Results from STAR at RHIC

Mirko Planinić for the STAR collaboration

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We will never see the whole body

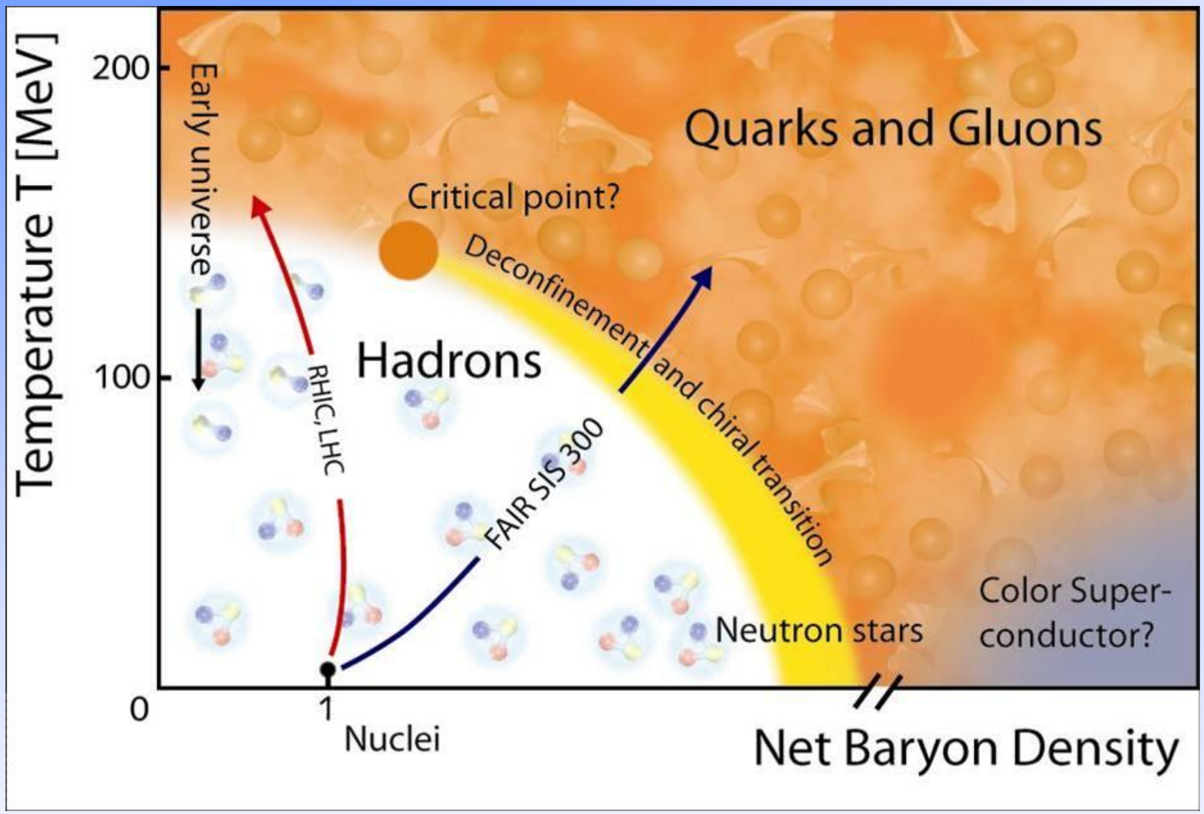
P.C. Sereno *et al.* **Science**, Nov. 13, 1298(1998).

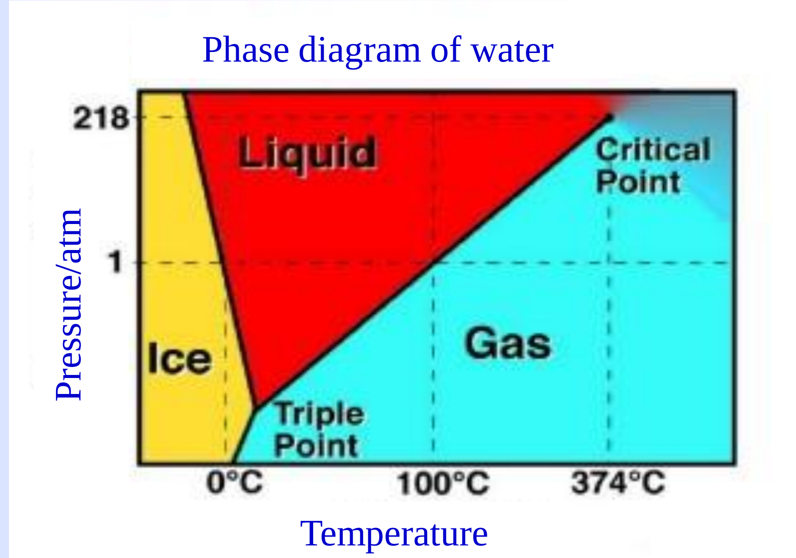
(Spinosaurid)

Mirko Planinić

LHC Days in Split 2010

Phase diagram of nuclear matter





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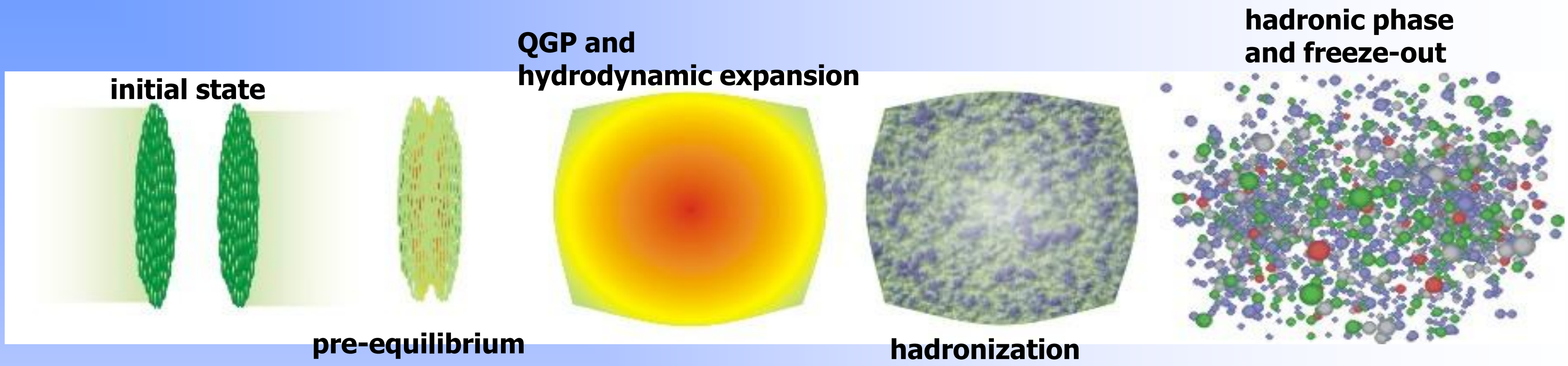
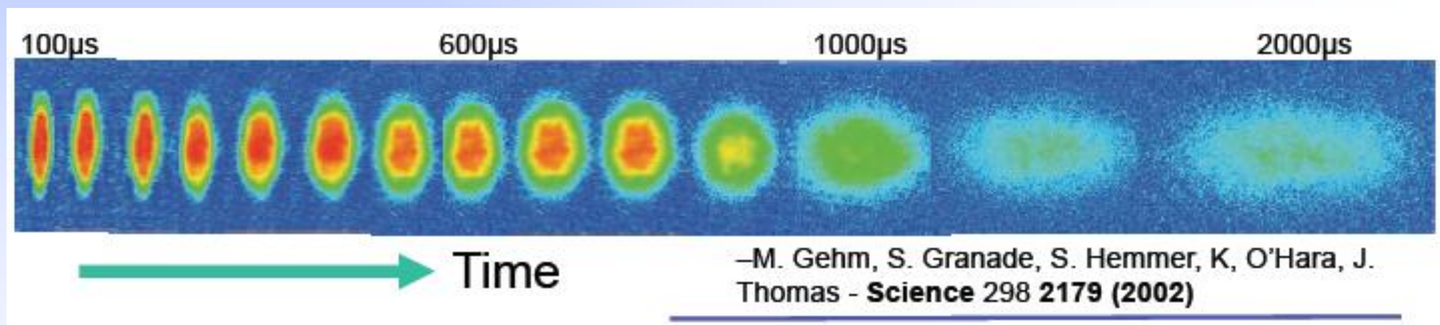
Stages of the collision ?

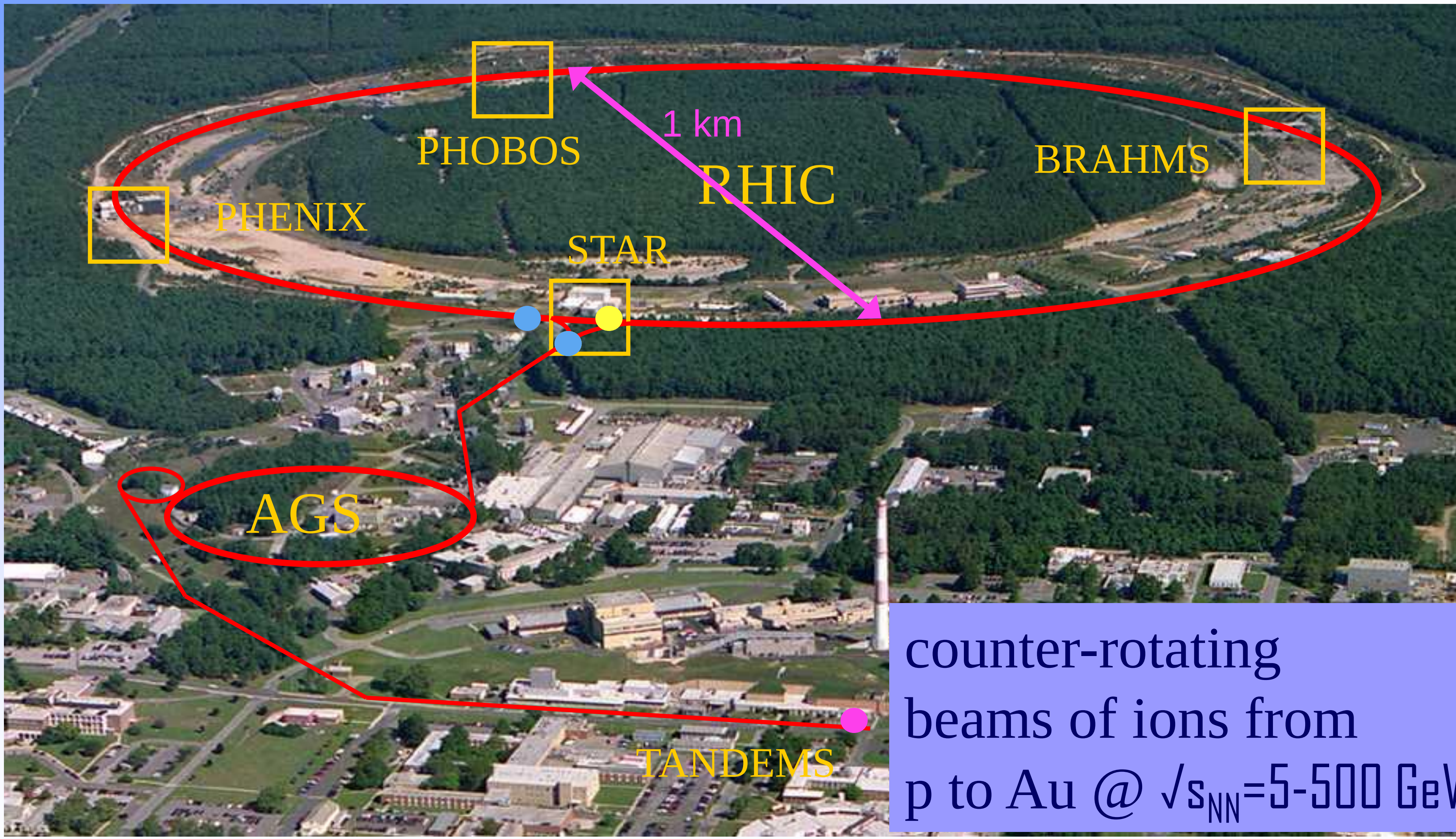


Animation by Jeffery Mitchell (B N L).



- We detect only signals from the last stage.
- In order to be sure that we have QGP we must understand all stages of collision (signatures).

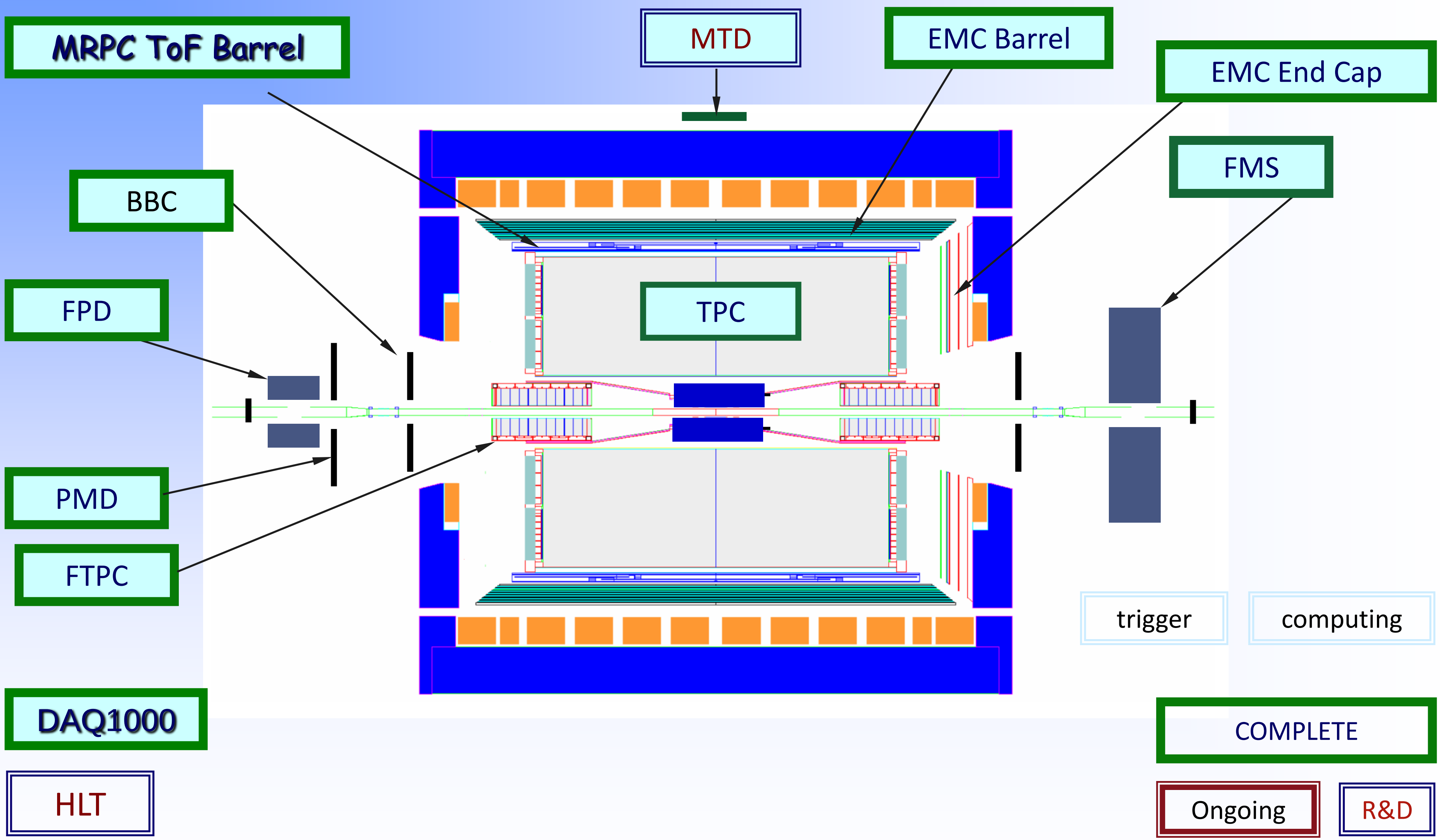
Relativistic Heavy Ion Collider (RHIC) at Brookhaven



counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

animation by Mike Lisa

STAR detector



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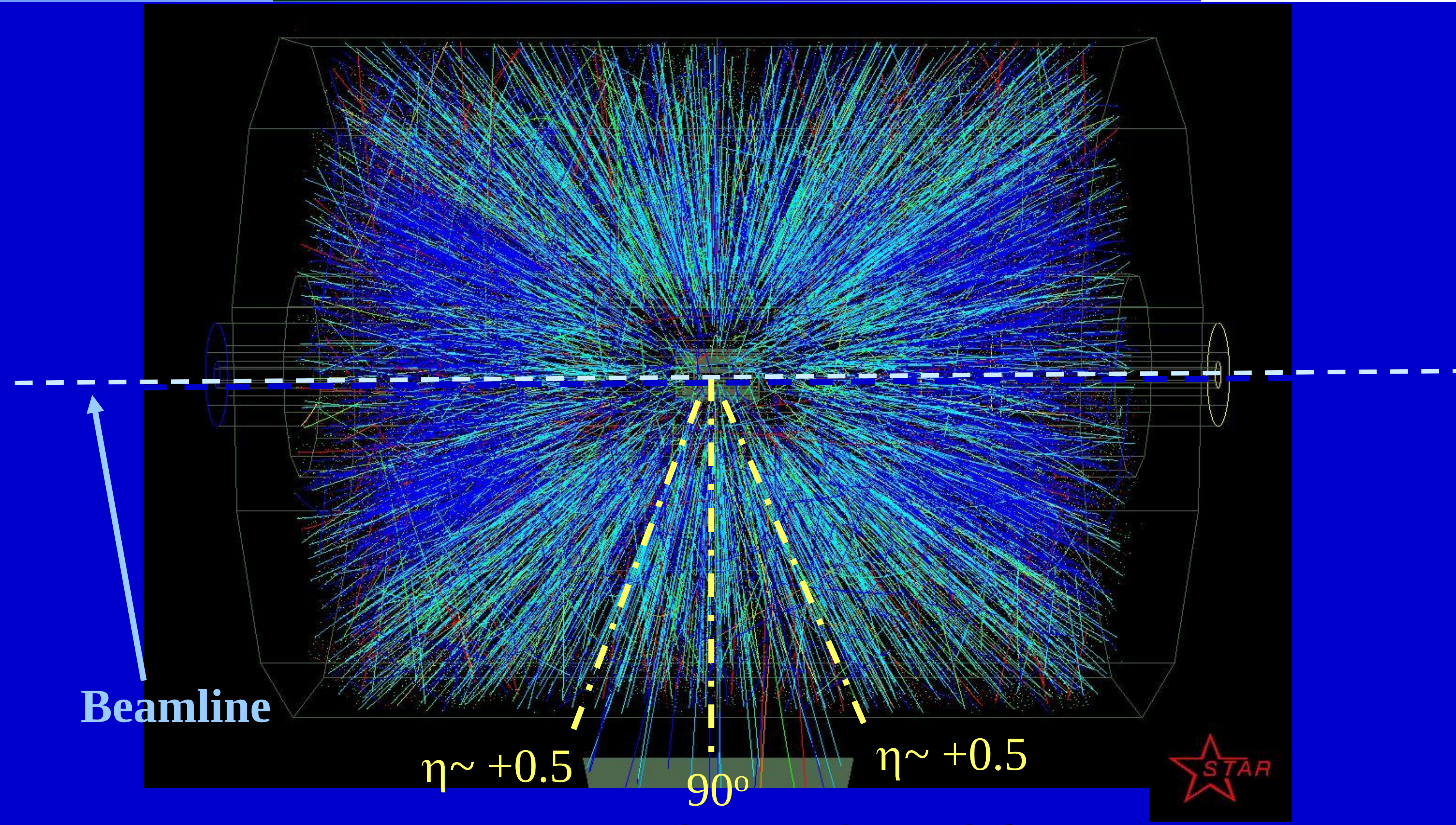
Au+Au @ STAR



creates over 5000 charged particles!

(~600 at ~ 90° to beamline)

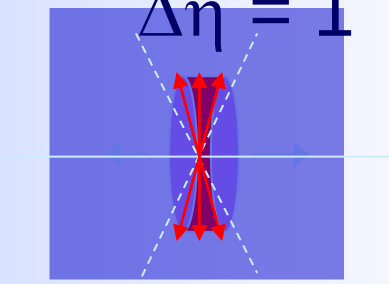
Did we reach critical energy density?

Lets do a coffee napkin estimate

Look at all produced particles in a Central ‘Head-on’ … si…

$$\left(\frac{dN}{d\eta}\right)_{all} \sim 1000 \qquad \langle E \rangle \sim 1 GeV$$

Δη = 1



Total energy released in Δη=1 is ~ 1000 GeV

Max initial overlap volume $\sim \pi R^2 (1\, fm) \sim 200\ fm^3$

Energy Density = Total Energy/Volume ~ 1000GeV/200 fm^3

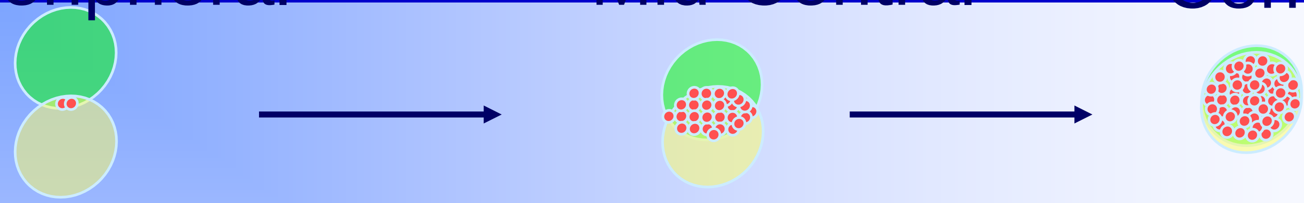
Initial Energy Density Estimate, **ε ~ 5 GeV**/fm^3

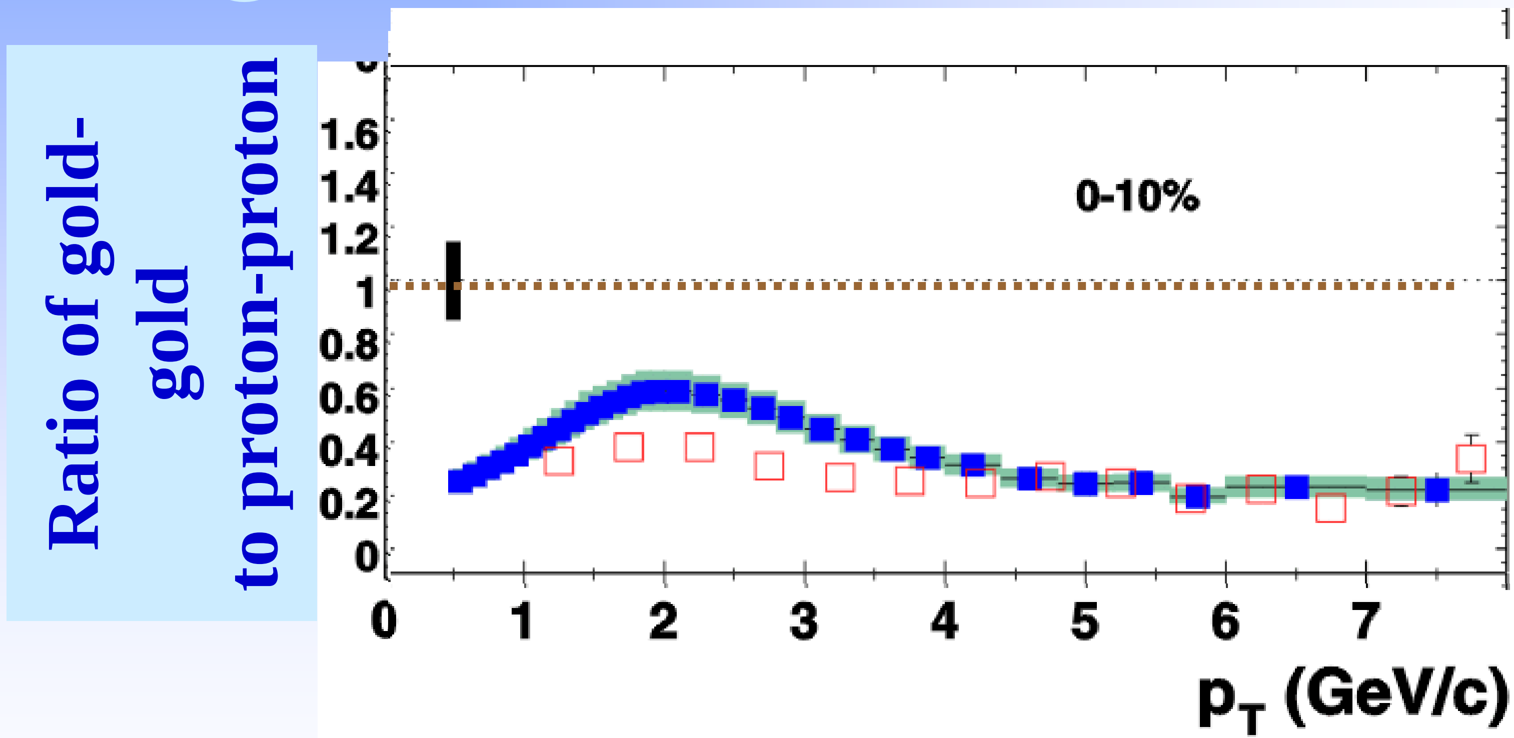
cold nuclear matter $\approx$ 0.13 GeV/fm^3

⇒ So the answer is YES, we are above the critical value of ~0.7 Gev/fm^3

Comparing High Momentum particles

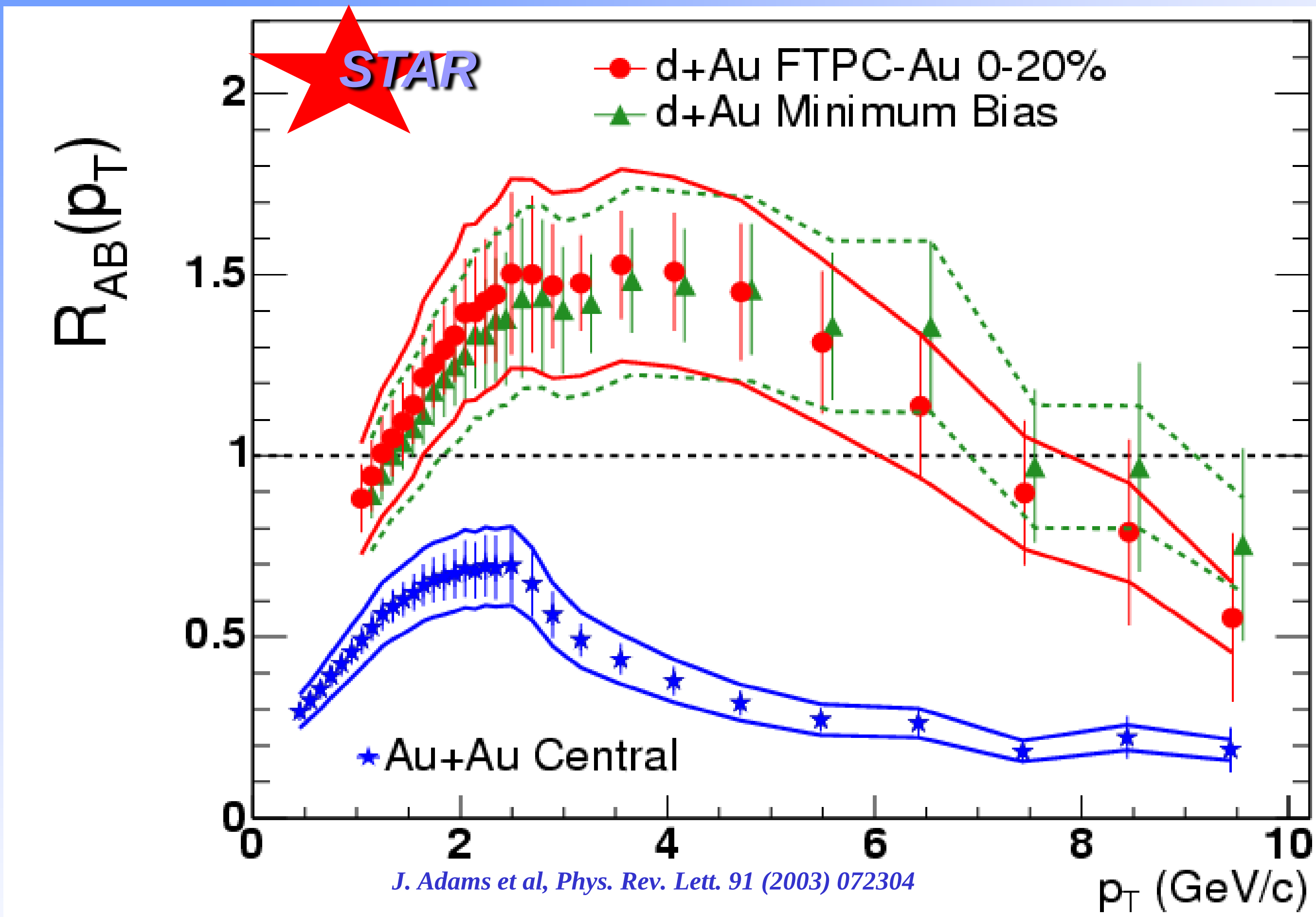
Peripheral Mid-Central Central





→ We “lose” high momentum (speed) particles for Central Collisions

High p_T suppression



$$R_{AB} = \frac{dN_{AB} / d\eta d^2 p_T}{T_{AB} d\sigma_{NN} / d\eta d^2 p_T}$$

p+p reference

$$T_{AB} = \langle N_{bin} \rangle / \sigma^{pp}_{inelastic}$$

Binary coll. scaling

$R_{AA} << 1$; $R_{dAu} > 1$ Confirms final state effects present

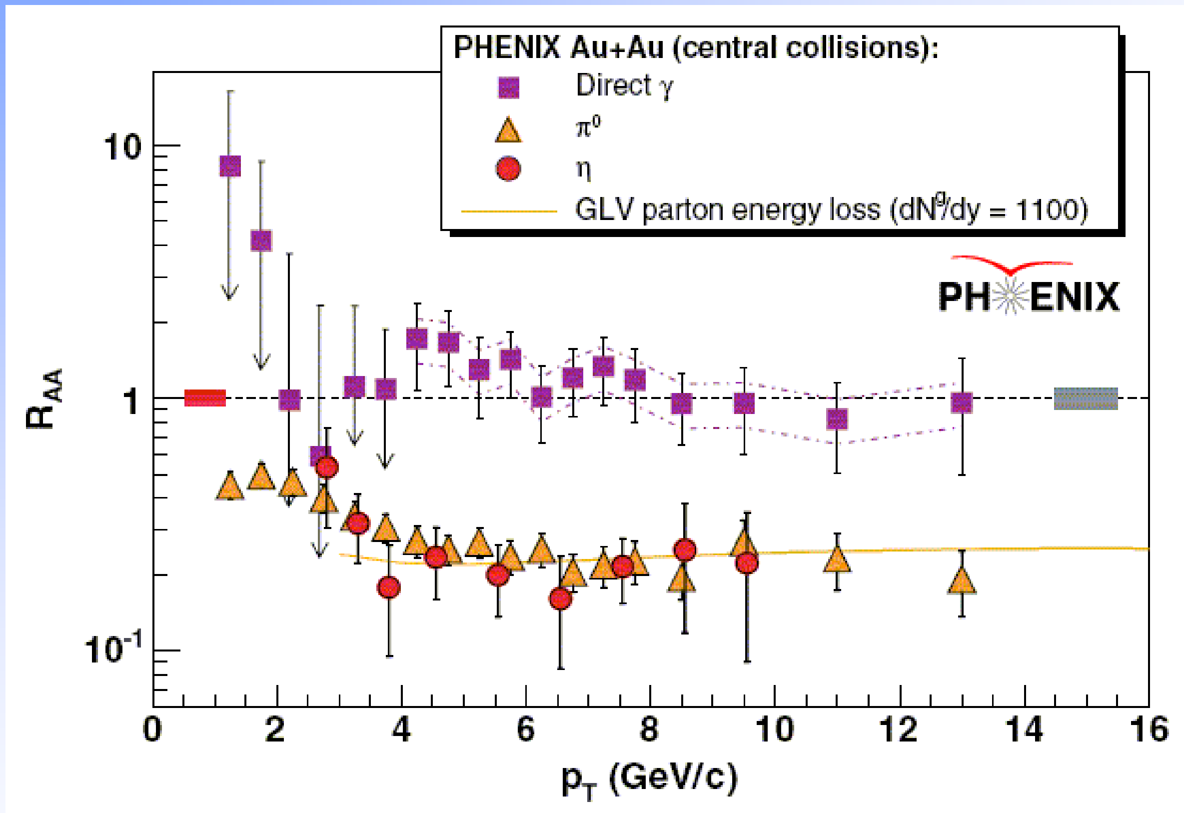
- p_T >5 GeV/c: suppression ~ independent of p_T.
- pQCD describes data only when energy loss included.

Confirming the probe

Photons - unsuppressed

Hadrons - suppressed

Survival Probability

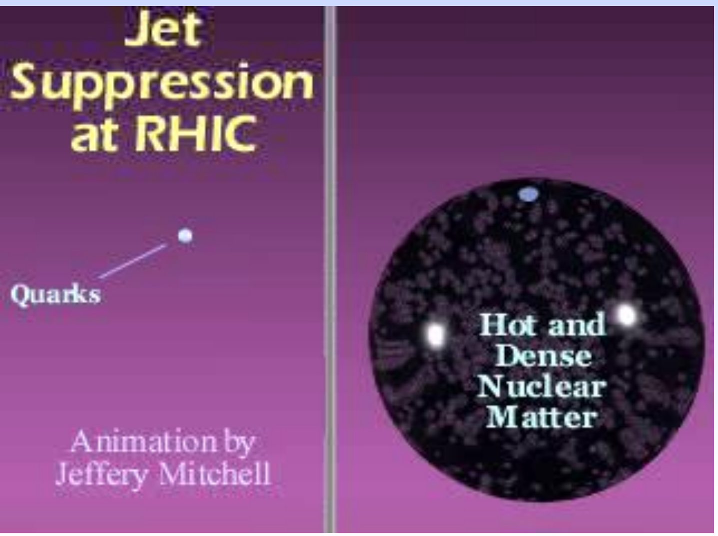


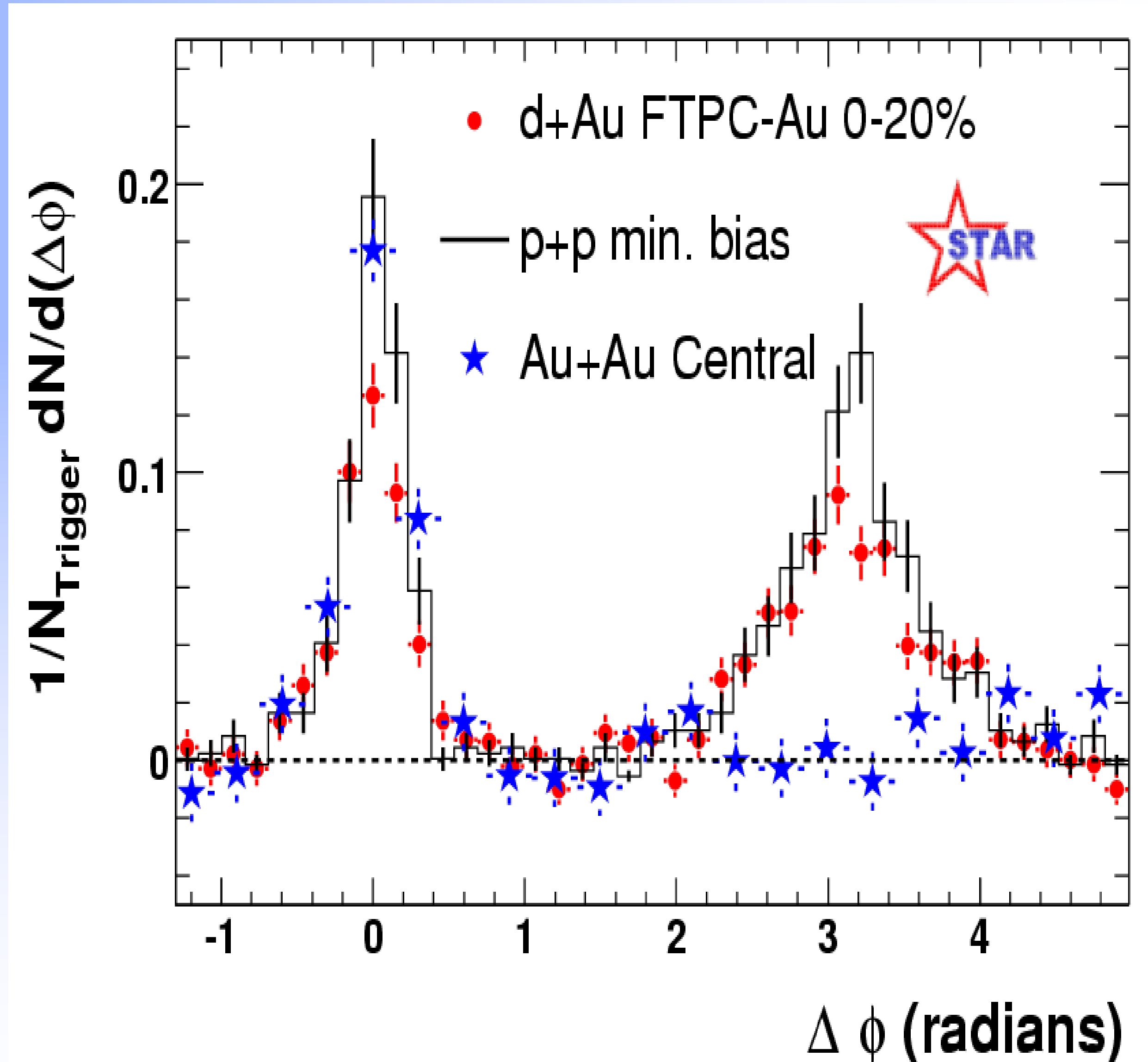
We have an understood and calibrated probe

Jet quenching

Jet correlations in central Gold-Gold.

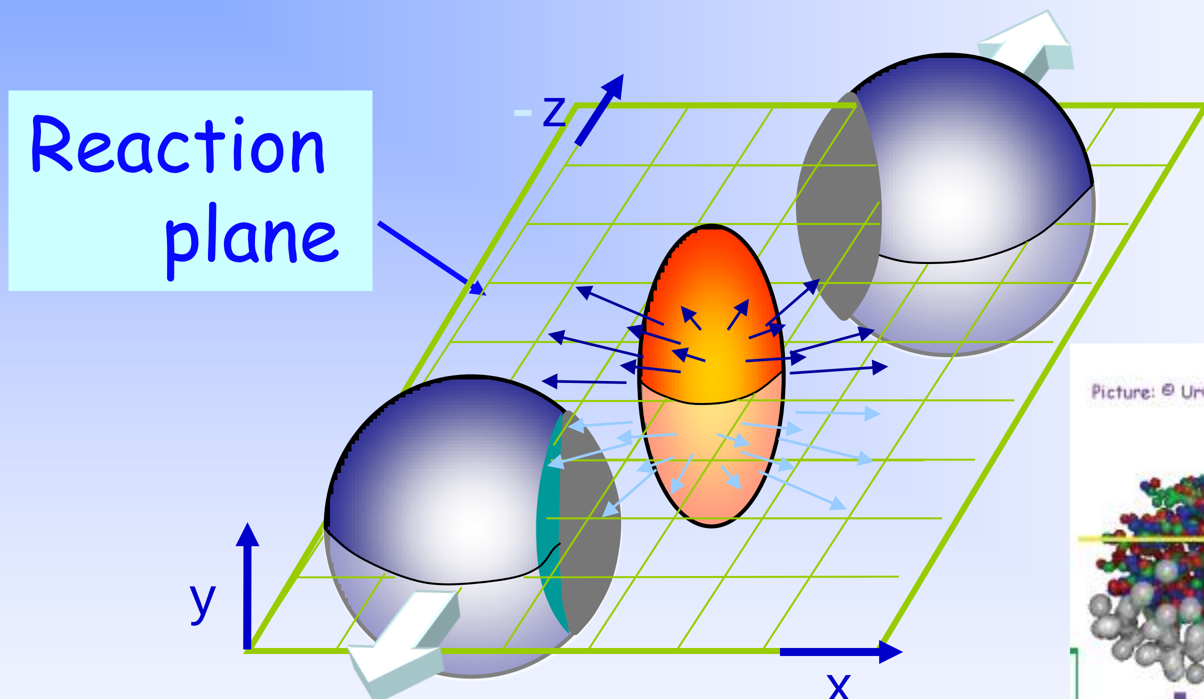
Away side jet reappears for particles p_T>200 MeV

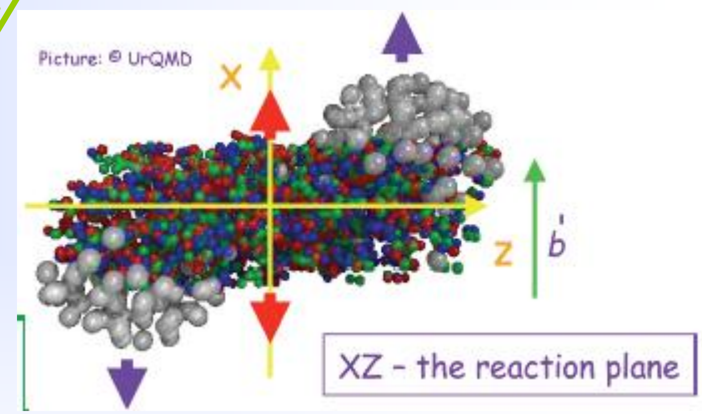




Particle emission patterns

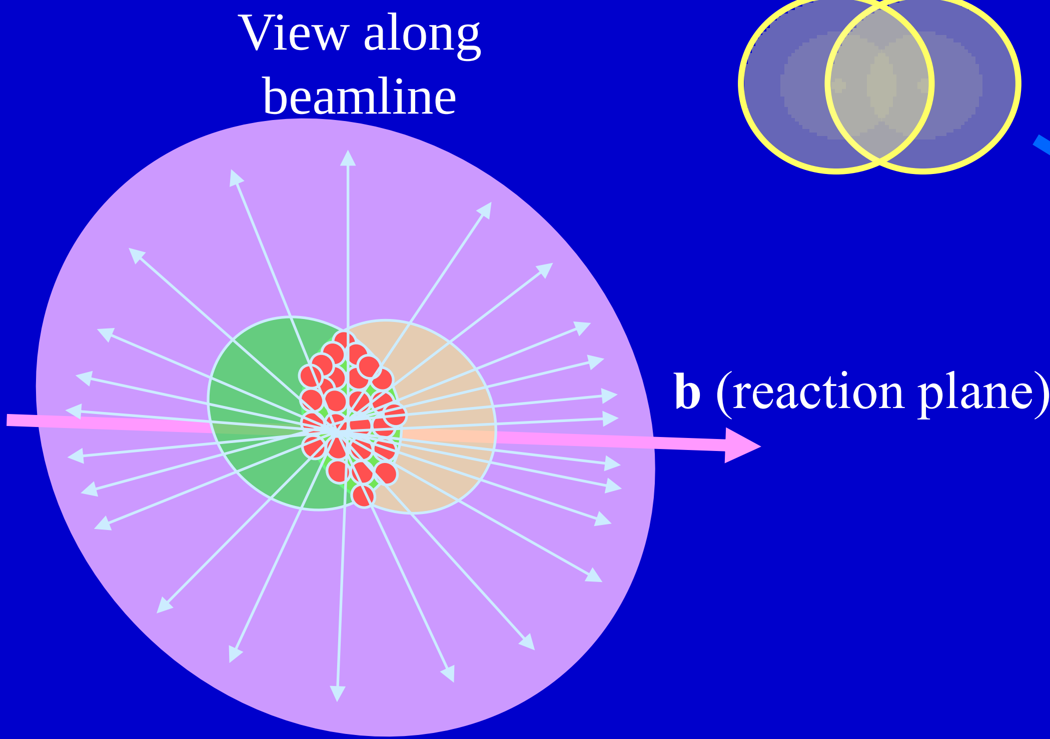
Peripheral Collisions: Overlap “hot spot” looks like an almond.

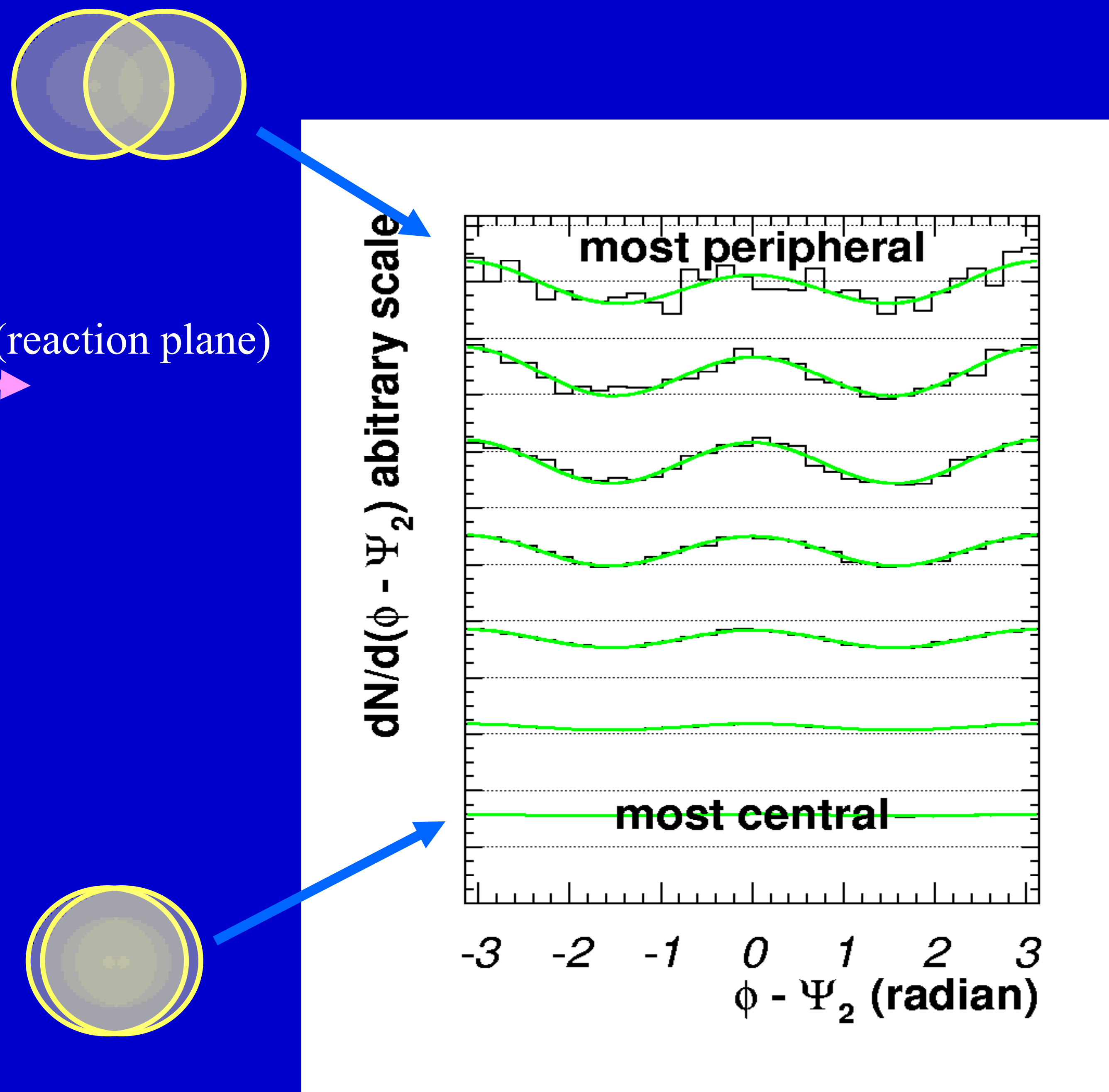




Do the particle emission patterns reflect this initial shape?

If they do – can learn more about timescales of the “cooling” process and help us distinguish between liquid and gas behavior



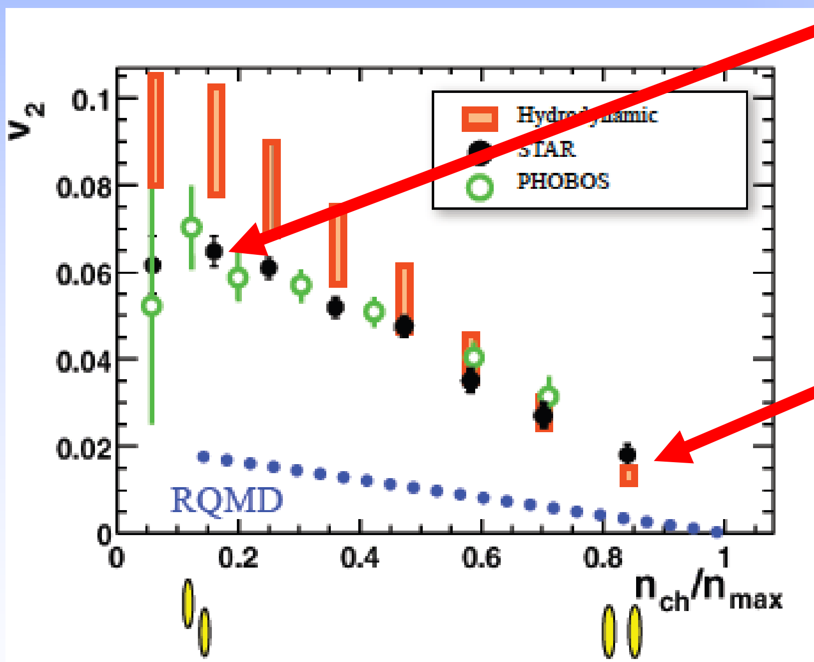


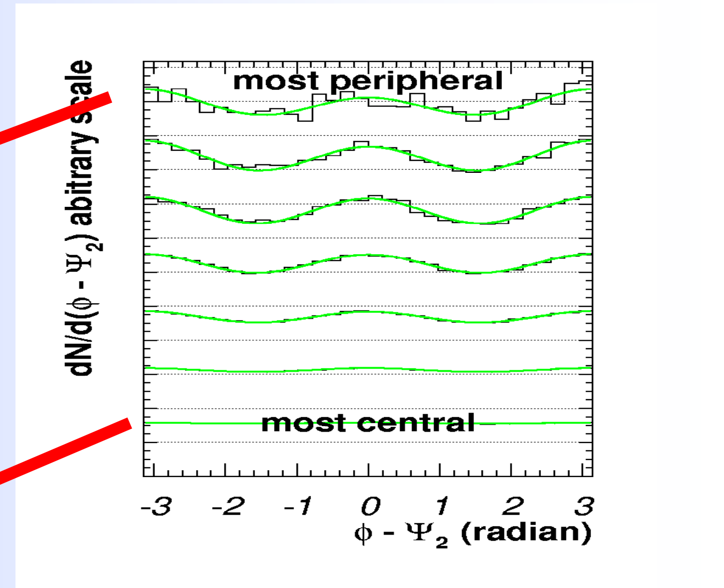
→ Emission patterns follow the shape of the overlap region.

Fourier analysis of emission patterns.

$$\frac{dN}{d(\phi - \theta_R)} = 1 + 2v_n \cos(n(\phi - \theta_R))$$

Extract *n*=2, elliptic flow





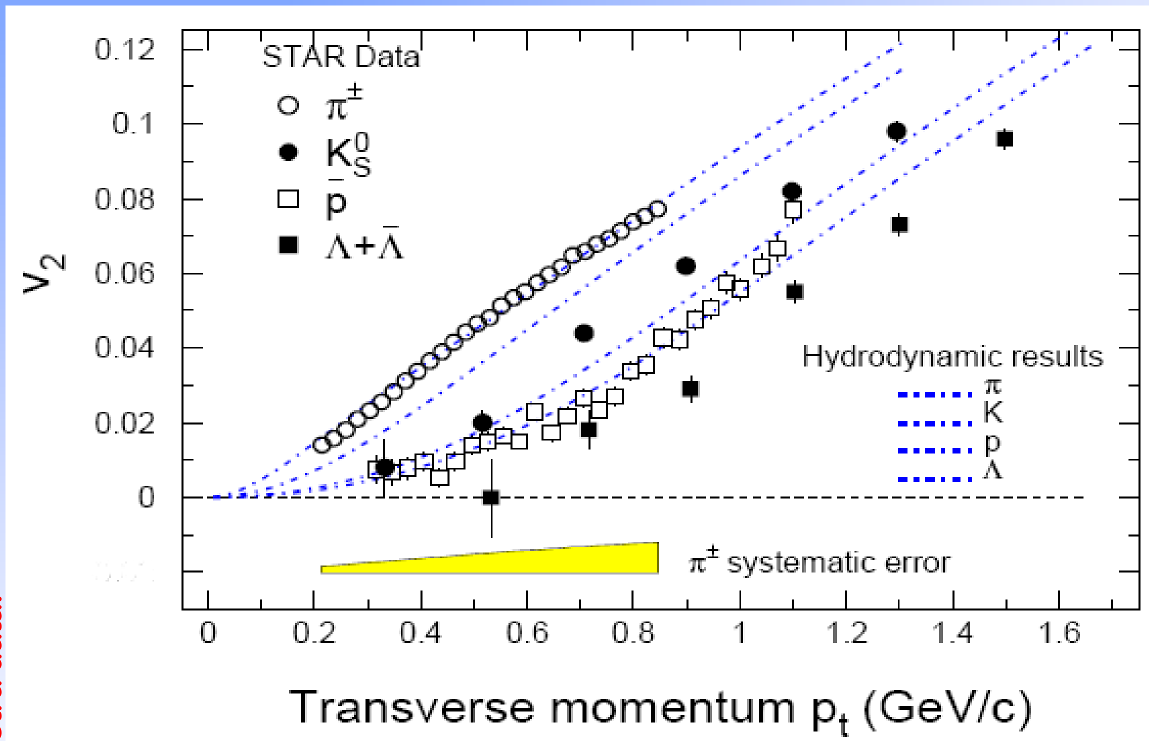
→Find significant values of v_2 for peripheral collisions.

→ Behaving like a liquid (collectively)

Elliptic flow observable is sensitive to early evolution of system

Large v_2 is an indication of early thermalization

Elliptic Flow for different particles



Hydro by Huovinen et al.
hydro tuned to fit central
spectra data.

STAR PRC 72 (05) 014904
200 GeV Au+Au
min-bias

First time hydro works: suggests early thermalization -

$\tau = 0.6$ fm/c

$\varepsilon = 20$ GeV/fm^3

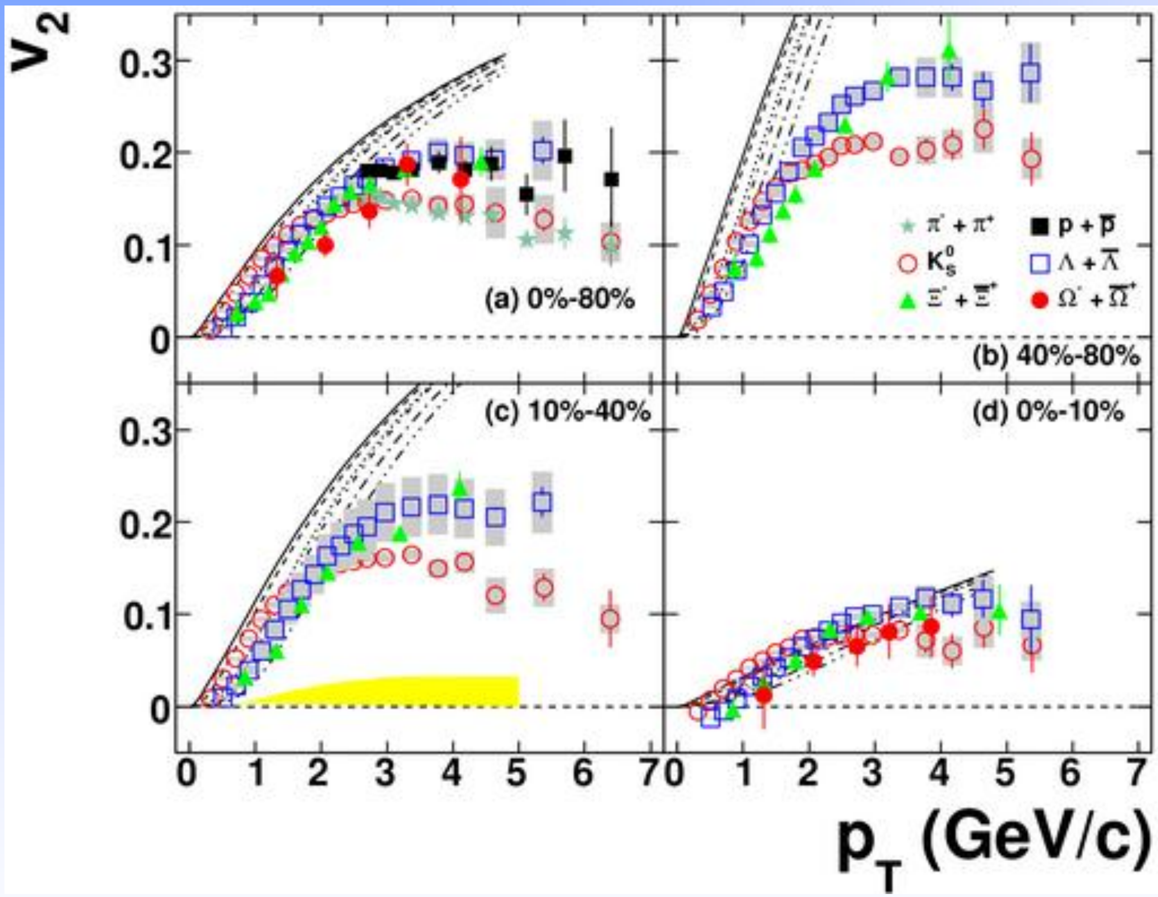
- Pure hydrodynamical models including QGP phase describe elliptic flow for many species

QGP-almost perfect fluid

→ v_2 is different for different particles

Elliptic flow v_2 large even for Ξ, Ω

Phys. Rev. C **77** (2008) 54901

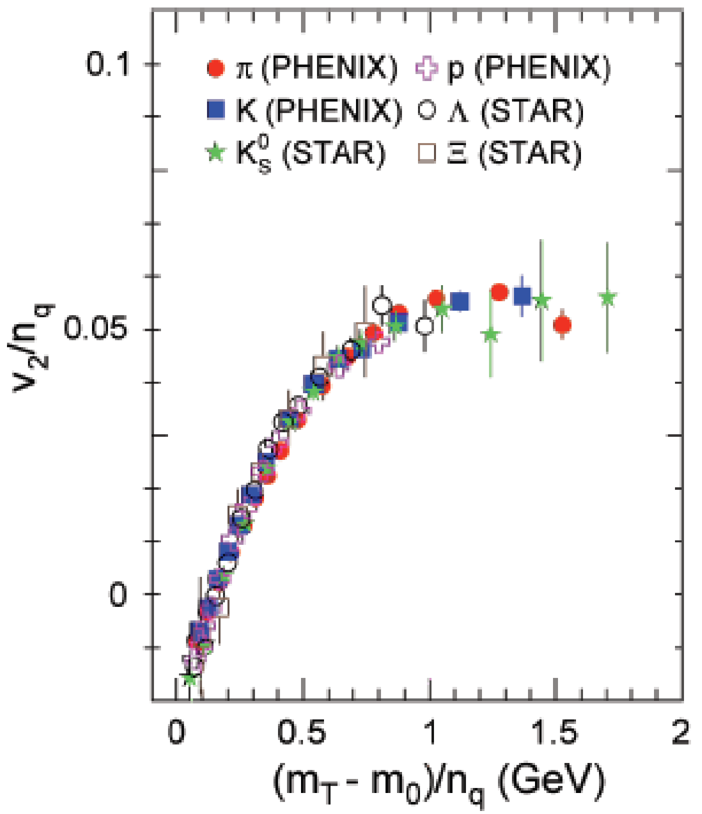


large v_2 (even Ξ, Ω): strong interactions at early stage

large v_2 of Ξ, Ω (low hadronic x-sections): partonic collectivity at RHIC.

Constituent quark scaling

$$m_T = \sqrt{p_T^2 + m_0^2}$$



The *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T\, d\phi} \propto 1 + 2\, v_2(p_T)\cos(2\phi)$$

is predicted to be *simple* at the quark level under

$p_T \rightarrow p_T/n$

$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)

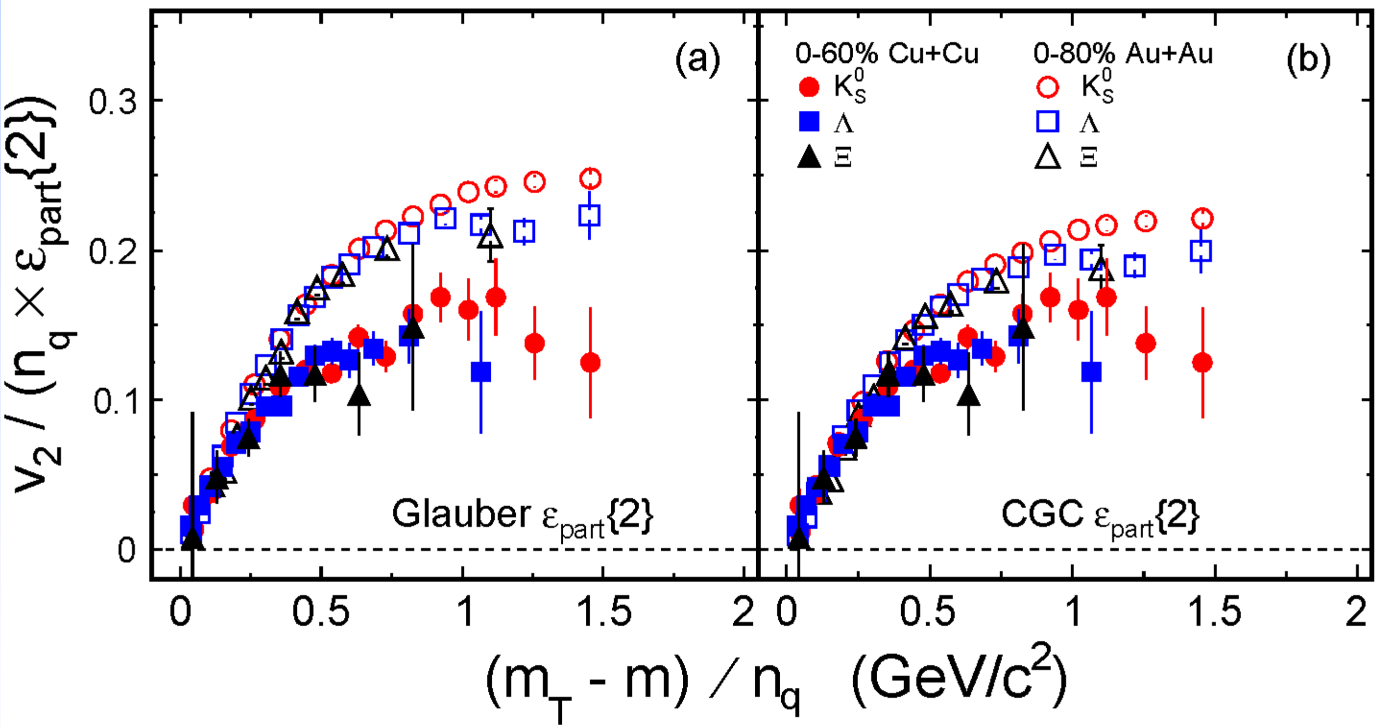
Works for p, (π), K^0_s, Λ, Ξ, Ω

Constituents of QGP are partons

v_2 - Cu-Cu vs Au-Au

Phys. Rev. C **81** (2010) 44902

Greater non-flow effects in Cu-Cu.



- Significantly smaller v_2 in Cu-Cu than in Au-Au for given centrality
- Scales with $v_2(N_{part})$
- Large non-flow effects at high p_T

Summary of what we learned at RHIC

- Energy density in the collision is way above that where hadrons can exist
- p-p reference measurements are well understood
- Large suppression of high pT hadrons
- Away side jets are suppressed
- Cold nuclear matter effects on jets are small
- The medium has quark and gluon degrees of freedom in initial stages
- The QGP is flowing like an almost "perfect" liquid

We have created new state of matter at RHIC the QGP

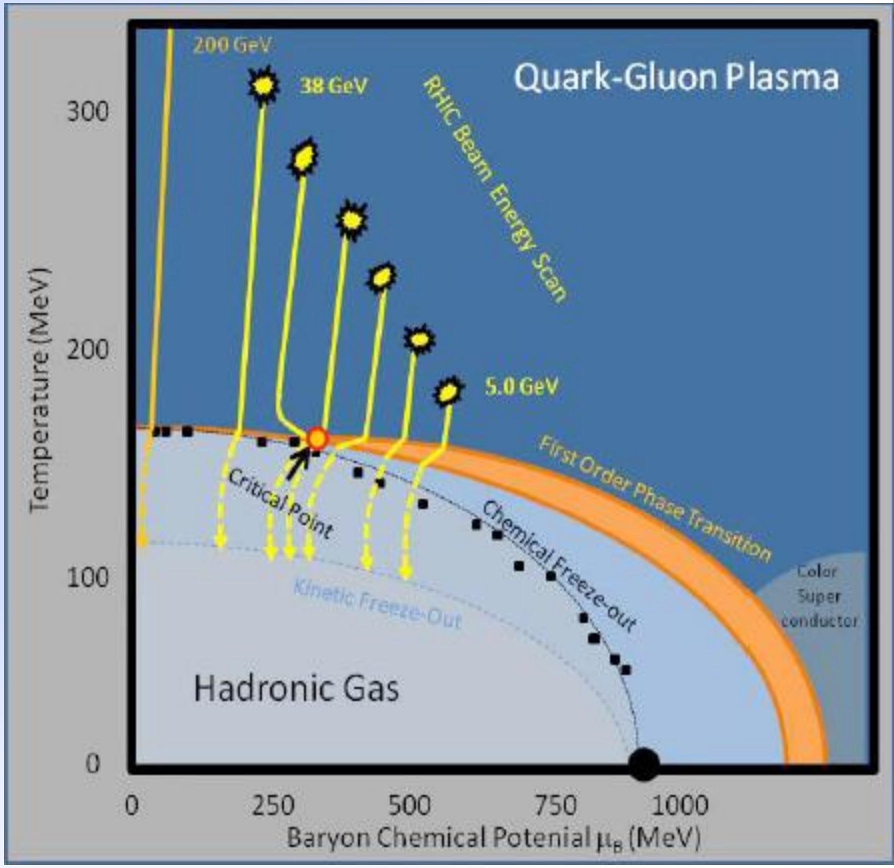
High pT results can be explained as due to significant partonic energy loss in the QGP before fragmentation

Main themes of the STAR Beam Energy Scan:

•Search for turn-off of major sQGP signatures already established at top RHIC energies

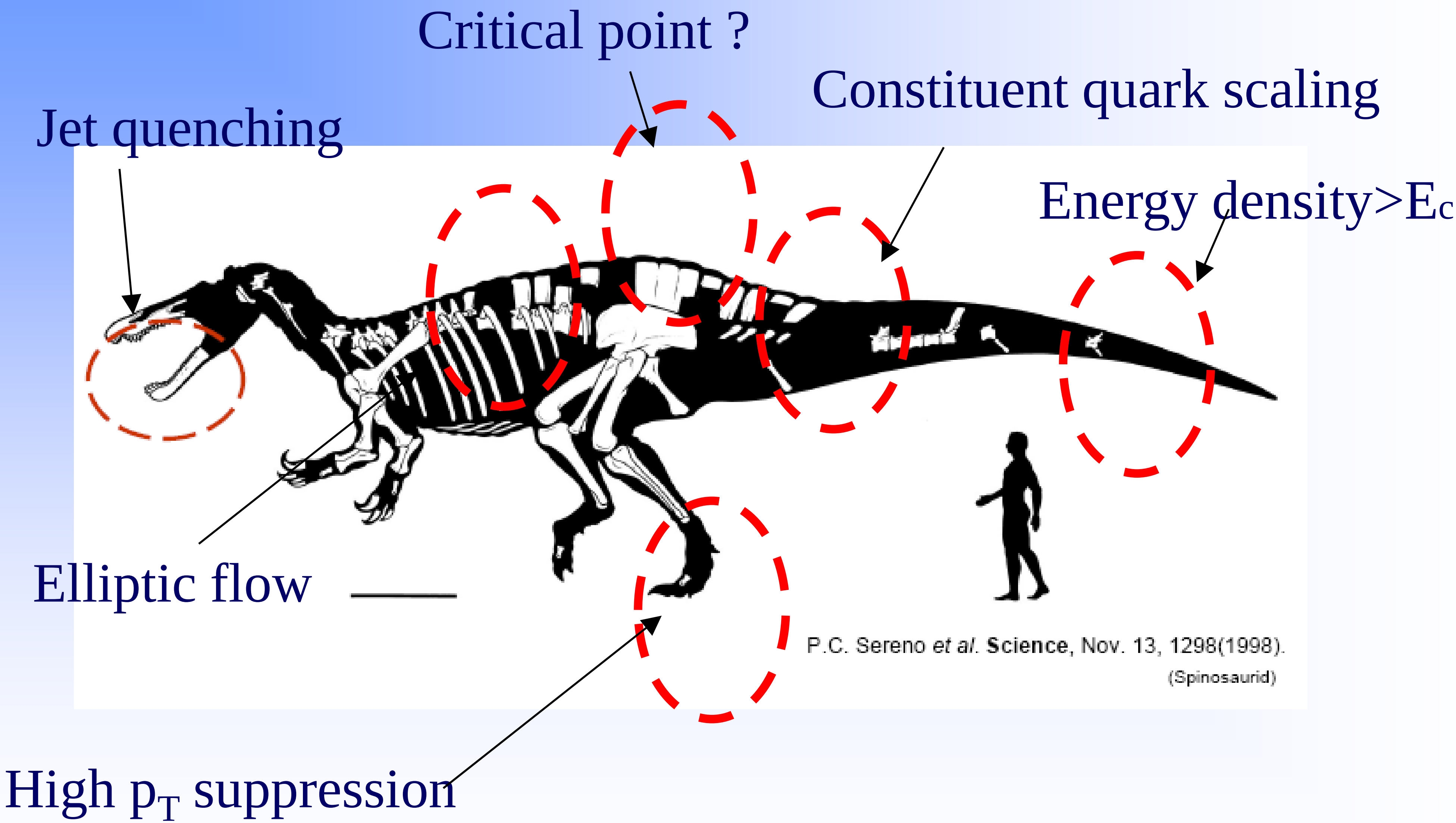
•Search for first order phase transition signatures

•Search for evidence of critical point



The search for the QCD Critical Point is a "must do" experiment
- BNL PAC recommendation, May 2008

We will never see the whole body



Heavy ions at the LHC

What are the initial conditions

Is gluon saturation seen?

Is $v_{2LHC} < v_{2RHIC}$?

Time evolution of the medium

Is QGP still strongly coupled?

Behaving like a perfect liquid or more gas like?

Energy loss similar to at RHIC?

What is mass/flavor dependence of the Eloss?

Heavy flavor copiously produced at RHIC?

RHICs higher luminosity and longer running time keep it competitive

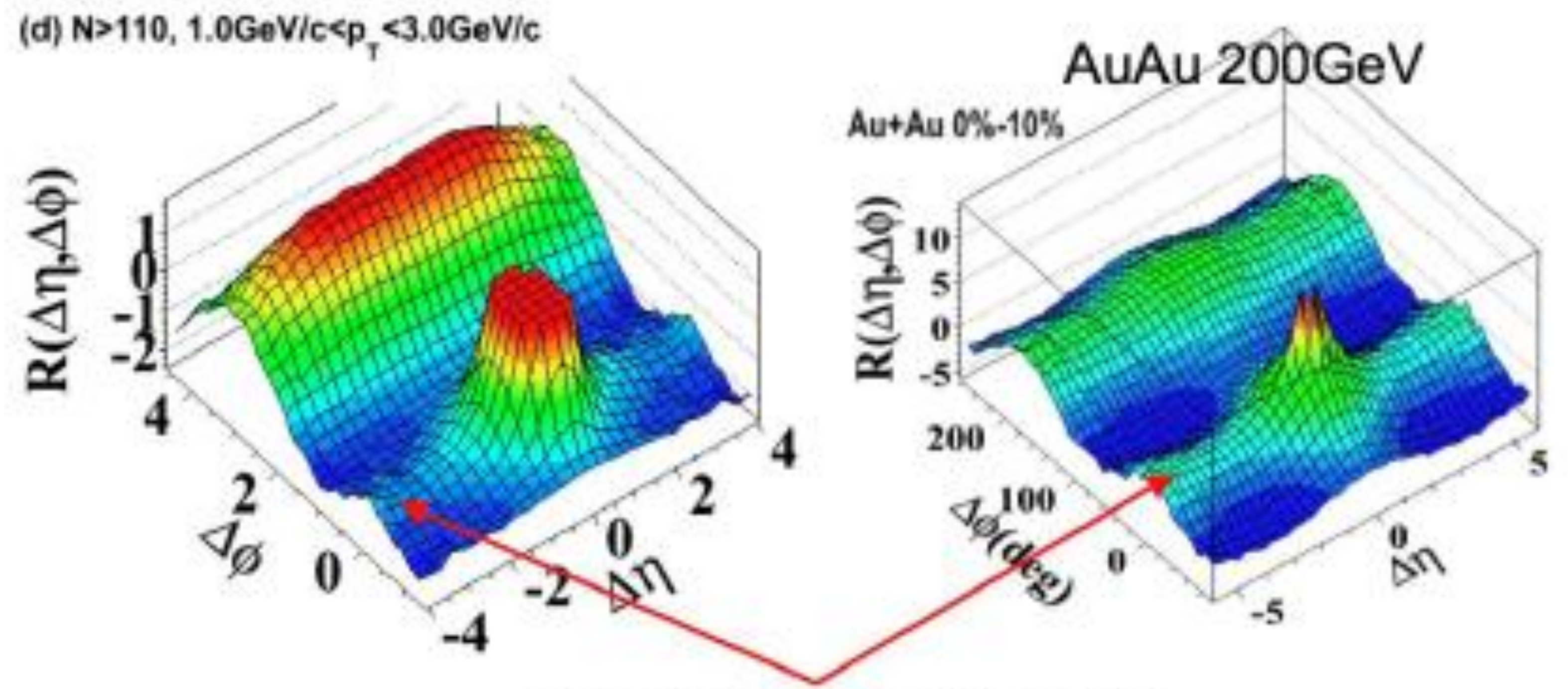
The expectation:

LHC plasma hotter, denser, longer lived

Thank you !

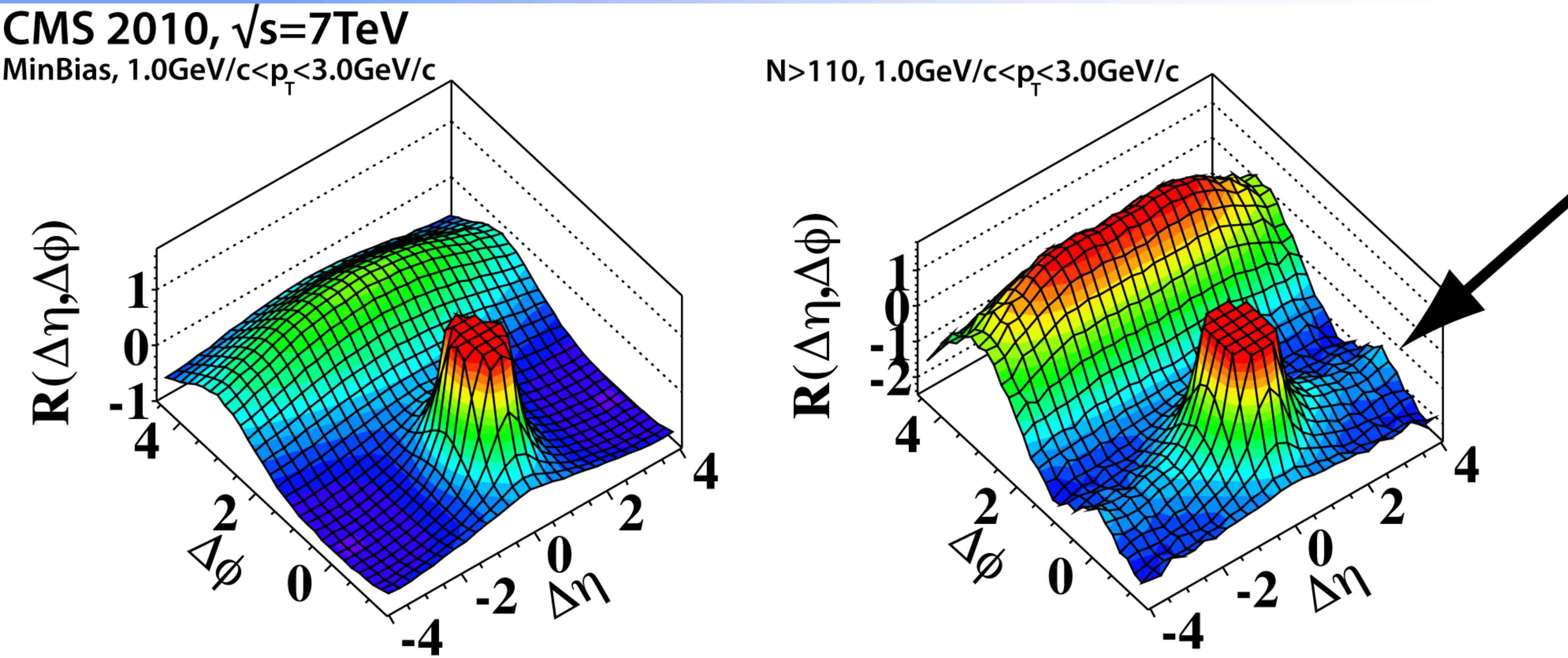
With the LHC and RHIC programs running in parallel the 2010's promise an exciting decade for Relativistic Heavy-Ion Collision Research

Backup –recent CMS results compared to AuAu



Similar "ridge" in high multiplicity pp
(even similar p_T dependence)

Recent CMS p+p results



STAR's beam energy scan RUN10

E_{CM}	System	Centrality	Statistics
39 GeV	Au+Au	min. bias	169M
11,5 GeV	Au+Au	min. bias	≥ 7,5M
7,7 GeV	Au+Au	min. bias	5M

Energy density in central Au-Au collisions

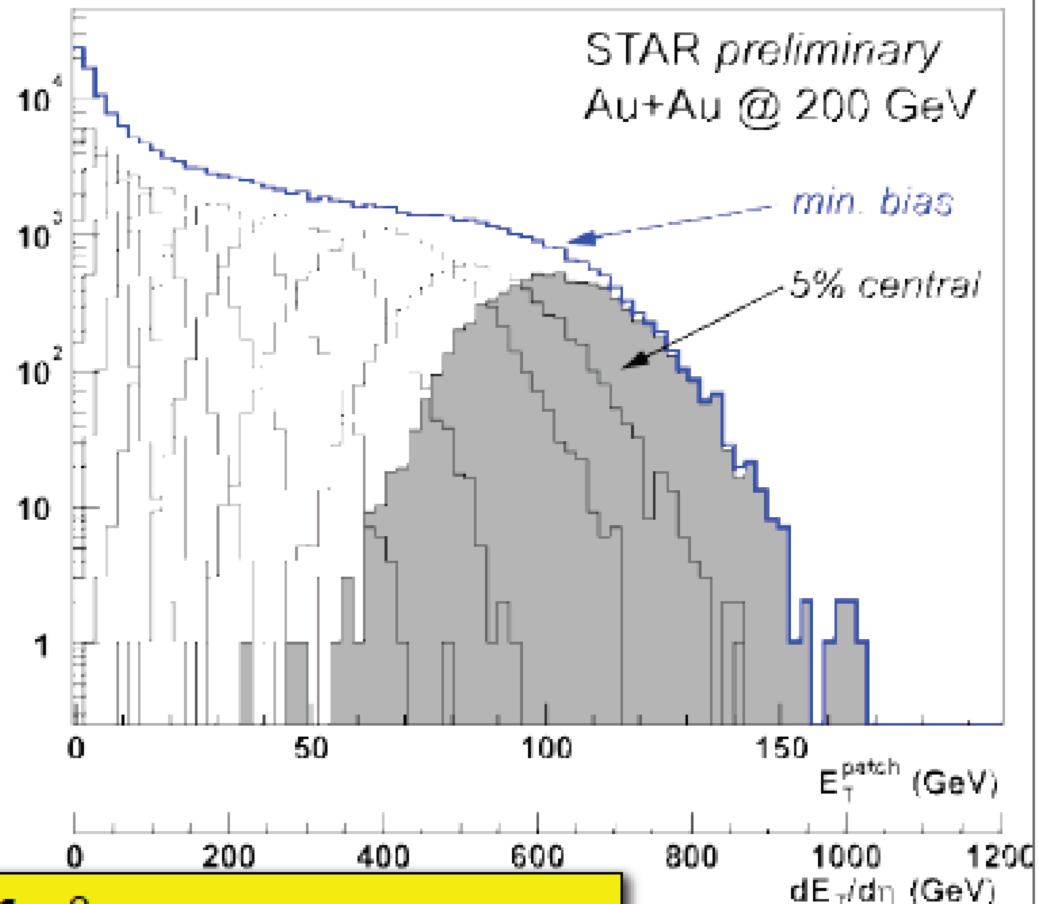
- use calorimeters to measure total energy
- estimate volume of collision

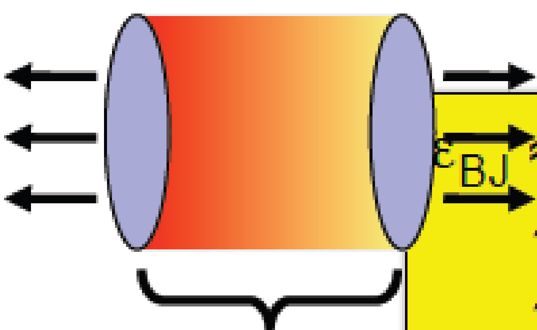
Bjorken-Formula for Energy Density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system ($t_0 \sim$ 1 fm/c)





$$dz = \tau_0 dy$$

$\varepsilon_{BJ} \approx$ 5.0 GeV/fm^3

~30 times normal nuclear density

~ 5 times > $\varepsilon_{critical}$ (lattice QCD)