New Results from RHIC

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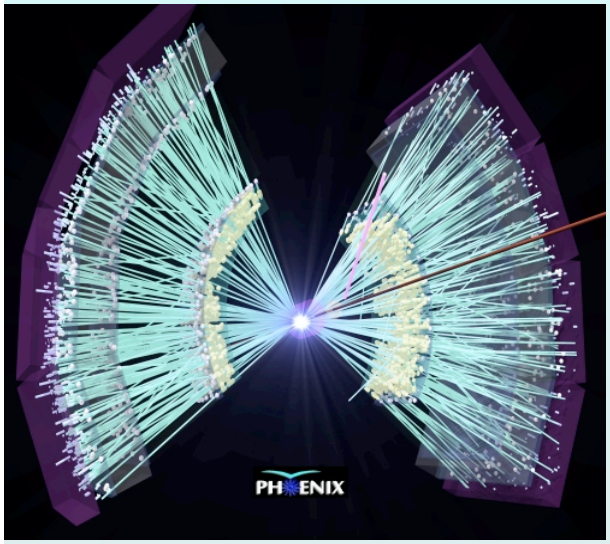
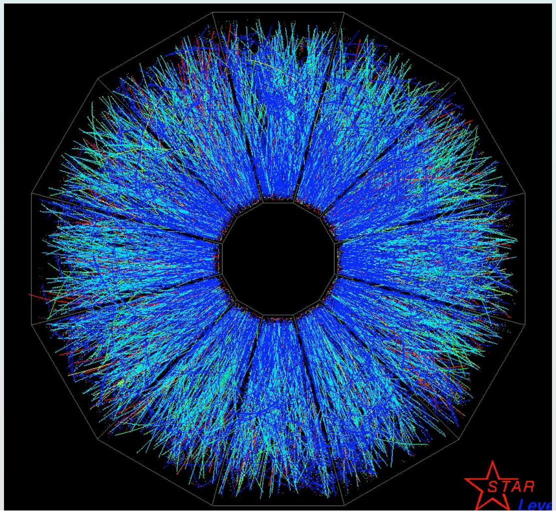
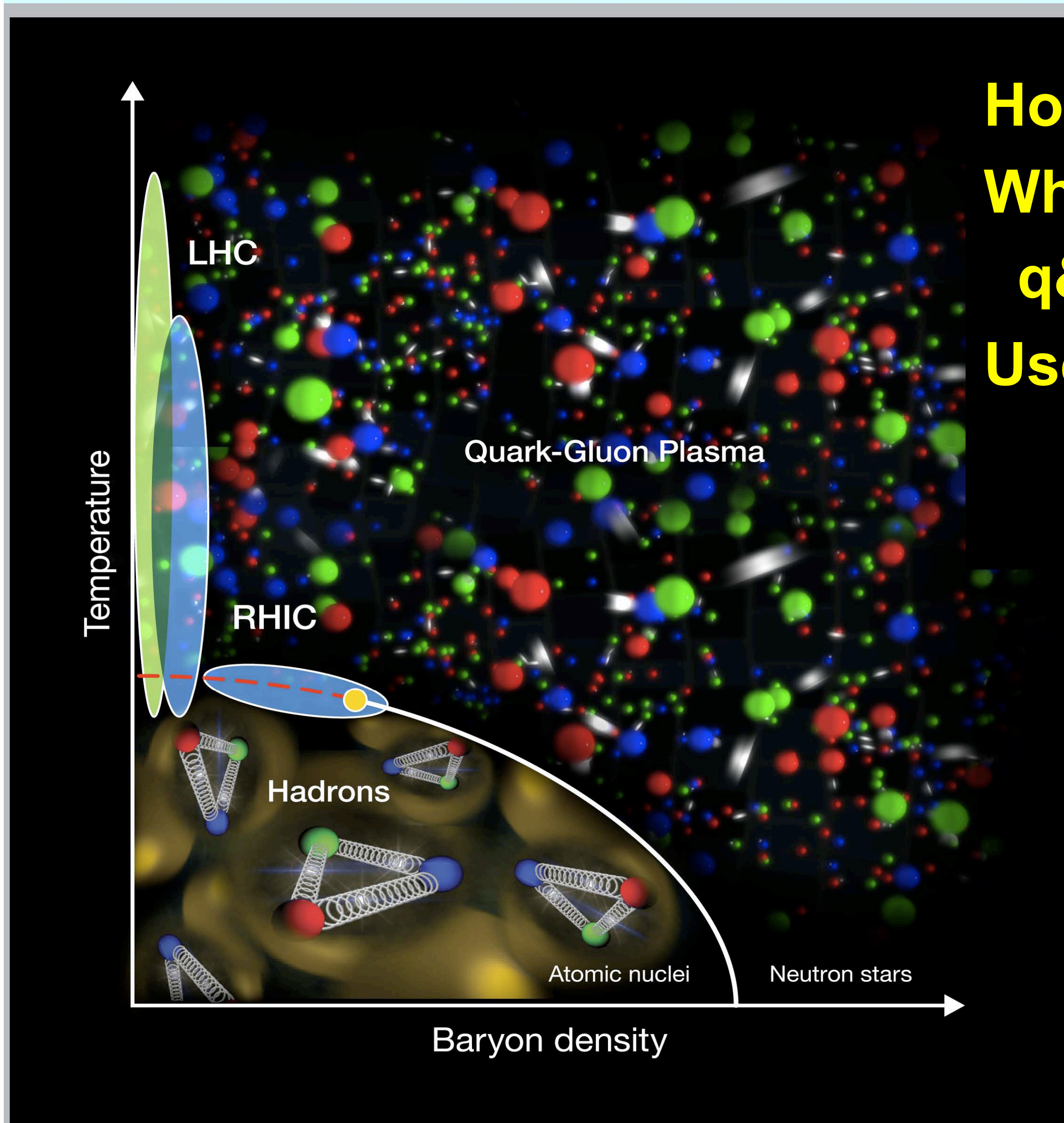


Erice School on Nuclear Physics

Sept. 17, 2012



Create the hottest matter on earth



How does it work?

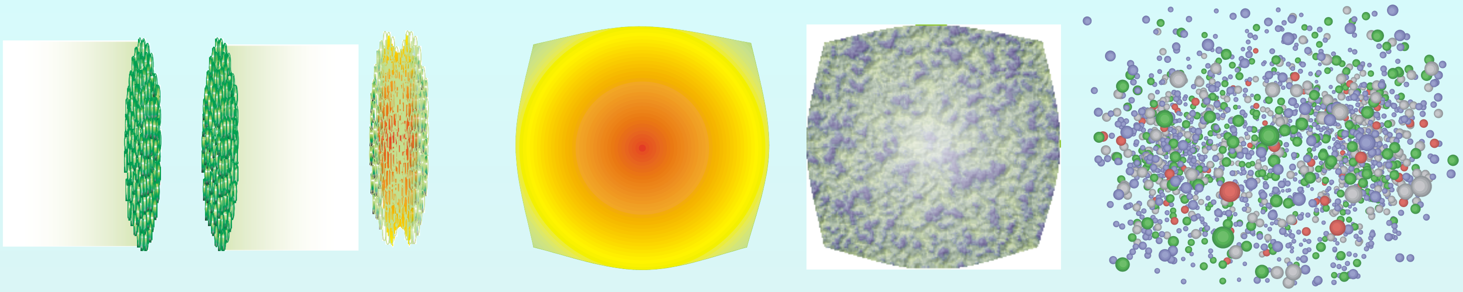
What's actually inside?

q&g or pure fields or?

Use RHIC & LHC together to figure out via T dependence

NB: Nu Xu will lecture on beam energy scan to study phase diagraom

RHIC news vs. time in the collision



Initial State Effects

γ_{dir}

jet & π^0 R_{dA}

J/ψ, ψ' R_{dA}

QGP properties

π^0 R_{AA}

γ_{dir}–h

Heavy q R_{AA}

J/ψ, Υ R_{AA}

Expansion & flow

N_{quark} scaling

U+U, Cu+Au

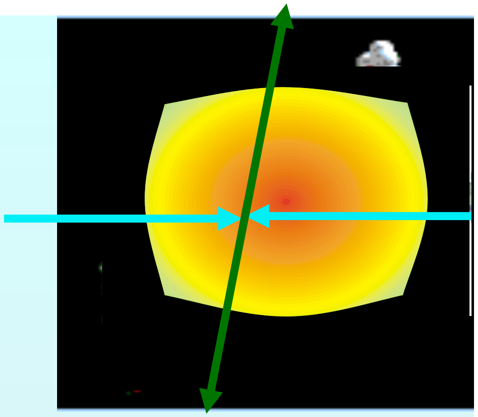
v_1, v_3, etc.

Hadron gas + final state effects

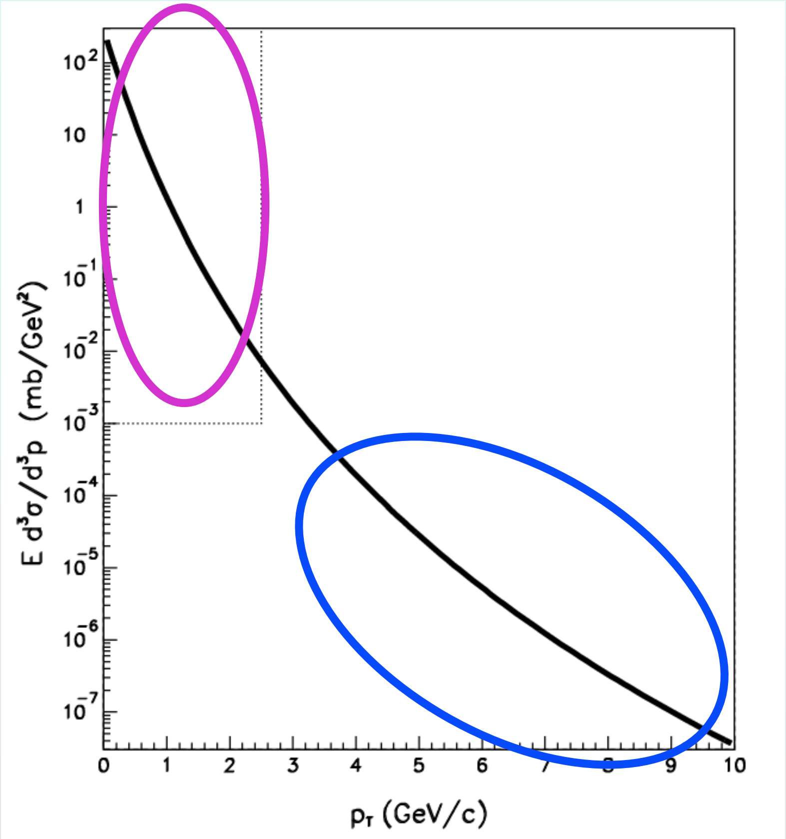
e^+e^-

J/ψ v_2

study plasma with radiated & "probe" particles

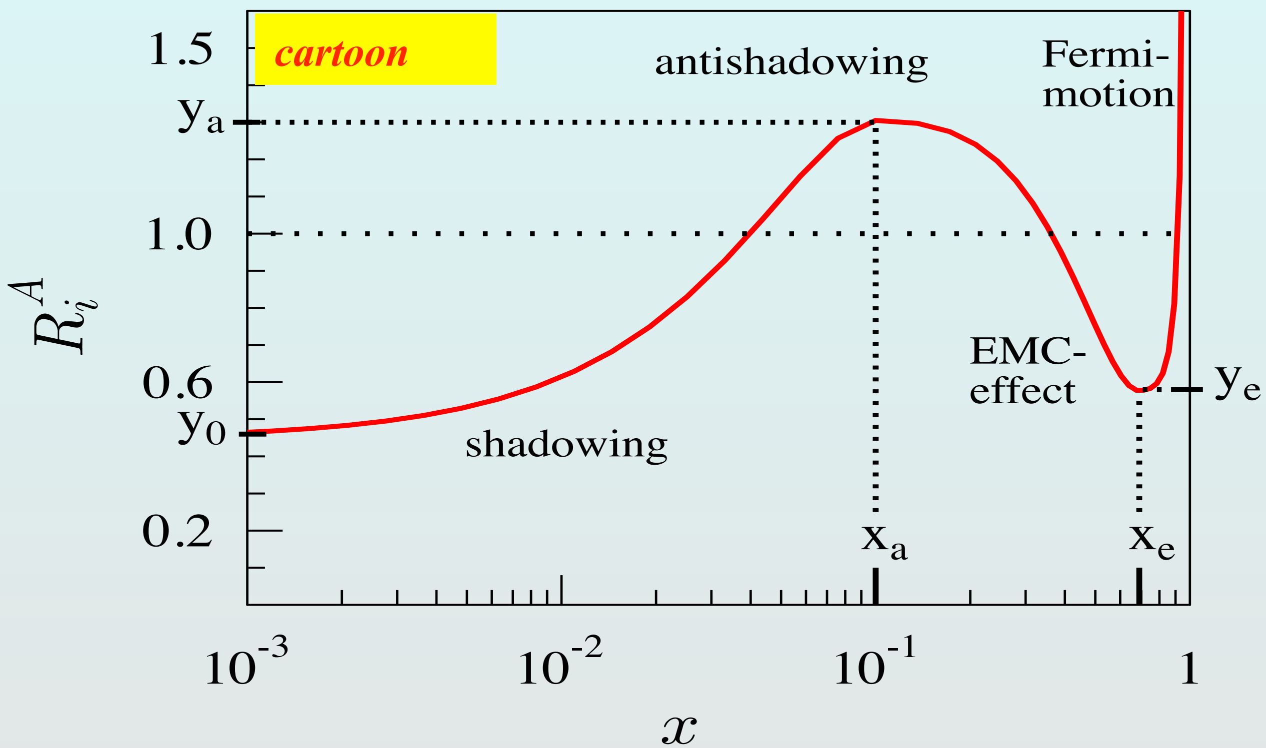


- as a function of transverse momentum
  - 90° is where the action is (max T, ρ)
    - p_L between the two beams: midrapidity
- p_T < 1.5 GeV/c
  - "thermal" particles
  - radiated from bulk medium
  - "internal" plasma probes
- p_T > 3 GeV/c
  - large E_{tot} (high p_T or M)
    - set scale other than T(plasma)
  - autogenerated "external" probe
  - describe by perturbative QCD
- control probe: photons
  - EM, not strong interaction
  - produced in Au+Au by QCD
    - Compton scattering



INITIAL STATE EFFECTS

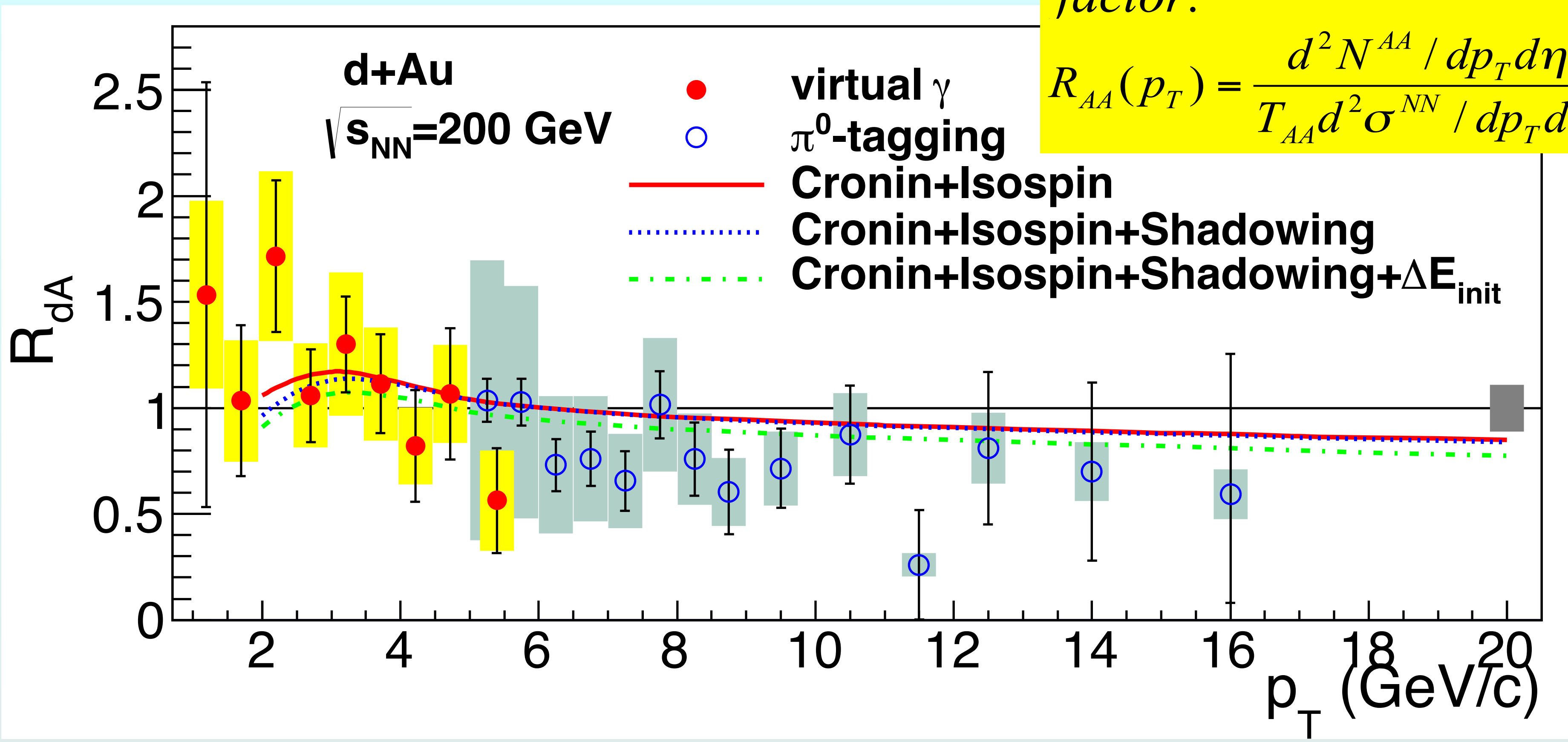
Formation of these probes is affected by the fact the struck partons are in nucleons bound in a nucleus



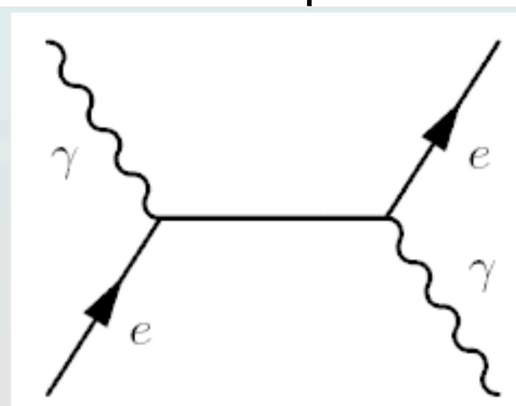
Hard probes in d+Au: γ_{direct}

Nuclear modification factor:

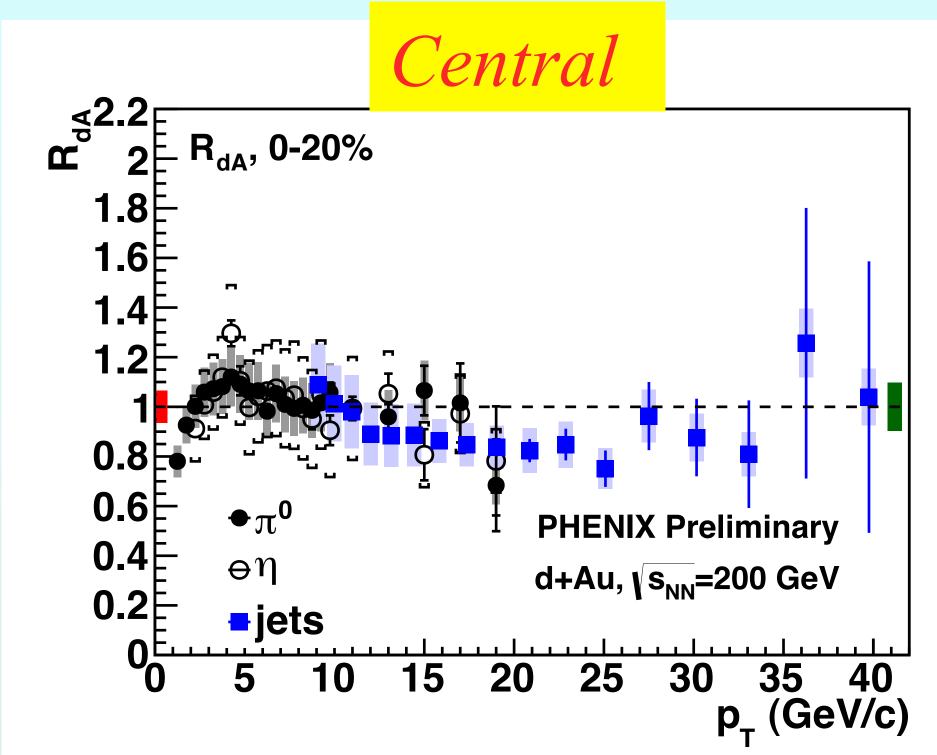
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

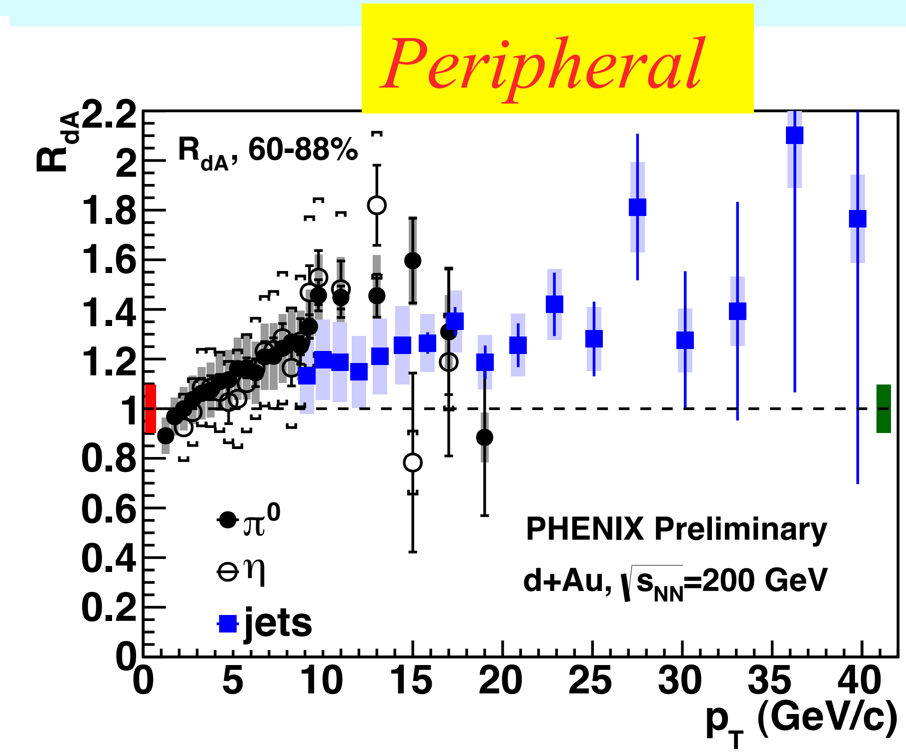


- No modification of direct photons in initial hard scattering and PDF compared to p+p at mid-rapidity



Suprising behavior of jets



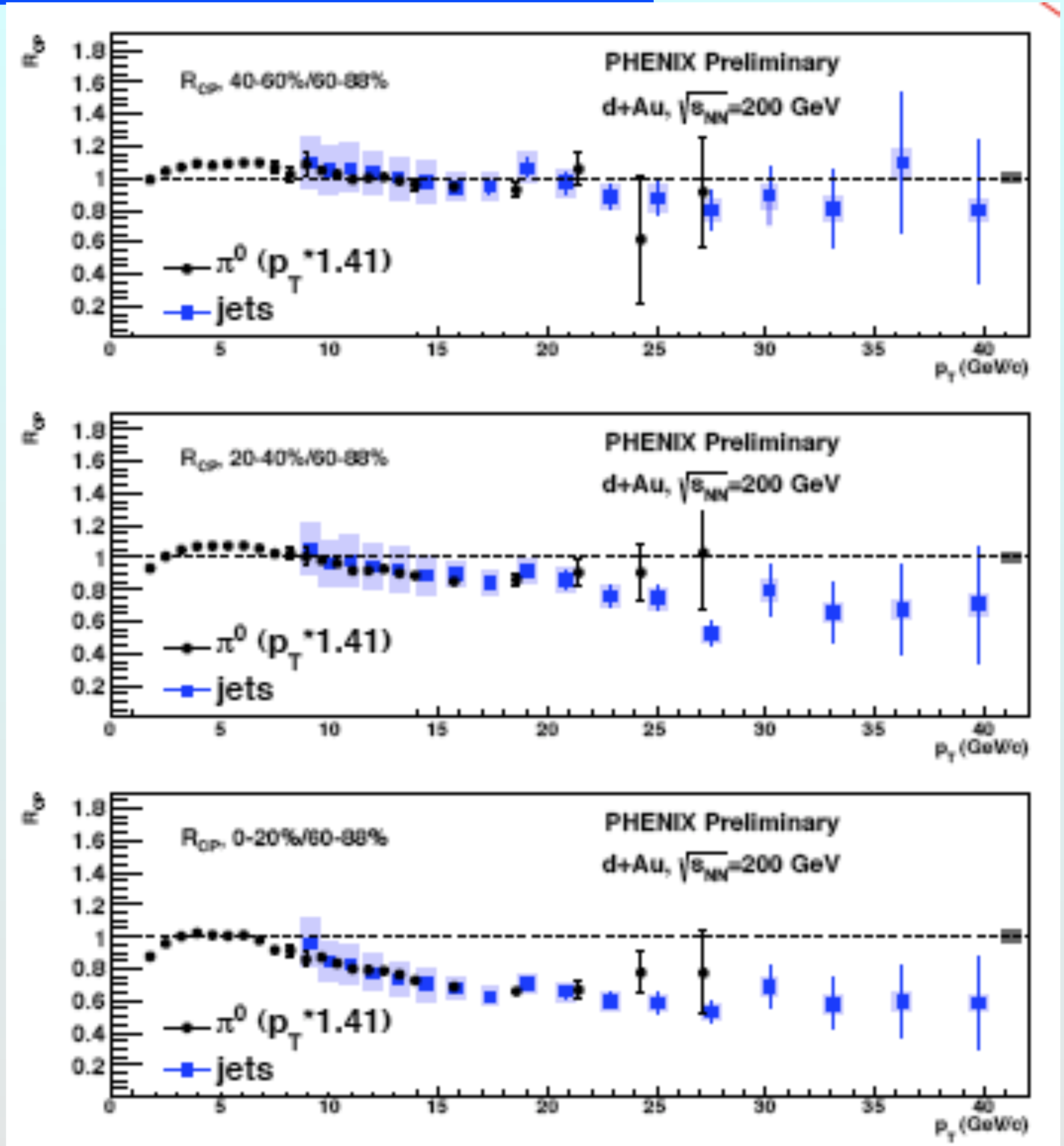


- Do not expect such a strong centrality dependence to the nuclear PDFs
- Under intense investigation!

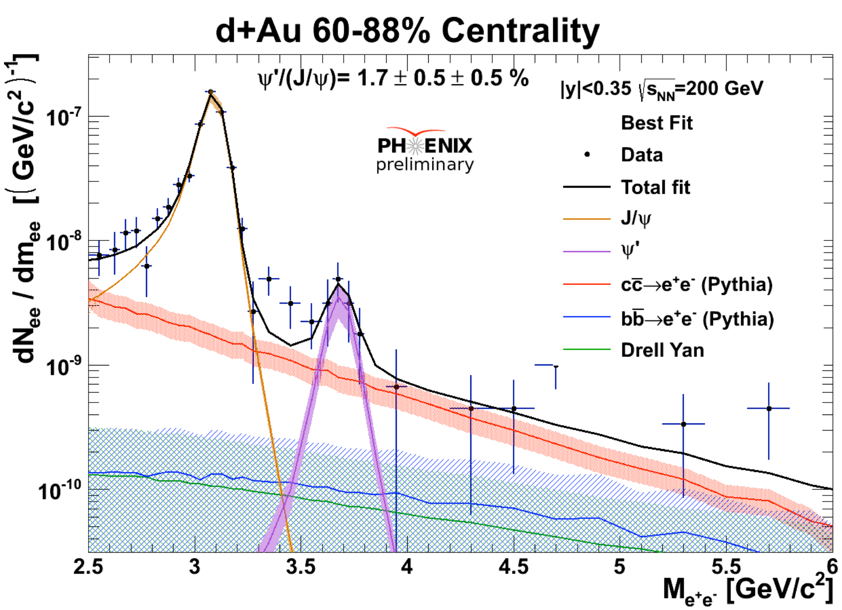
Do the π^0 and jets agree?

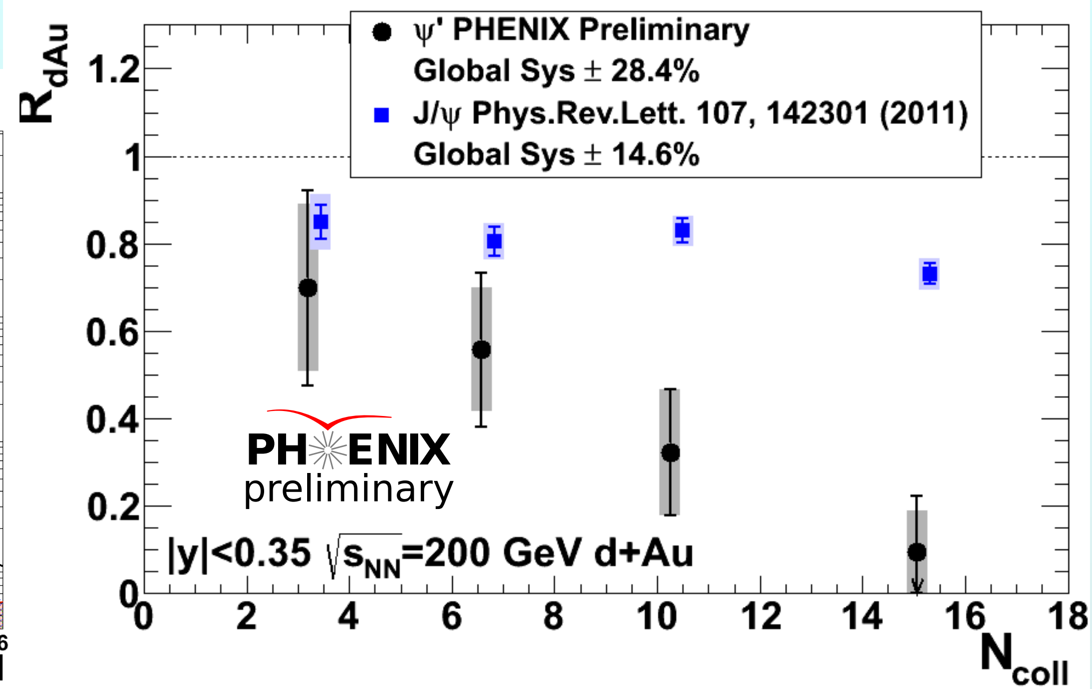
- Scale π^0 by 1/0.7 i.e. $1/\langle Z_{leading} \rangle$
- Agreement is excellent
- R_{cp} shows strong centrality dependence

Might the presence of a jet with p_T>10 GeV/c modify definition of a "peripheral d+Au collision"?



Initial state effects on charmonium

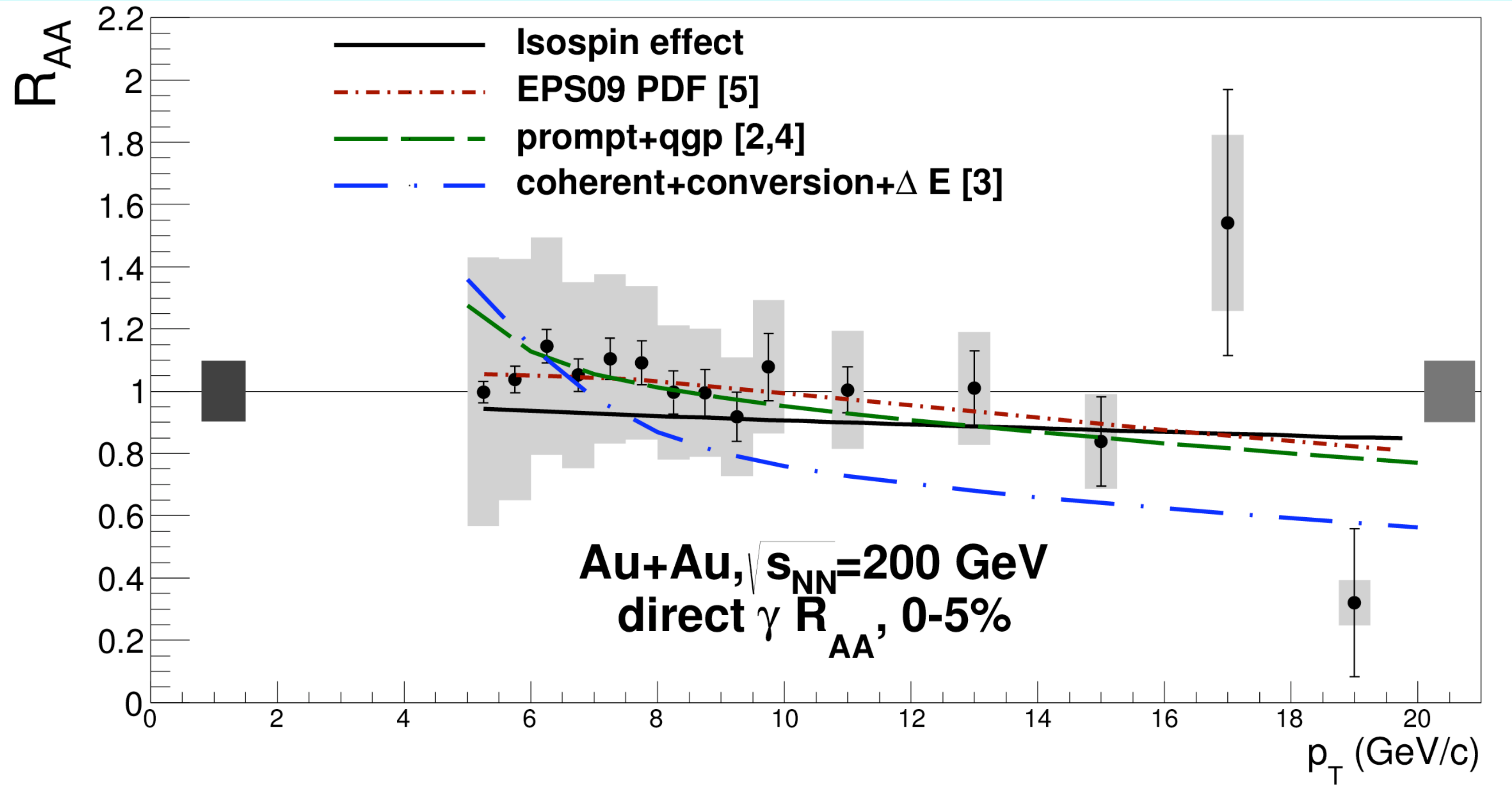




- Observe slight suppression of J/ψ
  - nPDFs affect formation cross section
  - Also collision with nucleons, comoving stuff can break up bound state into c and cbar
- ψ' a big surprise!
  - *ψ' / J/ψ* ratio should be unity when time in nucleus < formation time.

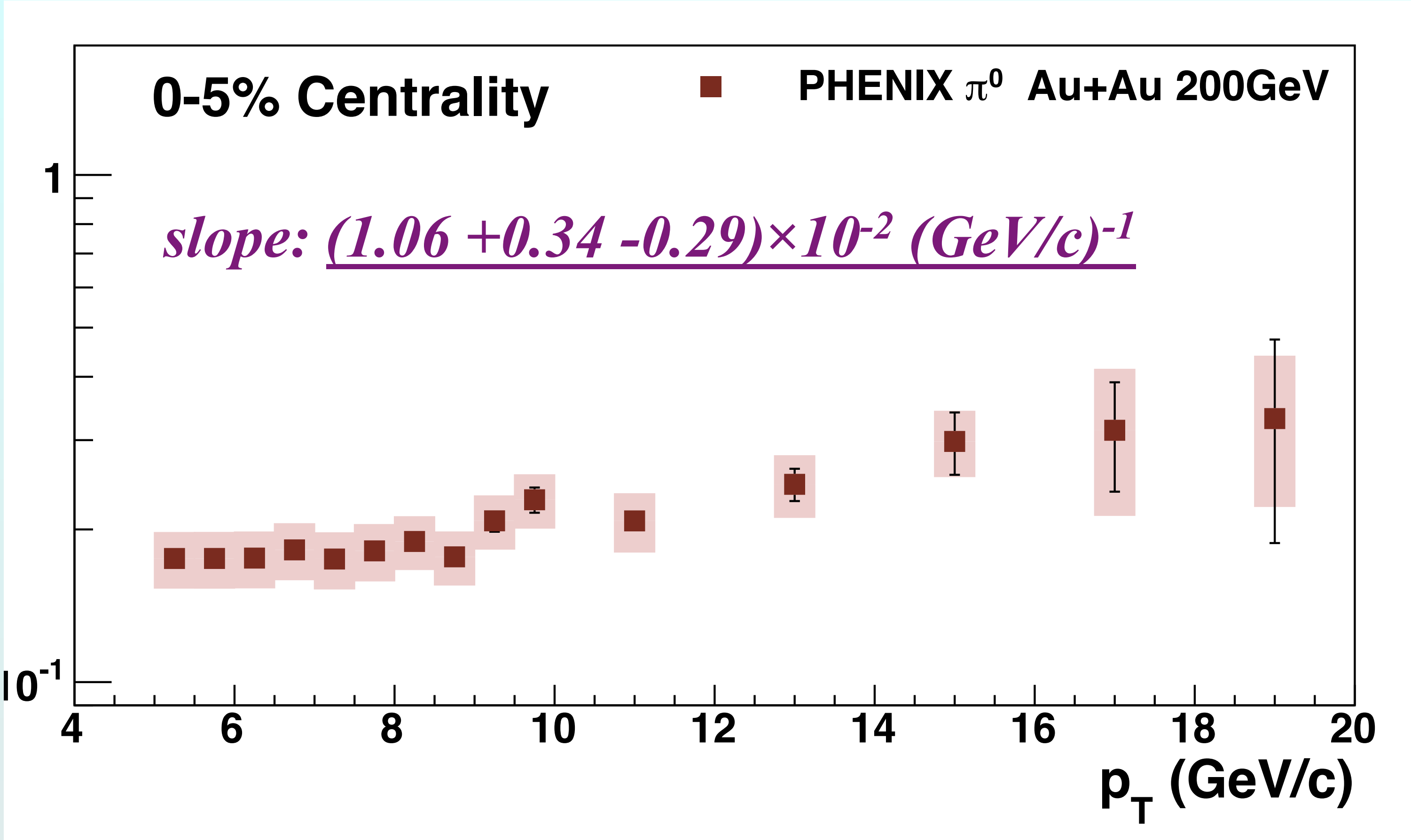
QGP probes
(the goal)

Direct photons Au+Au



- not significantly suppressed

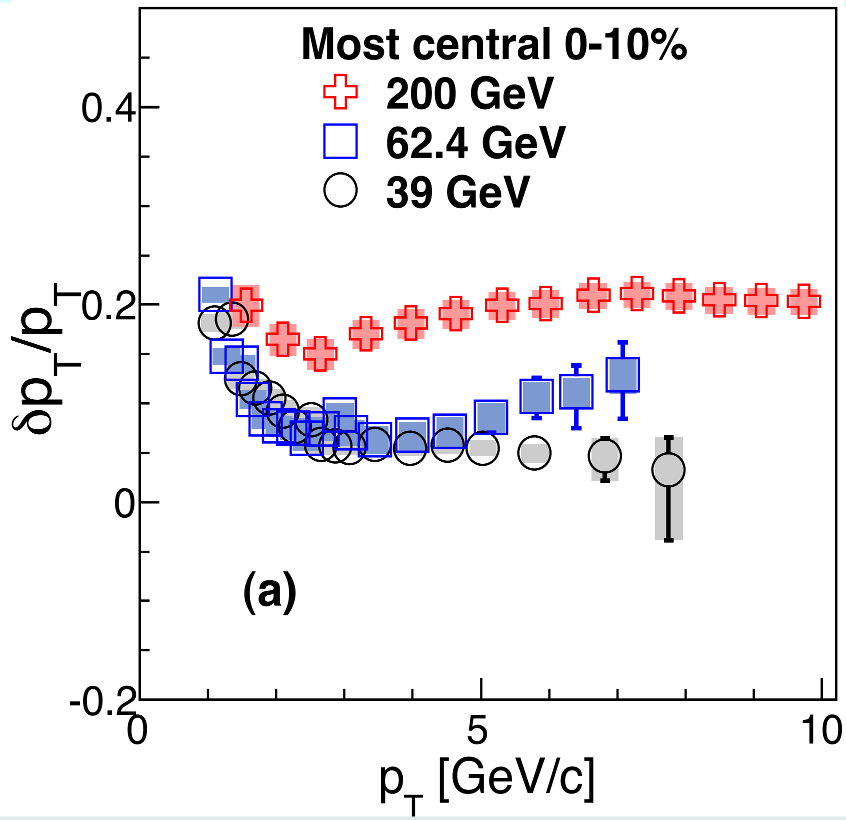
Single hadron suppression

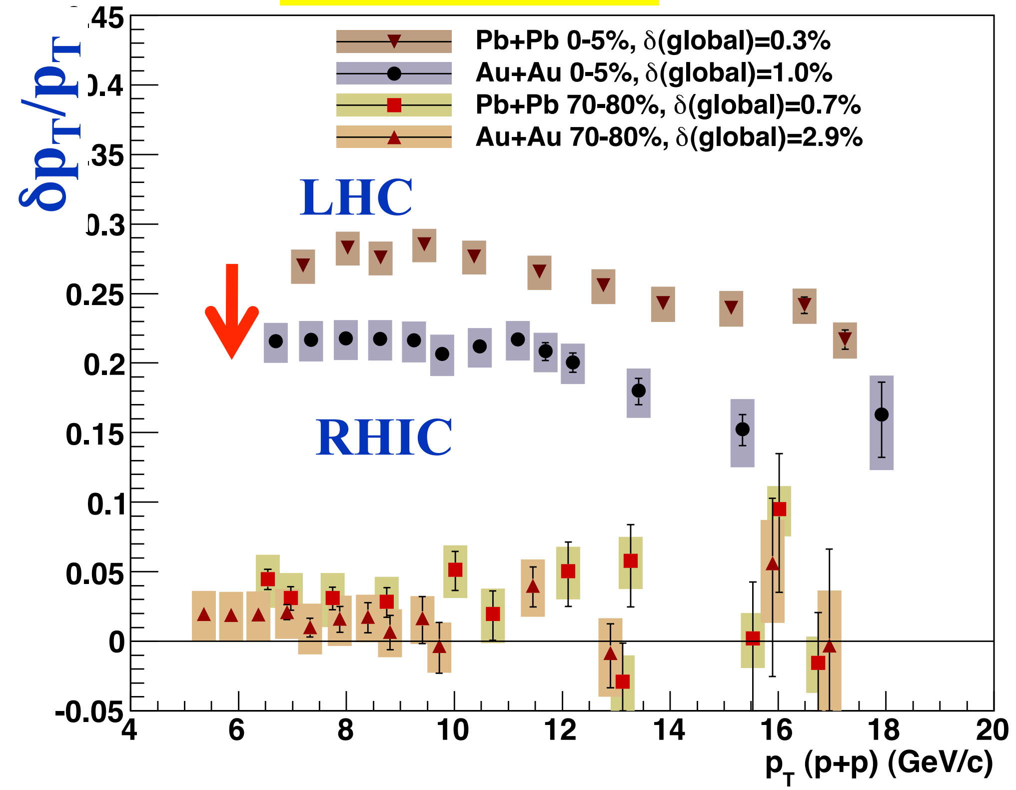


- R_{AA} at LHC is similar
- Spectral shape is not!

Similar R_{AA} ≠ same energy loss

arXiv:1208.2254





- Higher energy loss at LHC

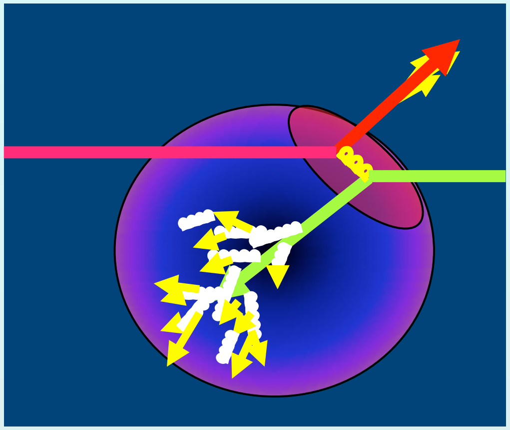
  Larger difference than apparent from RAA alone

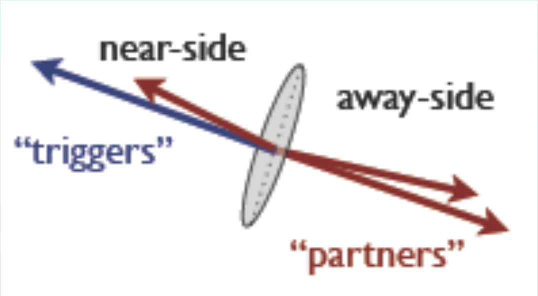
- Lower energy loss in lower energy RHIC collisions

  NB: look in kinematic region of jet fragments!

Where does the lost energy go?

- Thermalize in the plasma? Additional soft hadrons from induced gluon radiation? Plasma excitations?

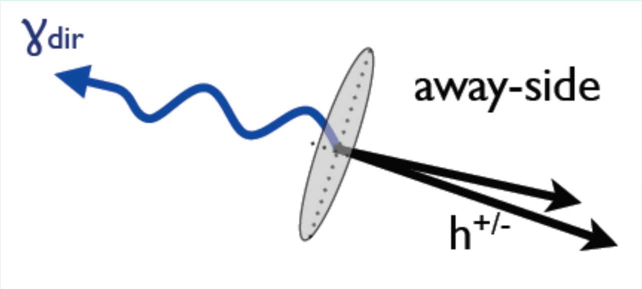




Jet fragmentation function: count partners per trigger

$z_T = p_{Ta}/p_{Tt} \sim z$ for γ trigger

$\xi = \ln(1/z_T)$

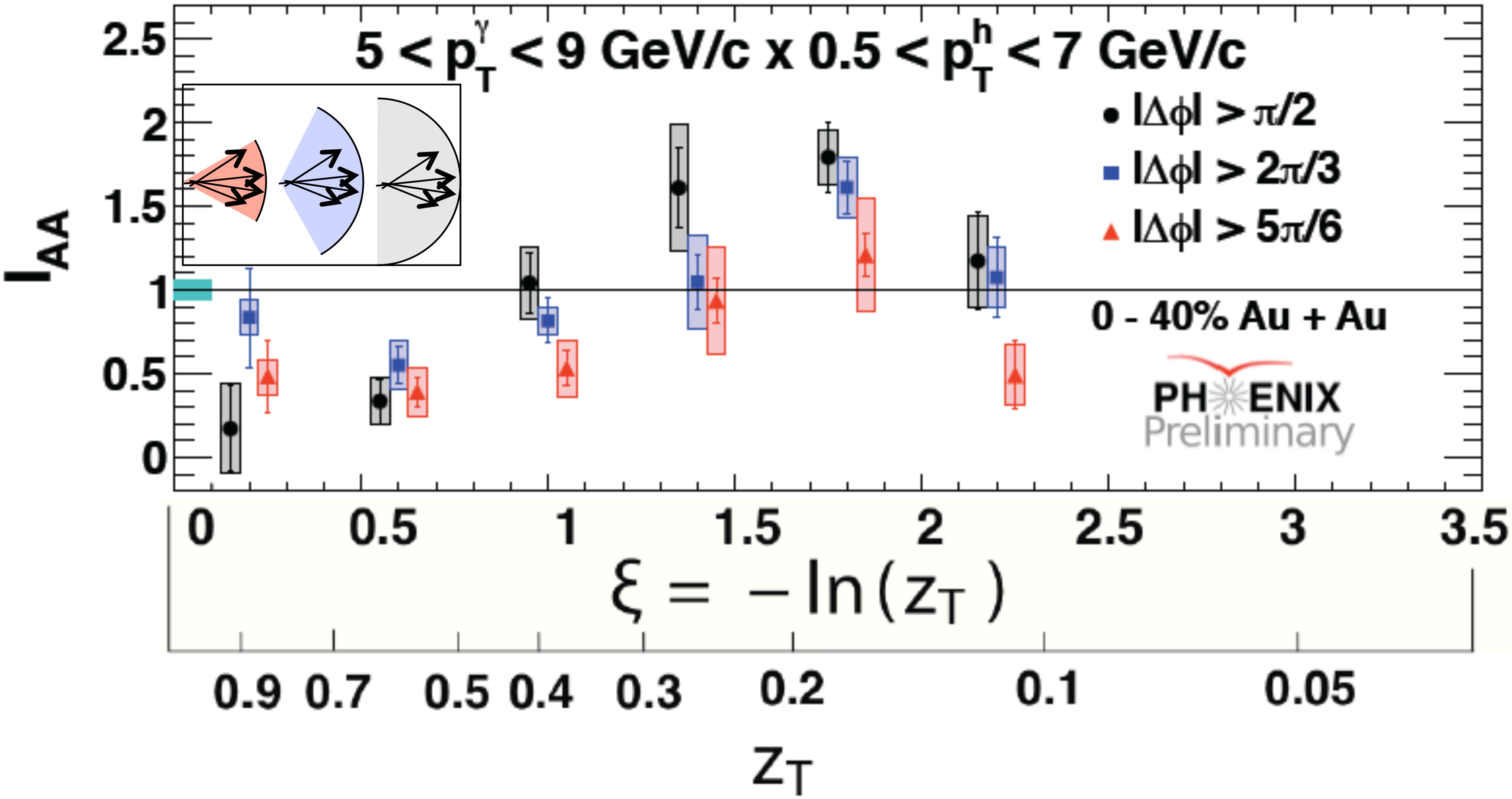


Modification factor like R_{AA}:

$$I_{AA} \equiv \frac{(1/N_{trig}dN/d\xi)_{AA}}{(1/N_{trig}dN/d\xi)_{pp}}$$

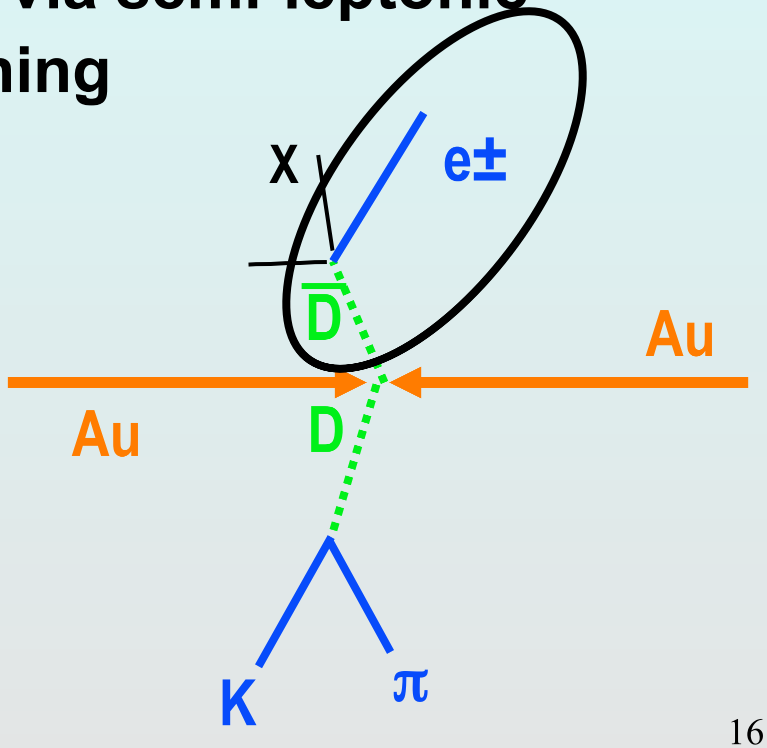
Find extra particles at low z

Low z_T away side particles distributed over wider angle

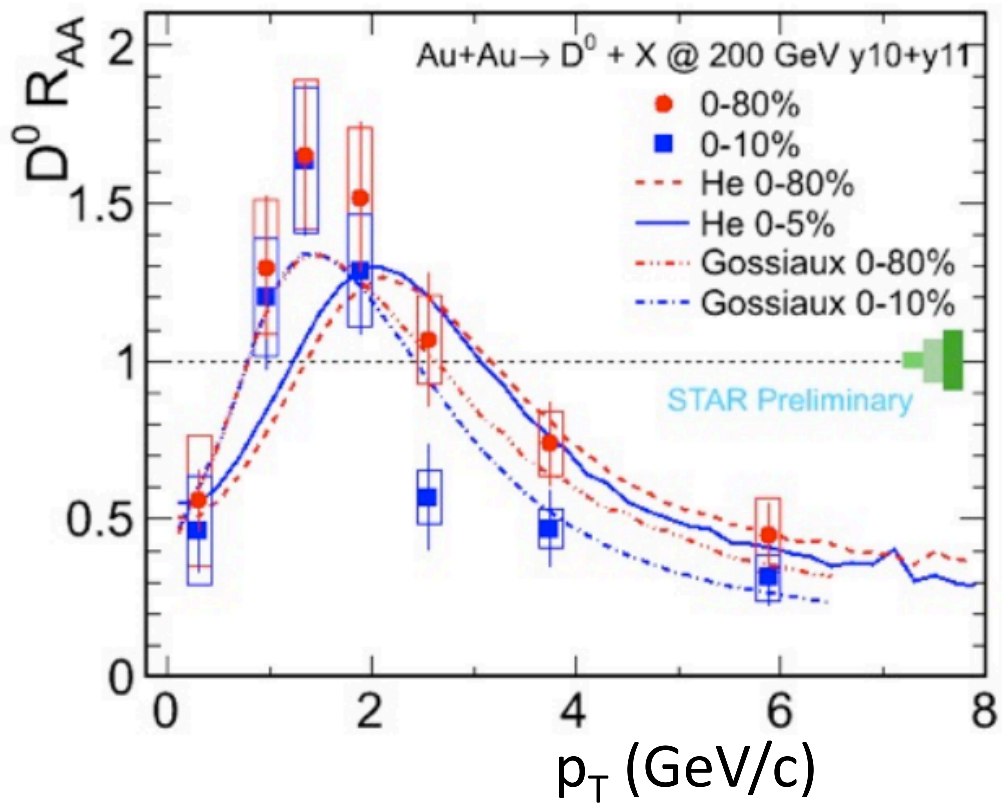


What happens to more massive probes?

- Diffusion of heavy quarks traversing QGP
  $M_c \sim 1.3\ GeV/c^2$
- Prediction: less energy loss than light quarks
  large quark mass reduces phase space for radiated gluons
- Reconstruct D or measure via semi-leptonic decays of mesons containing charm or bottom quarks



Open Charm Hadrons



Model curves: M. He, et al. arXiv: 1204.4442,
P. B. Gossiaux et al, arXiv: 1207.5445

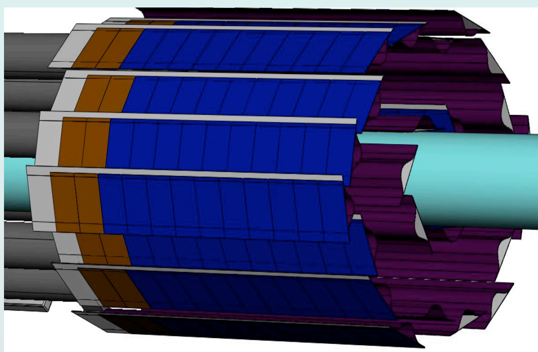
- **Year 2010 + 2011**
- **Charm cross section follows N_{bin} scaling**
  →improved precision
- **R_{AA} suppressed at p_T > 3 GeV/c.**
- **Hump structure in D^0 R_{AA} in low p_T – similar in theoretical calculations**
  Charm diffusion in sQGP
  Hadronization with flowing light quarks

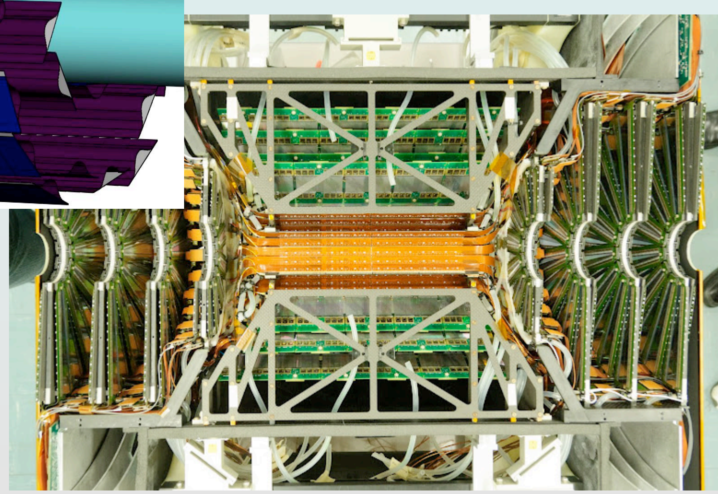
What about b quarks?

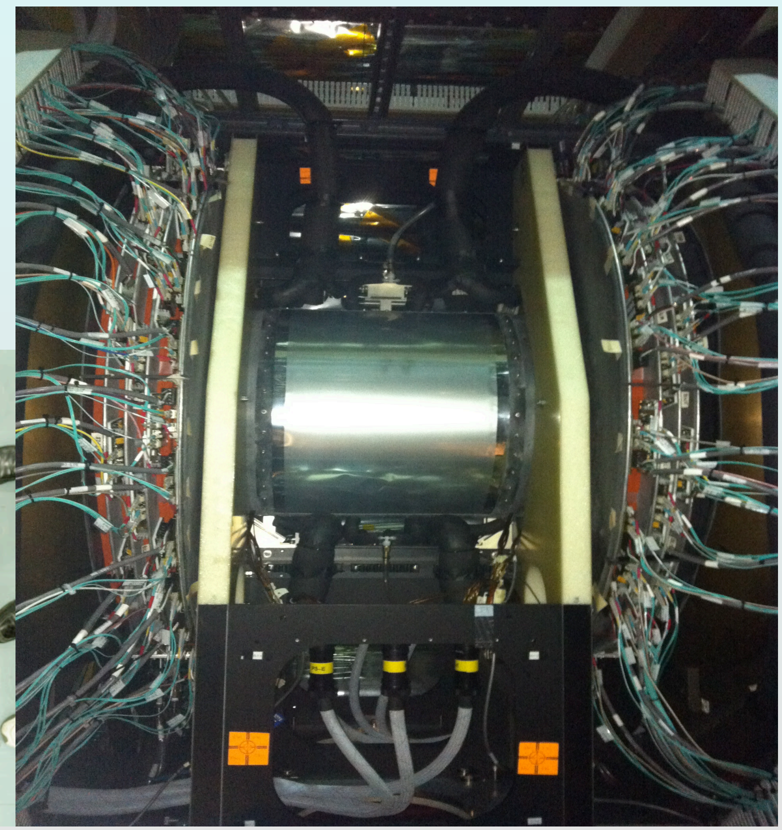
- What does *b* fate tell us about interactions in sQGP?
  $M_b \sim 4.2$ GeV/c^2

- Add silicon detector arrays around beam pipe to both PHENIX and STAR; ALICE already has one

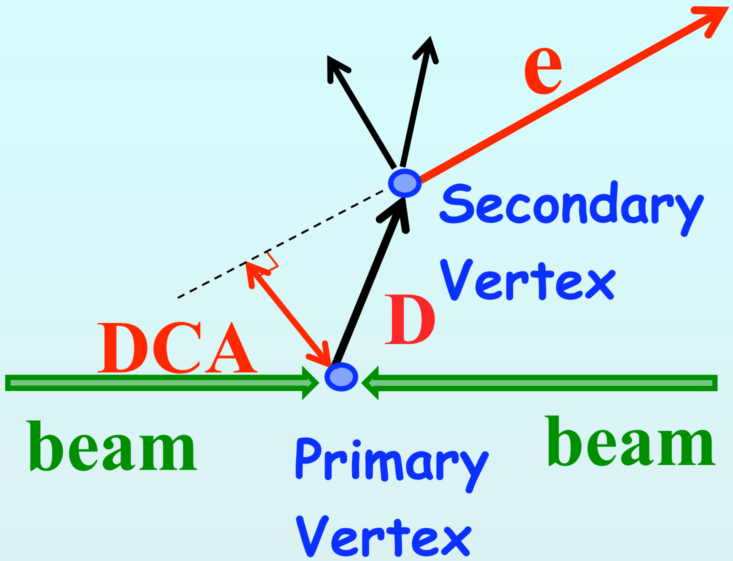
  Tag displaced vertex
  to separate c,b
  Reconstruct D & B mesons

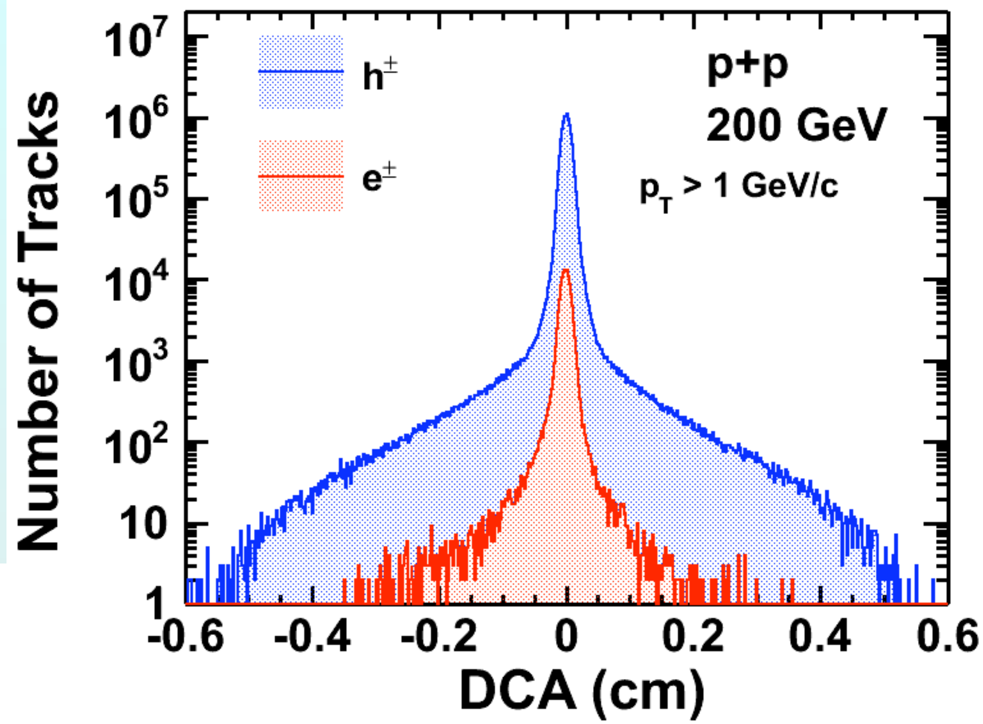


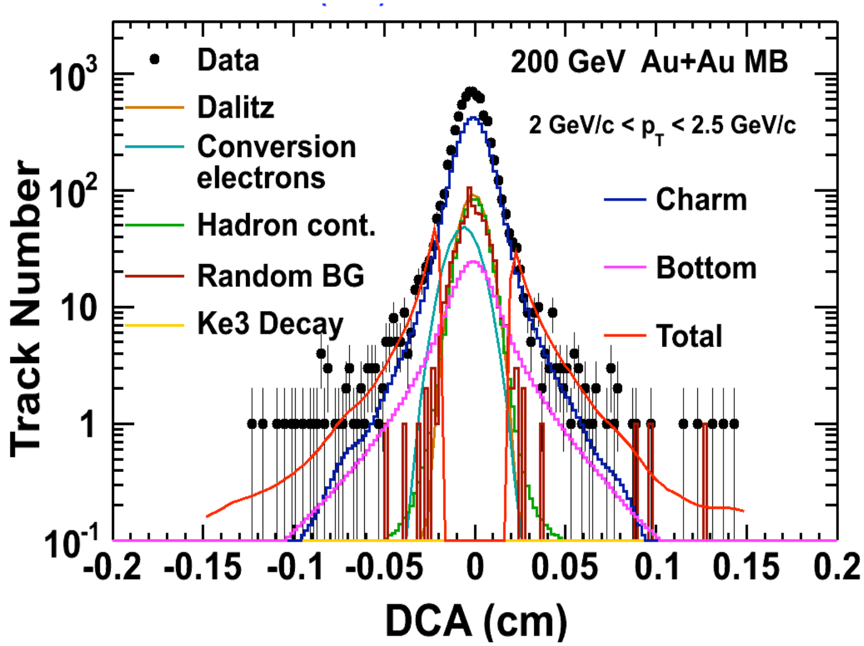




Measure distance of closest approach



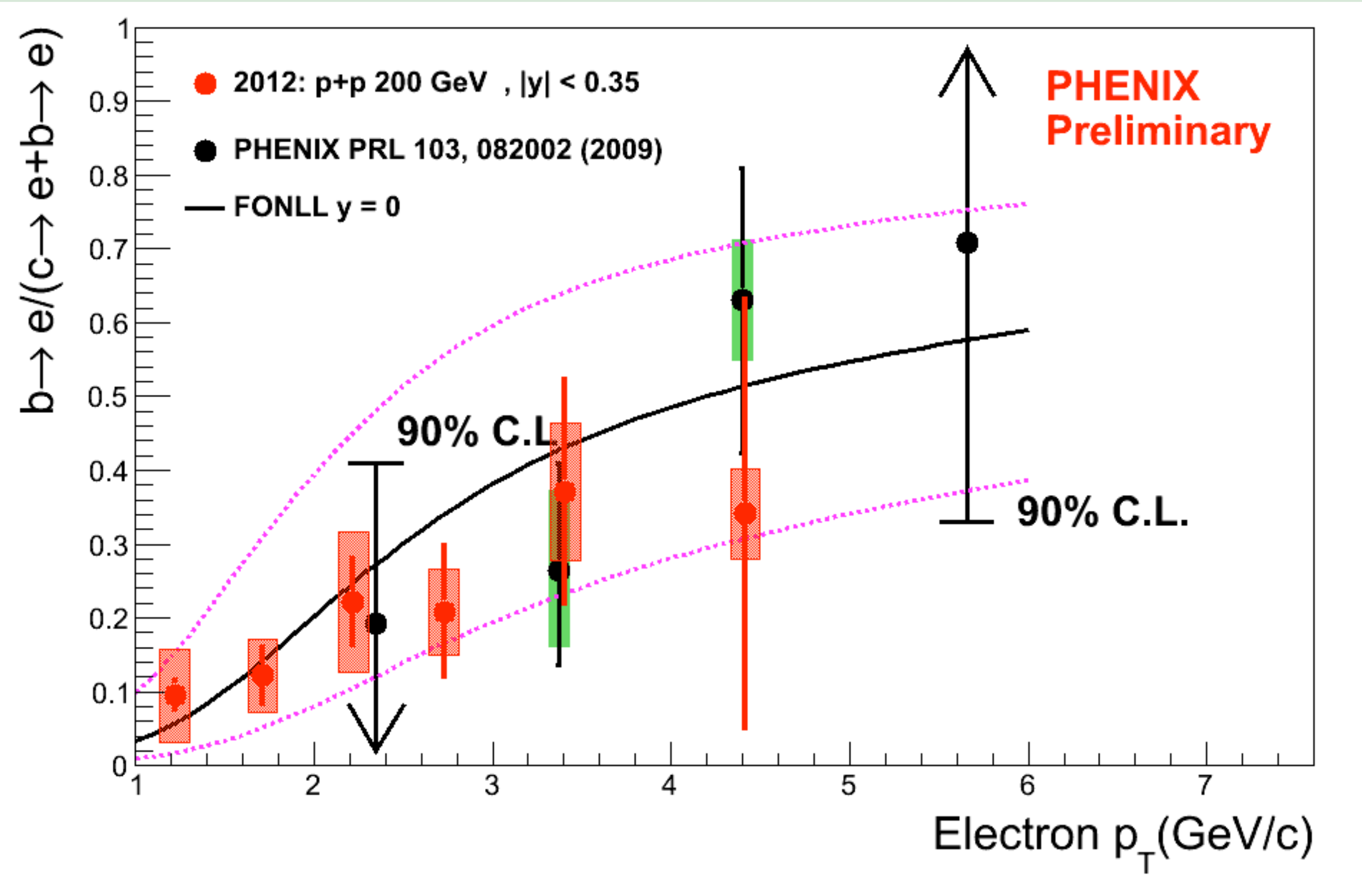




$$\frac{b \to e}{c \to e + b \to e} = 0.08 \pm 0.02$$

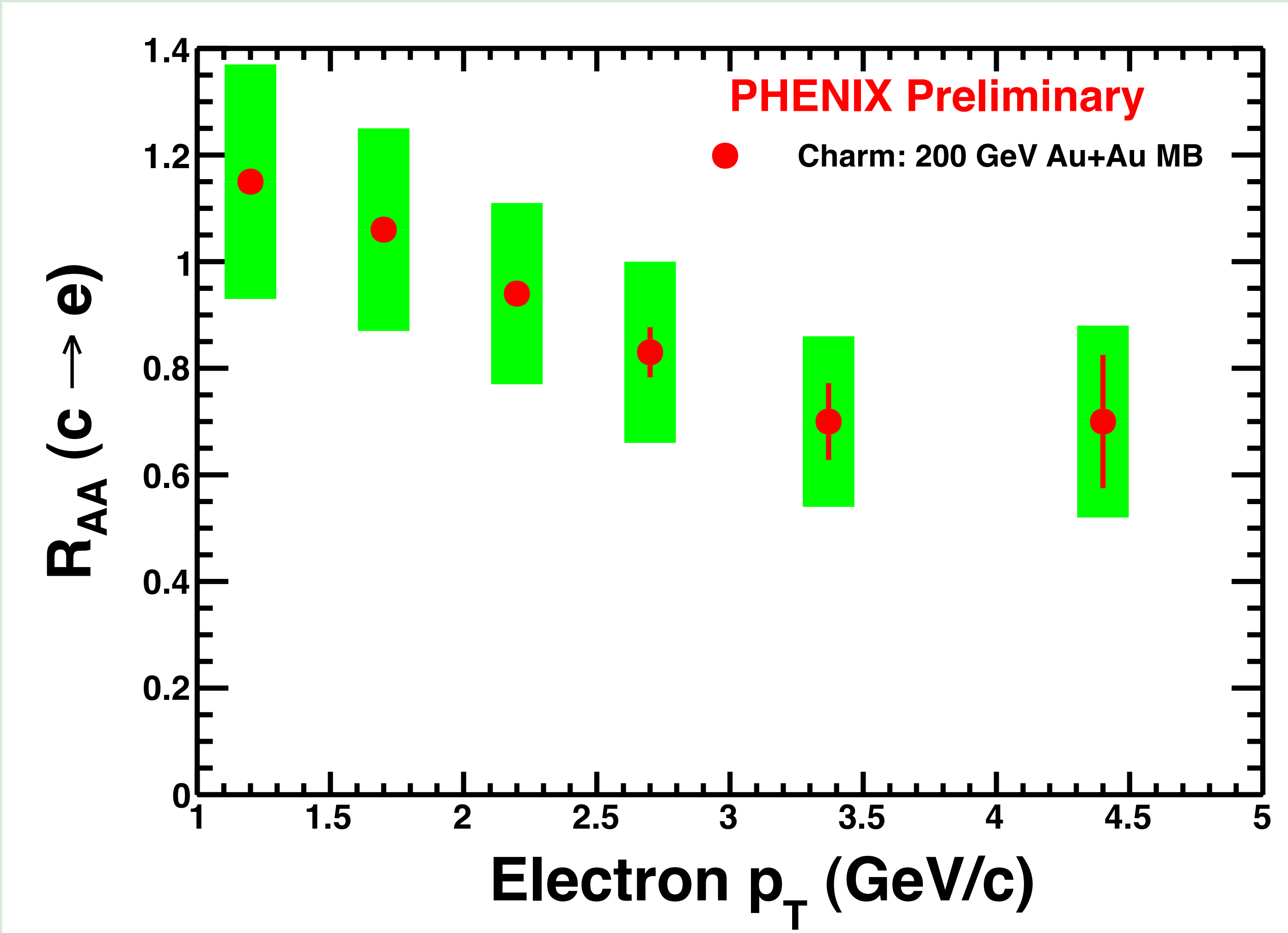
First direct c/b decomposition with new VTX detector

- New direct measurement of bottom fraction agrees with FONLL



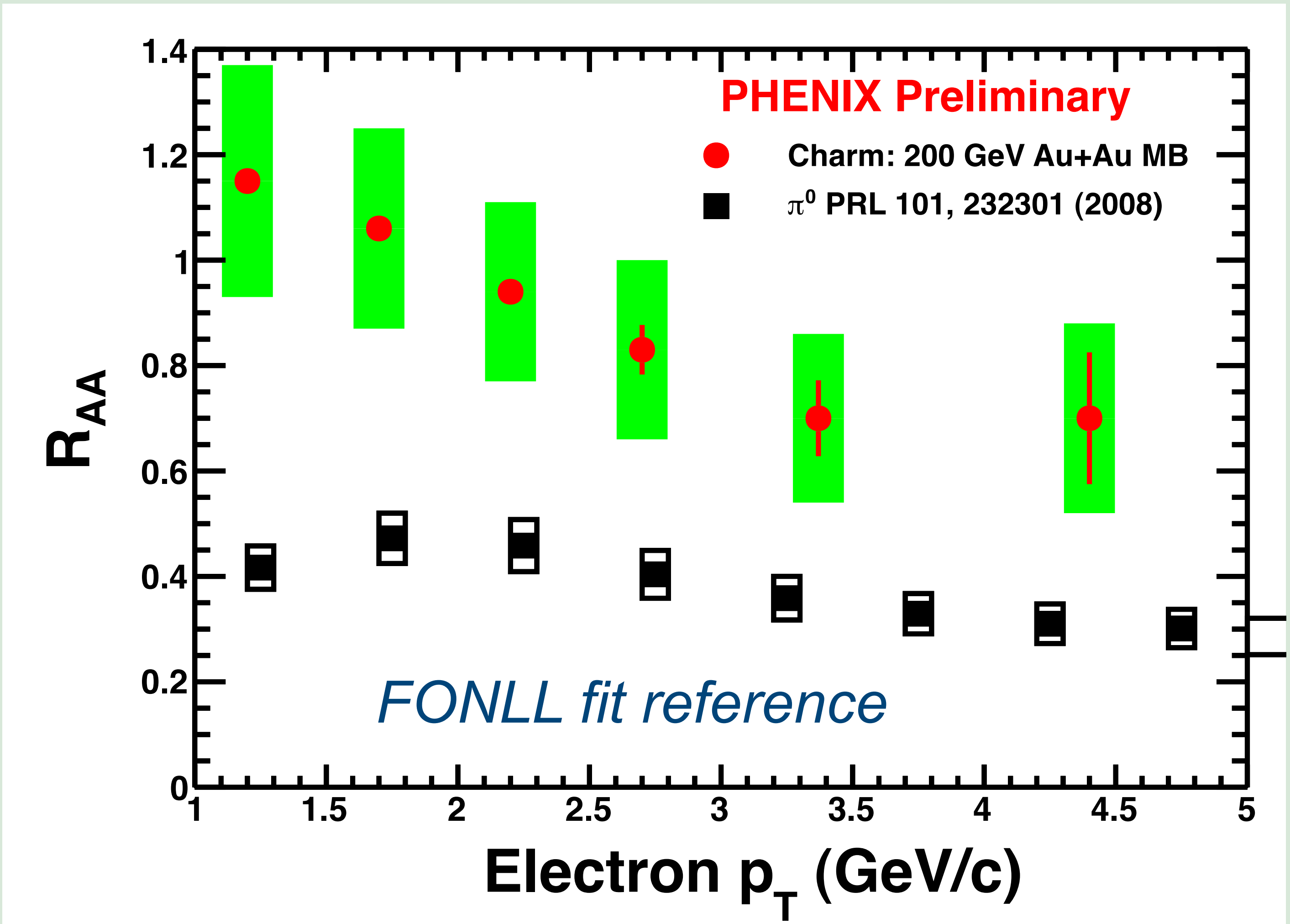
R_{AA} for c→e

Using fit with FONLL shape as reference



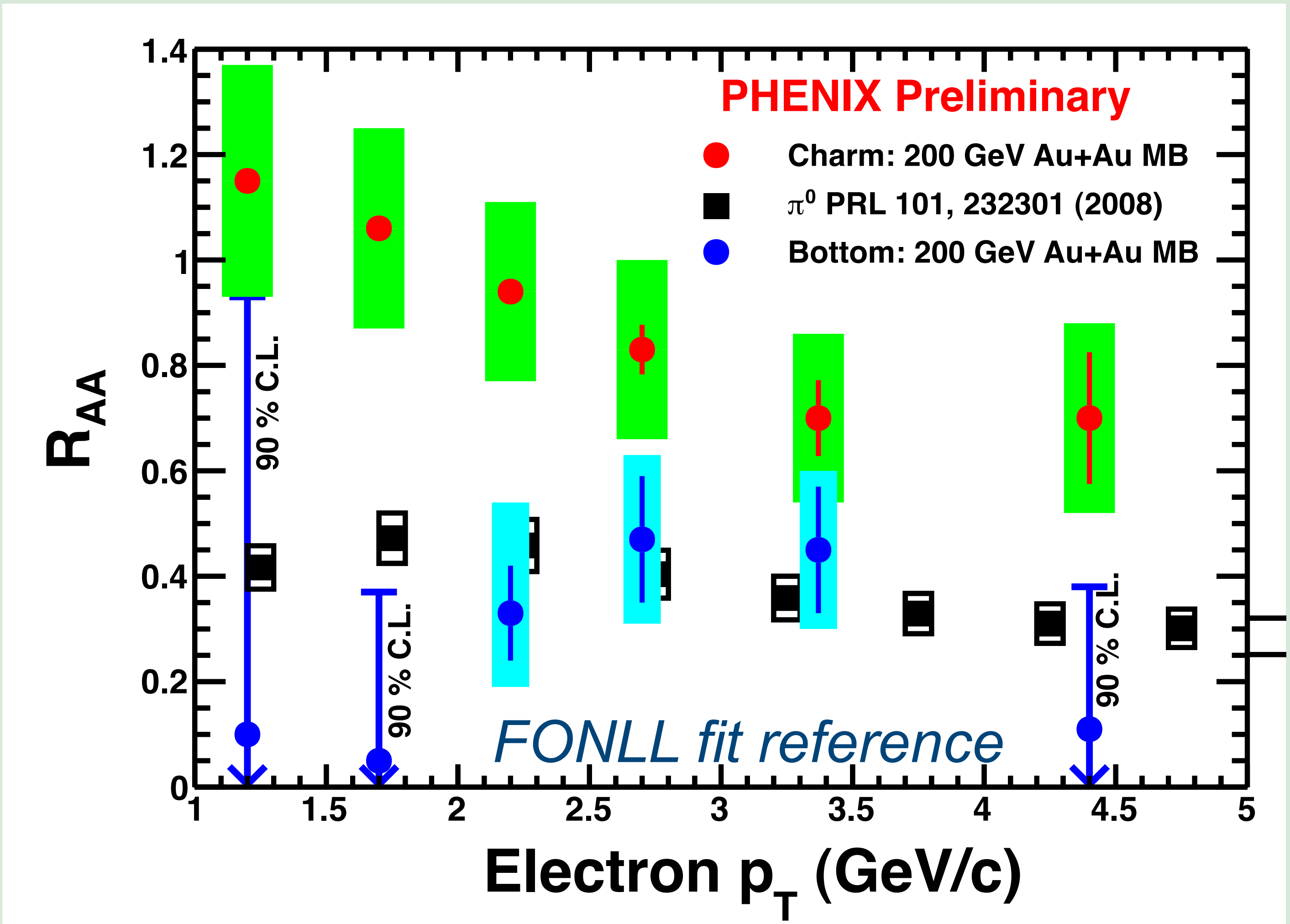
R_{AA} for c→e and π^0

Charm is less suppressed than light quarks



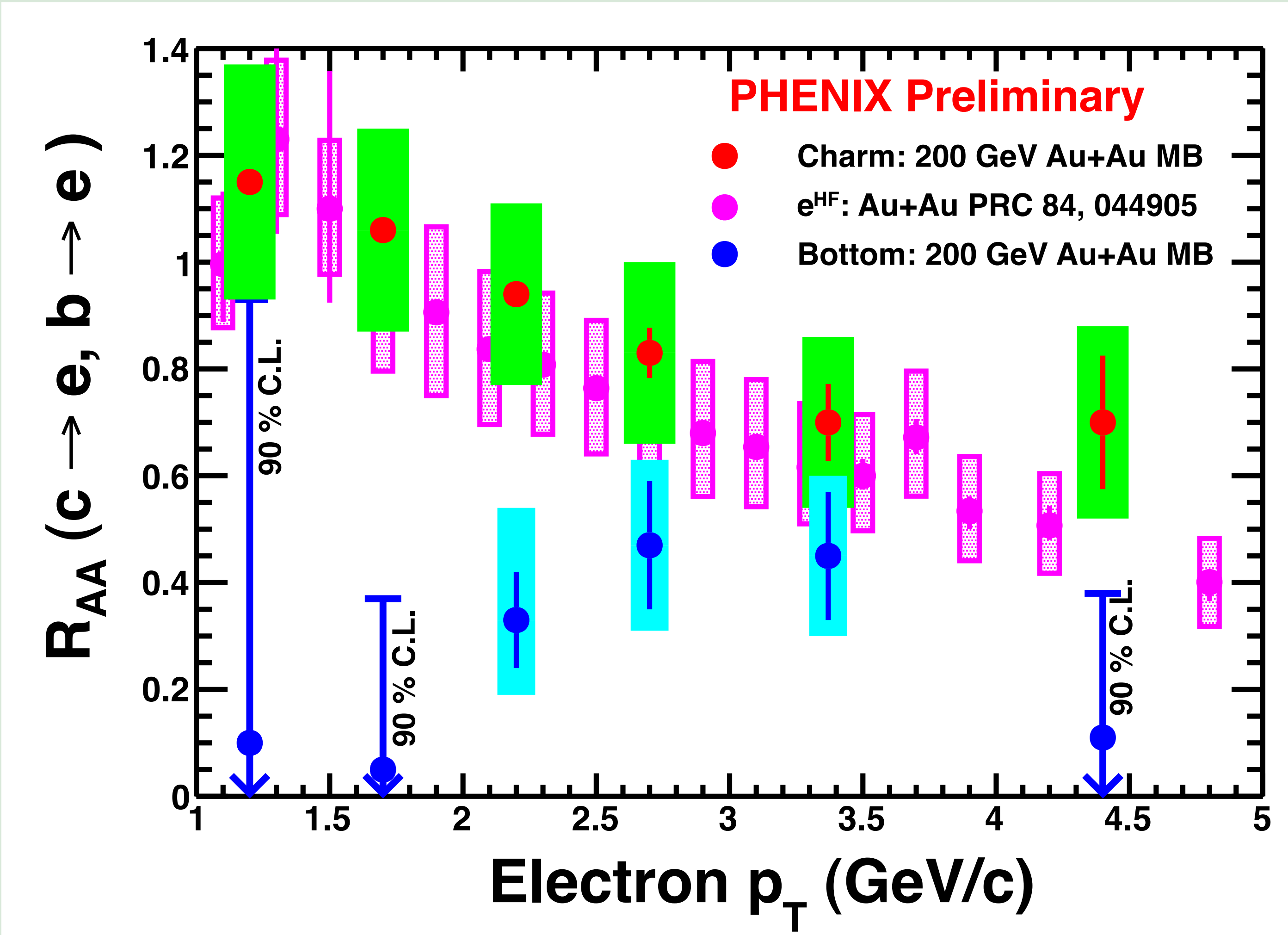
c→e vs. b→e

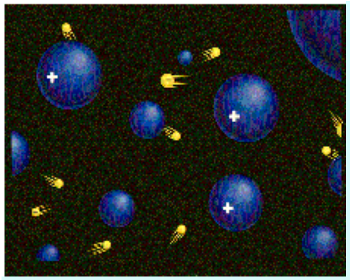
- Bottom appears more heavily suppressed!



Trends, including HF e

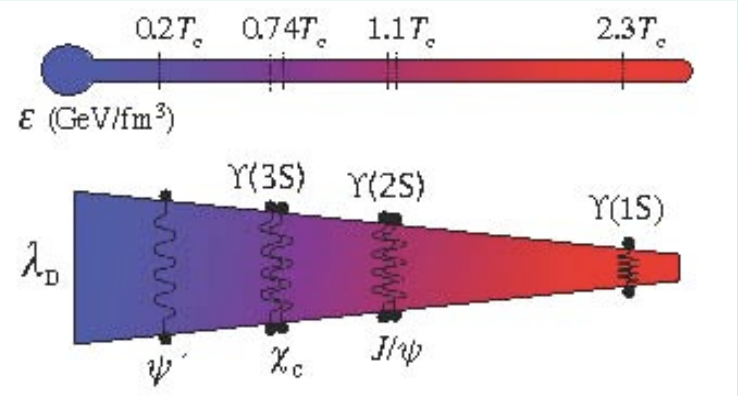
R_{AA} for c→e consistent with R_{AA} for HF electrons





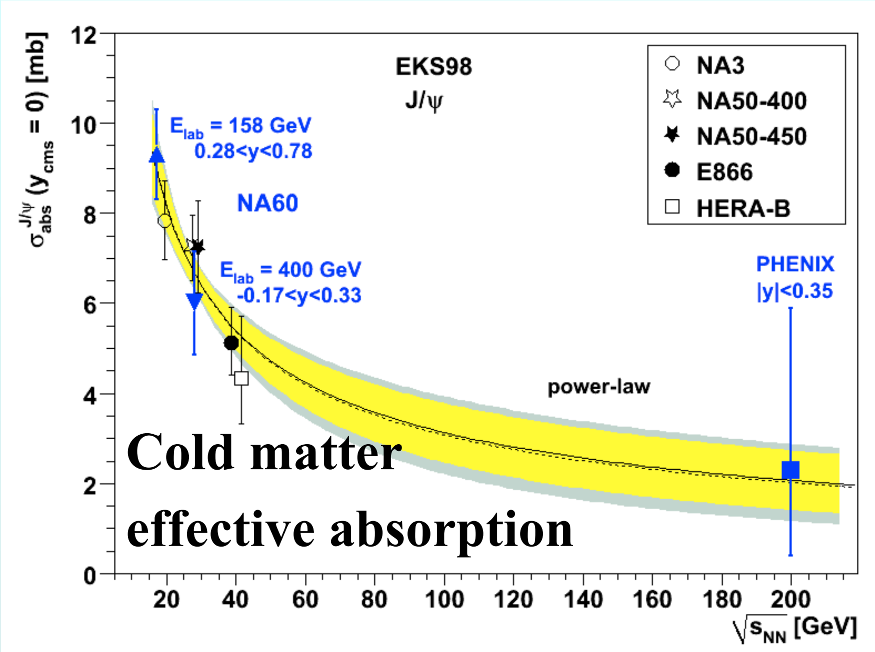
Is there a relevant color screening length?

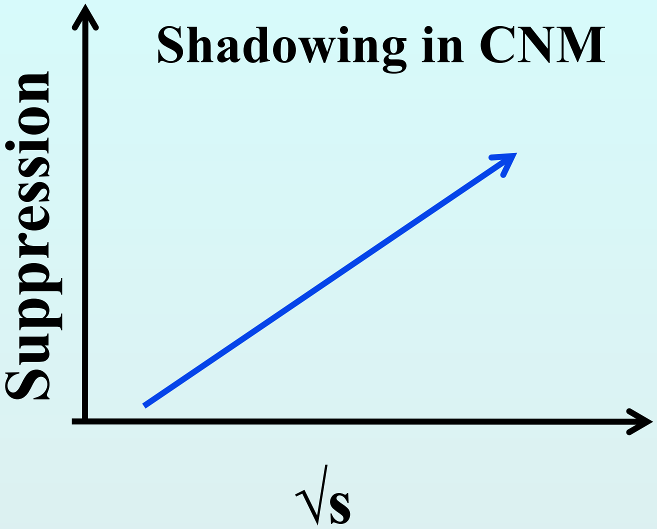
- Plasma: interactions among charges of multiple particles spreads charge into characteristic (Debye) length, λ_D
  particles inside Debye sphere screen each other
- Strongly coupled = few (~1-2) particles in Debye sphere
  Partial screening -> liquid-like properties
- *Test* QGP *screening with heavy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

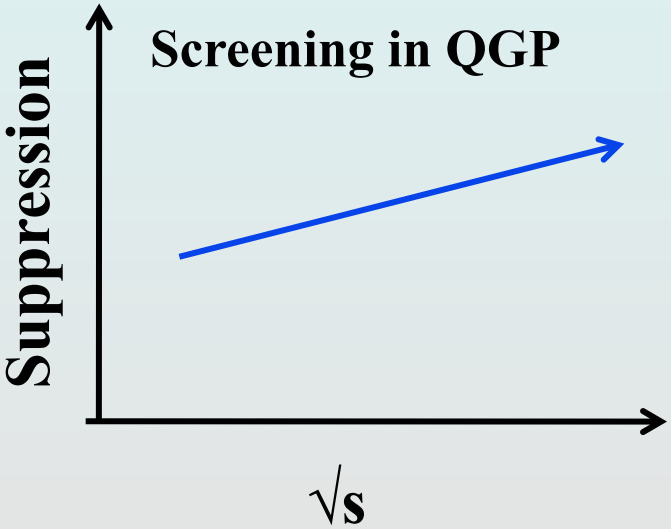


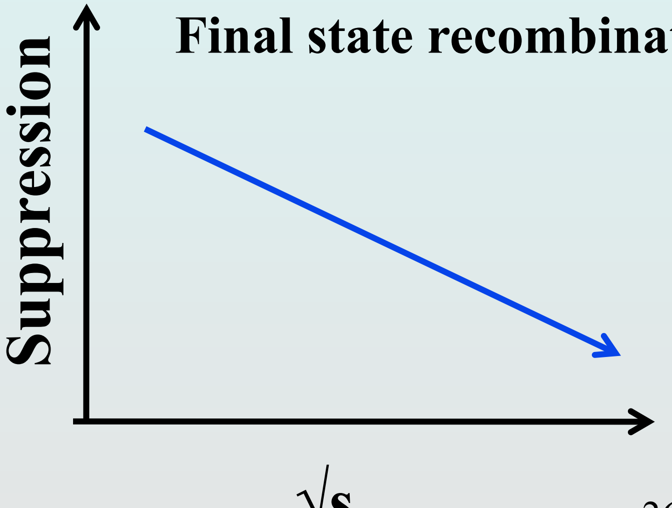
- Are residual correlations important?

√s dependence of suppression effects

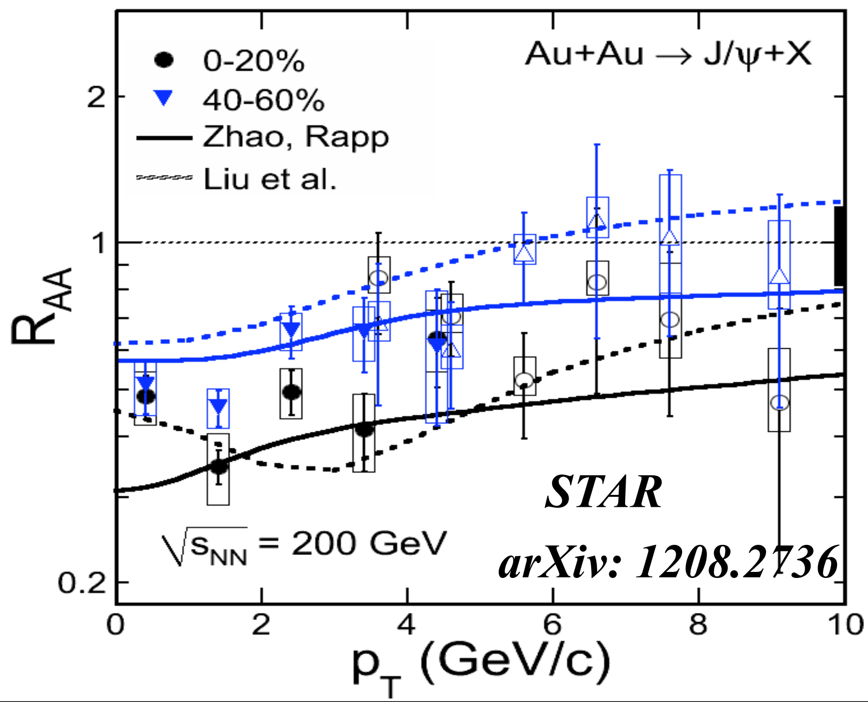


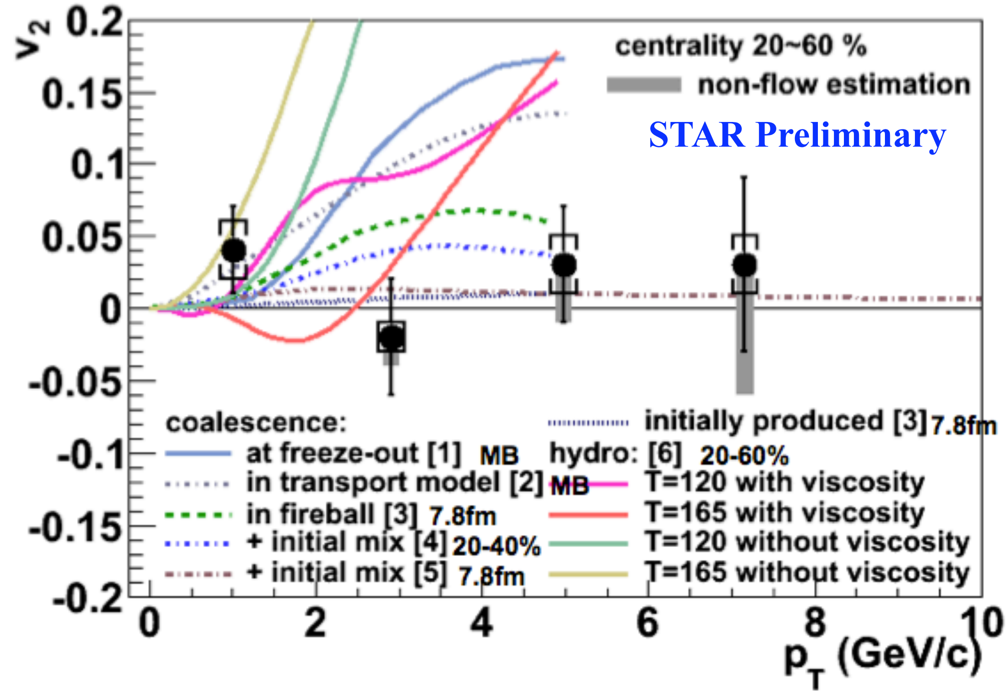






J/ψ Suppression and Elliptic Flow

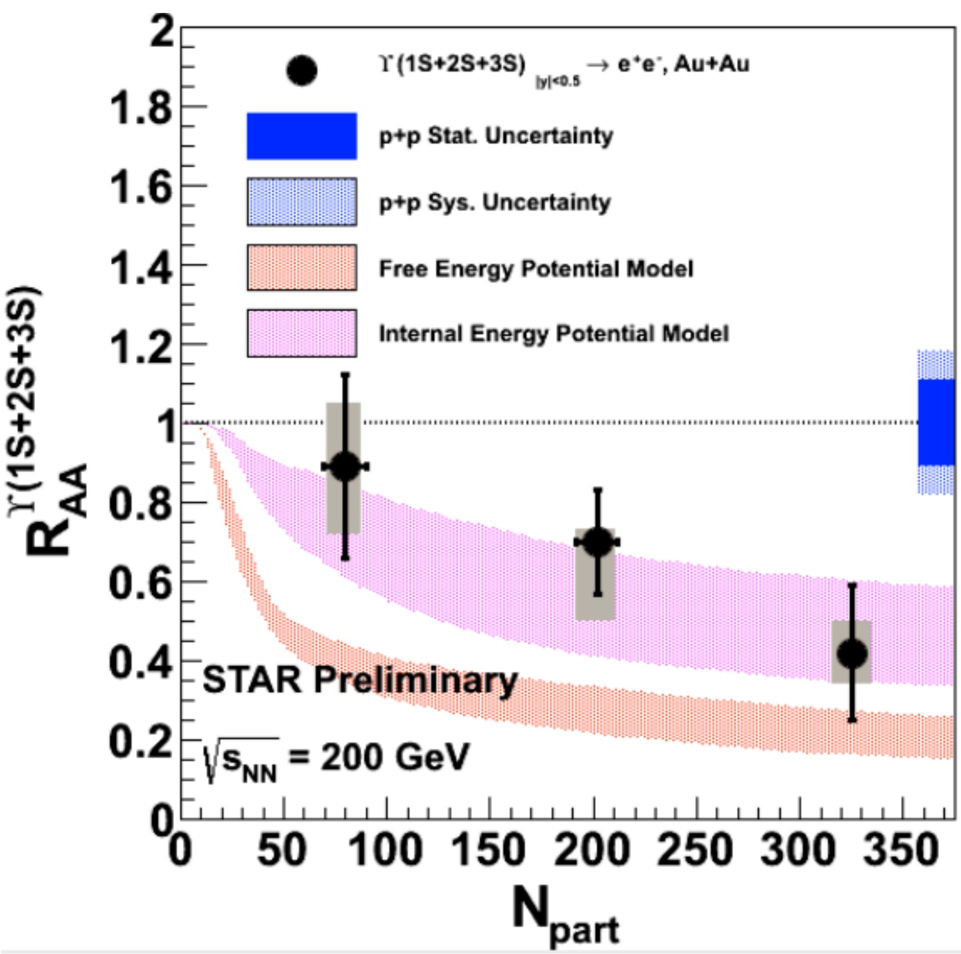




- Suppression at high p_T (central) systematically smaller than low p_T
- Consistent with calculations attributing high p_T suppression mainly to color screening.

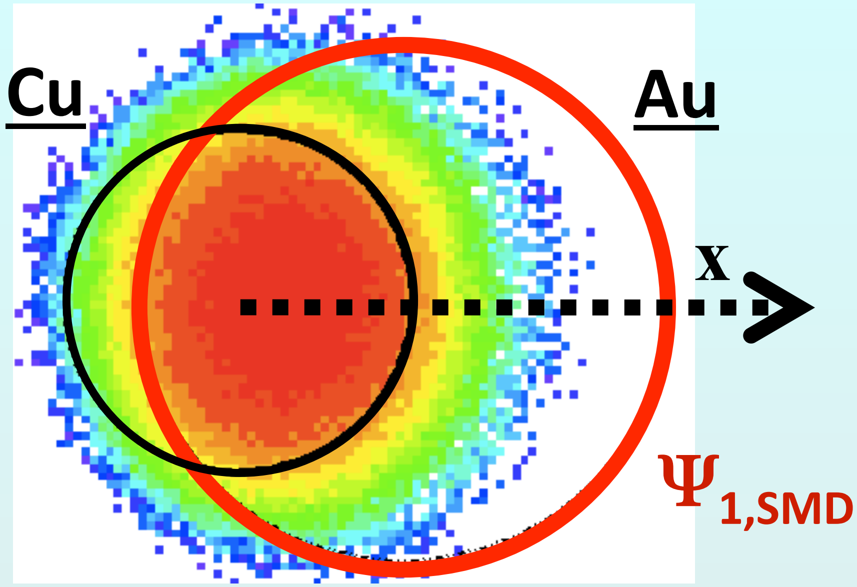
- v_2 consistent with zero at p_T > 2 GeV/c (20-60%)
- Disfavors coalescence of thermalized charm quarks as dominant source

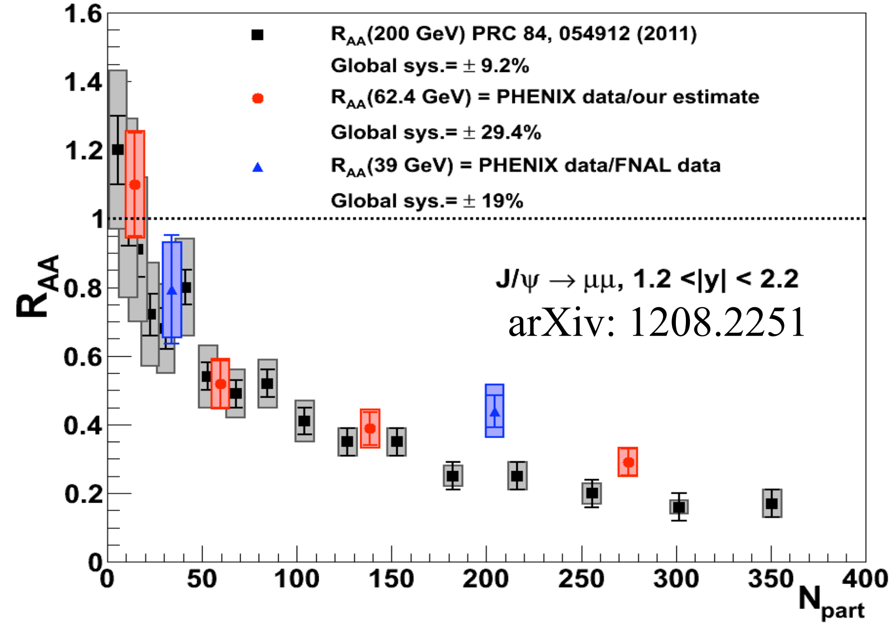
Upsilon Suppression: should be cleaner

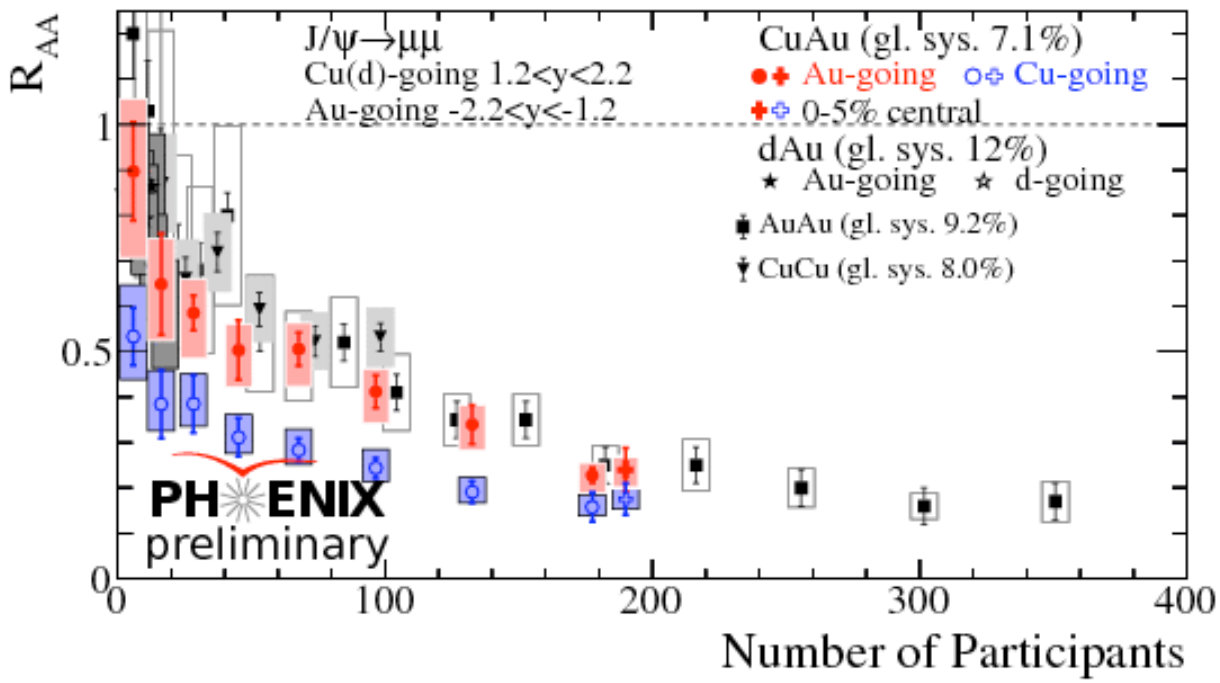


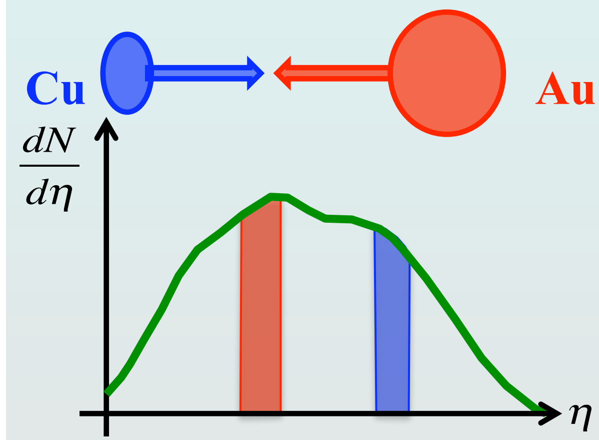
- 1S state is tightly bound
  - small nuclear absorption
  - (but 2S & 3S…)
- negligible contribution from regeneration (few b-bbar pairs)
- *but initial state formation effects still matter!*
- Centrality dependence with improved p+p reference
  - -consistent with the scenario that all excited states melt

Key knobs: √s and path dependence





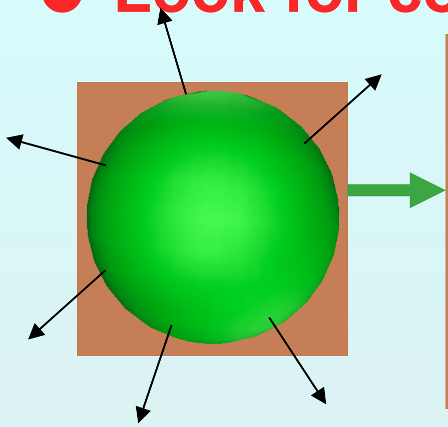


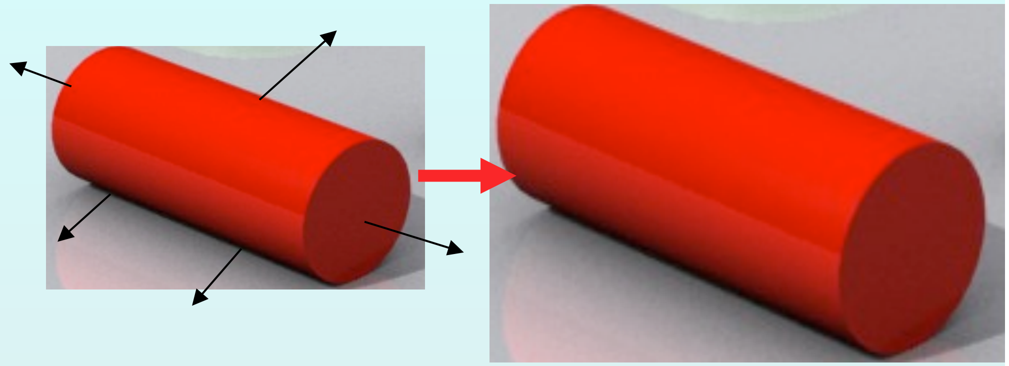


Expansion: Another great tool to study strong coupling

Does hot QCD matter exhibit collectivity?

- Look for collective flow via velocity boosts





- Is the expansion hydrodynamical?

  Model expansion of the system with fluid dynamics

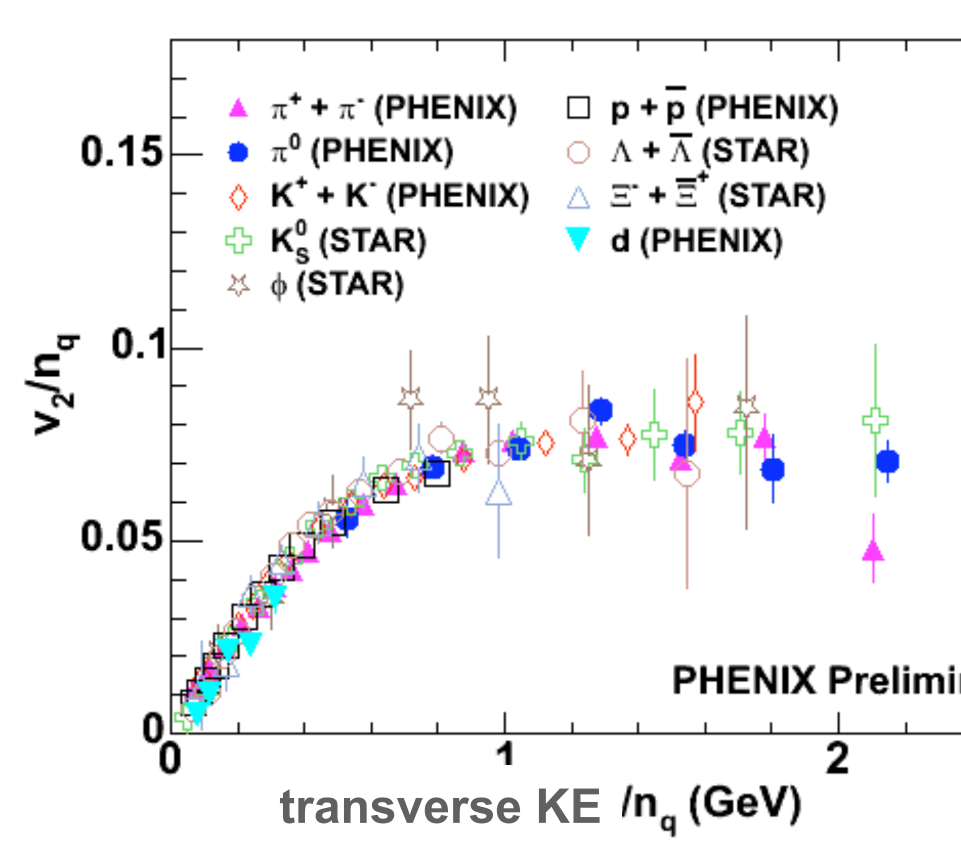
$$\partial_t \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} + \partial_x \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ u(e+p) \end{pmatrix} + \partial_y \begin{pmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ v(e+p) \end{pmatrix} -$$

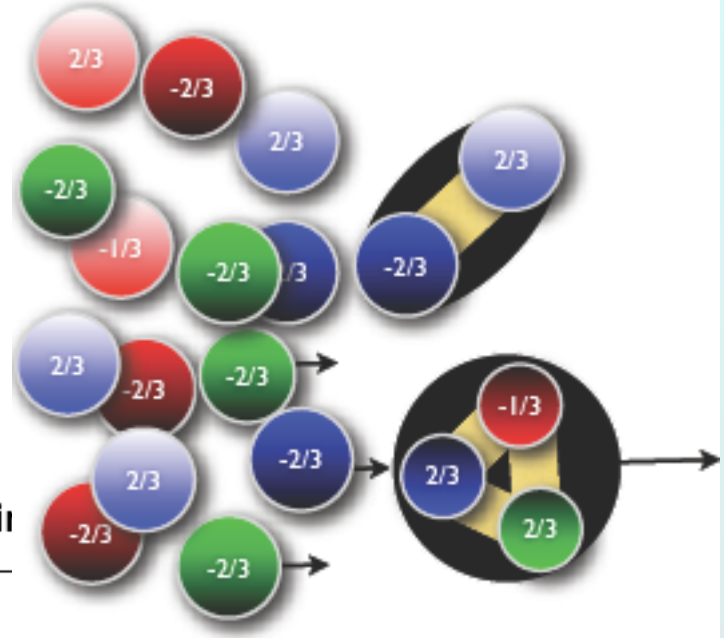
$$\partial_x \begin{pmatrix} 0 \\ \tau_{11} \\ \tau_{12} \\ \tau_{11} u + \tau_{12} v + k \partial_x \Theta \end{pmatrix} - \partial_x \begin{pmatrix} 0 \\ \tau_{21} \\ \tau_{22} \\ \tau_{21} u + \tau_{22} v + k \partial_y \Theta \end{pmatrix} = 0 \,,$$

where u and v are the components of the velocity, ρ the density, p the pressure, e total energy density, τ_{ij} the components of the viscous part of the stress tensor, Θ the absolute temperature and k is the heat conductivity.

Elliptic flow scales with number of quarks

B. Mueller, & friends





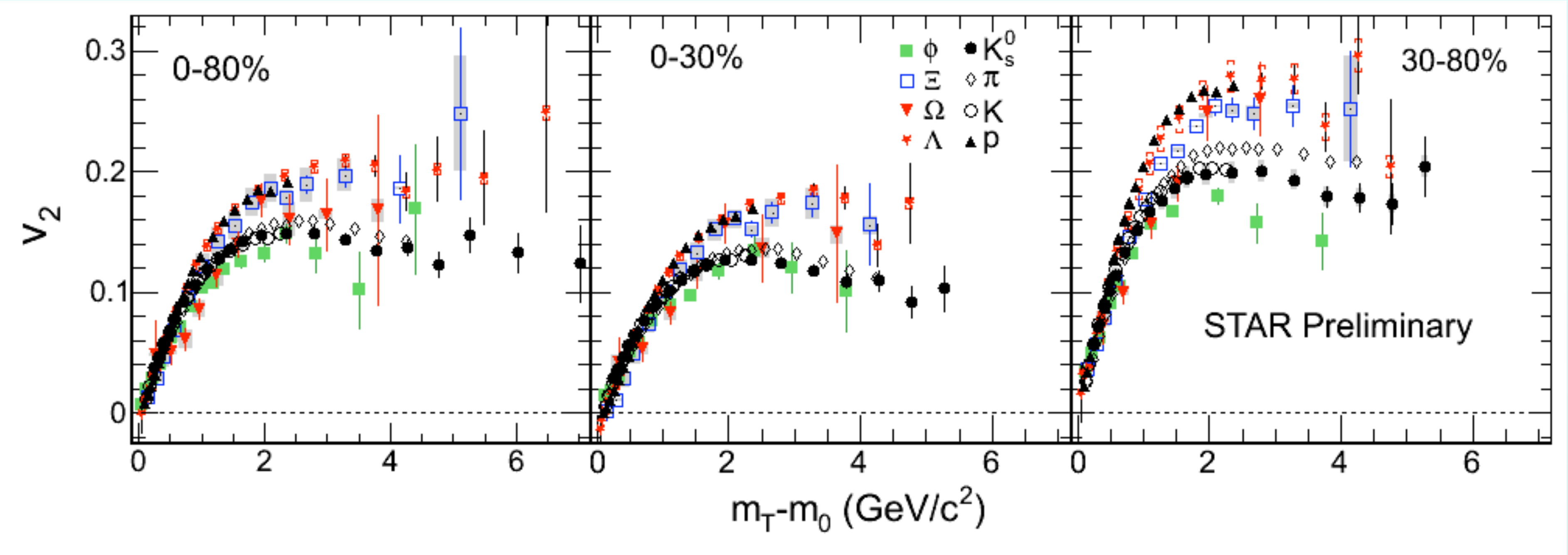
All particles flow as if frozen out from a flowing soup of constituent quarks

implication: valence quarks, not hadrons

pressure builds early, dressed quarks are

similar behavior seen at LHC

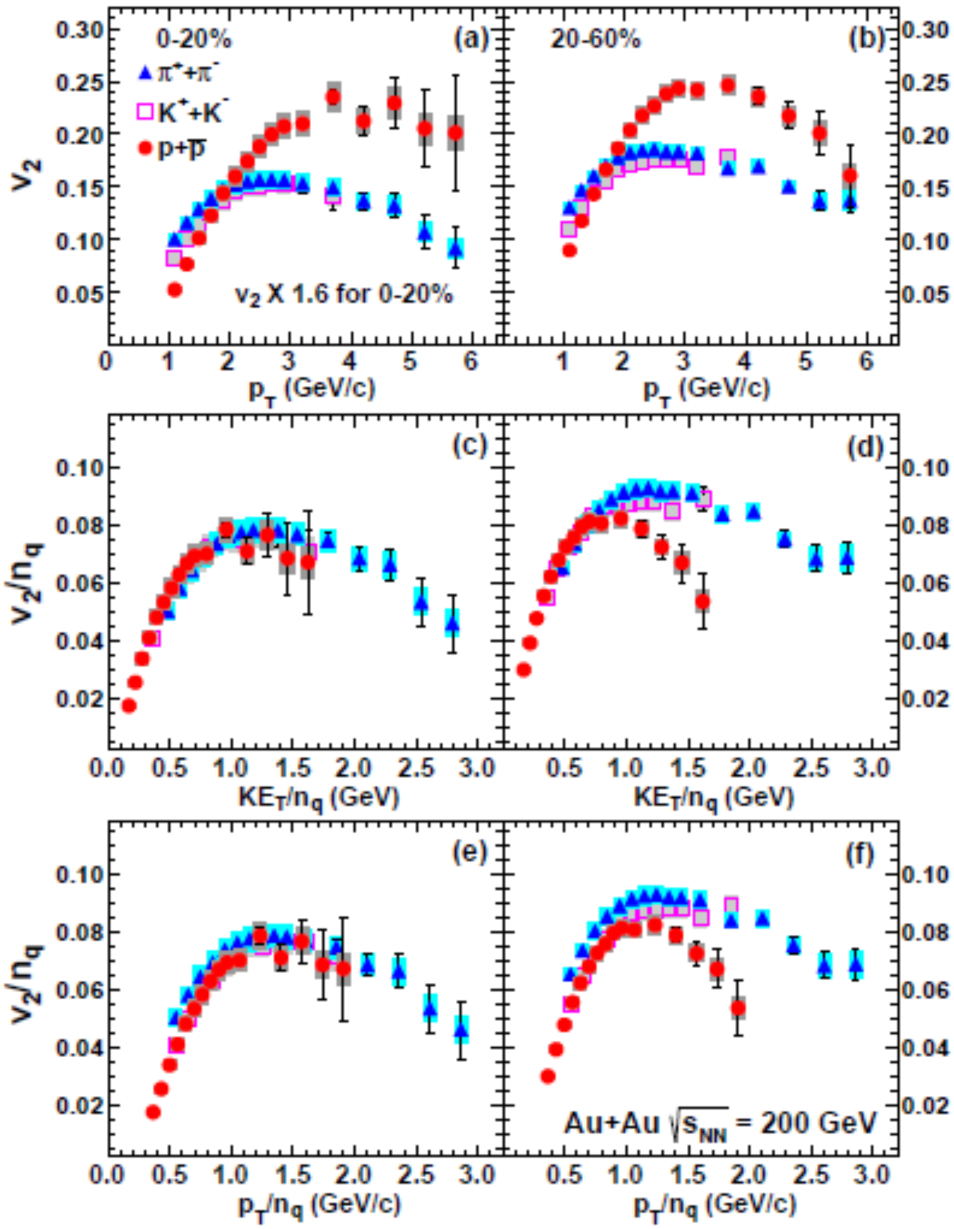
Multistrange quarks, with precision now



- **0-30%: baryon-meson grouping / NCQ scaling holds.**
- **30-80%: Multi-strange hadron v_2 deviate from NCQ scaling at m_T-m_0>1 GeV/c^2.**

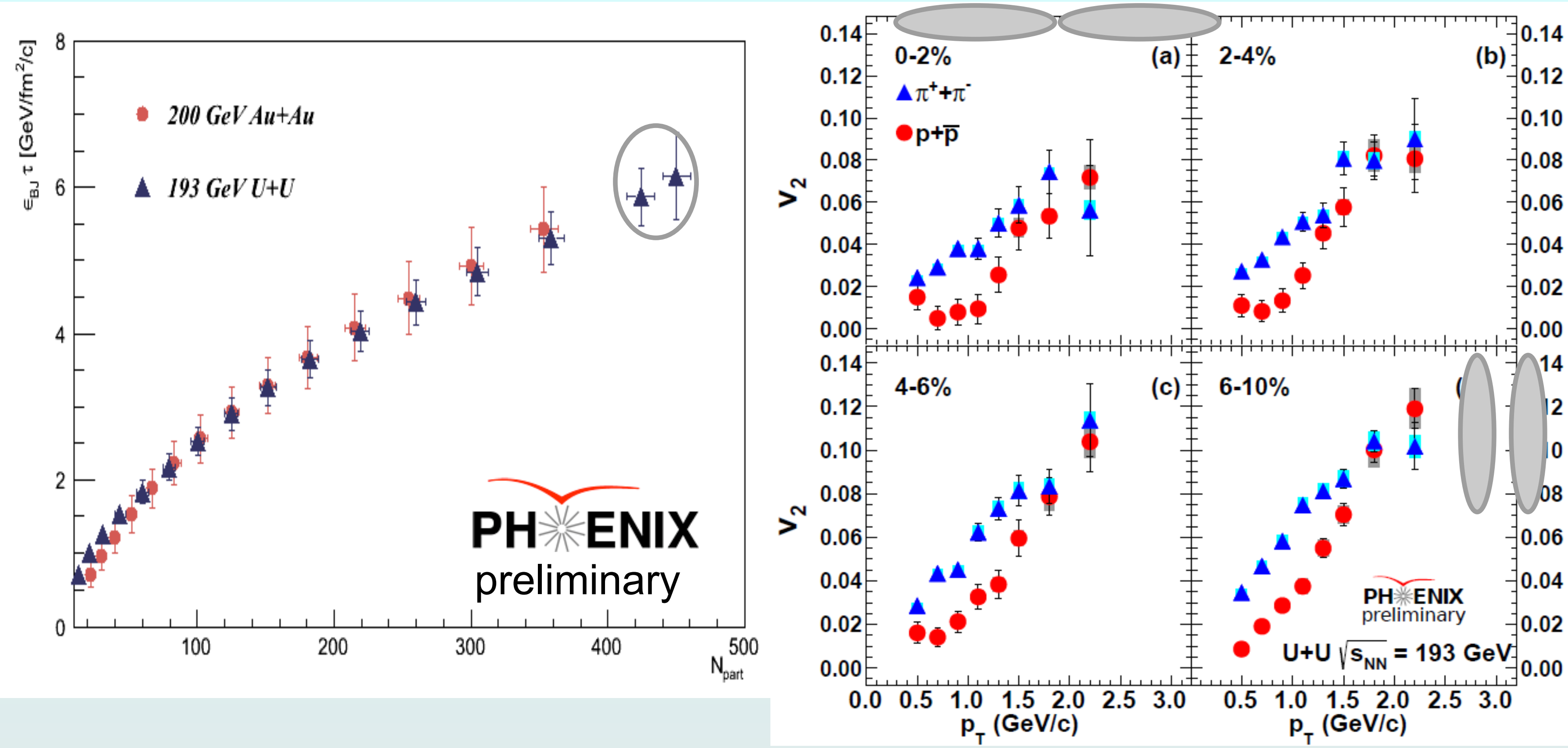
  ➔ Precision tool to constrain sQGP properties.

Precision from PHENIX



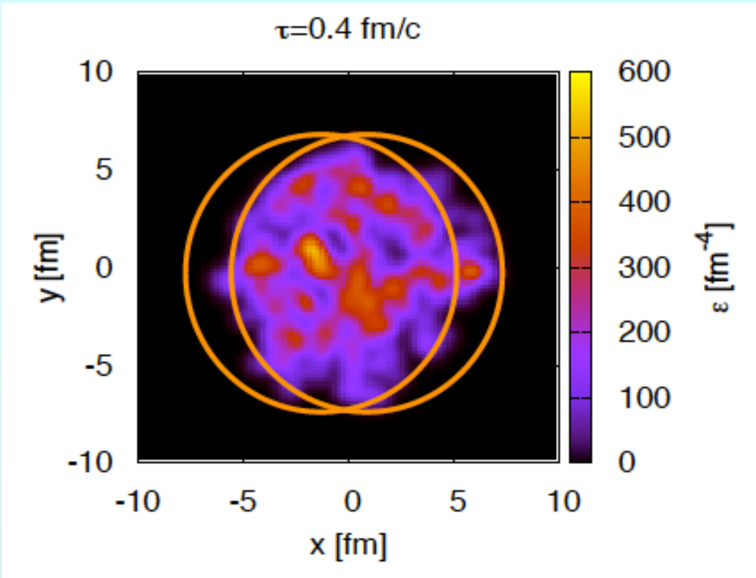
- In central Au + Au v_2 of protons is higher than pions to p_T= 6 GeV/c. In 20-60% centrality, they approach each other at high p_T.
- A break of n_q scaling is observed in 20-60% centrality at KE_T > 0.7 GeV. But in the 0-20% centrality, scaling still holds.
- Production at intermediate p_T for different centralities have different mix of jet fragments vs. coalescence of flowing medium

Control the geometry – try U+U



- The ετ only increases around 20% from 0-10% Au + Au to 0-1% U + U collision.
- Strong mass ordering for π & p v_2 in 0-2% central U + U collision at 193 GeV are observed even though the increase in ετ is relatively small. Radial flow or geometry?

Fluctuations matter!

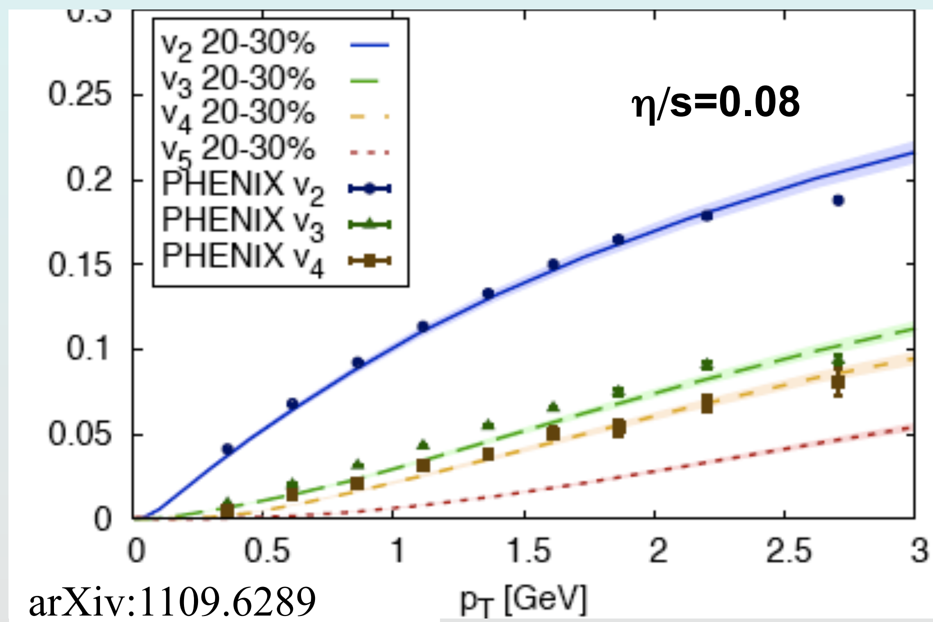


- Nucleons move around inside the nucleus

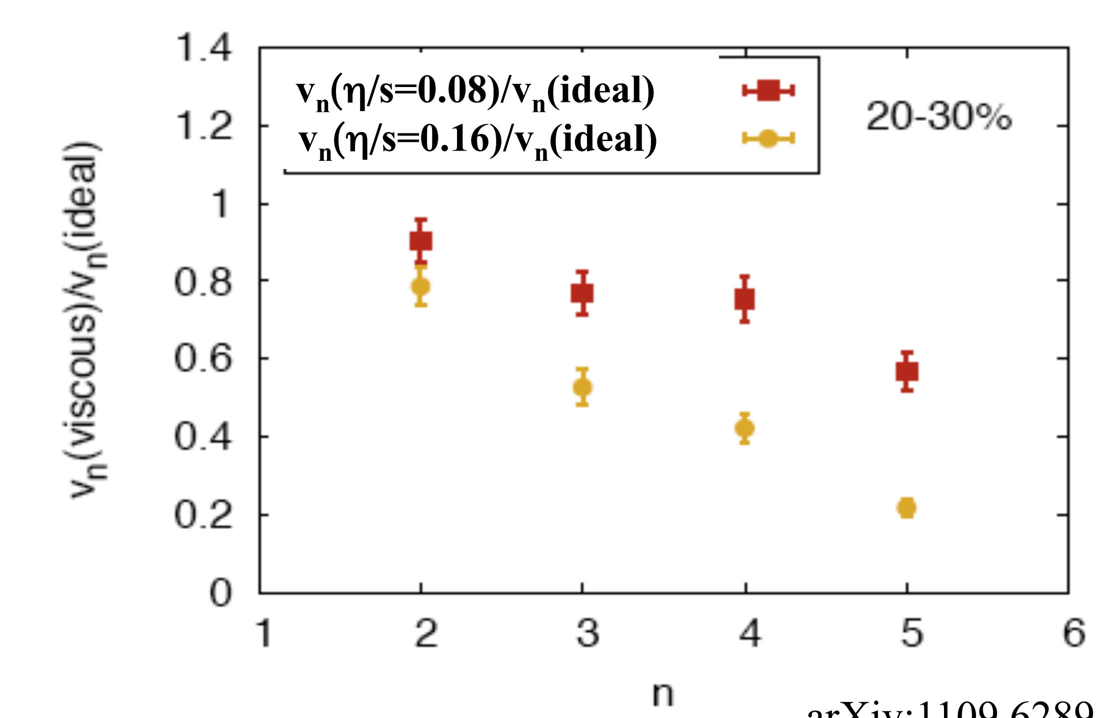
-> locations of NN scattering fluctuate

-> apparent symmetry effects yielding only even harmonics not realistic

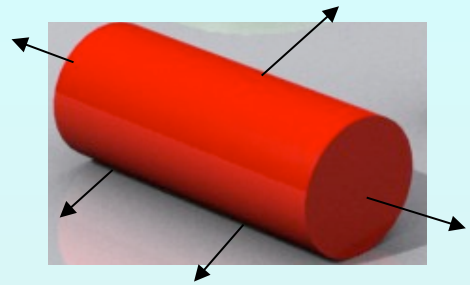
- Reproduce with hydro
- IF include fluctuating initial conditions
- Provides a tool to better pin down the viscosity/entropy ratio

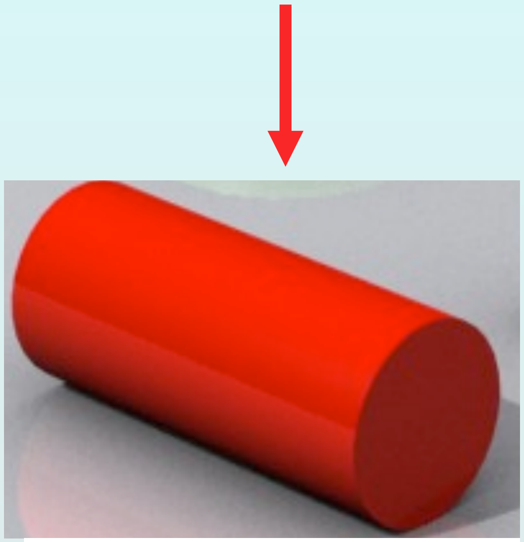


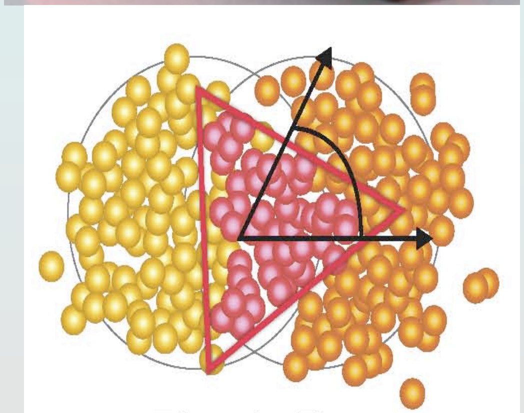
Higher moments more sensitive to viscosity



arXiv:1109.6289

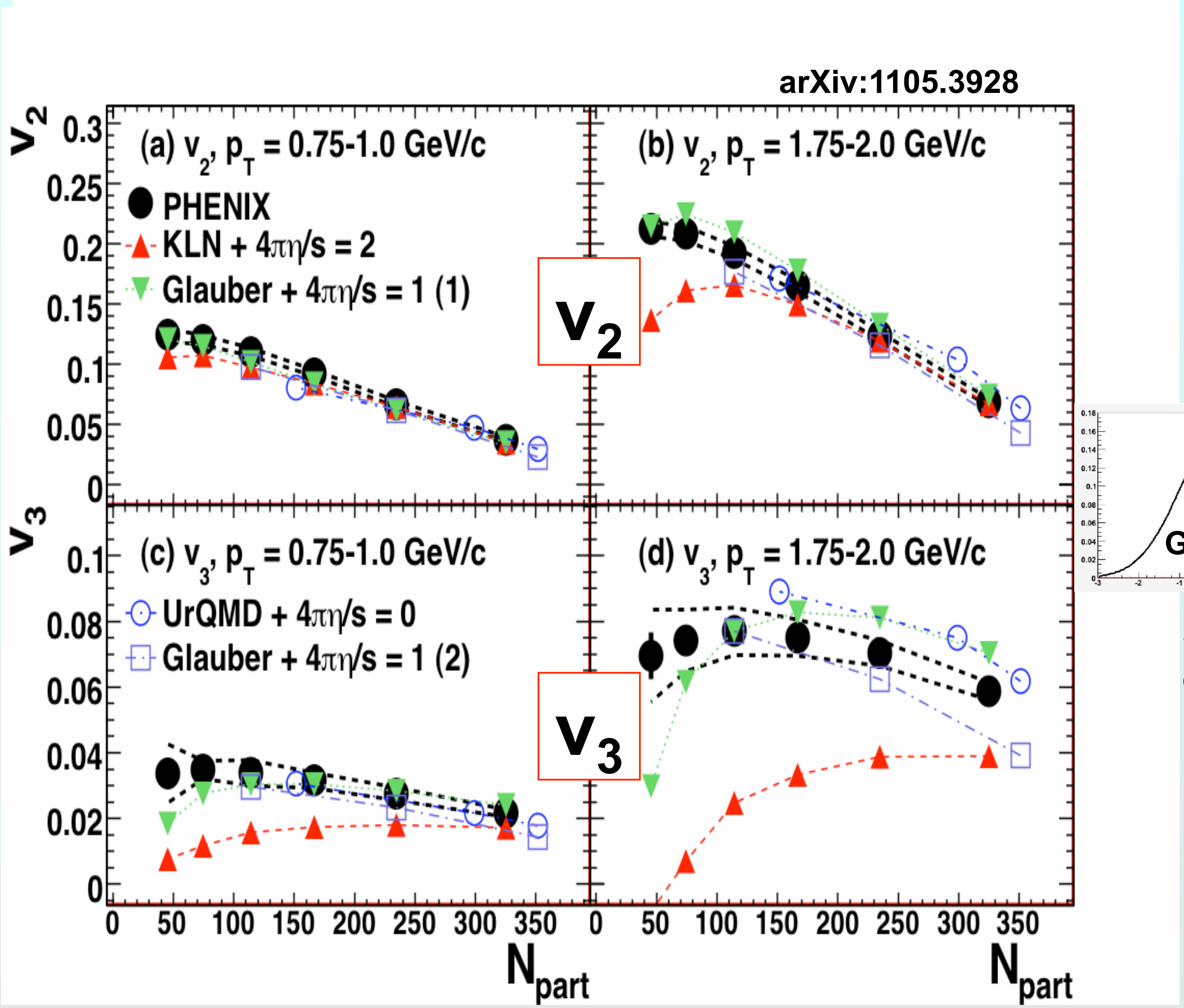


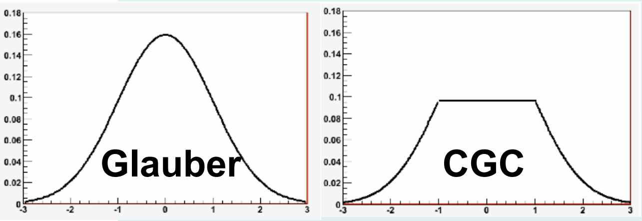




- Longitudinal expansion at v ~ c
- "freezes in" small shape perturbations
  e.g. triangular fluctuations (v_3)
- Viscosity opposes dissipation!

Data prefer smaller eccentricity & low η/s





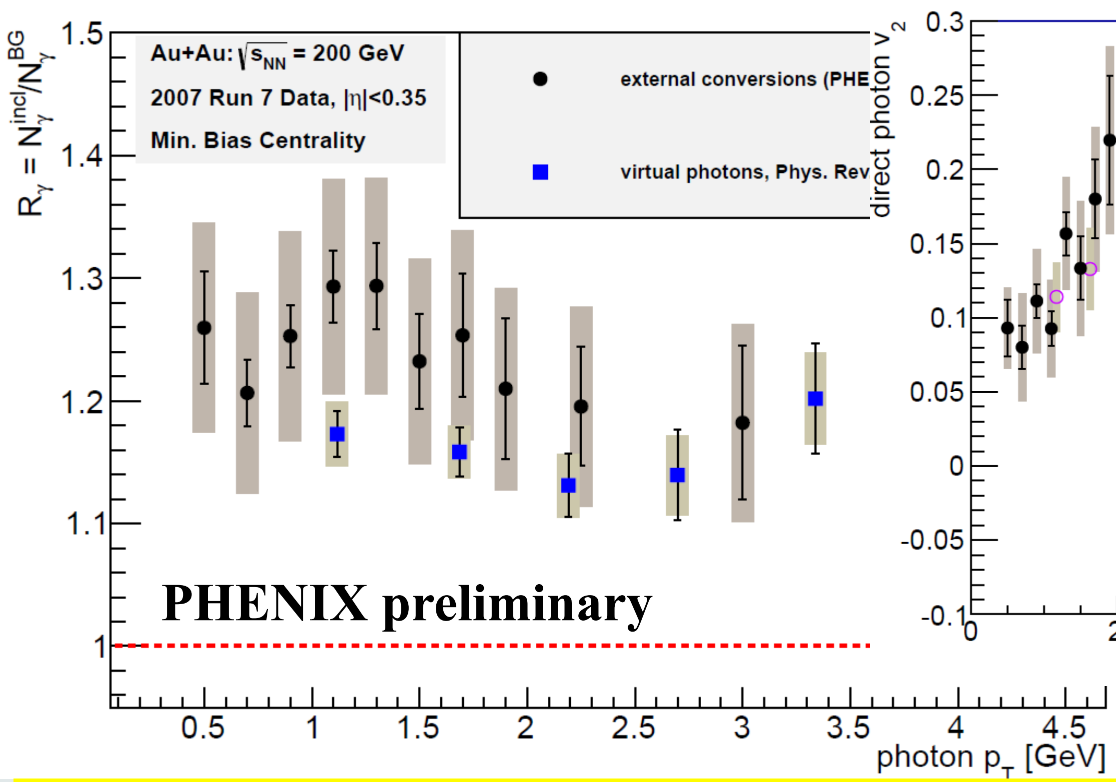
Smaller eccentricity

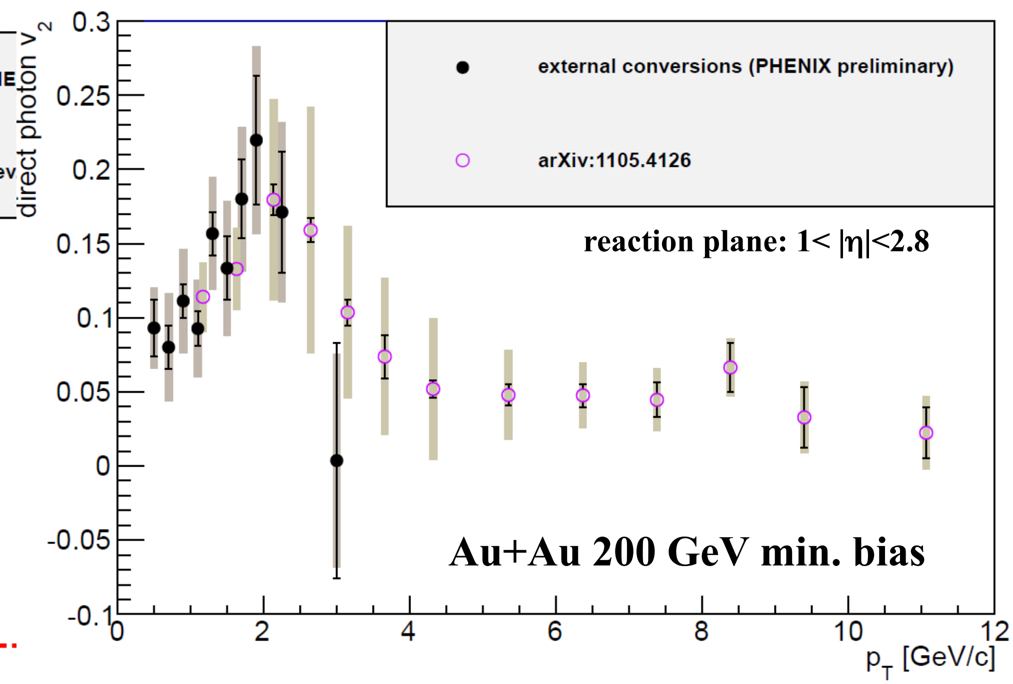
Larger eccentricity

Thermal radiation and hadron gas effects

New measurement of thermal photons

- **PHENIX has a new method to detect direct photons:**
  - **Use photon conversions to e^+e^-**
  - **Tag contribution from π^0 decays & compare to MC**
  - **Independent systematic uncertainties**

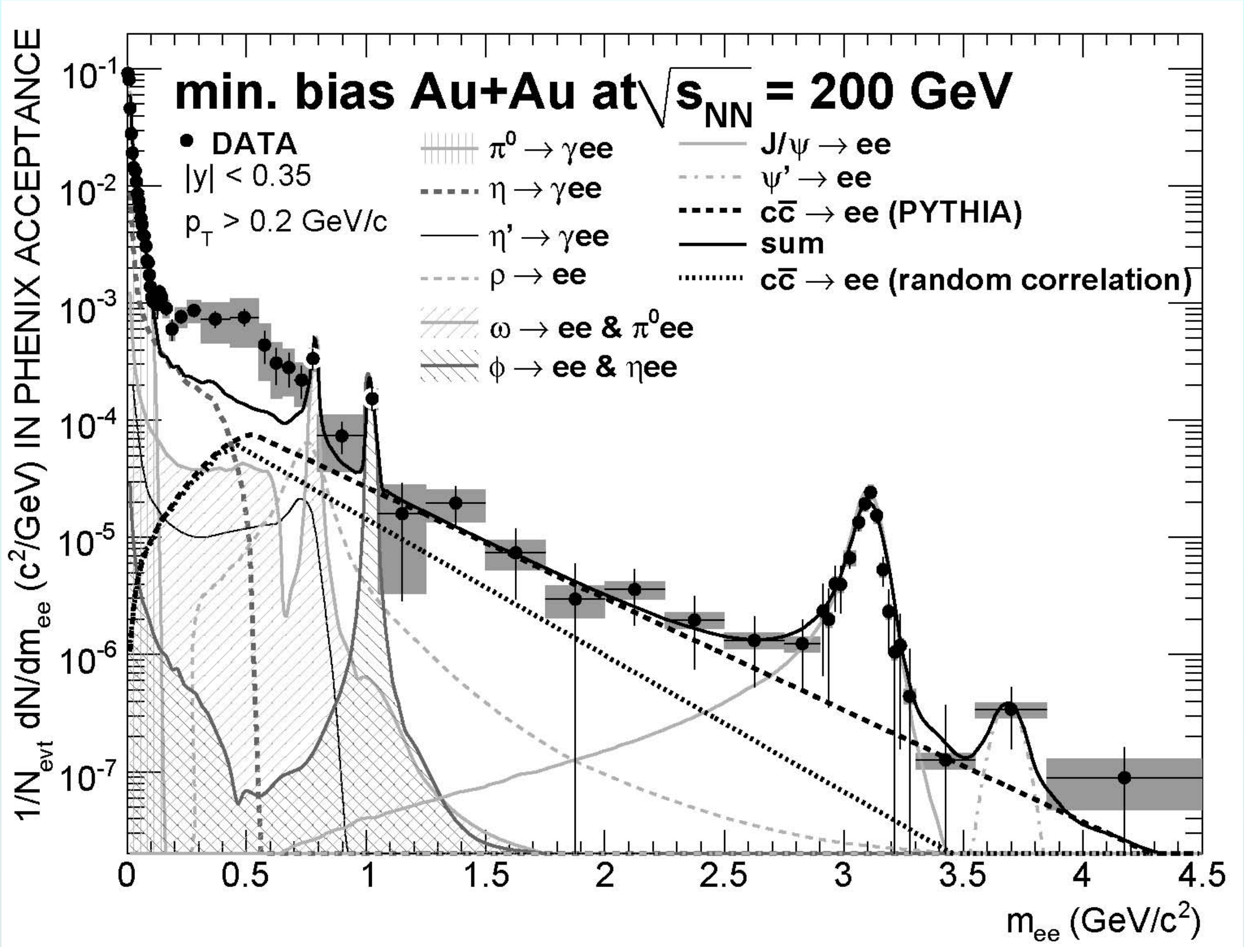




Results agree with earlier result on photon yield & flow!

How to reconcile yield (early emission) & large flow (late)?

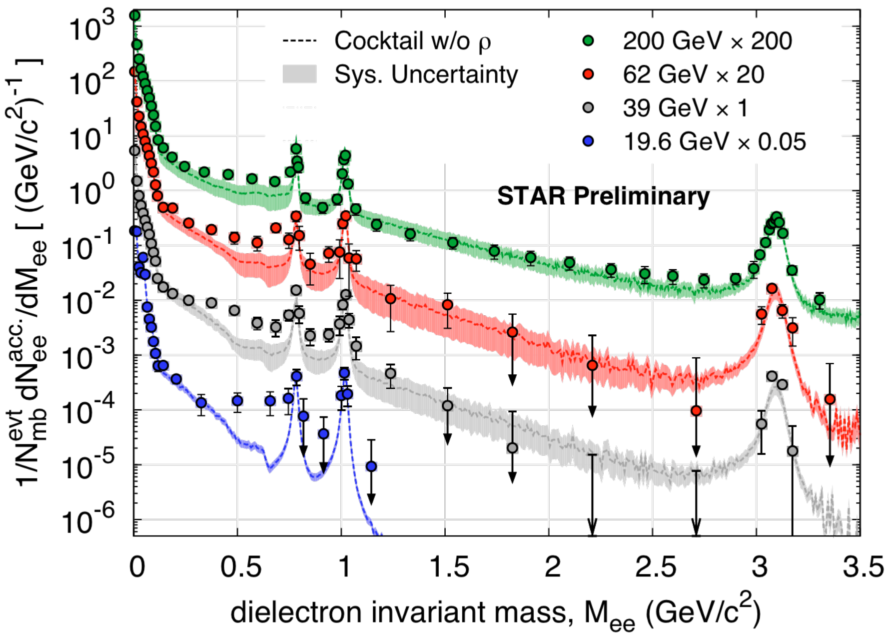
Dielectron puzzle



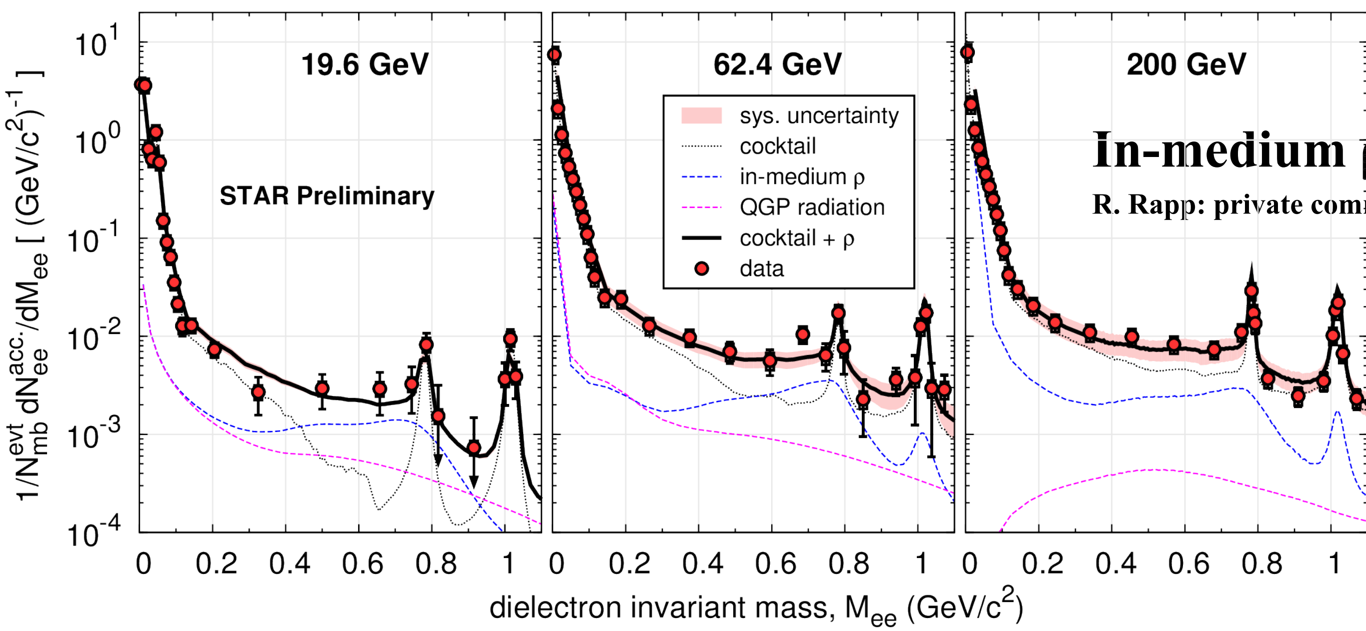
Previous PHENIX result

- **Excess difficult to understand**
- **Pre-equilibrium effect? (γ are surprising too)**

Dielectron Production



- Systematic look at dielectron mass spectra over broad energy range.
- In-medium *ρ* broadening with similar baryon densities from 19.6 - 200 GeV reproduce STAR LMR excesses.

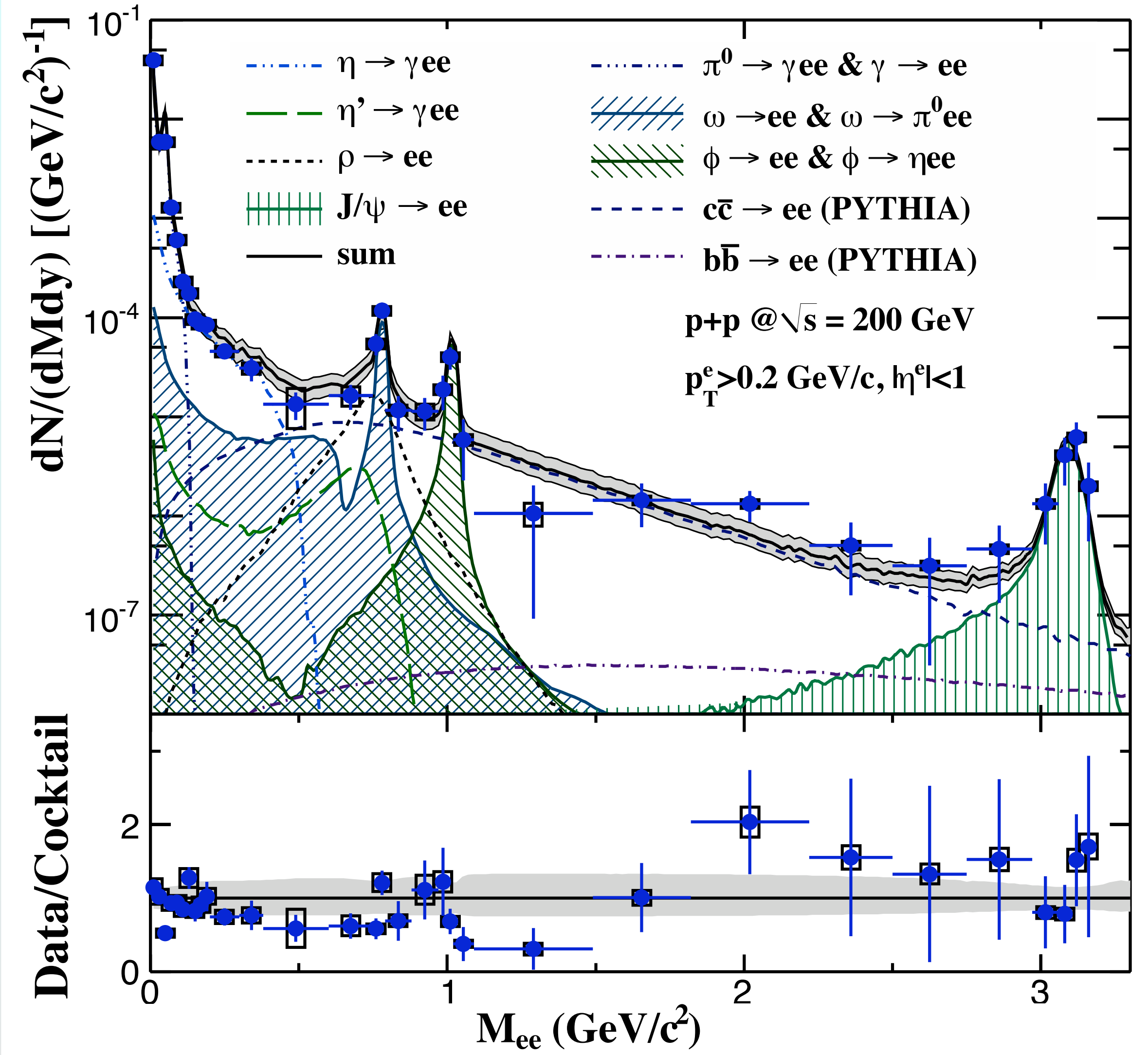


In-medium ρ broadening

R. Rapp: private communications

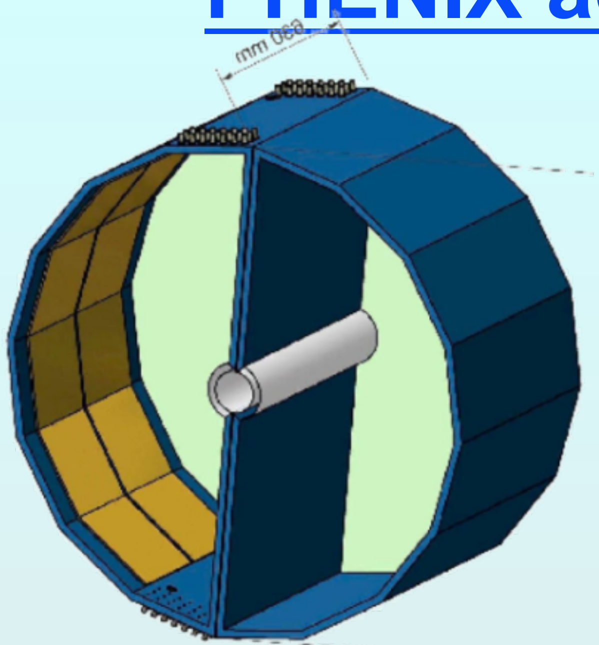
The devil is in the background

STAR - Phys. Rev. C 86, 024906 (2012)



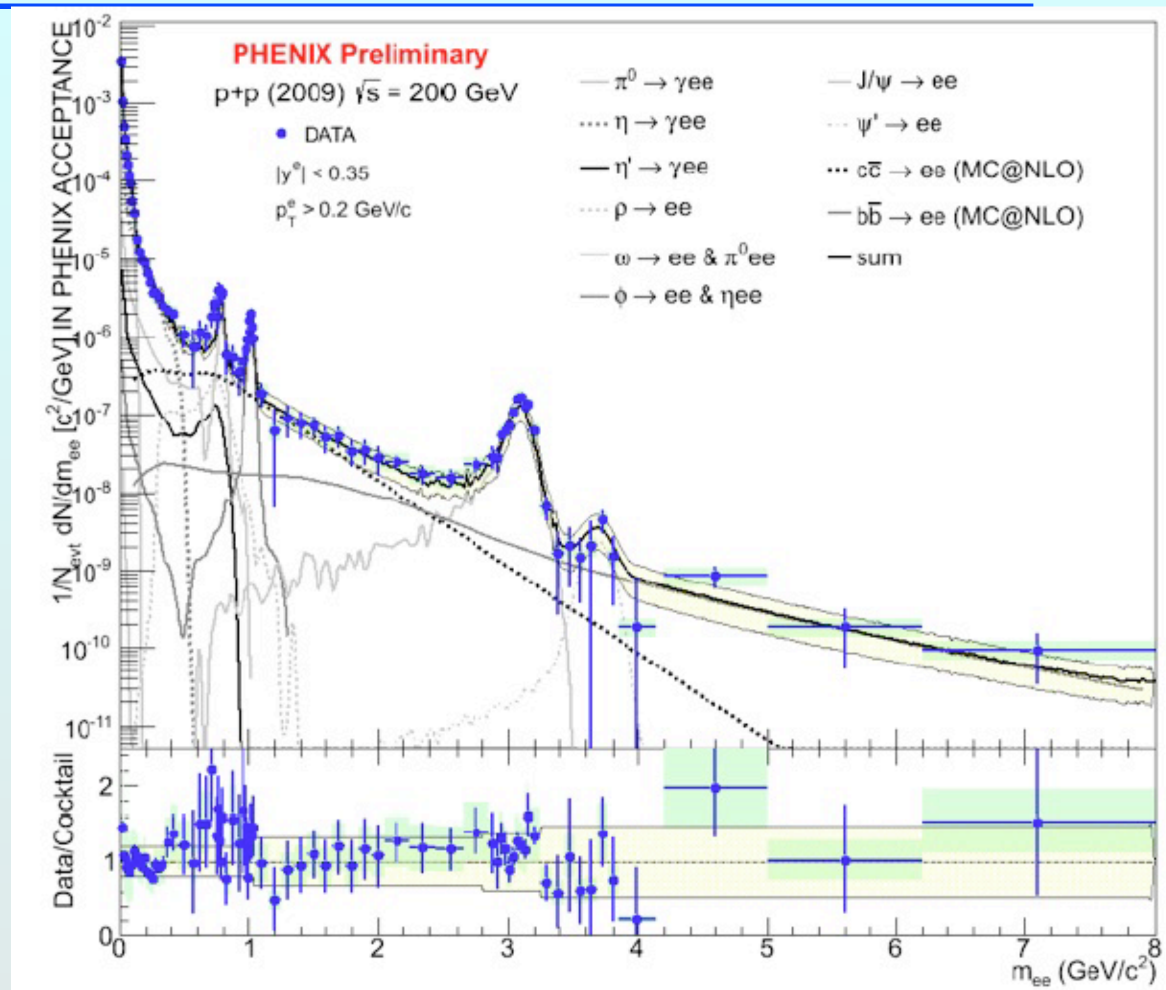
p+p at 200 GeV

PHENIX added hadron blind detector



Windowless CF4 Cherenkov detector; GEM/CSI photo cathode readout in B-field free region

Goal: improve S/B by rejecting conversions and π^0 Dalitz decays

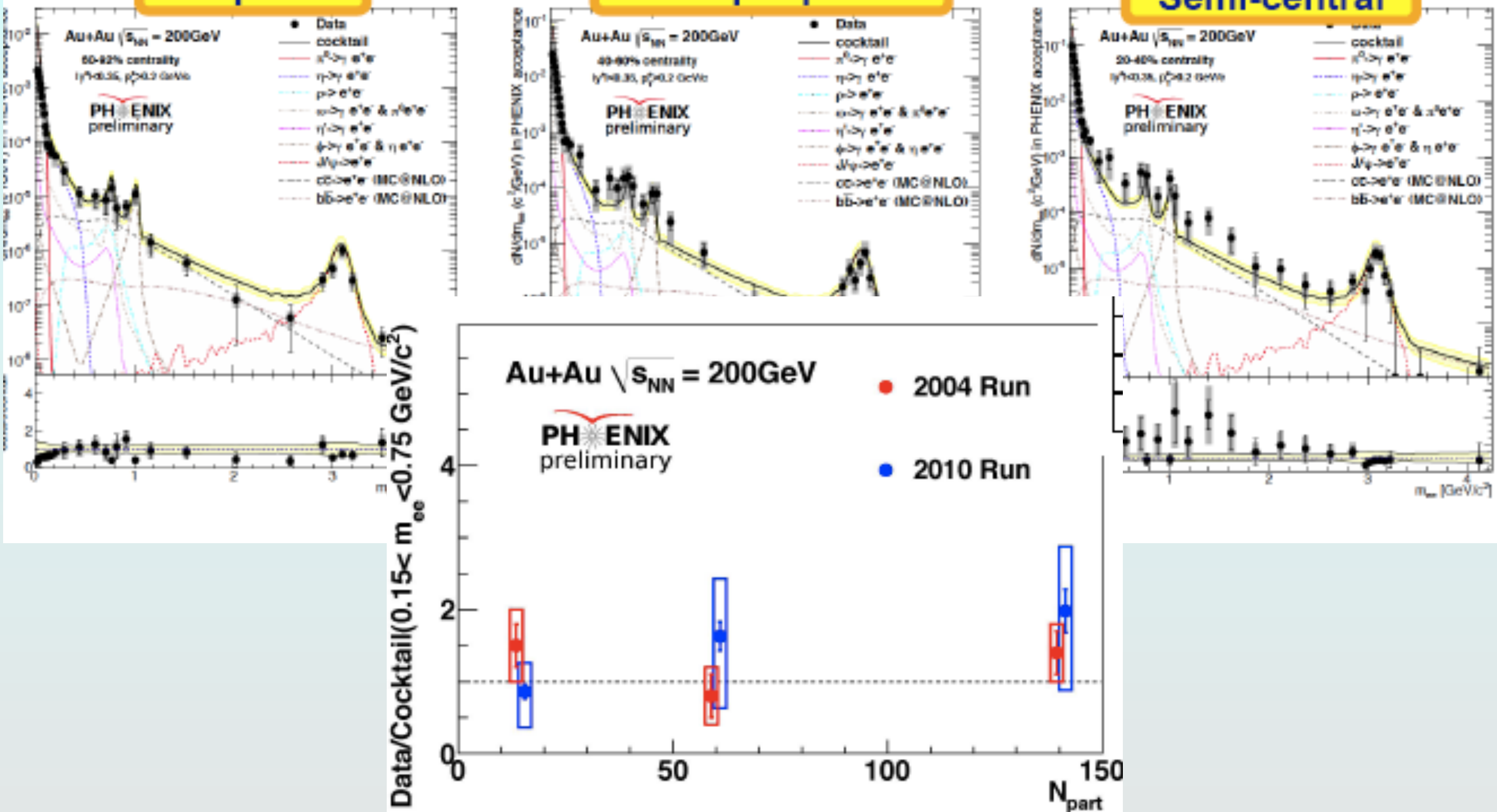


- Figure of merit: $N_0 = 322\ cm^{-1}$, 20 p.e. for a single electron
- Preliminary results:

  S/B improvement of ~5 wrt previous results w/o HBD

In Au+Au

Peripheral | **Semi-peripheral** | **Semi-central**



Consistent results

Stay tuned to this channel!

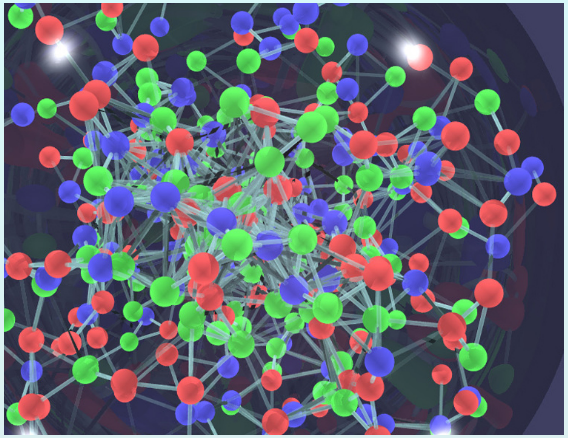
- **Backup**

Currently a raging debate

- Just *WHAT* is interacting in the hot dense plasma?

Individual gluons?

Pure fields?



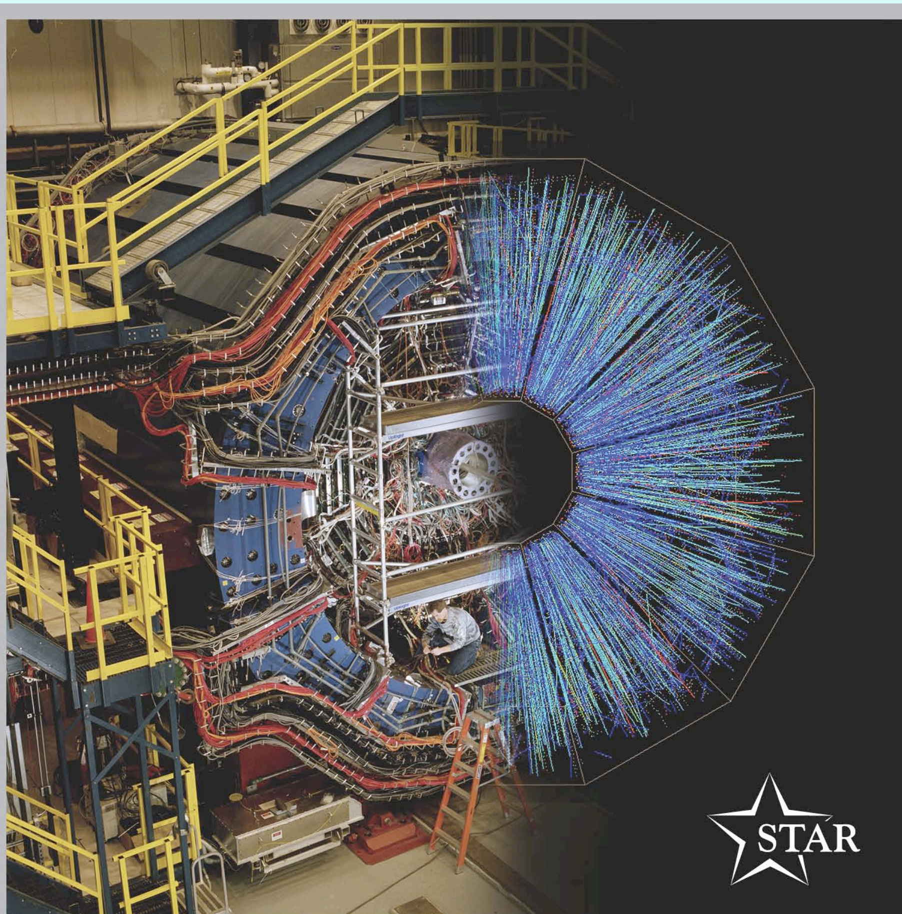
Multi-gluons that continuously split & re-form?

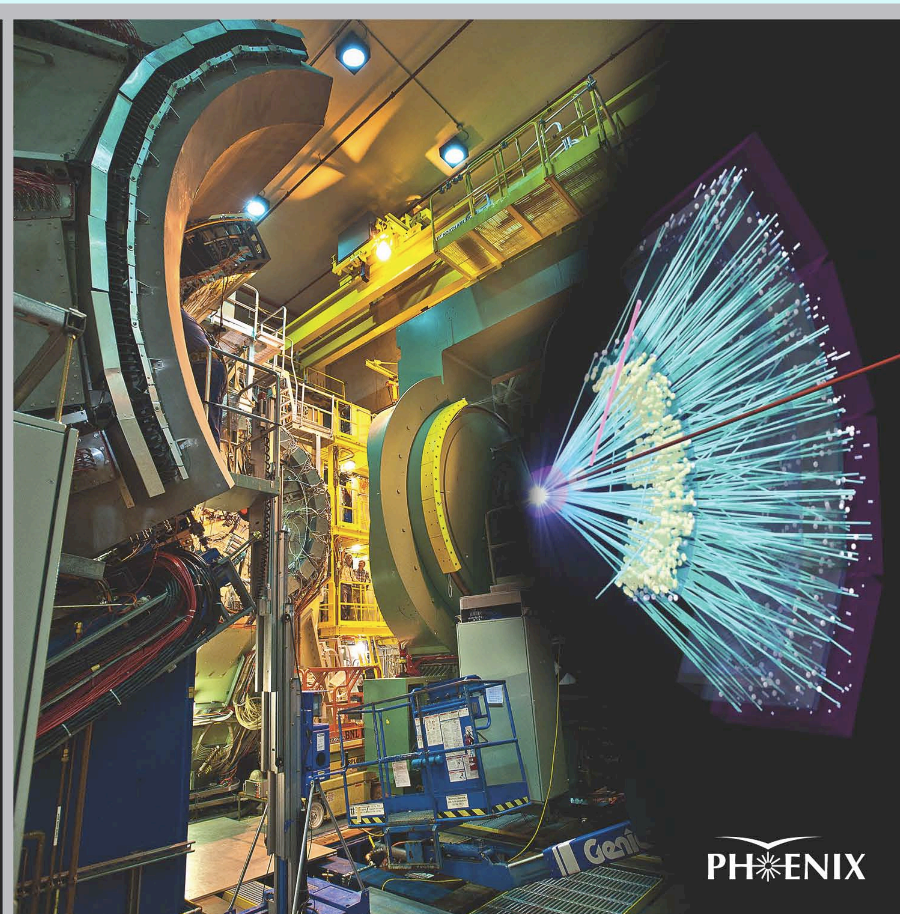
i.e. composite quasiparticles

(in classical liquids voids fill this role)

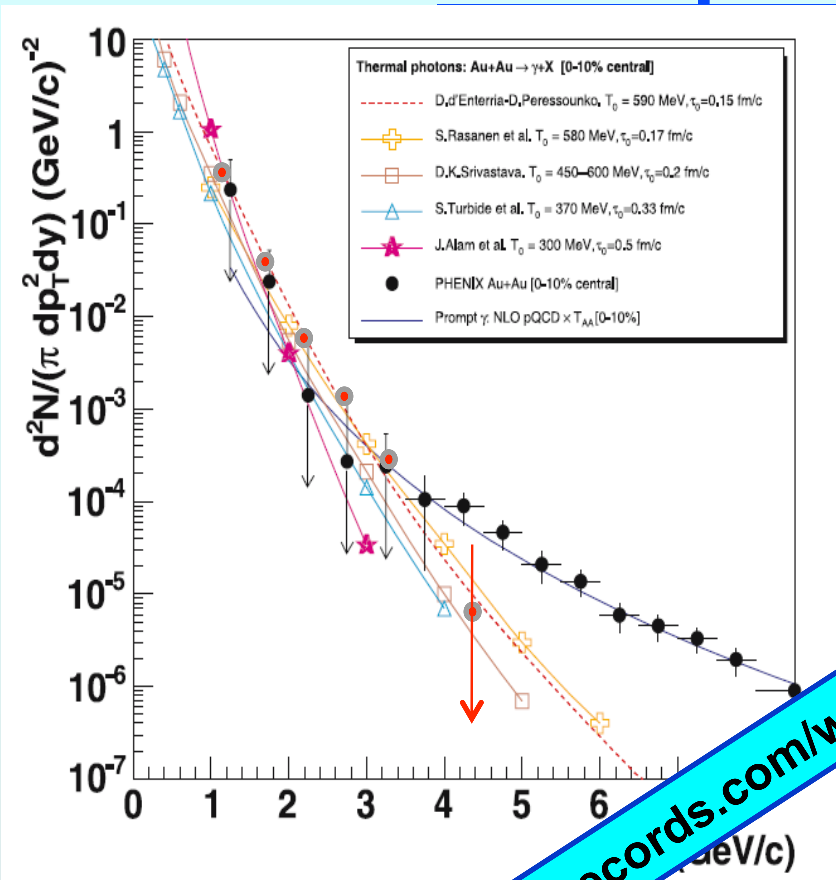
- Energy loss mechanism tests these ideas
- Quantify dynamical properties of this new material:
  Viscosity, speed of sound, diffusion
  i.e. transport of momentum, energy & particles

The experiments



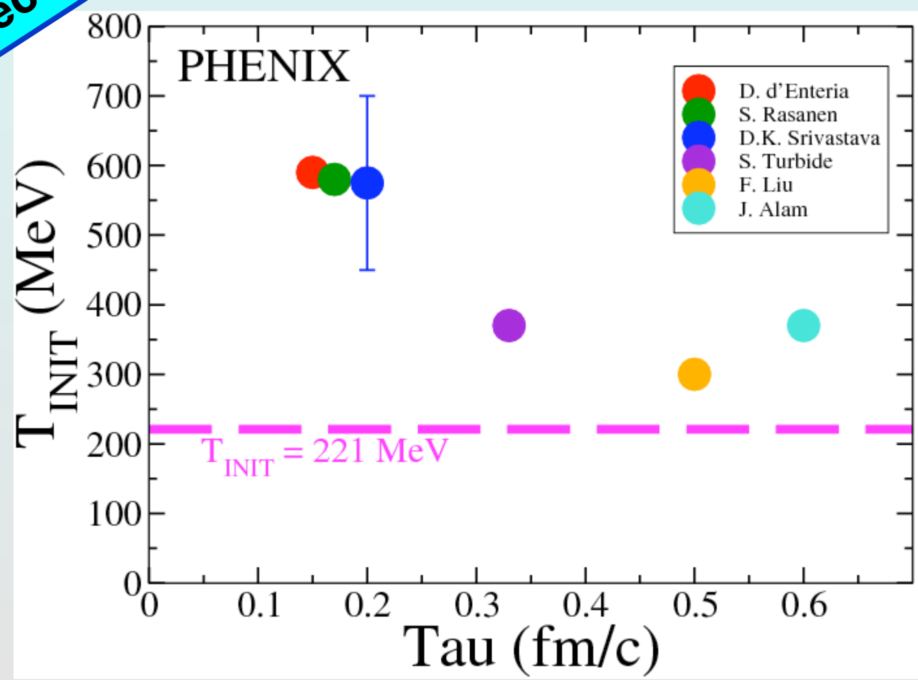


direct photons: $T_{init} > T_c$!



- **Exponential fit in p_T:** T_{avg} = 221 ±23 ±18 MeV

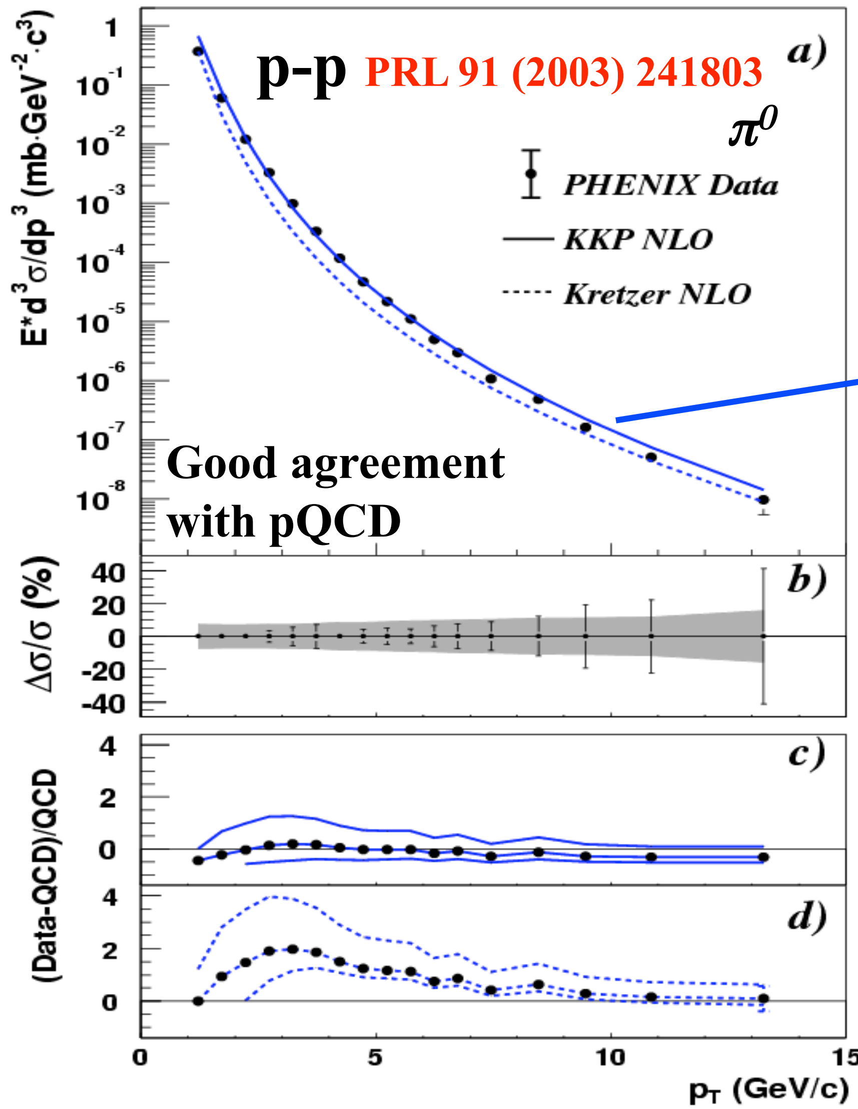
- **Multiple hydrodynamics models reproduce data** T_0 [illegible] 300 MeV

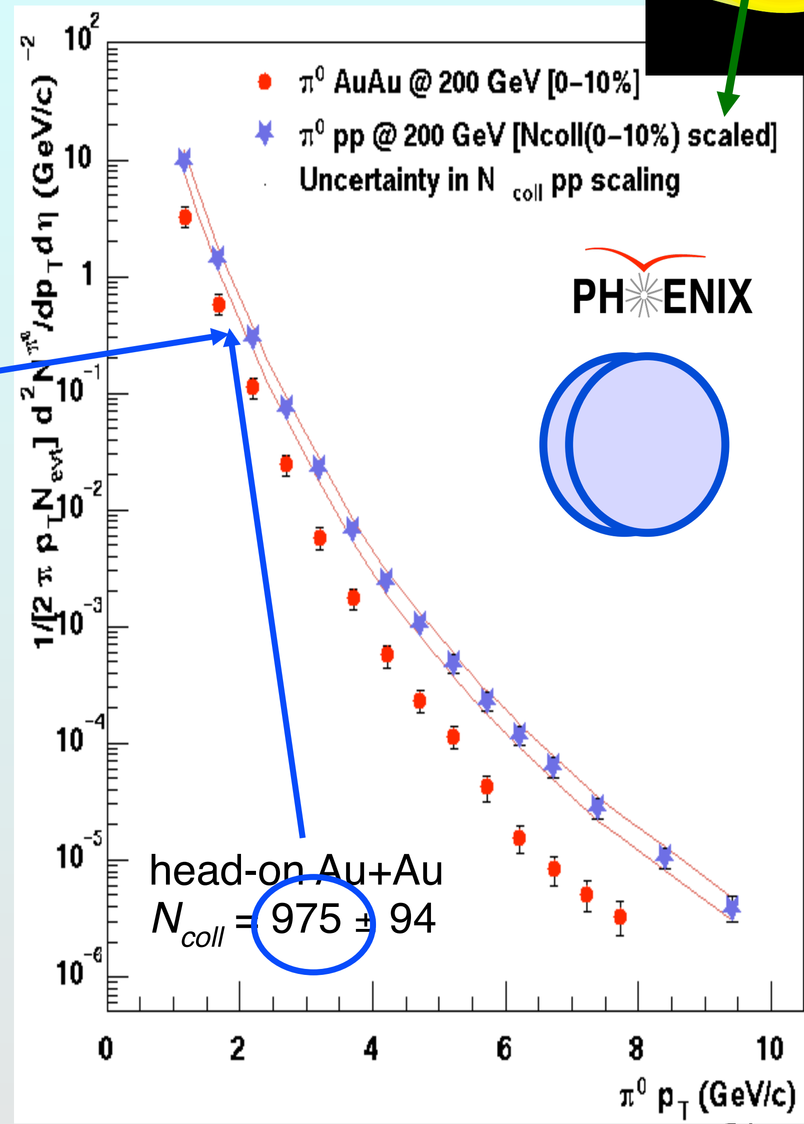


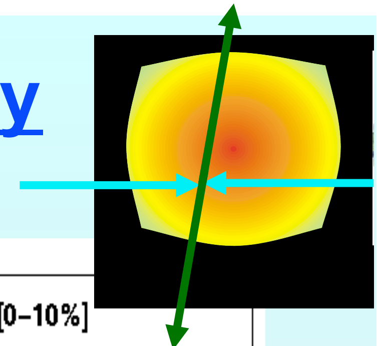
NB: T_c ~ 150 MeV
@ LHC: T_{avg} = 304±51 MeV
hydrodynamic T_{init} ~ 30% higher than at RHIC

http://www.guinnessworldrecords.com/world-records/10000/highest-man-made-temperature

“External” probe of plasma opacity

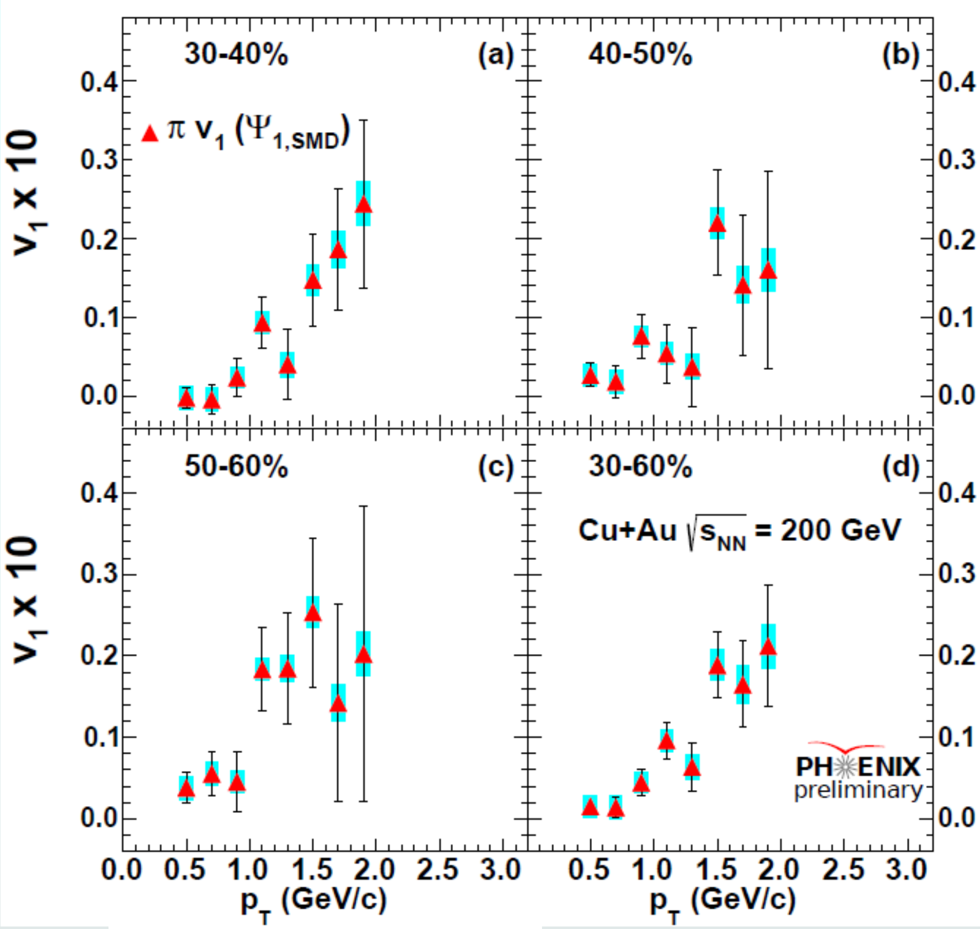


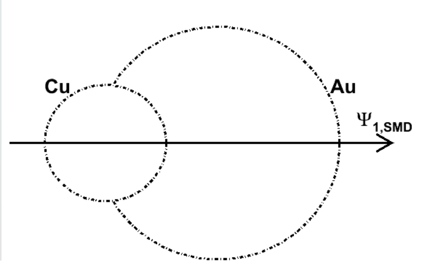




π v_1 in Cu + Au at 200 GeV

20% of full statistics

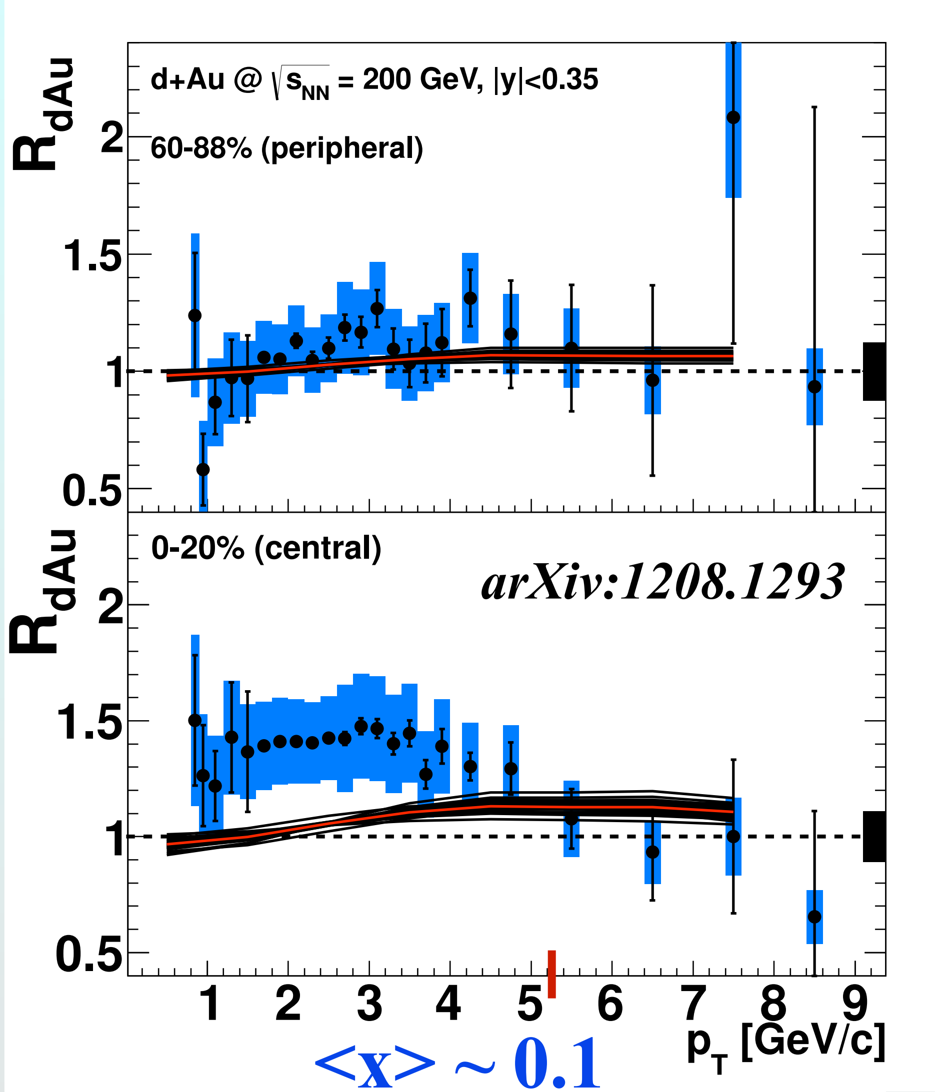




- Sizeable positive v_1 is observed at p_T > 1GeV/c with $\Psi_{1,smd}$, which direction is decided by the Au spectators. It indicates that there are more particles emitted from the Au side than from the Cu side .
- It may be due to asymmetric density profile, pressure gradient and anti-flow effect
- The v_1 of protons will be measured in near future after production of full statistics. It will help us to further address the physics of this positive v_1

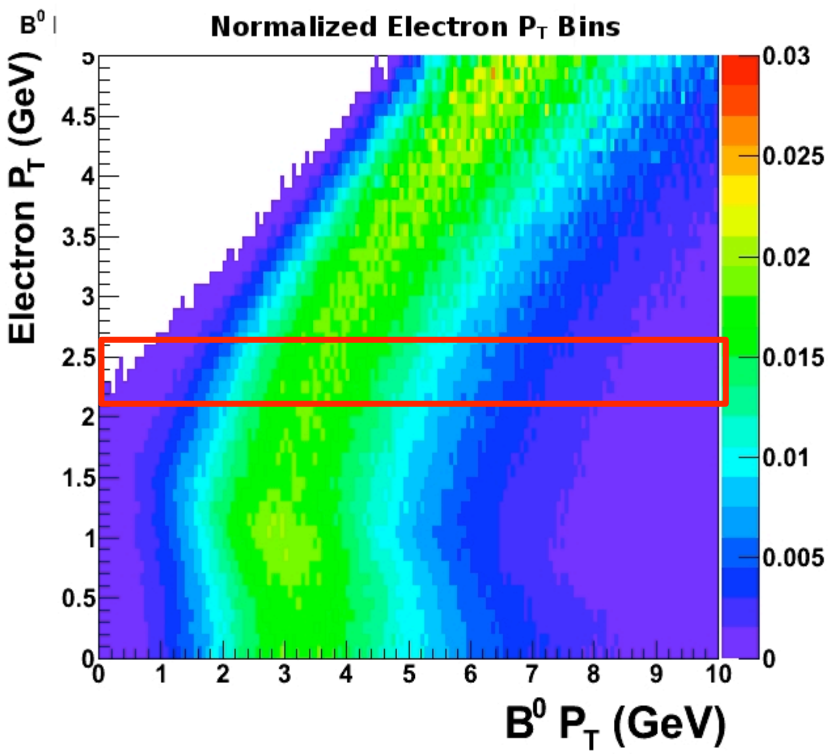
Comparison to EPS09 calculation

- Single electrons from heavy flavor semi-leptonic decays
- Enhancement at intermediate p_T
  → Cronin-like k_T scattering?
- No evidence of suppression
  → Au+Au effect entirely HNM?
- Detector configuration prevents measurement below p_T~0.8 GeV/c
- Shadowing-only calculation reproduces peripheral modification, but not central
- → Opposite of π^0 case
- → Need additional physics



<x> ~ 0.1

We measure electrons

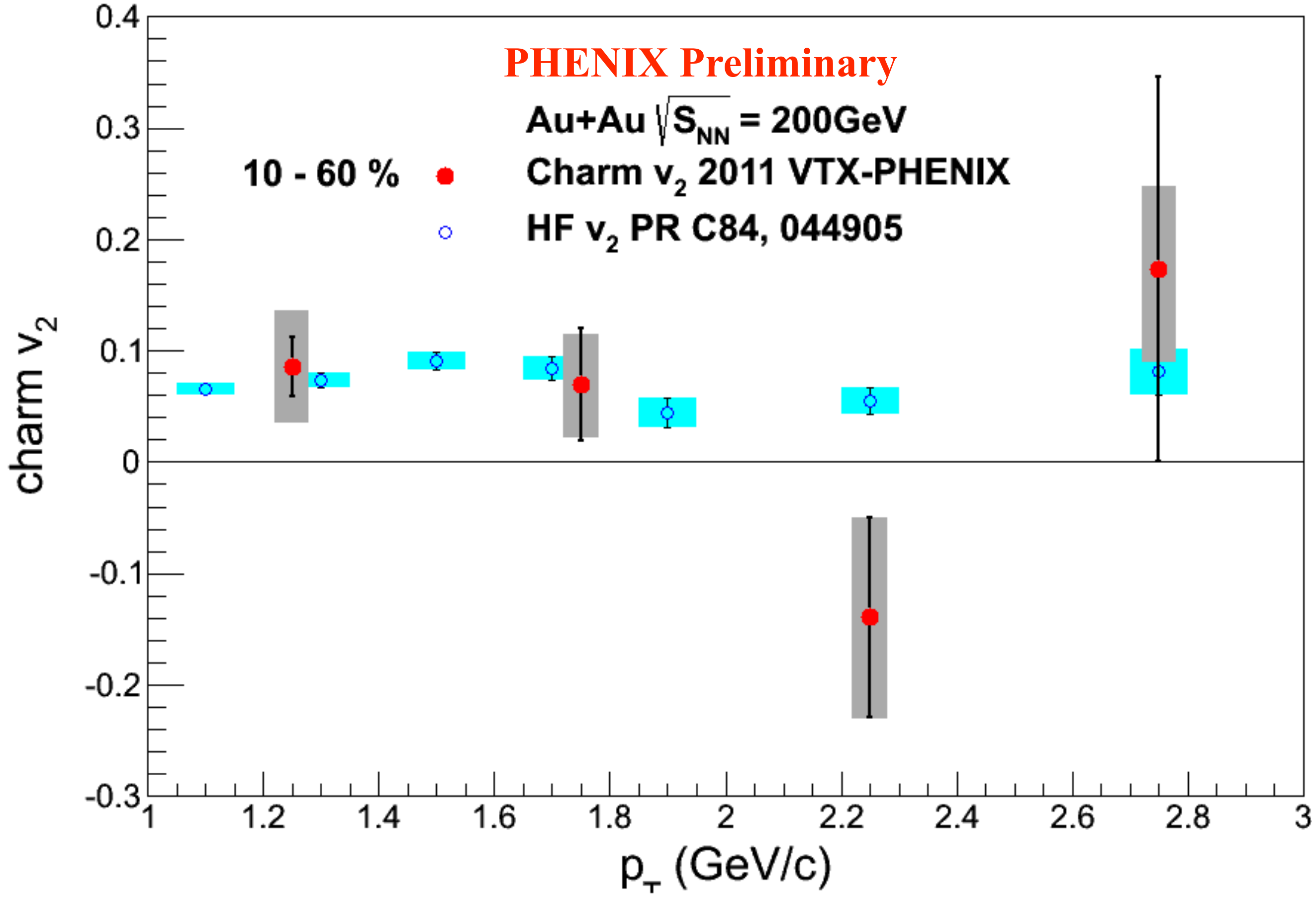


PYTHIA simulation of B^0 decays

Electrons with $2GeV/c<p_T<2.5GeV/c$ are coming from B mesons with $p_T=2-4GeV/c$ that have $\beta\gamma=0.4-0.8$

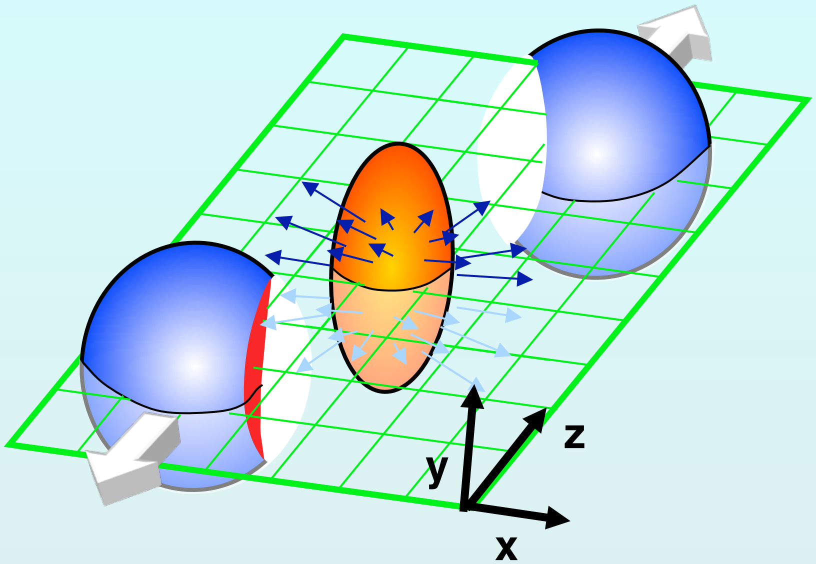
Charm v_2

Using DCA decomposition

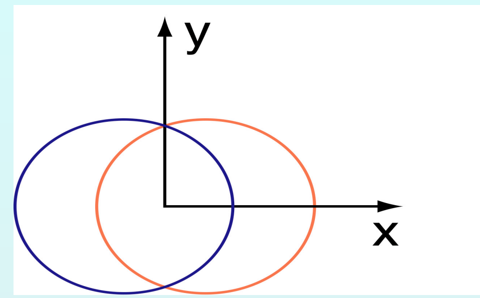


M. Kurosawa talk Parallel #3A talk on Wednesday

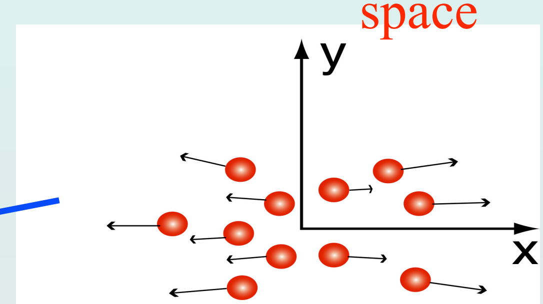
Watch QGP blow up → collective flow (v_2)

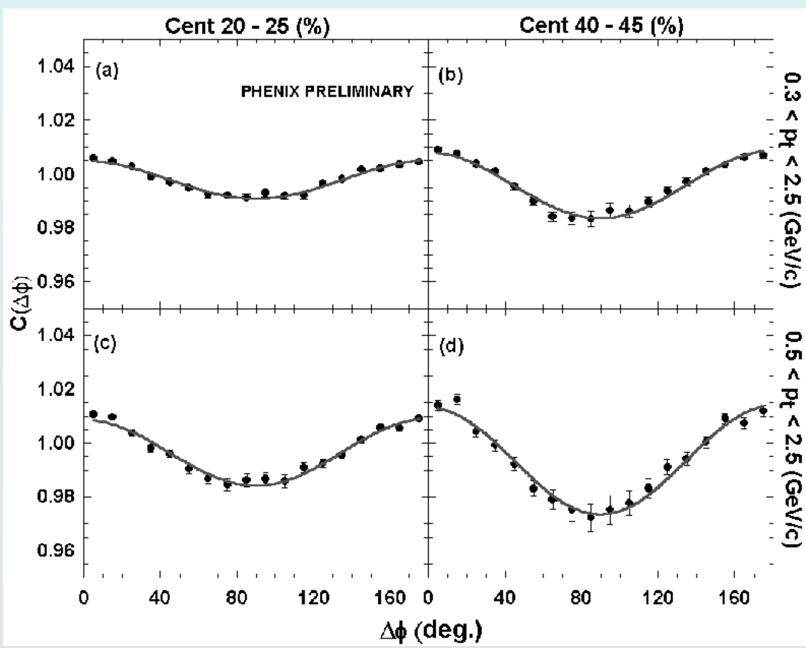


Almond shape overlap region in coordinate space



momentum space





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

"elliptic flow"

Surprise: viscosity/entropy is small

Viscosity: inability to transport momentum & sustain a wave

low viscosity → absorbs particles & transports disturbances

Viscosity/entropy near 1/4π limit from quantum mechanics!

∴ liquid at RHIC is "perfect"

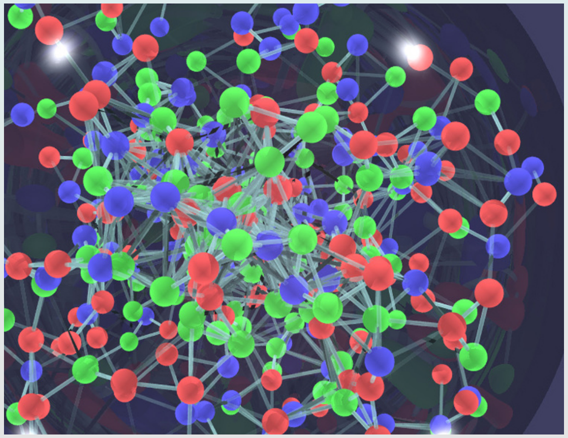
Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Good momentum transport: neighboring fluid elements "talk" to each other

→ QGP is strongly coupled

Should affect opacity :

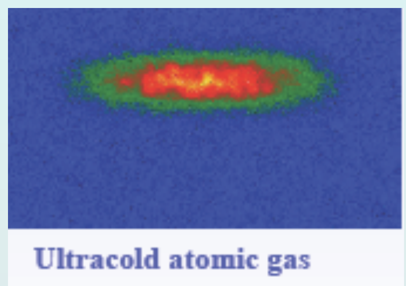
e.g. q,g collide with "clumps" of gluons, not individuals

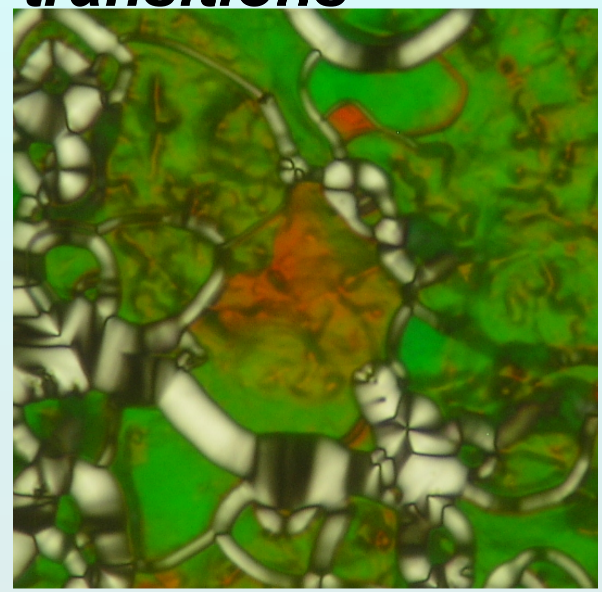


Many types of strongly coupled matter

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

Strongly correlated

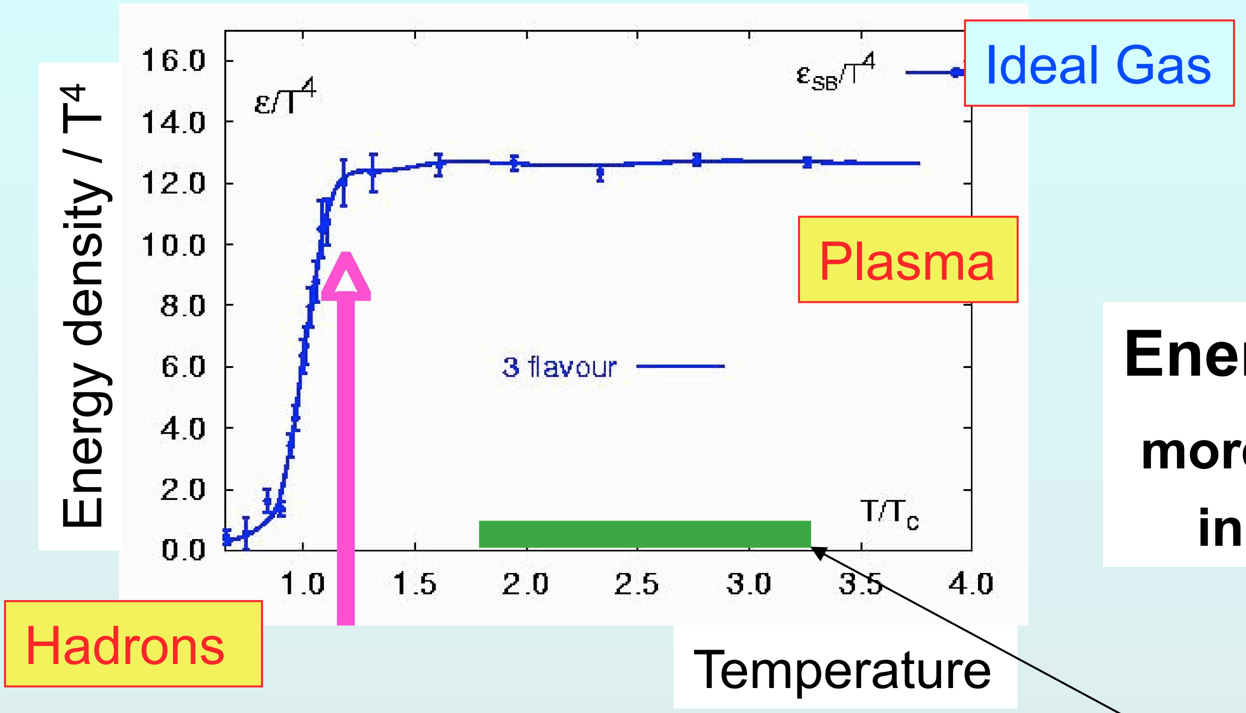
In all these cases have a competition:

Attractive forces ⇔ repulsive force or kinetic energy

High T_c superconductors: magnetic vs. potential energy

Result: many-body interactions, not pairwise!

So, it must be quark gluon plasma



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

Energy density ∝ T^4

more degrees of freedom in the plasma phase

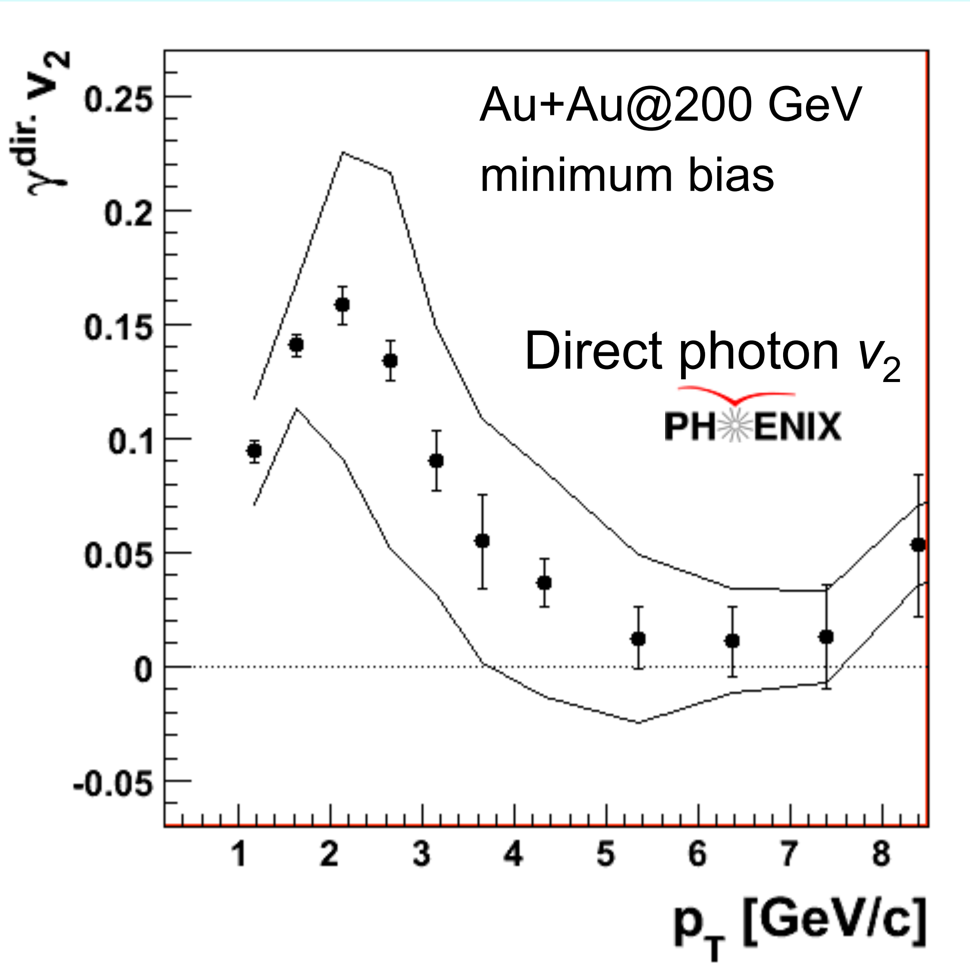
We are somewhere around here

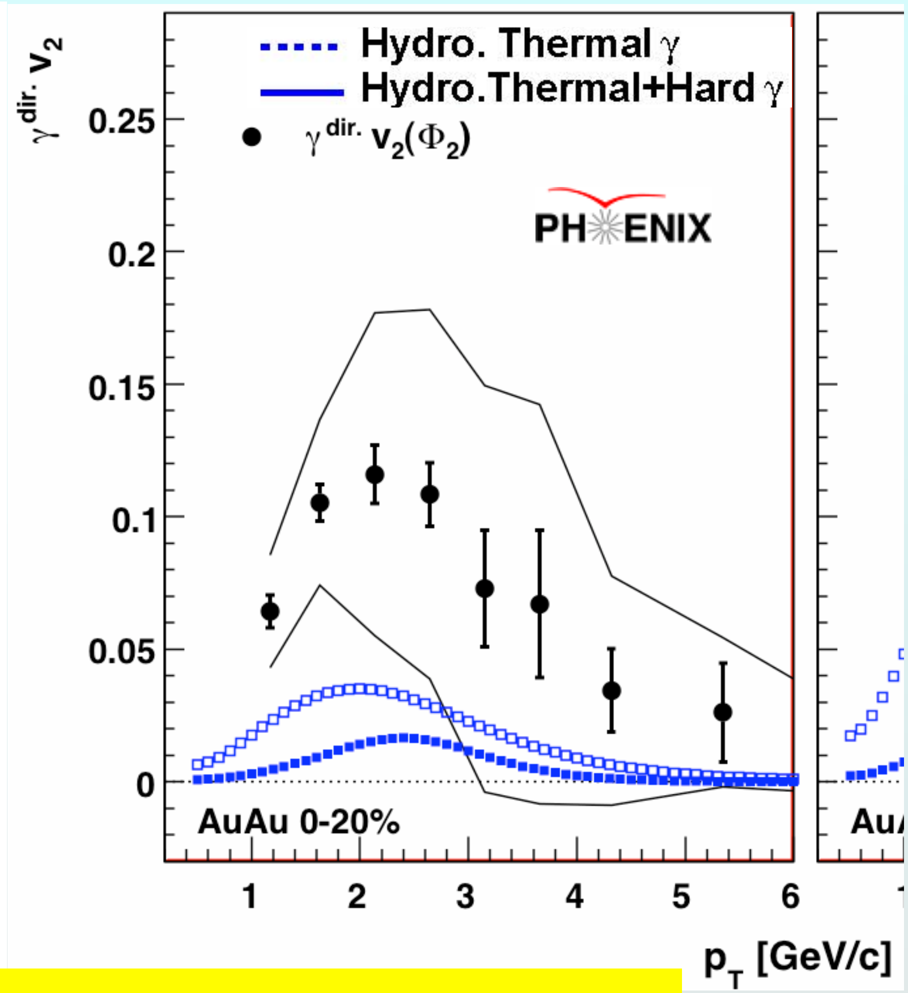
T_c ~ 150 MeV

ε ~ 3 GeV/fm^3

Thermal photons also flow!

arXiv:1105.4126

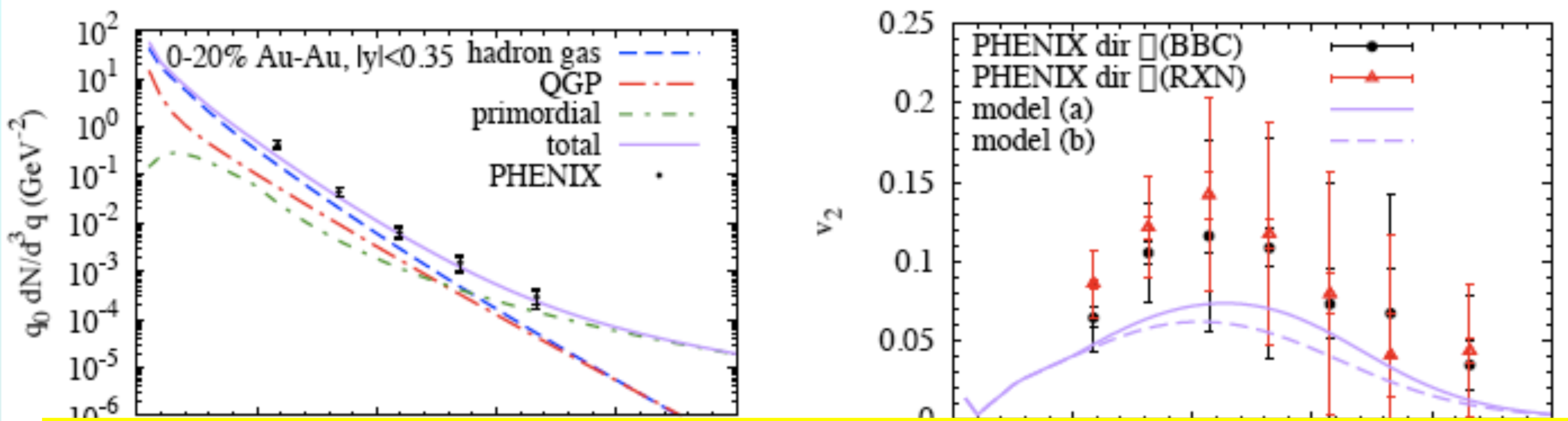




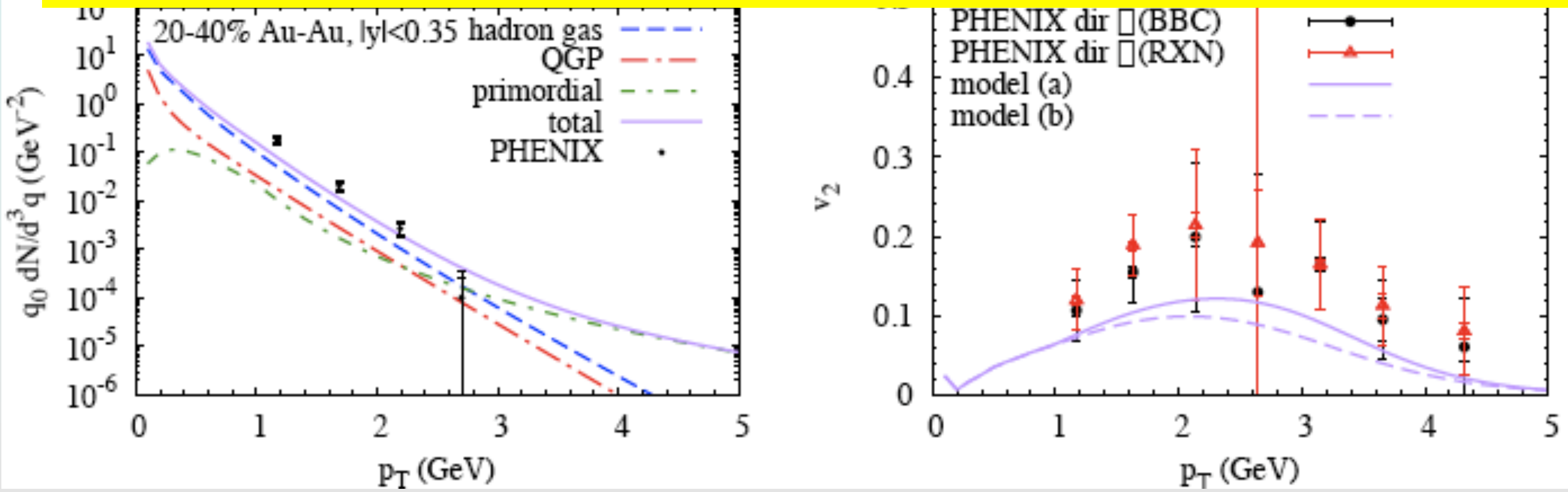
Flow magnitude is surprising. Can “extras” explain it?

+ photons from expanding hadron gas

vanHees, Gale & Rapp, arXiv:1108.2131



Answer = yes, if "extras" come from a very rapidly expanding hadron gas, that lives longer than initially expected



What are the properties of hot QCD matter?

- thermodynamic (equilibrium)
  T, P, ρ
  EOS (relation between 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
NB: we deal with strong, not EM force: exchange g instead of γ

measuring these is new for nuclear/particle physics!

Nature is nasty to us: does a time integral…

Lepton pair emission ↔ EM correlator

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

Emission rate of dileptons per volume

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

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

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

γ*→ee decay

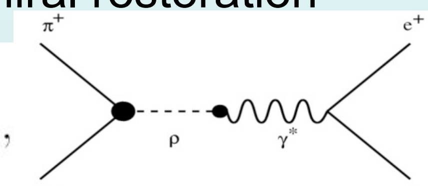
EM correlator
Medium property

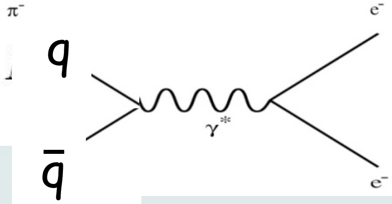
Boltzmann factor
temperature

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)

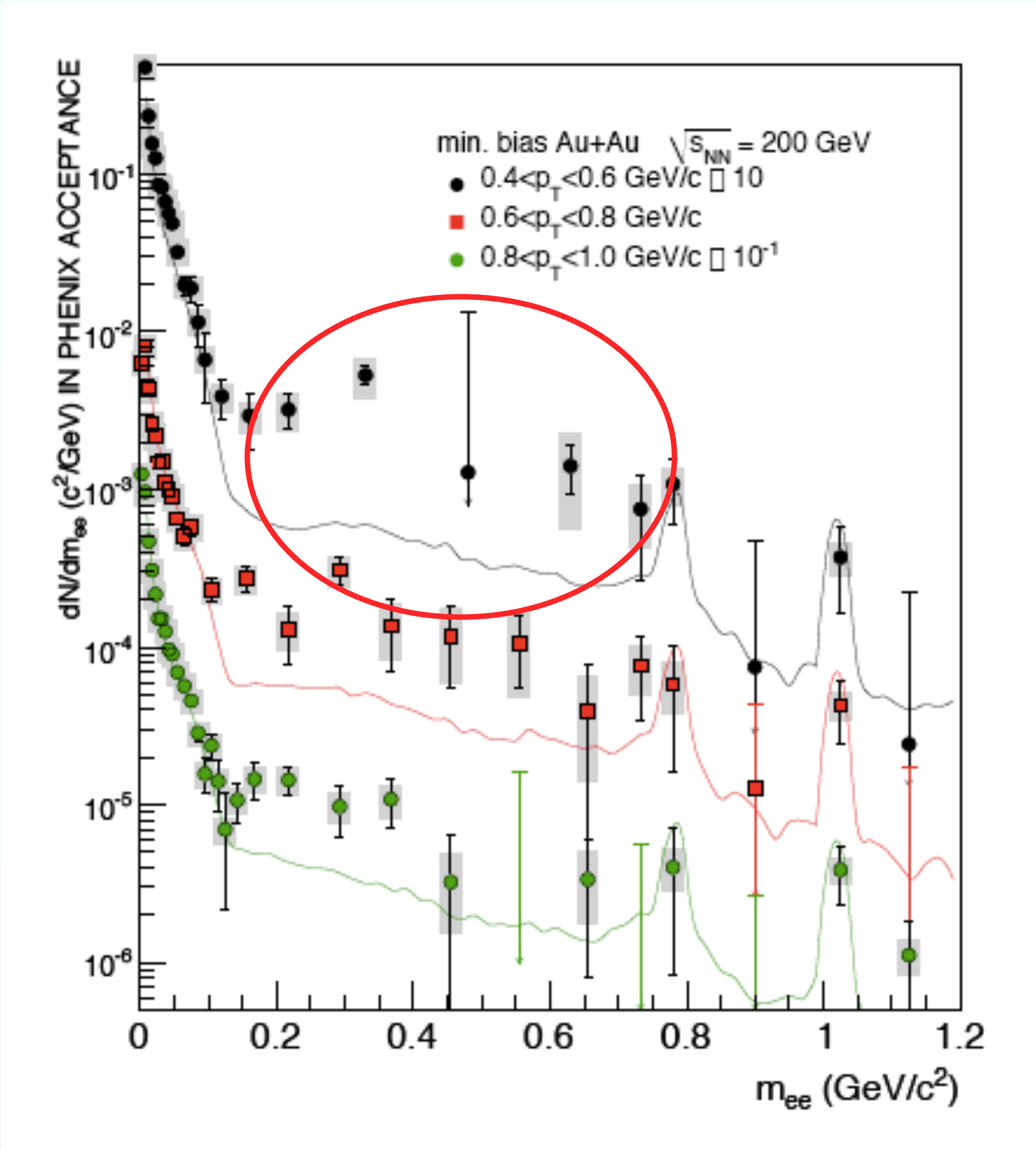
From emission rate of dileptons, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

e^+e^- looks intriguing

2004 data

arXiv: 0912.0244

PRC, in press



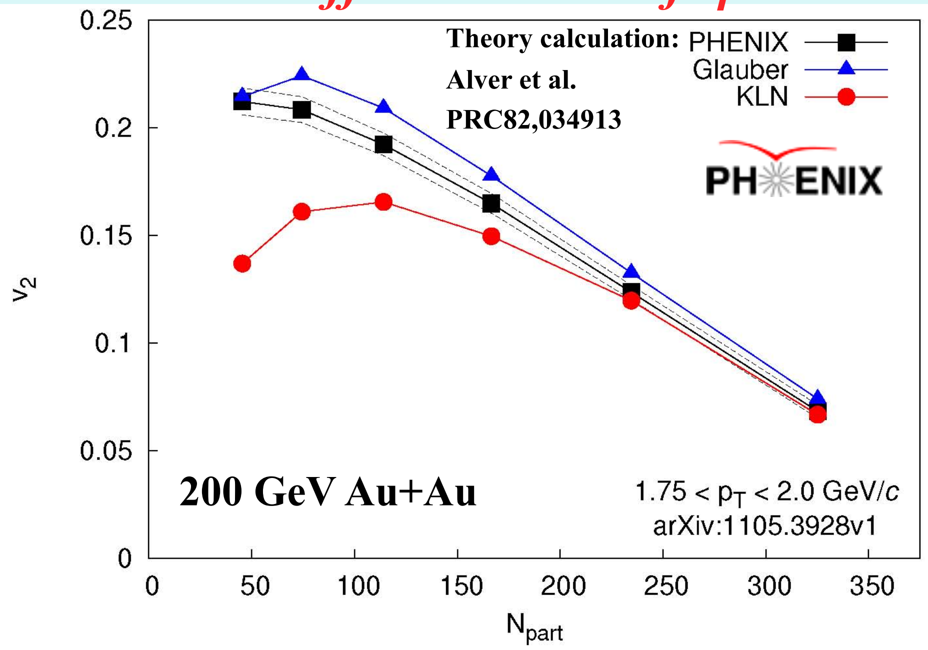
We're taking more, better data now

Fluctuations, flow and the quest for η/s

arXiv:1105.3928

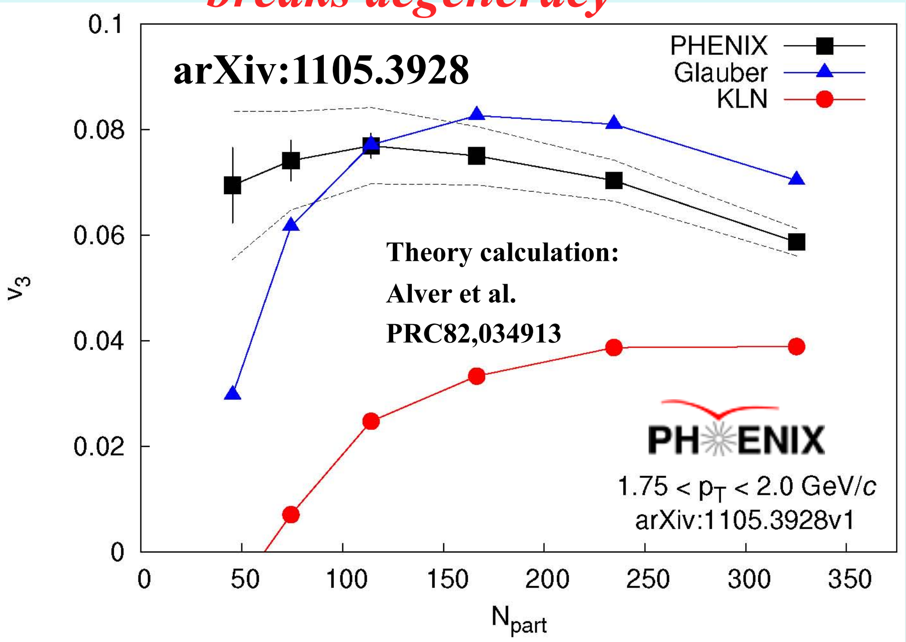
***v_2* described by both Glauber and CGC**

but different values of η/s



***v_3* described only by Glauber**

breaks degeneracy



Lappi, Venugopalan, PRC74, 054905

Drescher, Nara, PRC76, 041903

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

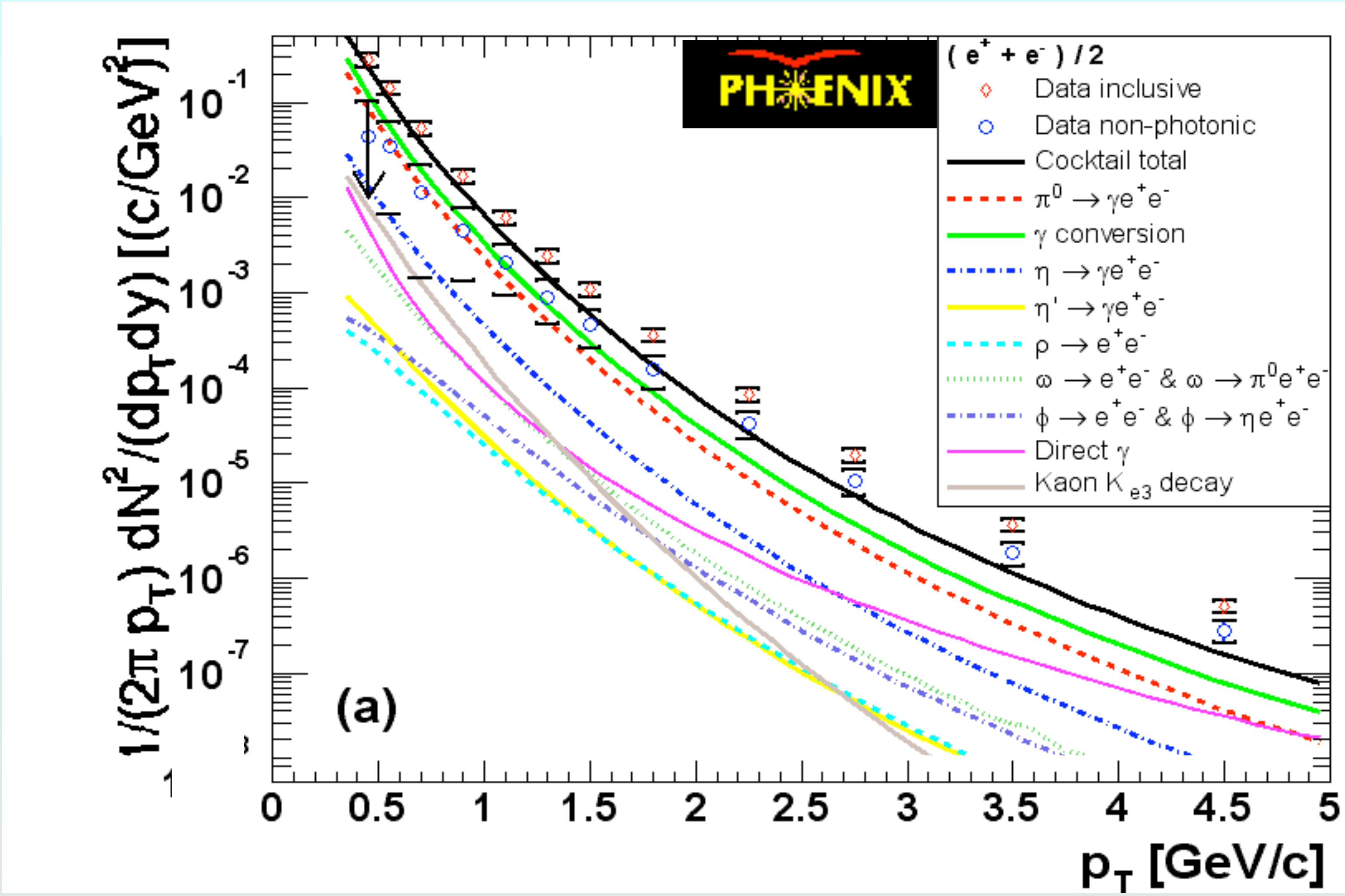
2 models with

Different fluctuations,

Eccentricity, ρ distribution

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

c,b decays via single electron spectrum



compare data to "cocktail" of (measured) hadronic decays

PRL 96, 032301 (2006)