Can we calculate and measure jet quenching in small systems?

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Qualitative considerations: theory

1. Observing jet quenching (JQ) establishes existence of final state interactions (FSI).
2. Favored (hydro/ transport) explanations of collectivity (v_n-flow) are based on FSI.
3. Small systems (pp, pA, periph. AA) show soft collectivity but (so far) no unambiguous JQ.

There is logical tension between these statements:
Either: No JQ in small systems. Then interpretation of their soft collectivity needs to involve no-FSI mechanisms.
Or: Improved experiments identify JQ in small systems. Then improved theory needs to relate this small JQ to soft collectivity.
The search for JQ in small systems can inform the quest for a unified dynamical description of hard and soft medium-effects.

What theory says? (imho)

Qualitatively, JQ and soft collectivity are related:

1. In weakly coupled systems:
   - hydrodynamization via bottom-up thermalization, governed by same $2 \to 2$ and $1 \to 2$ (LPM) collision kernels as JQ, efficient on short timescales [?].
2. In strongly coupled systems:
   - (almost) perfect fluidity and JQ-drag both unavoidable.

Quantitative statements uncertain or missing:

1. Many JQ codes not (yet?) explored for pp/pA
   - Does embedding jets in spatio-temporal evolution of pp or pA have higher uncertainties?
   - Do JQ models rely on resumming geometrically enhanced higher-twist effects $(\frac{A^{1/3}}{Q^2})$? If so, are they applicable to small systems?
   - In small systems, triggers on event activity like $dN^{\rm ch}/d\eta$ influence selection of hard probes. Many issues: What are suitable JQ observables? How to avoid / utilize trigger biases? $\Longrightarrow$ see experimental part
2. BDMPS-type JQ sensitive to $\hat{q} = \frac{\langle k_\perp^2 \rangle_{\rm med}}{\lambda_{\rm mfp}}$
   - insensitive to whether $\hat{q}$ built up by many soft or very few harder interactions $N_{\rm int}$.
   - but $\langle N_{\rm int} \rangle$ determines whether all "jets" suffer small or whether few jets suffer sizeable medium modifications $\Longrightarrow$ information beyond fluid dynamic averages $(T^{\mu\nu})$ likely relevant for quantitative description of JQ.

The medium in small systems

- Both almost perfect fluid models and transport with few scatterings [?] reproduce collectivity in small systems [?].
- Close to equilibrium, all QFTs carry hydro- and non-hydro degrees of freedom.
- Transport and Israel-Stewart theory can carry same hydro but different non-hydro excitations [?].

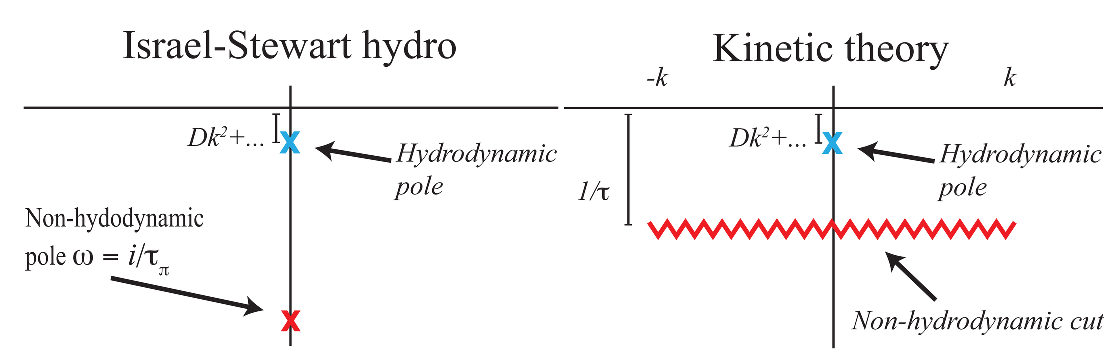
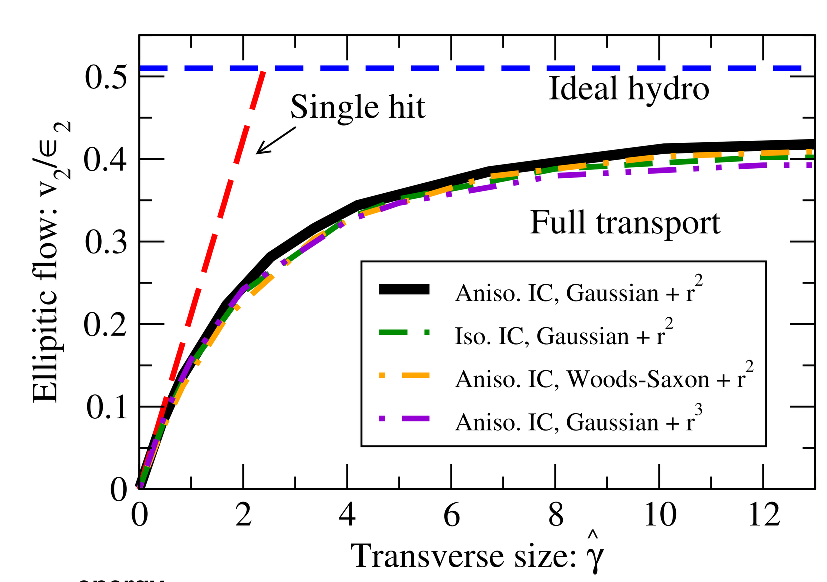


Figure 1: Pole structure of retarded correlator $G_R(\omega, k)$ (shear mode). **Non-hydro modes become more important in smaller systems [?].**

- In conformal systems without other intrinsic scale, opacity $\hat{\gamma} = \gamma R^{3/4} (\varepsilon_0 \tau_0)^{1/4}$, $(\gamma = \frac{\rm const.}{\eta/s})$, is only scaling variable [?],

$$\hat{\gamma} = \frac{0.11}{\eta/s} \left(\frac{1}{\pi f_{\rm work}(\hat{\gamma})} \right)^{1/4} \left(R \frac{dE_\perp}{d\eta_s} \right)^{1/4} .$$

- $\hat{\gamma} \gg 1 \Longrightarrow \hat{\gamma} = c_{\rm hyd} \left(\frac{dN}{d\eta} \right)^{1/3}$ multiplicity scaling.
- $\hat{\gamma} \lesssim 1 \Longrightarrow \hat{\gamma} = c_{\rm hyd} \left(R \langle p_\perp \rangle \frac{dN}{d\eta} \right)^{1/4}$ no multiplicity scaling.



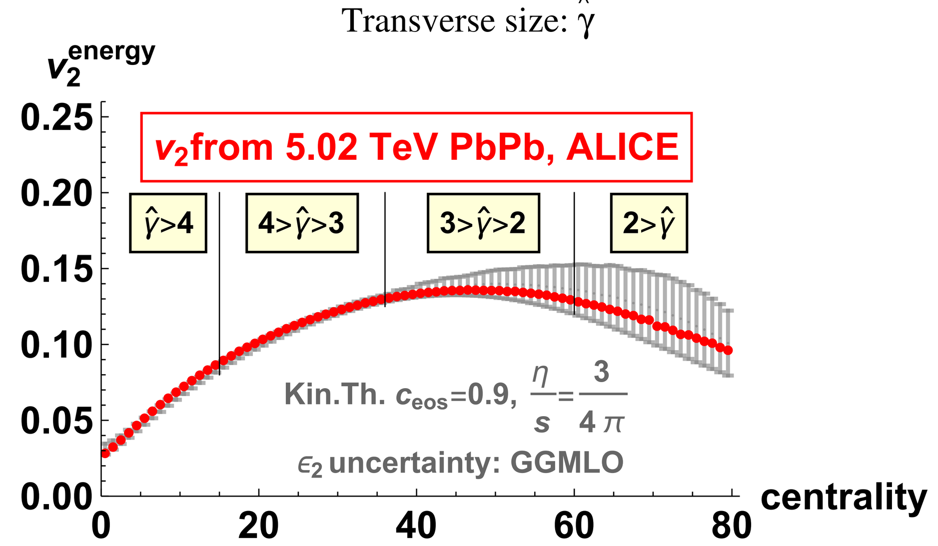


Figure 2: Small system soft collectivity may originate not at fluid dynamic limit. Kinetic transport: enhanced escape probability of particles/jets without scattering [?]. Figs. from [?].

Qualitative considerations: experiment

1. Jet quenching effects in small systems expected to be small; little guidance from theory
2. characterization of collision geometry in small systems is challenging: large relative fluctuations of Event Activity $\to$ large model dependence of $\langle T_{\rm pA} \rangle$

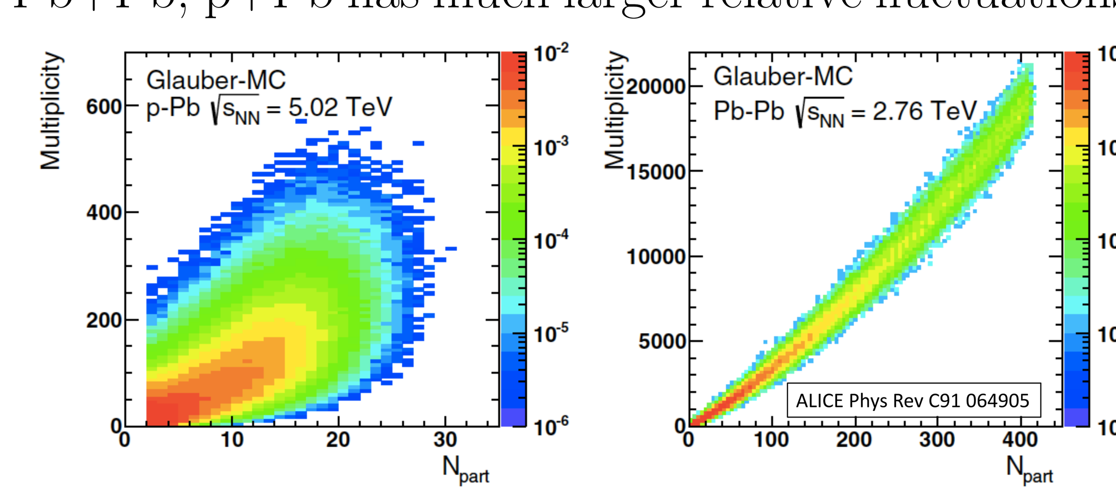
Choice of observables: jets, hadrons

- inclusive suppression
- triggered coincidence: recoil suppression and deflection
- jet substructure

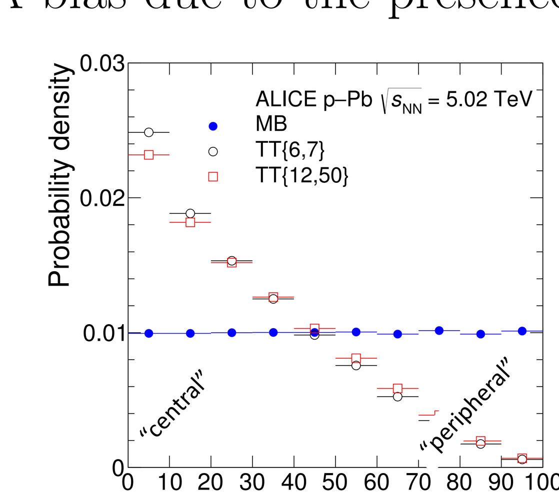
$\to$ require precise control over backgrounds, including MPIs
$\to$ independence of $\langle T_{\rm pA} \rangle$: coincidence, substructure observables
$\to$ kinematic range: low $p_{\rm T}^{\rm jet}$ may have largest relative modification/largest sensitivity
Optimum strategy: utilize tension between multiple observables with different parametric dependencies on e.g. $\hat{q}$ and L

EA and "centrality"

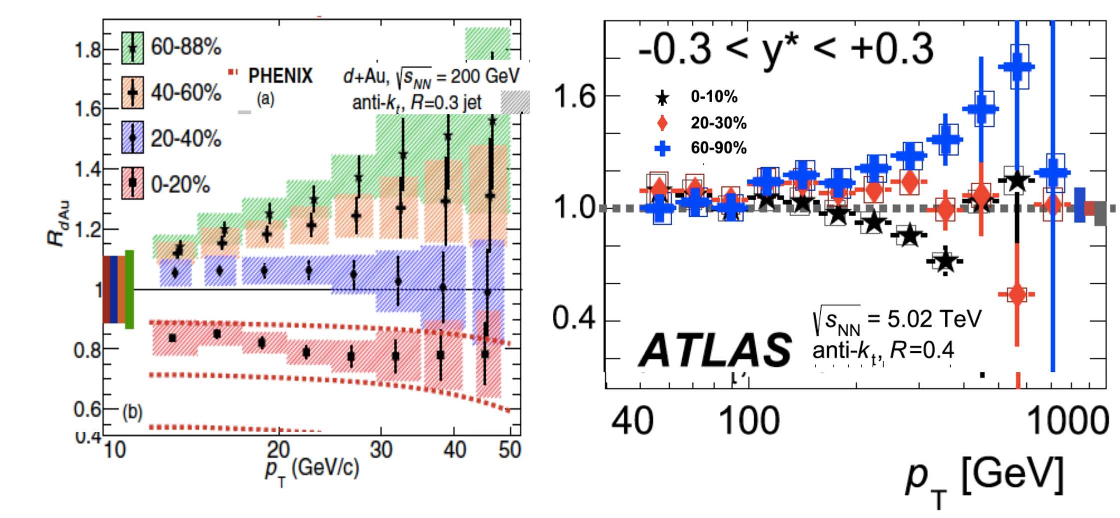
Glauber calculations showing correlation of forward multiplicity with calculated $N_{\rm part}$ for p+Pb and Pb+Pb; p+Pb has much larger relative fluctuations.

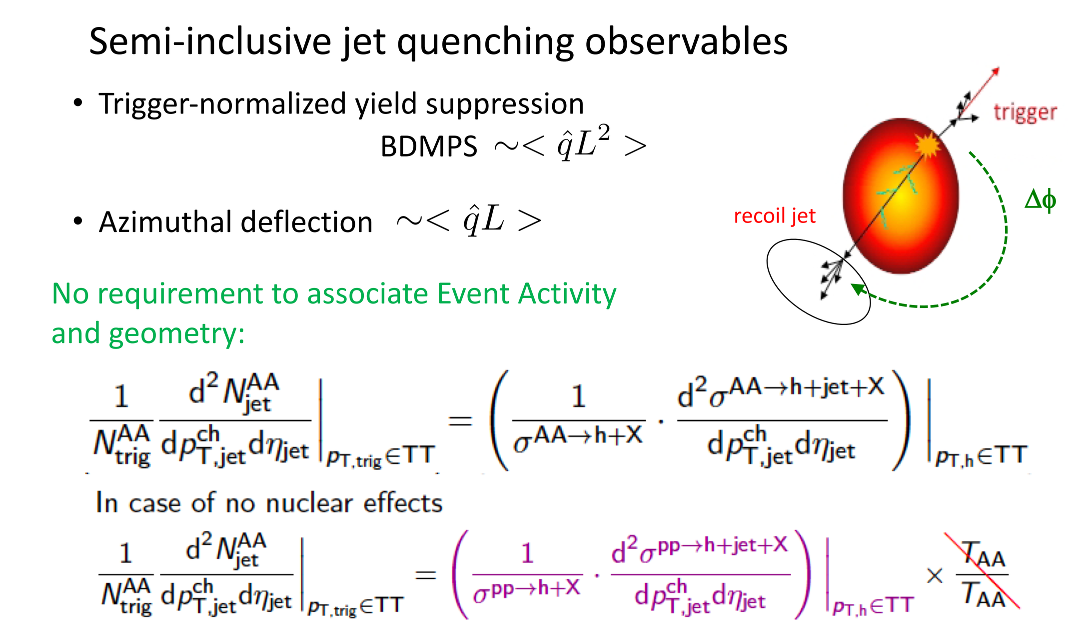


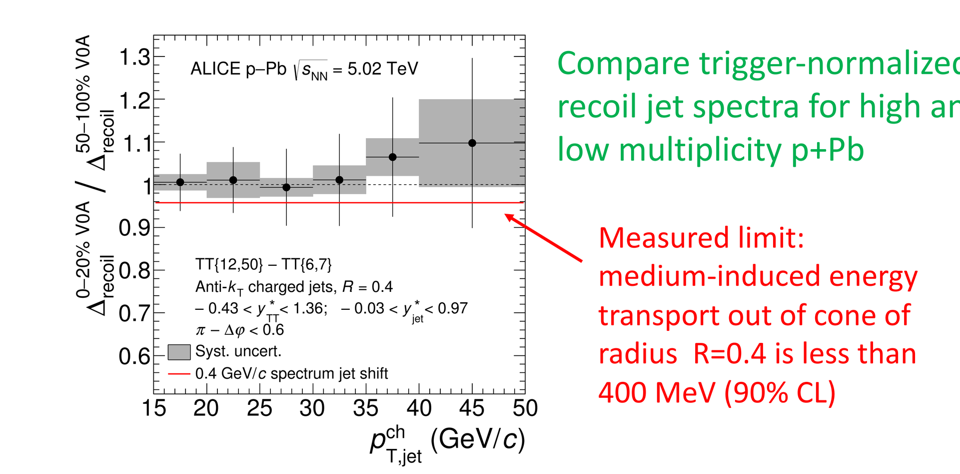
EA bias due to the presence of a hard process:



Inclusive $R_{\rm pA}$ and semi-inclusive jet measurements







Inclusive $R_{\rm pA}$ and semi-inclusive limit are not compatible [?]. My guess: uncorrected biases in $\langle T_{\rm pA} \rangle$ due to QCD correlations, beyond the increase in pp UE[?].

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