Brief overview of Heavy-Ion Physics

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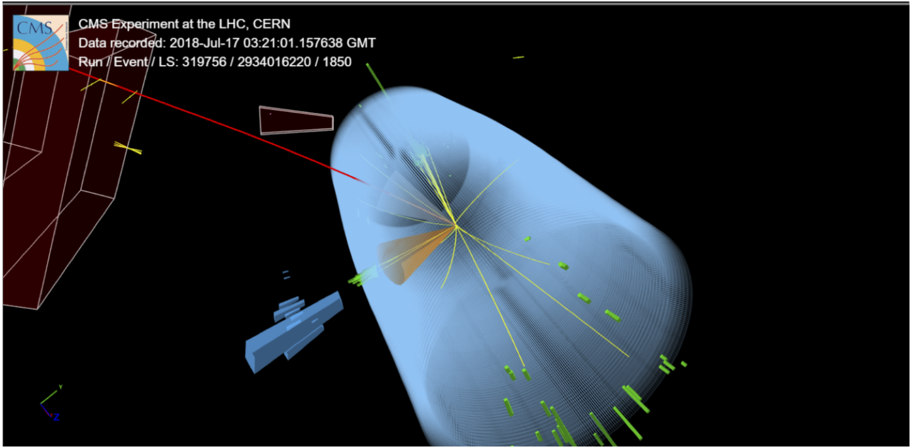
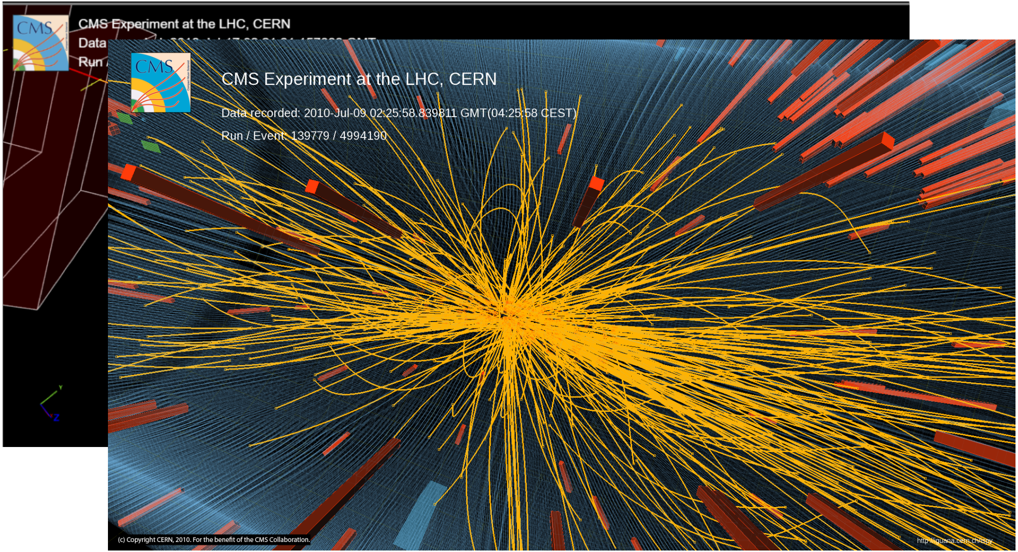
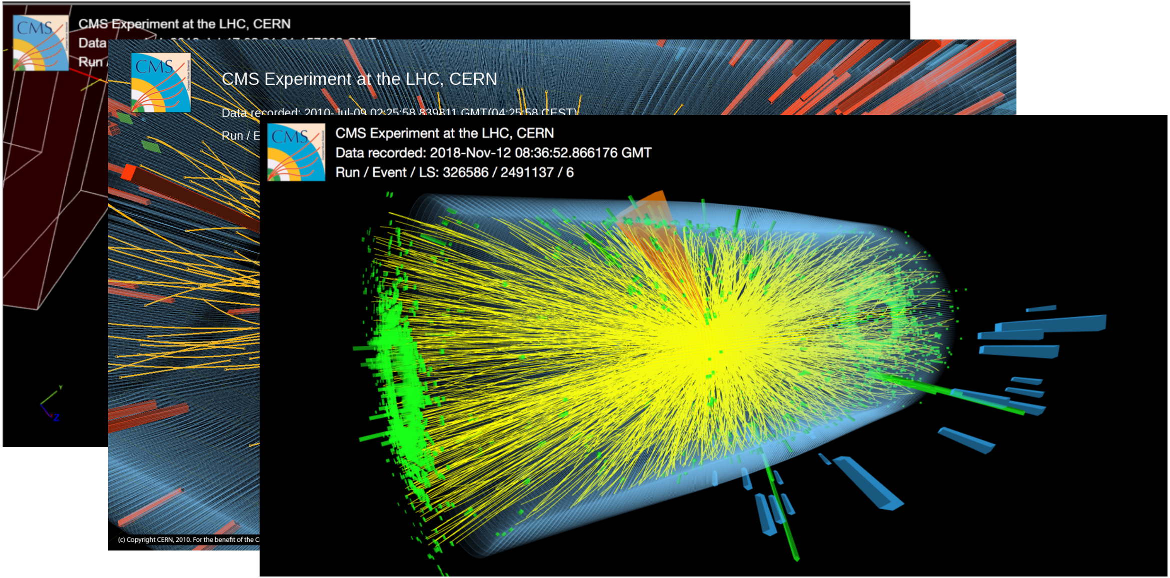
Heavy-Ion Physics: high energy $\Rightarrow$ high multiplicity



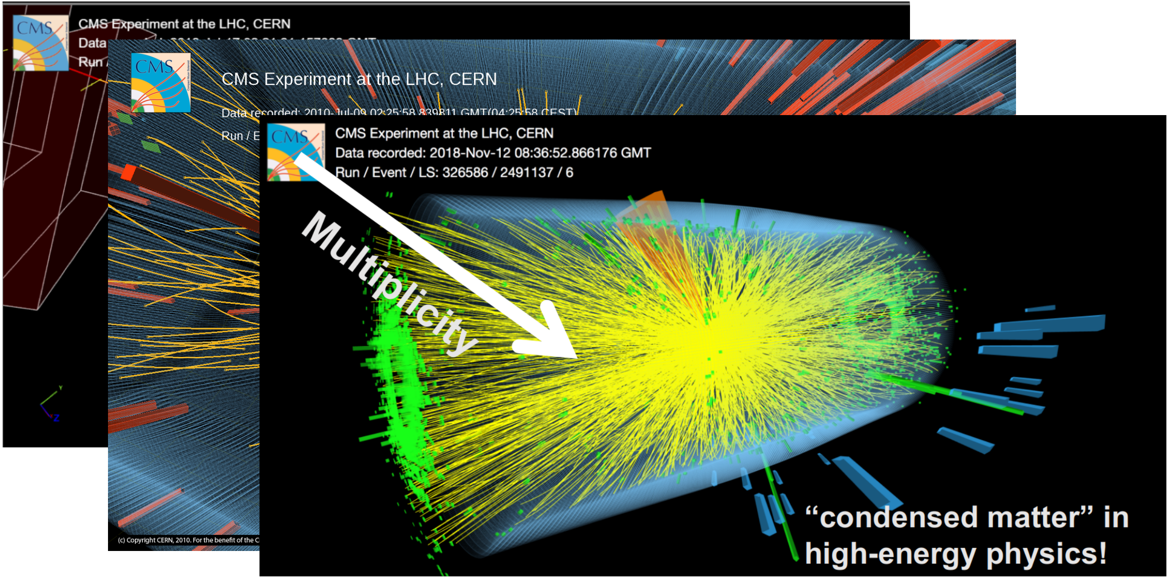
Heavy-Ion Physics: high energy ⇒ high multiplicity



Heavy-Ion Physics: high energy $\Rightarrow$ high multiplicity

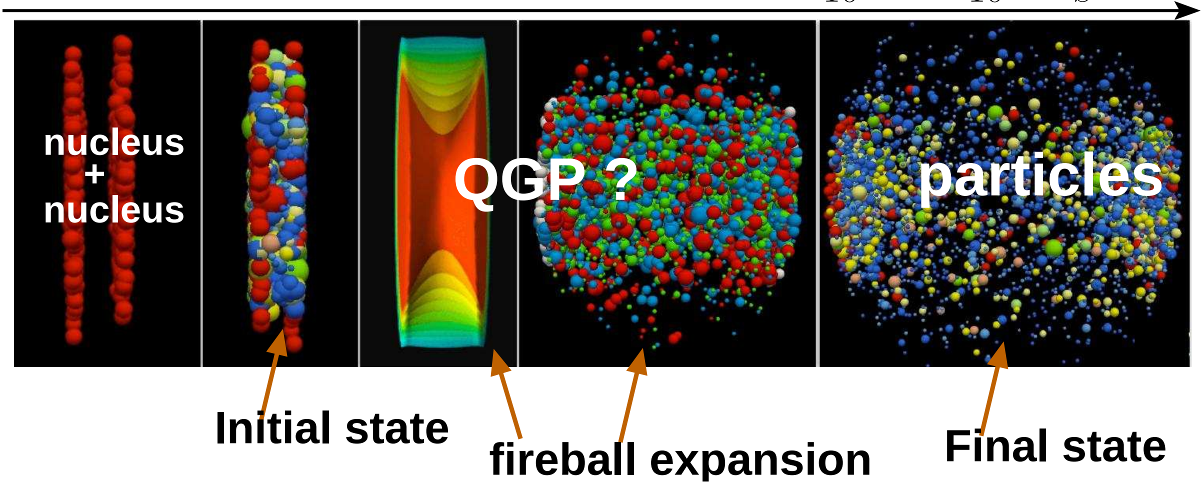


New Physics: high energy ⇒ high multiplicity



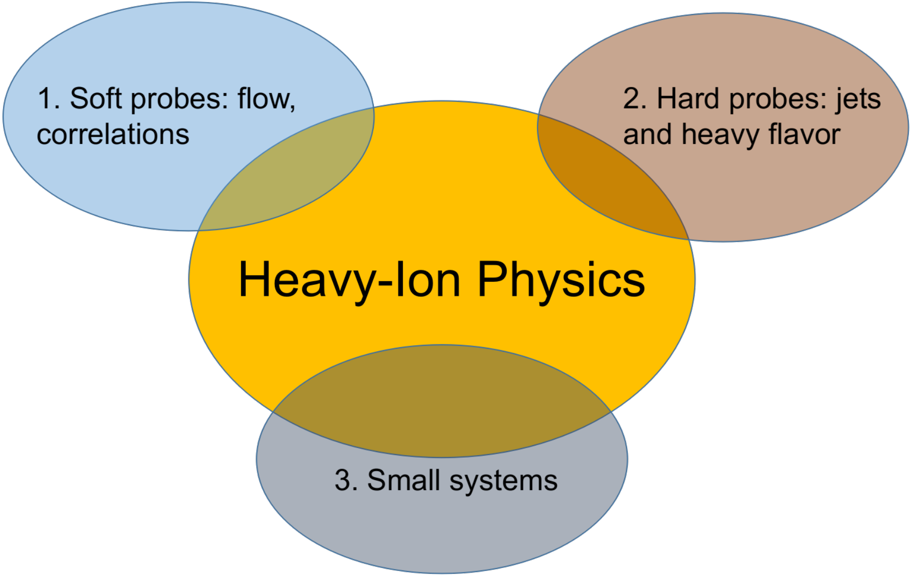
"Little Bang" in heavy-ion collisions

$10^{-23} \sim 10^{-22}$ s



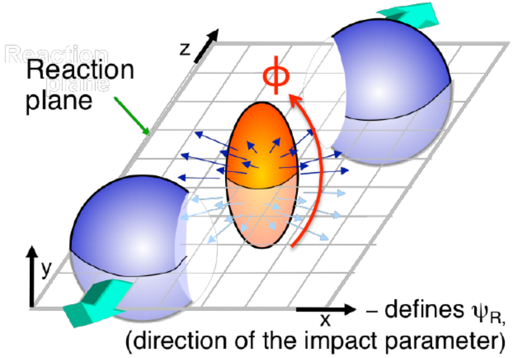
- **Quark-Gluon Plasma**: An expanding QCD fluid of energy scale Λ_{QCD}

Outline of the talk

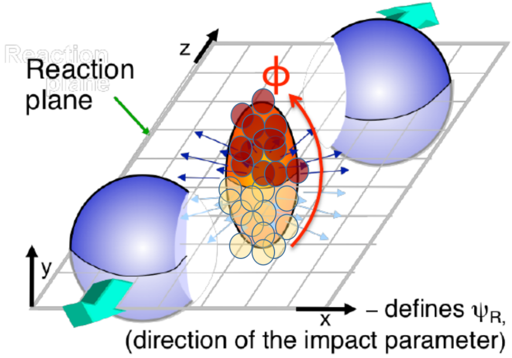


Collective flow

Smooth spatial anisotropy



Flucting spatial anisotropy

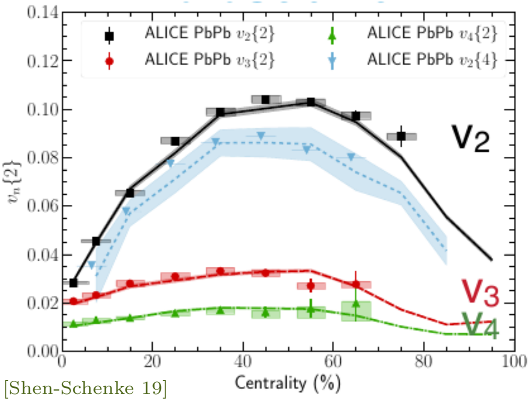


Spatial anisotropy + QGP fluid $\Leftrightarrow$ Anisotropy in momentum spectrum $\Leftrightarrow$ Collective flow V_n:

$$\frac{dN}{d\phi_p dp_T} \sim \sum_n v_n \exp[-in(\phi_p - \Psi_n)] \equiv \sum_n V_n(p_T) e^{-in\phi_p}$$

Collective flow in experiment and theory

Flow in experiment:



[Shen-Schenke 19]

Flow measured from multi-particle correlations:

magnitude v_n, fluctuations $P(v_n)$, correlations, ...

Flow in theory:

- QGP thermalization/hydrodynamization

  Applicability of hydro: $\mathcal{P}_L/\mathcal{P}_T \to 1$

- Relativistic hydrodynamics model,

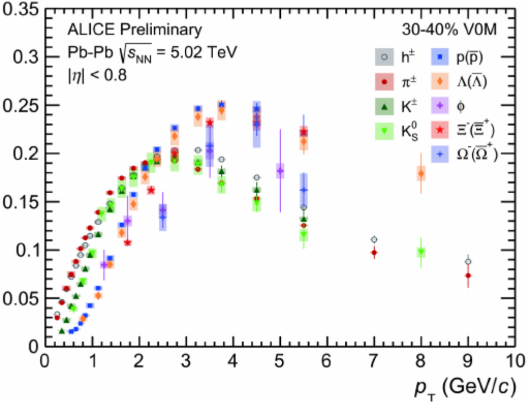
$$\begin{cases} \text{conservation law:} & \partial_\mu T^{\mu\nu} = 0 \\ \text{Lattice QCD:} & \mathcal{P} = \mathcal{P}(\epsilon), \quad c_s^2 = \partial\mathcal{P}/\partial\epsilon \\ \text{Inputs trans. coef.:} & \eta/s, \quad \zeta/s \end{cases}$$

- After hydro and particlization:

  $\to$ calculate flow in exp.

Collective flow at the LHC

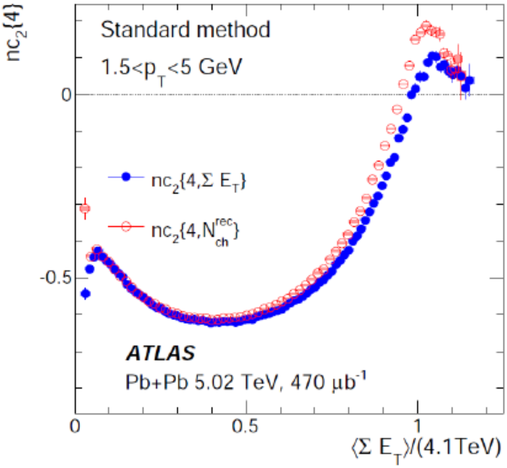
Fluctuations of v_2:



$v_2\{4\}(p_T)$:

$$P(v_n) \to v_2\{4\}^2 \sim 2\langle|v_2|^2\rangle^2 - \langle|v_2|^4\rangle \to \text{fluc. of spectrum}$$

Fluctuations of centrality

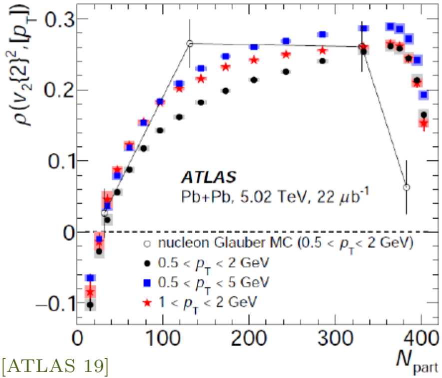


Normalized flow cumulant,

$$nc_2\{4\} = \frac{c_2\{4\}}{c_2\{2\}^2} \to \text{central collisions!}$$

Collective flow at the LHC

Correlations between v_2 and v_0:

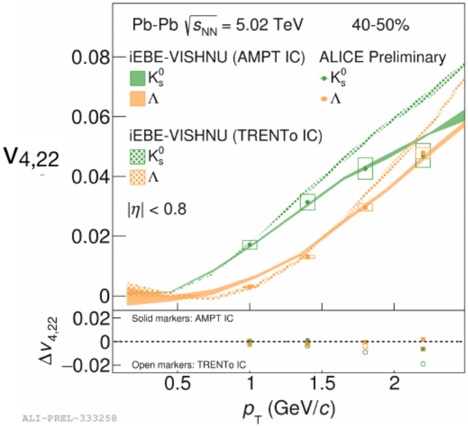


[ATLAS 19]

Flow coupling between v_0 and v_2

$$\text{nuclear geometry:} \quad \begin{cases} v_0 \sim \langle r^2 \rangle \\ v_2 \sim \langle x^2 - y^2 \rangle / \langle r^2 \rangle \end{cases}$$

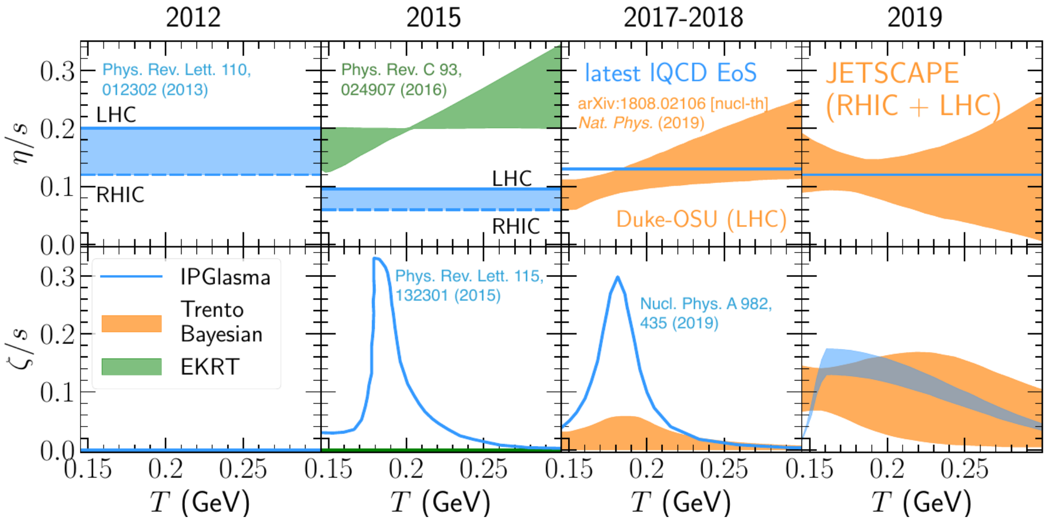
Nonlinear coupling between v_2 and v_4



Flow coupling between v_2 ad v_4,

$$V_4 = V_4^{\text{Linear}} + \underbrace{\chi_{4,22}|V_2|^2}_{V_{4,22}}$$

New constraints on the medium transport coefficients

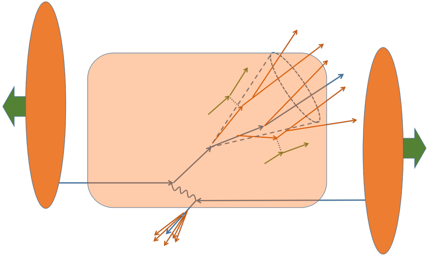


[figure from Chun Shen's QM19 talk]

Jets in Heavy-ion physics

- Produced in the initial hard scatterings: pQCD + nPDF.
- Tomographic probes of QGP: jet energy loss + properties of medium + hadronization.
- A lot of theoretical models have been proposed.

$$\text{E.g., JETSCAPE:} \begin{cases} \text{LBT with recoil} \\ \text{Trento (2+1D) initial condition + (2+1D) VISHNew hydro} \end{cases}$$



* Jet energy loss to the QGP medium.

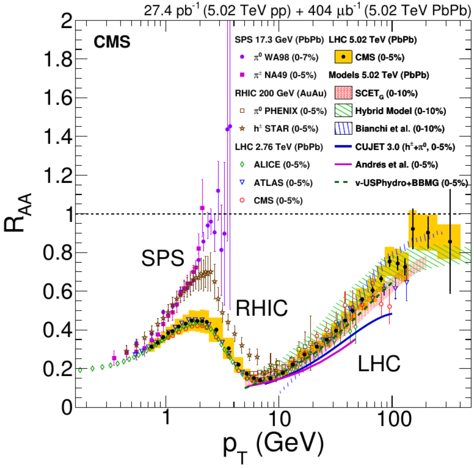
$$\text{quenching:} \begin{cases} R_{AA} = \dfrac{dN^{\mathrm{AA}}/dp_T d\eta}{\langle N_{\mathrm{bin}}\rangle dN^{\mathrm{pp}}/dp_T d\eta} \\ \\ \text{high-}p_T\ v_2, \text{tagged jets, Dijets, ...} \end{cases}$$

* QGP medium response to Jets.

shock, wake: Jet substructures

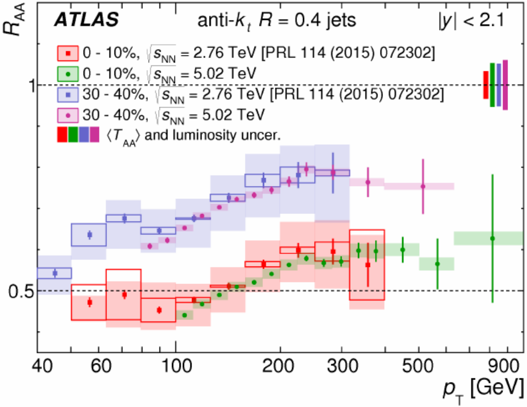
Jet quenching at the LHC

R_{AA} of charged hadrons:



[JHEP 04(2017)039]

R_{AA} of jets



Strong evidence of jet quenching:

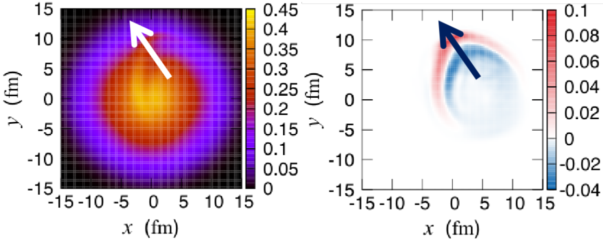
- R_{AA} suppression at high-p_T.
- Suppression increases with centrality.

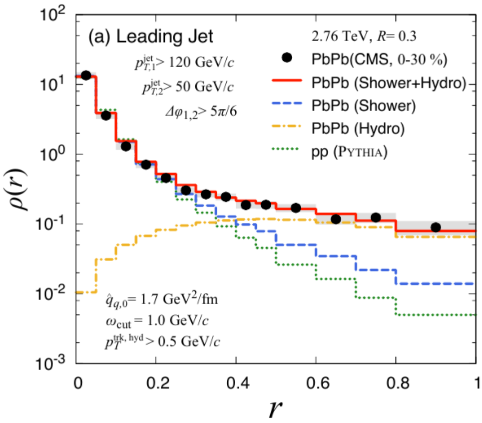
Jet substructure and jet-medium interaction

A combined treatment of jet and medium:

jet energy loss in QGP: $df/dt = C[f]$

QGP response: $\partial_\mu T^{\mu\nu} = j^\mu = \int p^\mu f$



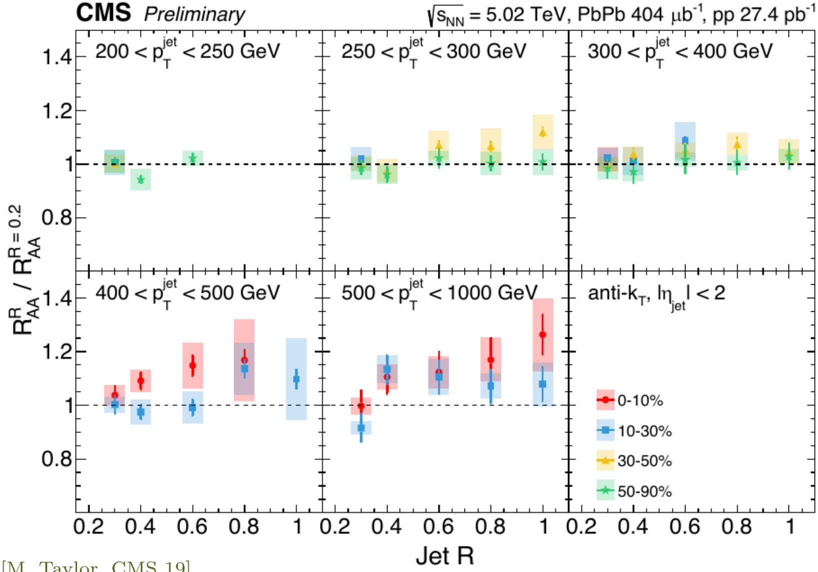


[Tachibana-Qin-Chang, 17]

- Mach cone structure is realized.
- Wake influences jets in large radii.

- $\rho(r)$ describes energy deposition vs. radius.
- Medium response dominates at large r.

R_{AA} as a function of R



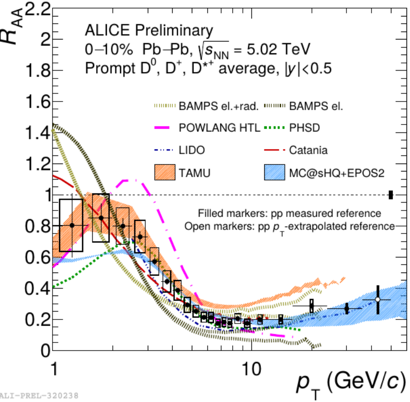
[M. Taylor, CMS 19]

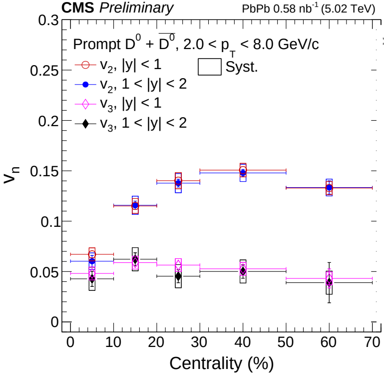
- A differential measurement of quenching wrt. jet radii.
- New and strong constraints on the jet energy loss mechanism.
- Medium response is essential for understanding the results!

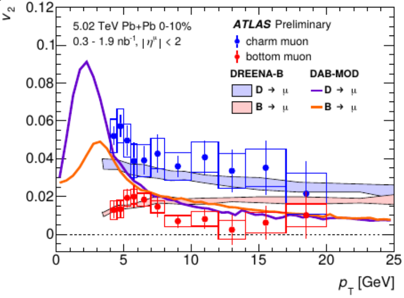
Open Heavy flavor

- Produced in the initial hard scatterings: pQCD + nPDF.
- Tomographic probes of QGP: diffusions/transport of heavy quarks in QGP + hadronization

E.g., Heavy quark transport: $$[\partial_t + \vec{v}\cdot\nabla + \vec{F}\cdot\nabla_p]f_Q = \underbrace{C[f_Q]}_{\text{transport coefficients}}$$

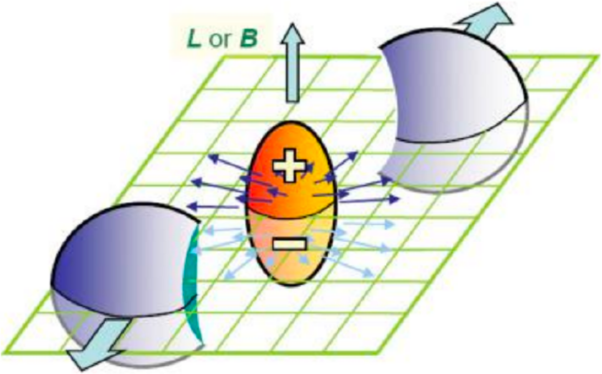


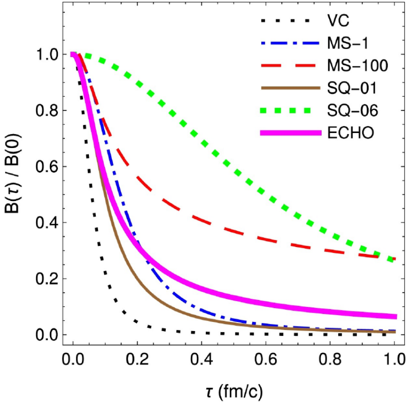




[ATLAS-CONF-2019-053]

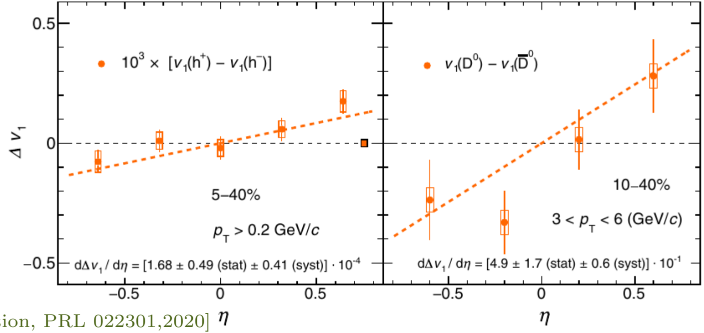
Open heavy flavor and magnetic field





- Generic B field created from Heavy-Ion collisions: strong ($eB \sim m_\pi^2$) but short-lived!
- Magnitude and life of B field are crucial to study the topological behavior in QCD: CME.
- Heavy flavor quarks produced dominantly from initial scatterings: ideal probe for B field.

Open heavy flavor and magnetic field



[ALICE collaboration, PRL 022301,2020]

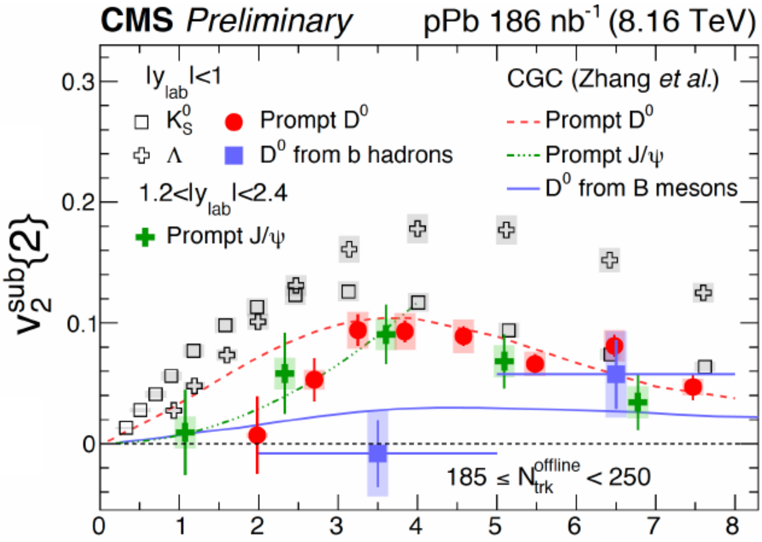
- Heavy flavor quarks pushed by external B field, the effect is stronger than charged hadrons:

$$\frac{d\Delta v_1(D)}{d\eta} \gg \frac{d\Delta v_1(h^{\pm})}{d\eta}$$

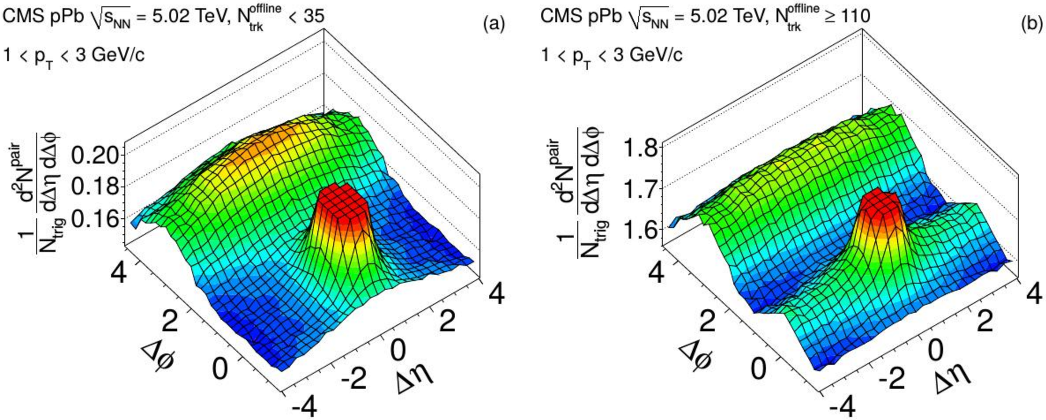
- But, the effect at the LHC is opposite to that from RHIC, and theoretical expectations!

$$\frac{d\Delta v_1(LHC)}{d\eta} \sim -\frac{d\Delta v_1(RHIC)}{d\eta}$$

Open heavy flavor flow in small system



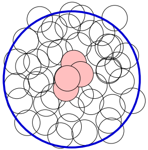
Fluidity in small colliding systems

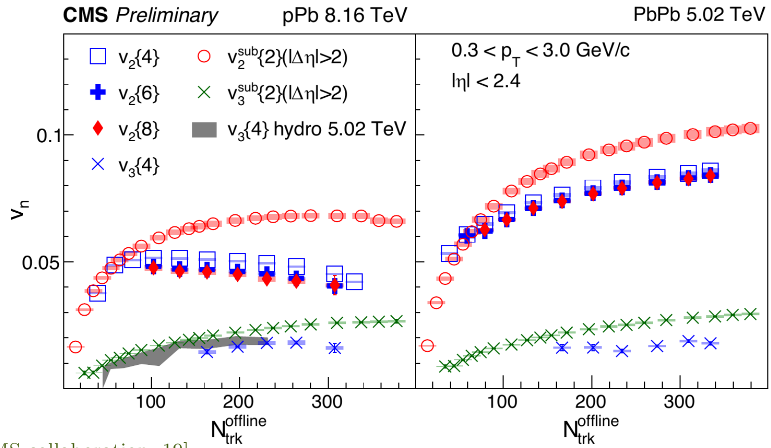


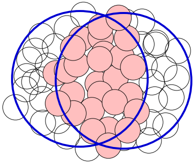
[CMS collaboration, 13]

- Flow from two-point correlation can be well described by hydrodynamics [Bozek 15, Romatschke 16, Schenke 17, Zhao-Song-Zhou 19, ...]

Flow in small systems: multi-particle correlations





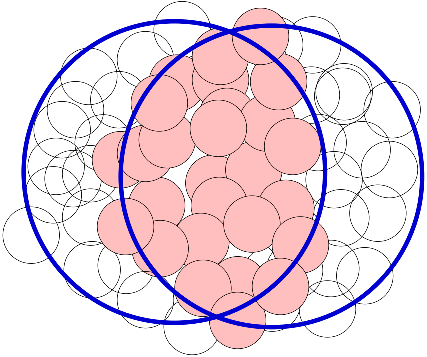


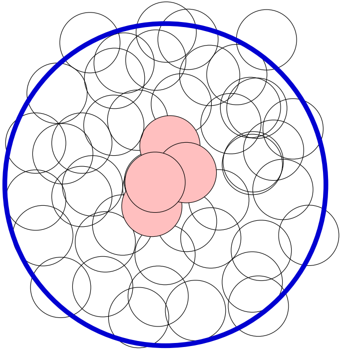
[CMS collaboration, 19]

- Hydro predicts quantitatively the universal non-Gaussianity in pA from IC (and for v_n):
  [Bzdak-Bozek-McLerran 16, LY-Ollitrault-Poskanzer 16]

$$v_n\{2\} > v_n\{4\} \gtrsim v_n\{6\} \gtrsim v_n\{8\}, \qquad \text{NOT JUST '}\approx\text{'}$$

Challenges of hydro in pA: system is out-of-equilibrium!



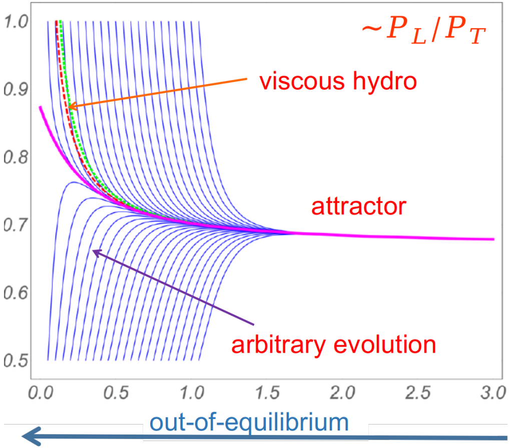


- From AA to pA system transverse size reduces, system is not thermalized!

$$L_{pA} \sim \frac{L_{AA}}{10} \sim O(1)\ \mathrm{fm} \quad \Rightarrow \quad \text{Kn increases}$$

- $\Rightarrow$ Hydrodynamics needs to be generalized to out of equilibrium!

Out-of-equilibrium hydrodynamics



- Non-hydro modes decay w.r.t. attractor solutions, so that hydro can be extended to out-of-equilibrium by attractor.
  [M. Heller, M. Spalinski, P. Romatschke, A. Kurkela, U. Wiedemann, ...]
- Theoretical framework of attractor has been developed up to 1+1D conformal flow
  [Denicol, Noronha, Strickland, Martinez, Yan, Blaizot, Yin, Brewer, ...]
- Phenomenoloigical applications of attractor.
  [Giacalone-Mazeliauskas-Schlichting 19, Kurkela-Mazeliasukas 19]

Summary

- Comprehensive and precise measurements achieved at the LHC.
- Collective flow investigated in various aspect: fluctuations, correlations, spectrum, ...
- Jet physics and heavy flavor with more differential analyses.

$$\text{Jet substructure} \Leftrightarrow \text{medium fluid response to jet}$$

- Fluidity of QGP in small system motivated the development of hydro in out-of-equilibrium.