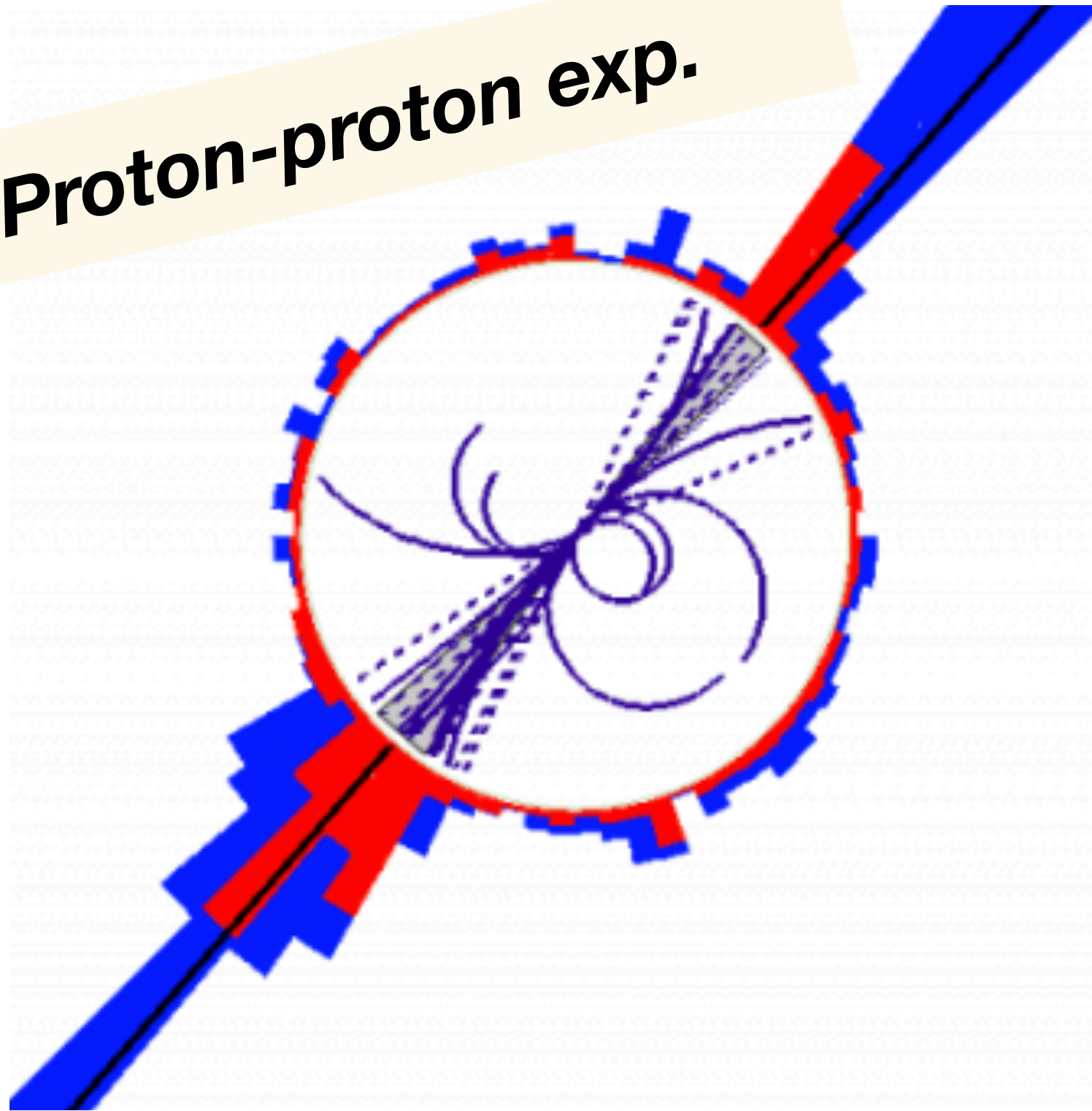
*The OPE limit of
ENCs in HICs*

*Track functions and jet
modifications*

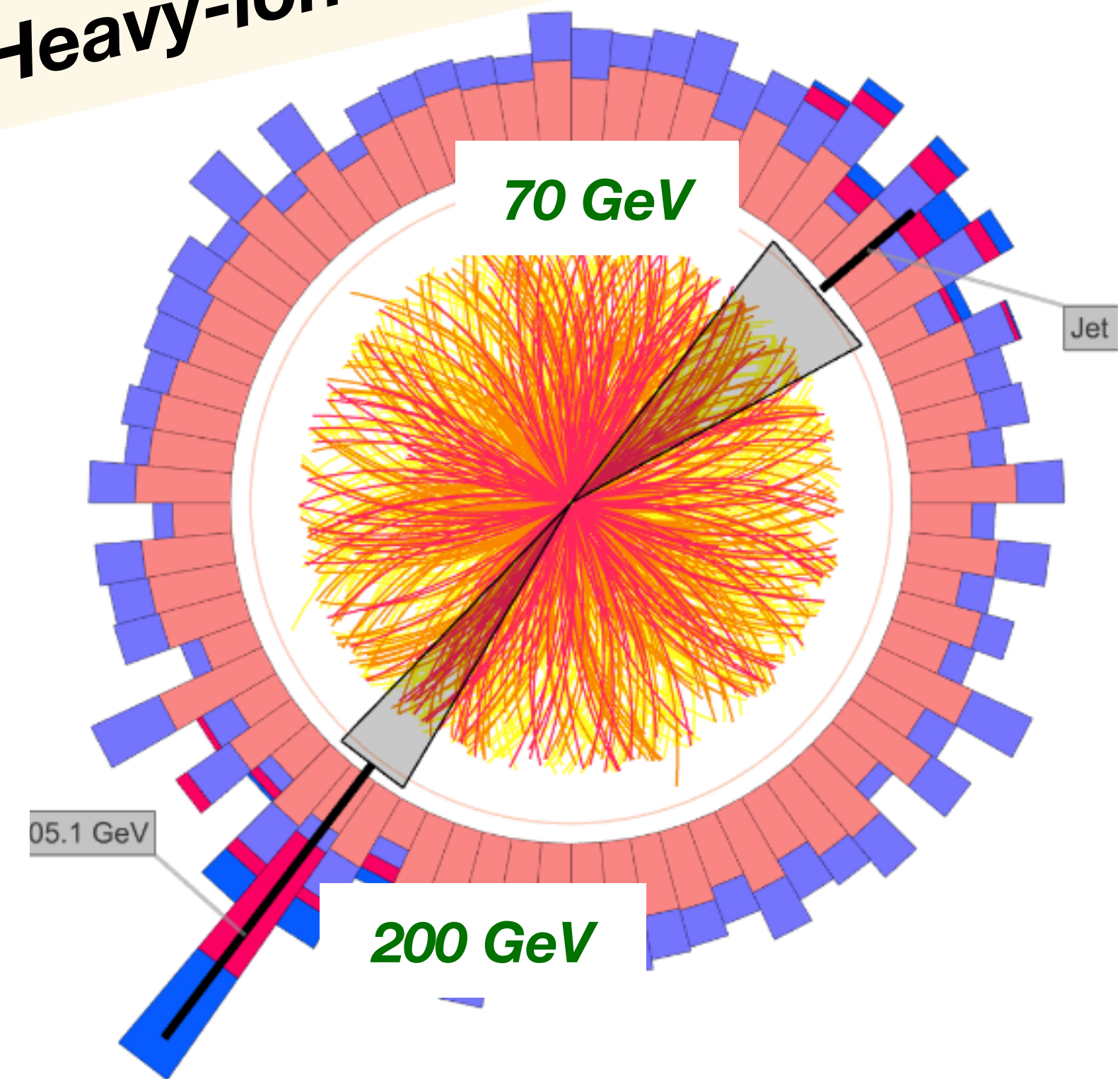
*Structure of QCD
matter from ENC*

Probing heavy ions collisions using jets

Proton-proton exp.



Heavy-ion exp.



Probing heavy ions collisions using jets

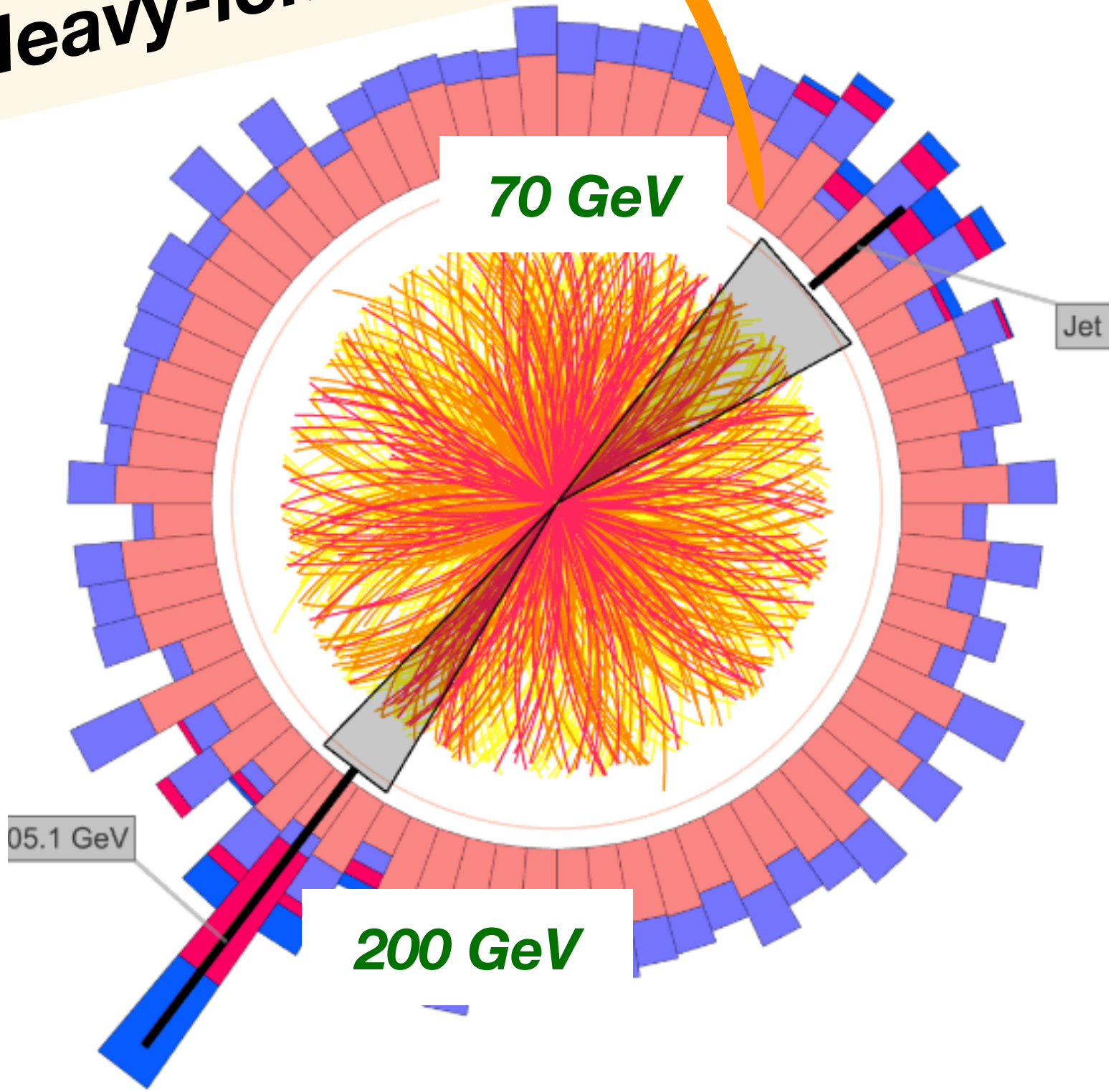
Initial blue quark

Final red quark

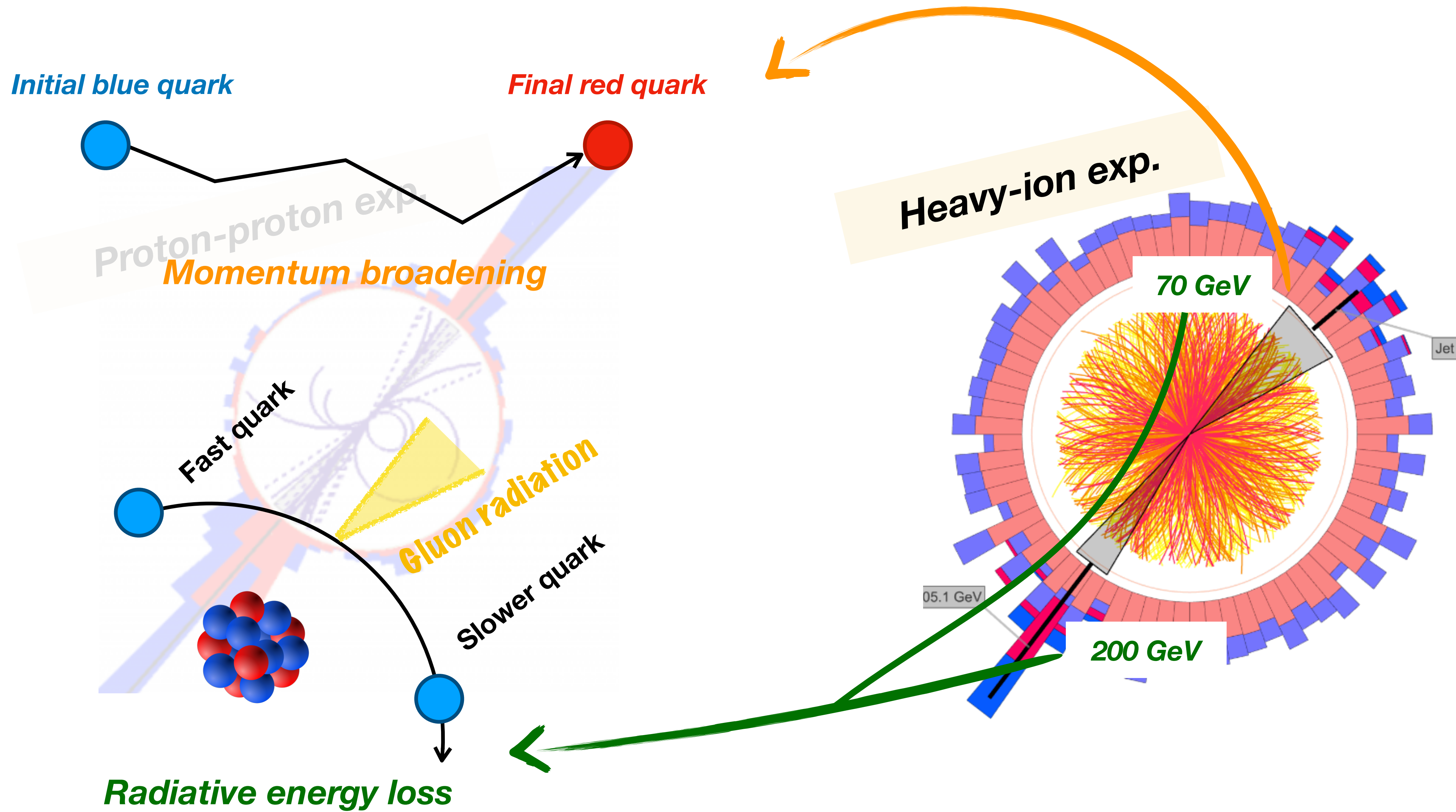


Momentum broadening

Heavy-ion exp.

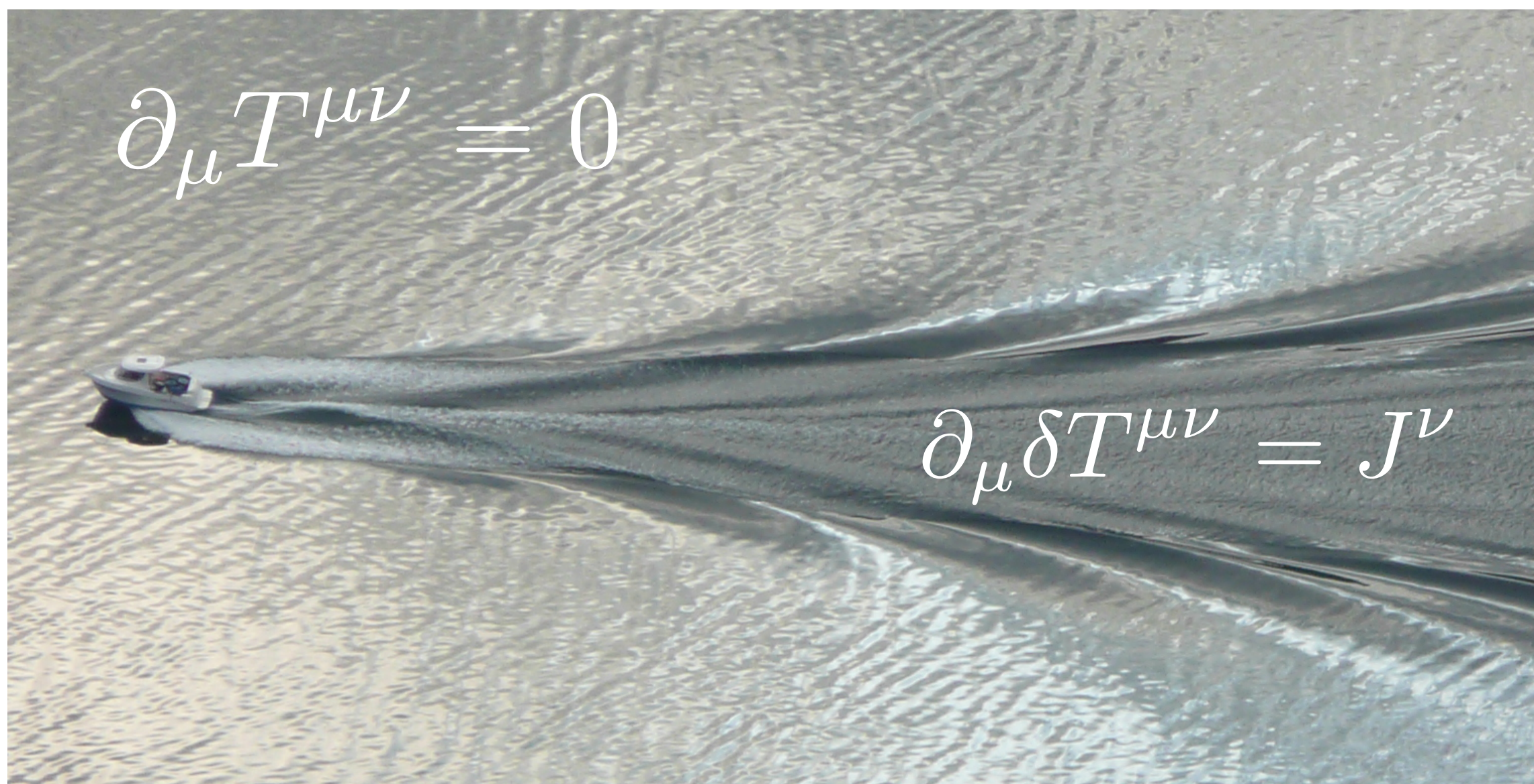


Probing heavy ions collisions using jets



Probing heavy ions collisions using jets

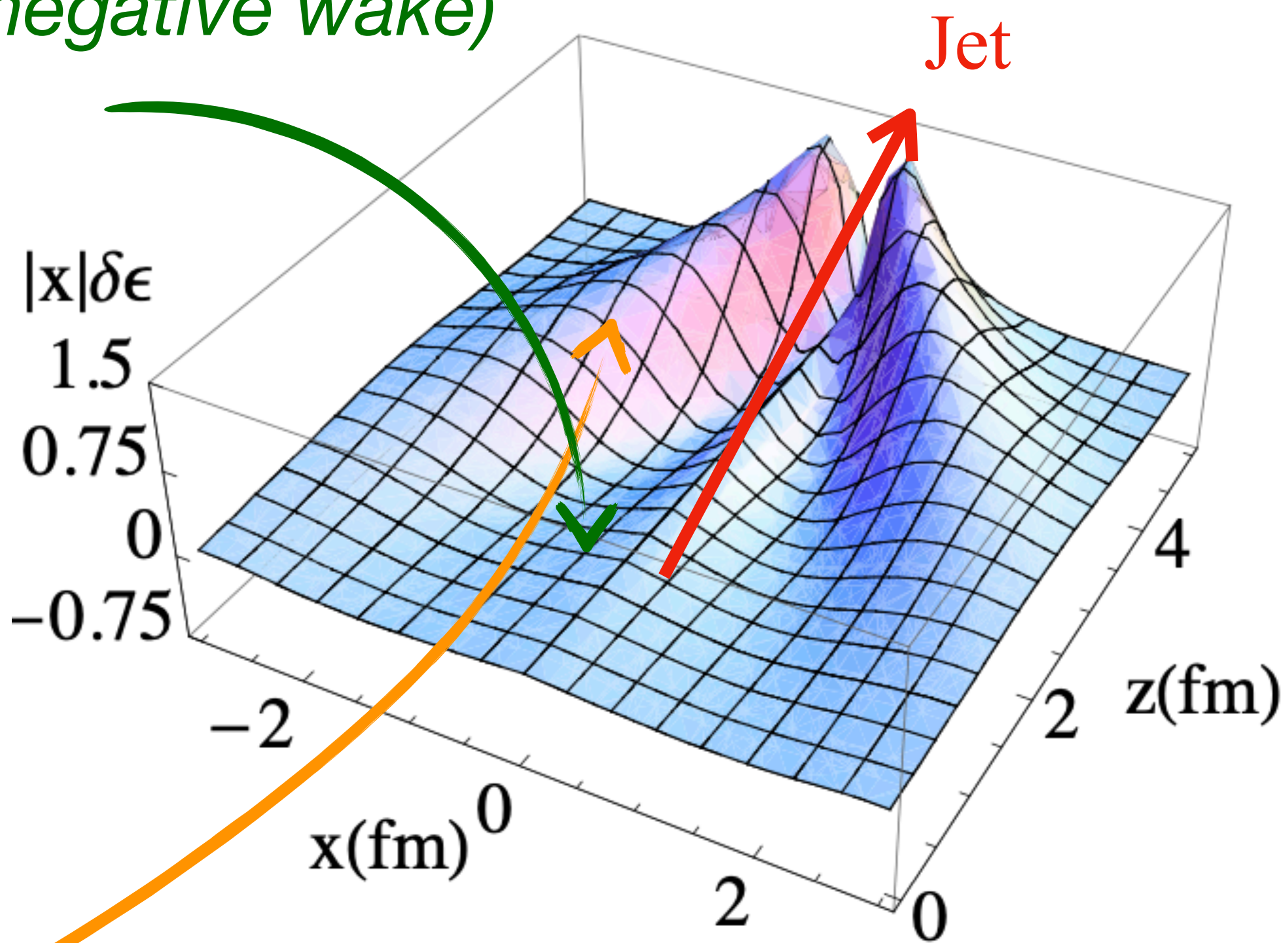
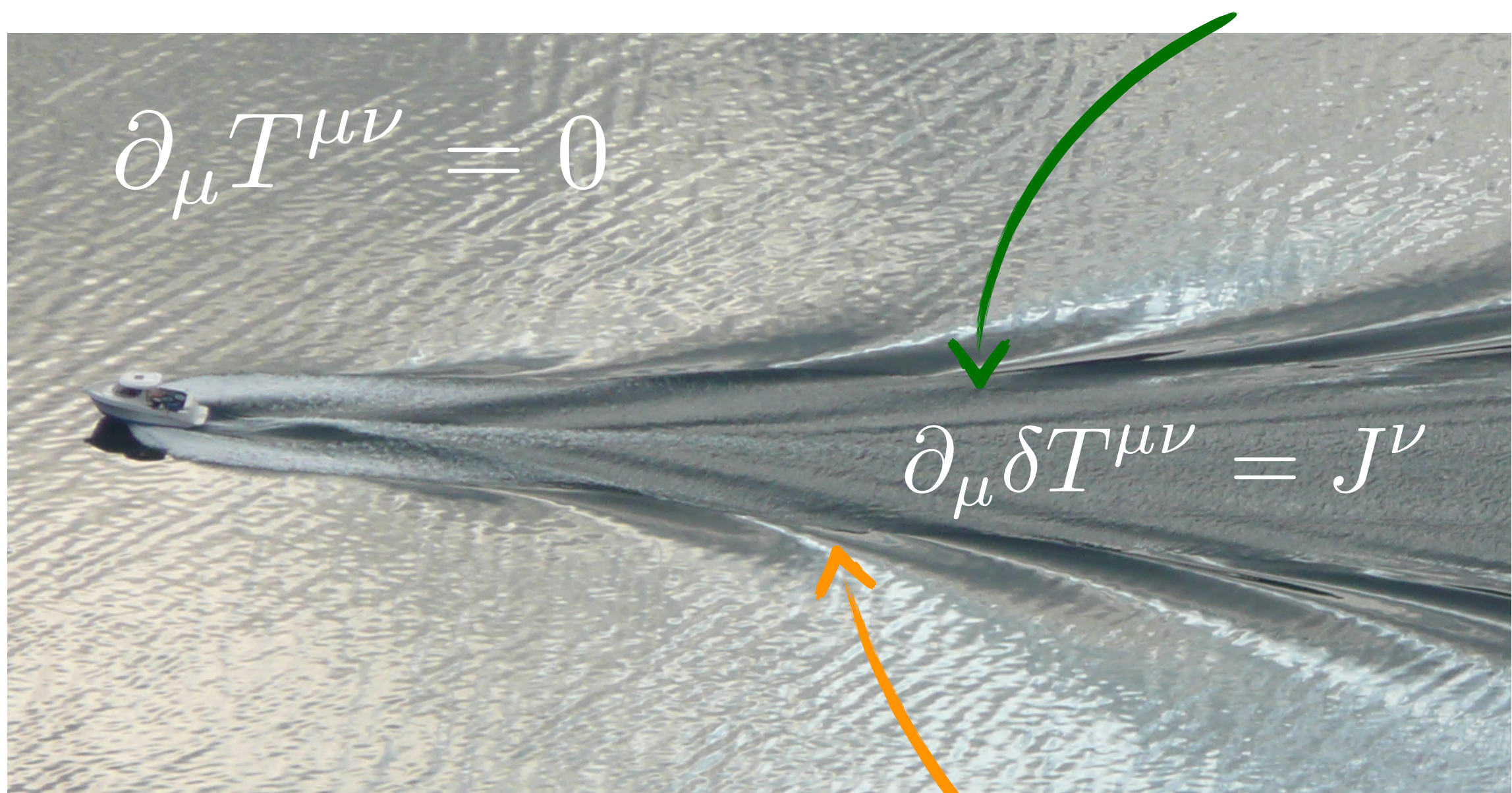
Jets *evolve on top of a bulk* which backreacts; this can inform about *dynamical properties of matter*



Probing heavy ions collisions using jets

Jets *evolve on top of a bulk* which backreacts; this can inform about *dynamical properties of matter*

Depletion of particles (negative wake)

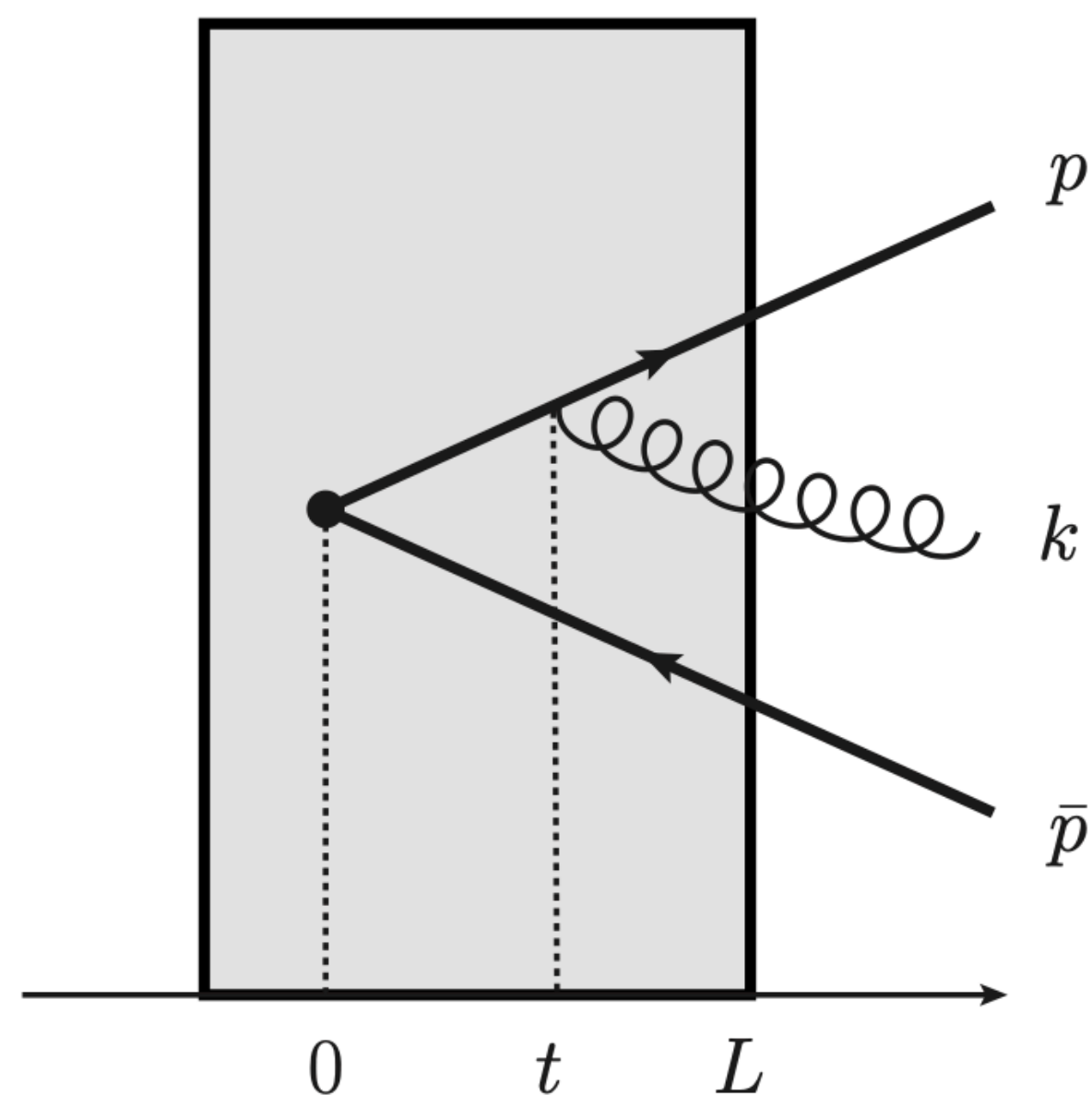


Mach cone structure [G.-Y. Qin, A. Majumder, H. Song, U. Heinz, 0903.22255]

Probing heavy ions collisions using jets

Breaking of angular ordering and evolution of color antennas has been widely explored

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



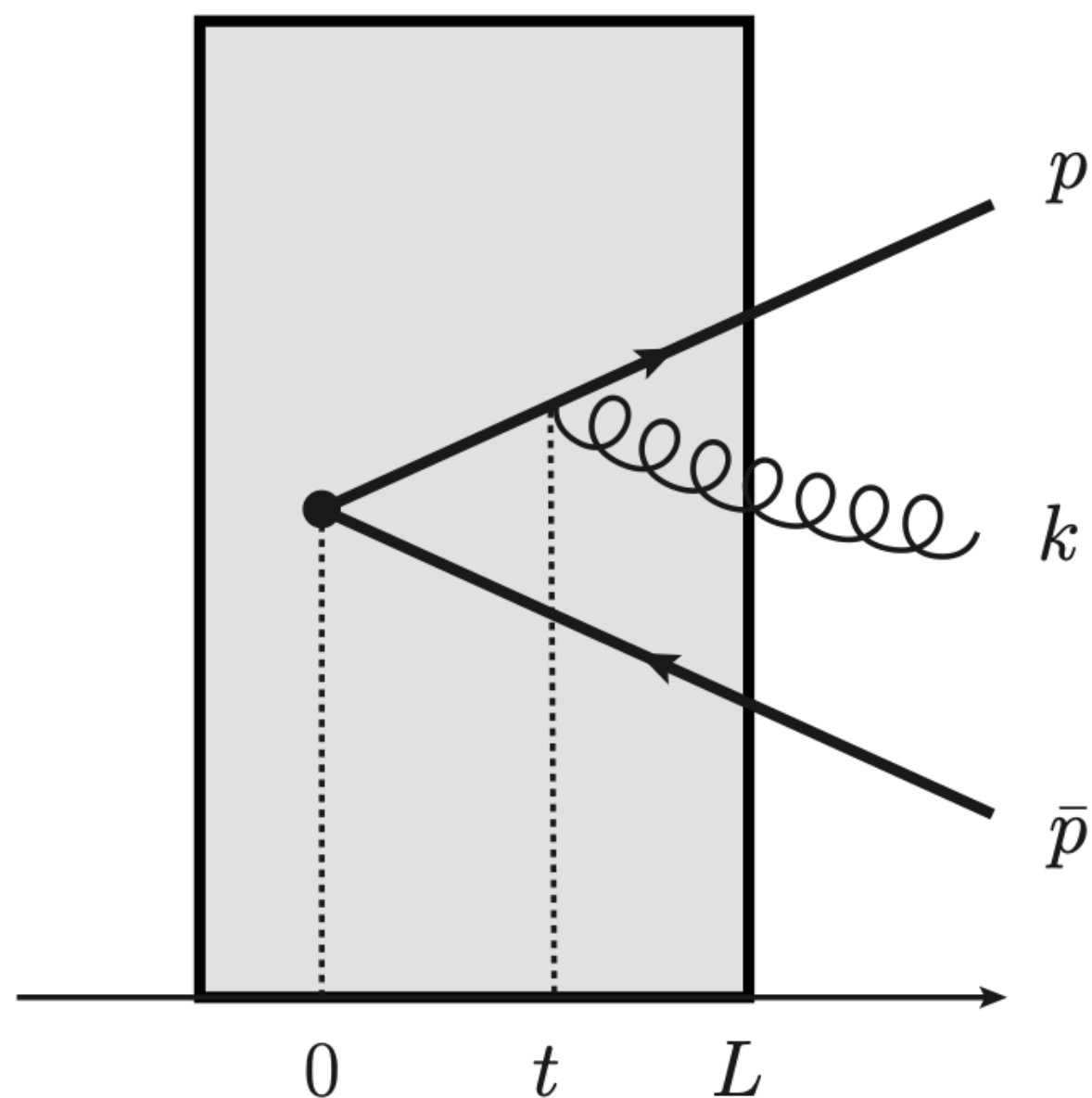
vacuum $\longrightarrow$ **angular ordering**

medium $\longrightarrow$ **“anti-angular ordering”**

Probing heavy ions collisions using jets

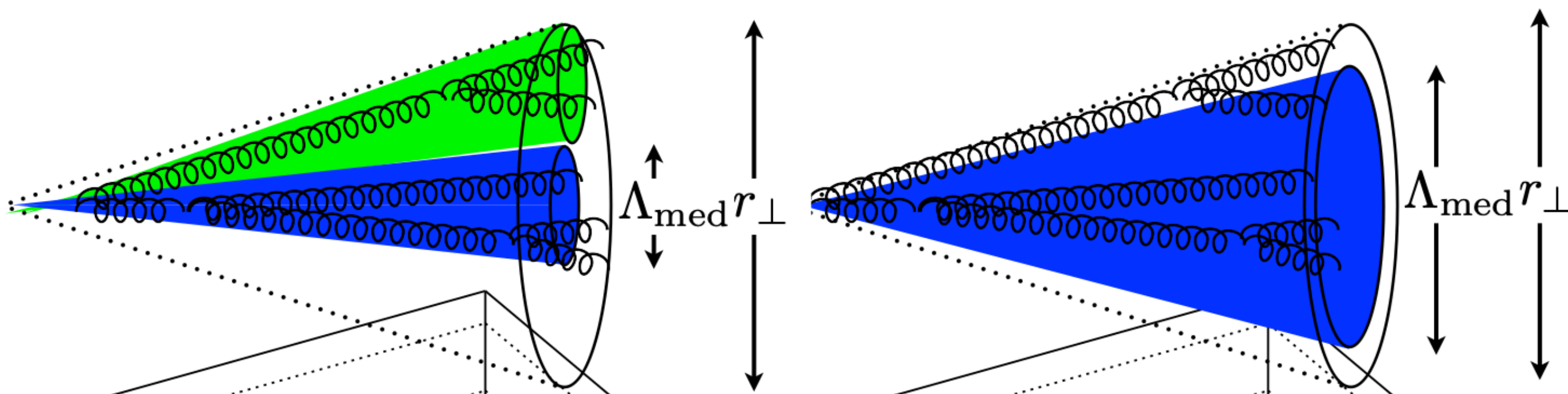
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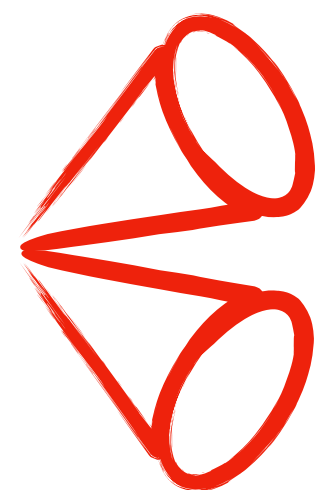


vacuum $\longrightarrow$ **angular ordering**

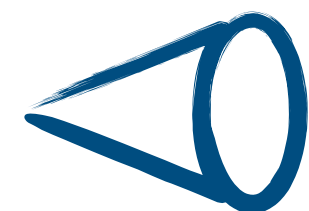
medium $\longrightarrow$ **“anti-angular ordering”**



“Two pronged”



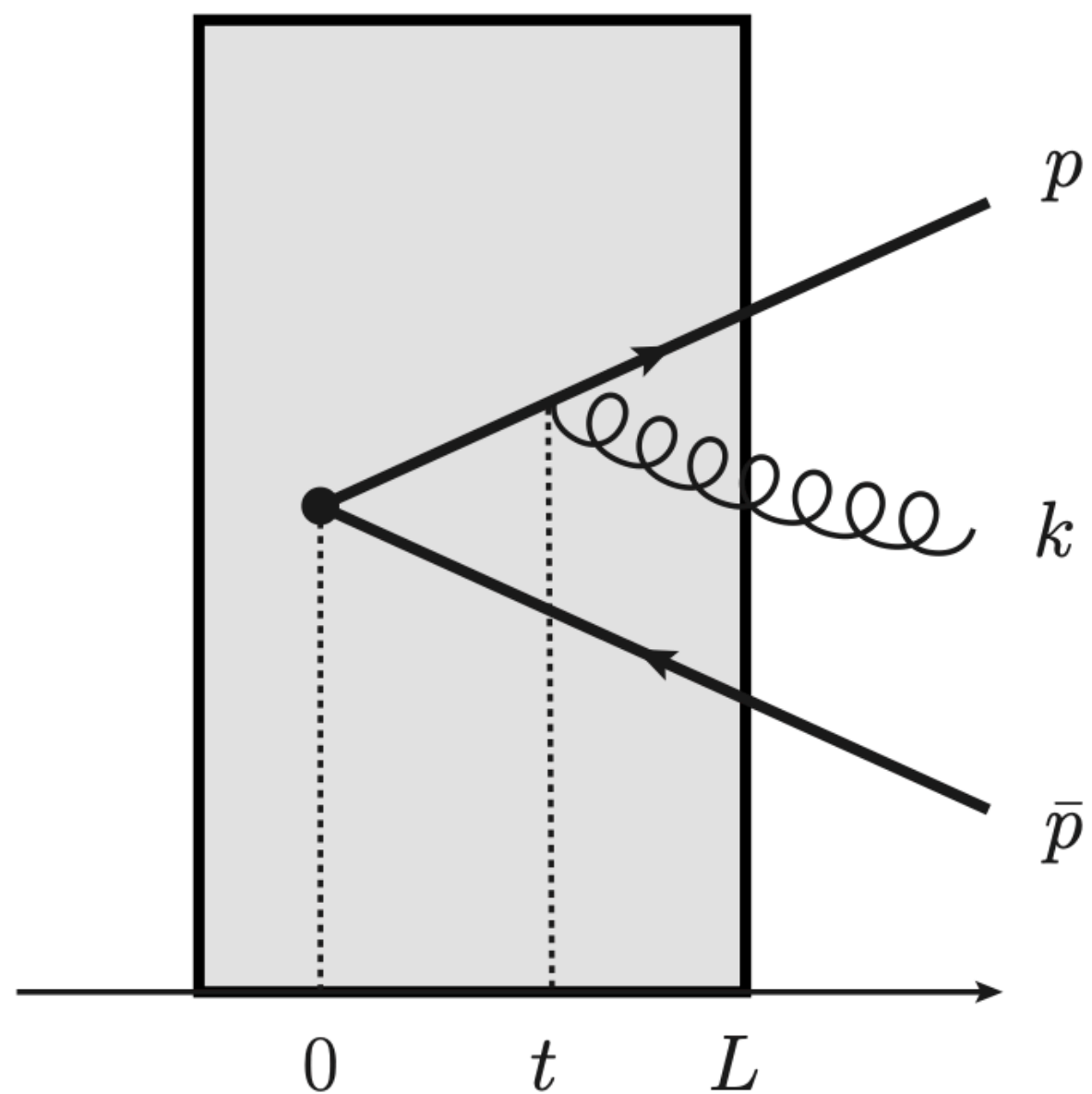
“One prong”



Probing heavy ions collisions using jets

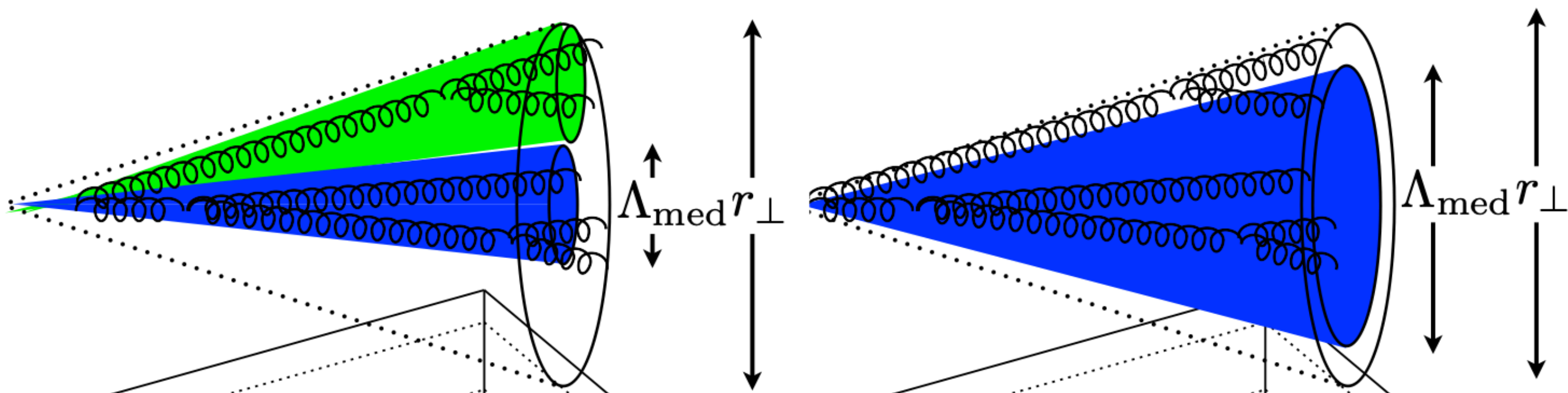
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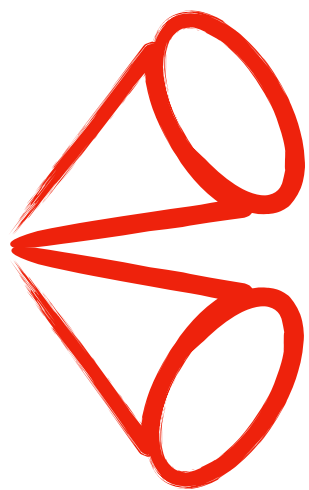


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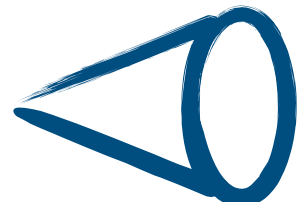
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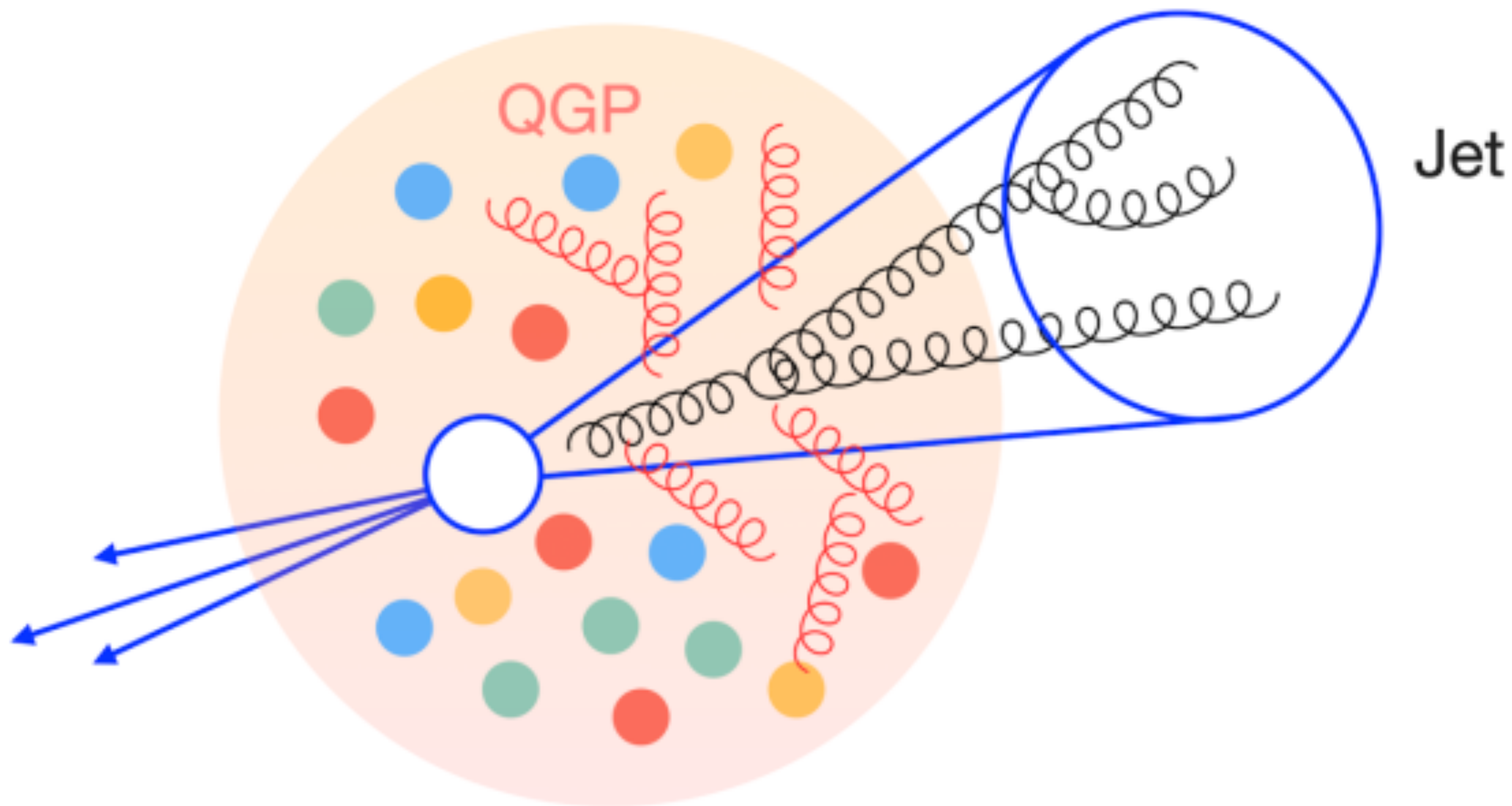
“One prong”



Observing this pattern gives evidence for Λ_{med}

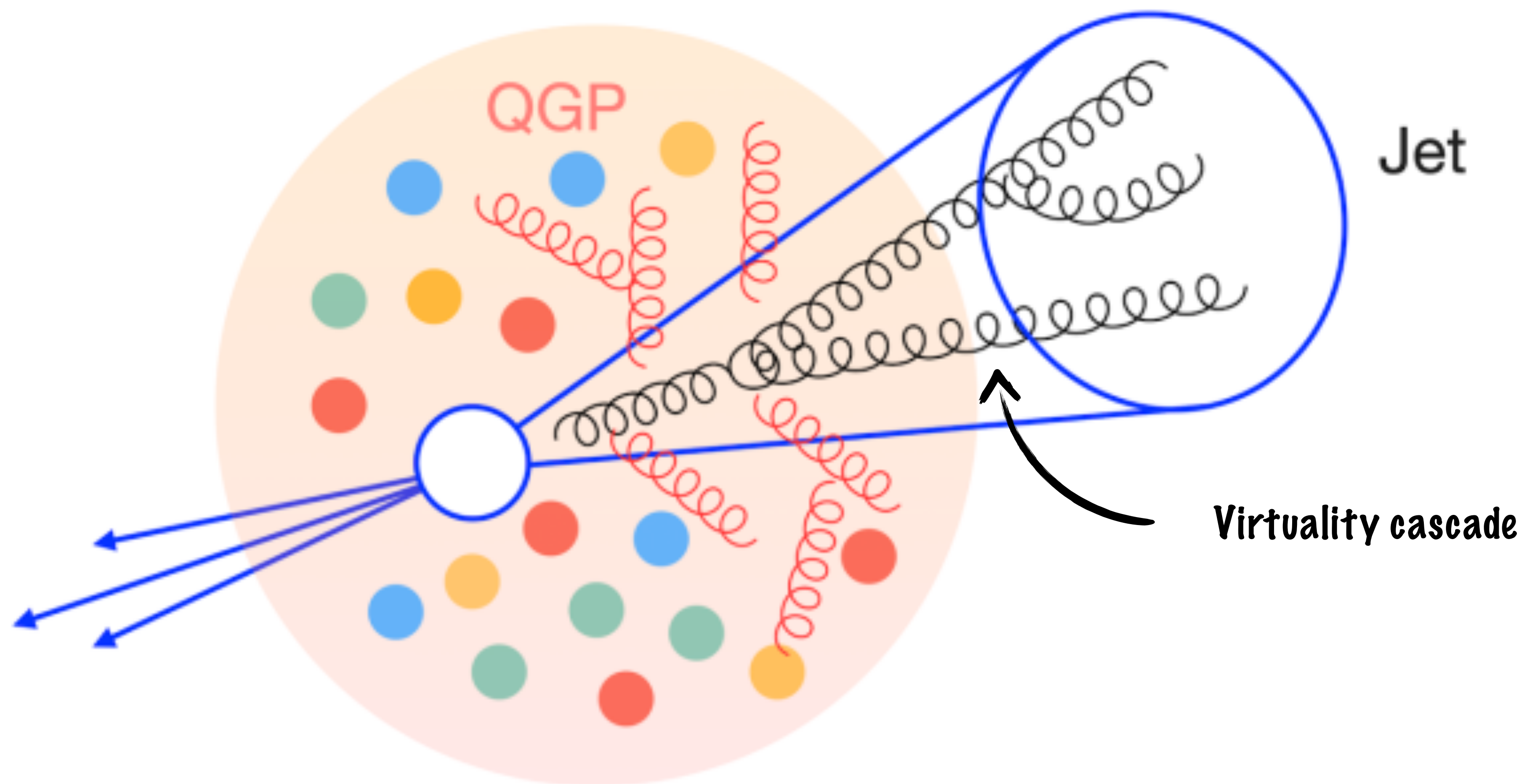
Probing heavy ions collisions using jets

In summary, the **current picture of jet evolution in the HICs** looks something like this:



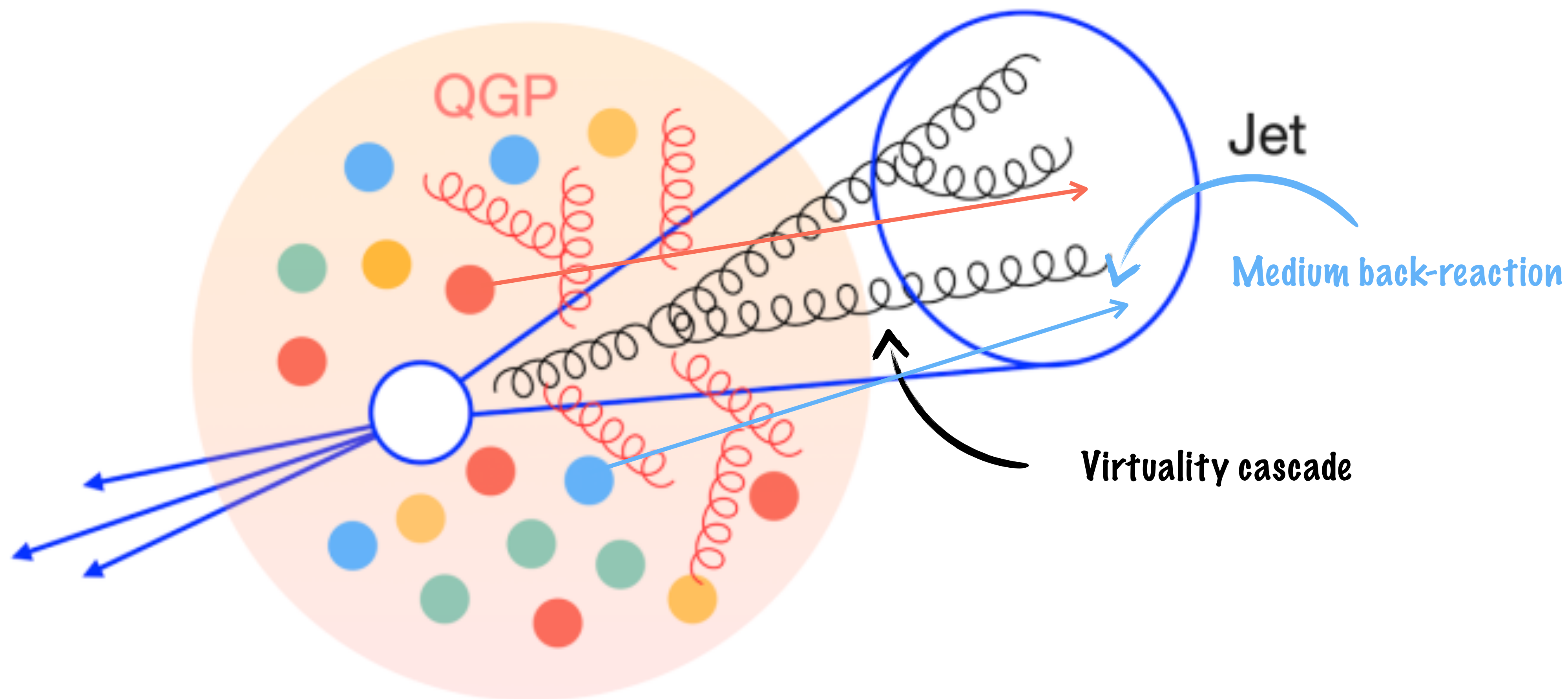
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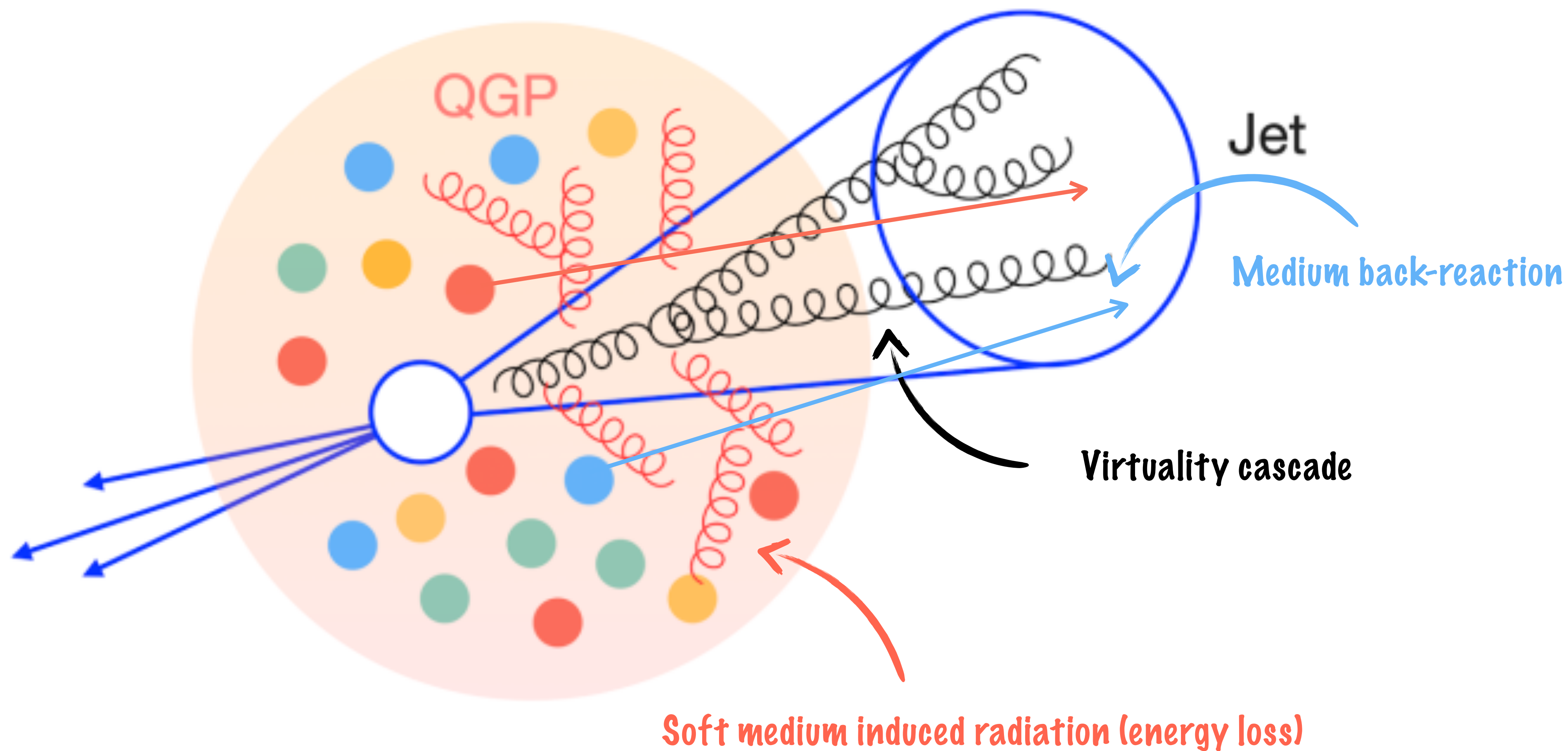
Probing heavy ions collisions using jets

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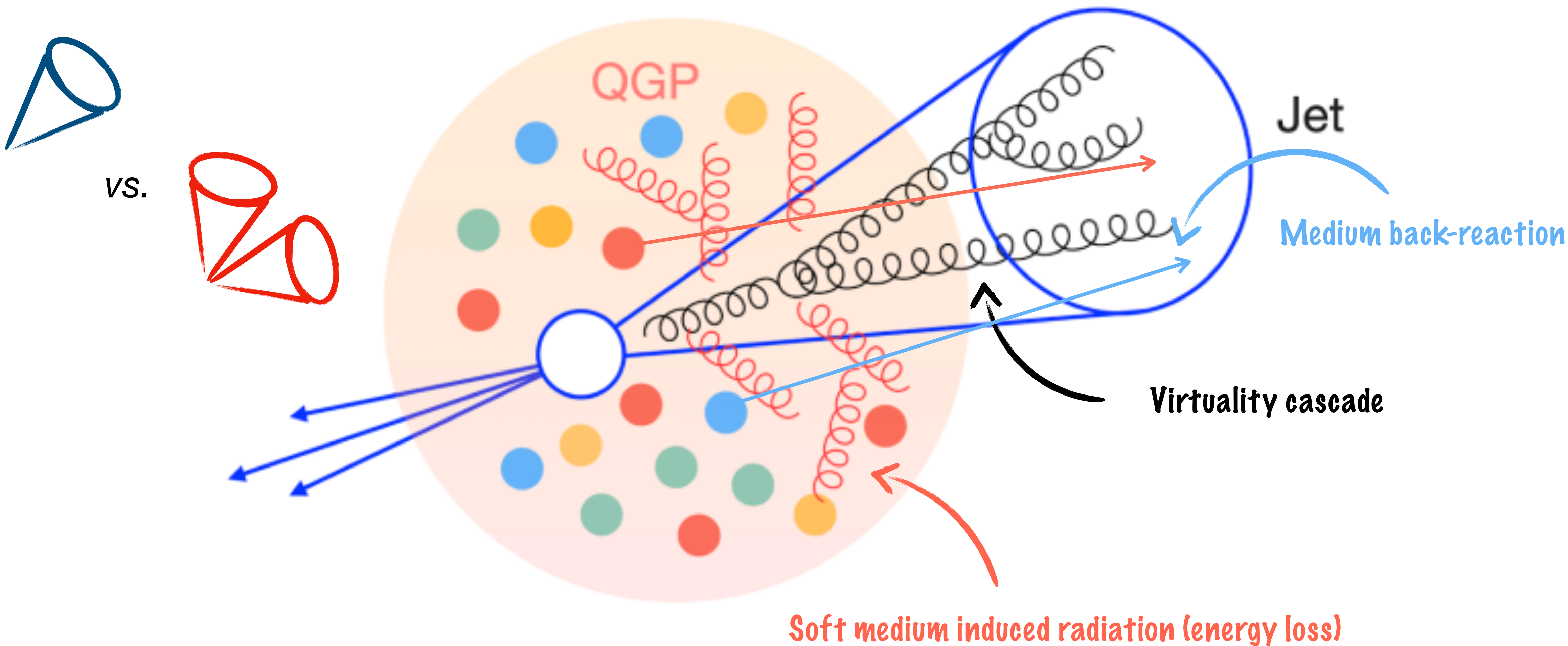
Probing heavy ions collisions using jets

In summary, the **current picture of jet evolution in the HICs** looks something like this:



Probing heavy ions collisions using jets

In summary, the **current picture of jet evolution in the HICs** looks something like this:



Energy correlators (ENCs) were first proposed in QCD in the late 1970s

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

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

■ N-particle cross-section

■ Energy weighting

2-point correlator

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

■ Restricted angular region

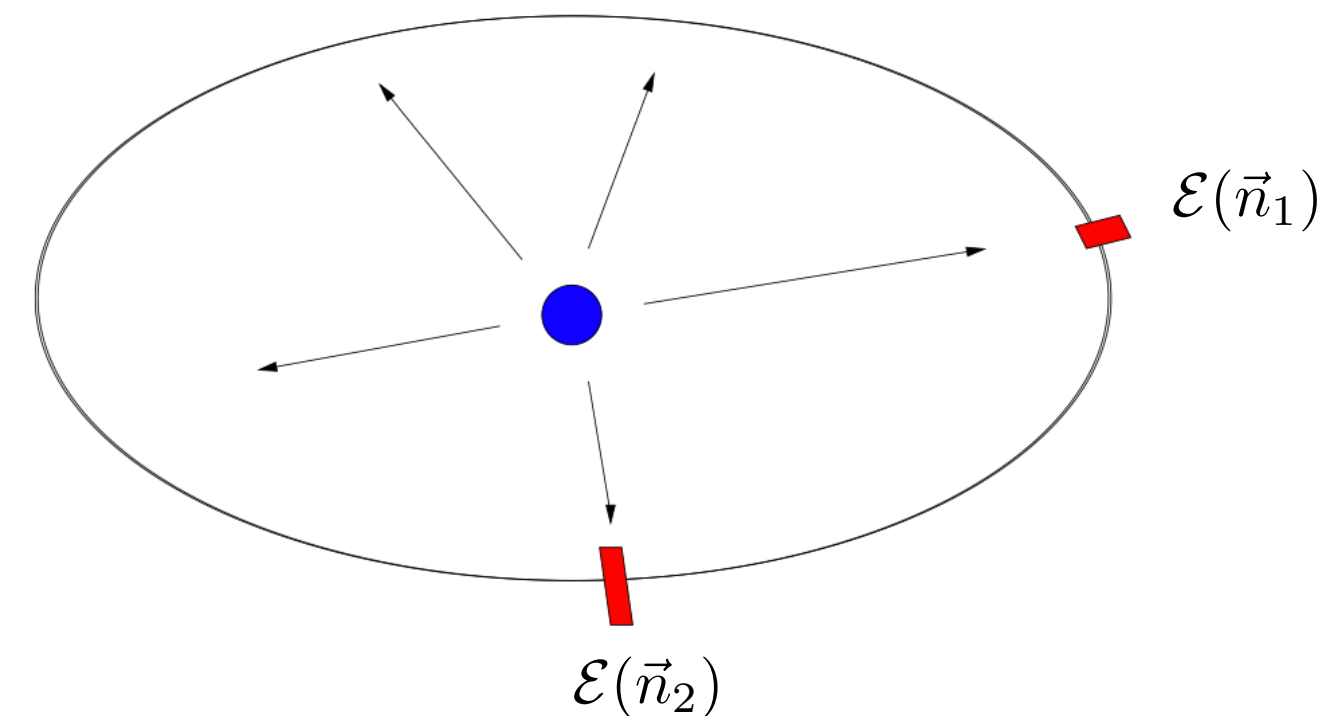
■ Form pairs out of N partons

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

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

$$\mathcal{E}(\vec{n}) = \lim_{r \rightarrow \infty} \int dt r^2 n^i T^{0i}(t, r \vec{n})$$

$$\langle 0 | J^\dagger \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) J | 0 \rangle$$



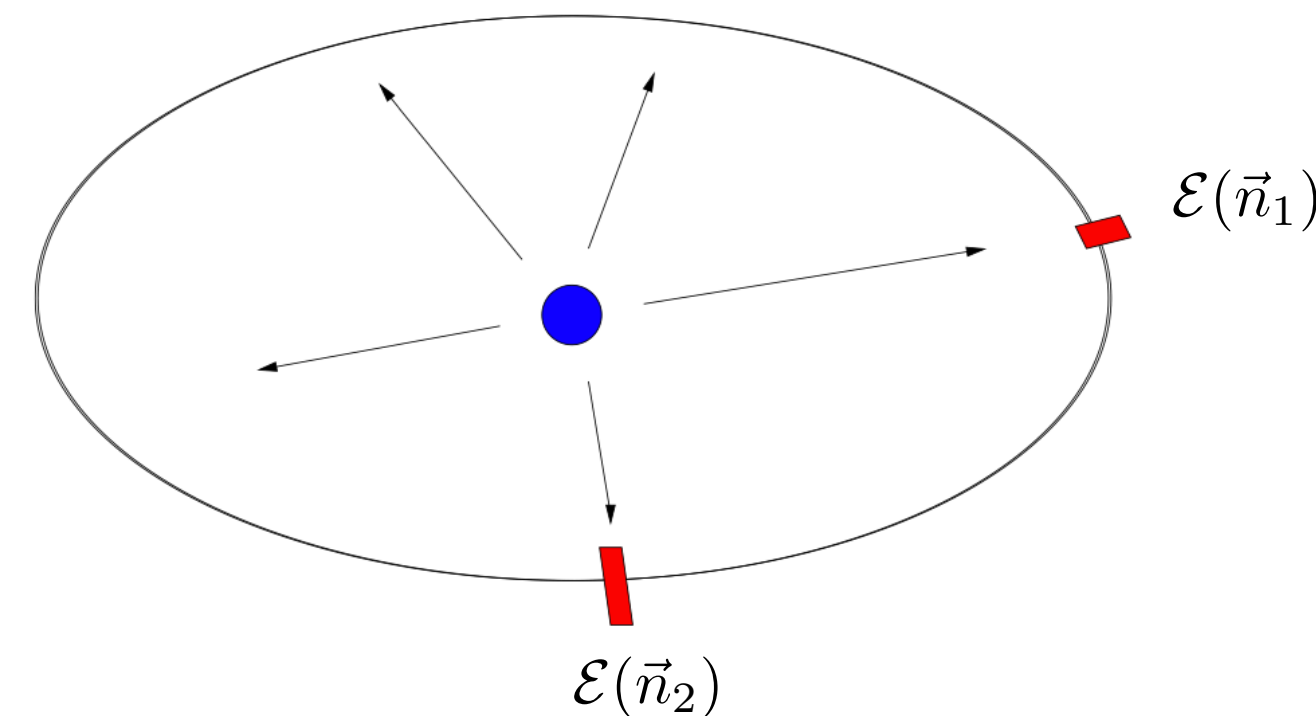
Properties of light-ray operators widely studied in CFTs

[see next talk by H. Chen]

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Properties of light-ray operators widely studied in CFTs

[see next talk by H. Chen]

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

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

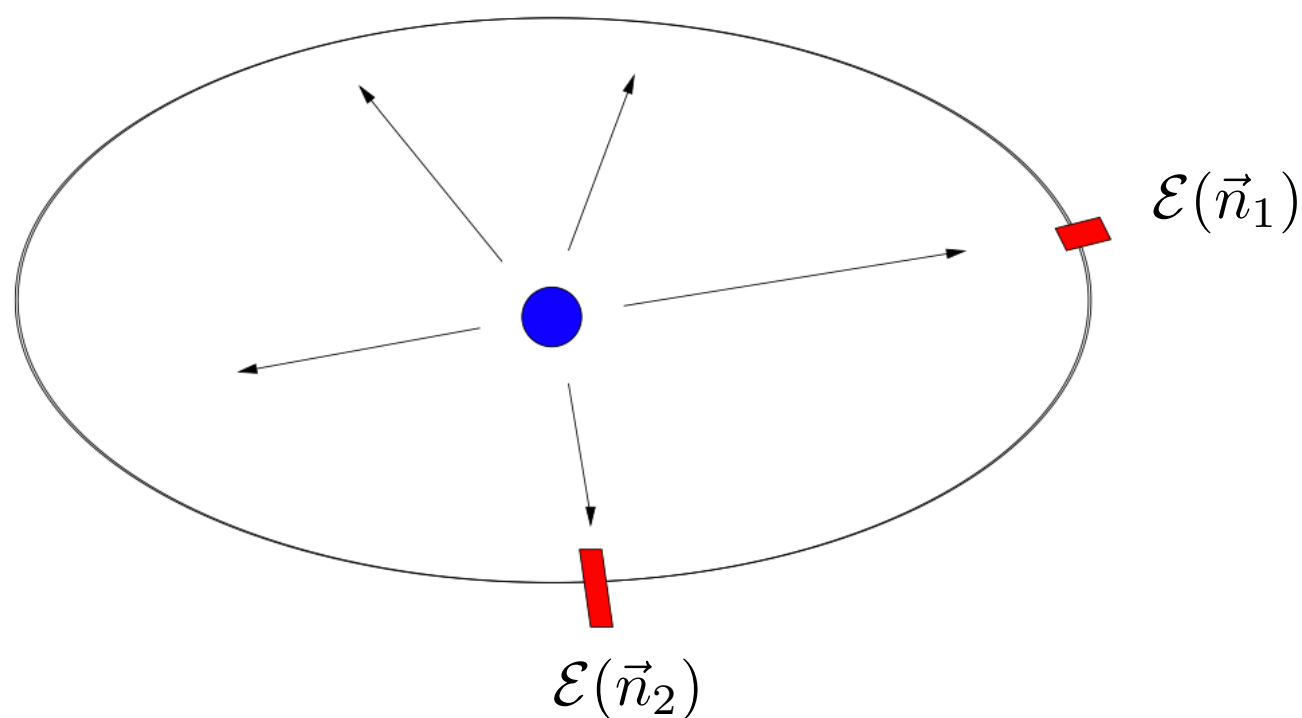
$\sim \frac{1}{\theta^\alpha}$
 at LO : $\alpha = 1$

deviations controlled by **anomalous scaling**

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

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Properties of light-ray operators widely studied in CFTs

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$$\frac{d\Sigma}{d\theta} = \int_z \frac{d\sigma}{\sigma d\theta dz} \underline{z(1-z)}$$

IR safe

??

$$(\text{HIC state}) \mathcal{E}(n_1) \mathcal{E}(n_2) \cdots \mathcal{E}(n_k) (\text{HIC state})$$

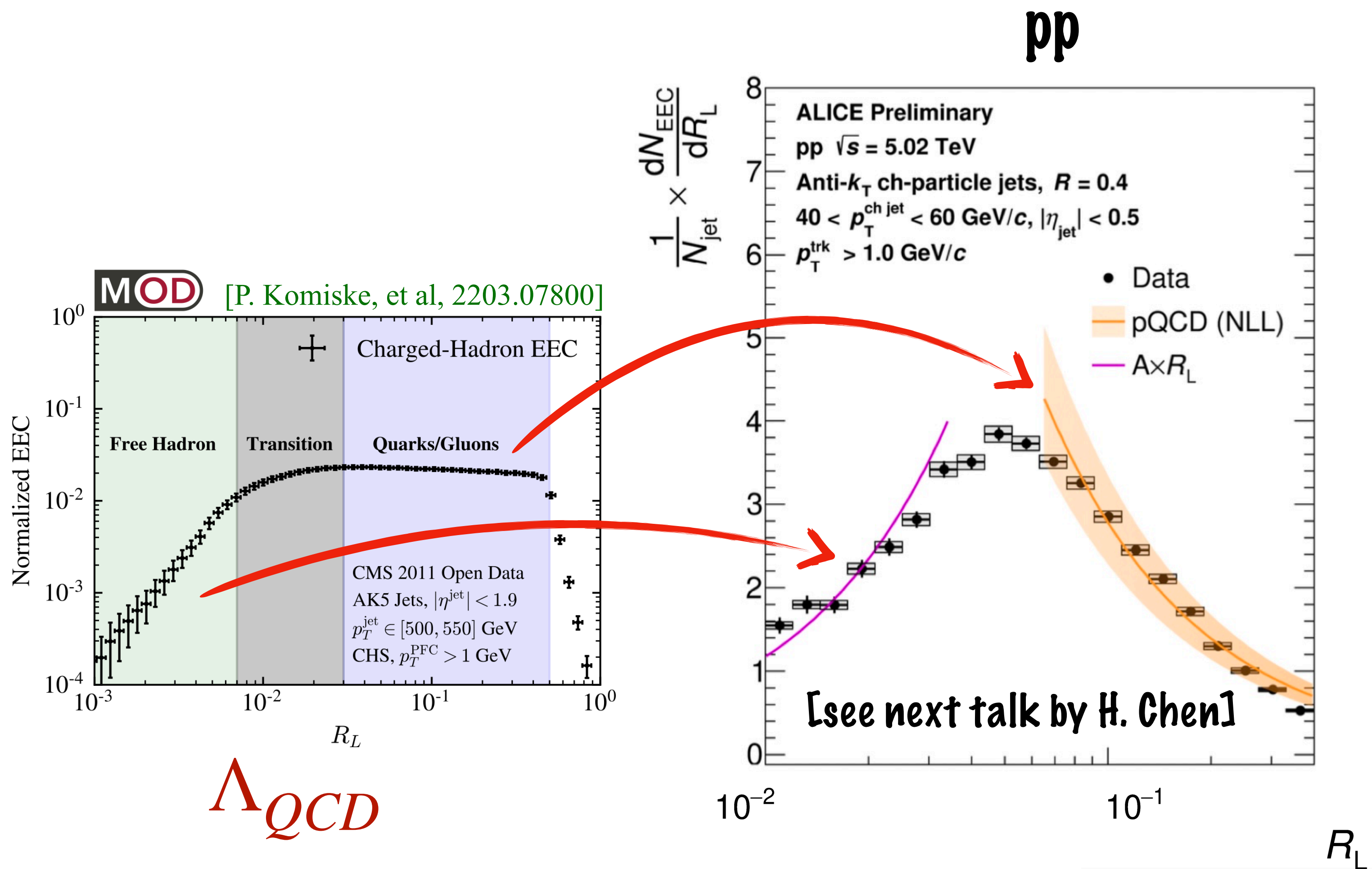
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deviations controlled by **anomalous scaling**

Energy correlators in HICs

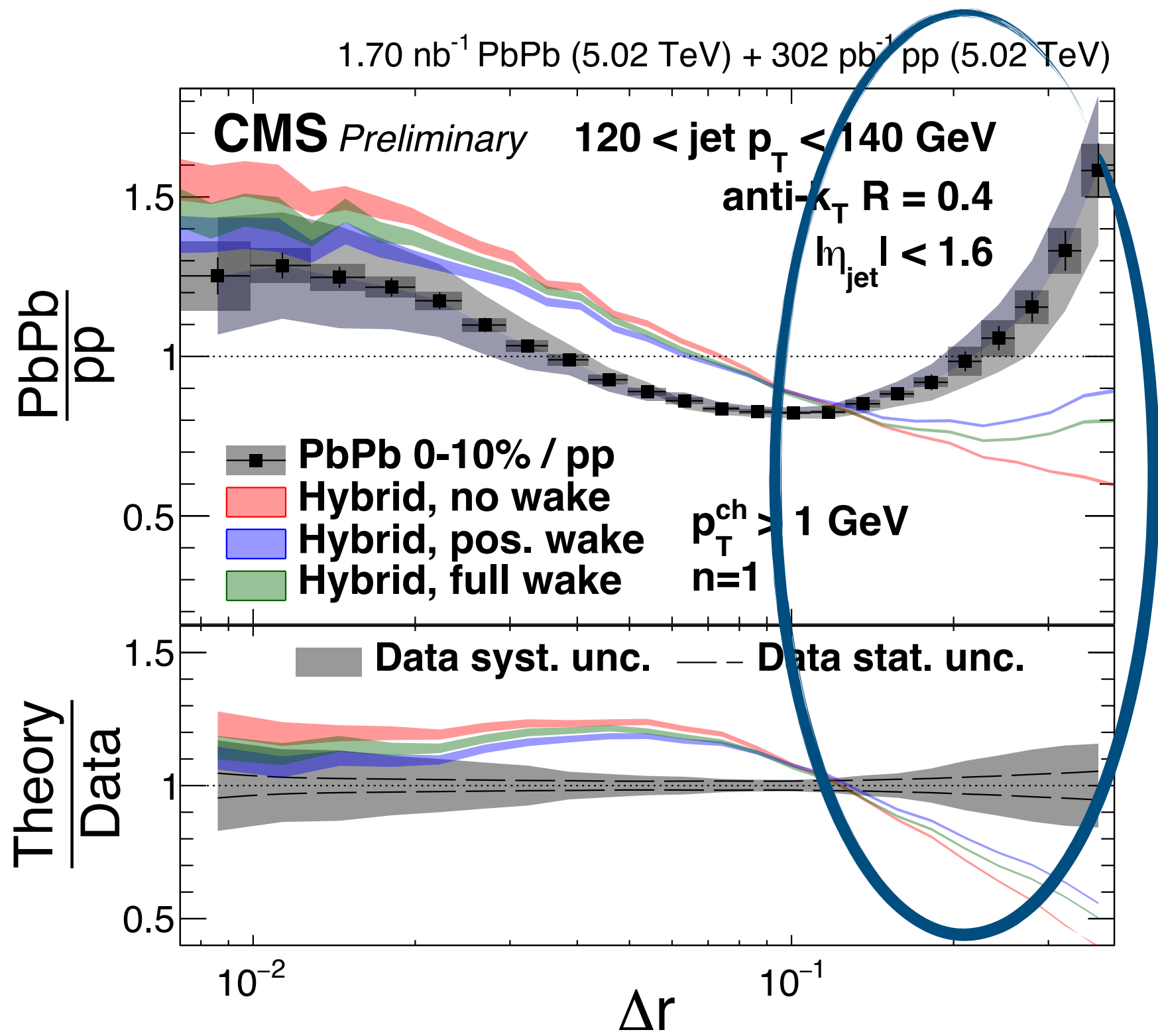
ENCs are of interest for HICs as they might allow to distinguish **new emergent scales**



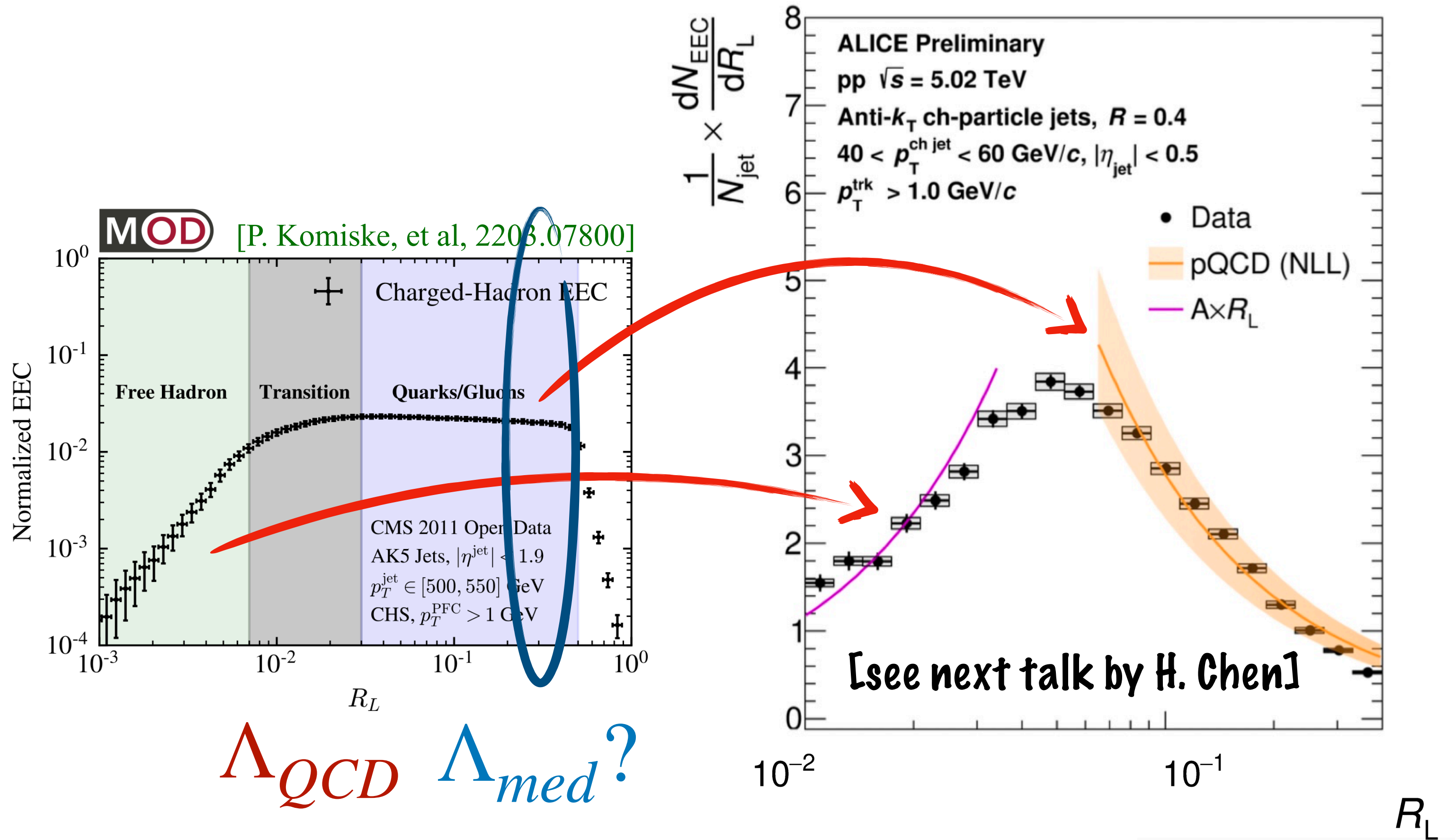
Energy correlators in HICs

ENCs are of interest for HICs as they might allow to distinguish *new emergent scales*

AA



pp



Let us consider first the EEC and include the perturbative corrections at leading accuracy

$$\frac{d\Sigma^{q \rightarrow qg}}{d\chi} \approx \frac{2\bar{\alpha}}{\chi} \int_0^1 dz \, z(1-z) P_{gq}(z) \left(\frac{1}{\chi^{\bar{\alpha}\gamma_{qq}(3)}} + F_{\text{med}}^{gq}(\chi, z) \right) Q_{qg}(p_t, \chi, z)$$

Resummation

Perturbative
medium correction

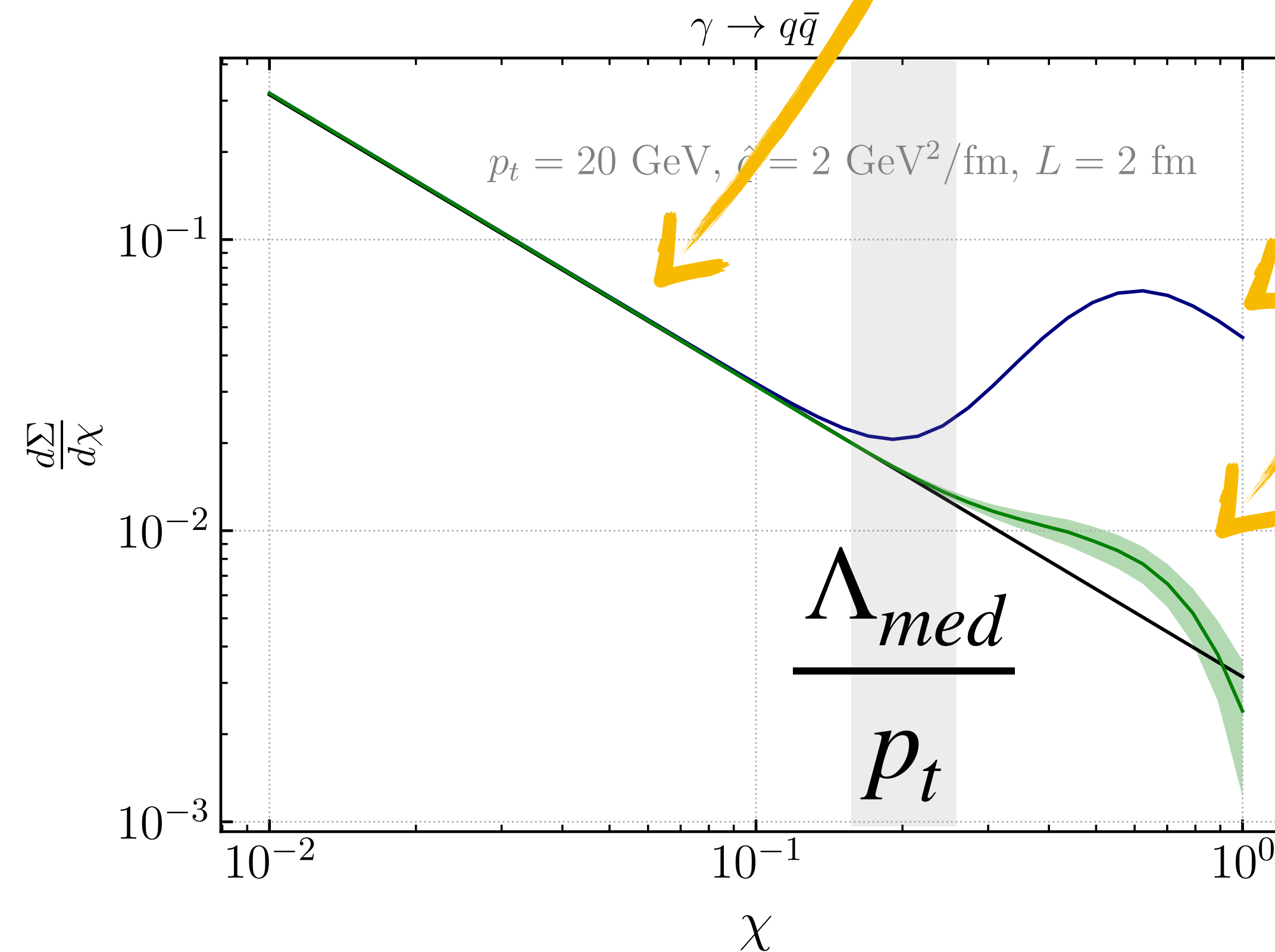
Energy loss
(non-perturbative)

Let us consider first the EEC and include the perturbative corrections at leading accuracy

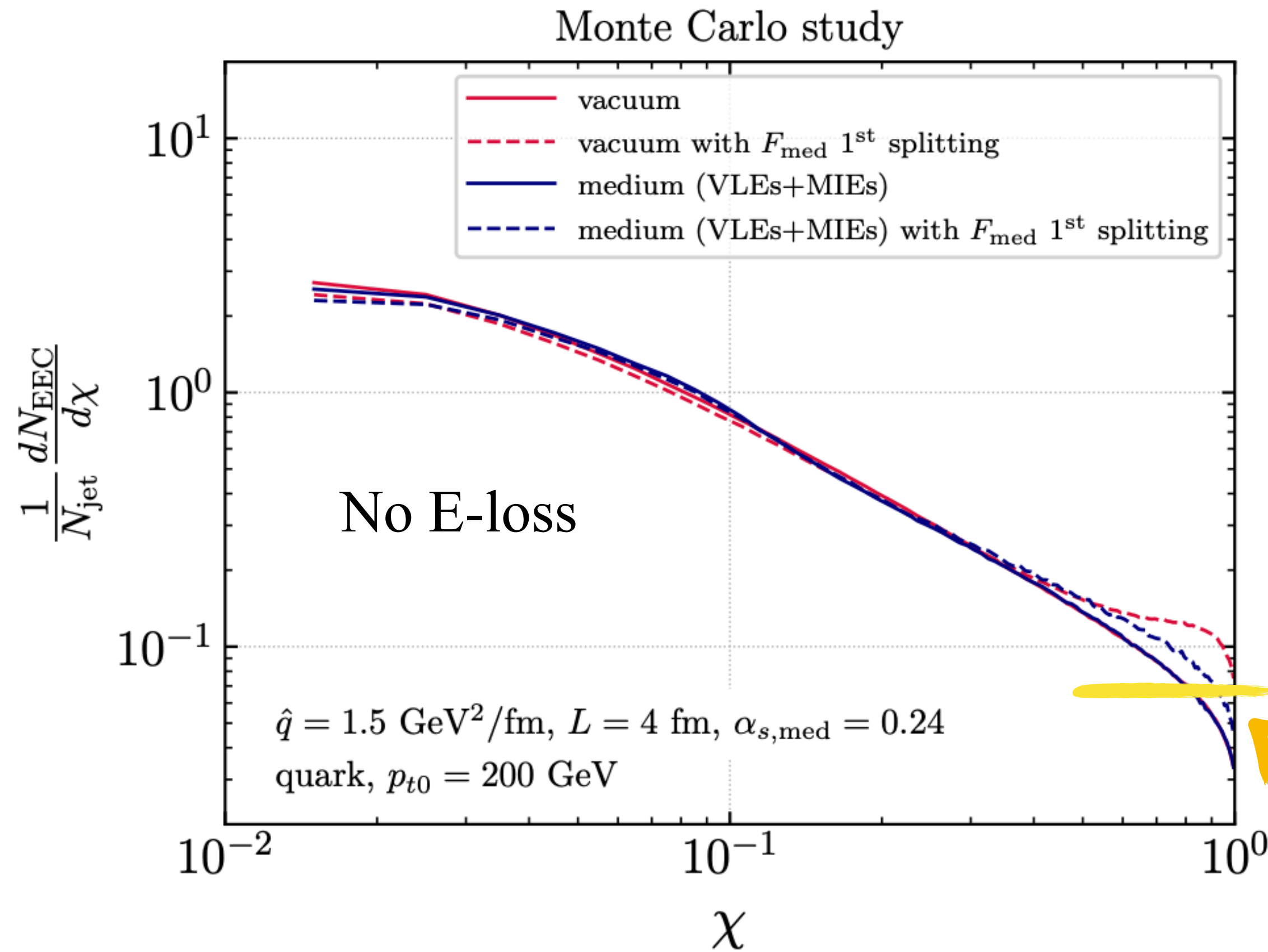
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Λ_{med}

is roughly indicated by
enhancement of large
angle sector

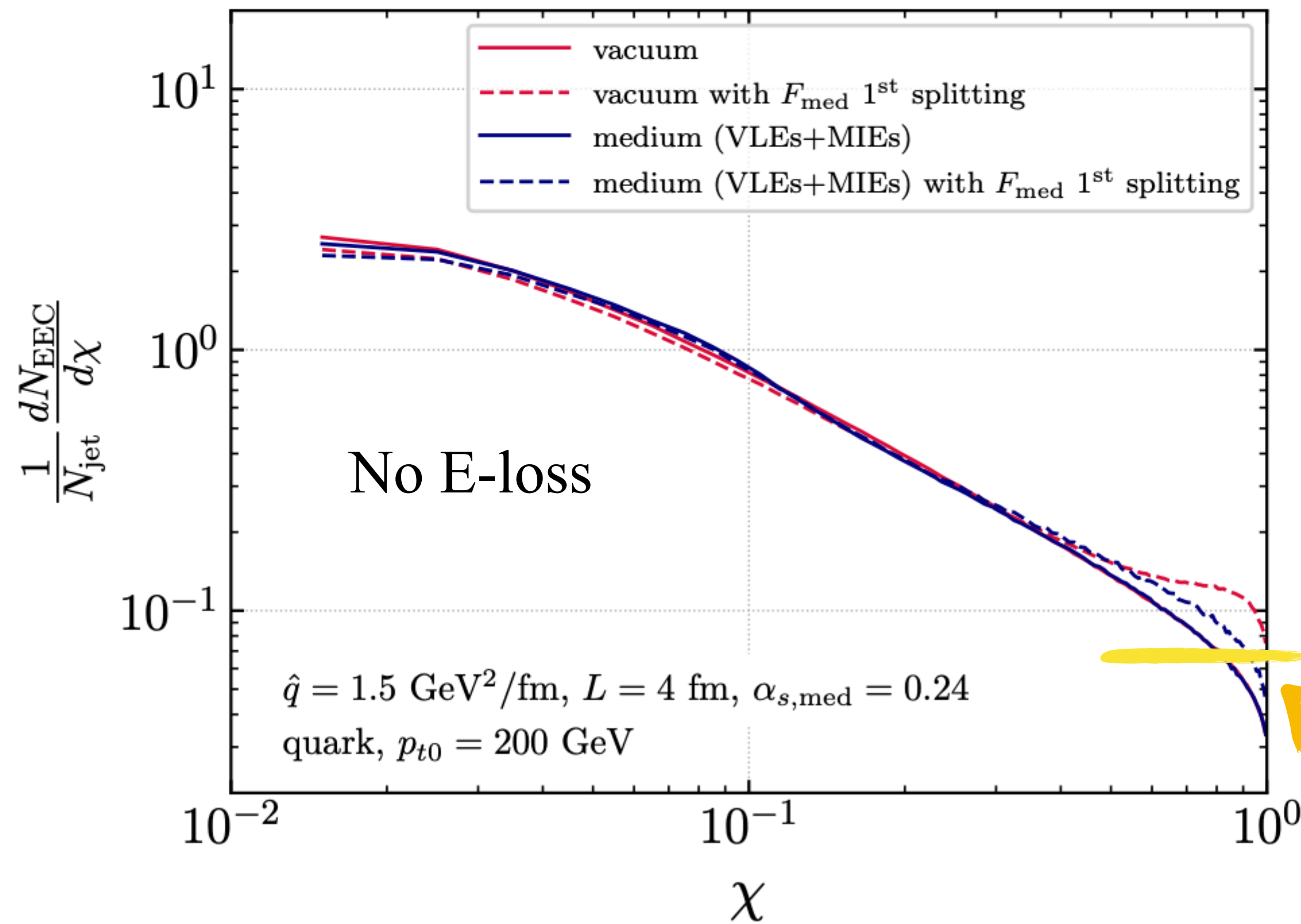


Uncertainties on LO matrix
element does not allow to fix
magnitude at this moment

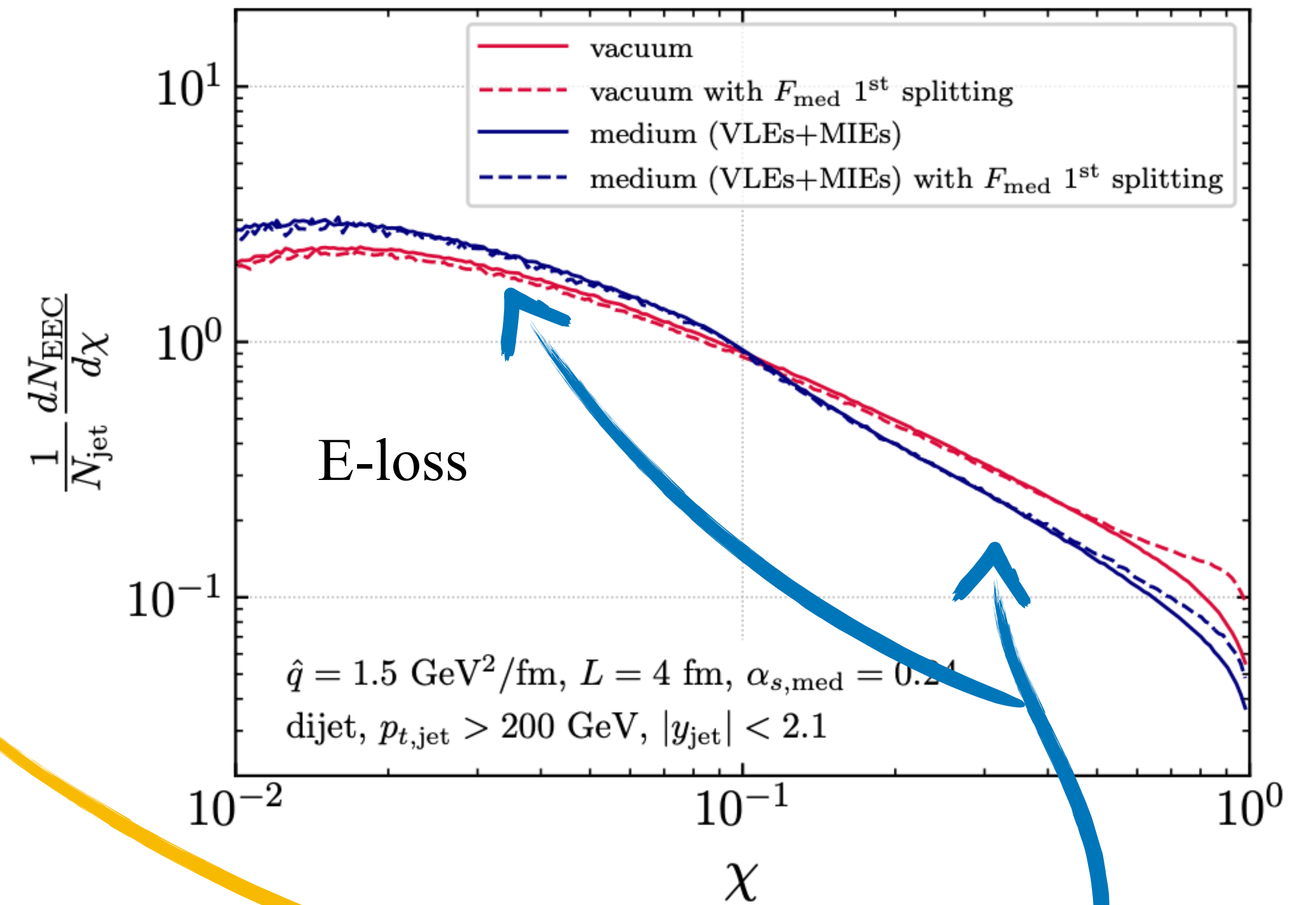


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Monte Carlo study

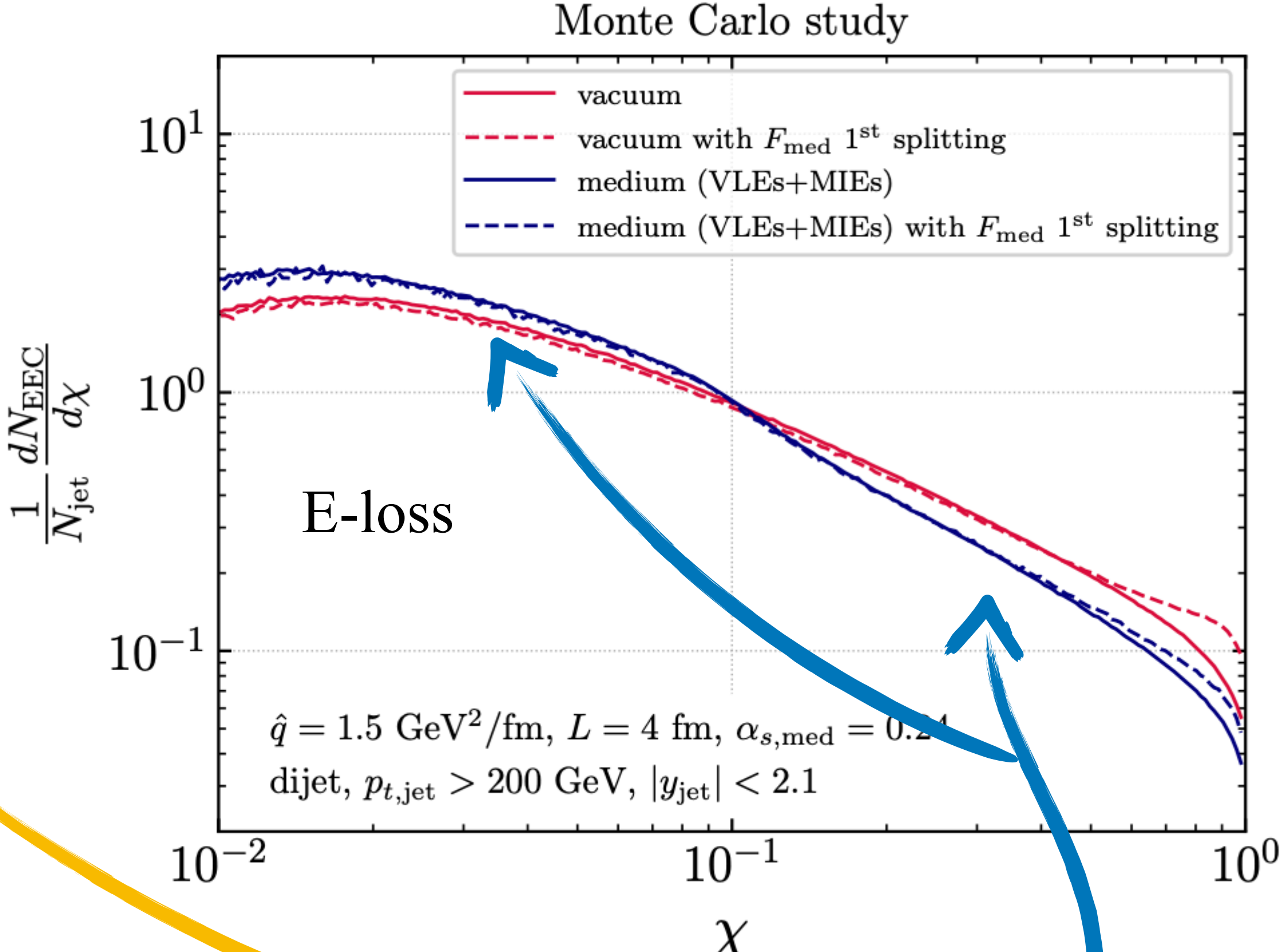
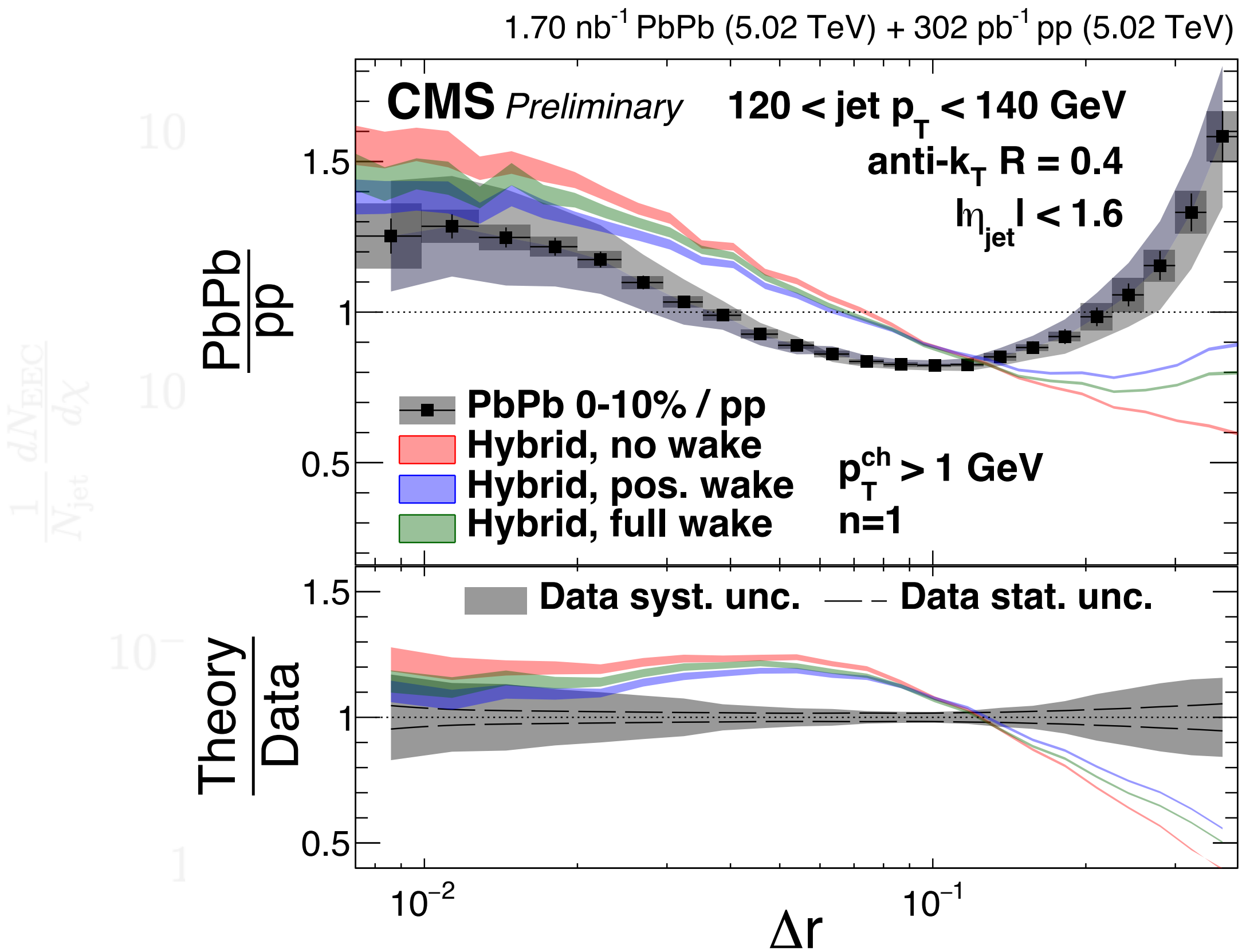


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**“Mixes” directly
with hard function**

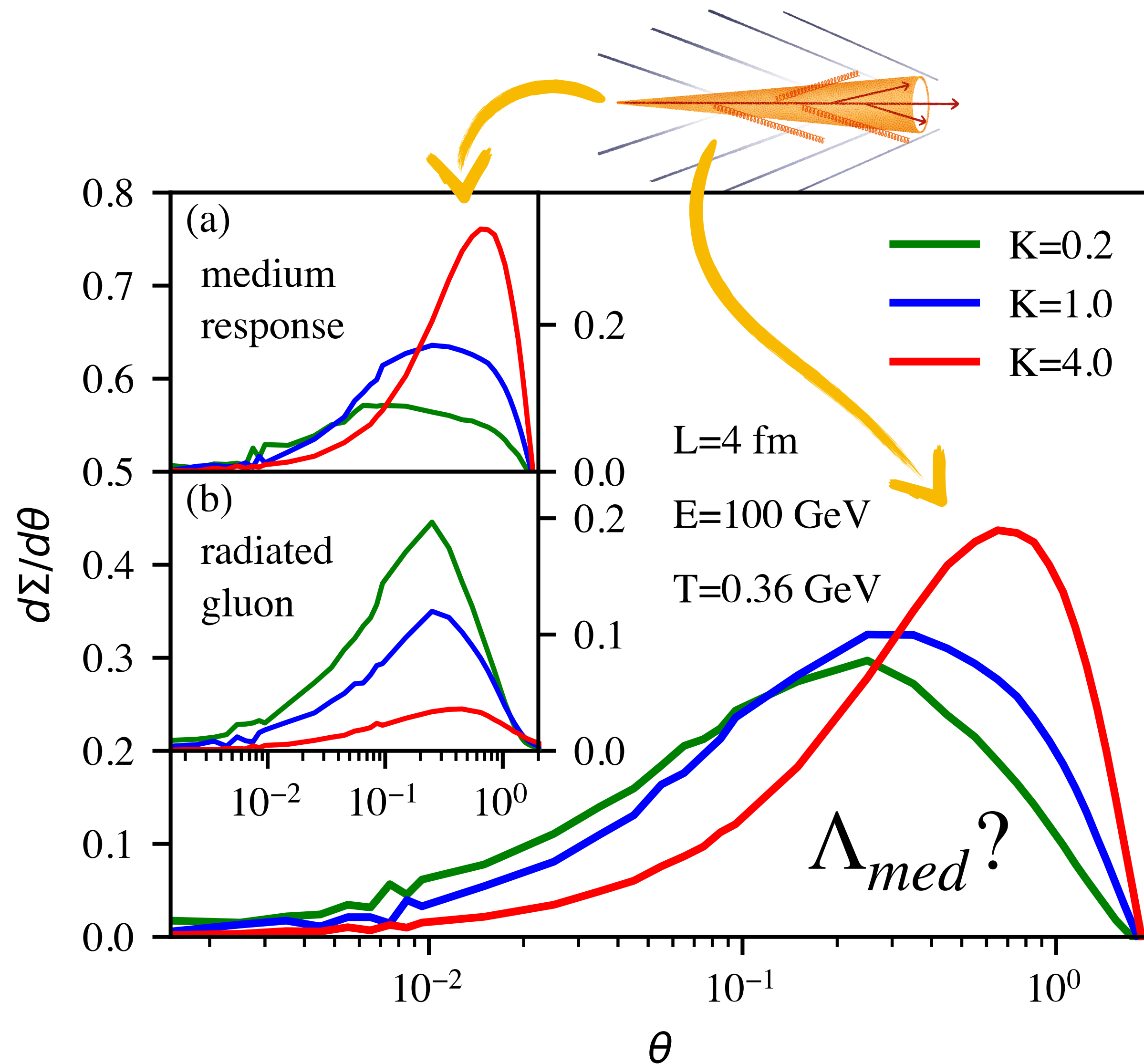


Similar shape to experimental data !
Is this everything ?

$$\left(\frac{1}{\chi^{-\bar{\alpha}\gamma_{qq}(3)}} + F_{\text{med}}^{gq}(\chi, z) \right) Q_{qg}(p_t, \chi, z)$$

“Mixes” directly
with hard function

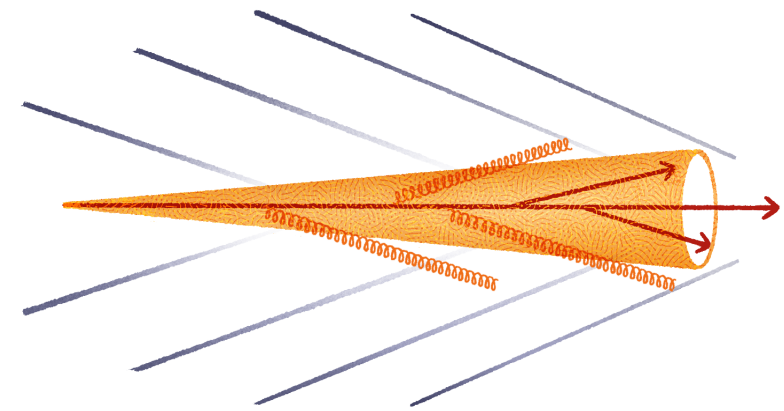
Energy correlators in HICs



From several MC models, **there seems to be large contribution to EEC** from the medium back reaction to jet

Can we understand this at the theory level for EECs ?

[Z. Yang, et al, 2310.01500]

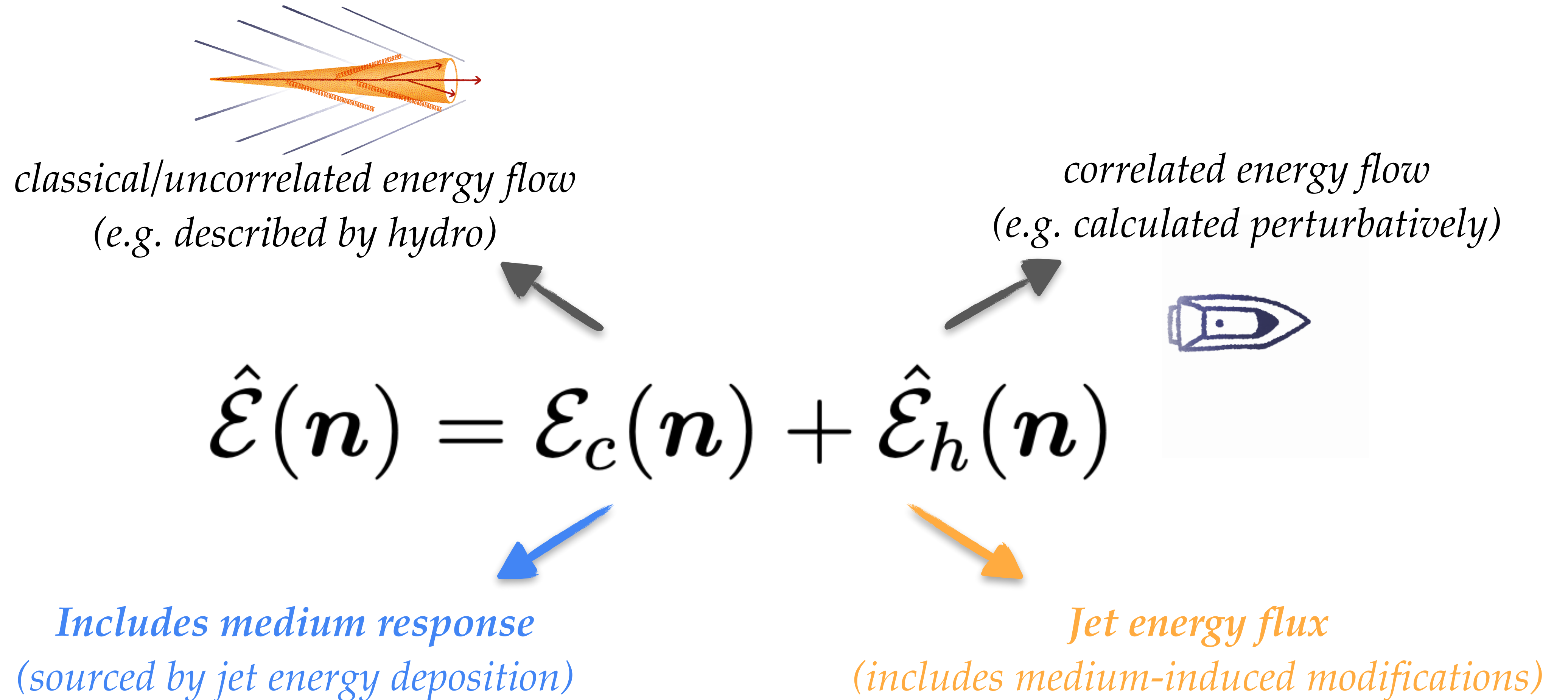


classical/uncorrelated energy flow
(e.g. described by hydro)

correlated energy flow
(e.g. calculated perturbatively)



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

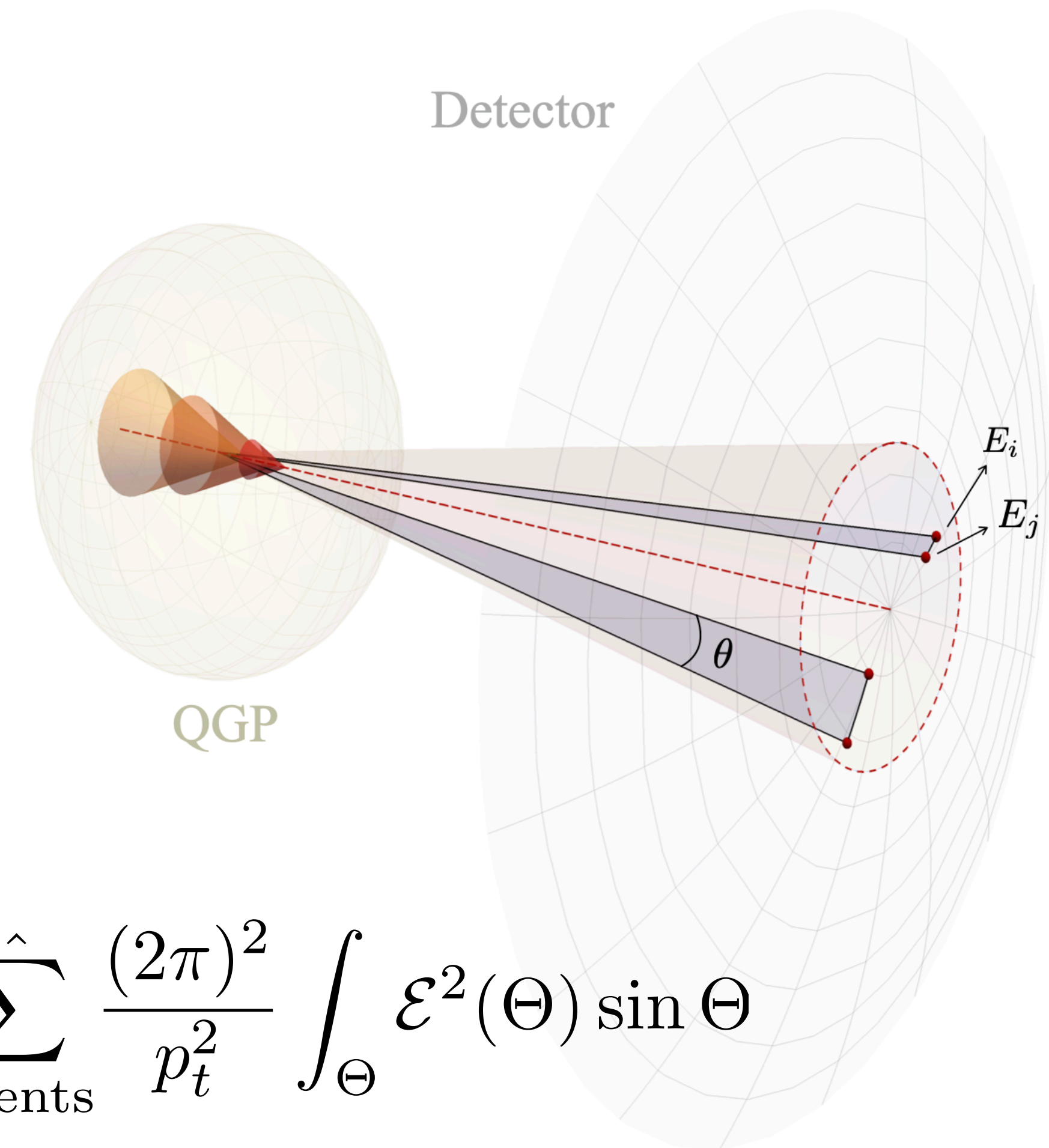


How are these two energy flows imprinted on ENC's ?

- We consider the evolution of the jet cascade in the presence of a **“hydro-ball state”**

[see L. Délacretza, et al, 1805.04194; for related formulation]

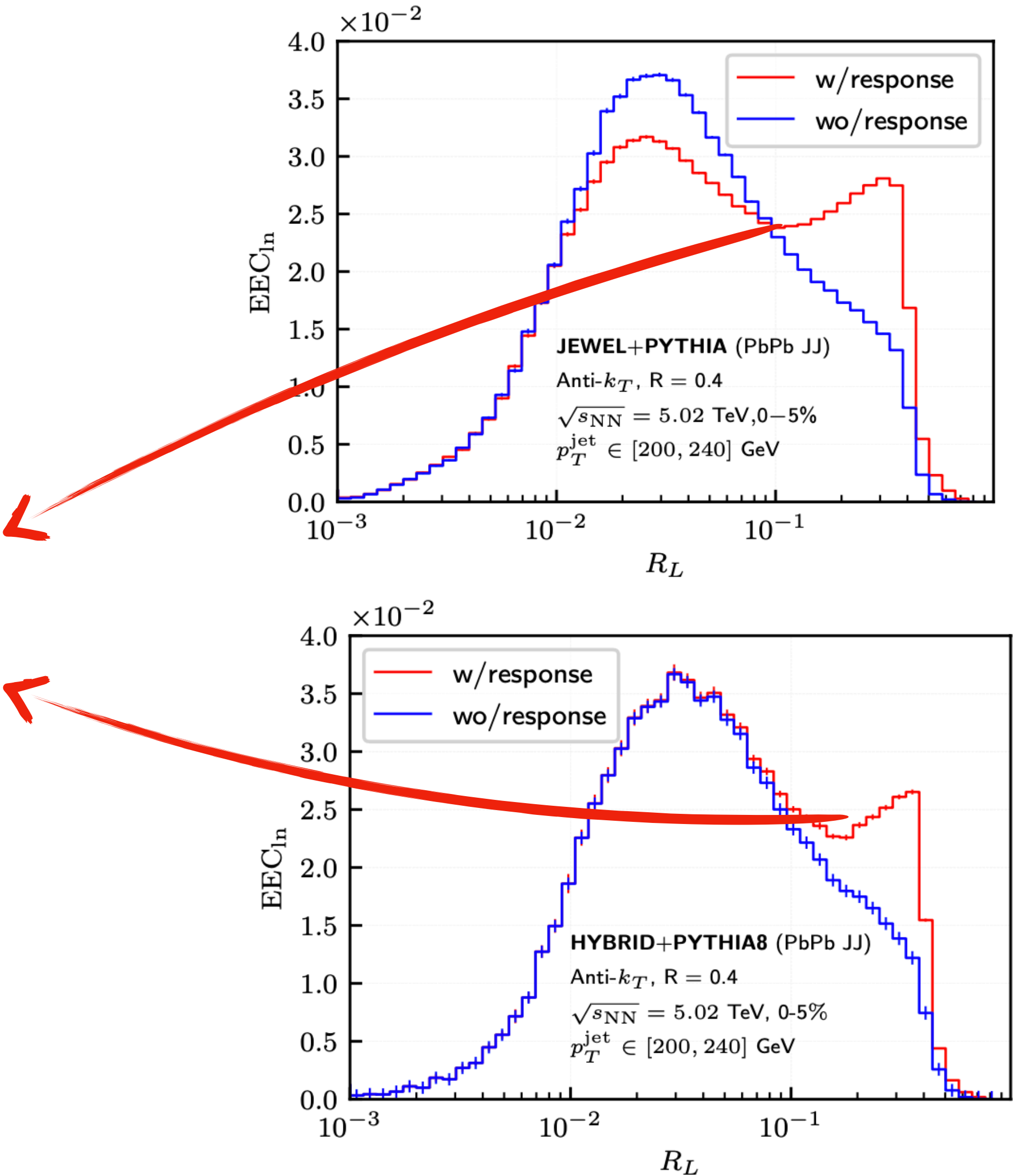
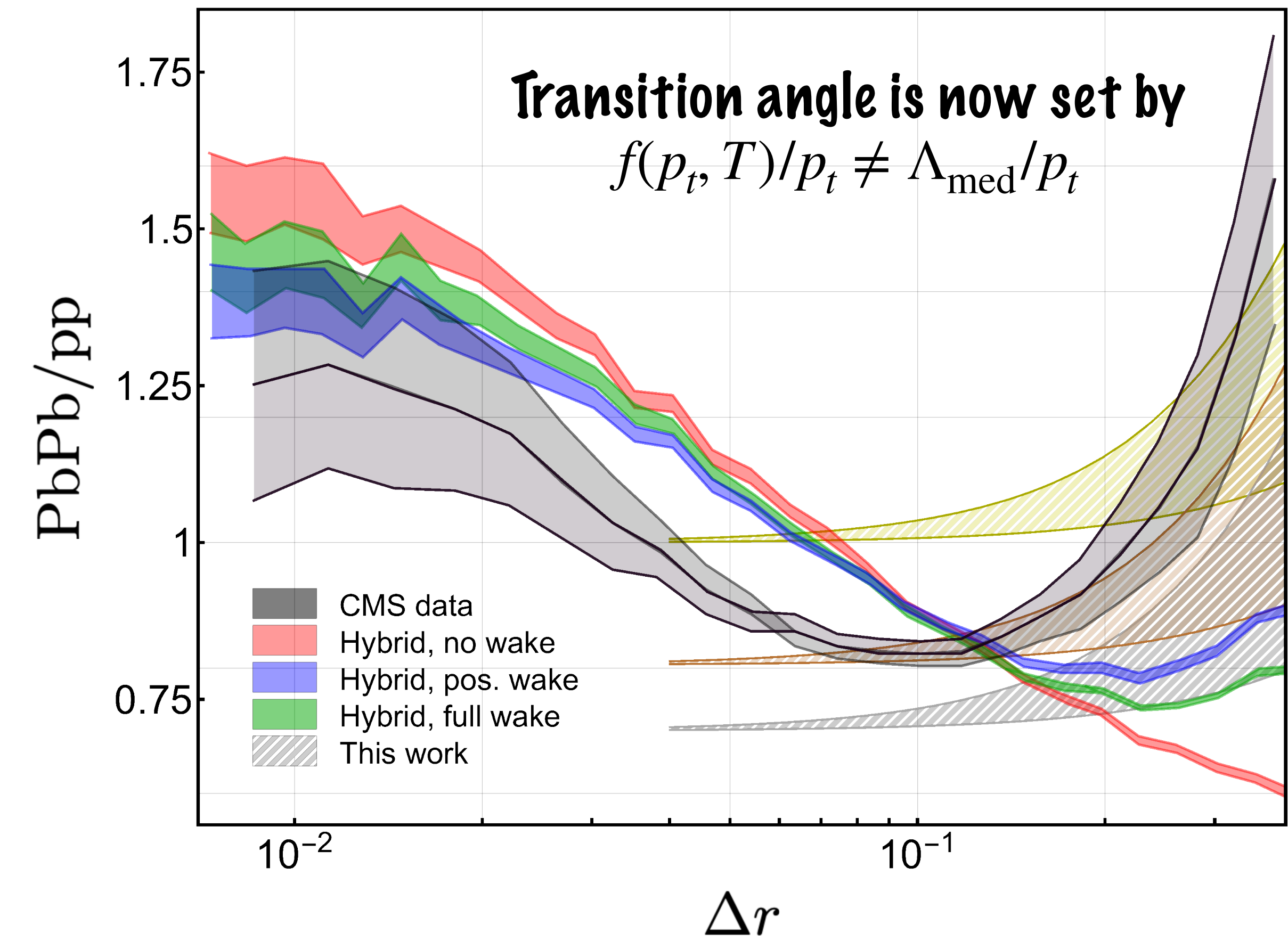
- The key point is that **jet couples to classical background**; all treatments of the medium in HICs fall back to this
- What would happen if a classical flow were plugged into the ECs?**



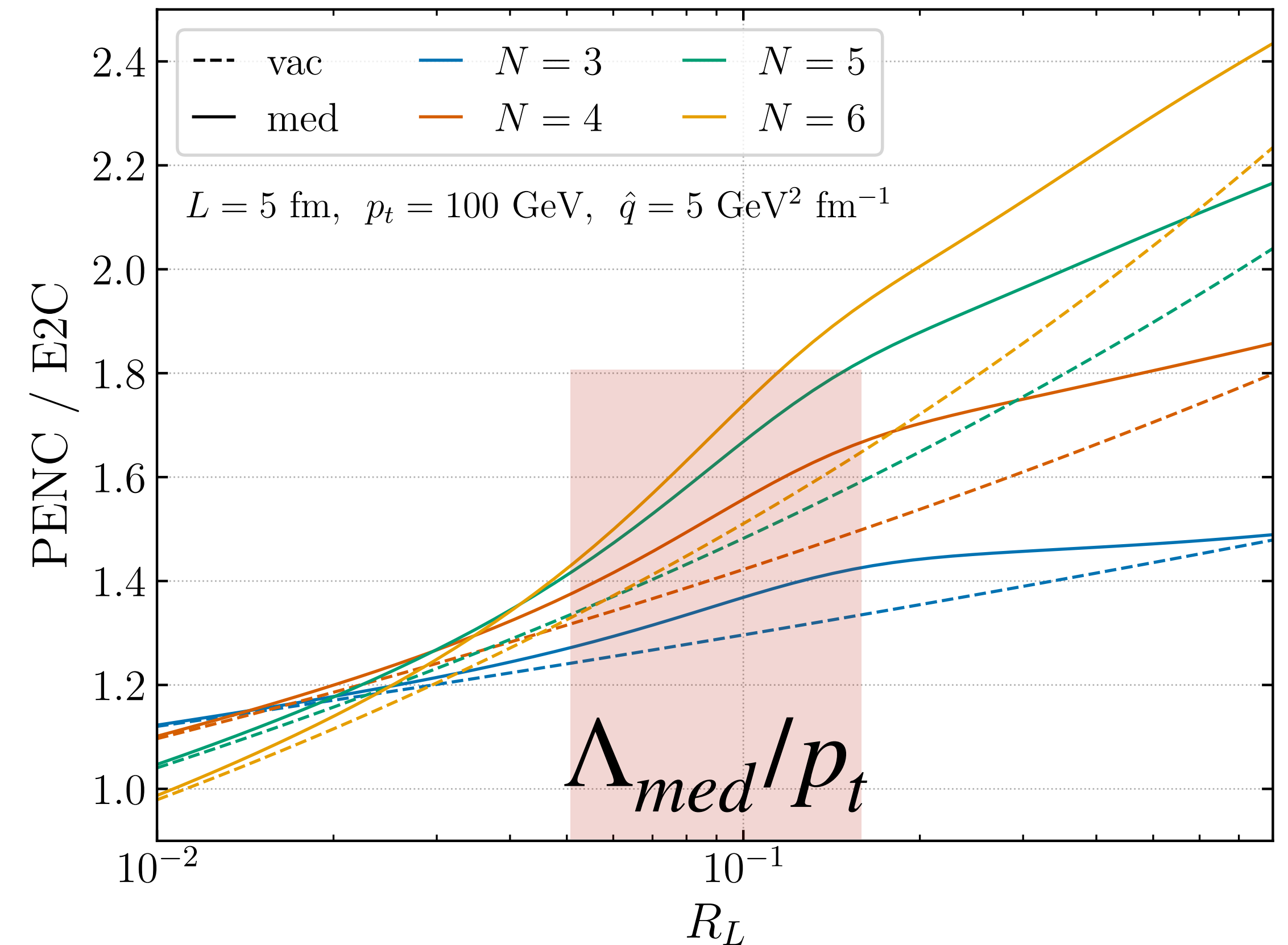
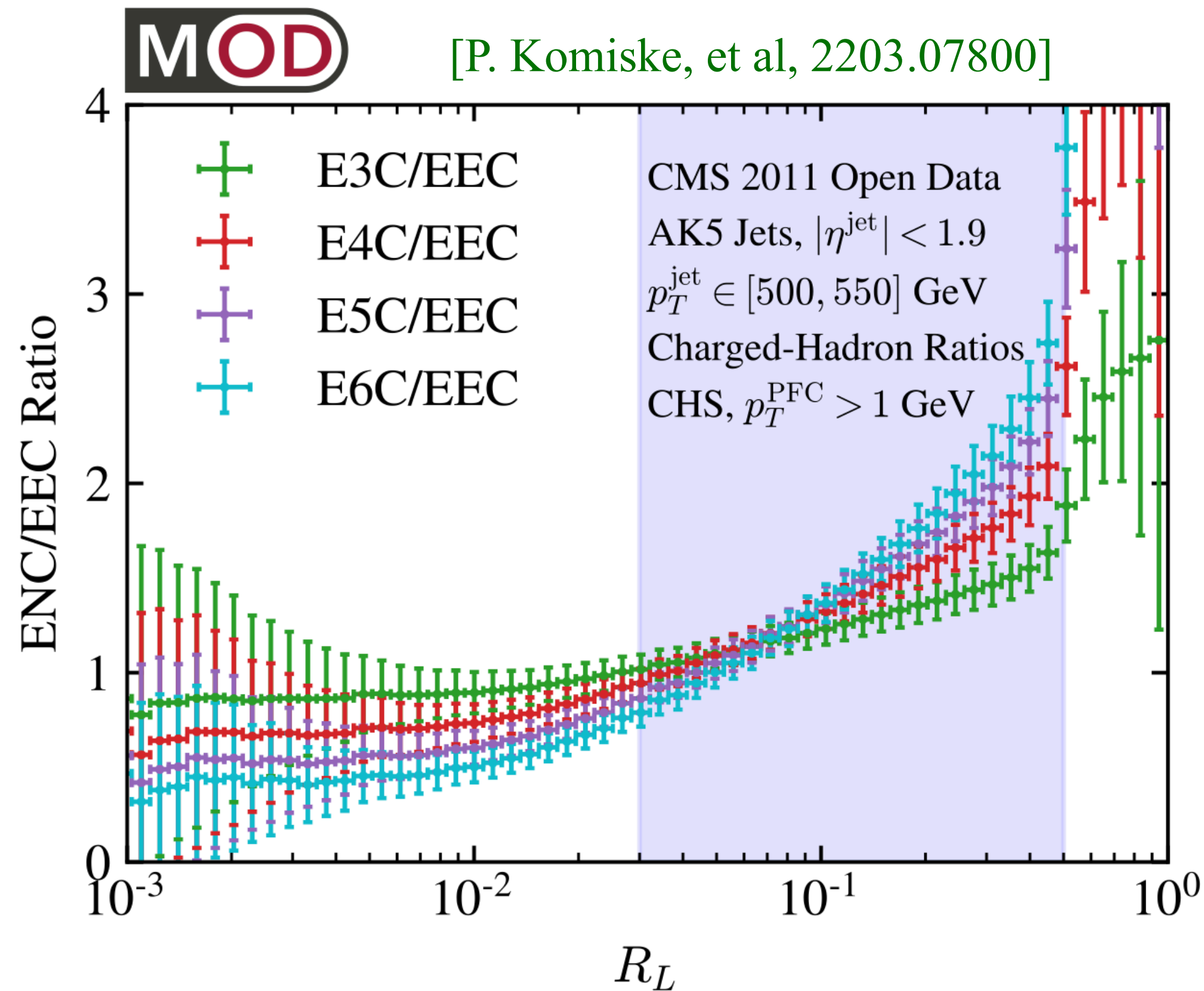
$$\frac{d\Sigma^{(2)}}{d\theta} \simeq \sum_{k=2} c_k^{(2)} \theta^{2k-3} \longrightarrow c_2^{(2)} = \hat{\sum}_{\text{events}} \frac{(2\pi)^2}{p_t^2} \int_{\Theta} \mathcal{E}^2(\Theta) \sin \Theta$$



Comparing to data, the large angle enhancement is qualitatively in agreement with hydro's prediction



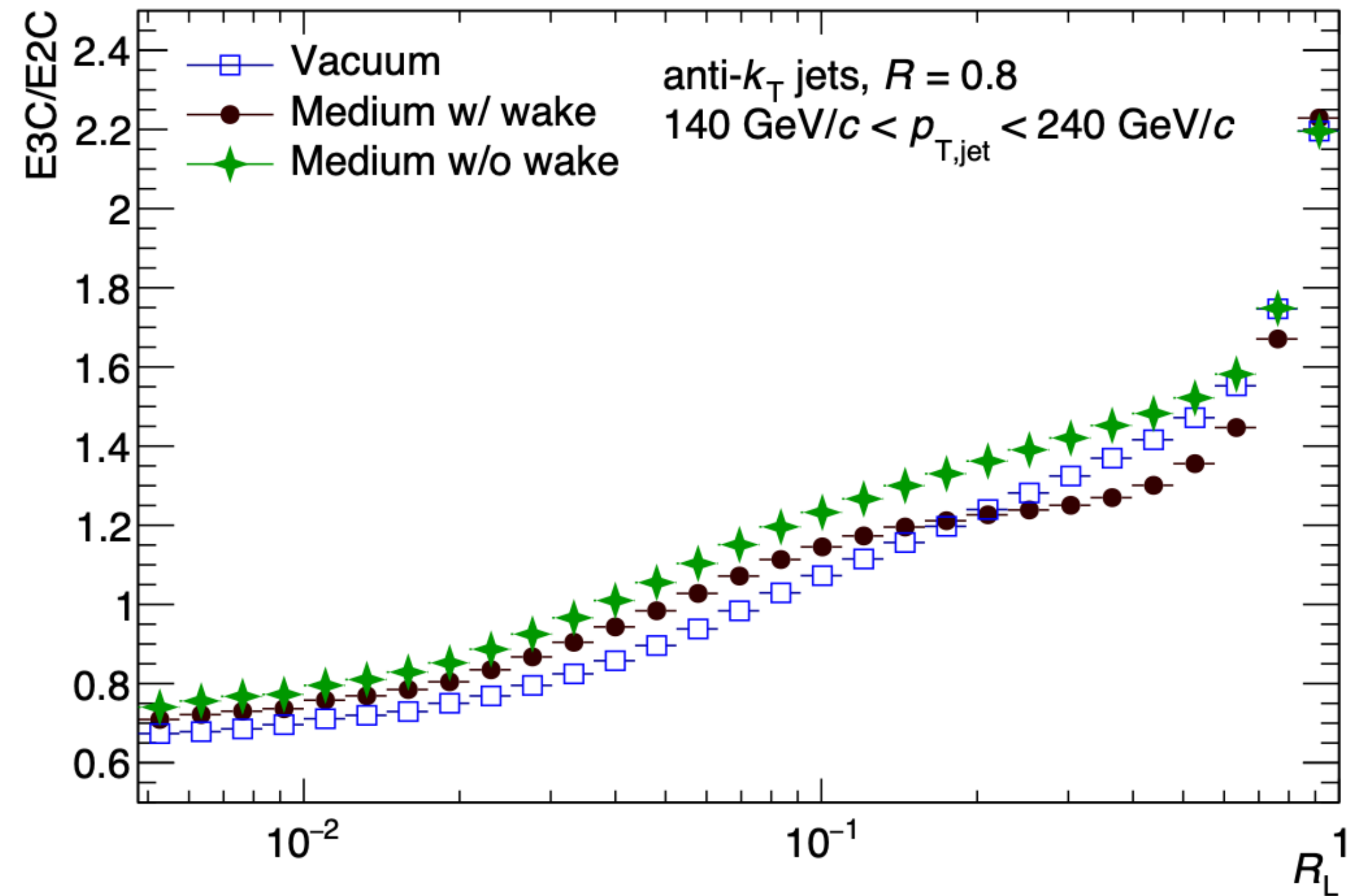
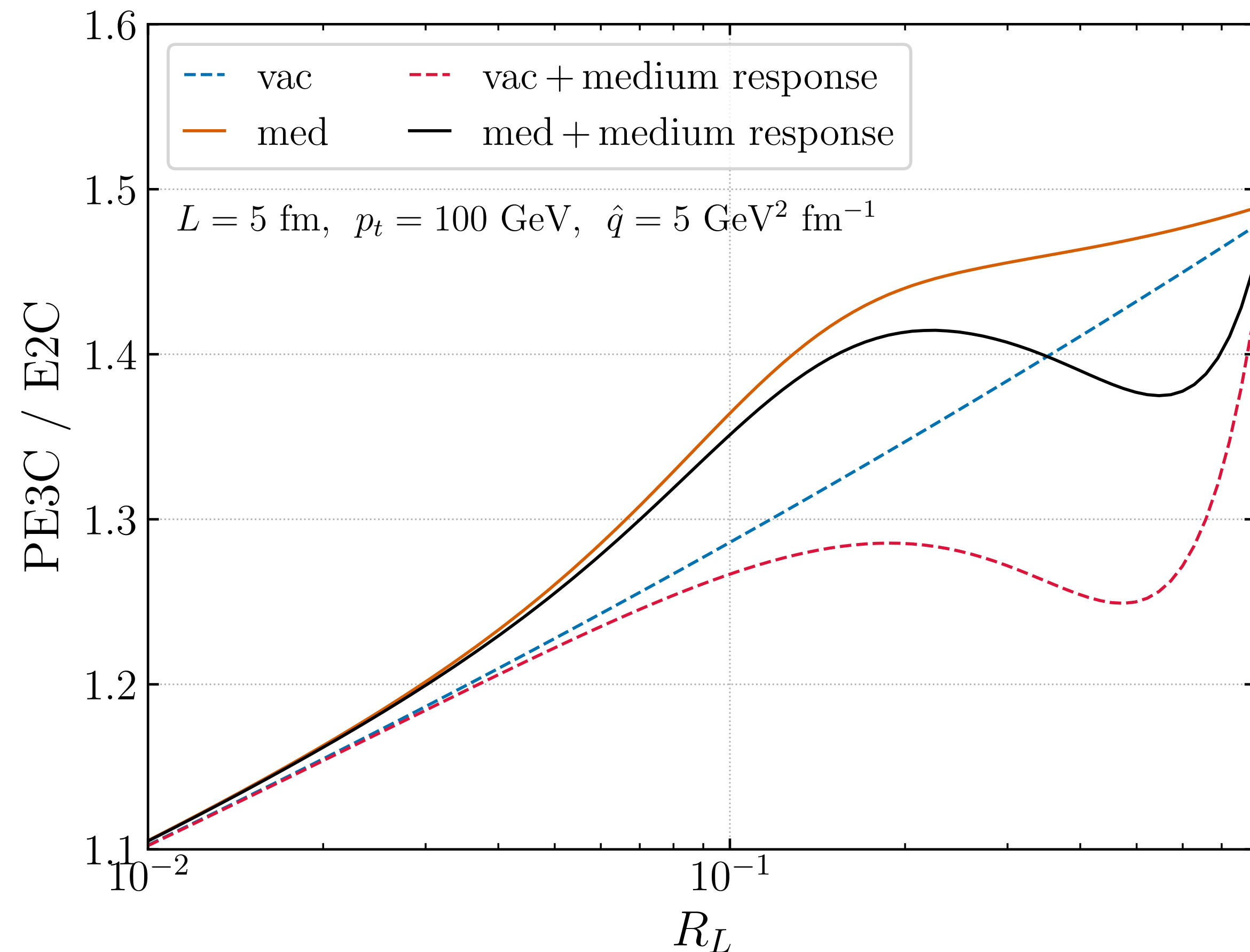
The same conclusions hold for higher point functions, where the shape can be non-trivial



$$\frac{d\Sigma_P^{(N)}}{dR_L} = \frac{\alpha_s R_L^{\frac{\alpha_s}{\pi} \gamma(N+1)}}{\pi R_L} \int_0^1 dz (1 - z^N - (1 - z)^N) \overset{\text{vac+med}}{P_{gq}}$$

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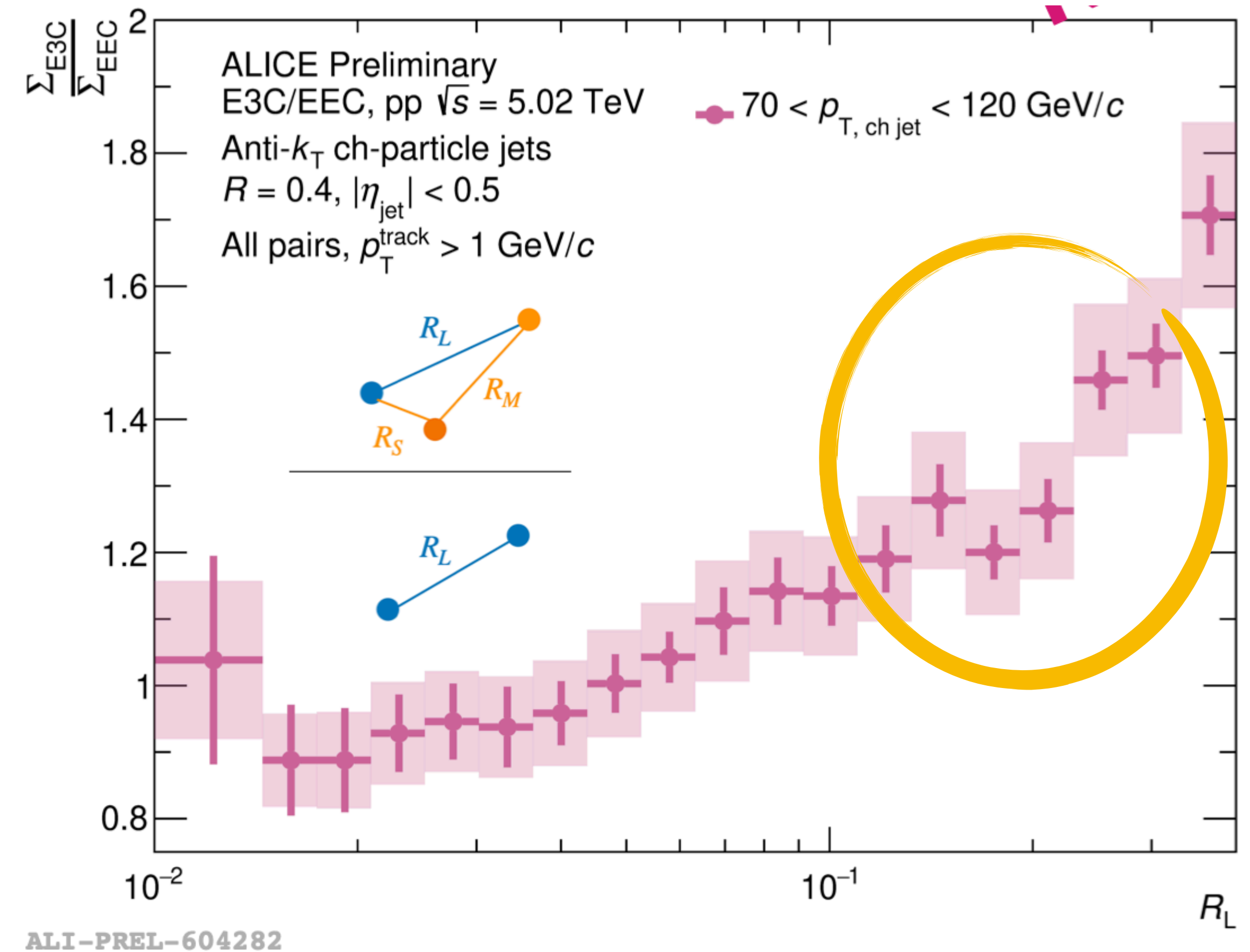
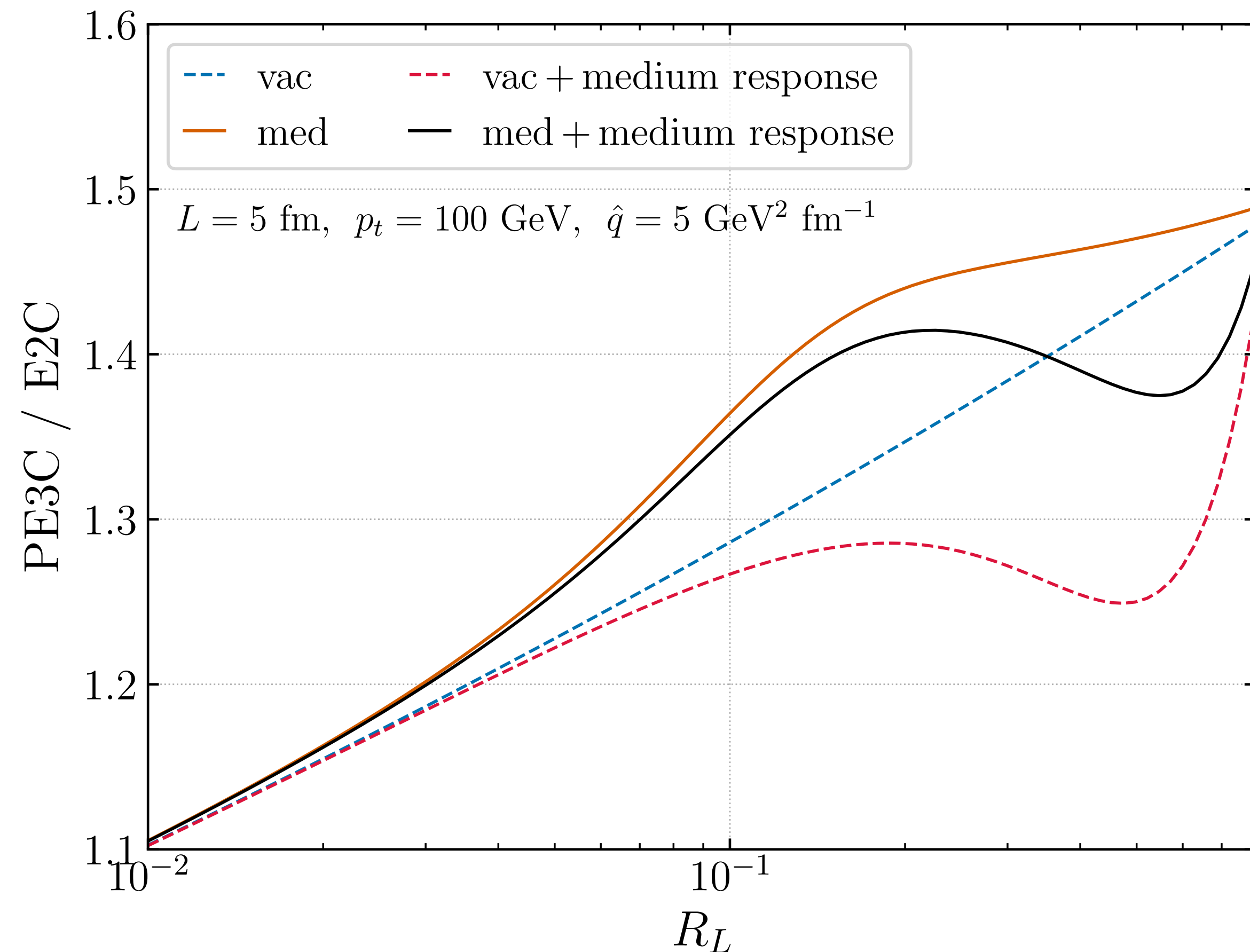
[Bossi et al., JHEP, 2024]



*Our physical picture of a classical energy flow is in **qualitative** agreement with MC models*

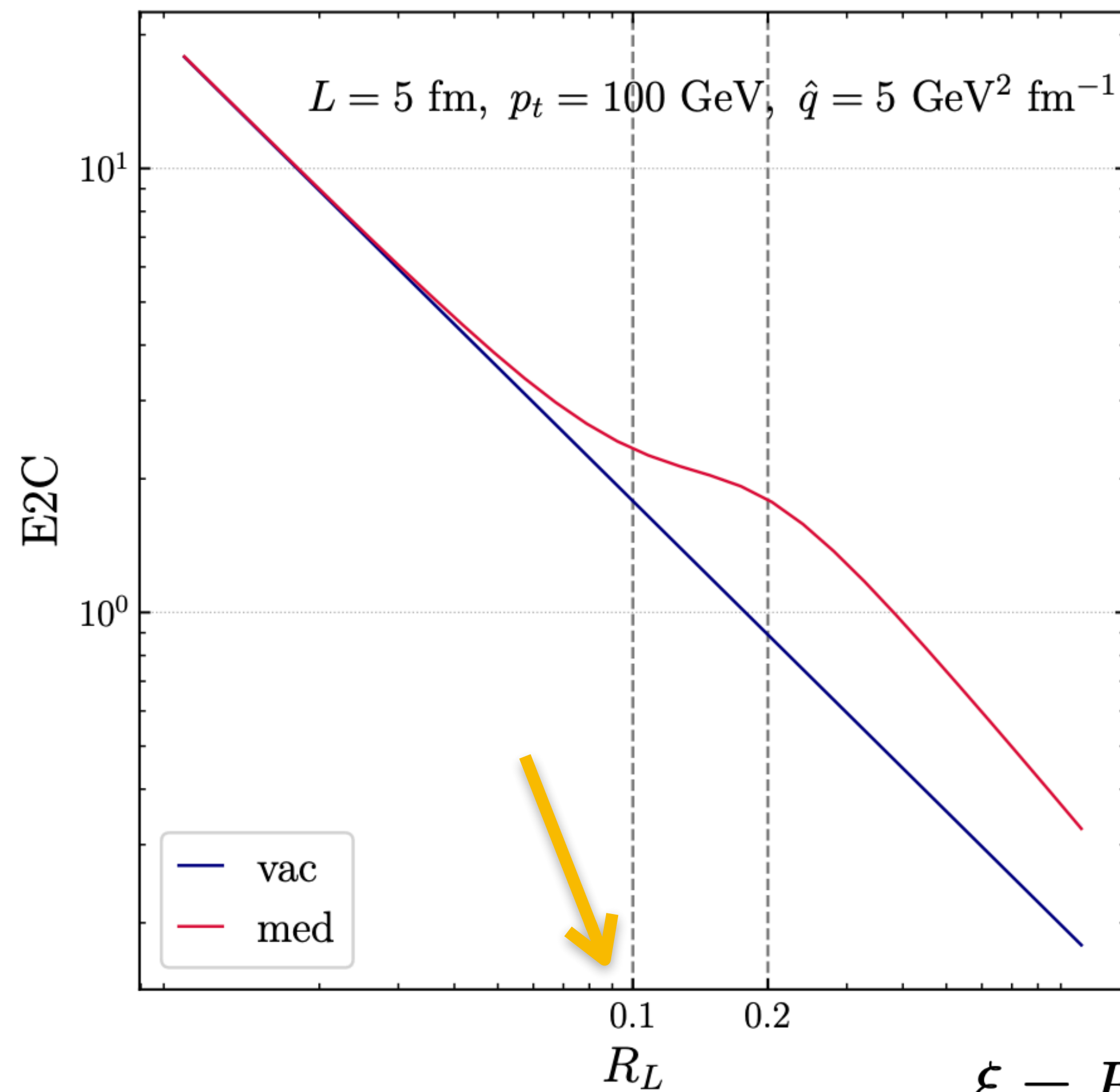
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[Ananya Rai, QM 25]



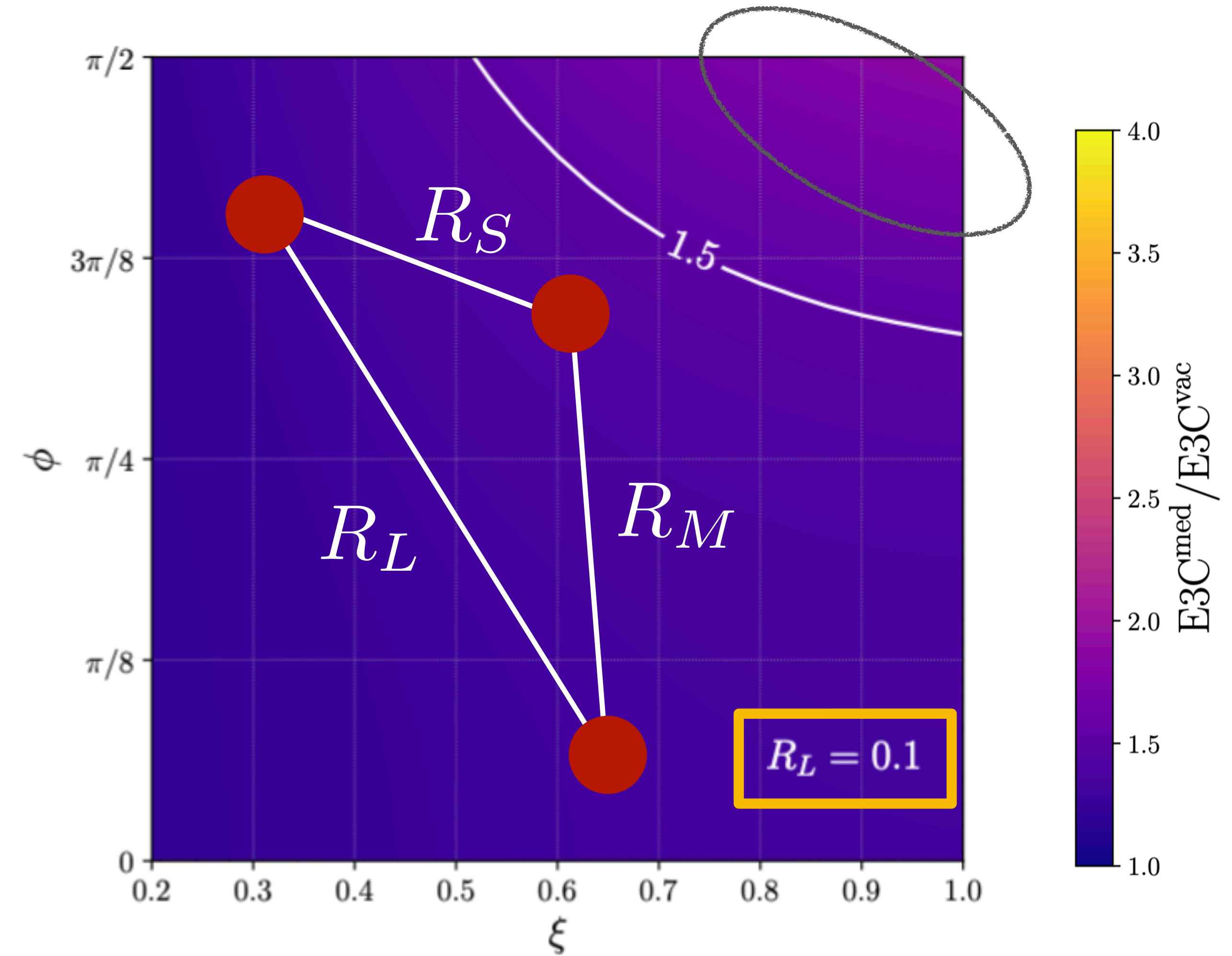
*Our physical picture of a classical energy flow is in **qualitative** agreement **with data ??***

These results generalize to the fully differential higher point functions

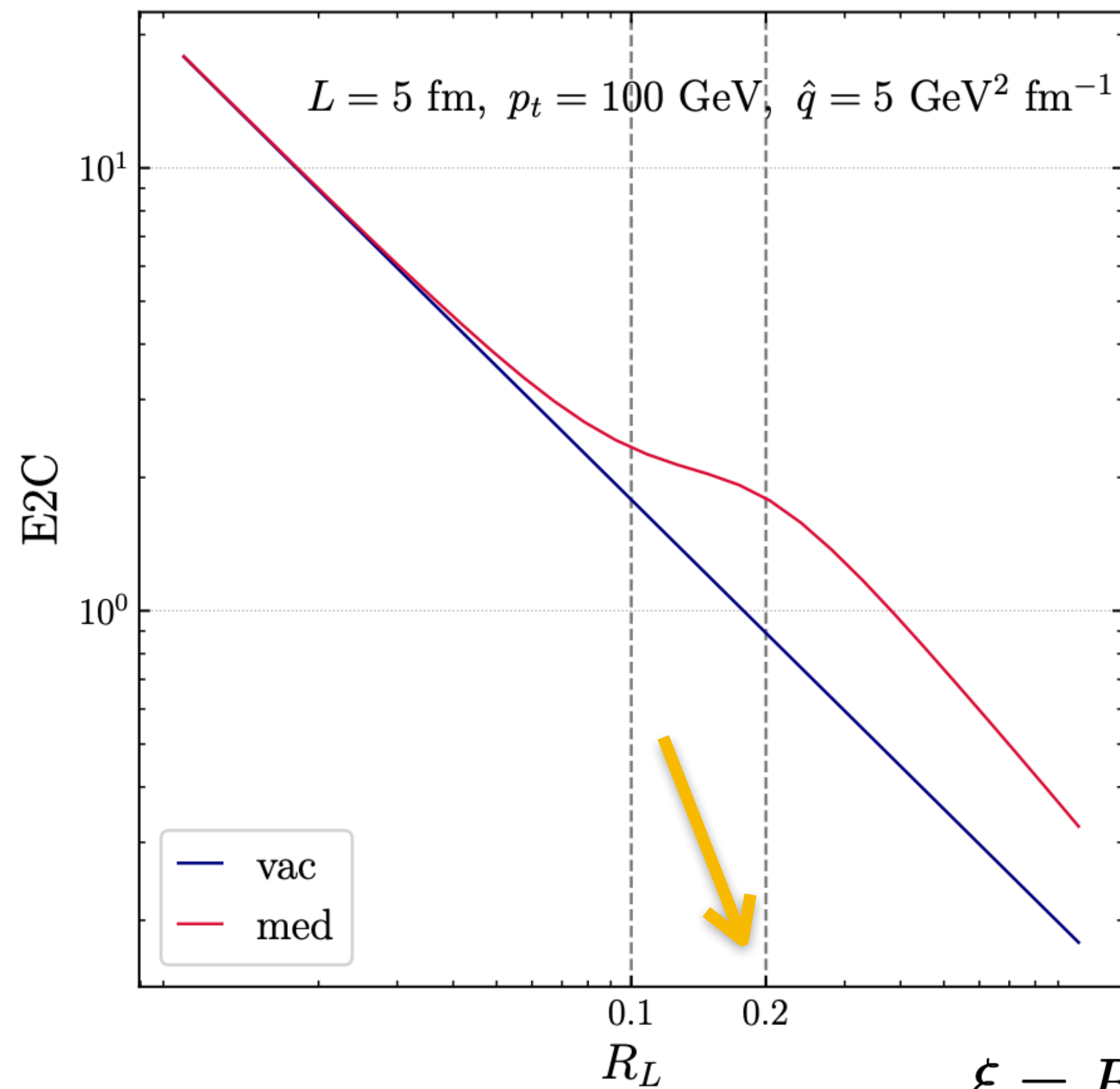


$$\xi = R_S / R_M$$

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

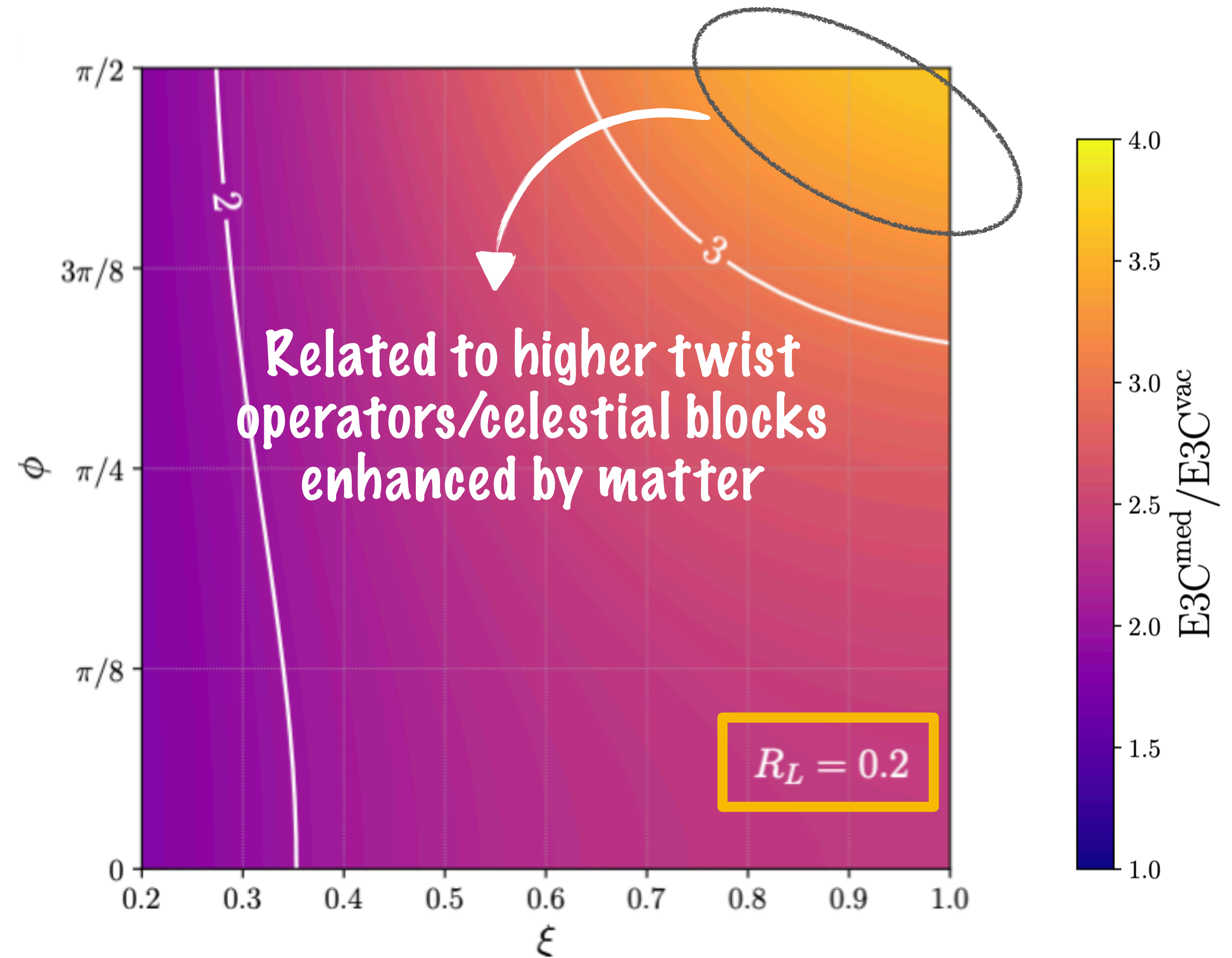


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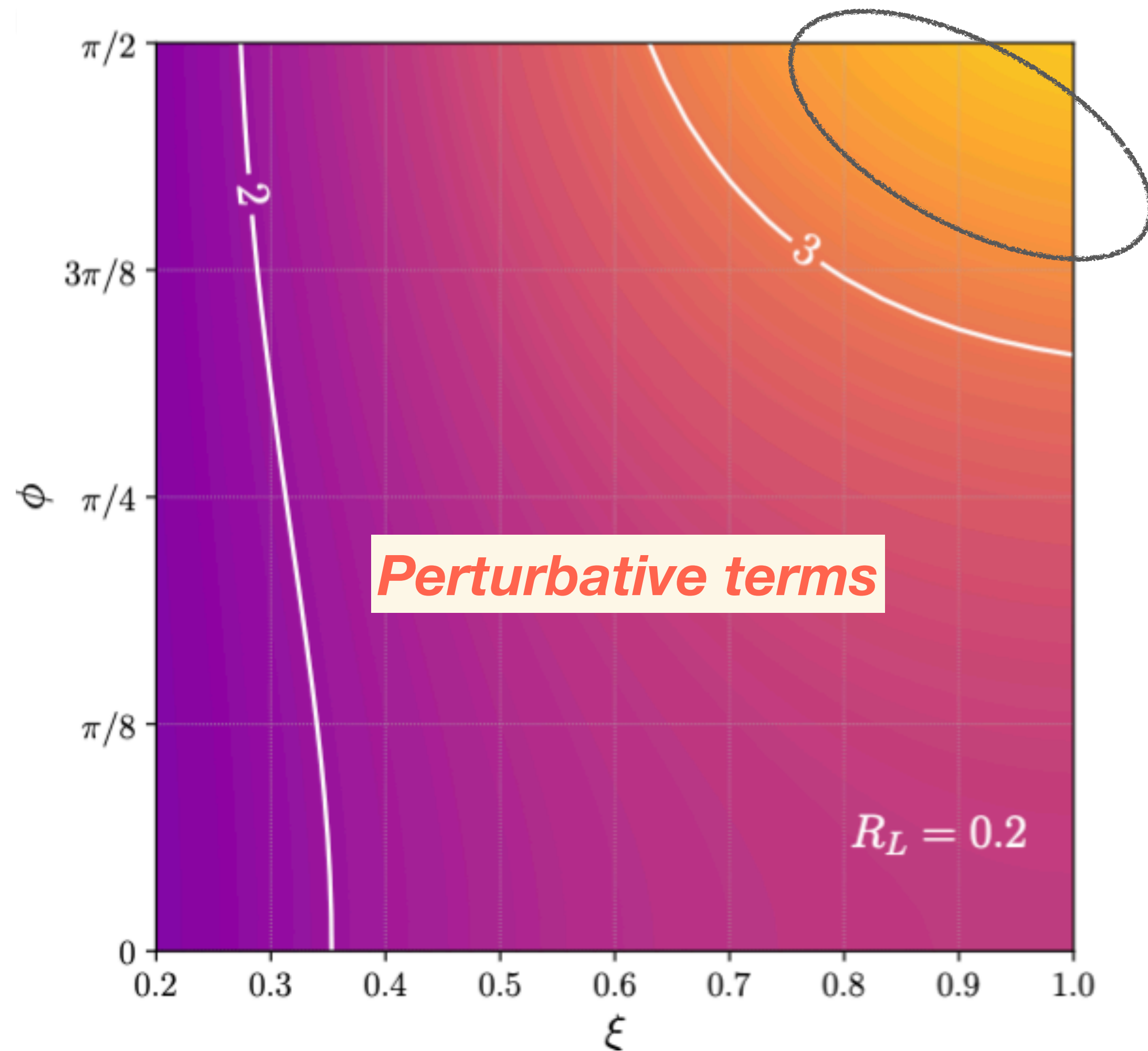


$$\xi = R_S/R_M$$

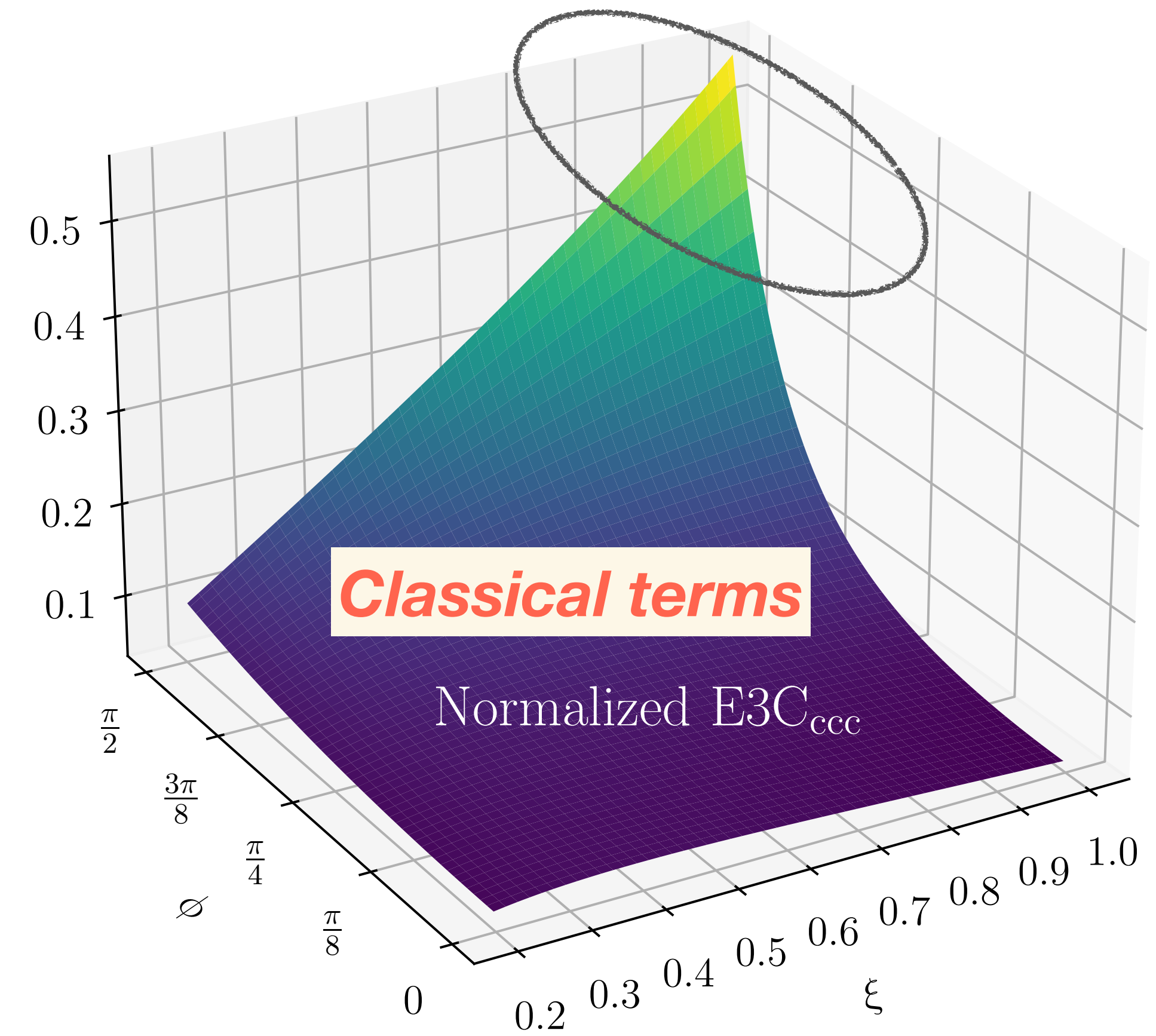
$$\sin^2 \phi = 1 - (R_L - R_M)^2 / R_S^2$$



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

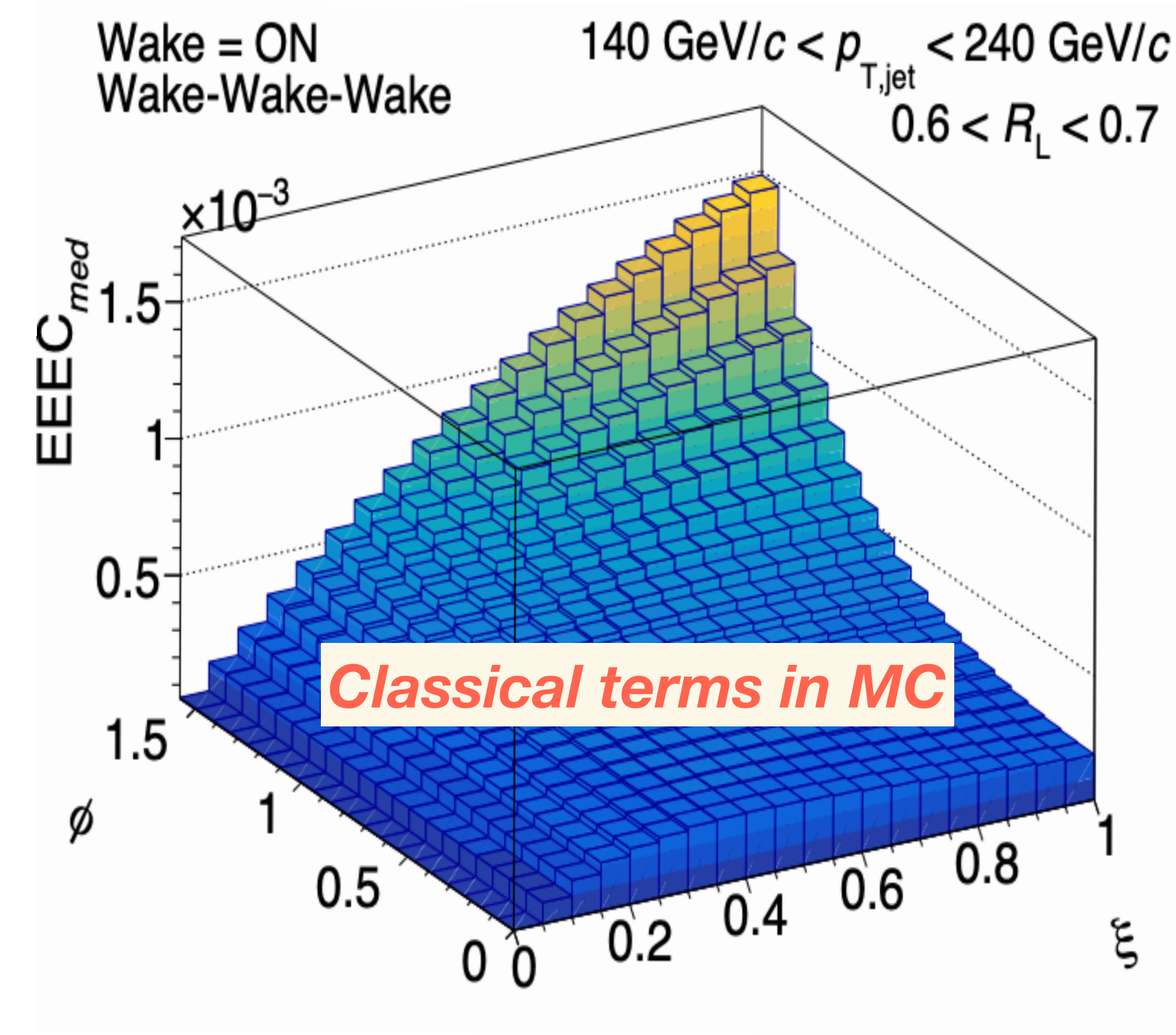


$$\langle \mathcal{E}_c(\mathbf{n}_1) \mathcal{E}_c(\mathbf{n}_2) \mathcal{E}_c(\mathbf{n}_3) \rangle = \mathcal{E}_c(\mathbf{n}_1) \mathcal{E}_c(\mathbf{n}_2) \mathcal{E}_c(\mathbf{n}_3)$$

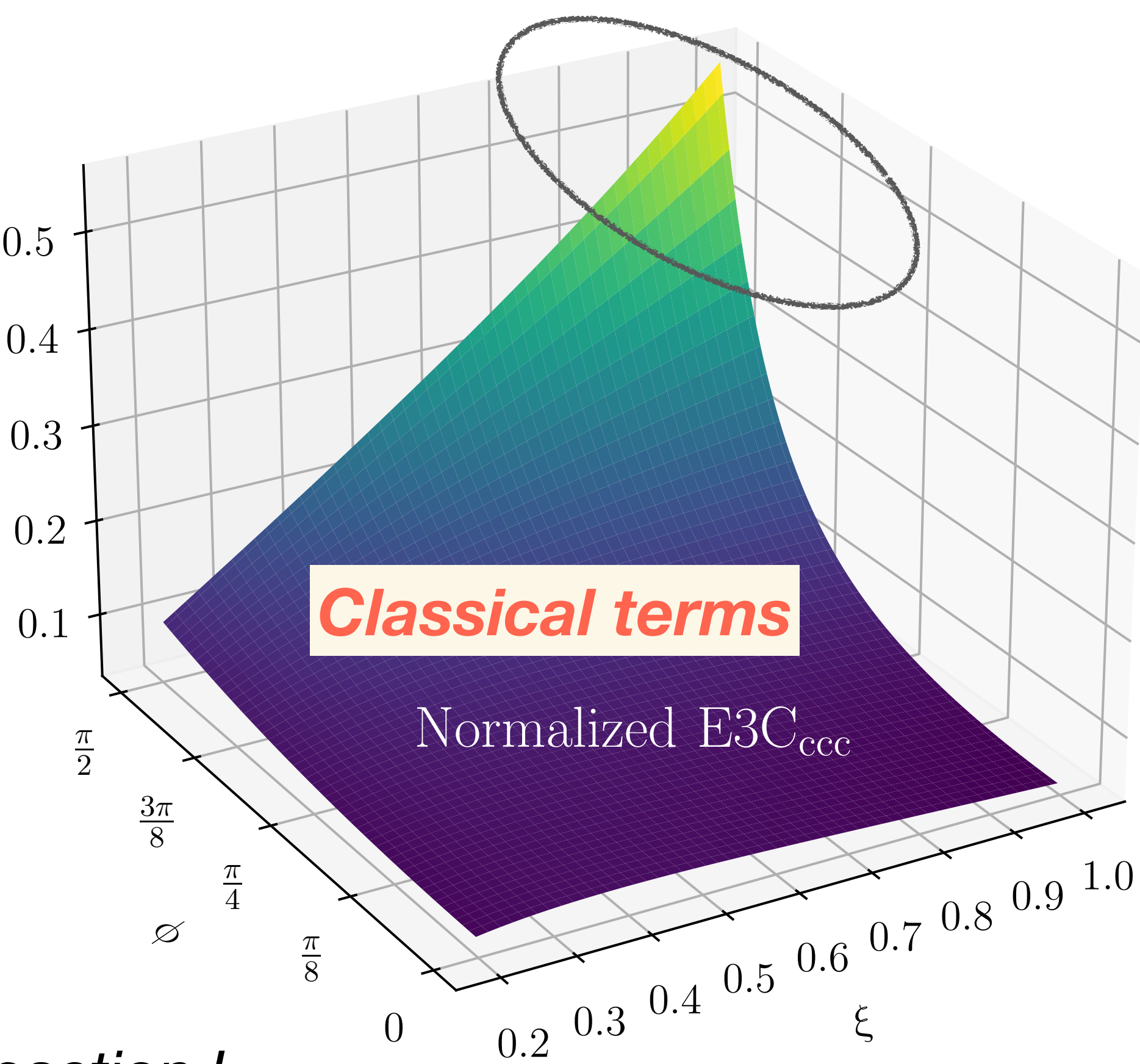




[Bossi et al., JHEP, 2024]



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



Again in agreement with MC models including hydro back-reaction !

- *ENCs offer a natural way to map the properties of jets in HICs;
first jet substructure observable which allows for a treatment of perturbative and soft physics in a theoretically clean way*

Conclusions

- *ENCs offer a natural way to map the properties of jets in HICs; **first jet substructure observable which allows for a treatment of perturbative and soft physics in a theoretically clean way***
- *Results shown are supported by **mapping to celestial block/light-ray OPE decomposition of the ENCs***

“Vacuum” OPE

$$\frac{d\Sigma_{\text{P,vac}}^{(N)}}{dR_L} = \sum_{k=1} a_{\tau,0}^{\text{P}(N)} R_L^{\tau-3} \Big|_{\tau=2k}$$

Collinear limit of classical flux

$$\frac{d\Sigma_{\text{P,response}}^{(N)}}{dR_L} = \sum_{k=2} c_{\tau}^{\text{P}(N)} [\mathcal{E}_c] R_L^{\tau-3} \Big|_{\tau=2k}$$

Collinear limit of perturbative medium induced modifications

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

Conclusions

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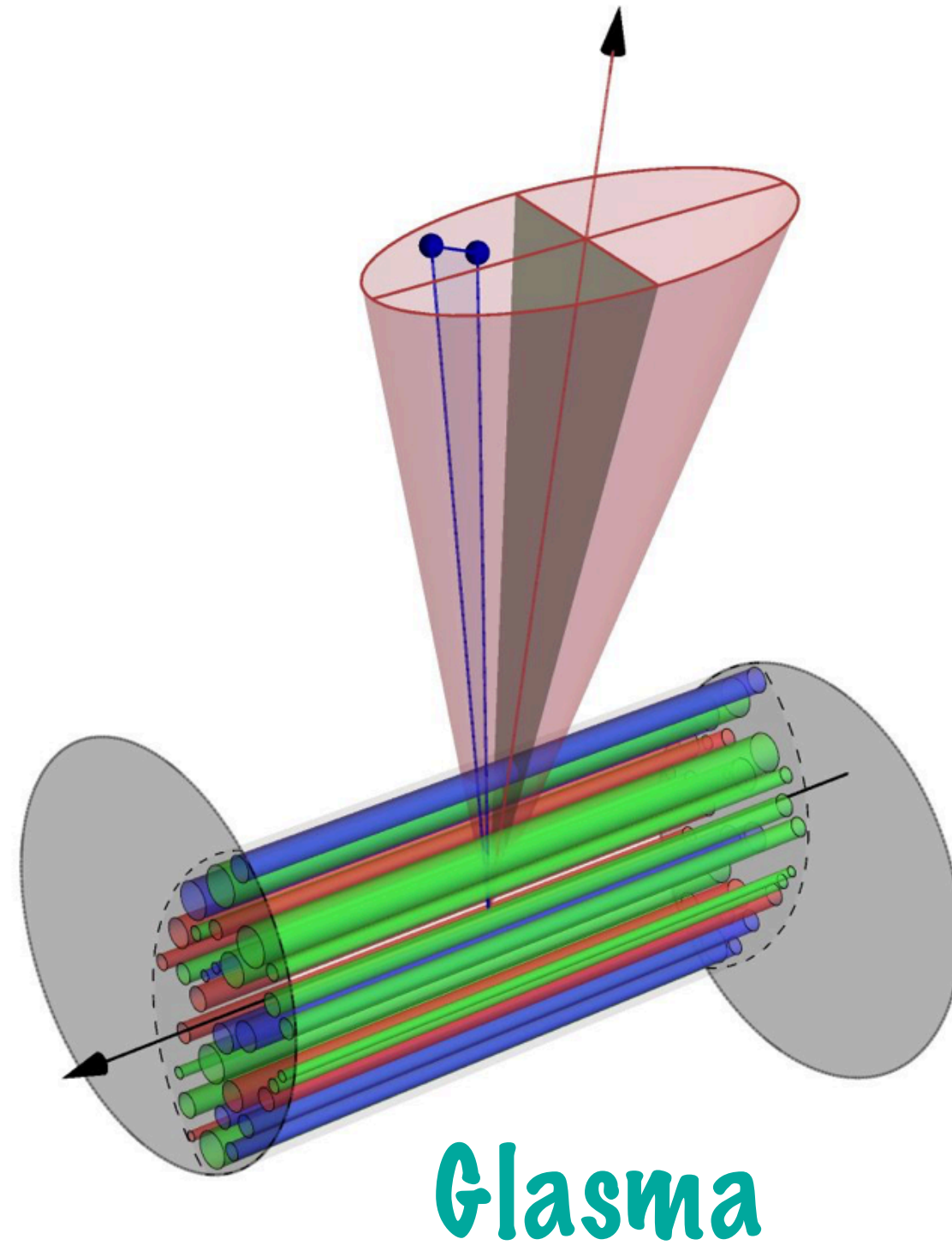
Collinear limit of classical flux

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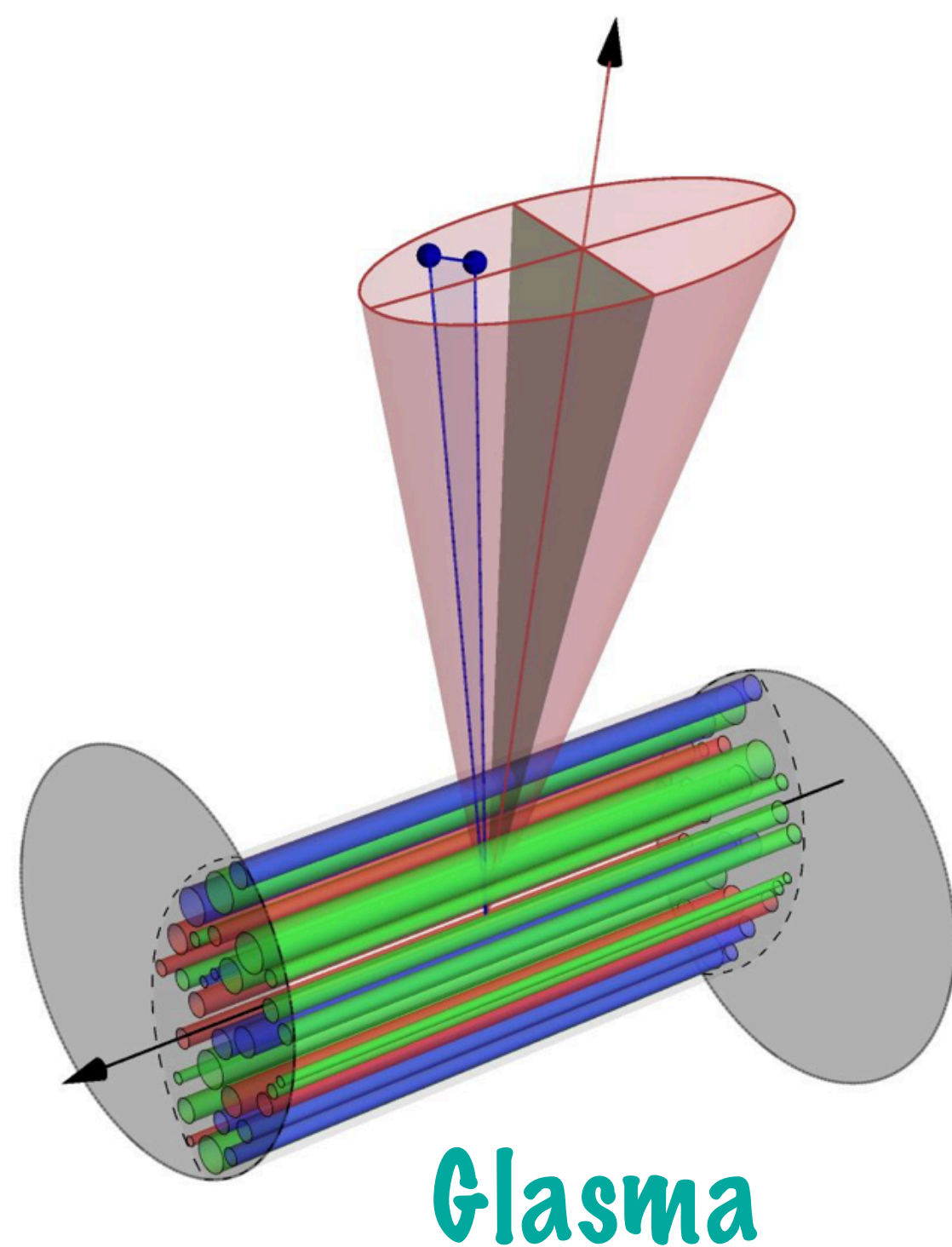
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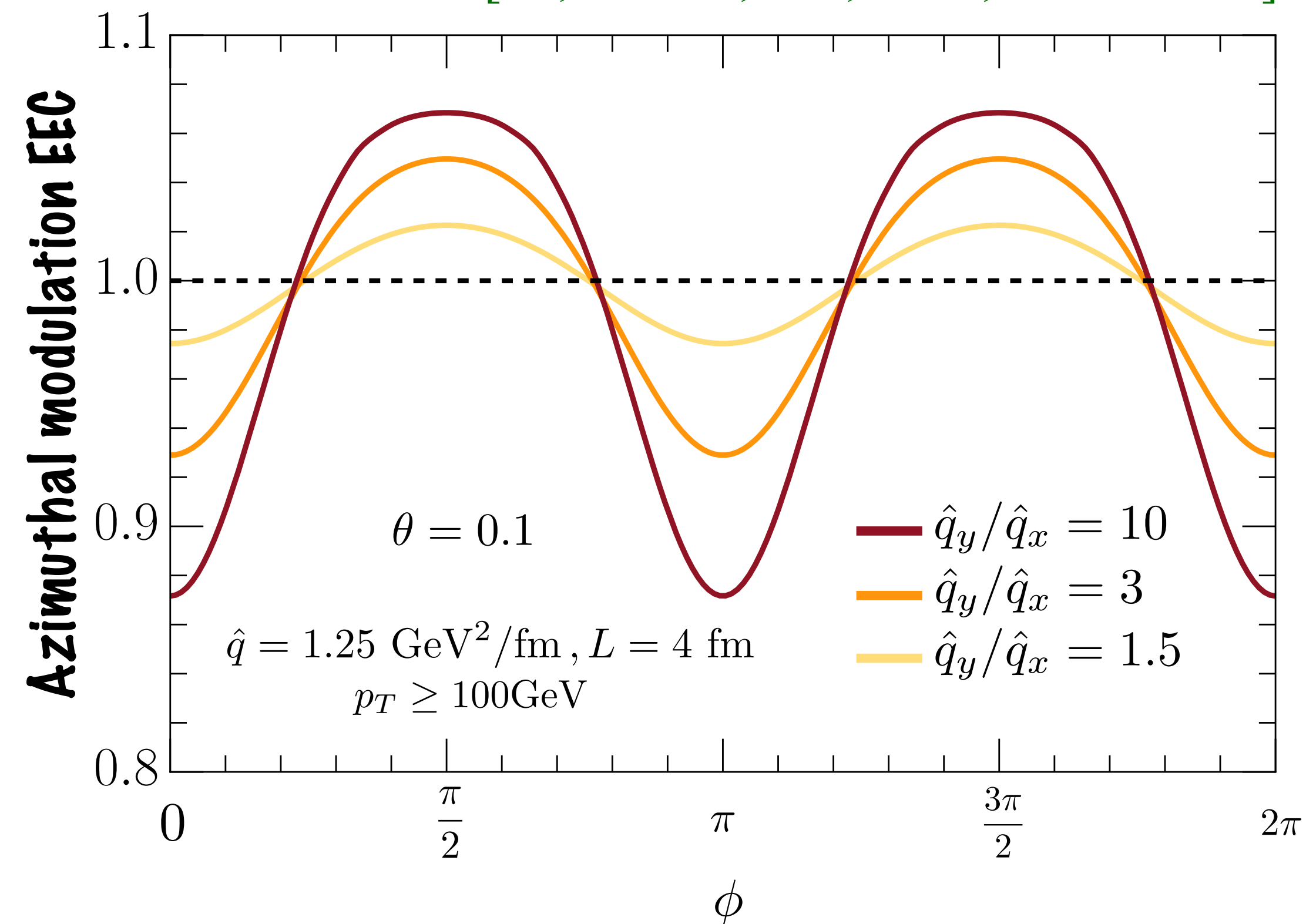
Outlook: ENCs and out-of-equilibrium QCD matter



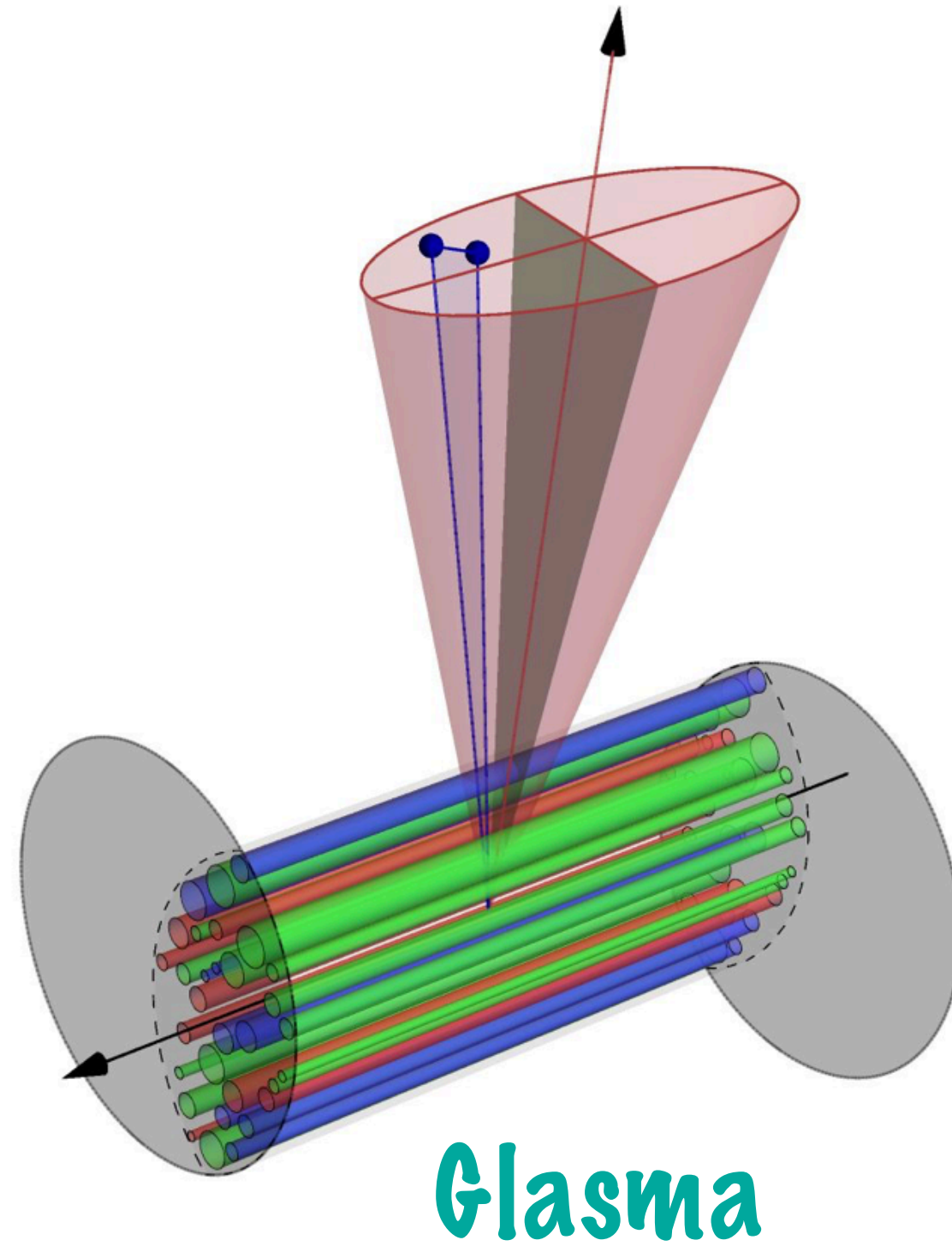
Outlook: ENCs and out-of-equilibrium QCD matter



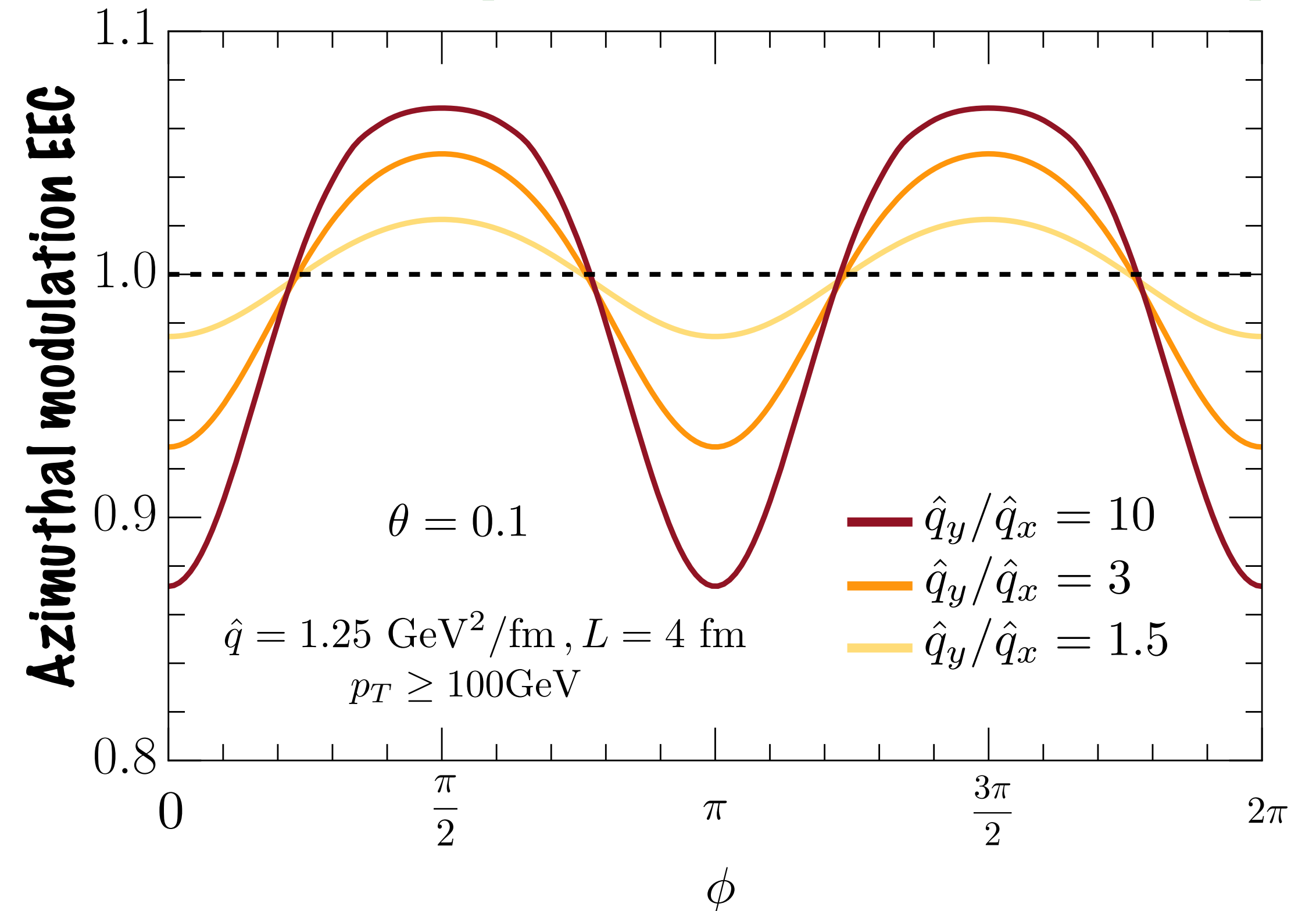
[JB, Brewer, Lee, Silva, 2508.19404]



Outlook: ENCs and out-of-equilibrium QCD matter



[JB, Brewer, Lee, Silva, 2508.19404]



General decomposition of EEC in such a state can be derived, including classical flows

[JB, Milhano, Sadofyev, Silva, in progress]

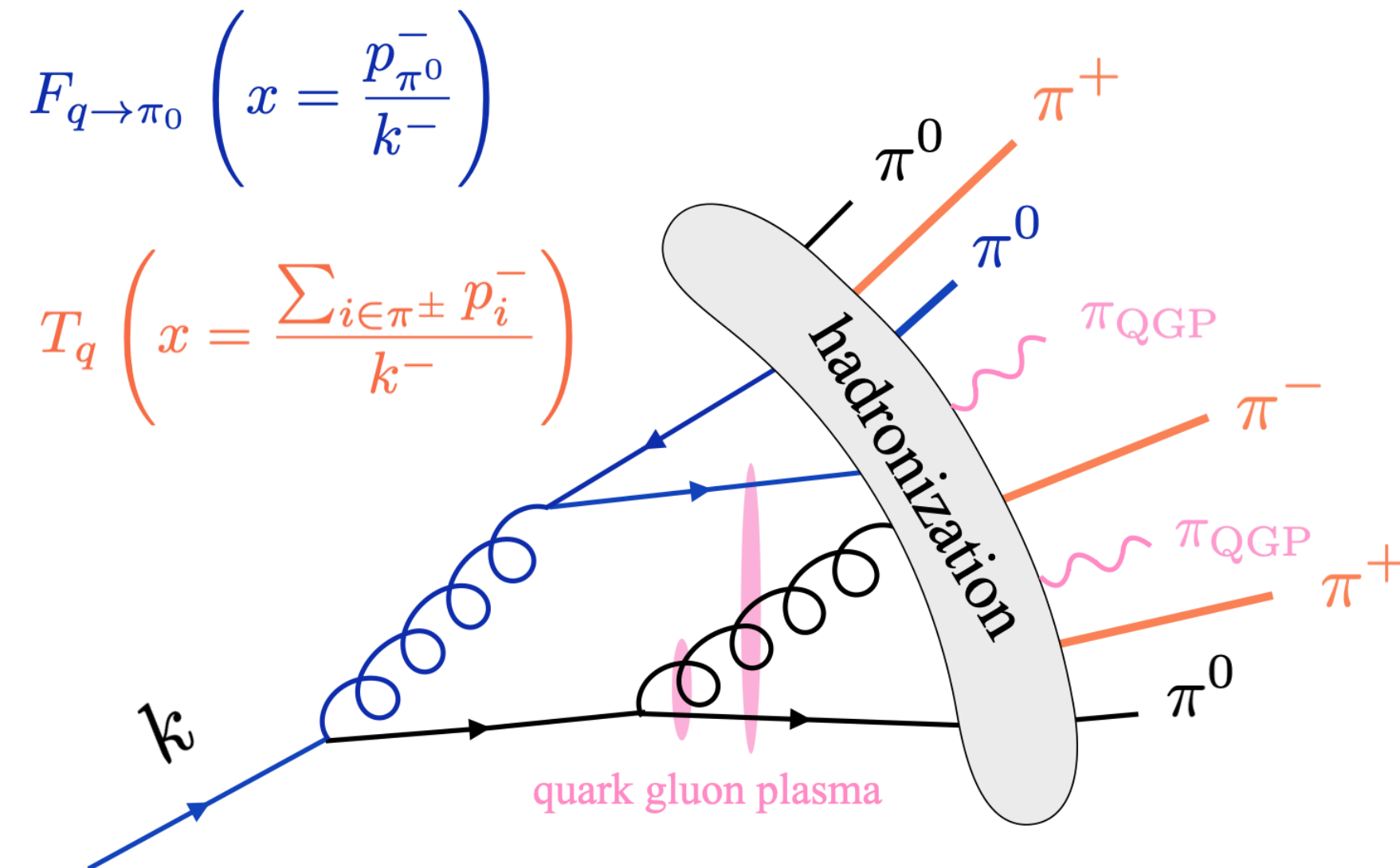
$$\frac{1}{\sin \Psi} \frac{d\Sigma}{d\chi d\Psi} = \underbrace{\sum_{\tau} (c_{\tau,0} + b_{\tau>2,0} + a_{\tau>2,0}) \chi^{\tau-3} + \sum_{\tau>2} (c_{\tau,2} + a_{\tau>2,2}) \chi^{\tau-3} \cos(2\Psi) + \sum_{\tau>4} (c_{\tau,4} + a_{\tau>2,4}) \chi^{\tau-3} \cos(4\Psi) + [J \geq 5]}_{J=3}$$

[matches light-ray decomposition in M. Kologlu, et al, 1905.01311; H. Chen, et al, 2505.16753]

Outlook: non-linear fragmentation in HICs

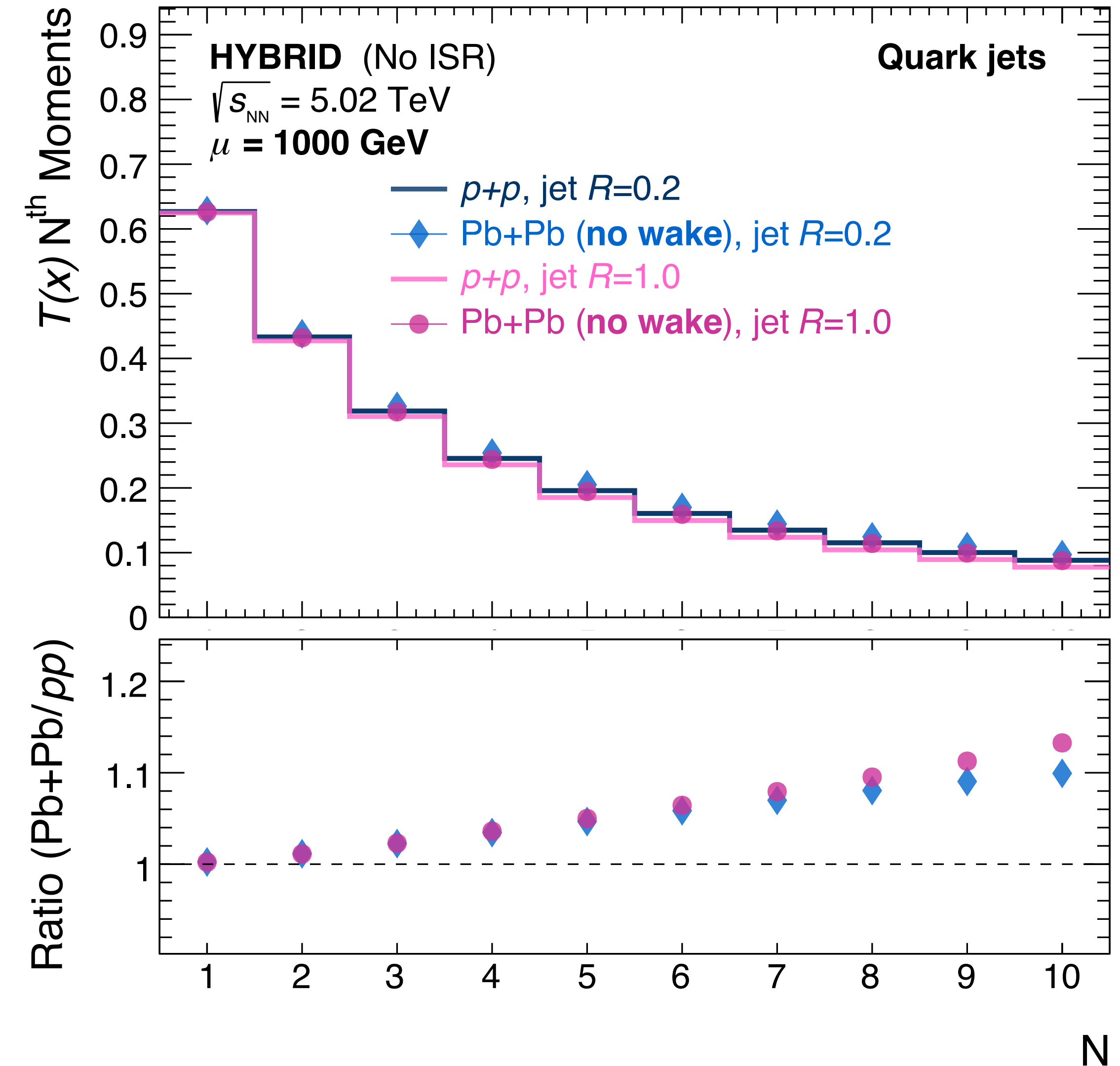
[JB, Y. Go, D. Pablos, in progress]

[JB, R. Szafron, 2401.04164]



$$T_q(x) = \int dy^+ d^2 y_\perp e^{ik^- y^+ / 2} \frac{1}{2N_c} \sum_{C,N} \delta \left(x - \frac{p_C^-}{k^-} \right) \times \text{tr} \left[\frac{\gamma^-}{2} \langle 0 | \psi(y^+, 0, y_\perp) | CN \rangle \langle CN | \bar{\psi}(0) | 0 \rangle \right]$$

$$\frac{d\Sigma^{(n)}}{d\theta}_{\text{tracks}} = \int_{E_1, E_2} \int_{x_1, x_2} x_1^n T(x_1) x_2^n T(x_2) \frac{E_1^n E_2^n}{Q^{2n}} \frac{d\sigma}{\sigma dz d\theta}$$



Thank you !

