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Dileptons and Charm Dynamics at FAIR energies

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27.02.2007 , CBM Workshop » What do we learn from dilepton measurements in heavy-ion collisions? »,
GSI, Darmstadt

Introduction

FAIR energies are well suited to study **dense and hot nuclear matter –**

- a phase transition to QGP ,
- chiral symmetry restoration,
- in-medium effects

Way to study:

Experimental **energy scan** of different **observables** in order to find an **‚anomalous‘** behaviour in comparison with theory

Observables for CBM:

- Excitation function of particle yields and ratios
- Transverse mass spectra
- Collective flow
- Dileptons
- Open and hidden charm
- Fluctuations and correlations
- ...

Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions

Basic concept of HSD

HSD – Hadron-String-Dynamics transport approach

- for each particle species *i* (*i* = *N*, *R*, *Y*, π, ρ, K, …) the phase-space density f_i follows the **transport equations**

$$\left(\frac{\partial}{\partial t} + \left(\nabla_{\vec{p}} H\right) \nabla_{\vec{r}} - \left(\nabla_{\vec{r}} H\right) \nabla_{\vec{p}} \right) f_i(\vec{r}, \vec{p}, t) = I_{coll}(f_1, f_2, ..., f_M)$$

with collision terms I_{coll} describing:

- elastic and inelastic **hadronic reactions:** baryon-baryon, meson-baryon, meson-meson
- formation and decay of **baryonic and mesonic resonances**
- **string** formation and decay (for inclusive particle production: BB –> X , mB –>X, X =many particles)

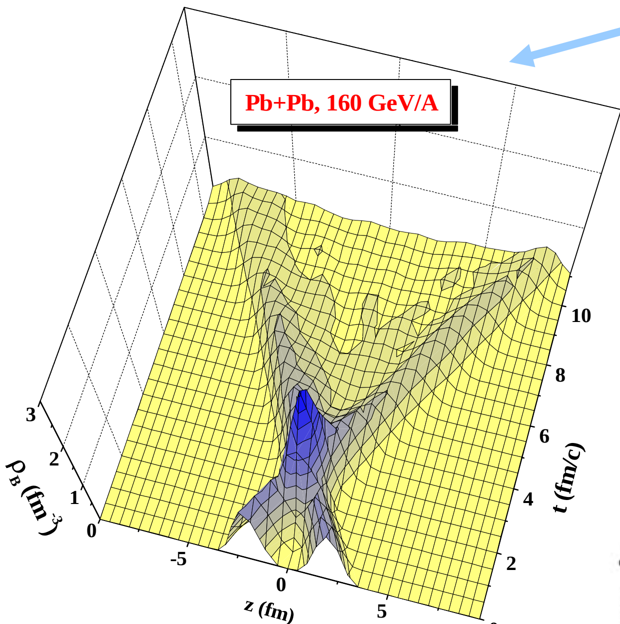
BB <–> B´B´, BB <–> B´B´m
mB <–> m´B´, mB <–> B´

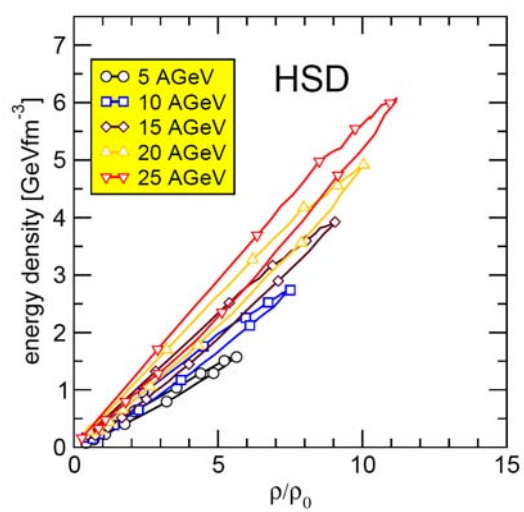
Baryons:
B=(p, n, Δ(1232), N(1440), N(1535), ...)
Mesons:
m=(π, η, ρ, ω, φ, ...)

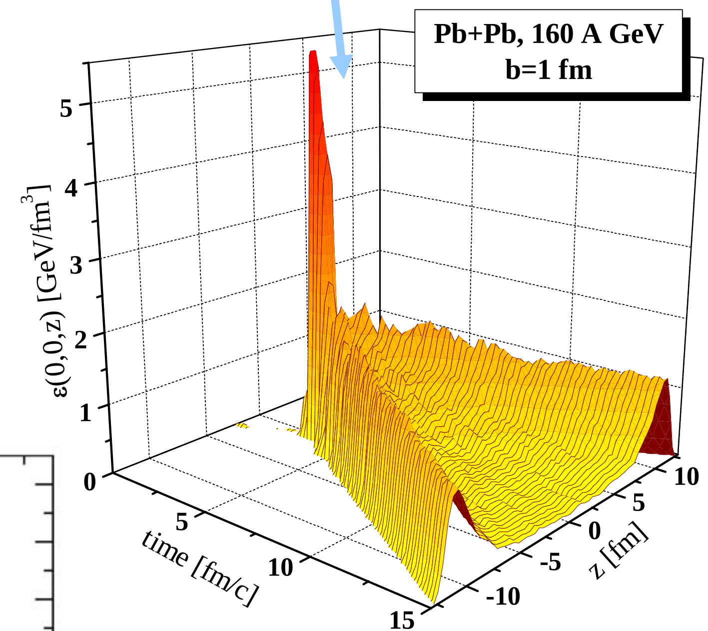
- implementation of **detailed balance** on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-particle reactions in HSD)
- **off-shell dynamics** for short-lived states

Dense and hot matter – average quantities

Time evolution of the baryon density and energy density







huge energy and baryon densities are reached ($\varepsilon > \varepsilon_{crit}$=1 GeV/fm^3) at FAIR energies (> 5 A GeV)

Changes of the particle properties in the hot and dense baryonic medium

In-medium models:

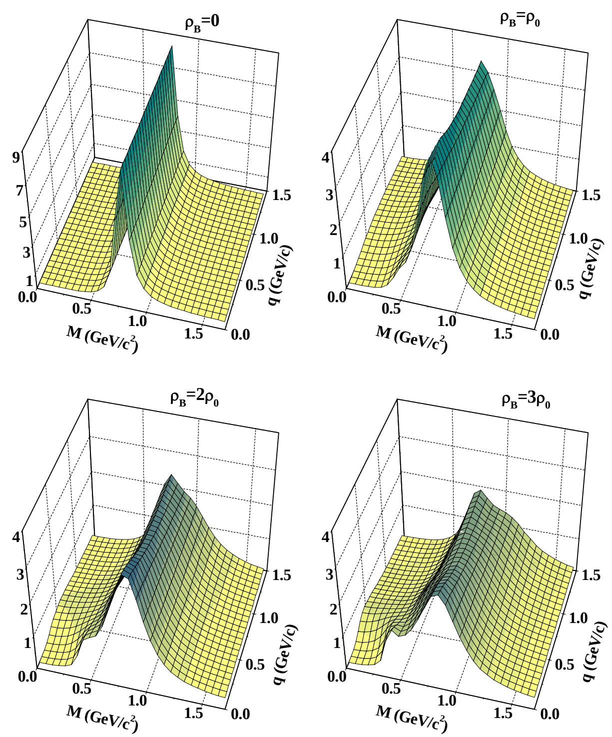
- chiral perturbation theory
- chiral SU(3) model
- coupled-channel G-matrix approach
- chiral coupled-channel effective field theory

predict changes of the particle properties in the hot and dense medium, e.g. **broadening of the spectral function**

ρ meson spectral function

$-\mathrm{Im}\, D_\rho\ (M, q, \rho_B, T)\ (\mathrm{GeV}^{-2})$

T=150 MeV



How to treat in-medium effects in transport approaches?

From on-shell to off-shell transport dynamics

W. Cassing et al., NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Off-shell transport approach:

Generalized transport equations on the basis of the Kadanoff-Baym equations for Greens functions

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Dynamical equations of motion for ‚test-particle' propagation in 8-dimensional phase space (r(t), p(t), E(t)):

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_{i} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

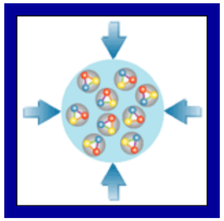
Application to strangeness:

In-medium transition rates with momentum, temperature and density dependent spectral function of antikaons from a coupled channel G-matrix approach

W. Cassing, L. Tolos, E.L.B., A. Ramos., NPA 727 (2003) 59

Application to dileptons:

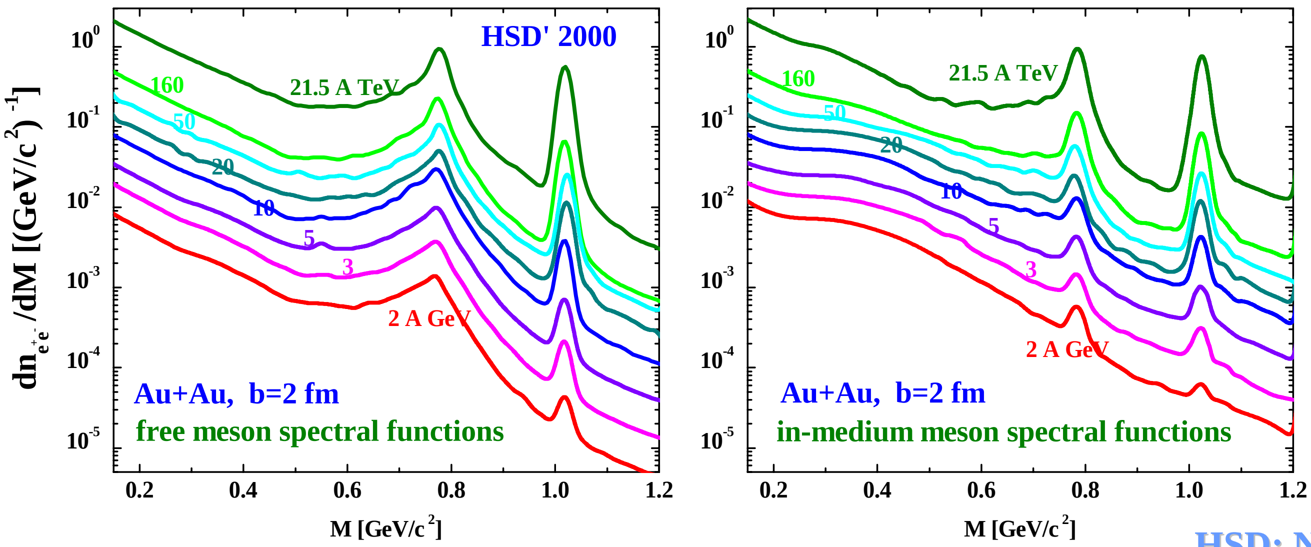
In-medium transition rates with momentum and density dependent dynamical spectral functions of vector mesons E.L..B., NPA 686 (2001), HSD predictions for CBM (2006)



Dileptons

Dileptons are an ideal probe for vector meson spectroscopy in the nuclear medium and for the nuclear dynamics !

Dileptons: excitation function for central Au+Au



HSD: NPA 674 (2000) 249

- In-medium effects can be observed at all energies from SIS to RHIC
- The shape of the theoretical dilepton yield depends on the actual model for the in-medium spectral function

=> energy scan will allow to distinguish in-medium scenarios

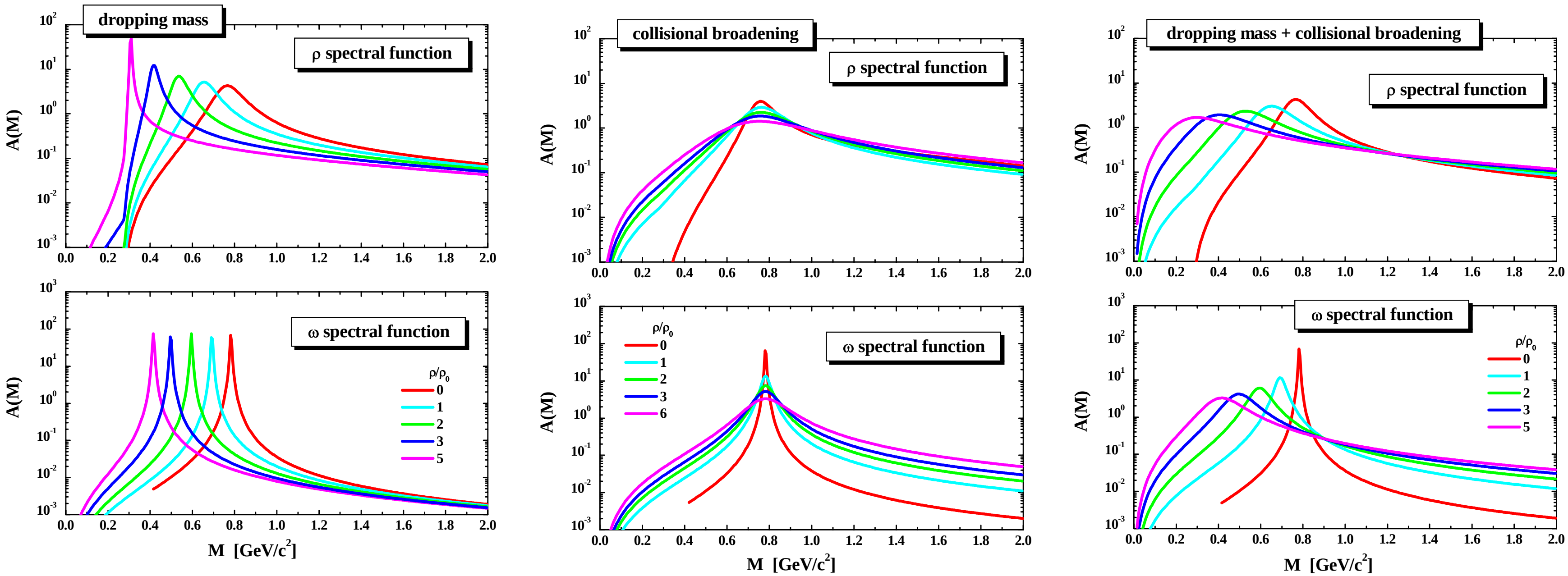
Modelling of in-medium spectral functions for vector mesons

In-medium scenarios:

dropping mass | **collisional broadening** | **dropping mass + coll. broad.**

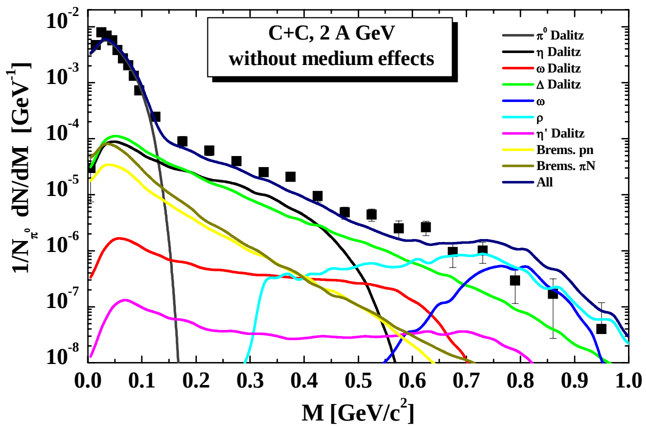
$m^* = m_0(1 - \alpha\rho/\rho_0)$

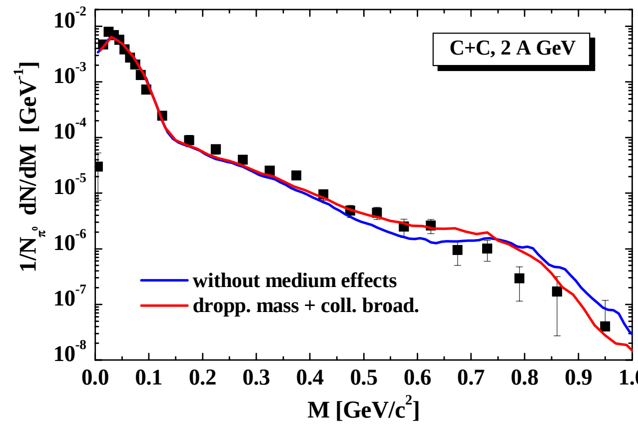
$\Gamma(M,\rho) = \Gamma_{vac}(M) + \Gamma_{CB}(M,\rho)$

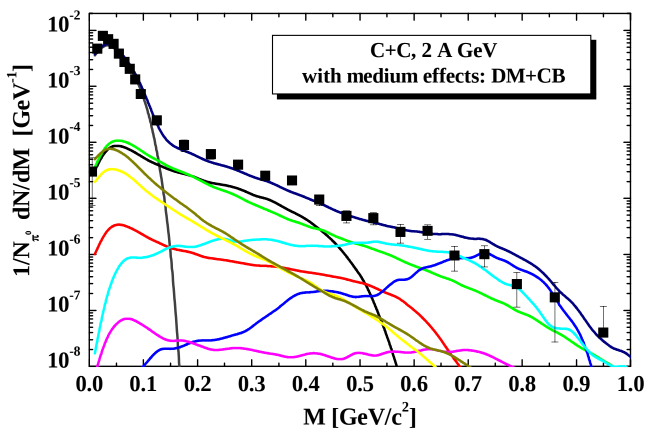


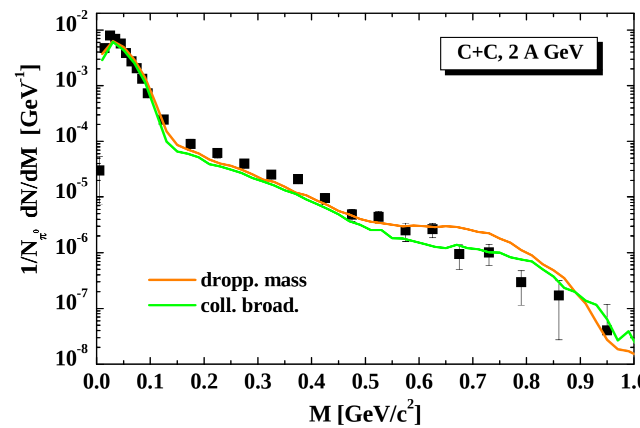
• **Note:** for a consistent off-shell transport one needs not only in-medium spectral functions but also in-medium transition rates for all channels with vector mesons, i.e. the full knowledge of in-medium off-shell cross sections $\sigma(s,\rho)$

Dileptons: HADES



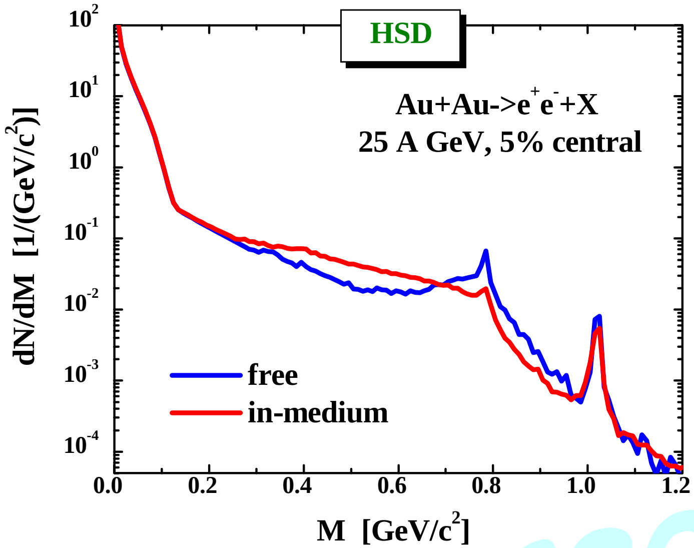


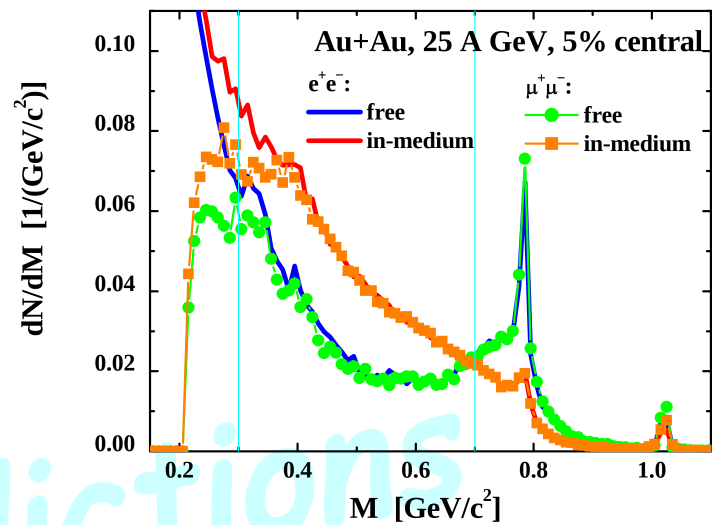


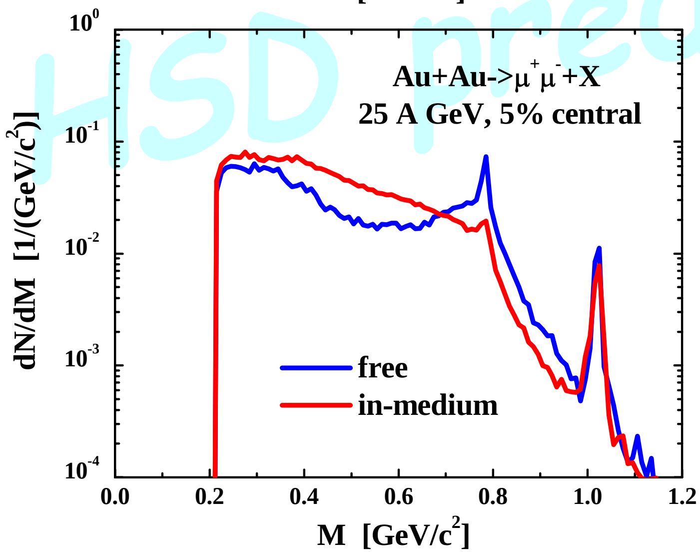


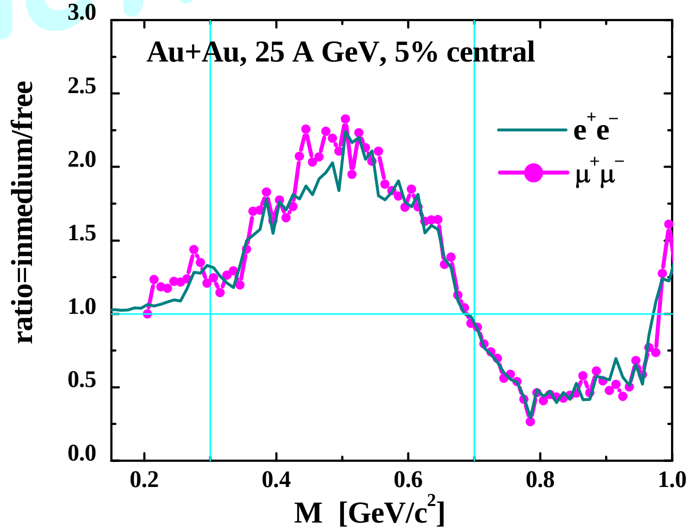
- HADES data show exponentially decreasing mass spectra
- Data are better described by in-medium scenarios with collisional broadening
- In-medium effects are more pronounced for heavy systems such as Au+Au

Dileptons – HSD predictions for CBM









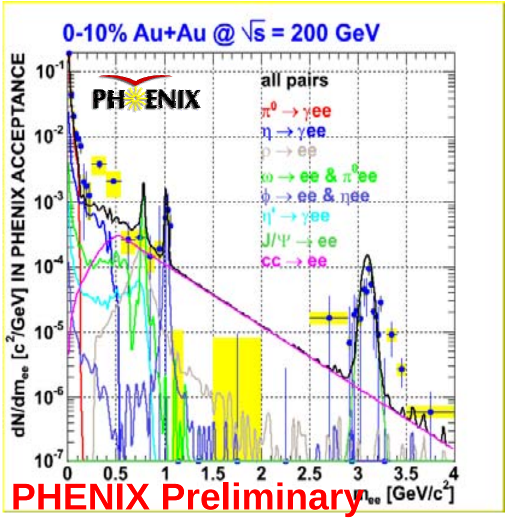
In-medium modifications of e+e- and μ+μ- spectra are very similar!

Dileptons at CBM: electrons or muons?

Muons !!!

✓ In-medium effects at low M are visible in μ+μ- spectra as well as in e+e- (cf. NA60)

✓ Mesurement of μ+μ- spectra will allow to study charm and charmonium dynamics !



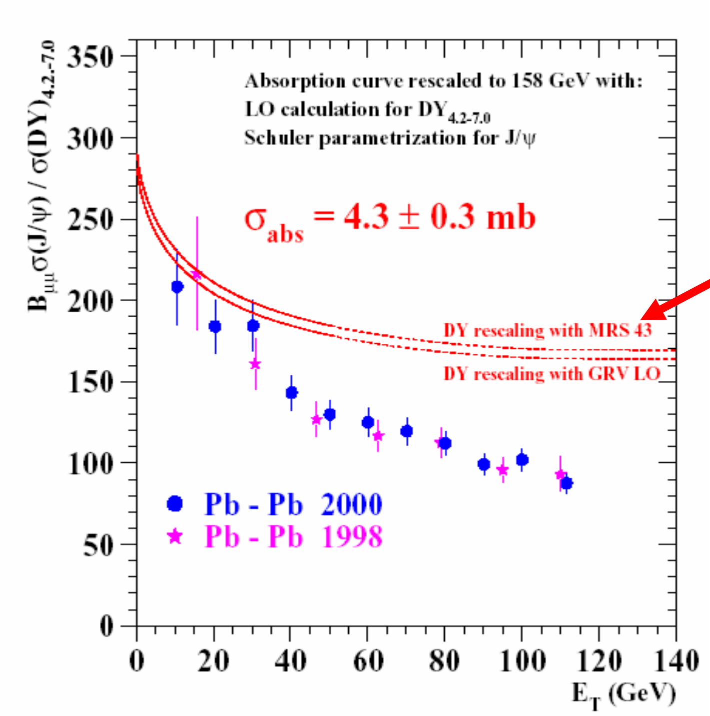
- Direct photons as a possible observable for CBM ?!

(cf. talk by Sergey Kiselev)

Open and hidden charm

Heavy flavor sector reflects the actual dynamics since heavy hadrons can only be formed in the very early phase of heavy-ion collisions at FAIR/SPS!

- **Hidden charm: J/Ψ , Ψ‘: Anomalous J/Ψ suppression in A+A (NA38/NA50/NA60)**



J/Ψ ‚normal‘ absorption by nucleons (Glauber model)

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Experimental observation: extra suppression in A+A collisions; increasing with centrality

Scenarios for charmonium suppression in A+A

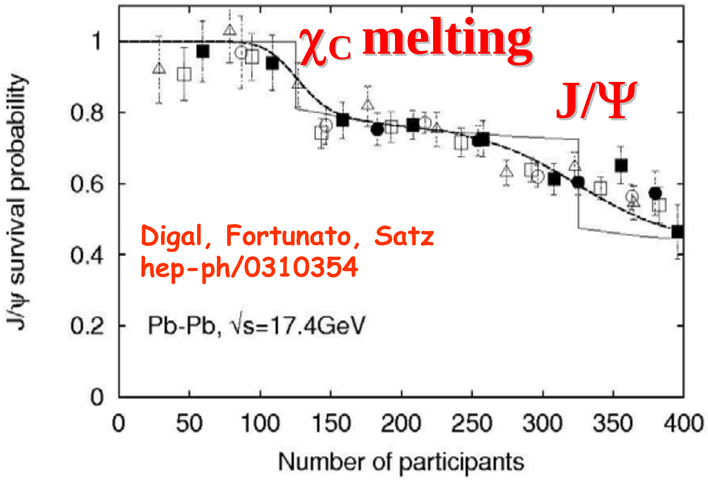
- **QGP threshold melting**

[Satz et al'03]

Quarkonium dissociation temperatures:

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Dissociation energy density $\varepsilon_d \sim (T_d/T_c)^4$



- **Comover absorption**

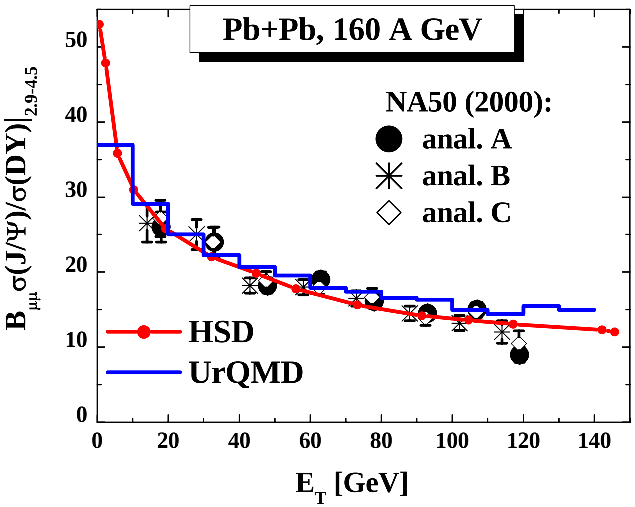
[Gavin & Vogt, Capella et al.`97]:

charmonium absorption by low energy inelastic scattering with ‚comoving' mesons (m=π,η,ρ,...):

J/Ψ+m <–> D+Dbar

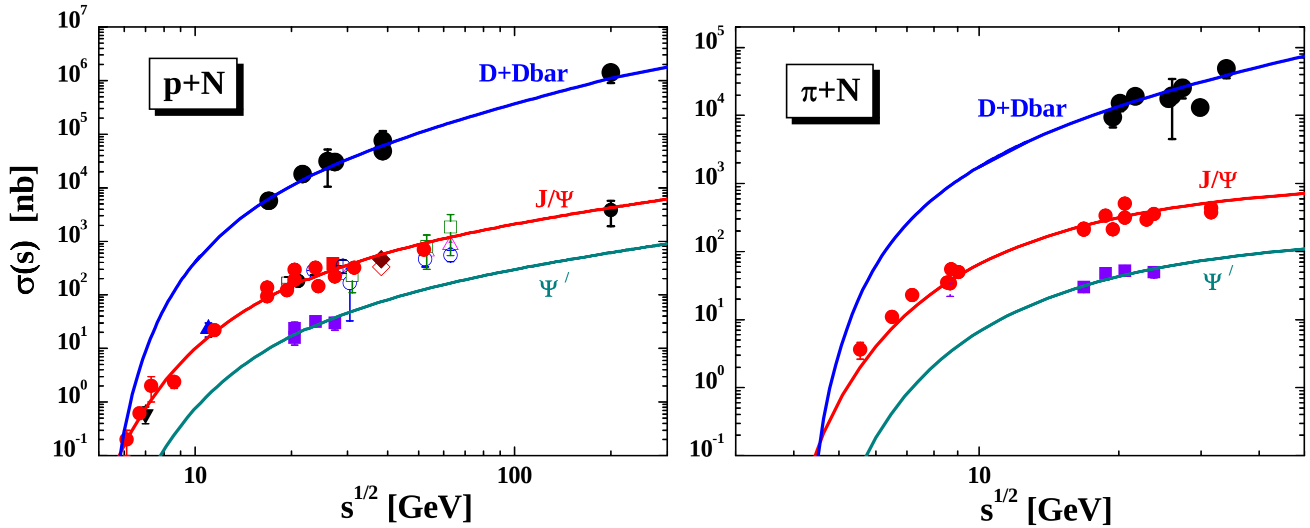
Ψ'+m <–> D+Dbar

χ_C+m <–> D+Dbar



Charm and Charmonium production and absorption in HSD

- Production $\sigma(J/\Psi)$ and $\sigma(\Psi')$: parametrization of the available exp. data



Coupled channel problem:

$$\sigma_{J/\Psi}^{exp} = \sigma_{J/\Psi} + B(\chi_c\text{->}J/\Psi)\ \sigma_{\chi c} + B(\Psi'\text{->}J/\Psi)\ \sigma_{\Psi'}$$

- Charmonium-baryon dissociation cross section can be fixed from p+A data

HSD-2003:

Pre-resonance c-cbar pairs (color-octet states): $\sigma_{cc\ B}$= 6 mb (τ_{cc}=0.3 fm/c)

Formed charmonium (color-singlet states): $\sigma_{J/\Psi\ B}$= 4 mb, $\sigma_{\chi\ B}$= 5 mb, $\sigma_{\Psi'\ B}$ = 8 mb

HSD-2006: $\sigma_{cc\ B} = \sigma_{J/\Psi\ B} = \sigma_{\chi\ B}$= 4.18 mb, $\sigma_{\Psi'\ B}$ = 7.6 mb

adopting a new Glauber fit from NA50

Modelling of the comover scenario in HSD

1. Charmonium dissociation cross sections with π, ρ, K and K* mesons

J/Ψ (χ$_c$,Ψ') + meson (π, ρ, K , K*) <-> D+Dbar

Phase-space model for charmonium + meson dissociation

$$\sigma_{1+2\to3+4}(s) = 2^4 \frac{E_1E_2E_3E_4}{s} |\tilde{M}_i|^2 \left(\frac{m_3+m_4}{\sqrt{s}}\right)^6 \frac{p_f}{p_i}$$

$$i = \chi_c, J/\Psi, \Psi'$$

$$|\tilde{M}_i|^2 = |M_i|^2 \quad \text{for} \quad (\pi,\rho) + (c\bar{c})_i \to D + \bar{D}$$

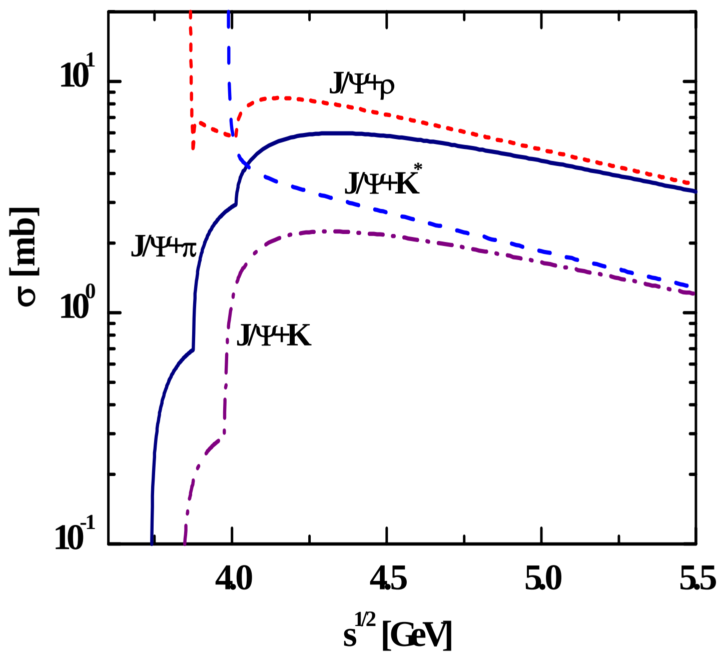
$$|\tilde{M}_i|^2 = 3|M_i|^2 \quad \text{for} \quad (\pi,\rho) + (c\bar{c})_i \to D^* + \bar{D},\ D + \bar{D}^*,\ D^* + \bar{D}^*$$

$$|\tilde{M}_i|^2 = \frac{1}{3}|M_i|^2 \quad \text{for} \quad (K,K^*) + (c\bar{c})_i \to D_s + \bar{D},\ \bar{D}_s + D$$

$$|\tilde{M}_i|^2 = |M_i|^2 \quad \text{for} \quad (K,K^*) + (c\bar{c})_i \to D_s + \bar{D}^*,\ \bar{D}_s + D^*,\ D_s^* + \bar{D},\ \bar{D}_s^* + D,\ \bar{D}_s^* + D^*$$

$$\text{set1}: \quad |M_{J/\Psi}|^2 = |M_{\chi_c}|^2 = |M_{\Psi'}|^2 = |M_0|^2$$

$$\text{set2}: \quad |M_{J/\Psi}|^2 = |M_{\chi_c}|^2 = |M_0|^2, \quad |M_{\Psi'}|^2 = 1.5\ |M_0|^2.$$



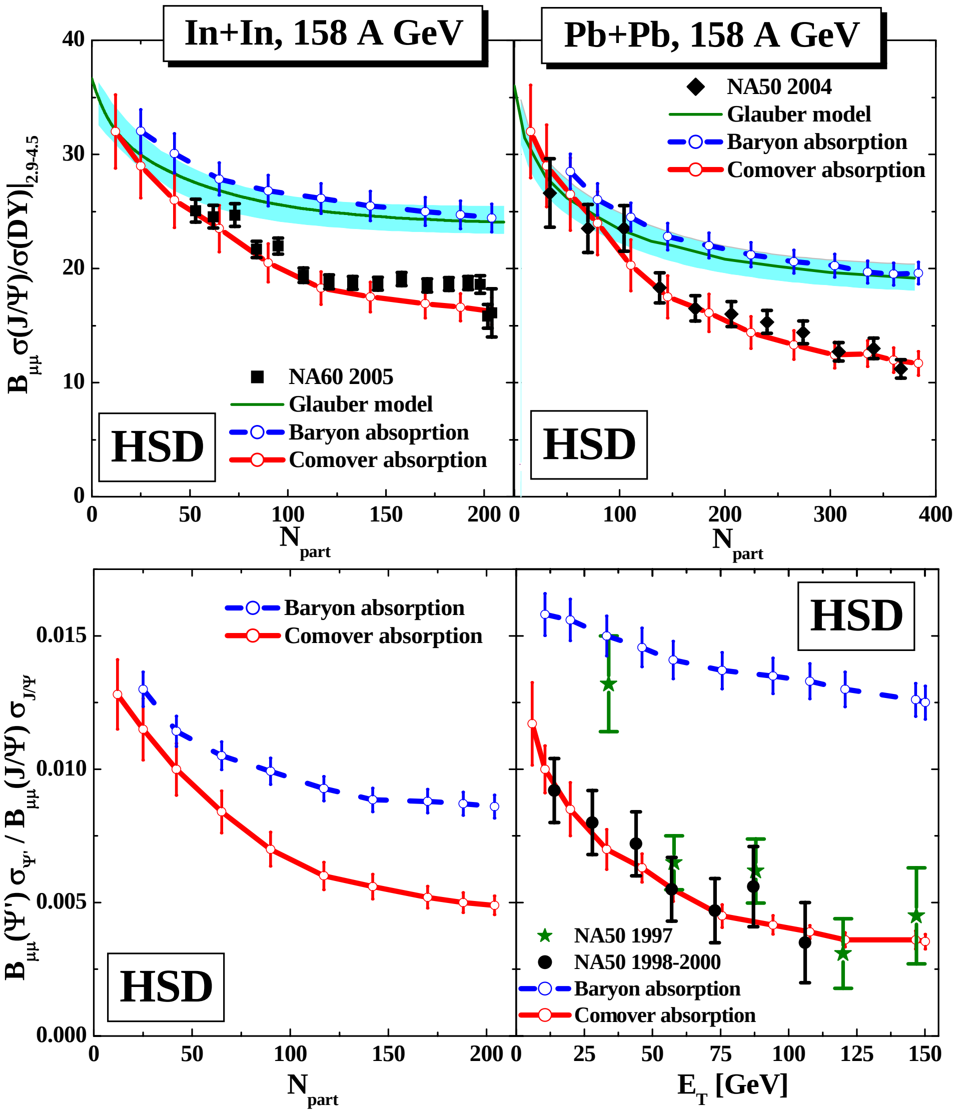
2. J/Ψ recombination cross sections by D+Dbar annihilation:

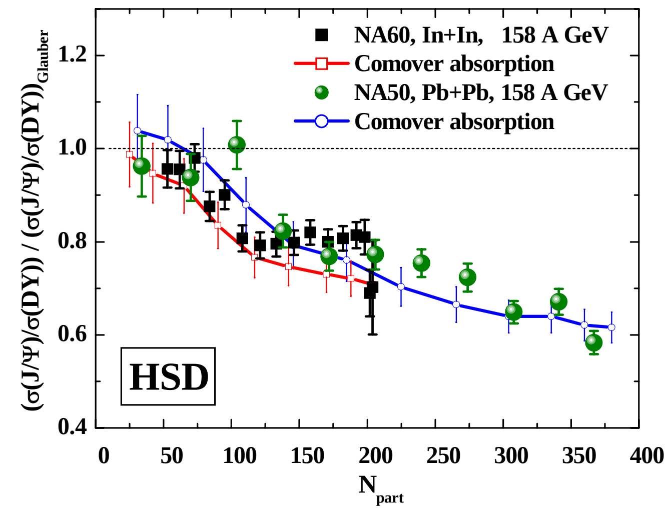
D+Dbar -> J/Ψ (χ$_c$,Ψ') + meson (π, ρ, K , K*)

are determined by detailed balance!

PRC 67 (2003) 054903

J/Ψ and Ψ´ suppression in In+In and Pb+Pb at SPS: Comover absorption



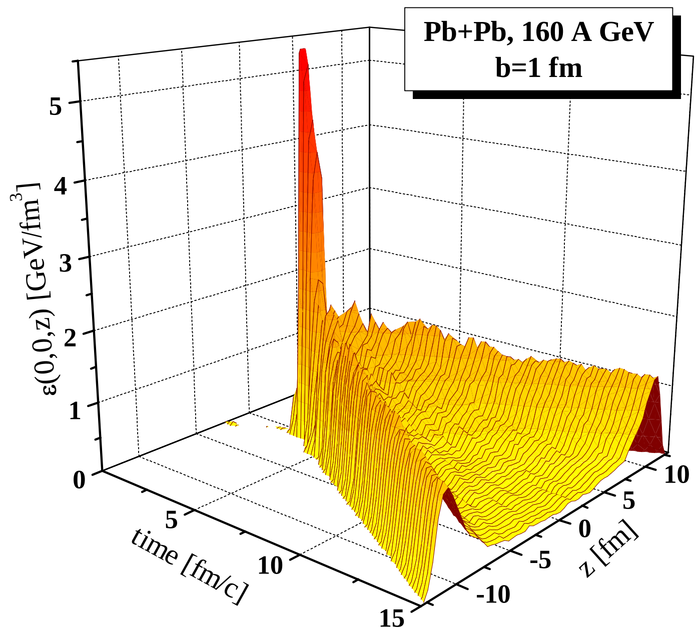


- Exp. data (NA50/NA60) for Pb+Pb and In+In at 160 A GeV are consistent with the comover absorption model for the same set of parameters!

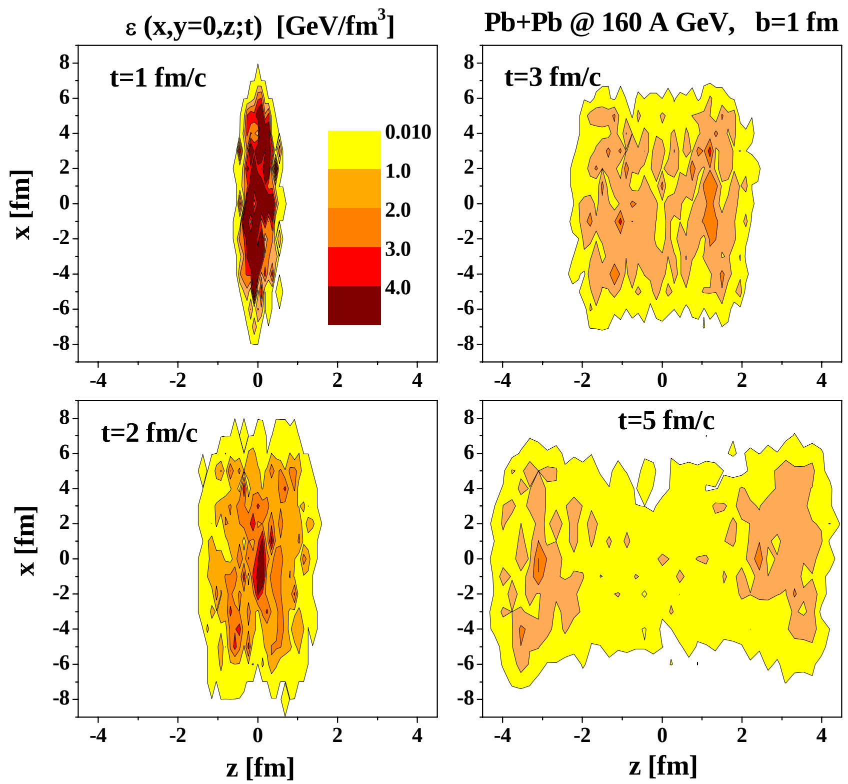
[Olena Linnyk et al., nucl-th/0612049, NPA07]

Modelling of the QGP melting scenario in HSD

Energy density ε (x=0,y=0,z;t) from HSD for Pb+Pb collisions at 160 A GeV



Energy density ε (x,y=0,z;t) from HSD for Pb+Pb collisions at 160 A GeV in terms of contour lines



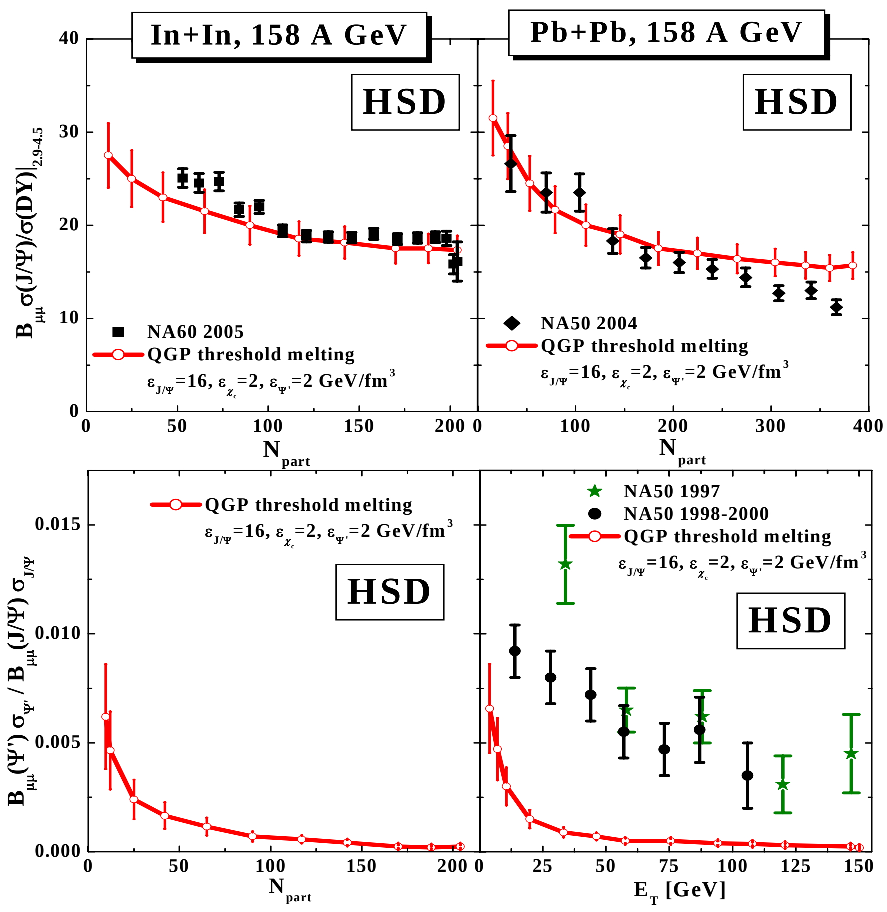
Set 1: threshold energy density:

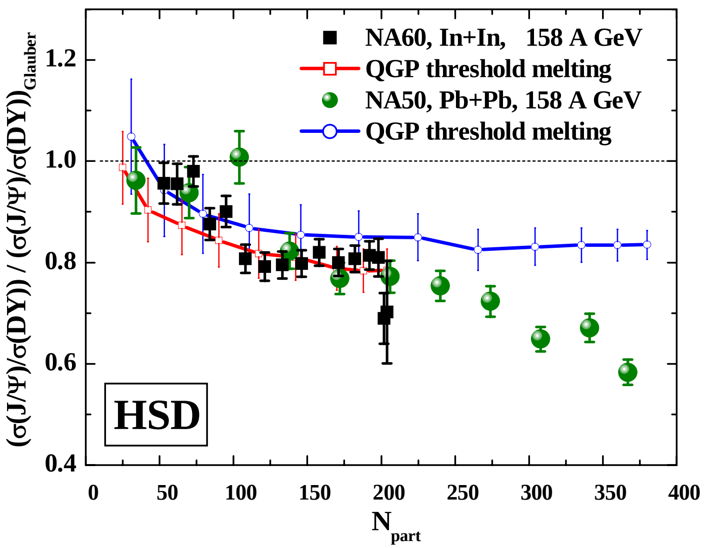
$\varepsilon(J/\Psi)=16$ GeV/fm^3, $\varepsilon(\chi_c)=2$ GeV/fm^3, $\varepsilon(\Psi')=2$ GeV/fm^3

[Olena Linnyk et al., nucl-th/0612049, NPA07]

J/Ψ and Ψ´ suppression in In+In and Pb+Pb at SPS: QGP threshold scenario

Set 1: ε(J/Ψ)=16 GeV/fm³, ε(χ_c) =2 GeV/fm³, ε(Ψ') =2 GeV/fm³



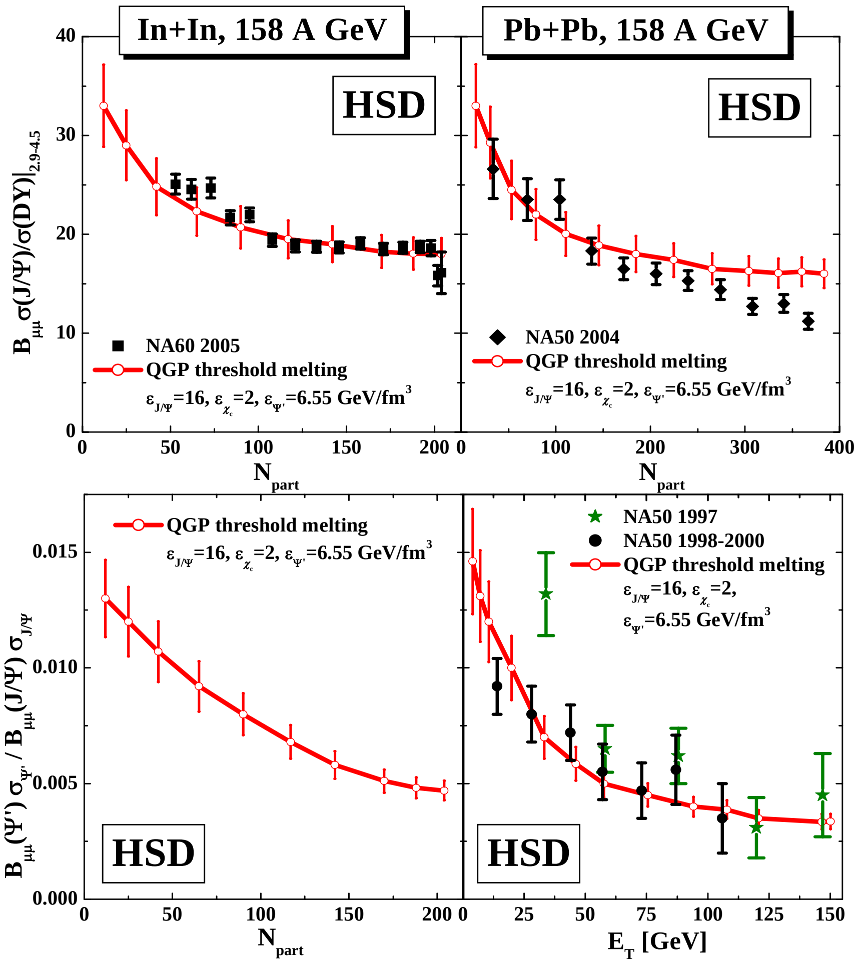


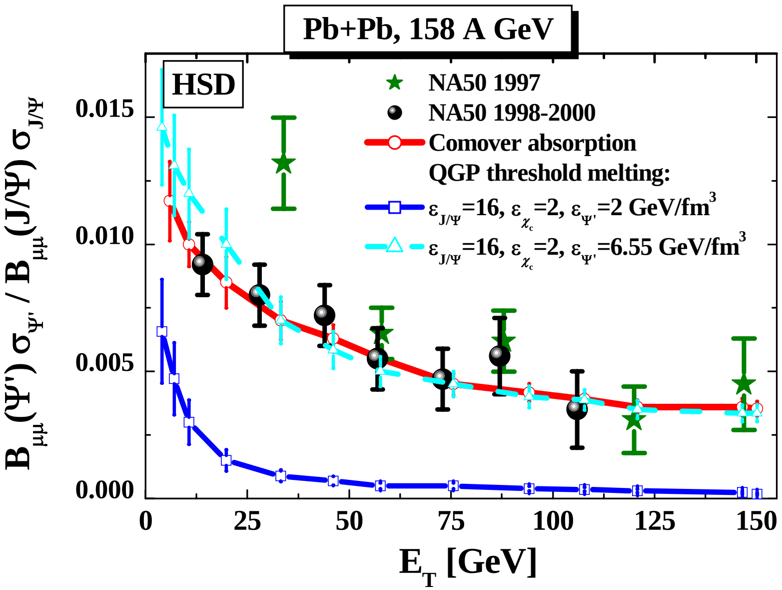
- **Set 1: QGP threshold melting scenario with dissociation energy densities** ε(J/Ψ)=16 GeV/fm³, ε(χ_c) =2 GeV/fm³, ε(Ψ') =2 GeV/fm³ **shows too strong Ψ' absorption which contradicts to the NA50 data!**

[Olena Linnyk et al., nucl-th/0612049, NPA07]

J/Ψ and Ψ´ suppression in In+In and Pb+Pb at SPS:
QGP threshold scenario II

Set 2: ε(J/Ψ)=16 GeV/fm³, ε(χ_c) =2 GeV/fm³, ε(Ψ') =6.55 GeV/fm³

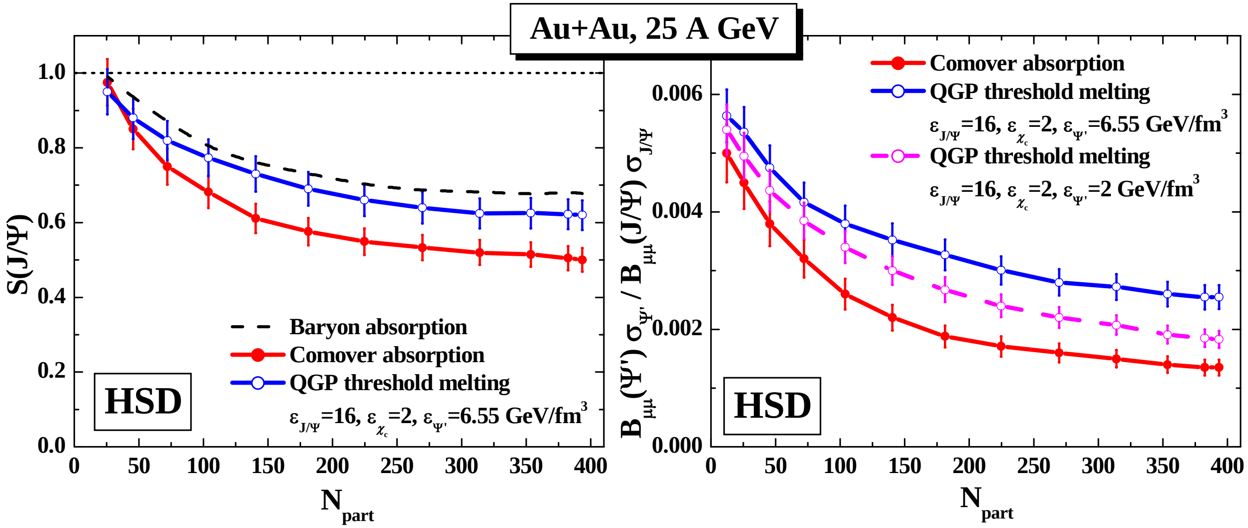




- **Set 2: an increase of the melting energy density ε(Ψ') =6.55 GeV/fm³ reduces the Ψ' suppression, but contradicts LQCD predictions for $T^d(\Psi') \sim 1.2\ T_C$!**

[Olena Linnyk et al., nucl-th/0612049, NPA07]

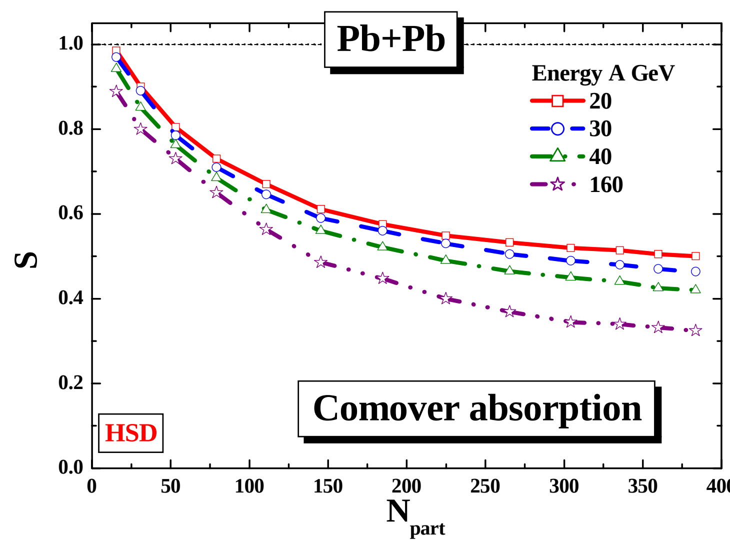
HSD predictions for J/Ψ and Ψ´ suppression in Au+Au at CBM energies



Different scenarios can be distinguished at FAIR energies:

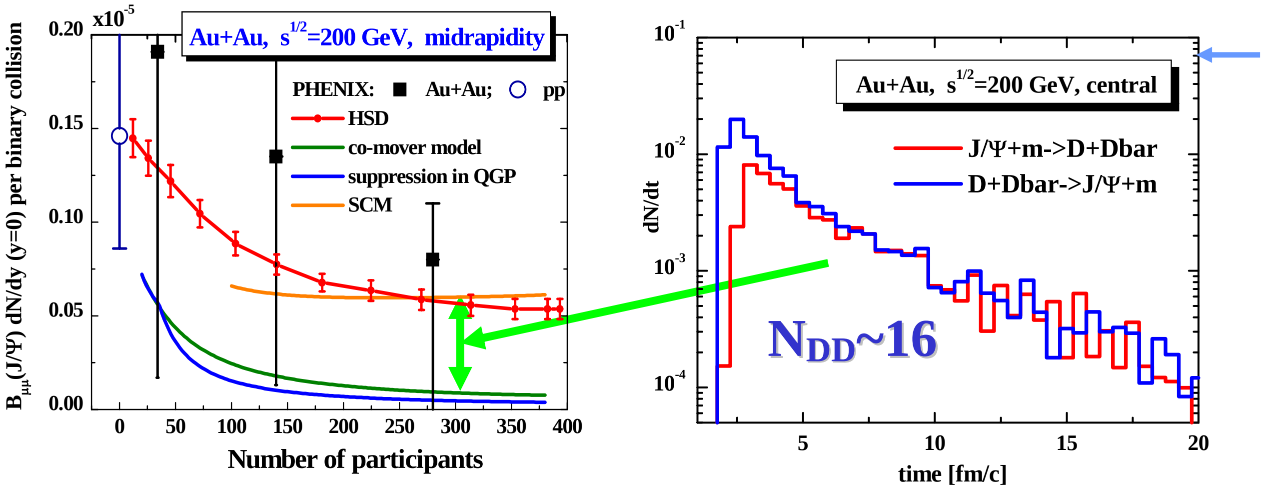
Ψ´ over J/Ψ ratio is lower in the comover absorption model since the average comover density decreases only moderately with lower bombarding energy whereas the energy density decreases rapidly =>

Comover scenario predicts a smooth excitation function whereas the „threshold melting scenario“ should show a step in the excitation function

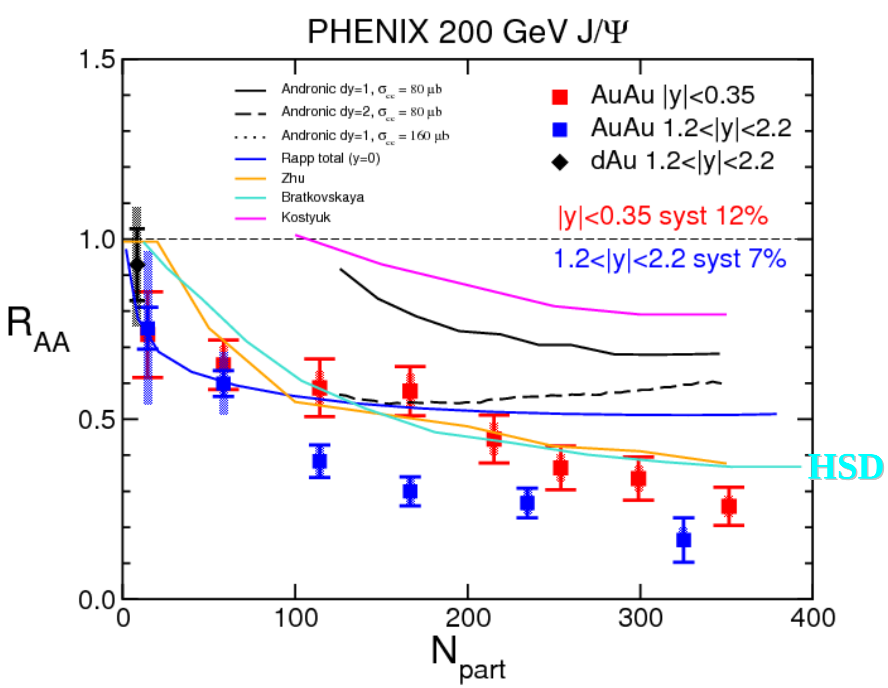


[Olena Linnyk et al., nucl-th/0612049, NPA07]

J/Ψ suppression in Au+Au at RHIC



Time dependence of the rate of J/Ψ absorption by mesons and recreation by D+Dbar annihilation

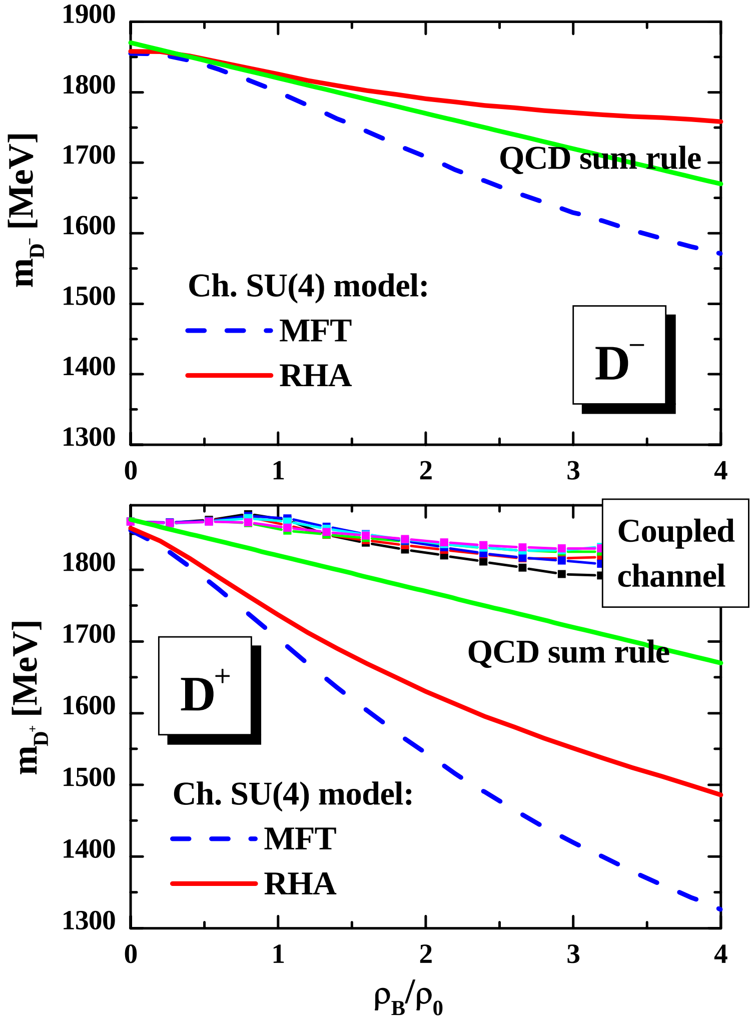


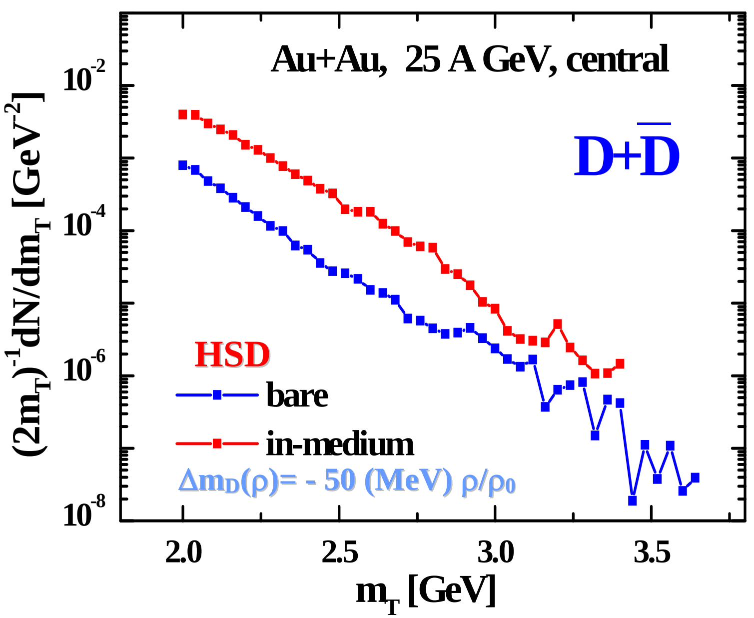
At RHIC the recreation of J/Ψ by D+Dbar annihilation is important !

New data with higher statistics are needed to clarify the nature of J/Ψ suppression!

HSD: PRC 69 (2004) 054903

D/Dbar-mesons: in-medium effects



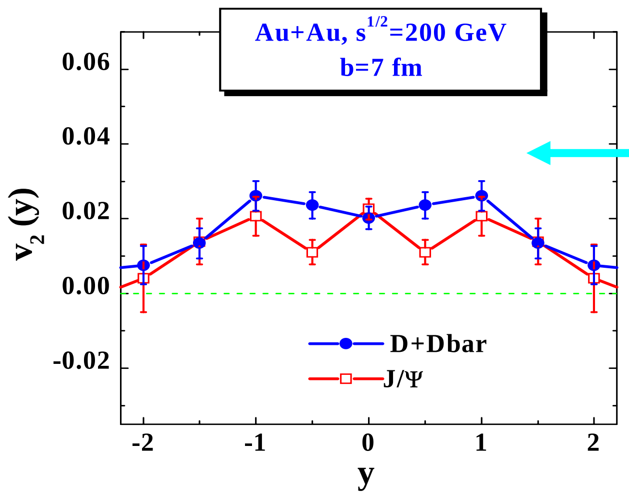


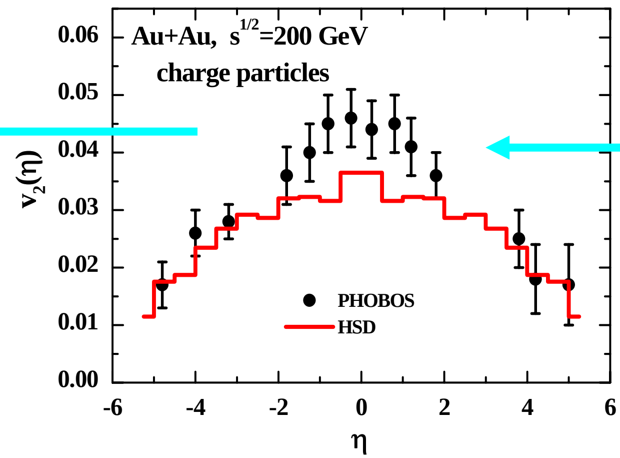
- **Dropping D-meson masses with increasing light quark density**
- **might give a large enhancement of the open charm yield at 25 A GeV !**
- **Charmonium suppression increases for dropping D-meson masses!**

Ch. SU(4): A. Mishra et al., PRC69 (2004) 015202
QCD sum rule: Hayashigaki, PLB487 (2000) 96
Coupled channel: Tolos et al., EPJ C43 (2005) 761

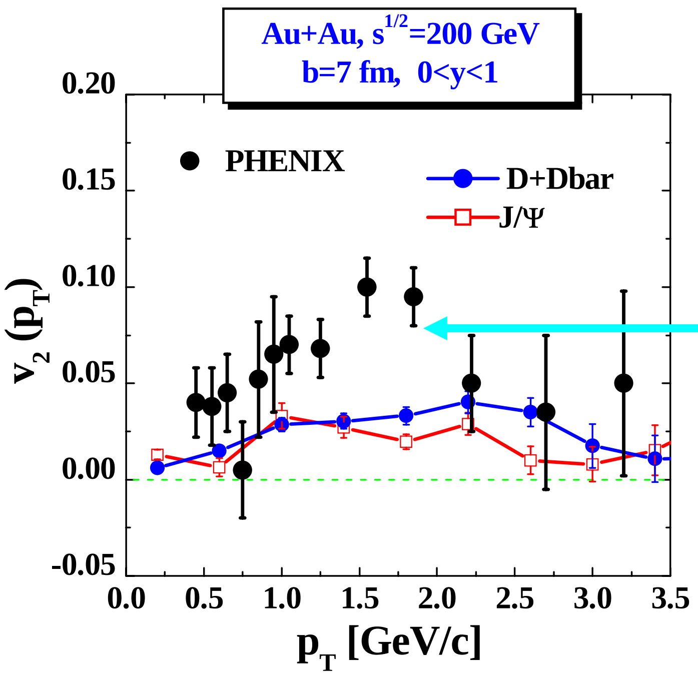
HSD: NPA691 (2001) 761

HSD: v_2 of D+Dbar and J/Ψ from Au+Au versus p_T and y at RHIC





Collective flow from hadronic interactions is too low at midrapidity !

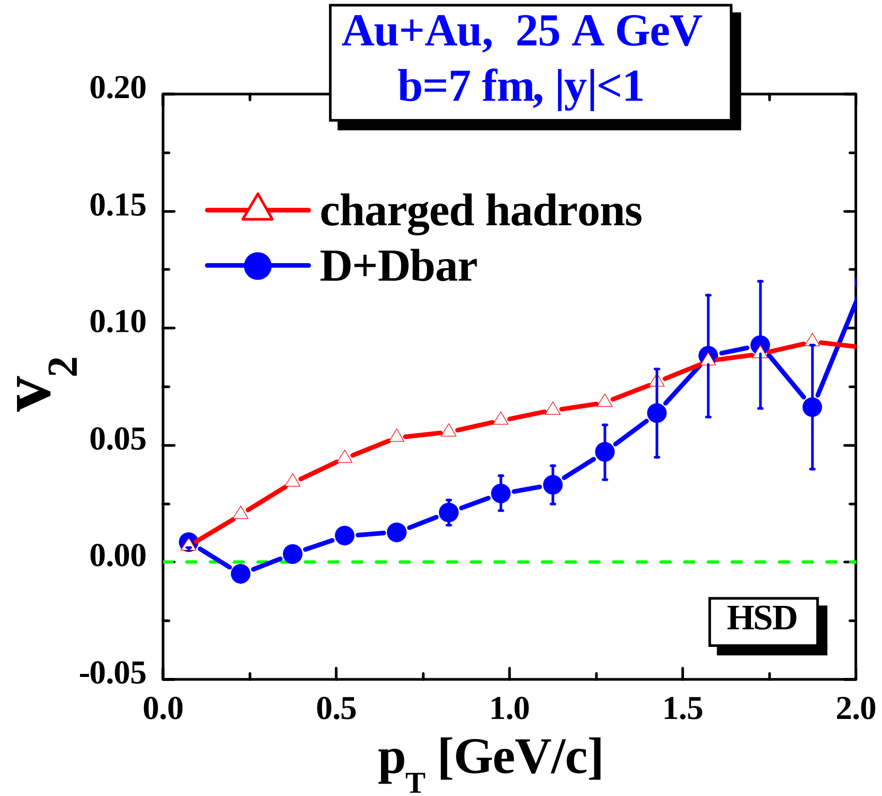


- **HSD: D-mesons and J/Ψ follow the charged particle flow => small v_2 < 3%**
- **Exp. data at RHIC show large collective flow of D-mesons up to v_2~10%!**

=> strong initial flow of non-hadronic nature!

PRC 71 (2005) 044901

HSD predictions for CBM - elliptic flow at 25 A GeV

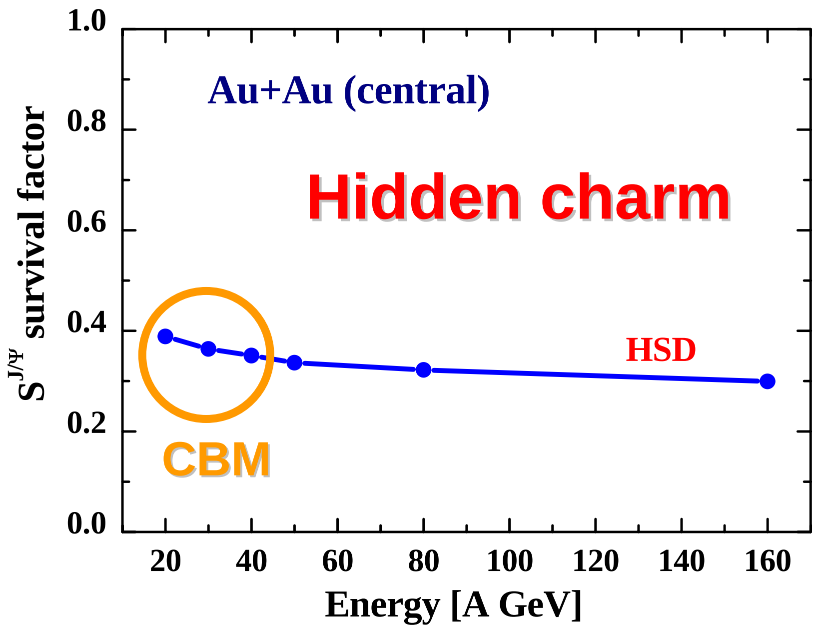


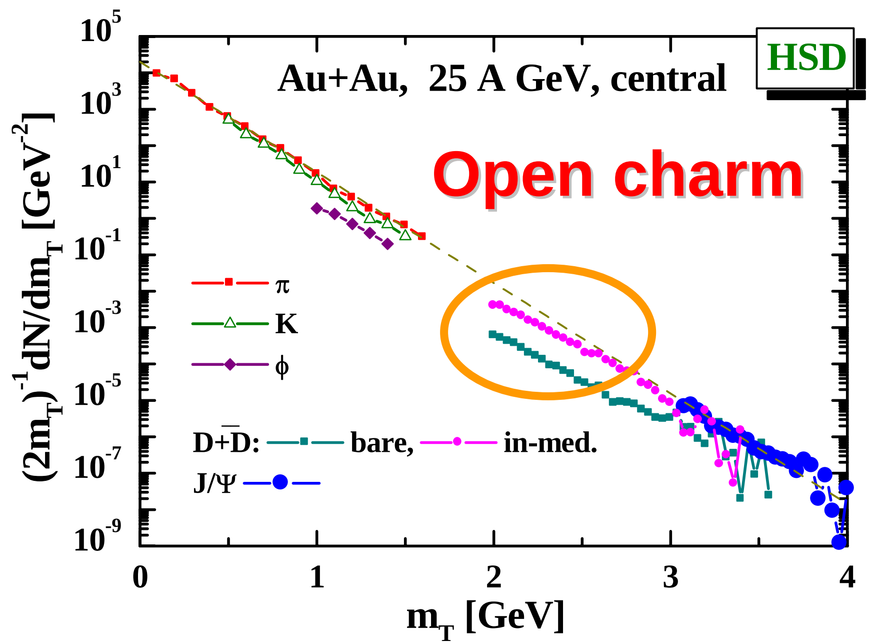
•HSD: D-mesons and J/Ψ follow the charged particle flow => small v_2

Possible observation at CBM: strong initial flow of D-mesons and J/Ψ due to partonic interactions!

Challenge for CBM!

Open and hidden charm – HSD predictions for CBM



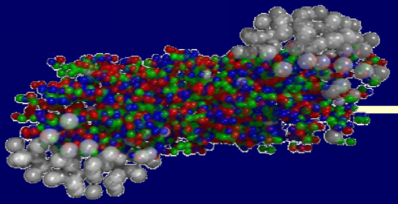


Open charm:

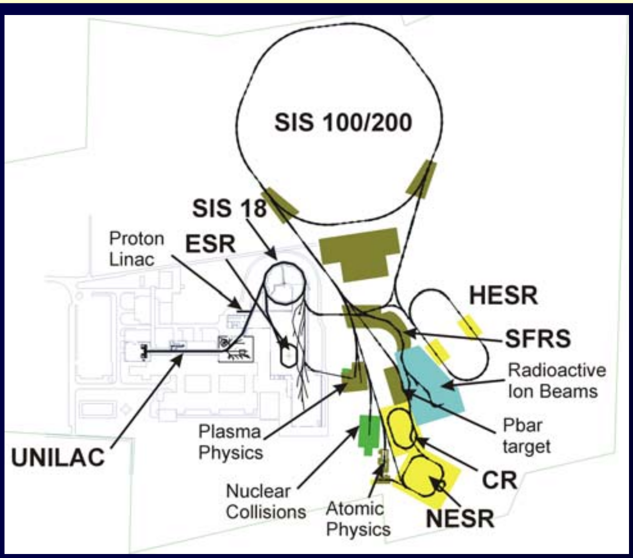
- **without medium effects:** suppression of D-meson spectra by factor ~ 10 relative to the global m_T-scaling
- **with medium effects:** restoration of the global m_T-scaling for the mesons

Hidden charm:

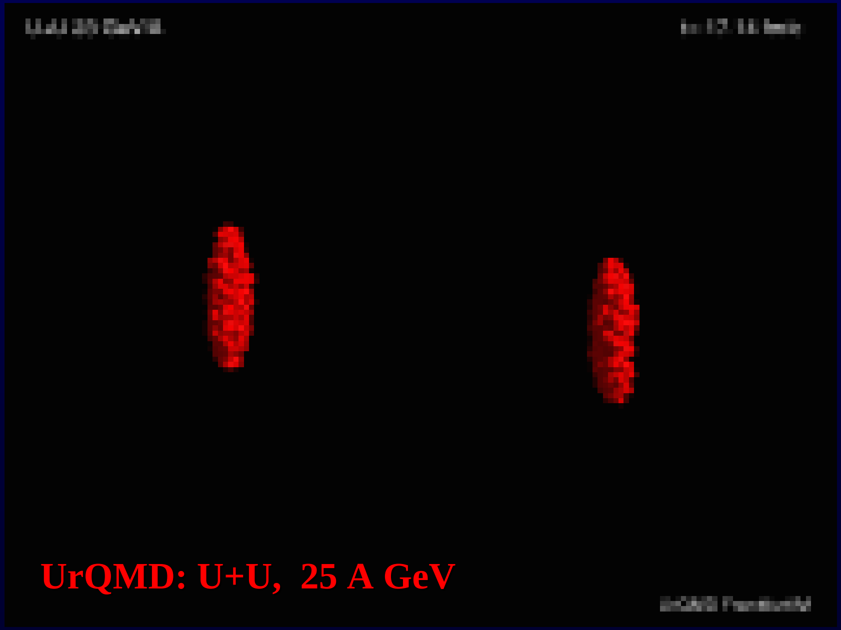
J/Ψ suppression due to comover absorption at FAIR is lower than at SPS



Summary



- FAIR is an excellent facility to study the properties of the sQGP (strongly interacting ‚color liquid') as well as hadronic matter



- Transport theory is the general basis for an understanding of nuclear dynamics on a microscopic level

Thanks

Olena Linnyk (FIAS)

Wolfgang Cassing (Giessen Uni.)

Andrej Kostyuk (FIAS)

Laura Tolos (FIAS)

Horst Stöcker (FIAS)

HSD
Collaboration
and Co