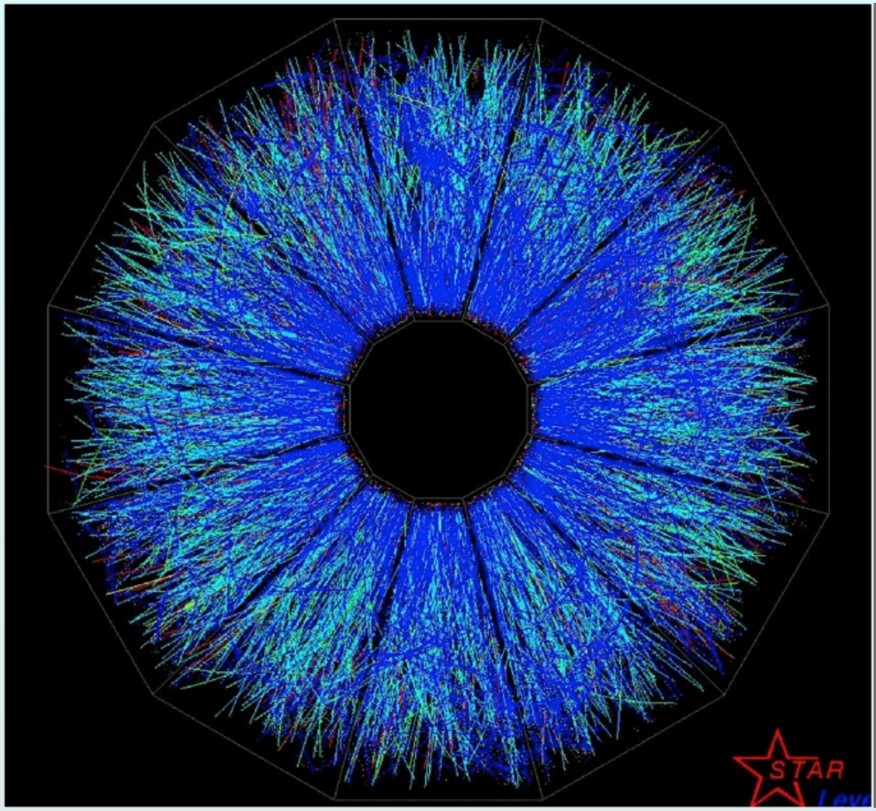
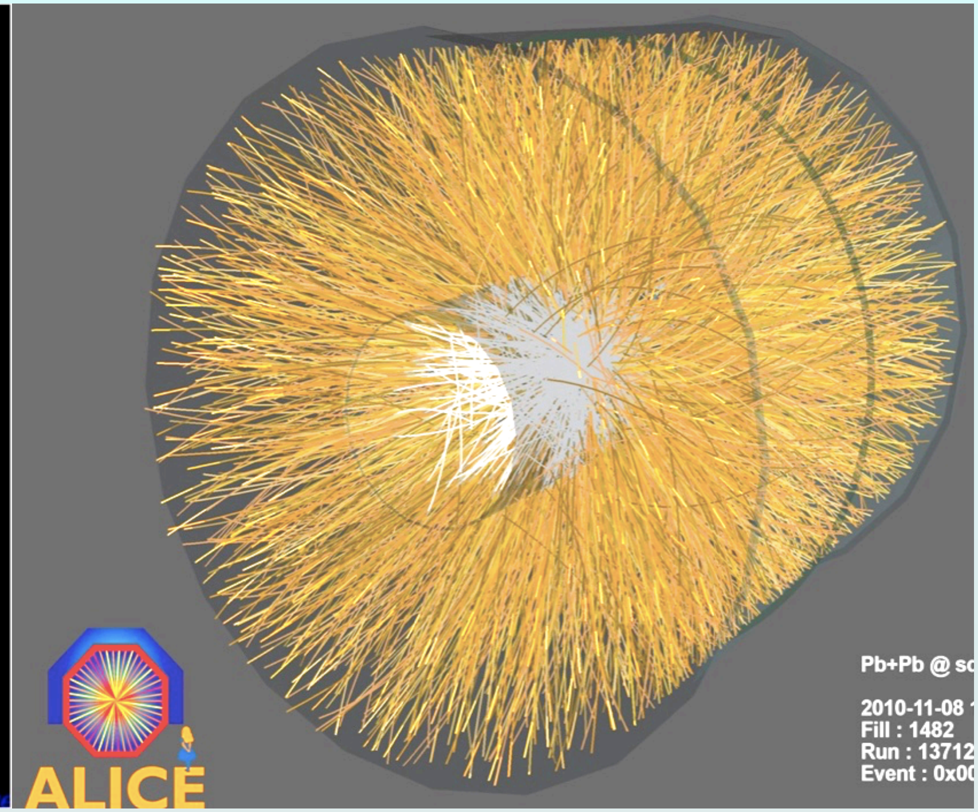
QCD from Heavy Ion Physics: What have we learned?





Barbara Jacak

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April 12, 2021

Outline

- A plasma of quarks and gluons
- Collectivity
  How we can measure it
  Behavior in small systems
- Hadronization insights
- Lessons from jet probes of QCD Matter
- Some conclusions & open questions

Heavy ion collisions

Large Hadron Collider

CERN in Geneva

Pb+Pb @ 2.76 & 5 TeV/A

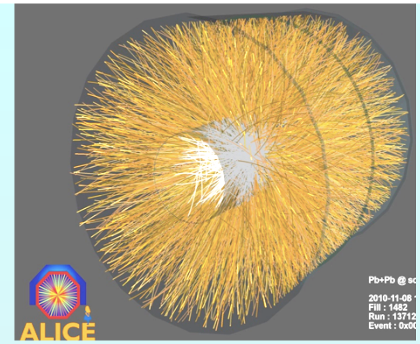
Relativistic Heavy Ion Collider

Brookhaven in New York

Au+Au @ 200 GeV/A

Collide heavy nuclei for max temperature & volume

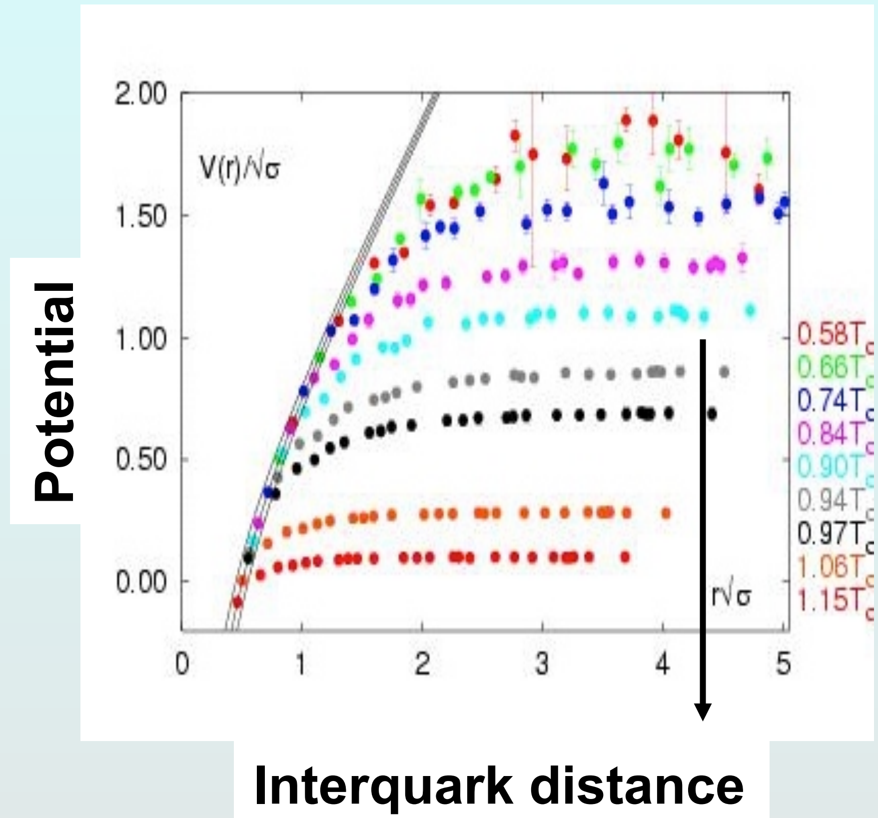
In hot QCD Matter



- ***At high temperature/density screening by produced colored particles***

- ***Expect phase transition to deconfined quark gluon plasma***

- ***Lattice QCD*** **→ T_c ~ 160 MeV**



How to study quark gluon plasma?

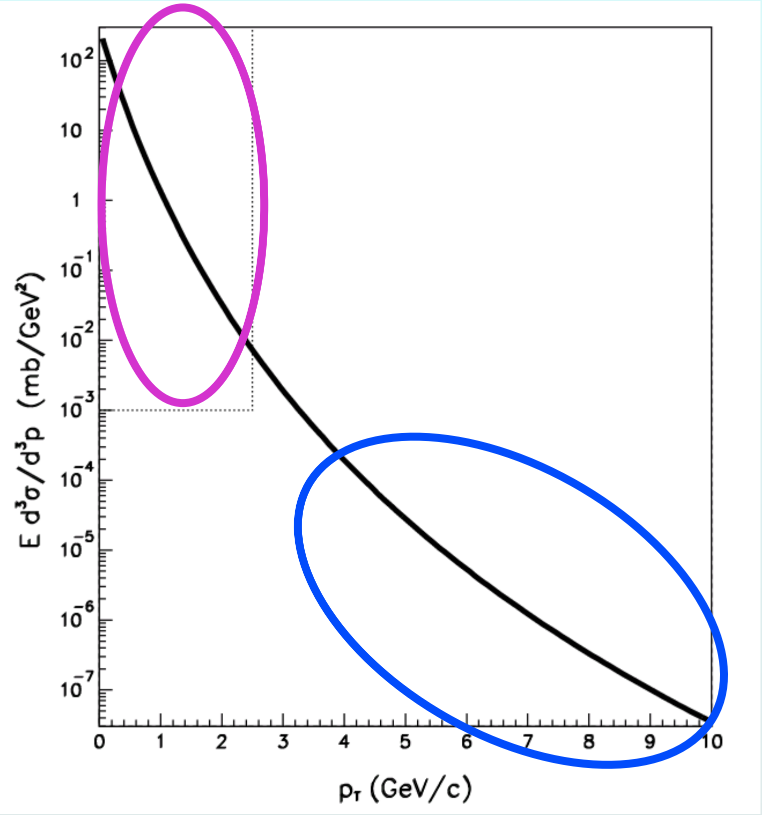
Use the particles coming out

- radiated from bulk medium
  "internal" plasma probes

- large E_{tot} (high p or M)
  set scale other than T(plasma)
  autogenerated "external" probe
  Calculate w/perturbative QCD

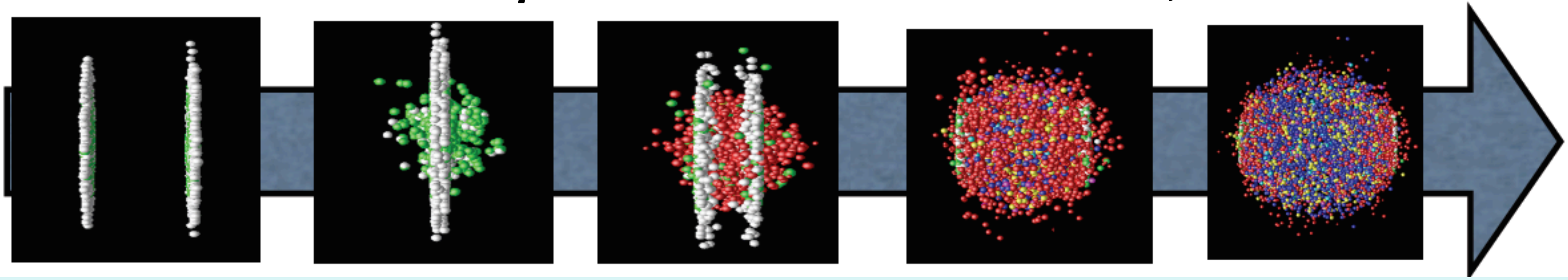
- control probe: photons
  EM, not strong interaction

- Control system: p+p collisions



Nuclear collision timeline

plasma lives ~3x10^{-23} seconds, ~10^{-12} cm across



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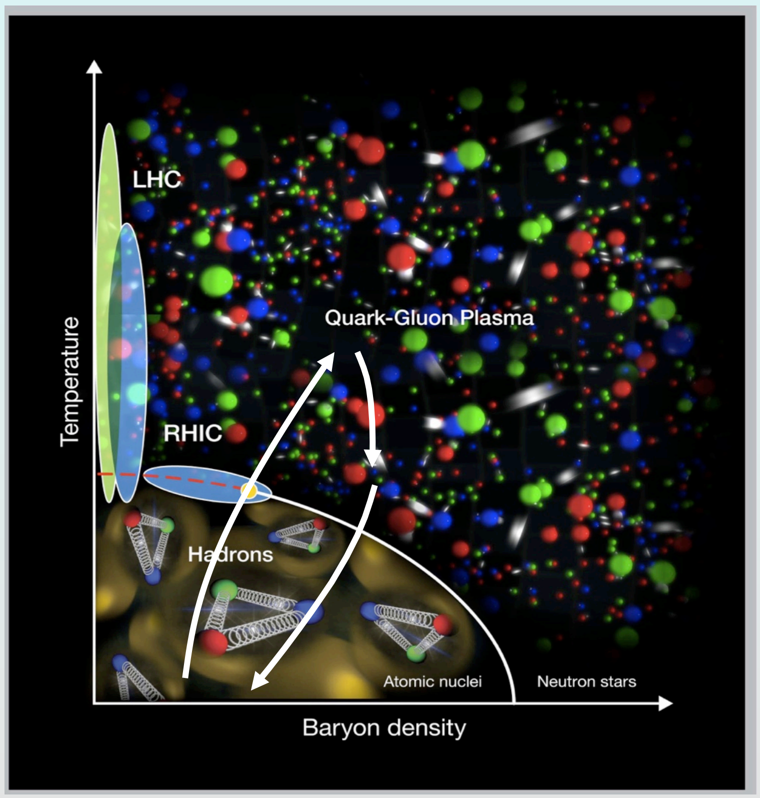
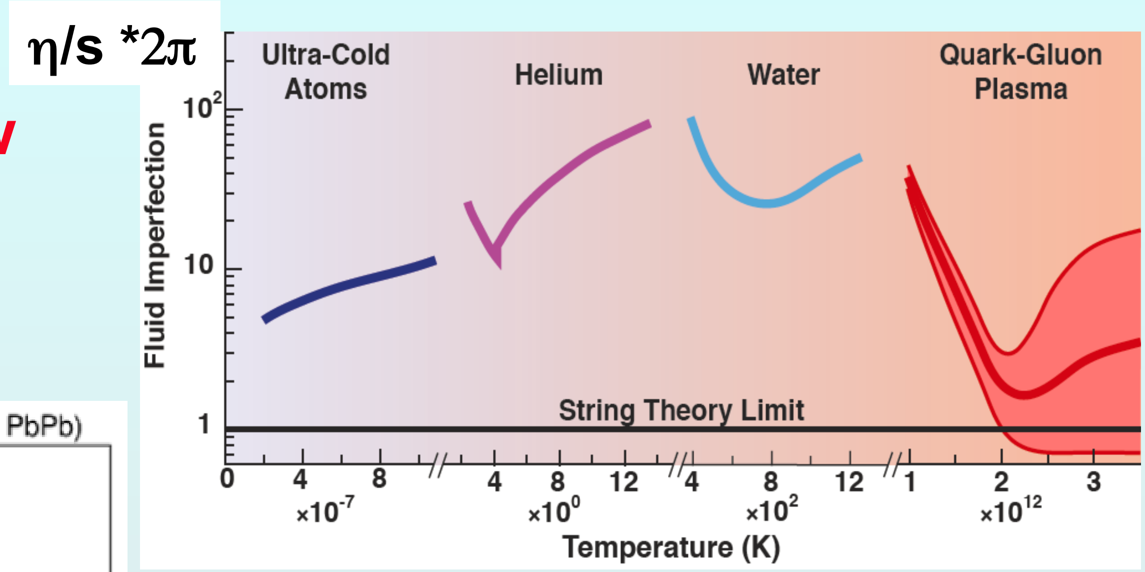
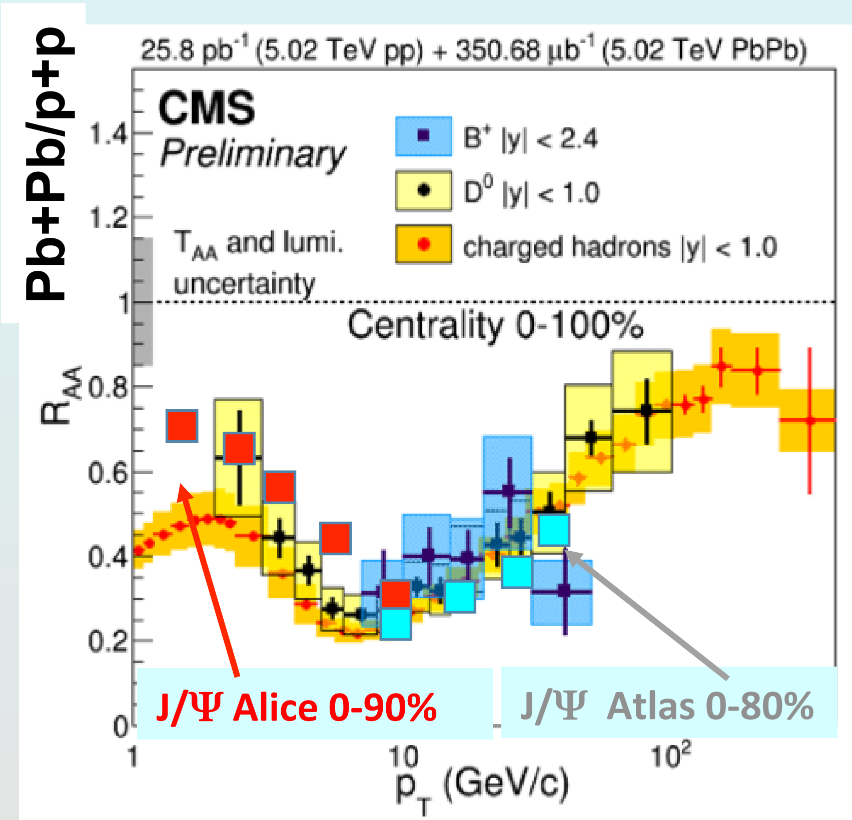


Quark Gluon Plasma: strongly coupled hot QCD matter

● hydrodynamic flow
Nearly perfect liquid

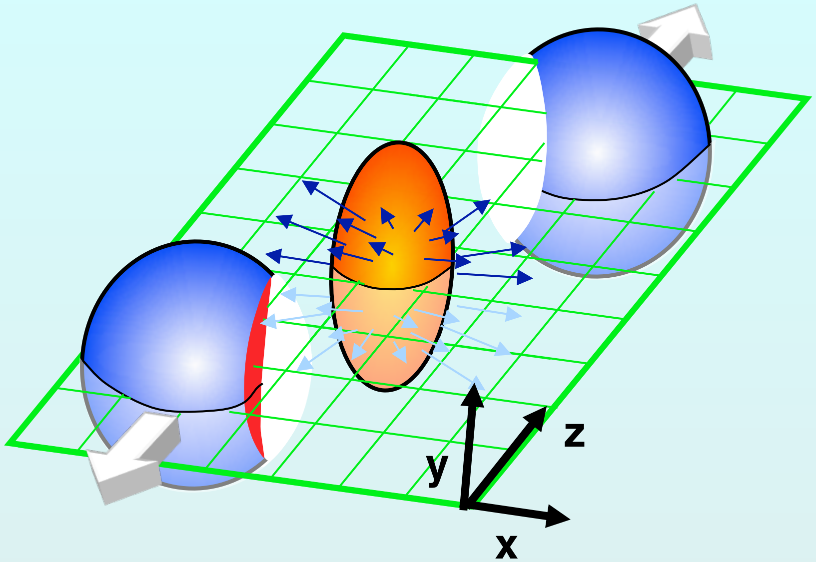


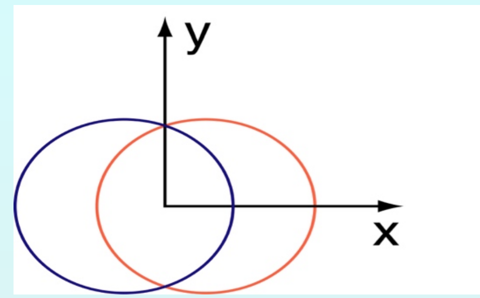


● QGP is very opaque to color-charged particles
Even heavy quarks!!

COLLECTIVITY

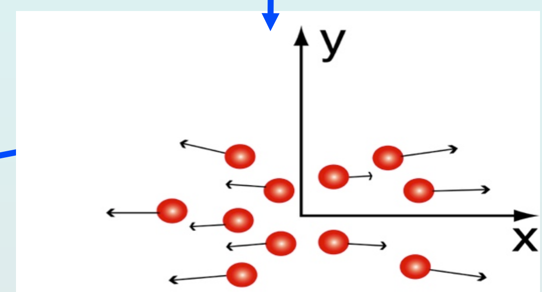
Measuring collective flow in QGP

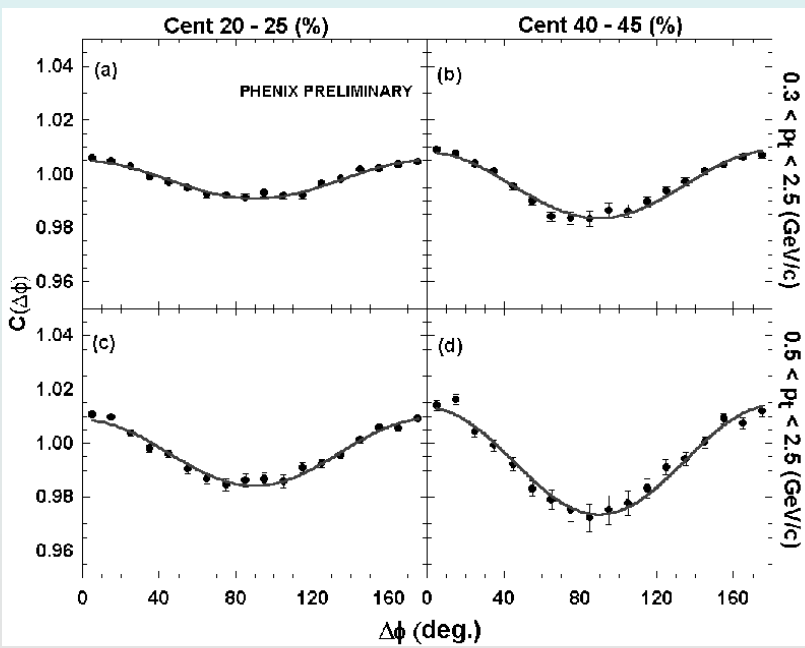




Almond shape overlap region in coordinate space

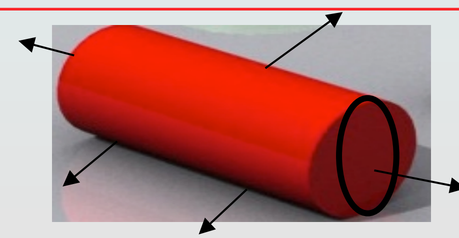
momentum space



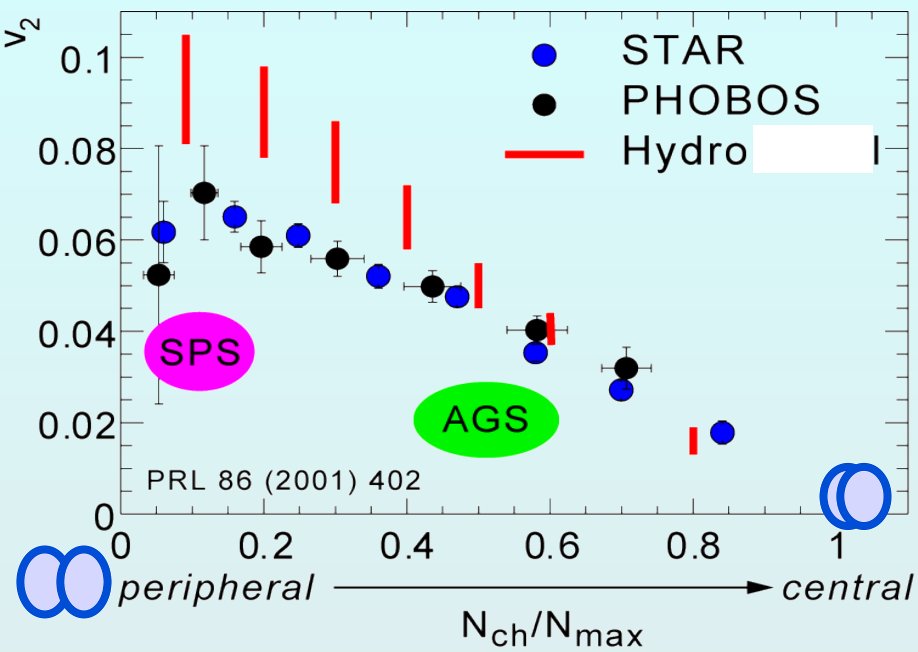


$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

"elliptic flow"

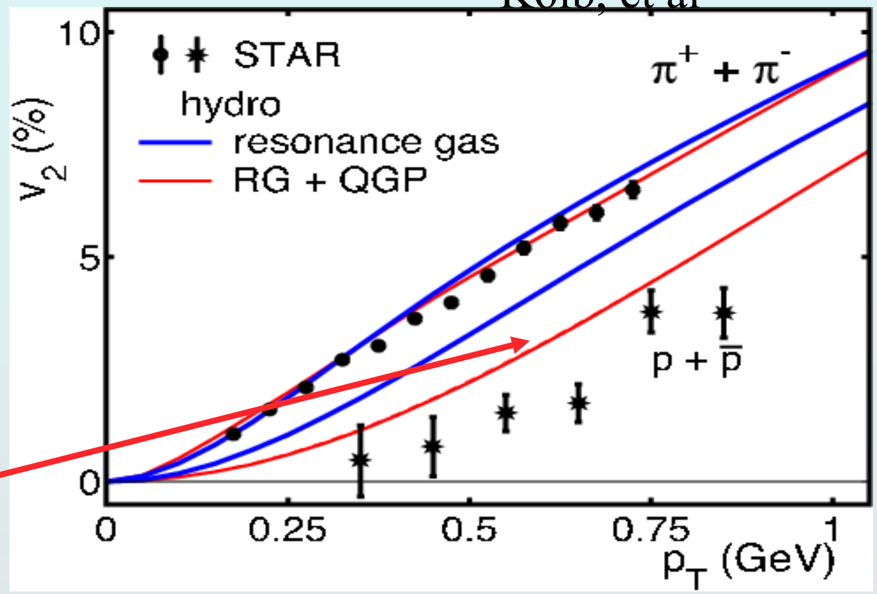


QGP flows like low-viscosity liquid



- large anisotropy!
- huge pressure buildup
- build up quickly, else hydro misses data

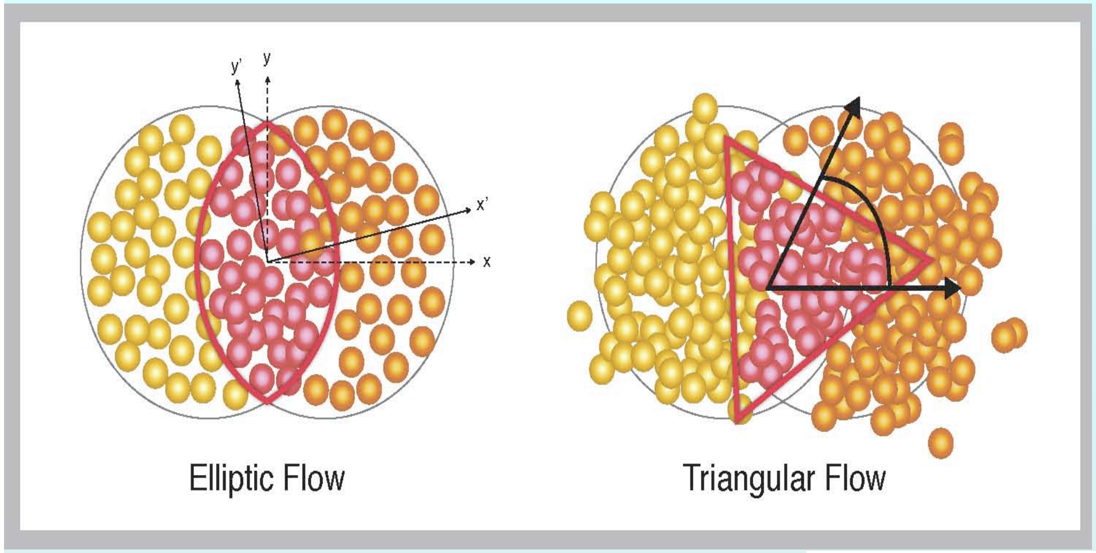
Kolb, et al



Hydrodynamics reproduces elliptic flow of q-$\bar{q}$ and 3q states
Mass dependence was first signal
QGP - NOT gas of hadrons

only works with viscosity/entropy ~ 0
"perfect" liquid (D. Teaney, PRC68, 2003)

Quantify viscosity: higher Fourier coefficients

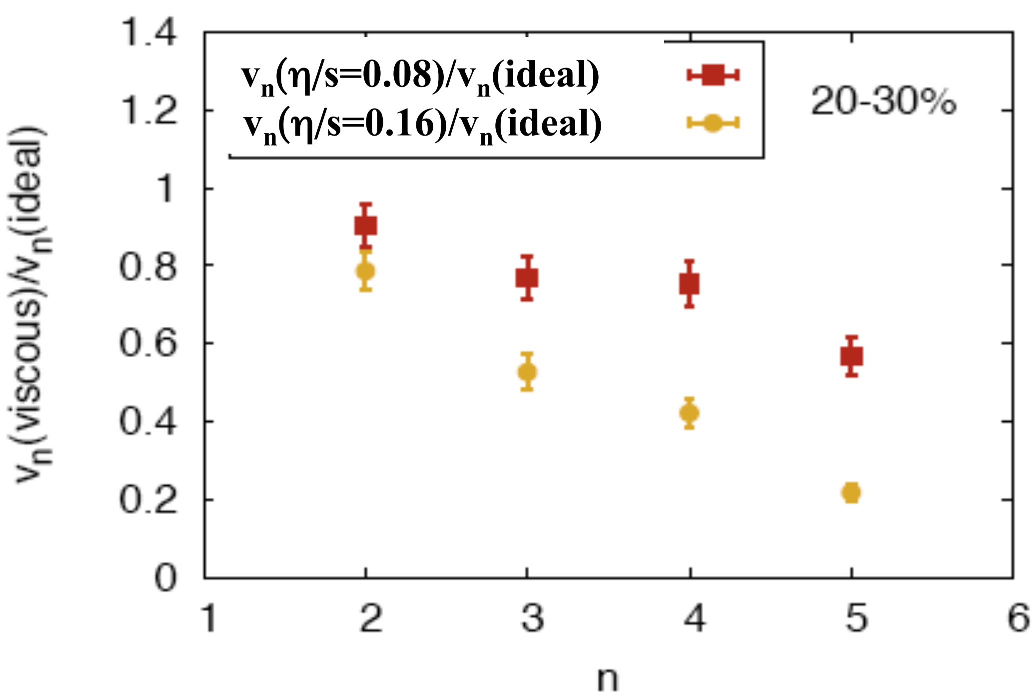


Nucleons move around inside the nucleus

-> locations of NN scattering fluctuate

- **Hydro gets it right if NN fluctuations included**
- **v_3, etc. more sensitive to the viscosity/entropy ratio (viscosity increases dissipation)**
- ***η/s (QGP) = 0.085 – 0.11***

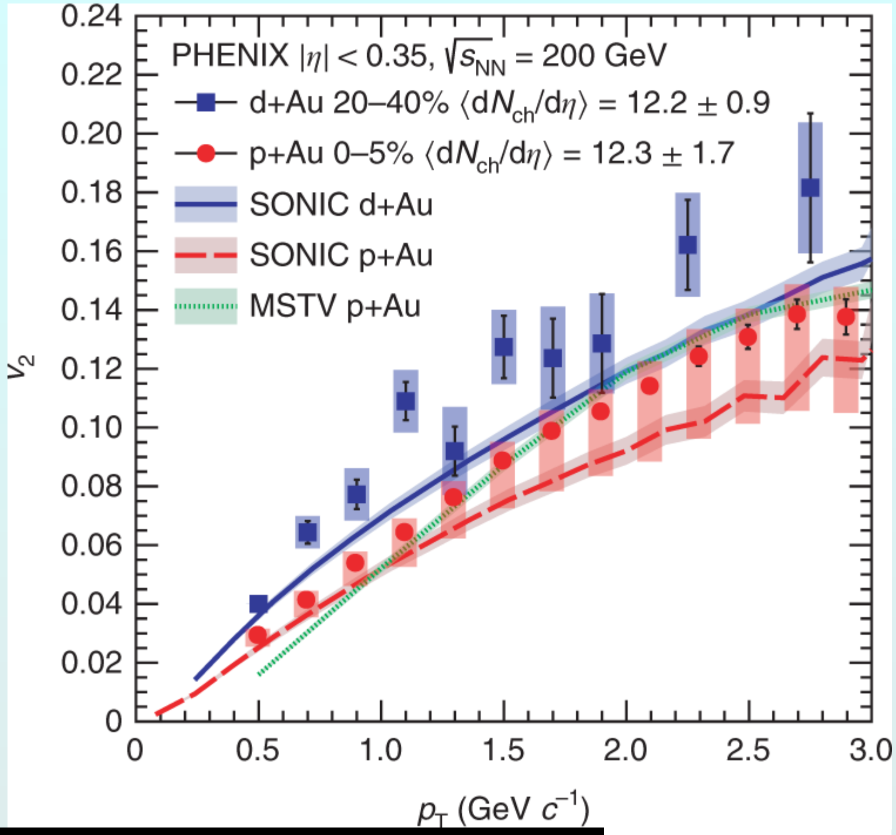
  From hydro vs. data



Eeek! Hydrodynamics in small systems!

PHENIX Collaboration

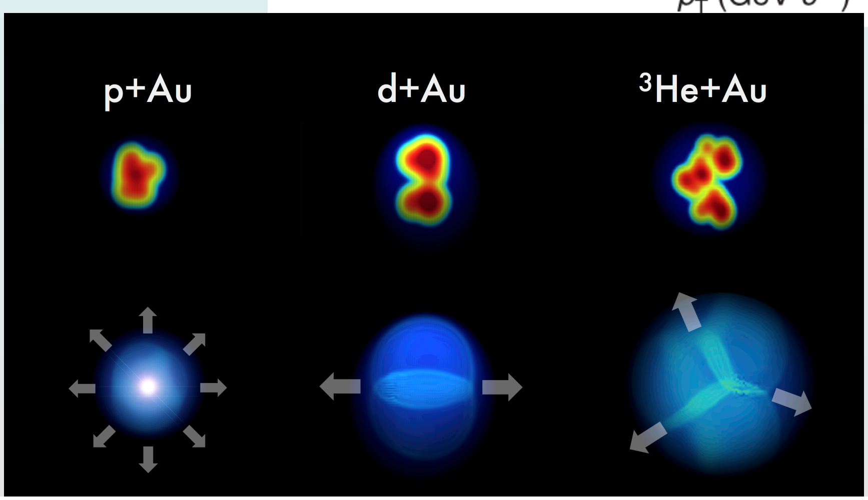
Nature Physics (2018)



Not big & dense

Yet we do see collective flow!

Seeded by initial geometry



How can pressure build up before this tiny system evaporates??

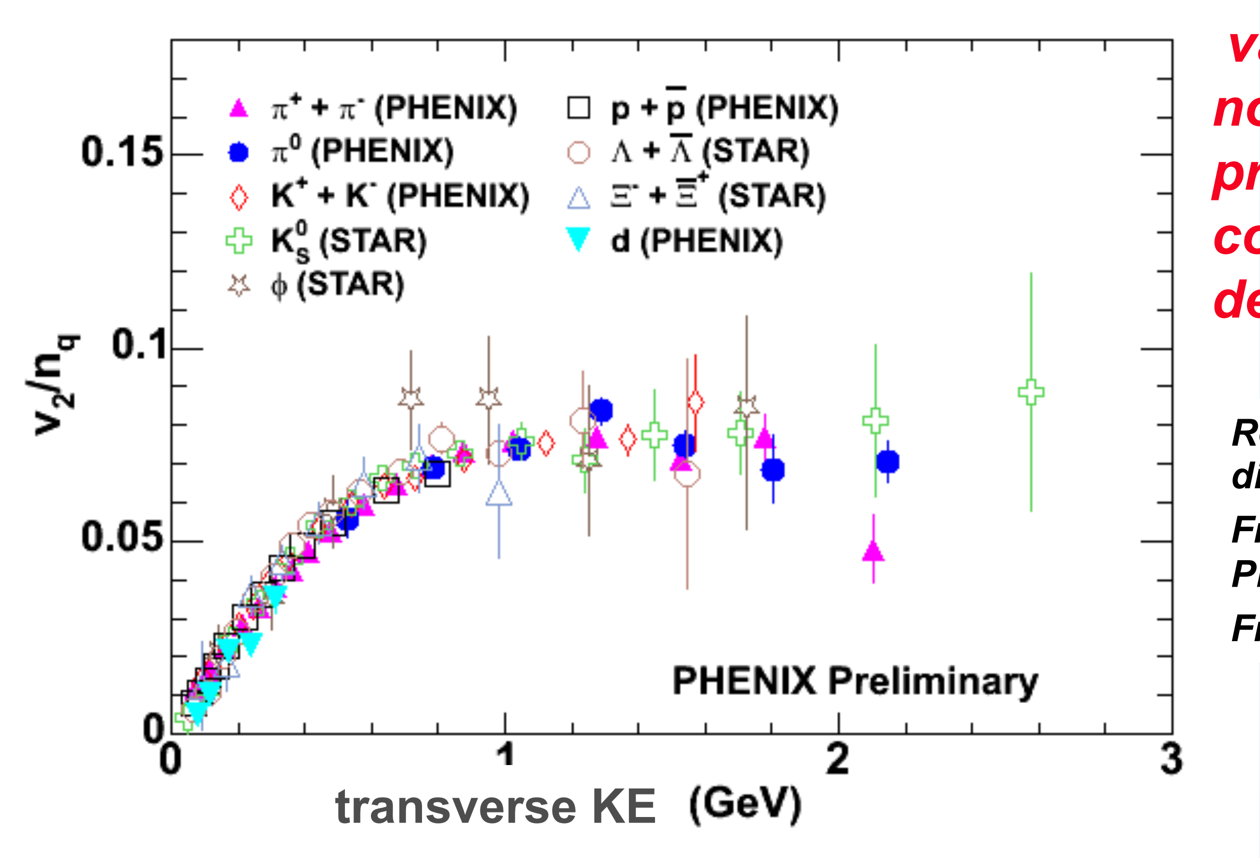
Mystery of rapid hydrodynamics*

- **One of the key questions for hot QCD**
  But it’s very hard to measure directly!
- **Coherent scattering?**
  - **Parton interactions in hot, dense QCD and cold, dense QCD at small x should be similar**
- **Rapid expansion driven loss of initial state memory (hydrodynamic attractor) causing out-of-equilibrium hydrodynamic behavior?**
- **Pre-existing many-body interactions?**

***** Full thermalization is not required for hydrodynamics***

HADRONIZATION

Hadronization of quark gluon plasma



valence quarks, not hadrons, are present when collective flow develops

Recombination from thermal distribution:

Fries, Mueller, Nonaka & Bass, PRC68, 044902 (2003)

Fries, J. Phys. G32, S151 (2006)

- ***dressed quarks are born of flowing field***
- ***hadronize by (simple) coalescence of co-moving quarks***
- ***quarks somehow (miraculously?) dressed by gluons***

Is phase space coalescence how hadrons form?

TRANSPORT IN QCD MATTER

Parton energy loss

- **Quantify by q-hat**

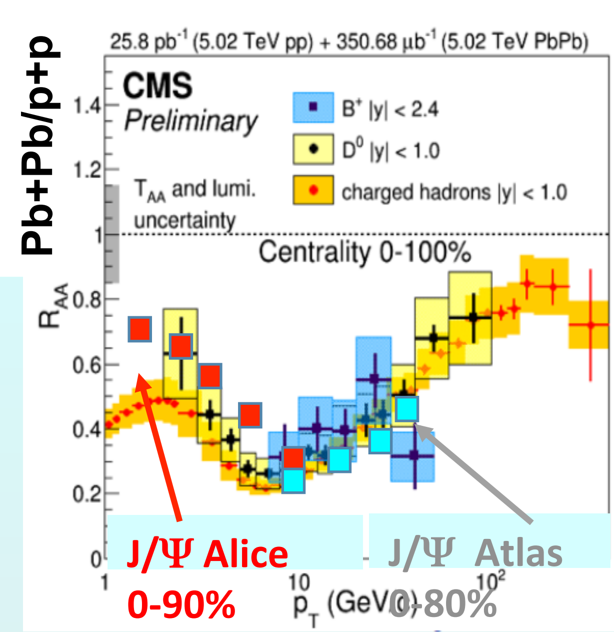
  $\hat{q} = \sqrt{\mu^2}/\lambda$ λ=mean free path;

  μ=typical p_T transfer per scatter

  $\sim k_T^2/l$

- **Constrain theory by measured R_{AA}**

  Parton interactions in expanding QGP



Many body q & g interactions!

- **For a 10 GeV parton**

  $\hat{q}$ **= 1.9 +/- 0.7 GeV²/fm @ T=470 MeV**

  1.2 +/-0.3 GeV²/fm @ T=370 MeV

  JET Collaboration PRC90, 014909 (2014)

  0.38 GeV²/fm @ 150 MeV(hot hadron gas)

  arXiv:1910.07027: Dorau, Rose, Pablos & Elfner

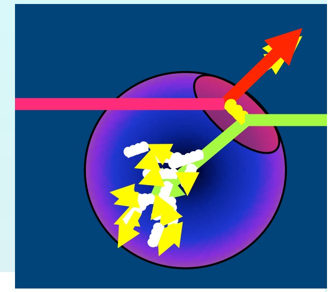
  0.02 GeV²/fm in cold nuclear matter

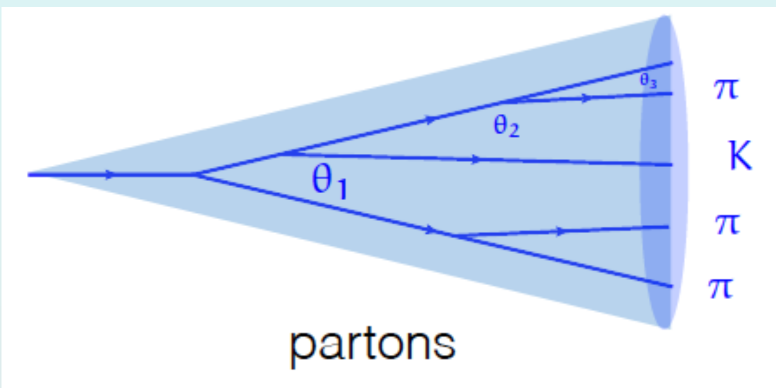
  arXiv:1907.11808: Ru, Kang, Wang, Xing & Zhang

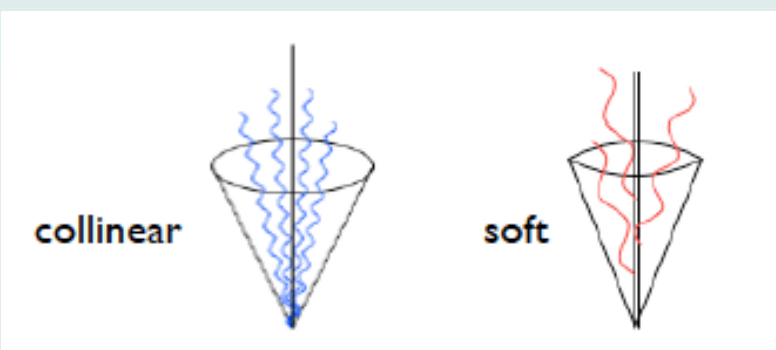
Probe of choice: jets

- q,g undergo probabilistic cascade of g emissions
- Total color charge & flavor are conserved
- Successive branchings are ordered in angle
- Color coherence suppresses large angle soft radiation

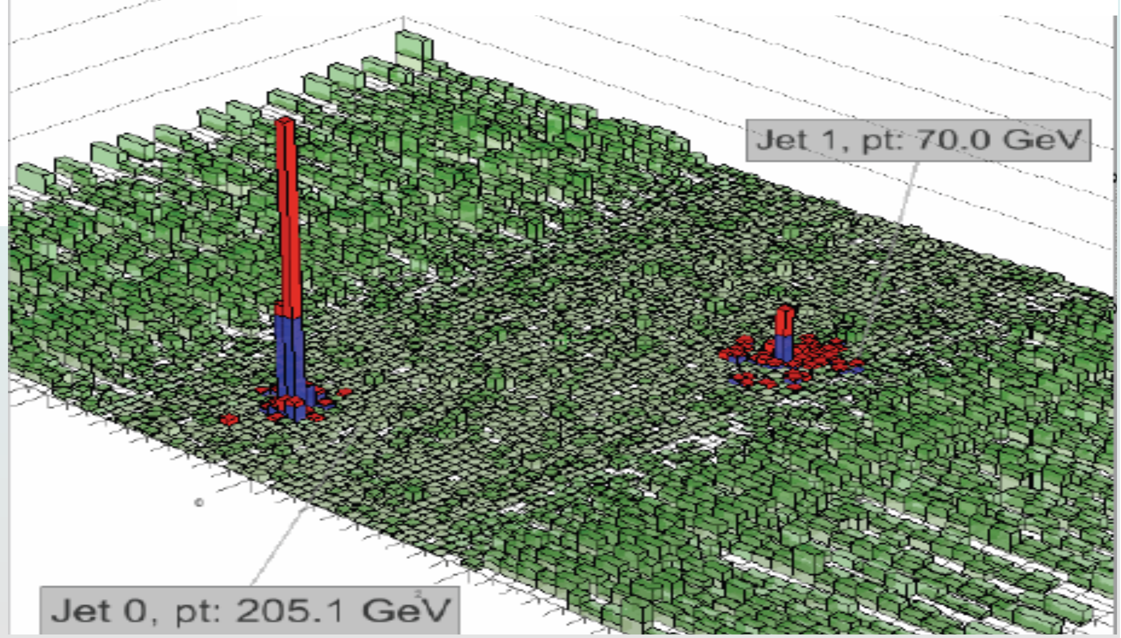
$$\theta_{jet} > \theta_1 > \ldots > \theta_n$$







Modified by color exchange with dense medium

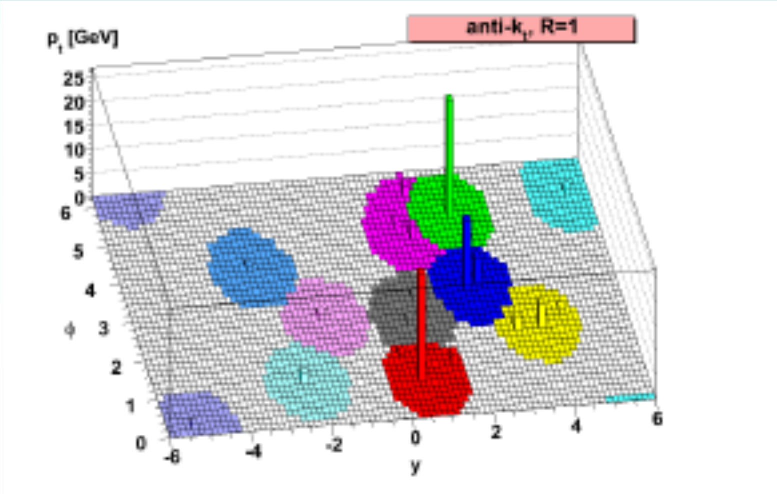


An issue: what's in a jet?

- **Which hadrons belong to the same jet?**
  In Pb+Pb: large underlying event of particles from other sources than this hard parton
- **Jet algorithm of choice: "anti-k_T"** *arXiv:1802.1189*
  Seed is hardest hadron or calorimeter tower
  Calculate distance to other particles:

$$d_{ij} = \min(k_{Ti}^{-2} k_{Tj}^{-2}) \frac{\Delta_{ij}^2}{R^2} \quad \text{and} \quad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

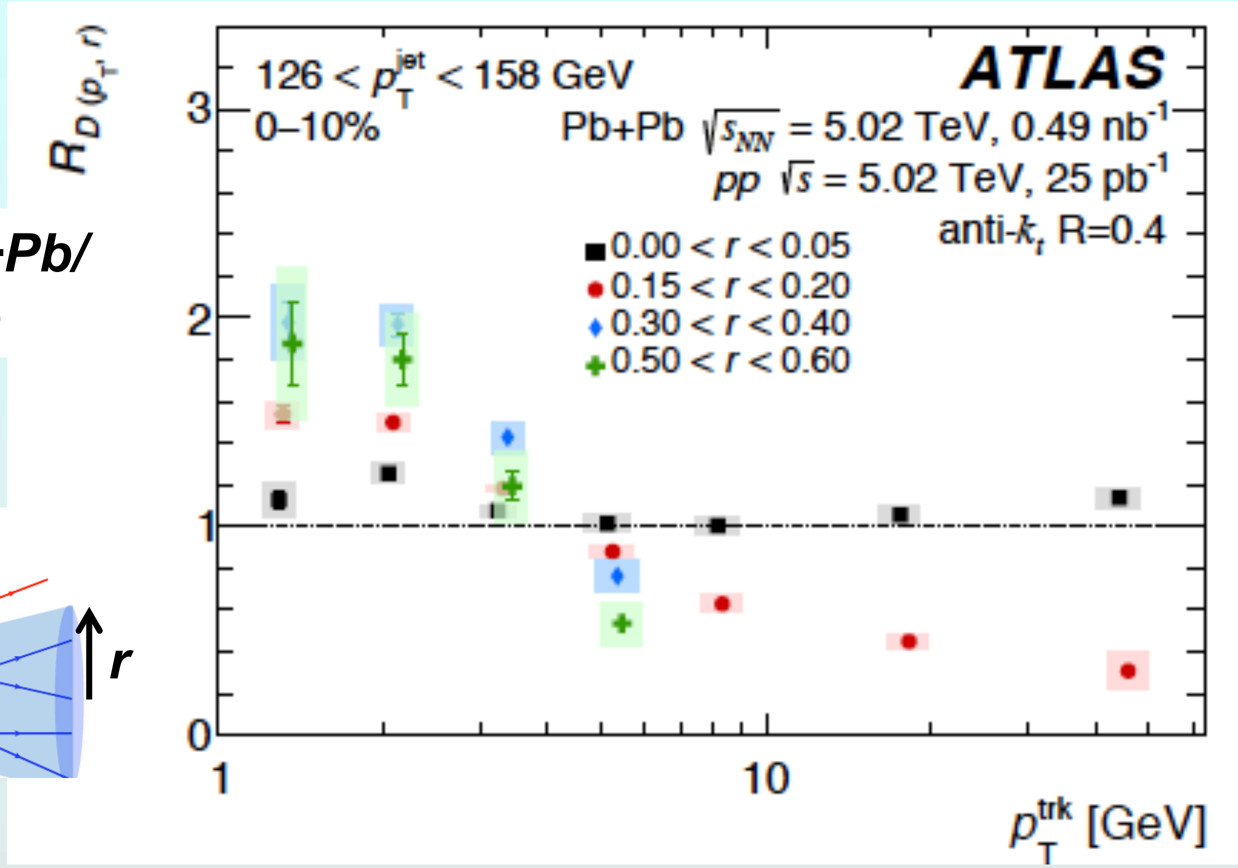
  Clusters softer particles with harder ones, until no more remain within distance of 2R



Typically, use R ~ 0.4 to allow statistical subtraction of the underlying event. But this misses some of the parton's energy.

R = 1.0 is better. Feasible in e+A

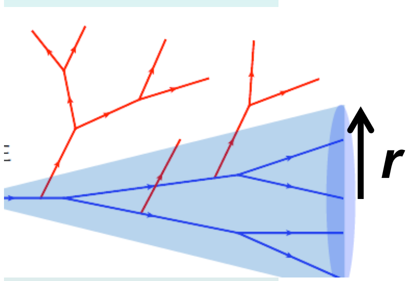
Looking differentially inside jets



arXiv: 1908.05264

See also: CMS arXiv: 1803.00042

Pb+Pb/ p+p



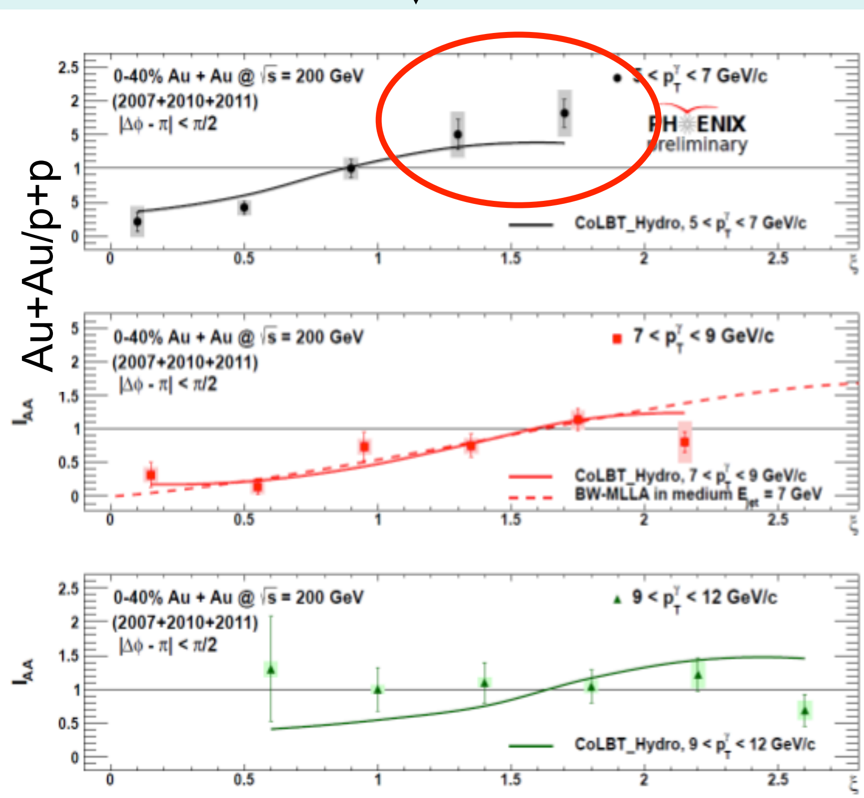
- **Excess soft particles at large jet radius**
- **Narrowing of higher p_T particle density**
- **Energy loss vs. medium response?**

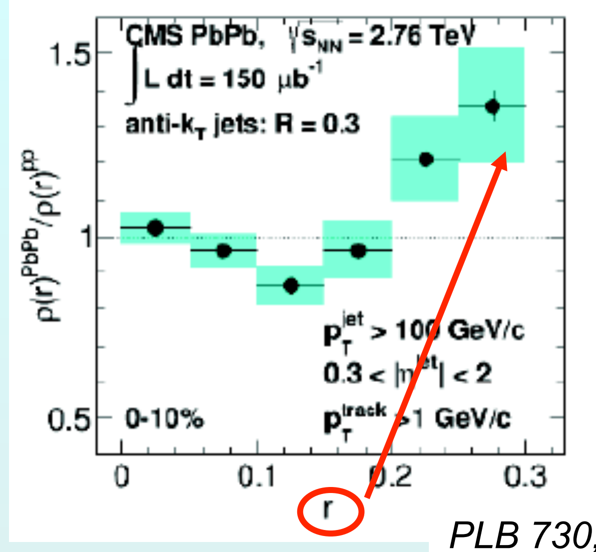
quantify: compare theory to the differential data

CoLBT-hydro, Hybrid, $SCET_G$

Jets get wider & "softer" in plasma

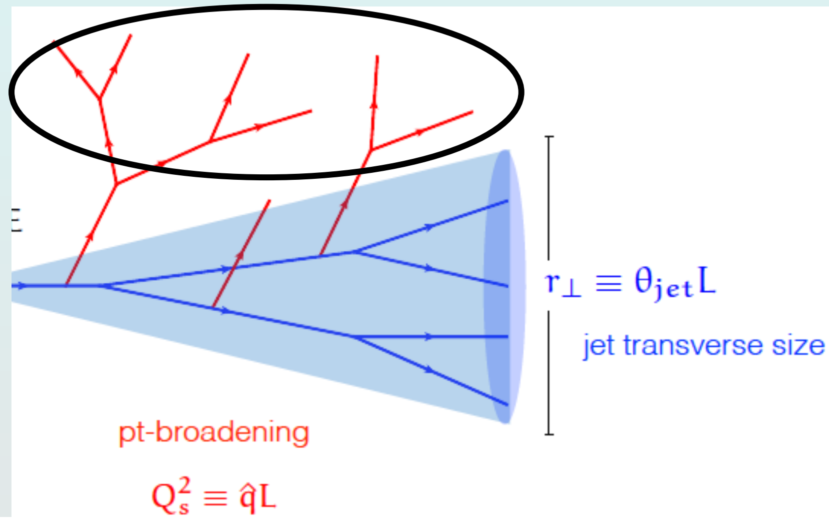
Au+Au/p+p:
Extra low momentum particles; high momenta suppressed





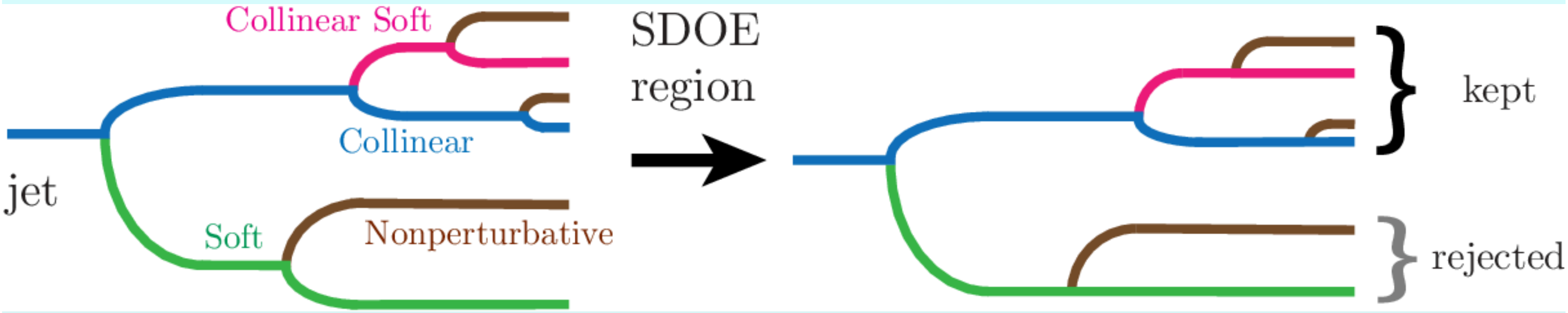
PLB 730, 243 (2014)

Pb+Pb/p+p:
Jets are wider in Pb+Pb



Medium induced radiation + medium response

Groom jet for pQCD analysis



- Collect particles into subjets
- Use "soft drop" algorithm to remove soft subjets

$$z \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$z < z_{\text{cut}} \theta^{\beta}$: drop the softer branch

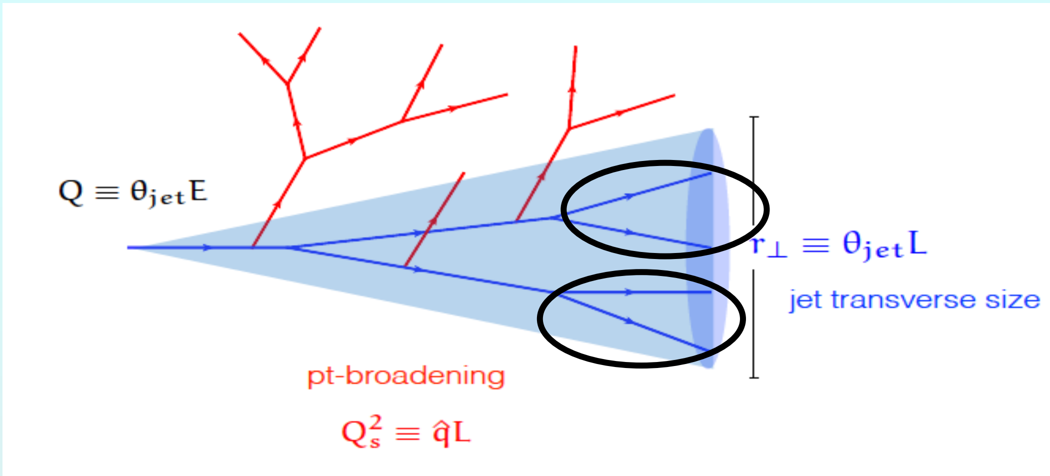
$$\theta \equiv \frac{\Delta R}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta \varphi^2}}{R}$$

typically, z_{cut} ~ 0.1-0.2 , β=0 or 1

- Removes soft radiation & non perturbative effects
  Allow access to perturbative splittings
  Also grooms away remaining underlying event

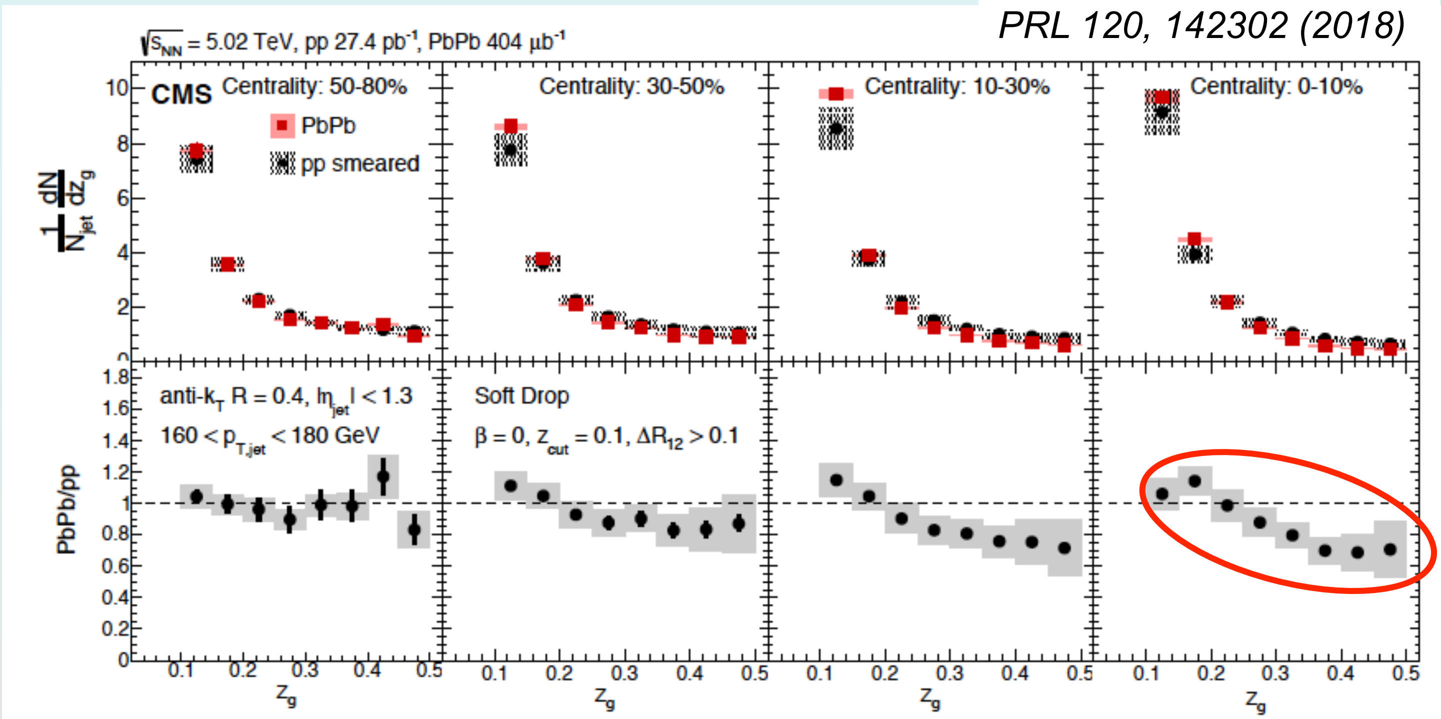
Is this soft stuff a way to study hadronization?

Collinear splitting



Can we see medium induced change in hard gluon splitting?

$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$



PRL 120, 142302 (2018)

Yes!

Experiment + Theory:

use the data to quantify energy, momentum transport

heavy quark energy loss

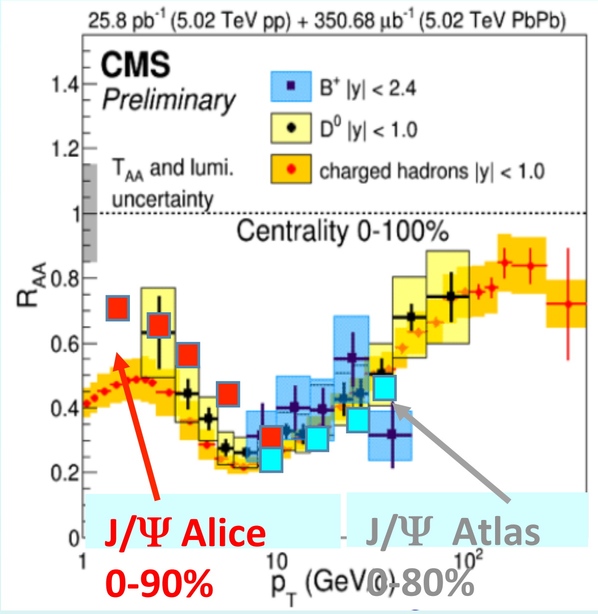
- **Soft gluon radiation spectrum**

$$dP = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{k_\perp^2\, dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E},$$

Large M suppresses small angle radiation (phase space effect)

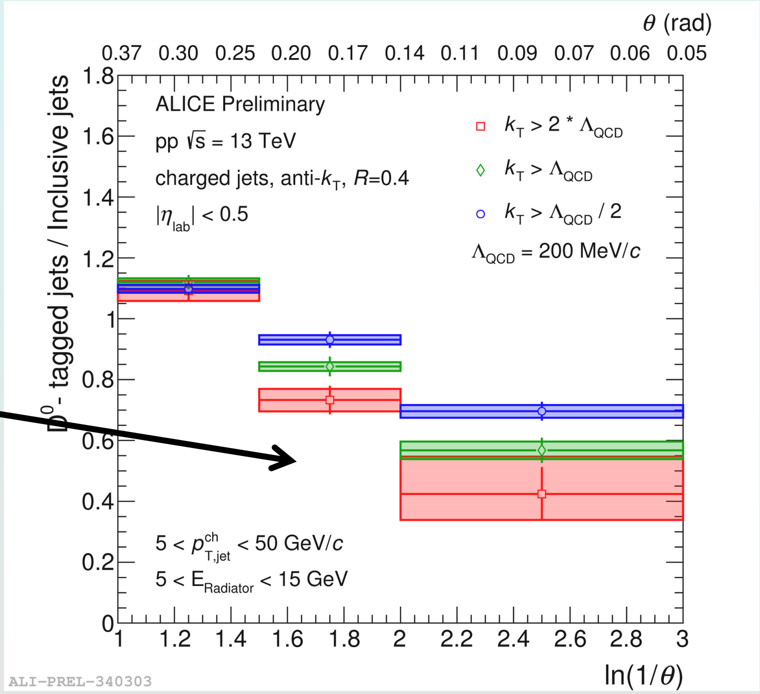
Known as "dead cone effect"

Dokshitzer, et al. J.Phys.G17,1602 (1991)
Dokshitzer & Kharzeev, PL B519, 199 (2001)



- **Observed by ALICE in charm tagged jets p+p collisions using jet reclustering!**
- **Does collisional energy loss make up for it? Medium induced radiation?**

Pb+Pb being analyzed

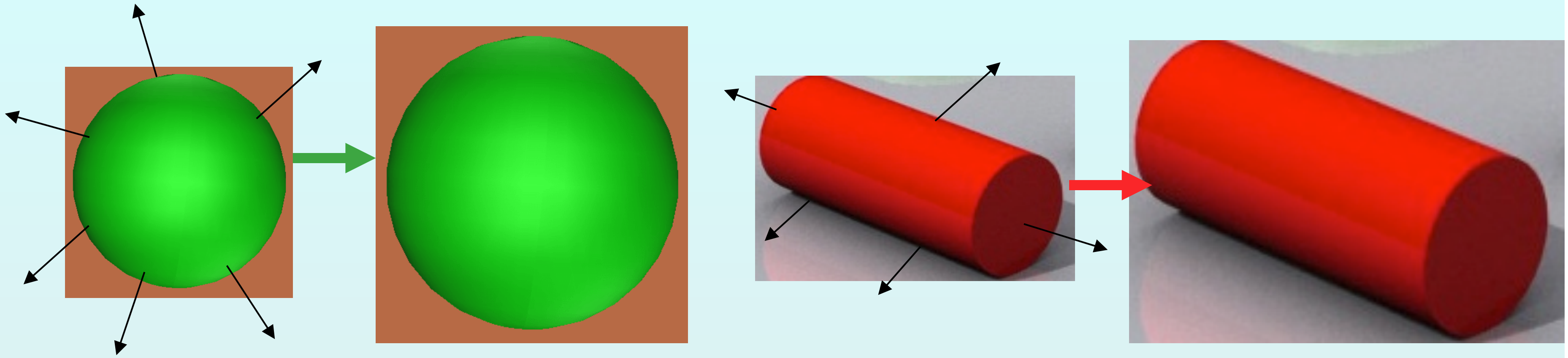


Conclusions

- **Many-body interactions in QCD ➔ plasma is strongly coupled**
  - **Low viscosity/entropy** ***η/s (QGP) = 0.085 – 0.11***
  - **opaque to transiting partons** ***qhat = 1-2 GeV^2/fm***
  - **Rapid hydrodynamization**
    - **Small systems also behave hydrodynamically**
    - **They seem unlikely to actually thermalize…**
- **Hadronization by "simple" quark coalescence works**
- **Parton splitting is modified by medium interactions**
  - **Jet structure shows scattering-induced radiation**
  - **Dead cone in charm quard radiation seen in p+p**
  - **Charm energy loss in Pb+Pb is large – collisional?**
- ***Is cold QCD matter strongly coupled too?***
  - ***The electron-ion collider will let us find out!***

- **Backup**

Collective flow from a velocity boost



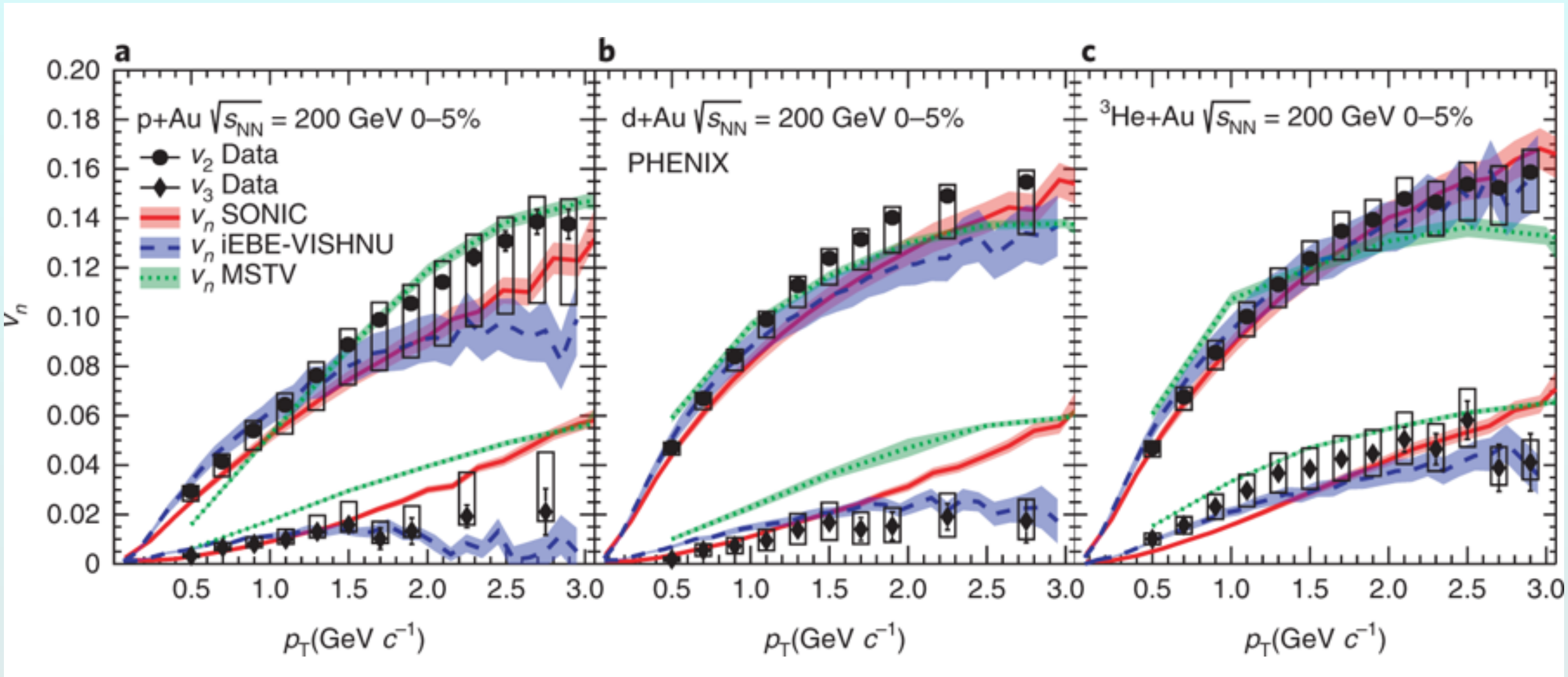
Model expansion of the system with fluid dynamics

$$\partial_t \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} + \partial_x \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ u(e+p) \end{pmatrix} + \partial_y \begin{pmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ v(e+p) \end{pmatrix} -$$

$$\partial_x \begin{pmatrix} 0 \\ \tau_{11} \\ \tau_{12} \\ \tau_{11} u + \tau_{12} v + k \partial_x \Theta \end{pmatrix} - \partial_x \begin{pmatrix} 0 \\ \tau_{21} \\ \tau_{22} \\ \tau_{21} u + \tau_{22} v + k \partial_y \Theta \end{pmatrix} = 0 \,,$$

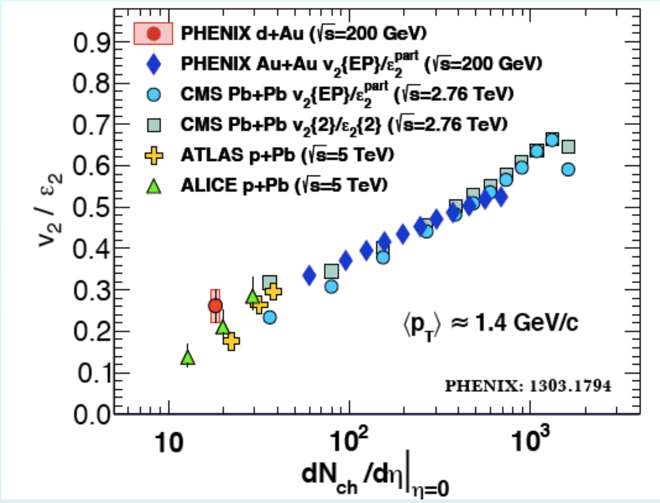
where u and v are the components of the velocity, ρ the density, p the pressure, e total energy density, τ_{ij} the components of the viscous part of the stress tensor, Θ the absolute temperature and k is the heat conductivity.

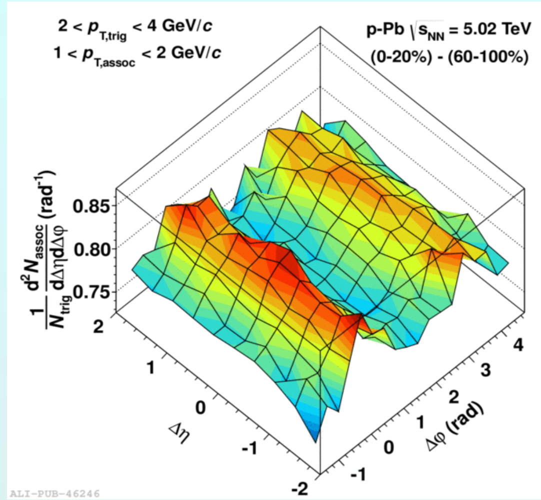
Hydro for p, d, ^{3}He + Au

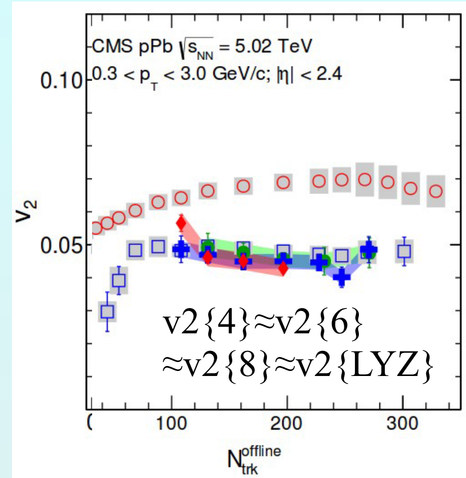


PHENIX Collaboration
Nature Physics (2018)

Is it really hydrodynamic? Looks like…





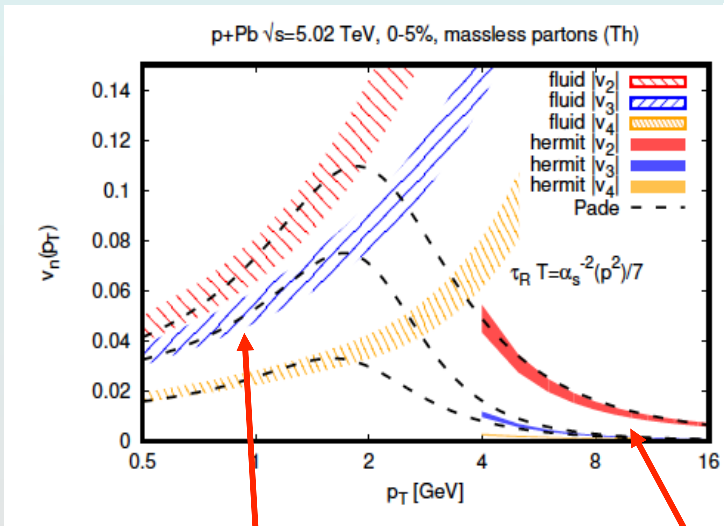


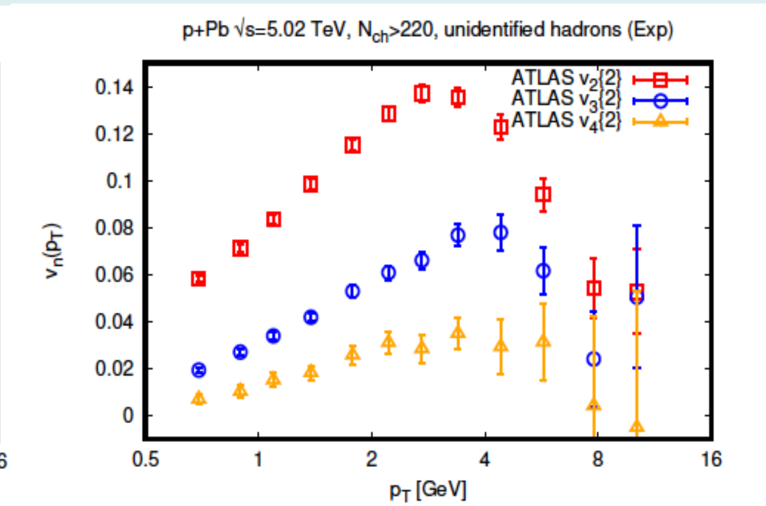
v_2/ε_2 changes smoothly; ridge is present; multi-particle correlations!

P. Romatschke,
arxiv:1802.06804

Model systems with >1 Gaussian hot spots

Reproduce v_2 vs p_T





~ hydrodynamical

~ free streaming

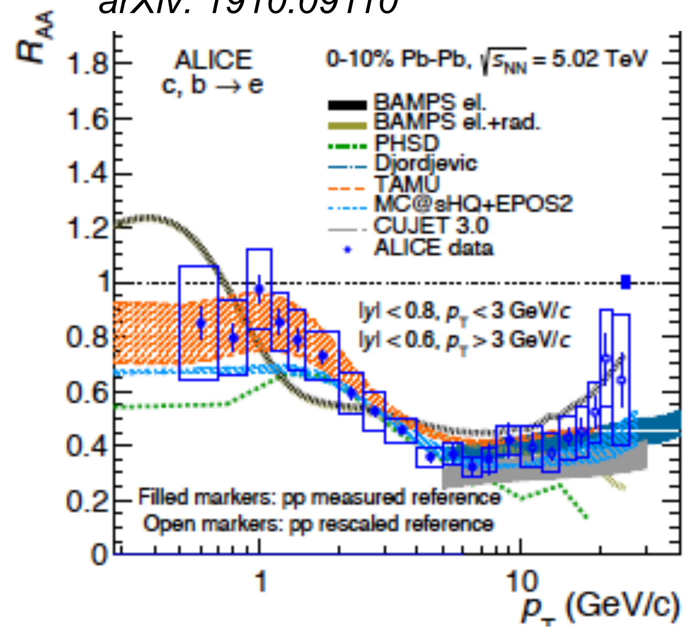
Heavy quarks

Lose energy too!

Dominated by collisions at low p_T

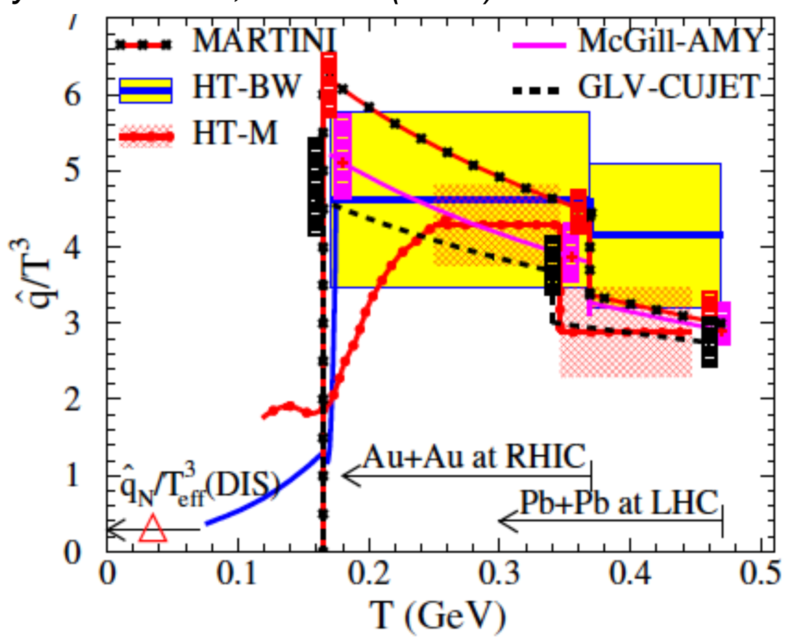
Radiation at high p_T

arXiv: 1910.09110

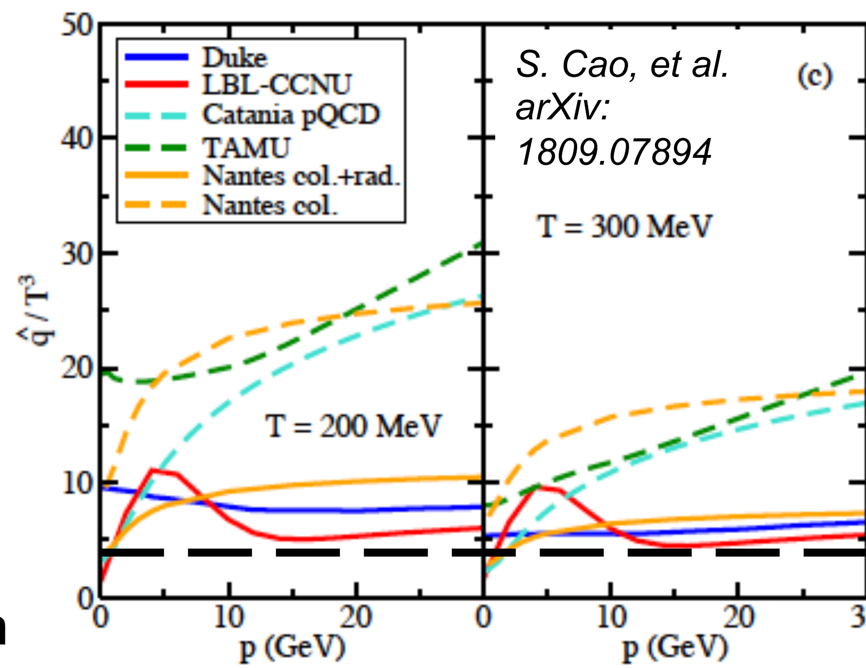


$$\hat{q} = \sqrt{\mu^2/\lambda}$$

Phys. Rev. C 90, 014909 (2014)

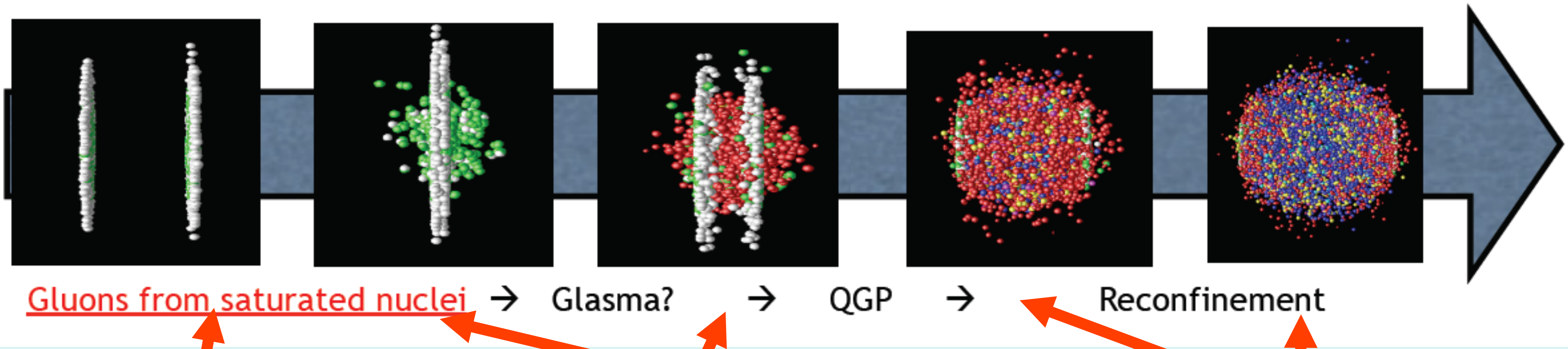


Light quark R_{AA} fits: JET collaboration



Heavy quark R_{AA} fits

How can the system become *matter*?



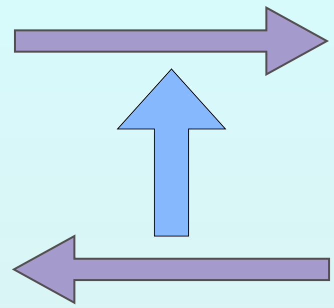
- Nuclear wave function at small x: 1) Nuclear structure functions Measure in pA/eA. 2) Structure vs. parton dynamics?

- Particle production at the beginning: 3) does it factorize? 4) Coherence among parton collisions?
- initial plasma formation: 5) How can the system reach ~ isotropy so fast?

- Probe medium with energetic partons (see jets): 6)modification of QCD radiation and hadronisation in the nuclear medium?

Small viscosity/entropy was surprising

Viscosity: ***inability*** to transport
momentum & sustain a wave
internal friction damps waves



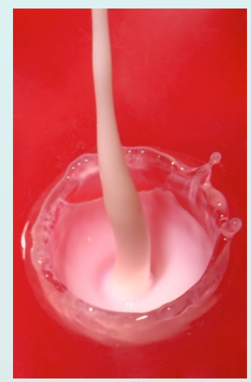
$$\eta \approx \frac{1}{3} n \bar{p} \lambda_f$$

$$\bar{p} \sim T$$

low η → large σ, transports momentum across fluid

normal QCD: σ not so large

large σ in QGP→ strongly coupled!

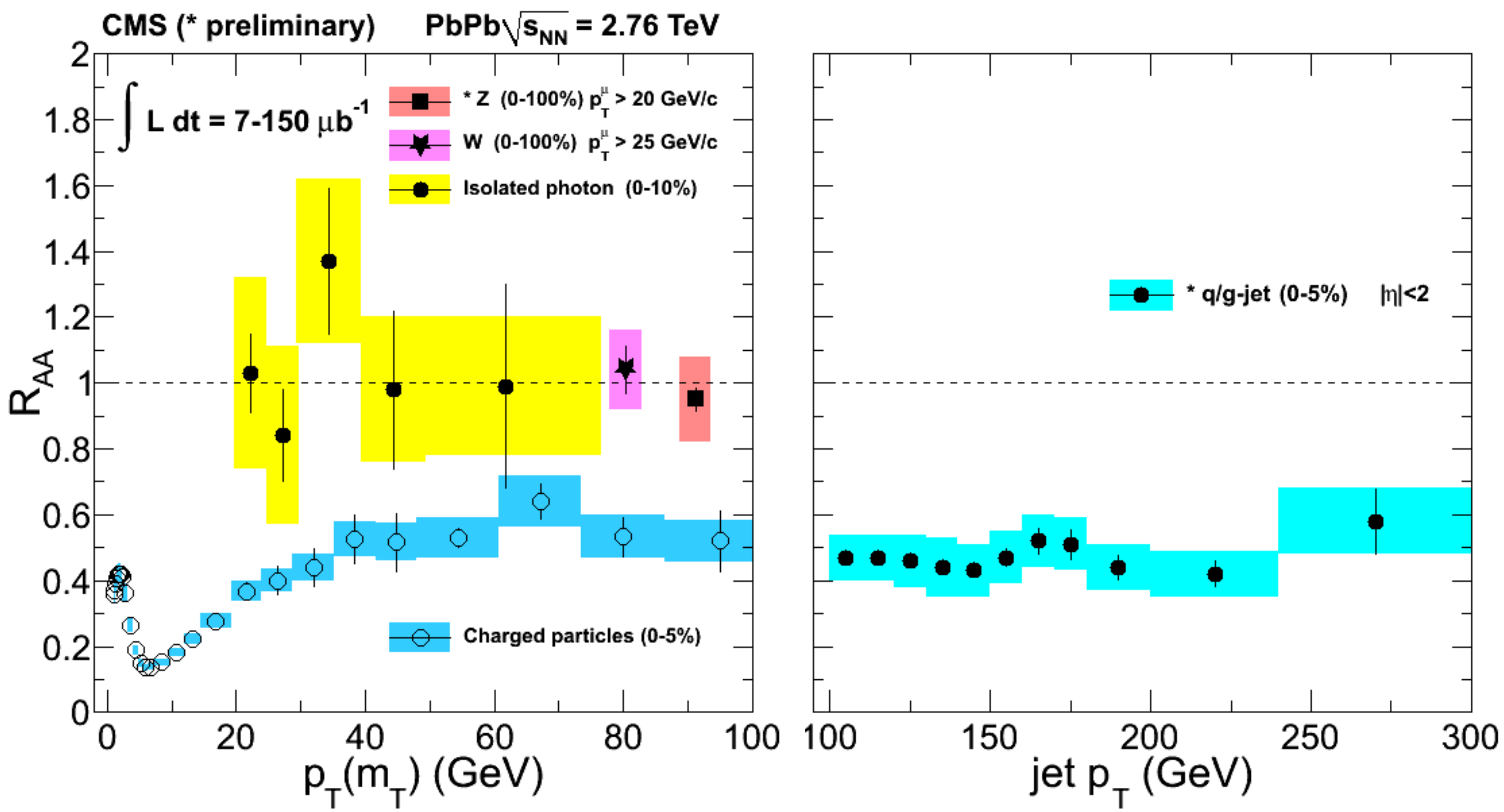


Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Viscosity/entropy found to be near the 1/4π limit from quantum mechanics!

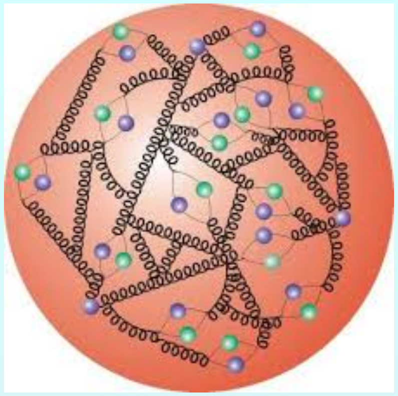
∴ liquid at RHIC is "perfect"

Energy loss even by very energetic q & g



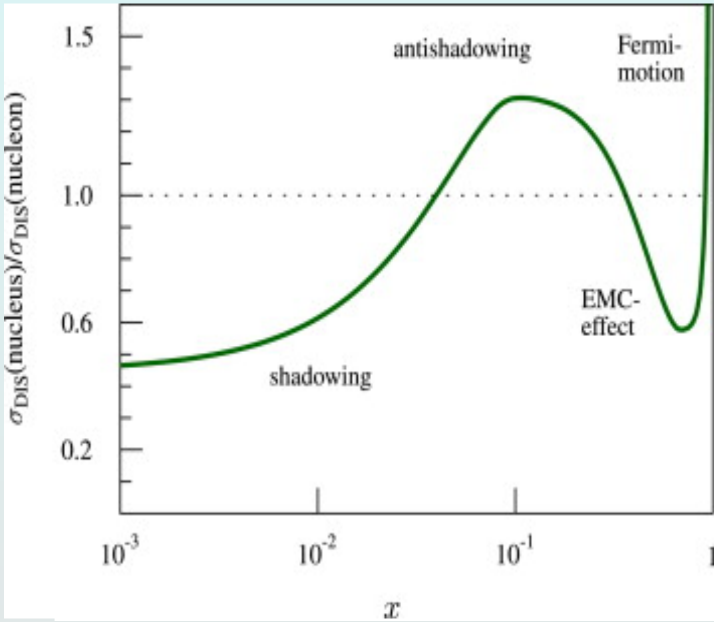
Where does the lost energy go?

Dense gluonic matter: in nuclei

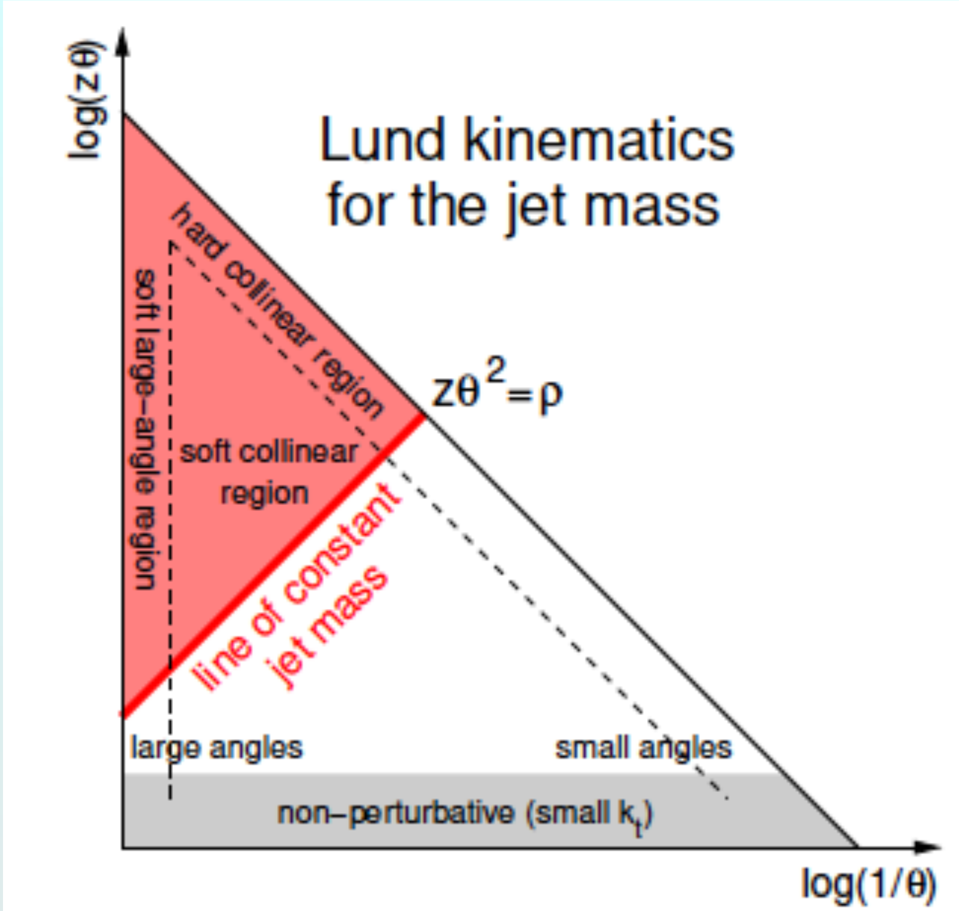


- **3 valence quarks + gluons + sea quarks**
  Gluons split into quarks + antiquarks
  Measured by scattering electrons (γ transfer)

- **Count quark and gluon densities vs. momentum fraction they carry**
  x is momentum fraction in ∞ momentum frame (i.e. in proton beam frame)
  Q^2 is photon virtuality (effective mass)



- **For p, n inside nucleus:**
  densities are different!
  q, g from different nucleons interact
  Higher density –> gluons can fuse
  @ higher x values than in isolated protons
  – Scale goes as $x_s \sim A^{1/3}$



Lund kinematics
for the jet mass
log(zθ)
log(1/θ)
zθ²=ρ
hard collinear region
soft large−angle region
soft collinear
region
line of constant
jet mass
large angles
small angles
non−perturbative (small k_t)