

recent developments in heavy-ion physics

a personal, not exhaustive, selection of results

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PURPOSE OF HEAVY-ION COLLISIONS

lose one month per year of pp data at peak luminosity ?

PURPOSE OF HEAVY-ION COLLISIONS

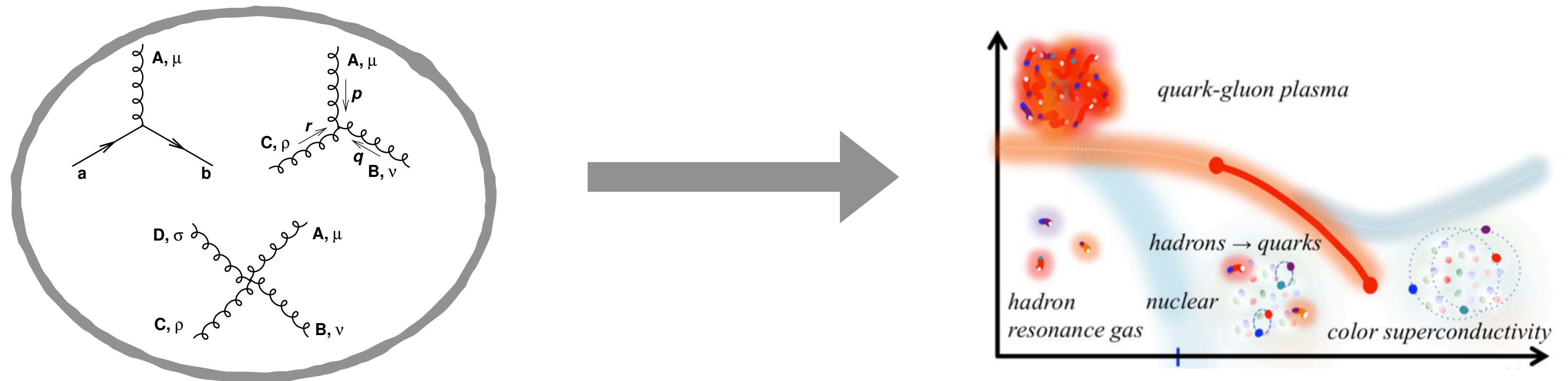
~~lose one month per year of pp data at peak luminosity ?~~

PURPOSE OF HEAVY-ION COLLISIONS

address the emergence of complexity in QCD

EMERGENT COMPLEXITY IN QCD

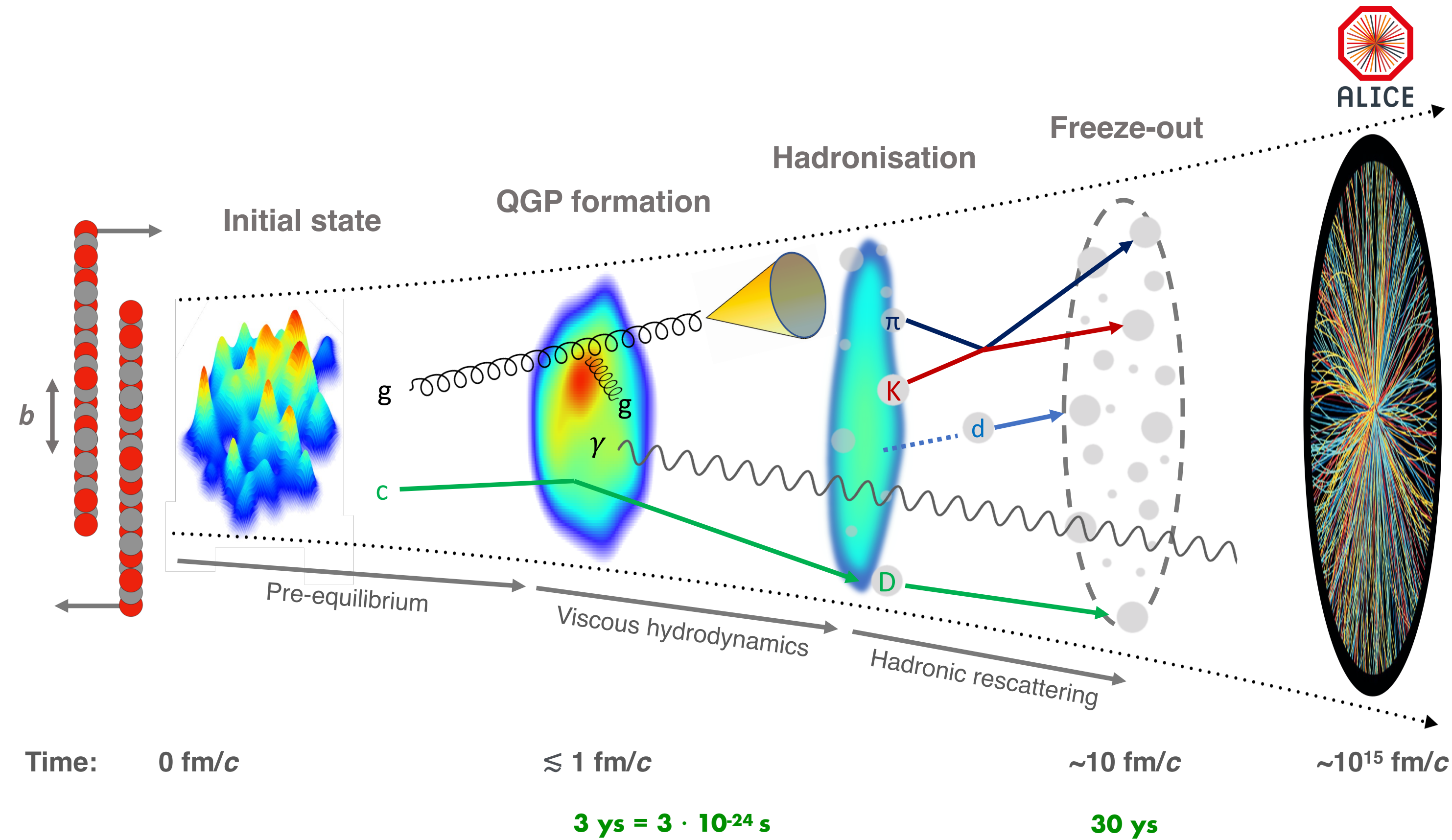
how diverse collective behaviour follows from the simple fundamental rules of QCD



HIC collisions as portal to emergent collectivity from fundamental degrees of freedom

[near-perfect fluidity, collective flow, hadronization, ...]

STAGES AND PROBES



soft probes

- sensitive to global [integrated] bulk QGP evolution
- resolve long wavelength behaviour

hard probes

- produced early and sensitive to wide range of dynamical scales
- potentially differential in time
- resolve short wavelength behaviour

different stages and scales of evolving QGP are resolved by different classes of probes

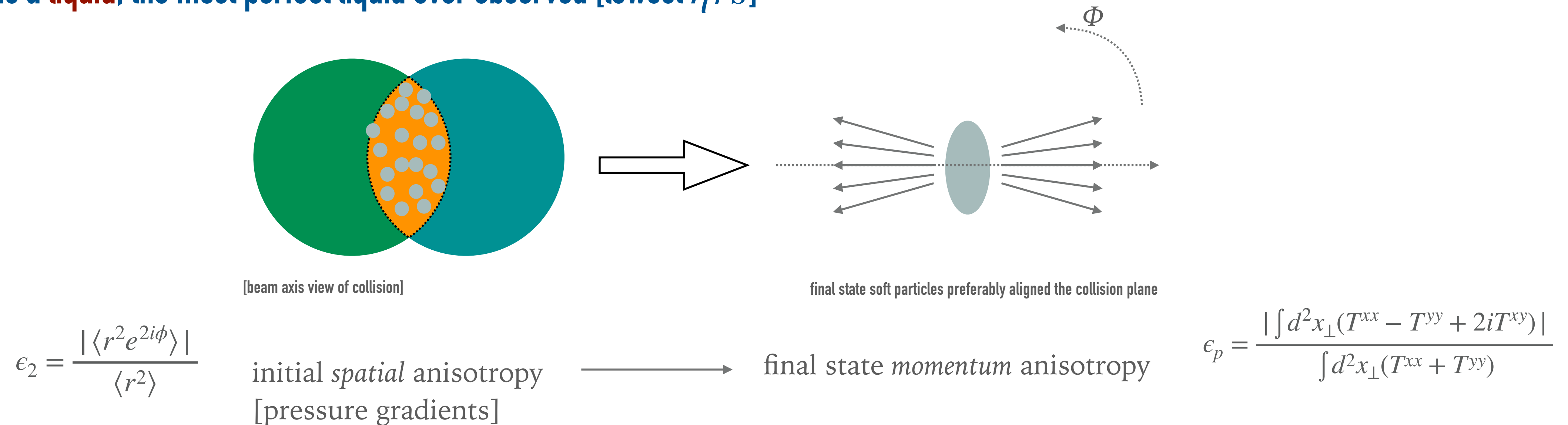
soft probes

A NEARLY-PERFECT LIQUID

the **P** in QGP stands for Plasma [named in the 1970s]

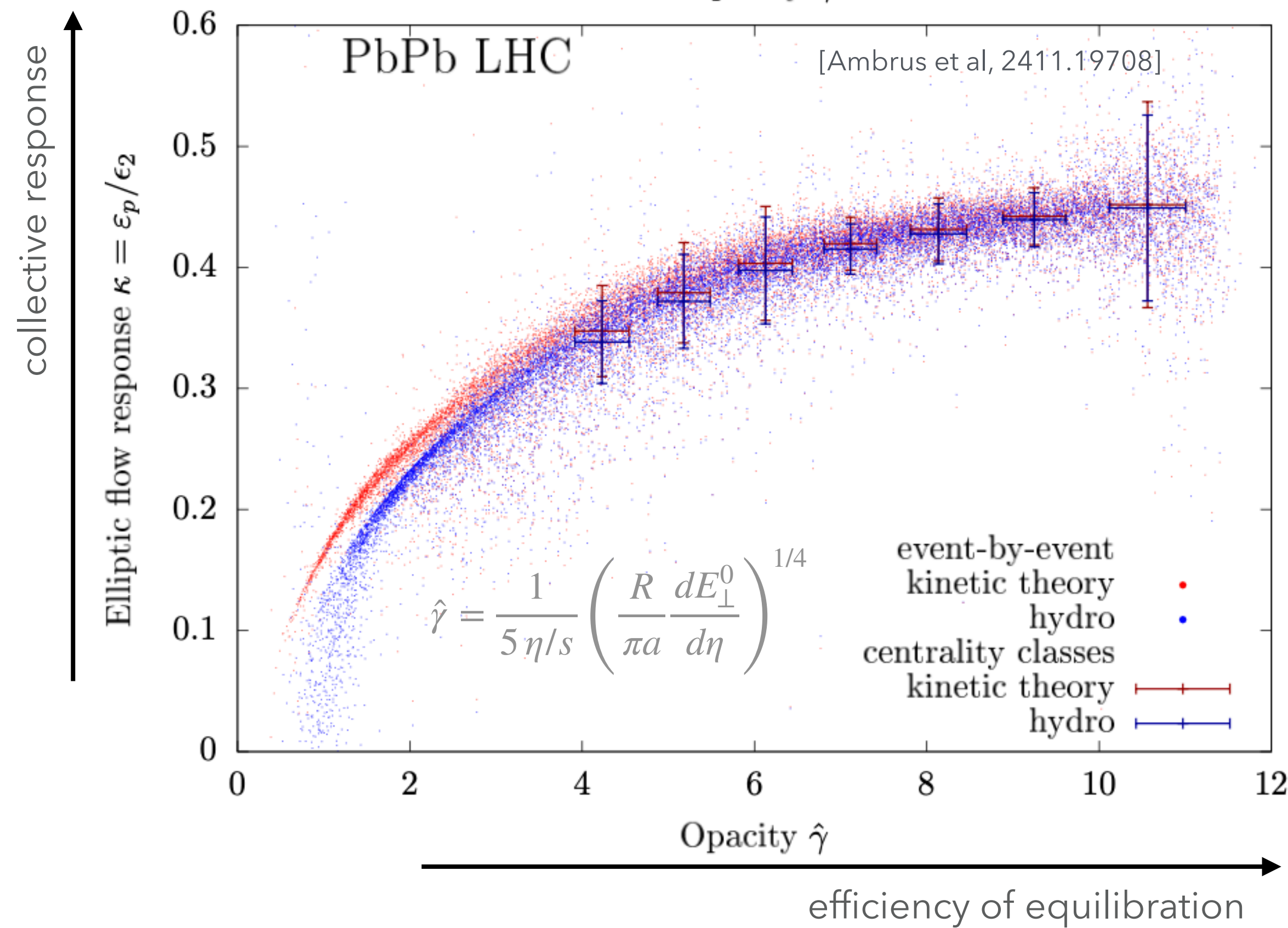
:: quarks and gluons not bound within hadrons with colour fields screened at characteristic Debye length $\lambda_D \sim 1/gT$

the QGP is a **liquid**, the most perfect liquid ever observed [lowest η/s]



liquids are described by hydrodynamics :: liquids flow :: liquids are strongly coupled

HOW DOES HYDRODYNAMICS COME INTO BEING



Kinetic Theory
[microscopic transport evolution]

$$p^{\mu} \partial_{\mu} f = C[f]$$

Hydrodynamics

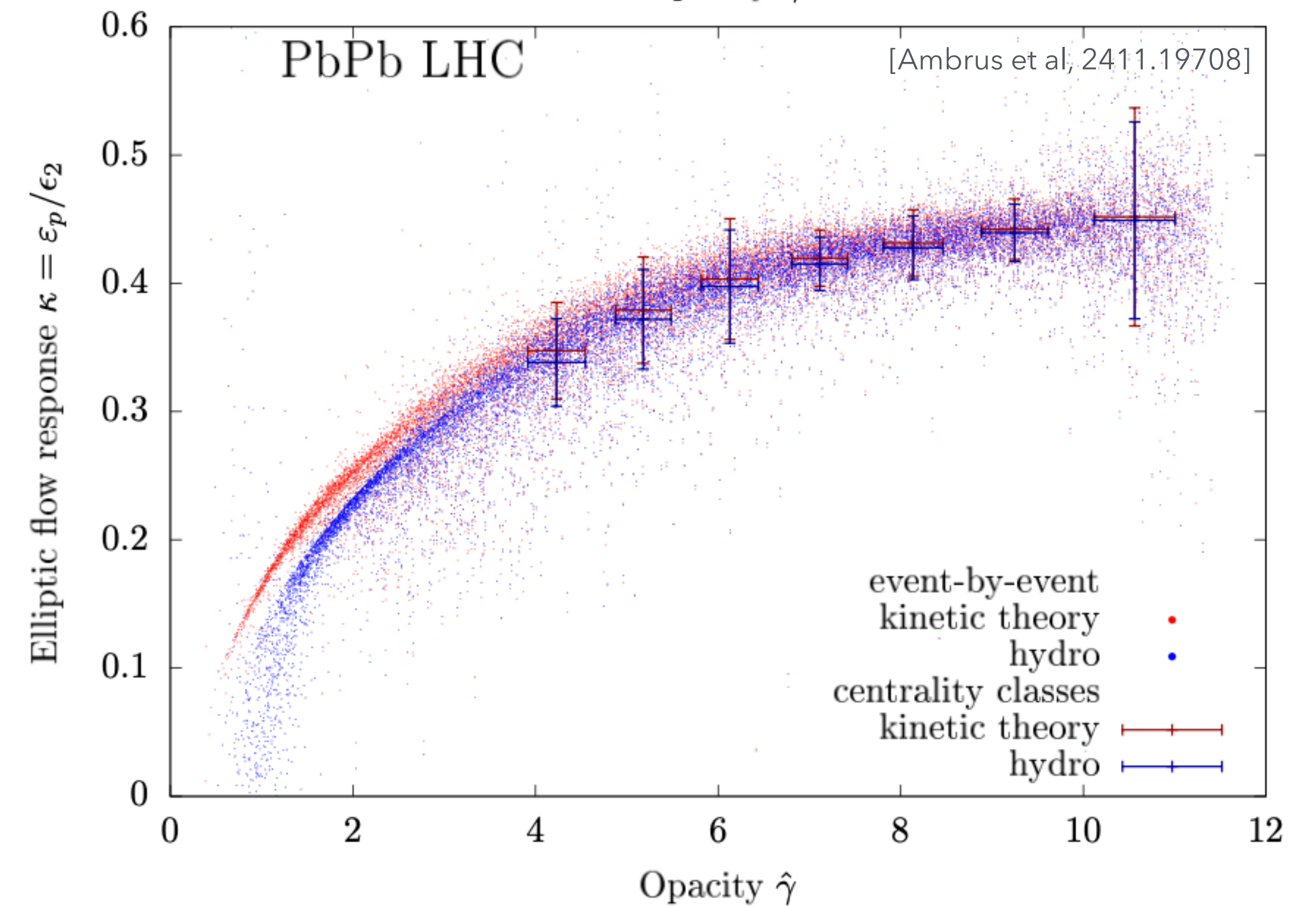
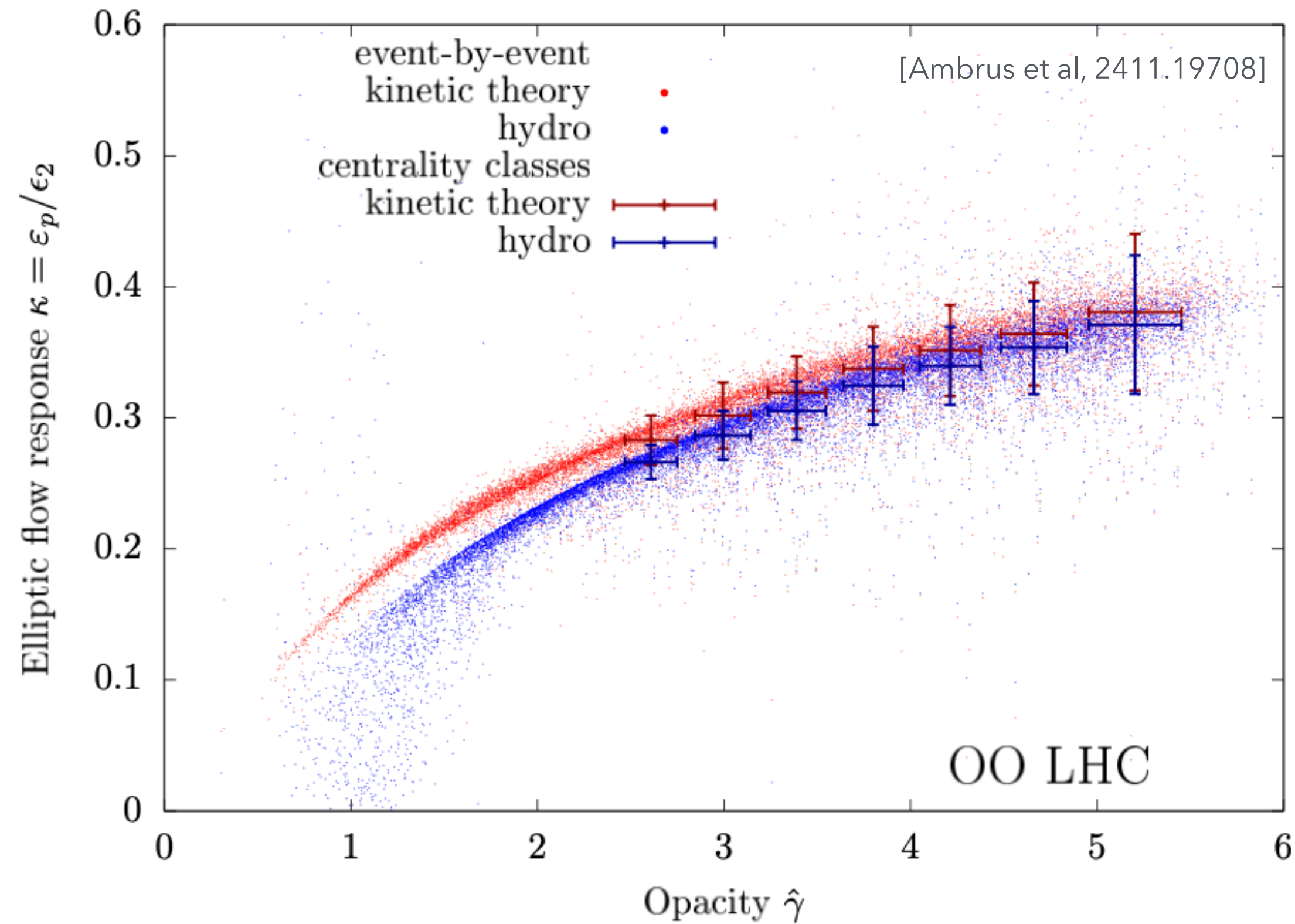
[macroscopic description]

$$\partial_{\mu} T_{\mu\nu} = 0; P = P(\epsilon)$$

for sufficiently large systems, microscopic and macroscopic descriptions merge

globally, hydrodynamics is all there is

HOW SMALL IS TOO SMALL?



collective behaviour **predicted and observed** in OO collisions, with out-of-equilibrium components persisting for most centralities

OO is large enough to form QGP

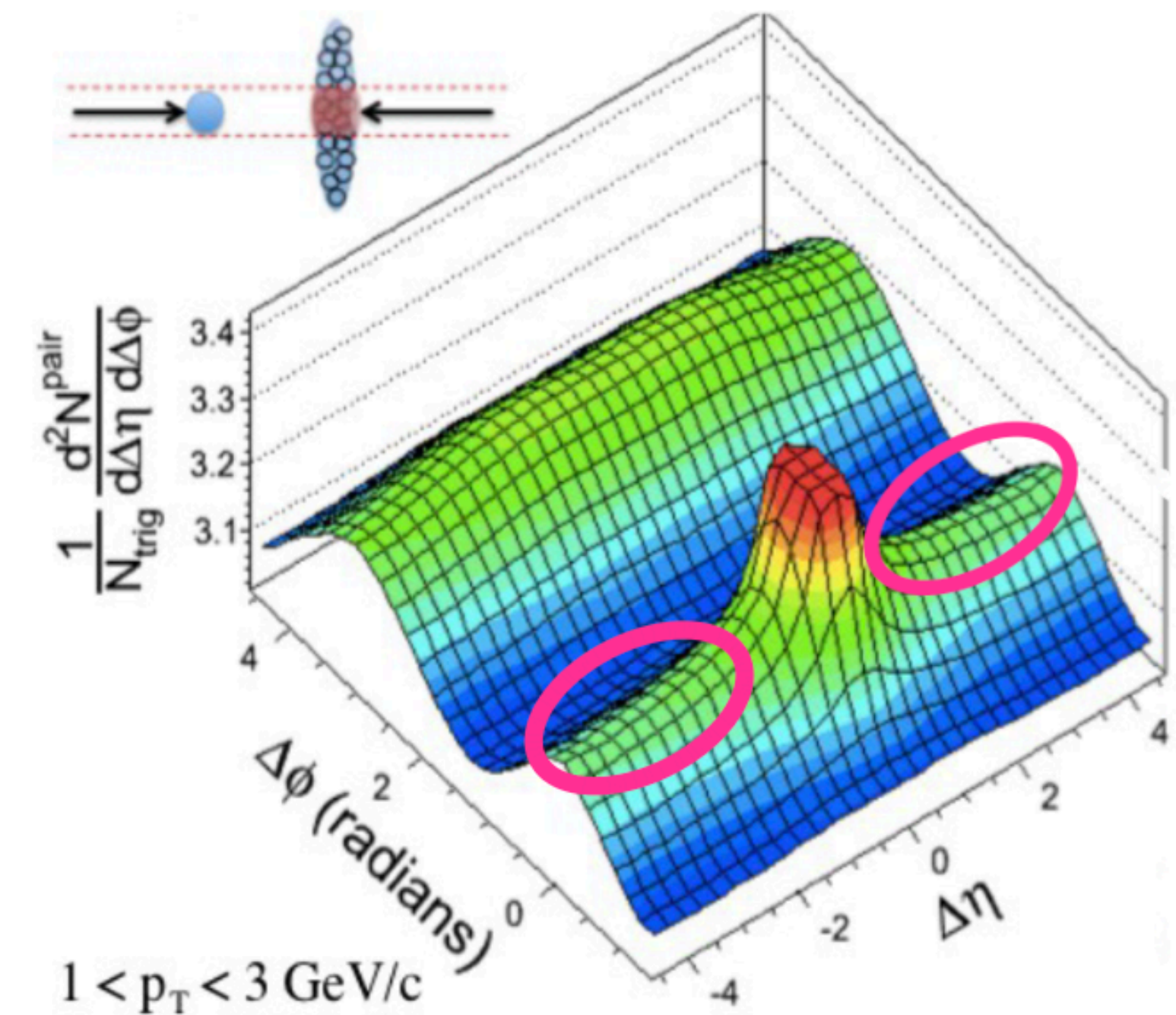
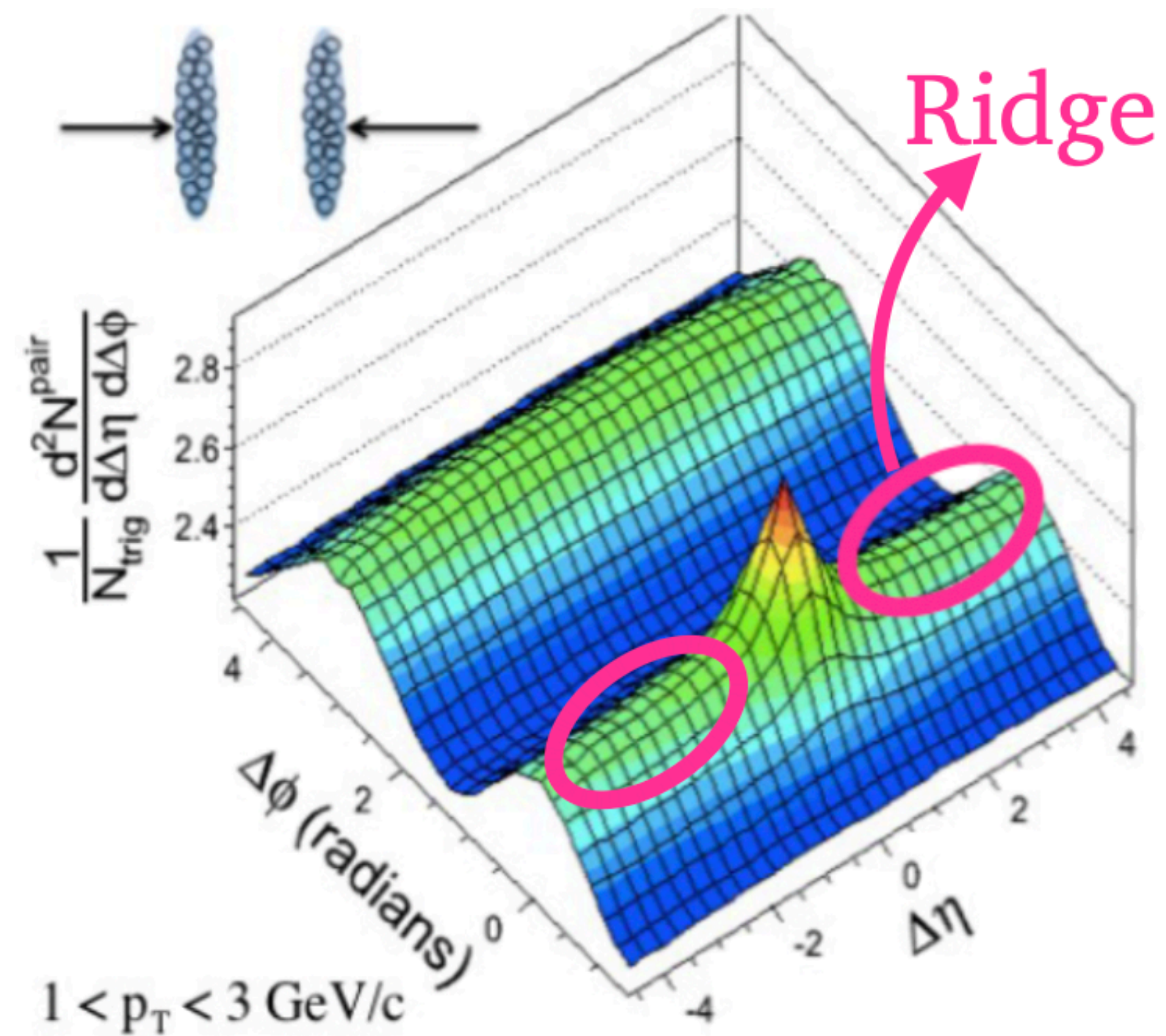
recent developments in **light- and heavy-ion** physics.....

a personal, not exhaustive, selection of results

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HOW SMALL IS TOO SMALL?

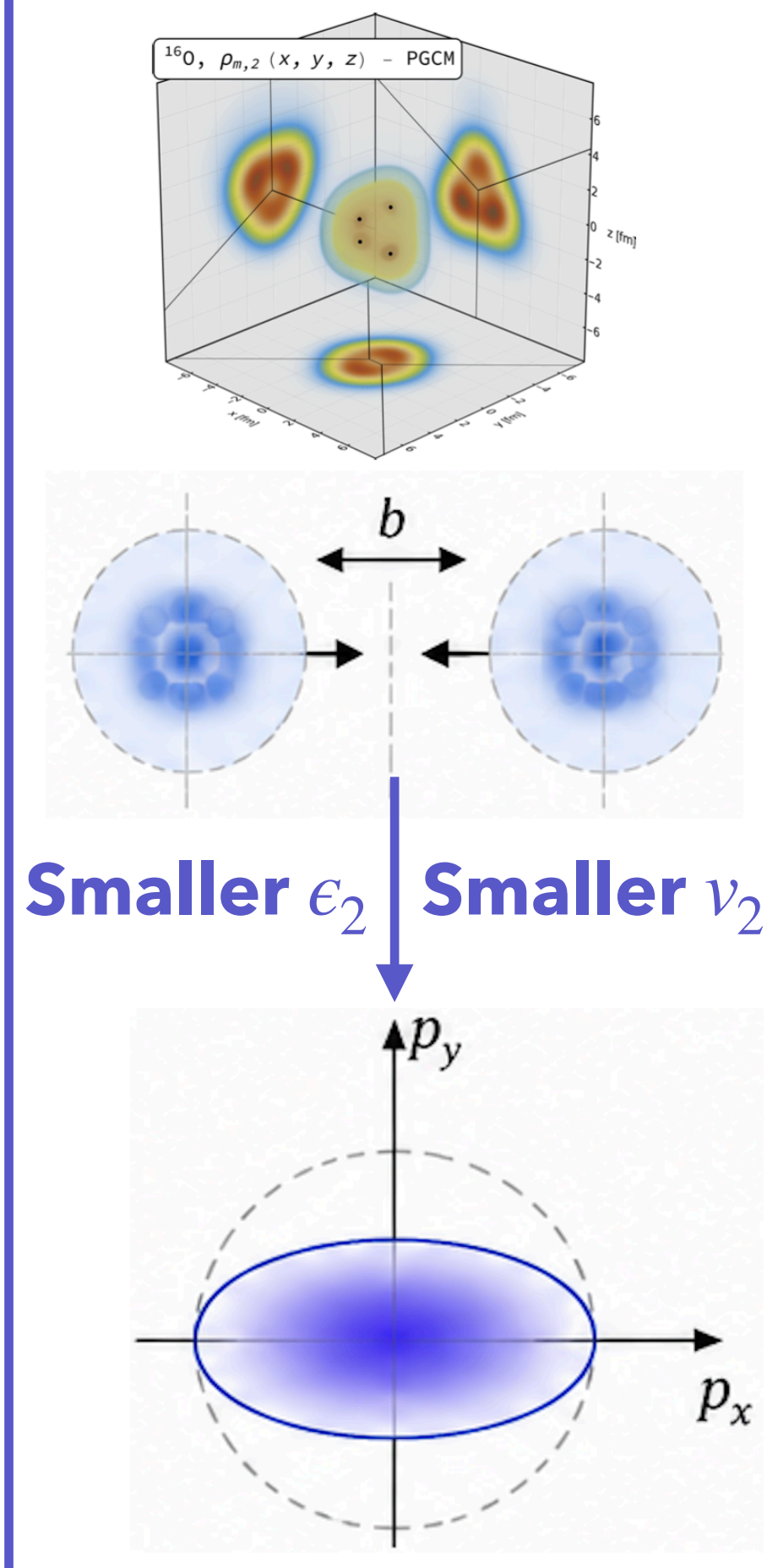
QGP creation firmly established for systems as small as OO [and NeNe] collisions



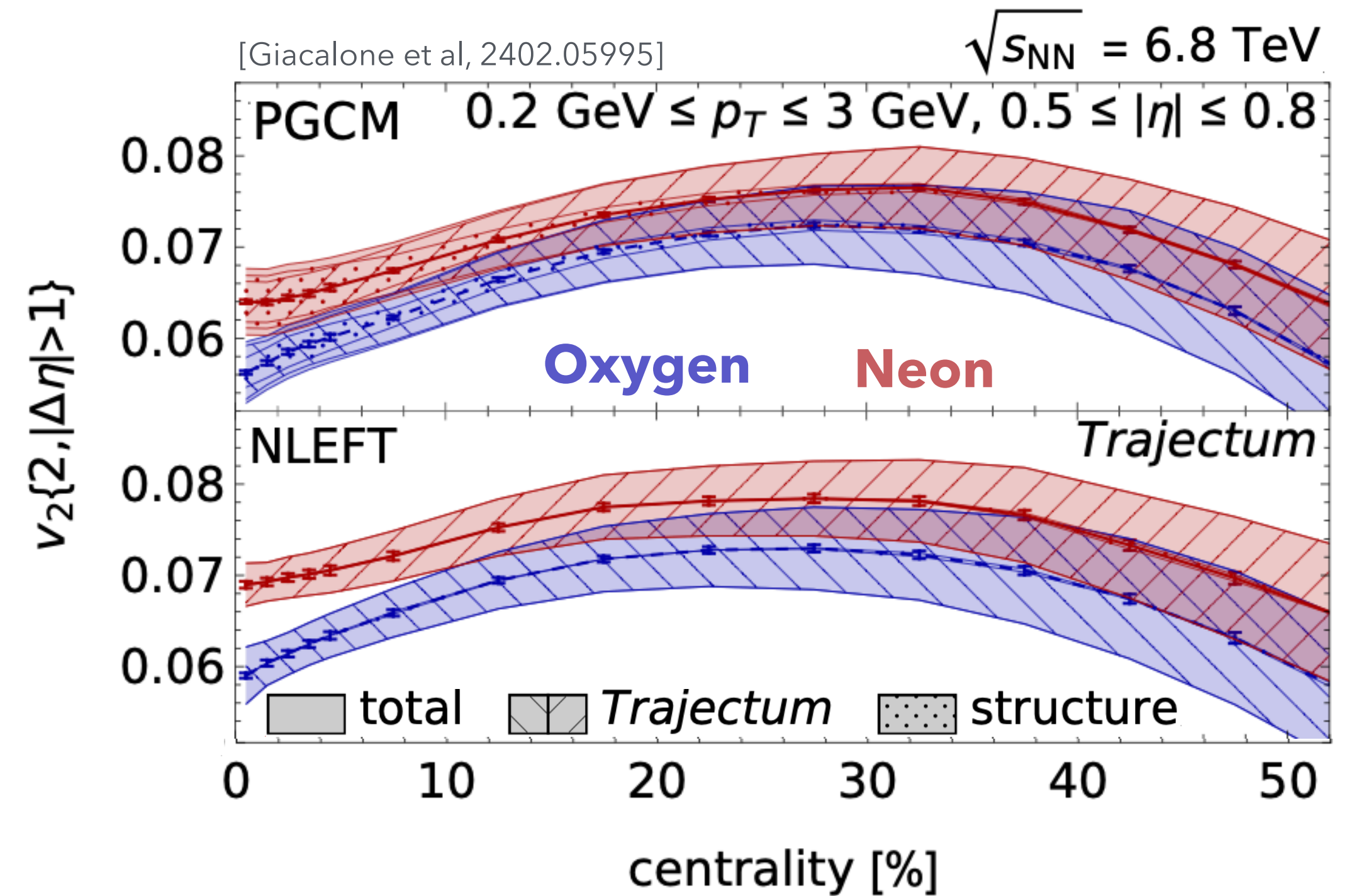
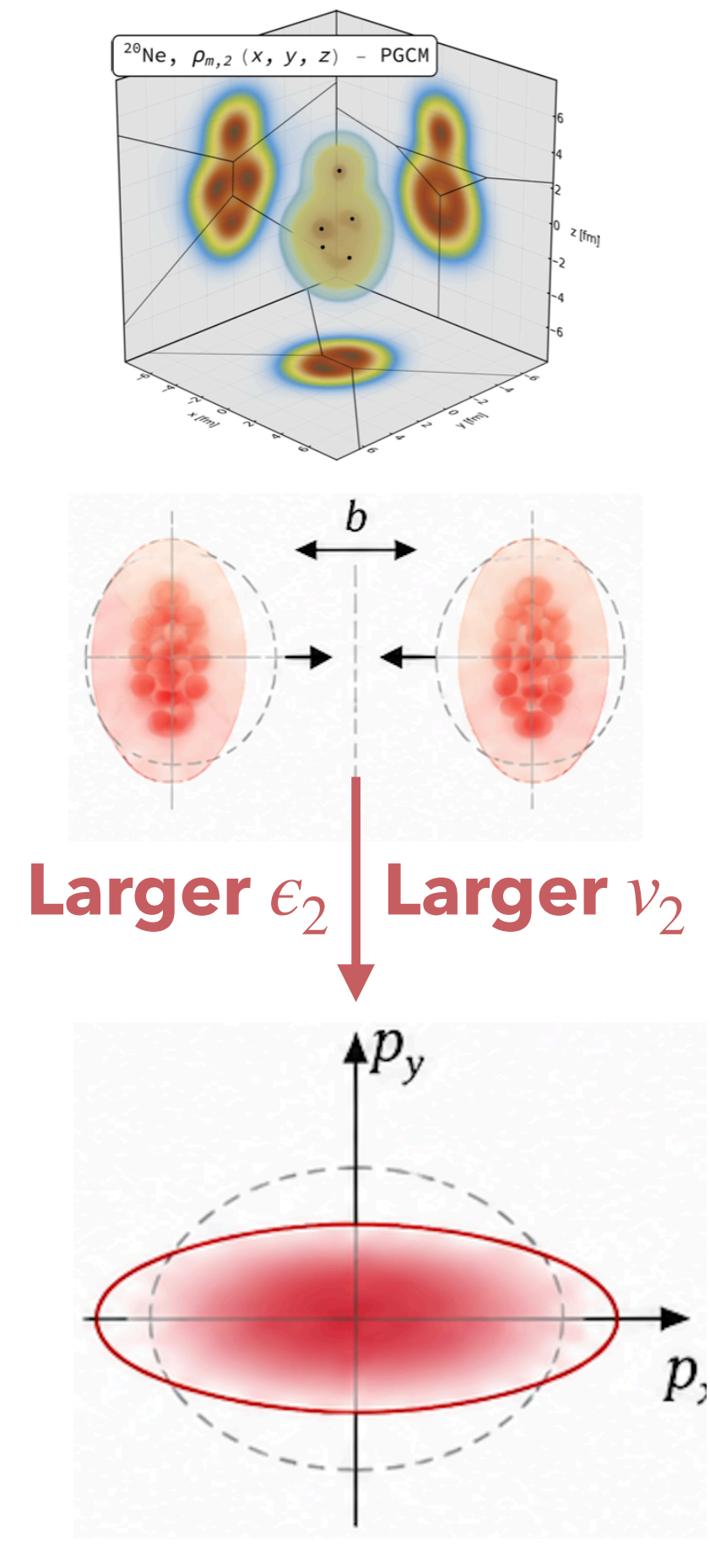
some evidence of collectivity in pPb [without jet quenching] :: in part reproduced by initial state effects

INITIAL STATE GEOMETRY AS A PRECISION TOOL

Oxygen: A = 16



Neon: A = 20



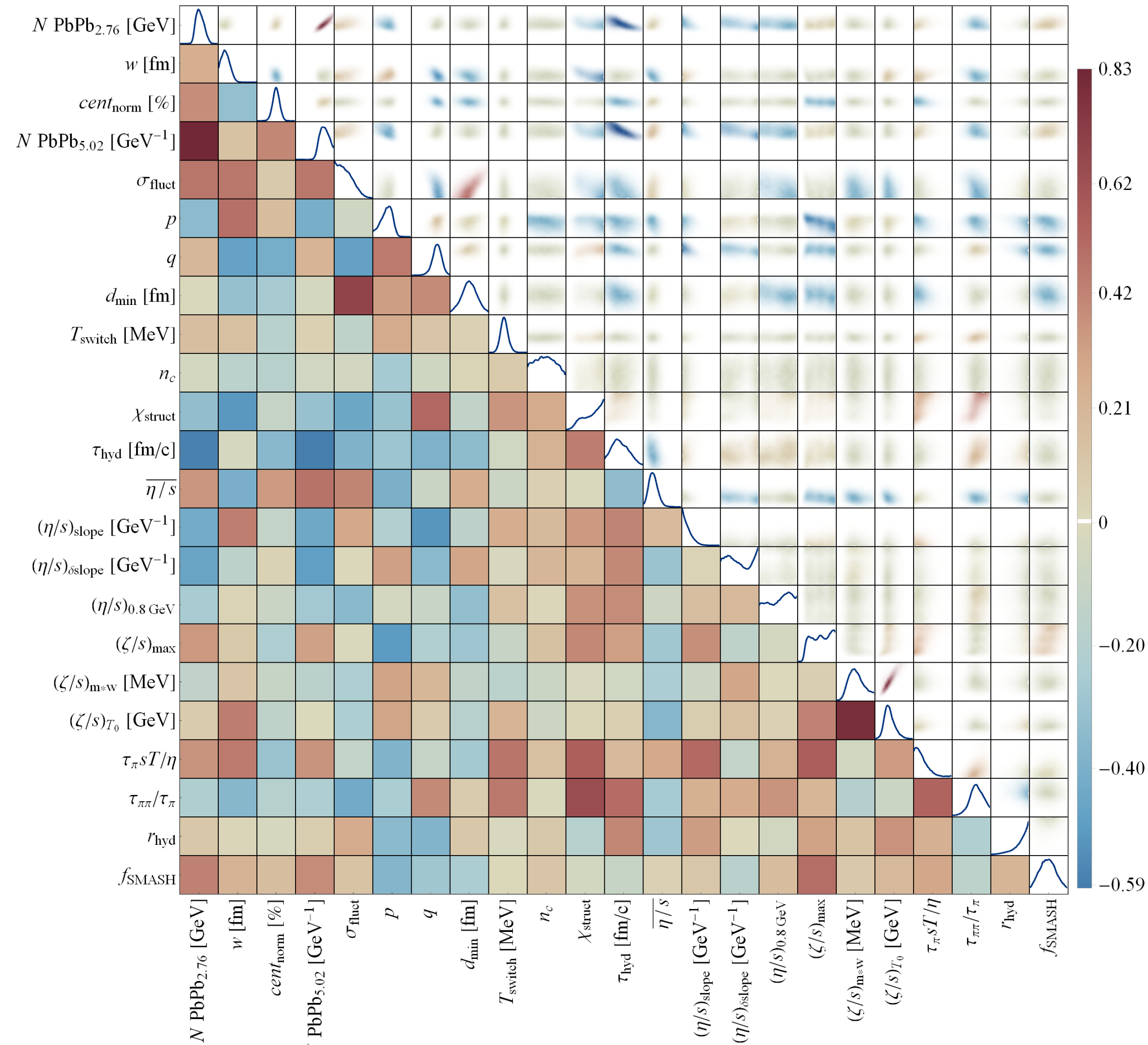
initial state geometry can be inferred from momentum anisotropies

EXTRACTING QGP PARAMETERS

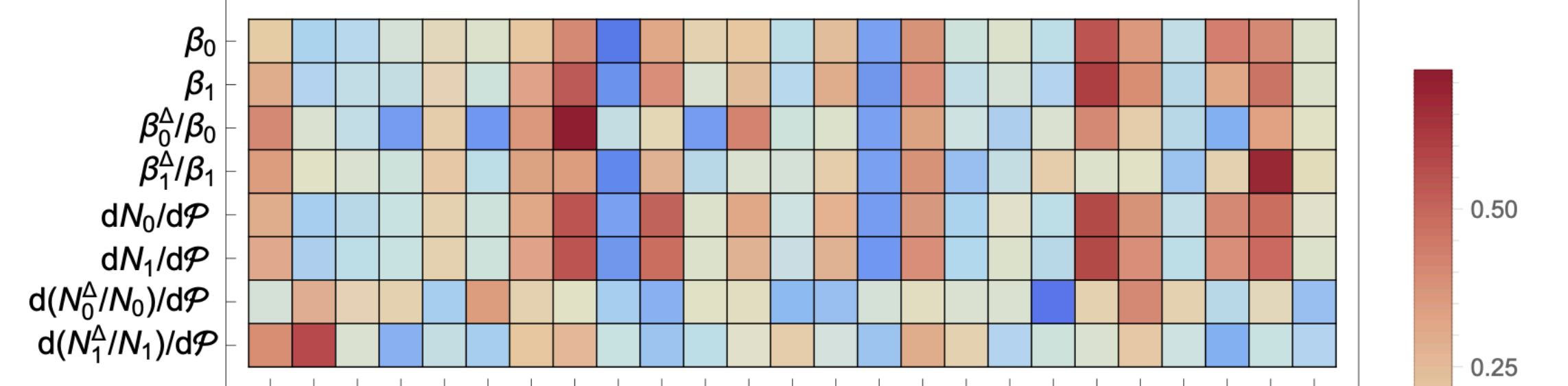
event-by-event hydro simulations + bayesian analysis [Trajectum]

[Nijs et al, 2304.06191]

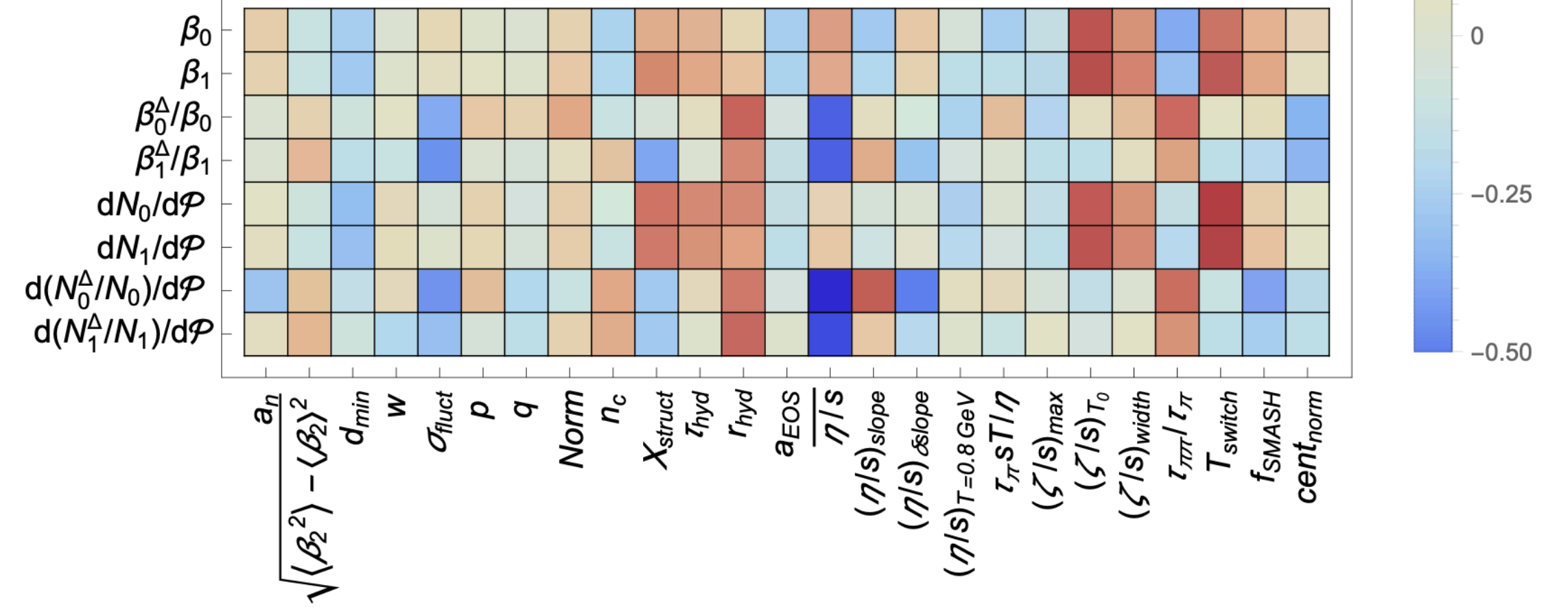
[Capelino et al, 2509.02335]



Central PbPb (0-5%)



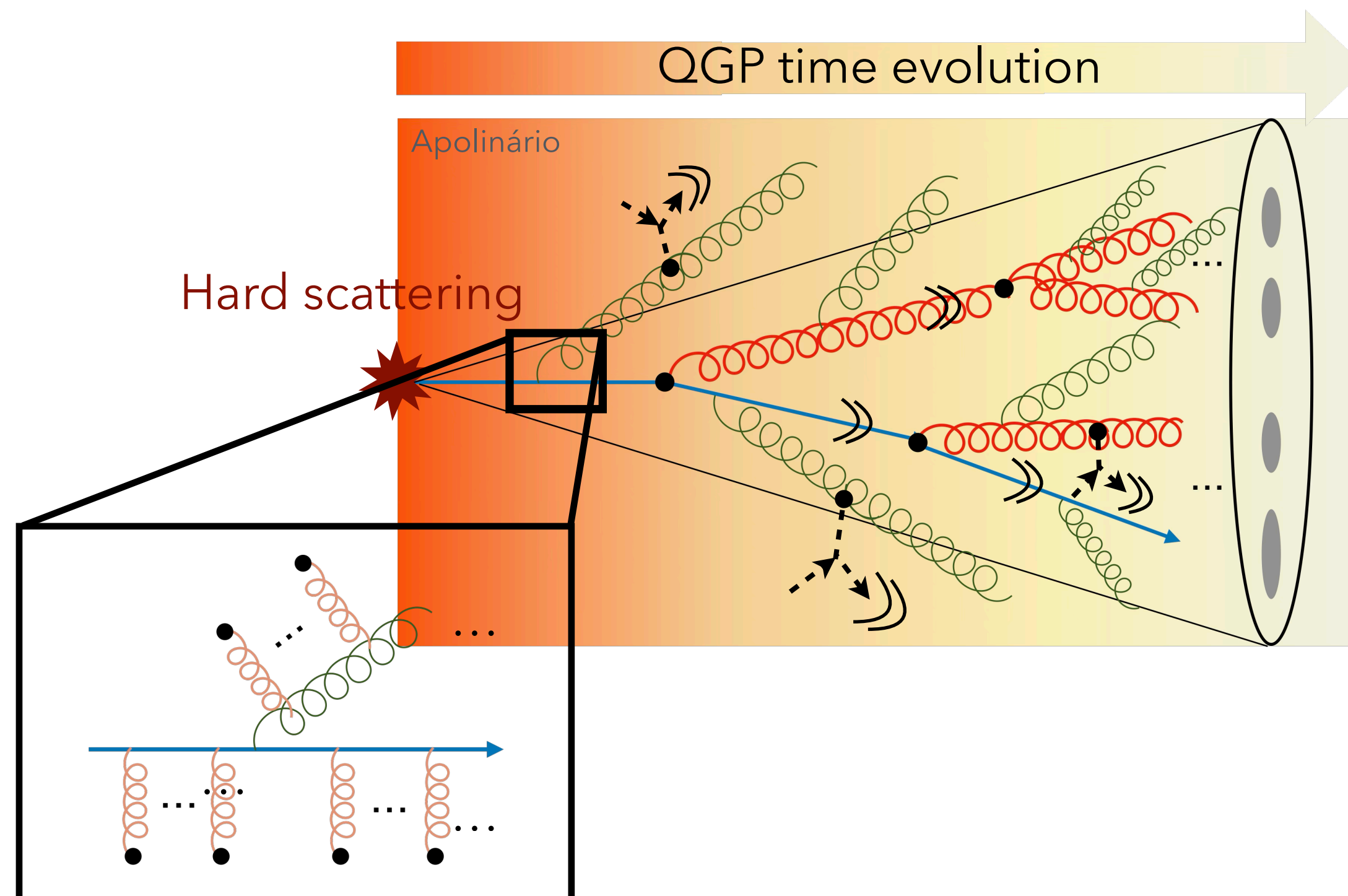
Peripheral PbPb (30-40%)



strong constrains from data
[observables-parameter correlation]

hard probes

JETS IN THE QGP



radiation pattern modified by parton-QGP interaction

- induced emissions
- partons transported out-of-cone
- modified colour coherence properties

QGP response to excitation by parton traversal

- novel jet component
- best hope for understanding equilibration dynamics [how perturbations hydrodynamize]

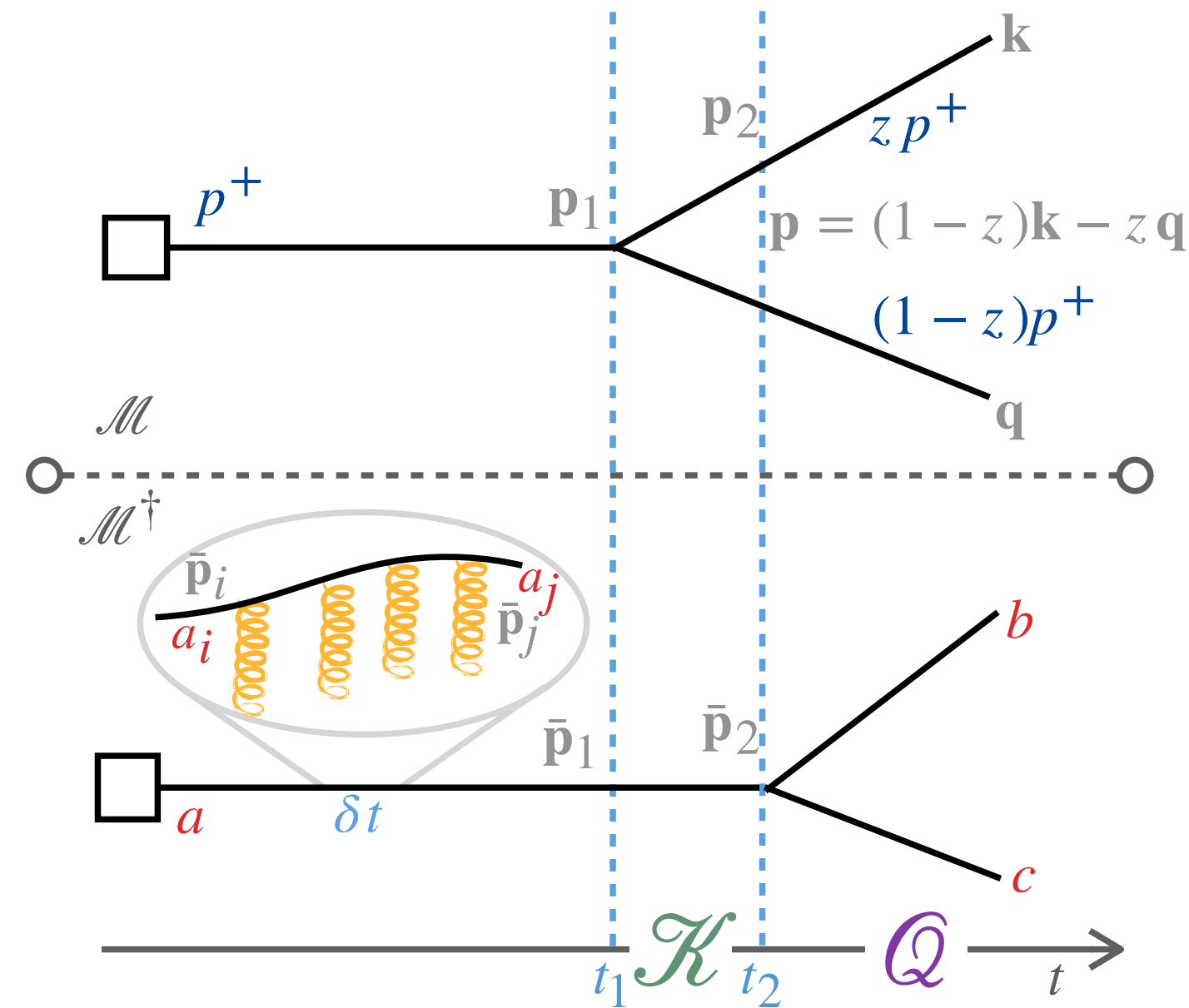
jets sensitive to interplay of wide range of shower scales with QGP evolving characteristic scales

EMISSION KERNELS

in-medium splittings first computed nearly 30 years ago

full resummation of interactions with QGP under several assumptions: soft limit + large N_c + unrealistic quadratic interaction potential [no high k_t tail]

finite [small] number of scatterings with QGP under several assumptions: soft limit + large N_c



path integrals over correlators of Wilson lines

unfeasible direct evaluation [Apolinário et al, 1407.0599]

recasting as system of coupled evolution equations for correlators [Caron-Huot, et al, 1006.2379]
[Andres et al, 2002.01517]
[Isaksen et al, 2303.12119]

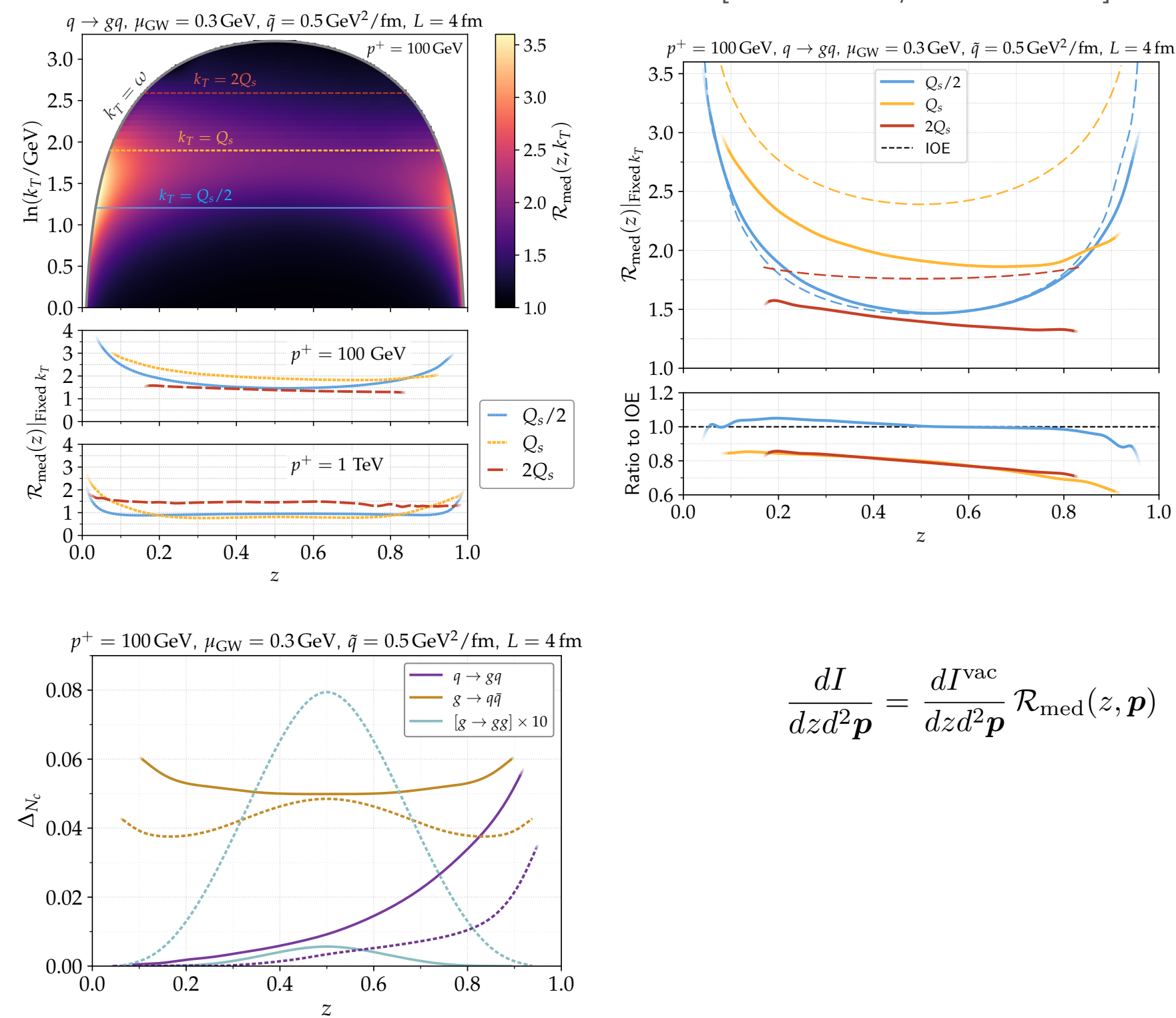
$$\frac{dI}{dz d^2\mathbf{p}} = \frac{\alpha_s P_{ba}(z)}{4\pi^2 \omega^2} \text{Re} \left[\int_{\mathbf{p}_1, \mathbf{p}_2, \bar{\mathbf{p}}_2, \bar{\mathbf{p}}} \int_0^\infty dt_1 \int_{t_1}^\infty dt_2 \delta_{\bar{\mathbf{p}}+\mathbf{p}}^{(2)} (\mathbf{p}_1 \cdot \bar{\mathbf{p}}_2) \mathcal{K}(\mathbf{p}_2, \mathbf{p}_1 | t_2, t_1) \mathcal{Q}(\mathbf{p}, \bar{\mathbf{p}}, \mathbf{p}_2, -\bar{\mathbf{p}}_2 | t_\infty, t_2) \right] \equiv \frac{dI^{\text{vac}}}{dz d^2\mathbf{p}} \mathcal{R}_{\text{med}}(z, \mathbf{p})$$

EMISSION KERNELS :: TOWARDS PRECISION

full solution [realistic interaction potential , finite N_c , exact longitudinal kinematics]

numerical solution based on Faber polynomial expansion

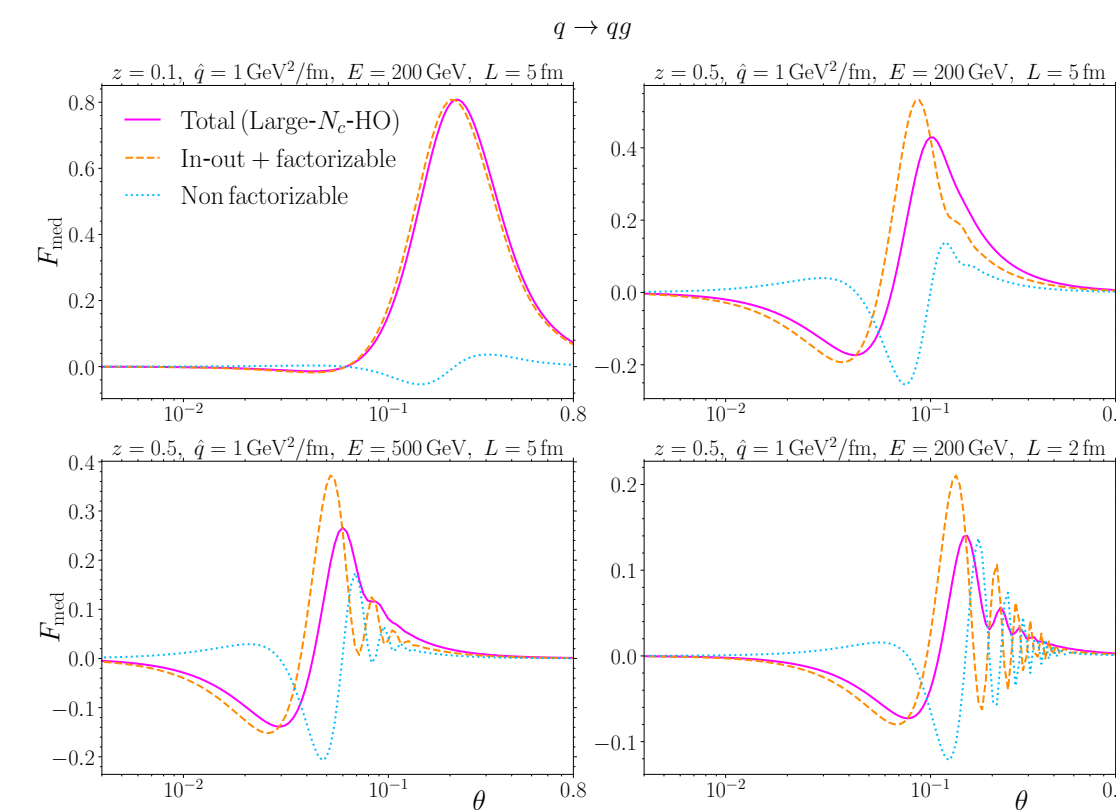
[Leitão et al, 2606.26039]



$$\frac{dI}{dzd^2\mathbf{p}} = \frac{dI^{\text{vac}}}{dzd^2\mathbf{p}} \mathcal{R}_{\text{med}}(z, \mathbf{p})$$

semi-analytical

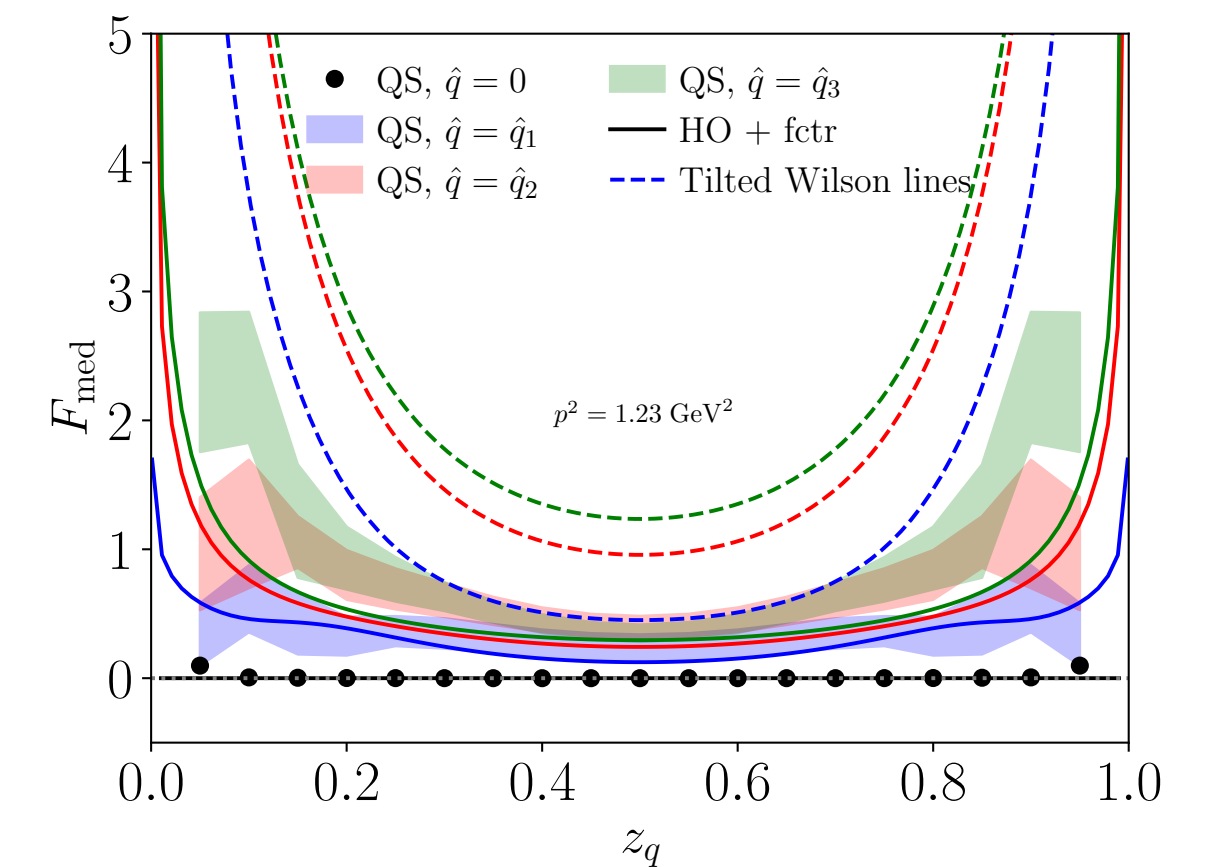
[Andres et al, 2603.27846]



quadratic potential; large N_c

analogous calculation with quantum algorithm

[Barata et al, 2604.11616]



unrealistic parameters; resource limited

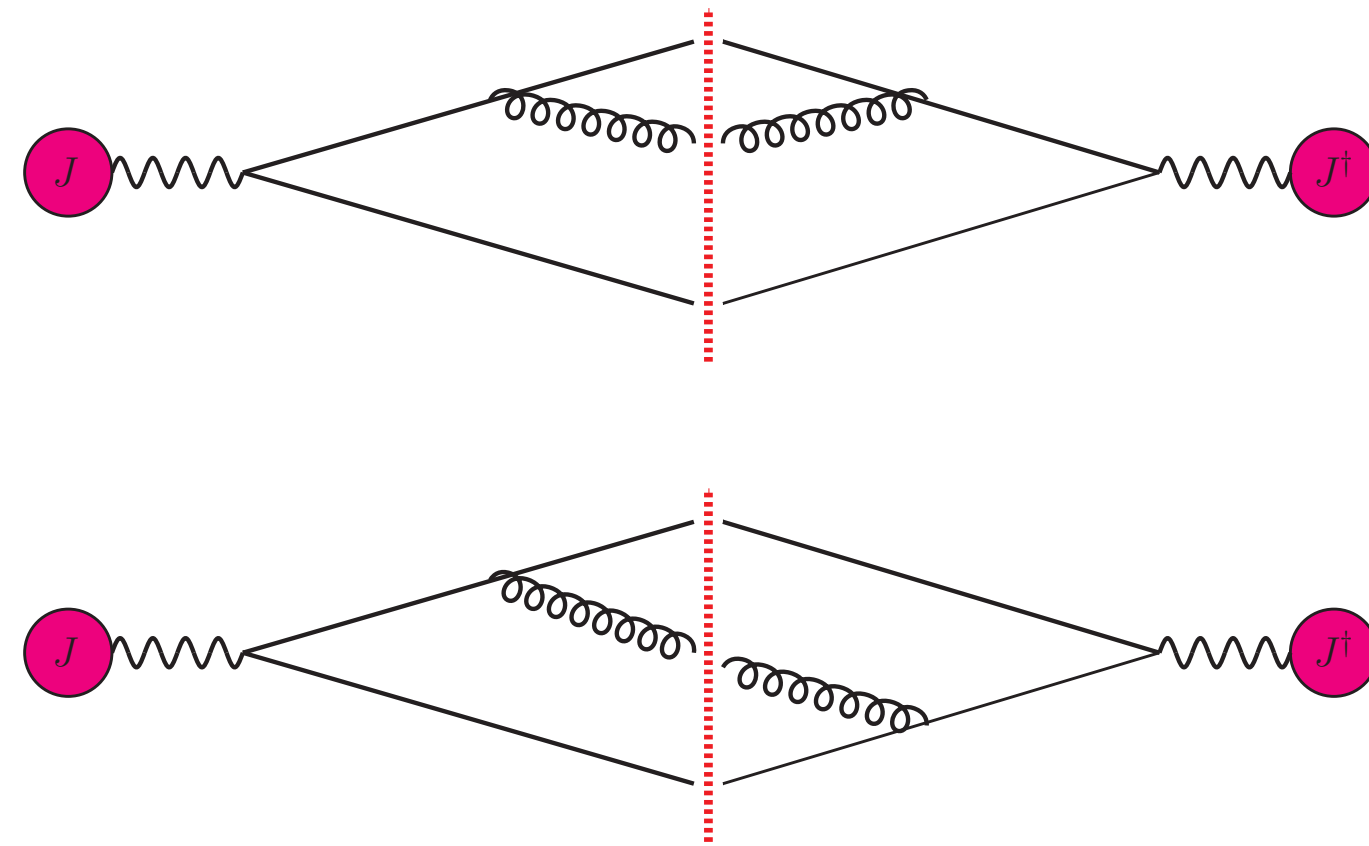
sizeable effects and significant deviations from approximate results across phase space
[phenomenological implications being assessed]

COHERENT EMISSION

interaction with QGP destroys colour coherence between emitters

[Mehtar-Tani, Salgado, Tywoniuk + collaborators [since 2010]]

[Casalderrey, Iancu:: 1105.1760; 1407.0599]



$$\mathcal{M}_{q\bar{q}g}^2 = 4 C_F g^2 \mathcal{M}_{q\bar{q}}^2 \left(\frac{1}{\kappa^2} + \frac{1}{\bar{\kappa}^2} - 2 (1 - \Delta_{med}) \frac{\kappa \cdot \bar{\kappa}}{\kappa^2 \bar{\kappa}^2} \right)$$

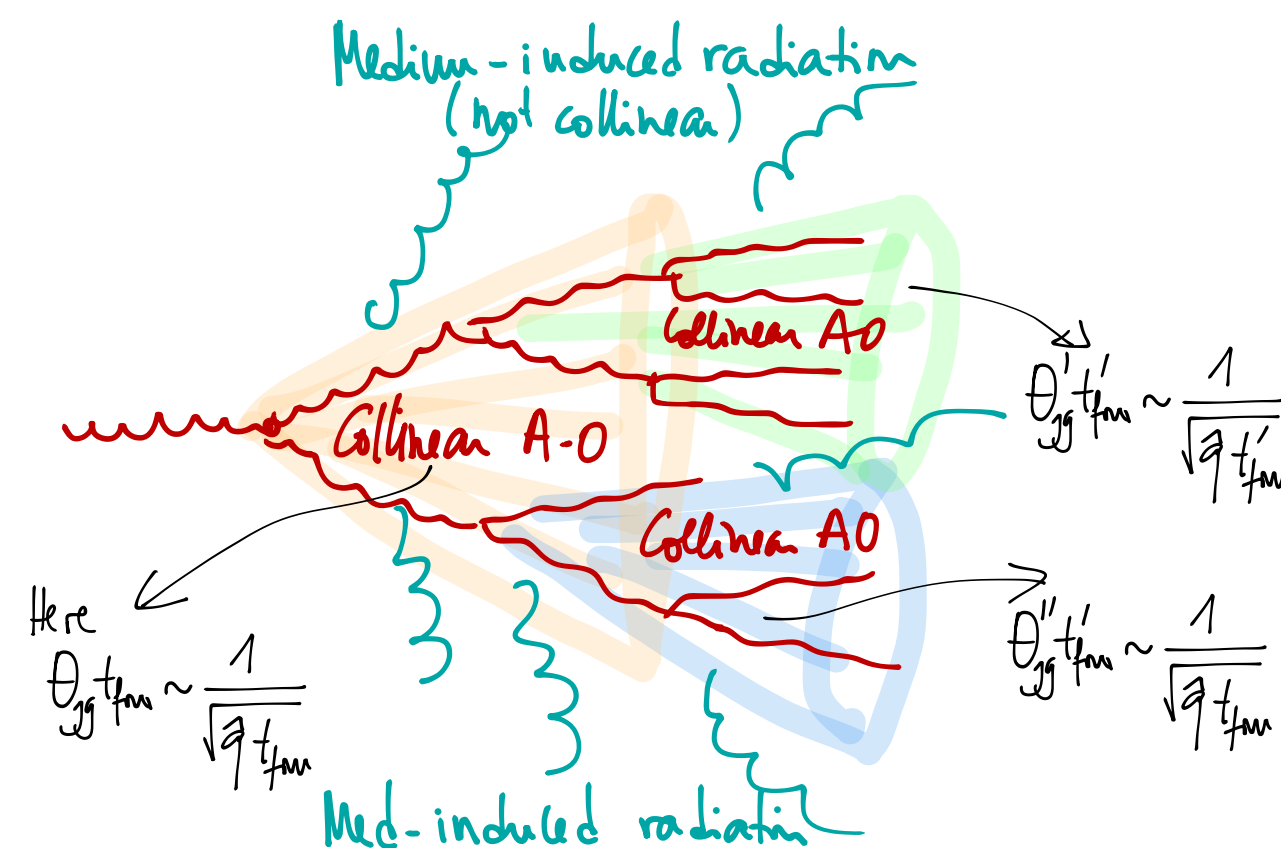
$$\Delta_{med} = \begin{cases} 0 & \text{for } L, \hat{q} \rightarrow 0 & \text{[angular ordering]} \\ 1 & \text{for } L, \hat{q} \rightarrow \infty & \text{[anti-angular ordering]} \end{cases}$$

with quadratic interaction potential and instantaneous antenna formation

$$\Delta_{med} = 1 - e^{-\theta_{q\bar{q}}^2 / \theta_c^2}$$

$$\theta_c = \sqrt{\frac{6}{\hat{q} L^3}}$$

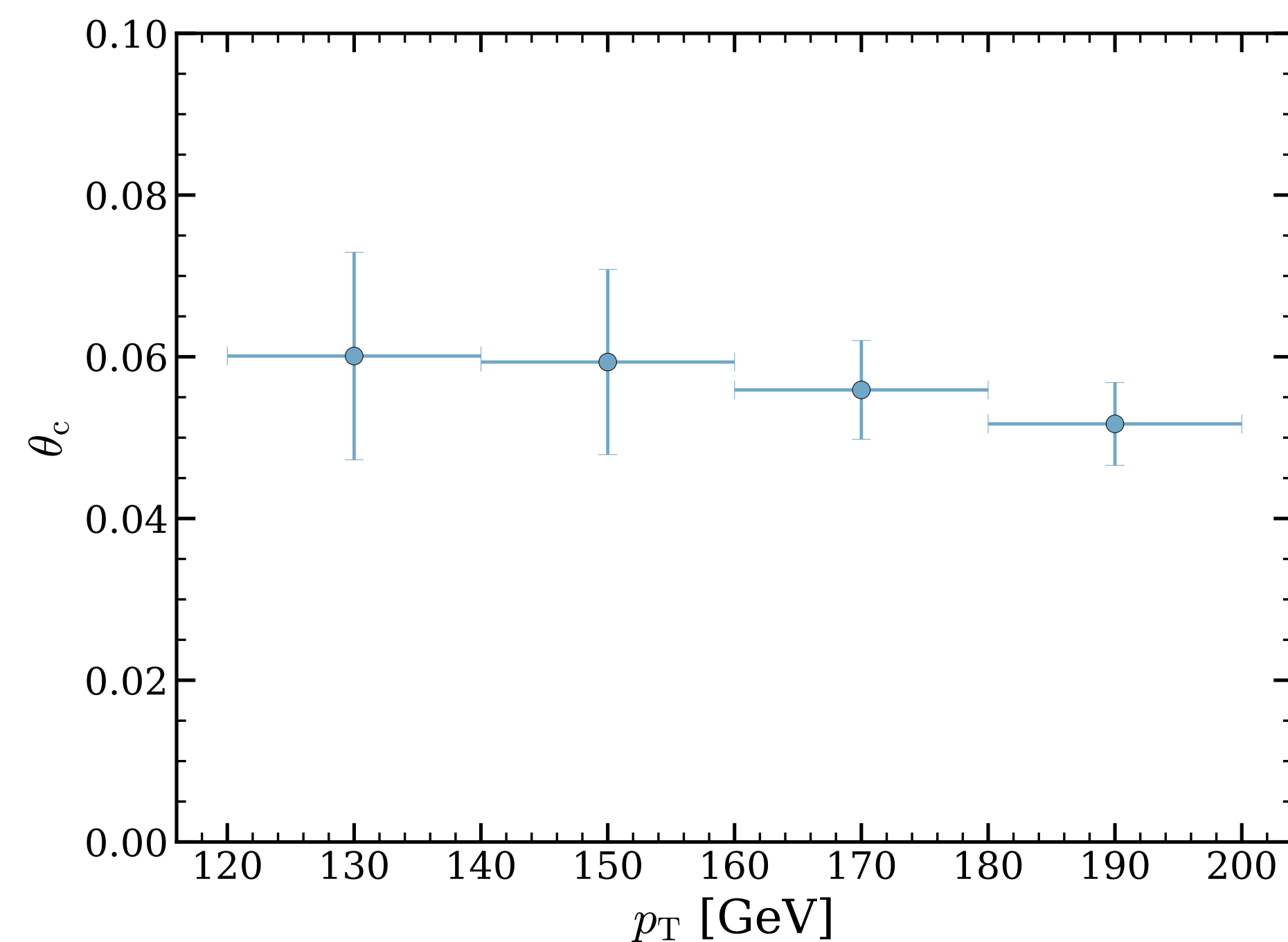
decoherence angle :: characteristic QGP scale



DECOHERENCE ANGLE FROM DATA

[Bossi et al, 2609.05609]

simultaneous fit of jet suppression and jet safe region of EEC allows for extraction of decoherence angle
[and quark and gluon quenching factors]



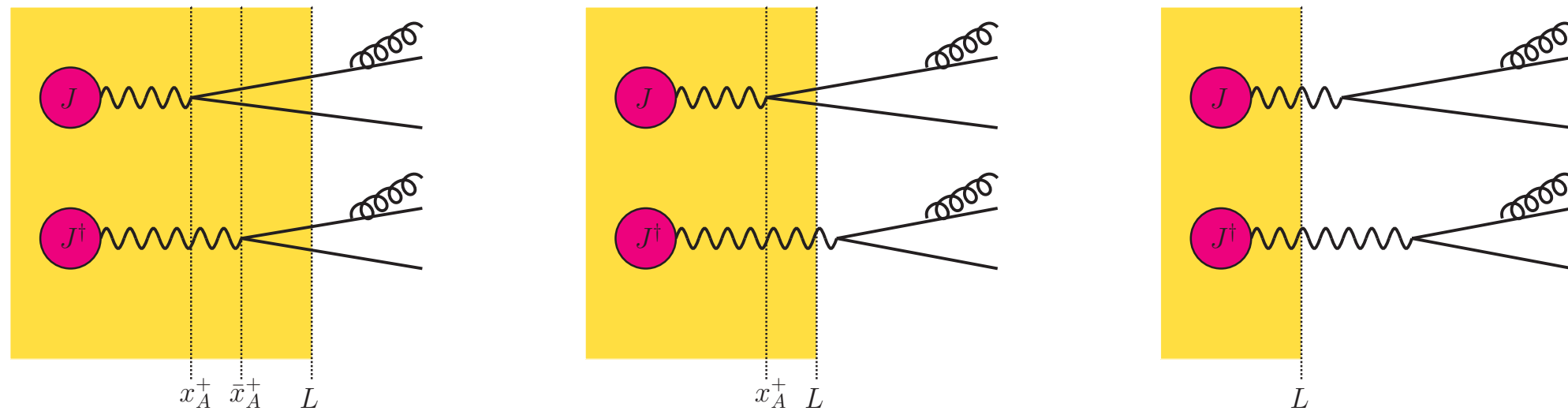
no significant jet p_T dependence as expected

extraction of a fundamental QGP property?

LIFE IS HARD

[Abreu et al, 2410.24135]

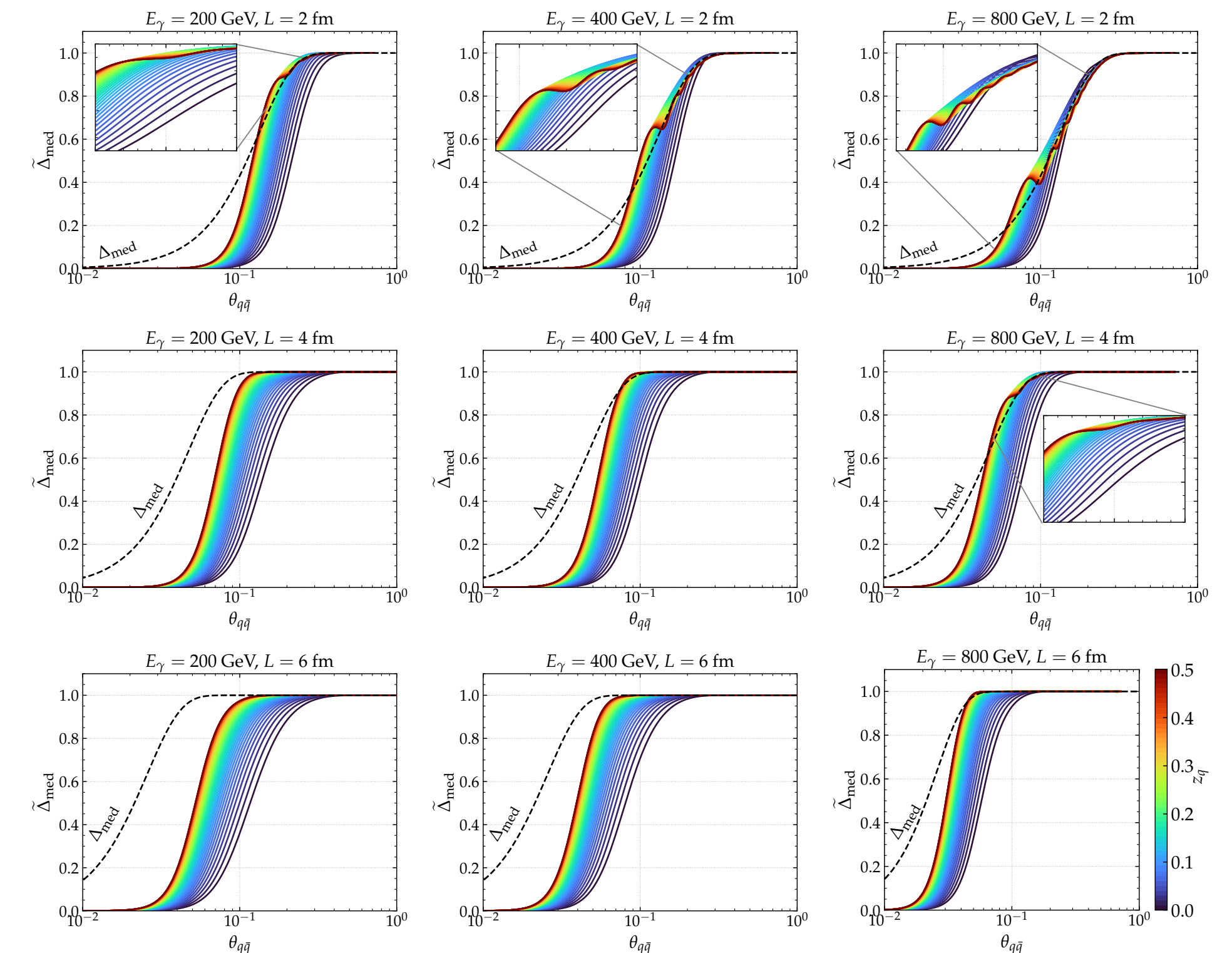
when formation time of antenna taken into account, antenna decoherence becomes kinematics dependent



$$\mathcal{M}_{q\bar{q}g}^2 = 4 C_F g^2 \mathcal{M}_{q\bar{q}}^2 (1 + F_{\text{med}}) \left[\left(\frac{1}{\kappa^2} + \frac{1}{\bar{\kappa}^2} - 2 \frac{\kappa \cdot \bar{\kappa}}{\kappa^2 \bar{\kappa}^2} \right) + 2 \frac{\kappa \cdot \bar{\kappa}}{\kappa^2 \bar{\kappa}^2} \tilde{\Delta}_{\text{med}} \right]$$

$$F_{\text{med}} = 2 \int_0^L \frac{d\bar{x}_A^+}{t_A} \int_0^{\bar{x}_A^+} \frac{dx_A^+}{t_A} \cos\left(\frac{\Delta x_A^+}{t_A}\right) \mathcal{S}^{(2)}(\bar{x}_A^+, x_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau)) \\ \times \mathcal{Q}^{(4)}(L, \bar{x}_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau), \bar{\mathbf{r}}_q^A(\tau), \bar{\mathbf{r}}_{\bar{q}}^A(\tau)) \\ - 2 \int_0^L \frac{dx_A^+}{t_A} \sin\left(\frac{L - x_A^+}{t_A}\right) \mathcal{S}^{(2)}(L, x_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau)) .$$

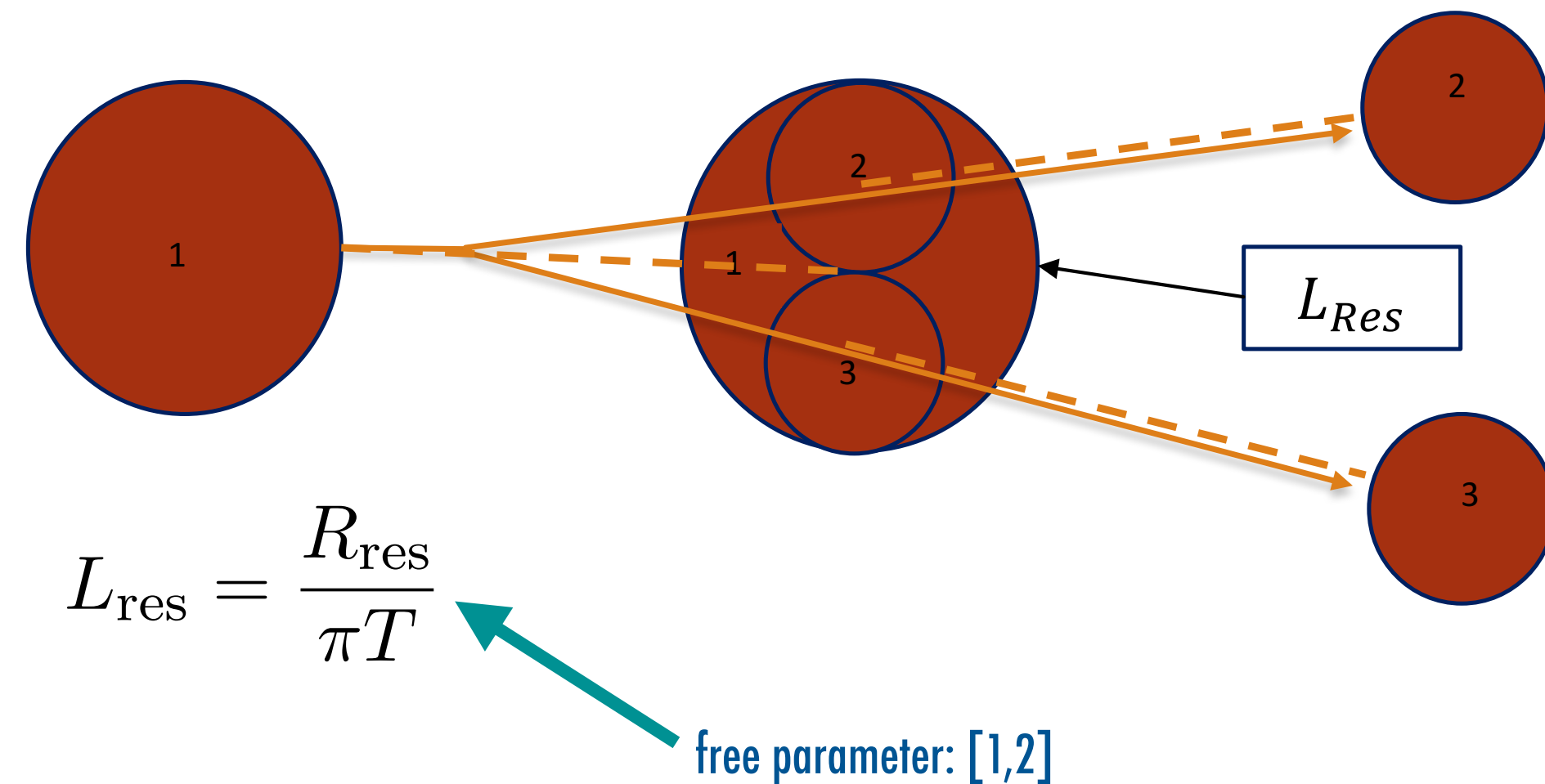
$$\tilde{\Delta}_{\text{med}} = \frac{2}{1 + F_{\text{med}}} \int_0^L \frac{d\bar{x}_A^+}{t_A} \int_0^{\bar{x}_A^+} \frac{dx_A^+}{t_A} \cos\left(\frac{\Delta x_A^+}{t_A}\right) \mathcal{S}^{(2)}(\bar{x}_A^+, x_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau)) \\ \times \left[\mathcal{Q}^{(4)}(L, \bar{x}_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau), \bar{\mathbf{r}}_q^A(\tau), \bar{\mathbf{r}}_{\bar{q}}^A(\tau)) \right. \\ \left. - \mathcal{S}^{(2)}(L, \bar{x}_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau)) \mathcal{S}^{(2)}(L, x_A^+; \mathbf{r}_q^A(\tau), \mathbf{r}_{\bar{q}}^A(\tau)) \right] .$$



no simple dependence on a decoherence angle

DECOHERENCE IN EVENT GENERATORS

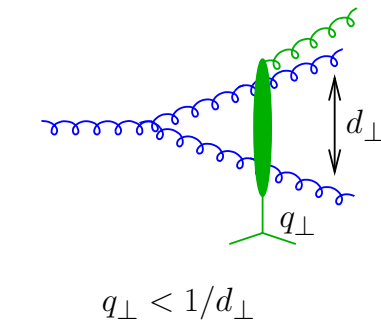
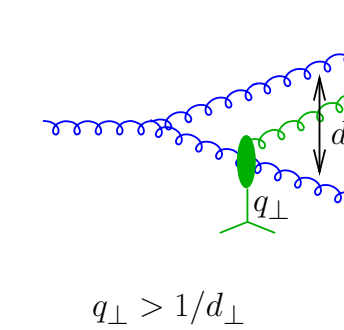
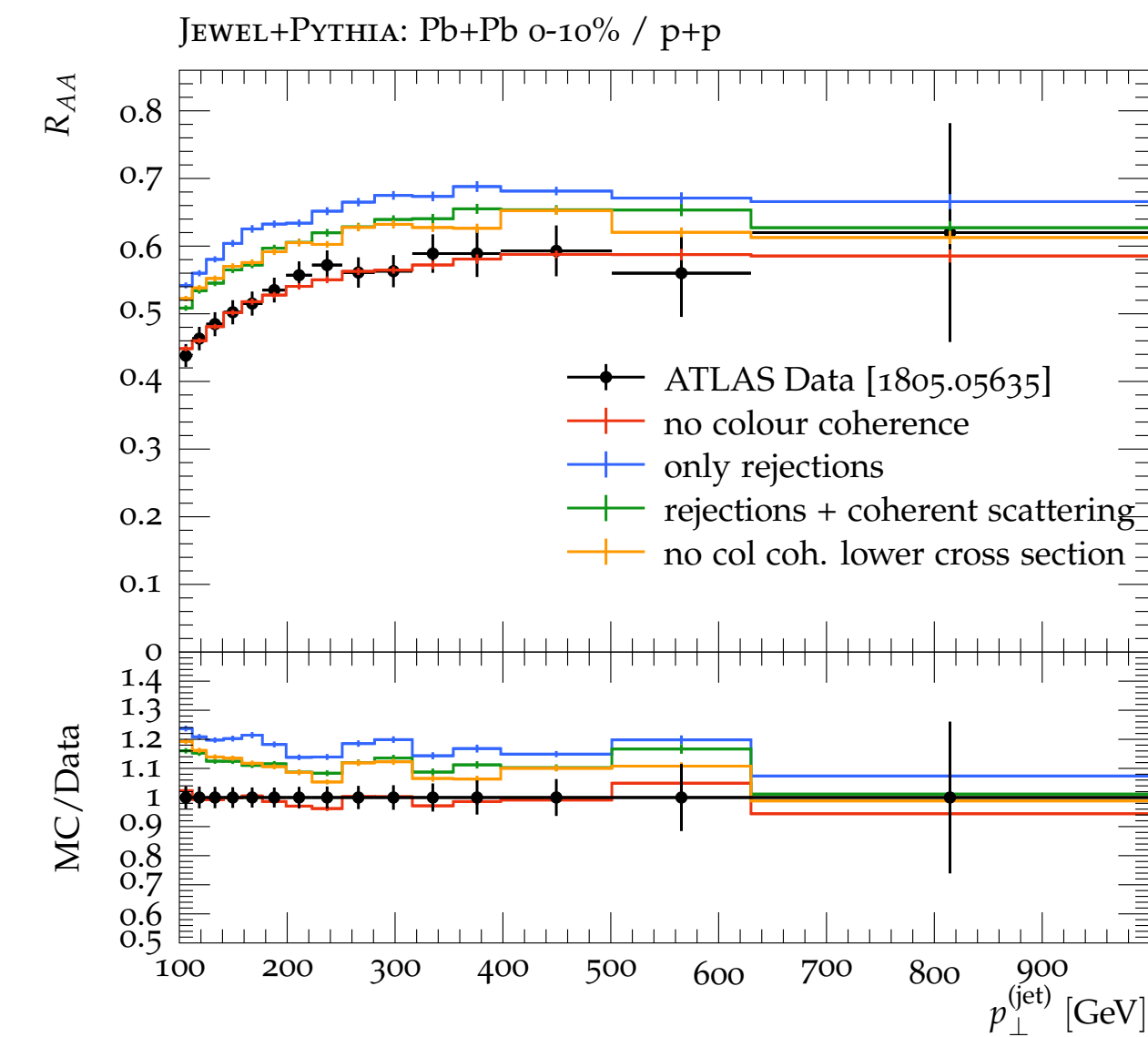
hybrid model [vacuum showers + holographic eloss]



resolution length [$\sim$ Debye length] to implement coherence effects

[Hulcher et al, 1707.05245]

JEWEL [pQCD with medium scatterings]

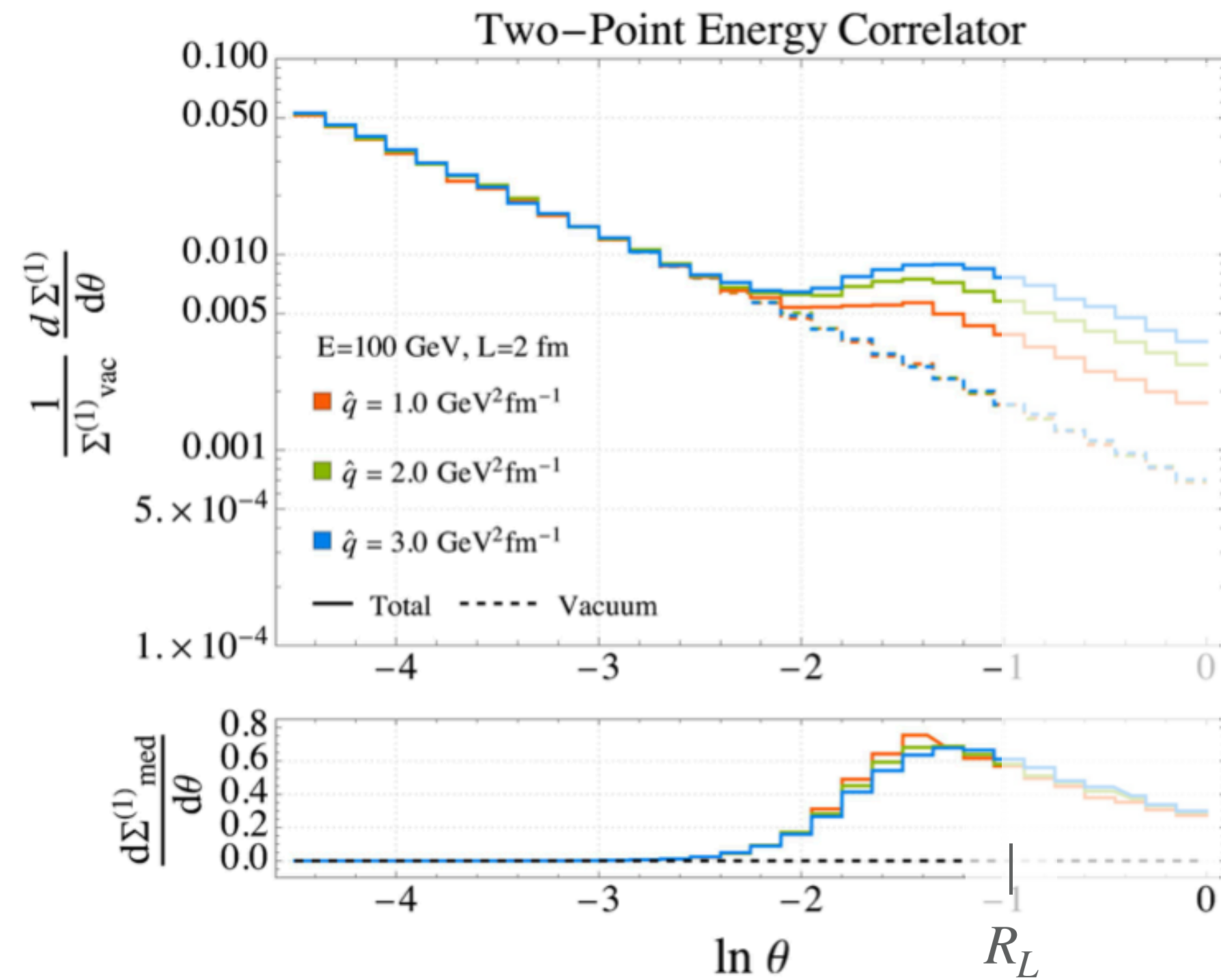


per-scattering dynamical implementation

[Zapp, 2604.13932]

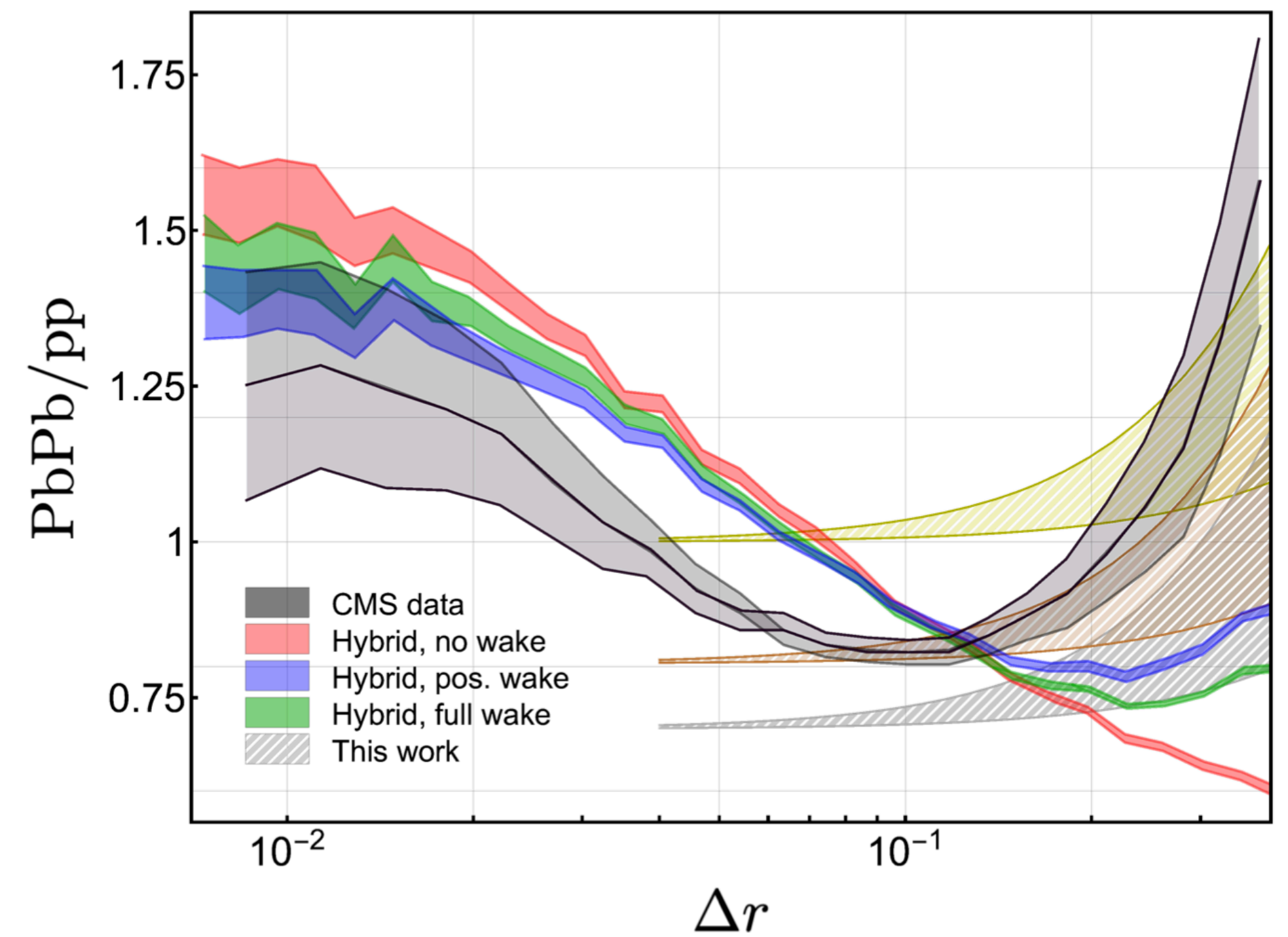
FRIEND AND FOE

EEC [ENC] sensitive to QGP effects



imprint of medium-induced radiation

[Andres et al, 2209.11236]



imprint of medium response

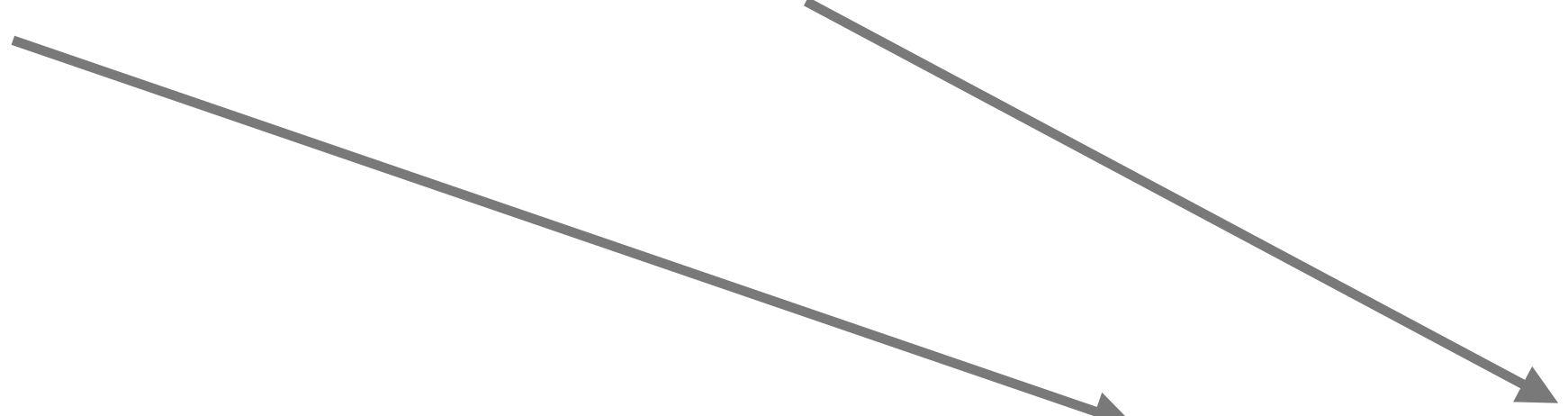
[Barata et al., 2412.03616]

contributions from different sources overlap

FRIEND AND FOE

contributions from quantum [radiation] and classical sources [hydro] overlap in 'OPE'

[Barata et al., 2410.24135]



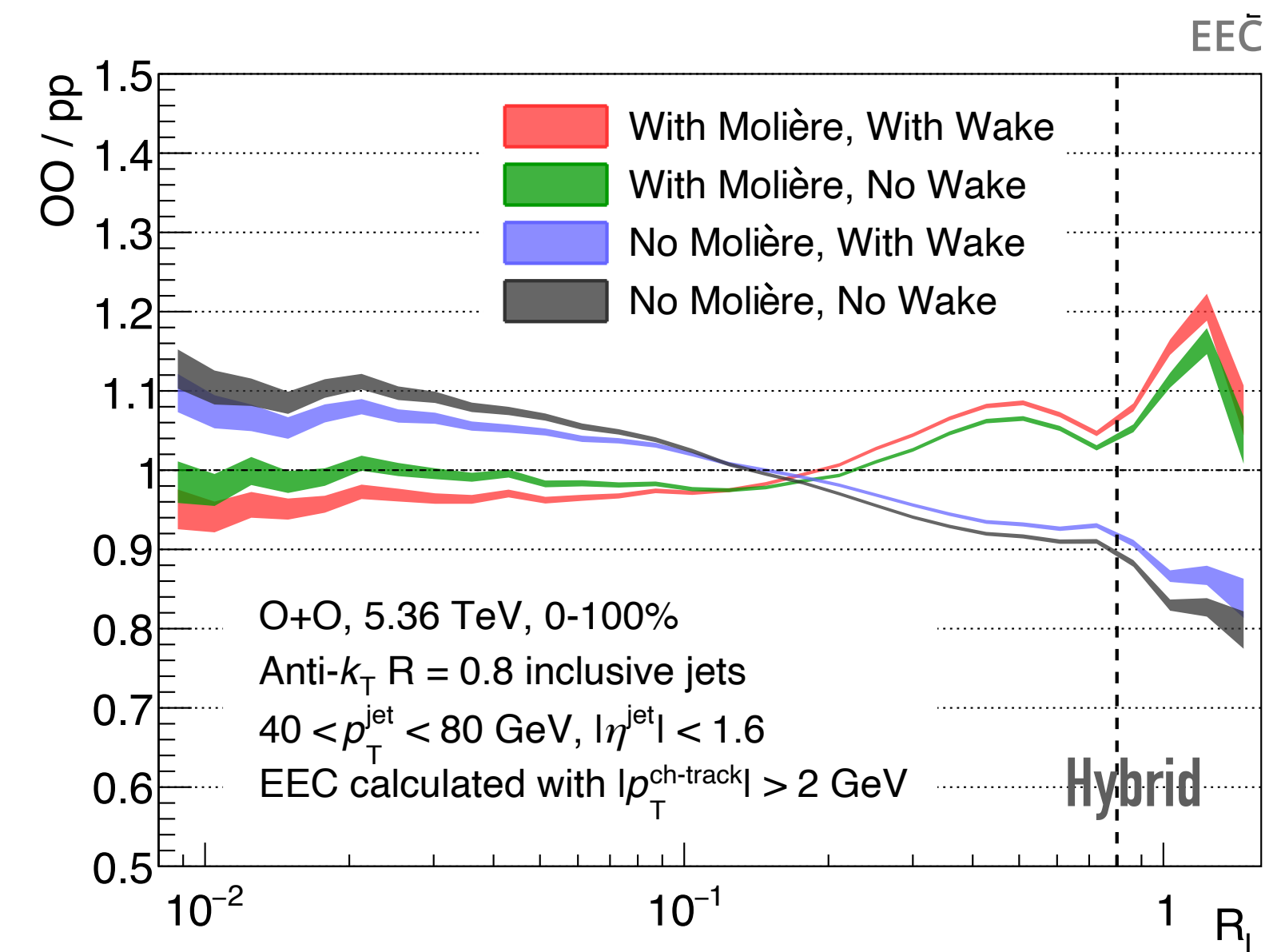
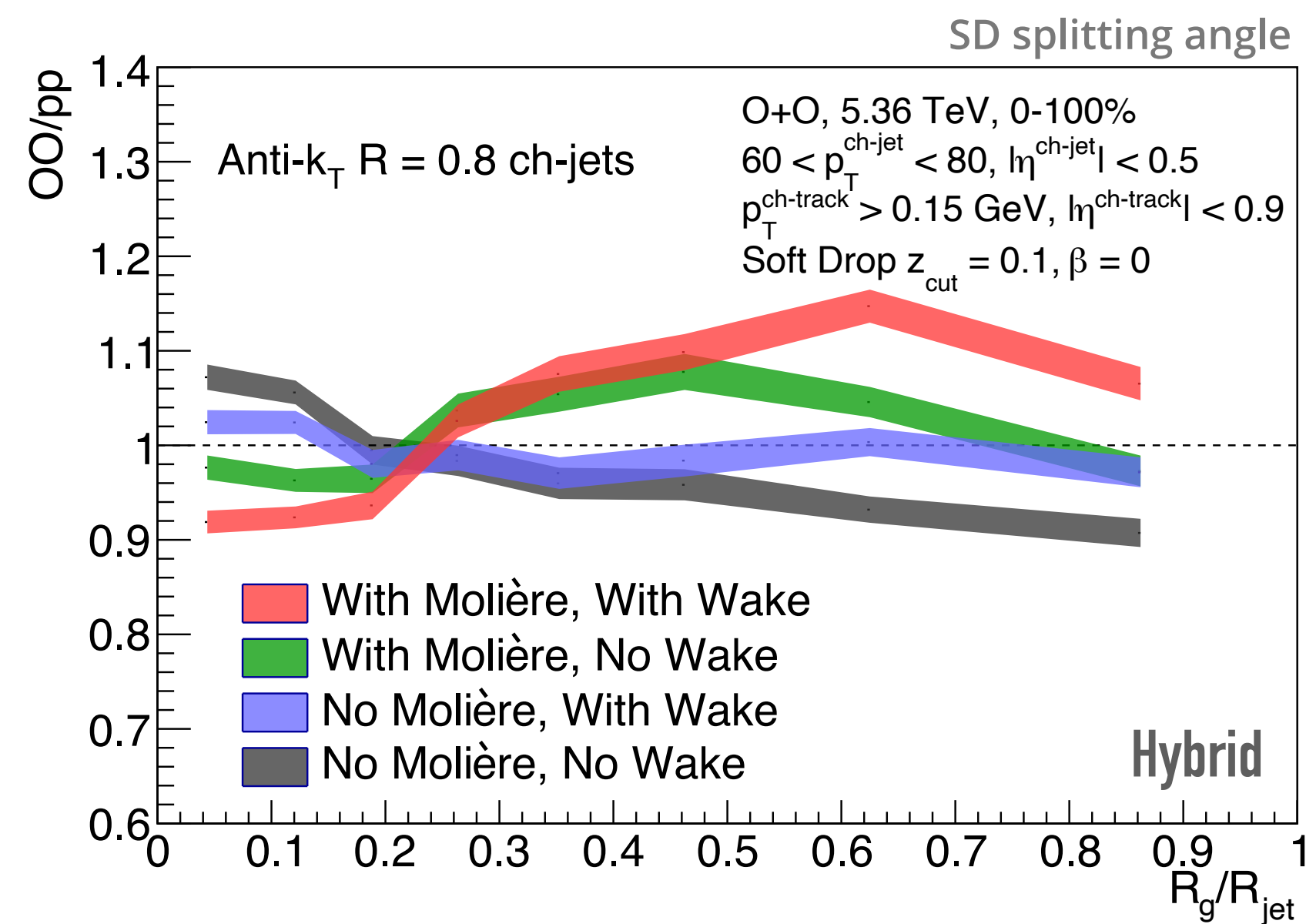
$$\frac{d\Sigma_P^{(N)}}{dR_L} = \sum_{\tau} \left\{ a_{\tau,0}^{P(N)} R_L^{-\delta_{\tau,2}\gamma(N+1)} + b_{\tau,0}^{P(N)} + c_{\tau}^{P(N)} \right\} R_L^{\tau-3}$$

several variations being considered as potential discriminators

WHAT DO SHOWER PARTONS INTERACT WITH ?

models/frameworks consider alternatively QGP quasi-particles or an evolving fluid

at some resolution scale [high enough momentum exchange], partons should resolve QGP quasi-particles
high-momentum scatterings should deviate partons



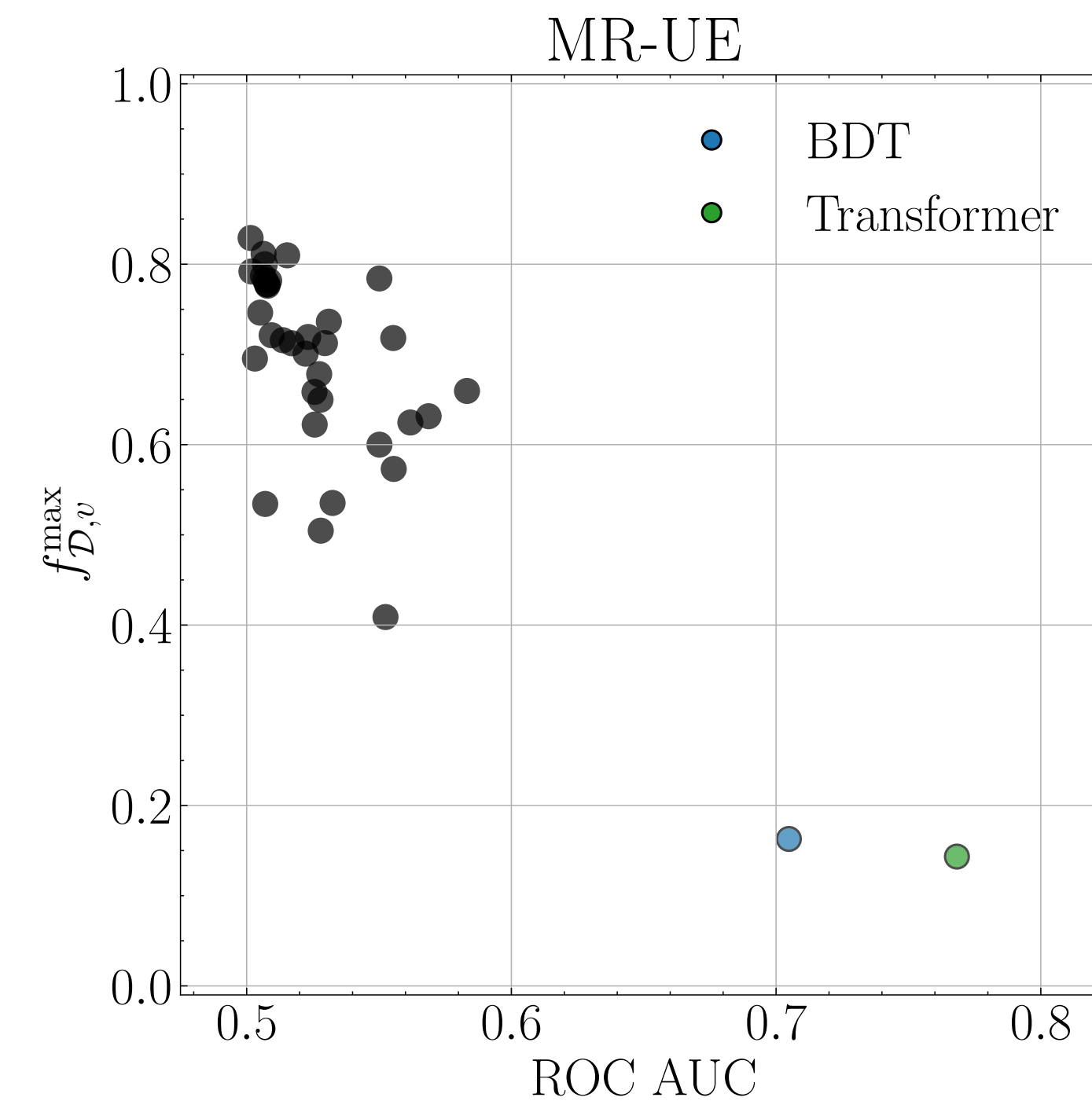
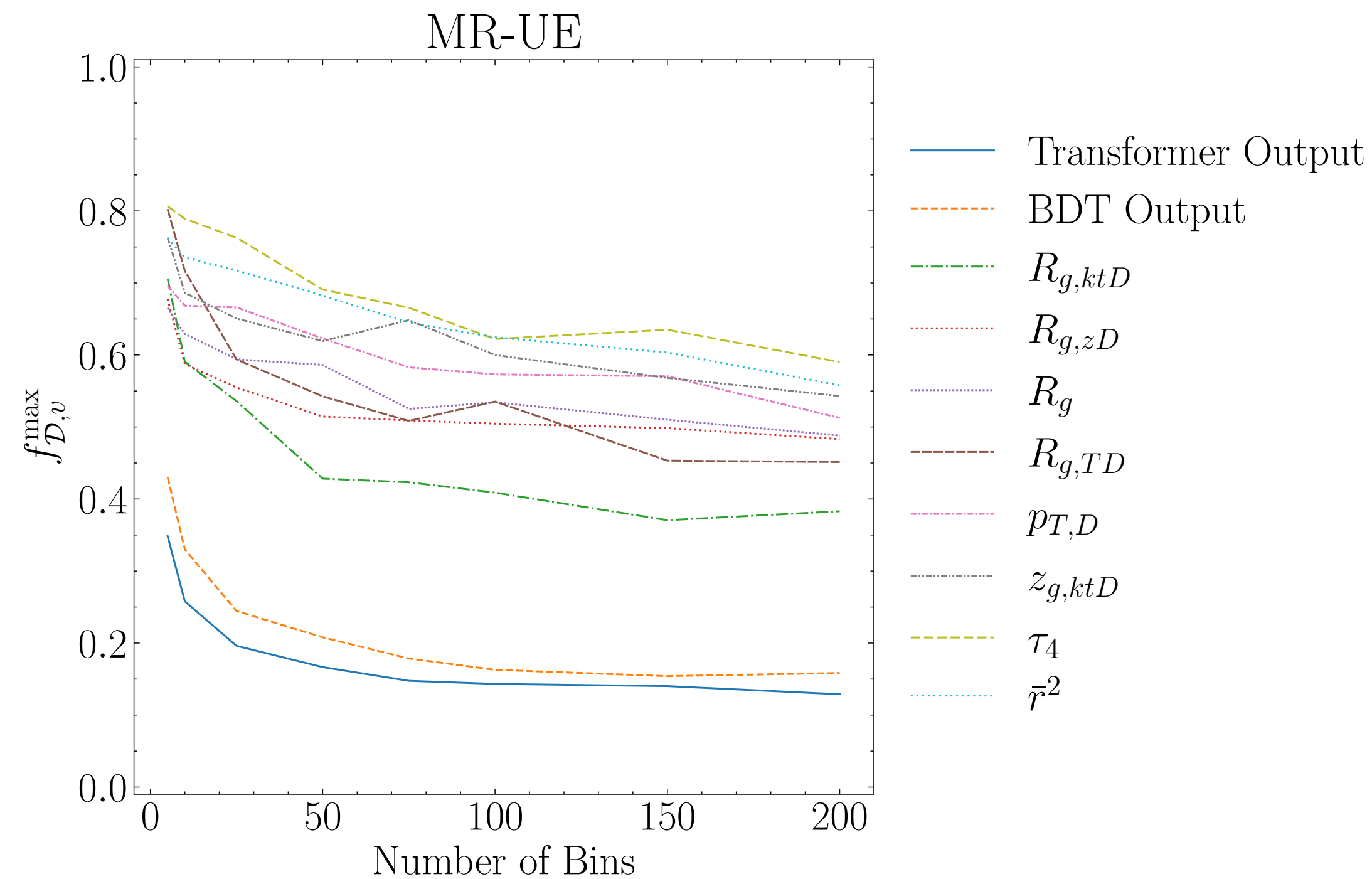
OO collisions, where overall jet modifications are small, should allow for observation of [semi-] hard scatterings

AN EXAMPLE, AMONG MANY, OF USE OF ML/DL

[Gonçalves et al., 2511.10724]

ML/DL architectures identify jet modifications beyond what is captured by single observables

fraction of jets that cannot be distinguished from [embedded] pp jets minimized by architecture sensitive to multi-particle correlations



strong suggestion of importance of observables based on multi-point correlators in QGP studies

EXCUSATIO.....

what I left out for no justifiable reason [a lot of activity; a lot of results]

- anything to do with heavy flavour and quarkonia
 - parton dynamics in anisotropic media and description of pre-hydrodynamical stage
 - simulation of concurrent jet dynamics and QGP evolution
 - SCET reformulation of jet dynamics
 - simulation/computation of medium response
 - jets as QGP chronometers
-
- anything else I may have overlooked ...

**But in reality we took a certain pleasure in this game,
being still close to the age when we believe we create
what we name.**

“Mais en réalité nous prenions un certain plaisir à ce jeu, étant encore rapprochés de l'âge où on croit qu'on crée ce qu'on nomme.”

Marcel Proust, À la recherche du temps perdu (1913)