# Heavy Quark and Quarkonia Mesurements

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*(Riken BNL Research Center, BNL)*

RHIC/AGS users meeting 2007

| Time | Speaker | Title |
|---|---|---|
| 9:00 – 9:35 | Peter Petreczky | Quarkonia on the lattice |
| 9:35 – 10:10 | Agnes Mocsy | Can quarkonia survive deconfinement? |
| | Coffee break | |
| 10:30 – 11:05 | Sasha Lebedev | Quarkonia production at PHENIX |
| 11:05 – 11:40 | Pibero Djawotho | Quarkonia production at STAR |
| 11:40 – 12:15 | Axel Drees | Heavy flavor at SPS (NA60) |
| | Lunch | |
| 14:00 – 14:35 | Sergey Butsyk | Open heavy flavor with the PHENIX detector |
| 14:35 – 15:10 | Jaro Bielcik | Open heavy flavor with the STAR detector |
| 15:10 – 15:45 | Ramona Vogt | Heavy flavor and quarkonia production in perturbative QCD |
| | Coffee break | |
| 16:05 – 16:40 | Magdalena Djordjevic | Heavy quark energy loss at RHIC |
| 16:40 – 17:15 | Ivan Vitev | Heavy mesons in dense QCD matter |
| | Adjourn | |

Thanks Alex, Maunal, Pibero and others for providing additional STAR information.

# Motivation for Studying Heavy Quarks

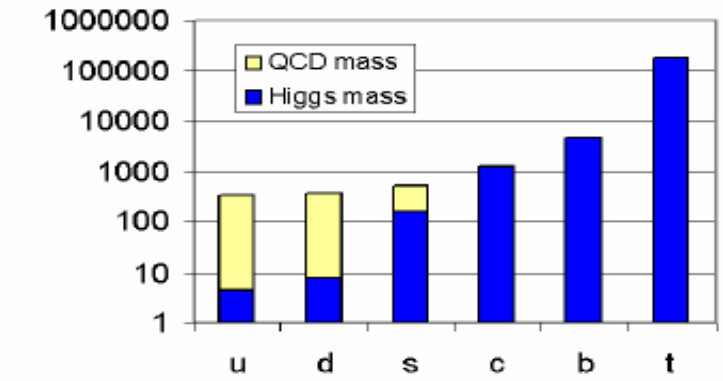
- Heavy quark mass are external parameter to QCD.

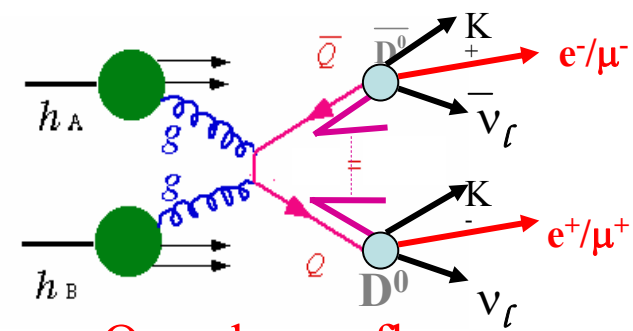
- Sensitive to initial gluon density and gluon distribution.

- energy loss feature different from light quarks. Its suppression and the flow capability provide key information on the hot/dense medium properties.

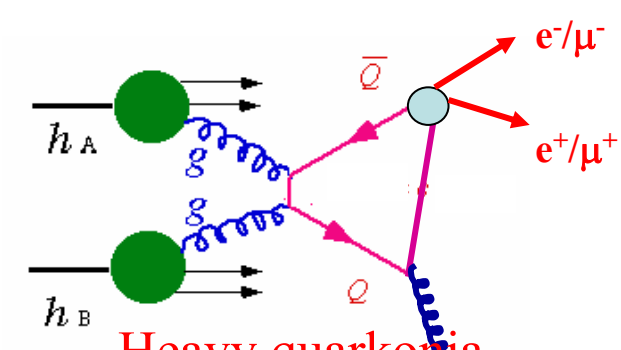
- Suppression or enhancement pattern of heavy quarkonium production reveal critical features of the medium.

- Cold Nuclear effect (CNM):
  - Different scaling properties in central and forward rapidity region CGC.
  - Gluon shadowing, etc



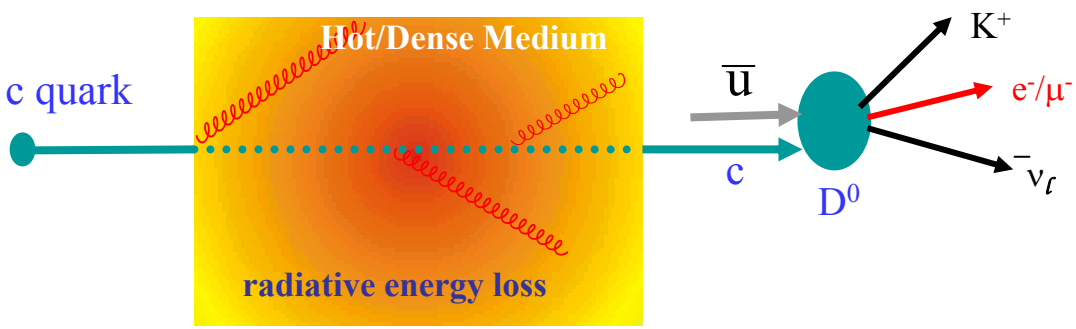




Open heavy flavor

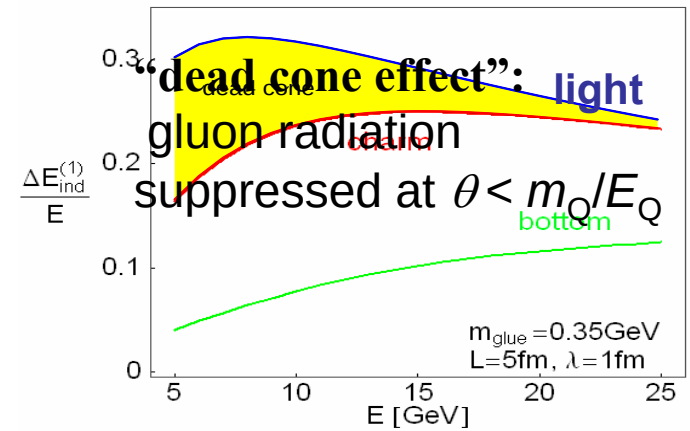


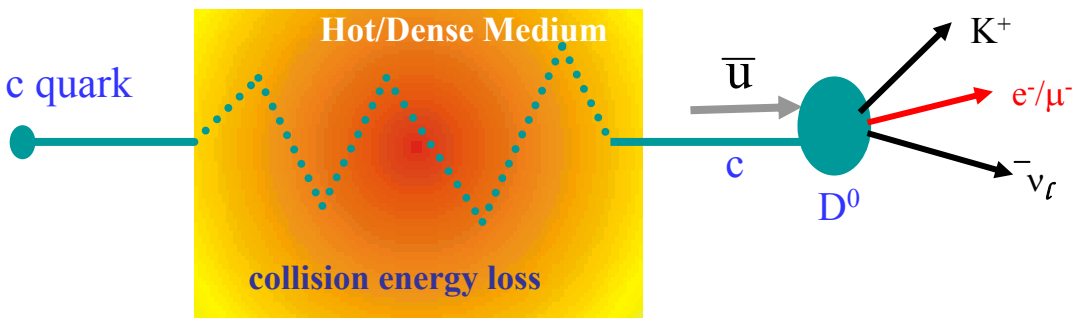

Heavy quarkonia

# Heavy Quark Energy Loss in the Medium

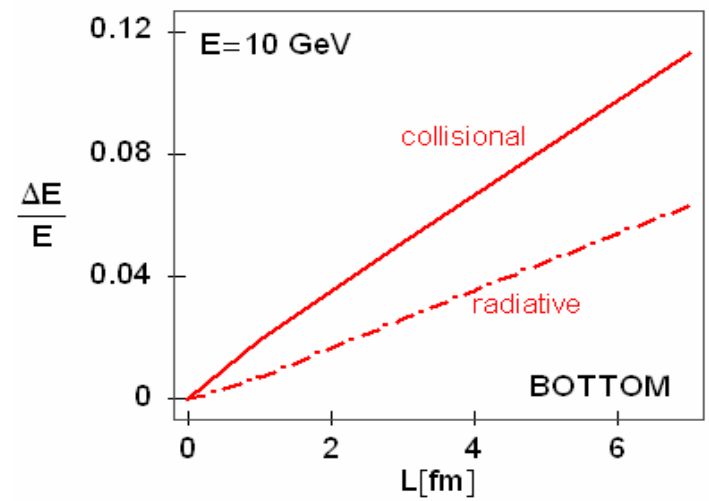


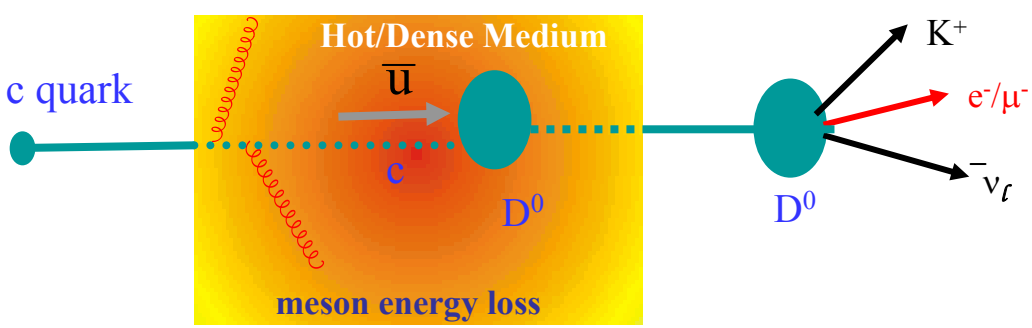

(D. kharzeev, M.Djordjevic *et al.* )



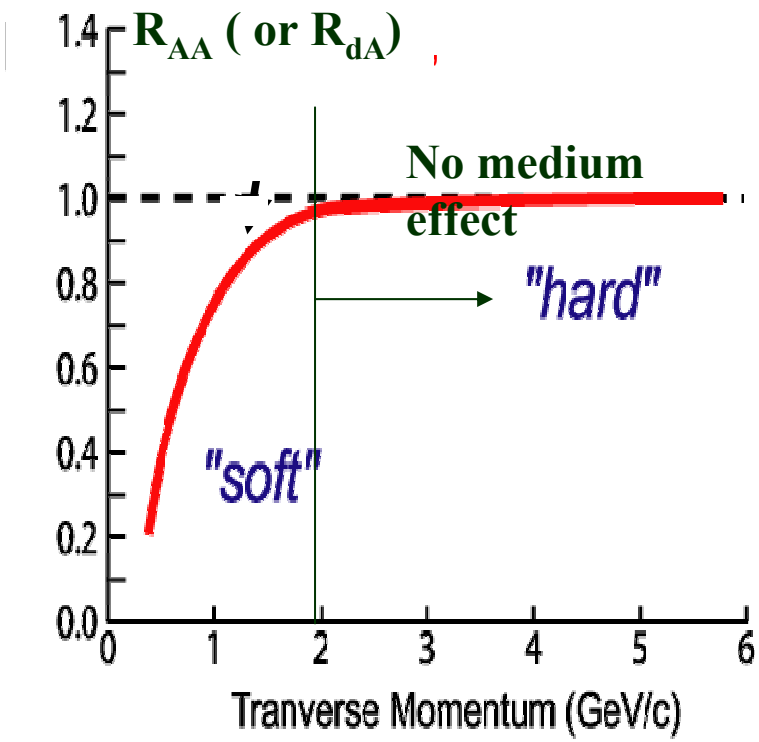

(Teany, Ralf, Denes et al.)

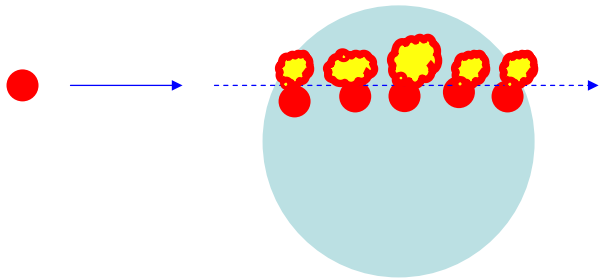



Ivan, et al

# Variables to quantify the medium effect



**5 N-N collisions**

<u>Heavy quarks are from Hard collision:</u>

•Each collision is separated clearly.

• In the absence of any nuclear effect,

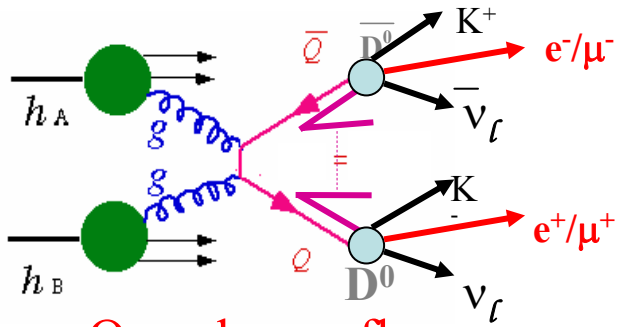
Yield(A+A) = yield(p+p)*N(collisions), i.e. scale with number of collisions (**Ncoll**)

$$R_{AA} = \frac{yield(Au + Au)}{yield(p + p) \cdot N(collisions)}$$

$$R_{dA} = \frac{yield(d + Au)}{yield(p + p) \cdot N(collisions)}$$

The larger the energy loss → The smaller the $R_{AA}$

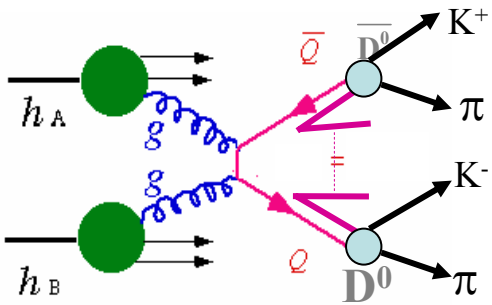
# How Measurements has been done




Open heavy flavor

**PHENIX Measurement**

- Little material to produce background.
- different methods

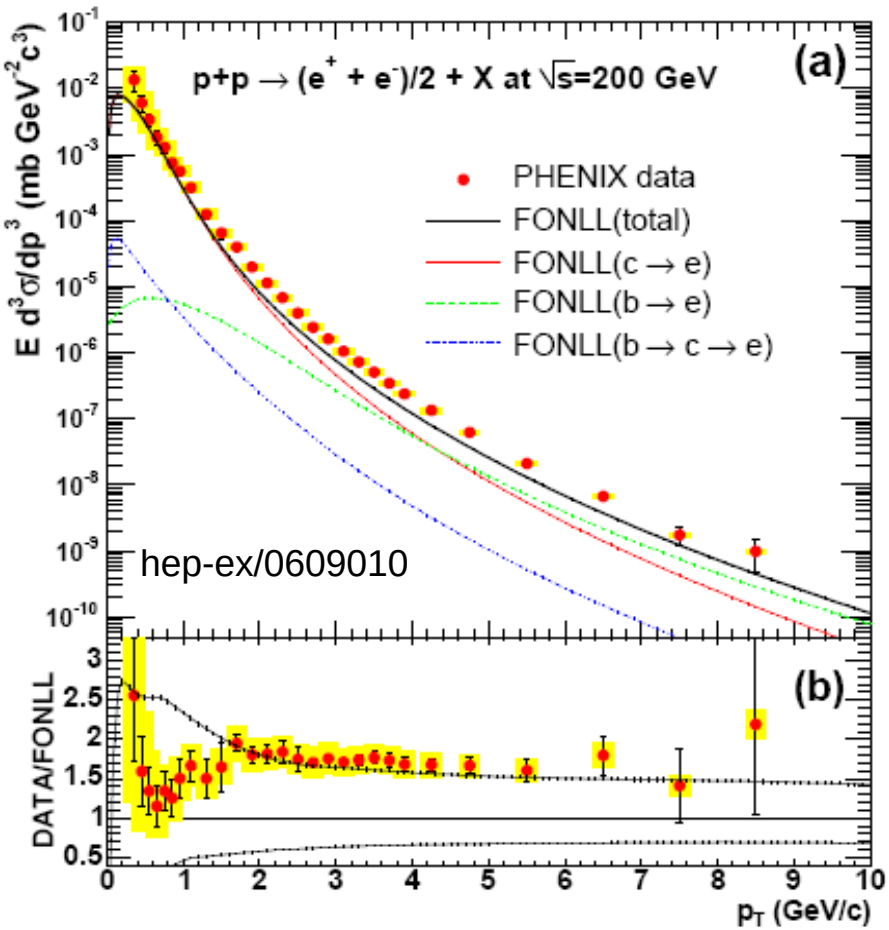


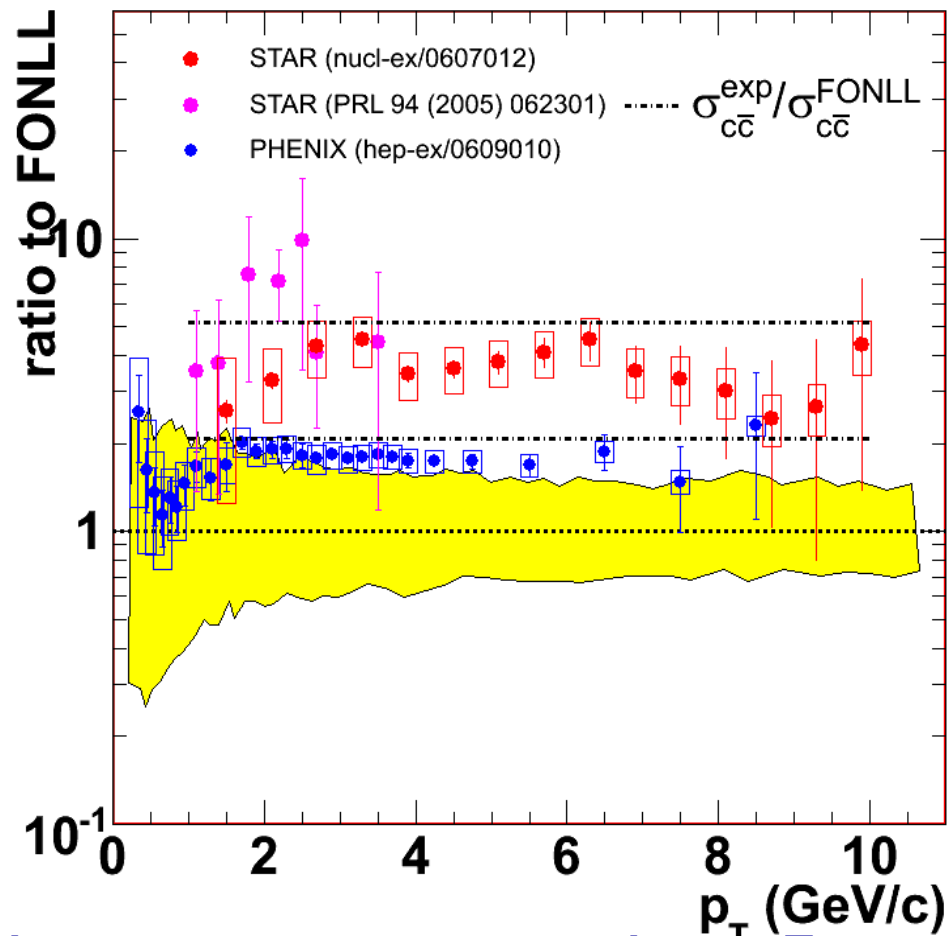

Open heavy flavor

**STAR Measurement**

- different measurements
- lots of material to produce background.

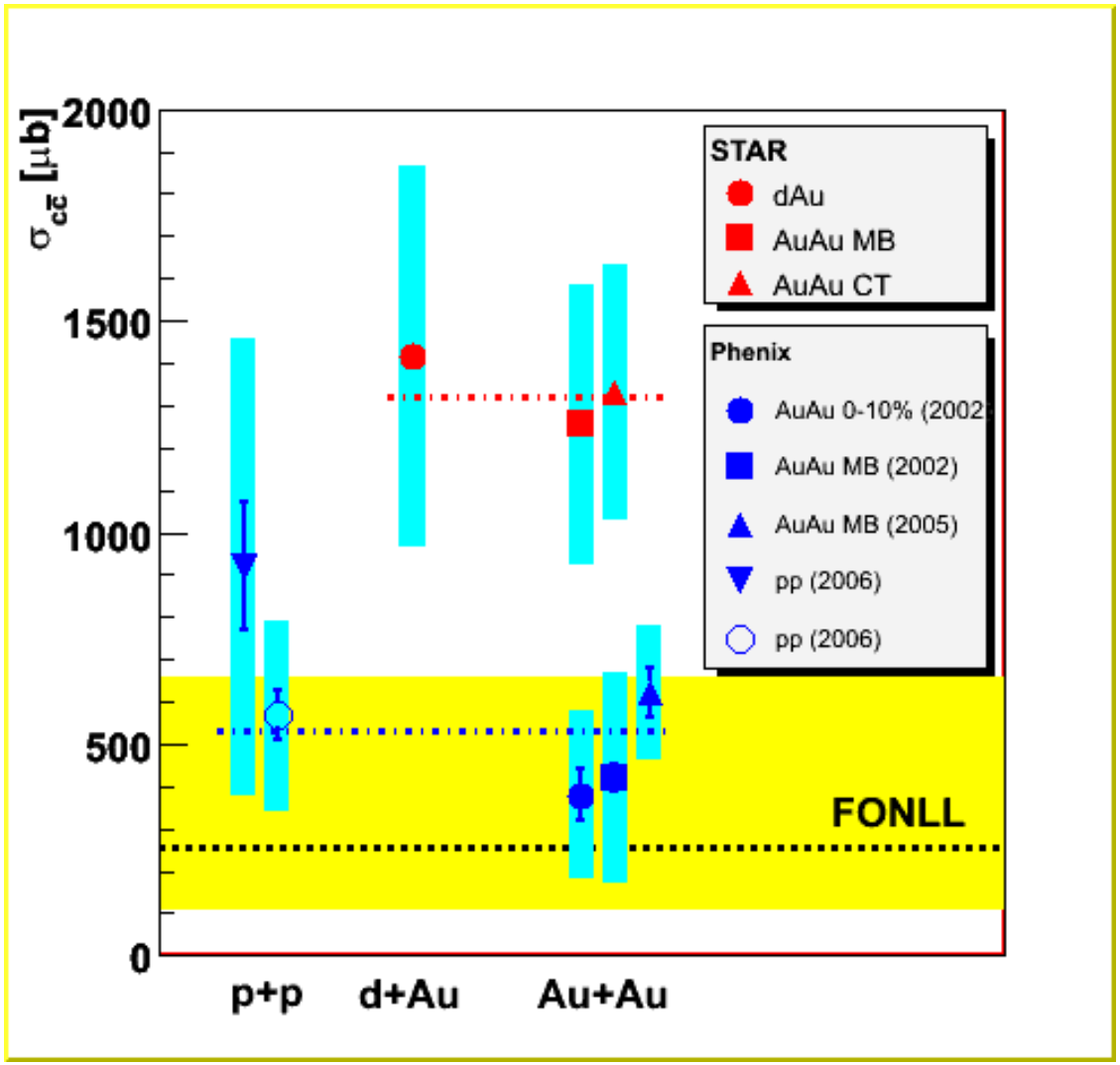
# Measurement in p+p collisions: the reference




- **Both PHENIX and STAR provide precise measurement extent to large pT.**
- **Within errors, PHENIX measurements agrees with FONLL calculation.**
- **But the two experiment disagree by a factor of two while both experiment are self-consistent on different type of measurements.**

# The difference also appears in Au+Au Collisions



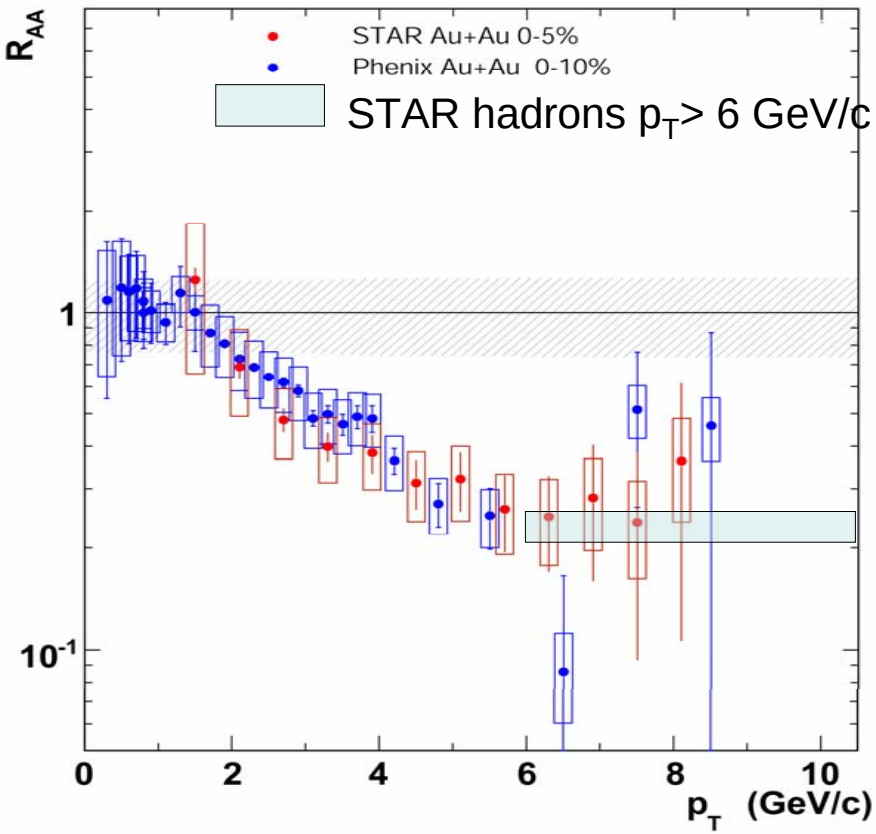

Road to the possible solution in the near future:

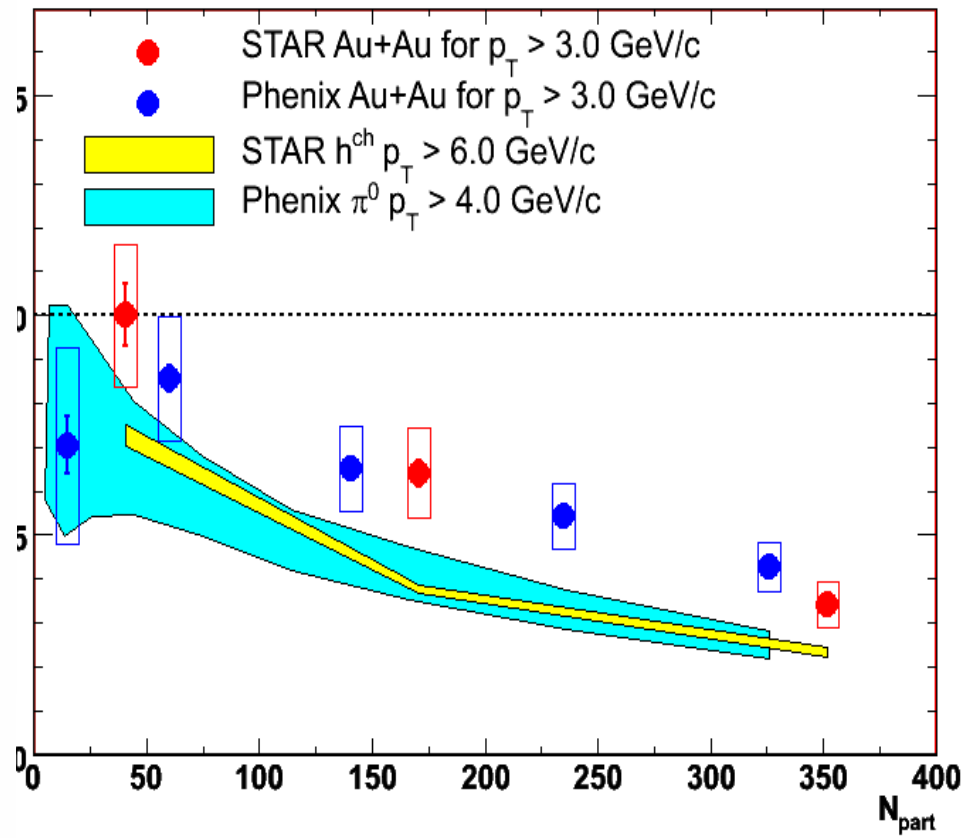
- **Direct D meson measurement from PHENIX.**
- **Low material run from STAR aiming at RUN8 and thereafter.**

**The difference is cancelled out when calculate $R_{AA}$**

- **The two experiment get consistent $R_{AA}$ !!**

# Measurements on $R_{AA}$ in Au+Au collisions



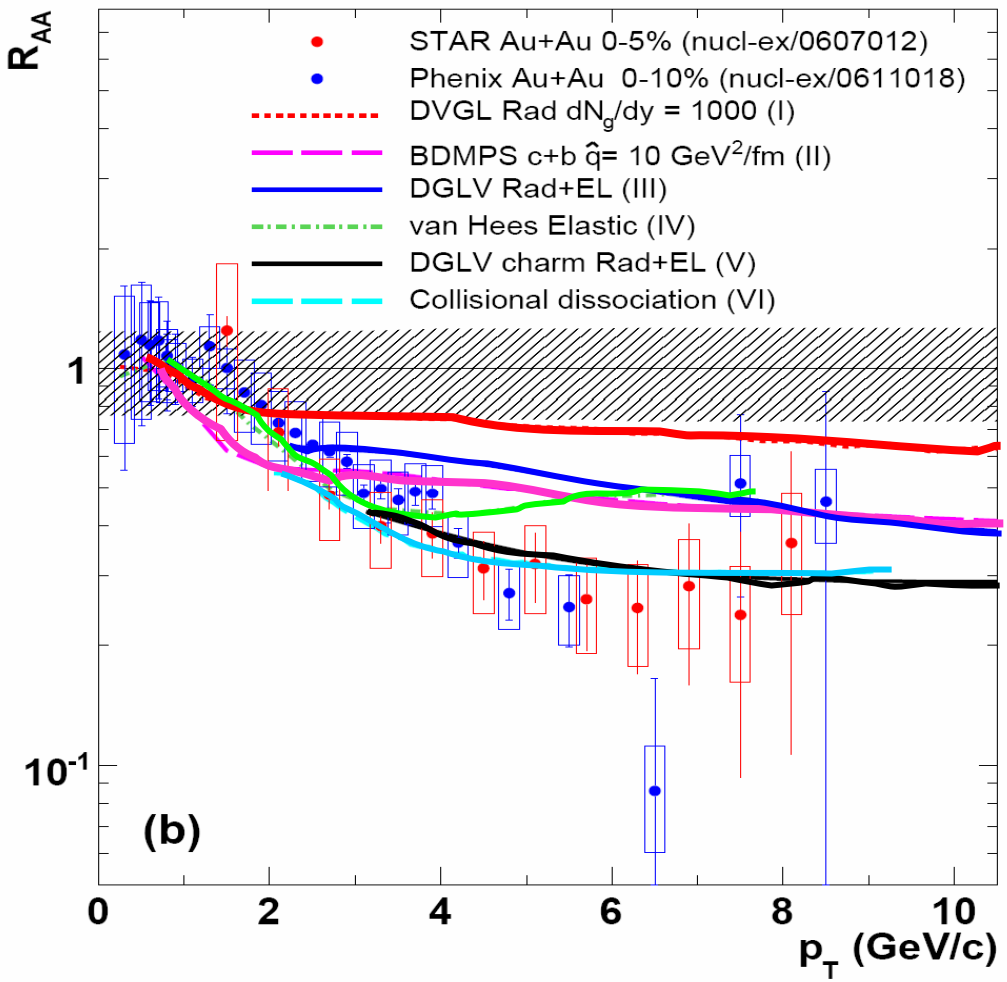




- large suppression of charm quark production is observed
- D meson probably less suppressed than light hadrons.
- Where the bottom show up in the spectrum?

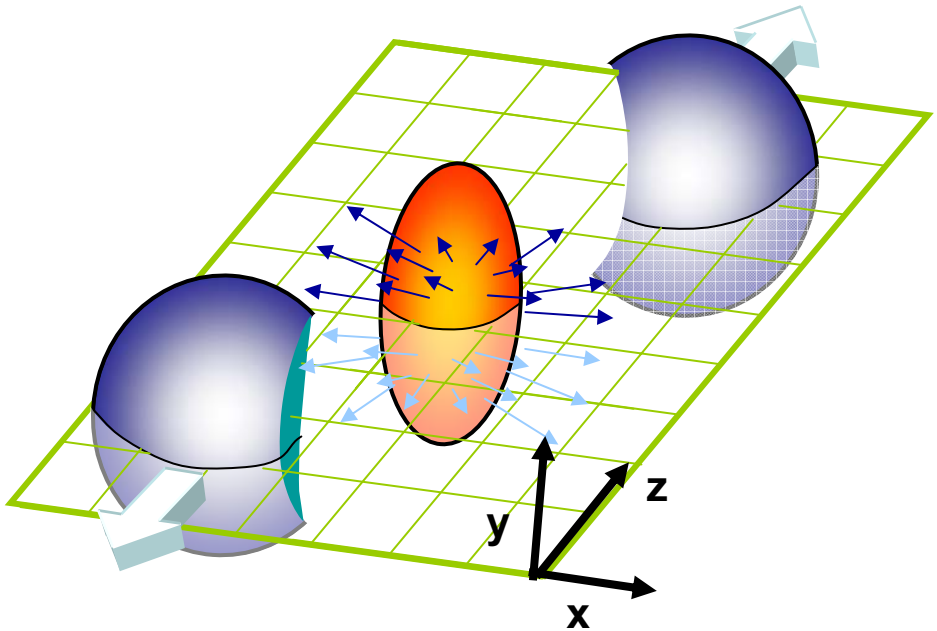
# Do we Understand the Result?

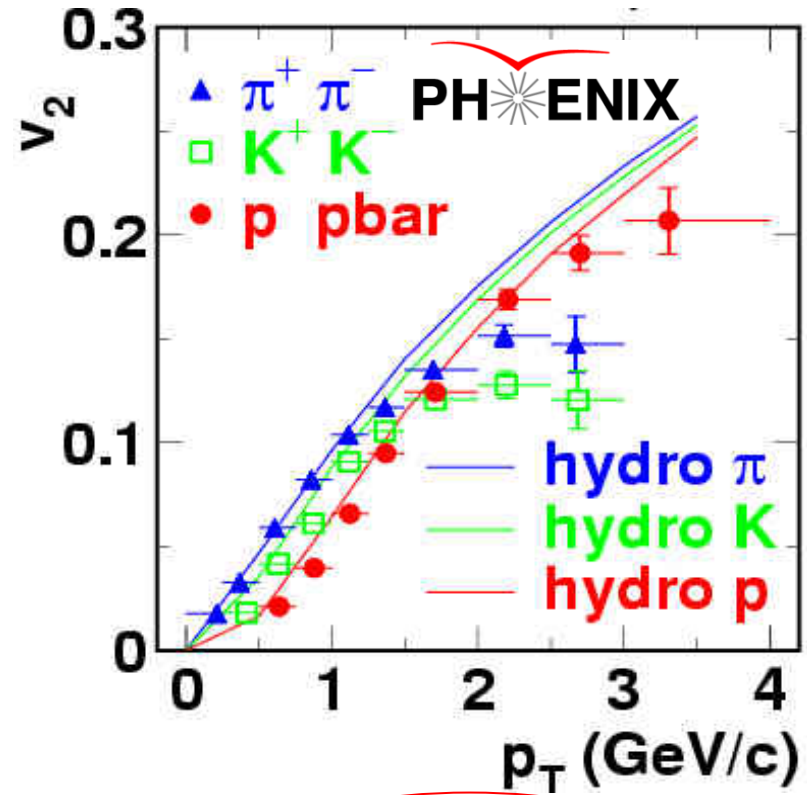
PHENIX nucl-ex/0611018
STAR nucl-ex/0607012

- Radiative Energy Loss with reasonable gluon densities do not explain the observed suppression
  - Djordjevic, Phys. Lett. B632 81 (2006)
  - Armesto, Phys. Lett. B637 362 (2006)
- Collisional EL may be significant for heavy quarks
  - Wicks, nucl-th/0512076
  - van Hess, Phys. Rev. C73 034913 (2006)
- heavy quarks fragment inside the medium and are suppressed by dissociation?
  - Adil and Vitev, hep-ph/0611109
  - Similar suppression for B and D at high-$p_T$



# Energy Loss and Flow are Closely connected



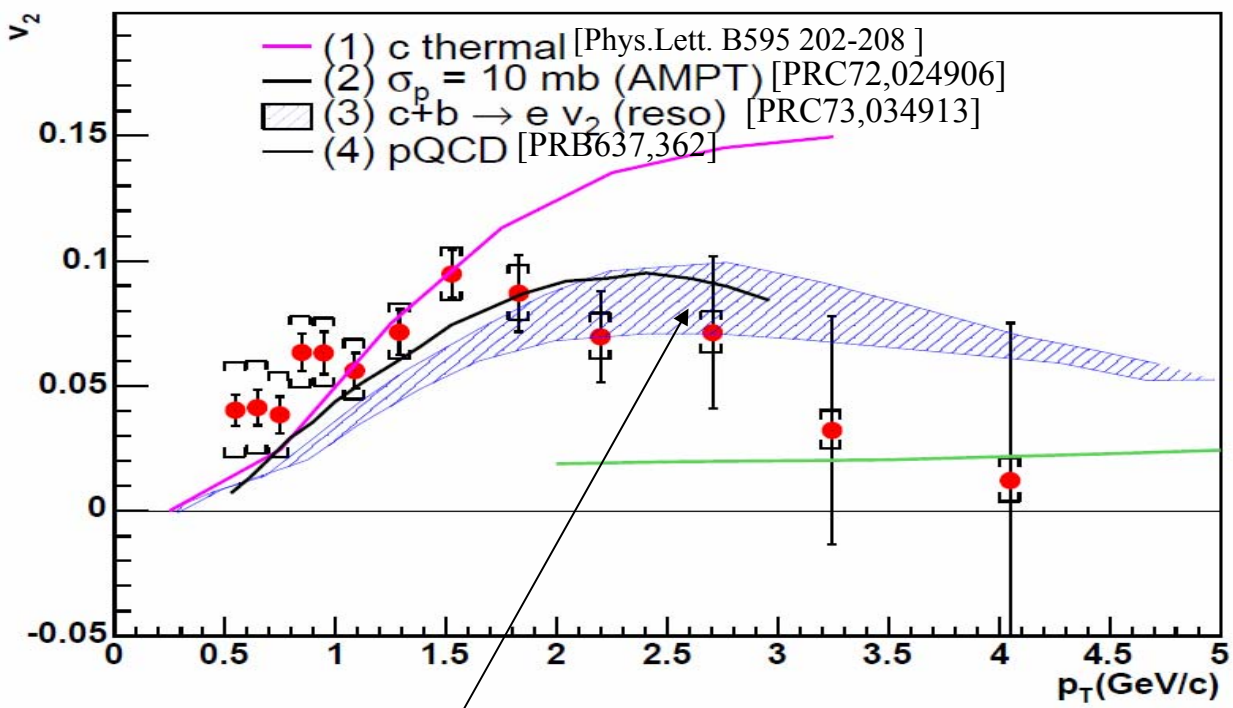




$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_r))),$$

$$V_2 = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$$

Charm was NOT expected to flow with the medium since it's too heavy !

# Flow of electrons from Charm and Bottom meson decay



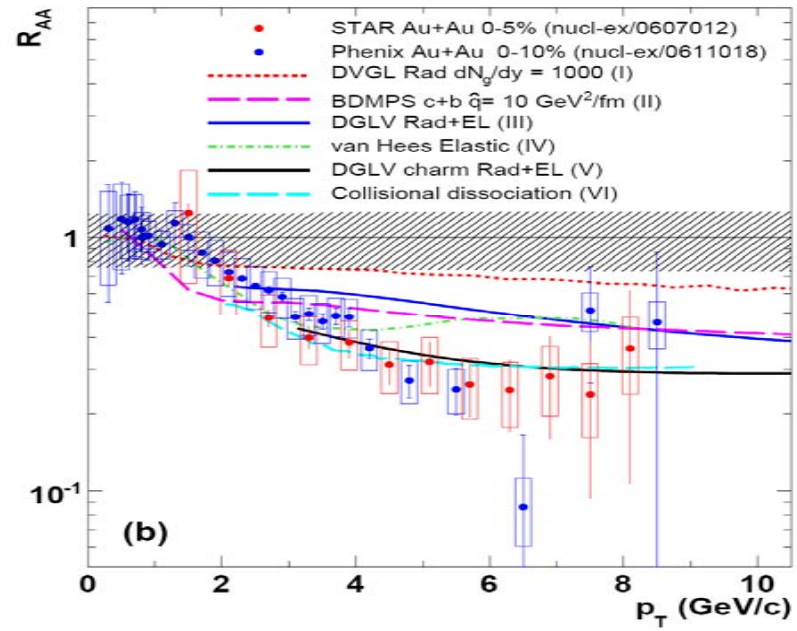

- Strong elliptic flow for non-photonic electron
- Main source is D meson -> indicate non-zero D $v_2$
- Charm $v_2$ also non-zero ?
- Bottom sneak in here?

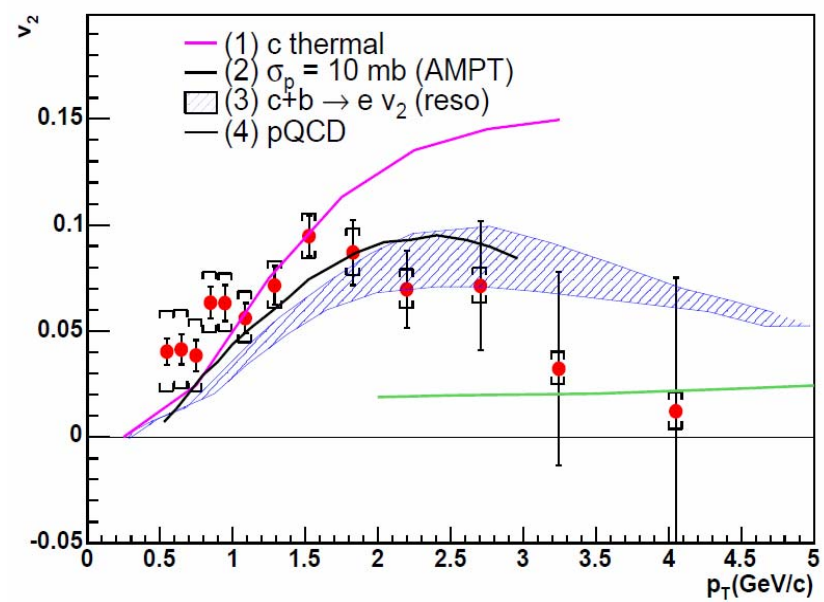
# Constraints of η/s from charm measurements

- "Perfect Fluid": viscosity close to quantum limit:

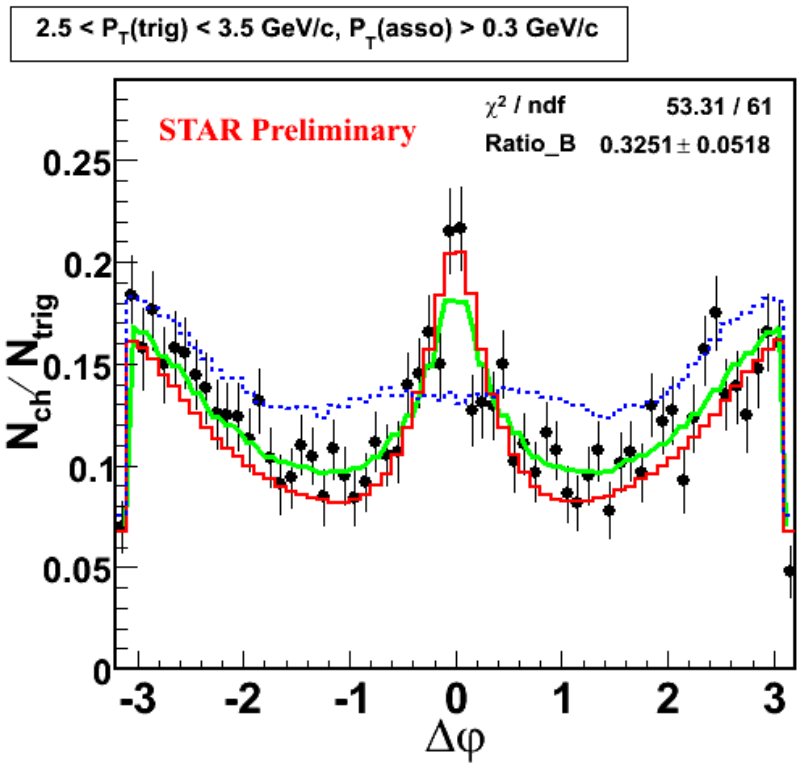
$$\eta(viscosity) \geq \frac{\hbar}{4\pi}(Entropy\ Density) \equiv \frac{\hbar}{4\pi}s$$

- Rapp and van Hees Phys.Rev.C71:034907,2005
  - Simultaneously describe PHENIX $R_{AA}(E)$ and $v_2(e)$ with diffusion coefficient in range $D_{HQ} \times 2\pi T \sim 4\text{-}6$
- Moore and Teaney Phys.Rev.C71:064904,2005
  - Find $D_{HQ}/(\eta/(e+p)) \sim 6$ for $N_f=3$
  - Calculate perturbatively, argue result also plausible non-perturbatively
- Combining
  - Recall $e+p = T\,s$ at $m_B=0$
  - This then gives **$\eta/s \sim (1.5\text{-}3)/4\pi$**

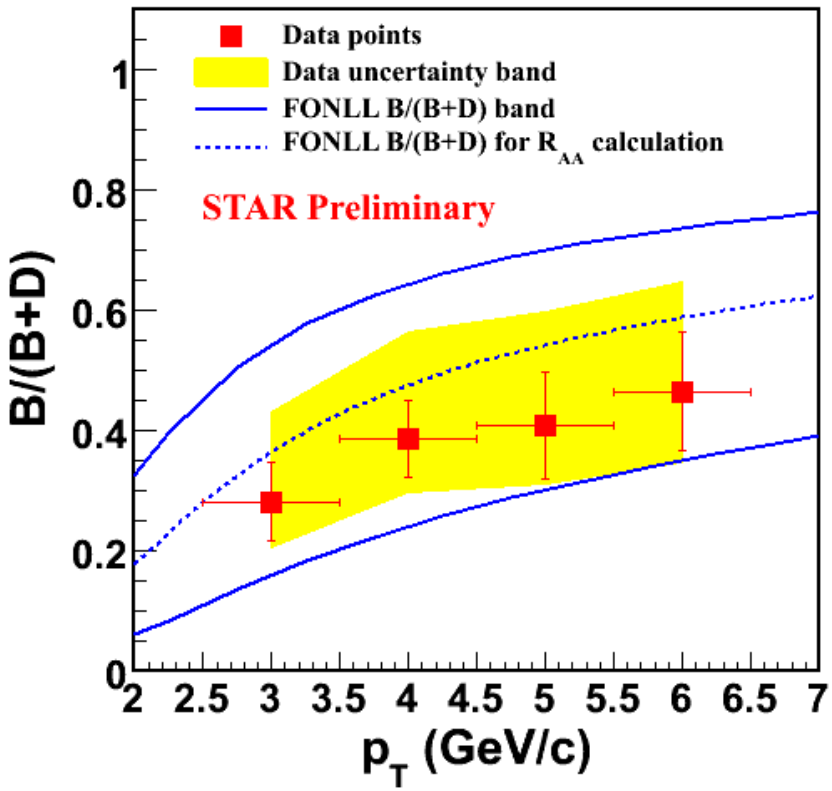


# One attempt to separate B and D mesons: e-hadron correlations in p+p: bottom vs. charm




$$\Delta\phi_{\exp} = R \cdot \Delta\phi_B + (1-R) \cdot \Delta\phi_C$$

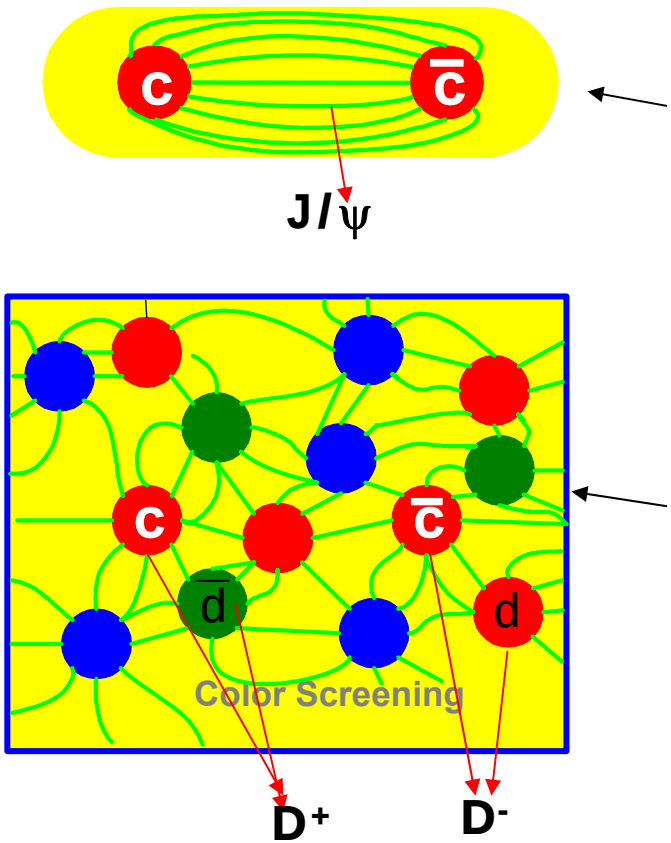


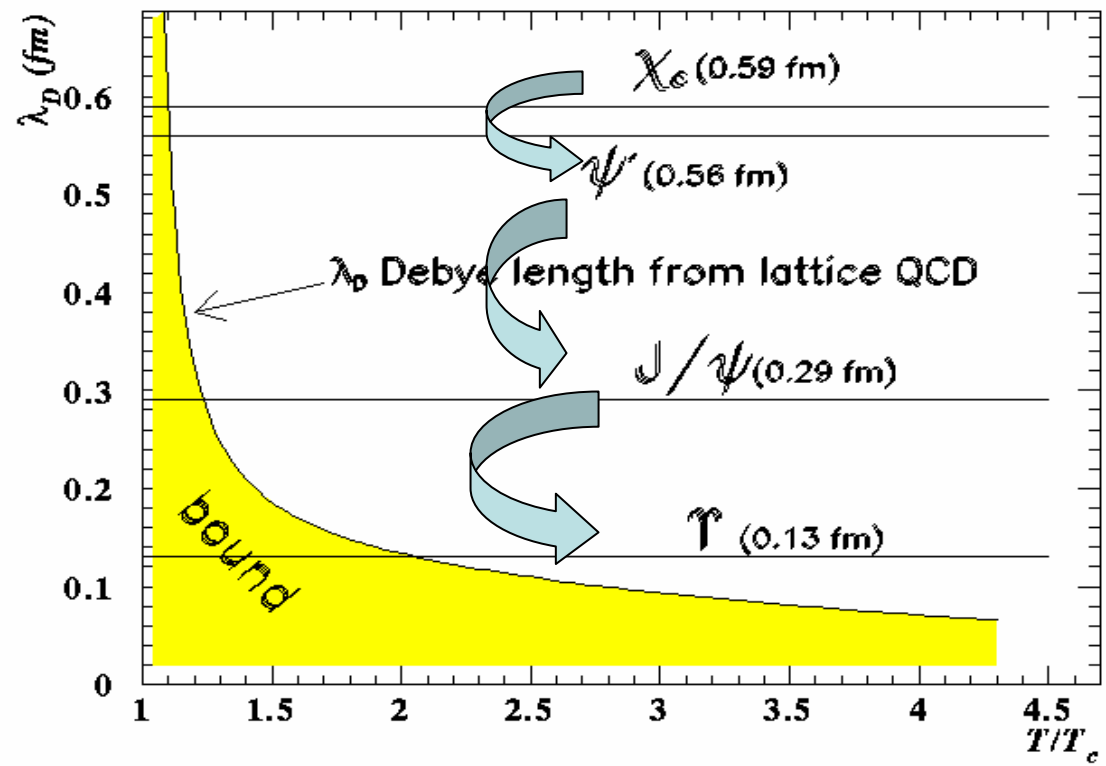

- PHENIX also doing charge correlation in the mass space. Results coming out soon.
- **Direct measurements via VTX upgrade is needed for Au+Au collisions**

# Quarkonia Suppression: “smoking gun” for QGP

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the $J/\psi$ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that $J/\psi$ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Physics Letter B Vol.178, no.4 1986



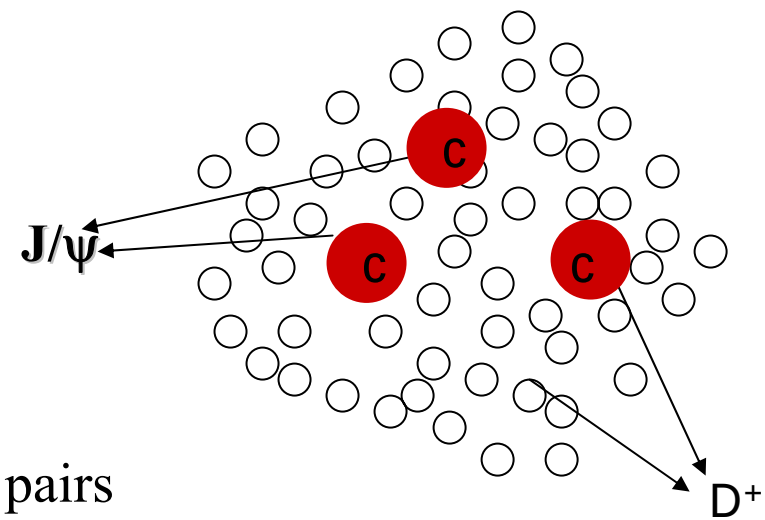




The melting sequence: $\chi_c$ -> $\Psi'$ -> $J/\psi$ -> Upsilon

# The life of J/ψ in the medium is very complicated

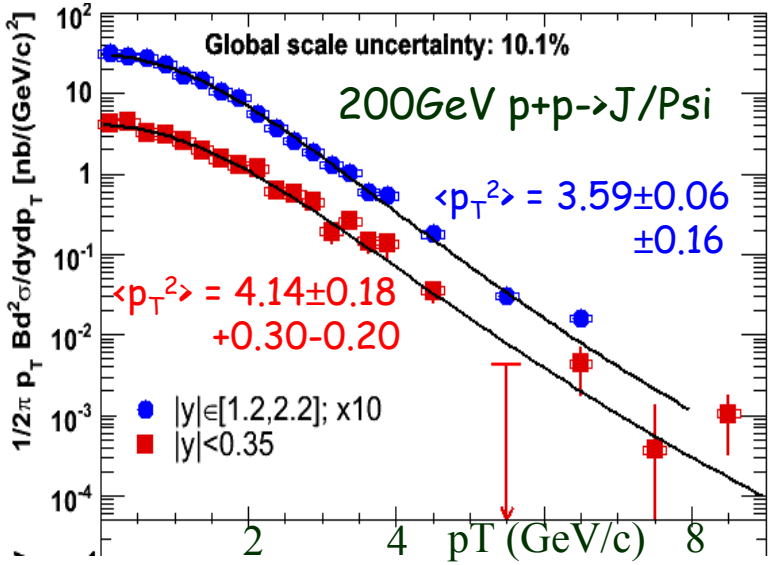
- Observed J/ψ is a mixture of direct production+feeddown.
  - All J/ψ ~ 0.6J/ψ(Direct) + ~0.3 $\chi_c$ + ~0.1ψ'
    - Important to disentangle different component (*through upgrade*)

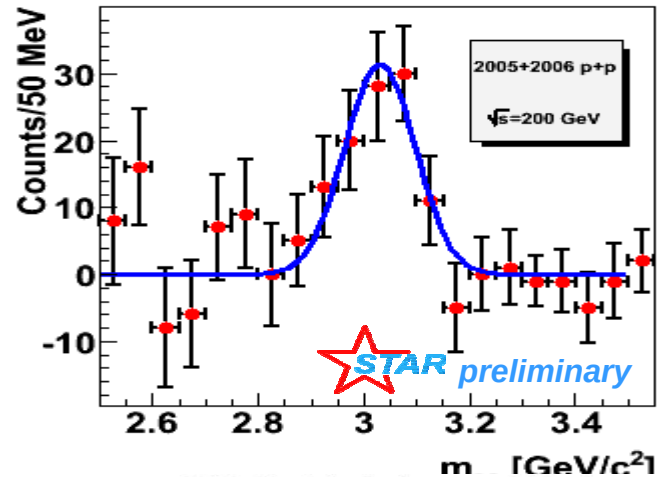
- Suppression and enhancement in the "cold" nuclear medium
  - Nuclear Absorption, Gluon shadowing, initial state energy loss, Cronin effect and gluon saturation (CGC)

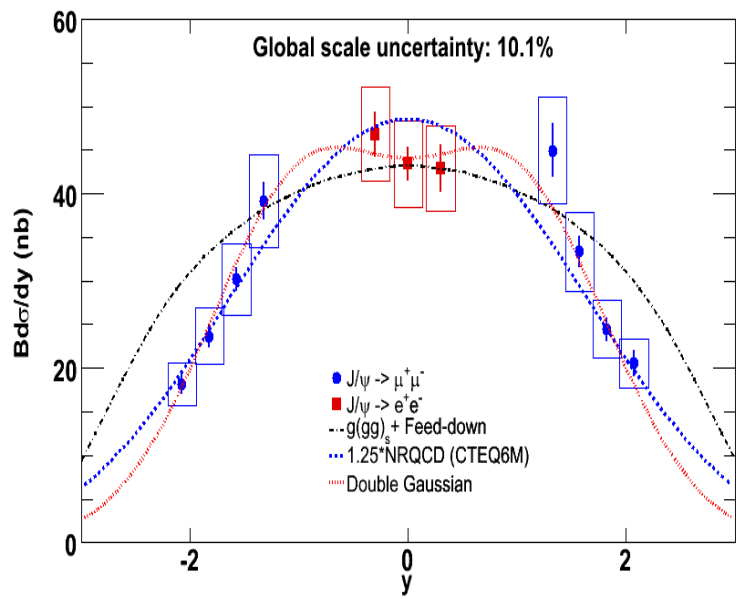


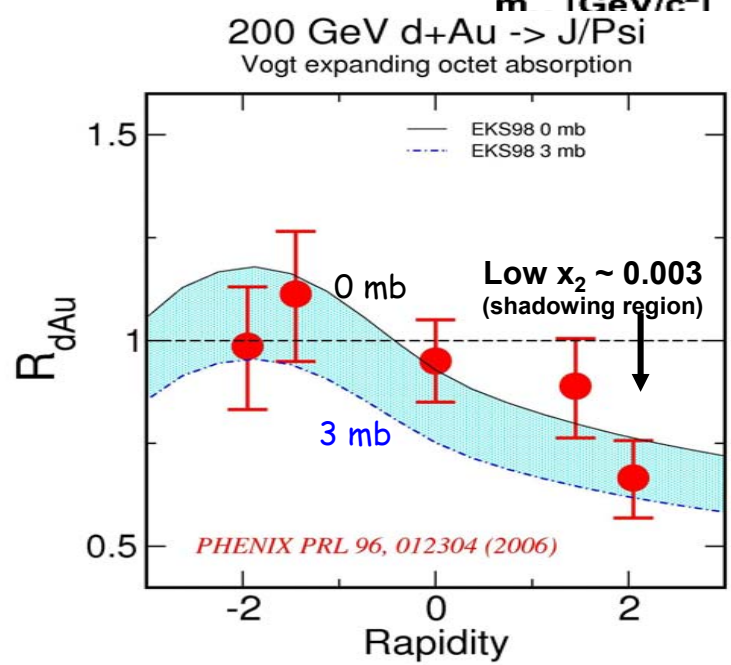

- Hot/dense medium effect
  - J/ψ dissociation, i.e. suppression
  - Recombination from uncorrelated charm pairs
  - Survival (or not) in the hot/dense medium from lattice calculation
    - See Agnes Mocsy's presentation during the workshop.

# J/ψ Baseline Measurement via p+p and d+Au collision



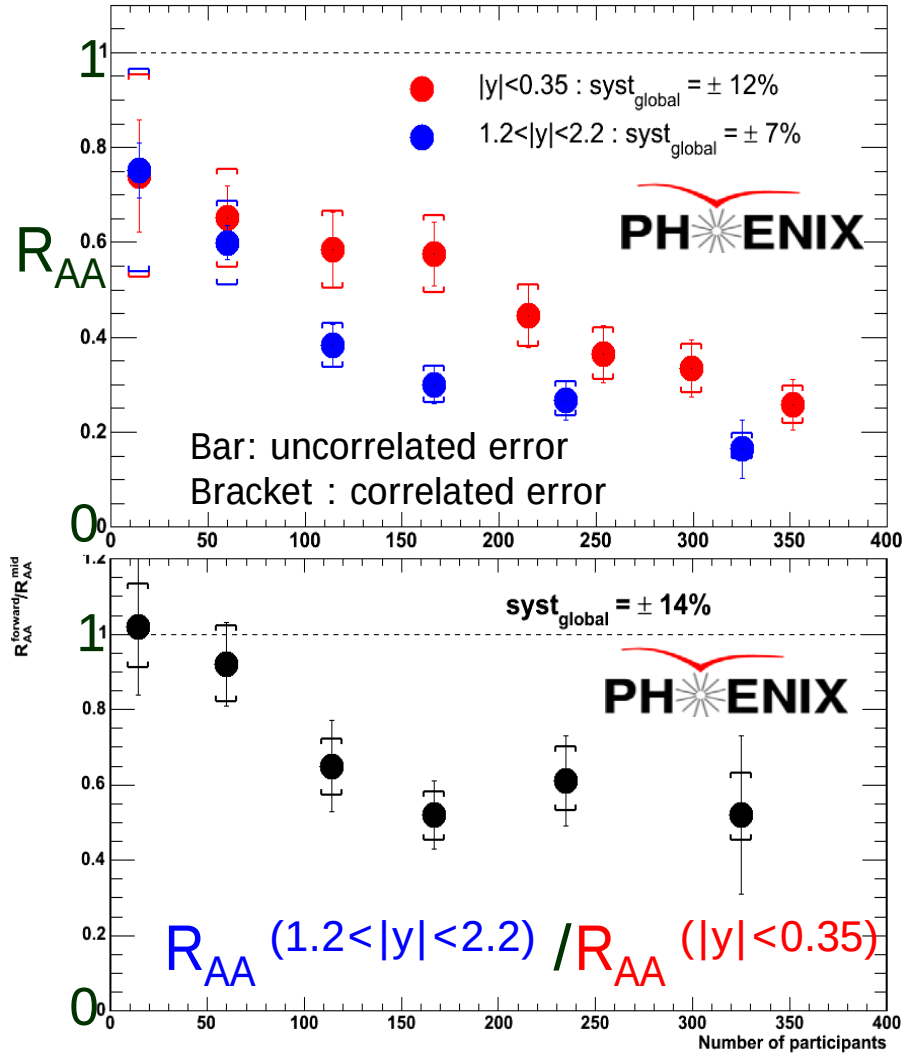



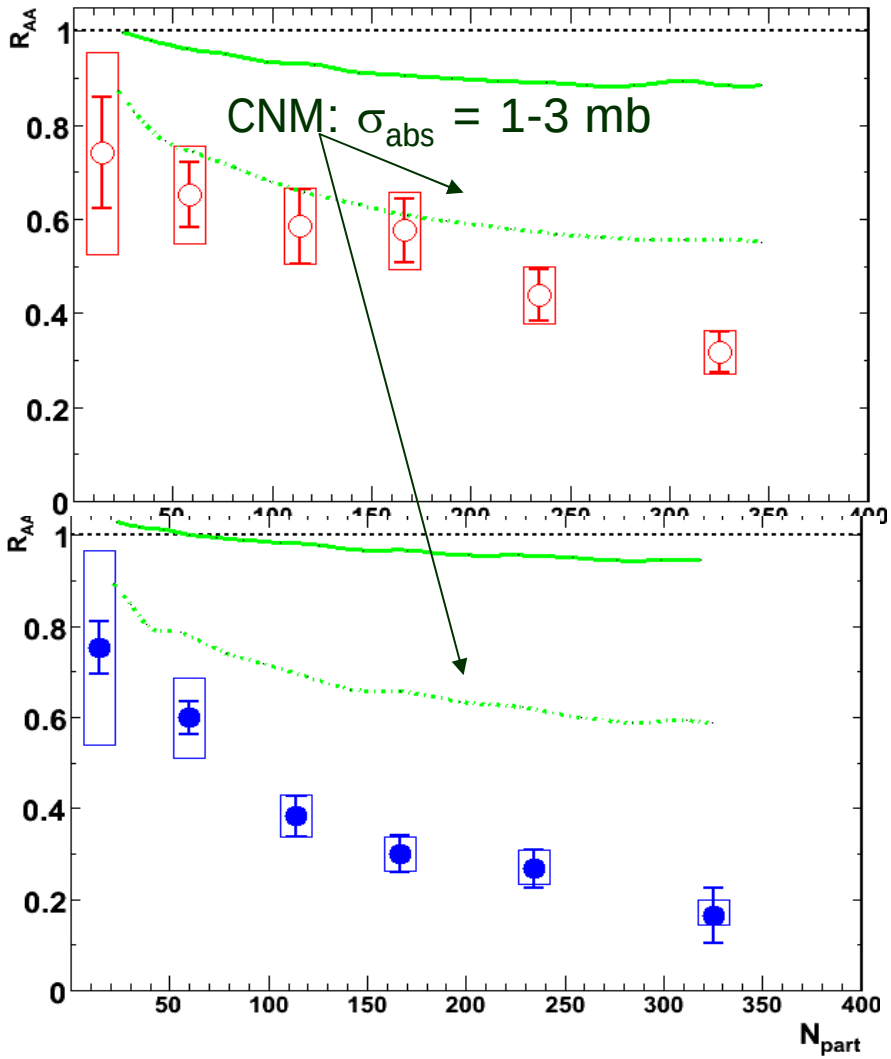




$B_{ll} * \sigma_{pp}(J/\psi) = 178 \pm 3(stat) \pm 53(sys) \pm 18(lum)$ nb

- high precision p+p results
- d+Au favor $\sigma_{ABS} \sim$ 0-3 mb.

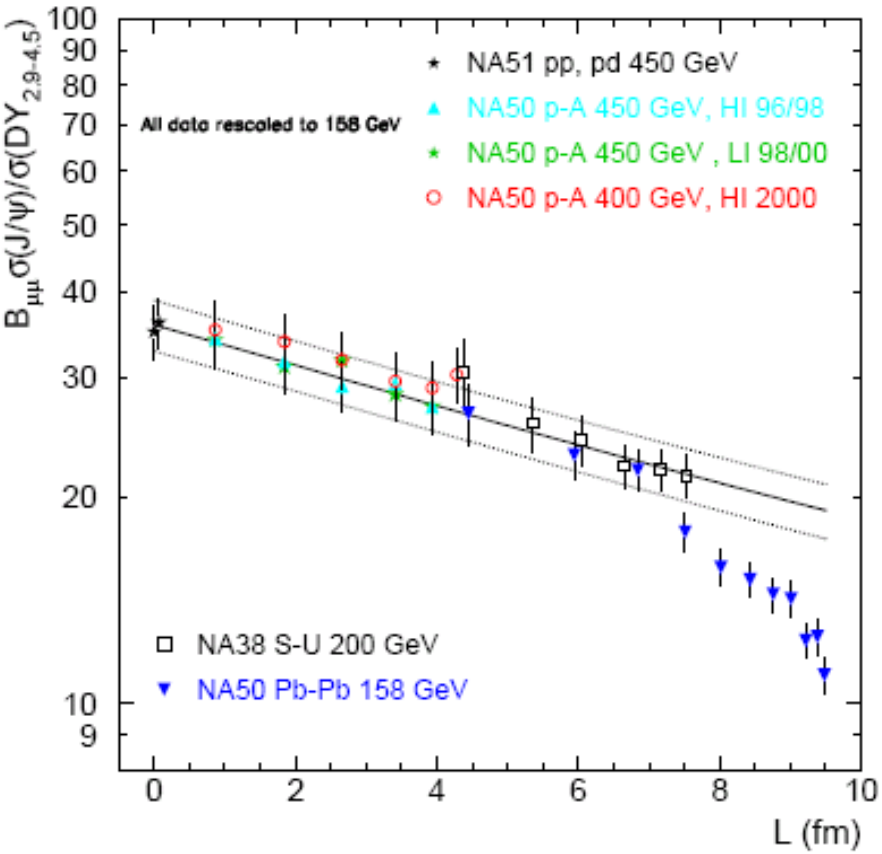
# J/ψ Suppression in Au+Au collisions

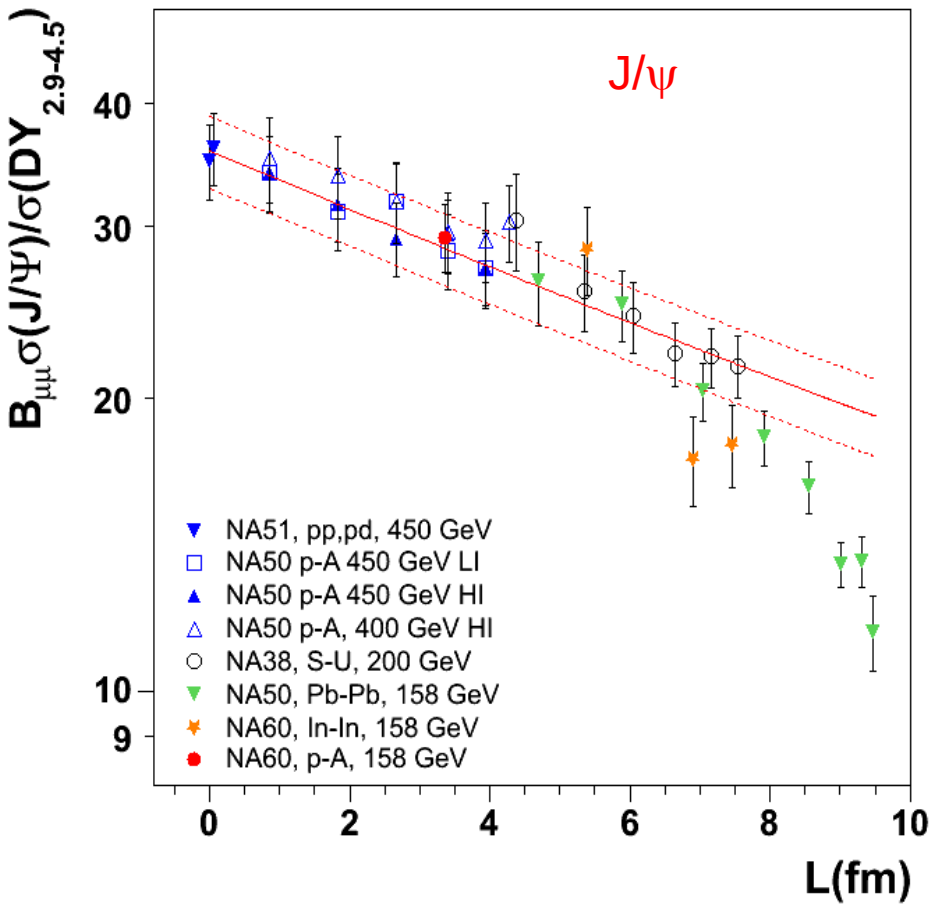



- Larger suppression in forward rapidity comparing to midrapidity.
- CNM suppression can not explain the results in Au+Au collisions

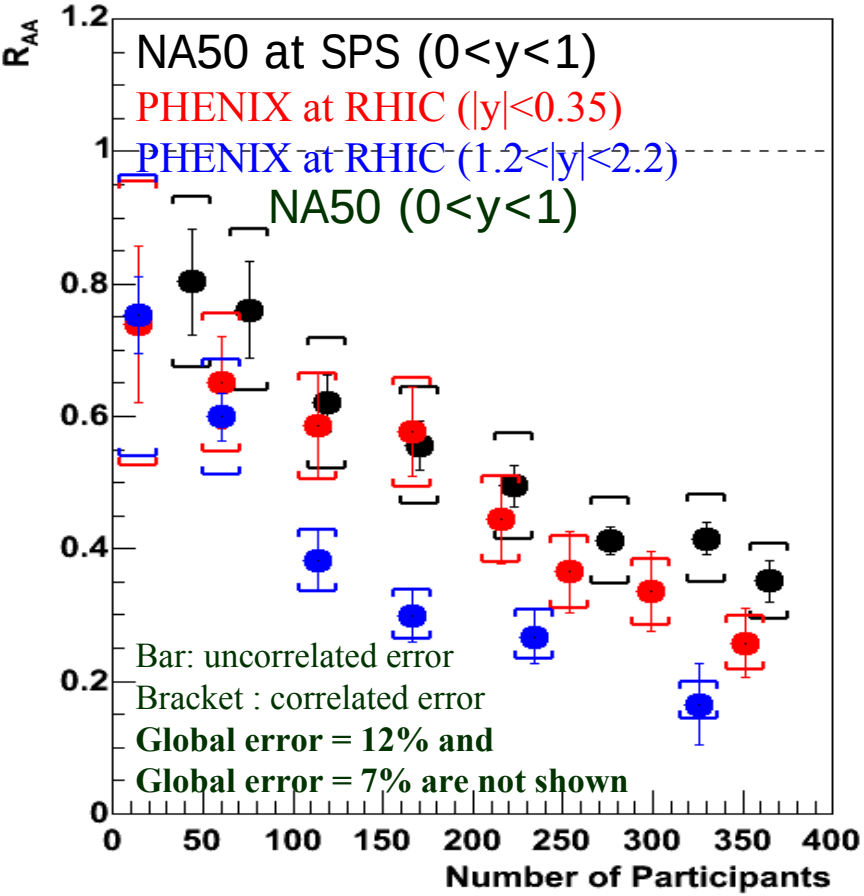
# SPS Results

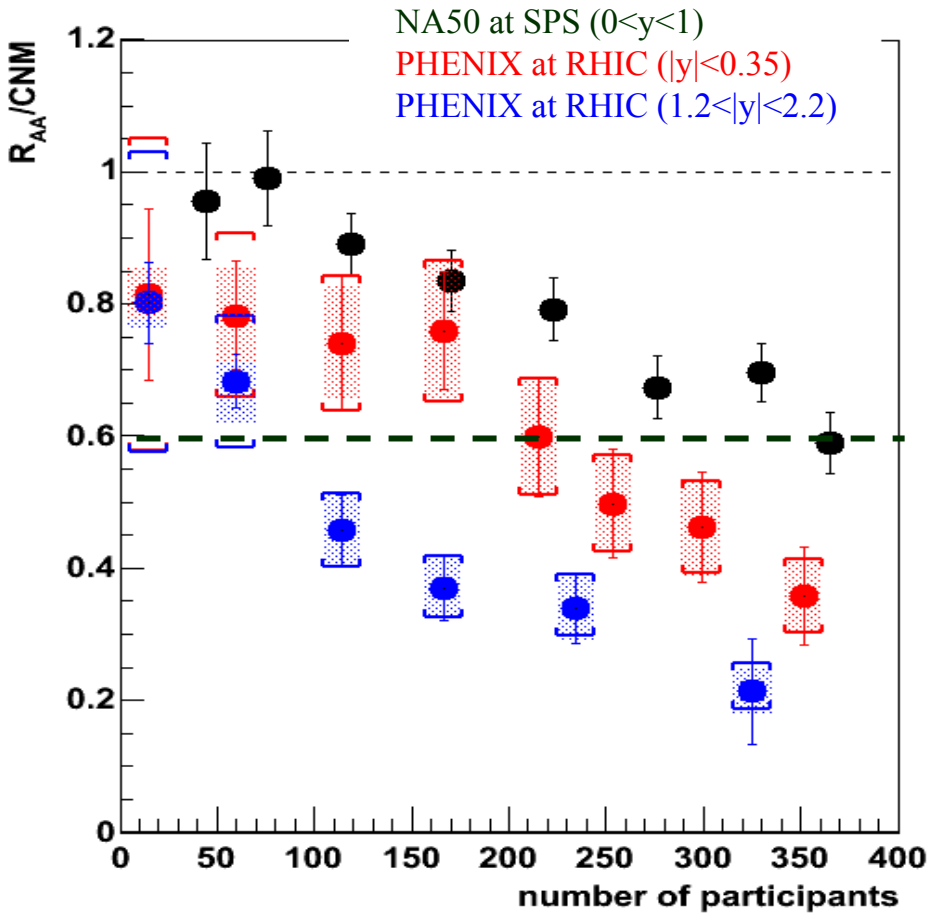



- NA50 observed anomalous J/psi suppression
- NA60 results are consistent with NA50.

# Comparing RHIC to SPS Suppression results

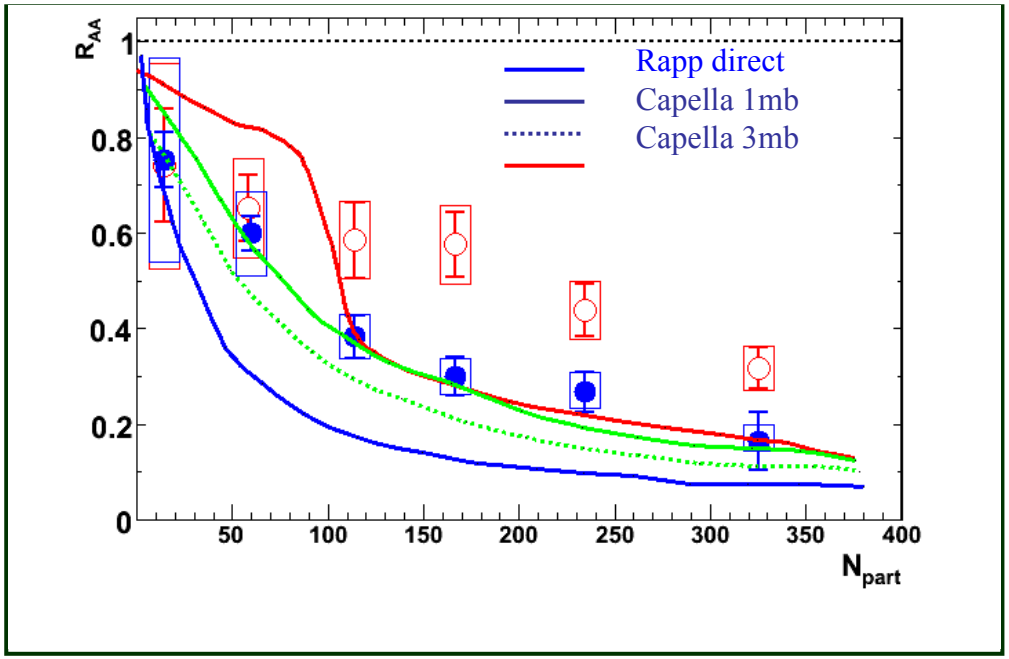


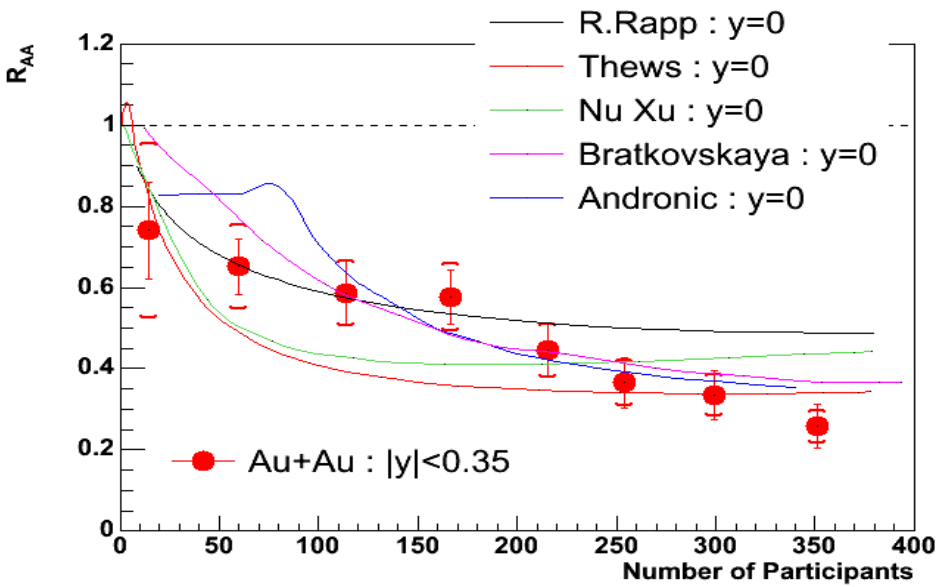




- Suppression pattern similar in RHIC and SPS.
- CNM effect not removed yet.

- After removing the CNM effect, differences start to show-up.
  - suppression at SPS consistent with the melting of psi' and chi_c?
  - Need more precise d+Au measurements

# Do we understand J/ψ results



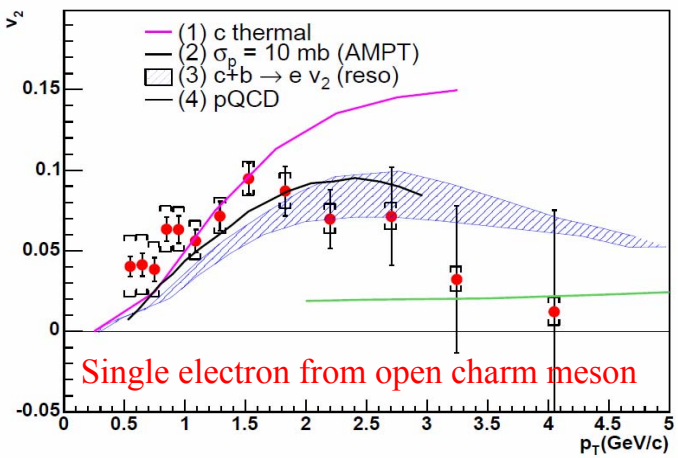




- **Models that include only anomalous suppression predict too much suppression for RHIC mid-rapidity**
- Satz - color screening in QGP with CNM added (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects (without regeneration)

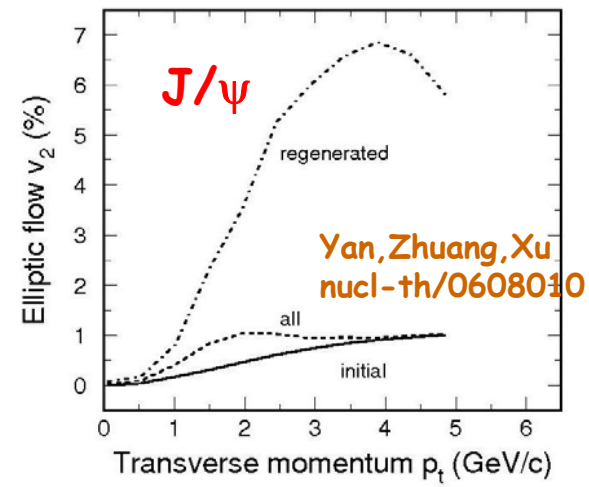
- **Models including both suppression and recombination match data better**
- R. Rapp(for y=0) PRL 92, 212301 (2004)
- Thews (for y=0) Eur. Phys. J C43, 97 (2005)
- Nu Xu *et al.* (for y=0) nucl-th/0608010
- Bratkovskaya *et al.* (for y=0) PRC 69, 054903 (2004)
- A. Andronic *et al.* (for y=0) nucl-th/0611023

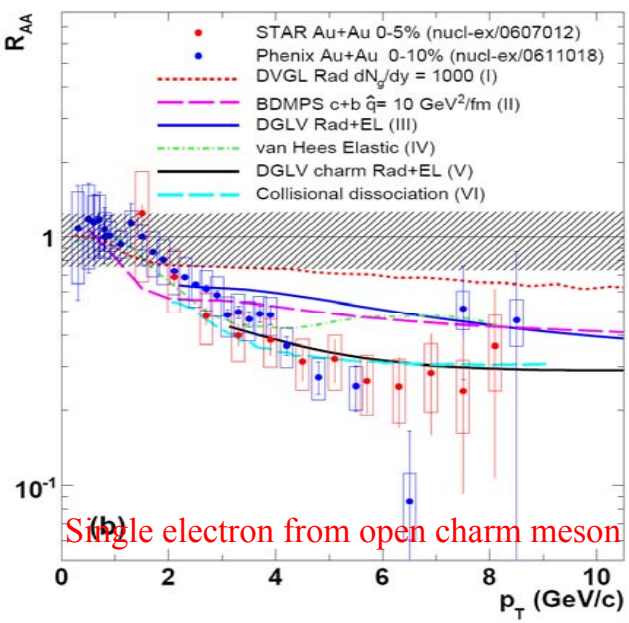
- **All seems to be somewhat more consistent with the data.**
- Other sensitive comparisons are needed

# Golden Comparisons

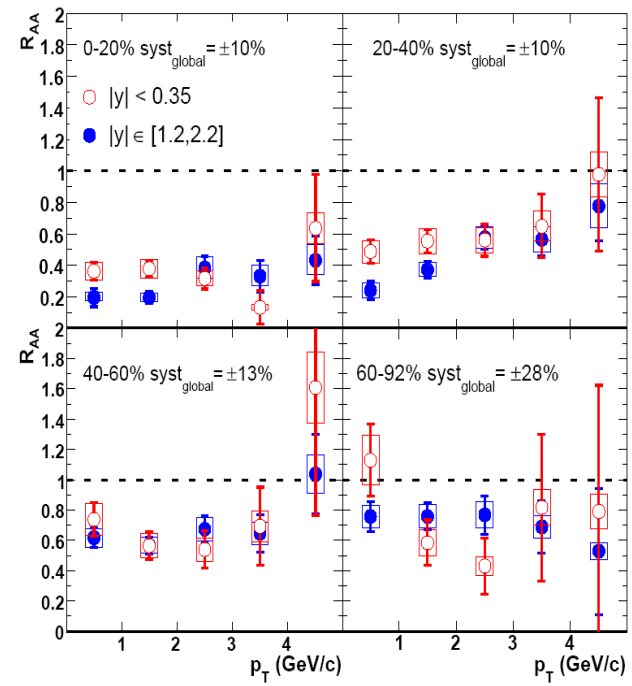



- Charm flows. If recombination is correct, J/Psi should also flow.
- PHENIX expect to accomplish in run7 with higher luminosity (x3) and better (~sqrt(3.5)) reaction plane resolution.

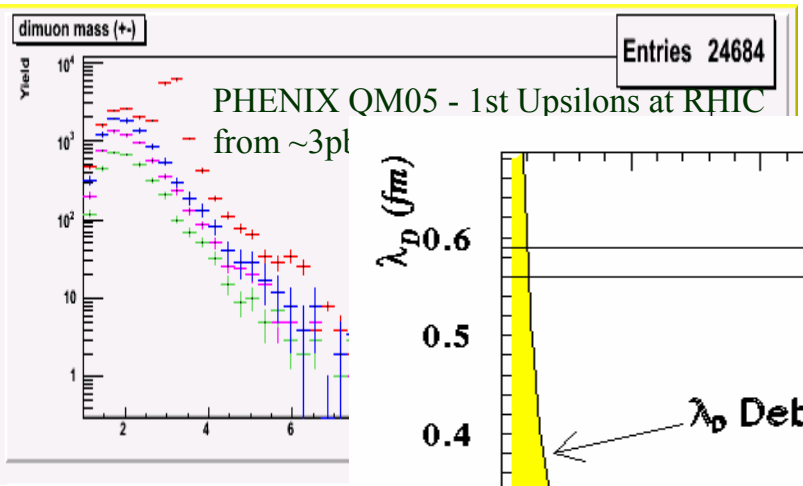


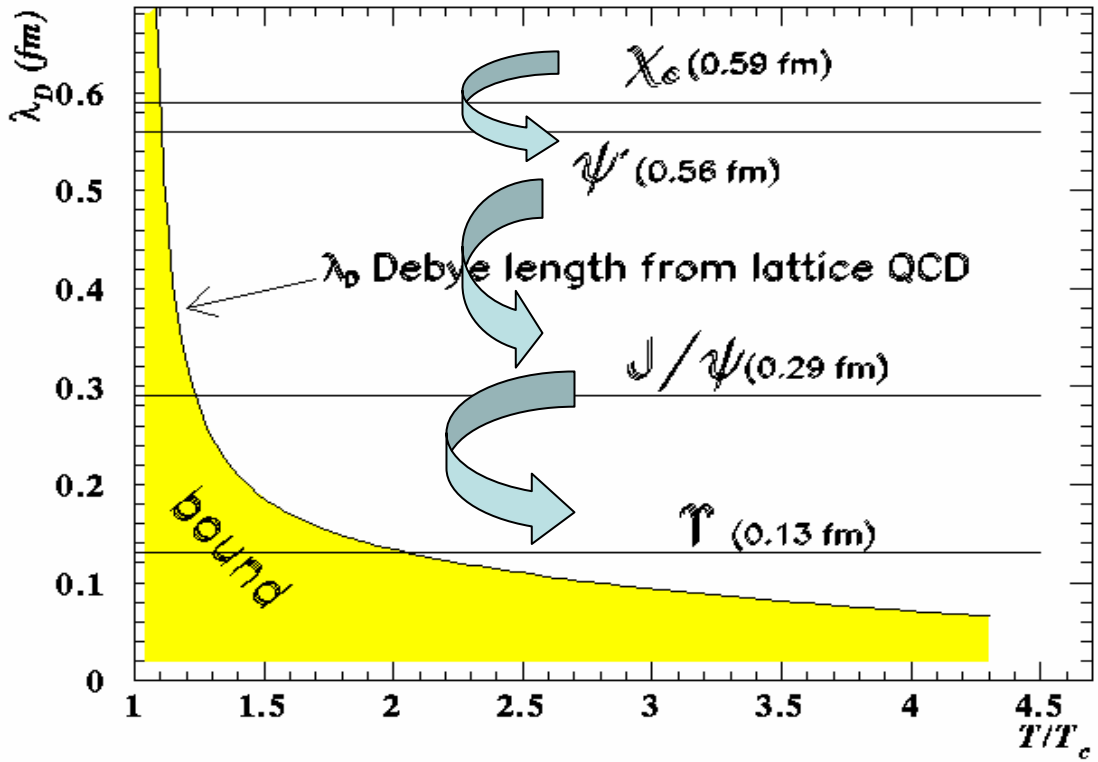



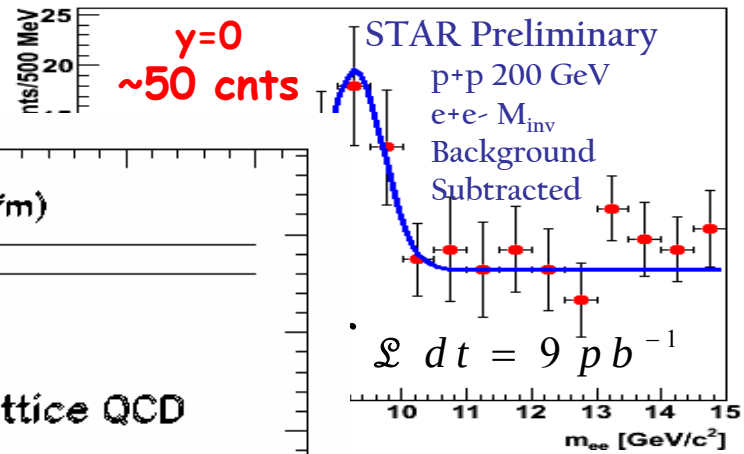

- Charm suppression increase at higher pT. If recombination is correct, J/Psi suppression should quadratically increased at higher pT.
- Not yet observed in PHENIX up to 5GeV.
- What the minimum pT to see the pattern?

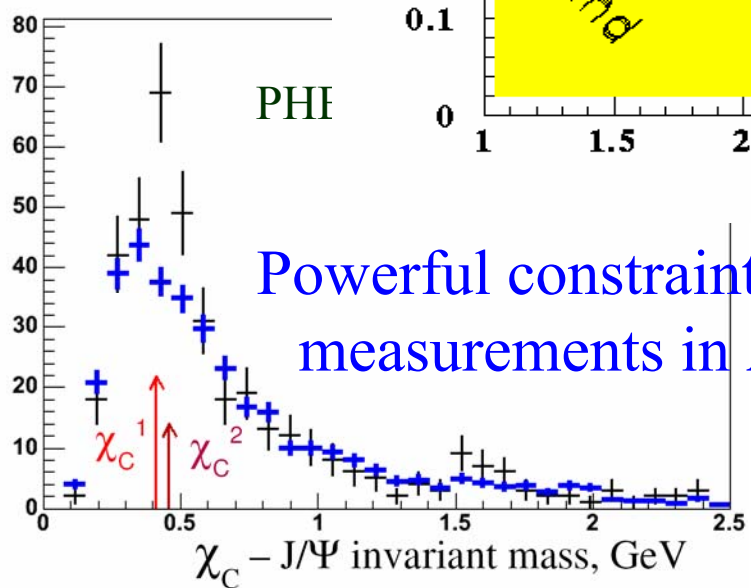


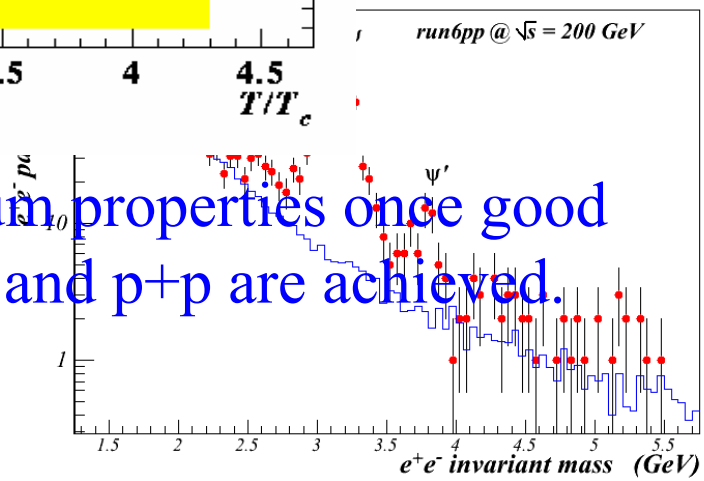
# A New Hope: Heavy quarkonia family




Powerful constraints on the medium properties once good measurements in Au+Au, d+Au and p+p are achieved.

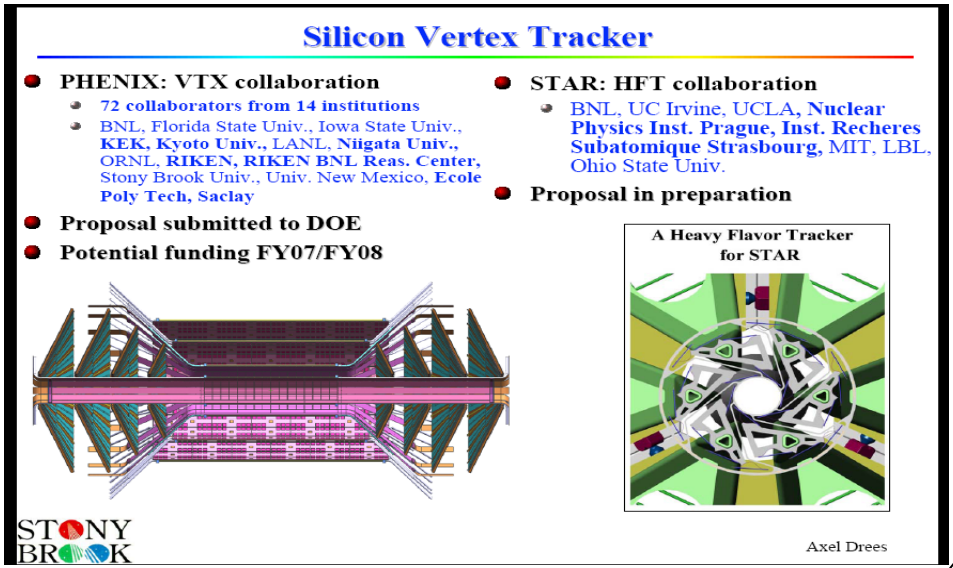
# The Road Ahead

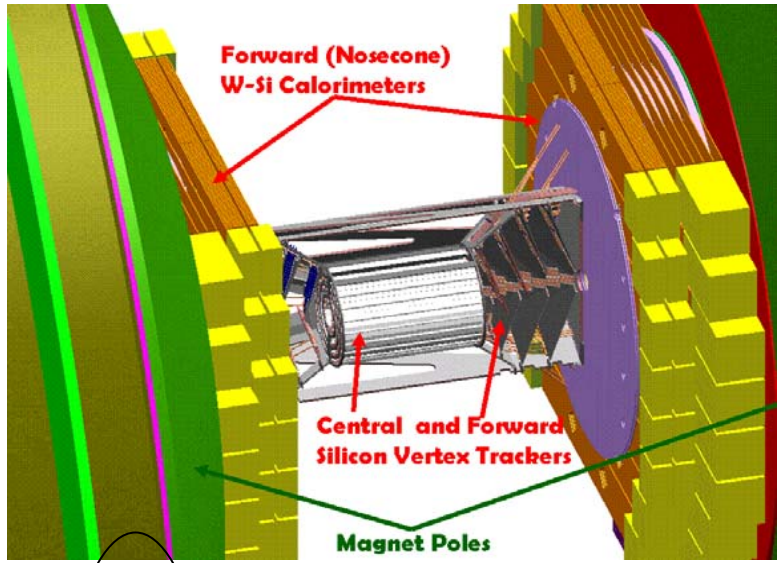
- constrained measurements
  - measure charm, bottom directly

- precise measurements
  - More luminosity.

# A bright near future at RHIC

## (See Ed O'brien and Jim Thomas's upgrade talks tomorrow)




| Signal | RHIC Exp. | Obtained | RHIC I (>2008) | RHIC II | LHC/ALICE+ |
|---|---|---|---|---|---|
| J/psi→$e^+e^-$ | PHENIX | ~800 | 3,300 | 45,000 | 9,500 |
| J/ps →$m^+m^-$ | | ~7000 | 29,000 | 395,000 | 740,000 |
| $\Upsilon \rightarrow e^+e^-$ | STAR | - | 830 | 11,200 | 2,600 |
| $\Upsilon \rightarrow m^+m^-$ | PHENIX | - | 80 | 1,040 | 8,400 |
| B→J/psi→$e^+e^-$ | PHENIX | - | 40 | 570 | N/A |
| B→J/psi→$m^+m^-$ | | - | 420 | 5,700 | N/A |
| $c_c \rightarrow e^+e^- g$ | PHENIX | - | 220 | 2,900* | N/A |
| $c_c \rightarrow m^+m^- g$ | | - | 8,600 | 117,000* | N/A |
| D→Kp | STAR | ~$0.4\times10^6$ (S/B~1/600) | 30,000** | 30,000** | 8000 |

.12 weeks Au+Au run ( $\int L_{eff}\,dt \sim 18\ nb^{-1}$)

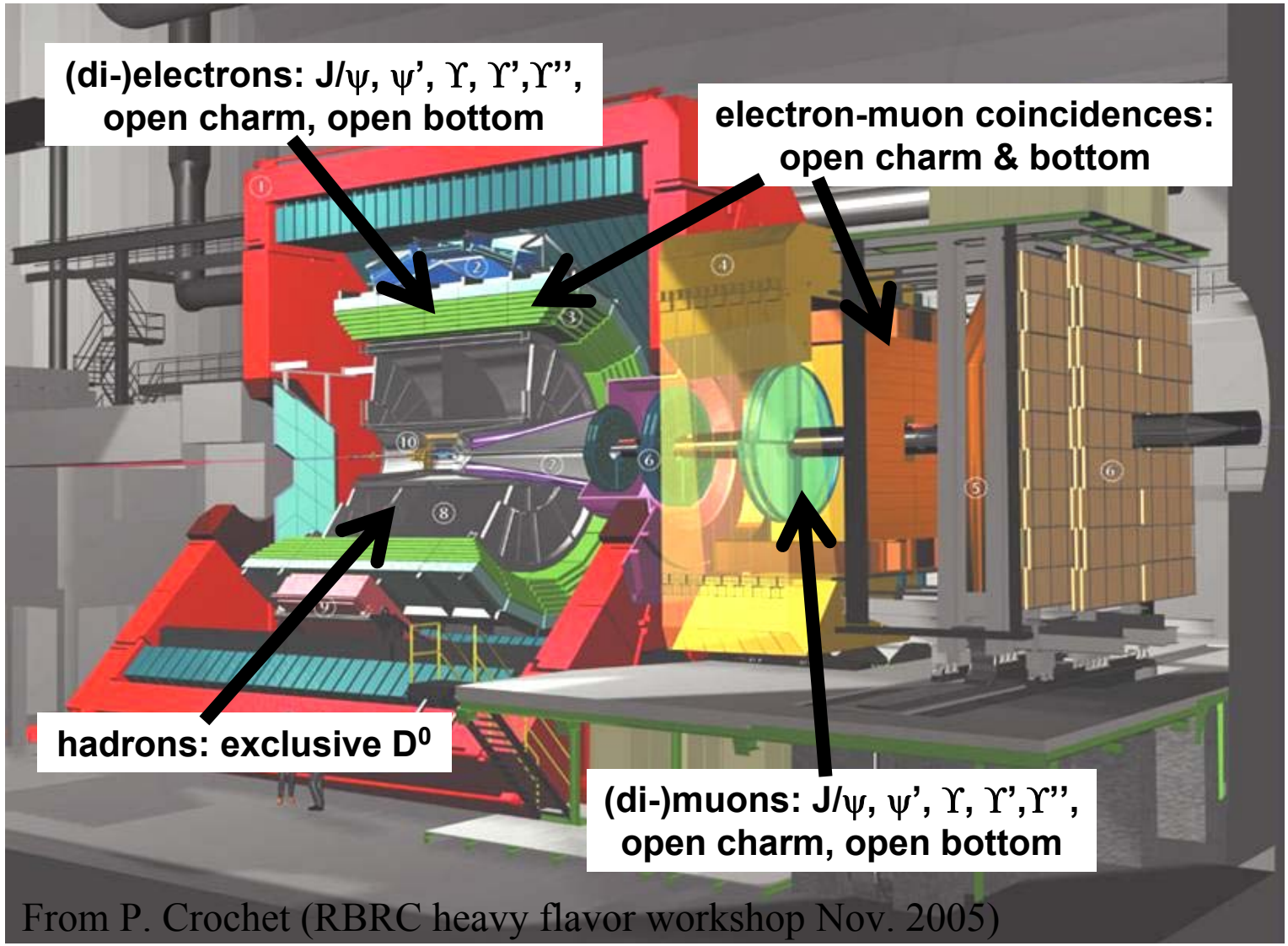
**.4 weeks of Pb+Pb at LHC.**

.*Large backgrounds, quality uncertain as yet

** Running at 100 Hz min bias

# and a bright future at LHC

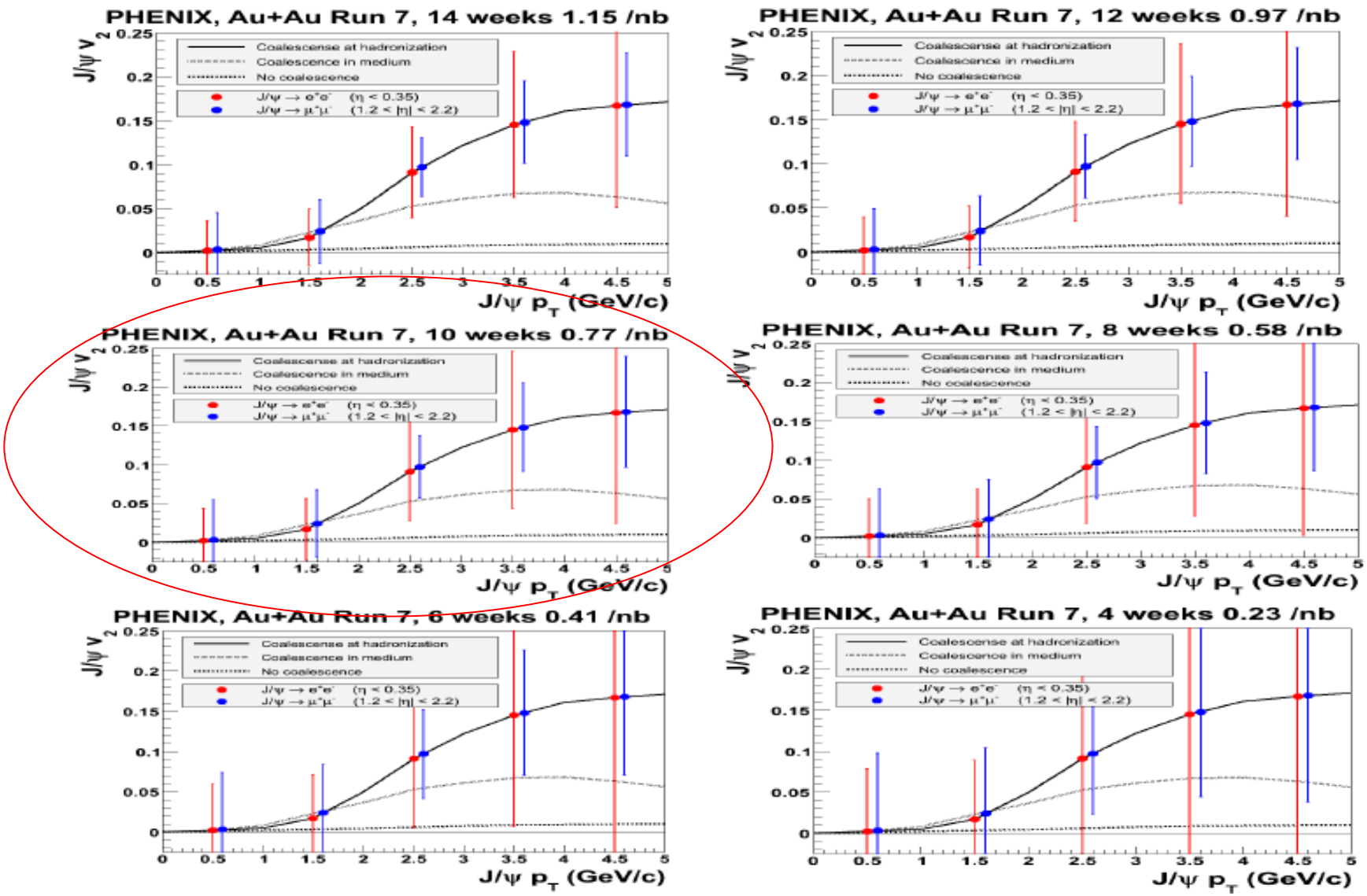
The matter created at RHIC and the one that will be created at LHC is expected to have different properties since the temperature at LHC will be much higher than at RHIC.




From P. Crochet (RBRC heavy flavor workshop Nov. 2005)

backup

# J/Psi v2 measurement projection

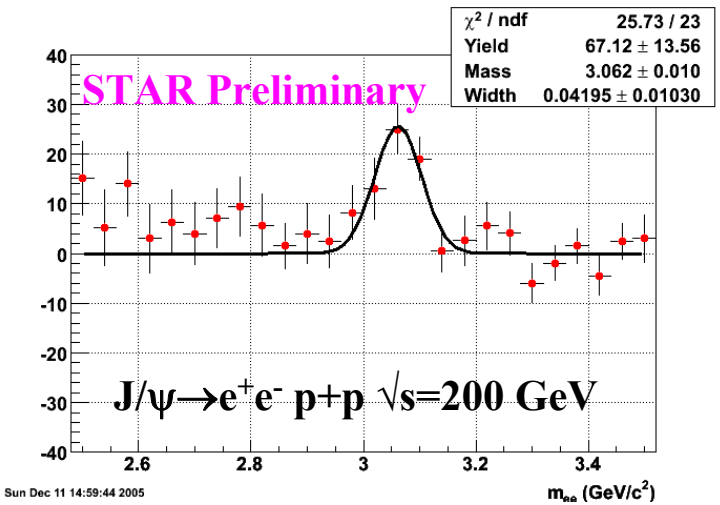


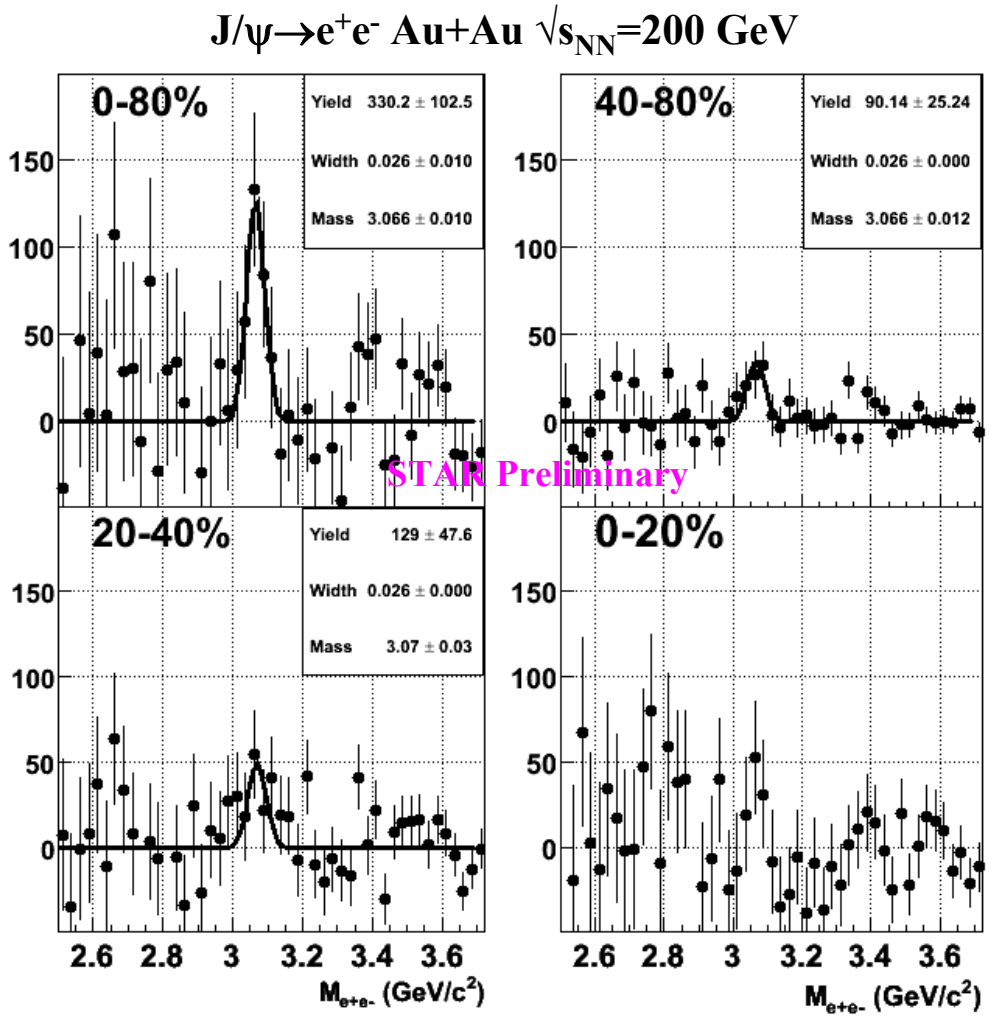

- Including the gain of a factor of 2 from HBD cut
- And gain from event mixing

# STAR J/ψ Signal

- Signal in 200 GeV p+p from 2005
  - Tested and working trigger in p+p
  - No trigger for AuAu until full ToF in 2009
- Also signal in Au+Au with TPC only
  - Large hadron contamination
  - Need full EMC

***Johann Gonzalez***



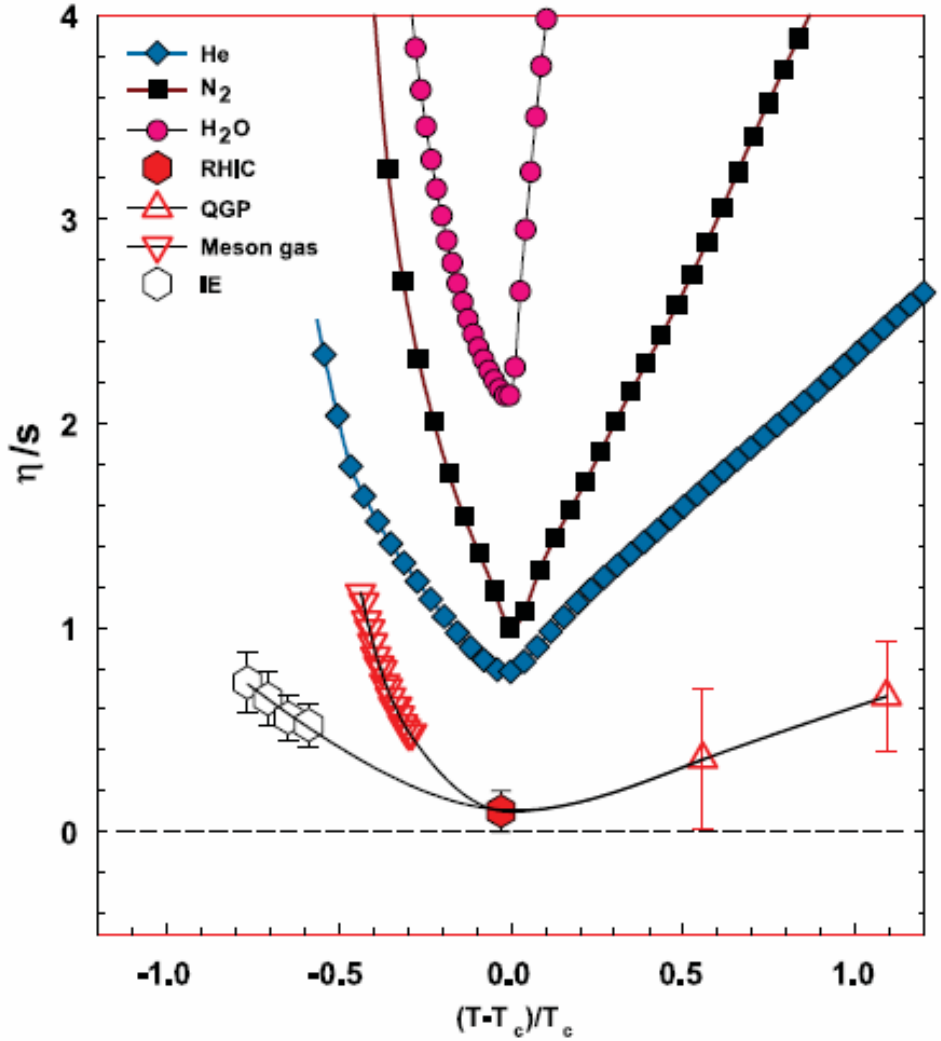
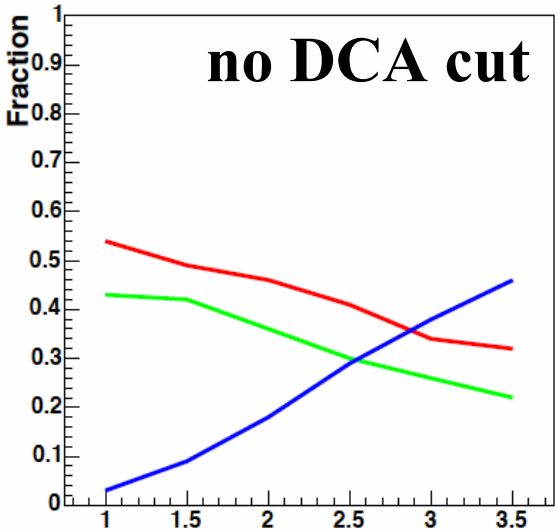
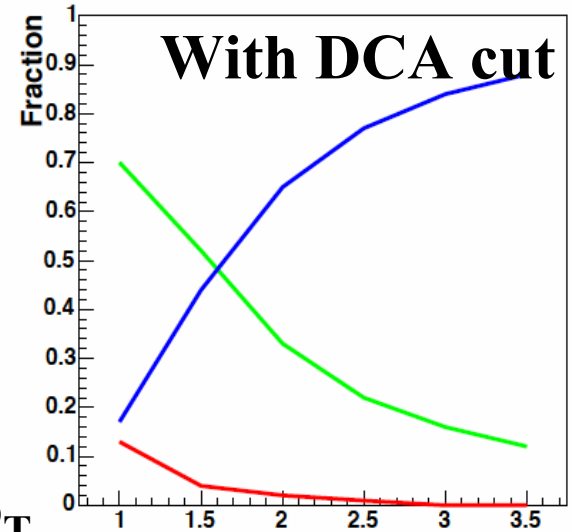


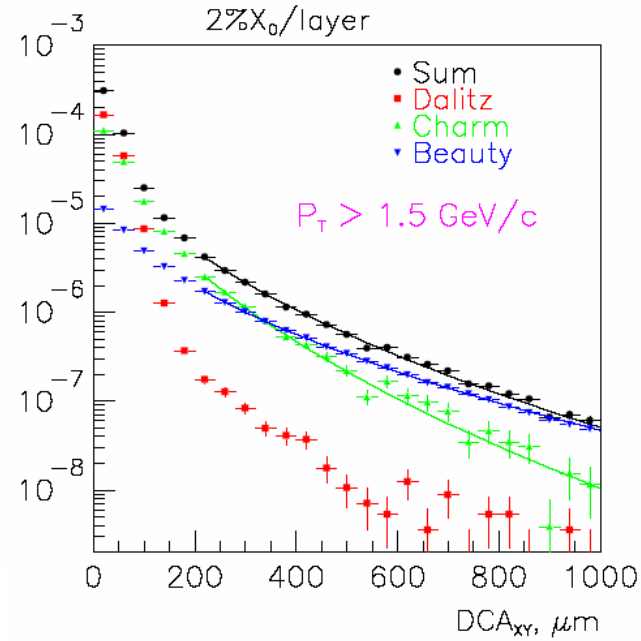

FIG. 3 (color). $\eta/s$ vs $(T - T_c)/T_c$ for several substances as indicated. The calculated values for the meson gas have an associated error of ~50% [46]. The lattice QCD value $T_c =$ 170 MeV [48] is assumed for nuclear matter. The lines are drawn to guide the eye.

# Fraction of electron source




$p_T$



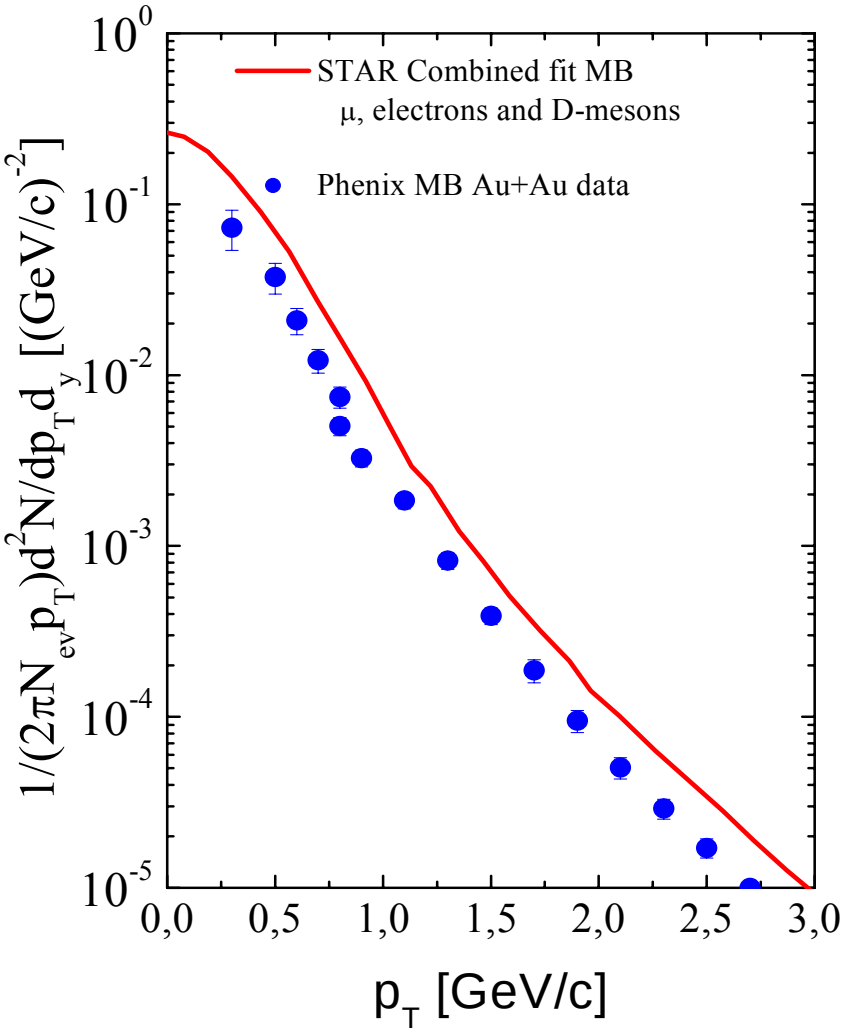

**Red : Dalitz+Conversion**

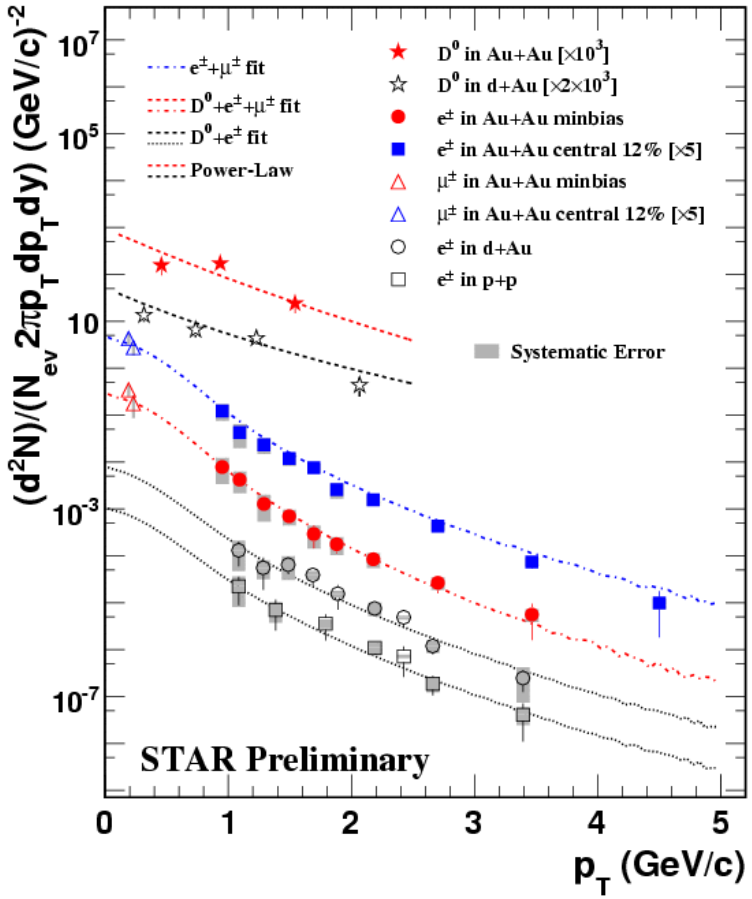
**Green : Charm**

**Blue : Beauty**

# Charm production at RHIC: spectra shape

- Is this shown only at high-$p_T$?



# Integrated $R_{AA}$ vs. $N_{part}$

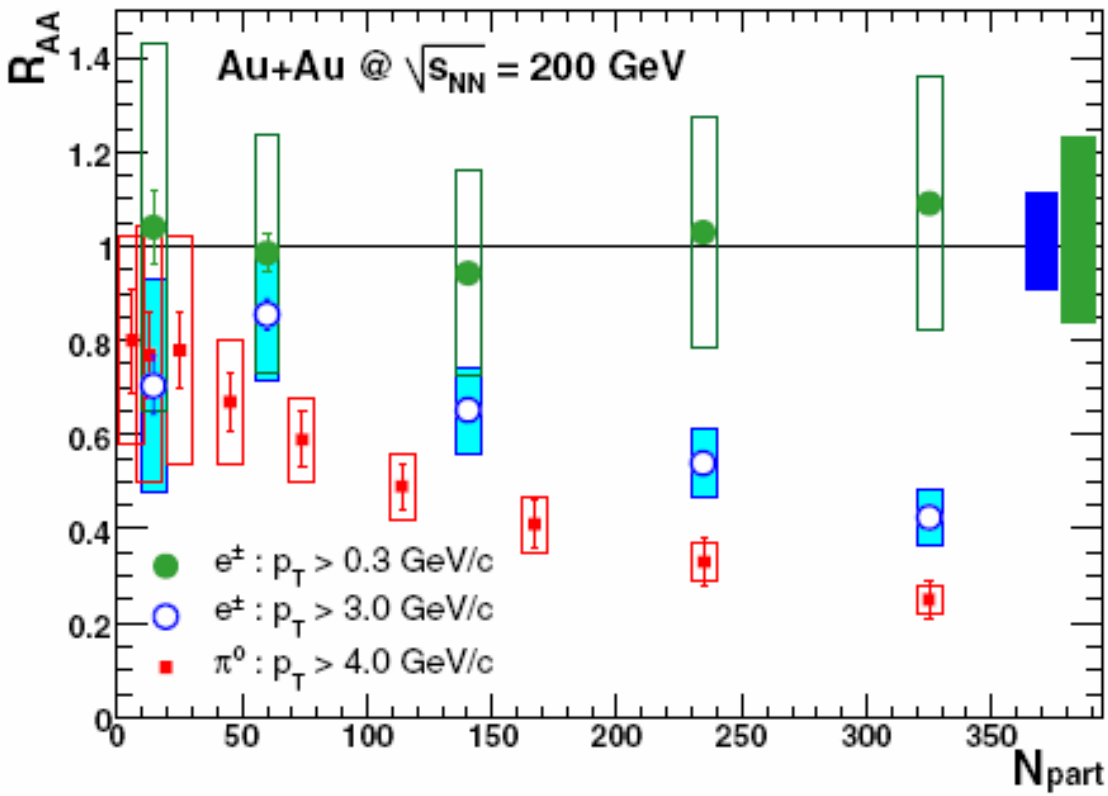



FIG. 2 (color online). $R_{AA}$ of heavy-flavor electrons with $p_T$ above 0.3 and 3 GeV/$c$ and of $\pi^0$ with $p_T > 4$ GeV/$c$ as function of centrality given by $N_{part}$. Error bars (boxes) depict statistical (point-by-point systematic) uncertainties. The right (left) box at $R_{AA} = 1$ shows the relative uncertainty from the $p + p$ reference common to all points for $p_T > 0.3(3)$ GeV/$c$.

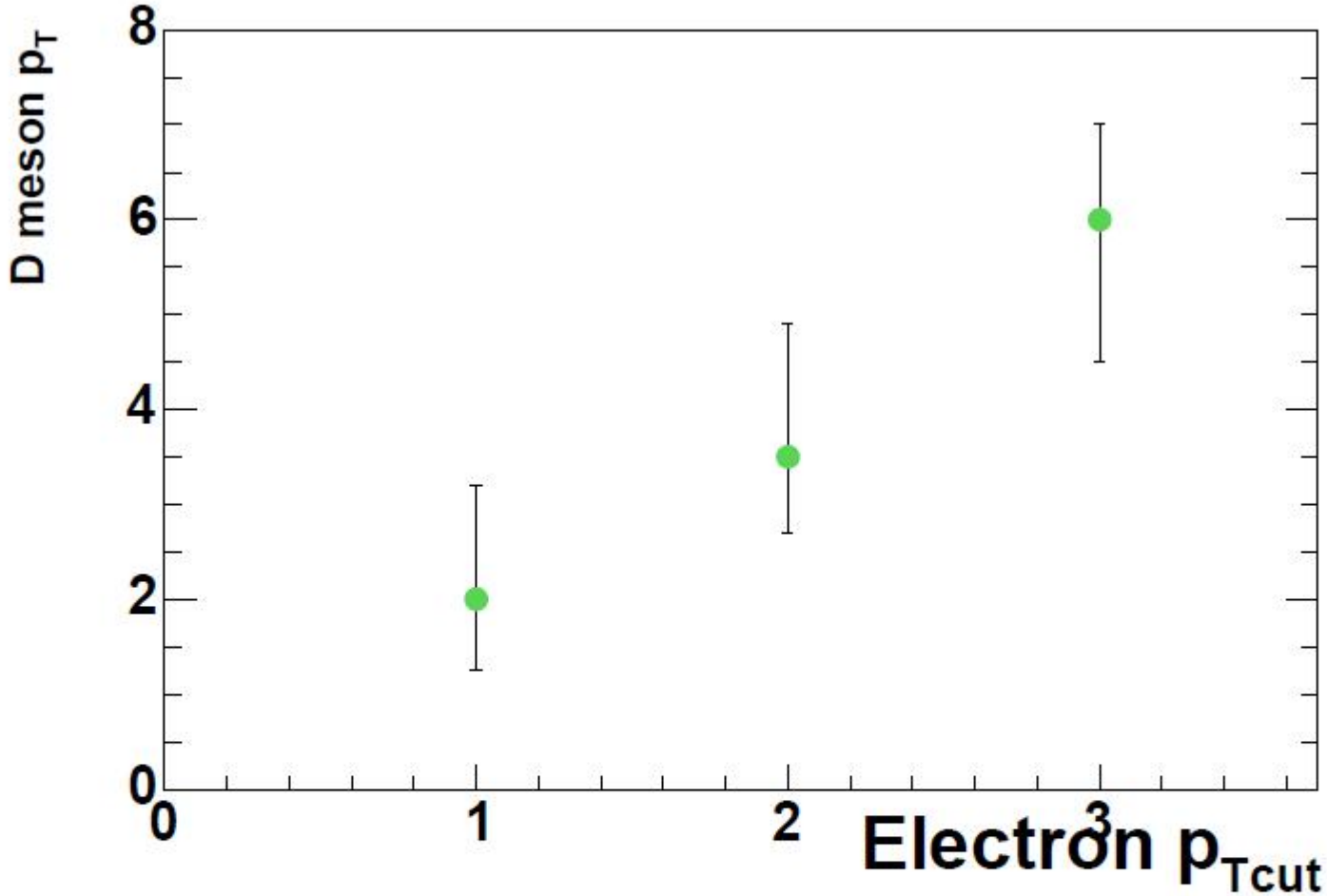
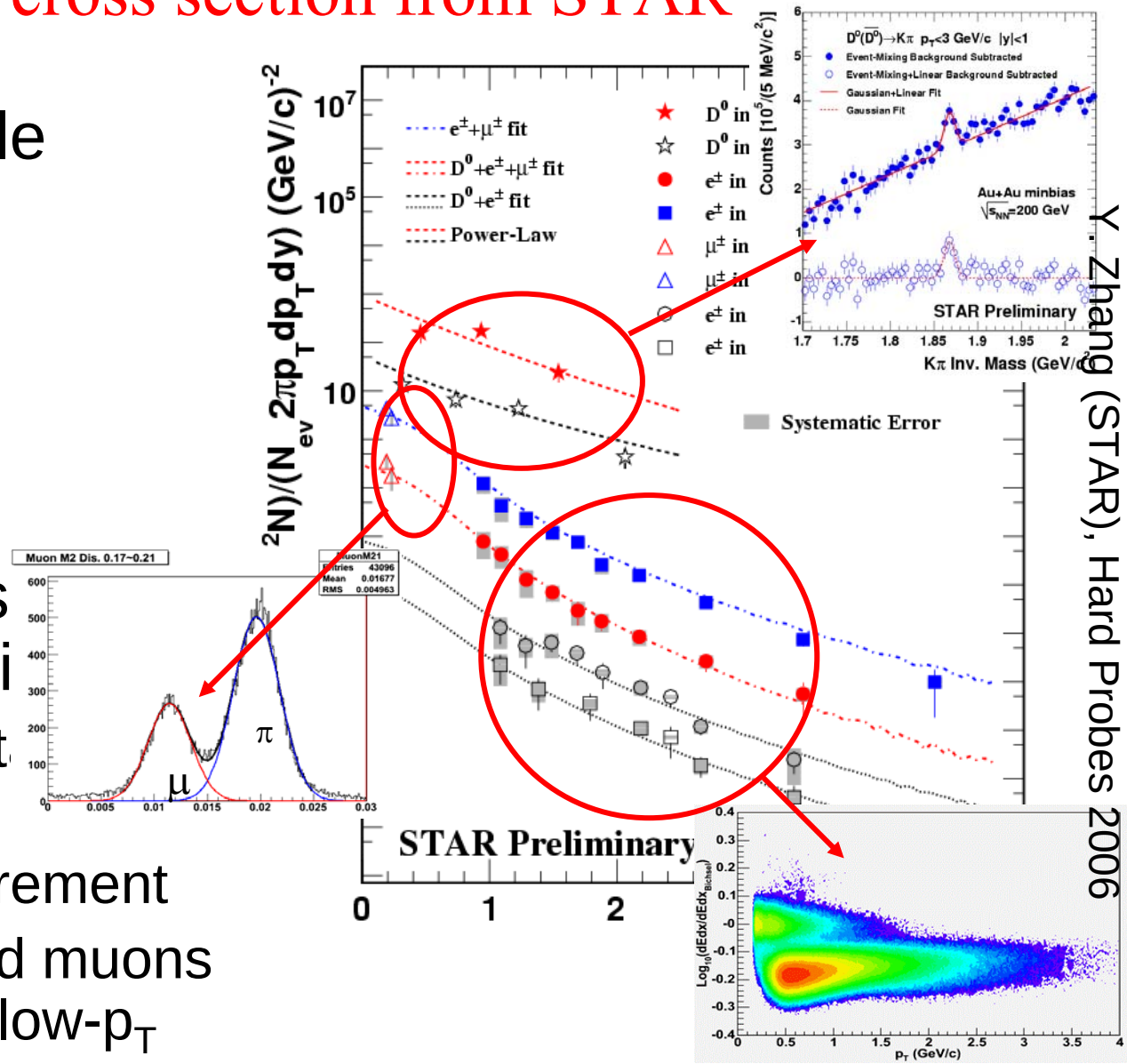



Figure 25 Correlation between the transverse momentum of the D mesons and the minimum $p_T$ cut applied to the electrons (using a DCA cut of 120μm). The points represent the most probable value of the D meson $p_T$ while the spread represents the (asymmetric) full width at half maximum.

# Charm cross section from STAR

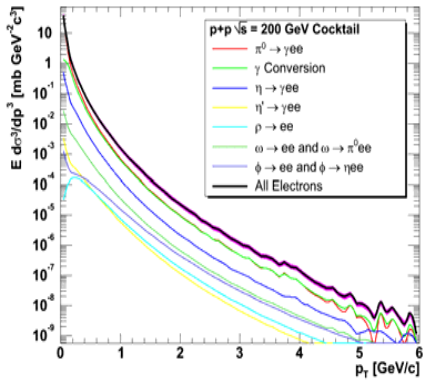
- Use all possible signals
  - D mesons
  - Electrons
  - Muons
- Charm cross s
  is well constrai
  - 95% of the tot
    section
  - Direct measurement
  - D-mesons and muons constrain the low-$p_T$ region




Y. Zhang (STAR), Hard Probes 2006

# Add this to previous slides with the result to balance with STAR

cocktail

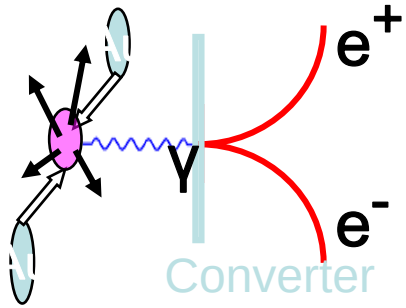



## Subtraction of "photonic" sources.

- conversion of photons from hadron decays in material
- Dalitz decays of light mesons ($\pi^0$, $\eta$, $\omega$, $\eta'$, $\phi$)

## Converter method

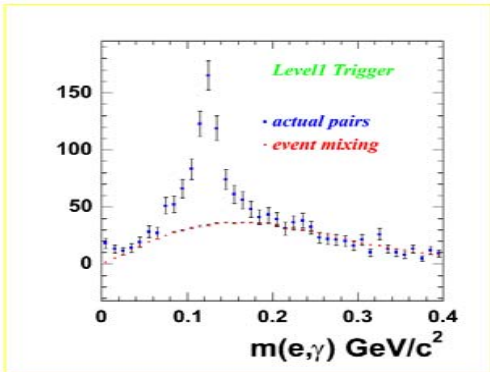
- Comparison of $e^{+/-}$ spectra with and without converter allows separation of photonic and non-photonic sources of single electrons.



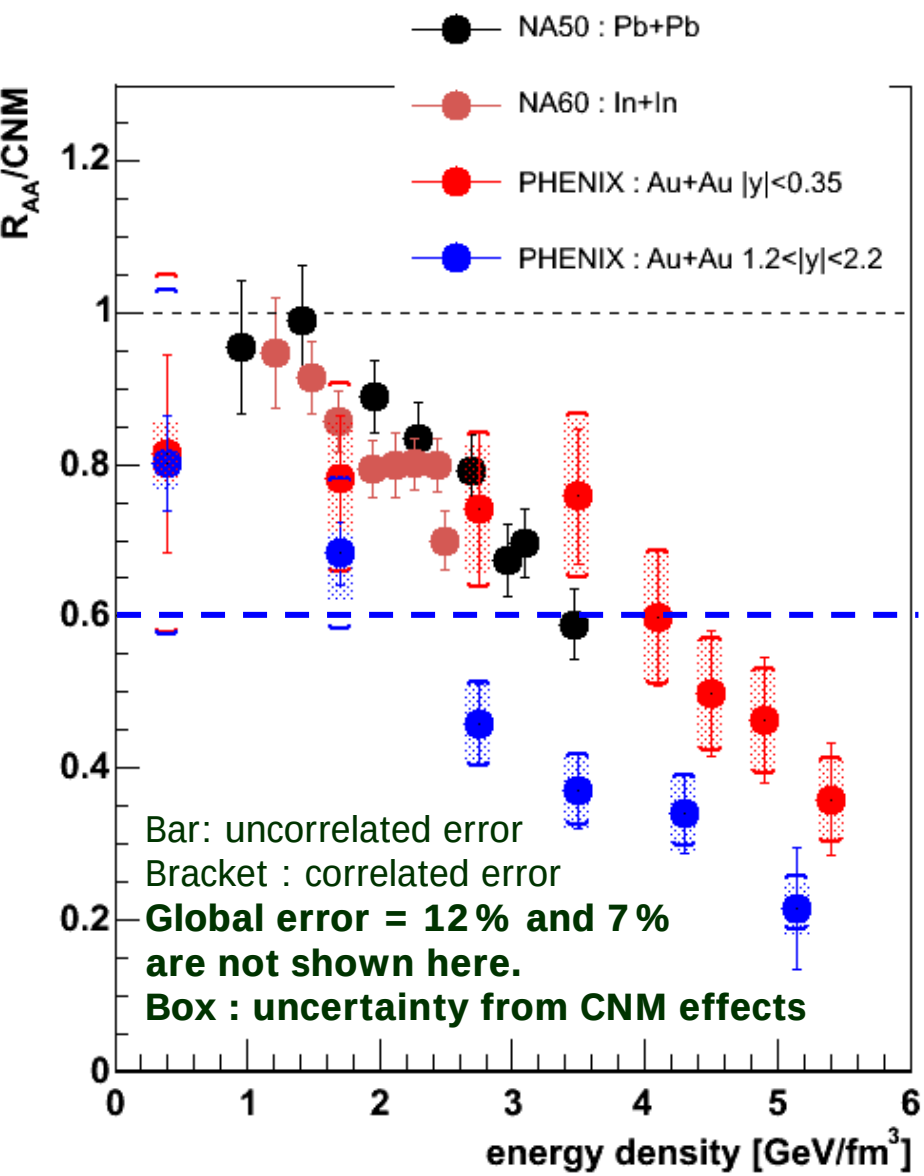

## measurement via γ-e coincidences

- Yield of γ-e in vicinity of π mass with mixed event subtraction

γ-e invariant mass



# A Further comparison after removing the CNM effect

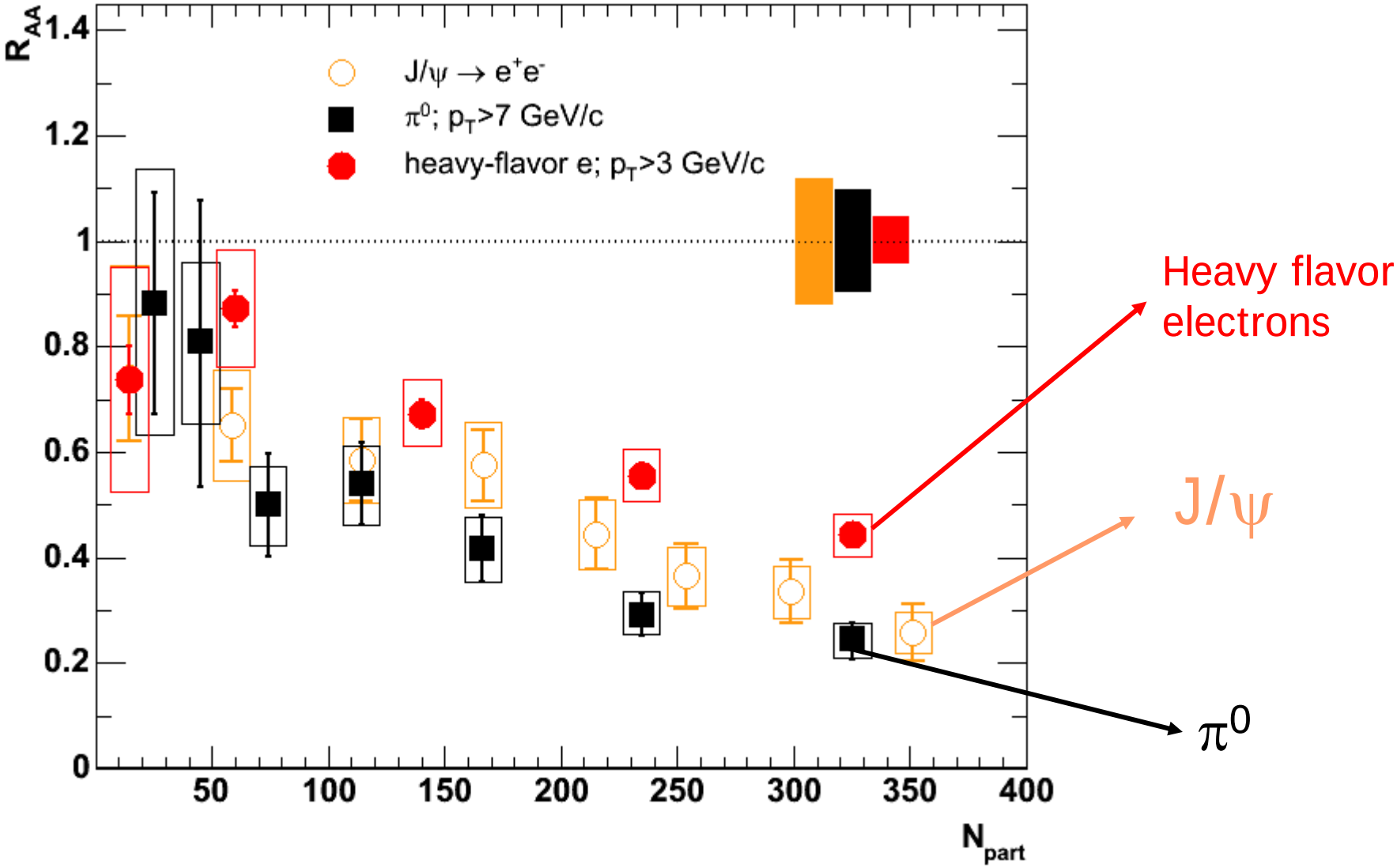



$$\varepsilon_{Bj} = \frac{1}{\tau_0 A_\perp} \frac{dE_T}{dy}\bigg|_{y=0}$$

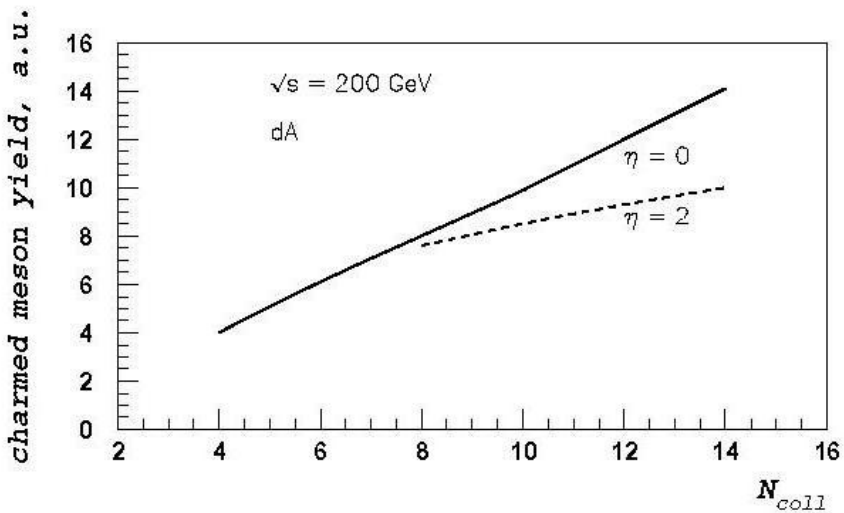
– Require $t_0 >> 2R/\gamma$
  - satisfied at RHIC but not sure about it at SPS.

- RHIC and SPS shows similar pattern in the same energy density region, i.e. <3.5GeV/fm^3, that is consistent with the melting of psi' and chi_c.
- RHIC data show more suppression at higher energy density
- Still have Large error and mainly from run3 d+Au. Larger luminosity d+Au run is needed.

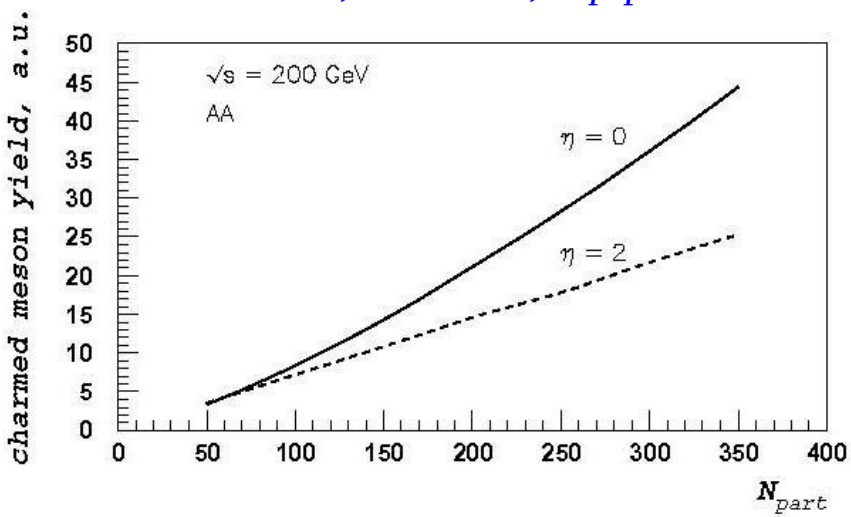
# J/y suppression vs. light hadrons



# Open Charm Measurement in forward region and CGC




*D.E. Kharzeev, K. Tuchin, hep-ph0310358*




In Central region: $Q_s$<m(cc) open charm production is expected to scale with $N_{coll}$

In forward region: $Q_s$>m(cc). Open charm production is expected to scale with $N_{part}$ *(AA)* and $\sqrt{N_{part}^{A}}$ *(pA)* in forward rapidity region.