Summary of Experimental results: Photons, Leptons and Heavy Quarks at QM2008

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Feb 9, 2008

QM2008, Jaipur, India

Three topics

- di-leptons/photons
  - NA60
  - RHIC
- heavy quarks
  - RHIC
- onium
  - RHIC

- **Concentrate on new information (subset)**
- **Will be RHIC-centric**
- **sincere apologies to folks with the very nice results from**
  - **the SPS (other than NA60),**
  - **lower energy experiments (HADES, KEK, JLAB,…)**
  - **and of course the RHIC folks whose results I do not mention**

Otherwise I would have to talk for 1 hr…

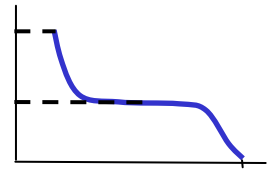
(just kidding – you don't want to listen to me for that long)

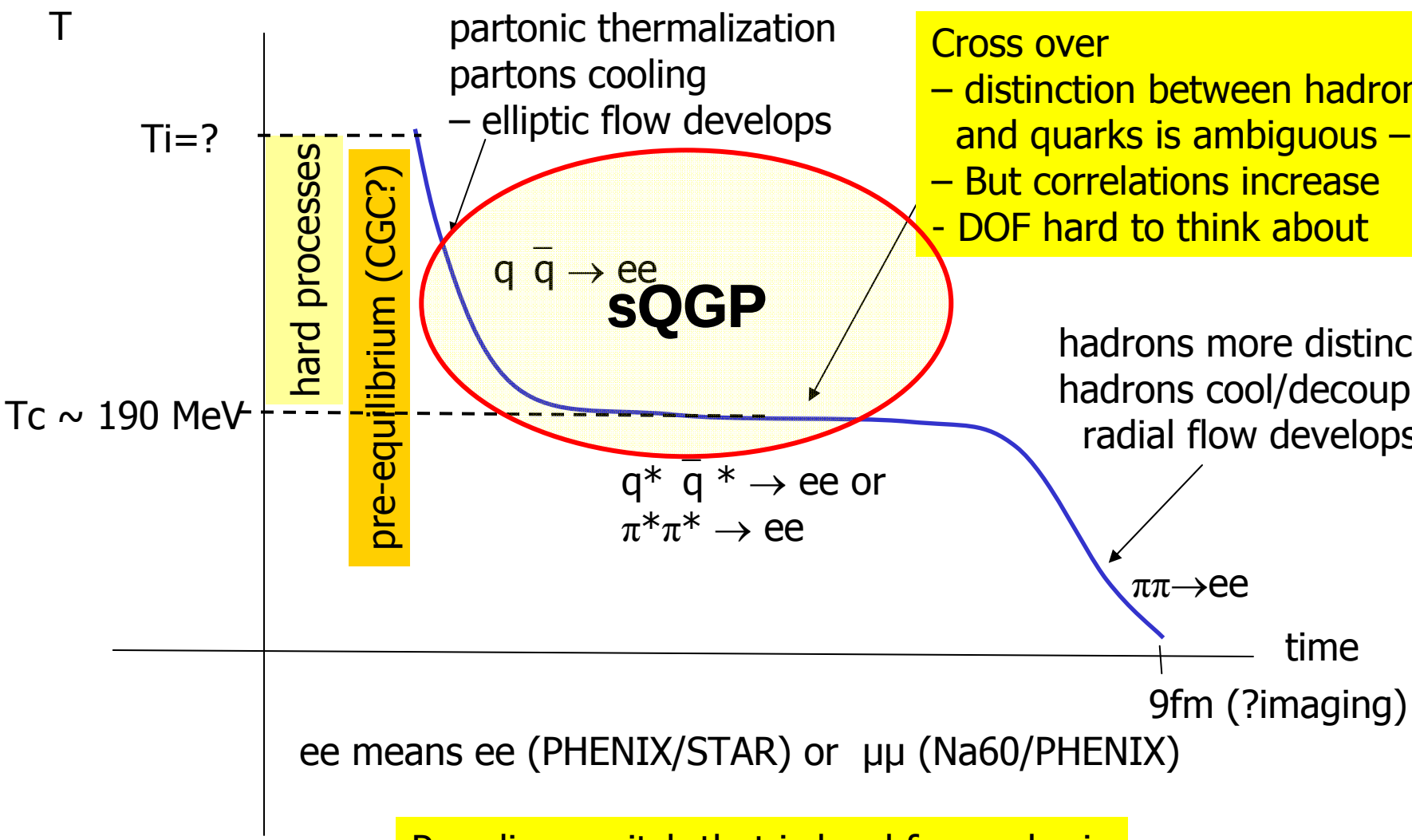
I have freely taken slides – THANKS!

Where are we? (RHIC)

- Evidence
  - suppression of high pt mesons
    - high energy density
  - flow
    - early thermalization -> thermal radiation?
  - charm quark- flow/suppression
    - Strongly interacting/low viscosity/entropy
      - what about B?
  - Constituent quark scaling
    - "quasi-particle DOF"
    - an exercise after QM – can you fit D's and B's into KE/nq scaling?
  - What about deconfinement? – the story of the J/psi
  - What about chiral symmetry restoration – low mass di-electrons
- Experimentally
  - Combinations – eg. flow of charm or j/psi (a big step forward for experiments)
  - correlations between various experimental observables – e.g. γ_{direct} or c/b: R_AA, v2, correlation functions

RHIC – a cartoon



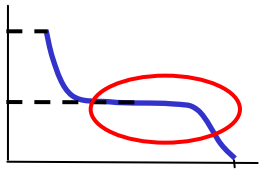


Cross over
– distinction between hadrons and quarks is ambiguous – q*
– But correlations increase
- DOF hard to think about

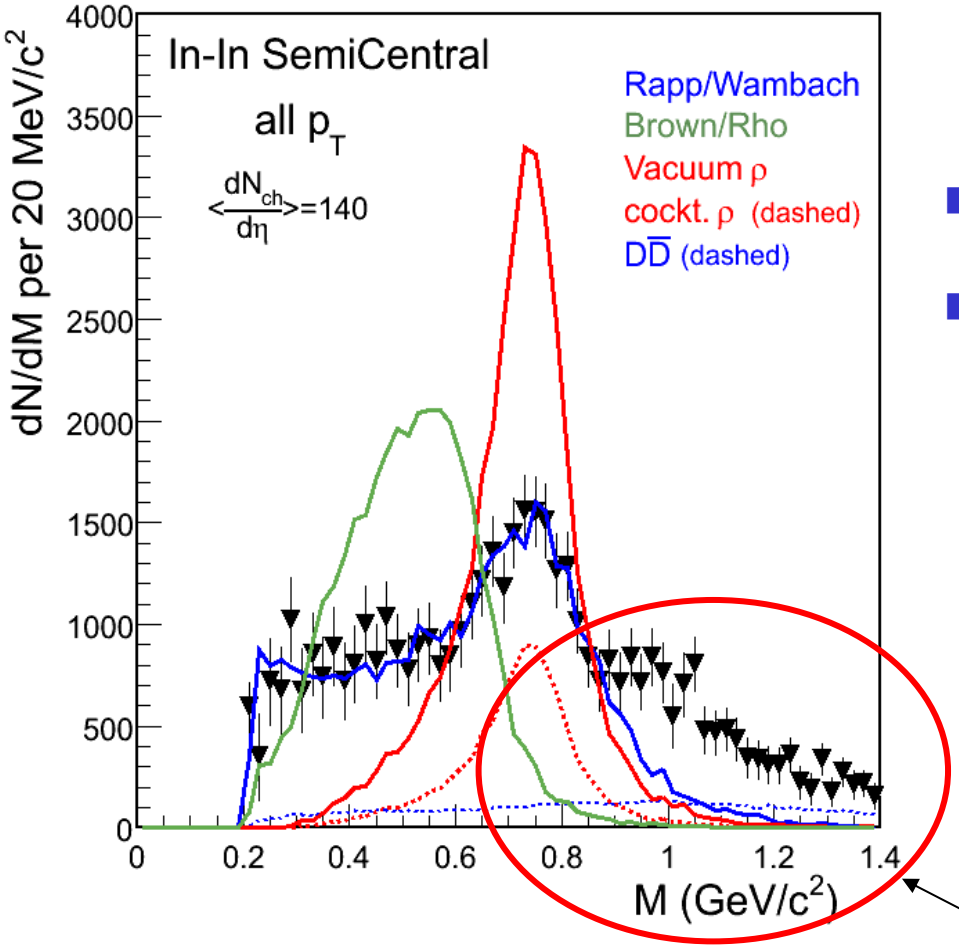
Paradigm switch that is hard for my brain

Di-leptons/virtual photons

NA 60 – Low mass di-muon spectrum



Phys. Rev. Lett. 96 (2006) 162302



Predictions by Rapp (2003) for all scenarios

- no mass shift of ρ
- models of in medium spectral function modification (i.e. ρ broadening) describe data below 900 MeV- beginning of restoration of chiral symmetry?

What is this?

NA 60 – Low mass di-muon spectrum

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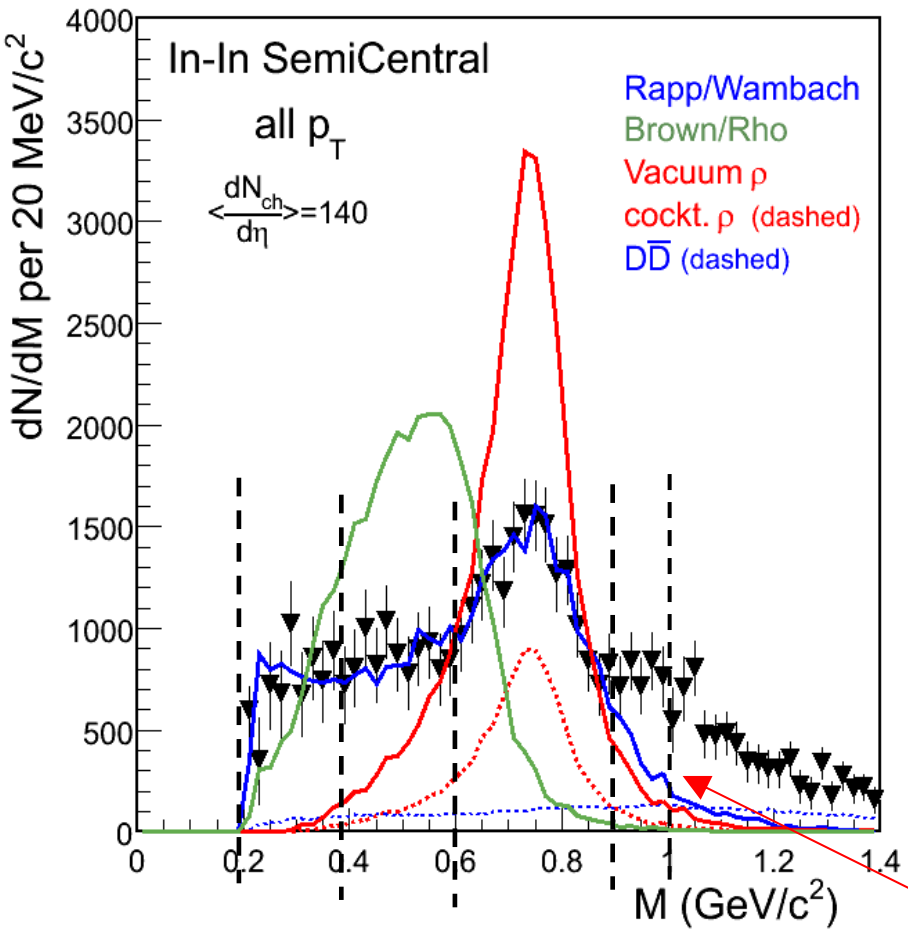
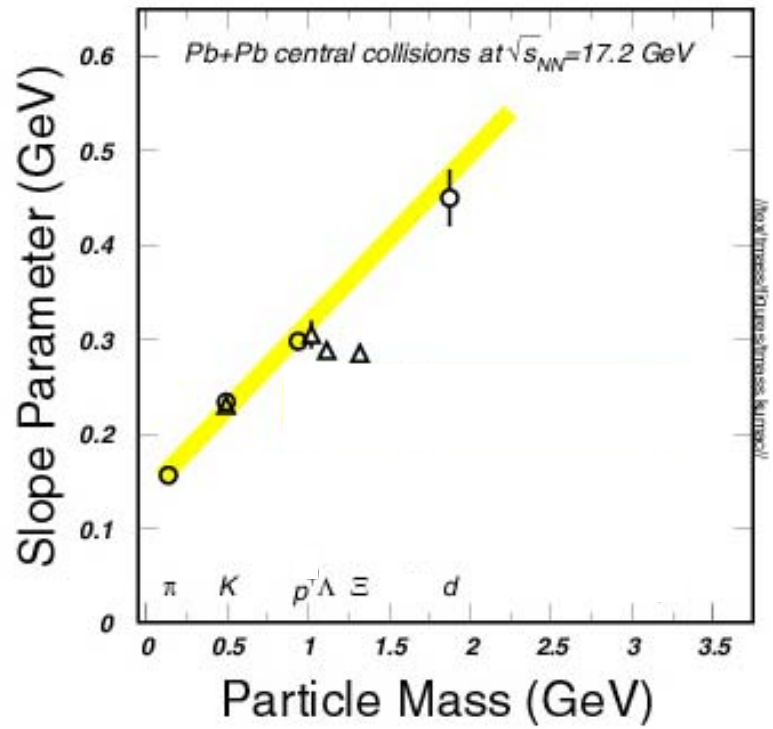




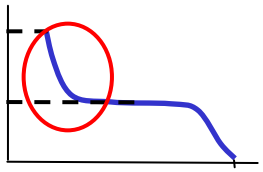
remember the "NuXu" plot?

mass ordering of slopes

➔Radial flow develops in hadronic stage.

Divide up mass spectrum and plot slopes

NA60 – a look at the slopes



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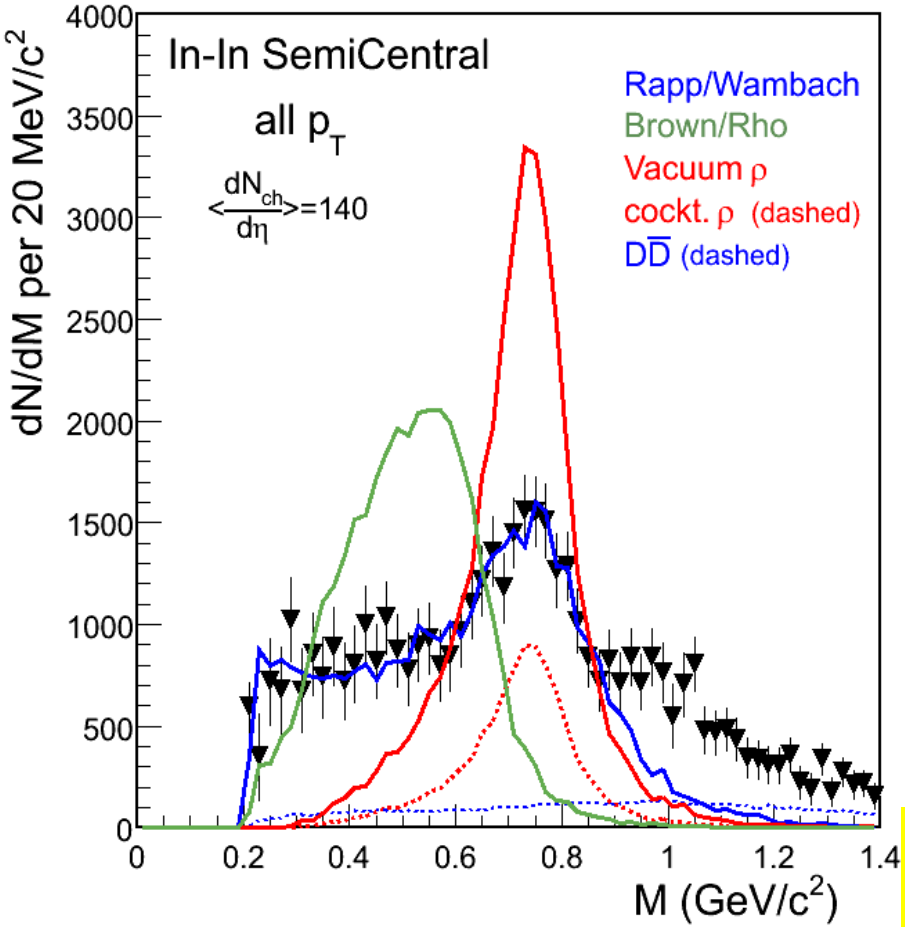
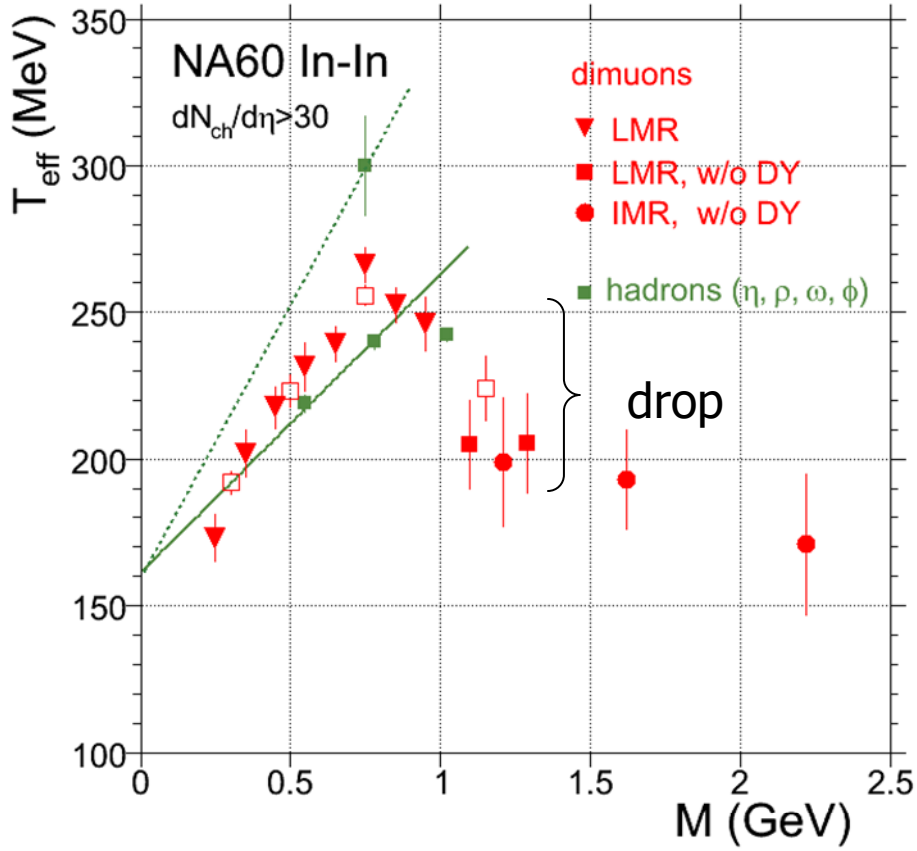
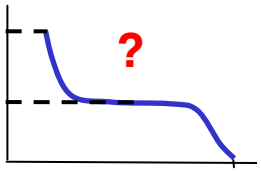




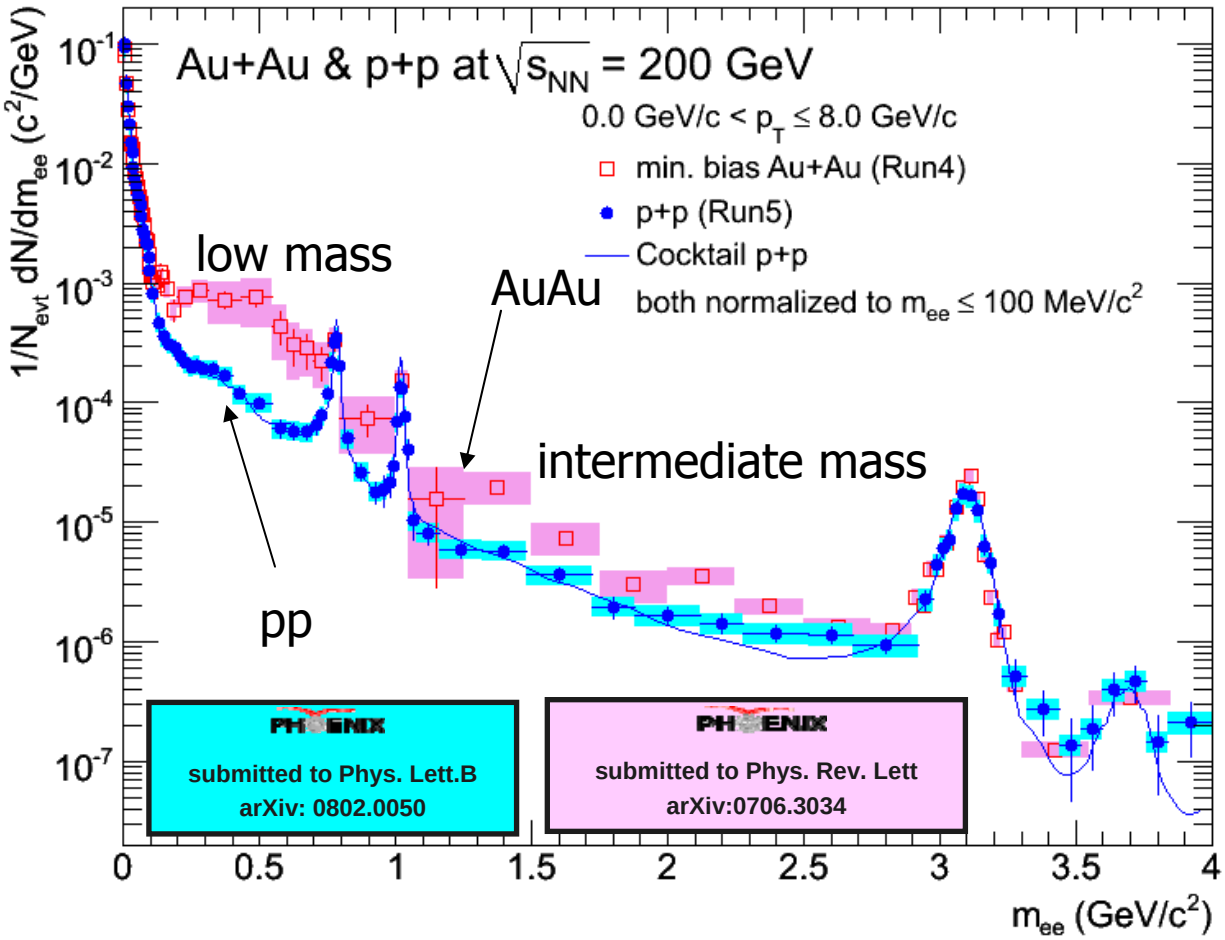
- T_{eff} rises in low mass region → radial flow of a hadronic source
- drop at M~1 GeV suggests partonic nature of equilibrated particles~thermal radiation?
- note: yield goes like $(dN_{ch}/dy)^2$

S. Damjanovic, Quark Matter 2008

PHENIX low mass dielectrons



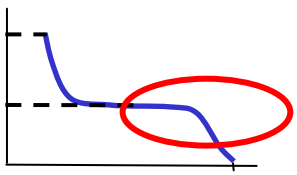
p+p NORMALIZED TO m_{ee}<100 MeV



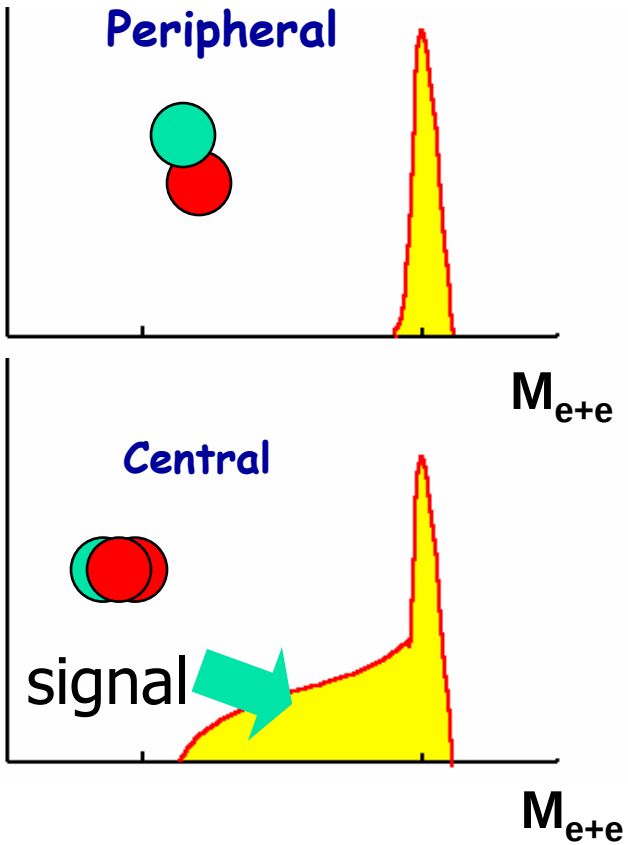
pp and AuAu normalized to π^0 region

p+p: follows the cocktail
Au+Au: large Enhancement in 0.15-0.75

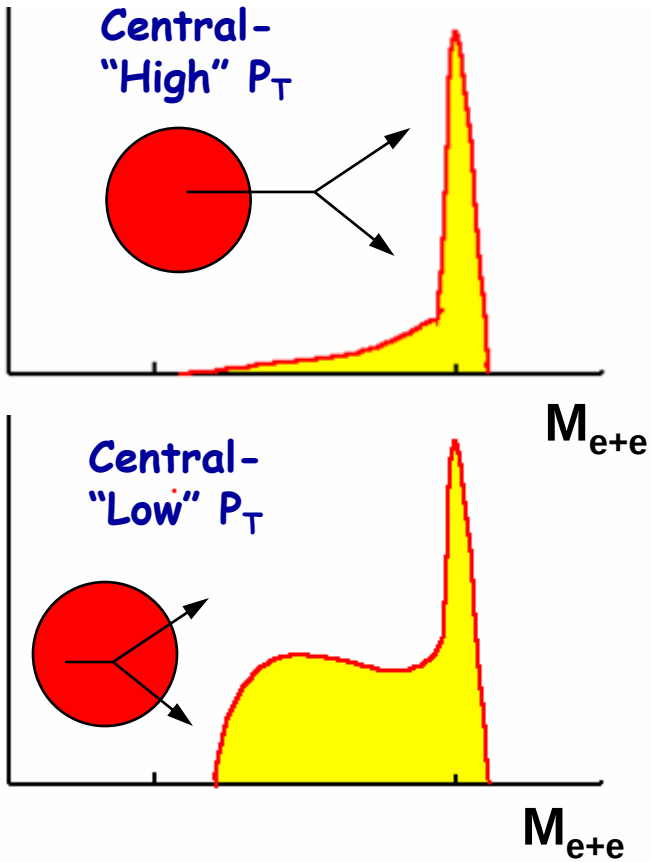
Experimental "Knobs" for in-medium modifications in a fireball



- Signal should increase with centrality

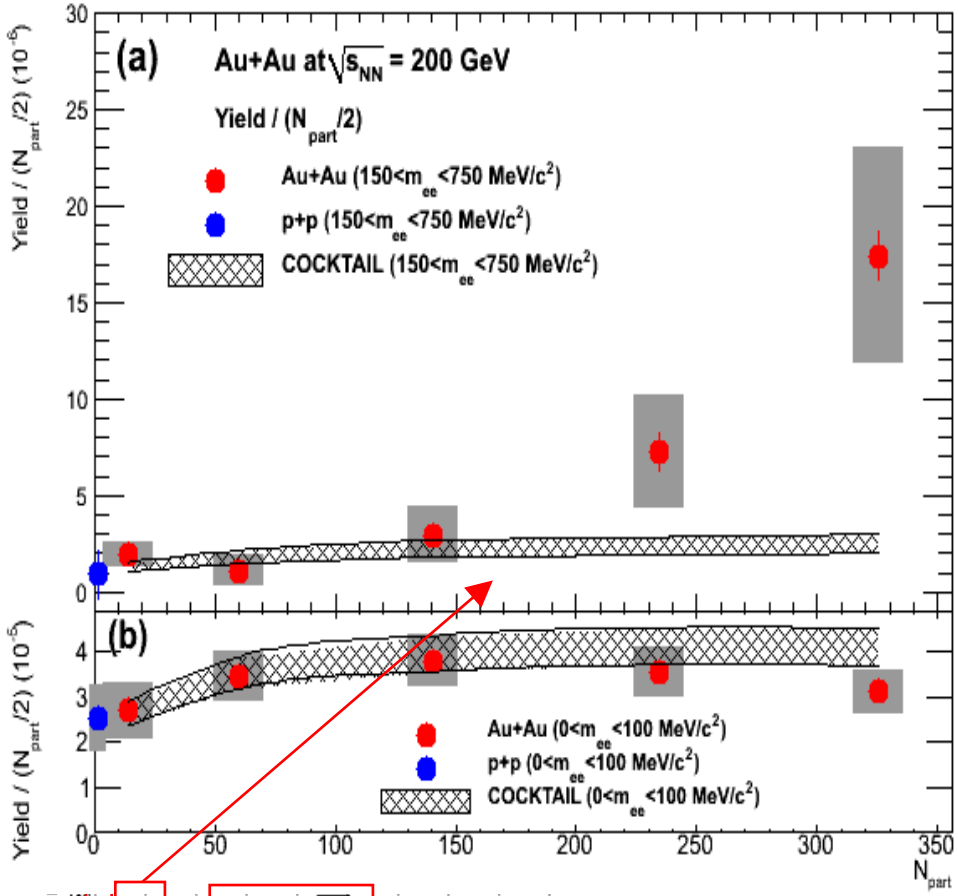


- Signal should increase at low pt



- Look for enhancement at low pt in central events

Centrality Dependency



π^0 **region:**

- Agreement with cocktail

Low Mass:

- yield increases with centrality
  - like $(dNch/dy)^2$

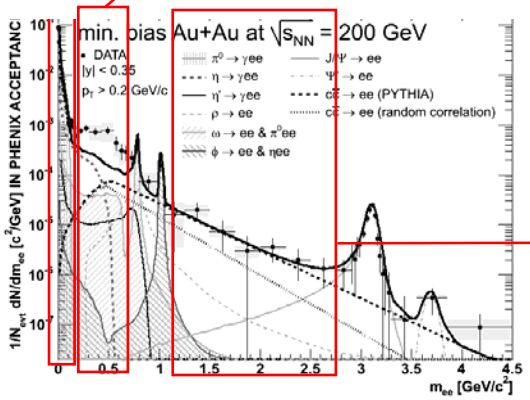
→ enhancement from binary annihilation (ππ or qq) ?

Intermediate Mass:

- yield increase proportional to N_{coll}

→ charm follows binary scaling

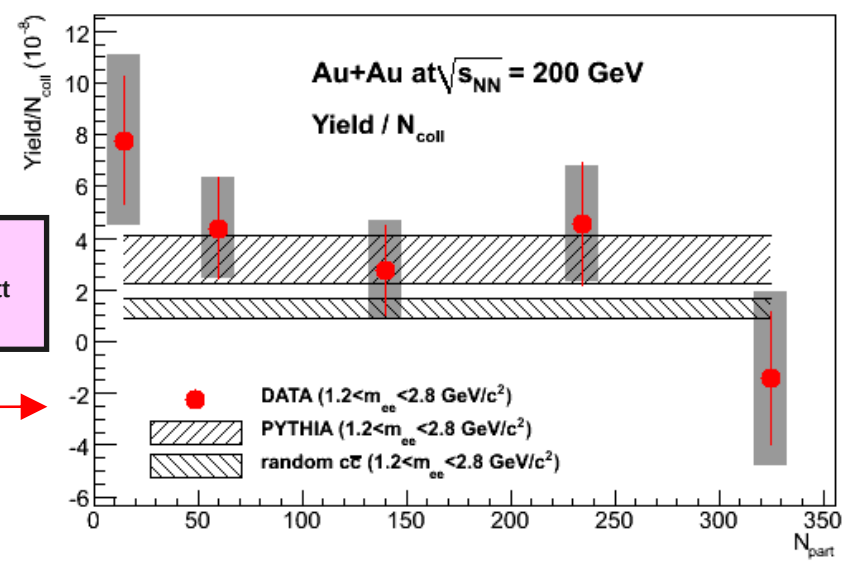
charm included in cocktail



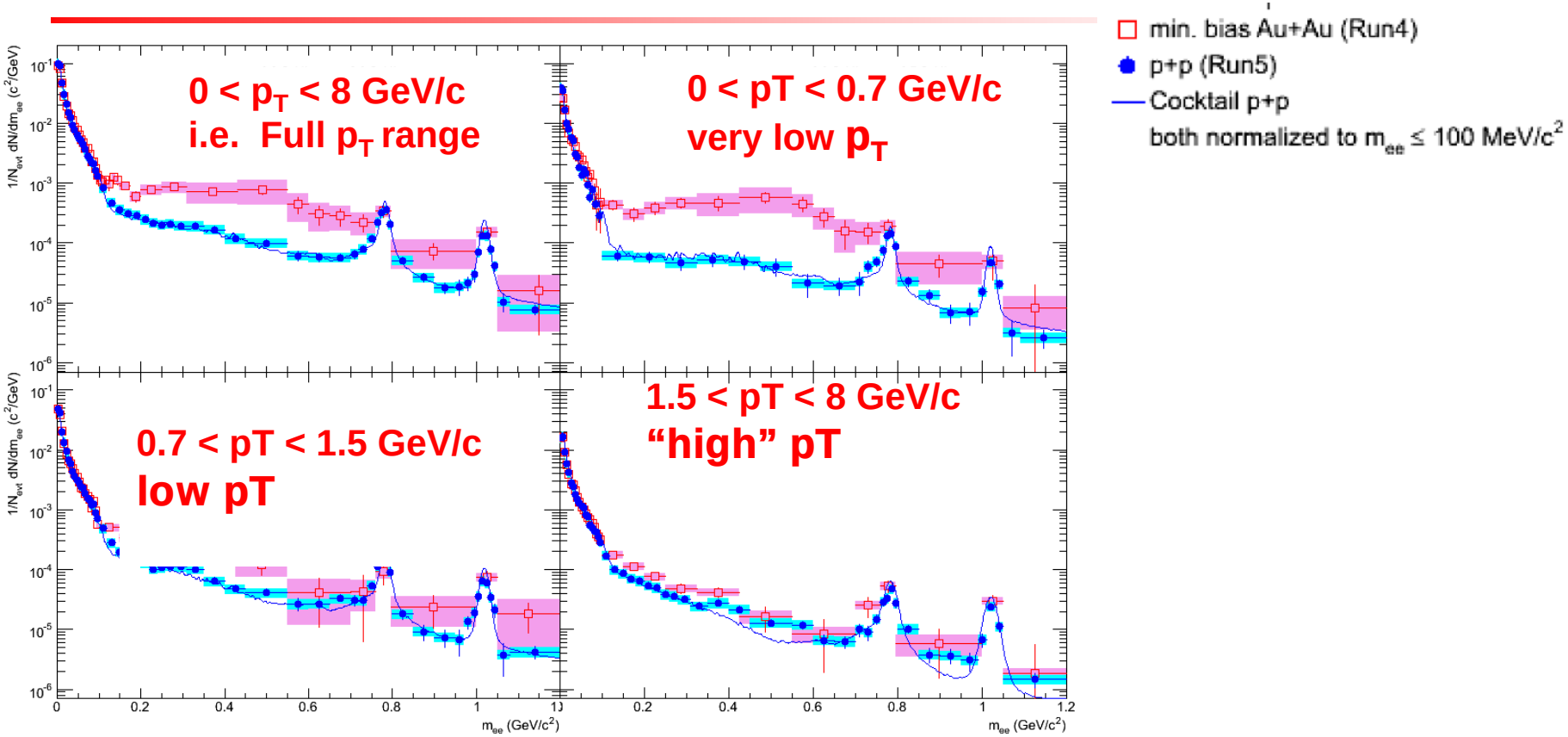
PHENIX

submitted to Phys. Rev. Lett

arXiv:0706.3034

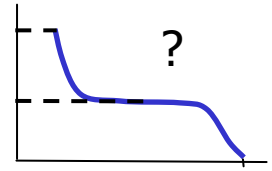


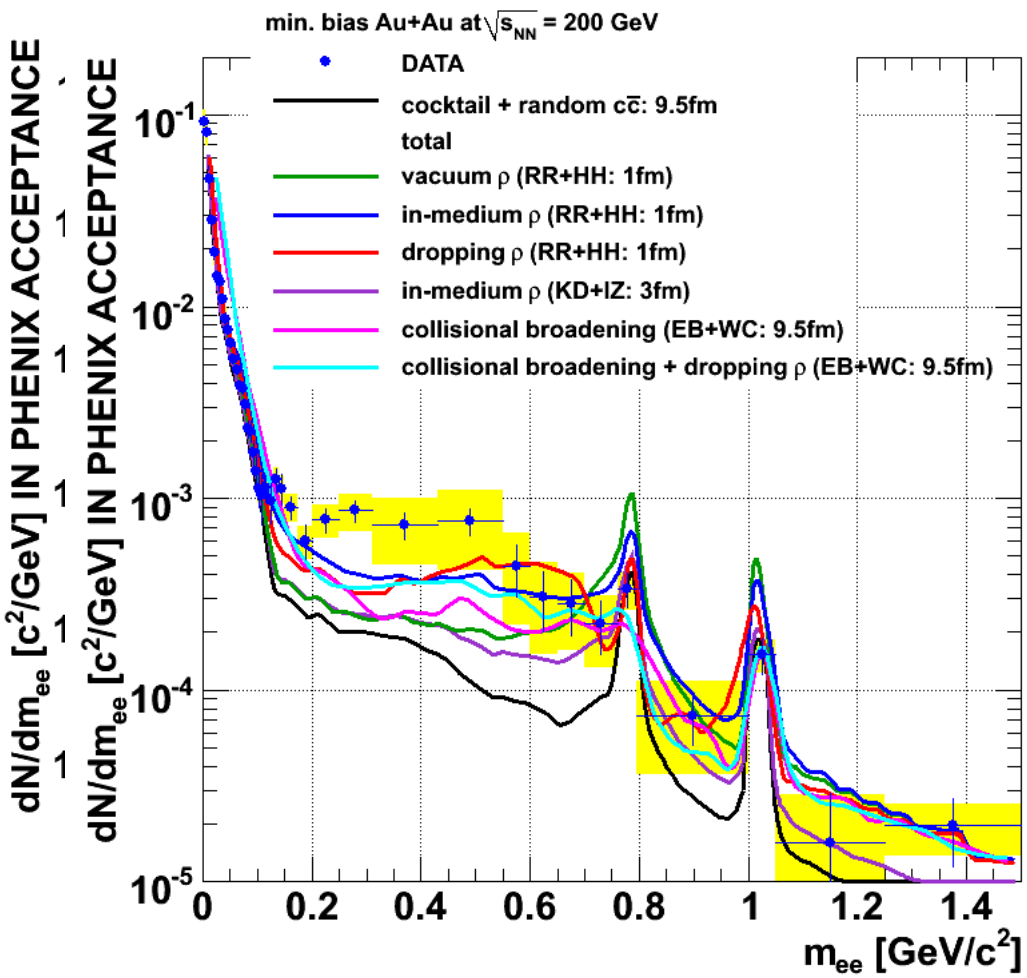
P_T dependence of Au+Au M_{ee}



- Low Mass excess is a low p_T enhancement strongest in central events
  Behaves like a modified hadron

Try hadronic scenarios





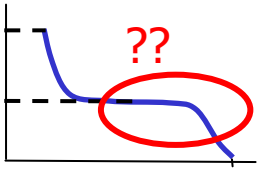
for 600-800 MeV

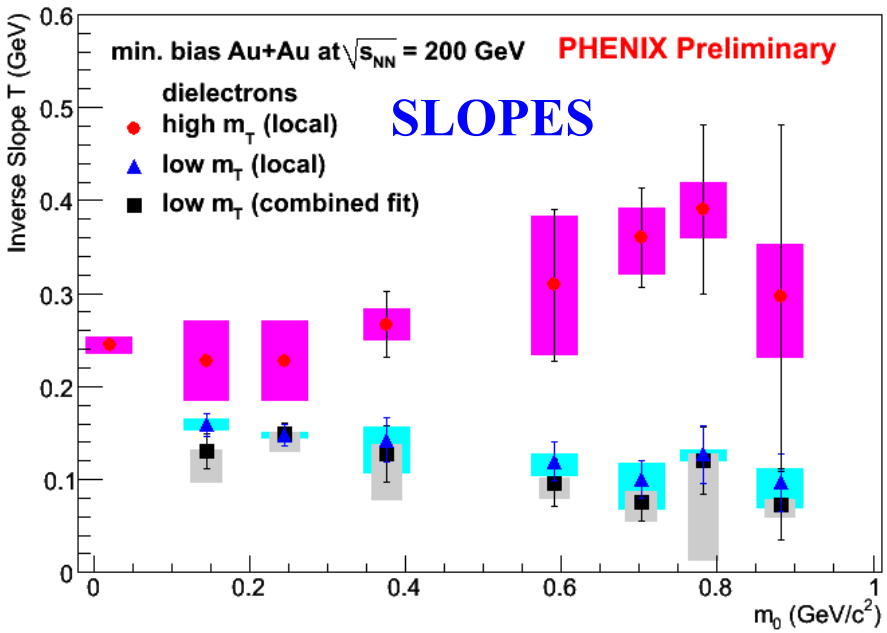
- Several theoretical schemes are OK, including dropping ρ mass

For 200-600 MeV

- none of the scenarios work
- Is there a partonic thermal component?

Cut up the mass region, fit the slopes





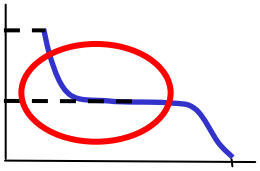
Single exponential fit:

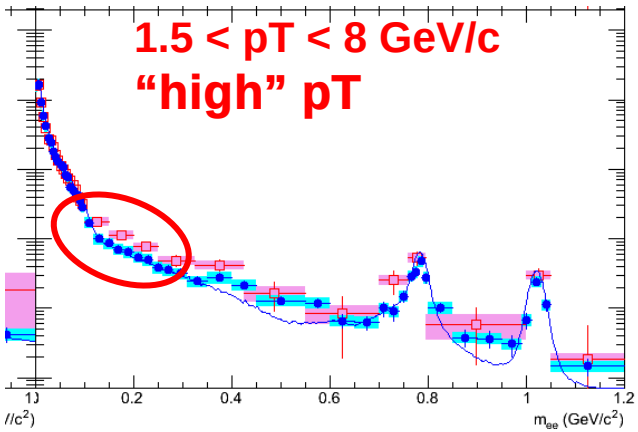
Low-pT: $0<m_T<1$ GeV

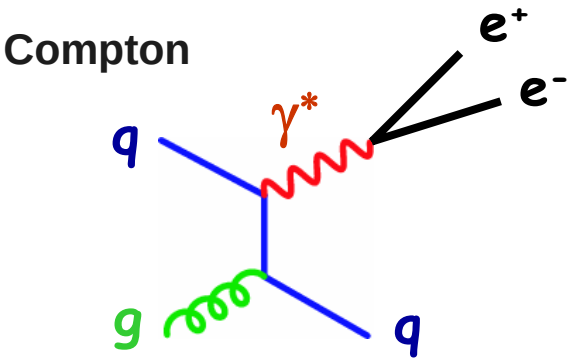
Intermediate pT: $1<m_T<2$ GeV

- **higher p_T: inverse slope increase with mass, consistent with radial flow – modified ρ?**
- **Low p_T:**
  - **inverse slope of 120MeV~ accounts for most of the yield**
  - **thermal? Slope seems low for partonic radiation. Perhaps ππ ??** (no rad flow?)
  - or perhaps we need to revisit the fit procedure?

Virtual photons





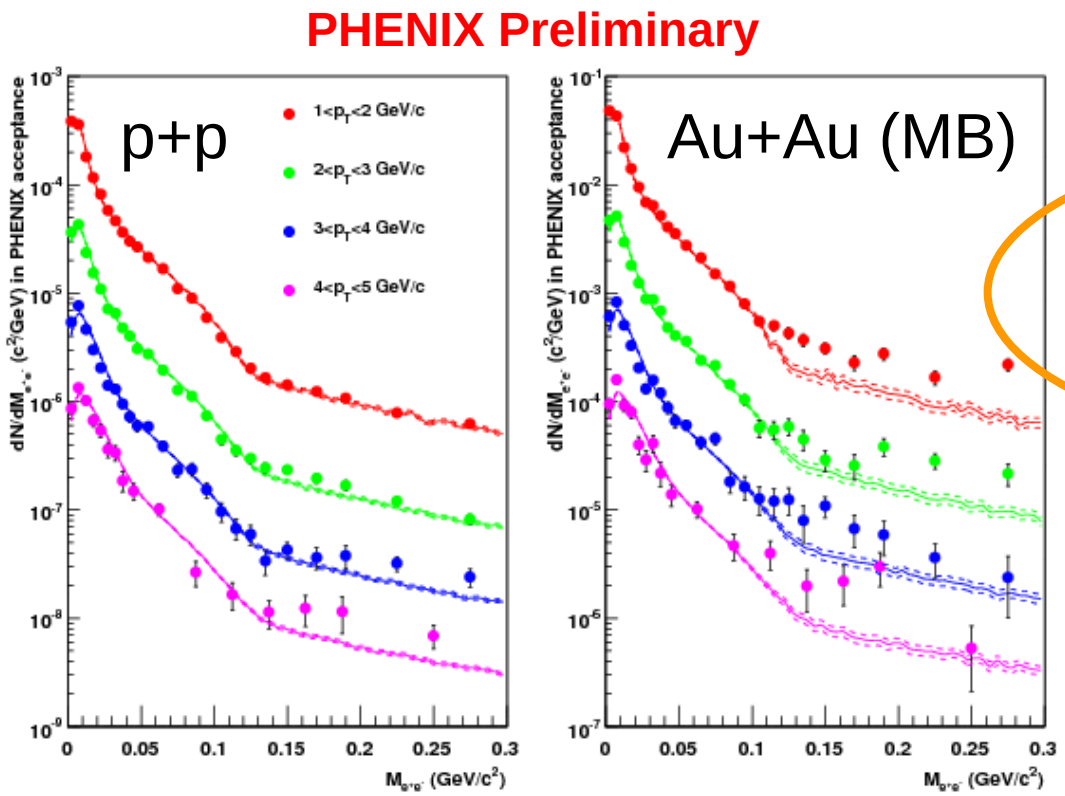


- Backgrounds – dalitz decays
  - trick : dalitz decays suppressed by factor

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} \propto \left(1-\frac{m_{ee}^2}{M^2}\right)^3$$

  - Use m_{ee}>M where M=M_π
  - Compare to cocktail

Cocktail comparison



$1 < p_T < 2$ GeV
$2 < p_T < 3$ GeV
$3 < p_T < 4$ GeV
$4 < p_T < 5$ GeV

QM2005

- Results from Au+Au

QM2008

- long awaited result from p+p
- important confirmation of method

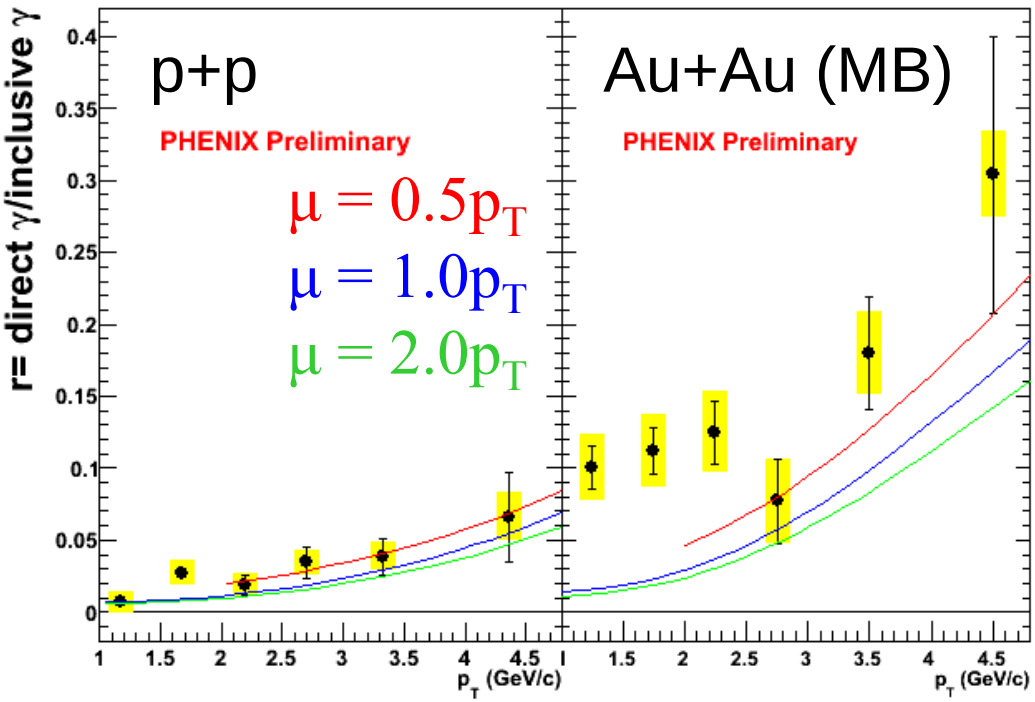
p+p

- Agreement of p+p data and hadronic decay cocktail
- Small excess in p+p at large m_{ee} and high p_T

Au+Au

- data agree for m_{ee} <50MeV
- Clear enhancement visible above for all p_T

Fraction of direct photons



- Fraction of direct photons
- Compared to direct photons from pQCD

p+p

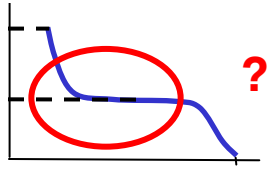
- Consistent with NLO pQCD

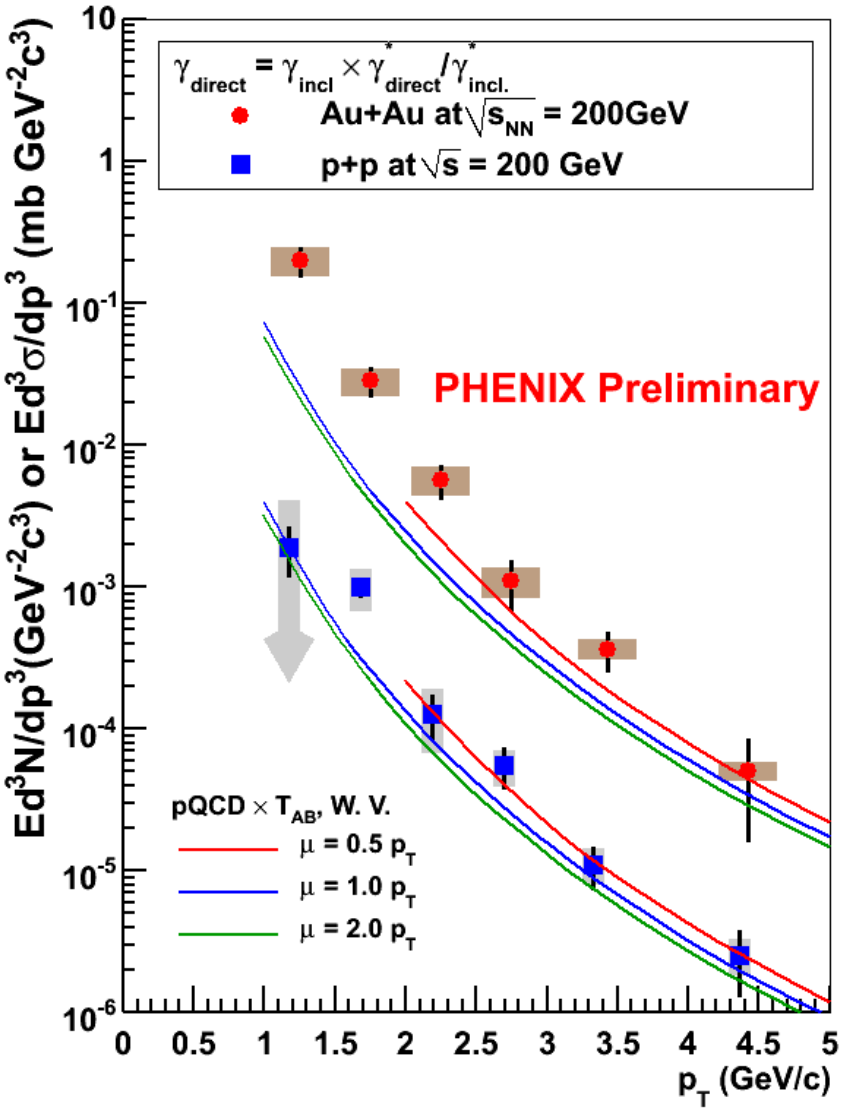
Au+Au

- Clear excess above pQCD

Now multiply by Inclusive γ yield

The spectrum





- Compare spectra to NLO pQCD

p+p

- consistent with pQCD

Au+Au

- above binary scaled pQCD
- If excess of thermal origin: inverse slope is related to initial temperature

- To do – fit for T!

$m_u \sim 3$ MeV
$m_d \sim 5$ MeV
$m_s \sim 100$ MeV
$m_c \sim 1{,}300$ MeV
$m_b \sim 4{,}700$ MeV

$\Lambda_{QCD} \sim 200$ MeV

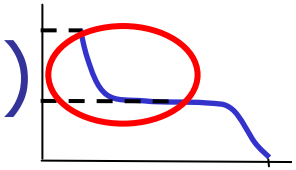
heavy quarks

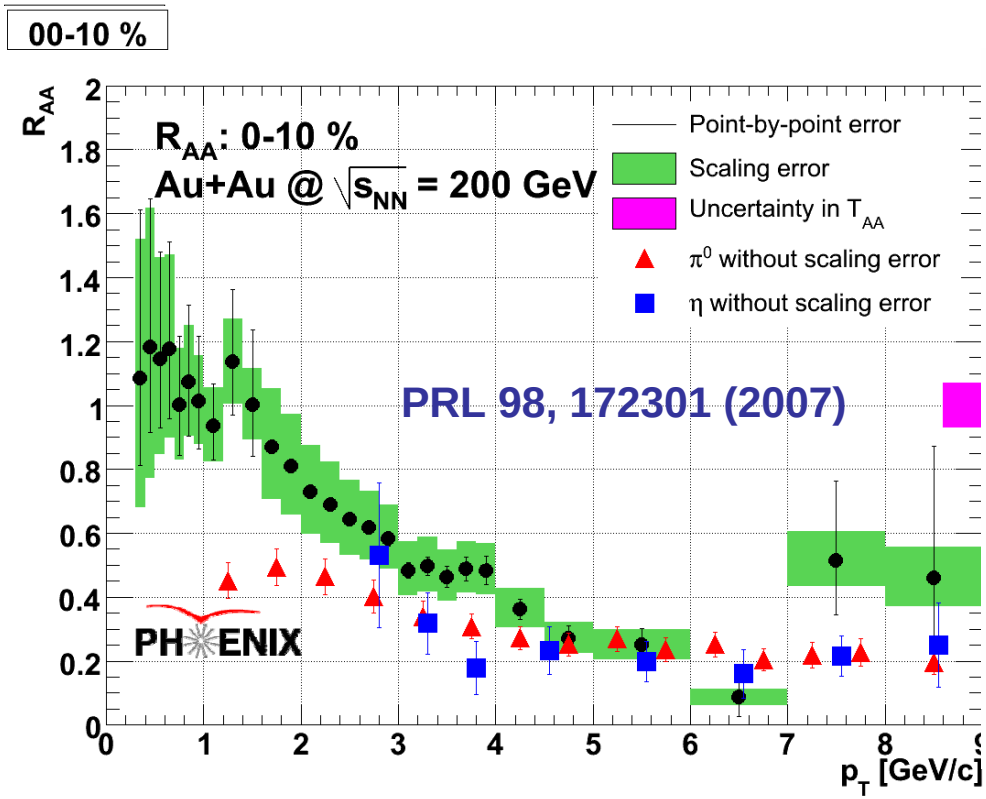
Pooh and Rabbit playing pooh sticks

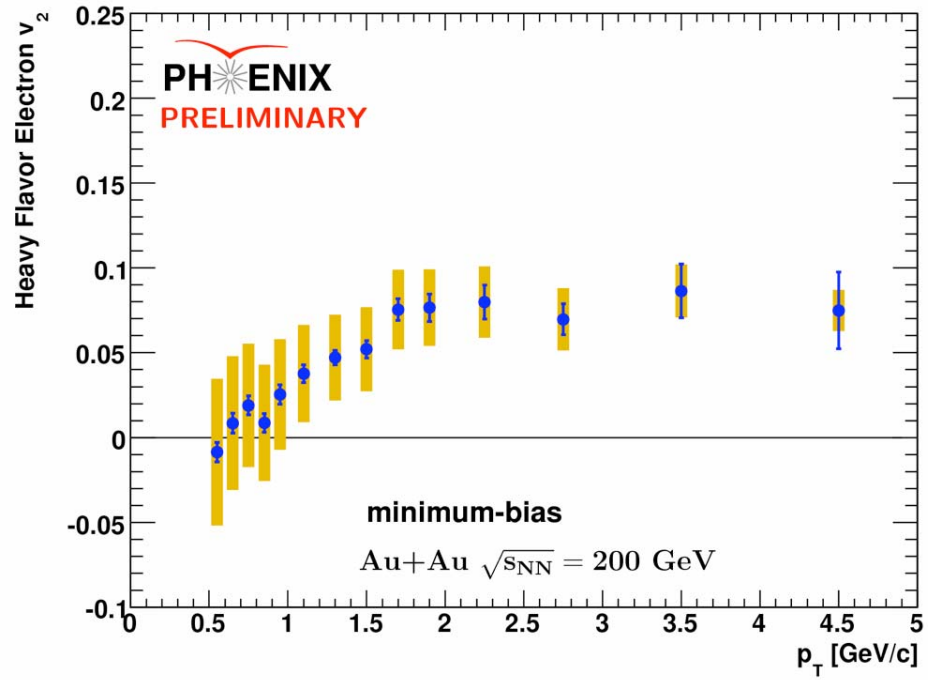
throw a ~~pebble~~ boulder in the stream

see if it moves

Centrality Dependence of R_{AA}
Non photonic electrons (aka charm+bottom)







- high p_T non-photonic $e^{\pm}$ suppression increases with centrality
- similar to light hadron suppression at high p_T
  - careful: decay kinematics!

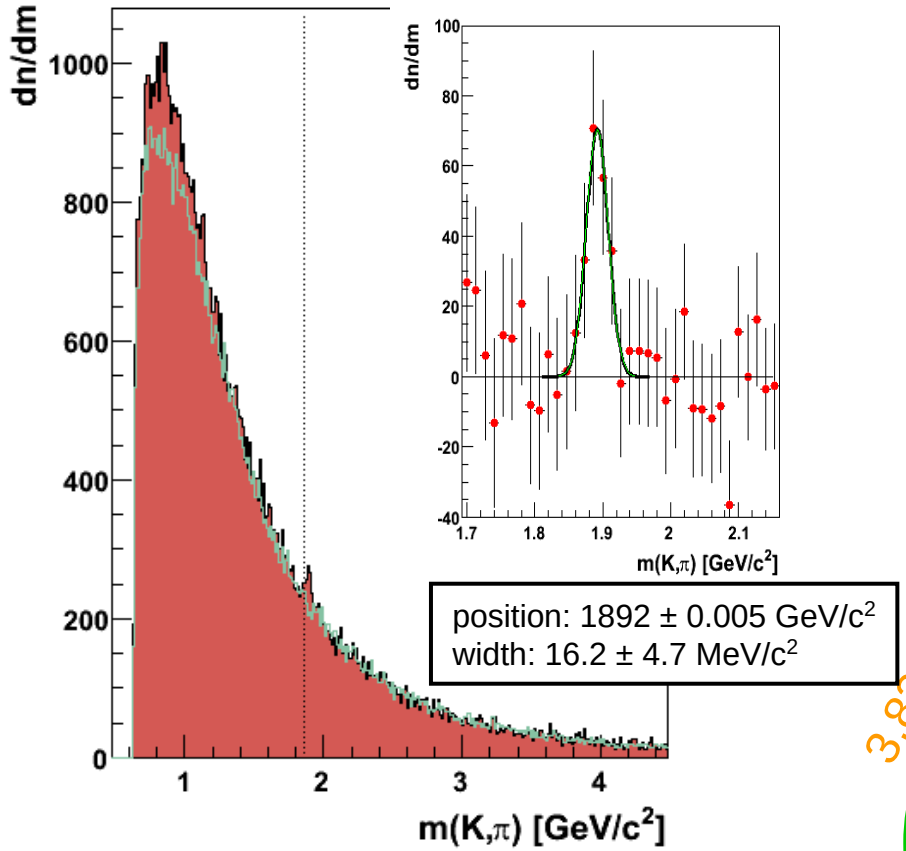
- updated result on flow of non-photonic $e^{\pm}$
  - saturation at p_T ~ 2.5 GeV

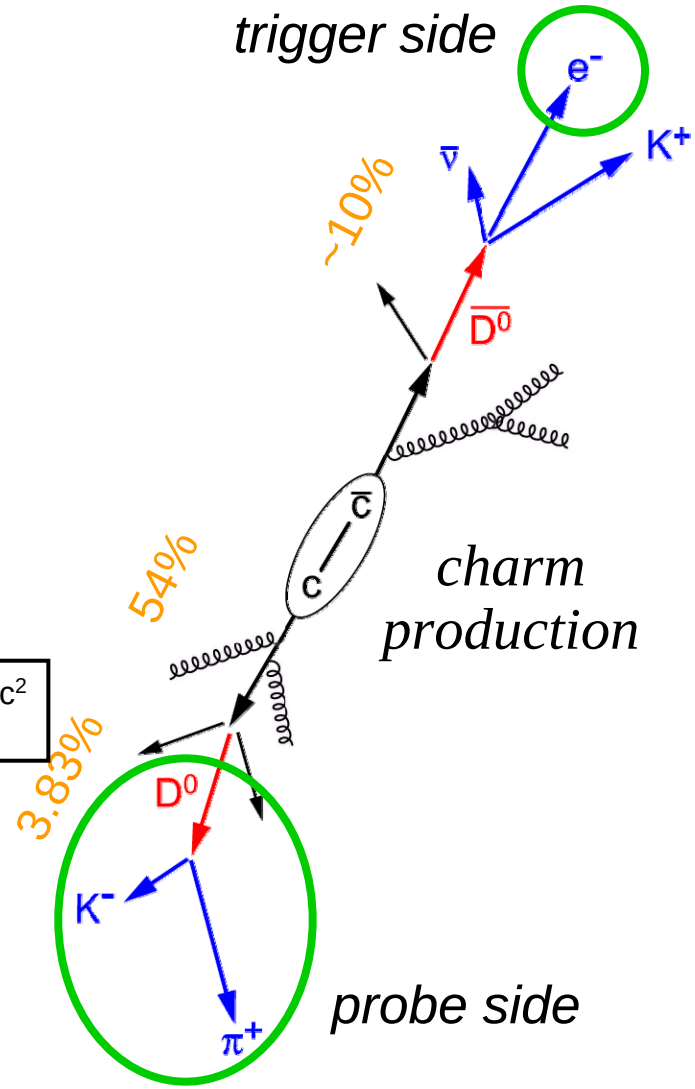
➔charm suppressed and thermalizes

What fraction of this is bottom?

Answer: measure B/B+C

w/ non-photonic electron trigger

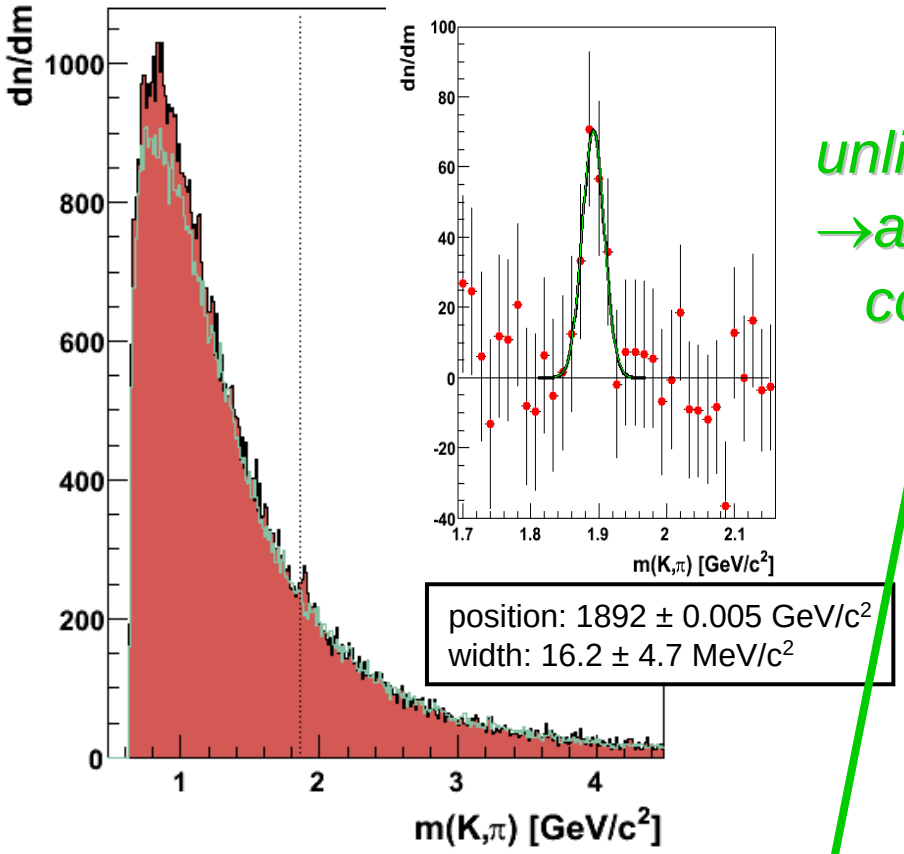


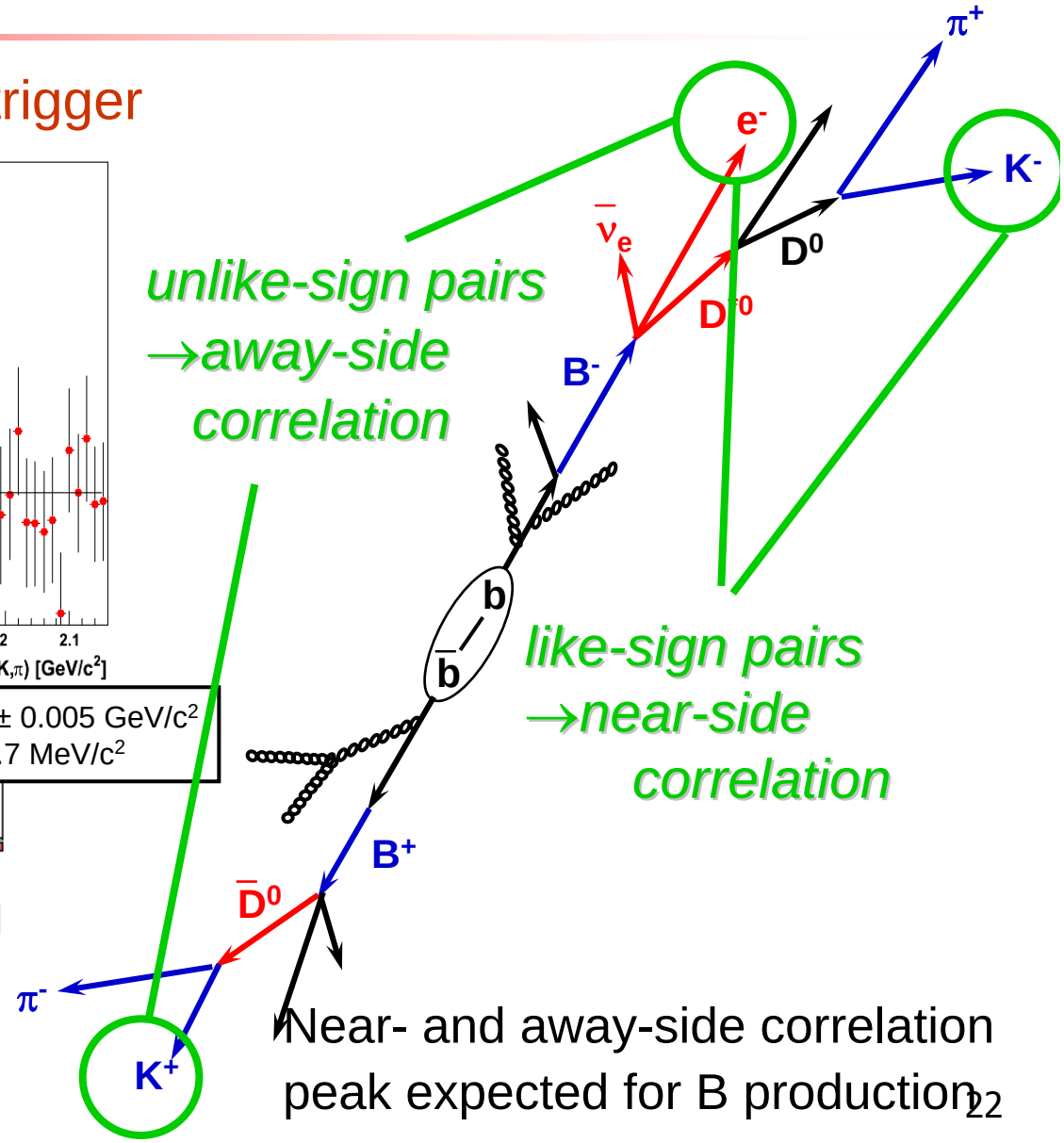


STAR (PHENIX also uses this technique)

STAR and PHENIX both have ways of separating charm and bottom

w/ non-photonic electron trigger





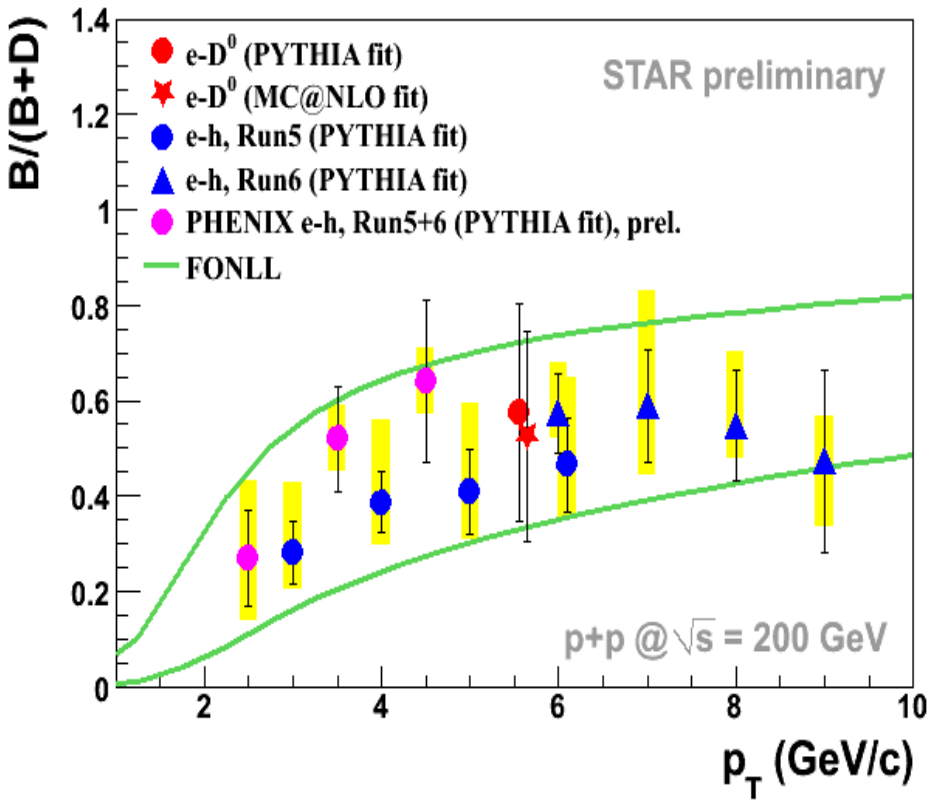
unlike-sign pairs →away-side correlation

like-sign pairs →near-side correlation

Near- and away-side correlation peak expected for B production

STAR

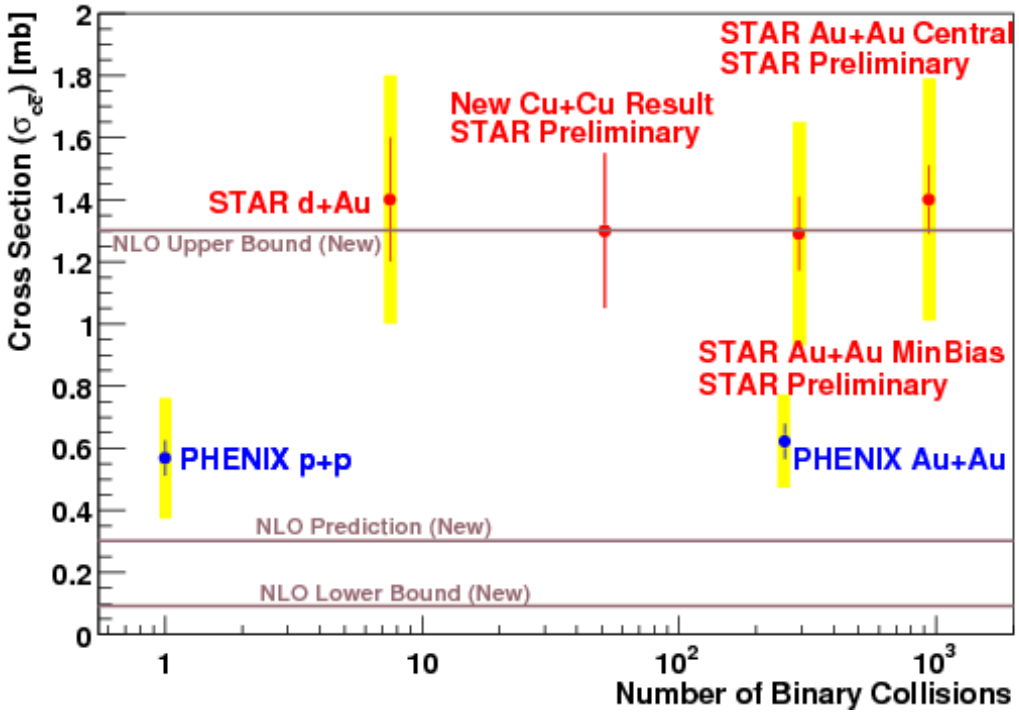
Bottom fraction



bottom is a substantial (~50%) fraction of non-photonic electron and dominates after 5 GeV

bottom is suppressed
bottom flows and is thermalized

A blemish….Charm cross-section

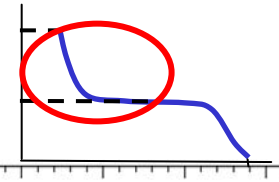


Both STAR and PHENIX are self-consistent.

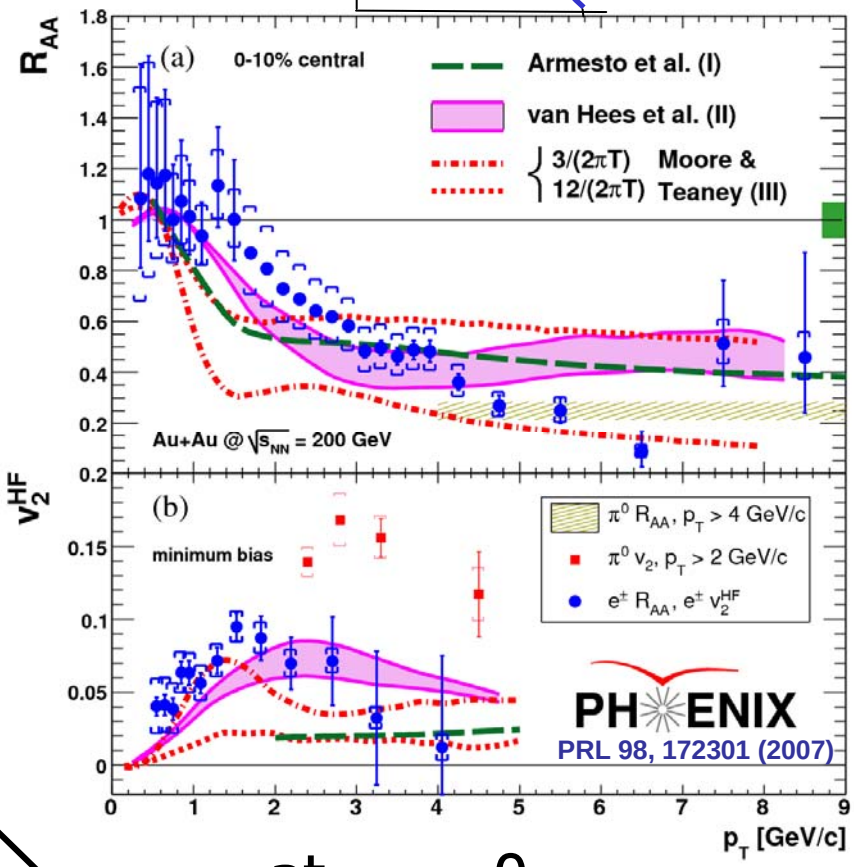
STAR results ~ 2 times larger than PHENIX

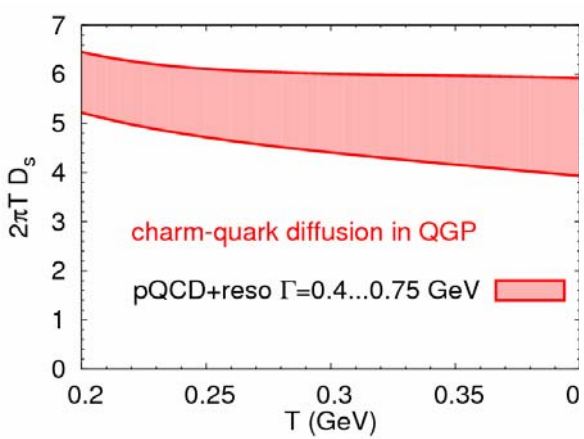
Some work to do for PHENX and STAR (another try…)

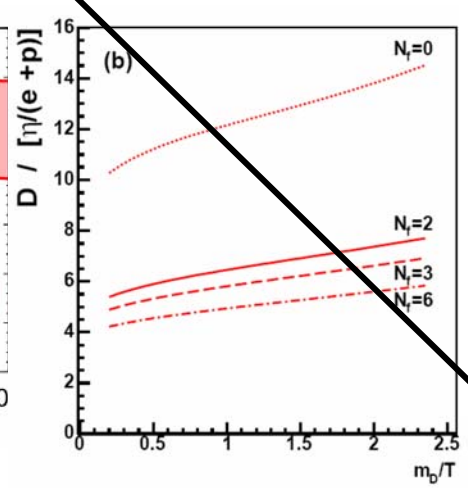
Estimating η/s



- transport models
  - Rapp & van Hees (PRC 71, 034907 (2005)
    - diffusion coefficient required for simultaneous fit of R_{AA} and v_2
      - $D_{HQ} x 2\pi T \sim 4\text{-}6$







- Moore & Teaney (PRC 71, 064904 (2005))
  - calculate perturbatively (and argue that plausible also non-perturbatively)
    - $D_{HQ} / (\eta/(\varepsilon+P)) \sim 6$ (for $N_f = 3$)

- at $\mu_B = 0$
  - $\varepsilon + P = Ts$
- then
  - $\eta/s = (1.3\text{-}2.0)/4\pi$

consistent with other calculations of η/s

Conclusion- heavy quarks

- B suppressed, and flows
  - this must mean thermalization of the B quark (or at least many of them)

- Mechanism? – clearly QCD but in the non perturbative regime
  - remember sQGP
    - ~non pertubative or hadronic methods
      - Vitev et al – B Meson suppression (like J/psi)
      - Rapp/Hess – resonant interactions of heavy quarks in sQGP with D/B mesons (remember hadrons/quark ambiguous)
      - AdSCFT –Teany, Castleberry Solana, AMY, Gubser etc

The J/psi

An interesting* story

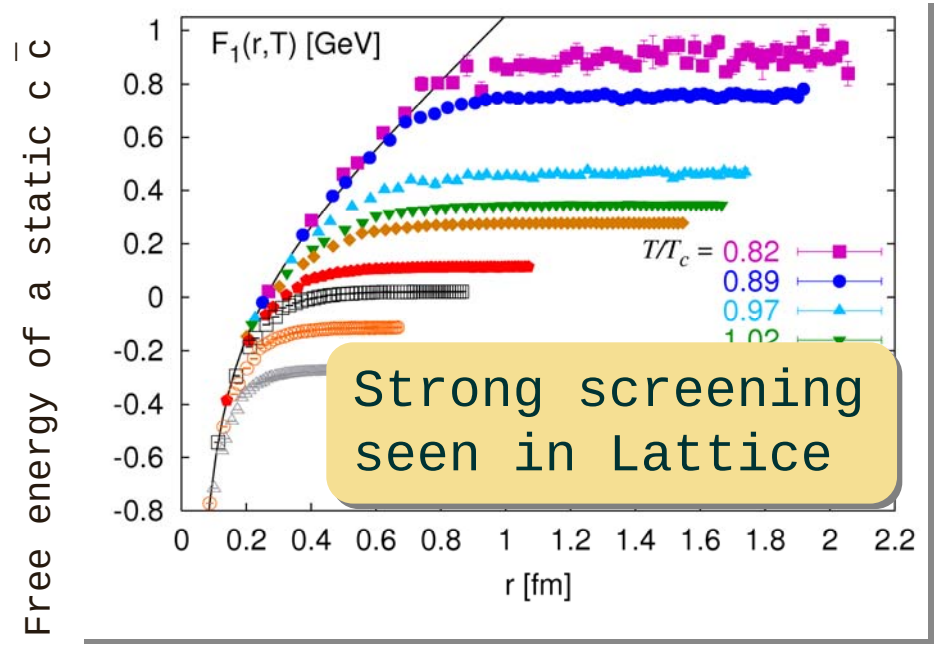
* depending on your mood you can take this to mean "exciting", "intriguing", "confusing" ...

Good news from the lattice

I hope this holds up...

- screening a good picture
  - We can use onium states as thermometer (OK - the lattice is static and we have to use a dynamical model...)

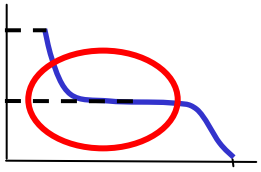
For the First Time
Agreement between potential model and lattice correlators to few % and for all states



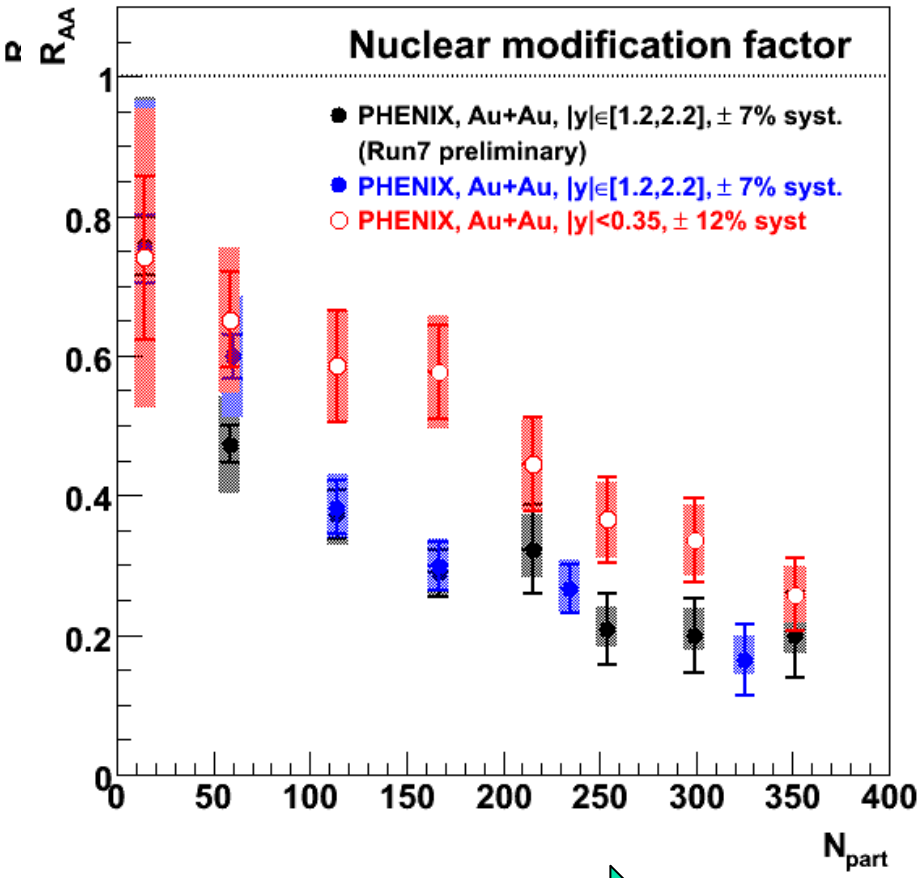
RBC-Bielefeld Collab. (2007)

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	~~2.10~~	~~1.16~~	~~1.12~~	~~$\geq$4.0~~	~~1.76~~	~~1.60~~	~~1.19~~	~~1.17~~
BUT	1.2	1.0	1.0	2.0	1.3	1.2		

What's new



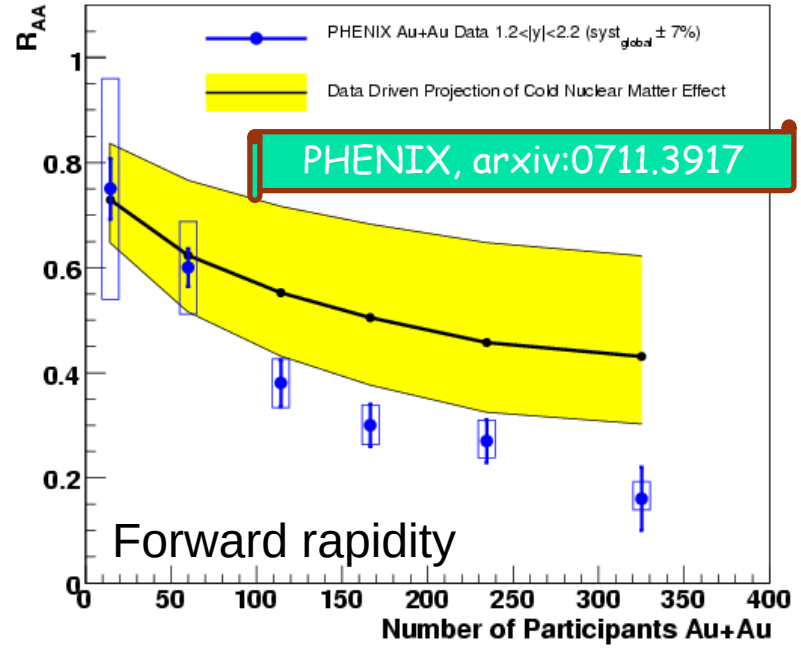
- CuCu and new Run-7 data confirms previous results
- @RHIC, there is more suppression at forward rapidity where the energy density is *lower*
- two ideas
  - final state:
    - recombination
  - initial state:
    - saturation (aka CGC)
    - shadowing

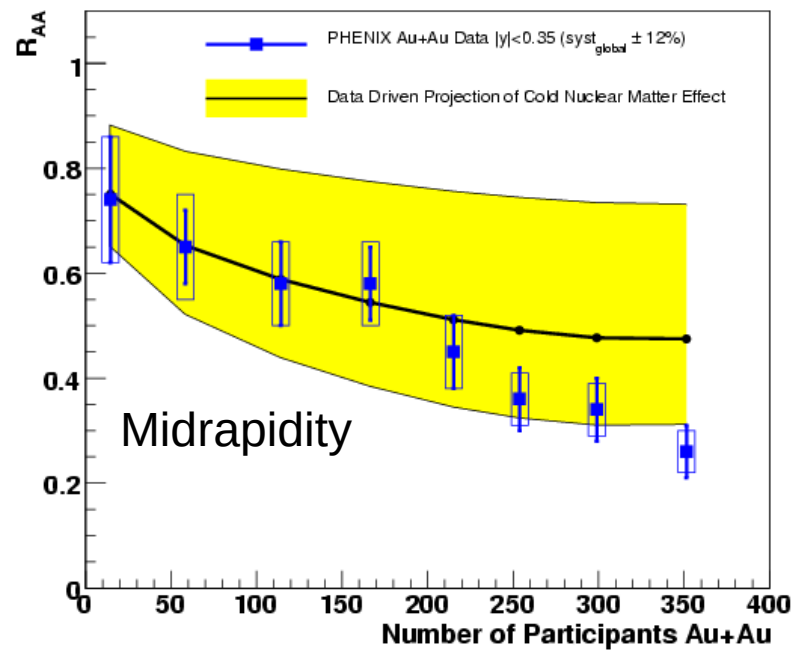


dAu should give us a handle on initial state effects

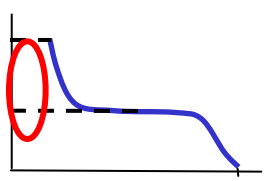
Cold matter. Using the dAu (reanalyzed data)

- In a Glauber data-driven model, propagate what we know from R_{dA}(y,centrality) to build up the a model for AuAu
  - No shadowing scheme nor absorption scheme

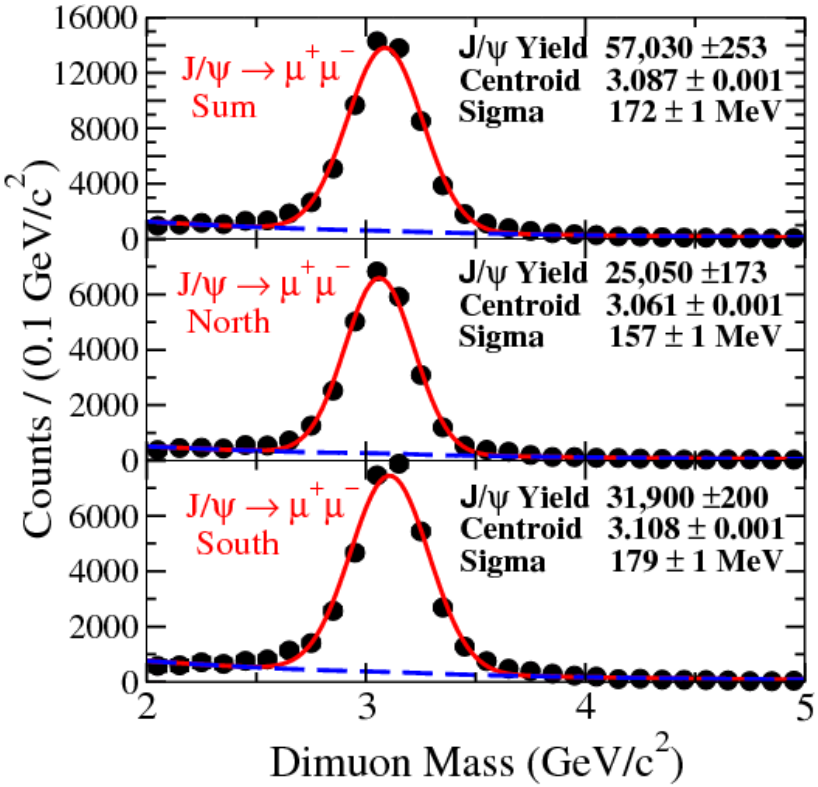


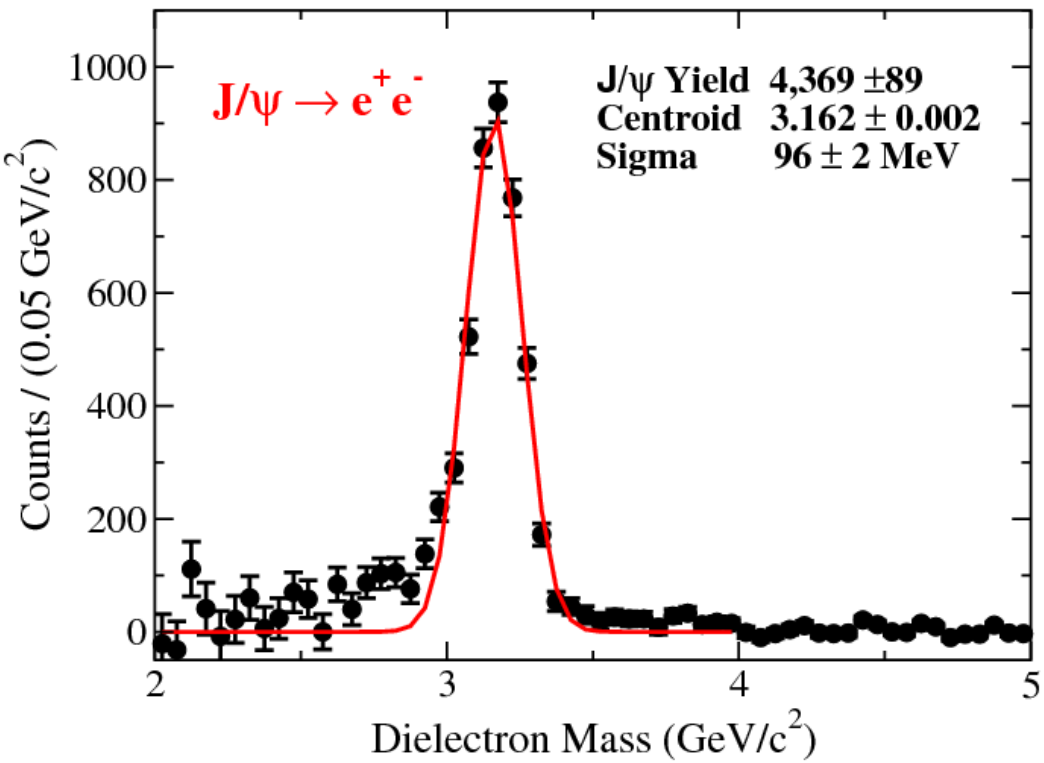


At the moment, the PHENIX dAu data is not good enough to say whether or not cold nuclear matter effects can totally explain the mid-rapidity data.



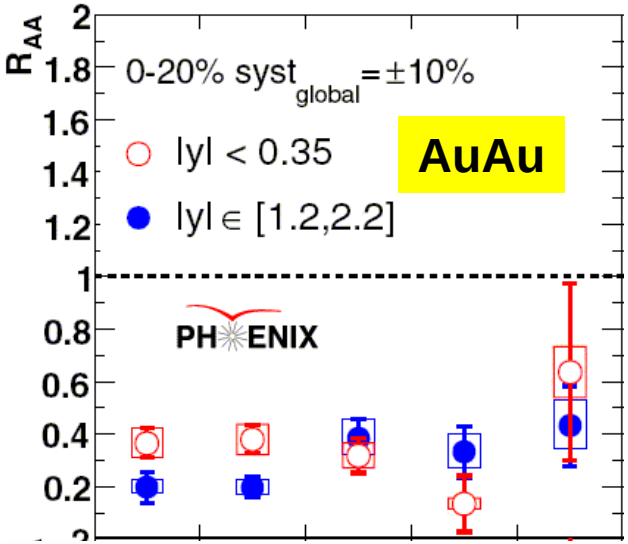
RHIC run 8 dAu ≈ 30 x run 3 !

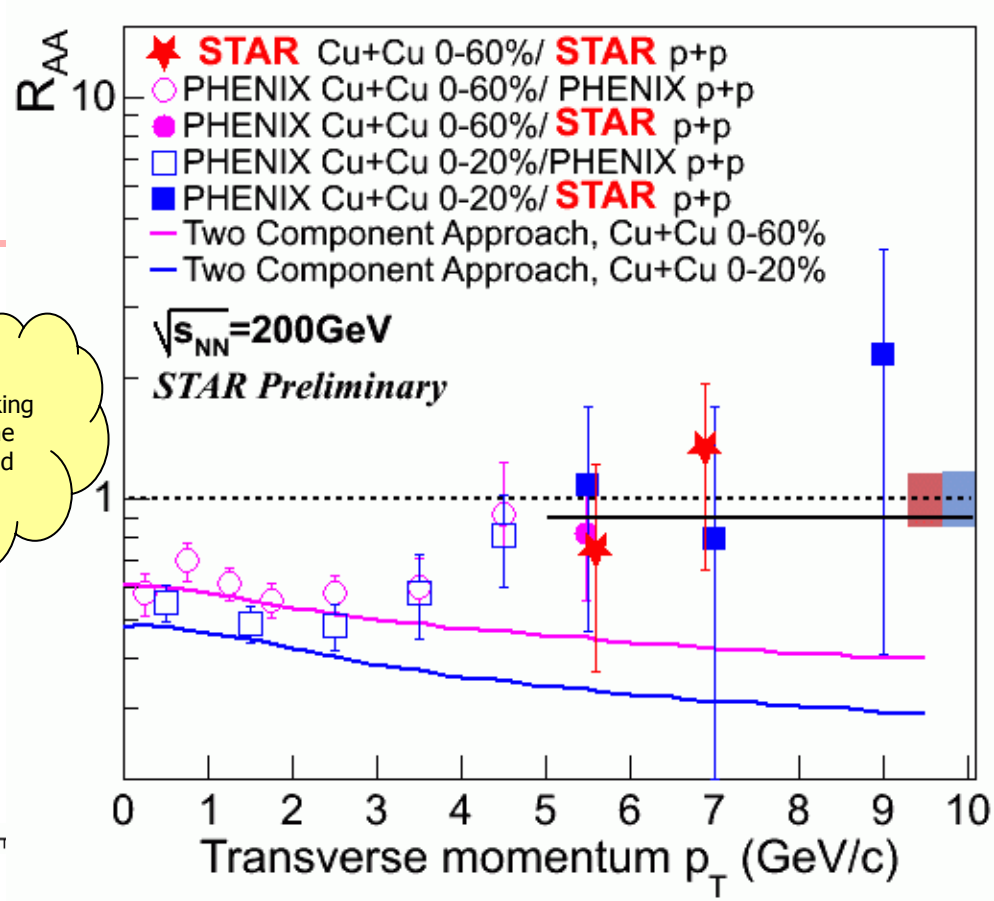


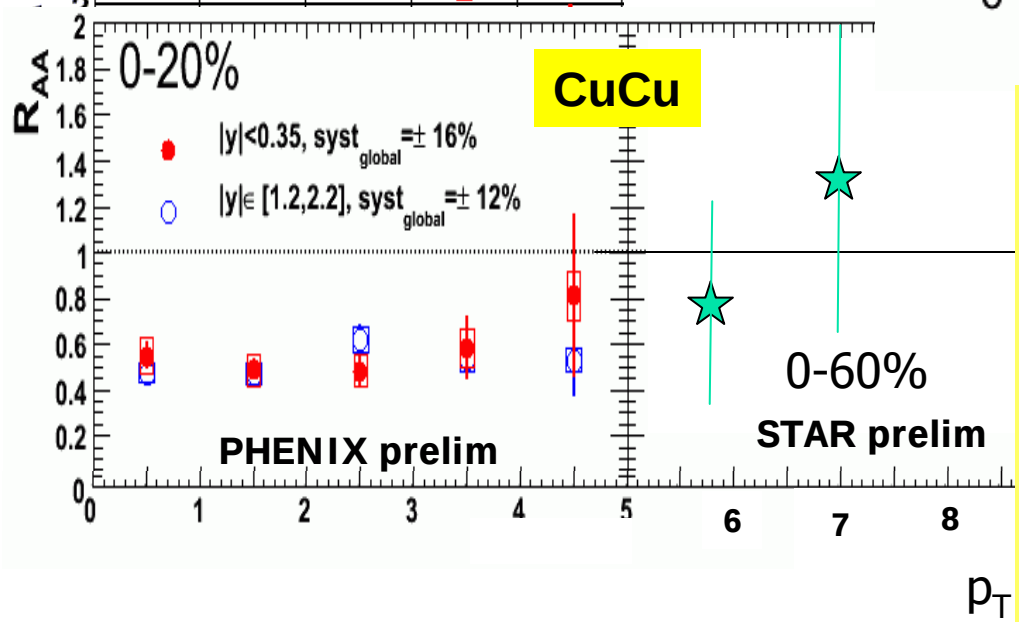


- "Let's wait for this run analysis before to say more about cold matter" Rafael GdC

R_{AA} at high p_T







Does the R_{AA} return to 1 at high p_T?
But there is energy loss of charm?

Could the $c\bar{c}$ be in a singlet state
(then it would be colorless and
pass freely through the sQGP)
Or maybe we are jumping to
conclusions – wait for more accurate
measurements

let me now draw a couple conclusions which (I think) will hold up

- B (bottom, beauty..) flows and is suppressed
  - B/(B+C) measured
  - v2 strength and R_AA suppression of c/b -> electrons in AA
- Dileptons and photons enhanced

(I ignore the J/ψ now since it still needs much more clarification – i.e. data and data analysis)

Good progress for 1 year… BUT

Can we begin to make these statements stronger?
What would it take for us to say
"charm and bottom are thermalized early"
"thermal radiation tell us the initial temperature is XX"

So what?

- There are clearly many questions to be answered
  - What are sources of the excess di-leptons/photons?
  - are they telling us a temperature? if so what is it?
  - How do the heavy quarks manage to become part of the bulk? – how strong is the "s" in sQGP? what is the viscosity (can we trust our calculation?)
  - Does the J/ψ show anomalous suppression? More at high y?

➔ It is an exciting time – we now have powerful tools to begin to answer these things

  - e.g. flow of J/ψ, correlations measurements (e.g. charm+jet….), excess dileptons/photons…