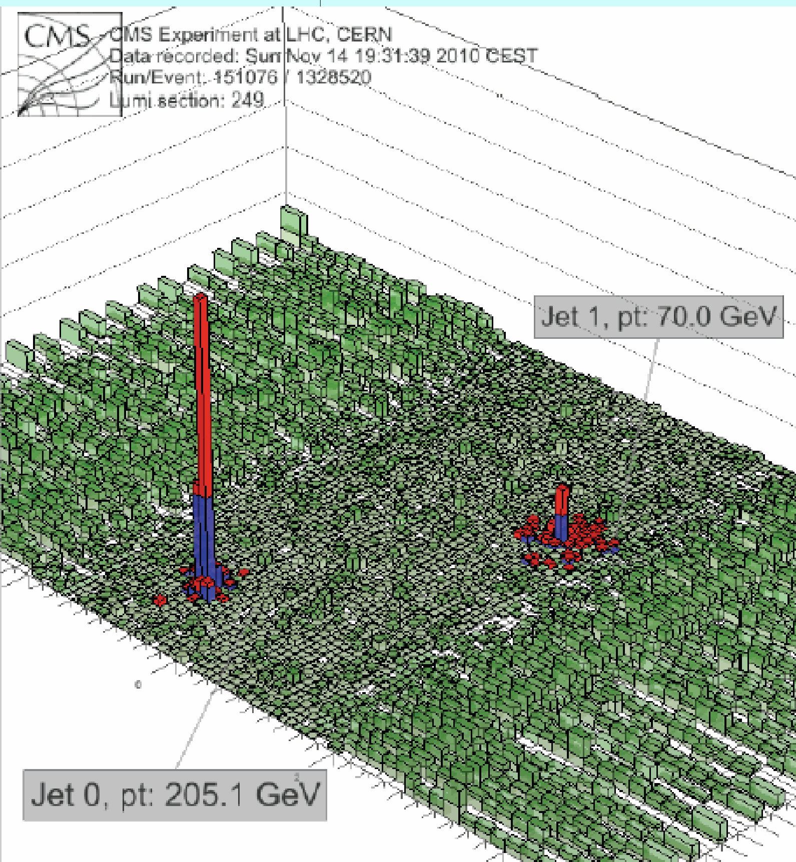
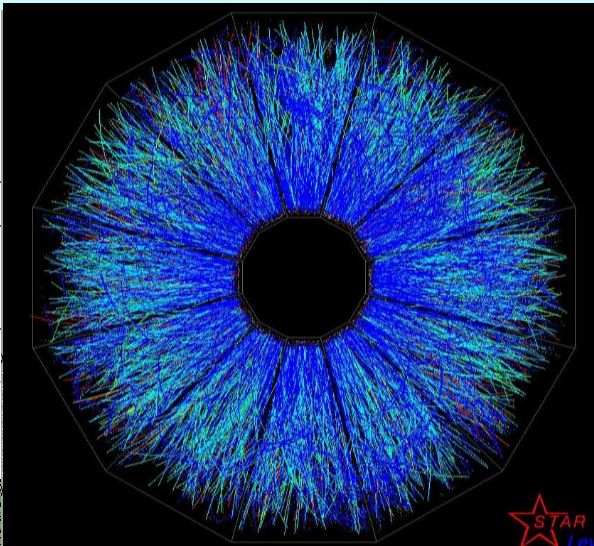
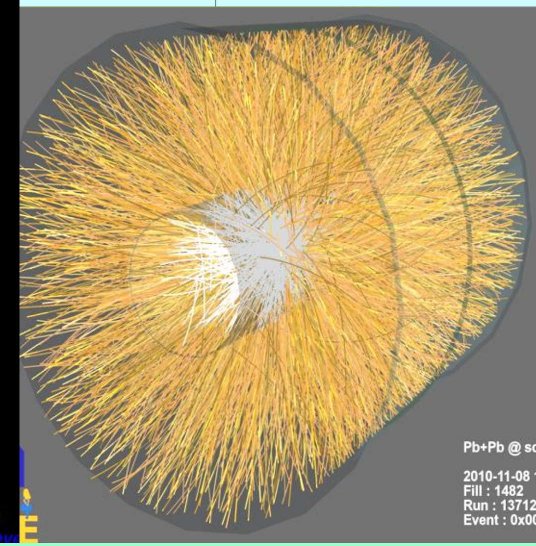
Report From the High Temperature Frontier







Barbara Jacak
Stony Brook University
August 10, 2011

Division of Particles and Fields of the American Physical Society
Brown University
August 8-13, 2011

What are the properties of hot QCD matter?

- **thermodynamic (equilibrium)**

  T, P, ρ

  Equation Of State (relation btwn T, P, V, energy density)

  v_{sound}, static screening length

- **transport properties (non-equilibrium)***

  particle number, energy, momentum, charge

  diffusion *sound* *viscosity* *conductivity*

In plasma: interactions among charges of multiple particles

charge is spread, screened in characteristic (Debye) length, λ_D

also the case for strong, rather than EM force

***measuring these is new for nuclear/particle physics!**

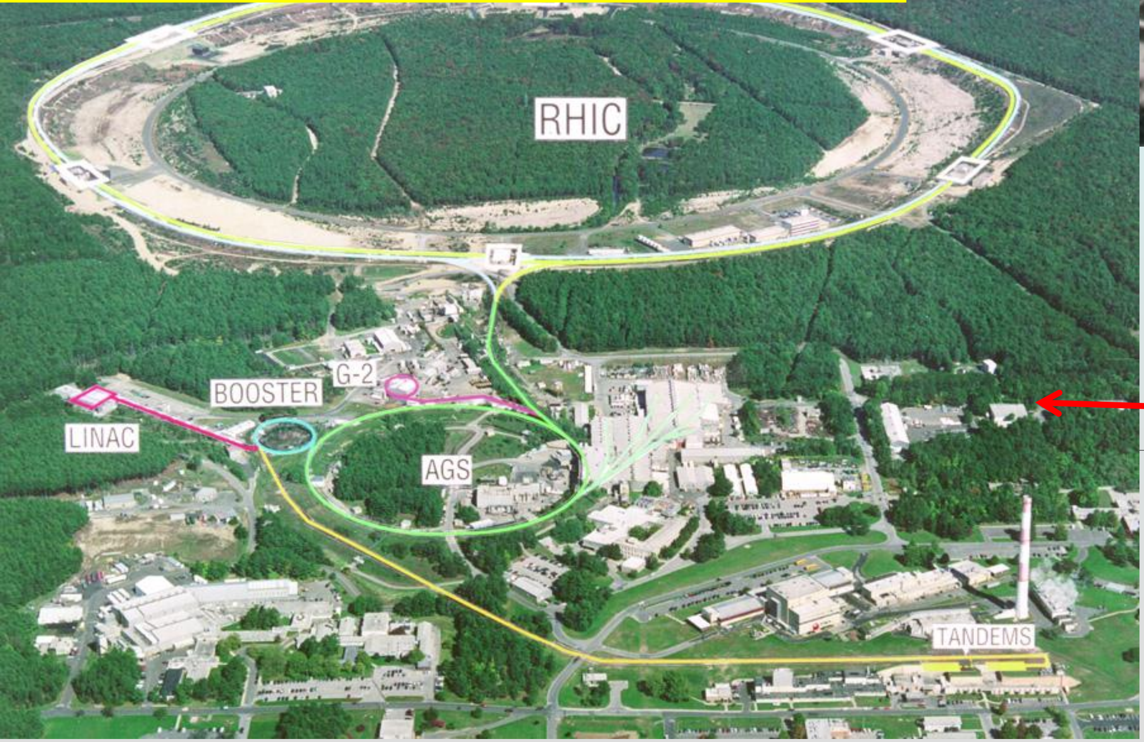
Nature is nasty to us: does a time integral…

Heat nuclei at both RHIC and LHC

Compare to:
p+p – no medium
p/d+A – cold nuclear matter effects

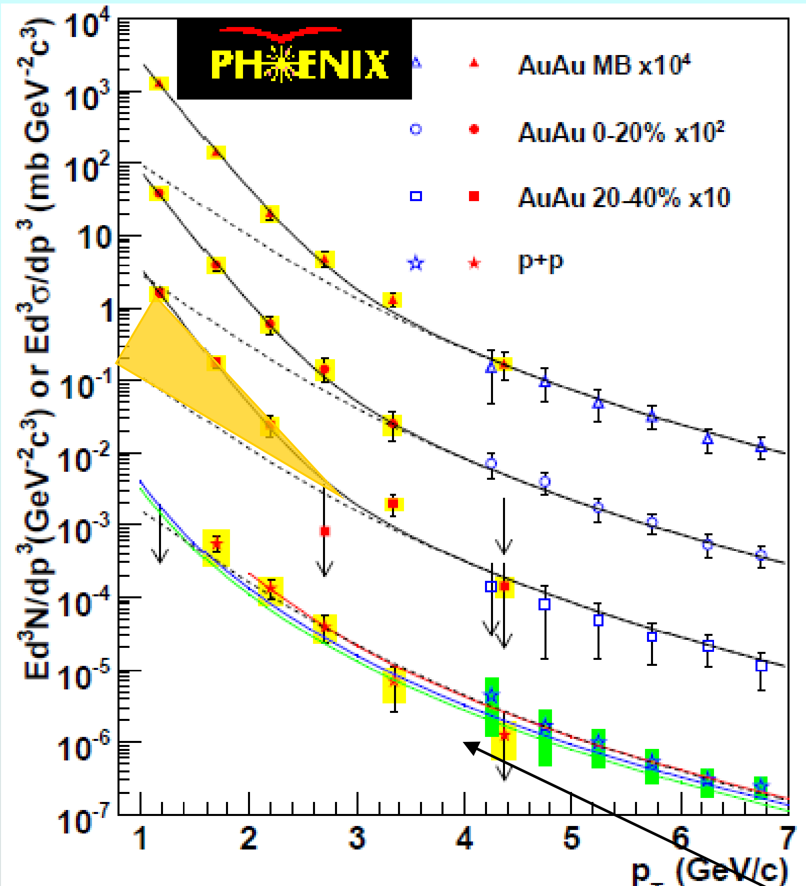
Pb+Pb at 2.76 TeV per NN

Au+Au at 200 GeV per NN

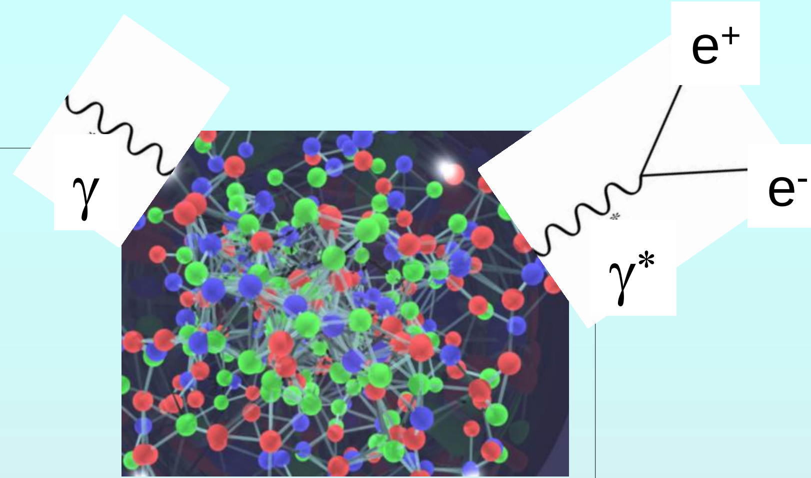


5 active experiments:
STAR, PHENIX
ALICE, ATLAS, CMS

Temperature reached? thermal radiation



PRL104, 132301 2010



Low mass, high p_T e^+e^- →

nearly real photons

Large enhancement above

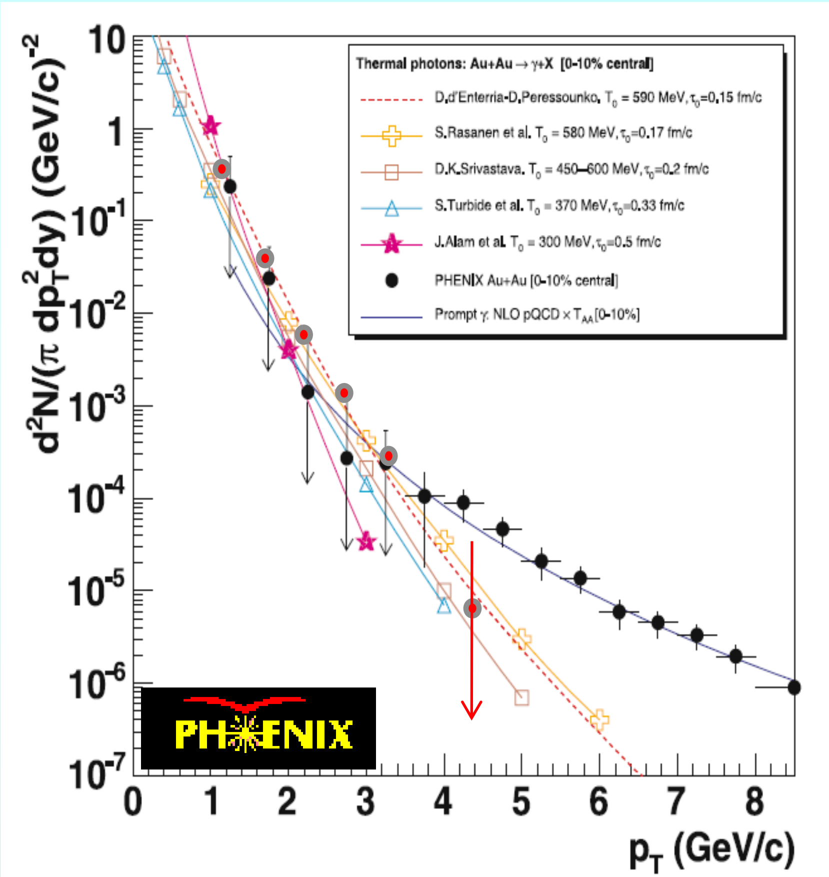
p+p in the thermal region

pQCD γ spectrum

(QCD Compton scattering)

agrees with p+p data

direct photons: $T_{init} > T_c$!



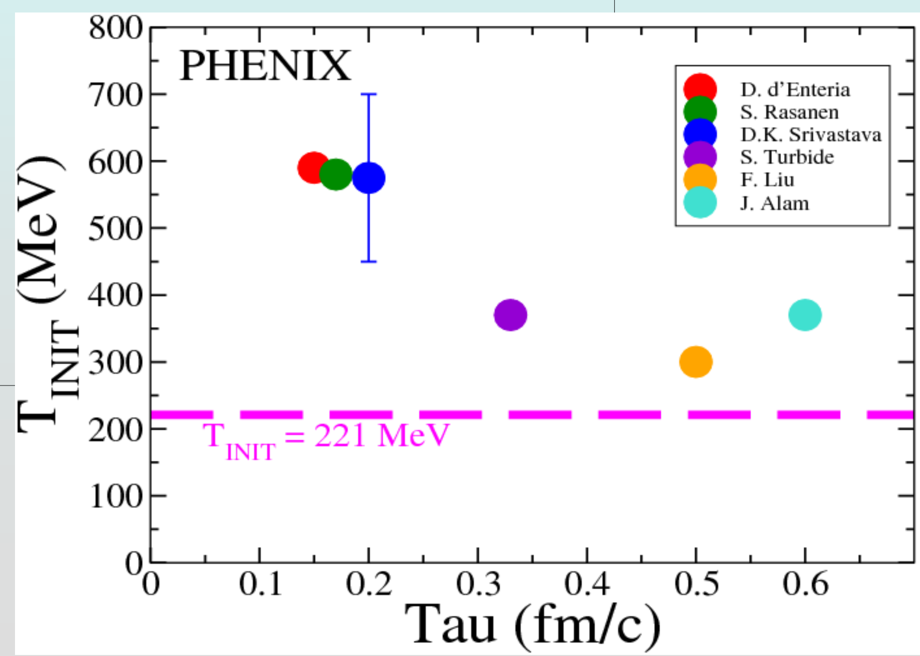
- **Exponential fit in p_T:**

T_{avg} = 221 ±23 ±18 MeV

- **Hydrodynamics models reproduce data (different τ_0)**

$T_{init} \geq 300$ MeV

> 4 trillion degrees!

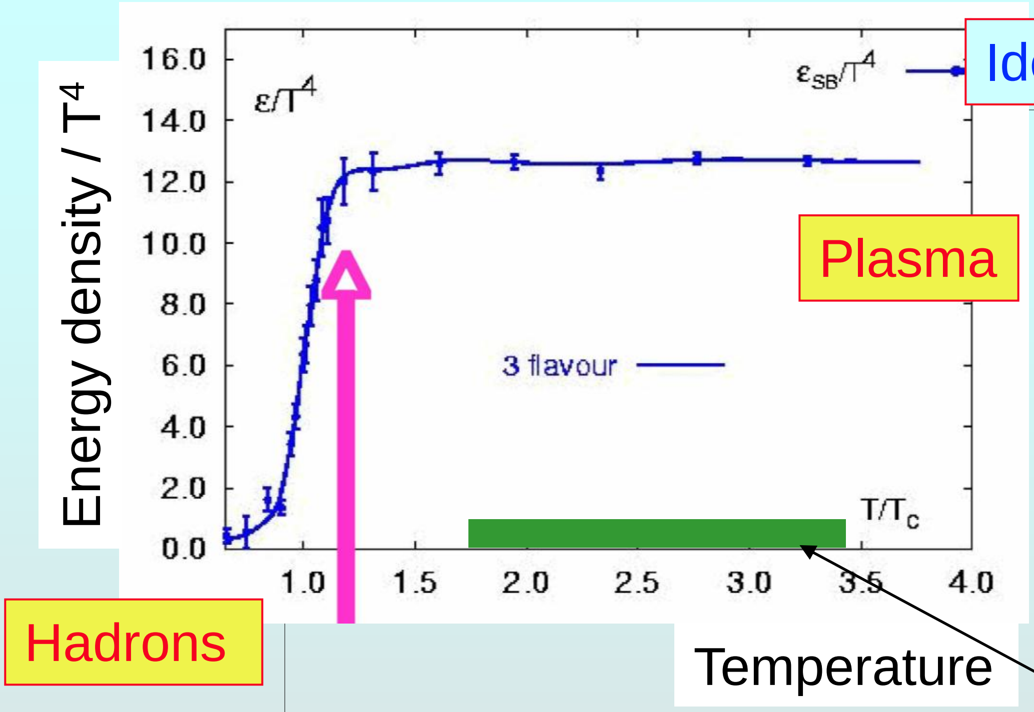


NB: T_c ~ 170 MeV

T_{init} at LHC ~ 30% higher

(by more indirect measures)

Now we are on the map



T_c ~ 170 ± 10 MeV

ε ~ 3 GeV/fm^3

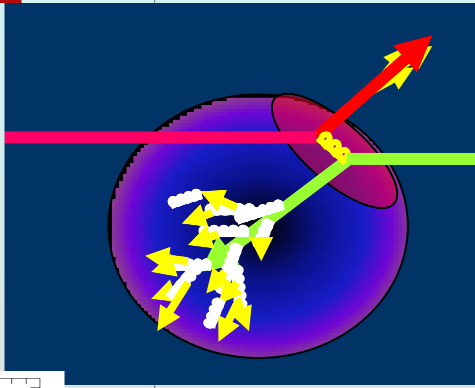
RHIC puts us here … what have we learned about QGP?

QCD matter at T =300-600 MeV (at RHIC)

- Collective flow with low viscosity/ entropy ratio: *"perfect liquid"*
  How low? Strong coupling…

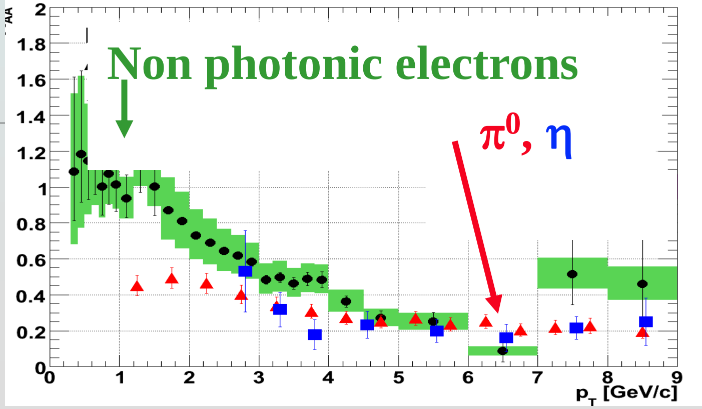
Example of the viscosity of milk. Liquids with higher viscosities will not make such a splash when poured at the same velocity.

- Opacity very high
  Plasma ~ stops quarks & gluons
  How and why? Strong coupling…



- Even heavy quarks lose energy & flow
  Not expected from pQCD; mechanism?
  -> strong coupling
  High mass scatterers?

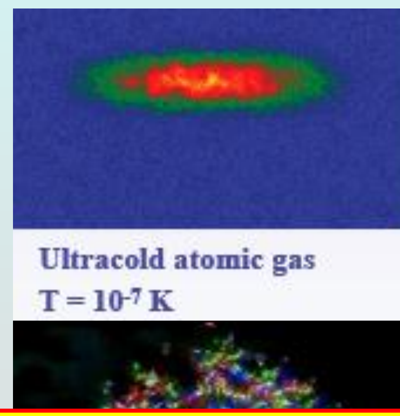
- J/ψ suppression indicates color screening
  How much?



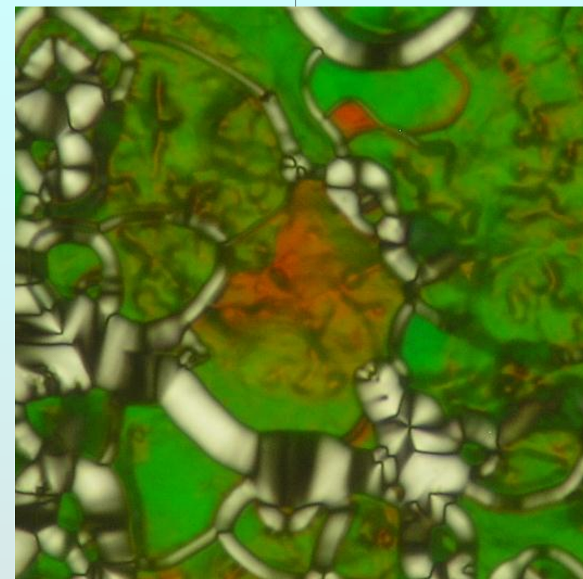
Strong coupling: forefront issue in other fields!

Quark gluon plasma is like other systems with **STRONG COUPLING**
– all exhibit liquid properties & phase transitions

Cold atoms: coldest & hottest matter on earth are alike!



Dusty plasmas & warm, dense plasmas have liquid and even crystalline phases



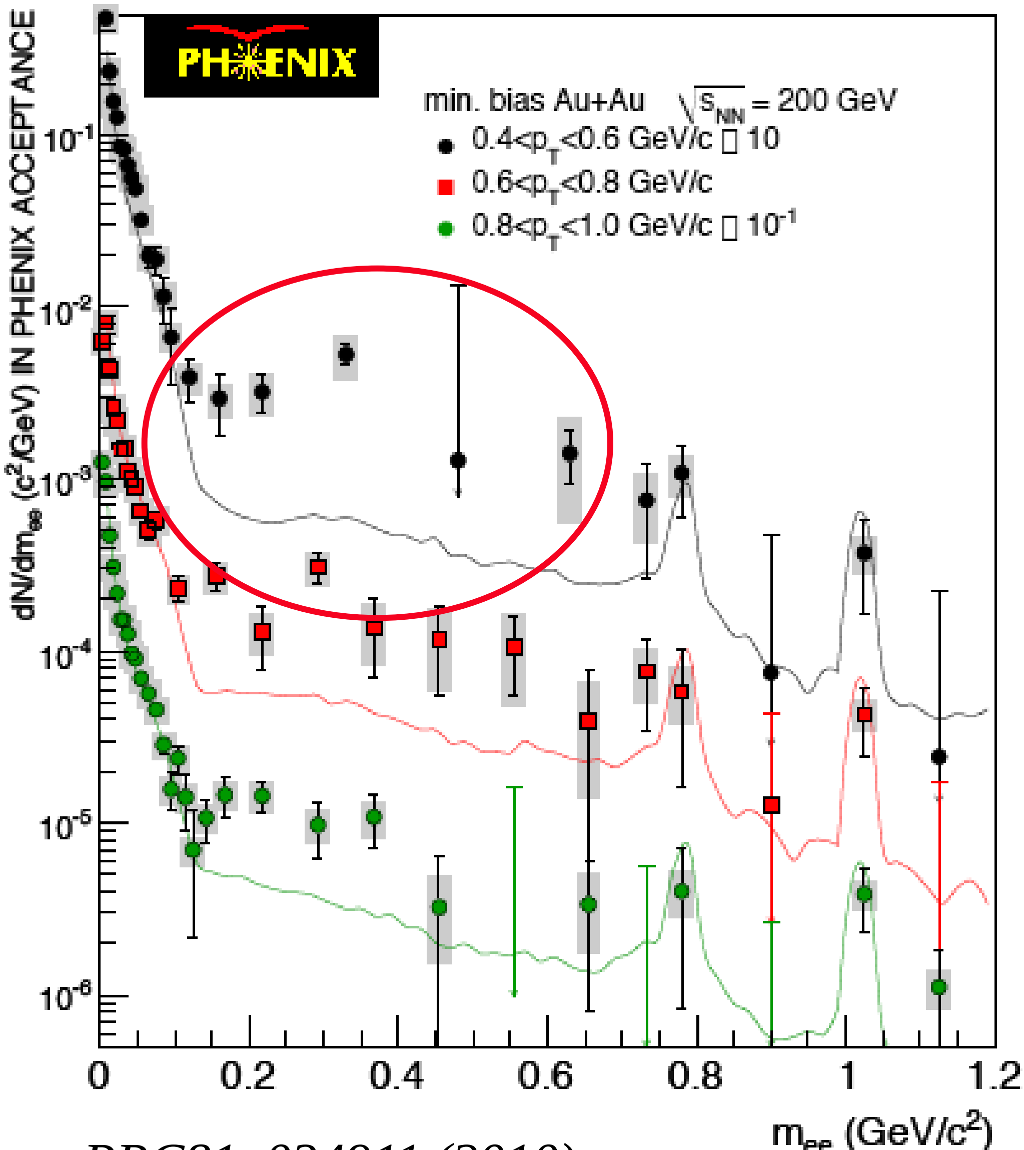
Strongly correlated condensed matter:

In all these cases have a competition:

Attractive forces ⇔ repulsive force or kinetic energy

Result: many-body interactions; quasiparticles exist?

e^+e^- excess at low mass, low p_T



PRC81, 034911 (2010)

Excess at

M_{ee} < 2-3 T_c

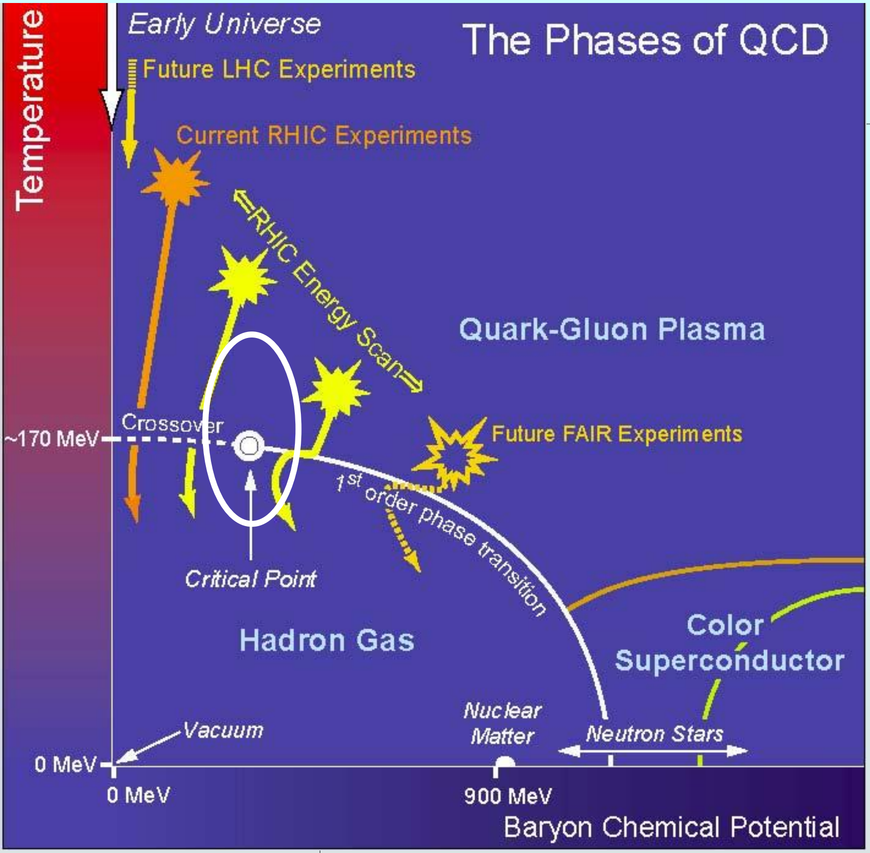
Non-perturbative radiation (lQCD)?

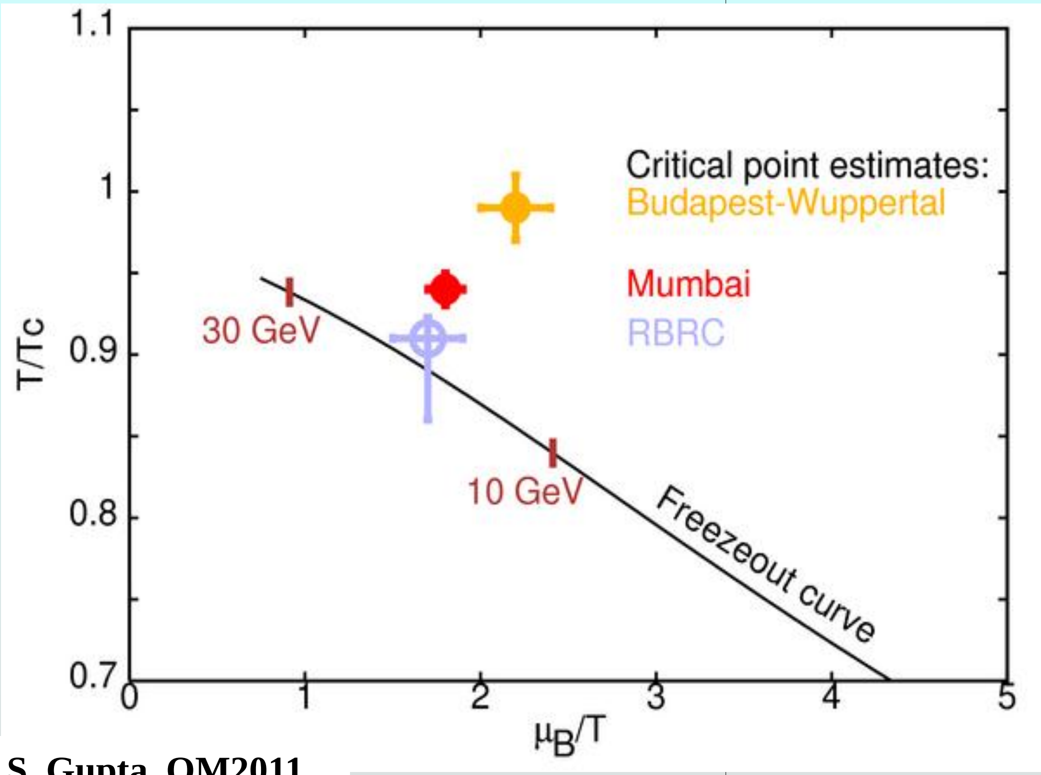
Rate boosted by correlations in medium?

Pre-equilibrium emission?

NEW RESULTS FROM HEAVY ION COLLISIONS AT RHIC AND THE LHC

Critical point search: low energy Au+Au @ RHIC



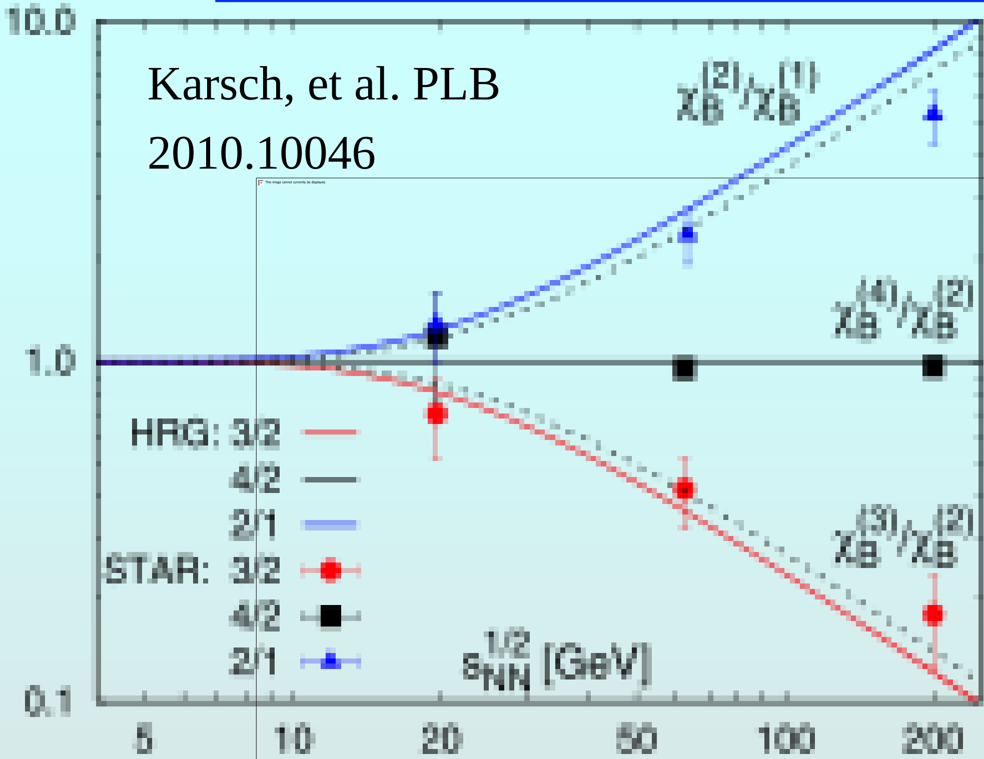


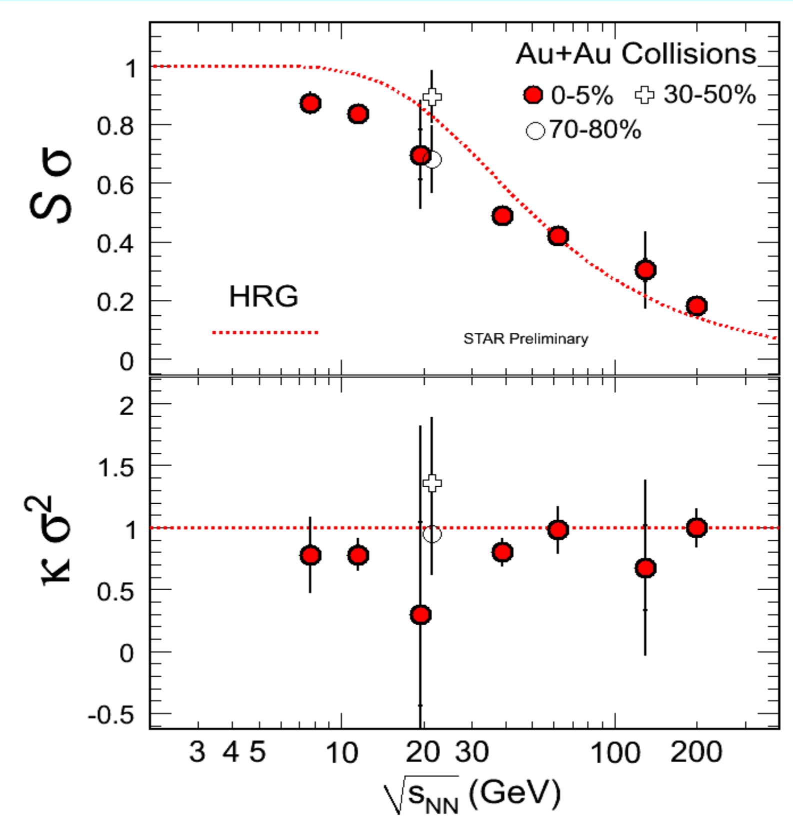
S. Gupta, QM2011

Tools:

Fluctuations, partonic collective flows

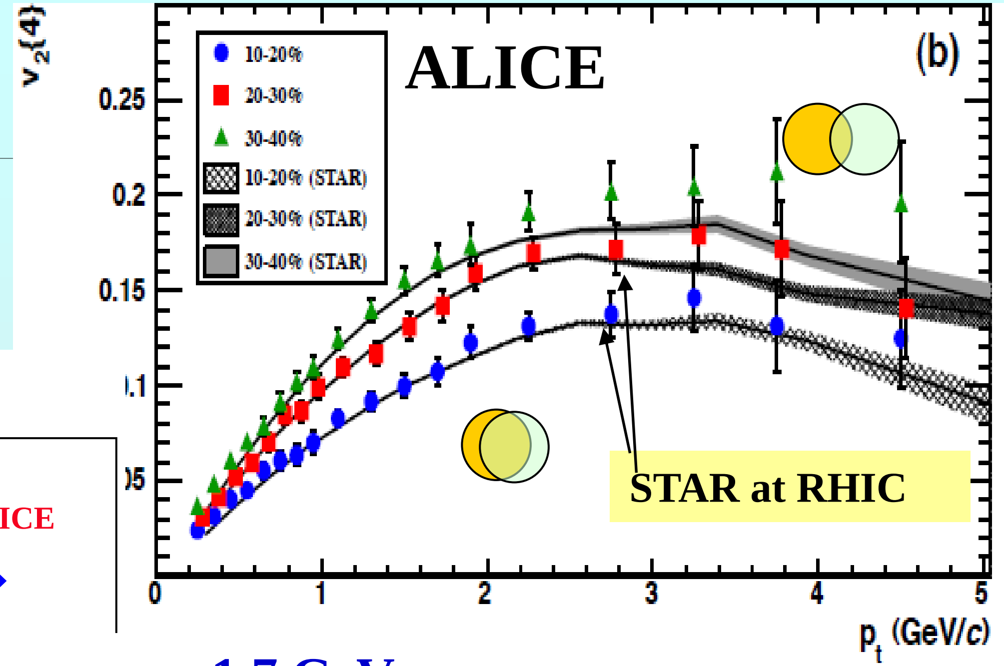
Fluctuations as Critical Point Signature

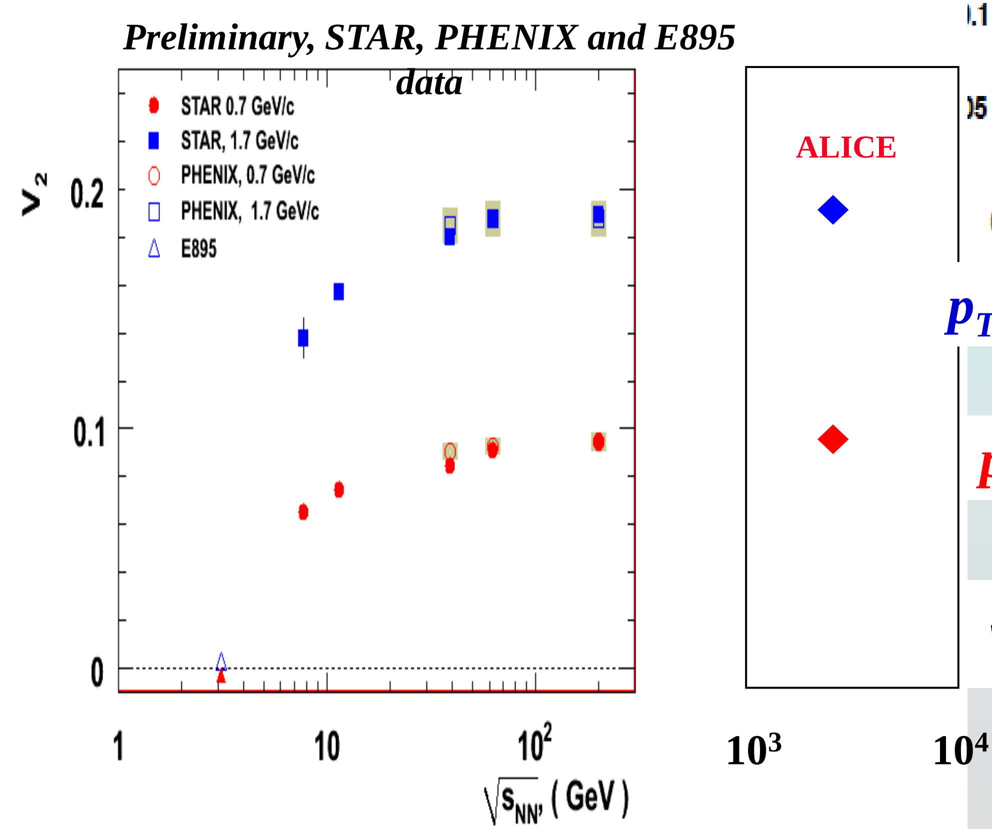




- Event-by-event net-baryon fluctuation ratios from STAR are so far consistent with the Hadron Resonance Gas
- Hadron freezeout not (yet) near critical point
- Calculations of higher moments from LQCD deviate from HRG calculations and may provide conclusive evidence for critical point if observed in data

Pb+Pb at LHC → similar flow as at RHIC





p_T = 1.7 GeV

p_T = 0.7 GeV

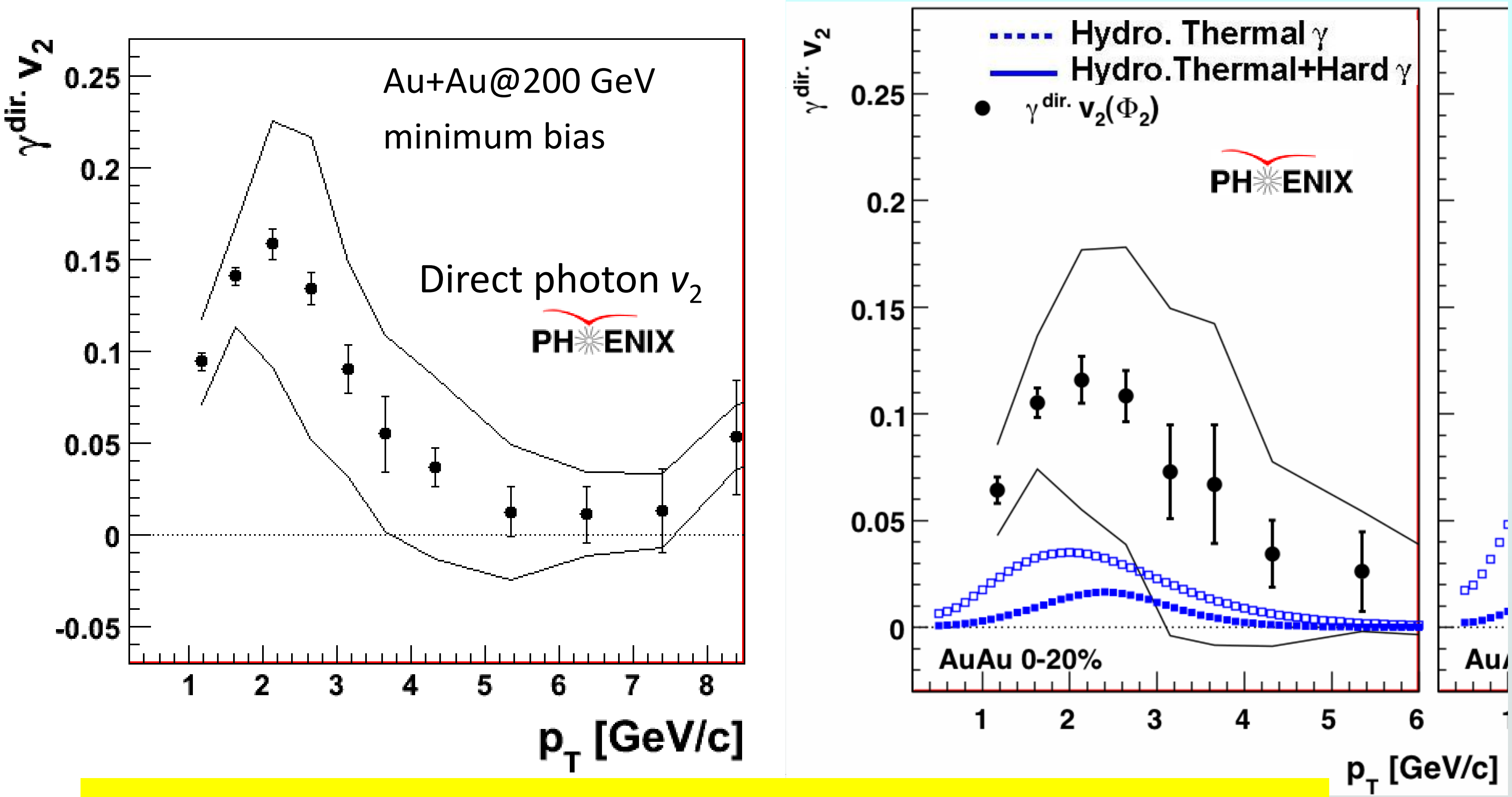
v_2 saturates @ $\lesssim$ 39 GeV

@ LHC T_{init} ~30% higher

η/s(t) sampled differently

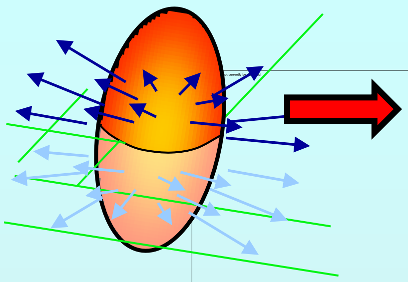
Thermal photons also flow!

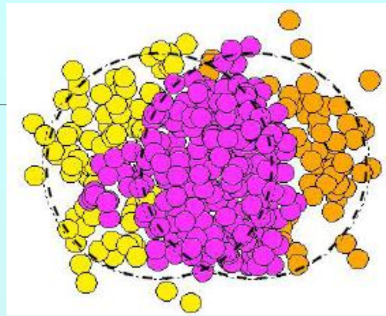
arXiv:1105.4126

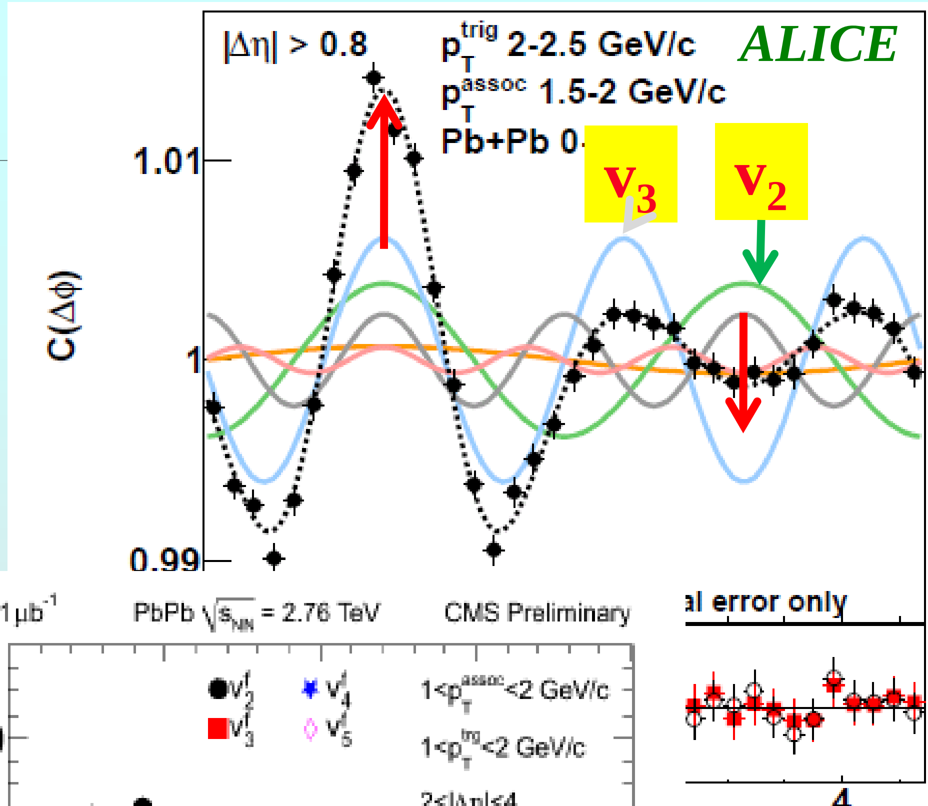


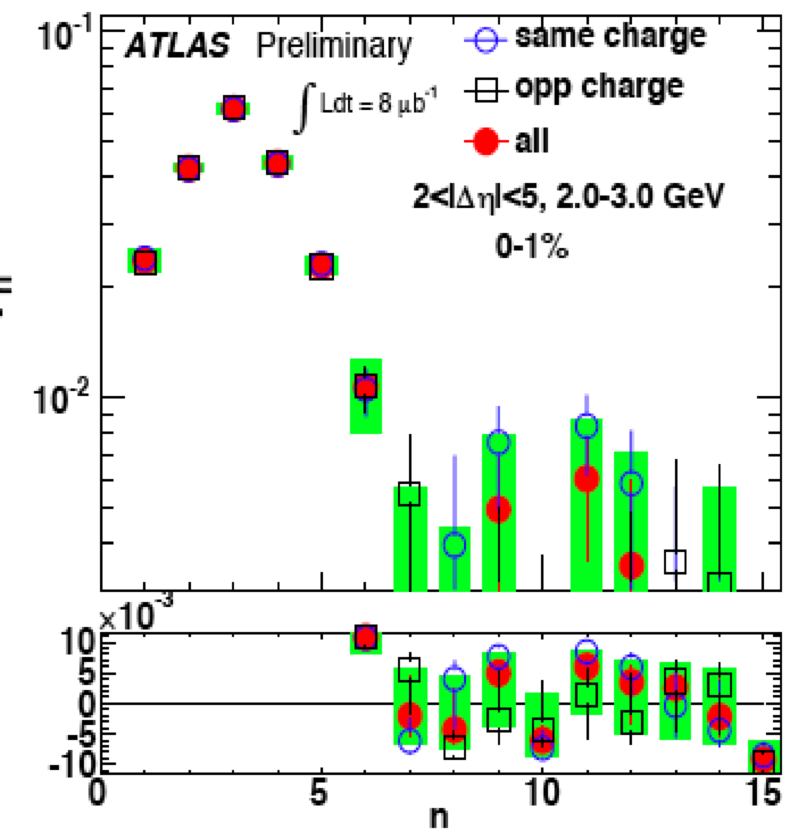
Flow magnitude is surprising. Can "extras" explain it?

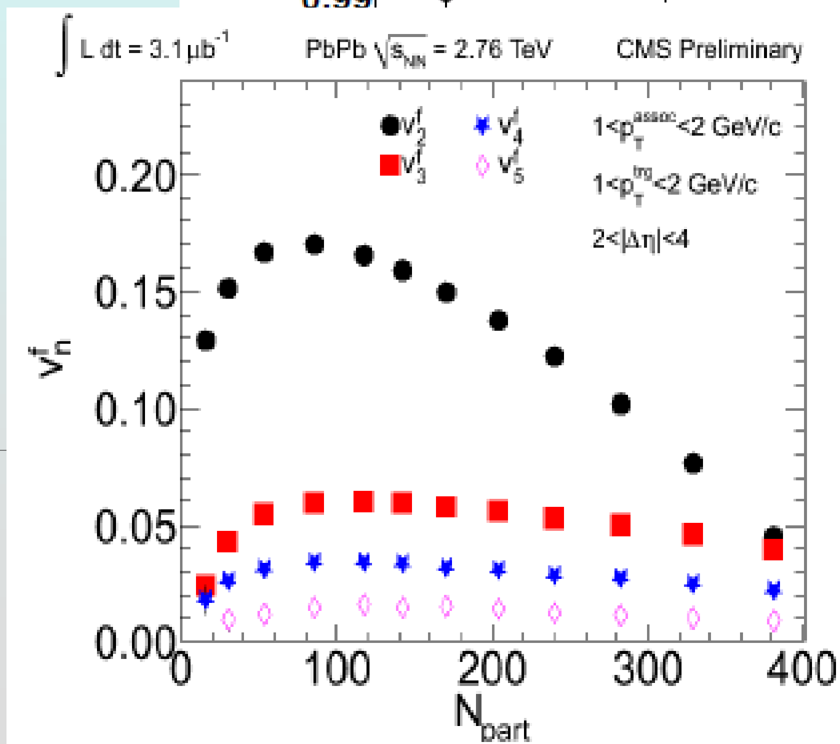
Initial nucleon positions fluctuate (& flow)











Perfect liquid? What's the viscosity of QGP?

- Use hydro with lattice EOS
- Set initial energy density to reproduce observed particle multiplicity
- Use various values of η/s

  Quantum mechanical lower bound is $1/4\pi$

  determined with help from AdS/CFT
- Constrain with data

  (Account for hadronic state viscous effects with a hadron cascade afterburner)

Fluctuations, flow and the quest for η/s

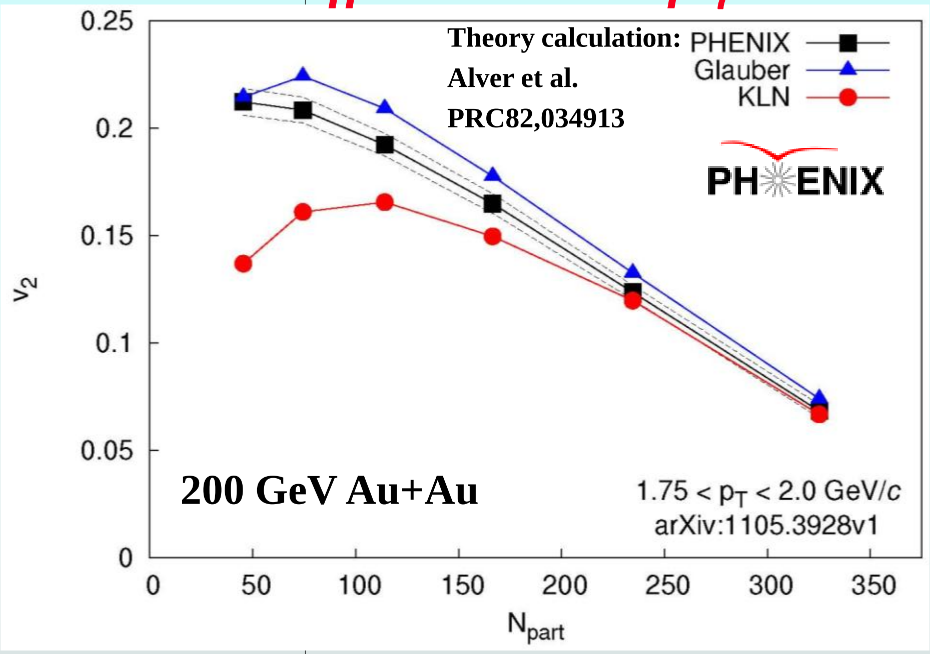
arXiv:1105.3928

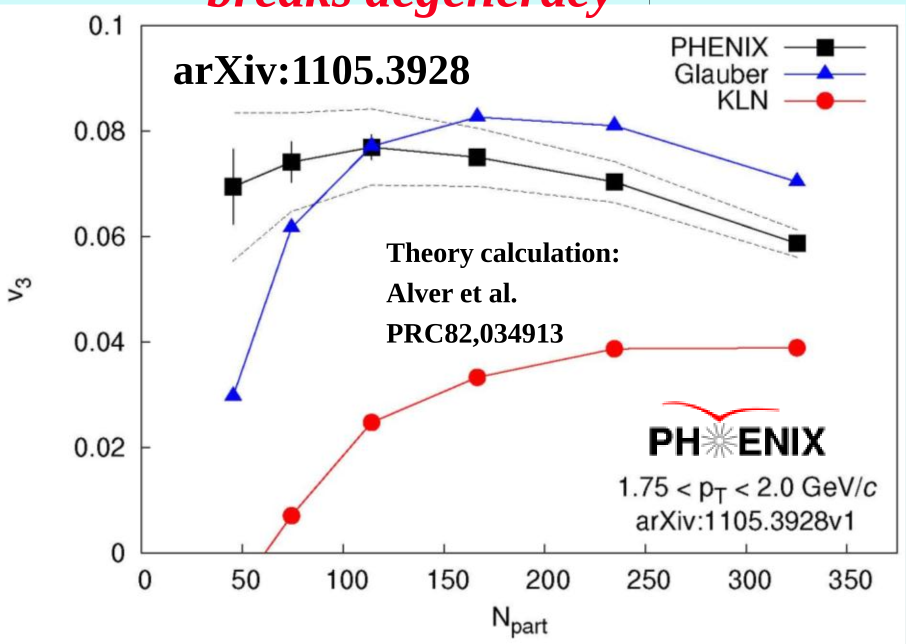
v_2 described by both Glauber and CGC

but different values of η/s

v_3 described only by Glauber

breaks degeneracy





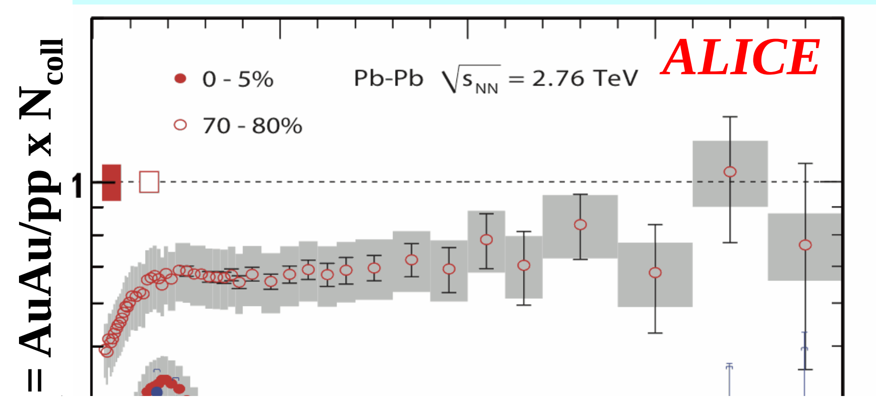
Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

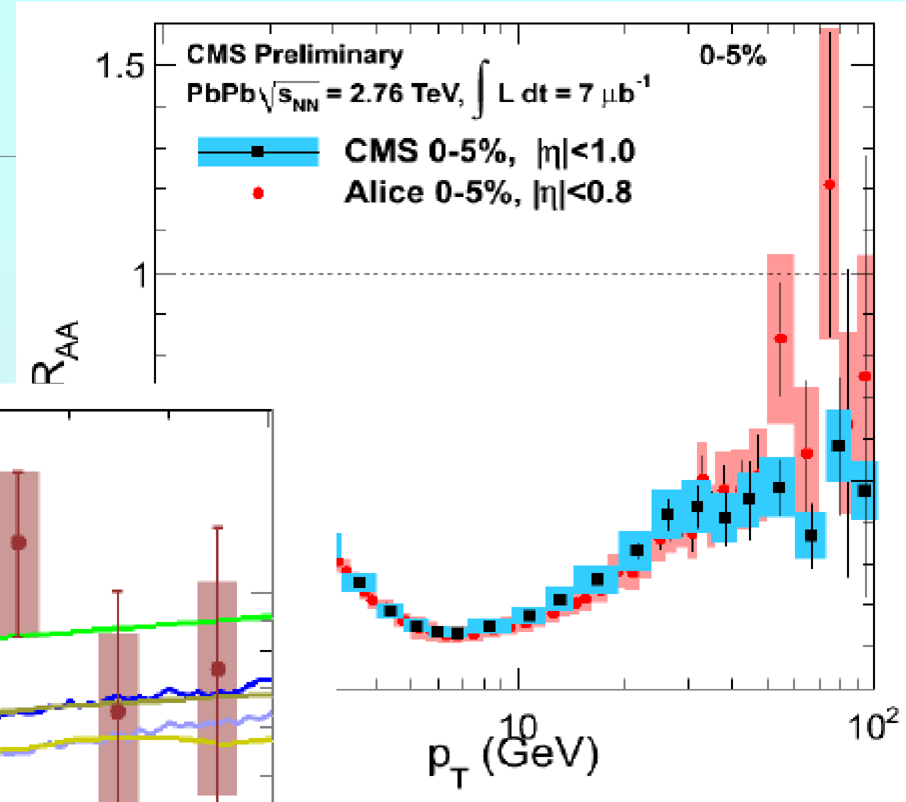
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

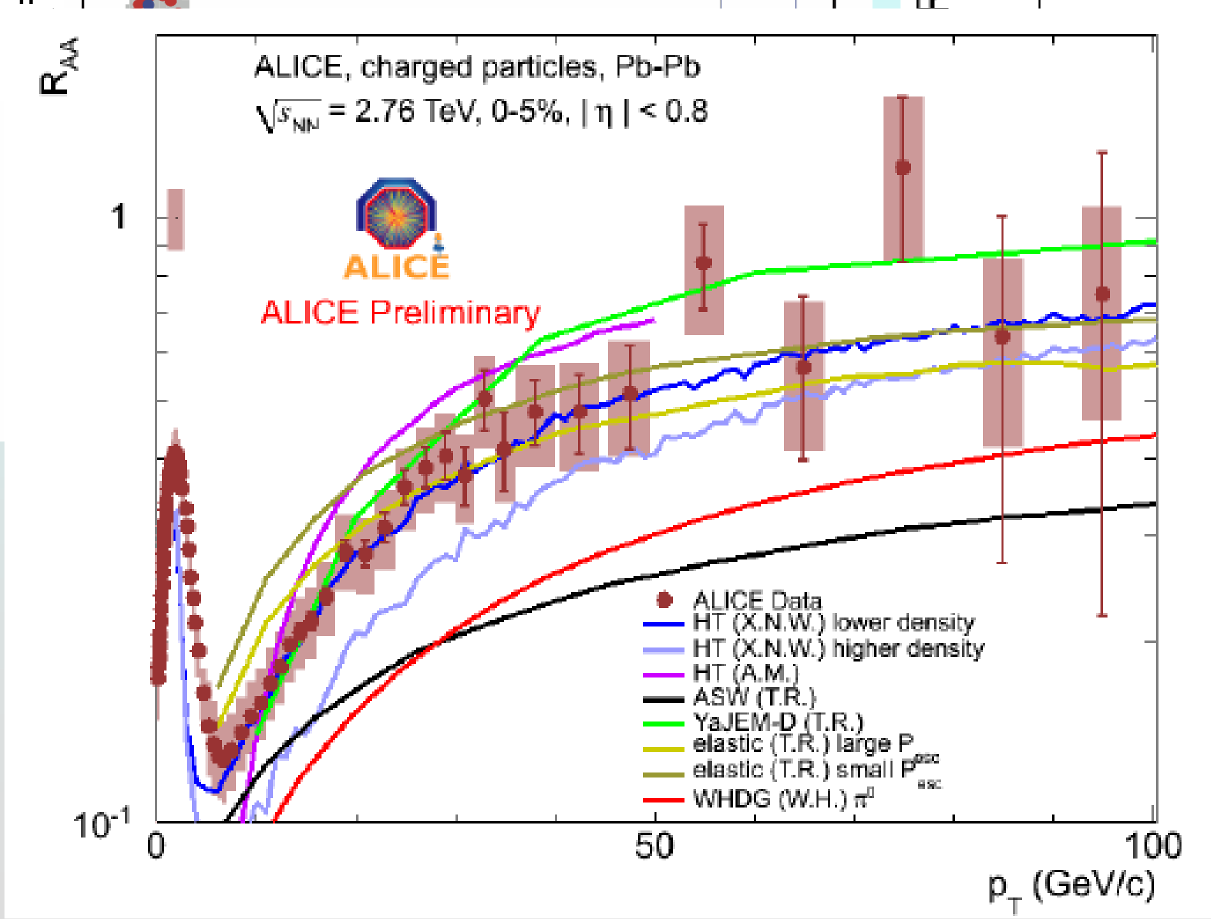
2 models with
Different fluctuations,
Eccentricity, ρ distribution

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

Energy loss in QGP



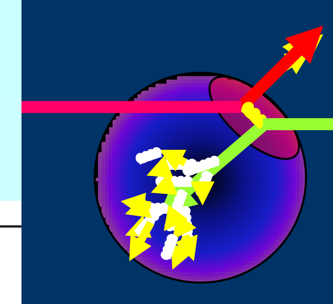


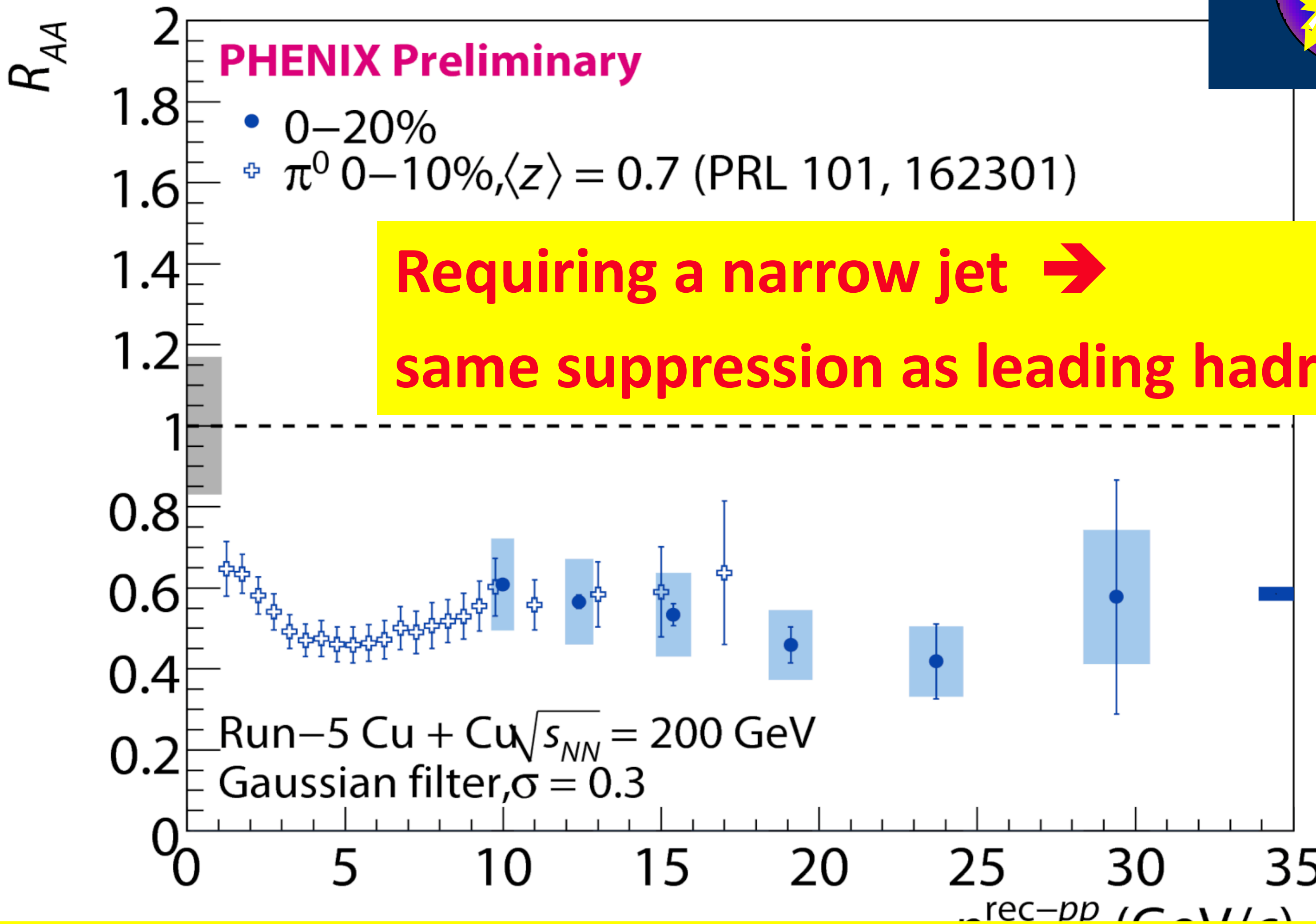


- pronounced p_T dependence of R_{AA} at LHC

→ sensitivity to details of the energy loss distribution

Reconstruct jets in heavy ion collisions

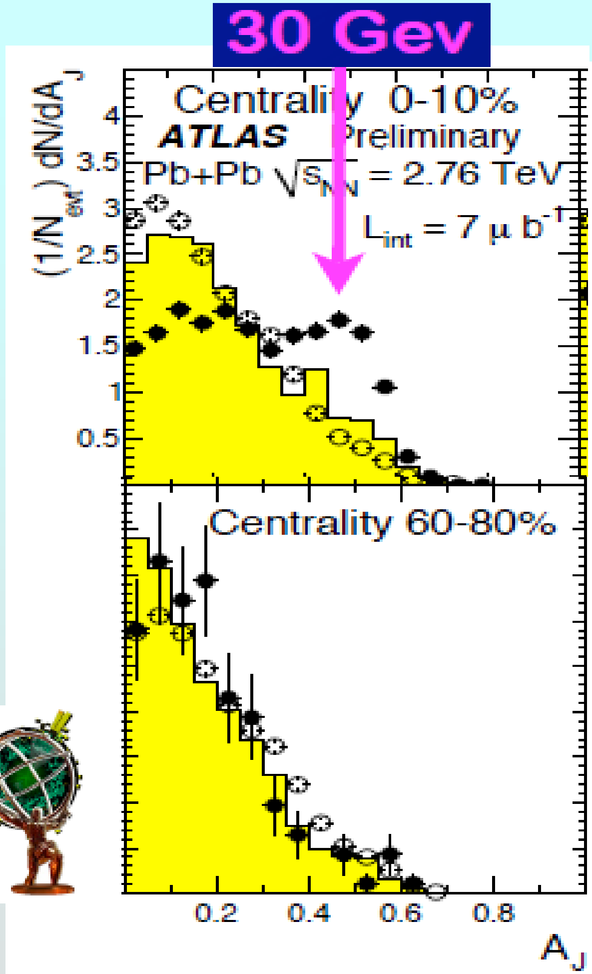


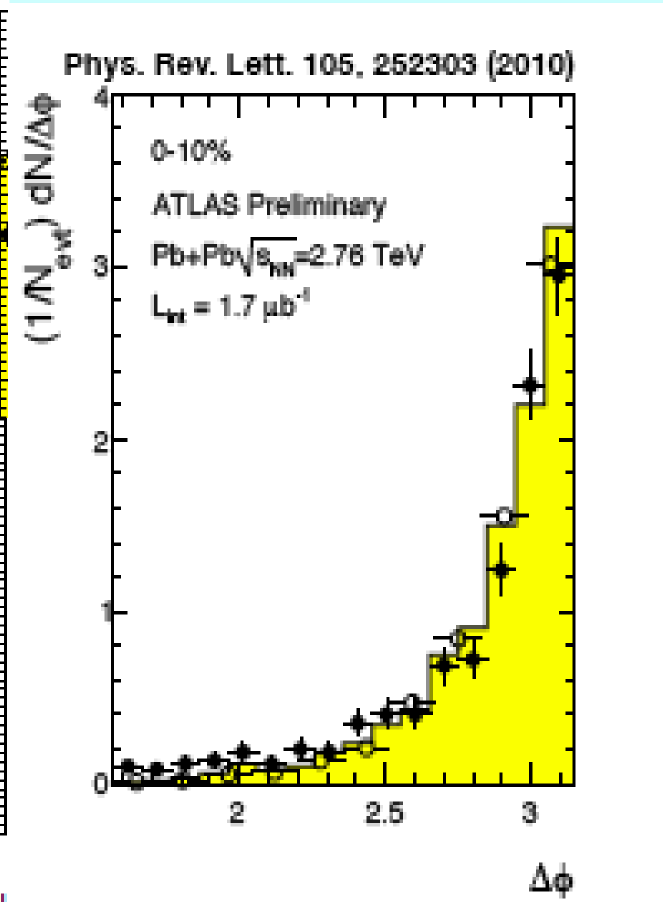


Requiring a narrow jet ➔ same suppression as leading hadron

Hard to reconcile if eloss = splitting *inside* jet cone

Much zippier jets in Pb+Pb at LHC!

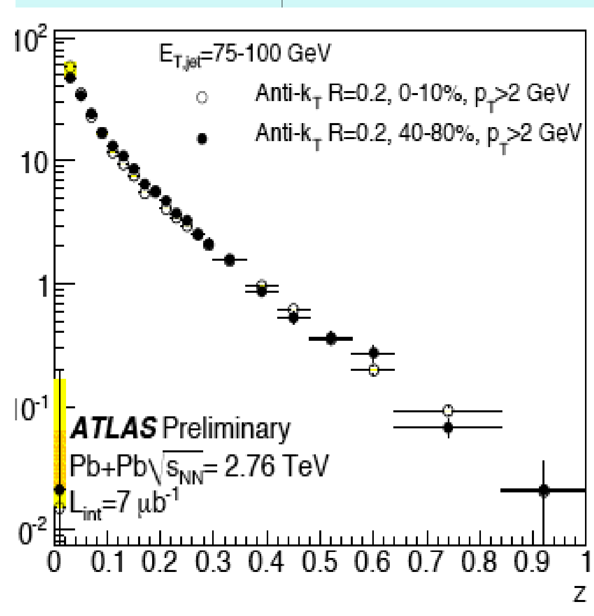




R = 0.4

E_{T1} > 100 GeV

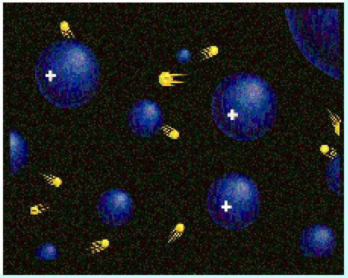
E_{T2} > 25 GeV



Similar R_{AA} as RHIC for 100 GeV → 250 GeV jets; R independent

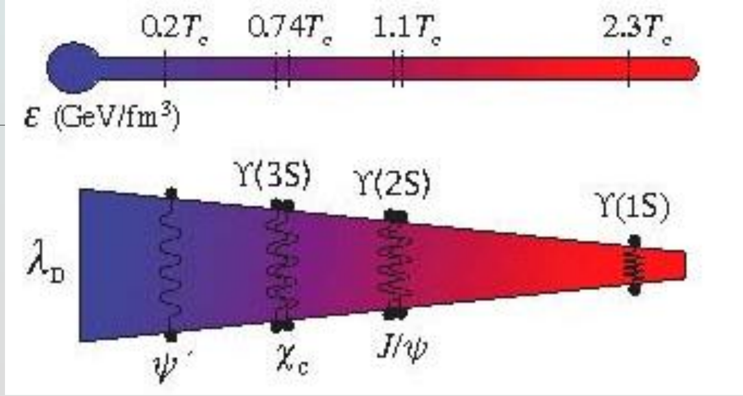
Energy loss →jet asymmetry; no decorrelation, Fragm.Fn. same!

CMS finds excess soft particles in interjet region…

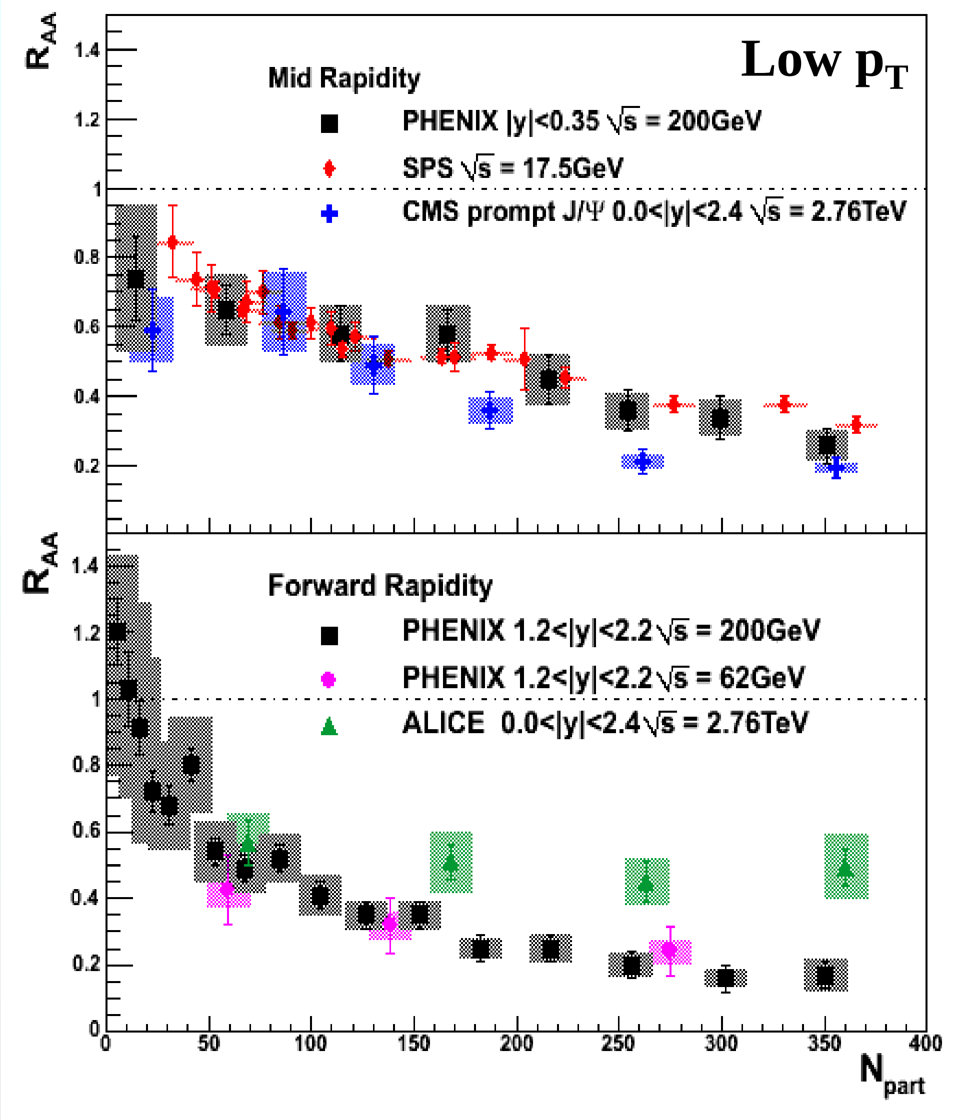


Is there a relevant screening length?

- Plasma: interactions among charges of multiple particles
  spreads charge into characteristic (Debye) length, λ_D
  particles inside Debye sphere screen each other
- Strongly coupled plasmas: few (~1-2) particles in Debye sphere
  Partial screening -> liquid-like properties
  sometimes even crystals!
- *Test with heavy quark bound states*
  Do they survive?
  All? None? Some? Which size?
- Are residual correlations important?



J/ψ vs. system size, √s



No clear suppression pattern with ε, T!

Why more suppression at y=2?

Breakup in hadron gas?

Final state coalescence of $q\bar{q}$?

To quantify color screening in quark gluon plasma:

study as function of √s, p_T, $\mathbf{r}_{onium}$

Also MUST measure J/ψ in d+A/p+A for cold matter effects: gluon shadowing, energy loss

J/ψ R_{AA} ~same from 17.5-200 GeV!

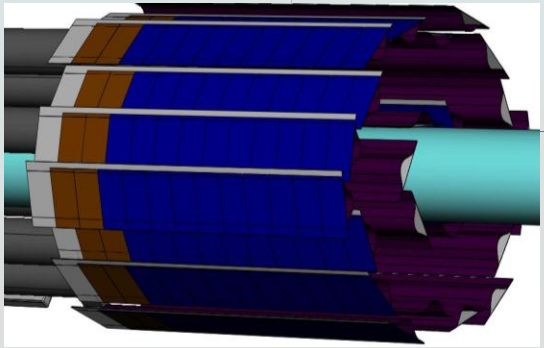
2.76 TeV direct J/ψ lower at mid-y, inclusive above at forward y

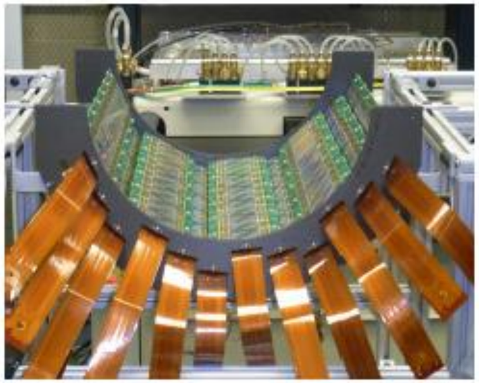
New questions from RHIC & LHC data!

1. At what scales is the coupling strong?
2. How is equilibration achieved so rapidly?
3. Nature of QCD matter at low T but high ρ?
4. What is the mechanism for quark/gluon-plasma interactions? For the plasma response?
   Is collisional energy loss significant?
5. Is there a relevant (color) screening length?
6. Are there quasiparticles in the quark gluon plasma? If so, when and what are they?

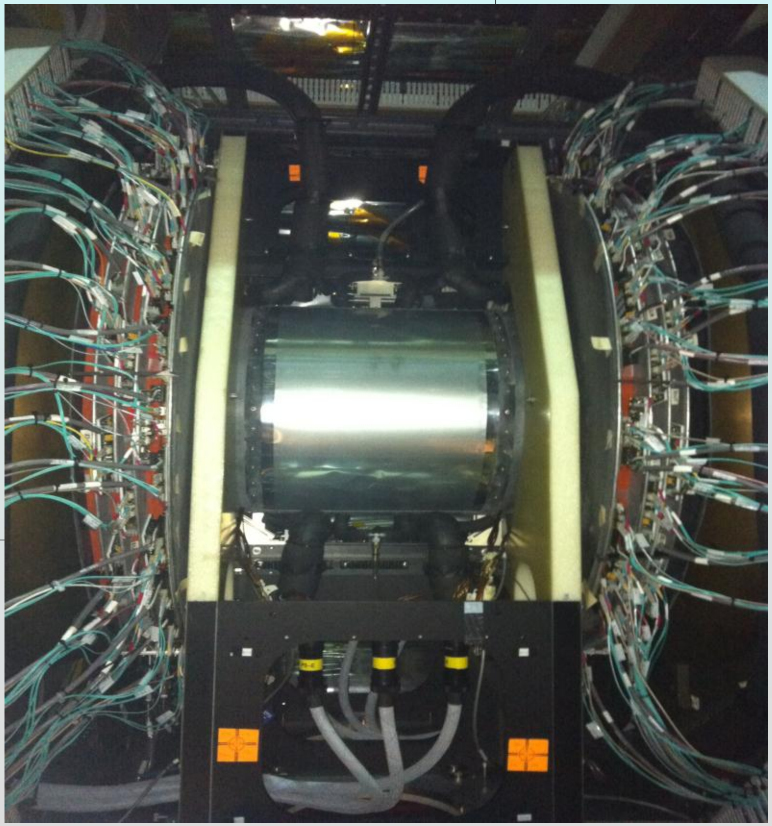
Next step for experiments:

- Do even *b* quarks come to a screeching halt?
  $M_b \sim 4.2$ GeV/c^2
  What does *b* fate tell us about interactions inside?
- Higher luminosity to access rarer (i.e. heavier) probes
- Add silicon microvertex detectors to both PHENIX and STAR
  Displaced vertex to separate c,b; reconstruct D & B mesons
- Vertex detectors in place @ LHC
- Address Q 1,4,6

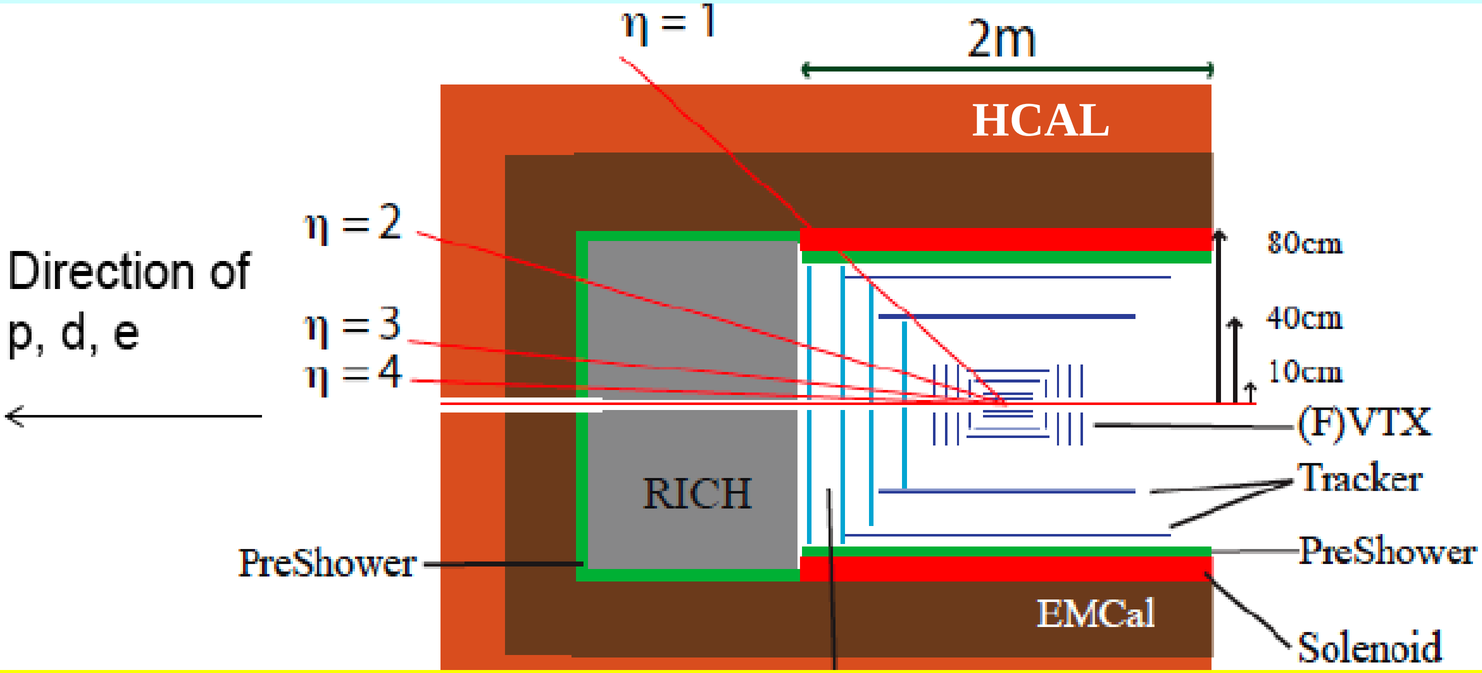




VTX Stripixel Layer 4



After 2015: Upgrade PHENIX



Focused on capabilities to answer compelling questions
Don't try to do everything

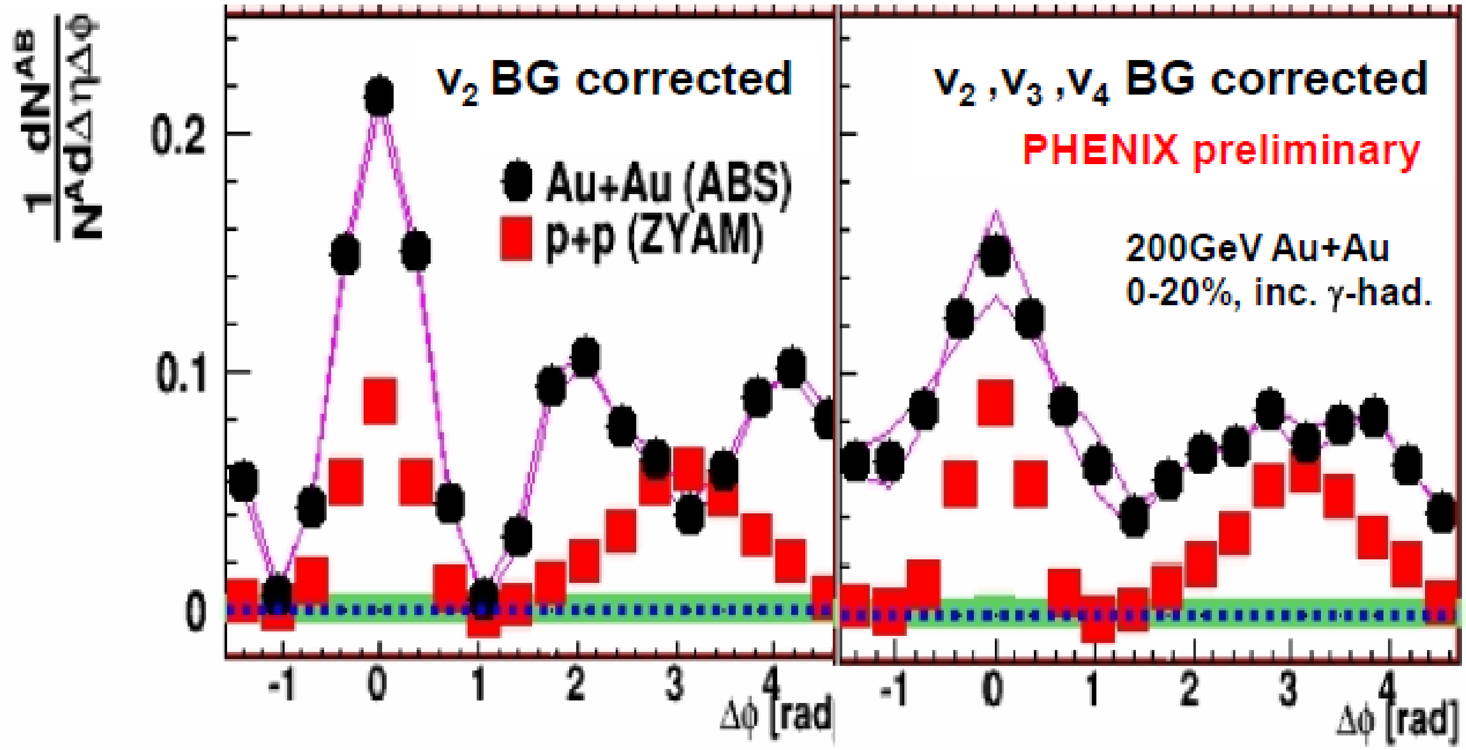
- Compact detector covering $-1 < \eta < 4$ **x50 acceptance for quarkonia, jets**
- Measure jets, electrons and photons in mid-rapidity → Measure QGP properties
- Gluon saturation physics at forward region ($\eta > 1$)
- First eRHIC detector (not yet optimized)

Conclusions

- T > Tc ; now study quark gluon plasma properties
  QGP behaves as a strongly coupled liquid
- Flow (pressure gradients) build up & saturate below 39 GeV
  Soft photons flow too!
- η/s near quantum limit; similar @ LHC and RHIC
  Uncertainties being reduced by higher harmonics of flow
- Parton energy loss large at low p_T @ LHC and RHIC
  At high p_T, hadron suppression less, but still substantial
  Jets suppressed from 10-250 GeV, but dijet correlation & fragmentation unchanged. WHERE is the lost energy??!!
- Need to understand onium suppression patterns in terms of medium effects on the correlation -> screening length
- The data raise entirely new questions!
  Answer by running time and p+A at LHC
  Upgrades at RHIC for heavy quark & jet probes of plasma

- **backup slides**

Flow subtraction/correction with measured v_n for central-central 2-particle correlation



mach-cone is mostly gone

remaining medium effect seen

(correlated pair yield by absolute normalization)

Calculating transport in QGP

weak coupling limit

perturbative QCD

kinetic theory, cascades

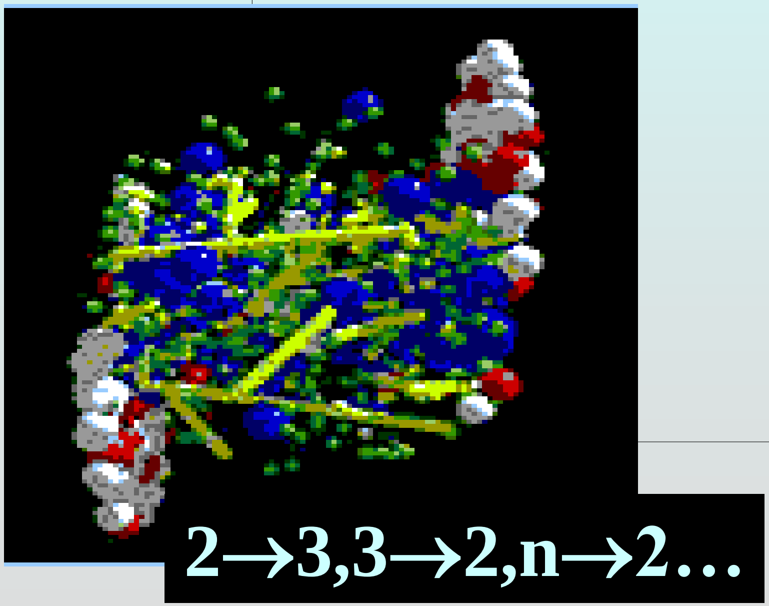
interaction of particles

∞ strong coupling limit

not easy! Try a pure field…

gravity ↔ supersym 4-d

(AdS/CFT)



Lepton pair emission ↔ EM correlator

e.g. Rapp, Wambach Adv.Nucl.Phys 25 (2000)

Emission rate of dileptons per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)\,f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}\left(1+\frac{2m_l^2}{M^2}\right)$$

$\gamma^* \to ee$ decay

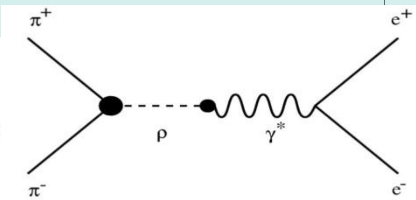
EM correlator
Medium property

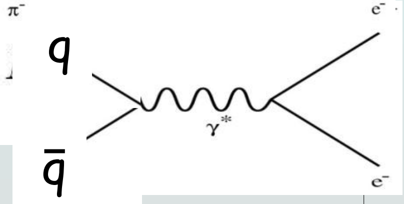
Boltzmann factor
temperature

Hadronic contribution
Vector Meson Dominance

→ Medium modification of meson
Chiral restoration

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M), \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q)^2, \end{cases}$$





$\bar{q}q$ annihilation

→ Thermal radiation from partonic phase (QGP)

From emission rate of dileptons, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

Suppression pattern ingredients

- Color screening

- Initial state effects

  Shadowing or saturation of incoming gluon distribution

  Initial state energy loss

  (calibrate with p+A or d+A)

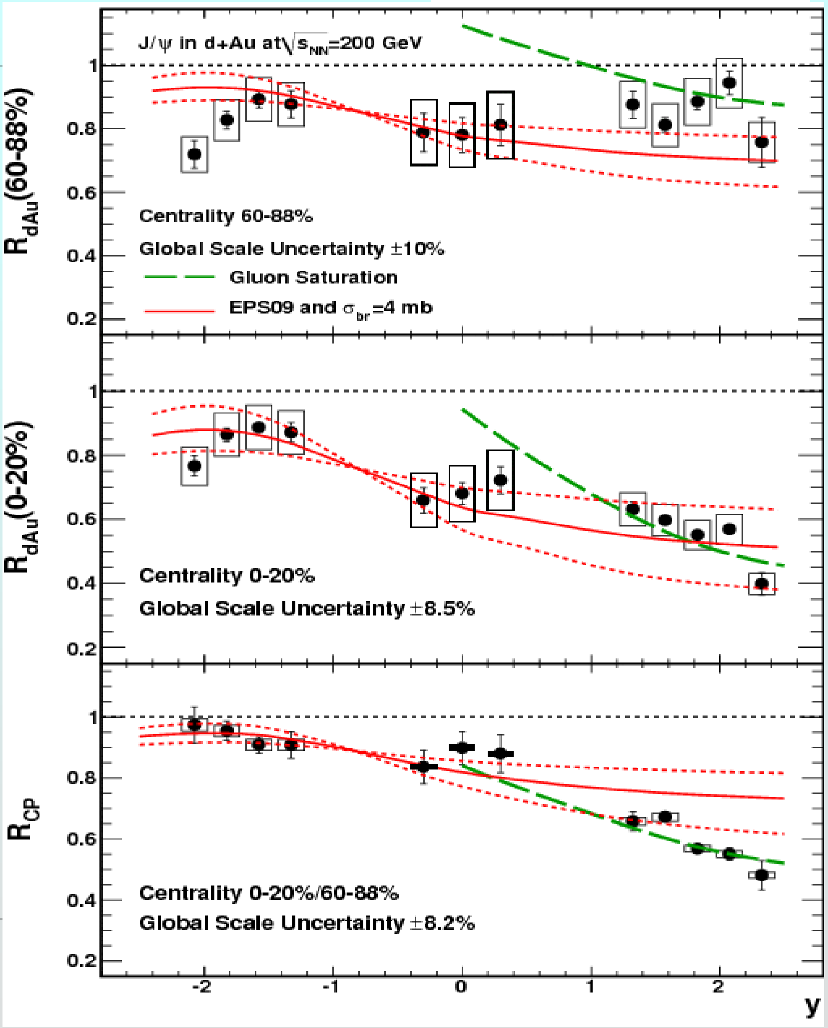
- Final state effects

  Breakup of quarkonia due to co-moving hadrons

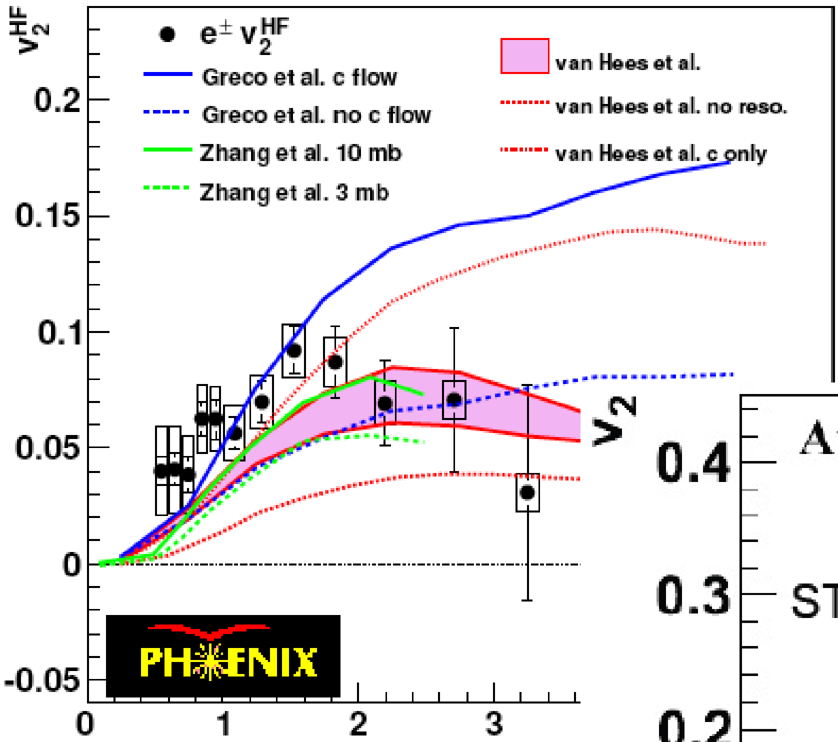
  Coalescence of q and qbar at hadronization

  (calibrate with A, centrality dependence)

arXiv:1010.1246



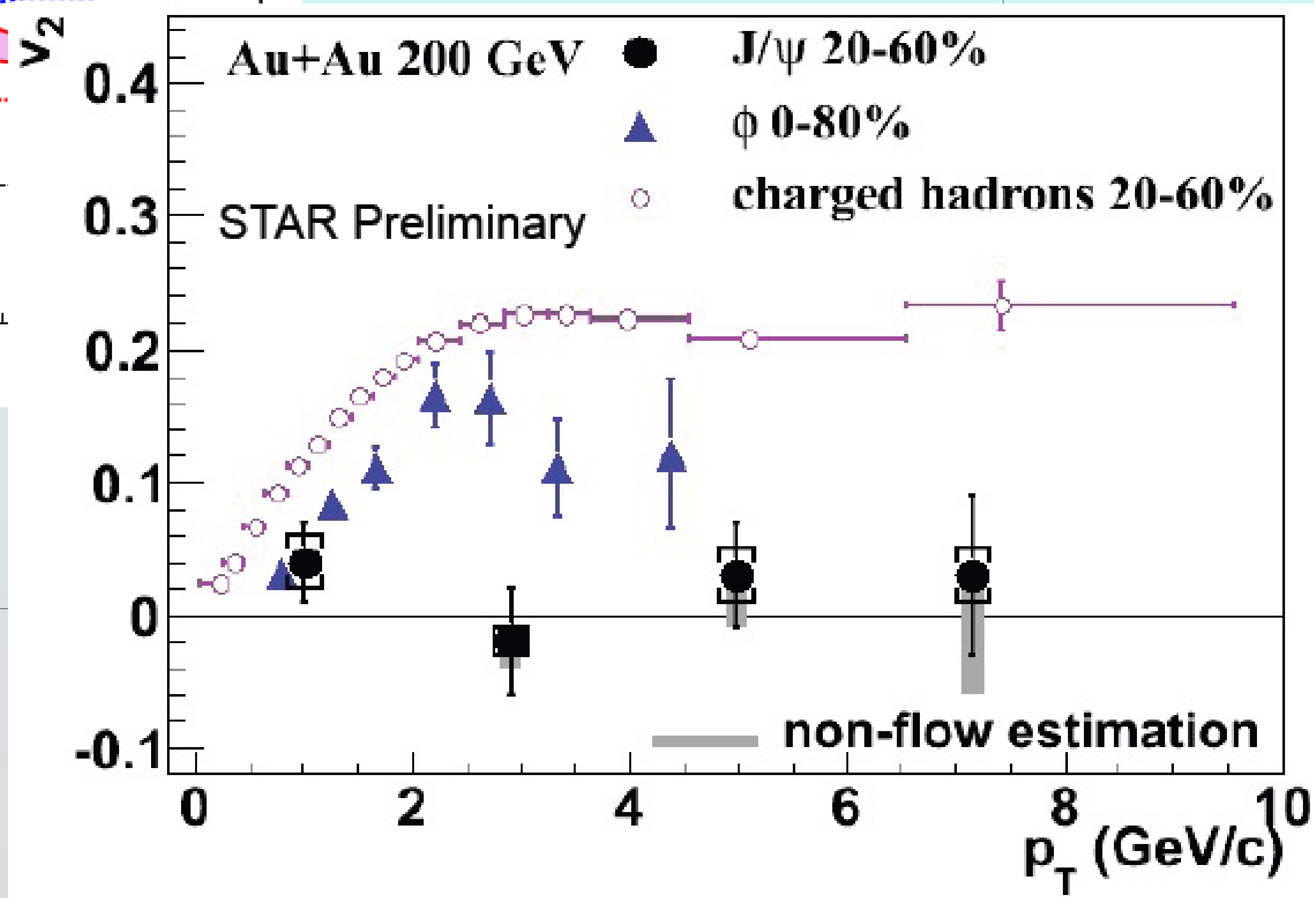
Expect if c-cbar pairs numerous or correlated



PRL.98: 172301,2007

Open charm flows

but J/ψ does not



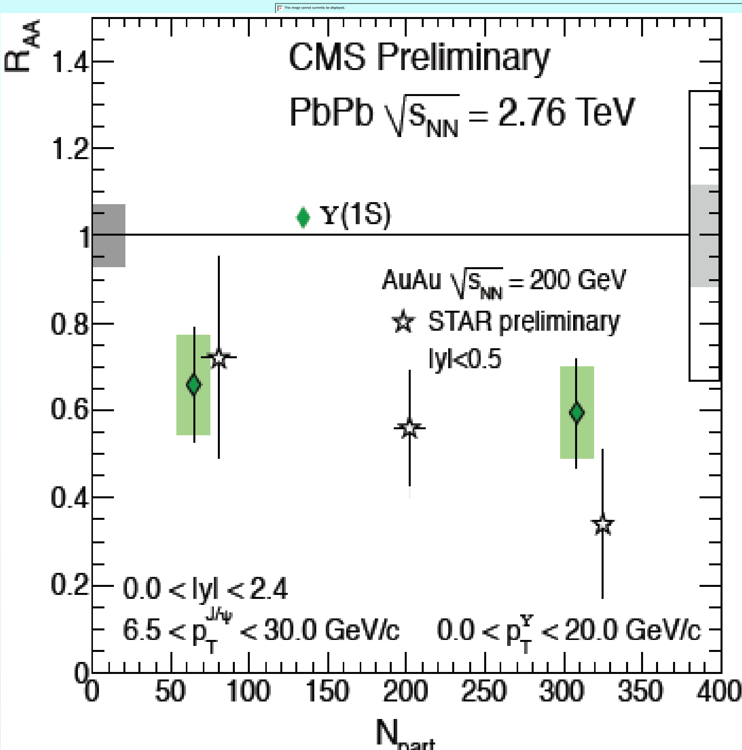
So, $c\bar{c}$ coalescence in final state @ RHIC is not large

Higher at LHC?

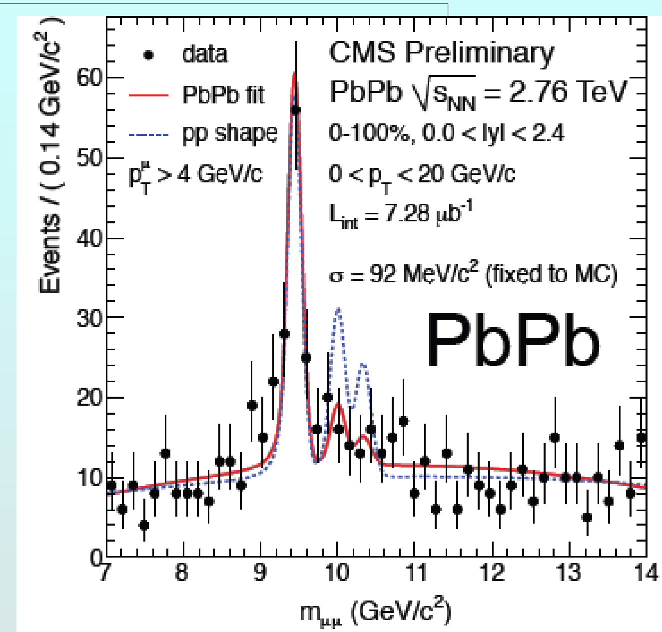
b-bar bound states

- Coalescence *could* be important at LHC

  More c-cbar pairs produced. Use b-bar to probe…



Υ (2S,3S) suppressed

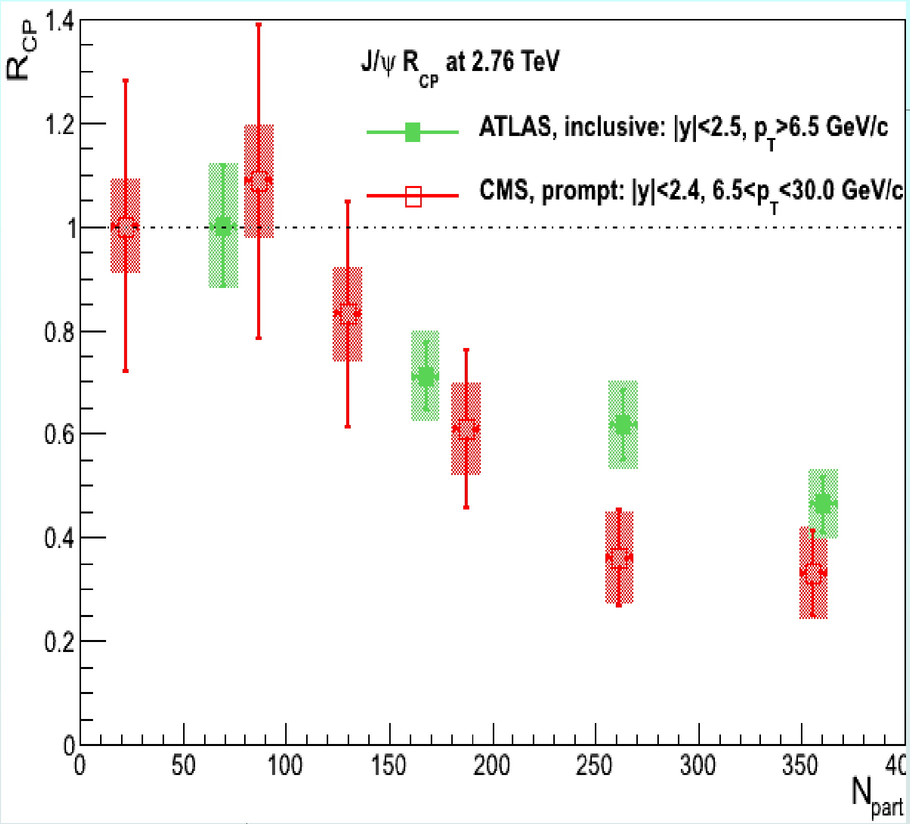


$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Does partial screening preserve correlations, enhancing likelihood of final state coalescence?
- arXiV:1010.2735 (Aarts, et al): ∏unchanged to 2.09T_c

  χ_b modified from 1-1.5T_c, then free

Prompt (CMS) vs. inclusive (ATLAS) J/ψ



- at high p_T, prompt J/ψ < inclusive?

  (b states less suppressed)

- recall:

√s dependence is weak

LHC less suppressed!

  Final state coalescence?

susceptibilities & net-baryon fluctuations

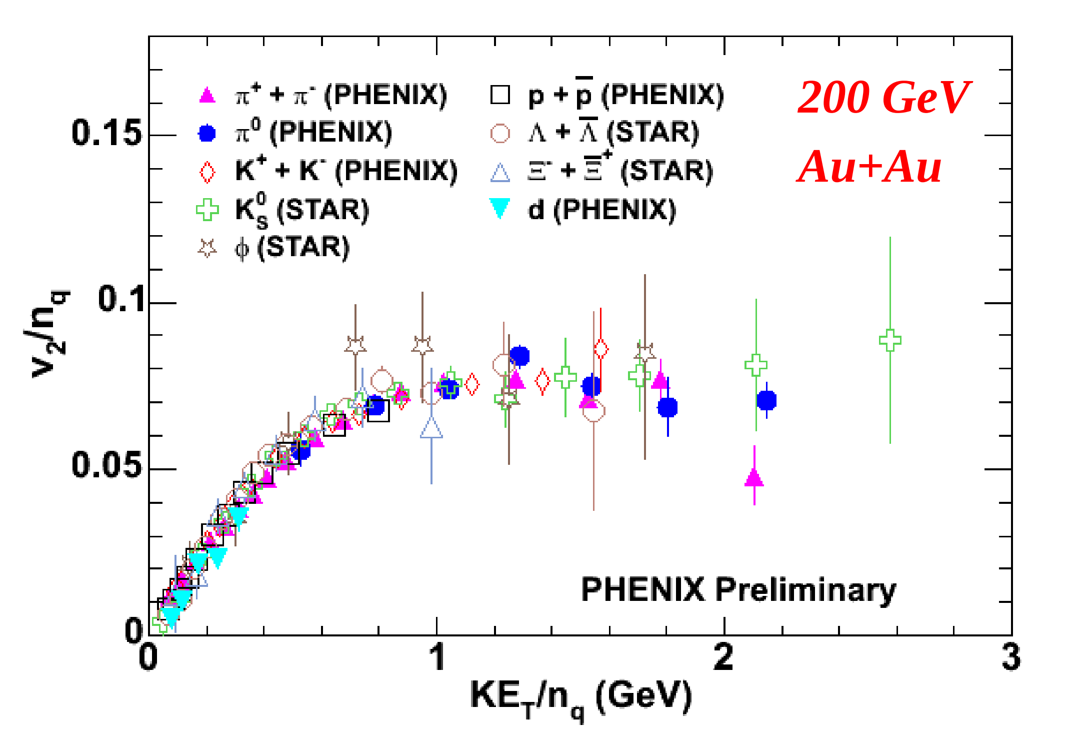
$$S\sigma = \frac{[B^3]}{[B^2]} = \frac{T\chi_B^{(3)}}{\chi_B^{(2)}},$$

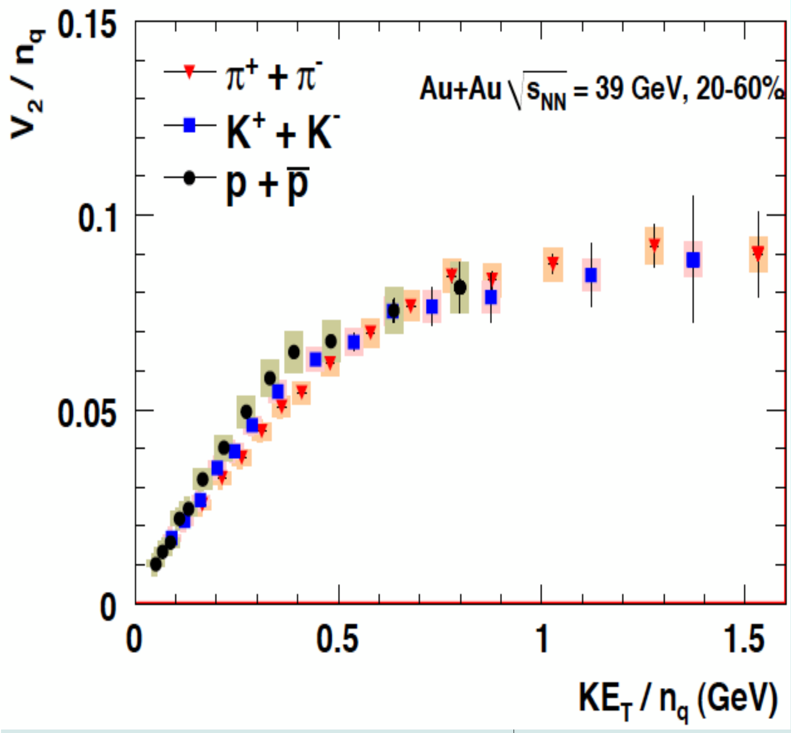
$$\kappa\sigma^2 = \frac{[B^4]}{[B^2]} = \frac{T^2\chi_B^{(4)}}{\chi_B^{(2)}},$$

$$\frac{\kappa\sigma}{S} = \frac{[B^4]}{[B^3]} = \frac{T\chi_B^{(4)}}{\chi_B^{(3)}},$$

Relation between the baryon susceptibilities, χ_B, and cumulants of the net-baryon fluctuations

Elliptic flow scales with quark number





implication: valence quarks, not hadrons, are relevant DOF

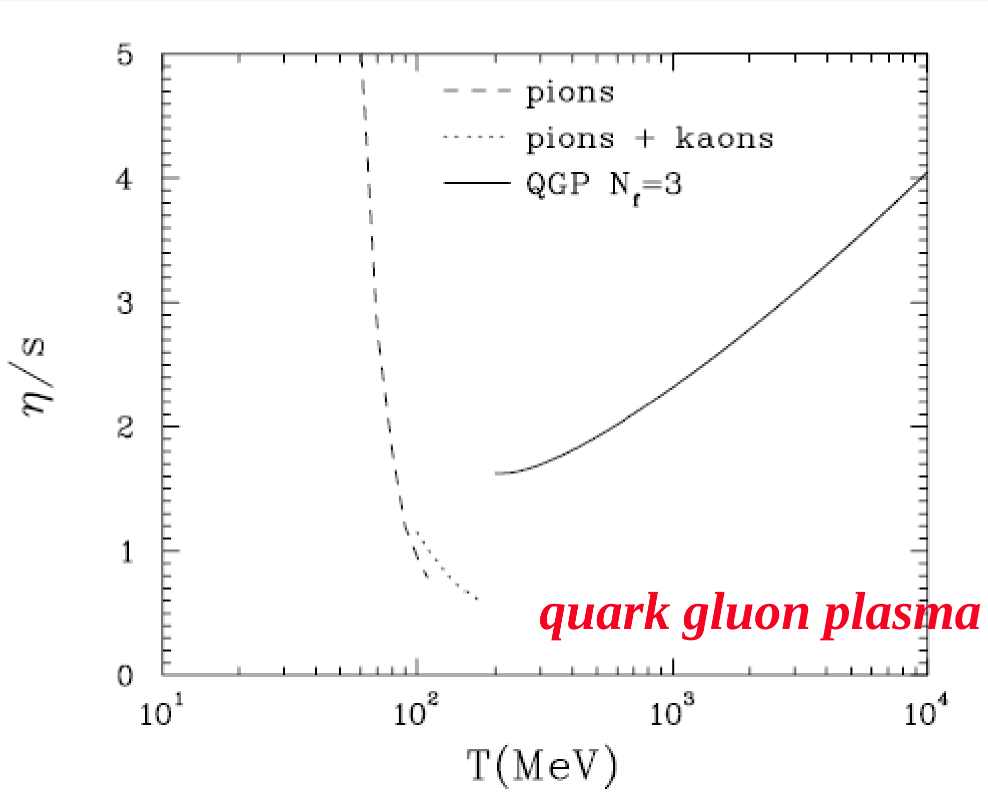
coalesce into hadrons when T falls below T_c

consistent with success of hydro with lattice EOS, but…

what gives? dressed quarks are born of flowing field?

Nb: strongly interacting liquids lack well-defined, long-lived quasi-particles

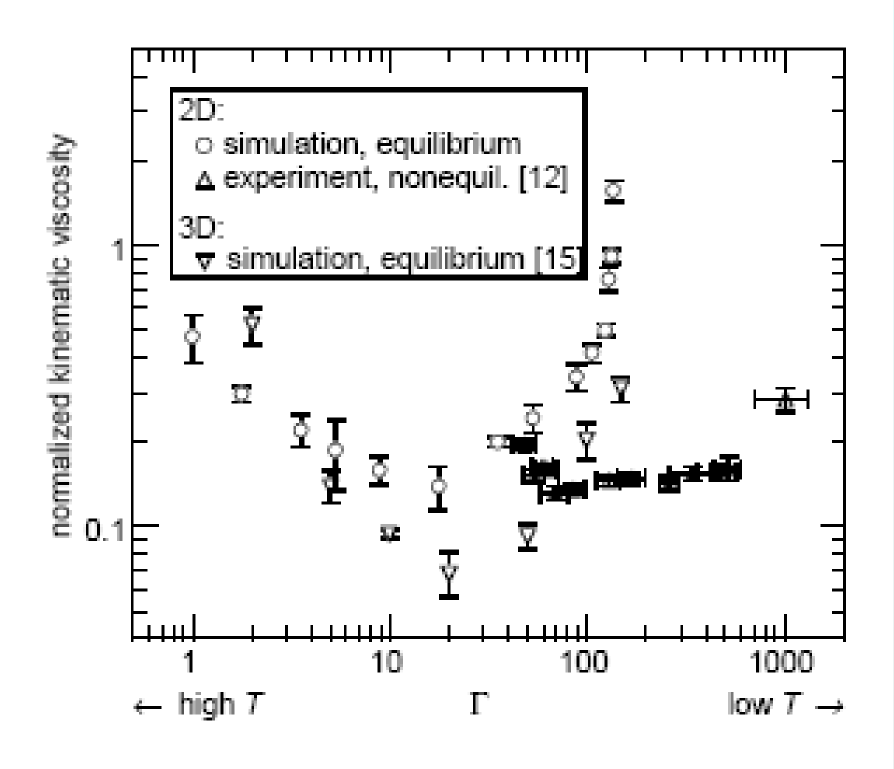
minimum η at phase boundary?



Csernai, Kapusta & McLerran
PRL97, 152303 (2006)

strongly coupled dusty plasma

B. Liu and J. Goree,



minimum observed in other strongly coupled systems –
kinetic part of η decreases with Γ while potential part increases

Insights, given first LHC results

- **Quarkonia energy dependence not understood!**

  Need charmonium and bottonium states at >1 $\sqrt{s}$ at RHIC

  + guidance from lattice QCD!

- **Jet results from LHC very surprising!**

  Steep path length dependence of energy loss

  also suggested by PHENIX high p_T v_2; AdS/CFT is right?

  Little modification of "jet" fragmentation function

  looks different at RHIC (different jet definition, energy)

  Lost energy goes to low p_T particles at large angle

  is dissipation slower at RHIC? Due to medium or probe?

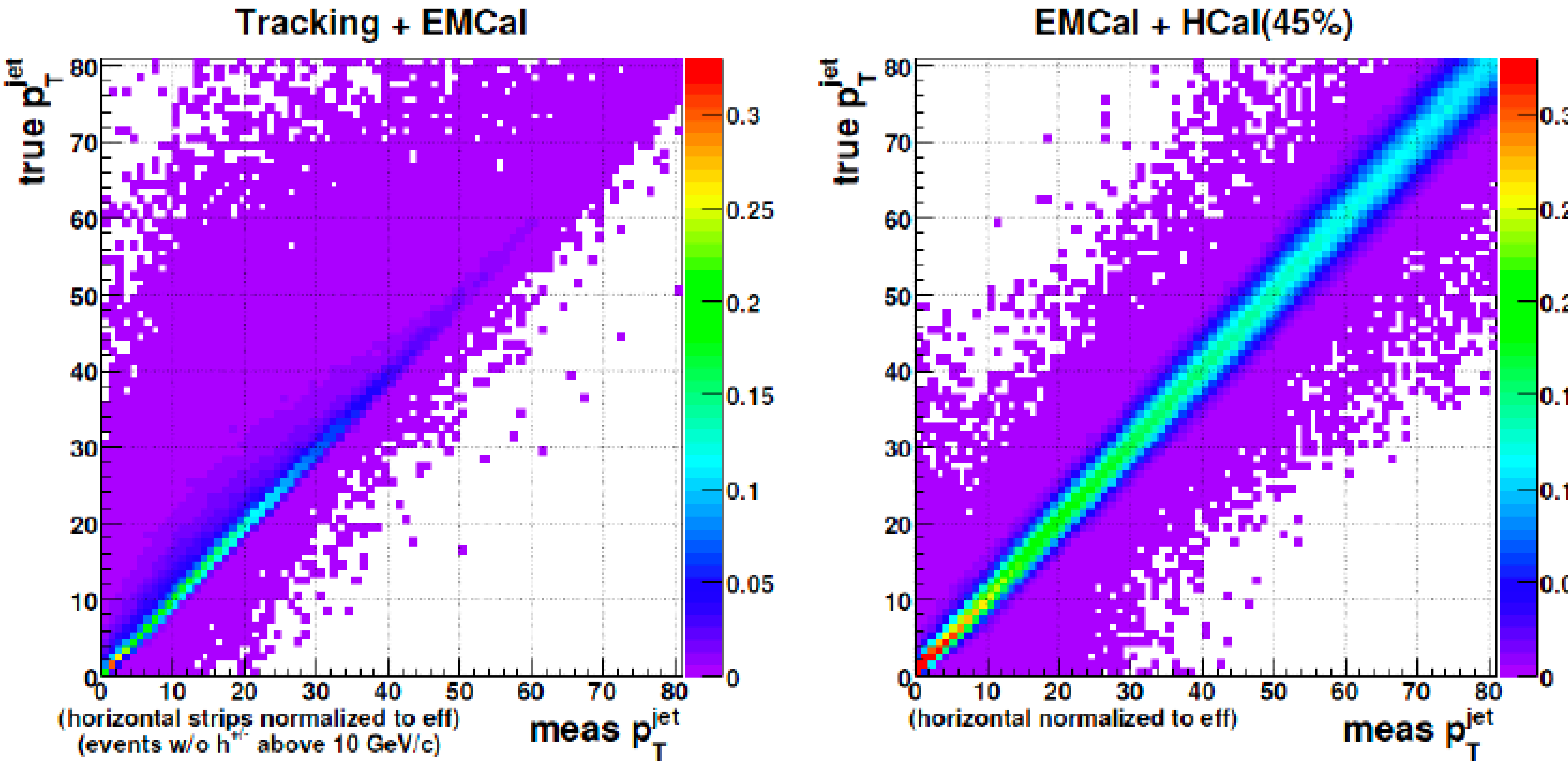
  Little modification of di-jet angular correlation

  appears to be similar at RHIC

- **Need full, calorimetric reconstruction of jets in wide y range at RHIC to disentangle probe effects/medium effects/initial state**

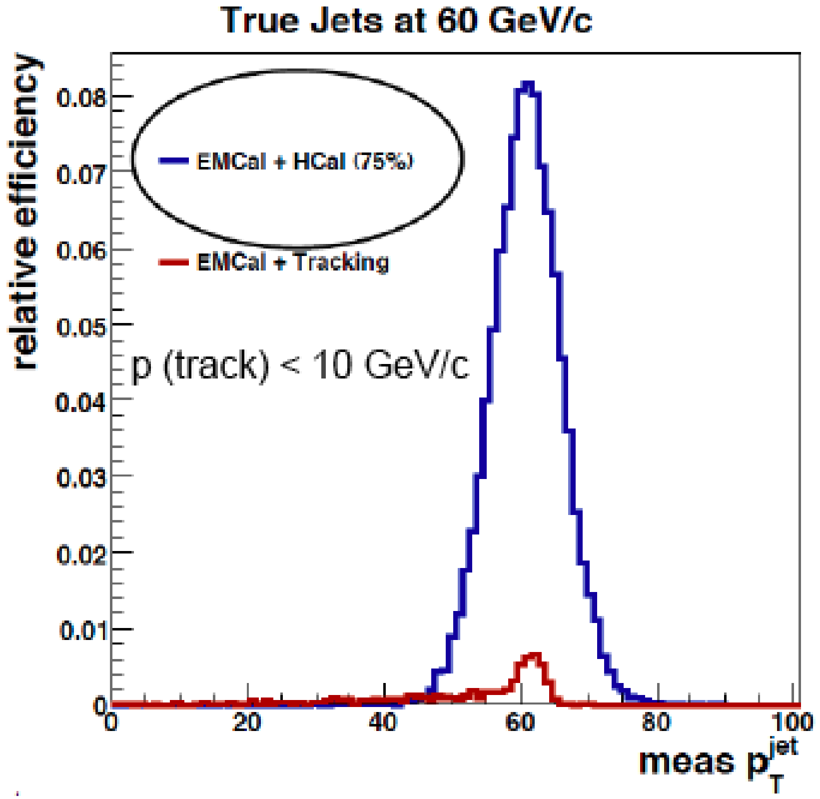
HCal improvement to Jet Energy Measurement

tracking p < 10 GeV/c required
to avoid fake jets

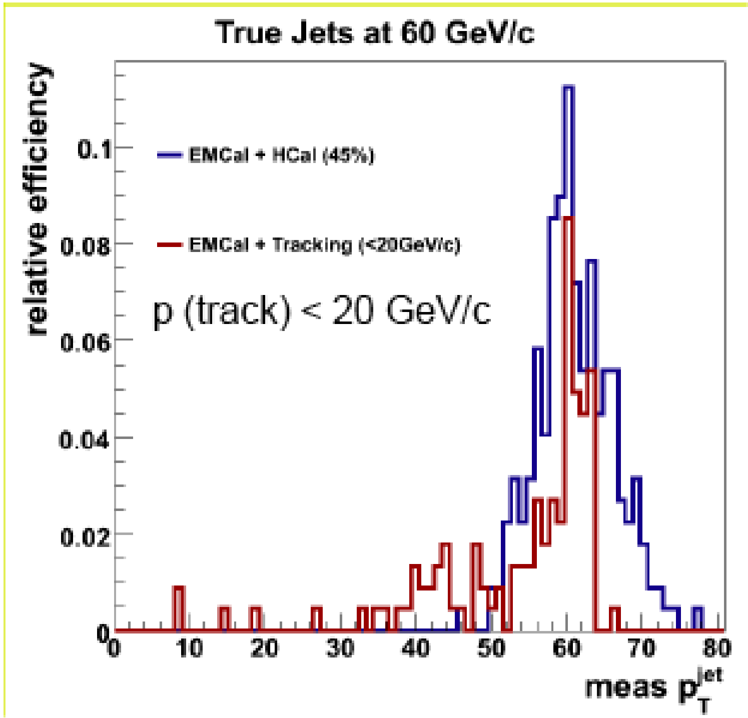


- No fake jet due to tracking background
- Catch neutral energy
- No asymmetric tail in measured energy → Essential for A_J measurement

HCal for jet measurement



With 10 GeV tracking cut off, only tiny fraction of jet can be reconstructed



With 20 GeV tracking cut off, still less than 1/3 of jet is reconstructed at proper energy

- For di-jet asymmetry (A_J) measurement, the tail is the killer
- Hcal eliminates the tail.
- Hcal is not the cost driver of sPHENIX

Beam Energy Scan

Large acceptance → Energy scan of rare probes at lower beam energy

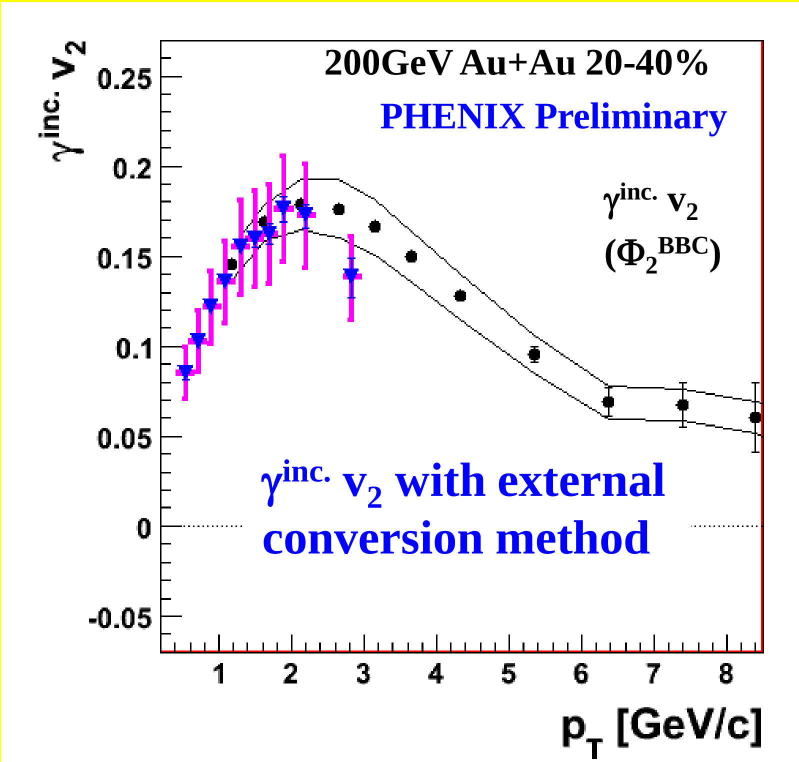
- Jets
- High p_T single hadrons
- Open heavy flavor
- Quarkonia

  repeat energy scan of 20 – 200 GeV with large acceptance detector to characterize the suppression as a function of sqrt(s)

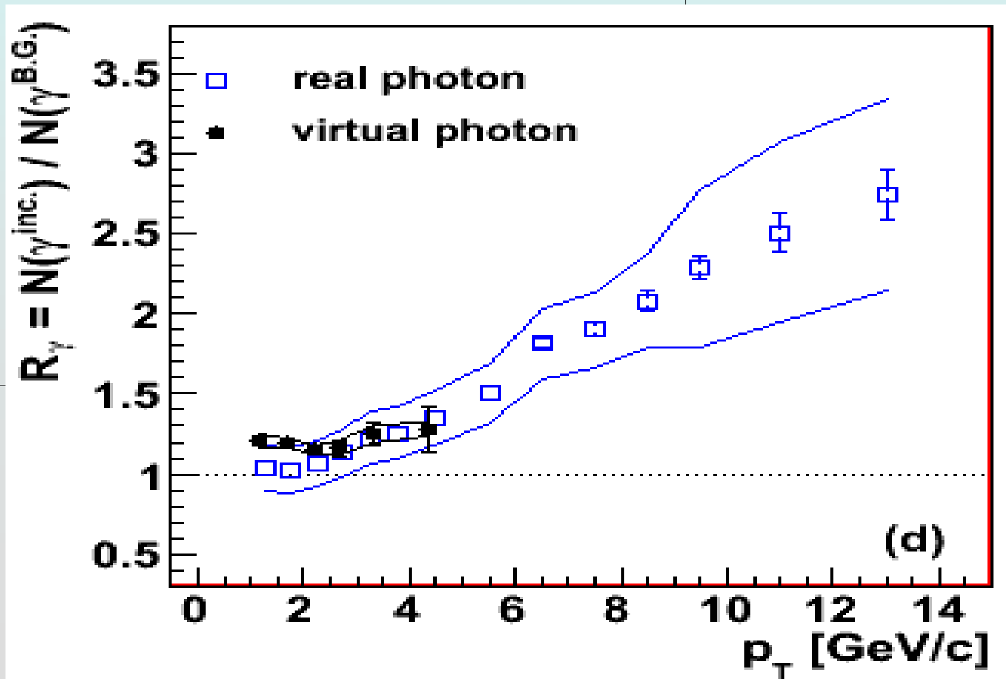
- Photon-hadron, Photon-jets

  Probe Energy loss and QGP response in lower beam energy

Direct photon flow ingredients



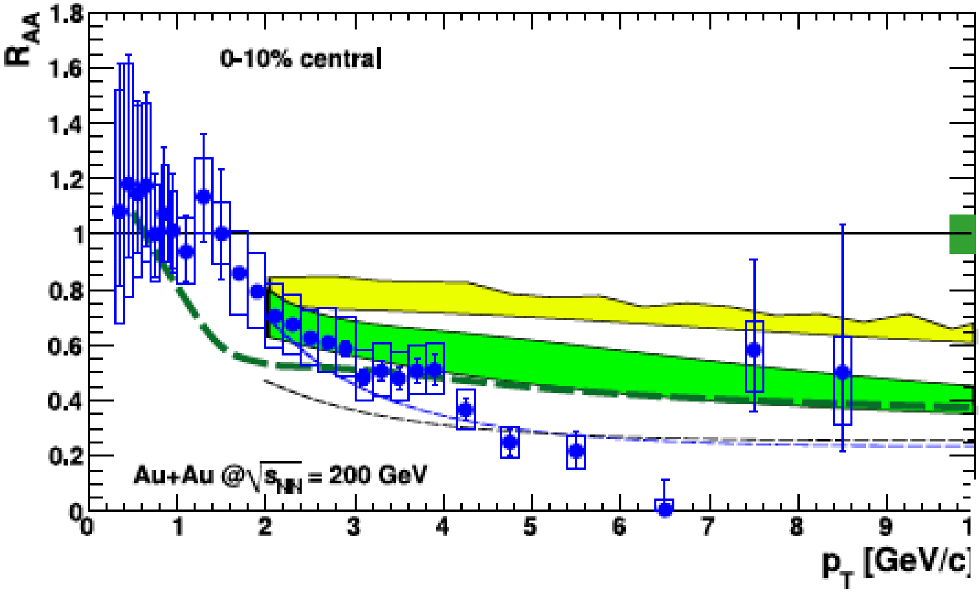
- **Key cross checks:**
  - **γinc are really γ's:**
    - **check using γ-> e+e-**
  - **Rγ for virtual vs. real γ**



heavy quark suppression & flow?

PRL.98: 172301,2007

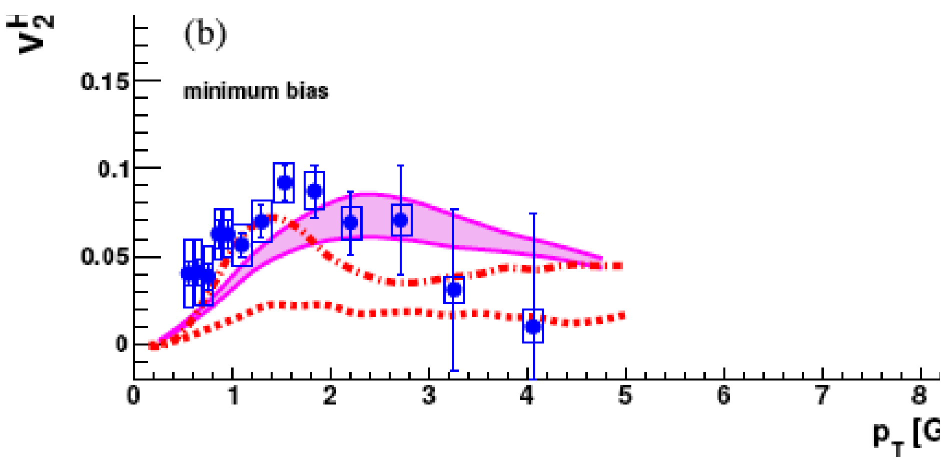
arXiV: 1005.1627

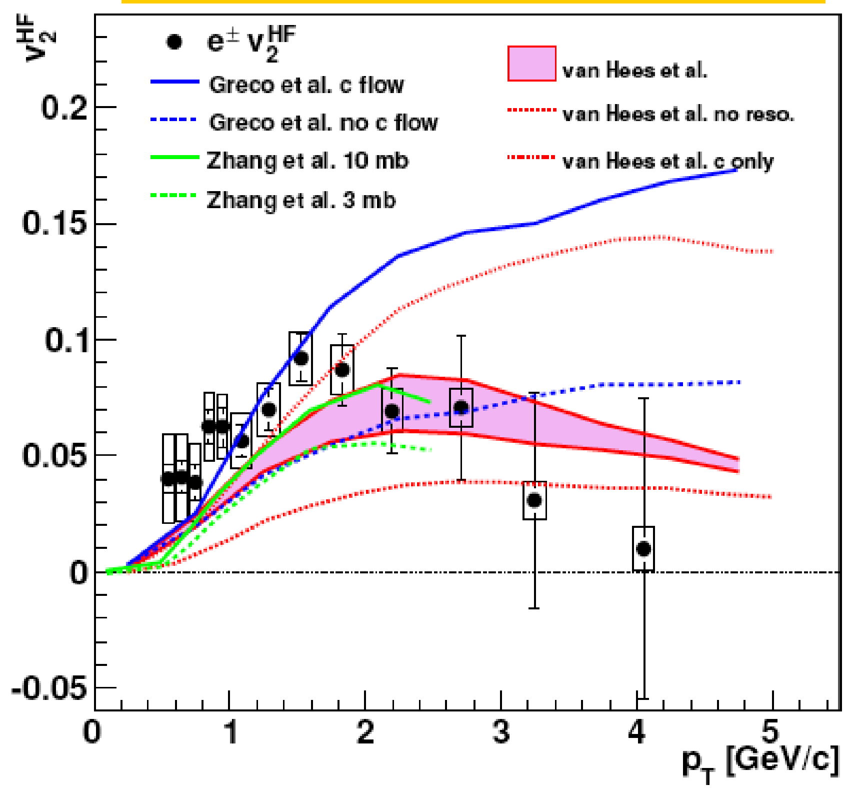


Collisional energy loss?

v_2 decrease with p_T?

role of b quarks?

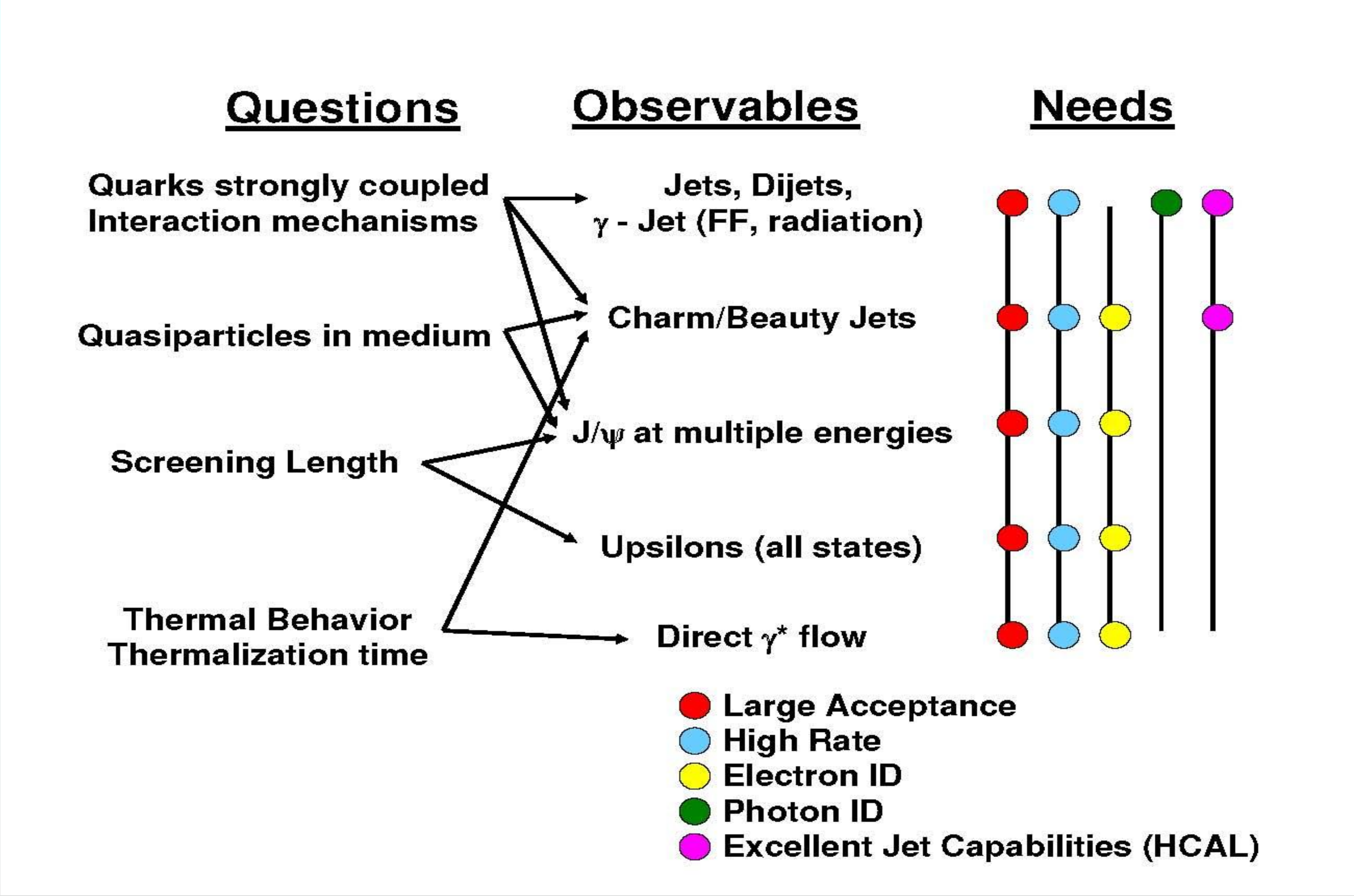




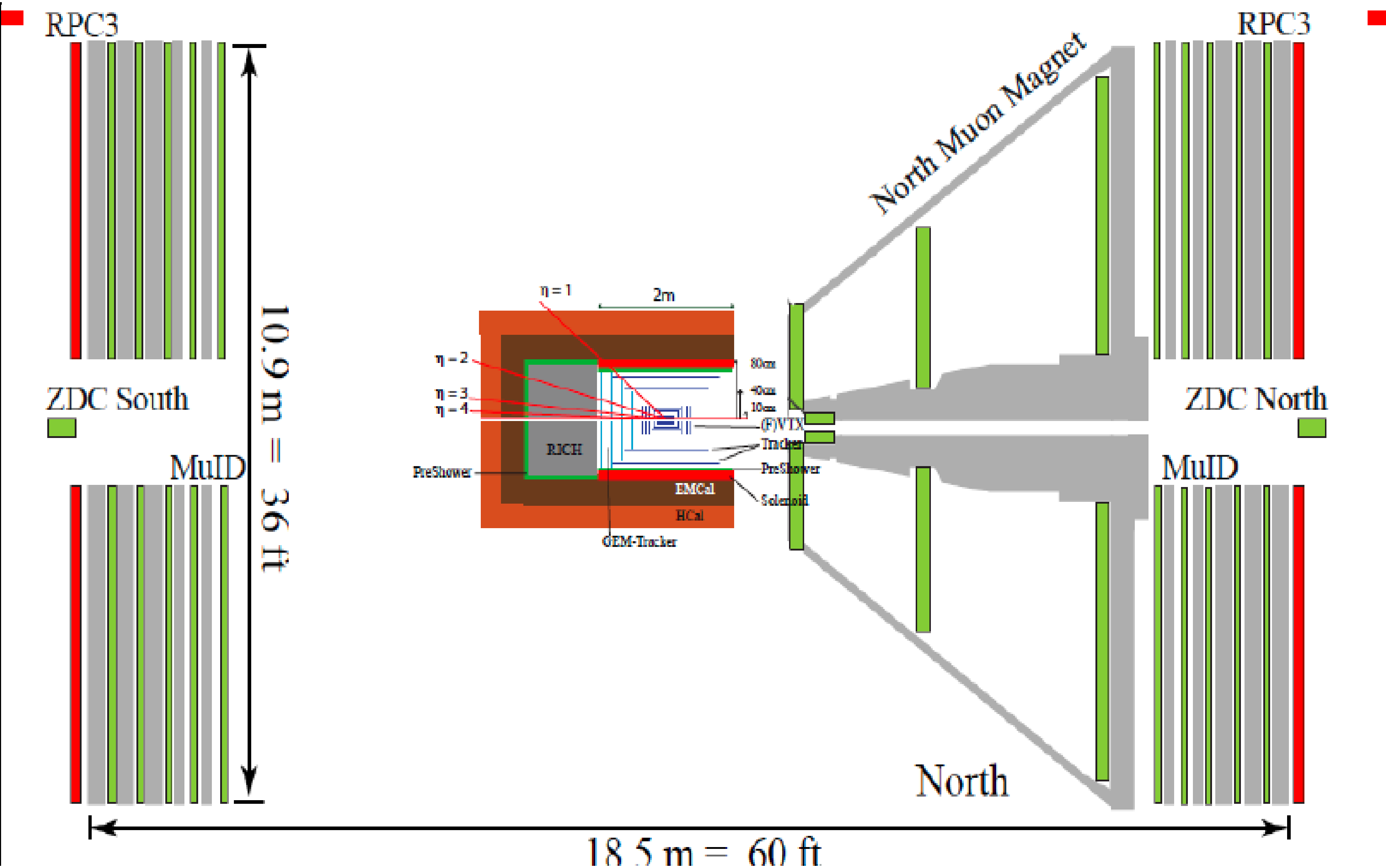
Mysteries in heavy ion physics

- **Energy loss mechanism** **NSAC milestone DM11, 12**
  - @ LHC 40 GeV jets opposing 100 GeV jets look “normal”
    - no broadening or decorrelation
    - no evidence for collinear radiation from the parton
  - @ RHIC low energy jets appear to show medium effects
    - but, “jet” is defined differently
  - → c & b to probe role of collisional energy loss ***VTX, FVTX***
  - → quantify path length dependence ***U+U, Cu+Au***
- **J/ψ suppression and color screening** **NSAC milestone DM5**
  - amazingly similar from √s=17-200 GeV; but initial states differ
  - not SO different at LHC
  - → Other states y & √s dependence (e.g. ψ’) ***FVTX, statistics***
  - → d+Au for initial state; 130 GeV Au+Au eventually?

To answer these questions



How does this happen?



Cost estimate

Carry over from existing PHENIX:

- VTX and FVTX
- EMCal in Forward Arm and perhaps barrel
- DAQ
- Infrastructure (LV, HV, Safety systems…)

What is new:

- 2-3T solenoid (R = 60-100 cm)
- Preshower detector
- Barrel EMCal (maybe new)

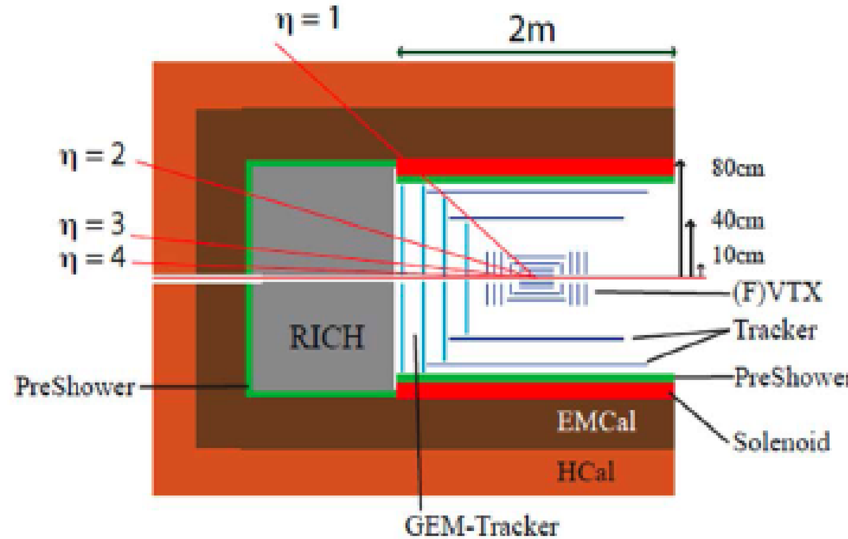
} $20M

- Hadronic Calorimetry } $8-10M
- Additional tracking layers of Si at ~ 40cm } $5-7M
- Forward Arm with RICH and GEM tracker } $10M

Other

- Forward magnet
- Forward HCAL
- Barrel trking layer ~60cm

} $10-15M



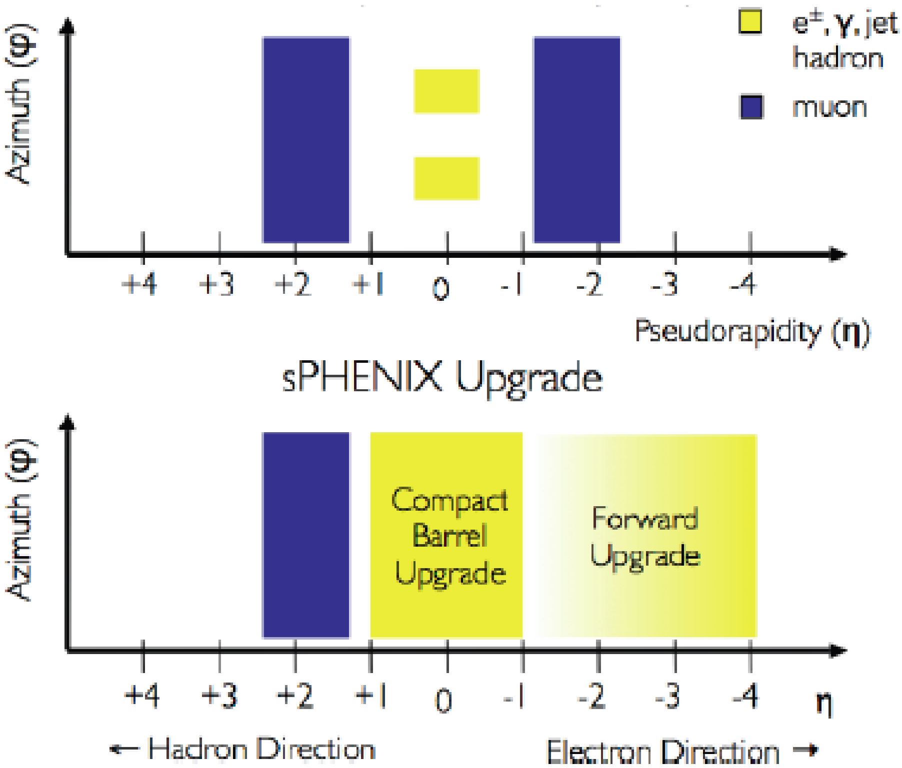
Can be built incrementally

All cost estimate include overhead and contingency

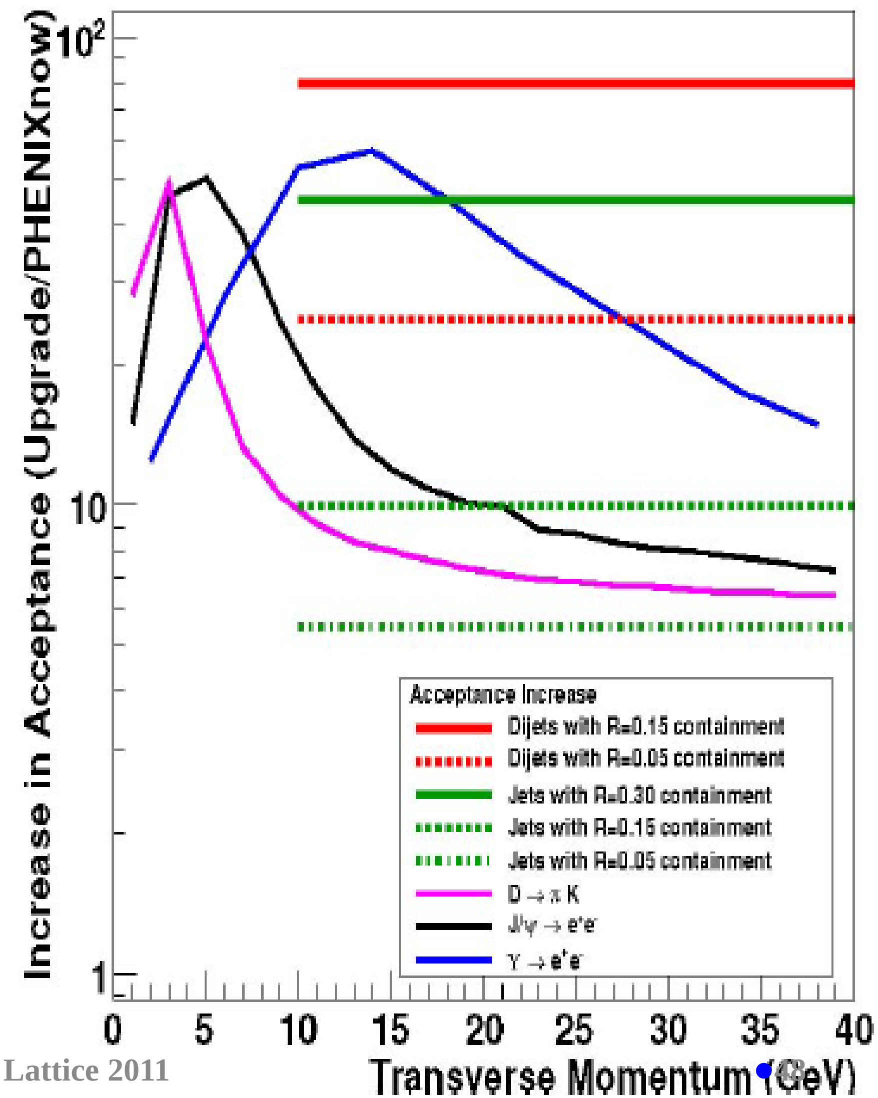
Total Project Cost $53-62M

- Approx ½ replacement cost of existing $130M PHENIX detector
- DOE contribution estimated to be 60% of total $32-44M
- Forward detector is key for eRHIC physics (part of eRHIC project?)

sPHENIX acceptance

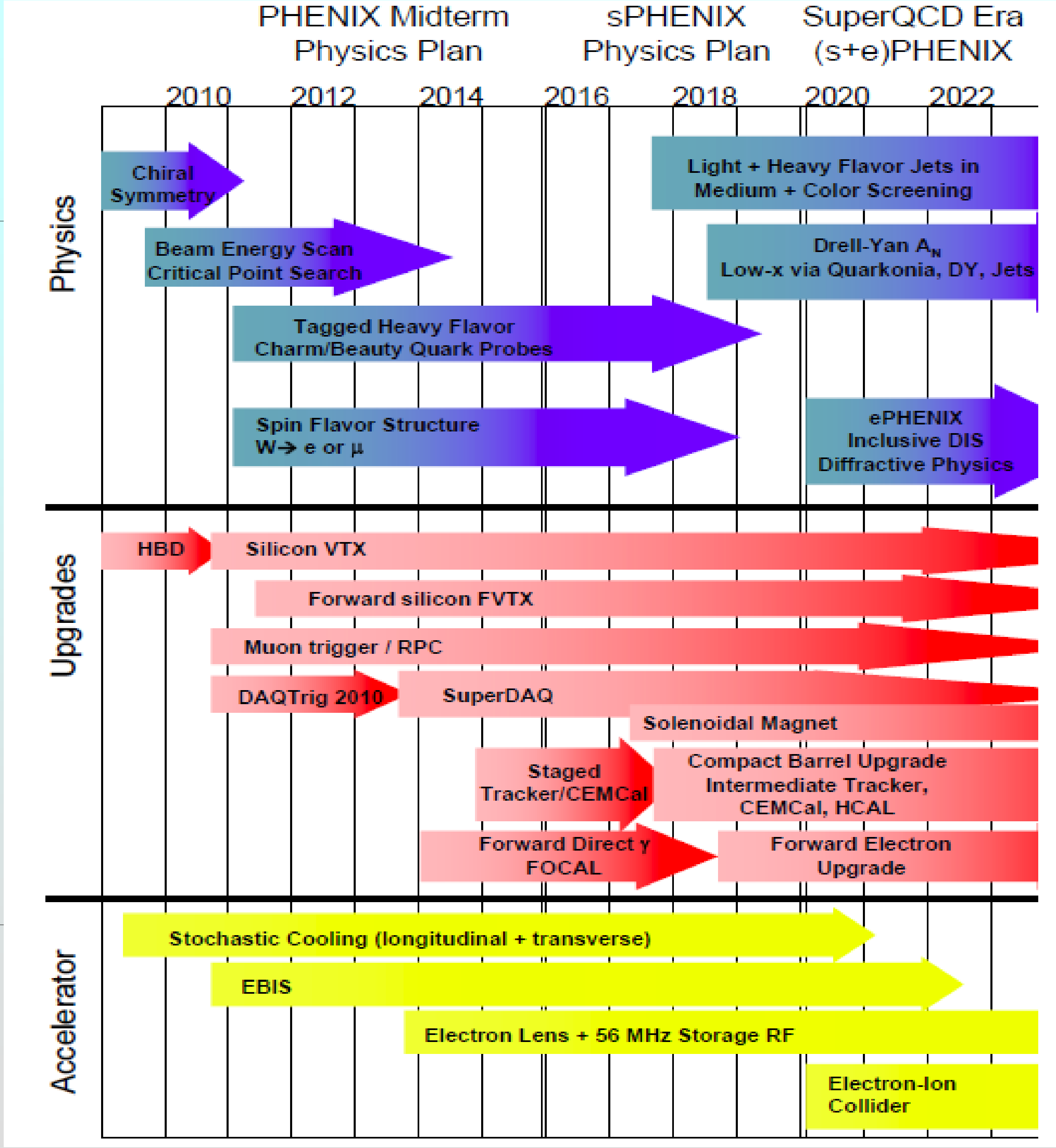


Much larger acceptance than PHENIX

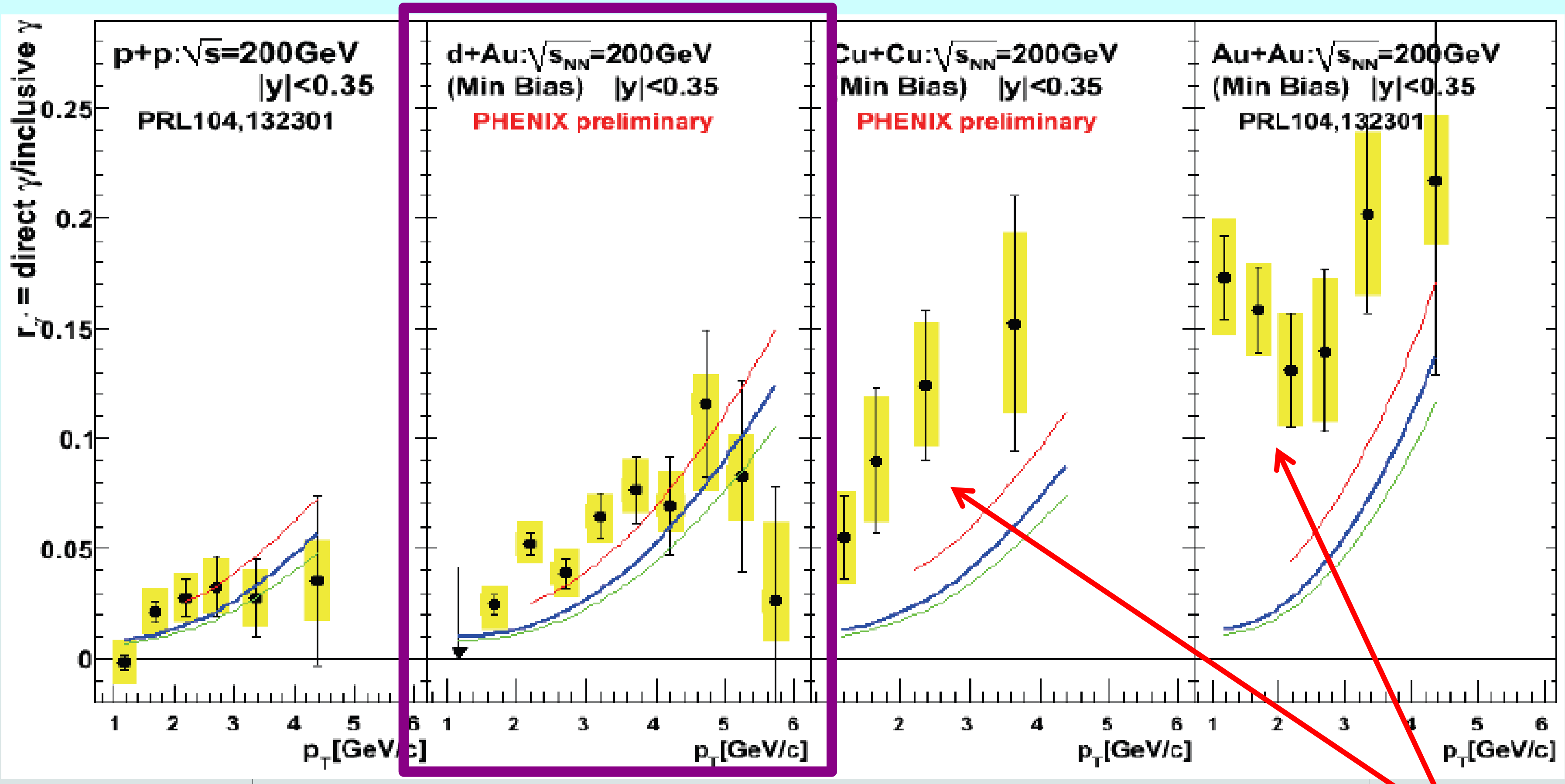


+ DAQ/Trigger: 50B events / year!

Our big picture plan



Thermal photons (virtual)



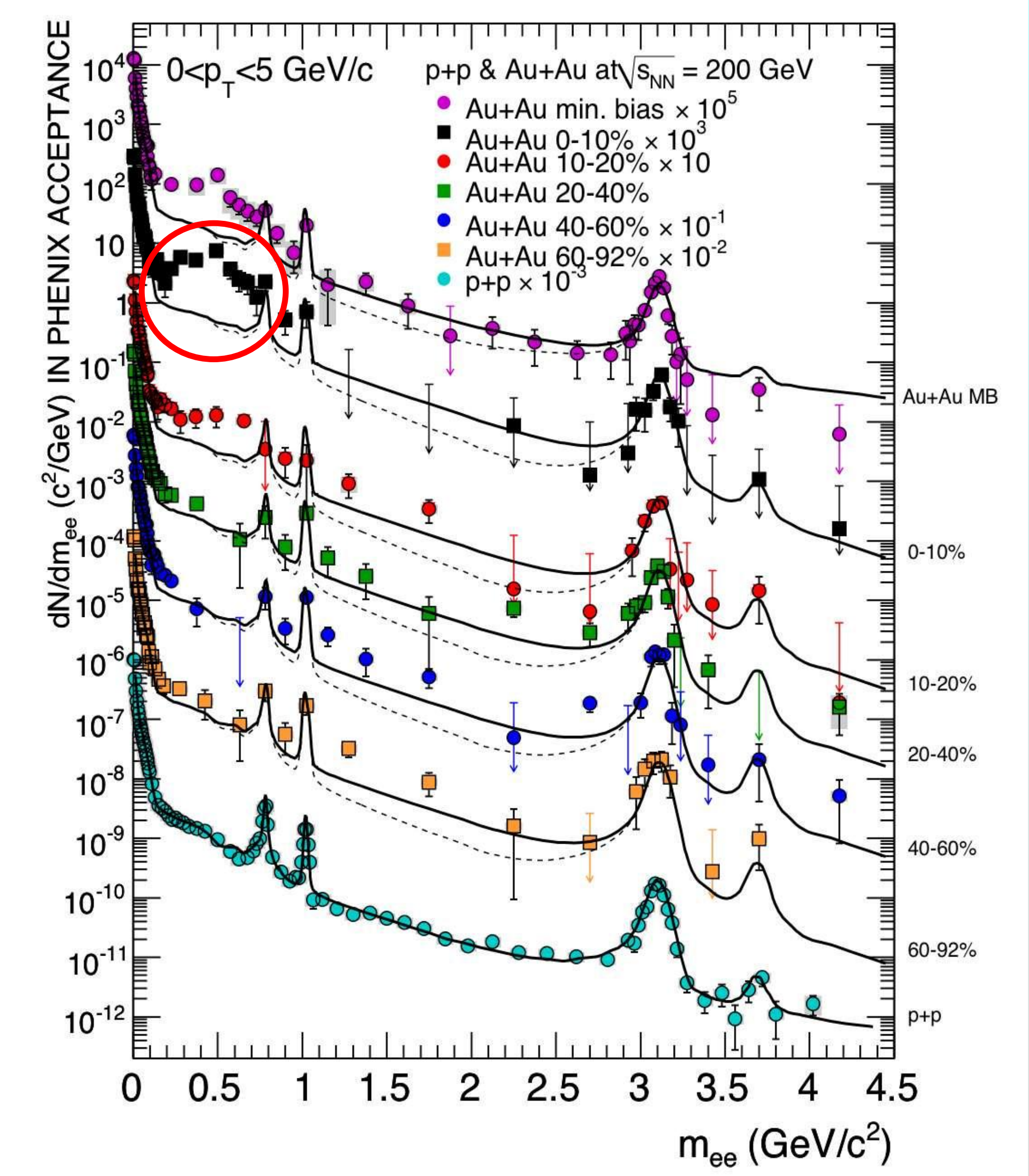
Observe excess photons beyond pQCD in AA collisions. In thermal p_T region

Dielectron production in $0.5 < m_{ee} < 1$ GeV

Significant excess in central collisions.

Dominantly at low p_T

We are investigating using Run-10 data with the HBD

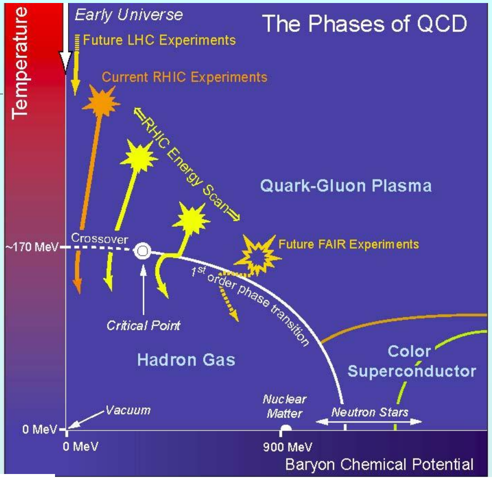


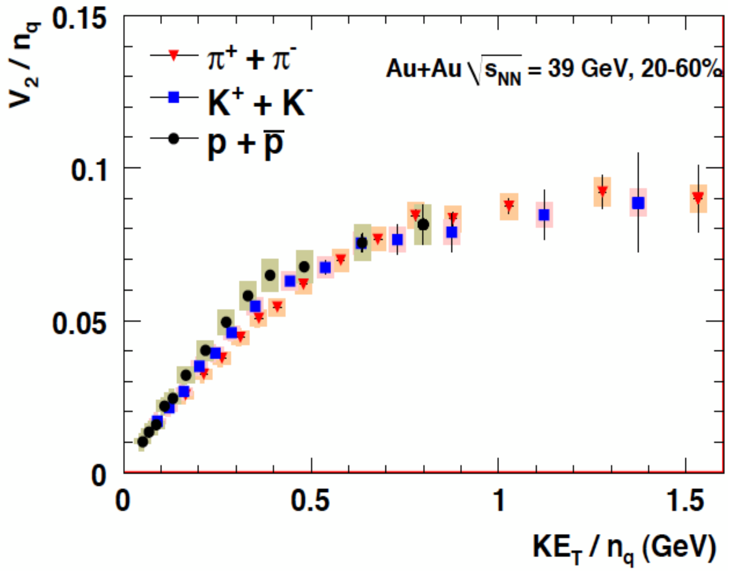
NSAC milestone DM6

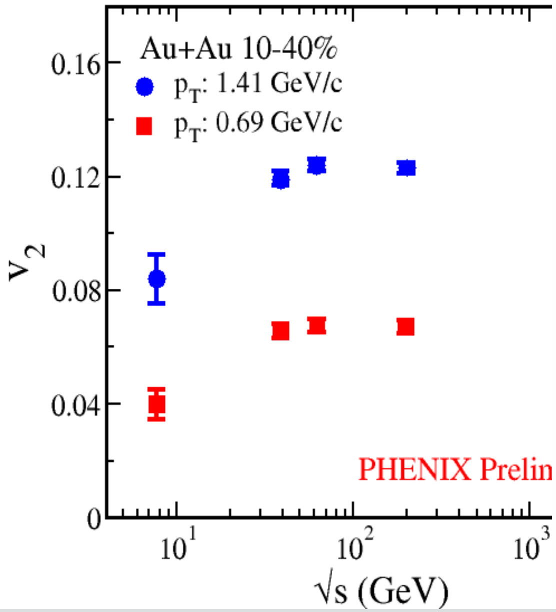
Beam Energy Scan in PHENIX

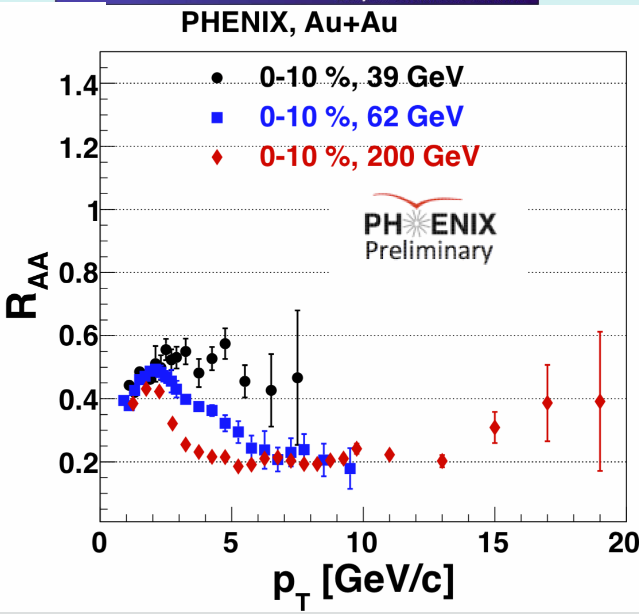
Is there a critical point separating 1st order phase transition & smooth cross-over?

- **Quark-number scaling of V_2**
  - saturation of flow vs collision energy
  - find η/s minimum at critical point from flow
- **Critical point searches via:**
  - fluctuations in $<p_T>$ & multiplicity
  - K/π, π/p, pbar/p chemical equilibrium
  - R_{AA} vs √s, ….



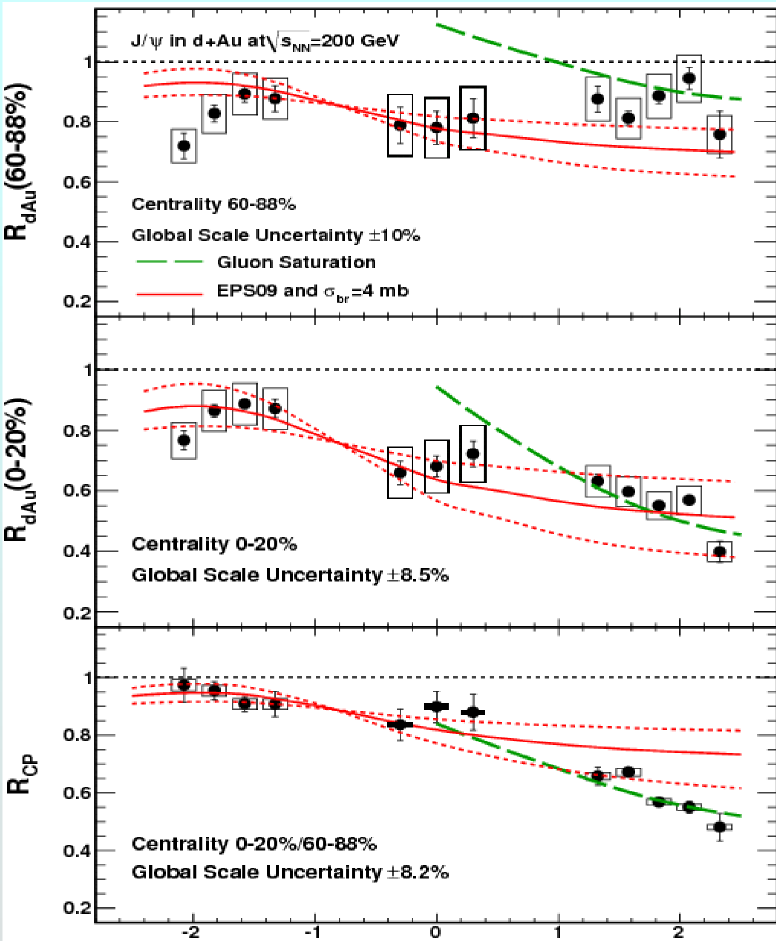




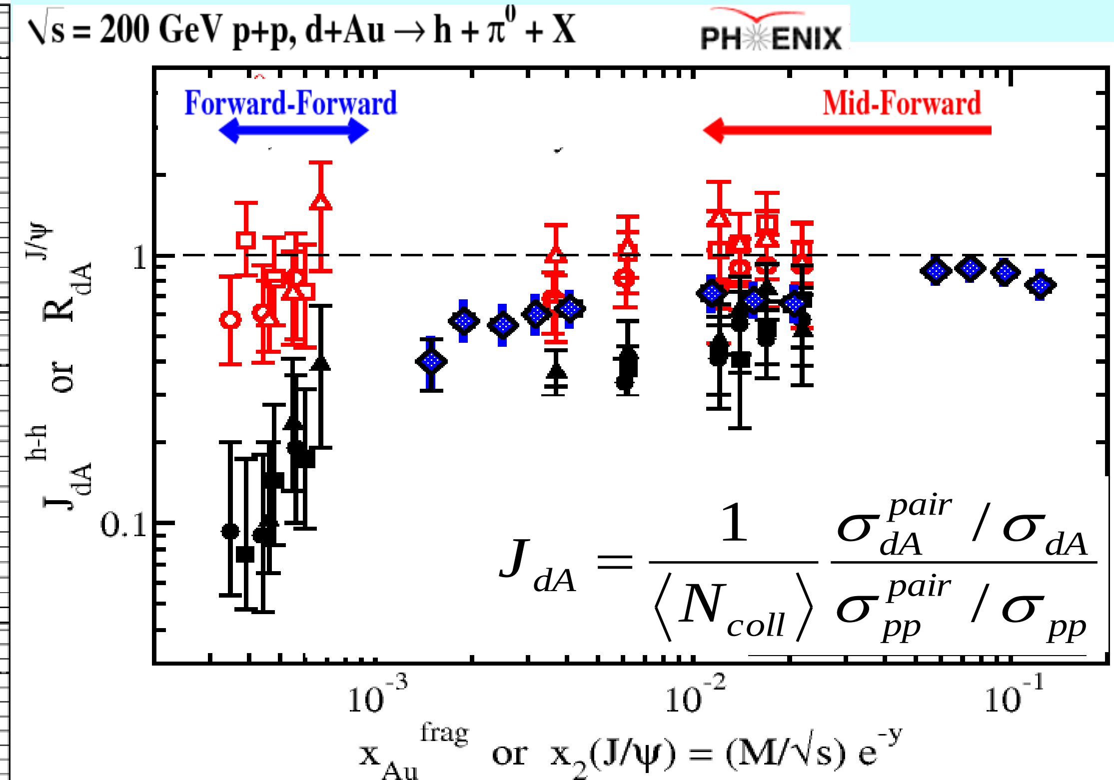


Dense gluonic matter (d+Au, forward y): large effects observed

arXiv:1010.1246



arXiv:1105.5112



Shadowing/absorption stronger than linear w/nuclear thickness

Di-hadron suppression at low x

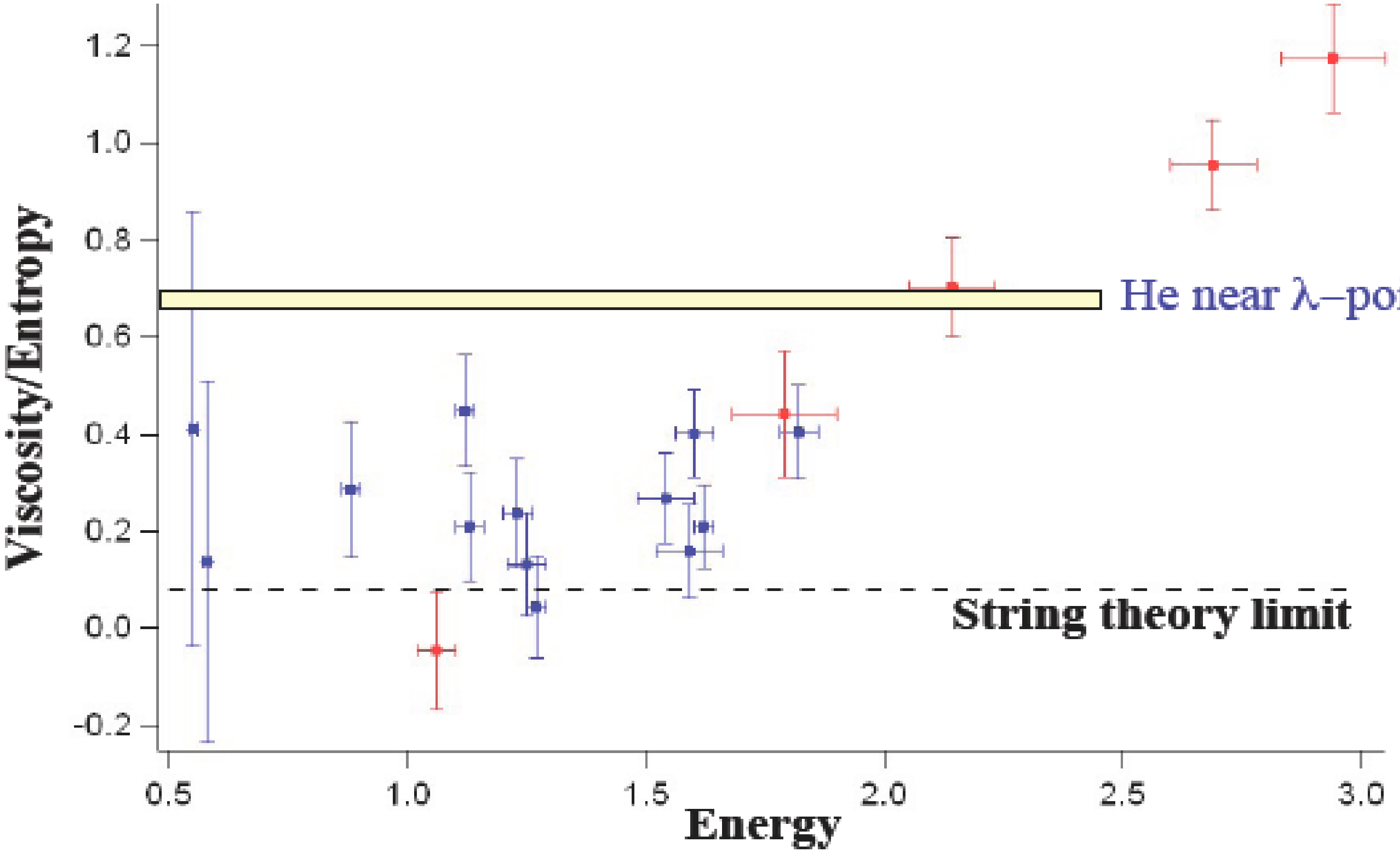
pocket formula (for 2➔2):

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

trend as, e.g. in CGC …

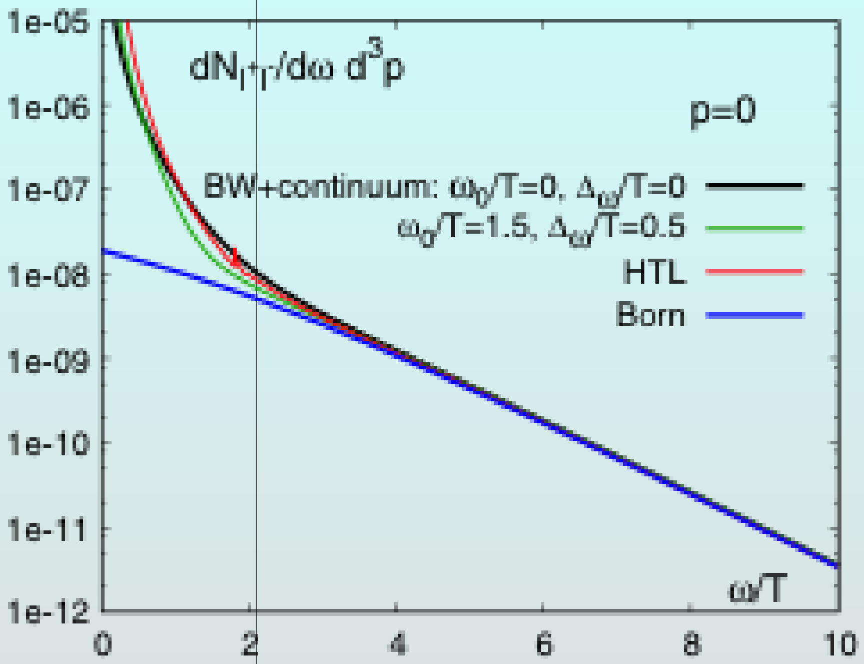
Viscosity/Entropy (natural units)

Duke Physics
Atom Cooling and Trapping



Calculate the correlator on the lattice

➔ non-perturbative contributions to thermal dilepton rates at low mass



From fit to lattice spectral fn. in Phys.Rev.D.83.034504 (2011)

- **For small energy, ω/T<(1-2) spectral function > free form**
- **For ω/T ≃ 1 thermal dilepton rate ~ order of magnitude > leading order Born rate**
- **for ω/T>~(2 − 4) the spectral function is close to the free form**

Heavy quark diffusion

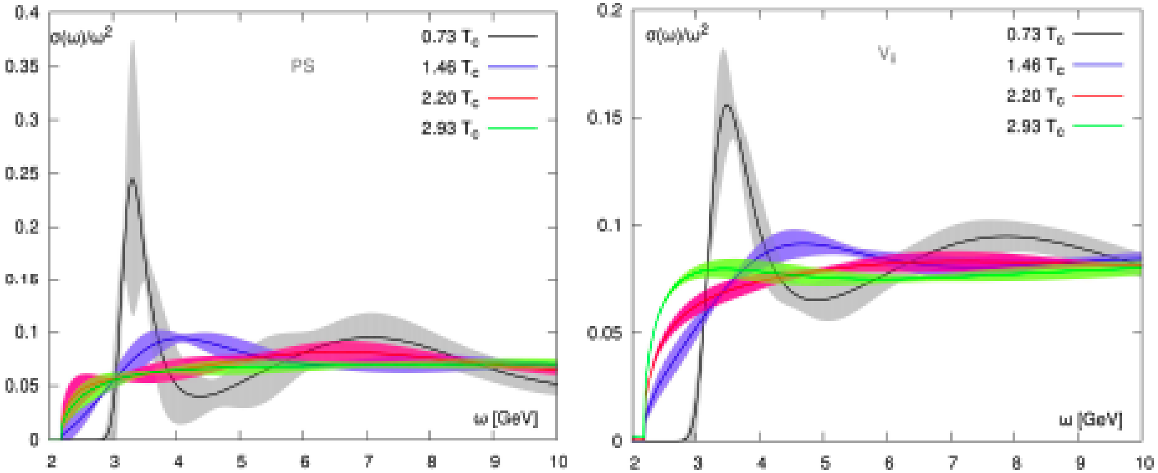


Figure 3. Uncertainties of output spectral functions in PS (left) and V_{ii} (right) channels at all available temperatures. The shaded areas are errors of output spectral functions from Jackknife and the solid lines inside the shaded areas are mean values of spectral functions.

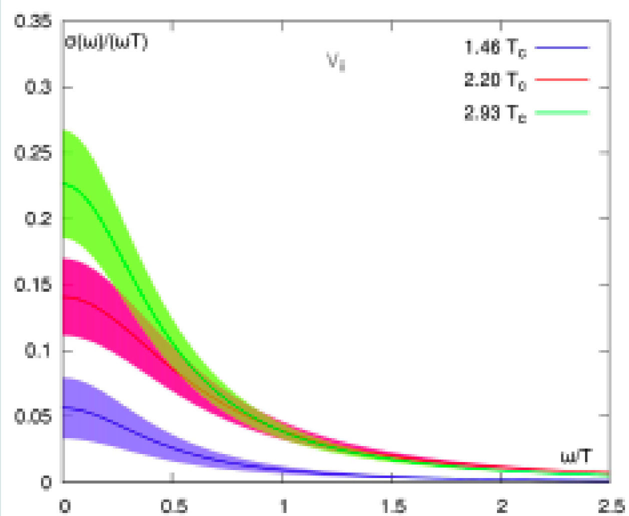
Ding, et al. arXiV: 1107.0311

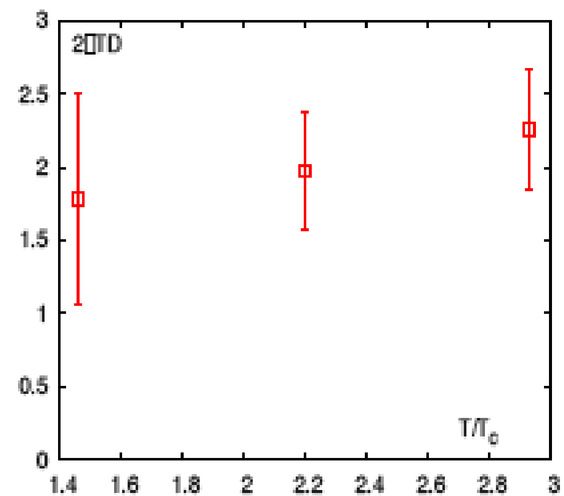
J/Ψ: Not yes/no!

Is the correlation gone @ T >1.5 T_c?

What happens at 1.0-1.2T_c?

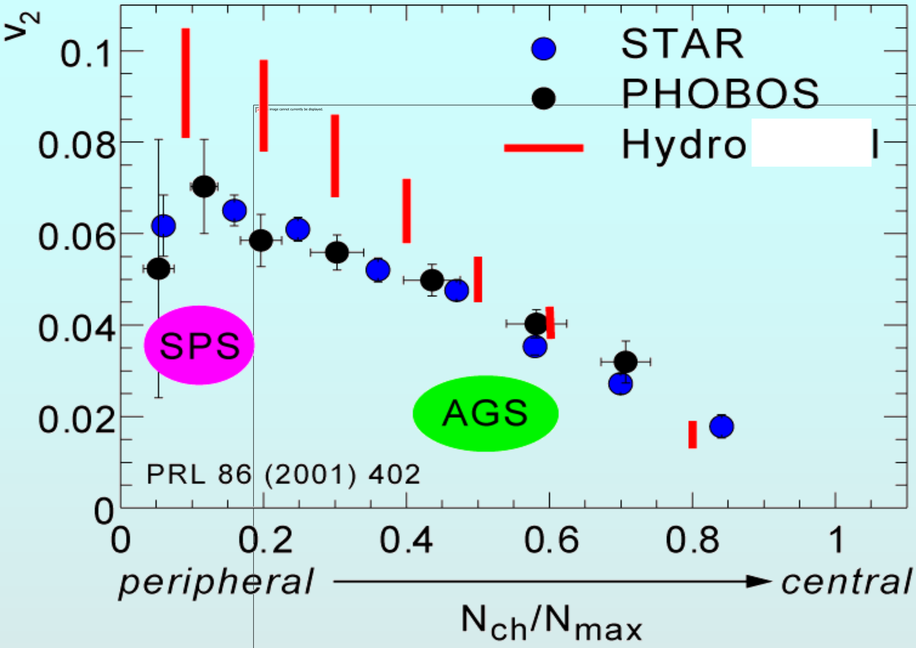
Is there observable evidence of partial screening?





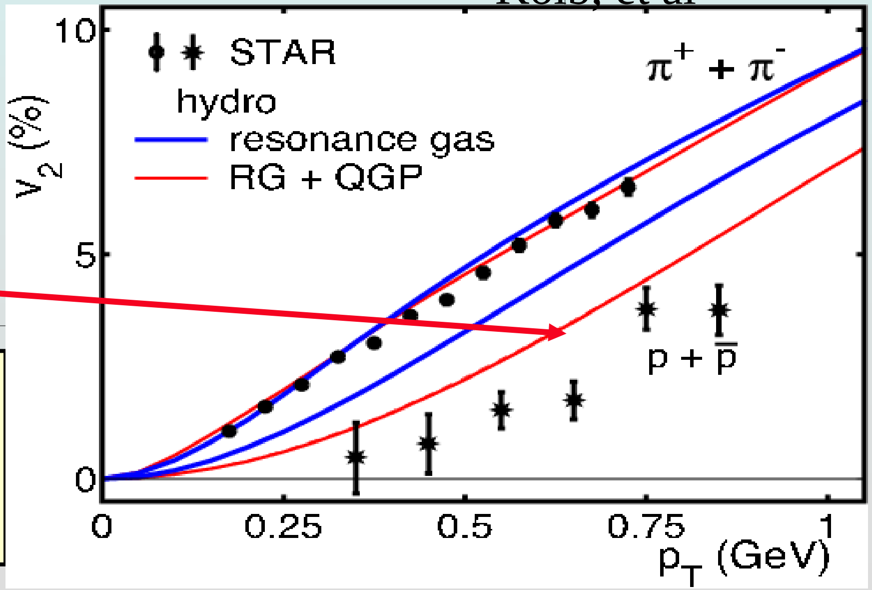
ociation of both J/ψ and η_c at $T \geqslant 1.46\ T_c$.

Matter flows like a ~ideal liquid



- **huge pressure buildup**
- **large anisotropy → rapid equilibration**

Kolb, et al



Hydrodynamics reproduces elliptic flow of q-$\bar{q}$ and 3q states
Mass dependence requires
soft EOS, NOT gas of hadrons

only works if viscosity/entropy is near the minimum for a quantum system (1/4π)
"perfect" liquid (D. Teaney, PRC68, 2003)

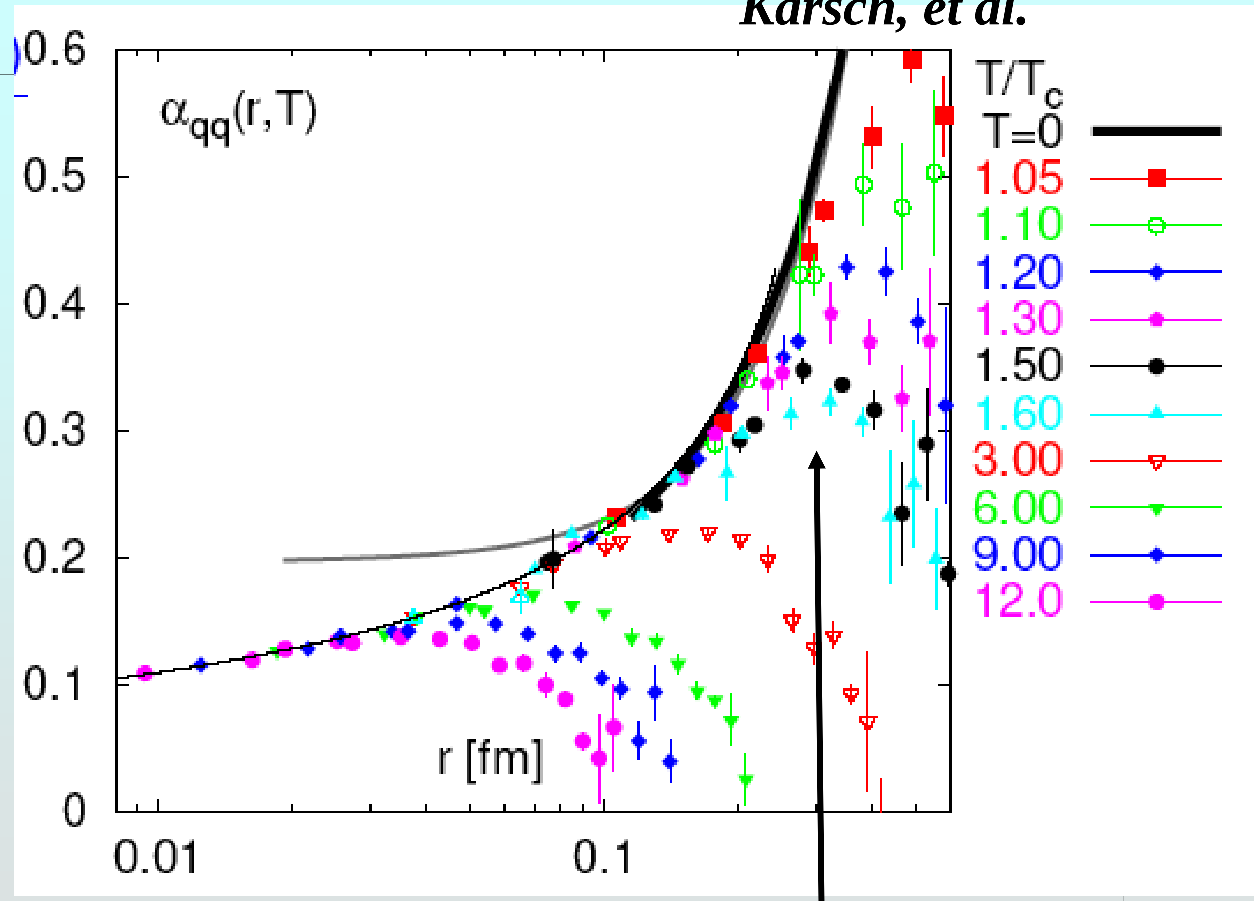
Beam Energy Scan at RHIC

$\sqrt{s_{NN}}$ (GeV)	Status	Experiment
5.0	TBD	STAR
7.7	analyzed	STAR PHENIX (limited statistics)
11.5	analyzed	STAR
19.6	Collected in 2011	STAR, PHENIX
27	Collected in 2011	STAR, PHENIX
39	analyzed	STAR, PHENIX
62	analyzed	STAR, PHENIX
130	collected in Run-1, analyzed limited statistics	STAR, PHENIX

don't give up! ask lattice QCD

Karsch, et al.

running coupling



coupling drops off for r > 0.3 fm

High $m_{eff} \rightarrow$ large collisional energy loss

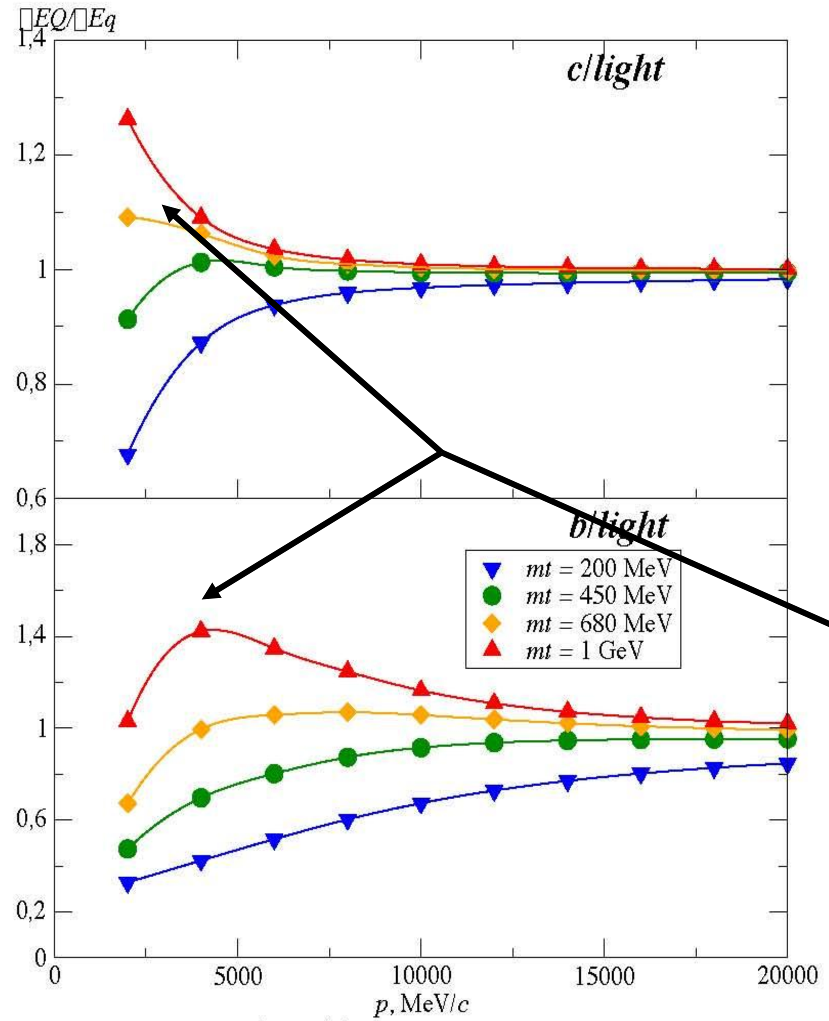
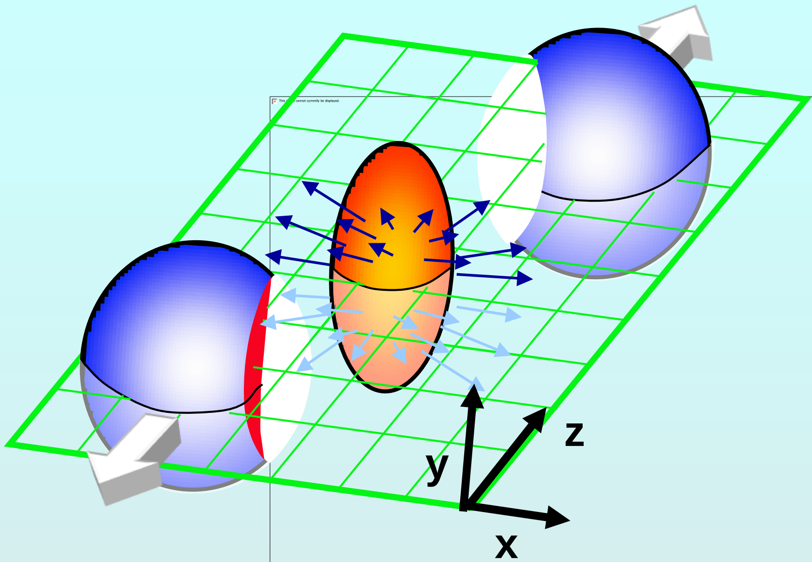


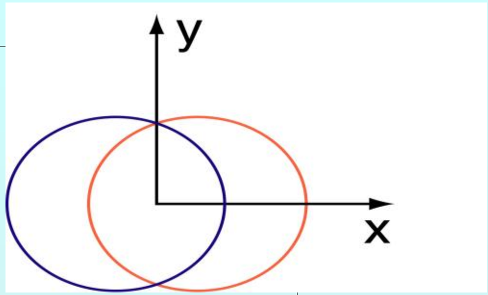
Fig. 3. The heavy-to-light ratio $\Delta E_Q/\Delta E_q$ of collisional energy loss for charm quarks (upper panel) and bottom quarks (lower panel), compared to that of light quarks (m_q = 200 MeV). The results for the numerator ΔE_Q and the denominator ΔE_q are the same as used for plotting Fig. 2.

R. Kolevatov &
U.A. Wiedemann
arXiV:0812.0270

- **Composite quasiparticles?**
- **b/c separation provides the test!**

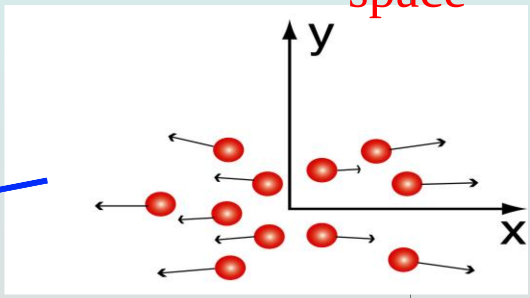
Collective motion & elliptic flow (v_2)

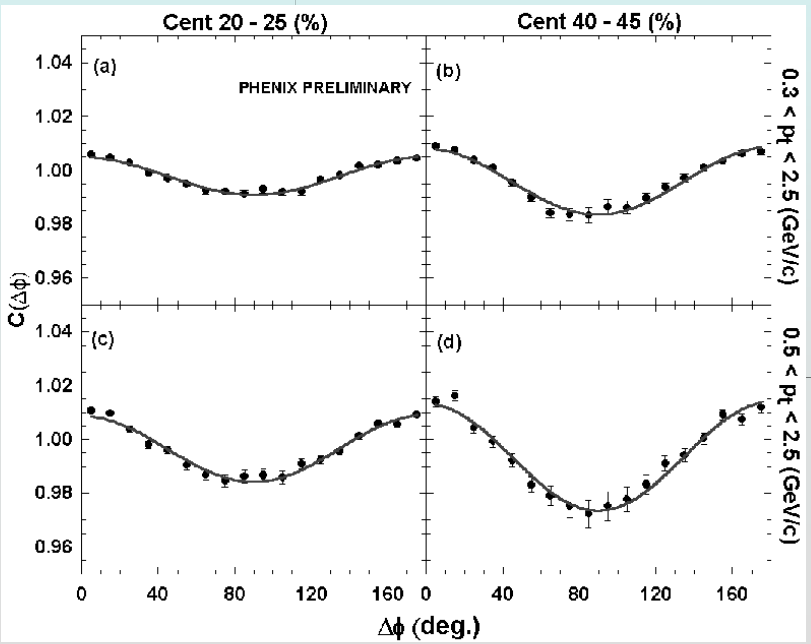




Almond shape overlap region in coordinate space

momentum space





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

hydrodynamics works!