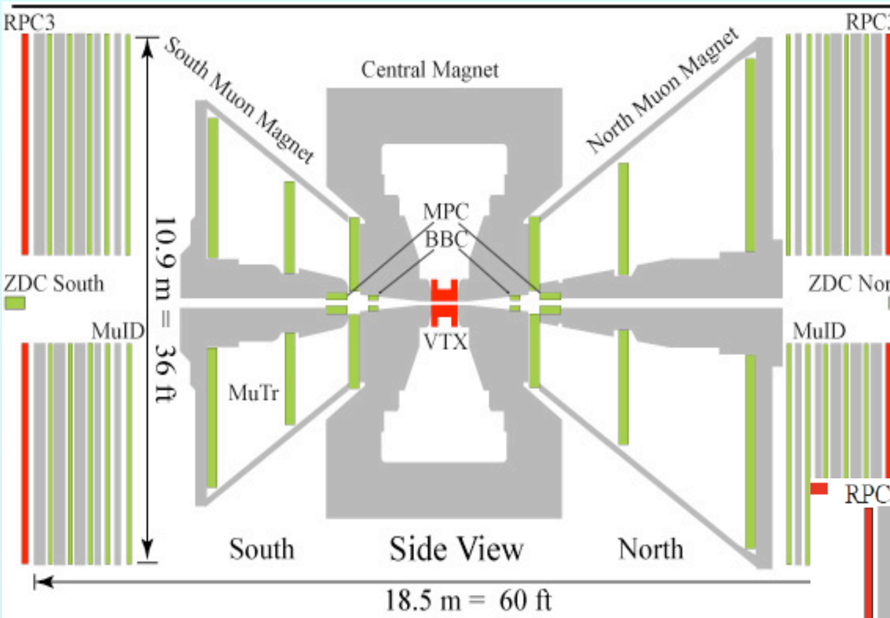
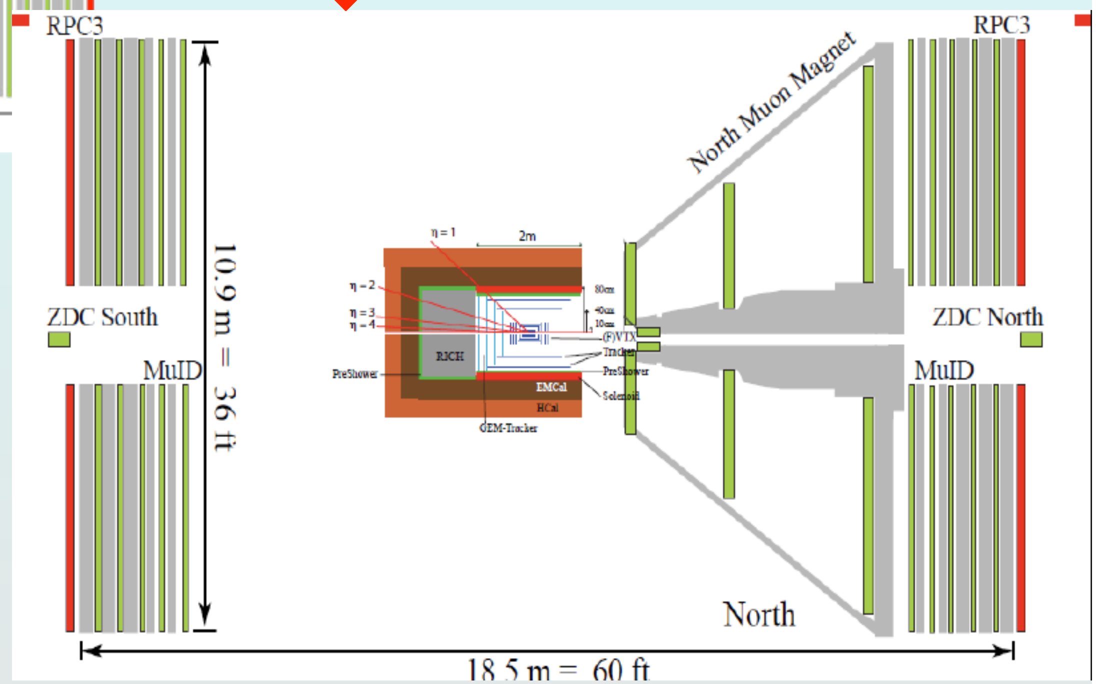
Decadal Physics Goals in Light of LHC Results





What physics?

Why?

Why at RHIC?

(a few examples, to get discussion going)

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B. Jacak Sept. 9, 2011

NEW questions due to RHIC discoveries

- Compelling goals for 2015+ - 2020
- Address with ion collisions

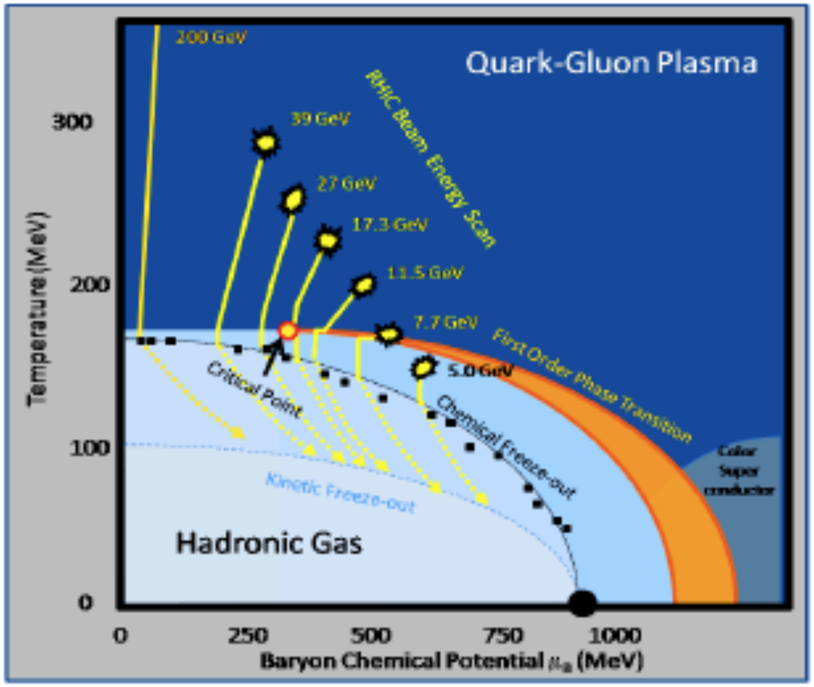
  Are quarks strongly coupled to the QGP at all scales?
  Are there quasiparticles at any scale?
  Mechanisms for parton-QGP interaction?
  and QGP response?
  Is there a relevant screening length in the QGP?
  How is rapid equilibration achieved?
  What is the structure of cold nuclei at small-x?

- Polarized proton running to answer

  Internal landscape of nucleons: Spin? parton correlations
  Color Interactions in QCD Drell Yan, jets A_N
  What governs hadronization?

RHIC: eight key unanswered questions

Hot QCD Matter



1: Properties of the sQGP

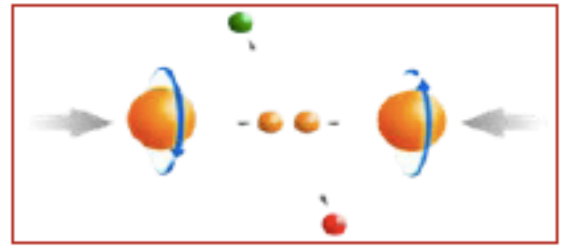
2: Mechanism of energy loss:
weak or strong coupling?

3: Is there a critical point, and if so, where?

4: Novel symmetry properties

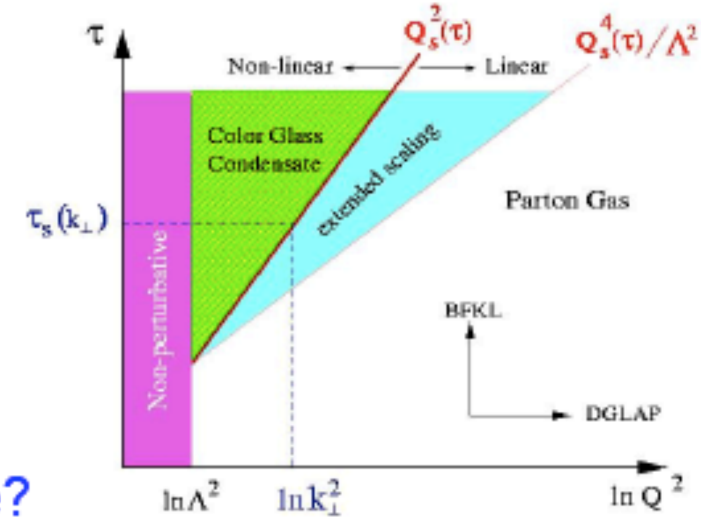
5: Exotic particles

Partonic structure



6: Spin structure of the nucleon

7: How to go beyond leading twist and collinear factorization?



8: What are the properties of cold nuclear matter?

Today's discussion

- How LHC informs approach to these questions
  Mostly we've learned about QGP at LHC, so I shall focus mostly upon the heavy ion questions.

- See Joe Seele's talk for spin physics discussions

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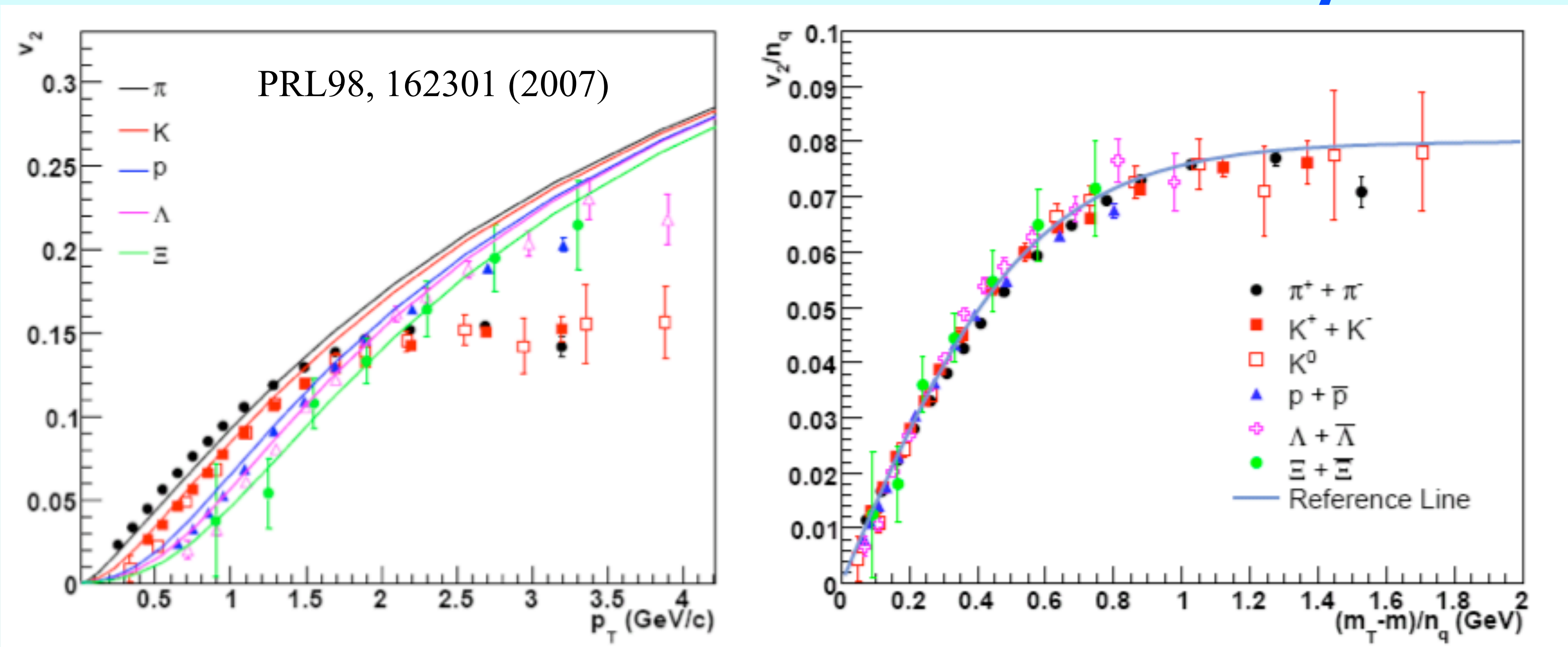
The bulk matter flows collectively



- Elliptic flow @ $p_T < 2$ GeV/c agrees with hydrodynamics

  ~ideal hydro flow

  Thermalization time < 1 fm/c

- Flow scales with # of valence quarks
- How is equilibration achieved so rapidly?
- Are there quasiparticles in the quark gluon plasma?
  If so, when and what are they?

LHC tells us

- QGP flow is very similar
  - Also must have very rapid equilibration at LHC
- Various clever theoretical ideas about rapid equilibration
  - Plasma instabilities (maybe growth is too self-killing?)
  - Holography to describe the early system
- Not so many ideas about experimental probes for *how* equilibration happens
- Hunting for quasiparticles
  - Are there composite quasiparticles (Al Mueller, Wiedemann)?
  - Theorists have suggested comparing collisional energy loss of different mass probes
  - Similar approach (and no knowledge yet) at RHIC/LHC
  - Will this be answered in next 5 years w/ vertex detectors?
  - *Any reason to prefer RHIC or LHC for this study?*

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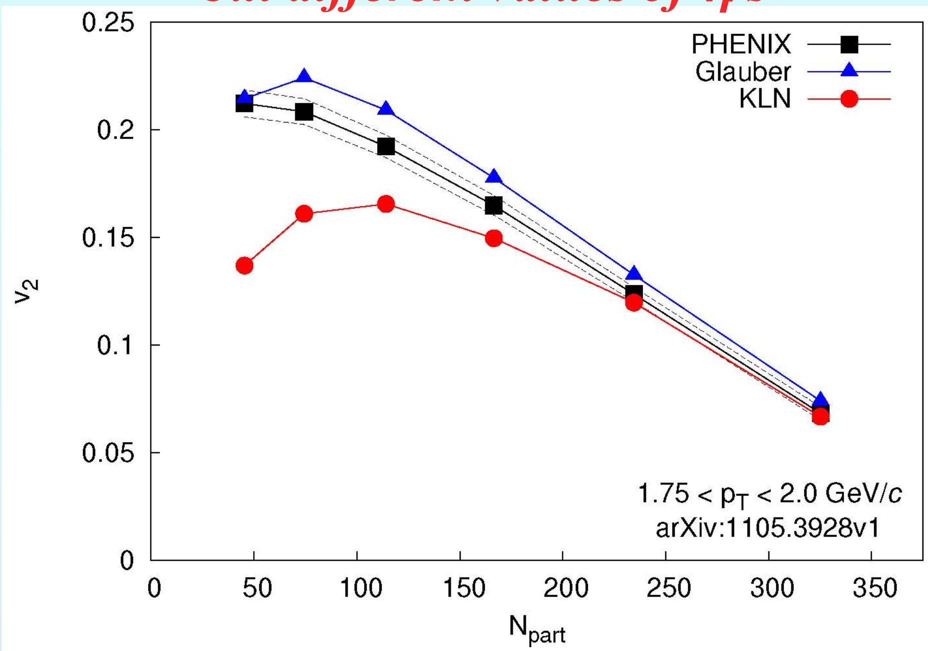
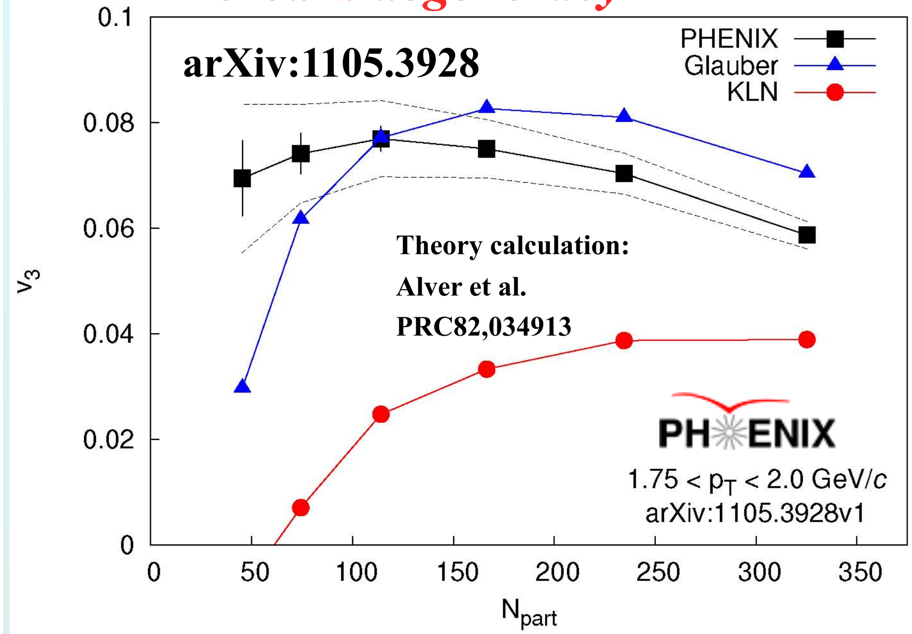
Quantify viscosity of QGP

***v_2* described by both Glauber and CGC**
but different values of η/s



***v_3* described only by Glauber**
breaks degeneracy



- **Low viscosity/entropy → good momentum transport**
  ∴ strong coupling
- **At what scales is the coupling strong?**
- **What are the initial conditions? Glauber, CGC, or ?**

v_3 and other higher harmonics

- Hot topic on both sides of the Atlantic

  Careful and systematic study could yield $\eta/s(T)$

- Study of v_2, v_3, v_n at low energies at RHIC a key part of this mapping

  Will be done with data from existing energy scan!

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Strong coupling at what scale?

- Test by using probes at different mass, p_T scales
- Heavy quark energy loss vs. gluons & light quarks
- Jets
  - At different energies (up to 40-50 GeV at RHIC)
  - Heavy quark jets using vertex detectors to tag
  - γ-jet coincidence to compare energy tagging by photon with reconstructed jet energy

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Energy Scan topics

- STAR question 3: Is there a critical point and if so, where?
  Unique to RHIC (at least until CBM at FAIR)

- STAR question 4: Novel symmetry properties
  Need to show they turn off when QGP cannot form
  Of course, LHC energies are key part of the scan, too

- I shall argue that PHENIX question about the color screening length is also an energy scan topic…

- Current energy scan is effective for *large cross section* observables. Need larger acceptance in ϕ, η and p_T to look at √s dependence of rarer probes.
  σ(√s) implies focus on upper part of RHIC √s range

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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

Hard probe insights from first LHC results

- **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**

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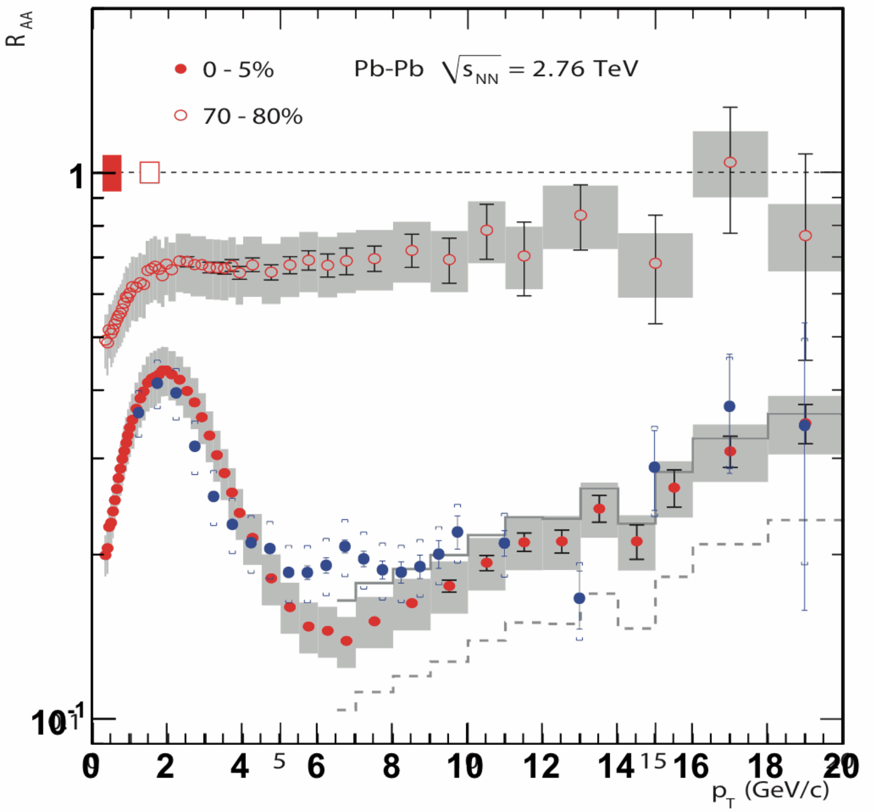
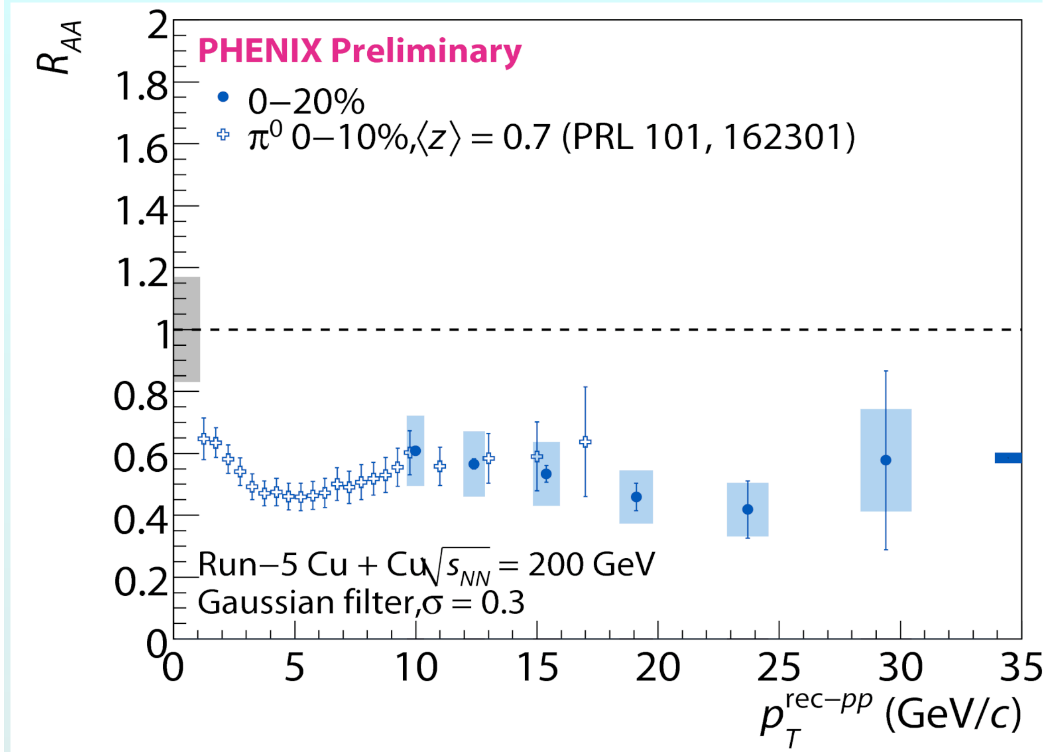
Why bother with jets at RHIC?





- 20-35 GeV jets may not be the same as 100 GeV jets!
- Requiring narrow jet -> same suppression as leading hadron

  Hard to reconcile if eloss is splitting *inside* the jet cone

  Jets of ~100 GeV don't seem to get wider at LHC

  CMS sees excess 1-2 GeV particles in *interjet* region

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Structure and correlations of 20-40 GeV jets

- Yet, we DO see hints of medium-induced fragmentation function changes in γ_{dir}-h (PHENIX) and jet-h (STAR) @ RHIC

- Fragmentation more affected by coherent scattering?
  Maybe parton virtuality vs. medium T, ρ, mfp matters?

- Perhaps more jet-medium effects (beyond eloss) at RHIC??
  Would really like to scan from ~T_c to 300 MeV to probe temperature dependence
  Control system size by asymmetric species (eg. Cu+U) to control for pathlength dependence

- More from Berndt on this subject

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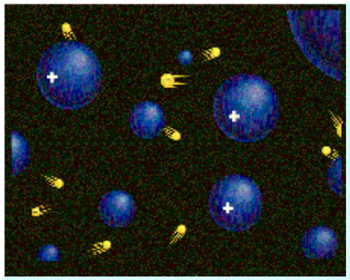
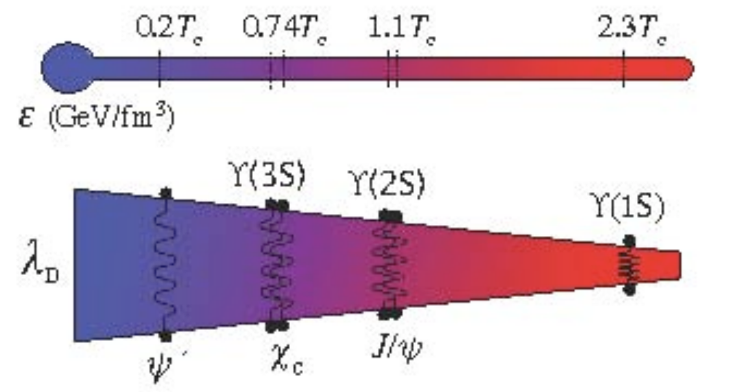


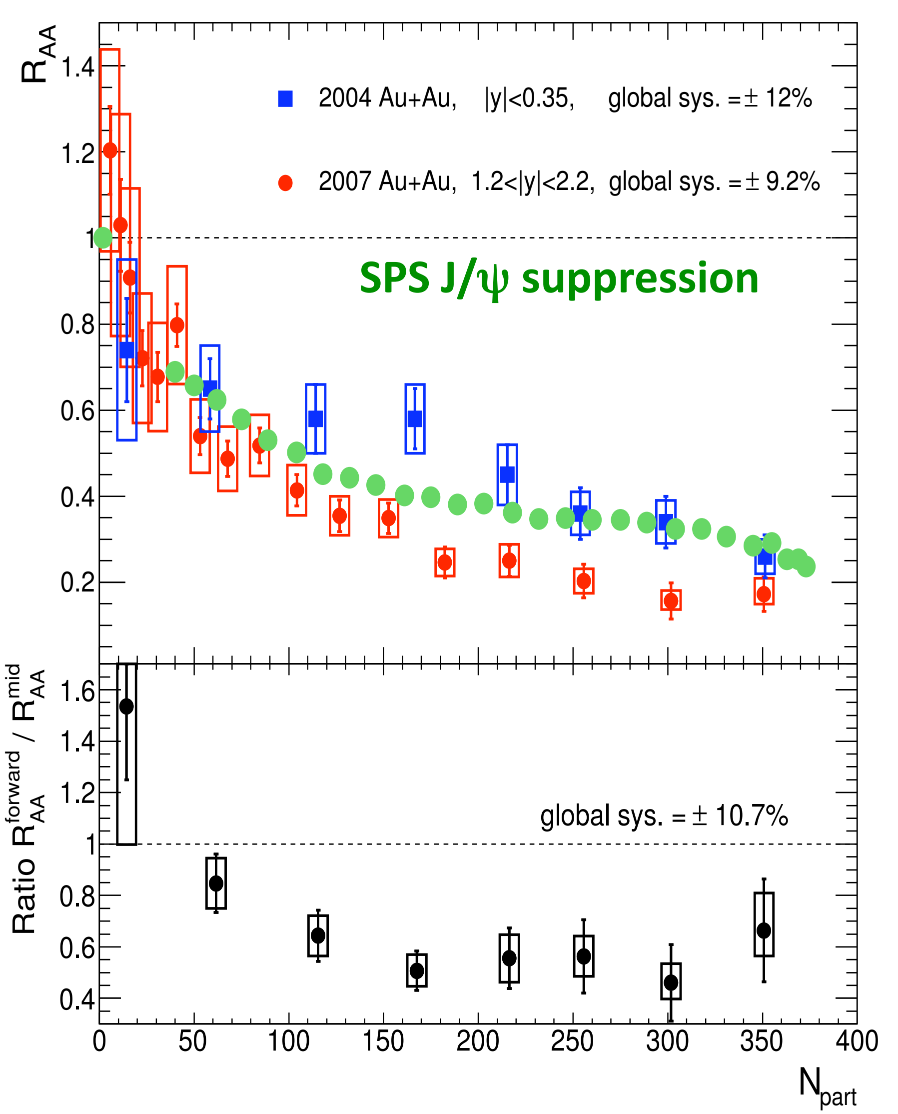
Is there a relevant screening length?

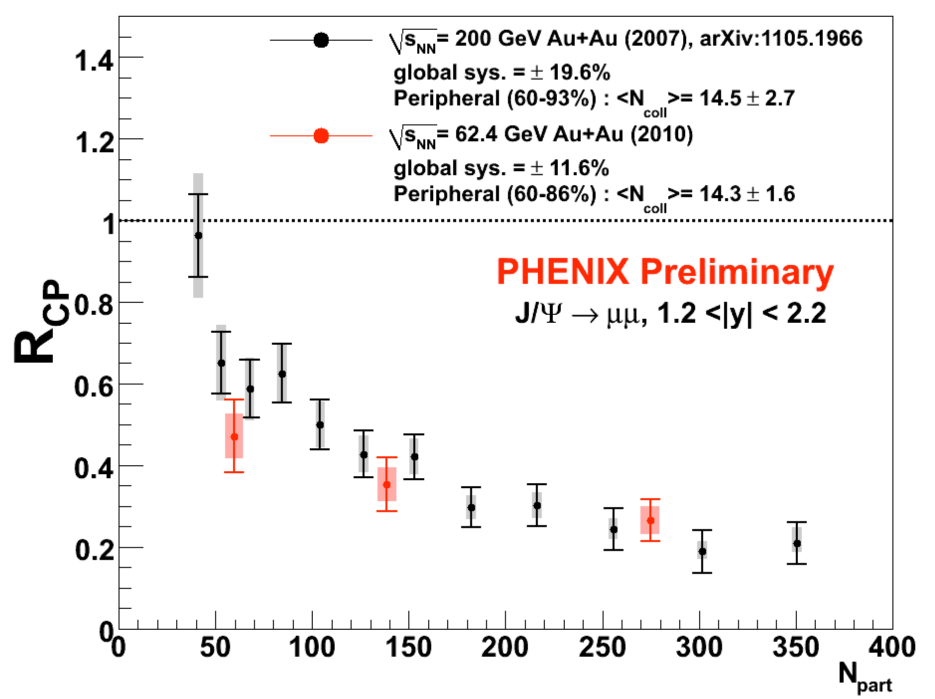
- Plasma: interactions among charges of multiple particles
  - spreads charge into characteristic (Debye) length, λ_D
  - multiple particles inside Debye sphere
    - they screen each other
  - plasma size > λ_D
- In strongly coupled plasmas: few (~1-2) particles in Debye sphere
  - Partial screening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



J/ψ vs. system size, √s (SPS to RHIC)

arXiv:1103.6269





No obvious pattern of the suppression with ε, T!

Why more suppression at y=2?

To understand color screening:

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

d+Au to disentangle cold matter effects

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)

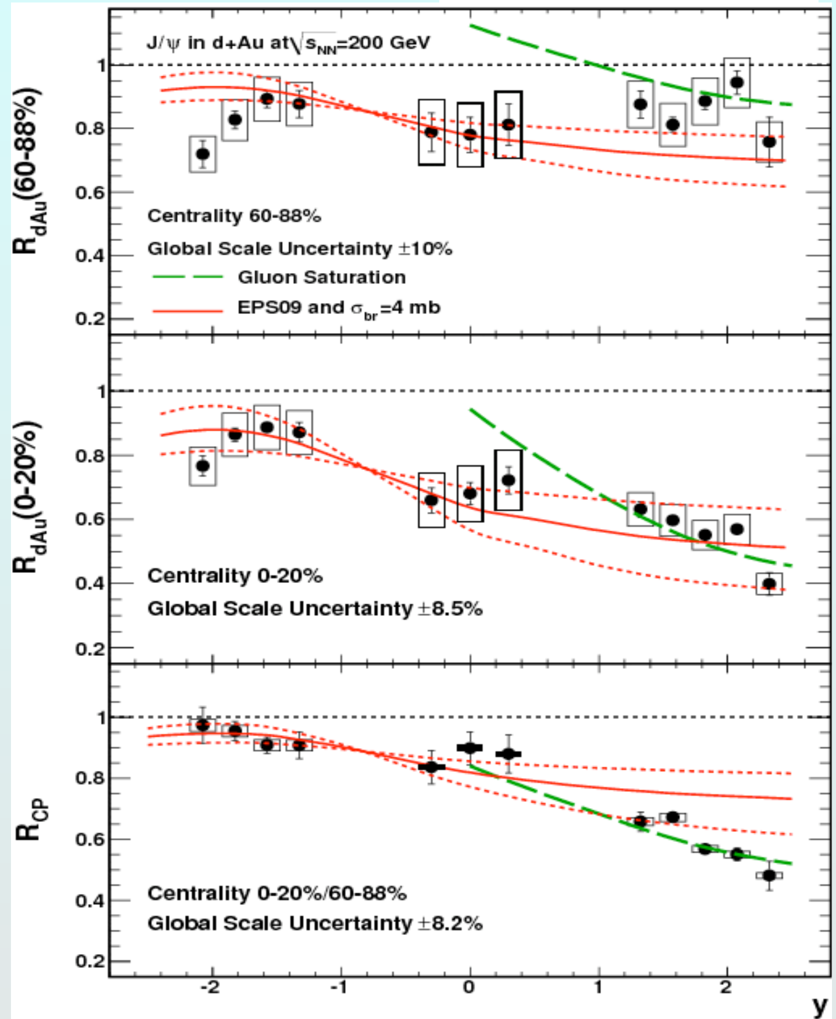
- Final state effects

  Breakup of quarkonia due to co-moving hadrons

  Coalescence of q and qbar at hadronization

  (calibrate with A, centrality dependence)

arXiv:1010.1246



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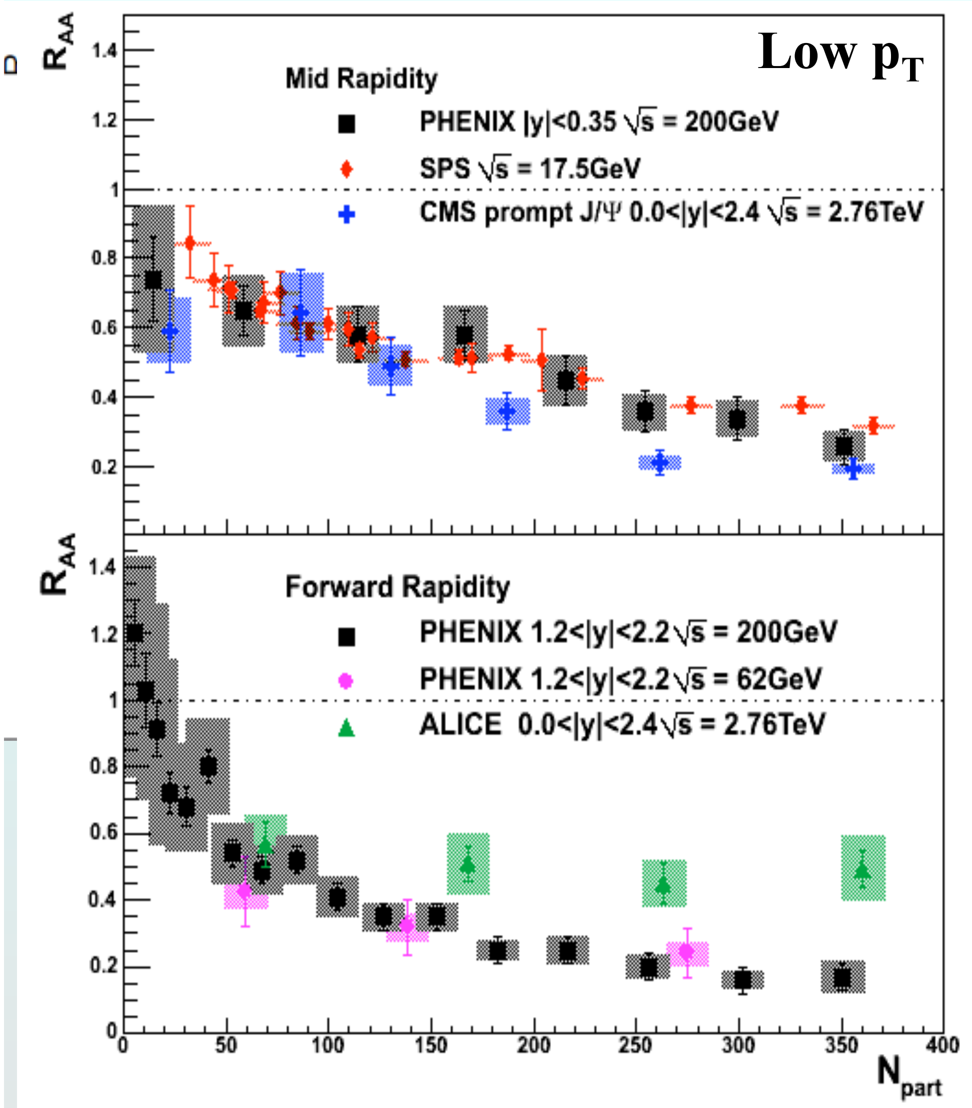
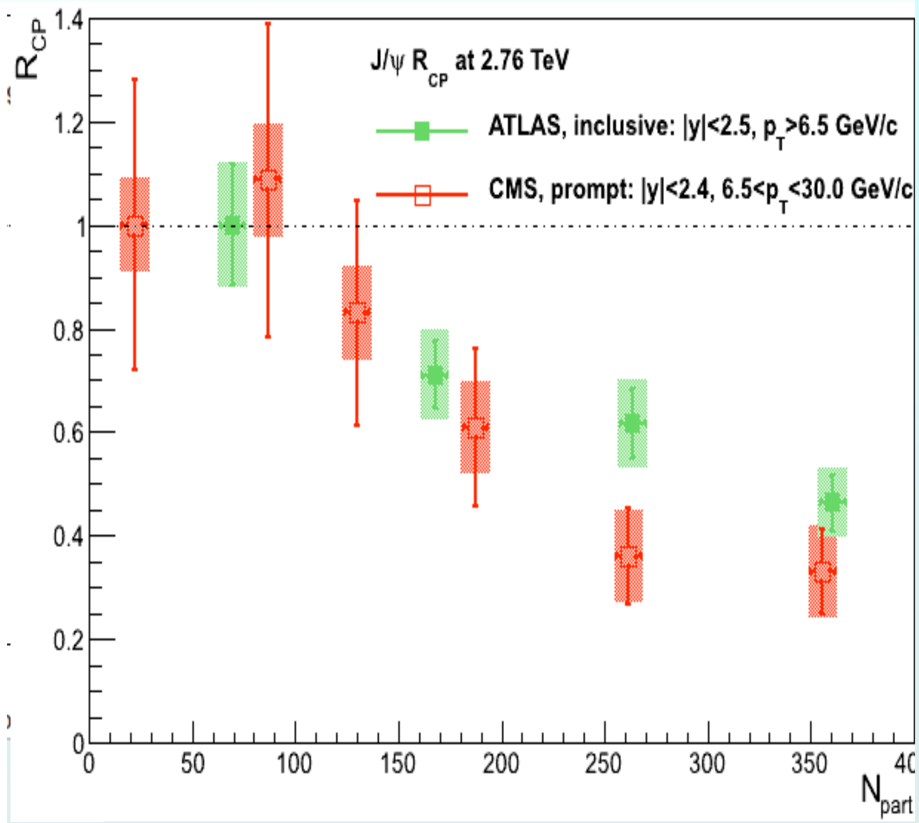
Look at higher √s at LHC





scale J/ψ Rcp to "R_{AA}" to compare

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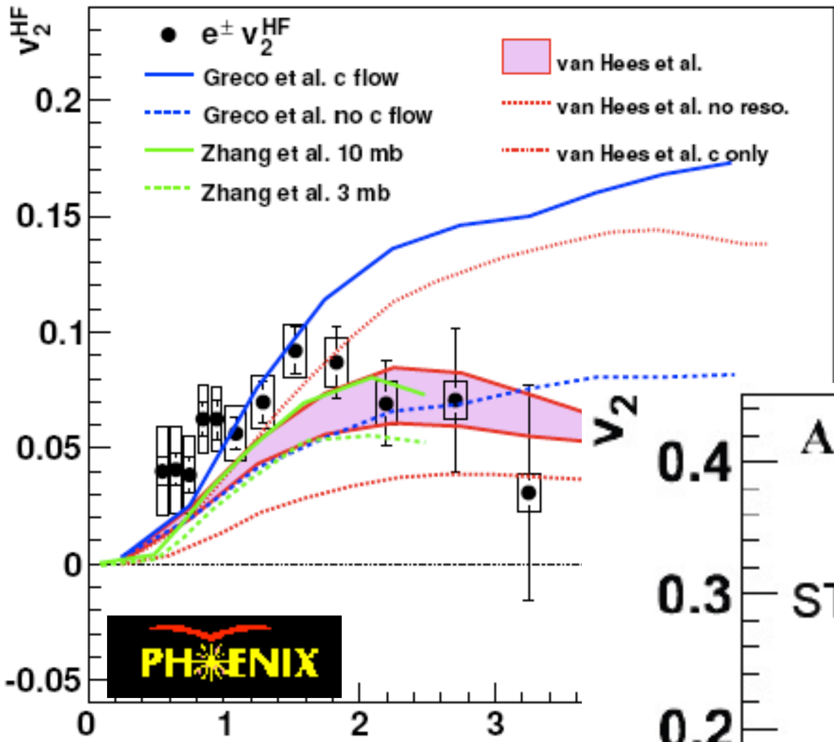
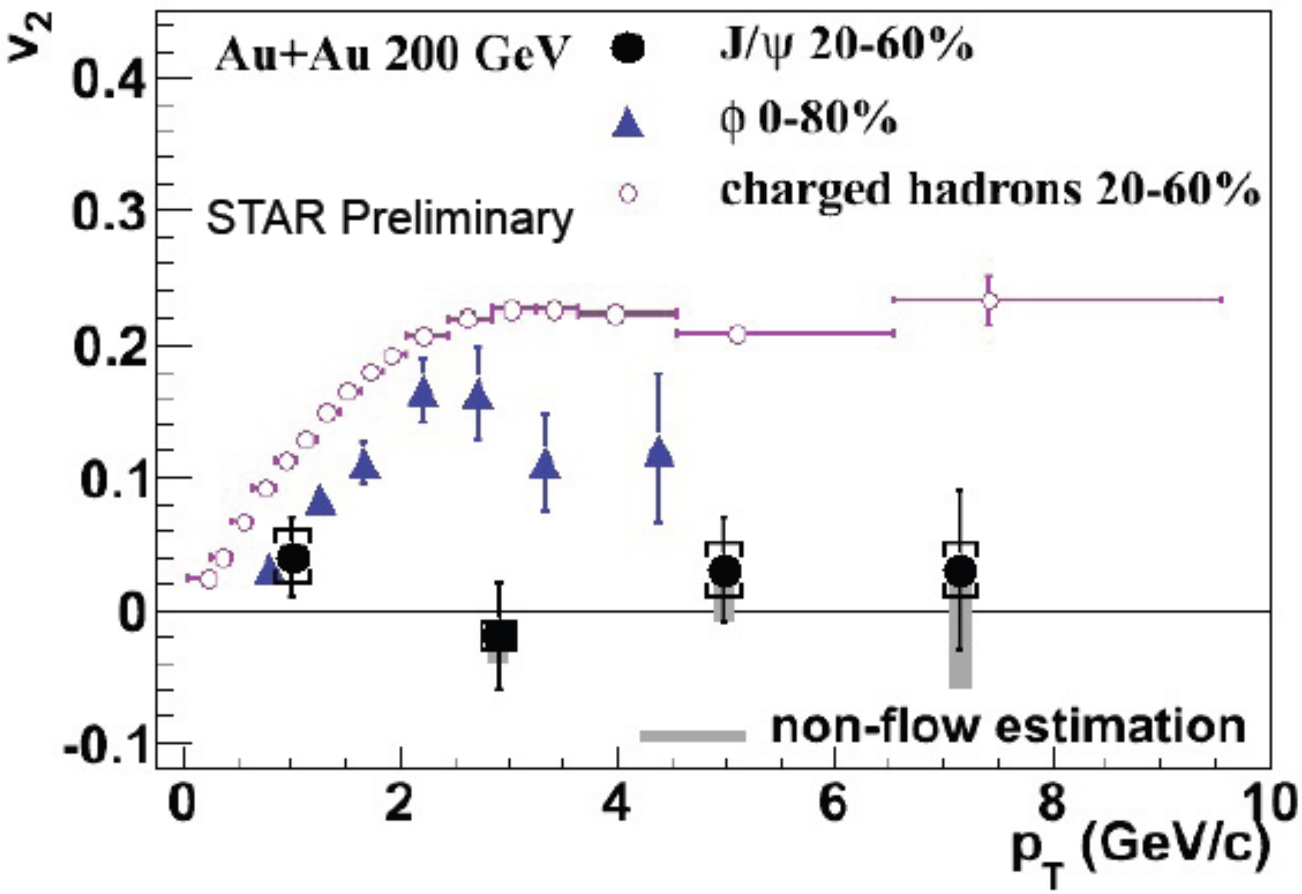
- prompt J/ψ < inclusive?
  (b states less suppressed)
- √s dependence is weak
  LHC less suppressed!
  Final state coalescence?

Expect if c-cbar pairs numerous or correlated



PRL.98: 172301,2007

Open charm flows



J/ψ seems not to

So coalescence @

RHIC is not large

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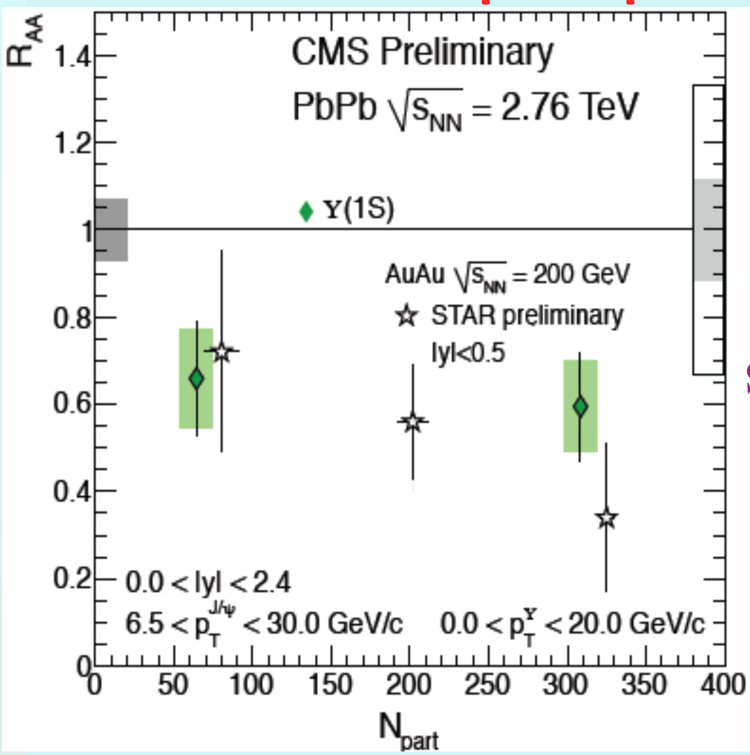
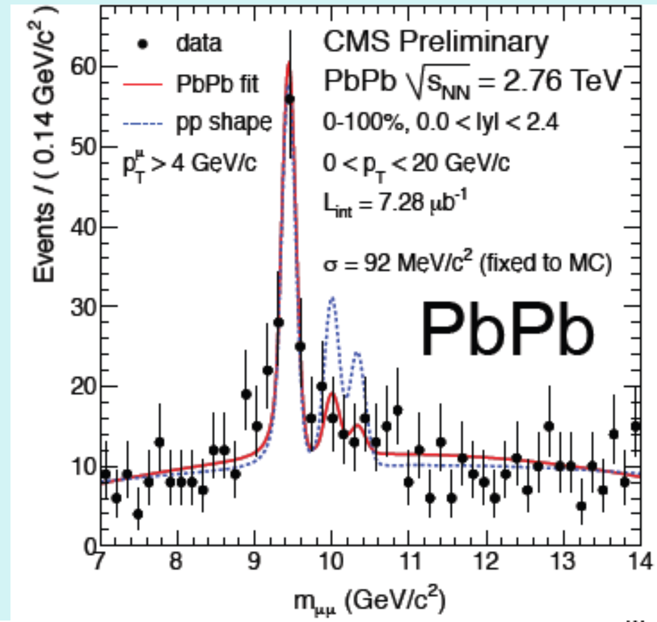
Need to understand quantitatively!

- **Coalescence *could* be important at LHC**

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



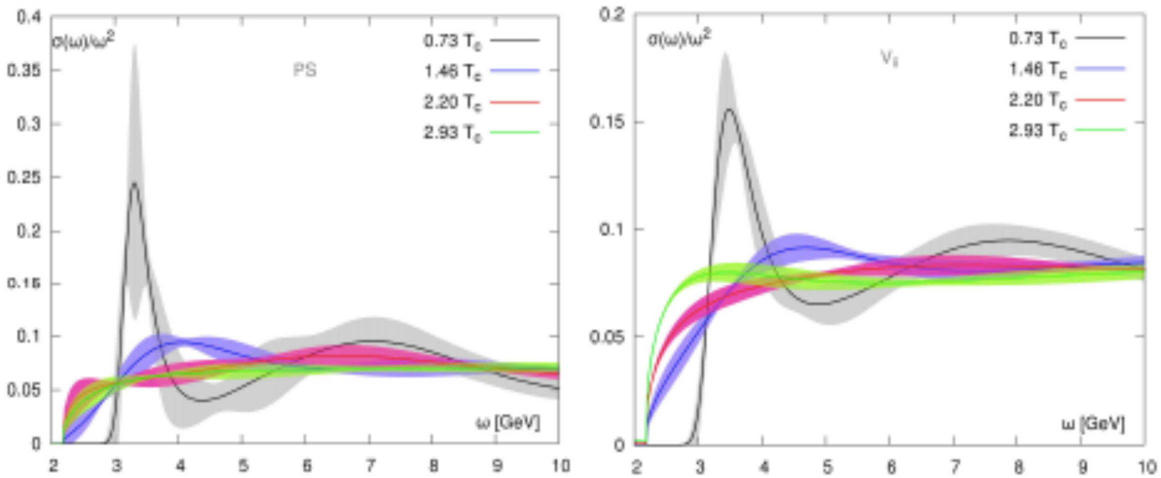
Υ (2S,3S) suppressed



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

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

  χ_b modified @ 1-1.5T_c, then free. Need Υ states at RHIC!



Ding, et al. arXiV: 1107.0311

Heavy quark diffusion

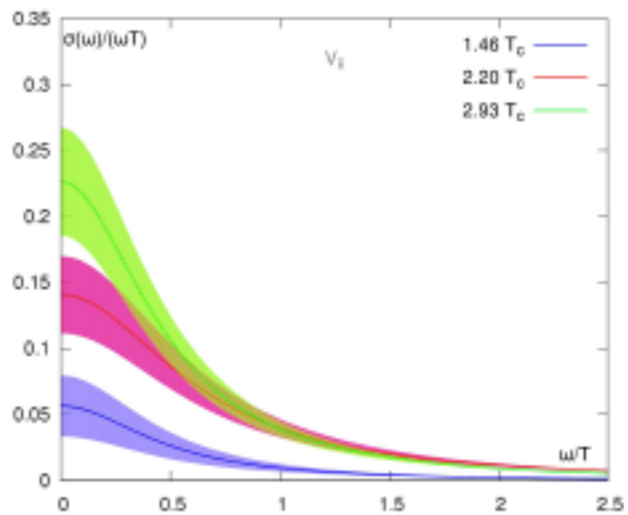
Figure 3. Uncertainties of output spectral functions in PS (left) and V_{ii} (right) channels at all available temperatures. The shaded areas are errors of output spectral functions from Jackknife and the solid lines inside the shaded areas are mean values of spectral functions.

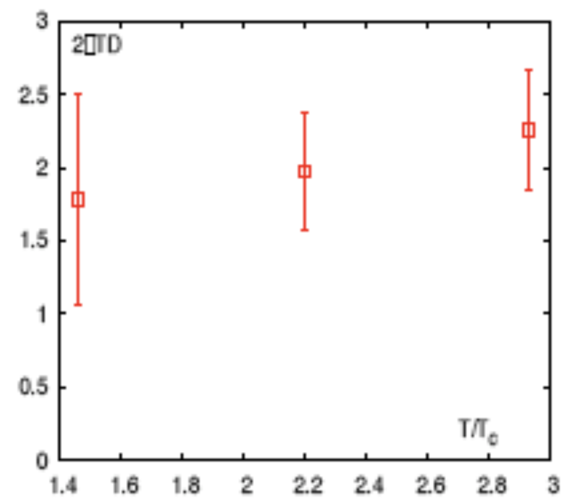
J/Ψ: Not yes/no!

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 $T \geqslant 1.46\ T_c$.

Need to:

- Understand onium suppression patterns in terms of medium effects on the correlation screening length
  - Relate correlator to screening length
  - Lattice should be able to do this…
  - Connect lattice results to observables!

- Update recombination calculations using correlator from the lattice in place of purely thermal quark distributions

- Must make sense of observed (non) dependence on √s
  - Experimental data on different c,b bound states
  - Measure as a function of T at >3 points!
    - This is a job for RHIC, down to ~ 40 GeV √s
    - Needs a large acceptance detector, sensitive at low p_T

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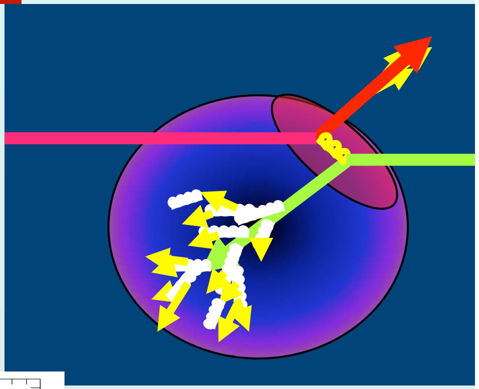
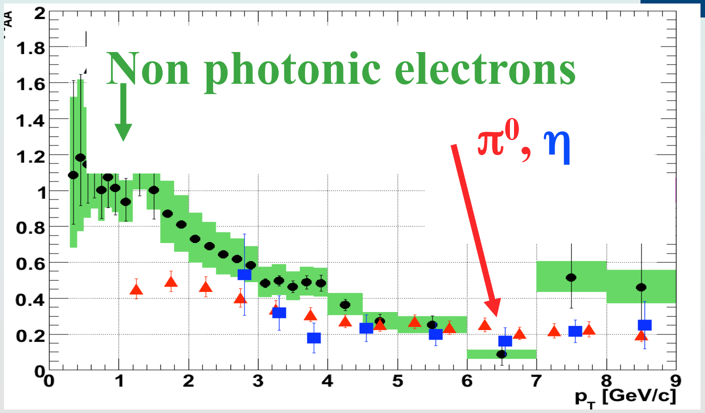
- **backup slides**

Context: QCD matter at T =300-600 MeV

- Collective flow with low viscosity/ entropy ratio: *"perfect liquid"*
  How low? Strong coupling…
- Opacity very high
  Effectively stops quarks & gluons
  How and why? Strong coupling…
- Even heavy quarks lose energy & flow
  Not expected from pQCD; mechanism?
  ->(very) strong coupling
- Color is screened
  How much?

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





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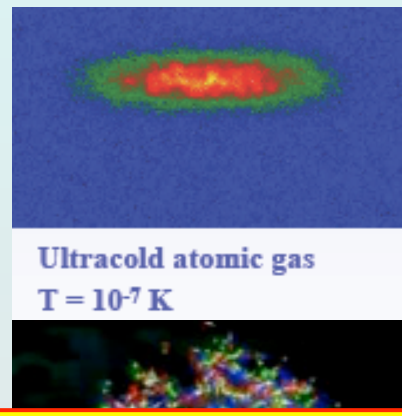
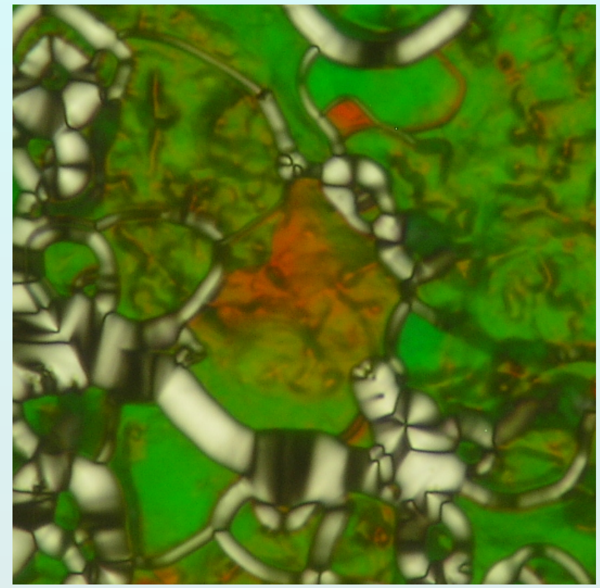
Similar to forefront question in other fields!

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

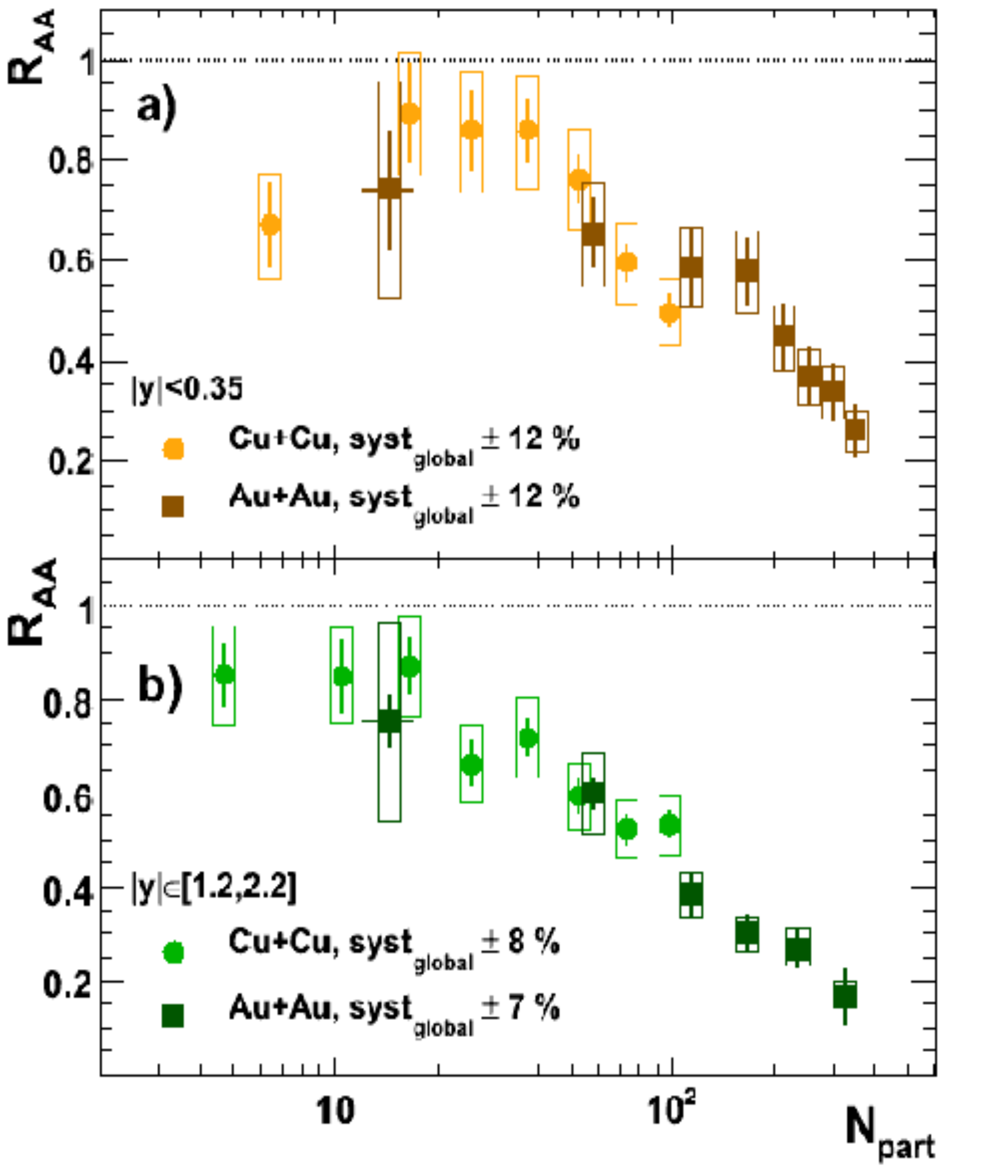
Strongly correlated condensed matter:

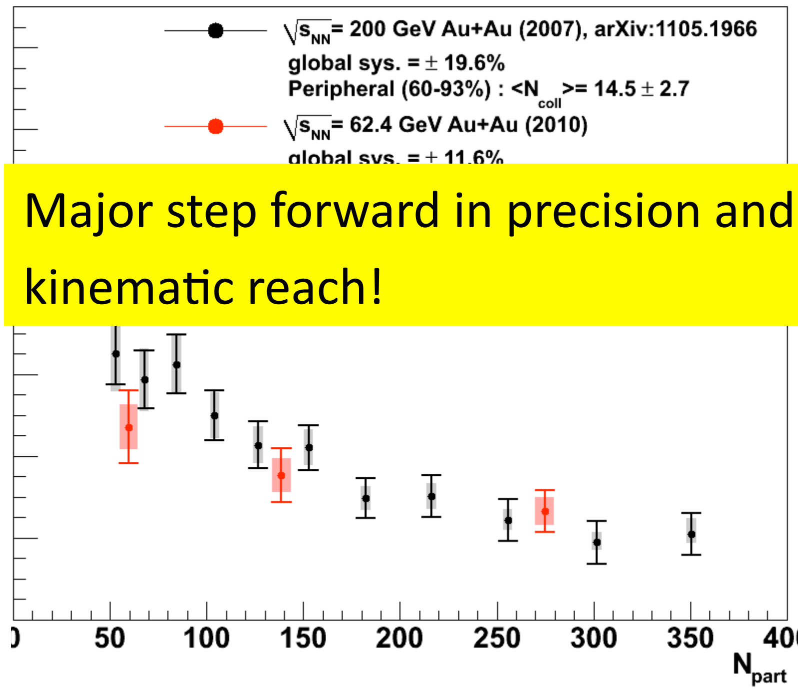
In all these cases have a competition:

Attractive forces ⇔ repulsive force or kinetic energy

Result: many-body interactions; quasiparticles exist?

J/ψ vs. system size, √s





Major step forward in precision and kinematic reach!

o obvious pattern of the
ppression with energy density.

understand color screening:
udy as function of √s, p_T, $\mathbf{r}_{onium}$ +
+Au to disentangle cold matter effects

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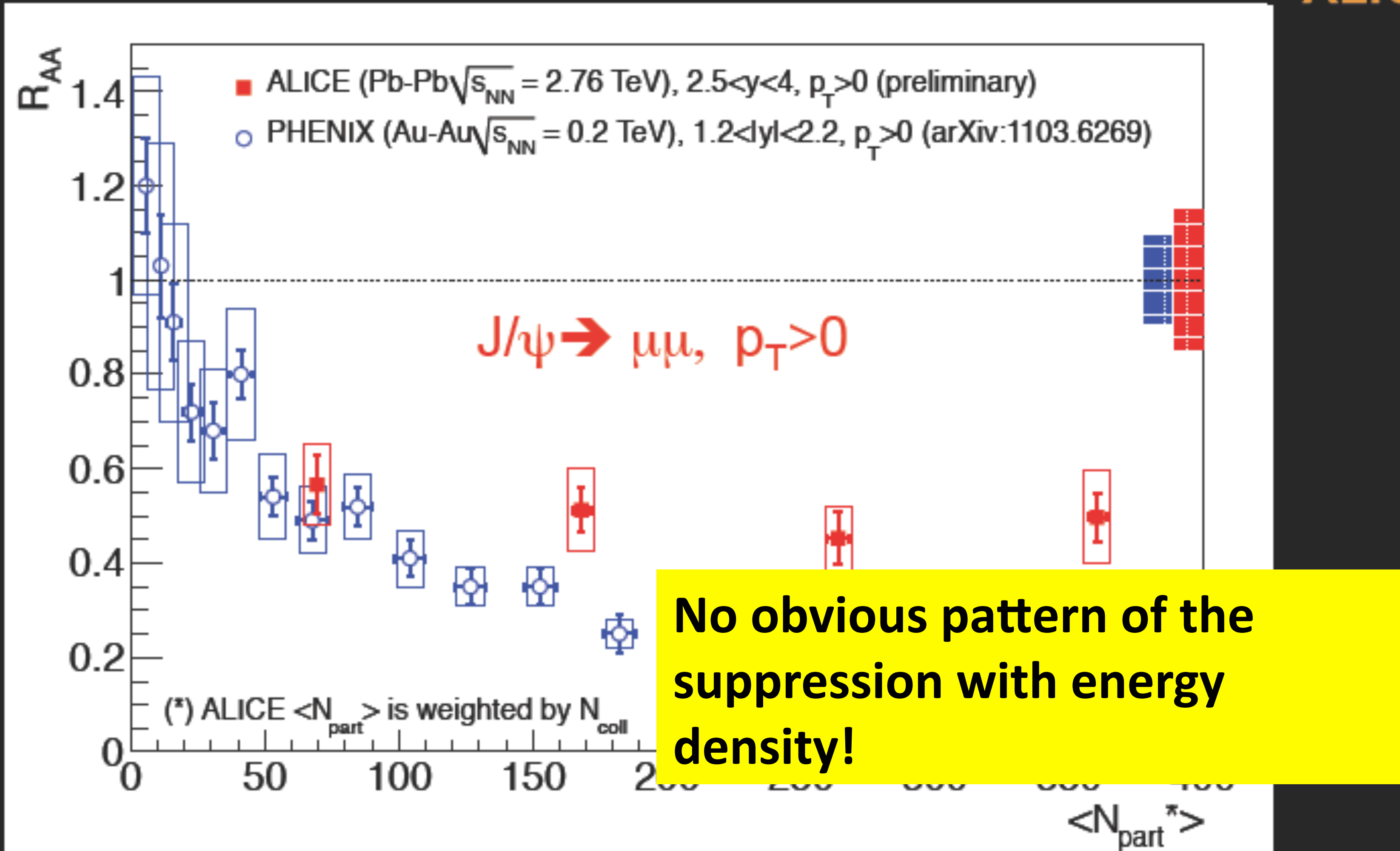
PRL101, 122301 (2008)

NSAC milestone DM5

J/ψ R_{AA} Centrality Dependence – LHC & RHIC

ALICE, G. Martinez-Garcia QM 2011



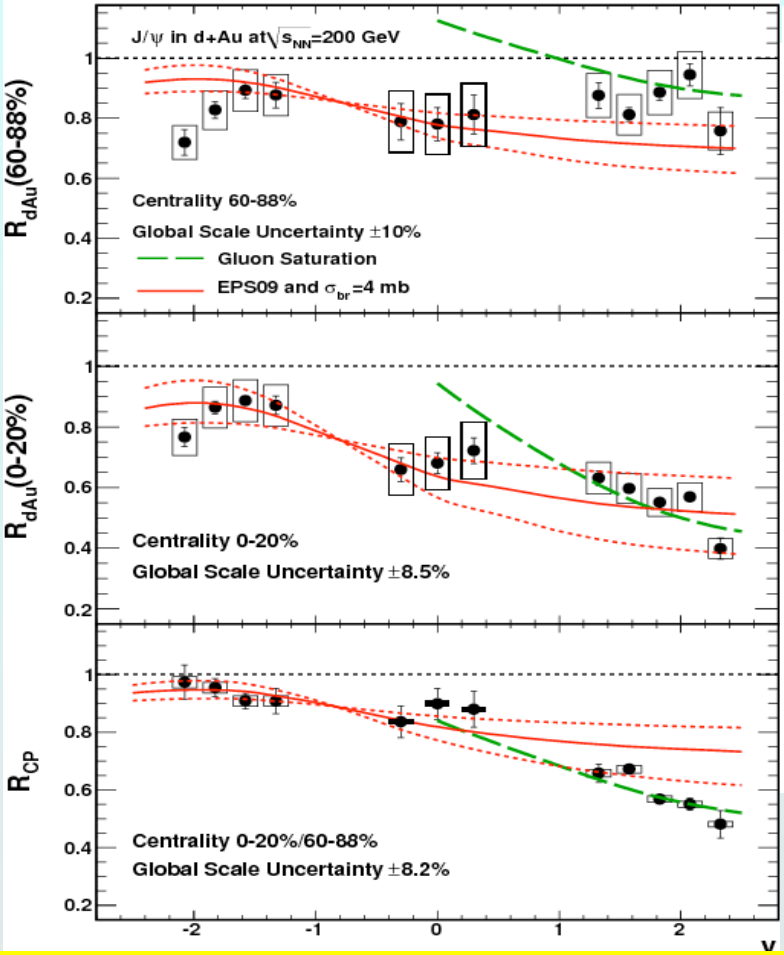
J/ψ R_{AA} larger at LHC (2.5<y<4) than at RHIC (1.2<|y|<2.2)

Similar to RHIC (|y|<0.35), except for most central bin

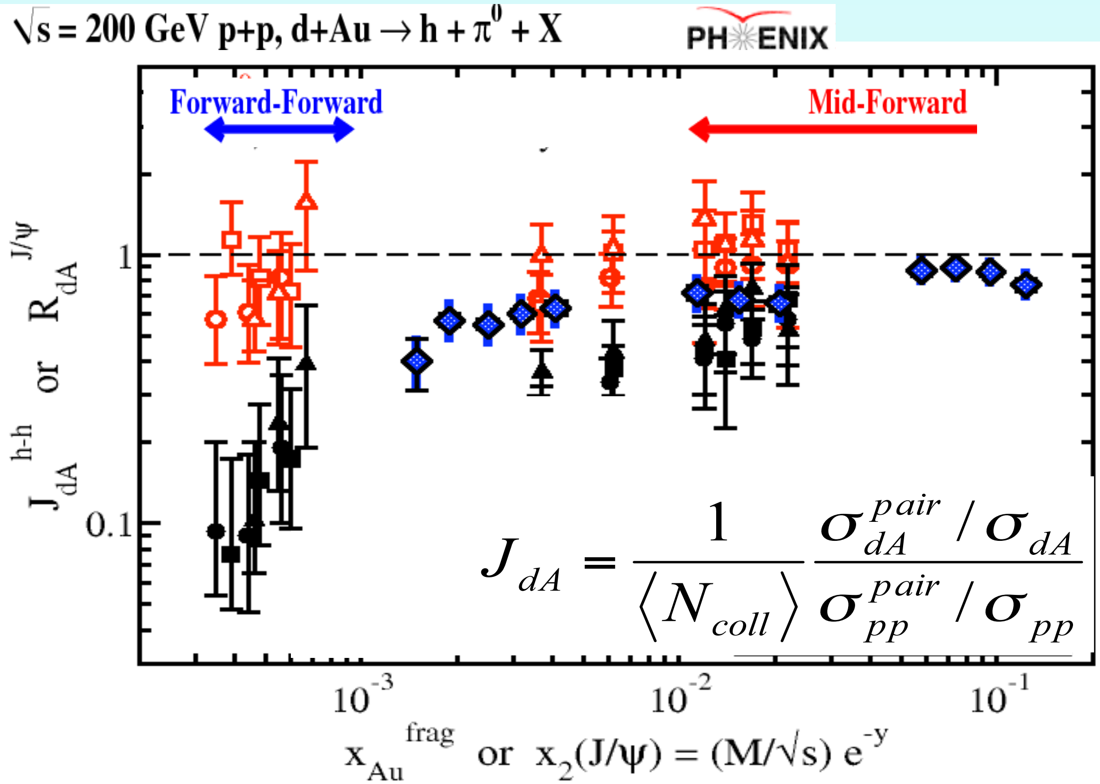
Note – $dN_{ch}/d\eta(N_{part})^{LHC} \sim 2.1 \times dN_{ch}/d\eta(N_{part})^{RHIC}$

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):

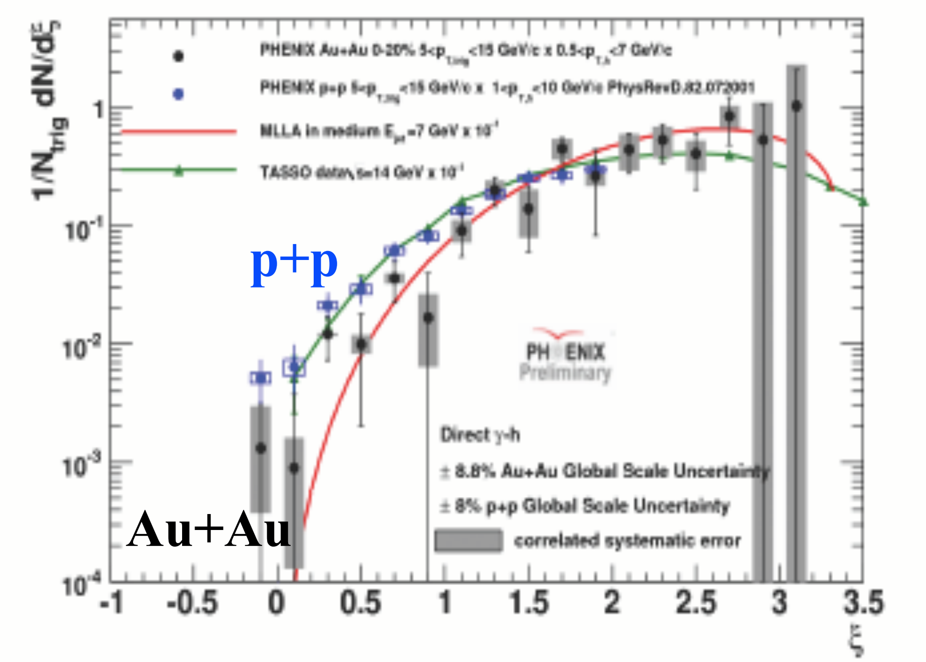
$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

PHENIX **Toward NSAC milestone DM8**

trend as, e.g. in CGC …

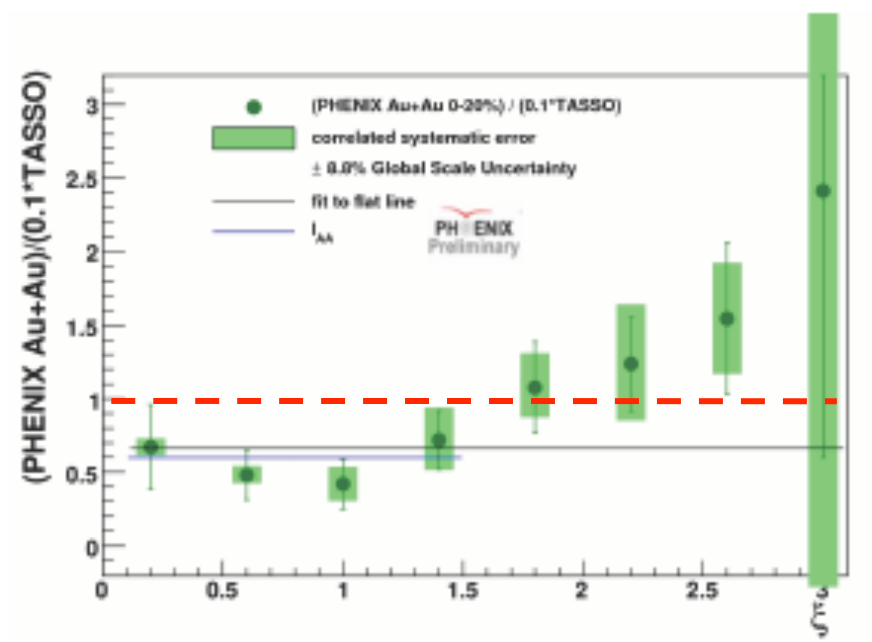
γ-jet correlations

Measure the fragmentation function



$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

Does QGP medium modify how q, g fragment into jets of hadrons?



$$\langle I_{AA} \rangle = 0.662 \pm 0.087$$

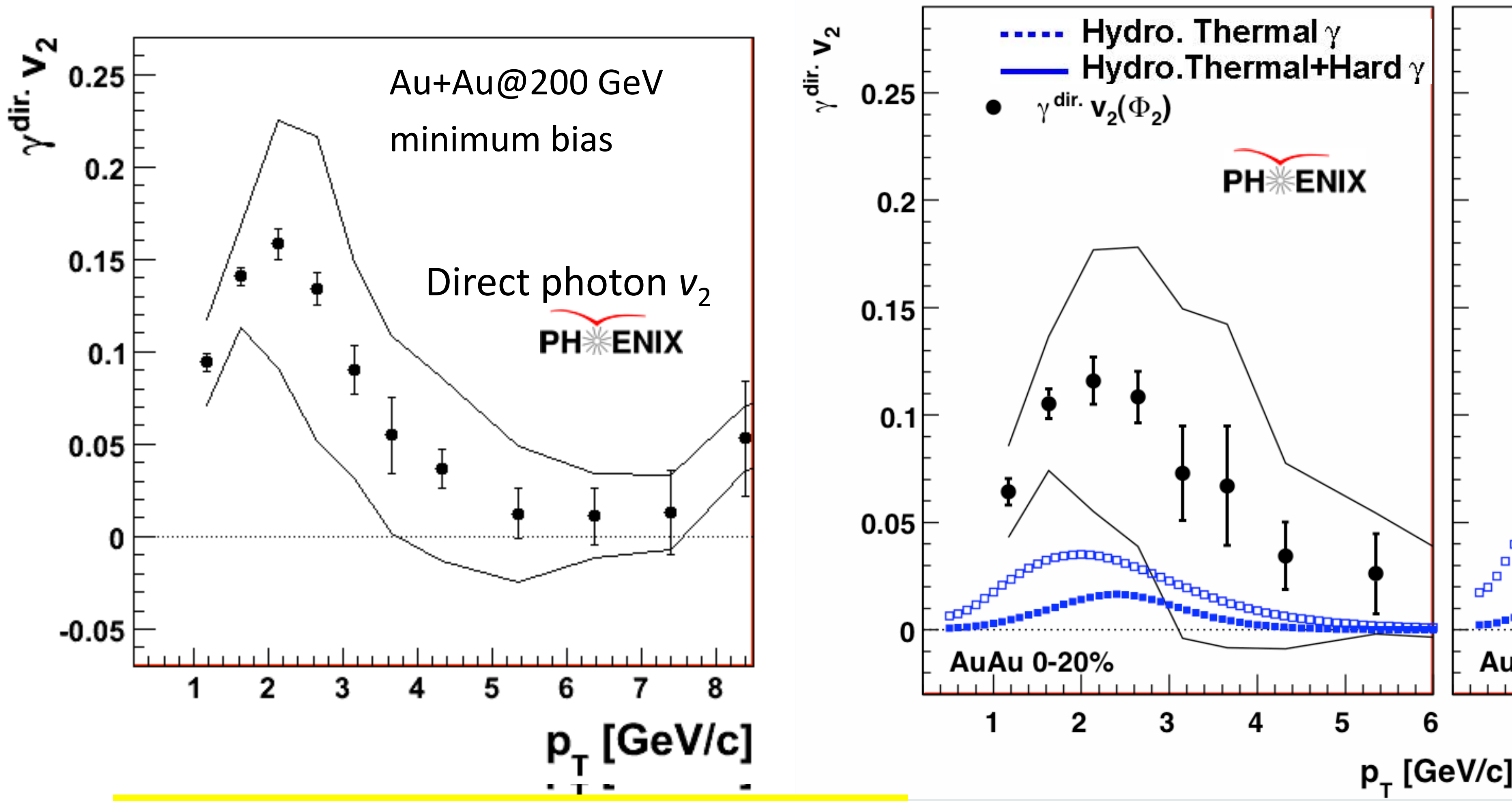
$$\chi^2 / NDF = 12.16 / 7$$

Differs from that in e^+e^- collisions!

PHENIX **Toward NSAC milestone DM11**

Direct photons flow!

arXiv:1105.4126



Flow magnitude is a real surprise!

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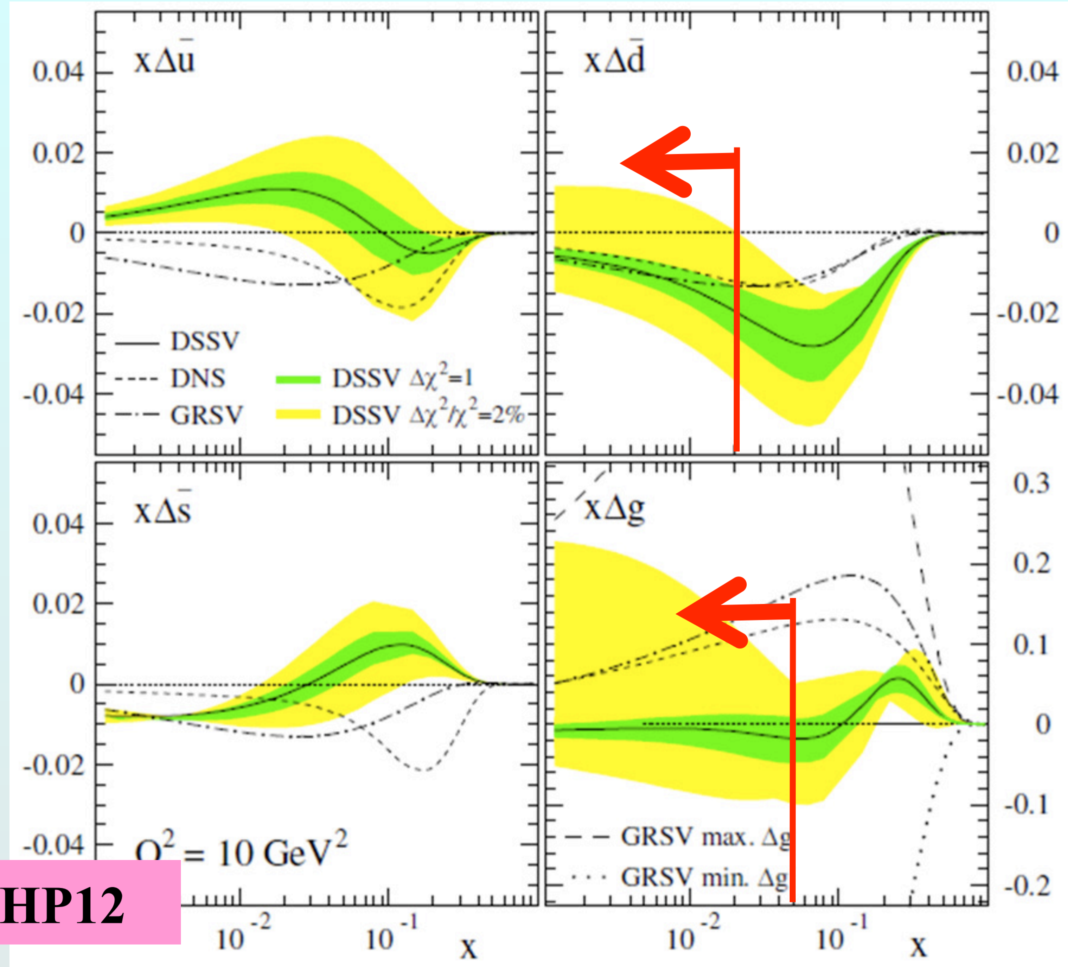
Toward NSAC milestone DM13

gluon & sea quark polarization

Current result from global fits

Still surprisingly small

See talk from Elke Aschenauer



Toward NSAC milestone HP12

- **500 GeV p+p: π^0 A_{LL} to constrain Δg (0.01<x<0.3)**
  central/forward correlations tag kinematics
- **W A_L at forward, backward, mid rapidity for $\Delta\bar{u}$, Δu, $\Delta\bar{d}$, Δd**

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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?

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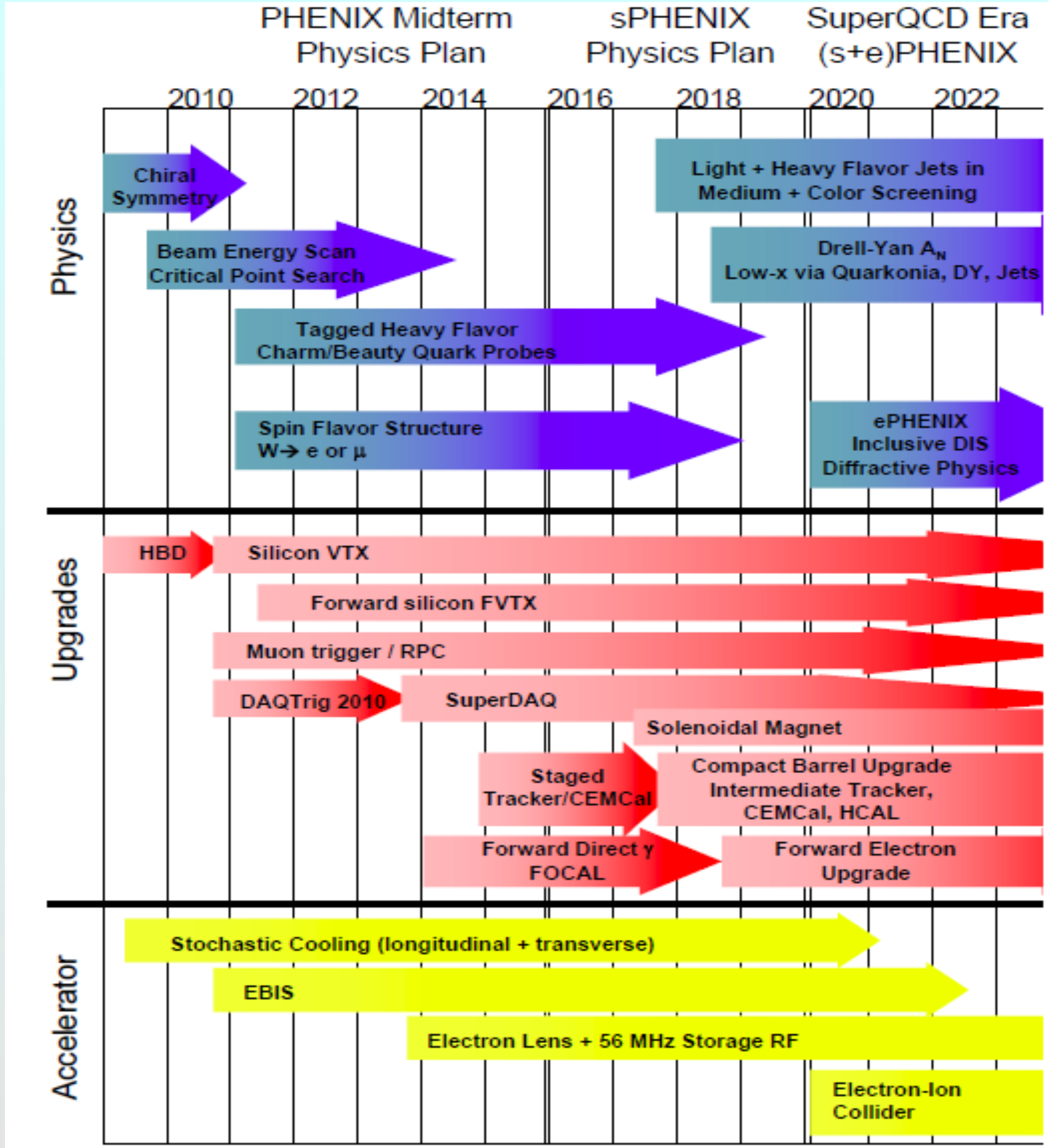
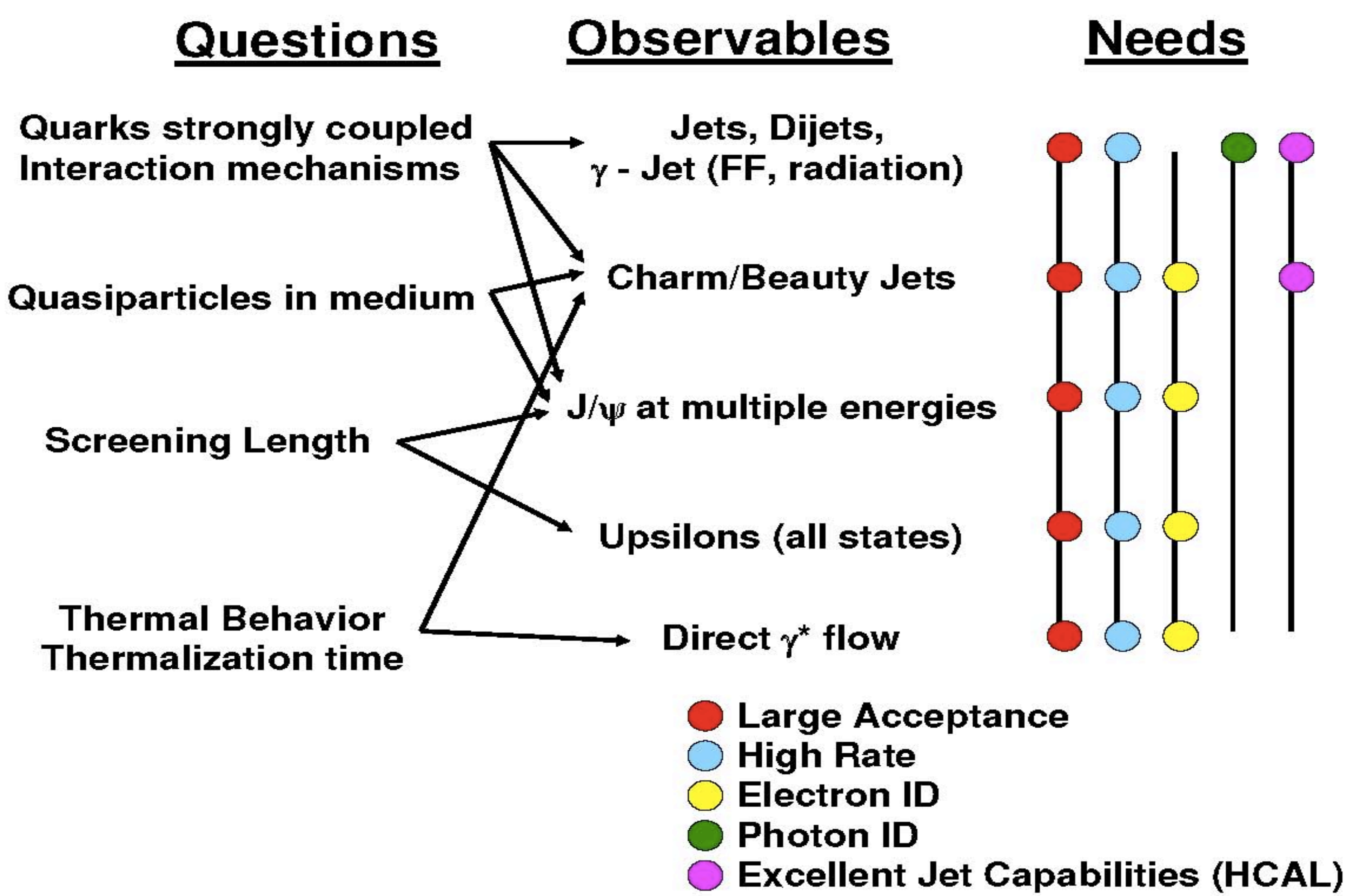
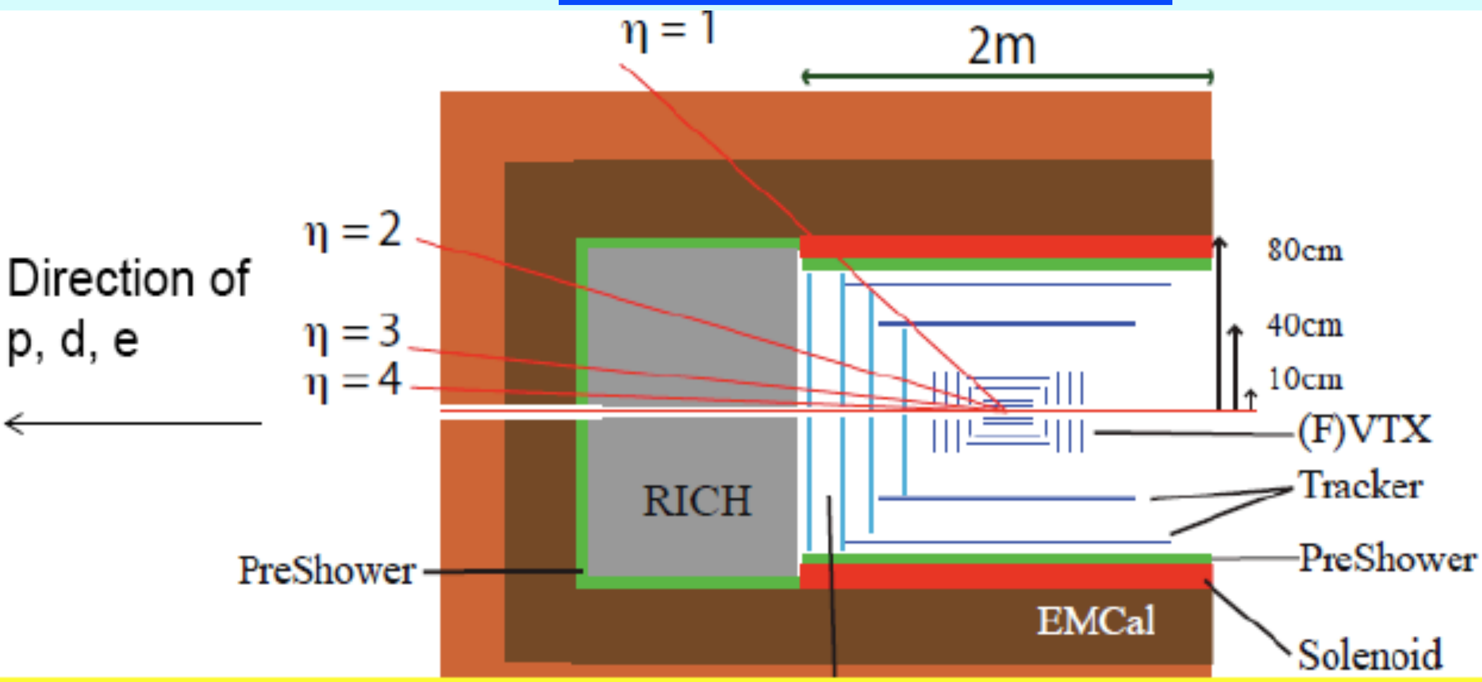
PHENIX-> sPHENIX-> ePHENIX plan



To answer these questions



Upgrade Concept



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

- Compact detector covering -1 < η < 4
- Measure jets, electrons and photons in mid-rapidity → Measure QGP properties
- Gluon saturation physics at forward region (η > 1)
- First eRHIC detector (not yet optimized)

Cost estimate

Carry over from existing PHENIX:

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

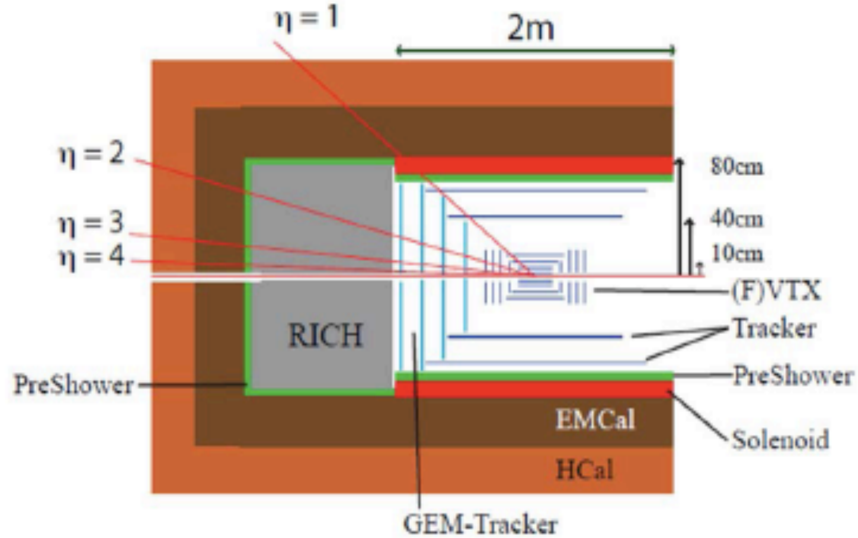
What is new:

- 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



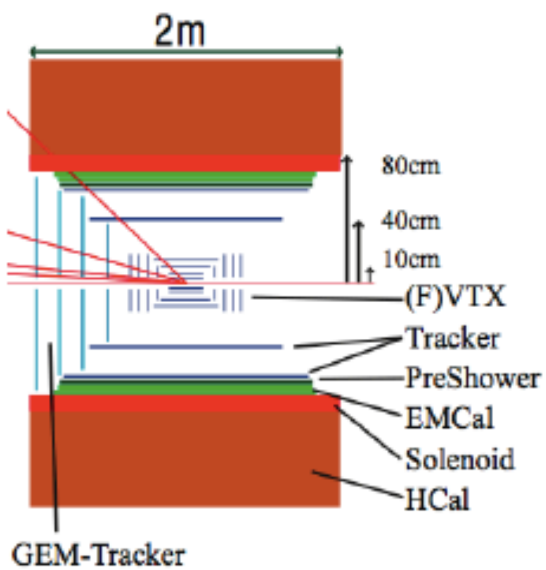
Can be built incrementally

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

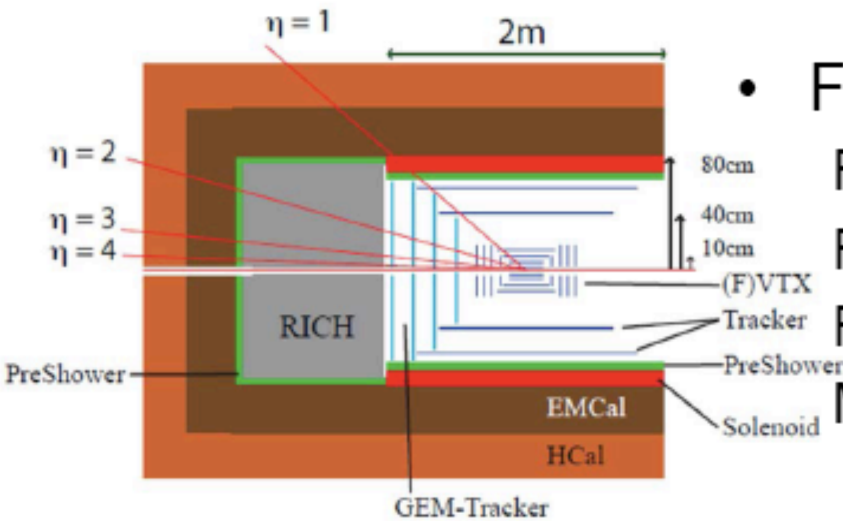


- Mid-rapidity detector

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

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

  Hcal — *Jets* 8-10M



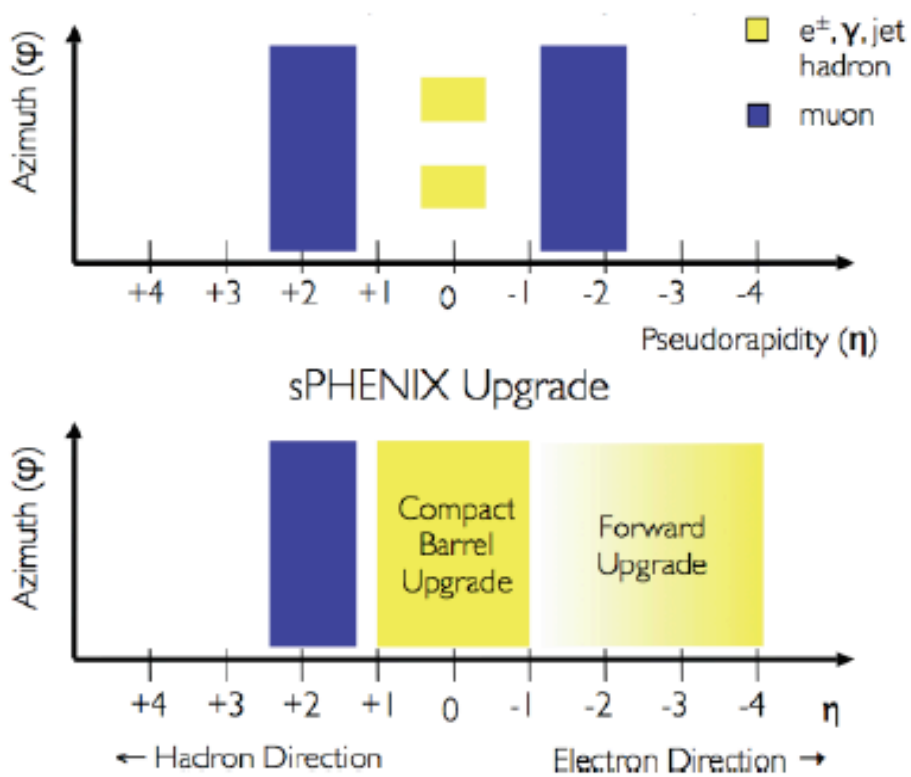
- Forward Detector

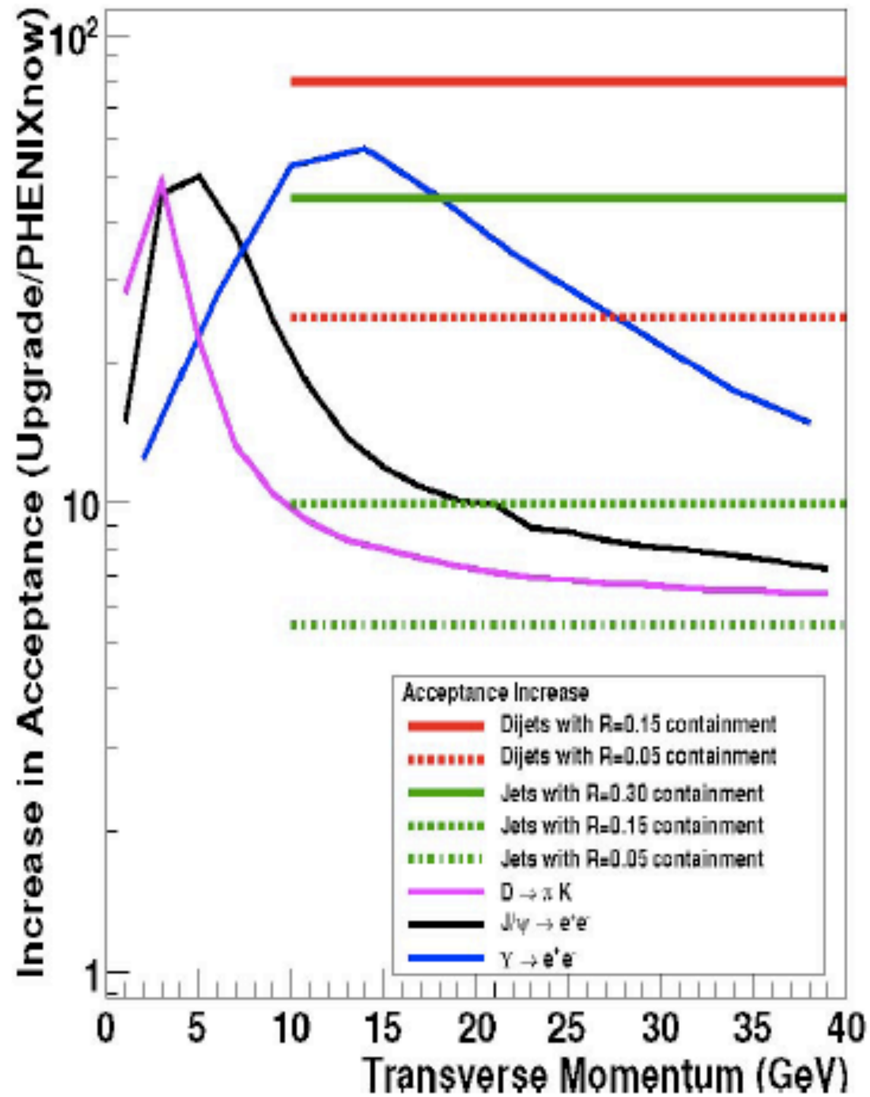
  RICH and GEM tracker — *CNM, eRHIC* 10M

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

sPHENIX acceptance

Much larger acceptance than PHENIX

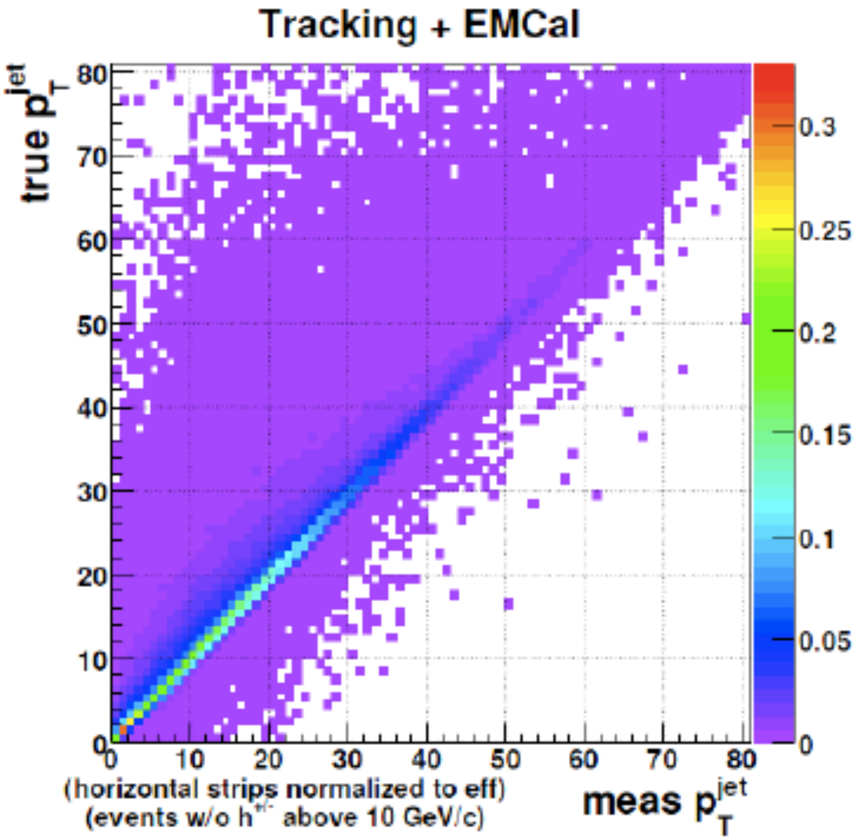


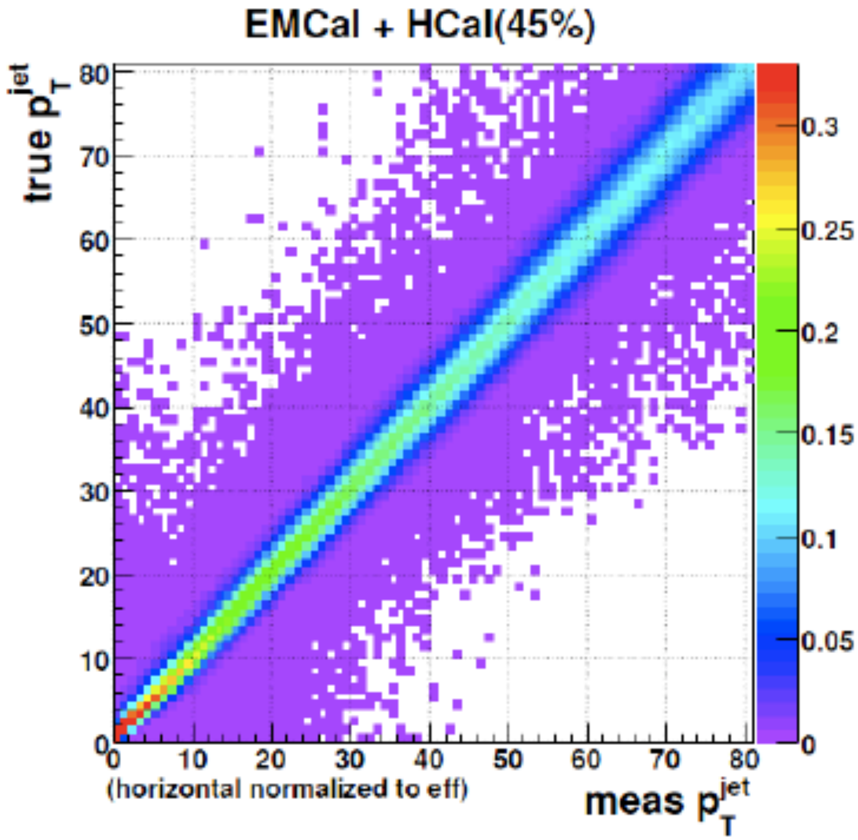


+ DAQ/Trigger: 50B events / year!

HCal improvement to Jet Energy Measurement

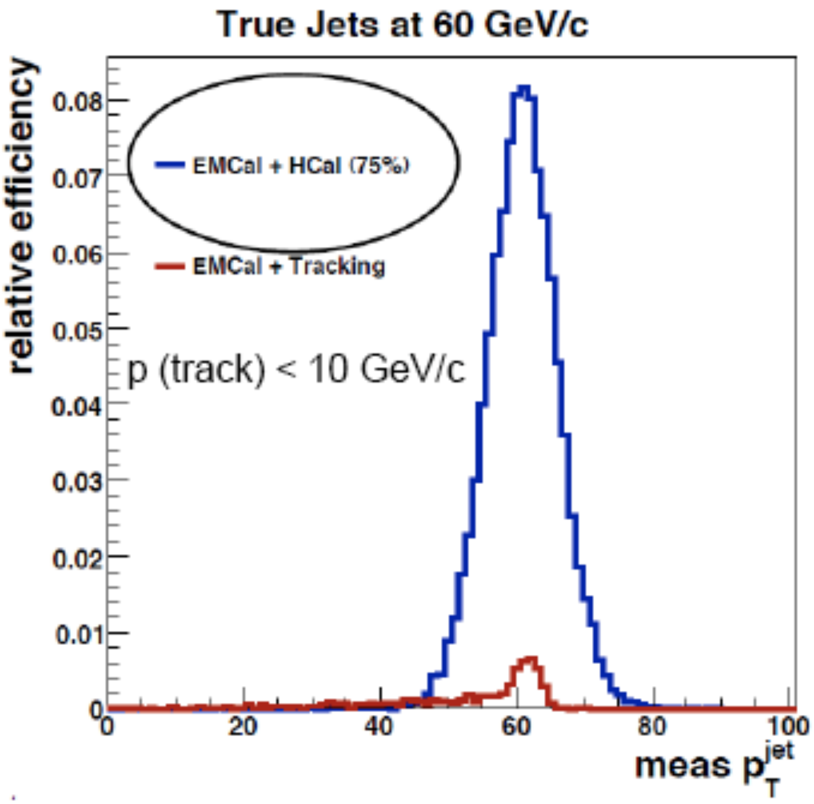
tracking p < 10 GeV/c required
to avoid fake jets

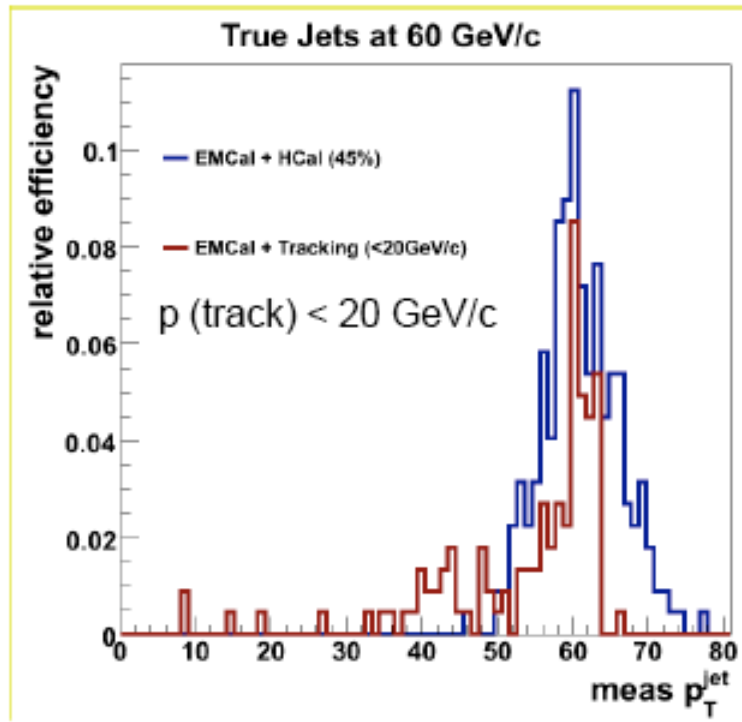




- No fake jet due to tracking background
- Catch neutral energy
- No asymmetric tail in measured energy → Essential for A_J measurement

HCal for jet measurement





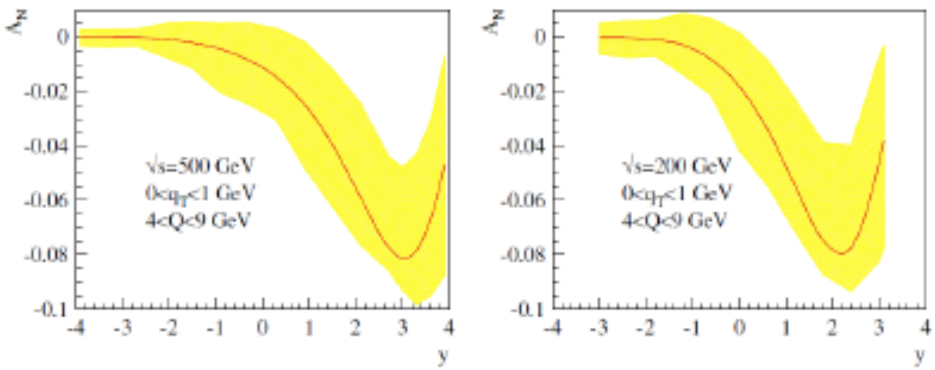
With 10 GeV tracking cut off, only tiny fraction of jet can be reconstructed

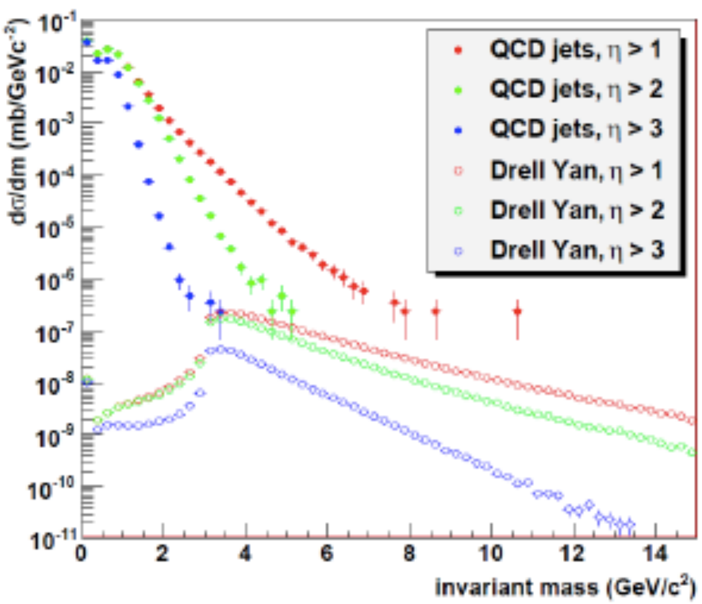
With 20 GeV tracking cut off, still less than 1/3 of jet is reconstructed at proper energy

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

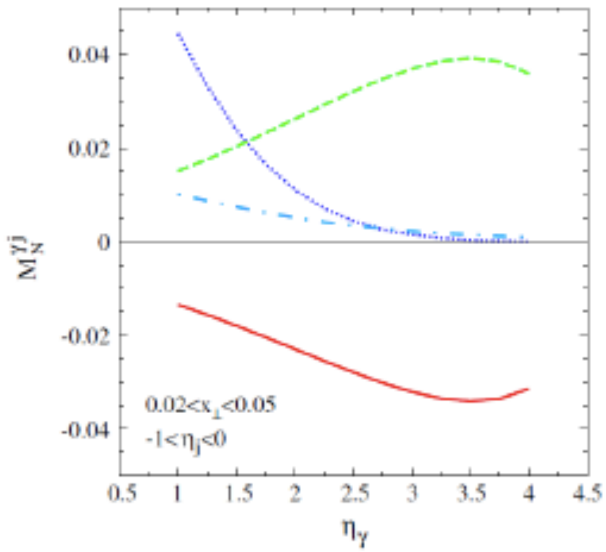
Spin Physics with sPHENIX

A_N of DY at forward rapdity

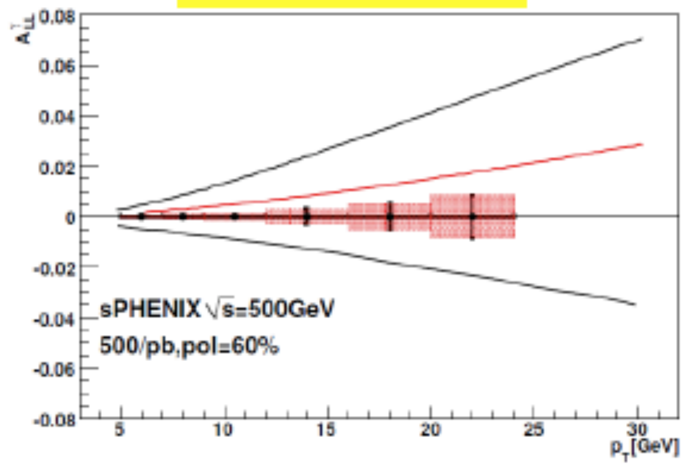




γ-jet transverse spin moment



A_{LL} of Direct γ

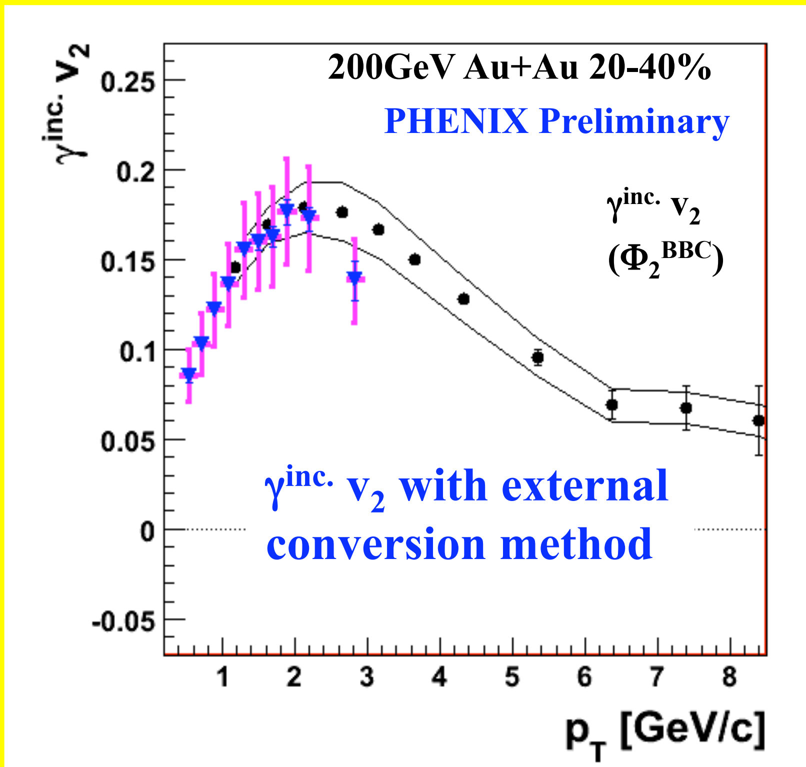


Forward physics upgrade

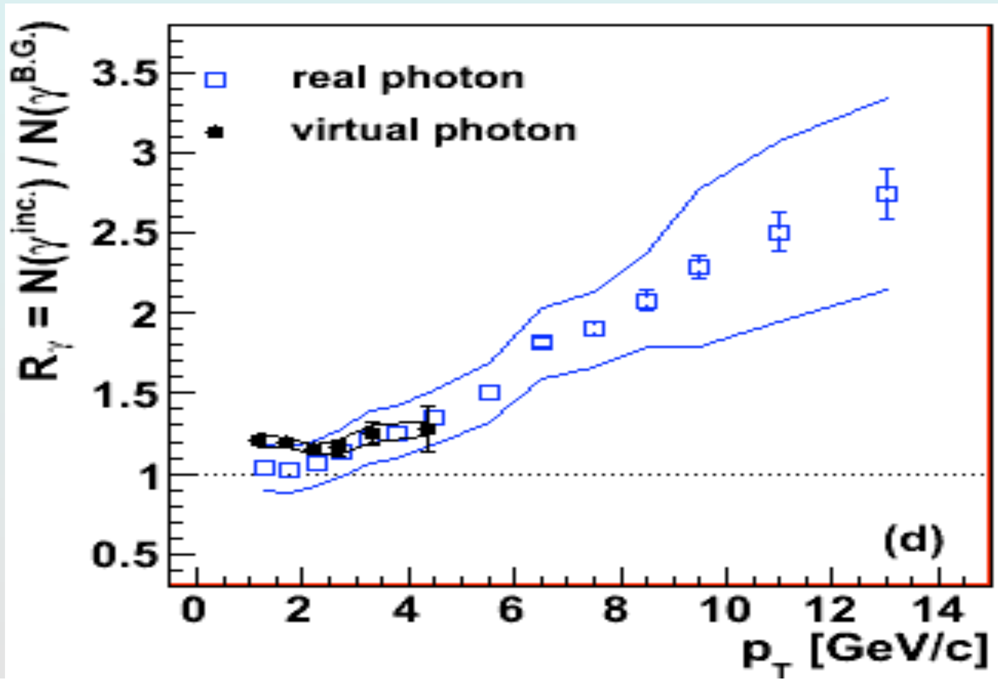
- **Transverse spin phenomena**
  - Reach high x_F at $|\eta| > 2$
  - Drell-Yan: test QCD prediction SIDIS vs. Drell-Yan
  - Separate Sivers and Collins; do flavor separated PDFs
- **Longitudinal spin phenomena**
  - Extend x coverage for ΔG and Δq
- **Drell-Yan in d+Au**
  - Quark distributions in nuclei
- **First EIC physics**
  - Polarized and unpolarized inclusive structure functions in ep and eA (F_2, F_L, F_3, g_1, g_2, g_5)
  - DVCS + other diffractive processes?

PHENIX

Direct photon flow ingredients



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



PHENIX

High m_{eff} → large collisional energy loss

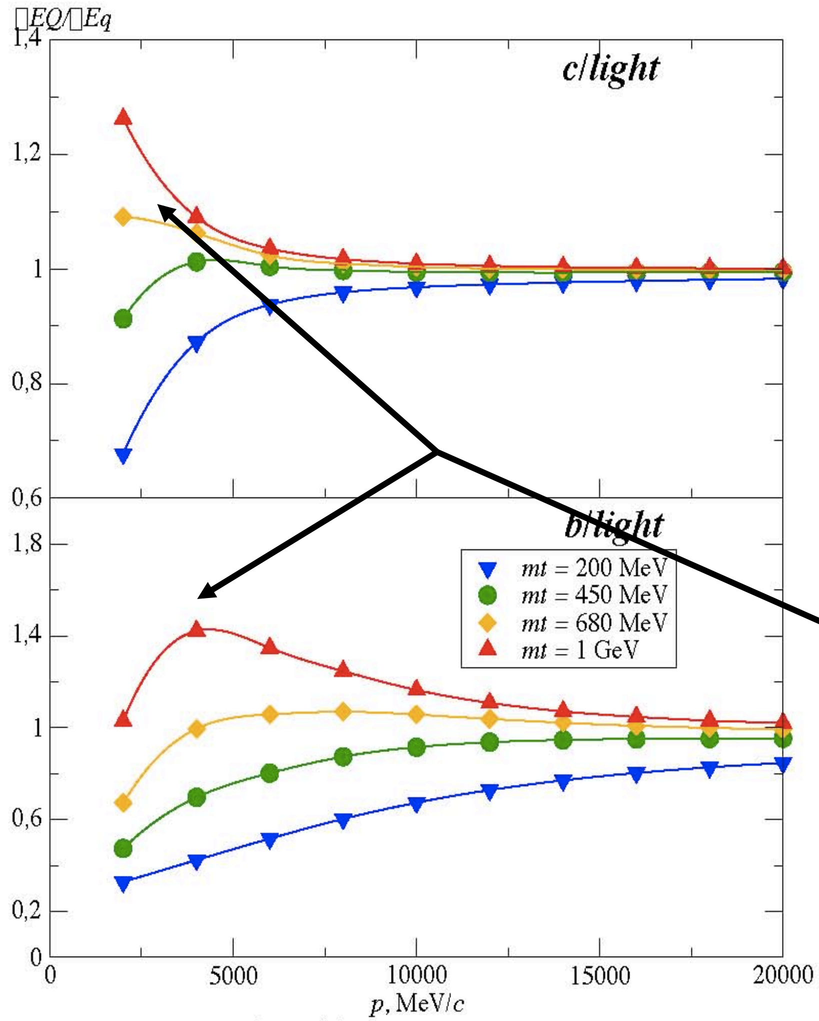


Fig. 3. The heavy-to-light ratio $\Delta E_Q/\Delta E_q$ of collisional energy loss for charm quarks (upper panel) and bottom quarks (lower panel), compared to that of light quarks (m_q = 200 MeV). The results for the numerator ΔE_Q and the denominator ΔE_q are the same as used for plotting Fig. 2.

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

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

PHENIX