The structure of energy correlators in HIC

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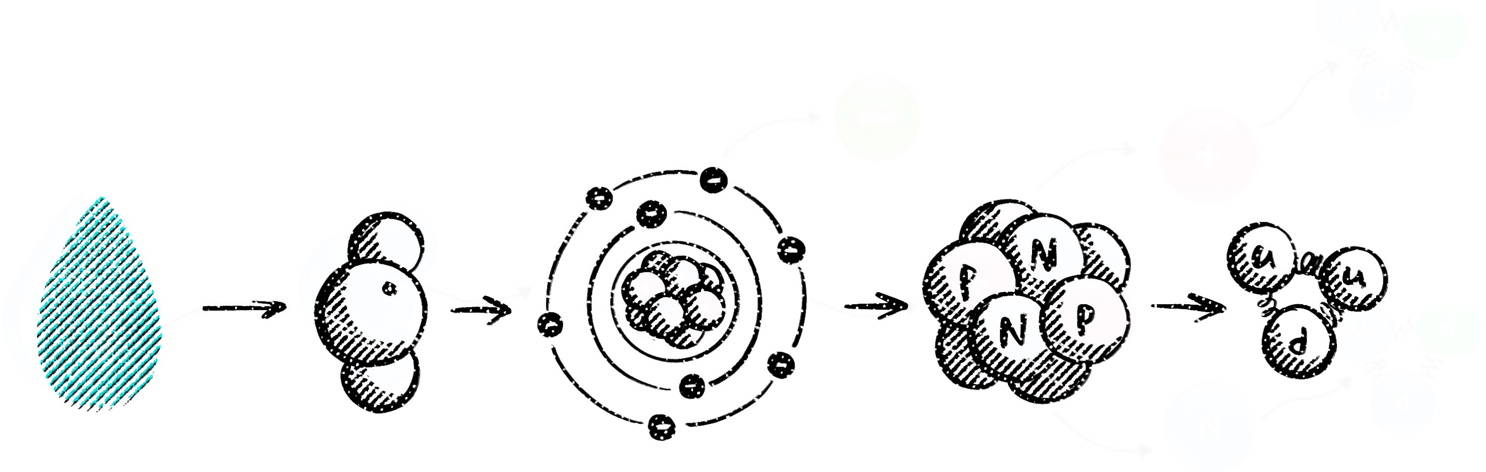
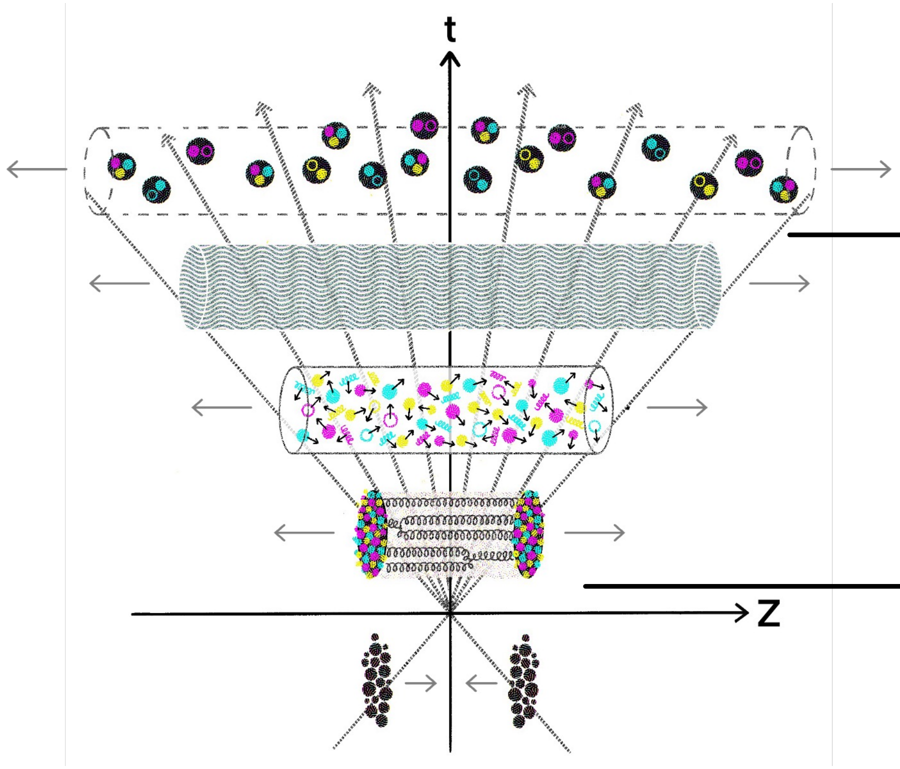
The origin of complex matter

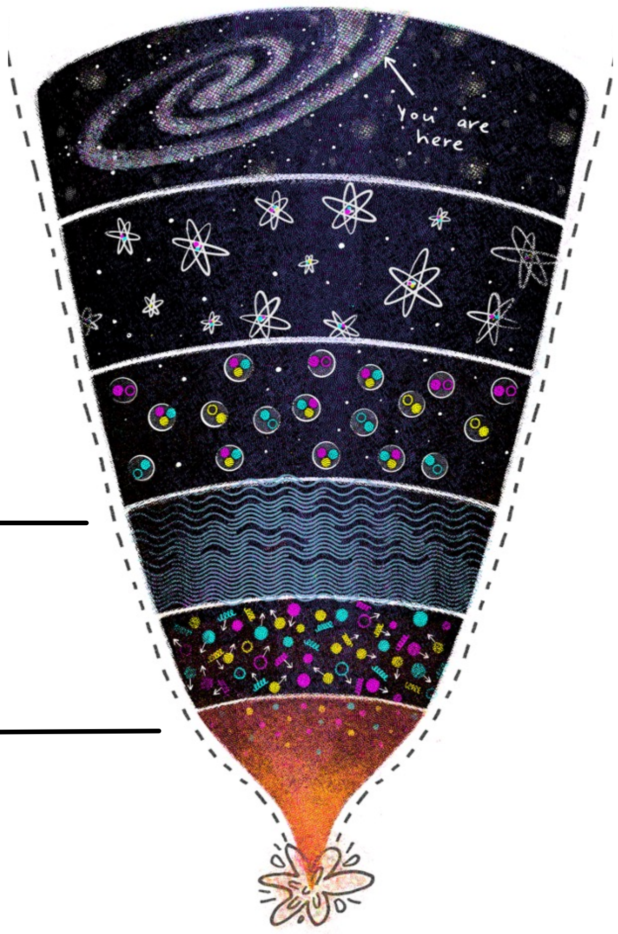


The origin of complex matter



Little Bang

emergence of complex matter can be probed in heavy-ion collisions (HIC)

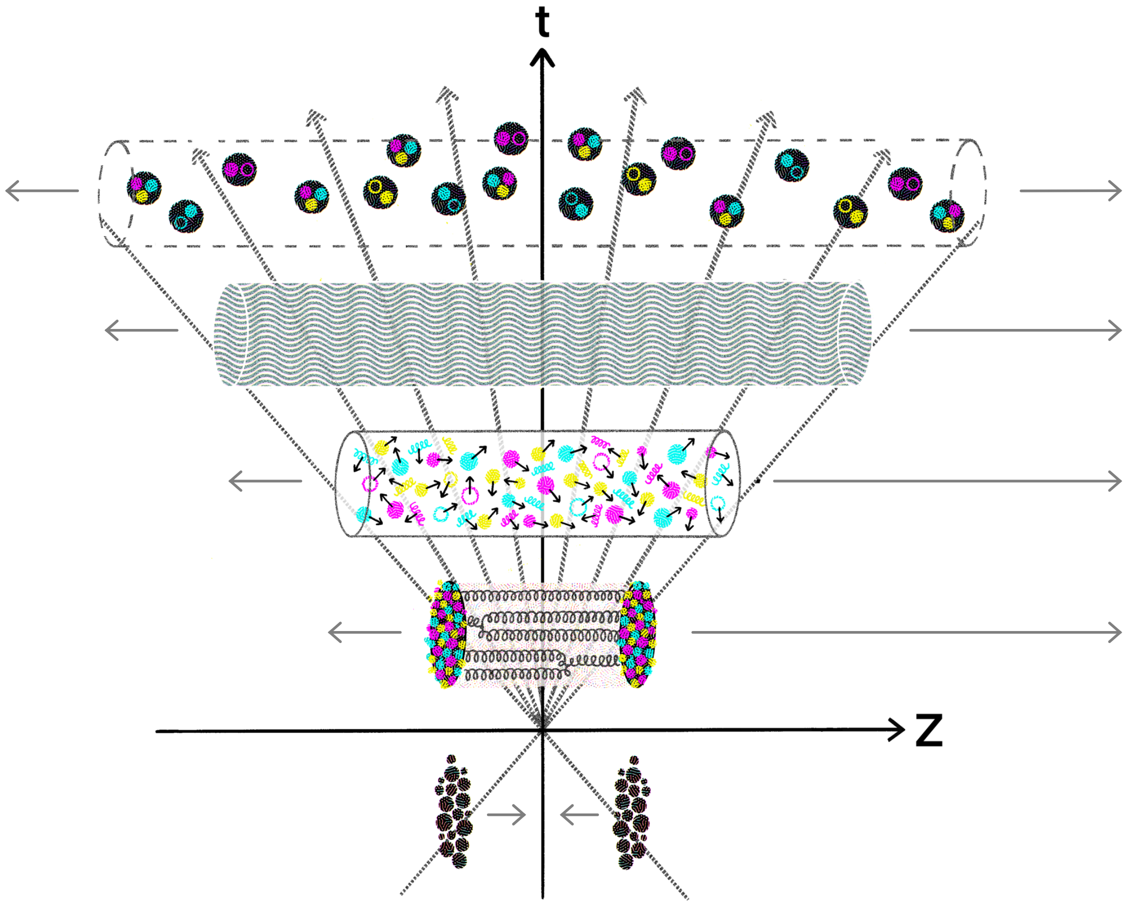


Big Bang

Some motivation

- Learning about QCD in Early Universe ("Big Bang" matter)
- Probing QCD phase diagram (extreme conditions)
- Understanding matter formation (and its evolution)
- Probing nuclear structure (probing partons)
- …
- Add your favorite option here

Heavy-ion collisions



before the collision

Phases of QCD matter in HIC:

hadron gas

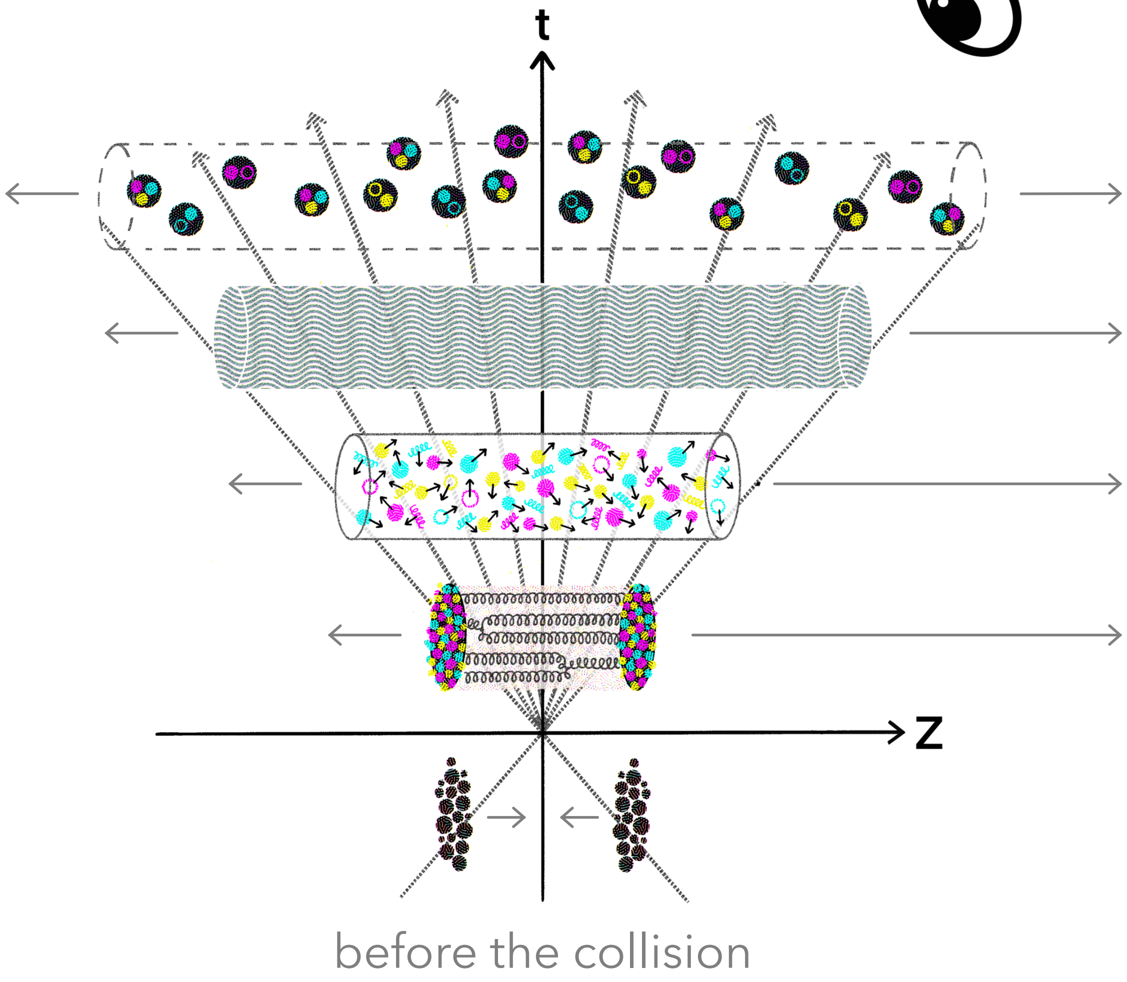
hydrodynamic Quark-Gluon Plasma (QGP)

non-equilibrium matter

glasma (strong color fields)

Matter produced in HIC undergoes multiphase evolution

Heavy-ion collisions



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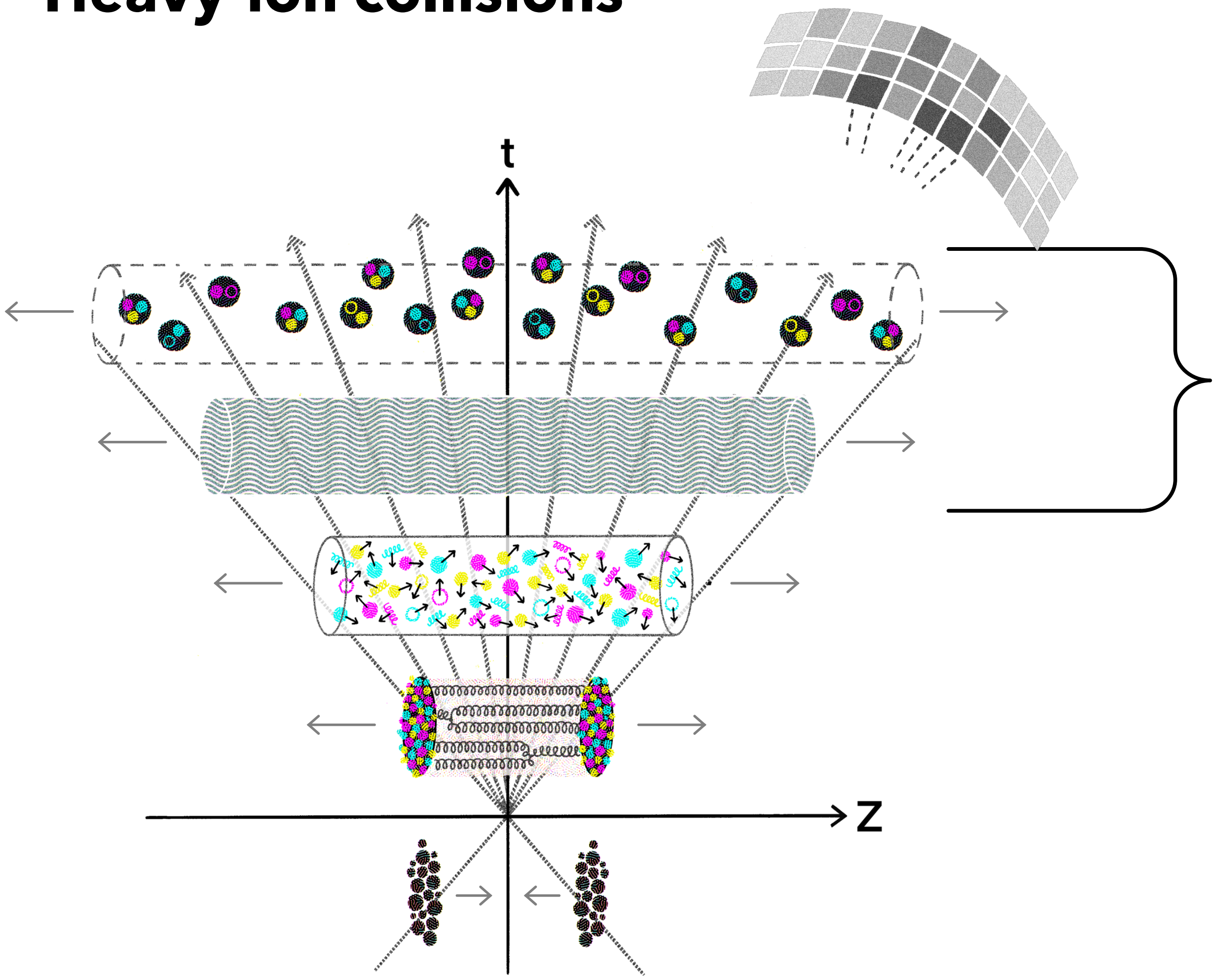
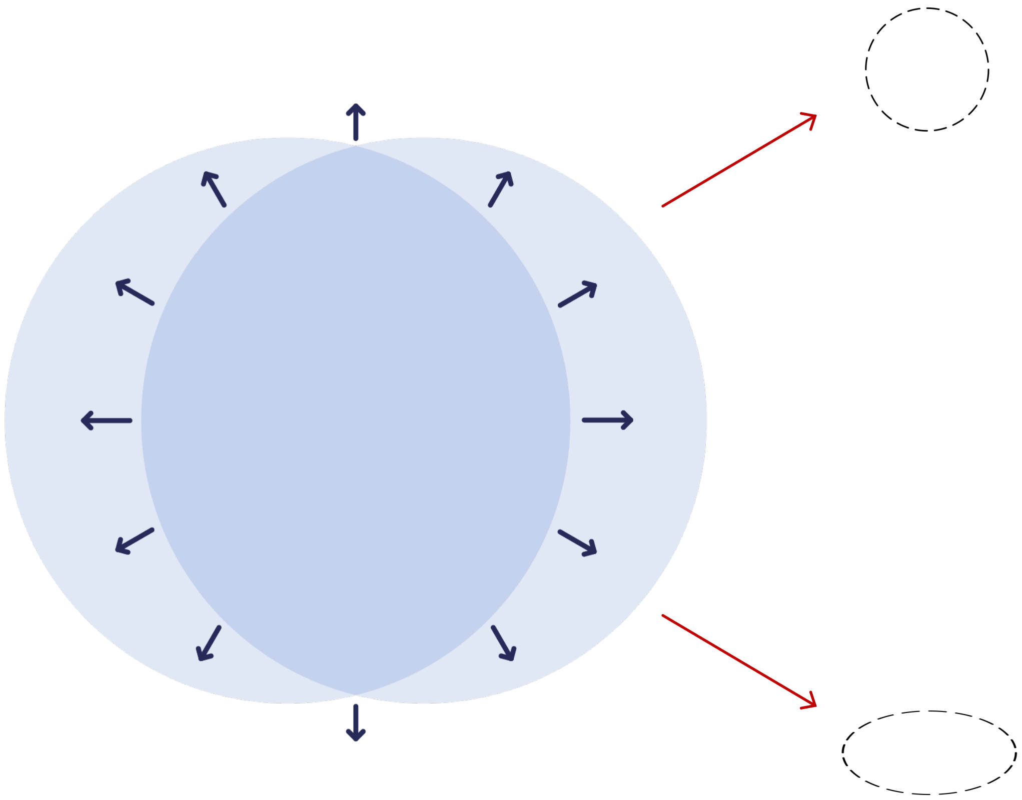


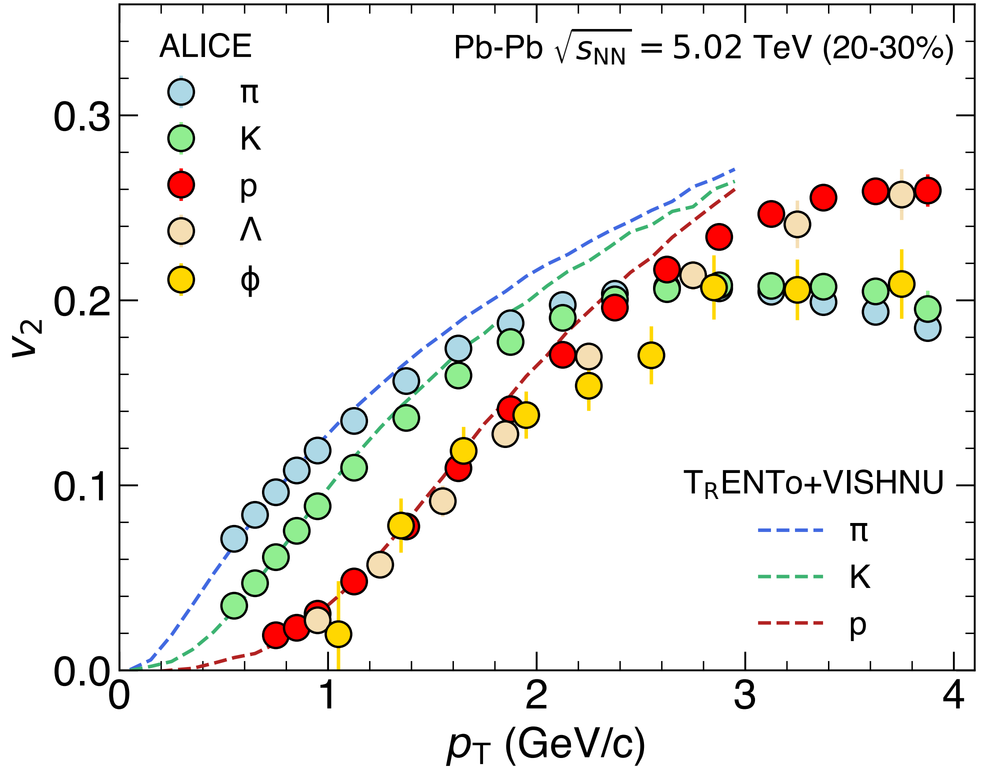
Final state dynamics and the hydrodynamic QGP phase

accessible

Hot QCD White Paper, arxiv: 2023.17254

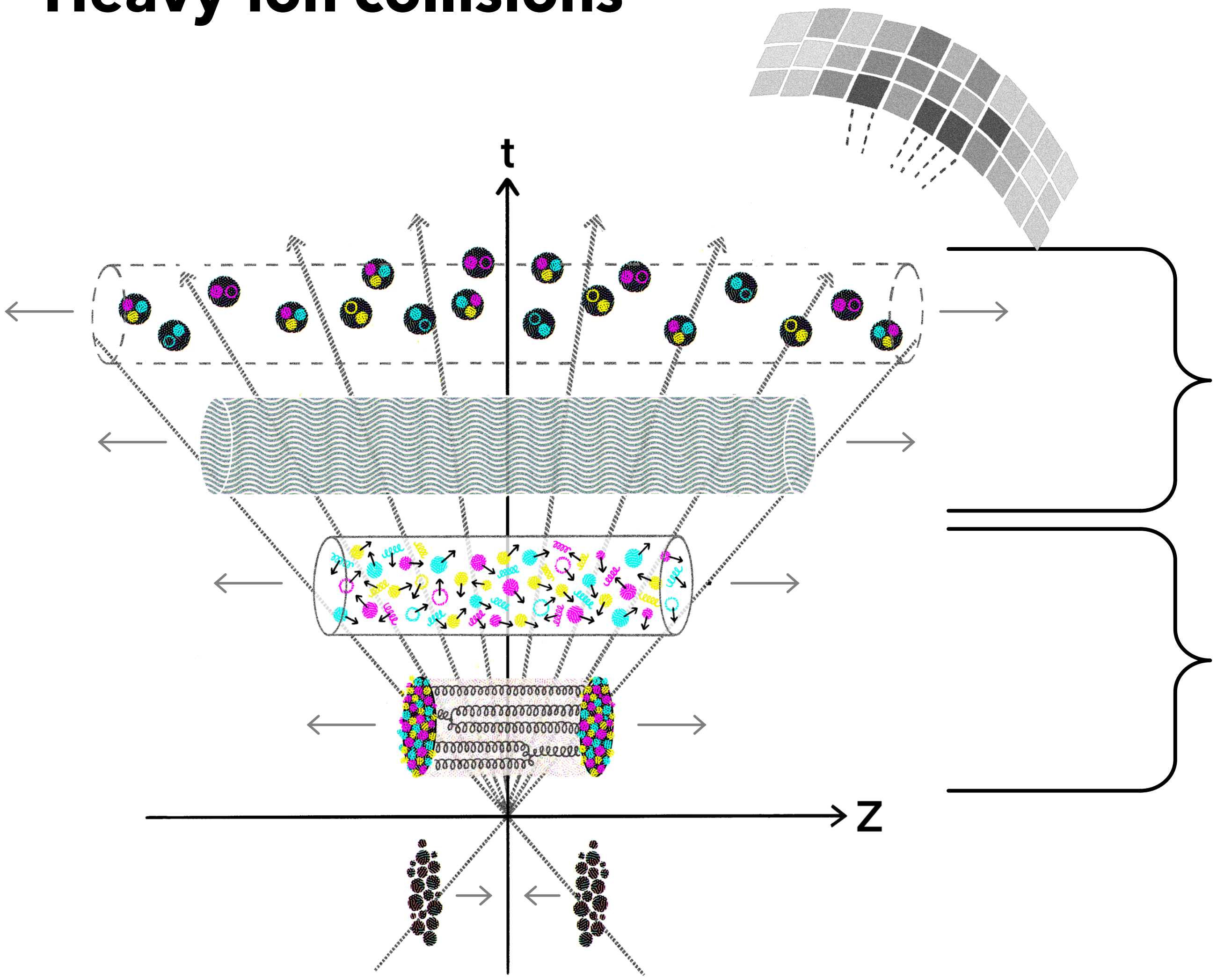
Probes of matter





$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos\left[\phi - \Psi_{RP}\right] + 2v_2 \cos\left[2(\phi - \Psi_{RP})\right] + \ldots$$

Heavy-ion collisions

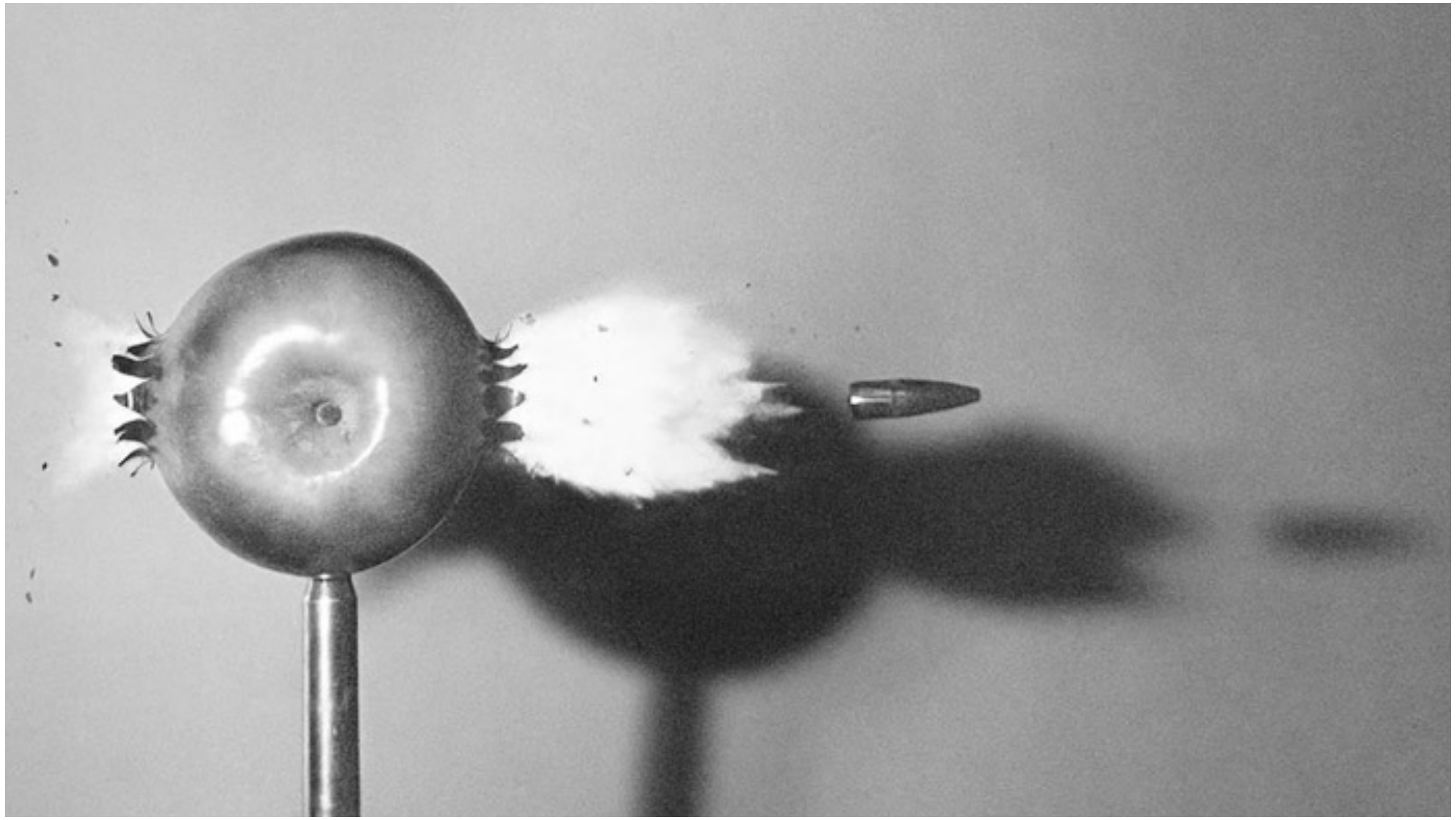


Final state dynamics and the hydrodynamic QGP phase — accessible

Formation of complex nuclear matter — non-accessible

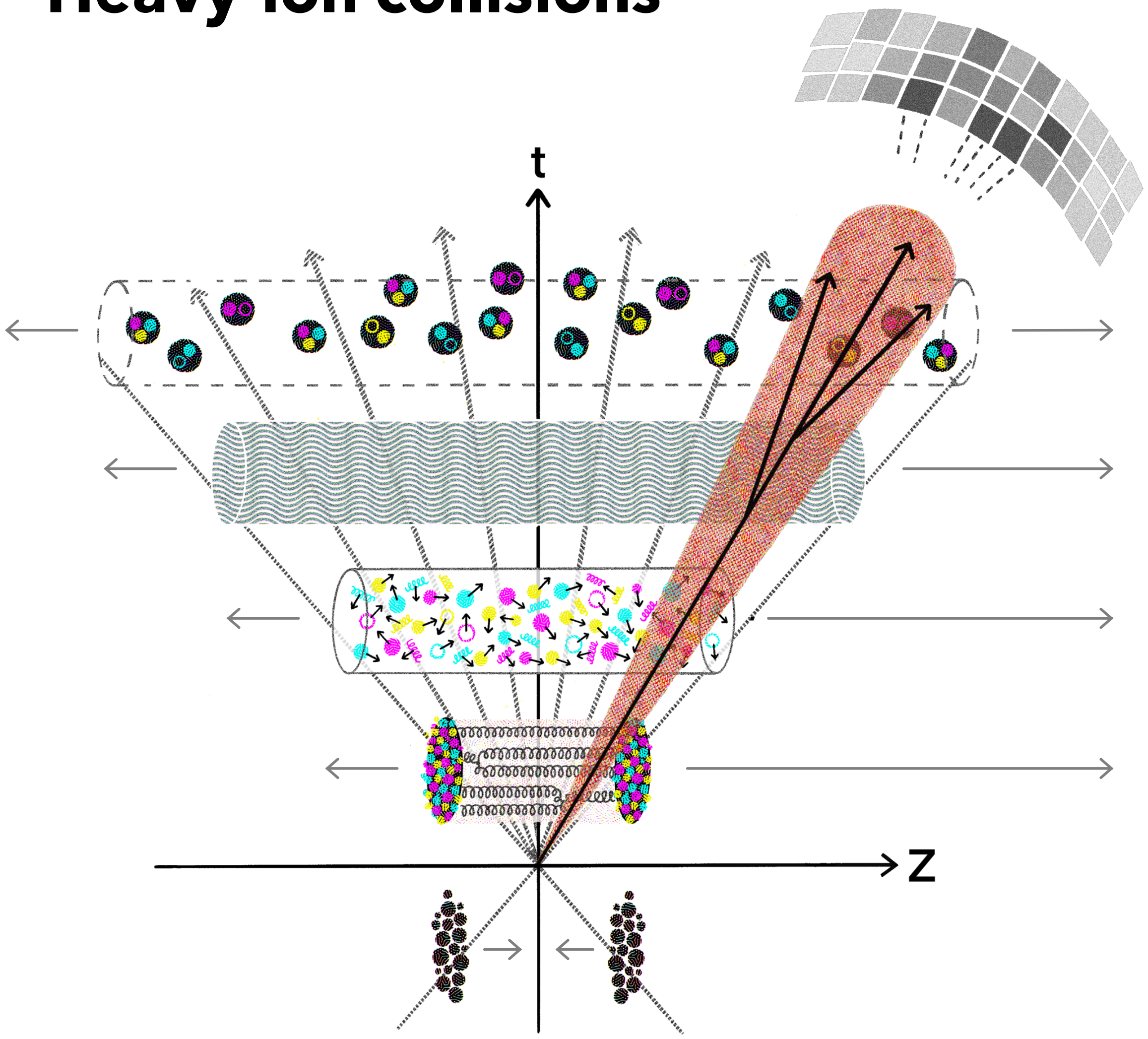
The primary goal of HIC programs worldwide

Hard probes




Final render
Ex: 75306
Se 1/1
Im 1/2
Lin: DCM
W: 4095 L: 2089
Acq tm: 09:52:07

Heavy-ion collisions



before the collision

Phases of QCD matter in HIC:

hadron gas

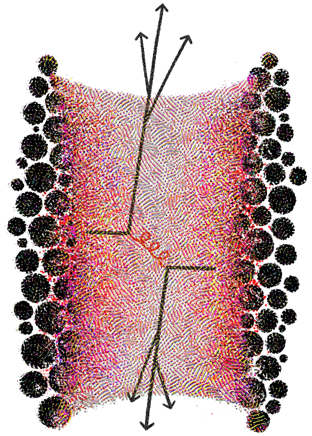
hydrodynamic QGP

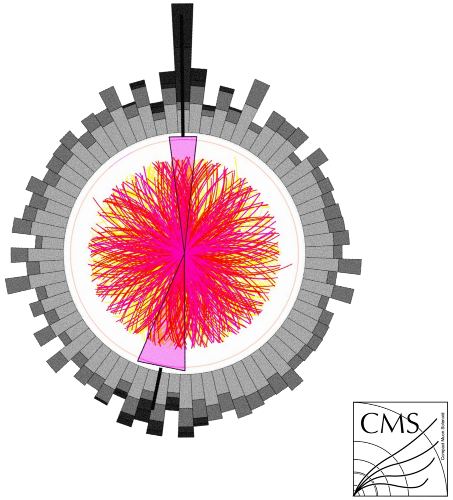
non-equilibrium matter

glasma (strong color fields)

Jets are a tool to probe
the early evolution of matter

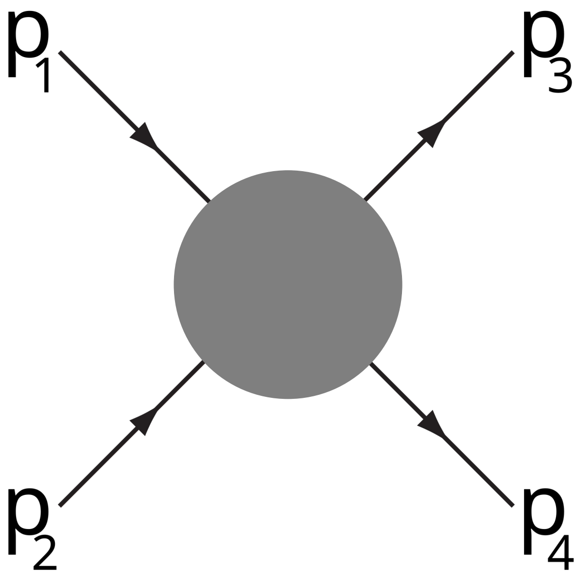
jet quenching

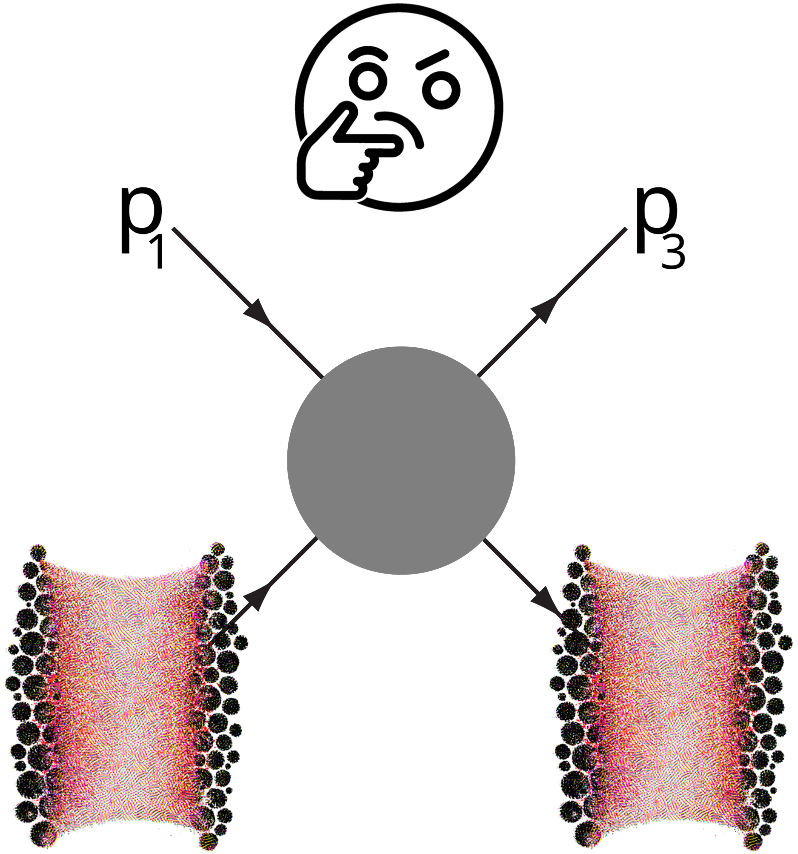




jets lose energy propagating
through nuclear matter

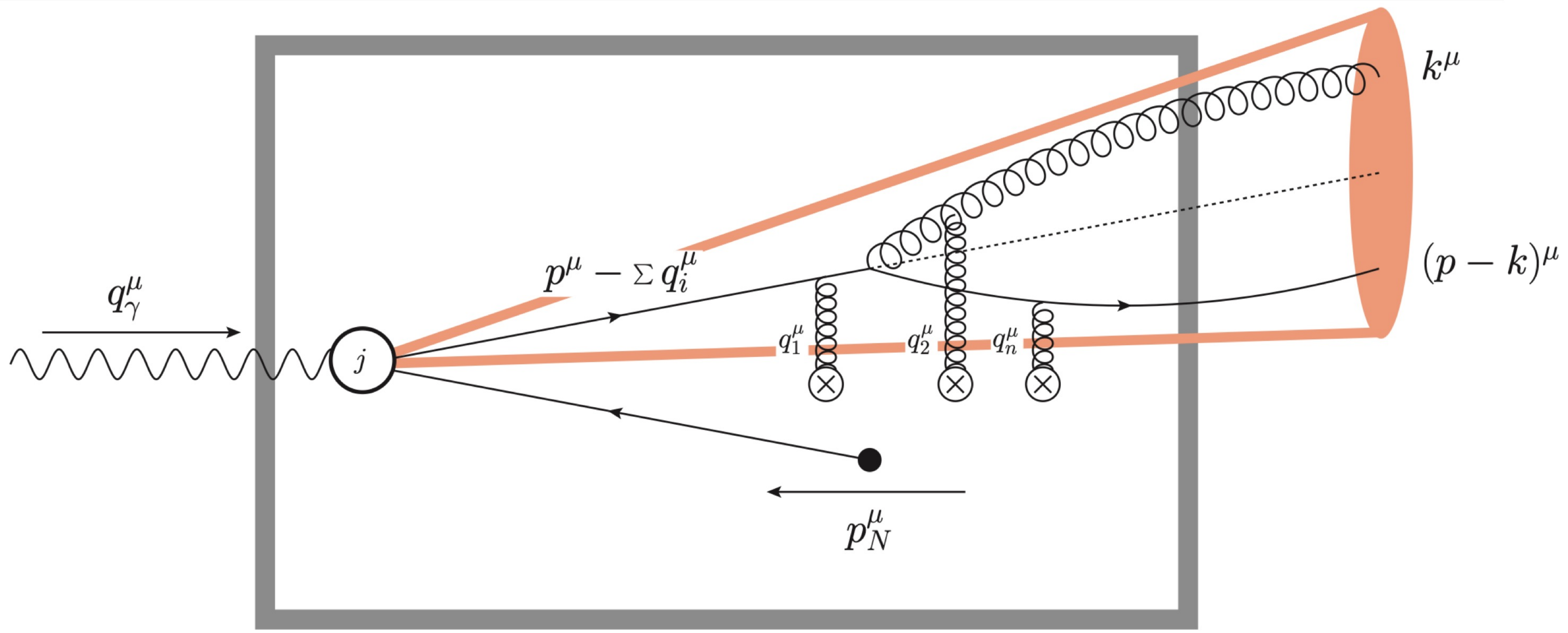
Jet quenching formalisms





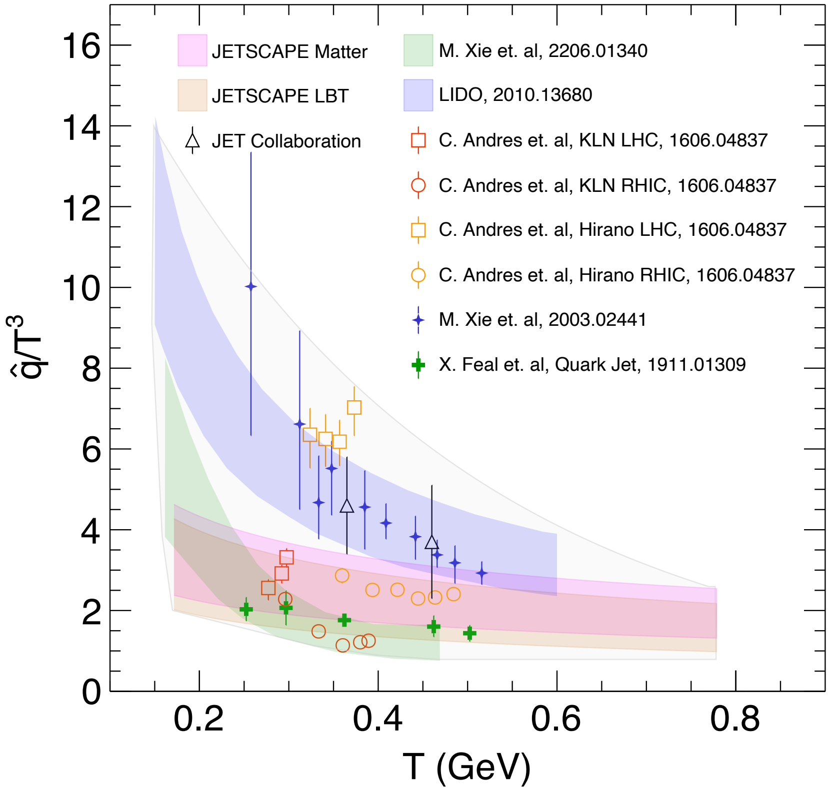
Jet quenching formalisms

R. Baier et al, NPB, 1997
B. G. Zakharov, JETP, 1997
R. Baier et al, NPB, 1998
M. Gyulassy et al, NPB, 2000
X.-F. Guo, X.-N. Wang, PRL, 2000
U. Wiedemann, NPB, 2000
M. Gyulassy et al, NPB, 2001
P. Arnold, G. Moore, L. Yaffe, JHEP, 2002
C. Salgado, U. Wiedemann, PRD, 2003



Jet quenching formalisms

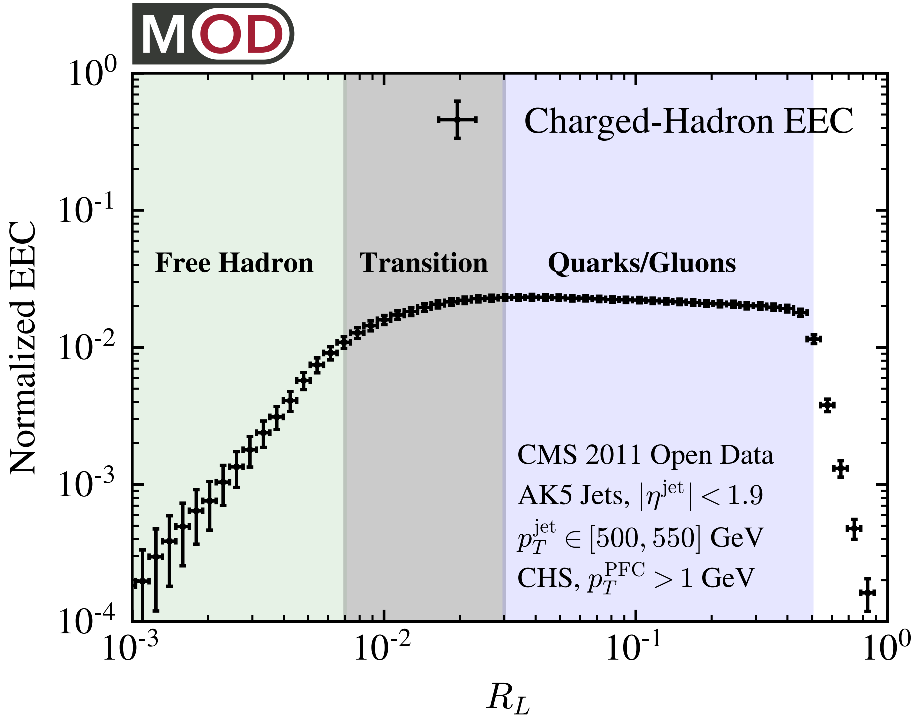
- Jets are observed only in the final state, yet they carry imprints of the matter phases throughout its evolution.
- Describing the scattering off matter requires an effective QCD framework with background stochastic fields.
- $\hat{q}$ is the first object to appear in jet quenching calculations and remains central to most phenomenological considerations.
- $\hat{q}$ is hard to measure or estimate in simulations



Theoretical uncertainties in $\hat{q}$ extracted in different works

EECs in HICs

$$\frac{d\Sigma}{d\theta} = \frac{1}{p_t^2} \int_{n_1, n_2} \langle \mathcal{E}(n_1) \mathcal{E}(n_2) \rangle \, \delta(n_1 \cdot n_2 - \cos\theta)$$

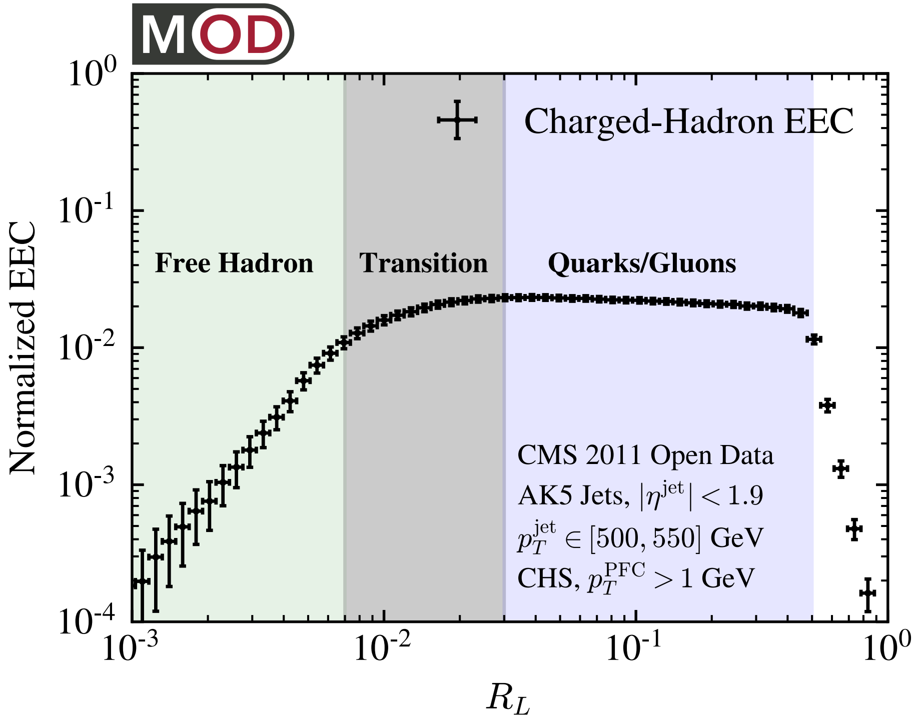


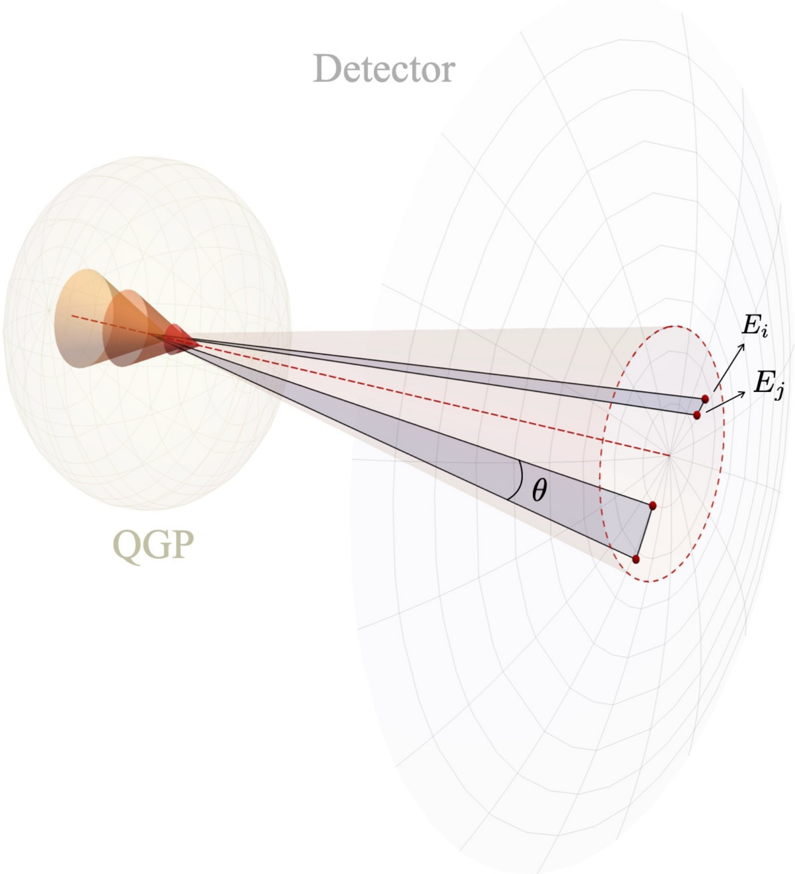
EECs in HICs

$$\langle \mathrm{HIC} | \mathcal{E}(n_1)\mathcal{E}(n_2) | \mathrm{HIC} \rangle$$

$$\uparrow$$

$$\frac{d\Sigma}{d\theta} = \frac{1}{p_t^2} \int_{n_1, n_2} \langle \mathcal{E}(n_1)\mathcal{E}(n_2) \rangle \, \delta(n_1 \cdot n_2 - \cos\theta)$$





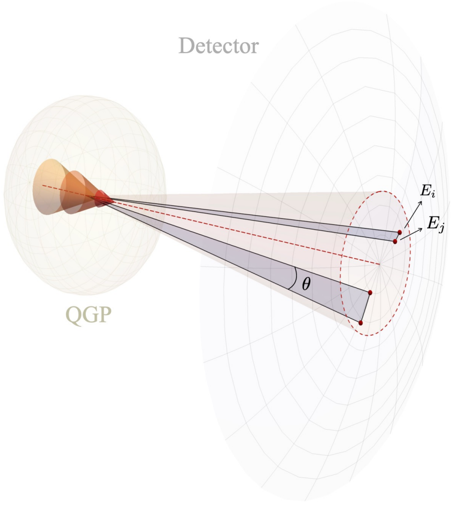
C. Andres et al, PRL, 2023
J. Barata et al, JHEP, 2024

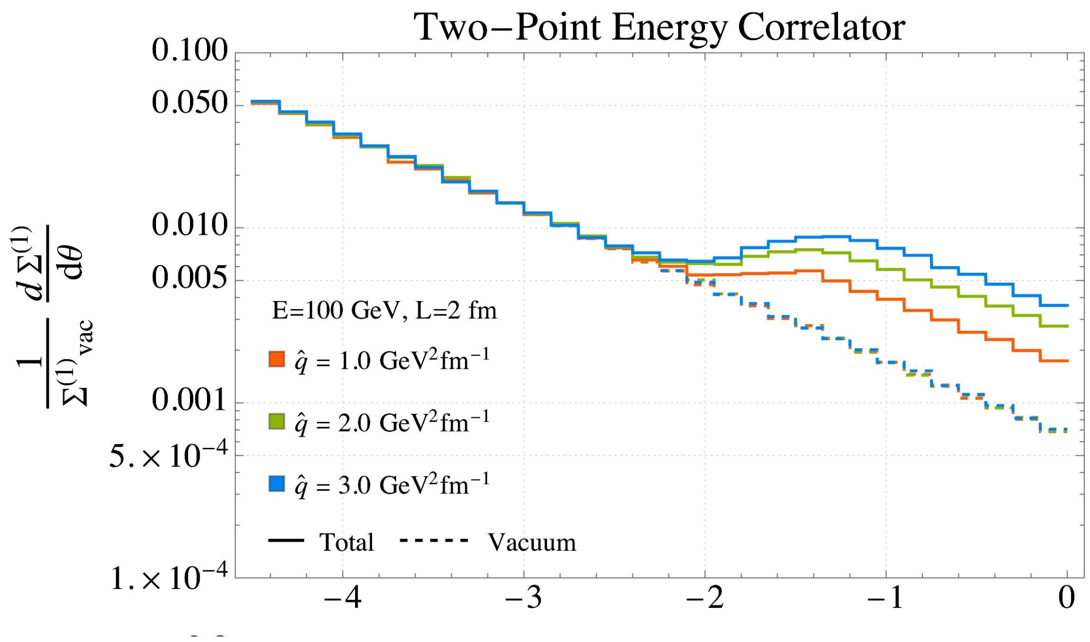
EECs in HICs

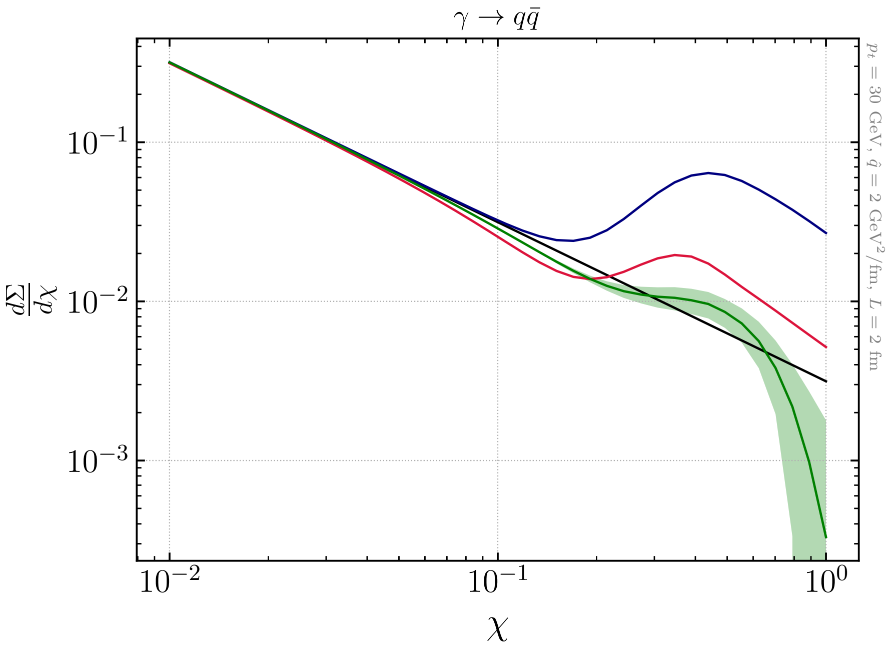
$$\langle \mathrm{HIC}|\mathcal{E}(n_1)\mathcal{E}(n_2)|\mathrm{HIC}\rangle$$

$$\uparrow$$

$$\frac{d\Sigma}{d\theta} = \frac{1}{p_t^2}\int_{n_1,n_2} \langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle\, \delta(n_1\cdot n_2 - \cos\theta)$$

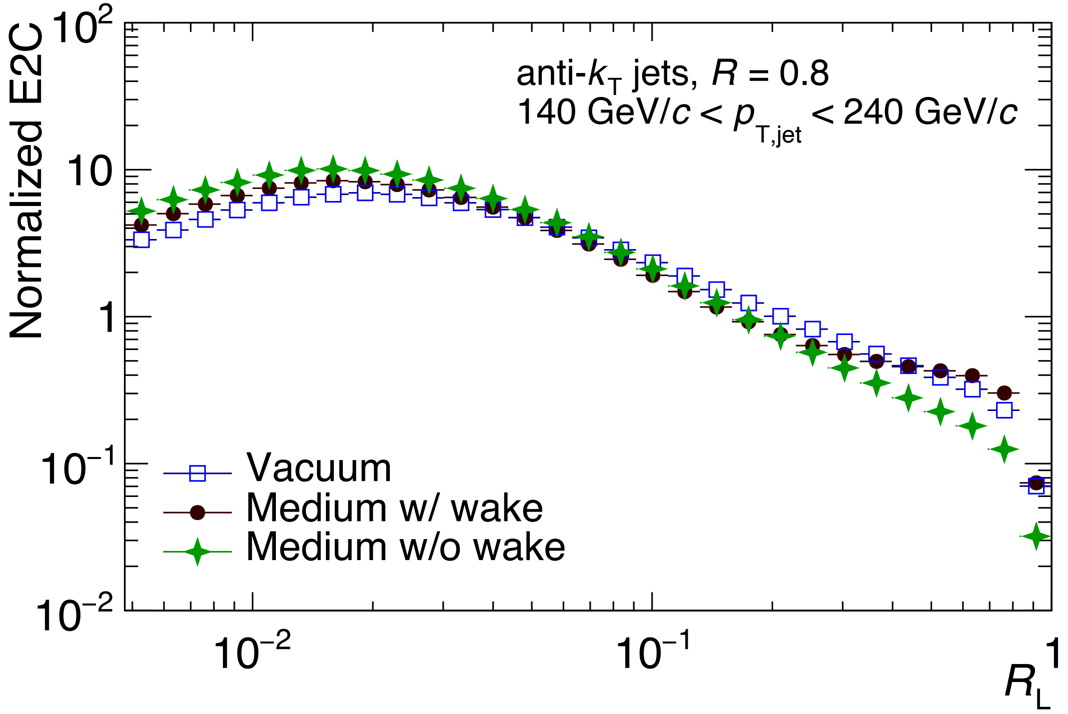


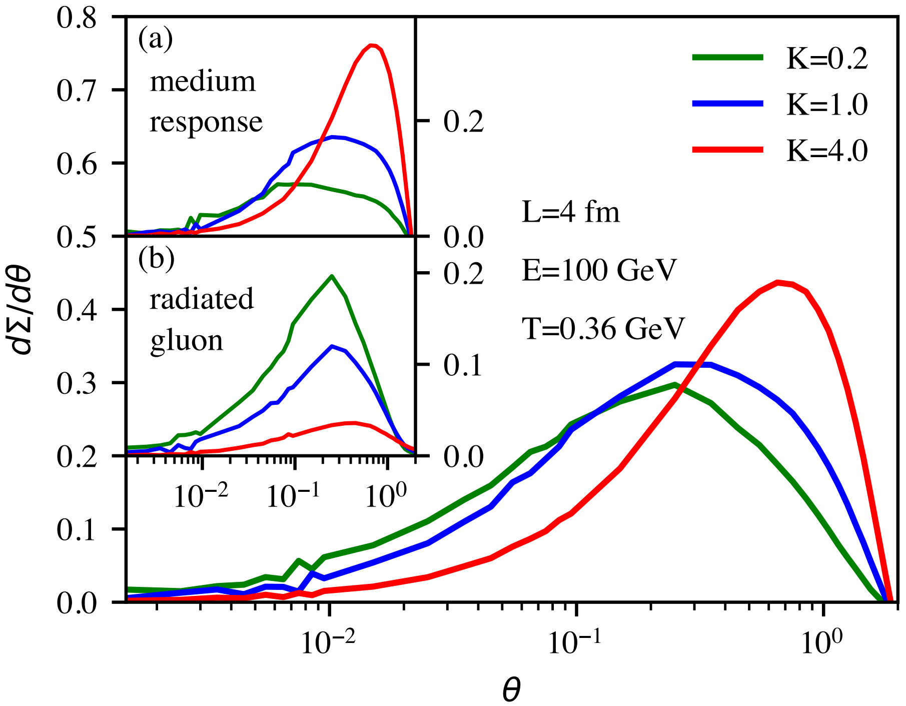




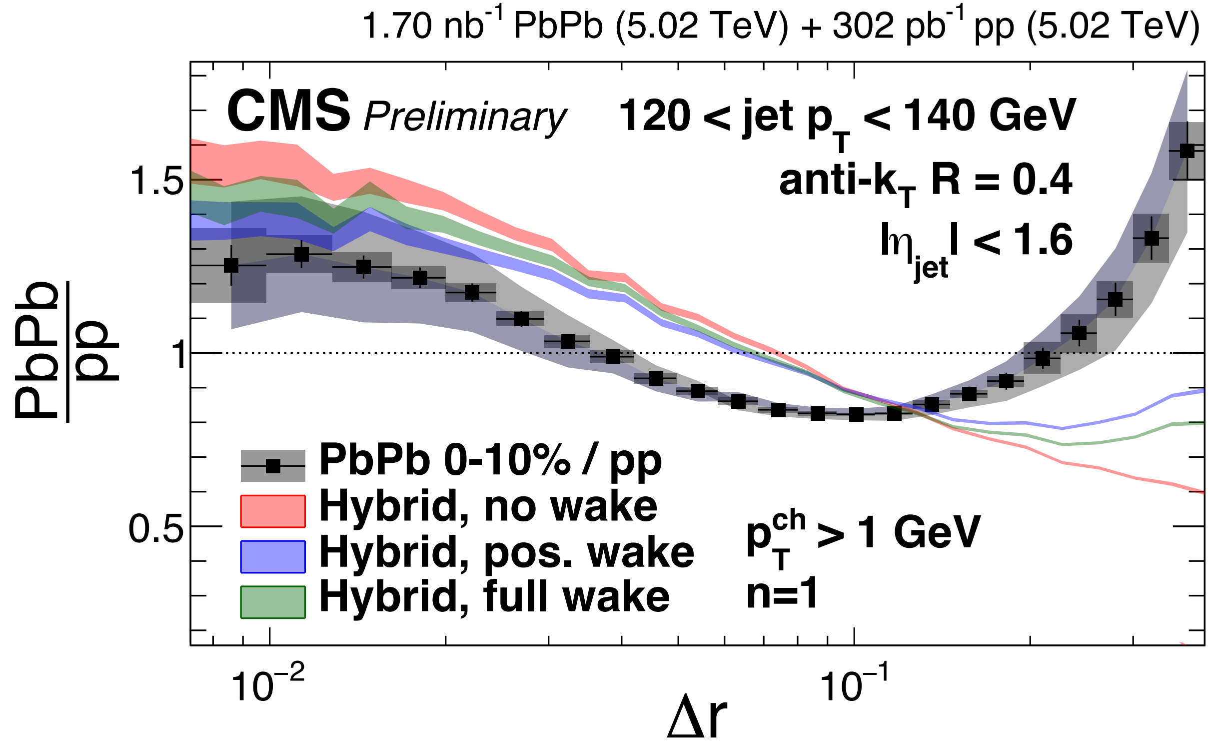
H. Bossi, A. S. Kudinoor, I. Moult, D. Pablos, A. Rai, K. Rajagopal, JHEP, 2024
Z. Yang, Y. He, I. Moult, X.-N. Wang, PRL, 2024

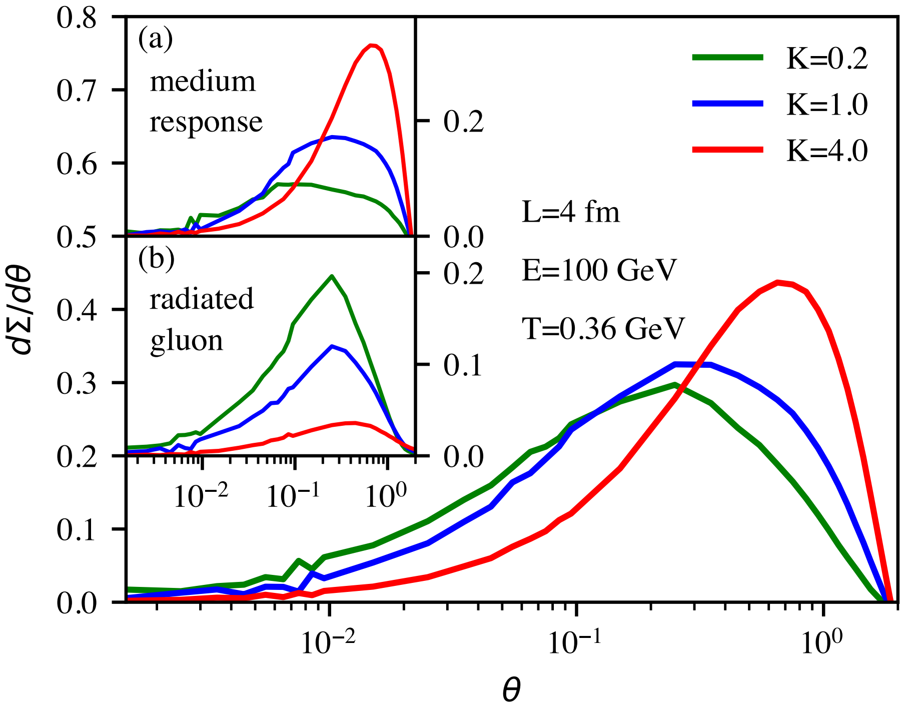
EECs in HICs





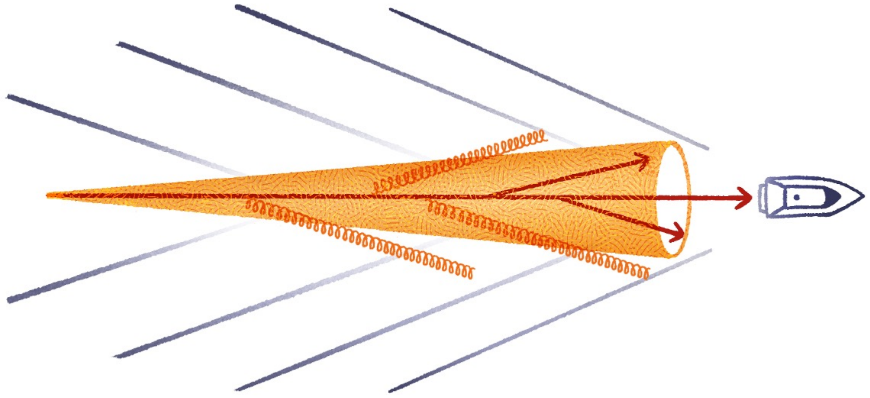
EECs in HICs

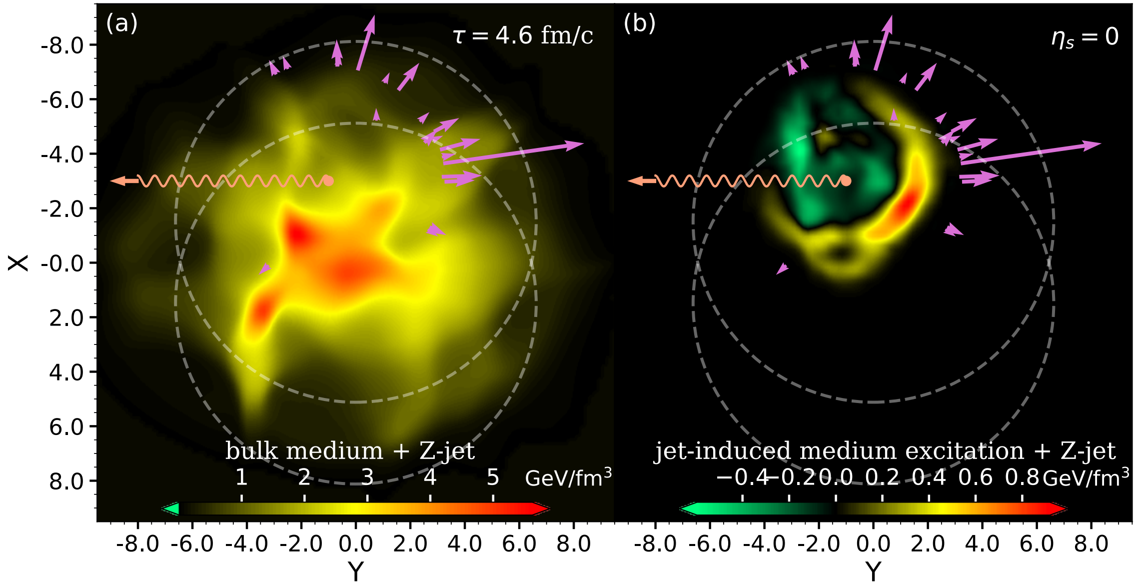

1.70 nb⁻¹ PbPb (5.02 TeV) + 302 pb⁻¹ pp (5.02 TeV)
CMS Preliminary
120 < jet p_T < 140 GeV
anti-k_T R = 0.4
$|\eta_{jet}|$ < 1.6
PbPb 0-10% / pp
Hybrid, no wake
Hybrid, pos. wake
Hybrid, full wake
p_T^{ch} > 1 GeV
n=1
PbPb/pp
Δr


(a)
medium response
(b)
radiated gluon
K=0.2
K=1.0
K=4.0
L=4 fm
E=100 GeV
T=0.36 GeV
dΣ/dθ
θ

Y. He, T. Luo, X.-N. Wang, Y. Zhu, PRC, 2015
Y. Tachibana, N.-B. Chang, G.-Y. Qin, PRC, 2017
J. Casalderrey-Solana et al, JHEP, 2021
W. Chen, Z. Yang, Y. He, W. Ke, L. Pang, X.-N. Wang, PRL, 2021
Z. Yang, T. Luo, W. Chen, L.-G. Pang, X.-N. Wang, PRL, 2023

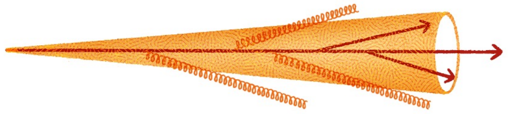
Probing the response



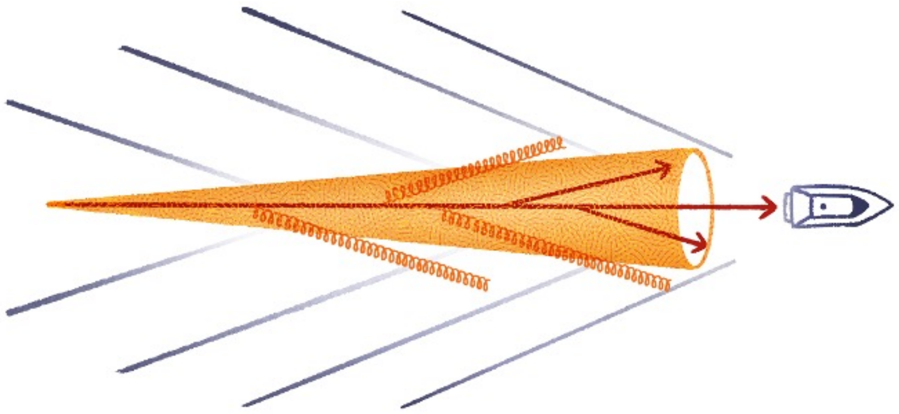


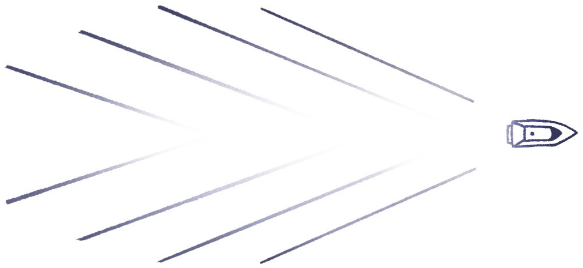
- Renewed interest in the medium response: recent consideration e.g. within CoLBT, JEWEL, Hybrid model
- Experimental needs, see e.g. ALICE, PRC, 2023; ATLAS, PRC, 2025; CMS, 2025

Probing the response



$$\partial_\mu T^{\mu\nu} = J^\nu$$

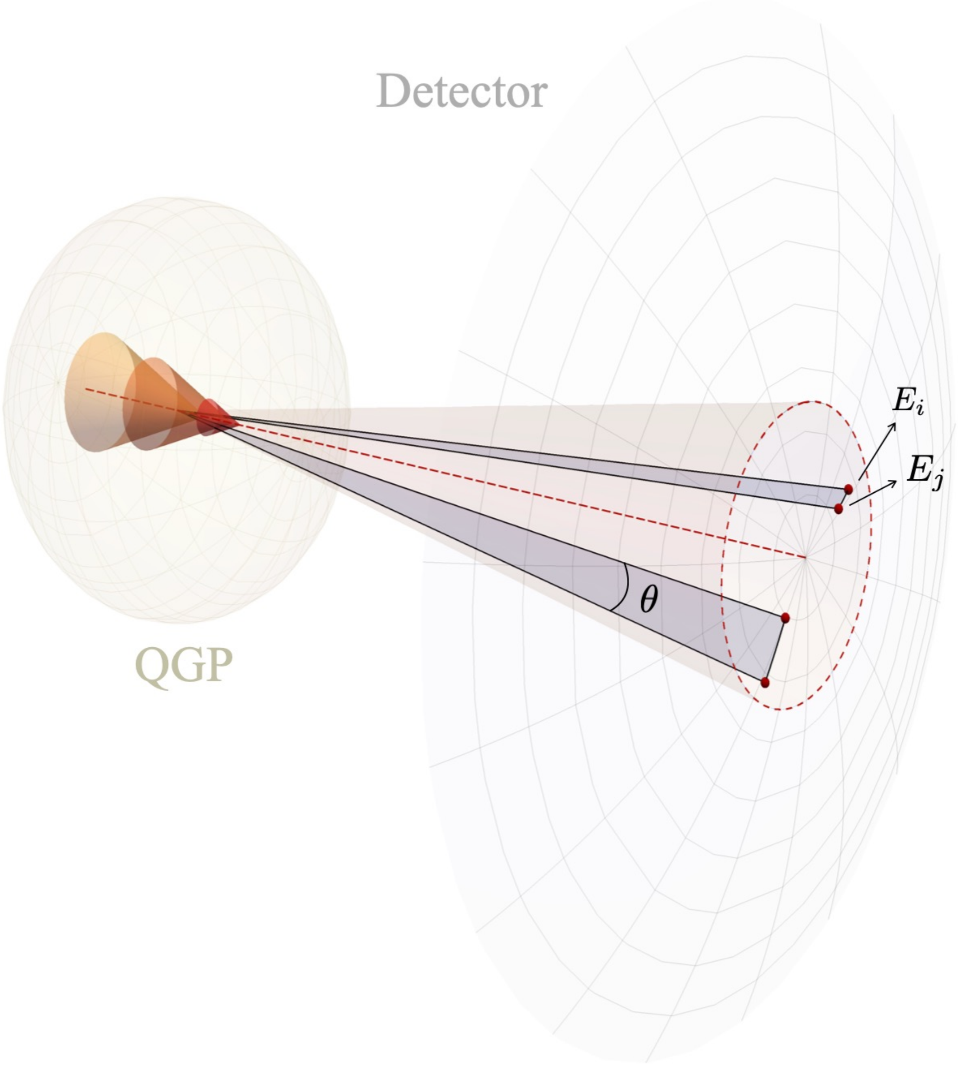




Probing the response

- The hydrodynamic description of a flowing medium is classical
- So are the most of the current treatments of the medium response
- **But what would happen if a classical flow were plugged into the ECs?**

$$\langle \mathcal{E}(\mathbf{n}_1)\mathcal{E}(\mathbf{n}_2)\rangle$$
$$\downarrow$$
$$\mathcal{E}(\mathbf{n}_1)\mathcal{E}(\mathbf{n}_2)$$



Probing the response

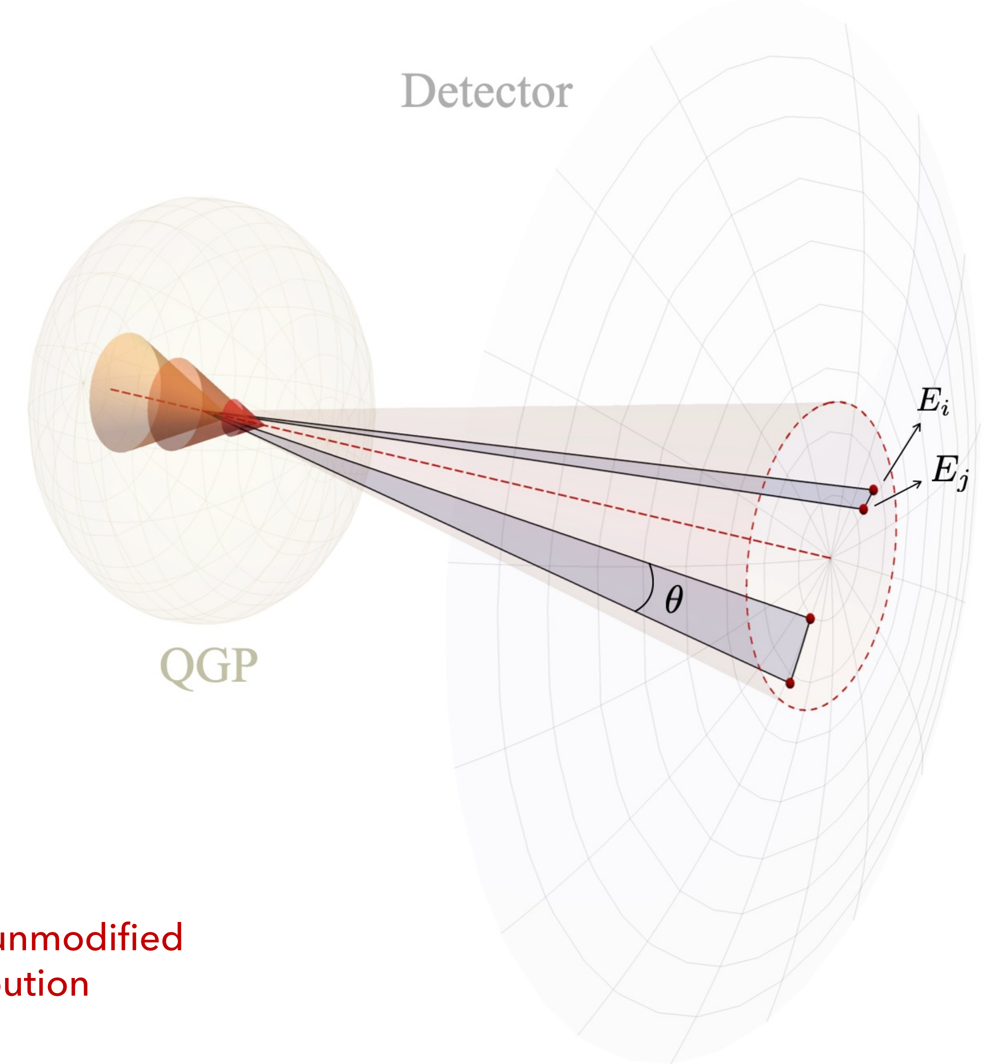
- The hydrodynamic description of a flowing medium is classical
- So are the most of the current treatments of the medium response
- **Uncorrelated energy flux contributes through geometric correlations**

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

↑

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

the leading structure is unmodified by the stochastic contribution



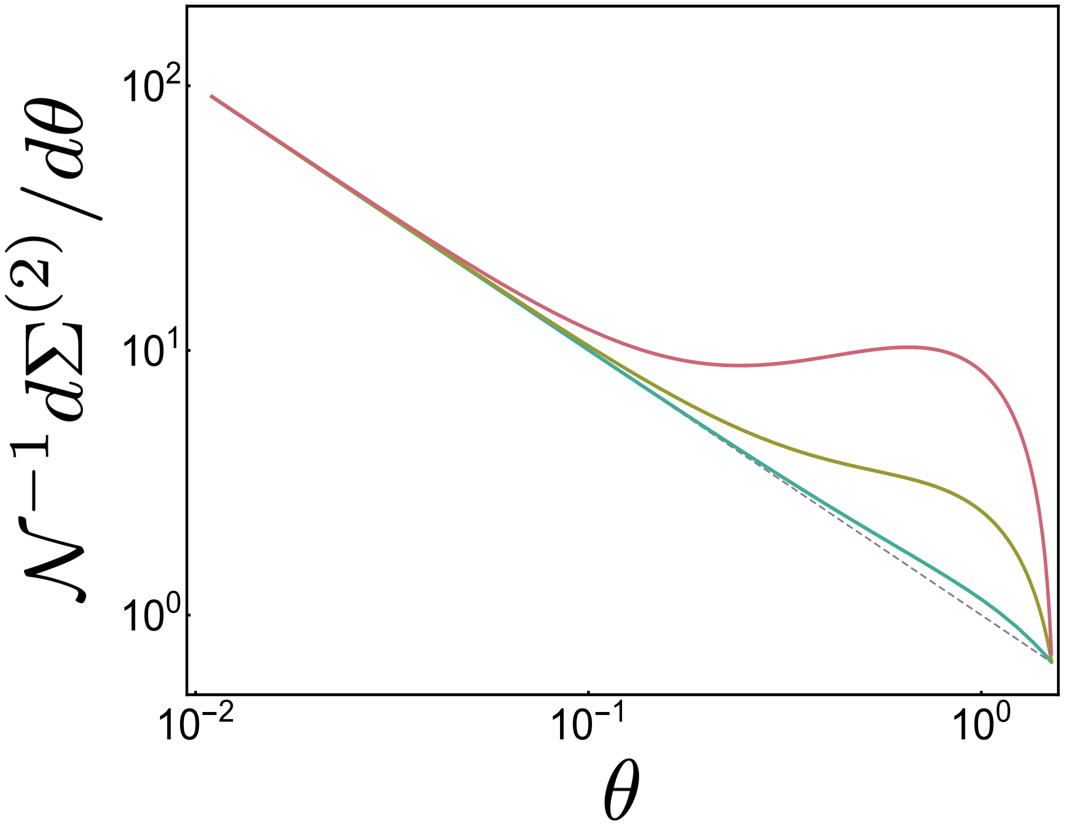
Probing the response

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

↓

$$\frac{d\Sigma^{(2)}}{d\theta} = \mathcal{N}\left[\frac{1}{\theta} + \mathsf{c}\,\frac{d\Sigma^{(2)}_{cc}}{d\theta}\right]$$

- Specific model is needed to fix the factors (cannot be done at this level)
- Classical flux leads to universal features (e.g. positivity of the leading term)
- The same behavior for different descriptions (hydro, EKT, etc)



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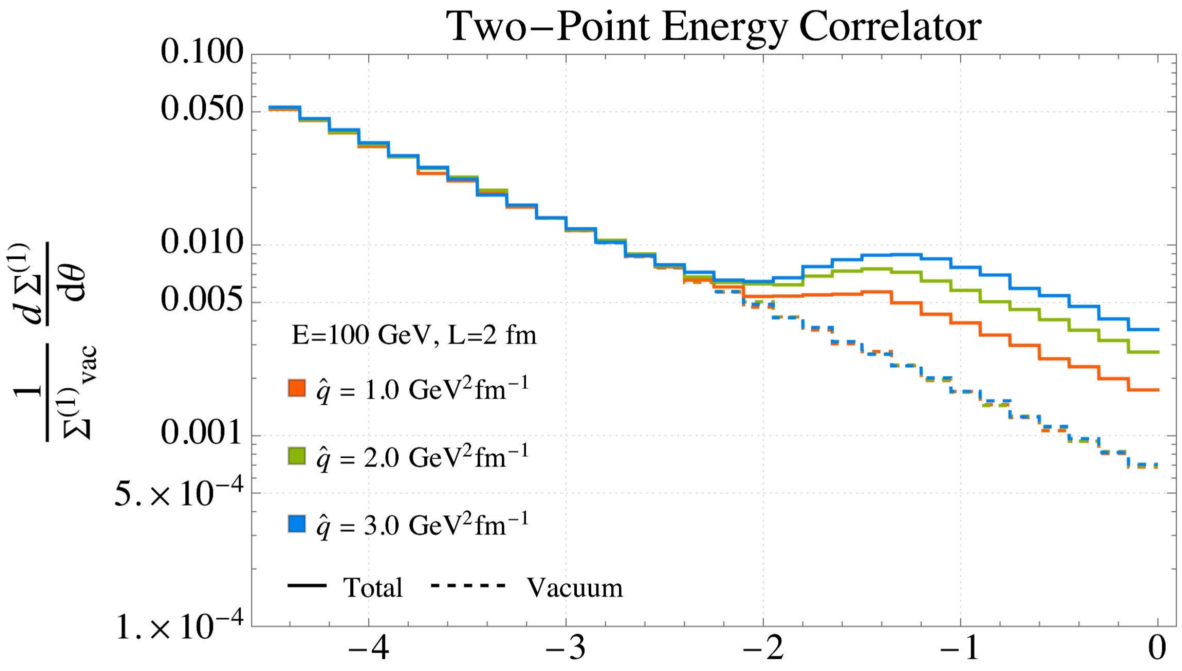

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Probing the response

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$\downarrow$

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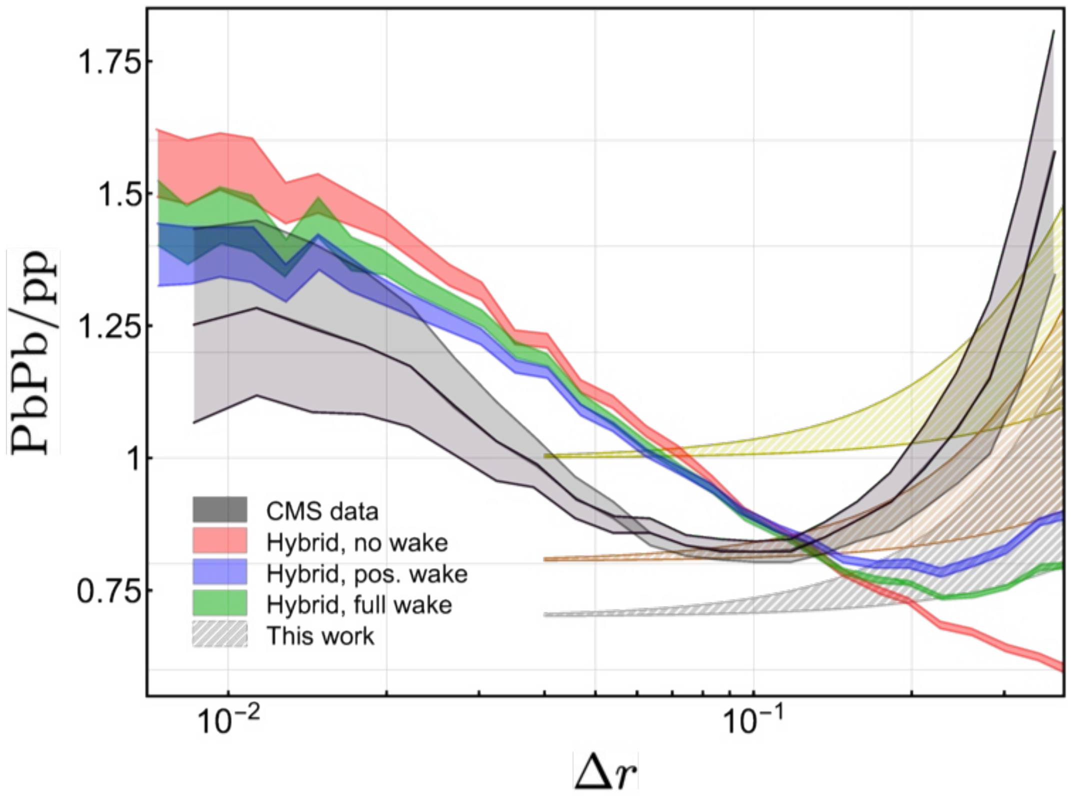
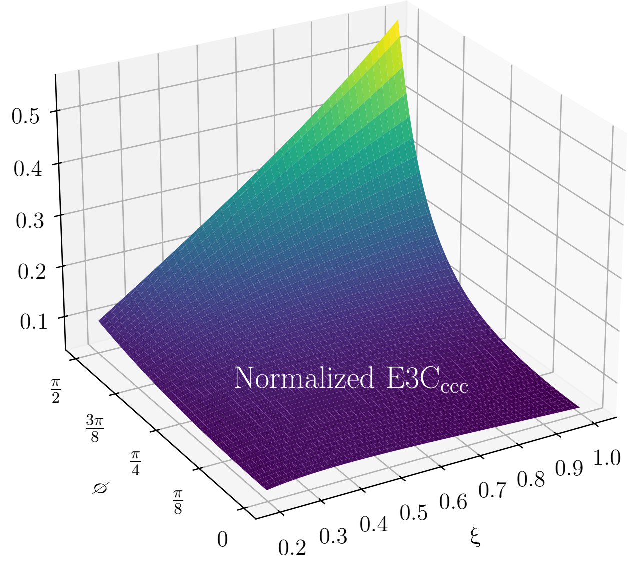


Probing the response

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

↓

$$\frac{d\Sigma^{(3)}_{ccc}}{dR_L d\xi d\phi} = \frac{4\pi^2 p_t^{-2} R_L^3 \int_\Theta \mathcal{E}^3(\Theta)\sin\Theta}{(1+\xi\cos\phi)^3\sqrt{4+4\xi\cos\phi-\xi^2\sin^2\phi}}$$



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$R_L > R_M > R_S$

$\xi = R_S/R_M$

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

Probing the response

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

$$\downarrow$$

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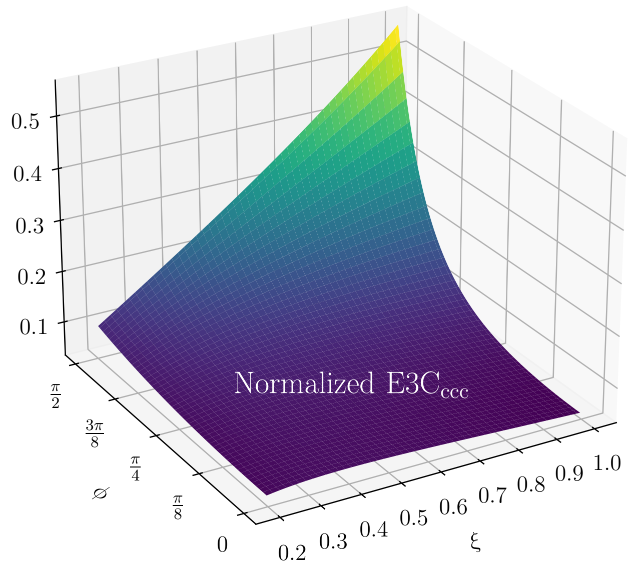

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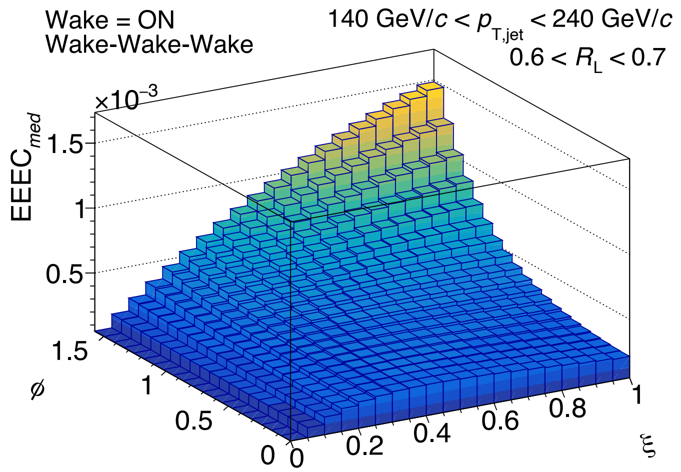


Probing the response

An illustration: $\mathcal{E}_c(\mathbf{n}) = \frac{\Delta}{\pi\theta_0} e^{-\theta^2/\theta_0^2}$ and no perturbative medium modification

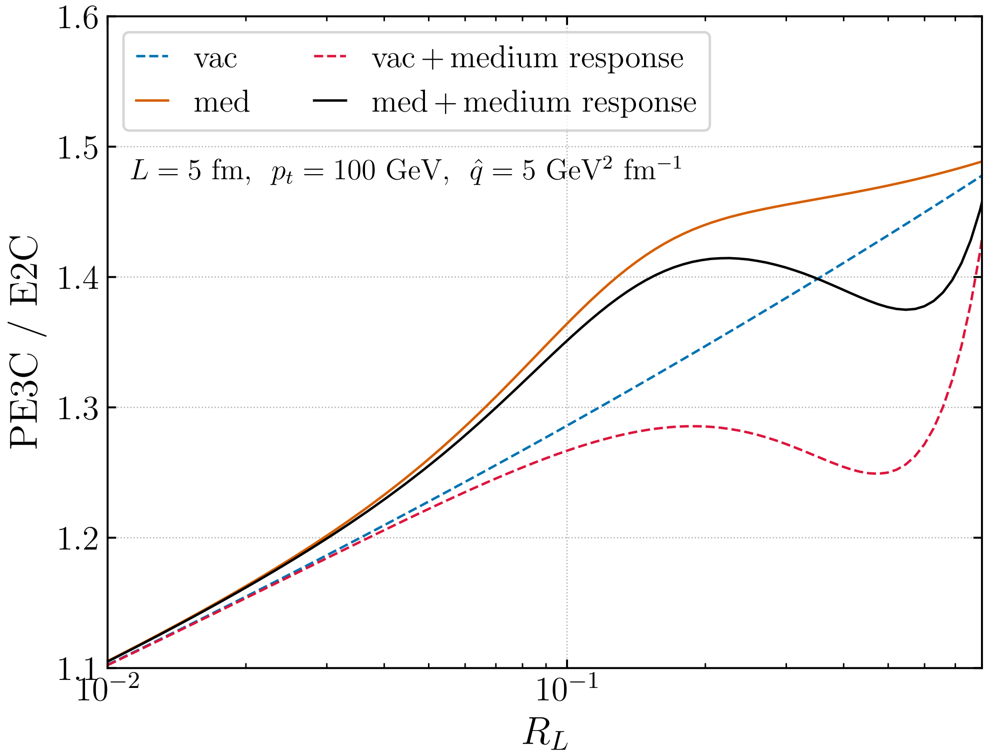
$$\frac{d\Sigma^{(2,3)}_{\mathrm{P,vac}}}{dR_L} \simeq a^{P(2,3)}_{2,0} R_L^{\gamma(3,4)-1}$$

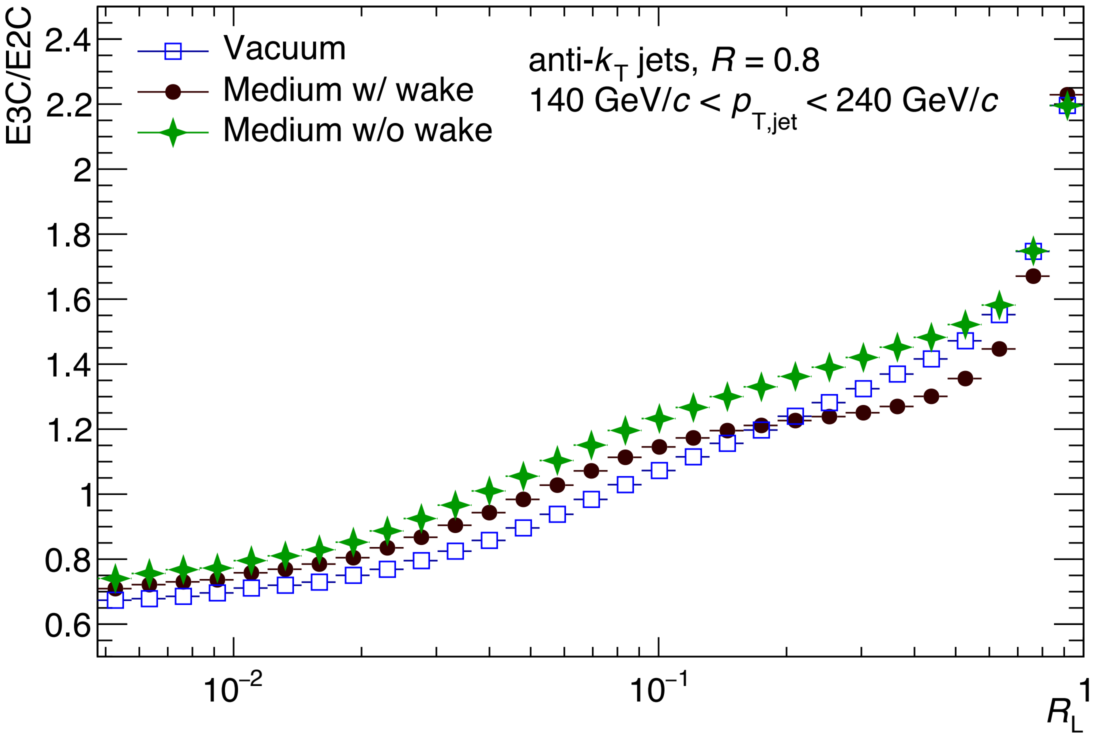
$$\left.\frac{\mathrm{PE3C}}{\mathrm{E2C}}\right|_{\mathrm{v+r}} = \left(\frac{a^{P(3)}_{2,0}}{R_L^{1-\gamma(4)}} + \frac{a^{P(3)}_{2,0}\Delta}{6\pi p_t} \mathcal{C}\, R_L^{1+\gamma(3)} + \frac{\Delta^3}{\theta_0^2 p_t^3} \left(\frac{2}{9} - \frac{\sqrt{3}}{6\pi} \right) R_L^3 \right) \left(\frac{a^{P(2)}_{2,0}}{R_L^{1-\gamma(3)}} + \frac{\Delta^2 R_L}{p_t^2 \theta_0^2} \right)^{-1}$$

chhh, regularized

Probing the response

An illustration: $\mathcal{E}_c(\mathbf{n}) = \dfrac{\Delta}{\pi\theta_0} e^{-\theta^2/\theta_0^2}$ and no perturbative medium modification





EECs in HICs

- The vac. PENC in the OPE limit:

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

- The medium-induced part of PENC:
(for a static and homogeneous matter)

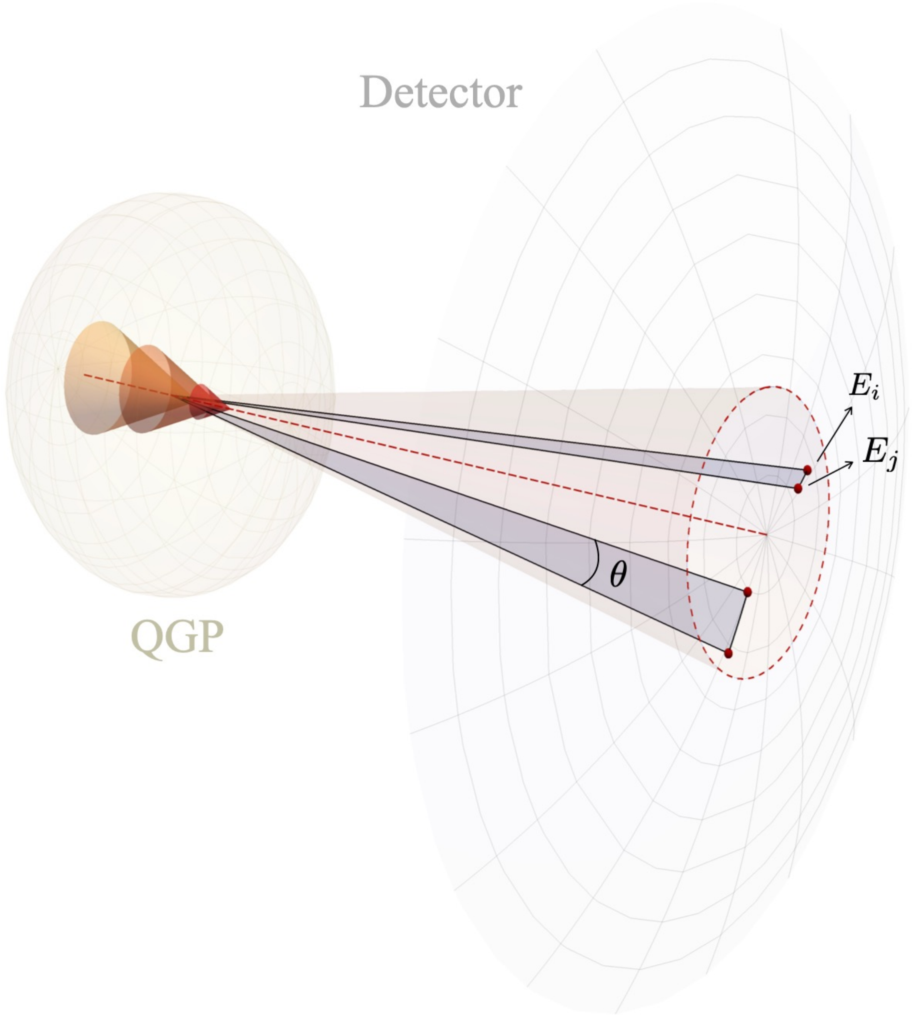
$$\frac{d\Sigma^{(N)}_{\mathrm{P,\,med\,(no\,vac)}}}{dR_L} = \sum_{k=2} b^{\mathrm{P}(N)}_{\tau,0}(\omega_c/p_t, \theta_c) R_L^{\tau-3}\Big|_{\tau=2k}$$

- The medium response contribution:
(no azimuthal structure, leading terms)

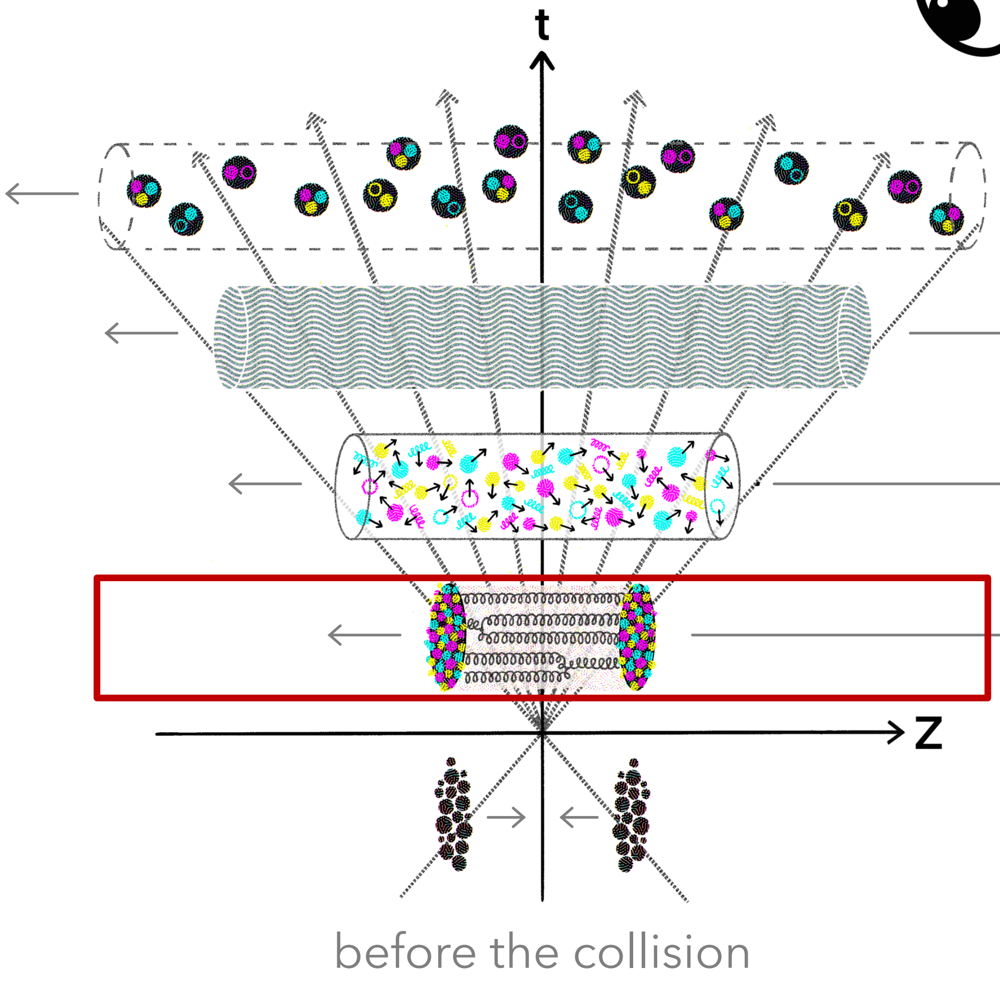
$$\frac{d\Sigma^{(N)}_{\mathrm{P,\,response}}}{dR_L} = \sum_{k=2} c^{\mathrm{P}(N)}_{\tau}\Big[\mathcal{E}_c\Big] R_L^{\tau-3}\Big|_{\tau=2k}$$

EECs in HICs

- Large charge EFT
- EECs in hydrodynamic state
- EECs with a fluid droplet



Initial stages in HICs



Phases of QCD matter in HIC:

hadron gas

hydrodynamic Quark-Gluon Plasma (QGP)

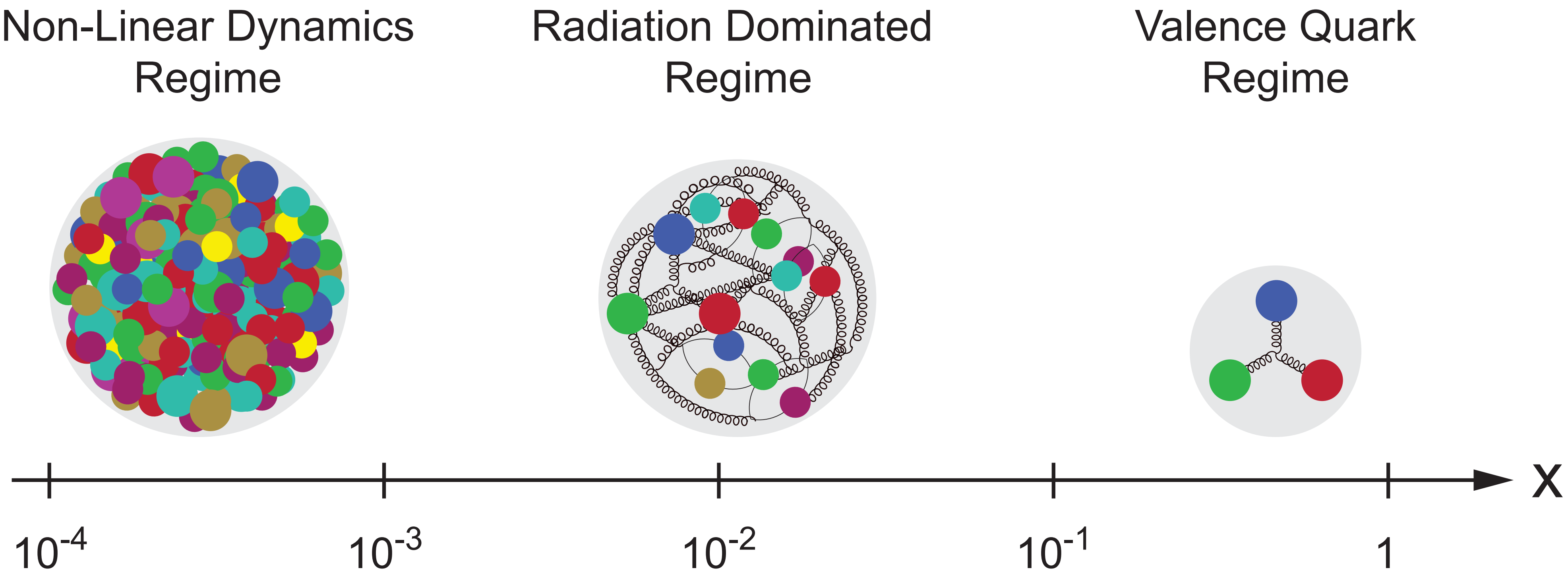
non-equilibrium matter

glasma (strong color fields)

Matter produced in HIC undergoes multiphase evolution

F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, review, 2010
E.C. Aschenauer et al., Rept.Prog.Phys. 82, 2019

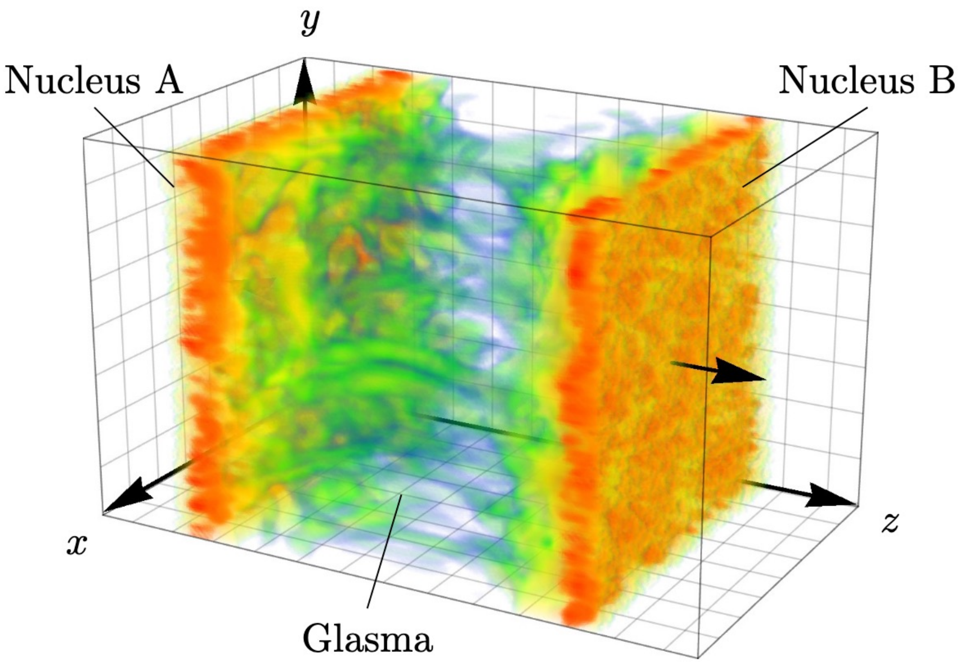
Color glass condensate

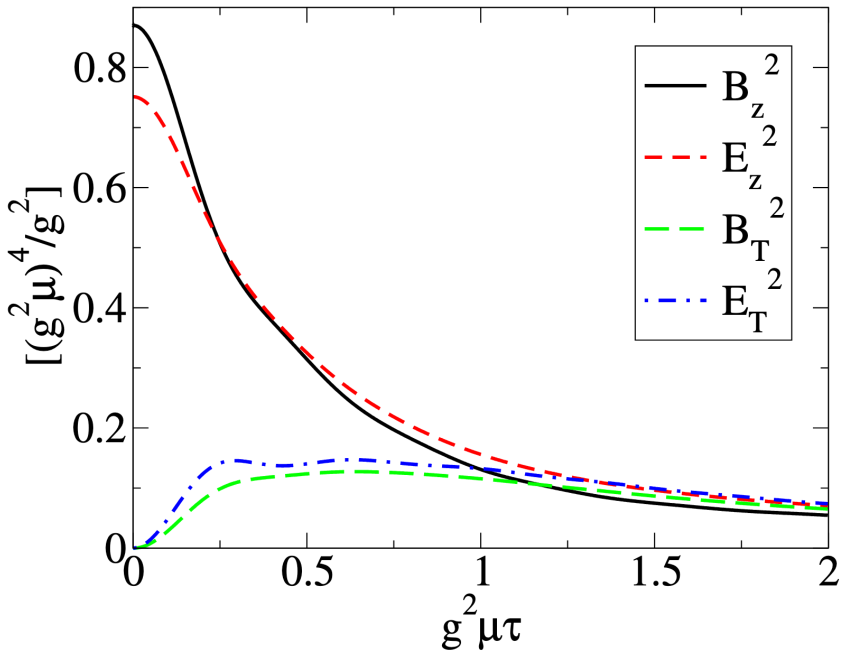


$dP \sim \frac{\alpha_s}{x} dx$ → large Q (resolution) small x (high density) → $D_\mu F^{\mu\nu} = J^\nu$

Glasma

from a paper by A. Ipp et al.

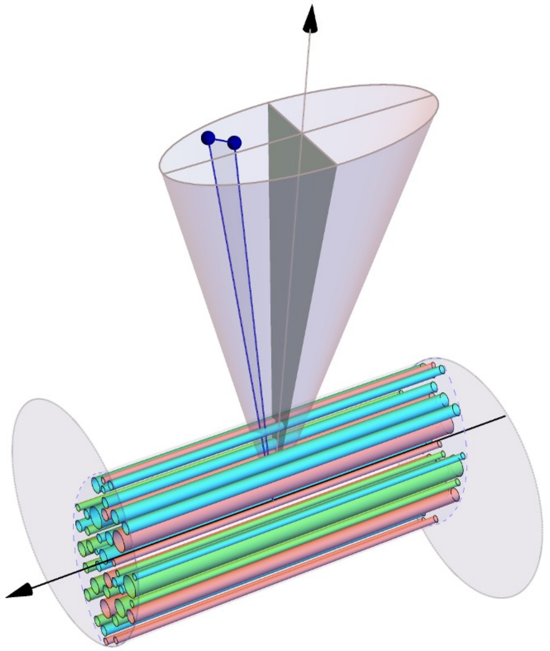




see e.g. P. Aurenche, B. G. Zakharov, PLB, 2012
A. Ipp, D. I. Müller, D. Schuh, PRD, 2020
A. Ipp, D. I. Müller, D. Schuh, PLB, 2020
M. Carrington, A. Czajka, S. Mrowczynski, PLB, 2022
M. Carrington, A. Czajka, S. Mrowczynski, PRC, 2022
D. Avramescu et al., PRD, 2023
J. Barata, S. Hauksson, X. Mayo López, AS, PRD, 2024
S. Hauksson, S. Jeon, C. Gale, PRC, 2022
K. Boguslavski et al., PRD, 2024
K. Boguslavski et al., PLB, 2024
K. Boguslavski, J. Barata, F. Lindenbauer, AS, 2025
M. Carrington, A. Czajka, S. Mrowczynski, NPA, 2020
K. Boguslavski et al., PRD, 2024
C. Gale et al., SQM2024
X. Du, PRC, 2024
D. Avramescu et al., PRD, 2025
D. Avramescu et al., PRL, 2025

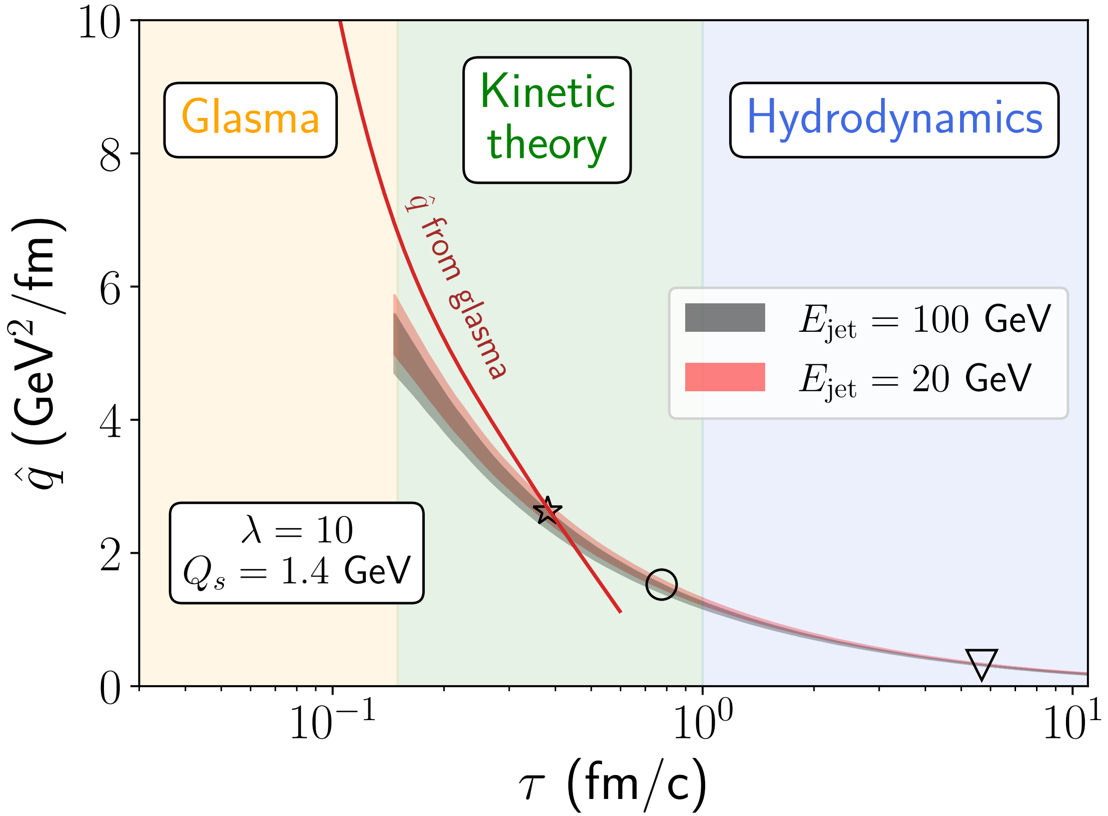
Initial stages in HICs

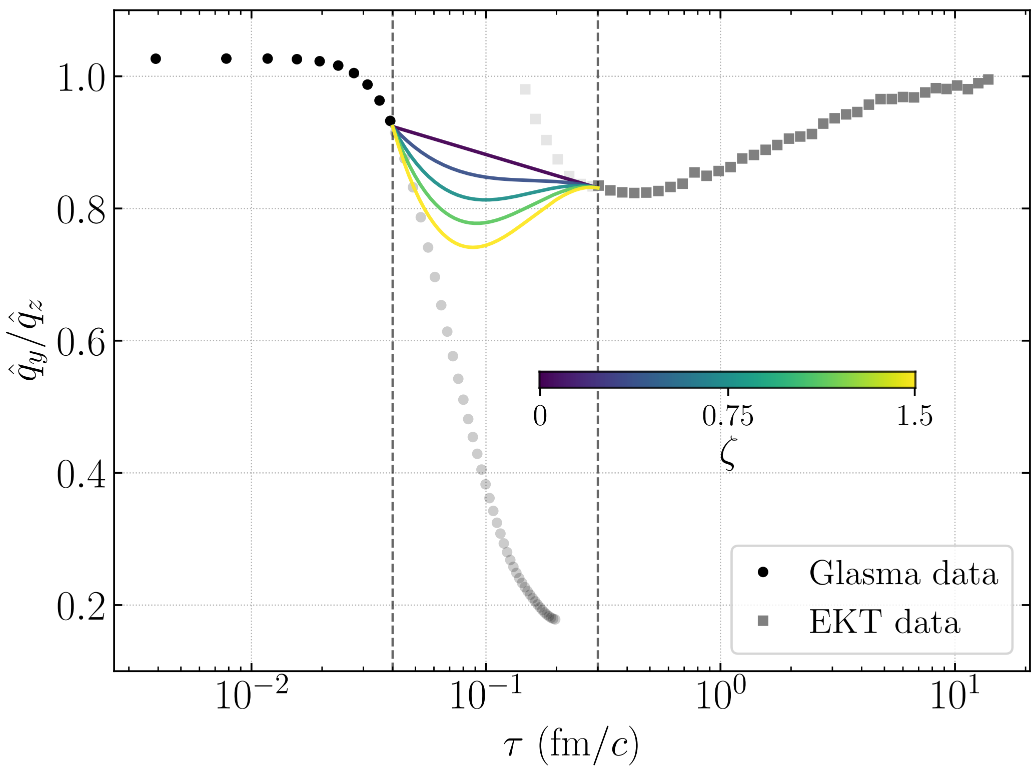
- $\hat{q}$ is extremely hard to access experimentally, but it provides an important measure for phenomenological estimates
- Large scale simulations, see e.g. JETSCAPE (PRC, 2021), suggest that a typical value for the QGP at $\mathrm{T} \sim 200\ \mathrm{MeV}$ is $\hat{\mathrm{q}} \sim 0.12\ \mathrm{GeV}^2/\mathrm{fm}$
- Historically, the glasma phase was assumed less relevant, but a series of recent works indicate that $\hat{\mathrm{q}} \geq 5\ \mathrm{GeV}^2/\mathrm{fm}$ during the first $0.3\ \mathrm{fm/c}$
- The simulations of the non-equilibrium dynamics within kinetic theory show continuity of $\hat{\mathrm{q}}$ consistent with these glasma phase values
- Similarly strong effects are also observed for heavy quarks



K. Boguslavski et al, PLB, 2024

Jet quenching during initial stages

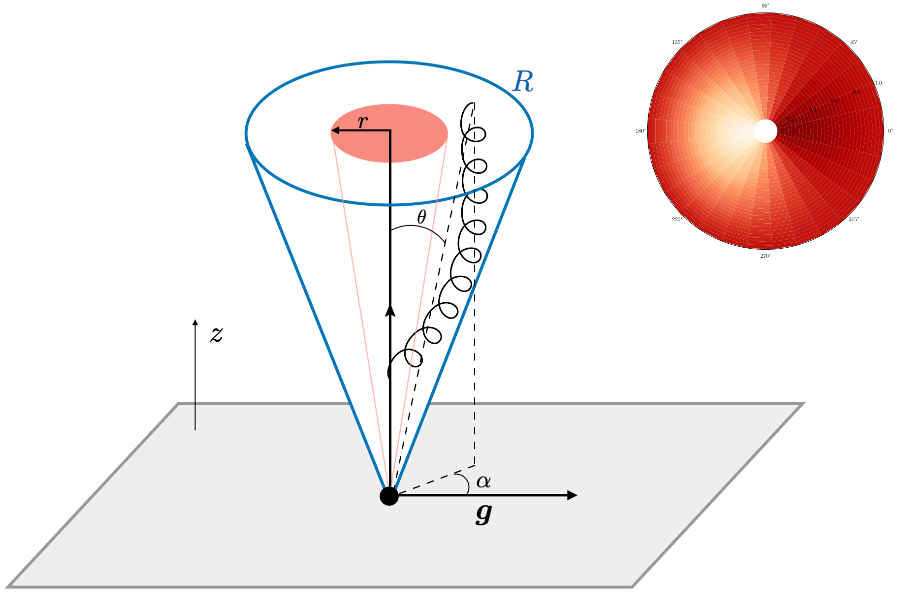


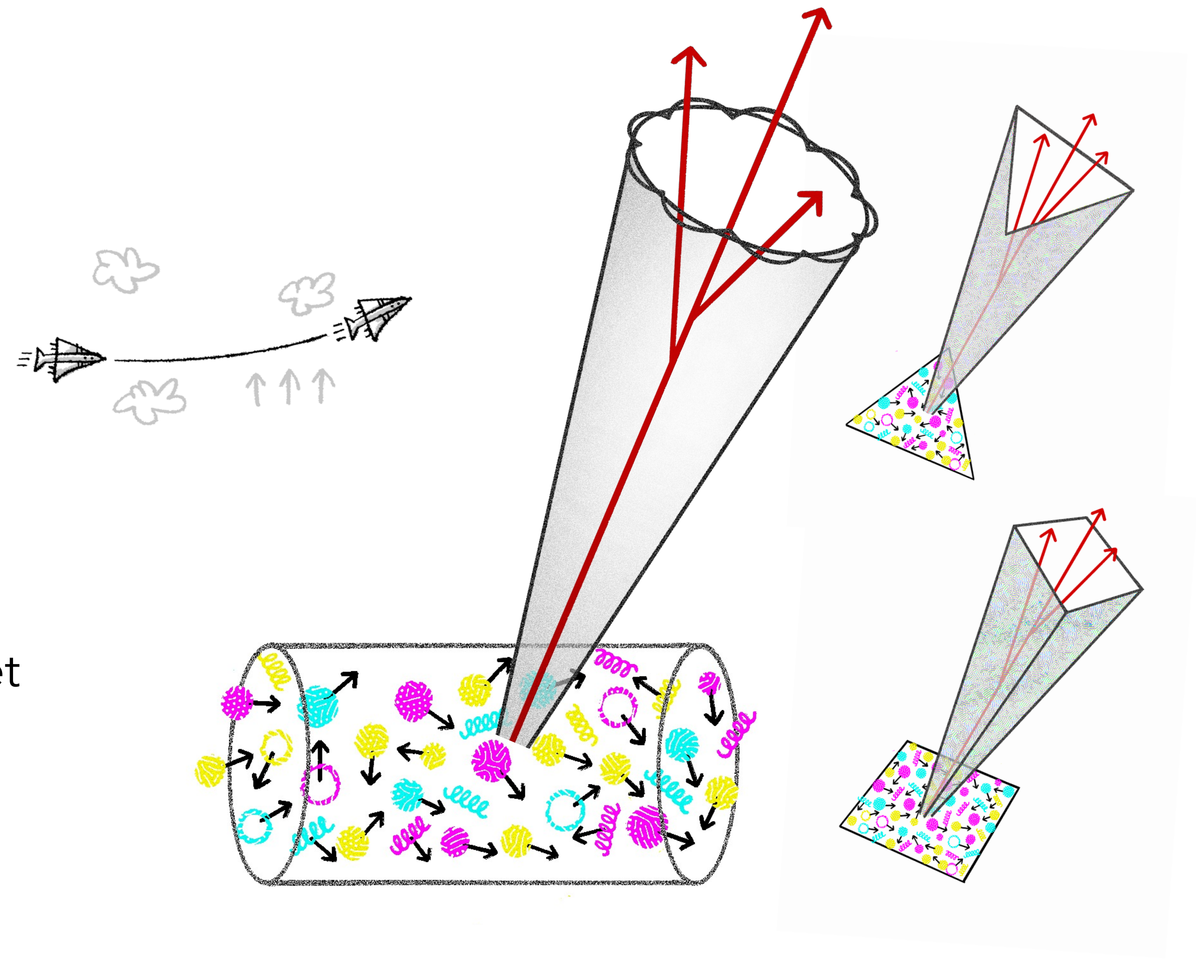


Are the glasma and pre-equilibrium broadening patterns fit together?

AS, M. Sievert, I. Vitev, PRD, 2021
J. Barata, X. Mayo Lopez, AS, C. Salgado, PRD, 2023
J. Barata, G. Milhano, AS, EPJC, 2024
J. Barata, C. Salgado, J. Silva, JHEP, 2024

Jets in anisotropic matter





- The matter affects the softer part of the jet
- It is imprinted in substructure (especially in its azimuthal part)
- Only very early estimates are out there, more progress is needed

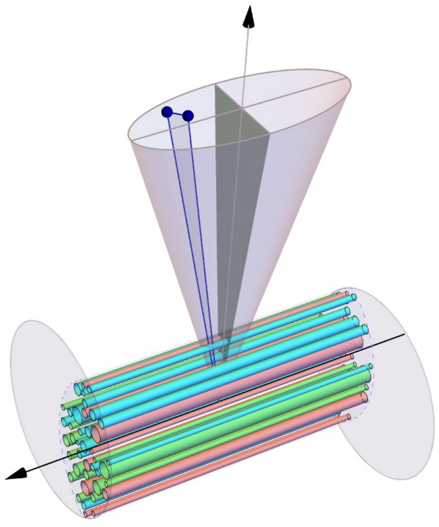
Jet quenching during initial stages

$$\frac{1}{\sin\chi\sin\Psi}\frac{d\Sigma}{d\chi d\Psi}\bigg|_{\eta=0} = \int_{n_1,n_2} \frac{\langle\mathcal{E}(n_1)\mathcal{E}(n_2)\rangle}{p_t^2}\,\delta(n_1\cdot n_2-\cos\chi)\,\delta\left(\frac{n_1-n_2}{|n_1-n_2|}\cdot b-\cos\Psi\right)\,,$$

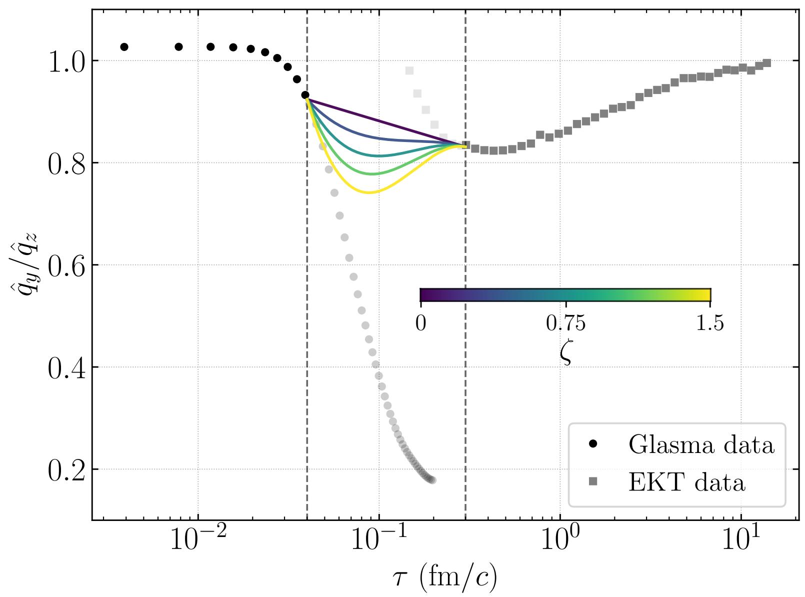
$$\langle\mathcal{E}(n_1)\mathcal{E}(n_2)\rangle = \frac{2p_t^2}{(1-n_1\cdot n_2)^3}\sum_{\delta,j}\int_\gamma \frac{c_{\delta,j,\gamma}}{2\pi i} w^\gamma G_{\delta,j,\gamma}(z,\bar{z})$$

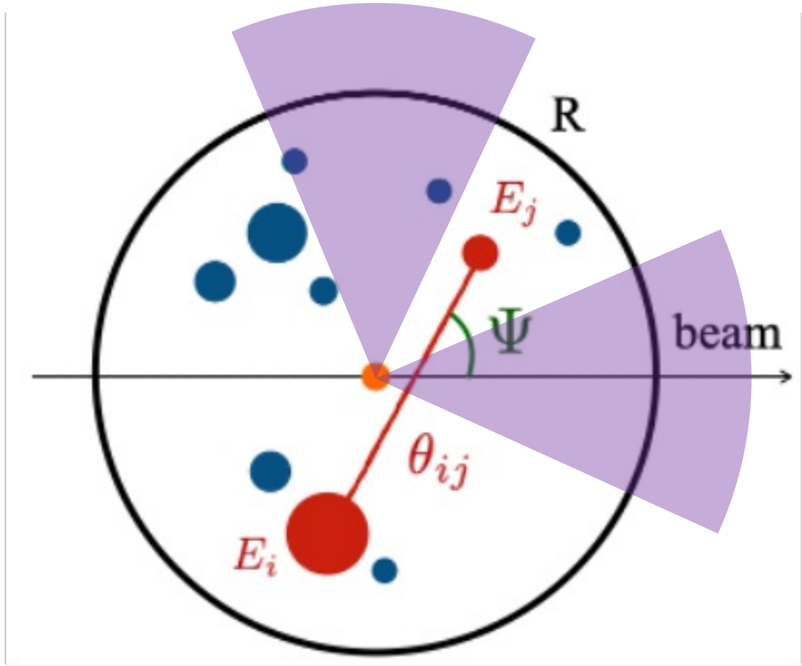
$$\frac{d\Sigma}{d\chi d\Psi} = \sum_{k=1}(c_{\tau,0}+b_{\tau>2,0}+a_{\tau>2,0})\,\chi^{\tau-3}$$
$$+\sum_{k=2}(c_{\tau,2}+b_{\tau>4,2}+a_{\tau>4,2})\,\chi^{\tau-3}\cos(2\Psi)$$
$$+\sum_{k=3}(c_{\tau,4}+b_{\tau>6,4}+a_{\tau>6,4})\chi^{\tau-3}\cos(4\Psi)+\ldots$$

- vacuum
- medium-induced
- response



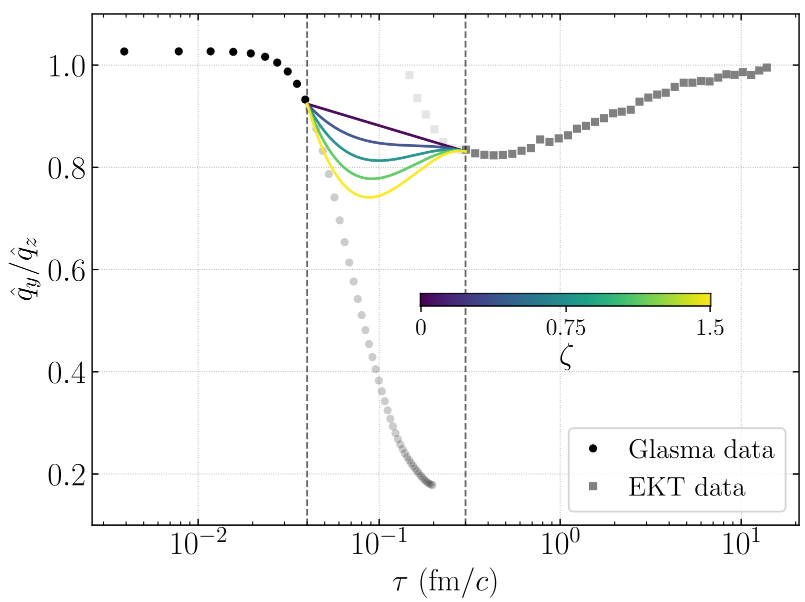
Clover EEC



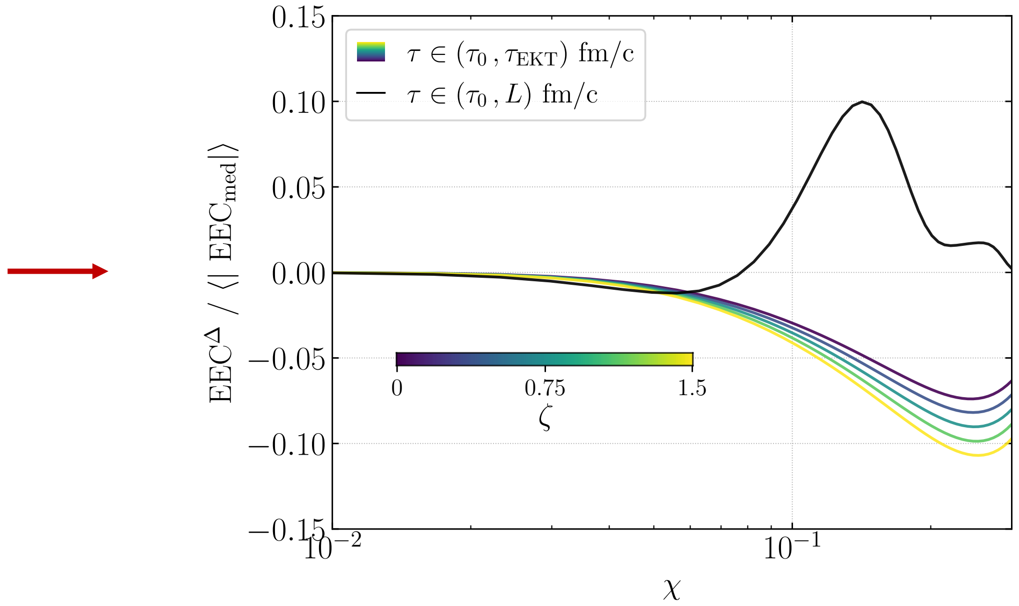


$$\frac{d\Sigma^{\Omega}}{d\chi} = \int_{\Omega} d\Psi \frac{d\Sigma}{d\chi d\Psi}$$

Clover EEC



$\hat{q}_y/\hat{q}_z$
τ (fm/c)
ζ
0
0.75
1.5
Glasma data
EKT data



$\tau \in (\tau_0\,,\tau_{\rm EKT})$ fm/c
$\tau \in (\tau_0\,,L)$ fm/c
$\rm EEC^{\Delta}\ /\ \langle|\ EEC_{med}|\rangle$
χ
ζ
0
0.75
1.5

Summary and outlook

- The "uncorrelated" energy fluxes lead to geometric correlations
- These contributions have highly universal structure, allowing to understand their qualitative features
- Only accounting for all the types of contributions one can systematically study the medium properties with ECs in HIC
- ECs suggest an alternative way to access the anisotropy of the medium properties
- The geometric contributions to ECs closely follow the pattern set by the celestial block decomposition