Heavy Quarks in the UrQMD hybrid approach

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Heavy flavor physics with CBM

Frankfurt, May 27th, 2014

HGS-HIRe for FAIR — Helmholtz Graduate School for Hadron and Ion Research

FIAS Frankfurt Institute for Advanced Studies

H-QM Helmholtz Research School Quark Matter Studies

Outline

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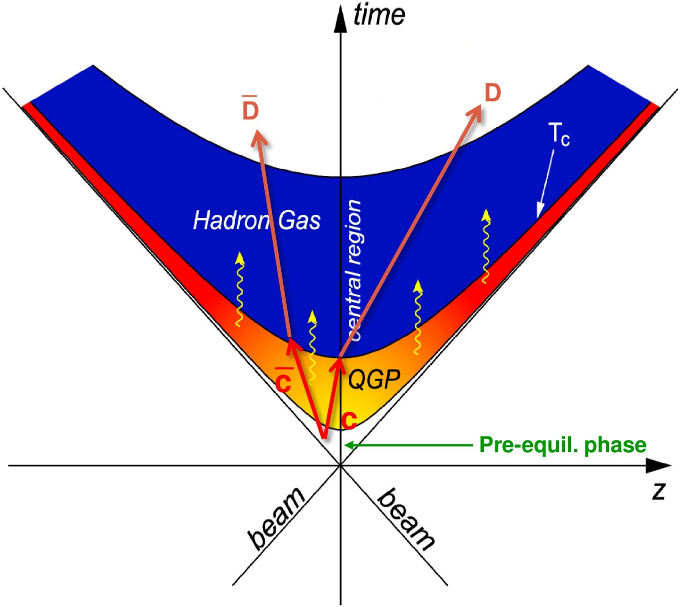
The evolution of heavy-ion collisions



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

  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

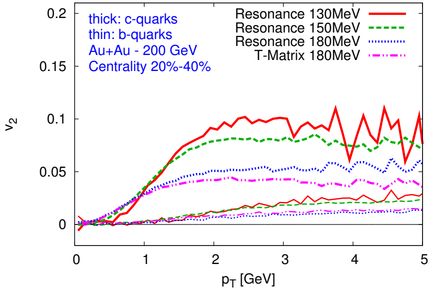
    H. van Hees and Ralf Rapp, 034907
  - T-Matrix approach ⇒ static quark-antiquark potentials are used to calculate the scattering-matrix elements for the elastic scattering of heavy quarks with light quarks

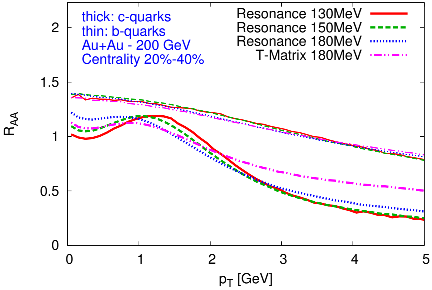
    H. van Hees and M. Mannarelli and V. Greco and R. Rapp, 192301
- calculation for different decoupling temperatures
- have a look at the influence of a k-factor on the results
- test of fragmentation (Peterson) and coalescence as hadronization mechanism

For the semileptonic decay to electrons we use PYTHIA

Outline

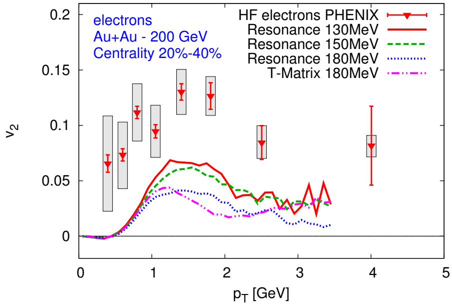
Results for charm and bottom quarks

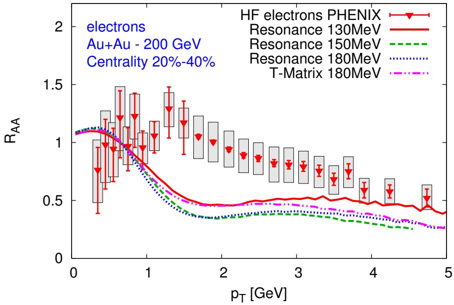




- Medium modification for charm quarks higher than for bottom quarks due to smaller mass
- resonance model and T-Matrix approach show similar results
- Elliptic flow strongly depends on decoupling temperature from the medium

v_2 and R_{AA} using Peterson fragmentation



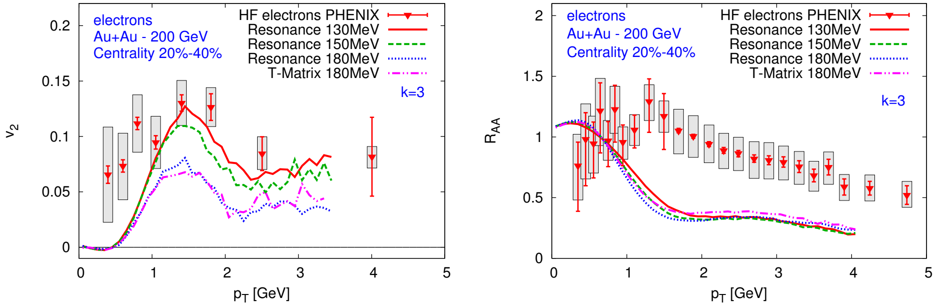


- modification for the flow is to low, for the R_{AA} to high
- Resonance model and T-Matrix approach show similar results

All RHIC results published in:

T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1212.0696

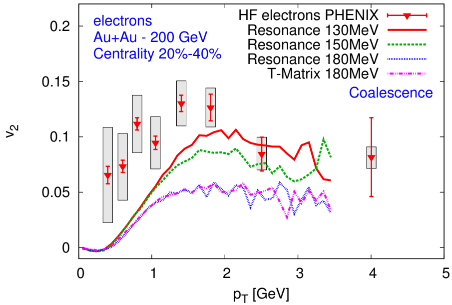
v_2 and R_{AA} using a k-factor of 3

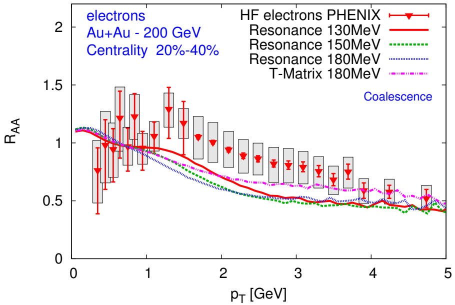


- v_2 description is improved, R_{AA} description gets worse
- the use of a k-factor does not allow for a consistent description of v_2 and R_{AA}

T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1212.0696

v_2 and R_{AA} using coalescence

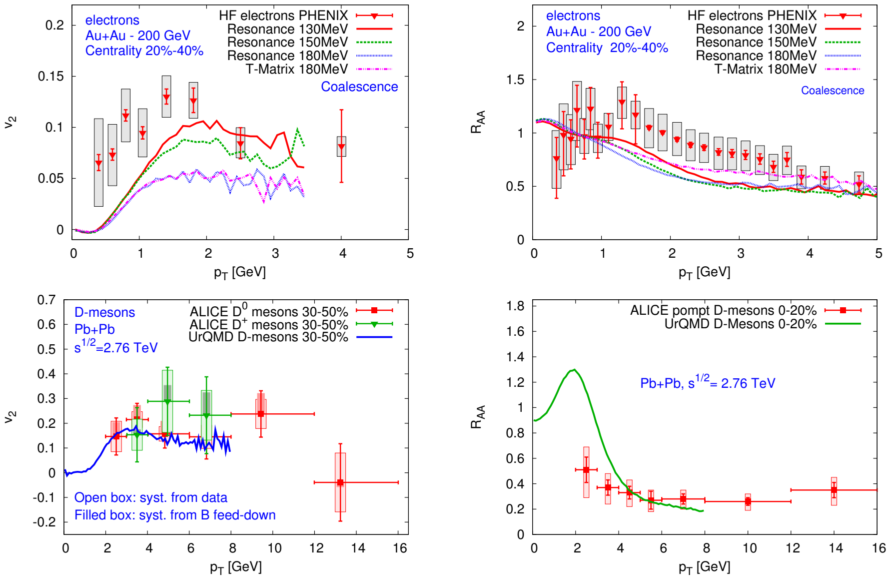




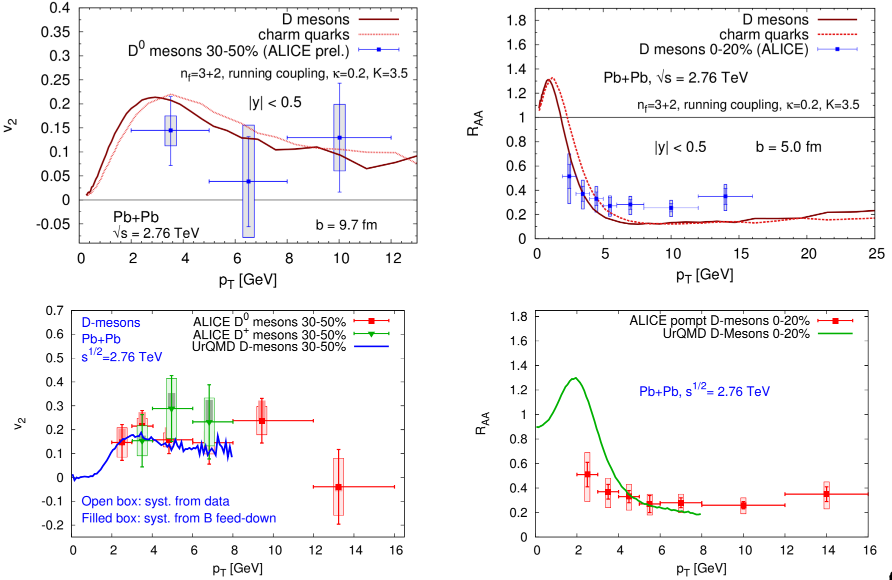
- the coalescence mechanism increases the input of the bulk medium on the heavy quarks
- coalescence improves our results considerably
- for low decoupling temperatures a reasonable agreement to data is reached

T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1212.0696

Results for D-mesons and non-photonic single electrons



Comparison to the BAMPS results

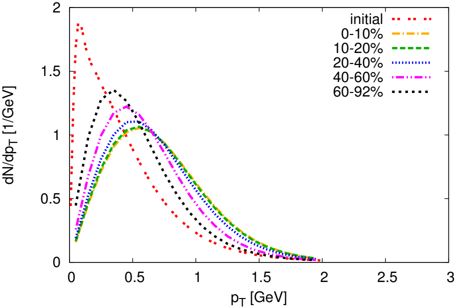


J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys.Lett. B717 (2012) 430-435

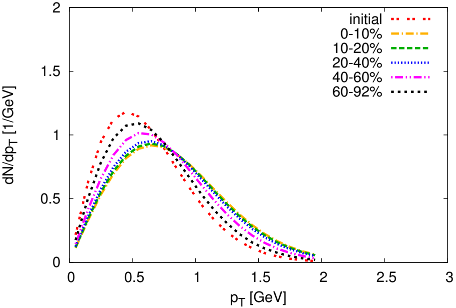
Outline

p_T-spectra for FAIR energies

- For FAIR we use the resonance model with a decoupling temperature of 130 MeV



HSD spectra

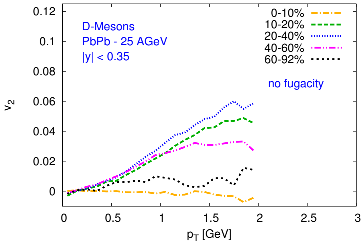


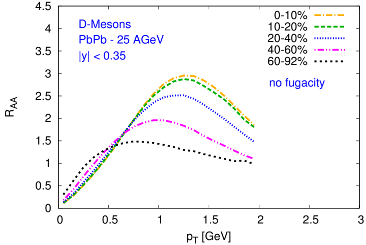
PYTHIA spectra

Pb+Pb, 25 AGeV

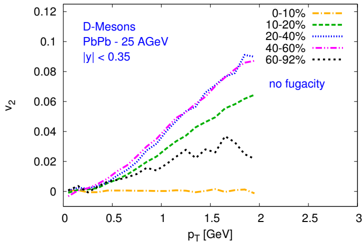
Centrality dependence of v_2 and R_{AA} at FAIR

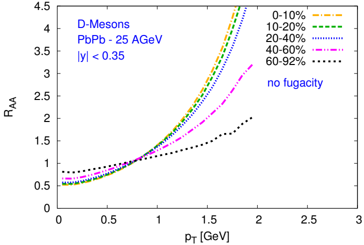
HSD





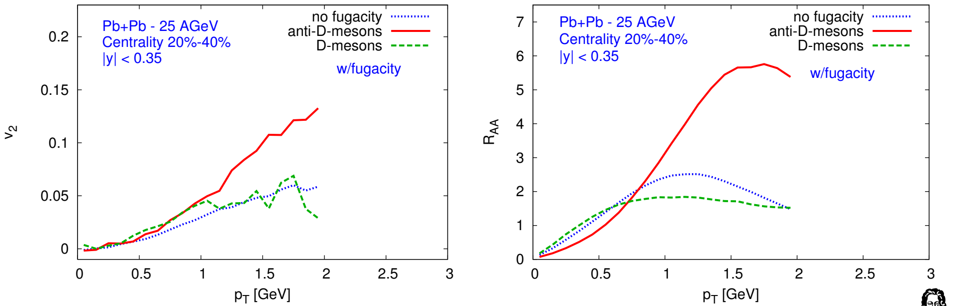
PYTHIA





D-mesons at FAIR as test for the resonance model

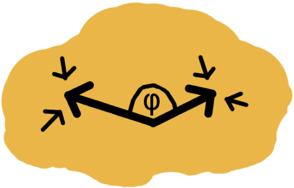
- Net baryon densities are much higher
  $\Rightarrow$ we need to correct our calculations for the different matter and anti-matter densities $\Rightarrow e^{-\mu_B/T}$
- Heavy quarks stay in the hot medium much longer
  $\Rightarrow$ quarks at low momentum are heated up

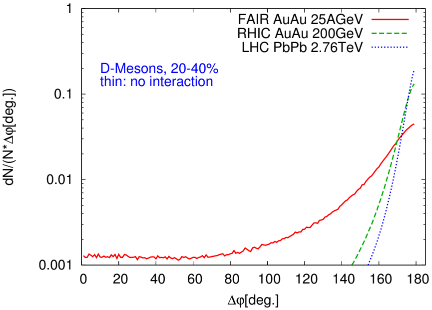


Outline

Correlations

- Correlations teach us more about the interactions in the medium
- Decay electrons of correlated D-mesons contribute to invariant mass spectrum
- Invariant mass spectrum can help us to estimate the thermal QGP background radiation





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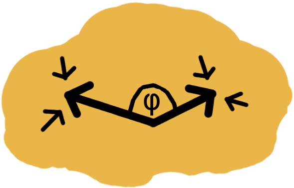

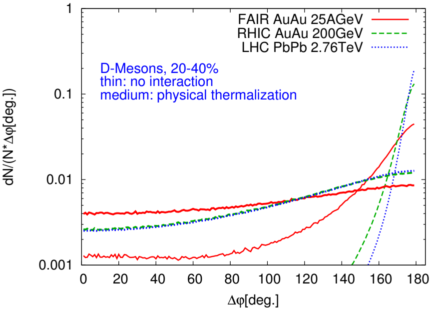

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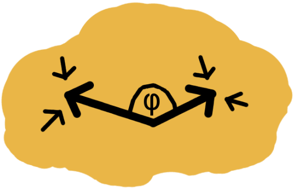
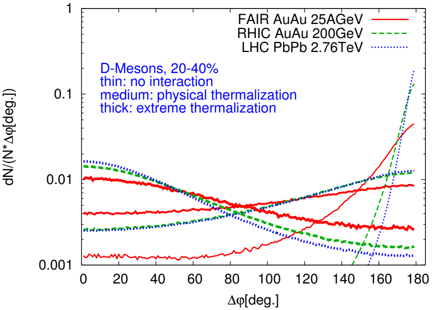
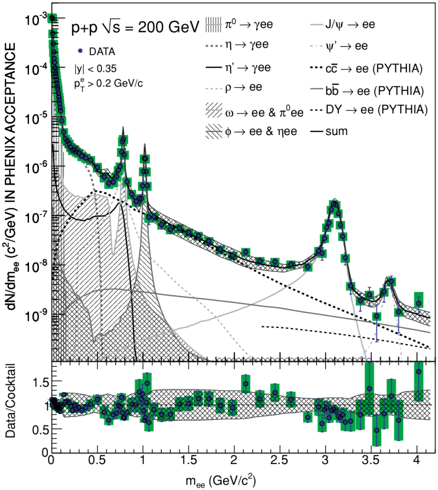
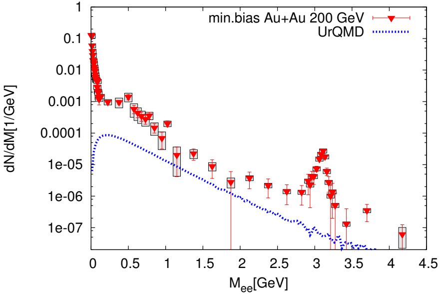




Estimation of thermal QGP radiation





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

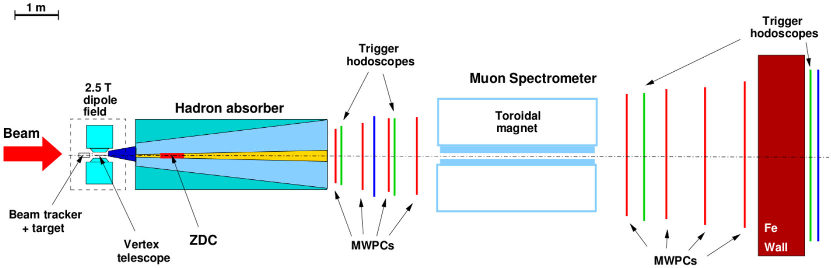
Outline

Summary

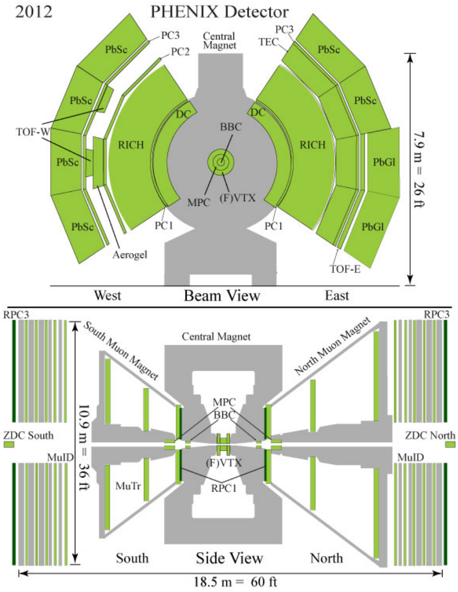
- heavy quarks are an excellent tool to probe the QGP
- heavy quark propagation in the QGP phase modelled utilizing a Langevin formalism
- late phase of the collision is very important
- use of a k-factor does not allow for a consistent description of both v_2 and R_{AA}
- coalescence mechanism accounts for the missing input from the bulk medium
- predictions for FAIR energies at different centralities, initial spectra are very important
- predictions at FAIR can serve as a test for the resonance model
- correlations and invariant mass spectra of D-Mesons and their decay products at FAIR, RHIC and LHC energy
- dilepton mass spectrum from D-meson decays leads to estimation of thermal QGP radiation

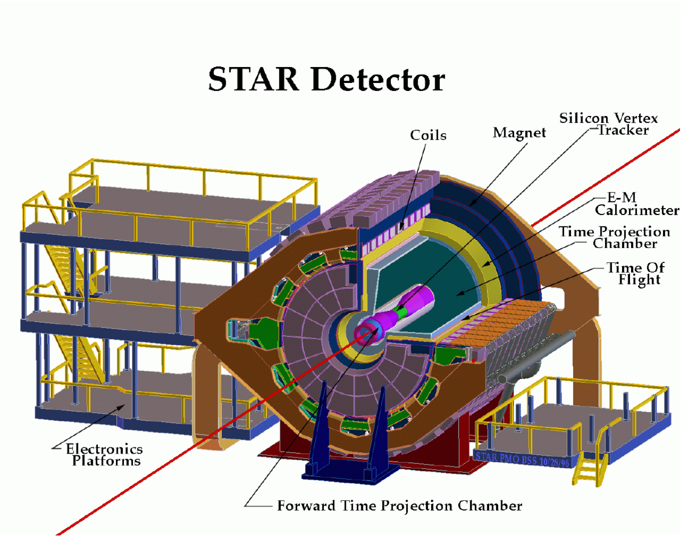
Backup

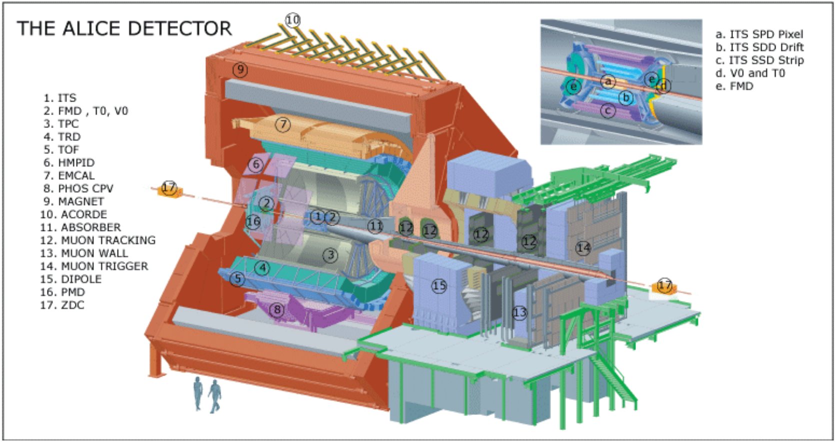
NA60


1 m
Beam
2.5 T
dipole
field
Hadron absorber
Trigger
hodoscopes
Muon Spectrometer
Toroidal
magnet
Trigger
hodoscopes
Beam tracker
+ target
Vertex
telescope
ZDC
MWPCs
MWPCs
Fe
Wall

PHENIX


2012
PHENIX Detector
PbSc
PC3
PC2
Central Magnet
TEC
PC3
PbSc
PbSc
PbSc
TOF-W
DC
DC
PbSc
BBC
RICH
RICH
PbSc
PbGl
MPC
(F)VTX
PbSc
PC1
PC1
PbGl
Aerogel
TOF-E
7.9 m = 26 ft
West
Beam View
East
RPC3
RPC3
South Muon Magnet
Central Magnet
North Muon Magnet
MPC
BBC
ZDC South
ZDC North
MuID
MuID
10.9 m = 36 ft
(F)VTX
MuTr
RPC1
South
Side View
North
18.5 m = 60 ft


STAR Detector
Coils
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber
STAR PMO BSS 10/28/96


THE ALICE DETECTOR
1. ITS
2. FMD , T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCAL
8. PHOS CPV
9. MAGNET
10. ACORDE
11. ABSORBER
12. MUON TRACKING
13. MUON WALL
14. MUON TRIGGER
15. DIPOLE
16. PMD
17. ZDC
a. ITS SPD Pixel
b. ITS SDD Drift
c. ITS SSD Strip
d. V0 and T0
e. FMD

Boltzmann-equation

$$\left(\frac{\partial}{\partial t} + \vec{v}\nabla_{\vec{x}} + \frac{1}{m}\cdot\vec{F}\nabla\vec{v}\right) f(\vec{x},\vec{v},t) = \left.\frac{\partial f}{\partial t}\right|_{coll}$$

$$\left.\frac{\partial f}{\partial t}\right|_{coll} = \int W(\vec{v}_1,\vec{v}_3,\vec{v}_3,\vec{v})\cdot$$

$$[f(\vec{x},\vec{v}_1,t)f(\vec{x},\vec{v}_2,t) - f(\vec{x},\vec{v}_3,t)f(\vec{x},\vec{v},t)]d\vec{v}_1 d\vec{v}_2 d\vec{v}_3$$

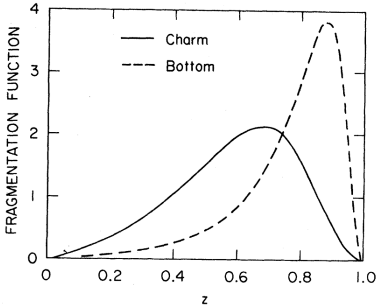
Petersen fragmentation

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

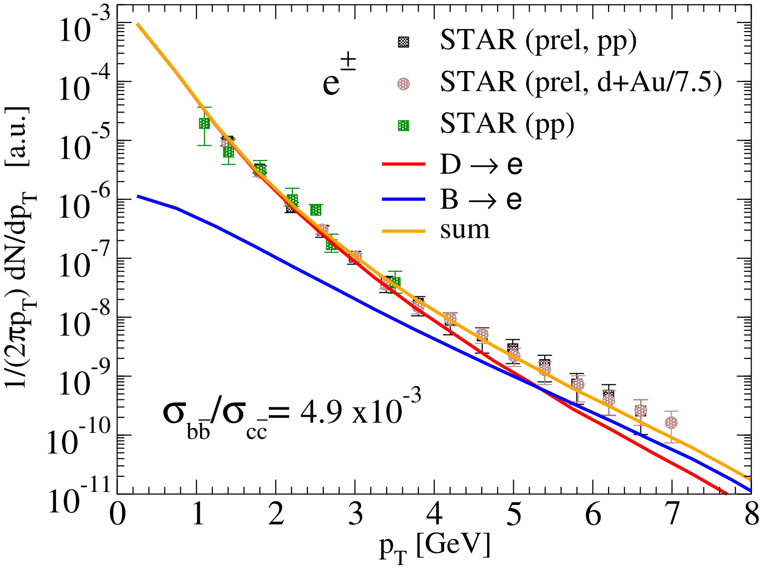
N: normalization constant

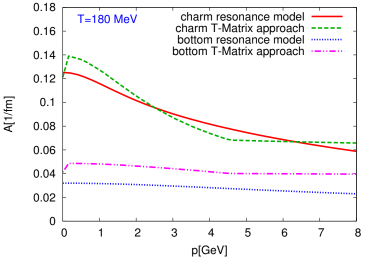
z: relative momentum fraction

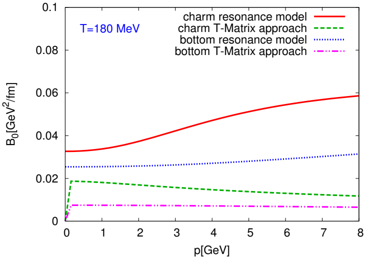
ϵ_Q: 0.05 (0.005) for charm (bottom)



RHIC initial spectrum




T=180 MeV
charm resonance model
charm T-Matrix approach
bottom resonance model
bottom T-Matrix approach
A[1/fm]
p[GeV]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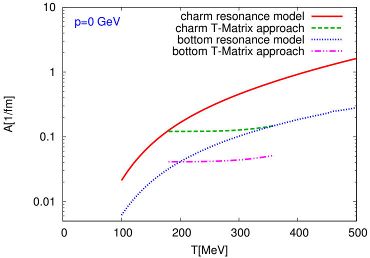
bottom T-Matrix approach
B_0[GeV^2/fm]
p[GeV]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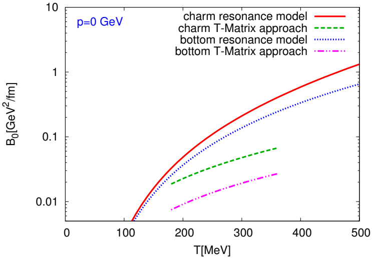
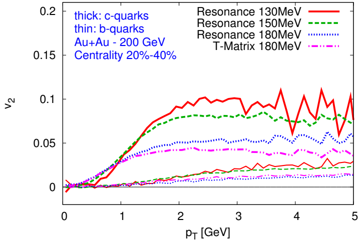
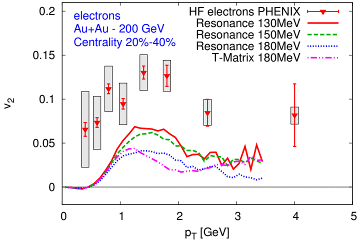
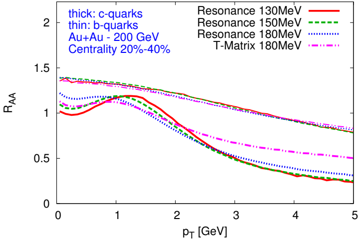
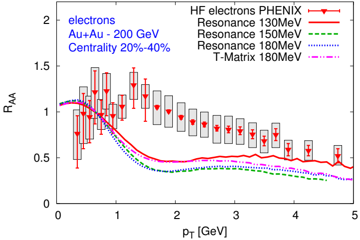

p=0 GeV
charm resonance model
charm T-Matrix approach
bottom resonance model
bottom T-Matrix approach
B_0[GeV^2/fm]
T[MeV]

Calculation using fragmentation

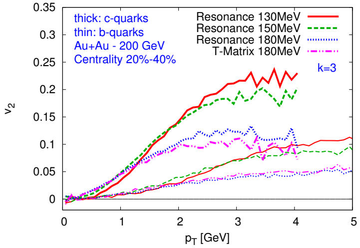


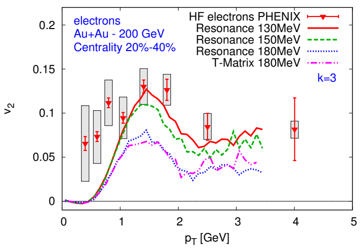


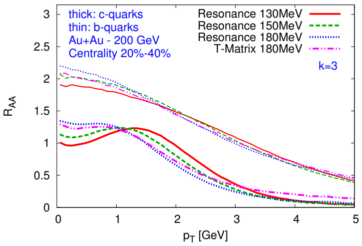


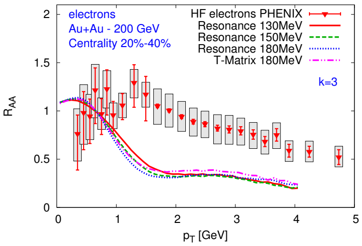


Calculation with k-factor

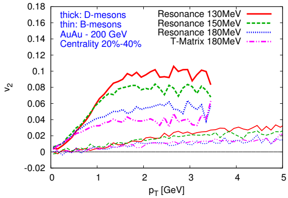


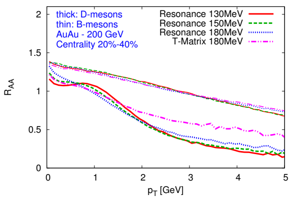


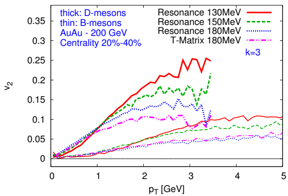


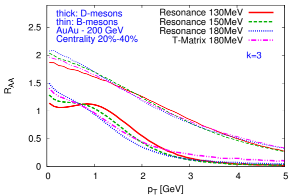


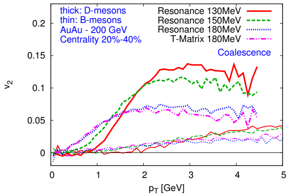
D-meson and B-meson spectra

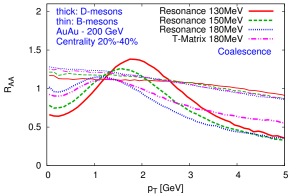




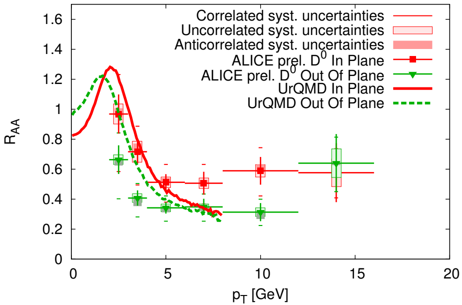


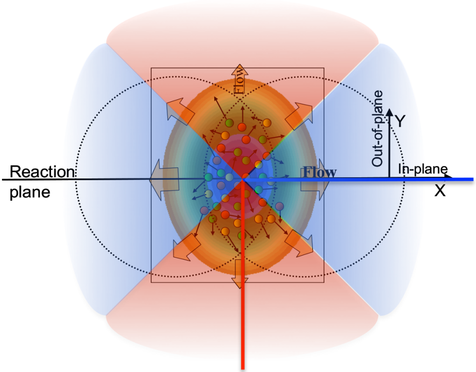






D-meson R_{AA} relative to the reaction plane





Cooper-Frye equation

$$E\,\frac{\mathrm{d}N}{\mathrm{d}^3p} = g_i \int_\sigma f(x,p)p_\mu \mathrm{d}\sigma_\mu$$

Hydrodynamics

$$\partial_\mu S^\mu \geq 0 \tag{1}$$

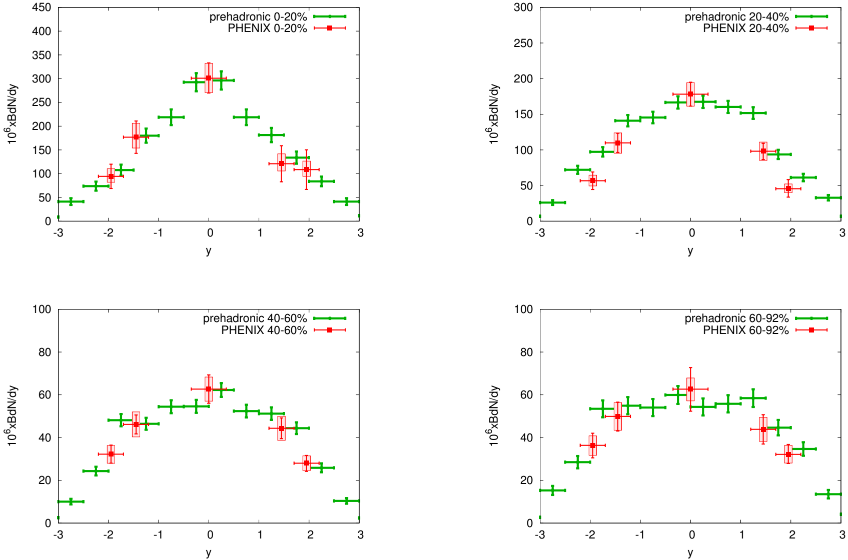
$$\partial_\mu T^{\mu\nu} = 0 \tag{2}$$

$$\partial_\mu N^\mu = 0 \tag{3}$$

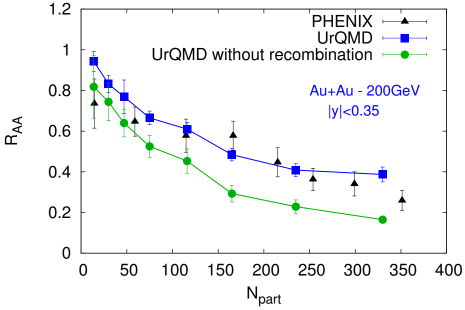
$$\begin{aligned} T^{\mu\nu} &= \frac{1}{(2\pi)^3}\int \frac{d^3p}{E} p^\mu p^\nu f(x,p) \\ &= (\epsilon + p)u^\mu u\nu - pg^{\mu\nu} \end{aligned} \tag{4}$$

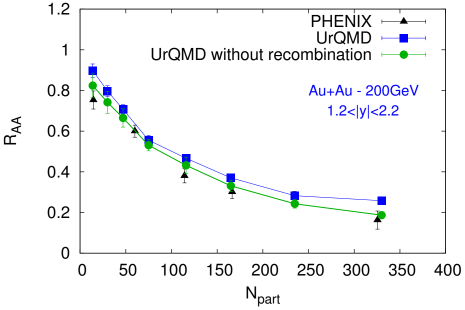
$$\begin{aligned} N^\mu &= \frac{1}{(2\pi)^3}\int \frac{d^3p}{E} p^\mu f(x,p) \\ &= nu^\mu \end{aligned} \tag{5}$$

Rapidity spectra

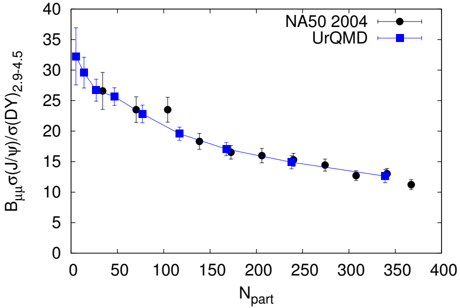


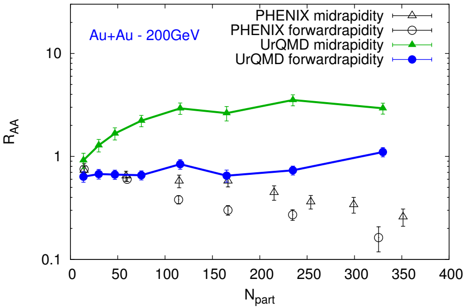
Recombination



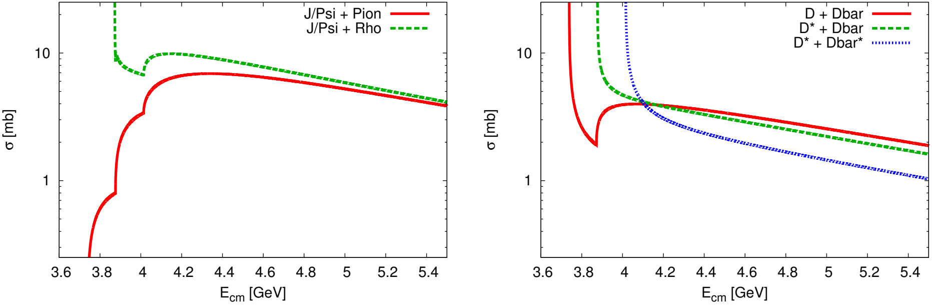


Hadronic approach





Two-body transition model



Two-body transition model

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

$$p_i = \sqrt{\frac{(s-(m_1+m_2)^2)(s-(m_1-m_2)^2)}{4s}}$$

$$p_f = \sqrt{\frac{(s-(m_3+m_4)^2)(s-(m_3-m_4)^2)}{4s}}$$

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

$$\begin{aligned}\mathscr{L}_{Dcq} =& \mathscr{L}_D^0 + \mathscr{L}_{c,q}^0 - \mathrm{i}G_S\left(\bar{q}\Phi_0^*\frac{1+\not{v}}{2}c - \bar{q}\gamma^5\Phi\frac{1+\not{v}}{2}c + h.c.\right)\\ &- G_V\left(\bar{q}\gamma^\mu\Phi_\mu^*\frac{1+\not{v}}{2}c - \bar{q}\gamma^5\gamma^\mu\Phi_{1\mu}\frac{1+\not{v}}{2}c + \mathrm{h.c.}\right),\end{aligned}$$

$$\begin{aligned}\mathscr{L}_{c,q}^0 &= \bar{c}(\mathrm{i}\not{\partial} - m_c)c + \bar{q}\,\mathrm{i}\not{\partial}q,\\ \mathscr{L}_D^0 &= (\partial_\mu\Phi^\dagger)(\partial^\mu\Phi) + (\partial_\mu{\Phi_0}^{*\dagger})(\partial^\mu\Phi_0^*) - m_S^2(\Phi^\dagger\Phi + \Phi_0^{*\dagger}\Phi_0^*)\\ &- \frac{1}{2}(\Phi_{\mu\nu}^{*\dagger}\Phi^{*\mu\nu} + \Phi_{1\mu\nu}^\dagger\Phi_1^{\mu\nu}) + m_V^2(\Phi_\mu^{*\dagger}\Phi^{*\mu} + \Phi_{1\mu}^\dagger\Phi_1^\mu),\end{aligned}$$

T-Matrix approach

$$\begin{aligned} T_{a,l}(E;q',q) = V_{a,l}(q',q) \\ &+ \frac{2}{\pi}\int \mathrm{d}k\ k^2 V_{a,l}(q',k) G_{Qq}(E,k) \\ &\times T_{a,l}(E;k,q)[1 - f_F(\omega_k^Q) - f_F(\omega_k^q)], \end{aligned}$$

$$G_{qQ}(E,k) = \frac{1}{E - (\omega_k^q + \mathrm{i}\Sigma_l^q) - (\omega_k^Q + \mathrm{i}\Sigma_l^Q)}$$

Fokker-Planck equation

$$\frac{\partial}{\partial t} f_Q(t,p) = \frac{\partial}{\partial p_i}\left(A_i(p) f_Q(t,p) + \frac{\partial}{\partial p_j}[B_{ij}(p) f_Q(t,p)]\right) \qquad (6)$$

Publications

- "Charmonium suppression in the UrQMD transport model"
  T. Lang, M. Bleicher, Acta Phys.Polon.Supp., 5:573578, 2012
- "Possibility for J/Ψ suppression in high multiplicity proton-proton collisions at $\sqrt{s_{NN}} = 7\,\text{TeV}$" T. Lang, M. Bleicher, Phys.Rev., C87:024907, 2013, arXiv:1302.0655

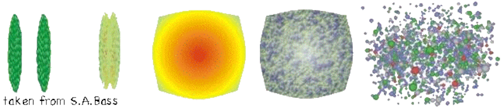
- "Heavy quark transport in heavy-ion collisions at RHIC and LHC within the UrQMD transport model"
  T. Lang, H. van Hess, J. Steinheimer, M. Bleicher, 2012, arXiv:1211.6912
- "Heavy quark transport at RHIC and LHC"
  T. Lang, H. van Hess, J. Steinheimer, M. Bleicher, J.Phys.Conf.Ser., 426:012032, 2013, 1212.0696
- "Charm quark transport in Pb+Pb reactions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ from a (3+1) dimensional hybrid approach"
  T. Lang, H. van Hess, J. Steinheimer, M. Bleicher, 2012, arXiv:1208.1643
- "Elliptic flow and nuclear modification factors of D-mesons at FAIR in a Hybrid-Langevin approach"
  T. Lang, H. van Hess, J. Steinheimer, M. Bleicher, 2013, arXiv:1305.1797
- "Dileptons from correlated D- and $\overline{\text{D}}$-meson decays in the invariant mass range of the QGP thermal radiation using the UrQMD-hybrid model"
  T. Lang, H. van Hess, J. Steinheimer, M. Bleicher, 2013, arXiv:1305.7377
- "Correlated D-meson decays competing against thermal QGP dilepton radiation" T. Lang, H. van Hess, J. Steinheimer, M. Bleicher, 2013, arXiv:1306.2798

The Ultrarelativistic 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

M. Bleicher et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896

The UrQMD-hybrid model



- Non-equilibrium initial conditions for the medium evolution
- Hydrodynamic medium evolution
- Freeze-out via hadronic cascade

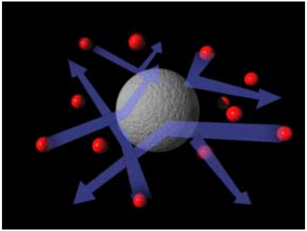
H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stöcker, Phys. Rev. C 78 (2008) 044901

How can we model heavy quarks in the QGP?

Heavy quarks are heavier than the bulk medium

- Background of light particles for the medium evolution
- Heavy quarks are put on top of this background medium
- Heavy quarks carry out a Brownian motion

- FRICTION and DRAG
  $\Rightarrow$ mean interaction with the medium
- DIFFUSION
  $\Rightarrow$ microscopic random hits from the medium



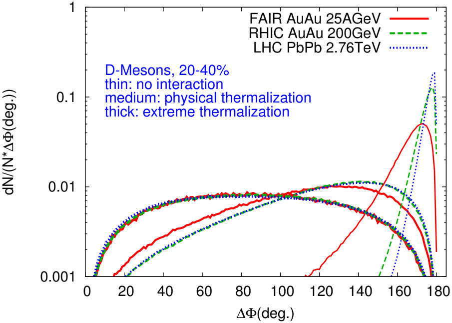
We initialize the heavy quarks

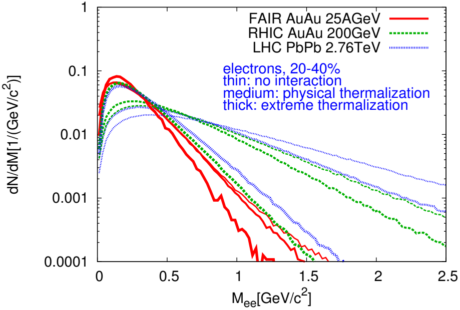
- Heavy quarks are placed at nucleus-nucleus collision space-time coordinates
- Momenta of the heavy quarks are fitted to experimental data

We propagate the heavy quarks

- Test of different drag and diffusion coefficients for heavy quark propagation
  - resonance model: open heavy-flavour resonances exist in the medium
  - T-Matrix approach: quark-antiquarks potentials for elastic scattering of heavy quarks with light quarks
- Calculation for different decoupling temperatures in case of the resonance model

Correlations and invariant mass spectrum





Invariant dilepton spectrum at RHIC