Symposium and 10th CBM Collaboration Meeting
September 25 – 28, 2007
Forschungszentrum
Dresden Rossendorf

Charm dynamics from transport calculations

Olena Linnyk

FIAS Frankfurt Institute for Advanced Studies

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:

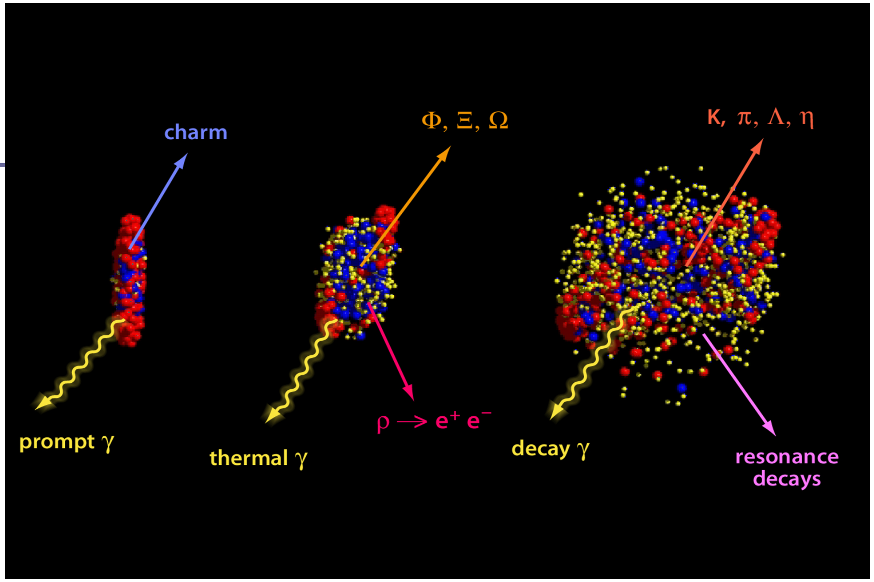
Experimental energy scan of different observables in order to find an ‚anomalous‘ behavior in comparison with theory

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

Signals of the phase transition:



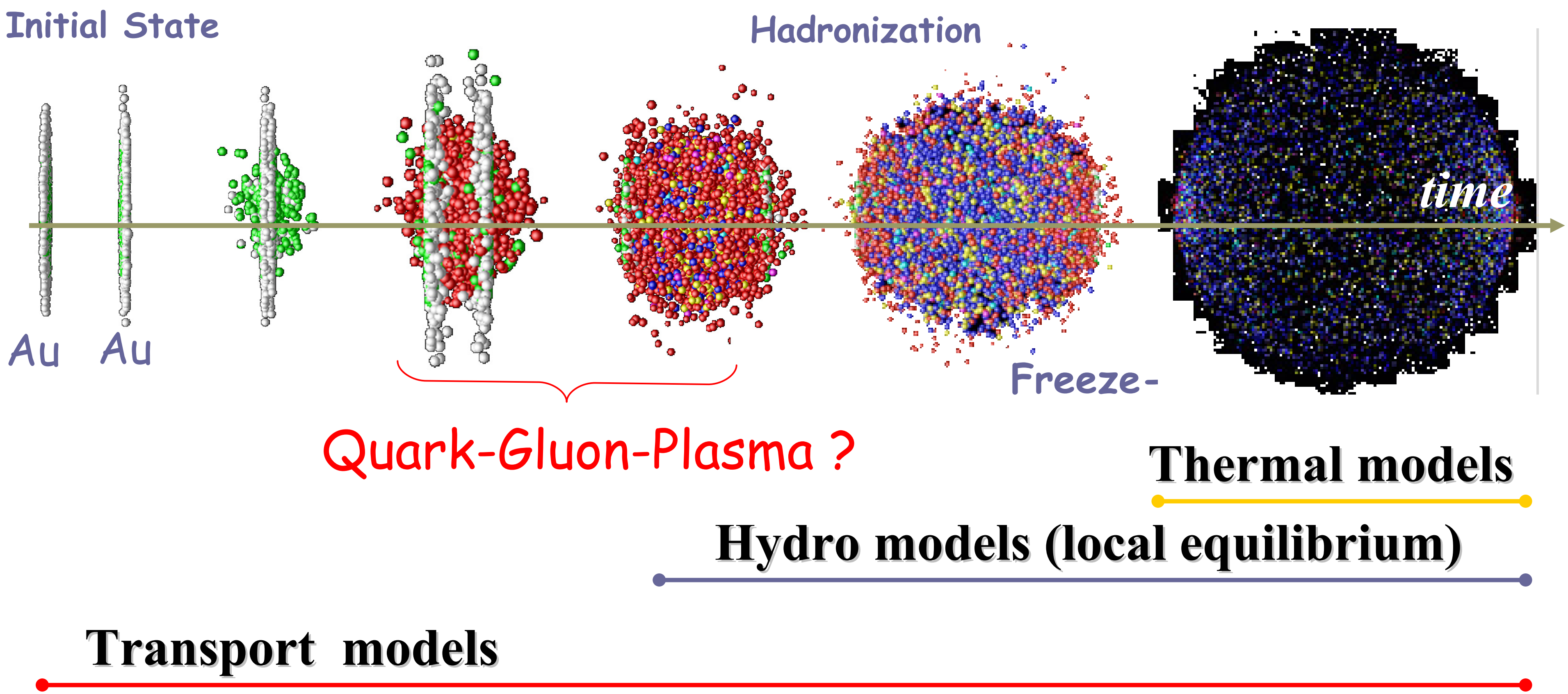
- Strangeness enhancement
- Multi-strange particle enhancement
- Charm suppression
- Collective flow (v_1, v_2)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!

Models for heavy ion collisions



Microscopical transport models provide the dynamical description of nonequilibrium effects in heavy-ion collisions

Basic concepts of Hadron-String Dynamics

- **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 the collision terms I_{coll} describing:

- **elastic and inelastic hadronic reactions** BB <–> B′B′, BB <–> B′B′m, mB <–> m′B′, mB <–> B′
- **formation and decay of baryonic and mesonic resonances**
- **string formation and decay** (for inclusive production: BB0AX, mB0AX, X =many particles)

- **Implementation of detailed balance on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-meson fusion reactions)**

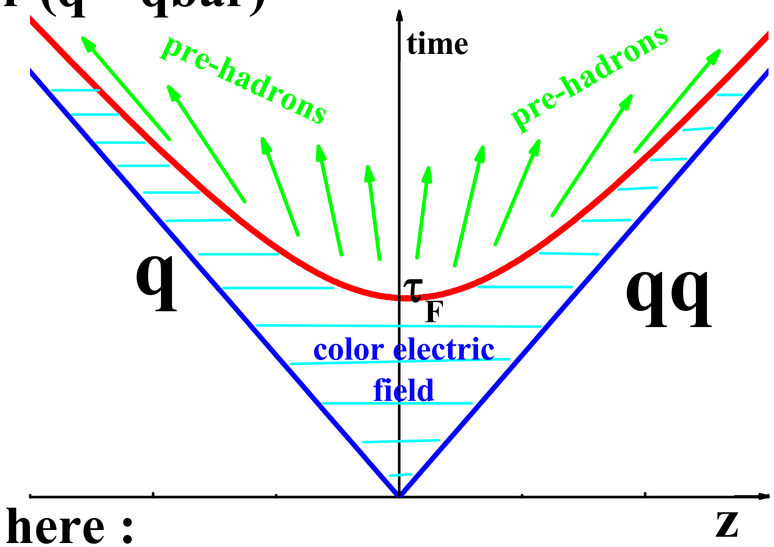
- **Off-shell dynamics for short living states**

Degrees of freedom in HSD

- **hadrons - baryons and mesons including excited states (resonances)**
- **strings – excited colour singlet states (qq - q) or (q – qbar)**

  Based on the LUND string model

  & perturbative QCD via PYTHIA
- **leading quarks (q, qbar) & diquarks (q-q, qbar-qbar)**



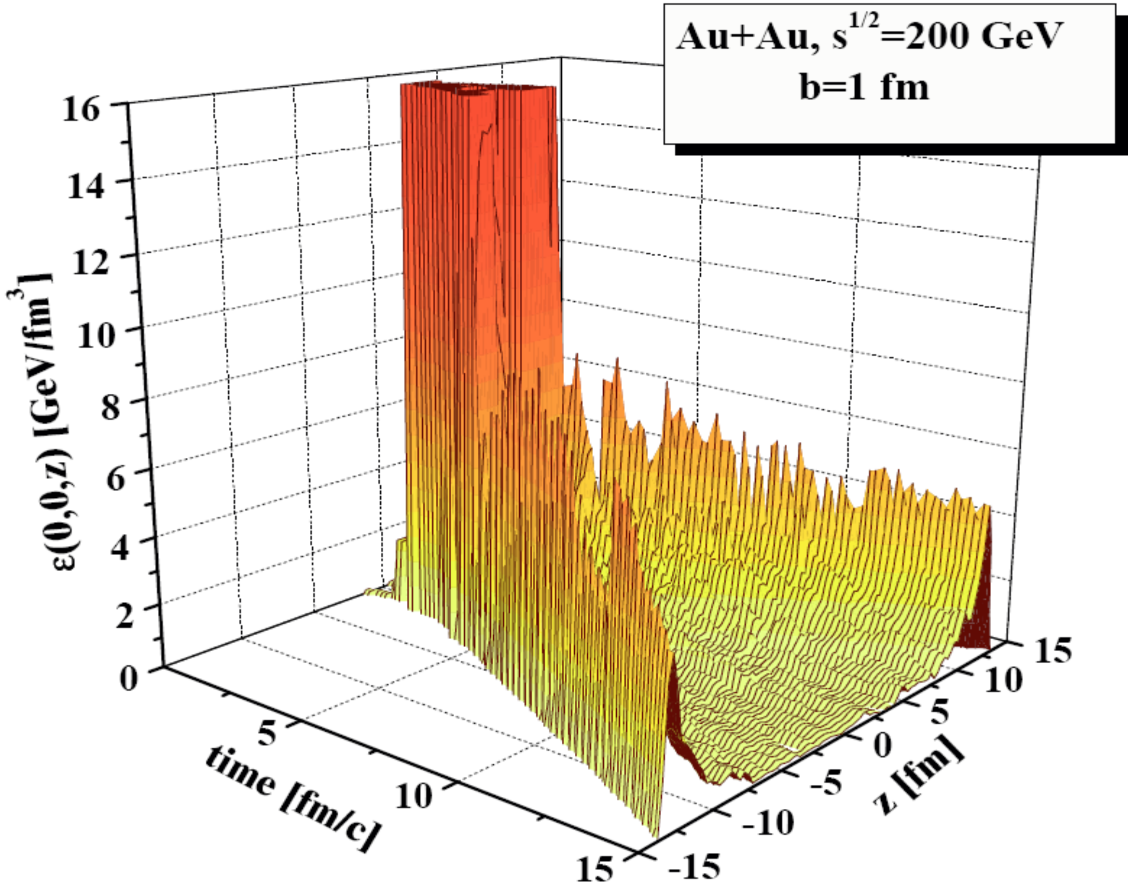
NOT included in the transport models presented here :

- **no explicit parton-parton interactions (i.e. between quarks and gluons) outside strings!**
- **no QCD EoS for partonic phase**

under construction:

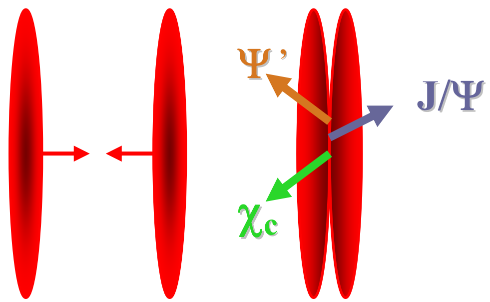
PHSD – Parton-Hadron-String-Dynamics W. Cassing arXiv:0704.1410

Time evolution of the energy density



HSD transport model allows to calculate the energy momentum tensor $T^{\mu\nu}(x)$ for all space-time points x and thus the energy density $\varepsilon(r,t)$ which is identified with $T^{00}(r,t)$

Local energy density ε *vs* Bjorken energy density ε_{Bj}



- **transient time for central Au+Au at 200 GeV:**

  $t_r \sim 2R_A/\gamma_{cm} \sim 0.13$ **fm/c**

- $\bar{c}c$ **formation time:**

  $\tau_C \sim 1/M_T \sim 1/4\text{GeV} \sim 0.05$ **fm/c** $< t_r$

- $\bar{c}c$ **pairs are produced in the initial hard NN collisions in time period** t_r

Bjorken energy density:

$$\varepsilon_{Bj} = \frac{1}{A_\perp \tau}\frac{dE_T}{dy}$$

A_T **is the nuclei transverse overlap area**

τ **is the formation time of the medium**

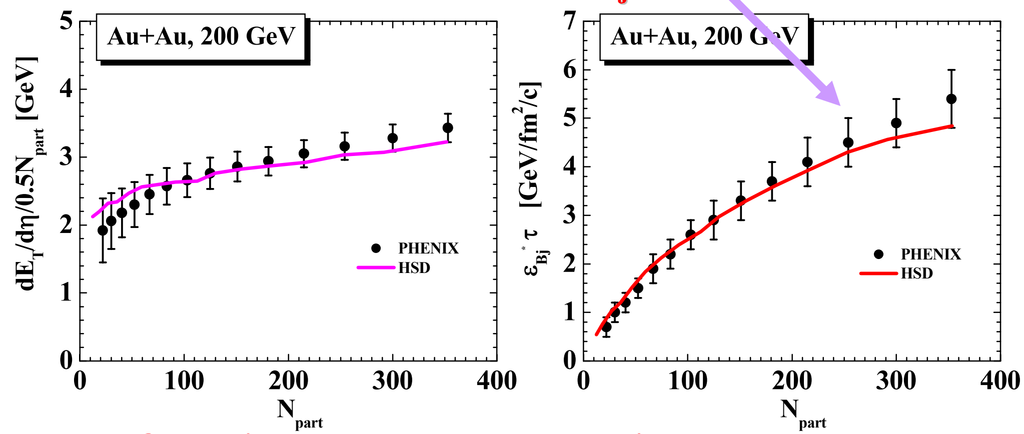
at RHIC $\varepsilon_{Bj}\,\tau \sim 5$ **GeV/fm²/c**

‚Local' energy density ε during transient time t_r **:**

$\varepsilon \sim 5[\text{GeV/fm}^2/\text{c}] / [0.13\ \text{fm/c}]$

$\sim 30\ \text{GeV/fm}^3$

accounting τ_C **:** $\varepsilon \sim 28\ \text{GeV/fm}^3$



✓ **HSD reproduces PHENIX data for Bjorken energy density very well**

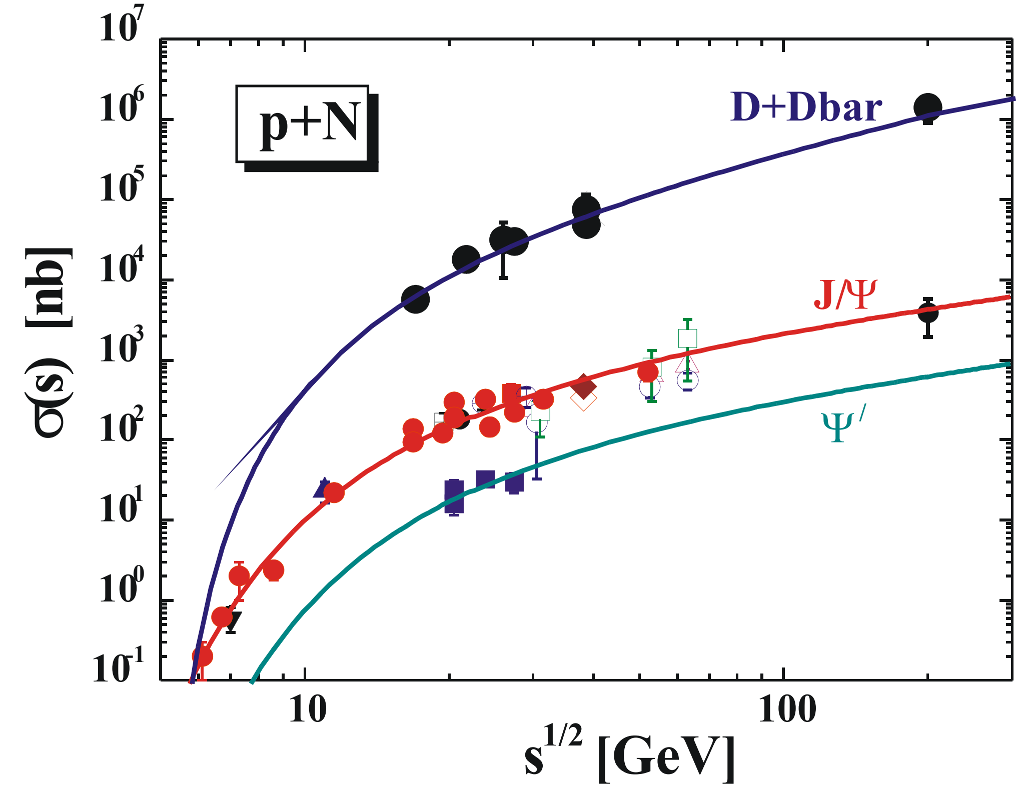
✓ **HSD results are consistent with simple estimates for the energy density**

Charmonium production in pN

Hard probe 0A binary scaling!

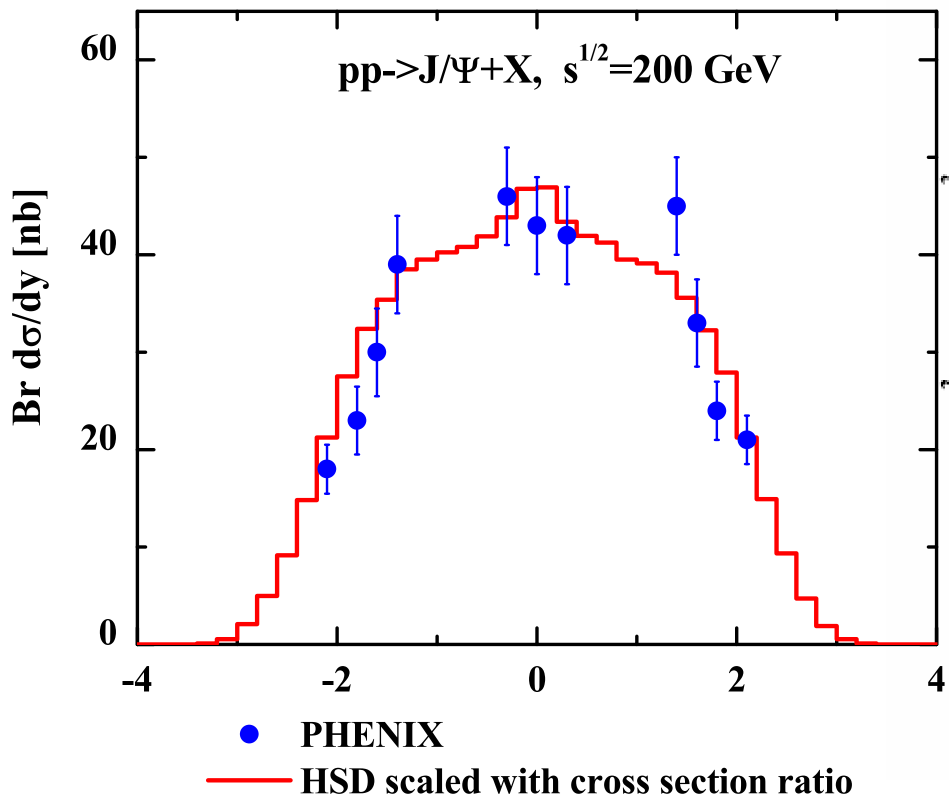
σ(J/Ψ) and σ(Ψ‵):
parametrization of the available experimental data

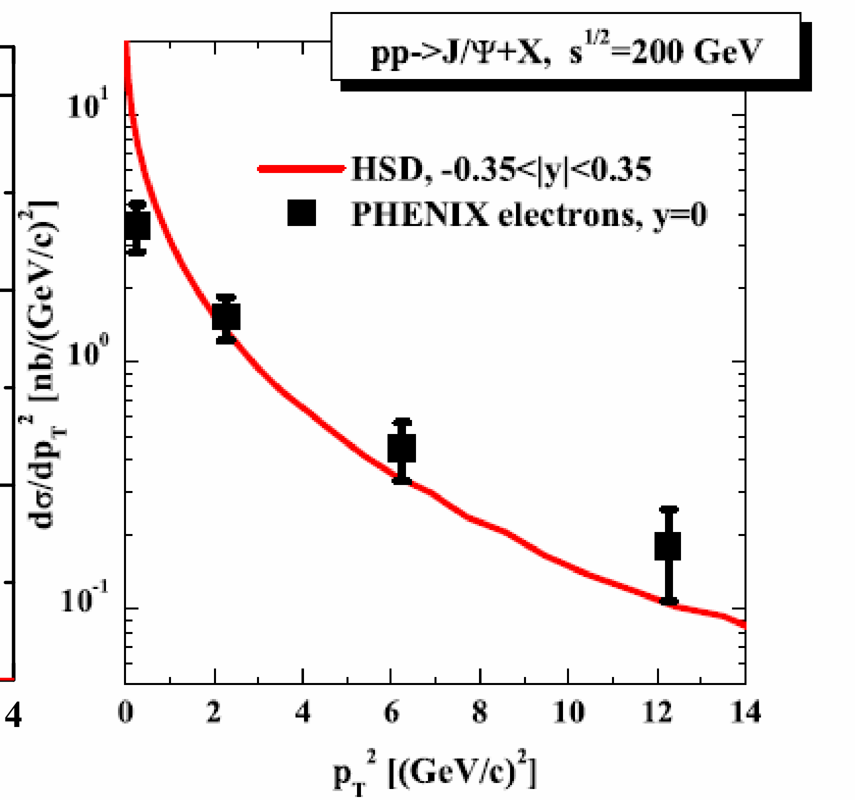
But data close to threshold
are still needed !
FAIR at GSI



$$\sigma_{J/\Psi}^{exp} = \sigma_{J/\Psi} + B(\chi_c\, 0\, A\, J/\Psi)\, \sigma_{\chi c} + B(\Psi' \text{->} J/\Psi)\, \sigma_{\Psi}'$$

Charmonium production in pN

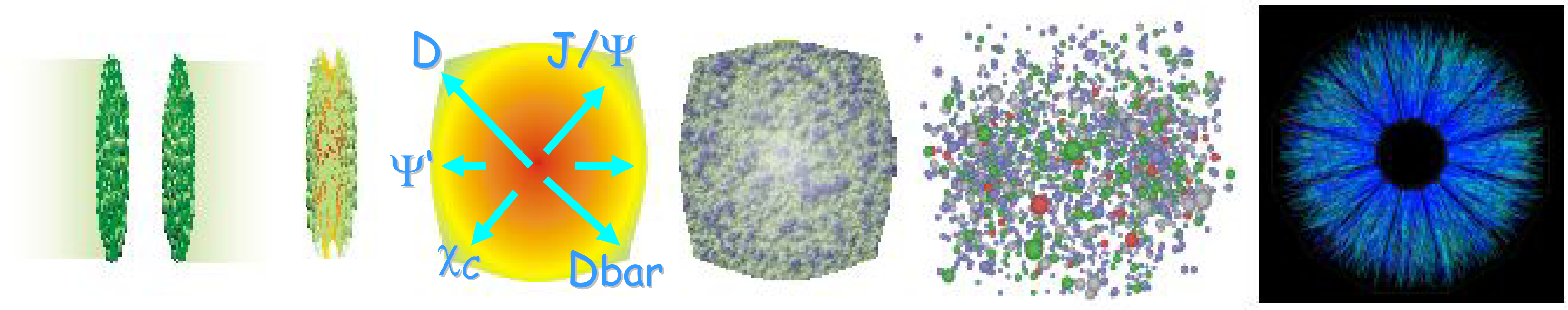




Differential cross section of charm production is successfully parametrized, too

Charmonium production *vs* absorption

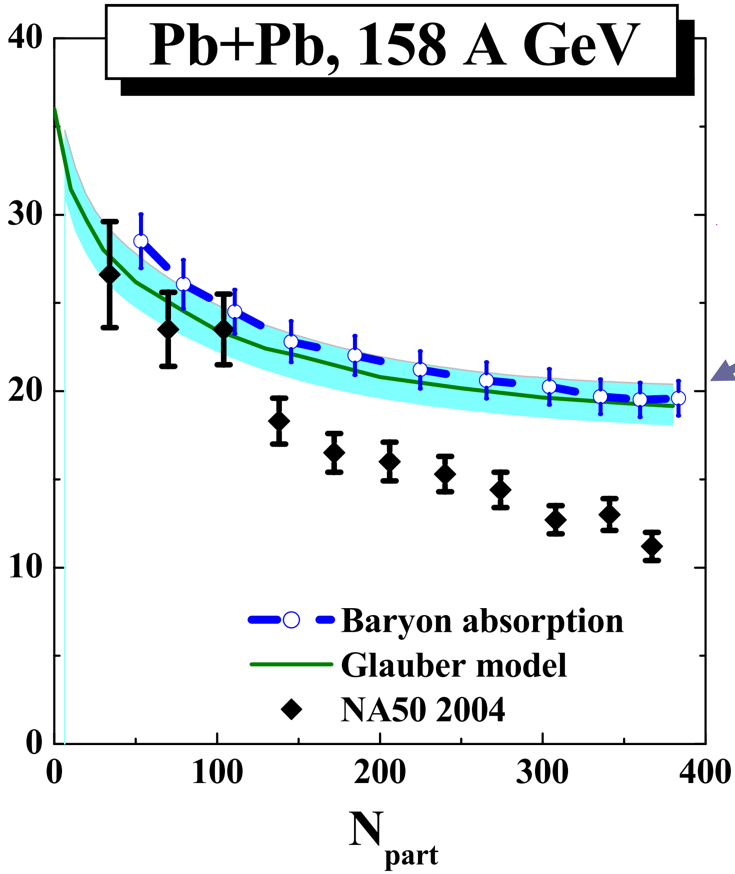
Charm sector reflects the dynamics in the early phase of heavy-ion collisions !



Charmonium is absorbed by

- Scattering on nucleons (normal nuclear absorption, as in *pA*)
- Interaction with secondary hadrons (comovers)
- Dissociation in the deconfined medium (suppression in QGP)

Anomalous J/Ψ suppression



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

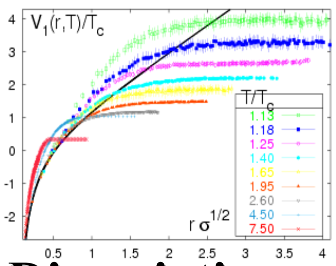
Experimental observation (NA38/50/60): extra suppression in A+A collisions; increasing with centrality

Scenarios for anomalous charmonium suppression

- **QGP colour screening**

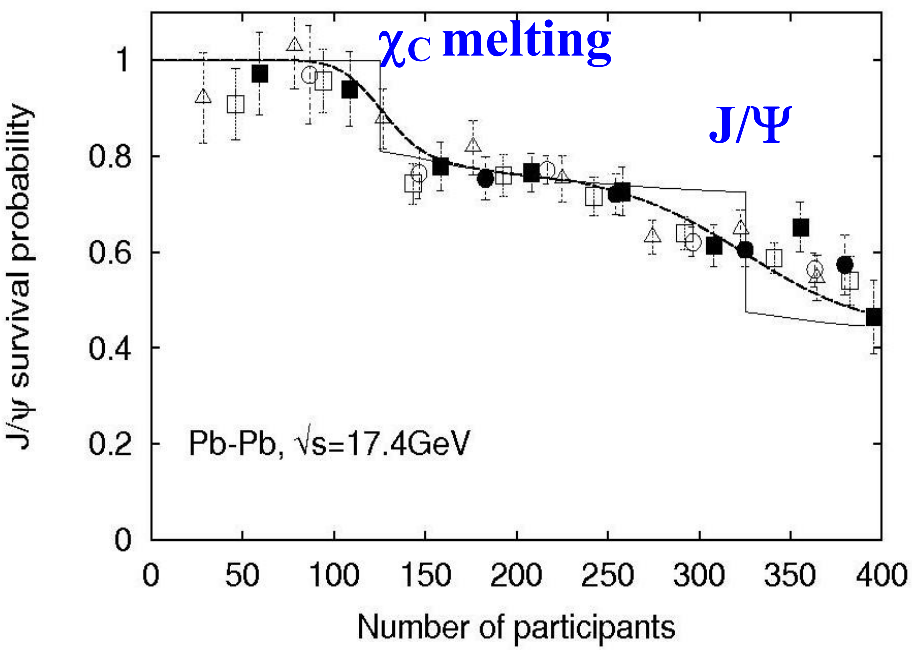
[Digal, Fortunato, Satz ’03]

Quarkonium dissociation T:



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

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



- **Comover absorption**

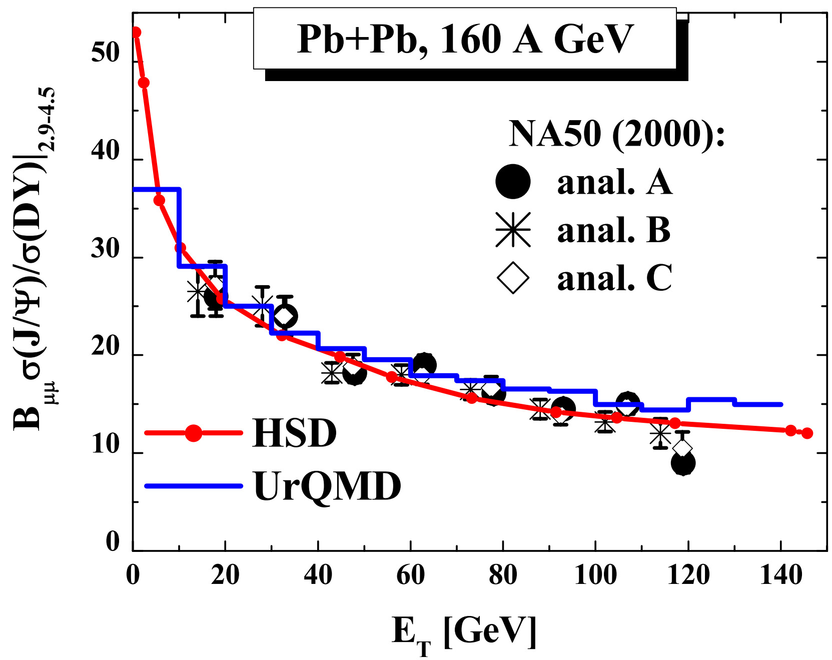
[Gavin & Vogt, Capella et al.`97]

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

J/Ψ+m ? 0 A D+Dbar

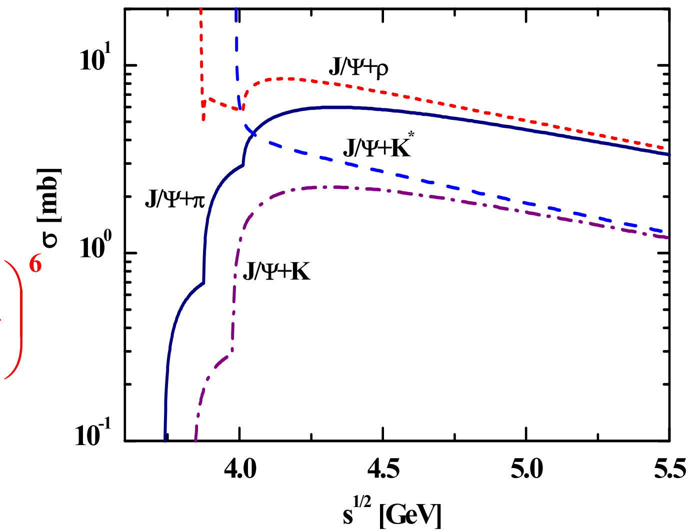
Ψ´ +m ? 0 A D+Dbar

χ_C +m ? 0 A D+Dbar



Modelling the comover scenario in HSD

1. Charmonia **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:

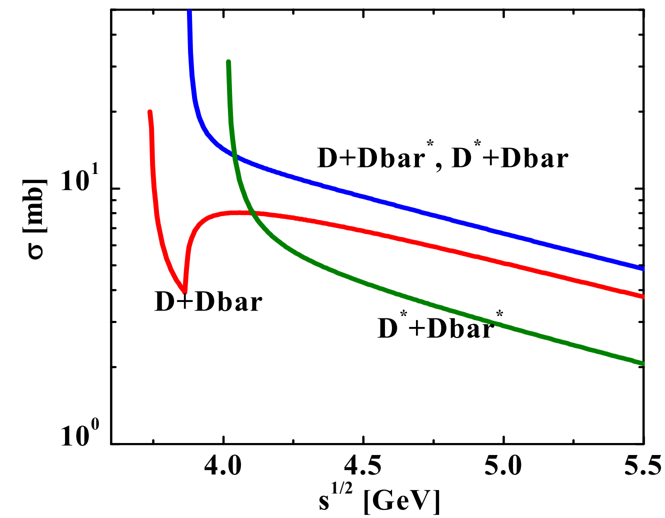
$$\sigma_{1+2->3+4}(s) = g_{isospin}\, 2^4 \frac{E_1 E_2 E_3 E_4}{s} |M_i|^2 \left(\frac{m_3 + m_4}{\sqrt{s}}\right)^6$$

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

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

constant matrix element

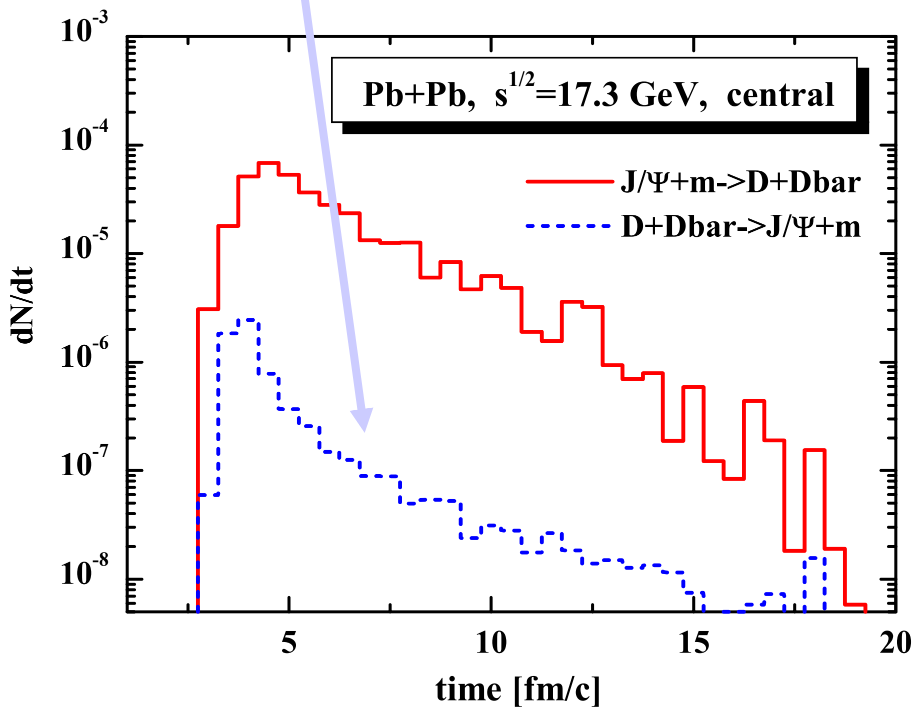
2. J/Ψ **recombination** cross sections by D+Dbar annihilation:
D+Dbar -> J/Ψ (χ_c, Ψ') + meson (π, ρ, K , K*)
are determined by **detailed balance!**

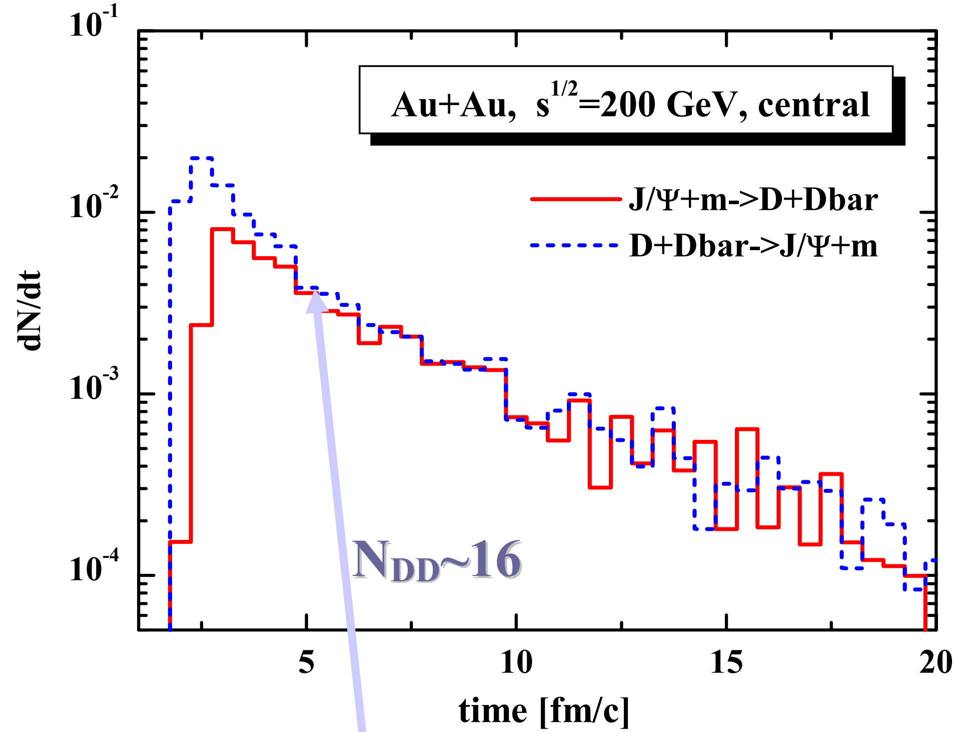


[PRC 67 (2003) 054903]

Charmonium recombination by DDbar annihilation

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

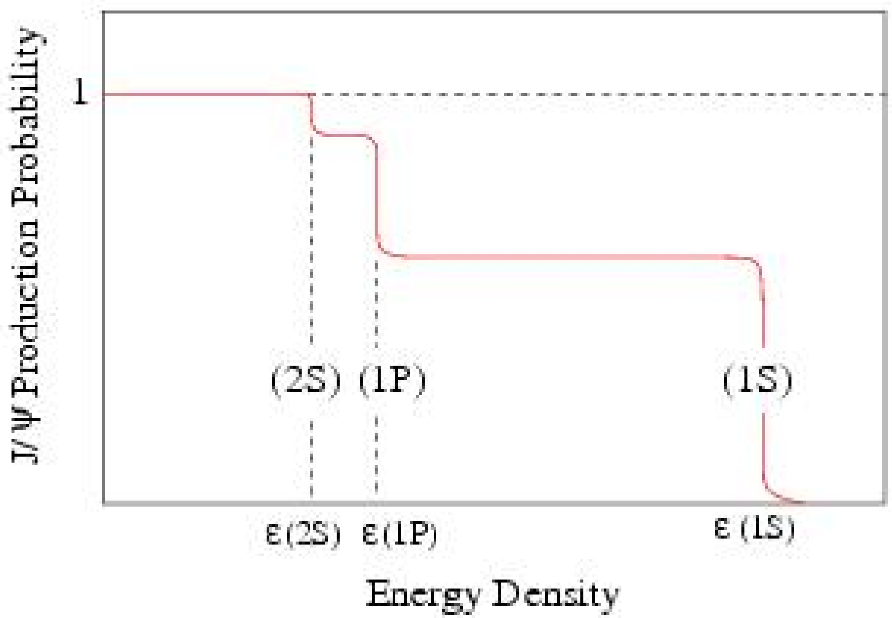


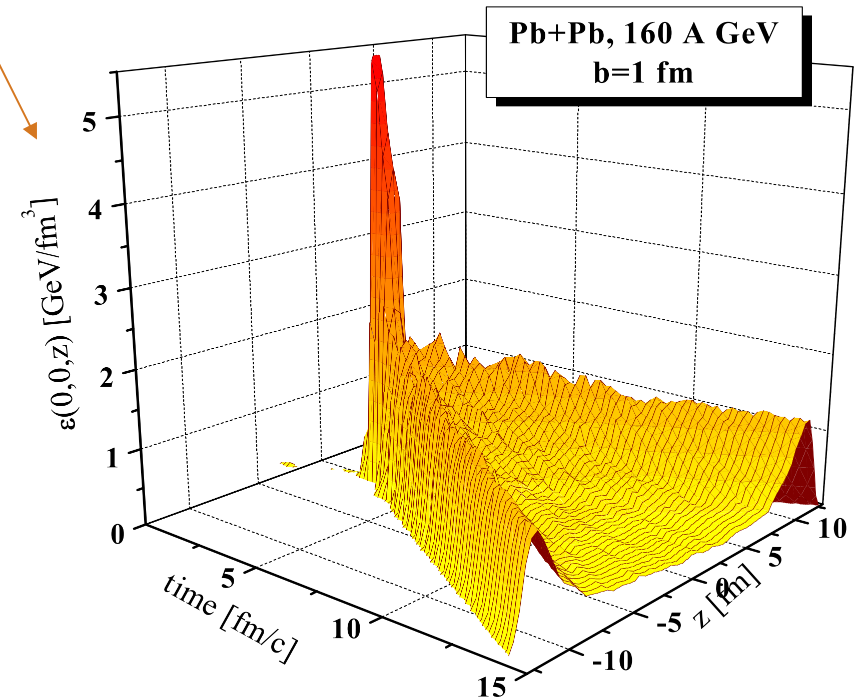


But at RHIC recreation of J/Ψ by D-Dbar annihilation is strong!

Modeling the QGP melting in HSD

Energy density ε (x=0,y=0,z;t) from HSD





Threshold energy densities:

J/Ψ melting: ε(J/Ψ)=16 GeV/fm^3

χ_c melting: ε(χ_c) =2 GeV/fm^3

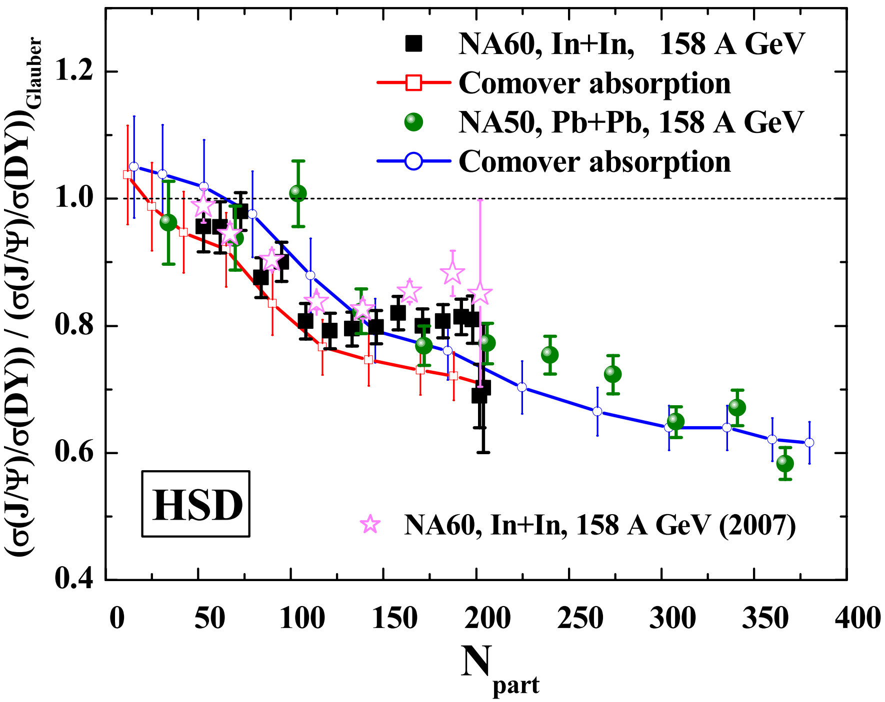
Ψ' melting: ε(Ψ') =2 GeV/fm^3

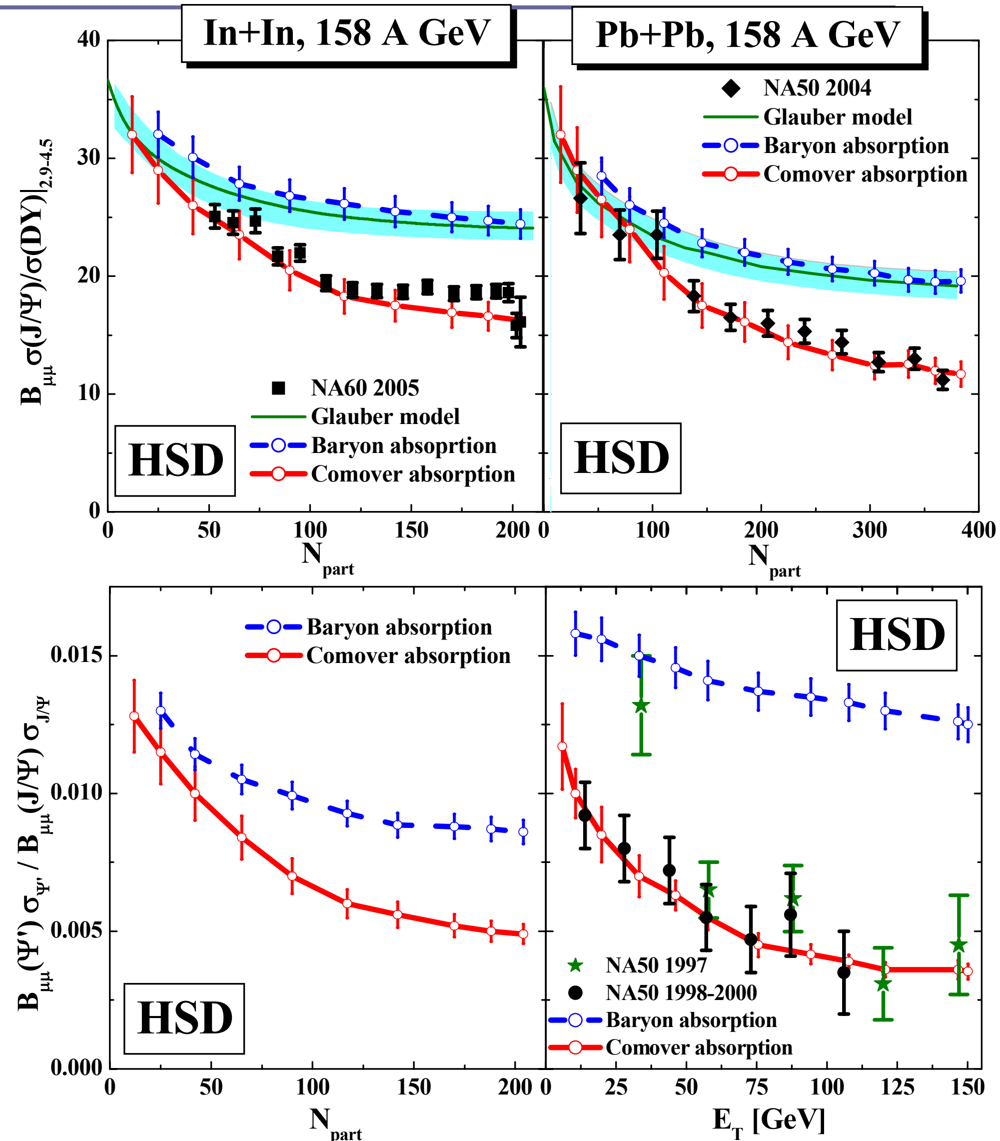
[OL et al., nucl-th/0612049, NPA 786 (2007) 183]

Comparison to data at SPS energy

Pb+Pb and In+In @ 158 A GeV

comover absorption

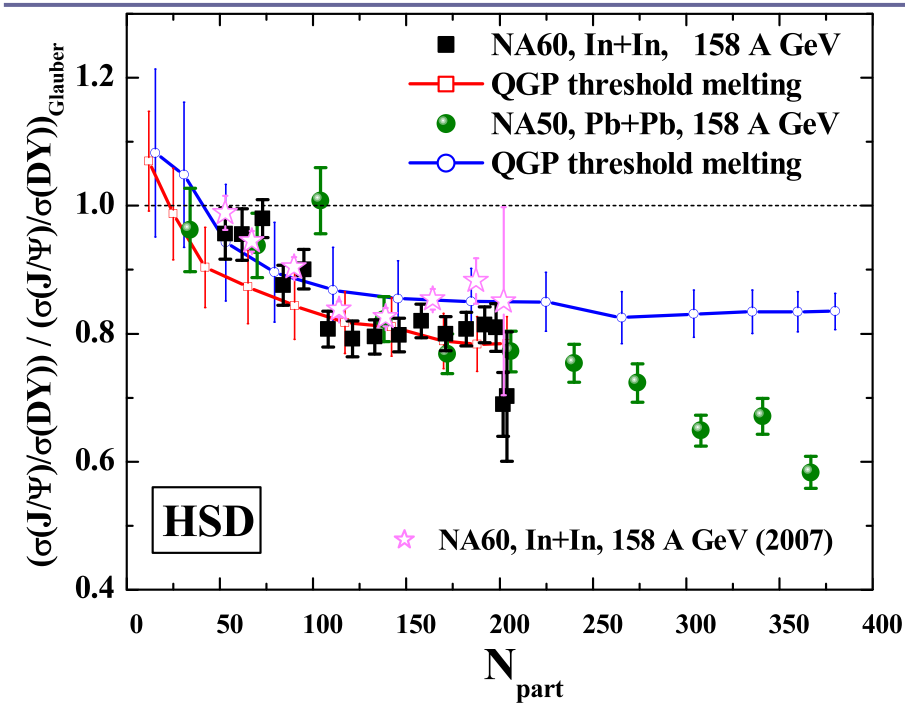


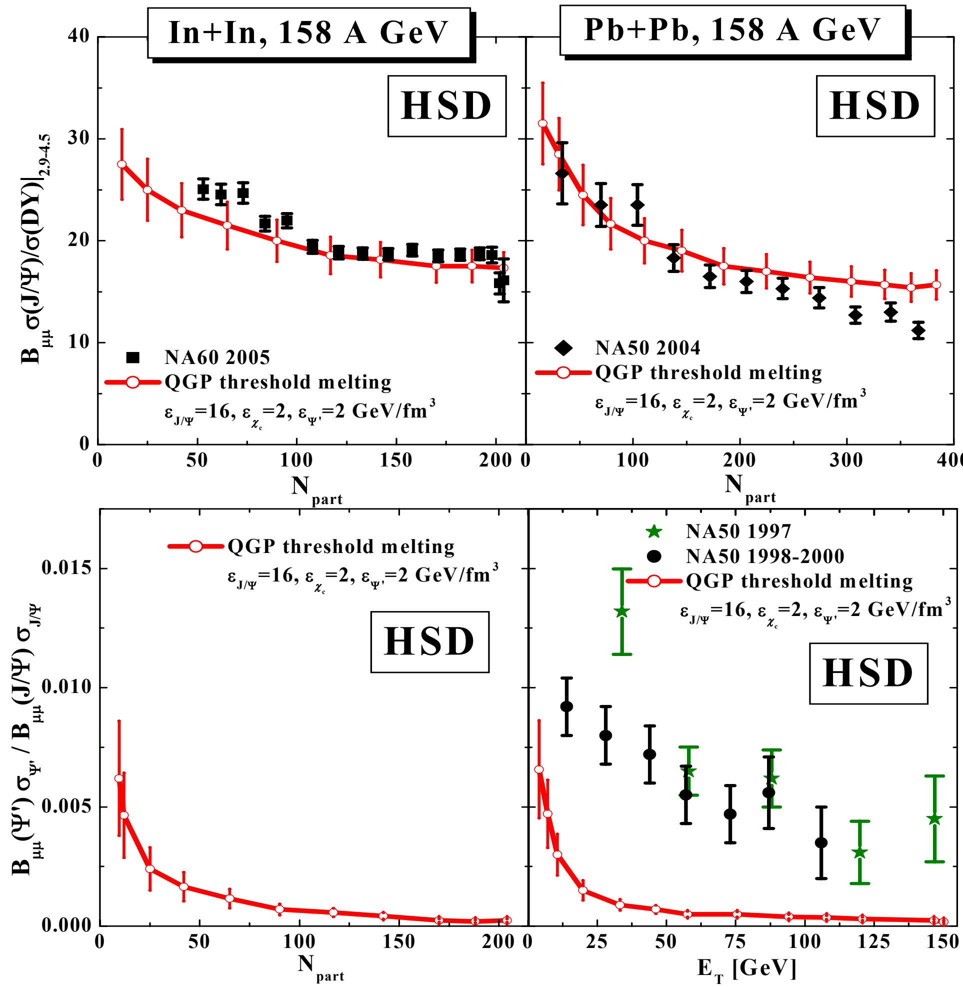


Pb+Pb and In+In @ 160 A GeV consistent with the comover absorption for the same parameter set!

[OL et al NPA786 (2007) 183]

Pb+Pb and In+In @ 158 A GeV
QGP threshold melting





\´ absorption too strong, which contradict data

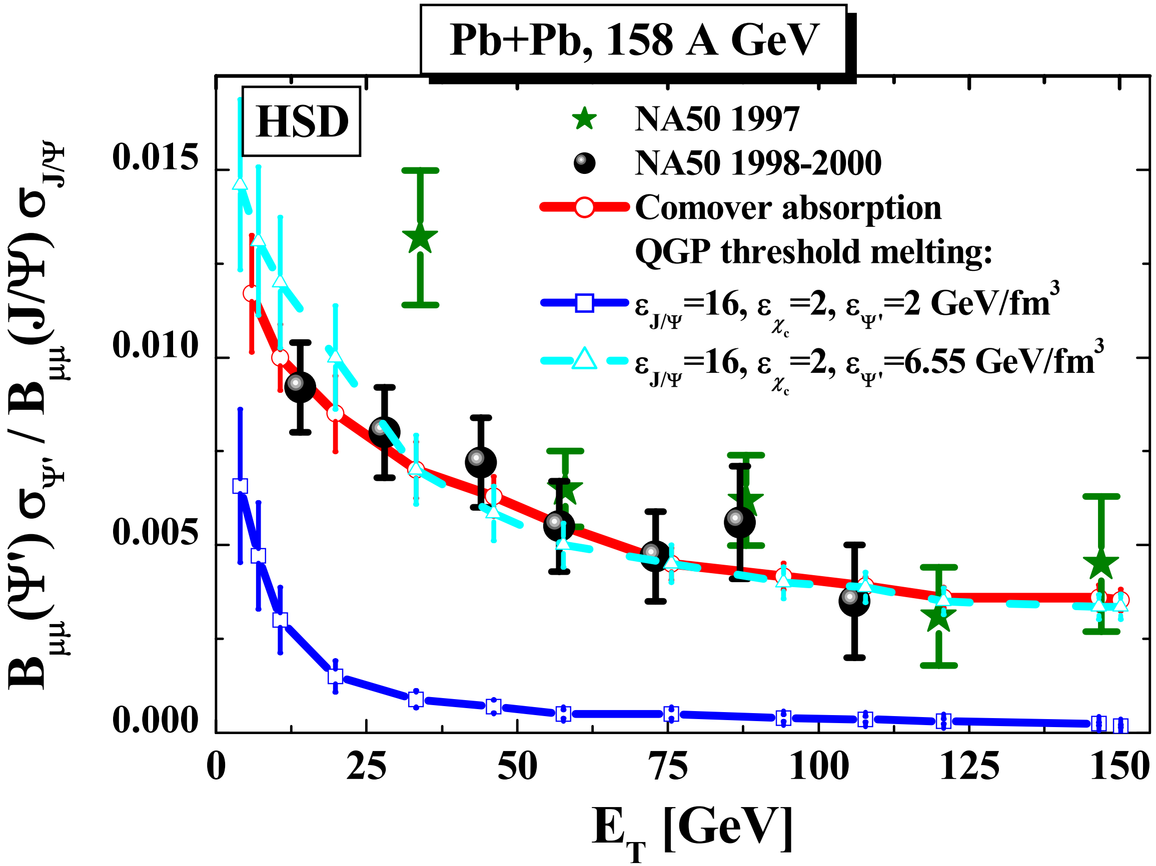
[OL et al NPA786 (2007) 183]

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

Ψ´ data contradict threshold melting scenario with lQCD ε^d

$\varepsilon(J/\Psi)$=16 GeV/fm³,
$\varepsilon(\chi_c)$ =2 GeV/fm³,
$\varepsilon(\Psi')$ =6.55 GeV/fm³

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



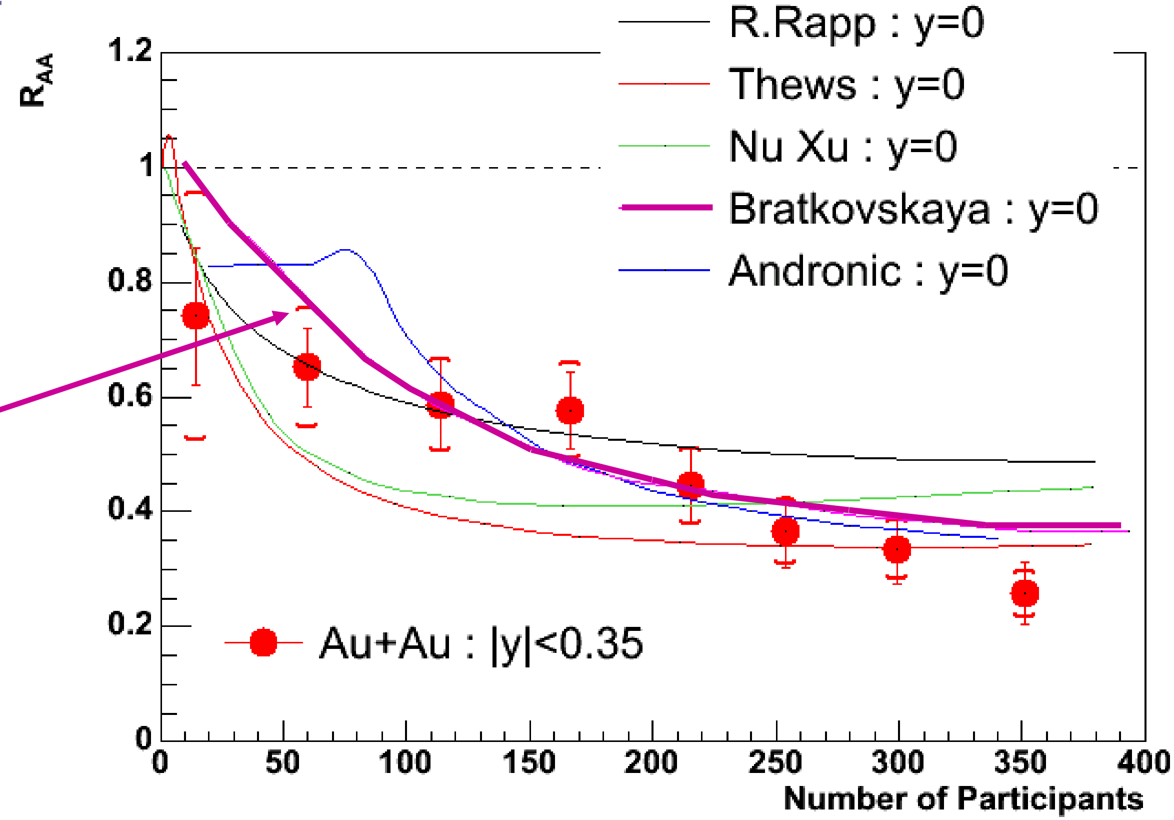
[OL et al., nucl-th/0612049, NPA07]

Comparison to data at RHIC energy

Comover absorption + regeneration
A successful prediction

Regeneration is essential!

HSD



NB:

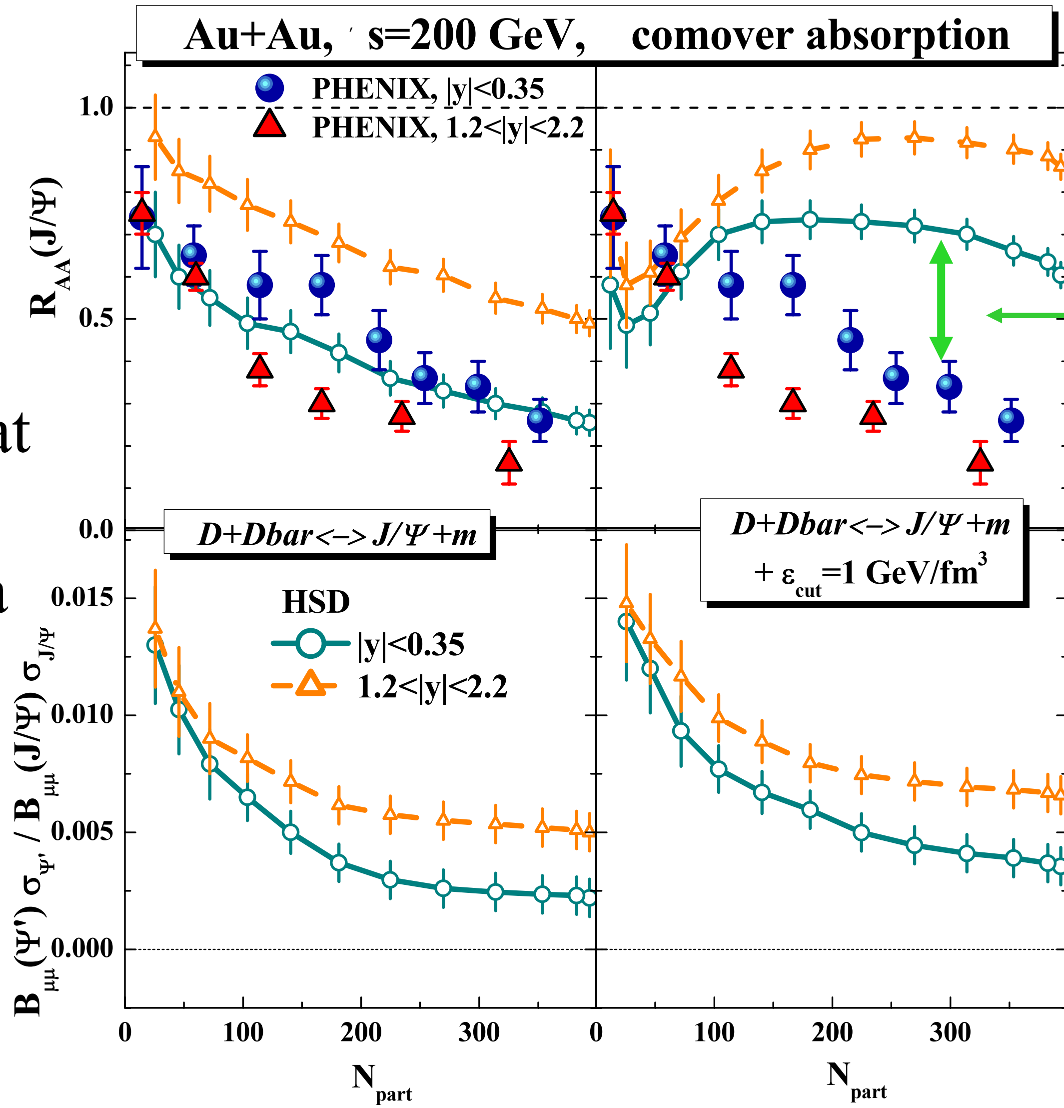
obtained assuming the existance of comovers throghout the collision, i.e. at all energy densities.

R. Rapp et al.PRL 92, 212301 (2004)
R. Thews et al, Eur. Phys. J C43, 97 (2005)
Yan, Zhuang, Xu, PRL97, 232301 (2006)
Bratkovskaya et al., PRC 69, 054903 (2004)
A. Andronic et al., NPA789, 334 (2007)

Au+Au @ $s^{1/2}$=200 GeV

Comover absorption + regeneration

In comover scenario, suppression at **mid-y** stronger than at **forward y**, unlike the data



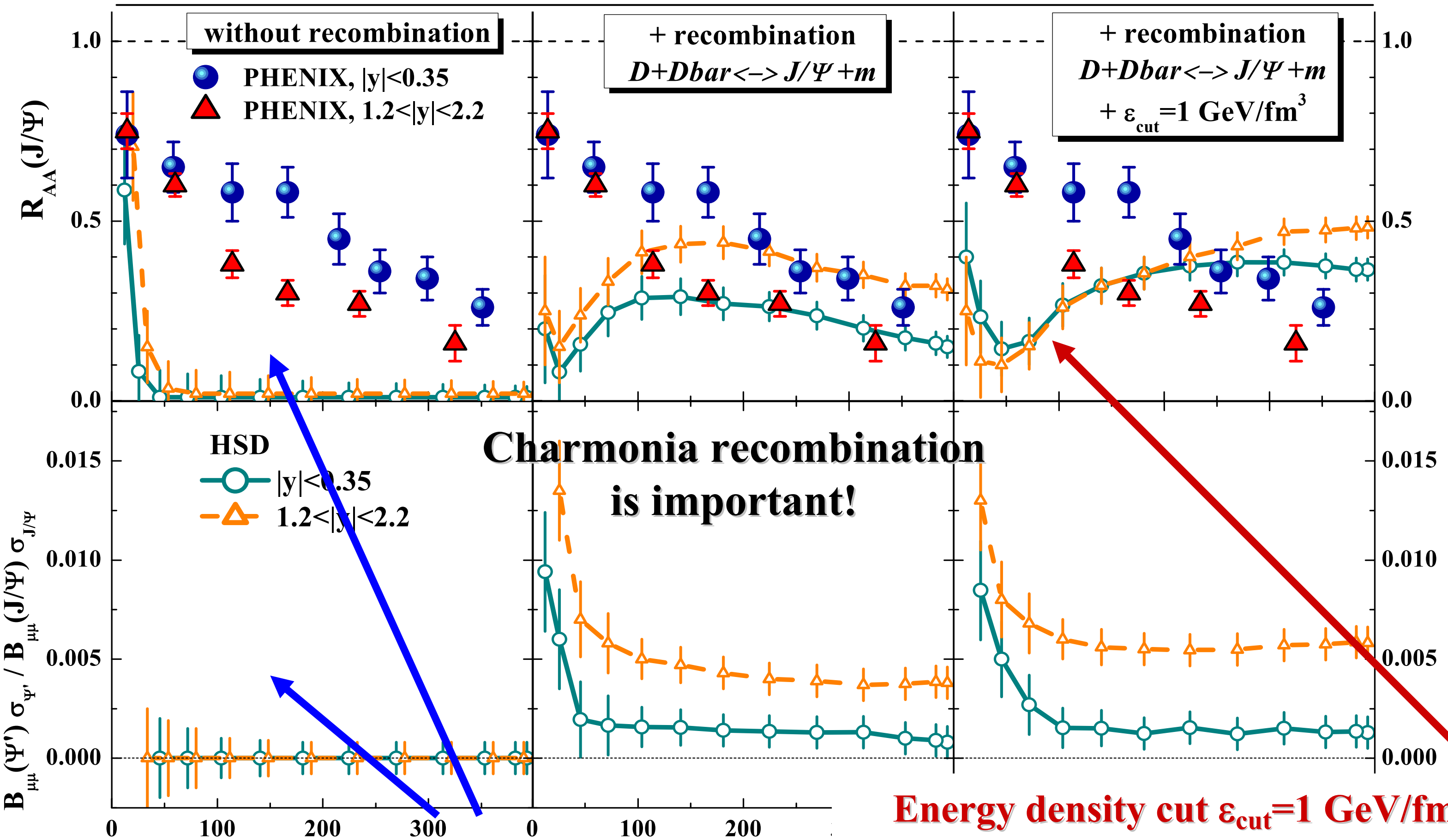
Space for parton phase effects

Energy density cut ε_{cut}=1 GeV/fm^3 reduces the meson comover absorption

[OL et al arXiv:0705.4443]

Au+Au @ $s^{1/2}$=200 GeV

Threshold melting



Charmonia recombination is important!

Satz's model: complete dissociation of

QGP threshold melting scenario is ruled out by PHENIX data!

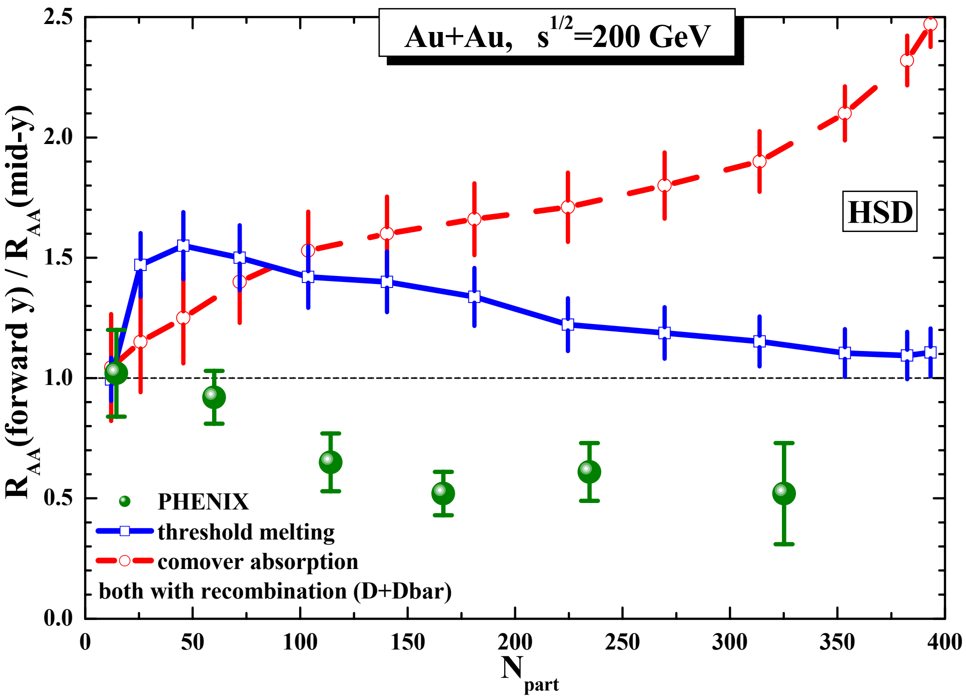
local energy densities !

Energy density cut ε_{cut}=1 GeV/fm^3 reduces the meson comover absorption, however, D+Dbar

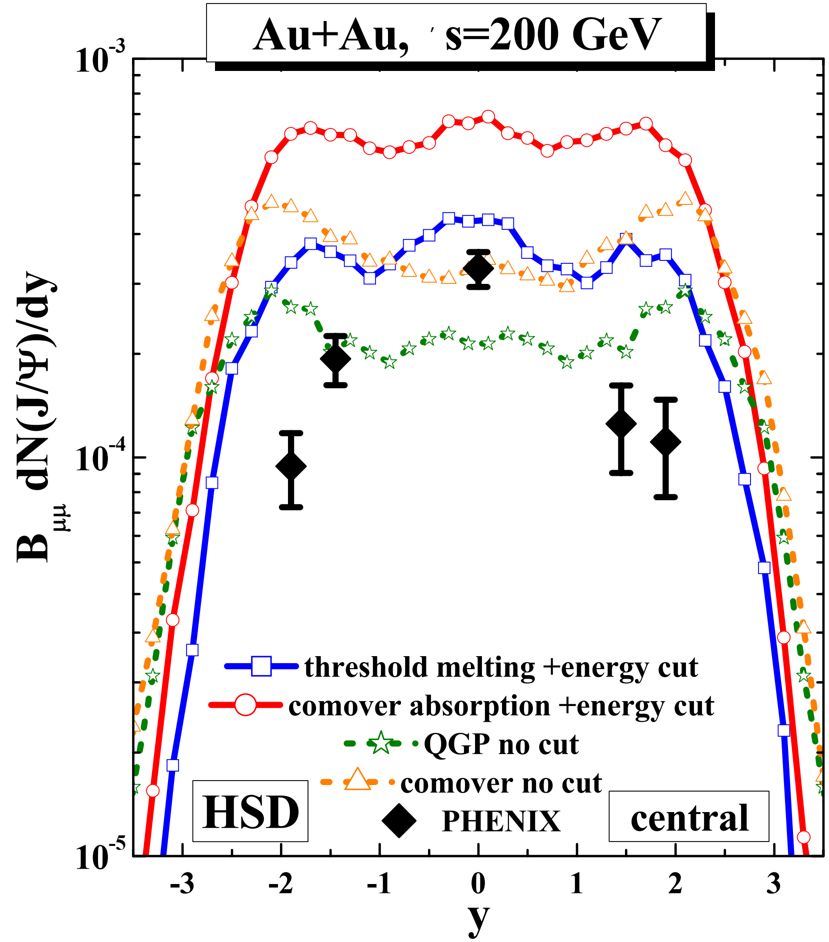
gh charmonia,

especially for peripheral collisions!

Rapidity !



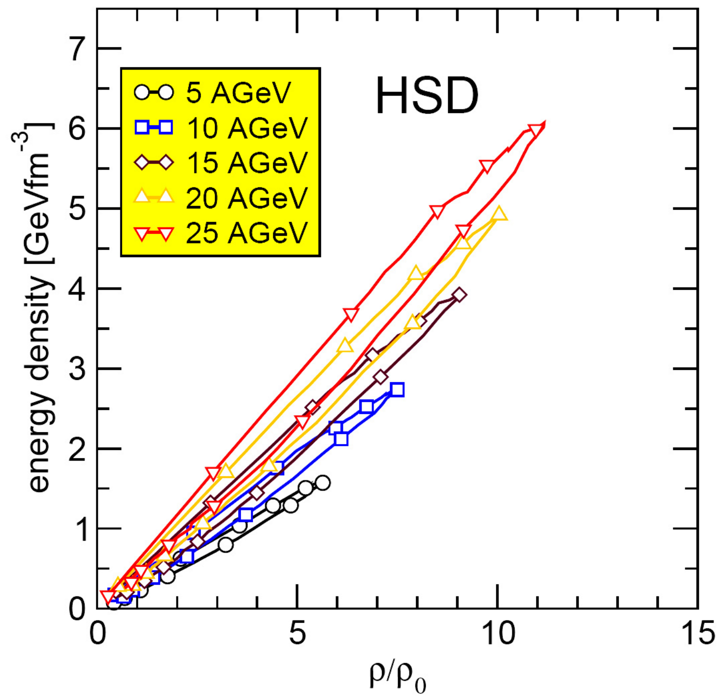
Au+Au, $s^{1/2}$=200 GeV
HSD
R_{AA}(forward y) / R_{AA}(mid-y)
N_{part}
PHENIX
threshold melting
comover absorption
both with recombination (D+Dbar)



Au+Au, √s=200 GeV
$B_{\mu\mu}$ dN(J/Ψ)/dy
y
threshold melting +energy cut
comover absorption +energy cut
QGP no cut
comover no cut
PHENIX
HSD
central

HSD predictions for FAIR energy

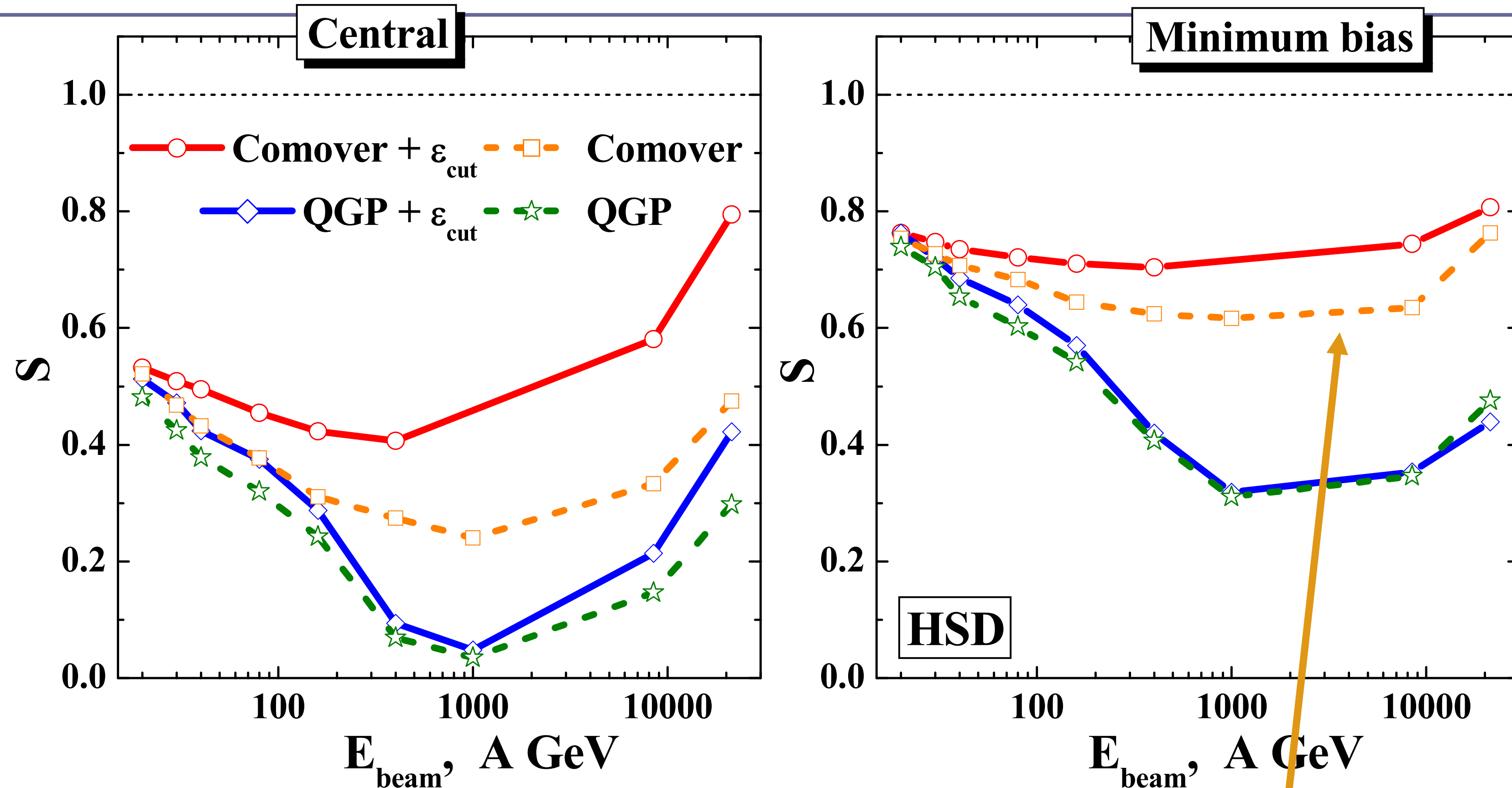
Energy density at FAIR



Huge energy density is reached ($\varepsilon > \varepsilon_{crit}$=1 GeV/fm^3) also at FAIR (> 5 A GeV).

Addtionally, high baryon density.

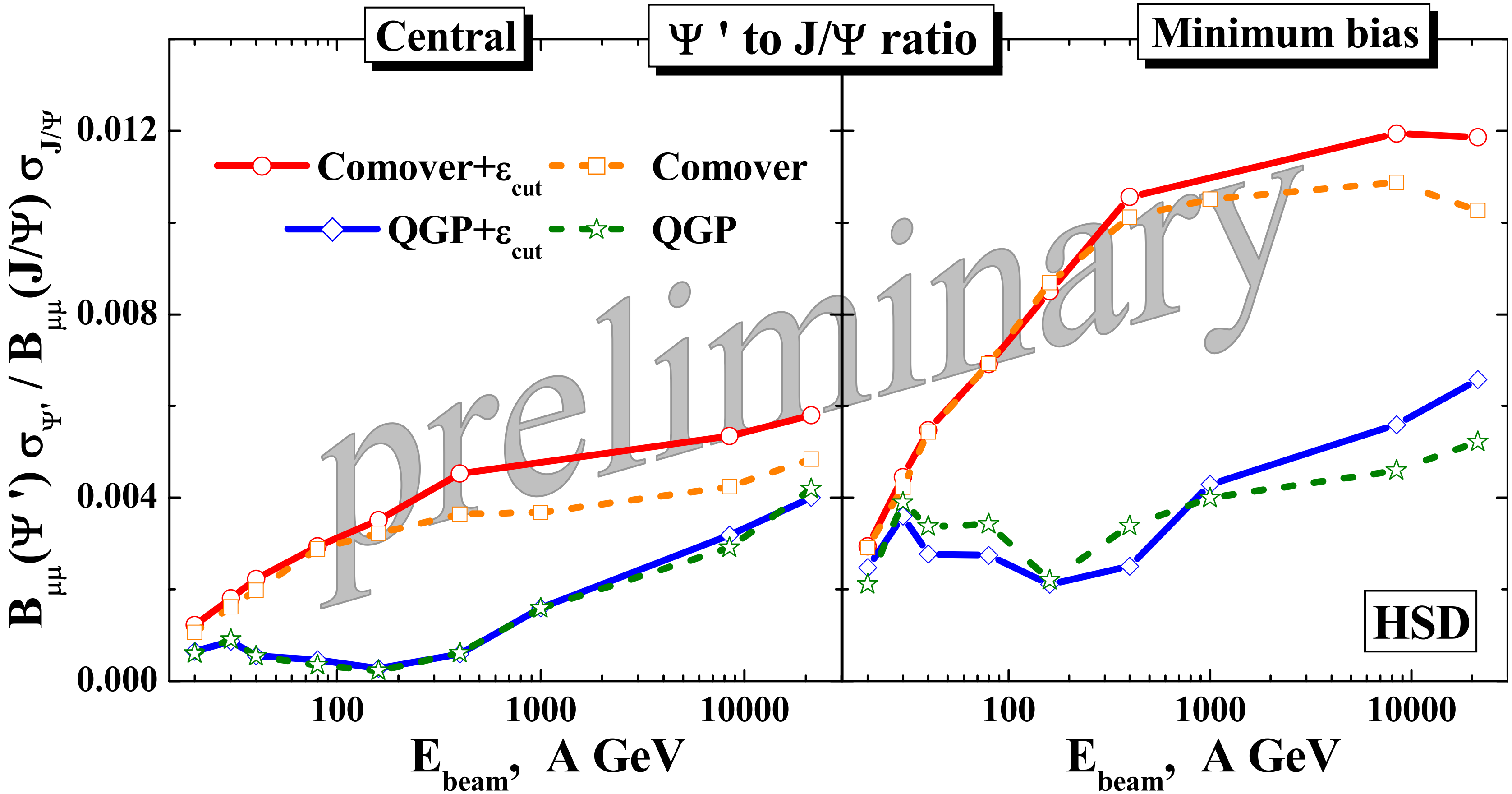
J/Ψ excitation function



Comover reactions in the hadronic phase give almost a constant suppression; pre-hadronic reactions lead to a larger recreation of charmonia with E_{beam} .

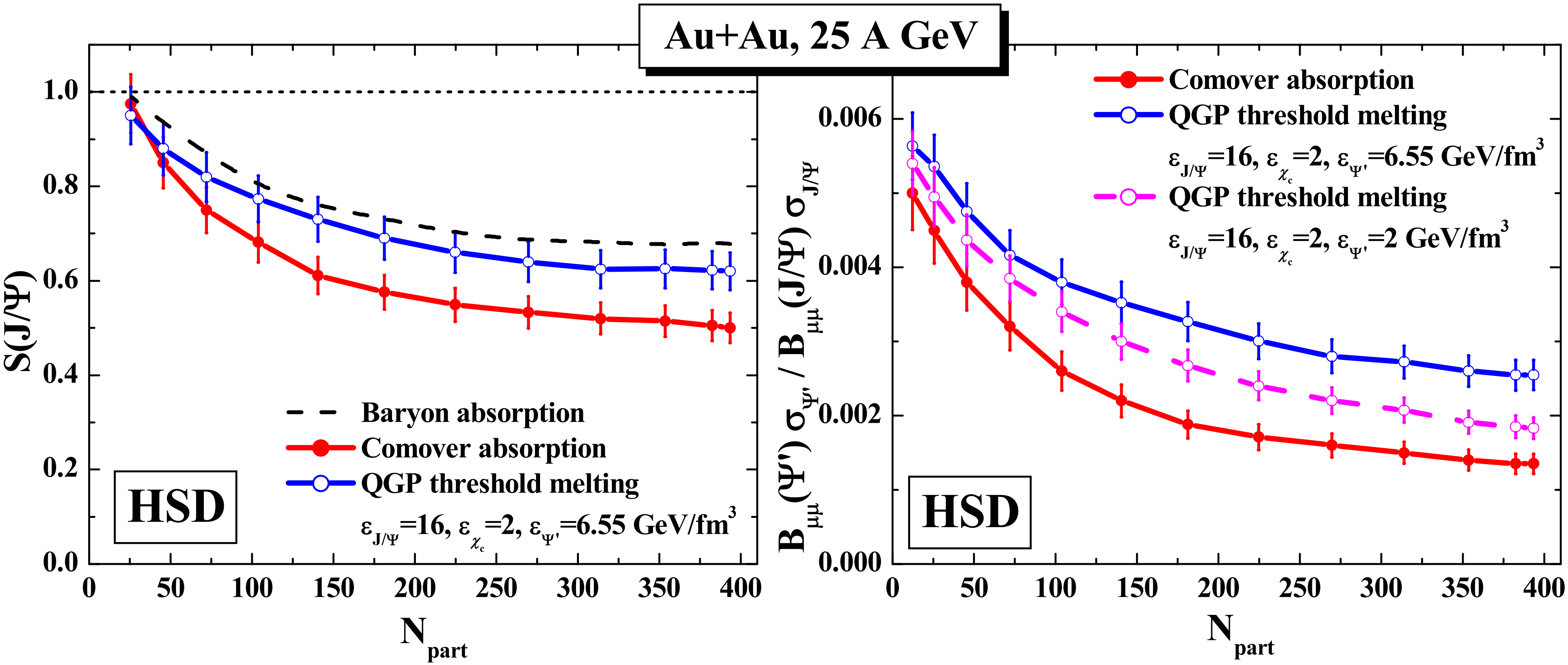
The J/Ψ melting scenario with hadronic comover recreation shows a maximum suppression at E_{beam} = 1 A TeV; exp. data ?

\´ excitation function



Different scenarios can be distinguished at FAIR energies:
Comover scenario predicts a smooth excitation function whereas the ‘threshold melting’ shows a step in the excitation function

Predictions for J/Ψ and Ψ´ suppression in Au+Au at **CBM**

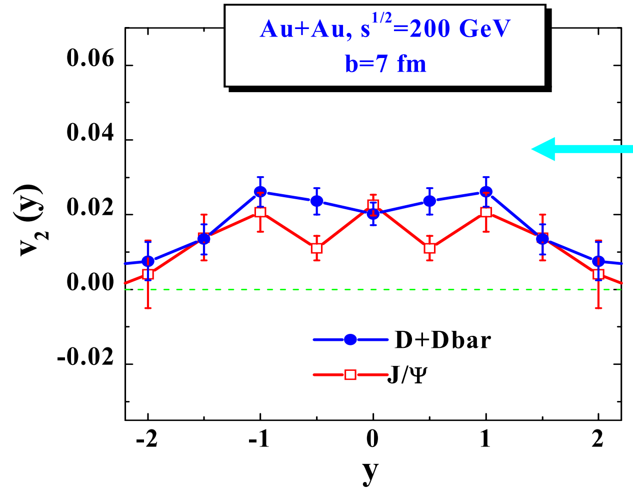


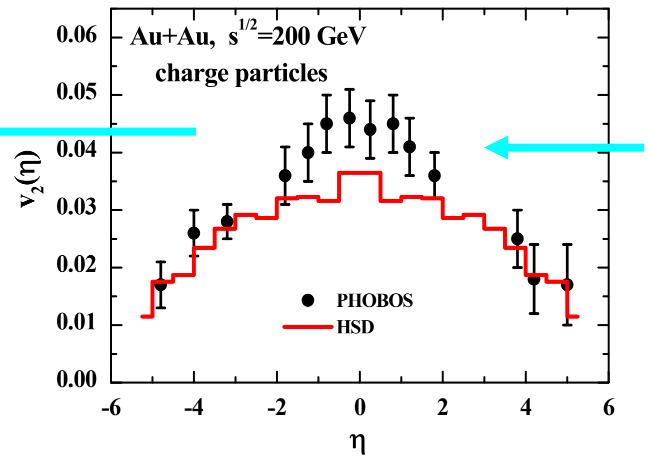
Possible mechanisms can be disentangled:

Ψ´/(J/Ψ) is lower in the ‚comover absorption' since the average comover density decreases only moderately with lower bombarding energy whereas the energy density falls rapidly

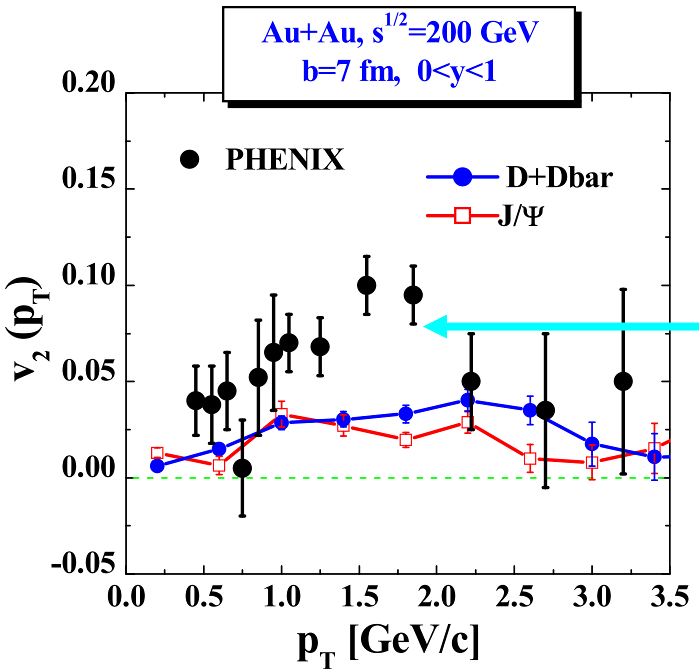
[OL et al., nucl-th/0612049, NPA07]

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 !

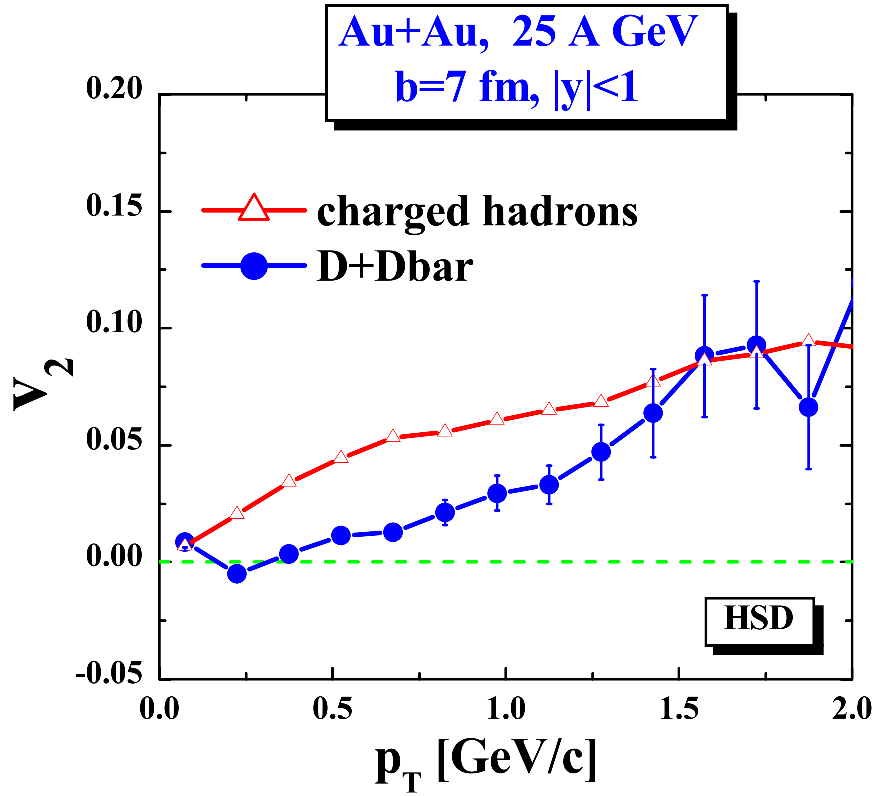


- **HSD: D-mesons and J/Ψ follow the charged particle flow => small $v_2 < 3\%$**
- **Exp. data at RHIC show large collective flow of D-mesons up to $v_2 \sim 10\%$!**

=> strong initial flow of non-hadronic nature!

[E. Bratkovskaya et al 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!

Summary

- 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* @ 158 A GeV, while Ψ´ data are in conflict with the melting scenario.
- Comover absorption and colour screening fail to describe *Au+Au* at $s^{1/2}$=200 GeV at mid- and forward rapidities simultaneously.
- Deconfined phase is clearly reached at RHIC, but a theory having the relevant/proper degrees of freedom in this regime is needed to study its properties (→PHSD).

PHSD - transport description of the partonic and hadronic phases

E. Bratkovskaya, W. Cassing, H. Stöcker

Thank you!

Transport aproach (HSD, UrQMD, ...)

- Non-equilibrium
  -> full evolution of the collision

- Universality
  -> large range of $s^{1/2}$ from one code
  -> predictions
  -> exitation functions

- High presicion
  -> distinguish physical mechanisms
  -> possibility of verification by exp