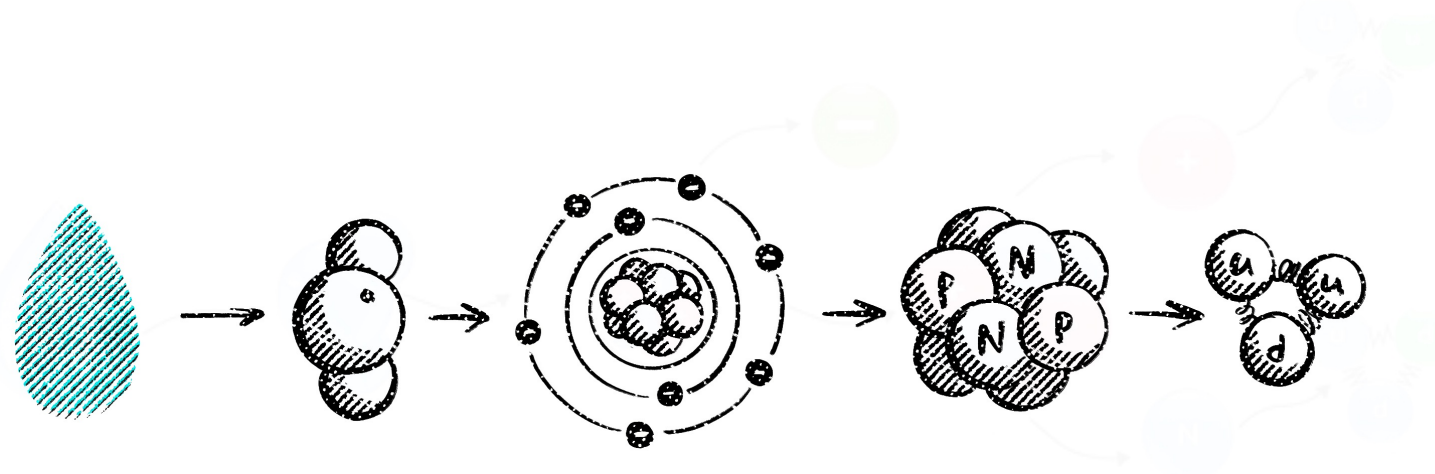


Early-Time Dynamics of Heavy-Ion Collisions through Energy Correlators

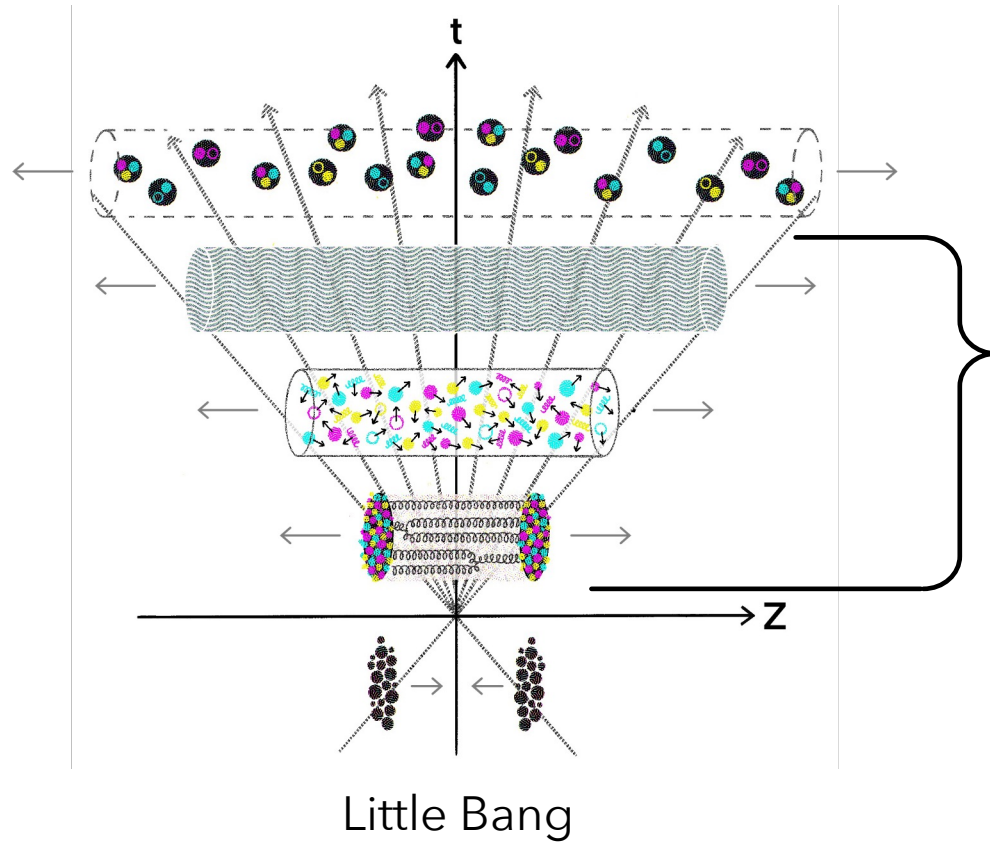
for EMMI Workshop: Probing the early stages with jets

Andrey Sadofyev
UPV/EHU & Ikerbasque

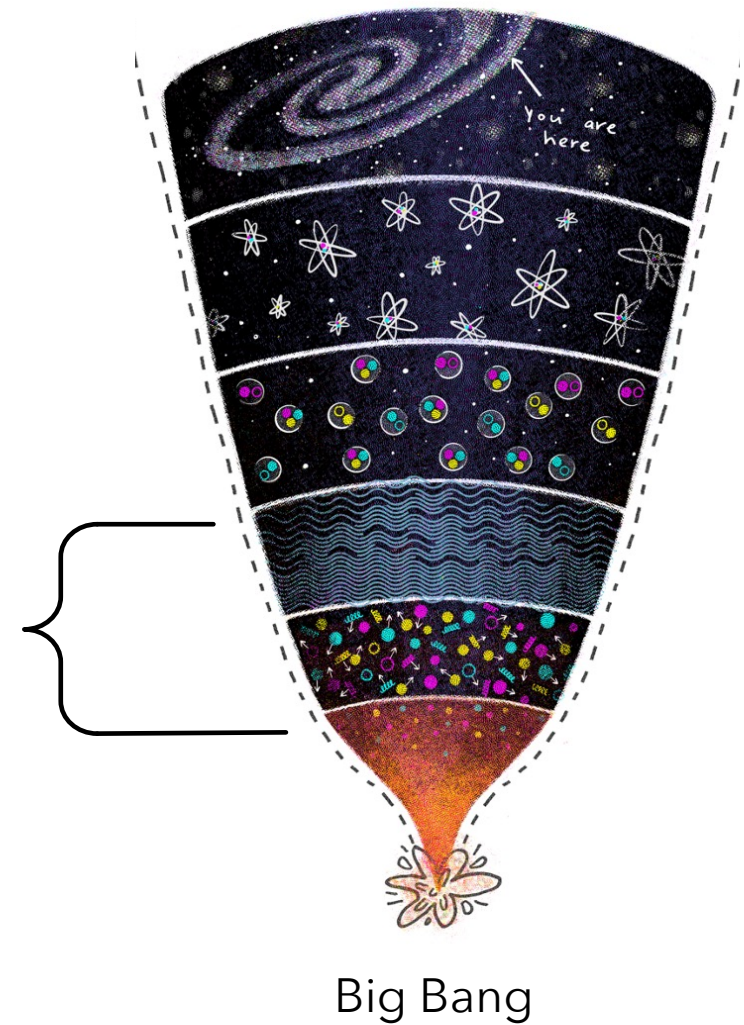
The origin of complex matter



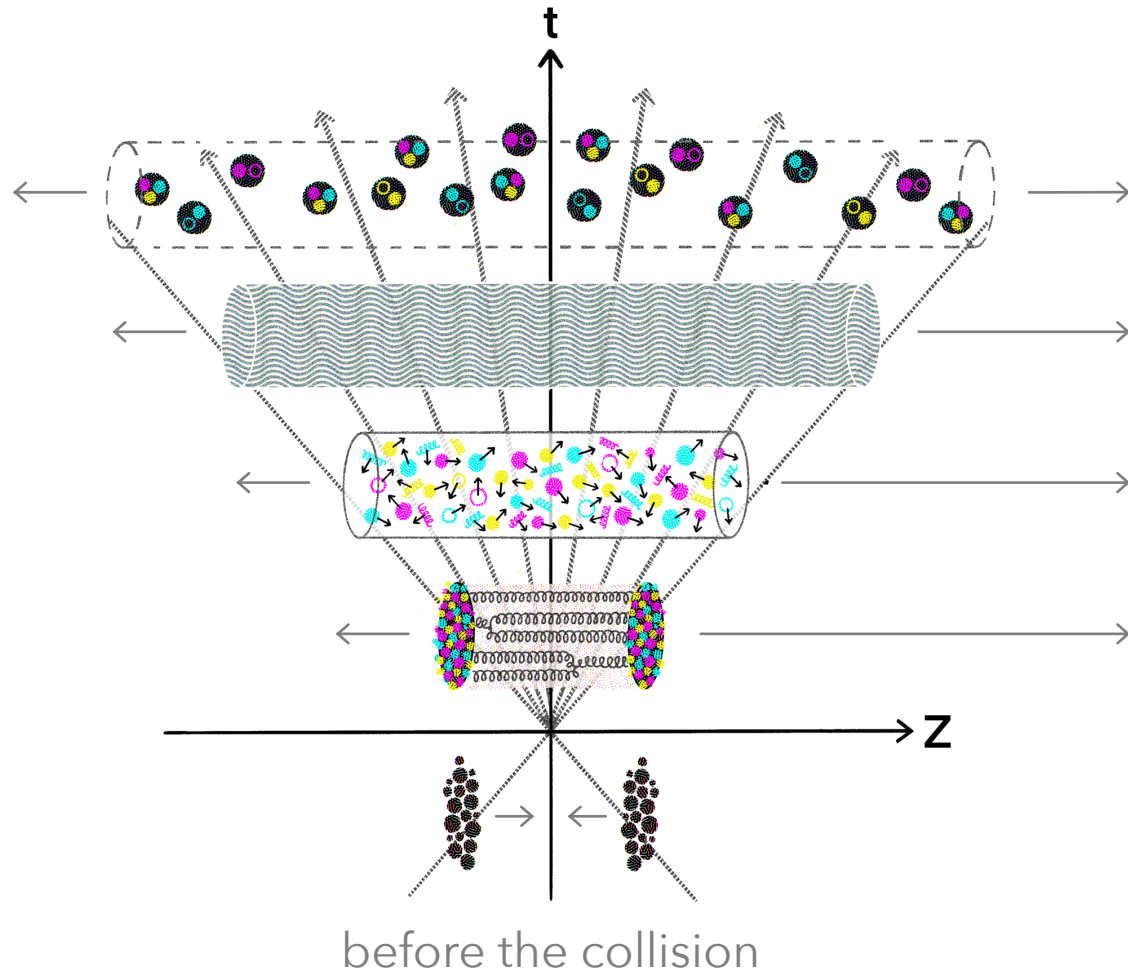
The origin of complex matter



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



Heavy-ion collisions



Phases of QCD matter in HIC:

hadron gas

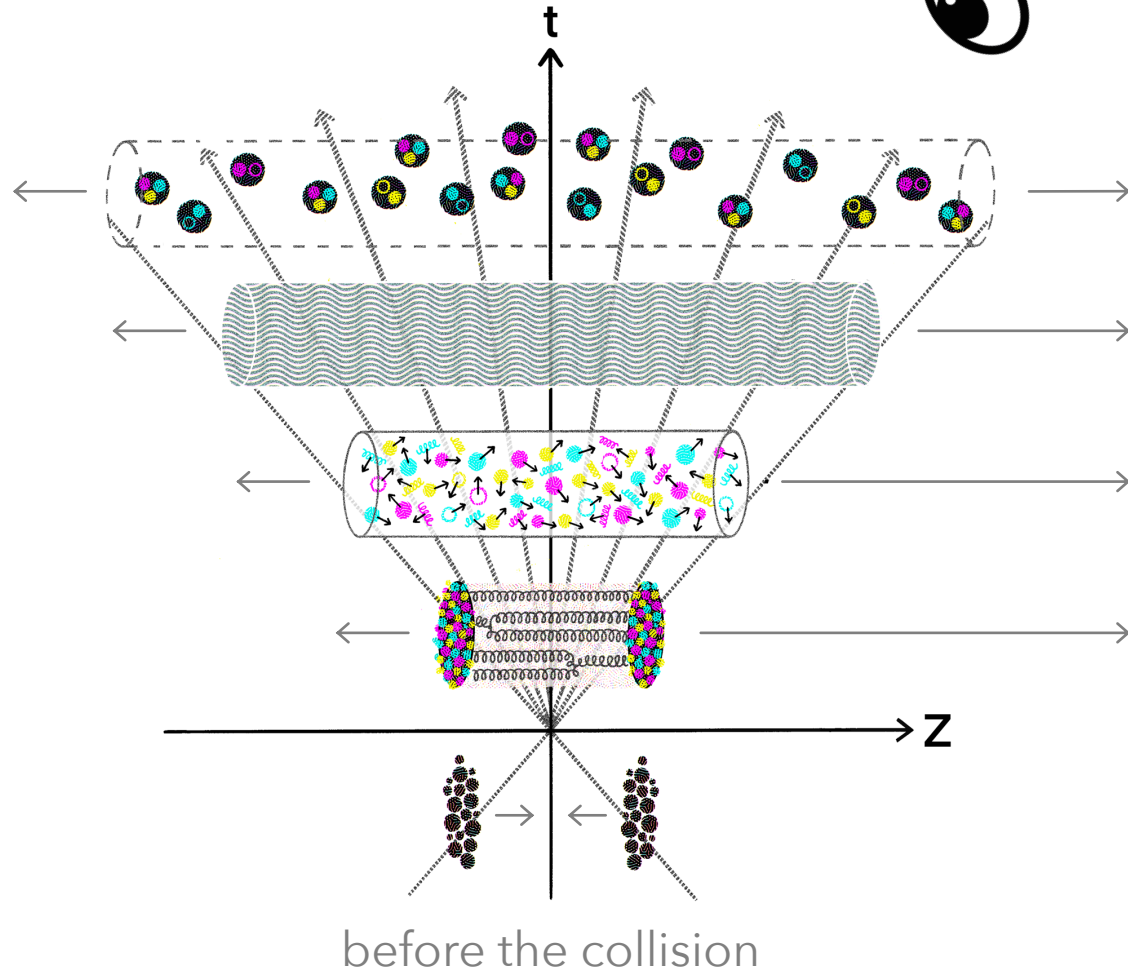
hydrodynamic Quark-Gluon Plasma (QGP)

non-equilibrium matter

glasma (strong color fields)

Matter produced in HIC undergoes multiphase evolution

Heavy-ion collisions



Phases of QCD matter in HIC:

hadron gas

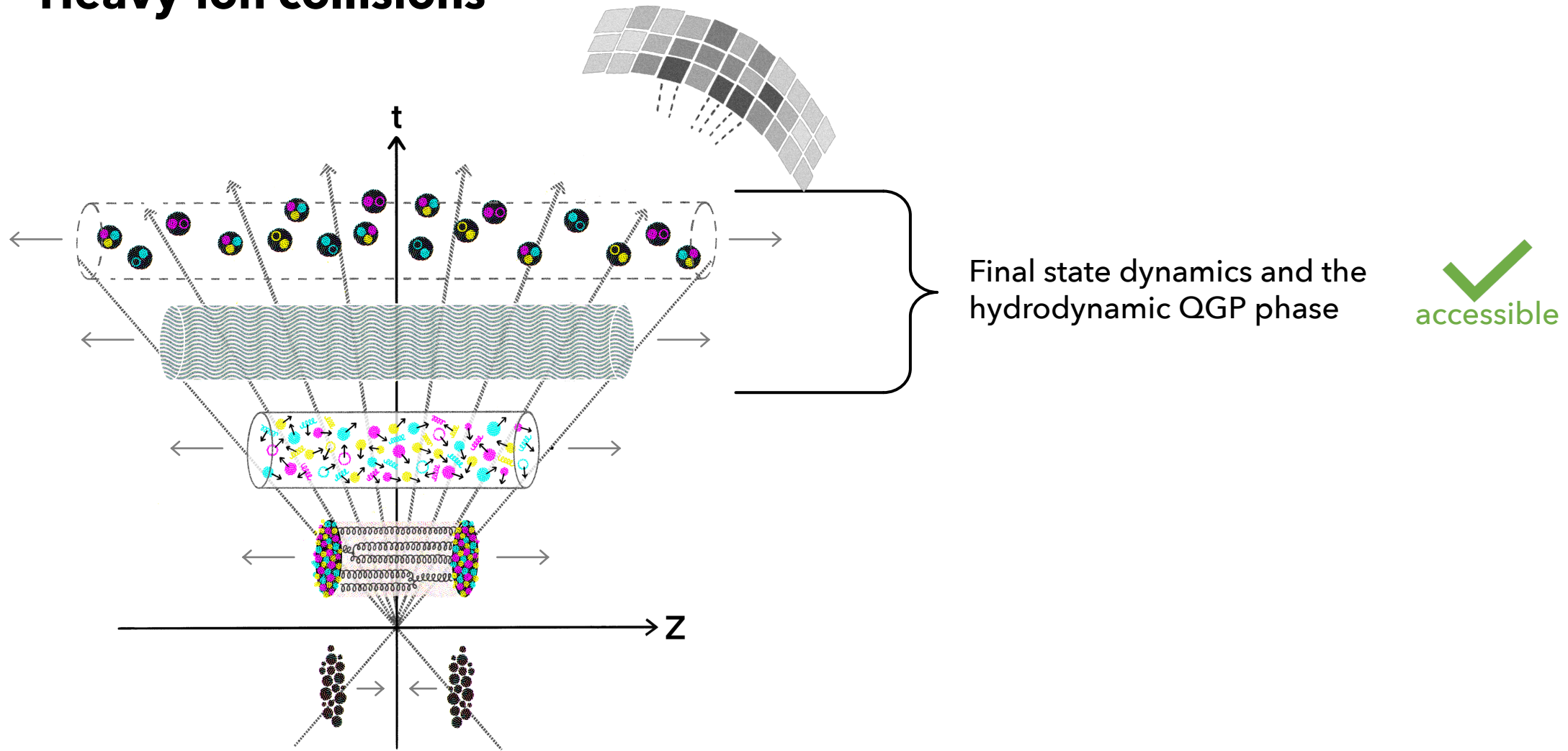
hydrodynamic Quark-Gluon Plasma (QGP)

non-equilibrium matter

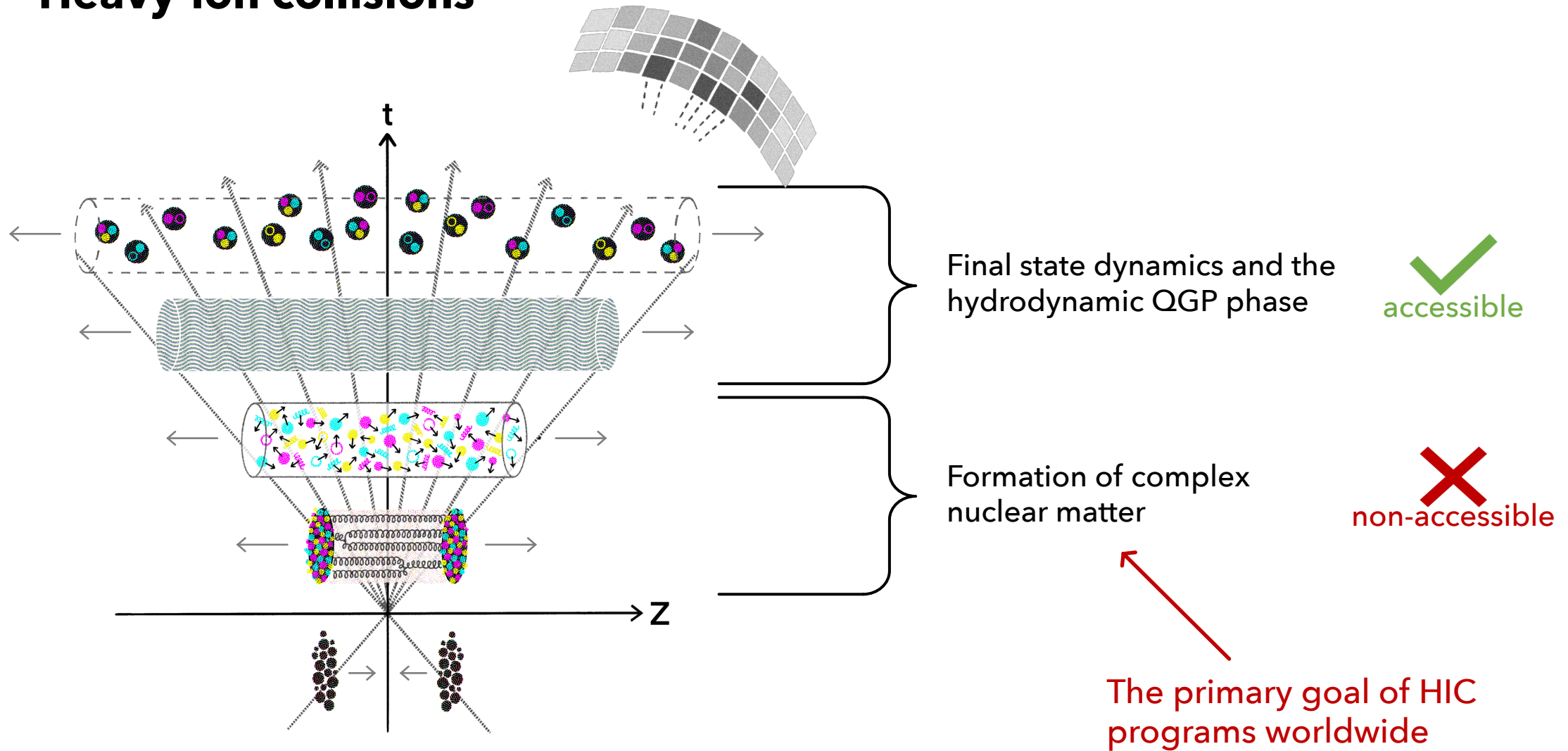
glasma (strong color fields)

Matter produced in HIC undergoes multiphase evolution

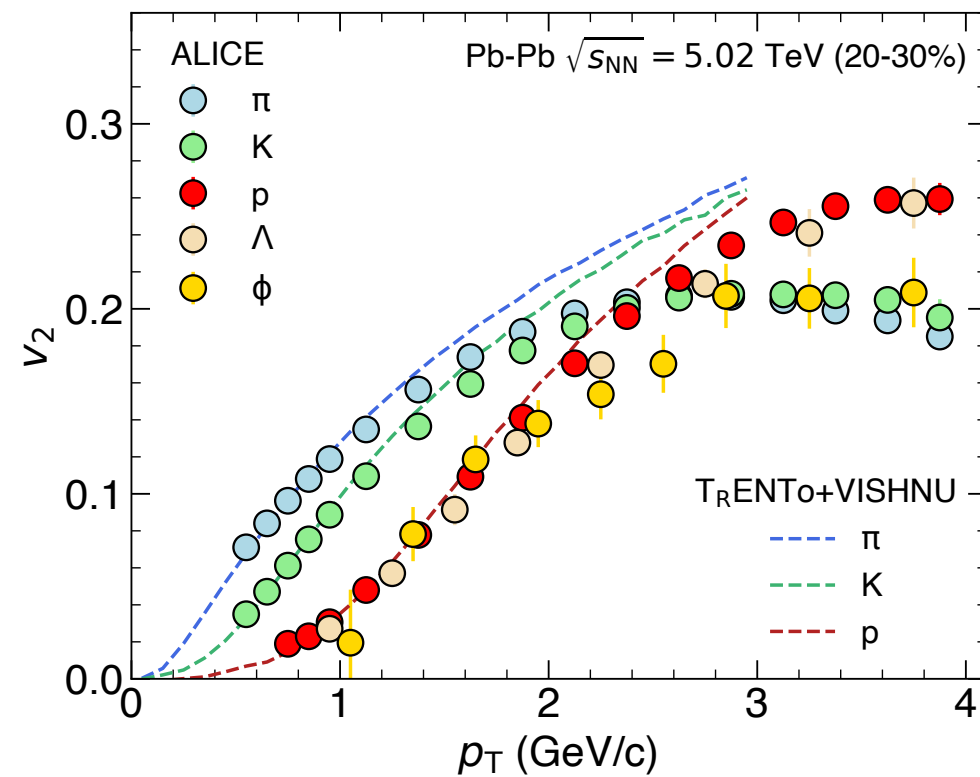
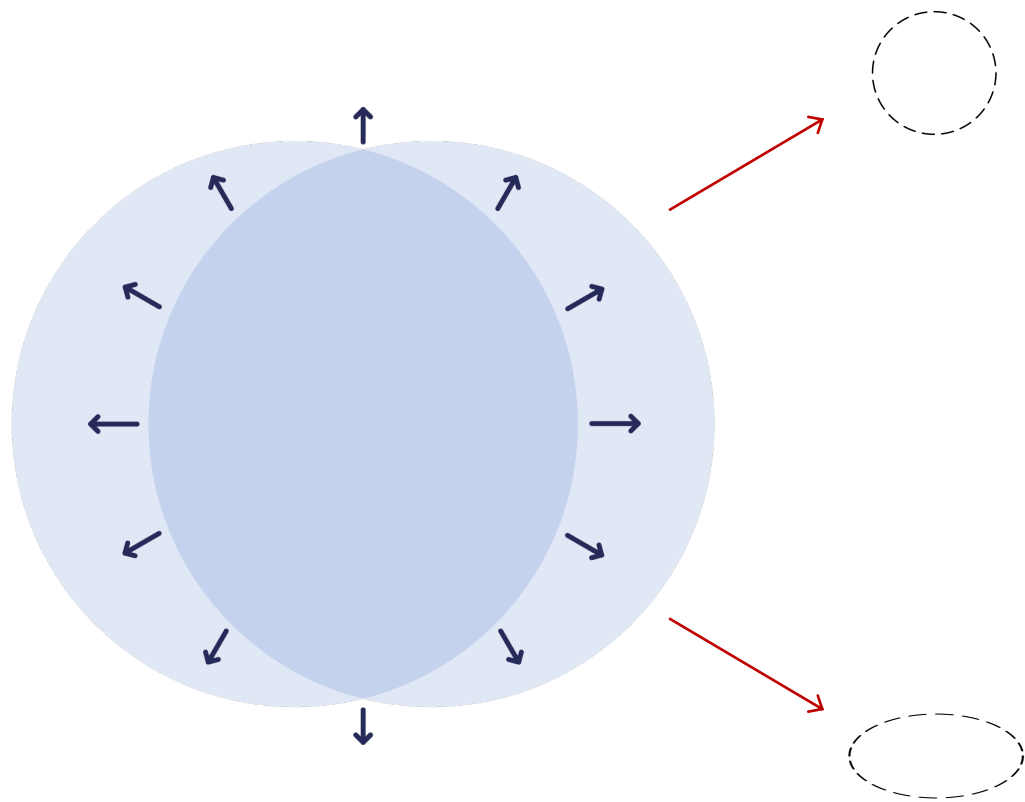
Heavy-ion collisions



Heavy-ion collisions

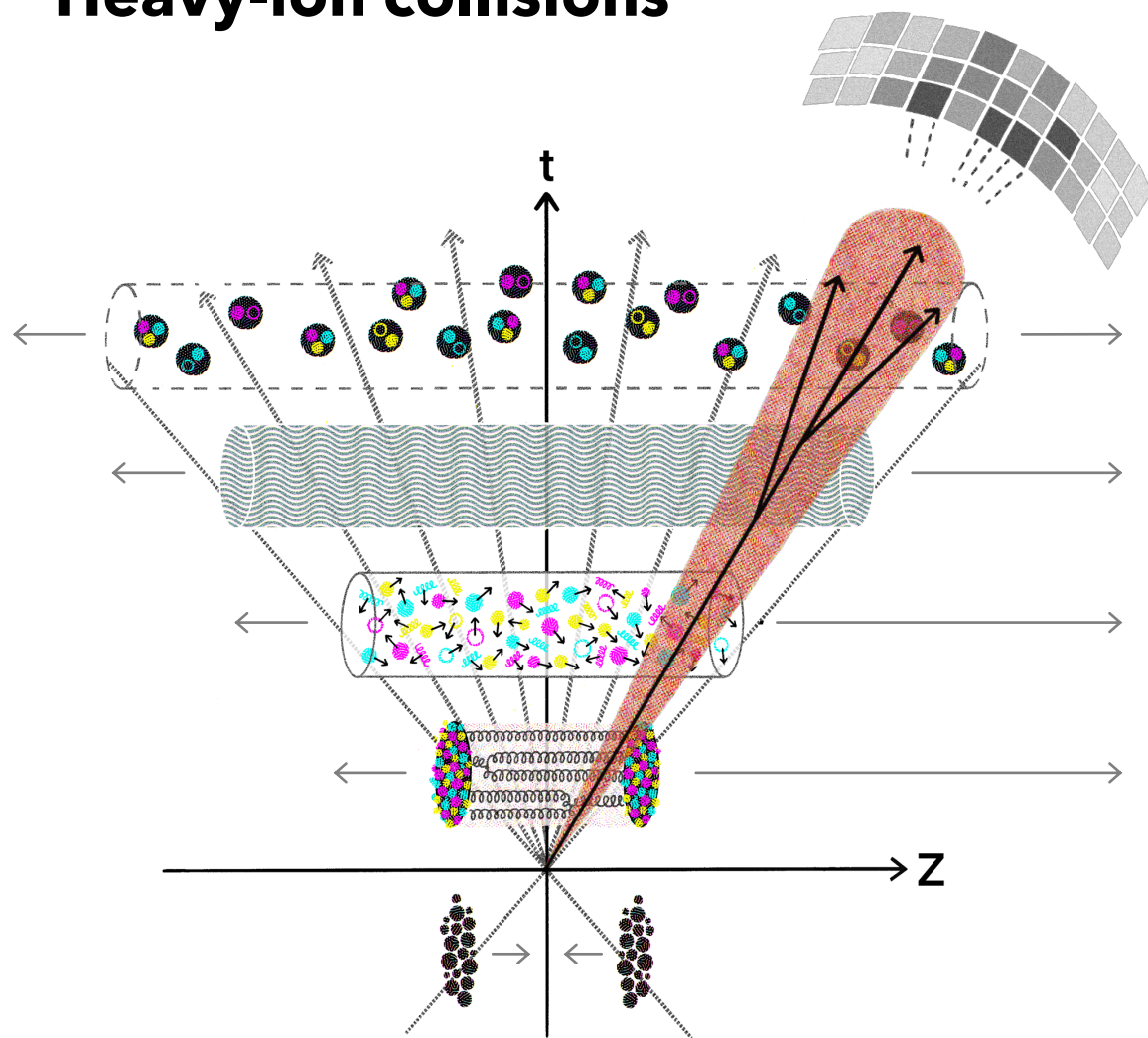


Probes of matter



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

Heavy-ion collisions



Phases of QCD matter in HIC:

hadron gas

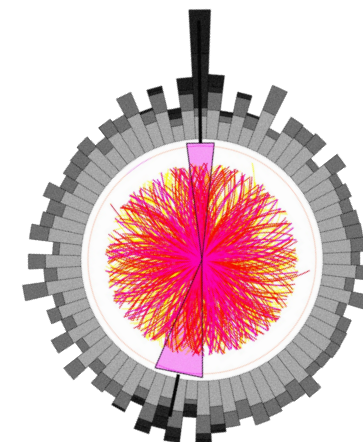
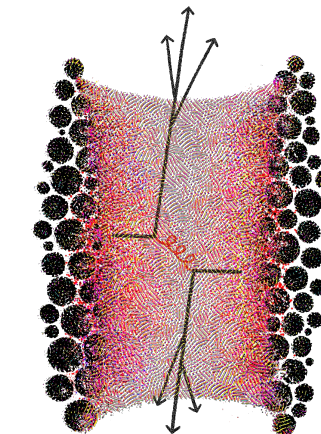
hydrodynamic QGP

non-equilibrium matter

glasma (strong color fields)

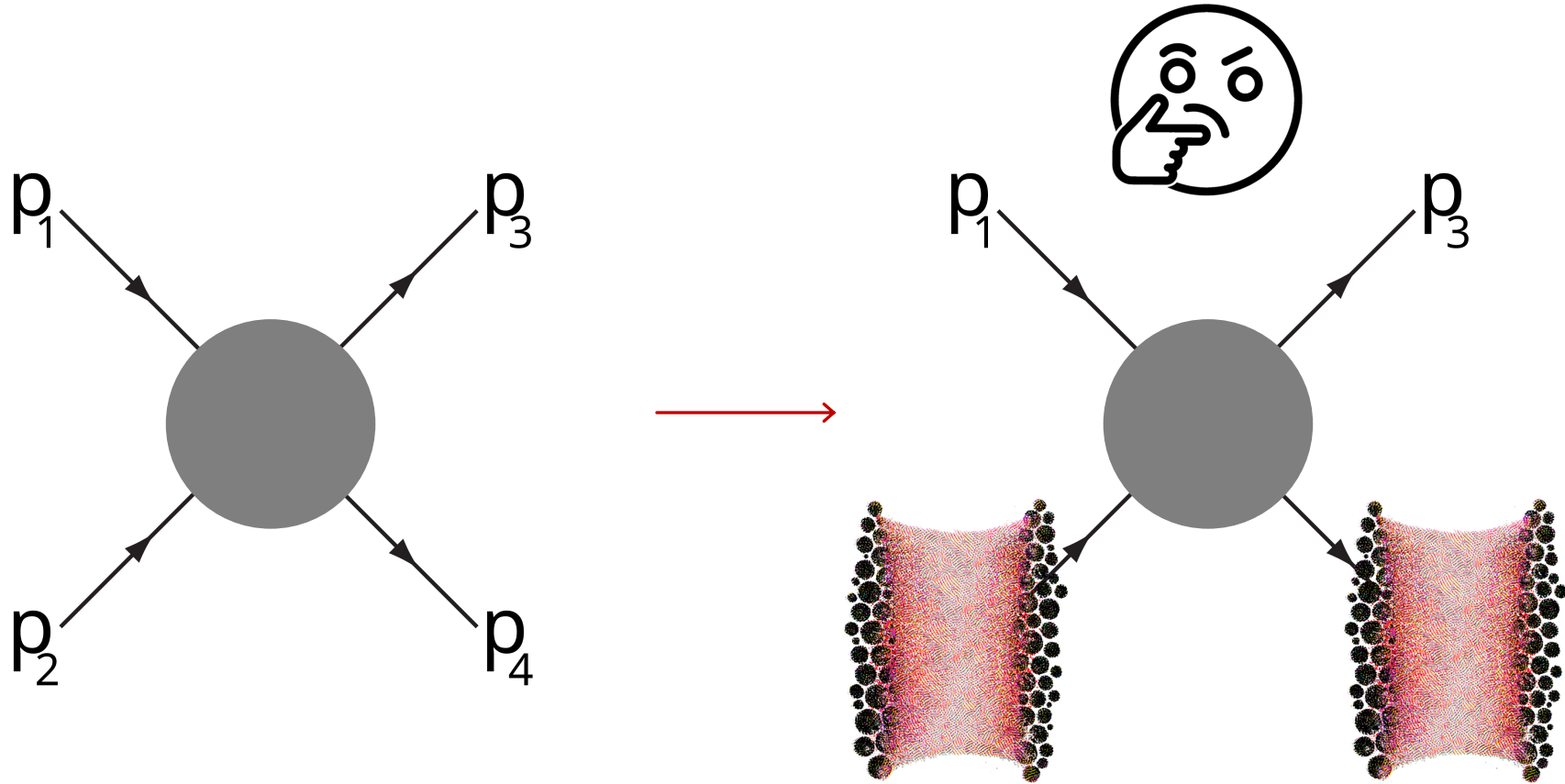
Jets are a tool to probe
the early evolution of matter

jet quenching



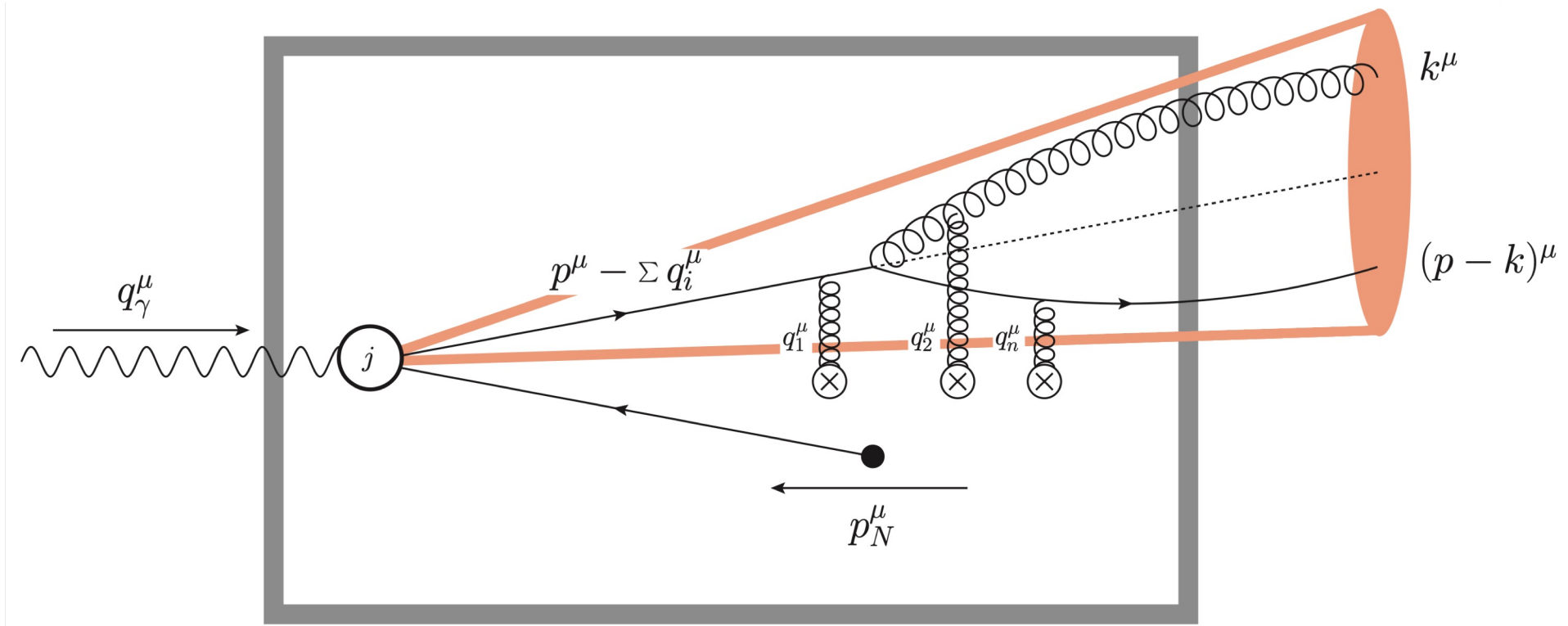
jets lose energy propagating
through nuclear matter

Jet quenching formalisms



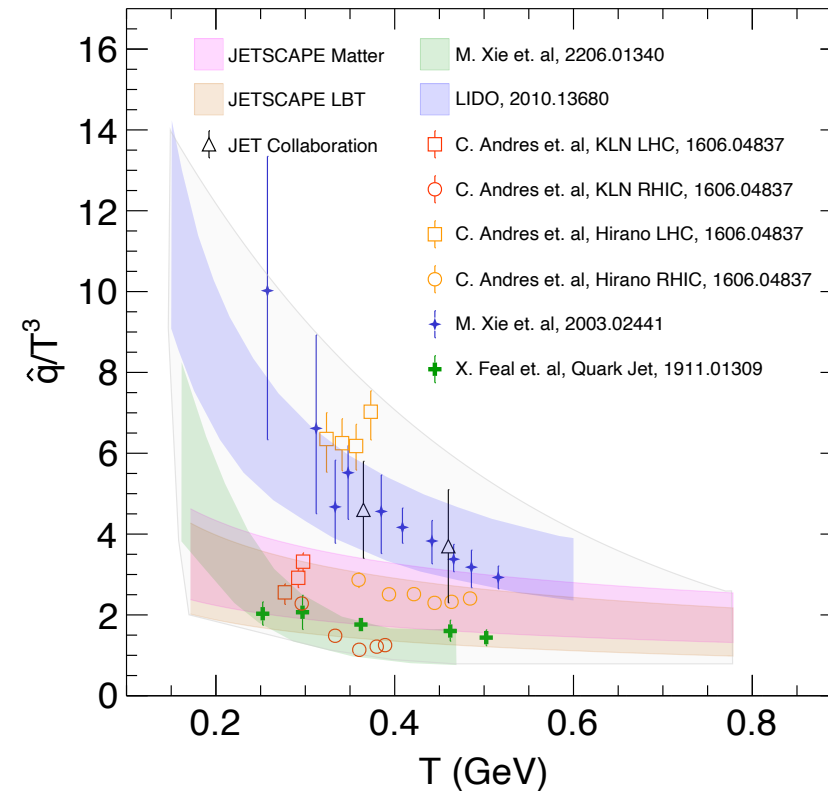
Jet quenching formalisms

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

Energy correlators

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)

An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \rightarrow \text{hadrons}$ at energy W . It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

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

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

Energy correlators

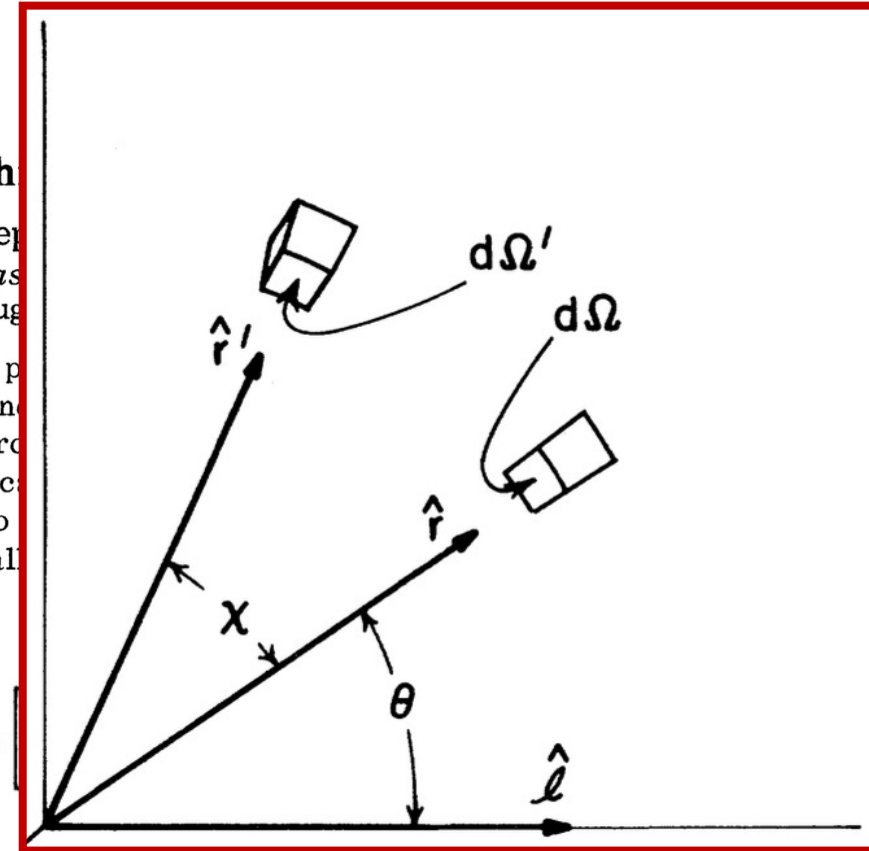
Energy Correlations in Electron-Positron Annihilation

C. Louis Basham, Lowell S. Brown, Stephen J. Brodsky
Department of Physics, University of Washington
 (Received 21 August 1979)

An experimental measure is presented for a part of the energy correlator. This measure involves the asymmetry in the energy of hadrons produced in the process $e^+e^- \rightarrow \text{hadrons}$. The reasons: It is reliably calculable in asymptotic QCD, and the corrections due to nonperturbative effects vanish rapidly (order $1/W^2$) in the limit of large energy. It is straightforward to determine experimentally.

$$\frac{d\Sigma}{d\Omega} = \sum_{N=2}^{\infty} \int \sum_{a=1}^N E_a^{-1} d^3p_a \frac{d^N\sigma}{E_1^{-1} d^3p_1 \cdots E_N^{-1} d^3p_N} S_N$$

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



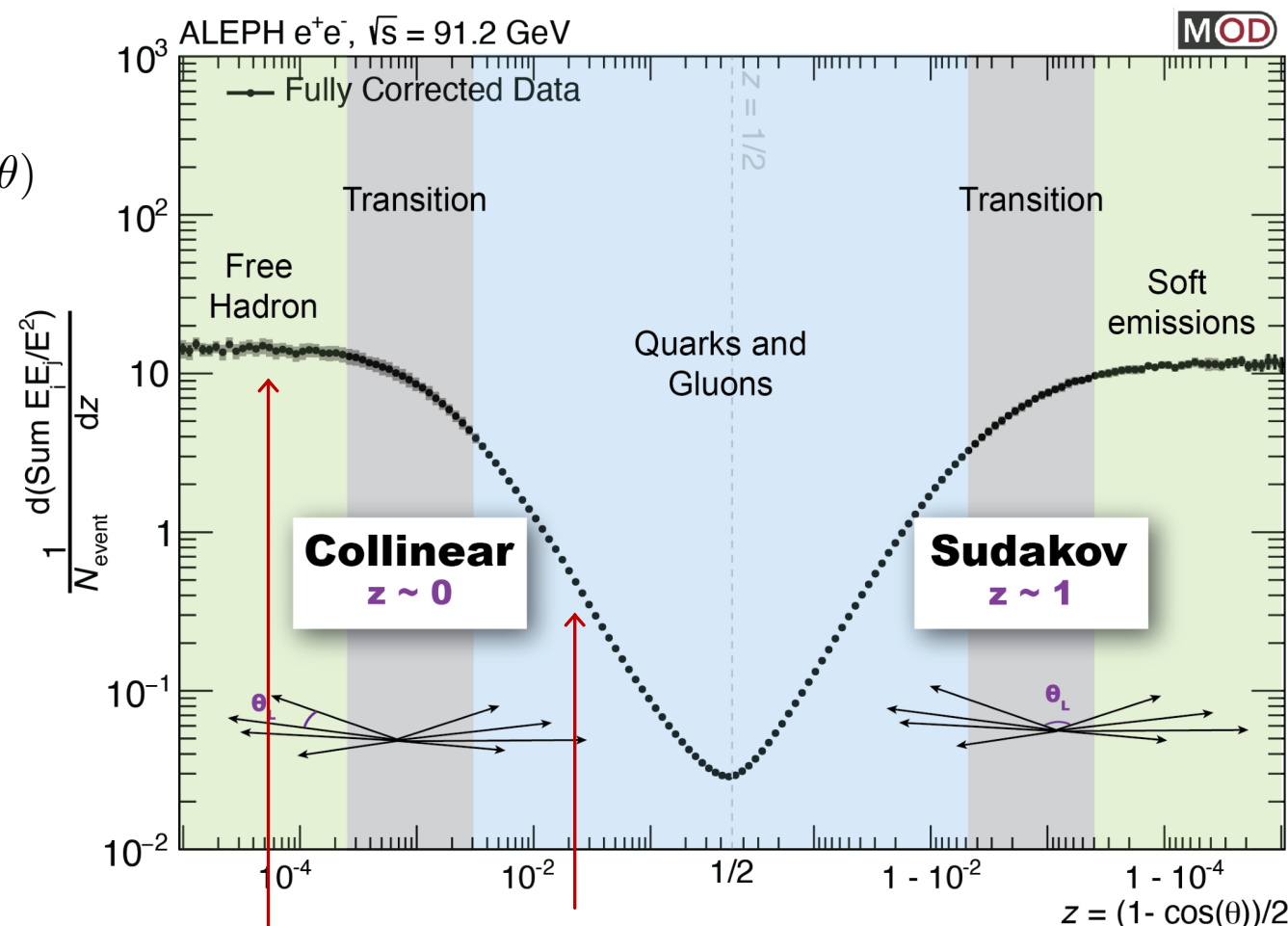
Energy correlators

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



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

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



2025 HB - Finalization of Result

$$\frac{d\Sigma}{d\theta} = \frac{1}{\theta^{1-\gamma(3)}} + \dots$$

$$\frac{d\Sigma}{d\theta} \sim \theta + \dots$$

EECs in HICs

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

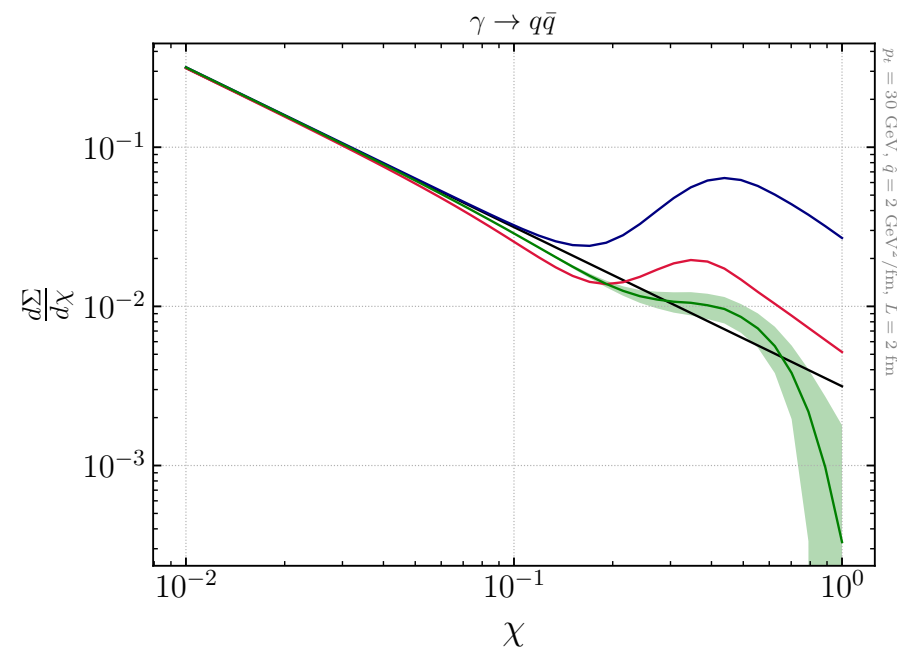
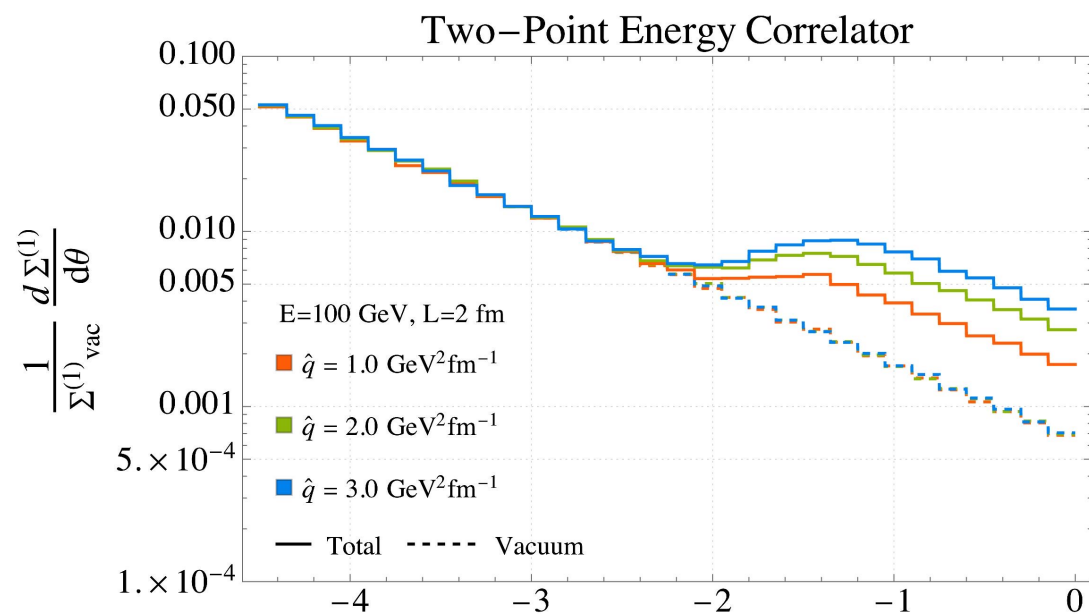
$$\frac{d\Sigma}{d \cos \theta} = \frac{1}{p_t^2} \int_{n_1, n_2} \langle \mathcal{E}(n_1) \mathcal{E}(n_2) \rangle \delta(n_1 \cdot n_2 - \cos \theta)$$

- Using some semi-realistic state (extremely hard)
- Focusing on a few hard particles (of the jet) with matter being a background
- Medium response to the jet
- Focusing on the soft particles and their correlations
- ...

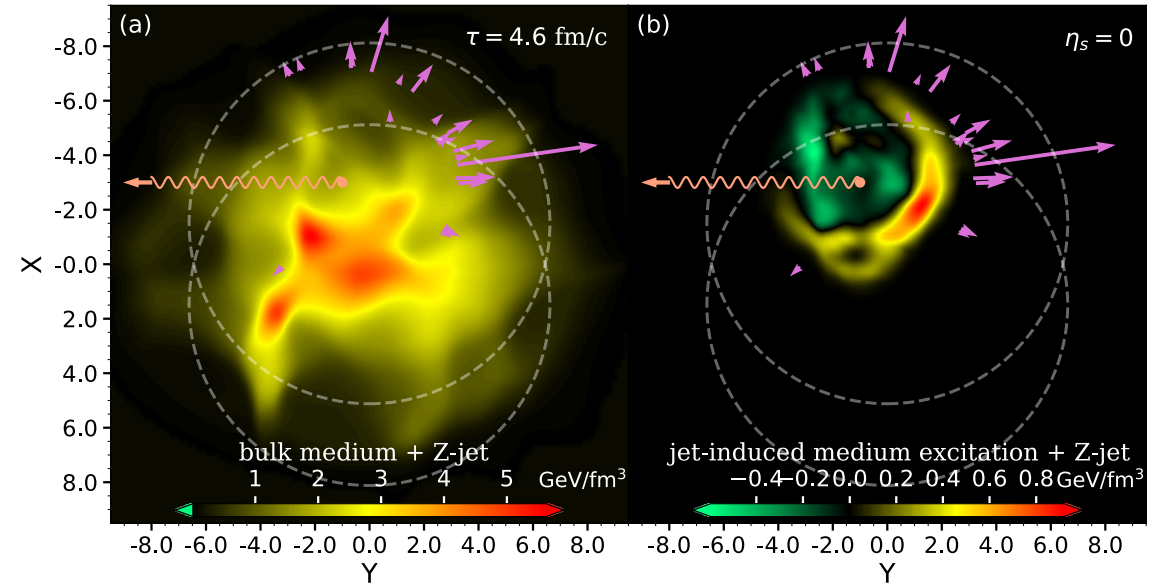
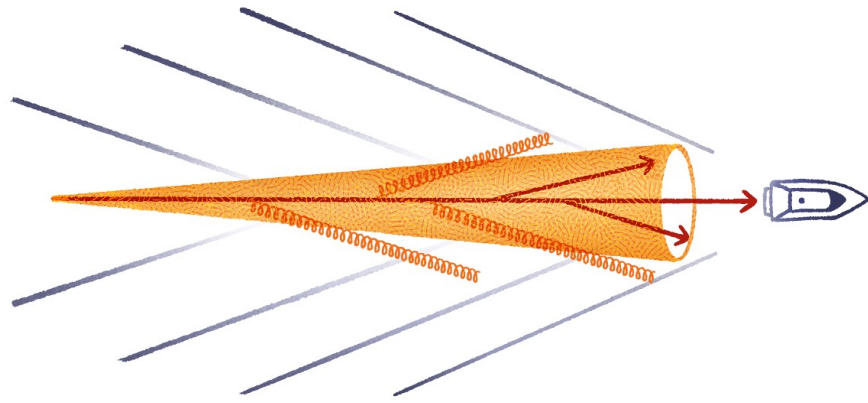
EECs in HICs

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

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



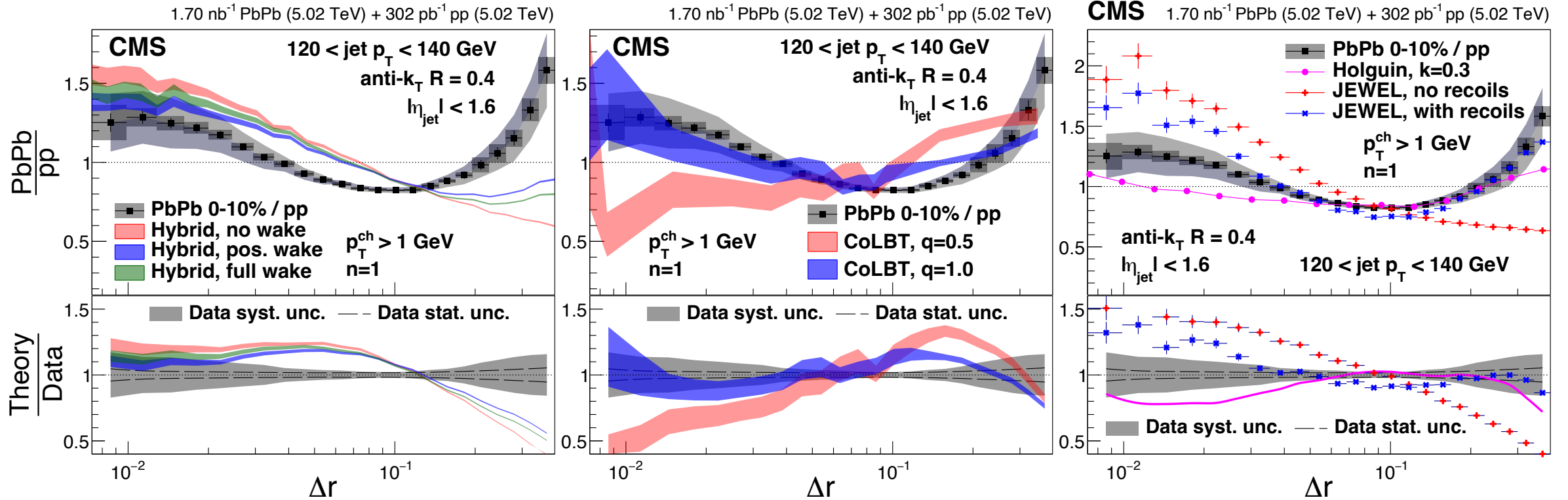
EECs in HICs



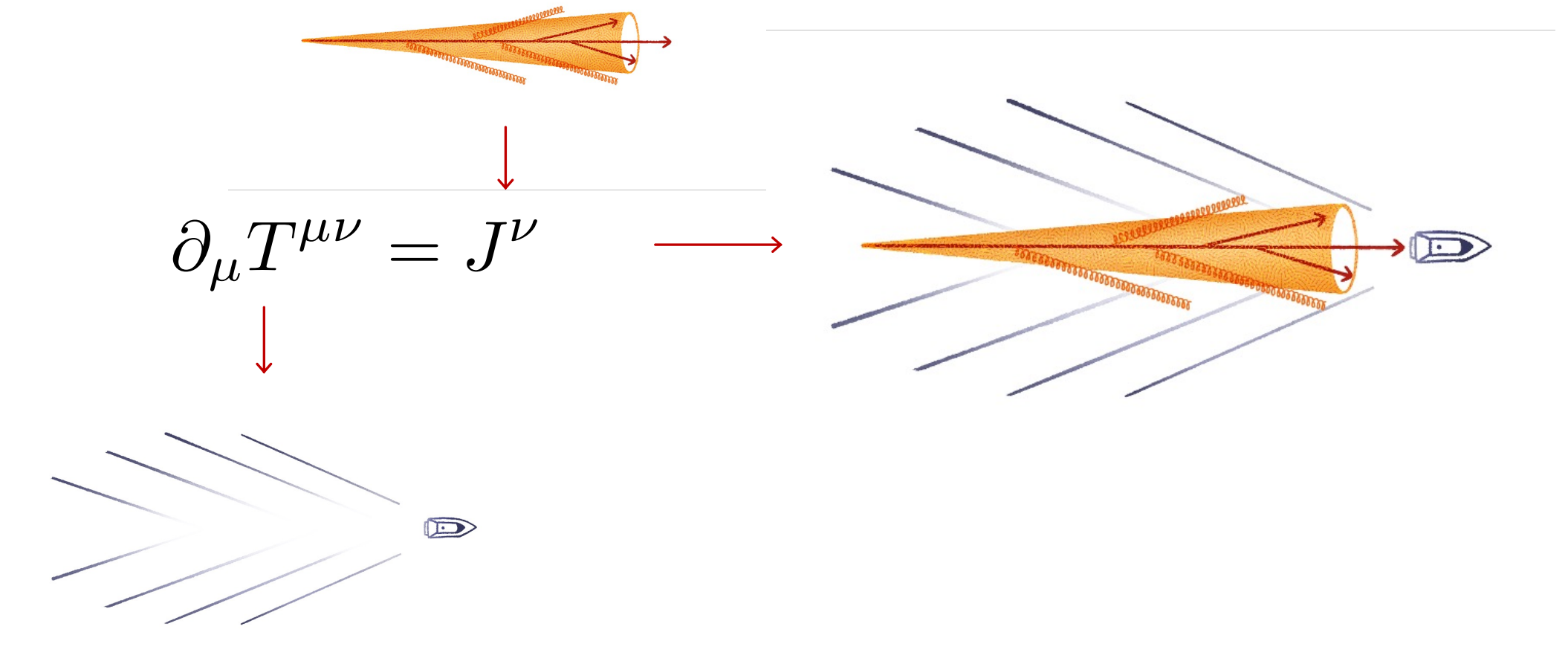
- Renewed interest in the medium response: recent consideration e.g. within CoLBT, JEWEL, Hybrid model
- Experimental needs, see e.g. ALICE, PRC, 2023; ATLAS, PRC, 2025; CMS, 2025

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

EECs in HICs



Probing the response



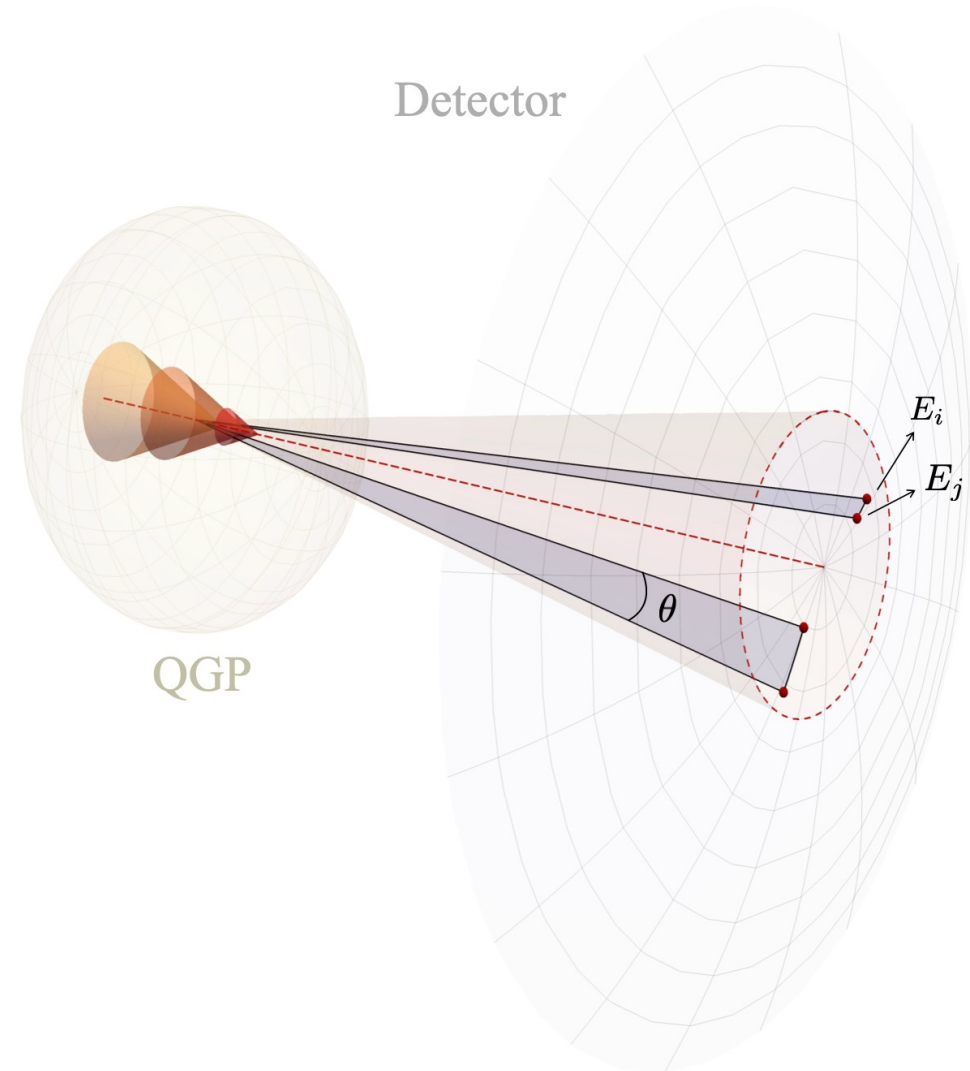
Probing the response

- 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?**

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

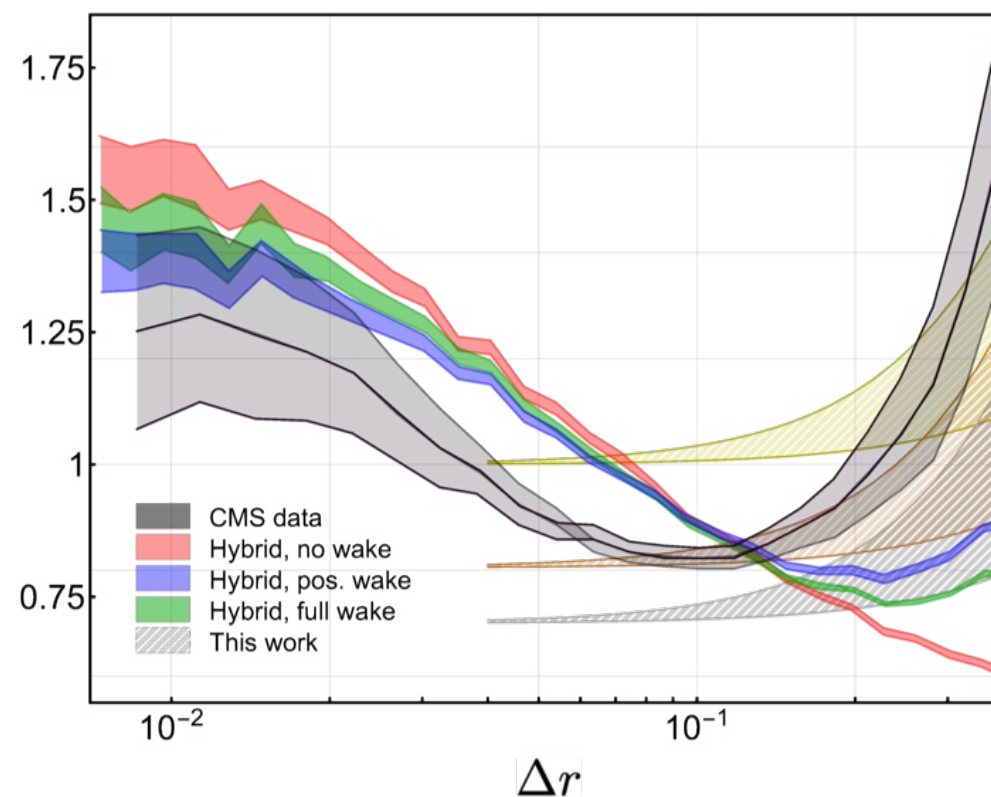
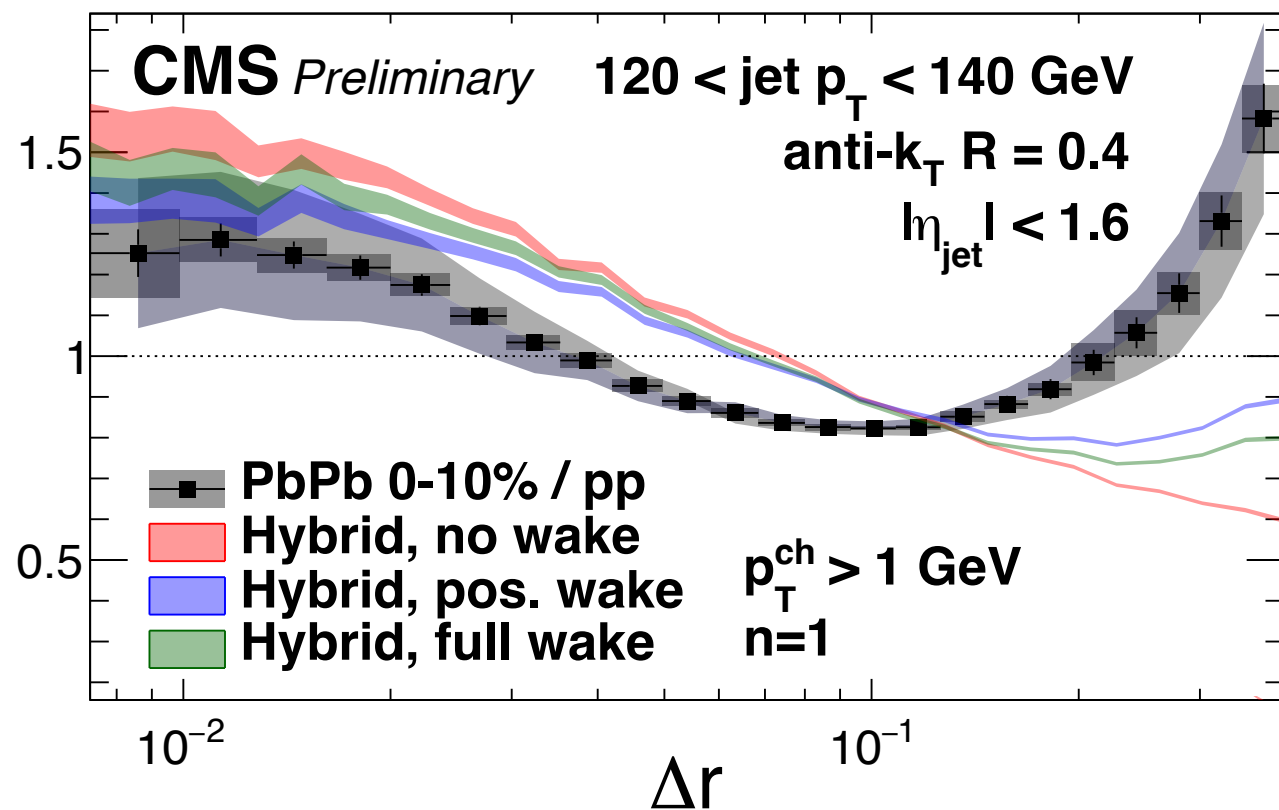


$$\mathcal{E}(\mathbf{n}_1) \mathcal{E}(\mathbf{n}_2)$$

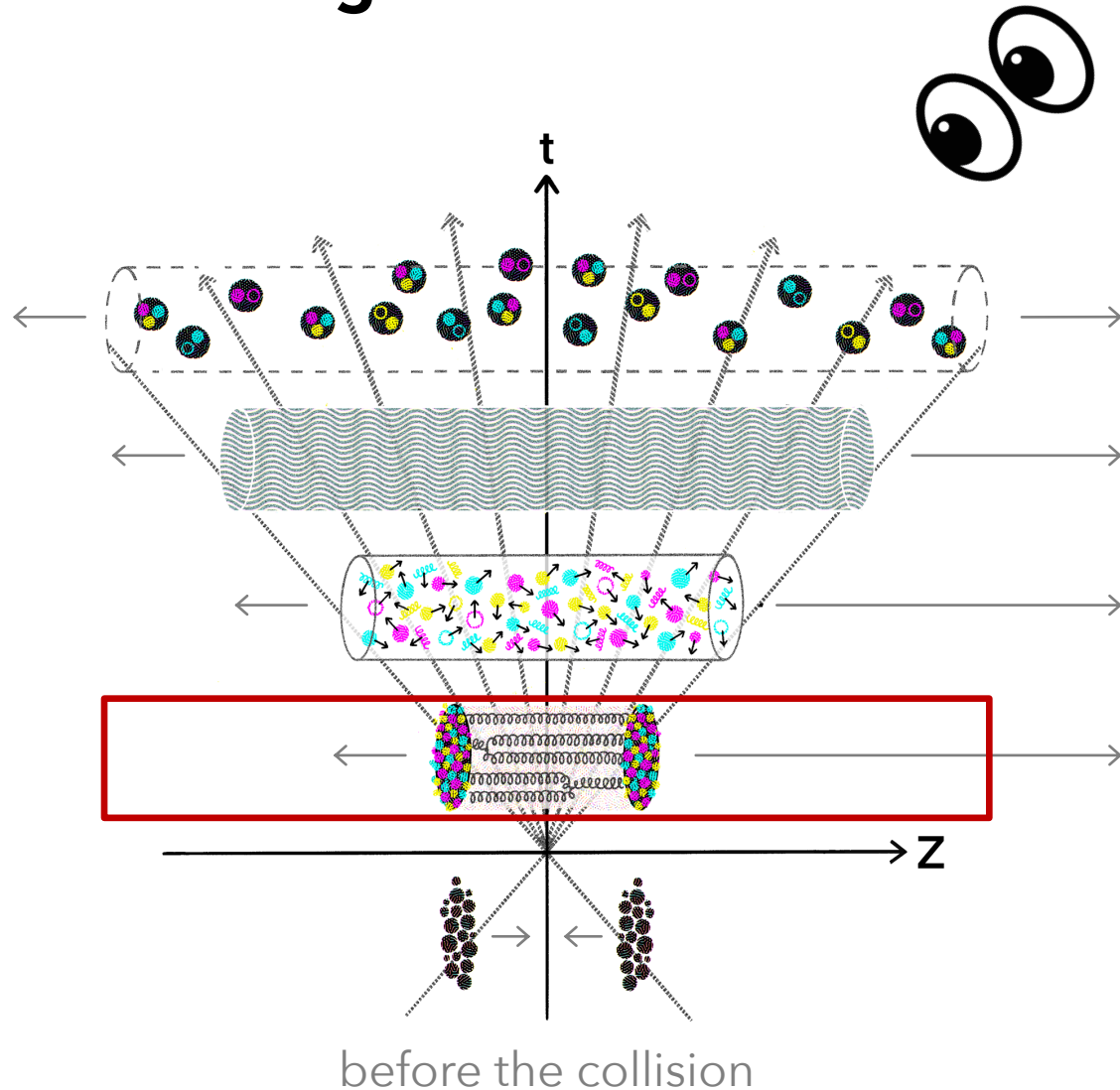


Probing the response

1.70 nb⁻¹ PbPb (5.02 TeV) + 302 pb⁻¹ pp (5.02 TeV)



Initial stages in HICs



Phases of QCD matter in HIC:

hadron gas

hydrodynamic Quark-Gluon Plasma (QGP)

non-equilibrium matter

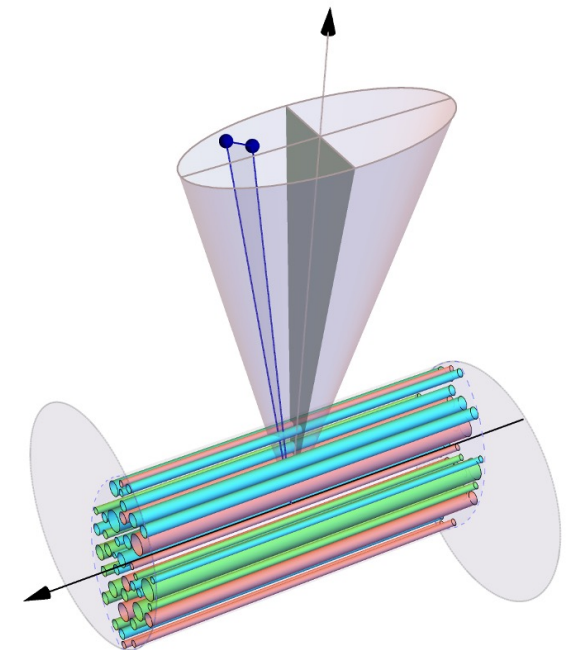
glasma (strong color fields)

Matter produced in HIC undergoes
multiphase evolution

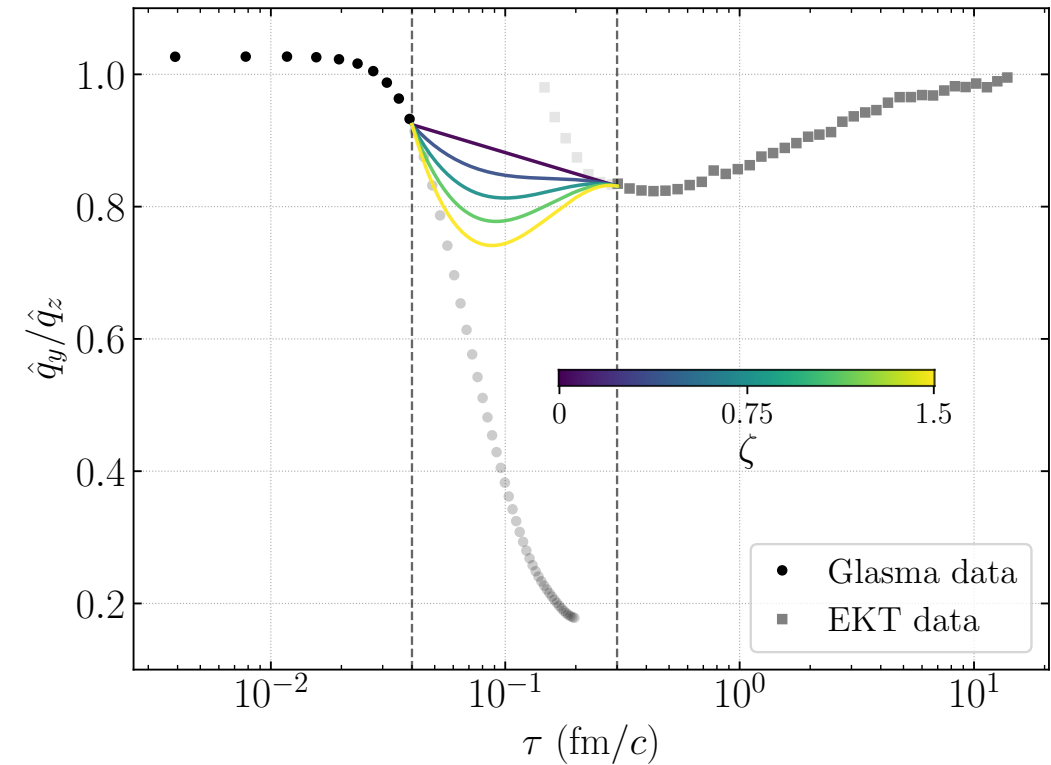
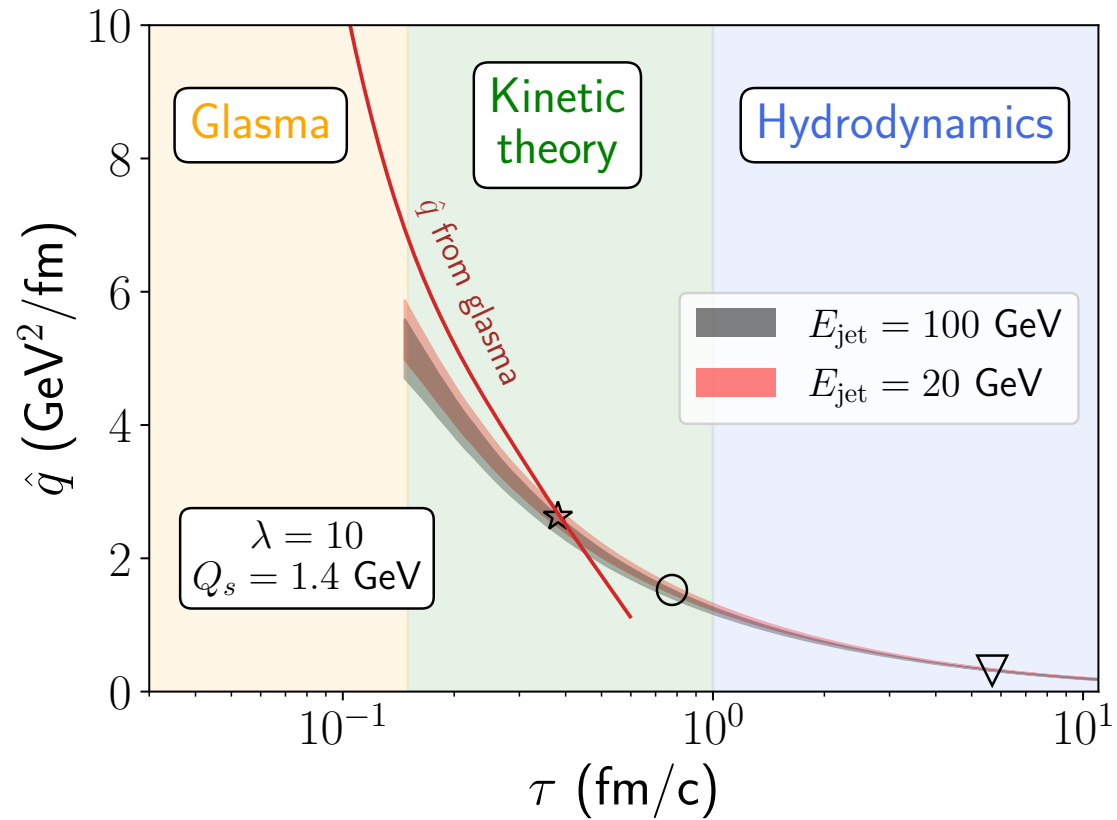
Initial stages in HICs

- $\hat{q}$ 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 $T \sim 200$ MeV is $\hat{q} \sim 0.12 \text{ GeV}^2/\text{fm}$
- Historically, the glasma phase was assumed less relevant, but a series of recent works indicate that $\hat{q} \geq 5 \text{ GeV}^2/\text{fm}$ during the first $0.3 \text{ fm}/c$
- The simulations of the non-equilibrium dynamics within kinetic theory show continuity of $\hat{q}$ consistent with these glasma phase values
- Similarly strong effects are also observed for heavy quarks

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



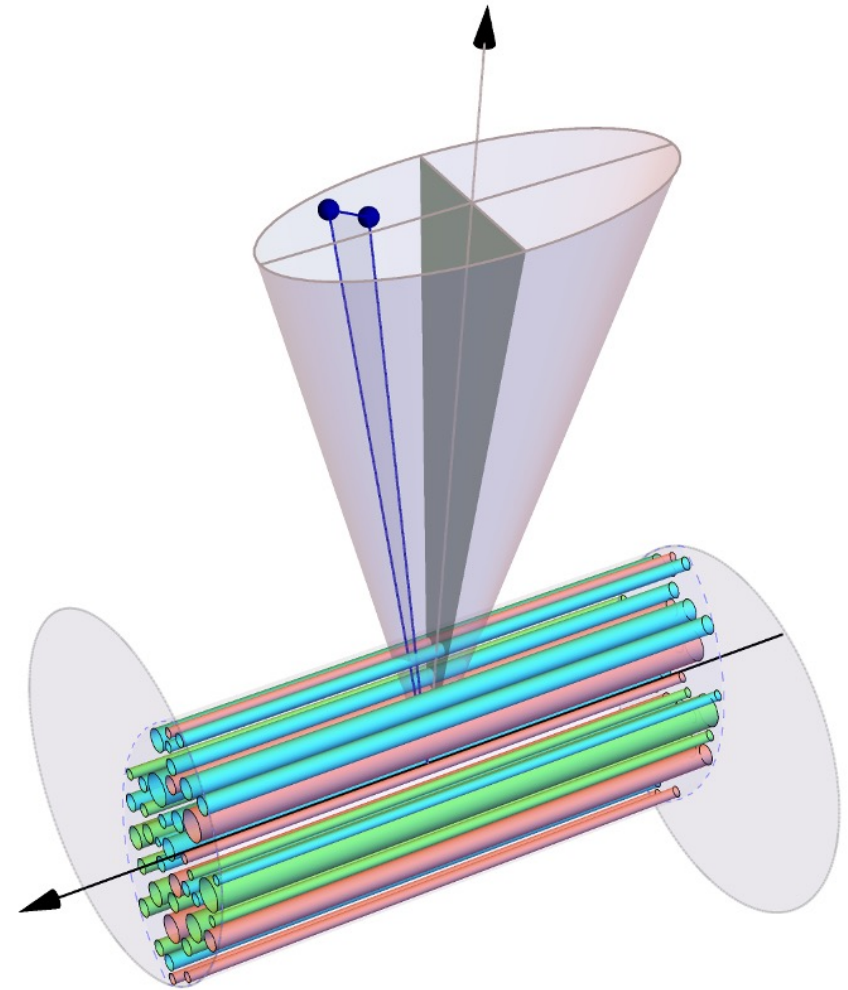
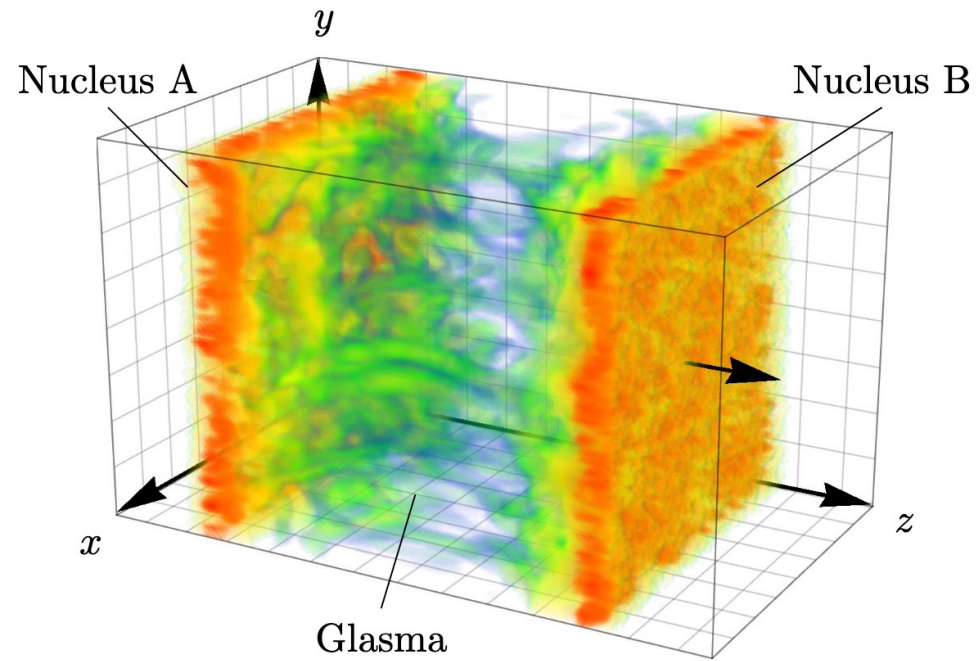
Initial stages in HICs



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

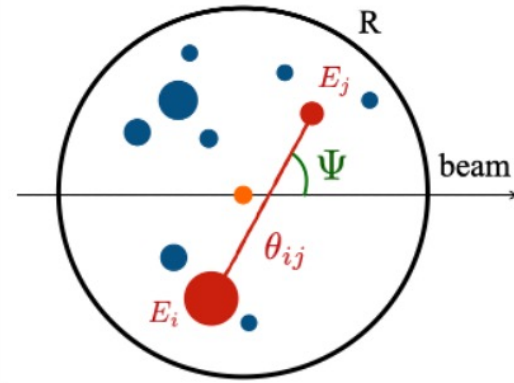
EECs in initial stages

from a paper by A. Ipp et al.



EECs in initial stages

$$\left. \frac{1}{\sin \chi \sin \Psi} \frac{d\Sigma}{d\chi d\Psi} \right|_{\eta=0} = \int_{\mathbf{n}_1, \mathbf{n}_2} \frac{\langle \mathcal{E}(\mathbf{n}_1) \mathcal{E}(\mathbf{n}_2) \rangle}{p_t^2} \delta(\mathbf{n}_1 \cdot \mathbf{n}_2 - \cos \chi) \delta \left(\frac{\mathbf{n}_1 - \mathbf{n}_2}{|\mathbf{n}_1 - \mathbf{n}_2|} \cdot \mathbf{b} - \cos \Psi \right),$$



$$\left. \frac{1}{\sin \chi \sin \Psi} \frac{d\Sigma}{d\chi d\Psi} \right|_{\eta=0} = \sum_{i \neq j} \frac{E_i E_j}{p_t^2} \delta(\cos \theta_{ij} - \cos \chi) \delta \left(\frac{\theta_{jb} - \theta_{ib}}{\theta_{ij}} - \cos \Psi \right),$$

EECs in initial stages

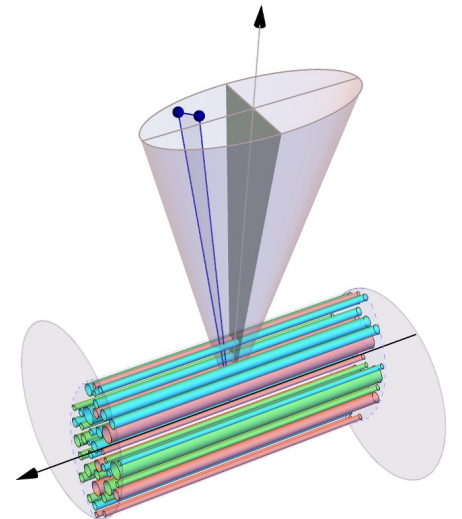
$$\left. \frac{1}{\sin \chi \sin \Psi} \frac{d\Sigma}{d\chi d\Psi} \right|_{\eta=0} = \int_{\mathbf{n}_1, \mathbf{n}_2} \frac{\langle \mathcal{E}(\mathbf{n}_1) \mathcal{E}(\mathbf{n}_2) \rangle}{p_t^2} \delta(\mathbf{n}_1 \cdot \mathbf{n}_2 - \cos \chi) \delta \left(\frac{\mathbf{n}_1 - \mathbf{n}_2}{|\mathbf{n}_1 - \mathbf{n}_2|} \cdot \mathbf{b} - \cos \Psi \right),$$

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

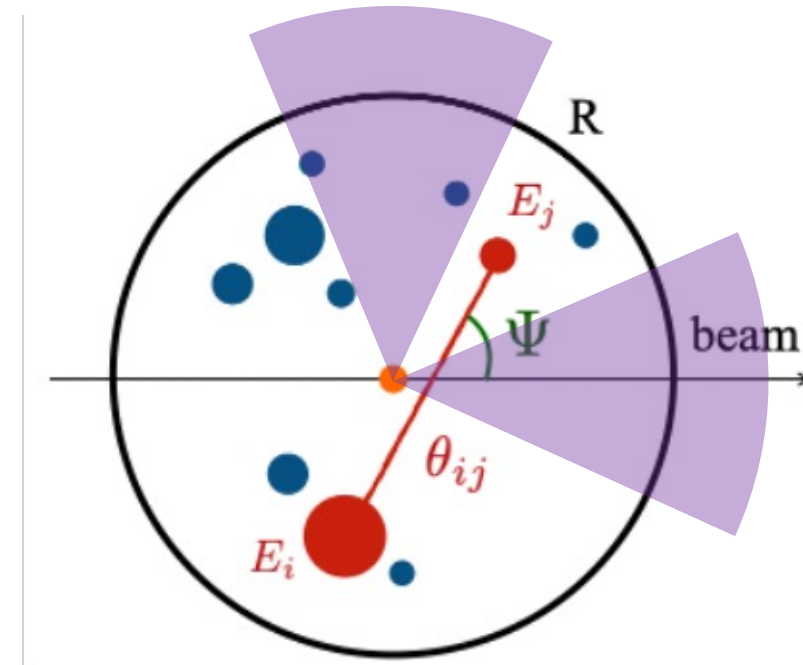
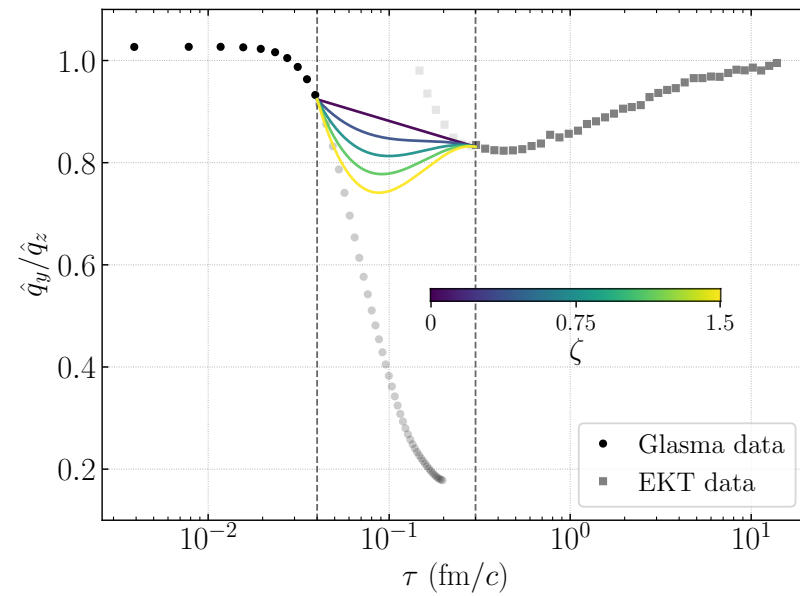
$$\frac{d\Sigma}{d\chi d\Psi} = \sum_{k=1} (c_{\tau, 0} + b_{\tau > 2, 0} + a_{\tau > 2, 0}) \chi^{\tau-3}$$

$$+ \sum_{k=2} (c_{\tau, 2} + b_{\tau > 4, 2} + a_{\tau > 4, 2}) \chi^{\tau-3} \cos(2\Psi) \\ + \sum_{k=3} (c_{\tau, 4} + b_{\tau > 6, 4} + a_{\tau > 6, 4}) \chi^{\tau-3} \cos(4\Psi) + \dots$$

- vacuum
- medium-induced
- response

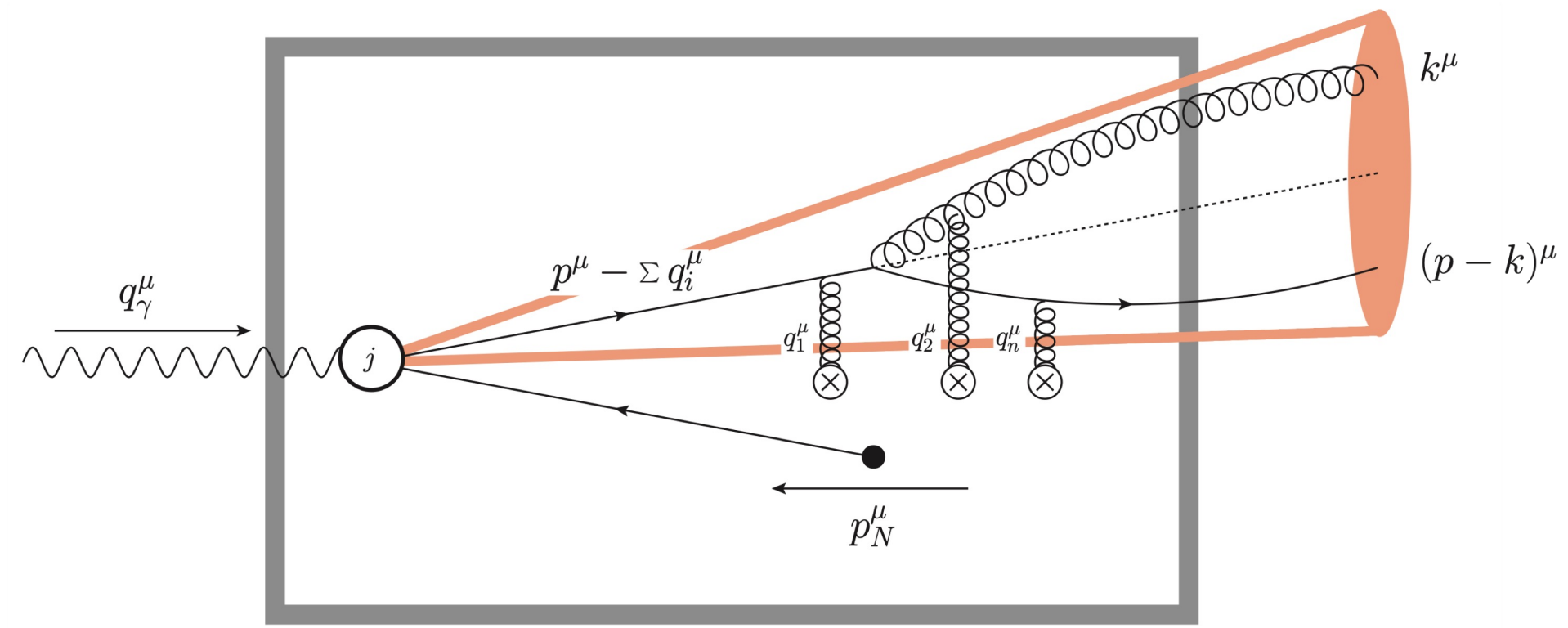


Clover EEC



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

EECs in initial stages



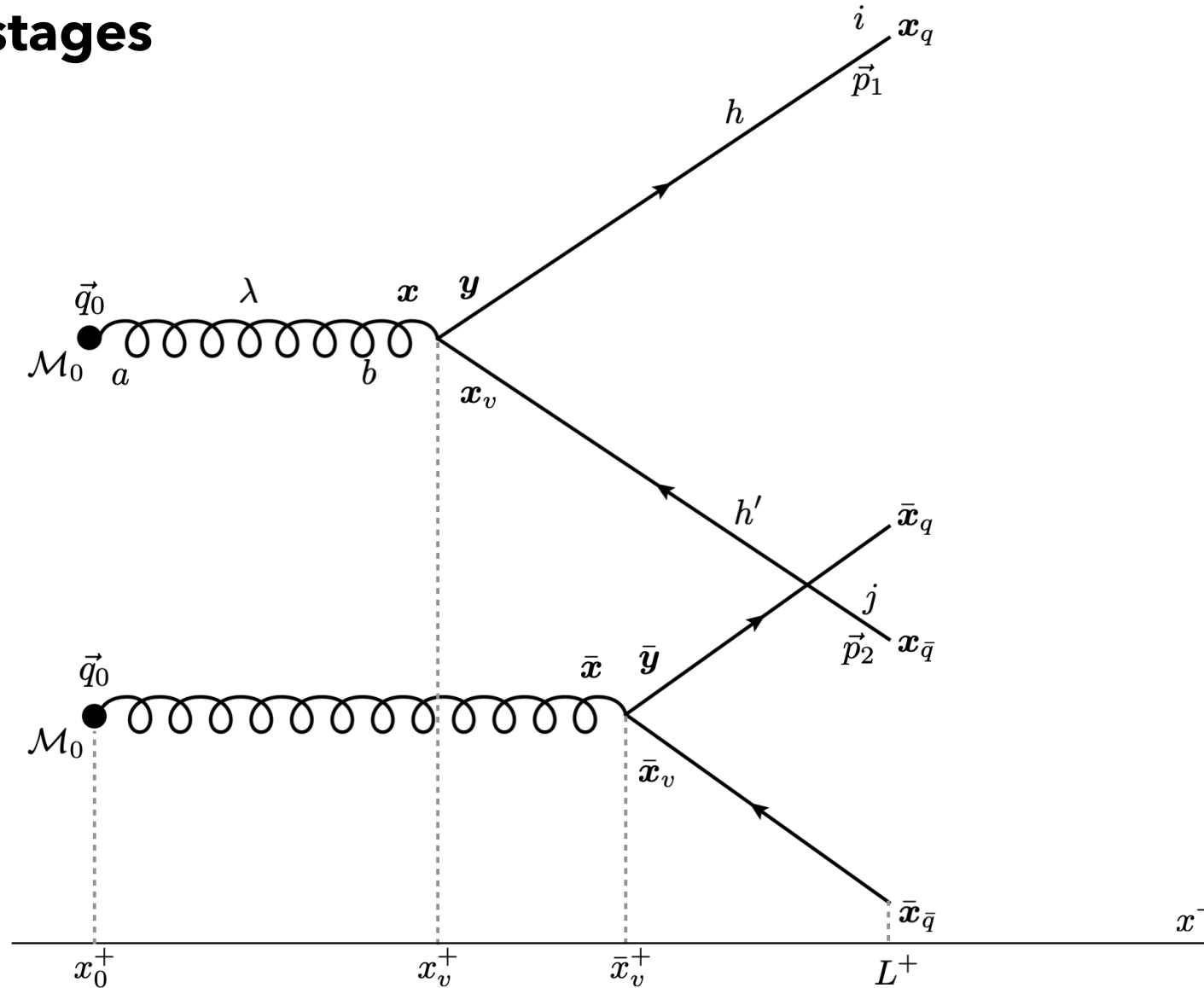
EECs in initial stages

$$\frac{d\Sigma}{d\chi d\Psi} = \int_0^1 dz \, z(1-z) \frac{d\sigma}{\sigma_0 dz d\chi d\Psi}$$

$$\frac{d\Sigma}{d\chi d\Psi} = v_0^{\text{EEC}}(\chi, \xi) + \sum_{n=1}^{\infty} v_{2n}^{\text{EEC}}(\chi, \xi) \cos(2n\Psi)$$

$$v_{2n}^{\text{EEC}}(\chi, \xi) = \frac{1}{\pi} \int_0^{2\pi} d\Psi \, \frac{d\Sigma}{d\chi d\Psi} \cos(2n\Psi)$$

EECs in initial stages



EECs in initial stages

$$(2\pi) \frac{d\sigma^{\text{in-in}}}{\sigma_0 dz d\chi d\Psi} = \frac{\alpha_s}{\pi} T_F \omega \chi 2\text{Re} \int_T -i \frac{\sqrt{c_{1\parallel}} \sqrt{c_{1\perp}}}{\sqrt{c_{3\parallel}} \sqrt{c_{3\perp}}} e^{-i \frac{m_Q^2}{2\omega} \Delta t} \exp \left\{ i \frac{\omega \chi^2}{4} \left(\frac{\cos^2 \Psi}{c_{3\parallel}} + \frac{\sin^2 \Psi}{c_{3\perp}} \right) \right\} \\ \times \left[\frac{1}{2} P_{qg}(z) \left(c_{1\parallel} + c_{1\perp} + \left(\frac{c_{1\parallel} c_{2\parallel}}{c_{3\parallel}} + \frac{c_{1\perp} c_{2\perp}}{c_{3\perp}} \right) + i \frac{\omega \chi^2}{2} \left(\frac{c_{1\parallel} c_{2\parallel}}{c_{3\parallel}^2} \cos^2 \Psi + \frac{c_{1\perp} c_{2\perp}}{c_{3\perp}^2} \sin^2 \Psi \right) \right) + \frac{m_Q^2}{4\omega} \right],$$

$$(2\pi) \frac{d\sigma^{\text{in-out}}}{\sigma_0 dz d\chi d\Psi} = \frac{\alpha_s}{\pi} T_F \frac{\omega \chi}{\chi^2 + 2(m_Q/\omega)^2} 2\text{Re} \int_0^{L^+} dt i \frac{\sqrt{c_{1\parallel}} \sqrt{c_{1\perp}}}{\sqrt{c_{2\parallel}} \sqrt{c_{2\perp}}} e^{-i \frac{m_Q^2}{2\omega} \Delta t} \\ \times \exp \left\{ -i \frac{\omega \chi^2}{4} \left(\frac{\cos^2 \Psi}{c_{2\parallel}} + \frac{\sin^2 \Psi}{c_{2\perp}} \right) \right\} \left[P_{qg}(z) \left(\frac{c_{1\parallel}}{c_{2\parallel}} \cos^2 \Psi + \frac{c_{1\perp}}{c_{2\perp}} \sin^2 \Psi \right) \chi^2 - i \left(\frac{m_Q}{\omega} \right)^2 \right],$$

$$(2\pi) \frac{d\sigma^{\text{out-out}}}{\sigma_0 dz d\chi d\Psi} = \frac{\alpha_s}{\pi} T_F \frac{\chi}{(\chi^2 + 2(m_Q/\omega)^2)^2} \left(P_{qg}(z) \chi^2 + 2 \left(\frac{m_Q}{\omega} \right)^2 \right),$$

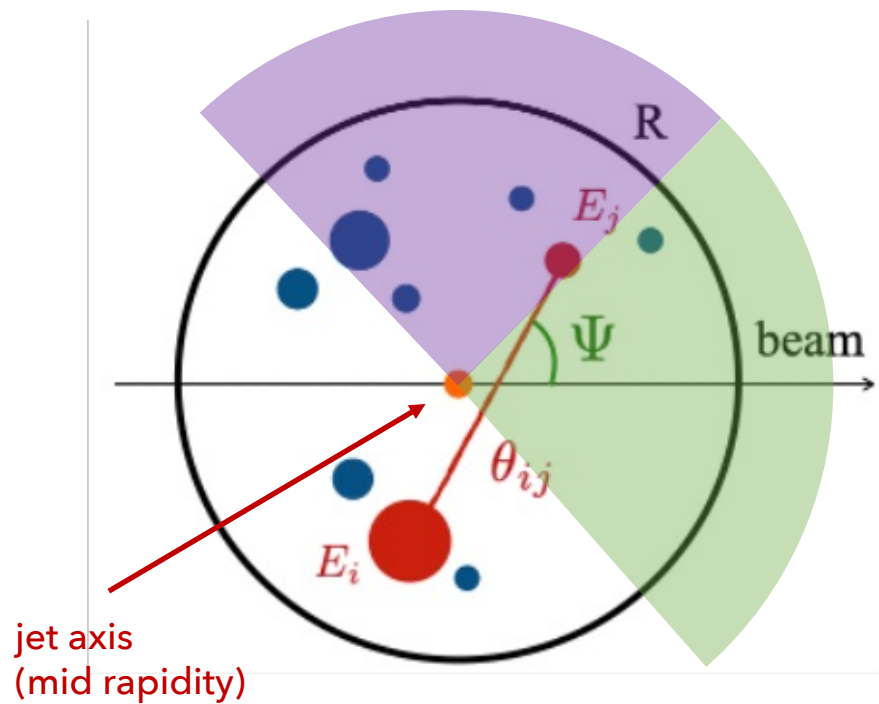
EECs in initial stages

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

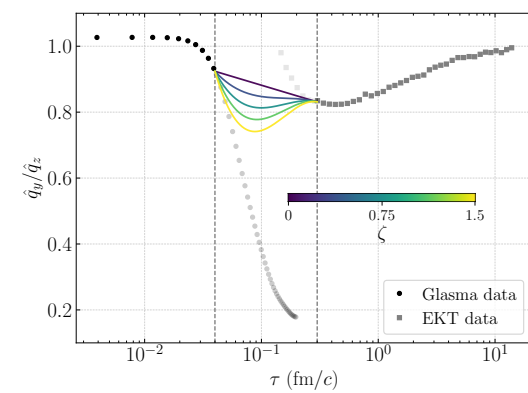
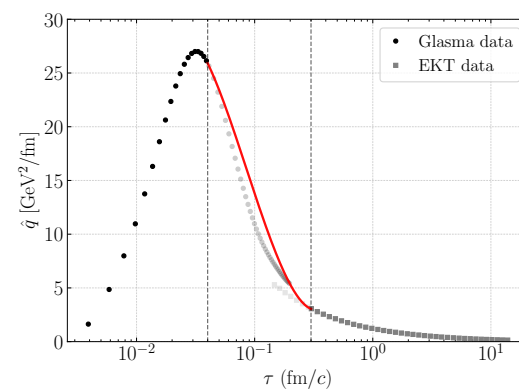
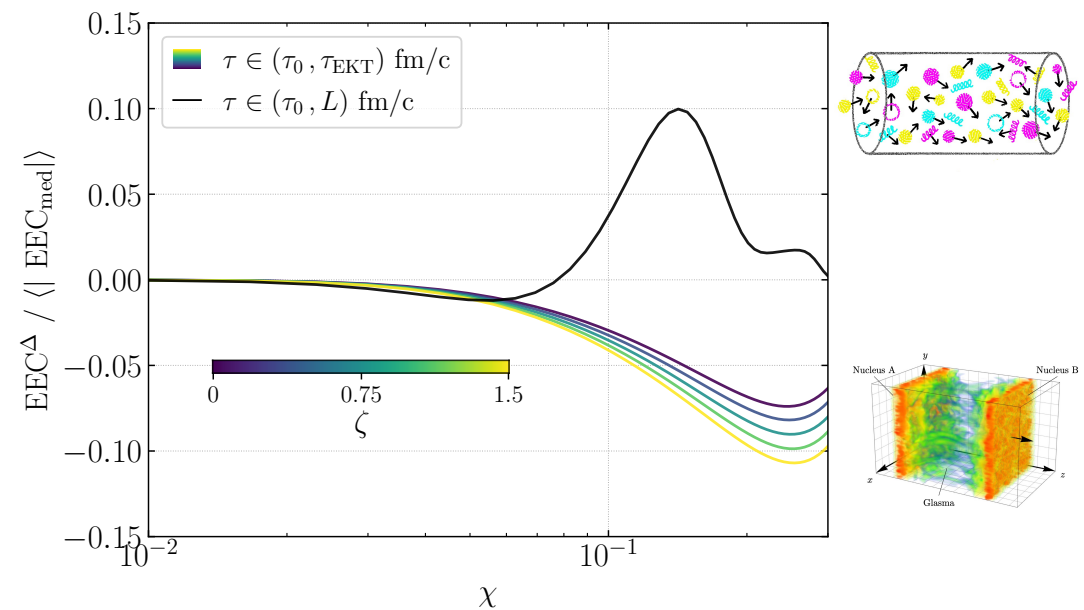
$$\frac{d\Sigma_{\text{IS}}^\Delta}{d\chi} = 2v_2^{\text{EEC}}(\chi) + \mathcal{O}(\xi^3 \chi^7)$$

$$v_{2n}^{\text{EEC}}(\chi) = \sum_{k=n+2} v_{2n,2k}^{\text{EEC}} \chi^{2k-3+s}, \quad n \geq 1$$

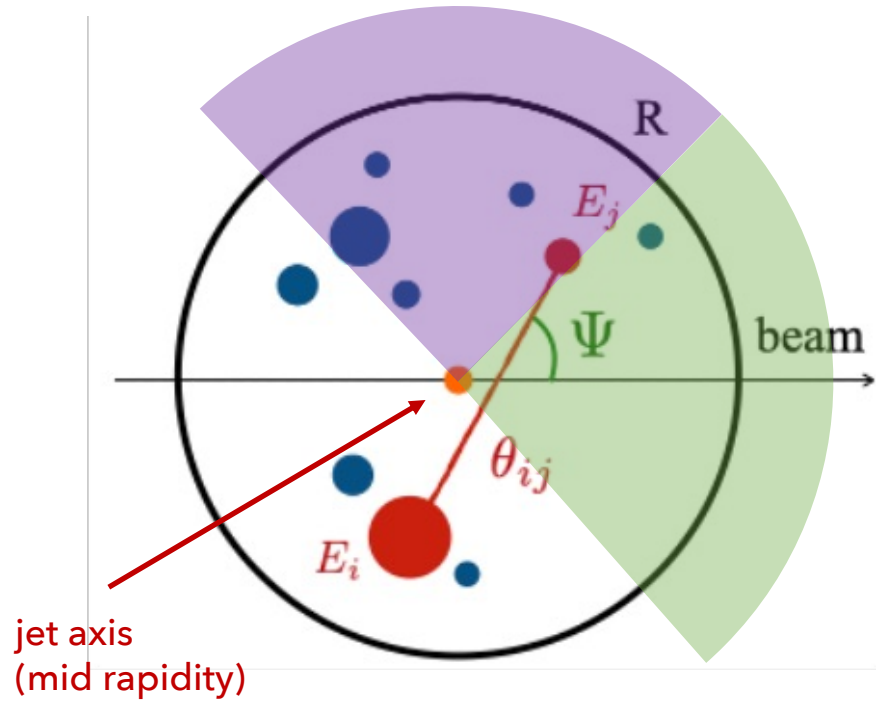
Clover EEC



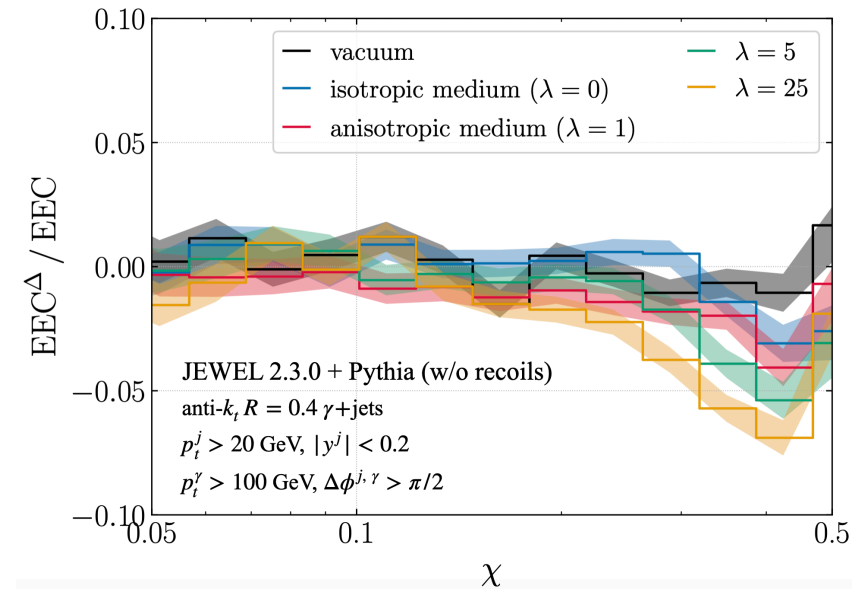
$$\frac{d\Sigma^\Omega}{d\chi} = \int_\Omega d\Psi \frac{d\Sigma}{d\chi d\Psi}$$



Clover EEC



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

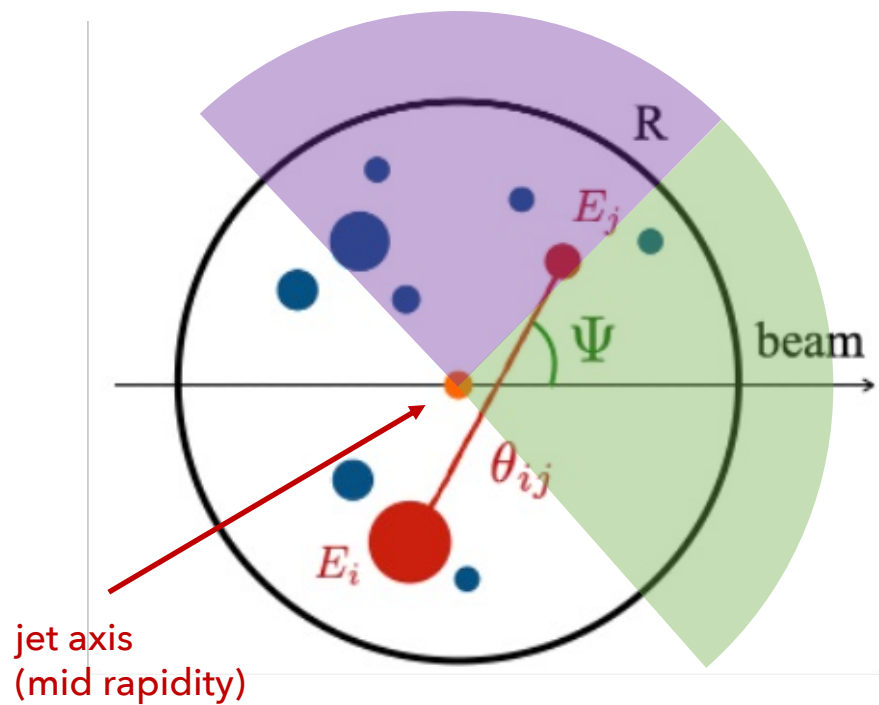


$$T(\eta_s) = (1 + \lambda \eta_s^2) T_{\text{default}}$$

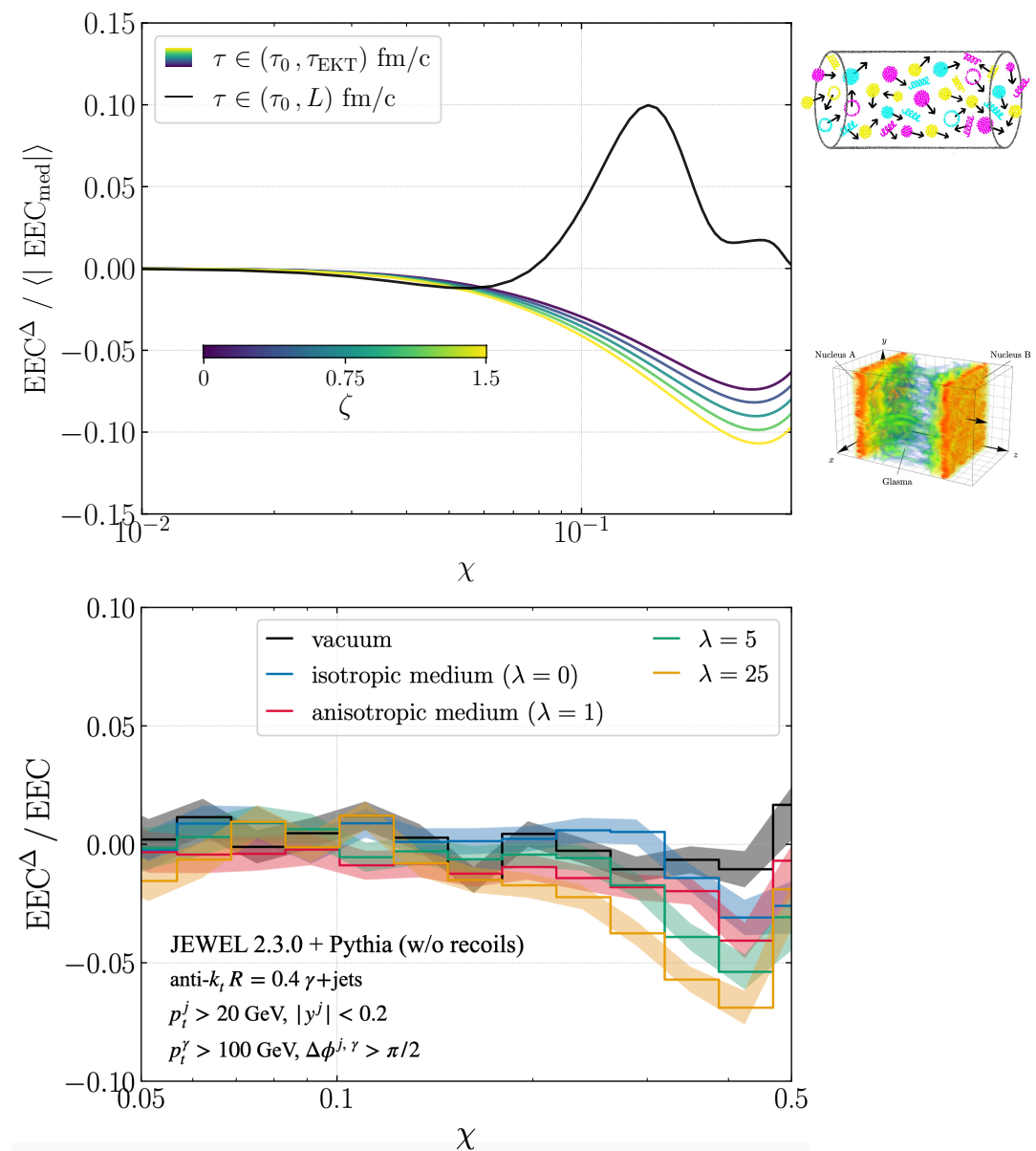
$$\left. \frac{\partial^2 T}{T^3 \partial z^2} \right|_{z=0} = \frac{1}{3} \frac{1 + 6\lambda}{f^2 T_i^2 (\tau_i t^2)^{2/3}}$$

$$\text{for } \lambda \in (0, 1, 5, 25) \rightarrow (0.09, 0.6, 3, 13)$$

Clover EEC



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



Summary and outlook

- Correlations of the energy fluxes have a highly **universal structure**, allowing us to understand their qualitative features
- Only by **accounting for all types of contributions** can we systematically study medium properties with ECs in HIC
- Initial stages and evolution effects lead to **distinct directional patterns**, which may help us distinguish them
- ECs offer **an alternative way to probe medium anisotropy**
- The physics becomes more ~~complicated~~ interesting, but that also calls for **stronger cross-talk between theory and experiment**