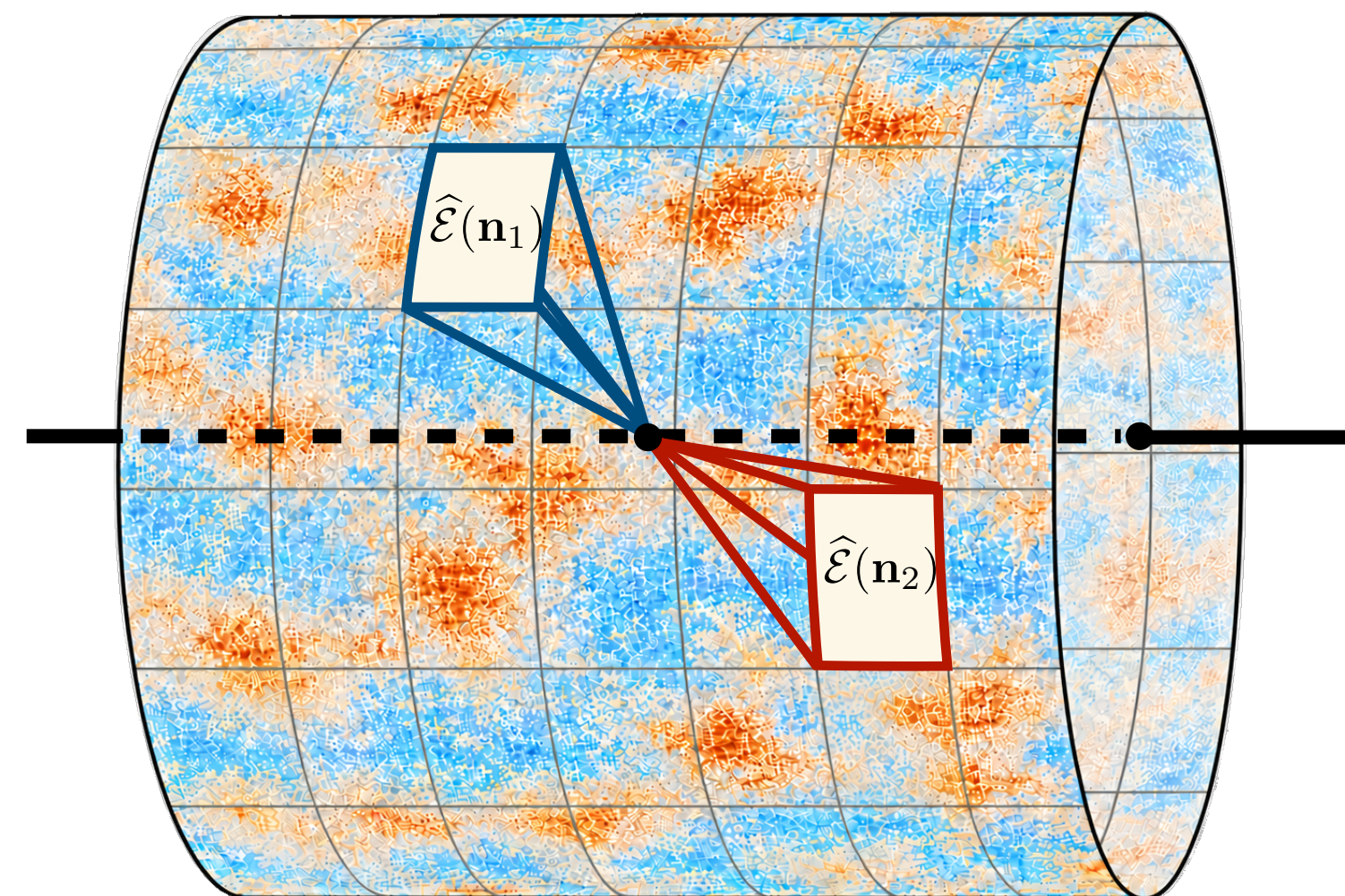


Describing physical systems with detector operators

SUBATECH, 10th September 2026



Mainly based on: 2412.03616, 2503.13603, 2508.19404, 2604.21971 and wip

João Barata, CERN-TH

How to test a theory

[Caron-Huot, et al, 2209.00008]



One natural way to study a theory is to
measure it locally ...

$$\langle \hat{O}(x) \hat{O}(0) \rangle$$

... we are however **never allowed** to ask such
questions at colliders

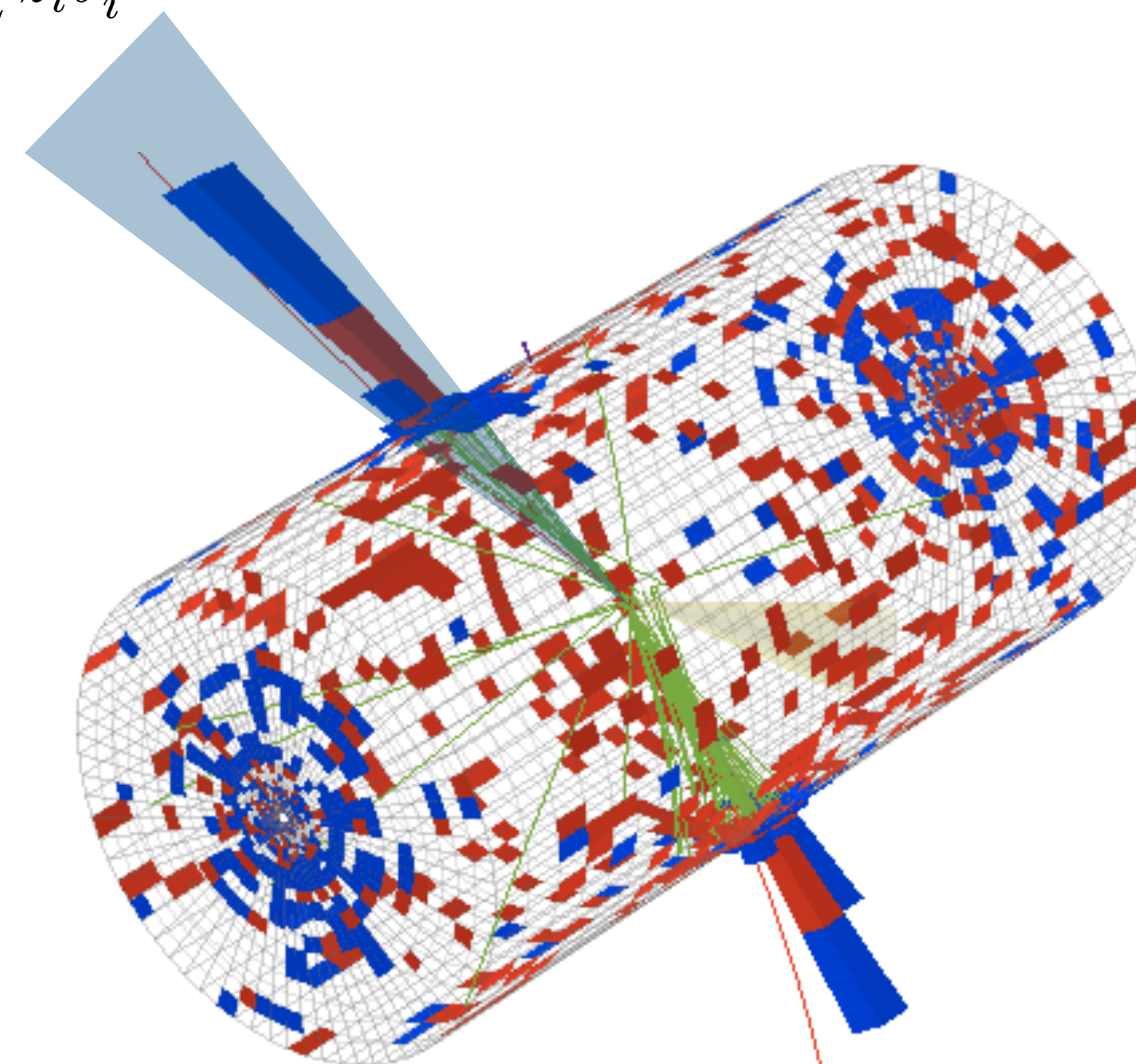
How to test a theory

[Caron-Huot, et al, 2209.00008]

$$O_{m^2} = \sum_i z_i \theta_i^2$$



≈

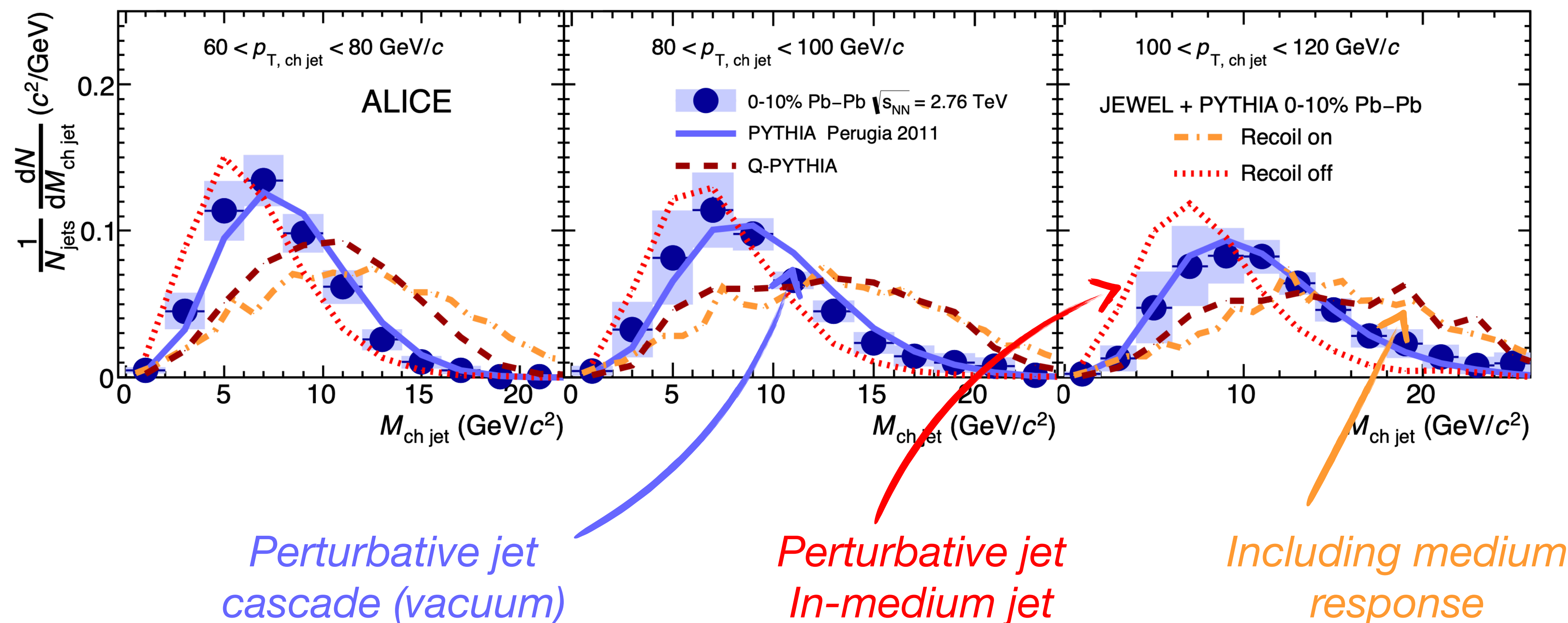


Instead one can compute “shapes” of final state particle distributions

$$\int d^4x e^{iq^\mu x_\mu} \langle \Omega | \underbrace{\hat{O}(x)}_{\text{hammer}} \mathcal{M}[\hat{o}] \underbrace{O^\dagger(0)}_{\text{hammer}} | \Omega \rangle, \quad \text{e.g.} \quad \mathcal{M}[\hat{o}] = \delta(\hat{o} - o)$$

How to test a theory

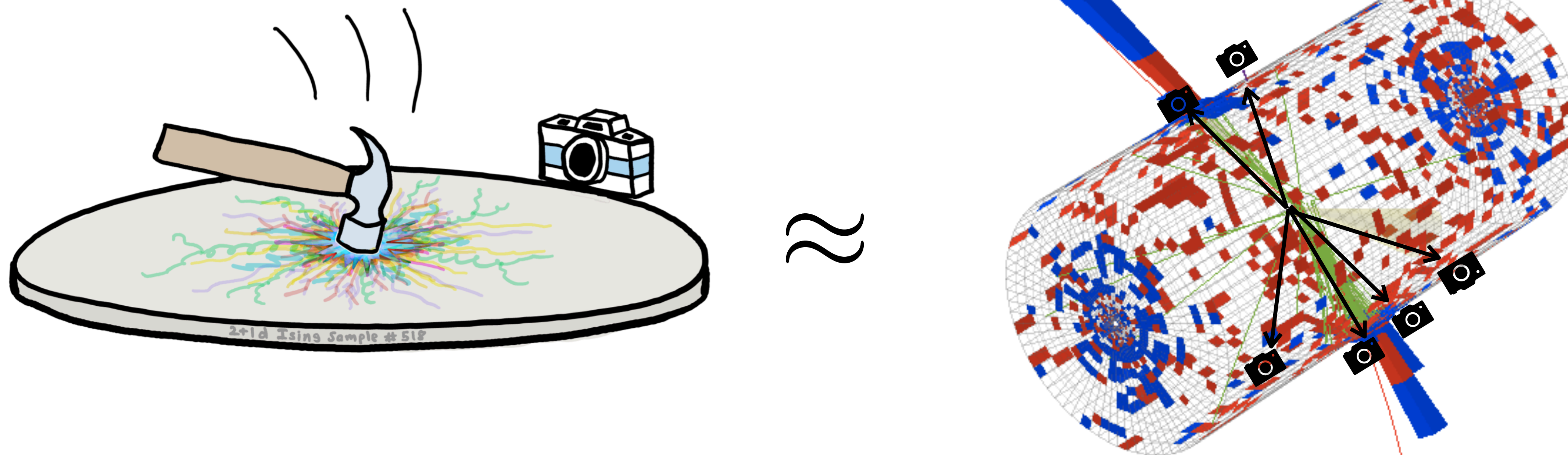
[Caron-Huot, et al, 2209.00008]



“Shape” observables are badly defined from **QFT** point of view and this propagates down to **experimental** level

How to test a theory

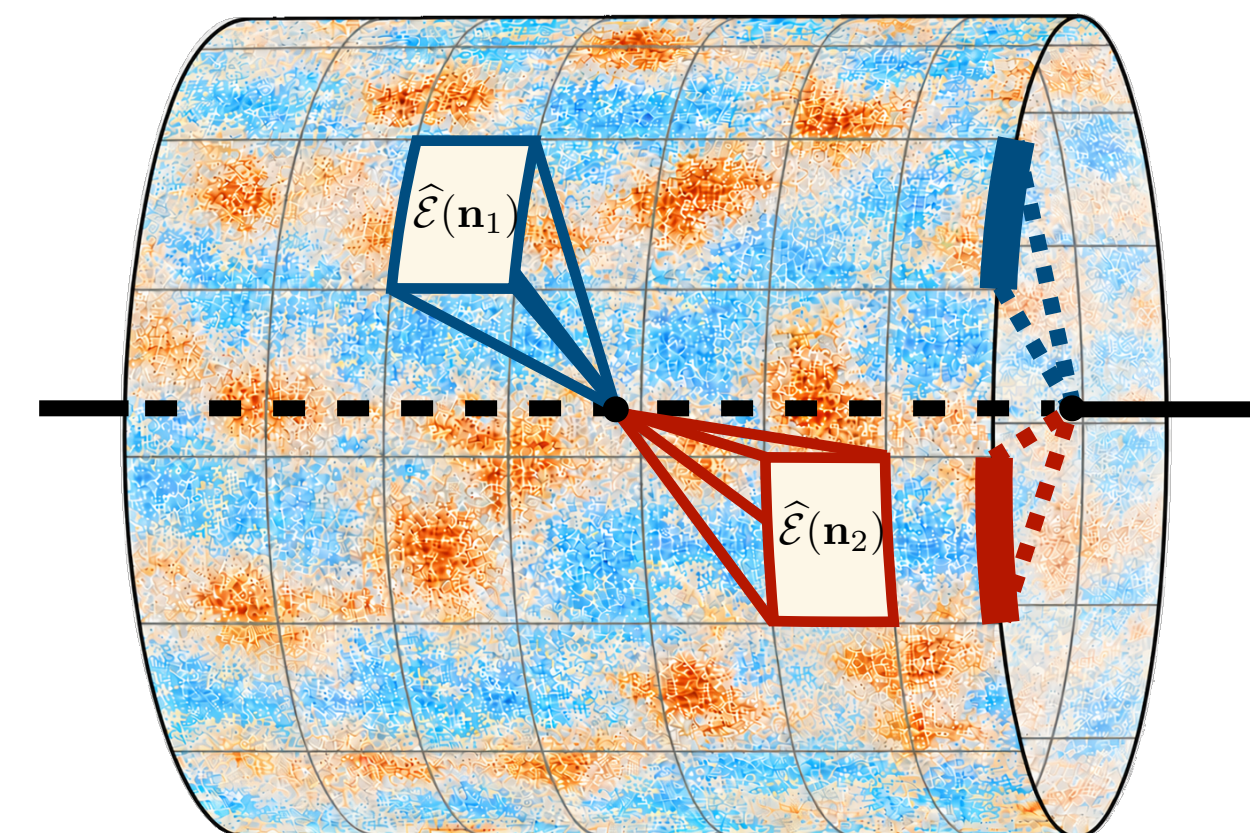
[Caron-Huot, et al, 2209.00008]



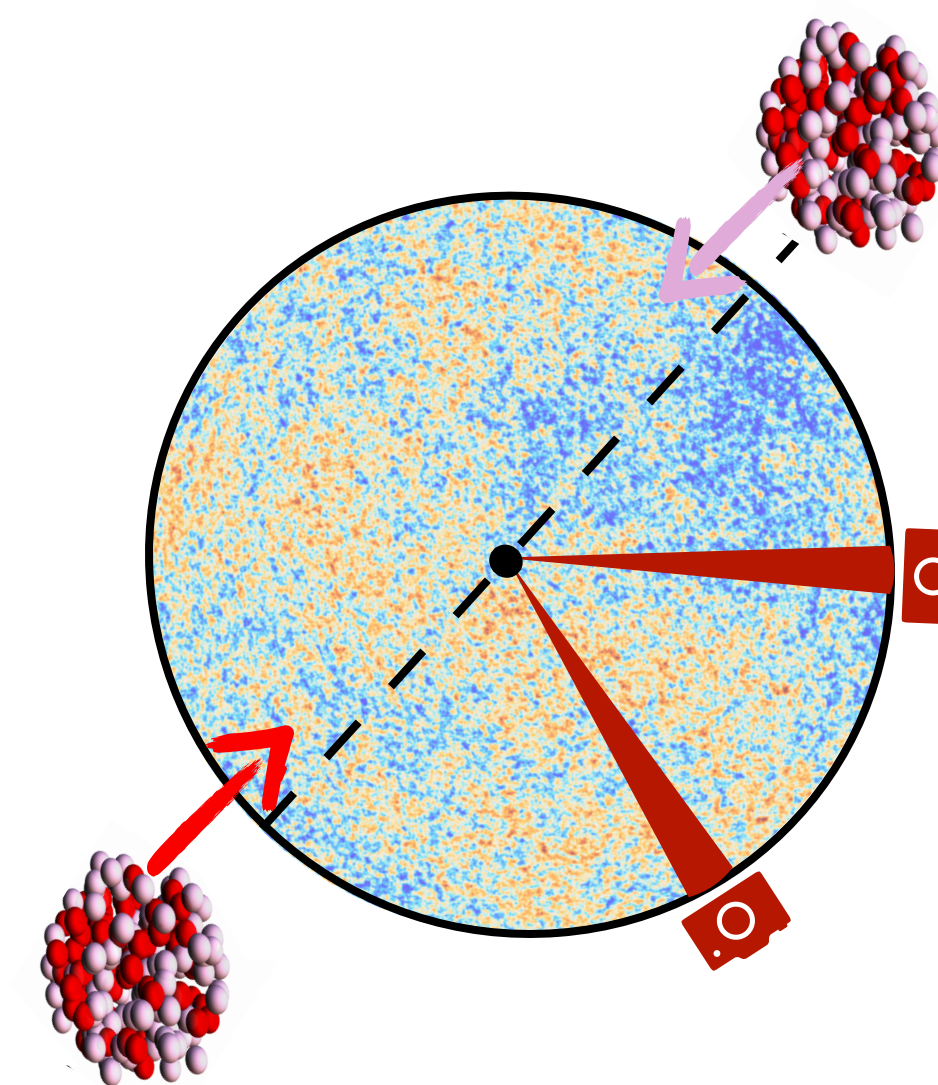
Recent push towards reformulating collider observables in terms of flows of conserved charges

$$\int d^4x e^{iq^\mu x_\mu} \langle \Omega | \hat{O}(x) \mathcal{E}(\vec{n}_1) \cdots \mathcal{E}(\vec{n}_N) \hat{O}(0) | \Omega \rangle, \quad \text{where} \quad \mathcal{E}(\vec{n}) | P \rangle = \sum_i E_i \delta(\Omega_{\vec{n}} - \Omega_{\vec{k}_i}) | P \rangle$$

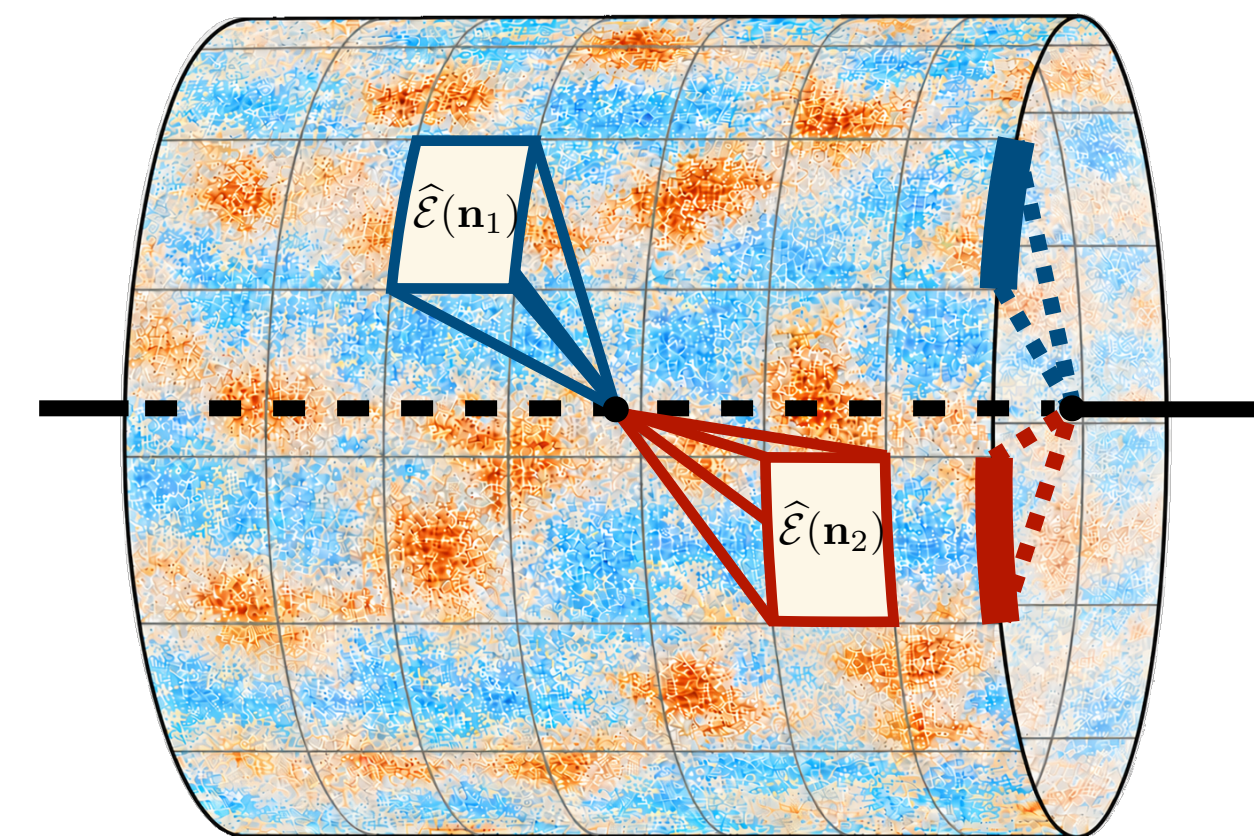
Detector operators and energy correlators



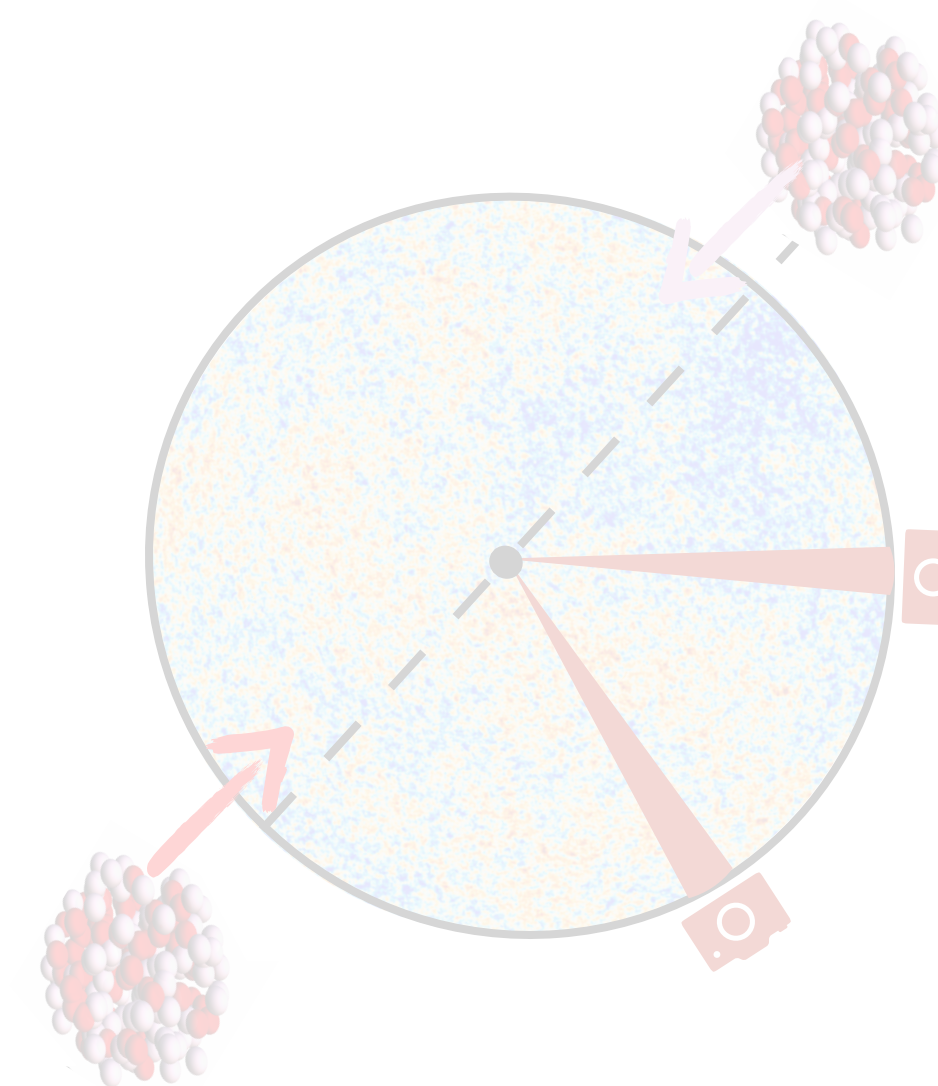
Energy correlators in HICs



Detector operators and energy correlators

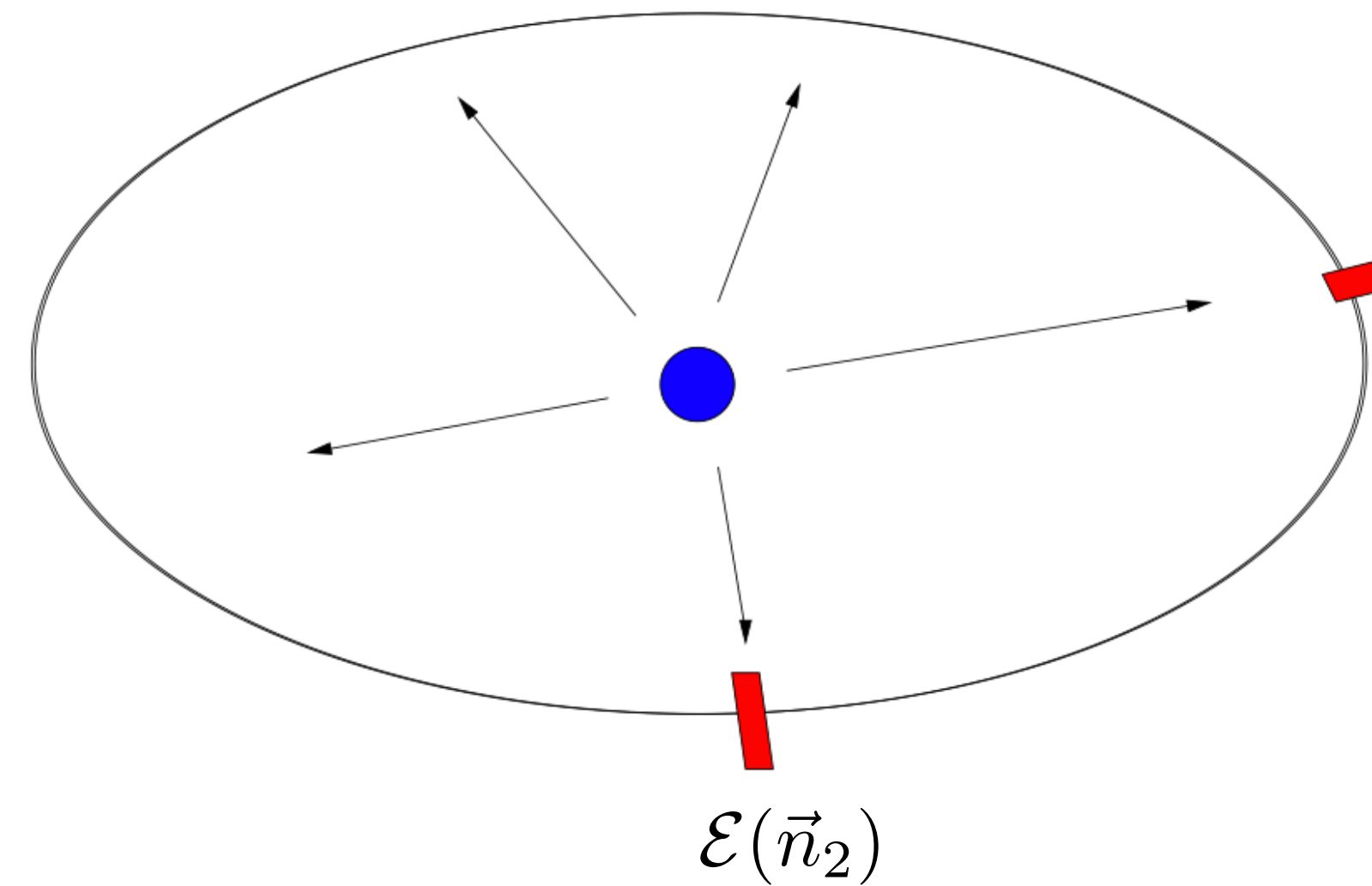


Energy correlators in HICs



Energy flow operator revival [Hoffmann, Maldacena (2008)]:

Local correlations in a given QFT can be directly connected to **correlations between detectors**

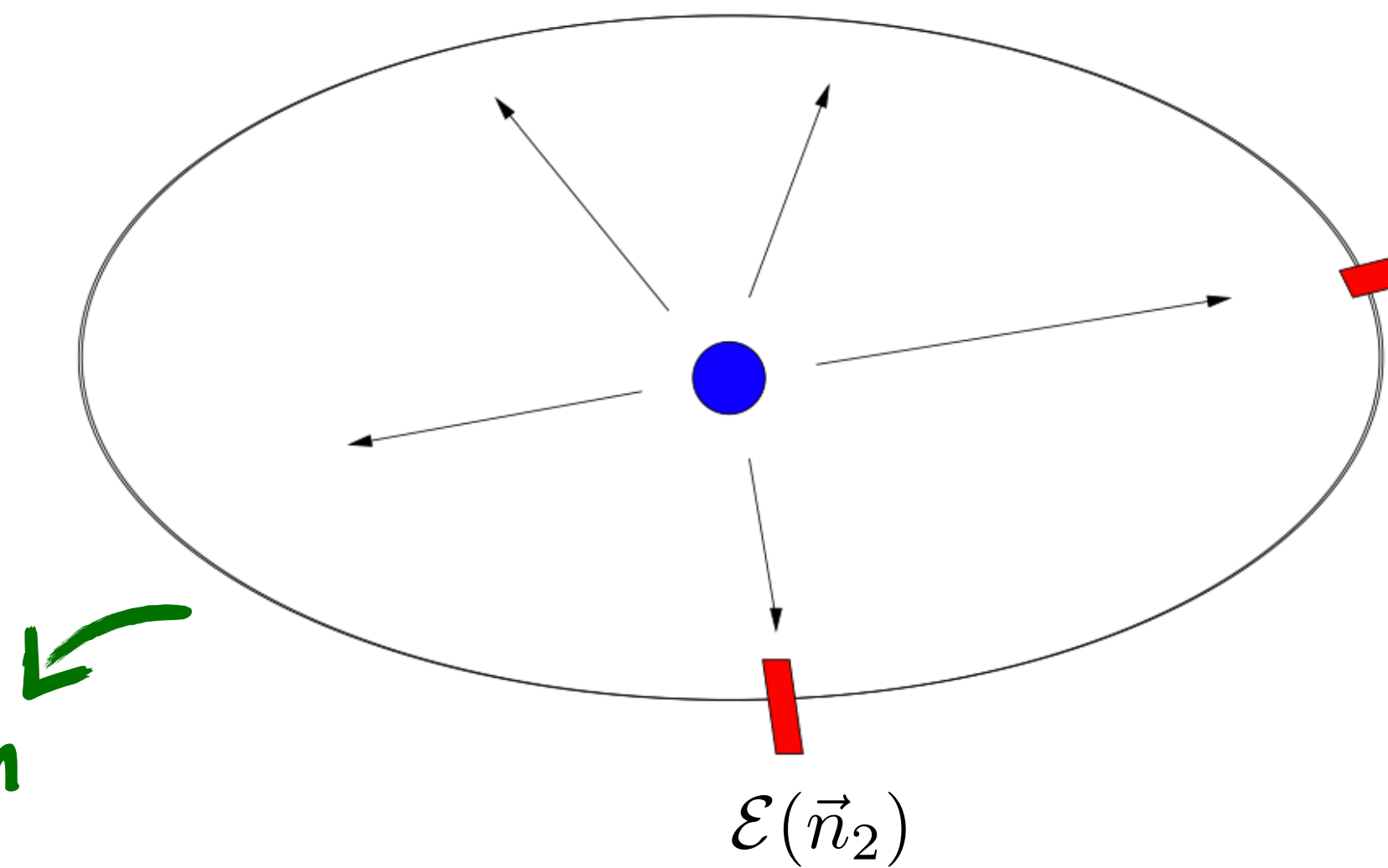


[Stern, 1970s]

[Svesnikov, Tkachov, 1990s]

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[Sternan, 1970s]

$\mathcal{E}(\vec{n}_1)$ [Svesnikov, Tkachov, 1990s]

Cross-section level definition

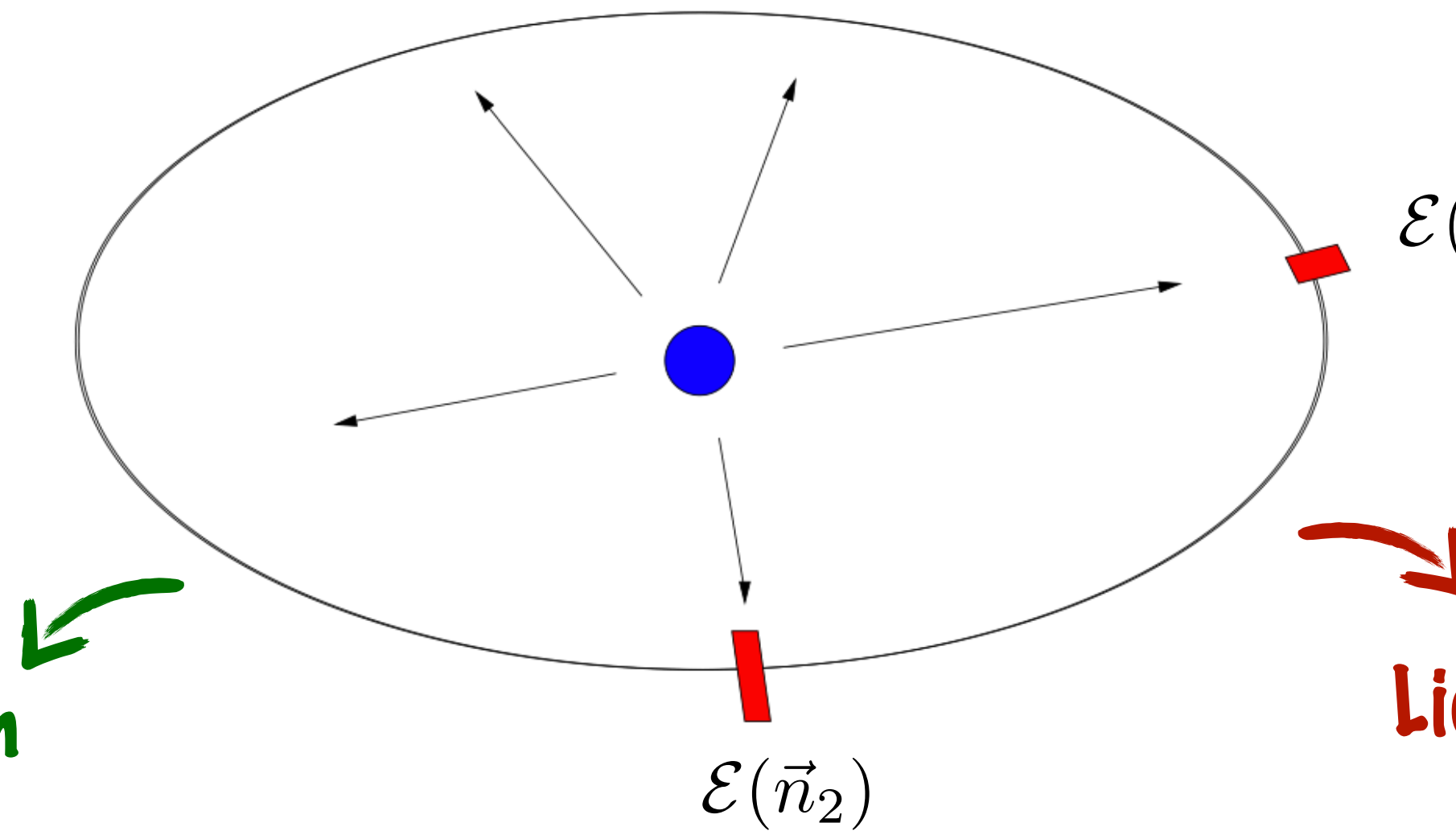
[Basham, et al, 1970s]

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

Useful for contributions computed from cross-sections

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$$S_N \left[\sum_{b=1}^N \frac{E_b}{W} \delta(\Omega_b - \Omega) \right]$$

Light-ray operator based definition

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

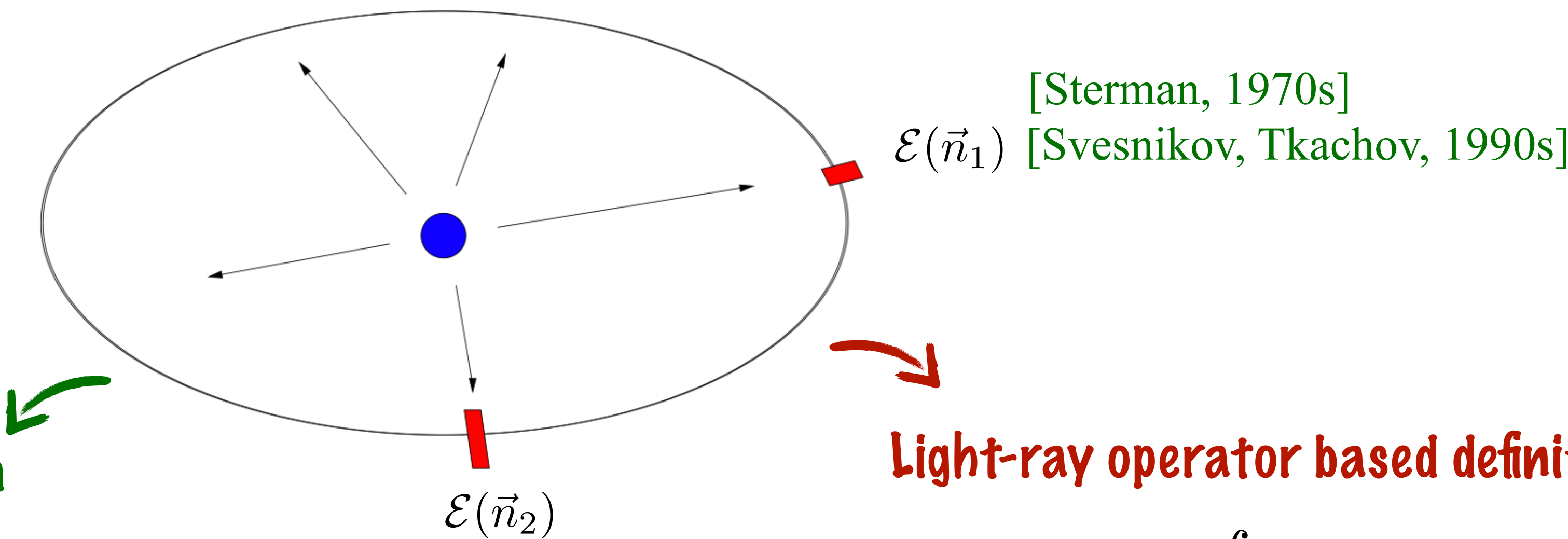
$$d\Sigma \sim \langle \Omega | J^\dagger \mathcal{E}(\vec{n}) J | \Omega \rangle$$

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Allows to constrain result from symmetry arguments beyond S-matrix picture

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Experiment

$$d\Sigma \sim \langle \Omega | J^\dagger \mathcal{E}(\vec{n}) J | \Omega \rangle$$

Useful for contributions computed from cross-sections

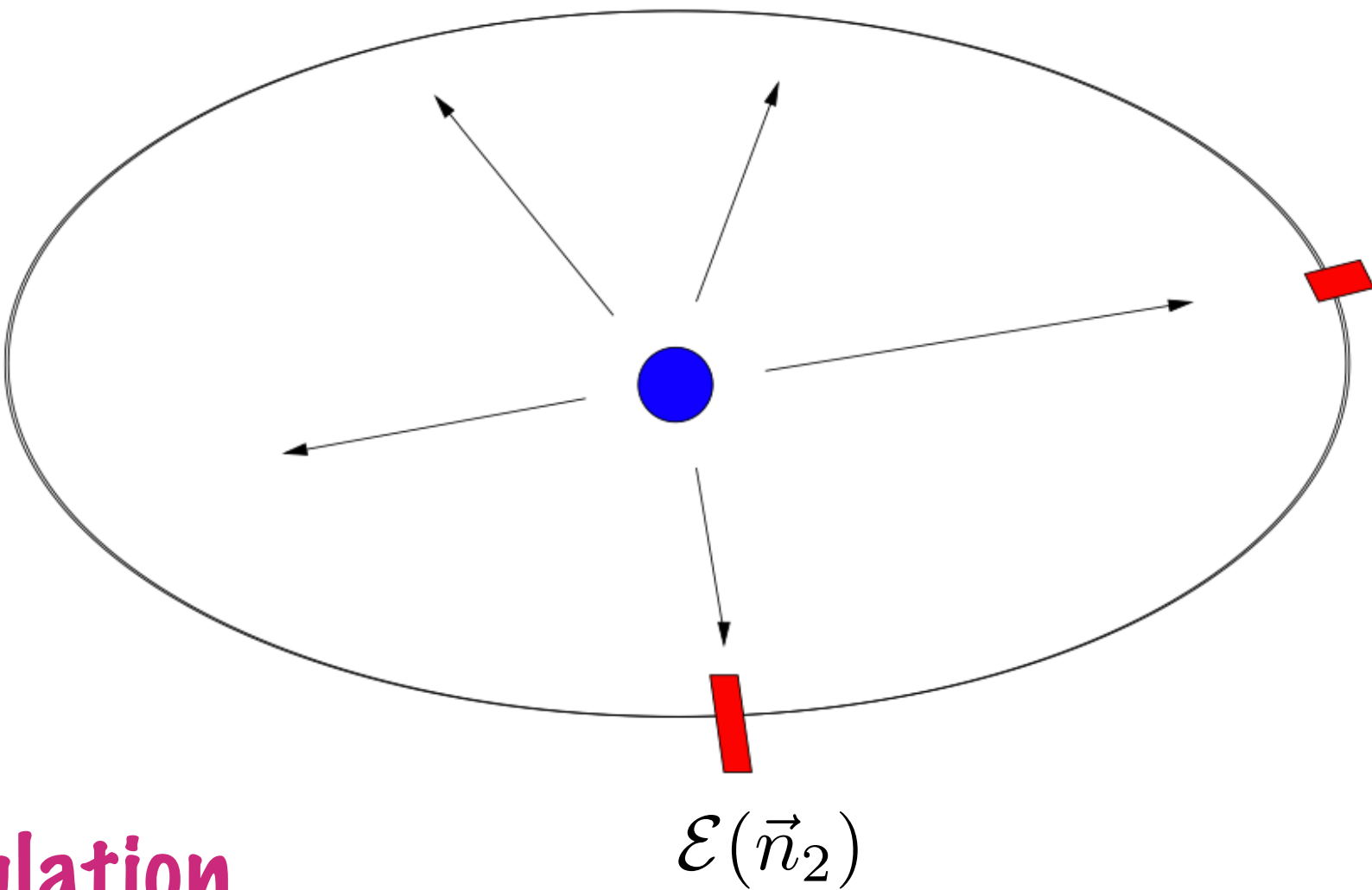
$$\mathcal{E}(\mathbf{n})|\text{out}\rangle = \sum_{i \in \text{out}} E_i \delta^{(2)}(\mathbf{n}_i - \mathbf{n})|\text{out}\rangle$$

Allows to constrain result from symmetry arguments beyond S-matrix picture



Energy flow operator revival [Hoffmann, Maldacena (2008)]:

Local correlations in a given QFT can be directly connected to **correlations between detectors**



[Sternan, 1970s]
[Svesnikov, Tkachov, 1990s]

General cross-section formulation

$$\langle \mathcal{E}(n_1) \cdots \mathcal{E}(n_k) \rangle = \int d\sigma \varepsilon(n_1) \cdots \varepsilon(n_k)$$

[Bellin et al, 2026]

Detector Operator decomposition

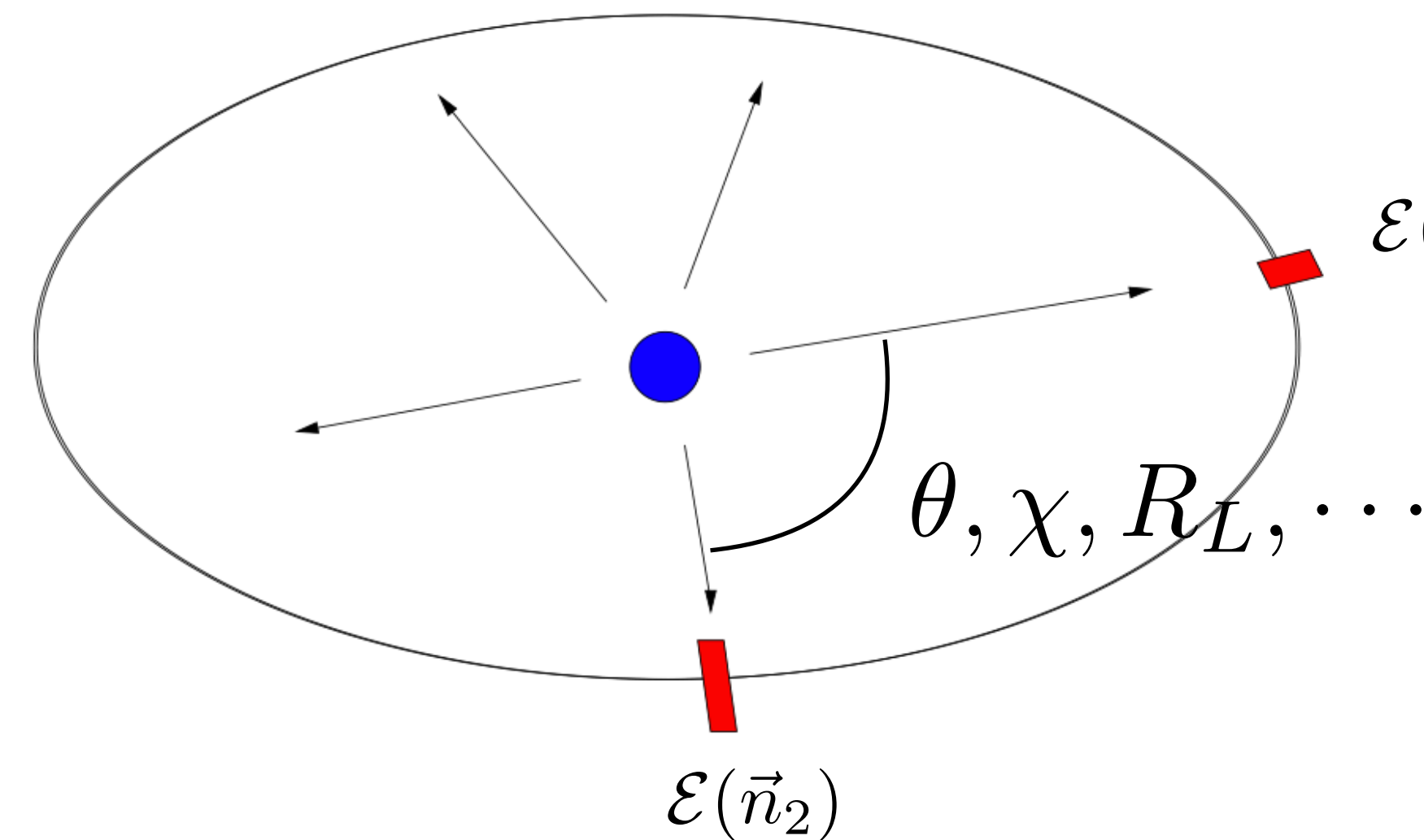
$$\lim_{n_1 \rightarrow n_2} \mathcal{E}(n_1) \mathcal{E}(n_2) = \frac{1}{x_L} \vec{C} \cdot \vec{\mathbb{O}}_{\tau=2}^{[J=3]}(n_2) + \cdots$$

Collider operator basis

$$\delta(e - \hat{e}) = \delta(e) + \hat{e} \delta^{(1)}(e) + \cdots + \frac{\hat{e}^n}{n!} \delta^{(n)}(e) + \cdots$$

Energy flow operator revival [Hoffmann, Maldacena (2008)]:

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$\mathcal{E}(\vec{n}_1)$ [Svesnikov, Tkachov, 1990s]

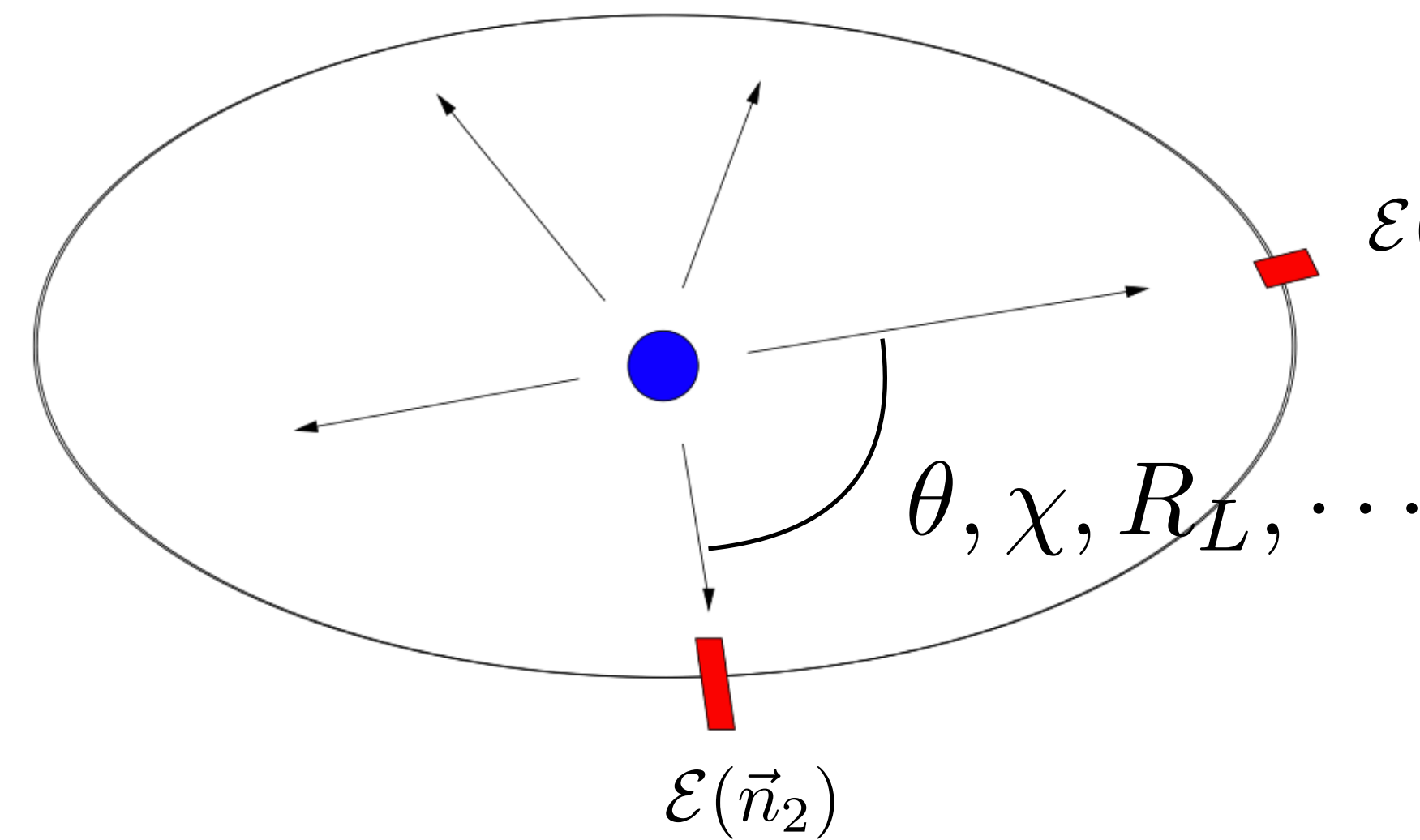
$$\frac{d\Sigma}{d\theta} = \int_{\vec{n}_1, \vec{n}_2} \frac{\langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \rangle}{p_t^2} \delta(\vec{n}_1 \cdot \vec{n}_2 - \cos \theta) \quad \longleftrightarrow \quad \frac{d\Sigma}{d\theta} = \int_z \frac{d\sigma}{\sigma d\theta dz} \underbrace{z(1-z)}_{\text{IR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

$$\sim P(z) \frac{1}{\theta}$$

In the collinear limit: $\sim \frac{1}{\theta^\alpha}$ with exponent determined by anomalous scaling

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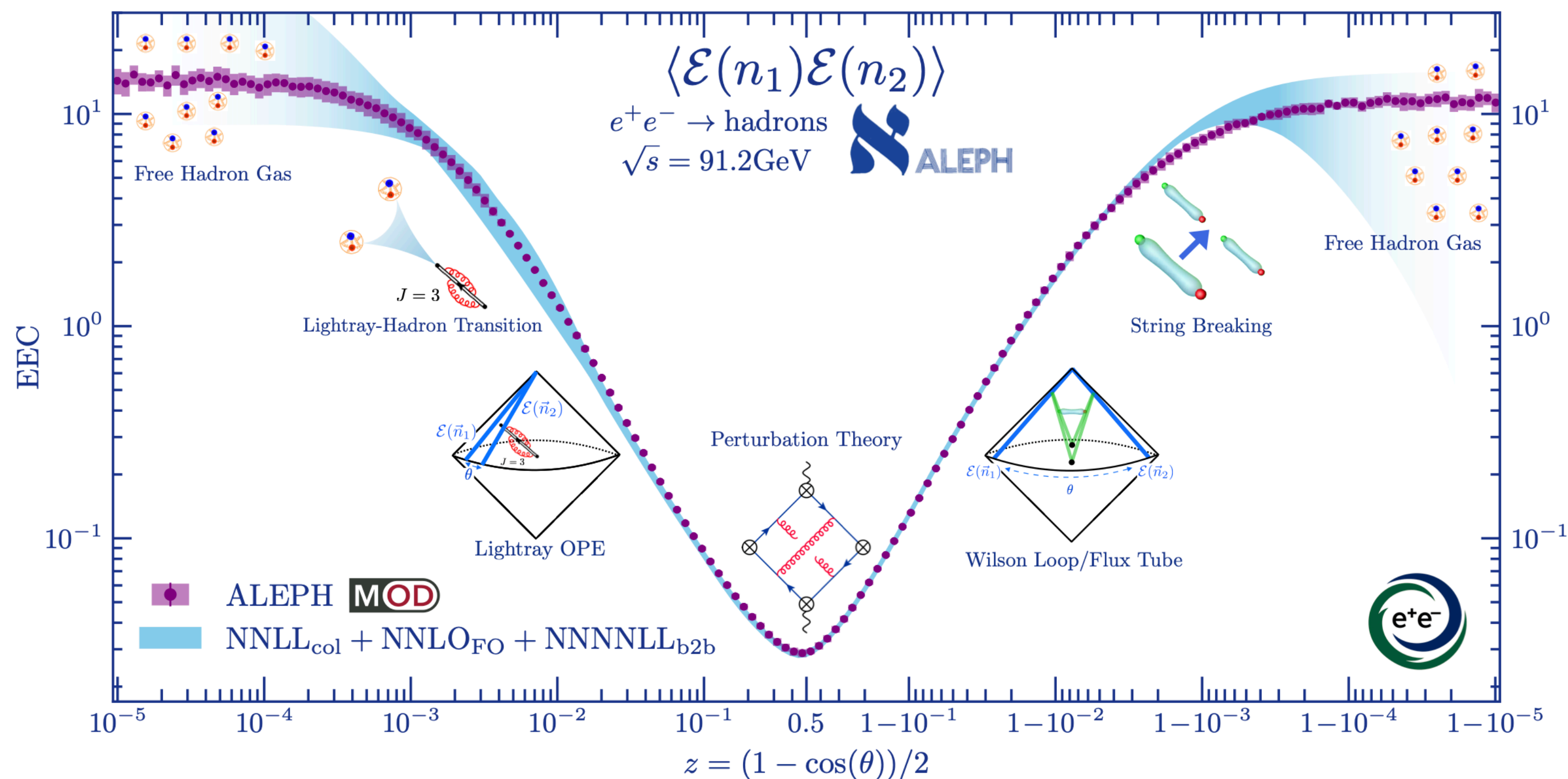
In the collinear limit: $\sim \frac{1}{\theta^\alpha}$ with exponent determined by anomalous scaling

In HICs: New angular scaling connected to properties of matter!

EECs across collisional systems: e+e- and pp

EEC gives a clean separation between different physical regimes

[EP Alliance, 2511.00149]

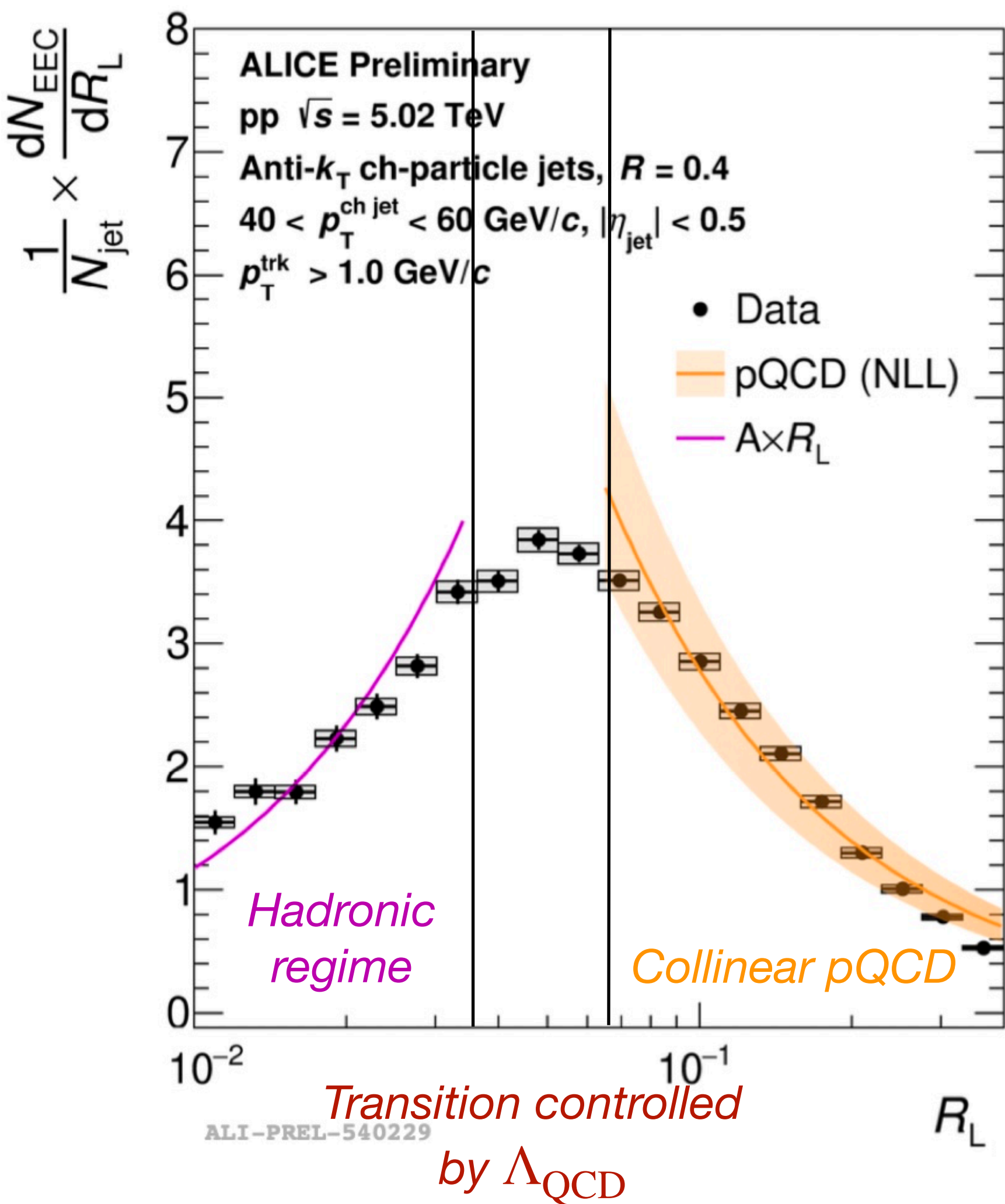


[Basham, et al, 1970s]

[Sternan, et al, 1970s]

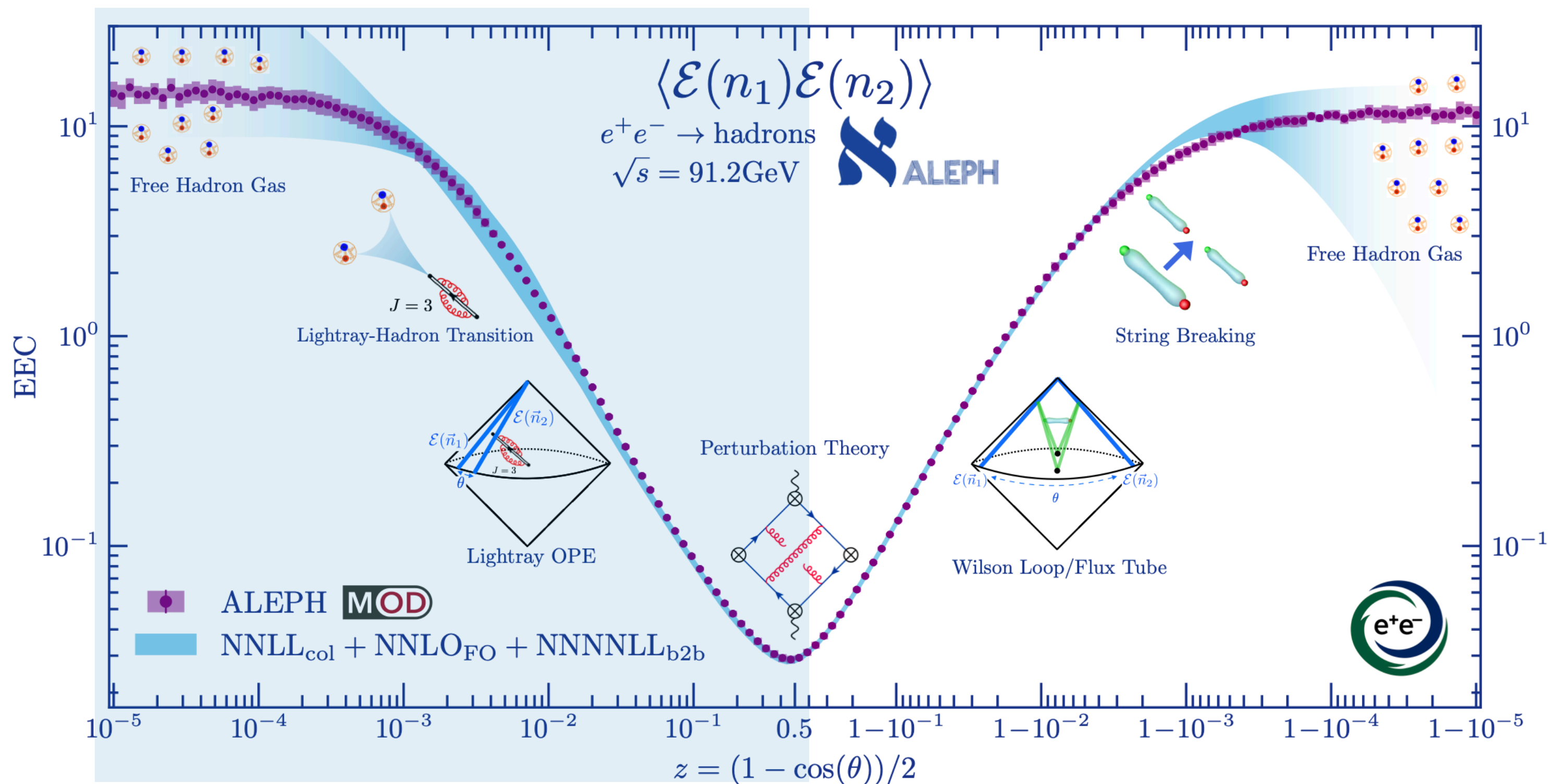
$$\frac{d\Sigma}{d \cos \theta} = \sum_{i \neq j} \frac{E_i E_j}{E^2} \delta(\mathbf{n}_i \cdot \mathbf{n}_j - \cos \theta)$$

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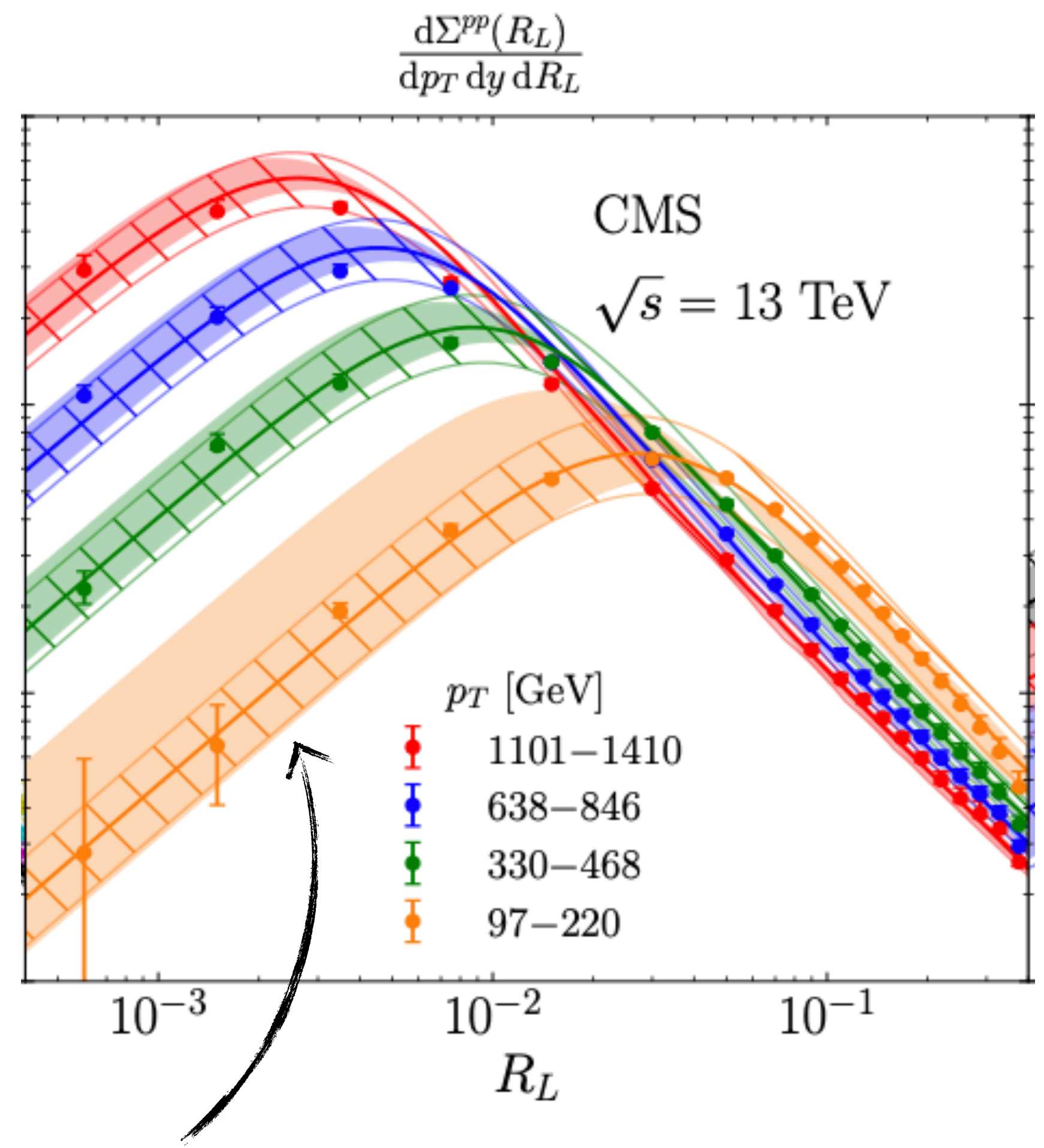
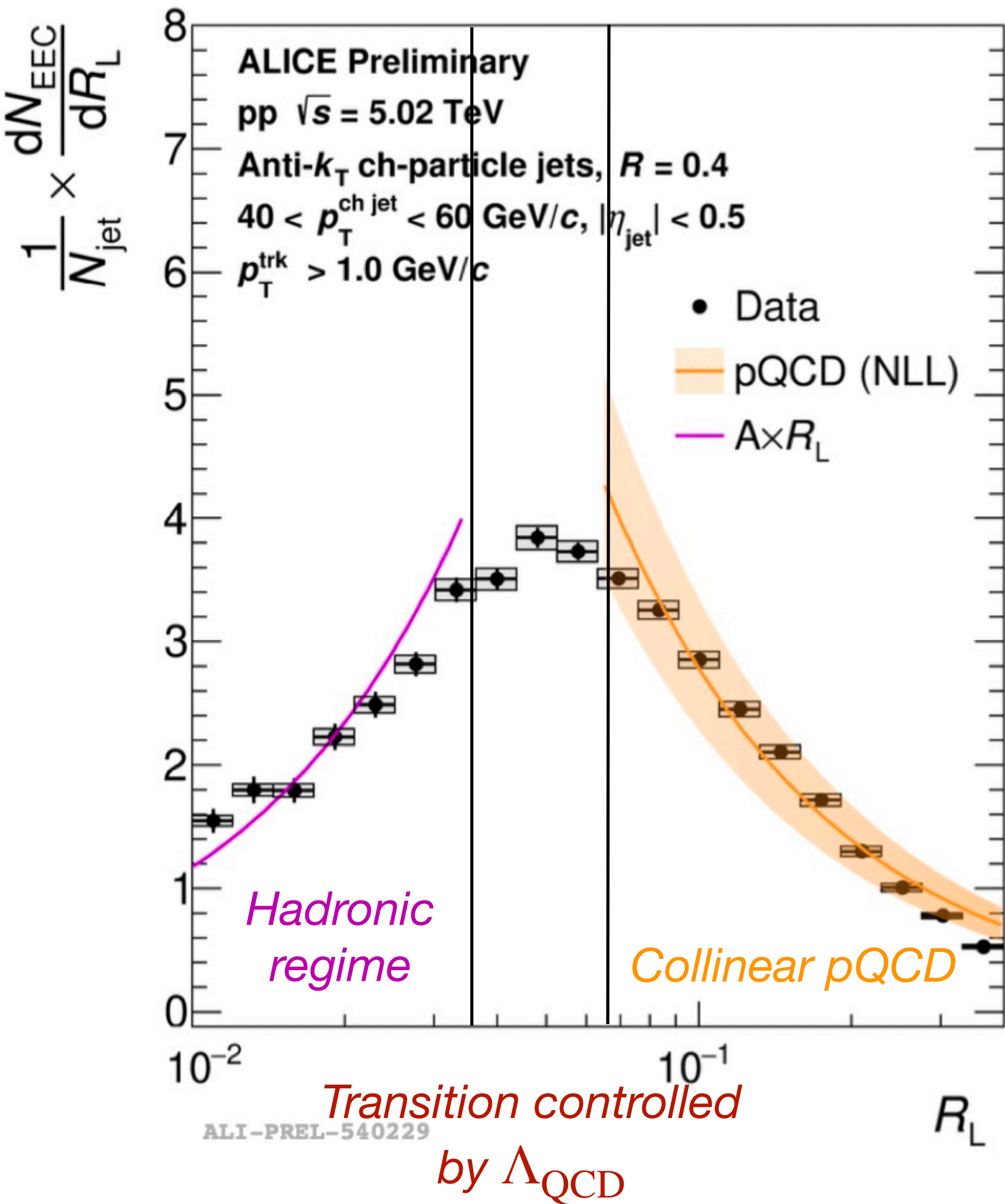
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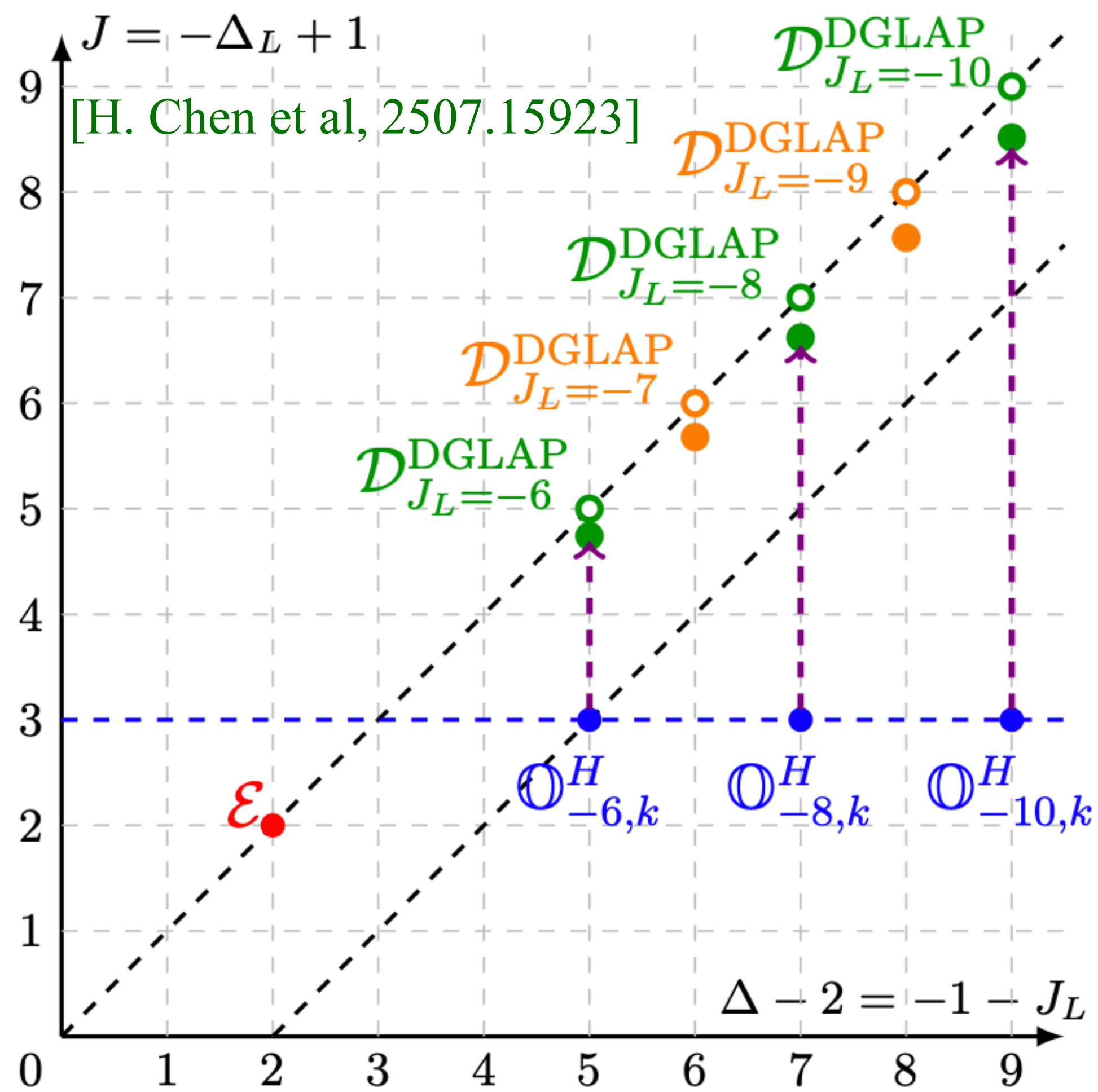
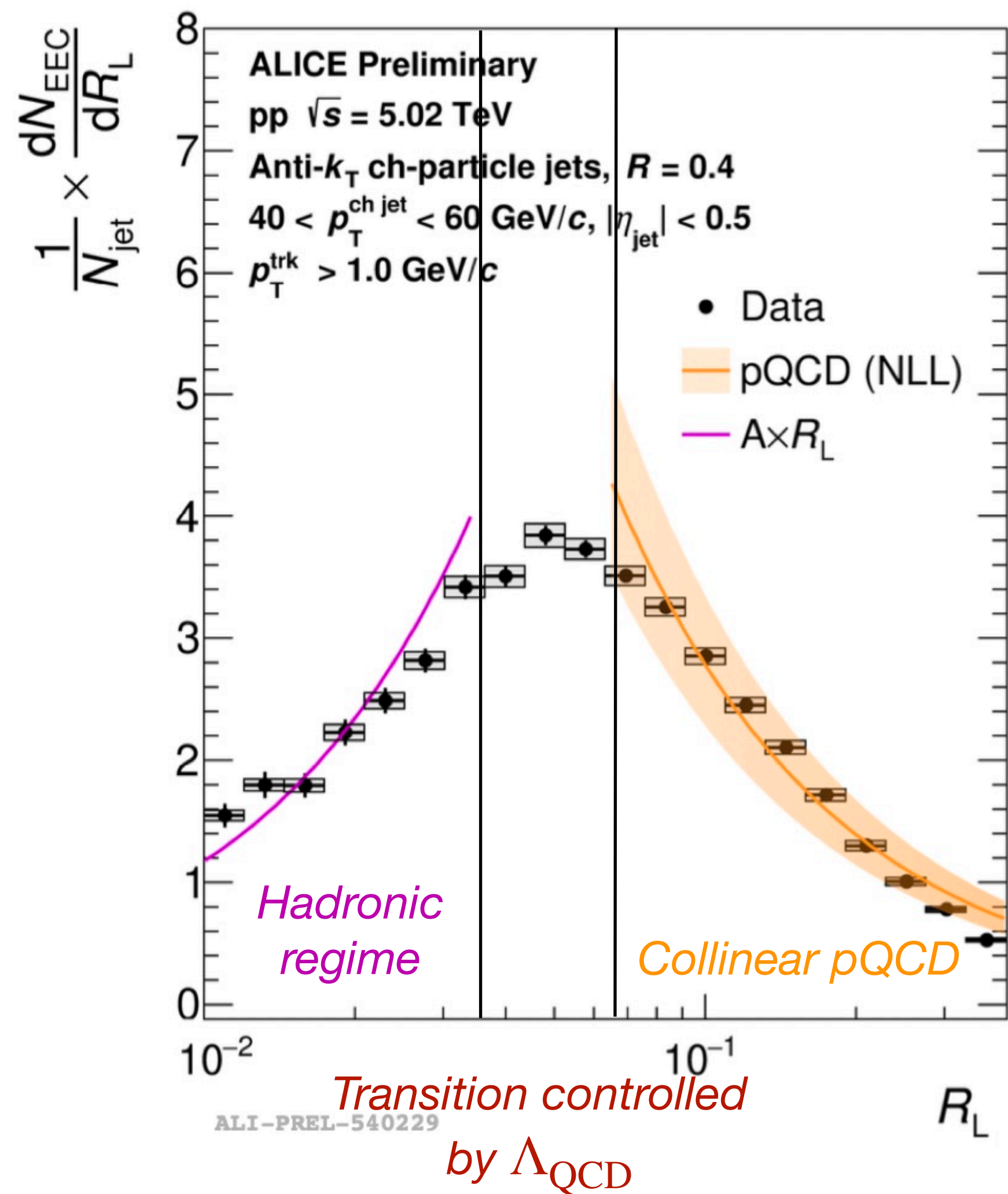


$$j^i(b, \mu_{b_*}) = j_{\text{pert}}^i(b_*, \mu_{b_*}) j_{\text{np}}^i(b) \quad j^i(b) = \sum_{h_1 h_2} \int d^2 \mathbf{p}_1 d^2 \mathbf{p}_2 dz_1 dz_2 (z_1 z_2) e^{i \mathbf{b} \cdot (\mathbf{p}_1/z_1 - \mathbf{p}_2/z_2)} \mathbb{D}_{h_1 h_2}^i(z_1, z_2, \mathbf{p}_1, \mathbf{p}_2)$$

EEC gives a clean separation between different regimes

Valid from pp to e^+e^- :
universality of jet function

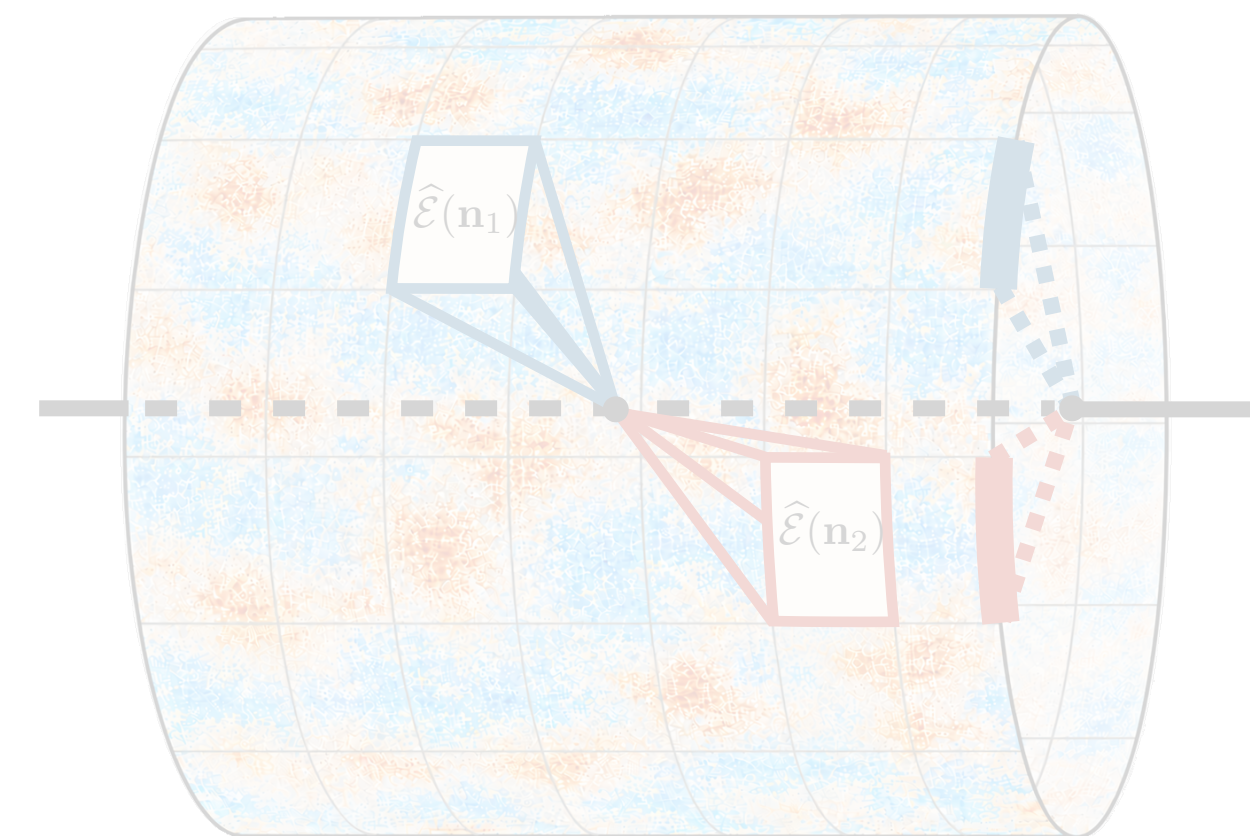
Hadronic phase well described
from dihadron FFs



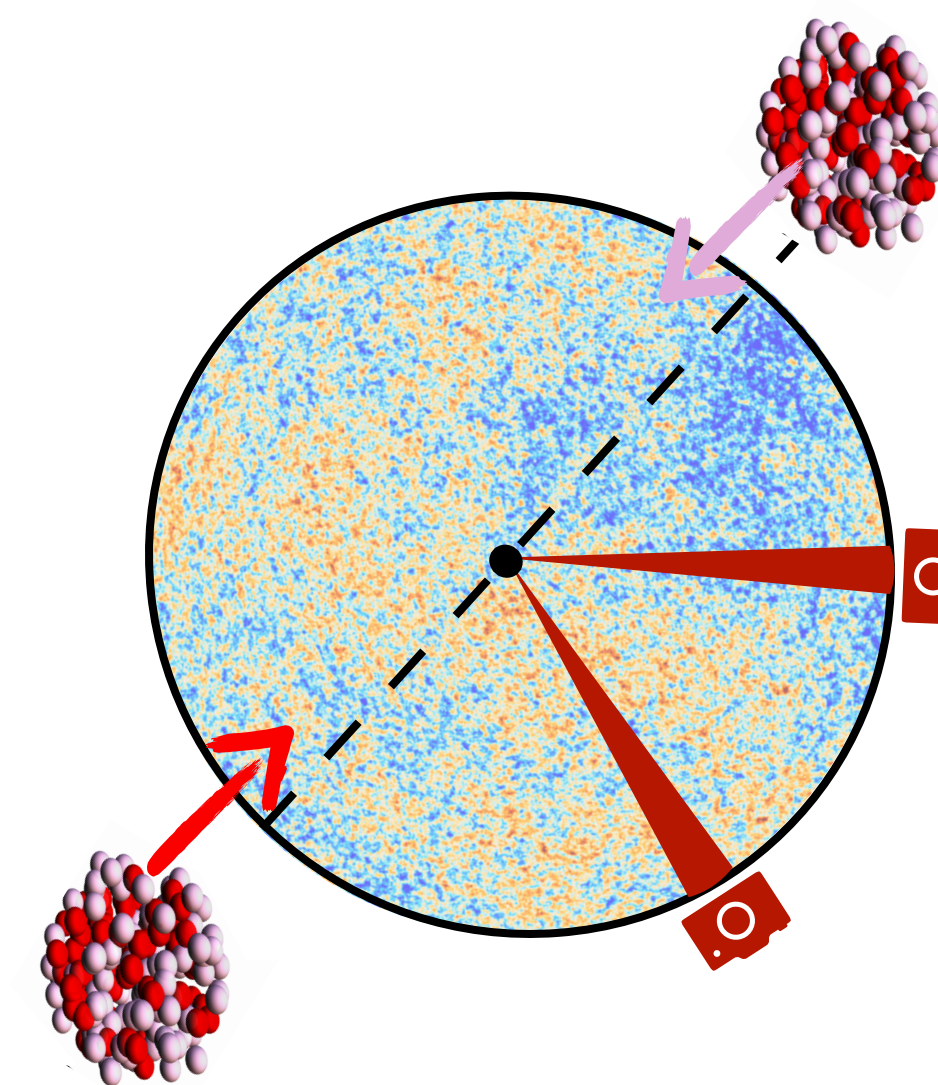
$\mathcal{O}_{\text{hadrons}}$ $\rightarrow$ $\mathcal{D}_{\text{detector}}$

EEC gives a clean separation between different regimes

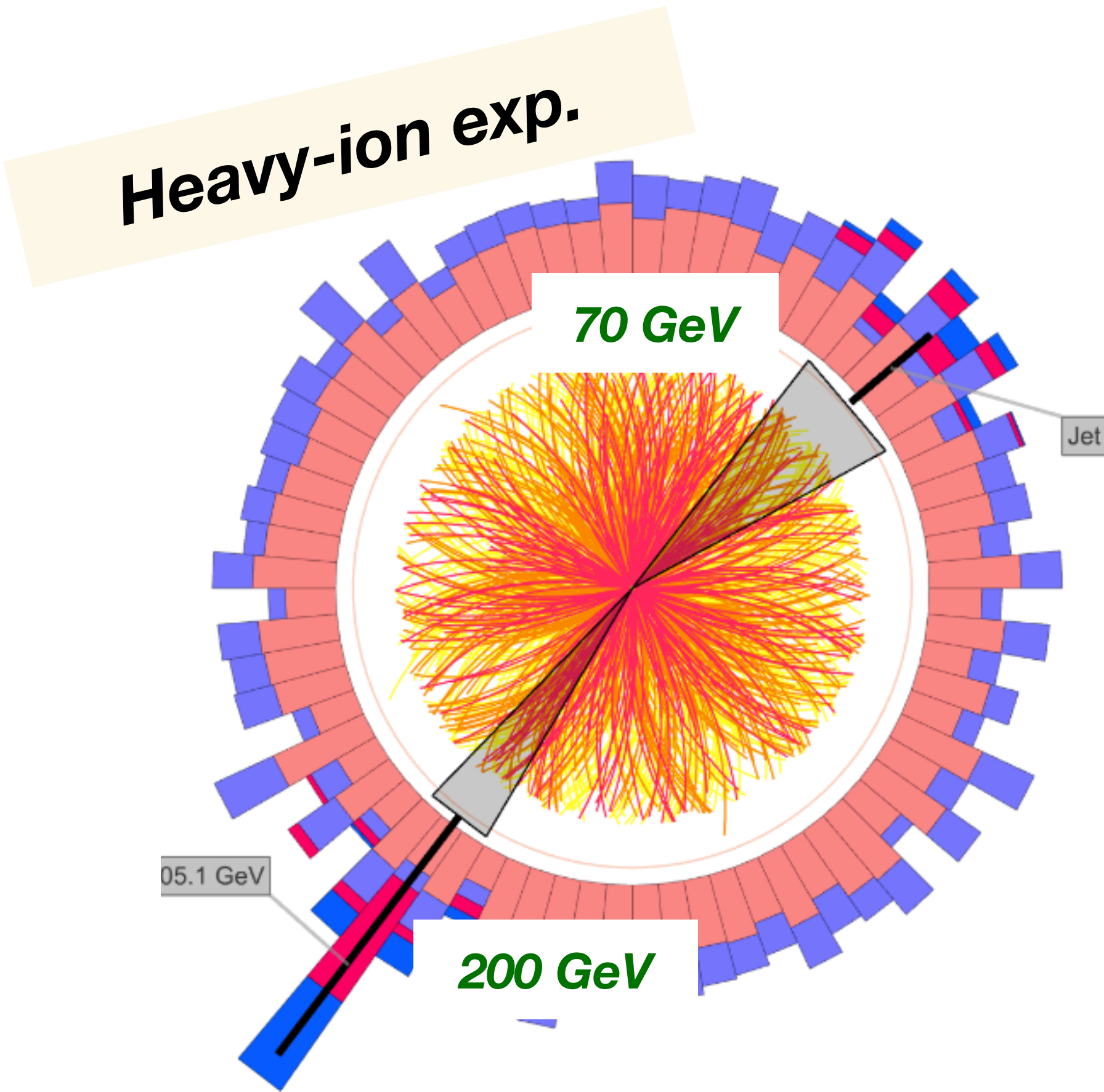
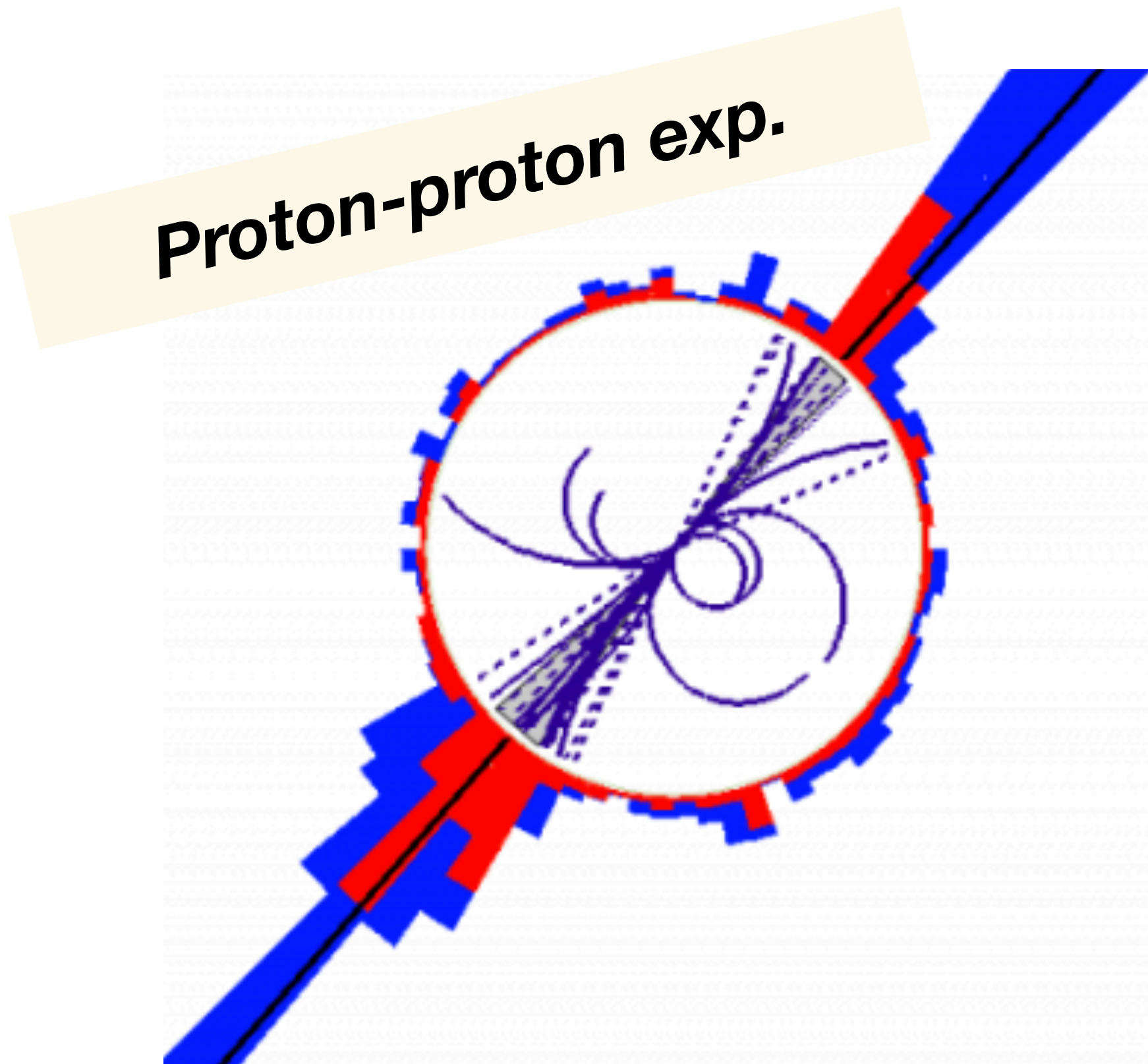
Detector operators and energy correlators



Energy correlators in HICs



Probing heavy ion collisions using jets



Energy correlators in HICs: perturbative contribution

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

$$\frac{d\Sigma^{q \rightarrow qg}}{d\chi} \approx \frac{2\bar{\alpha}}{\chi} \int_0^1 dz z(1-z) P_{gq}(z)$$

Simplest form from general factorization formula:

$$\begin{aligned} \frac{d\Sigma_H(z)}{d\eta dp_T} = & \sum_{i,j,k} \int \frac{dx_i}{x_i} f_{i/p}(x_i, \mu) \int \frac{dx_j}{x_j} f_{j/p}(x_j, \mu) \int \frac{dz_k}{z_k} \mathcal{H}_{ij}^k(x_i, x_j, \eta, p_T/z_k, \mu) \\ & \left[\int_0^1 dy y^2 \mathcal{J}_{kl} \left(z_k, y, \ln \frac{p_T^2 R^2}{z_k^2 \mu^2}, \mu \right) J_H^l \left(\ln \frac{y^2 4 p_T^2 z}{\mu^2}, m_Q, \mu \right) \right] \\ & \rightarrow \delta(y-1) \delta(1-z_k) \end{aligned}$$

single flavor, ignore IS effects

for complete calculation in HICs see [JB, Brewer, Lee, Silva, 2508.19404 + wip]

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Will not discuss matter effects here ↖ **Resummation** ↖ **Perturbative medium correction** ↖ **Energy loss (non-perturbative)**

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Resummation Perturbative medium correction Energy loss (non-perturbative)

Short note on energy loss: [Baier et al, hep-ph/0106347]

$$\frac{d\sigma^{\text{medium}}(p_{\perp})}{dp_{\perp}^2} = \int d\epsilon D(\epsilon) \frac{d\sigma^{\text{vacuum}}(p_{\perp} + \epsilon)}{dp_{\perp}^2} +$$

$$\frac{d\sigma^{\text{vacuum}}(p_{\perp} + \epsilon)/dp_{\perp}^2}{d\sigma^{\text{vacuum}}(p_{\perp})/dp_{\perp}^2} \simeq \left(\frac{p_{\perp}}{p_{\perp} + \epsilon} \right)^n$$

$$\frac{d\Sigma^{\text{Eloss}}}{d\chi} = (Q_q, Q_g) \cdot \mathcal{J}(\chi) \otimes \mathcal{H}(p_t)$$

Q-weights encode NP process of fast thermalization of gluon energy to the bulk

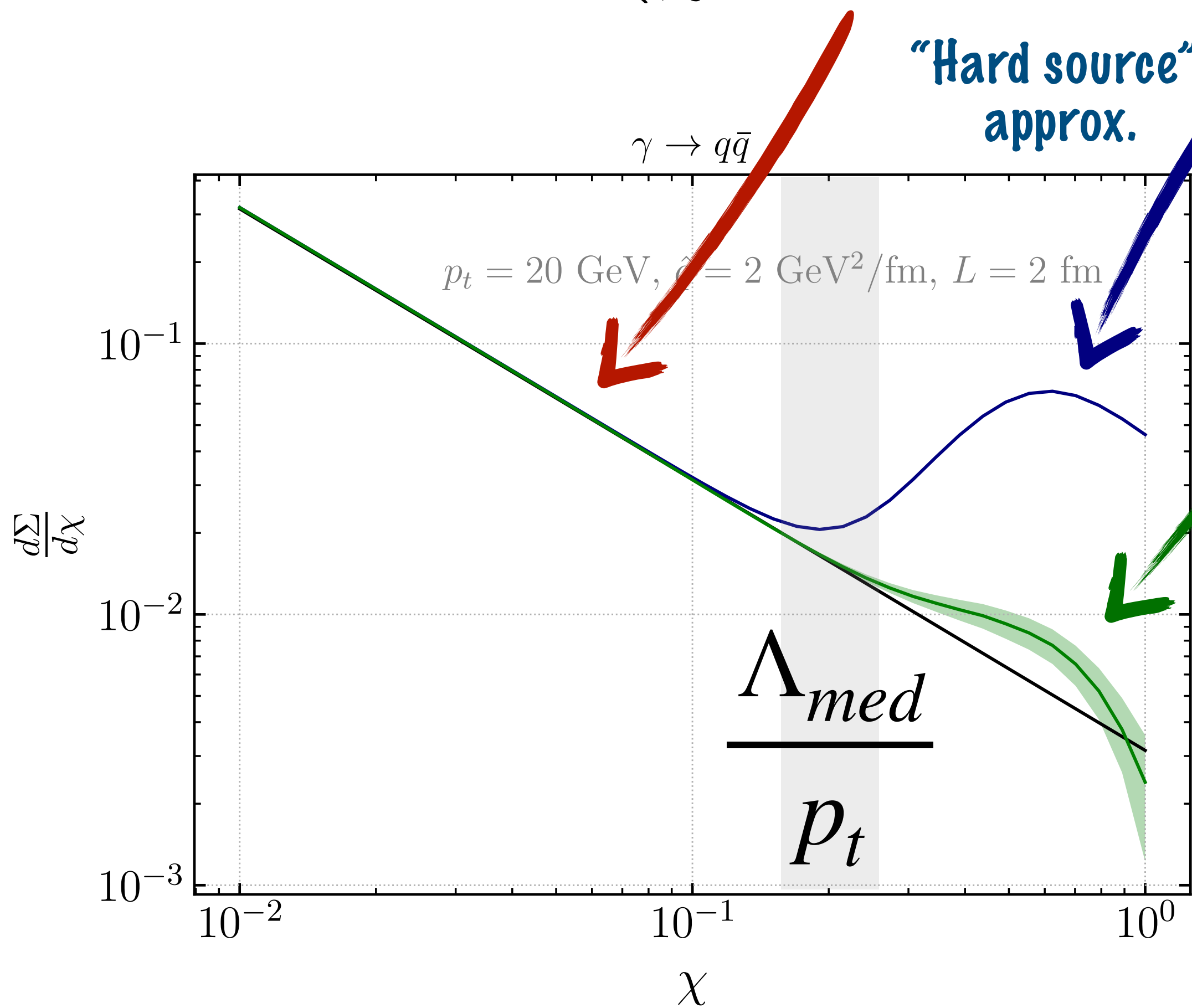
Energy correlators in HICs: perturbative contribution

[JB, Caucal, Soto-Ontoso, Szafron, 2312.12527]

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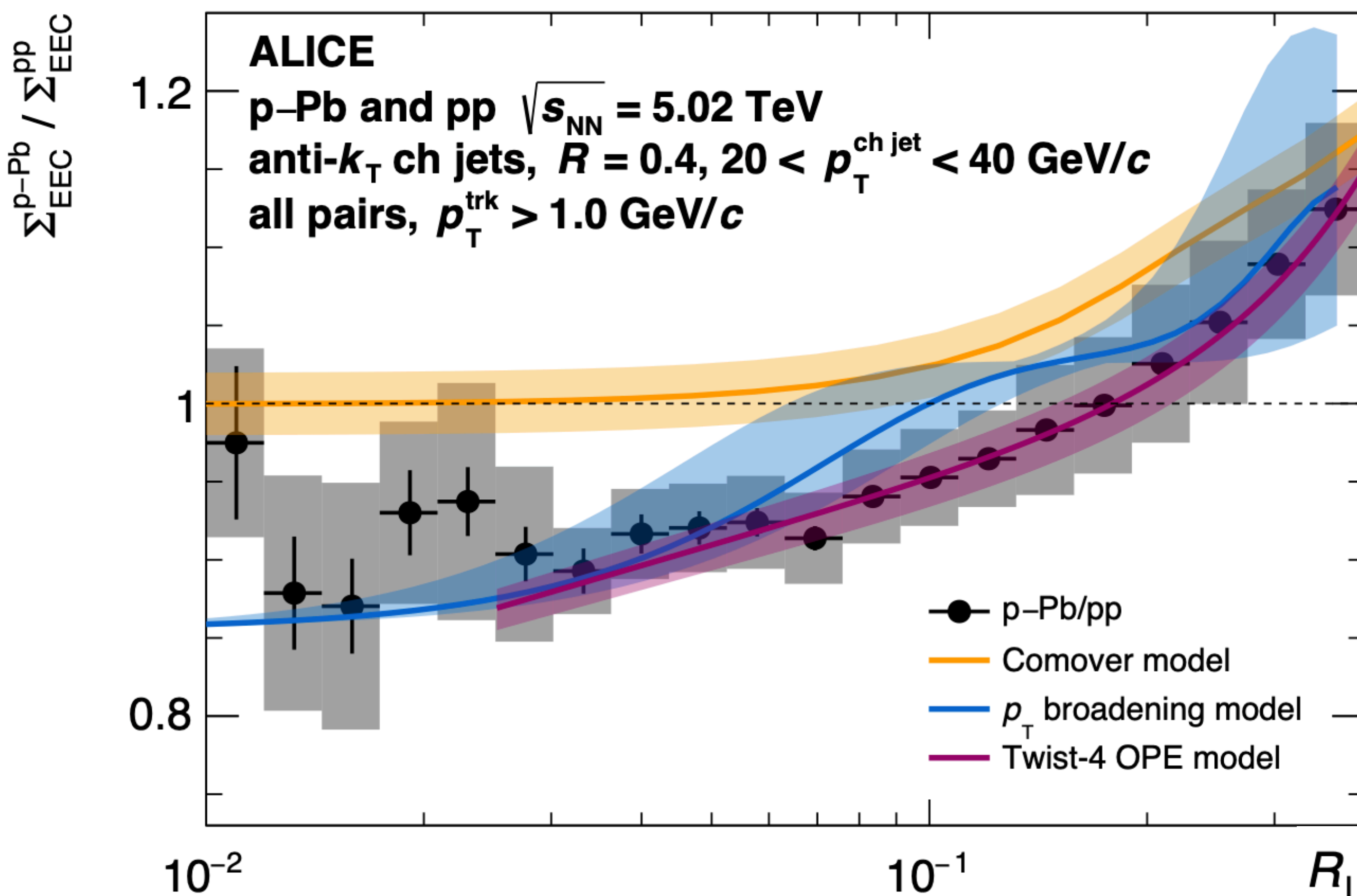
Λ_{med}
is roughly indicated by
enhancement of large
angle sector



Any “model” predicts large
angles enhancement

EECs across collisional systems: pPb

[ALICE, 2606.18143]



Several theory models roughly capture **large angle enhancement**

[Fu, Muller, Sirimanna, 2411.04866]

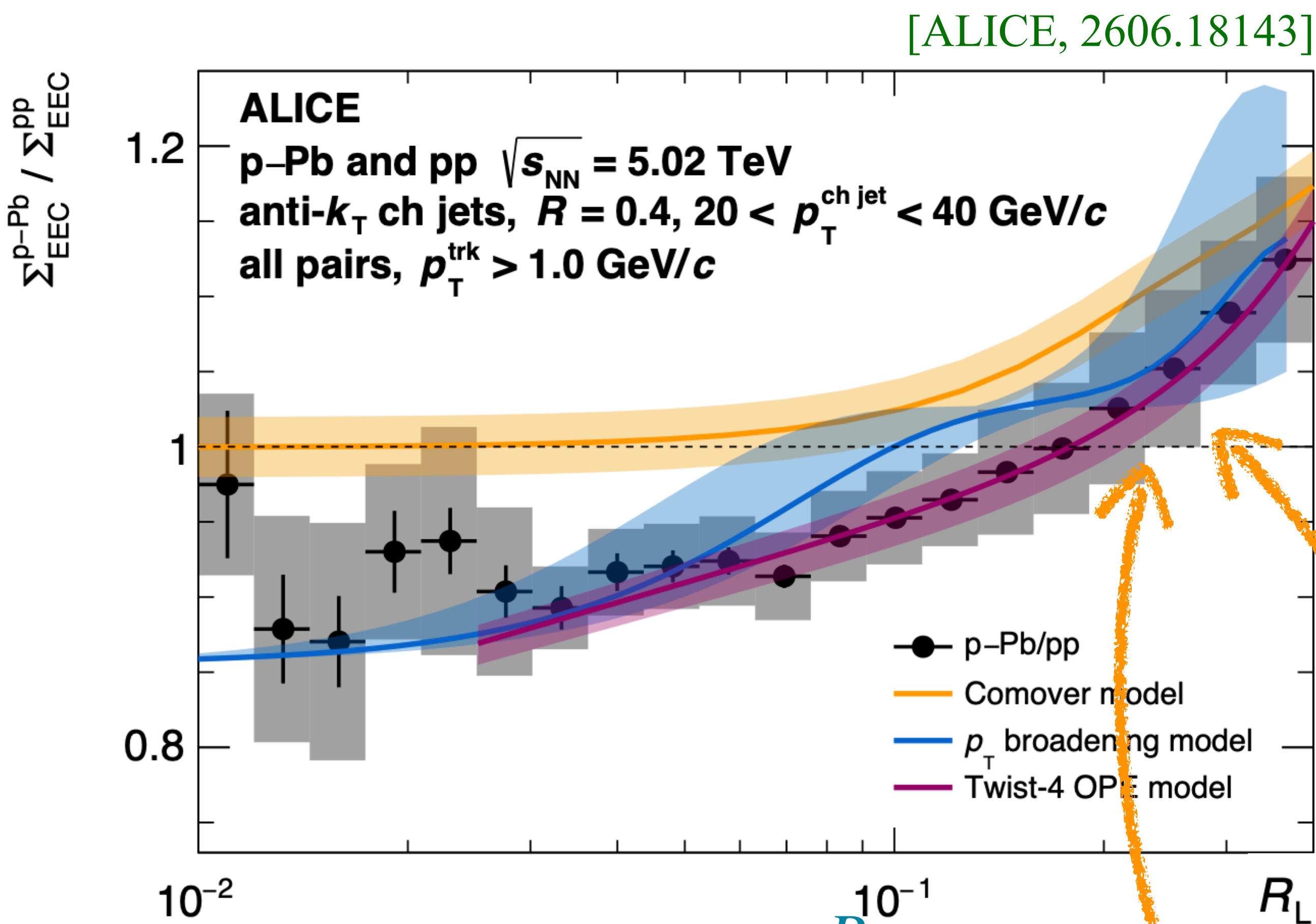
[JB, Kang, Mayo, Penttala, 2411.11782]

[Andres, Dominguez, Holguin, Marquet, 2411.15298]

[Ke, Mecaj, Vitev, 2512.11952]

This observation is interesting taking into account $R_{pA} \sim 1$

EECs across collisional systems: pPb



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This observation is interesting taking into account $R_{pA} \sim 1$

In the collinear limit the EEC takes a **simple form set by symmetry**

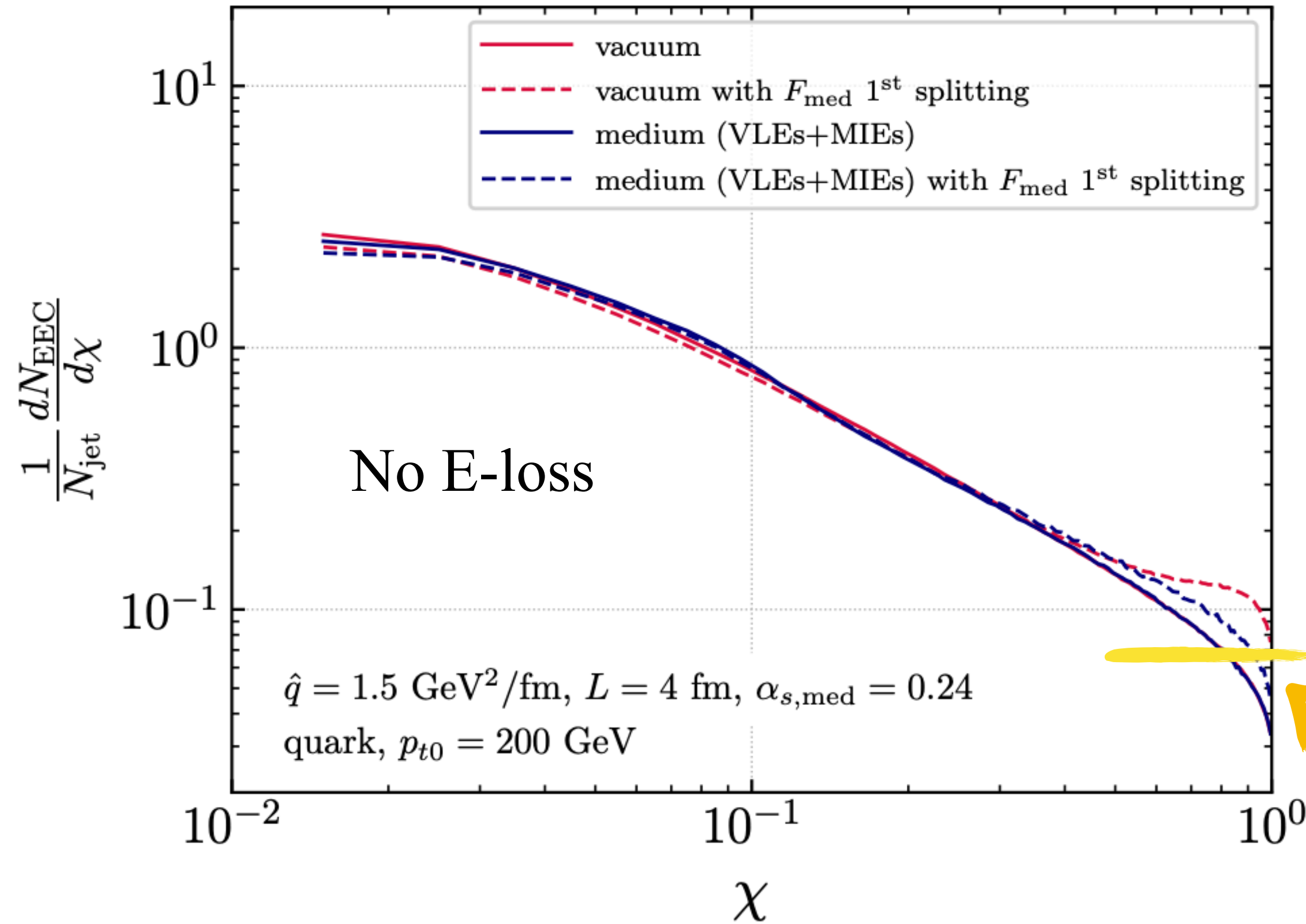
$$\frac{d\Sigma_P}{dR_L} = \frac{a_{2,0}^P}{R_L} + a_{4,0}^P R_L + a_{6,0}^P R_L^3 + \dots$$

Coefficients encode theory dependent dynamical data !

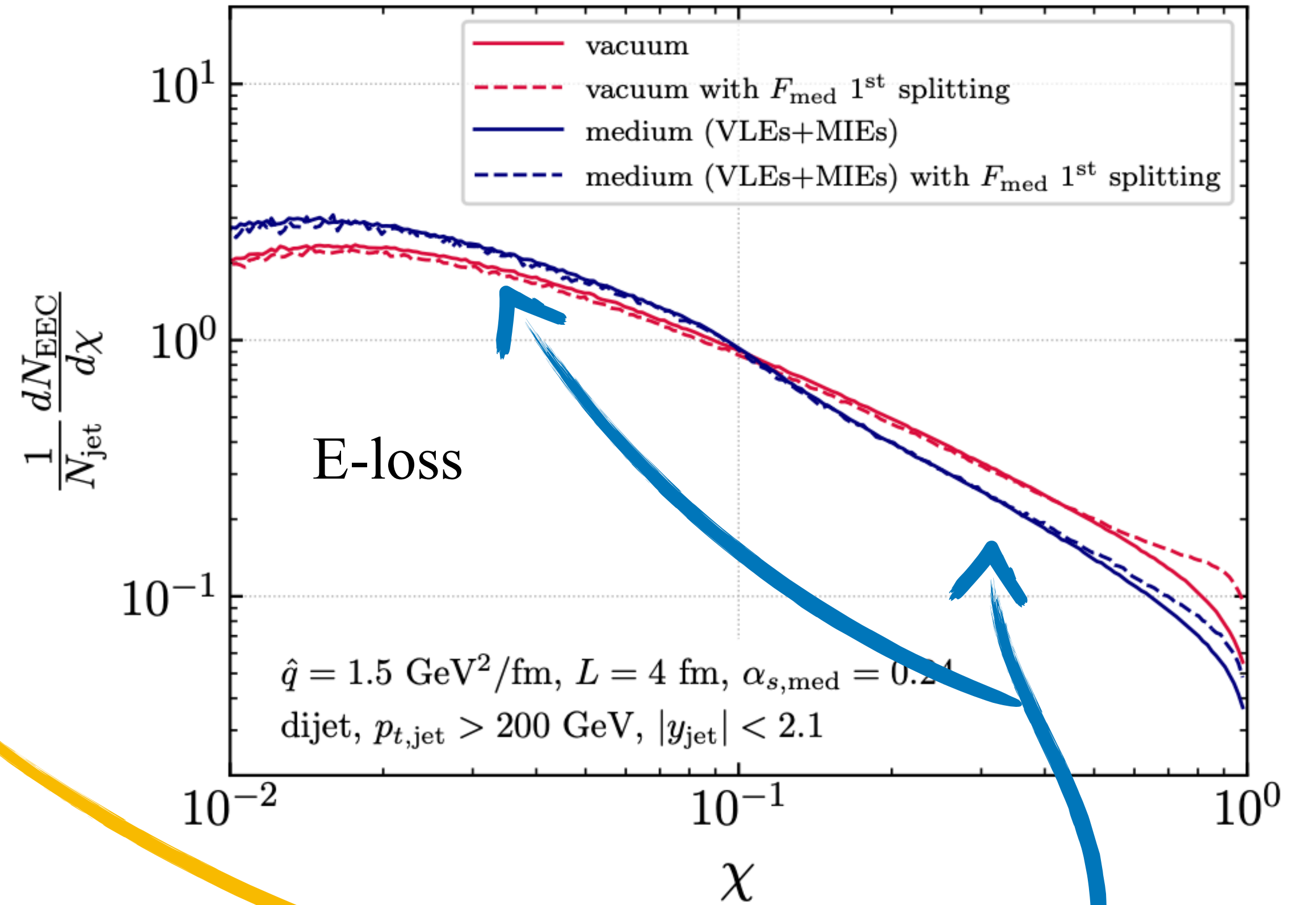
Energy correlators in HICs: perturbative contribution

[JB, Caucal, Soto-Ontoso, Szafron, 2312.12527]

Monte Carlo study



Monte Carlo study



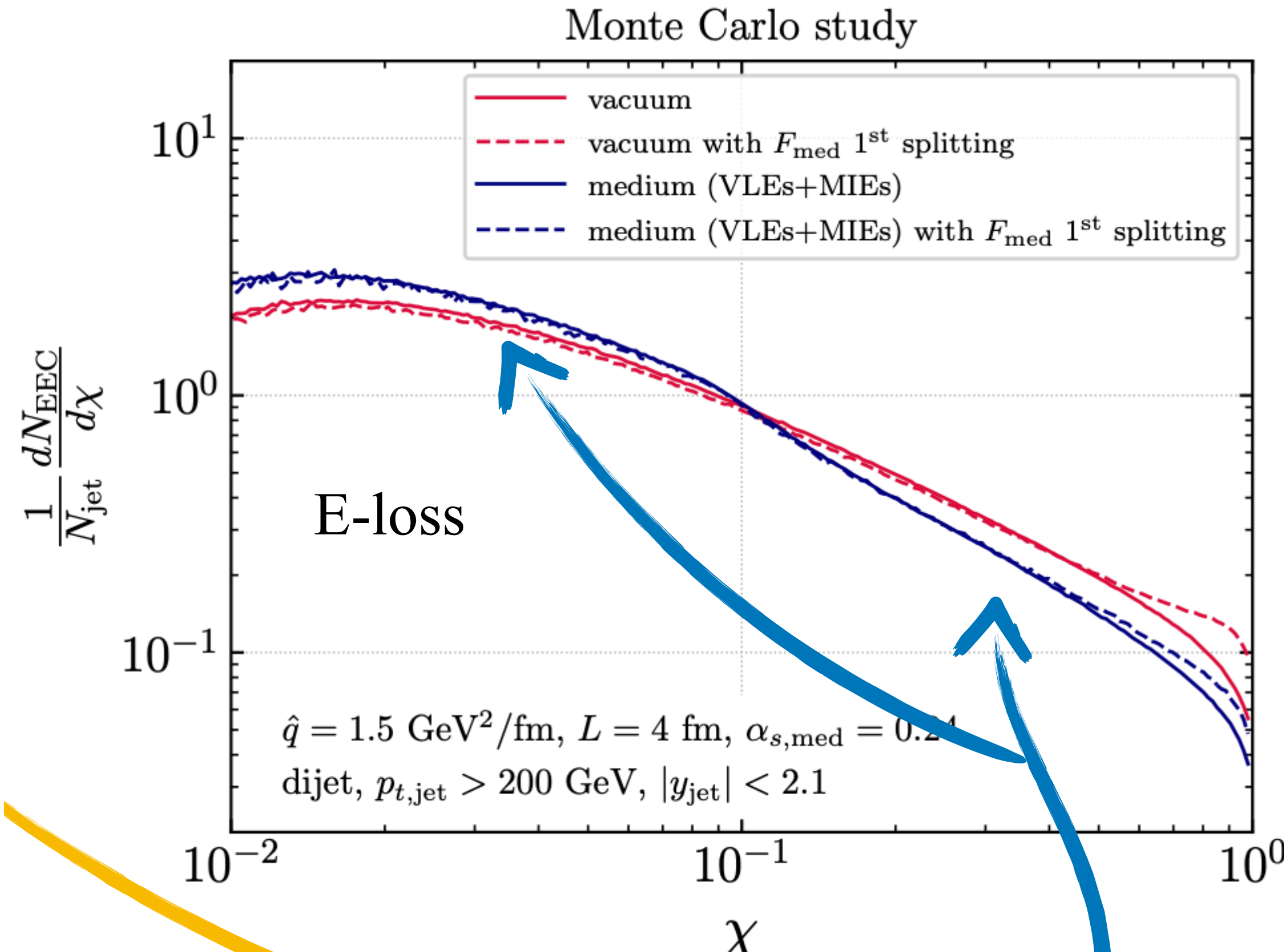
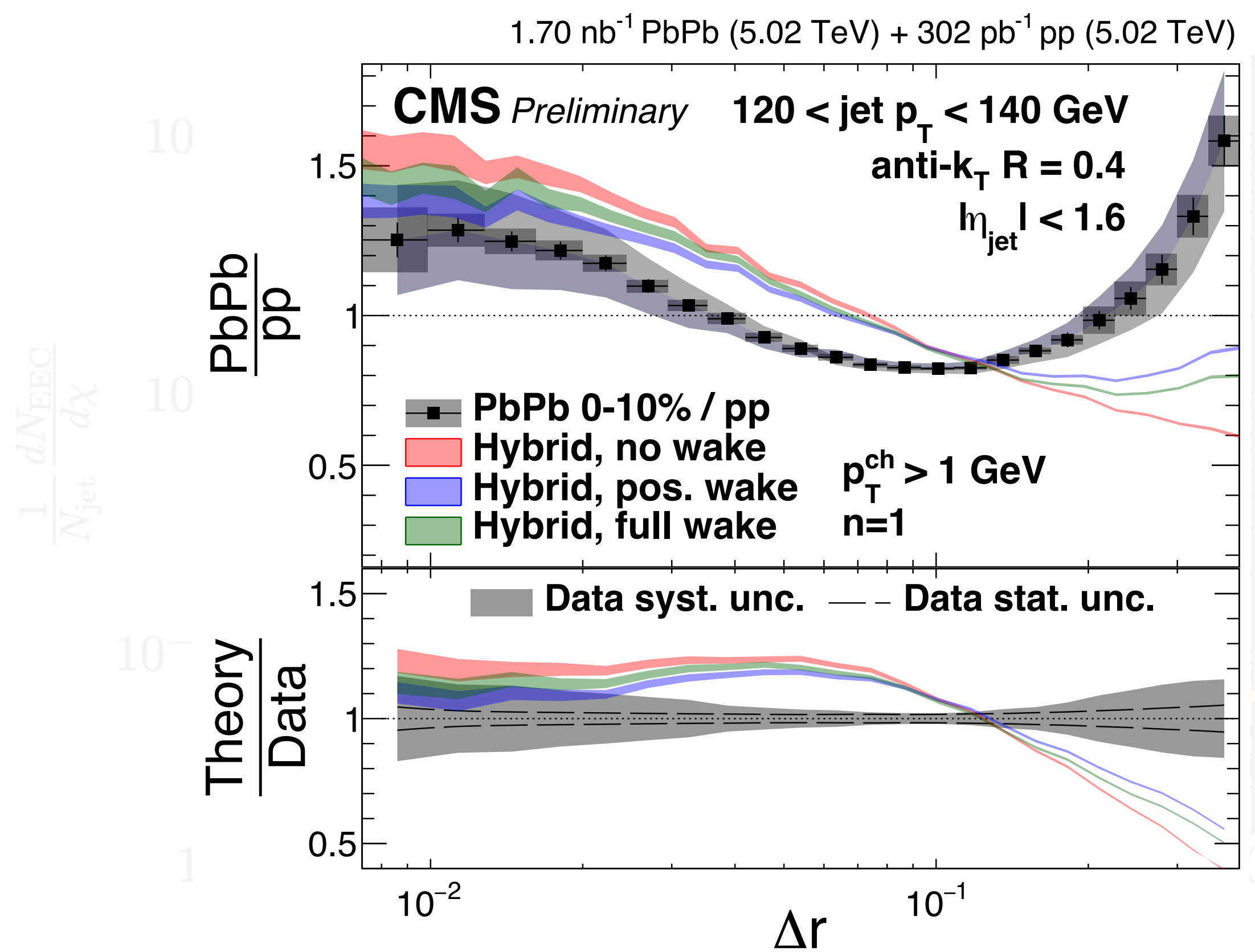
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**“Mixes” directly
with hard function**

Energy correlators in HICs: perturbative contribution



[JB, Caucal, Soto-Ontoso, Szafron, 2312.12527]



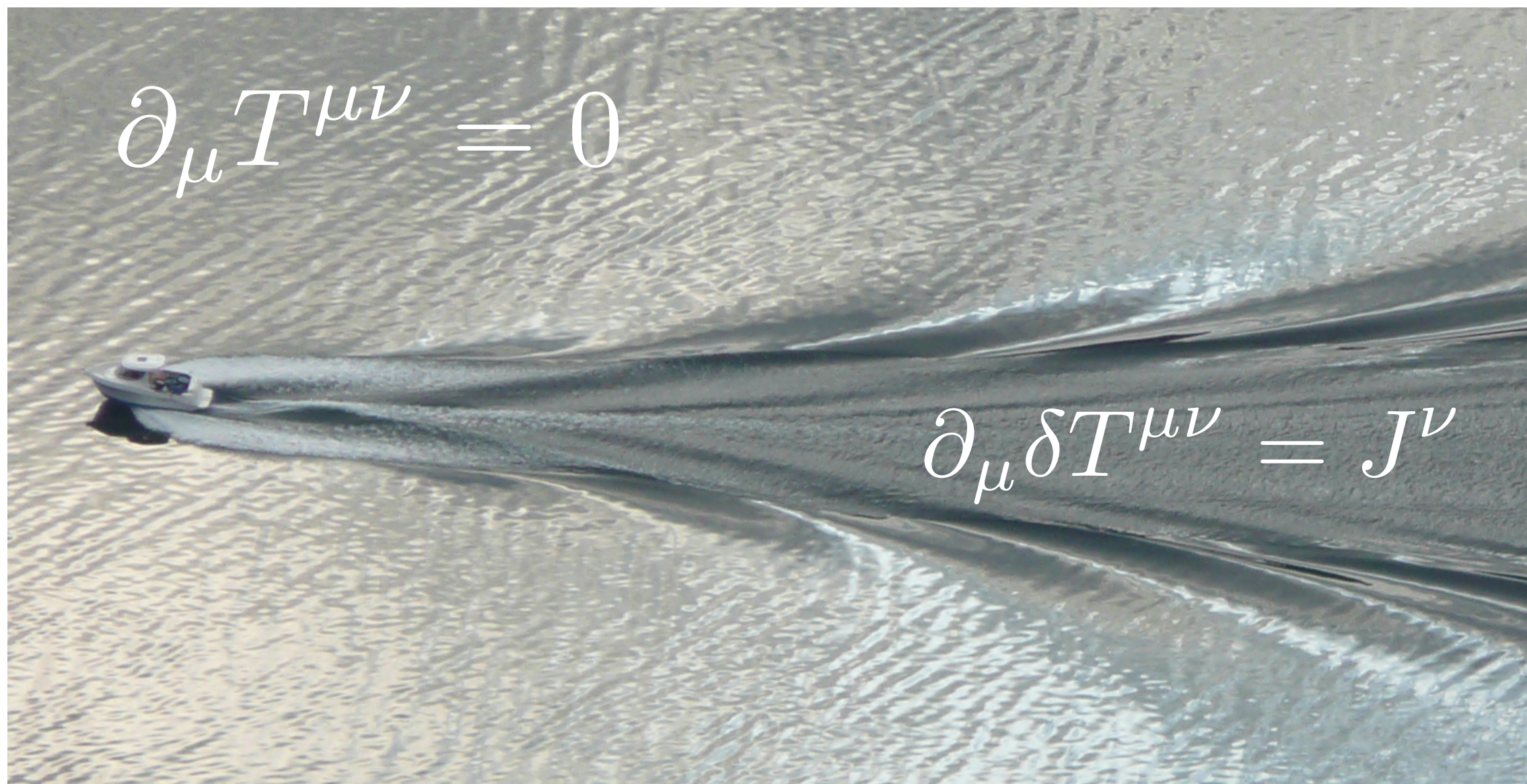
Similar shape to experimental data !
Is this everything ?

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

“Mixes” directly
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Probing heavy ion collisions using jets

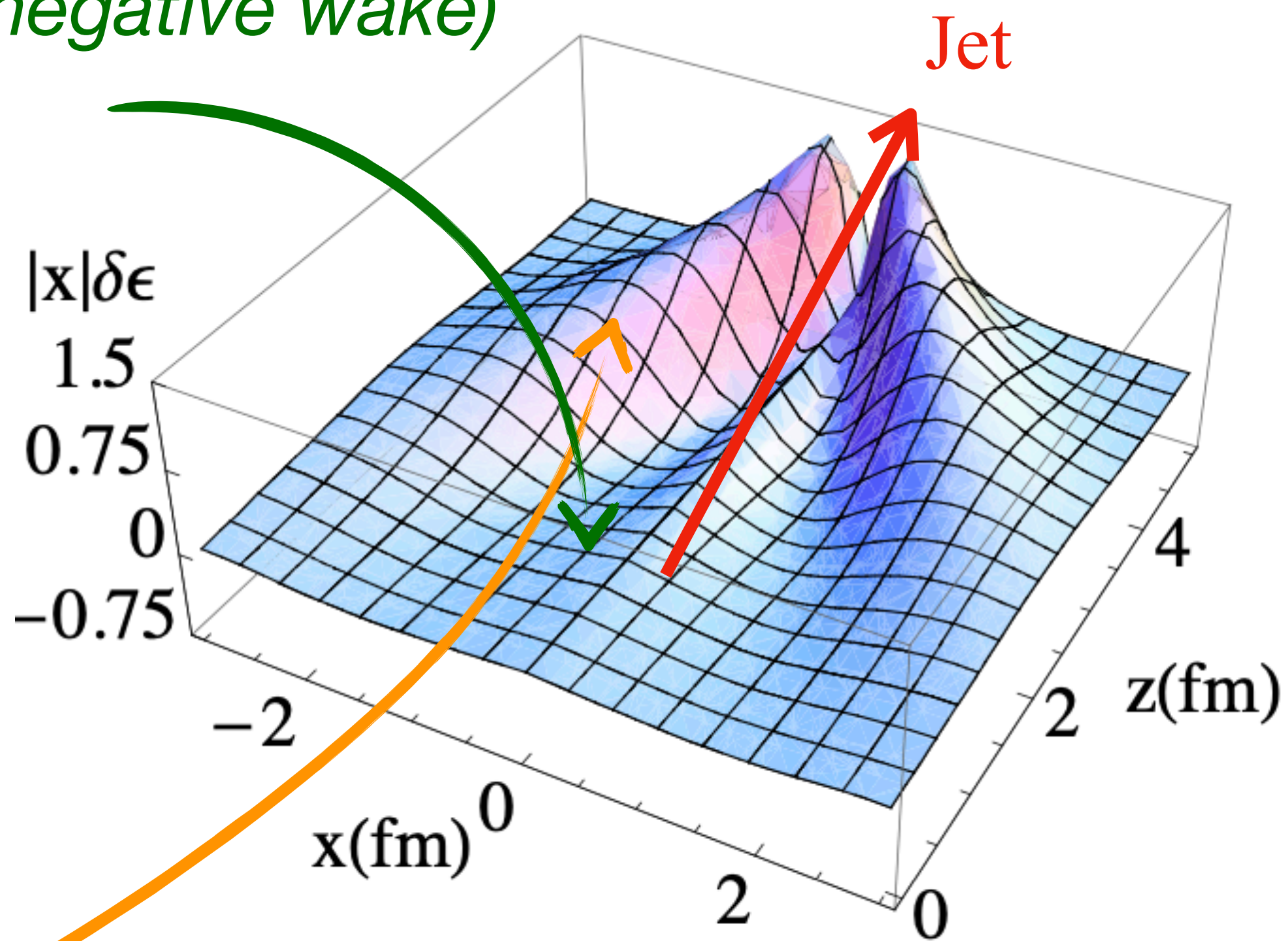
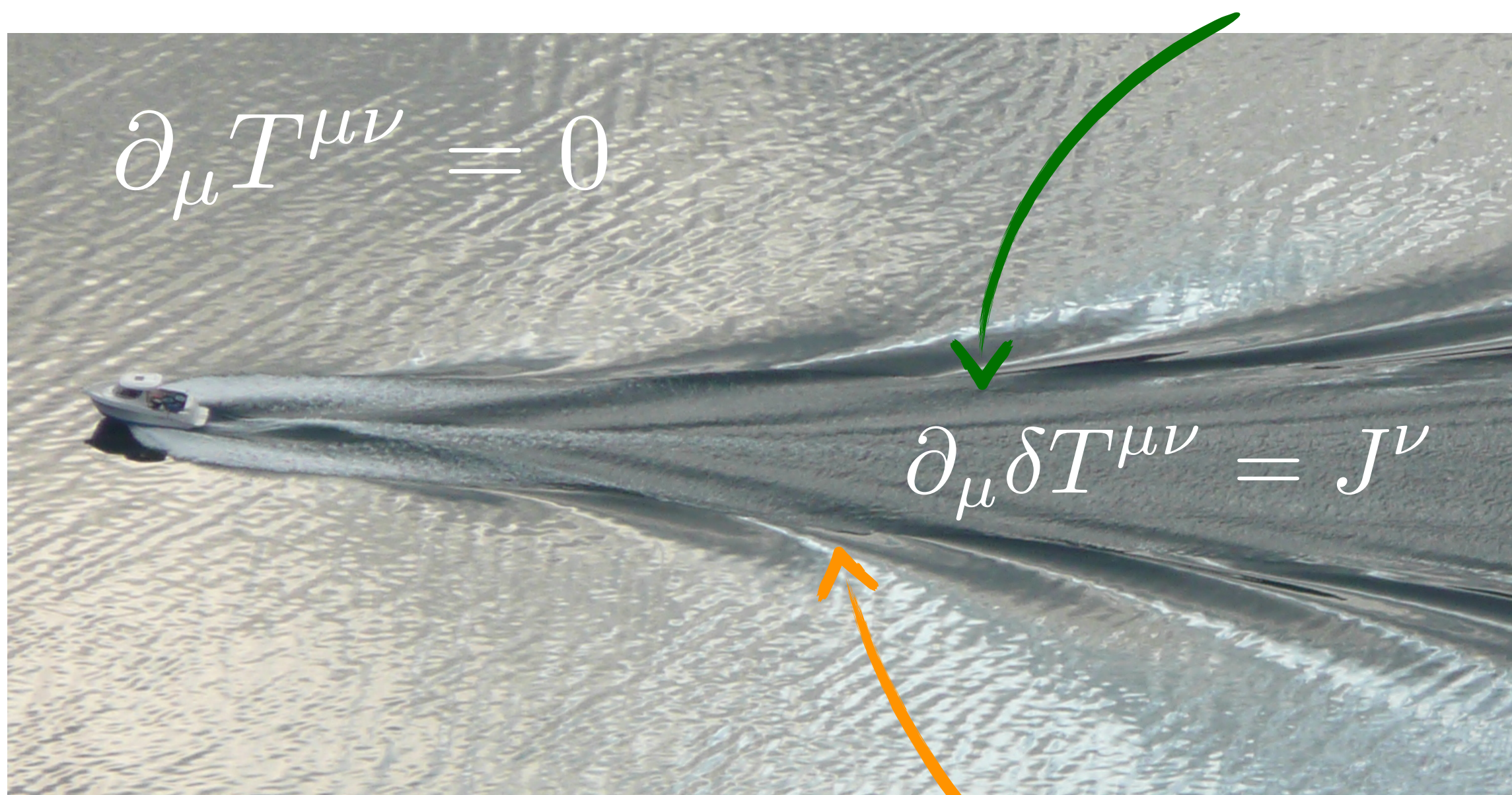
Jets *evolve on top of a bulk* which backreacts; this can inform about *dynamical properties of matter*



Probing heavy ion 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)

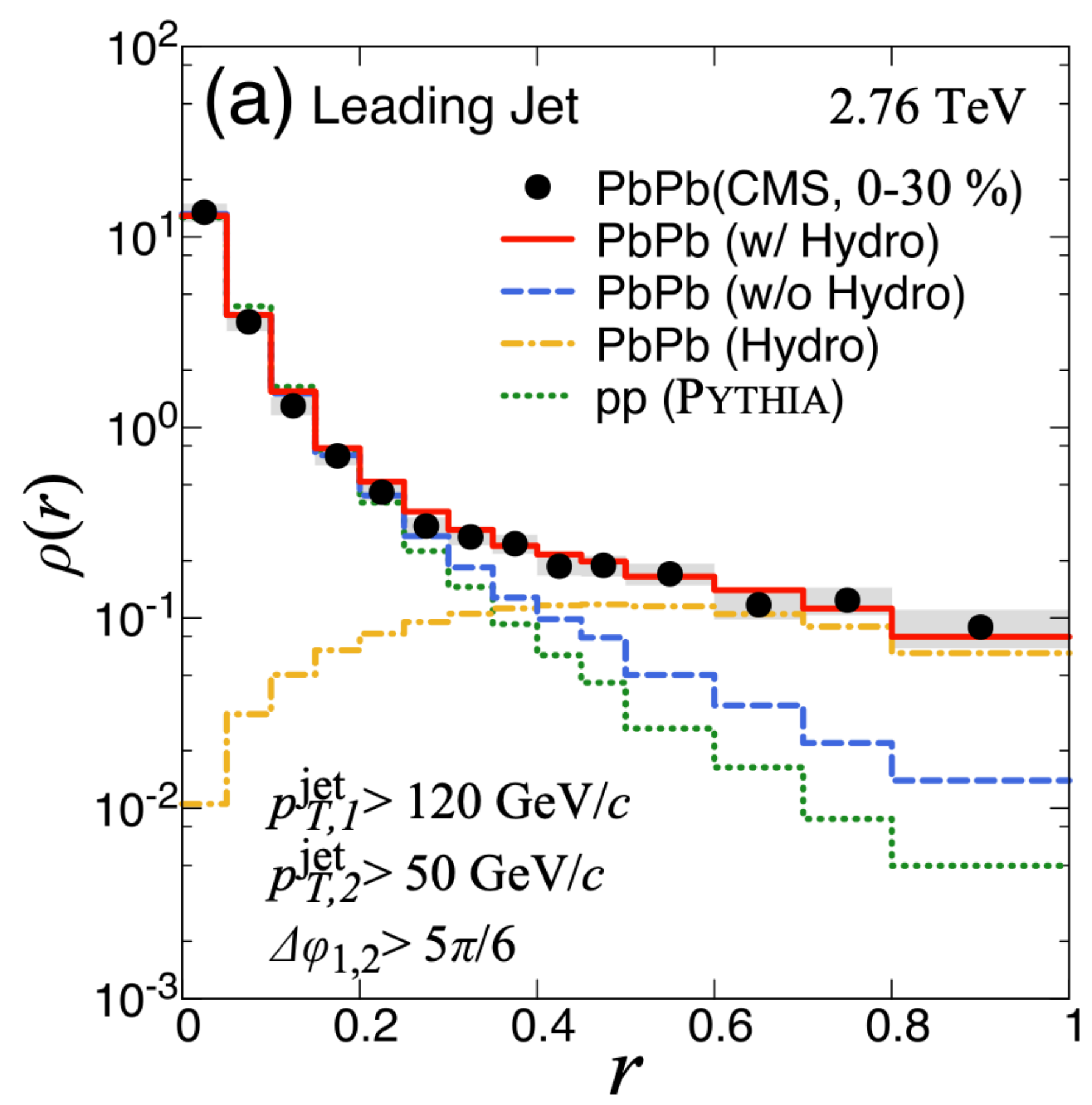


Mach cone structure

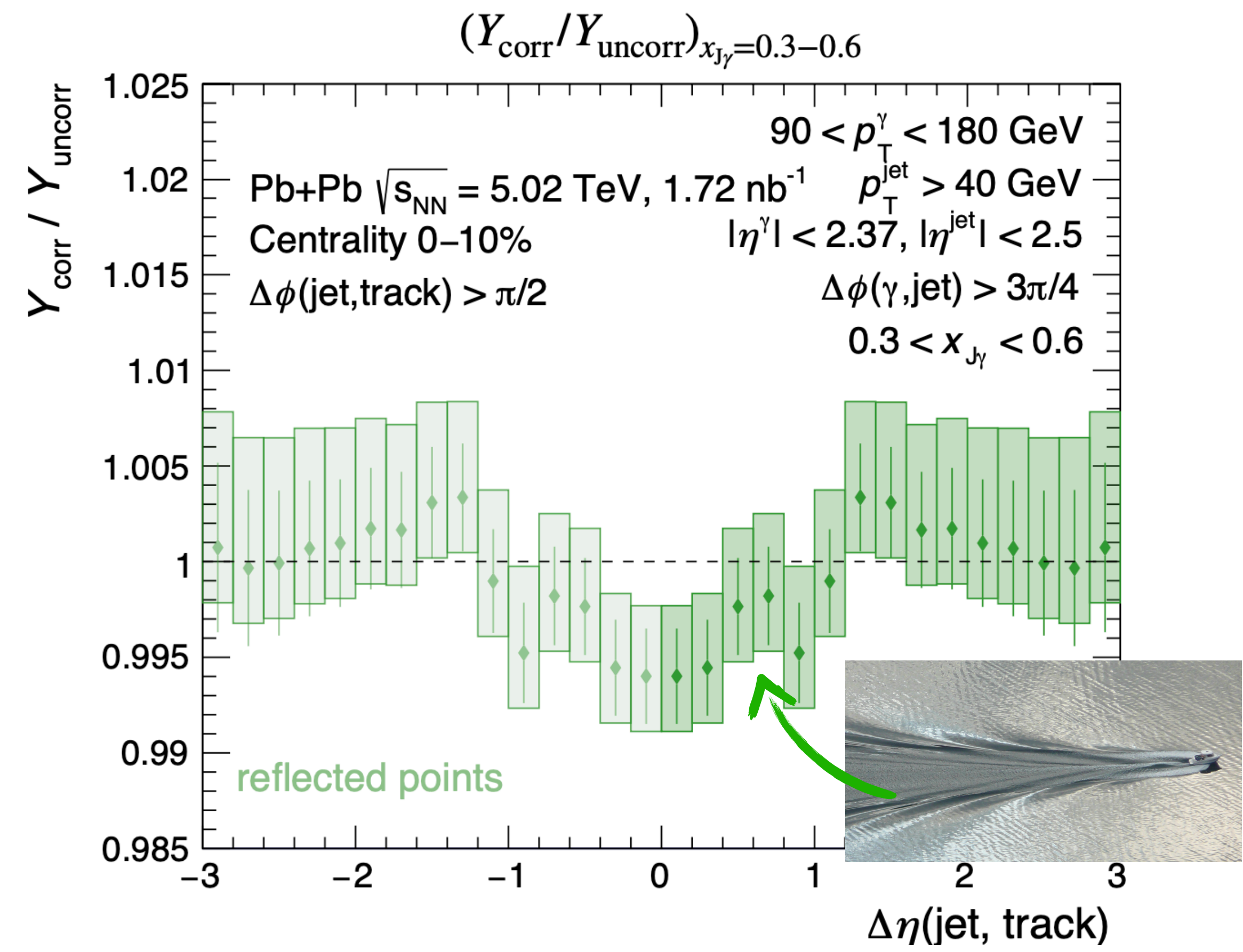
[G.-Y. Qin, A. Majumder, H. Song, U. Heinz, 0903.22255]

Probing heavy ion collisions using jets

[Tachibana et al, 1701.07951]



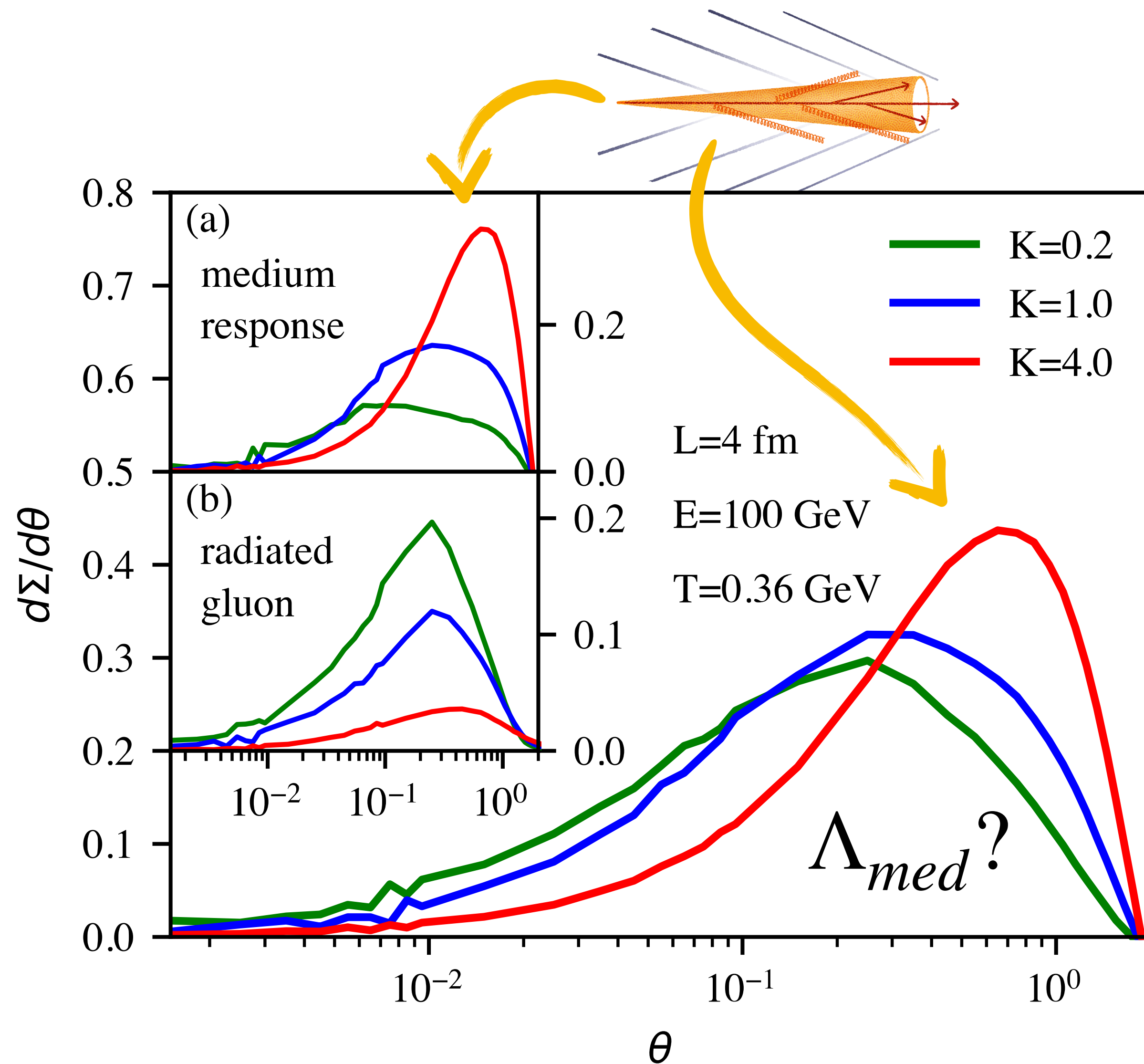
[ATLAS, 2408.08599]



The effects of **hydro response** on jets should be **non-negligible**

Still, **hard to get sharp experimental confirmation** of this effect

Energy correlators in HICs: hydrodynamic response



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]

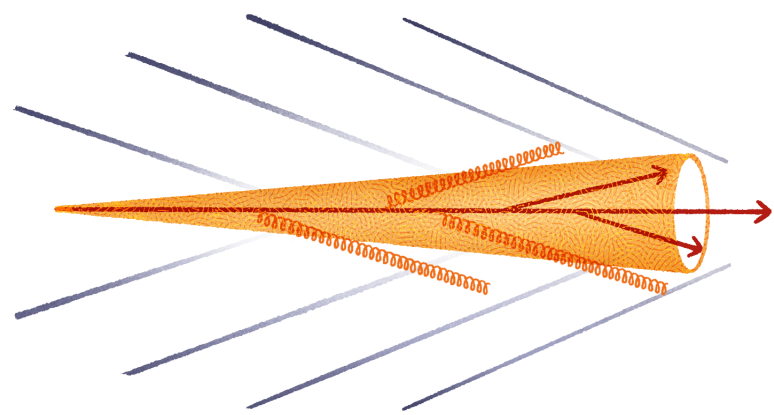
Energy correlators in HICs: hydrodynamic response



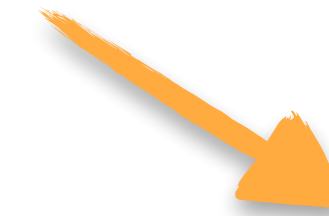
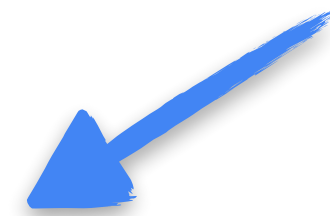
[JB, Kuzmin, Milhano, Sadofyev, 2412.03616]

The key observation is that **jets couple to a classical background**;
General angular dependence can be predicted !

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



*Includes medium response
(sourced by jet energy deposition)*



*Jet energy flux
(includes medium-induced modifications)*

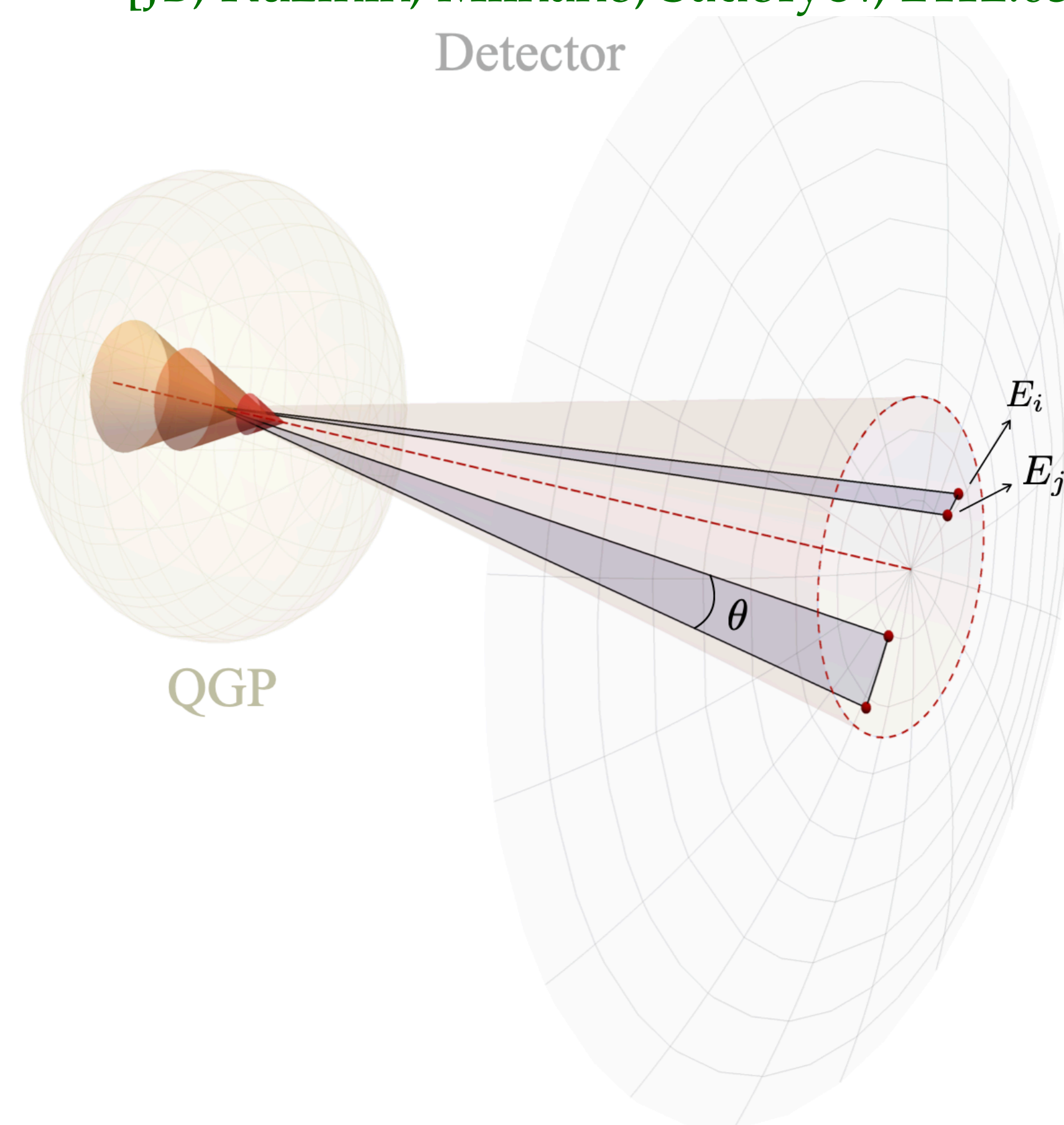
How are these two energy flows imprinted on ENC's ?

Energy correlators in HICs: hydrodynamic response

[JB, Kuzmin, Milhano, Sadofyev, 2412.03616]

*To deal with hydro/classical flows we
consider the evolution of jets inside
finite sized “hydro-balls”*

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



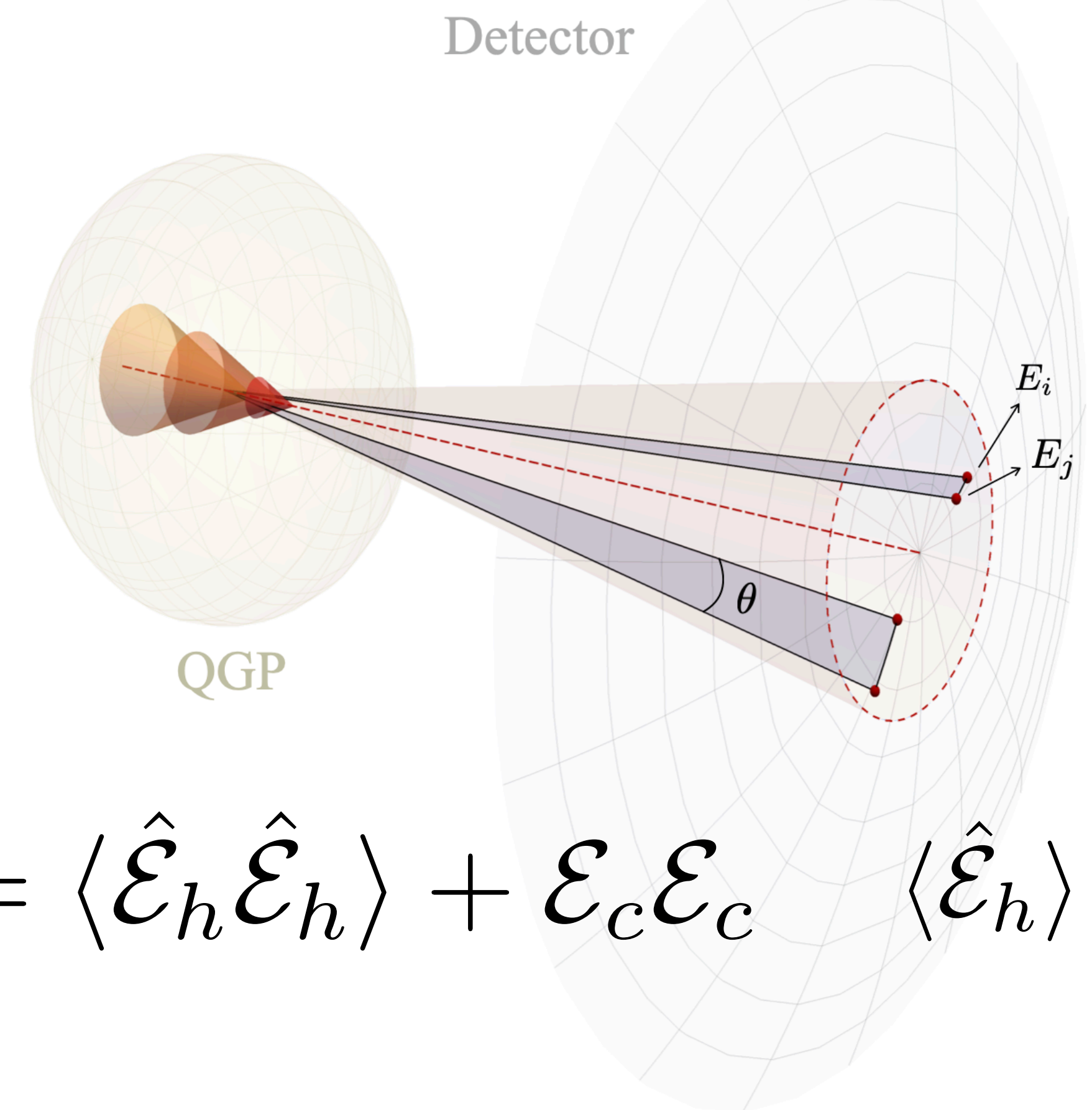
Energy correlators in HICs: hydrodynamic response

[JB, Kuzmin, Milhano, Sadofyev, 2412.03616]

To deal with hydro/classical flows we consider the evolution of jets inside **finite sized “hydro-balls”**

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

This allows for explicit calculation of the angular structure of the classical response terms



$$\langle \hat{\mathcal{E}} \hat{\mathcal{E}} \rangle = \langle \hat{\mathcal{E}}_h \hat{\mathcal{E}}_h \rangle + \mathcal{E}_c \mathcal{E}_c \quad \langle \hat{\mathcal{E}}_h \rangle = 0$$

$$\frac{d\Sigma^{(2)}}{d\theta} \simeq \sum_{k=2} c_k^{(2)} \theta^{2k-3}$$

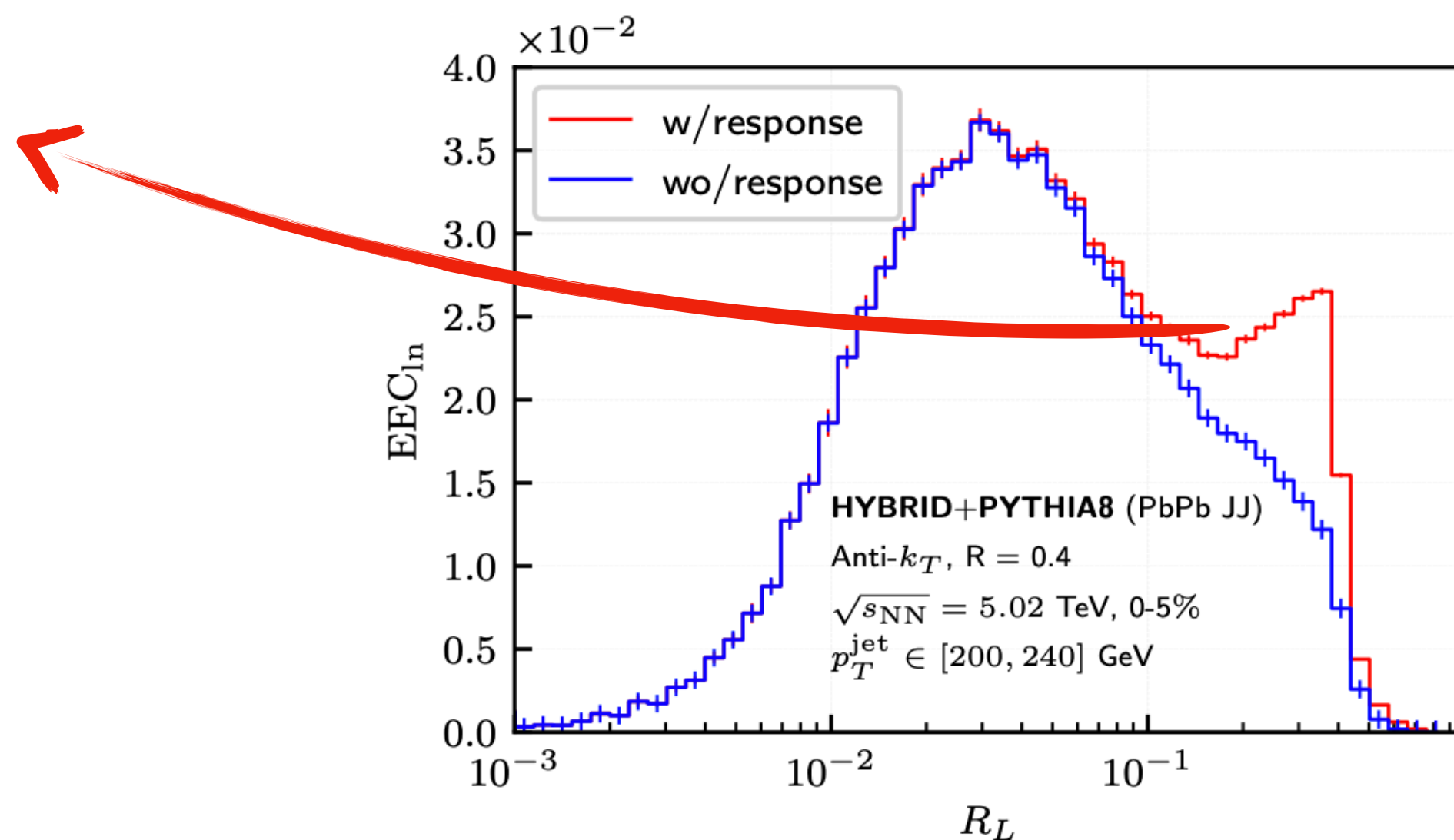
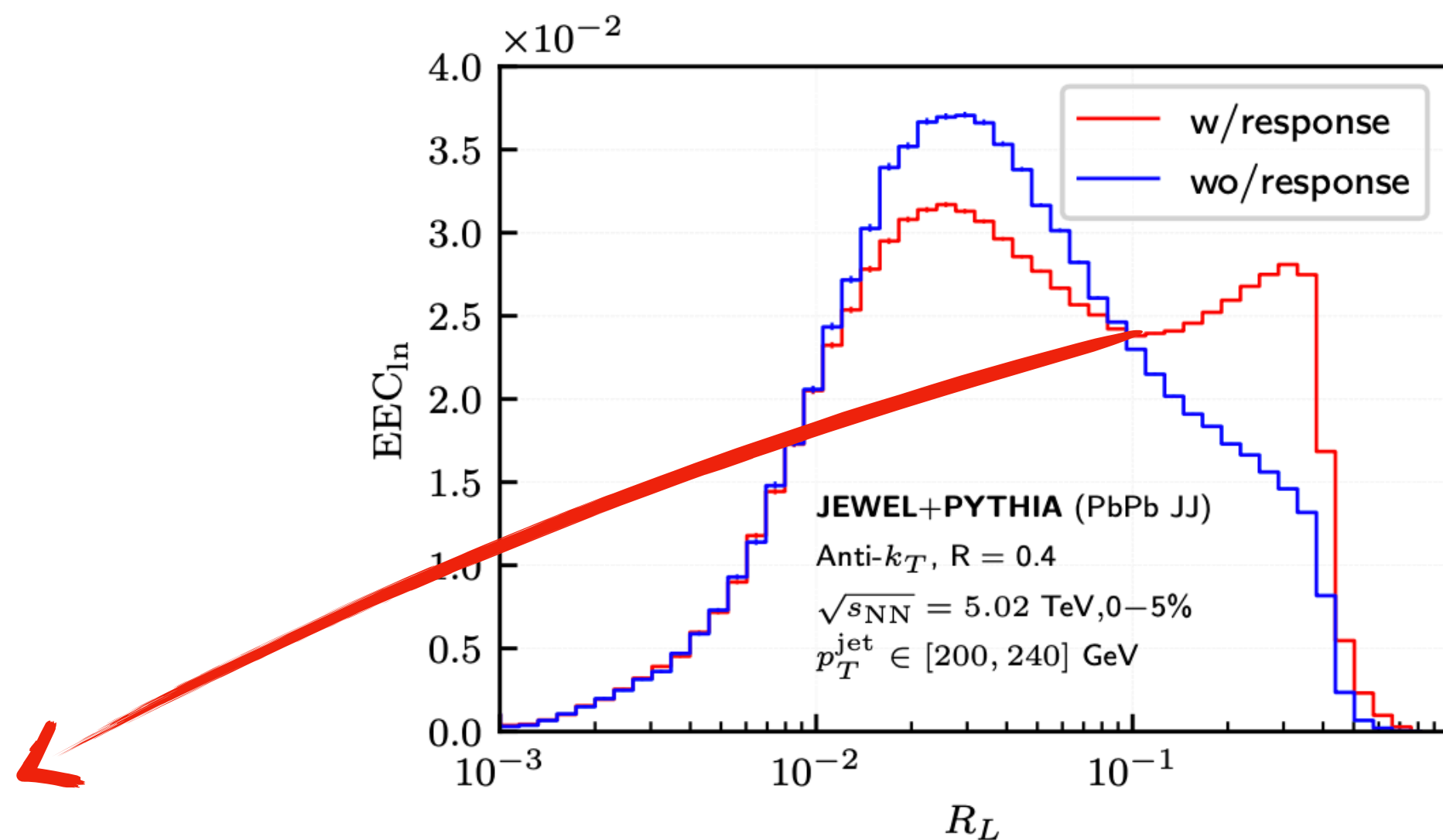
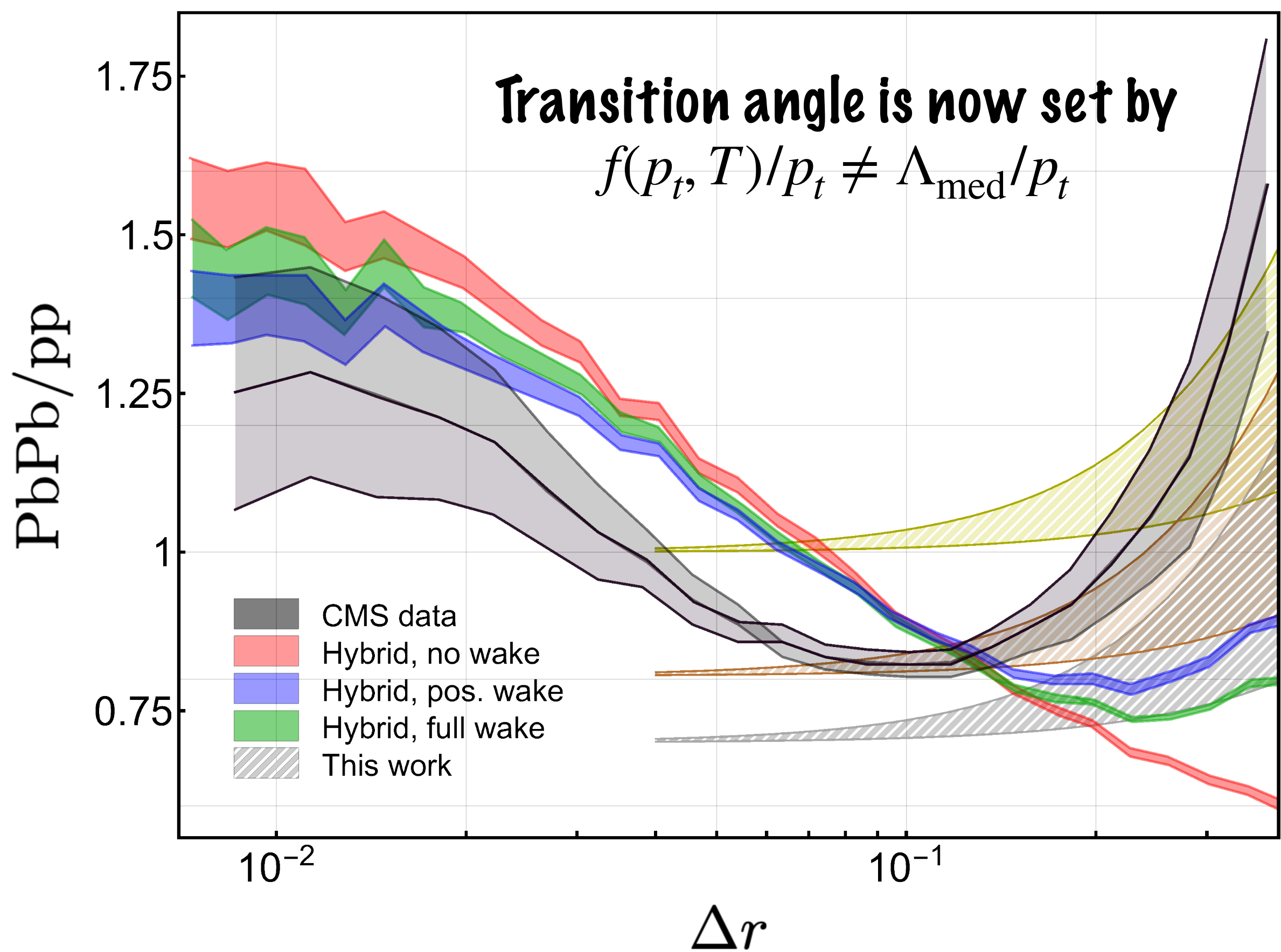


$$c_2^{(2)} = \sum_{\text{events}} \frac{(2\pi)^2}{p_t^2} \int_{\Theta} \mathcal{E}^2(\Theta) \sin \Theta$$

Energy correlators in HICs: hydrodynamic response

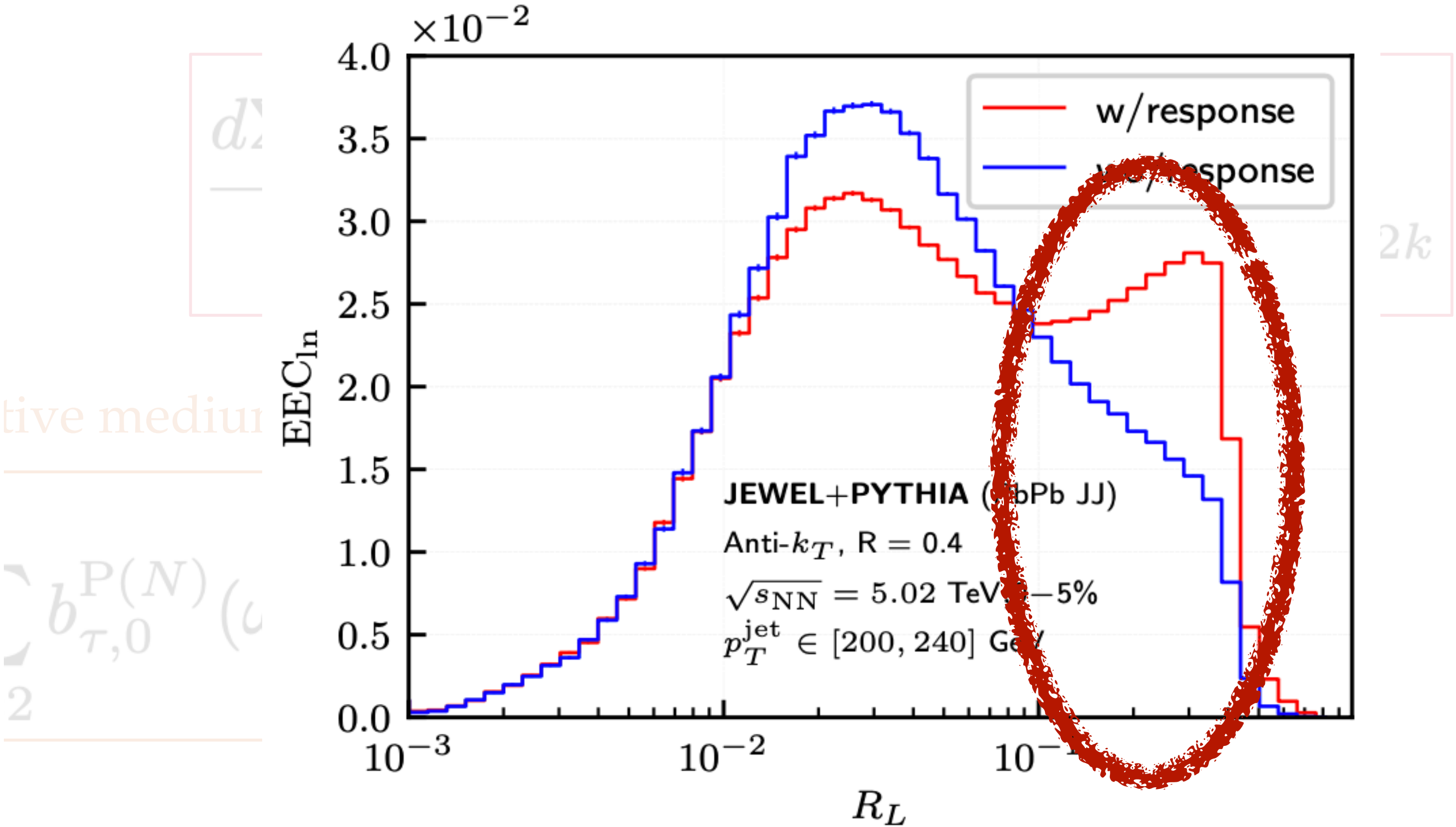
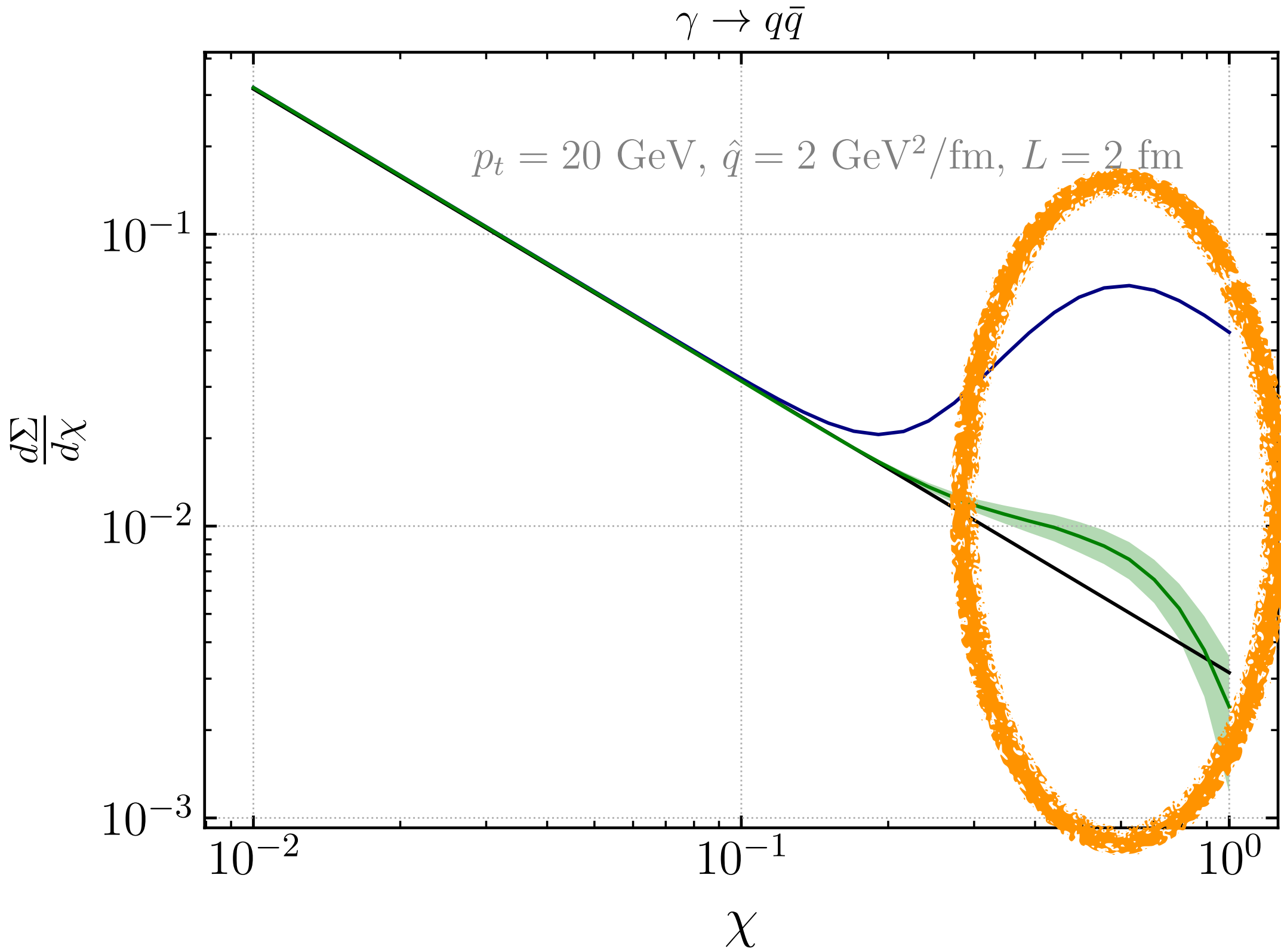
[JB, Kuzmin, Milhano, Sadofyev, 2412.03616]

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





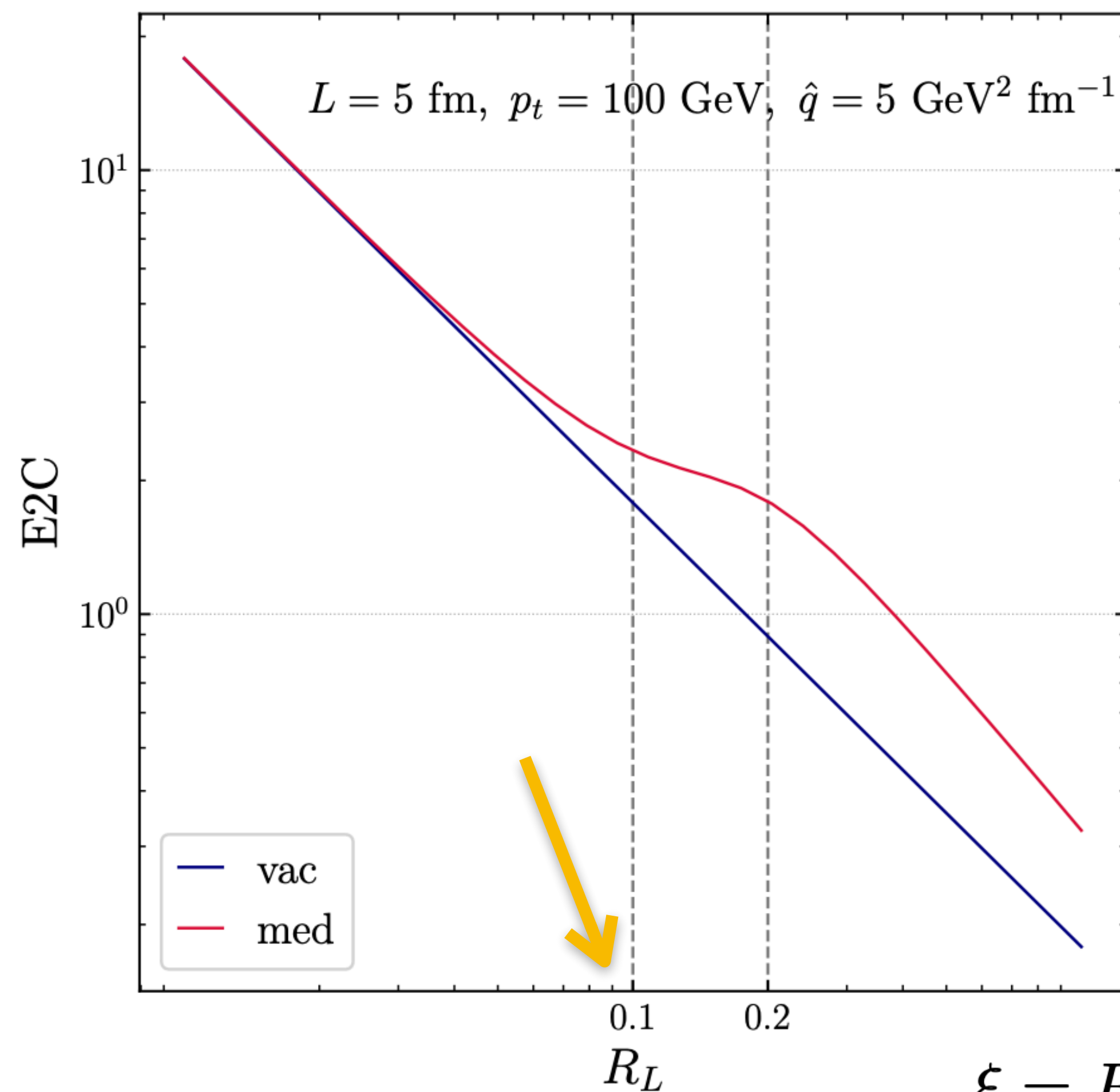
What is the main lesson for phenomenology ?



(Classical) observable is highly degenerate :

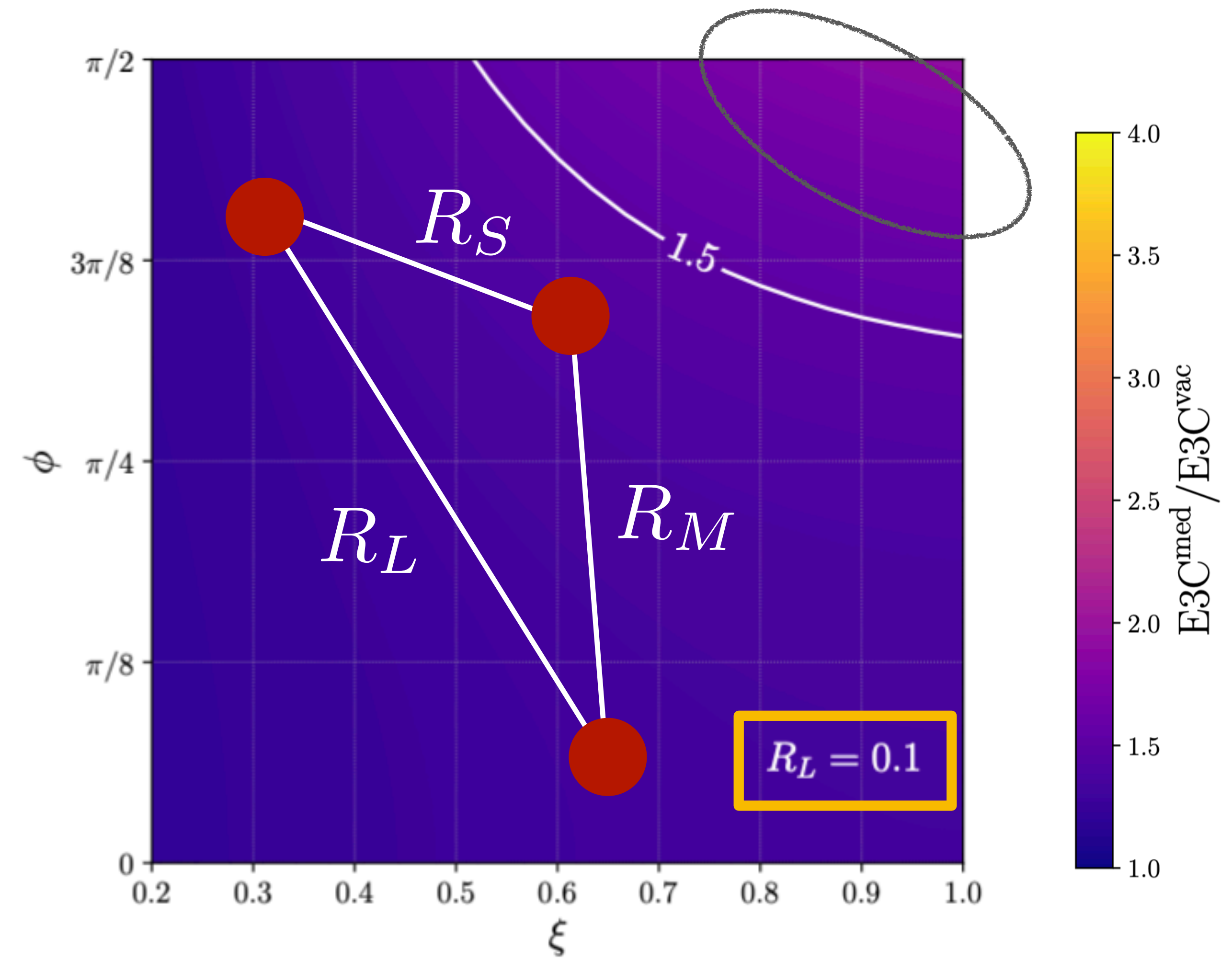
$$\frac{d\Sigma_P^{(3)}}{dR_L} = \frac{a_{2,0}^{P(3)}}{R_L} + \left(a_{4,0}^{P(3)} + b_{4,0}^{P(3)} + c_4^{P(3)} \right) R_L + \dots$$

These results generalize to the fully differential higher point functions

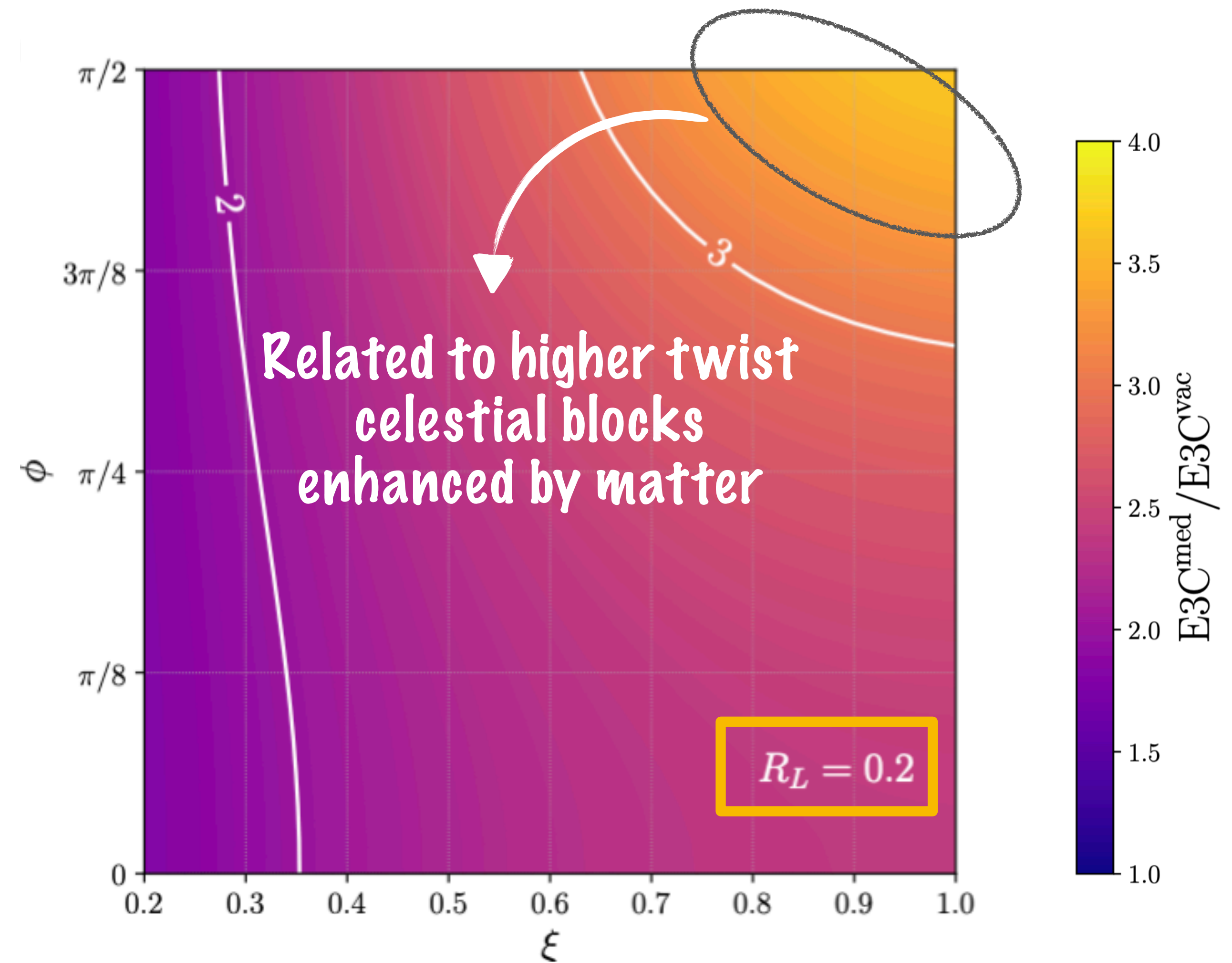
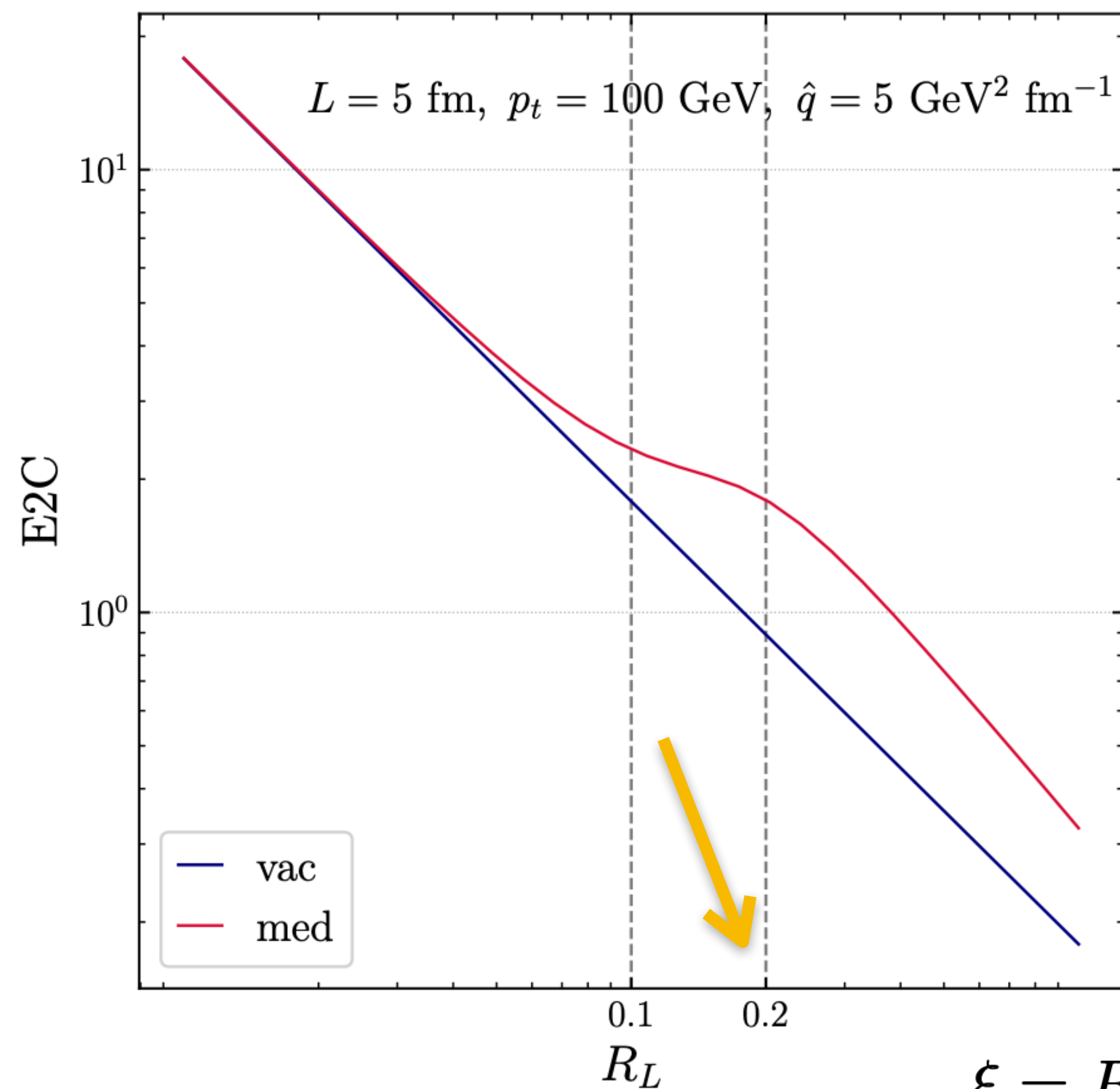


$$\xi = R_S / R_M$$

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



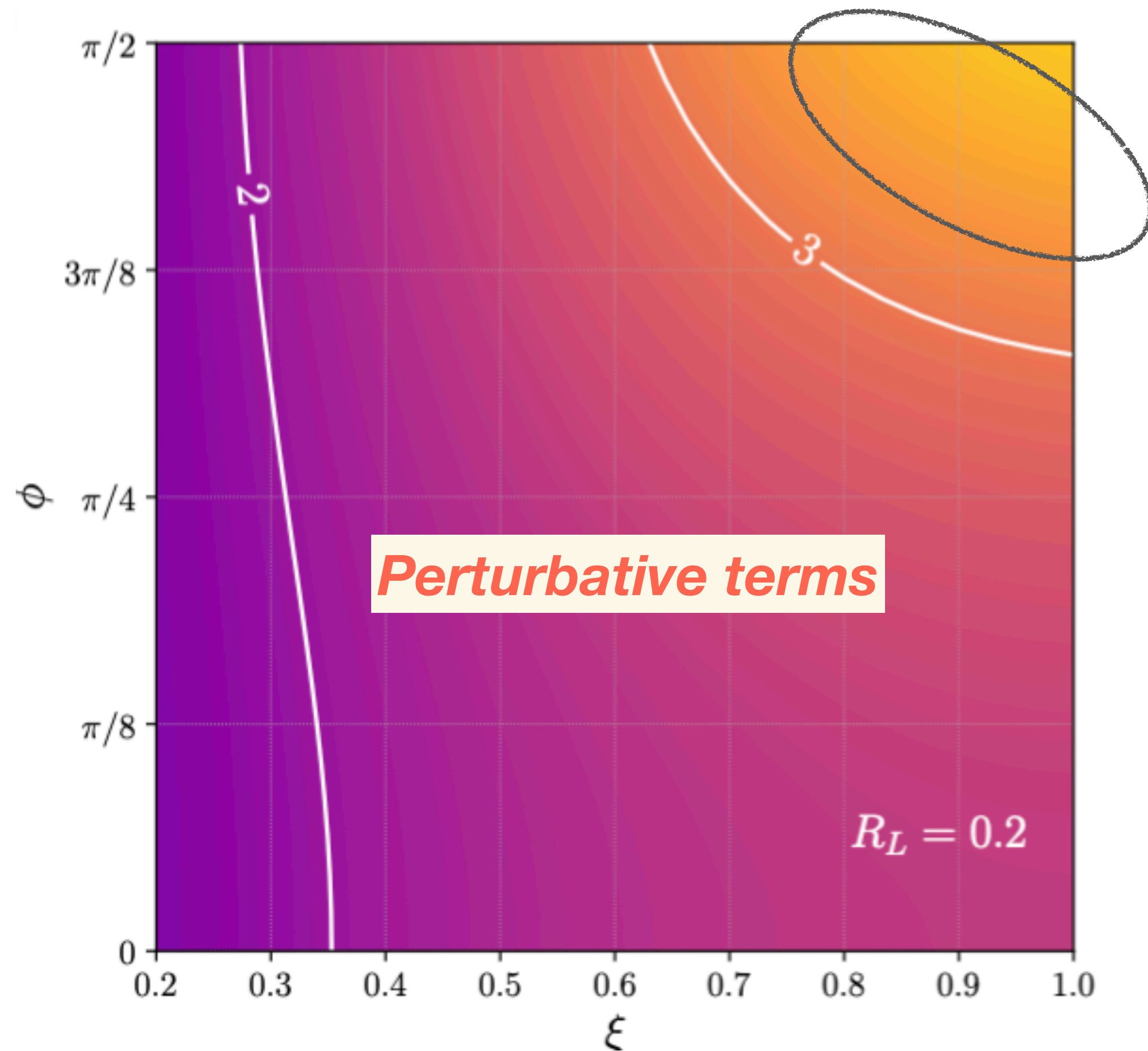
These results generalize to the fully differential higher point functions



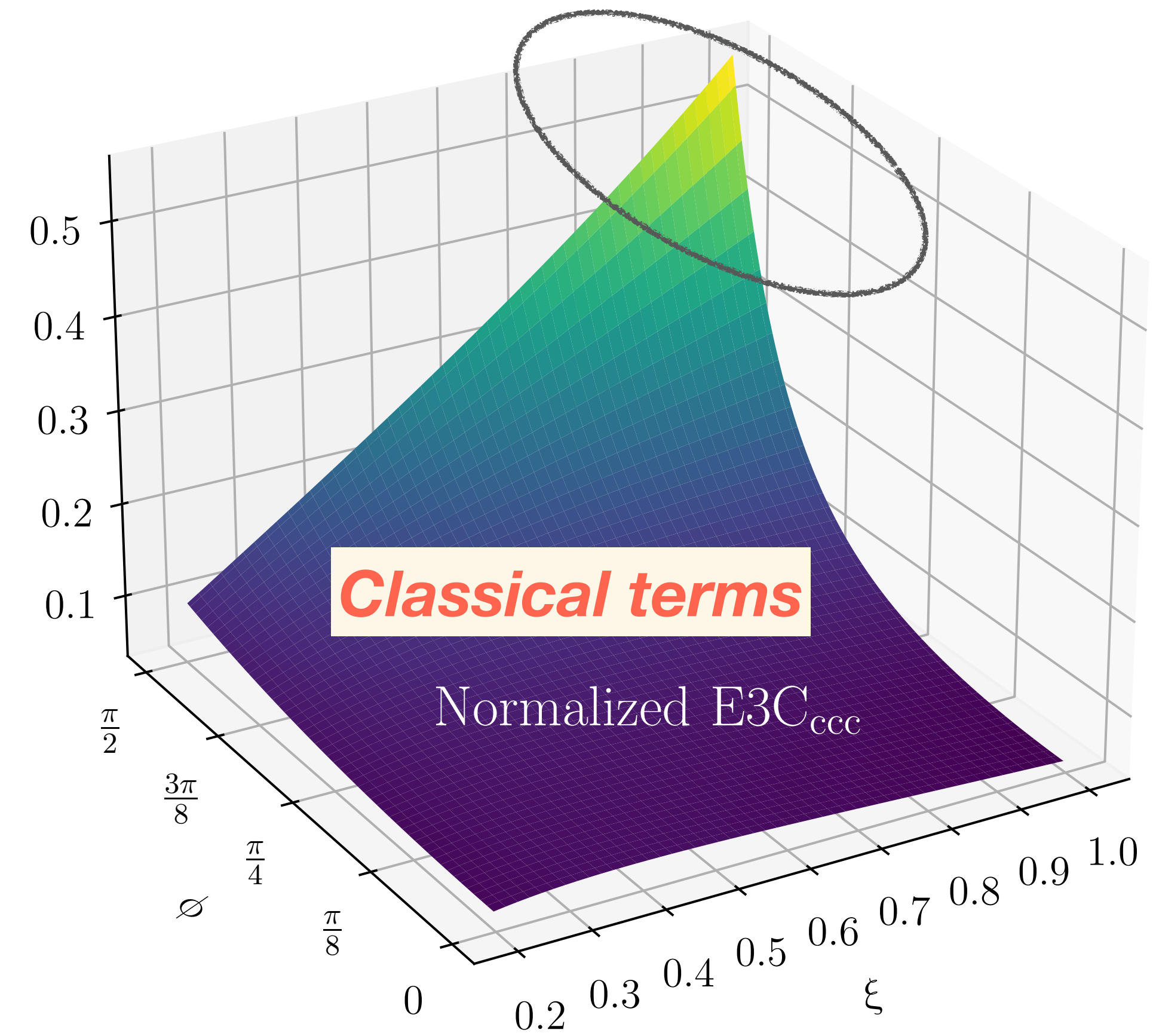
$$\xi = R_S/R_M$$

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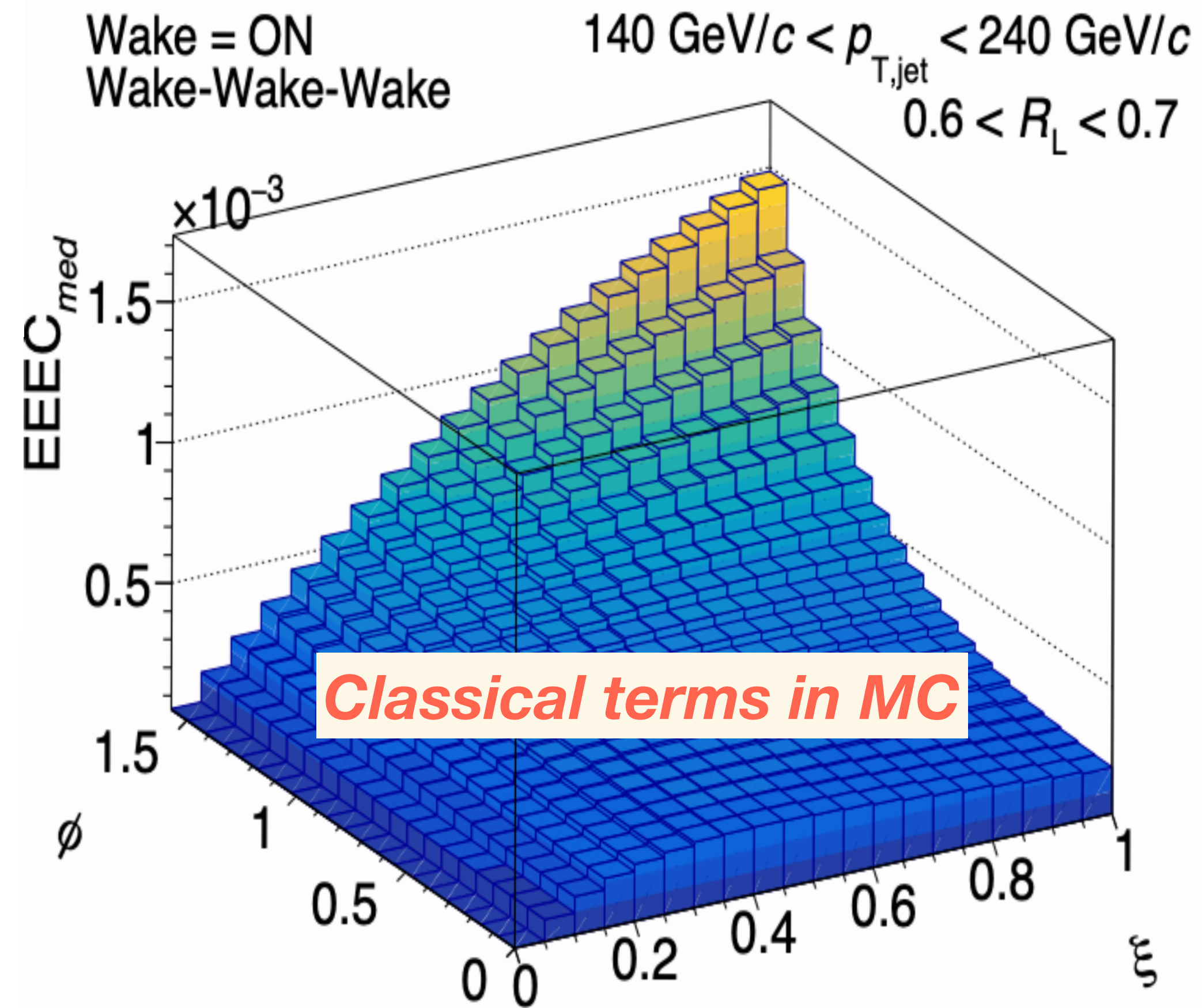
$$\langle \hat{\mathcal{E}}_h(\mathbf{n}_1) \hat{\mathcal{E}}_h(\mathbf{n}_2) \hat{\mathcal{E}}_h(\mathbf{n}_3) \rangle$$



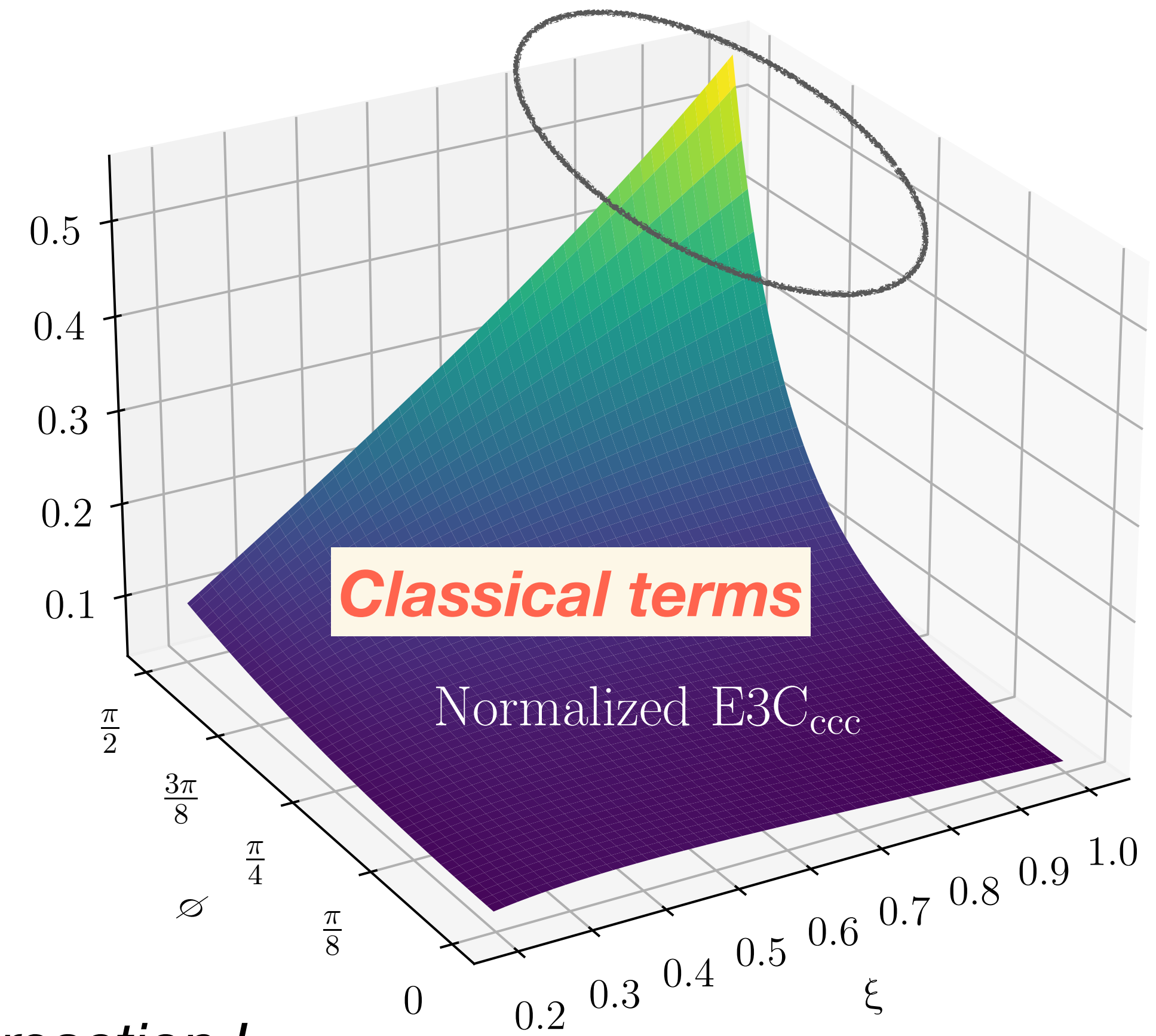
$$\langle \mathcal{E}_c(\mathbf{n}_1) \mathcal{E}_c(\mathbf{n}_2) \mathcal{E}_c(\mathbf{n}_3) \rangle = \mathcal{E}_c(\mathbf{n}_1) \mathcal{E}_c(\mathbf{n}_2) \mathcal{E}_c(\mathbf{n}_3)$$



[Bossi et al., JHEP, 2024]



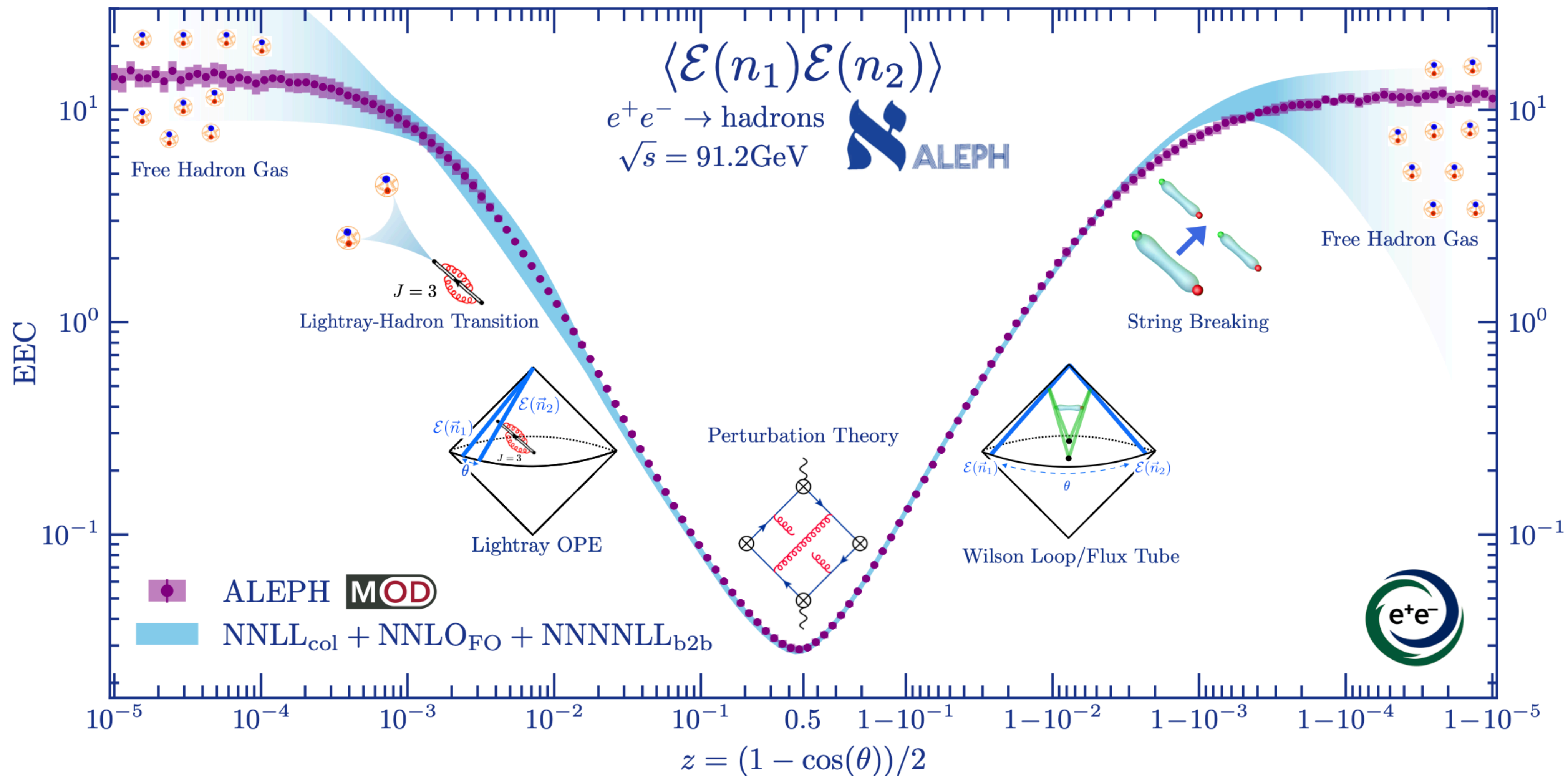
$$\langle \mathcal{E}_c(\mathbf{n}_1) \mathcal{E}_c(\mathbf{n}_2) \mathcal{E}_c(\mathbf{n}_3) \rangle = \mathcal{E}_c(\mathbf{n}_1) \mathcal{E}_c(\mathbf{n}_2) \mathcal{E}_c(\mathbf{n}_3)$$



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

Energy correlators of the bulk matter

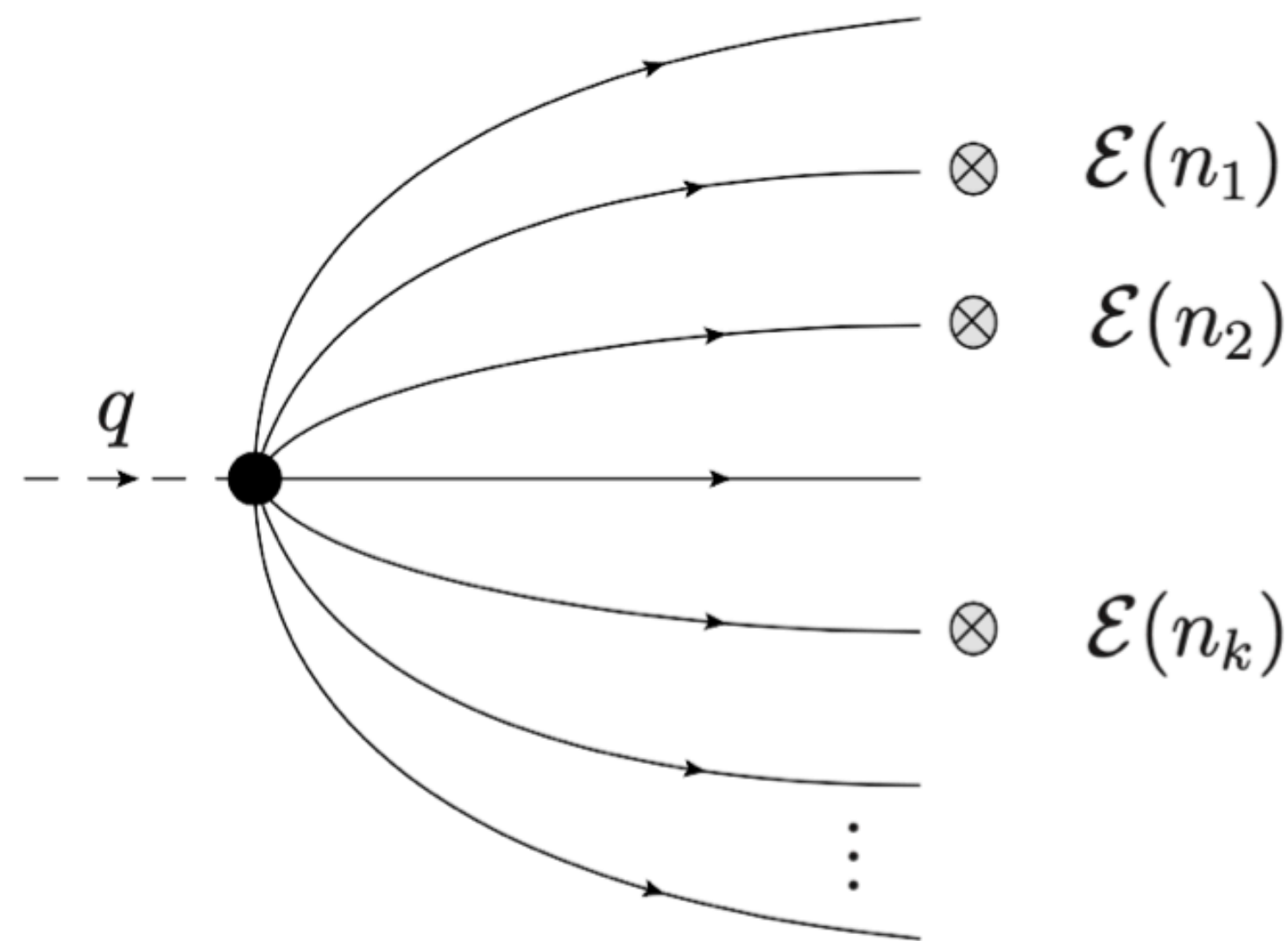
[EP Alliance, 2511.00149]



*EECs have been extended to characterize full e^+e^- events, providing one more **precision test of QCD***

Can this discussion be generalized to understand directly the bulk matter?

$$\langle \text{HIC state} | \mathcal{E}(n_1) \mathcal{E}(n_2) \cdots \mathcal{E}(n_k) | \text{HIC state} \rangle \quad ??$$



*Closely related to EECs on **states generated by heavy operators** in CFTs*

$$\langle Q | \mathcal{E}(n_1) \mathcal{E}(n_2) | Q \rangle = \langle \mathcal{E}(n_1) \rangle \langle \mathcal{E}(n_2) \rangle + \frac{1}{\Delta_Q} \langle \delta \mathcal{E}(n_1) \delta \mathcal{E}(n_2) \rangle + \dots$$

[Chicherin et al, 2306.14330]

[Cuomo et al, 2503.21867]

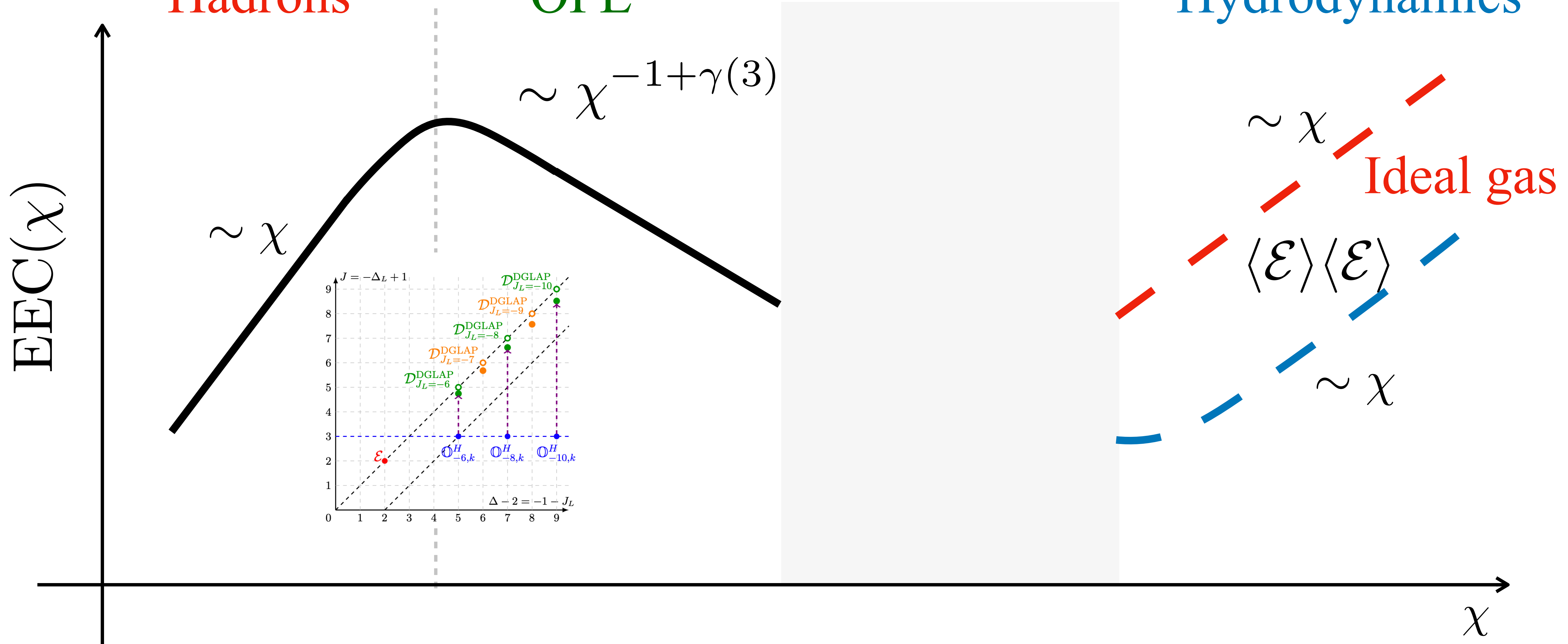


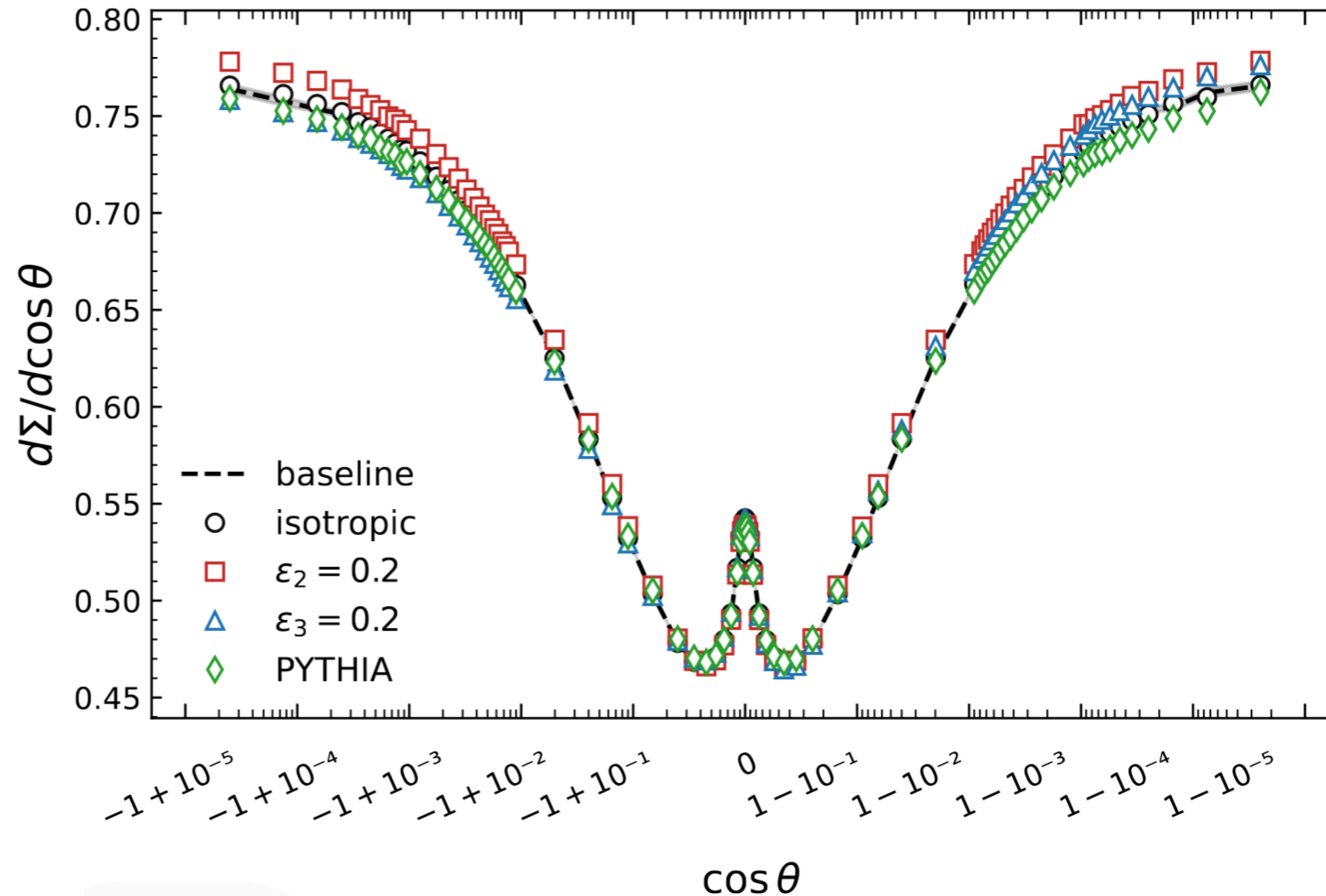
This suggest a generic form for the EEC structure measured in QCD matter bulk states

Hadrons

OPE

Hydrodynamics

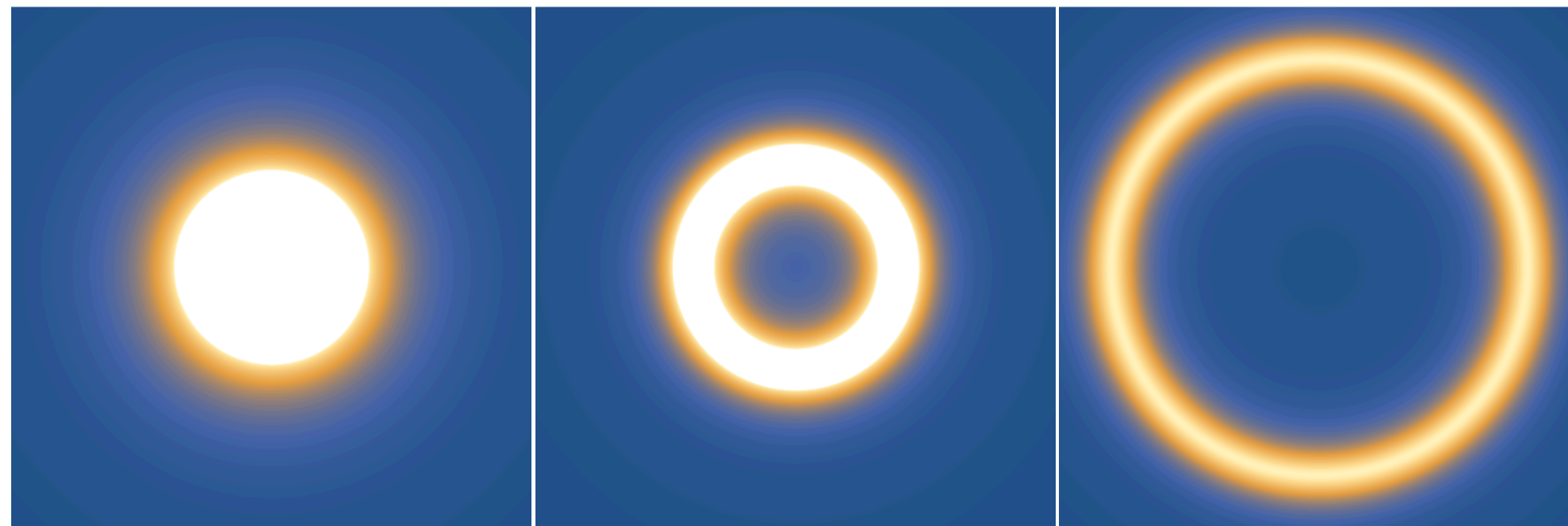




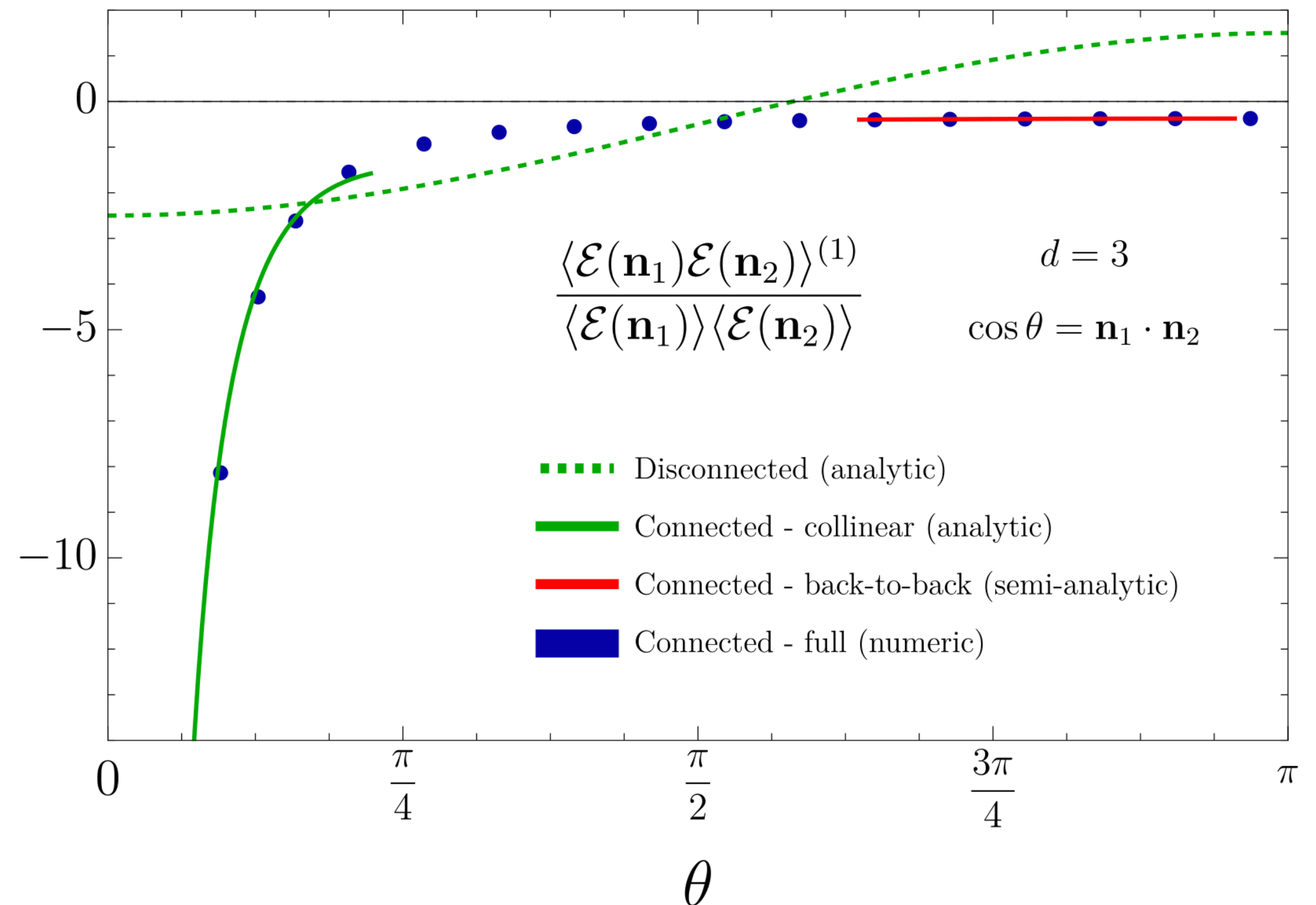
*EECs allow to fully characterize the entire HIC event, exactly recovering form **obtained from geometrical correlations***

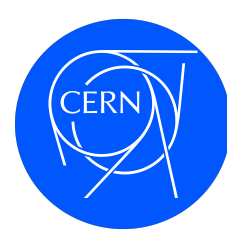
Can this discussion be generalized to understand fluctuations ?

$$\langle Q | \mathcal{E}(n_1) \mathcal{E}(n_2) | Q \rangle = \langle \mathcal{E}(n_1) \rangle \langle \mathcal{E}(n_2) \rangle + \frac{1}{\Delta_Q} \langle \delta \mathcal{E}(n_1) \delta \mathcal{E}(n_2) \rangle + \dots$$



[Cuomo et al, 2503.21867]

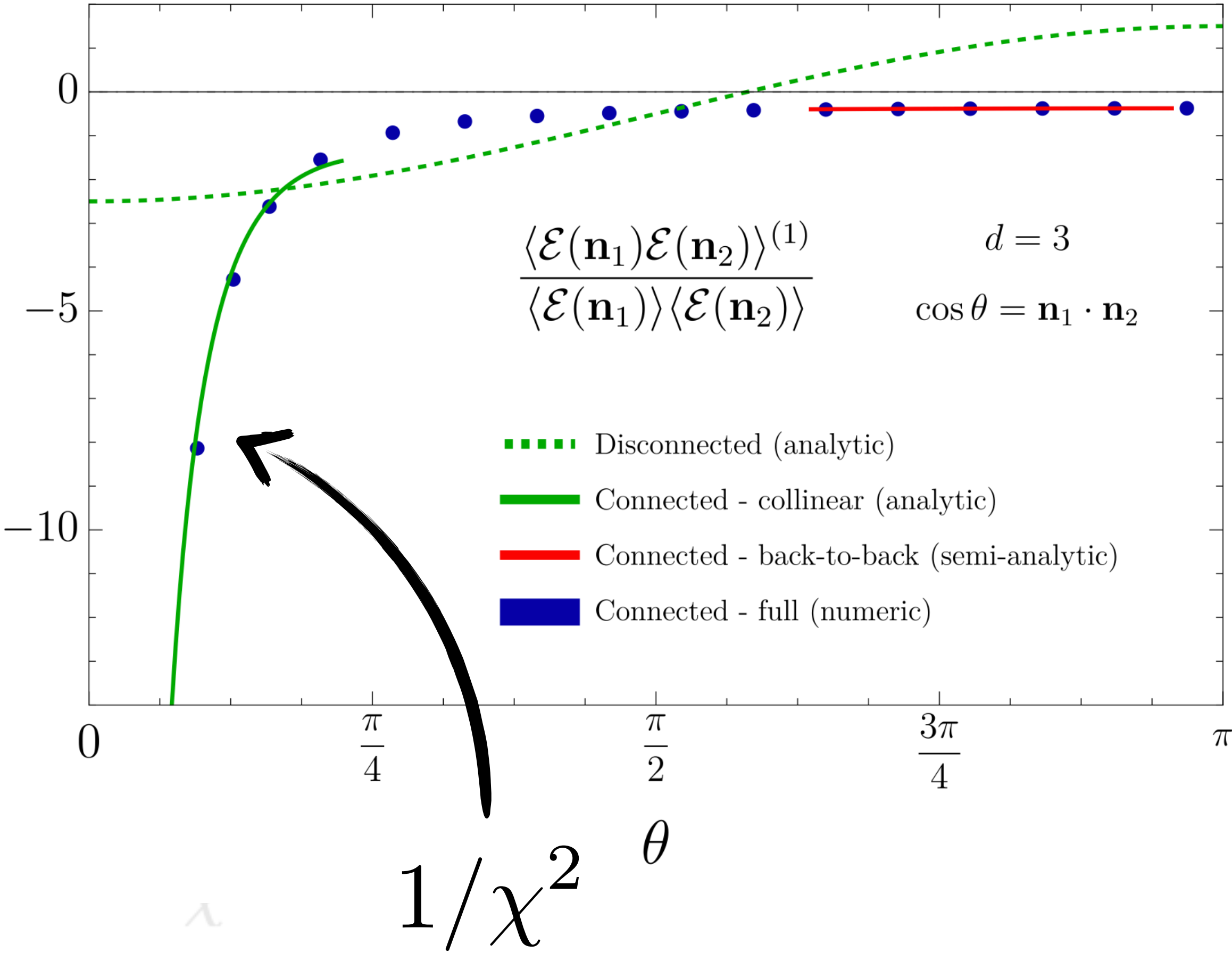
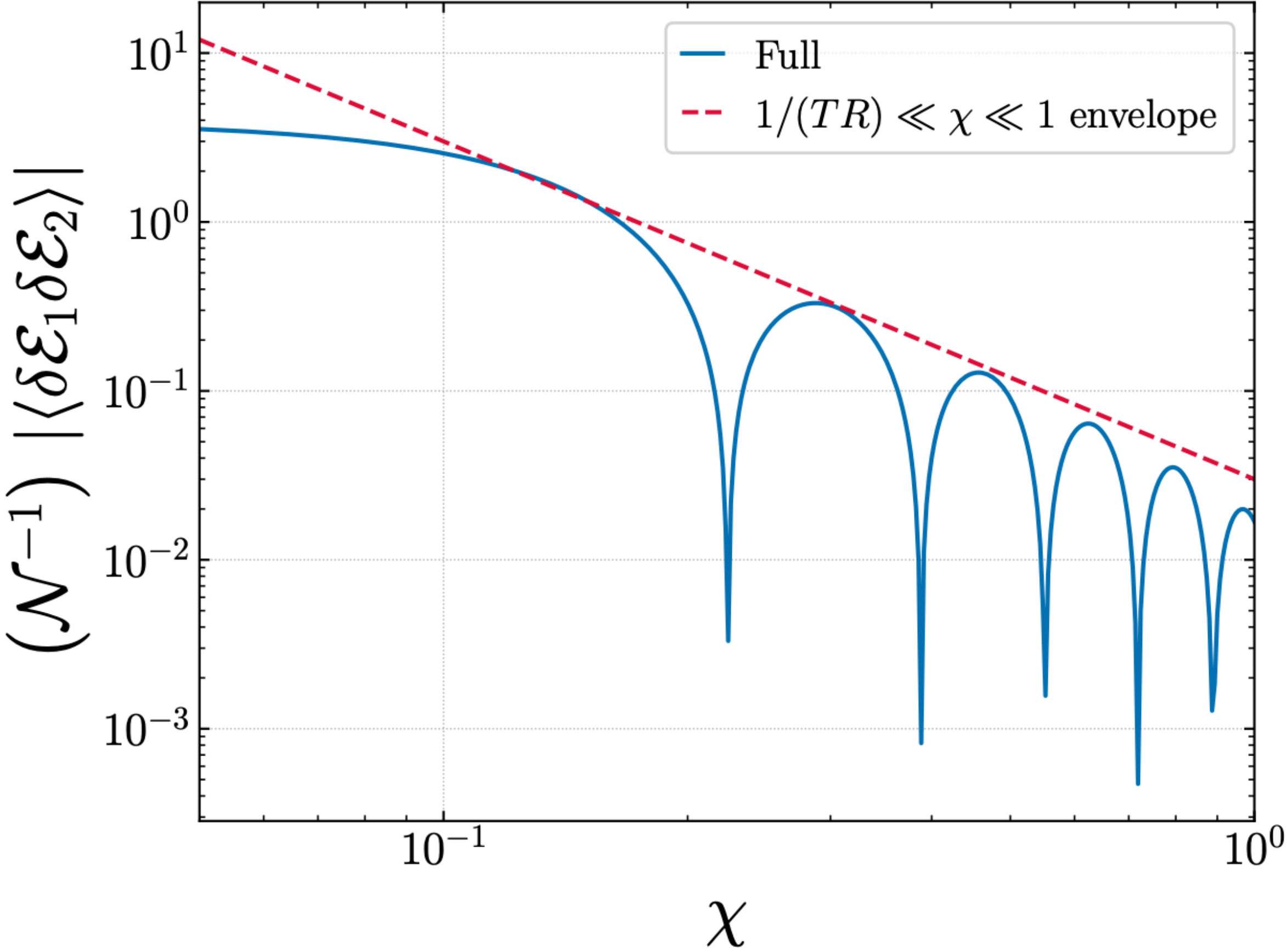


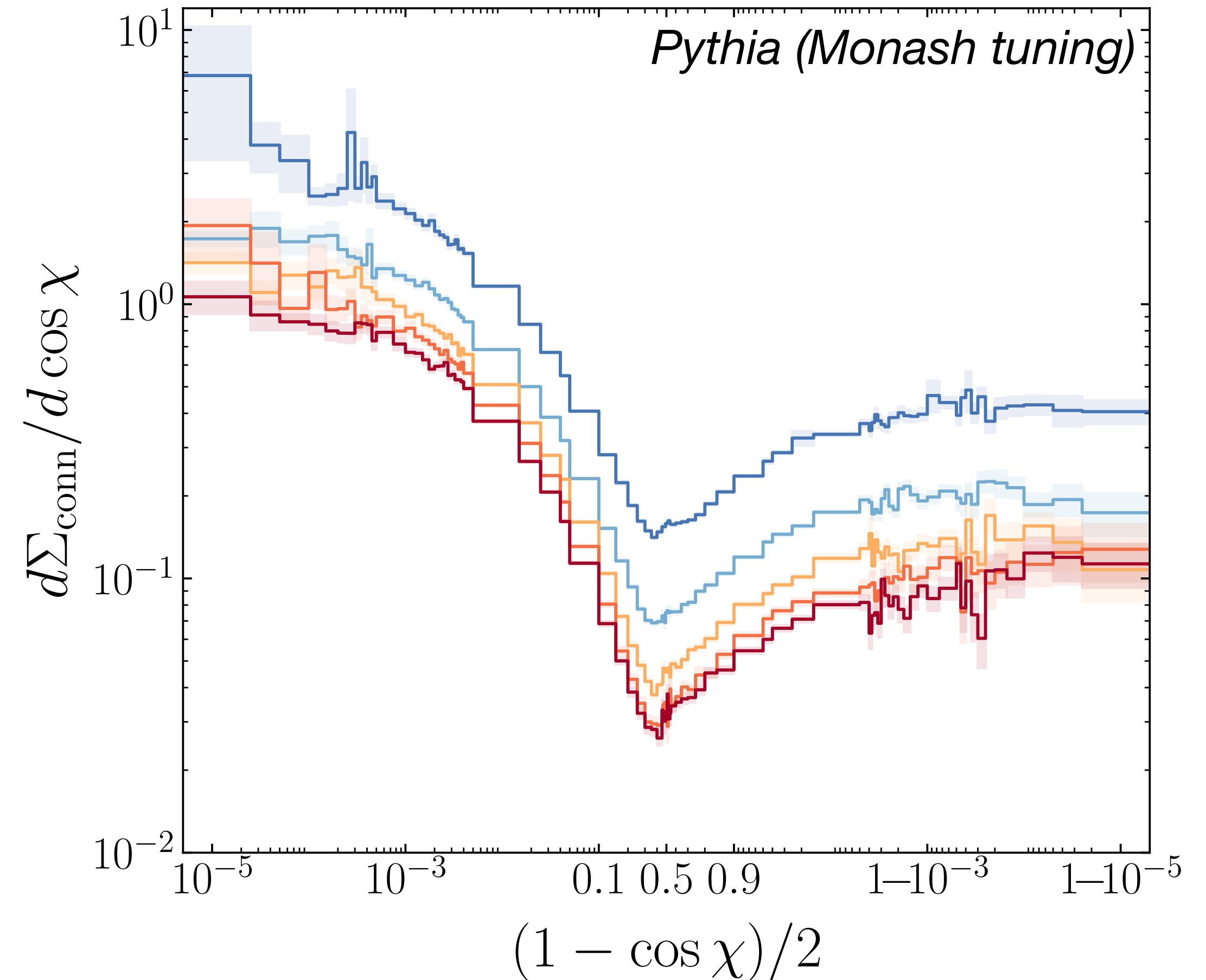
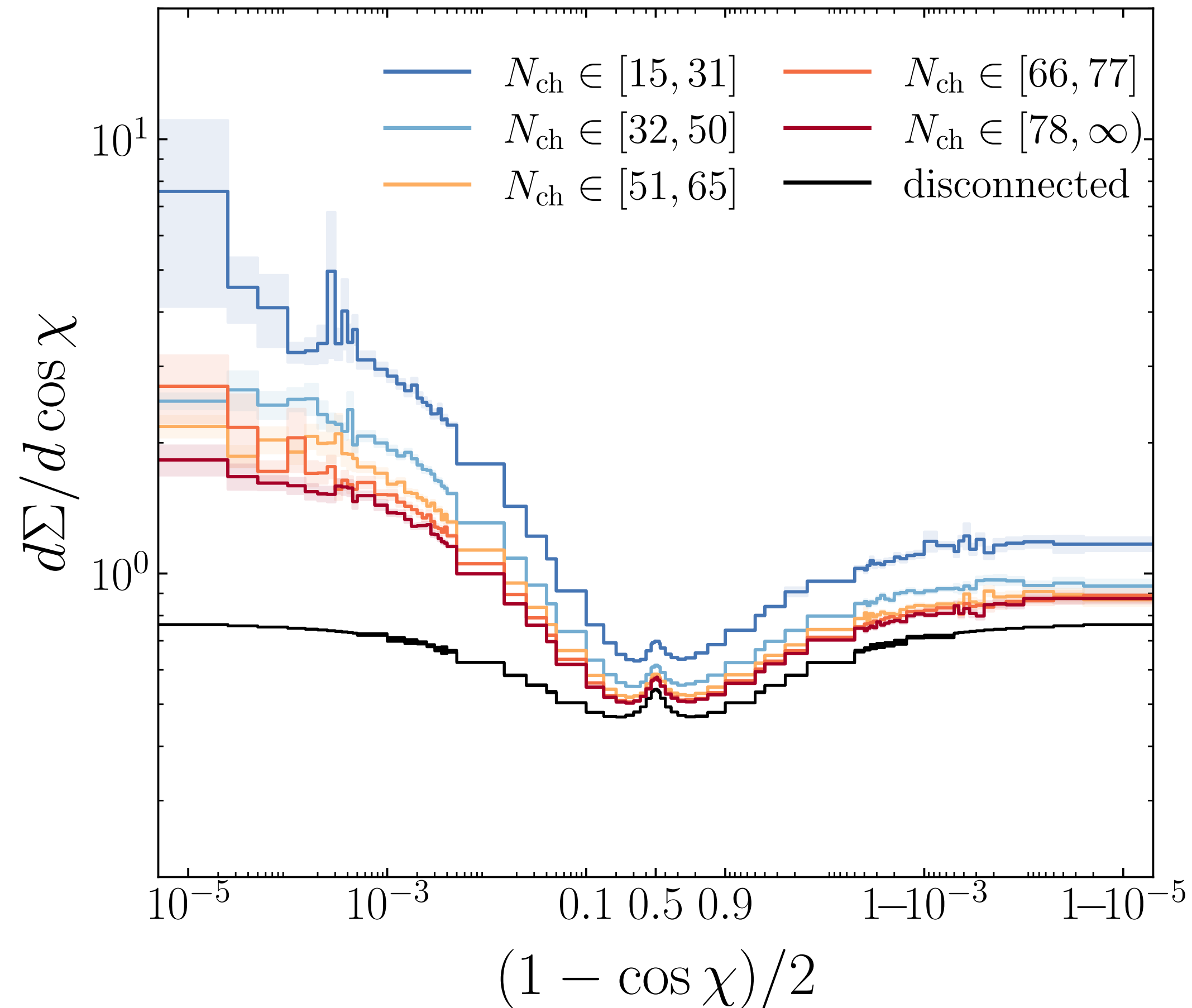


Can this discussion be generalized to understand directly the bulk matter? Yes

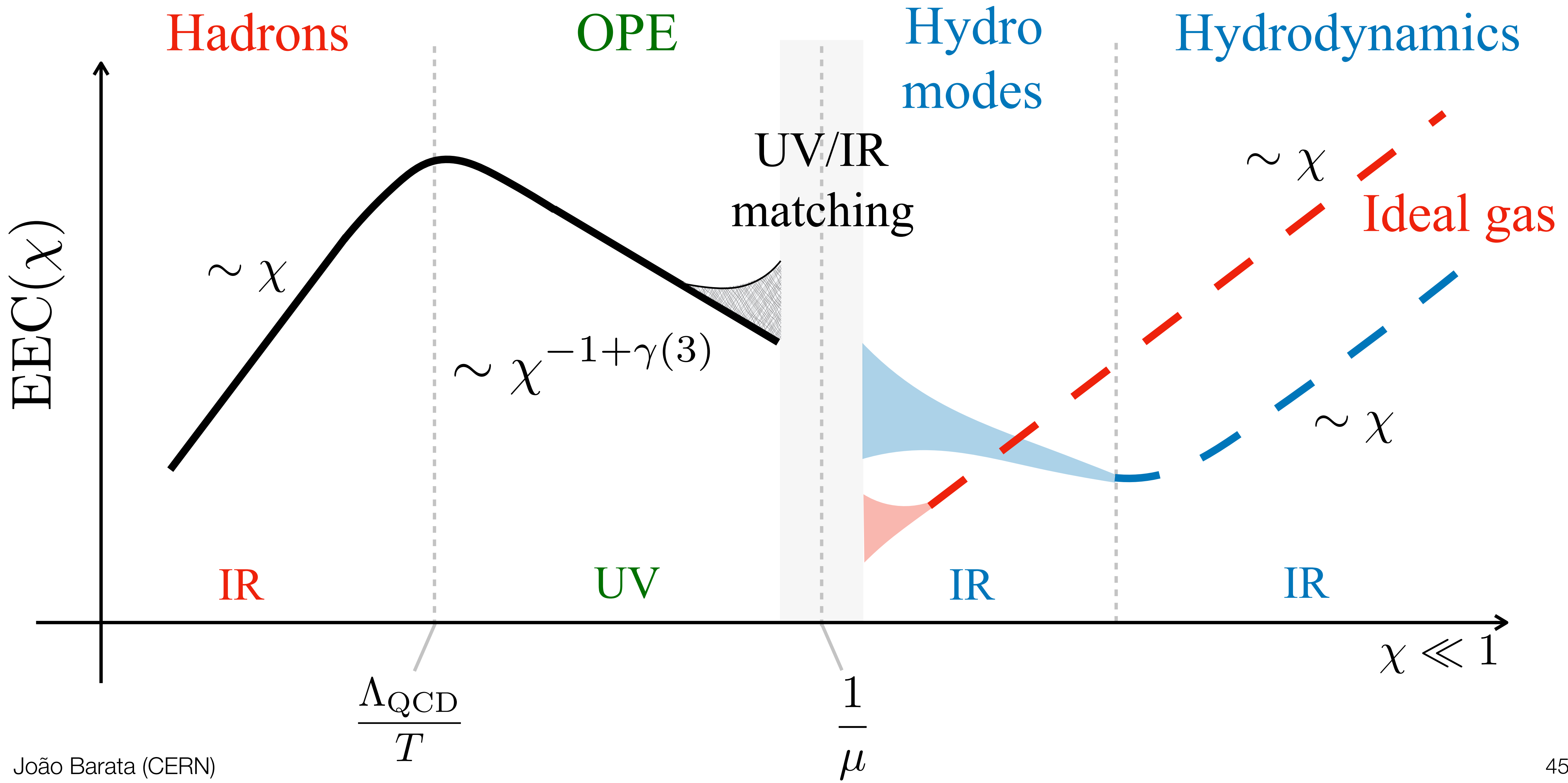
$$\langle \delta \mathcal{E}(\mathbf{n}_1) \delta \mathcal{E}(\mathbf{n}_2) \rangle_{\text{conn}} = R^4 \int_0^{t_{\text{max}}} dt_1 \int_0^{t_{\text{max}}} dt_2 n_{1i} n_{2j} \langle \delta T_{0i}(t_1, R\mathbf{n}_1) \delta T_{0j}(t_2, R\mathbf{n}_2) \rangle$$

$dt_2 n_{1i} n_{2i} \langle \delta T_{0i} [\text{Cuomo et al, 2503.21867}] \rangle$



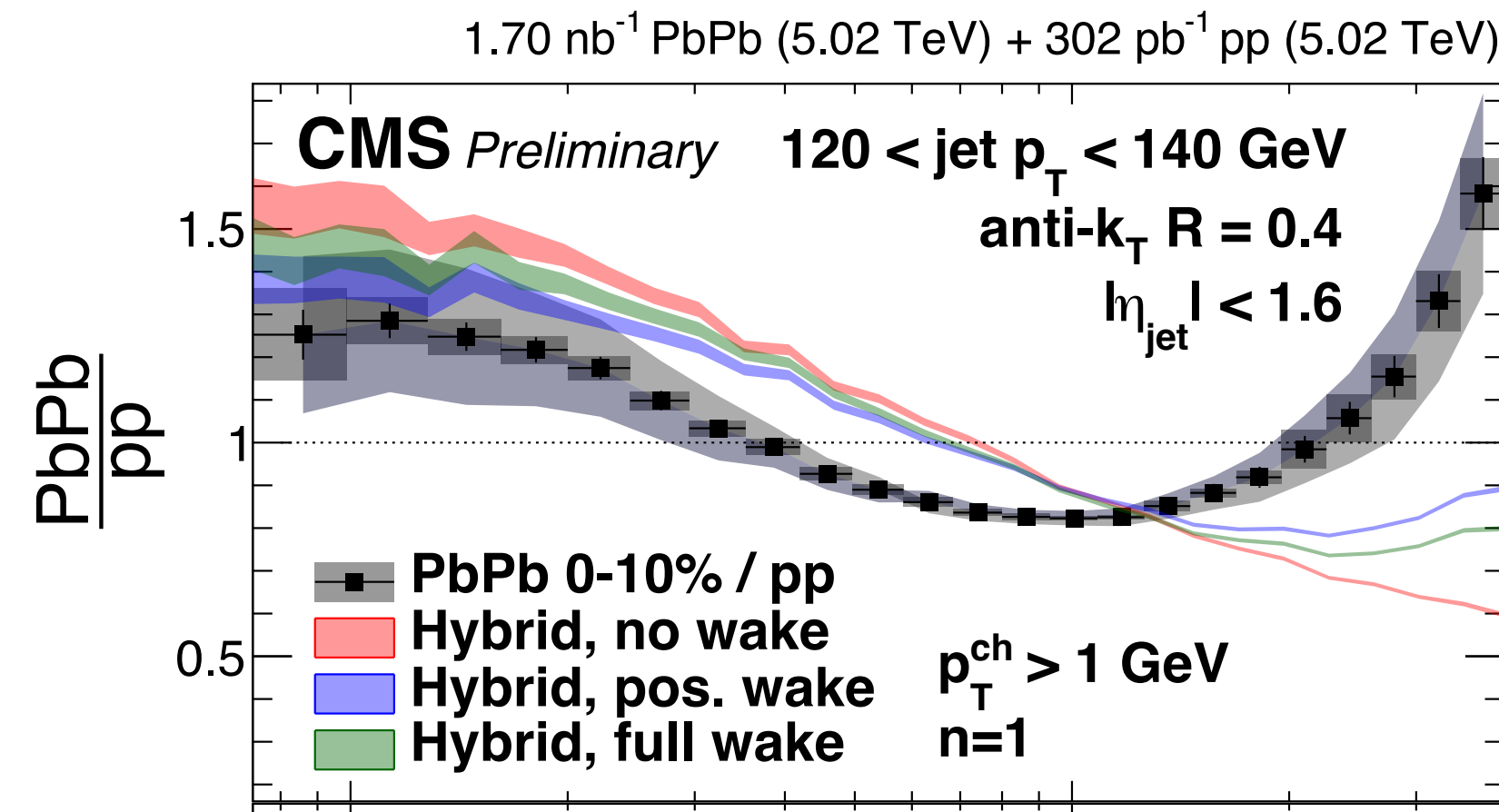


*EECs allow to fully characterize the entire HIC event, exactly recovering form **obtained from geometrical correlations***

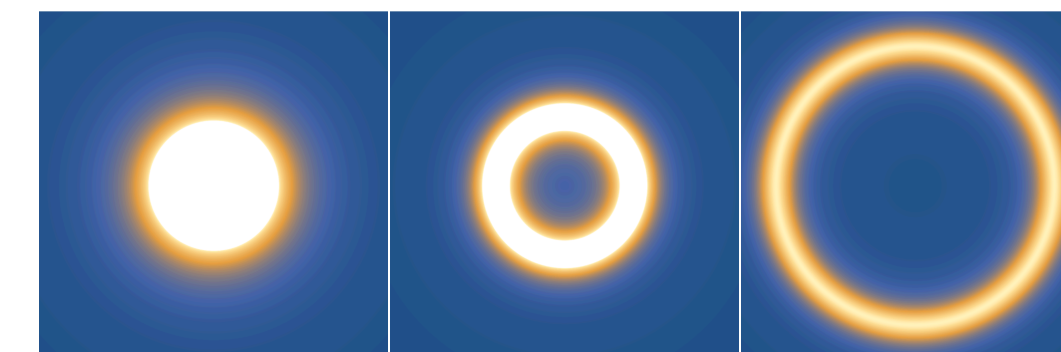
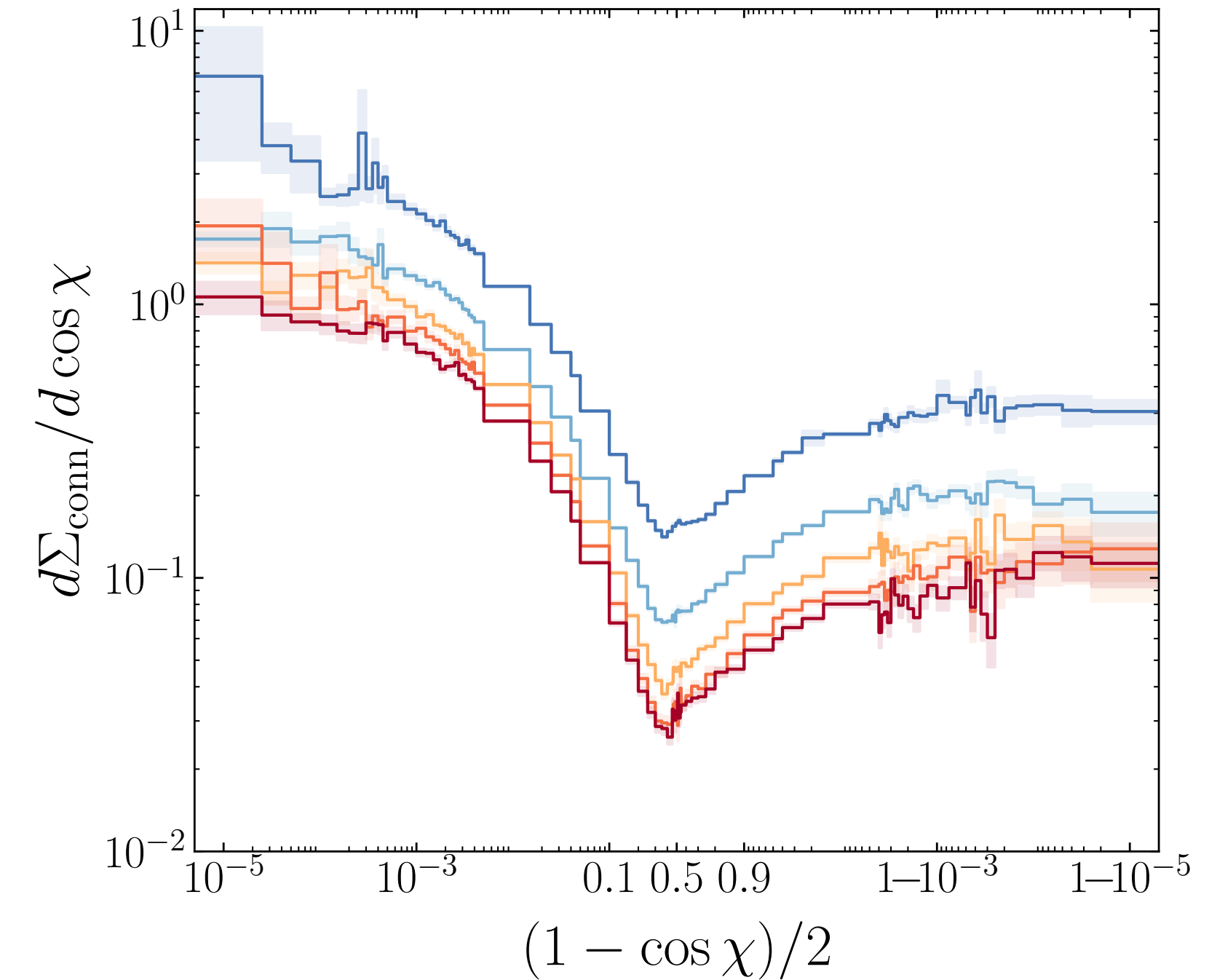
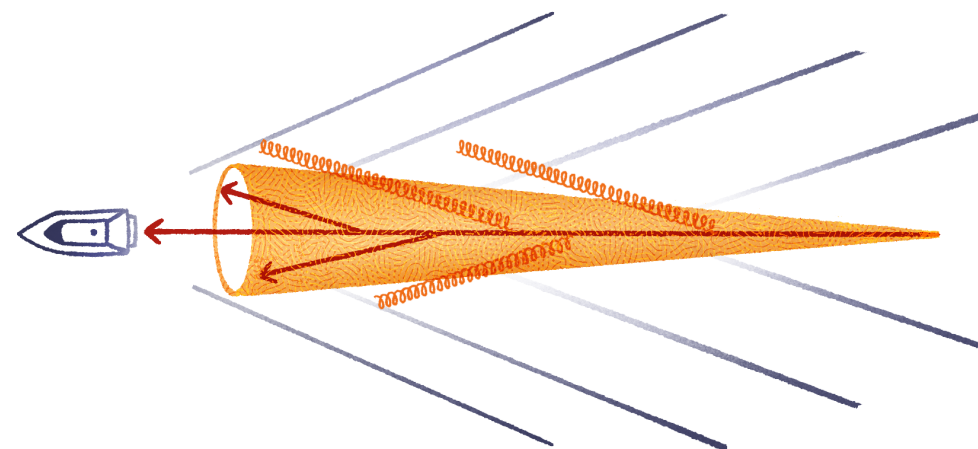


Conclusion

*ENCs offer a way to treat jets in HICs in a **consistent and clean** theoretical picture*

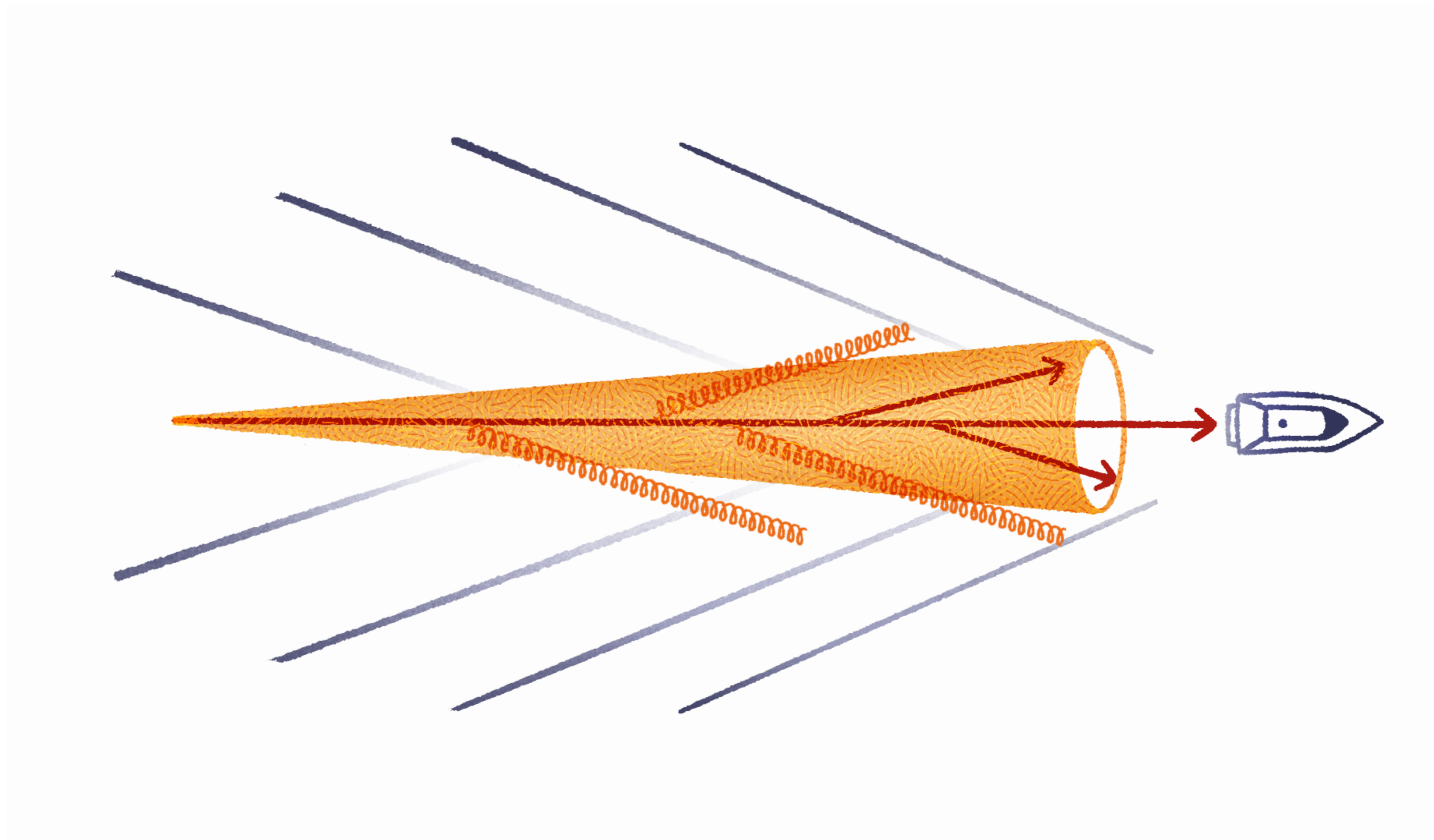


$$\frac{d\Sigma_P^{(3)}}{dR_L} = \frac{a_{2,0}^{P(3)}}{R_L} + \left(a_{4,0}^{P(3)} + b_{4,0}^{P(3)} + c_4^{P(3)} \right) R_L + \dots$$



These observables can be extended beyond jet physics in HICs, and allow for conceptually new description of QCD systems

Thank you !



The structure of ENCs, in the conformal limit, is determined by symmetry arguments

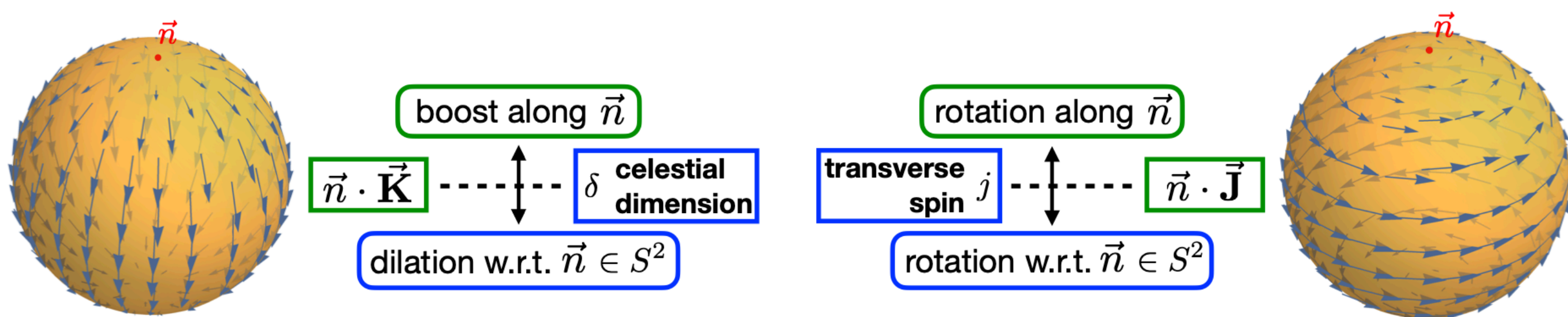
“dynamical” coefficient

$$\langle \mathcal{E}(n_1) \mathcal{E}(n_2) \rangle = \sum_{\delta, j} \int_{\gamma} \frac{c_{\delta, j, \gamma}}{2\pi i} w^{\gamma} G_{\delta, j, \gamma}(z, \bar{z})$$

Celestial block of celestial dimension δ and transverse spin j

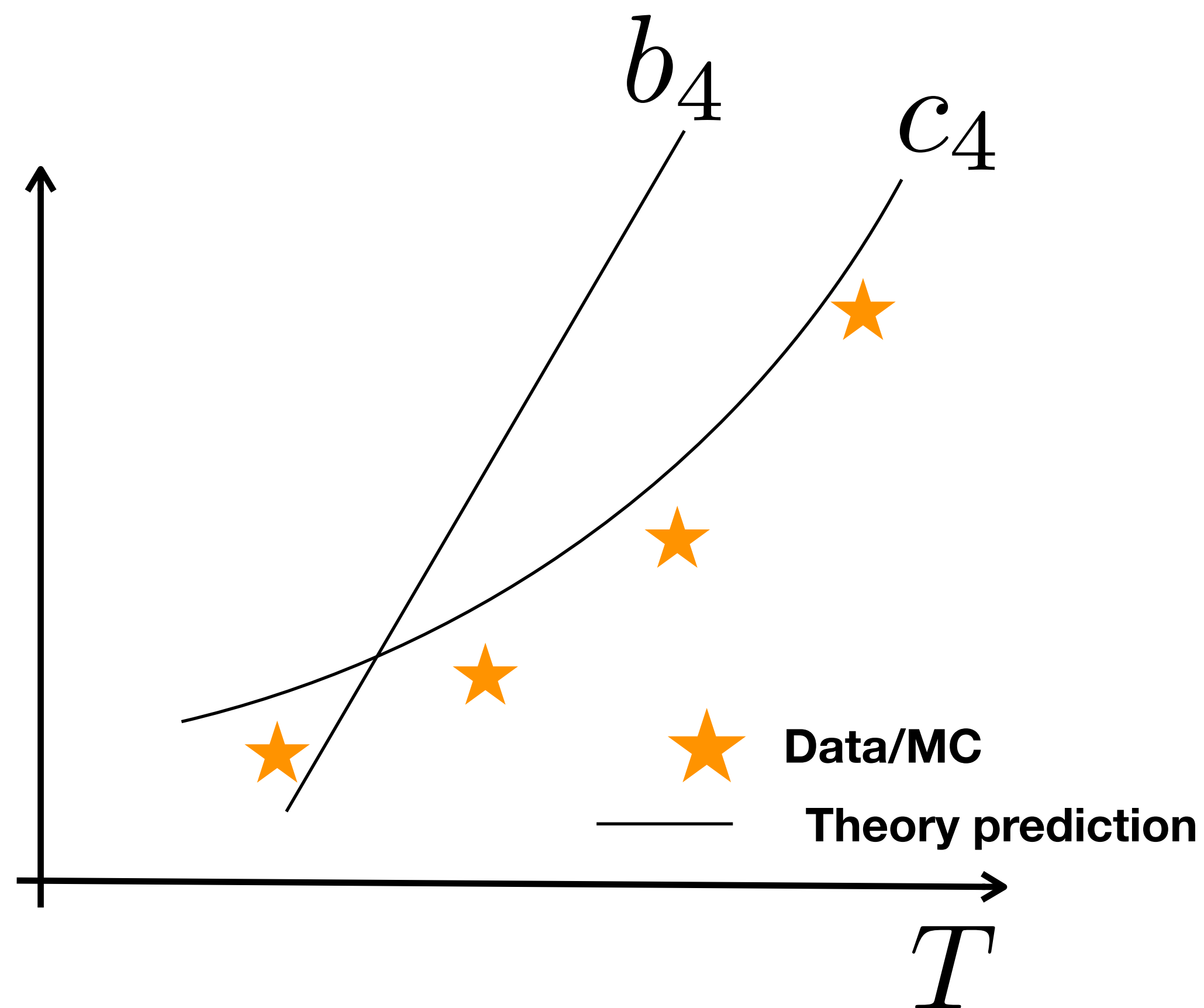
In the collinear limit this structure reduces to the usual expression obtained in QCD

$$\frac{d\Sigma}{d\chi} = \sum_{\tau} c_{\tau, 0} \chi^{\tau-3}$$



Next steps for Pheno/Exp:

Is there a way to separate these different contributions ?



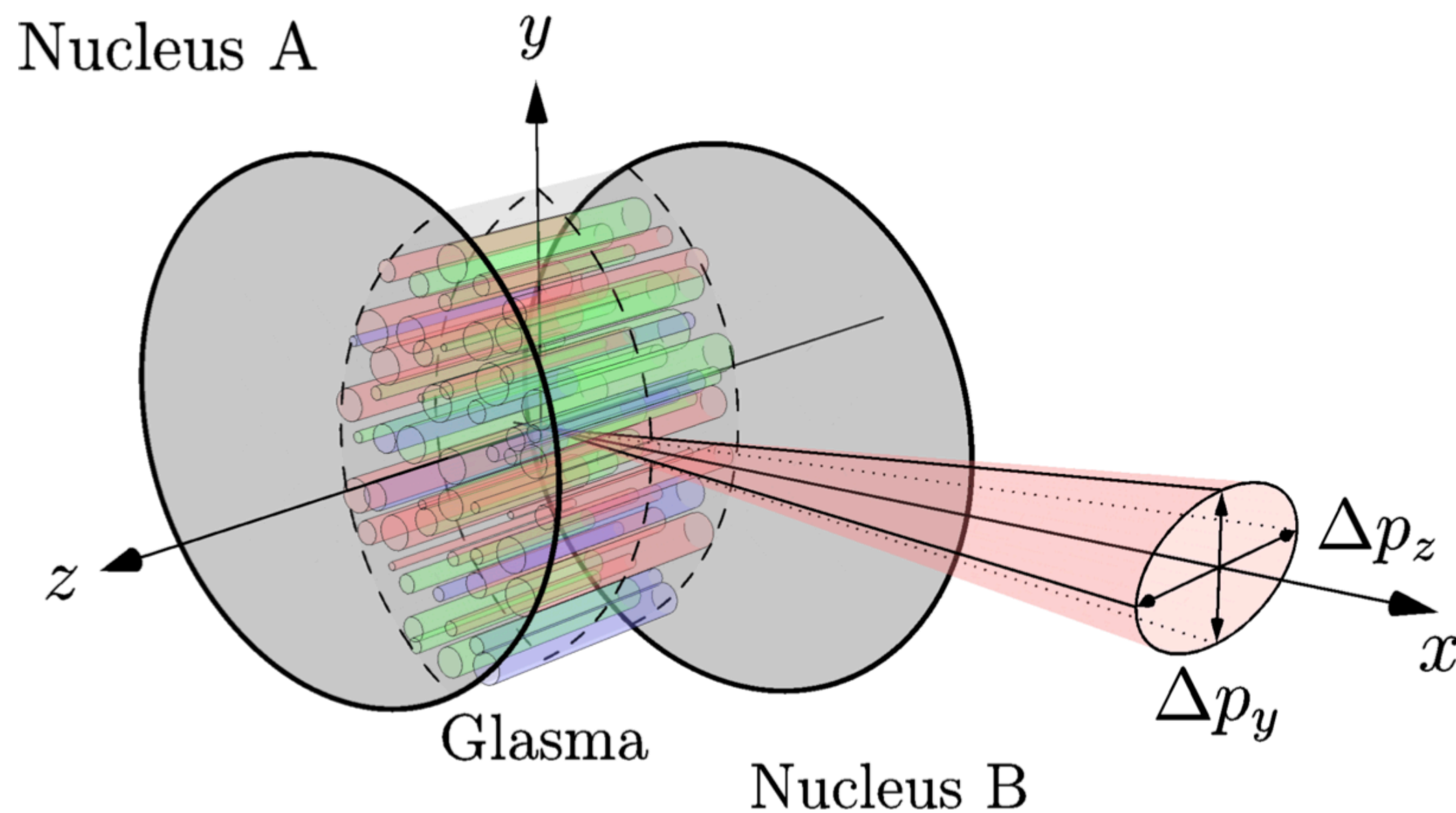
Can this be tested across system sizes?

The same questions apply for pure bulk/min bias observable ?

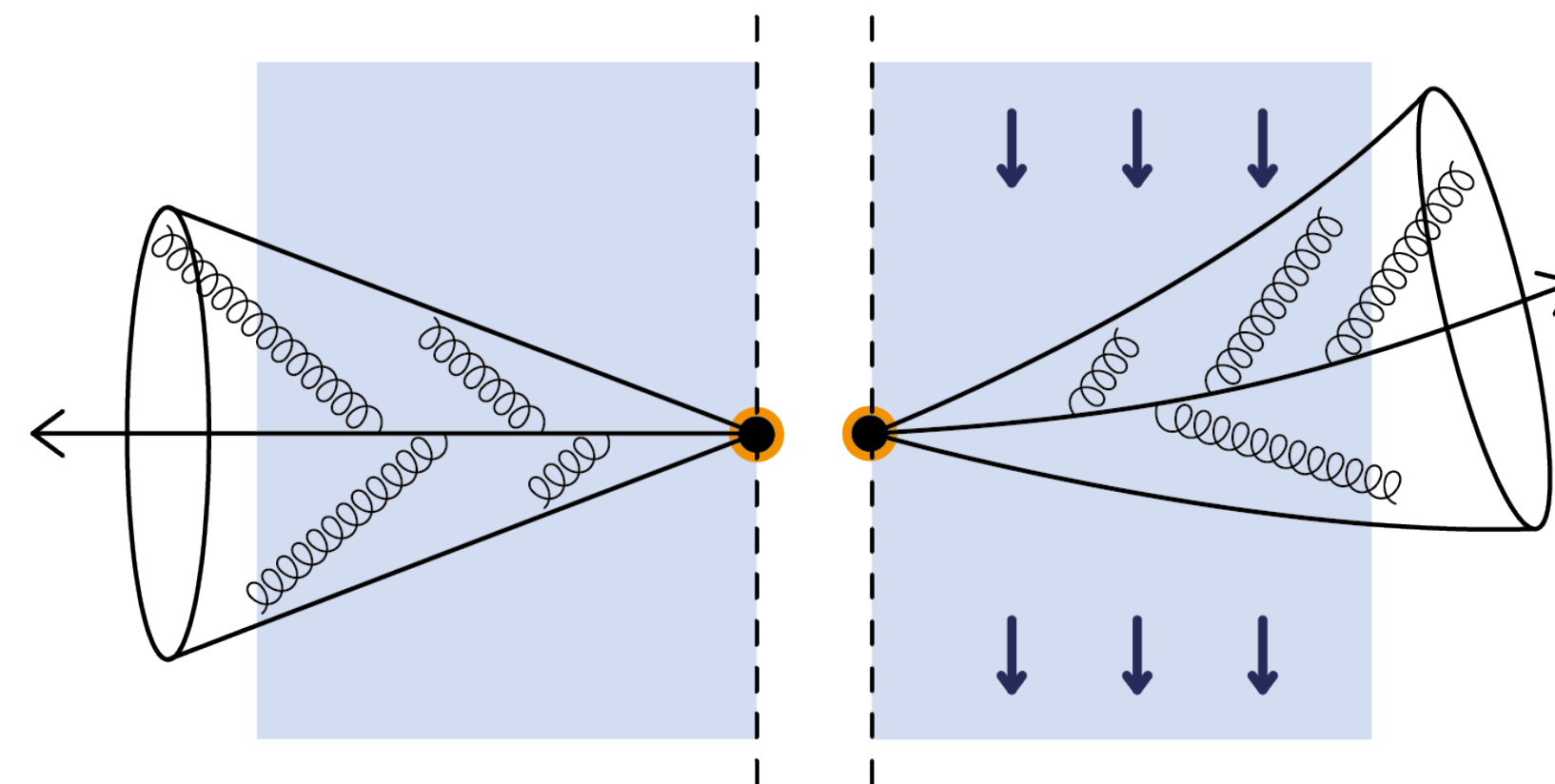
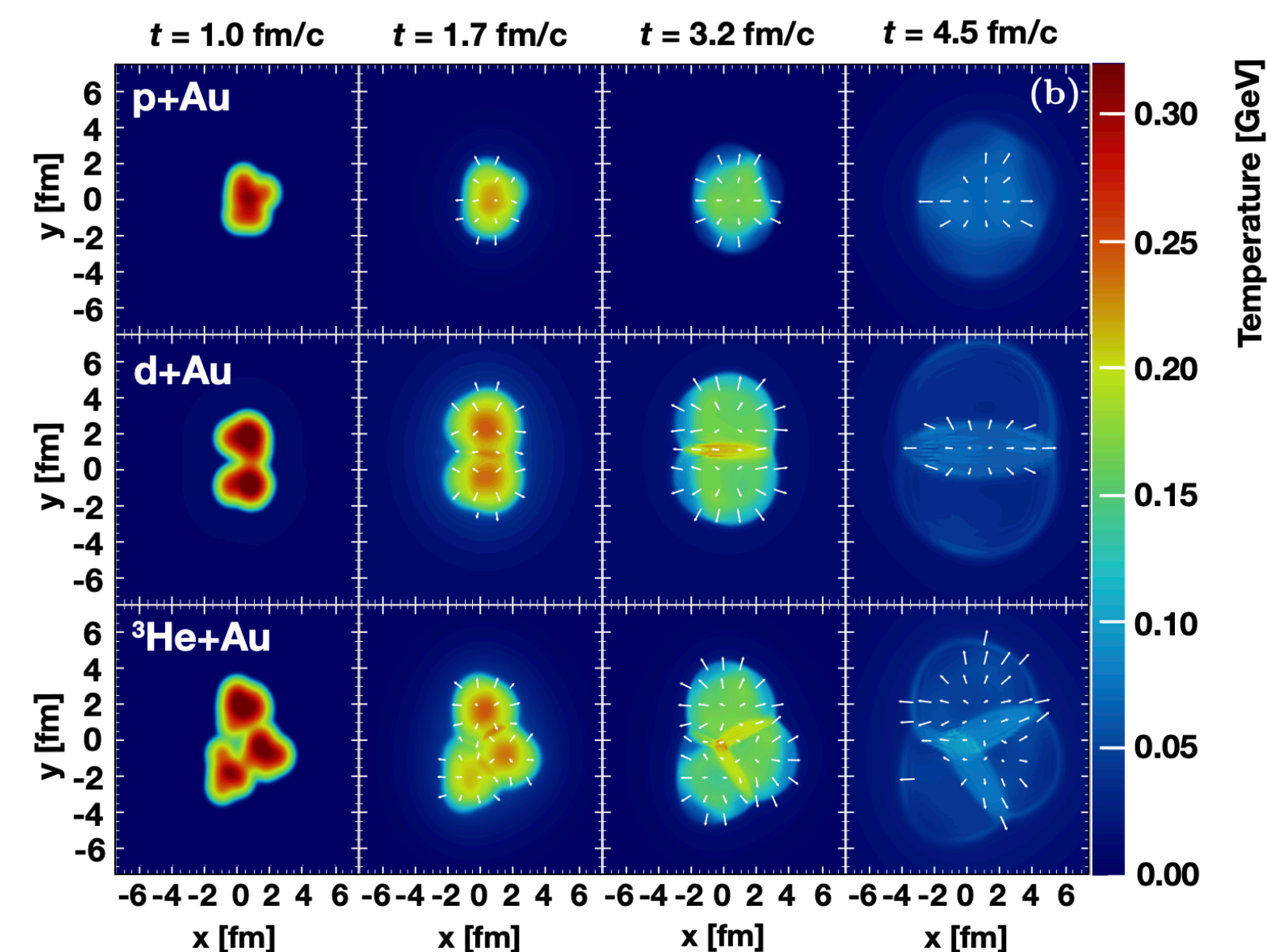
$$\frac{d\Sigma_P^{(3)}}{dR_L} = \frac{a_{2,0}^{P(3)}}{R_L} + \left(a_{4,0}^{P(3)} + b_{4,0}^{P(3)} + c_4^{P(3)} \right) R_L + \dots$$

Spatial structure of matter from EECs

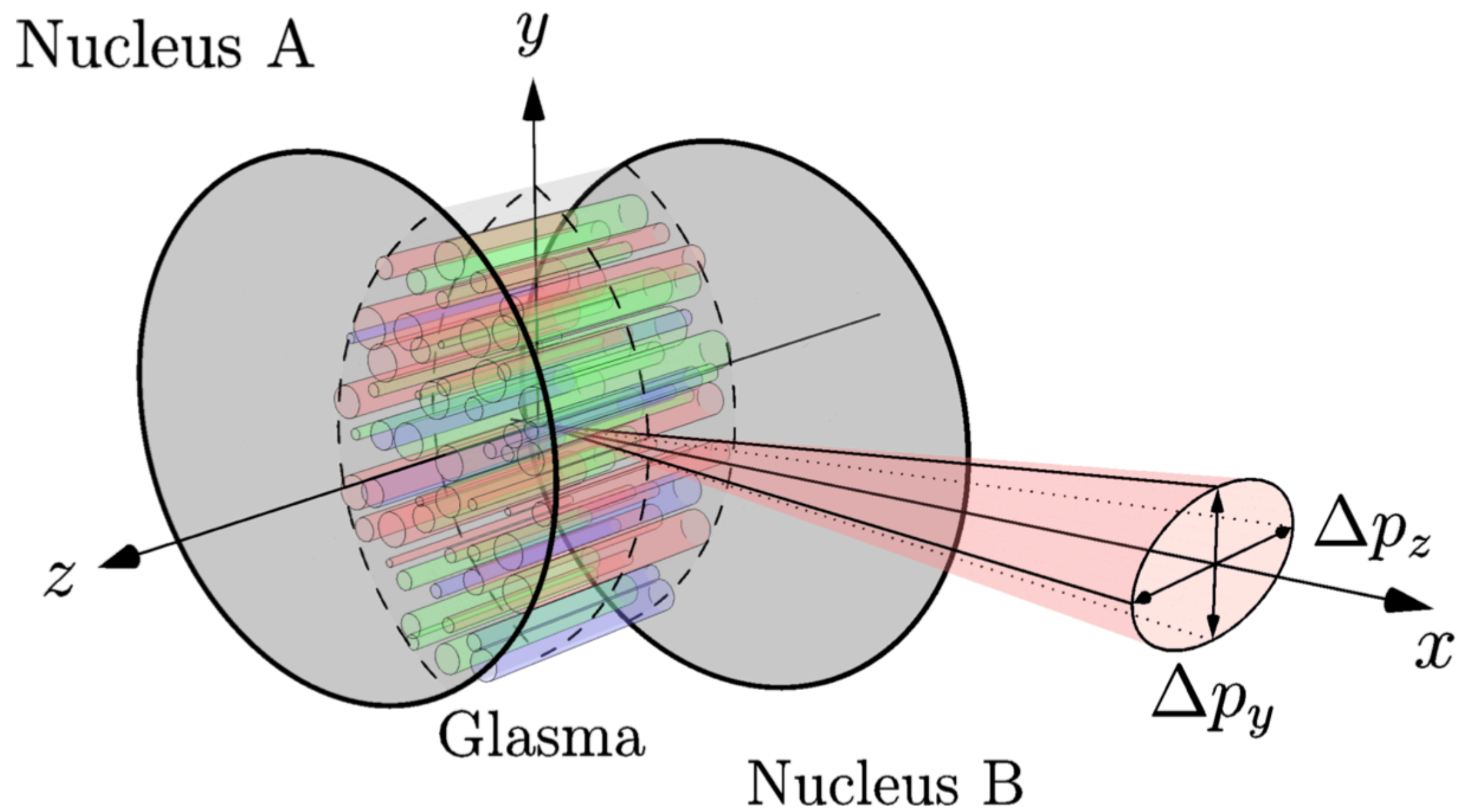
Bulk matter produced in HICs can have more complex geometry than the simple QGP-like picture I have discussed



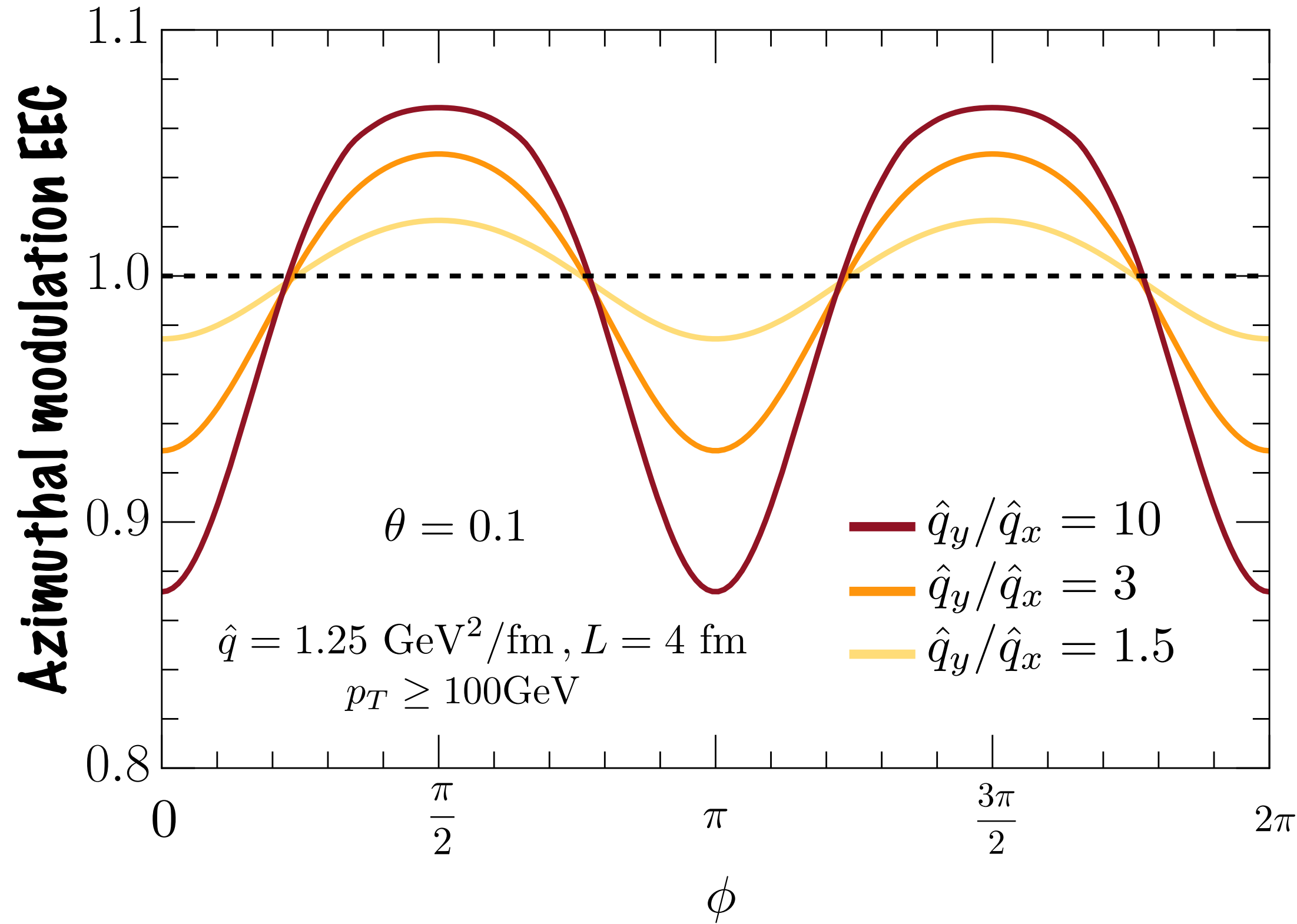
Jets are optimal candidates to resolve some of these features



Spatial structure of matter from EECs



[JB, Brewer, Lee, Silva, 2508.19404]



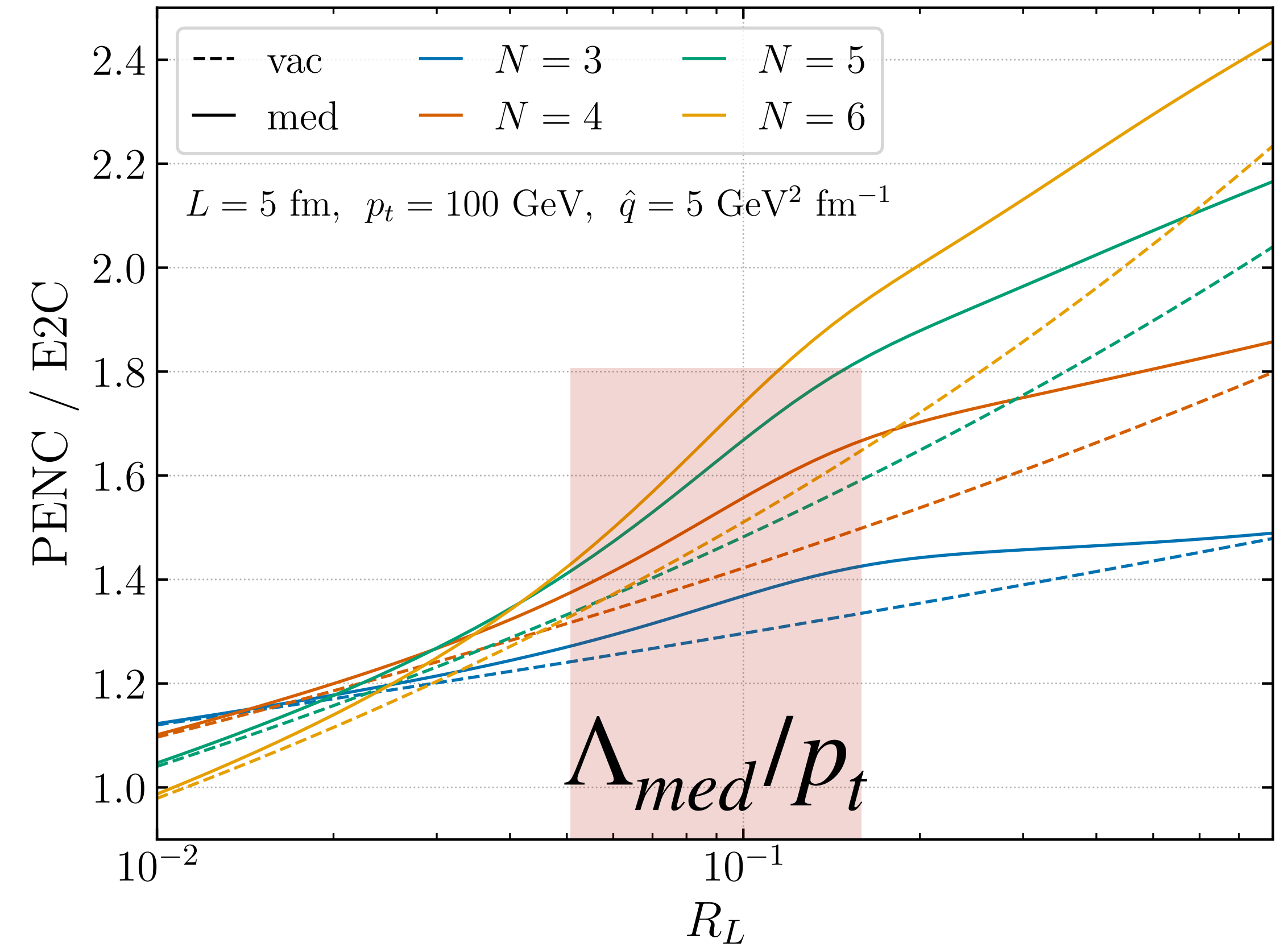
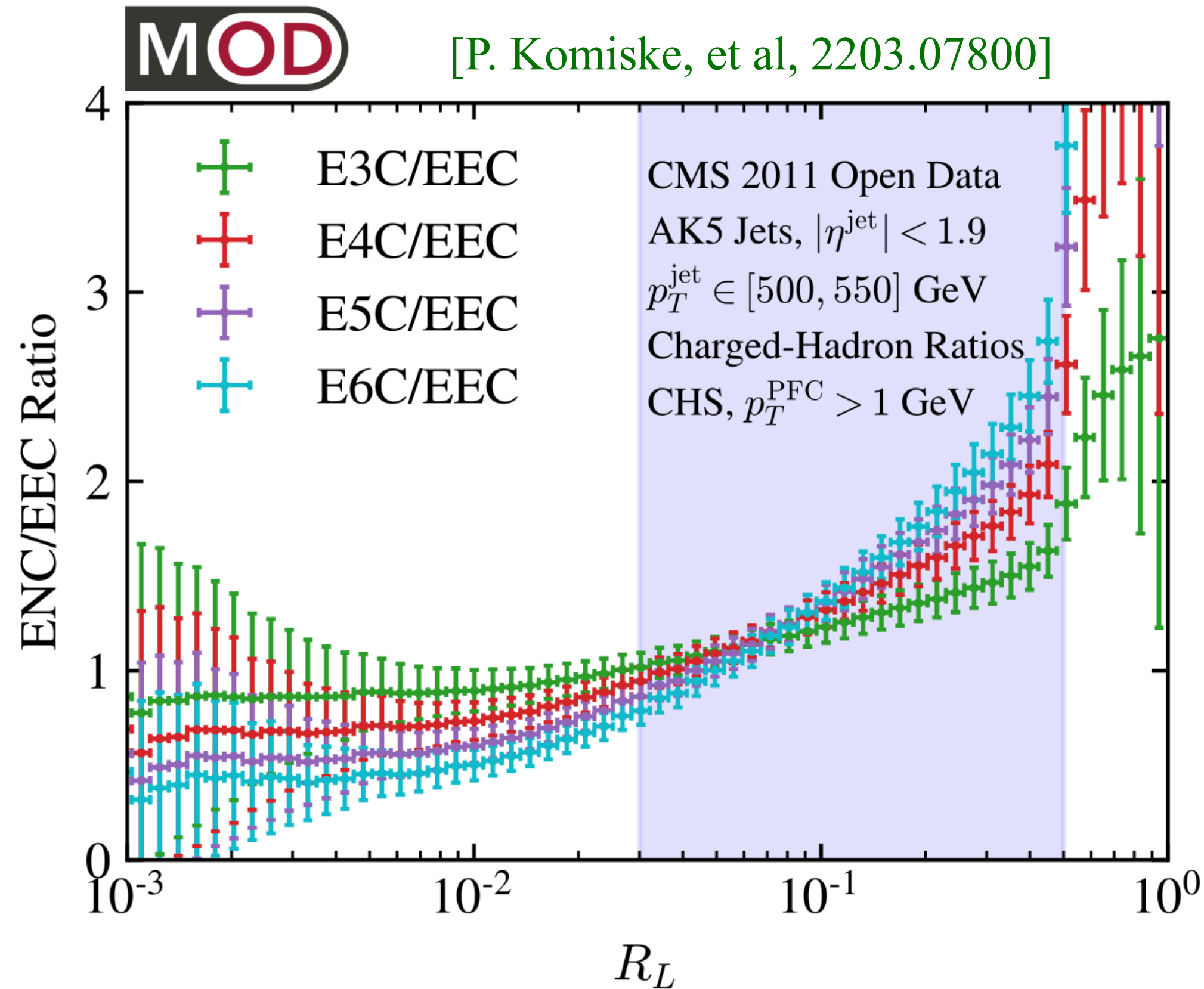
General decomposition of EEC in such a state can be derived, including classical flows

[JB, Milhano, Sadofyev, Silva, wip]

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

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

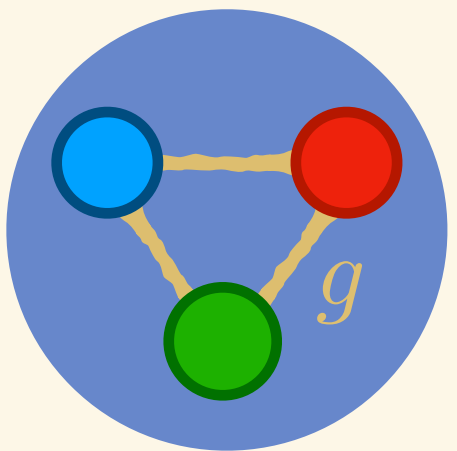
The same conclusions hold for higher point functions, where the shape can be non-trivial



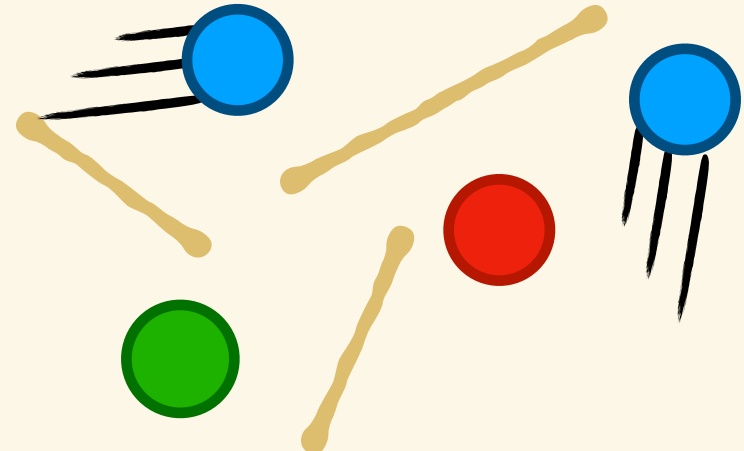
$$\frac{d\Sigma_P^{(N)}}{dR_L} = \frac{\alpha_s R_L^{\frac{\alpha_s}{\pi} \gamma(N+1)}}{\pi R_L} \int_0^1 dz (1 - z^N - (1 - z)^N) P_{gq}^{vac+med}$$

The Standard Model of heavy ion collisions

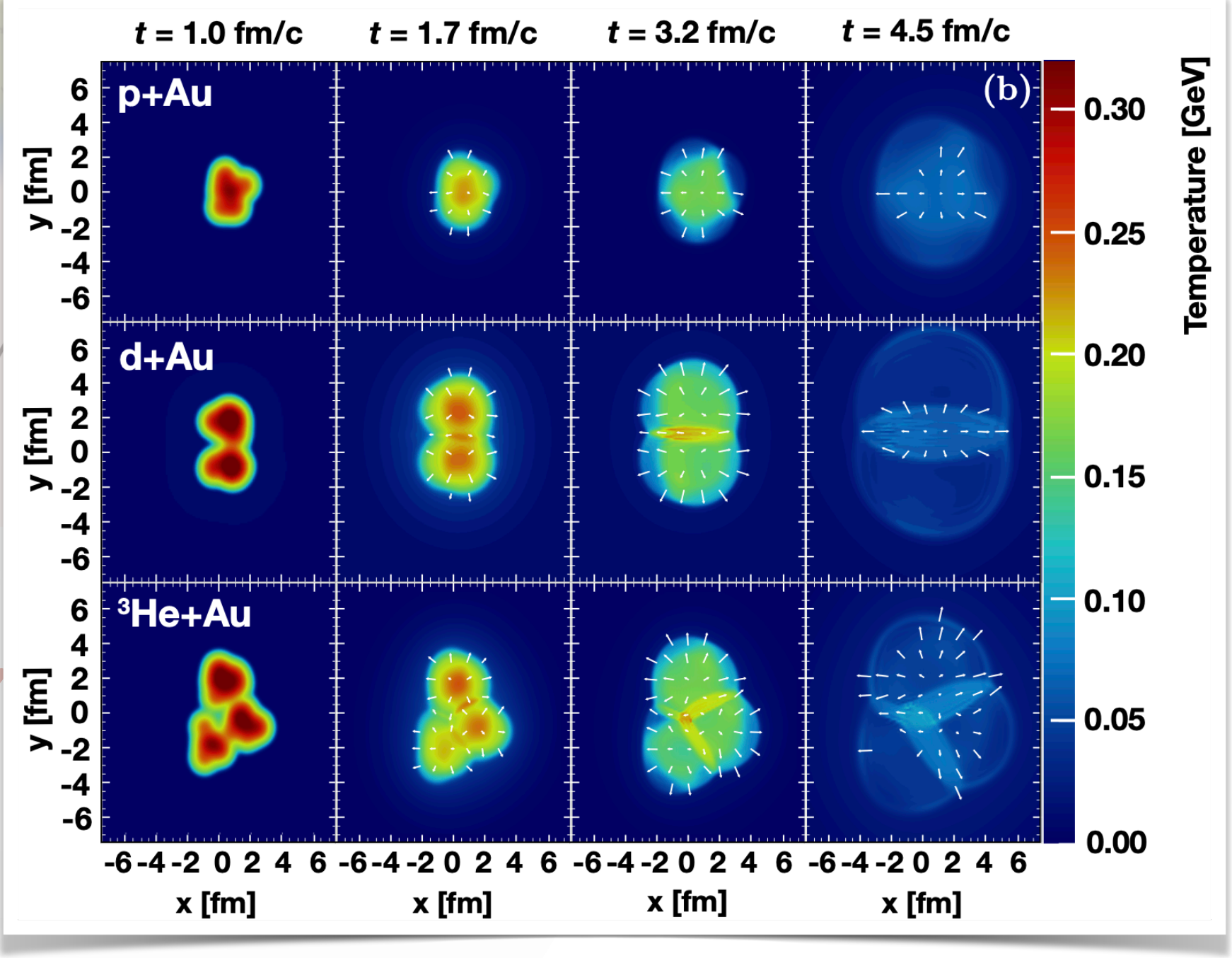
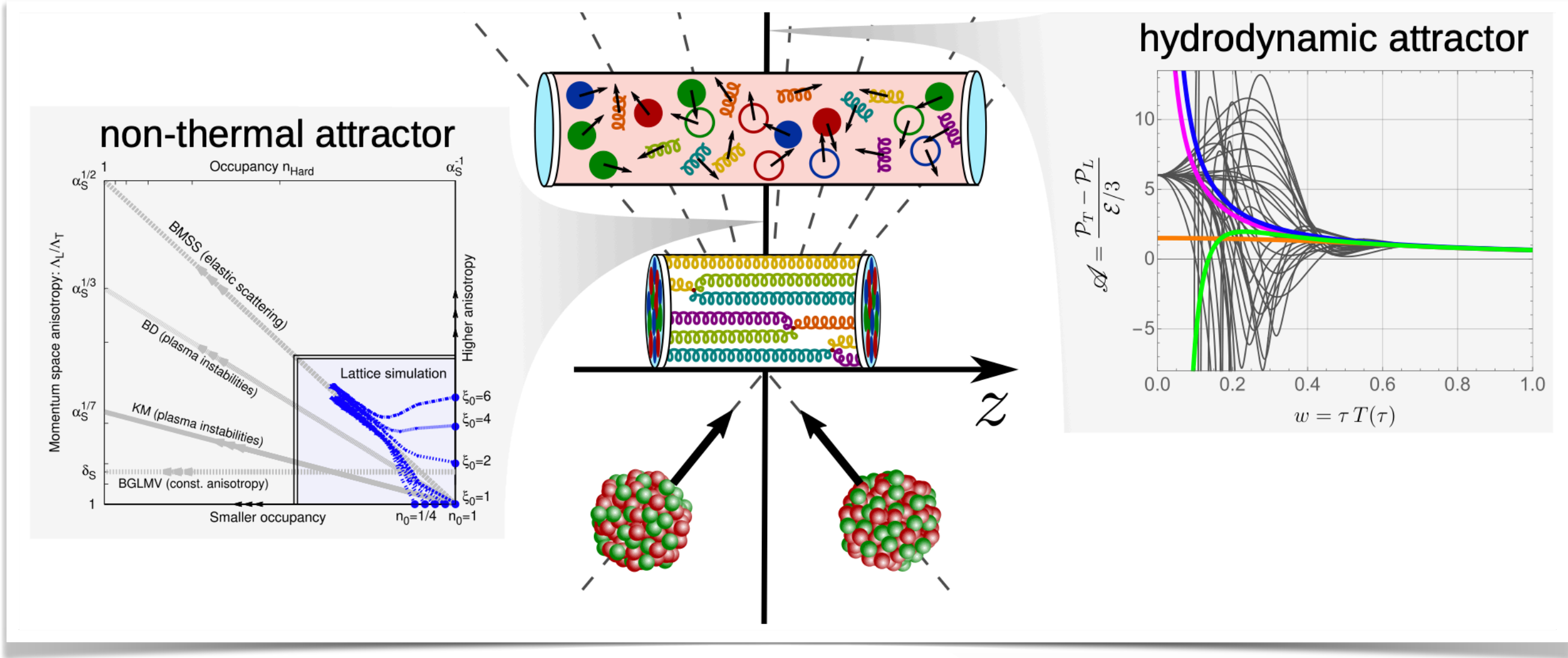
The Quark Gluon Plasma



Heat Pressure =



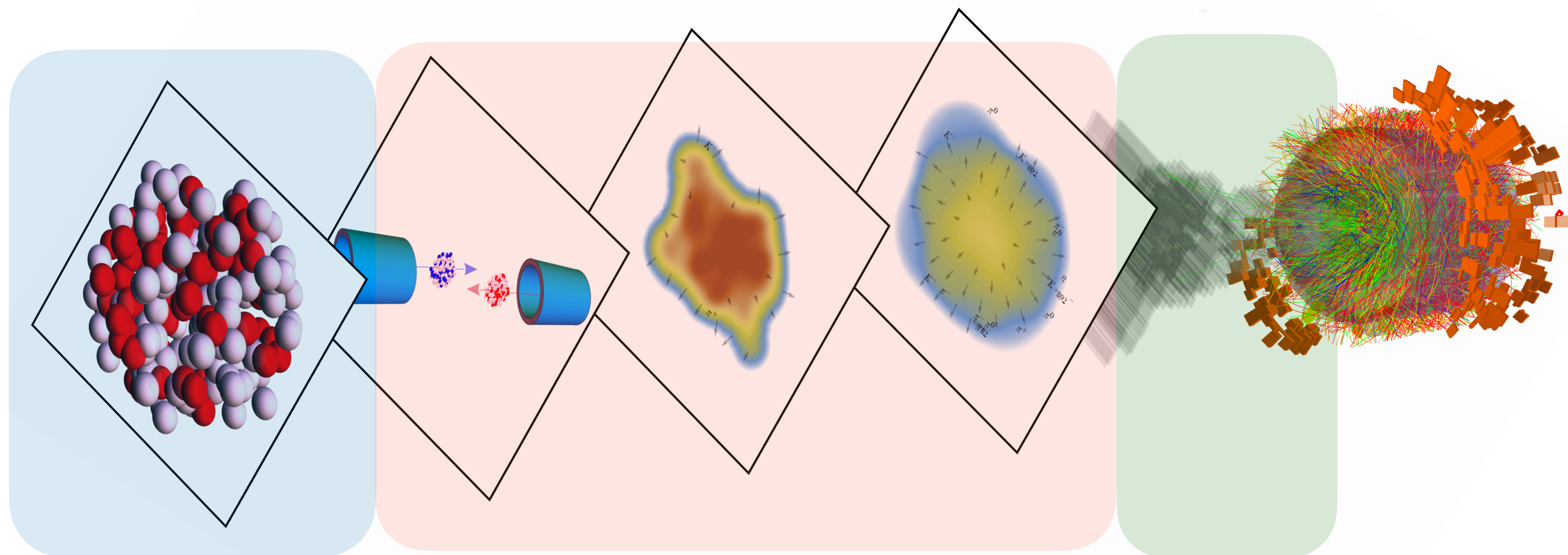
[PHENIX collaboration, 2018]



[Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299]

The Standard Model of heavy ion collisions

*Many questions remain open about **validity and emergence** of this “Standard Model” picture of HICs from the QFT and experimental perspectives*



CGC, IS models, ...

Kinetic theory, hydro, ...

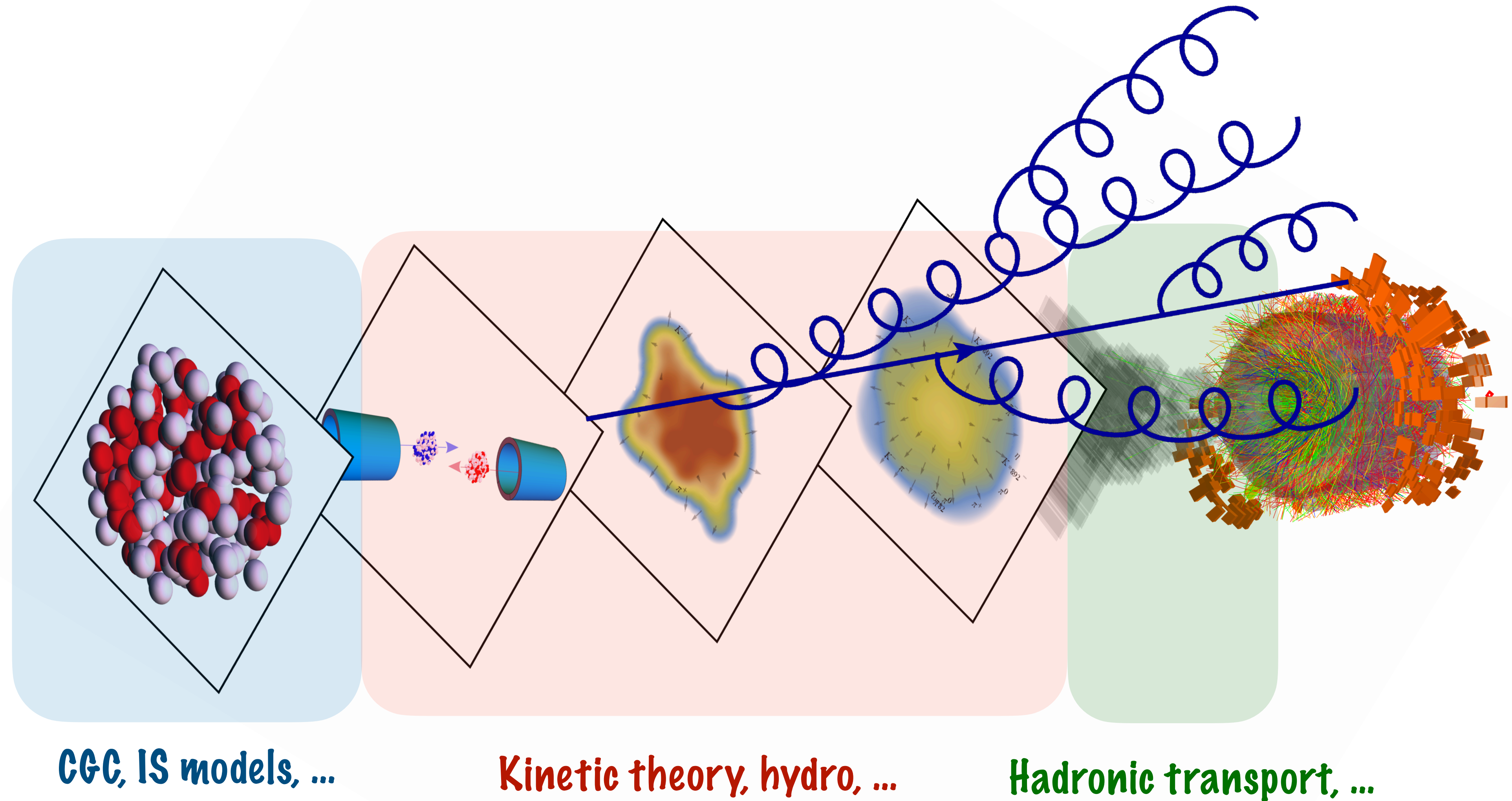
Hadronic transport, ...

**No confirmation of saturation/
CGC picture**

No test of out of equilibrium dynamics

**Lacking connection between
observables and theory**

Probing heavy ion collisions using jets



Jets allow for a QCD driven exploration of the intermediate matter states in HIs

Probing heavy ion collisions using jets

Initial blue quark

Final red quark

Momentum broadening

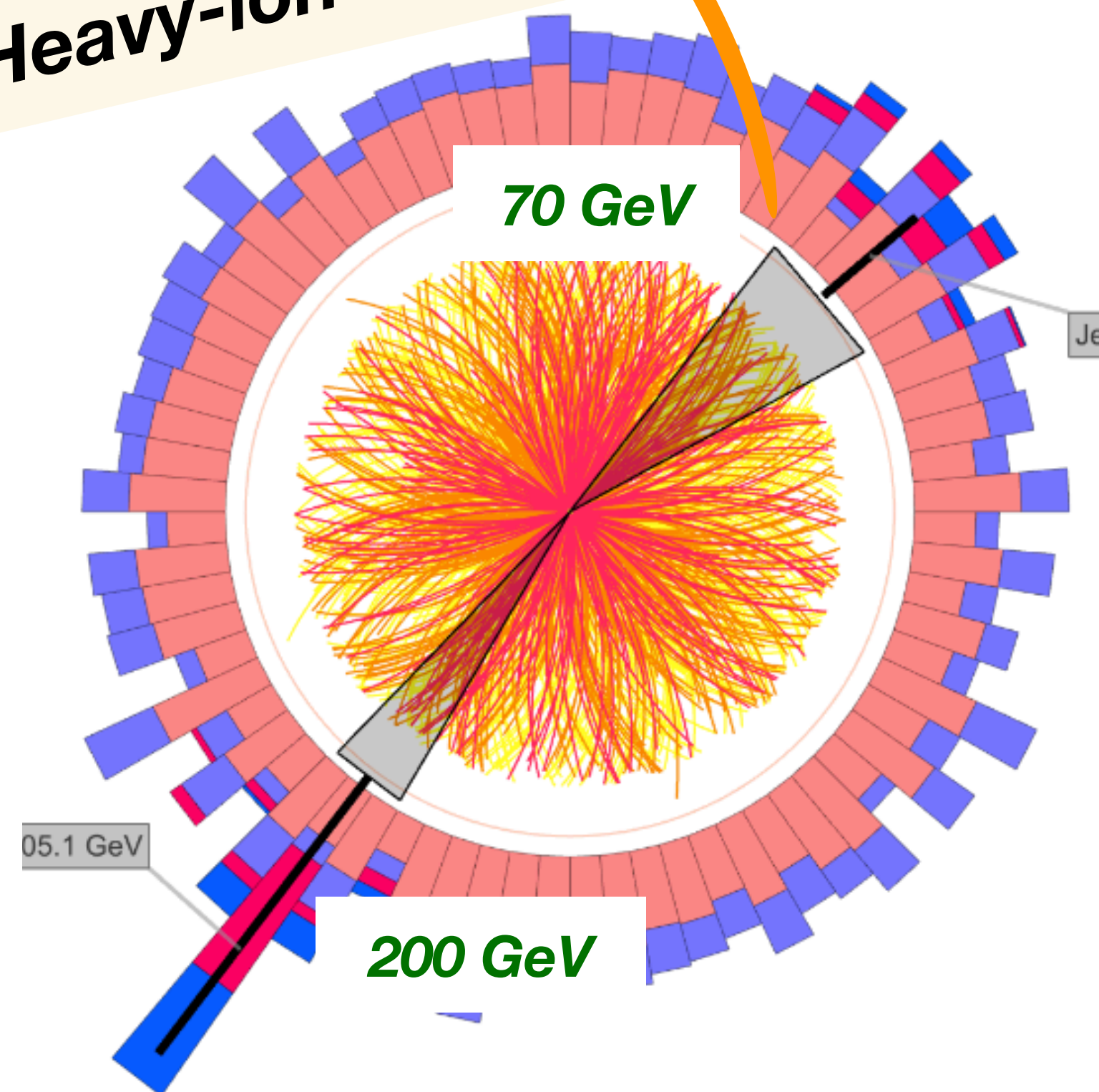
$$\langle \mathbf{k} \rangle = 0$$

$$\langle \mathbf{k}^2 \rangle \sim \hat{q} L$$

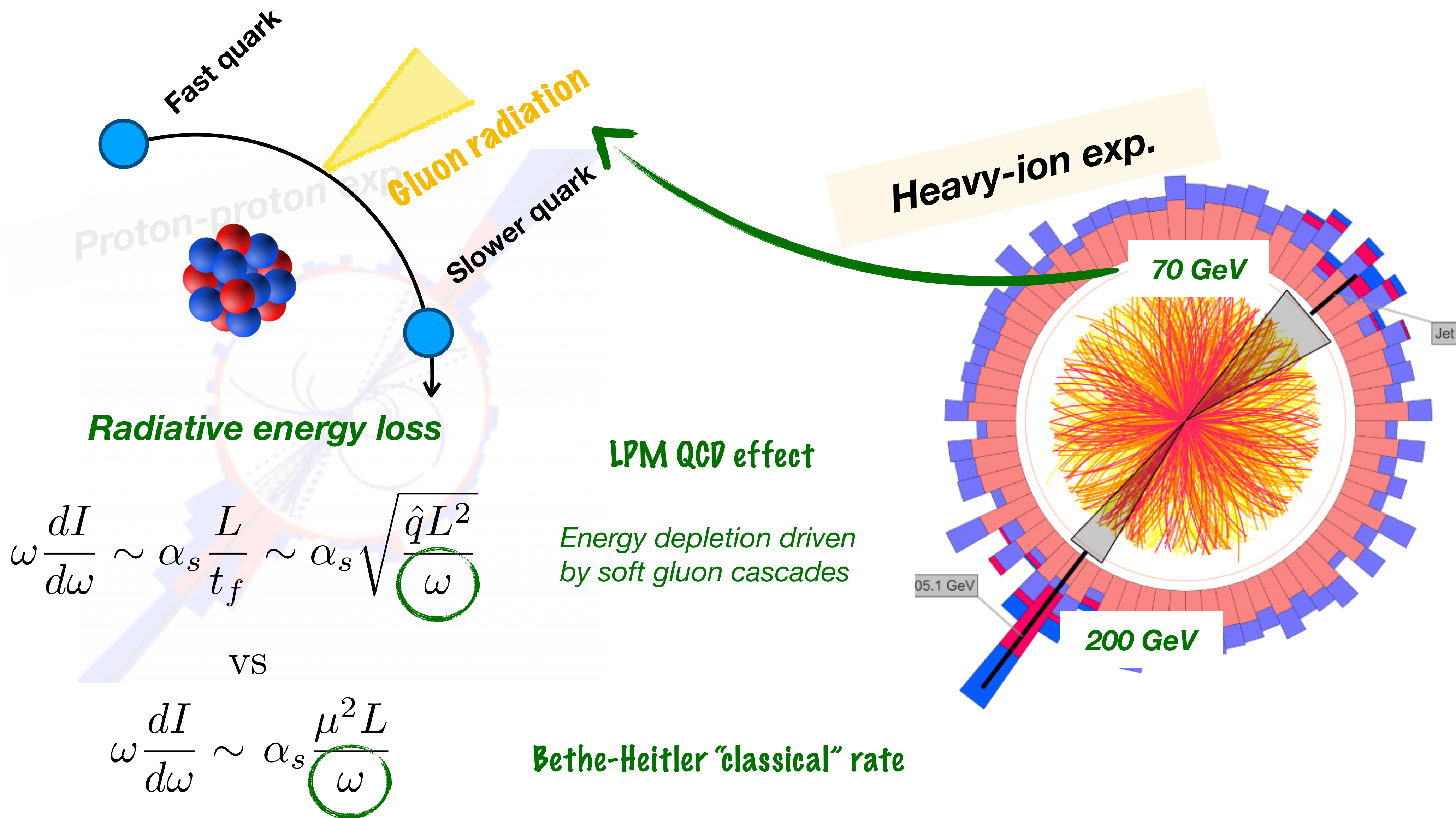
Jet transport coefficient,
diffusion constant

Light-cone time evolved in matter

Heavy-ion exp.



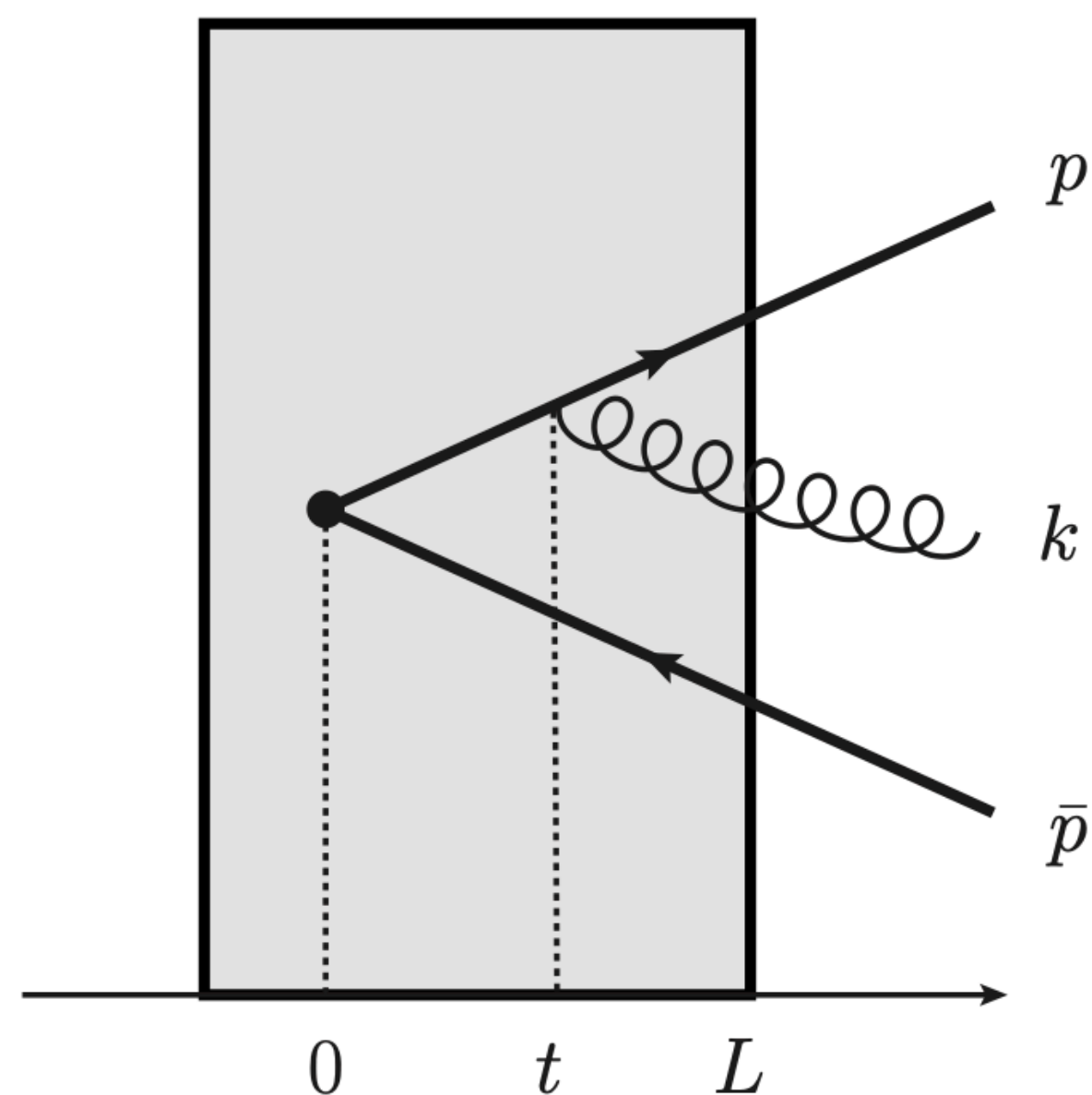
Probing heavy ion collisions using jets



Probing heavy ion 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]



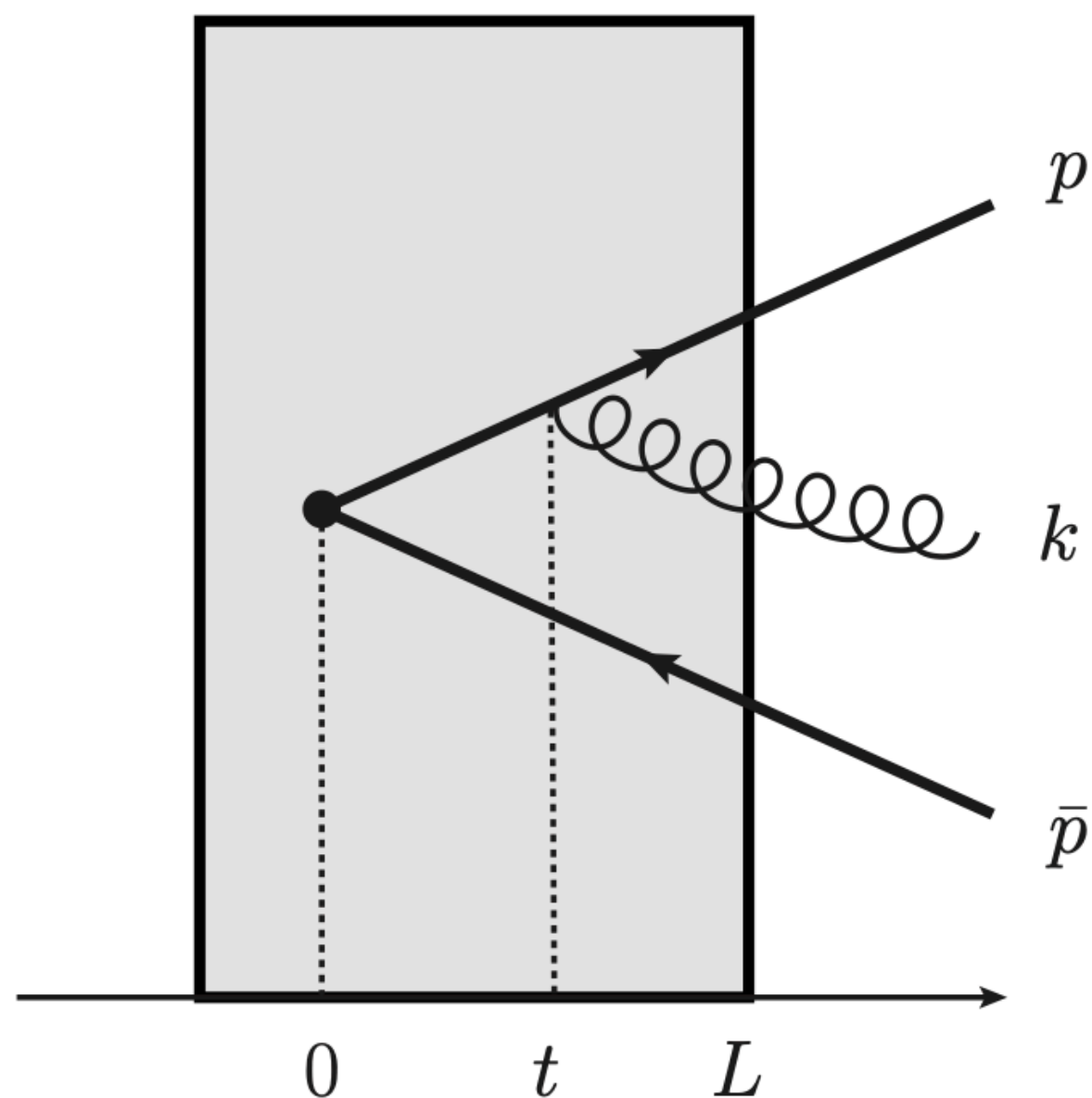
vacuum $\longrightarrow$ **angular ordering**

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

Probing heavy ion collisions using jets

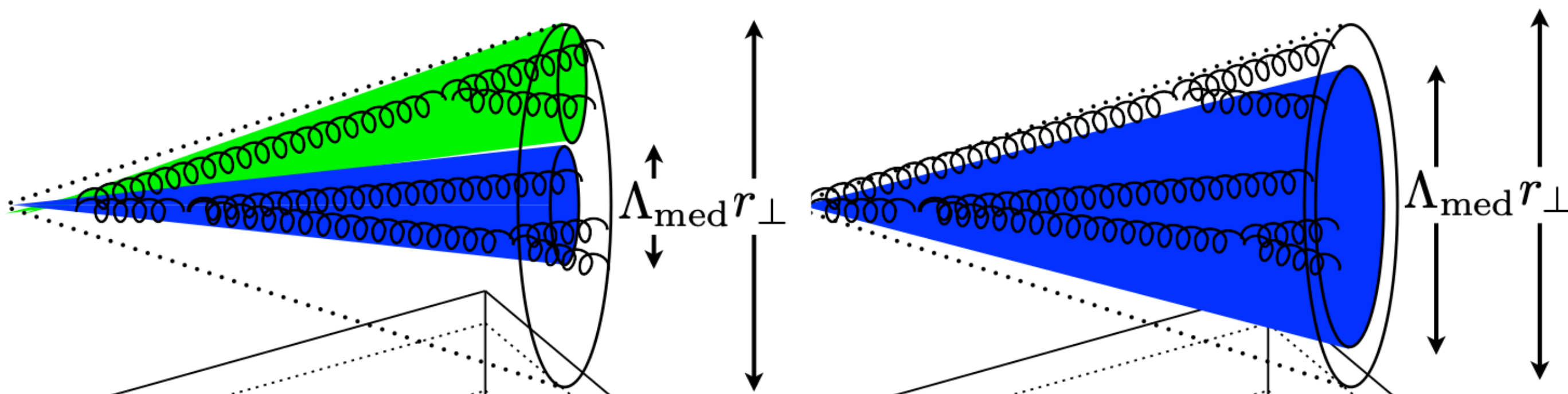
Breaking of angular ordering and evolution of color antennas has been widely explored

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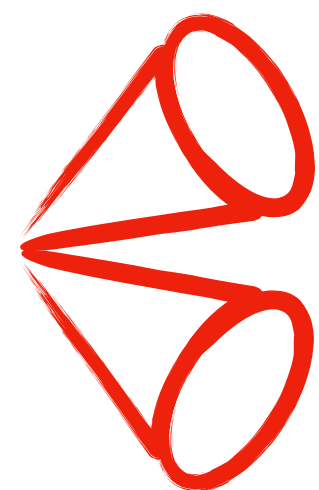


vacuum $\longrightarrow$ angular ordering

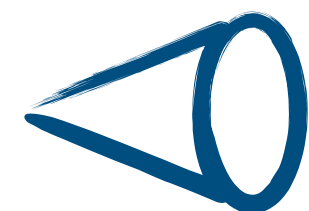
medium $\longrightarrow$ “anti-angular ordering”



“Two pronged”



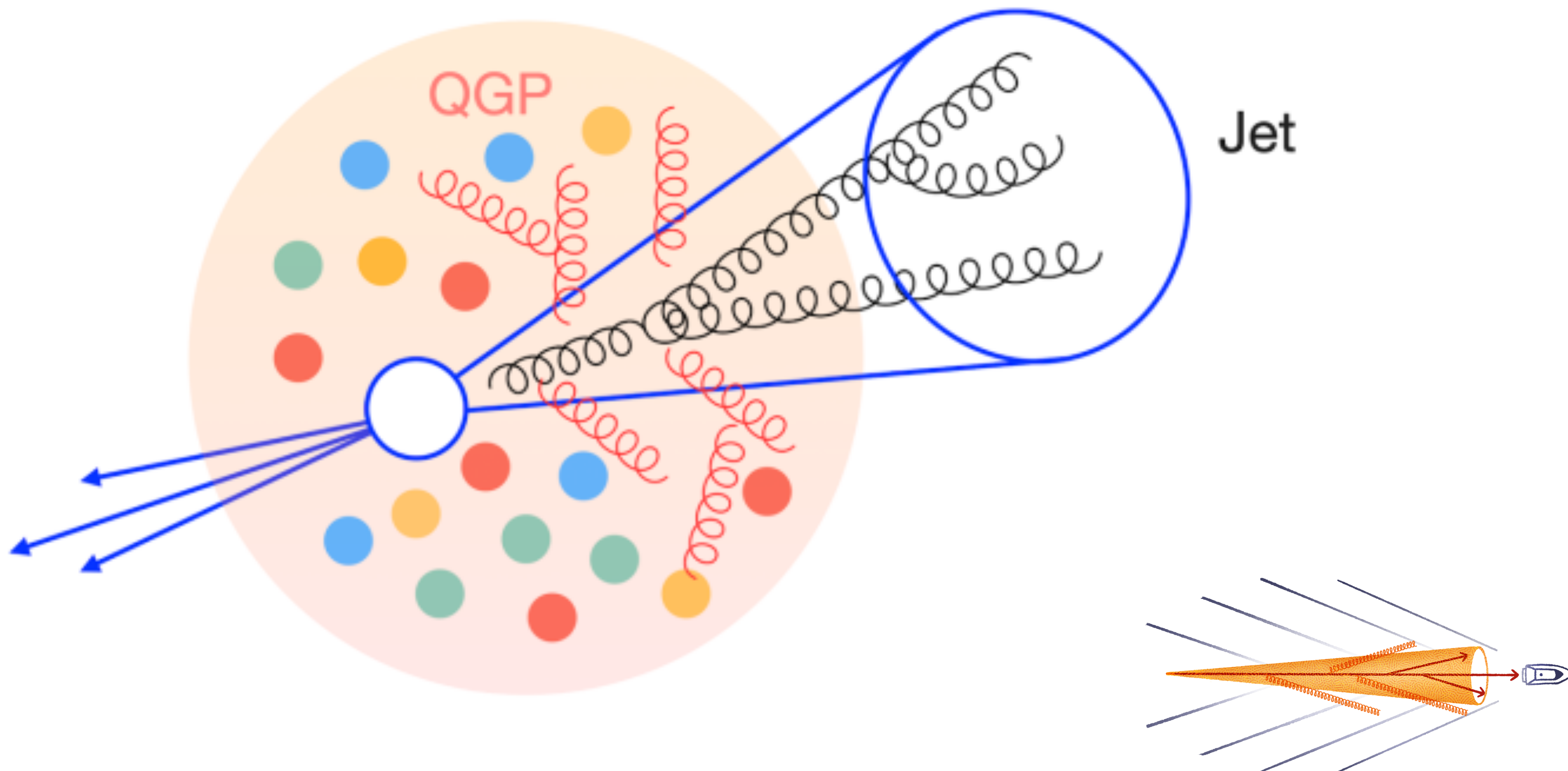
“One prong”



Observing this pattern gives evidence for Λ_{med}

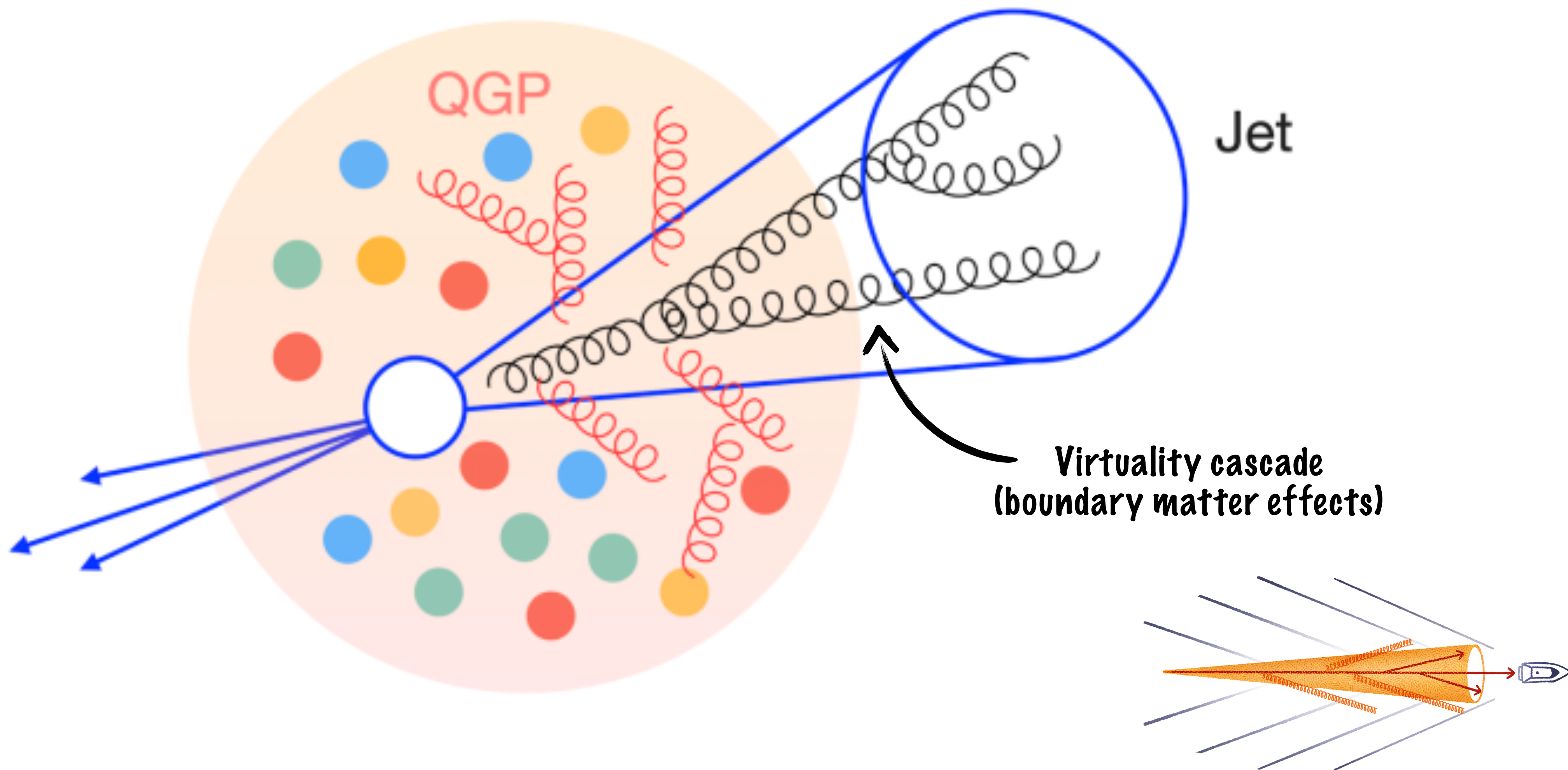
Probing heavy ion collisions using jets

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



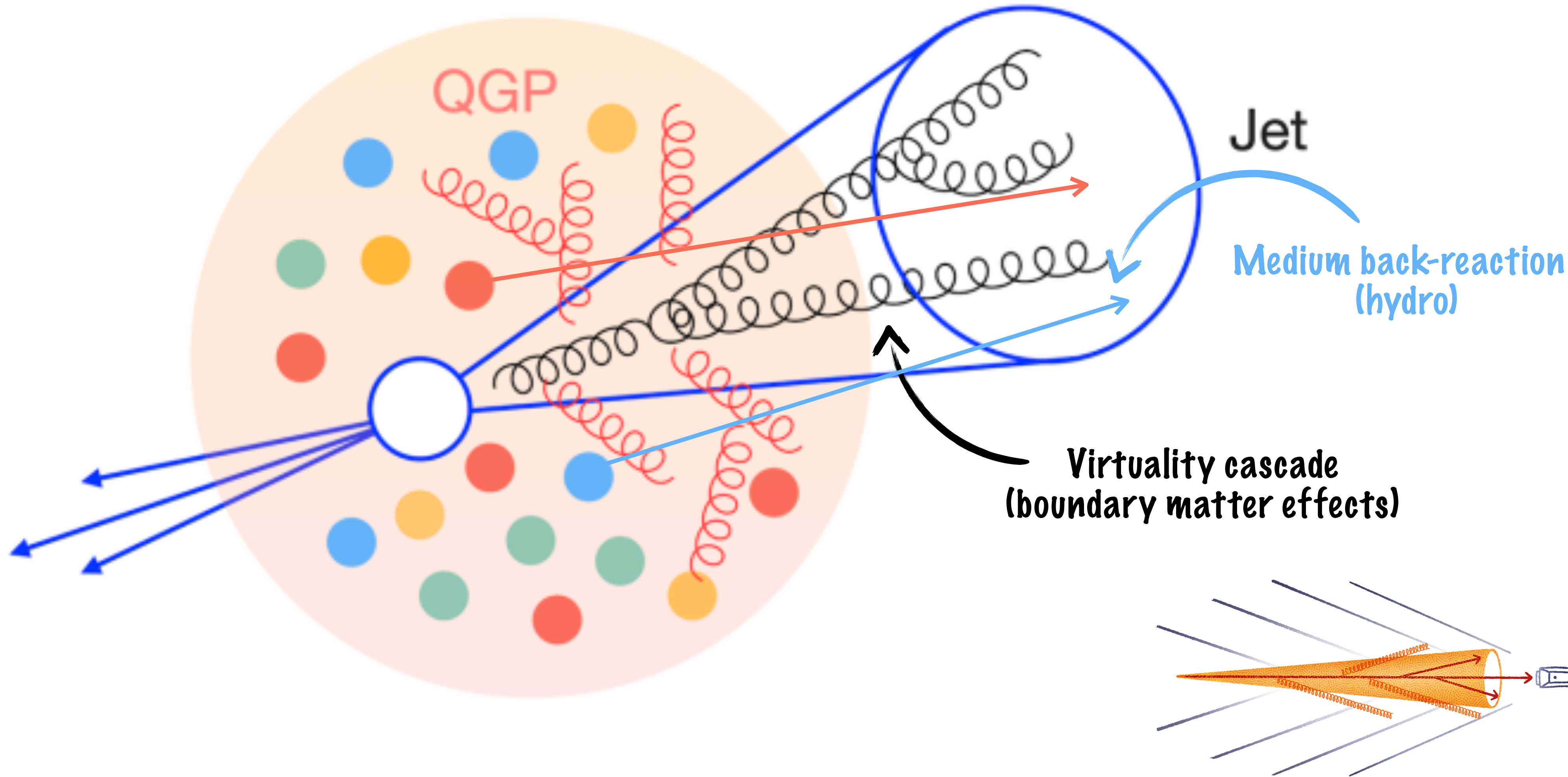
Probing heavy ion collisions using jets

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



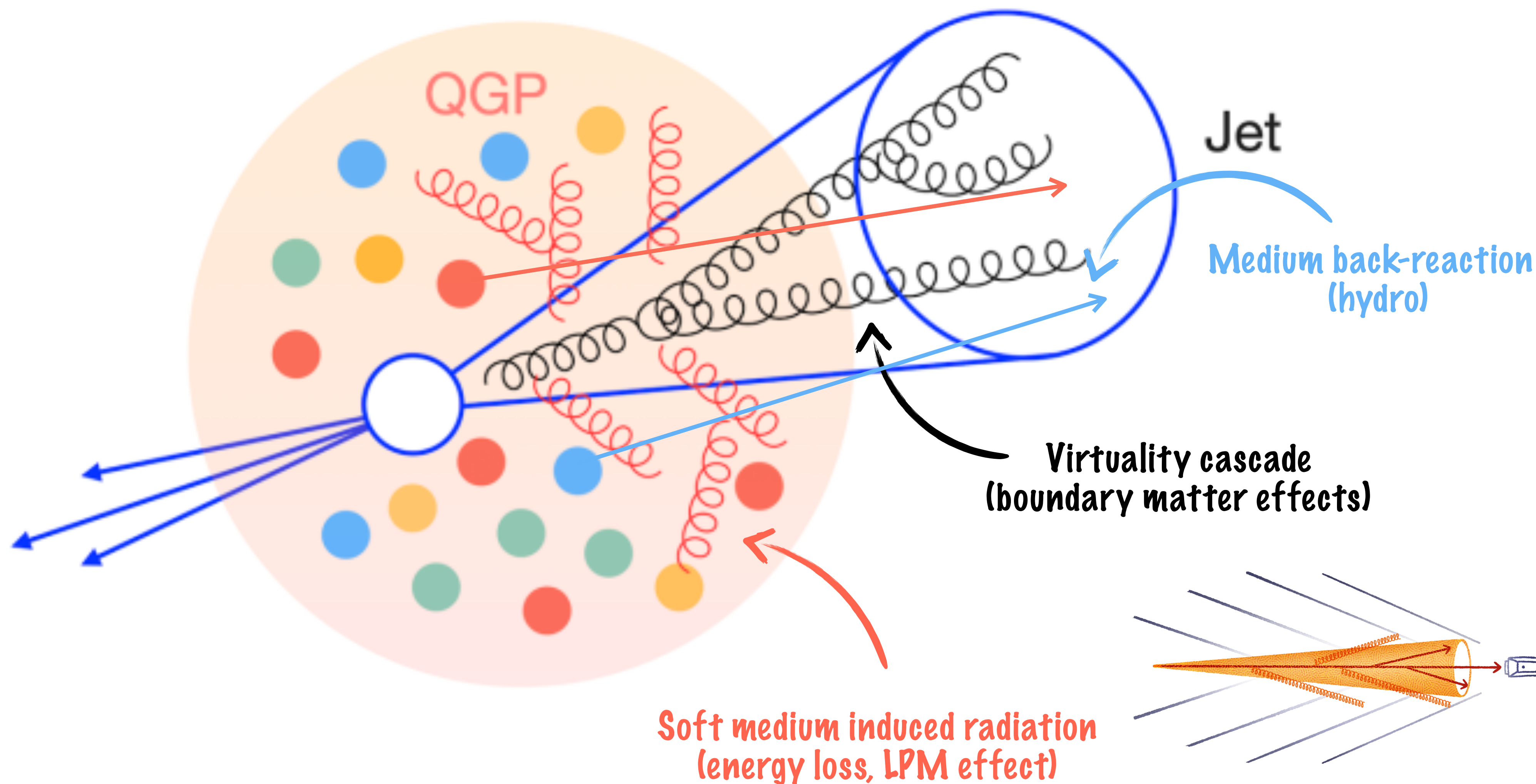
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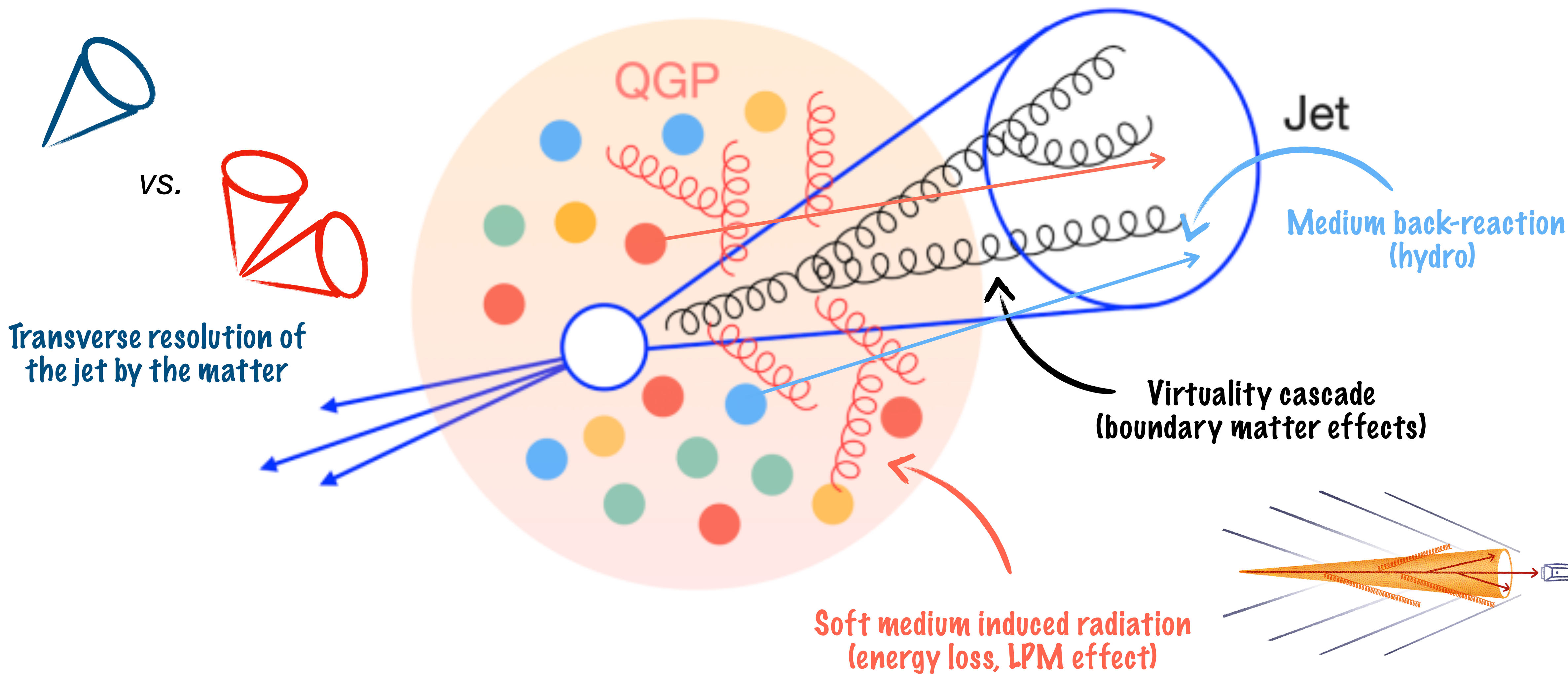
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Interactions with medium can be described via exchange of soft gluons

[PS-Z, early 2000s]

$A^{-,a}(x)$ $p \sim gT$

[BDMPS-Z, early 2000s]

At high energies this is equivalent to 2d non-rel. QM: [Susskind, 1960s]

$$\mathcal{G}(\boldsymbol{x}_2, t_2; \boldsymbol{x}_1, t_1) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r} \exp \left(\frac{i\omega}{2} \int_{t_1}^{t_2} dt \dot{\boldsymbol{r}}^2 \right) \mathcal{W}_r$$

Wilson line along forward light-cone

Motion in transverse direction;
partial sub-eikonal order effect

Any cross-section boils down to computing correlation functions of such objects

$$d\sigma \sim \langle \mathcal{T} \prod^{\text{QCD vertices}} \{\mathcal{G}, \Gamma\} \rangle_{\text{matter}}$$

