FIAS Frankfurt Institute for Advanced Studies

Heavy quarks and high p_T in nuclear collisions

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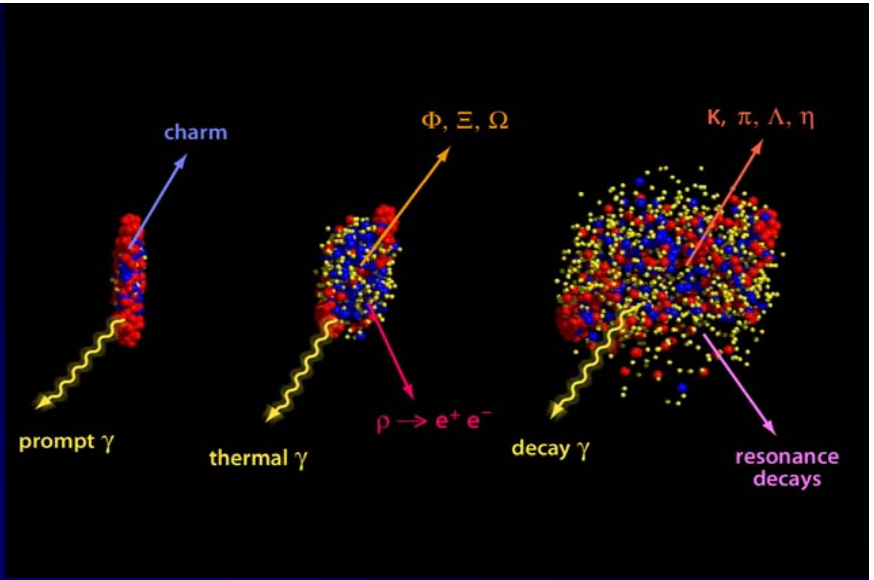
13.09.2007 , Meeting of the Virtual Institute for Strongly Interacting Matter (VI-SIM), "Heavy Ion Physics Perspectives“, Monbachtal e.v., Bad Liebenzell

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!

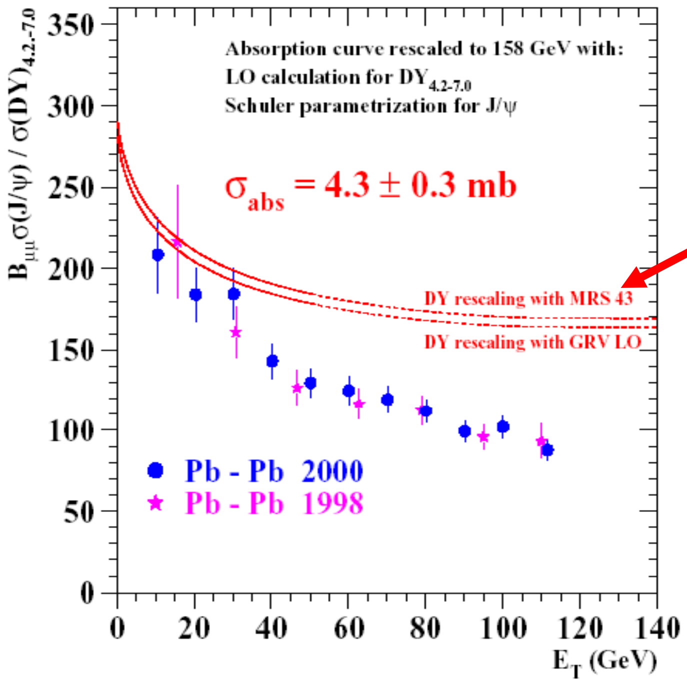
Microscopical transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions

Open and hidden charm

‚Anomalous‘ J/Ψ suppression in A+A

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

- **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

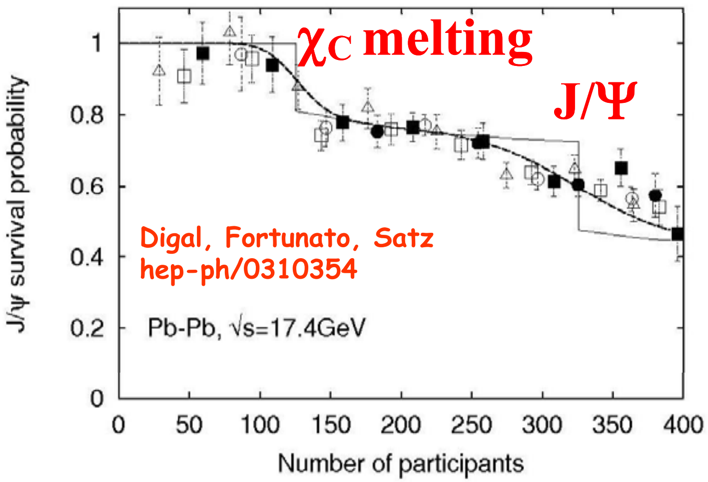
- **QGP threshold melting**

[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 $\varepsilon_d \sim 2(T_d/T_c)^4$



- **Comover absorption**

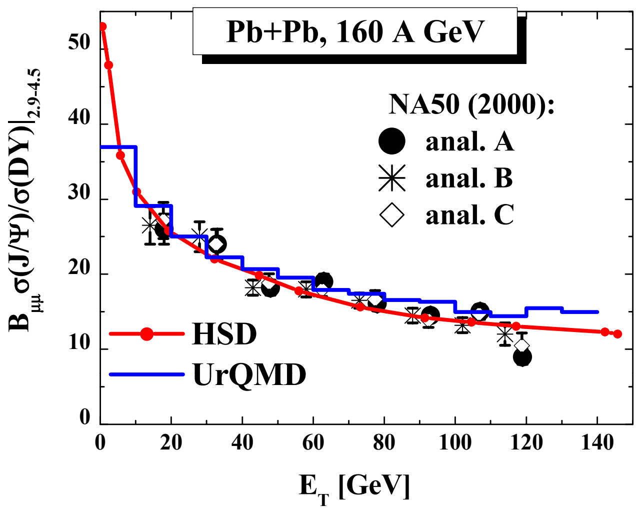
[Gavin & Vogt, Capella et al.`97]:

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

J/Ψ+m <–> D+Dbar

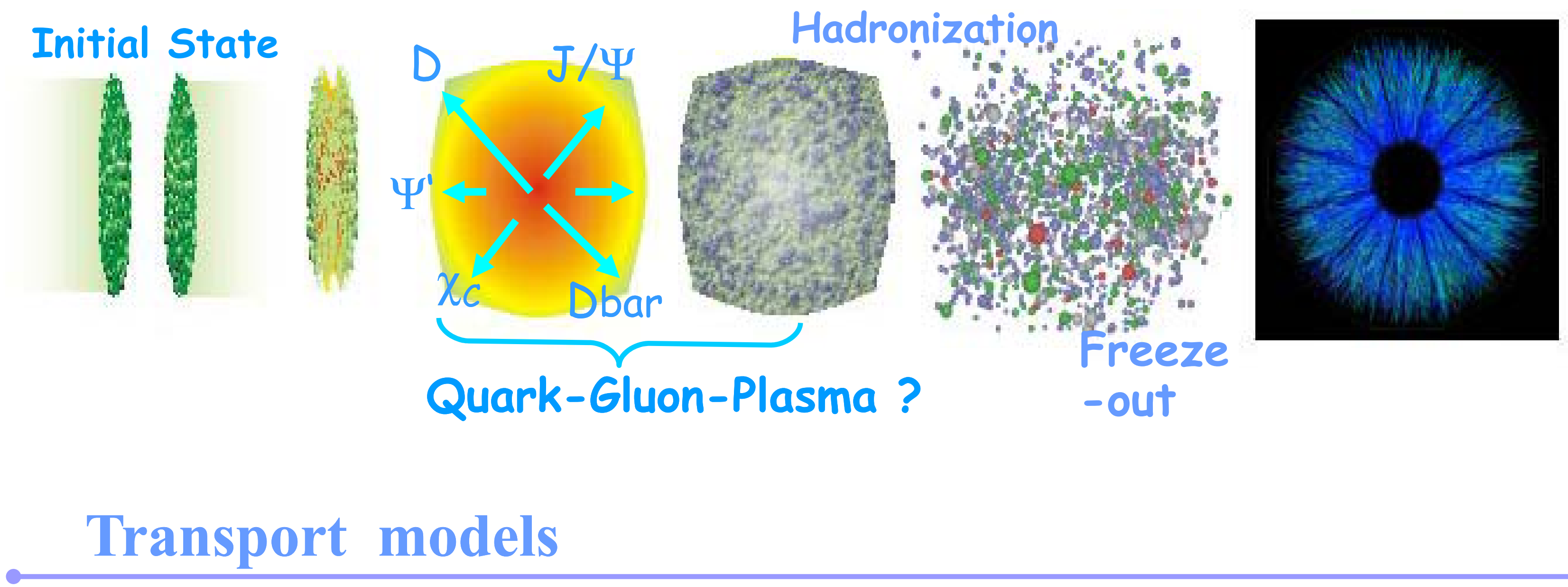
Ψ'+m <–> D+Dbar

χ_C+m <–> D+Dbar



Charmonium dynamics -> HSD

Check scenarios for charmonium suppression in A+A using microscopic transport models



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

HSD – Hadron-String-Dynamics transport approach

Charm and Charmonium production and absorption in HSD

- Charmonium = hard probe

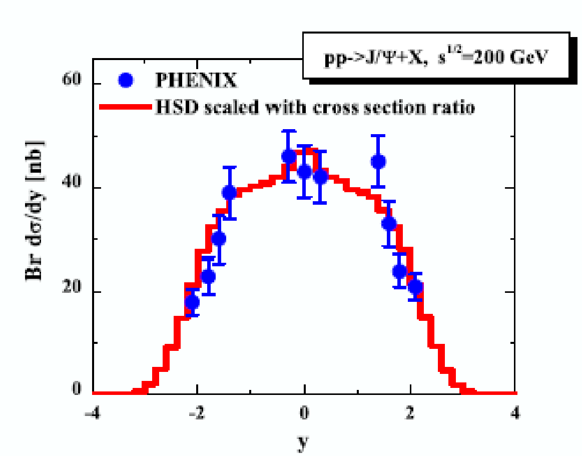
  => binary scaling!

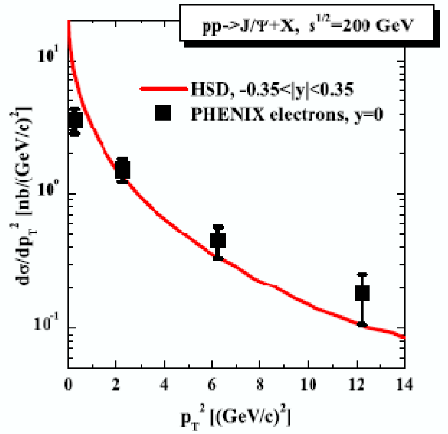
- Production $\sigma(J/\Psi)$ and $\sigma(\Psi')$ in N+N and π+N collsions: parametrization of the available exp. data

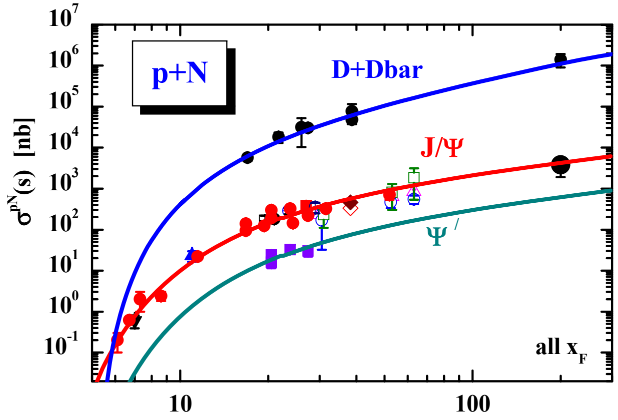
Coupled channel problem:

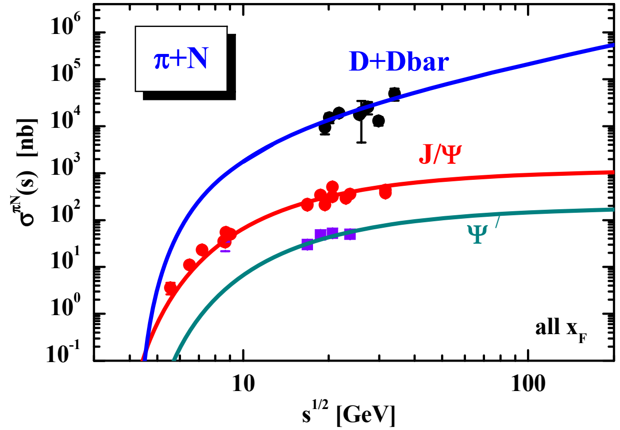
$$\sigma_{J/\Psi}^{exp} = \sigma_{J/\Psi} + B(\chi_c \to J/\Psi)\, \sigma_{\chi_c} + B(\Psi' \to J/\Psi)\, \sigma_{\Psi'}$$

- y-, p_T – distributions of J/Ψ in pp at RHIC are controlled by the PHENIX data :









Charmonia-baryon dissociation cross sections

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

- Charmonia-baryon dissociation cross sections 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-2006/2007:

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

adopting a new Glauber fit from NA50

Modelling of the comover scenario in HSD

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

$J/\Psi\ (\chi_c, \Psi') + \text{meson}\ (\pi, \rho, K, K^*) <-> D + \bar{D}$

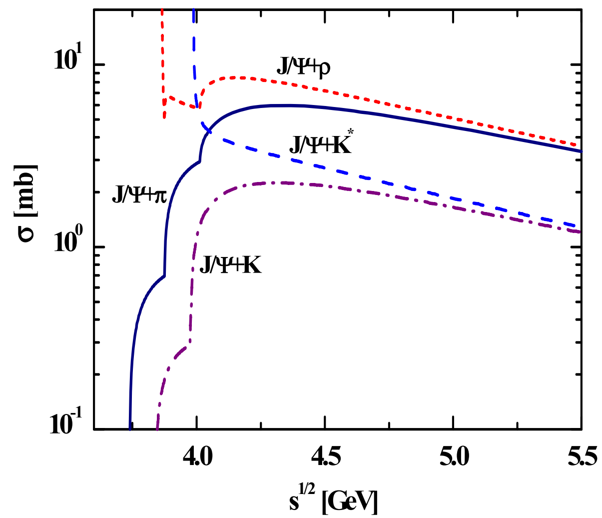
- **Phase-space model for charmonium + meson dissociation:**

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

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

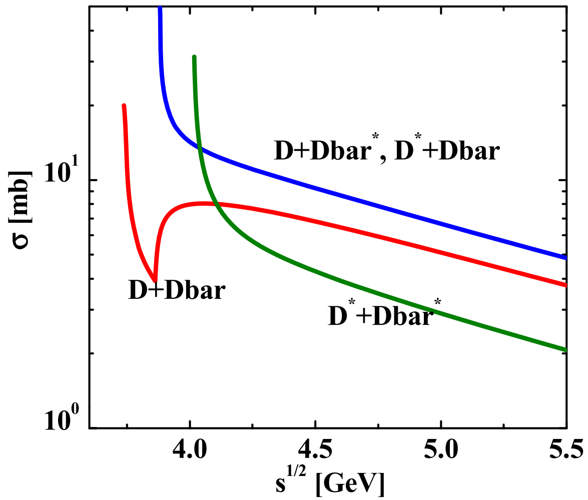
$$|M_{J/\Psi}|^2 = |M_{\chi_C}|^2 = |M_{\Psi'}|^2 = |M_0|^2$$

constant matrix element



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

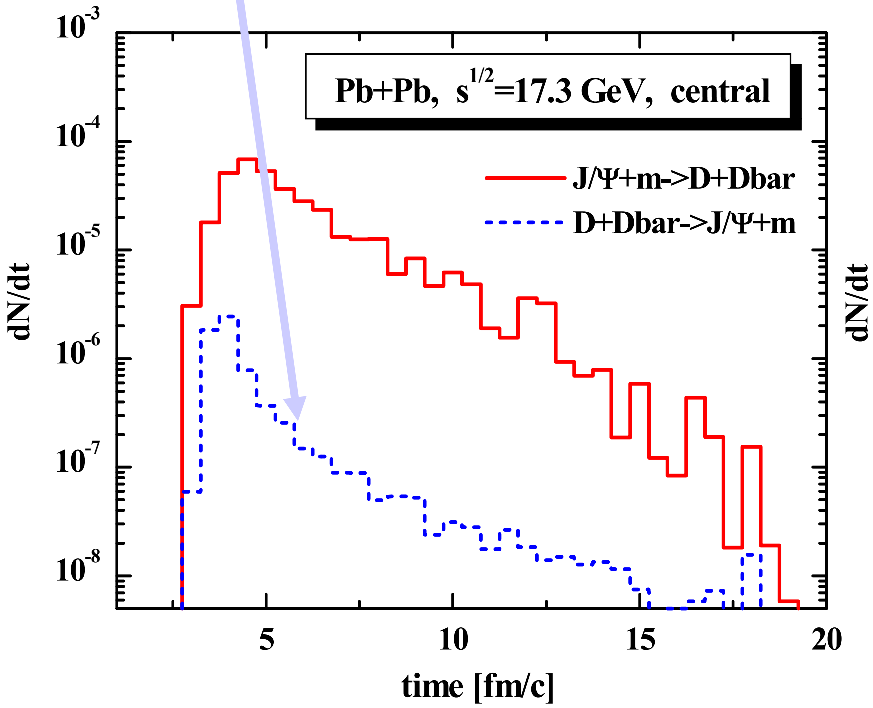
D+Dbar -> J/Ψ (χc, Ψ') + meson (π, ρ, K, K*) are determined by detailed balance!

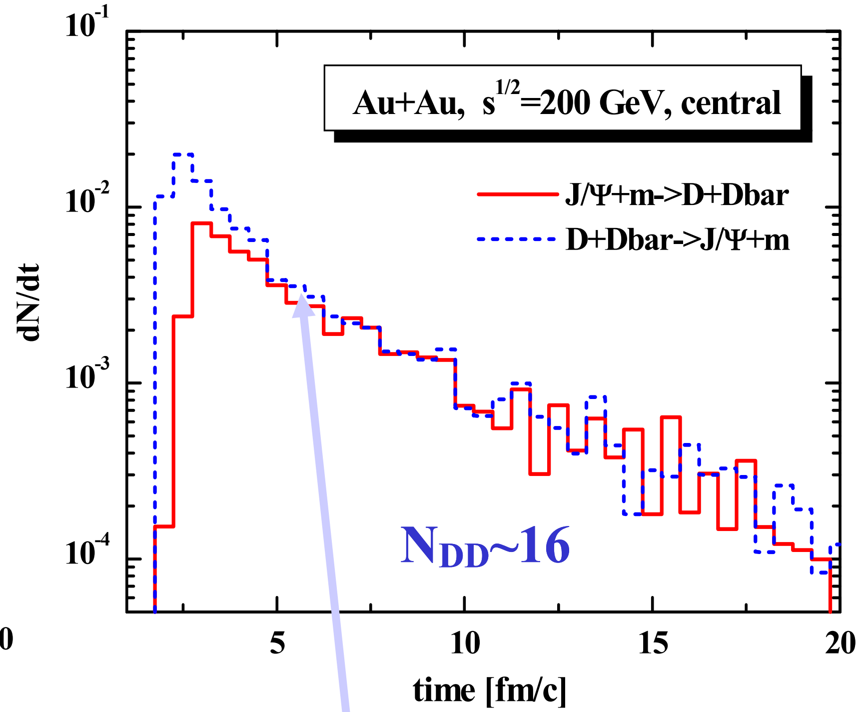


PRC 67 (2003) 054903

Charmonium recombination by D-Dbar annihilation

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

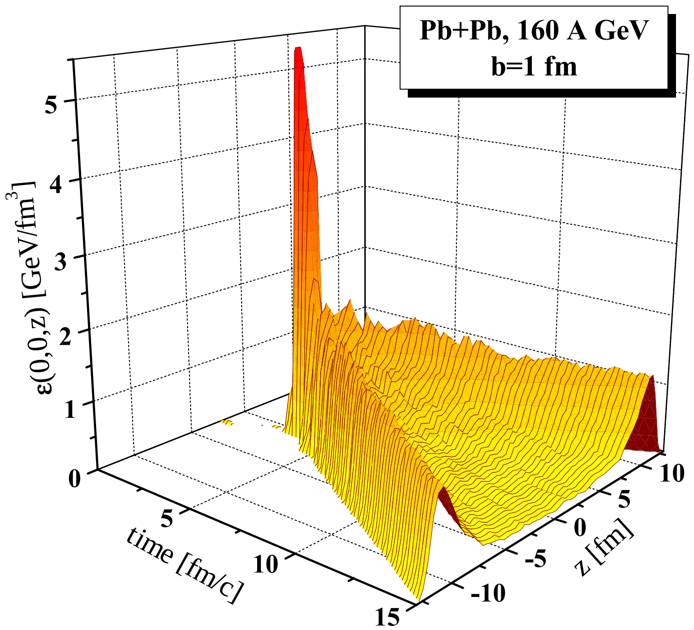




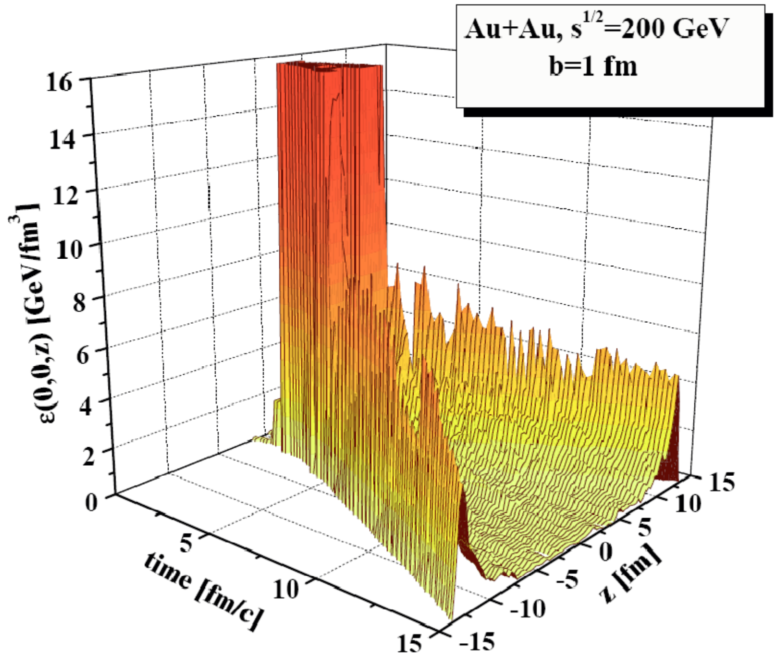
But at RHIC recreation of J/Ψ by D+Dbar annihilation is strong!

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



Threshold energy densities:

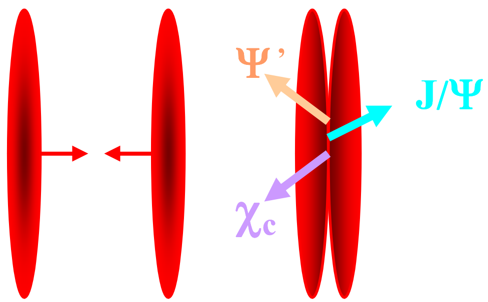
J/Ψ melting: $\varepsilon(J/\Psi)=16$ GeV/fm³

χ_c melting: $\varepsilon(\chi_c)=2$ GeV/fm³

Ψ' melting: $\varepsilon(\Psi')=2$ GeV/fm³

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

‚Local' energy density ε versus Bjorken energy density ε_{Bj}



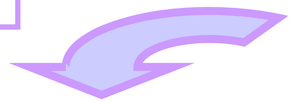
- transient time for central Au+Au at 200 GeV:
  $t_r \sim 2R_A/\gamma_{cm} \sim 0.13$ fm/c
- c-cbar formation time:
  $\tau_C \sim 1/M_T \sim 1/4\text{GeV} \sim 0.05$ fm/c $< t_r$
- c-cbar pairs are produced in the initial hard NN collisions in time period t_r

- Bjorken energy density:

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

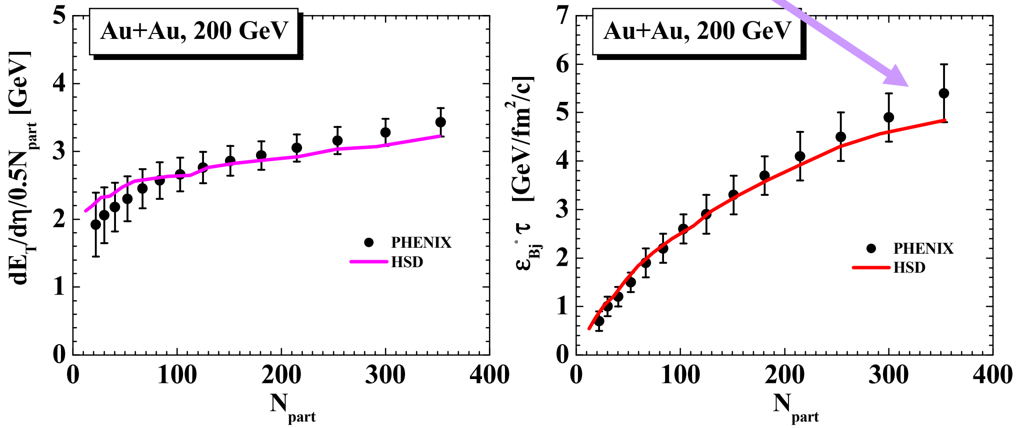
A_T is the nuclei transverse overlap area
τ is the formation time of the medium

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



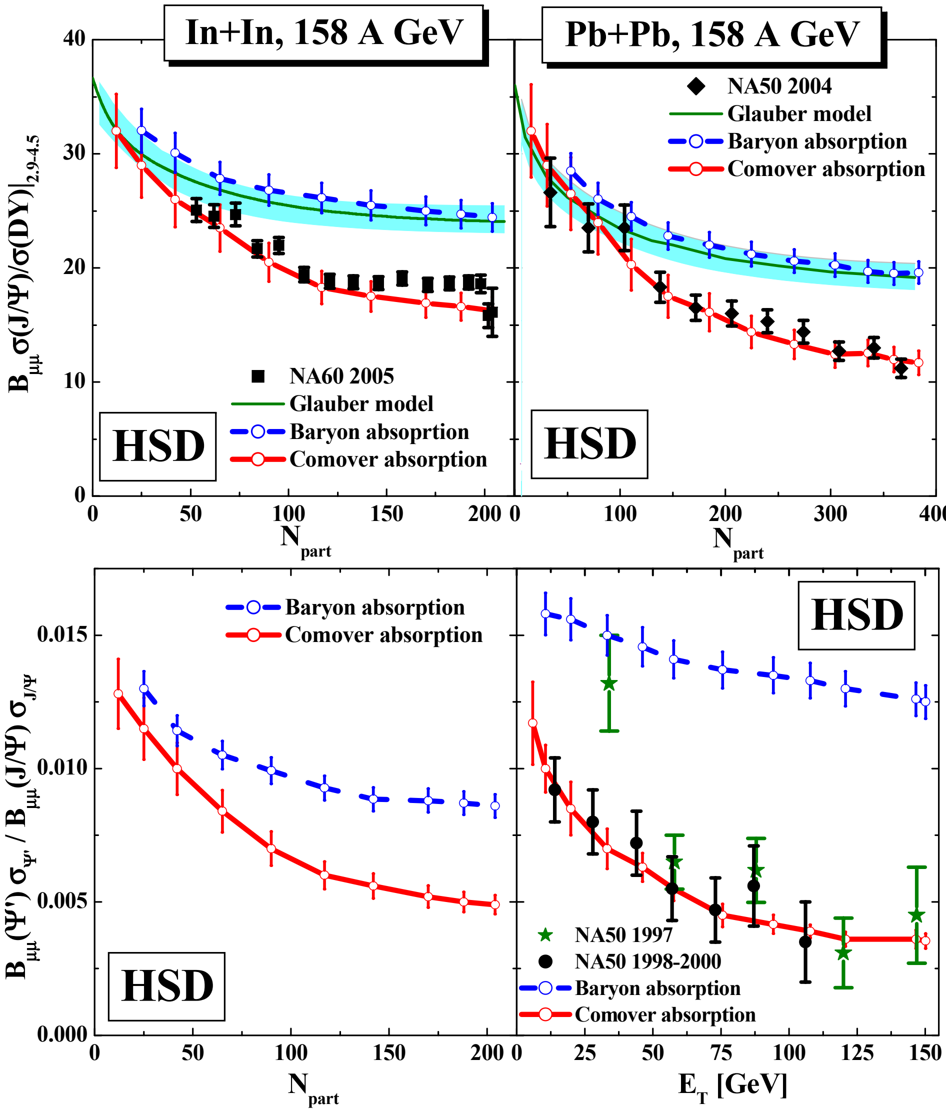
‚Local' energy density ε during transient time t_r :
$\varepsilon \sim 5[\text{GeV/fm}^2/\text{c}] / [0.13 \text{ fm/c}]$
~ 30 GeV/fm³

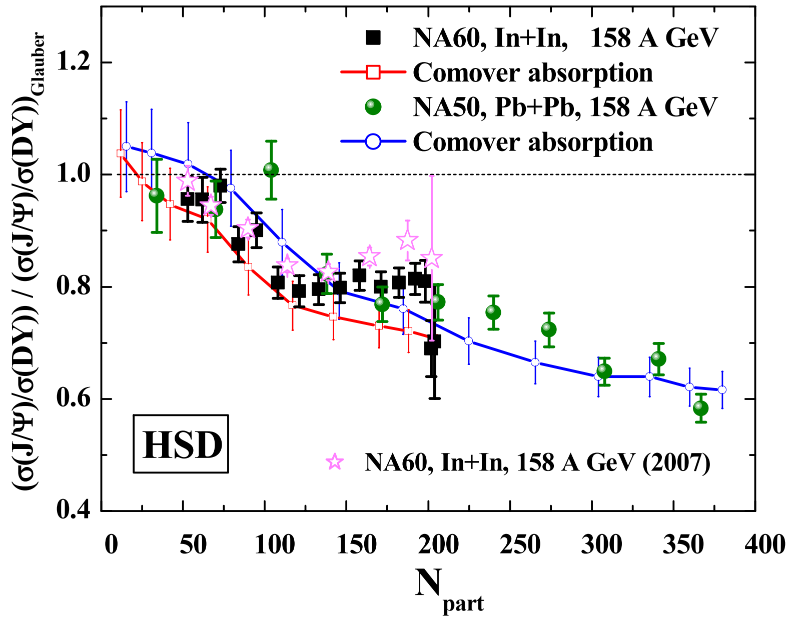
accounting τ_C : $\varepsilon \sim 28$ GeV/fm³



✓ HSD reproduces PHENIX data for Bjorken energy density very well
✓ HSD results are consistent with simple estimates for the energy density

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



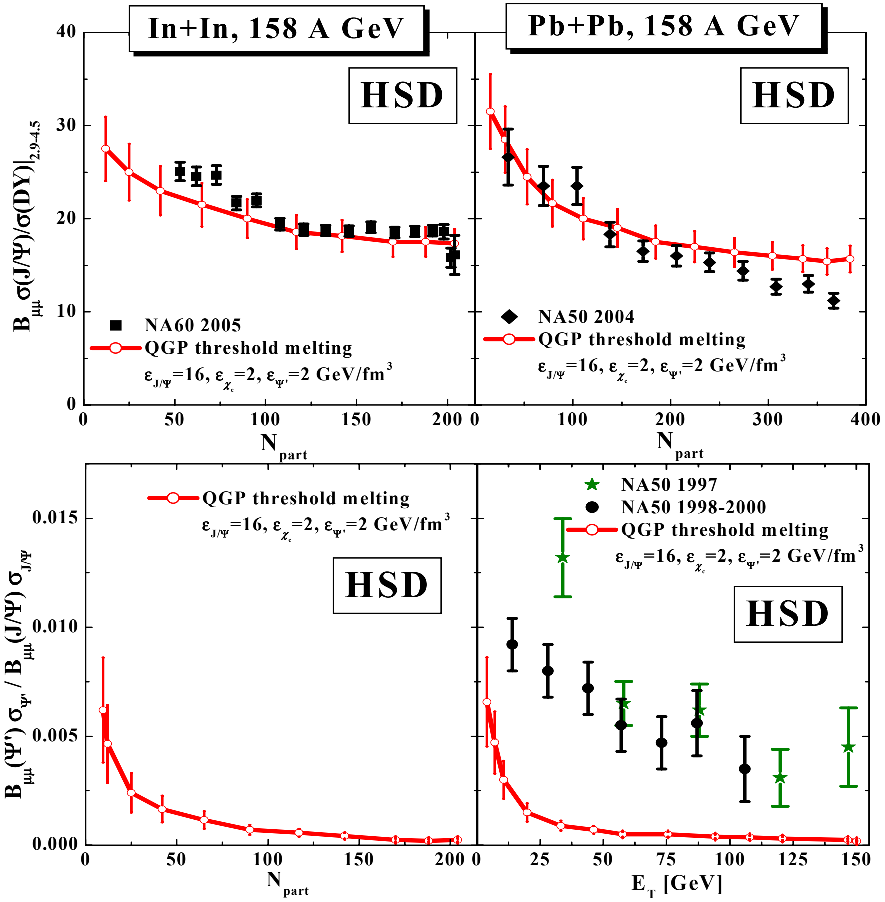


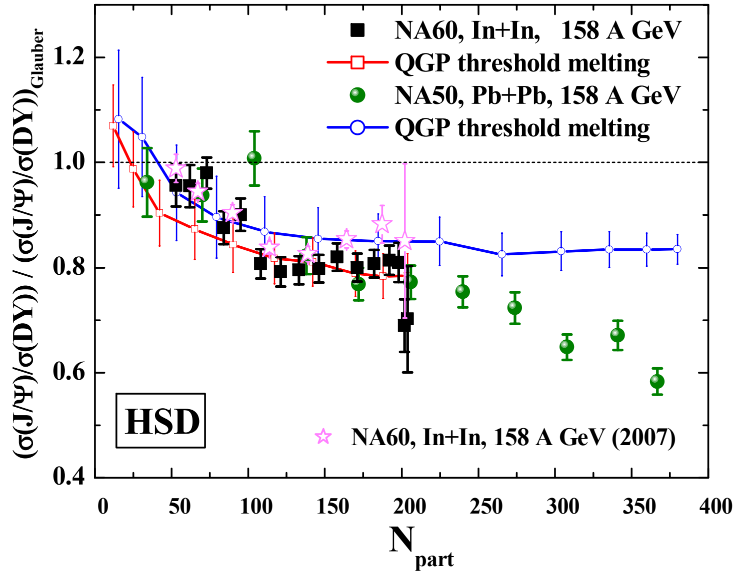
- Exp. data (NA50/NA60) for Pb+Pb and In+In at 160 A GeV are consistent with the comover absorption model for the same set of parameters!

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

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

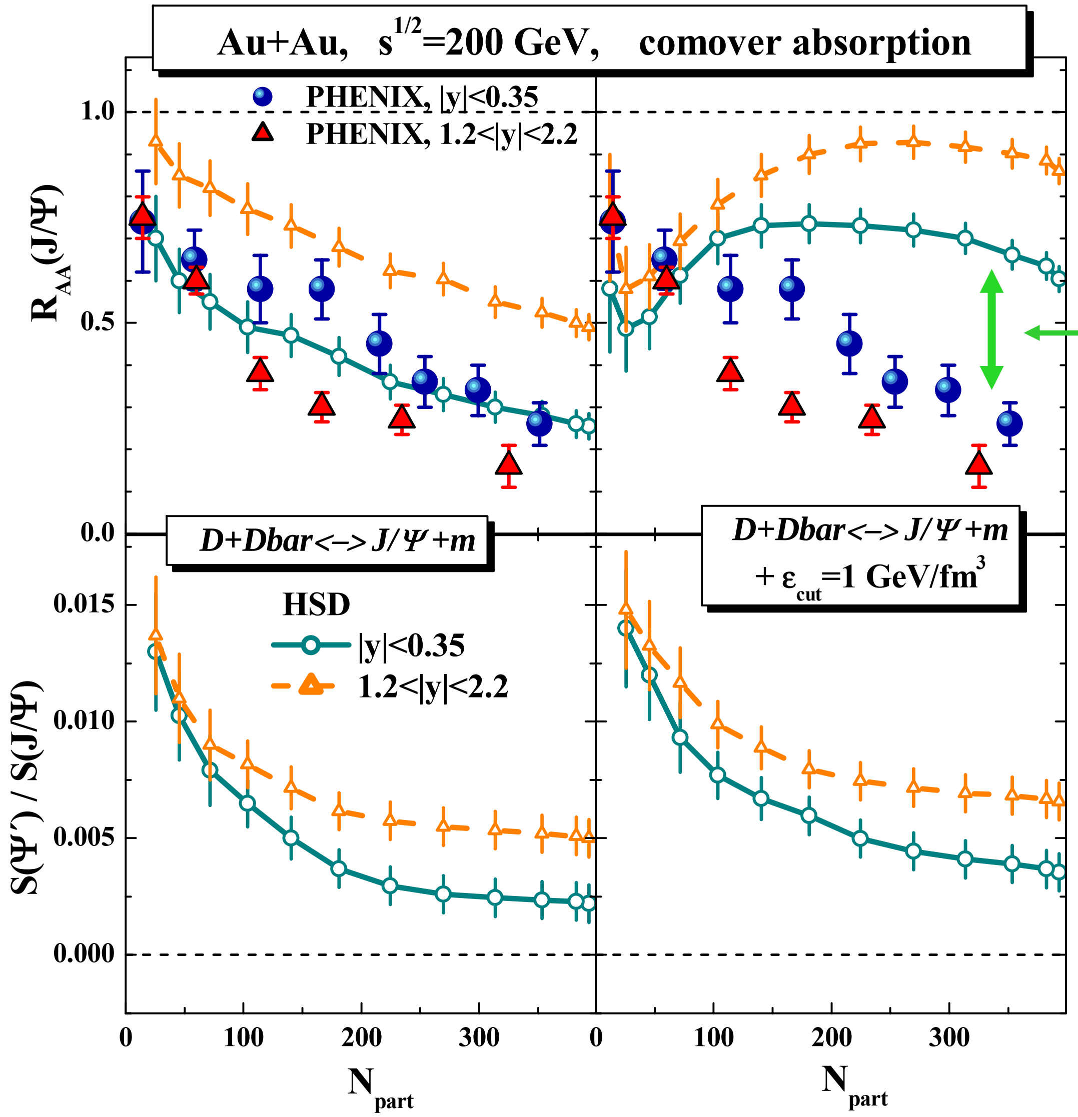




- **Set 1: QGP threshold melting scenario with dissociation energy densities ε(J/Ψ)=16 GeV/fm³, ε(χ$_c$) =2 GeV/fm³, ε(Ψ′) =2 GeV/fm³ shows too strong Ψ′ absorption which contradicts to the NA50 data!**

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

J/Ψ and Ψ′ suppression in Au+Au at RHIC:
Comover absorption



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

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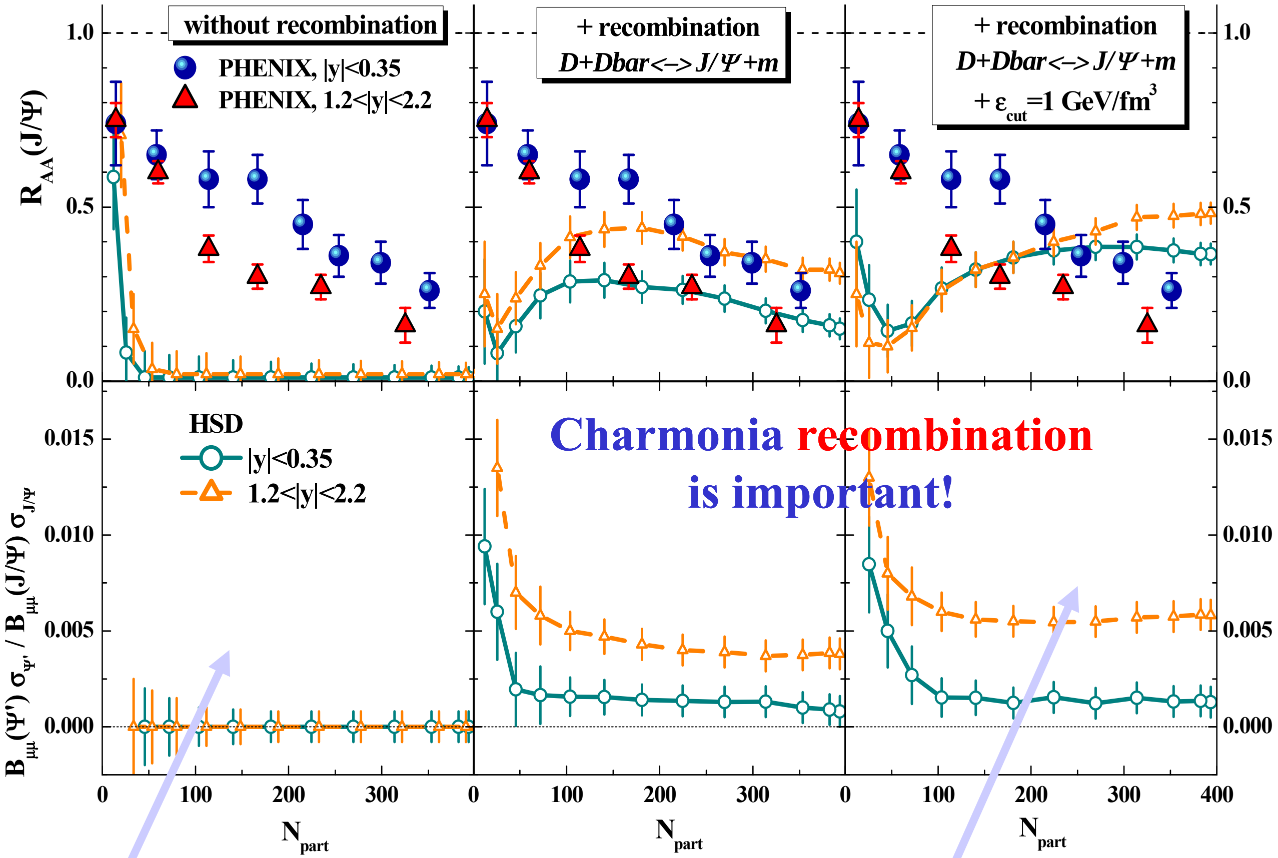
Space for partonic effects

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

[Olena Linnyk et al., arXiv:0705.4443, PRC'07, in press]

J/Ψ and Ψ´ suppression in Au+Au at RHIC: QGP threshold scenario

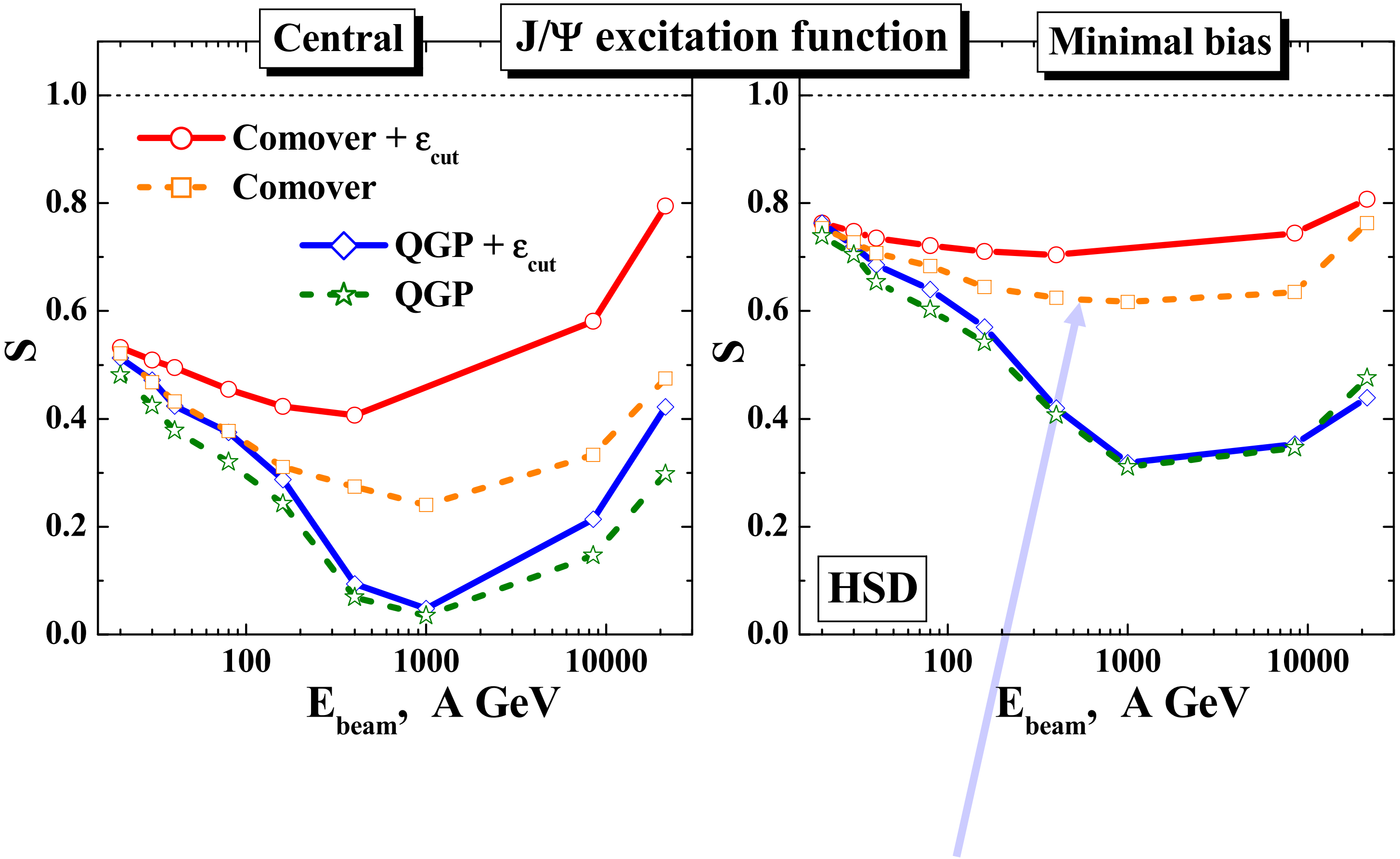


Satz's model: complete dissociation of initial J/Ψ and Ψ´ due to the huge local energy densities !

Energy density cut ε_{cut}=1 GeV/fm^3 reduces the meson comover absorption, however, D+Dbar annihilation can not generate enough charmonia, especially for peripheral collisions!

QGP threshold melting scenario is ruled out by PHENIX data!

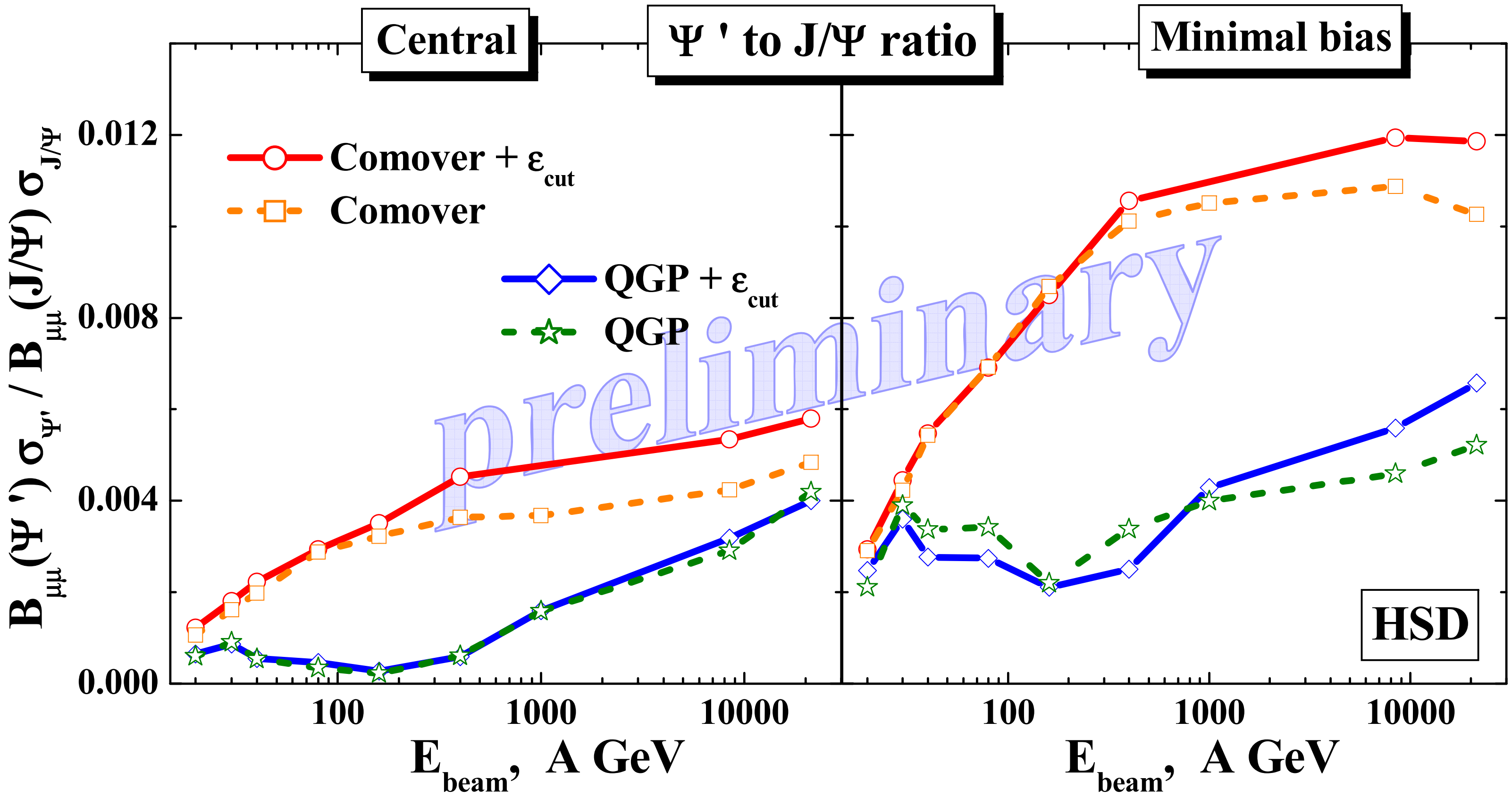
J/Ψ excitation function



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

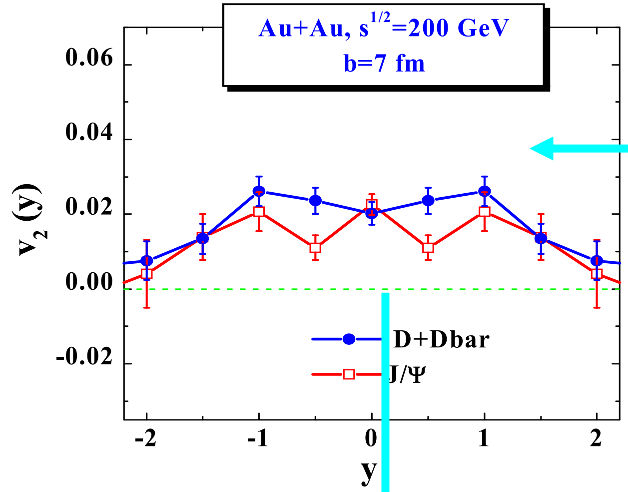
- The J/Ψ **melting scenario** with hadronic comover recreation shows a **maximum suppression** at E_{beam} = 1 A TeV; exp. data ?

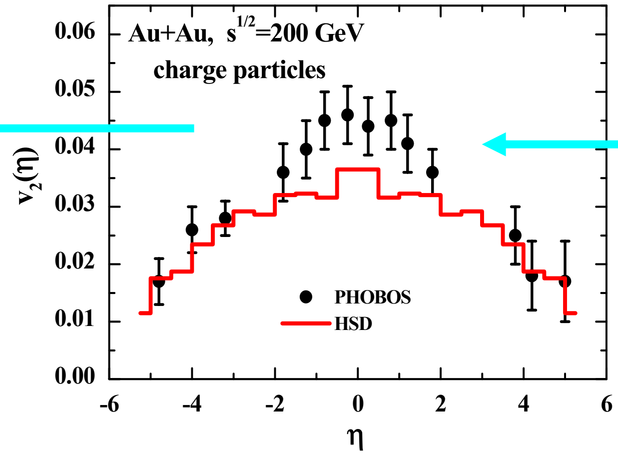
Ψ´ excitation function



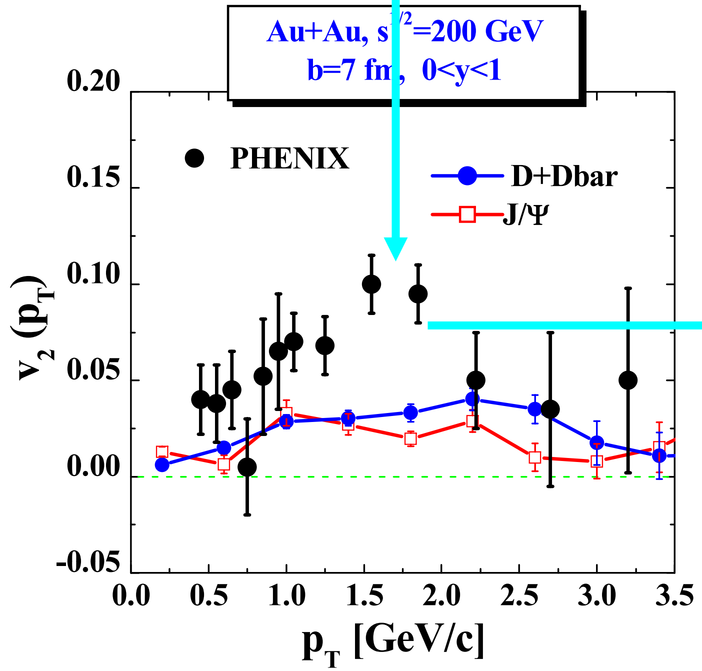
Ψ´ suppression provides independent information on absorption versus recreation mechanisms !

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 !



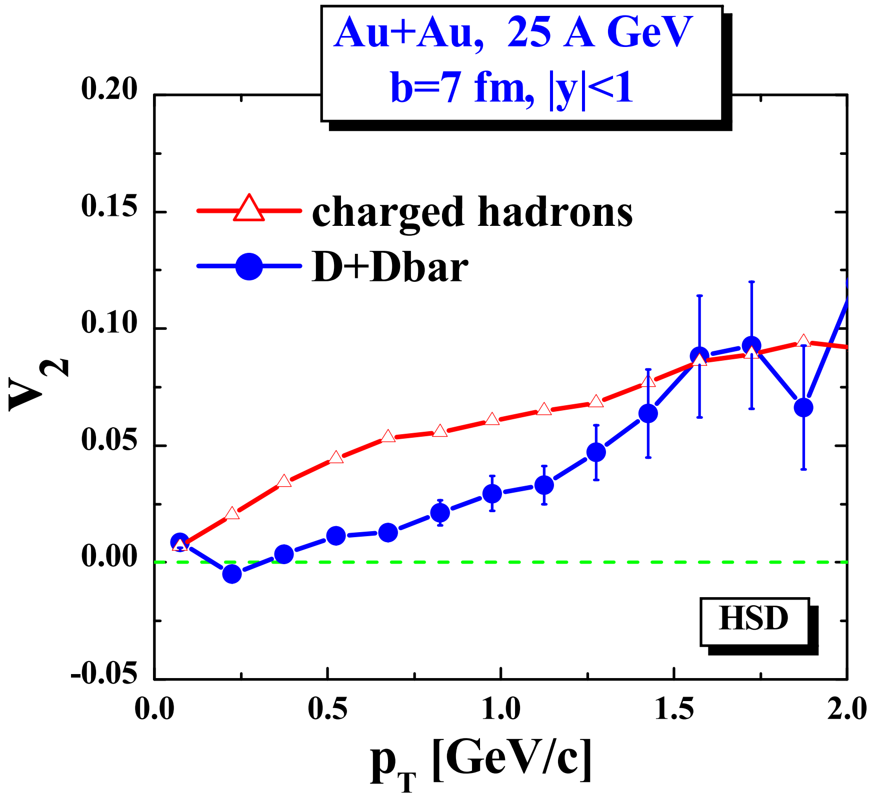
- **HSD:** D-mesons and J/Ψ follow the charged particle flow => **small $v_2 < 3\%$**

- **Exp. data at RHIC** show **large** collective flow of D-mesons up to **v_2~10%!**

=> strong initial flow of non-hadronic nature! (cf. AMPT by Che-Ming Ko)

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**

AMPT with string melting shows much stronger v_2!
(Che-Ming Ko)

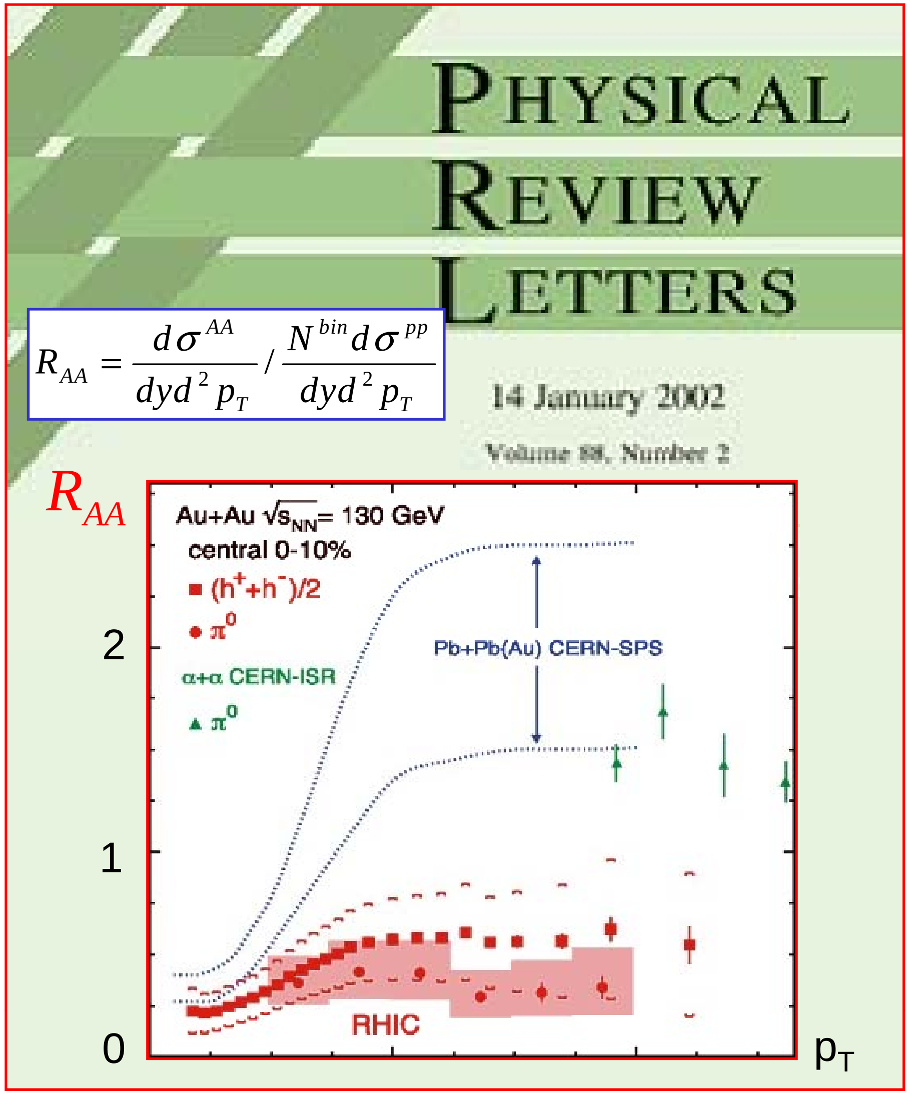
Possible observation at CBM:
strong initial flow of D-mesons and J/Ψ due to partonic interactions!

Challenge for CBM!

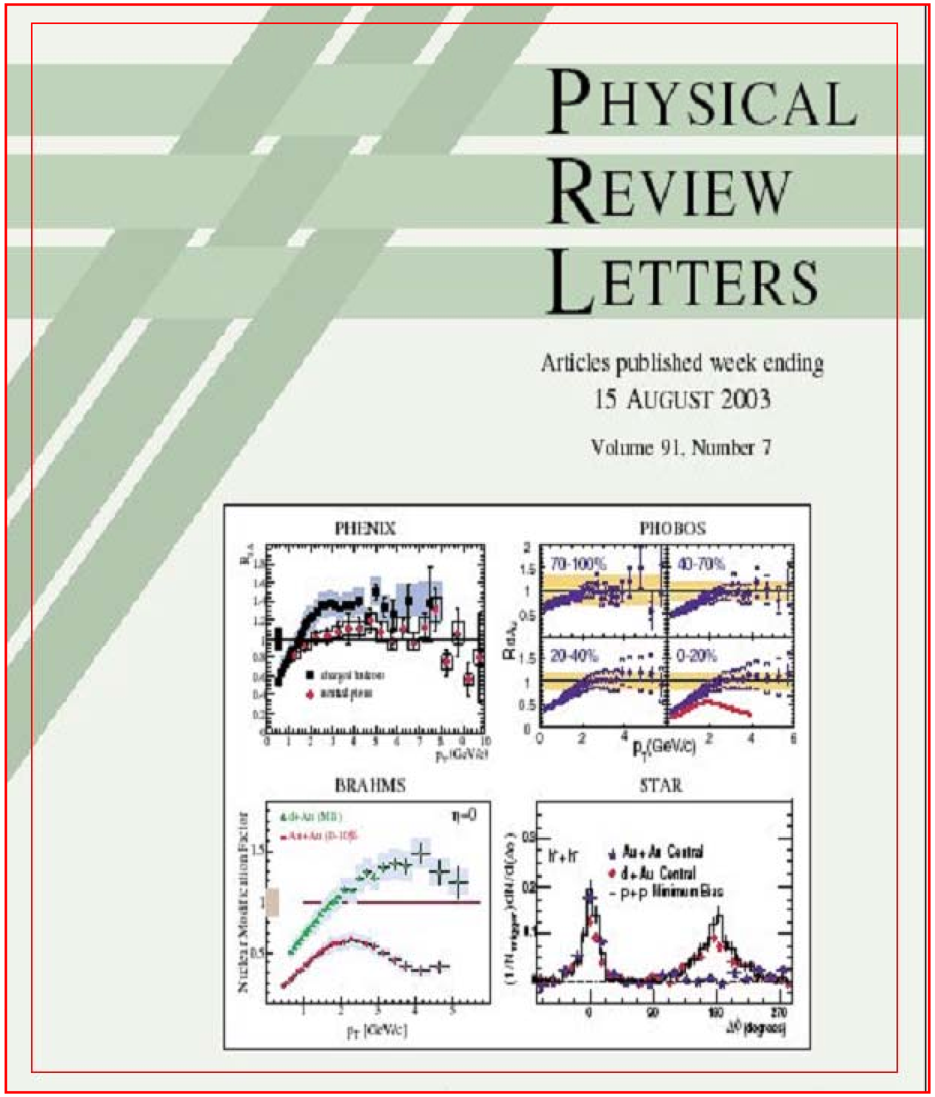
Summary I.

- 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.
- 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 huge plasma pressure ?!

High p_T suppression of hadrons



$$R_{AA} = \frac{d\sigma^{AA}}{dyd^2p_T} / \frac{N^{bin} d\sigma^{pp}}{dyd^2p_T}$$



High p_T suppression of hadrons: exp. observables

Nuclear Modification Factor:

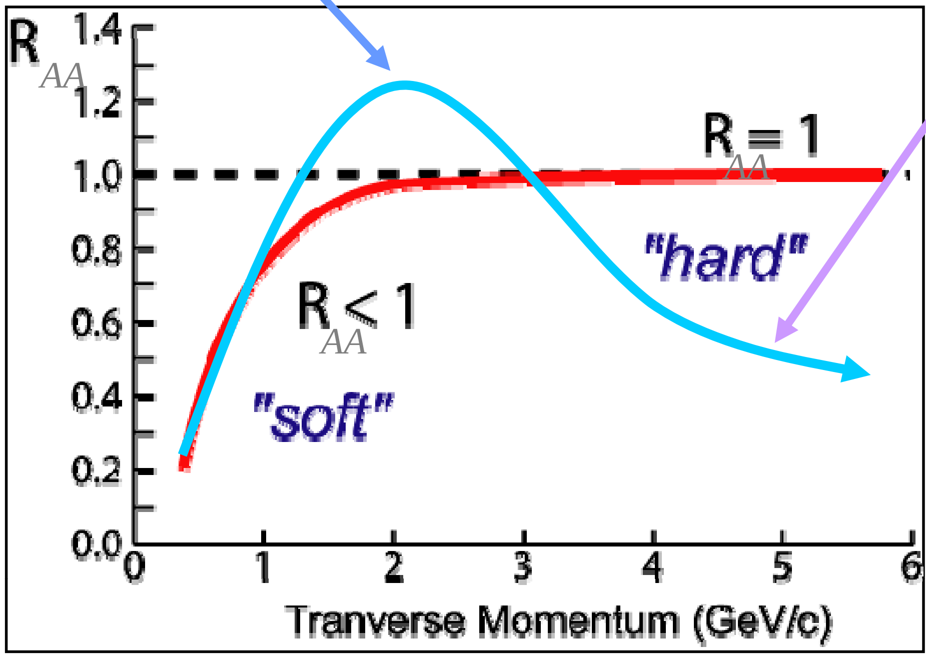
$$R_{AA}(p_T) \propto \frac{\sigma_{AA}}{\langle N_{coll} \rangle \cdot \sigma_{pp}}$$

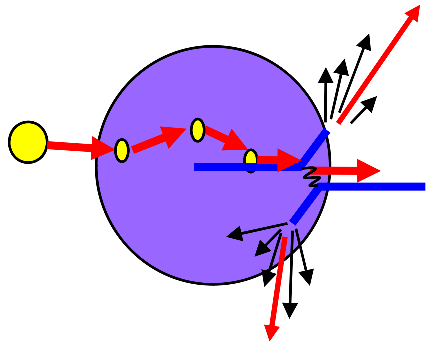
Probe: initial + final state effects

Cronin effect

"jet quenching"

hadronic + partonic suppression





$R_{AA} < 1$ in regime of soft physics

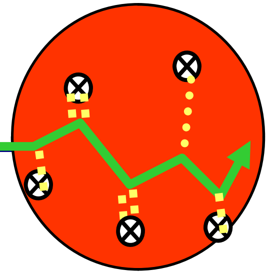
$R_{AA} = 1$ at high-p_T where hard scattering dominates

$R_{AA} > 1$ - Cronin Effect

Suppression:

$R_{AA} < 1$ at high-p_T "jet quenching"

Cronin effect at RHIC (HSD)



Cronin effect: initial state semi-hard gluon radiation increases p_T spectra already in p+A or d+A

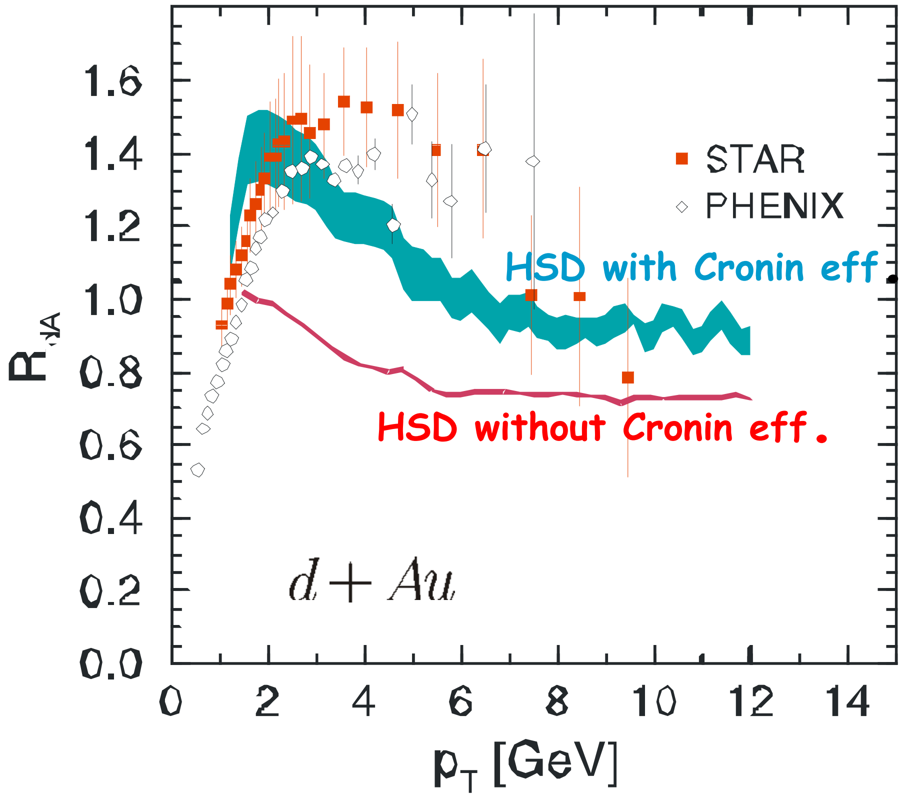
Dynamical modeling of the Cronin effect in HSD:

$$<k_T^2>_{AA} = <k_T^2>_{PP} (1 + a\, N_{Prev})$$

N_{Prev} = number of previous collisions (dynamically calculated for each hadron!)

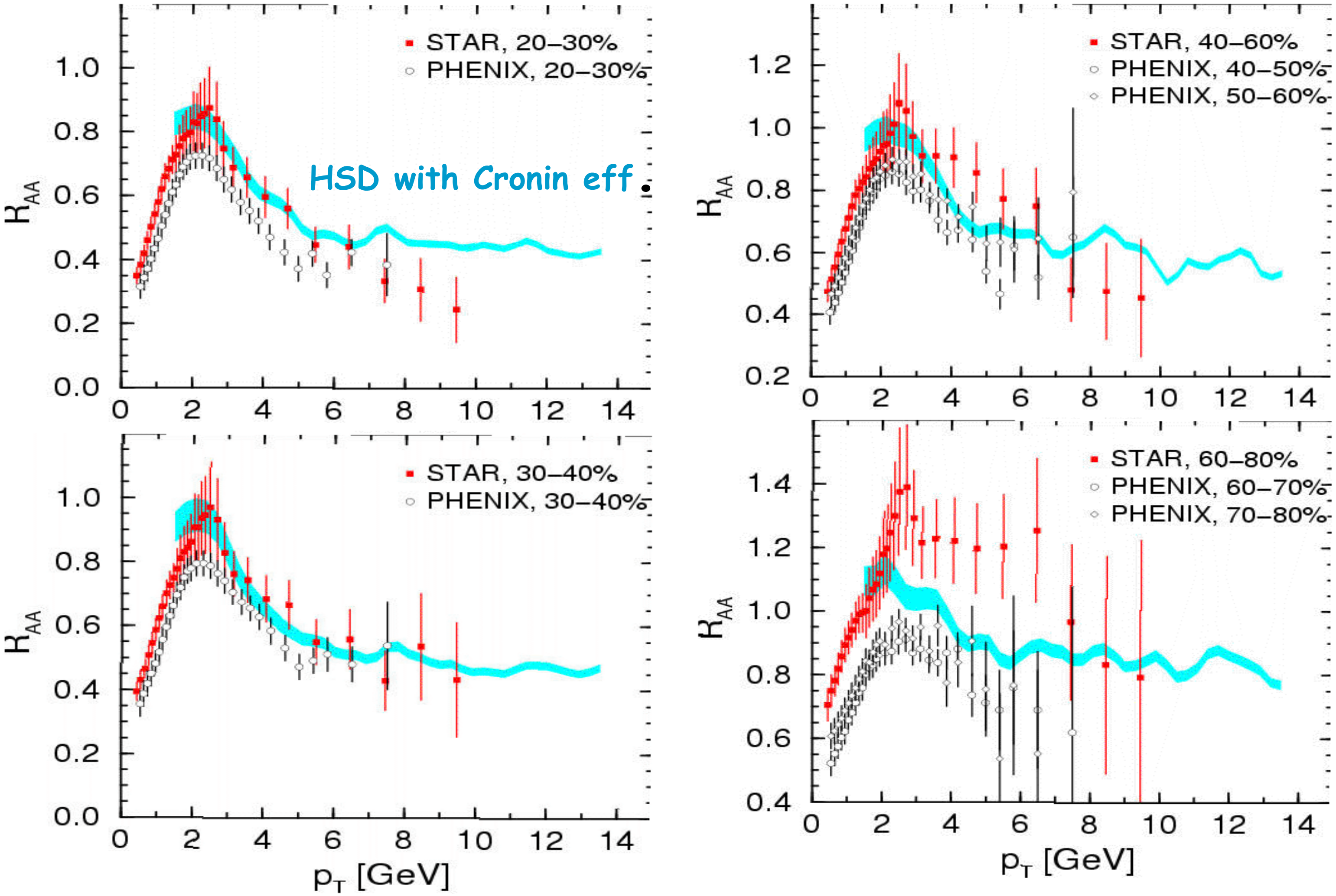
parameter a = 0.25 – 0.4

$$R_{dA}(p_T) = \frac{1/N_{dA}^{event} \cdot d^2N_{dA}/dydp_T}{< N_{coll} > /\sigma_{pp}^{inelas} \cdot d\sigma_{pp}/dydp_T}$$



W. Cassing, K. Gallmeister and C. Greiner, Nucl. Phys. A 735 (2004) 277

High p_T suppression in non-central Au+Au (HSD)



• Hadron-string model with Cronin effect provides ~ enough high p_T suppression for non-central Au+Au

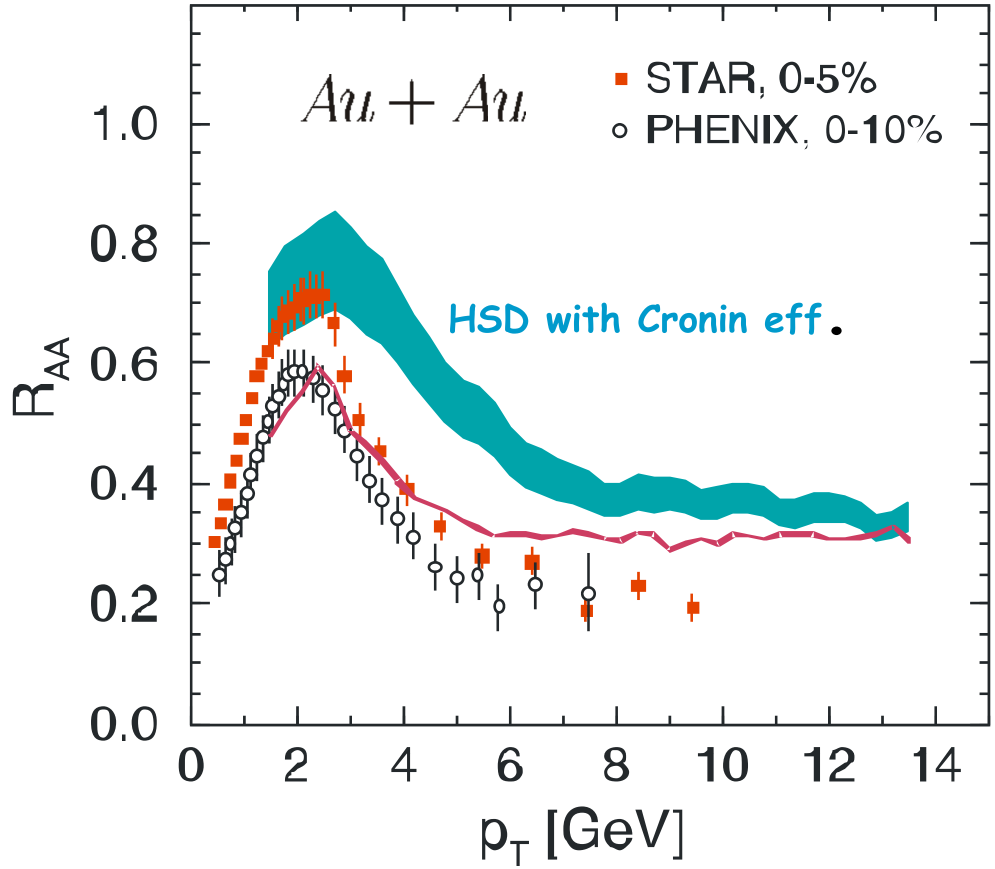
Cronin effect in central Au+Au at RHIC (HSD)

$$R_{AA}(p_T) = \frac{1/N_{AA}^{event} \cdot d^2N_{AA}/dydp_T}{< N_{coll} > /\sigma_{pp}^{inelas} \cdot d\sigma_{pp}/dydp_T}$$

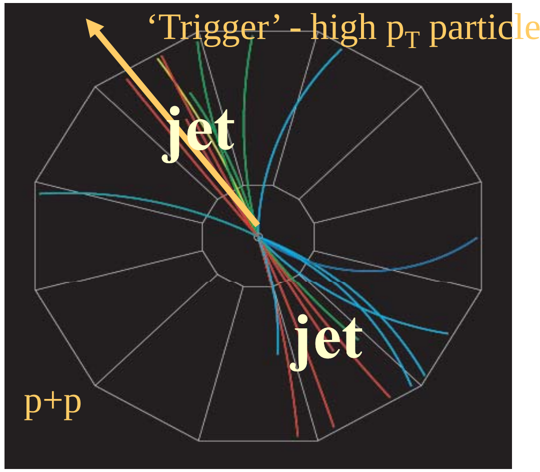
- Hadron-string model doesn't provide enough high p_T suppression for central Au+Au

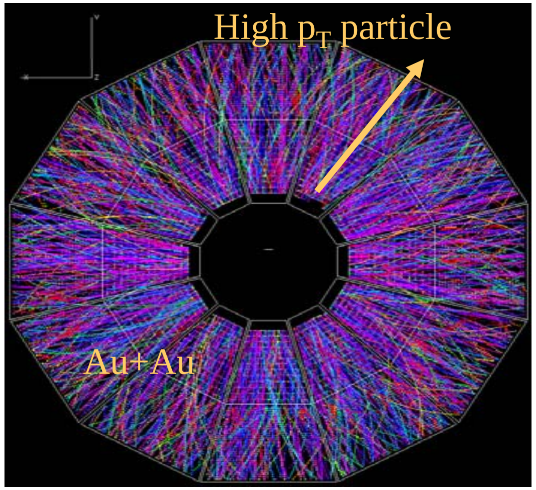
→ Extra suppression :

from early partonic phase ?!

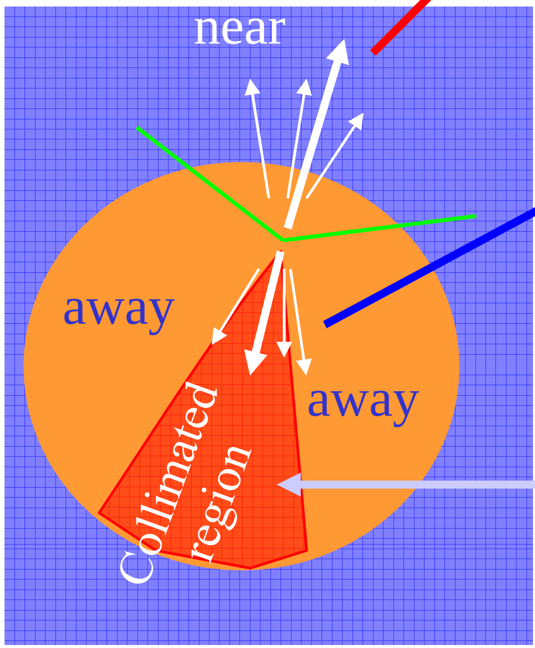


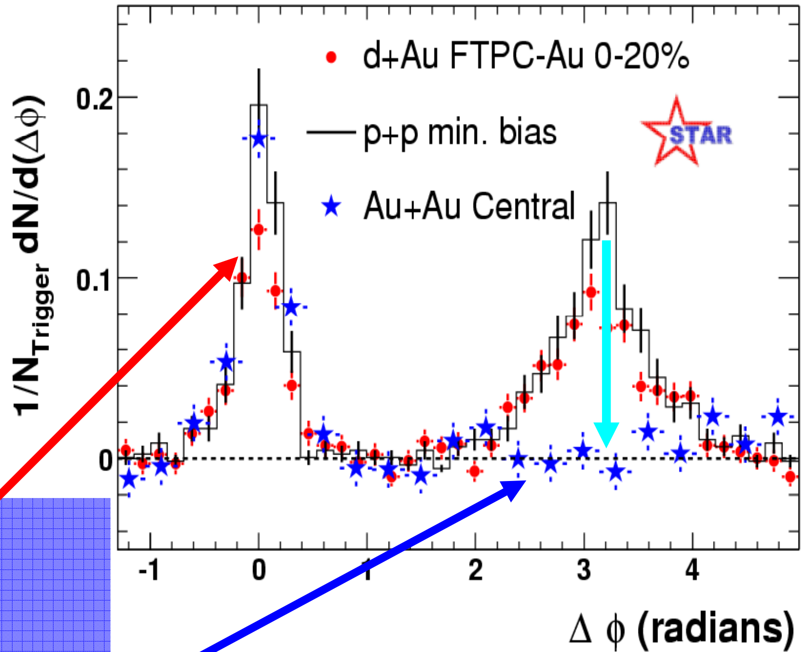
Jet suppression: dN/dφ





4<p_T(trigger)<6 GeV/c
p_T(assoc.)>2 GeV/c

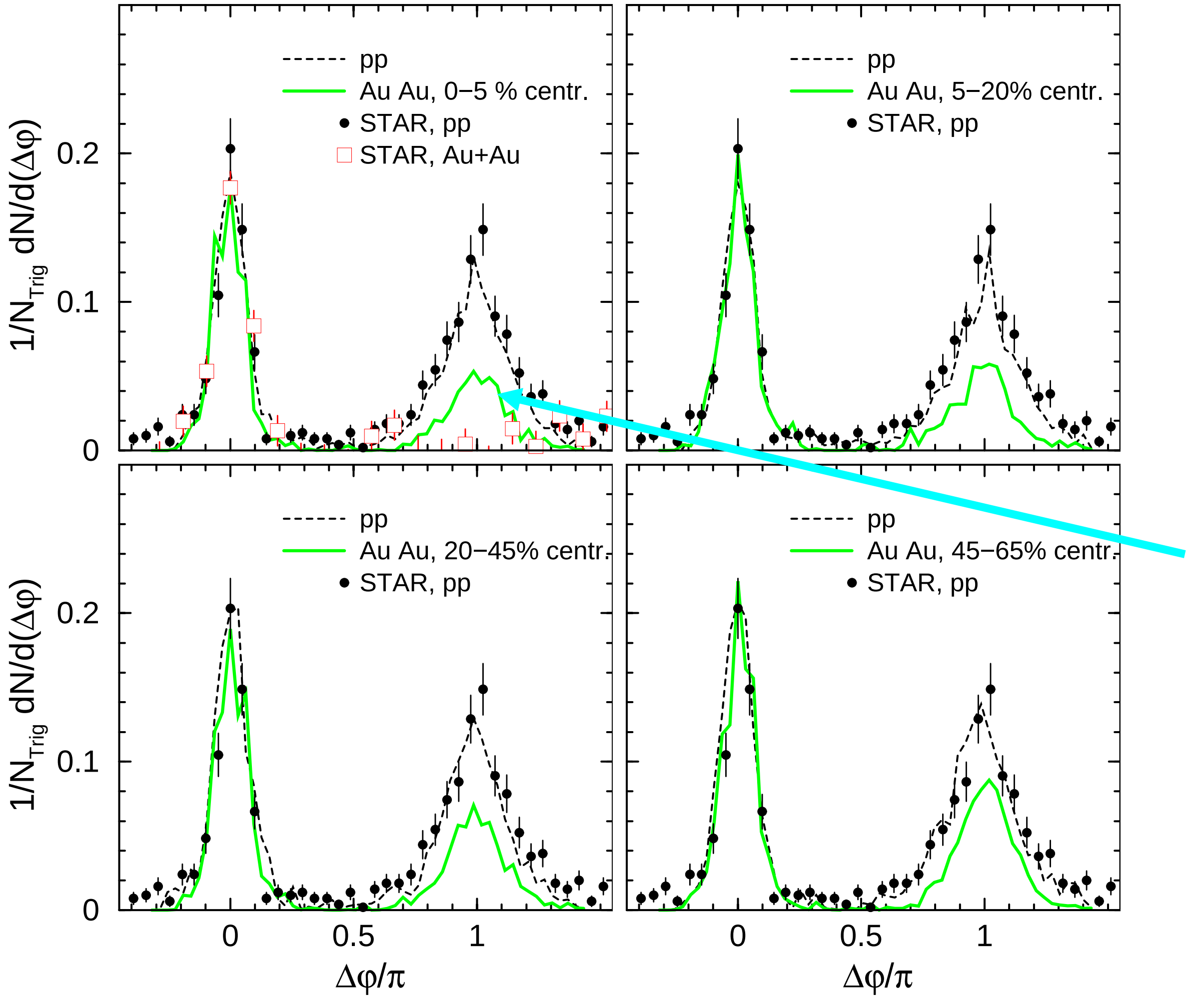




QGP suppression ?!

jet energy loss in the medium

Jet suppression: dN/dφ



- **The jet angular correlations for pp are fine!**
- **Au+Au: The near-side jet angular correlation is well described, but the suppression of the far-side jet is too low!**

Cassing et al., NPA 748 (2005) 241

Summary II.

- **Cronin effect (initial state semi-hard gluon radiation) increases p_T spectra already in p+A or d+A**

- **The attenuation of high p_T-hadrons (R_{AA}) is well reproduced in the hadron-string approach for non-central Au+Au collisions at top RHIC energies, however, underestimated in central Au+Au collisions.**

- **The jet angular correlations for pp are fine, however, the suppression of the ‚far-side' jet is underestimated in central Au+Au collisions at $s^{1/2}$ = 200 GeV**

➔ **System interacts more strongly in the early phase than hadron-like matter !**

Outlook

- A deconfined phase is clearly reached at RHIC, but a theory having the relevant/proper degrees of freedom (quarks and gluons) in this regime is needed to study its transport properties.

HSD → Parton-Hadron-String-Dynamics (PHSD)

PHSD –
transport description of the partonic and hadronic phase

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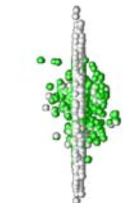
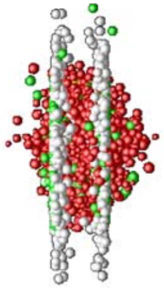
HSD Collaboration and Co

Outlook: PHSD - basic concepts



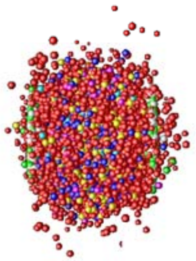
Initial A+A collisions – HSD: string formation and decay to pre-hadrons



Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) approximation to QCD

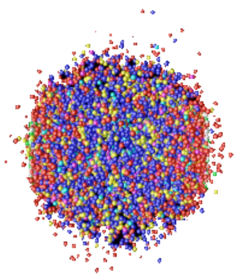
DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Partonic phase: quarks and gluons (= ‚dynamical quasiparticles‘) with off-shell spectral functions (width, mass) defined by DQPM



elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM

- ✓ **q + qbar (flavor neutral) <=> gluon (colored)**
- ✓ **gluon + gluon <=> gluon (possible due to large spectral width)**
- ✓ **q + qbar (color neutral) <=> hadron resonances**

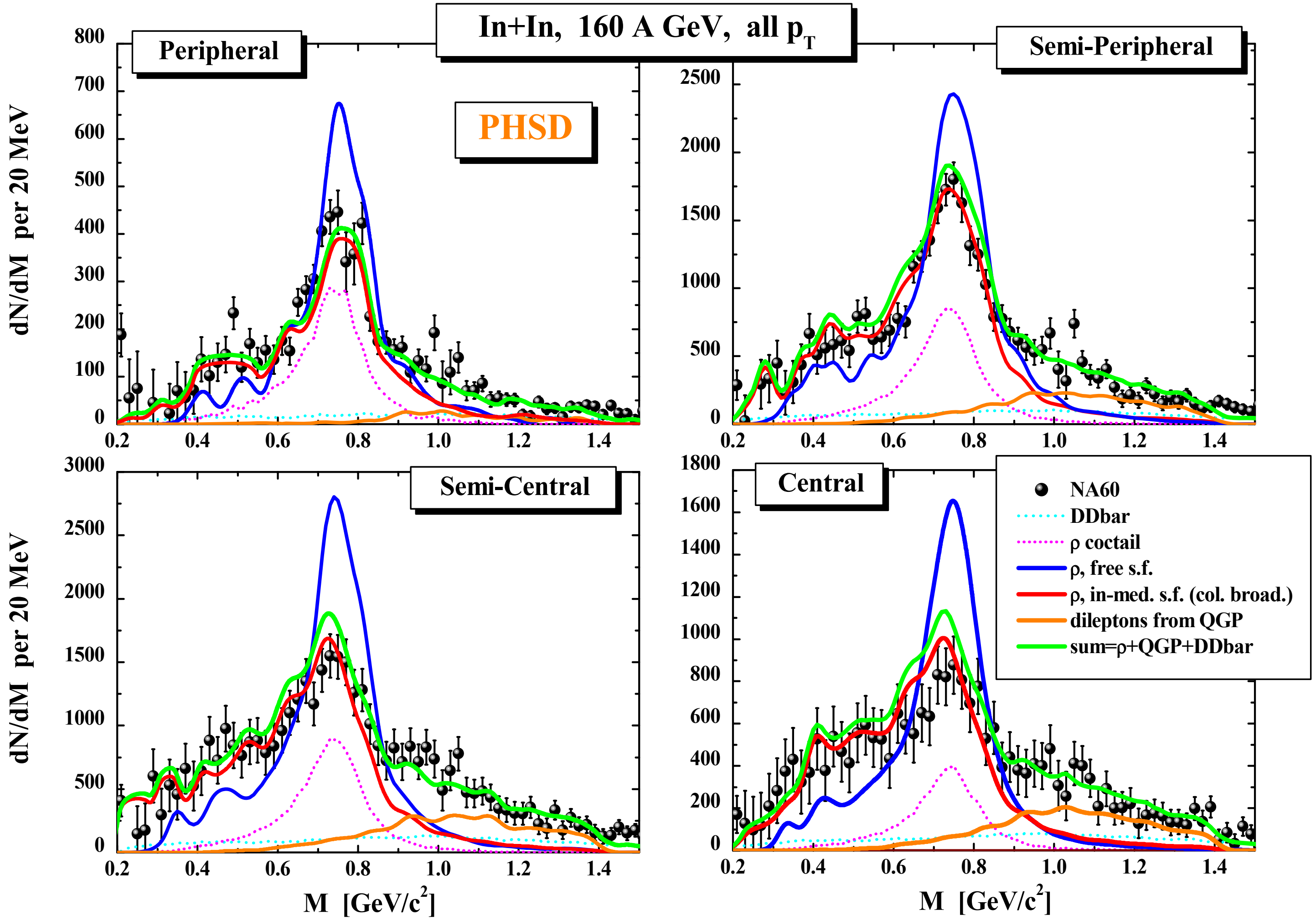


Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:

gluons → q + qbar; q + qbar → meson; q + q +q → baryon

Hadronic phase: hadron-string interactions – off-shell HSD

Dilepton radiation from the sQGP – NA60



Conjecture: the sQGP shows up already at SPS energies !