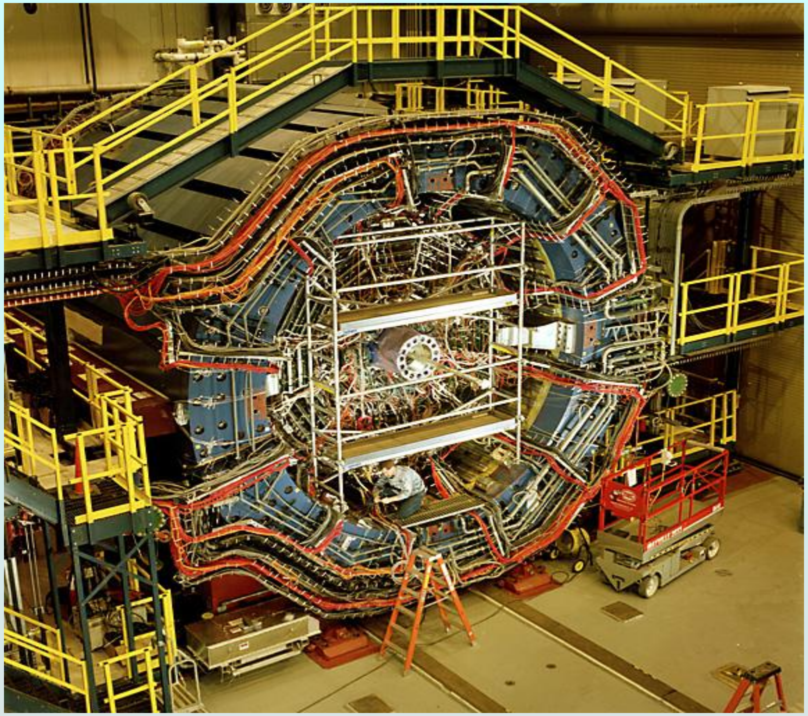
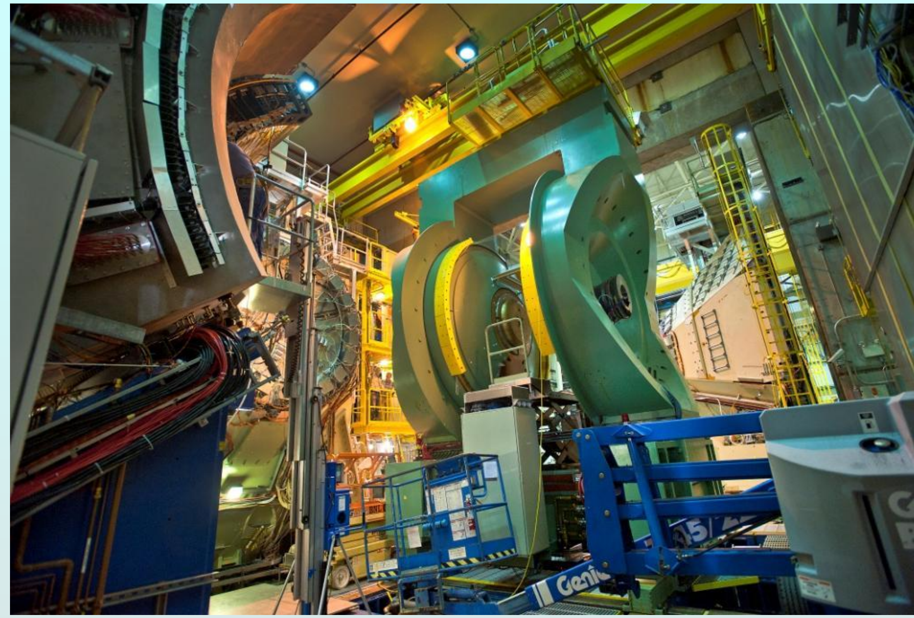
Strongly Coupled Plasma: Properties and Critical Point Search

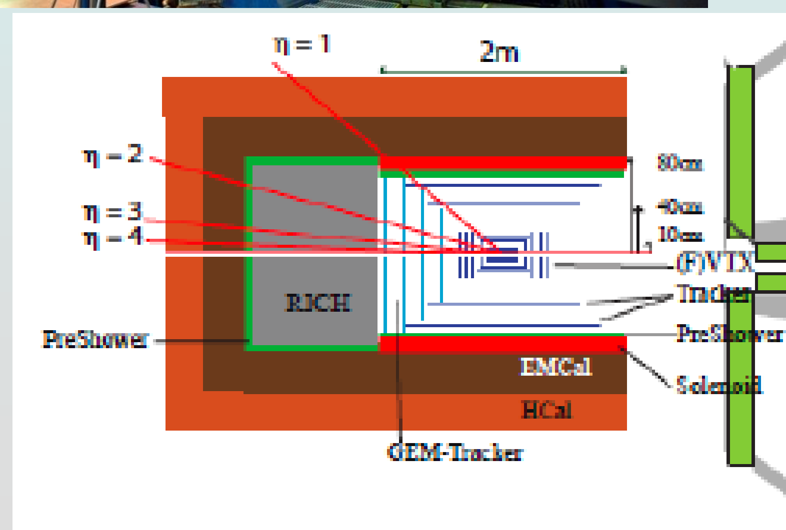




Barbara Jacak, Stony Brook

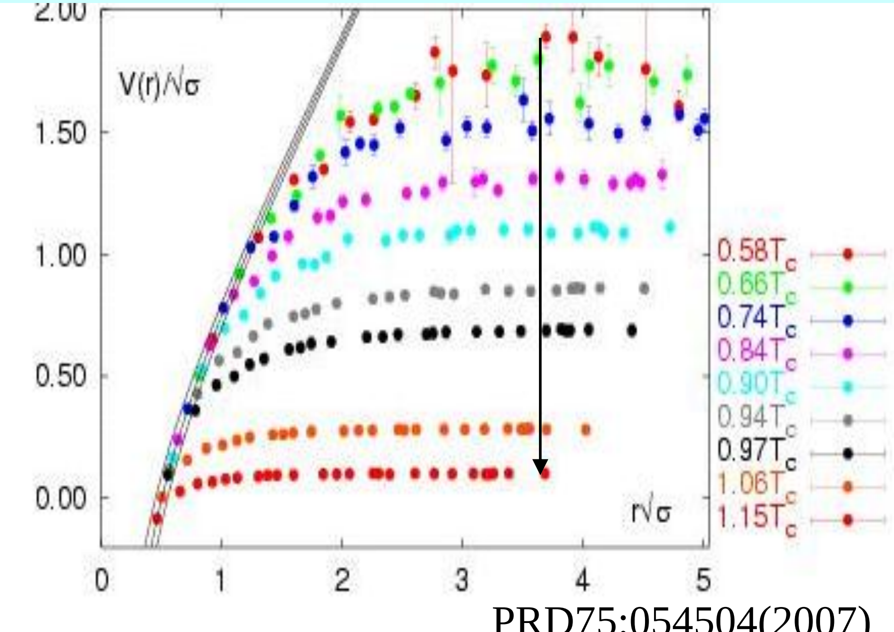
October 4, 2010

ICFA Seminar, CERN

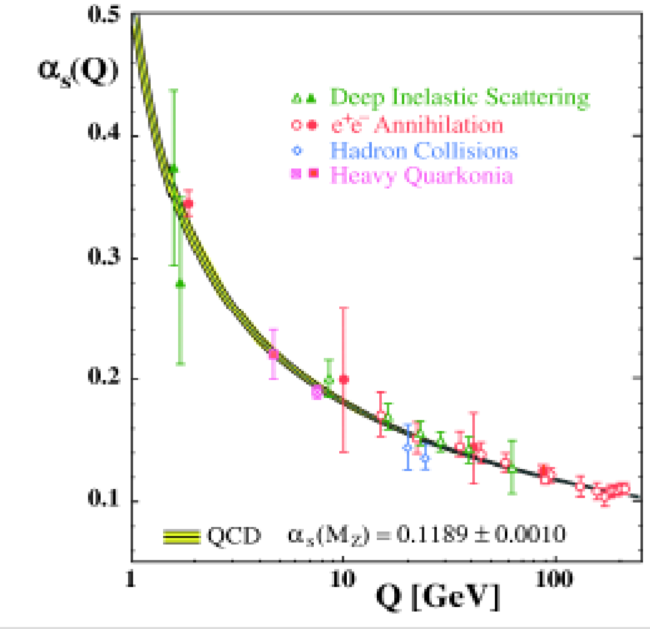


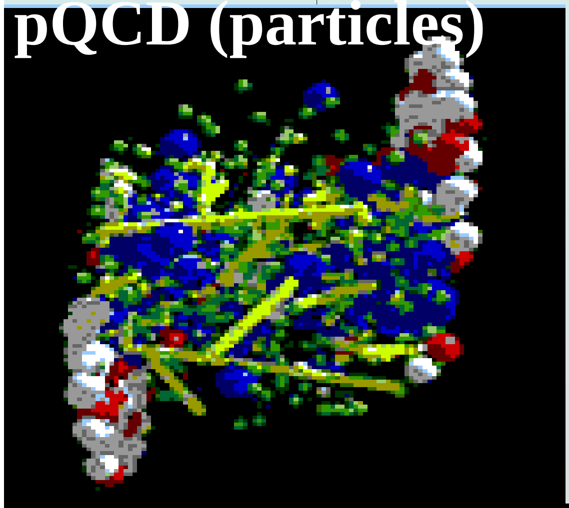
Why Quark Gluon Plasma?

- QCD predicts: @ high T color screening reduces confining potential
- Tc ~ 155 MeV
- Asymptotic freedom in the medium?



PRD75:054504(2007)





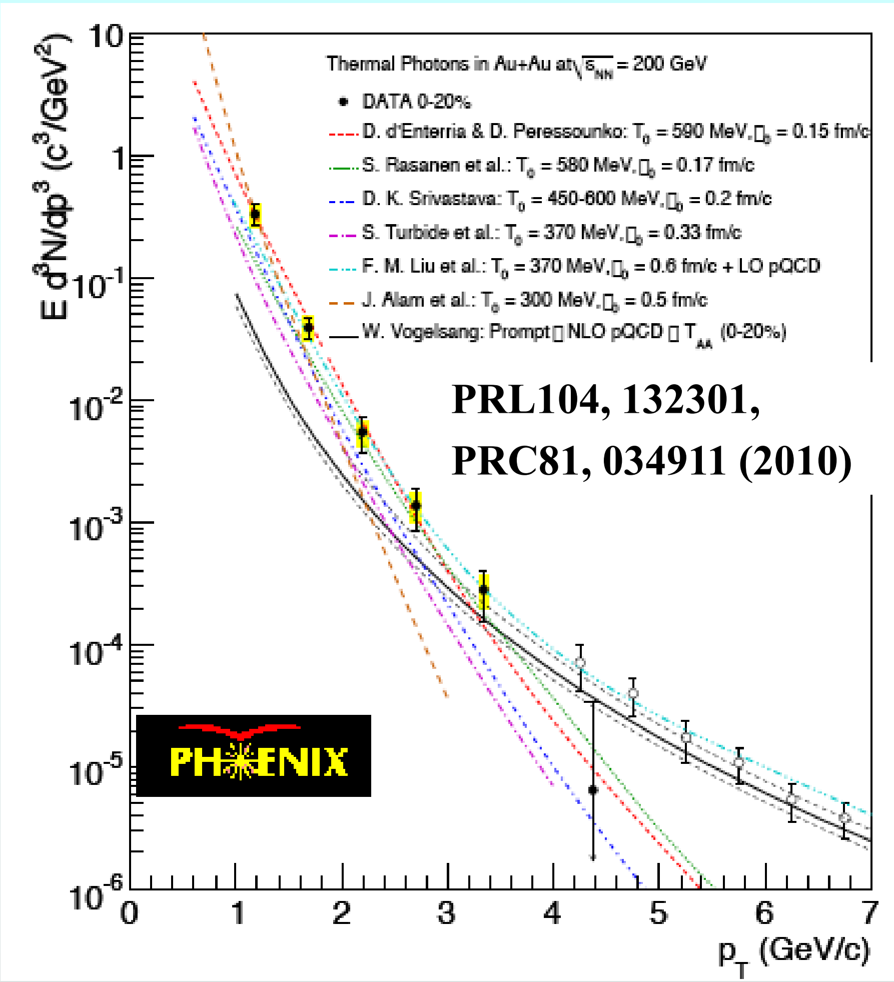
2→3,3→2,n→2…

Explore the region near T_c

Relativistic Heavy Ion Collider at Brookhaven

SPS at CERN

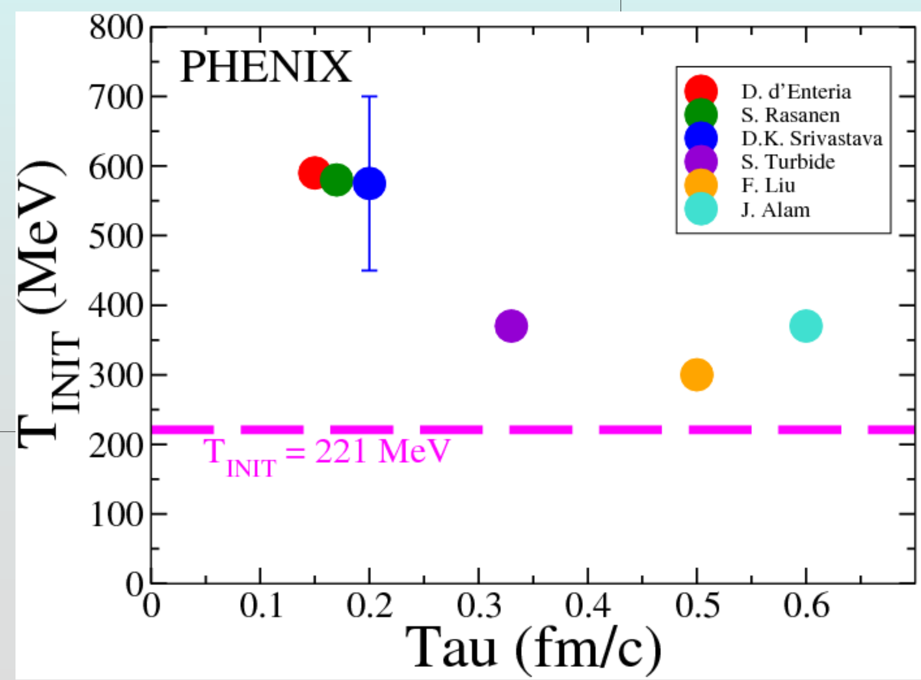
γ_{dir} shows $T_{initial} > T_c$ at RHIC



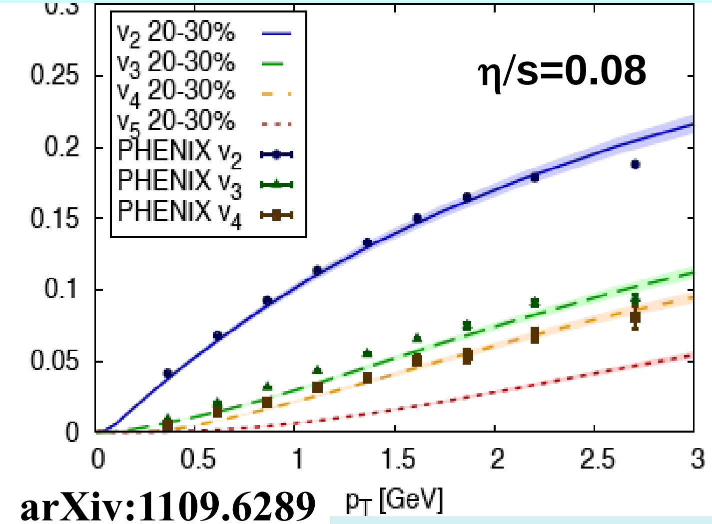
PRL104, 132301,
PRC81, 034911 (2010)

✓ **Exponential fit p_T spectrum slope = 221 ±23 ±18 MeV**

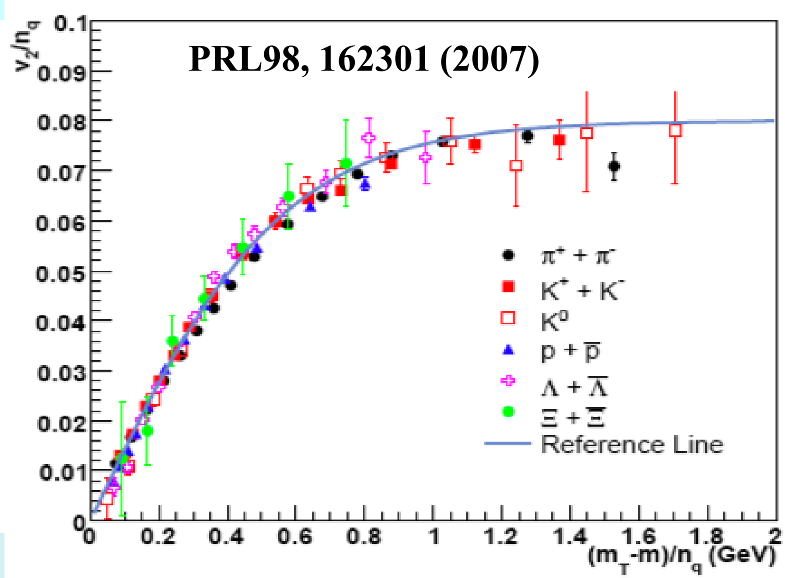
✓ **Hydrodynamics reproduces γ's; vary thermalization time $T_{init} \geq 300$ MeV, $\tau < 1$ fm/c**

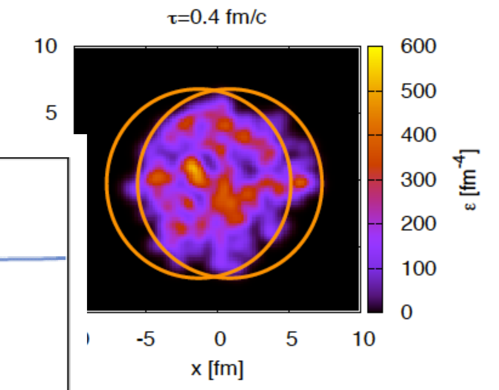


Bulk matter flows collectively



arXiv:1109.6289





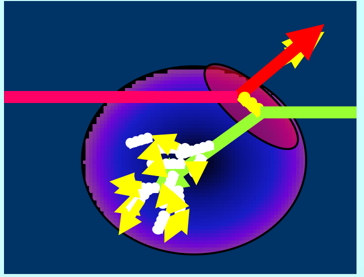
ourier analyze
article emission
attern

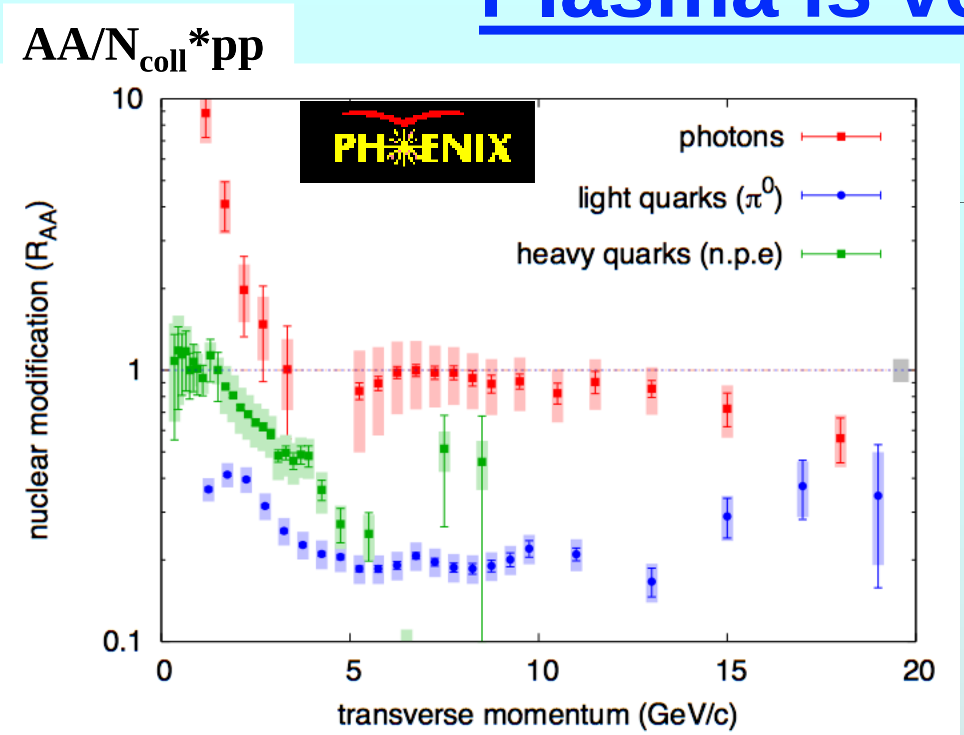
- ✓ Hydrodynamic flow of hadrons @ p_T < 2 GeV/c
- ✓ Nearly <u>ideal</u> hydro flow! η/s near quantum bound 1/(4π)
- ✓ Thermalization in < 1 fm/c

<u>Low η/s→ good momentum transport ∴ strong coupling</u>

- *How can equilibration be achieved so rapidly?*
- *What are the initial conditions?*
- *Are there quasiparticles in the quark gluon plasma? If so, when and what are they?*

Plasma is very opaque





✓ Colored particles suffer large energy loss

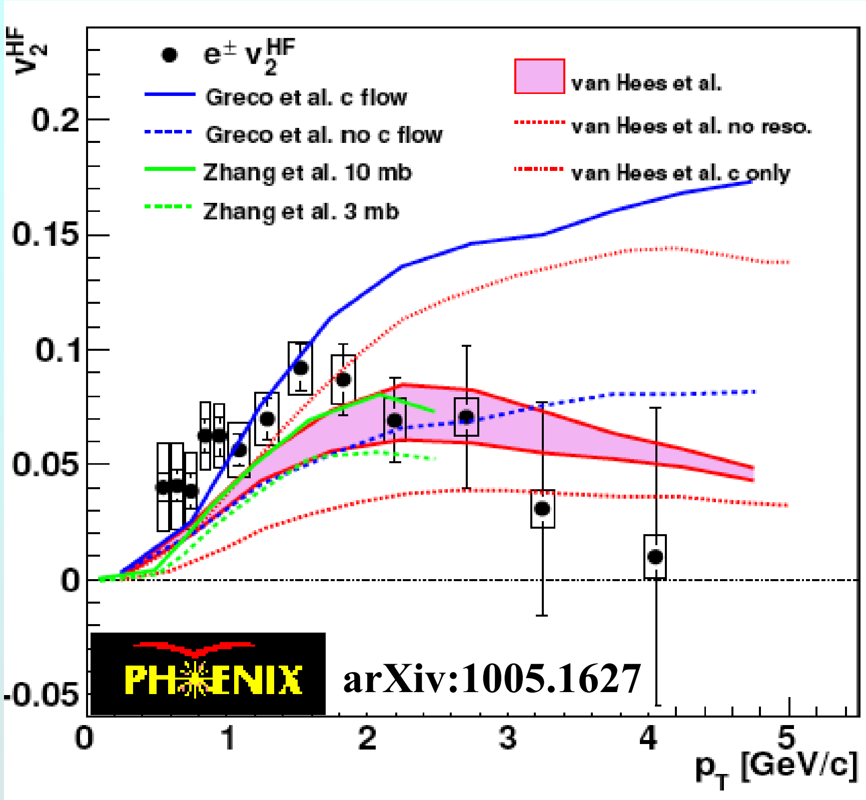
✓opaque up to high p_T

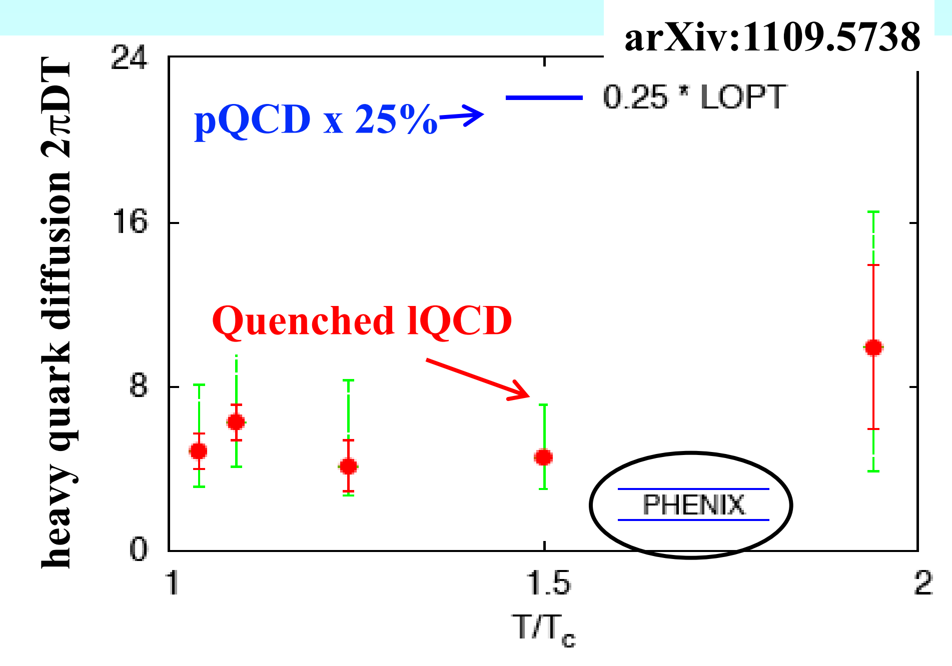
A challenge for pQCD (g radiation dominated)

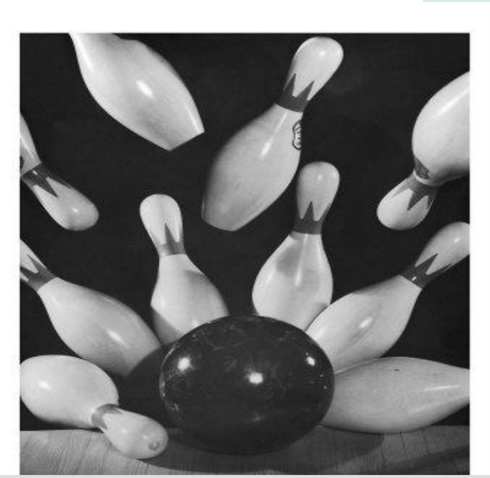
Radiation + collisional energy loss?

- ***At what scales (distance, E, M) is coupling strong?***
- ***What mechanisms for parton-plasma interactions? For plasma response?***

Even heavy quarks lose energy & flow!





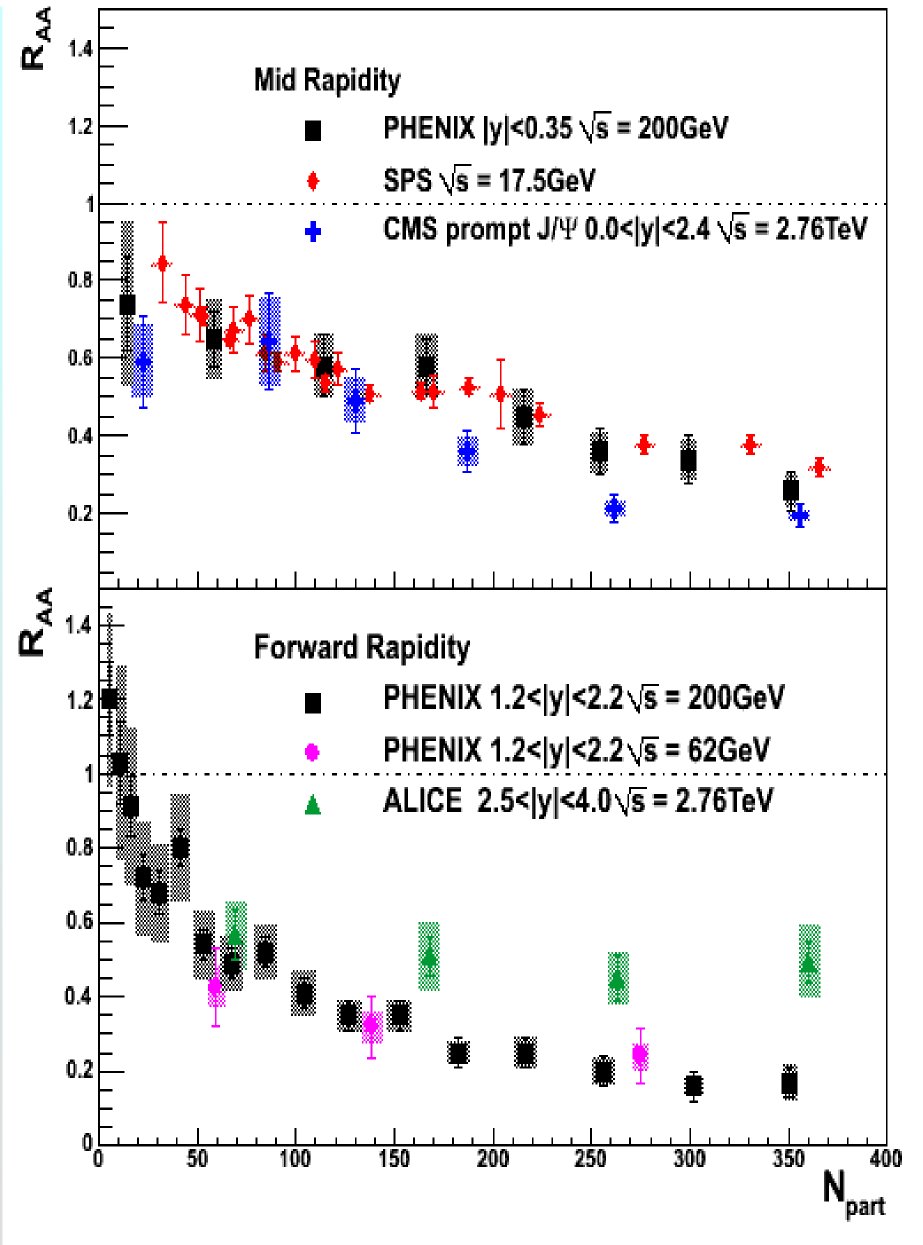


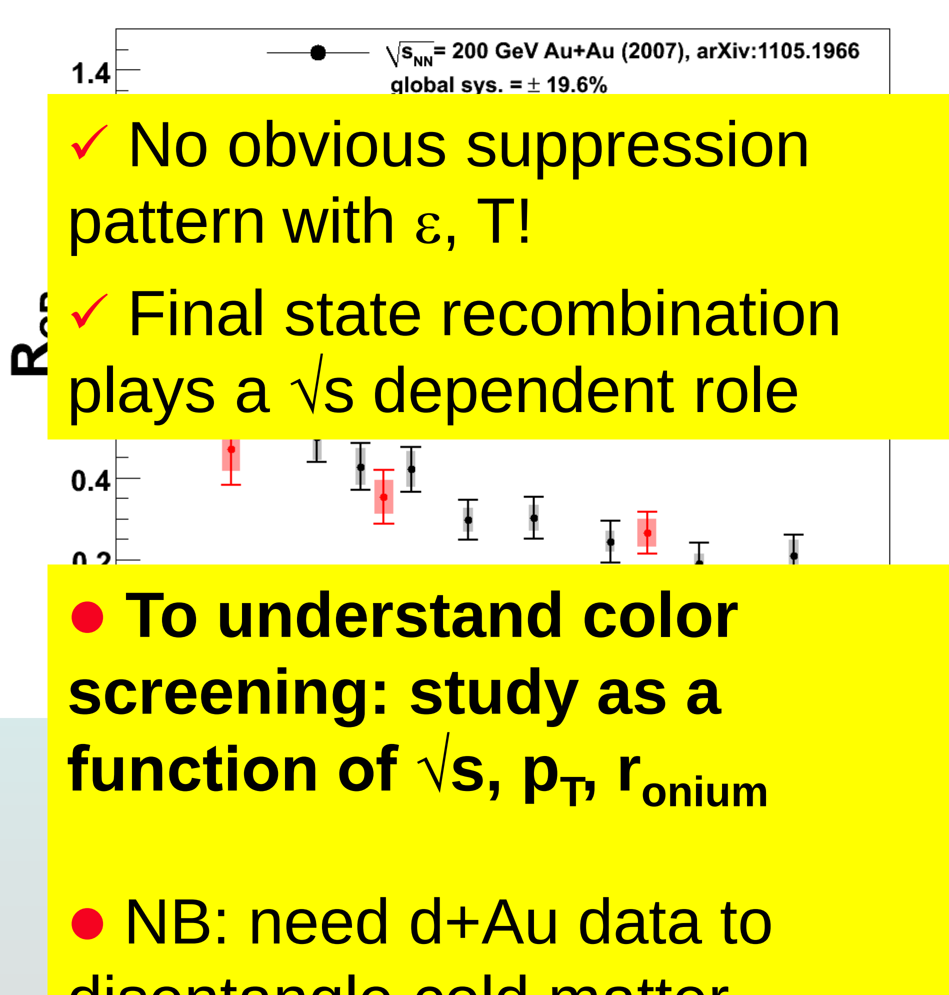
- At what scales (distance, E, M) is the coupling strong?
- What is the parton-plasma interaction?
  Is there a plasma response?
- Are there quasiparticles?

added evidence for strong coupling!

J/ψ: color screening in QGP?

AA/N_{coll}*pp

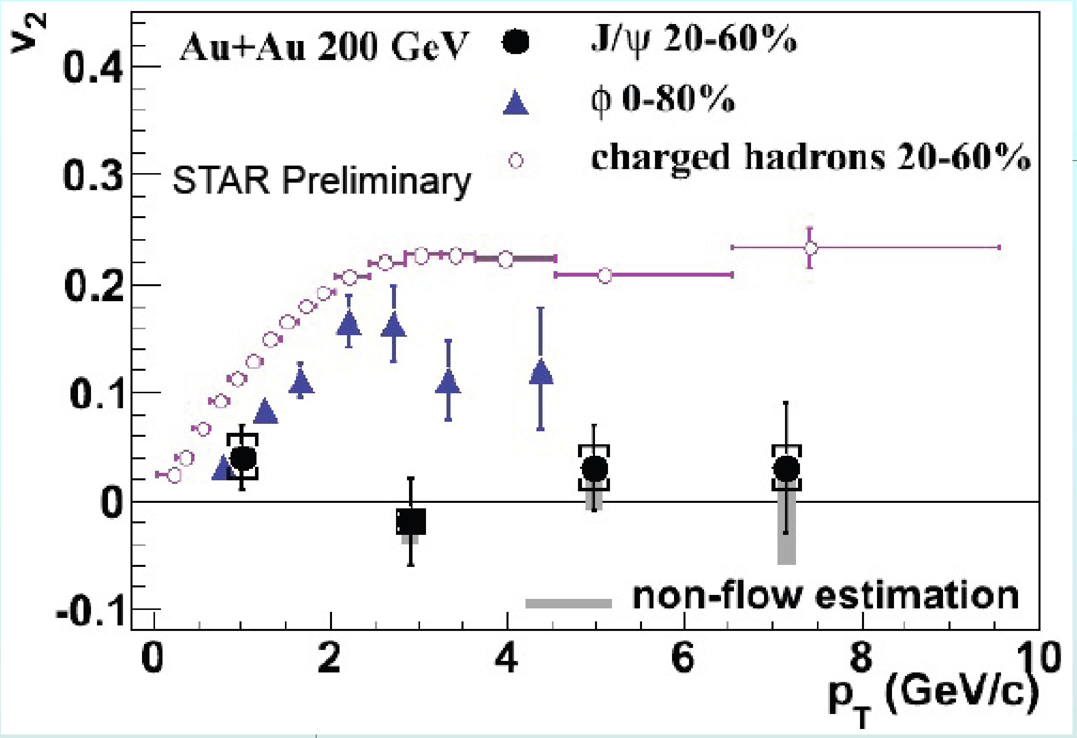




- ✓ No obvious suppression pattern with ε, T!
- ✓ Final state recombination plays a √s dependent role

- **To understand color screening: study as a function of √s, p_T, r_{onium}**
- NB: need d+Au data to disentangle cold matter effects in initial state

Effect of final state $c\bar{c}$ coalescence?



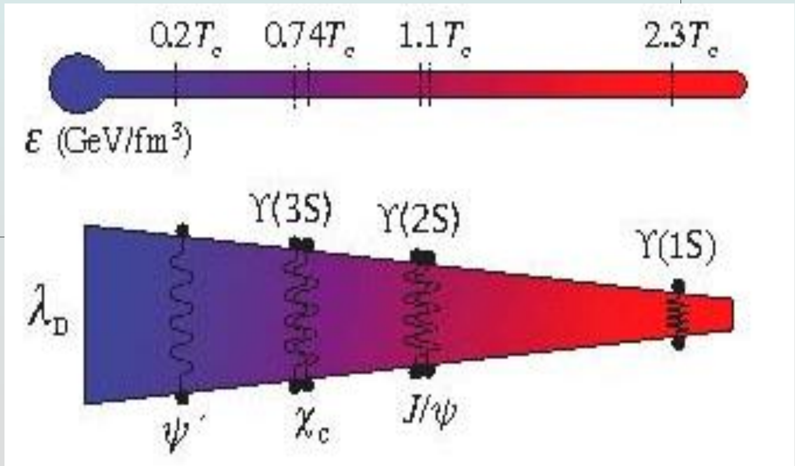
Open charm flows but J/ψ does not

➔c-cbar coalescence @ RHIC is not large

Correlations remain in QGP due to strong coupling?

Need ϒ 1S, 2S, 3S

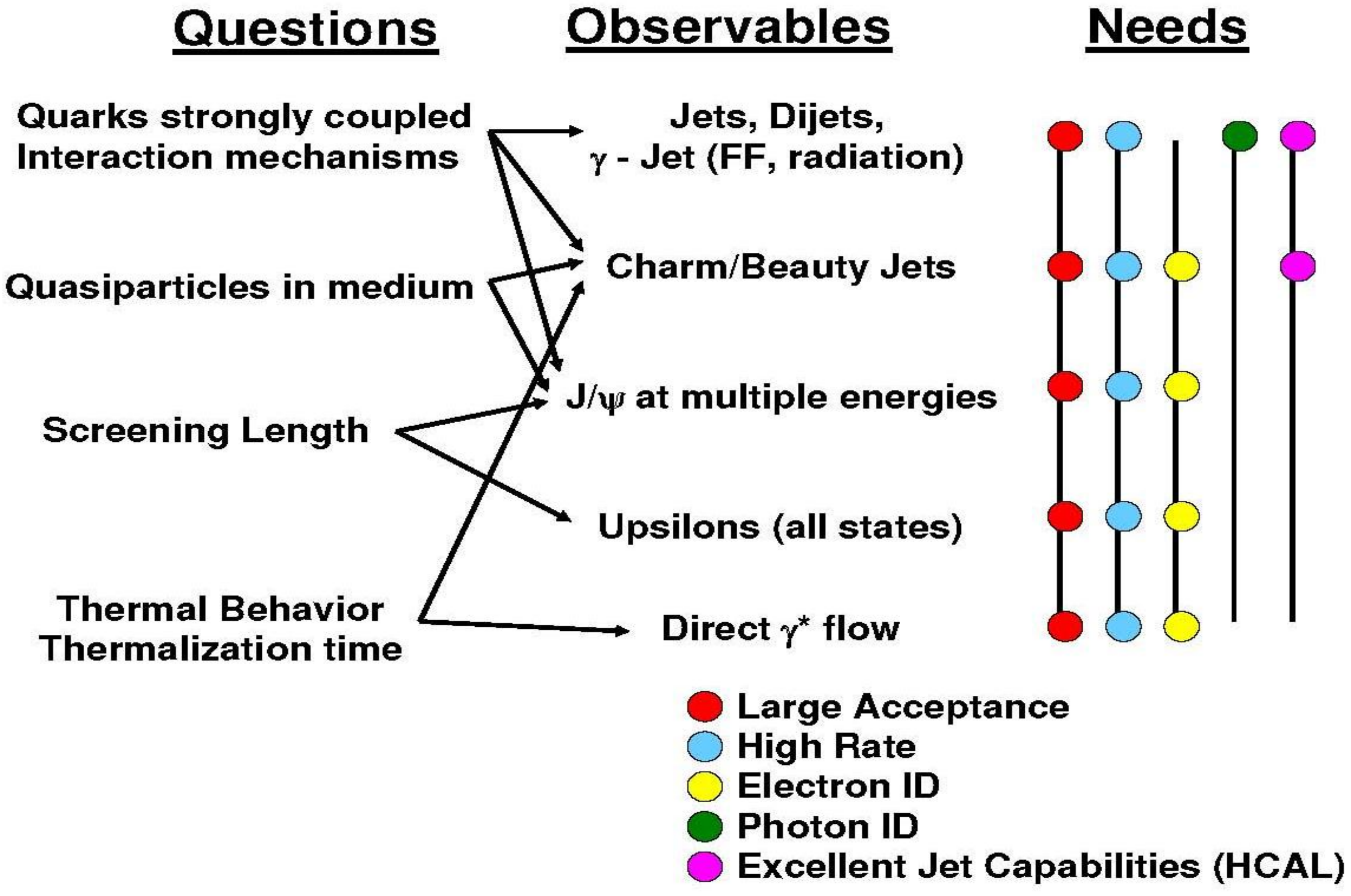
● *Is there a relevant color screening length?*



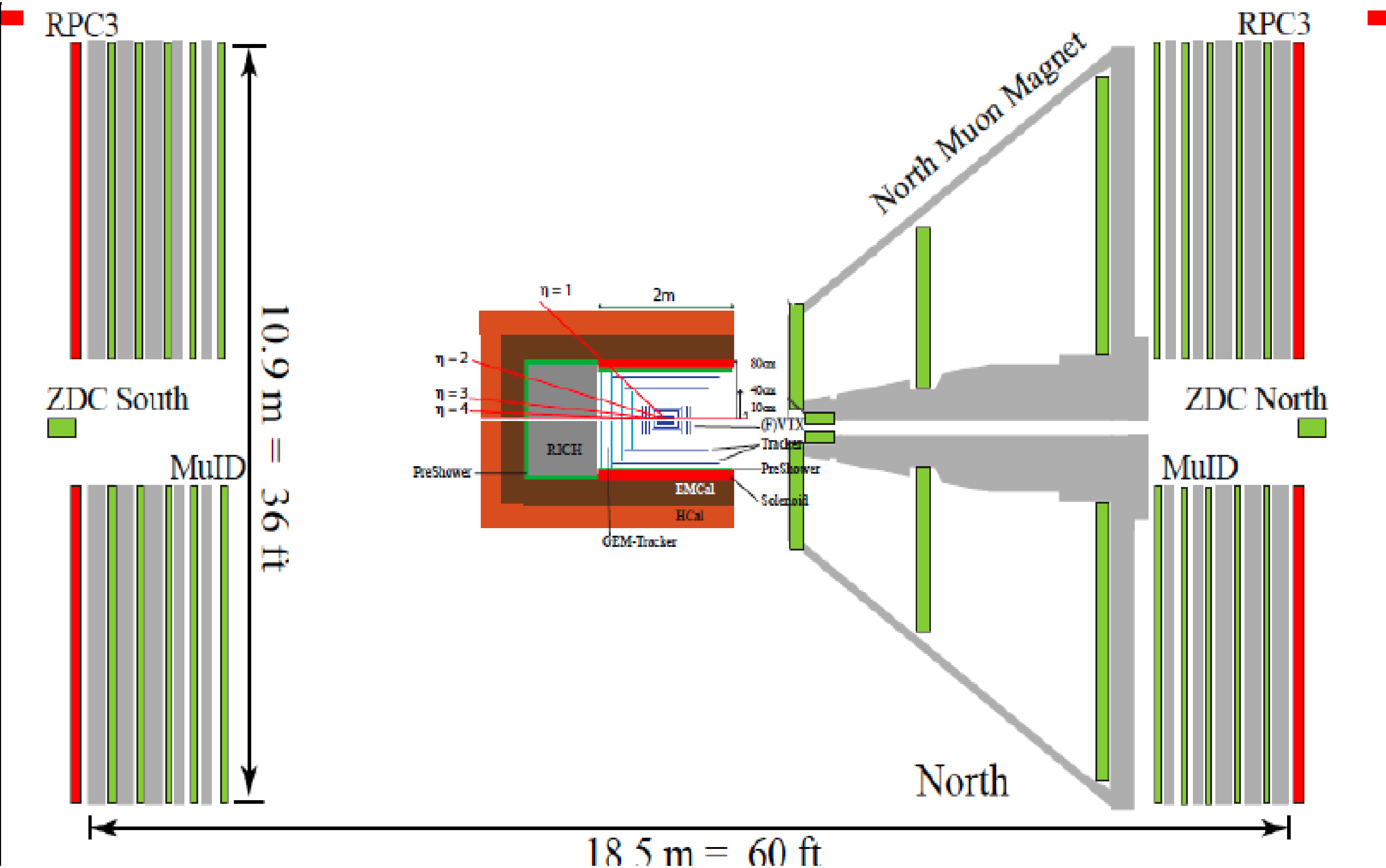
New questions from RHIC & LHC data!

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

To answer these questions



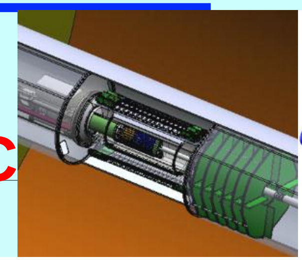
Upgrade PHENIX to answer the questions

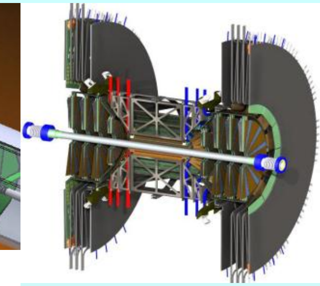


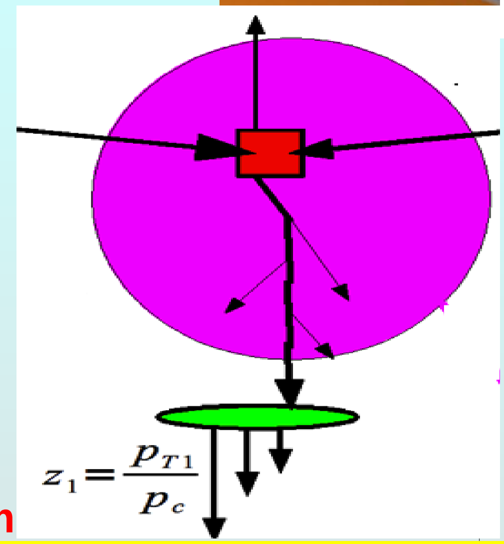
Compact, hermetic, EM + hadron calorimetry

Use RHIC's key capabilities*

- Coupling scale & quasiparticle search
  - charm hard(not thermal) probe @ RHIC
  - c vs. b in QGP
- parton-plasma interaction
  - Jets ≤ 50 GeV, γ-jet
  - E_{jet}, ℓ, q_{mass}, angle dep. of dE/dx
  - Jet virtuality ~ medium scale
- Screening length
  - study as function of $\sqrt{s}$, p_T, r_{onium}
- Thermalization mechanism
  - γ_{dir} yield, spectra & flow
- QCD in cold, dense (initial) state
  - y dependence in d+Au
  - Gluon saturation scale?
  - EIC







Au+Au
Cu+Au
U+U

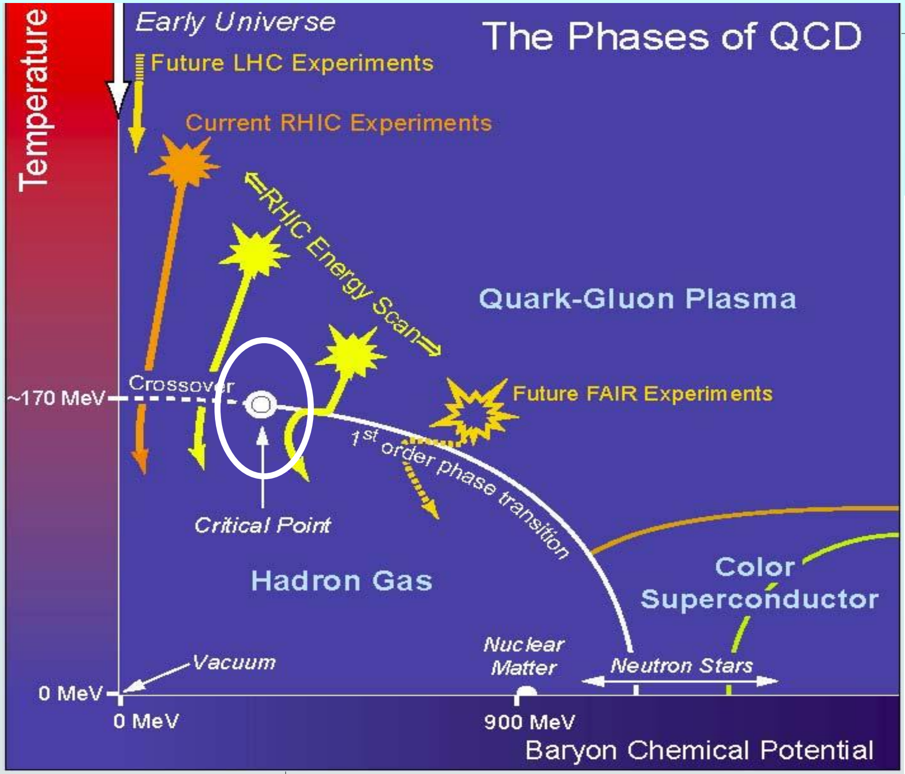
rare probe scan:
50<$\sqrt{s}$ <200 GeV &
asymmetric systems

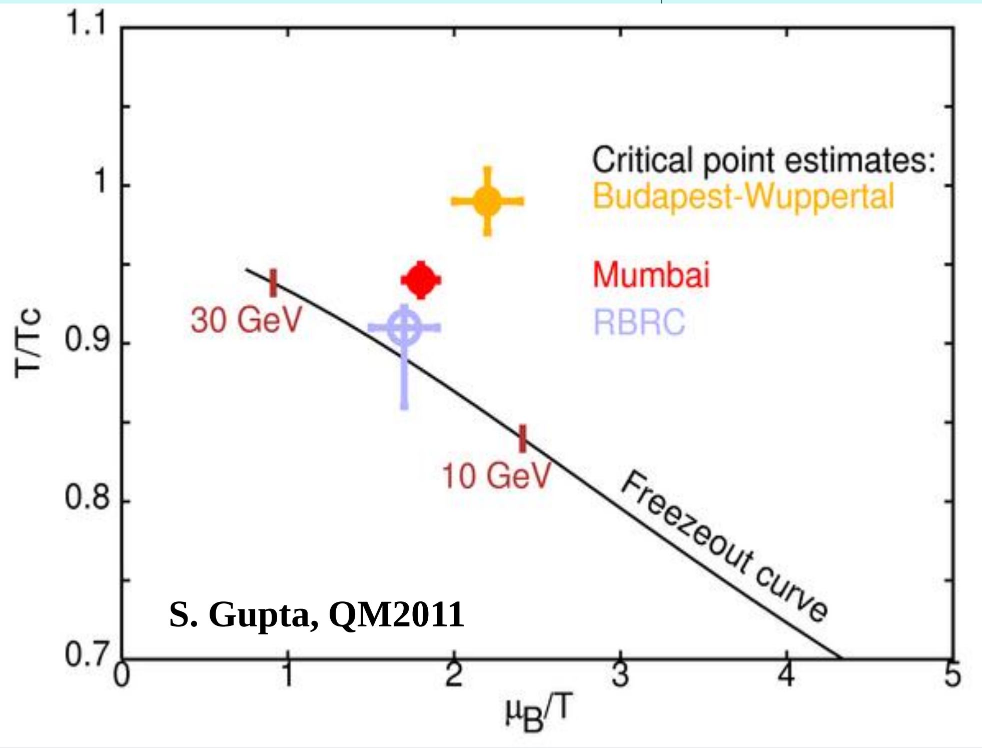
Luminosity x10 at RHIC

Large acceptance in both STAR & PHENIX

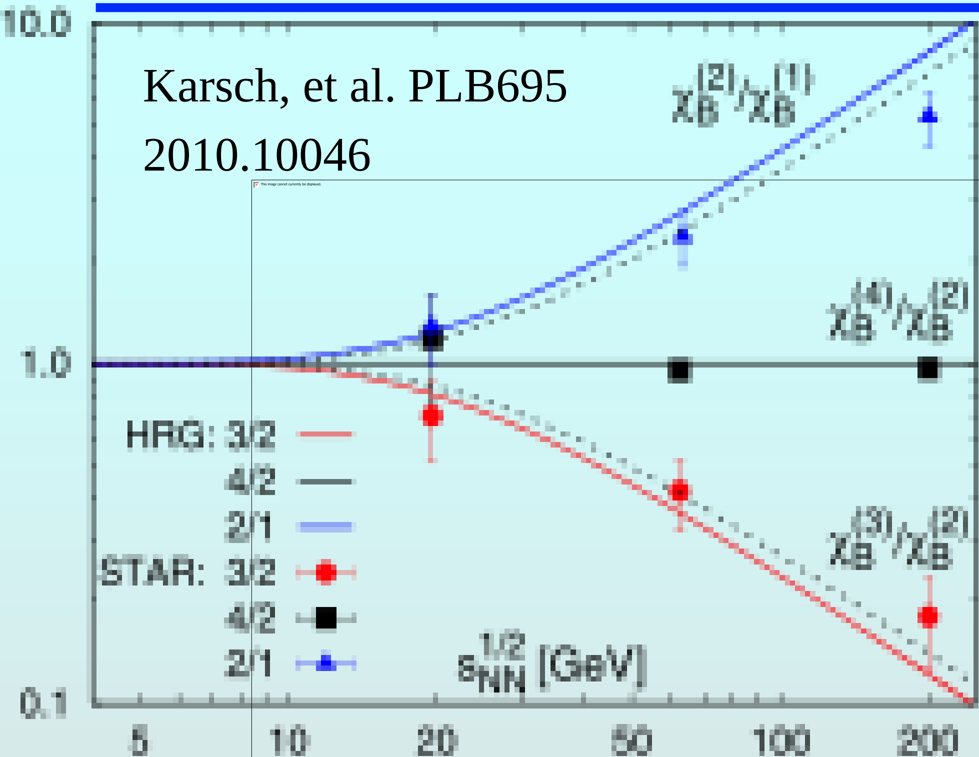
*In the era of P

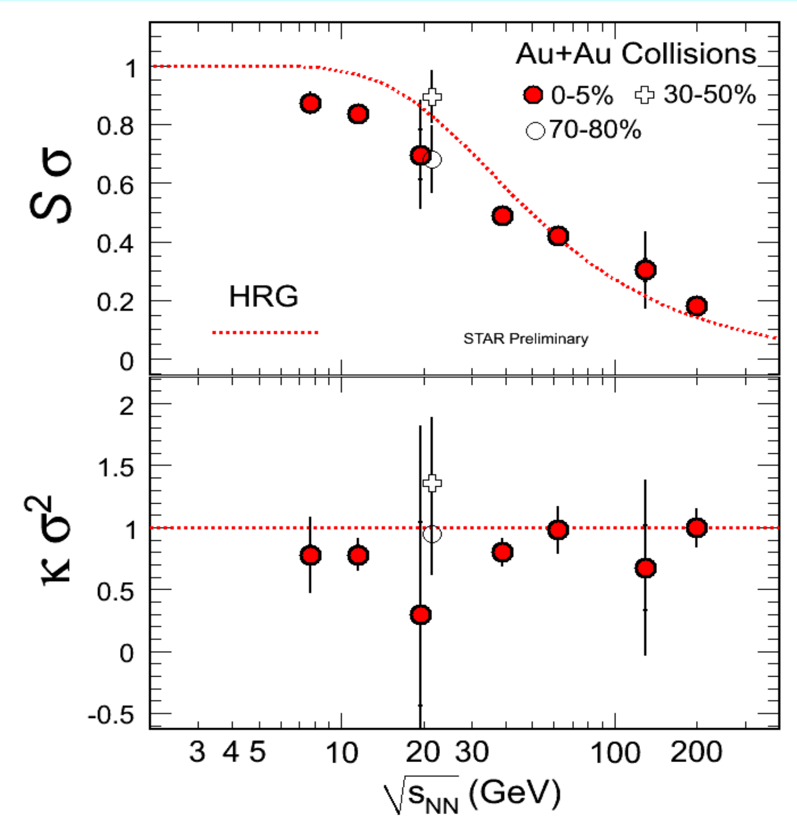
Can we locate the QCD critical point?





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

Beam Energy Scan Plans

RHIC (Au+Au)

$\sqrt{s_{NN}}$ (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

SPS

species	Status	year
p+p	done	2009-2011
Be + Be	Next for NA61	2011-2012
Ar + Ca	NA61	2014
Xe + La	NA61	2015
Pb + Pb	NA49 did	1996-2002
p+Pb		2012/2014

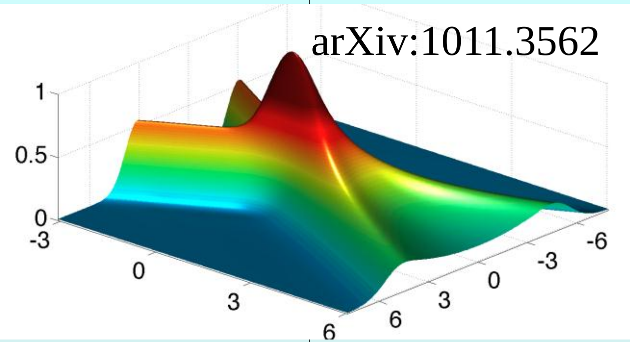
SPS scan:

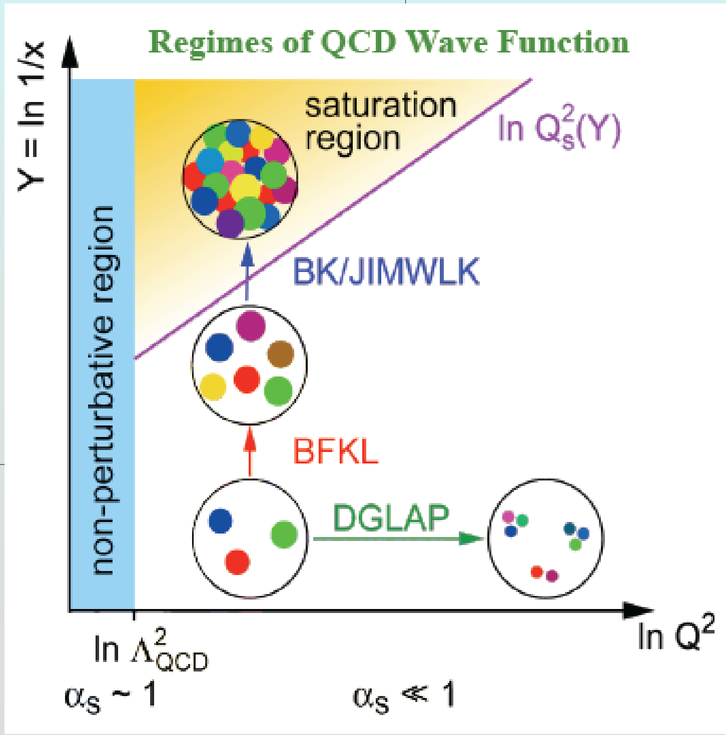
13, 20, 30, 40, 80, 158 GeV/A

Search also for onset of deconfinement

Rapid thermalization?

- Parton cascade is simply not fast enough
- A number of cool, inventive ideas
  Plasma instabilities?
  v. strong coupling (holographic)
    -> hydro valid after 3 sheet thicknesses!
  Shatter a color glass condensate?

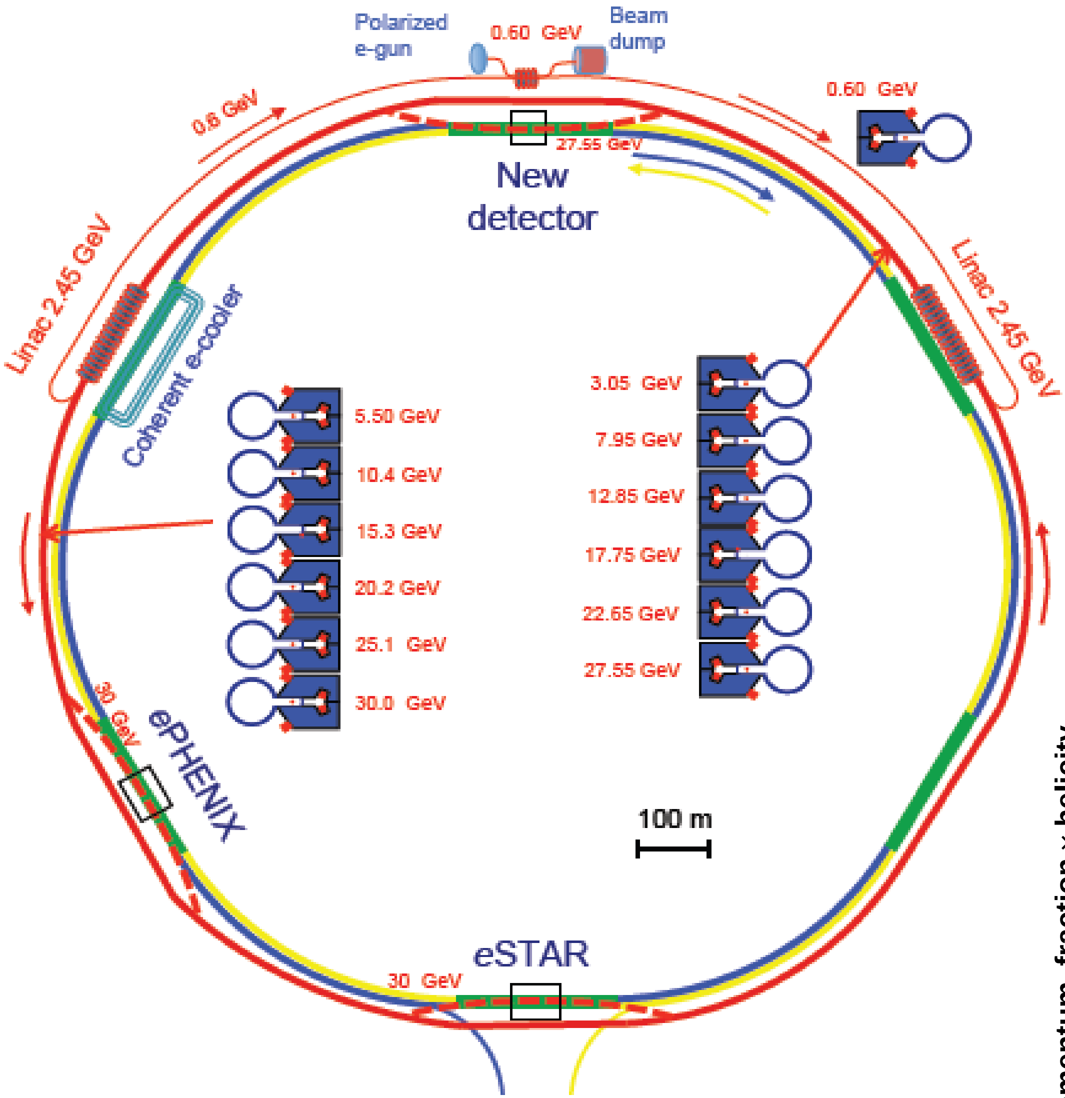


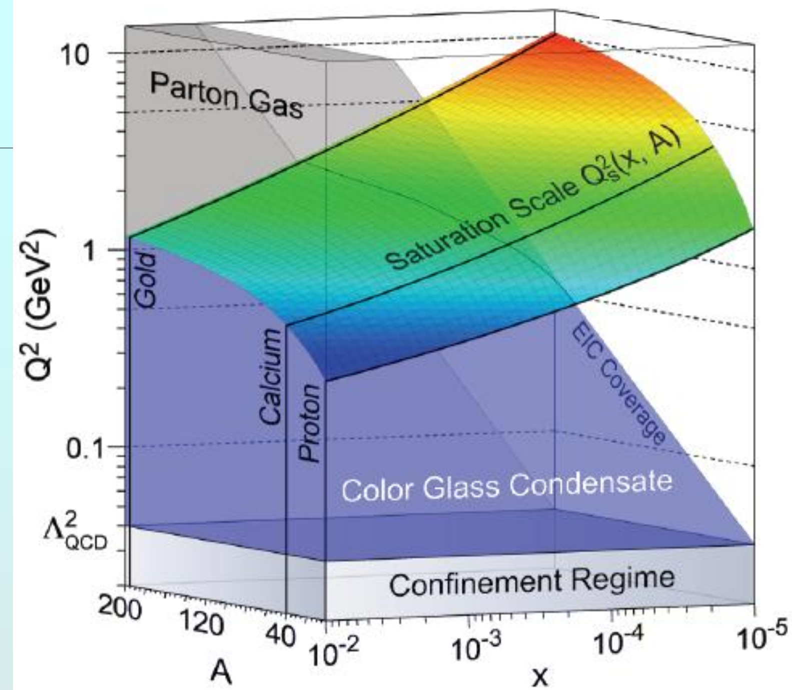


- A paucity of predicted experimental observables
  Needs more theory work
- Understanding the initial state (cold gluonic matter) is key

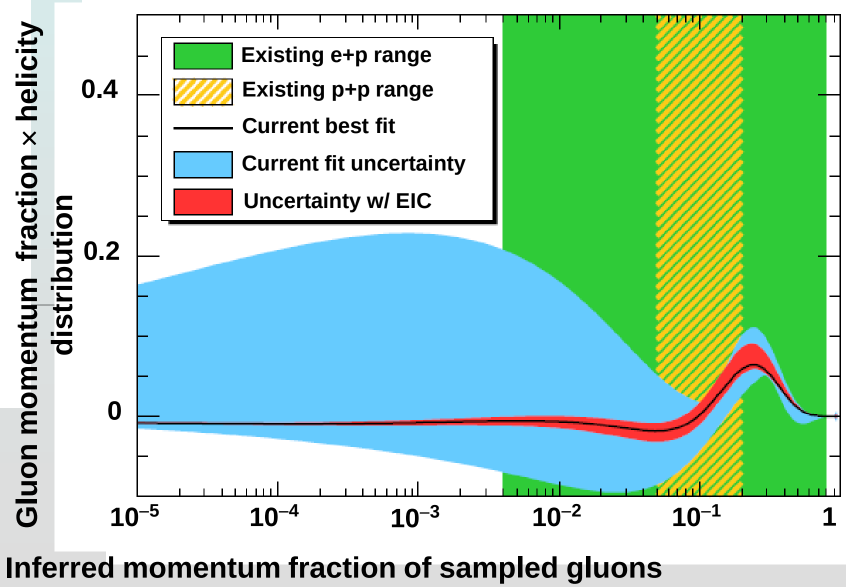
Electron-ion collider; e-$\vec{p}$ collider

10x100





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$



RHIC's future - hot and exciting

- **Near-term (2011-2016)** **Stochastic cooling ➔ 4 x 10^{27}; Cu+Au**

  New microvertex detectors for heavy quark probes

  Quantify properties of near-perfect fluid QGP (v_n)

  Quantify features of the QCD phase diagram

  Study novel symmetries, exotic particles

- **Medium-term (2017-2022) Upgraded detectors**

  Upgrade PHENIX: compact, large acceptance jet, quarkonia, photon detector

  Add forward spectrometer, muon telescope to STAR

  Attack the list of new QGP questions

  Study parton transverse spin in polarized p+p

- **Long-term (≥ 2023) Electron-Ion Collider**

  Add ~5 GeV (upgradable to 30 GeV) electron Energy Recovery Linac inside RHIC tunnel

  e+A, e+$\vec{p}$ ($^3\vec{He}$) for GPDs, Δg, gluonic cold matter

- **Backup**

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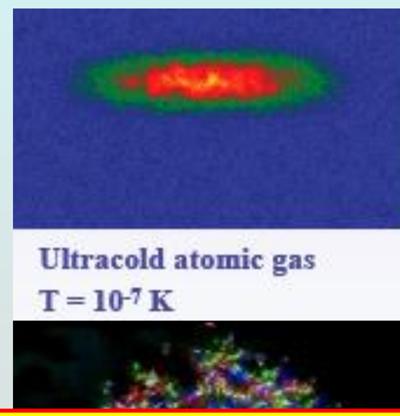
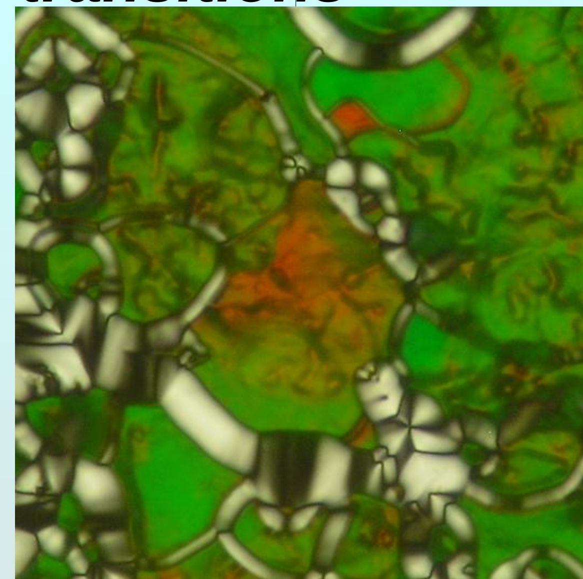
Many types of strongly coupled matter

Quark gluon plasma is like other systems with strong coupling - all flow and exhibit 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?

Properties of hot QCD matter?

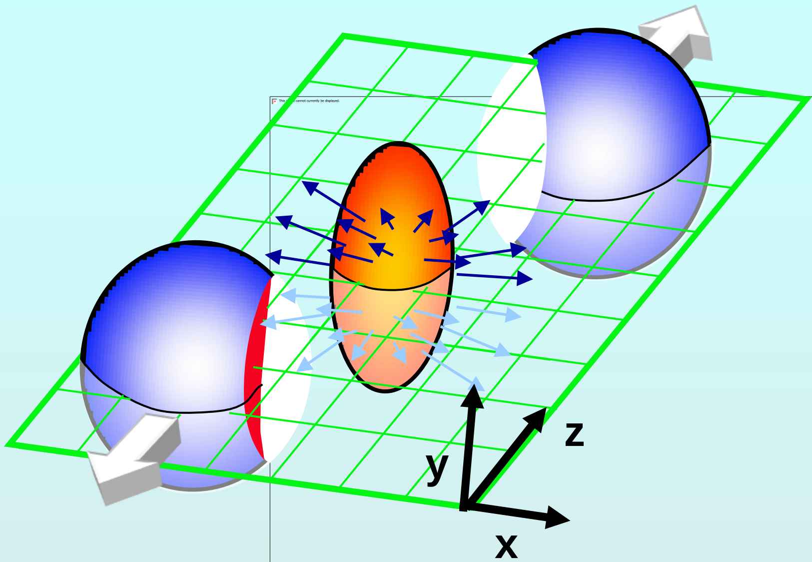
- **thermodynamic (equilibrium)**
  T, P, ρ
  Equation Of State (relation btwn T, P, V, energy density)
  v_{sound}, static screening length

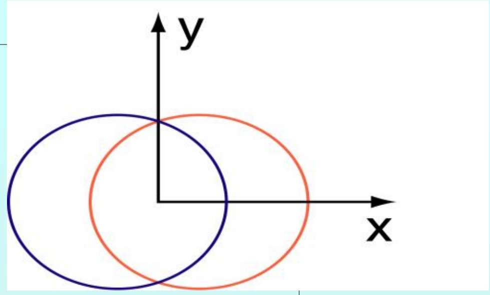
- **transport properties (non-equilibrium)***
  particle number, energy, momentum, charge
  diffusion sound viscosity conductivity

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…

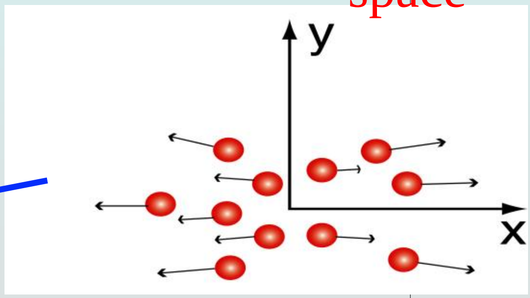
Measuring collective flow: start with v_2

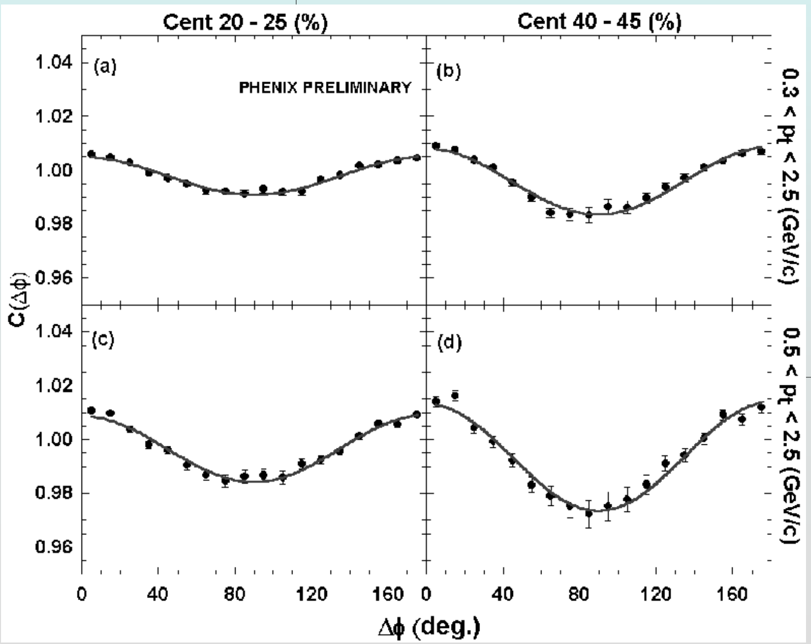




Almond shape overlap region in coordinate space

momentum space

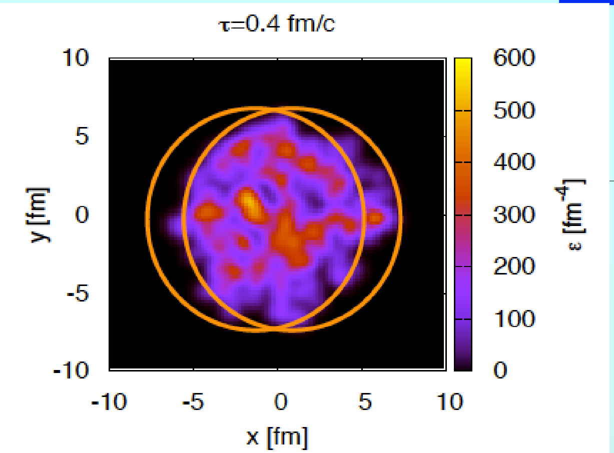


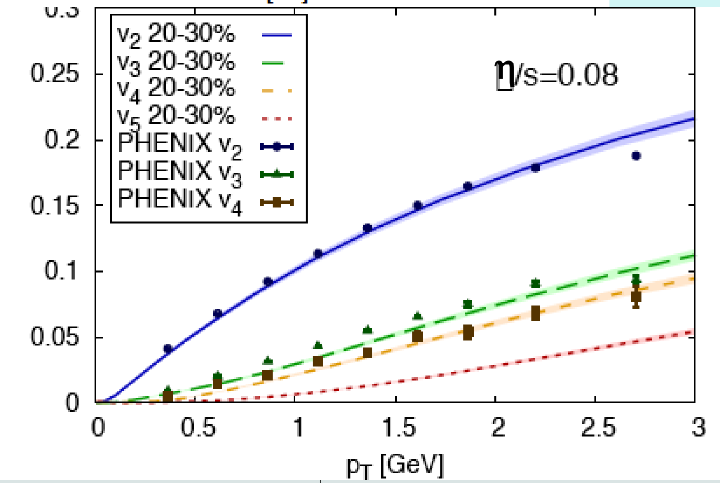


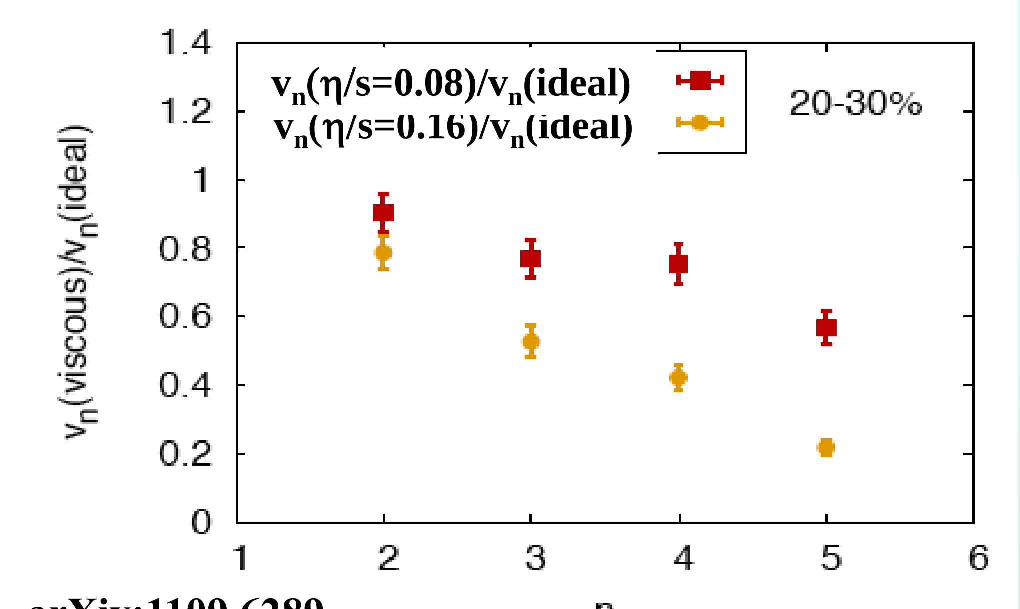
$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

"elliptic flow"

Quantify the viscosity







arXiv:1109.6289

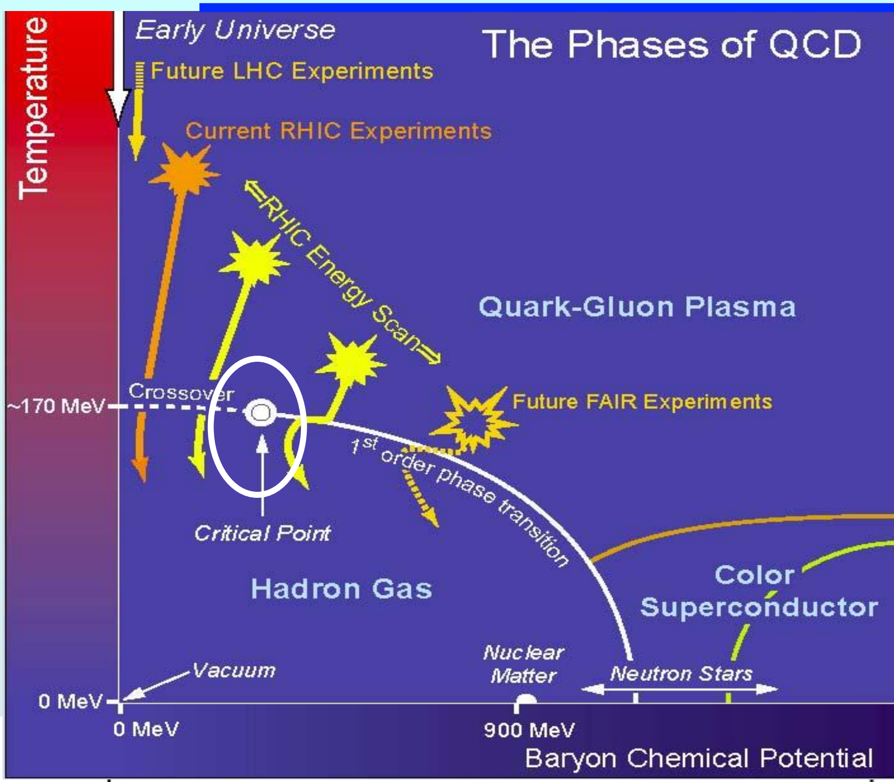
✓ Viscosity/entropy ratio near quantum bound $1/(4\pi)$

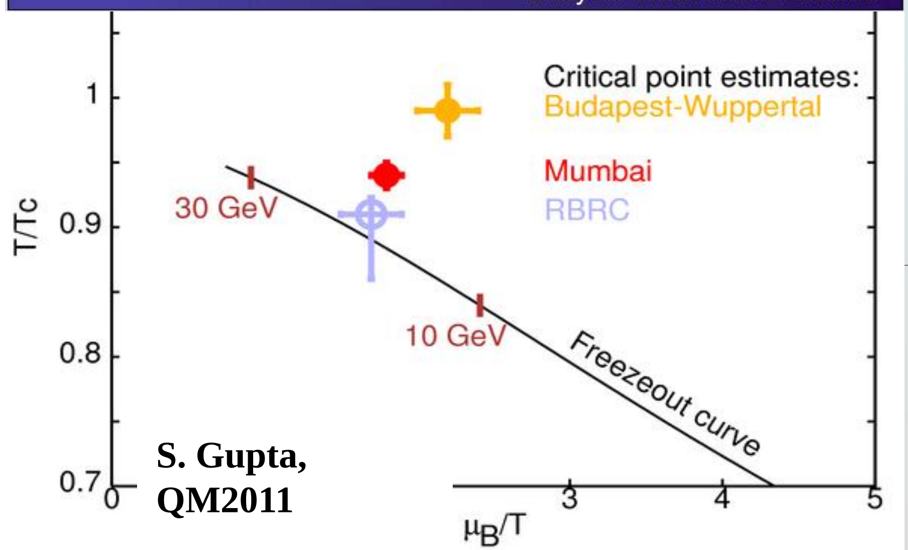
➔Low viscosity/entropy → very good momentum transport

∴ strong coupling

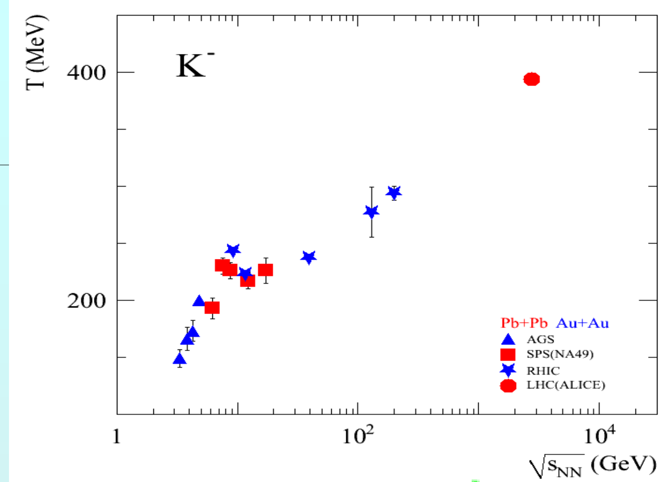
- *At what scales is the coupling strong?*
- *What are the initial conditions?*

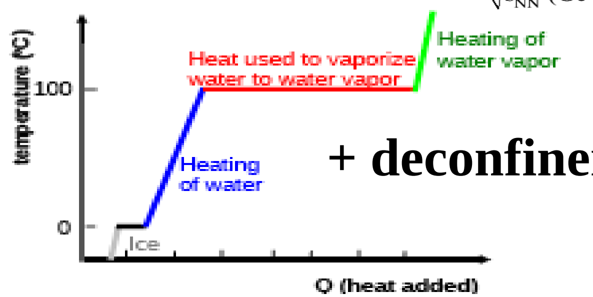
Can we locate the QCD critical point?



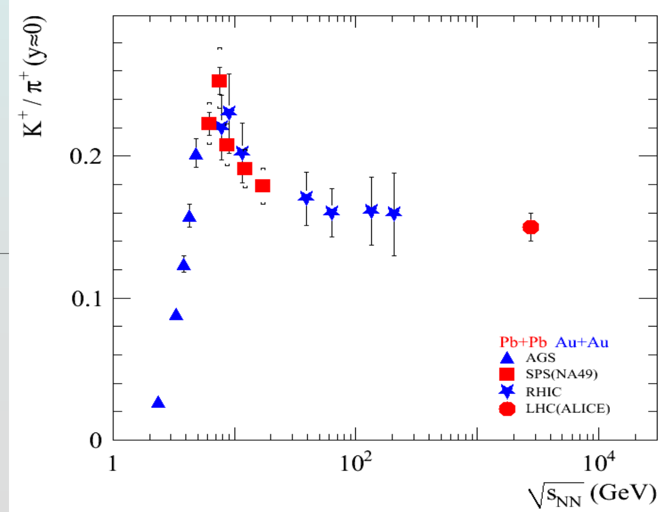


S. Gupta, QM2011





+ deconfinement onset



Early hard probe insights from LHC

- **Quarkonia energy dependence not understood!**

  Need charmonium and bottonium states at >1 √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?

  Unmodified fragmentation function of reconstructed jets

  looks different at RHIC, depends on "jet" definition?

  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

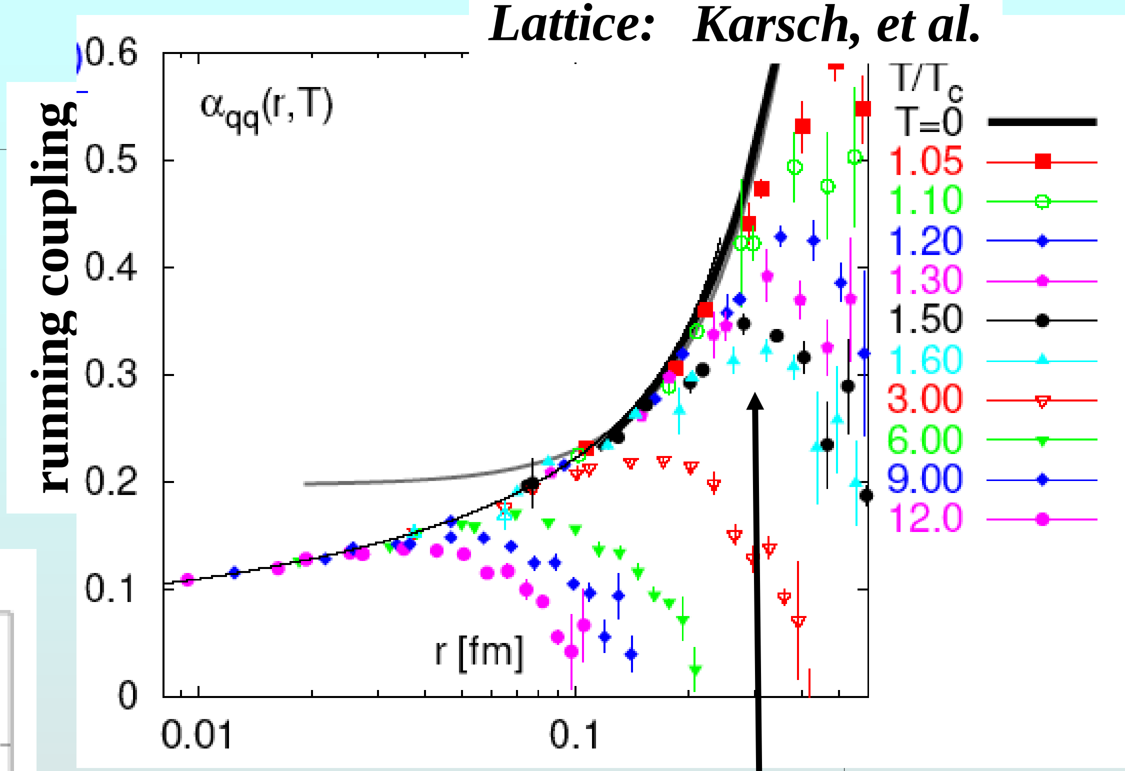
  appears to be similar at RHIC

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

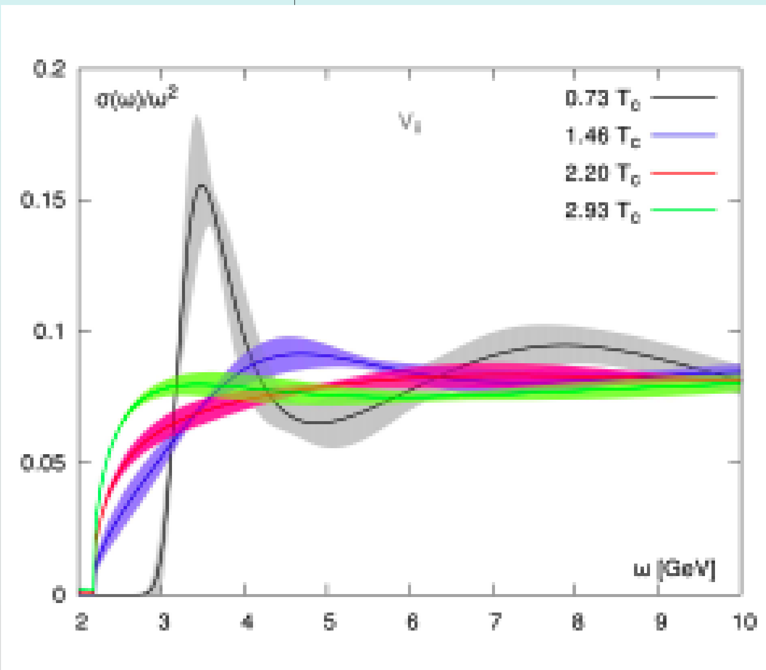
Is there a relevant screening length?

- **Strongly coupled matter: few particles in Debye sphere - decreases screening!**

Lattice: Karsch, et al.



coupling drops off for r > 0.3 fm

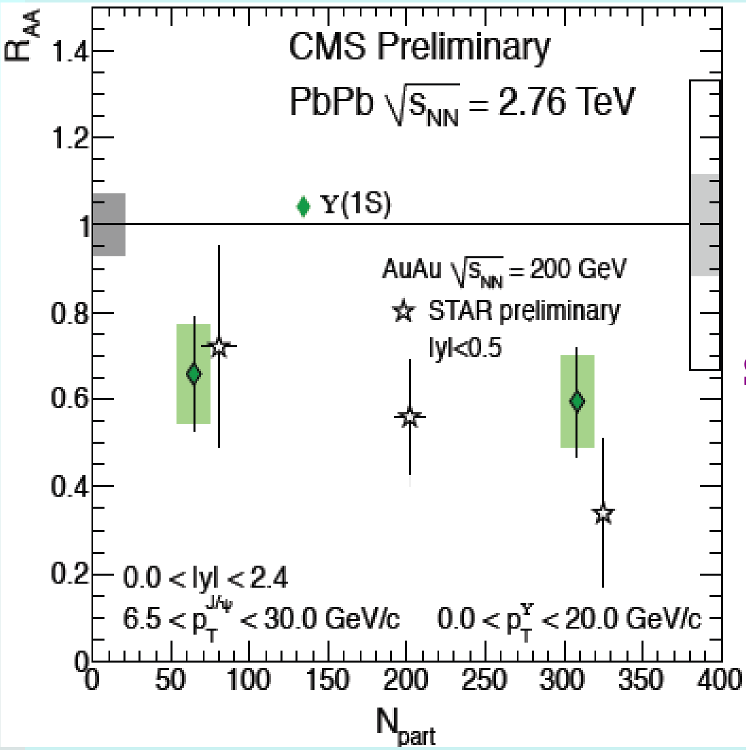


Ding, et al. arXiV: 1107.0311

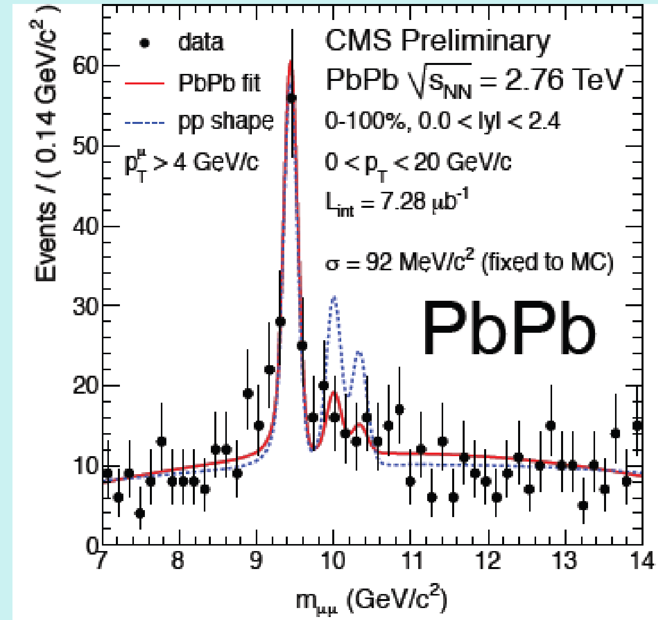
LQCD spectral functions show correlation remaining at $T>T_c$
Partial screening?

Need to understand quantitatively!

- **Coalescence *could* be important at LHC**
  More c-cbar pairs produced. Use b-bar to probe…



Υ (2S,3S) suppressed



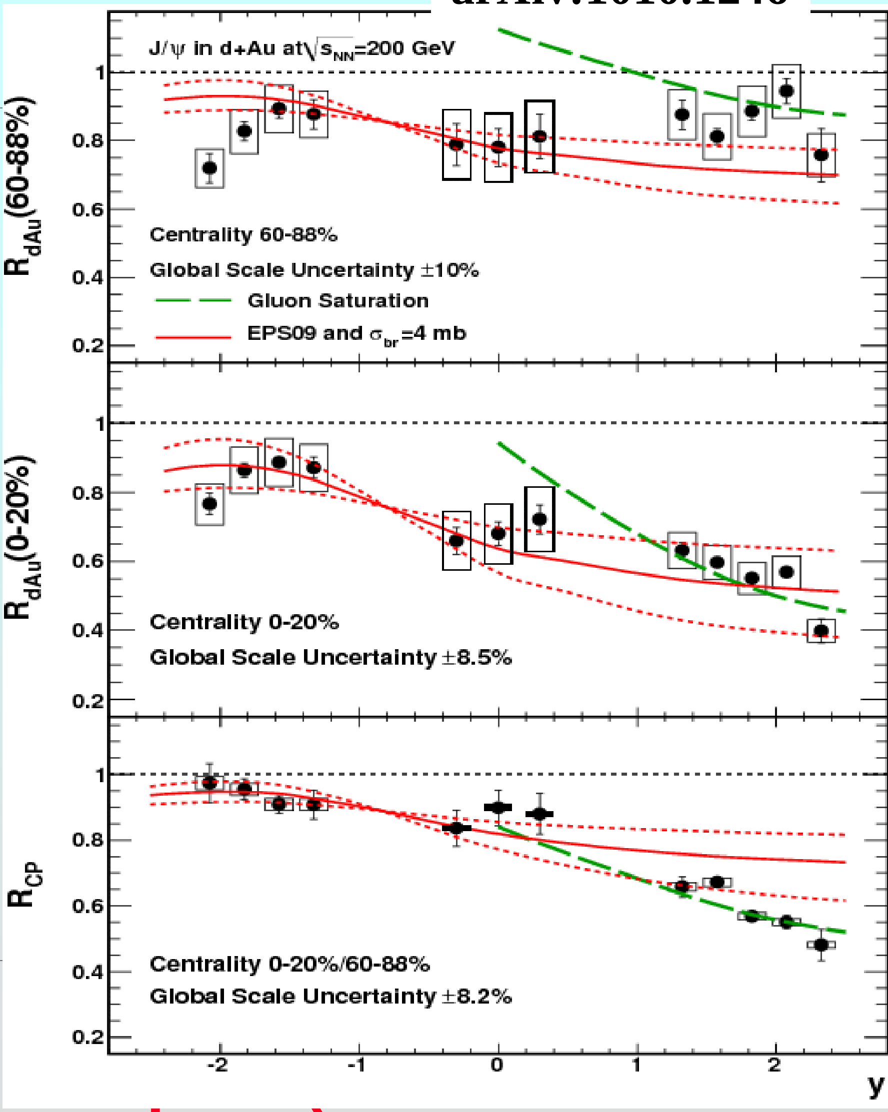
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- **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 @ 1-1.5T_c, then free. Need ∏states at RHIC!

Suppression pattern ingredients

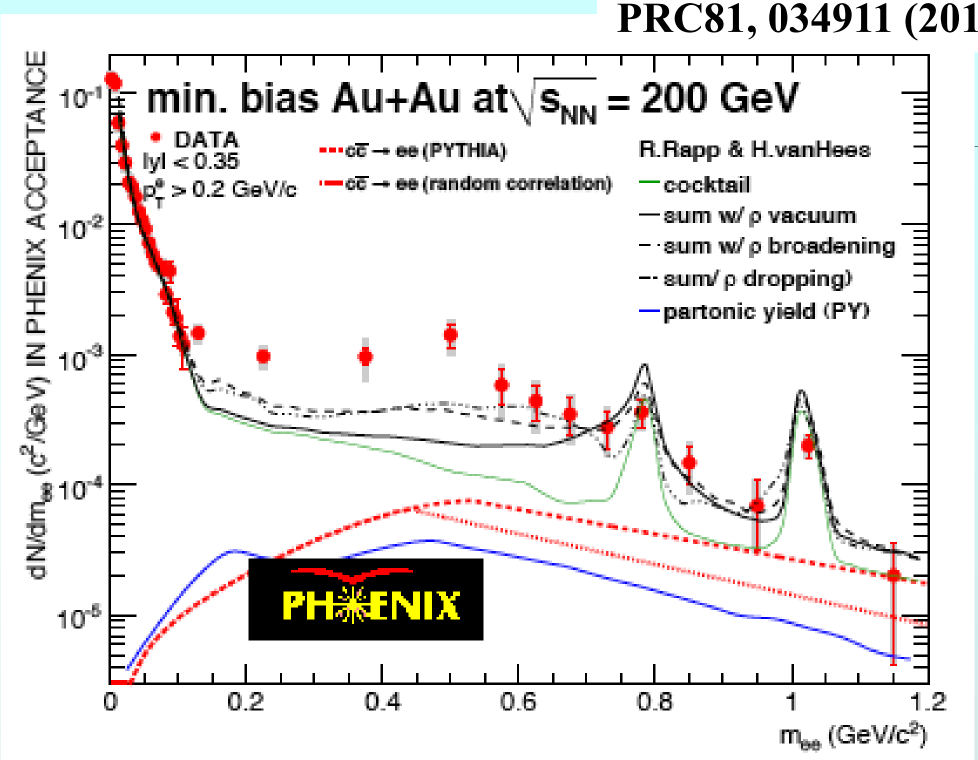
- **Color screening**
- **Initial state effects**
  - Shadowing or saturation of incoming gluon distribution
  - Initial state energy loss
  - (calibrate with p+A or d+A)
- **Final state effects**
  - Breakup of quarkonia due to co-moving hadrons
  - Coalescence of q and qbar at hadronization
  - (calibrate with A, centrality dependence)

arXiv:1010.1246

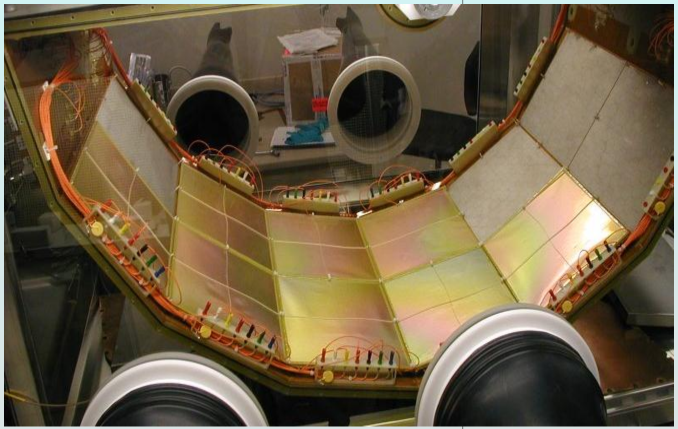


Evidence of chiral symmetry restoration?

PRC81, 034911 (2010)



- Excess low mass e+e-
- New data at 200 GeV + 62.4 and 39 GeV
- Hadron Blind Detector to improves S/B!



- *Are chiral and deconfinement transitions at same T?*
- *Spectral function modification?*
- *Source of the low mass excess? Pre-equilibrium??*

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

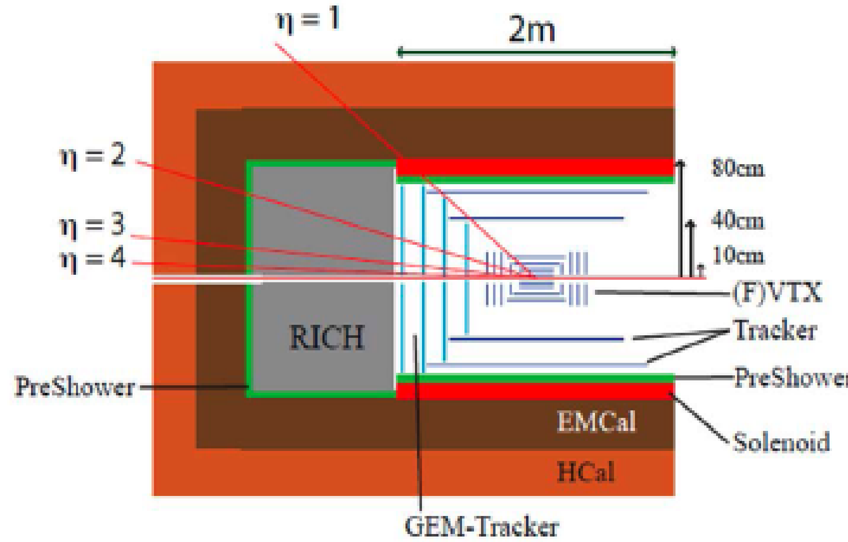
- Hadronic Calorimetry } $8-10M
- Additional tracking layers of Si at ~ 40cm } $5-7M
- Forward Arm with RICH and GEM tracker } $10M

Other

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

} $10-15M

All cost estimate include overhead and contingency

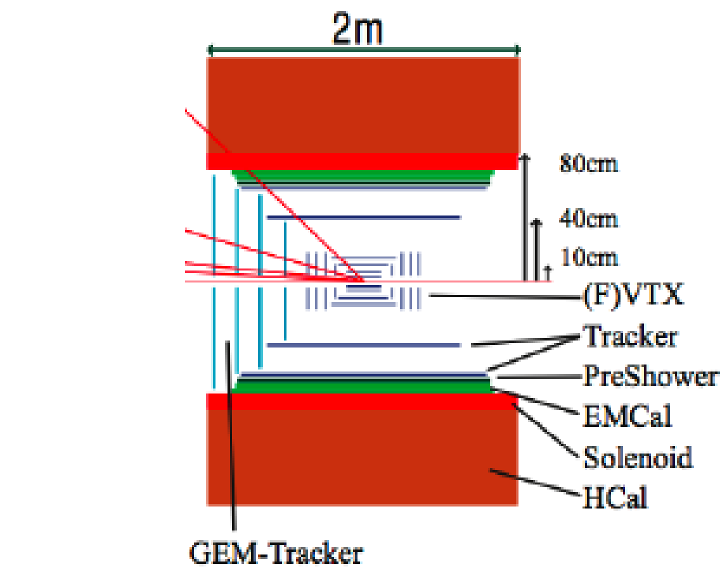


Can be built incrementally

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?)

Staging

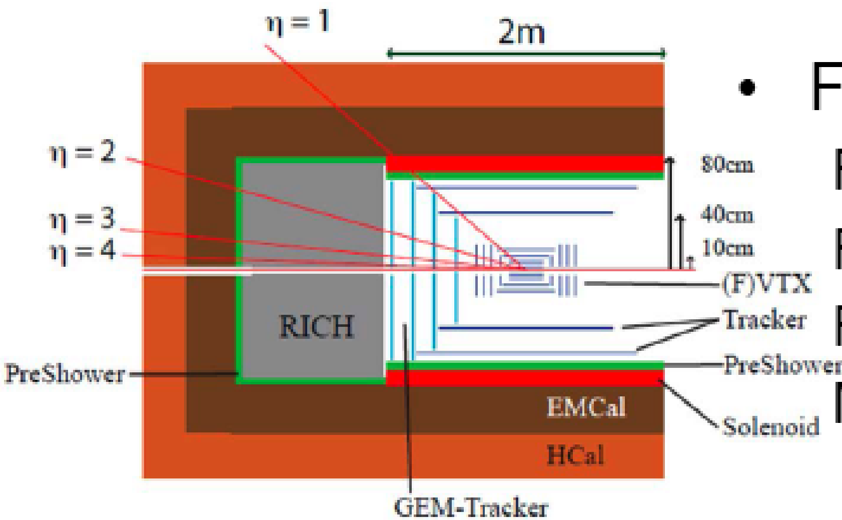


- Mid-rapidity detector

Additional (Si) tracking — *High stat. charm* *5-7 M*

Solenoid
pre-shower
EMCal — *Direct γ, π^0* *Quarkonia* *20 M*

Hcal — *Jets* *8-10M*

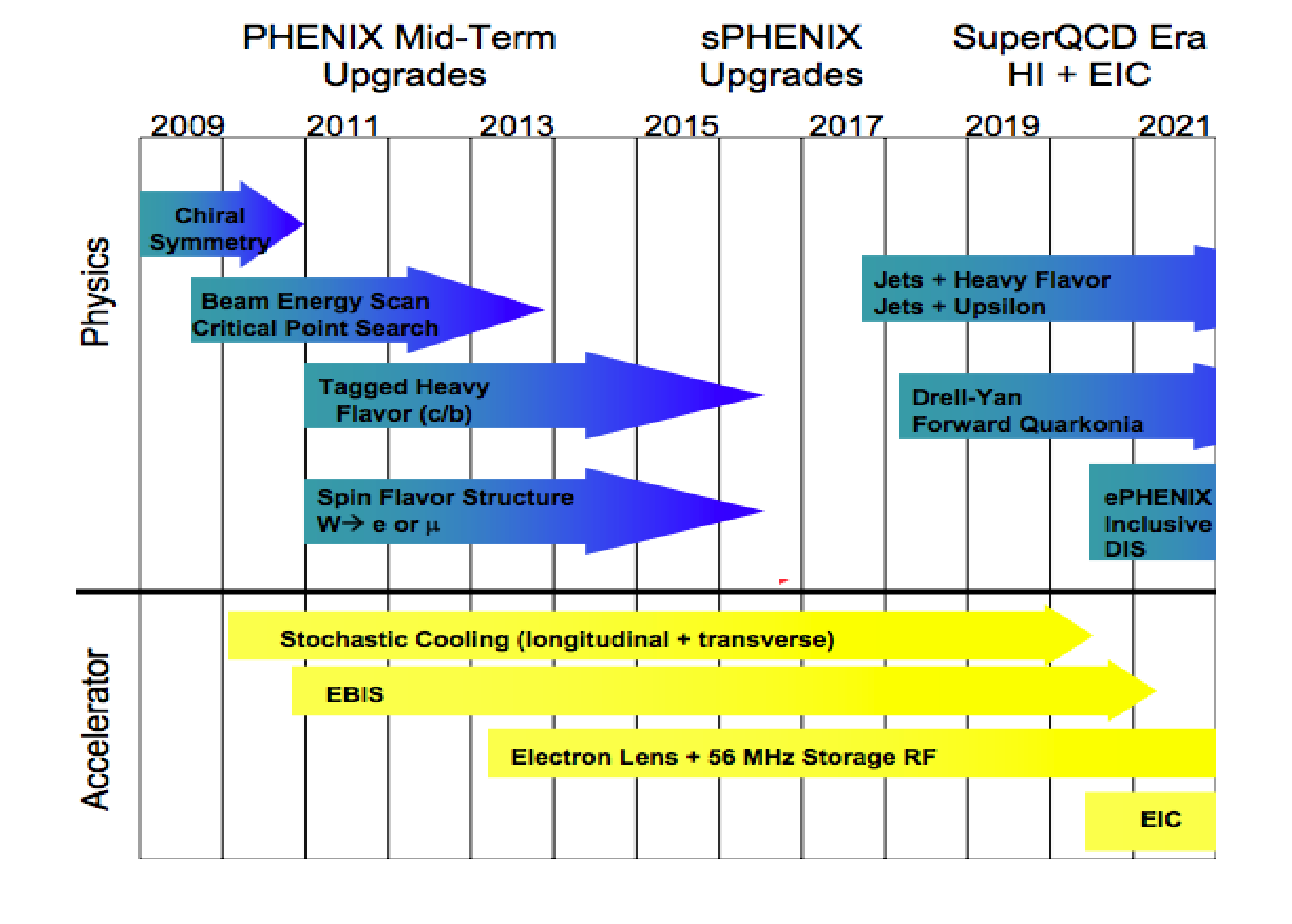


- Forward Detector

RICH and GEM tracker — *CNM, eRHIC* *10M*

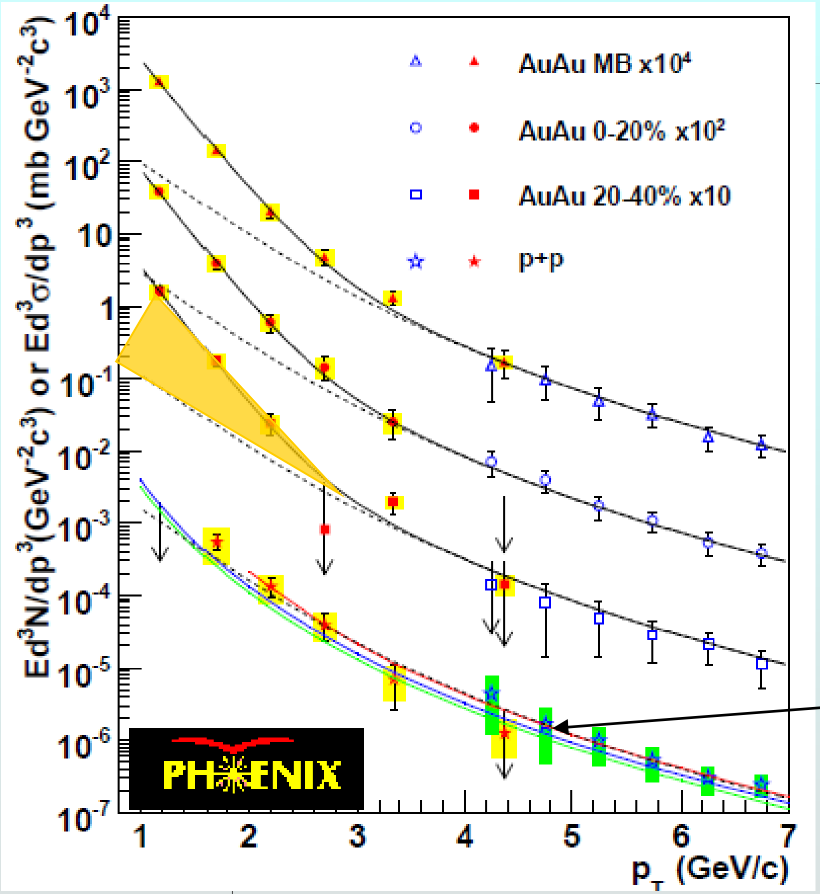
Forward magnet
Forward Hcal
More barrel tracker — *Saturation* *QGP @ Fwd* *eRHIC* *10-15M*

Upgrades schedule

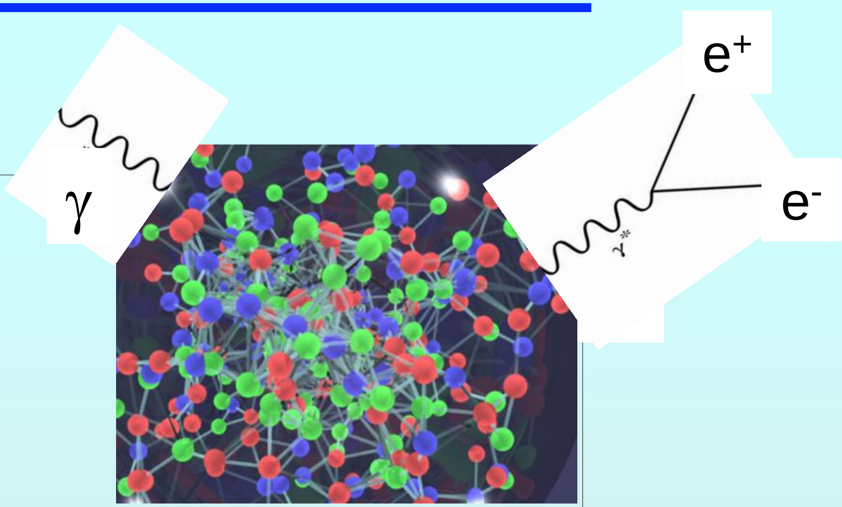


Exciting new physics opportunities in the coming decade!

Thermal radiation



PRL104, 132301 (2010)

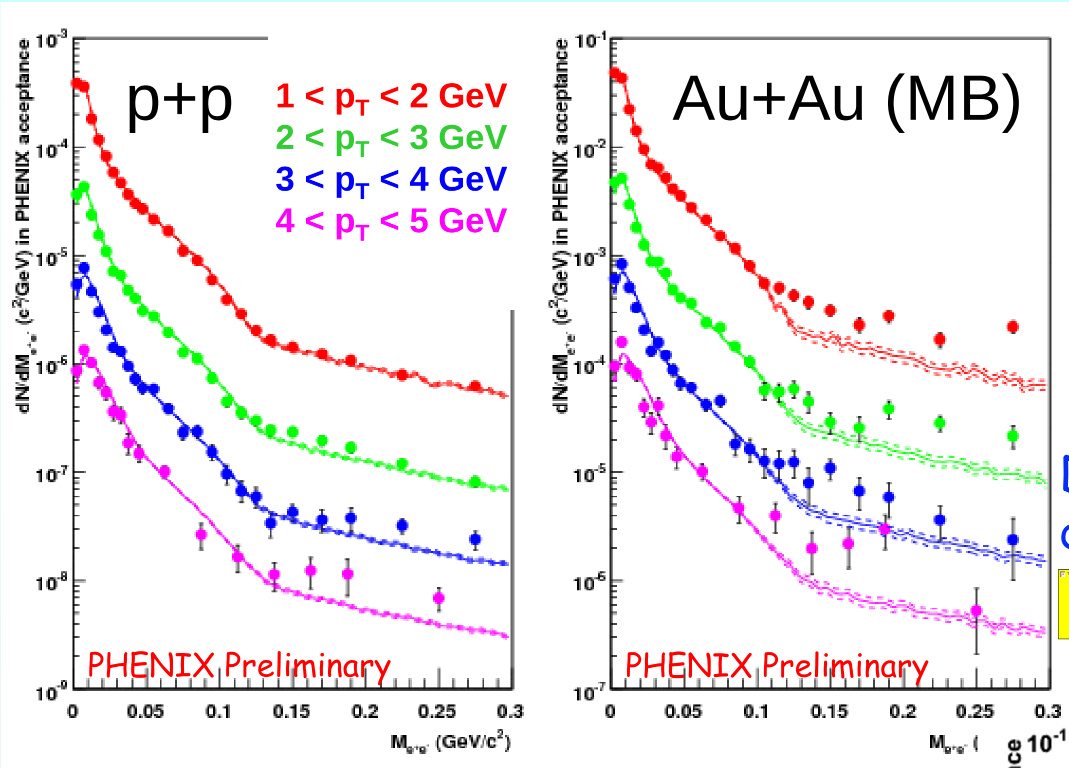


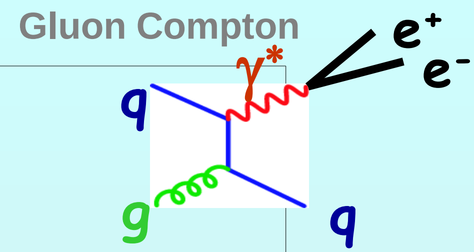
Low mass, high p_T e^+e^- → nearly real photons

pQCD γ spectrum (Compton scattering @ NLO) agrees with p+p data

Large enhancement above p+p in the thermal region

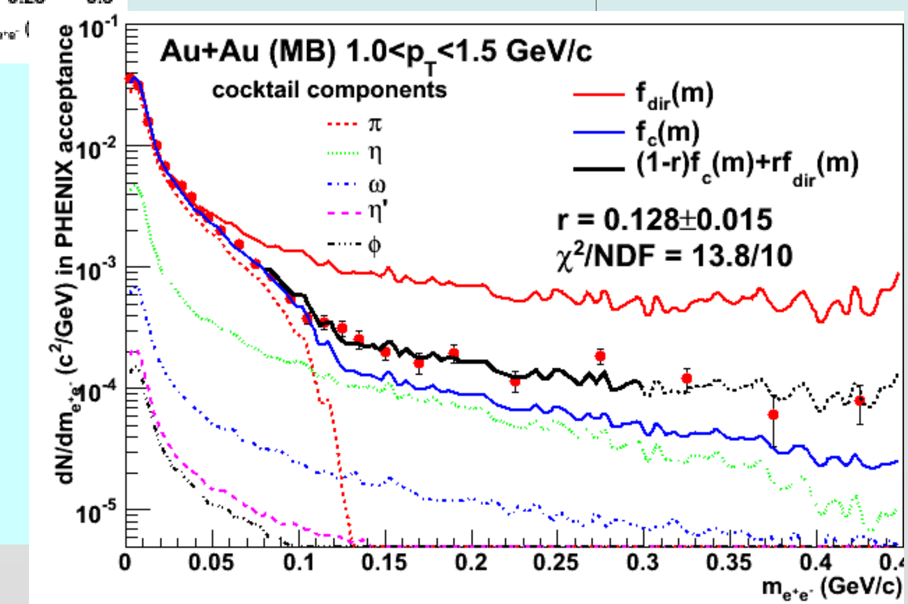
Dileptons at low mass and high p_T





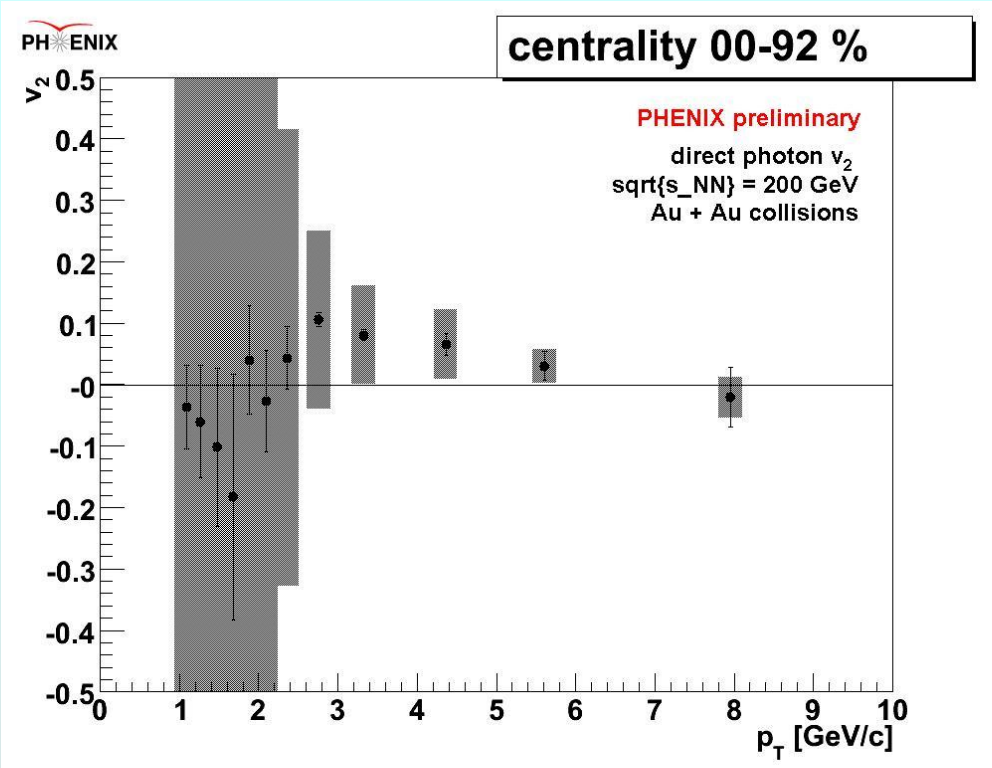
Direct γ^*/Inclusive γ^* determined by fitting each p_T bin

r : direct γ^*/inclusive γ^*

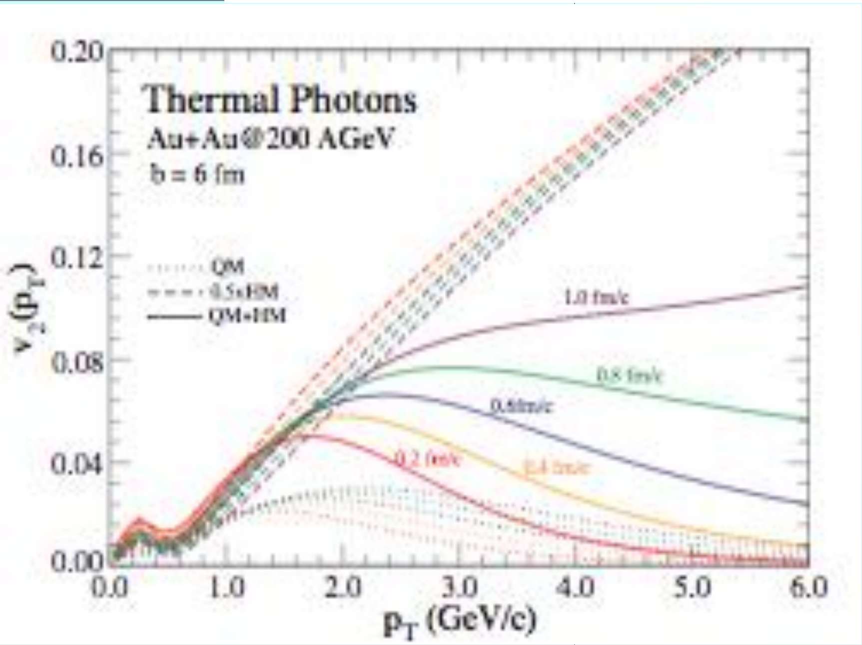


- $m < 2\pi$ only Dalitz contributions
  - p+p: no enhancement
  - Au+Au: large enhancement at low p_T
- A *real* γ source $\rightarrow$
  virtual γ with v. low mass
- We assume internal conversion of direct photon → extract the fraction of direct photon

Pre-equilibrium flow prior to τ_0?



Chatterjee, Srivastava & Heinz
PhysRevC79, 021901,'09



- **Do the direct photons flow?**
- **First step: compare to hydro *after* equilibration**

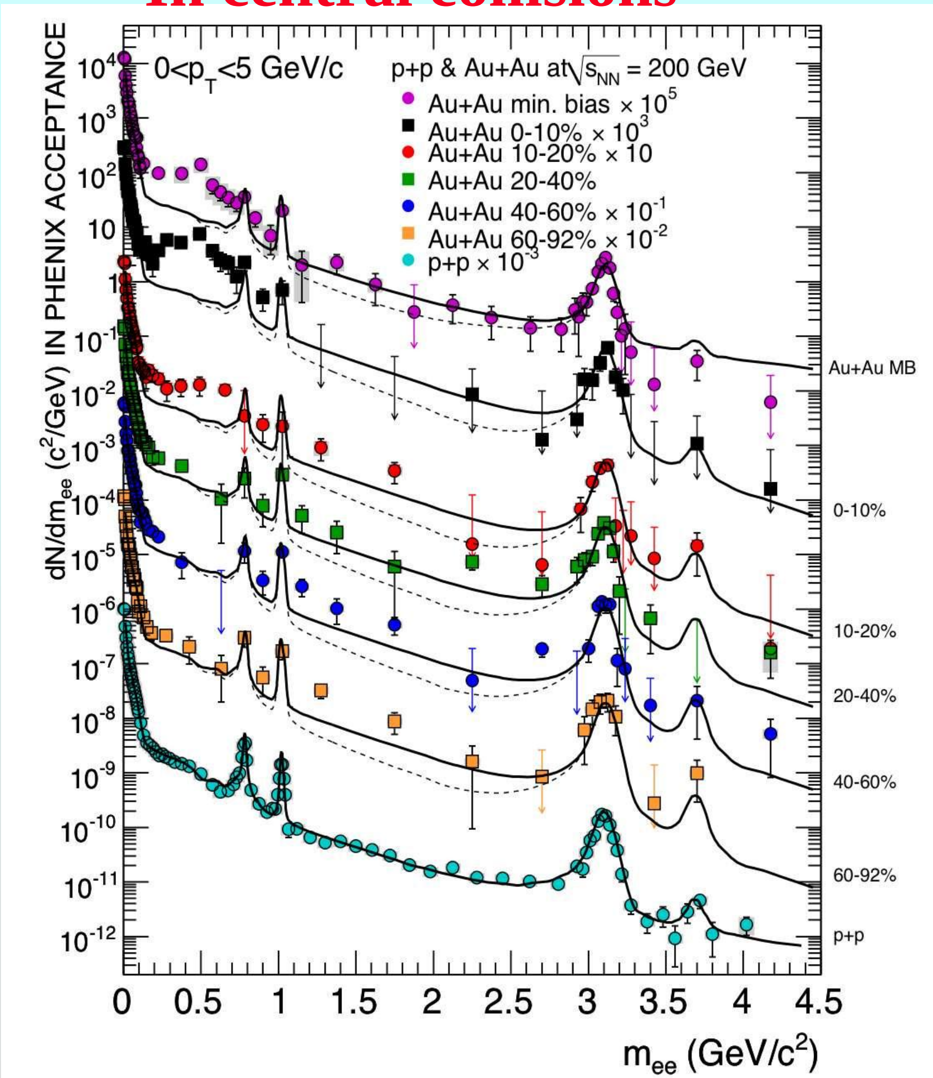
  Experiment homework: smaller errors $2<p_T<4$ GeV/c

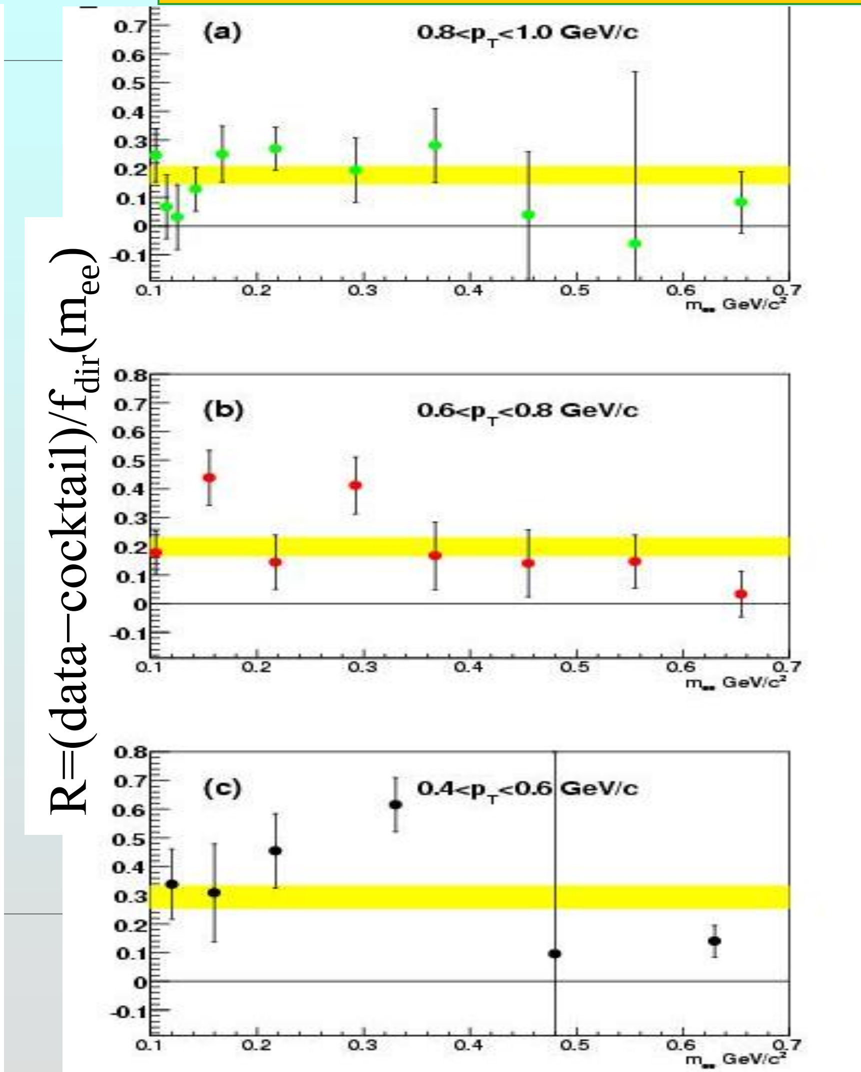
  Theory homework - pre-equilibrium v_2 magnitude?

low mass di-electron excess

Run-4 *PRC81, 034911 (2010)*

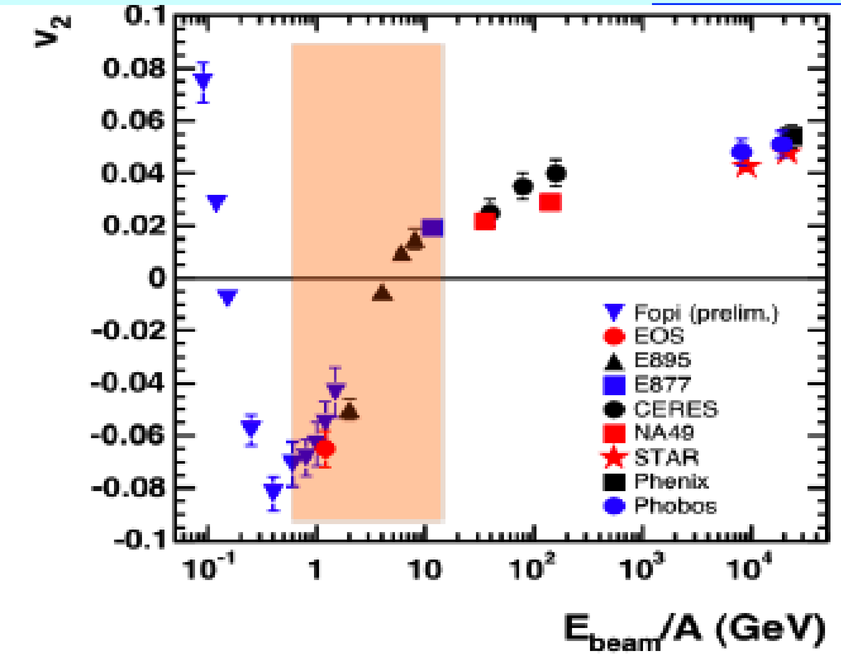
In central collisions



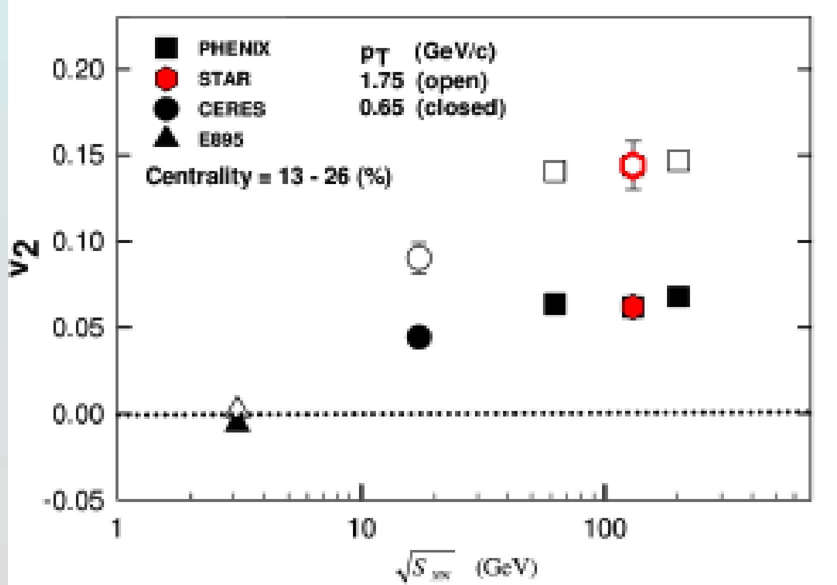


and low p_T

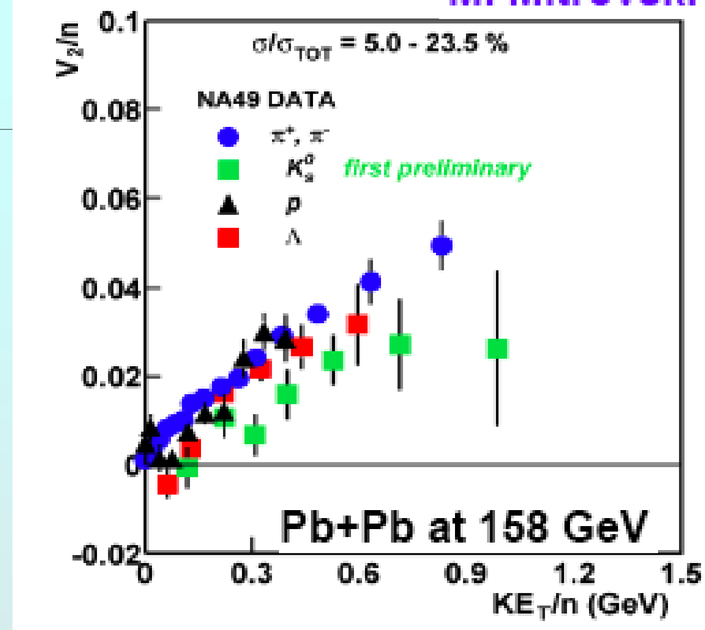
√s dependence



Phys. Rev. Lett. 94, 232302 (2005)



M. Mitrovski



Quark number Scaling works at √s = 62

@ 17 GeV?