# Heavy-Quark Kinetics in the QGP at LHC

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# Outline

Heavy-quark observables at RHIC

- non-photonic single electrons in HIC (from $D$ and $B$ decays)
- large supression (small $R_{AA}$) at high $p_T$
- large anisotropic flow ($v_2$)
- Heavy quarks thermalize $\Rightarrow$ Strong interactions with bulk matter!

Heavy Quarks in the QGP

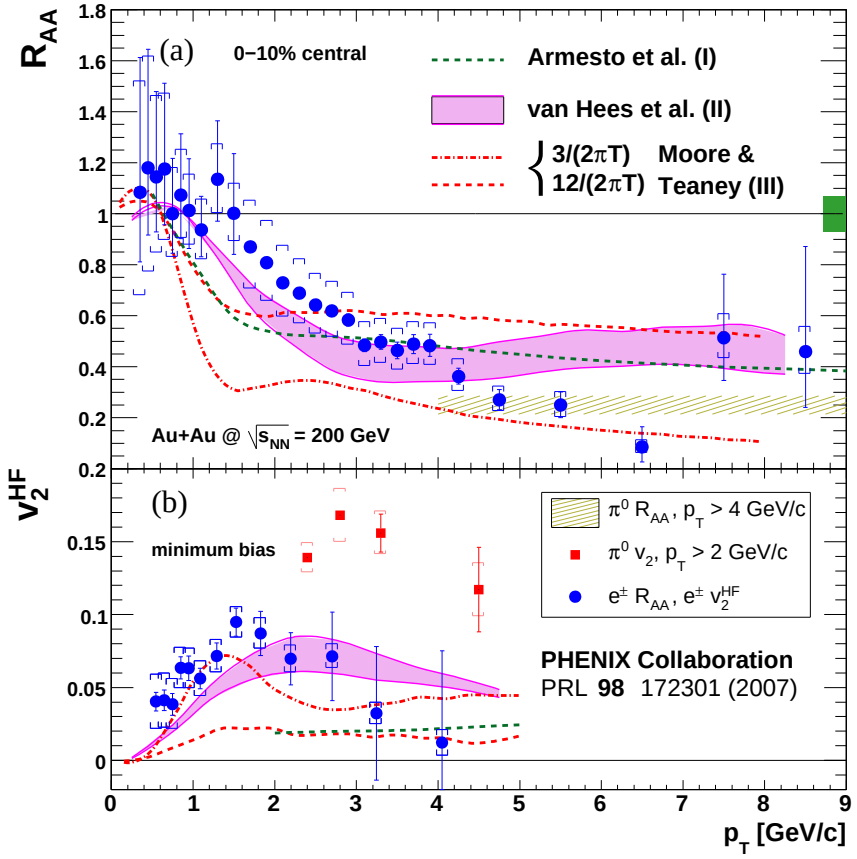
- initial hard production
- interaction with the flowing plasma treated dynamically!
  - Langevin simulations for heavy quarks in expanding fireball
  - non-perturbative mechanism for elastic scattering
- Hadronization via quark coalescence + fragmentation
- Consistency between $R_{AA}$ and $v_2$

Predictions for LHC

- non-photonic single electrons
- $D$ and $B$ mesons

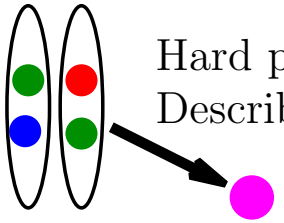
A glance at $J/\Psi$

# Heavy-quark observables at RHIC



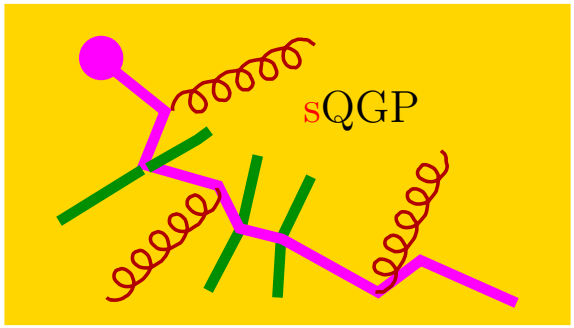

- non-photonic single electrons from $D$- and $B$-meson decays
- observables for heavy quarks in QGP!
- large suppression and $v_2$
- HQs thermalize with medium
- Challenge for theory
- sQGP: non-perturbative effects

# HQ's hard production – diffusion in sQGP – hadronization

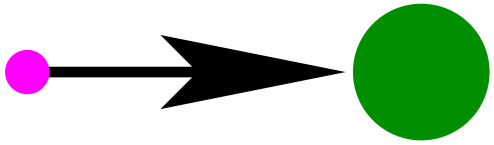


Hard production
Described by PDF's + pQCD (PYTHIA)

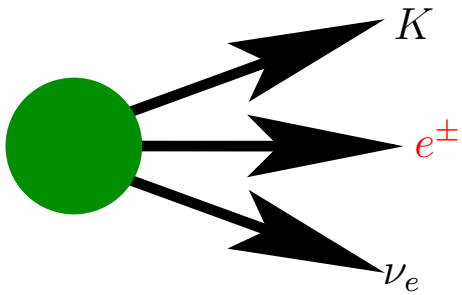
c, b quark




HQ rescattering in QGP: Langevin
here: collisional energy loss
non-perturbative effects (sQGP)
HvH, V. Greco, R. Rapp, PRC **73**, 034913 (2006)



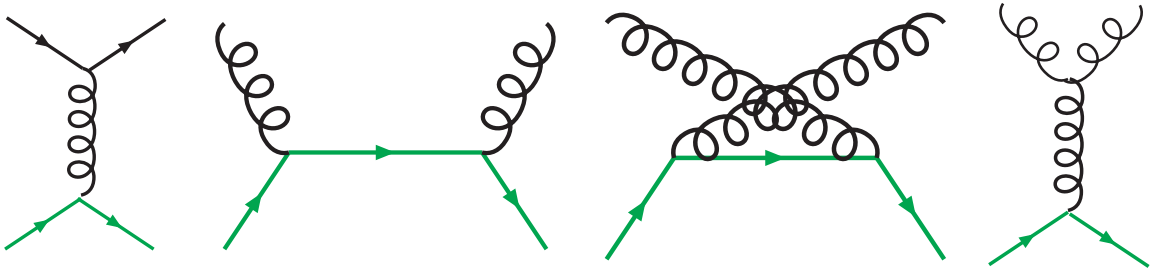
Hadronization to D, B mesons
via quark coalescence + Fragmentation
V. Greco, C. M. Ko, R. Rapp, PL **B595**, 202 (2004)
LQ's: cascade with 2-body coll. ($\langle v_2 \rangle$=7%)
(M. Colonna, G. Ferini, M. Di Toro)



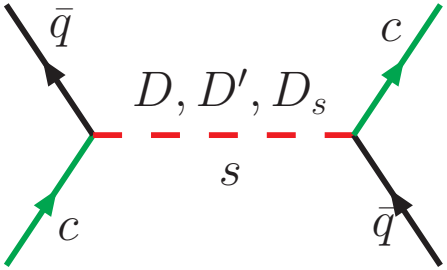

Semileptonic decay
$\Rightarrow$ "non-photonic" electron observables

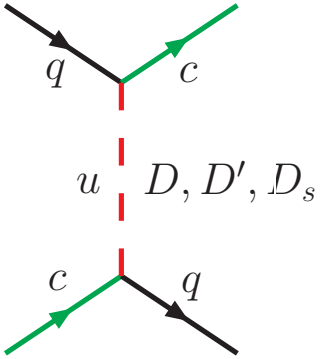
# Elastic scattering of heavy quarks in the QGP

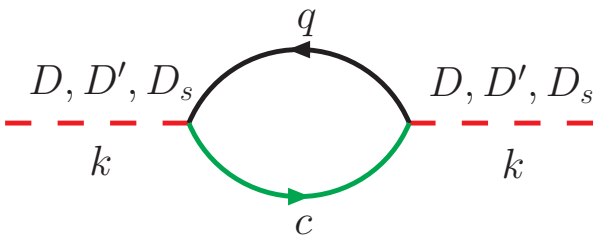
- PQCD scattering: $\alpha_s = 0.4$, $\mu_g = gT$



- Non-perturbative $c$-$\bar{q}, q$ scattering via resonances in sQGP
  HvH, R. Rapp, PRC **71**, 034907 (2005)




- $m_c = 1.5$ GeV, $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
- $m_b = 4.5$ GeV, $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV

# Relativistic Langevin in fireball with anisotropic flow

Expanding fireball

Anisotropic flow profile

$T_{\text{initial}} \simeq 520$ MeV

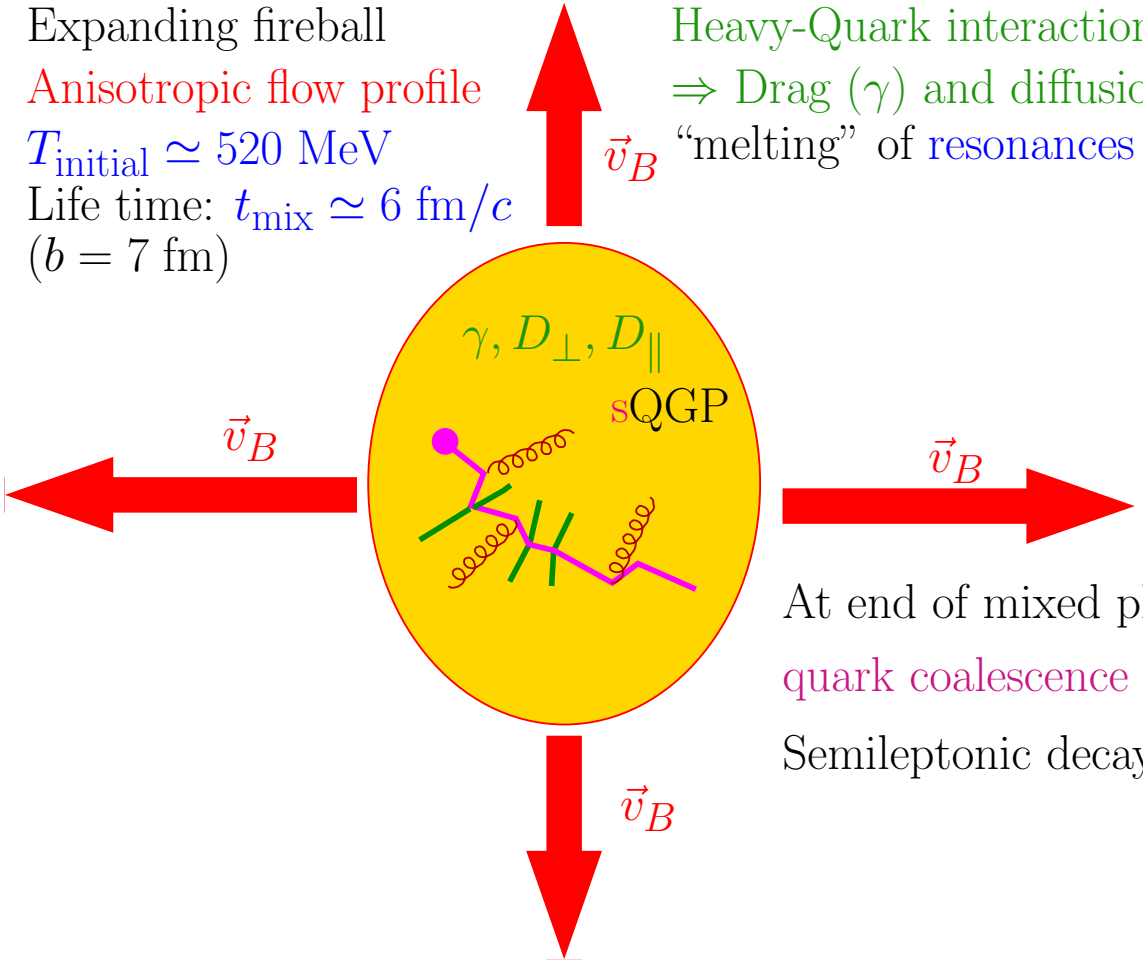
Life time: $t_{\text{mix}} \simeq 6$ fm/$c$

($b = 7$ fm)

Heavy-Quark interactions

$\Rightarrow$ Drag ($\gamma$) and diffusion coefficients ($D_\perp$, $D_\parallel$)

"melting" of resonances at $T = 2T_c$



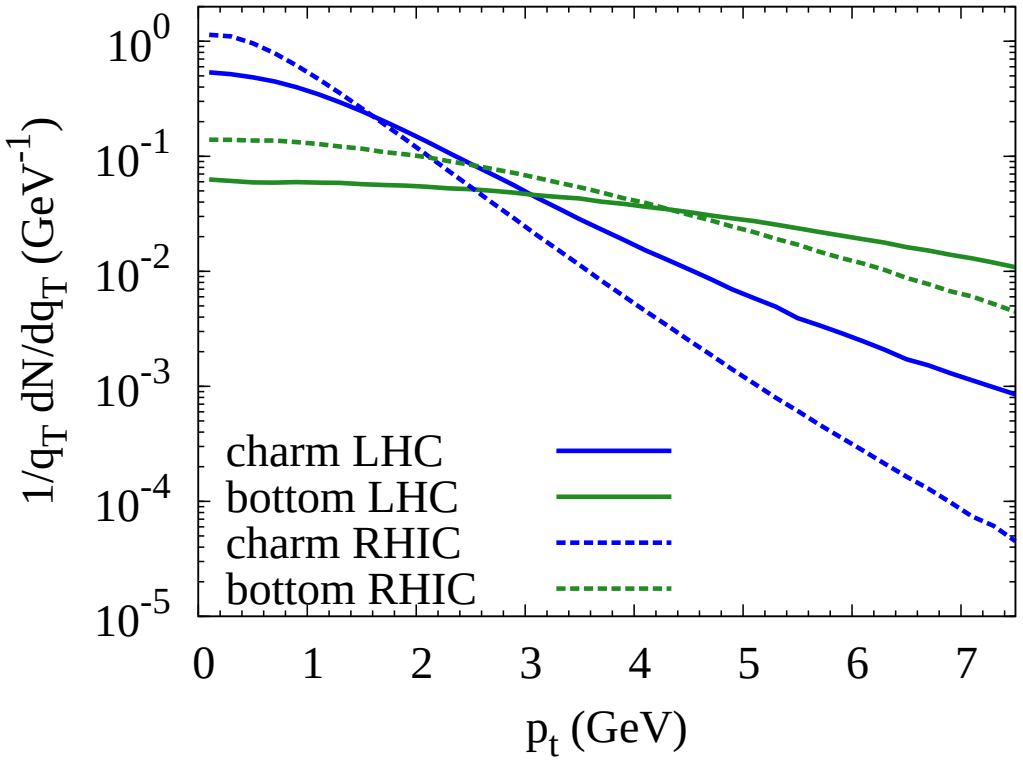

At end of mixed phase:

quark coalescence + fragmentation

Semileptonic decay of $D/B$ to $e^\pm$

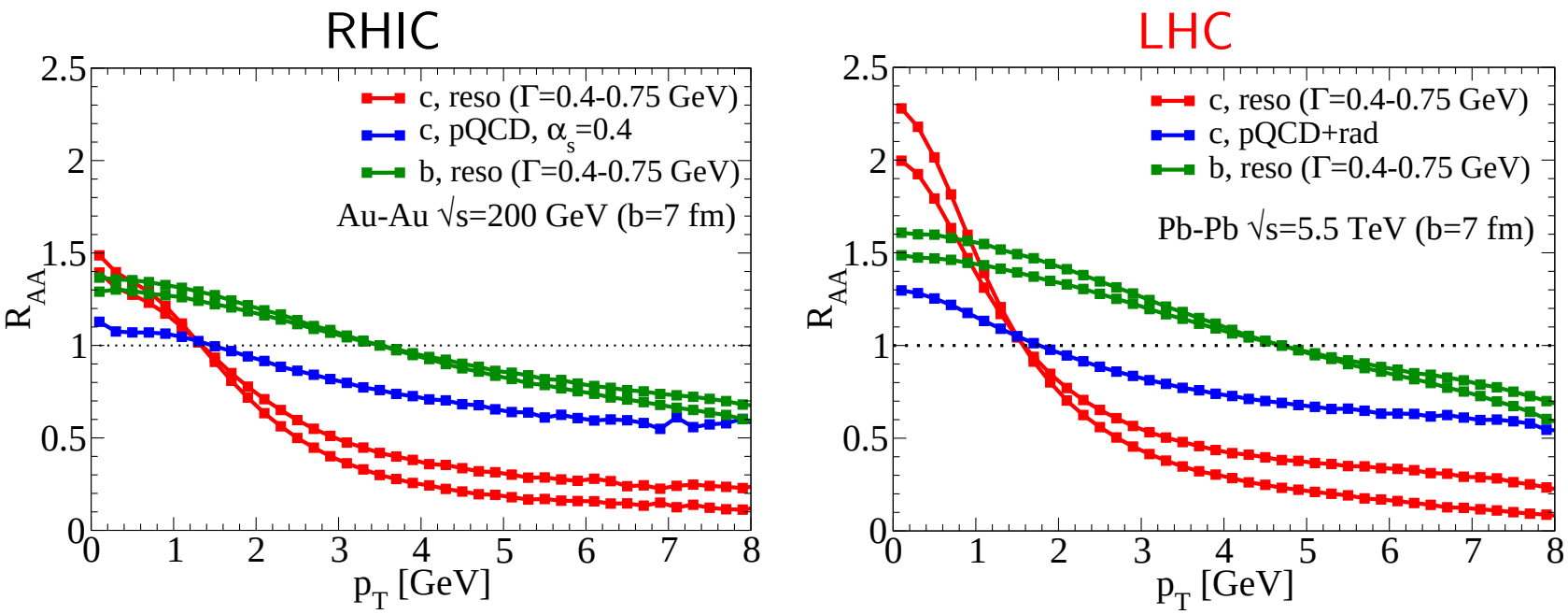
$$\frac{\partial f(t,\vec{p})}{\partial t} = \frac{\partial}{\partial p_i}\left[p_i \gamma(t,|\vec{p}|) + \frac{\partial}{\partial p_j} D_{ij}(t,\vec{p})\right] f(t,\vec{p})$$

# Initial quark spectra



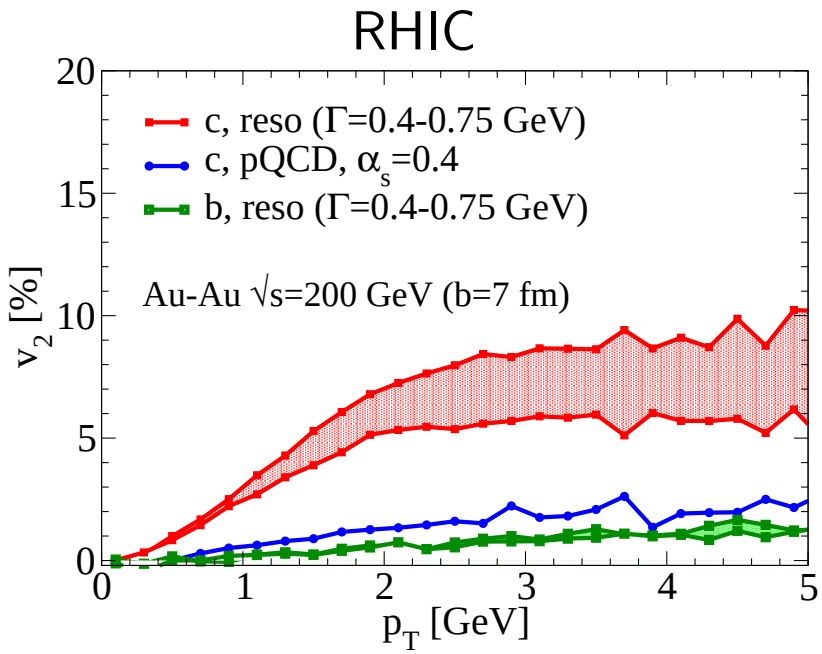

- here: normalized to 1
- from PYTHIA
- LHC spectra considerably harder!

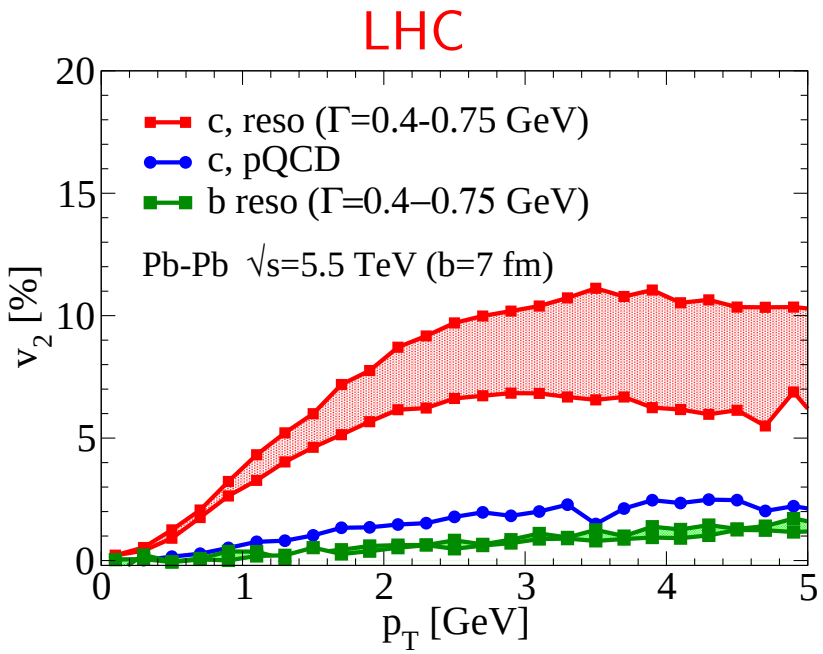
# Heavy-quark $R_{AA}$




- Suppression: $R_{AA} \sim$ the same at RHIC and LHC!
  - Reason: initial spectra harder at LHC
  - Resonances ineffective ("melted") at early stages!

# Heavy-quark $v_2$

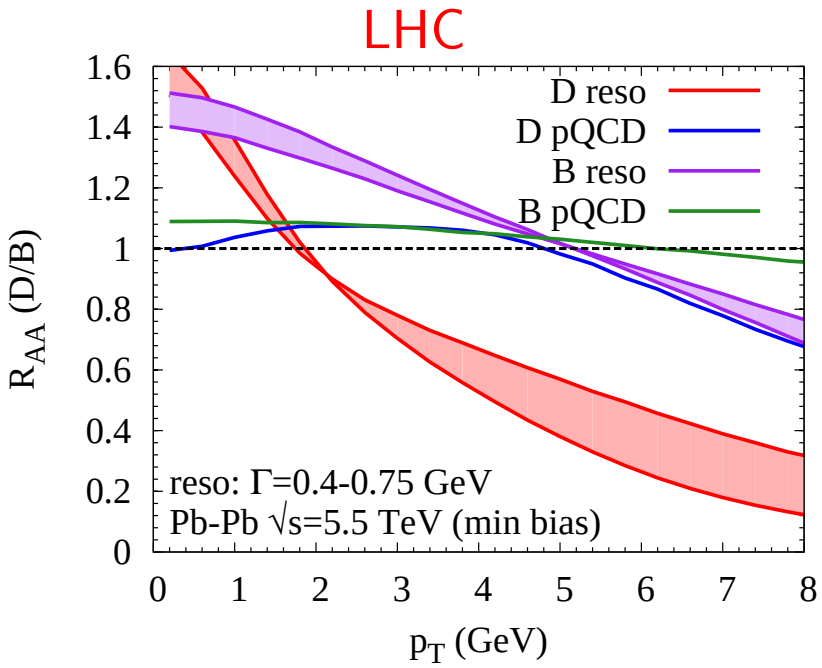


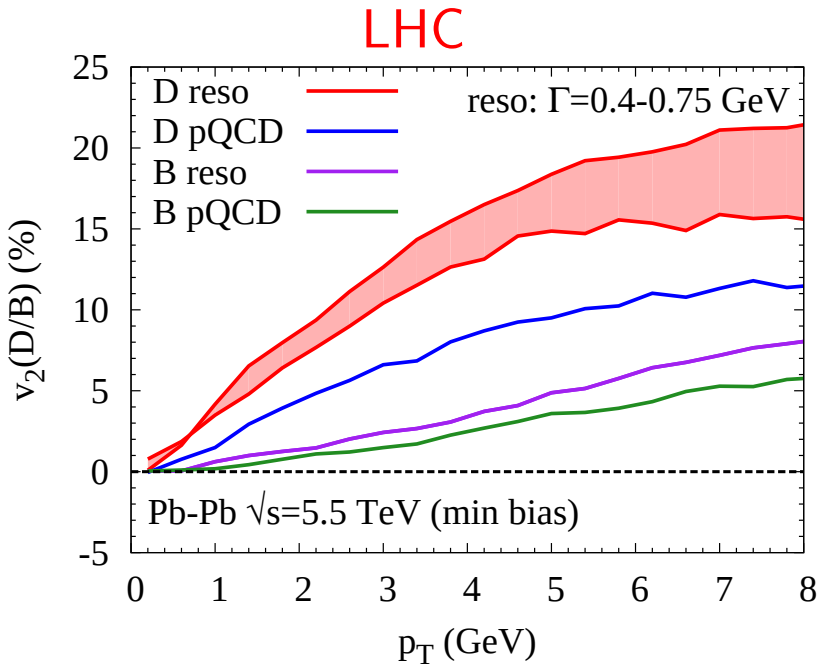




- $v_2 \sim$ the same at RHIC and LHC
  - NB: resonances become effective after anisotropic flow has built up
  - HQ's dragged with the flow at later stages

  $\Rightarrow$ $v_2$ slightly higher for low $p_T$

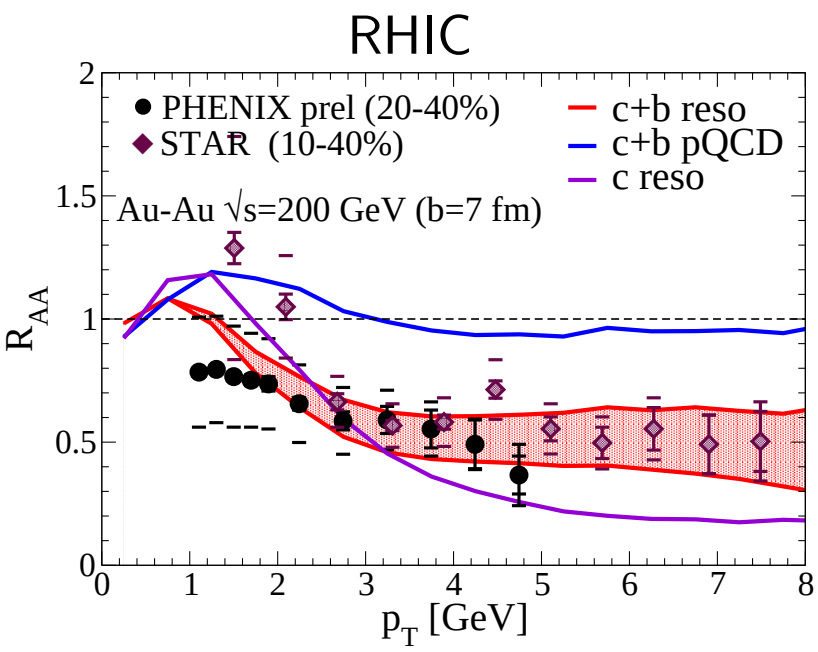
# $R_{AA}$ and $v_2$ for D/B mesons at LHC

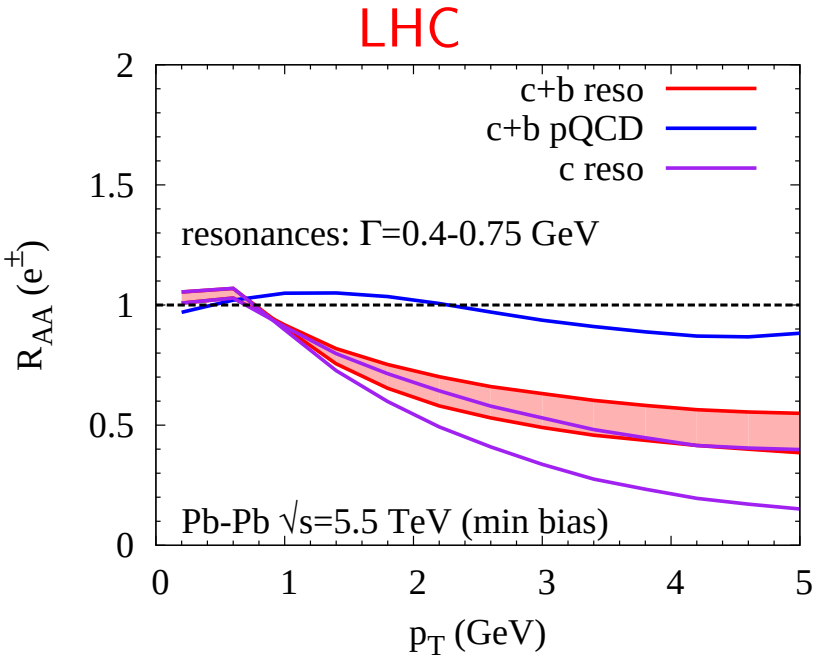



- $D$ and $B$ mesons via coalescence + fragmentation
- coalescence leads to increase in both, $R_{AA}$ and $v_2$

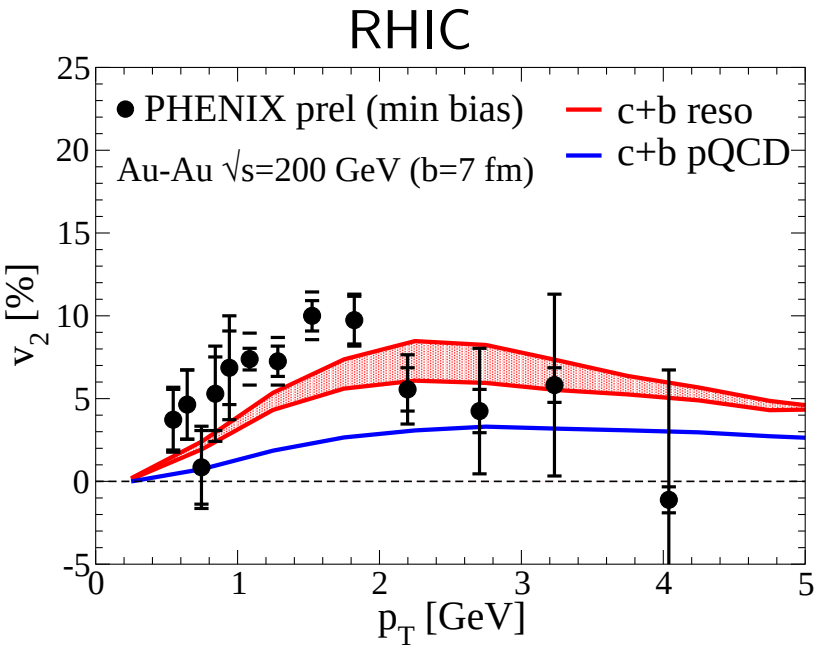
# $R_{AA}$ for non-photonic electrons

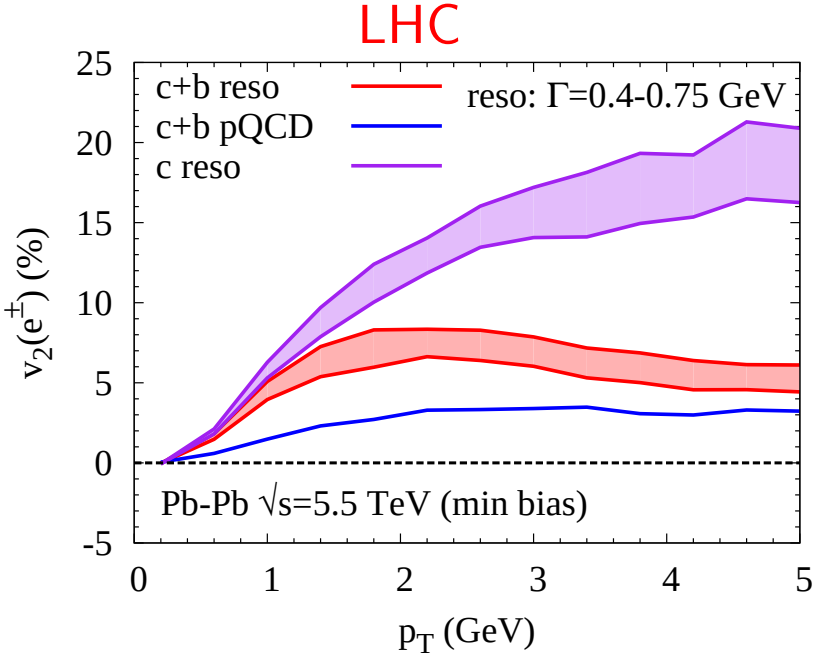



- $D$ and $B$ mesons via coalescence + fragmentation
- electrons from $D$- and $B$-meson decays
- coalescence leads to increase of $v_2$ compared to fragmentation only

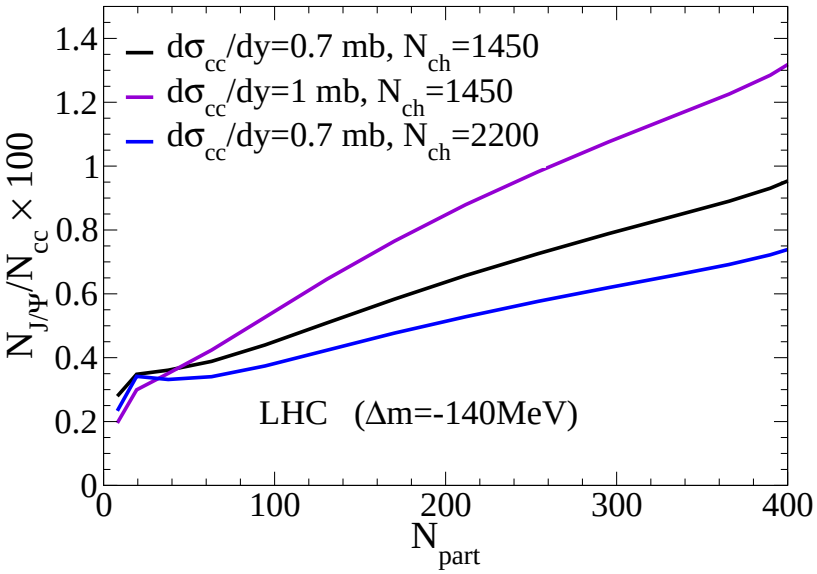
# $v_2$ for non-photonic electrons

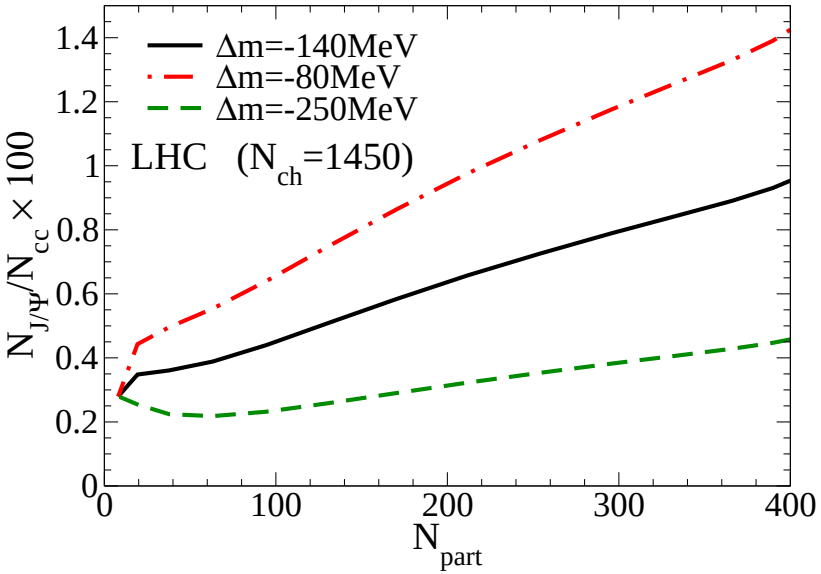



- $D$ and $B$ mesons via coalescence + fragmentation
- coalescence leads to increase of $v_2$ compared to fragmentation only

# A glance at $J/\Psi$




- Work by X. Zhao, R. Rapp
- Uncertainty in $N_{\text{ch}}$: $N_{\text{ch}} \uparrow \Rightarrow V \uparrow \Rightarrow \gamma_c \downarrow$, $N_{J/\Psi} = \gamma_c^2 V n_{J/\Psi}$
- cross-section uncertainty: $\sigma_{cc} = 6 \ldots 9$ mb
- $\Delta m$: in-med. binding energies for open charm mesons: lower open-charm masses $\Rightarrow$ more $c$'s in open charm
- includes feed down and incomplete-thermalization correction for $\Upsilon$: L. Grandchamp et al, Phys. Rev. C **73**, 064906 (2006)

# Conclusions

- Heavy Quarks in the sQGP
  - Heavy-quark kinetics with relativistic Langevin simulation
  - non-pert. elastic $Qq(\bar{q})$ collisions
  - Hadronization: Quark coalescence + fragmentation
  - Coalescence increases $R_{AA}$ and $v_2$
- Predictions for LHC compared to RHIC
- D/B mesons / non-photonic electrons:
  - $R_{AA}$ and $v_2$ very comparable with RHIC
  - reason: harder initial spectra
  - Resonances in sQGP only effective at temperatures $T \lesssim 2T_c$
- Predictions for $J/\Psi$