Open and hidden charm dynamics

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Introduction

Heavy-ion collisions are well suited to study **dense and hot nuclear matter** –

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

Observables :

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

The way to study:

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

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

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

with collision terms I_{coll} describing:

- elastic and inelastic hadronic reactions:
  baryon-baryon, meson-baryon, meson-meson

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

- formation and decay of
  baryonic and mesonic resonances

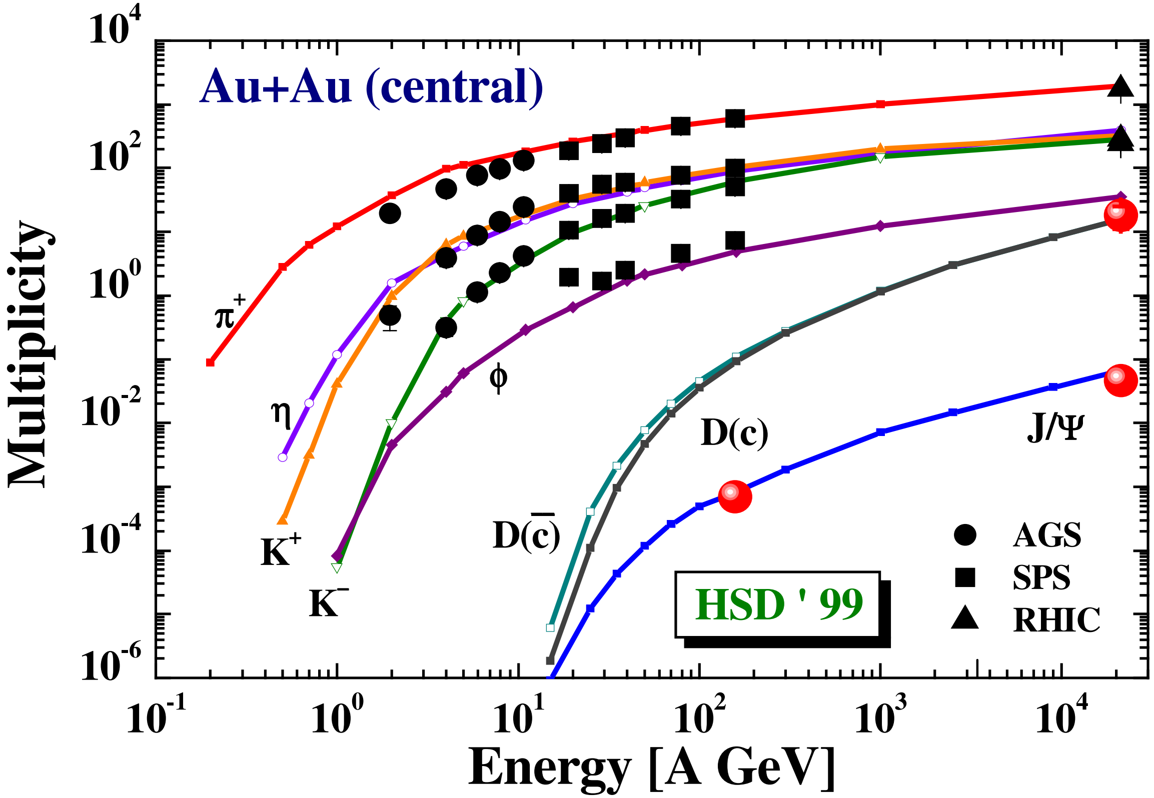
  and strings - excited color singlet states *(qq - q)* or *(q – qbar)* -
  (for inclusive particle production: BB –> X , mB –>X, X =many particles)

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

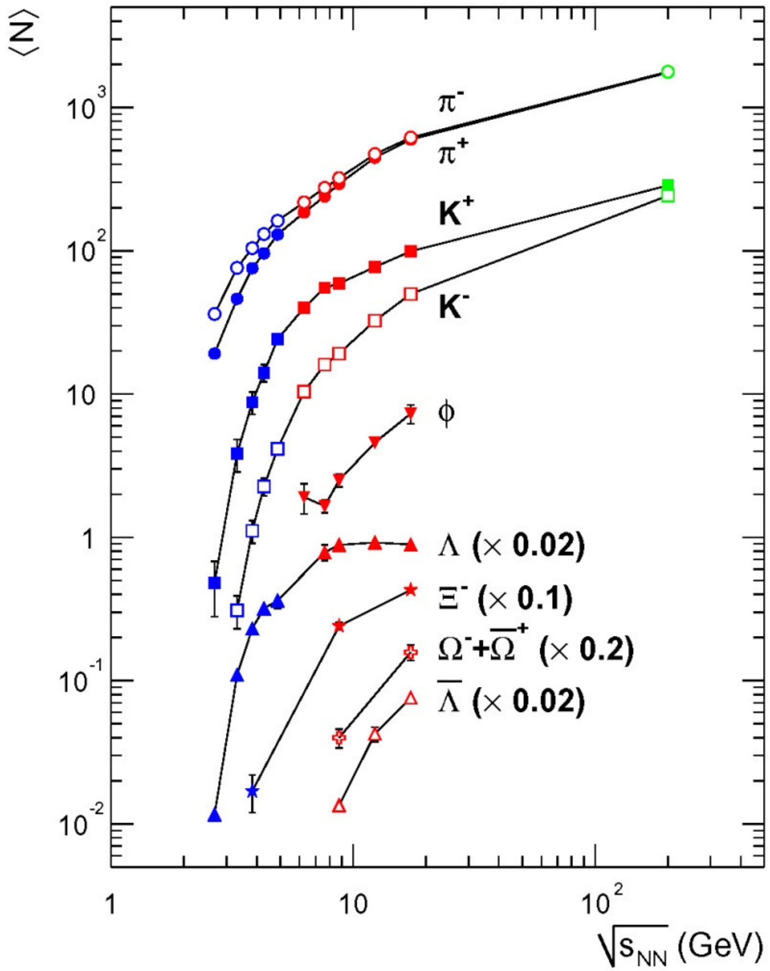
- implementation of detailed balance on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-particle reactions in HSD !)
- off-shell dynamics for short-lived states

HSD – a microscopic model for heavy-ion reactions

- very good description of particle production in pp, pA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (~20 TeV) energies



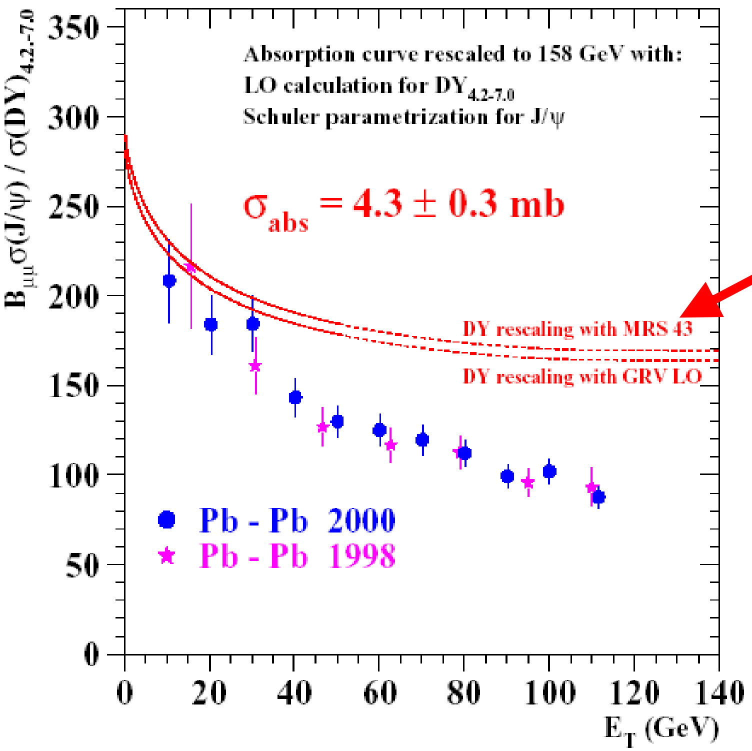
AGS NA49 BRAHMS



Open and hidden charm

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

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



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

||

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

I.-II. Scenarios for charmonium suppression in A+A

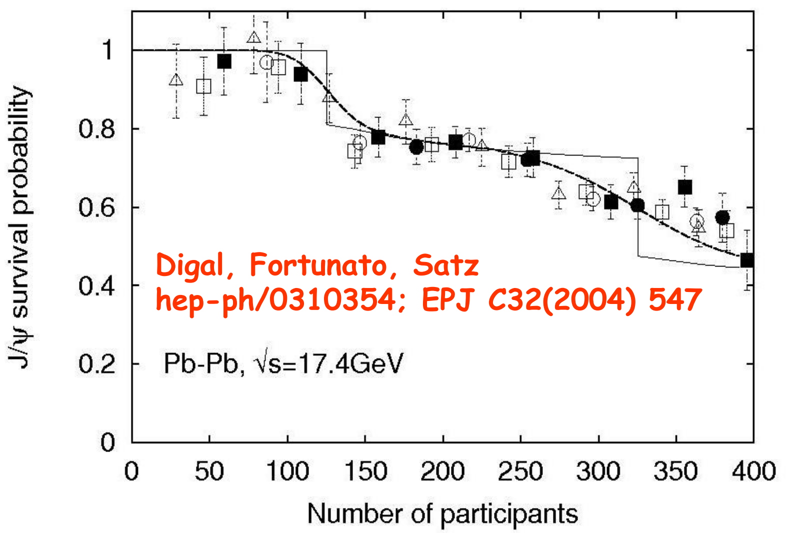
I. QGP threshold melting

[Satz et al'03]

Quarkonium dissociation temperatures:

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

Dissociation energy density $\varepsilon_d \sim 2(T_d/T_c)^4$



II. Comover absorption

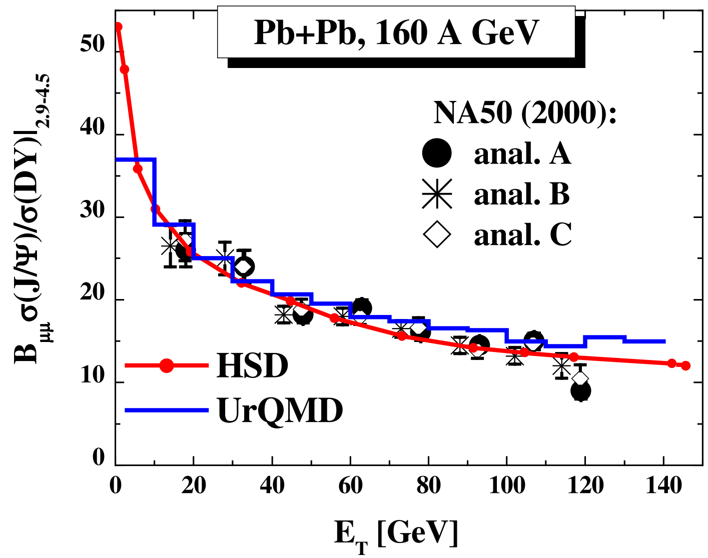
[Gavin & Vogt, Capella et al.`97]:

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



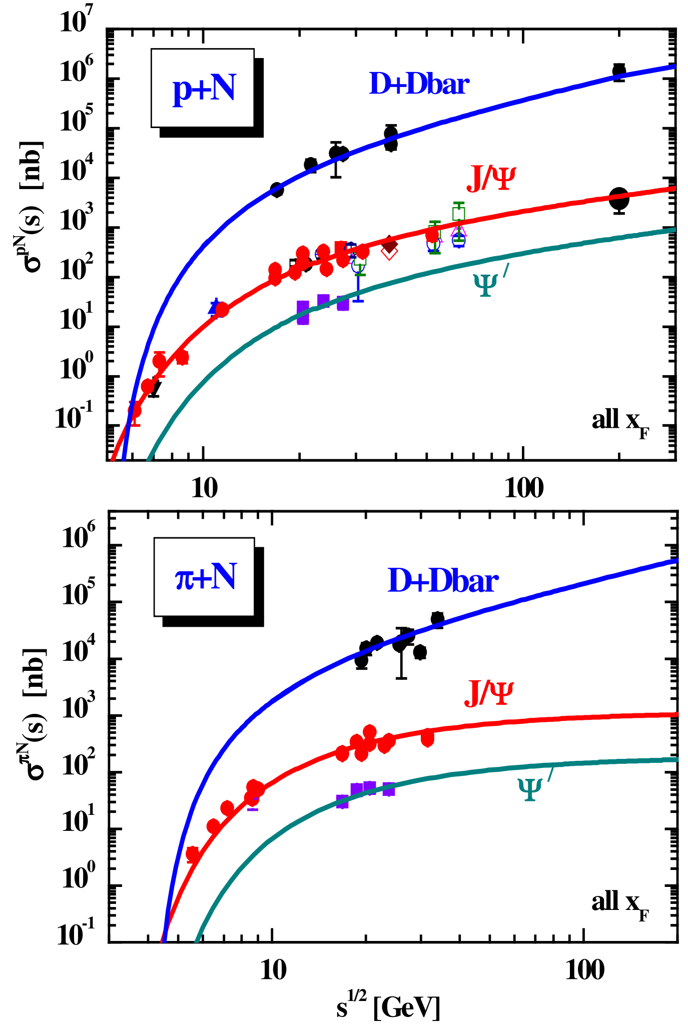
Charm and Charmonium production and absorption in HSD

- Charm 'chemistry': $D^+, D^-, D^0, \overline{D}^0, D^{*+}, D^{*-}, D^{*0}, D^{*0}, D_S^+, D_S^-, D_S^{*+}, D_S^{*-}$, $J/\Psi, \Psi', \chi_C$

- Production $\sigma(D)$, $\sigma(J/\Psi)$ and $\sigma(\Psi')$ in N+N and π+N collsions: parametrization of the available exp. data

Coupled channel problem:

$$\sigma_{J/\Psi}^{exp} = \sigma_{J/\Psi} + B(\chi_c \rightarrow J/\Psi)\ \sigma_{\chi_c} + B(\Psi' \rightarrow J/\Psi)\ \sigma_{\Psi'}$$



- Charmonia-baryon dissociation cross sections can be fixed from p+A data:

$$J/\Psi\ (\chi_c, \Psi') + B \rightarrow D + Dbar + X$$

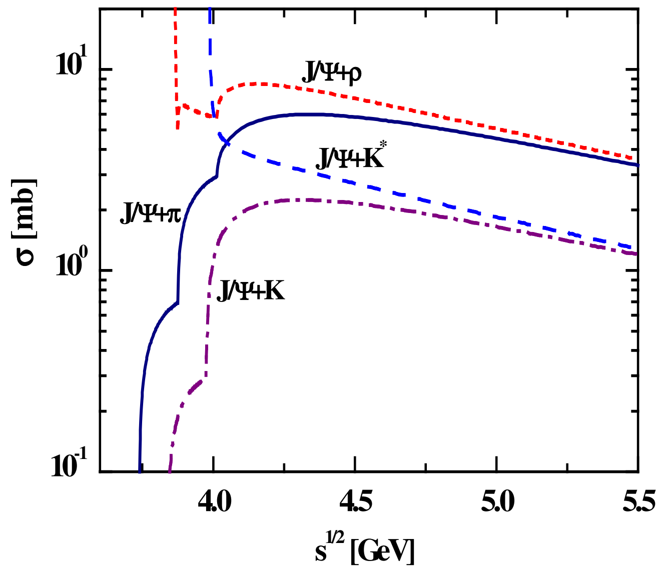
$\sigma_{cc\ B} = \sigma_{J/\Psi\ B} = \sigma_{\chi\ B} = 4.18$ mb, $\sigma_{\Psi'\ B} = 7.6$ mb
(adopting a Glauber fit from NA50)

- Charm = hard probe => binary scaling!

II. Modelling of the comover scenario in HSD

1. Charmonia dissociation cross sections with formed 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:**

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

$$i = \chi_C, \; J/\Psi, \; \Psi'$$

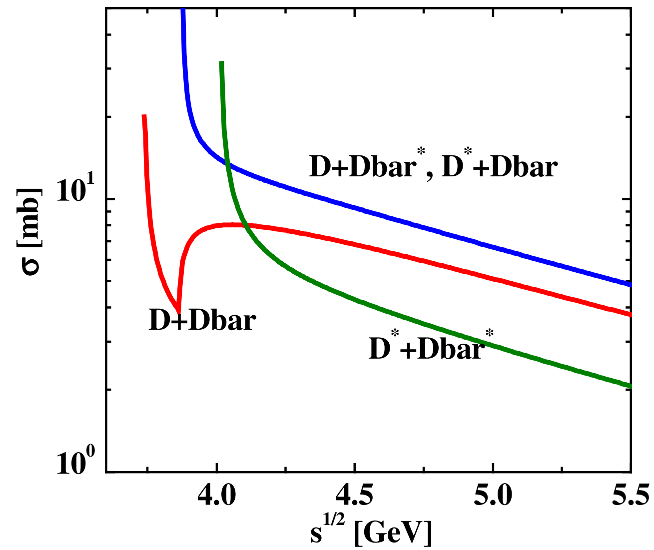
$$|M_{J/\Psi}|^2 = |M_{\chi_C}|^2 = |M_{\Psi'}|^2 = |M_0|^2$$

constant matrix element

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!

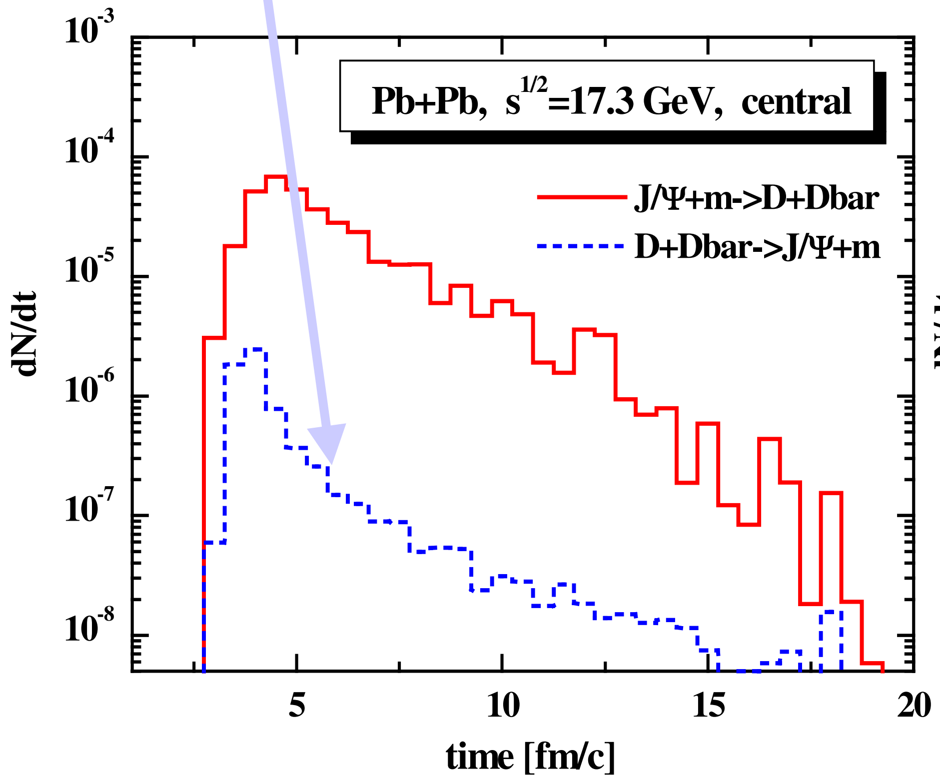


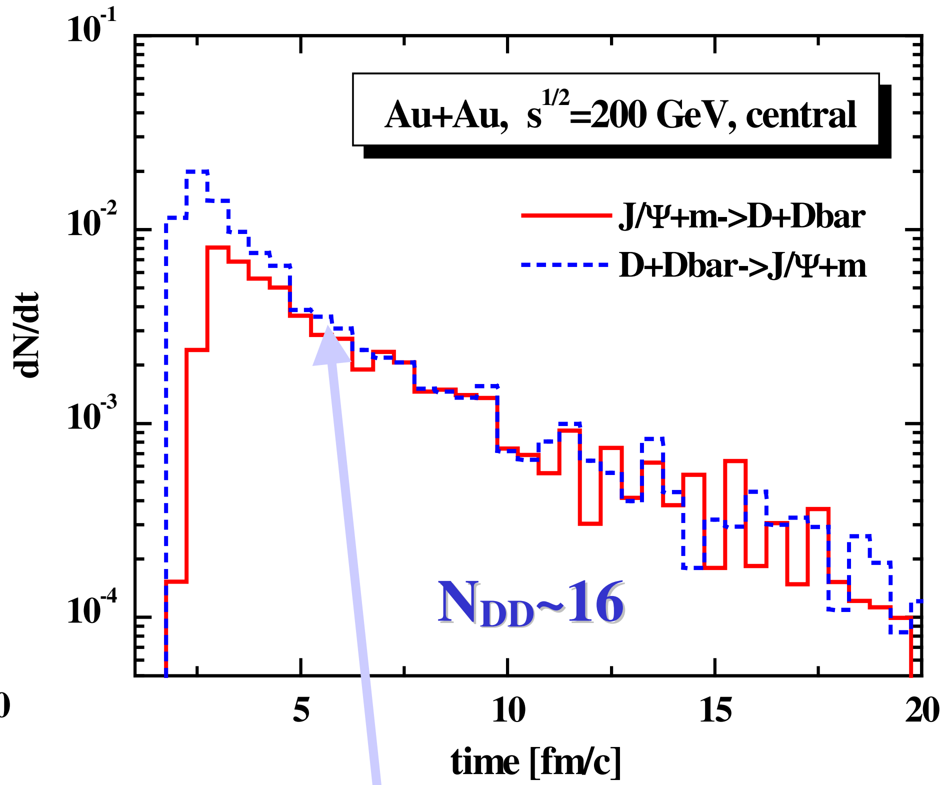
Note: comover dissociation as well as DDbar recombination can occur only if the local energy density at the collision point $\varepsilon < 1 GeV/fm^3$

PRC 67 (2003) 054903

Charmonium recombination by D-Dbar annihilation

At SPS recreation of J/Ψ by D+Dbar annihilation is negligible



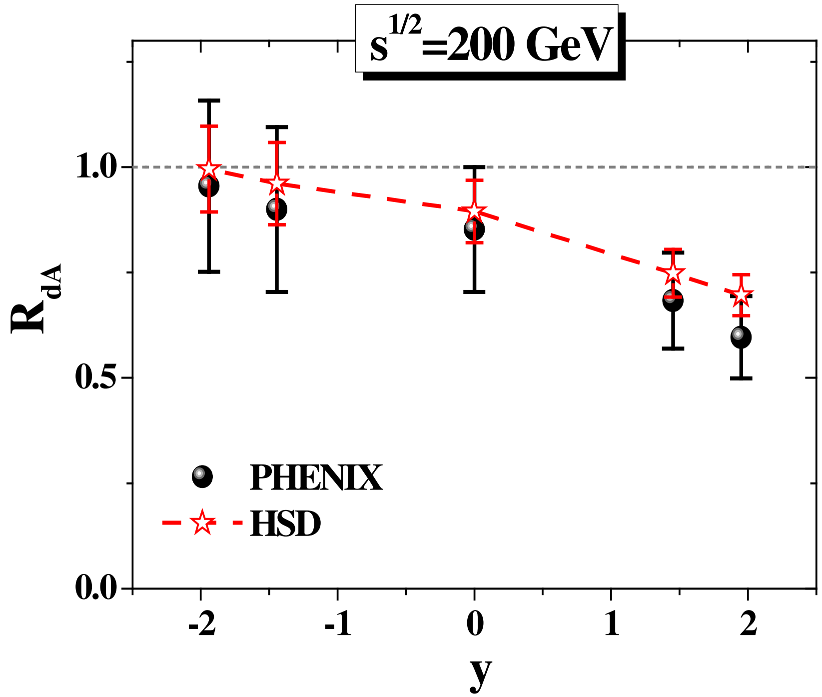


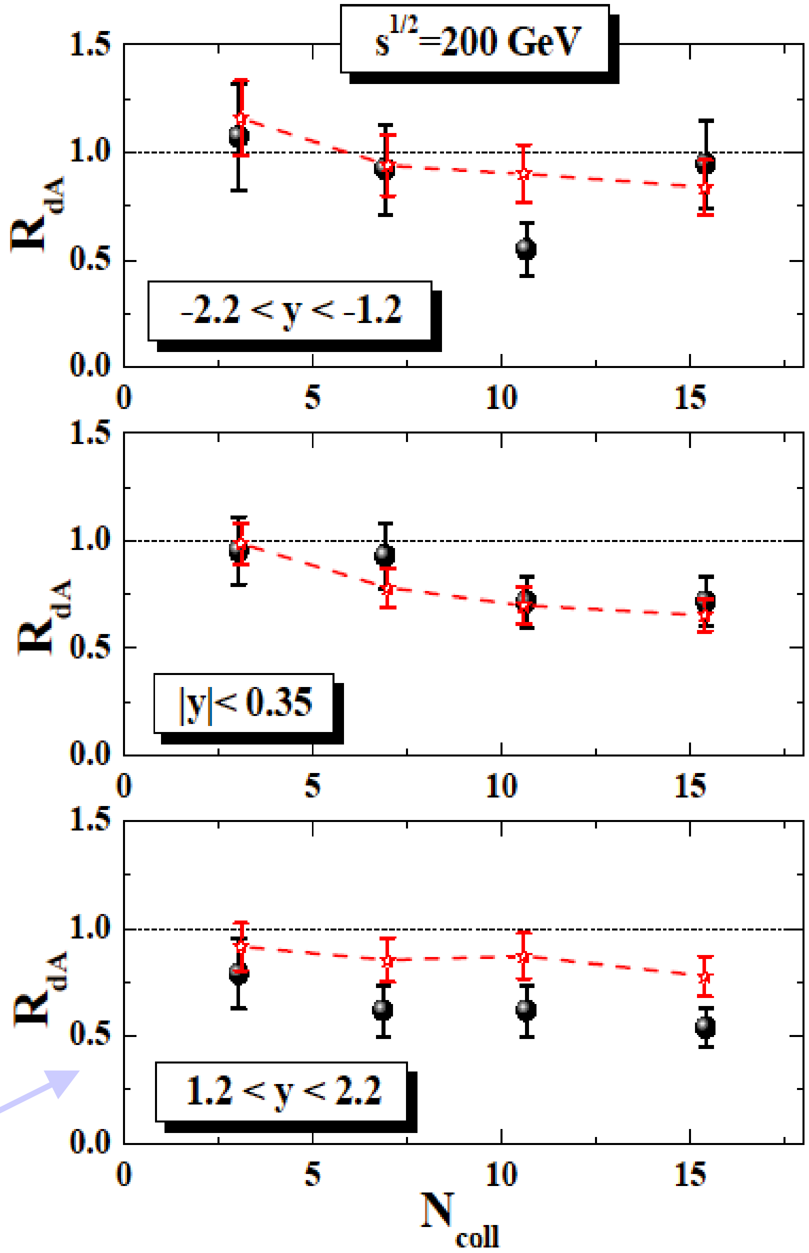
but at RHIC recreation of J/Ψ by D+Dbar annihilation is strong!

PRC 67 (2003) 054903

Suppression in dA at RHIC

$$R_{dA} \equiv \frac{dN^{dAu}_{J/\Psi}/dy}{\langle N_{coll}\rangle \cdot dN^{pp}_{J/\Psi}/dy},$$



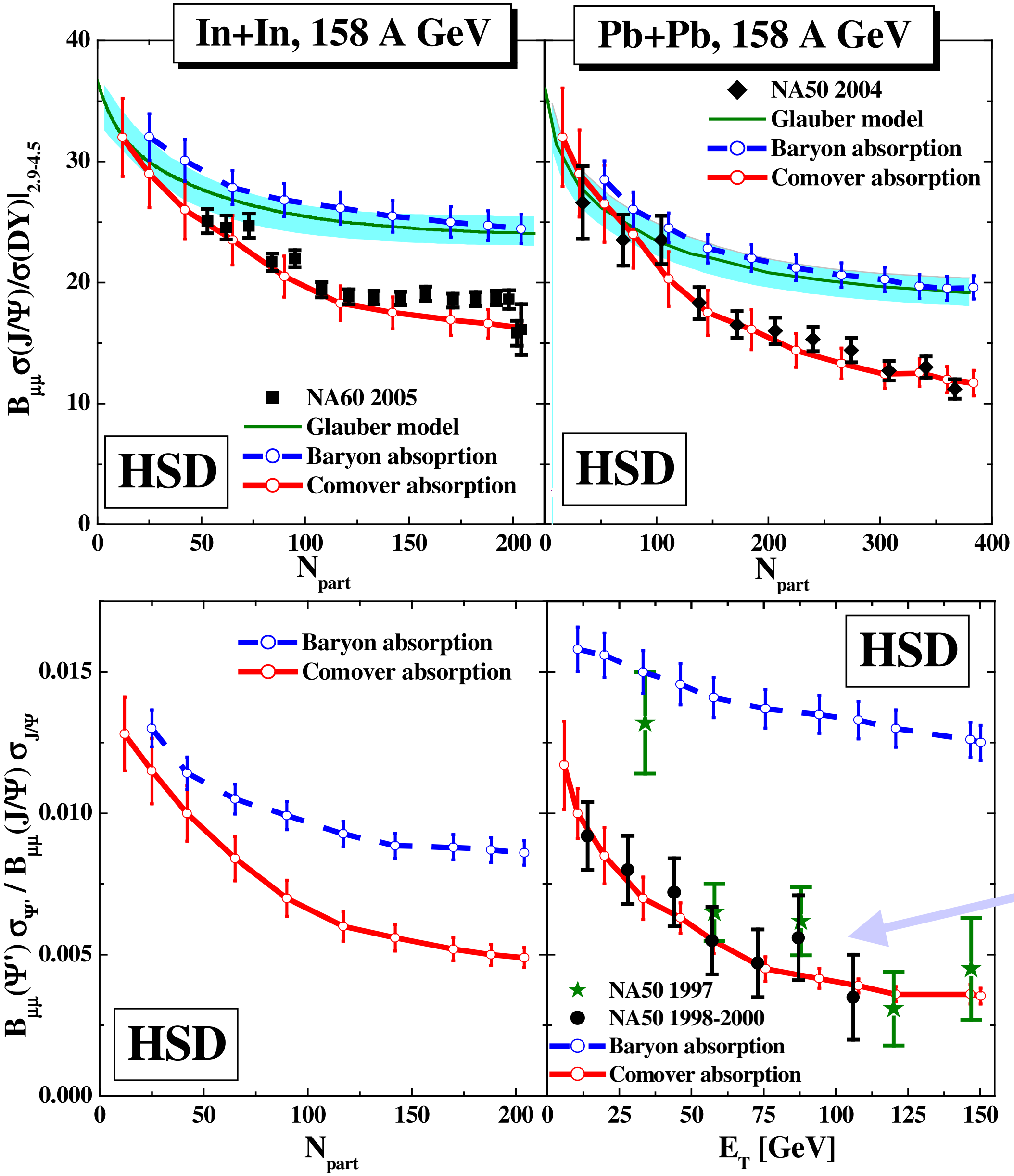


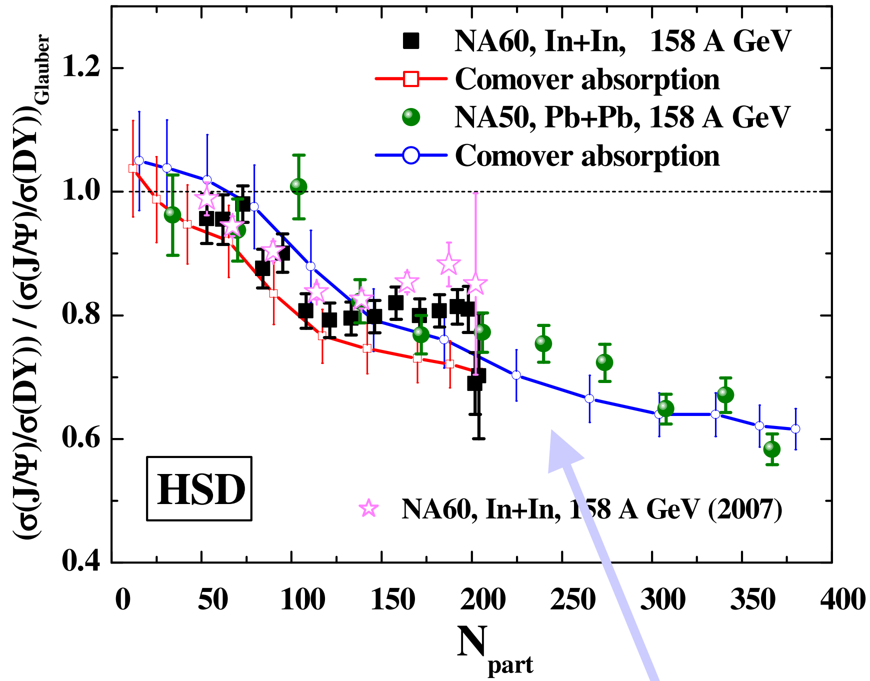
‚Cold nuclear matter‘ effects:

- Charmonium is absorbed by scattering on baryons
- Indication for shadowing effect at forward y

[O. Linnyk et al., arXiv:0808.1504; Int J Mod Phys E17 (2008) 1367]

J/Ψ and Ψ´ suppression in In+In and Pb+Pb at SPS:
(II.) Comover absorption (+ recombination by D-Dbar annihilation)



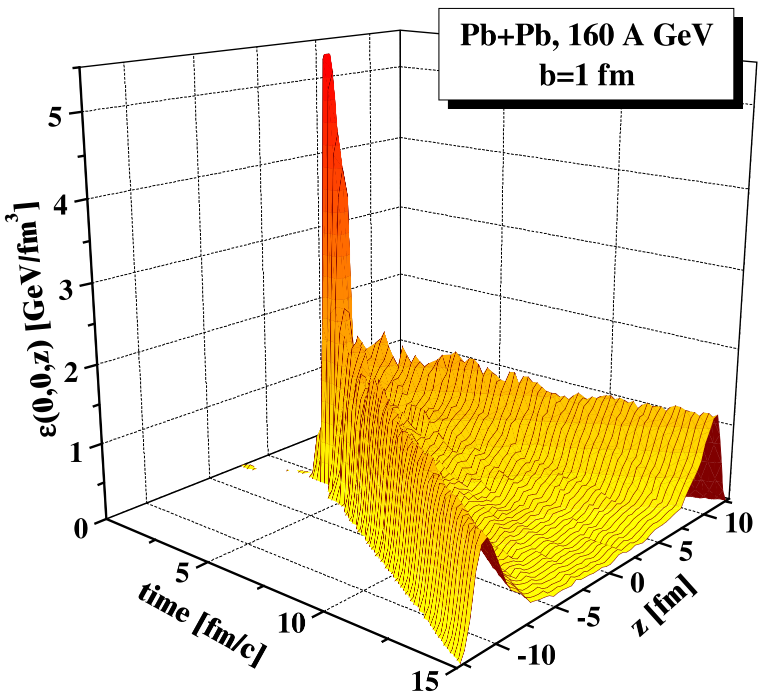


- Exp. data (NA50/NA60) for J/Ψ and Ψ´ suppression for Pb+Pb and In+In at 160 A GeV are consistent with the comover absorption model for the same set of parameters!

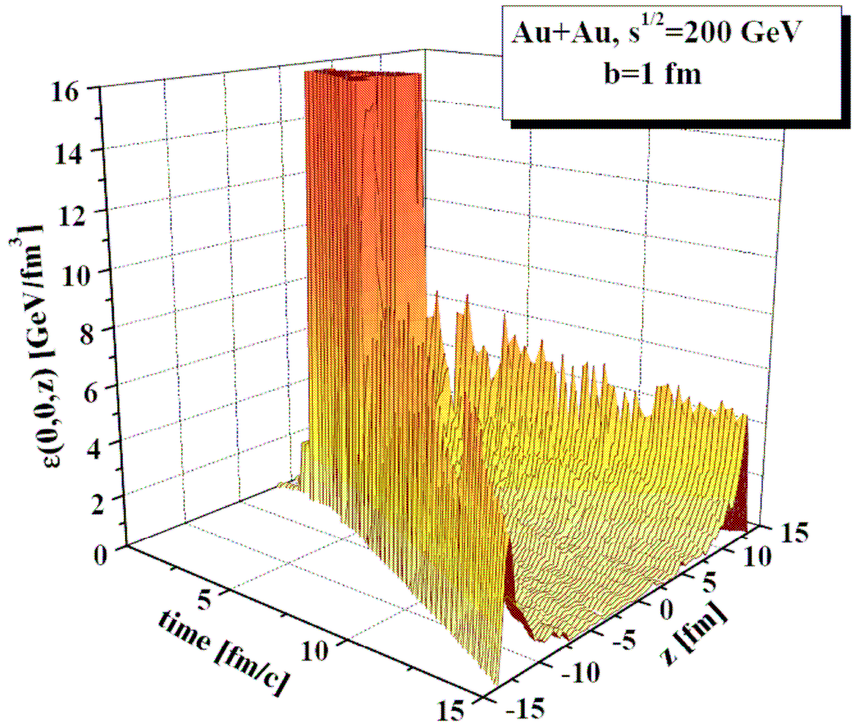
[Olena Linnyk et al., nucl-th/0612049, NPA 786 (2007) 183]

I. 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=0,y=0,z;t) from HSD
for Au+Au collisions at 21300 A GeV



Dissociation threshold energy densities:

J/Ψ melting: $\varepsilon(J/\Psi) = 16$ GeV/fm^3

χ_c melting: $\varepsilon(\chi_c) = 2$ GeV/fm^3

Ψ' melting: $\varepsilon(\Psi') = 2$ GeV/fm^3

Melting temperature:

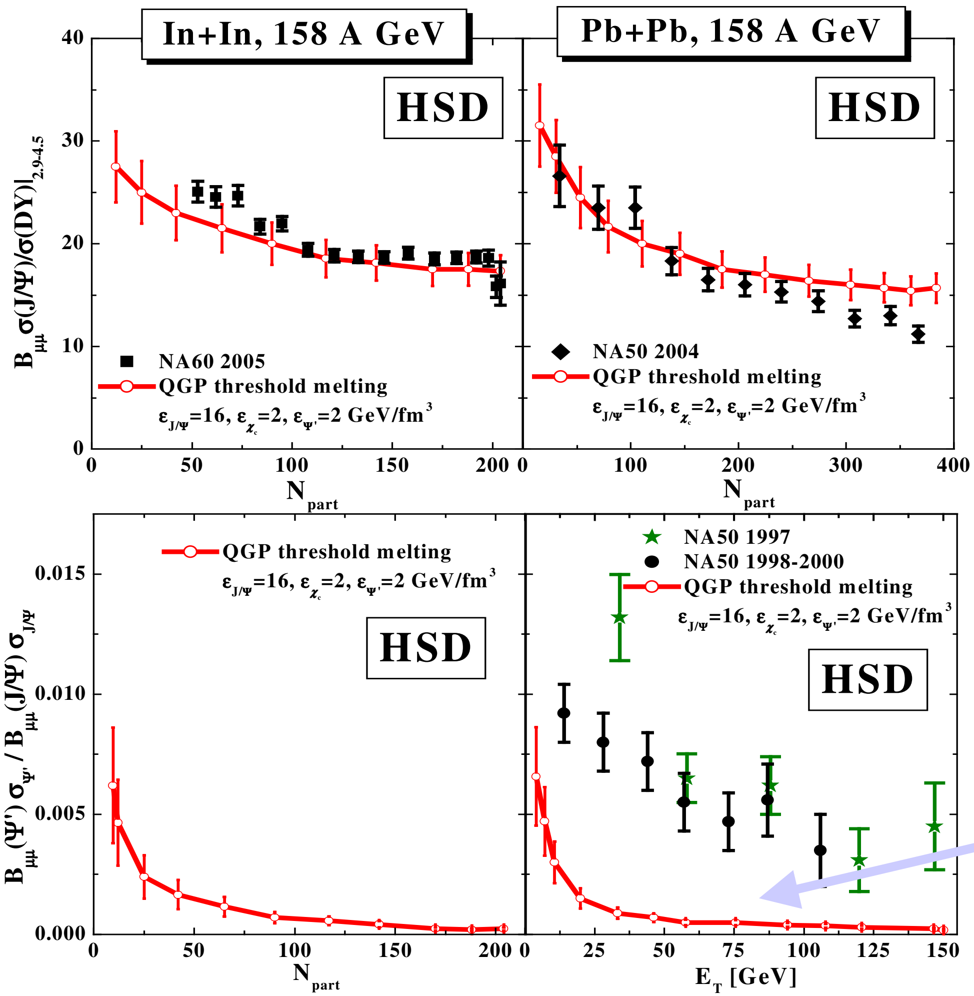
$T(J/\Psi) < 1.6$–$2\ T_C$

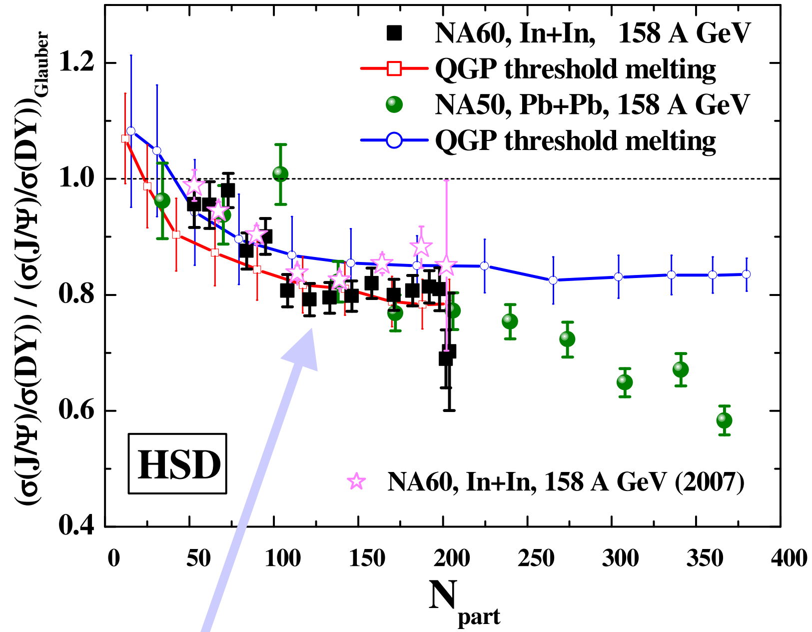
$T(\chi_c) < 1$–$1.2\ T_C$

$T(\Psi') < 1$–$1.2\ T_C$

J/Ψ and Ψ' suppression in In+In and Pb+Pb at SPS: (I.) QGP threshold melting scenario

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



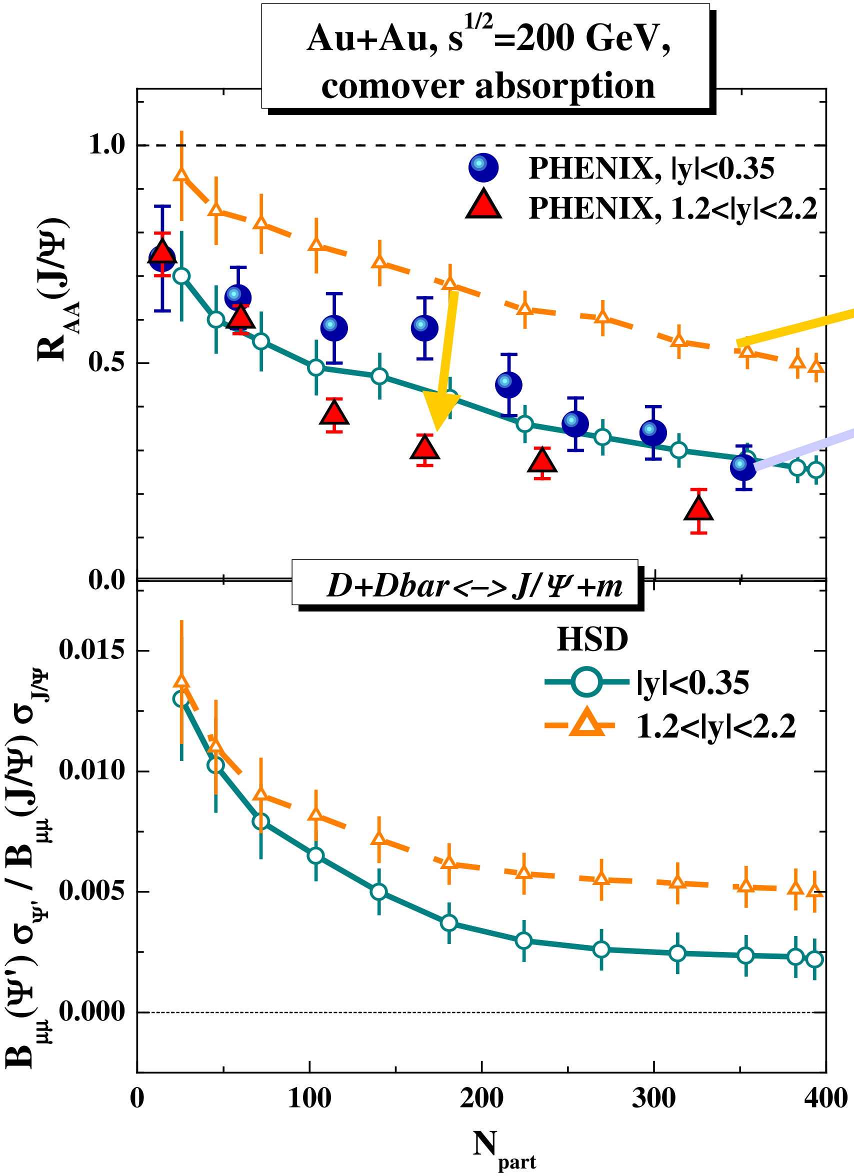


- **J/Ψ suppression is qualitatively described,**

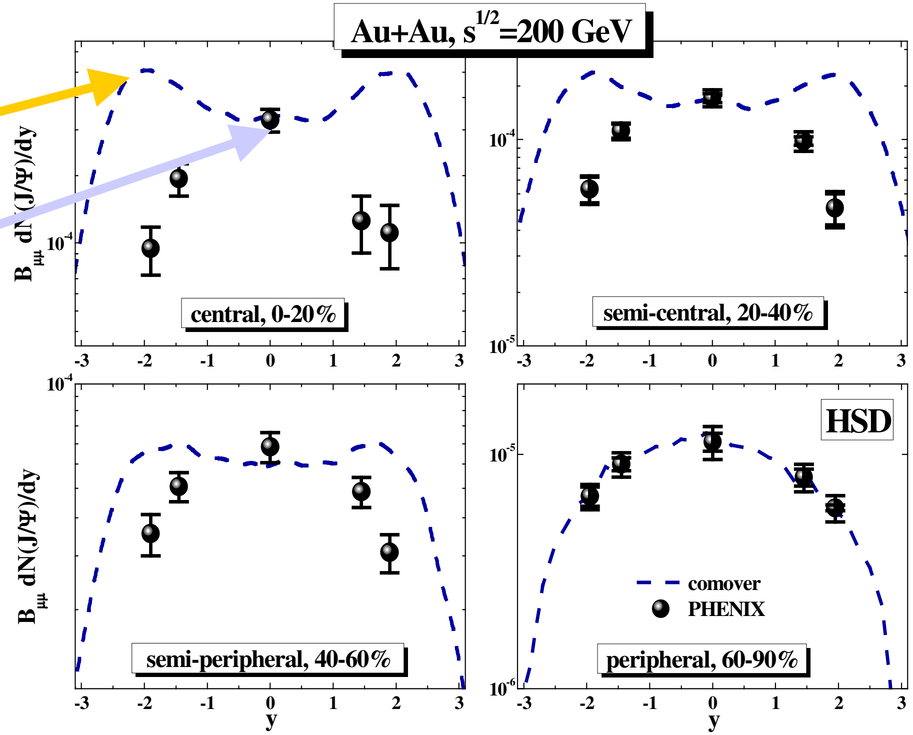
  but QGP threshold melting scenario shows a too strong Ψ' absorption, which contradicts the NA50 data!

[Olena Linnyk et al., nucl-th/0612049, NPA 786 (2007) 183]

J/Ψ and Ψ´ suppression in Au+Au at RHIC:
(II.) Comover absorption (+ recombination by D-Dbar annihilation)



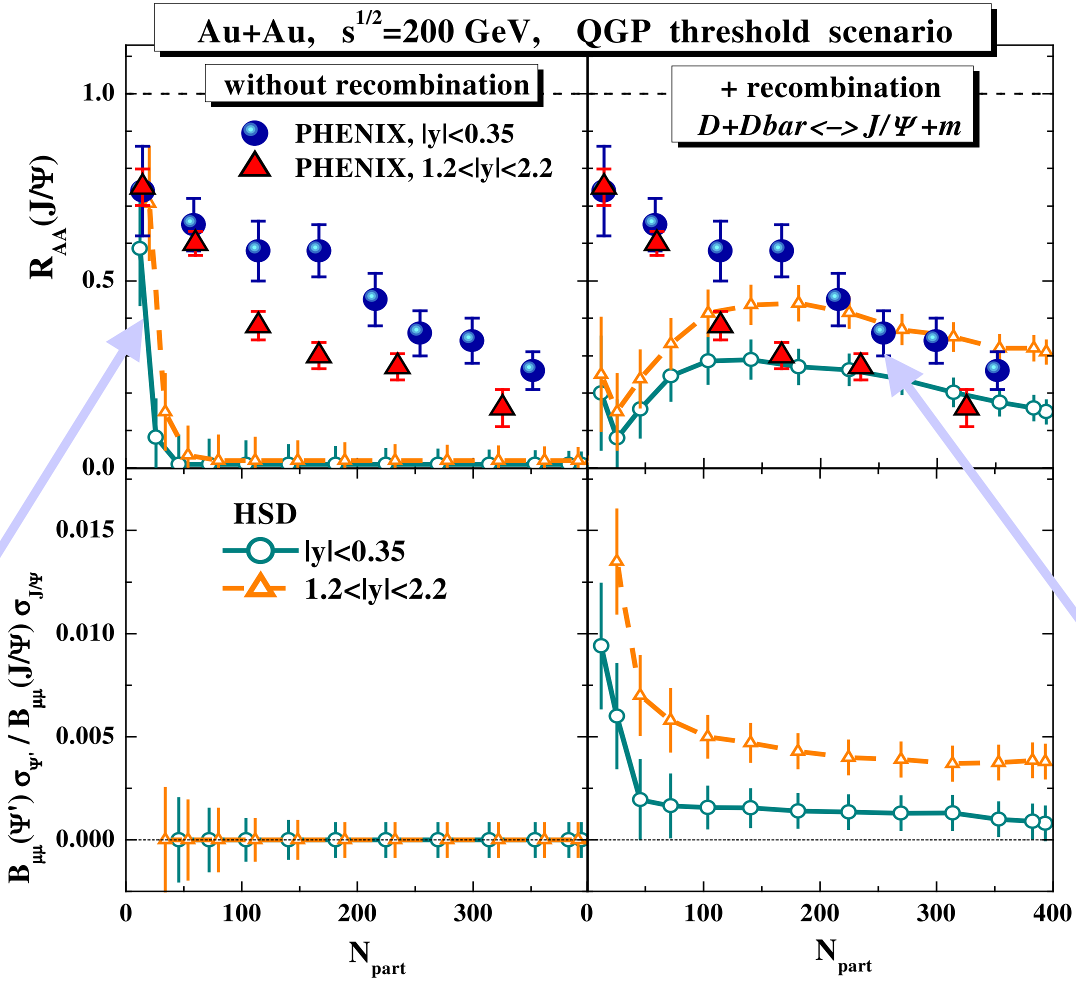
Olena Linnyk et al.,
nucl-th/0612049, NPA 786 (2007) 183;
arXiv:0801.4282, NPA 807 (2008) 79



In the comover scenario the J/Ψ suppression at mid-rapidity is stronger than at forward rapidity, unlike the data!

Pure comover scenario is ruled out by PHENIX data!

J/Ψ and Ψ´ suppression in Au+Au at RHIC:
(I.) QGP threshold melting scenario



[Olena Linnyk et al., arXiv:0705.4443, PRC 76 (2007) 041901]

Melting model: complete dissociation of initial J/Ψ and Ψ´ due to the huge local energy densities !

Charmonia recombination by D-Dbar annihilation is important, however, it can not generate enough charmonia, especially for peripheral collisions!

QGP threshold melting scenario is ruled out by PHENIX data!

Summary for the scenarios (I.-II.)

I. QGP ‚threshold melting‘

versus experimental data

	SPS	RHIC
J/Ψ survival :	$\pm$	—
Ψ'/ J/Ψ ratio :	—	?

II. Hadronic comover absorption (+ recombination by D-Dbar annihilation)

versus experimental data

	SPS	RHIC
J/Ψ survival :	+	—
Ψ'/ J/Ψ ratio :	+	?

Comover absorption and threshold melting scenarios are ruled out by experimental data

evidence for non-hadronic interaction ?!

III. Scenarios for charmonium suppression in A+A

III. Pre-hadronic interaction scenario :

- early interactions of charmonium (ccbar) and D-mesons with unformed (i.e. under formation time $t = \gamma\,\tau_F$, τ_F ~0.8 fm/c in the hadron rest frame) baryons and mesons - pre-hadrons
- + comover absorption with recombination by D-Dbar annihilation

Dissociation cross sections of charmonium by pre-hadrons:

$\sigma^{dis}_{cc\ pre\text{-}Baryon} = 5.8$ mb,

$\sigma^{dis}_{cc\ pre\text{-}meson} = 2/3\ \sigma^{dis}_{cc\ pre\text{-}Baryon}$

Fitted to PHENIX data

Elastic cross sections with prehadrons:

Charmonium - prehadrons:

$\sigma^{el}_{cc\ pre\text{-}Baryon} = 1.9$ mb,

$\sigma^{el}_{cc\ pre\text{-}meson} = 2/3\ \sigma^{el}_{cc\ pre\text{-}Baryon}$

D-meson - prehadrons:

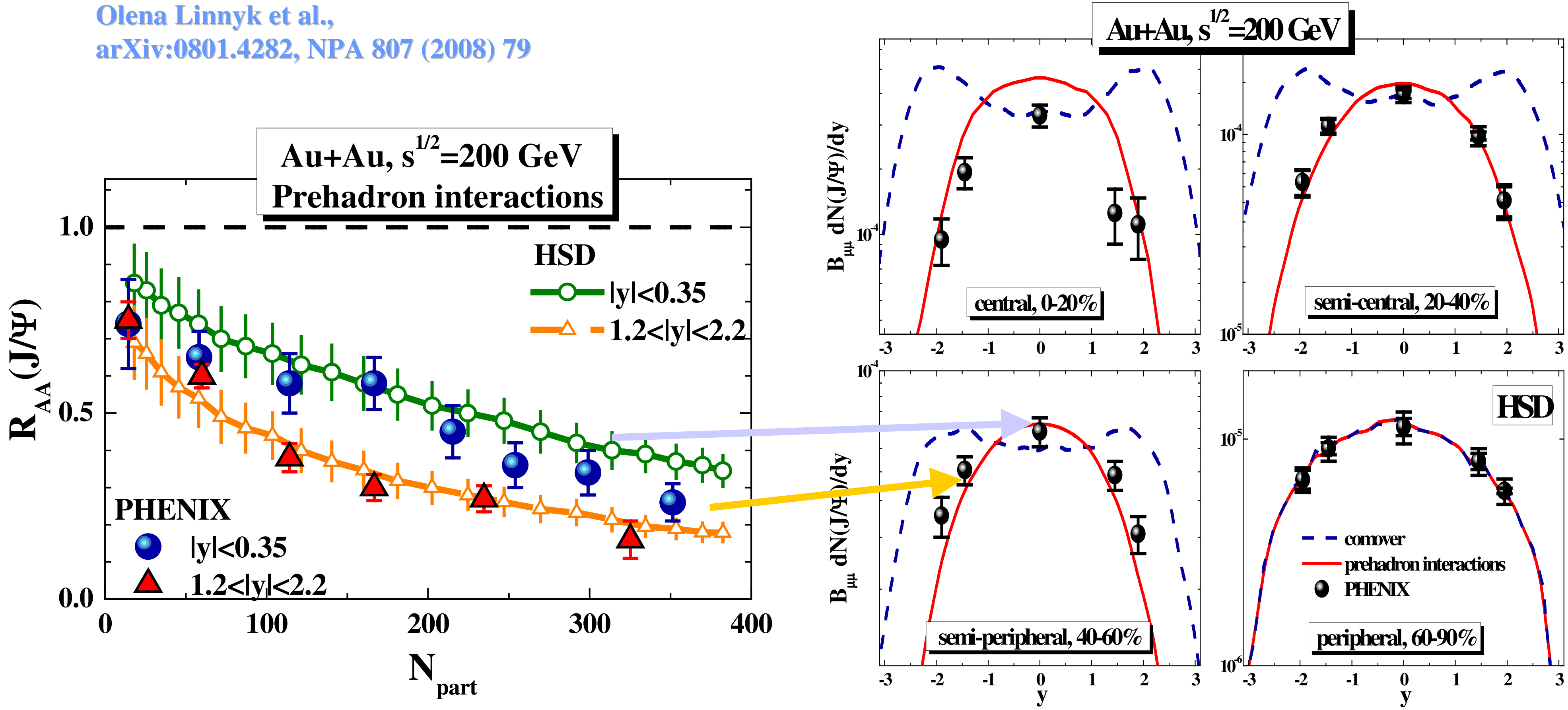
$\sigma^{el}_{D\ pre\text{-}Baryon} = 3.9$ mb,

$\sigma^{el}_{D\ pre\text{-}meson} = 2/3\ \sigma^{el}_{cc\ pre\text{-}Baryon}$

ⓘ Pre-hadronic interaction scenario only ‚simulates' the interactions in the QGP in the Hadron-String model without (!) explicit partonic interactions and phase transition => NOT (yet!) a consistent description ! => PHSD

J/Ψ and Ψ´ suppression in Au+Au at RHIC:
(III.) Pre-hadronic interaction scenario

Olena Linnyk et al.,
arXiv:0801.4282, NPA 807 (2008) 79

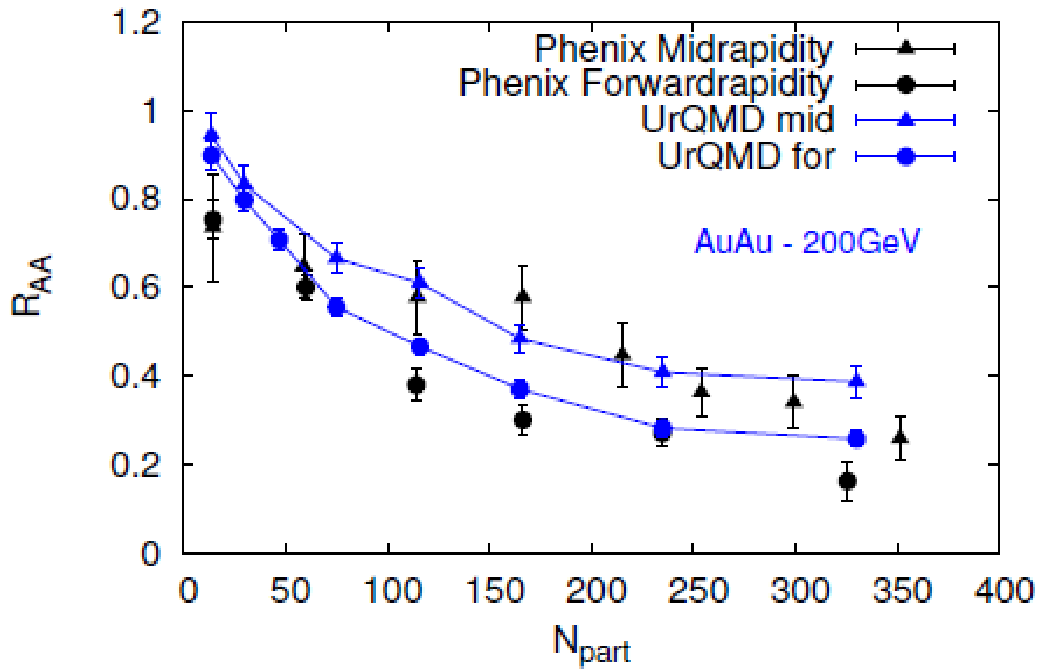


In the prehadronic interaction scenario the J/Ψ rapidity distribution has the right shape like the PHENIX data! => can describe the RHIC data at $s^{1/2}$=200 GeV for Au+Au at mid- and forward-rapidities simultaneously.

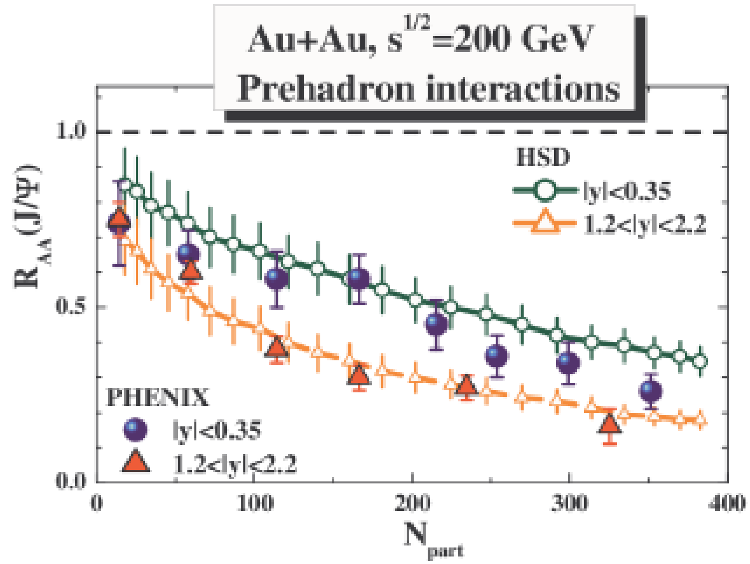
Realization of pre-hadronic interaction scenario in UrQMD

RHIC

Our model can reproduce rapidity dependence at RHIC



- same cross sections used as at SPS energies



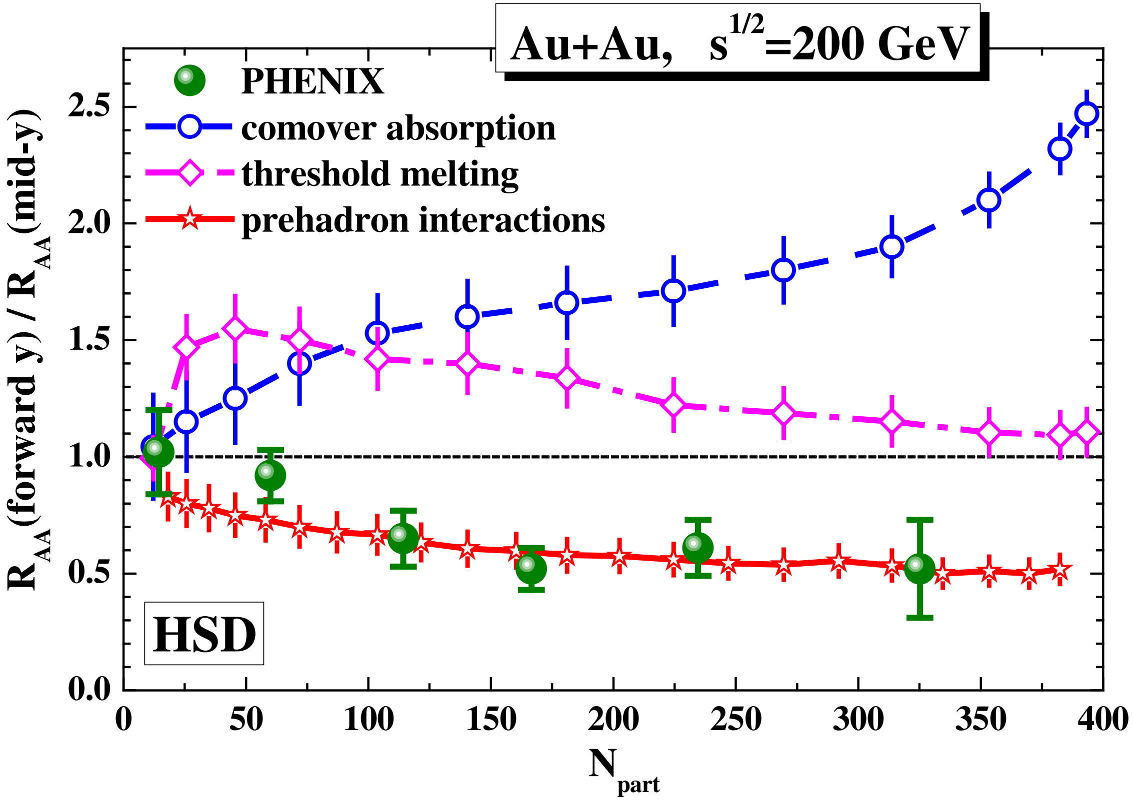
$Au - Au, s^{1/2} = 200\ GeV$

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

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

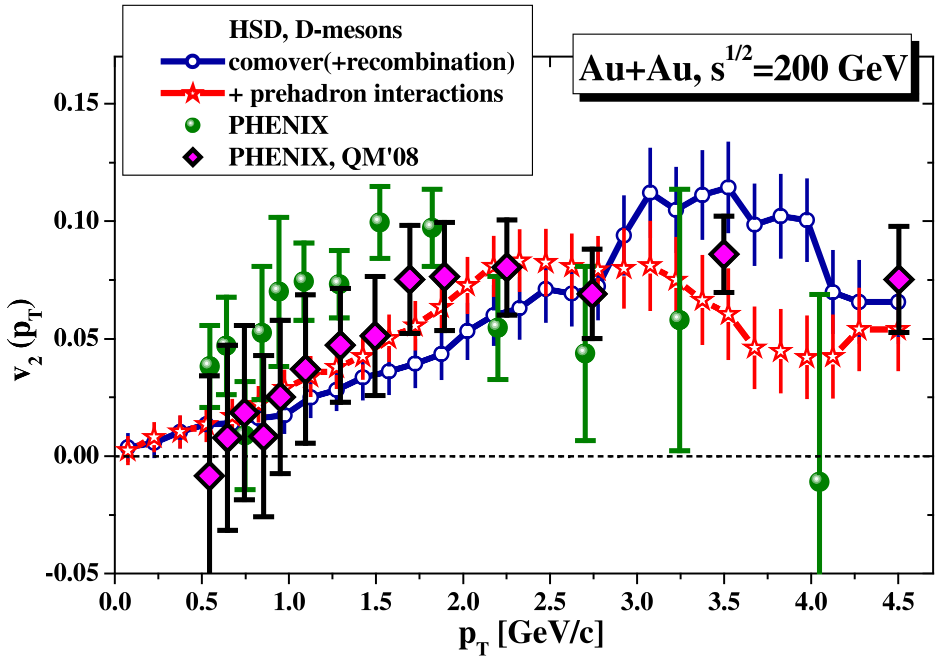
J/Ψ and Ψ´ suppression in Au+Au at RHIC

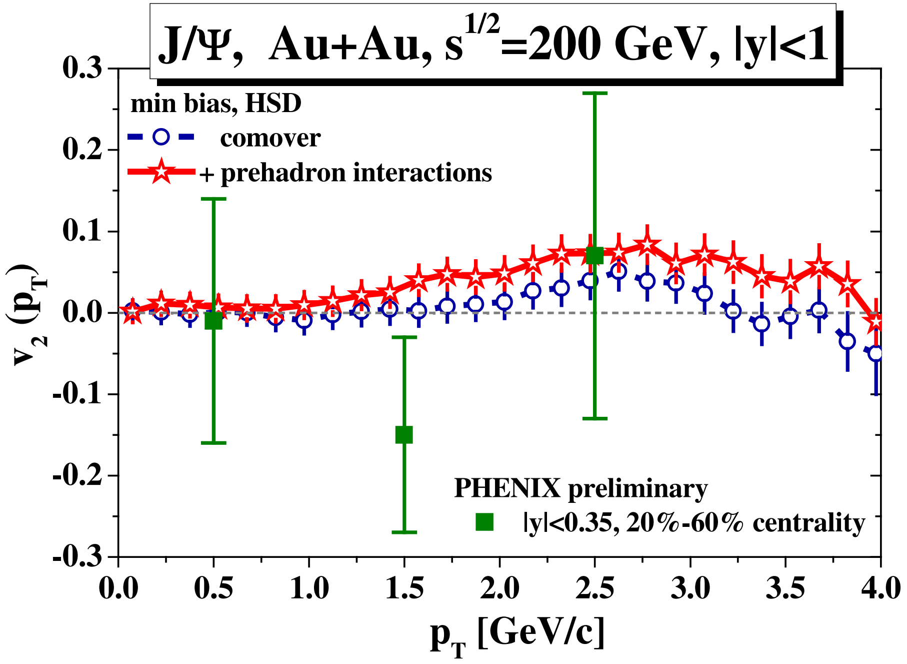
Olena Linnyk et al.,
arXiv:0801.4282, NPA 807 (2008) 79



PHENIX data: → evidence for non-hadronic interactions of charm degrees of freedom !

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





- Pre-hadronic interactions lead to an increase of the elliptic flow v_2
- The pre-hadronic interaction scenario is ~consistent with the preliminary PHENIX data on the D-mesons v_2

=> strong initial flow of non-hadronic nature!

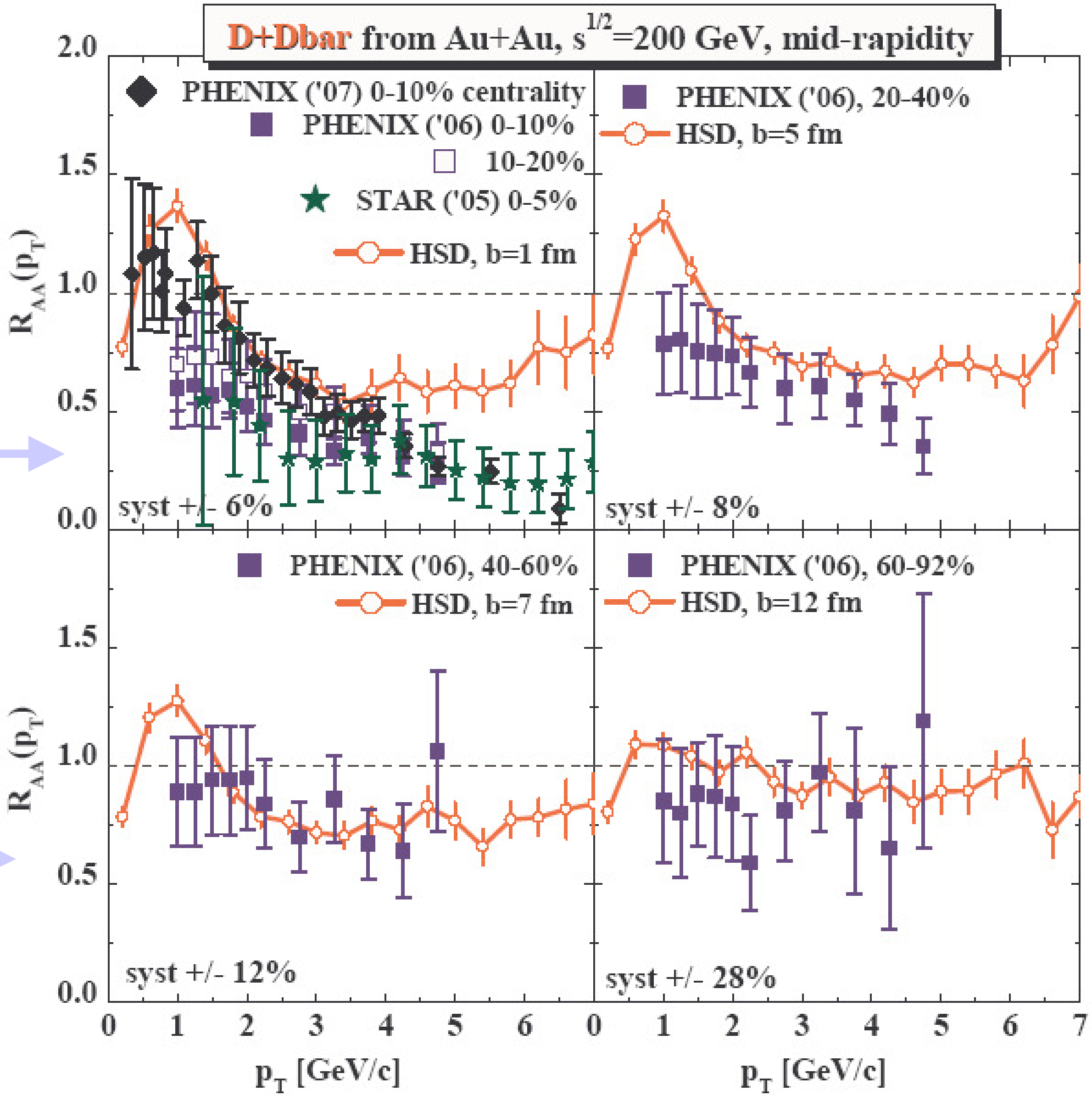
[Olena Linnyk et al., arXiv:0801.4282, NPA 807 (2008) 79]

Quenching of D mesons at RHIC

$$R_{AB} = \frac{N_\psi^{AB}}{N_\psi^{PP} \langle N_{coll} \rangle}$$

- Evidence of additional **high p_T suppression** in the most central collisions.

- Suppression of D mesons in **peripheral** collisions is consistent with a purely hadronic scenario.



[O. Linnyk et al., arXiv:0808.1504; Int J Mod Phys E17 (2008) 1367]

Summary I

- J/Ψ probes early stages of fireball and HSD is the tool to model it.
- Comover absorption and threshold melting: both reproduce J/Ψ survival in Pb+Pb as well as in In+In at SPS, while Ψ´/J/Ψ data appear to be in conflict with the ‚melting scenario‘.
- Comover absorption and threshold melting fail to describe the RHIC data at $s^{1/2}$=200 GeV for Au+Au at mid- and forward-rapidities simultaneously
- Prehadronic interaction scenario can describe the RHIC data at $s^{1/2}$=200 GeV for Au+Au at mid- and forward-rapidities simultaneously
- STAR data on v_2 of high p_T charged hadrons and charm D mesons are not reproduced in the hadron-string picture

➔ evidence for a plasma pressure ?!

Outlook I: open problems

- Energy, rapidity, p_T - dependent hadronic absorption cross sections

from experiments : systematic energy and system scan for p+A

- Explicit dynamics of c-cbar in the QGP phase !

Theory - modeling of parton-hadron phase transition based on lQCD EoS and off-shell parton transport:
Parton-Hadron-String-Dynamics (PHSD)

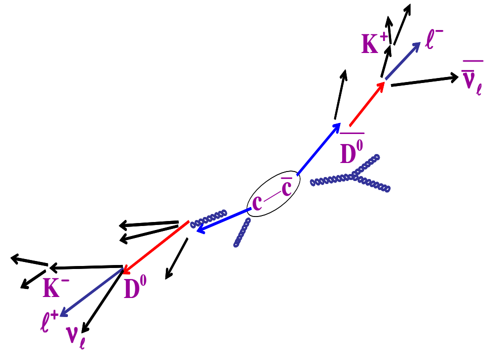
✓ *Work in progress - Hamza Berrehrah et al.*

Open and hidden charm via dileptons

Open and hidden charm via dileptons

❑ Correlated charm pair production: c-cbar → D+Dbar

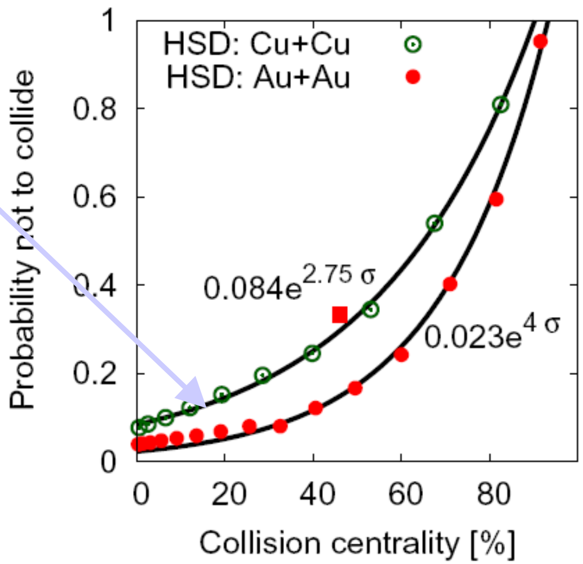
However, the initial charm correlations are partly lost due to collisional (rescattering) and radiative energy loss



❑ Contribution to dileptons: correlated pairs and uncorrelated D-Dbar meson pairs (have a different slope)

In central collisions the correlated charm pairs are strongly suppressed

RHIC: $s^{1/2}$=200 GeV



❑ Modeling of charm (and beauty) production for dileptons:

based on an extended statistical hadronization model (SHM) – from Jaakko Manninen

J. Manninen, E.B., W. Cassing, O. Linnyk, Eur. Phys. J. C71 (2011) 1615

+ at RHIC: suppression of correlated charm pairs due to the hadronic rescattering – from HSD

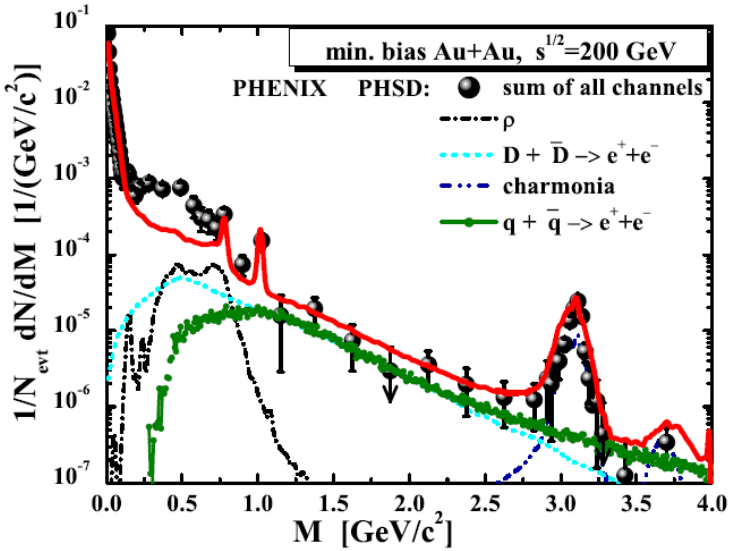
O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

+ at LHC: collisional and radiative energy loss – from Pol-Bernard Gossiaux and Jörg Aichelin

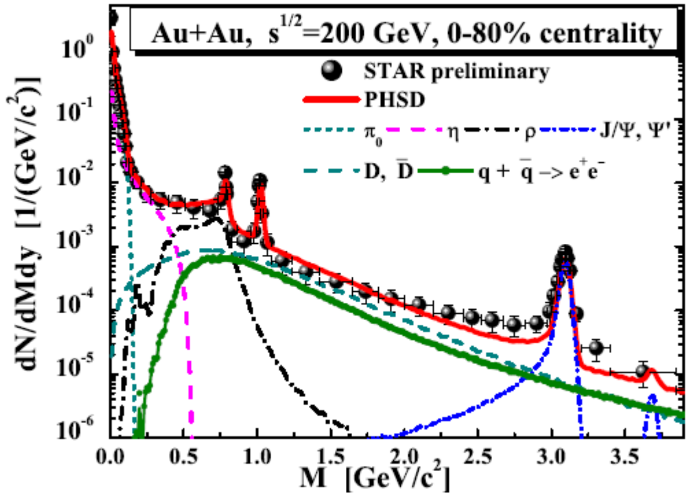
O. Linnyk, W. Cassing, J. Manninen, E. L. B., P. B. Gossiaux, J. Aichelin, T. Song, C. M. Ko , arXiv:1208.1279

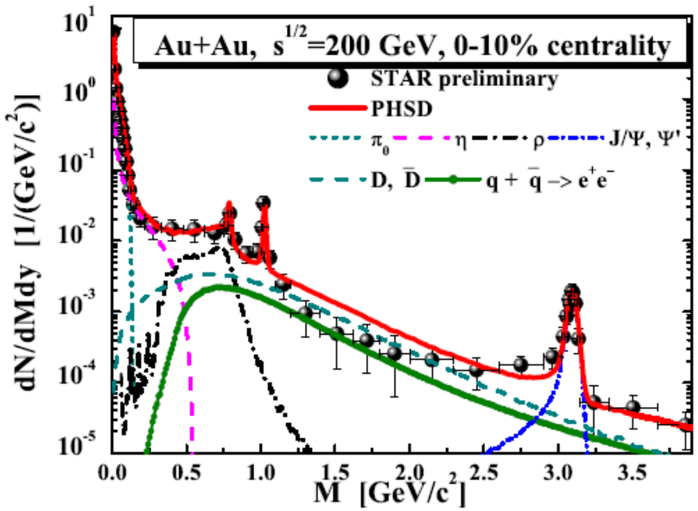
Open and hidden charm via dileptons

PHSD vs. PHENIX data



PHSD vs. STAR data





At M> 1.2 GeV the dilepton yield from

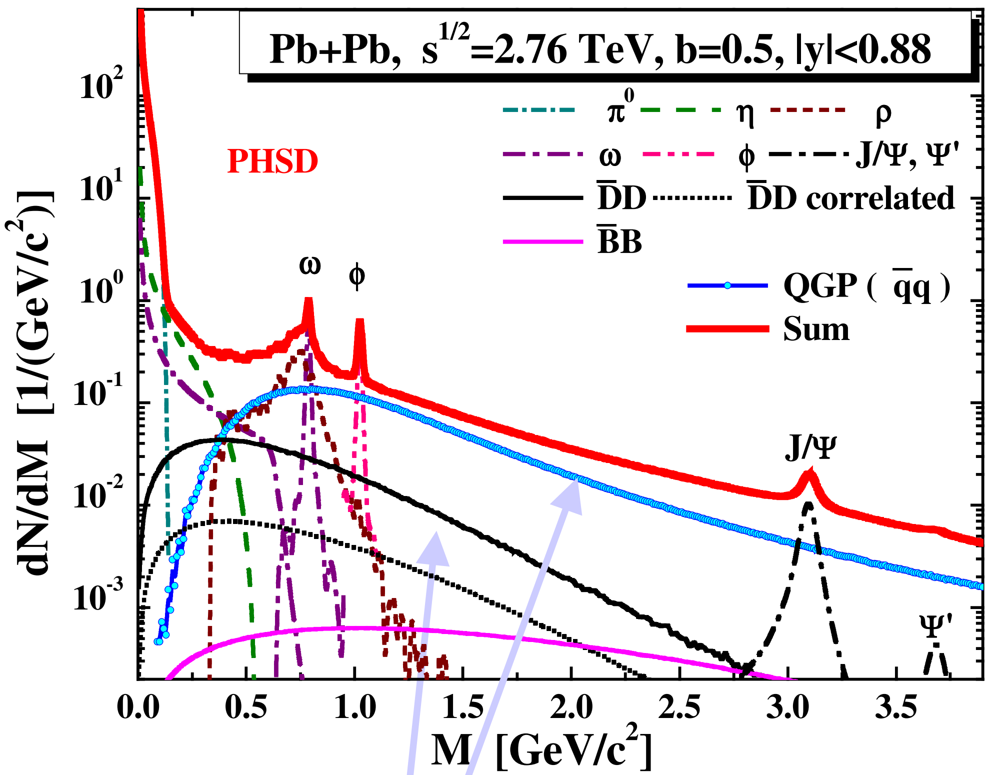
- ❑ open charm: D+Dbar → e+e-
- ❑ hidden charm: J/Ψ→ e+e-

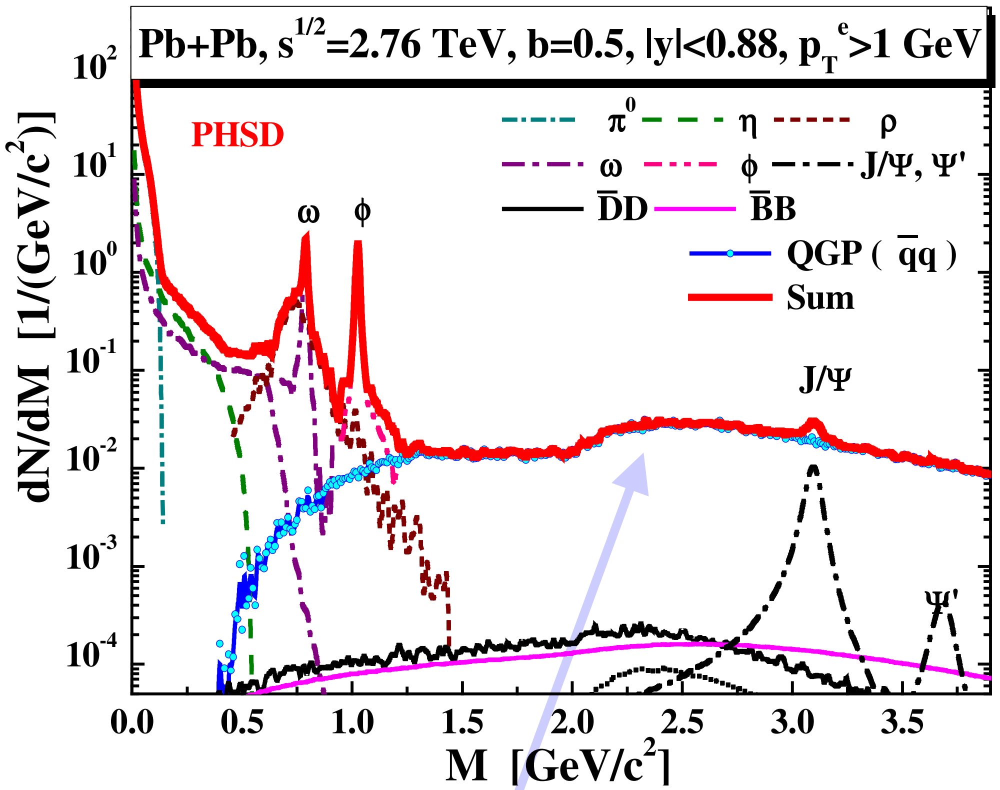
dominate over QGP contribution (or of the same order) !

➔ charm vs. QGP

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

Predictions for LHC





QGP(qbar-q) dominates at M>1.2 GeV

p_T cut enhances the signal of QGP(qbar-q)

- D-, B-mesons energy loss from Pol-Bernard Gossiaux and Jörg Aichelin
- J/Ψ and Ψ’ nuclear modification from Che-Ming Ko and Taesoo Song

O. Linnyk, W. Cassing, J. Manninen, E. L. B., P. B. Gossiaux, J. Aichelin, T. Song, C. M. Ko , arXiv:1208.1279

Summary and outlook II

- Open and hidden charm and bottom contribute to the **dilepton production** from SPS to LHC energies
- Charm has a large influence on the interpretation of dilepton data for M>1.2 GeV: **charm vs. QGP**
- Initial c-cbar correlations in the charm production are partly lost due to **collisional (rescattering) and radiative energy loss**

Outlook:

Dynamical calculation of the collisional and radiative energy loss in PHSD

✓ *Work in progress - Hamza Berrehrah et al.*

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