Theory of heavy (and light!)-ion collisions

Jasmine Brewer

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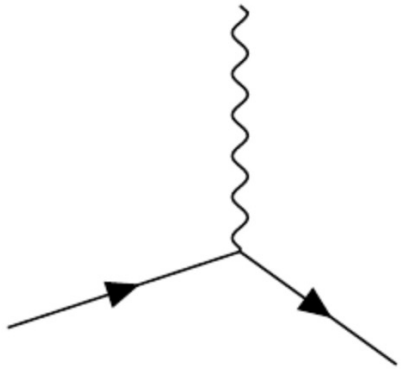
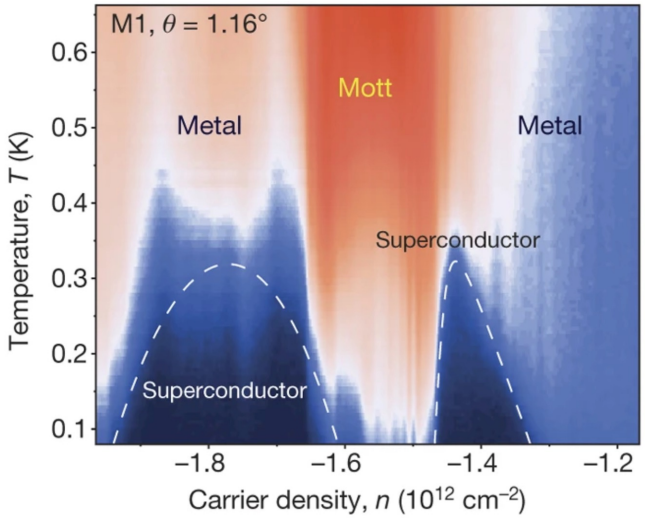
Special thanks to Samuel Abreu, Simon Grosse-Holz, Aleksas Mazeliauskas, Wilke van der Schee, and Urs Wiedemann

QED

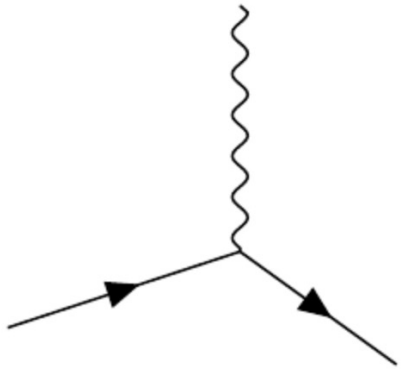


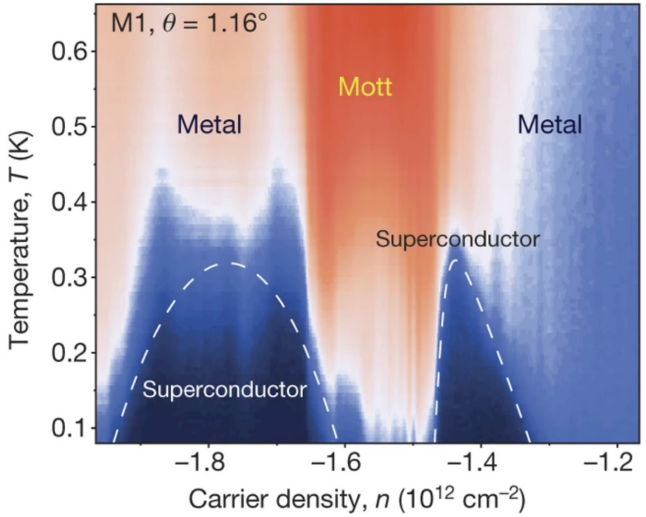


Magic angle graphene

Cao et. al. *Nature* **556**, 43–50 (2018)

QED





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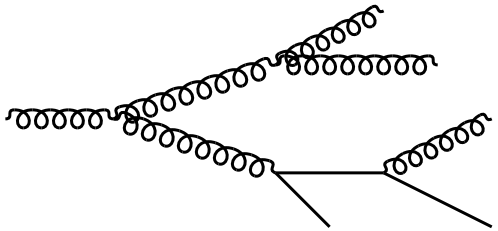
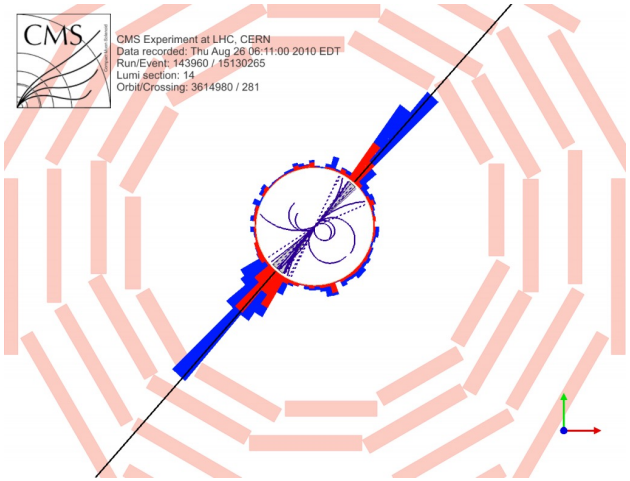
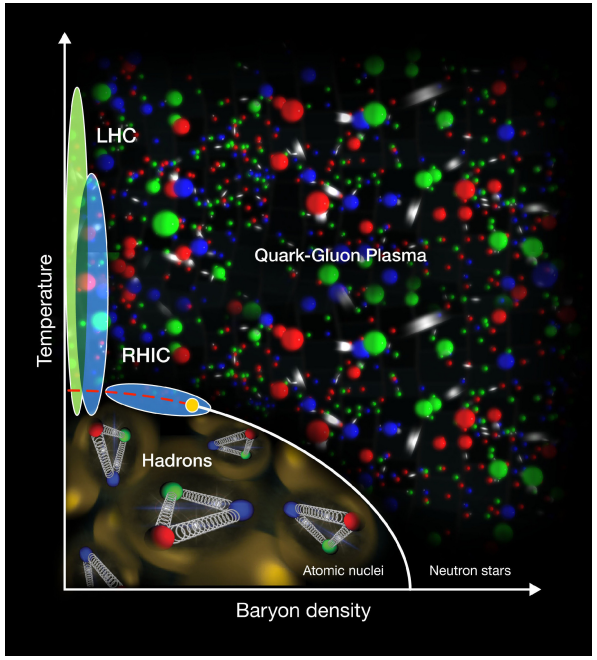
QCD





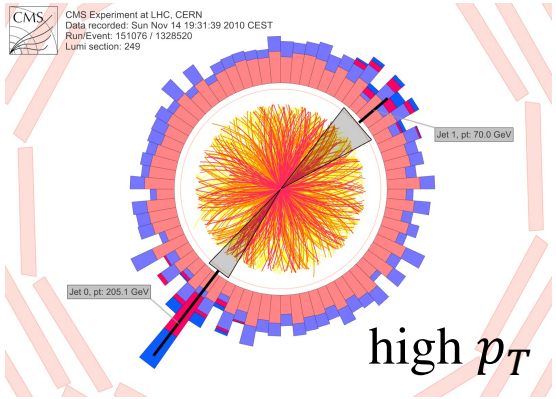


Understanding the fundamental interactions is just the beginning!

Evidence for the formation of dense QCD medium

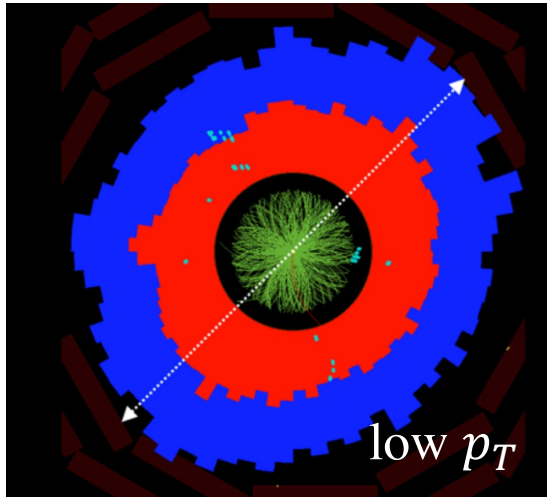
~ 100 GeV

Suppressed yield of high-energy probes (hadrons, jets, heavy flavor, ..)

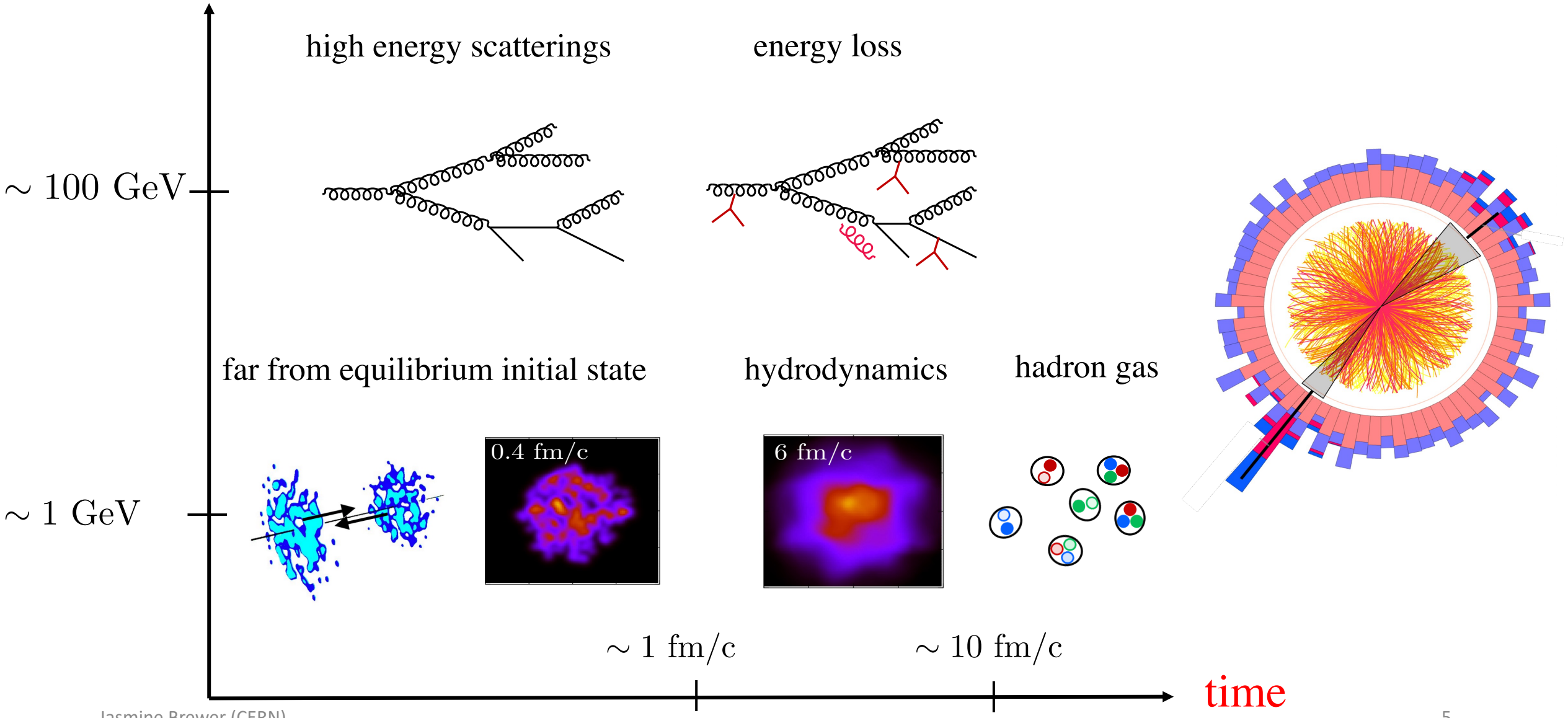


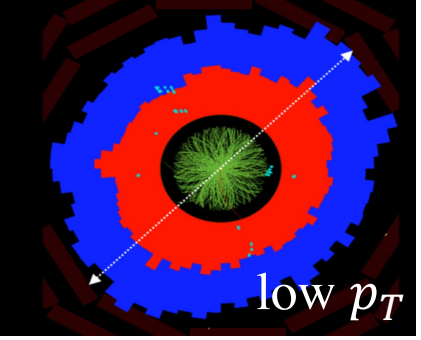
~ 1 GeV

Collective behavior of low-p_T particles



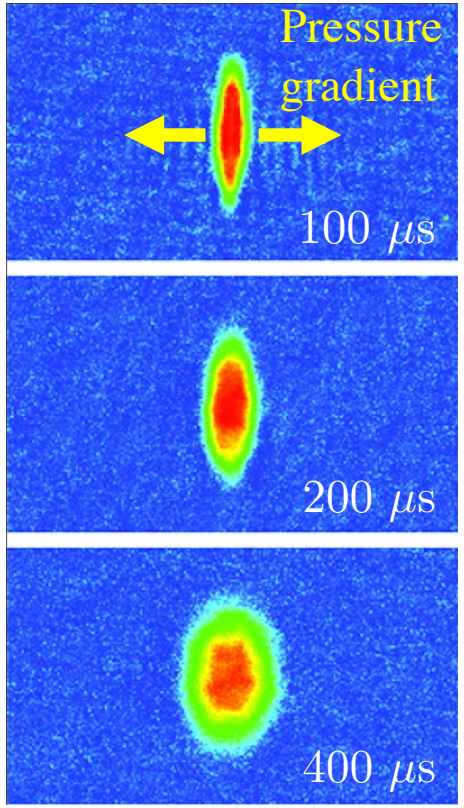
Heavy-ion collisions





Long-range correlations as a characteristic signature of collectivity

Heavy-ion collisions have initial ellipticity



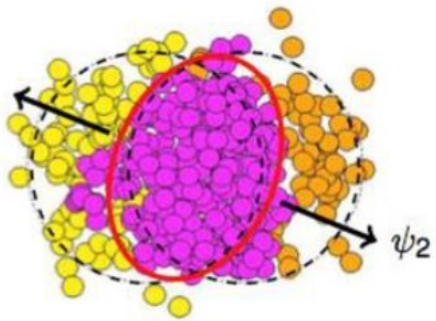
Degenerate Fermi gas

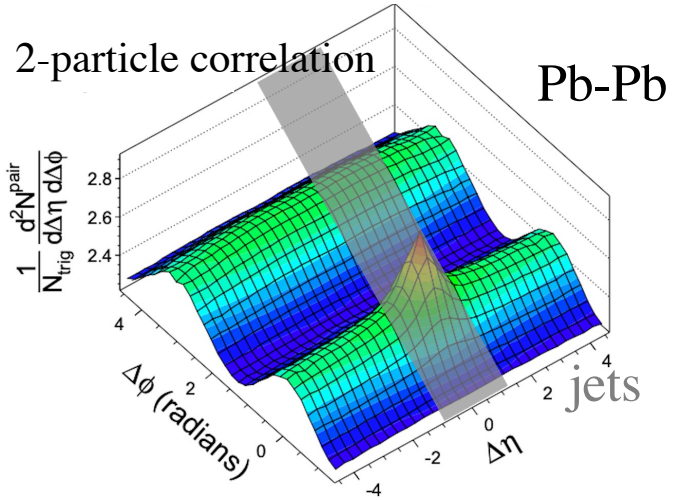
O'Hara et. al. *Science* 13 Dec 2002

spatial anisotropy

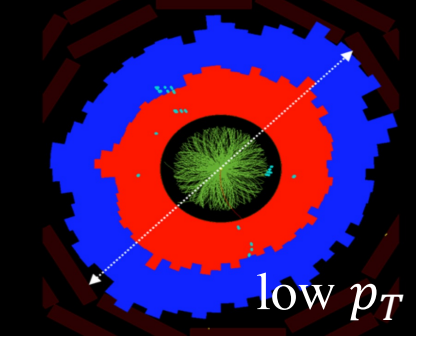
↓

momentum anisotropy





$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi)$$



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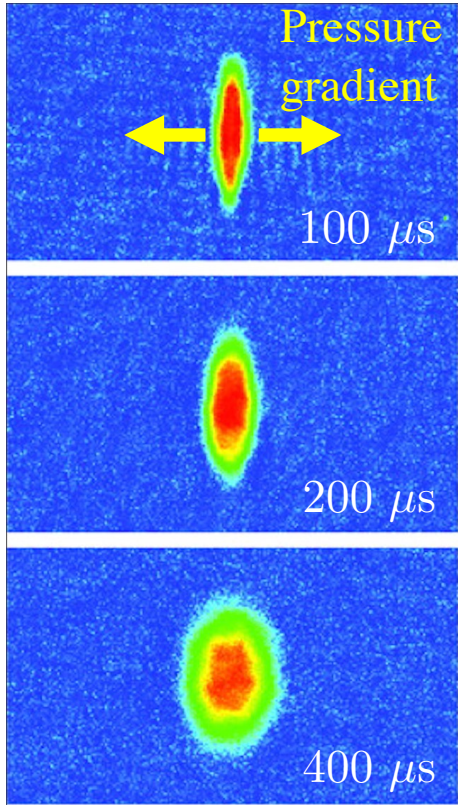

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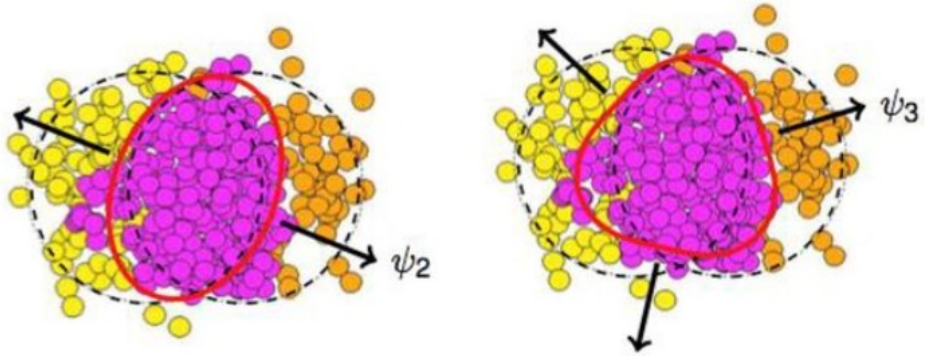
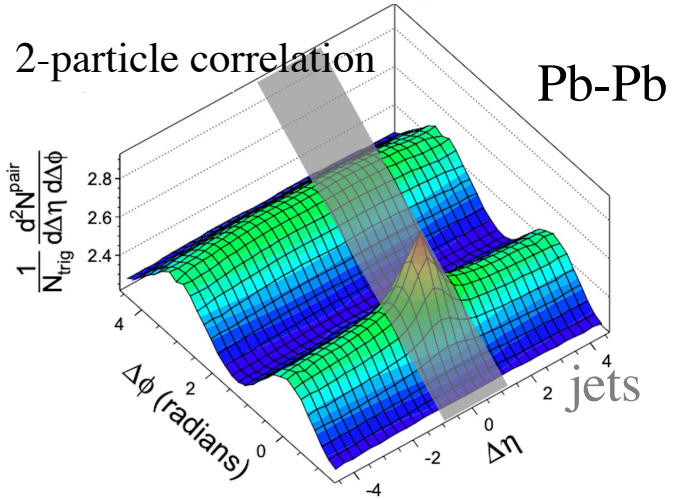
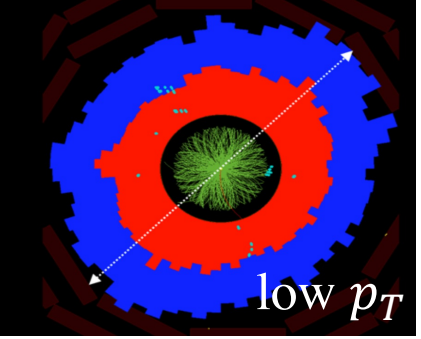
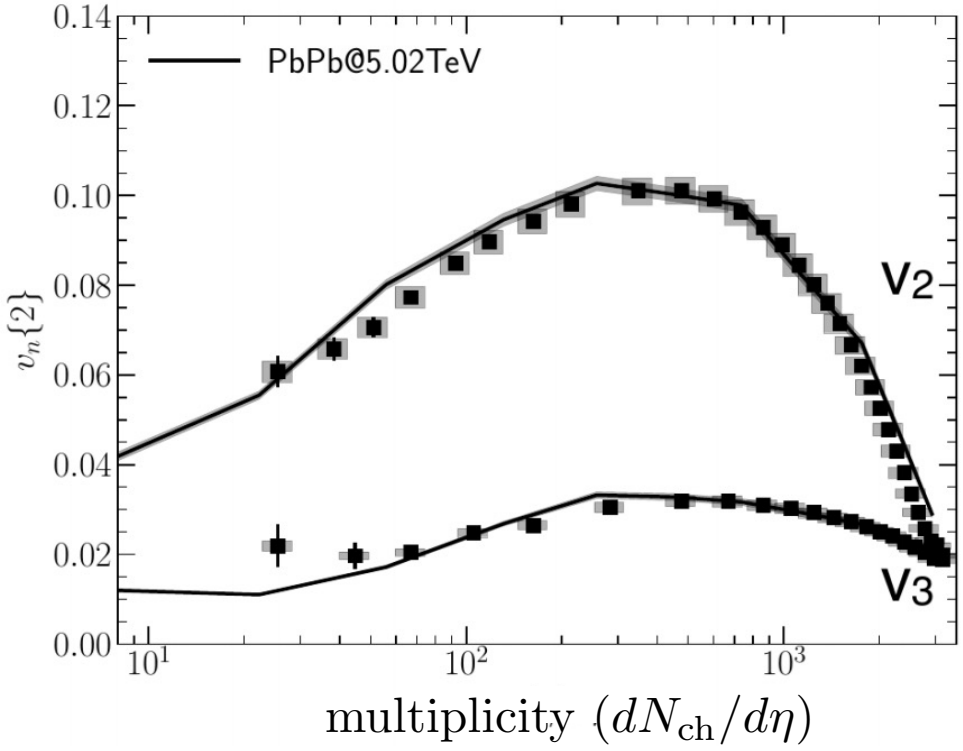




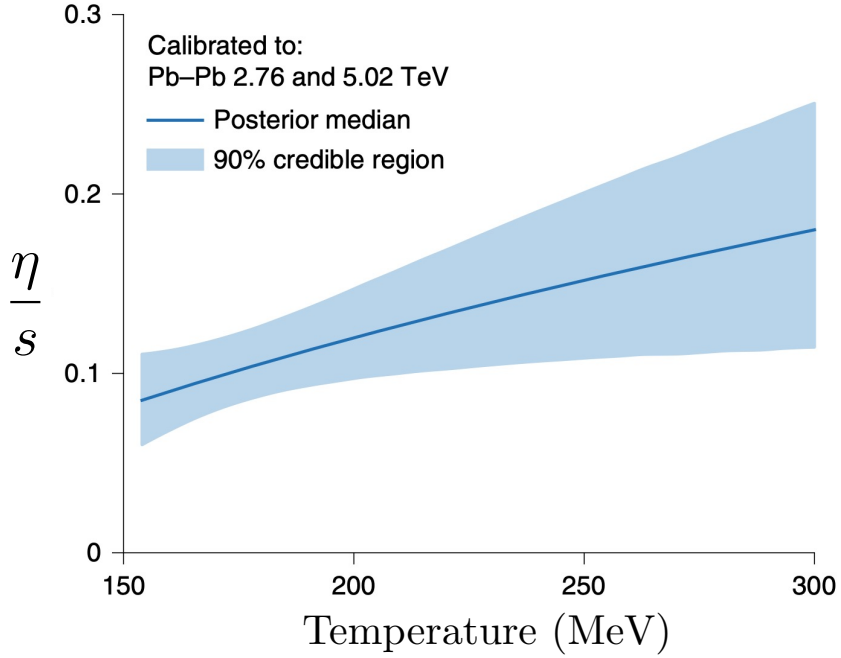
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots$$



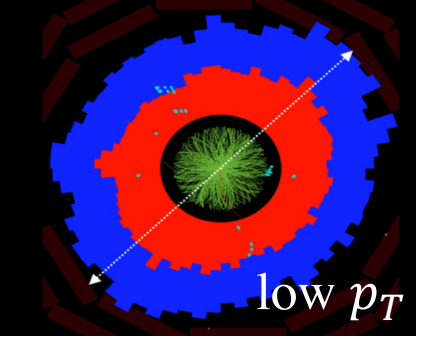
Azimuthal correlations captured by hydrodynamics and constrain transport coefficients of the QGP



Schenke, Shen, Tribedy [2005.14682], Chun Shen QM'19



Bernhard, Moreland, Bass *Nature Phys*. 15 (2019) 11



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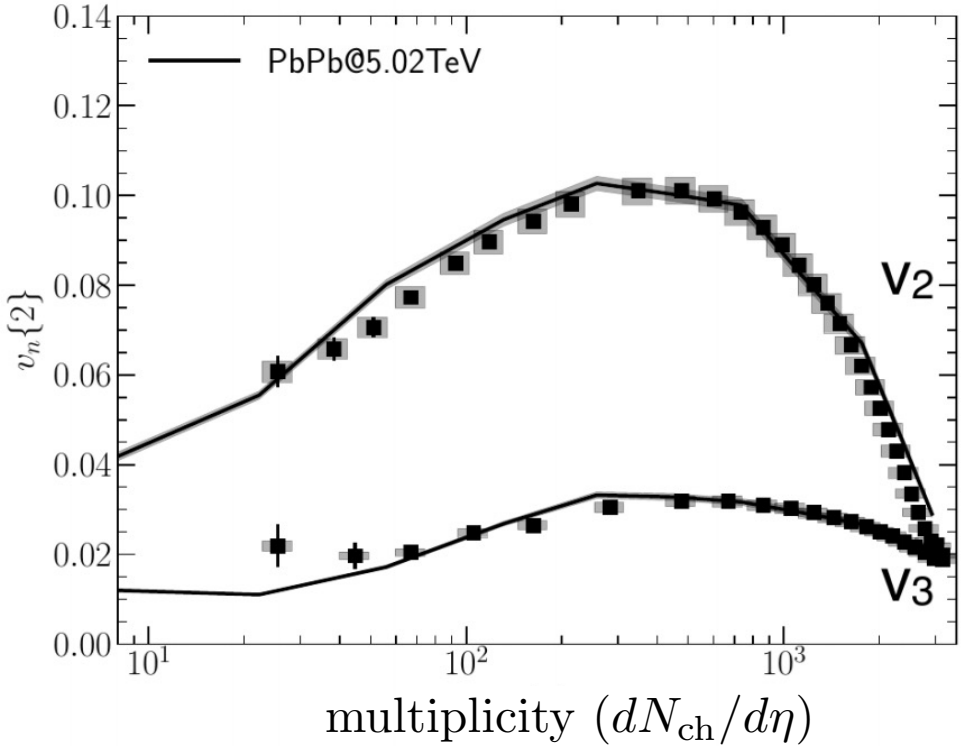
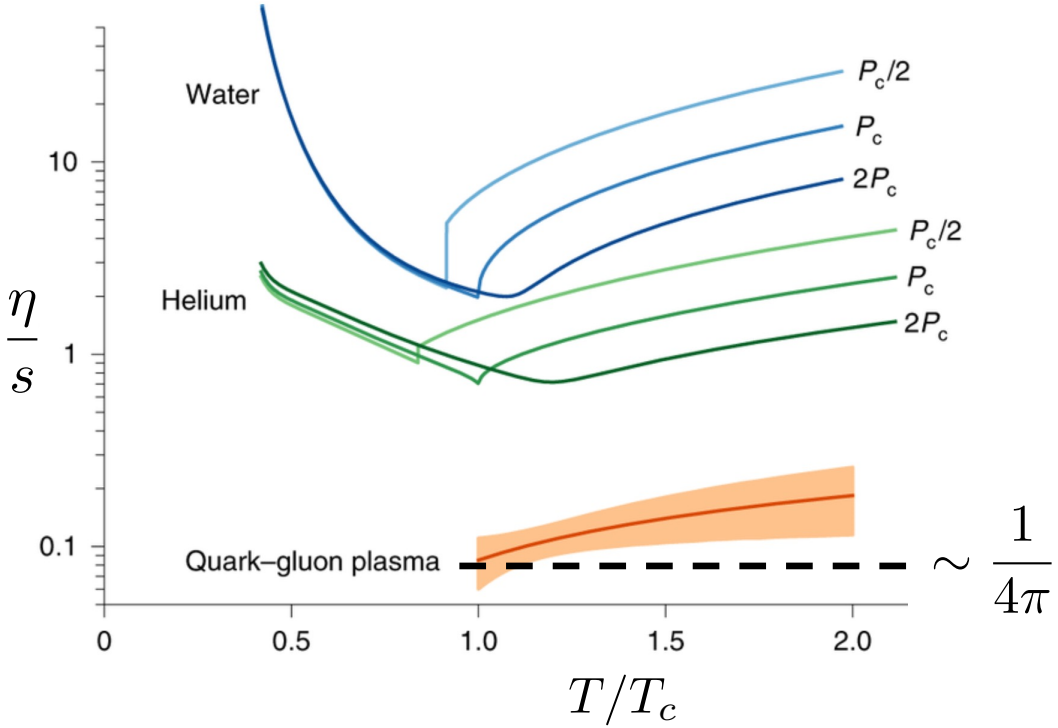
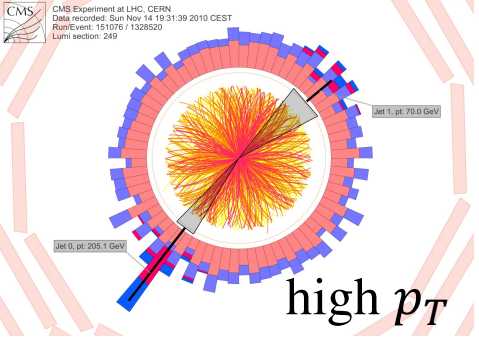


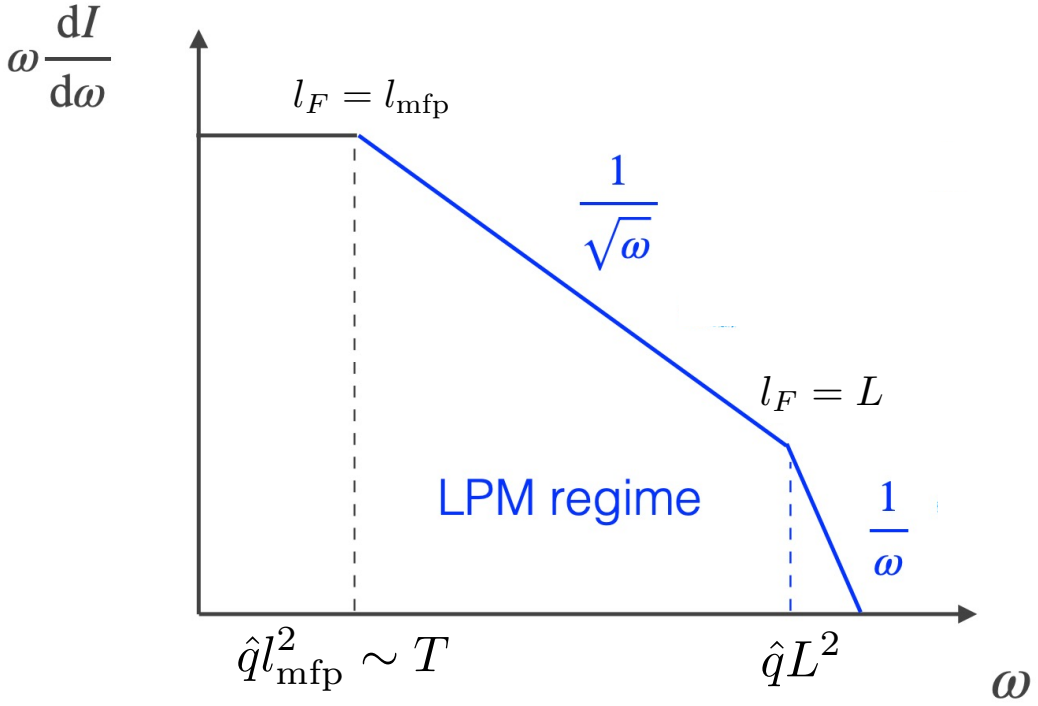
Schenke, Shen, Tribedy [2005.14682], Chun Shen QM'19



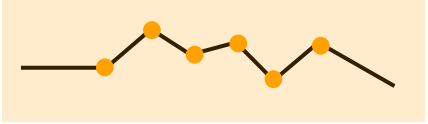
Bernhard, Moreland, Bass *Nature Phys*. 15 (2019) 11
Kovtun, Son, Starinets [0405231]



Energy loss of a parton in finite-temperature QCD



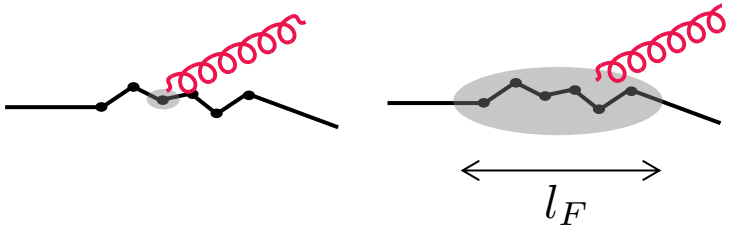
Parton undergoes transverse momentum diffusion

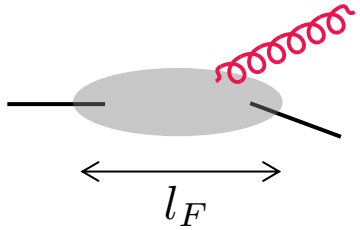


$$\hat{q} \equiv \frac{d\langle k_\perp^2 \rangle}{dt}$$

Kicks occasionally induce gluon radiation

Radiation can't be resolved instantaneously

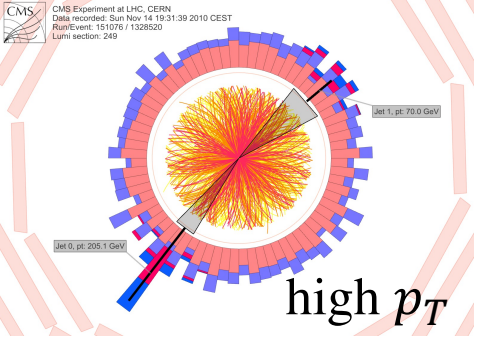




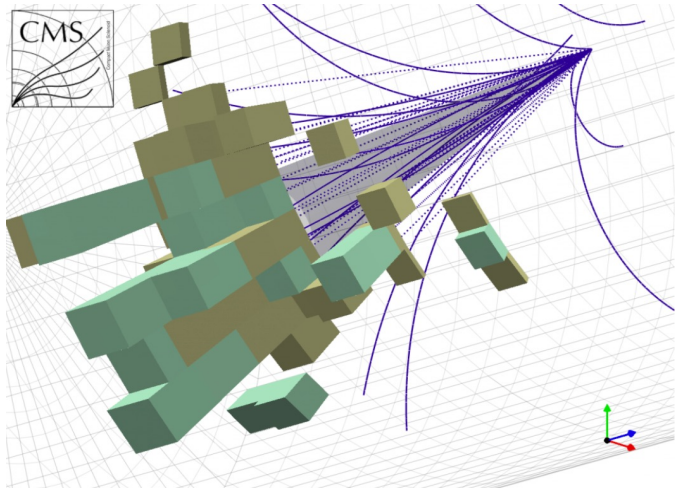
$$l_F \propto \sqrt{\omega}$$

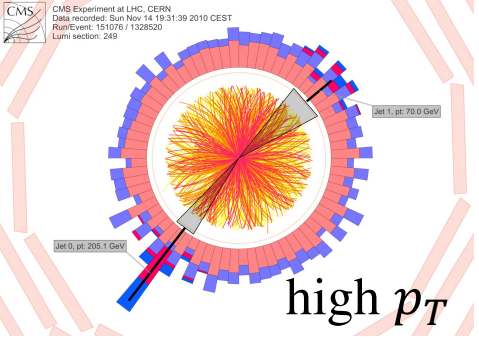
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996), Zakharov (1996)
Arnold, Moore, Yaffe (2003)

Fig: adapted from Yacine Mehtar-Tani QM'19



Jet modification





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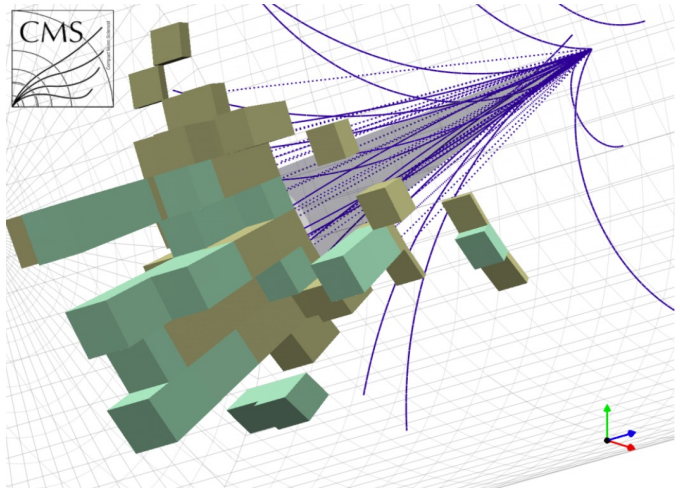
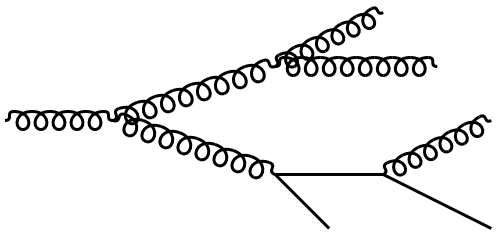
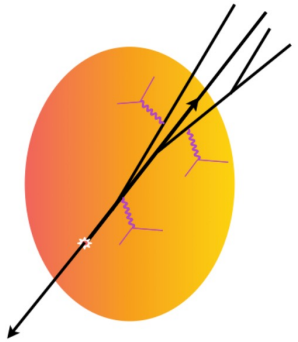


Momentum space

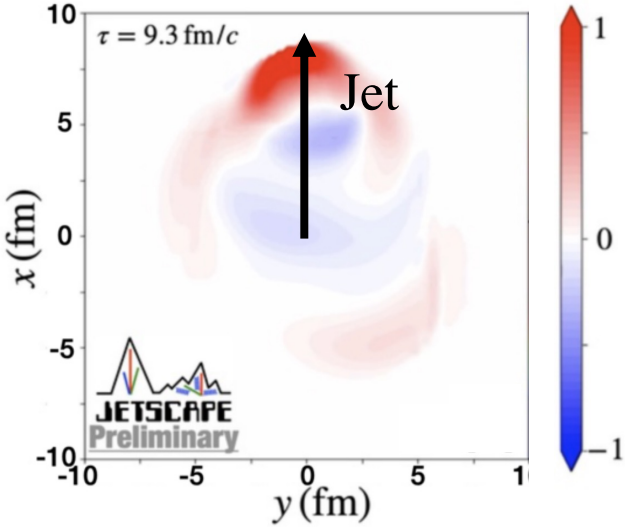


formation time

Position space

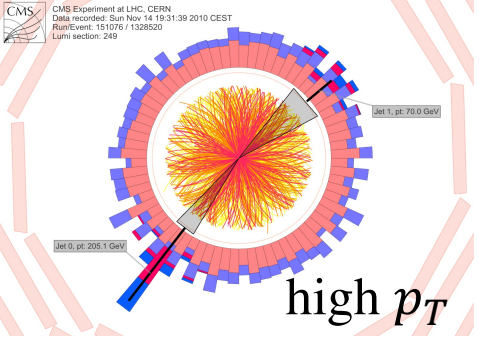


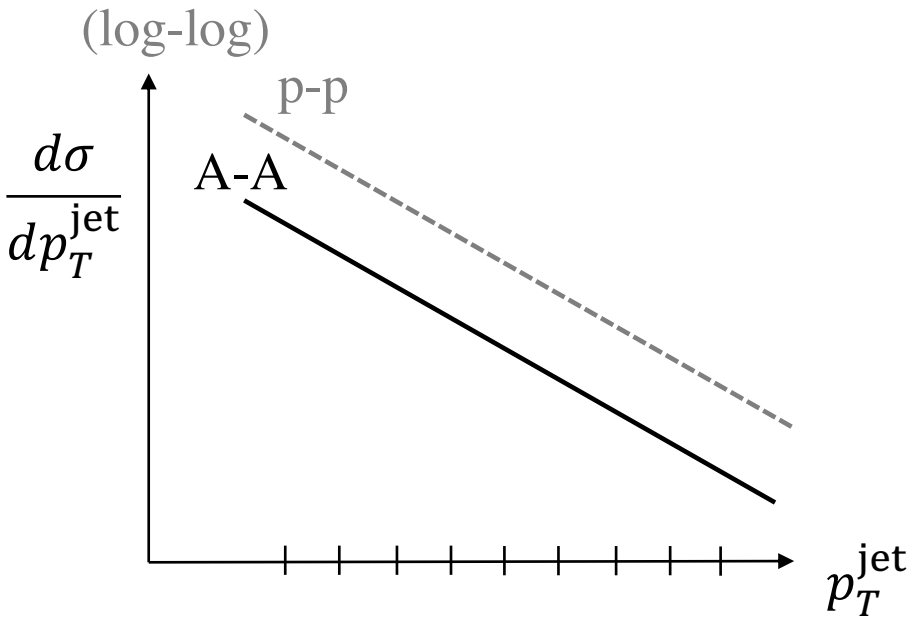
Change in temperature from jet

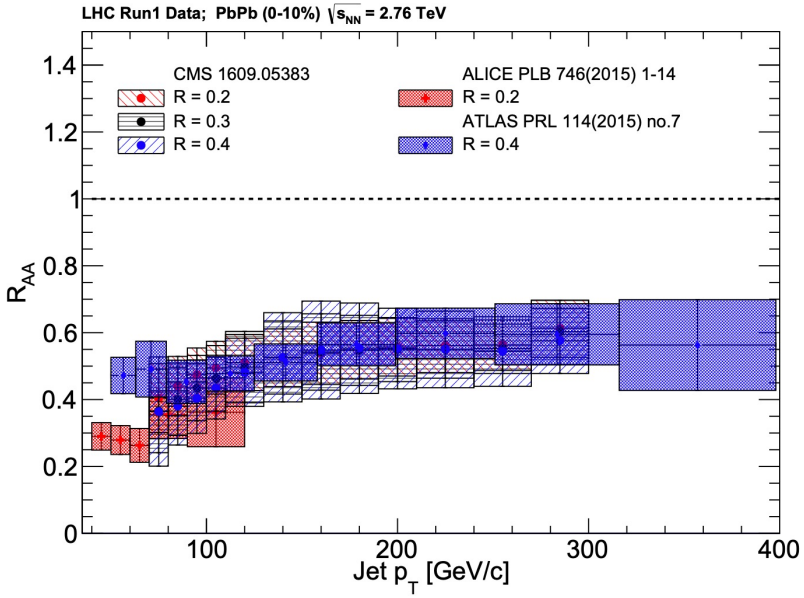


Tachibana (JETSCAPE) [2002.12250]

Jet modification

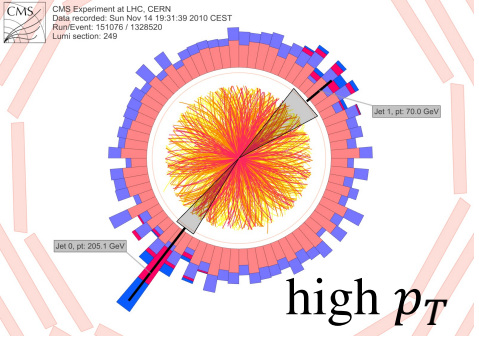


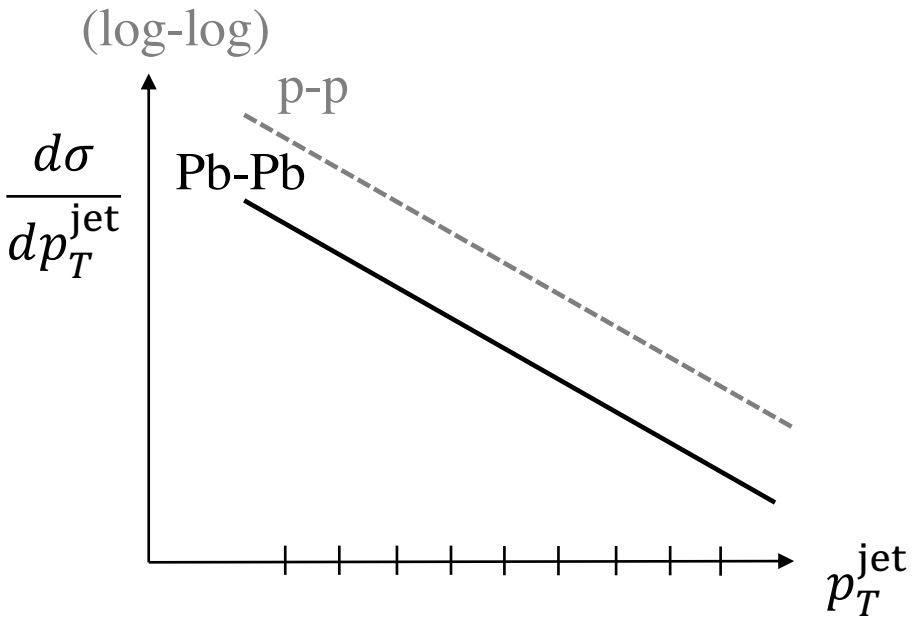


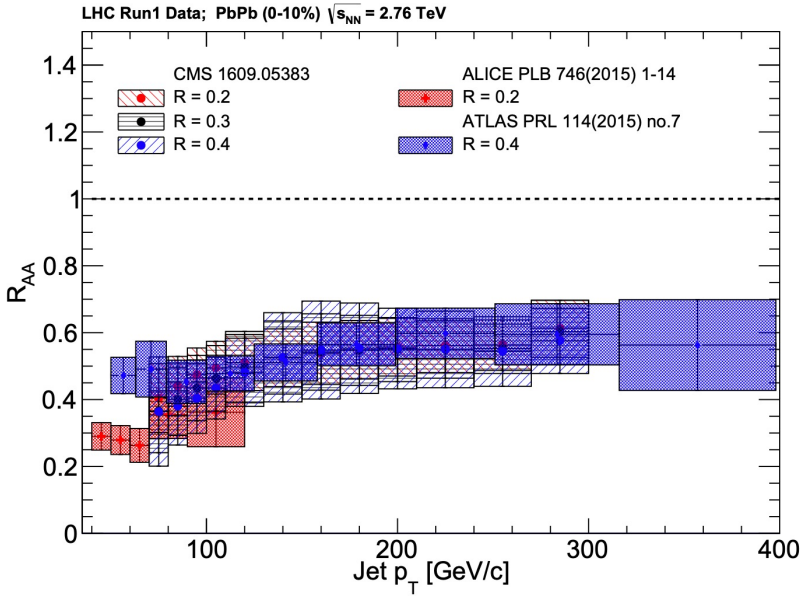


R. Elayavalli, from [1705.01974]

Jet modification







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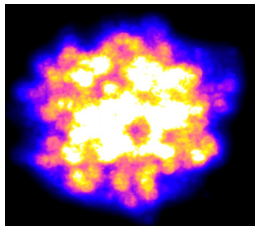
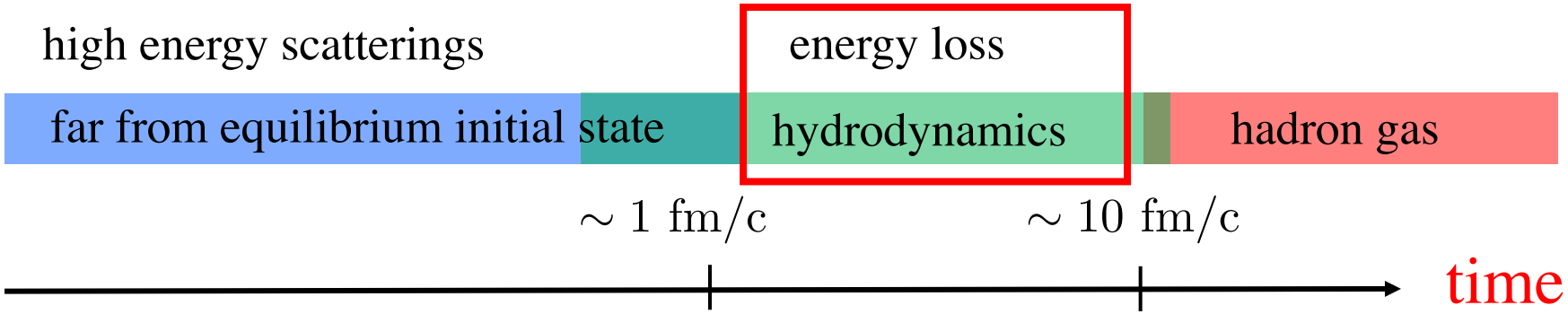
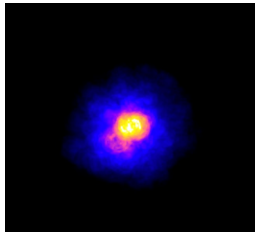
Beyond energy loss: Jet (sub)structure modification by the medium

Pushing our knowledge of heavy-ion physics in smaller systems

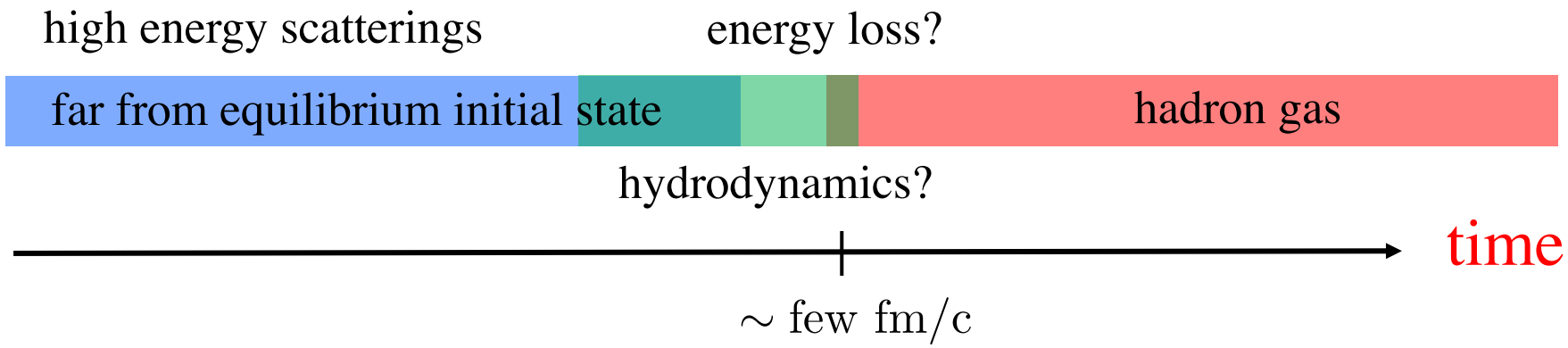


Heavy-ion collisions



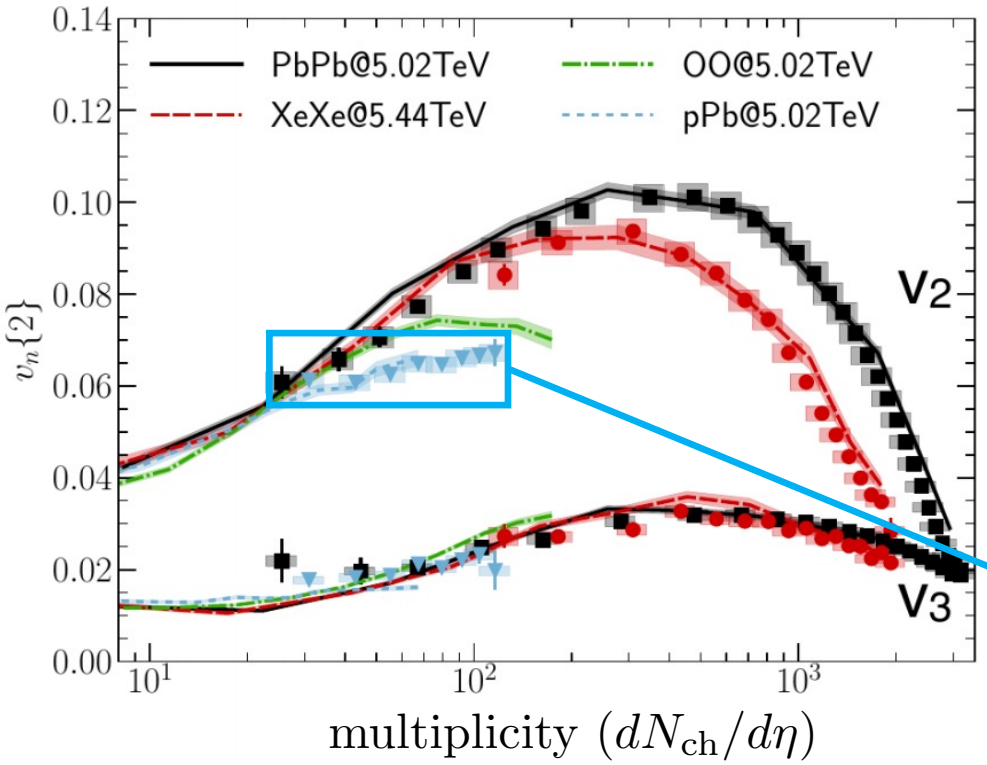


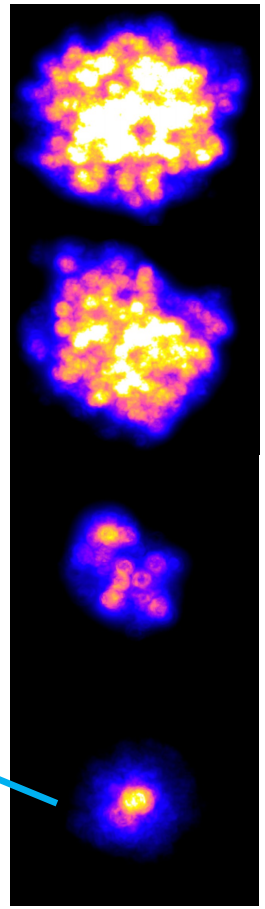
Smaller systems (e.g. p-Pb)



Flow-like correlations in small systems

No observed energy loss



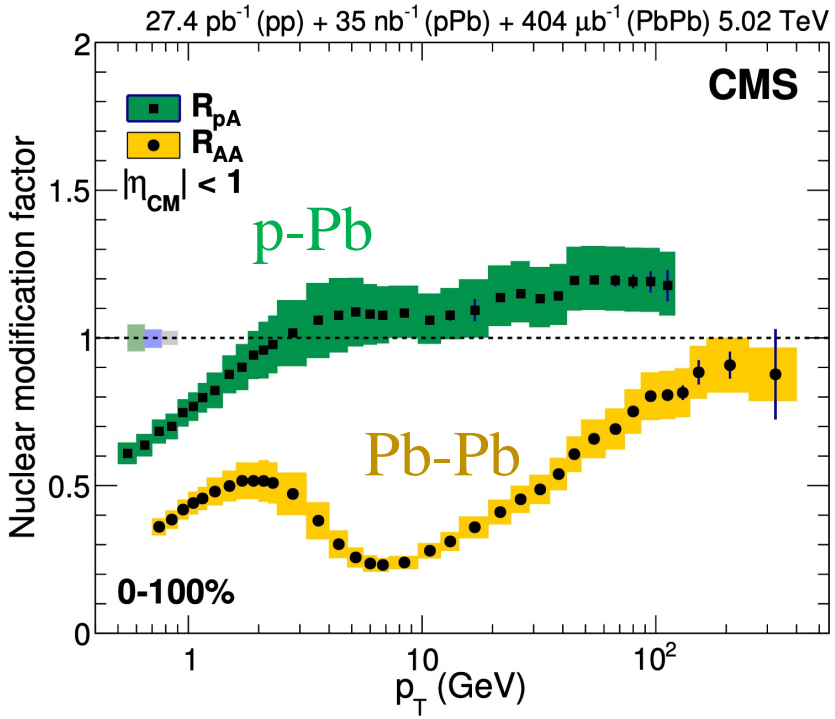


Pb-Pb

Xe-Xe

O-O

p-Pb



Schenke, Shen, Tribedy [2005.14682], Chun Shen QM'19

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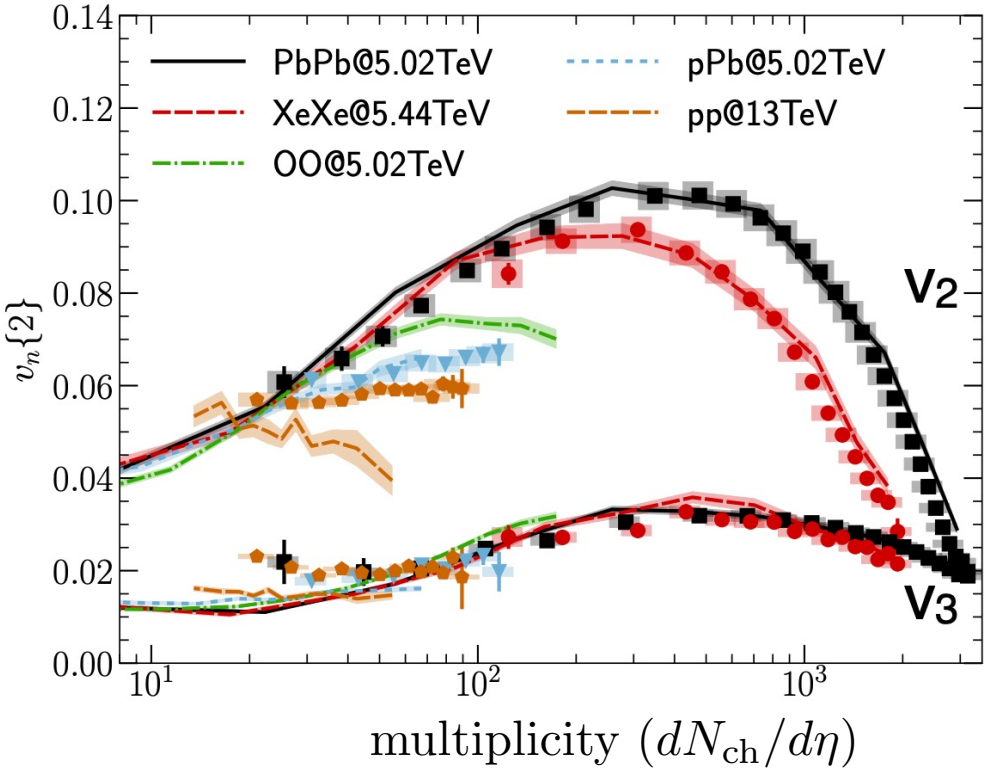

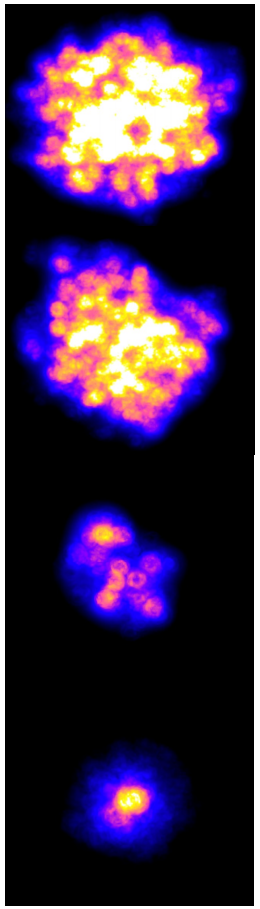

Pb-Pb

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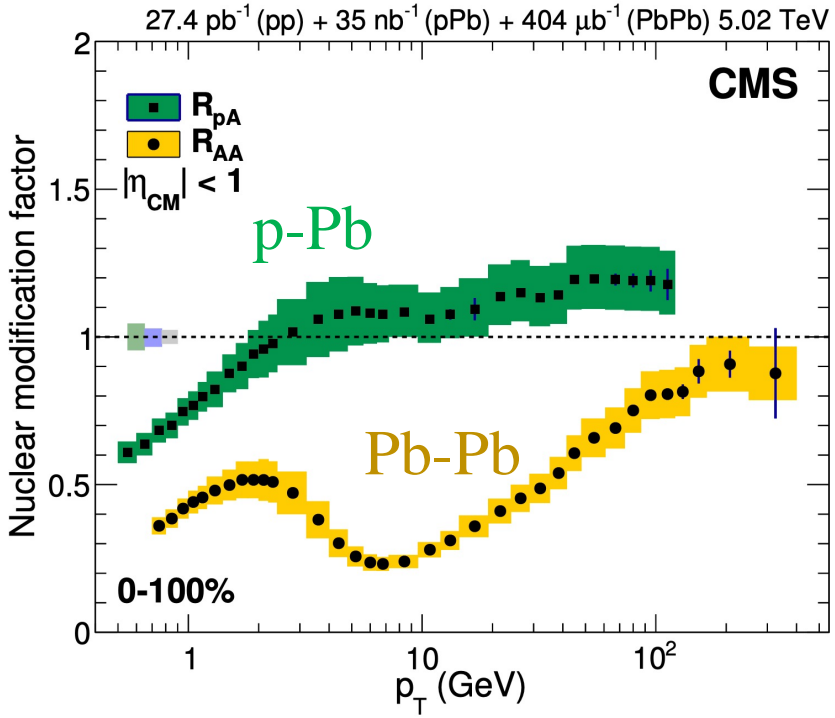
O-O

p-Pb

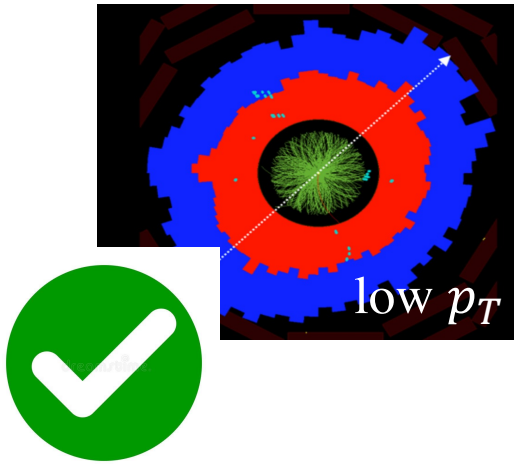
No observed energy loss

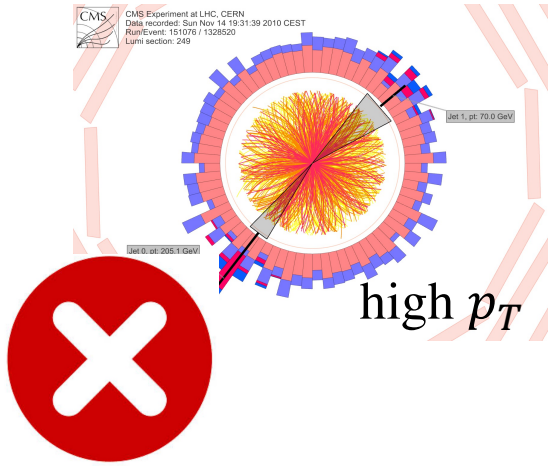


Schenke, Shen, Tribedy [2005.14682], Chun Shen QM'19

Challenges and opportunities for theory in small systems

p-Pb:





Are v_n a signature of final-state collectivity?

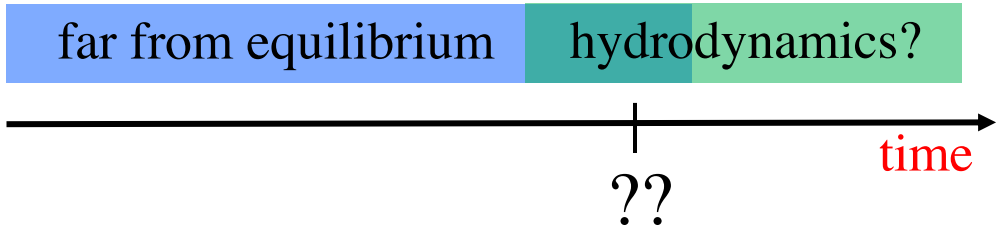
- Applicability of hydrodynamics far-from-equilibrium
- Initial- and final-state effects in v_n

Is no energy loss consistent with final-state collectivity?

- Thermalization, hydrodynamization, and jet quenching

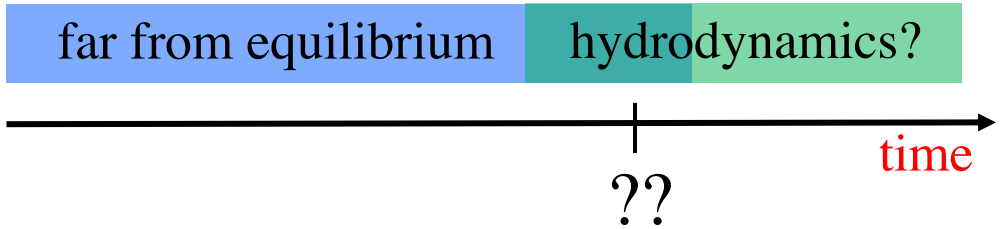
Flow in small systems challenges the standard view of hydrodynamics

"close" to (local) equilibrium,
conservation laws dominate
(gradient expansion)

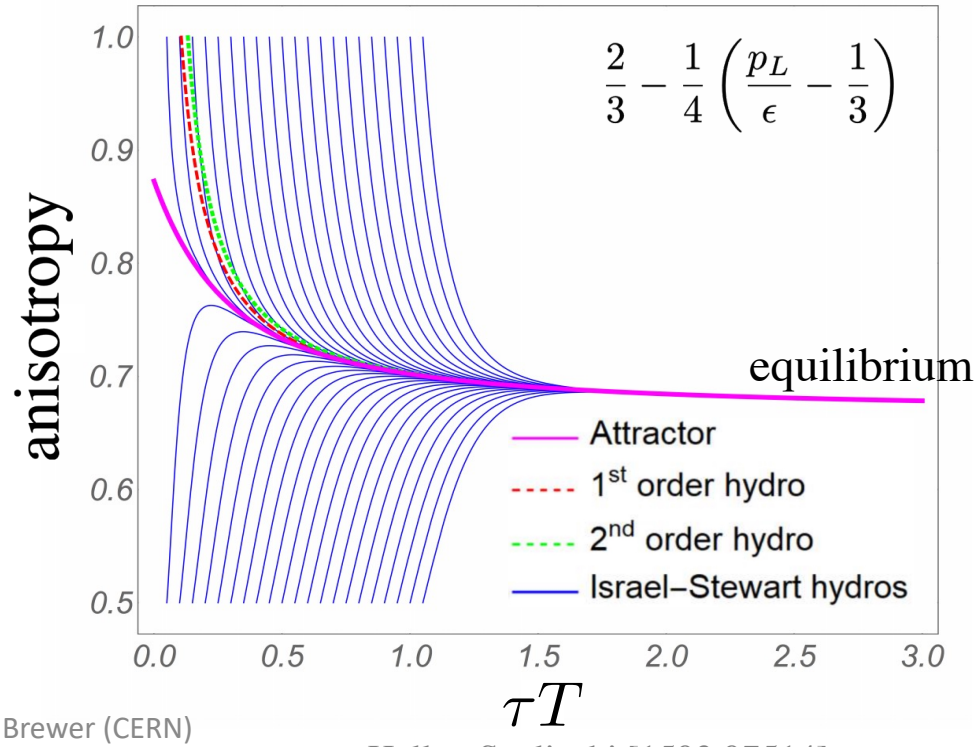


Flow in small systems challenges the standard view of hydrodynamics

"close" to (local) equilibrium, conservation laws dominate (gradient expansion)

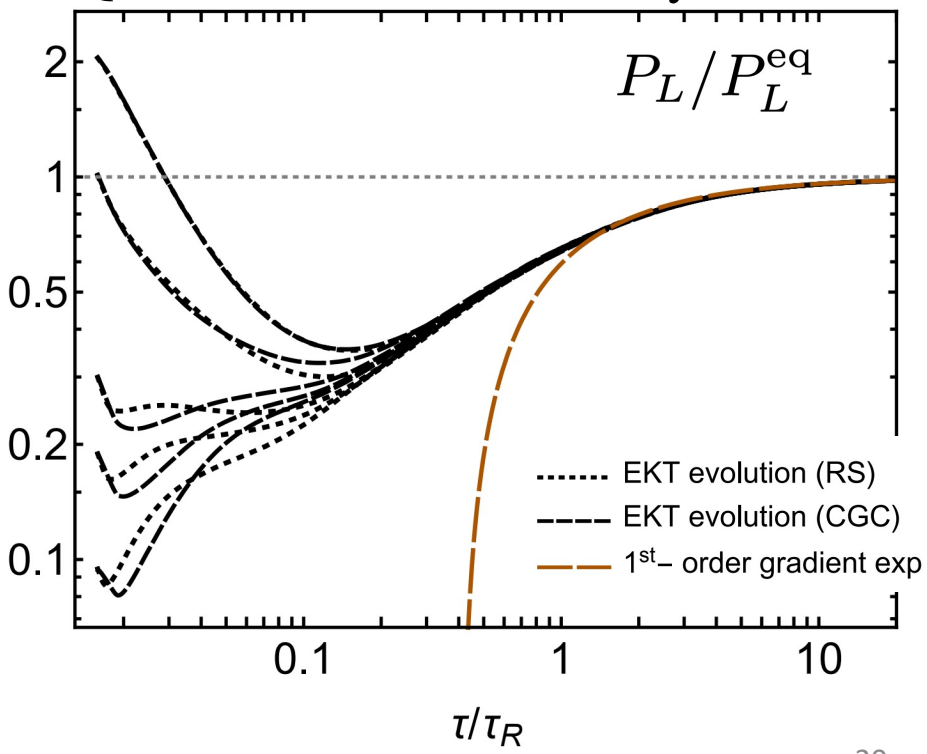


Far-from-equilibrium universality in relativistic hydrodynamics



Heller, Spalinski [1503.07514]

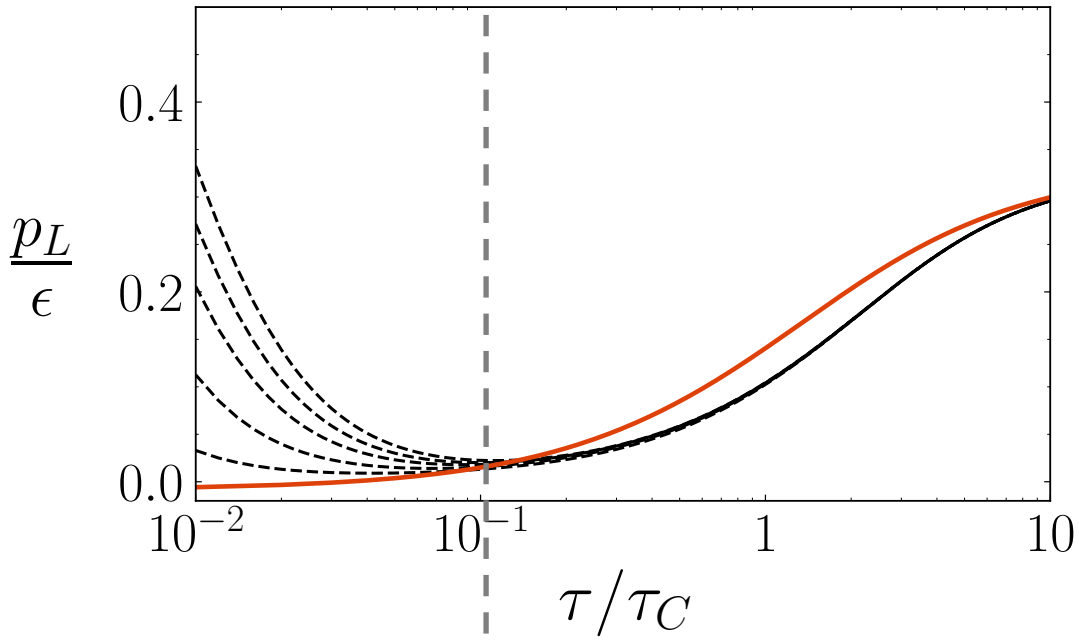
QCD effective kinetic theory



Almaalol, Kurkela, Strickland [2004.05195]

Implications for theory

Far-from-equilibrium generalized hydrodynamic modes

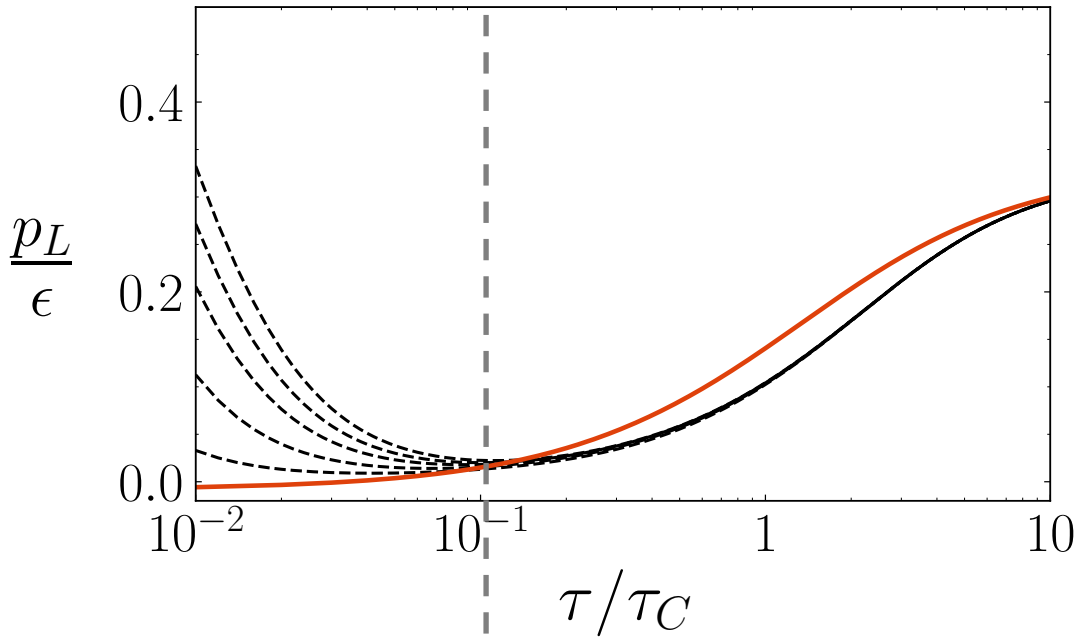


Reduction in degrees of freedom to "pre-hydrodynamic" mode

JB, Yan, Yin [1910.00021]

Implications for theory

Far-from-equilibrium generalized hydrodynamic modes

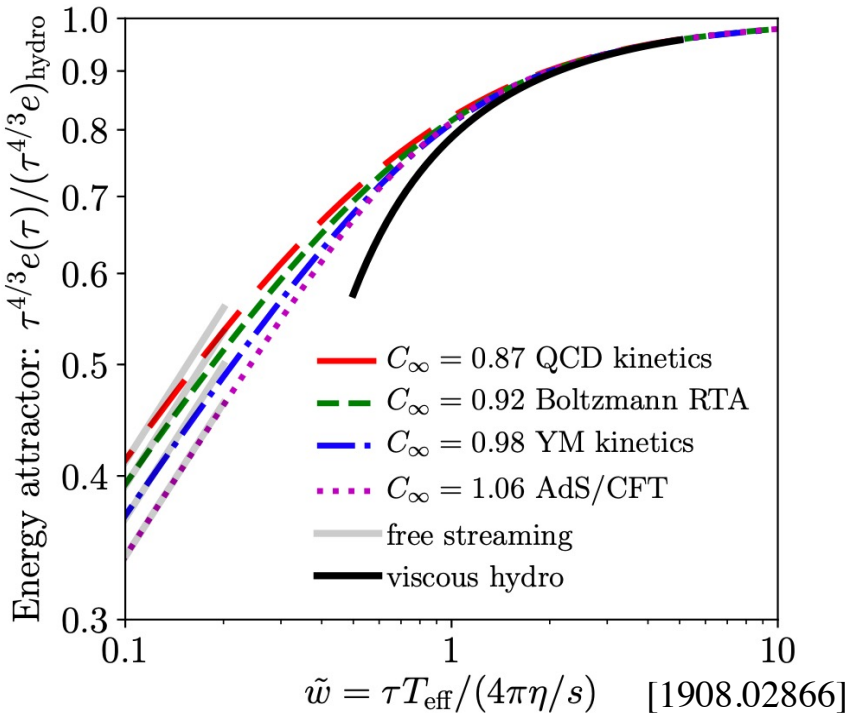


Reduction in degrees of freedom to "pre-hydrodynamic" mode

JB, Yan, Yin [1910.00021]

phenomenology

Similar attractor across very different theories

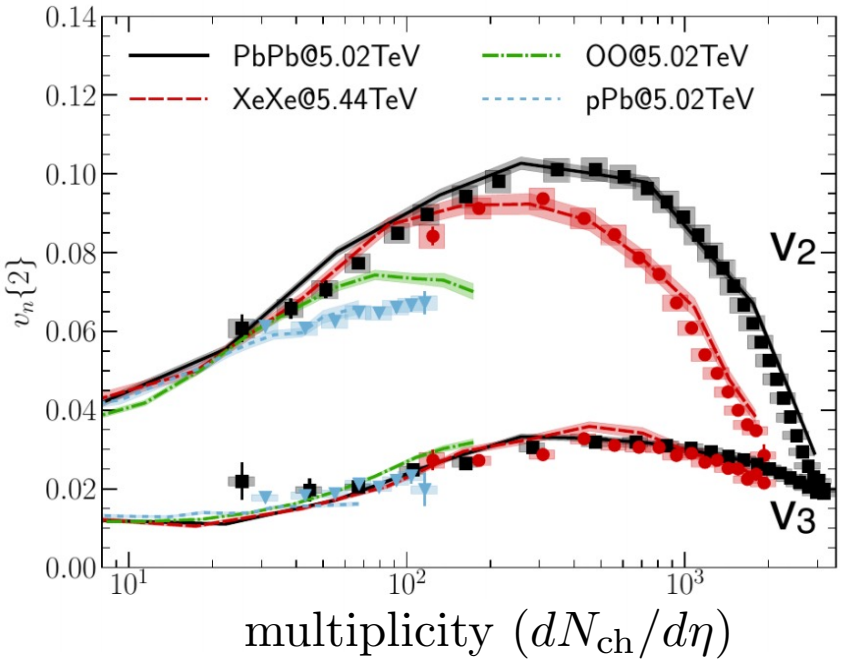


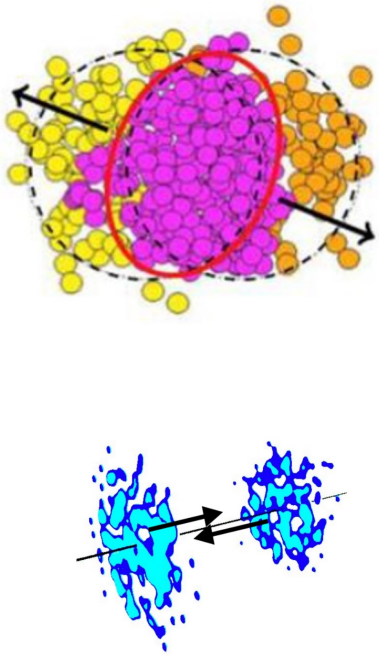
[1908.02866]

Enables estimate of entropy production in heavy-ion collisions

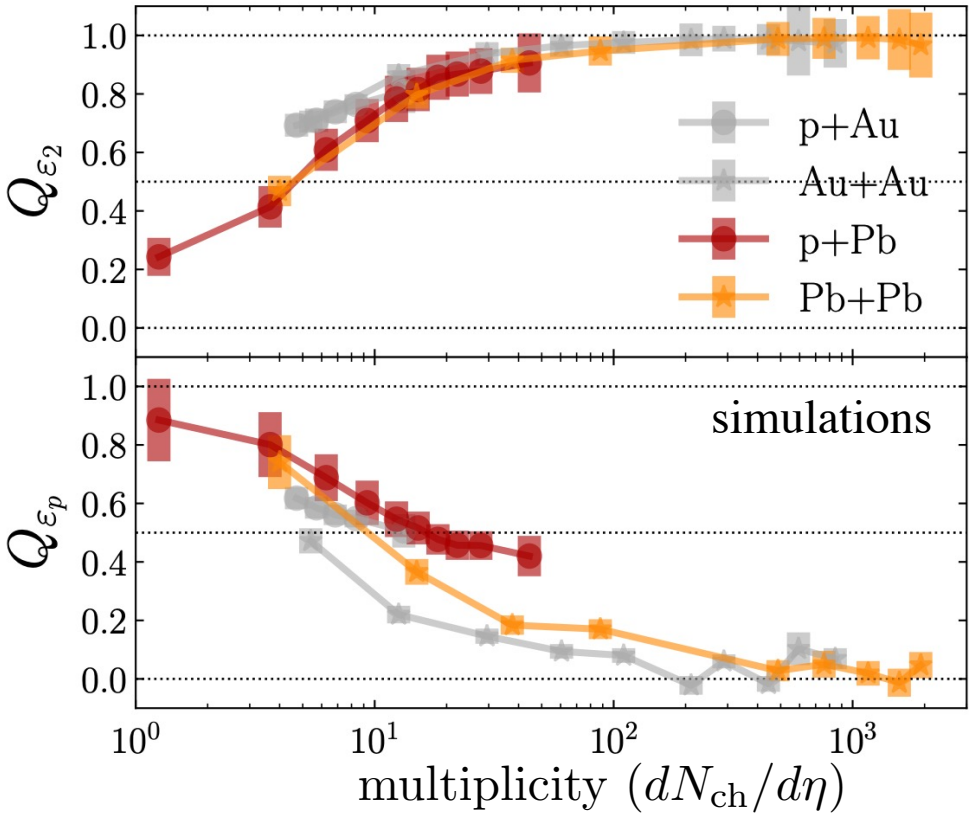
Giacalone, Mazeliauskas, Schlichting [1908.02866]

Origins of azimuthal correlations in small and large systems



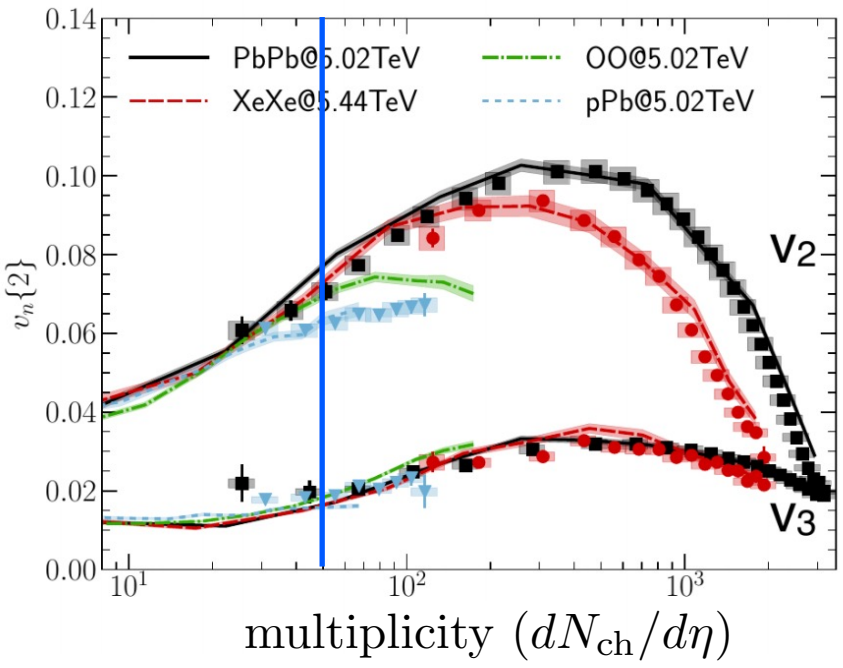


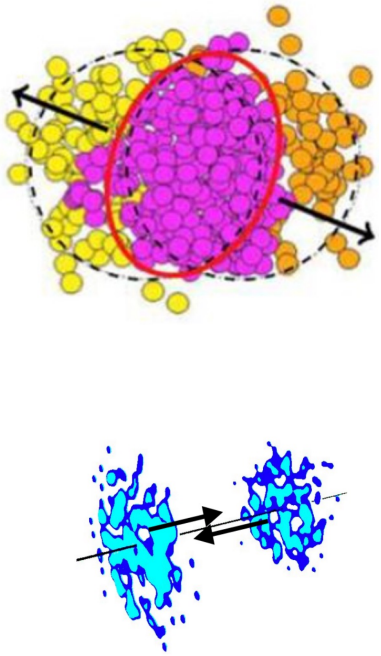
Correlation of v_2 with…



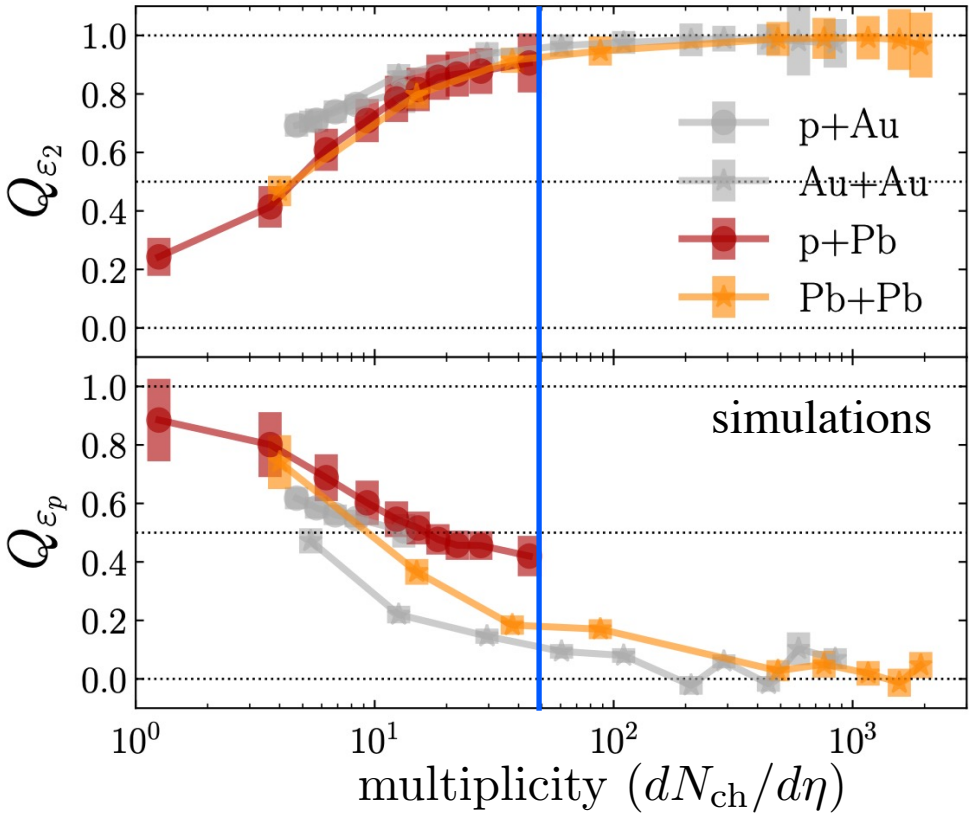
Schenke, Shen, Tribedy [1908.06212], Schenke QM'19

Origins of azimuthal correlations in small and large systems





Correlation of v_2 with initial…



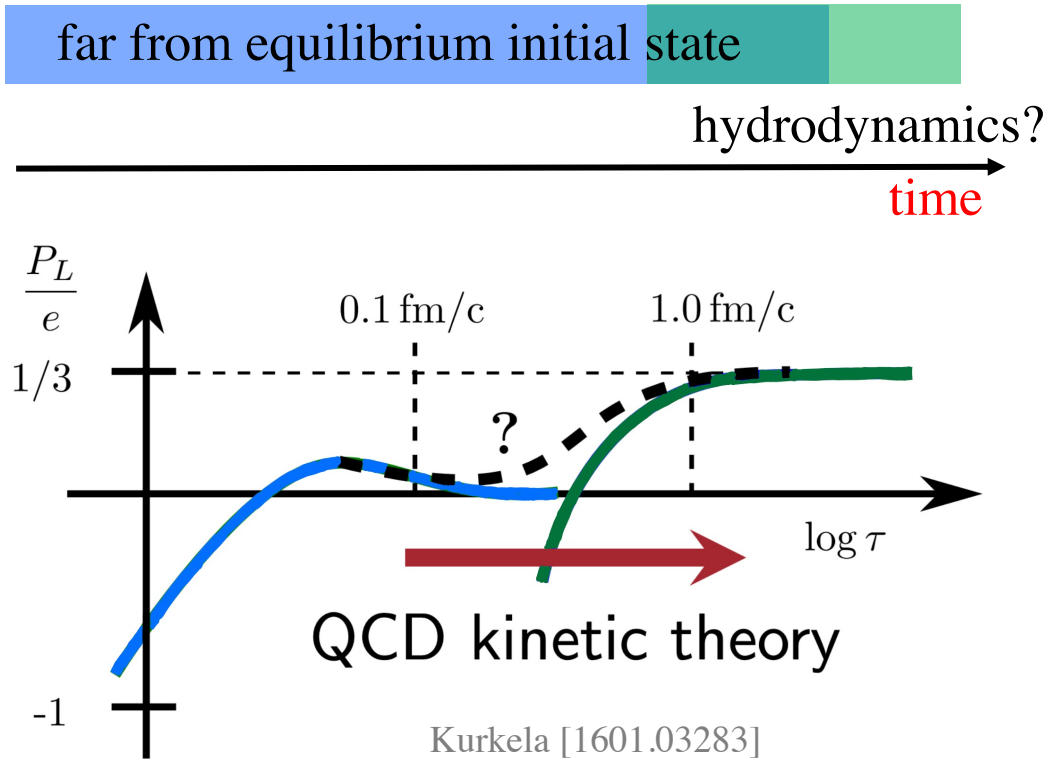
Initial-state dominated ⟷ Final-state dominated

Schenke, Shen, Tribedy [1908.06212], Schenke QM'19

Observables to distinguish initial- versus final-state effects

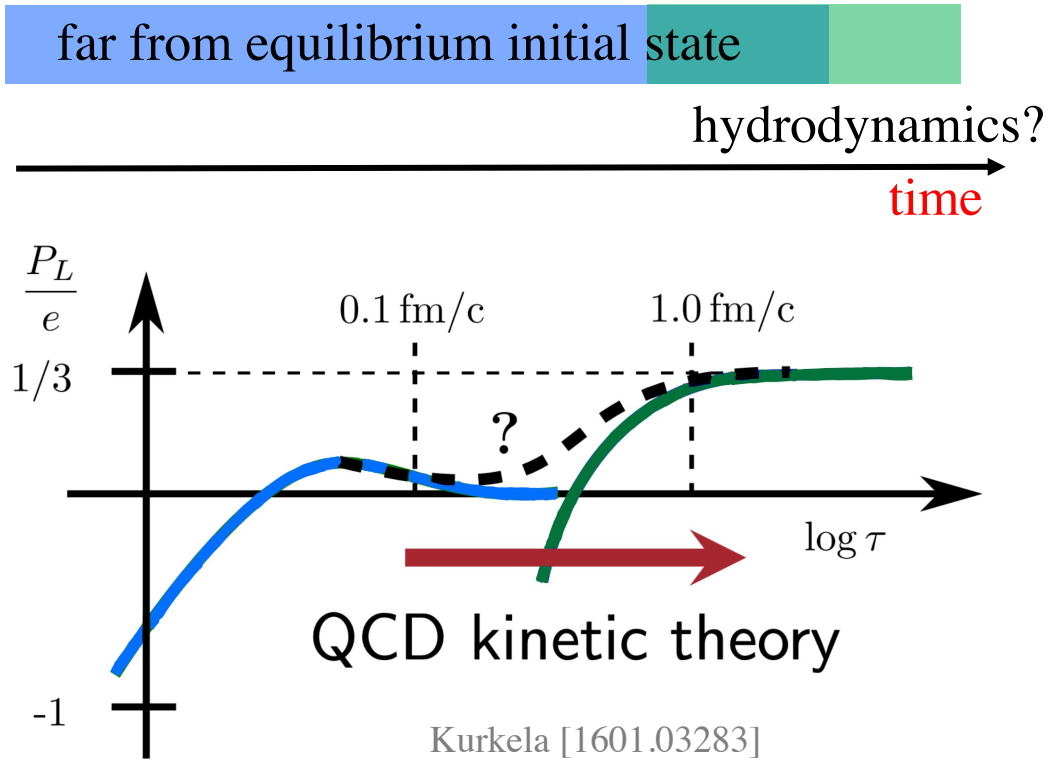
Giacalone, Schenke, Shen [2006.15721]

Connecting the initial state to hydrodynamics: thermalization in kinetic theory



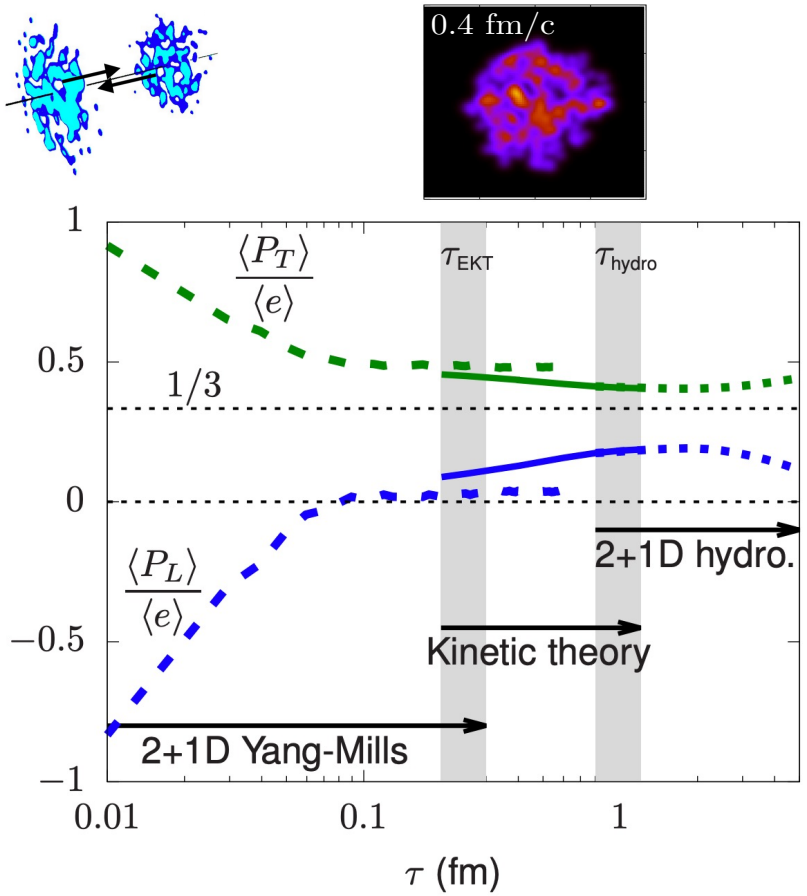
Kurkela [1601.03283]

Connecting the initial state to hydrodynamics: thermalization in kinetic theory



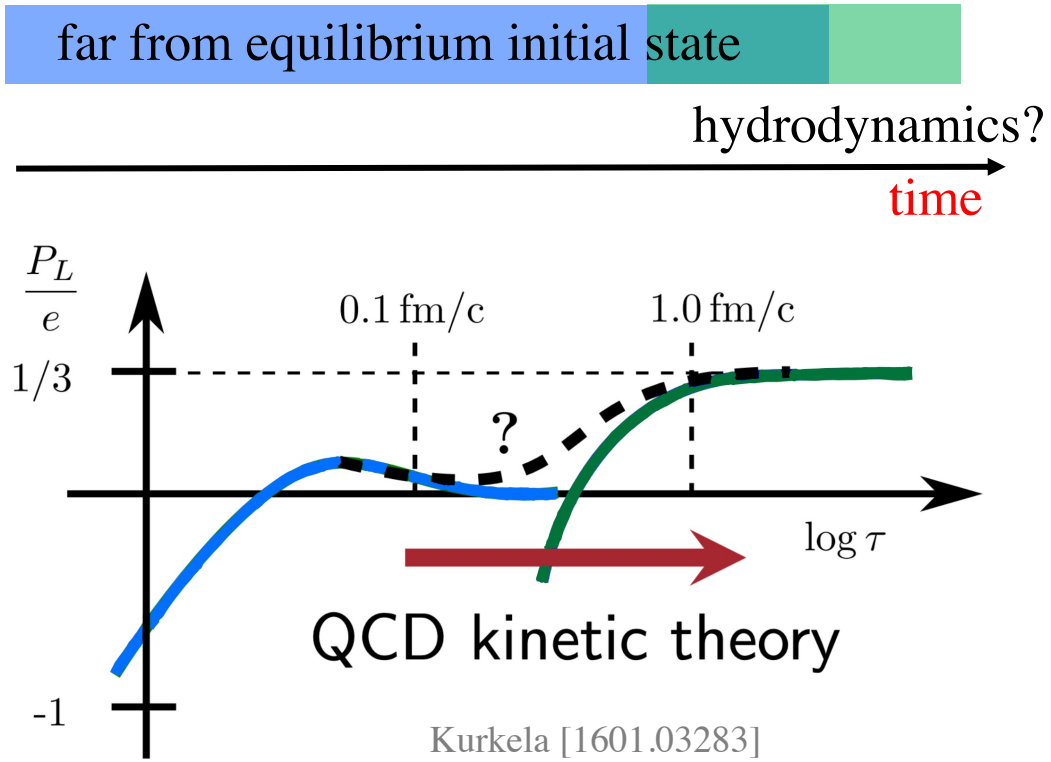
Kurkela [1601.03283]

- Motivated initial conditions for hydrodynamics
- Reduced sensitivity to starting time of hydro



Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney [1805.01604, 1805.00961]

Connecting the initial state to hydrodynamics: thermalization in kinetic theory



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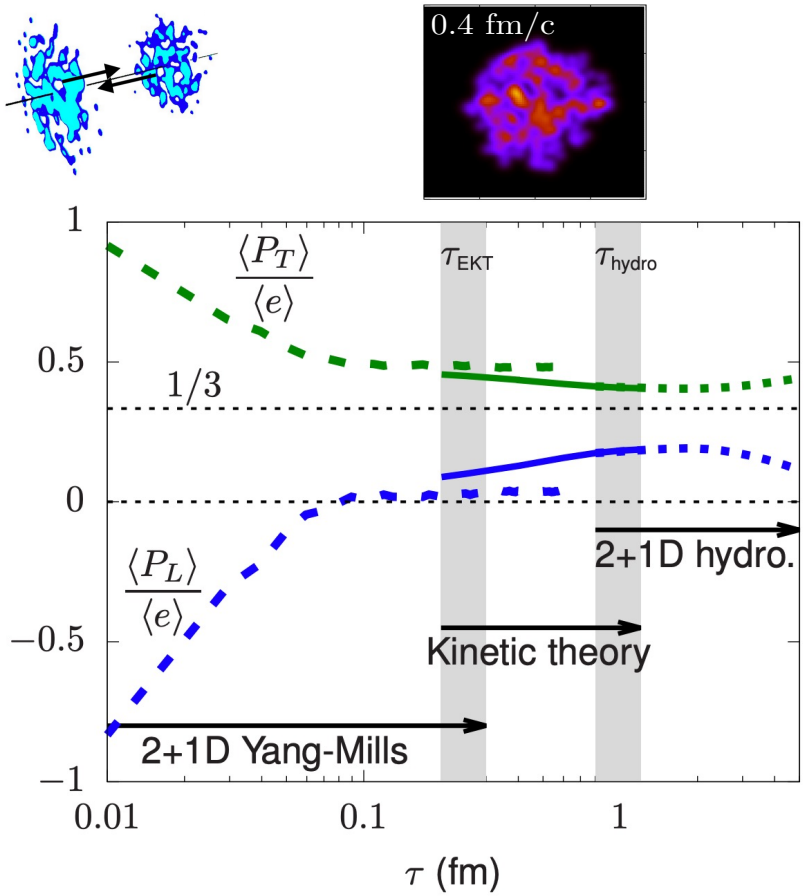

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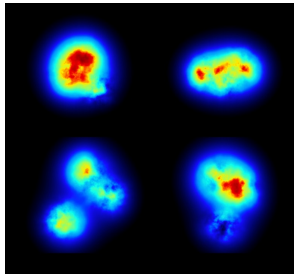
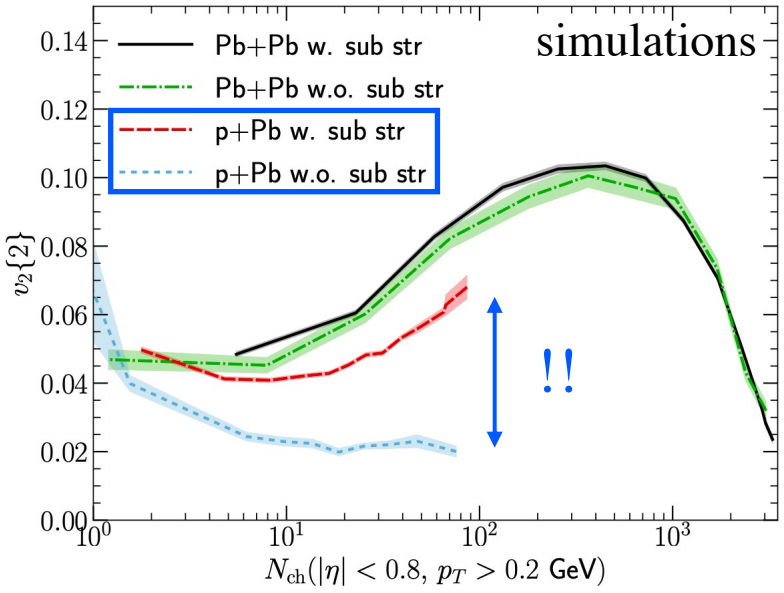
Jet quenching in kinetic theory? Moore, Schlichting, Schlusser, Soudi [2105.01679]

Opportunities of light ions for study of small systems

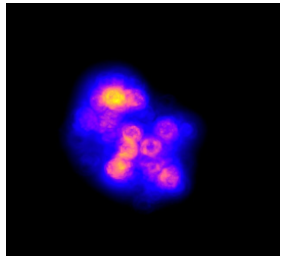
Challenge: geometry of p-Pb very sensitive to spatial structure of the proton



(Bjoern Schenke)



Chun Shen OppO'21

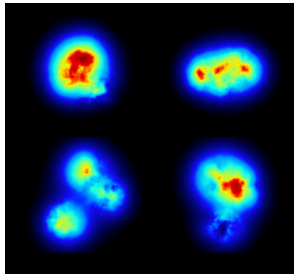


OO:

- similar multiplicity
- heavy-ion-like geometry

Opportunities of light ions for study of small systems

Challenge: geometry of p-Pb very sensitive to spatial structure of the proton



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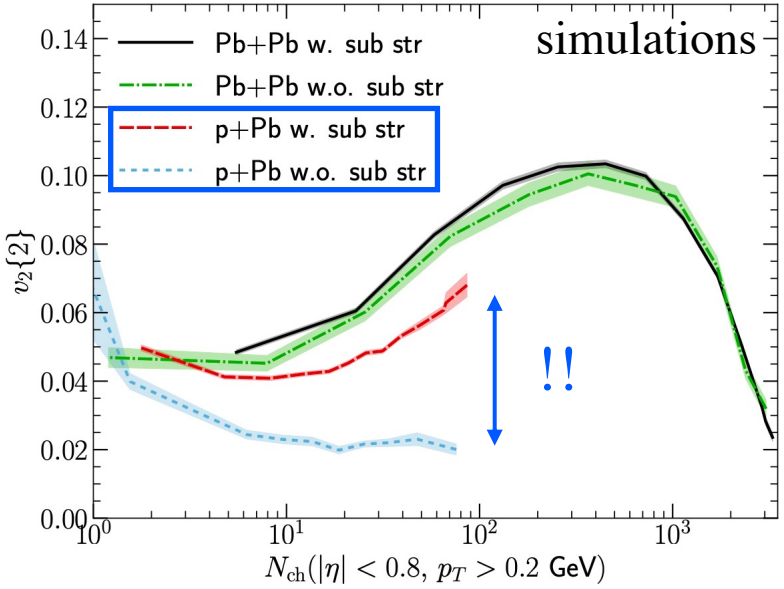
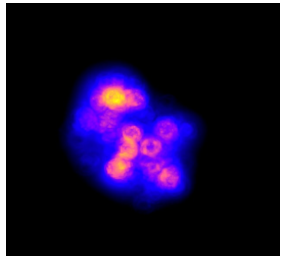


Chun Shen OppO'21

JB, Mazeliauskas, van der Schee [2103.01939]



OO:

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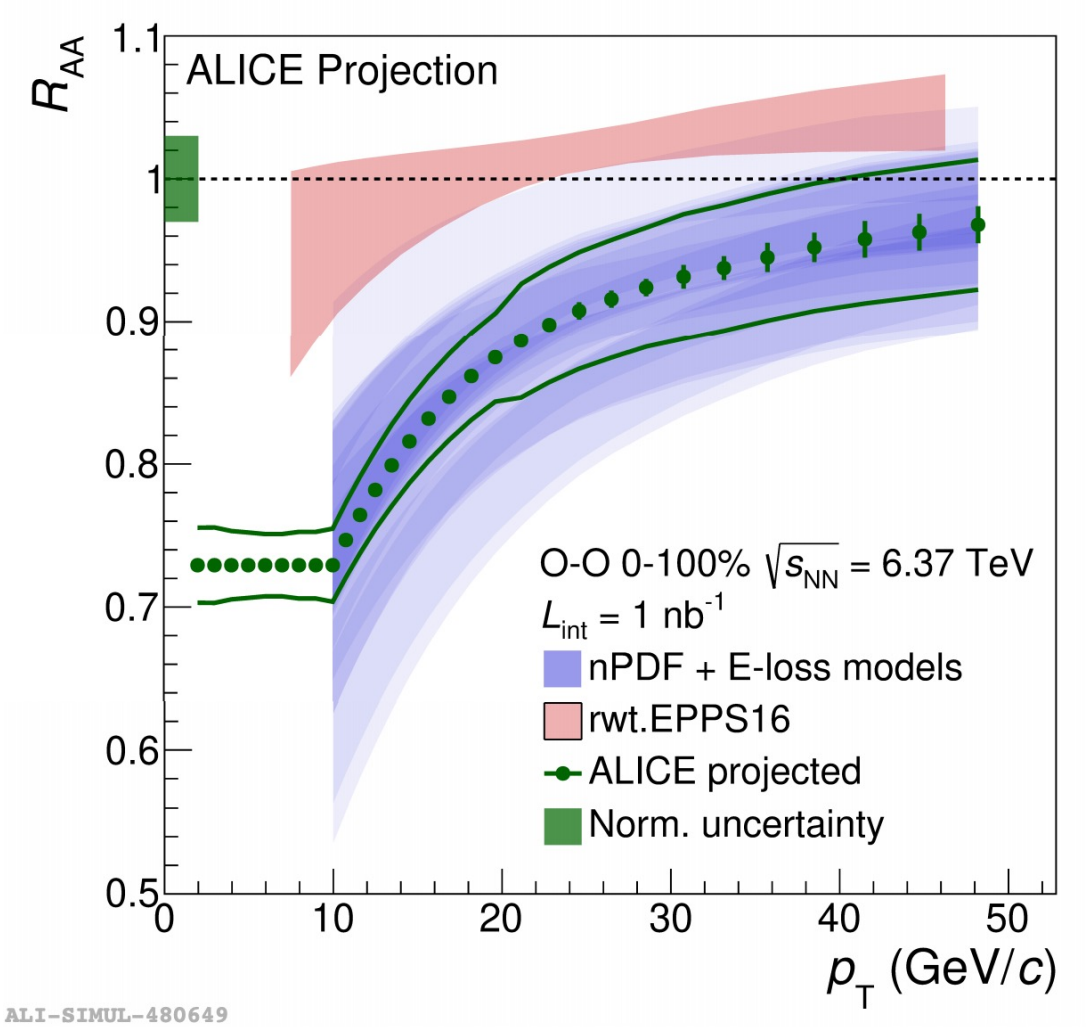
Opportunities of light ions for study of small systems

ALICE projections to distinguish energy loss in O-O from baseline

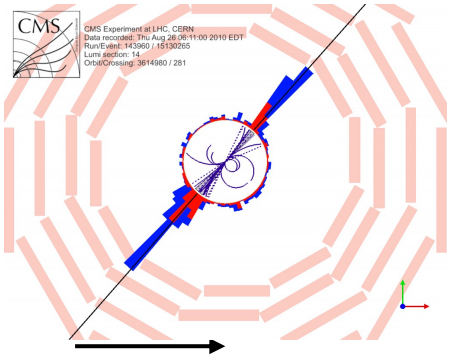


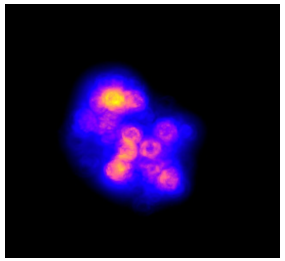
JB, Mazeliauskas, van der Schee [2103.01939]

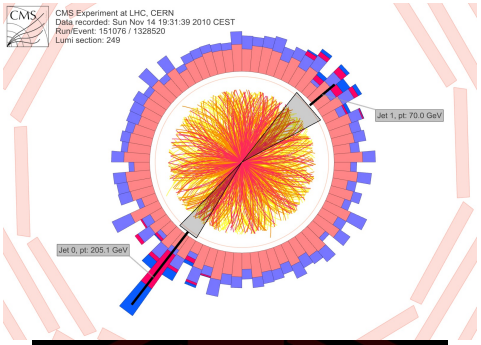
Vytautas Vislavicius OppO'21

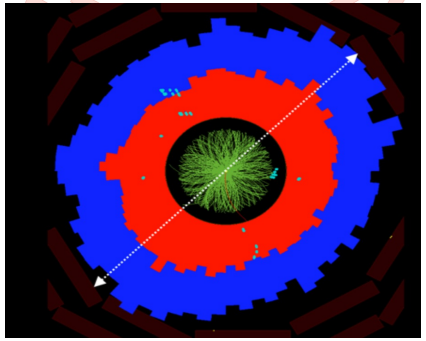
Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann [2007.13754, 2007.13758]

Outlook: opportunities for theory in small systems









Novel access to far-from-equilibrium QCD matter

Precision high-energy physics at high multiplicity → ← Precision heavy-ion physics