A Langevin approach for heavy quark propagation at FAIR energies

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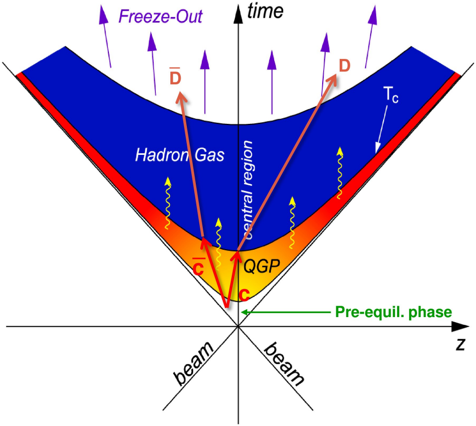
FAIRNESS

Thanks to Marcus Bleicher, Hendrik van Hees, Jan Steinheimer

Outline

Outline

Why are we interested in heavy quarks?



- heavy quarks are produced in the beginning of heavy ion collisions in hard processes
- they traverse the whole medium evolution
- they do not fully thermalize
- therefore they are an ideal probe for the early phase of heavy ion collisions

Background medium for the heavy quark propagation

For the medium description we use the UrQMD hybrid model

H. Petersen, J. Steinheimer, G. Burau, M. Bleicher, and H. Stoecker, Phys. Rev. C 78, 044901 (2008)

- medium is not homogeneous
- it combines the advantages of hadronic transport theory and ideal fluid dynamics
- realistic and well tested model for the background medium
- UrQMD is used to calculate the initial state of a heavy ion collision for the hydrodynamical evolution

  M. Bleicher, E. Zabrodin, C. Spieles, S. Bass, C. Ernst, et al., J. Phys. G 25, 1859
- event-by-event fluctuations are included

The propagation of heavy quarks

In this environment heavy quarks are placed and propagated using a Langevin approach

- because heavy quarks are much heavier than the medium consisting of light quarks we can assume a diffusion treatment, this mean a Brownian motion
- collision term of the Boltzmann-equation can be approximated by a Fokker-Planck equation
- this can be mapped in a stochastic Langevin equation

R. Rapp and H. van Hees, (2009), published in Quark Gluon Plasma 4, World Scientific, p.111,arXiv:0903.1096 [hep-ph]

Implementation of our model

- heavy quarks (charm and bottom) are placed at nucleus-nucleus collision space-time-coordinates using UrQMD
- momenta of the heavy quarks are fitted to experimental data (HSD in case of FAIR calculations)

  O. Linnyk, E. L. Bratkovskaya and W. Cassing, Int. J. Mod. Phys. E **17** (2008) 1367
- hydro evolution is started
- heavy quarks are propagated at each hydro time step in the hot medium using the correspondent cell properties (velocities, temperatures, length of time-step, γ-factor)
- for all particles at each time-step the temperature is checked regarding a hadronization

What did we do?

- test of different drag and diffusion coefficients for heavy quark propagation
  - Resonance model ⇒ HQET (heavy quark effective theory) calculation that assumes that open heavy-flavor resonances survive the phase transition

    H. van Hees and Ralf Rapp, 034907
  - T-Matrix approach ⇒ static quark-antiquark potentials are used to calculate the scattering-matrix elements for the elastic scattering of heavy quarks with light quarks

    H. van Hees and M. Mannarelli and V. Greco and R. Rapp, 192301
- calculation for different decoupling temperatures in case of the Resonance model
- have a look at the influence of a k-factor on the results
- test of fragmentation and coalescence as hadronization mechanism

Comparing our calculation to data using fragmentation

- We use Peterson fragmentation to hadronize charm and bottom quarks:

$$D_Q^H(z) = \frac{N}{z[1-(1/z)-\epsilon_Q/(1-z)]^2}$$

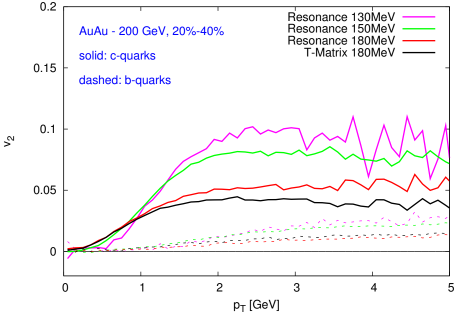
with $\epsilon_Q = 0.05$ (0.005) for charm (bottom) quarks

C. Peterson, D. Schlatter, I. Schmitt, and P. M. Zerwas, Phys. Rev. D 27, 105 (1983)

For the semileptonic decay to electrons we use PYTHIA

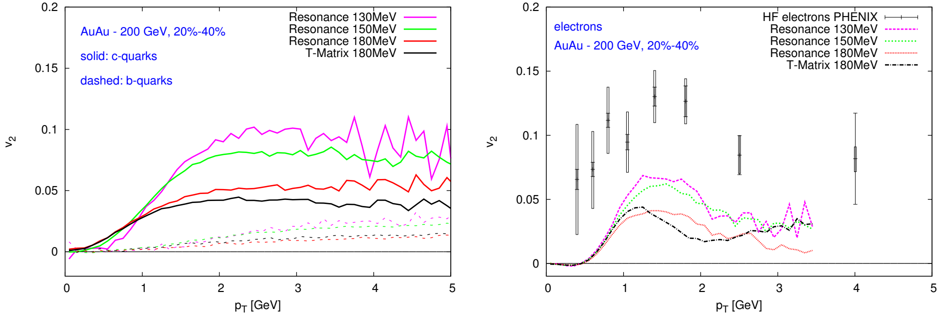
Outline

Elliptic flow in AuAu at RHIC energies



- one decoupling temperature for T-Matrix, different ones for Resonance model
- medium modification of charm quarks much higher than for bottom quarks
- increasing flow up to $p_T \approx 2\, GeV$
- late phase of the collision has a considerable effect on the v_2
- medium modification for T-Matrix slightly smaller than for Resonance model

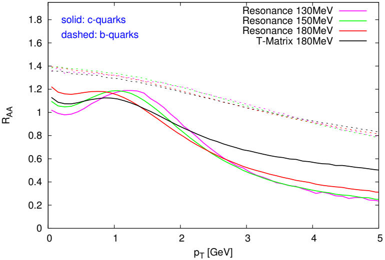
Elliptic flow in AuAu at RHIC energies

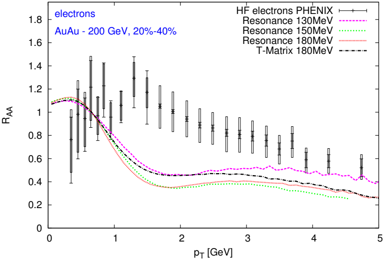


- decay to electrons shifts the spectra to smaller p_T
- bottom takes over between 1 GeV and 2 GeV
- v_2 too small compared to data, shape similar
- negative v_2 at very small p_T where particles are pushed away

Huovinen, P. and Kolb, P.F. and Heinz, Ulrich W. and Ruuskanen, P.V. and Voloshin, S.A., Phys. Lett. B, 2001, 503, 58-64

Nuclear modification factor

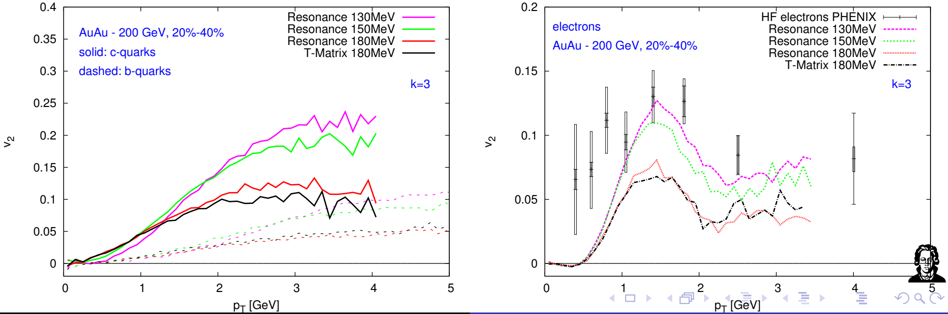




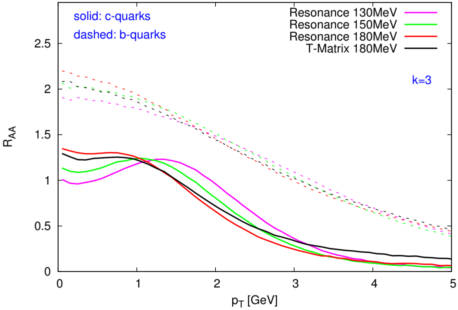
- dip due to low p_T particles that are pushed to higher p_T due to the radial flow
- better results for small decoupling temperature due to higher flow that pushes particles to higher p_T
- calculation below the experimental measurements for intermediate p_T

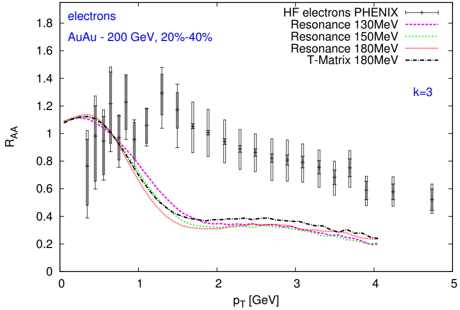
Elliptic flow using a k-factor of 3

- all coefficients multiplied by 3
  $\Rightarrow$ stronger coupling to the medium
- a k-factor can correct our flow calculations so they fit to the experimental data
- only at low p_T we see to low flow due to depletion effect



Nuclear modification factor using a k-factor of 3





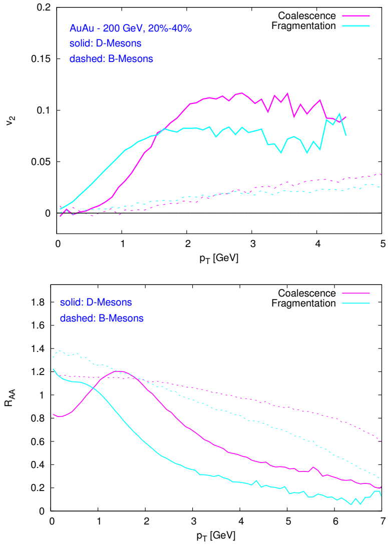
- using the k-factor suppresses the heavy quarks even stronger
- larger flow cannot drag heavy quarks to higher p_T

k-factor does not lead to a consistent description of v_2 and R_{AA}

Comparing our calculation to data using coalescence

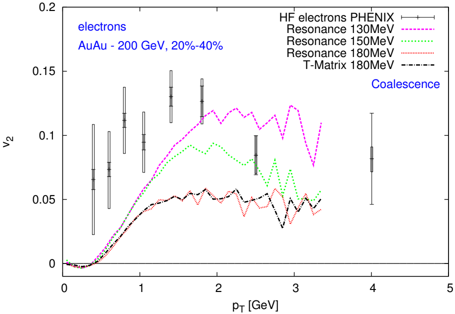
- coalescence should be important especially at low momenta
- We use the hydro model to implement coalescence
  $\rightarrow$ adding the momenta of the heavy quarks with light quarks from the surrounding medium
- momenta are taken from the hydro cell velocities
- mass of the light quarks is 369 MeV
- so far we neglected the thermal momenta of the light quarks

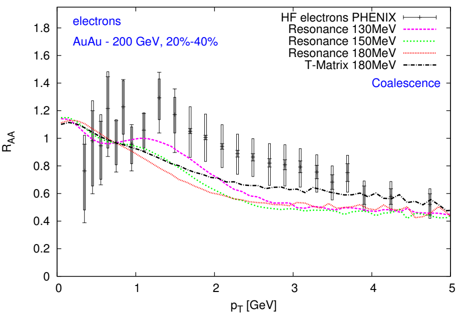
Coalescence versus fragmentation



- the coalescence mechanism increases the input of the bulk medium on the heavy quarks
- higher v_2
- more pronounced depletion effect
- more pronounced dip in the R_{AA} spectrum
- heavy quarks are dragged to higher p_T bins

Results for the coalescence model



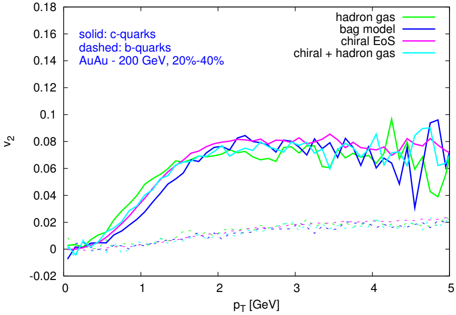


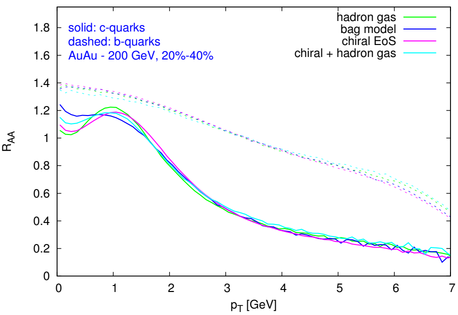
- the light quarks contribute a considerable fraction to the v_2 and R_{AA}
- rather nice agreement with data without using of a k-factor reached

Different equations of state

Results sensitive on the background medium

P. B. Gossiaux et al.,Phys. Rev. C, 2011, 2012.05.10



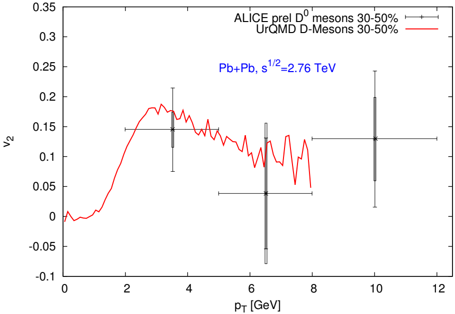


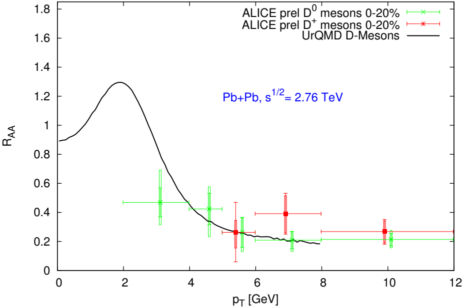
- v_2 and R_{AA} barely depend on the realistic EoS used

Paper for RHIC results in preparation

v_2 and R_{AA} at LHC

- same coefficients, hadronization temperature etc.



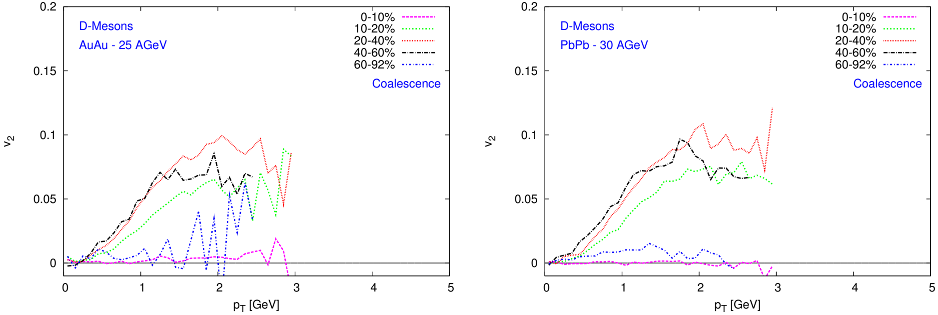


- for LHC energies we reach a nice agreement to measured date within the error bars

T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1208.1643

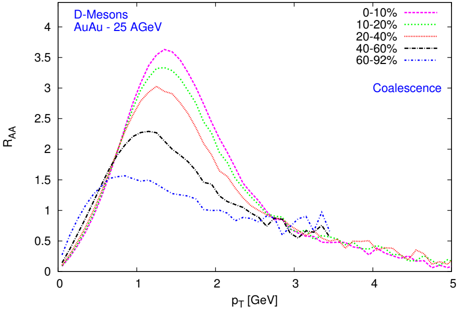
Prediction for the elliptic flow v_2 at FAIR

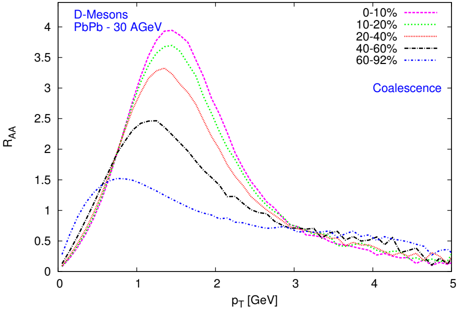
Two different systems



- highest flow in the centrality range 20-40%
- size of flow in similar to that calculated at RHIC and LHC
- flow in case of PbPb slightly higher

Prediction for the nuclear modification factor R_{AA} at FAIR

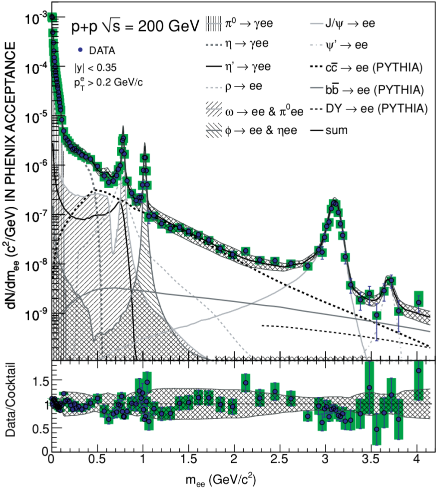




- larger R_{AA} modification at FAIR than at RHIC and LHC
  Due to
- p_T distribution
  $\Rightarrow$ quarks are dragged out of low p_T bins
- stronger interaction at FAIR energies

Outline

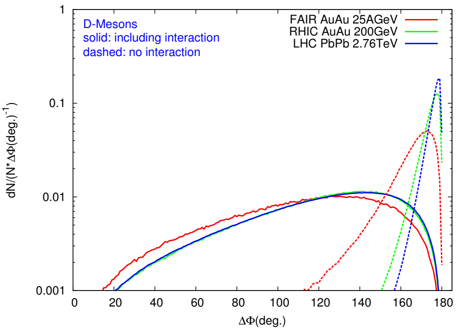
Correlations of D-Mesons



A. Adare *et al.*, Phys. Rev. C **81** (2010) 034911

- we use the same model as before for this calculation
- c-quarks have to be produced in back to back reactions due to conservation laws
- correlation can show the strength of the medium interaction of heavy mesons
- experimentally interesting because D-decay is the main background for QGP dilepton radiation

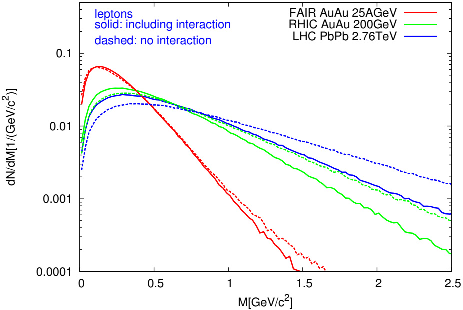
Correlation of D-Mesons in dependence of the medium modification



- in case of no interactions only coalescence determines peak structure
- almost all charm quarks interact with the hot medium
- highest medium modification for FAIR energies
- RHIC and LHC show almost same behavior

Correlation study in UrQMD: X. Zhu *et al.*,Phys. Lett. B **647** (2007) 366

Invariant mass of dileptons from D-Mesons



- slope depends on the collision energy strongly
- in case of no interactions slope broadens
- slope gives us a hint on the thermalization of heavy quarks in the medium

Outline

Summary and Outlook

- Langevin approach in UrQMD hydro for quark propagation
- coalescence mechanism needed to describe experimental measurements at RHIC
- use of a k-factor does not allow for a consistent description of both v_2 and R_{AA}
- late phase of the collision is very important
- we can describe LHC measurements
- prediction for FAIR energies at different centralities, strong medium modification
- correlations and invariant mass spectra of D-Mesons and their decay products at FAIR, RHIC and LHC energy
- comparison of the invariant mass spectra to data
- implementation of a hadronic afterburner in the UrQMD transport model to simulate the whole evolution

Outline

Charmonium suppression

- Normal suppression
  - dissociation by nucleons
  - can explain suppression except for central collisions
- Comover sceanrio
  - dissociation by comoving mesons
  - can explain charmonium R_{AA} at SPS energies
- Recombination
  - principle of detailed balance requires recombination
  - formation rate proportional to the square of the number of unbound charm quarks
- Charmonium melting
  - spectral function of charmonia broadens in QGP
  - dissociation gets more likely
  - complete breakup only at very high temperatures

Implementation to UrQMD

- implementation of J/Ψ, χ_c, Ψ' and D-Mesons
- momenta fitted to experimental data
- charm production points determined using Glauber model
  $\Rightarrow$ UrQMD prerun to write down nucleon collision points
- we use a hadronic and a prehadronic phase

Hadronic phase

- elastic cross sections from effective Lagrangian calculations

  Ziwei Lin, C M Ko, J.Phys. G:Nucl.Part.Phys. 27 (2001) 617-623
- inelastic meson cross sections from two-body transition model fitted to data from Pb+Pb at SPS

  E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C67, 054905 (2003)
- constant cross sections with baryons

  E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C67, 054905 (2003)

Assumptions for a prehadronic phase

- implementation of a prehadronic phase to UrQMD to mime QGP ($\varepsilon > 0,6\,\mathrm{GeV}/\mathrm{fm}^3$)

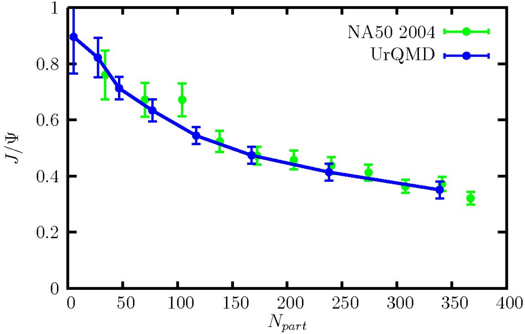
  S. Borsanyi *et al.*, JHEP **1009** (2010) 073

- no formation times $\Rightarrow$ prehadronic cross sections
- no recombination of D-Mesons above phase transition temperature
- at very high densities breakup of charmonium particles

  C.Miao, A.Mocsy, P.Petreczky, arXiv:1012.4433

  - breakup temperature 12 Gev for J/Ψ and 5 GeV for χ_c and Ψ'
  - charmonia have to stay in this hot medium for a proper time of 1 fm/c

SPS



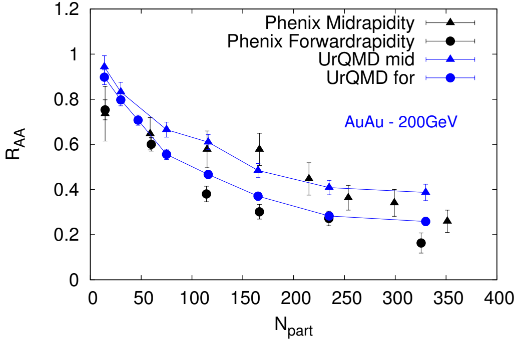
$Pb - Pb, p_{lab} = 158\ GeV$

B.Alessandro et al. (NA50 Collab.), Eur.Phys.J. C39 (2005) 335-345

- prehadronic cross sections are fitted to SPS data
- R_{AA} has not been measured at SPS $\Rightarrow$relative J/Ψ-yield
- shape fits well

RHIC

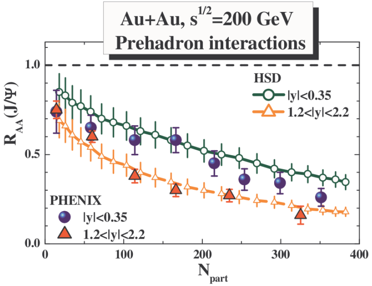
Our model can reproduce rapidity dependence at RHIC



$Au - Au, s^{1/2} = 200\ GeV$

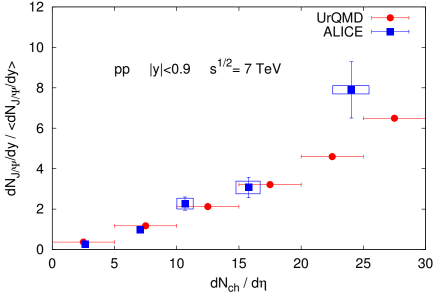
PHENIX, A. Adare et al., Phys. Rev. Lett. 98, 232301 (2007)

- same cross sections used as at SPS energies



E.Bratkovskaya et al., Int.J.Mod.Phys. E17 (2008) 1367-1439

Possible J/Ψ suppression in pp at LHC

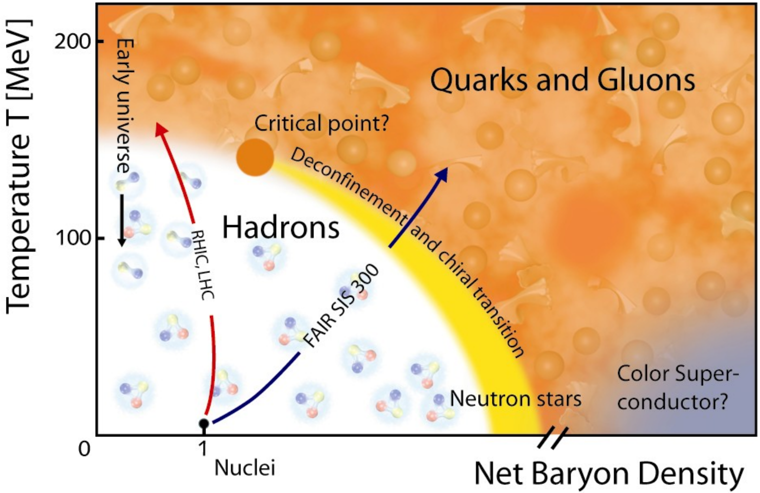


- initial $dN_{ch}/d\eta$ taken from E. G. Ferreiro and C. Pajares, arXiv:1203.5936.

- J/Ψ yield in pp used as reference value for heavy ion collisions
- high energy density $\rightarrow$ comparable to energy densities in heavy ion collisions at SPS and RHIC energies
- possible suppression can be tested using different multiplicity bins

Similar study of medium modification of charm quarks in pp done by S.Vogel et al. (Phys.Rev.Lett 107 (2011) 032302)

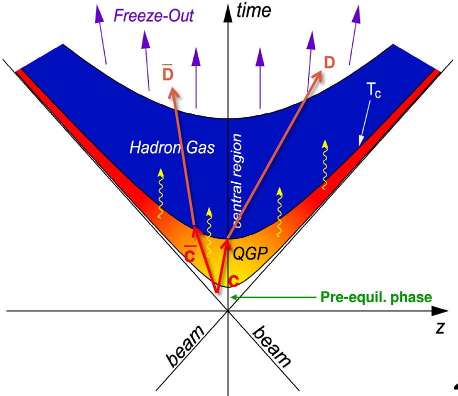
QCD phase diagram



Time evolution in HIC

- Charmonium: $c + \bar{c} \quad \rightarrow J/\Psi, \chi_c, \Psi'$
- Open Charm: $c +$ light quark $\quad \rightarrow$ D-Mesons

- Charm quark mass $\approx 1.5\ GeV$
- charm production at early stage of collision in hard processes
- hadronization when the system cools down
- ideal probe for the whole collision



Debye screening in QGP

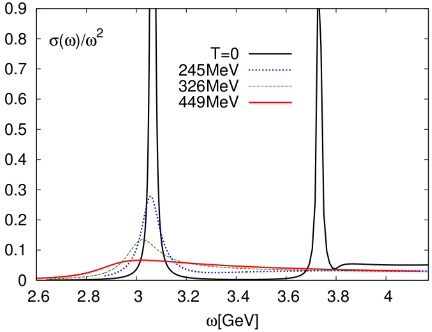
In 1986 T. Matsui and H. Satz proposed that charmonium will be suppressed in QGP.

- charmonium is produced in the initial phase of a heavy ion collision in hard processes
- interaction of c and $\bar{c}$ is weakened by color Debye screening
- charmonium gets dissociated and recombines after QGP phase transition to hadron gas

$\Rightarrow$ suppression of charmonium and enhancement of open charm mesons

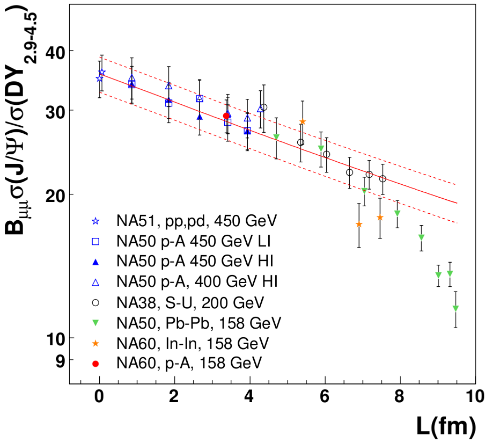
Charmonium melting

- spectral function of charmonium can be calculated using lattice QCD, it broadens in QGP
- dissociation is more likely
- width of the spectral function can be interpreted as life time
- complete breakup only at very high temperatures



C.Miao, A.Mocsy, P.Petreczky, arXiv:1012.4433

Normal suppression



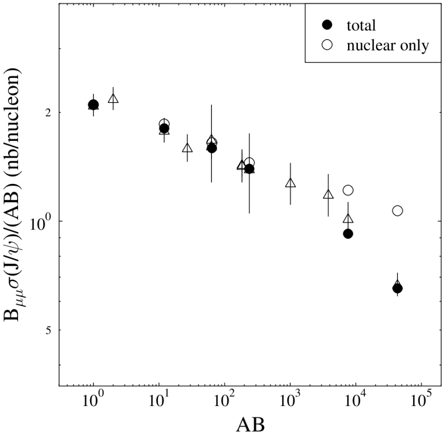
NA50, B. Alessandro et al., Eur. Phys. J. C39, 335 (2005)

- "Anomalous" suppression in central collisions?
- Can hadronic scatterings explain suppression?

Comover scenario

S. Gavin and R. Vogt
Nucl. Phys. B345 (1990) 104.

- charmonium can be dissociated by inelastic scatterings with comoving mesons
- cross sections are in the order of some mb
- gets important in a dense medium, that means central collisions and high collision energies
- improves description of data

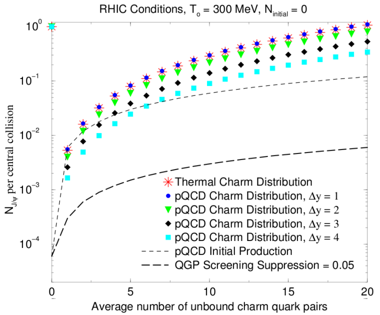


C.Spieles et al., arXiv:9902337v1

Regeneration

- R.L.Thews (R. L. Thews, J. Rafelski, Nucl.Phys. A698 (2002) 575-578) predicts recombination of heavy quarks and anti-quarks which originate from different space-time regions
- formation rate proportional to the square of the number of unbound charm quarks

$\Rightarrow$ J/Ψ-enhancement at RHIC and LHC



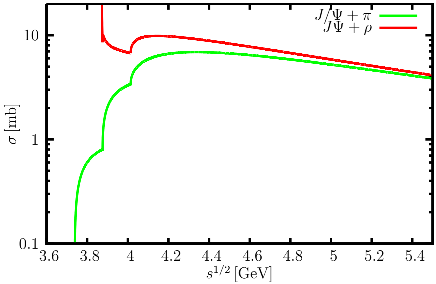
UrQMD

Ultra-Relativistic Quantum Molecular Dynamics Model

- non-equilibrium transport model
- classical trajectories in phase-space (relativistic kinematics): evolution of phase space distribution via Boltzmann equation
- includes all particle resonances and decays up to 2.1 GeV
- cross sections from measurements, additive quark model and detailed balance
- applicable to a huge range of collision energies
- can be coupled with different other models, for example hydro

Dissociation cross sections

$$\sigma_{1+2\to 3+4}(s) = 2^4 \frac{E_1 E_2 E_3 E_4}{s} |M_i|^2 \left(\frac{m_3 + m_4}{\sqrt{s}} \right)^6 \frac{p_f}{p_i}$$

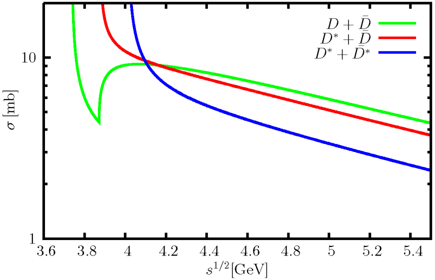


- cross sections with baryons independent on energy
  J/Ψ : 4, 18 mb
  χ_c : 4.18 mb
  Ψ' : 7.6 mb
- meson dissociation from π-, ρ, K and K^*-mesons

E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C67, 054905 (2003)

Regeneration cross sections

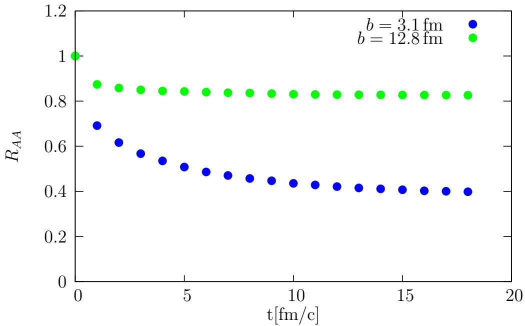
$$\sigma_{3+4\to 1+2}(s) = \sigma_{1+2\to 3+4}(s)\frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\frac{p_f^2}{p_i^2}$$



- $D\bar{D} \to J/\Psi$
- increased cross section for excited D-Mesons
- suppression for strange mesons

E. L. Bratkovskaya, W. Cassing, and H. Stoecker, Phys. Rev. C67, 054905 (2003)

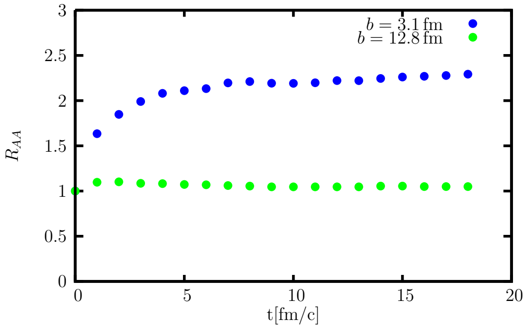
SPS - time evolution



$Pb - Pb, p_{lab} = 200\ GeV,\ 0 < y_{cm} < 1$

- $b = 12.8\ fm$
- $b = 3.1\ fm$

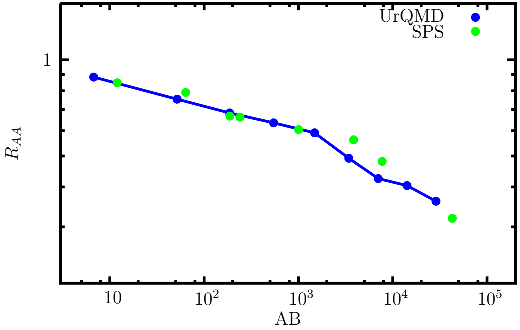
RHIC - Time evolution



$Au - Au, s^{1/2} = 200\ GeV,\ |y| < 0.35$

- $b = 3.1\ fm$
- $b = 12.8\ fm$

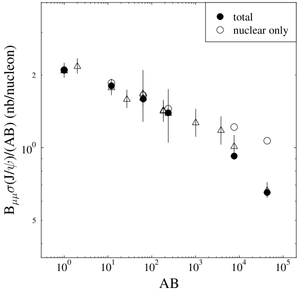
SPS



$Pb - Pb, p_{lab} = 200\ GeV$

M.C. Abreu et al. (NA50 Collab.), Phys. Lett. B410 (1997) 327, 337

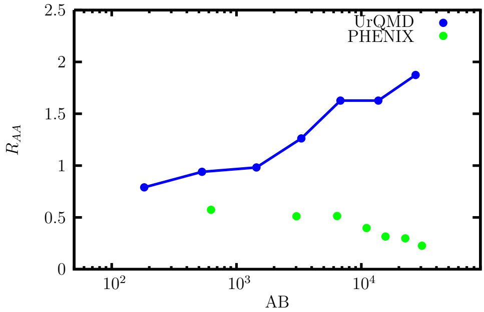
Implementation reproduces schematic calculation of C.Spieles et.al.



C.Spieles et al., arXiv:9902337v1

RHIC - centrality dependence

We can NOT describe charmonium suppression using a purely hadronic model

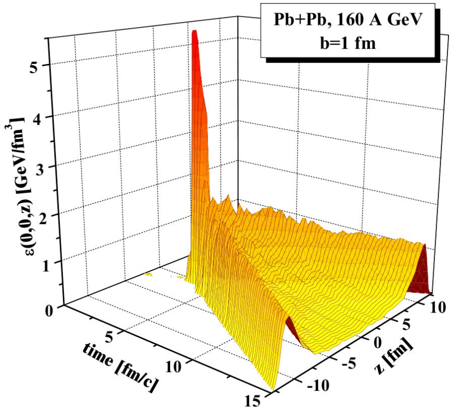


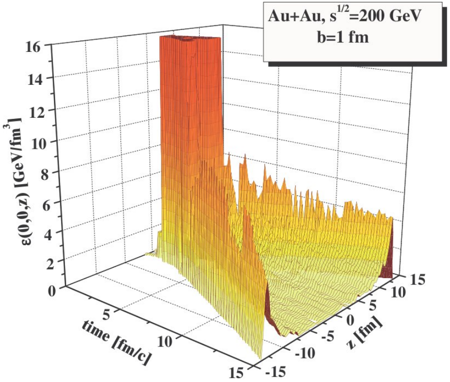
Apparently strong recombination

$Au - Au, s^{1/2} = 200\ GeV,\ |y| < 0.35$

PHENIX, A. Adare et al., Phys. Rev. Lett. 98, 232301 (2007)

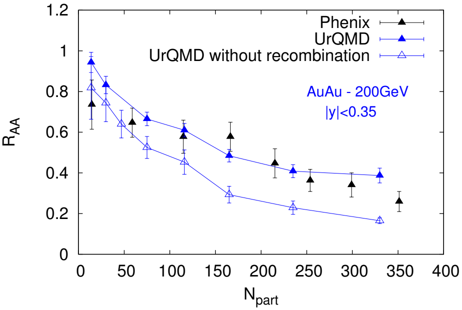
Energy density in heavy ion collisions



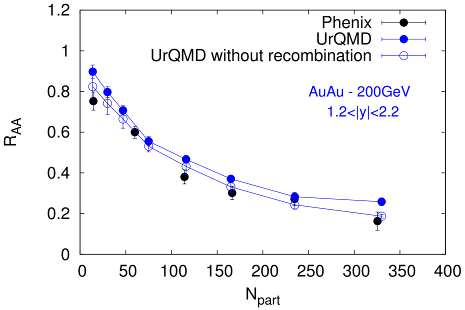


Contribution of recombination

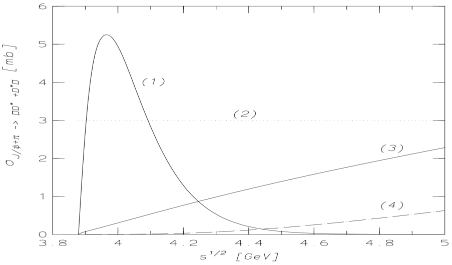
Mid-Rapidity



Forward-Rapidity



Different cross sections

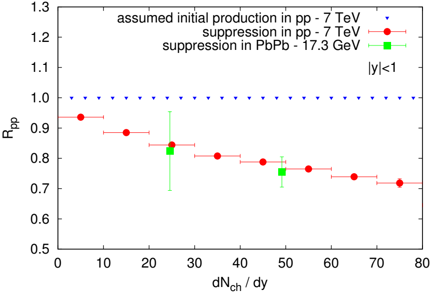


P.Braun-Munzinger, K.Redlich, Eur.Phys.J. C16 (2000) 519-525

- a lot of cross sections on the market
- possibility to test cross sections

1. non-perturbative quark-exchange model (K.Martins et al.)
2. constant cross section of 3 mb (R. Vogt et al.)
3. meson exchange model (S.G. Matinian et al.)
4. perturbative QCD (D. Kharzeev et al.)

Possible J/Ψ suppression in pp at LHC



- suppression reaches up to 30%
- J/Ψ suppression not dependent on collision energy but on particle multiplicity
- measurements at higher particle multiplicities would be helpful

$$R_{pp} = \frac{dN^{final}_{J/\Psi}/dy|_{|y|\leq 1}}{dN^{initial}_{J/\Psi}/dy|_{|y|\leq 1}}$$

Similar study of medium modification of charm quarks in pp done by S.Vogel et al. (Phys.Rev.Lett 107 (2011) 032302)