Summary of Heavy Flavor Workshop (June 21, 2005)

Organizers: Tony Frawley and Manuel Calderon

Six 1 hour talks - two experiment and four theory:

- Quarkonia in Ultrarelativistic Heavy-Ion Collisions **Ralf Rapp**
- Heavy Flavor results from PHENIX **Dongjo Kim**
- Jpsi production in dA collisions **Kirill Tuchin**
- Heavy Flavor results from STAR **Frank Laue**
- Heavy quark production and energy loss **Carlos Salgado**
- The opaque plasma and charm **Denes Molnar**

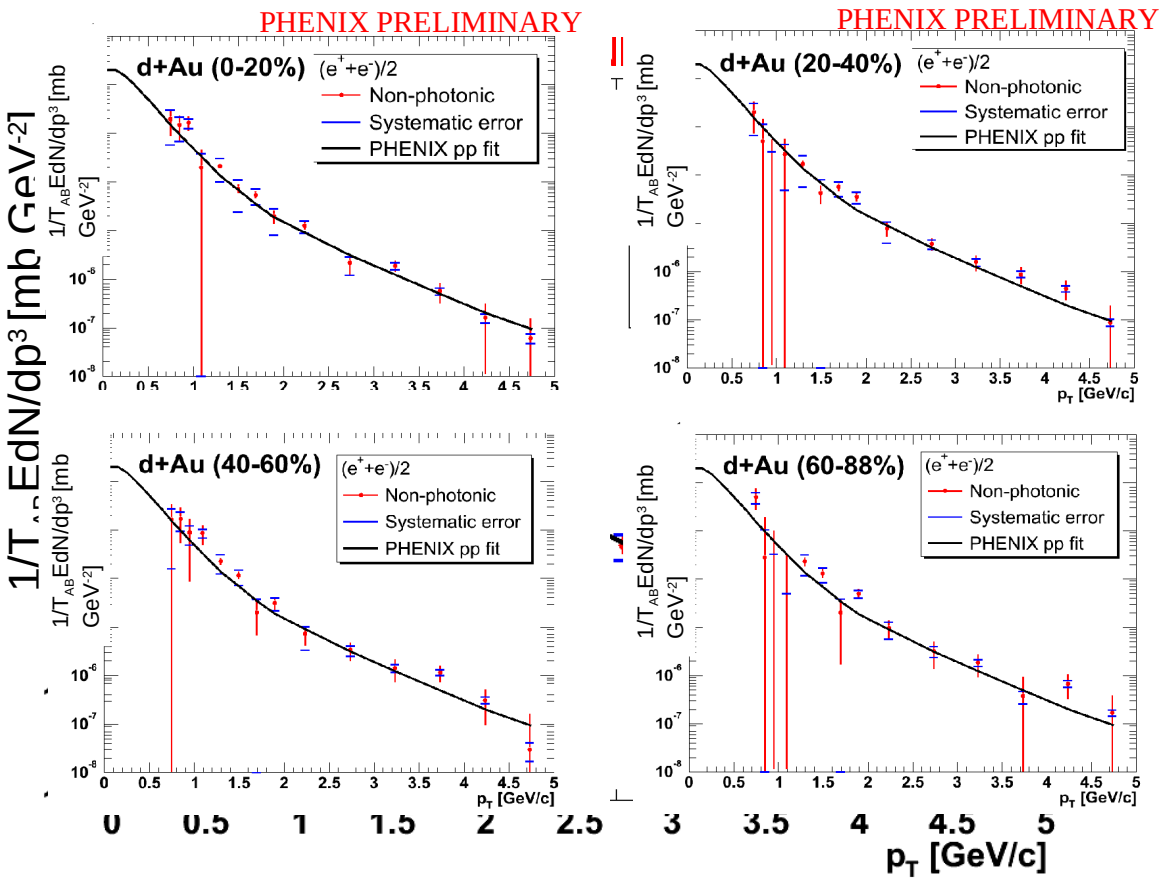
Heavy Flavor Results from PHENIX

2005 RHIC & AGS Annual Users' Meeting
June 20-25, 2005, BNL

DongJo Kim

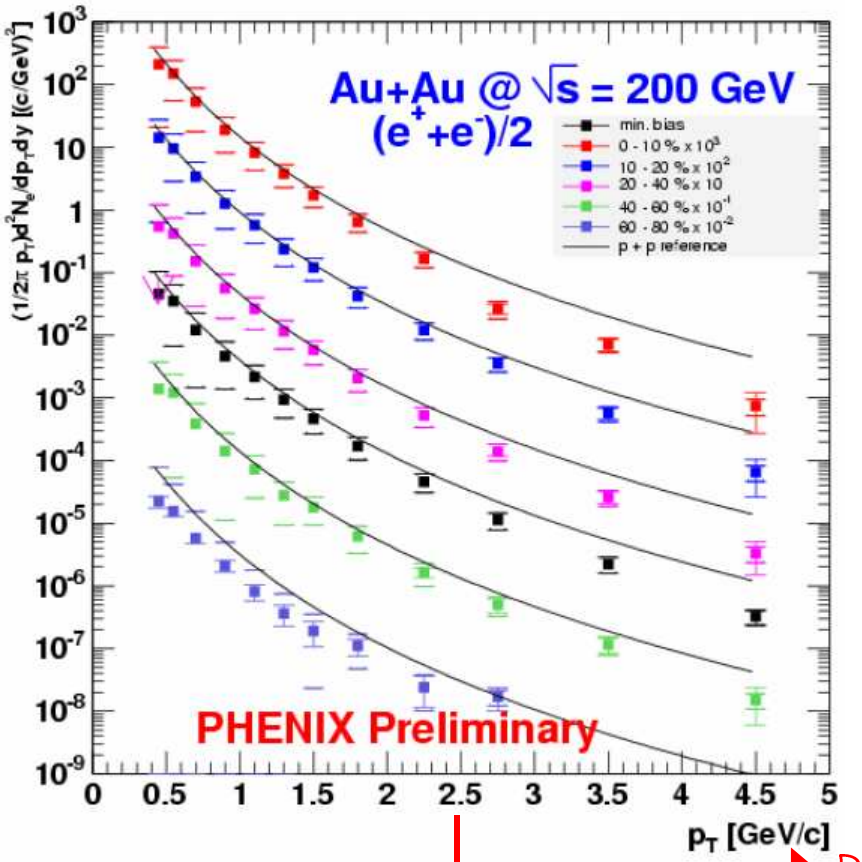
Yonsei University for PHENIX collaboration

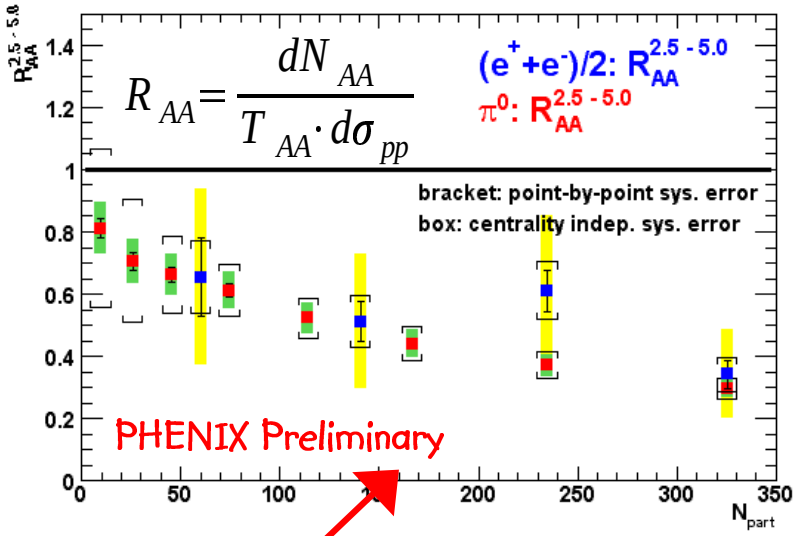
Non-Photonic Single Electron Spectra
d-Au √s = 200 GeV



- Scale with number of collision in d-Au collision
- no indication of shadowing effect at mid-rapidity.

Charm $R_{AA}(p_T) \neq 1$

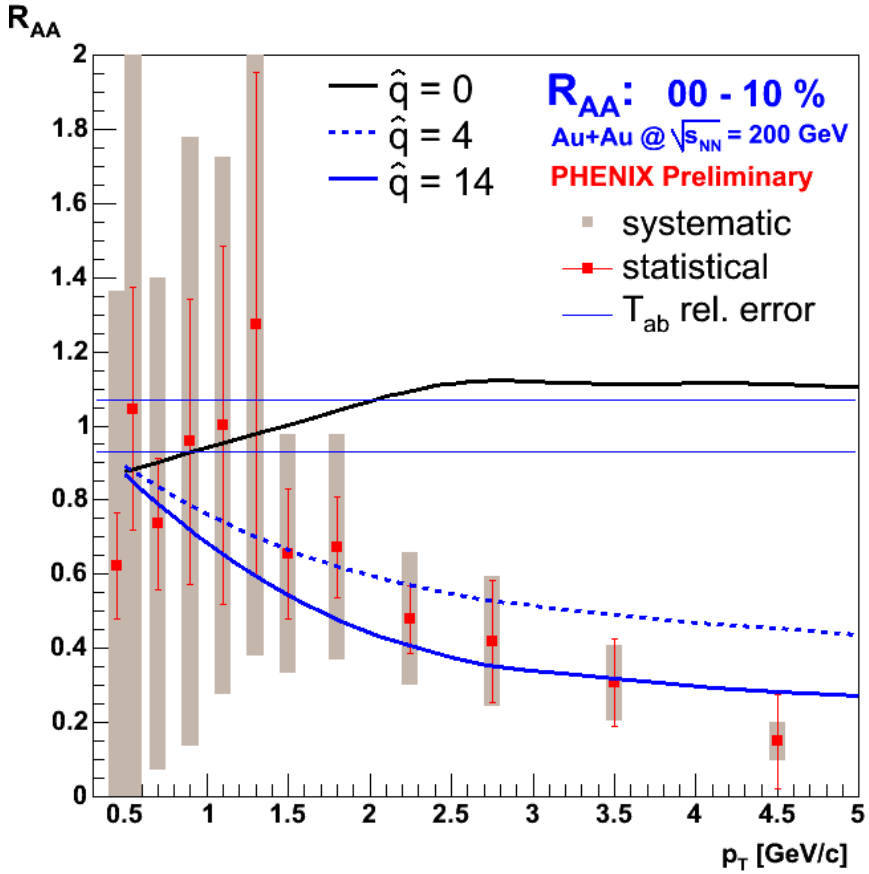




R_{AA} with yield above 2.5 GeV/c

- Need to go to cocktail analysis to obtain sufficient statistics at high-p_T.
- Will lower systematics at low-p_T by combining with converter method.

Theory Comparison



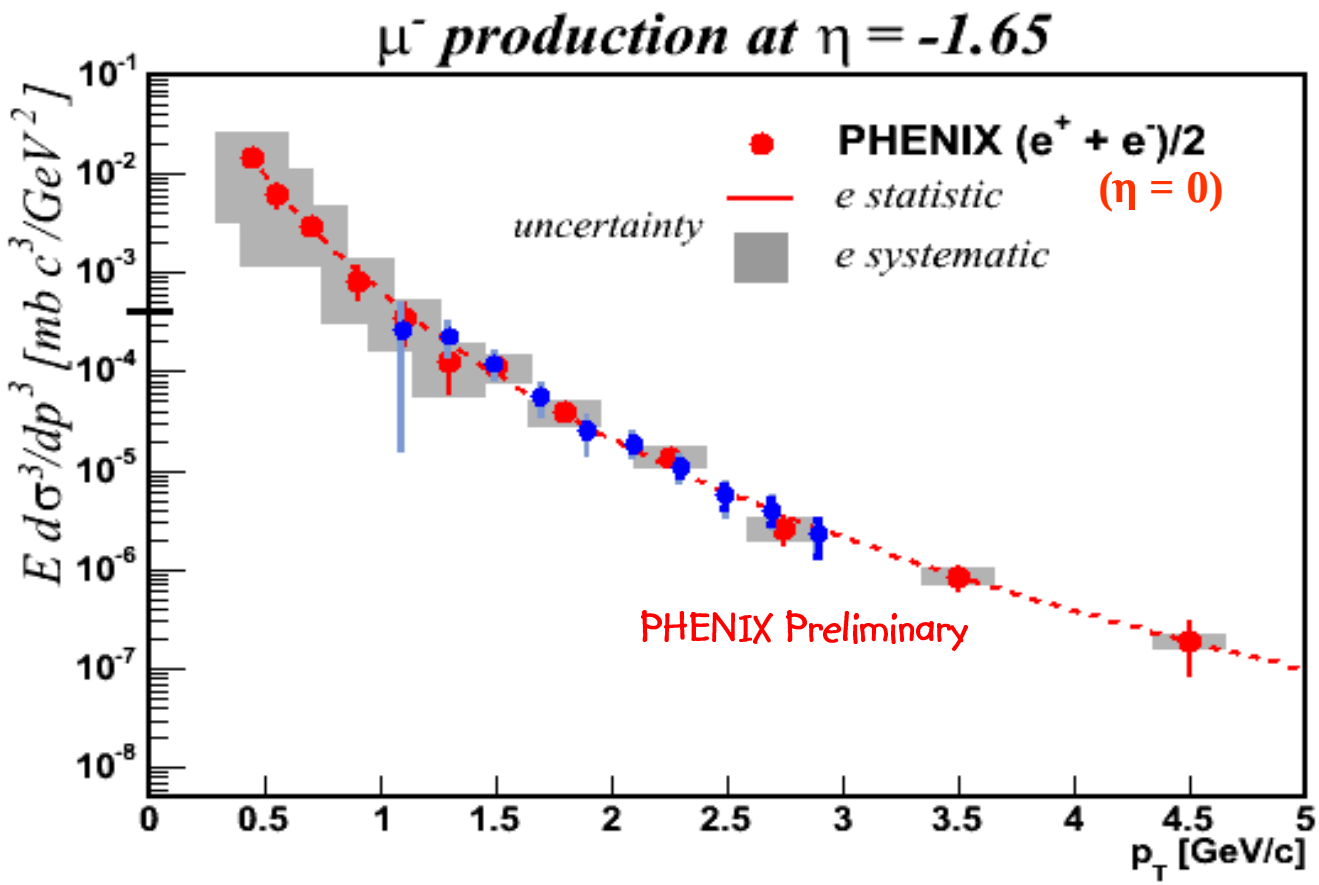
- Observed suppression is in good agreement with theoretical predictions for the final state energy loss of heavy flavor
- Charm only component is used for comparison, Bottom electron contribution need to be taken into account at $p_T > 4$ GeV/c

See talk by Carlos Salgado for theory plot.

Theory curves from N. Armesto, *et al.*, hep-ph/0501225

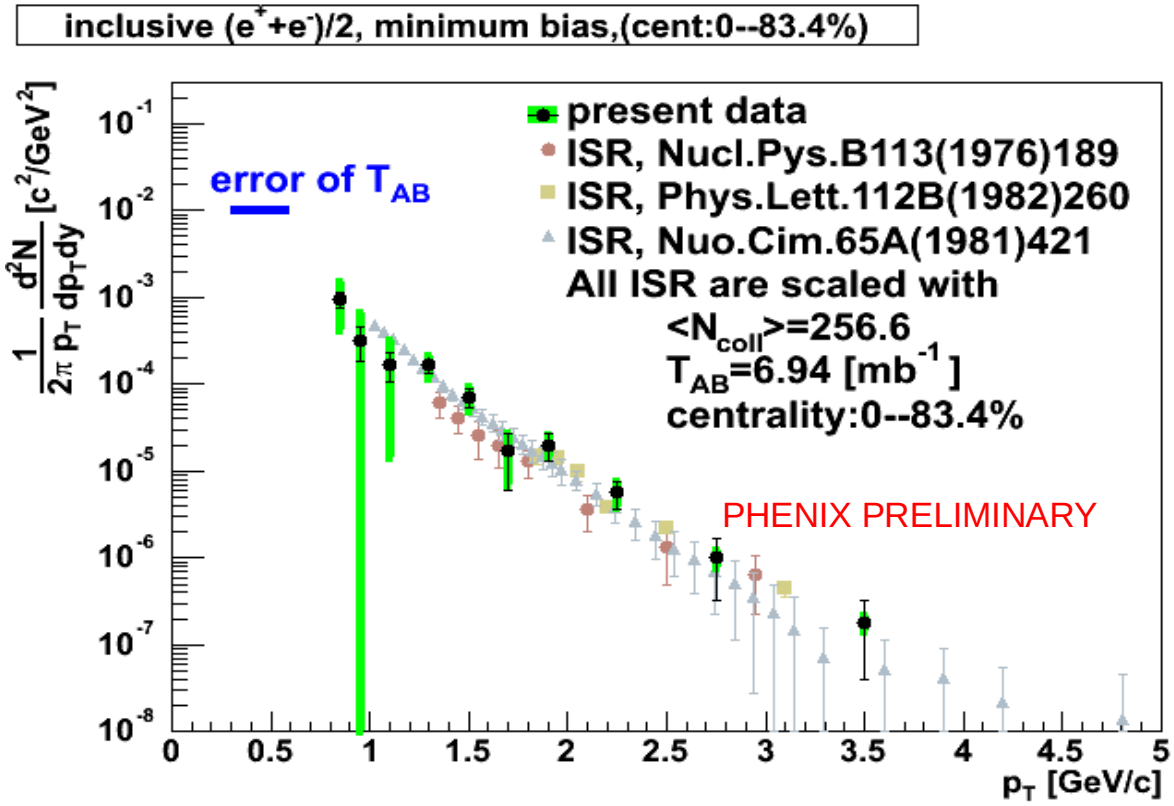
First result from PHENIX for heavy flavor single muons!

Measuring Heavy Flavor at Forward Rapidity in the PHENIX Muon Arms,p-p 200GeV



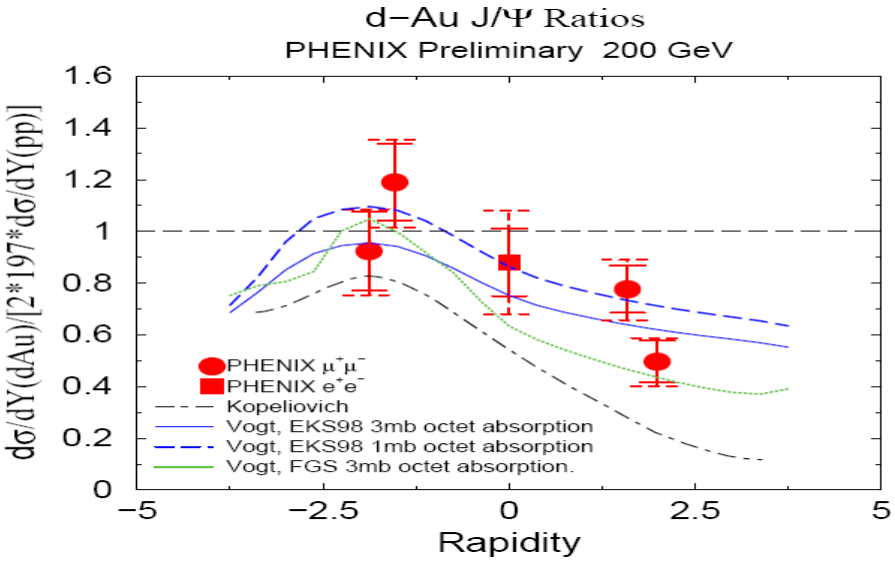
PHENIX Non-Photonic Single Electron Spectra
Au-Au @ √s = 62.4 GeV

- Spectra agree with the ISR *p-p* data scaled by T_{AB} i.e. with the number of binary collisions Ncoll with uncertainty.

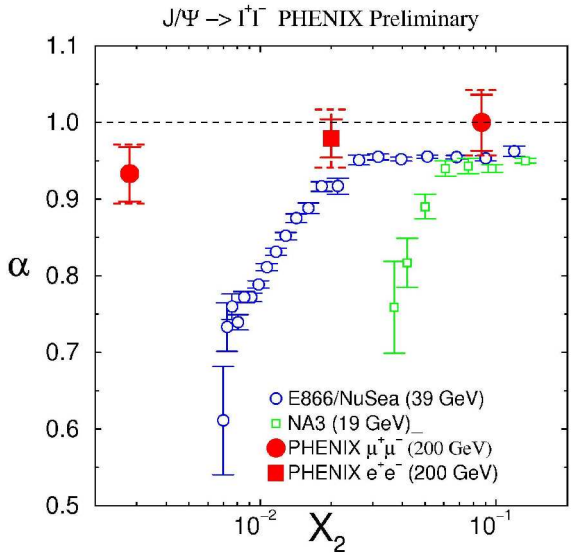


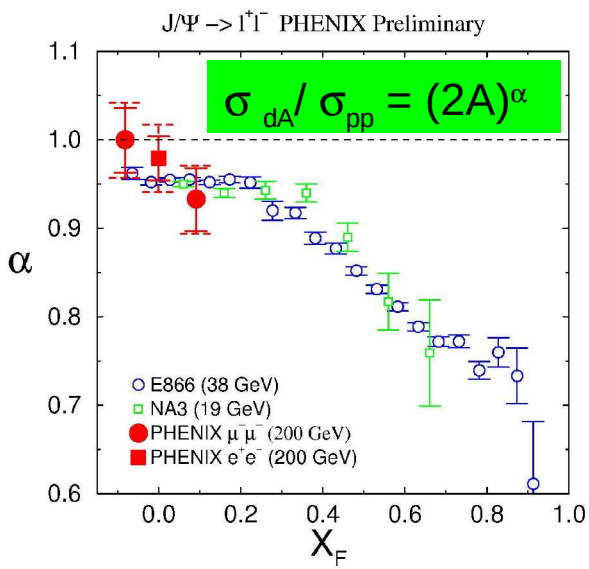
$$T_{AB} = \frac{\langle N_{\text{binary}} \rangle}{\sigma_{pp\ \text{inel.}}}$$

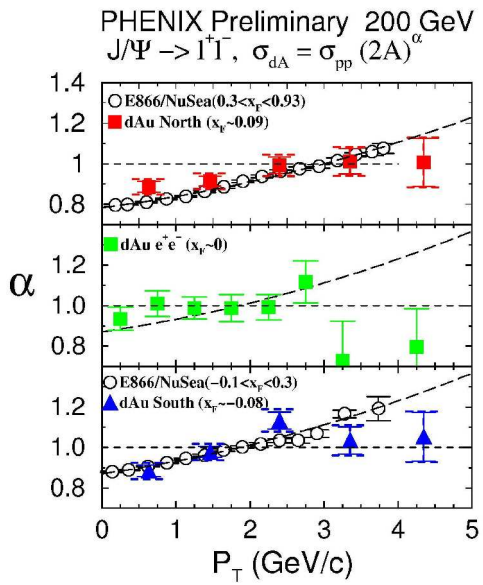
Nuclear modifications in d-Au collisions



Modest cold nuclear effects seen, but data are not sufficient to completely understand those effects.

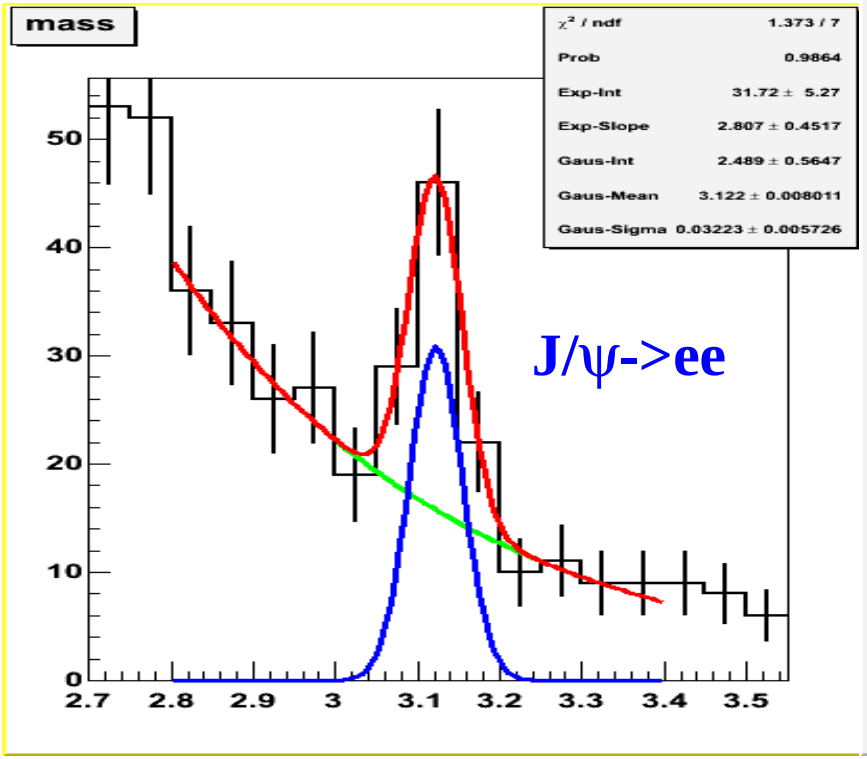


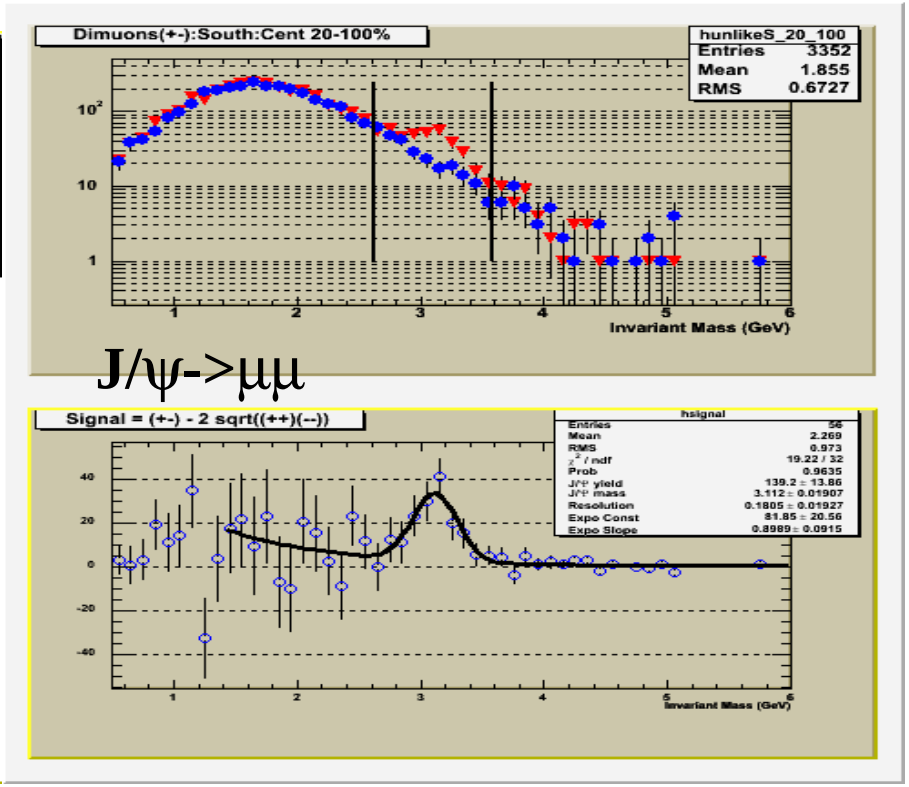




J/ Ψ Signal in Au-Au Collisions

- RUN2 Au-Au data disfavor enhancement
- RUN4 has accumulated 50 times(~240mb-1) more data and already see clear J/Ψ signal from a small portion of AuAu *(data less than 10%).*

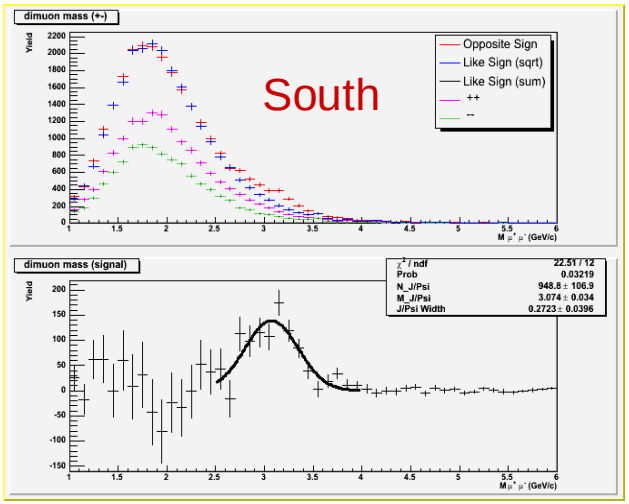


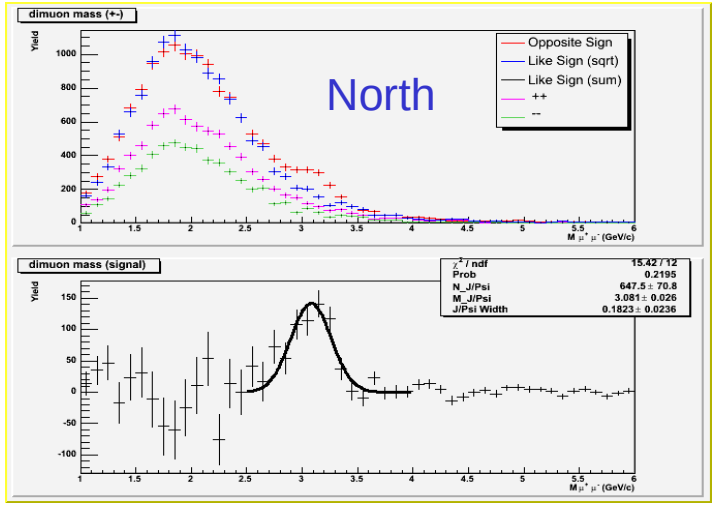


~ 600 J/psi's mid-rapidity, ~2k forward-rapidity

Cu-Cu 200GeV

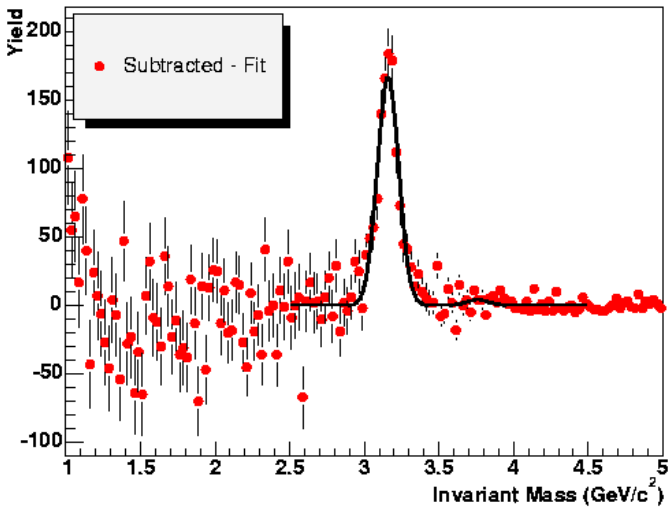
Forward rapidity J/ψ->μμ ~13k J/psi's

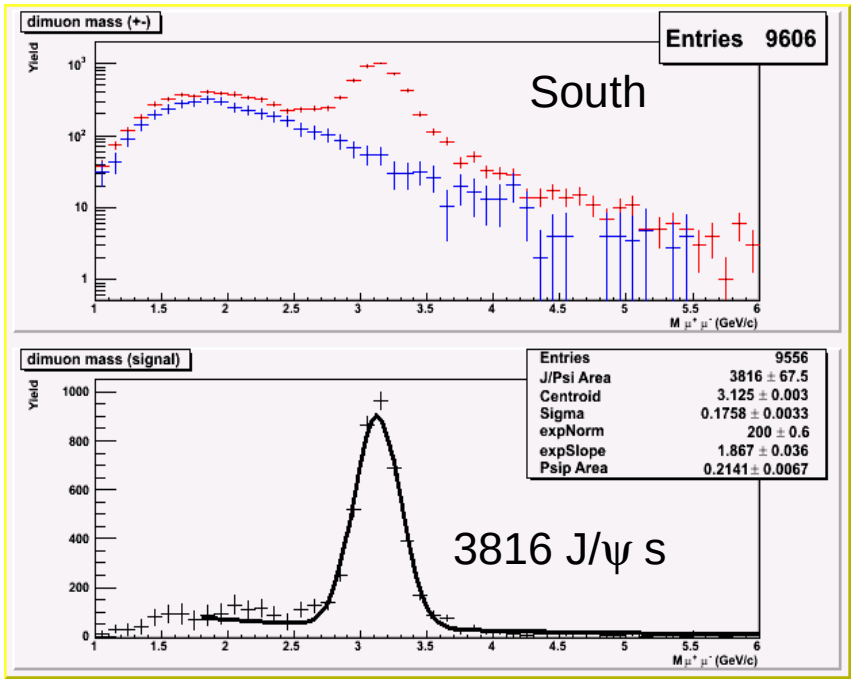




Better reference
Run 5 pp 200GeV
June 12th (~2.17 pb^{-1})

Mid rapidity J/ψ->ee ~1.2k J/psi's

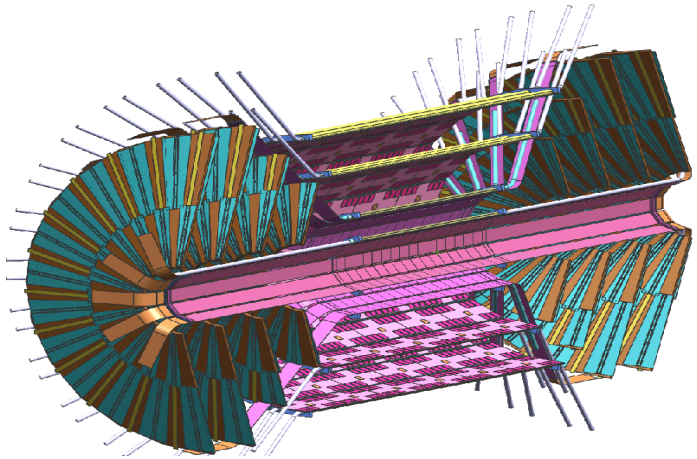


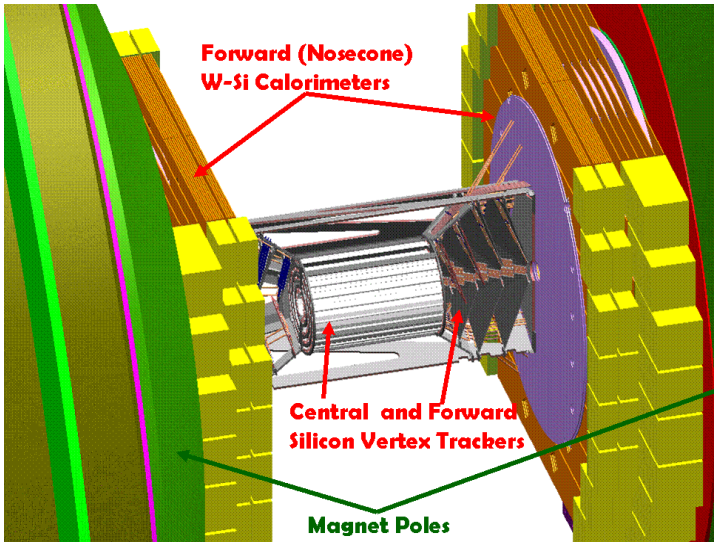


Planned PHENIX Upgrades for heavy flavor

Silicon Vertex Detector

(displaced vertex heavy flavor measurements)



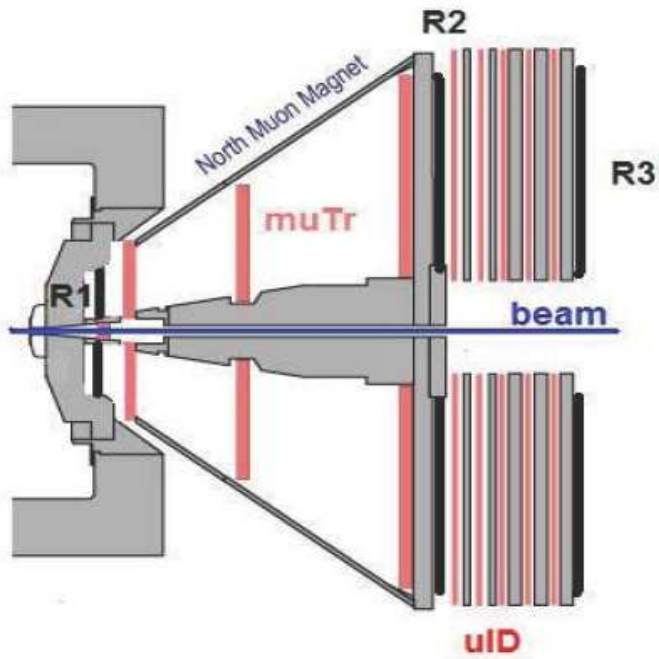


Nose Cone Calorimeter

($\chi_c \rightarrow J/\psi + \gamma$, jets: $0.9 < |\eta| < 3.5$)

Muon Trigger Upgrade

(High luminosity triggering, high multiplicity background rejection)

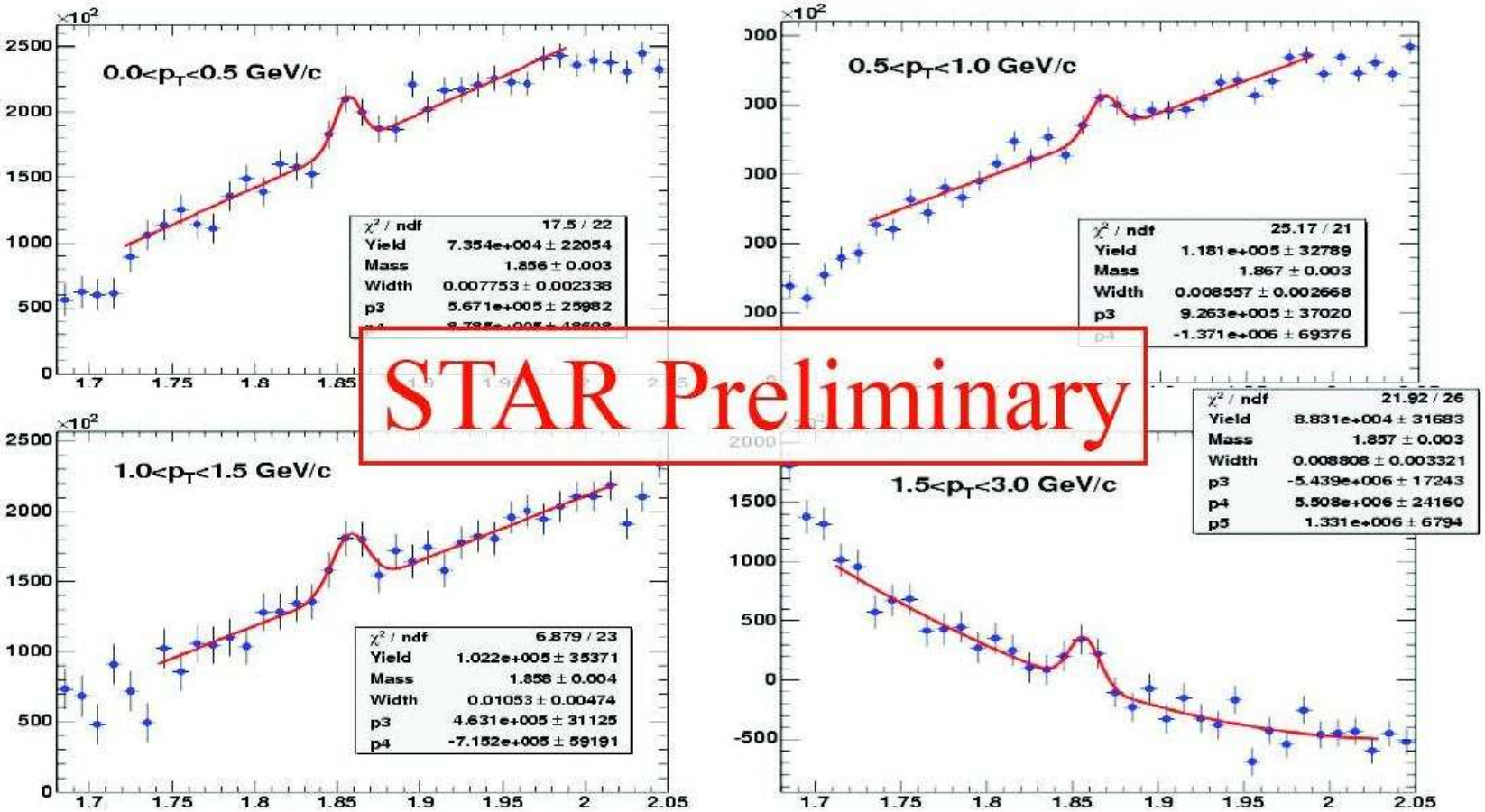


Heavy Flavor Physics with the STAR Experiment

Frank Laue(BNL)
for the
STAR Collaboration

AGS/RHIC Users Meeting
June-21th 2005

Preliminary D0 Results in Au+Au at 200 GeV

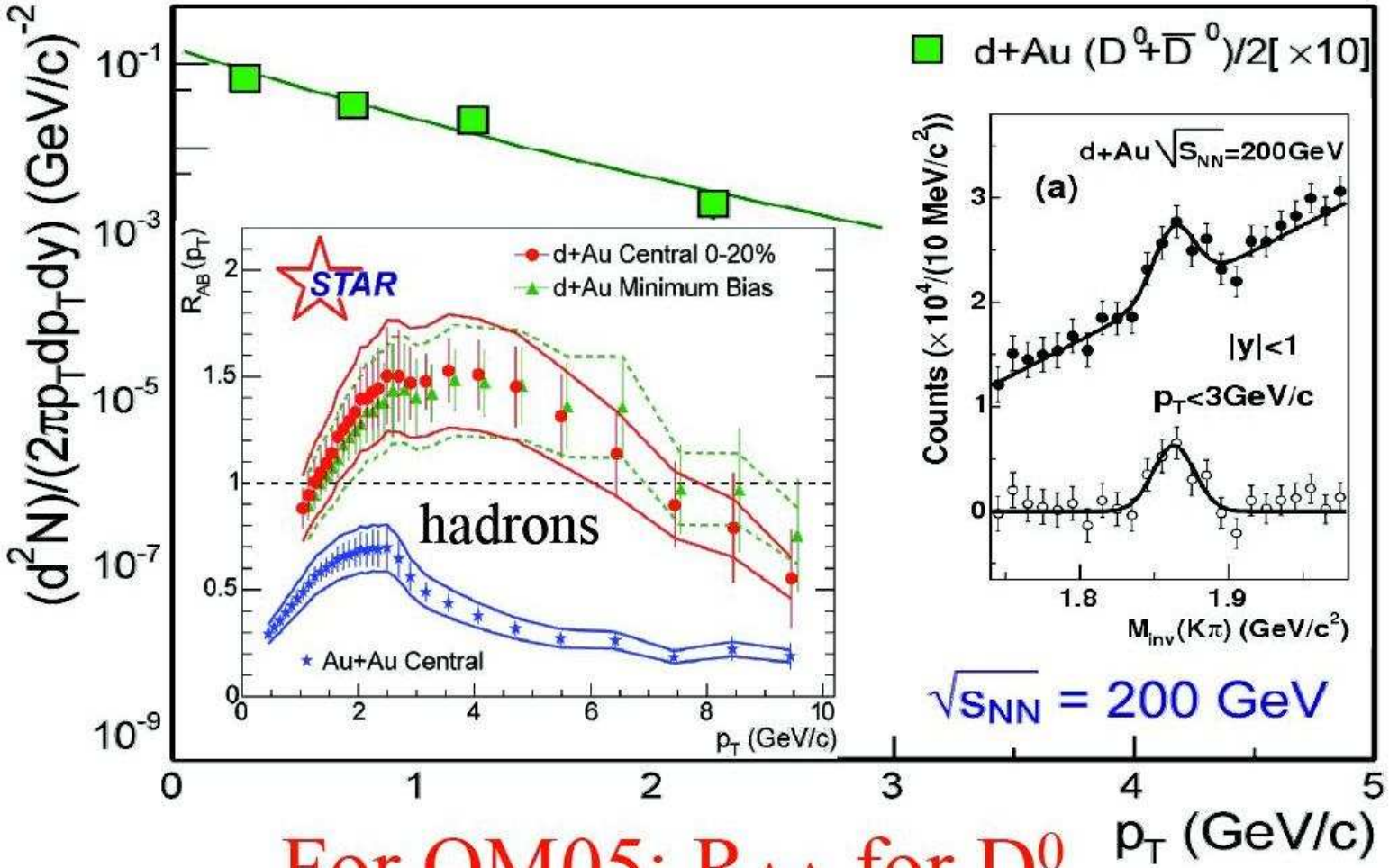


- ★ changing residual background shapes due to worsening PID at higher pT
- ★ efficiency calculations (spectra) in progress; ready for QM2005

D^0 Mesons in d+Au

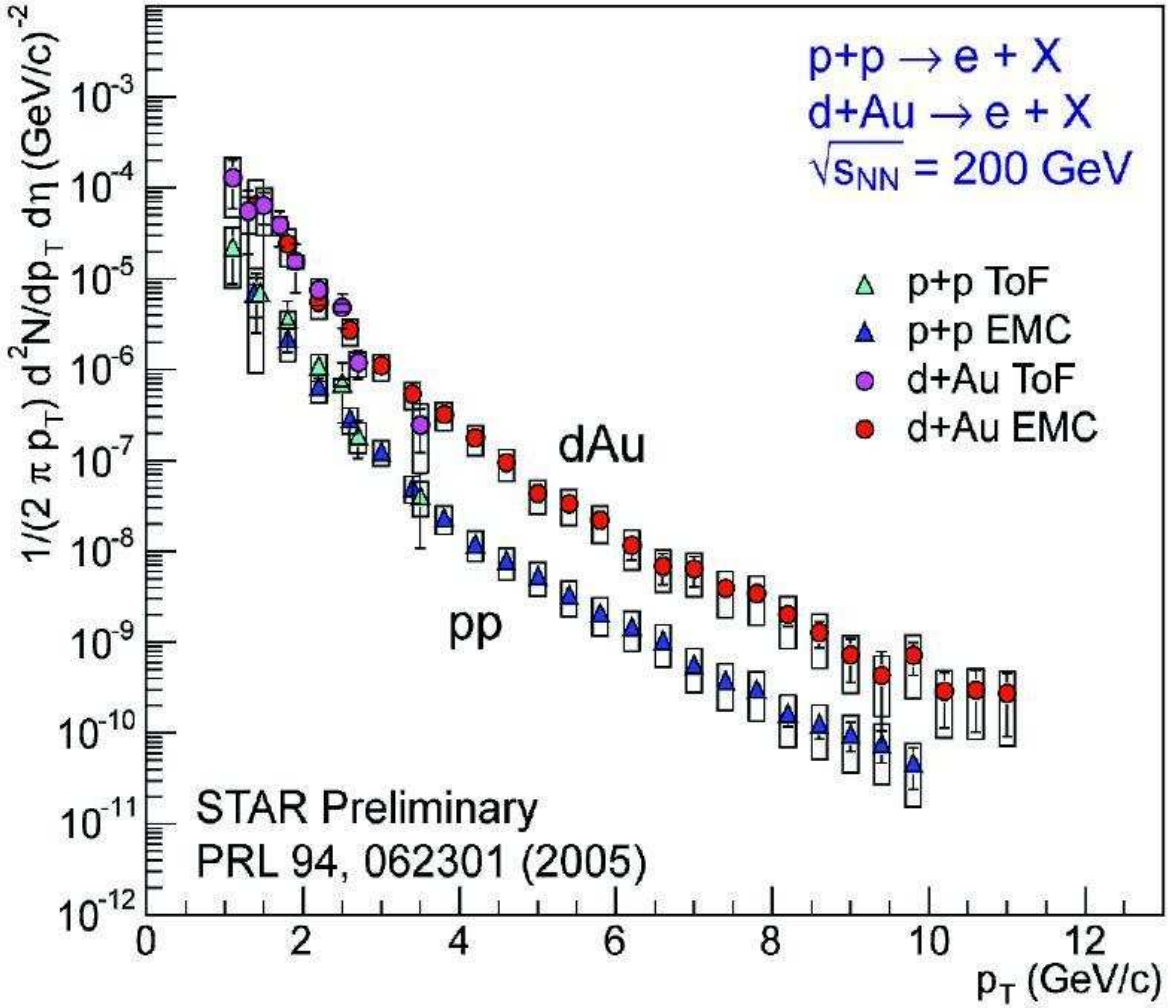
$dN/dy = 0.028 \pm 0.004(stat) \pm 0.008(sys)$ $\langle pT \rangle = 1.24 \pm 0.8$ GeV/c

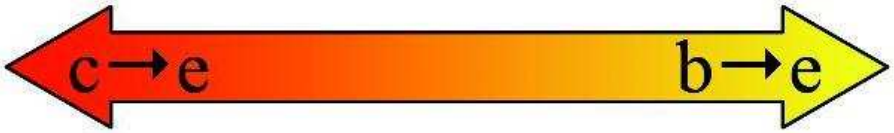
PRL 94, 062301 (2005)



For QM05: R_{AA} for D^0

Non-Photonic Single Electron Spectra in p+p and d+Au



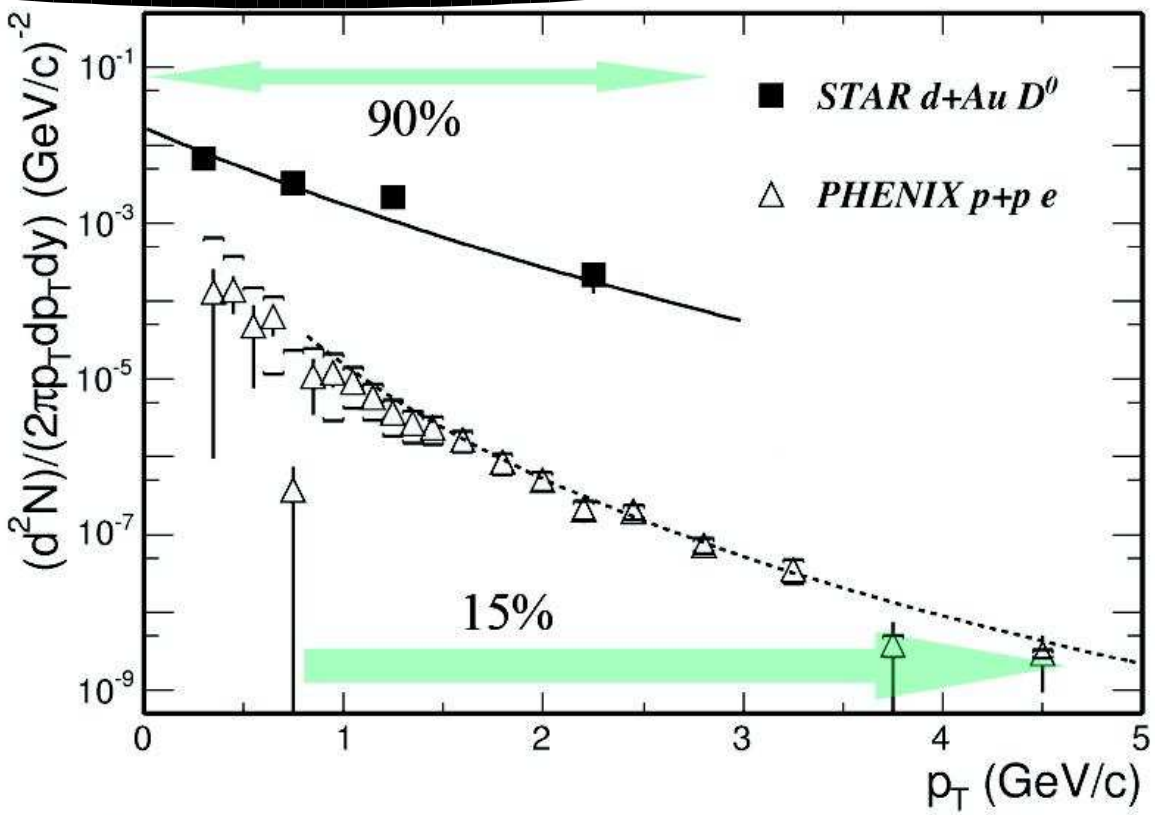


- ★ 6 order of mag.
- ★ nice overlap between detectors
- ★ EMC extends out pT reach well into the bottom regime
- ★ Au+Au data ready for QM 2005
  - ★ R_{AA} for electrons

Discrepancy between STAR and PHENIX ?

Combined fit of STAR D^0 and PHENIX electrons:

No discrepancy: σ_{cc}=1.1± 0.1 ± 0.3 mb



STAR: PRL 94, 062301 (2005)
PHENIX p+p (QM04): S. Kelly et al. JPG30(2004) S1189

v_2 of Non-Photonic Electrons

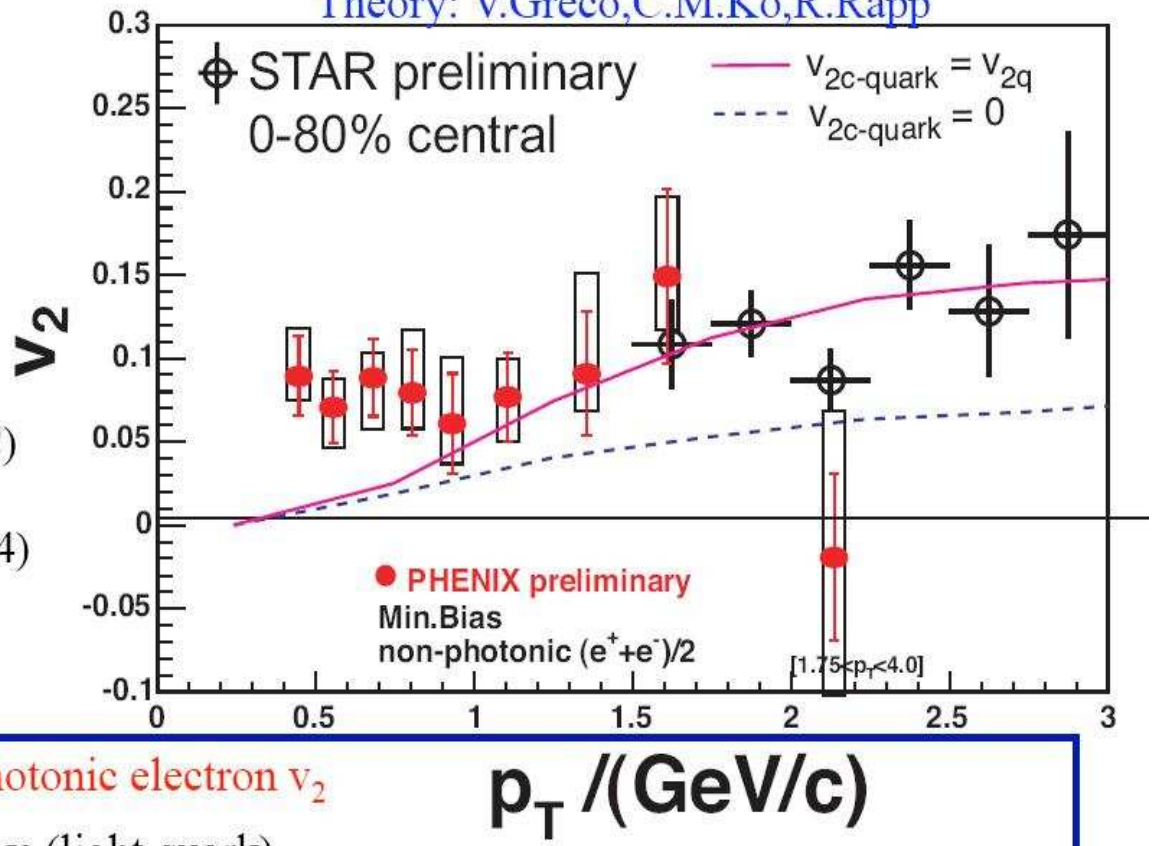
Phenix : Min. Bias

Star: 0-80%

STAR: stat. errors only

Phenix:
nucl-ex/0404014 (QM2004)
nucl-ex/0502009 (submitted to PRC)
Star:
J. Phys. G 190776 (Hot Quarks 2004)
J. Phys. G 194867 (SQM 2004)

Theory: V.Greco,C.M.Ko,R.Rapp



⇒ Indication of strong non-photonic electron v_2

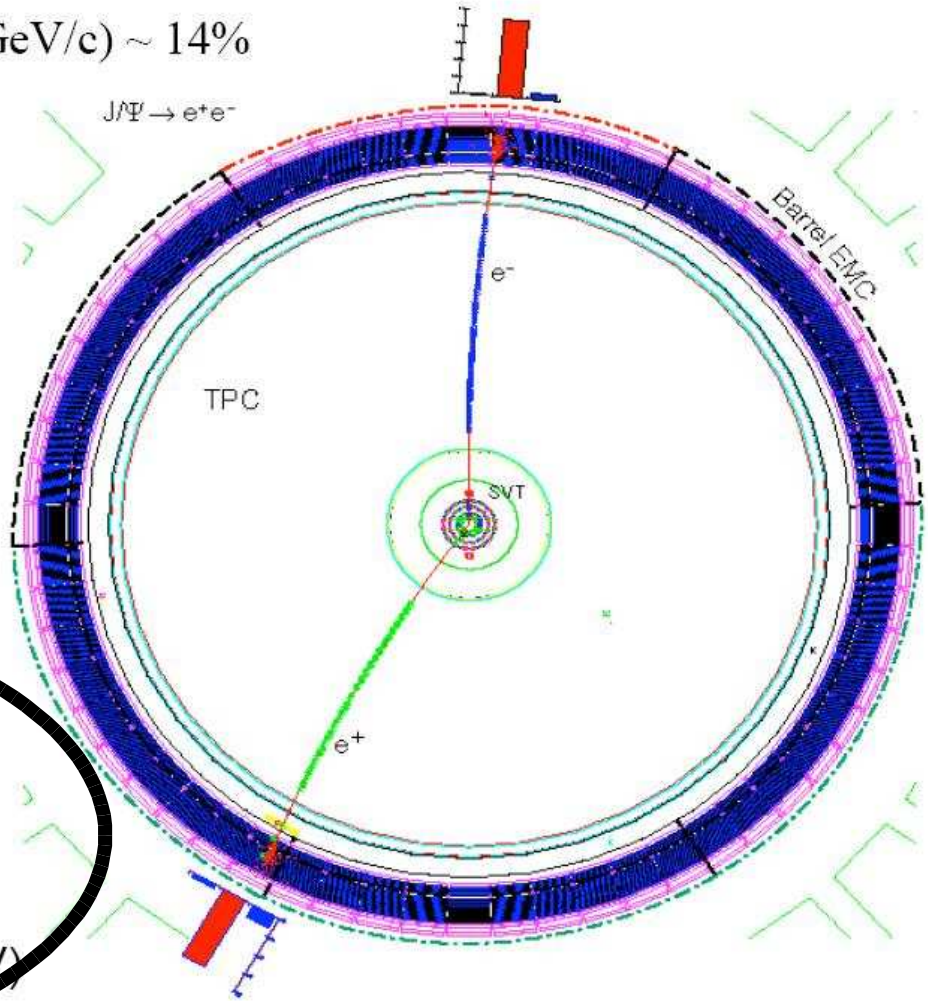
- ★ consistent with $v_2(c) = v_2$(light quark)
- ★ smoothly extending from PHENIX results
- ★ Teany/Moor ⇒ D $(2\pi T) = 1.5$ ($\alpha_s = 1$?) ⇒ expect substantial suppression R_{AA}
- ★ Greco/Ko ⇒ Coalescence model (shown above) appears to work well

Topological EMC triggers

- Large acceptance $|\eta|<1$, high tracking efficiency (90%), good $e^{\pm}$ id, 10^5 hadron rejection
  - J/Ψ: acceptance × efficiency ($p_T^e > 1.2$ GeV/c) ~ 10%
  - Υ: Acceptance × efficiency ($p_T^e > 3.5$ GeV/c) ~ 14%
- Signal-to-Background Ratios
  - S/B > 1: 1 for Υ
  - S/B = 1:25 – 1:100 for J/Ψ

    $S_{eff} = S/(2(B/S)+1)$

    Υ significance close to that of J/Ψ
- Without Trigger (min. bias running):
  - Min bias (100 Hz): 18 J/Ψ
  - 0.02 Υ per hour running



Topological EMC triggers

- Upsilon (all collisions systems)
- J/Psi (light systems or high-p_T)
  - Acc. $|y|<1$: L0 Eff

    0.11 (½ barrel) 0.61 (E>1GeV)

    0.22 (¾ barrel) 0.37 (E>1.2GeV)

STAR Upgrades to come: Full ToF-barrel and HFT

Heavy Flavor Tracker (HFT)

- ★ Two layers
  - ★ 1.6 cm radius
  - ★ 4.8 cm radius
- ★ 24 ladders
  - ★ 2 cm by 20 cm
- ★ MIMOSA A[illegible]nor (CMOS)
  - ★ Precise [illegible]nd low power
  - ★ 50 μ[illegible] cooling
  - ★ 0.36% r[illegible]length

secondary vertex reconstruction

Time-of-Flight: MRPC

- ★ π/K separation up to 1.6 GeV/c
- ★ p/K separation up to 3 GeV/c
- ★ Thus cover wider [illegible] of (p,K,π) p_T
- ★ Full ToF: [illegible]

excellent particle id

Quarkonia in Medium and in Heavy-Ion Collisions

Ralf Rapp

Cyclotron Institute

+ Physics Department

Texas A&M University

College Station, USA

Heavy-Flavor Workshop
RHIC & AGS Annual Users Meeting
BNL, 21.06.05

Highlights of discussion

Resonance rescattering (via unbound "D" states) causes much shorter c quark thermal equilibration times in plasma.

Assume J/ψ state persists for **$T < 2\ T_c$** (Lattice).

Dissociation in QGP by gluon absorption (larger ε_B), quasifree dissociation (lower ε_B) → J/ψ lifetime in plasma.

Regeneration of J/ψ calculated from detailed balance (equilibrium abundance limited by **primordial cc pair number** and **competition with open charm states**, and depends on **c quark momentum distribution**).

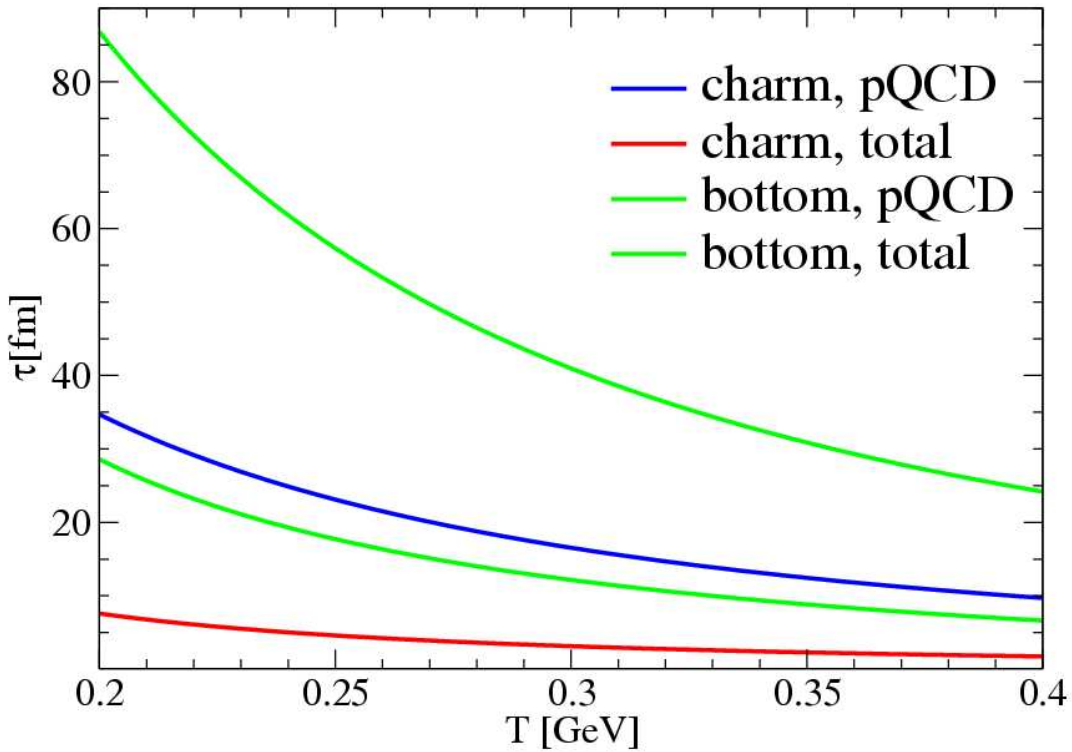
Calculation uses **in-medium masses** of open charm, **reduced J/ψ binding** with higher T, incomplete thermalization of c quarks in early stages.

Mixed and hadronic phases included, but they have **little effect** on J/ψ yield.

2.3 Bottom vs. Charm Thermalization in QGP

[van Hees+RR '04]

Thermalization Times



Thermalization times with resonance rescattering of heavy quarks.

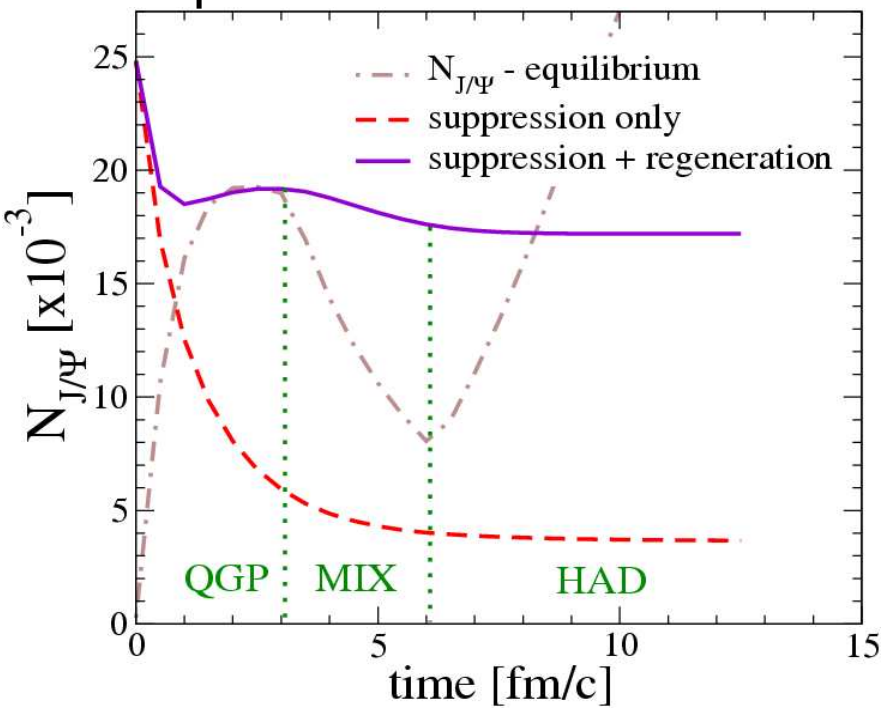
- charm quark equilibration time ~ fireball lifetime
- bottom quarks do not thermalize (RHIC)

3.4 Time Evolution of Quarkonia at RHIC

Solve kinetic rate-equation:

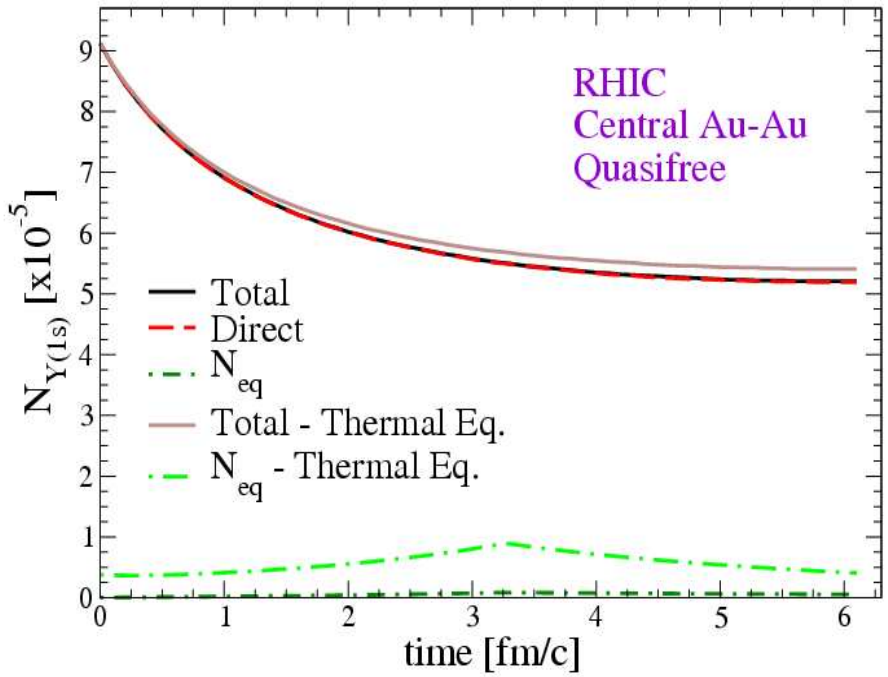
$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left(N_\psi - N_\psi^{eq} \right)$$

J/ψ in Central Au-Au



- **Equilibration close to T_c ?!**

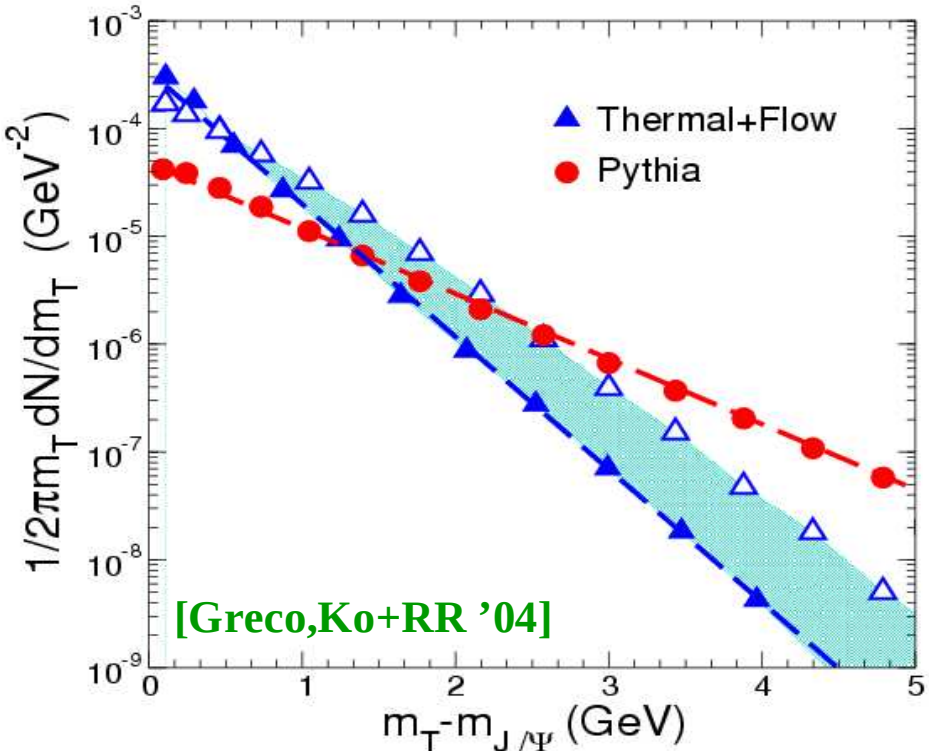
Upsilon

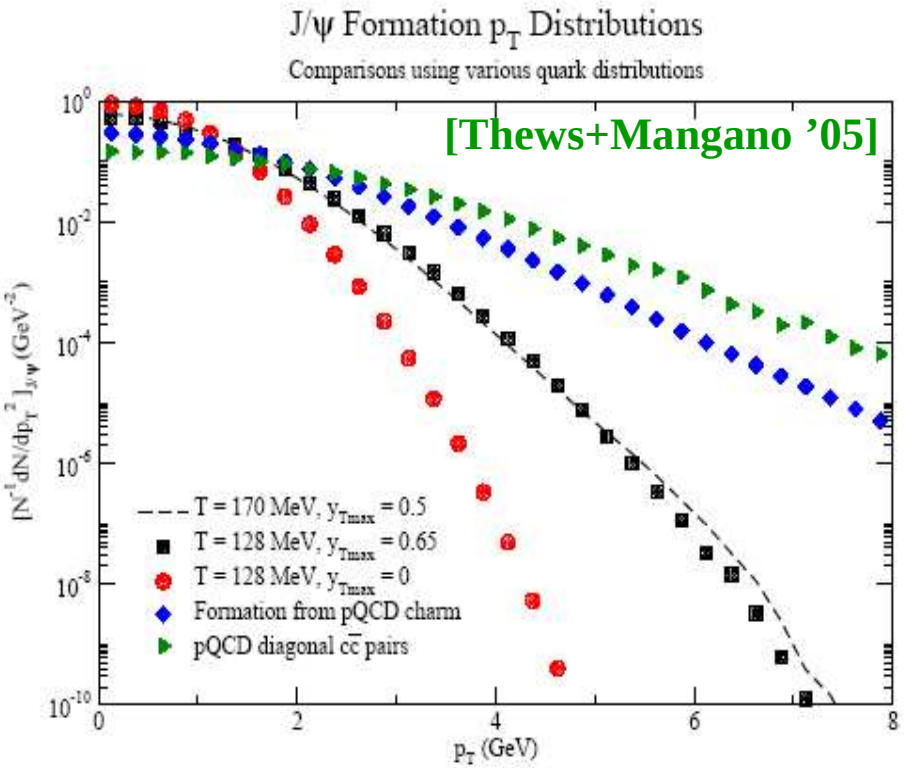


- **Suppression only!**
- **importance of screening**

4.1.2 J/ψ p_t-Spectra in Au-Au at RHIC

Quark Coalescence at T_c



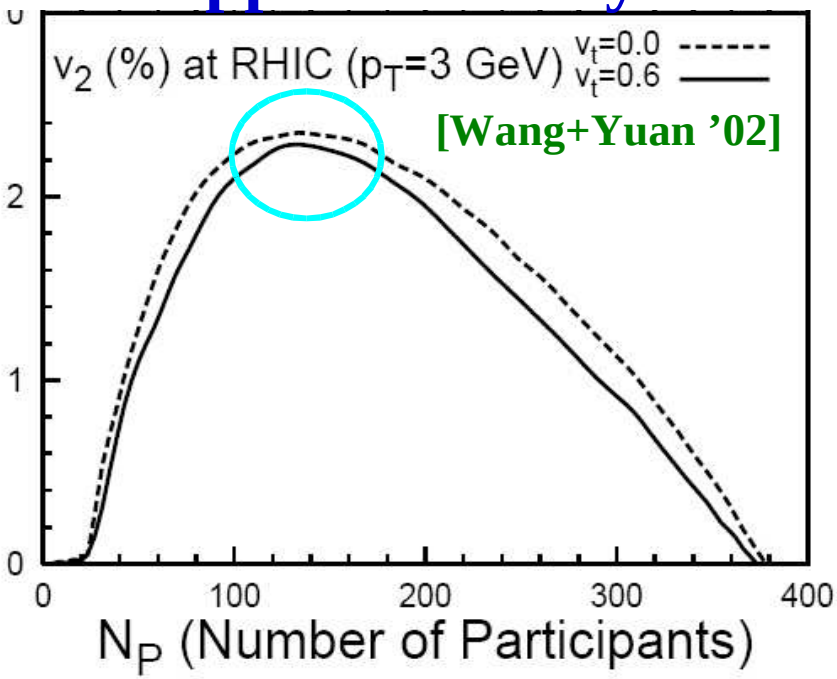


- total yields different by factor 3
- large sensitivity to radial flow ($\beta_{t,max}$=*0.5-0.65*)

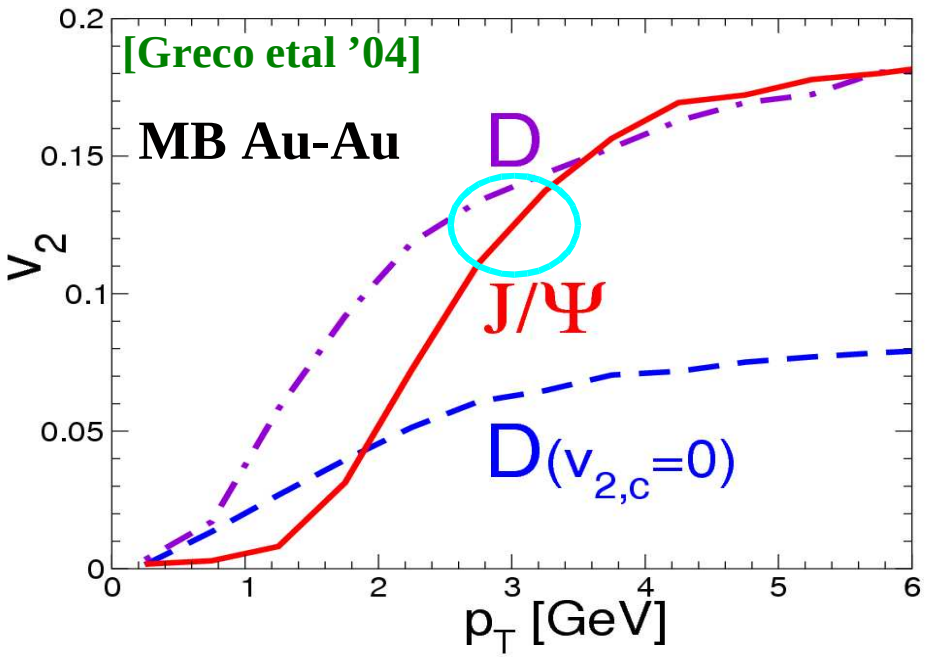
4.1.3 Scrutinizing Charmonium Regeneration II:

J/ψ Elliptic Flow

Suppression only



Thermal Coalescence at *T*

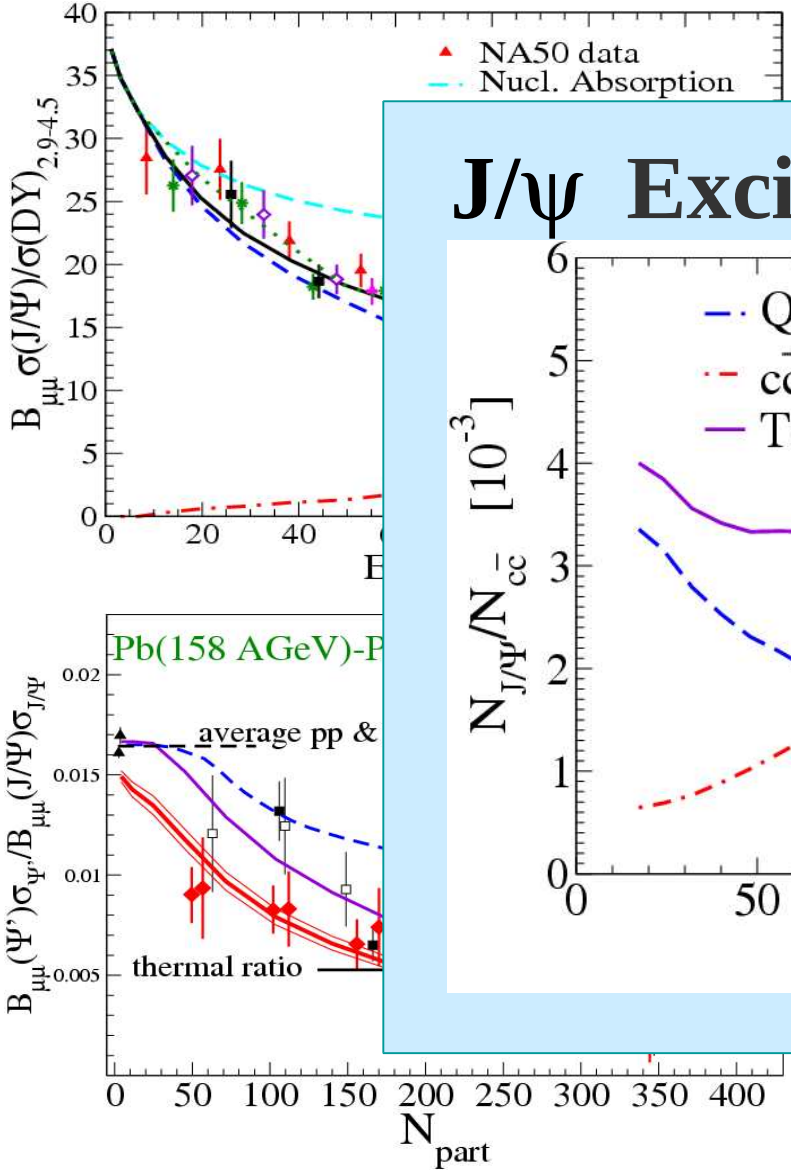


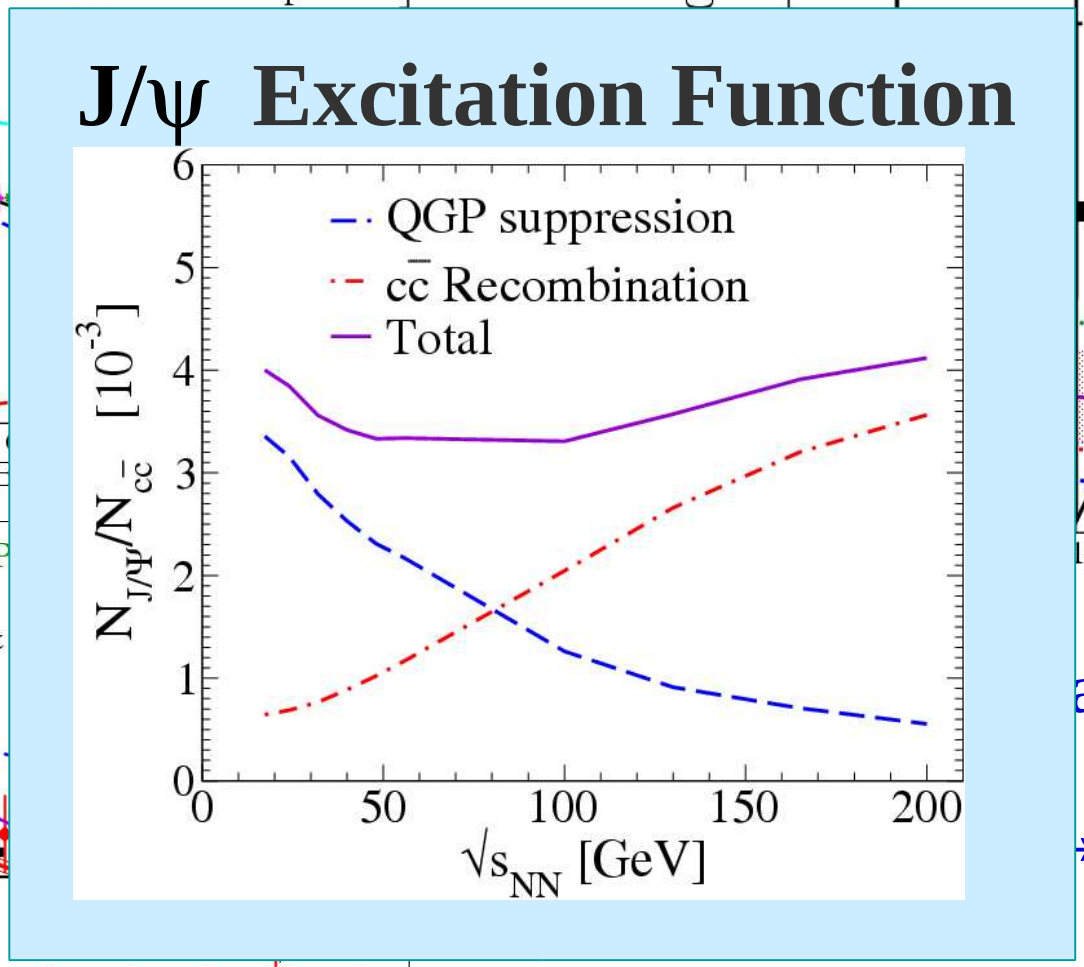
- factor **~5** different!
- transition in p_t!?

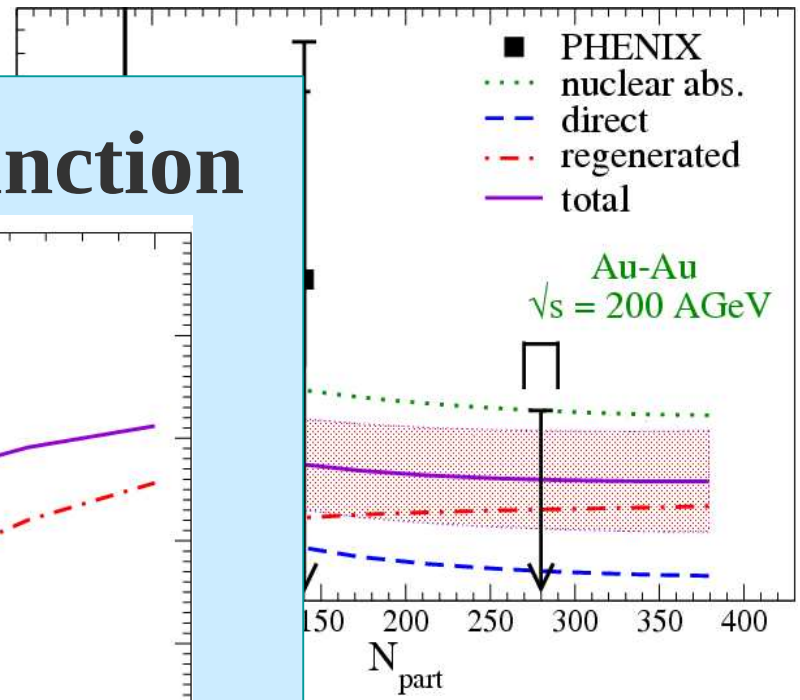
4.) Charmonium in A-A

SPS **RHIC**

[Grandchamp +RR '03]





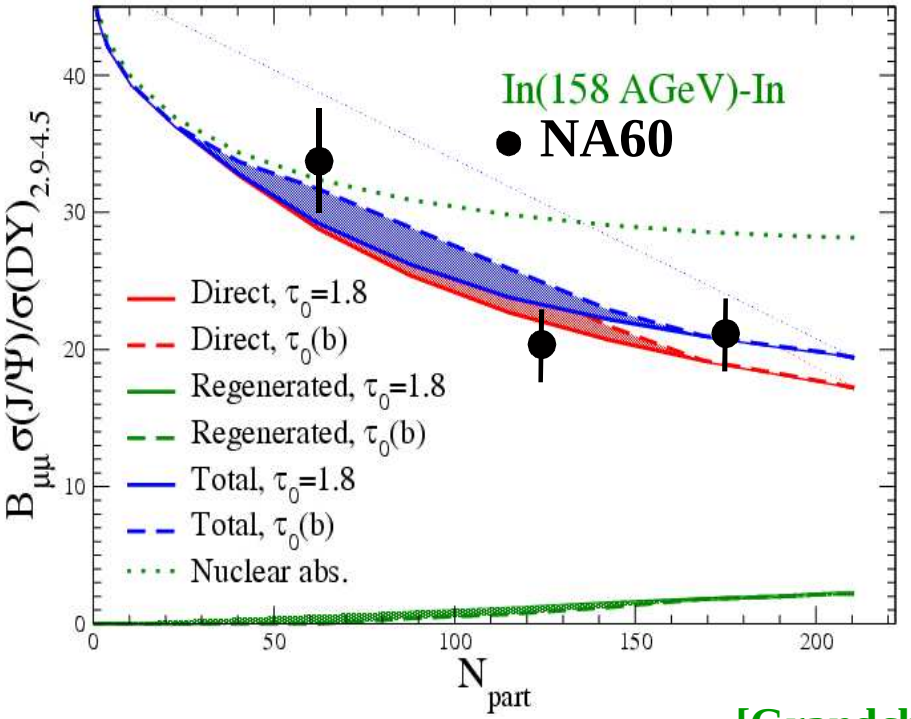


ation dominant

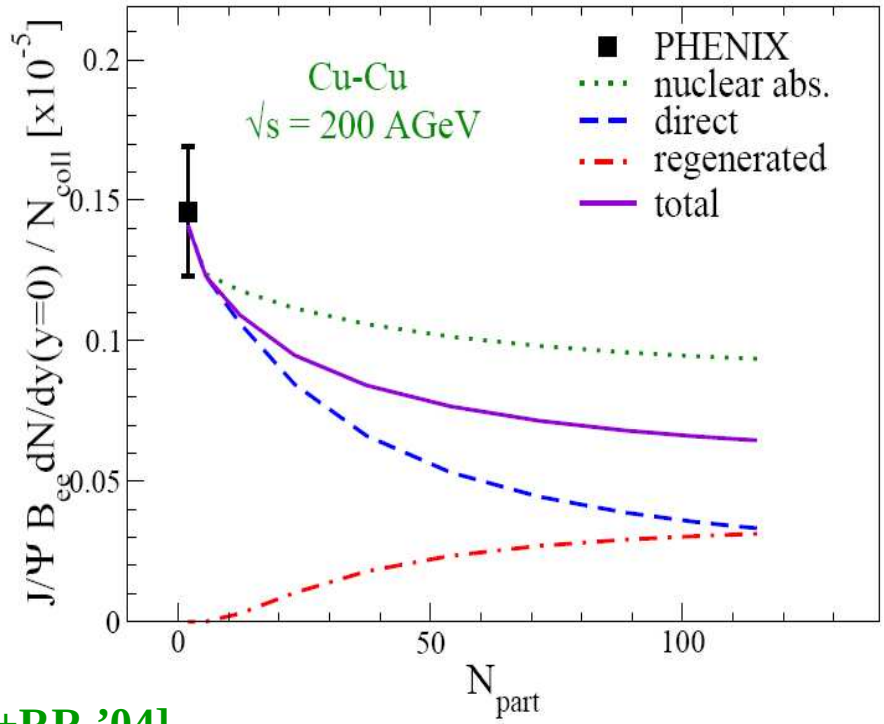
→ rapidity, $\sqrt{s}$, A

4.2 Intermediate-Mass Ions

SPS



RHIC

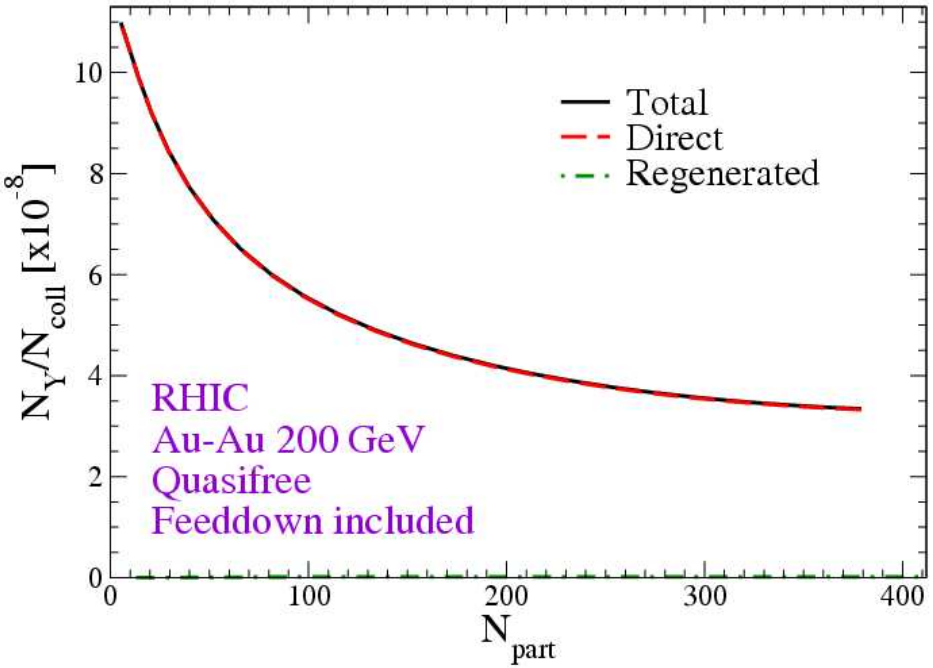


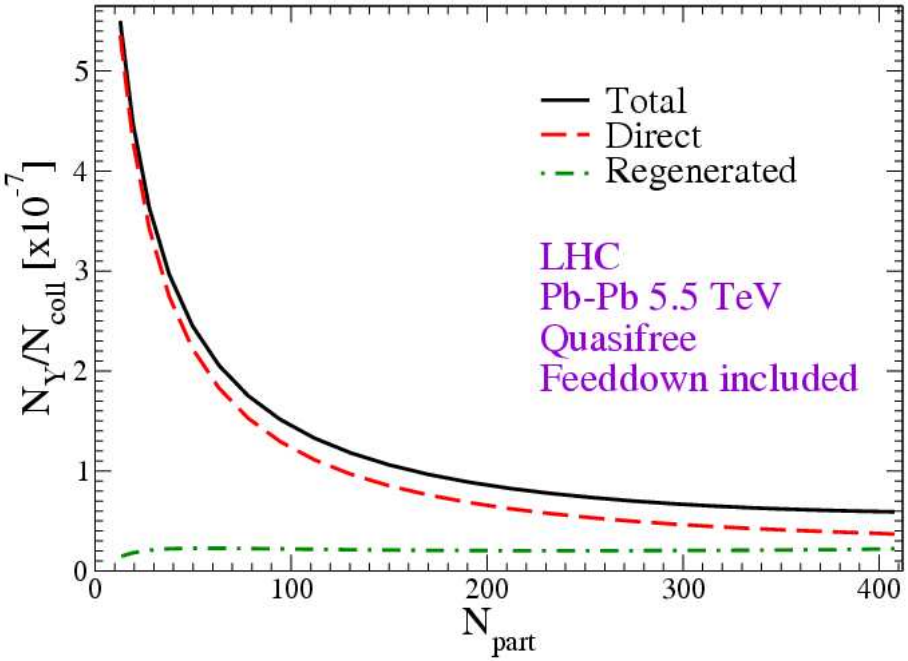
[Grandchamp+RR '04]

- **suppression prevalent**
- **onset of regeneration**

4.3 Upsilon at RHIC and LHC

RHIC **LHC**





[Grandchamp,Lumpokins,Sun,van Hees+RR '05]

- **bottomonium suppression as unique QGP signature ?!**

J/ψ production in dA collisions

Kirill Tuchin

AGS/RHIC Users Meeting, June 21, 2005, BNL

Described a model of J/ψ production in the parton saturation model (color glass condensate).

At **forward rapidity** at RHIC, the c-c production time (~1/2*m) is **longer than the interaction time**. So charm is coherently produced by the nuclear color field in dAu at RHIC at forward rapidity.

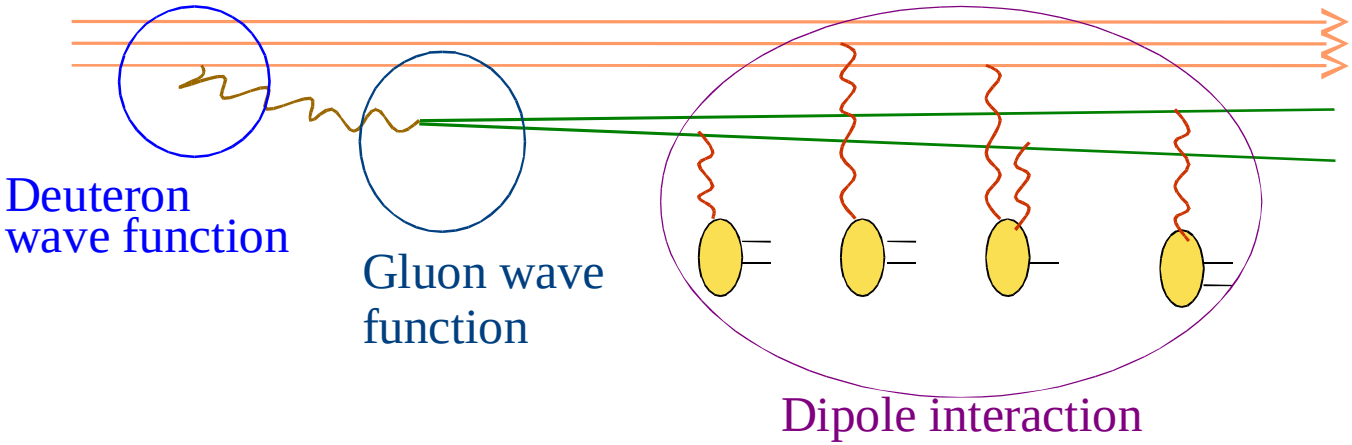
In the Color Glass Condensate model, coherent production occurs when $Q_s > m$.

Coherent production dominates at y ~ 2 - 3. The model breaks down at **y ~ -1** at RHIC**.**

Expect very large saturation effects on charm production at LHC.

Dipole model (I)

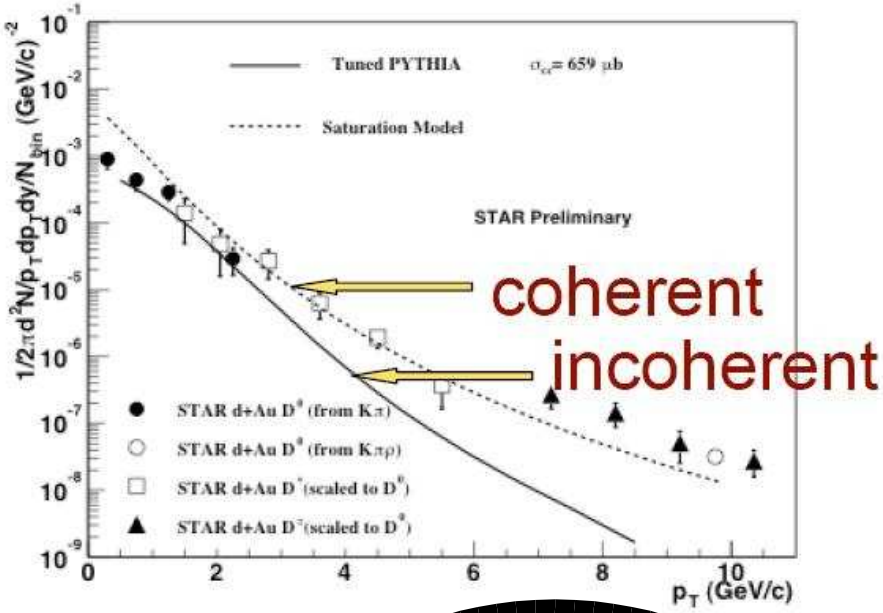
- Since $\tau_P >> \tau_{int}$ all dipoles $\underline{x}$-$\underline{x}_0$, $\underline{y}$-$\underline{x}_0$, $\underline{x}_1$-$\underline{z}_1$ etc. are frozen during the interaction (recall: color *glass*)
- There are two stages in a scattering process:
  - Development of a dipole system long before the interaction.
  - Instantaneous interaction of dipoles with the target.



Open Charm Spectrum in dA

The effect of saturation on spectrum at y=0:

Kharzeev, K.T., 2003; K.T. 2004.



Experimental fit: $\sim(1+p_T/p_0)^{-n}$ with p_0=1.32 GeV/c

$\sim Q_s$

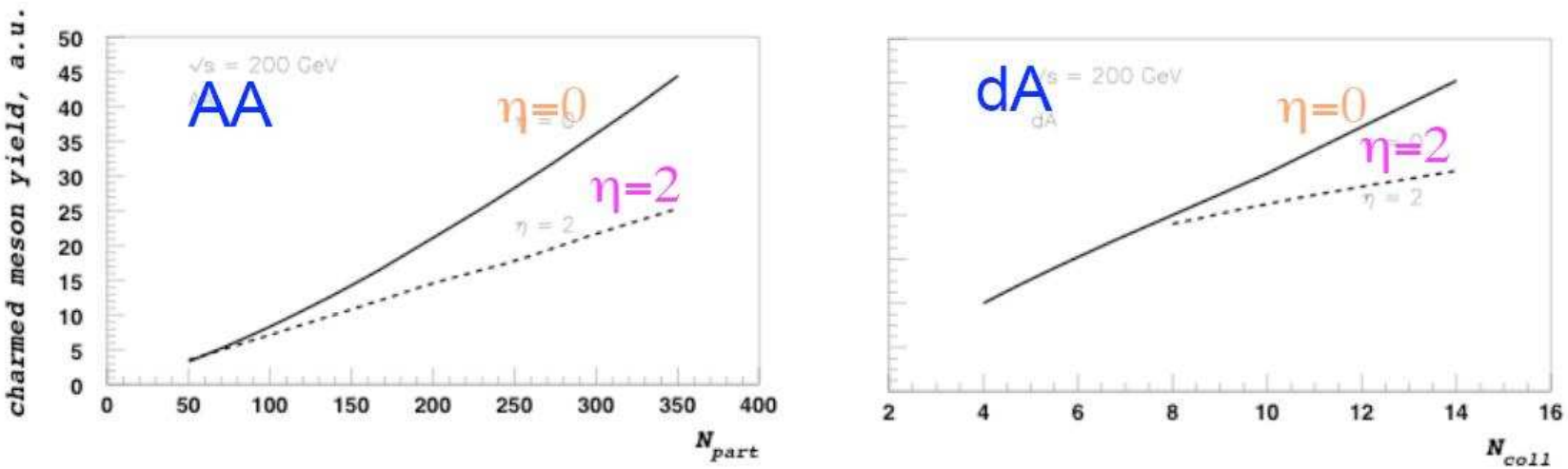
Open charm production

- Strong field of a nucleus influences heavy quark production if

$$Work = gE\lambda \sim Q_s^2/m \geq m \Rightarrow Q_s > m$$

At RHIC $Q_s=1.4e^{0.15\eta}$ GeV (at b=0), while $m_c=1.3$ GeV

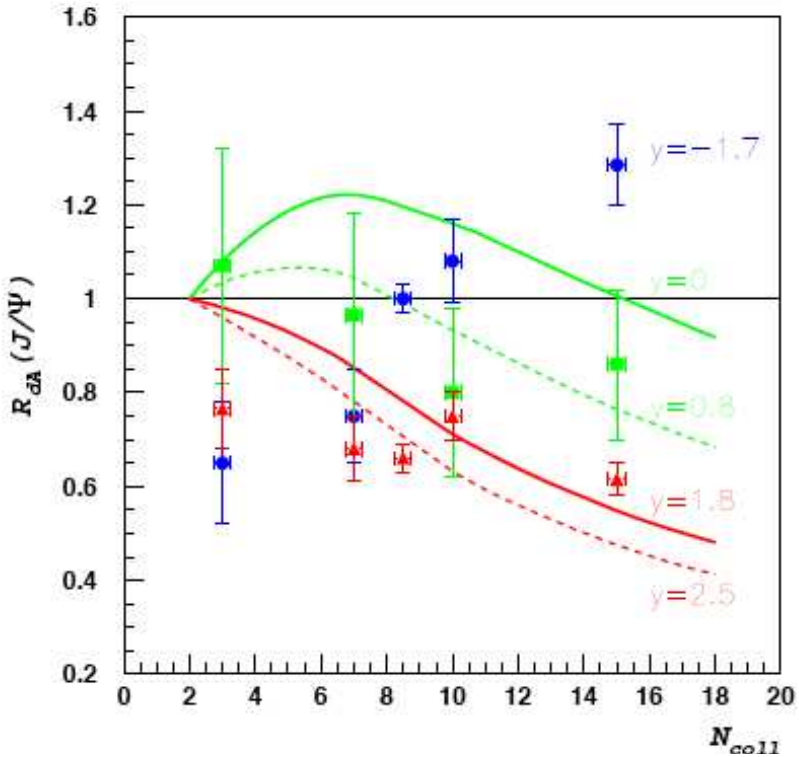
Thus, we expect suppression of charm in pA and AA relative to pp at η~2-3.



Kharzeev, K.T., 2003; K.T. 2004.

This effect is important for PHENIX muon arm rapidity!

J/ψ production in dA (II)

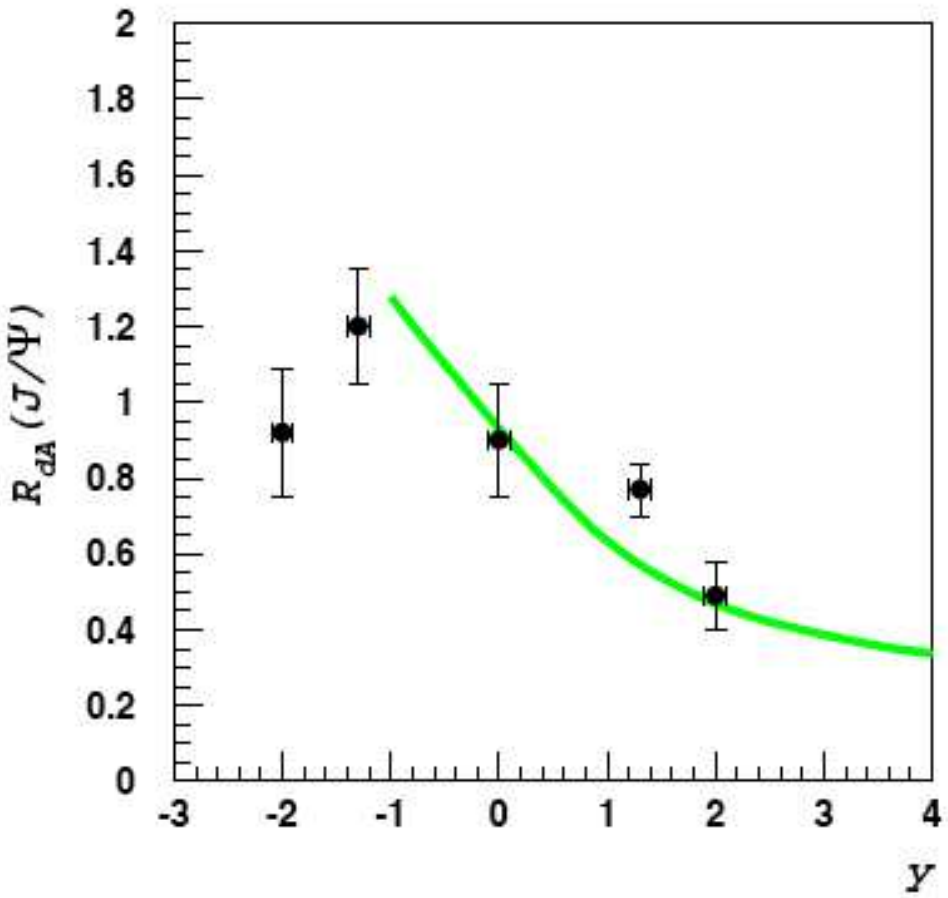


1) Collinear factorization: x_1 and x_2 scaling.
2) Shadowing models: x_2 scaling
3) Saturation: no scaling

$M_\psi < Q_s$: $$R_{pA}(J/\Psi) = \frac{M_\psi^4\, xG(x_1, Q_A^2)}{40\, A^{1/3}\, xG(x_1, Q_p^2)\, Q_{sp}^4(x_2)} \sim \frac{e^{-2\lambda y}}{s^\lambda\, N_{\rm coll}}$$

1) Production is suppressed as a function of s and y.
2. x_1 and x_2 scaling of R_{dA} is broken down.

J/ψ production in dA (II)



Conclusions (I)

- k_T-factorization seems to be a reasonable approximation.

- If the gluon saturation is the mechanism responsible for light hadron production at midrapidity at RHIC, then it should also be responsible for open charm production at somewhat higher energies / rapidities.

  ✓ production pattern is similar : e.g.Cronin effect, anomalous suppression;

  ✓Although there are differences: e.g. correlations, flow.

  ☐ so far in agreement with data.

Heavy quark production and energy loss

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pQCD calculations of heavy quark energy loss in medium.

- Heavy quarks provide a different example of medium induced gluon radiation from light parton jets.
- Energy loss suppression is different in detail in medium than in vacuum, but energy loss is still smaller for heavy quarks.
- **But** the mass effects are smaller for smaller lengths. Argues that surface emission (**trigger bias**) can explain the observed similarity of light quark and charm suppression.
- Proposes **massive/light particle ratio vs p_T** as a signature of medium effects. Theoretically less dangerous at LHC energy.

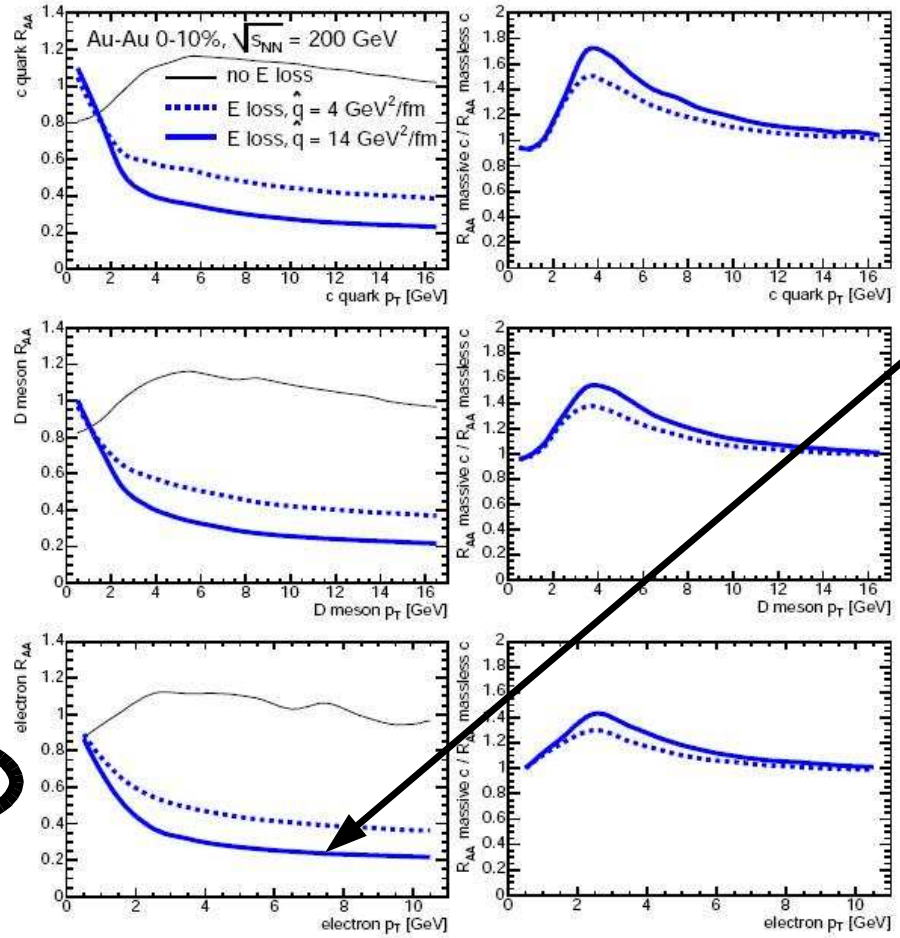
Results for RHIC

R_{AA} for:

c quark

D meson

electron

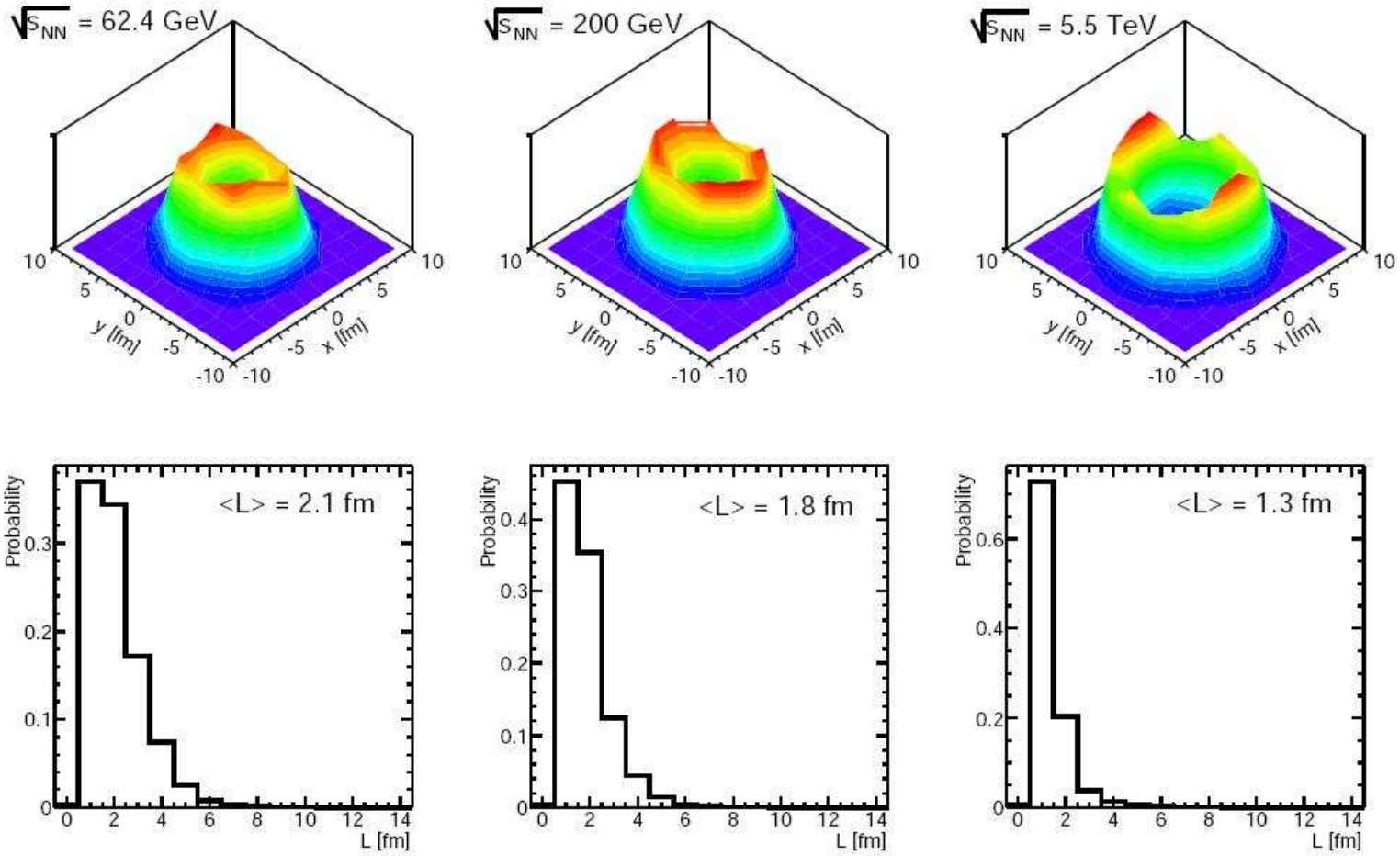


Agrees very well with PHENIX data

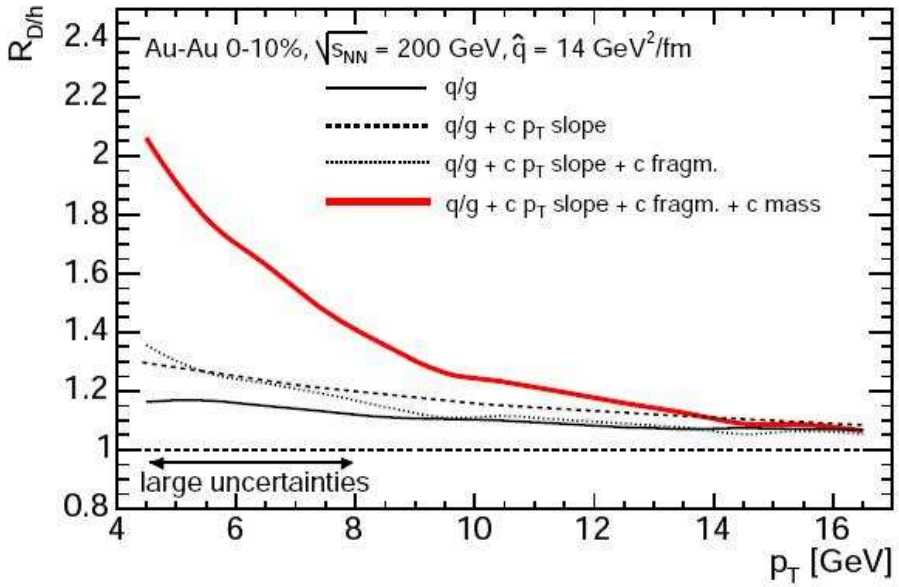
[Armesto, Dainese, Salgado, Wiedemann (2005)]

Surface emission with mass terms

- ⇒ Suppression for charm and light quarks very similar unexpected?
- ⇒ Remeber that mass effects small for small lenghts



Massive over light particle ratio

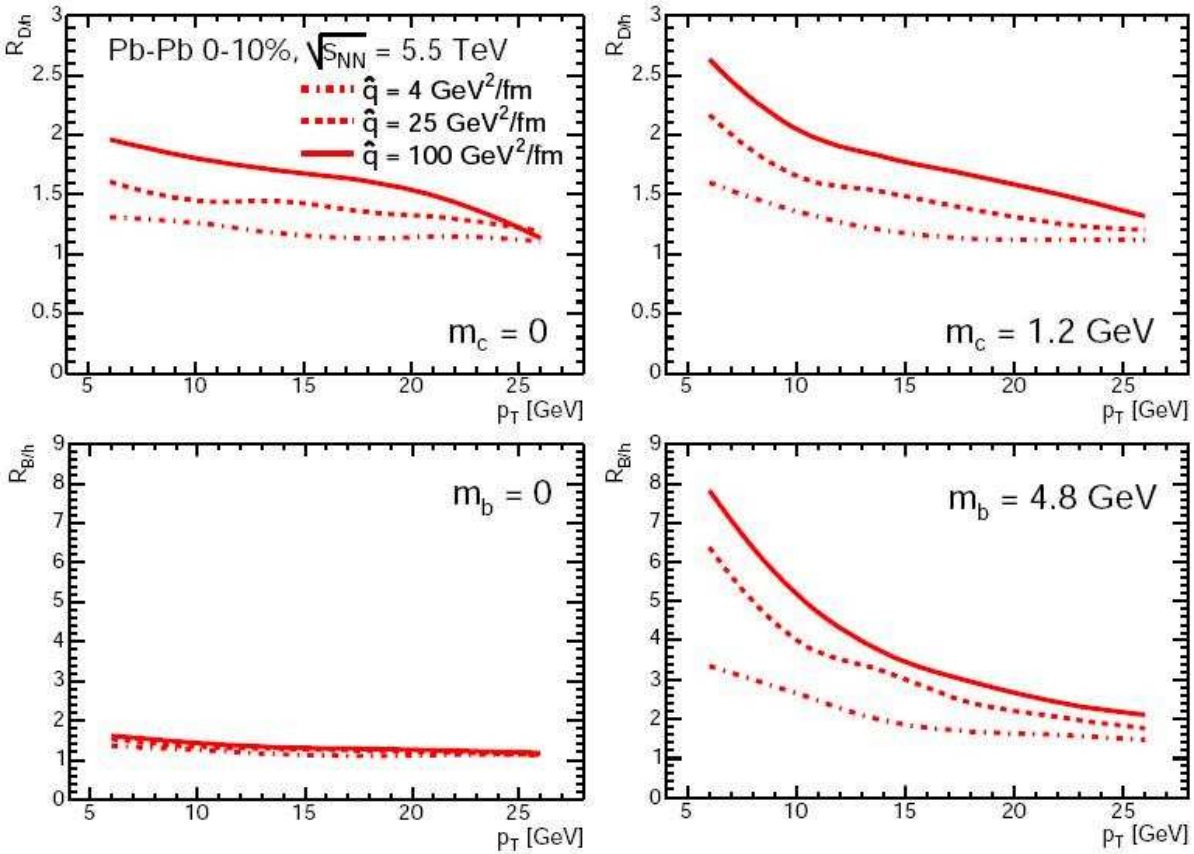


[Armesto,Dainese,Salgado,Wiedemann 2005]

- Quark vs gluon energy loss: $\Delta E^g = N_C/C_F \Delta E^{q,\mathrm{m}=0}$
  - Increases $R_{D/h}$
- Light-particle spectrum slope larger than massive one
  - Increases $R_{D/h}$
- charm fragmentation harder
  - Decreases $R_{D/h}$
- Heavy quark suppression of gluon radiation ('dead-cone')
  - Increases $R_{D/h}$

Heavy-to-light ratios at the LHC

⇒ D/h and B/h ratios for the LHC



[Armesto, Dainese, Salgado, Wiedemann (2005)]

The opaque plasma and charm

Denes Molnar
Ohio State University, Columbus, OH, USA

RHIC/AGS Users Meeting

June 21, 2005, RIKEN/BNL Research Center, Upton, NY

- motivation, covariant transport theory
- lessons from light sector at RHIC
- results for charm
- open issues: secondary charm, hadronization, coherence

Molnar's Parton Cascade (MPC)

Elementary processes: elastic $2 \to 2$ processes + $gg \leftrightarrow q\bar{q}$, $q\bar{q} \to q'\bar{q}'$ + $ggg \leftrightarrow gg$

Equation for $f^i(x,\vec{p})$: $\quad i = \{g, d, \bar{d}, u, \bar{u}, ...\}$

$$
\begin{aligned}
p_1^\mu \partial_\mu \tilde{f}^i(x,\vec{p}_1) \;=\; & \frac{\pi^4}{2} \sum_{jkl} \iiint_{2\,3\,4} \left(\tilde{f}_3^k \tilde{f}_4^l - \tilde{f}_1^i \tilde{f}_2^j \right) \left| \bar{\mathcal{M}}_{12\to 34}^{i+j\to k+l} \right|^2 \delta^4(12-34) \quad \swarrow 2 \to 2 \\
& + \frac{\pi^4}{12} \iiiint_{2\,3\,4\,5} \left(\frac{\tilde{f}_3^i \tilde{f}_4^i \tilde{f}_5^i}{g_i} - \tilde{f}_1^i \tilde{f}_2^i \right) \left| \bar{\mathcal{M}}_{12\to 345}^{i+i\to i+i+i} \right|^2 \delta^4(12-345) \quad \swarrow 2 \leftrightarrow 3 \\
& + \frac{\pi^4}{8} \iiiint_{2\,3\,4\,5} \left(\tilde{f}_4^i \tilde{f}_5^i - \frac{\tilde{f}_1^i \tilde{f}_2^i \tilde{f}_3^i}{g_i} \right) \left| \bar{\mathcal{M}}_{45\to 123}^{i+i\to i+i+i} \right|^2 \delta^4(123-45) \quad \swarrow 3 \leftrightarrow 2 \\
& + \tilde{S}^i(x,\vec{p}_1) \quad \leftarrow \textbf{initial conditions}
\end{aligned}
$$

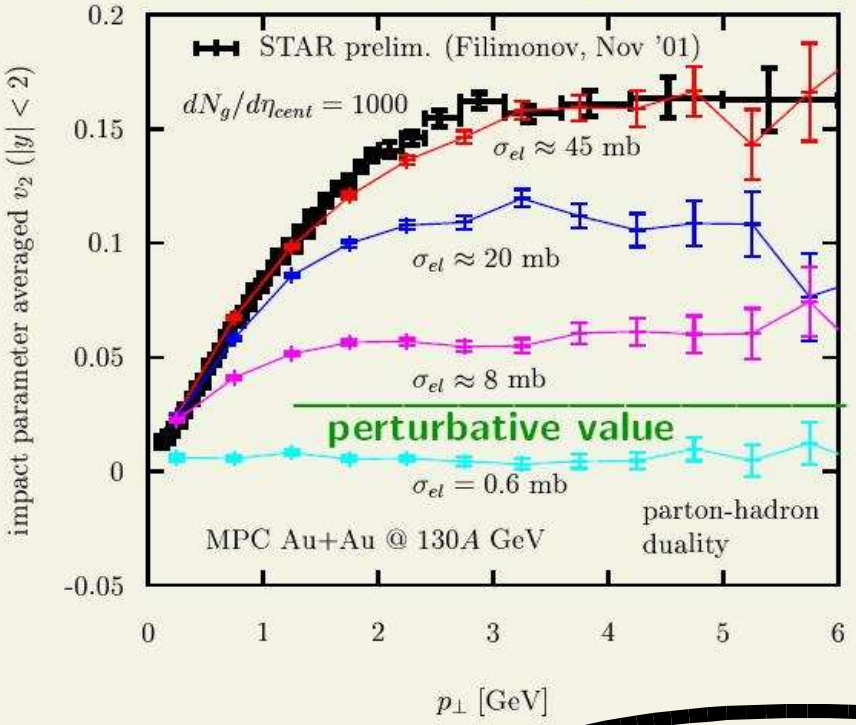
with shorthands:

$$
\tilde{f}_i^q \equiv (2\pi)^3 f_q(x,\vec{p}_i), \quad \int_i \equiv \int \frac{d^3p_i}{(2\pi)^3 E_i}, \quad \delta^4(p_1+p_2-p_3-p_4) \equiv \delta^4(12-34)
$$

Very large opacity at RHIC

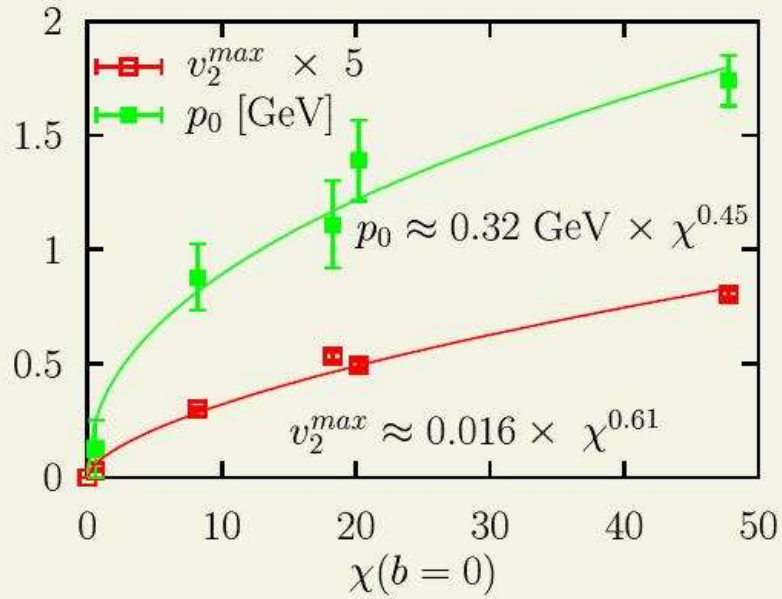
Au+Au @ 130 GeV, $b = 8$ fm from covariant transport

DM & Gyulassy, NPA 697 ('02): $v_2(p_T, \chi)$



nonlinear opacity dependence

$$v_2(p_T, \chi) \approx v_2^{max}(\chi) \tanh(p_T/p_0(\chi))$$



super-opaque plasma - $15\times$ perturbative opacities $N_{coll}(b{=}0) \sim 70$, $\lambda_{MFP} \sim 0.1$fm

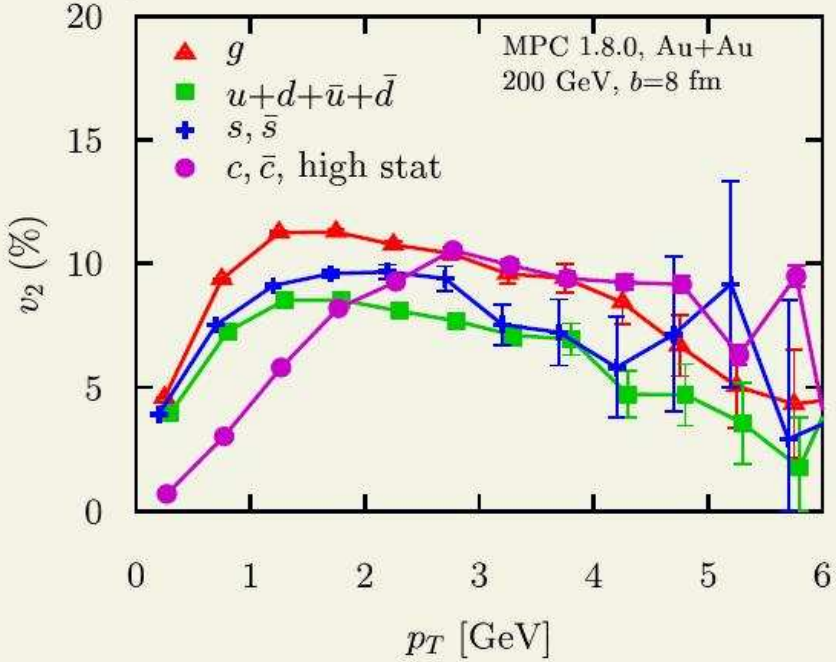
(saturated gluon $\frac{dN^{cent}}{d\eta} = 1000$, $T_{eff} \approx 0.7$GeV, $\tau_0 = 0.1$fm, 1 parton $\rightarrow$ 1 π hadr.)

Charm v_2 from transport theory

Most efficient $2 \to 2$ process: $gc \to gc$ $\quad \frac{d\sigma_{gc\to gc}}{dt} \sim \frac{2\pi\alpha_s^2}{(t-\mu_D)^2} + \ldots$

average mom. transfer: $\Delta q^2 \sim \mu_D^2 \ln \frac{6ET}{\mu_D^2(1+M^2/6ET)}$

DM ('04):



Au+Au @ 200GeV, $b = 8$ fm

from MPC 1.8.0 w/ elastic & inelastic $2 \to 2$

$\sigma_{gg\to gg} = 10$ mb

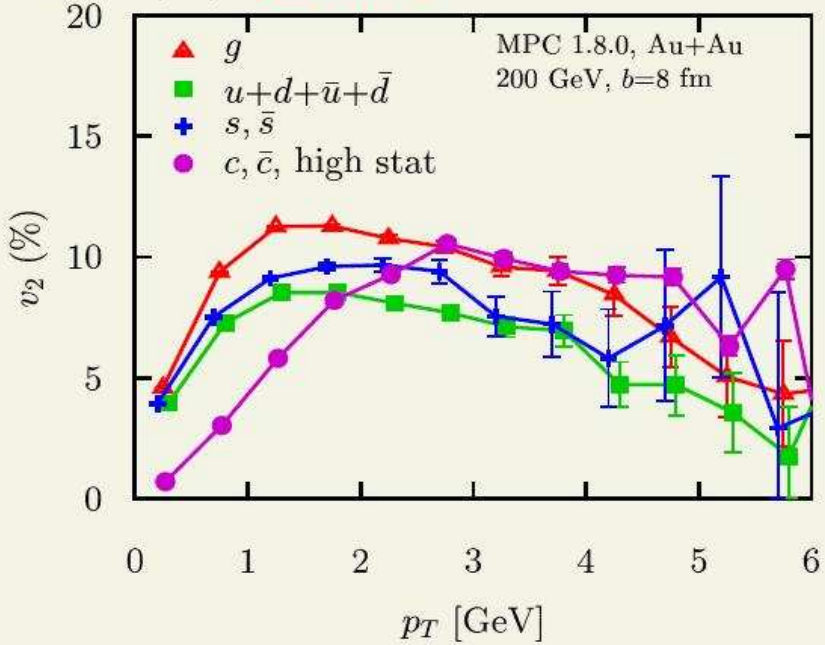
($\mu_D = 0.7$ GeV, $m_c = 1.2$ GeV, pQCD + saturation initconds, $\frac{dN^{parton}}{d\eta}(b{=}0) = 2000$)

- **charm should flow - above $p_T \approx 2.5 - 3$ GeV same v_2 as light partons**
- **at low p_T charm v_2 rises slower $\sim$ resembles the hydro mass effect**

Prelim. data indicate charm flow

parton transport MPC 1.8.0 **vs** **indirect $D(qc)$ meson measurement:**

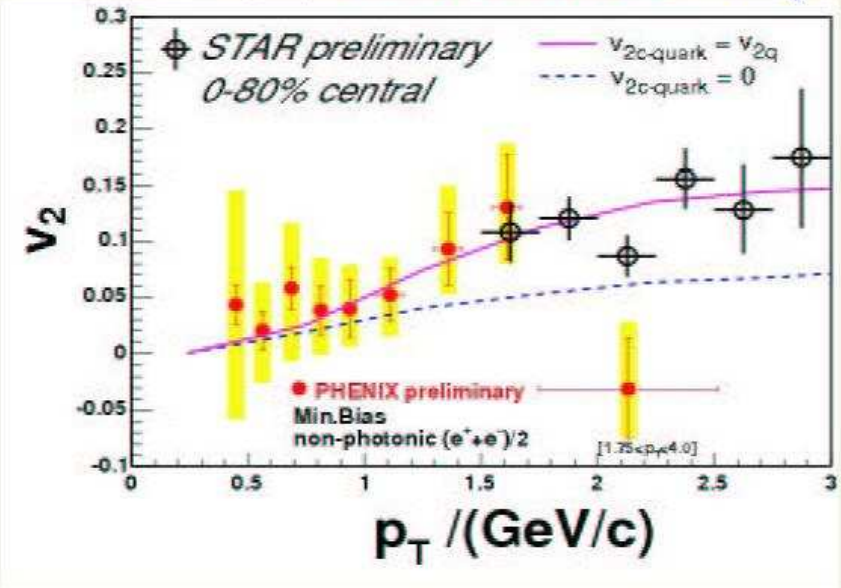
DM, JPG ('04): **parton v_2**



elastic & inel. $2 \to 2$

$6\times$ perturbative opacities

PHENIX, STAR ('04): **decay electron v_2** $\approx v_2^D$



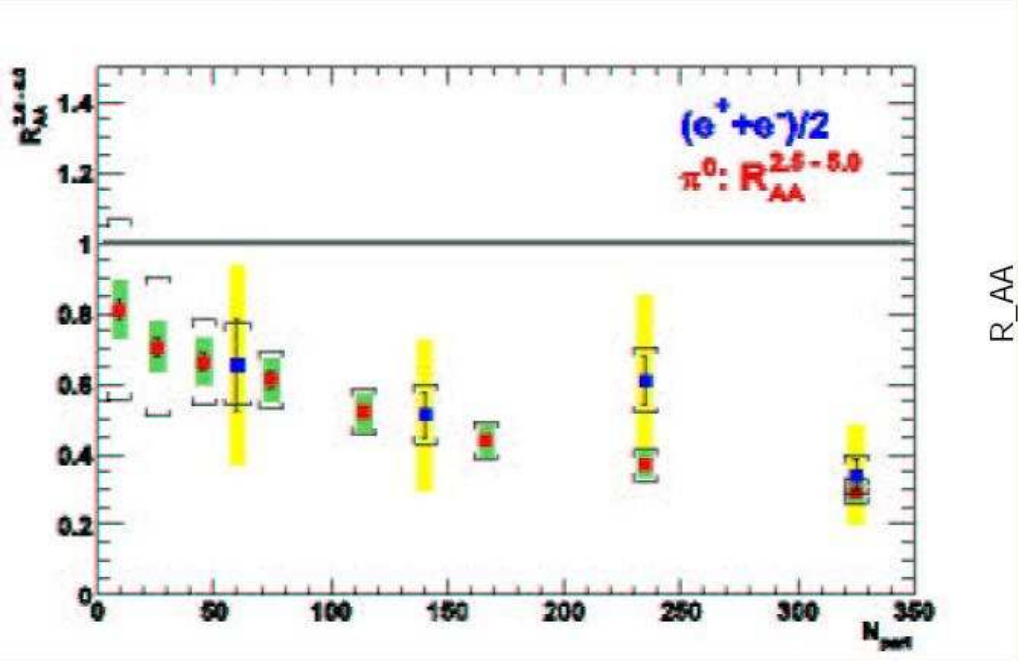
uses decay electrons: $D \to K^{(*)}\,\nu\, e$

e's from hadron decays and γ-conversion subtracted
$\equiv$ "non-photonic"

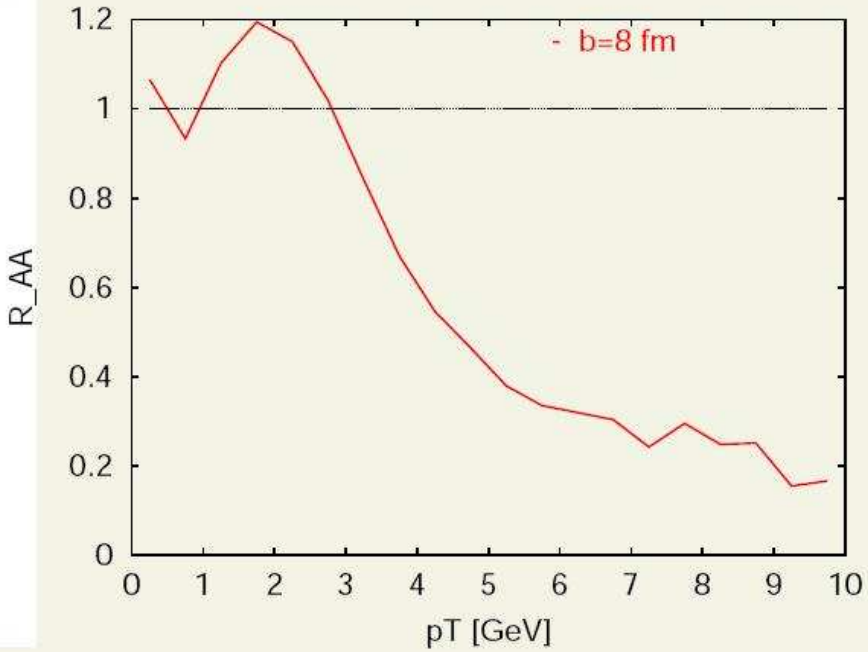
qualitative agreement, now detailed studies needed - $v_2(b, \chi, \sqrt{s})$

Comparison to prelim. RHIC data

PHENIX '05: **light vs heavy R_{AA}**



DM '04:



data show little difference between light and heavy flavor (for $p_T > 2-2.5$ GeV)

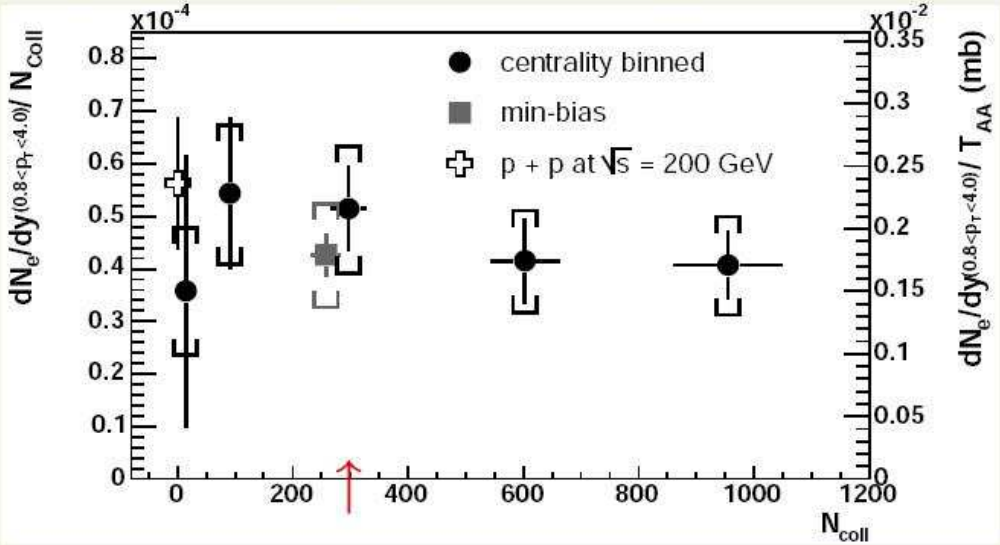
agreement for charm looks better (light $R_{AA} < 0.2$ too low from transport)

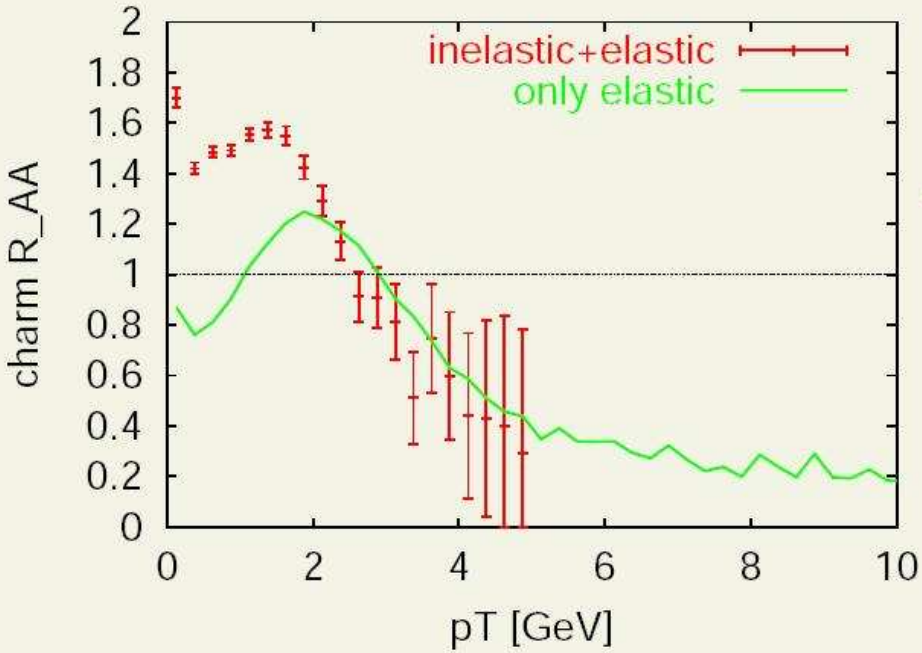
radial flow peak near pT ~ 2 GeV for charm

Open issues

- **secondary (thermal) charm**
- **hadronization (coalescence)**
- **coherence effects**

BUT: data PHENIX, PRL94 '05 - no secondary charm (collision scaling)





← **transport: secondary charm at low-pT**

from gluon fusion $gg \to c\bar{c}$