Collective Flow, R_{AA} and Heavy Flavor Rescattering

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April 28, 2005

Outline

1. Open Charm and Bottom
   - Motivation
   - Chiral Heavy-Quark Model
   - Heavy-quark rescattering in QGP
   - Non-photonic $e^{\pm}$ Observables: v_2 and R_{AA}
   - Conclusions and Outlook I

2. Bottomonia at RHIC
   - Dissociation Cross Sections
   - Rate Equation
   - Υ vs. J/ψ at RHIC
   - Conclusions and Outlook II

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- Measured p_T spectra and v_2 of non-photonic single electrons
- coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium

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- What is the underlying microscopic mechanism for thermalization?
  - pQCD elastic HQ scattering: need unrealistically large α_s [Moore, Teaney '04]
  - Gluon-radiative energy loss: need to enhance transport coefficient $\hat{q}$ by large factor [Armesto et al '05]

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- Assumption: survival of D- and B-meson resonances in the sQGP
- facilitates elastic heavy-quark rescattering

Free Lagrangian: Particle Content

- Chiral symmetry $\mathrm{SU}_V(2) \otimes \mathrm{SU}_A(2)$ in light-quark sector of QCD

$$\mathscr{L}_D^{(0)} = \sum_{i=1}^{2} [(\partial_\mu \Phi_i^\dagger)(\partial^\mu \Phi_i) - m_D^2 \Phi_i^\dagger \Phi_i] + \text{massive (pseudo-)vectors } D^*$$

- Φ_i: two doublets: pseudo-scalar $\sim \binom{\overline{D^0}}{D^-}$ and scalar
- Φ_i^*: two doublets: vector $\sim \binom{\overline{D^{0*}}}{D^{-*}}$ and pseudo-vector

$$\mathscr{L}_{qc}^{(0)} = \bar{q} \mathrm{i} \partial\!\!\!/ q + \bar{c}(\mathrm{i}\partial\!\!\!/ - m_c)c$$

- q: light-quark doublet $\sim \binom{u}{d}$
- c: singlet

Interactions

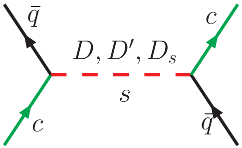
- Interactions determined by chiral symmetry
- For transversality of vector mesons:
  heavy-quark effective theory vertices

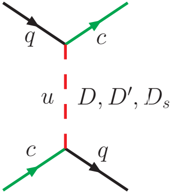
$$\begin{aligned}\mathscr{L}_{\text{int}} = & -G_S \left(\bar{q}\frac{1+\not{v}}{2}\Phi_1 c_v + \bar{q}\frac{1+\not{v}}{2}\mathrm{i}\gamma^5\Phi_2 c_v + h.c.\right) \\ & - G_V \left(\bar{q}\frac{1+\not{v}}{2}\gamma^\mu\Phi_{1\mu}^* c_v + \bar{q}\frac{1+\not{v}}{2}\mathrm{i}\gamma^\mu\gamma^5\Phi_{2\mu}^* c_v + h.c.\right)\end{aligned}$$

- v: four velocity of heavy quark
- in HQET: spin symmetry $\Rightarrow G_S = G_V$

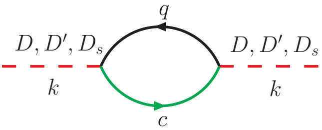
Resonance Scattering

- elastic heavy-light-(anti-)quark scattering





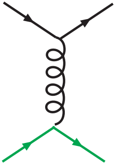
- D- and B-meson like resonances in sQGP

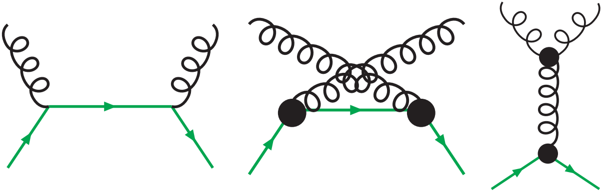


- parameters
  - $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
  - $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV

Contributions from pQCD

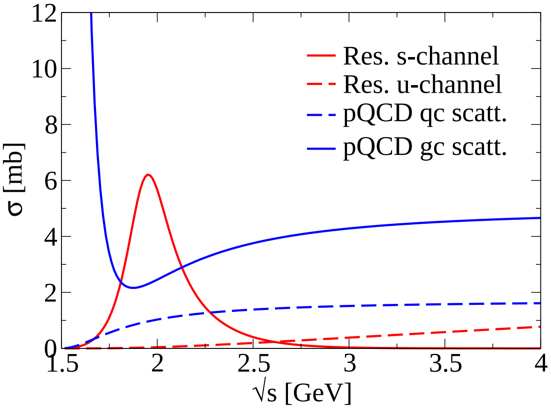
- Lowest-order matrix elements (Combridge '79)





- In-medium Debye-screening mass for t-channel gluon exchange:
  $\mu_g = gT$, $\alpha_s = 0.4$

Cross sections



- total pQCD and resonance cross sections: comparable in size
- BUT pQCD forward peaked ↔ resonance isotropic
- resonance scattering more effective for friction and diffusion

The Fokker-Planck Equation

- heavy particle (c,b quarks) in a heat bath of light particles (QGP)

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

- Assumption: Relevant scattering processes are soft

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- $A(t,p)$ friction (drag) coefficient $= 1/\tau_{\text{eq}}$
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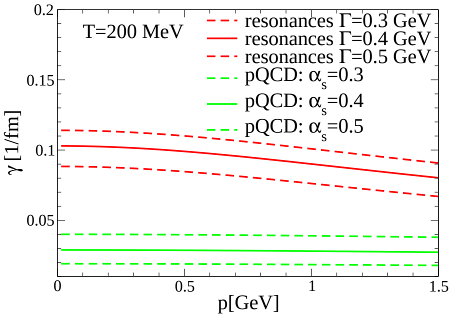
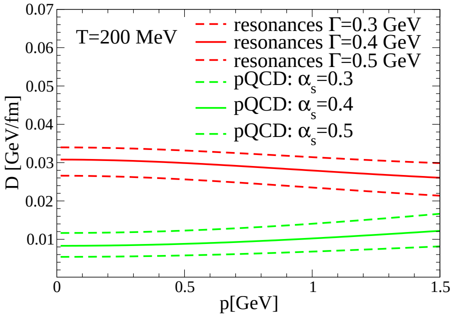
- to ensure correct equilibrium limit: $B_1(t,p) = T(t) E_p A(t,p)$ (Einstein dissipation-fluctuation relation)

Drag and Diffusion: pQCD vs. resonance scattering

- 3-momentum dependence

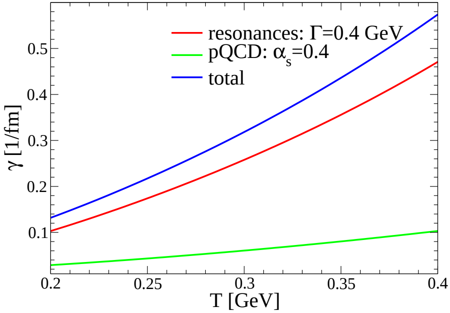


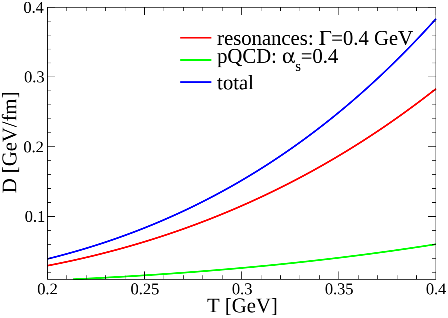


- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

The Coefficients: pQCD vs. resonance scattering

- Temperature dependence





Time evolution of the fire ball

- Elliptic fire-ball parameterization
  fitted to hydrodynamical flow pattern [Kolb '00]

$$V(t) = \pi(z_0 + v_z t) a(t) b(t), \quad a, b\text{: half-axes of ellipse,}$$
$$v_{a,b} = v_\infty[1 - \exp(-\alpha t)] \mp \Delta v[1 - \exp(-\beta t)]$$

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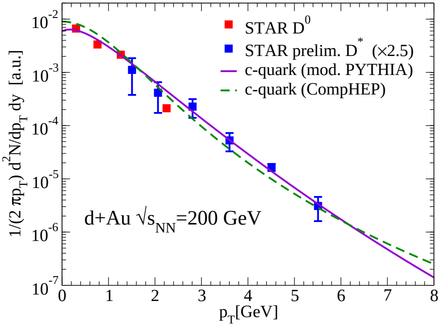
- Isentropic expansion: $S = \text{const}$ (fixed from N_{ch})
- QGP Equation of state:

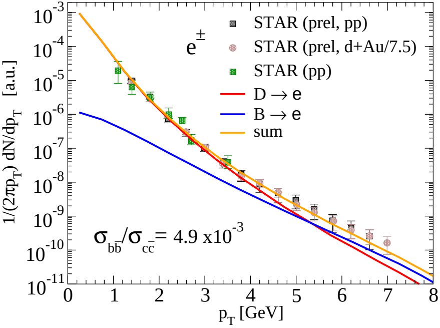
$$s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5 n_f^*), \quad n_f^* = 2.5$$

- obtain $T(t) \Rightarrow A(t,p)$, $B_0(t,p)$ and $B_1 = TEA$
- for semicentral collisions ($b = 7$ fm): $T_0 = 340$ MeV,
  QGP lifetime $\simeq 5$ fm$/c$.
- simulate FP equation as relativistic Langevin process

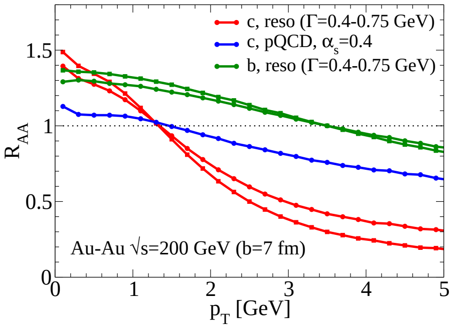
Initial conditions

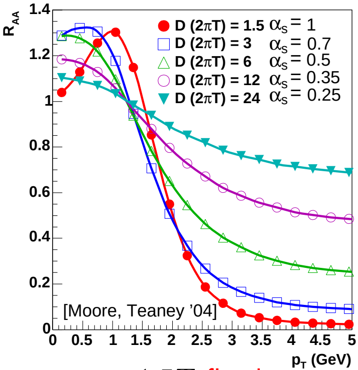
- need initial p_T-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio





Spectra and elliptic flow for heavy quarks





- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances ⇒ c-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro

- $\mu_D = 1.5T$ fixed
- $2\pi T D \simeq \frac{3}{2\alpha_s^2}$

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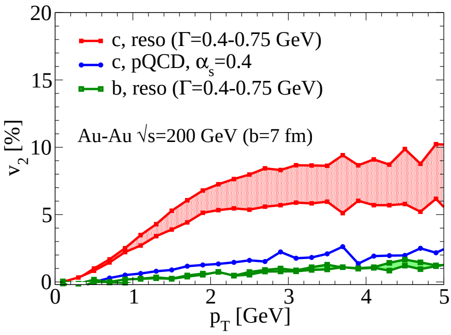
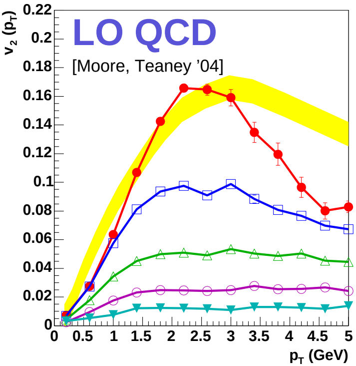
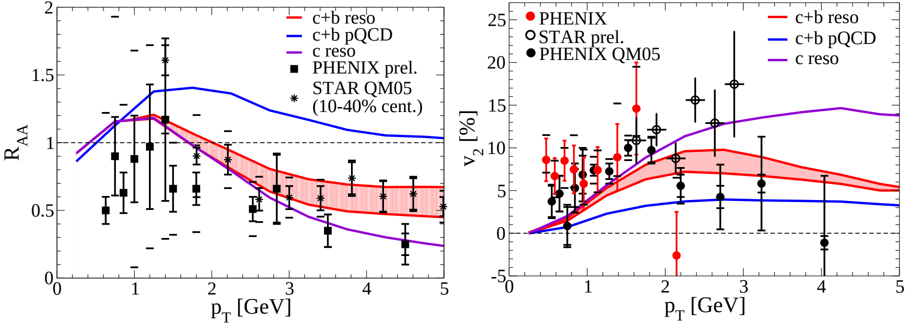




- Hadronization: Coalescence with light quarks (fixed before [Greco et al 03]) + fragmentation ($c\bar{c}$, $b\bar{b}$ conserved)
- single electrons from decay of D- and B-mesons



- Hadronization: Fragmentation only
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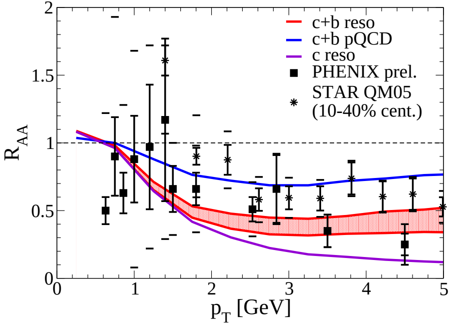

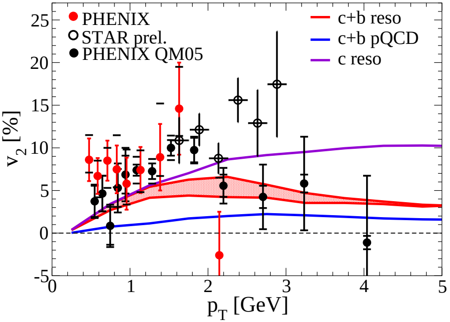

Conclusions and Outlook I

- Assumption: survival of resonances in the (s)QGP
- nonperturbative re-interactions of heavy quarks in QGP
- Observables via Langevin approach and coalescence+fragmentation
  - Elastic resonance scattering $\Rightarrow R_{AA}^{(c)} \simeq 0.2$, $v_2^{(c)} \simeq 0.1$ without upscaling of cross sections
  - small effects on bottom quarks
  - Heavy-light quark coalescence enhances $v_2^{(e)}$ and R_{AA} for $p_T \simeq 2$ GeV
  - bottom dominates for $p_T > 3.5$ GeV $\Rightarrow$ reduced suppression, $v_2^{(e)}$
- For details, see: HvH, R. Rapp, Phys. Rev. C 71, 034907 (2005) [nucl-th/0412015], HvH, V. Greco, R. Rapp [nucl-th/0508055,hep-ph/0510050]

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- Further investigations
  - improved (softer) fragmentation
  - better control of coalescence/fragmentation ratio
  - implementation of gluon-radiation processes
  - quantitative consequences for quarkonia

Bottomonia at RHIC

Motivation

- Matsui & Satz (1986):
  Quarkonia suppression due to colour screening as signature of QGP in heavy-ion collisions
- sQGP: from lQCD $Q\bar{Q}$ resonances survive at $T > T_c$

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  - J/ψ and η_c "melt" at $T_{\text{diss}}^{(J/\psi)} \simeq 2T_c$
  - Υ: $T_{\text{diss}}^{\Upsilon} \simeq 4T_c$
- Resonances facilitate secondary regeneration of quarkonia in QGP

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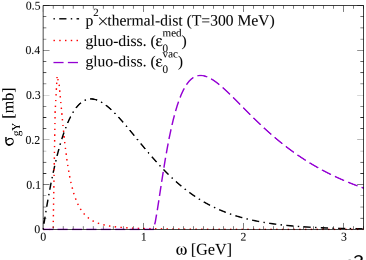
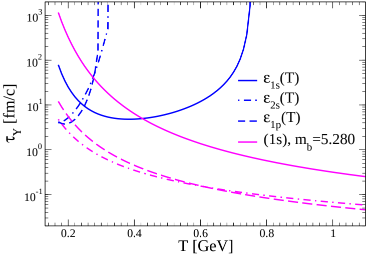
- $c\bar{c}$ recombination substantial part of final J/ψ yield at RHIC [Braun-Munzinger et al 01, Thews et al 01, Grandchamp, Rapp 01]
- J/ψ suppression dominant at SPS
- Bottomonium at RHIC?
  similar to Charmonium at SPS?

Dissociation Cross Sections

- Need Dissociation Cross Sections to evaluate Υ yield
- Usual mechanism: Gluo dissociation (in dipole approximation)
- Problem: becomes inefficient for loosely bound states





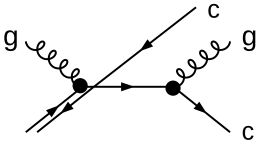
$$\Gamma_{\Upsilon} = \tau_{\Upsilon}^{-1} = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} f_{q,g}(\omega_k, T) v_{\text{rel}} \sigma_{\Upsilon}^{\text{diss}}(s)$$

$$m_{\Upsilon} = 2 m_b(T) - \epsilon_{\Upsilon}(T) = \text{const}$$

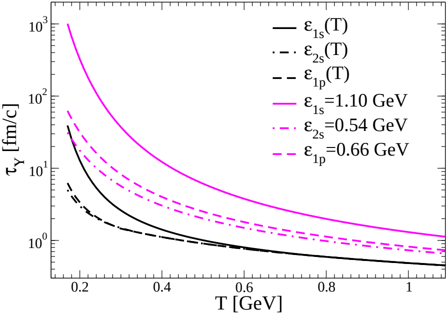
- $\epsilon_{\Upsilon}(T)$ from Schrödinger eq. with screened Cornell potential [Karsch, Mehr, Satz 88]

Dissociation Cross Sections

- breakup mechanism for loosely bound states: quasifree dissociation



- use LO pQCD cross sections for elastic scattering [Combridge 79]



- Color screening reduces Υ lifetime by factor of 10!

- Rate Equation (detailed balance!)

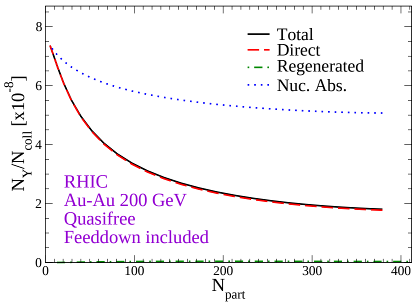
$$\frac{\mathrm{d}N_Y}{\mathrm{d}t} = -\Gamma_Y \left[\underbrace{N_Y}_{\text{loss}} - \underbrace{N_Y^{(\text{eq})}}_{\text{gain}} \right]$$

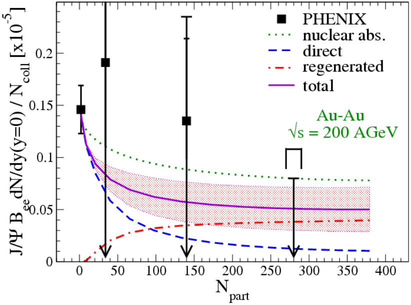
- Fugacities for $b\bar{b}$-pair number conservation

$$N_{b\bar{b}} = \frac{1}{2}\gamma_b N_{\text{open}} \frac{I_1(\gamma_b N_{\text{open}})}{I_0(\gamma_b N_{\text{open}})} + \gamma_b^2 N_{\text{hidden}}$$

- Initial conditions from hard production only $(m_b \gg T_0)$

Υ vs. J/ψ at





[Grandchamp et al 03]

- Suppression prevalent effect
  - color screening in QGP
  - suppression of higher bottomonia and feeddown to Υ
- with vacuum Υ: thermal suppression for Υ negligible
  magnitude of suppression sensitive to color screening
- J/ψ: yield dominated by regeneration

Conclusions and Outlook II

- rate-equation approach to evaluate Υ abundances
- Suppression predominant effect at RHIC (and LHC)
- At LHC: substantial fraction of total Υ yield due to regeneration
- Color screening main microscopic mechanism for suppression
- For details see: L. Grandchamp, , S. Lumpkins, D. Sun, HvH., R. Rapp [hep-ph/0507314]

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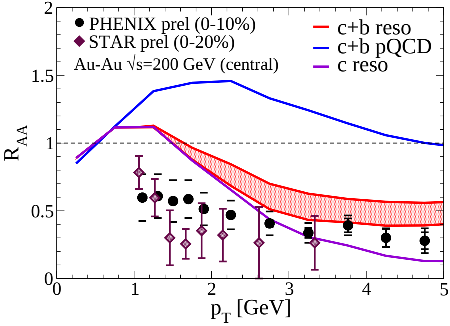
- Future work
  - more microscopic approach for dissociation-regeneration processes
  - p_T spectra (v_2) for bottomonia

Backup Slides

- Central Collisions
- single electrons from decay of D- and B-mesons

- Hadronization: Coalescence + fragmentation



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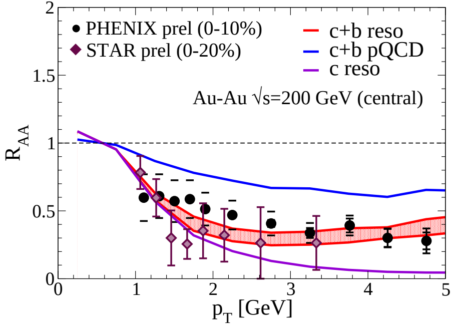
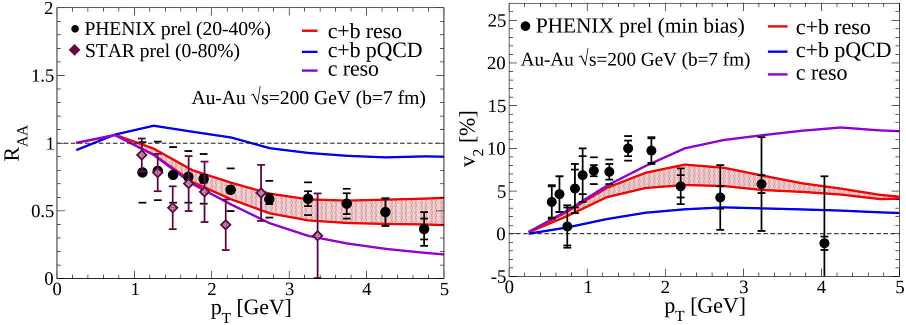
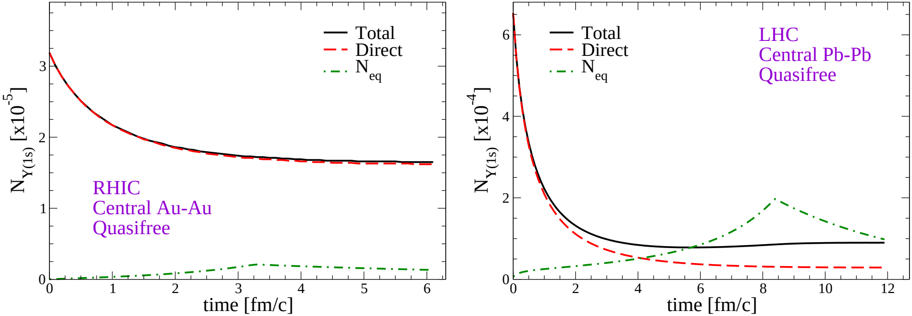


Observables: p_T-spectra (R_{AA}), v_2

- Hadronization: 0.5Coalescence + fragmentation ($c\bar{c}$, $b\bar{b}$ conserved)
- single electrons from decay of D- and B-mesons



Υ evolution RHIC vs. LHC



- At both LHC and RHIC: Suppression prevalent effect
- mostly due to Debye screening of color potential