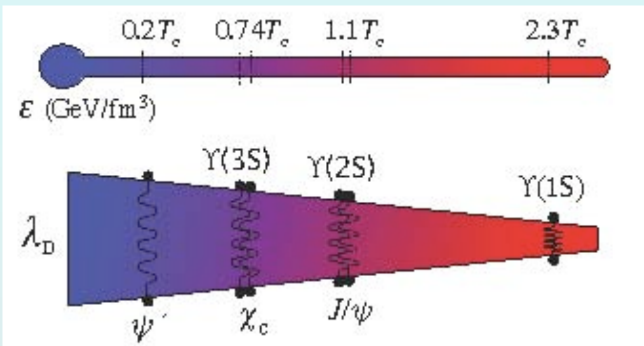
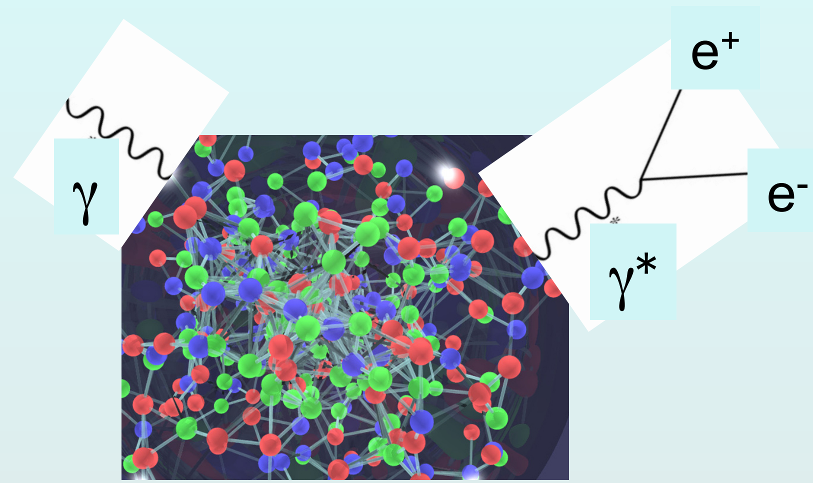
Lecture 2
Screening and EM probes





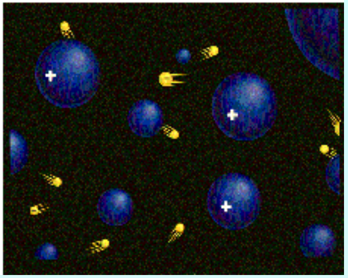
Barbara Jacak

UC Berkeley & LBNL

June 25, 2015

Outline

- Color screening and effects of strong coupling
- J/ψ, ψ' and ϒ production to probe color screening
- Quark correlator from lattice QCD
- A thermometer: photon and dilepton emission



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**

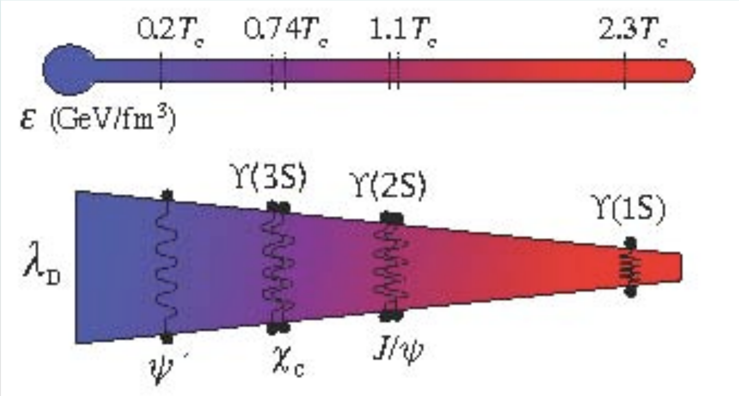
- **Strongly coupled plasmas: few (~1-2) particles in Debye sphere Partial screening -> liquid-like properties sometimes even crystals!**

- ***Test* QGP *screening with heavy quark bound states***

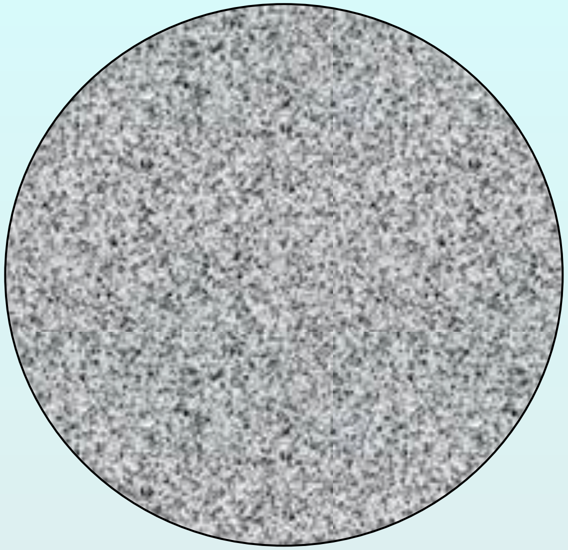
  $c + \bar{c}$ and $b + \bar{b}$: J/ψ & Y

  Do they survive?

  All? None? Some? Which size?



Bound states: lose some and gain some



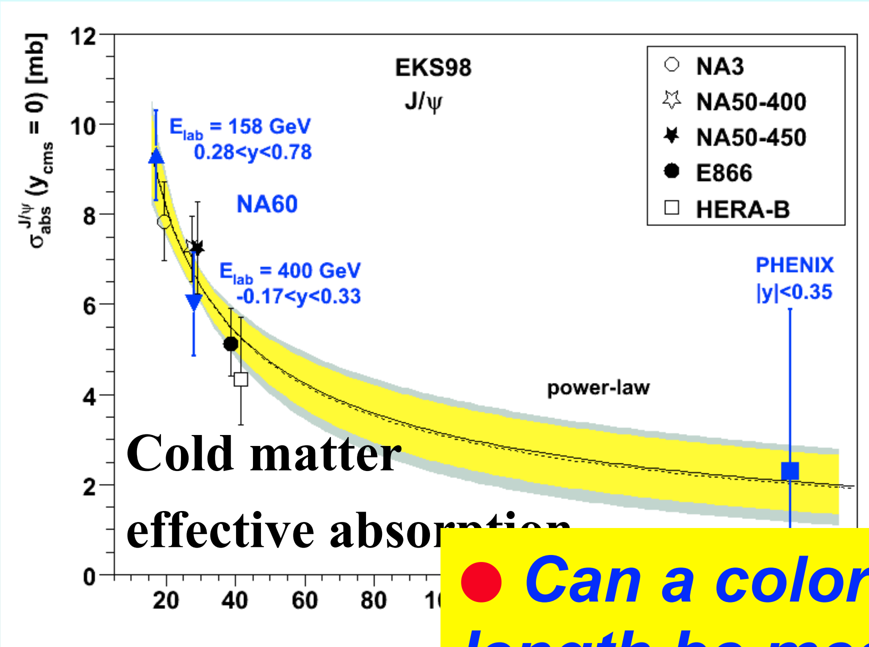
Drop of QGP filled with gluons + some quarks

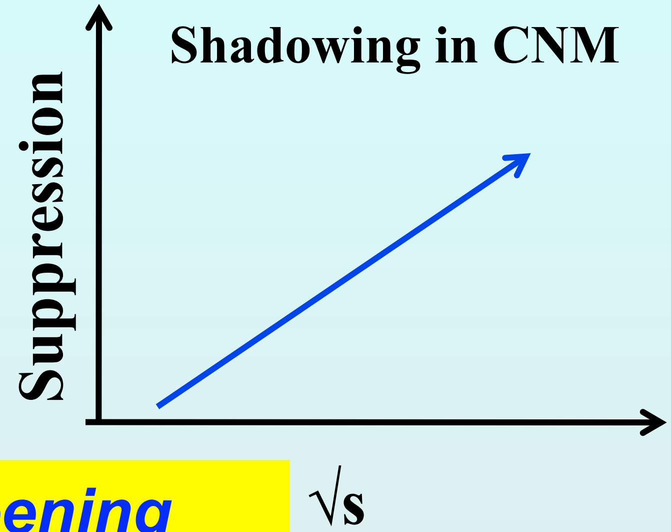
- QGP screens primordial bound c-cbar and b-bbar bound states
  - They melt in the plasma!
  - depends on binding energy (i.e. size of the bound state)
- quarks find one another when the system falls below T~150 MeV – form the hadrons we observe
- Occasionally a c can find a cbar
  - Probability increases with the number of c-cbar pairs made
  - Increases with beam energy

Measure energy, quark mass dependence to sort out (b's are rare)

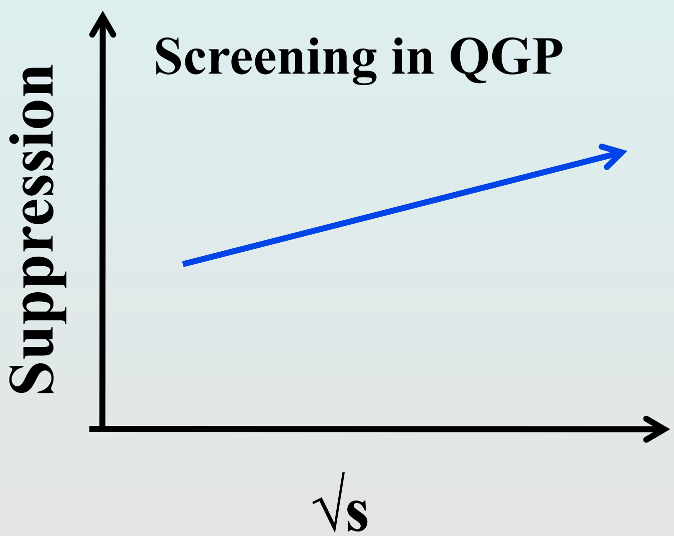
Initial state affects c&b – study p+A!

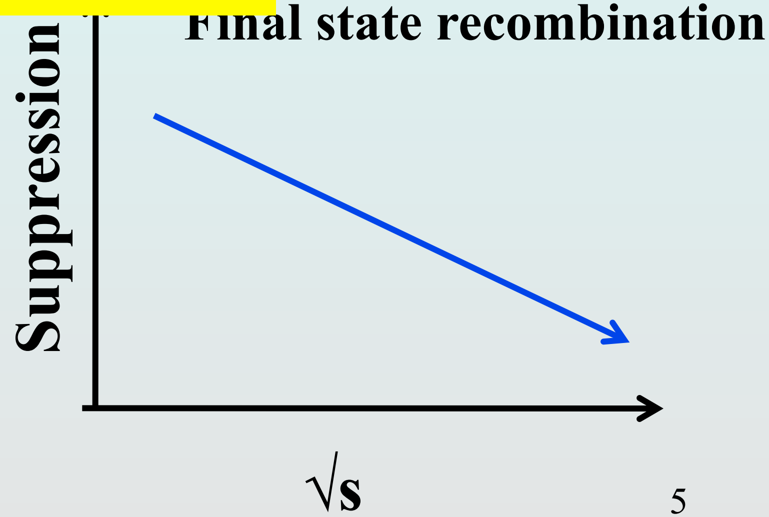
√s dependence of suppression effects





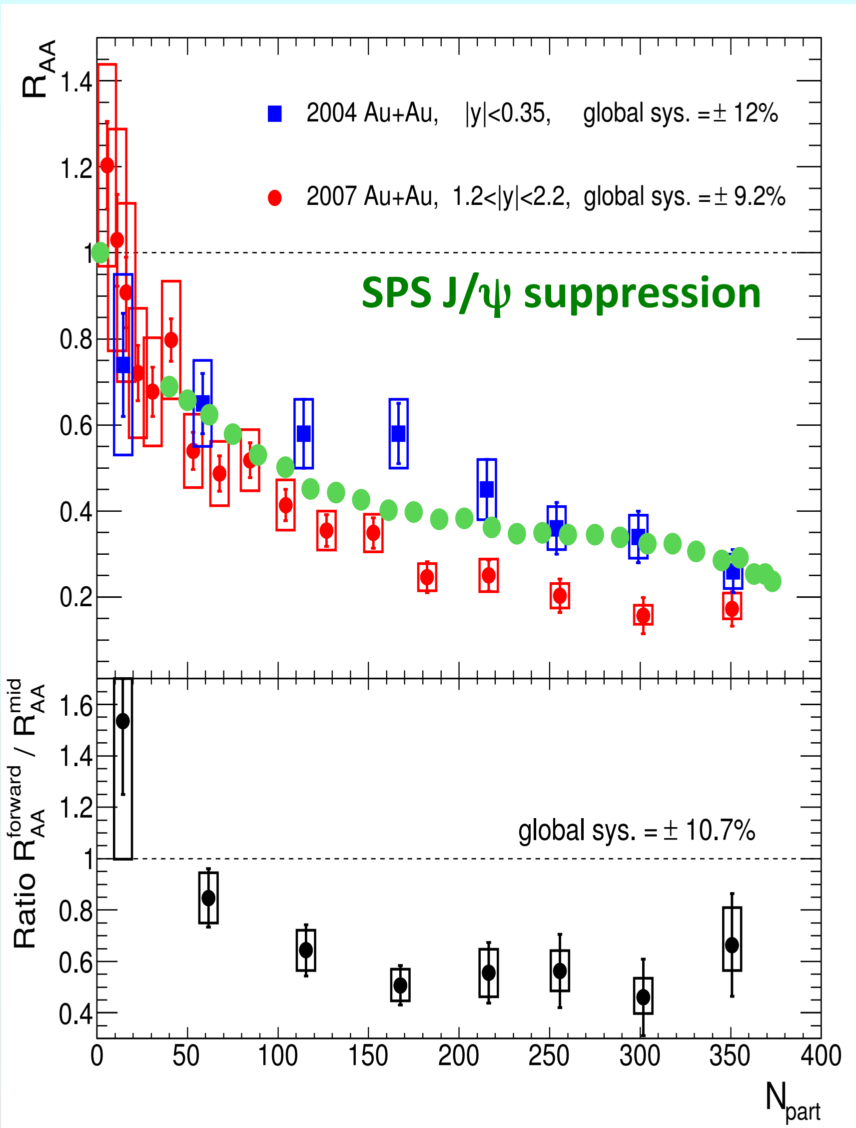
● ***Can a color screening length be measured?***

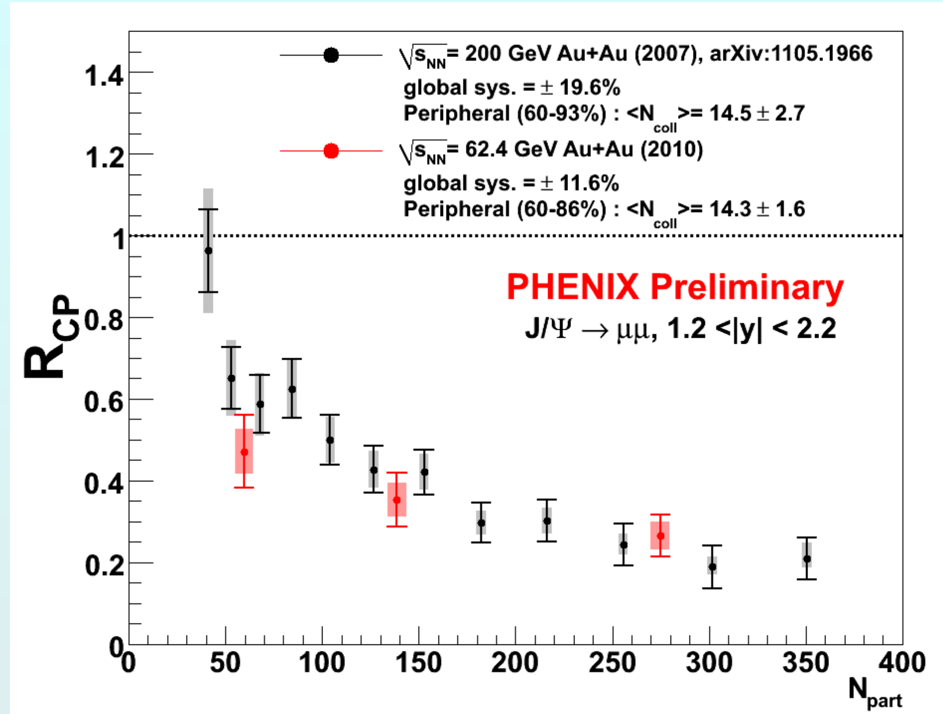




J/ψ suppression

arXiv:1103.6269





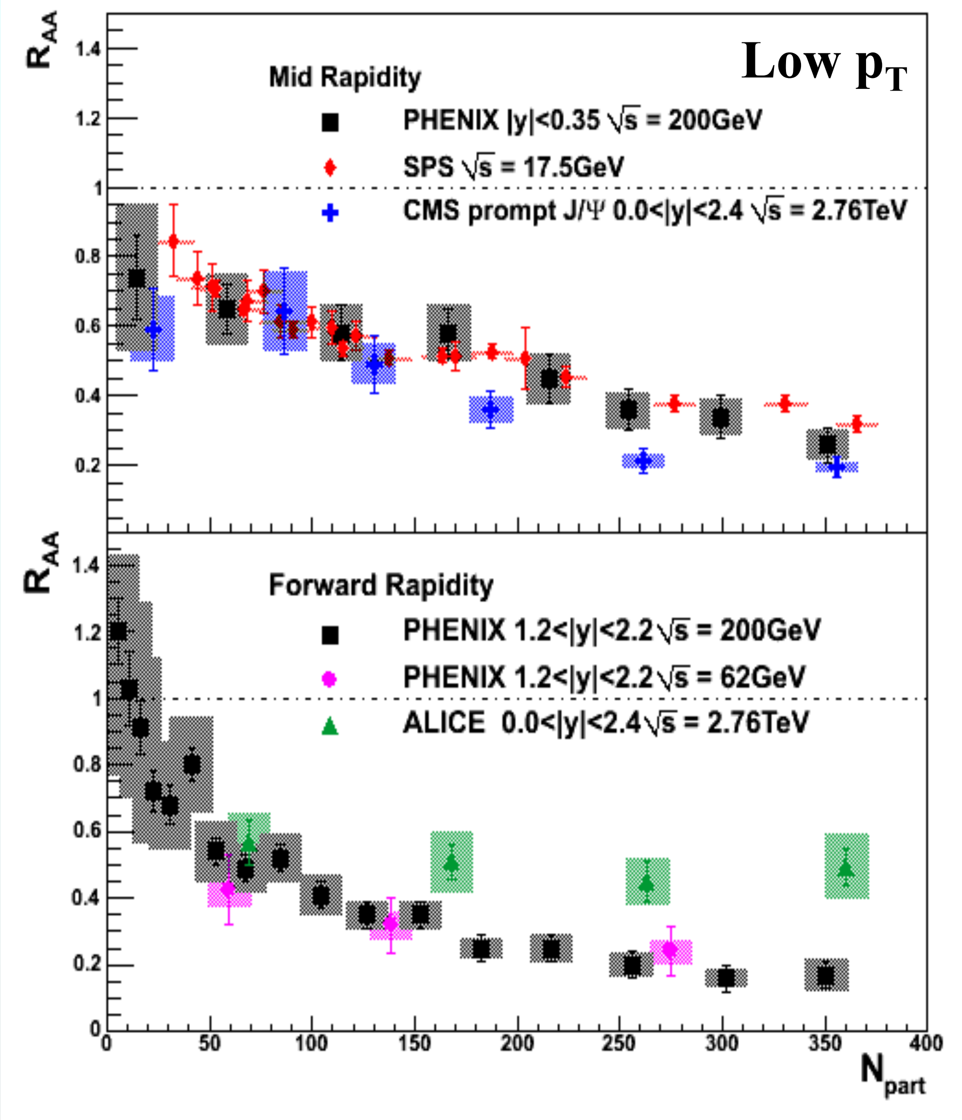
No obvious pattern of the suppression with energy density.

To understand color screening:

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

d+Au to disentangle cold matter effects

J/ψ vs. system size, √s



No clear suppression pattern with √s, T!

Why more suppression at y=2?

Late break-up?

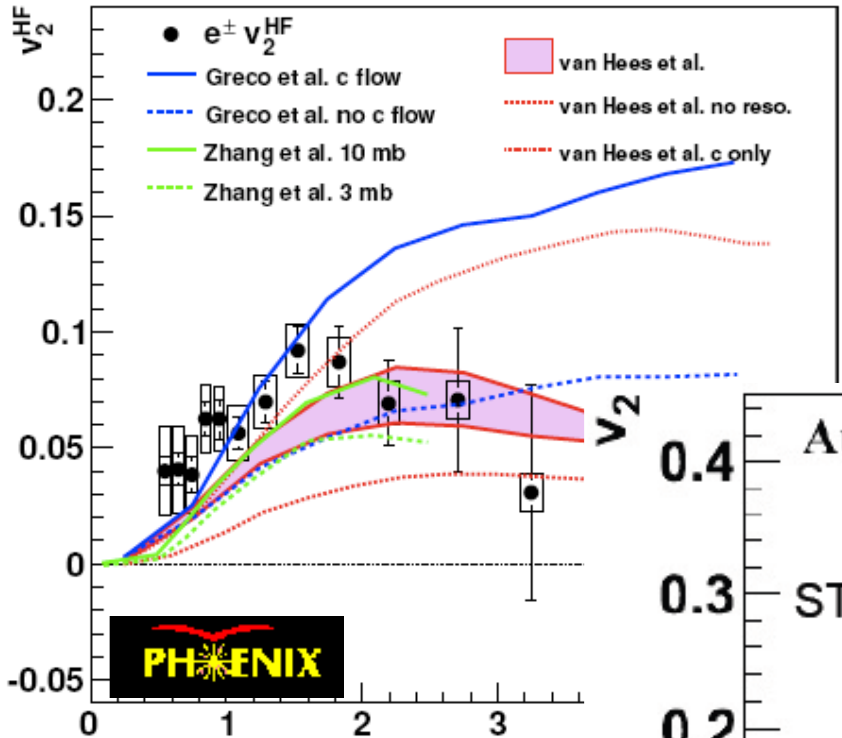
Final state coalescence of $q\bar{q}$?

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

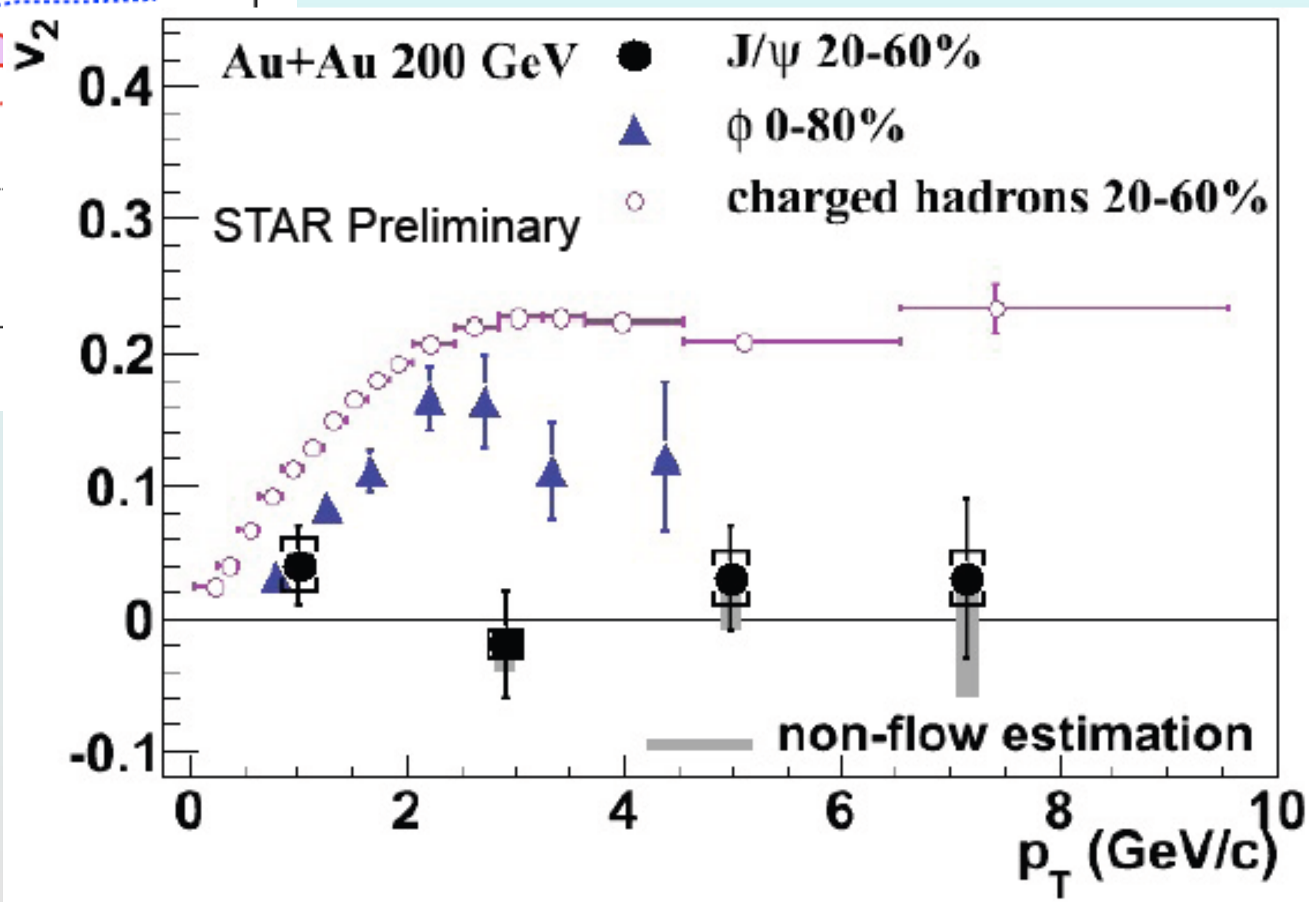
Expect if c-cbar pairs numerous or correlated



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?

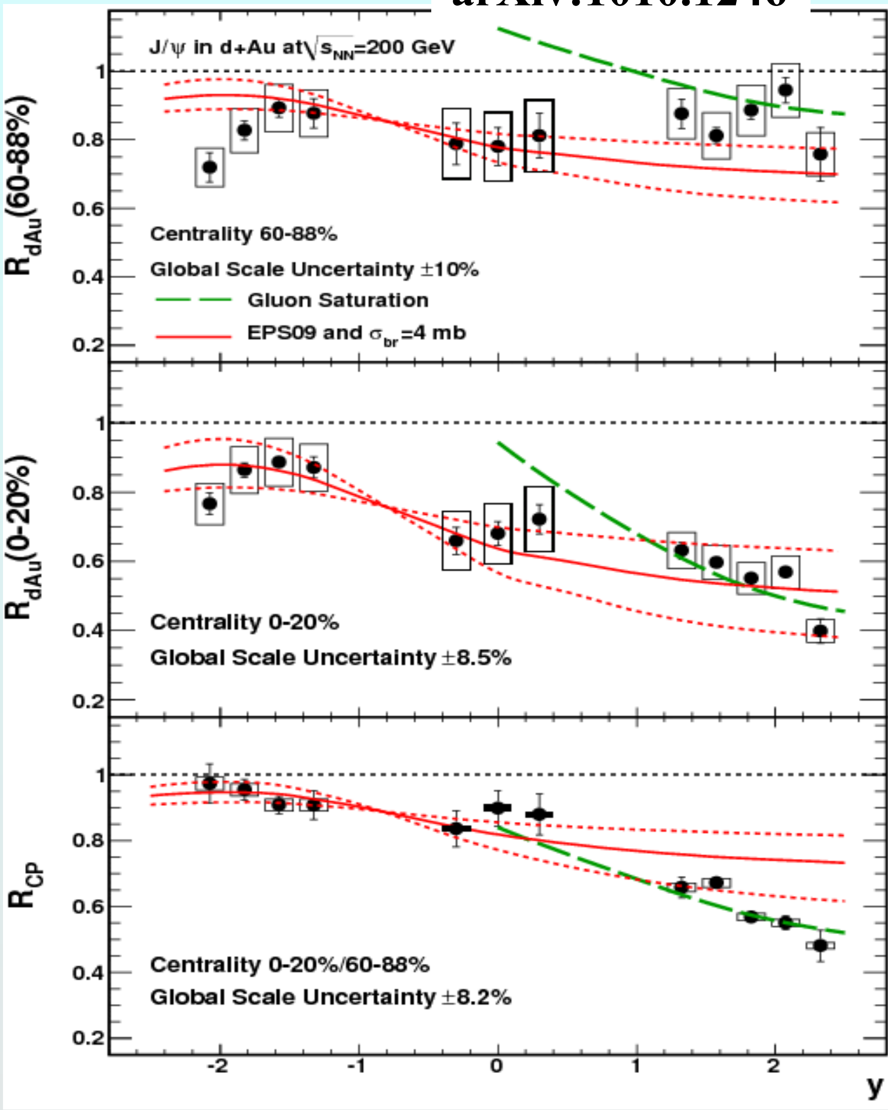
Suppression pattern ingredients

- Color screening
- Final state coalescence

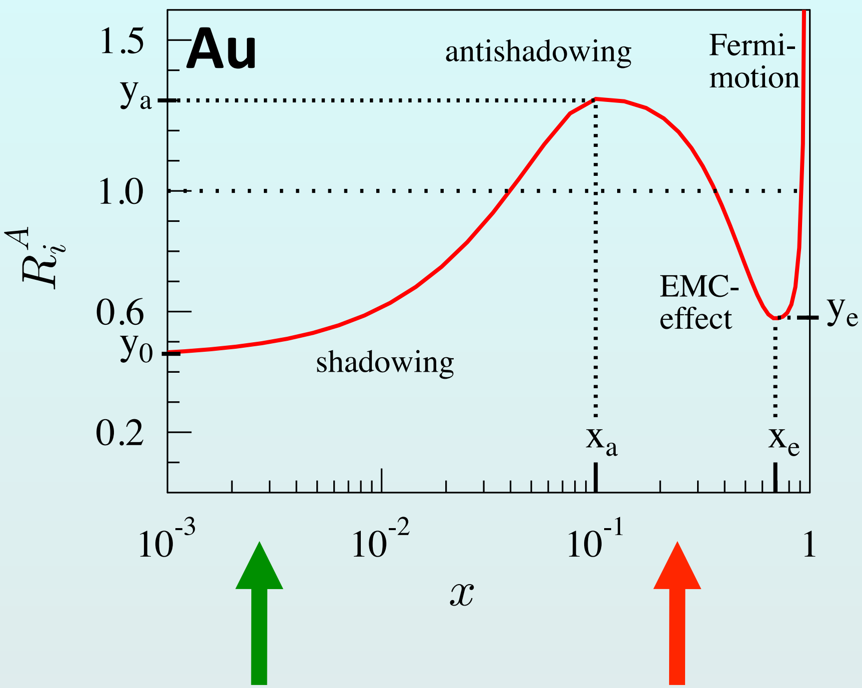
- Initial state effects
  - Shadowing or saturation of incoming gluon distribution
  - Initial state energy loss
  - (calibrate with p+A or d+A)

- Final state effects
  - Breakup of quarkonia due to co-moving hadrons
  - (calibrate with A & centrality dependence)

arXiv:1010.1246

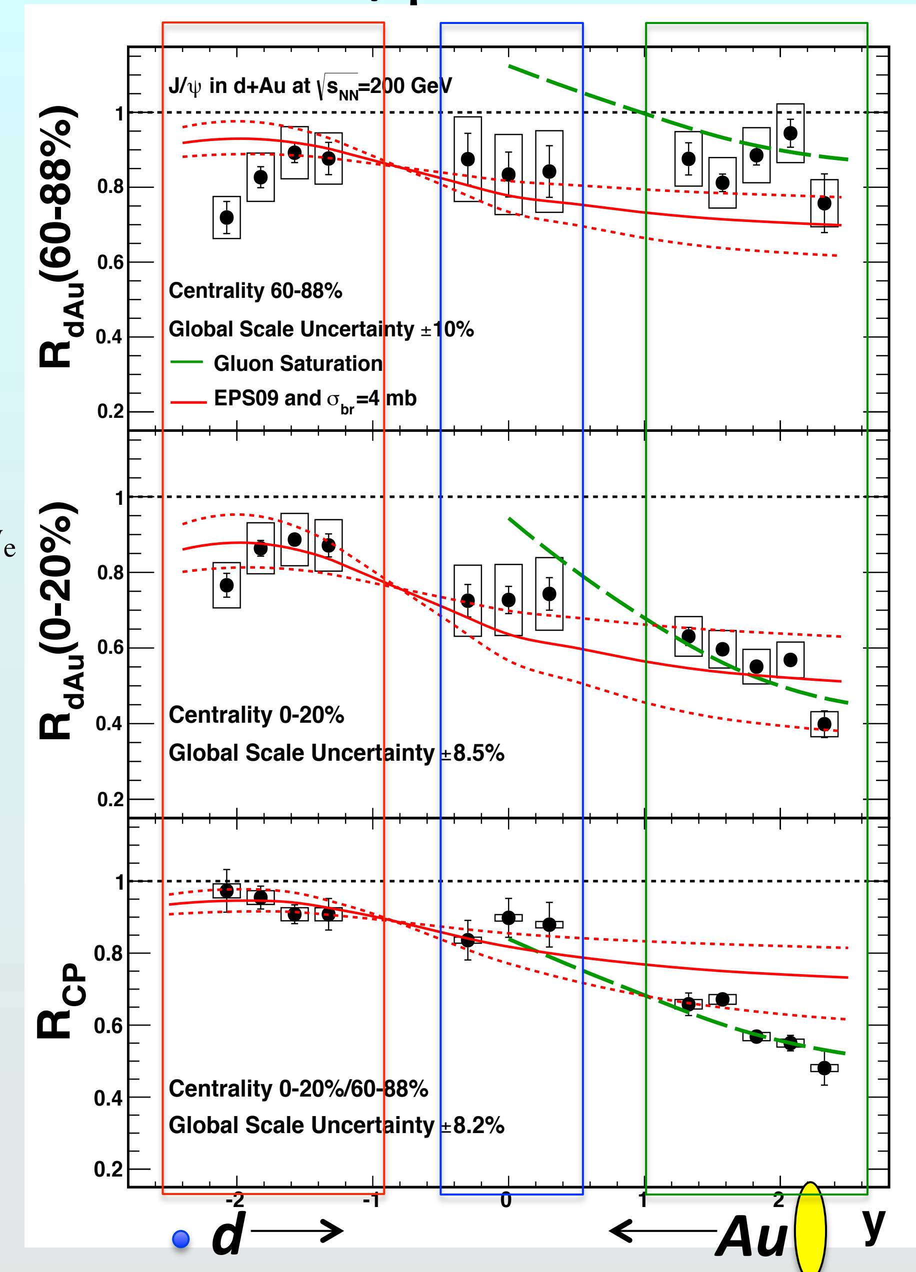


d+Au -> J/ψ from PHENIX



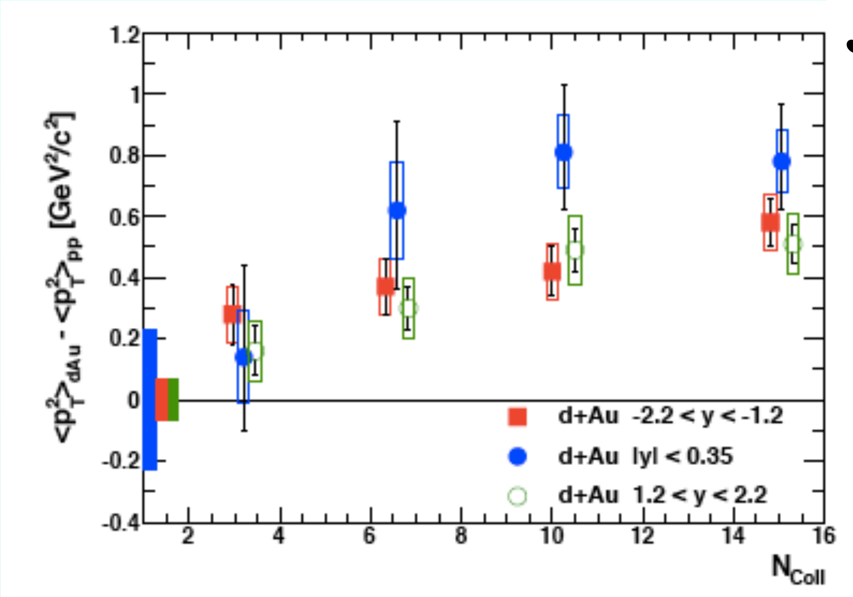
Forward
+ y
d-going

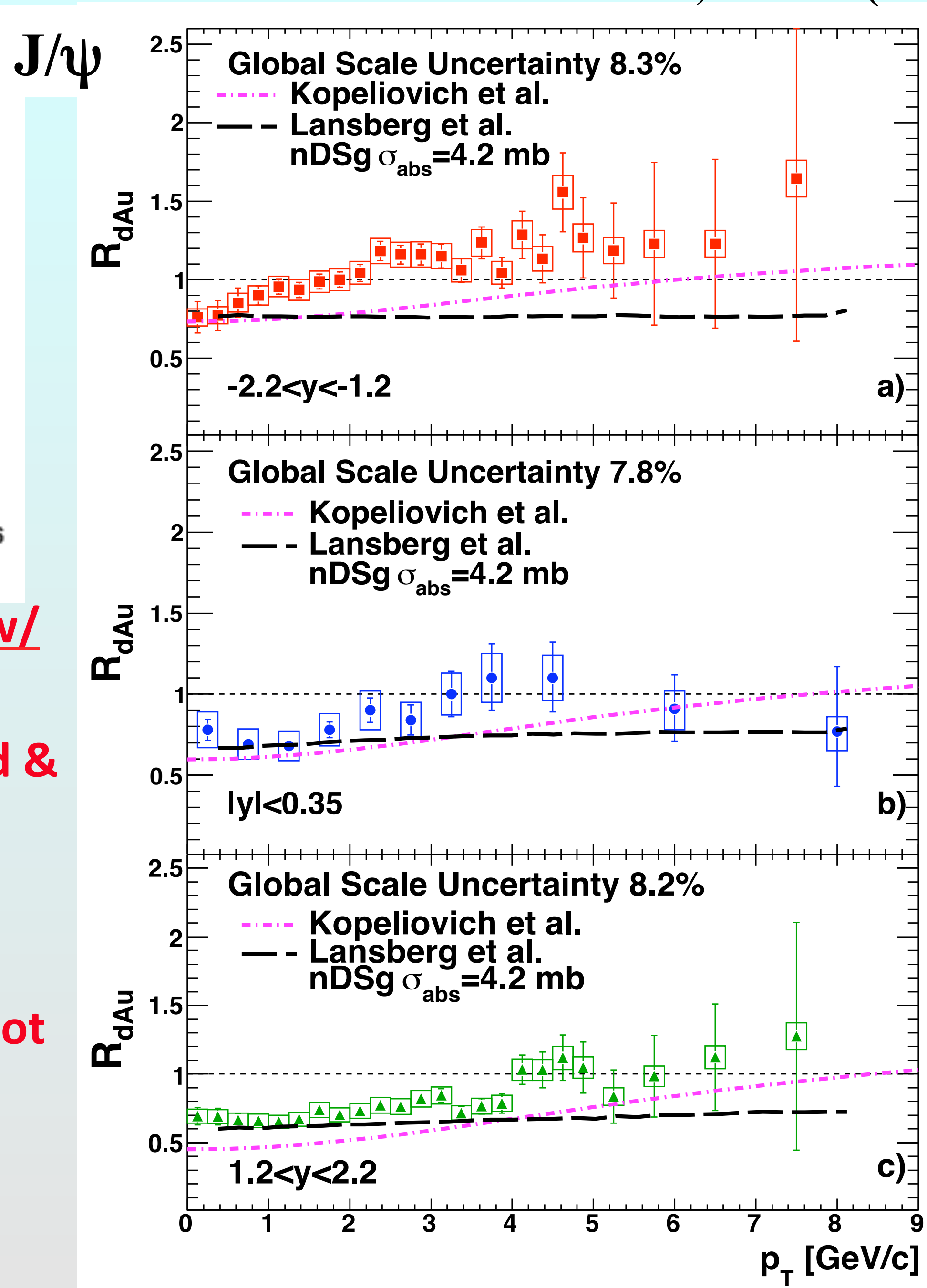
Backward
- y
Au-going



Shadowing, breakup & Cronin effect

PRC87, 034911 (2013)



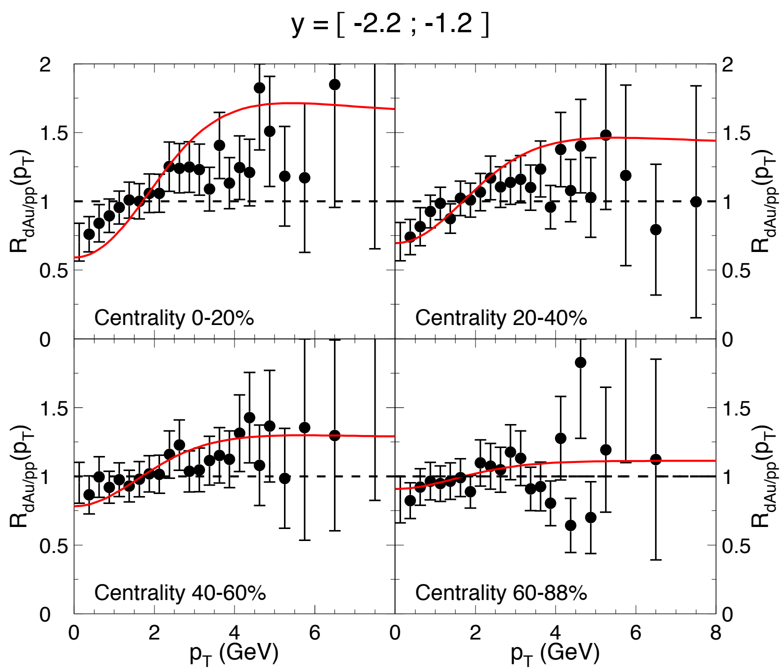


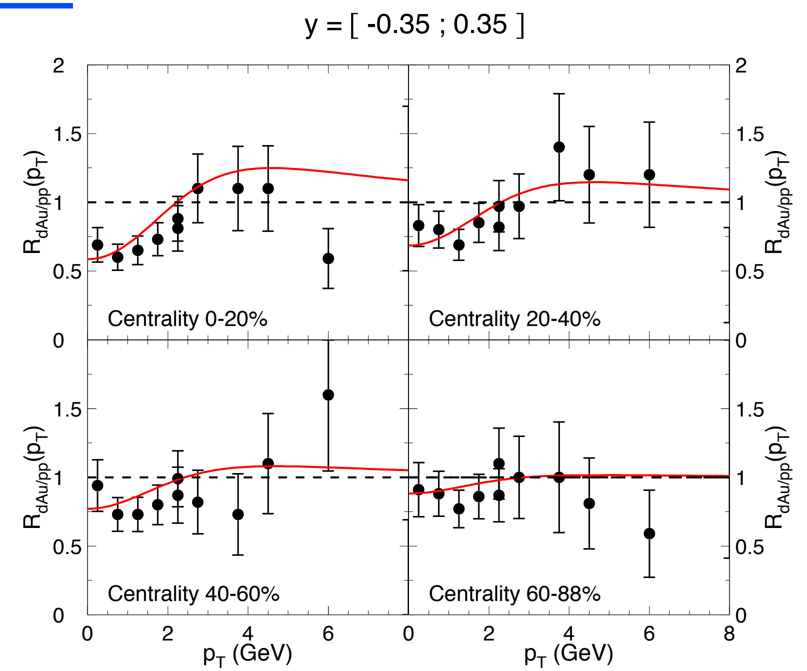
- ✦ p_T broadens (multiple scattering) w/ N_{coll}; effect stronger at y=0
- ✦ J/ψ suppressed to higher p_T @ mid & forward y (lower x in Au);
- ✦ R_{dA}>1 at high p_T backward (Cronin effect in Au nucleus)
- ✦ p_T, y, centrality dependence was not reproduced by the models

d+Au -> J/ψ

but

Arleo, et al 1304.090

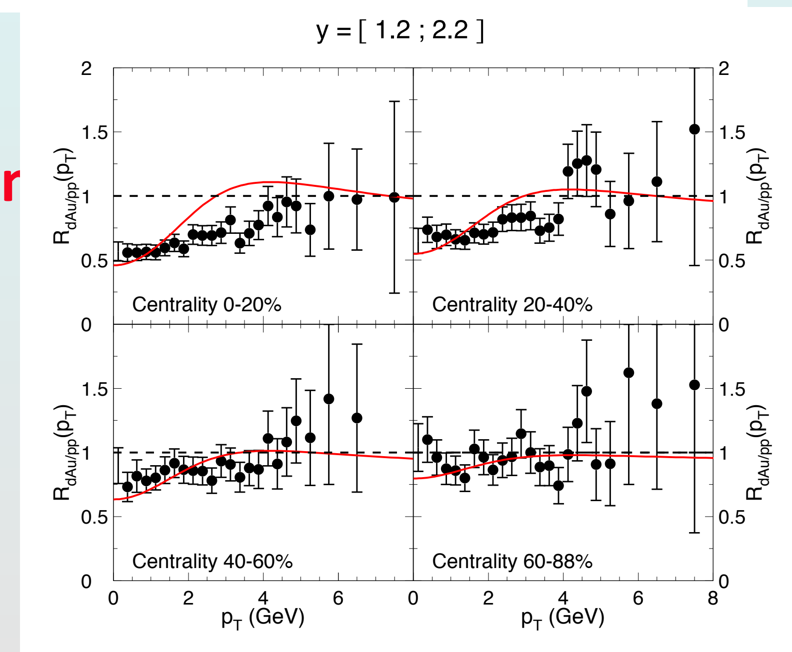




coherent parton energy loss and p_T broadening from multiple scattering in the nucleus is consistent with data!

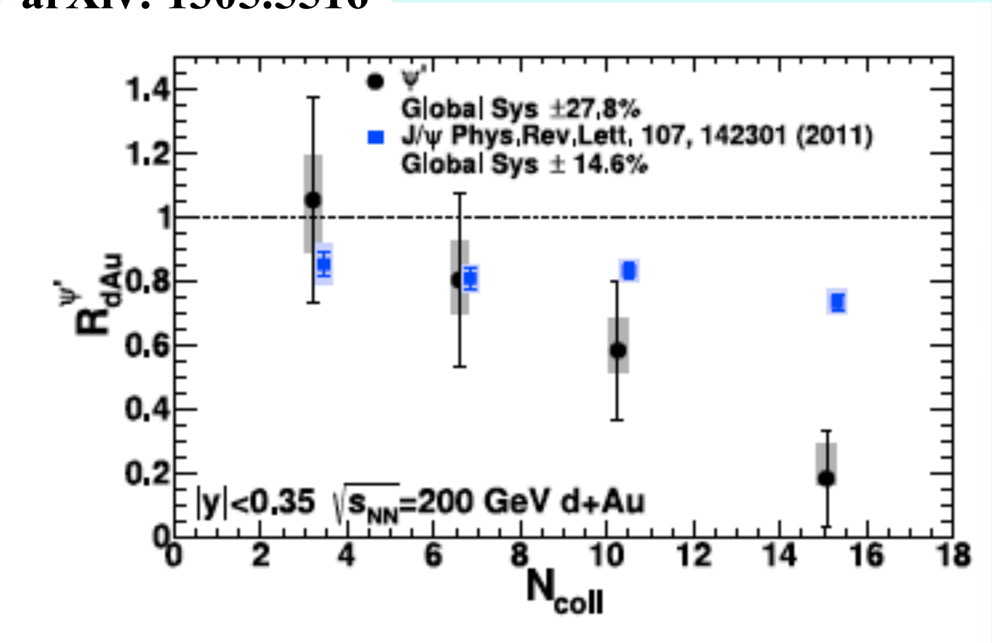
$\hat{q}_0 = 0.075\ GeV^2/fm$

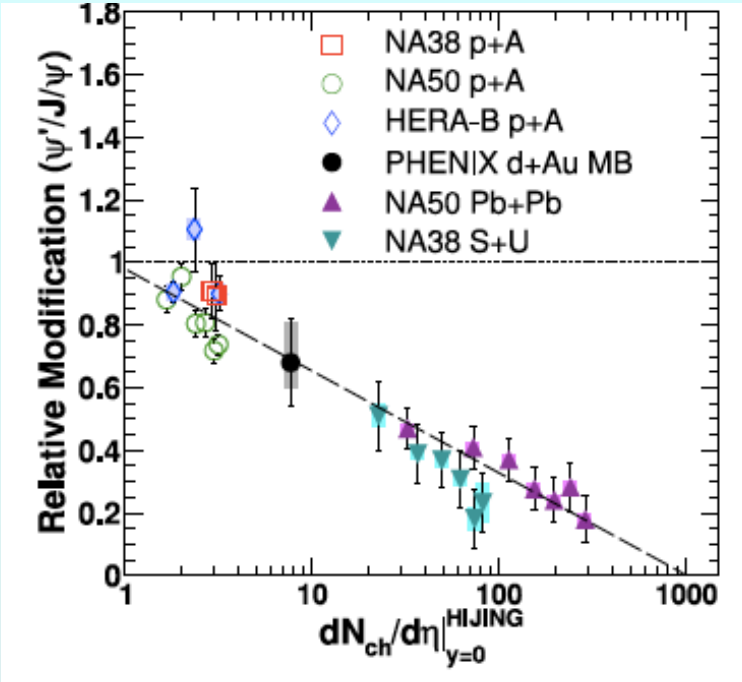
Dynamics of the probe & structure of the medium mix!!



Larger, less tightly bound c-cbar: ψ'

arXiv: 1305.5516





- Clearly more suppressed than J/ψ
- Cannot be shadowing or parton energy loss

  These are initial state effects & affect c-cbar precursor

- ψ'/ J/ψ decreases linearly with $dN_{ch}/d\eta$
- Break-up of some sort!

  early or late?

Heavy quark diffusion

Ding, et al. arXiV: 1107.0311

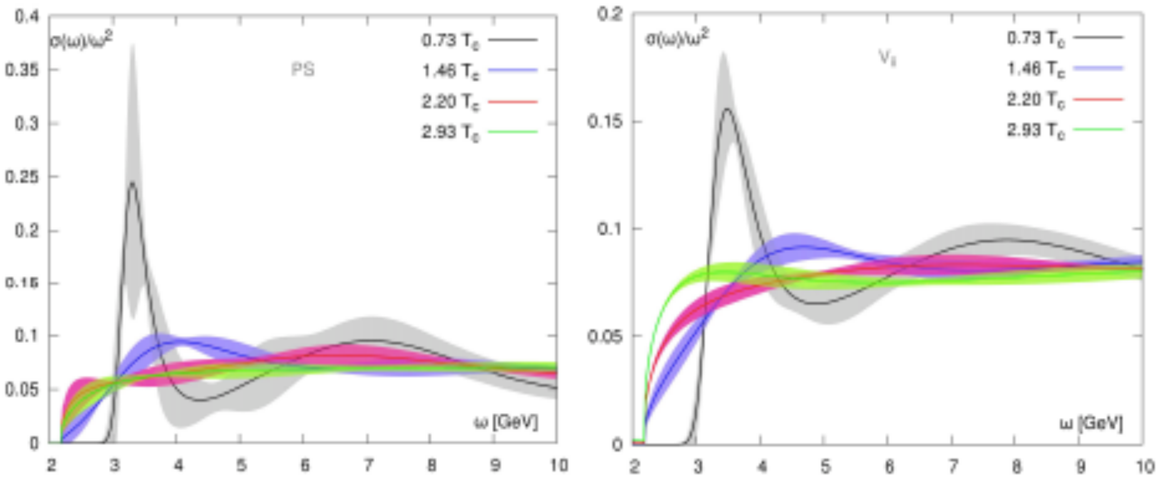


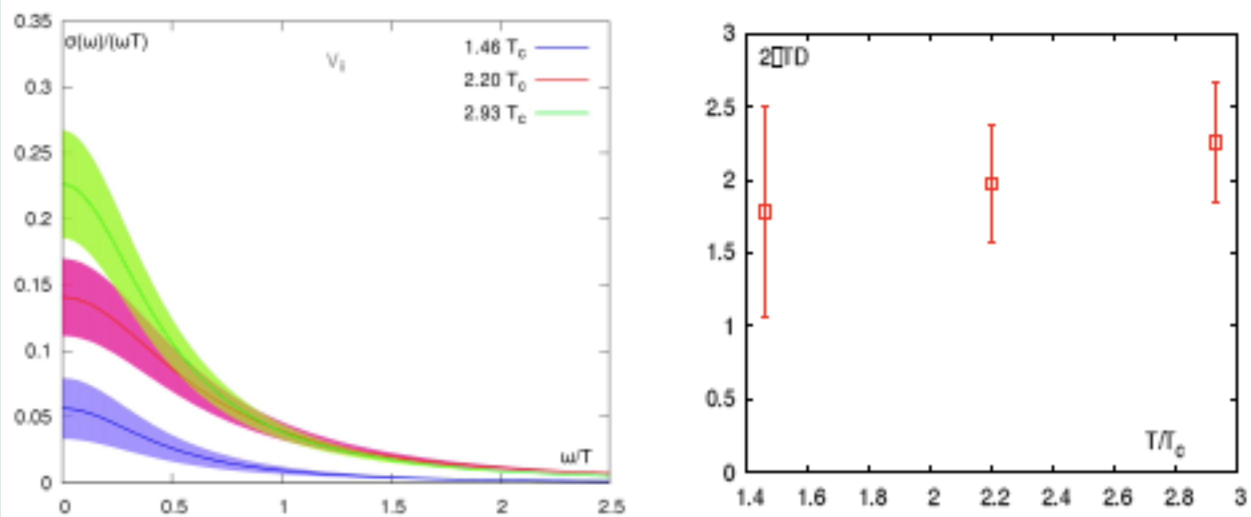
Figure 3. Uncertainties of output spectral functions in PS (left) and V_{ii} (right) channels at all available temperatures. The shaded areas are errors of output spectral functions from Jackknife and the solid lines inside the shaded areas are mean values of spectral functions.

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?

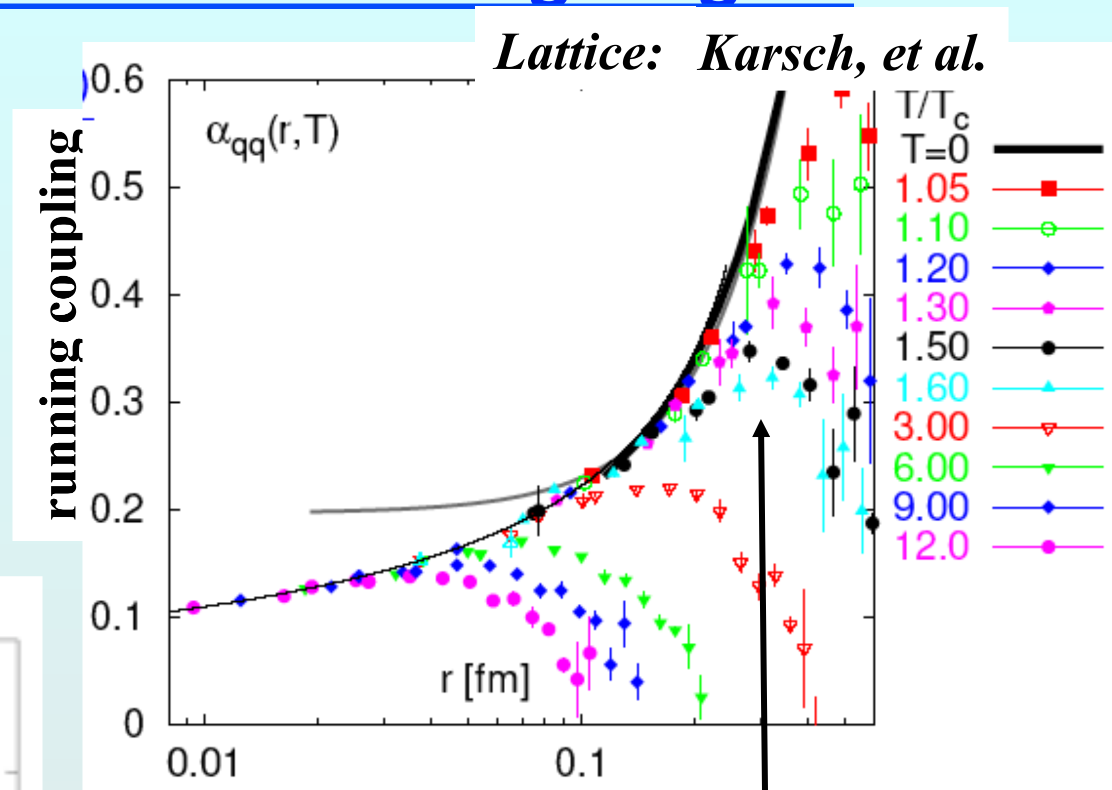


ociation of both J/ψ and η_c at $T \geqslant 1.46\ T_c$.

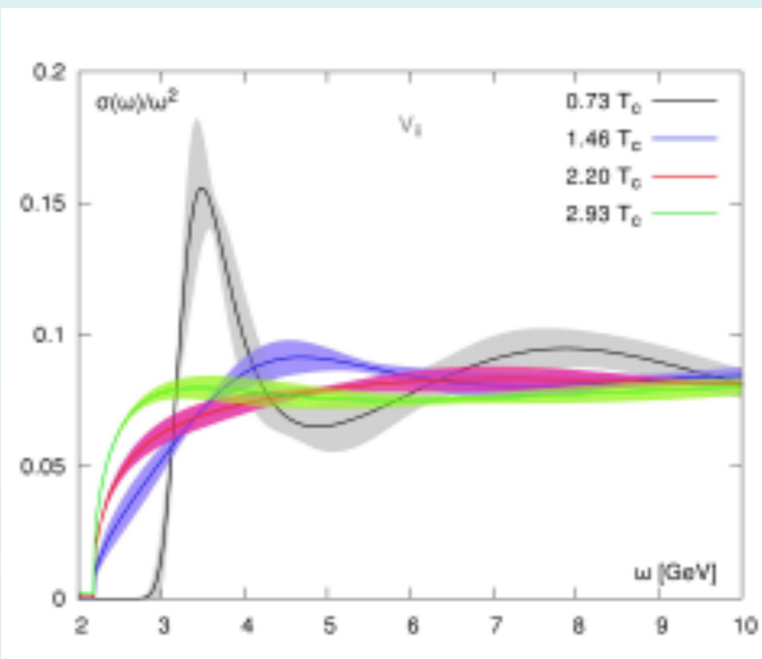
Is there a relevant screening length?

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

Lattice: Karsch, et al.



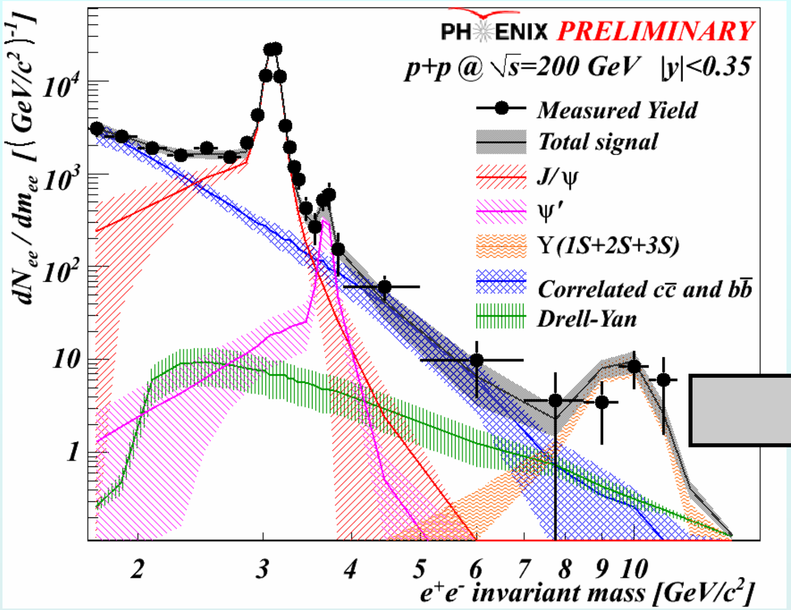
coupling drops off for r > 0.3 fm

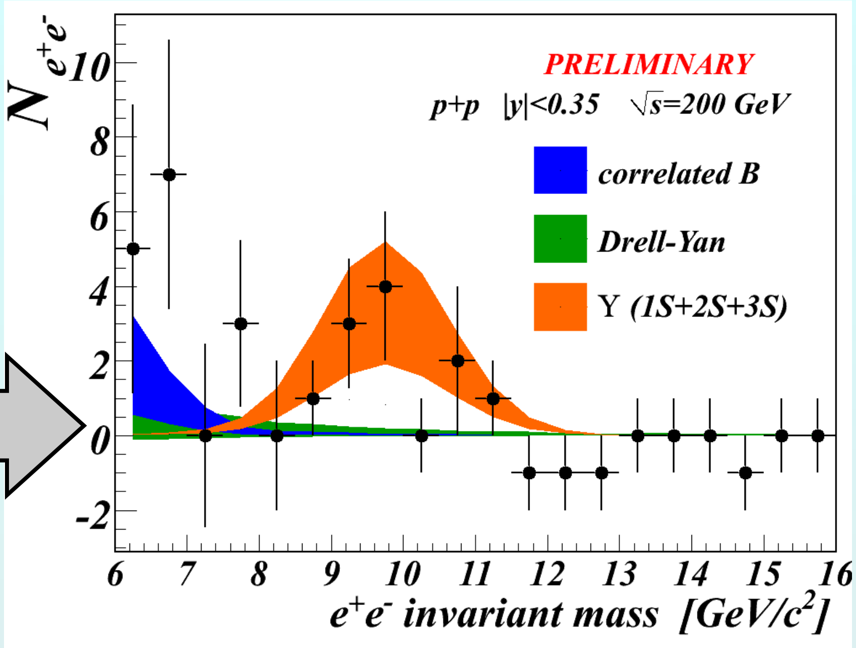


Ding, et al. arXiV: 1107.0311

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

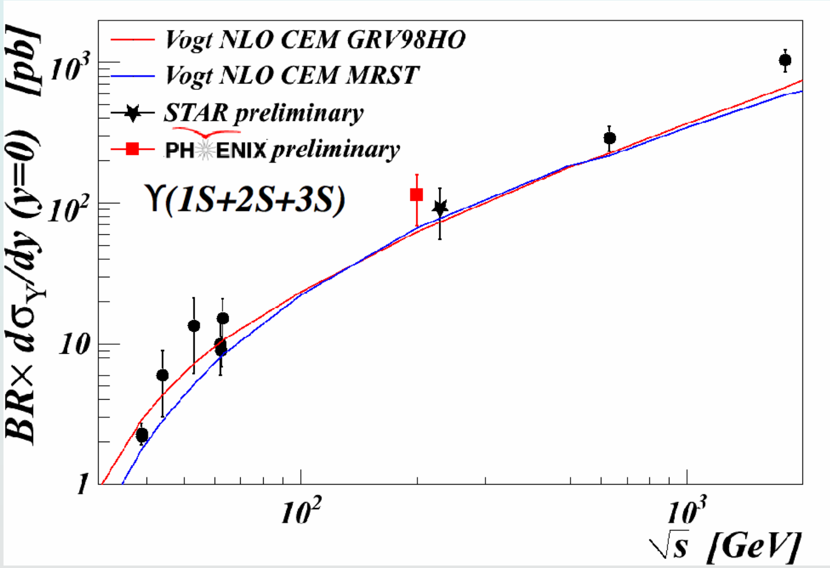
Upsilon in p+p



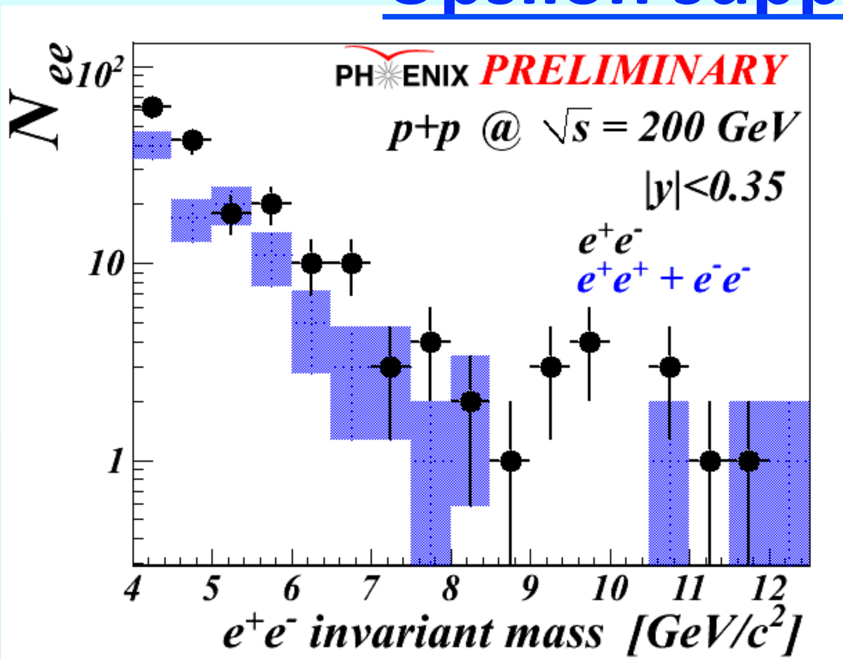


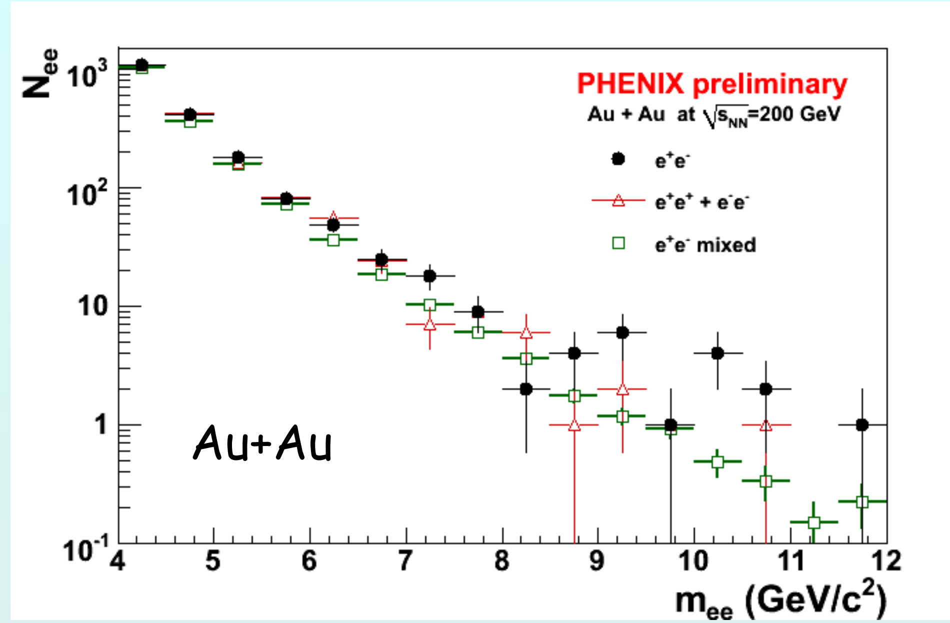
Cross section follows world trend

$$BR * \frac{d\sigma}{dy}\Big|_{|y|<0.35} = 114^{+46}_{-45}\, pb$$



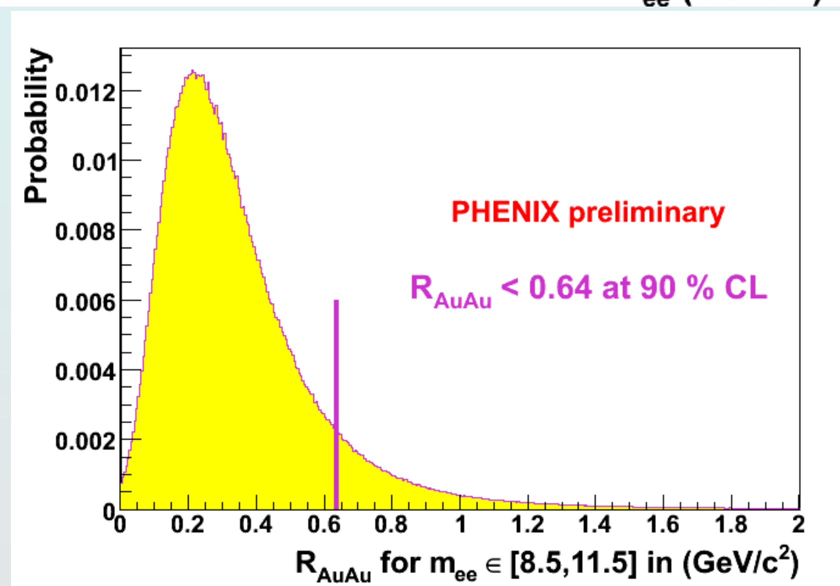
Upsilon suppressed in Au+Au!





	p+p	Au+Au
N[8.5,11.5]	10.5(+3.7/-3.6)	11.7(+4.7/-4.6)
$N_{J/\Psi}$	2653 ±70±345	4166 ±442(+187/-304)
$R_{AA}(J/\Psi)$	---	0.425 ±0.025±0.072

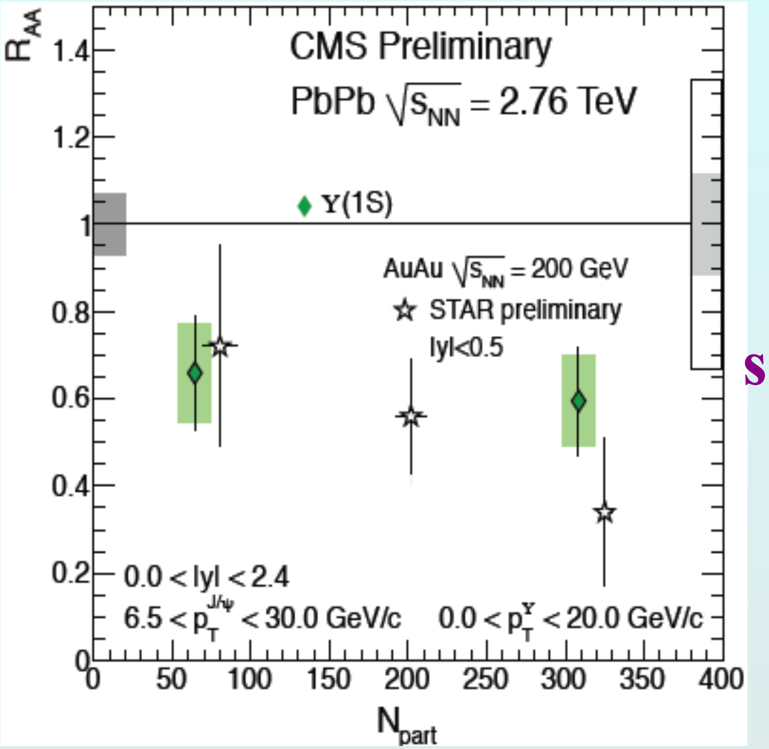
R_{AA} [8.5,11.5] < 0.64 at 90% C.L.



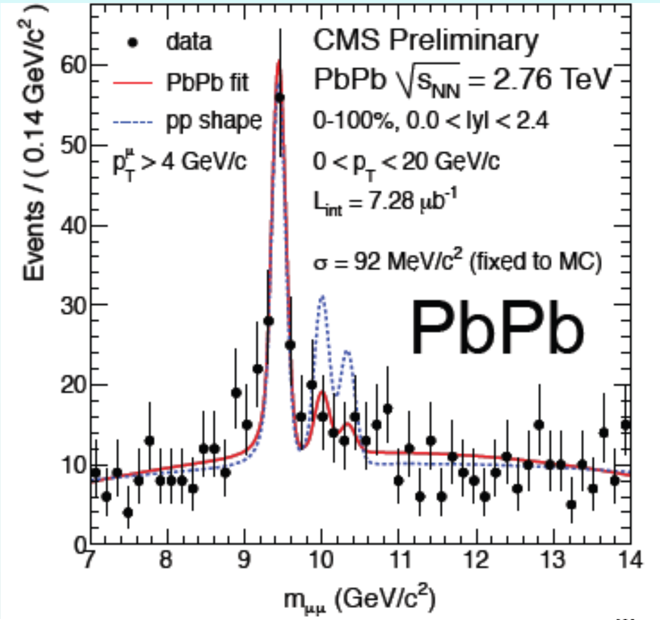
b-bar bound states at the LHC

- Coalescence *could* be important at LHC

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



ϒ (2S,3S) suppressed

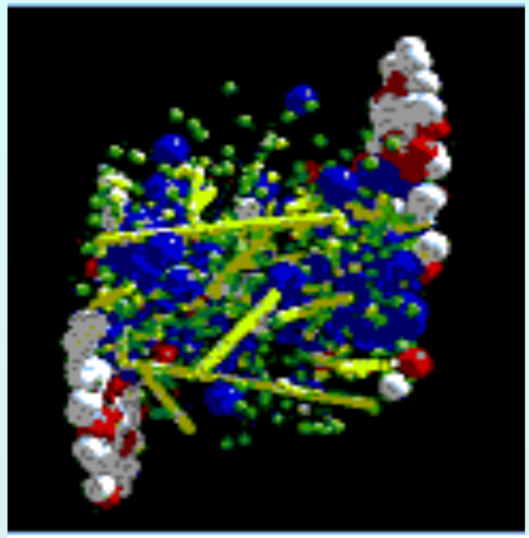


$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- 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 from $1\text{-}1.5T_c$, then free

Hottest Science Experiment on the Planet*

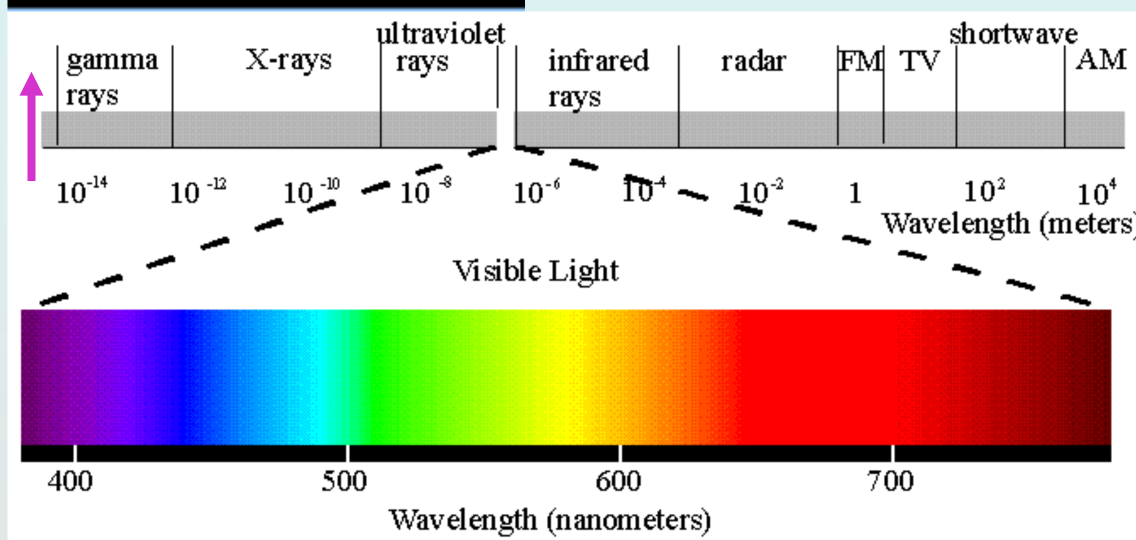


plasma lives for 3×10^{-23} s

droplet is 10^{-12} cm across

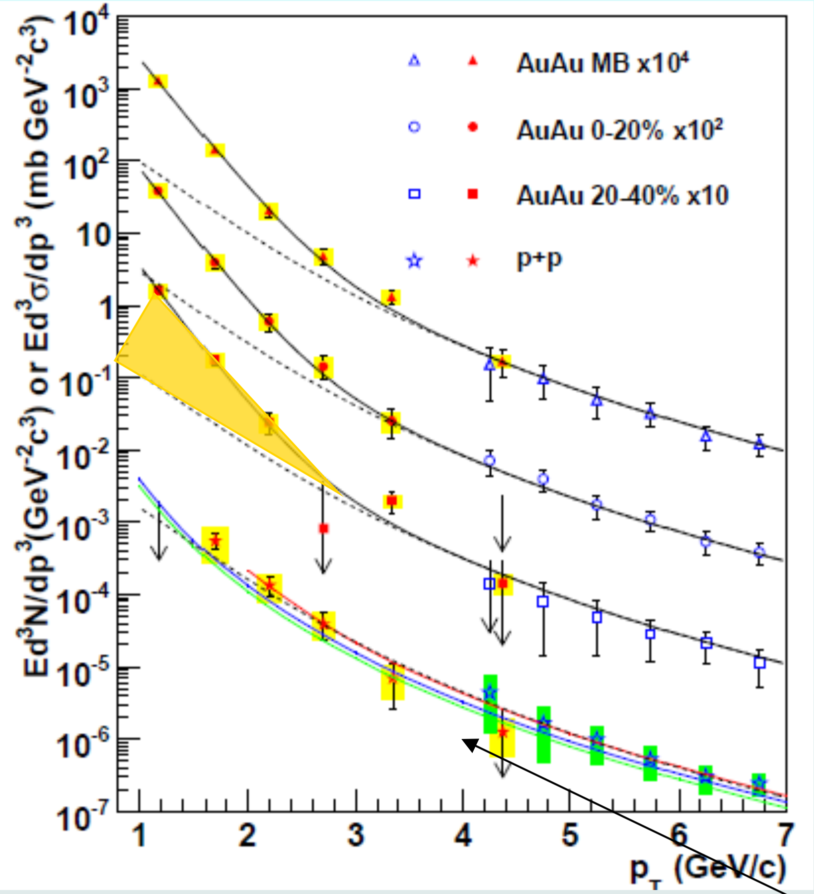
can't use a thermometer!

So we look at the light

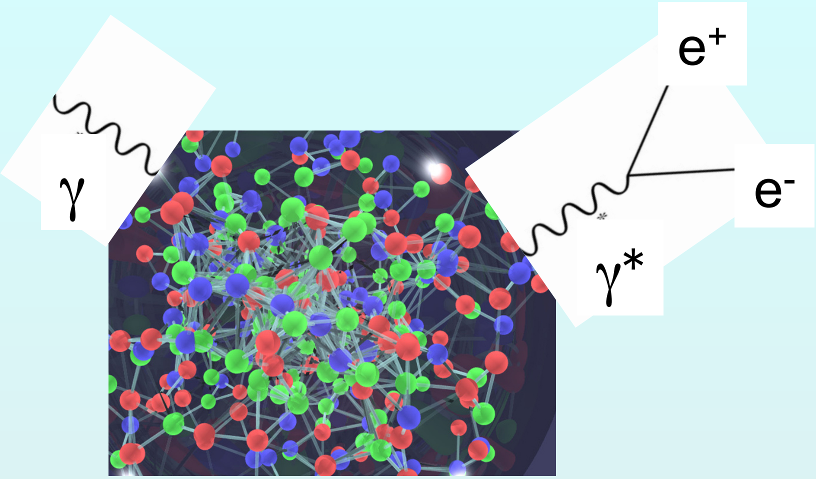


* According to Discover Magazine

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

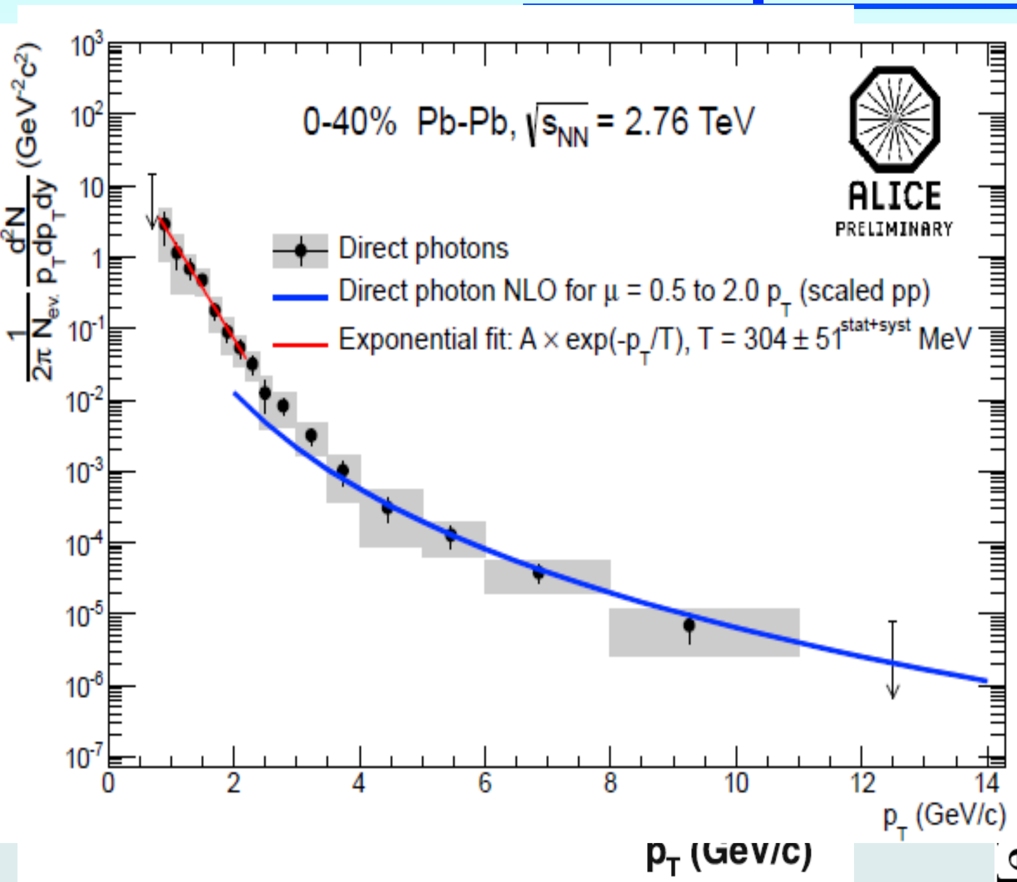
Analogy to the bronze is not quite right

- Similar to black body radiation, but…
- The photons are not bouncing around in equilibrium with QGP
  - Produced by interactions among partons in equilibrium
  - Exit the plasma with no further (strong) interactions

- The plasma is not static
  - It is expanding at v=c longitudinally and v~0.5c radially
  - Photons arise from velocity boosted partons

- What to do about this?
- Use our hydrodynamics models!

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

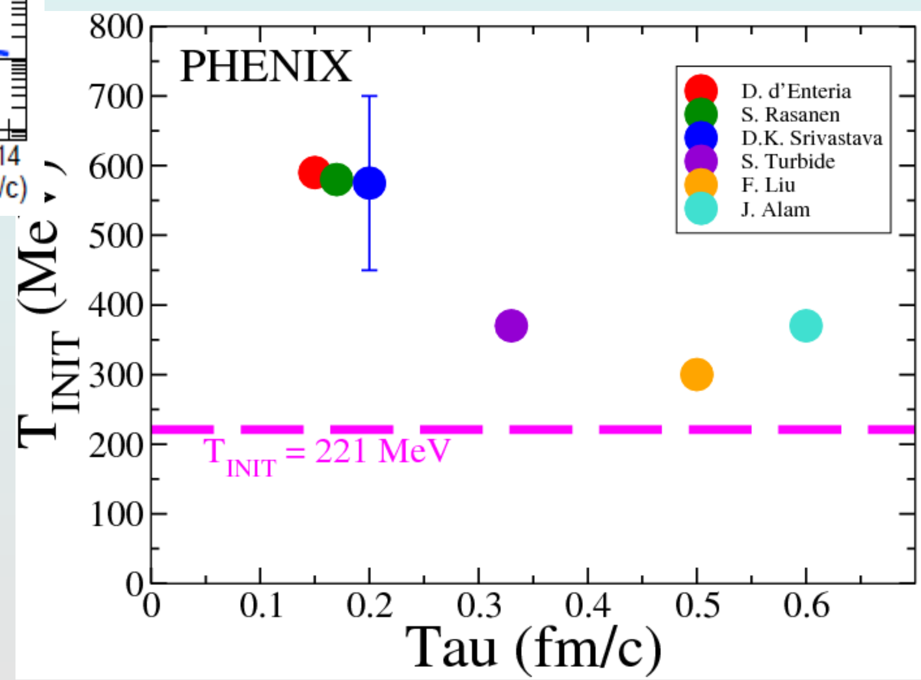


- **Exponential fit in p_T:**

***T_{avg}* = 221 ±23 ±18 MeV**

- **Multiple hydrodynamics models reproduce data**

$T_{init} \geq$ 300 MeV

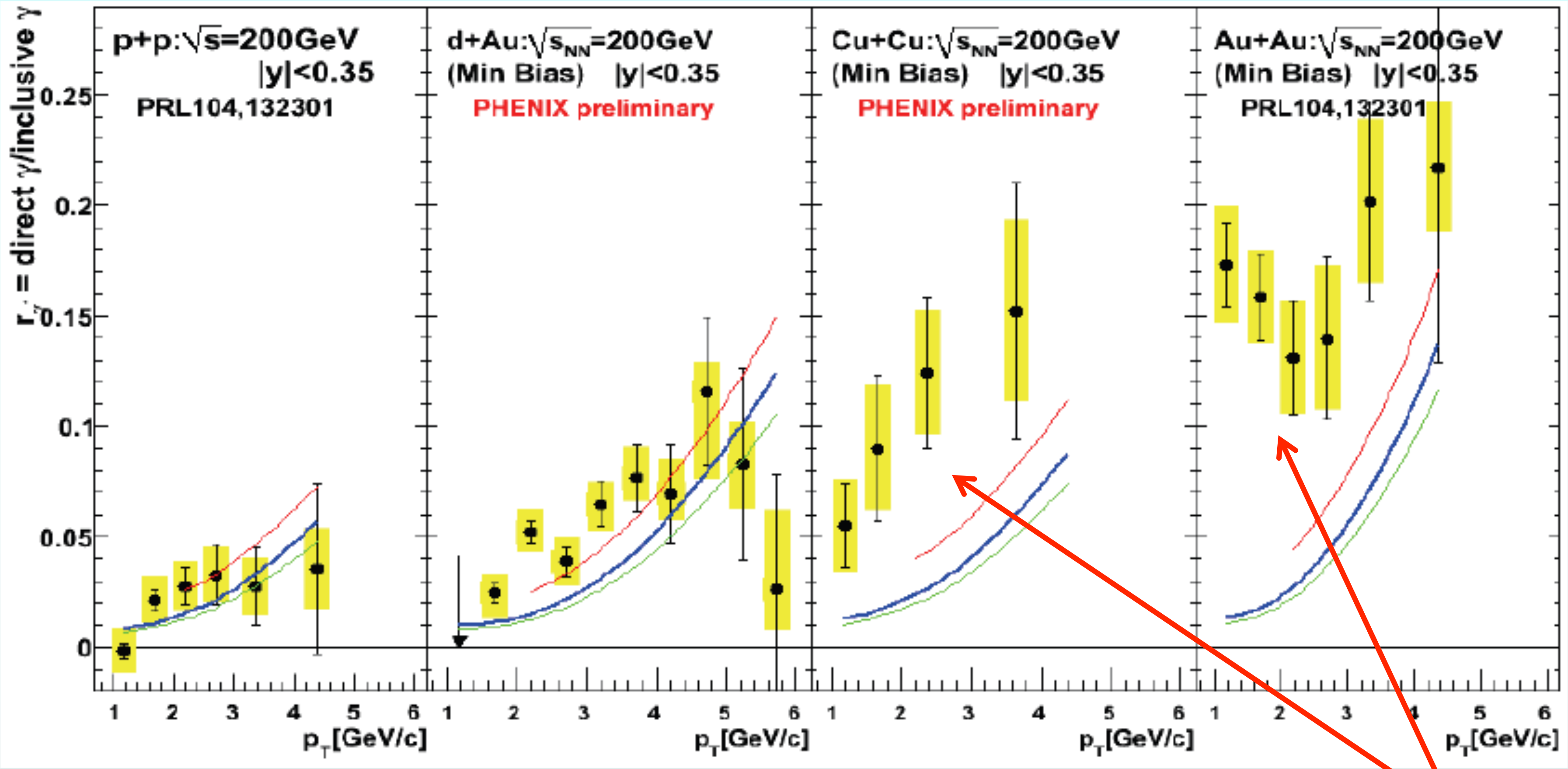


NB: T_c ~ 150 MeV

@ LHC T_{avg} = 304±51 MeV

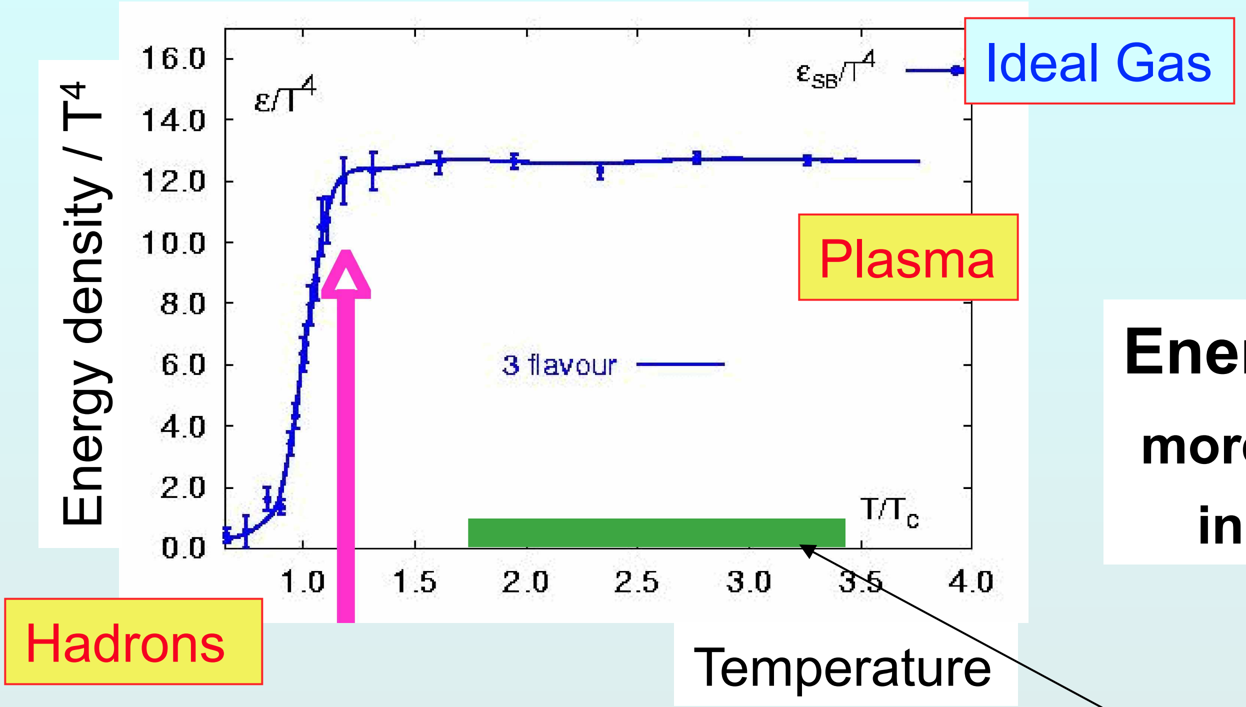
hydrodynamic T_{init} ~ 30% higher than at RHIC

Thermal photons (virtual)



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

Now we are on the map



$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Energy density ∝ T⁴

more degrees of freedom in the plasma phase

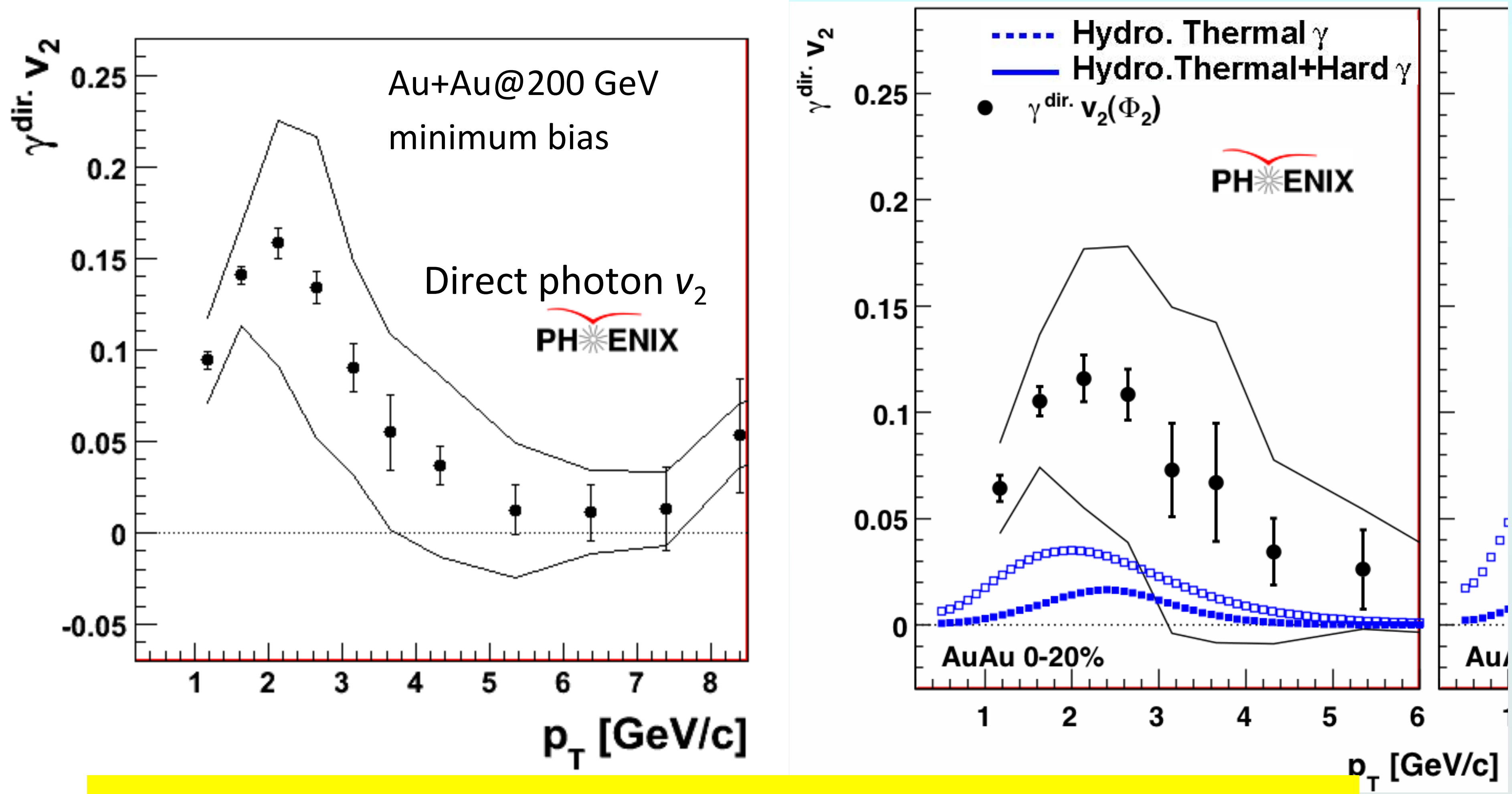
We are here

T_c ~ 150 ± 10 MeV

ε ~ 3 GeV/fm³

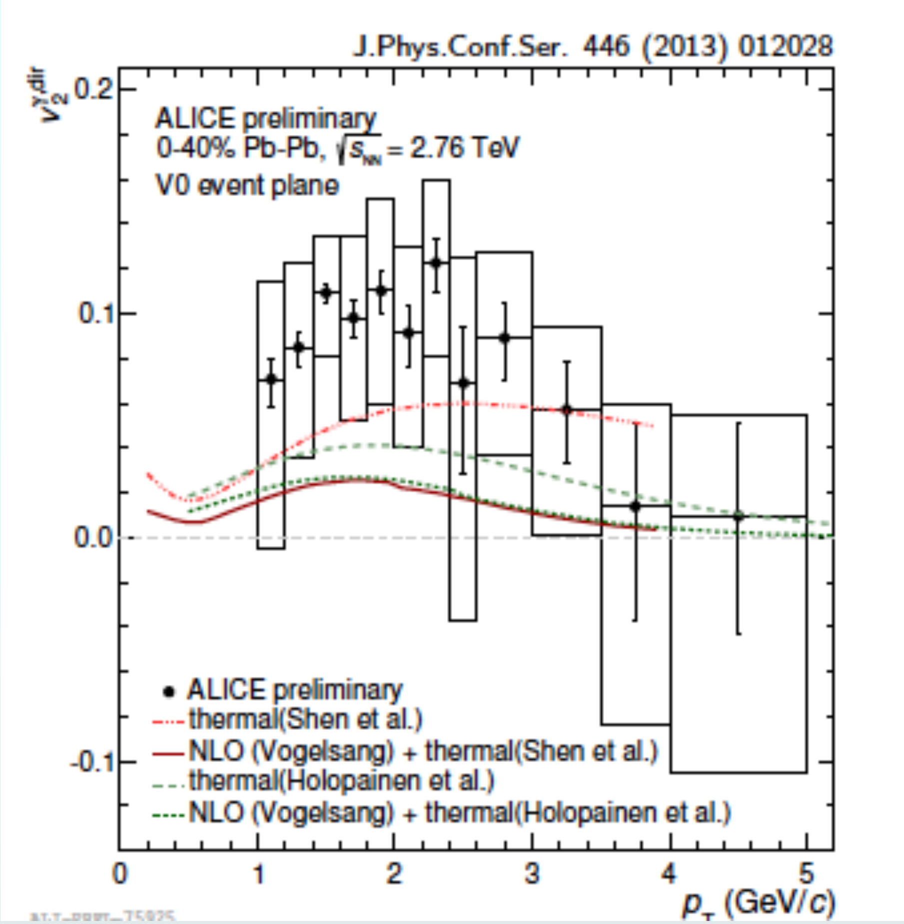
Thermal photons also flow!

arXiv:1105.4126



Flow magnitude is surprising – T^4 dominance = early γ's
Still a mystery, but suggests pre-equilibrium flow…

Direct photons also flow in Pb+Pb at LHC

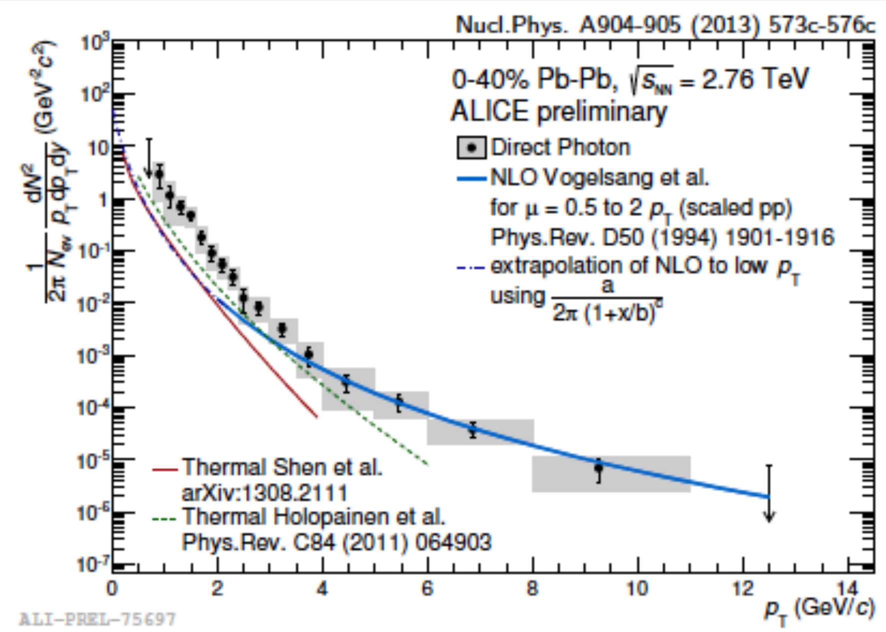


- What does this mean?
- Early emission ➔ many γ

  T is max early (rate as AT^4)
- Large flow ➔late emission

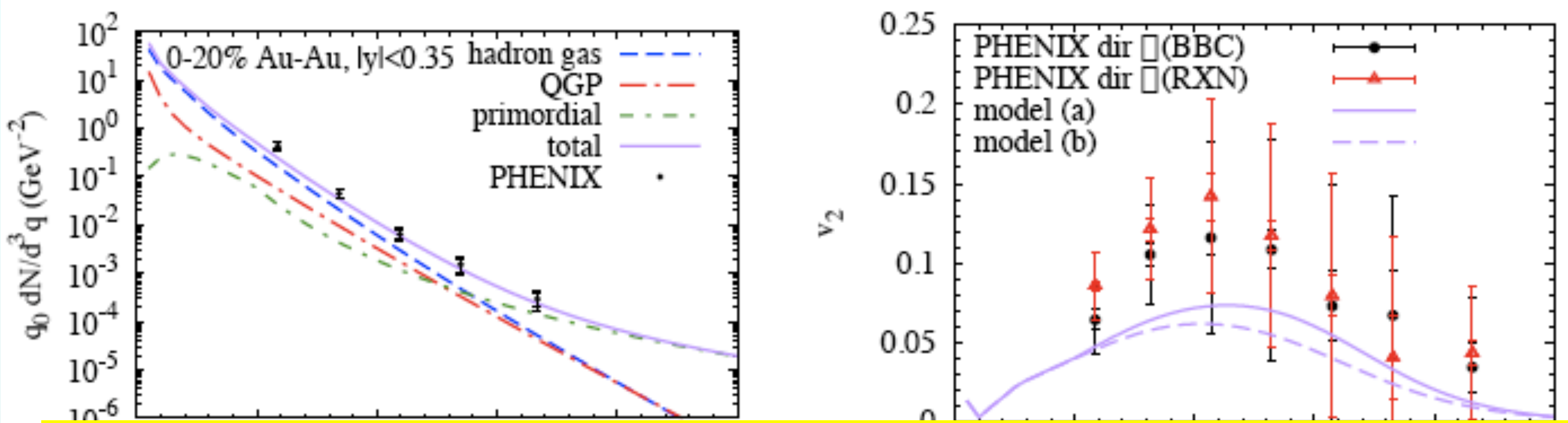
  Time to build up

  T drops by expansion

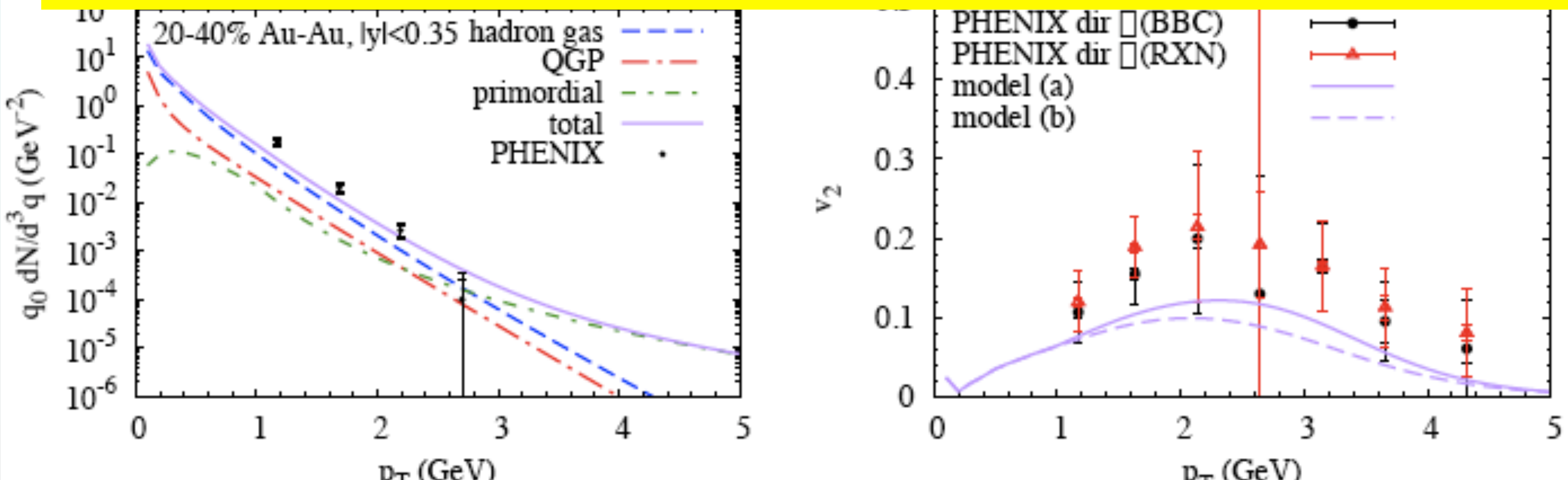


Where do photons come from?

vanHees, Gale & Rapp, arXiv:1108.2131



Should flow, if "extras" come from a very rapidly expanding hadron gas, that lives longer than initially expected



Lepton pair emission ↔ EM correlator

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

Emission rate of dileptons per volume

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

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

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

γ*→ee decay

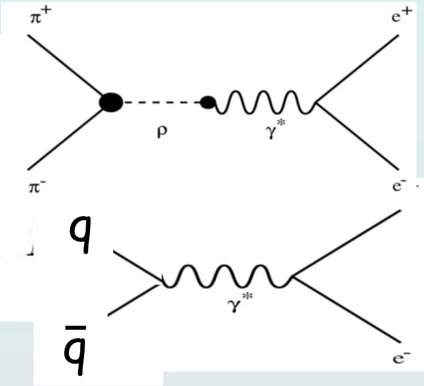
EM correlator
Medium property

Boltzmann factor
temperature

Hadronic contribution
Vector Meson Dominance

→ Medium modification of meson
Chiral restoration

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



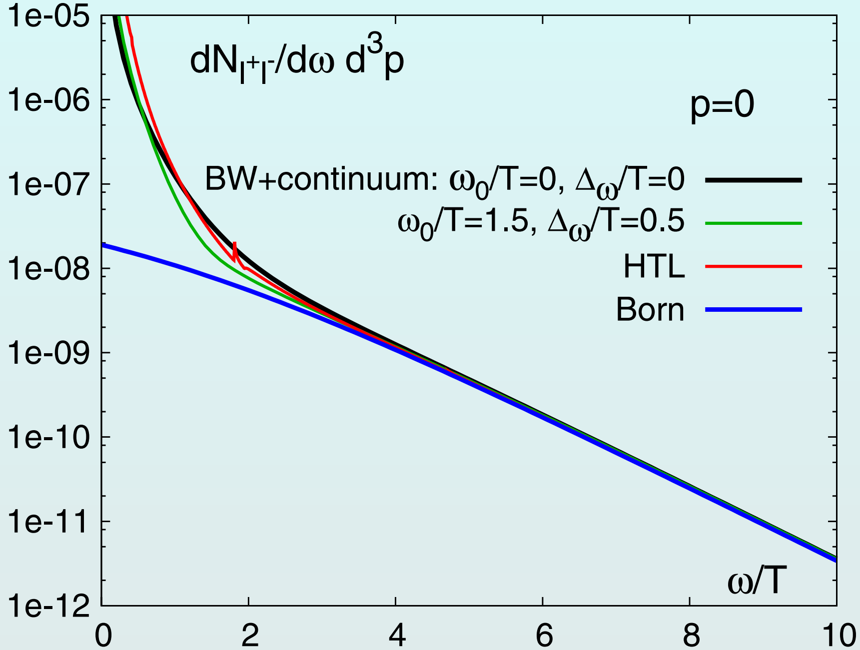
$q\bar{q}$ annihilation

→ 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.

Calculate the correlator on the lattice

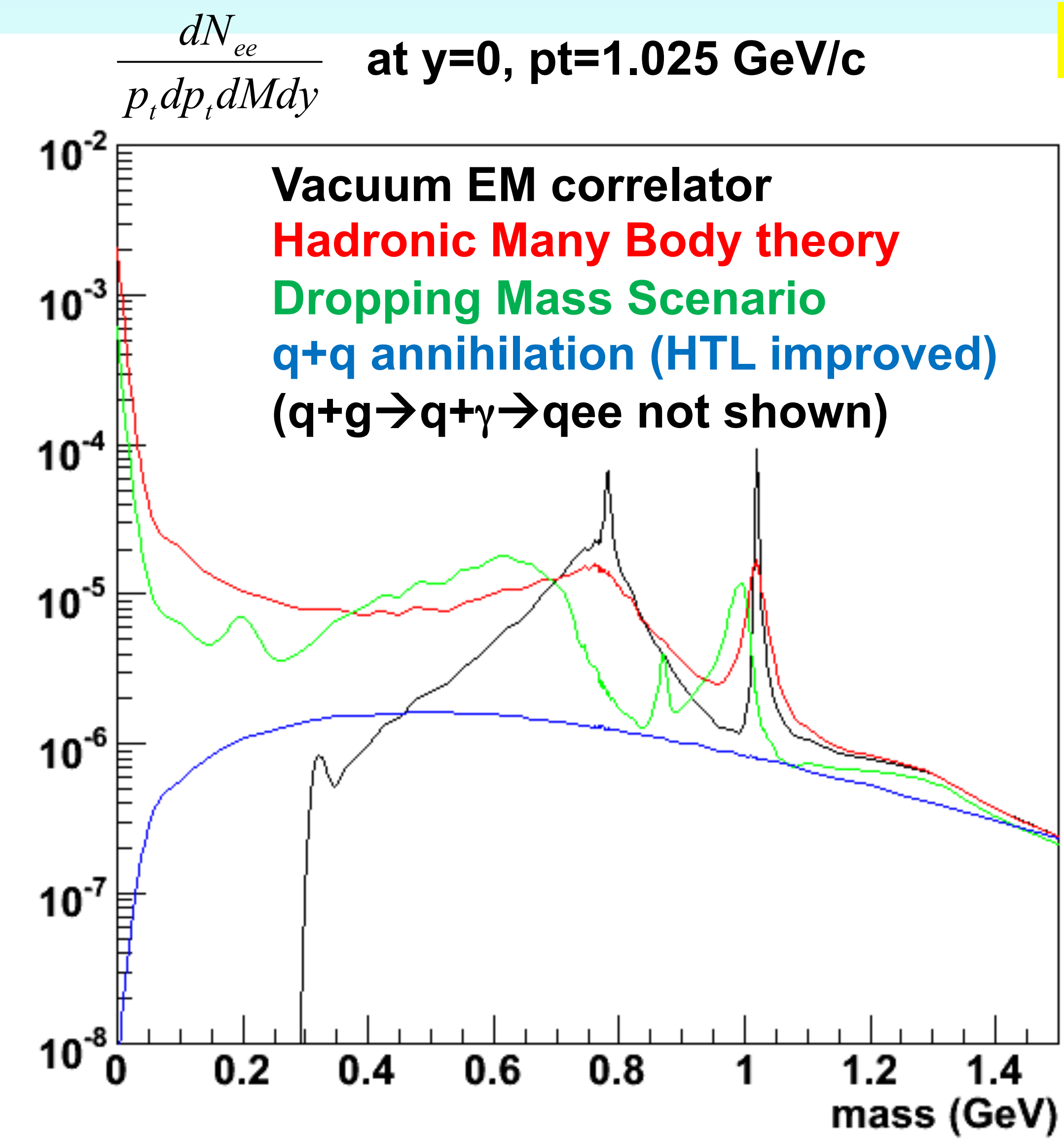
➔ **non-perturbative contributions to thermal dilepton rates at low mass**



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

- **For small energy, $\omega/T<(1\text{-}2)$ spectral function > free form**
- **For $\omega/T \simeq 1$ thermal dilepton rate ~ order of magnitude > leading order Born rate**
- **for $\omega/T>\sim(2-4)$ the spectral function is close to the free form**

Theory prediction of dilepton emission



Theory calculation by Ralf Rapp

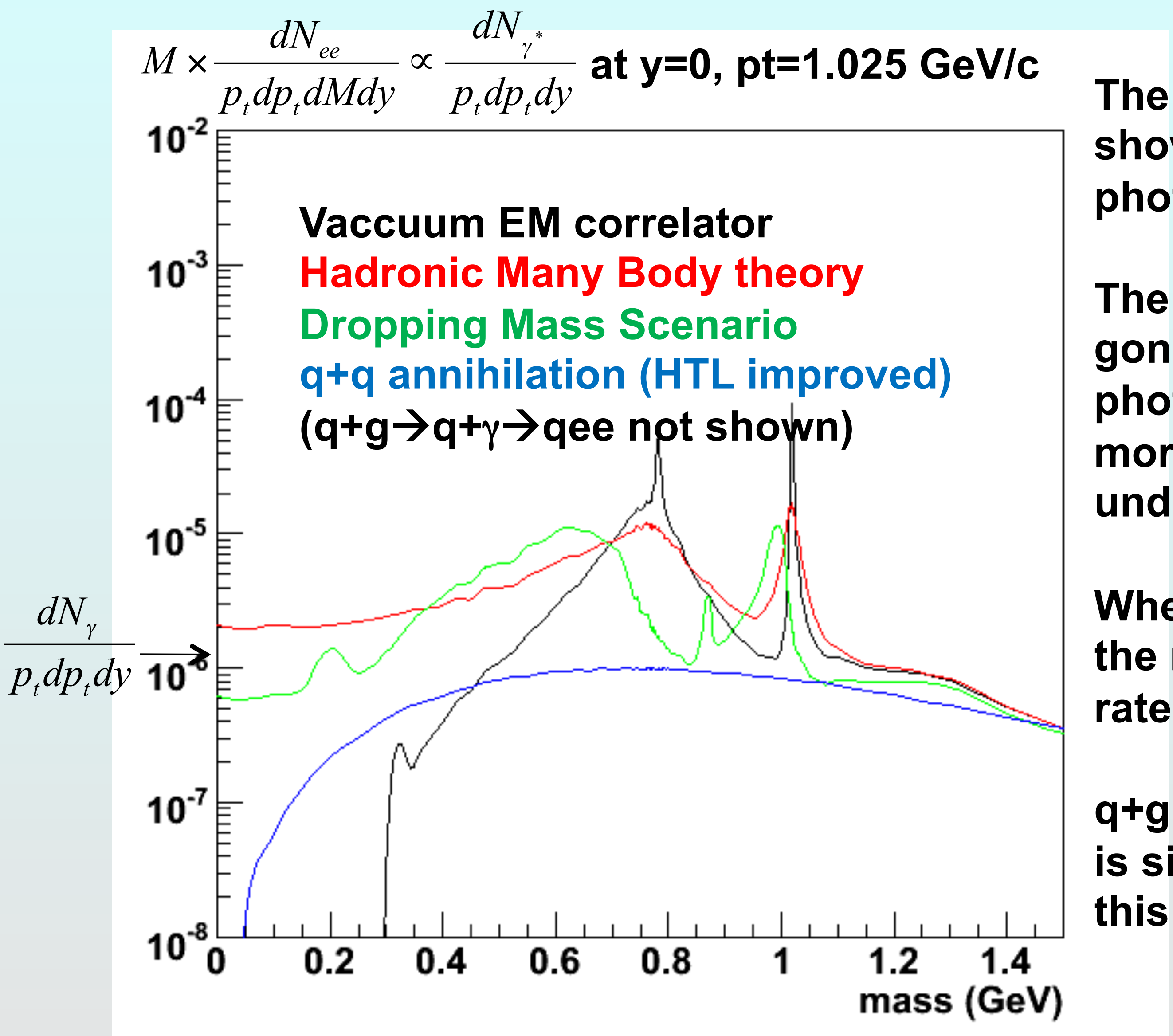
Usually the dilepton emission is measured and compared as dN/dptdM

The mass spectrum at low pT is distorted by the virtual photon→ee decay factor 1/M, which causes a steep rise near M=0

qq annihilation contribution is negligible in the low mass region due to the m2 factor of the EM correlator**

In the calculation, partonic photon emission process q+g→q+γ→q+e^+e^- not included

Virtual photon emission rate



The same calculation, but shown as the virtual photon emission rate.

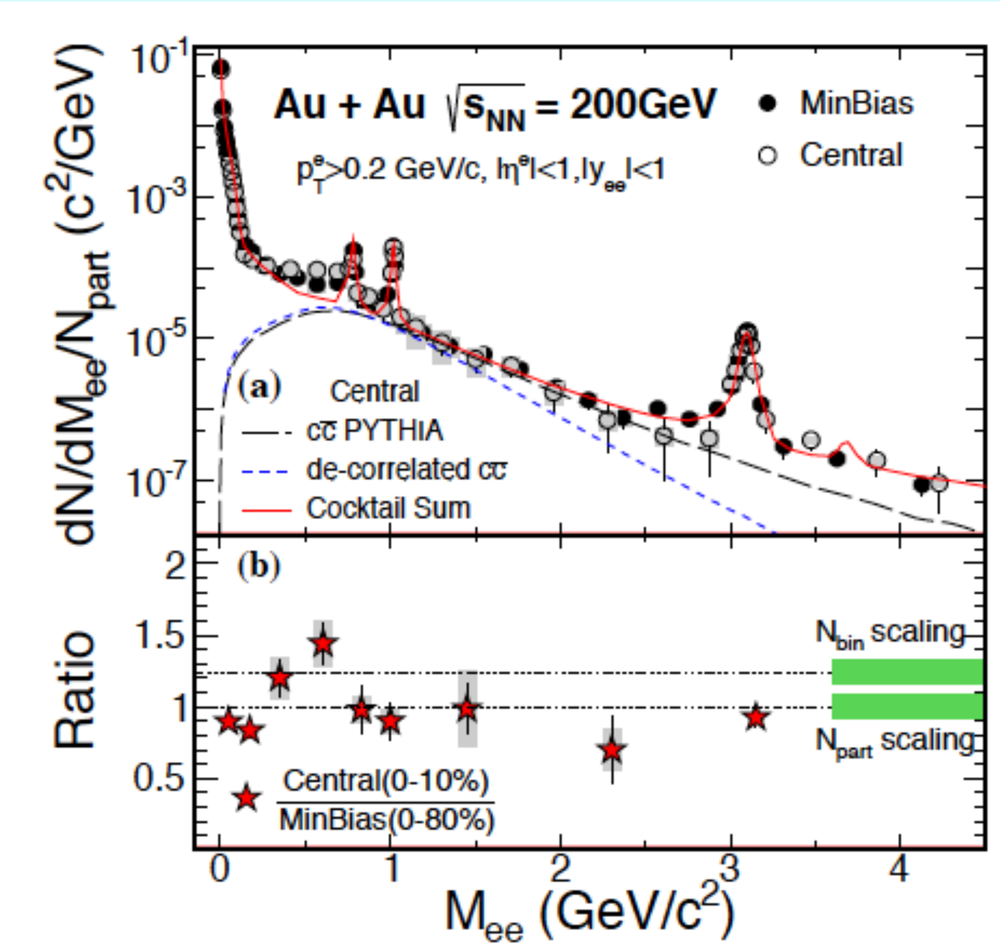
The steep raise at M=0 is gone, and the virtual photon emission rate is more directly related to the underlying EM correlator.

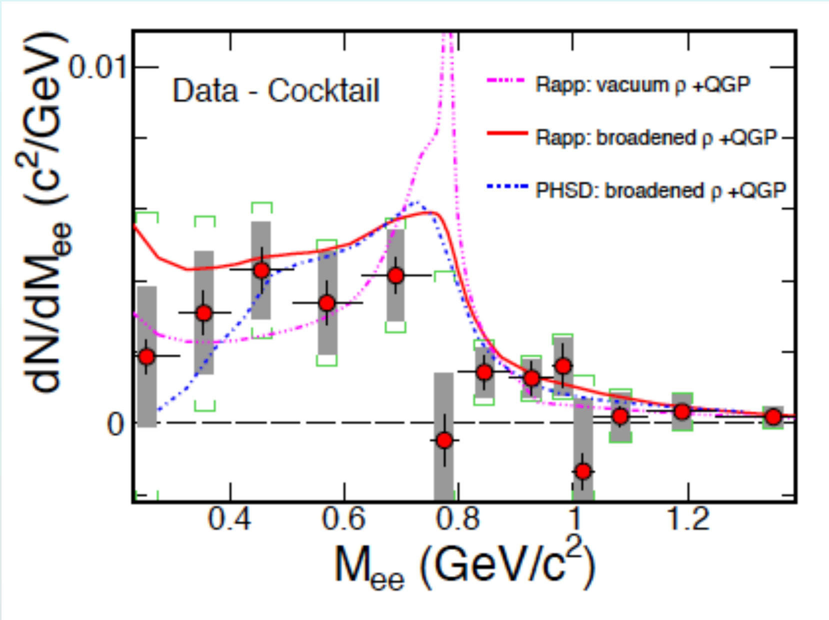
When extrapolated to M=0, the real photon emission rate is determined.

q+g→q+γ* is not shown; it is similar size as **HMBT** at this pT

What about low mass, low p_T di-electrons?

STAR. arXiv: 1504.01317





- **backup slides**

AdS/CFT references

- There are thousands!
- Original paper: J.Maldacena, arXiv:hep-th/9711200

  8001 citations!!

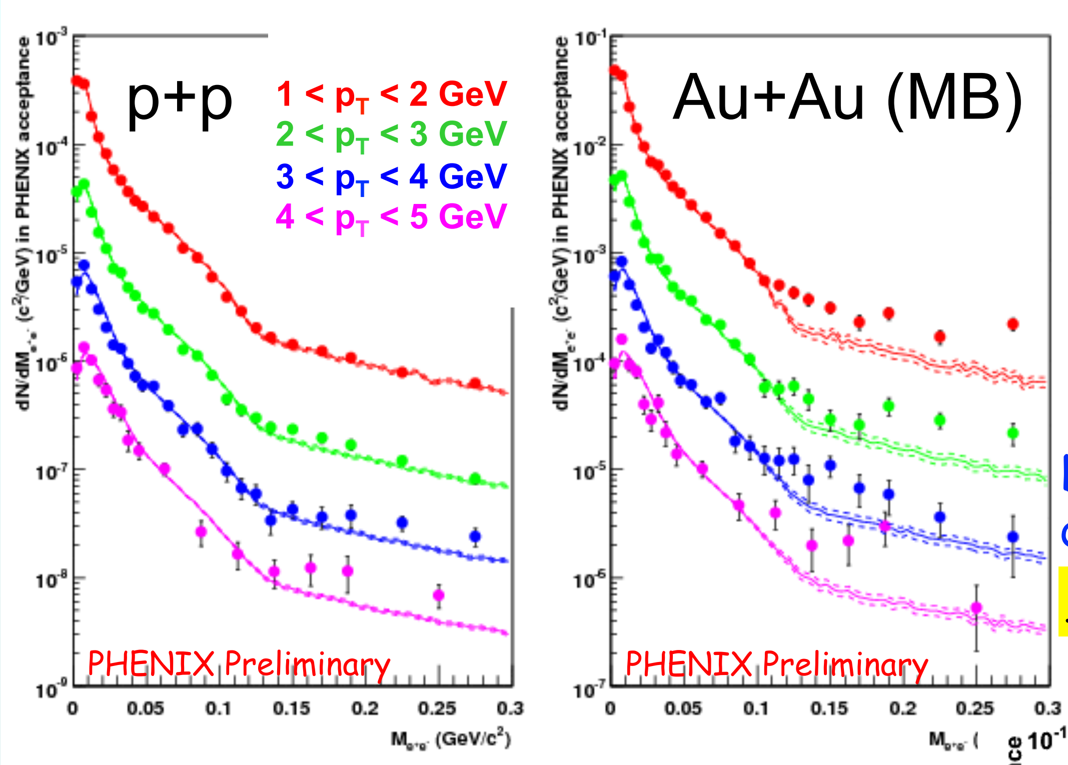
Aharony, Gubser, Maldacena, Ooguri & Oz, Phys. Rept.323, 183 (2000)&arXiv:hep-th/9905111

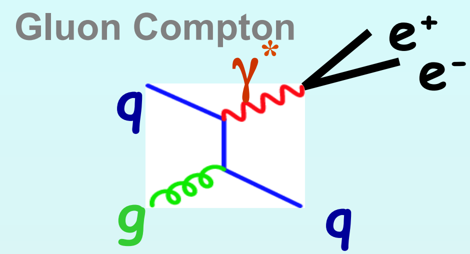
2633 citations!

- Quantum Phase Transitions: Herzog, Kovtun, Sachdev & Son, arXiv:hep-th/0701036
- Condensed Matter: S. Sachdev, arXiv:1108.1197 (a review)
- Holographic Liquids: Nickel and Son, arXiv: 1009.3094
- Quark Gluon Plasma (a non-technical review + references):

  S.S. Gubser, arXiv: 1103.3636

Dileptons at low mass and high p_T



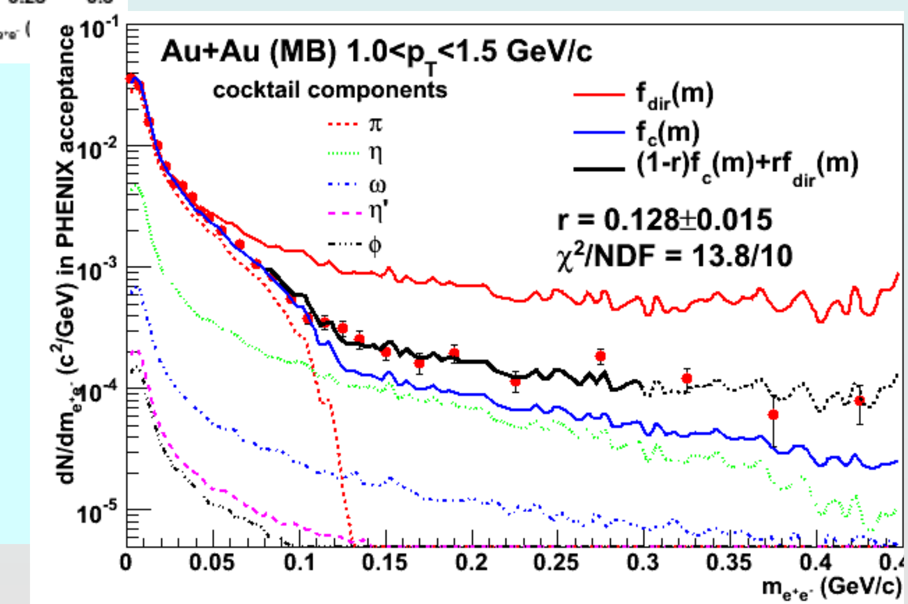


Direct γ^*/Inclusive γ^* determined by fitting each p_T bin

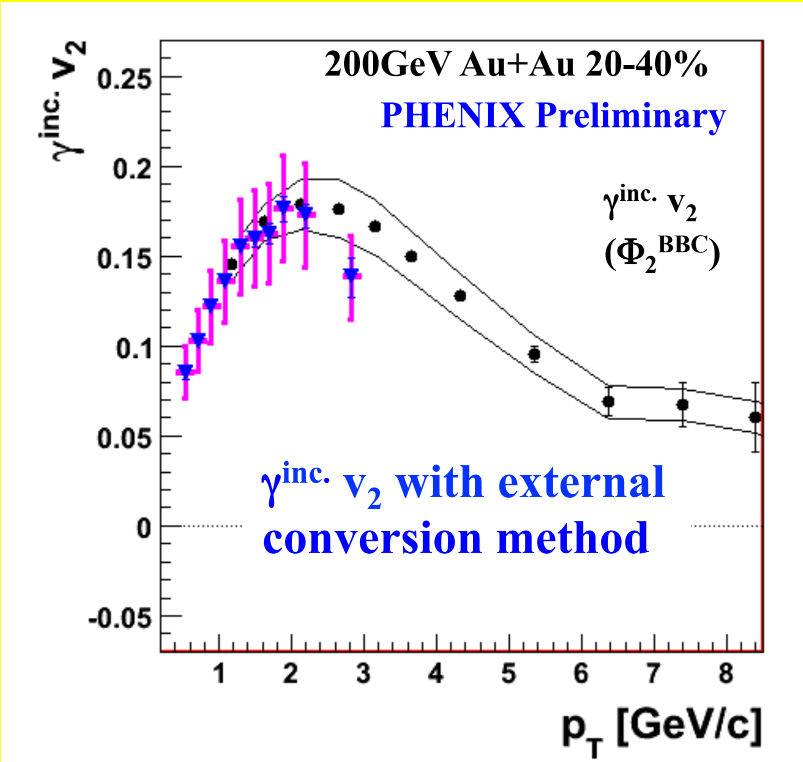
$$f_{data}(M_{ee}) = (1-r)\cdot f_{cocktail}(M_{ee}) + r\cdot f_{direct}(M_{ee})$$

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 → *virtual* γ with v. low mass
- We assume internal conversion of direct photon → extract the fraction of direct photon



An experimental aside



- ***Direct photon flow ingredients***
- ***Measure v_2 of inclusive (all) γ's***
- ***Measure v_2 of π^0's, calculate decays***

Find ratio $\gamma_{all}/\gamma_{decays}$ (R_γ), then use

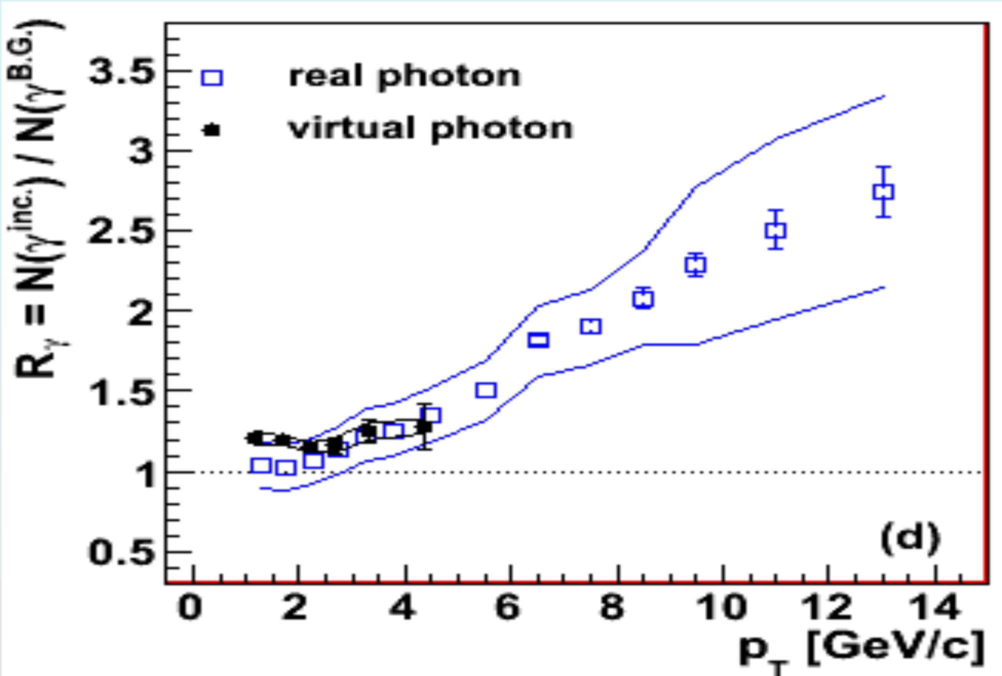
$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - v_2^{BG}}{R_\gamma - 1}$$

Key cross checks:

γinc are really γ's:

check using γ-> e+e-

Rγ for virtual vs. real γ

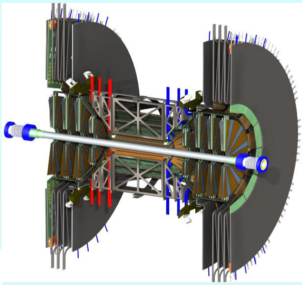


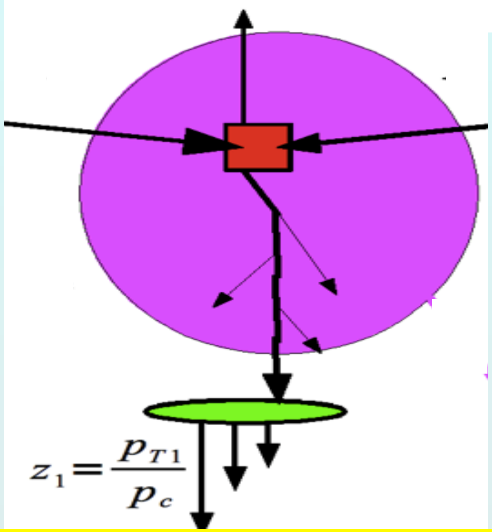
New questions from RHIC & LHC data!

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?

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

Luminosity x10 at RHIC

Large acceptance

➔rare probe scan: $50 < \sqrt{s} < 200$ GeV

➔ asymmetric systems

*In the era of P

When you think of studying heavy ion collisions, think strings!


i’m in ur fizx lab
testn ur string therry

Insights, given 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?

  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

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?

Beam Energy Scan

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

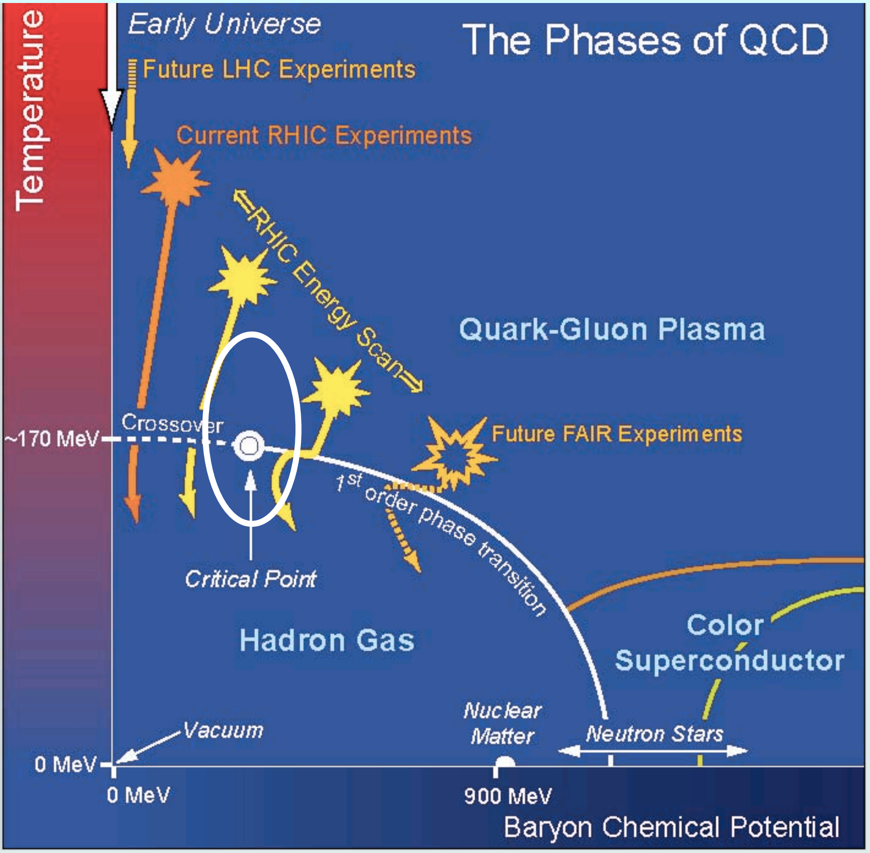
- Jets
- High p_T single hadrons
- Open heavy flavor
- Quarkonia

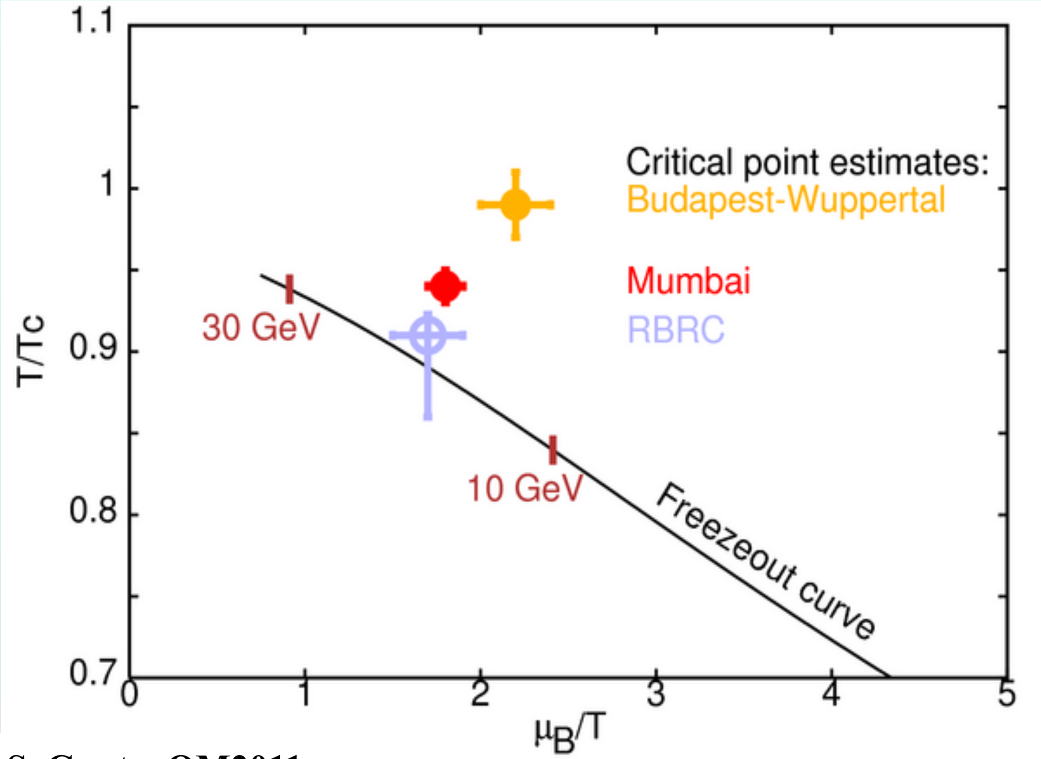
  repeat energy scan of 20 – 200 GeV with large acceptance detector to characterize the suppression as a function of sqrt(s)

- Photon-hadron, Photon-jets

  Probe Energy loss and QGP response in lower beam energy

Critical point search: low energy Au+Au @ RHIC





S. Gupta, QM2011

Tools:

Fluctuations, partonic collective flows

susceptibilities & net-baryon fluctuations

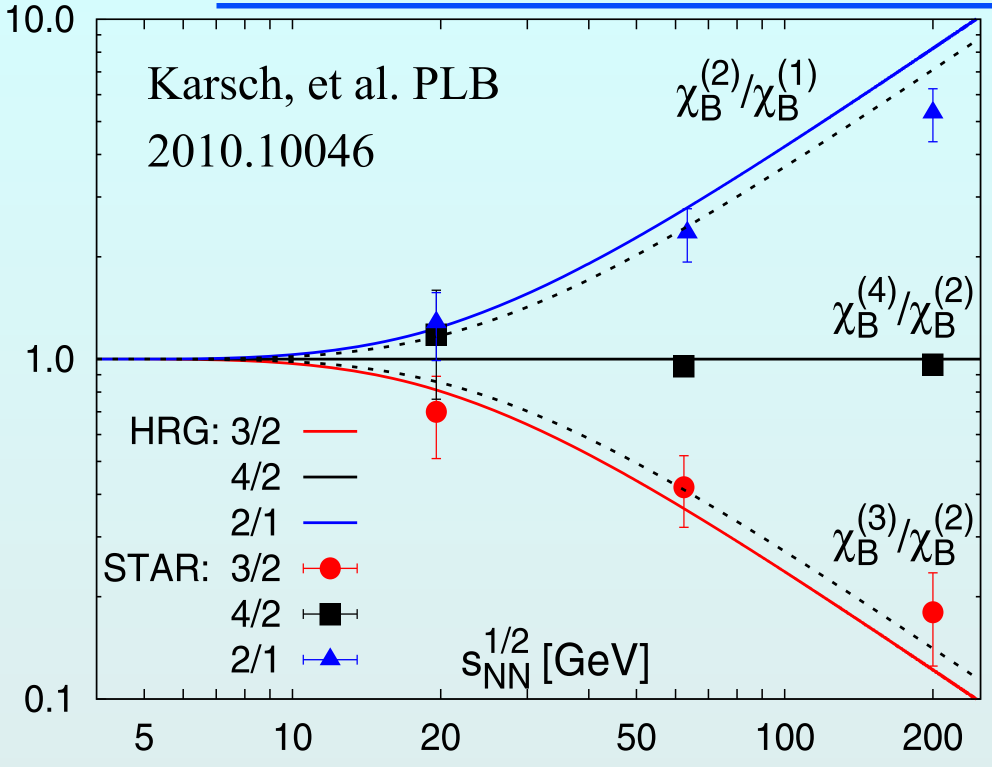
$$S\sigma = \frac{[B^3]}{[B^2]} = \frac{T\chi_B^{(3)}}{\chi_B^{(2)}},$$

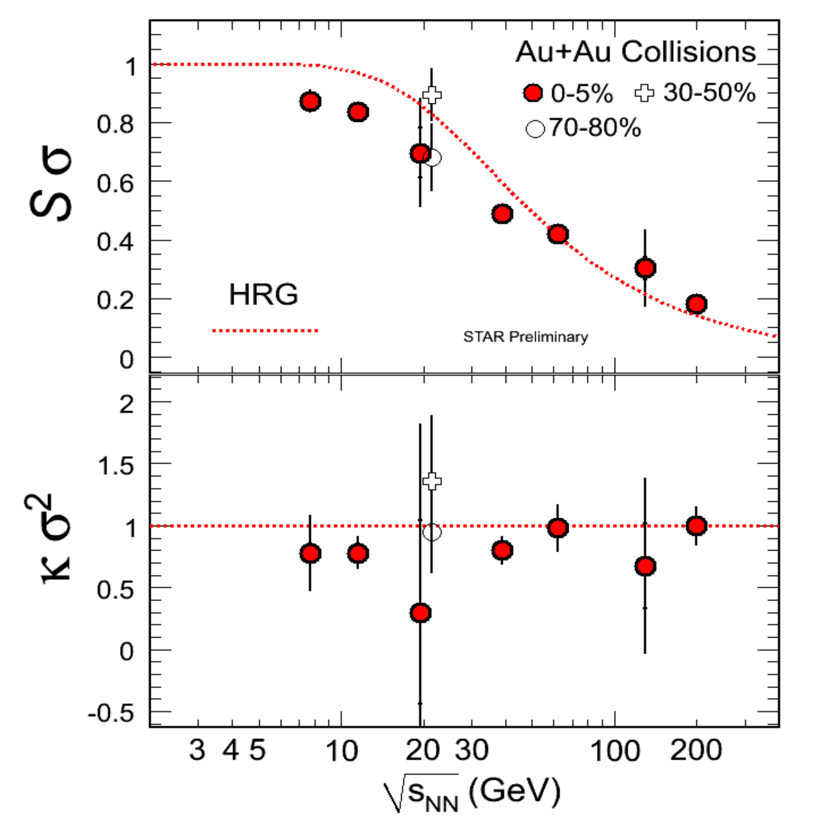
$$\kappa\sigma^2 = \frac{[B^4]}{[B^2]} = \frac{T^2\chi_B^{(4)}}{\chi_B^{(2)}},$$

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

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

Fluctuations as Critical Point Signature



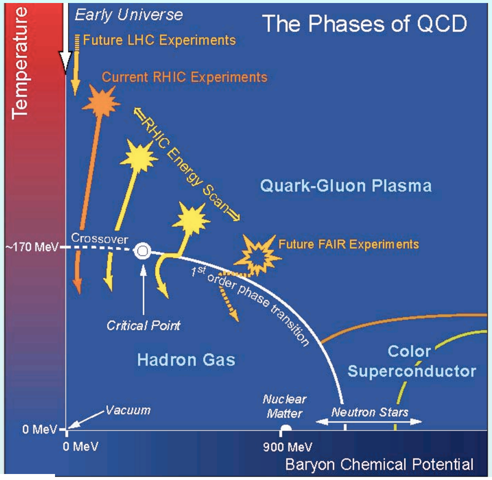


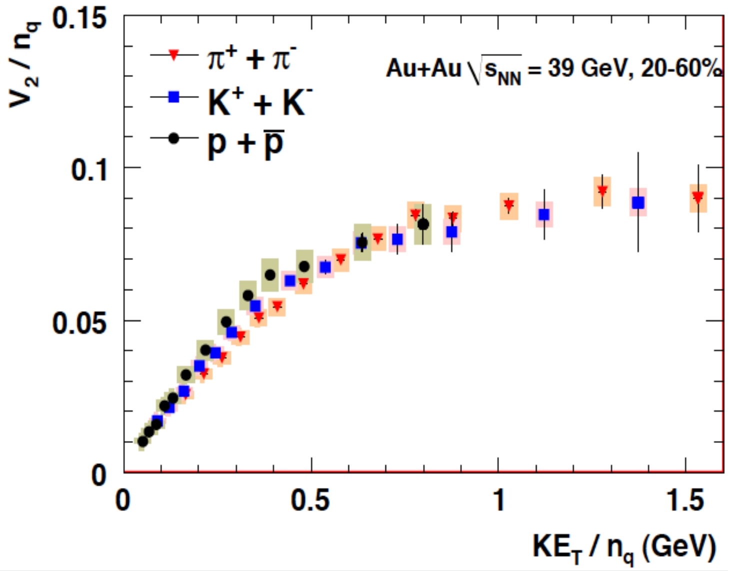
- Event-by-event net-baryon fluctuation ratios from STAR are so far consistent with the Hadron Resonance Gas
- Hadron freezeout not (yet) near critical point
- Calculations of higher moments from LQCD deviate from HRG calculations and may provide conclusive evidence for critical point if observed in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

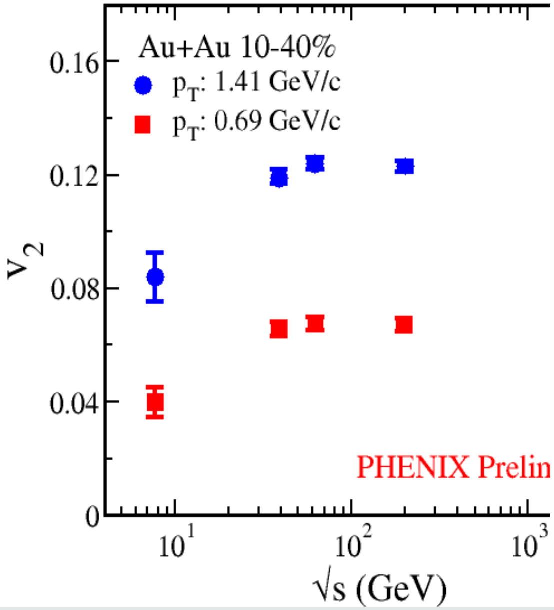
Beam Energy Scan in PHENIX

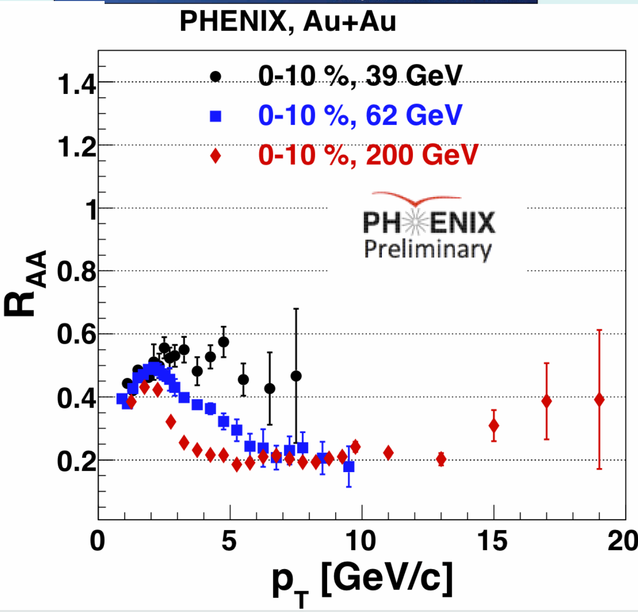
Is there a critical point separating 1st order phase transition & smooth cross-over?

- **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 $\langle p_T \rangle$ & multiplicity
  - K/π, π/p, pbar/p chemical equilibrium
  - R_{AA} vs $\sqrt{s}$, ...



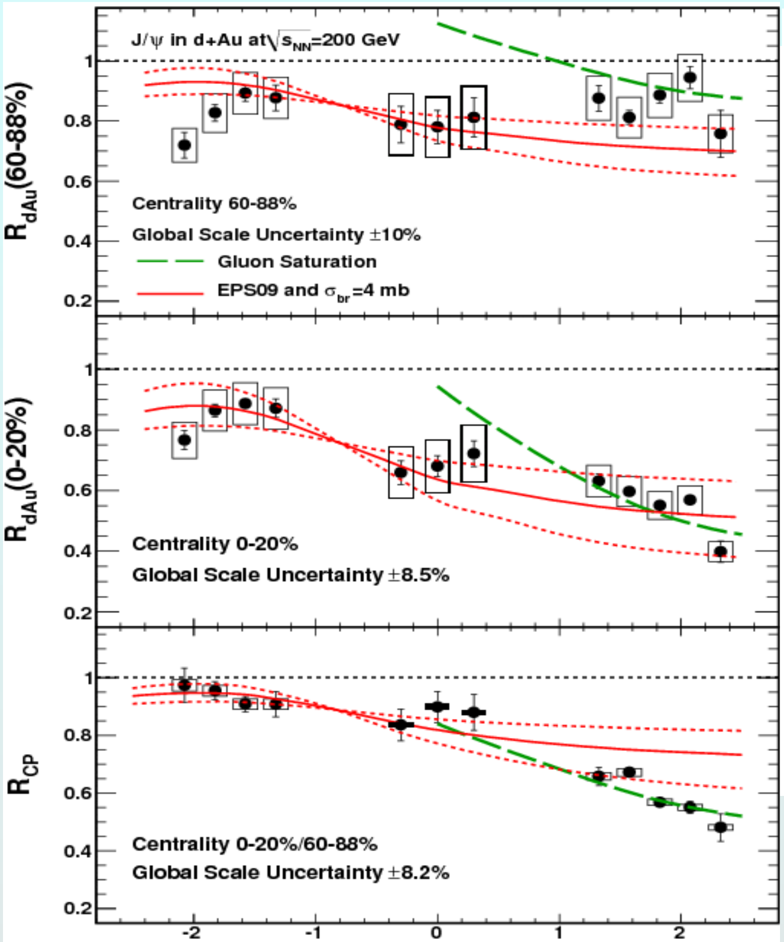




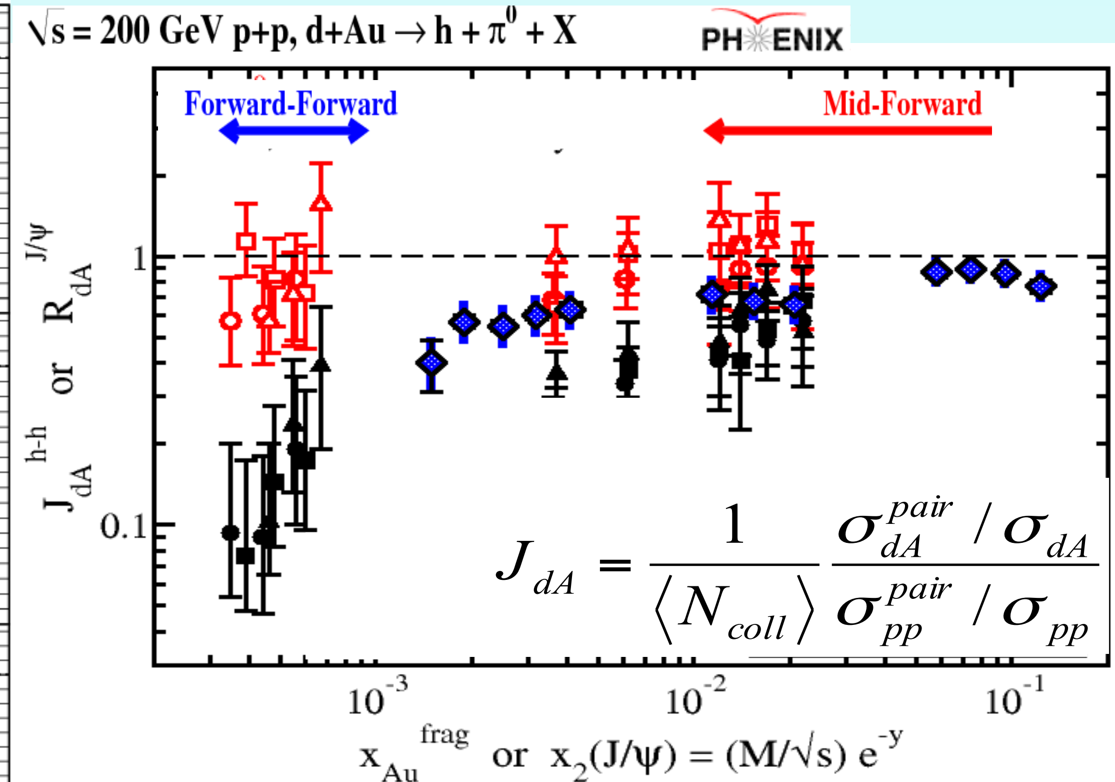


Dense gluonic matter (d+Au, forward y): large effects observed

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 …