Heavy Quark and Quarkonia dynamics in the QGP

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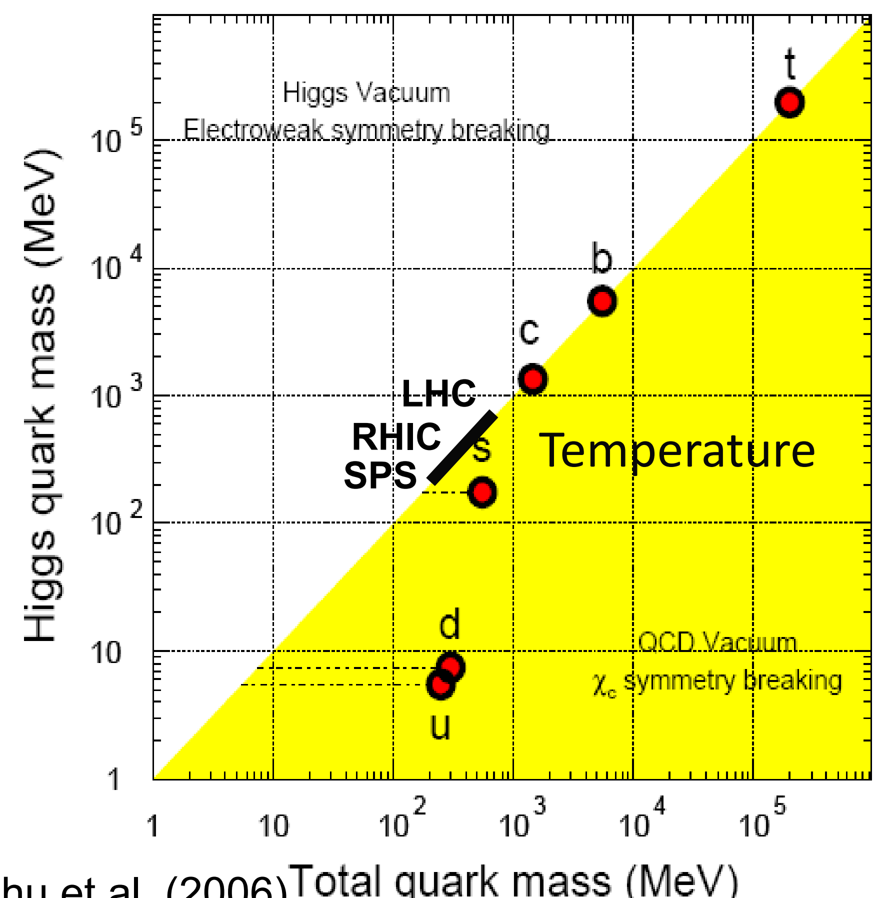


Zhu et al. (2006)

Winter Workshop “Advances in QCD@LHC”- Les Houches, 14-18 February 2011

Specific of Heavy Quarks

Comparing m_{HQ} to Λ_{QCD} and T

- $m_{c,b} >> \Lambda_{QCD}$ produced by pQCD processes (out of equil.)
- $\tau_0 \sim 1/m_{c,b} << \tau_{QGP}$ they go through all the QGP lifetime
- $m_{c,b} >> T_0$ *no thermal production*
- $\tau_{eq} > \tau_{QGP} >> \tau_{q,g}$ carry more information
- $m >> T \rightarrow q^2 << m^2$ transport reduced to Brownian motion
- $q_0 << |\vec{q}|$ Concept of potential V(r) <-> lQCD

QGP structure in the Heavy Quark sector

Outline

Open Heavy Flavor B and D

- ❖ Non perturbative HQ interaction: $Q\bar{q}$ resonances
  - problematic R_{AA}- v_2 relation for jet quenching (+ elastic)
  - Resonant D-like scattering at $T>T_c$
- ❖ Relevance of Hadronization mechanism for HQ

Quarkonia

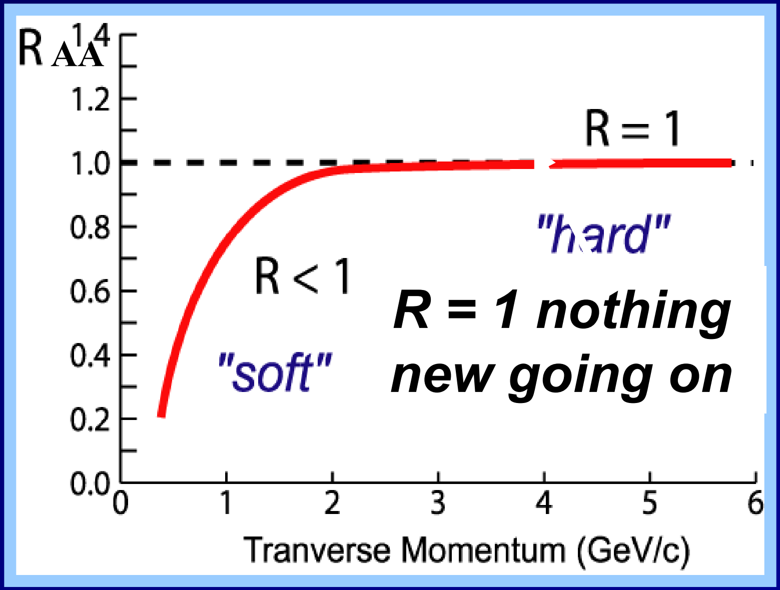
- ❖ Link J/Ψ <–> D with a dominance of regeneration
  - one underlying c distribution

Two Main Observables in HIC

❖ Nuclear Modification factor

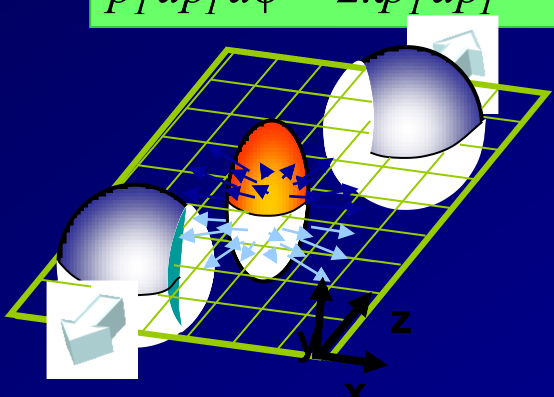
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{NN}/dp_T d\eta}$$

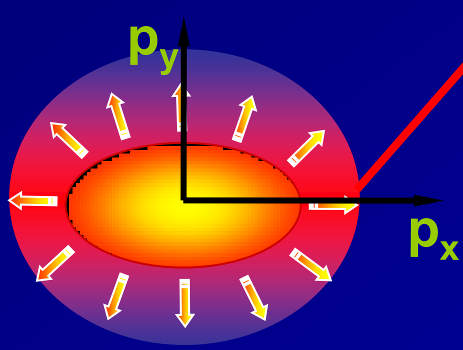
- Modification respect to pp
- Decrease with increasing partonic interaction

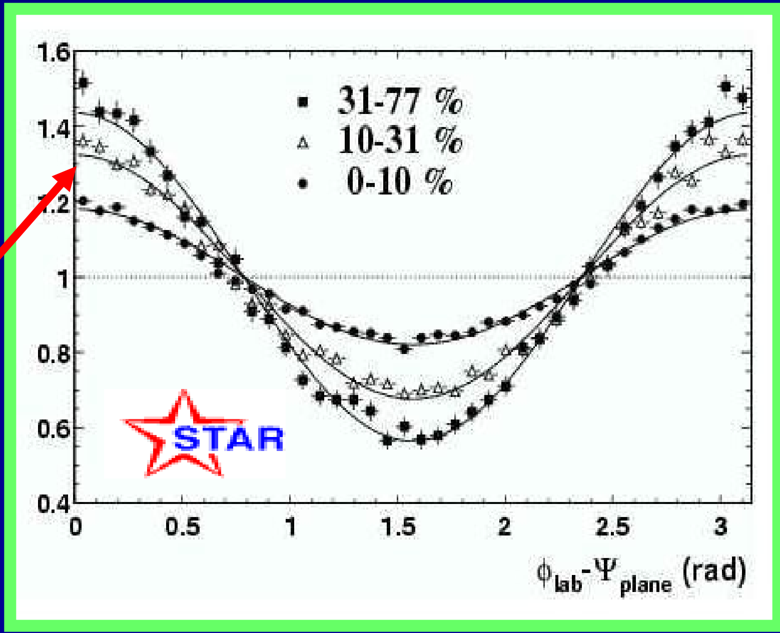


❖ Anisotropy p-space: Elliptic Flow v_2

$$\frac{dN}{p_T dp_T d\varphi} = \frac{dN}{2\pi p_T dp_T}\left[1 + 2v_2\cos(2\varphi) + \ldots\right]$$



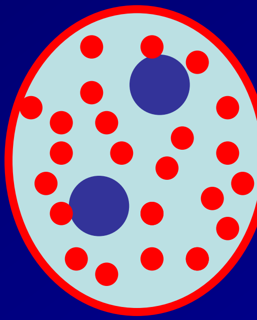




Increases with interaction!

Ideas about Heavy Quarks before RHIC

1) $m_Q >> m_q$ HQ not dragged by the expanding medium:

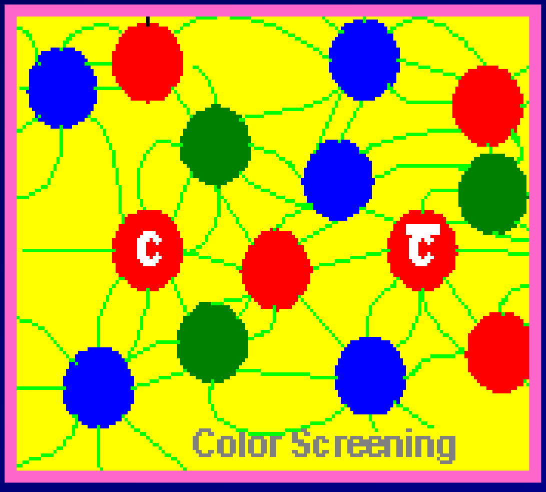


- *spectra close to the pp one*
- *small elliptic flow v_2*

2) $m_Q >> \Lambda_{QCD}$ provide a better test of jet quenching:

- *Color dependence: $R_{AA}(D/h)$*
- *Mass dependence: $R_{AA}(B/D/h)$*

3) $\bar{Q}Q$ Quarkonium dissoved by charge screening: Thermometer

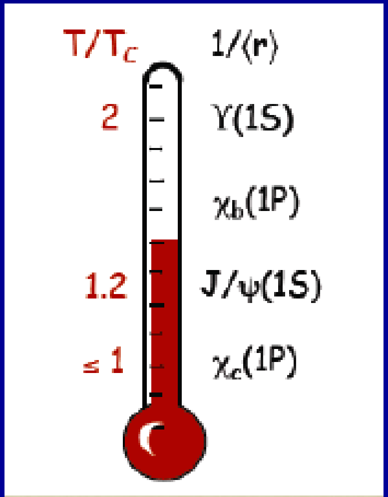


$$V \approx -\alpha_{eff} \frac{e^{-m_D r}}{r}$$

$$r_{Q\bar{Q}} \approx \frac{1}{m_D} \approx \frac{1}{gT}$$

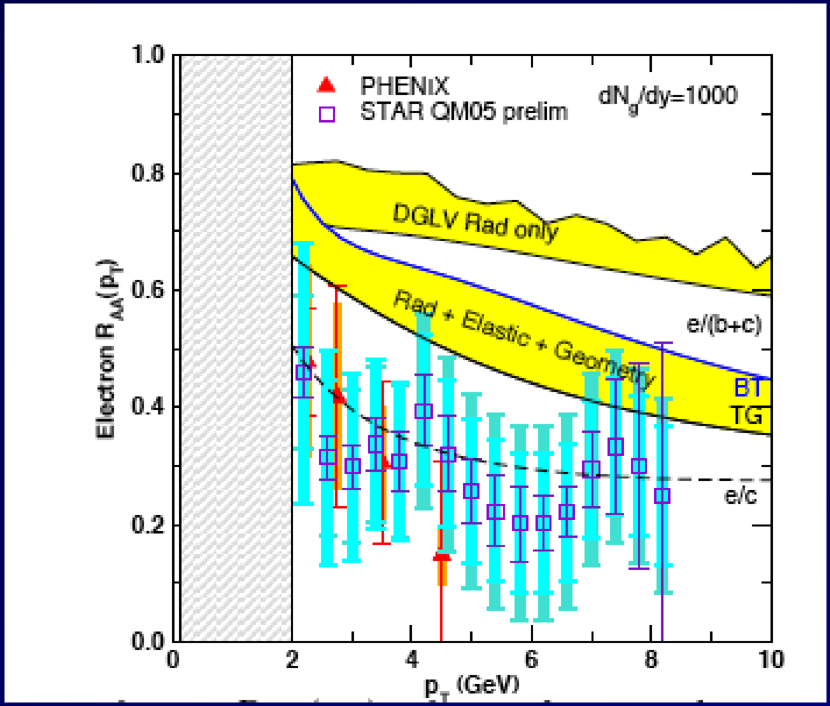
χ_c, J/Ψ, χ_b, Υ, ...

More binding smaller radius
higher temperature



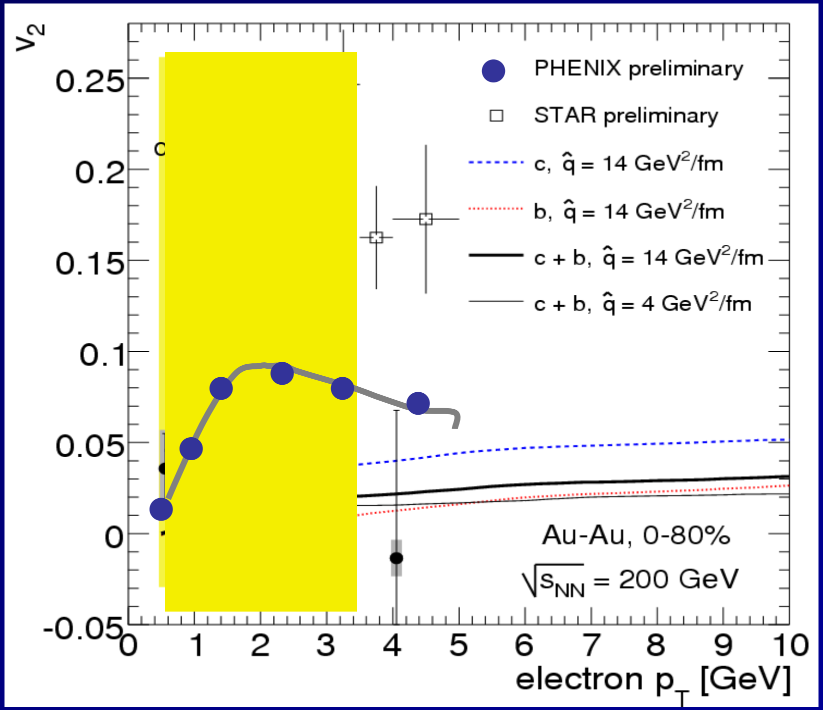
Problems with ideas 1 & 2

Strong suppression



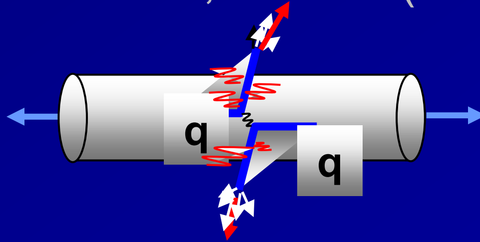
S. Wicks et al. (QM06)

Large elliptic Flow



N. Armesto et al., PLB637(2006)362

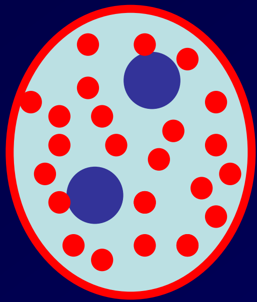
- Radiative energy loss not sufficient
- Charm seems to flow like light quarks



<u>Heavy Quark strongly dragged by interaction with light quarks</u>

pQCD does not work may be the real cross section is a K factor larger

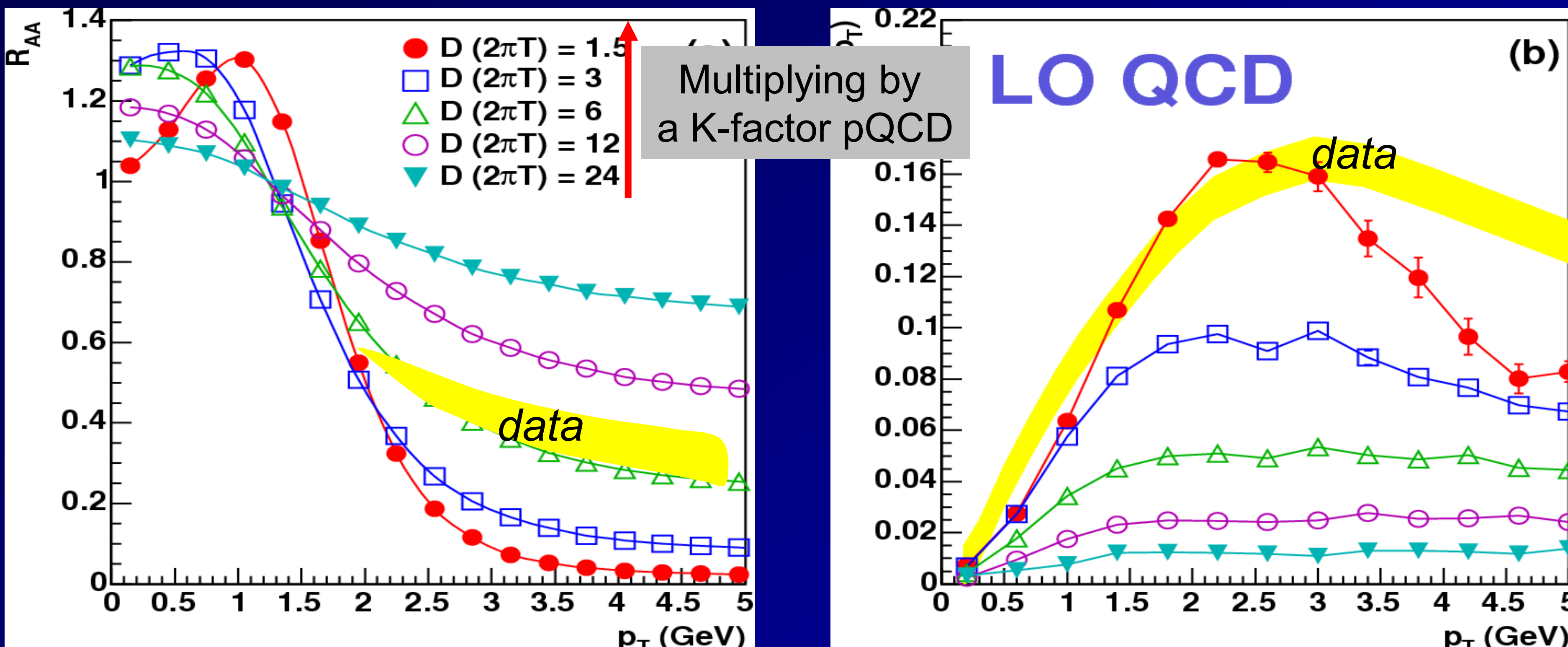
Charm dynamics with upscaled pQCD cross section



Fokker-Plank for charm interaction in a hydro bulk

Diffusion coefficient

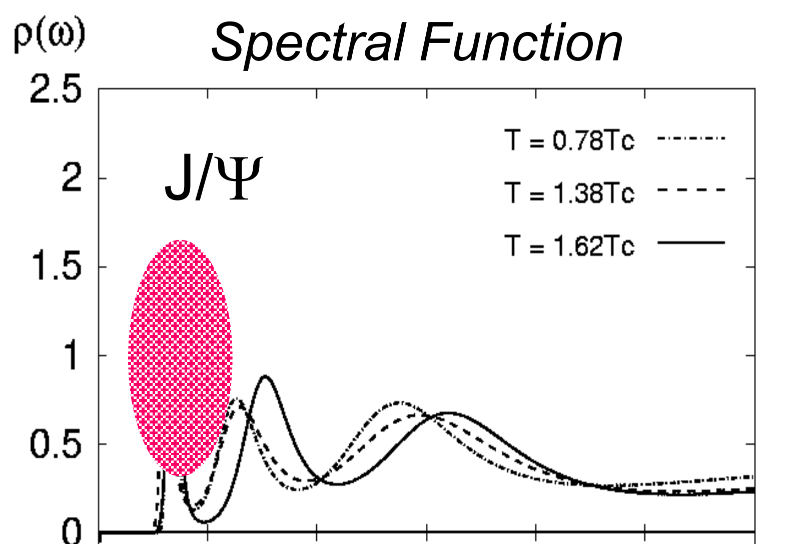
$$D \propto \int d^3k \left| M_{g(q)c}(k,p) \right|^2 k^2$$



Moore & Teaney, PRC71 (2005)

It’s not just a matter of pumping up pQCD cross section: too low R_{AA} or too low v_2

Indications from lQCD

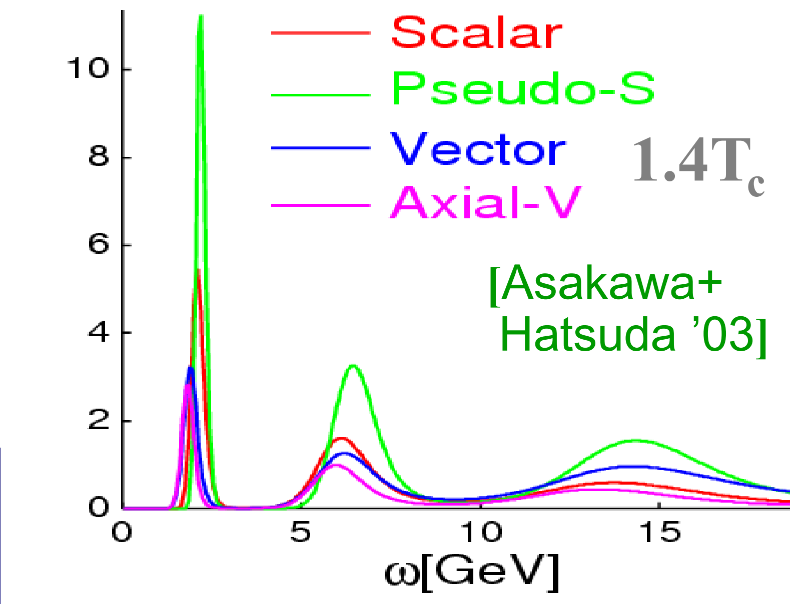


J/ψ (**p** = **0**) disappears around 1.7 T_c

We do not know what is behind ρ(ω):
bound states, resonances, …

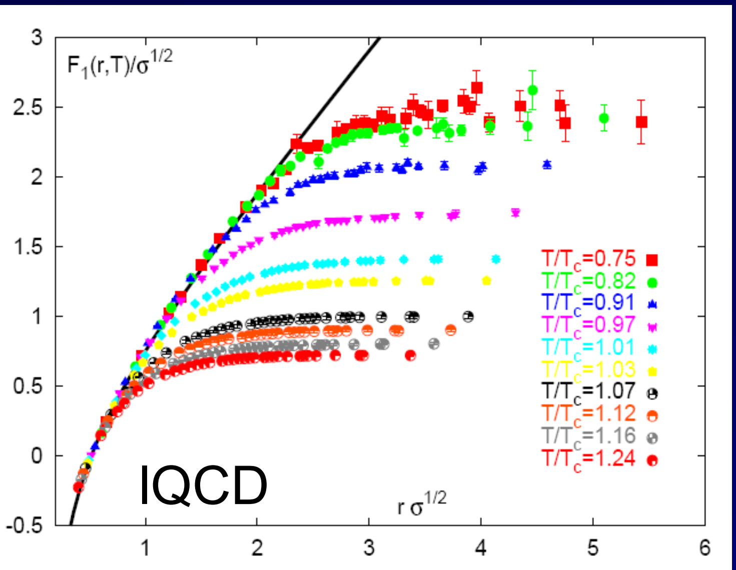
$c\bar{q}, \bar{c}q$ *does not undergo a free scattering,*
but there are remants of confinement!?
Look at the scattering under
a V(r) derived from lQCD

"Light"-Quark Resonances



There can be $Q\bar{q}$ (D-like)
resonant scattering!?

V_{lQCD} gives resonance states!



Kaczmarek et al., PPS 129,560(2004)

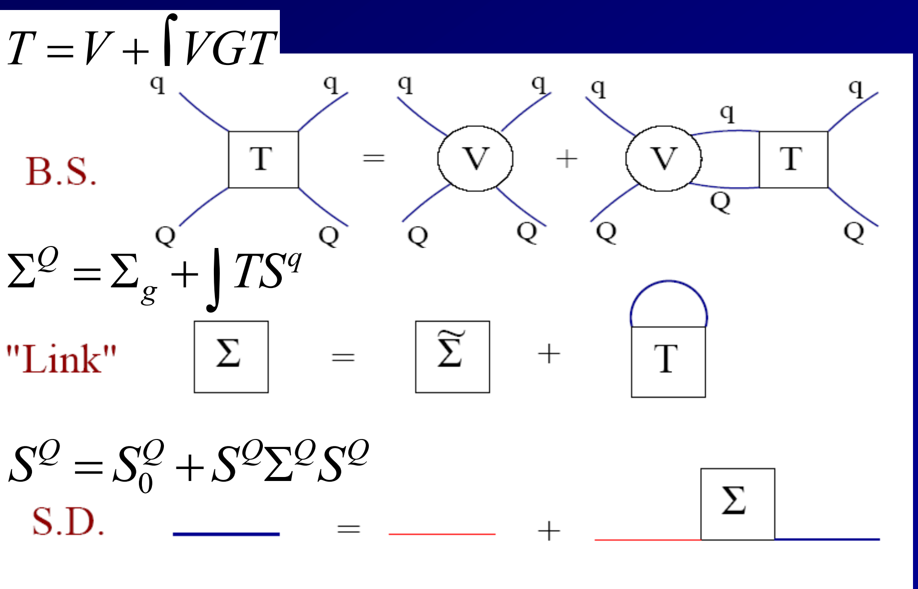
$$U_1 = F_1 - T\frac{dF_1}{dT}$$

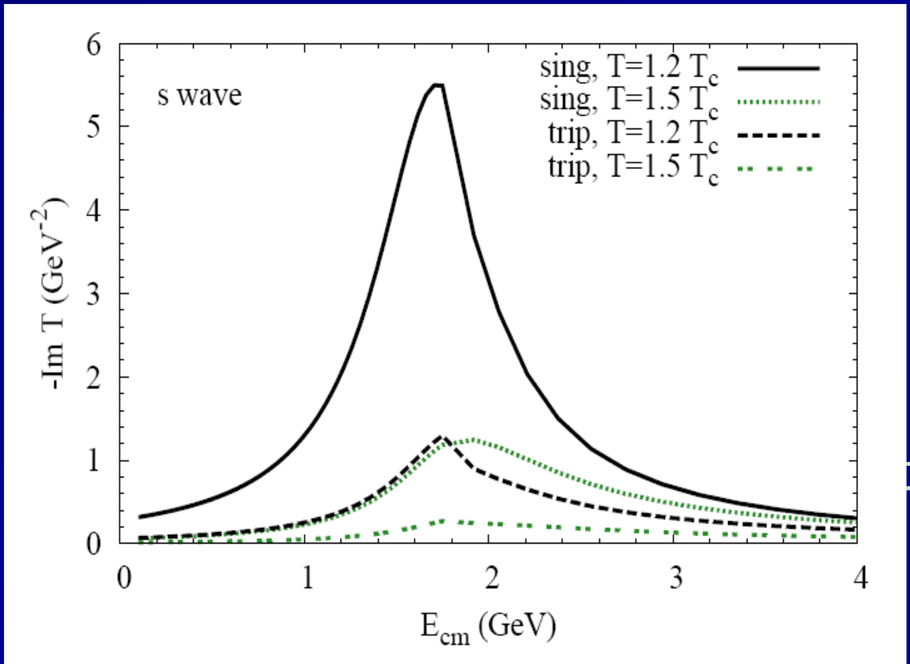
$$V_1(r,T) = U_1(r,T) - U_1(\infty,T)$$

Scattering states included:

Singlet + Octet –triplet -sextet

"Im T" dominated by meson and diquark channel



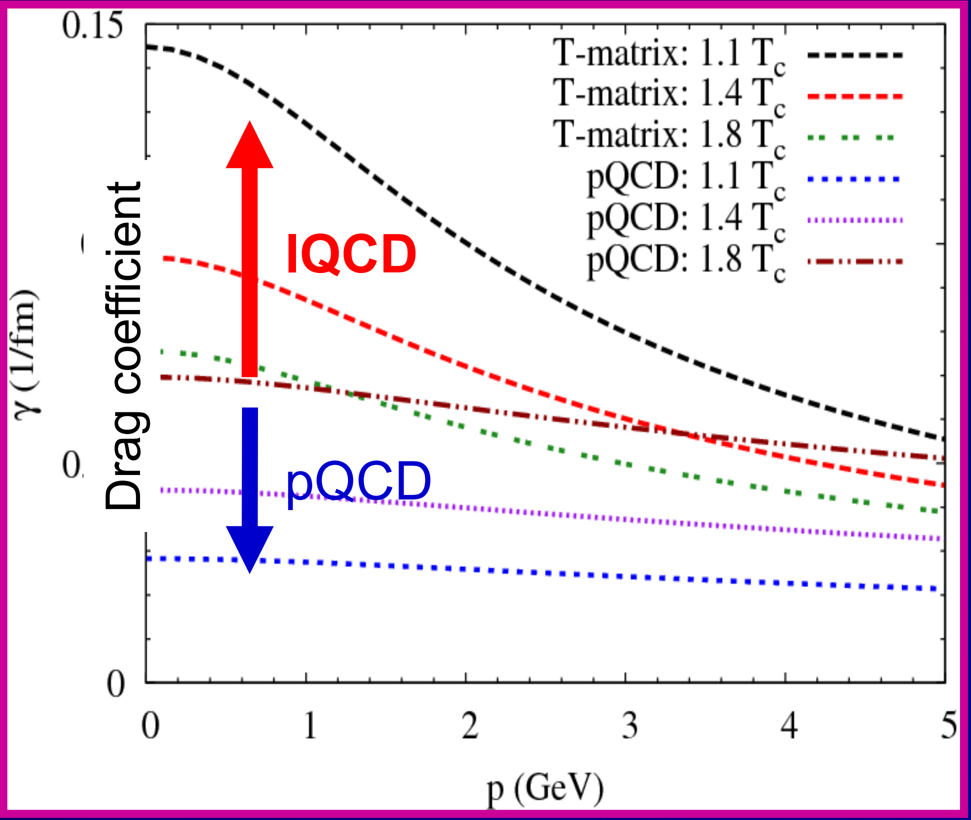


Drag Coefficient from lQCD-V(r)

Opposite T-dependence of γ not a K-factor difference

$$\gamma p = \int d^3k \left| M(k,p) \right|^2 p$$

Drag coefficient
γ= D/mT



ImT increase with temperature compensates for decreasing scatterer density

With lQCD- V(r):

–> one can expect more V_2 with the same R_{AA} because there is a strong interaction just when v_2 is formed.

Does it solve the problem of "too low R_{AA} or too low v_2" ?

The modeling

c,b quarks

HQ scattering in QGP

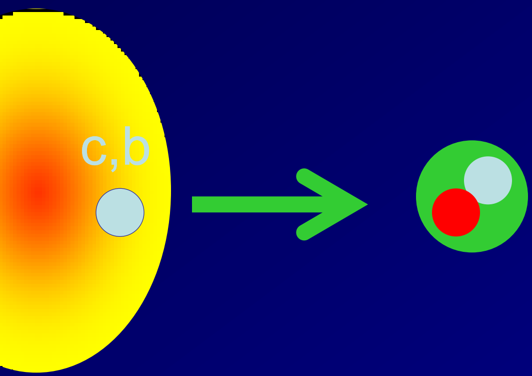
$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D \frac{\partial^2 f_{c,b}}{\partial p^2}$$

$T \ll m_Q$

From scattering matrix $|M|^2$

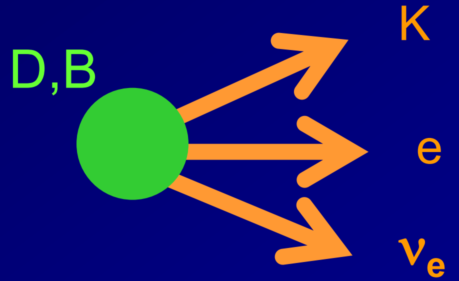
$$\gamma p = \int d^3k |M(k,p)|^2 p$$
$$D = \frac{1}{2} \int d^3k |M(k,p)|^2 p^2$$

- Elastic pQCD
- **T-matrix V(r)-lQCD**



Hadronization

$$\frac{d^3 N_{D,B}}{d^3 P} = C_{D,B} \int_{\Sigma} f_{c,b} \otimes f_{\bar{q}} \otimes \Phi_M + \int_{\Sigma} f_{c,b} \otimes D_{c,b \to D,B}$$

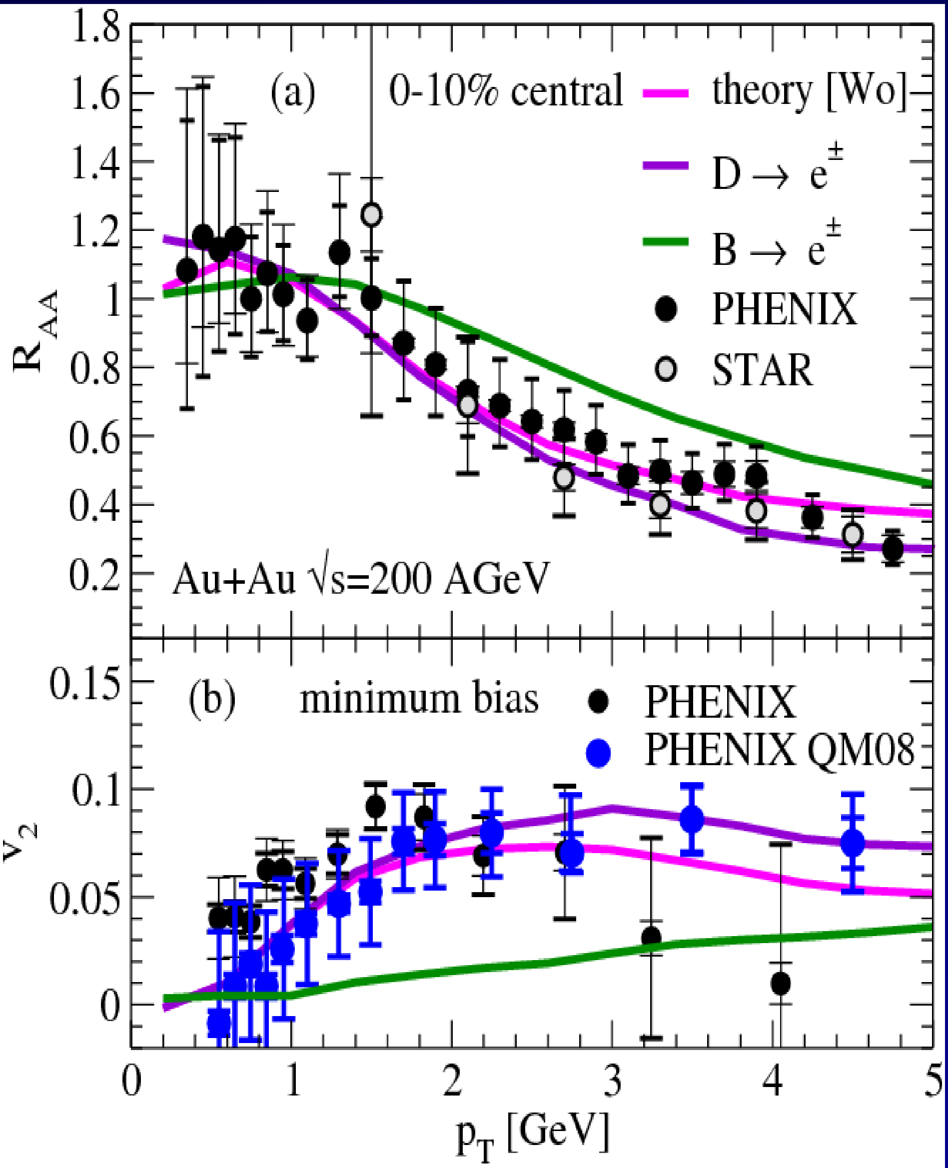


Semileptonic decay

R_{AA} & v_2 of "non-photonic" e

(with B contamination ☹)

T-matrix calculation vs PHENIX data



Hees-Rapp-Greco, PRL100 (2008)

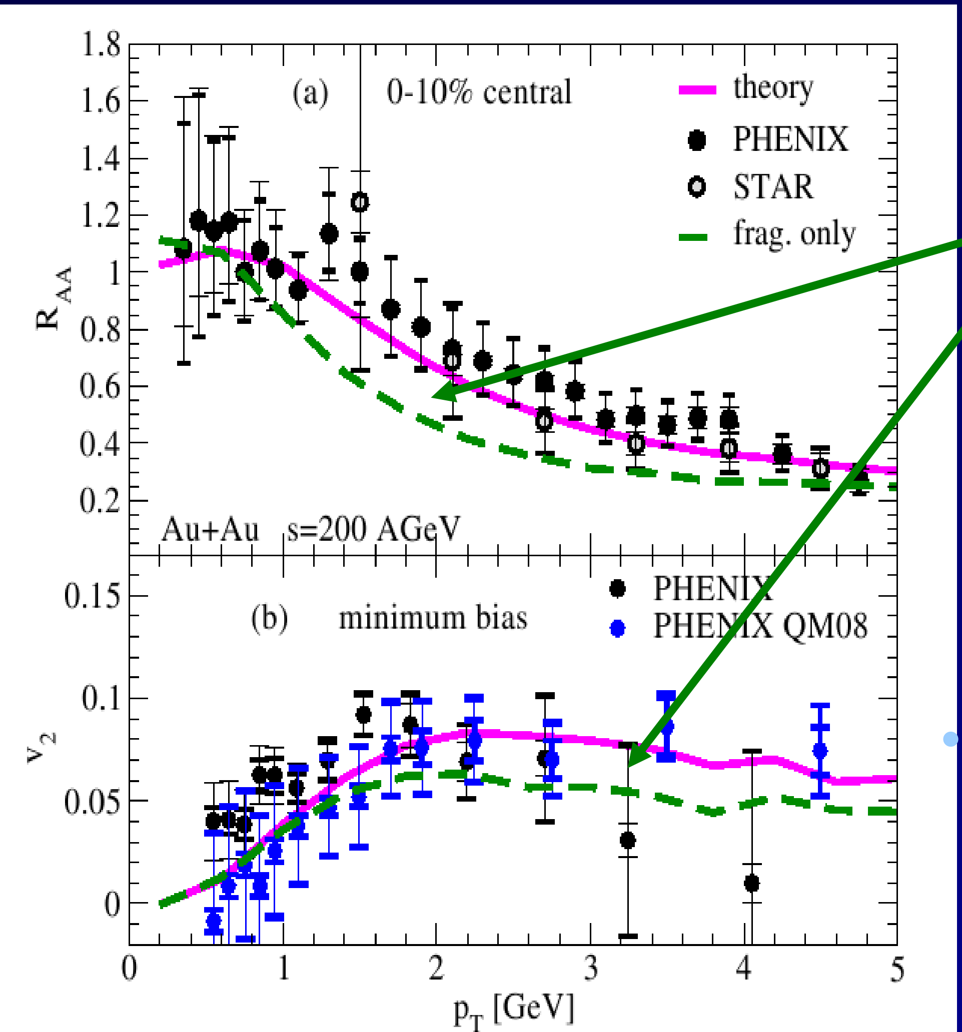
One can get both R_{AA} and v_2 with no free tunable parameters:

<u>Essential at LHC the possibility to disentangle B and D</u>

<u>Uncertainties:</u>

- parametrization of V(r)
- **extraction of V(r) (U vs F)**

Impact of hadronization mechanism



Hees-Mannarelli-Greco-Rapp, PRL100 (2008)

Impact of hadronization

Coalescence increase both R_{AA} and v_2 toward agreement with data

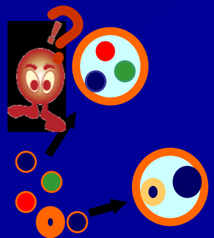
- resonant states naturally merging into a coalescence mechanism

$$\frac{d^3N_{D,B}}{d^3P} = C_{D,B}\int_\Sigma f_{c,b}\otimes f_{\bar{q}}\otimes\Phi_M + \int_\Sigma f_{c,b}\otimes D_{c,b\to D,B}$$

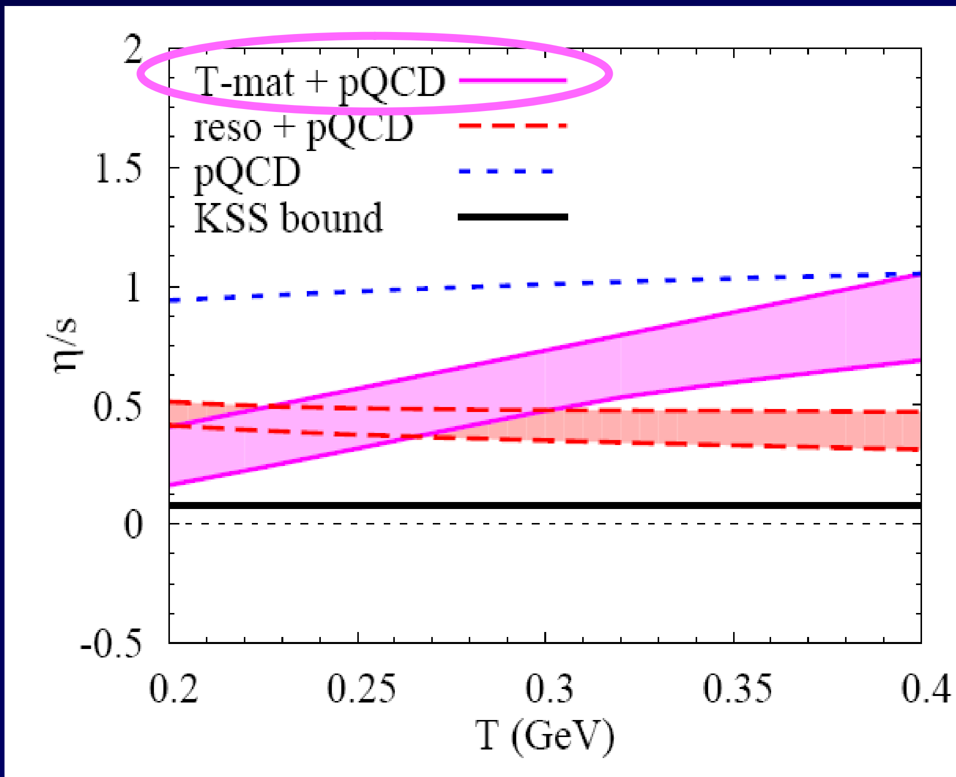
add quark momenta

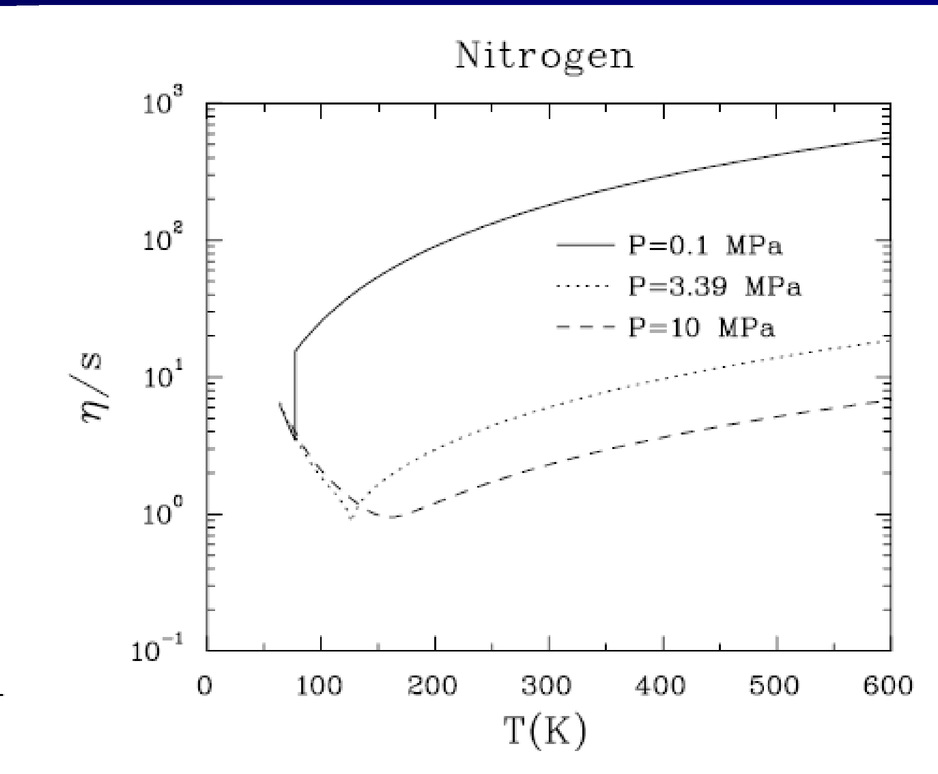
f_q from π, K

Greco,Ko,Levai - PRL90



From the point of view of the shear viscosity





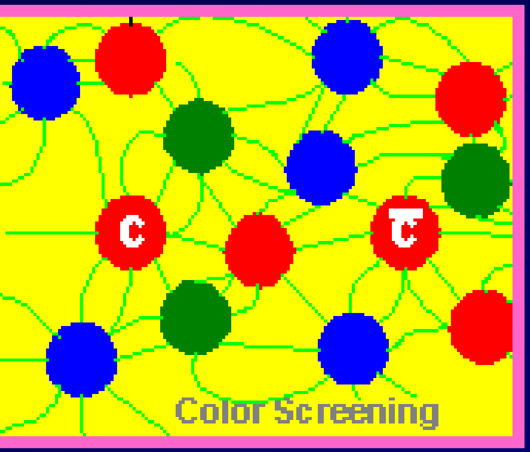
Csernai et al., PRL96(06)

HQ are more sensitive to the details of dynamics ($t_{eq} \sim t_{QGP}$)

It is necessary an interaction that increases as T -> T_c,

i.e. when we approach the phase transition

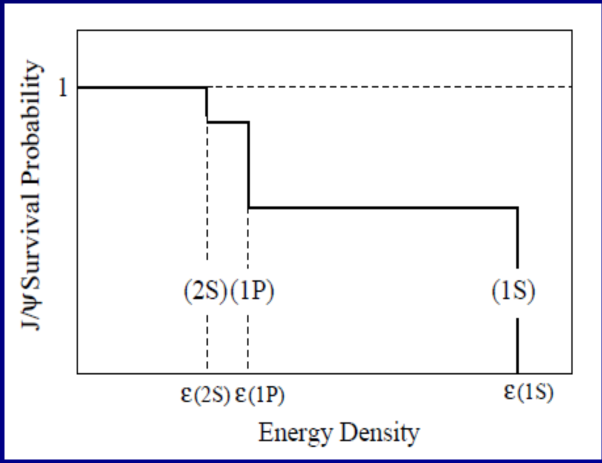
The long standing issue of Quarkonia Suppression



$$r_\Psi \approx \frac{1}{m_D} \approx \frac{1}{gT}$$

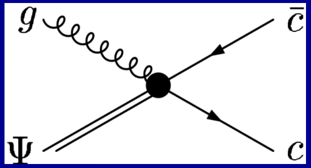
$\Psi = \chi_c, J/\Psi, \chi_b, Y, \ldots$

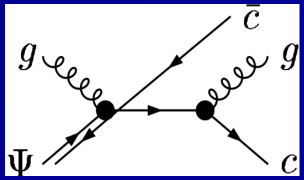
More Quarkonia dissolved with increasing energy density!?



The Quarkonium Yield involves (problems with ideas 3):

- $T_{diss}(\Psi)$ distruction and absence of formation at $T > T_{diss}$
- $\Gamma_{inel}(\Psi)$ formation and destruction ($g\Psi \to c\bar{c}$, $g\Psi \to c\bar{c}g$)





Dynamics of Quarkonia in the QGP

- Boltzmann-like transport or Rate equations:

$$p^\mu \partial_\mu f_\Psi(\vec{r},t;\vec{p}) = -\omega_p \, \Gamma_\Psi(\vec{r},t;\vec{p}) \; f_\Psi(\vec{r},t;\vec{p}) + \omega_p \, \beta_\Psi(\vec{r},t;\vec{p})$$

dissociation regeneration

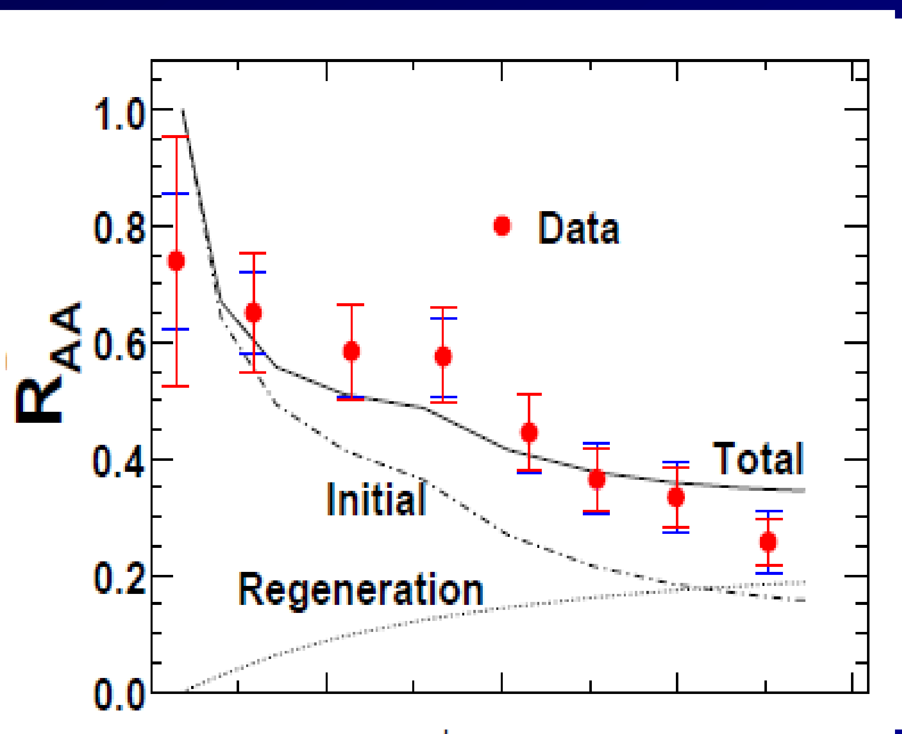
$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left(N_\psi - R N_\psi^{eq}\right)$$

Non-equilibrium effect

$$R = 1 - \exp\left(-\int d\tau / \tau_{eq}(T)\right)$$

- Include in-medium effects in Γ_ψ , β_ψ

which depend on σ^* , $\varepsilon_{bind}(T)$, m*



Rapp/NuXu

At SPS the suppression explained with no regeneration

At RHIC more suppression? No because of regeneration ~ N_c^2

$$dN_{c\bar{c}} / dy \approx 0.1 \quad (SPS)$$
$$dN_{c\bar{c}} / dy \approx 2.5 \quad (RHIC)$$

At RHIC models with no regeneration predicted too much suppression…

<u>except the simple ones</u>

<u>saying J/Ψ survives up T~ 2T_c</u>

Two opposite scenarios & all the intermediate ones

Trying to sinthetize about 100 papers … in 1 slide

1) STRONG BINDING:

T_{diss}~ $2T_c$ negligible suppression of J/Ψ

SPS & RHIC Similar because of the absence of χ_c, Ψ' feedown

2) WEAK BINDING:

T_{diss}~ T_c strong suppression increasing with energy

SPS & RHIC similar because at RHIC

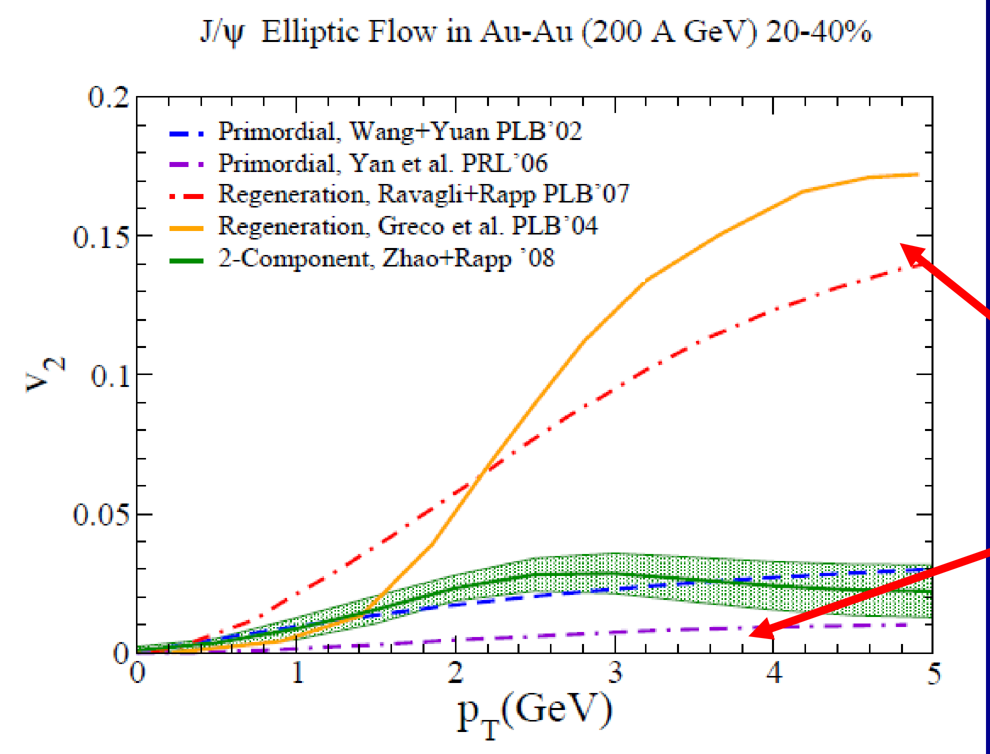
the regeneration compensates (it was a prediction)

Partially posible also du to the uncertainty in the charm yield

The way out is to look at Open Heavy Flavor to see Hidden Heavy Flavor

Quarkonium <–> Heavy-Quark

- We can go beyond the J/Ψ yield and thanks to the strong charm collective dynamics distinguish primordial from $\bar{c}c$ coalescence:
  - softer p_T spectra of J/Ψ <–> dN/dp_T of D
  - Large elliptic flow $v_2(\Psi)$ <–> $v_2(D)$



$V_{2\Psi}$ ALLOWS TO ESTIMATE N_{COAL}/N_{PRIM} FROM THE KNOWLEDGE OF V_{2D}

100% regeneration through $v_{2c}(p_T)$ infereed from D spectrum

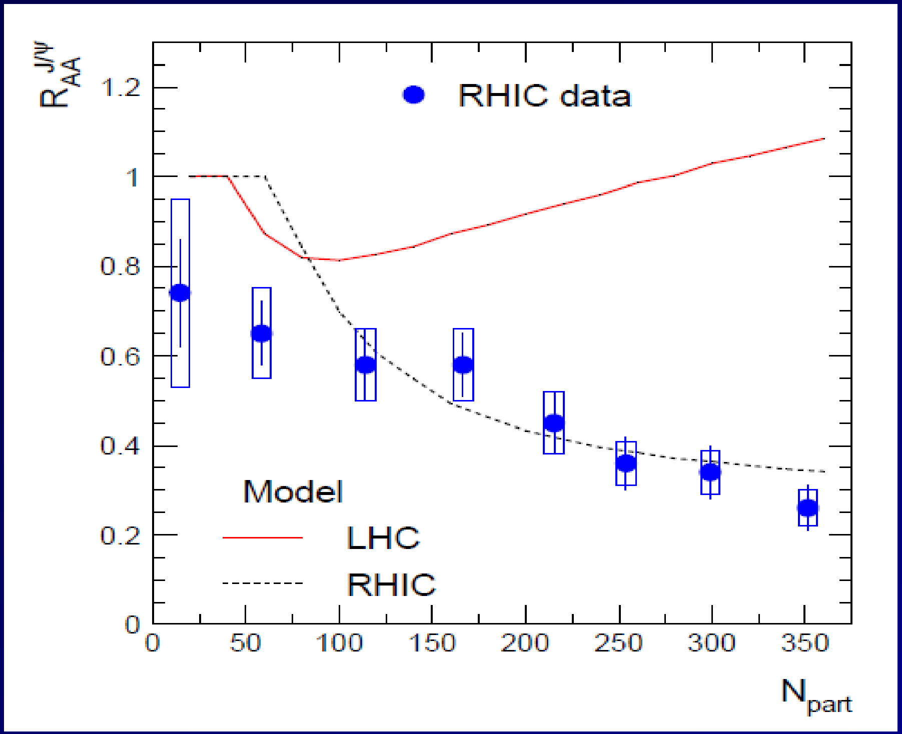
100% primordial J/Ψ

<u>At LHC the regeneration component should dominate</u>

Rapp, Blaschke, Crochet, Prog.Part.Nucl.Phys.65(2010)

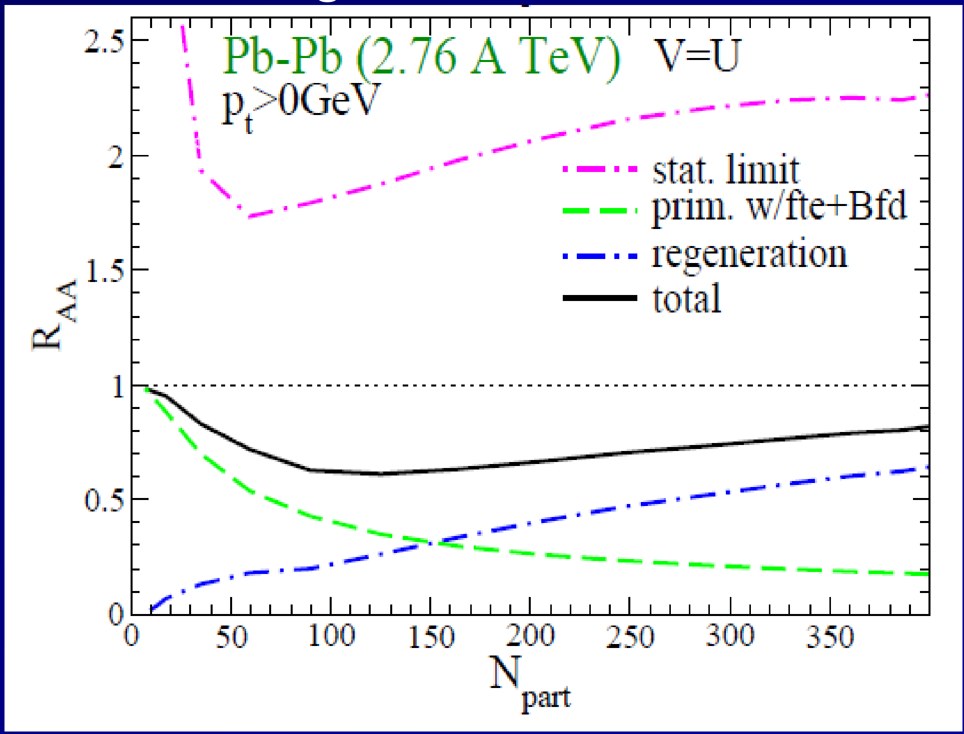
Enhancement of J/Ψ at LHC!?

Pure statistical model at T_c
+ corona effect



A. Andronic, P. B-M., et al., NPA 789 (2007)

Including both suppression and regeneration during all the evolution



Rapp R., X. Zhao, arXiV:1102.2194[hep-ph]

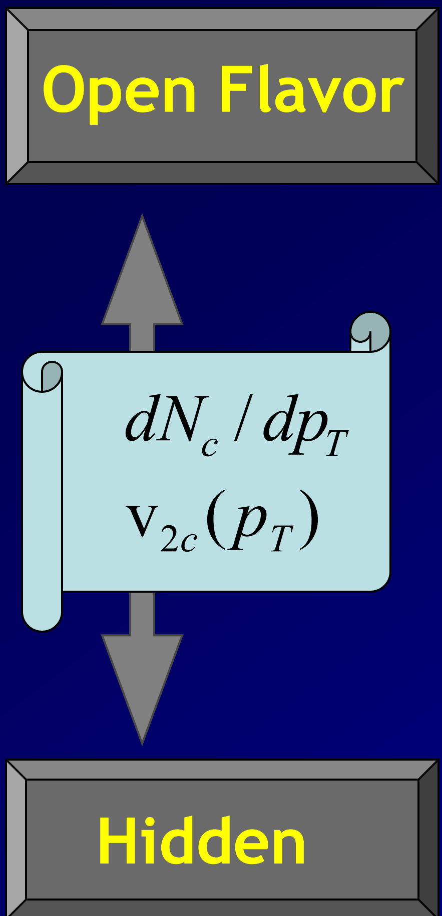
$$dN_{c\bar{c}}/dy \approx 0.1 \quad (SPS)$$

$$dN_{c\bar{c}}/dy \approx 2.5 \quad (RHIC)$$

$$dN_{c\bar{c}}/dy \approx 15-20 \quad (LHC)$$

$$N_{J/\psi} \propto N_{c\bar{c}}^2$$

Summary



- ❖ Heavy quarks entails npQCD dynamics:
  - meson-like and diquark resonant scattering in QGP
  - solves the problematic R_{AA} - v_2 correlation
  - associated to a η/s (T) typical of phase transitions
  - **need to disentangle B and D**

- ❖ Relevance of hadronization via coalescence
  - resonant scattering is a precusor

- ❖ A new era for the understanding of c quarkonia
  - dN/dp_T & v_2 (p_T) for both *open* and *hidden* HF can be linked to one underlying c distribution

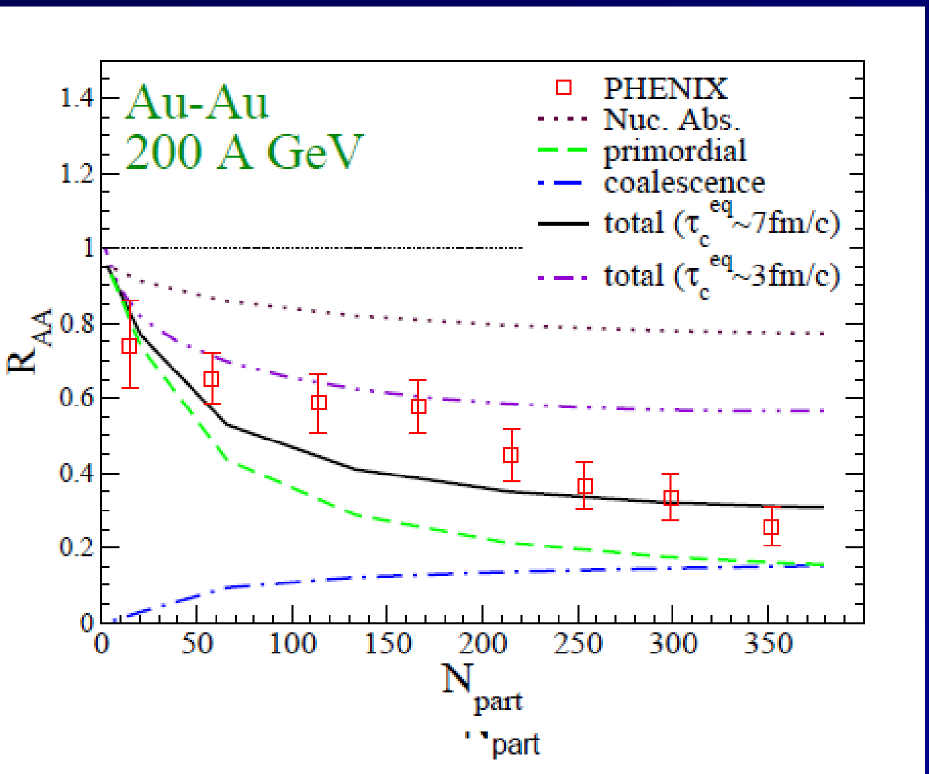
Greco, Ko, Rapp-PLB595(04)

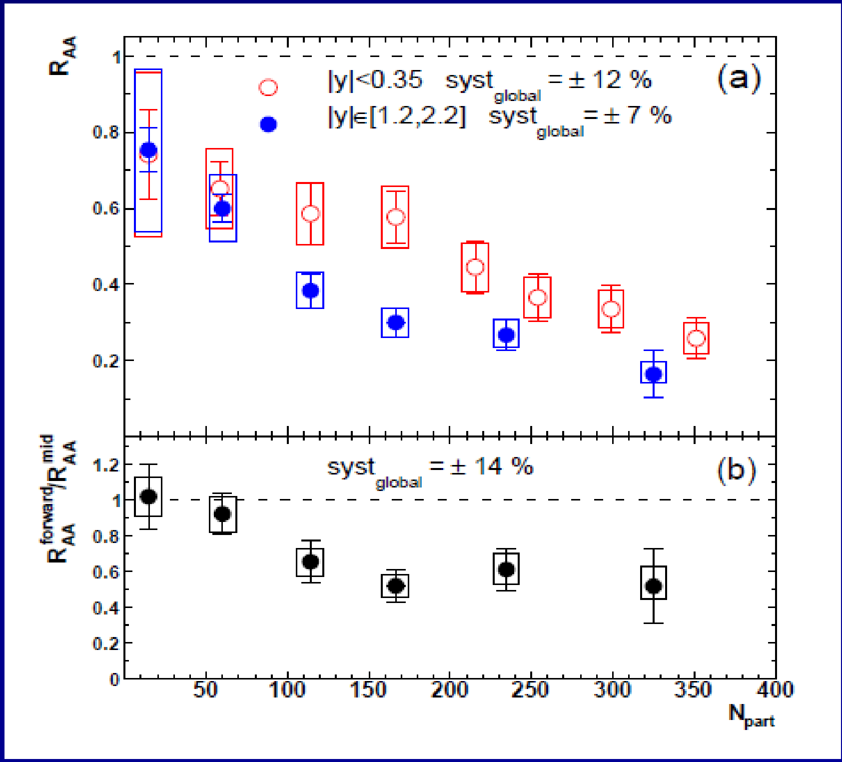
Signatures of a coalescence component!?

At SPS observed a suppression of about a factor 2

$$N_{c\bar{c}} \approx 0.17 \quad (SPS)$$
$$N_{c\bar{c}} \approx 10-20 \quad (RHIC)$$
$$N_{c\bar{c}} \approx \quad (LHC)$$

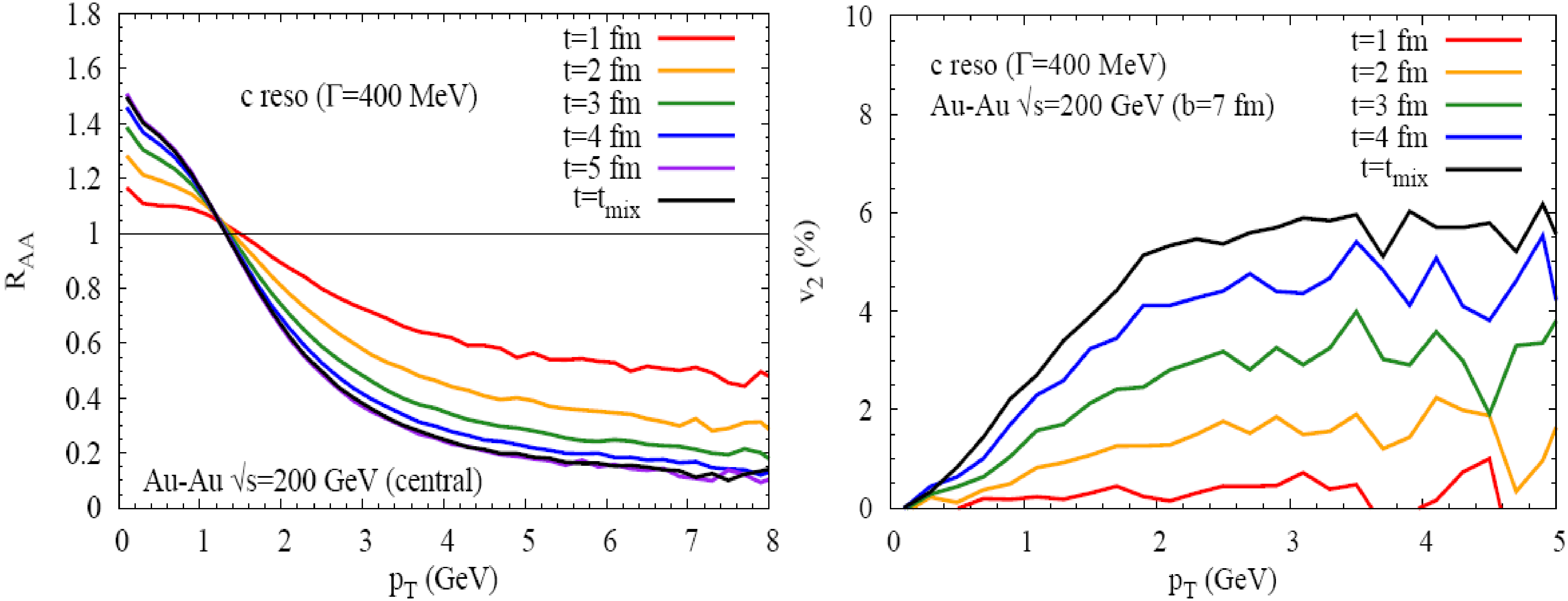
J/Y can come not from the initially produced
Not suppressed but from the abundant charm
can recombine





Less suppression at midrapidity!
Because of more regenration

R_{AA} and v_2 generation with time



RAA generated earlier than v2

V2 grows almost linearly

From RHIC to LHC?

For min. bias.

Hydro bulk dN/dy=1100 (dN/dy=2200 for central)

T_{init}= 3 T_c

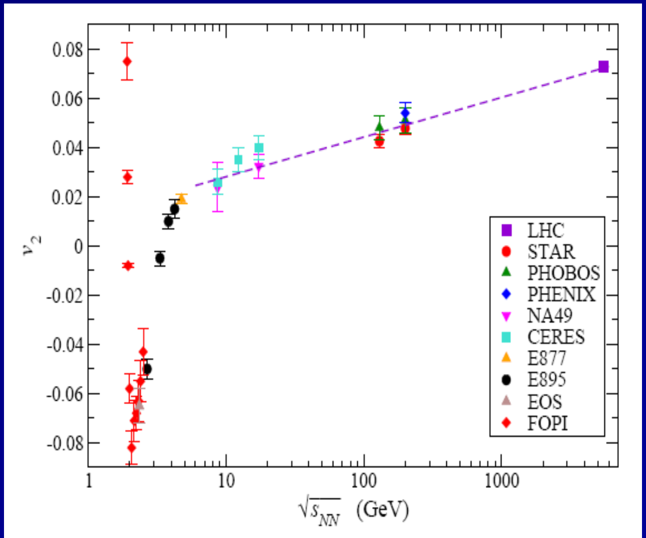
Radial flow β_{max}=0.68

V_{2q} light quark =7.5 % (hydro or numerology)

$v_{2q}(p_T)$ from a cascade [Ferini,Colonna, Di Toro,VG]

dN/d^2p_T of b,c from PYTHIA (ALICE PPR-JPG32)

Resonances off $T>2T_c$

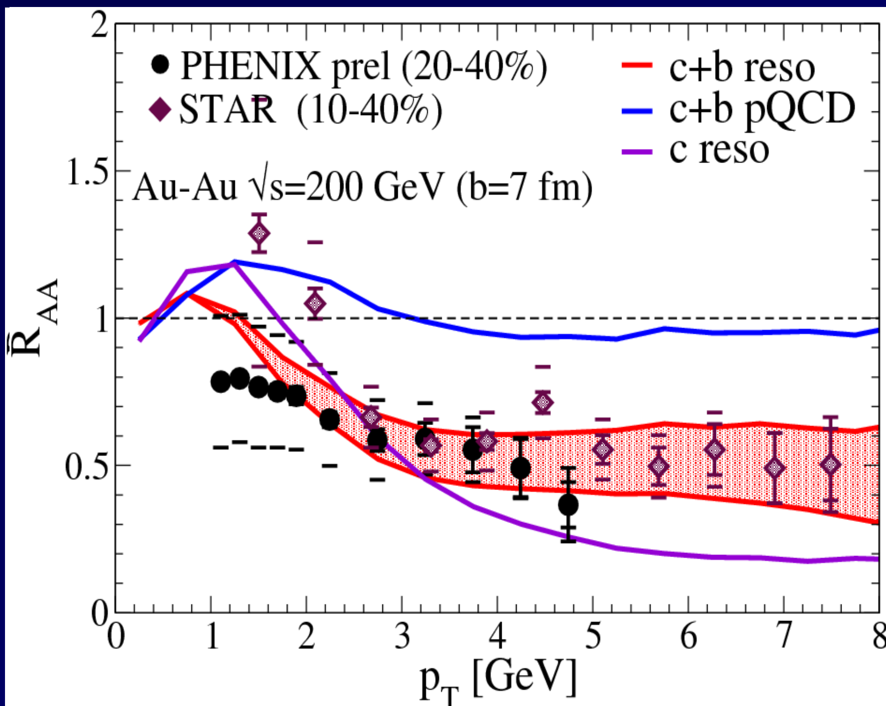


Borghini-Wiedemann,JPG3508)

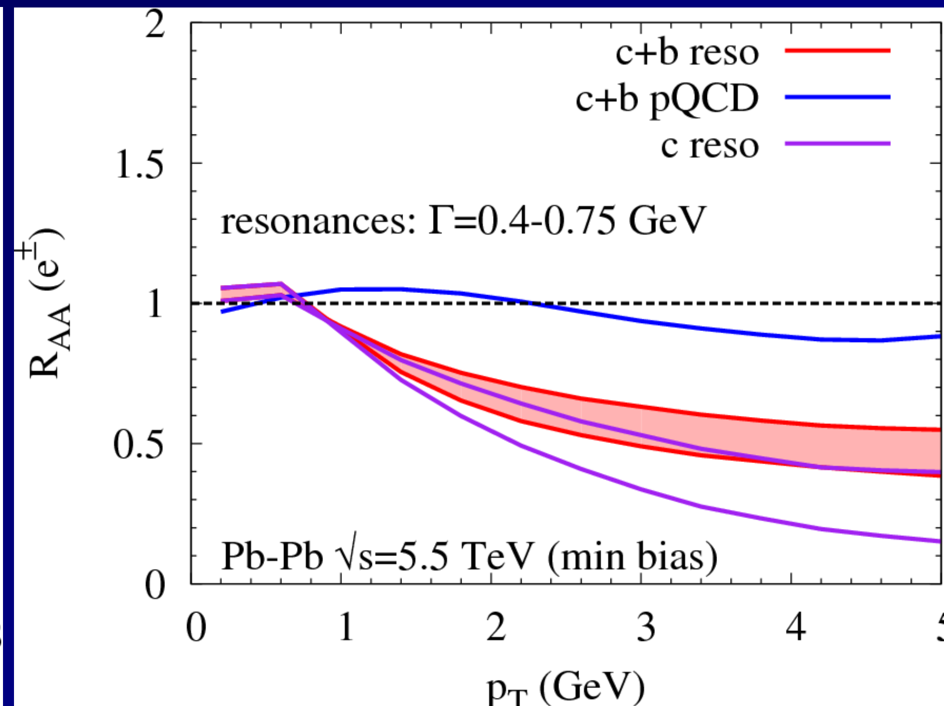
Calculation not done with lQCD, but $\mathcal{L}_{Dcq} = G_D\, \bar{q}\, \frac{(1+\not{v})}{2} \Gamma\, \phi_D\, c + \mathrm{h.c.}$

From RHIC to LHC - R_{AA}

RHIC



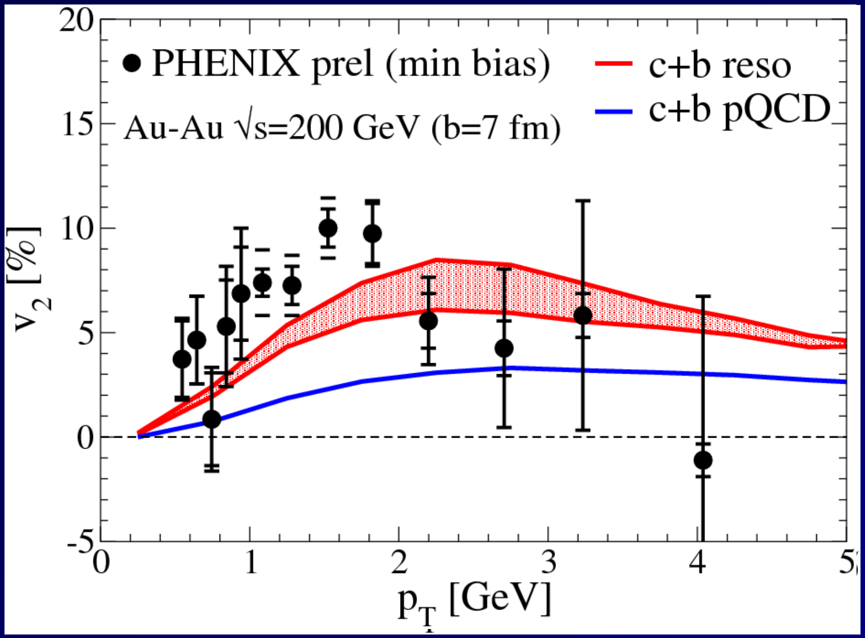
LHC



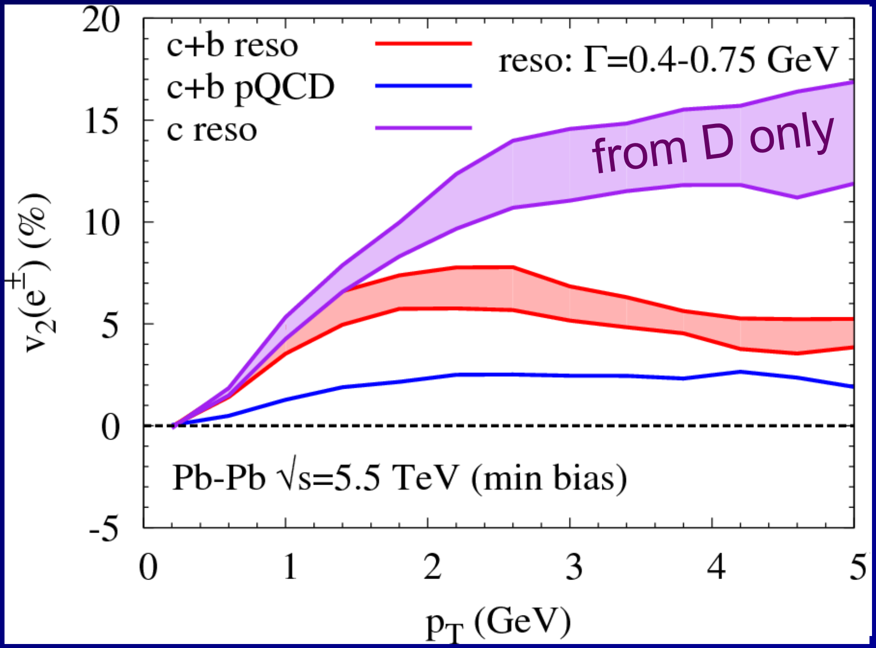
- Suppression: R_{AA} similar at RHIC and LHC!
  - Harder initial spectra at LHC
  - Resonance ineffective (“melted” $T>2T_c$) at early stage!
- **For 3-body scattering opposite behavior !**

From RHIC to LHC – $v_{2\ \mathrm{electrons}}$

RHIC



LHC

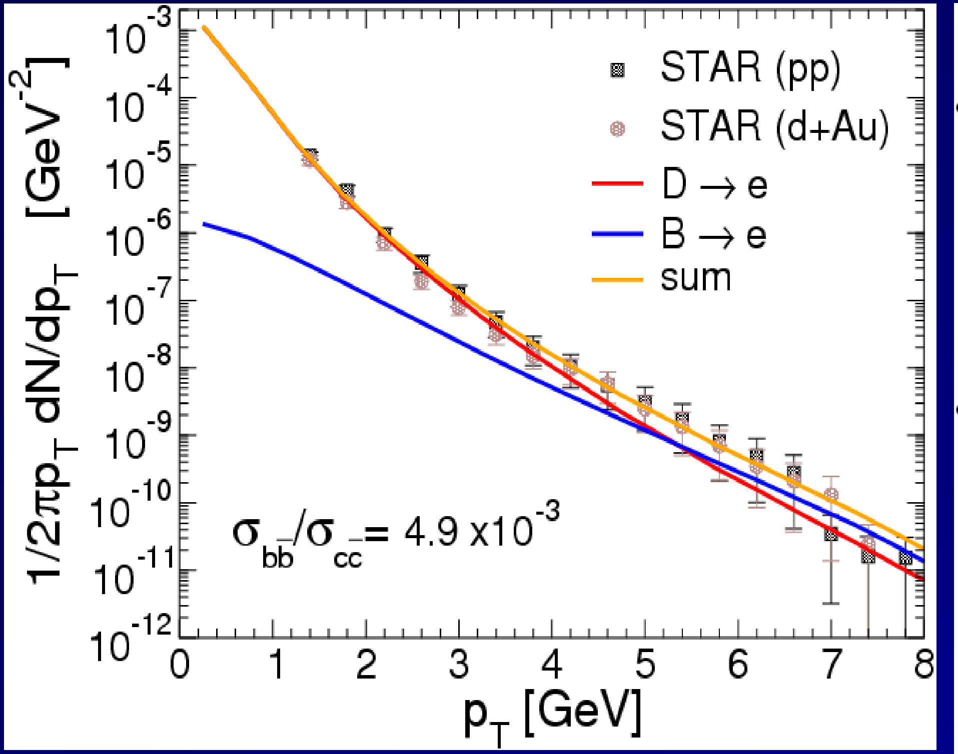


- ❖ v_2 similar at RHIC and LHC!
  - ➢ Resonance effective when anisotropy is reduced
  - ➢ Strong drag with the bulk flow at later stage!
  - ➢ v_2 slightly higher at low p_t
- ❖ **For 3-body scattering opposite behavior !**

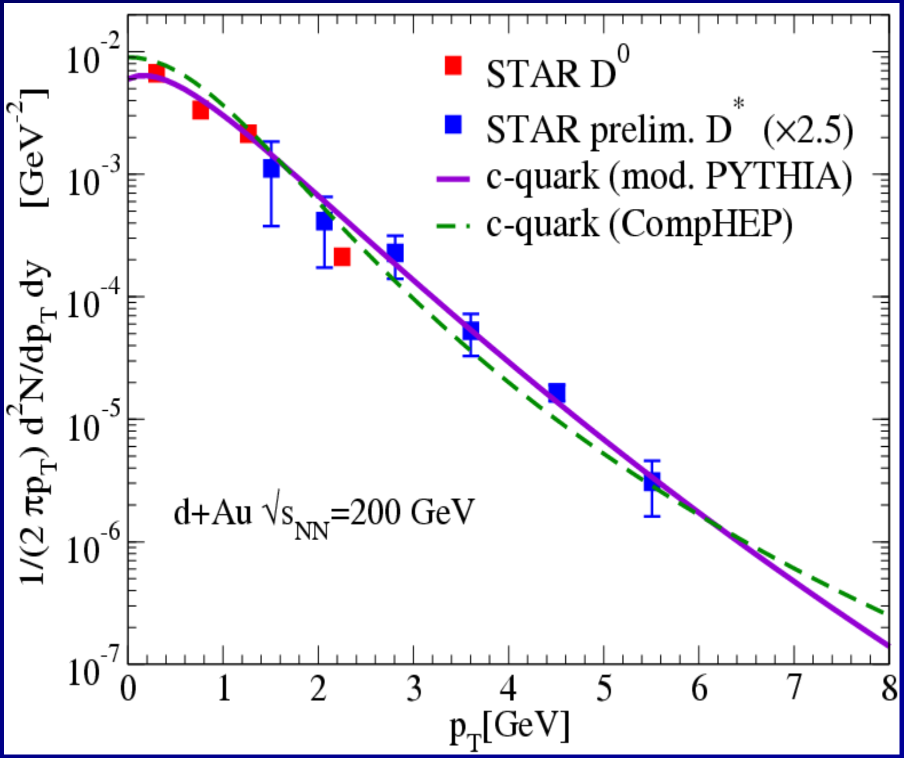
What is measured till now is the single e

$D \rightarrow K l \nu_l$ $B \rightarrow D l \nu_l$ the lepton can be reconstructed

Single-Electron Decays



D-Mesons

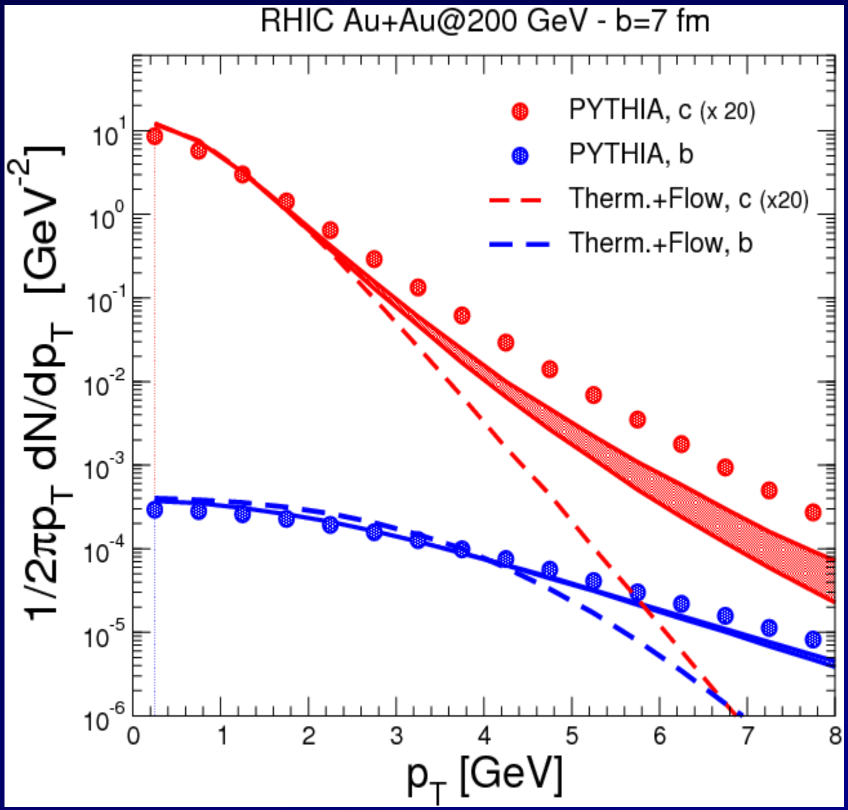


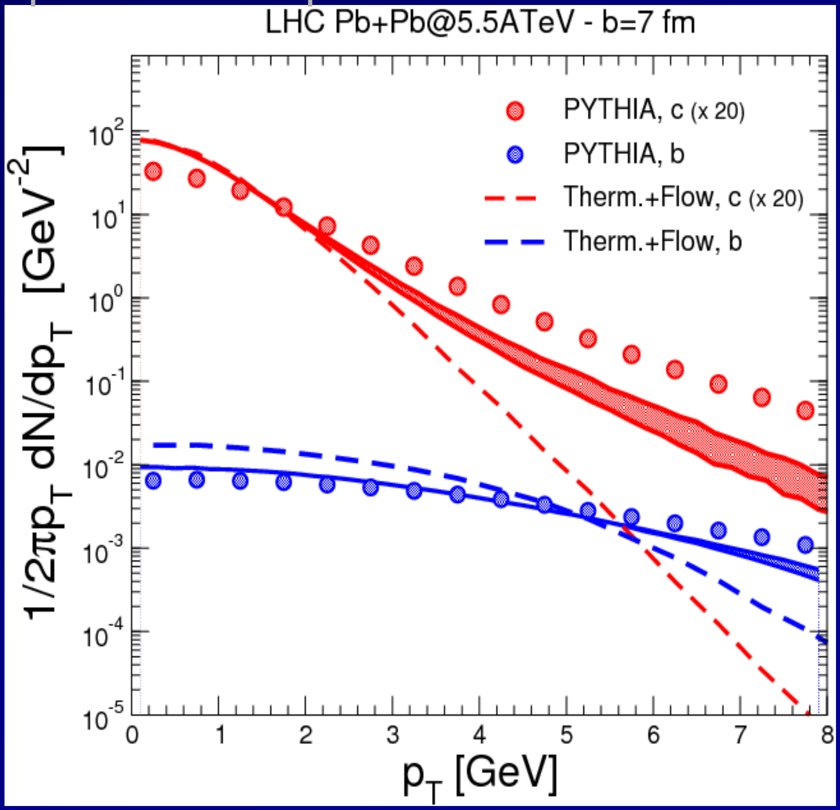
- bottom crossing at *5GeV* !?
- strategy: fix charm with D-mesons, adjust bottom in $e^{\pm}$-spectra

b/c similar to pQCD Cacciari, Nason, Vogt, PRL95(2005)

Charm Thermalization

Shadowing not included yet!
Spectra same parameter of PPR-ALICE





- LHC spectra considerably harder !
  - At Tc charm nearly thermalized
  - Resonances switched-off at 2 Tc

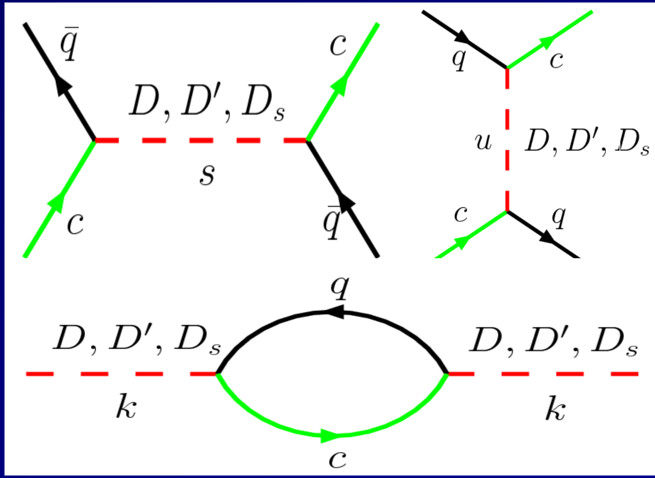
Open-Charm Resonances in QGP

As first test we used an effective model:

$$\mathcal{L}_{Dcq} = G_D\, \bar{q}\, \frac{(1+\not{v})}{2}\, \Gamma\, \phi_D\, c + \text{h.c.}$$

$$\Gamma = 1, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu$$

2 parameters: G_D , m_D

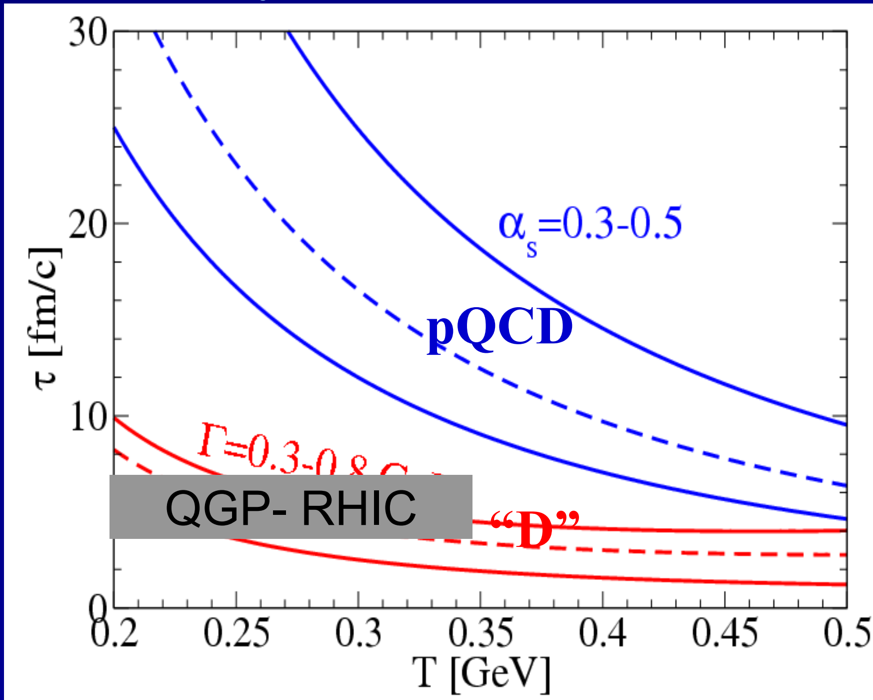


- **Assuming Φ field pseudo/scalar + axial/vector "*D*-like" mesons [chiral + HQ(spin) symmetry]**
- **cross section ISOTROPIC**

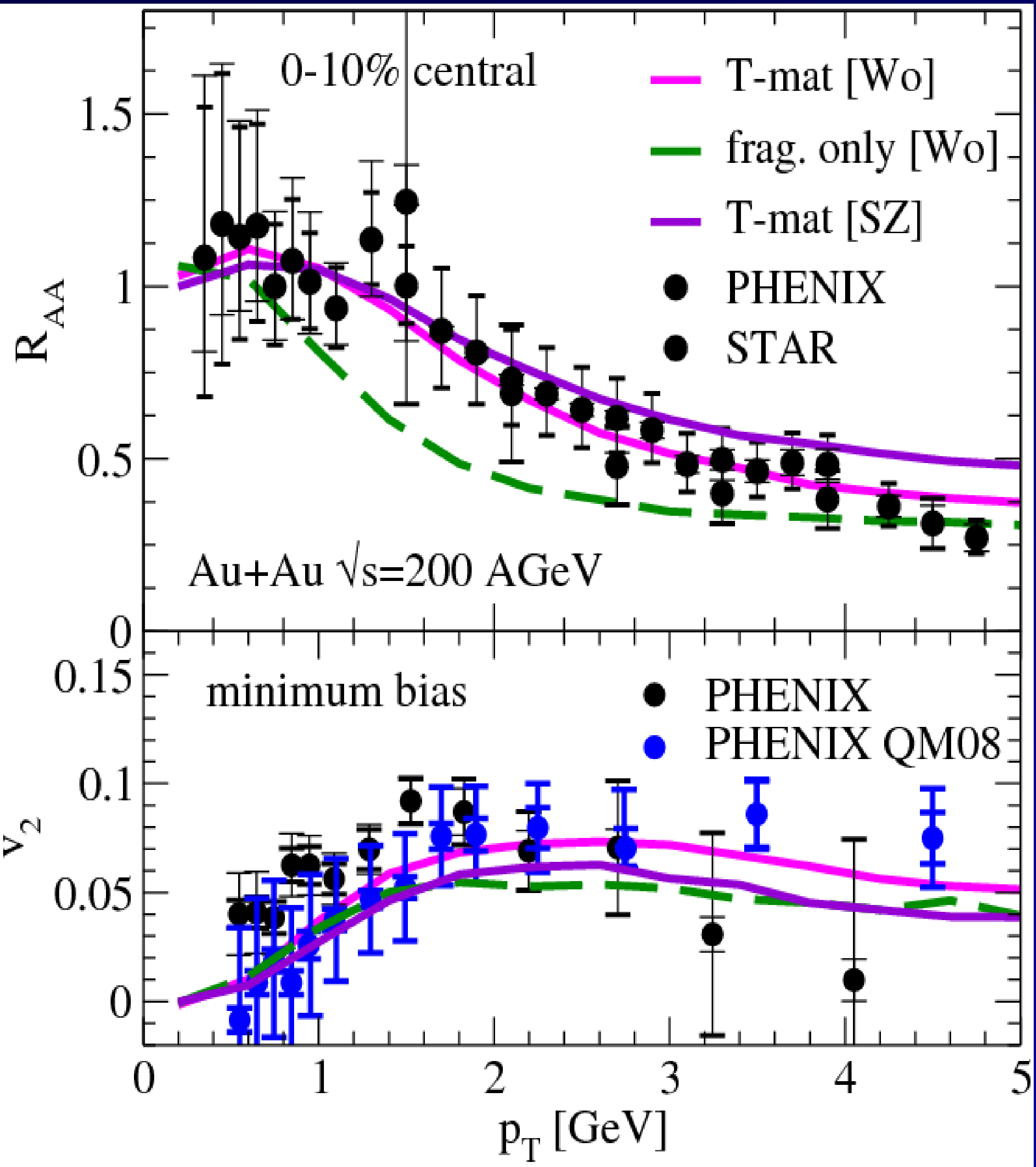
❖ t_{eq} down to 5 fm/c at RHIC !

Ok, but can it describe R_{AA} and v_2?

Equilibration time



Uncertainty from potential parametrization



[Wo] quenched lQCD

Wong, PRC72(05)

[SZ] unquenched lQCD

Shuryak-Zahed, PRD70

Moderate dependence on parametrization!

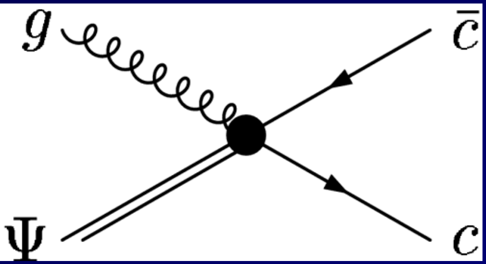
In medium scattering

Dynamical dissociation

(QQ) + g ⟶ Q + Q + X

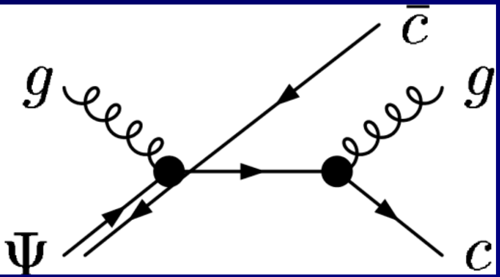
$$(\tau_\Psi)^{-1} = \sum_{i=q,g} \int \frac{d^3k}{(2\pi)^3} f^i(k_0,T)\,\sigma_\Psi^{QG}\, v_{rel}$$

- ✓ Quarkonia dissociated also below T_{Diss}
- ✓ Lifetime of the QGP is essential



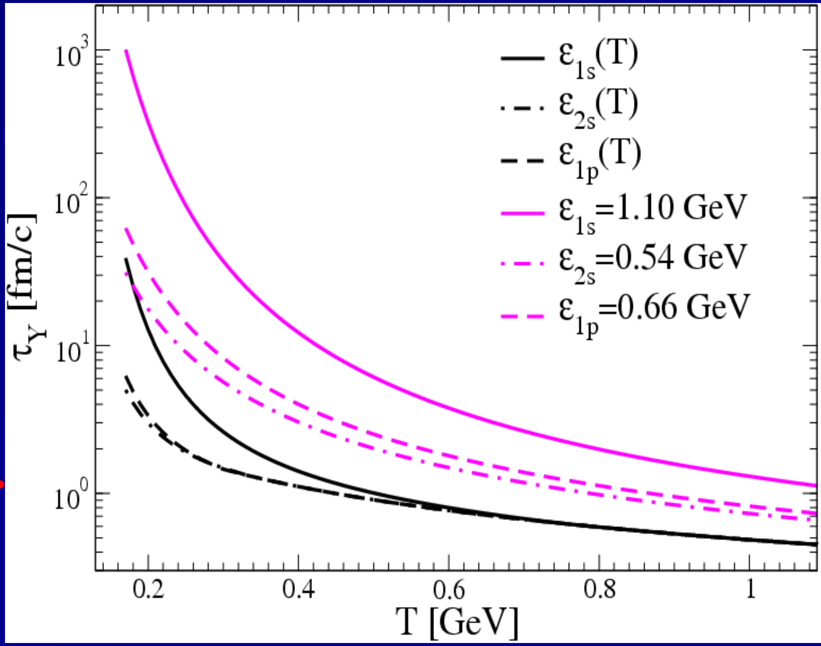
gluon-dissociation inefficient for $m_\psi \approx 2\, m_c$ *

"new" mechanism



"quasifree" dissoc.

[Grandchamp '01]

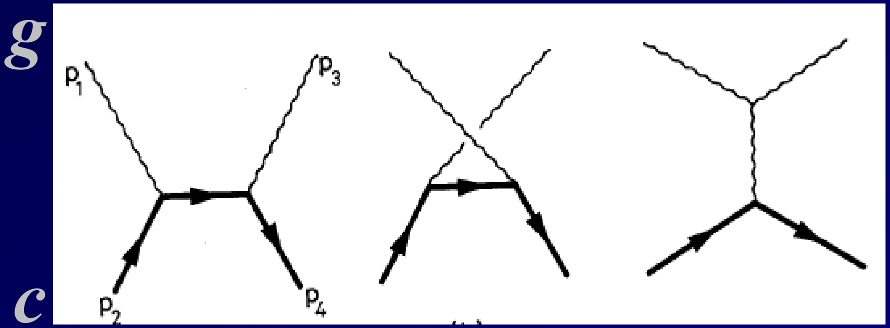


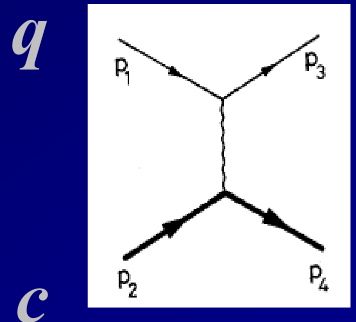
Calculation of Collisional energy loss

Transport Equation in quasi-particle approx.

$$\left[\frac{\partial}{\partial t}+\frac{\vec{p}}{E}\frac{\partial}{\partial \vec{x}}\right]f(x,p,t)=\int d^3k\left[w(p+k)f(p+k)-w(p,k)f(p)\right]$$

w(p,k) directed linked to the cross section





[Svetitsky '88,
Braaten '91,
Mustafa etal '98,
Molnar etal '04
Zhang etal. '04,
Teaney+Moore'04]

- dominated by *t*-channel gluon-ex in ***gc→gc***:

Expanding w(p,k) around p~k :
dominated by soft scattering:
(resonable for heavy quarks)

$$\frac{\partial f}{\partial t}=\gamma\frac{\partial(pf)}{\partial p}+D\frac{\partial^2 f}{\partial p^2}$$

Fokker-Plank equation
Background not affected
by heavy quarks

$$\gamma p=\int d^3k\, w(k,p)\, k$$ scatt. rate

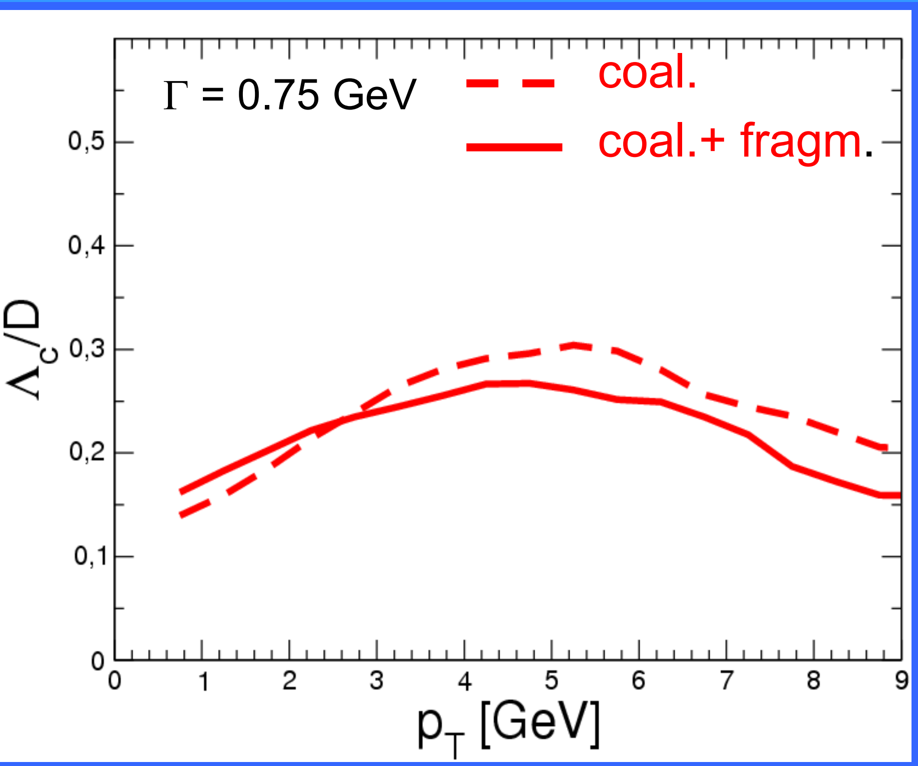
$$D=\frac{1}{2}\int d^3k\, w(k,p)\, k^2$$ diff. const.

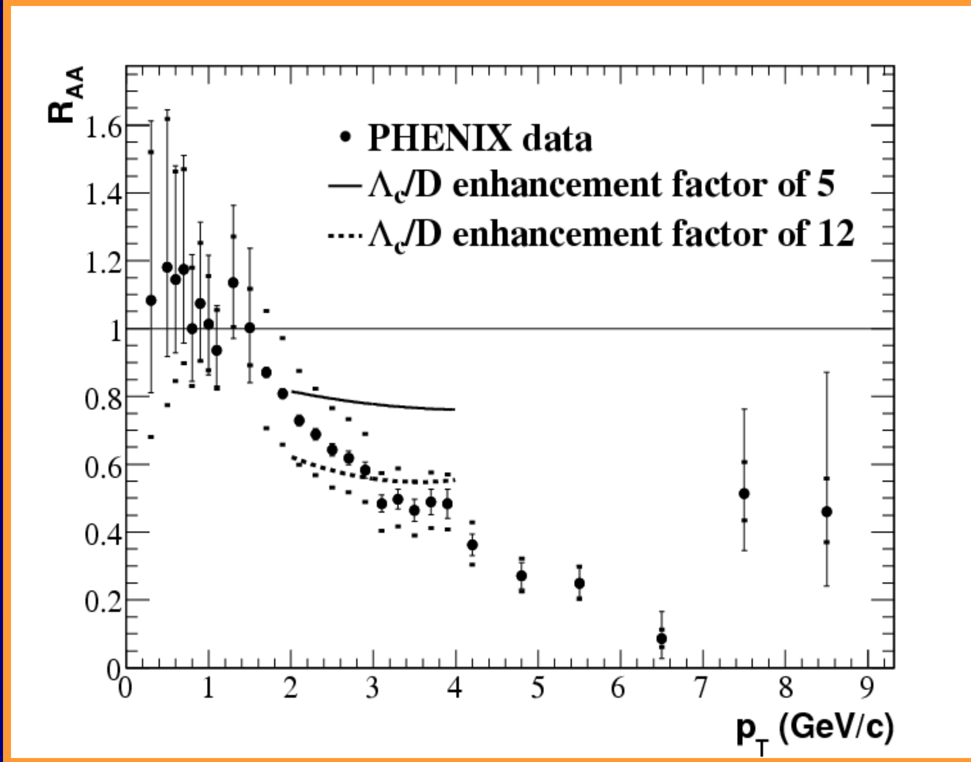
Drag & Diffusion p-indipendent

$$-\frac{dE}{dx}=\gamma p$$

Baryon contamination due to coalescence … !?

P. Soresen, nucl-ex/0701048
G. Martinez-Garcia et al., hep-ph/0702035





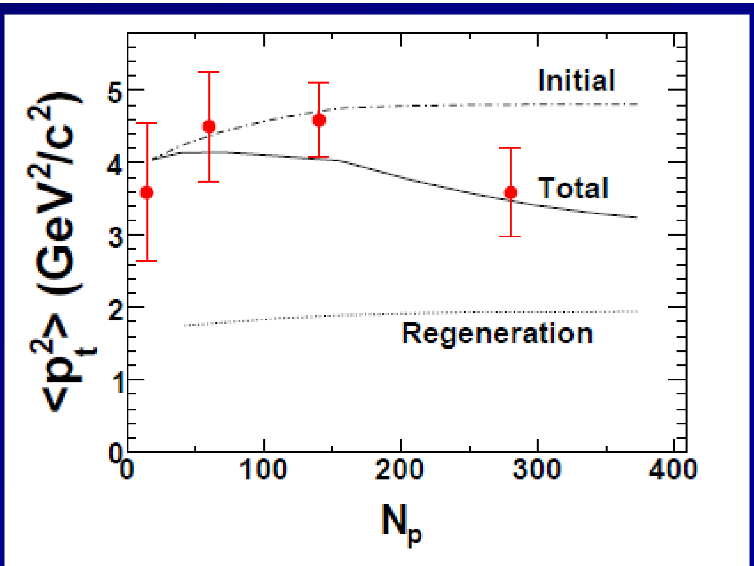
- Contamination of Lc in single e : enhance v_{2e}: $v_{2\Lambda c} > v_{2D}$
- enahencement modest + BRe 4.5%

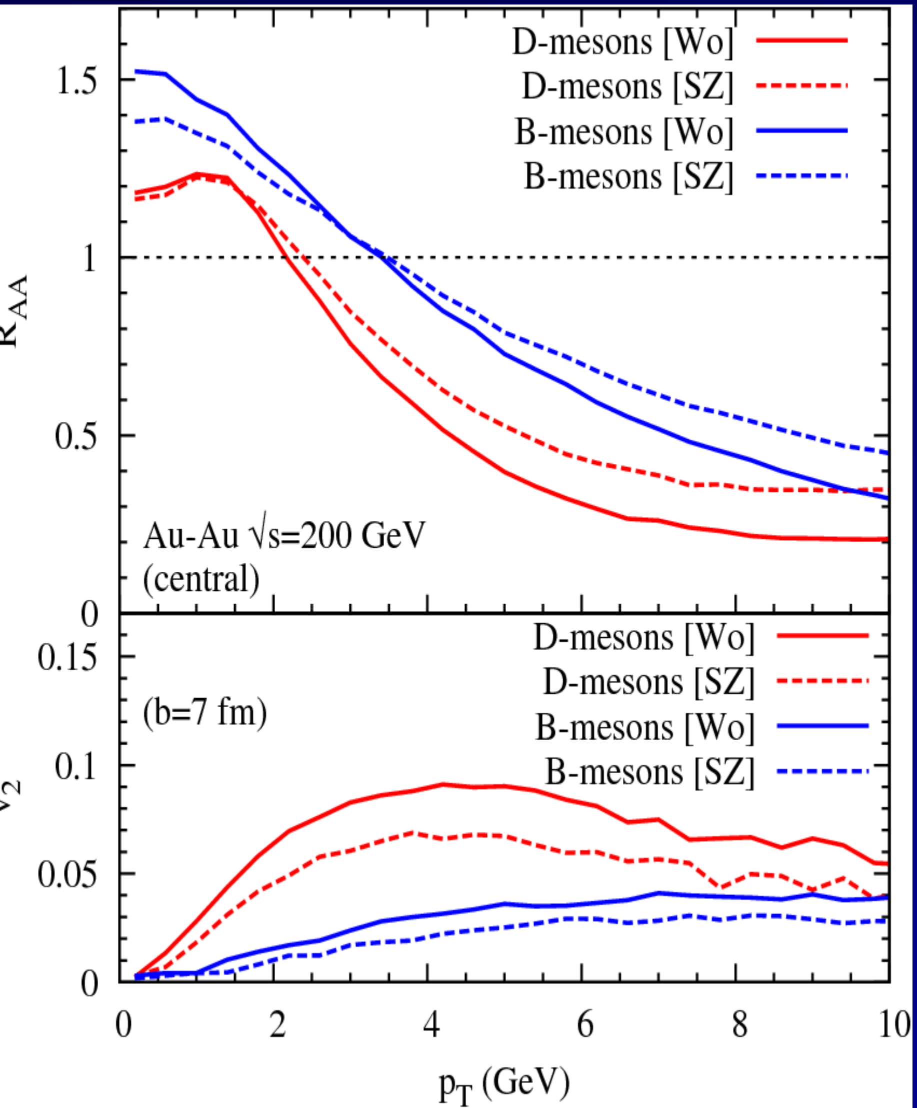
Apparent reduction if $\Lambda_c/D \sim 1$ consistent with RHIC data (pt~2-4 GeV)

$$G_\alpha(\tau, p; T) = \int_0^\infty \frac{d\omega}{2\pi}\ \rho_\alpha(\omega, p; T)\ K(\omega, \tau; T)$$

with the finite-T kernel

$$K(\omega, \tau; T) = \frac{\cosh[(\omega(\tau - 1/2T)]}{\sinh[\omega/2T]}\ .$$




D-mesons [Wo]
D-mesons [SZ]
B-mesons [Wo]
B-mesons [SZ]
Au-Au √s=200 GeV
(central)
(b=7 fm)
p_T (GeV)
0
2
4
6
8
10
1.5
1
0.5
0.15
0.1
0.05