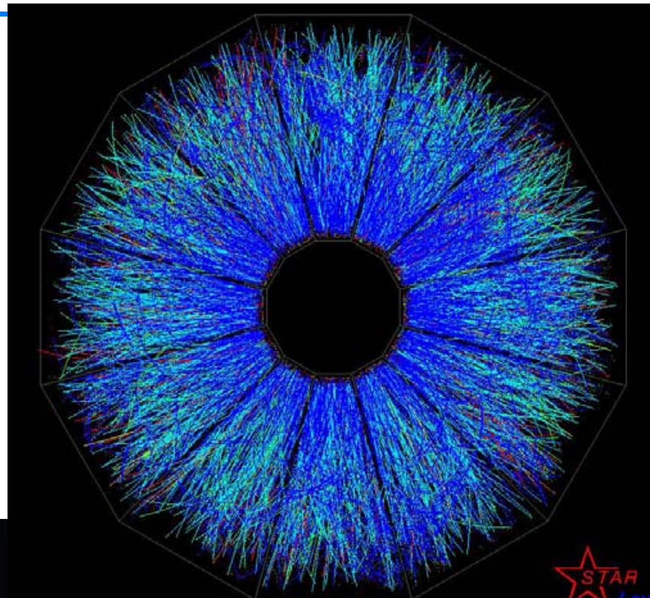
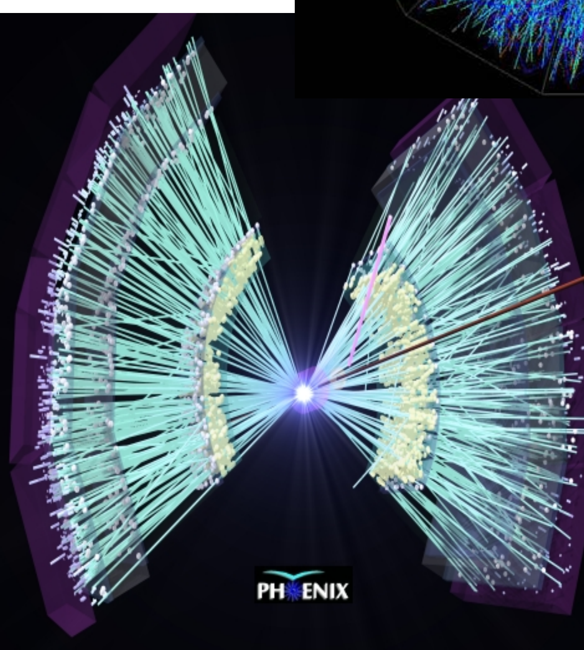
Experimenting with Strongly Coupled QCD Matter at RHIC





Barbara Jacak
Stony Brook

Nonequilibrium dynamics at KITP

February 26, 2008

outline

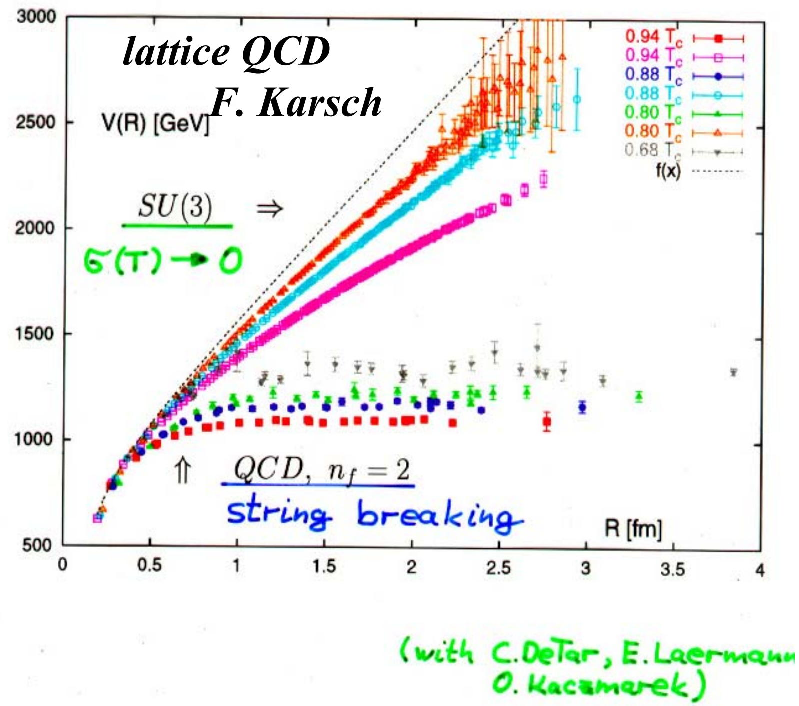
- **We already know from RHIC**
  opaque, flowing, rapidly thermalized QCD matter

- **Nonequilibrium dynamics: isotropization**
  EM observables

- **Nonequilibrium probes of the equilibrated matter**
  transport of momentum into QCD matter
  transport of energy by QCD matter
  heavy quark diffusion and viscosity

properties of QCD matter

- **thermodynamic (equilibrium)**
  T, P, ρ
  EOS (related T,P,V)
  v_{sound}, static screening length



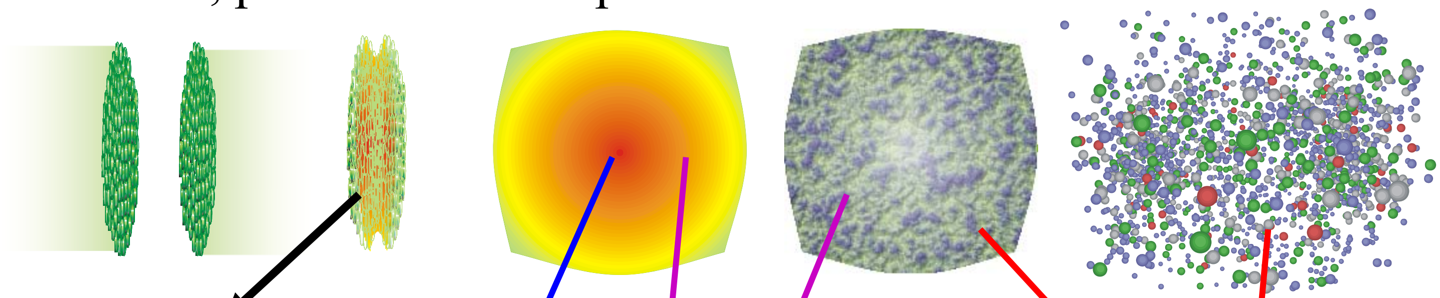
- **approach to thermalization**

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

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

challenge: heavy ion collisions & cosmology

ε, pressure builds up



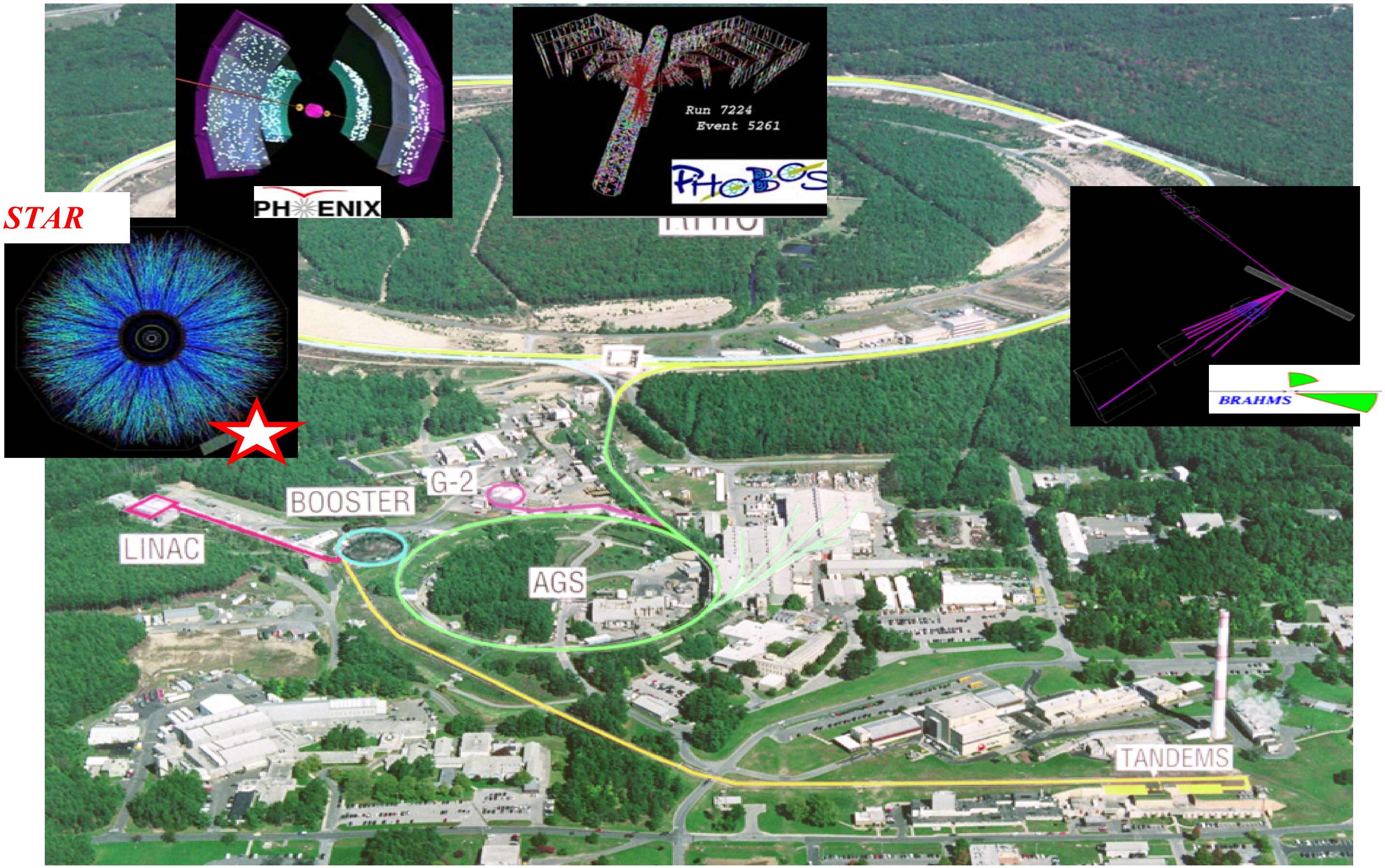
Hard scattered q,g
(short wavelength)
probes of plasma
formed color-screened QGP

thermal radiation
(γ, γ*→ **e^+e^-**, μ+μ−)

π, **K**, **p**, **n**, φ, Λ, Δ, Ξ, Ω, **d**,
Hadrons reflect (thermal) properties
when inelastic collisions stop
(chemical freeze-out).

not possible to measure as a function of time
nature integrates over the entire collision history

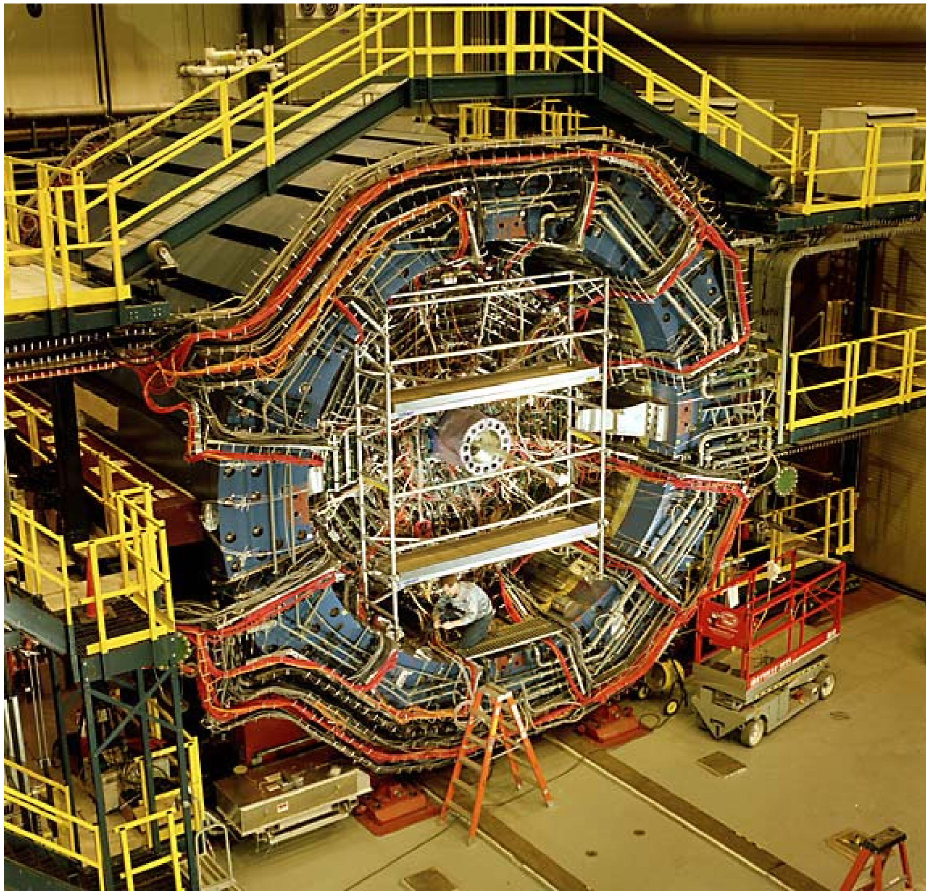
RHIC at Brookhaven National Laboratory



Collide Au + Au ions for maximum volume

$\sqrt{s}$ = 200 GeV/nucleon pair, p+p and d+A to compare

The Tools



STAR
specialty: large acceptance measurement of hadrons

PHENIX
specialty: rare probes, leptons, and photons

study plasma by radiated & "probe" particles

- as a function of transverse momentum

  $p_T = p \sin\theta$ (with respect to beam direction)

  90° is where the action is (max T, ρ)

  p_L midway between the two beams: midrapidity

- $p_T < 1.5$ GeV/c

  "thermal" particles

  radiated from bulk of the medium

  "internal" plasma probes

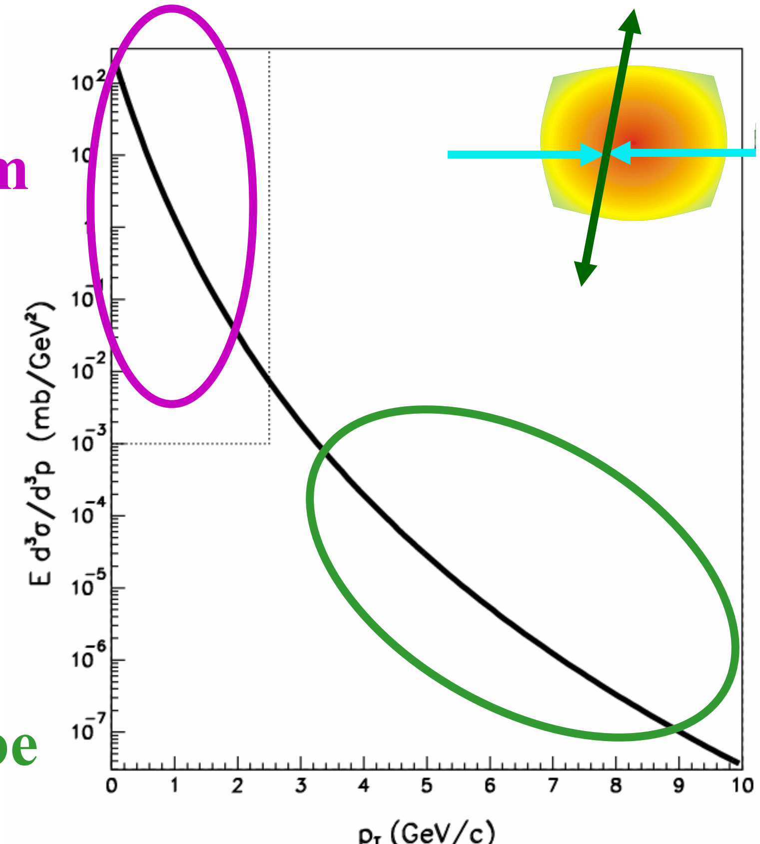
- $p_T > 3$ GeV/c

  jets (hard scattered q or g)

  heavy quarks, direct photons

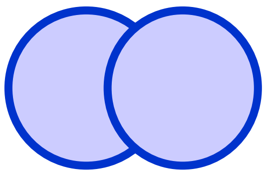
  describe by perturbative QCD

  produced early→"external" probe

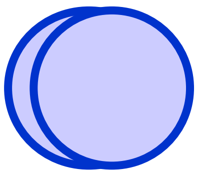


a bit of geometry, terminology

- baseline for heavy ions are p+p collisions
- peripheral collisions (large impact parameter) are like a handful of p+p collisions
- central (small impact parameter) collisions produce largest plasma volume, temperature, lifetime
- report centrality as fraction of total A+A cross section
  - » 0-5% = very central

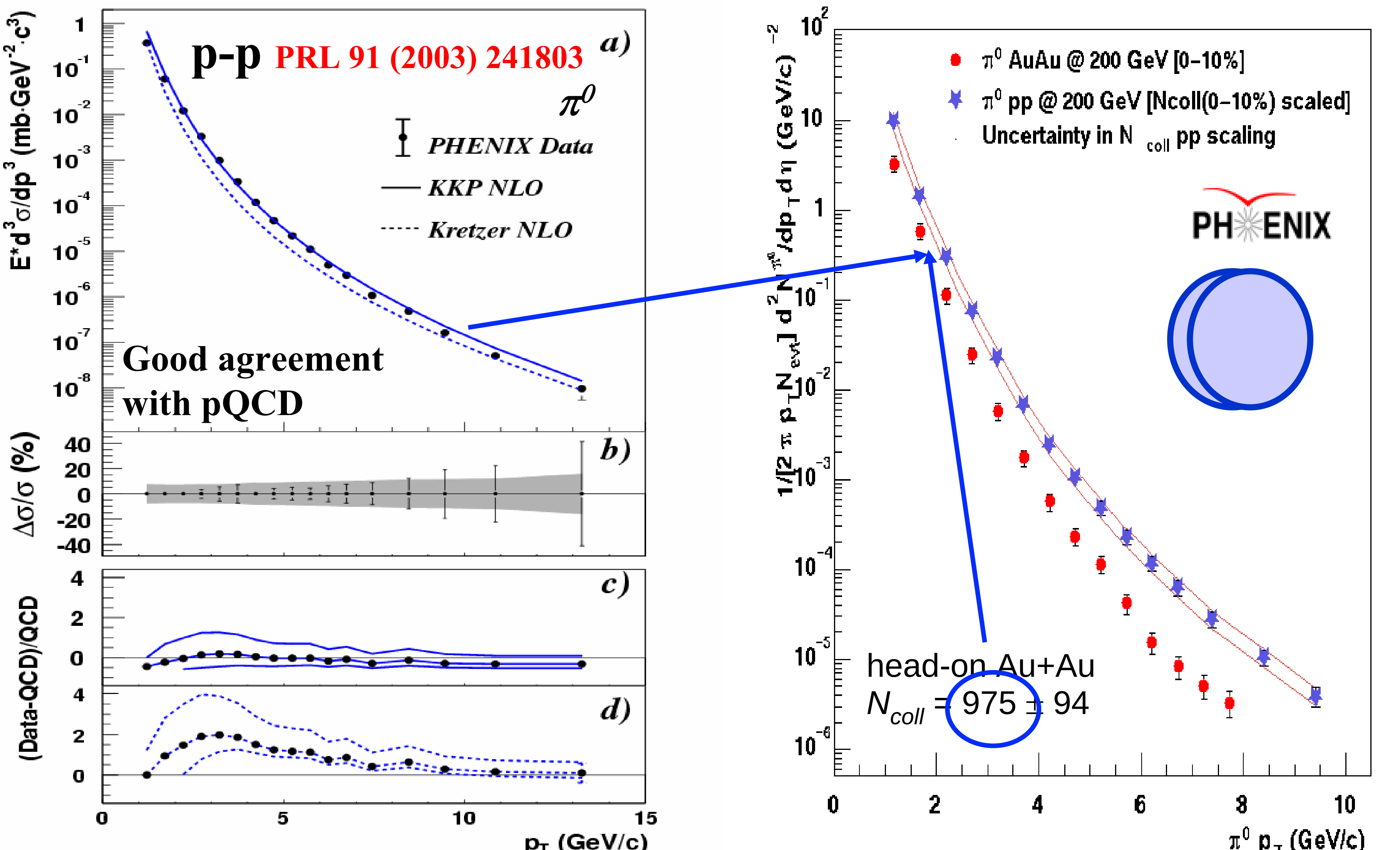


peripheral:
few participant nucleons (small N_{part})
few NN collisions (N_{coll})

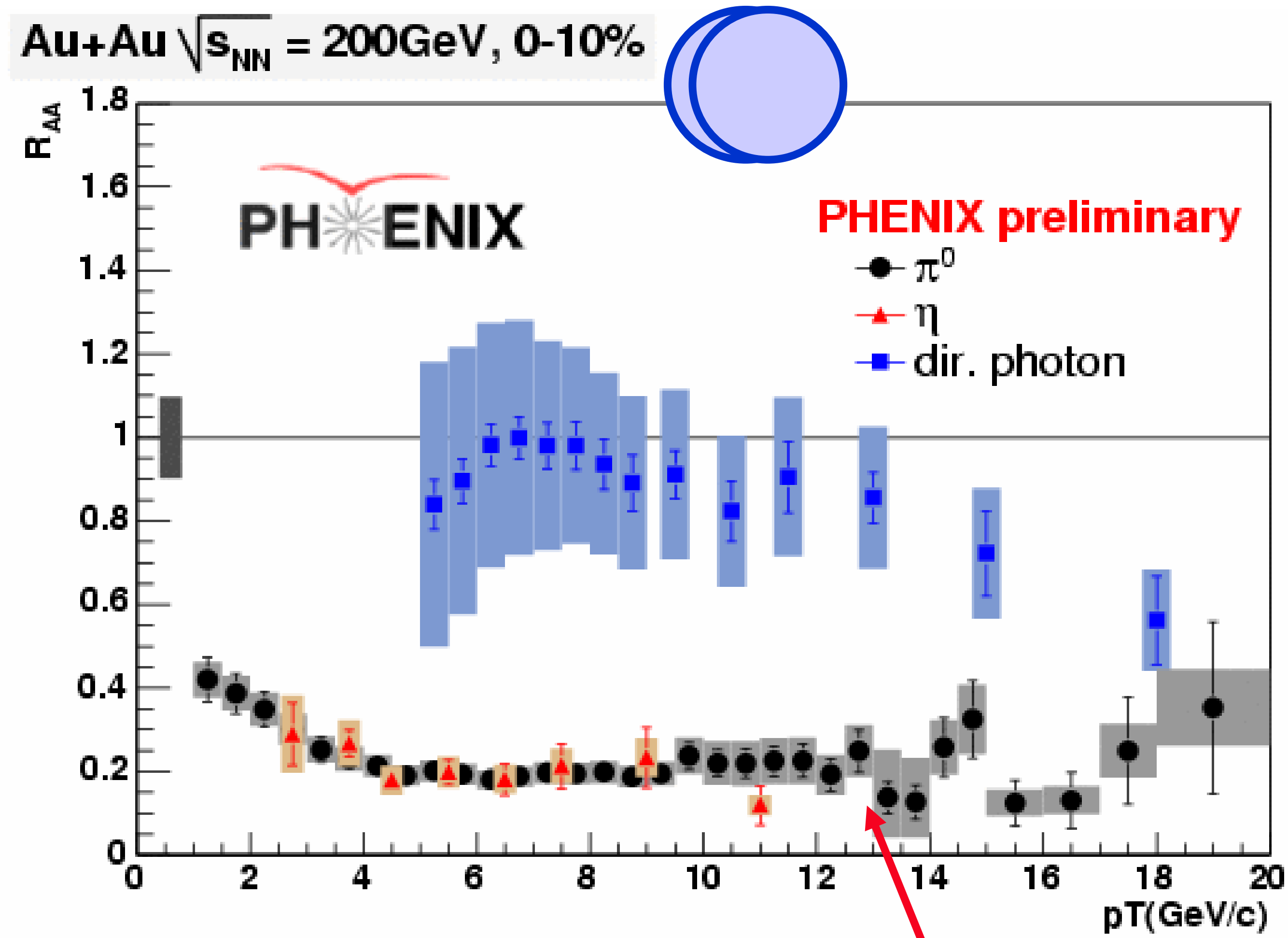


central:
large N_{part} & N_{coll}
Ncoll near 1000 in ~ head-on Au+Au

Establish that matter is opaque



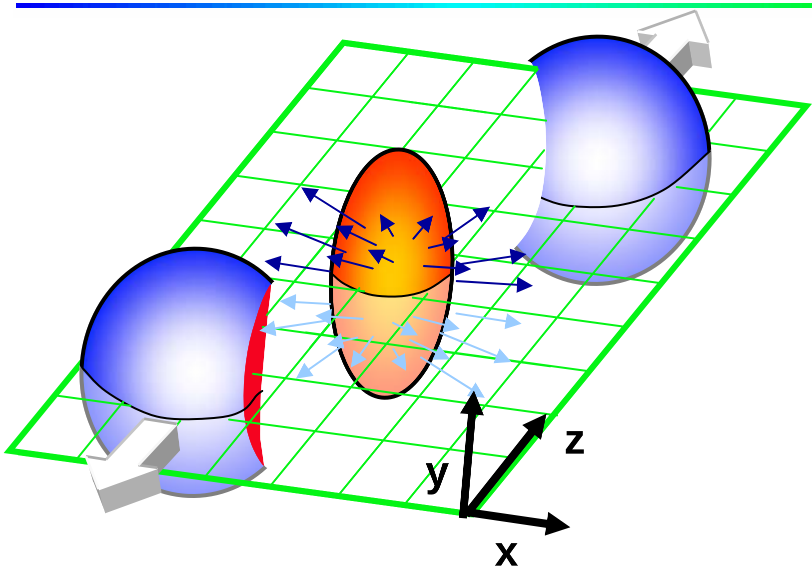
colored objects lose energy, photons don't

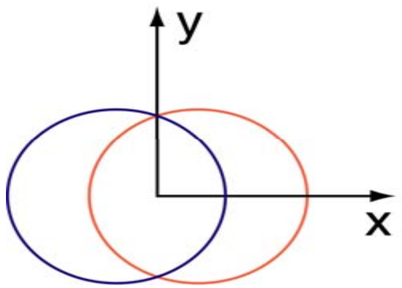


$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

how opaque is hot QCD matter?

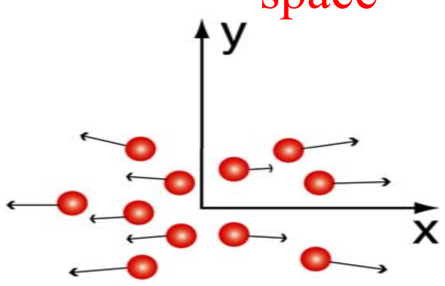
Collectivity: measuring elliptic flow (v_2)

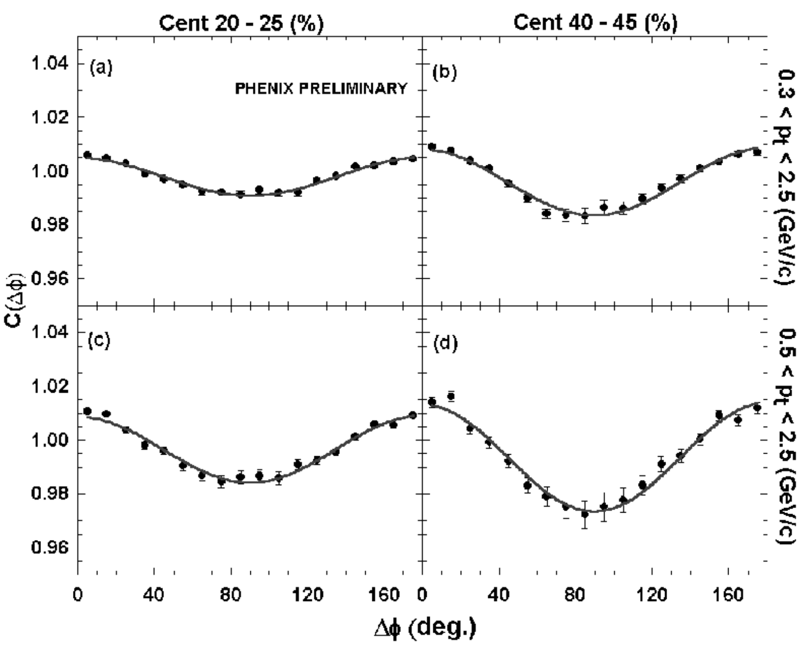




Almond shape overlap region in coordinate space

momentum space





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

"elliptic flow"

v_2 is large & reproduced by hydrodynamics

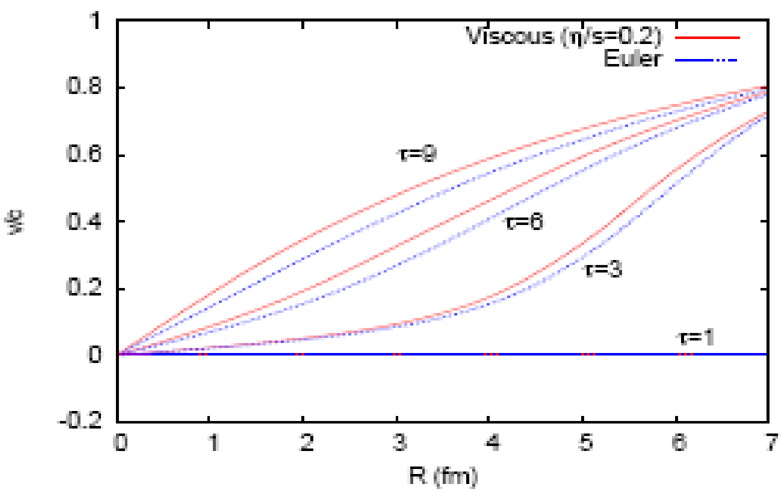
must begin hydro in < 1 fm/c

viscosity must be ~ 0 - 0.1

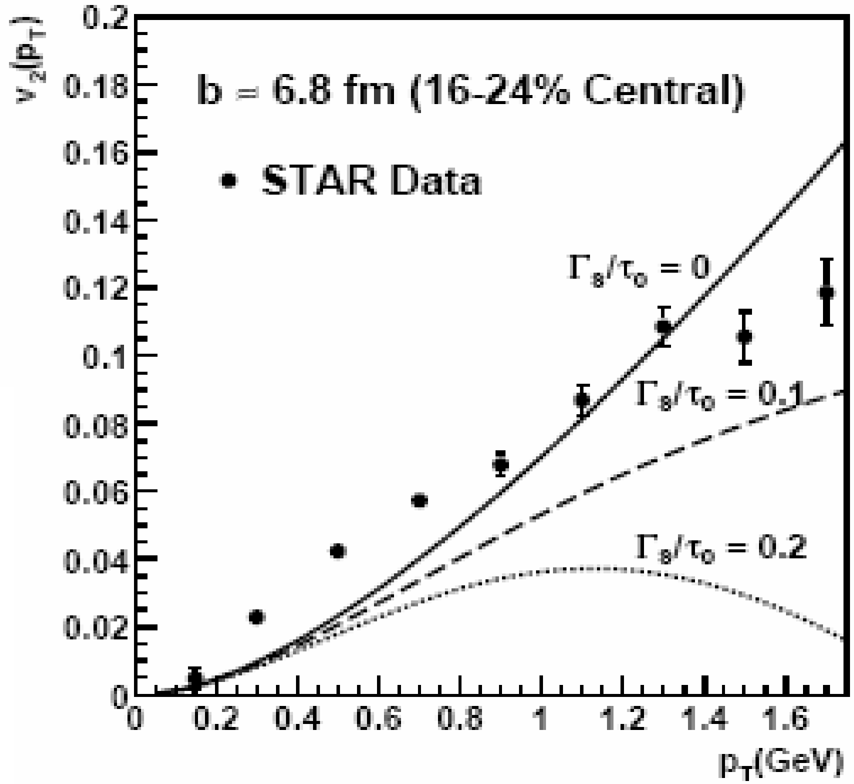
i.e. "perfect" liquid

viscosity decreases longitud.

pdV work → higher transverse velocity



D. Teaney, PRC68, 034913 (2003)



data constrains hydro: as in plasma physics

First indication of small η/S

isotropization of incoming momentum in <1 fm/c

- is really ***FAST!!***
- not possible by partonic interactions with perturbative cross sections
- first indication that coupling is strong

  also: α_s not small at RHIC

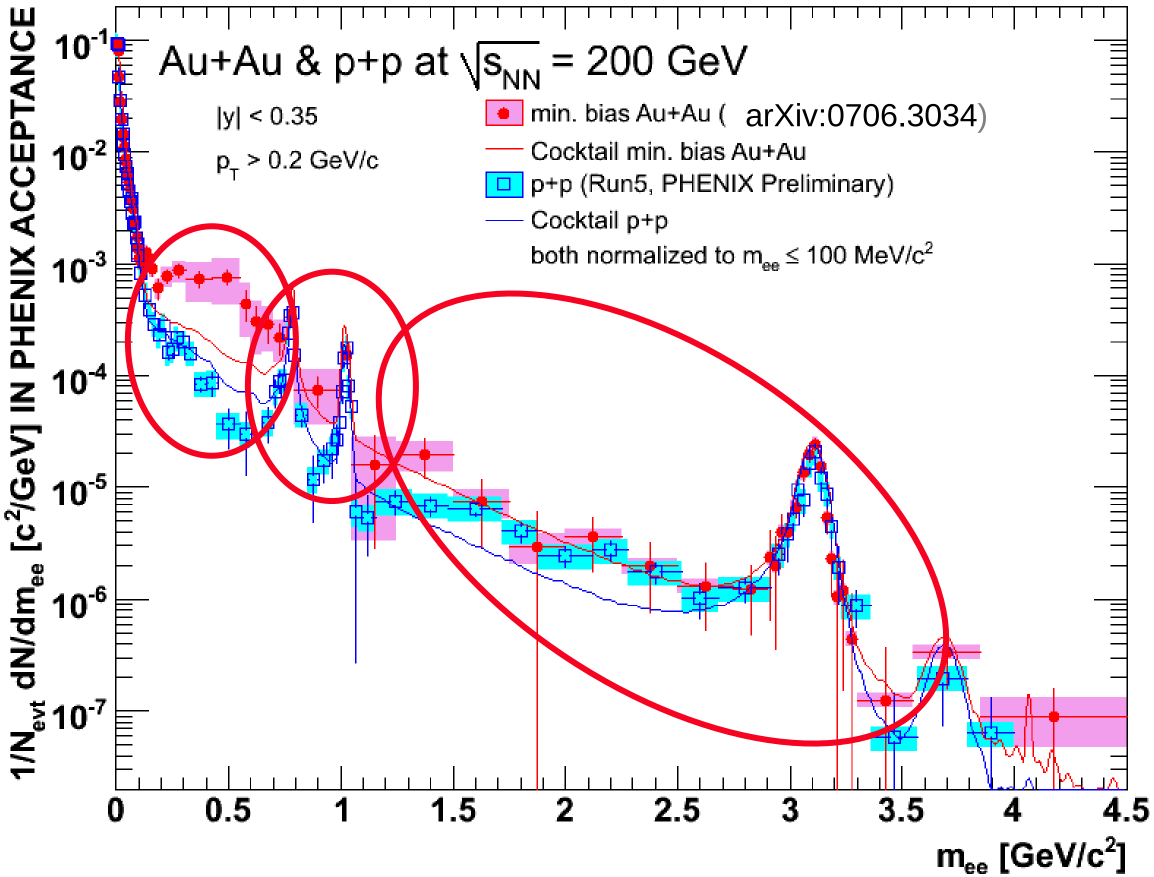
  gluon density in sphere with $r_{Debye} \sim 1$

  liquid behavior is typical of strongly coupled plasma
- mechanism: plasma instability?
- need experimental observables sensitive to nonequilibrium processes

  electromagnetic probes not perturbed by equilibrated plasma at later times

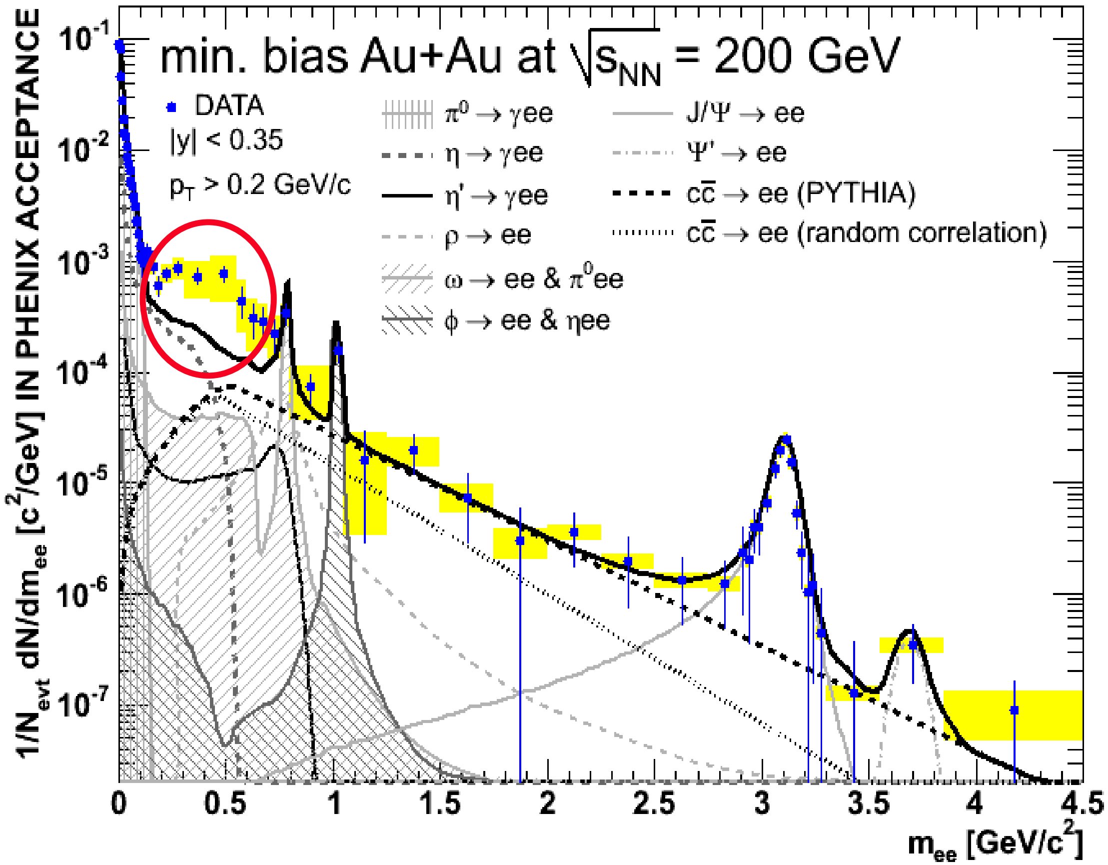
Begin with leptons: γ* → e^+e^- pairs

p+p and Au+Au normalized to π^0 region



- Au+Au agrees with p+p at resonances (ω, φ)
- Enhancement for $0.2 < m_{ee} < 0.8$ GeV
- Also excess ρ: π+π→ ρ during hadron gas phase
- Agree at 1.2 < m < 3 GeV and J/Ψ by coincidence (J/Ψ scales as π^0 due to scaling as N_{coll} + suppression)

excess is in central collisions



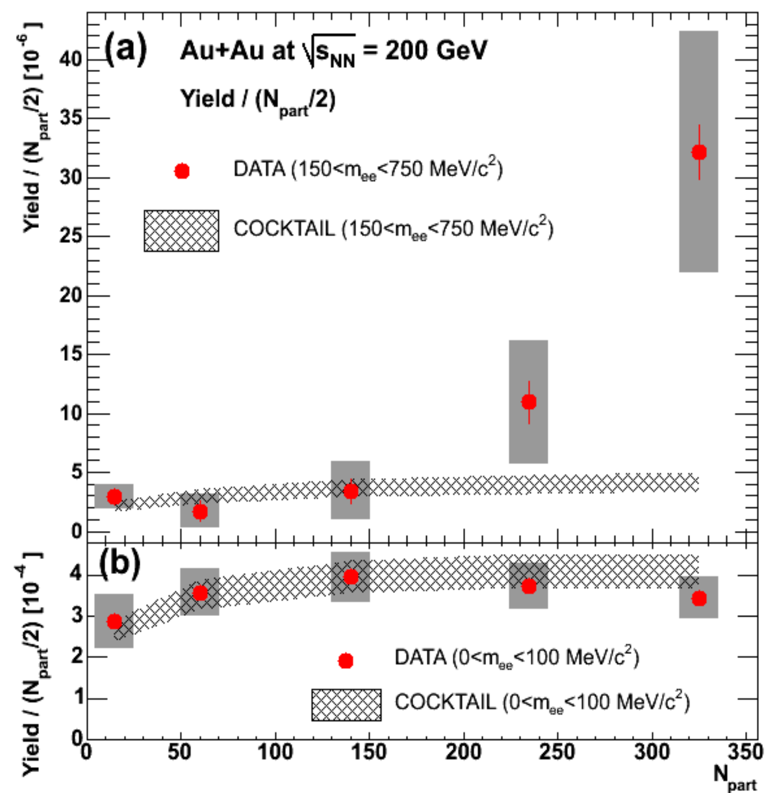
PHENIX
submitted to Phys. Rev. Lett
arXiv:0706.3034

yield excess grows faster than N_π

large excess below ρ

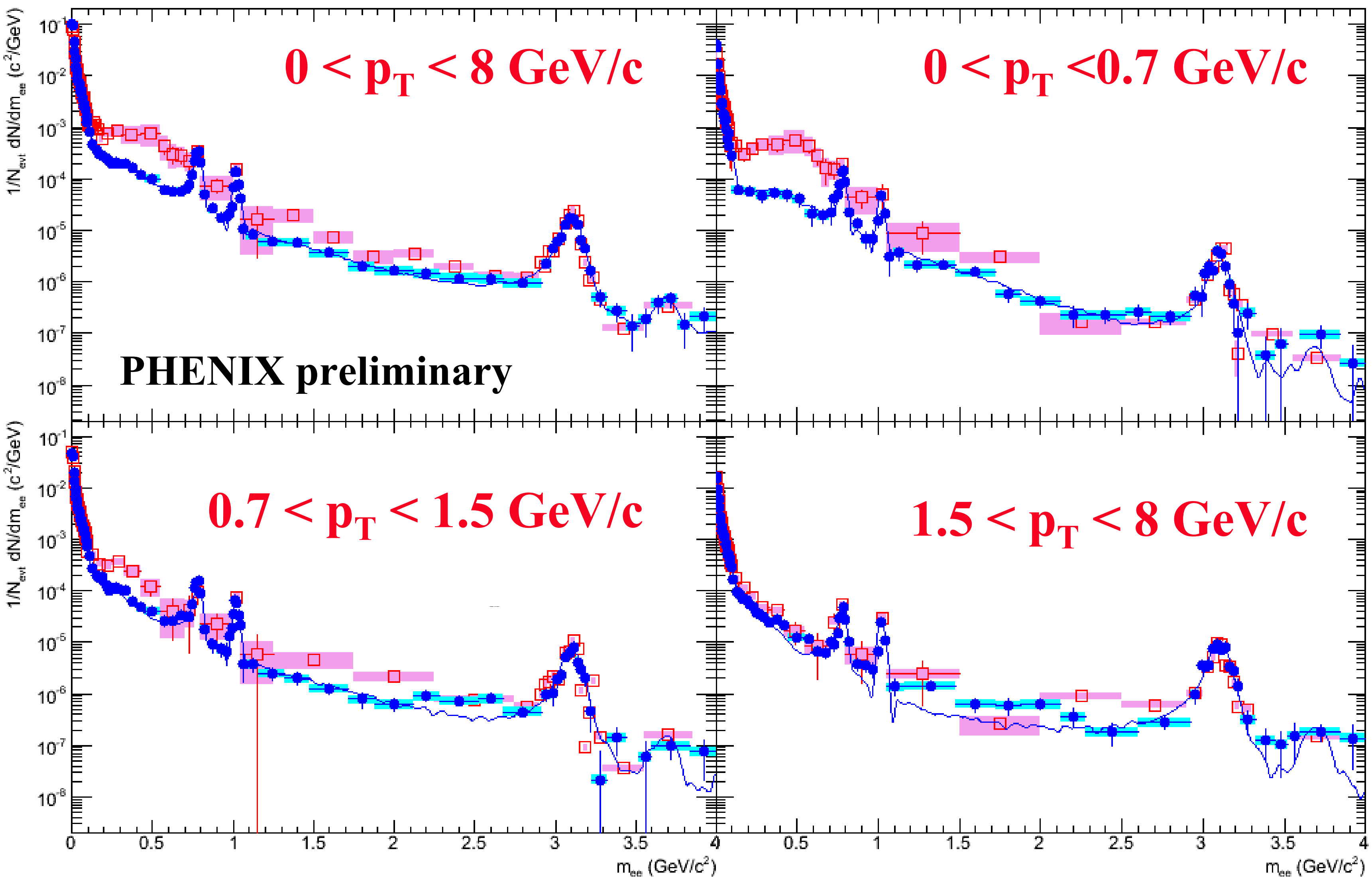
$q+\bar{q} \rightarrow \gamma^* \rightarrow e+e-$?

thermal radiation



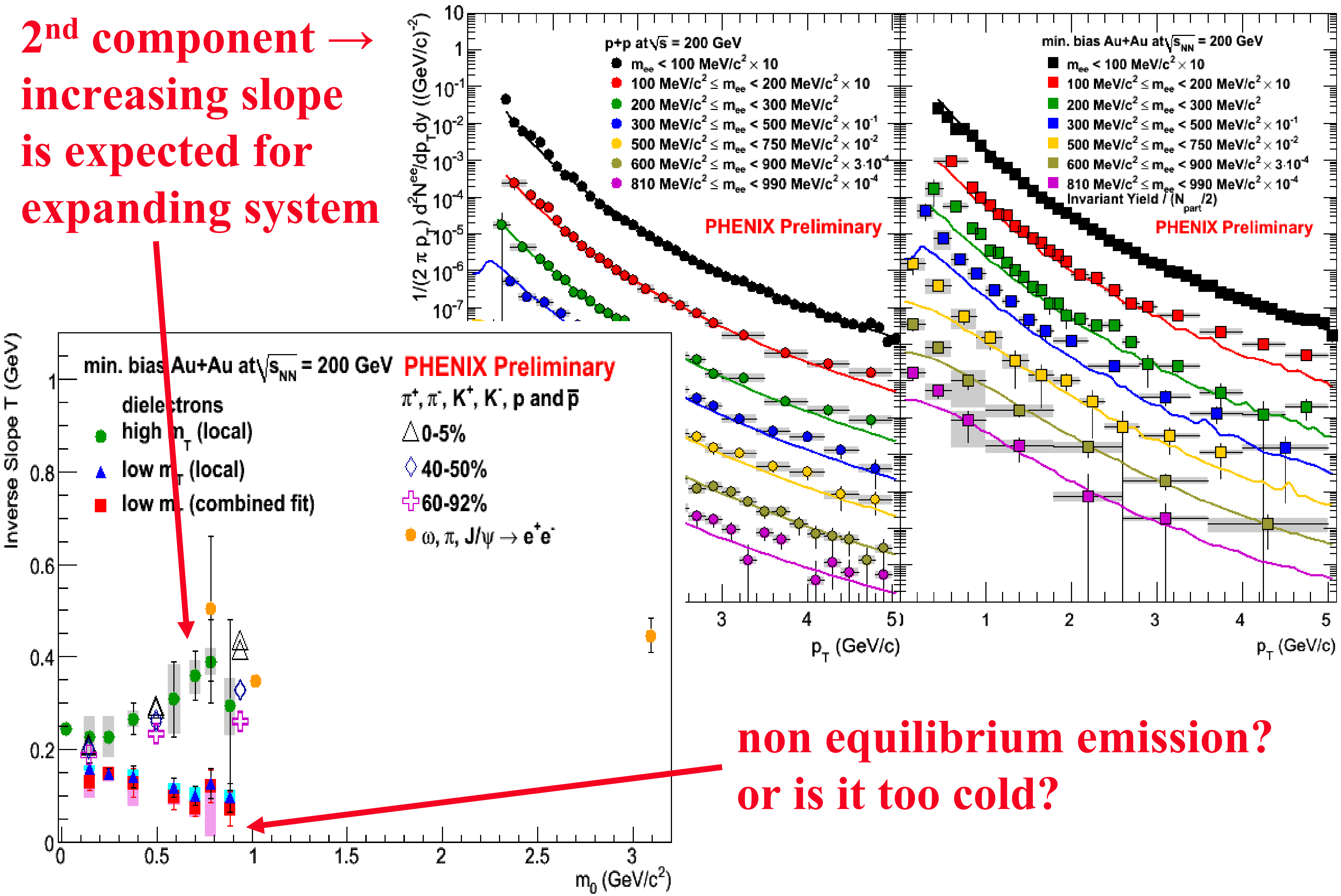
low mass excess is dominantly at low p_T

200 GeV Au+Au



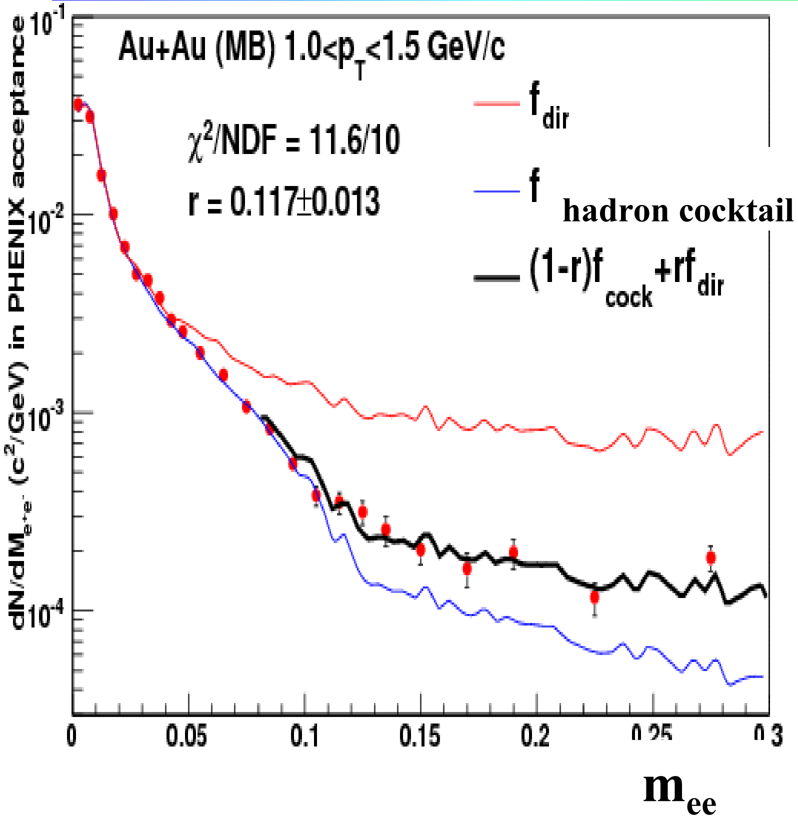
p_T distribution is mysterious

2^{nd} component → increasing slope is expected for expanding system



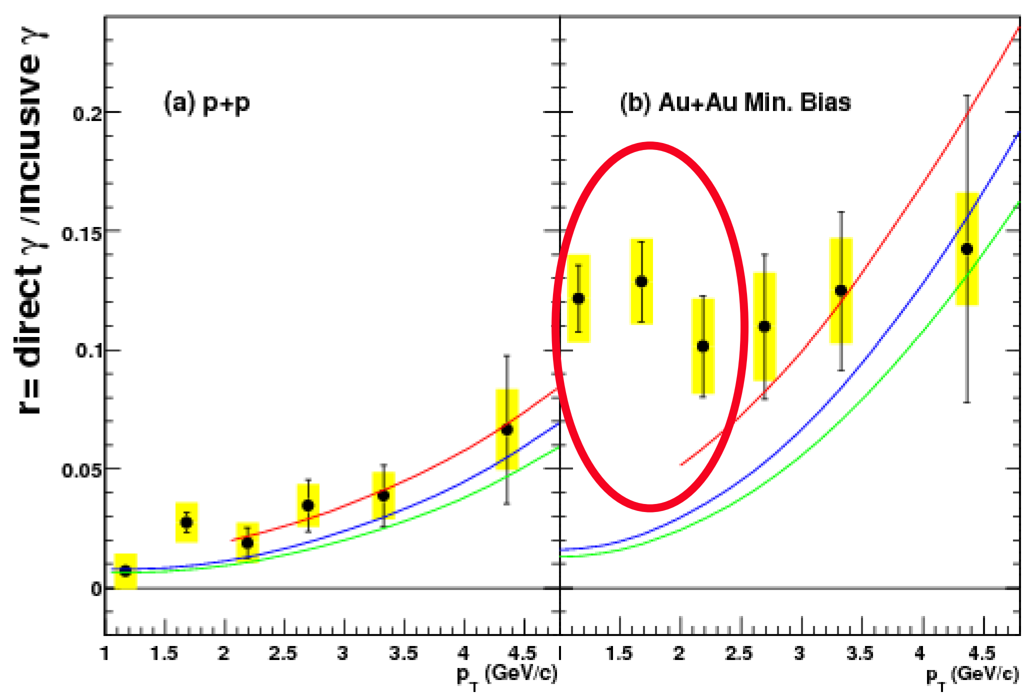
non equilibrium emission? or is it too cold?

direct photons via e+e-

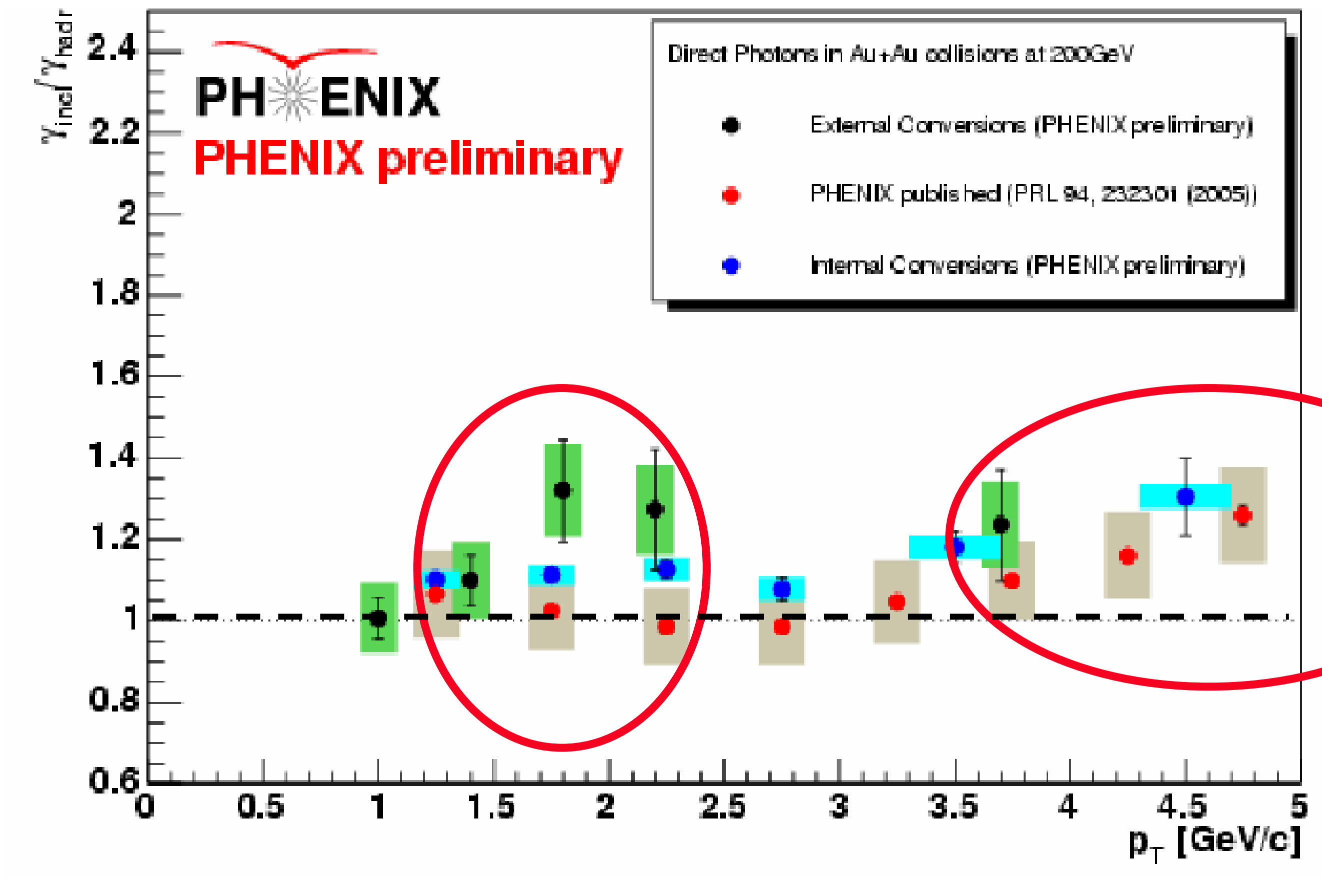


for low mass, $p_T > 1$ GeV/c direct γ^* fraction of inclusive γ^* (mostly π^0, η) is ≈ real γ fraction of γ (mostly π^0, η)

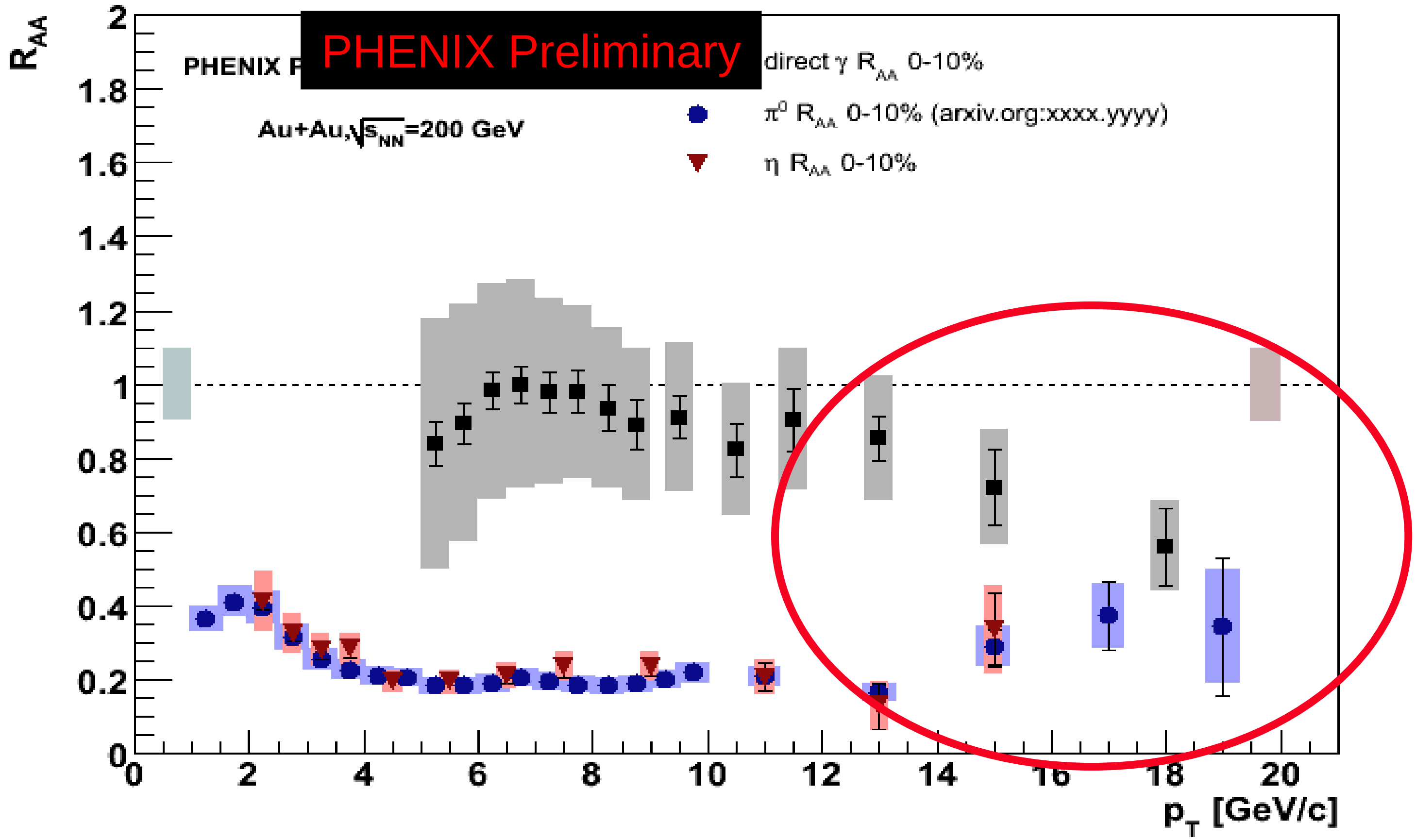
low mass and $p_T \gg m_{ee}$ dominated by decay of γ^* (kinematic bias against hadron decay background)



low pT direct γ and QCD direct γ



High p_T direct photons



interesting things at p_T>15 GeV/c?

transport properties of hot QCD matter

- **to characterize material, typically one measures**

  transport coefficients:

  particle number, energy, momentum, charge

  diffusion ***sound*** ***viscosity*** ***conductivity***

- **also**

  transverse momentum deposition into the medium: $\hat{q}$

- **emission from the bulk can reflect collective motion**
- **but other useful probes require**

  auto-generation in the heavy ion collision

  large Q^2 processes to separate production & propagation

  large E_{tot} (high p_T or M) to set scale other than T(plasma)

tranport step 1: dump momentum into the medium

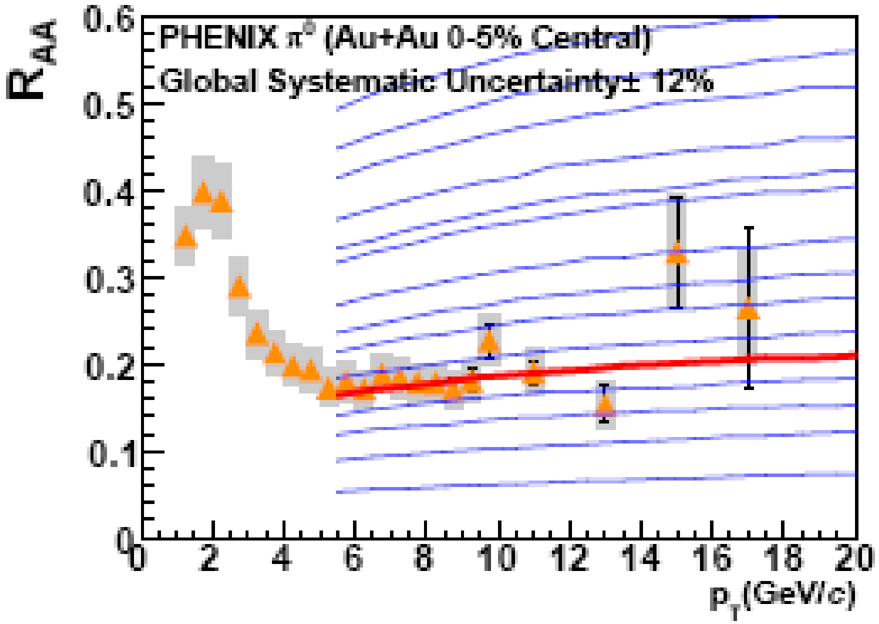
energy/momentum is transferred to the medium
how to quantify this & the medium's response?

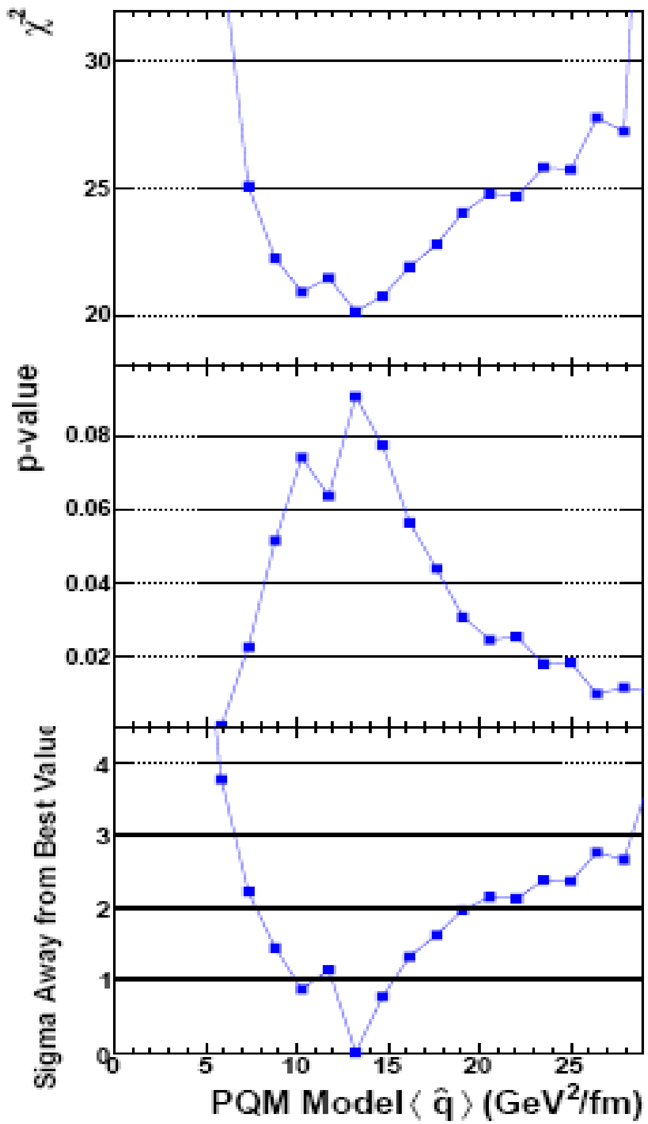
- **define a transport parameter e.g. $\hat{q}$:**
  $\langle p_T^2 \rangle$ transfer from medium to fast quark/gluon per unit path length
- **cannot measure directly**
  use data to constrain models with varying $\hat{q}$
  model high p_T pion suppression
  energy/momentum loss of fast quark to medium dominantly via gluon radiation
  this radiation calculable with pQCD
- **also calculable via AdS/CFT**
  in that case $\hat{q}$ is a measure of temperature, T

extract $\hat{q}$ using high p_T data, get a big number!

C. Loizides

Eur.Phys.J. C49 (2007) 339

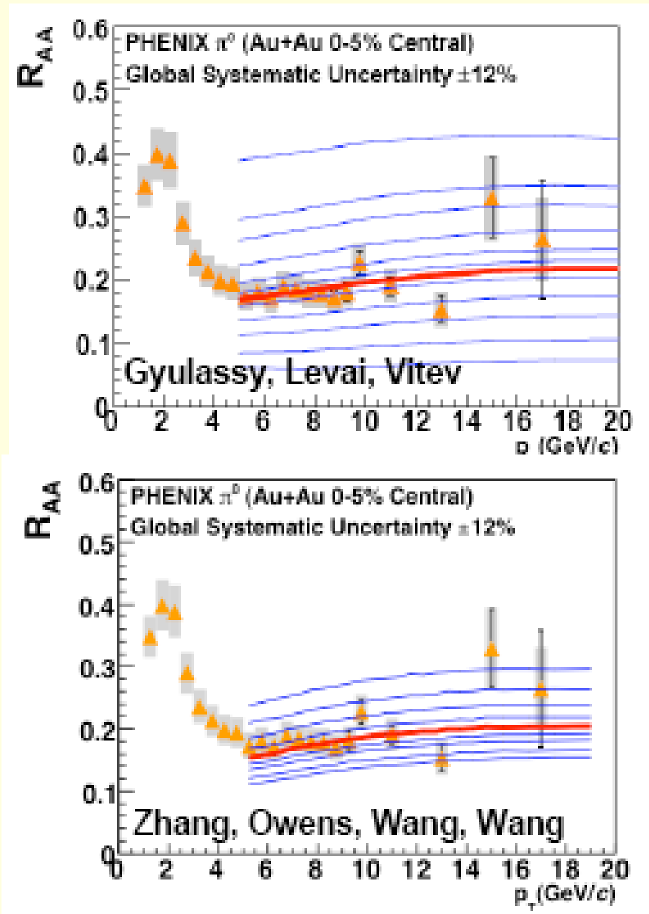




pQCD favors ~1 (Baier);
AdS/CFT ~4.5 GeV^2/fm
(Rajagopal, Wiedemann)

momentum exchange: non-equilibrium process

PHENIX, arXiv:0801.1655 [nucl-ex]



Most models approach perturbatively

Some include feedback to parton
Geometry details vary

In strong coupling: $\hat{q} \propto \sqrt{N_{DOF}}$

$$\hat{q} = c\sqrt{g_{YM}^2 N}\; T^3$$

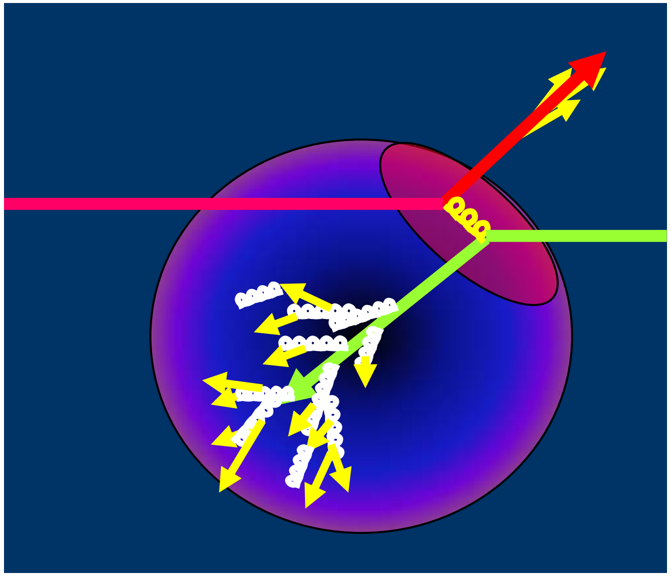
It does not seem that the answers hang together

Results (1σ range): Caveat: theoretical uncertainties not included

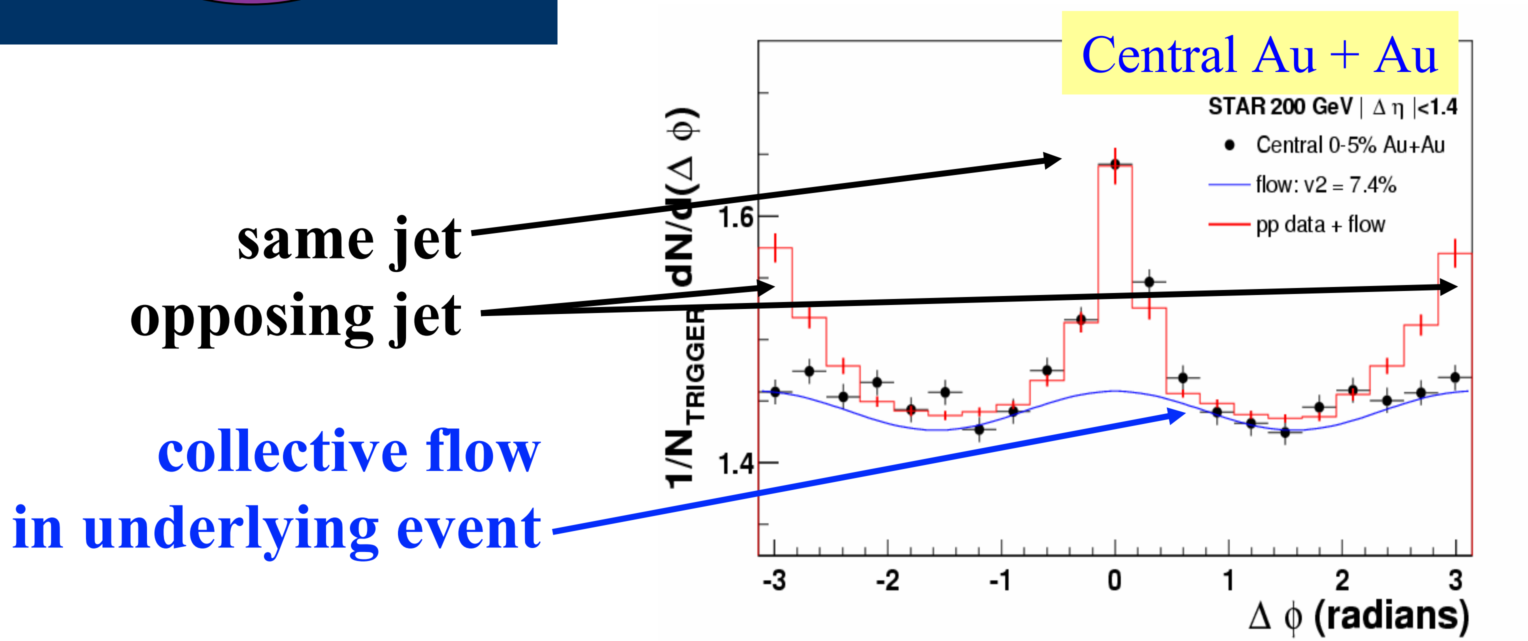
PQM	GLV	WHDG	ZOWW
$\hat{q} = 13.2^{+2.1}_{-3.2}$ GeV^2/fm	$dN^g/dy = 1400^{+270}_{-150}$	$dN^g/dy = 1400^{+200}_{-540}$	$\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm^3

 Klaus Reygers, QM 2008

medium transport of deposited energy?



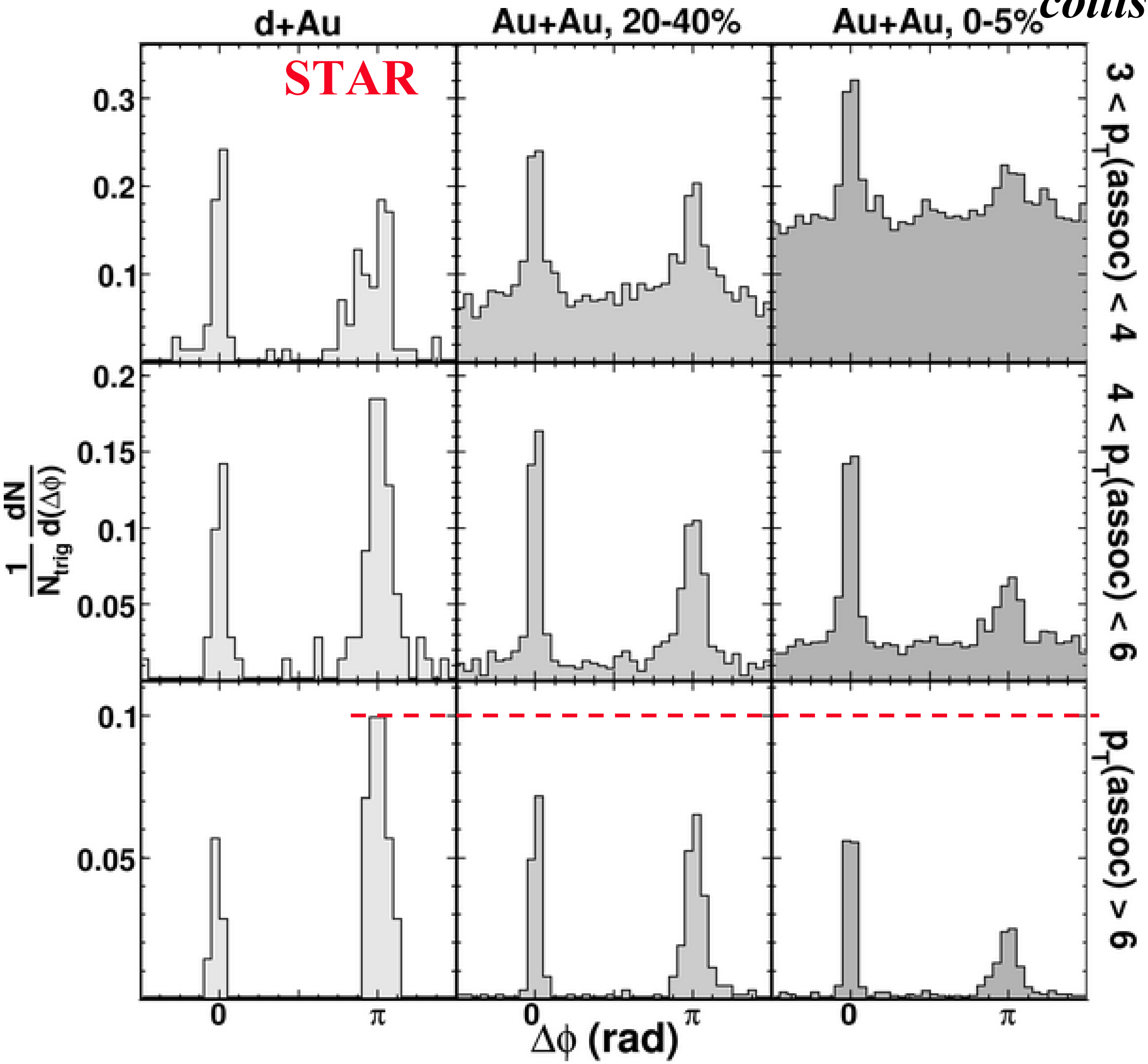
- **study using hadron *pairs***
- **high p_T trigger to tag hard scattering**
- **second particle to probe the medium**



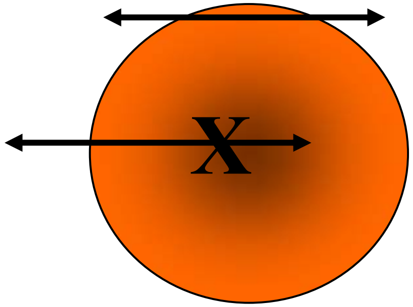
at high momentum, jets punch through

Phys.Rev.Lett. 97 (2006) 162301

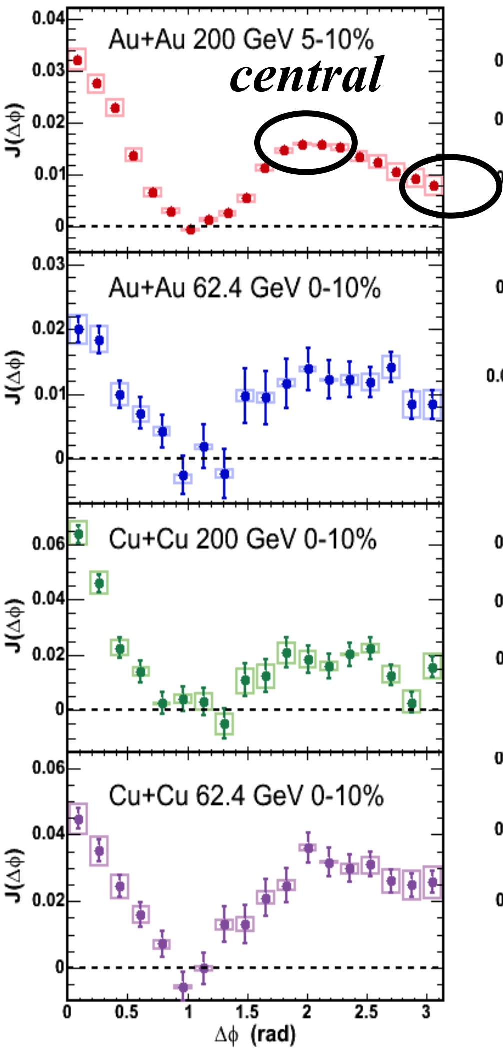
central collisions



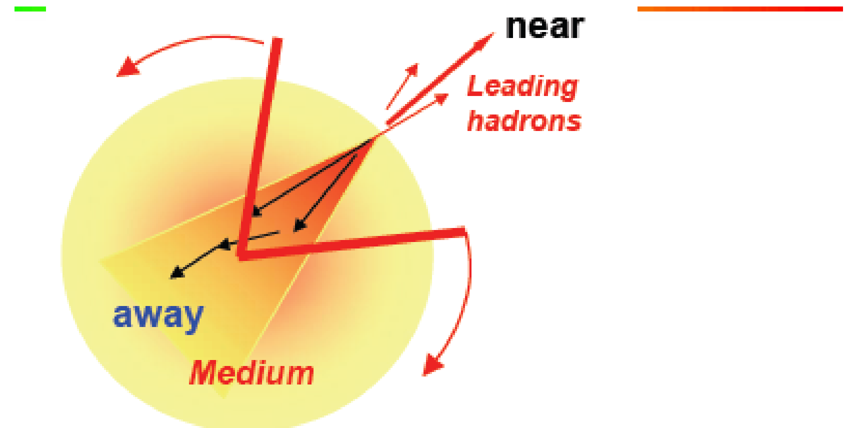
on away side:
same distribution of particles as in p+p but ~5 times fewer!
expected for opaque medium

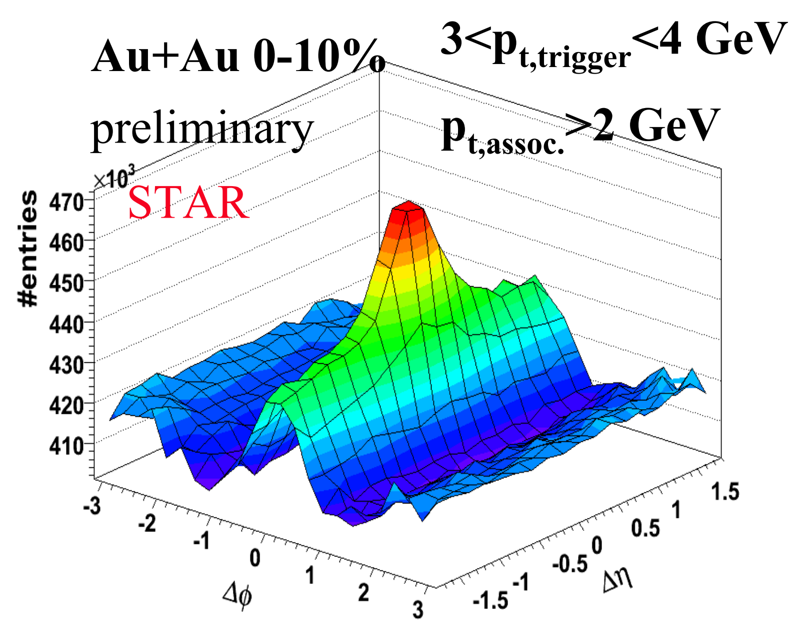


lower p_T looks funny: medium responds to the “lost” energy

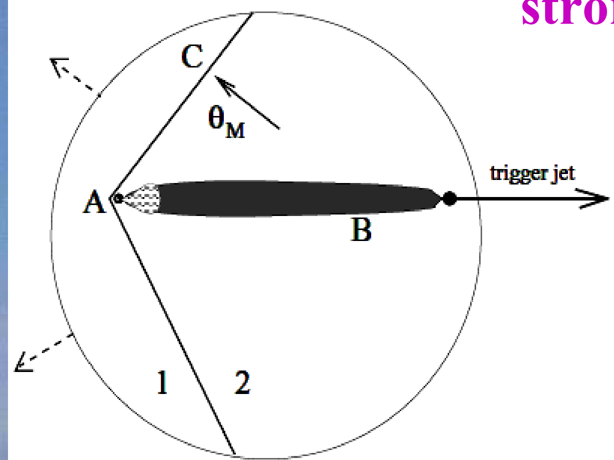


$1 < p_{T,a} < 2.5 < p_{T,t} < 4$ GeV/c

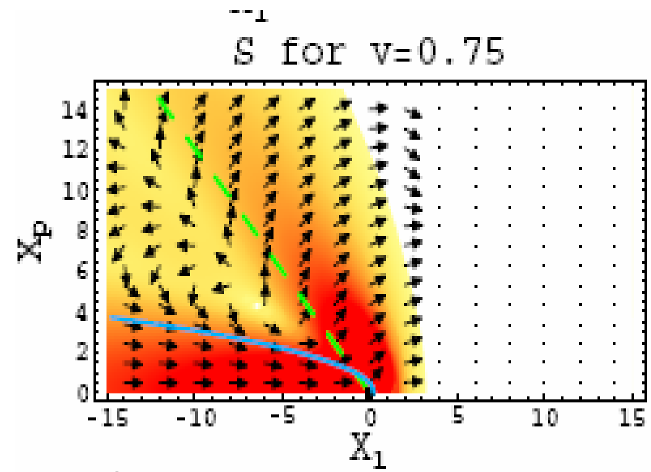




lost energy excites a sound (density) wave?



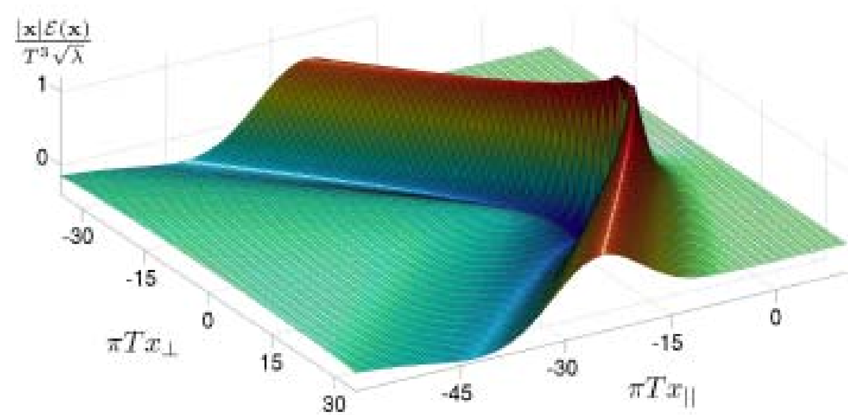
strong coupling: ask AdS/CFT
answer: yes it does!



Gubser, Pufu, Yarom 0706.4307(hep-th)

if shoulder is sound wave…
LOCATION at $\phi=\pi$ +/-1.23=1.91,4.37
$\rightarrow$ speed of sound $\cos\phi_m=c_s$~0.35-0.4
(c_s^2=0.33 in QGP,~0.19 in hadron gas

relative excitation of sound and diffusion wake in intense study
data →sound mode large



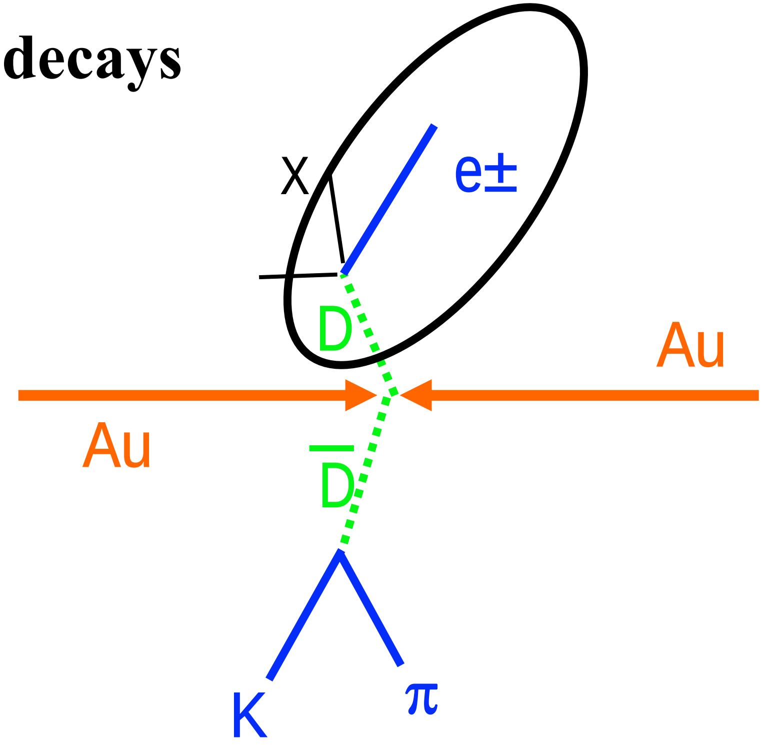
Chesler & Yaffe, 0706.0368(hep-th)

Diffusion of heavy quarks traversing QGP

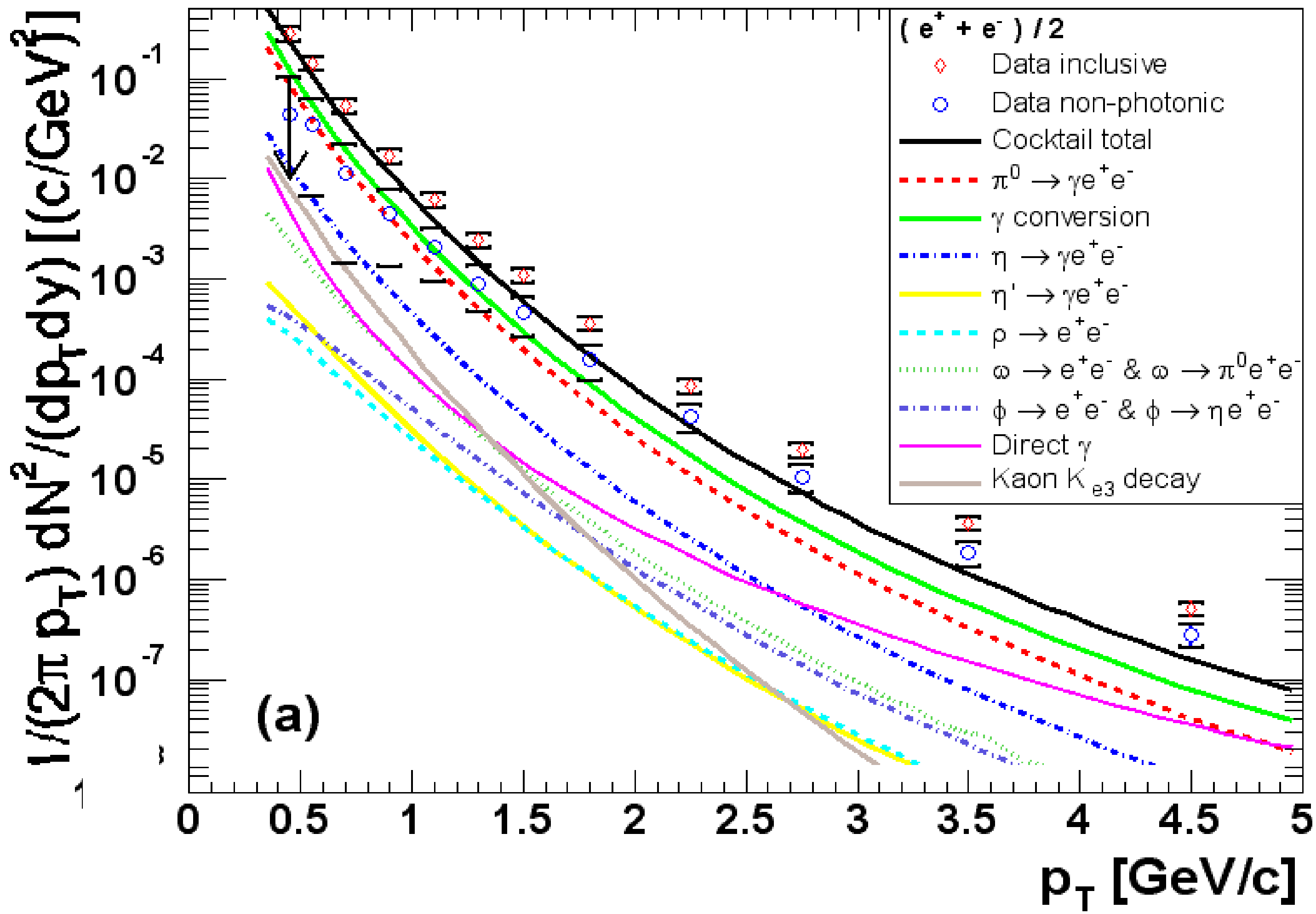
- **How do they interact?**
- **Prediction: lower energy loss than light quarks**

  large quark mass reduces phase space for radiated gluons

- **Measure via semi-leptonic decays of mesons containing charm or bottom quarks**



c,b decays via single electron spectrum



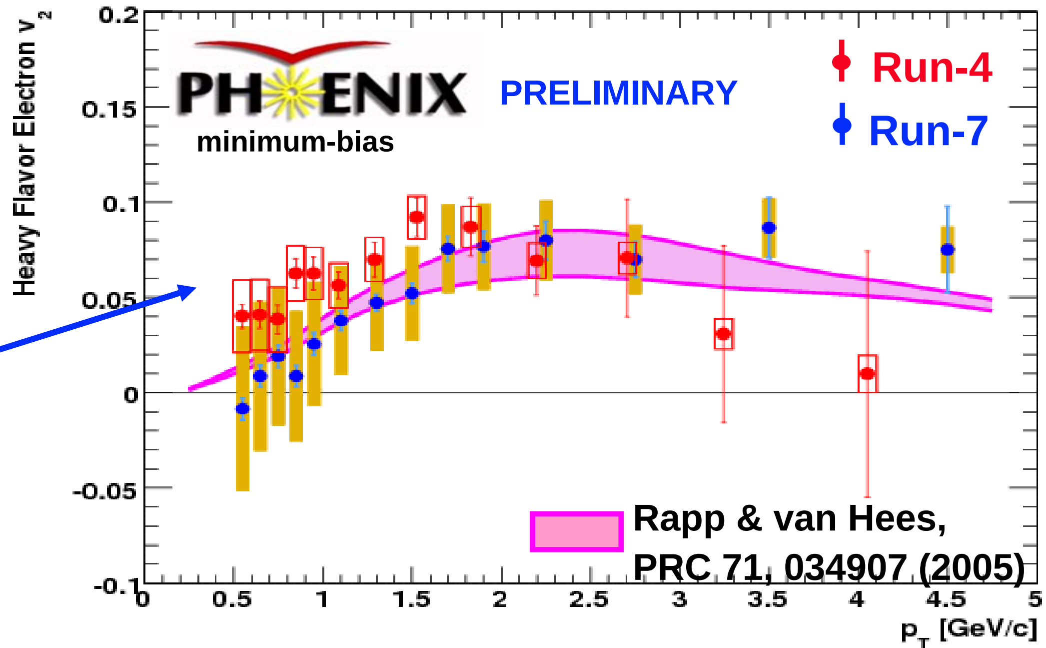
compare data to "cocktail" of hadronic decays

sufficient interaction to equilibrate??

- Like putting a rock in a stream and watching if the stream can drag it along…
- Measure correlation of $e^{\pm}$ with the light hadrons (i.e. v_2)
- NB: rate of equilibration gives information on the viscosity of the liquid!

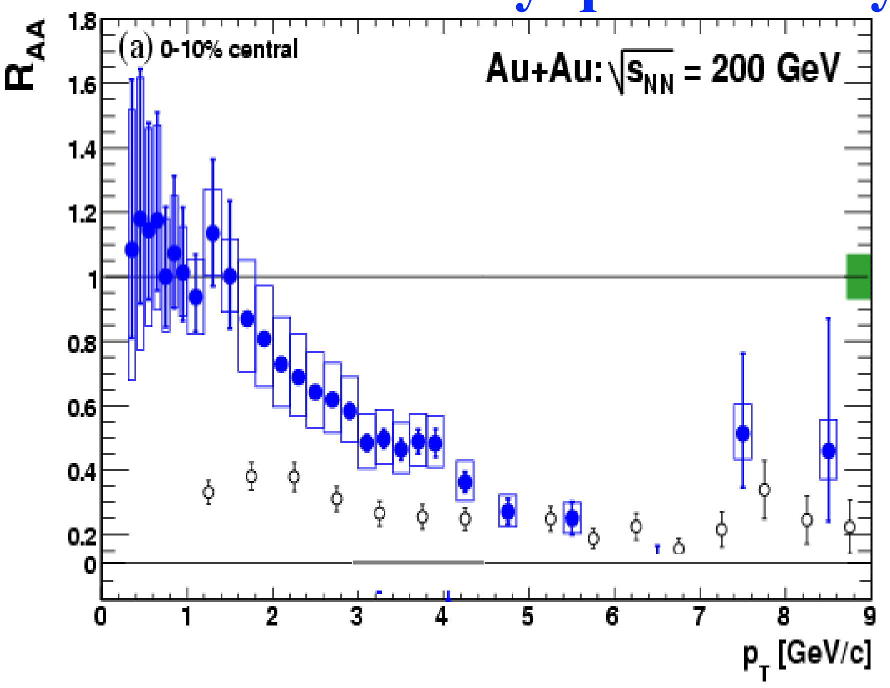
analogy from J. Nagle

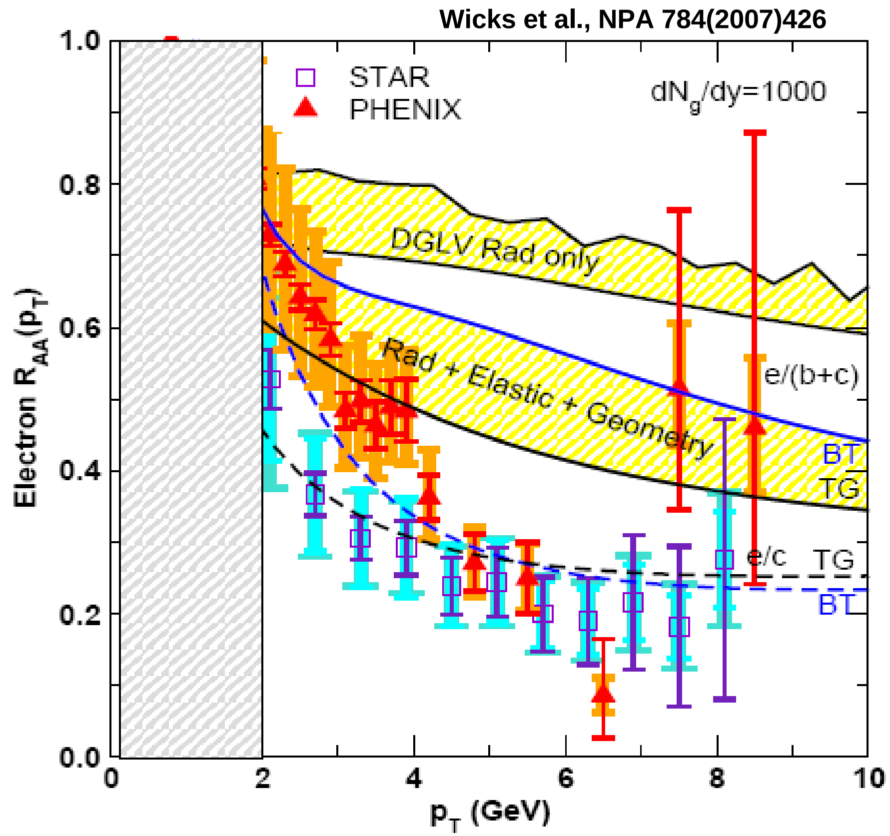
Heavy quarks do flow!!
Use to probe transport properties of QGP!



and heavy quarks lose substantial energy

e± from heavy quark decay





pQCD: energy loss dominantly bremsstrahlung (radiate gluons)

plasmas have collisions among constituents! including it helps

larger than expected scattering σ → stronger coupling

heavy quark transport: diffusion & viscosity

- **diffusion = brownian motion of particles**

  definition: flux density of particles J = -D grad n

  particle concentration

- **integrating over forward hemisphere:**

  D = diffusivity = 1/3 <v> λ

  so D = <v>/ 3nσ *λ = mean free path*

D ∝ collision time, determines relaxation time

Langevin: equation of motion for diffusion thru a medium

drag force ↔ random force ↔ $\langle \Delta p_T^2 \rangle$/unit time ↔ D*

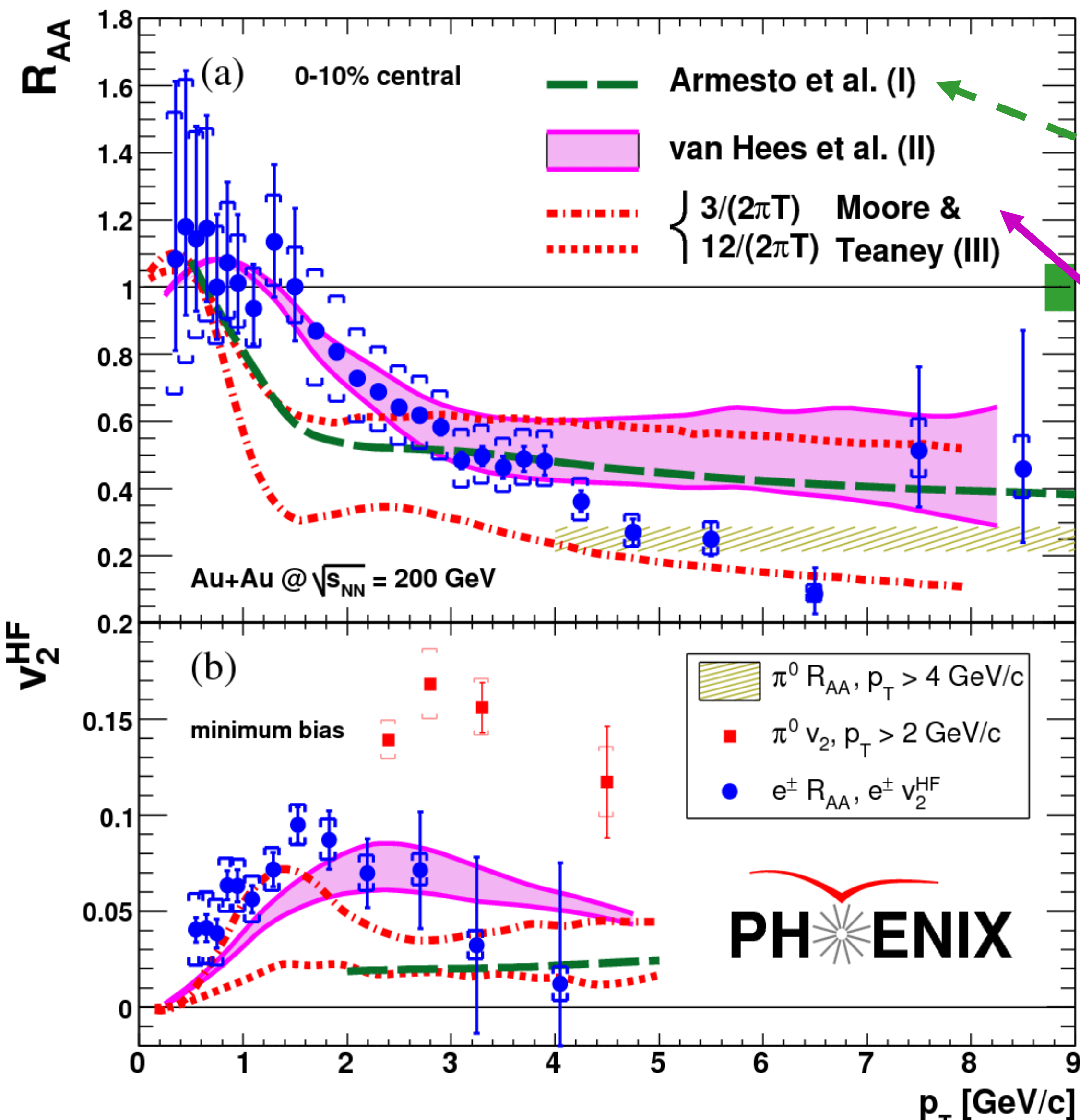
note: viscosity is ability to transport momentum

η = 1/3 ρ <v> λ so D = η/ρ ~ η/S → measure D get η!

** G. Moore and D. Teaney, hep-ph/0412346*

confronting mechanisms with data

PRL98, 172301 (2007)



Radiative energy loss alone: fails to reproduce v_2

Heavy quark transport model (i.e. diffusion) shows better agreement with R_{AA} and v_2

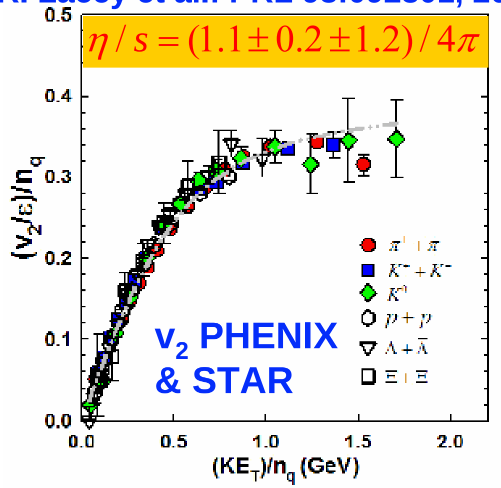
Though agreement with data is so-so, slow relaxation ruled out by v_2

***D ~ 4-6/(2πT)* for charm**

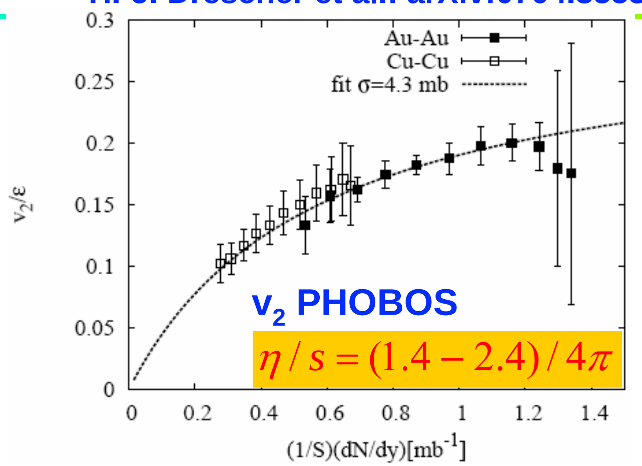
$\eta/S = (1.3 – 2.0)/ 4\pi$

Comparison with other estimates

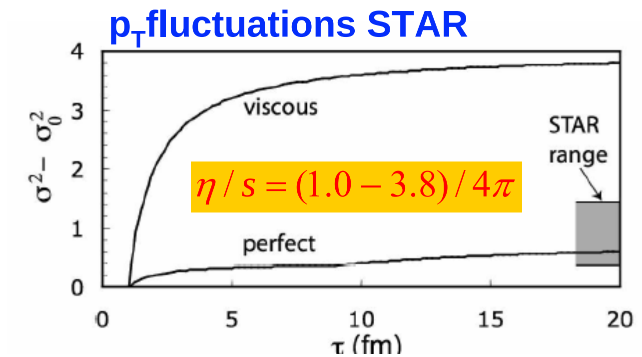
R. Lacey et al.: PRL 98:092301, 2007



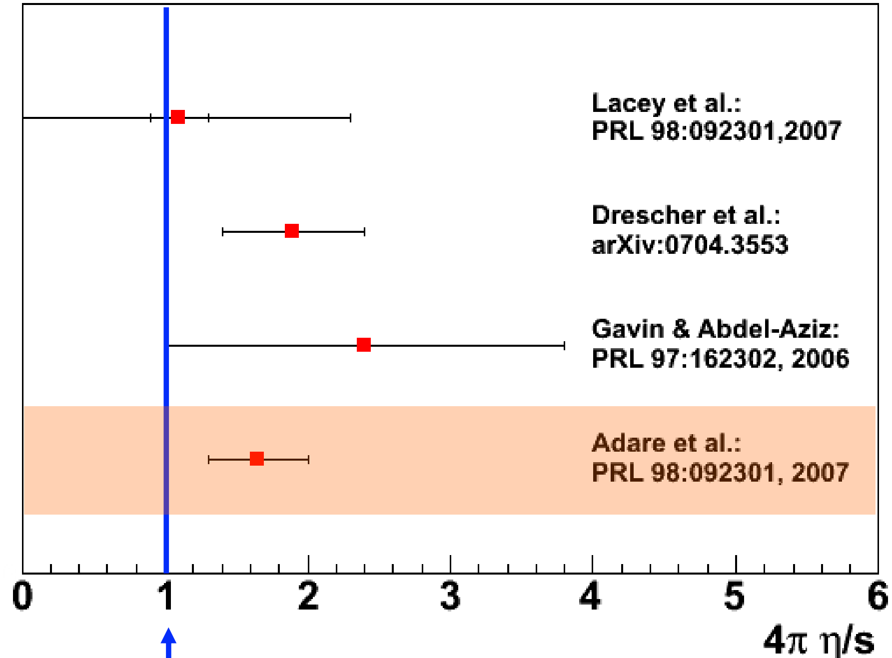
H.-J. Drescher et al.: arXiv:0704.3553



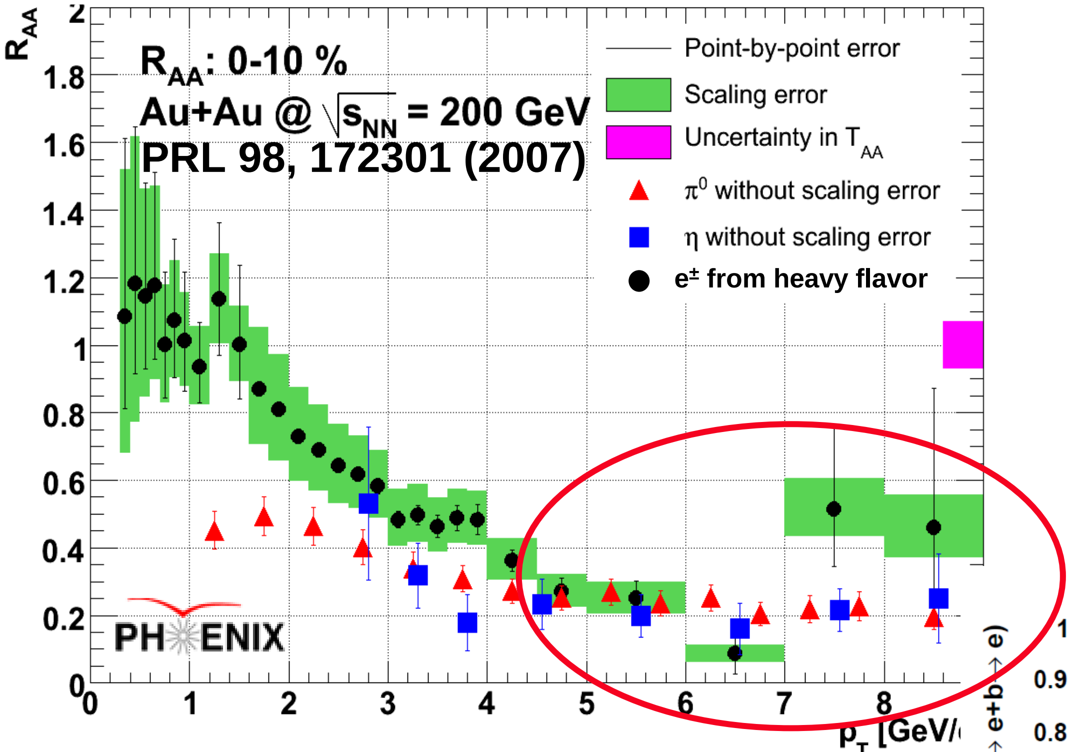
S. Gavin and M. Abdel-Aziz: PRL 97:162302, 2006



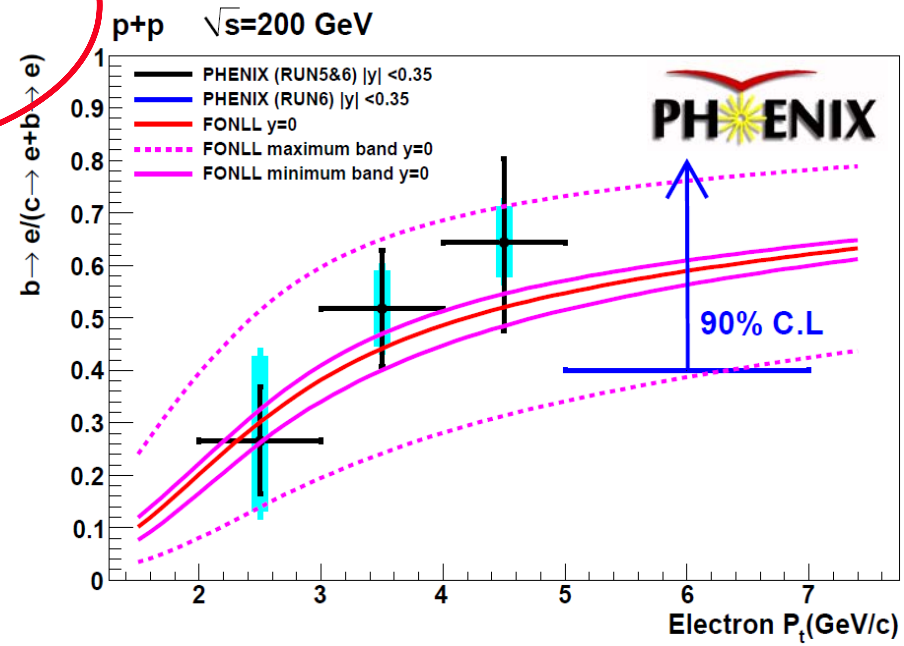
- estimates of η/s based on flow and fluctuation data
  - indicate small value as well
  - close to conjectured limit
  - significantly below η/s of helium (4πη/s ~ 9)



What about b quarks?



b quark contribution to single electrons becomes significant. do they also lose energy?



Conclusions

- Enhanced dileptons and photons (also at lower √s at SPS)
  soft but no flow; hadronic??
  need to constrain $T_{initial}$!
- Energy loss is large. Mechanism & magnitude??

PQM	GLV	WHDG	ZOWW
$\hat{q} = 13.2^{+2.1}_{-3.2}$ GeV^2/fm	$dN^g/dy = 1400^{+270}_{-150}$	$dN^g/dy = 1400^{+200}_{-540}$	$\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm^3

  and/or $\alpha_s \sim 0.27$
- Deposited energy shocks the medium. Mach cones?
  $c_s \sim (0.35 – 0.4)$ c (closer to hadron gas than QGP)
  expected diffusion wake AWOL (baryon enhancement?)
- Heavy quark diffusion, hadron v_2, fluctuations →viscosity
  $\eta/S = (1 – 3)/ 4\pi$ close to conjectured bound
- First hint of b decays, maybe not gobbled up by medium?

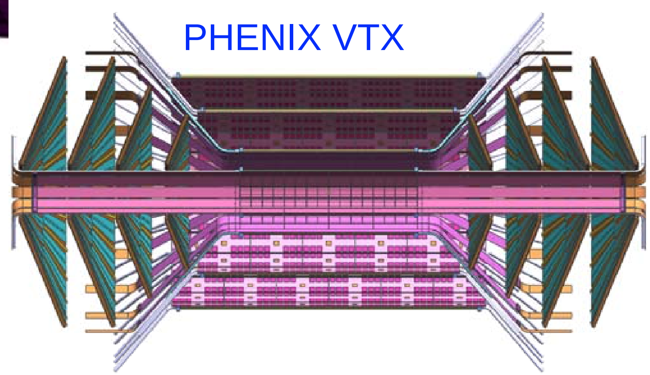
Impact on cosmological models

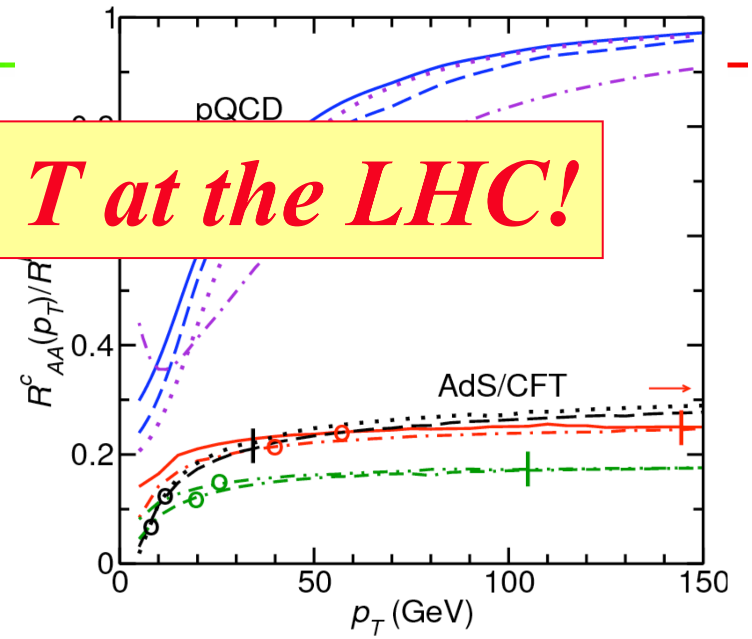
- ??
- How does the strong coupling affect evolution?
- Do we care about fluctuations and correlations after inflation??

for further (experimental) progress

Si vertex detectors

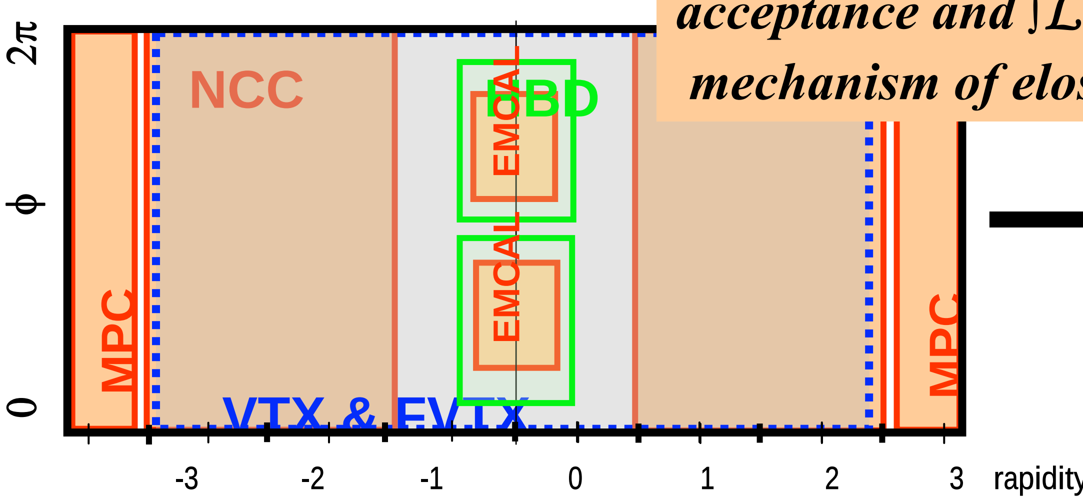
STAR HFT

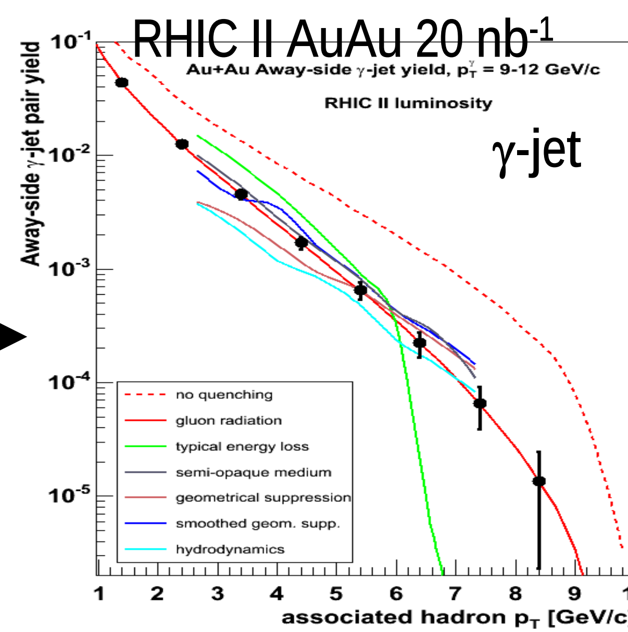




and do it again at higher T at the LHC!

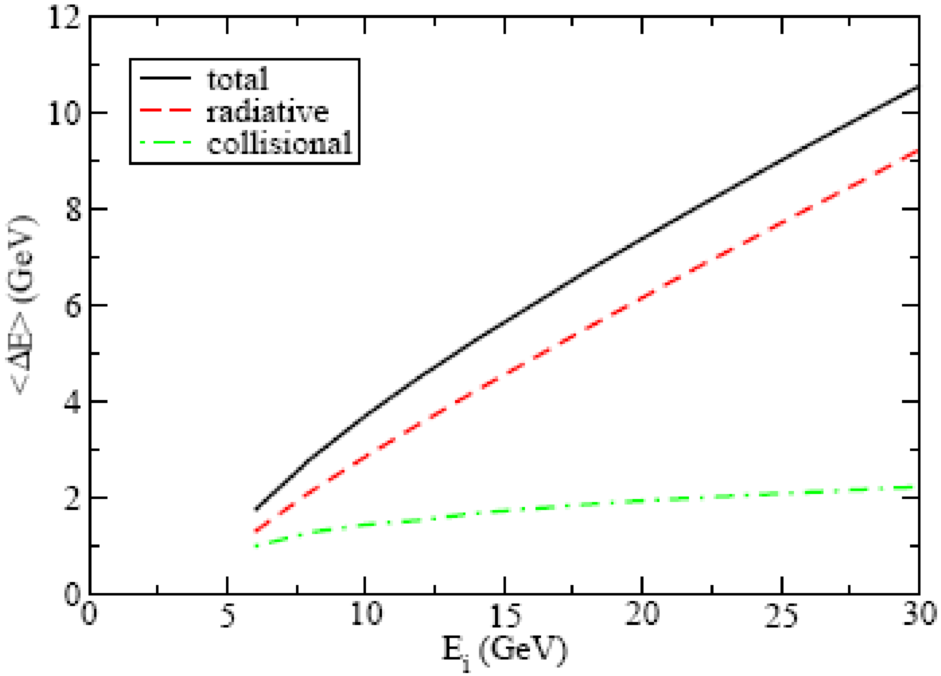
acceptance and ∫ℒ
mechanism of eloss



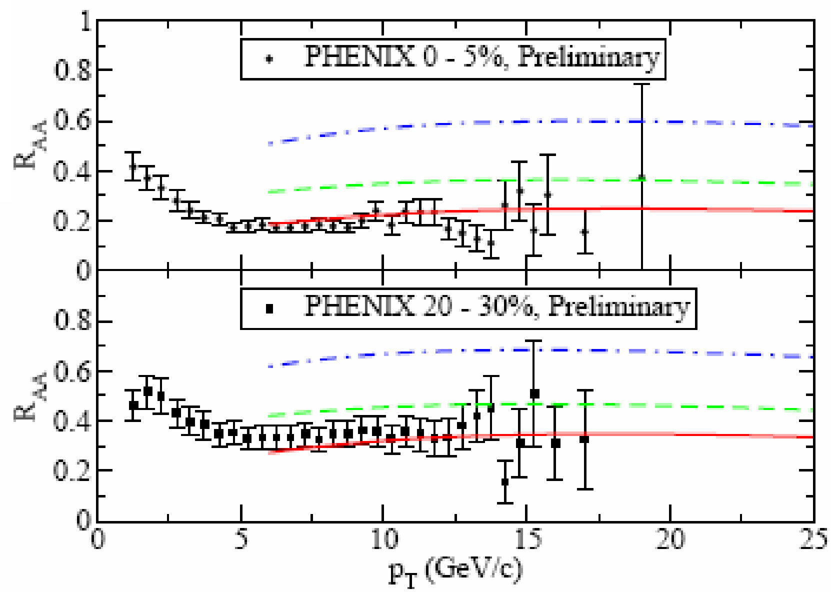


- **backup slides**

LPM effect up to $\mathcal{O}(g_s)$ + (3+1)d hydro + collisions



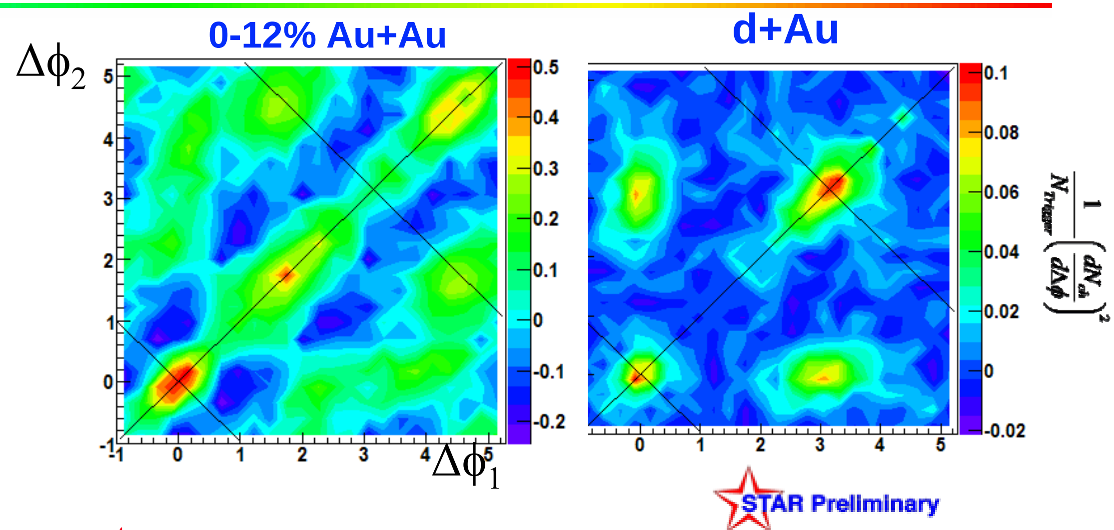
Qin, Ruppert, Gale, Jeon, Moore and Mustafa, 0710.0605



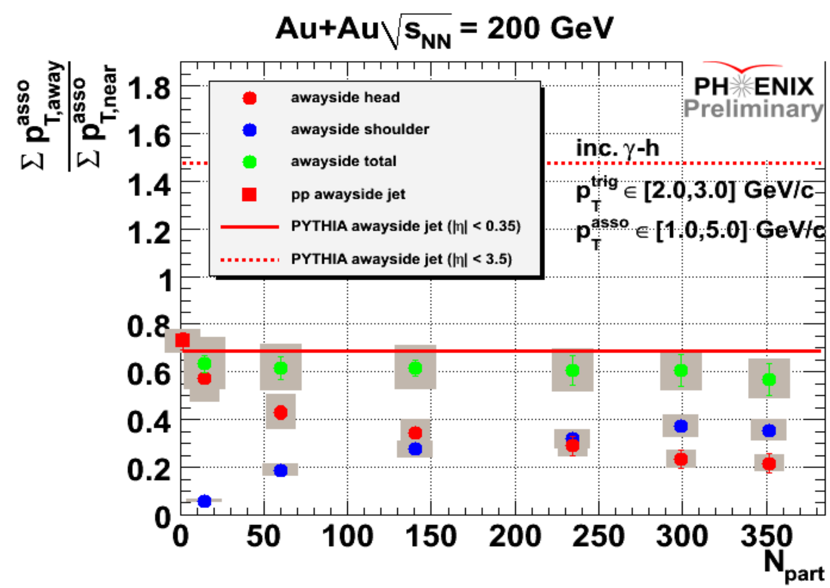
Fix initial state by constraining hydro with particle spectra
Reproduce observed energy loss vs. centrality using $\alpha_s = 0.27$

more complex jet fragment measurements

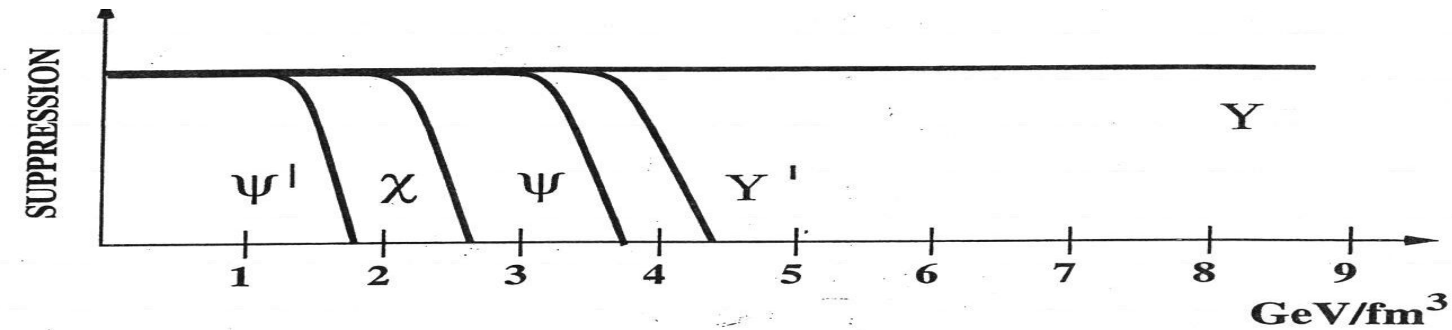
- 3 – particle correlations consistent with Mach-cone shoulder

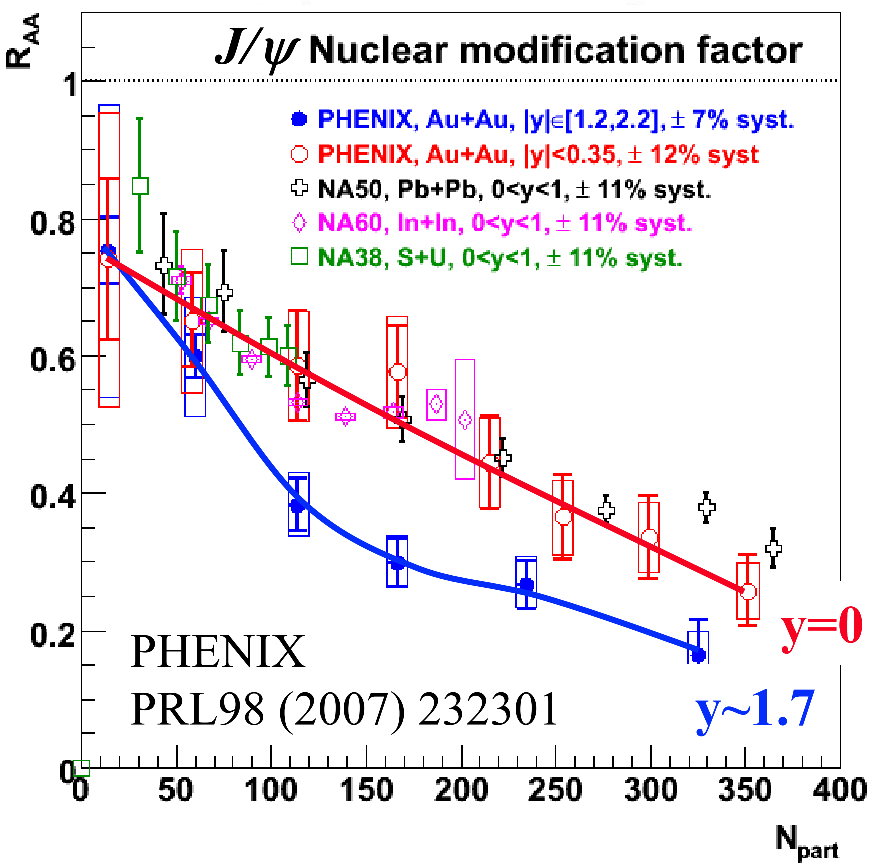


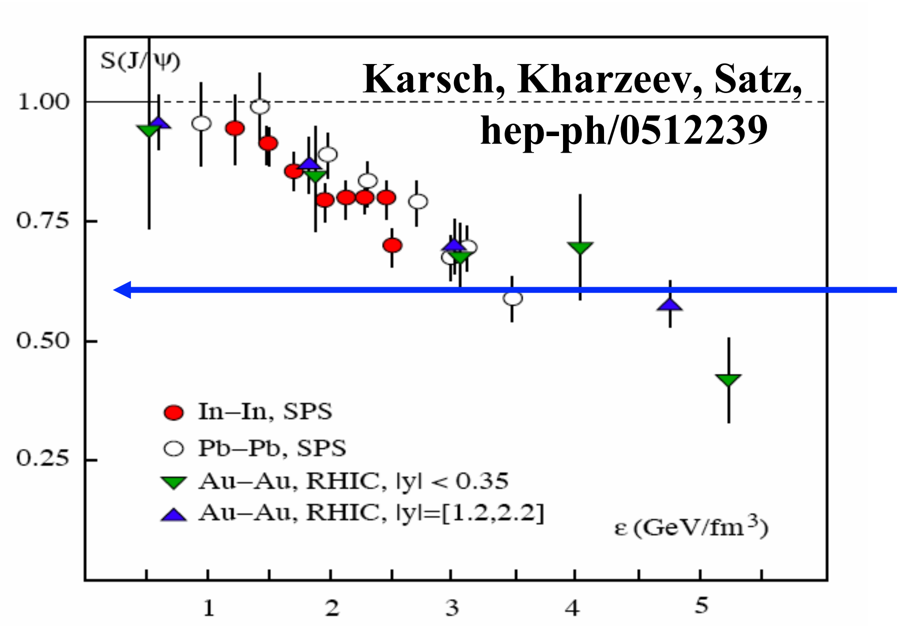
- sum of jet fragment momentum
  - increases together on trigger and away sides
  - momentum loss in punch-thru jet balanced by momentum in the shoulder peak
  - evidence for wakes?



screening length: onium spectroscopy





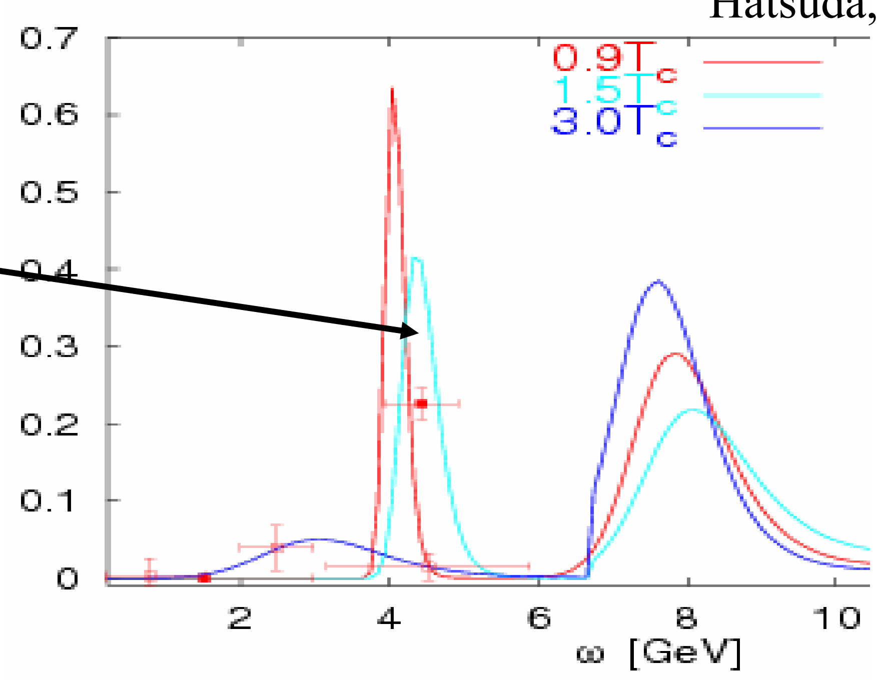


40% of J/ψ from χ and ψ' decays they are screened but direct J/ψ not?

what does non-perturbative QCD say?

Hatsuda, et al.

Lattice QCD shows heavy $q\bar{q}$ correlations at $T > T_c$, also implying that interactions are not zero



Big debate ongoing whether these are resonant states, or "merely" some interactions

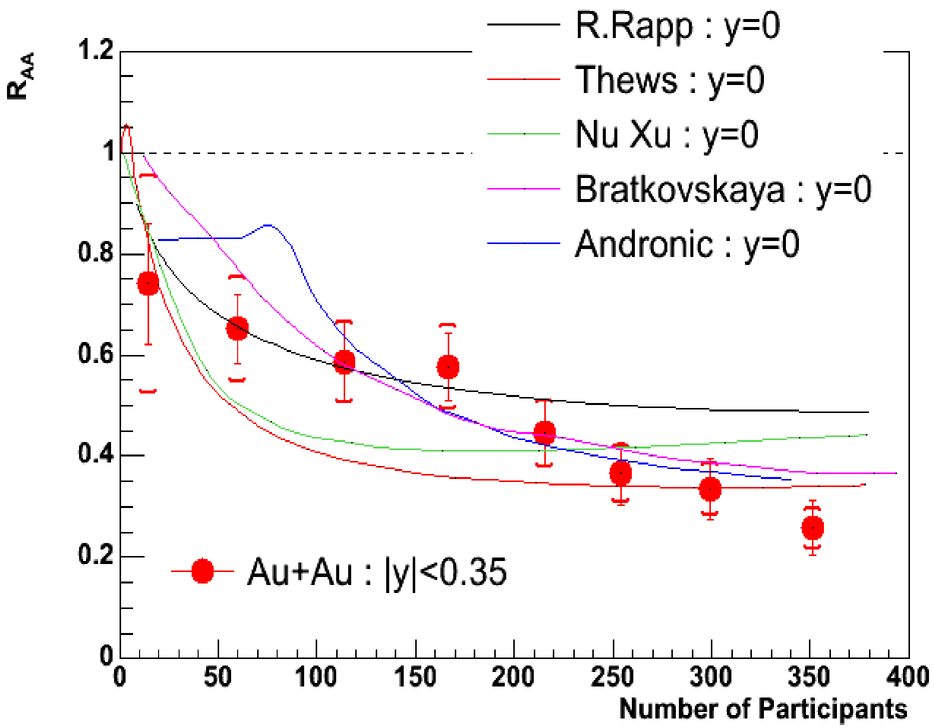
Color screening – yes!
but not fully…
Some J/ψ may emerge intact

J/ψ is a mystery at the moment!

Others may form in final state if c and cbar find each other

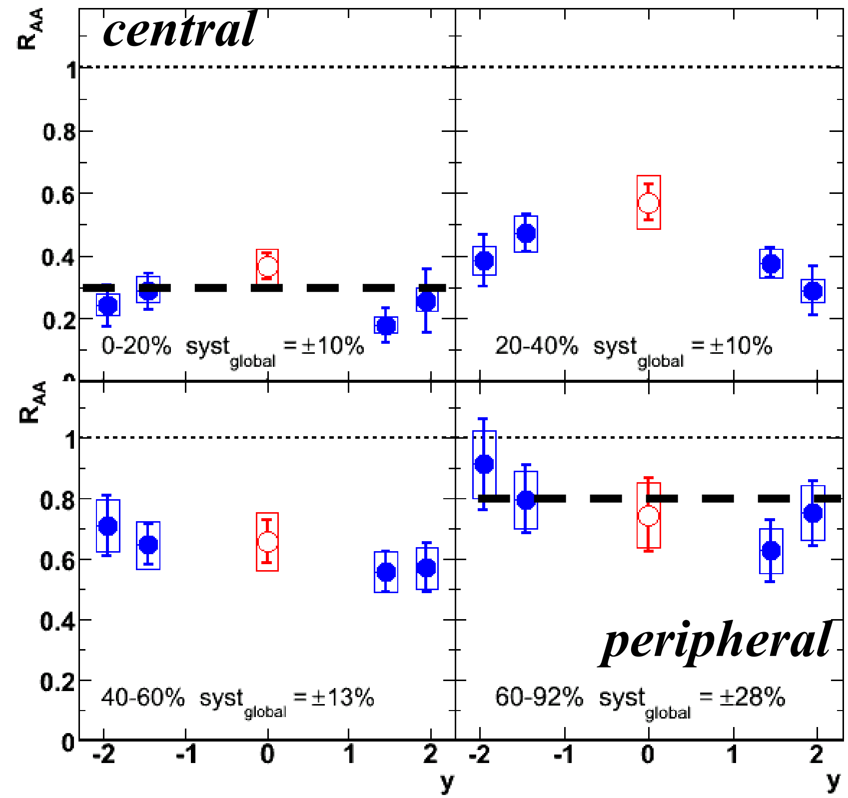
are J/ψ's regenerated late in the collision?

$c + \bar{c}$ coalesce at freezeout → J/ψ



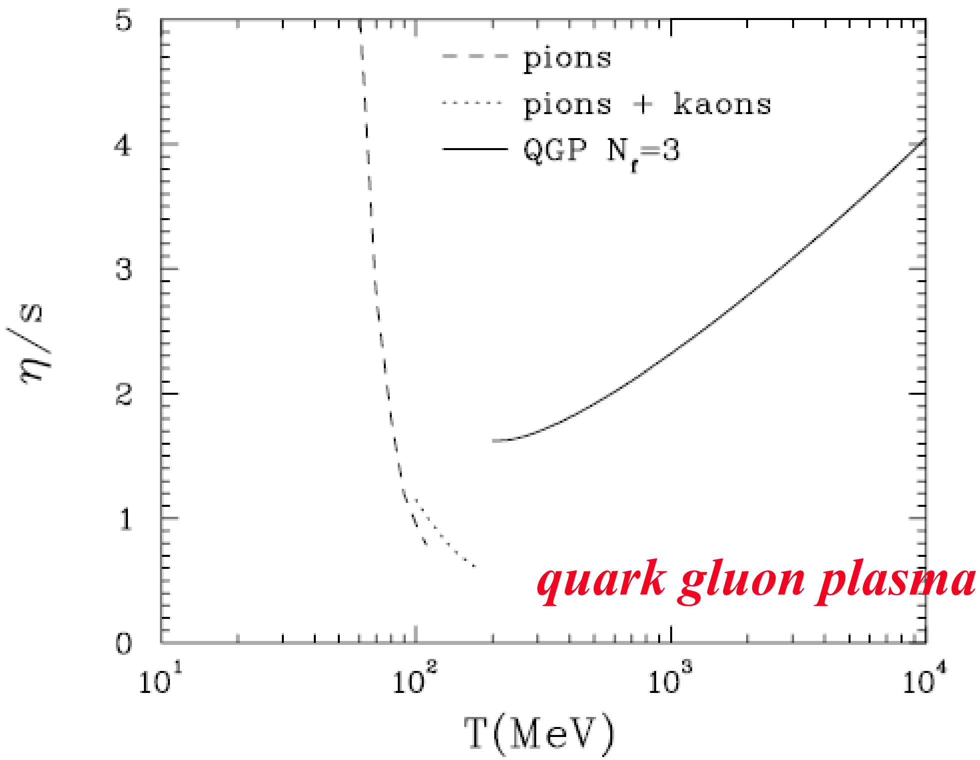
R. Rapp et al.PRL 92, 212301 (2004)
R. Thews et al, Eur. Phys. J C43, 97 (2005)
Yan, Zhuang, Xu, PRL97, 232301 (2006)
Bratkovskaya et al., PRC 69, 054903 (2004)
A. Andronic et al., NPA789, 334 (2007)

should narrow rapidity dist.
… does it?



J/ψ is a mystery at the moment!

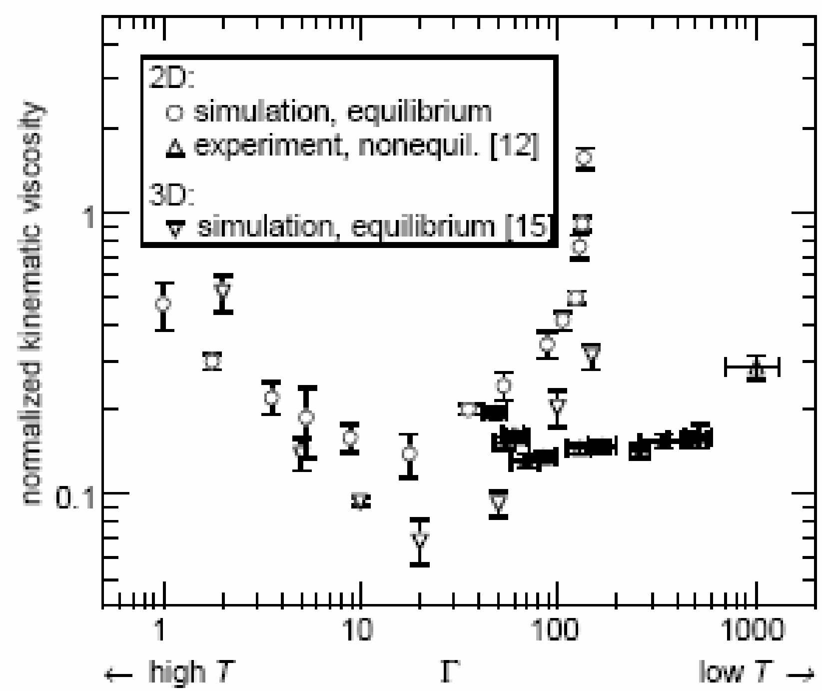
minimum η at phase boundary?



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

calculating transport in QGP

<u>weak coupling limit</u>

perturbative QCD

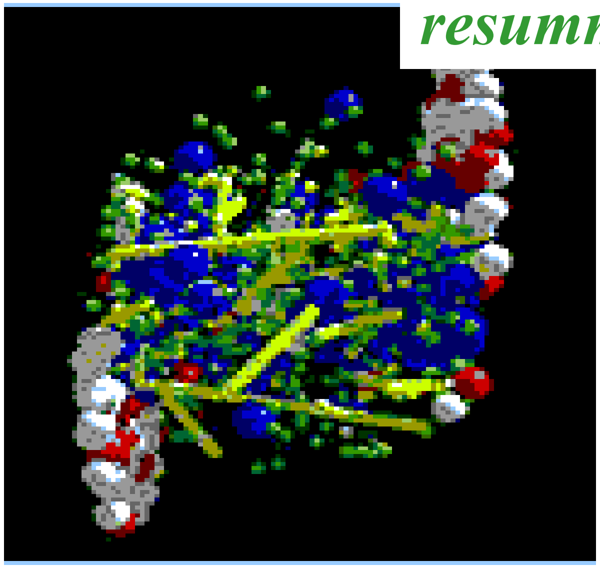
kinetic theory, cascades

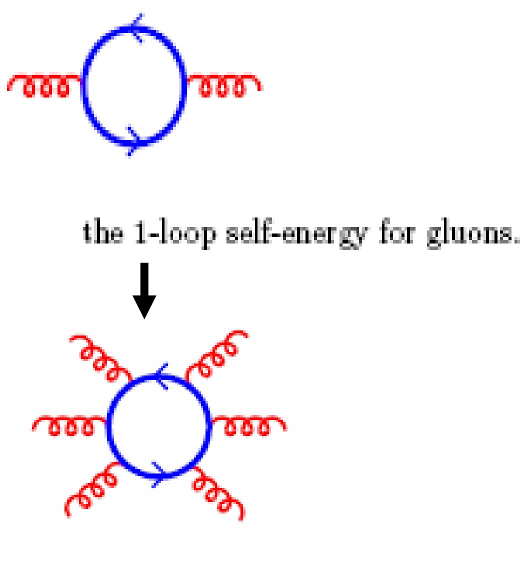
<u>strong coupling limit</u>

not so easy!

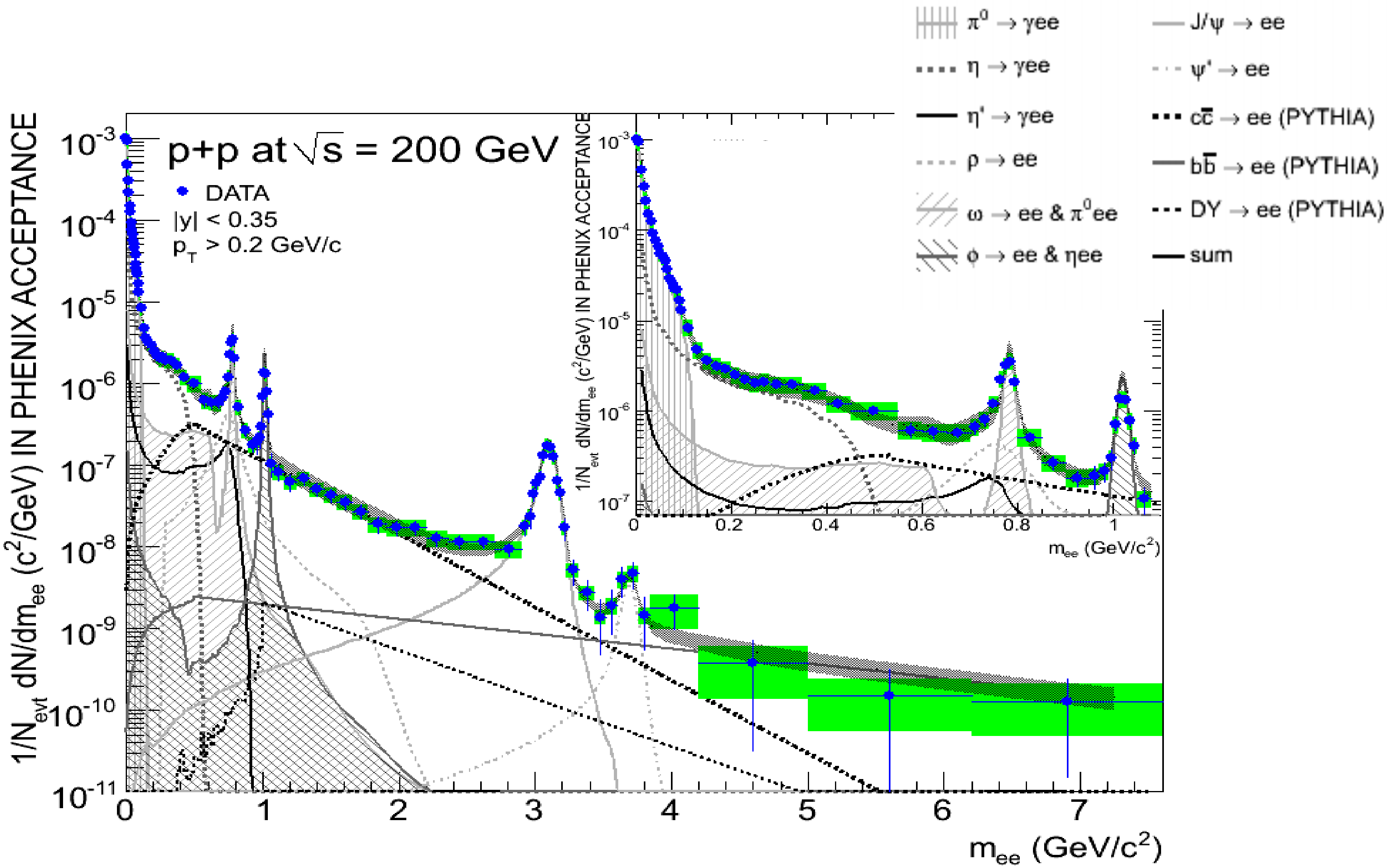
gravity ↔ supersym 4-d QCD-like theory

resummation of hard thermal loops

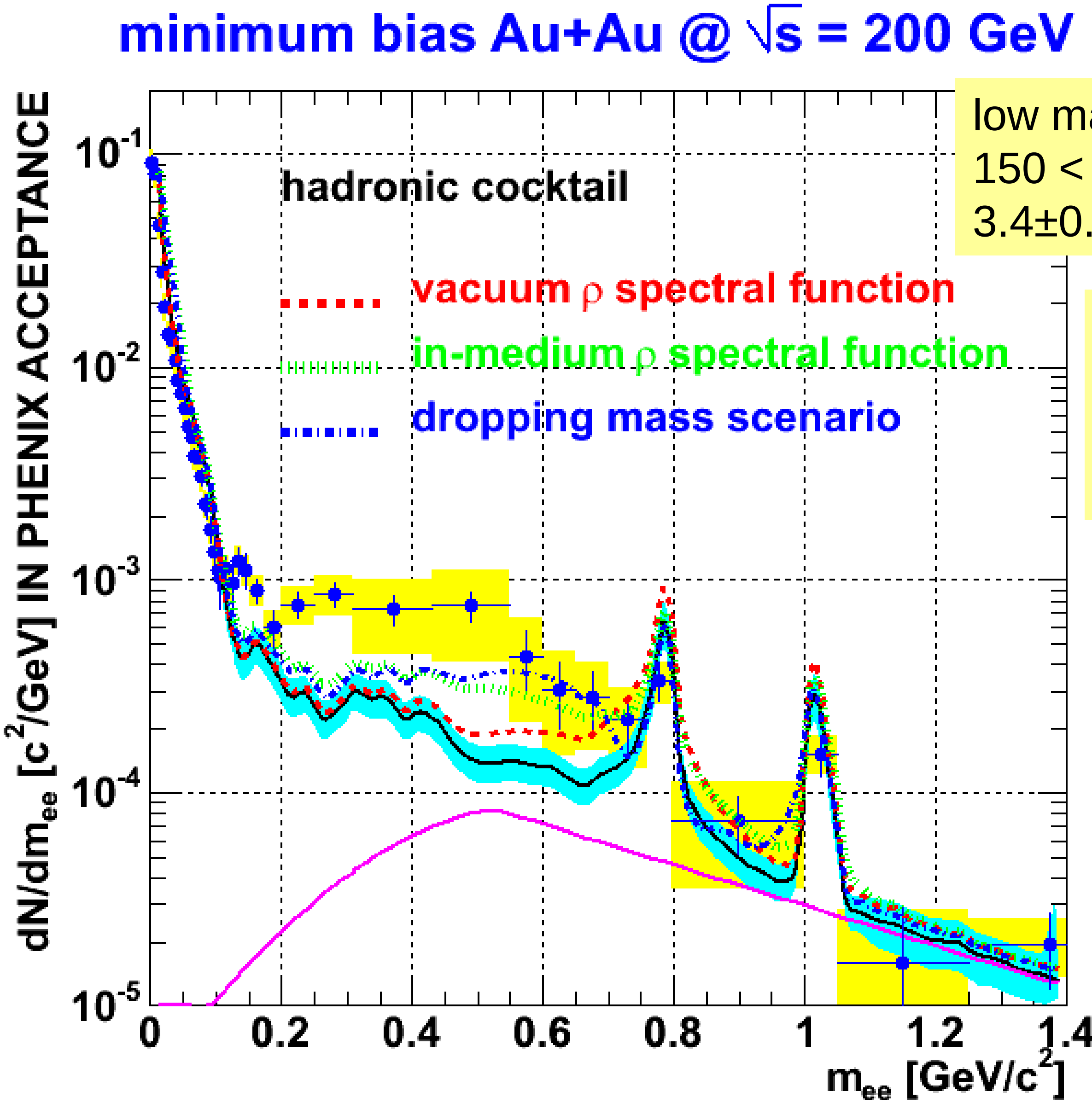




dielectron spectrum vs. hadronic cocktail



Comparison with conventional theory

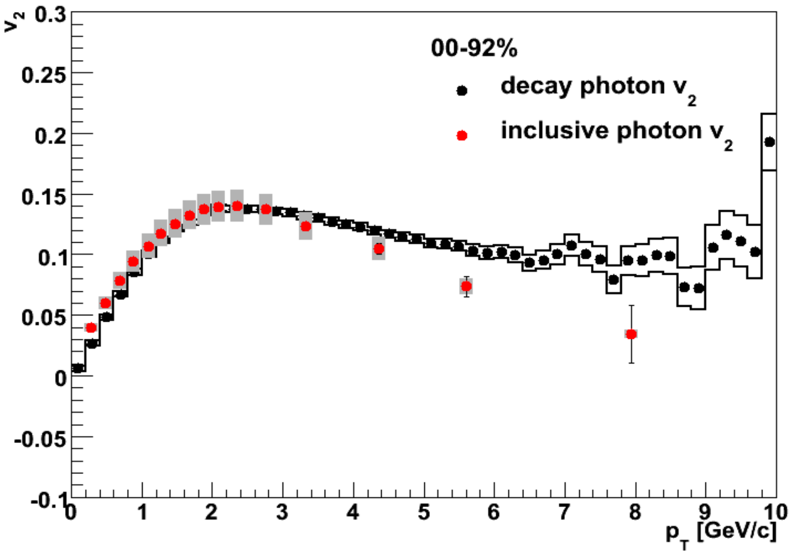


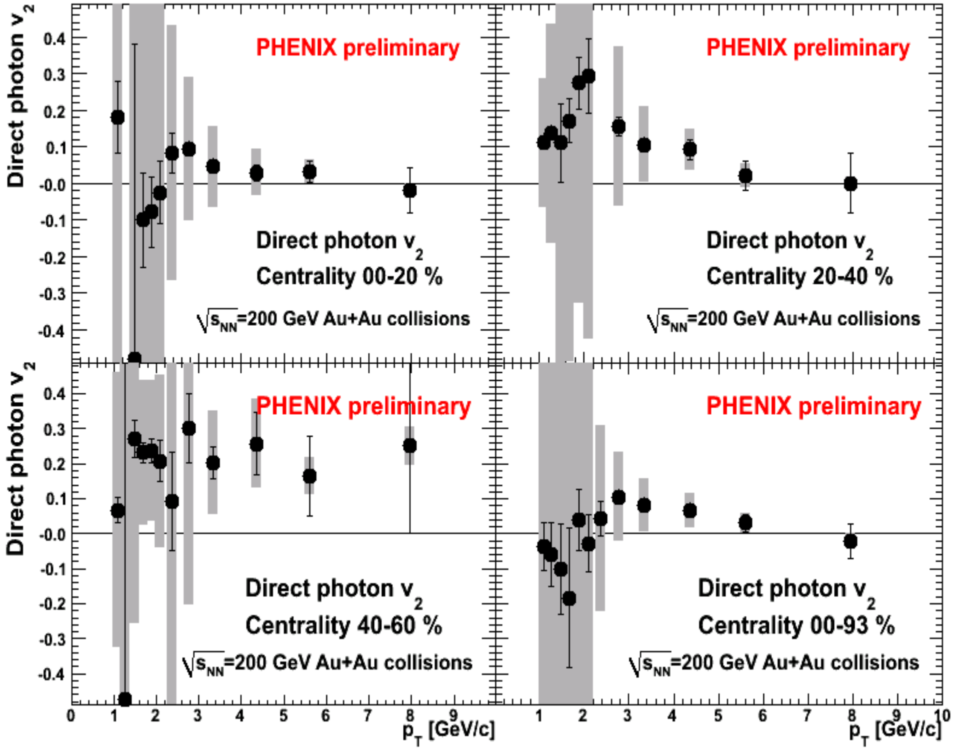
low mass enhancement at
$150 < m_{ee} < 750$ MeV
3.4±0.2(stat.) ±1.3(syst.)±0.7(model)

calculations: min bias Au+Au
they include:
QGP thermal radiation
chiral symmetry restoration

R.Rapp, Phys.Lett. B 473 (2000)
R.Rapp, Phys.Rev.C 63 (2001)
R.Rapp, nucl/th/0204003

Direct photon v_2





$$v_2^{dir.photon} = \frac{R * v_2^{inc photon} - v_2^{BG\_photon}}{R-1}$$


i'm in ur fizx lab
testn ur string therry