Tests for collective behaviour in heavy ion collisions

based on 0708.0035,nucl-th/0703031,nucl-th/0702013

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Carlo Rubbia asked: "Out of the zillion graphs you show at your conference, which graph shows the QGP"? Several are claimed to, but they apply at different energies/sizes, so we can not answer at what point we do not have QGP!

At what point have we created the "liquid" state instead of a rarified gas of particles? Perhaps it was with us all along, there is something profound about QCD we did not understand, and at RHIC the "new state" is just more evident. Can we rule out this hypothesis?

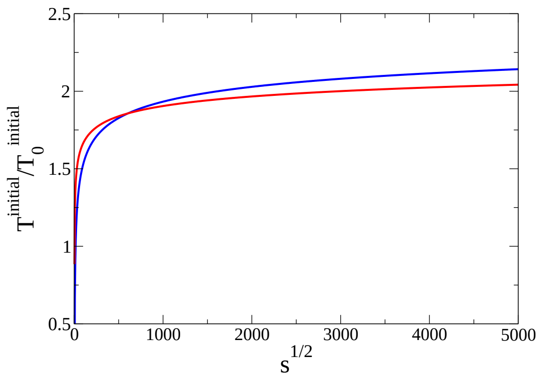
The 10^n dollar (provocative) question

What evidence do we have that the stuff created in RHIC heavy ion collisions is in fact different from the stuff created in d-Au,p-p etc. collisions, rather than a smaller, shorter lived, possibly less thermalized system (possibly not!) with the same DoFs?

To answer this, we need to explore scaling (or its violation!) across different $\sqrt{s}, A, N_{part}, dN/dy, y$

We know experimentally that $\frac{dN}{dy} \sim \ln \sqrt{s}$ taking Bjorken approximation (holds at all energies? y_{lim} also $\sim \ln \sqrt{s}$)

$$T_{initial} \sim \ln \ln \sqrt{s} \quad (Massive) \qquad T_{initial} \sim \left(\ln \sqrt{s} \right)^{1/3} \quad (Massless)$$



In other words, temperature varies slowly with energy. Properties of soft medium should change smoothly as well. Which observable is best at showing regime where something funny happens?

Jets and coalescence are probably lousy observables to do scaling studies

Jets

$$N_{jets} \sim N_{collisions} f(L)$$

$N_{collisions}$ varies very fast with $\sqrt{s}, A$ and dominates at low $\sqrt{s}, A$ even if suppression present.

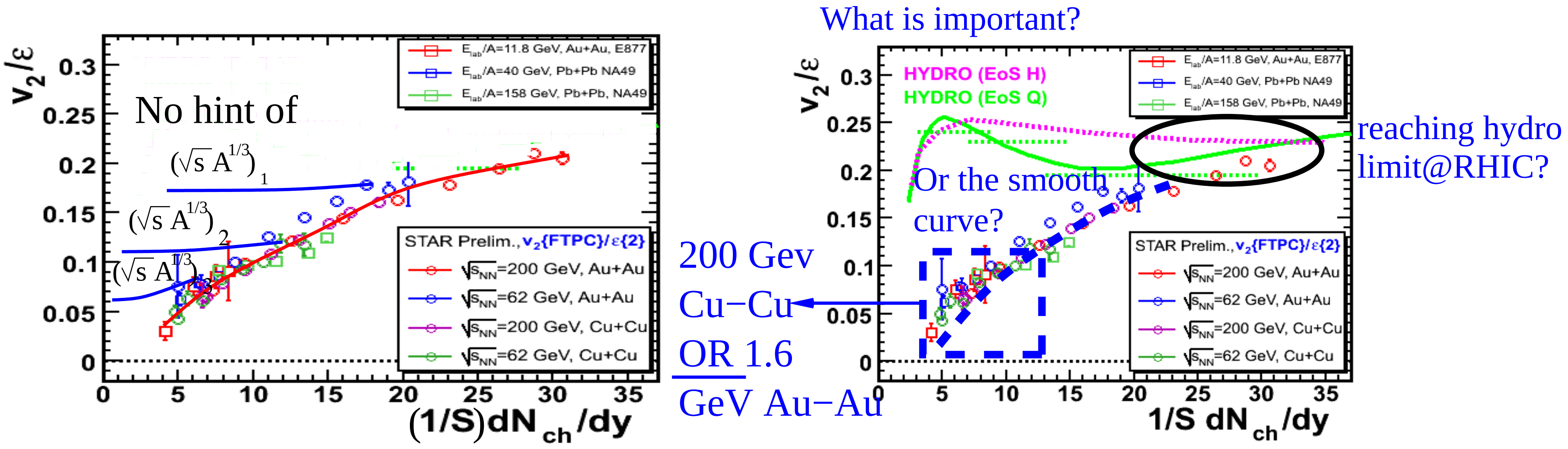
- Energy loss models fit SPS enhancement with same formalism as RHIC suppression
- How do we know d-Au@RHIC did not create d-sizedchunk of "hot" matter, and $N_{collisions}$ increase with N_{part} just overpowers $f(L)$?

Coalescence At $\mu_B \geq T$ $\rho_q \gg \rho_{\overline{q}}$ and admixture of mesons from baryonic resonances becomes important. This messes up coalescence even if at hadronization quarks coalesce and there are no further reinteractions.

v_2? scaling seems to be there! too much of it!

There might well be v_2 for p-p, but it is not a measurable quantity.

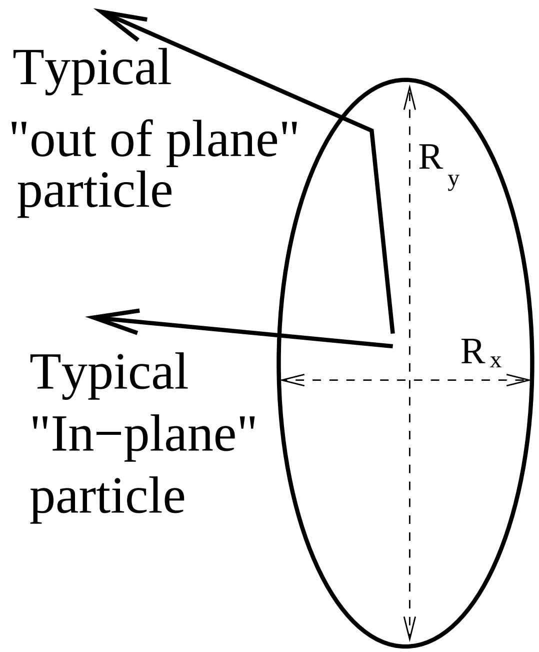
Indirect evidence points to v_2 NOT being in any-way special for large systems. (GT Phys.Rev.C76:024903,2007. e-Print: nucl-th/0702013)



Scaling across $\sqrt{s}$, A:If $\frac{1}{S}\frac{dN}{dy}\Big|_{cu-cu}^{200GeV} = \frac{1}{S}\frac{dN}{dy}\Big|_{Au-Au}^{1.6GeV}$, $\frac{v_2}{\epsilon}$ equal too!

Why plot $\frac{v_2}{\epsilon}$ vs $\frac{1}{S}\frac{dN}{dy}$?

H. Heiselberg and A. M. Levy,PRC **59**, 2716 (1999) nucl-th/9812034



$$l_{mfp} \sim R \quad 1 \quad Interaction/particle/lifetime$$

Boltzmann equation with these initial conditions...

$$\frac{v_2}{\epsilon} \propto \frac{\langle \sigma_{ij} v_{ij} \rangle}{R_x R_y} \frac{dN}{dy}$$

A break of this scaling would have signalled a sudden change in $\langle \sigma_{ij} v \rangle$, driven perhaps by the transition from a weakly coupled hadron gas to a weakly coupled quark-gluon gas.

...But what does this have to do with an ideal fluid, where $l_{mfp}/R \ll 1$

H.J. Drescher, Borghini, Dumitru, Gombeaud, Ollitraut, 0704.3553

$$v_2 \sim \underbrace{v_2|_{ideal}}_{\sim\epsilon} \left(1 - a \underbrace{\frac{l_{mfp}}{R}}_{=Kn}\right)$$

So...

$$\frac{v_2}{\epsilon} \simeq \underbrace{\frac{v_2}{\epsilon}\Big|_{ideal}}_{constant} \frac{1 + O(Kn^2)}{1 + \frac{Kn}{K_0}}$$

K_0 is a parameter, ~ 1, dependant on the microscopic details of the DoFs.
Calculated from a kinetic model to be ~ 0.7

Particle density n assuming boost-invariance goes as

$$n \sim \frac{1}{\tau_0 S}\frac{dN}{dy}$$

The initial mean free path is related to the cross-sectional area and density ($l_{mfp} = \frac{1}{\sigma n(\tau_0)}$) while τ_0 is the time-scale for v_2 building up ($\tau_0 \sim \frac{R}{c_s}$) Thus, assuming constant c_s and we recovered the Heiselberg-Levy scaling within hydro

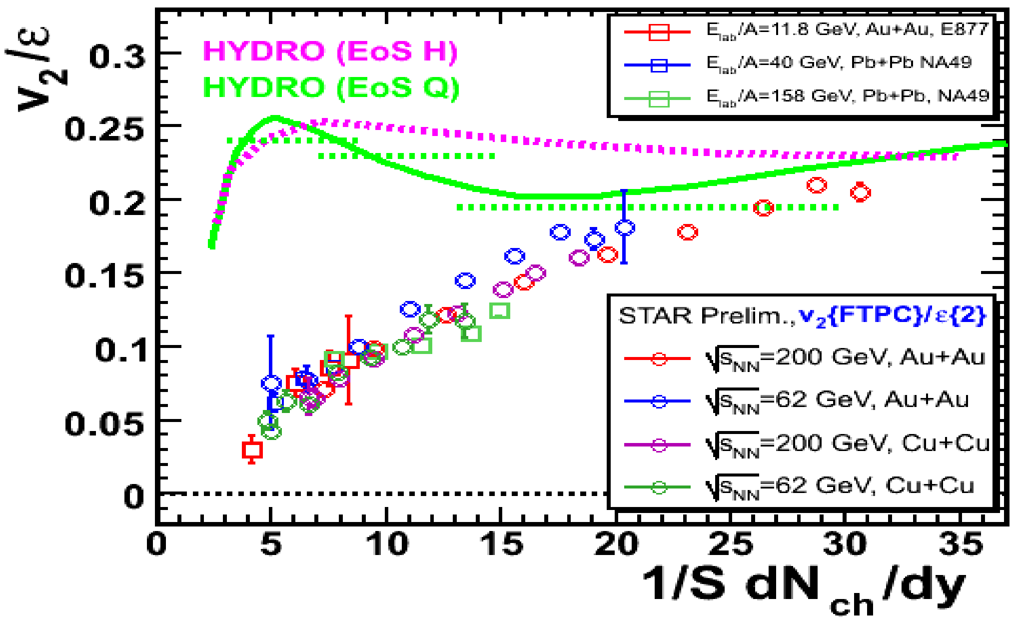
$$Kn^{-1} = \frac{\sigma}{S}\frac{dN}{dy}c_s \qquad \frac{v_2}{\epsilon} = \frac{Kn^{-1}}{Kn^{-1} + K_0^{-1}}$$

But...

- Proportionality constants profoundly different.
  Heiselberg-Levy case, $\langle \sigma v \rangle$.
  Dumitru et al, $\langle \sigma \rangle \underbrace{c_s}_{\neq \langle v \rangle !!}$)
  So transition from dust-like to fluid-like regime should most likely break v_2/ϵ vs $\frac{1}{S}\frac{dN}{dy}$ scaling.

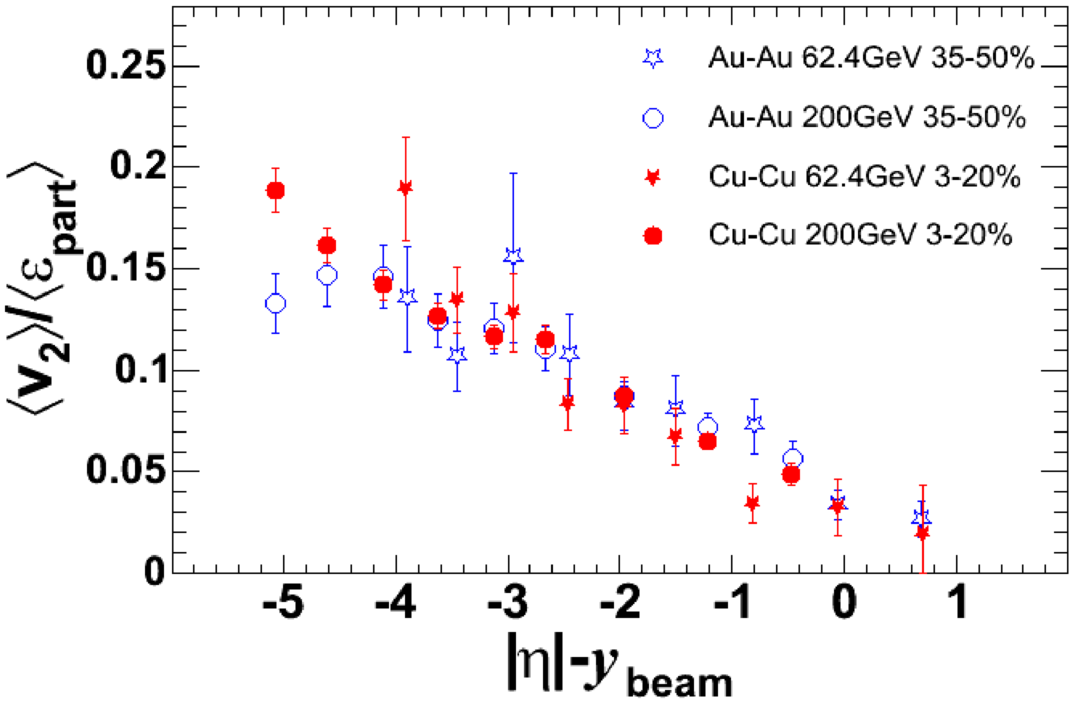
- There is no such thing as $\left.\frac{v_2}{\epsilon}\right|_{ideal}$. What about...
  - Initial $c_s/EoS(\sim QGP$at some $\sqrt{s}$, $\sim HG$ @others, mixed @others)
  - Initial longitudinal (Bjorken/Landau/...?) or transverse (Glauber/CGC?) structure? Dependence on $\sqrt{s}, A$?

- dependance of $Kn = \frac{l_{mfp}}{R}$on $\sqrt{s}/A$ not trivial: l_{mfp} depends on intensive quantities such as initial energy density, R is of course extensive.



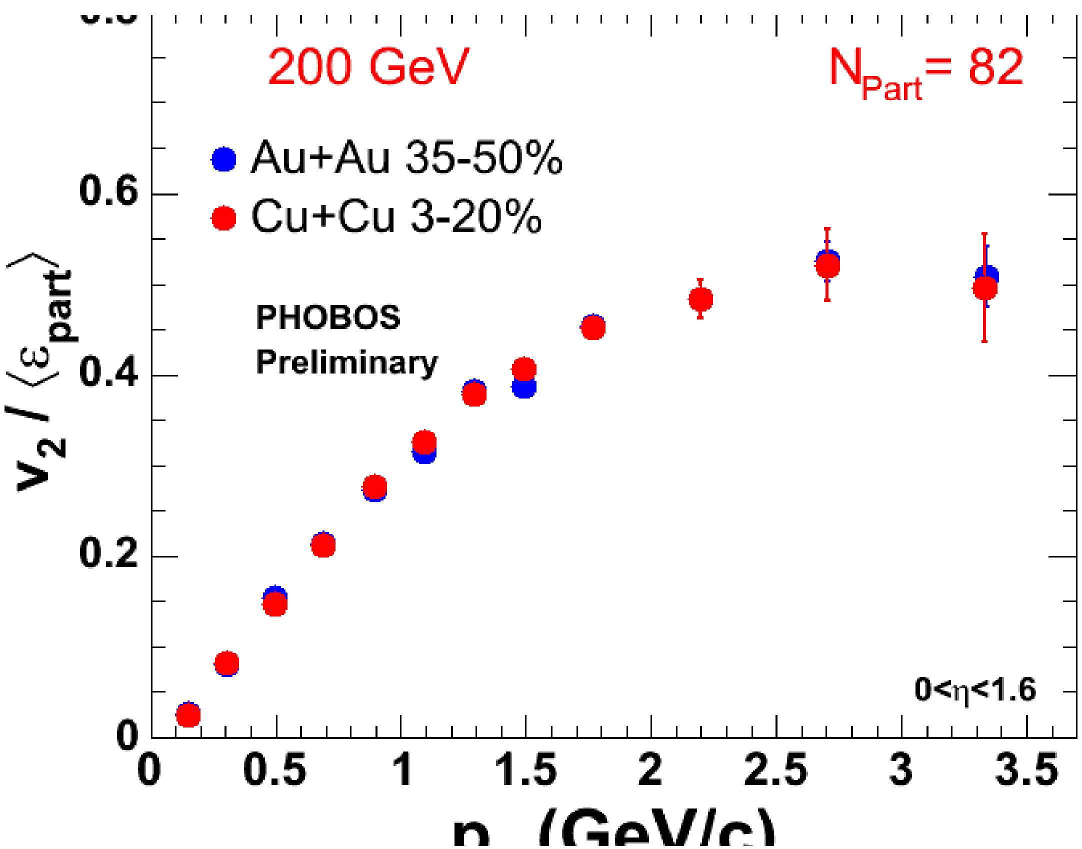
v_2/ϵ is <u>the same</u> for a given $\frac{1}{S}\frac{dN}{dy}$, <u>even if the energy is very different</u>!!!!

If same $\frac{1}{S}\frac{dN}{dy}$, agreement could extend to η bins (PHOBOS)

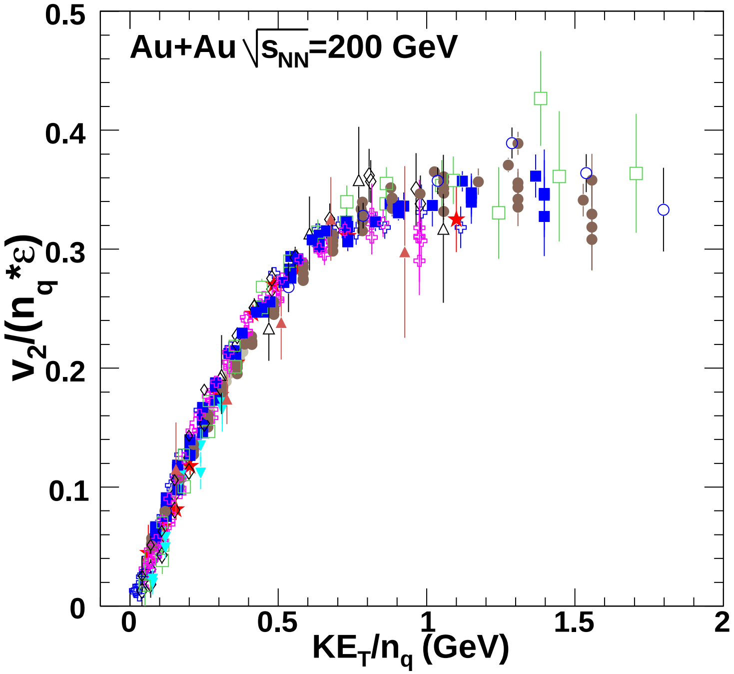


So need 3D viscous hydro to model it, if it can be done

p_T bins (PHOBOS)



And, when combined with coalescence, particle species (Lacey,Taranenko)



(So this is a Partonic effect?)

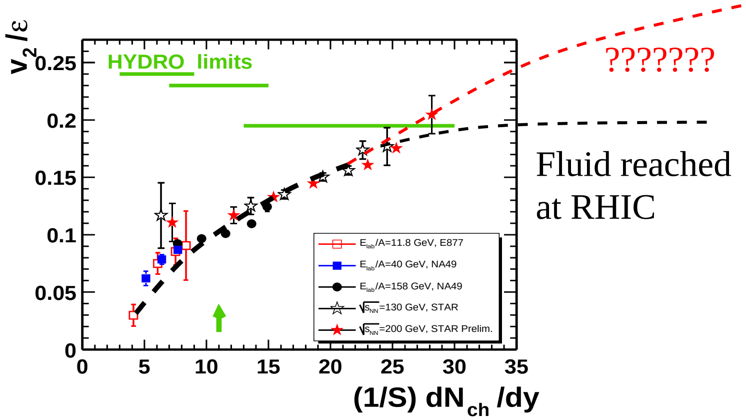
We found ...tantalizing signs of having produced matter that is opaque, and locally equilibrated

We failed to find ...

- An understanding of when does this state arise
- A link of its properties with fundamental theory

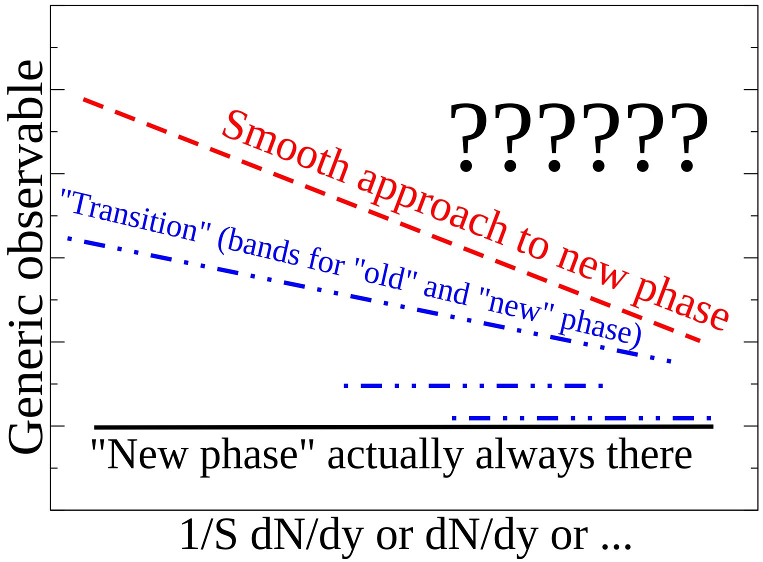
What next: Experiment

- Higher energy: LHC (<u>very</u> high energy collisions). by extrapolation $T_{LHC} \sim 3T_{RHIC}$ not much more than RHIC (few surprises, but more probes to better study medium)



Hey, perhaps we are all wrong! But predicting is hard, especially when we predict the future!

- Lower energy: <u>how</u> is hydro approached? thresholds? critical points? etc. Will we find more kinks, divergences etc. in soft signatures?



The job of theorists here is to devise experimental measurements <u>appropriate</u> for exploring scaling and the violation thereof. Kinks? Transitions? Bands?

v_2 fluctuations (http://arxiv.org/nucl-th/0703031)

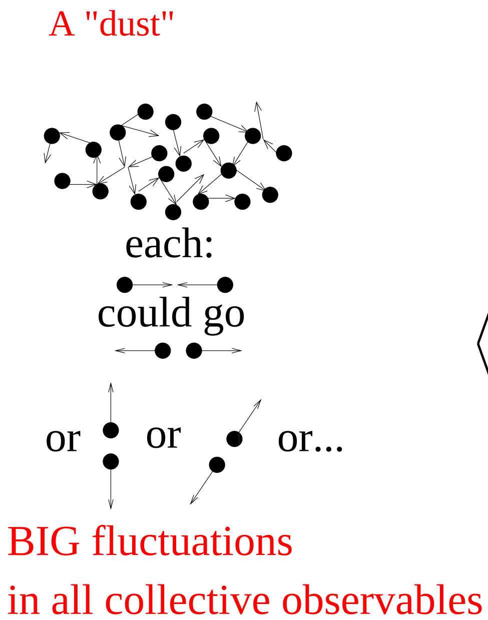
Initial eccentricity fluctuations If hydro not turbulent

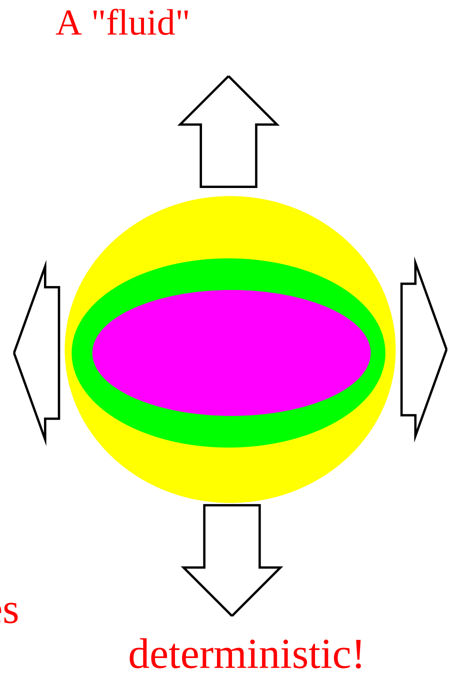
$$\delta v_2 = a_1 \delta\epsilon + a_2 (\delta\epsilon)^2 + ...$$

(chaos would imply something like $\delta v_2 \sim \delta\epsilon e^{\tau} \sim \delta\epsilon e^{dN/dy}$)
Boost-invariant simulations show that $v_2 \propto \epsilon$ (2nd order coefficient small) so

$$\frac{\delta v_2}{v_2} = \frac{\delta\epsilon}{\epsilon}$$

but this is not the only source of fluctuations!





finite mean free path

Imperfection of fluid $\Rightarrow$ fluctuation in momentum observabled due to <u>random</u> nature of microscopic dynamics

How big?

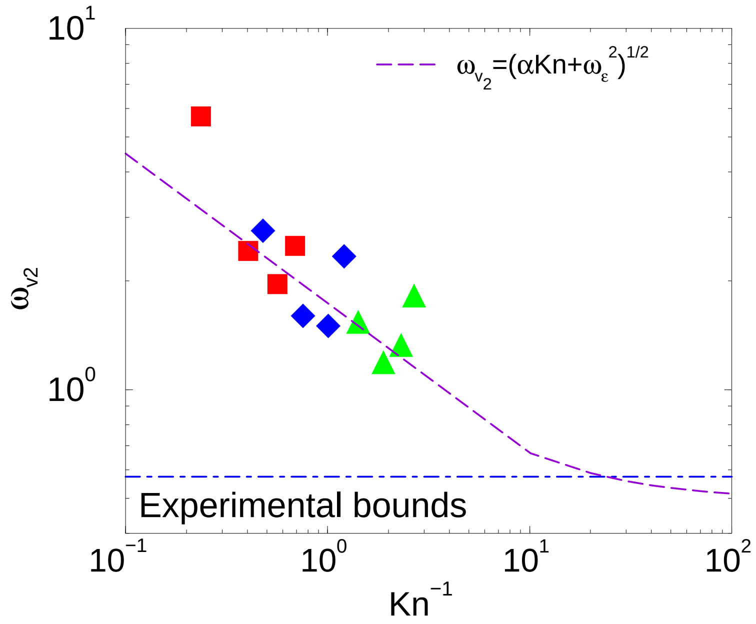
Assume no correlations between initial state and "dynamical" fluctuations, and "Poissonian" scaling of fluctuations with inverse Knudson number

$$\left\langle (\Delta v_2)^2 \right\rangle = \sqrt{\langle (\Delta \epsilon)^2 \rangle + \frac{\alpha}{N^2_{collisions}}}$$

$$\left\langle (\Delta v_2)^2 \right\rangle = \sqrt{\frac{\langle (\Delta \epsilon)^2 \rangle}{\left\langle \epsilon \right\rangle^2} + \beta \frac{l_{mfp}}{L}}$$

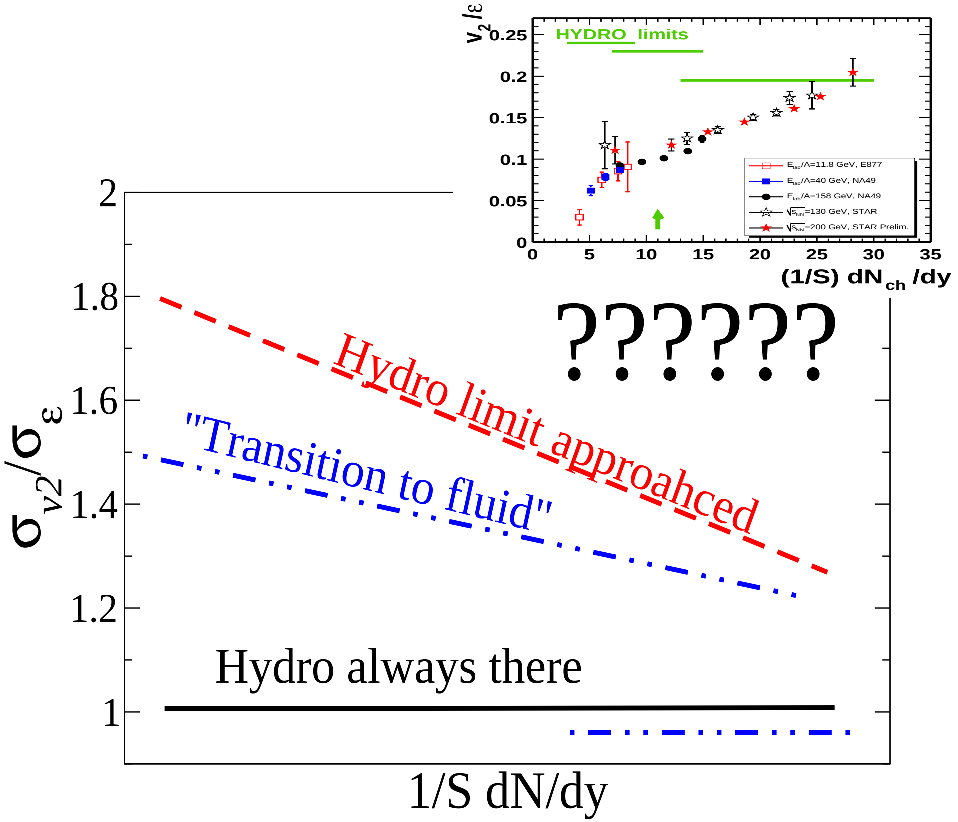
use molecular dynamics to tune β and mean free path.

uRQMD with "tuned" σ (as a toy model)



work in progress (comparison with partonic QMD), but in principle could be a powerful indicator of good fluidity.

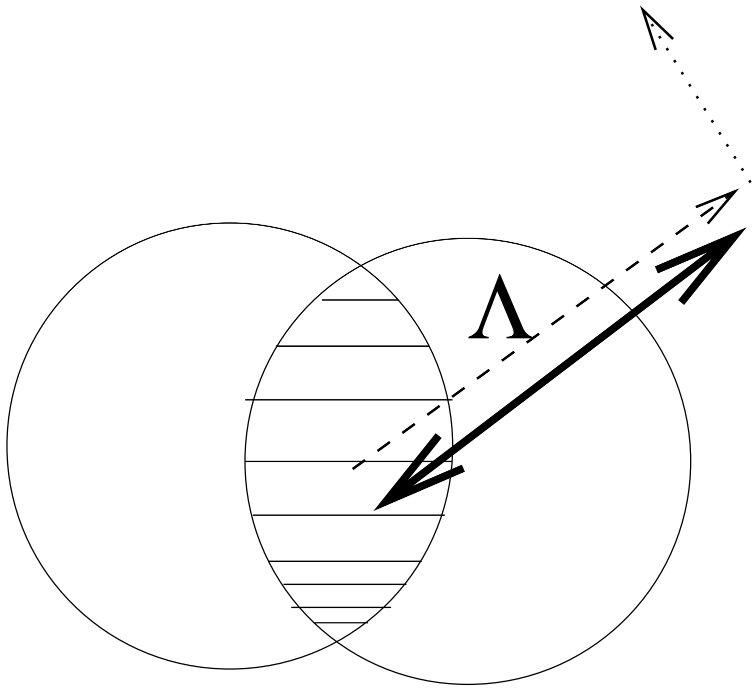
Rise of $\frac{\left\langle(\Delta v_2)^2\right\rangle}{v_2}$ at lower $\sqrt{s}$ ABOVE $\frac{\left\langle(\Delta \epsilon)^2\right\rangle}{\epsilon}$ $\longrightarrow$ transition to fluid?



An energy/size scan of the v_2 fluctuation would help clarifying weather the "perfect fluid" is transition,approach,or is always there!

Polarization and perfect fluidity

(P.Hoyer, PLB187 162 (1987) (a pretty prophetic paper): In a perfect fluid, because of local isotropy, no polarization production is possible. Hoyer suggested measuring production plane since its $\neq 0$ in p-p



So far measured at AGS only, and compatible with $p-p$.
Order of magnitude estimate for mean free path correction and local vorticity:

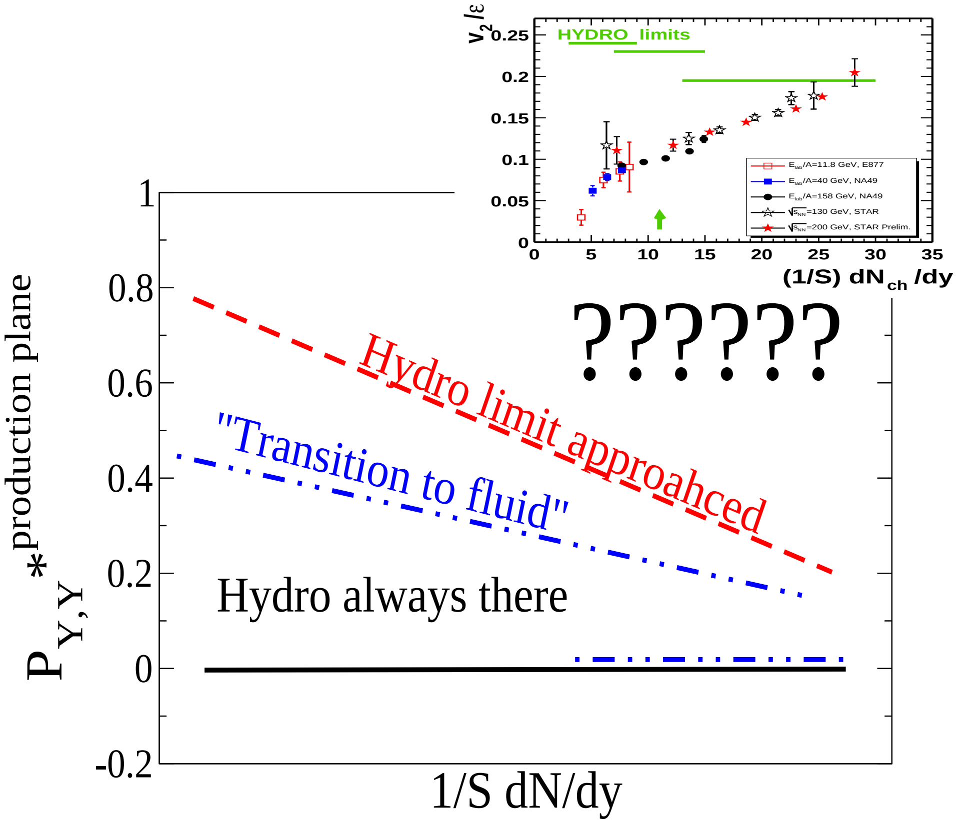
$$P_q^i \sim \tanh\left[\frac{l_{mfp}}{T}\left(\epsilon_{ijk}\frac{d\left\langle \vec{p}_i\right\rangle}{d\vec{x}_j}\right)\right]$$

Sudden jumps in polarization observable in $\sqrt{s}$ OR A $\leftarrow$ transition!

Problem:This probes the mean free path,potentially, at the very end including hadronic phase. A locally isotropic QGP followed by an succession of elementary hadronic collisions <u>could</u> produce polarization (Barros and Hama, 0712.3447)

Zero result $\longrightarrow$ "perfect fluid",fast f.o.

Sudden transitions with $\sqrt{s} \longrightarrow$ transition to fluid



Potentially this is exactly what we are looking for! A signature for fluidity not requiring a large system!

Polarization (GT et al,PRC76:044901,2007)

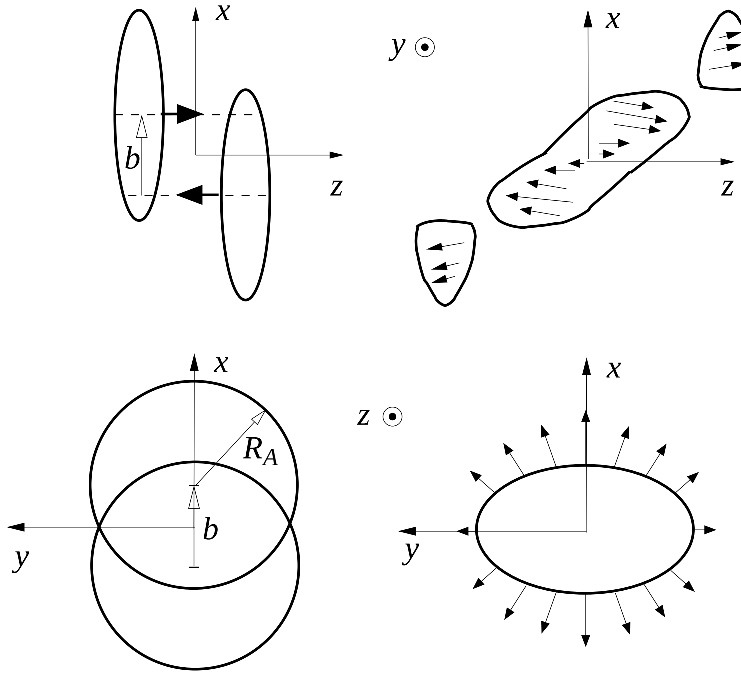
Bad news: Polarization is a mess
many factors, at all stages of collision, contribute to the final observable

Good news: Polarization is a

$$m\vec{e}ss = \begin{pmatrix} mess \\ mess \\ mess \end{pmatrix}$$

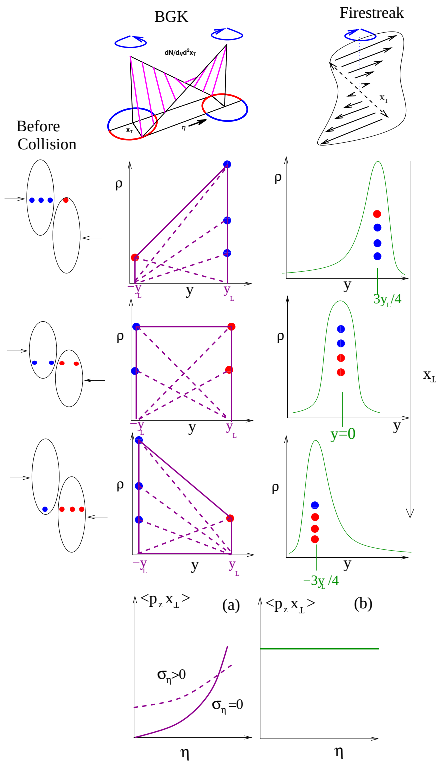
Many directions possible. Comparing directions $\longrightarrow$ understanding physics

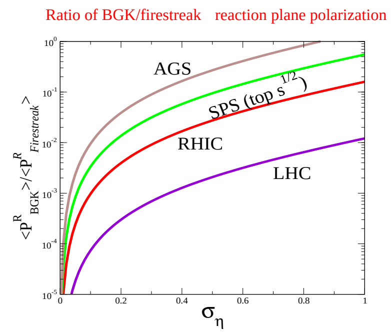
Global polarization and initial conditions (Liang et al,PRL, nucl-th/0410079)



Initial angular momentum in non-central collisions ⇒ quark polarization due to QCD spin-orbit interactions ⇒ hadron polarization due to local hadronization (coalescence? angular momentum conservation?)

But signature depends crucially on <u>localization</u> of produced partons in z (Firestreak/Bjorken initial condition).





Probe of "Bjorken" conditions, if not of hydro. Small mfp could spoil it.

Thermalization of jets in-medium
A couple of considerations on "mach cones"
(Betz,Rischke,Gyulassy,Stoecker,GT,QM2008 talk),

Jet-flow correlations assume jets, so could lead to a scaling variable.! But... an unambiguous signature of Mach-cones would prove thermalization of the energy released by the jet, the opposite does not followMach cones require:

- A linearized energy deposition
- A constant energy deposition (Bethe-Heitler limit)
- Steady state in x-vt

These conditions are independent of the degree of thermalization, and might well fail in HICs even if we have a perfect fluid

More robust signatures of thermalization required.
The right question is not "are there Mach cones"? But "to what extent is the energy/momentum deposited by the jet thermalized.

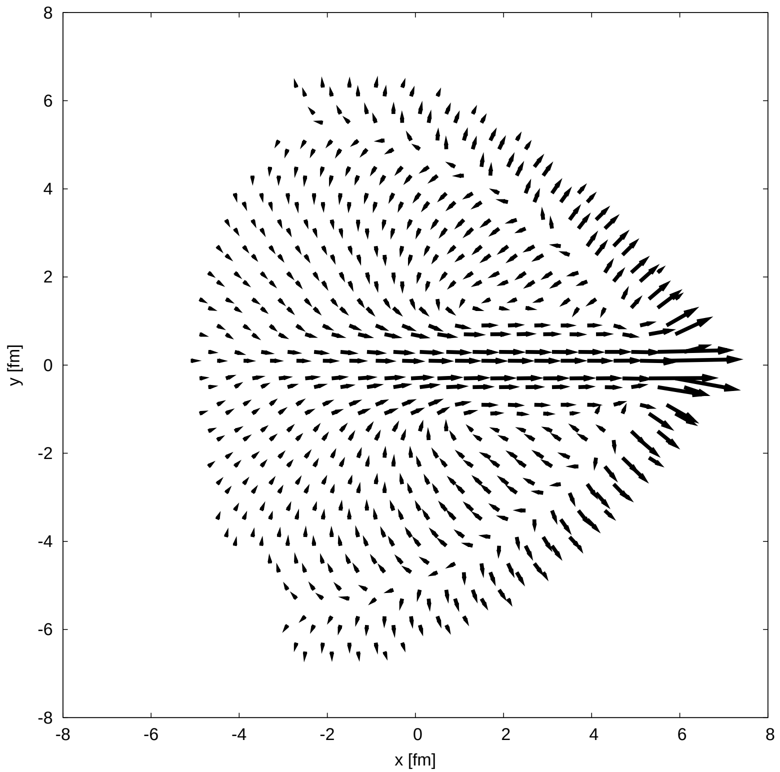
Composition of away-side peak w.r.t. medium could be such a signature

- Is the chemical composition of the away-side peak that of the medium?
  Fragmentation and such would mean away-side $\sim$ p-p composition.
  We know from STAR, QM, that Λ/K associated with near-side is compatible with p-p, ridge more in-medium.

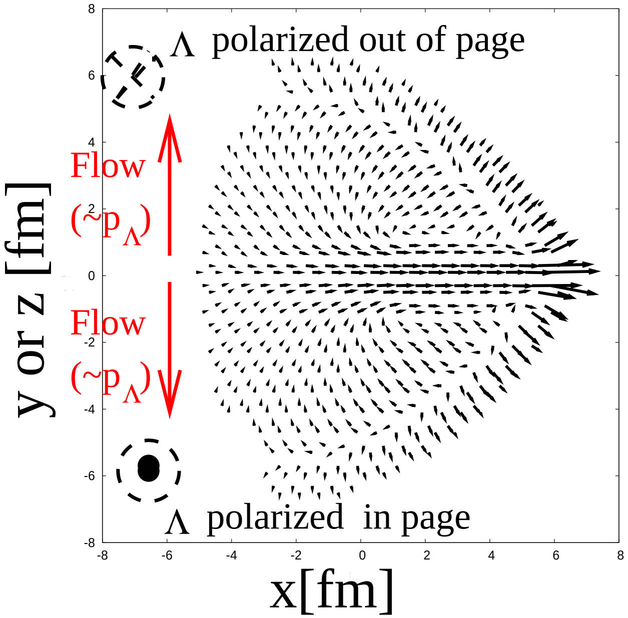
- Is momentum spectrum of away-side particles exponential, with same $T_{freezeout}$ as rest of system, but more flow?

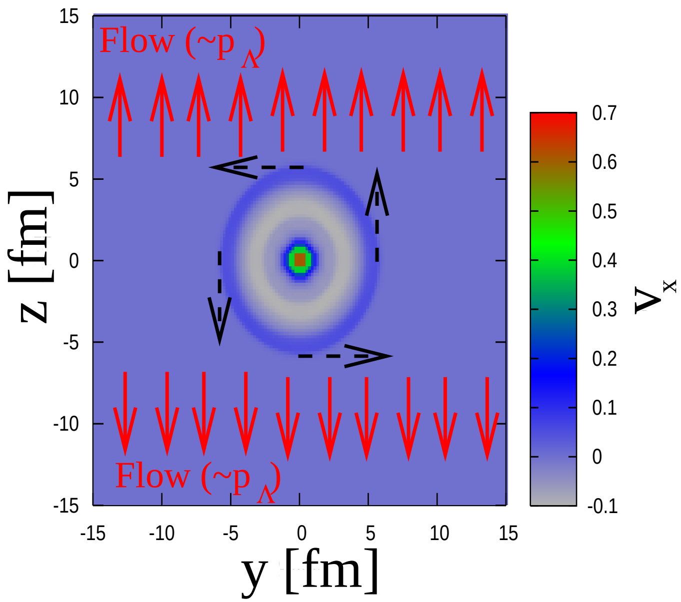
Investigations with non-linear hydro in progress, see B.Betz QM talk.
"Crazy" idea: non-linear hydro $\longrightarrow$ vortices!

Polarization due to jets (ie vortices!)



independently from initial conditions, the momentum deposition by jets results in a net vorticity. Spin-orbit@f.o.$\rightarrow$jet-induced polarization!





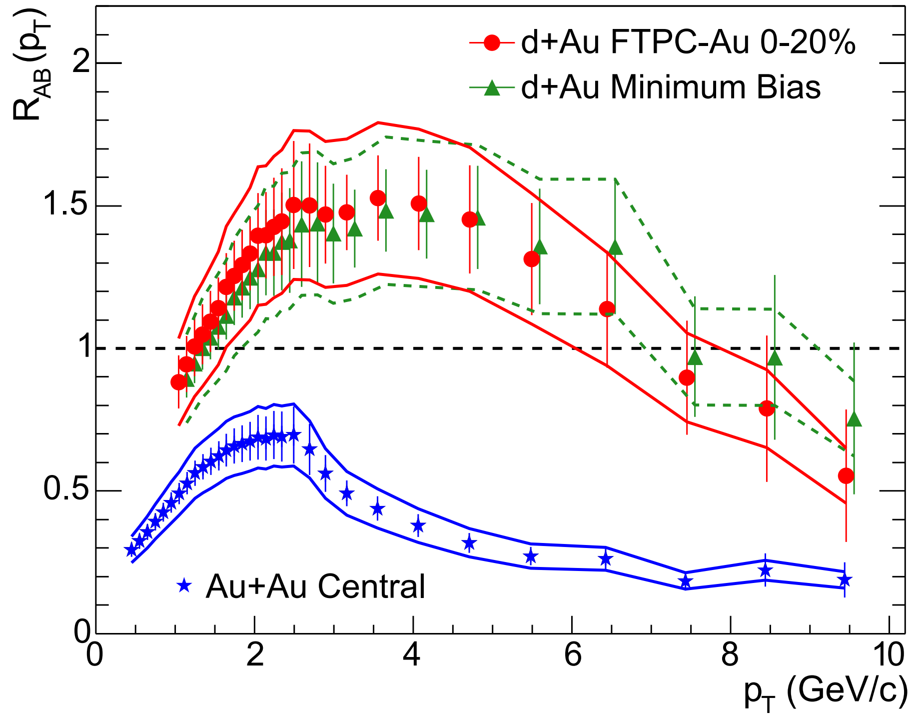
Choose plane defined by jet ($\perp$vortex) and Λ $\vec{p}$ (correlated with flow), Observation of polarization $\longrightarrow$ vorticity in QGP. Very cool, <u>AND</u> probe for fluidity (No pQCD mechanism)

Conclusions and outlook

- not clear when fluid-like regime forms
- transitions in viscosity,EoS also not apparent.
- Need more "creative" signatures of fluidity
  - v_2 fluctuations
  - Polarization (and lack of)
  - Jet-flow correlations (mach cones and beyond)

BACKUP SLIDES

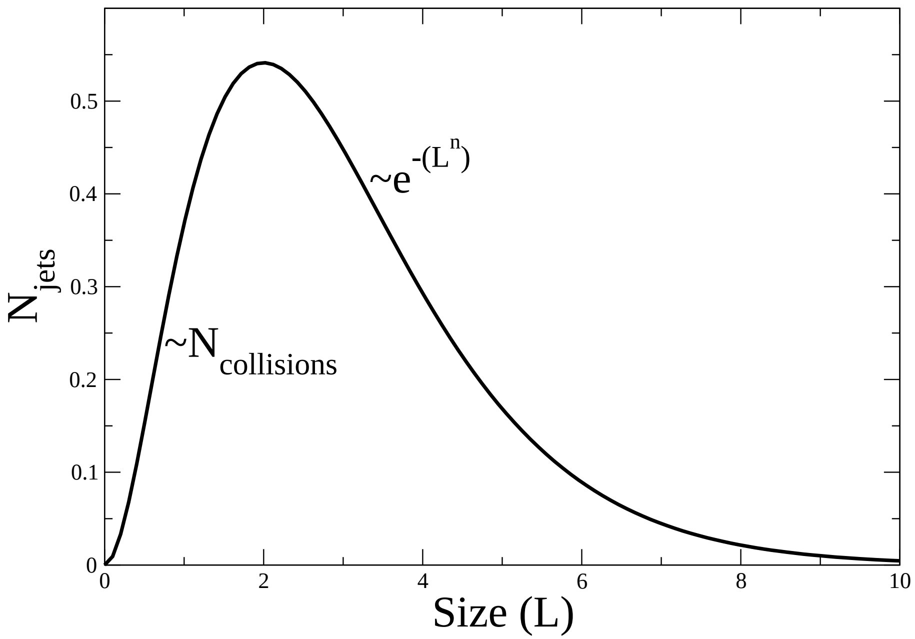
Jets?! Maybe!



Scaling dependance on centrality for d-Au,Au-Au collisions markedly different

But NOT necessarily!

$$N_{jets} \sim N_{collisions} f(L) \sim A^2 f(A^{n/3})$$



Can jets rule out a scenario where

- The intensive properties of the system (EoS, degree of equilibration,...) are exactly the same for p-p,p-A,A-A but the system in p-p,p-A is smaller, shorter-lived
- In small systems, power term dominates, in larger systems exponential term dominates

We note, here, the good scaling of R_{AA} with N_{coll}/N_{part} noticed by PHOBOS (nucl-ex/0302015,PLB578(2004),297)

Scaling of jets across $\sqrt{s}$ probably too complicated to be ever "nice"!