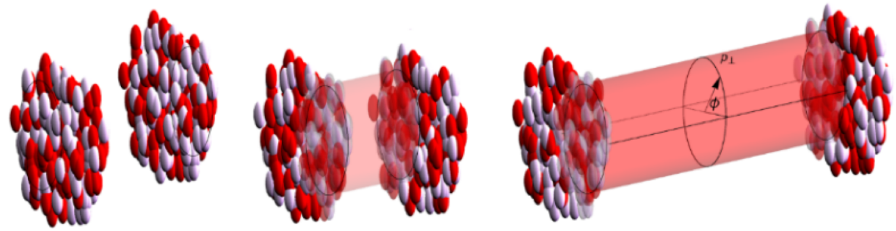
Ultra-relativistic nucleus-nucleus collisions

from B.C. (before Corona) to A.D. (after domestication)



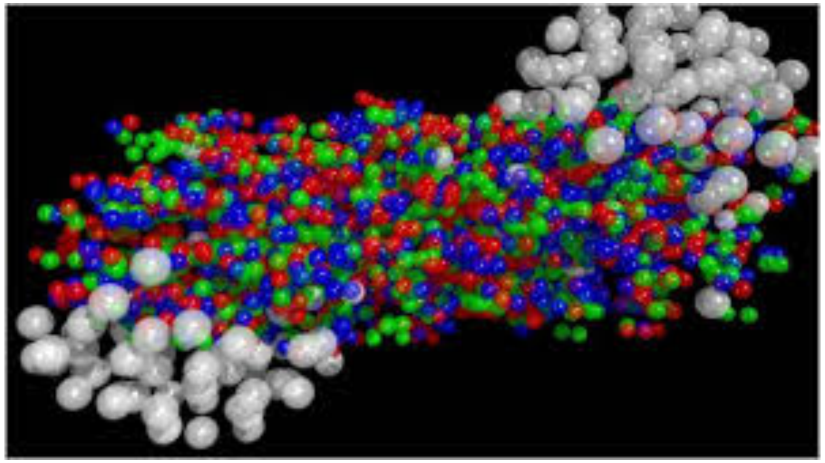
Urs Achim Wiedemann

9 September 2021

Heavy Ion Physics ⇔ High Energy Physics

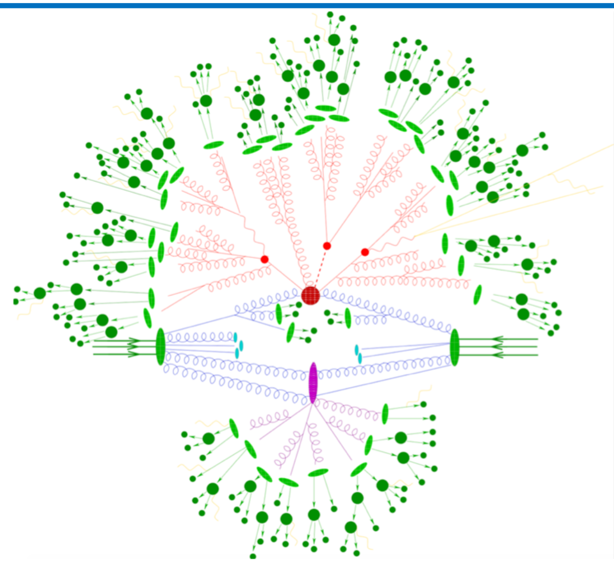
common starting point:
non-abelian quantum field theory

HIP: *How do non-abelian quantum field theories give rise to fundamental equilibrium and out-of equilibrium properties?*



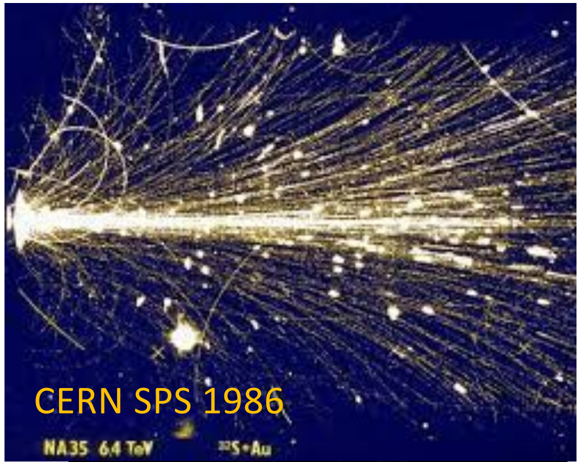
⇒ **Maximal energy within sizeable volume**

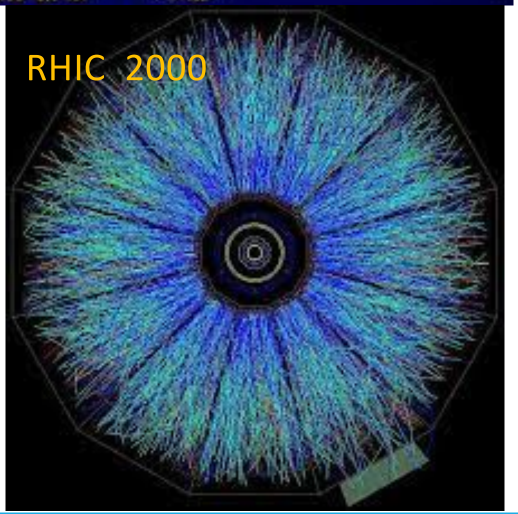
HEP: *What are the fundamental constituents and the laws governing their interactions?*

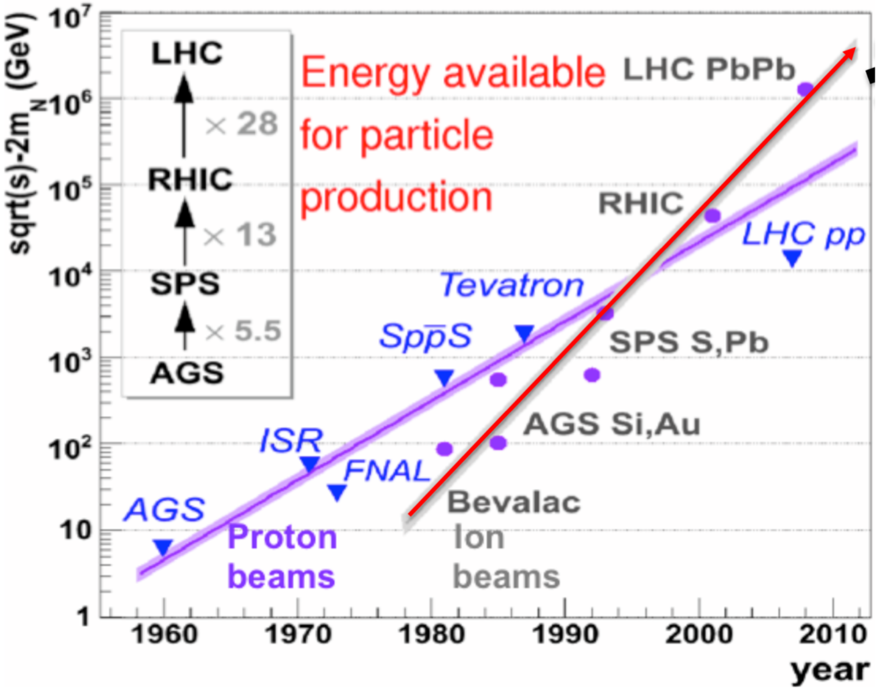


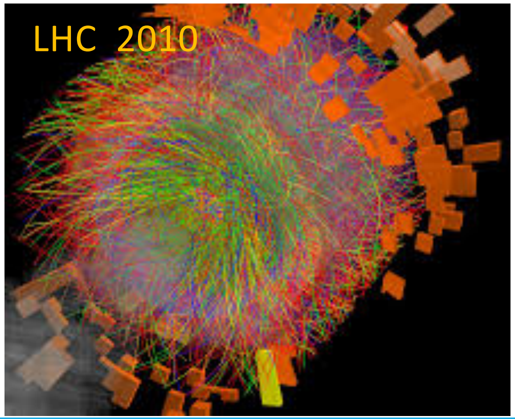
⇒ **Maximal energy within smallest possible volume**

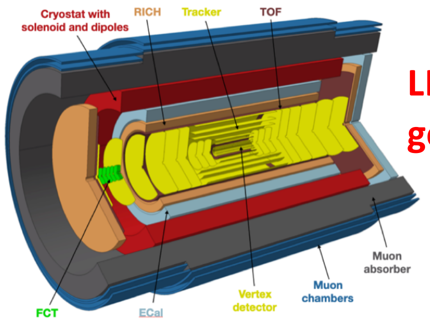
From B.C. … to A.D.





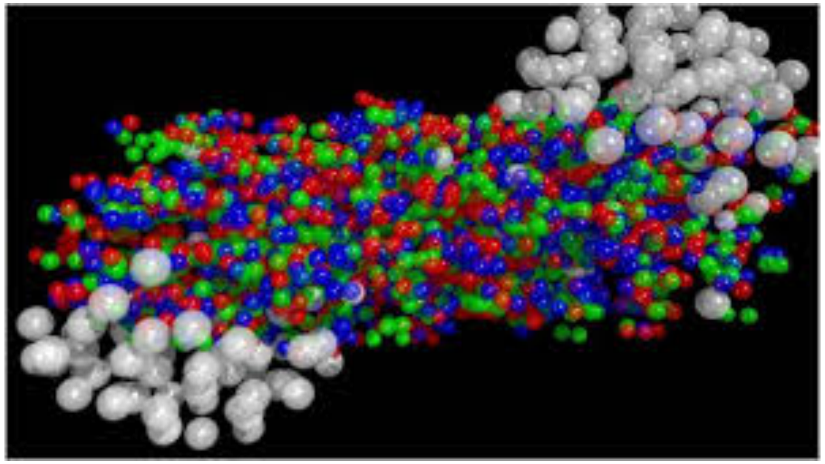


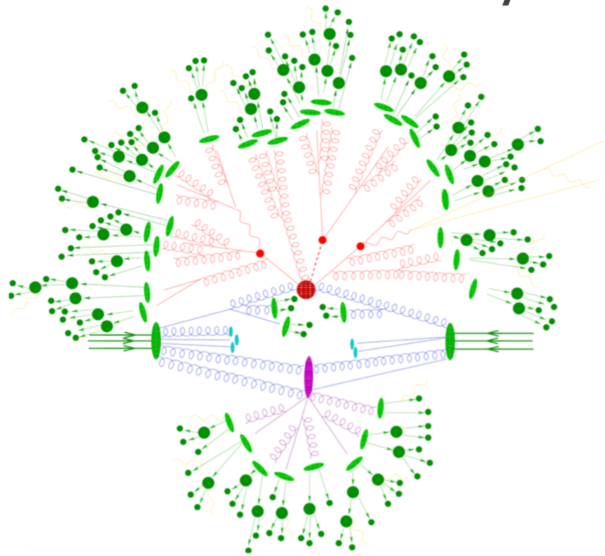




LHC 2nd generation

HIP and HEP picture collisions differently





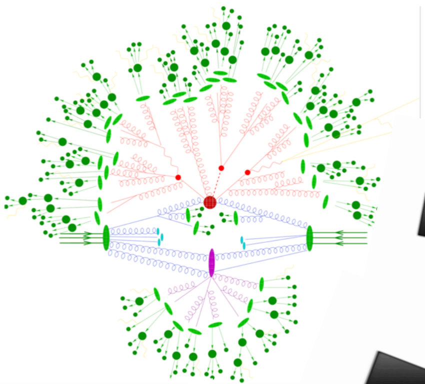
Close to perfect fluid; "collectivity"

Free-streaming but fragmenting "gas"

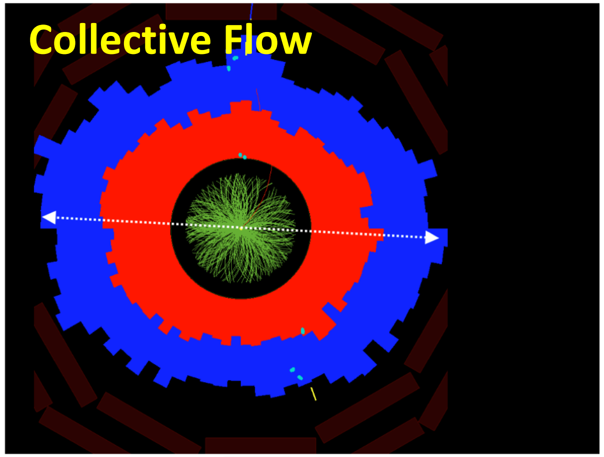
- How can one quantify unambiguous signs of collectivity? ✓ advanced
- Which mechanisms/which degrees of freedom lead to collectivity? at beginning
- How does collectivity emerge with system size, energy density, …? at beginning
- What are the properties of deconfined dense QCD matter? ✓ advanced

HEP picture does not account for HIP phenomenology

New phenomena in Pb-Pb collisions



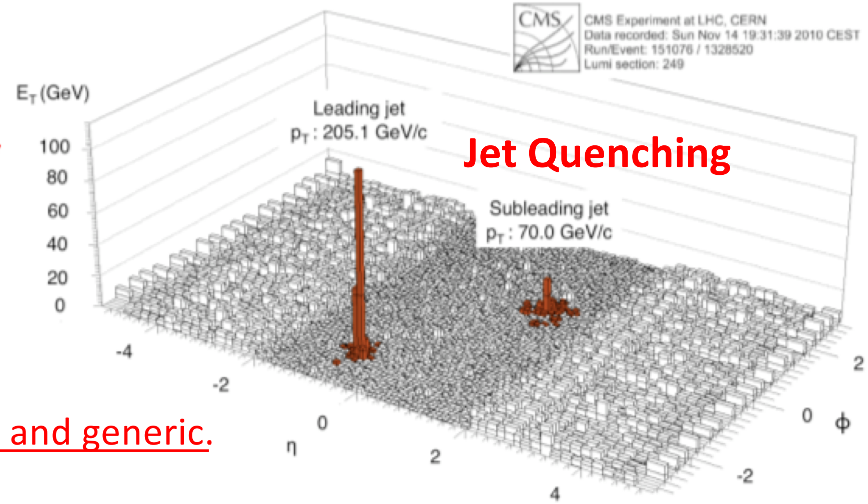
$$\text{"Pb+Pb} \neq \sum_{\text{incoherent}} (p+p)\text{"}$$

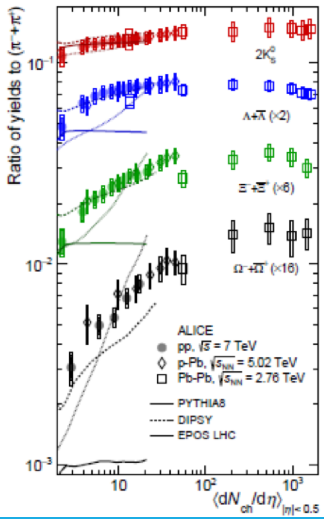


$$\int_0^{2\pi} d\phi \frac{dN^{\text{ch}}}{d\phi} e^{i2\phi} = v_2 \propto \frac{1}{\sqrt{N_{\text{ch}}}}$$

$$A_J^{\text{p+p}} = A_J^{\text{Pb+Pb}}$$

$$A_J \equiv \frac{E_{\perp 1} - E_{\perp 2}}{E_{\perp 1} + E_{\perp 2}}$$





Strangeness enhancement, arm hadronization, ...

Phenomena are numerically large and generic.

QCD fluid dynamics as a model of collectivity

- based *only* on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2^{nd} law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- sensitive *only* to properties of matter that are

calculable from first principles in quantum field theory

Lattice QCD =>

Finite Temp pQCD =>

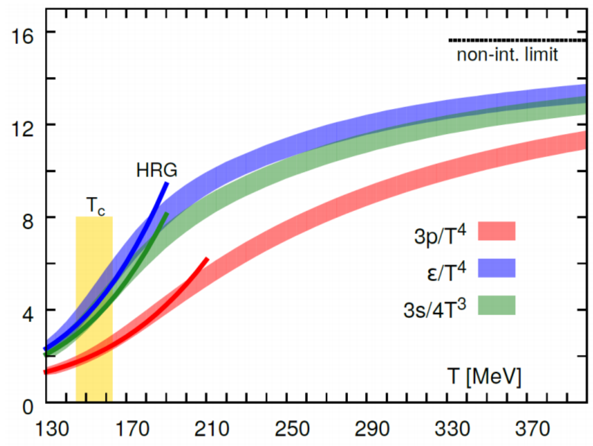
AdS/CFT =>

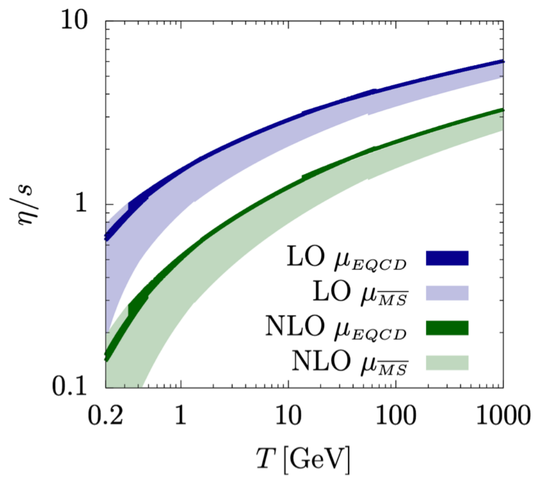
- **EOS**: $\varepsilon = \varepsilon(p,n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

- **transport coefficients**: shear η, bulk ξ viscosity, …

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

- **relaxation times**: τ_π, τ_Π, …





D. Bazavov et al, The equation of state in (2+1)-flavor QCD, Phys. Rev. D90 (2014) 094503 S. Borsanyi et al, JHEP 09 (2010) 073
J. Ghiglieri, G. Moore, D. Teaney, QCD Shear Viscosity at (almost) NLO, JHEP 03 (2018) 179

How to test fluid (and non-fluid) properties?

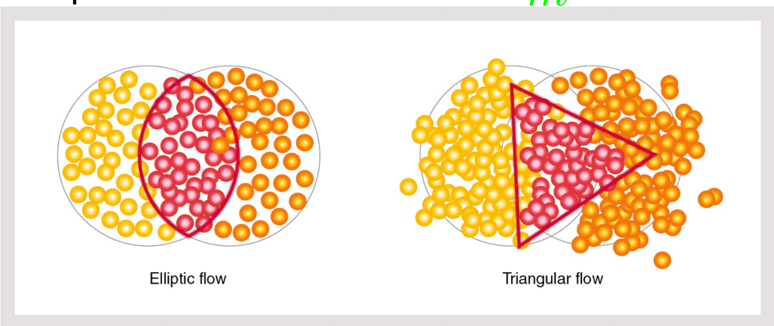
- **Excite medium**
- **Listen to response**
- Analyze

In theory:

$$G_{\mathrm{R}}^{\mu\nu,\alpha\beta} = \frac{\delta T^{\mu\nu}}{\delta h_{\alpha\beta}}$$

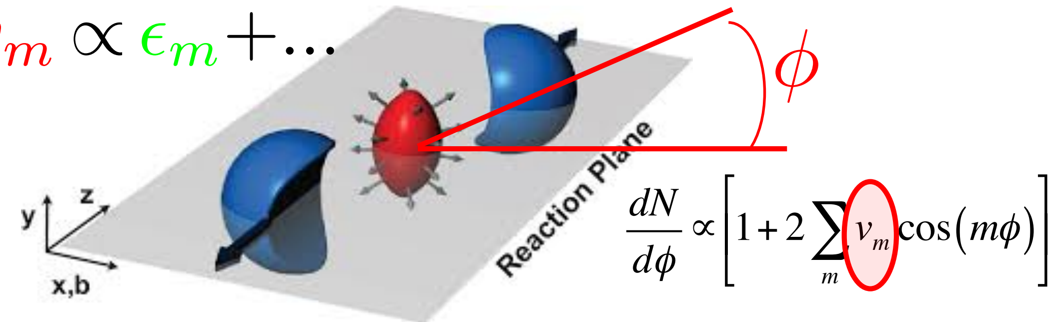
In experiment:

Prepare different **excitations** ϵ_m



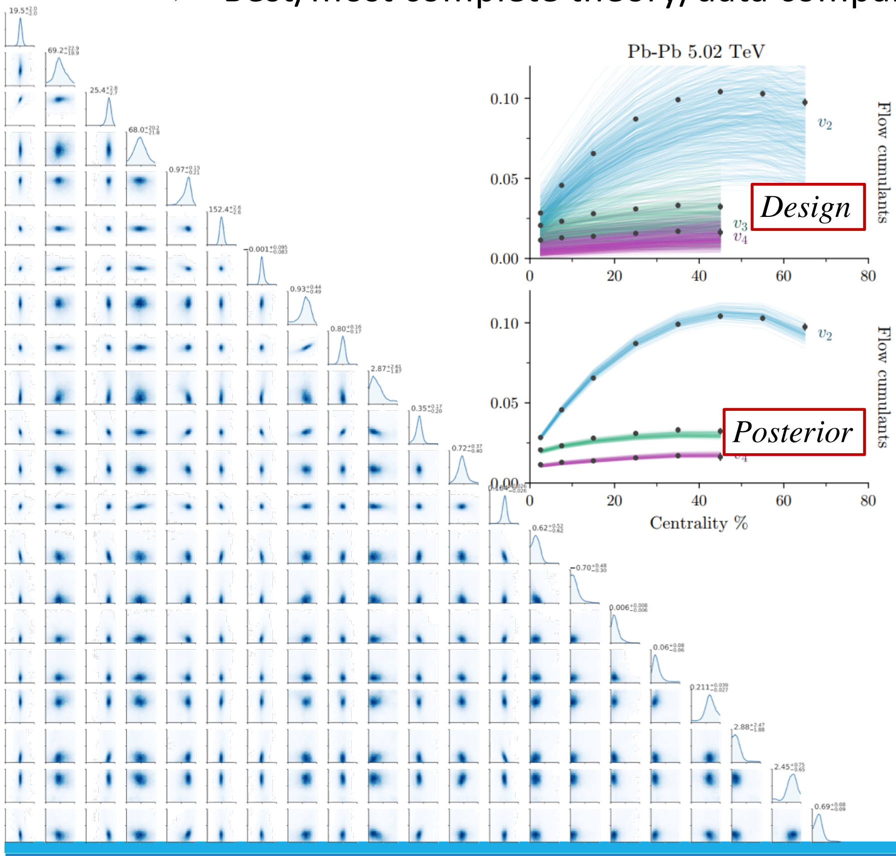
measure their **response**

$$v_m \propto \epsilon_m + \ldots$$

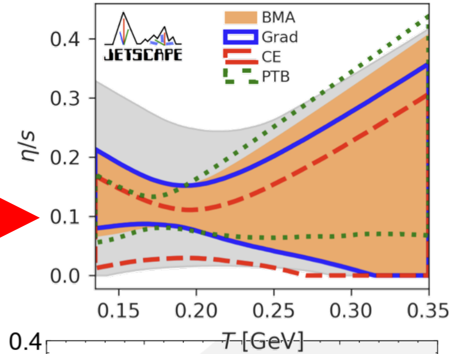


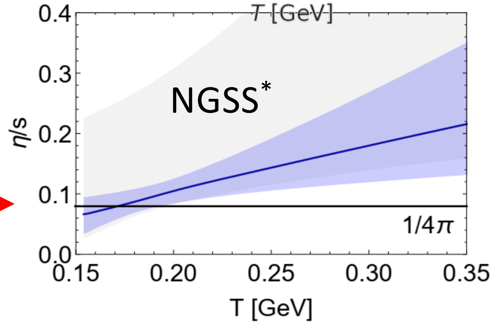
Bayesian Inference (“hydro fits”)

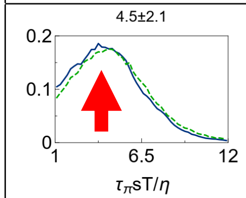
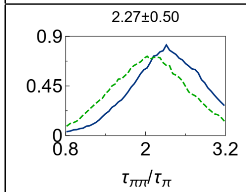
- More than fluid dynamics but constrains fluid dynamics
- Best/most complete theory/data comparison at soft p_T



State of the art:
514 data points, 20 parameters,
constraining QCD transport properties.
Reaching PDG-grade quality





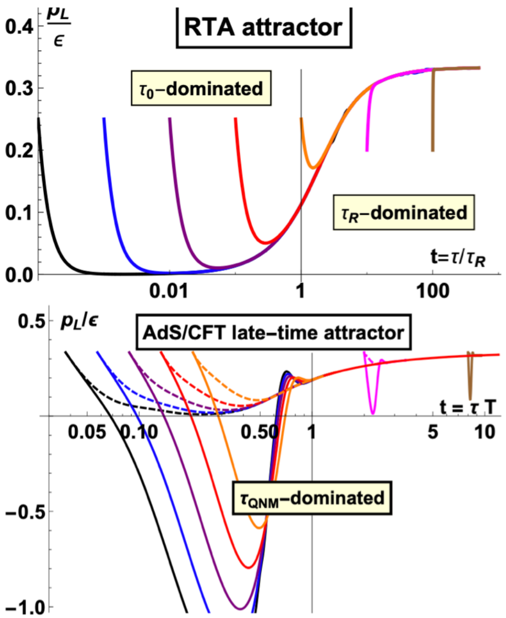
	NGSS*	AdS/CFT	kinetic theory
$\frac{\tau_\pi sT}{\eta}$		$4-\log(4)\approx 2.61$	5
$\frac{\tau_{\pi\pi}}{\tau_\pi}$		$\frac{88}{35(2-\log 2)}\approx 1.92$	$\frac{10}{7}\approx 1.43$

Steffen Bass, A data-driven approach to quantifying the shear viscosity of nature’s most ideal liquid, https://www.youtube.com/watch?v=MGE8K8IY4cg

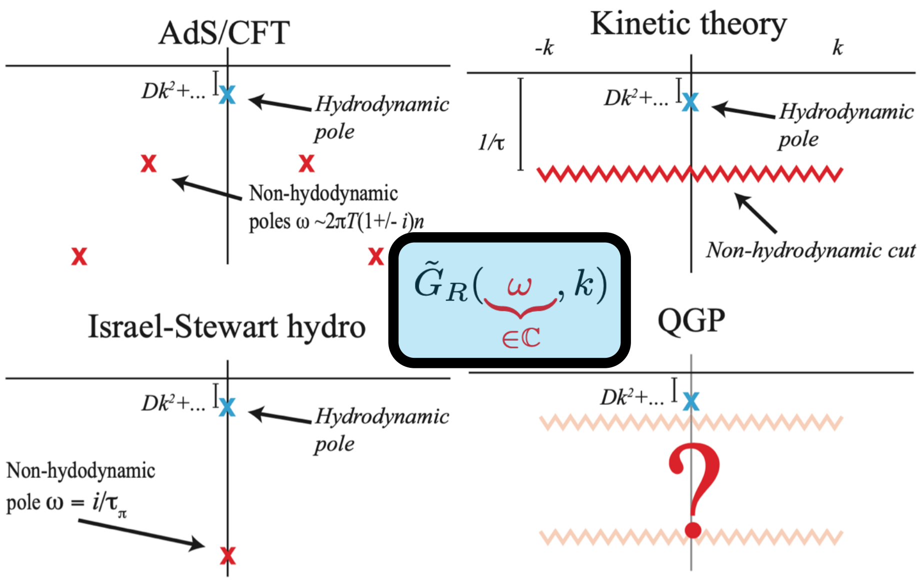
*G. Nijs, U. Gursoy, W. v.d. Schee, R. Snellings, arXiv:2010.15130, arXiv:2010.15134

Do we understand how QCD hydrodynamizes?

- Hydrodynamization in 1+1D systems is understood, "reasonably efficient"
  Almalool, Brewer, Blaizot, Chesler, Denicol, Heller, Kurkela, Janik, Martinez, Noronha, Romatschke, v.d. Schee, Shi, Spalinsky, Strickland, Svensson, Taghavi, Wiedemann, Witaszczyk, Wu, Yan
- Expansion-driven early time attractor
  hydrodynamic late-time attractor



- All thermal QFTs show universal hydrodynamic excitations and QFT-specific non-hydro excitations.



- At stake:
  understanding the excitation spectrum of thermal QCD

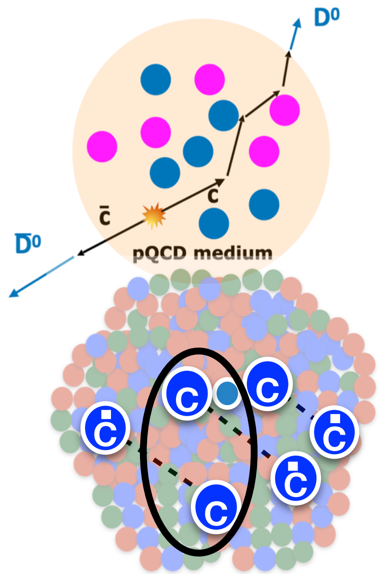
  Difficulty: non-hydro modes are short-lived and thus "subleading" for collective phenomena in large systems.

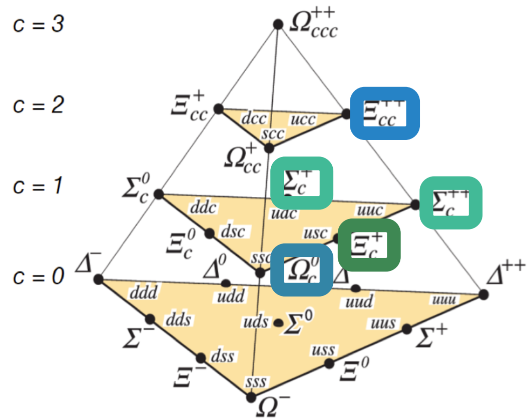
How to make progress on the origin of fluid-like behavior?

- Quantify transport of conserved (on QCD time-scale) charges
  i.e. <u>heavy flavor transport</u>

  Figs. G.M. Innocenti, ALICE-3 studies

  - correlations of conserved charges test isotropization
  - isotropization = testing origin of recombination
  - inroad to understanding charm enhancement?





double-c (~fb^{-1} region)

At stake: <u>establishing the common dynamical origin of low-pt collective flow and hadro-chemistry</u>

- Light Ion Beams (e.g. O+O, O+p) to change system size R

  - ❑ Smallest wavenumber $k \sim \frac{1}{R}$
  - ❑ Longest propagation time $t \sim R$

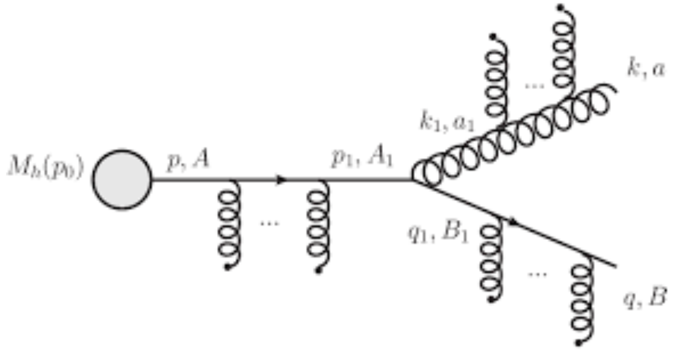
$$G_R(t,k) = \underbrace{c_{\rm hyd}\ \exp\left[-\Gamma_s k^2 t\right]}_{\text{reduced for smaller R}} + \underbrace{c_{\text{non-hyd}}\ \exp\left[-t/\tau_R\right]}_{\text{enhanced for smaller R}}$$

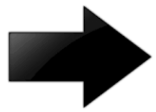
At stake: <u>characterizing the onset of collectivity, establishing the common dynamical origin of pp and PbPb collisions</u>

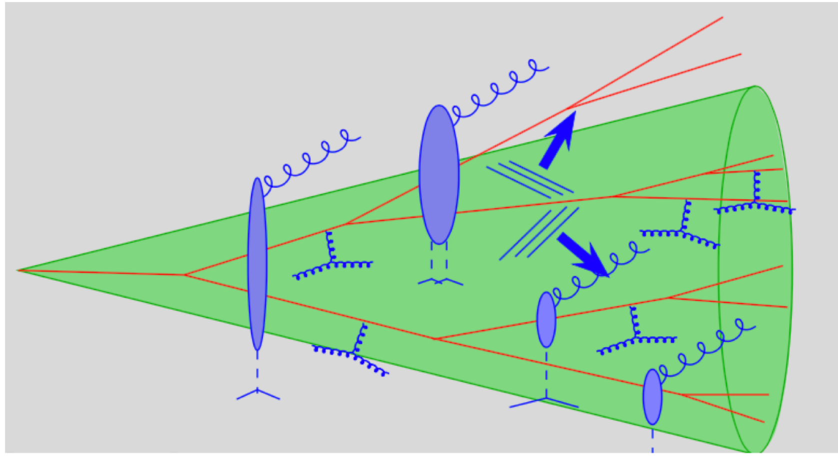
J. Brewer, A. Mazeliauskas, W. v.d.Schee, arXiv:2103.01939

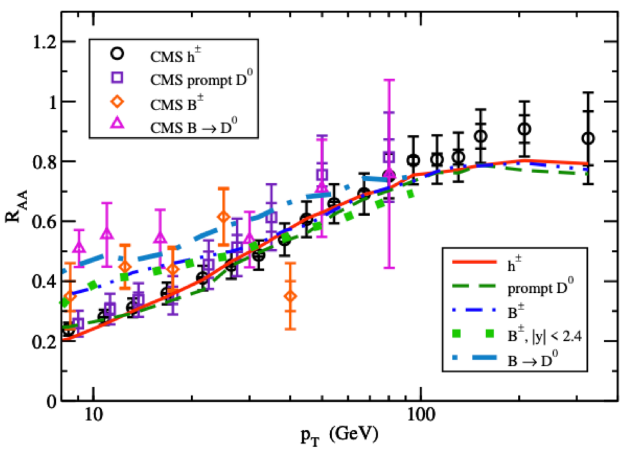
Partonic rescattering as a model of jet quenching

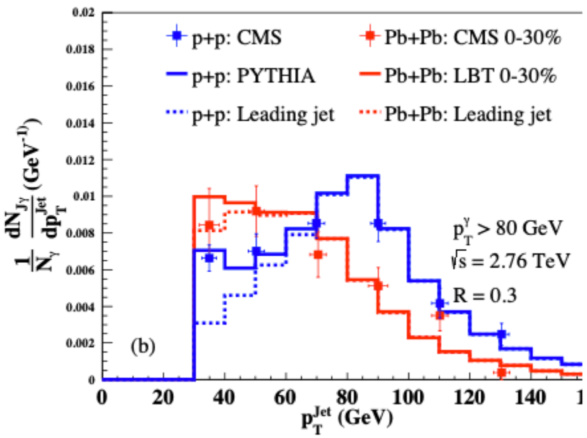
Medium-modified parton showers are basis of jet quenching models

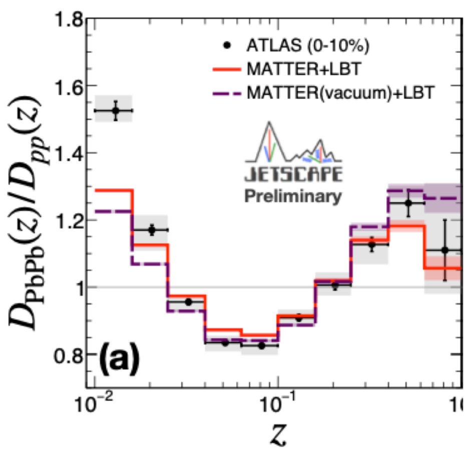


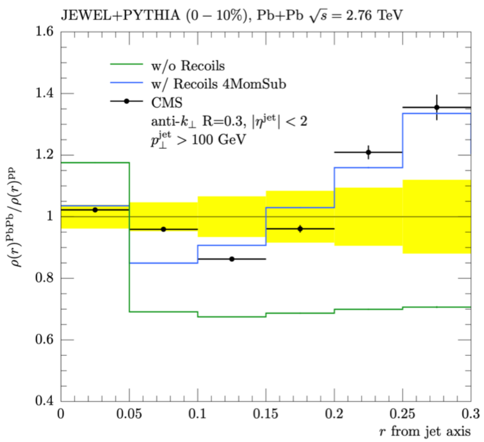












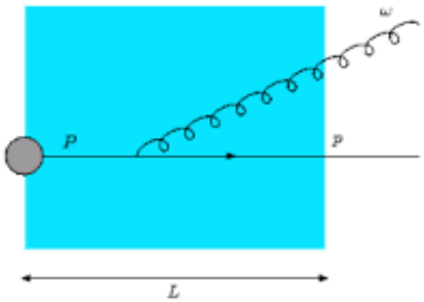
Figures from: Shanshan Cao & Xin-Nian Wang, arXiv:2002.04028
Raghav Elayavalli & Korinna Zapp, arXiv:1707.01539

Quenching models: Q-Pythia, Q-Herwig, JEWEL, LBT, MATTER, MARTINI … HYBRID is different

X.N. Wang, Jet tomography of hot and cold nuclear matter, https://www.youtube.com/watch?v=a69d22ZiiT8

Jet quenching – conceptually unique features

- spatio-temporal ordering of parton showers



In vacuum

- Time $\tau_{\rm form}^{\rm vac} \simeq \frac{\omega}{k_\perp^2} = \frac{1}{\Theta^2\,\omega}$
- Soft gluons late

Not accessible in p+p

In medium

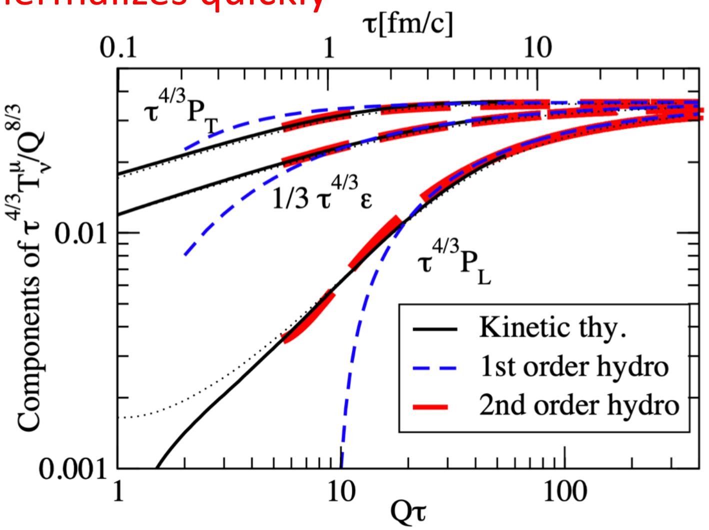
- Time $\tau_{\rm form}^{\rm med} \simeq \frac{\omega}{k_\perp^2} = \sqrt{\frac{\omega}{\hat{q}}}$
- Soft gluons first

Accessible in A+A

- Jet quenching is a partonic kinetic transport theory that thermalizes quickly*

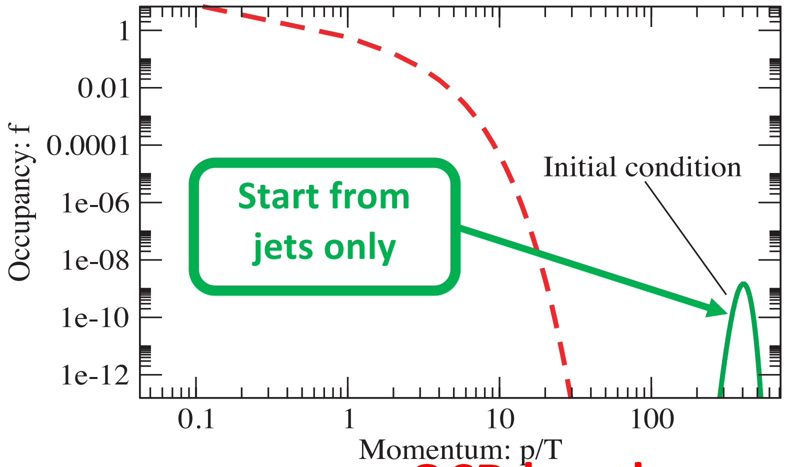
$$\partial_t f_g(x,p) = -C_{2\to 2}[f] - C_{1\to 2}[f]$$

- Hard partons p>> T
- Embedded in medium
- 1->2 LPM (and DGLAP)
- 2->2 elastic



* A. Kurkela & Y. Zhu, Phys. Rev. Lett. 115 (2015) 18, 182301
R. Baier, A.H. Mueller, D. Schiff, D.T. Son, 'Bottom up' thermalization in heavy ion collisions, Phys. Lett. B502 (2001) 51

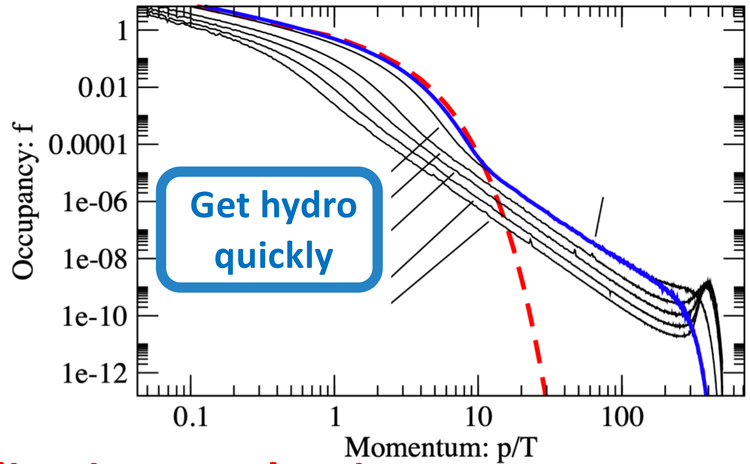
Jet quenching = fast perturbative hydrodynamization



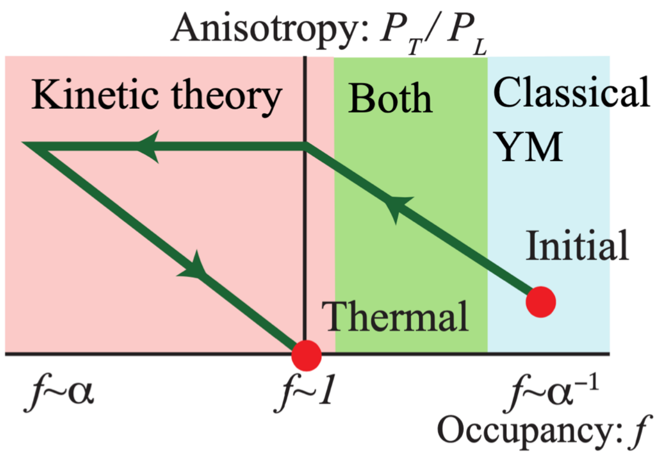
"Bottom-up"

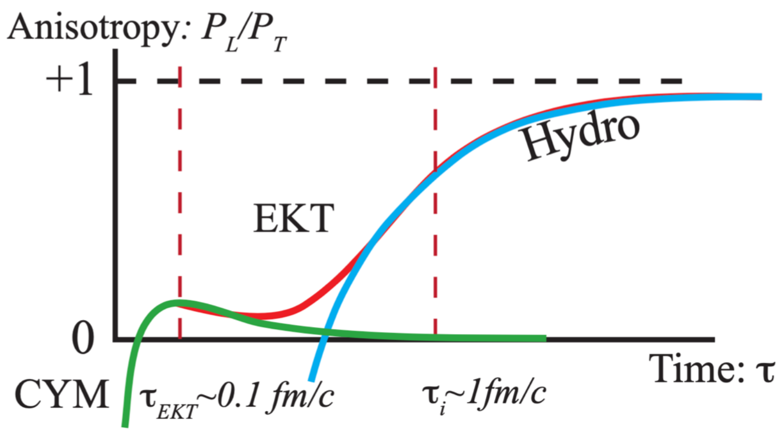
$\partial_t f_g(x,p) = -C_{2\to 2}[f] - C_{1\to 2}[f]$

idealized $\alpha_s \ll 1$



pQCD has the most remarkable thermalization mechanism



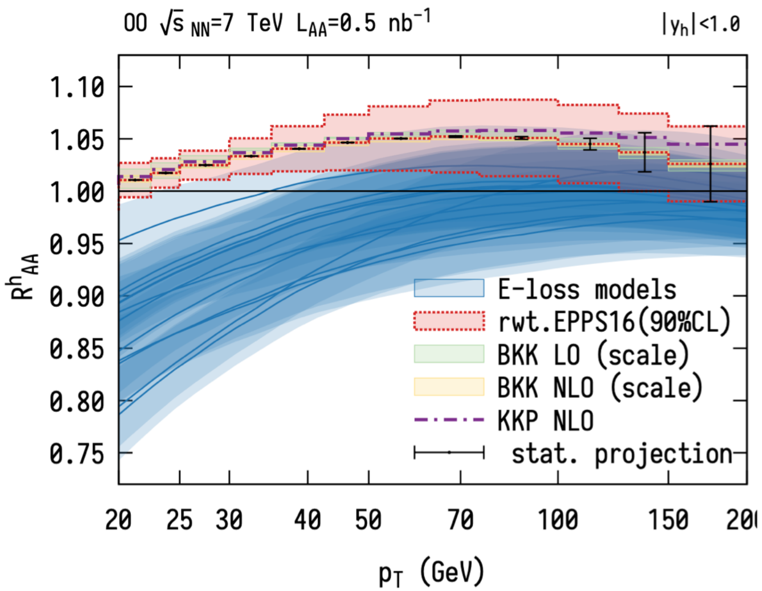


R. Baier, A.H. Mueller, D. Schiff, D.T. Son, 'Bottom up' thermalization in heavy ion collisions, Phys. Lett. B502 (2001) 51

A. Kurkela, E. Lu Phys.Rev.Lett. 113 (2014) 18; A. Kurkela, Y. Zhu Phys.Rev.Lett. 115 (2015) 18

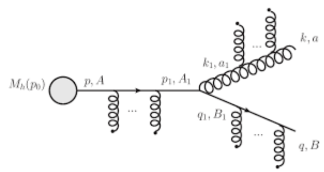
Jet quenching – challenges

➢ Establishing jet quenching in small systems in which flow exists



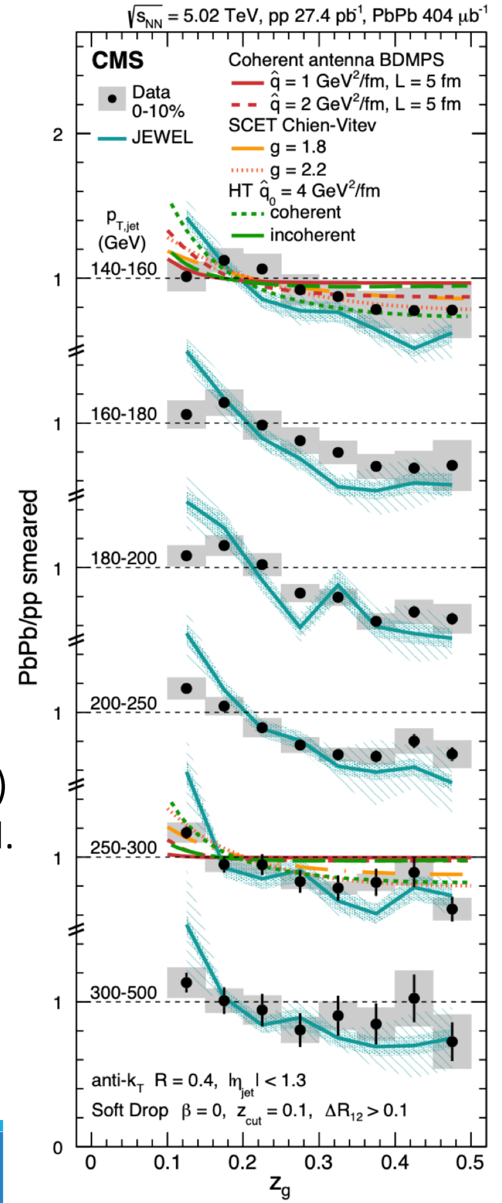
At stake: **common dynamical origin of collective flow and jet quenching**

➢ Testing the microscopic dynamics of medium-modified parton splitting



Challenge: **applying modern jet substructure measurements to high-multiplicity events.**

First efforts (e.g. z_g – distributions) promising but much more needed.

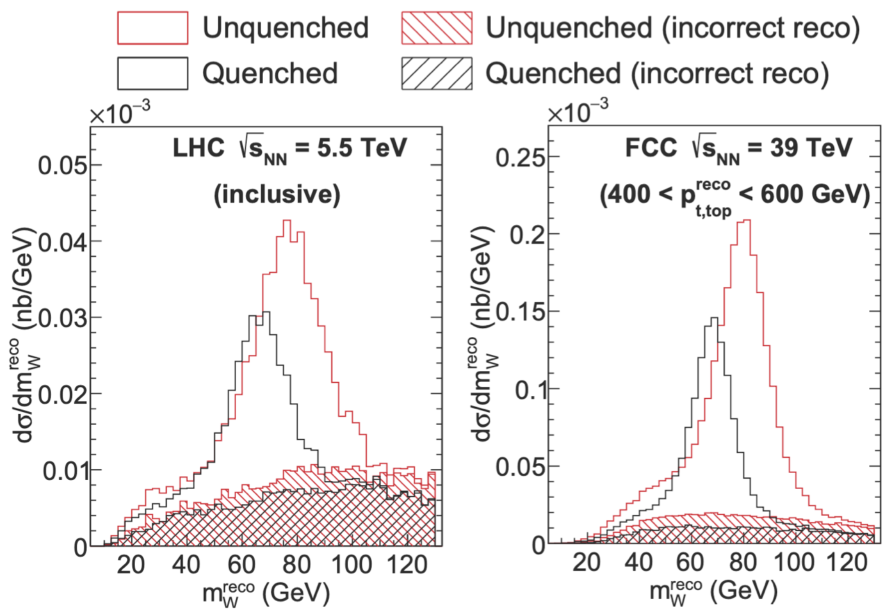


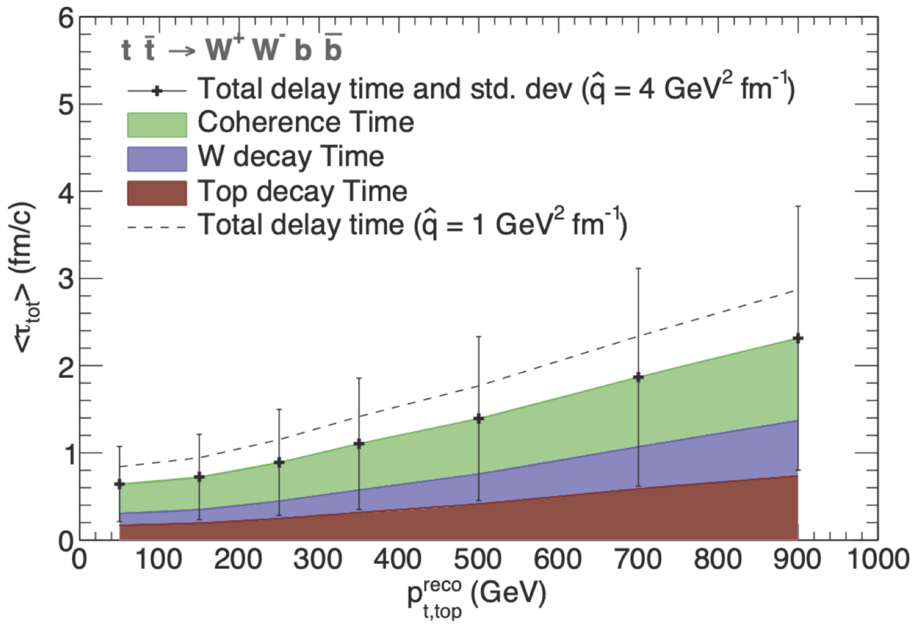
*A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. v.d. Schee, UAW, Phys.Rev. C 103 (2021) 5,054903 and Phys.Rev.Lett. 126 (2021) 19, 192301
CMS Coll, Phys. Rev. Lett. 120 (2018) 14

Jet quenching – challenges .... cont'd

- Testing spatio-temporal embedding

(Extreme) example: $t\bar{t} \to W^+W^-b\bar{b} \to \mu\nu q\bar{q}b\bar{b}$

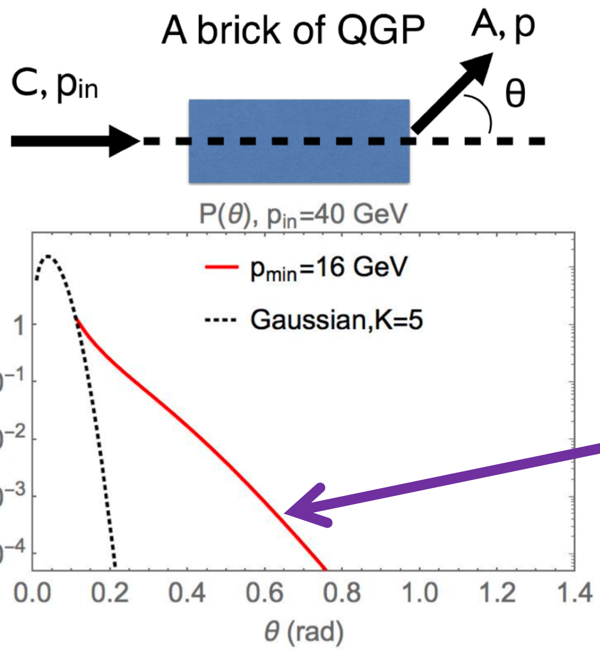




Challenge: **develop techniques to determine spatio-temporal ordering for more abundant signals.**

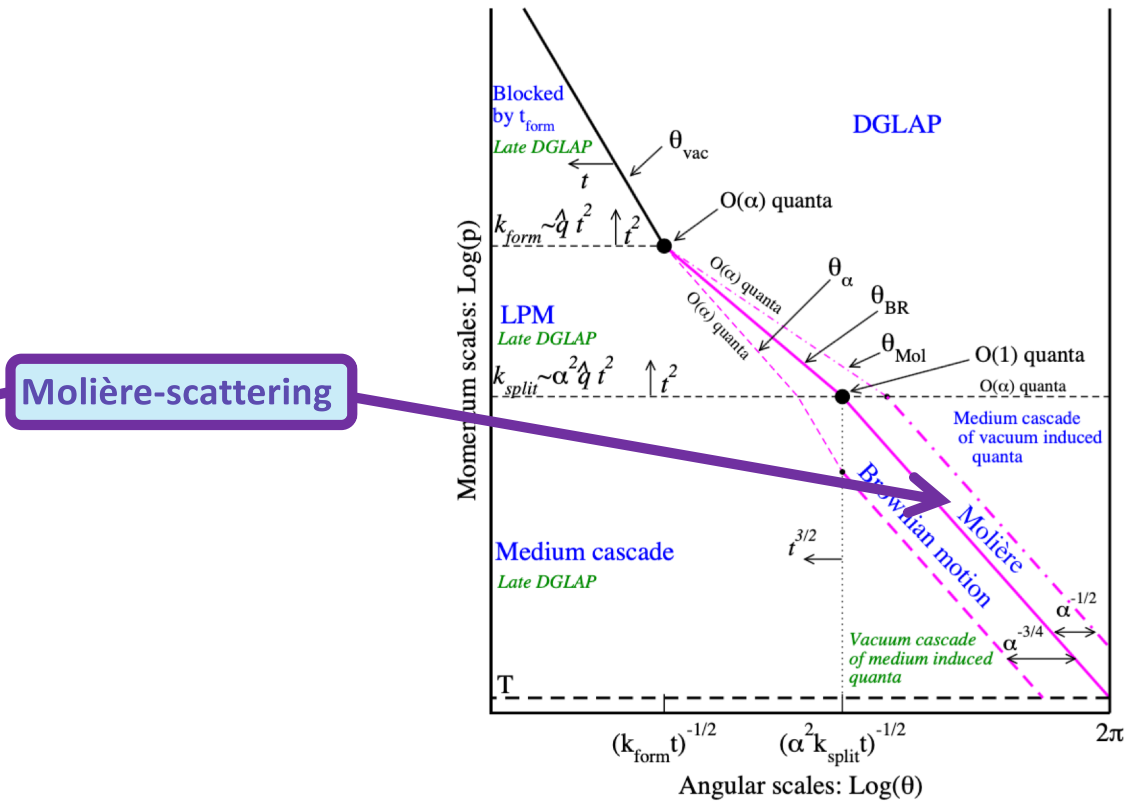
Jet quenching – challenges .... cont'd

- Characterizing jet-medium interactions:
  The thought experiment



At stake: **resolving constituents of medium via large-angle scatterings in jets.**

Challenge: **finding observables sensitive to a narrow corner of the phase space of medium-modified parton showers.**

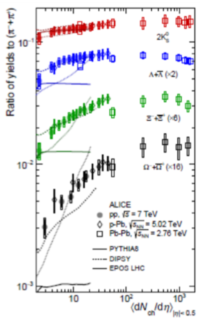


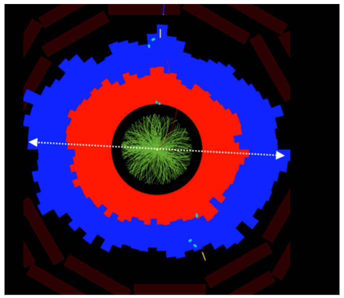
F. D'Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172
A. Kurkela and UAW, Phys.Lett. B740 (2015) 172

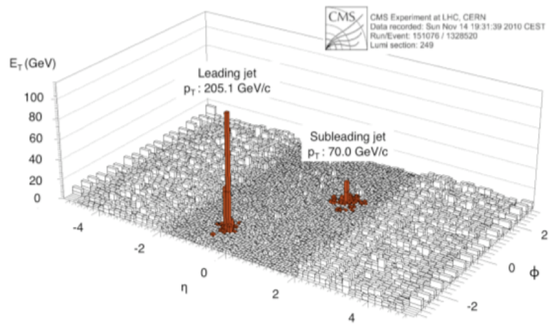
Summary

I have given examples of how the interplay between theory and future experimentation can allow us to

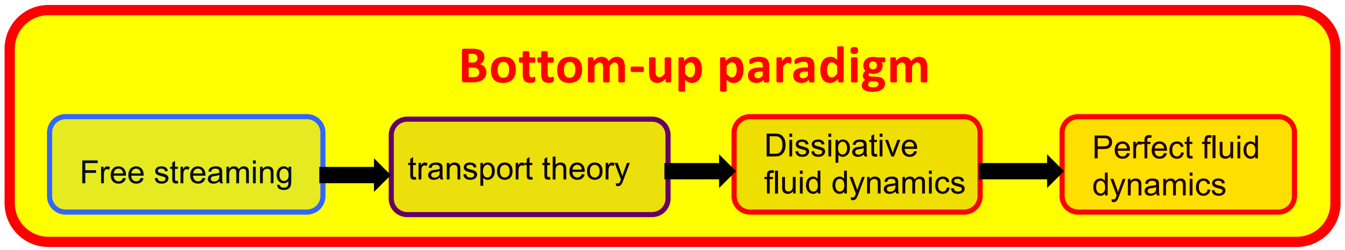
- identify the common dynamical origin of the robust collective phenomena observed in A+A







- understand how collectivity arises with system size from p+p => p+A => A+A



Z. Citron et al., Report of Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams, arXiv:1812.06772

D. Adamova et al, A next-generation LHC heavy-ion experiment, arXiv:1902.01211