Institut für
Theoretische Physik I

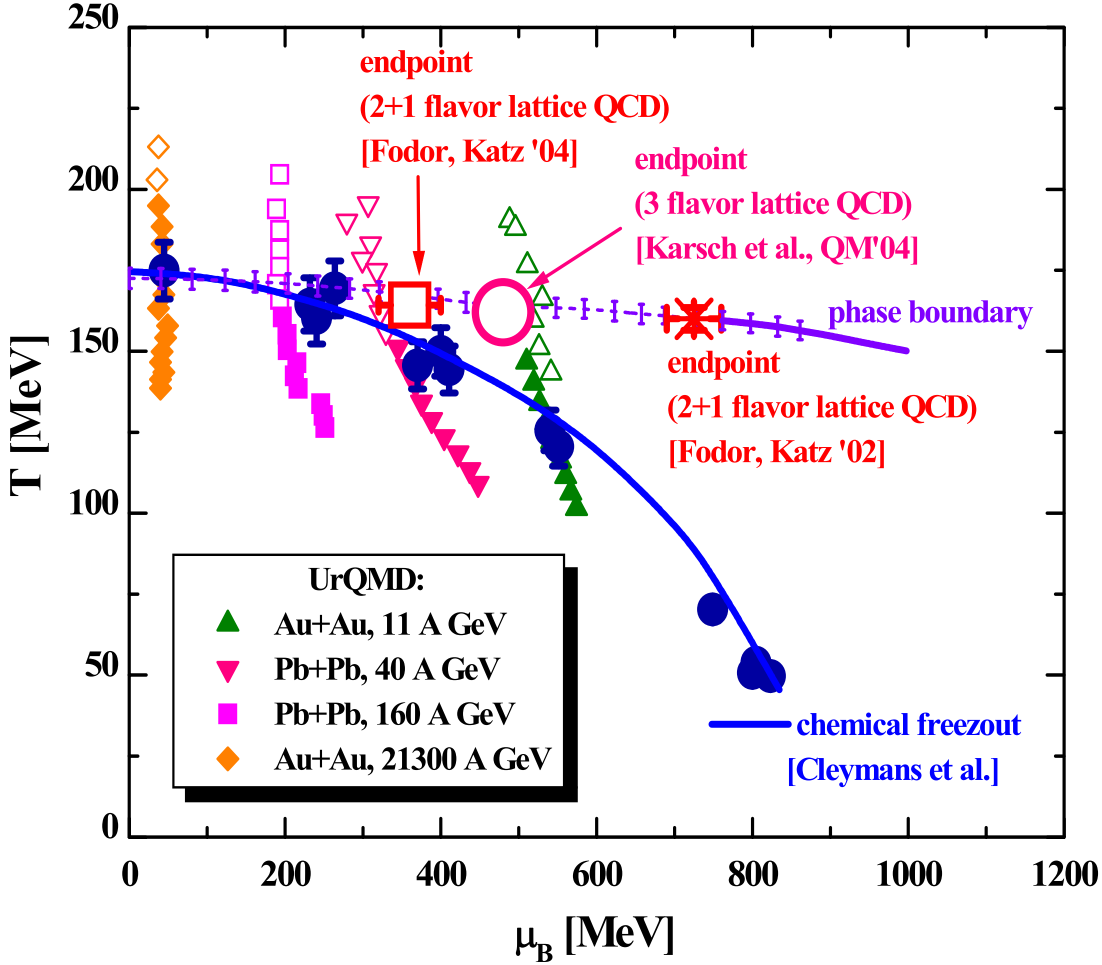
JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

# Charm in transport

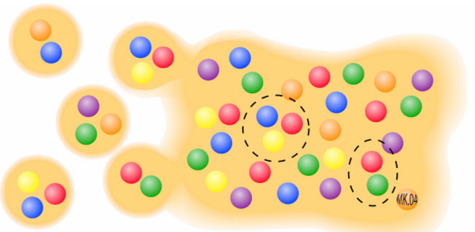
Wolfgang Cassing

Trento, 31.05.2006

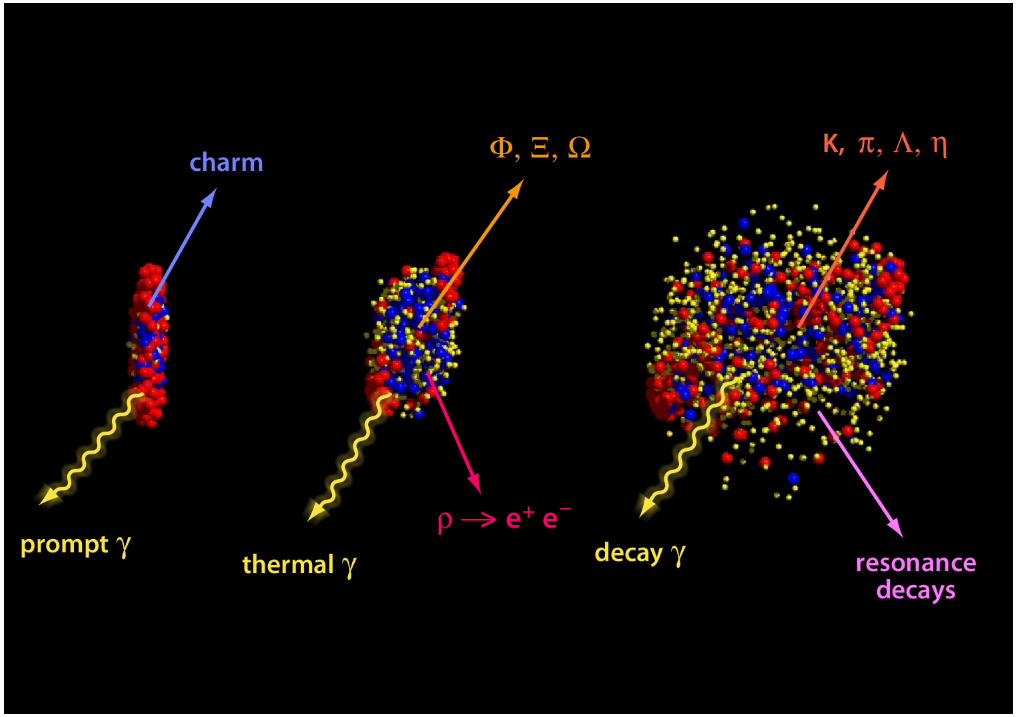
# The phase diagram of QCD




- UrQMD initial energy density is **higher** than the boundary from LQCD
- Tri-critical point reached somewhere between 20 and 40 A GeV
- -> we are probing a **new phase of matter** already at **the AGS!**



# Signals of QGP




- Charm suppression
- Collective flow ($v_1$, $v_2$) of charm particles

- further signals of QGP:

  (not covered in this talk)

➤ Strangeness enhancement

➤ Multi-strange particle enhancement in Au+Au

➤ Jet quenching and angular correlations

➤ High $p_T$ suppression of hadrons

➤ Nonstatistical event by event correlations ...

# Concepts: HSD

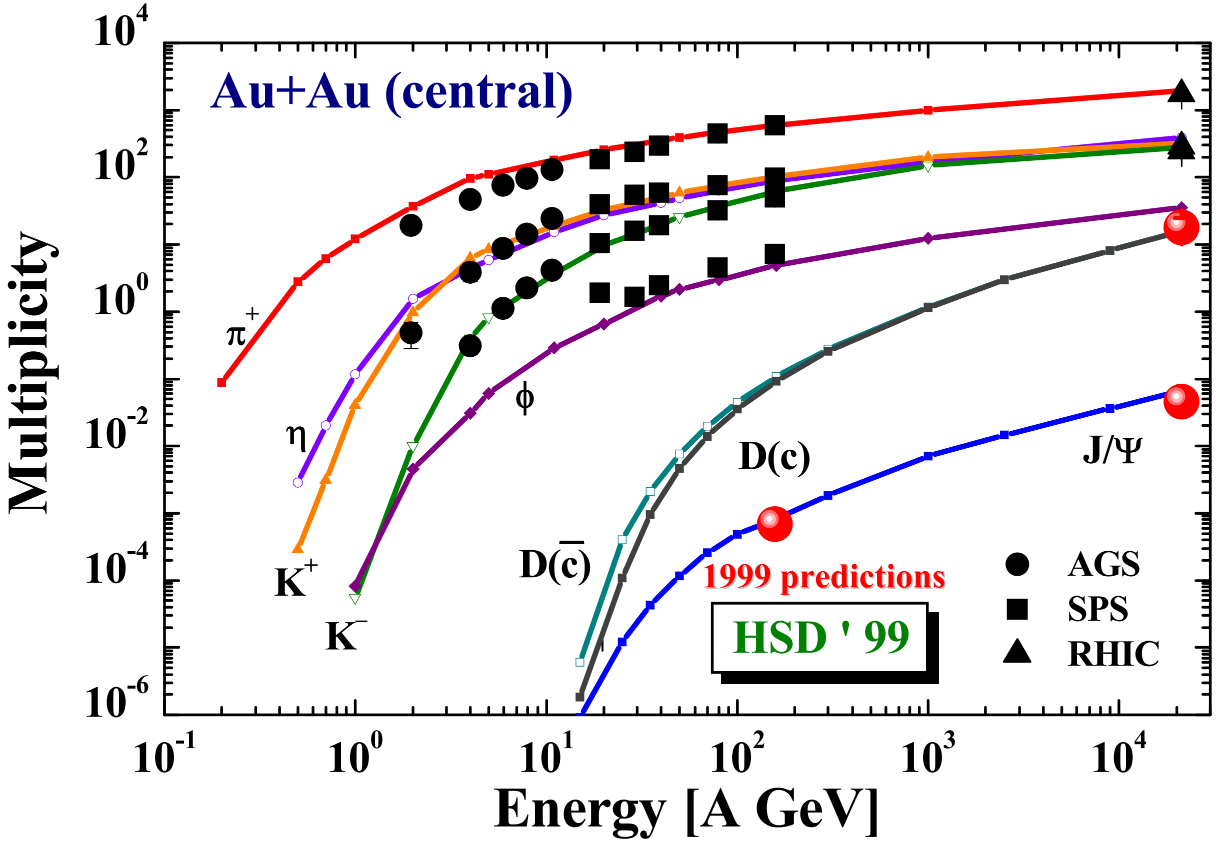
**HSD – Hadron-String-Dynamics transport approach**

- **Solution of the transport equations with collision terms describing:**
  - **elastic and inelastic hadronic reactions:**
    **baryon-baryon, meson-baryon, meson-meson**
  - **formation and decay of baryonic and mesonic resonances**
  - **string formation and decay**
- **Implementation of detailed balance on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-meson fusion reactions in HSD)**
- **Degrees of freedom:**
  **baryons + mesons including excited states**
  **strings; q, qbar, (qq), (qbar qbar) (no gluons in HSD!)**

http://www.th.physik.uni-frankfurt.de/~brat/hsd.html

# HSD – a microscopic transport model for heavy-ion reactions

- very good description of particle production in pp, pA reactions
- unique description of nuclear dynamics from low (~100 A MeV) to ultrarelativistic (21.3 A TeV) energies



# Charmed particles

## ‚Open' charm

### Mesons:

$D^{+}(c\bar{d})$ $D^{-}(\bar{c}d)$

$D^{0}(c\bar{u})$ $\bar{D}^{0}(\bar{c}u)$

$D^{*+}(c\bar{d})$ $D^{*-}(\bar{c}d)$

$D^{*0}(c\bar{u})$ $\bar{D}^{*0}(\bar{c}u)$

$D_s^{+}(c\bar{s})$ $D_s^{-}(\bar{c}s)$

$D_s^{*+}(c\bar{s})$ $D_s^{*-}(\bar{c}s)$

$m_D = 1.864$ GeV

### Baryons:

$\Lambda_C^{+}(udc)$

$\Sigma_C^{+}(udc)$

...

$m_{\Lambda_C} = 2.284$ GeV

## ‚Hidden' charm

$c\bar{c}$ mesons

$\eta_C(1S)$ 2979.8 MeV

$J/\Psi(1S)$ 3096.8 MeV

$\chi_{C0}(1P)$ 3415.0 MeV

$\chi_{C1}(1P)$ 3510.5 MeV

$\chi_{C2}(1P)$ 3556.2 MeV

$\Psi(2S)$ 3685.9 MeV

$\Psi(3770)$ $> 2m_D = 3729$ MeV

$\Psi(4040)$

$\Psi(4160)$

...

### Decays:

$c\bar{c} \to$ hadrons

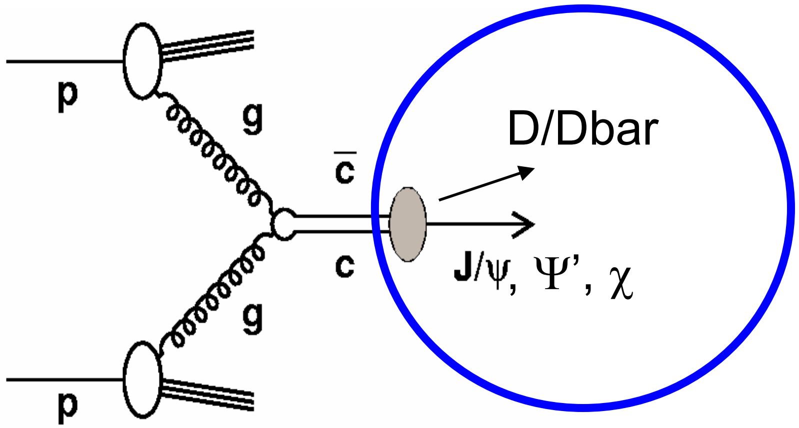
$\to$ hadrons $+ \gamma$

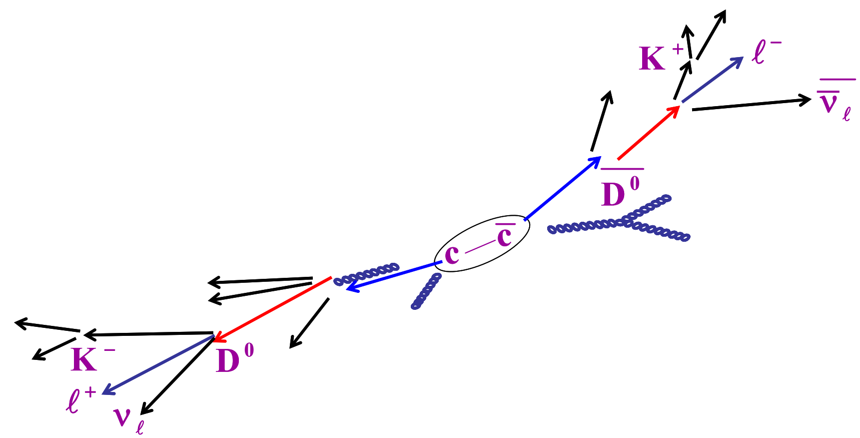
$\chi(\Psi') \to J/\Psi + \gamma$

$J/\Psi(\Psi') \to e^+e^-$

$\Psi(3770) \to D\bar{D}$

# Open and hidden charm production in pp collisions




pQCD to calculate c-cbar production (PYTHIA)

Note:

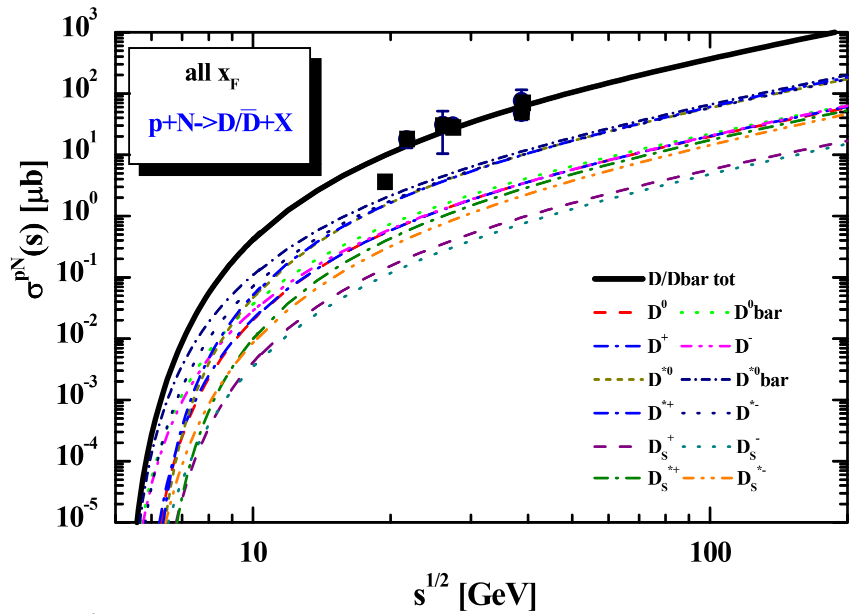
- much of J/Ψ comes from feed-down from higher resonances (Ψ', $\chi_c$)
- D-Dbar mesons are coming in pairs from one vertex

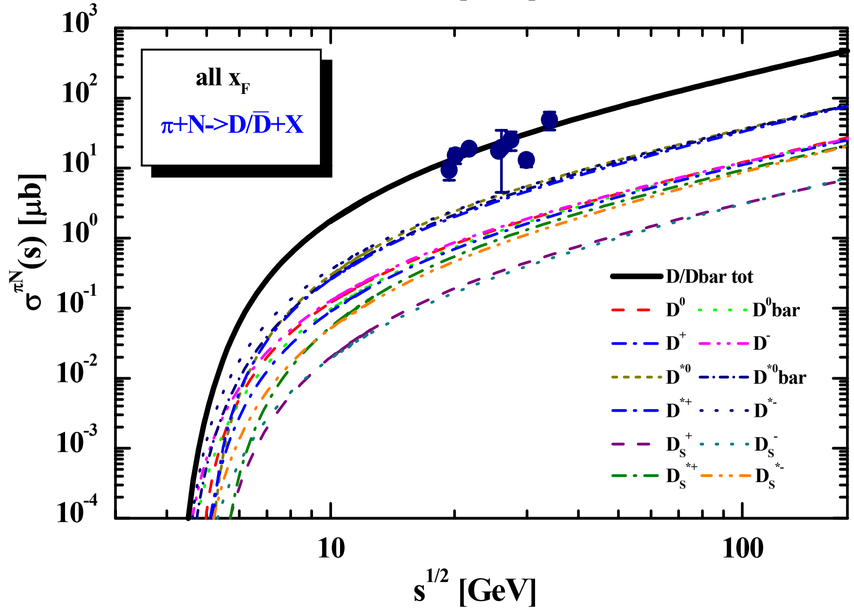
# D/Dbar production cross sections in pN and πN

**σ(D/Dbar):**

parametrization of PYTHIA scaled by factor K to the available experimental data

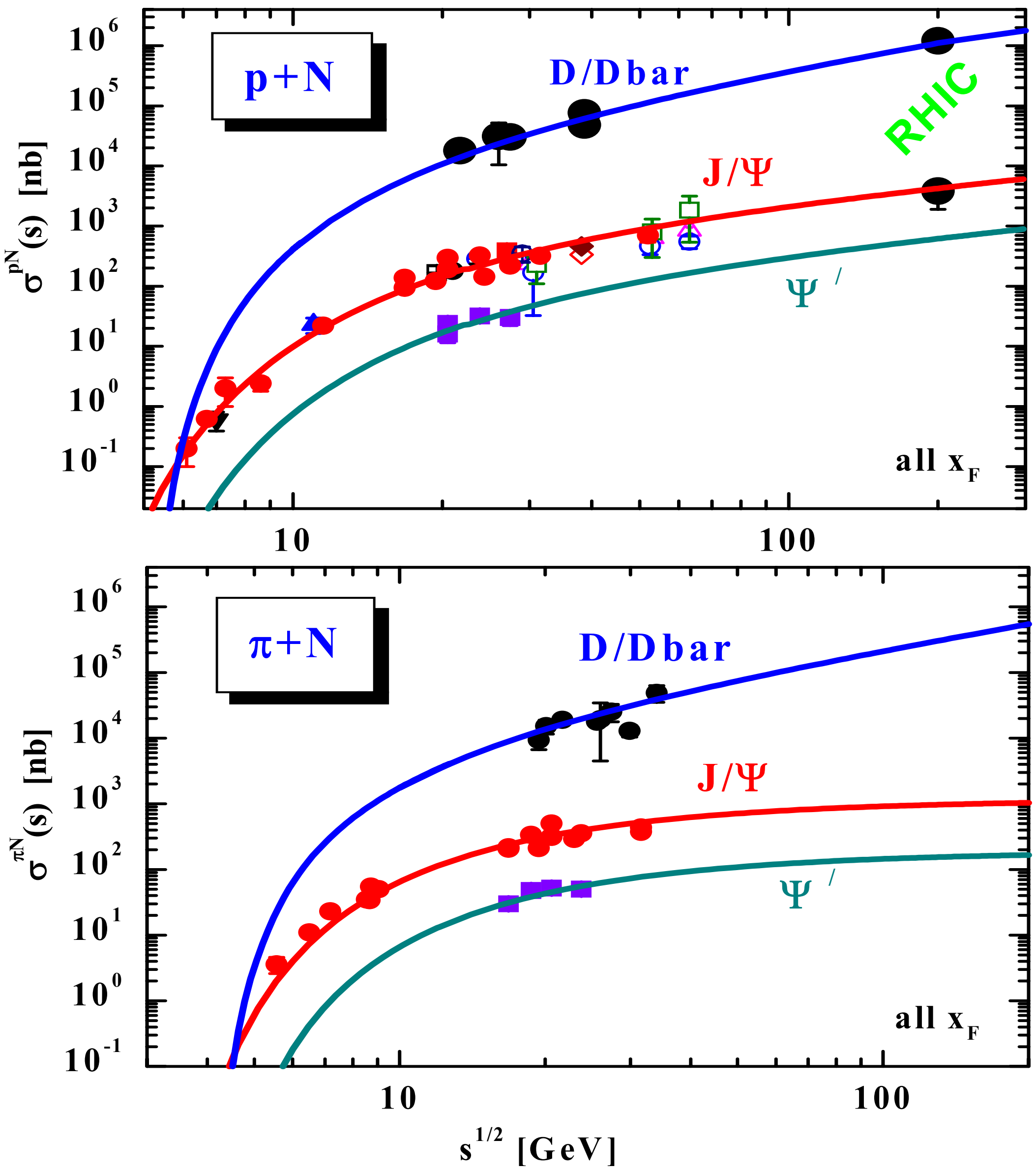
+ threshold extrapolation




K(pN)=12, K(pN)=7 (for $m_c$=1.5 GeV, $k_T$=1 GeV, MRS G structure function

# D/Dbar, J/Ψ and Ψ' production cross sections in pN and πN

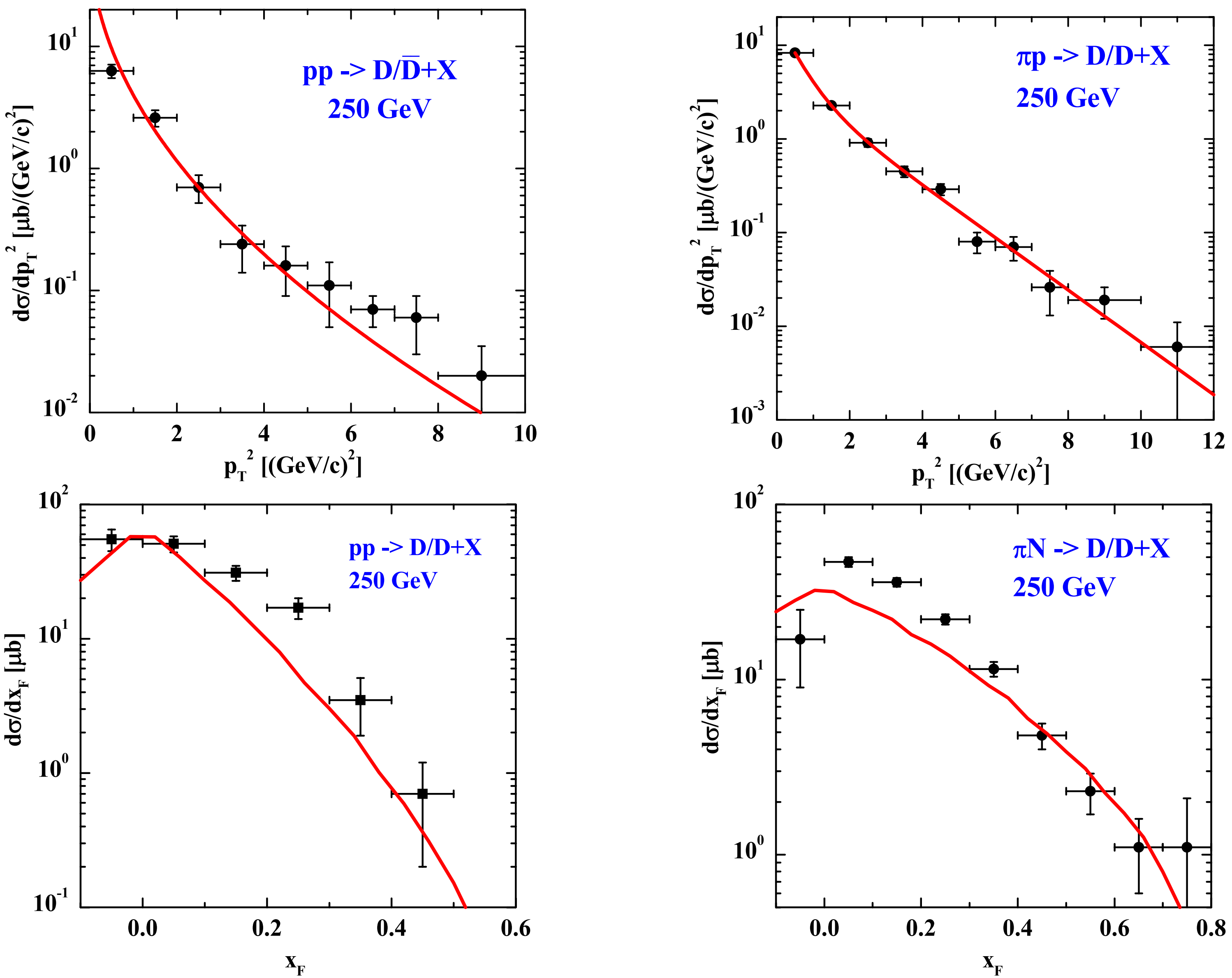



σ(J/Ψ) and σ(Ψ' ): parametrization of the available exp. data

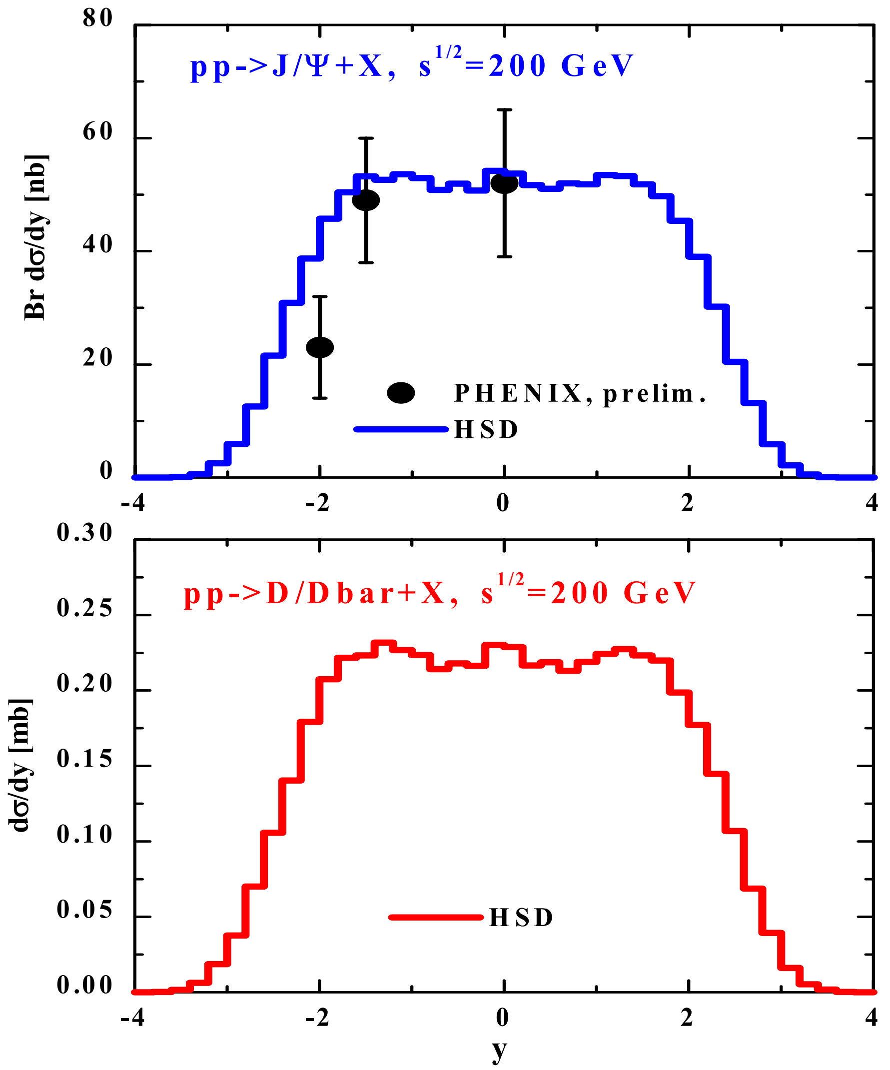
New data from RHIC are compatible with the extrapolation from 2000

But data close to threshold are still needed !

# Differential cross sections for D/Dbar production in pN and πN



# dN/dy for D/Dbar, J/Ψ and Ψ' production in pp at RHIC



# Open charm and charmonium dynamics in HSD
# - 2003 -

# Charmonium chemistry

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

$$\sigma_i^{NN}(s) = f_i\ a\ \left(1 - \frac{m_i}{\sqrt{s}}\right)^{\alpha} \left(\frac{\sqrt{s}}{m_i}\right)^{\beta} \theta(\sqrt{s} - \sqrt{s_{0i}}),$$

$i = J/\Psi, \chi_c, \Psi'$, $\sqrt{s_{0i}} = (m_i + 2m_N)^2$

**Fraction of charmonium states $i$:**

$f_{\chi_c} = 0.636,\ f_{J/\Psi} = 0.581,\ f_{\Psi'} = 0.21$

**fixed to reproduce the experimental ratio**

$$\frac{B(\chi_{c1} \to J/\Psi)\sigma_{\chi_{c1}} + B(\chi_{c2} \to J/\Psi)\sigma_{\chi_{c2}}}{\sigma_{J/\Psi}^{exp}} = 0.344 \pm 0.031$$

**measured in $pp$ and $\pi N$ reactions by E705, WA11**
**and averaged $pp$ and $pA$ ratio** $(B_{\mu\mu}(\Psi')\sigma_{\Psi'})/(B_{\mu\mu}(J/\Psi)\sigma_{J/\Psi}) \simeq 0.0165$

# Open charm and charmonium dynamics in HSD transport approach - 2003

**Dissociation cross section of charmonia with baryons:**

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

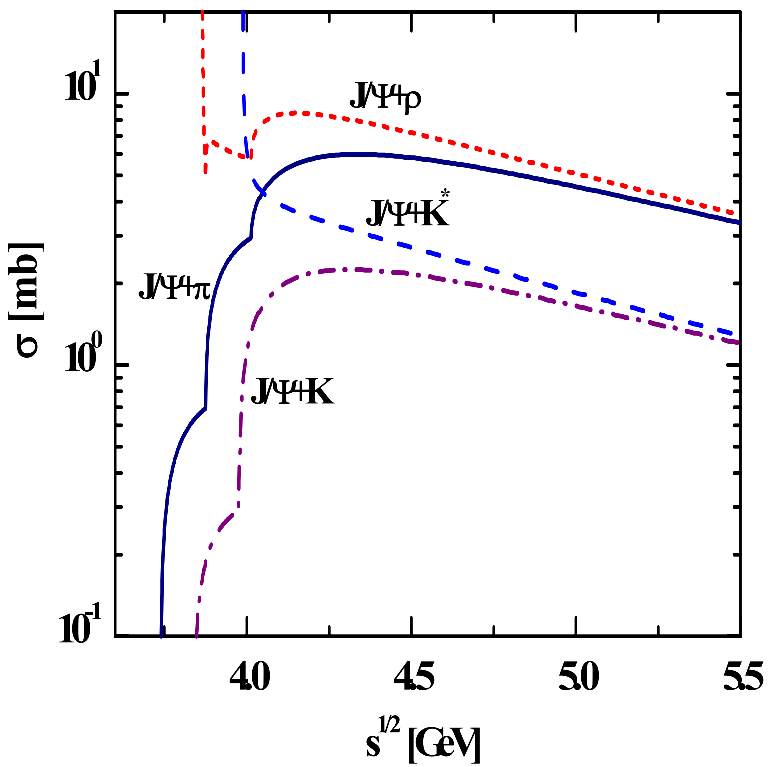
**Formed charmonium (color-singlet states):**
$\sigma_{J/\Psi\ B}$= 4 mb, $\sigma_{\chi\ B}$= 5 mb, $\sigma_{\Psi 0\ B}$ = 8 mb

# J/Ψ dissociation cross sections with π, ρ, K and K* mesons

## Phase-space model for charmonium + meson dissociation

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

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




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

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

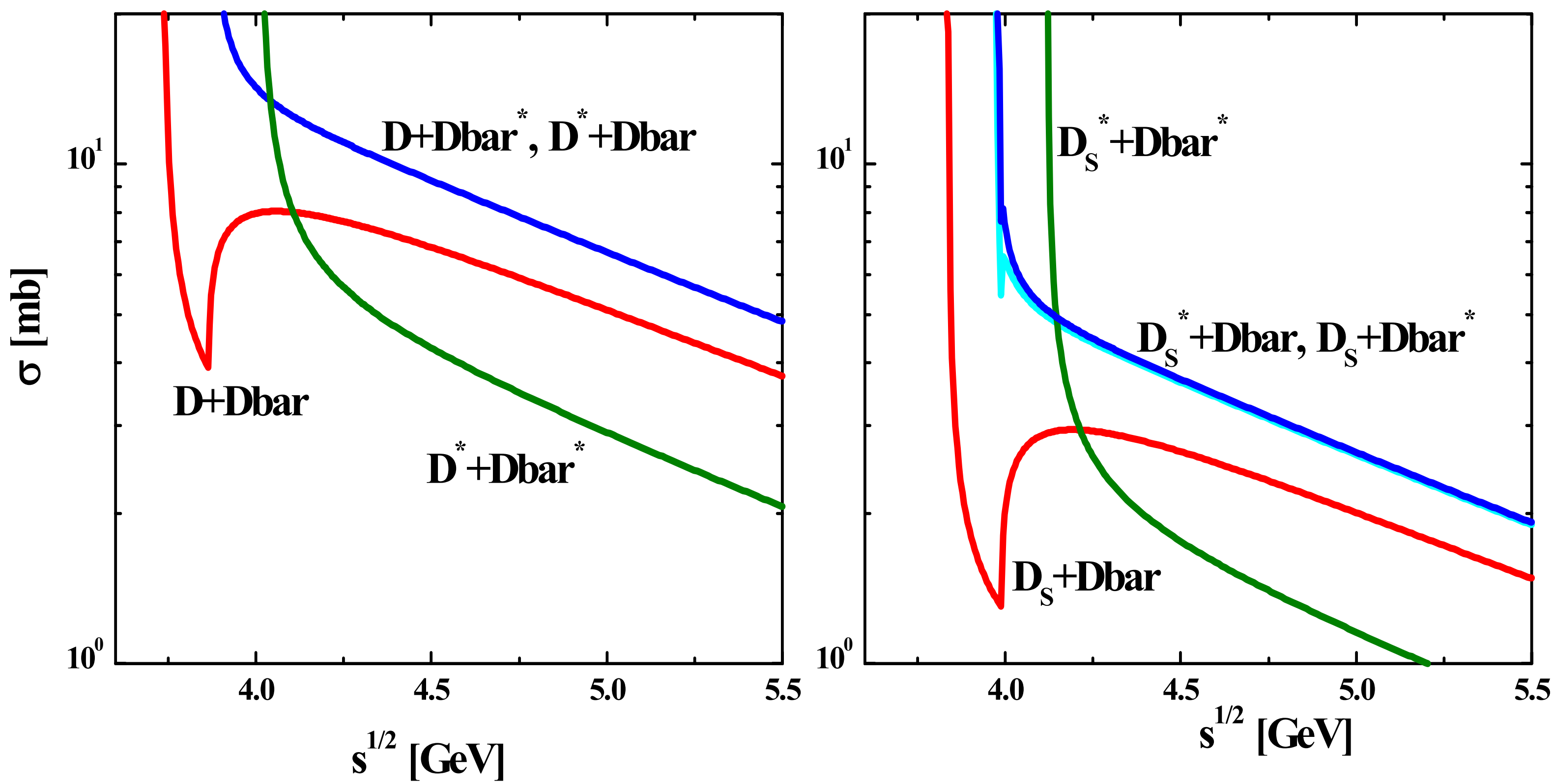
$$|\tilde{M}_i|^2 = \frac{1}{3}|M_i|^2 \quad \text{for} \quad (K,K^*) + (c\bar{c})_i \to D_s + \bar{D}, \quad \bar{D}_s + D$$

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

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

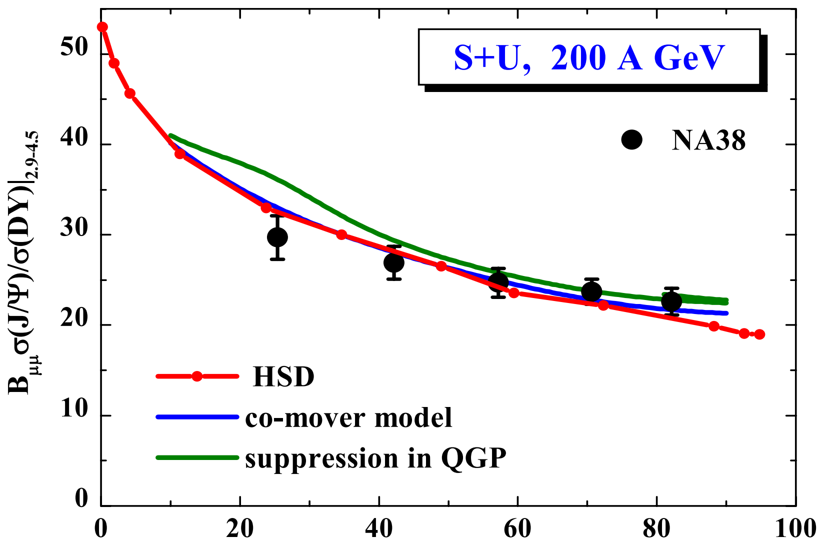
$$\text{set2}: \quad |M_{J/\Psi}|^2 = |M_{\chi_c}|^2 = |M_0|^2, \quad |M_{\Psi'}|^2 = 1.5\ |M_0|^2.$$

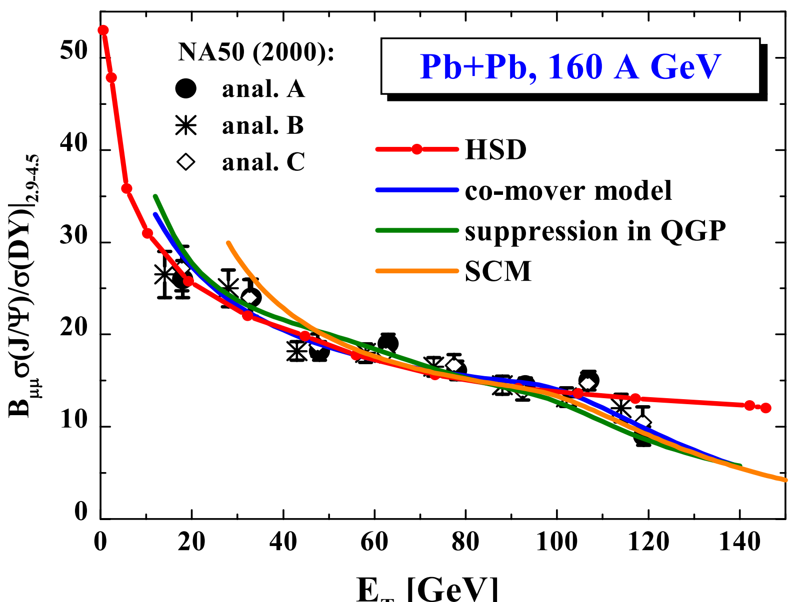
# J/Ψ recombination cross sections by D/Dbar interactions with π, ρ, K and K* mesons




Inverse cross sections determined by detailed balance!

# J/Ψ suppression in S+U and Pb+Pb at SPS




**Models:**

- Comover model in the transport approach – HSD/UrQMD

- Comover model in the Glauber approach:

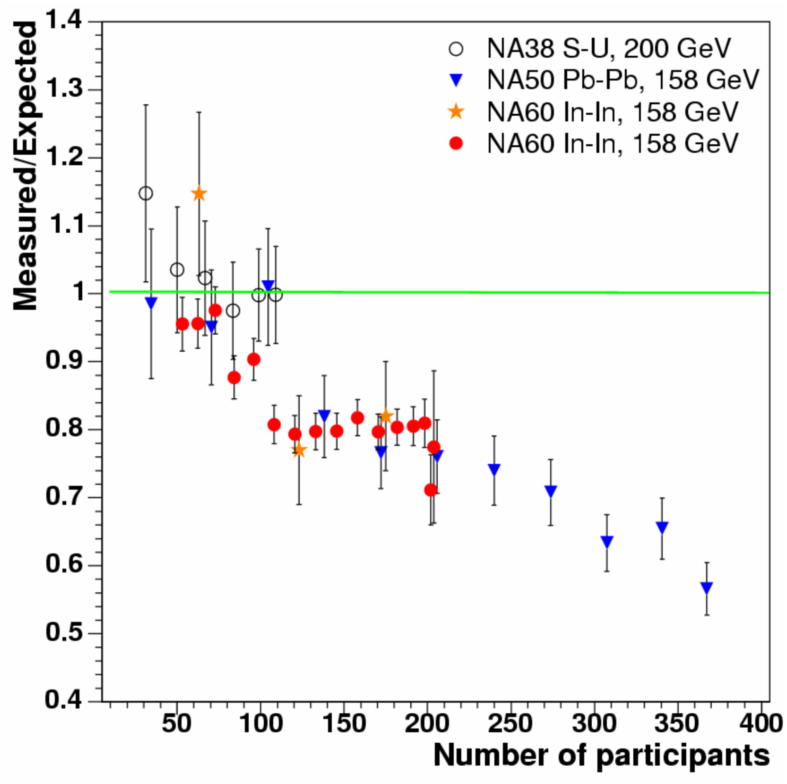
(1) without transition to QGP:
Charmonia suppression increases gradually with energy density [Capella et al.]

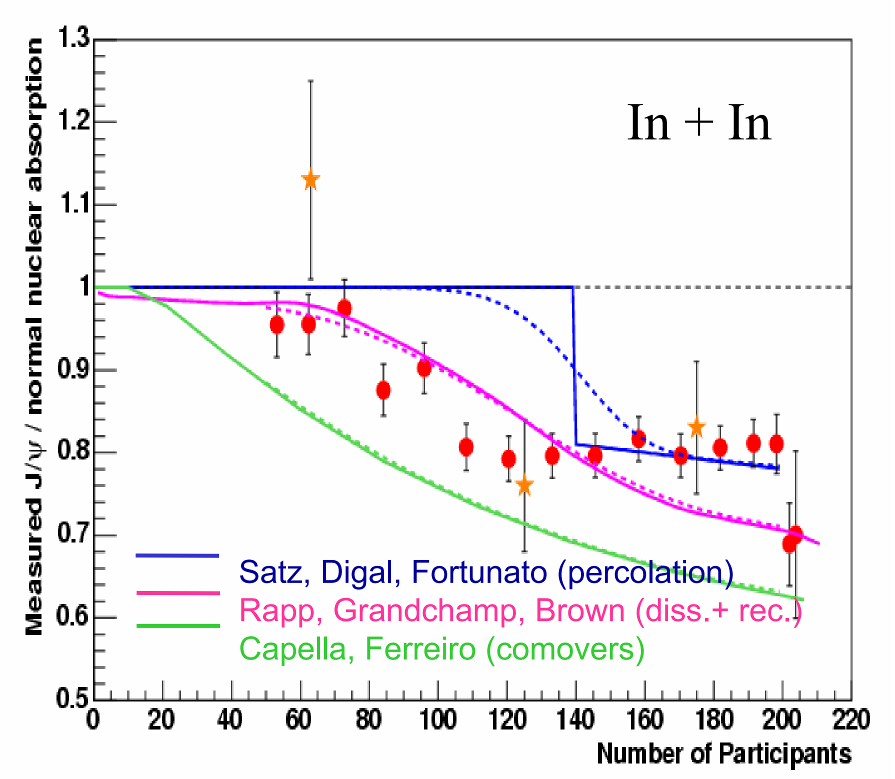
(2) with transition to QGP:
Charmonia suppression sets in abruptly at threshold energy densities, where $\chi_C$ is melting, J/Ψ is melting [Blaizot et al.]

- Statistical coalescence model (SCM) [Kostyuk et al.]

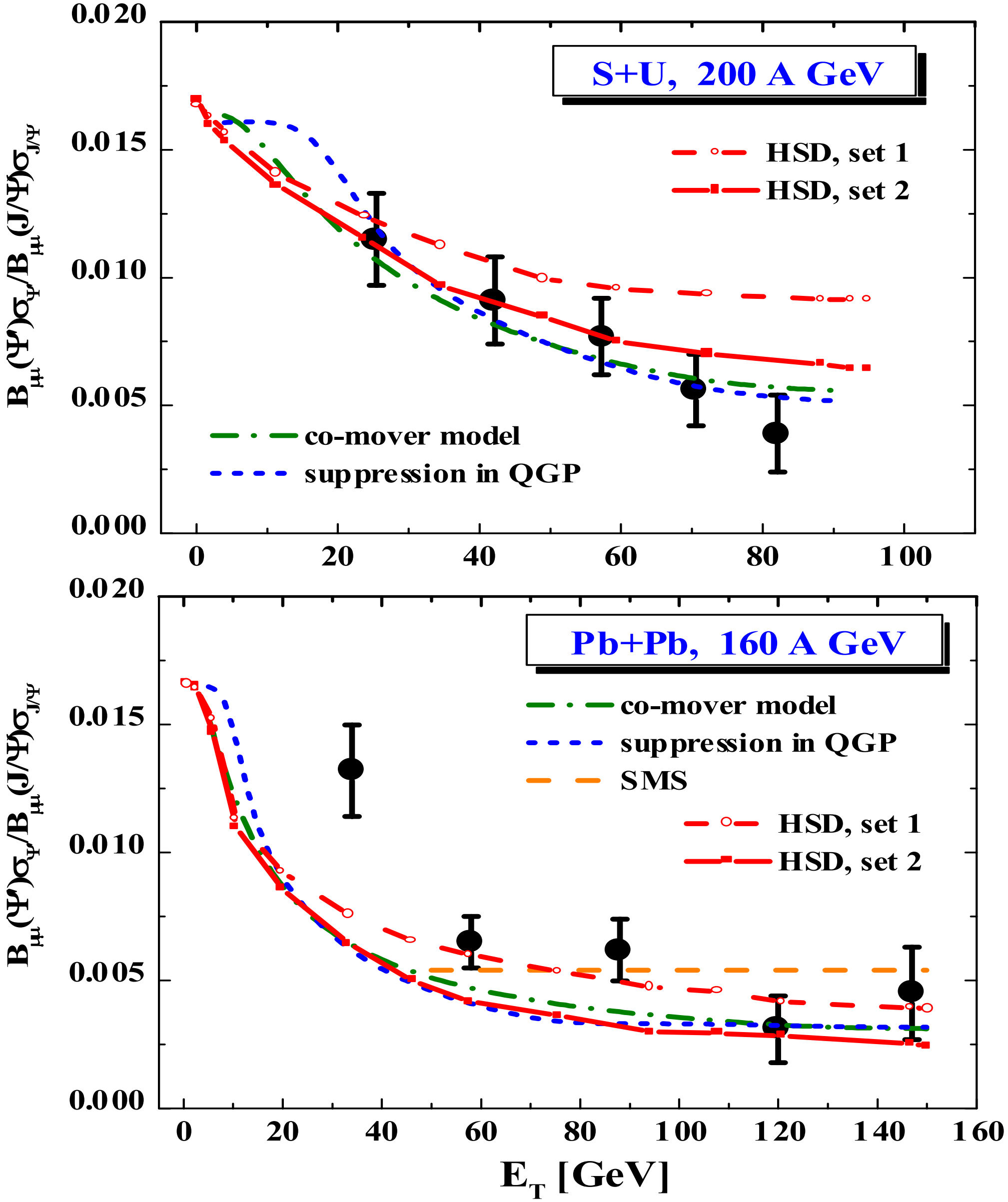
PRC 69 (2004) 054903

# J/Ψ suppression in In+In and Pb+Pb at SPS



# Ψ' suppression in S+U and Pb+Pb at SPS

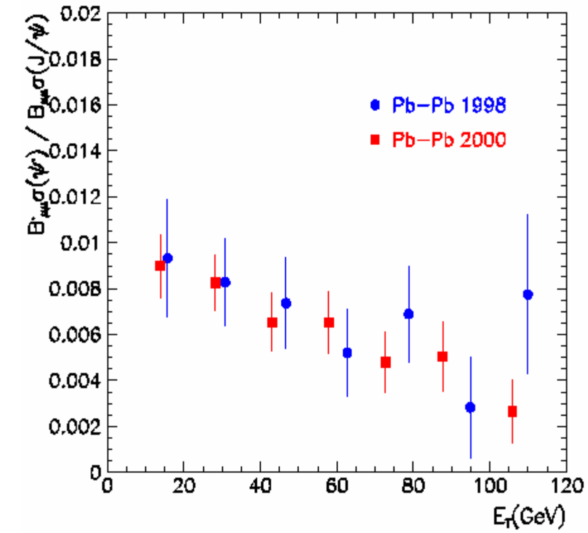



Matrix element for
Ψ' + mesons <-> D+Dbar

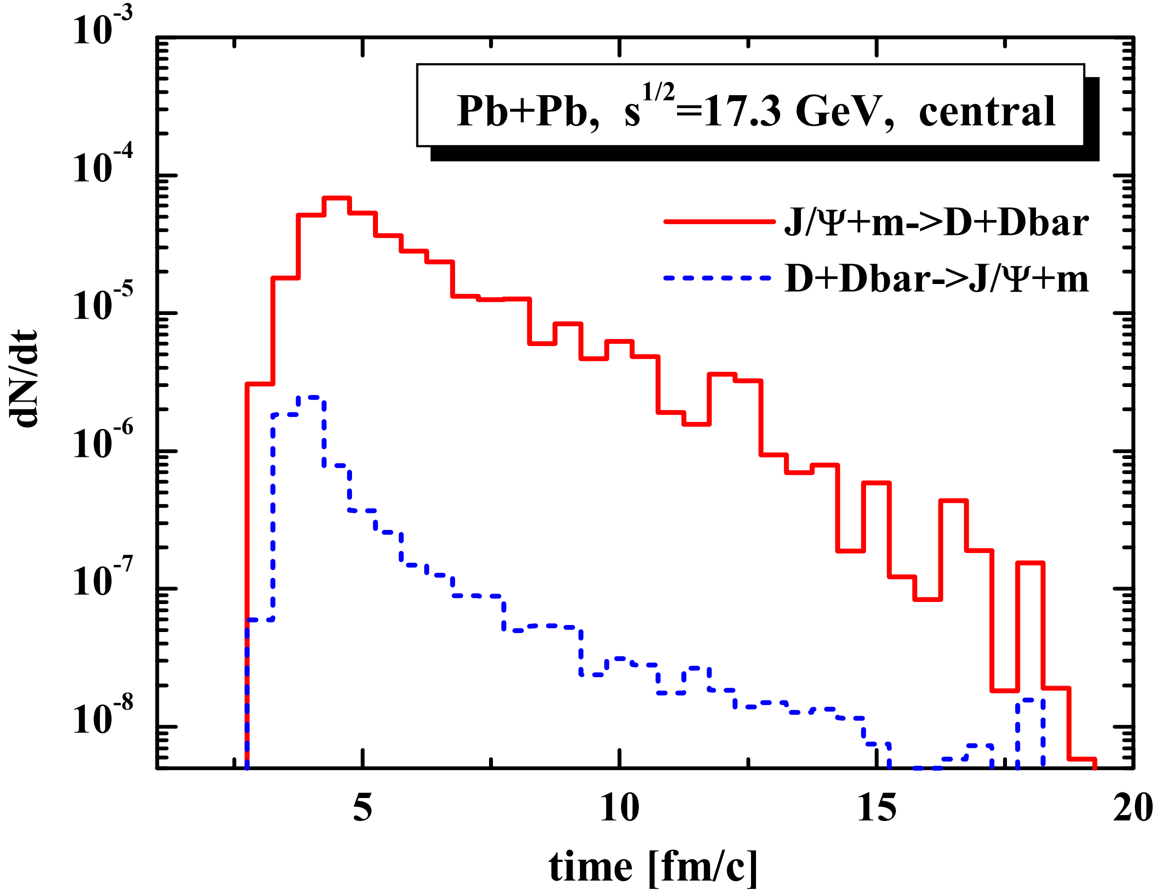
Set 1:
$|M_{J/\Psi}|^2=|M_{\chi_C}|^2=|M_{\Psi'}|^2=|M_0|^2$

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

$|M_{\Psi'}|^2= 1.5\ |M_0|^2$

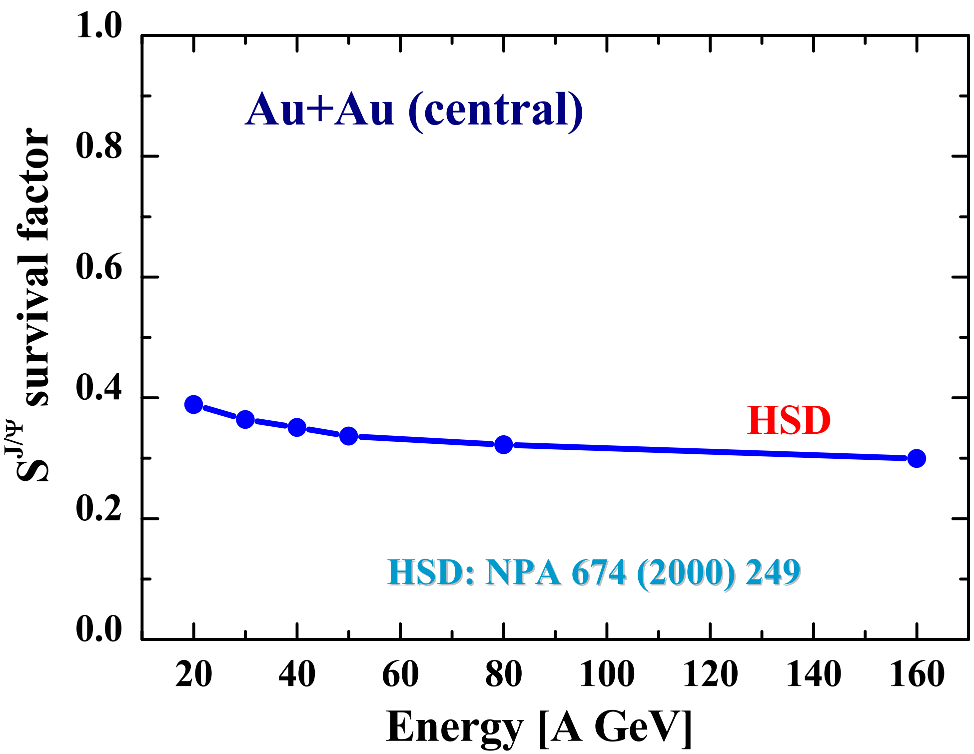


# Time dependence of the rate of J/Ψ absorption by mesons and recreation by D-Dbar annihilation in Pb+Pb at SPS




At SPS (and FAIR) recreation of J/Ψ by D-Dbar annihilation is negligible !

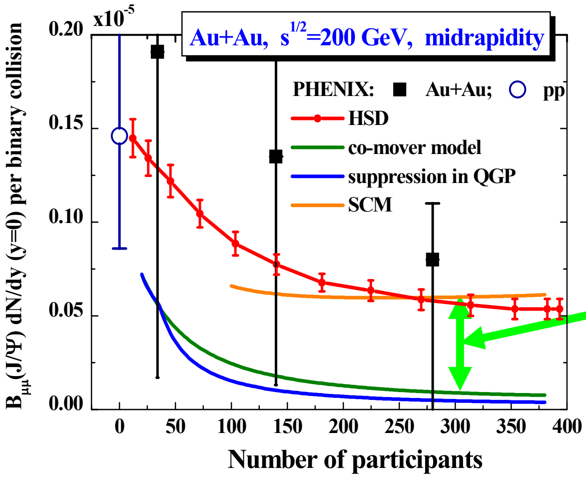
# J/Ψ suppression in Au+Au at FAIR and SPS

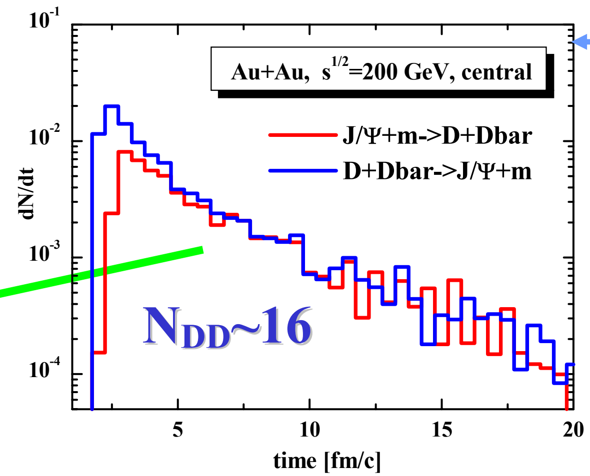



**is dominated by dissociation with baryons;**

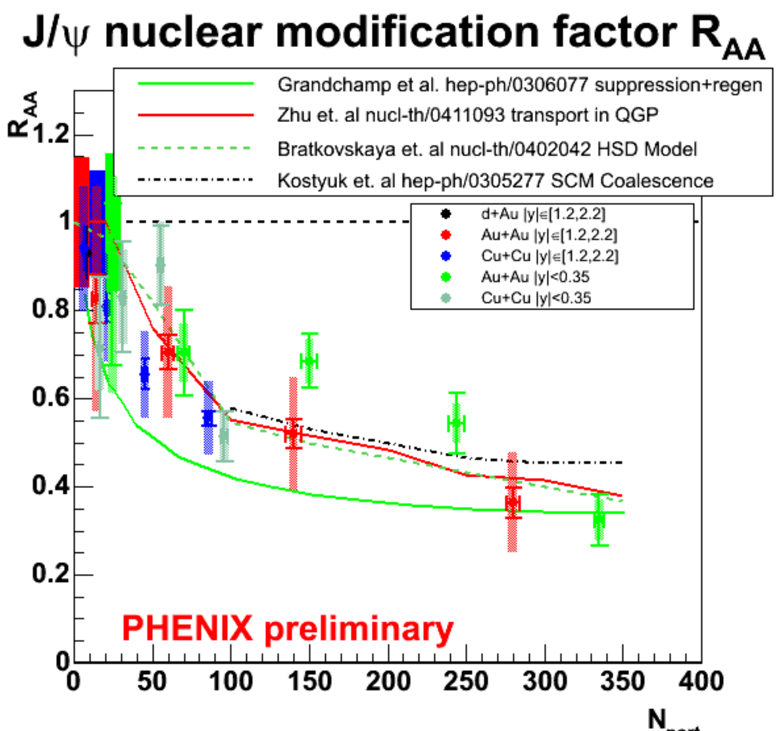
**comover channels increase with bombarding energy !**

# 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



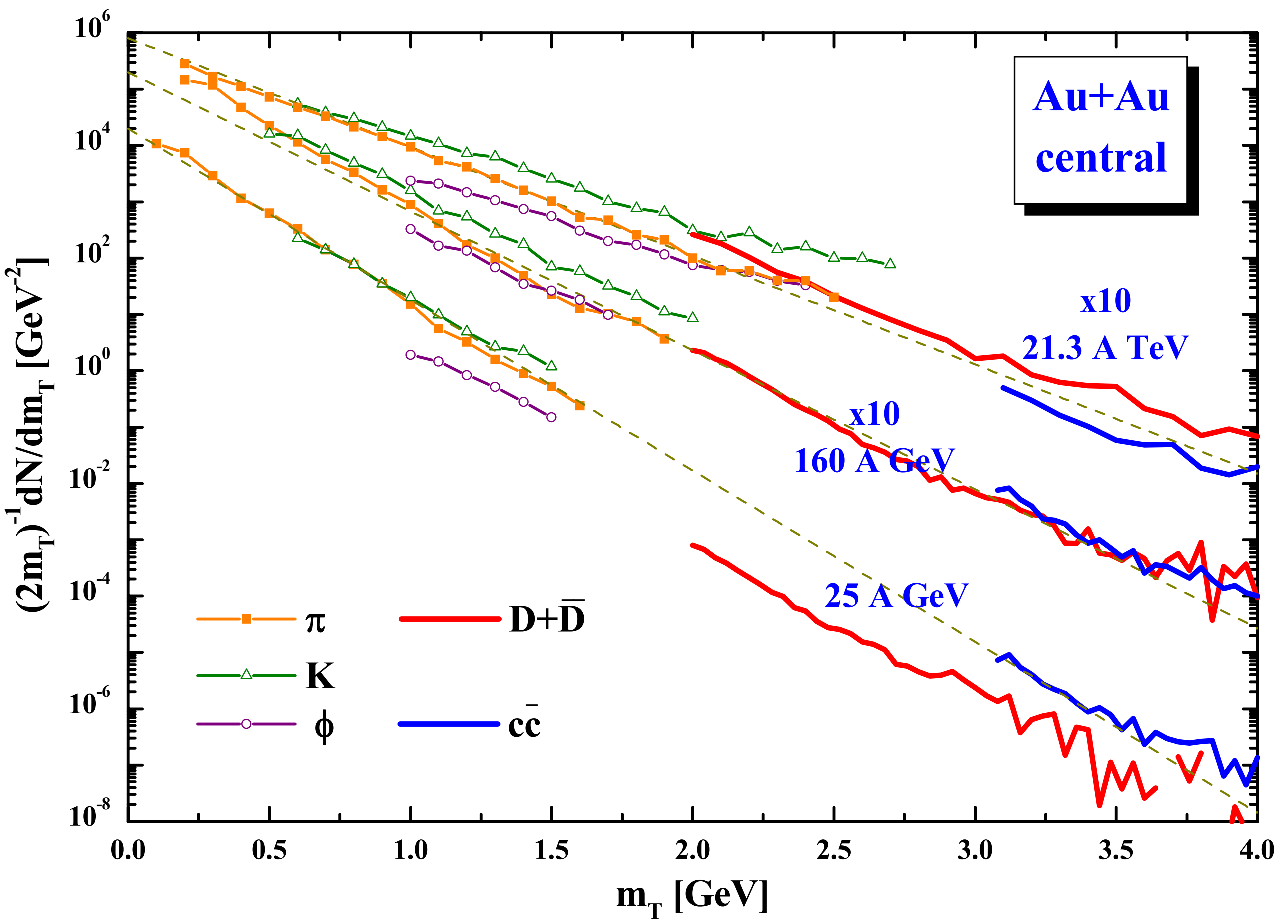

At RHIC the recreation of J/Ψ by D+Dbar annihilation is important !

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

HSD: PRC 69 (2004) 054903

# Open charm:
# D/Dbar mesons

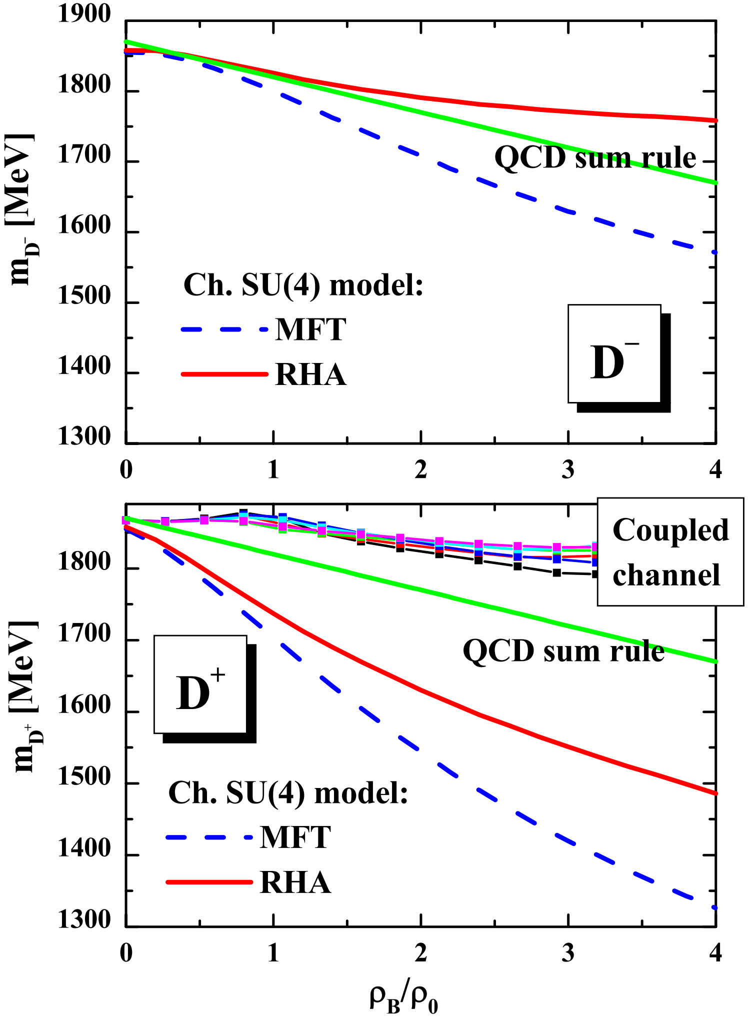
# Meson transverse mass spectra from central Au+Au

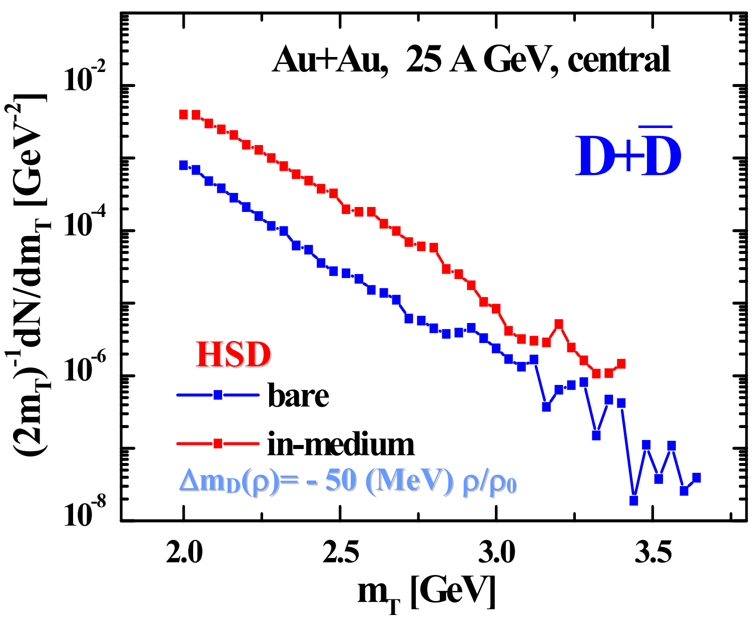



- Without rescattering - there is a rough $m_T$ scaling of all produced mesons
- With rescattering – ‚violation' of $m_T$ scaling
- Note: in-medium effects change the slope of the $m_T$ spectra

HSD: NPA 691 (2001) 753

# 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

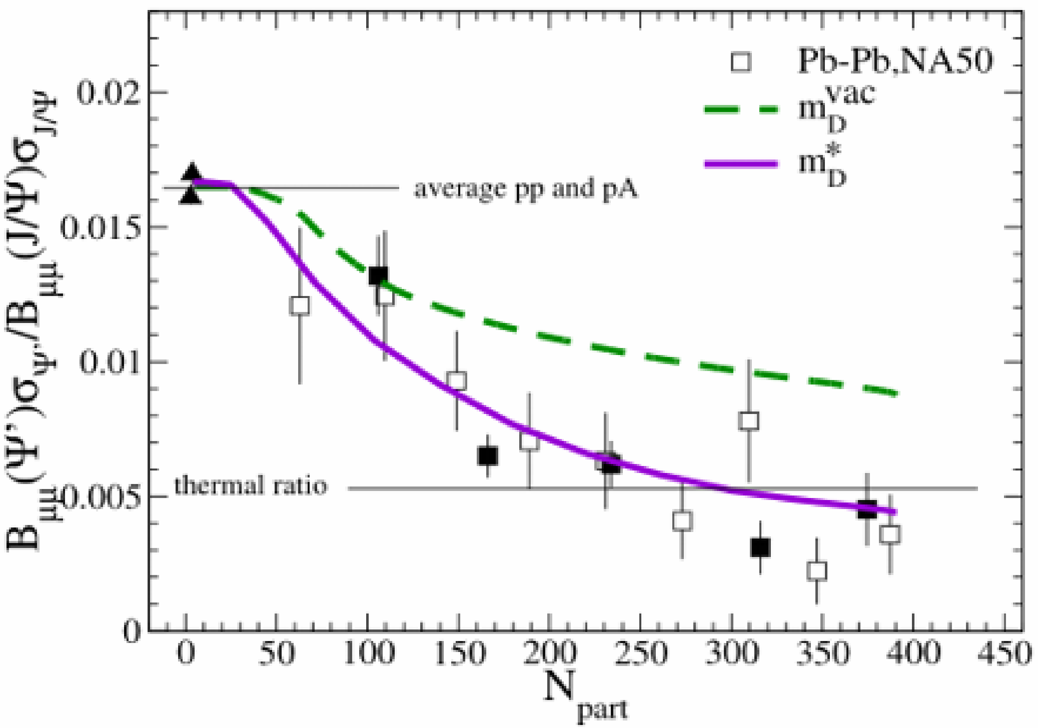
QCD sum rule: Hayashigaki, PLB487 (2000) 96

Coupled channel: Tolos et al., EPJ C43 (2005) 761

HSD: NPA691 (2001) 753

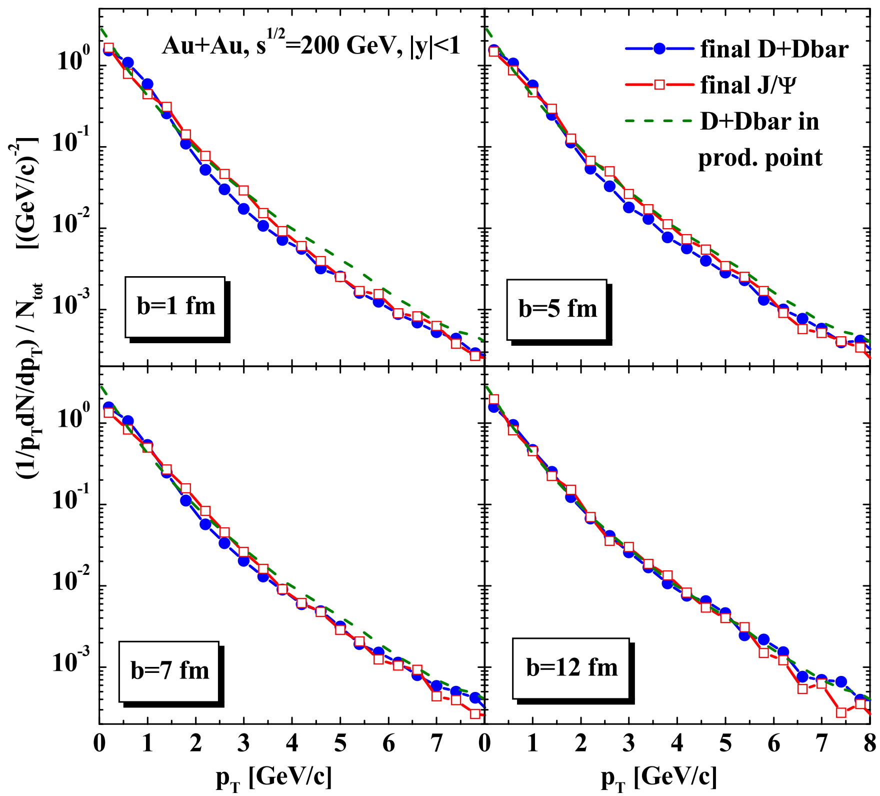
# D/Dbar in-medium effects -> J/Ψ and Ψ' suppression

In-medium reduction of D/Dbar masses might have a strong influence on Ψ' suppression due to the opening of the Ψ'->D Dbar decay channel [Rapp, Brown et al.]

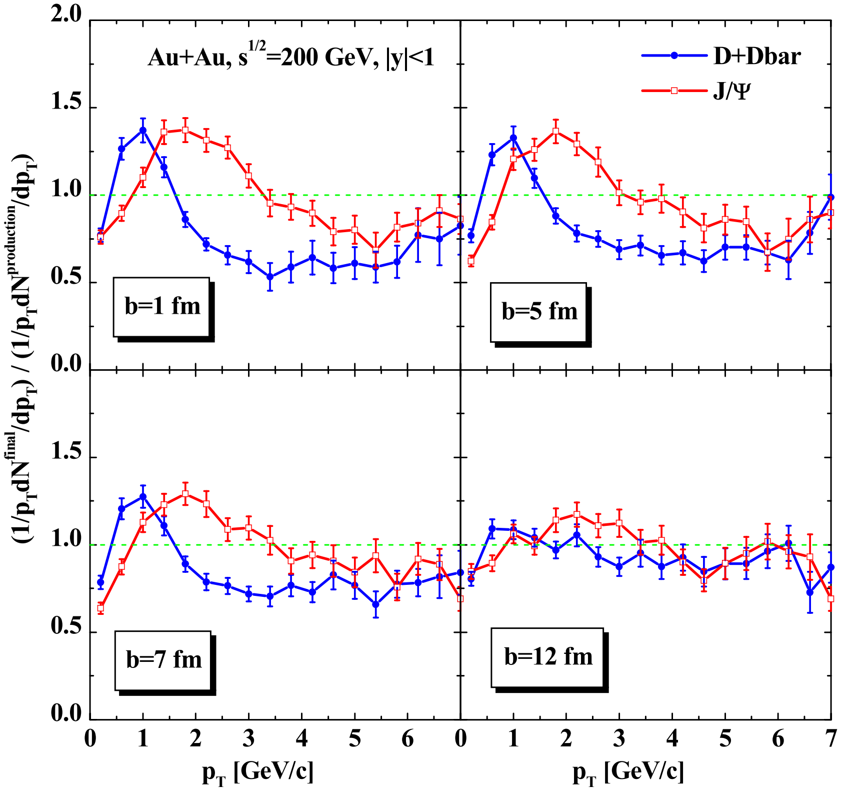


# Transverse momentum spectra at RHIC
## - centrality dependence -

$p_T$ spectra at midrapidity



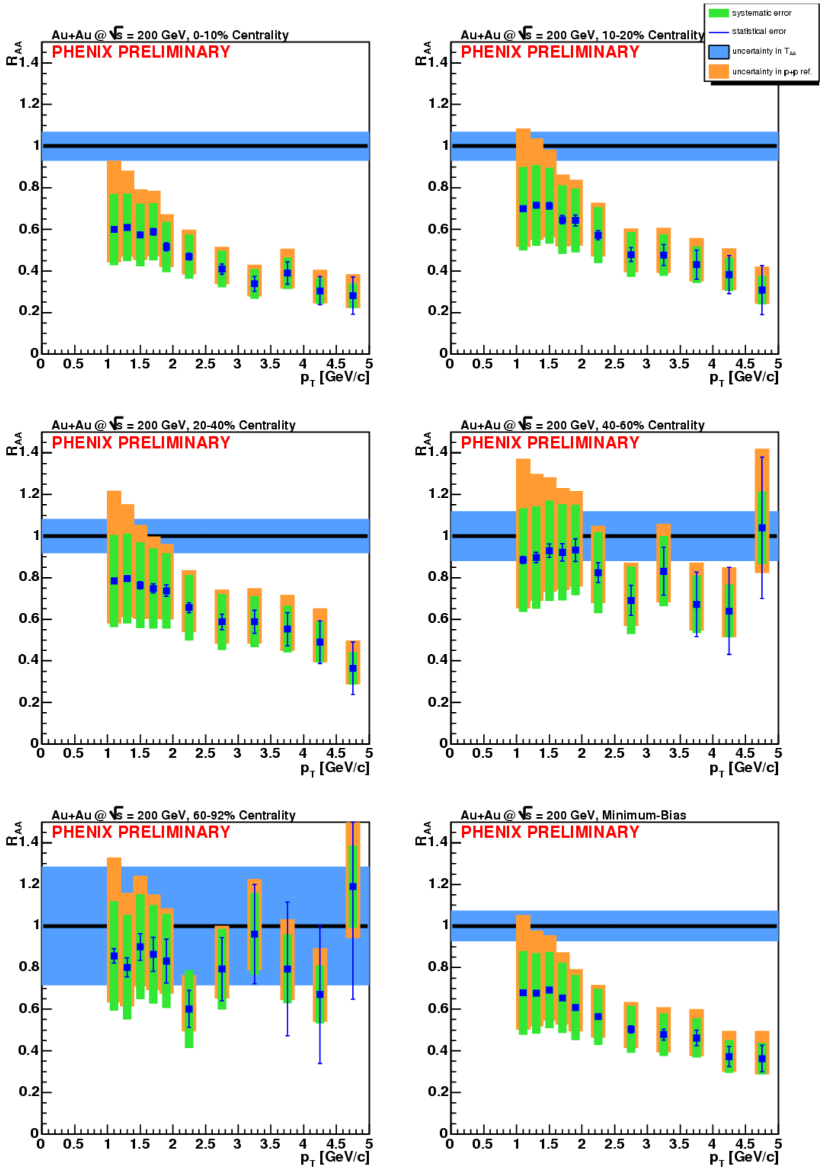

nuclear modification versus $p_T$

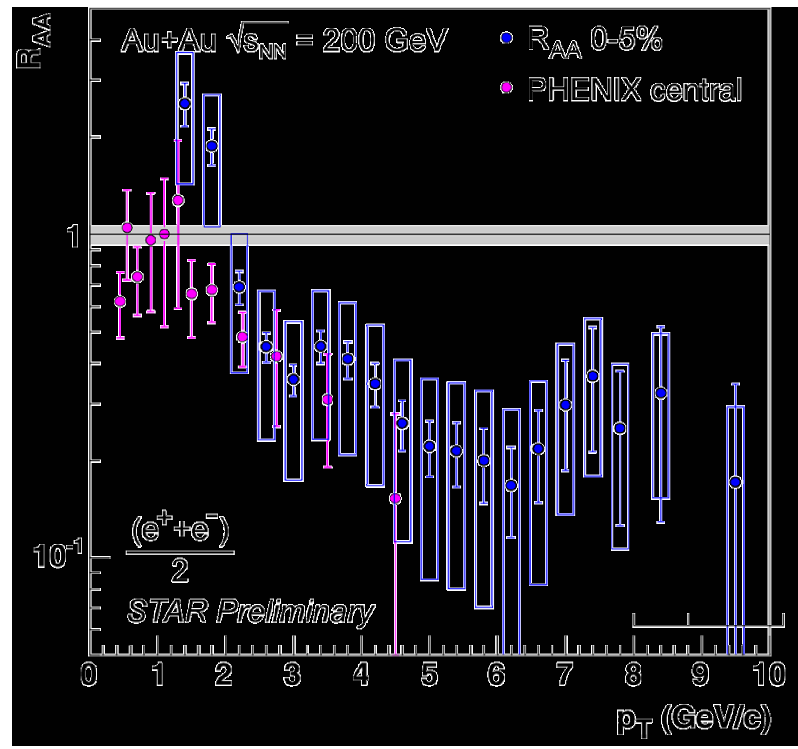



High $p_T$ suppression from ‚hadronic‘ rescattering is not strong enough !

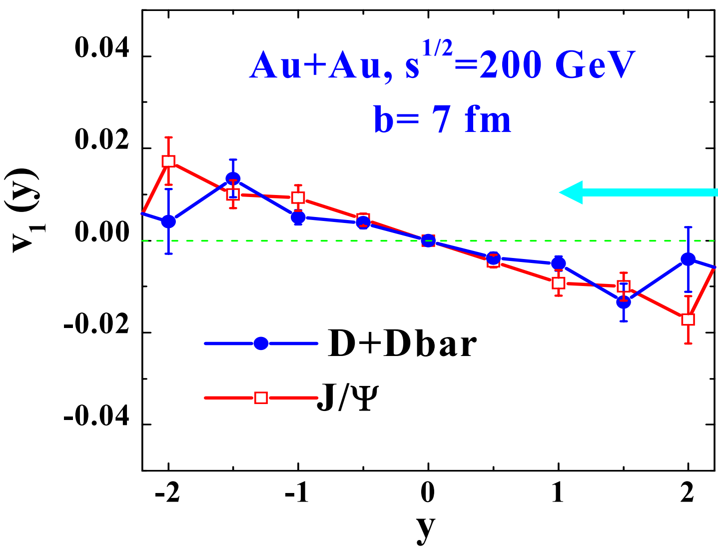
HSD: PRC 71 (2005) 044901

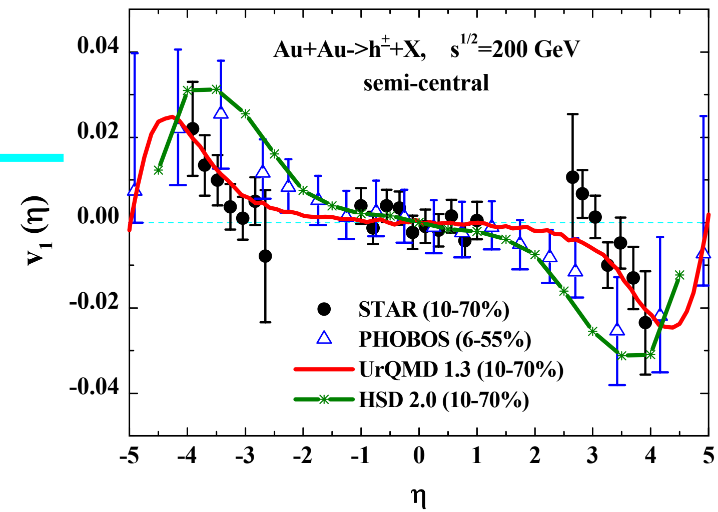
# Non-photonic leptons from PHENIX and STAR

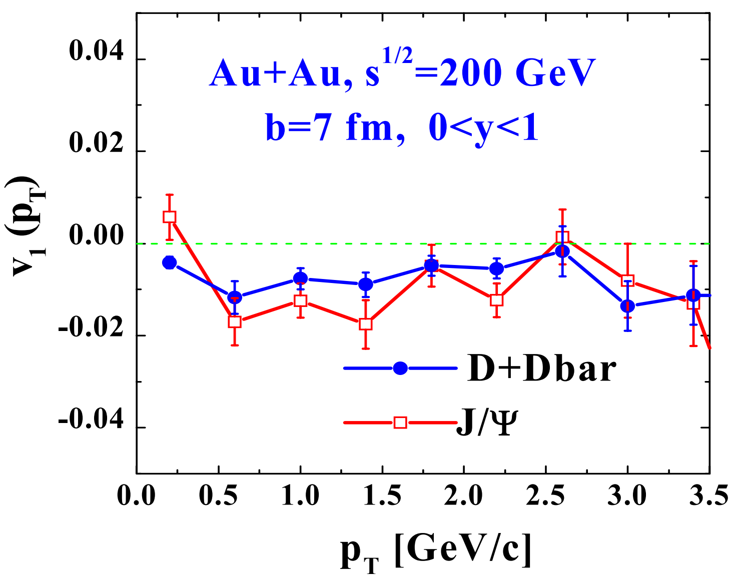


# Collective flow: $v_1$ of D+Dbar and J/Ψ from Au+Au versus $p_T$ and y at RHIC



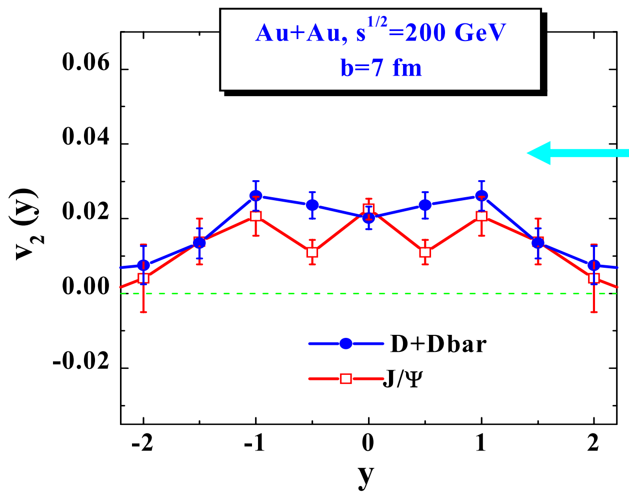



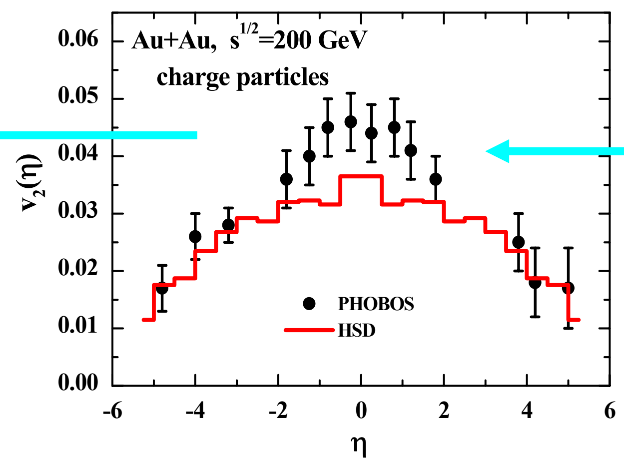




**D-mesons and J/Ψ follow roughly the charged particle flow around midrapidity !**

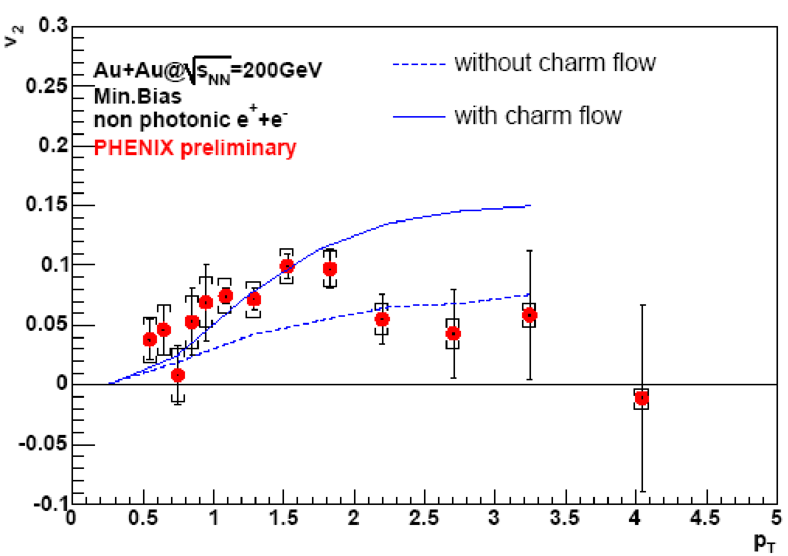
PRC 71 (2005) 044901

# Collective flow: $v_2$ 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 $v_2 < 3\%$
- PHENIX data show very large collective flow of D-mesons $v_2 \sim 10\%$ for $1 < p_T < 2$ GeV/c !

=> strong initial flow of non-hadronic nature!

PRC 71 (2005) 044901

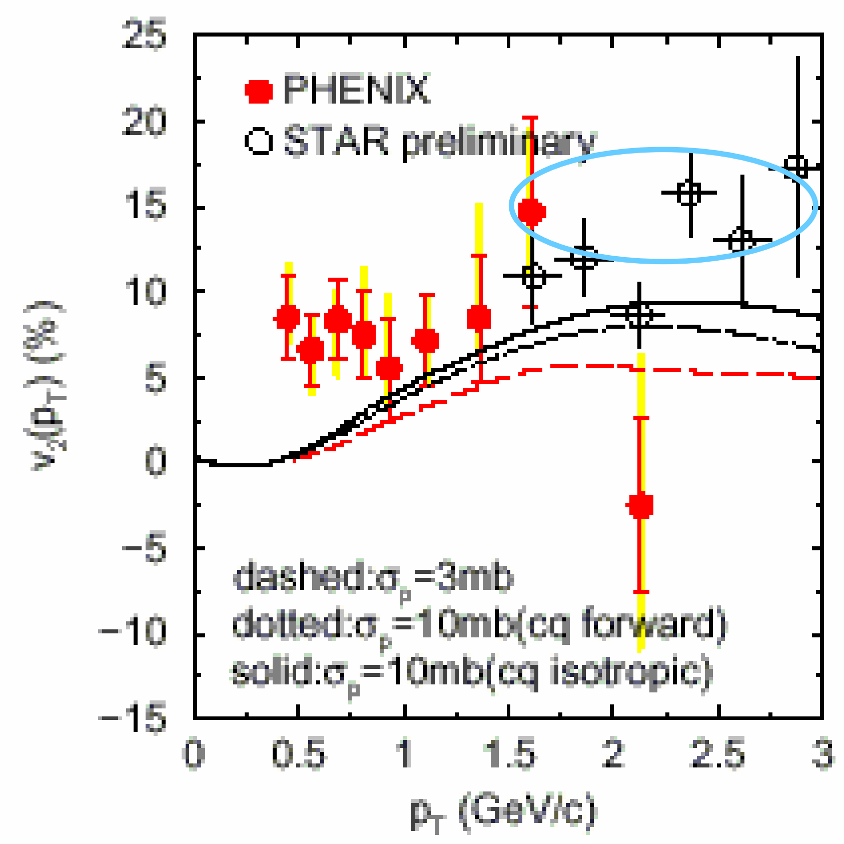
# AMPT model: $v_2$ of D+Dbar from Au+Au versus $p_T$ at RHIC

- **AMPT multi-phase transport model:**
  **(B. Zhang, L.-W. Chen and C.-M. Ko)**

**Minijet partons from hard proceses (ZPC- Zang's parton cascade) + strings from soft processes (HIJING)**

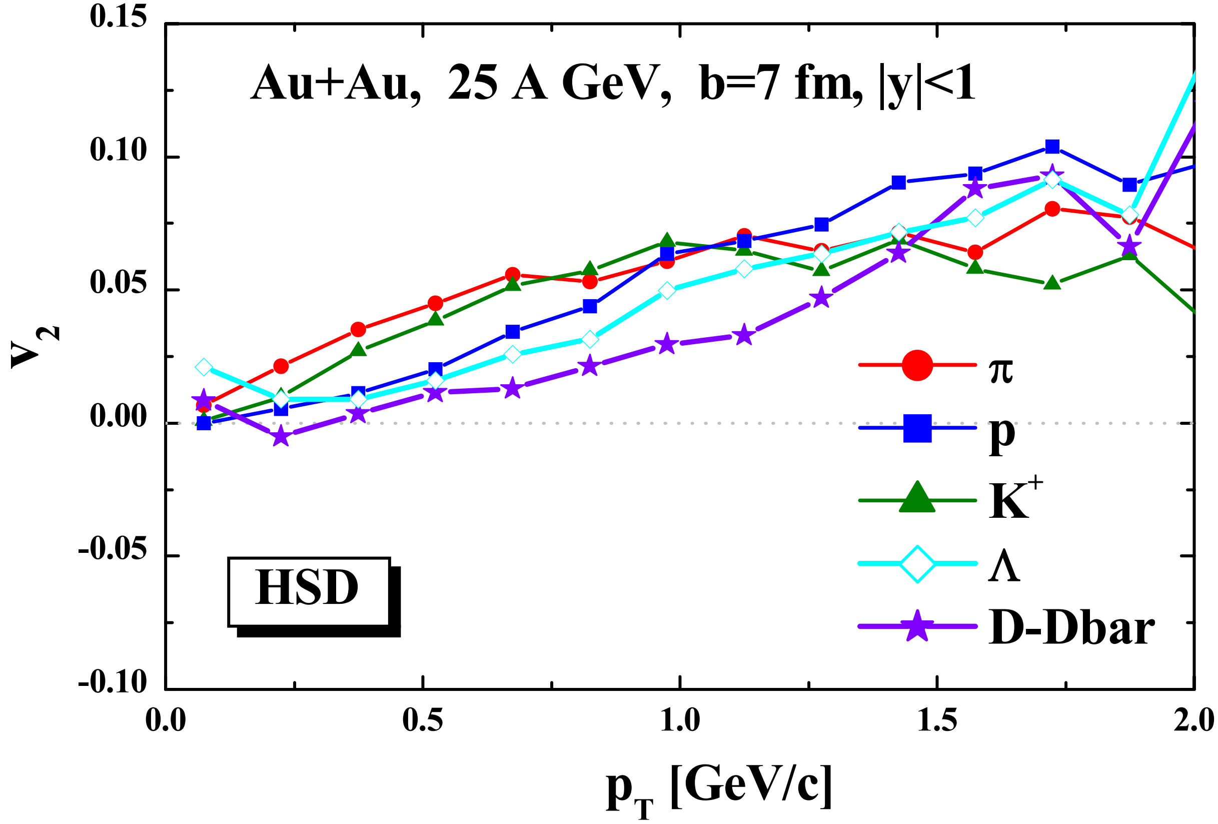
- **Parton (q, qbar) scattering cross sections (3-10 mb)**

**„To describe the large electron elliptic flow observed in available experimental data requires a charm quark scattering cross section that is much larger than given by perturbative QCD"**
**[PRC 72 (2005) 024906]**




**QGP is NOT an ideal gas as described by pQCD!**

# Collective flow: $v_2$ of D+Dbar and hadrons at FAIR

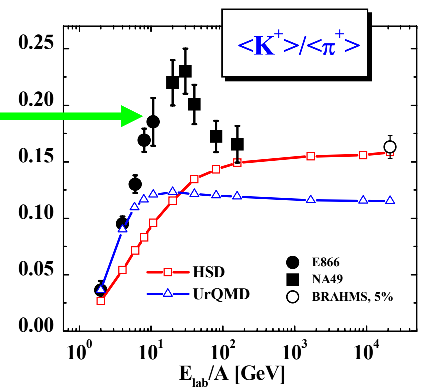



Mass ordering of elliptic flow according to hadronic interactions

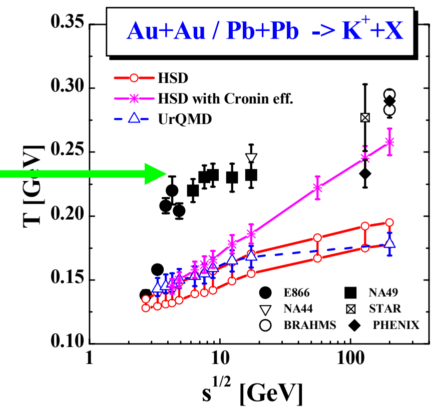
# Summary

## Strangeness signals of QGP:

,horn' in $K^+/\pi^+$

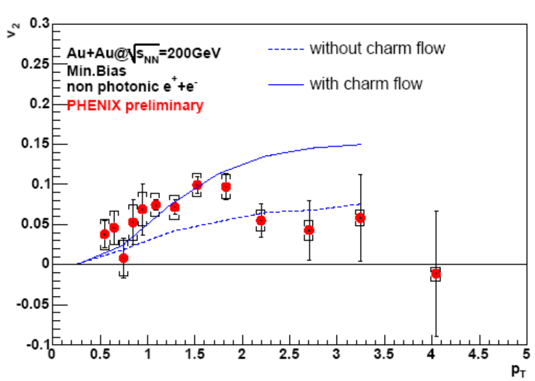



,step' in slope T




Exp. data are not reproduced in terms of hadron-string picture => evidence for nonhadronic degrees of freedom

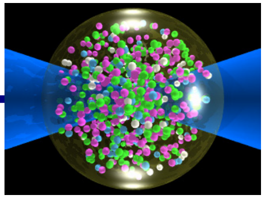
- ## Charm signals of QGP:




PHENIX at RHIC observed very strong collective flow $v_2$ of charm D-mesons

=> evidence for strong nonhadronic interactions in the very early phase of the reaction

# Outlook



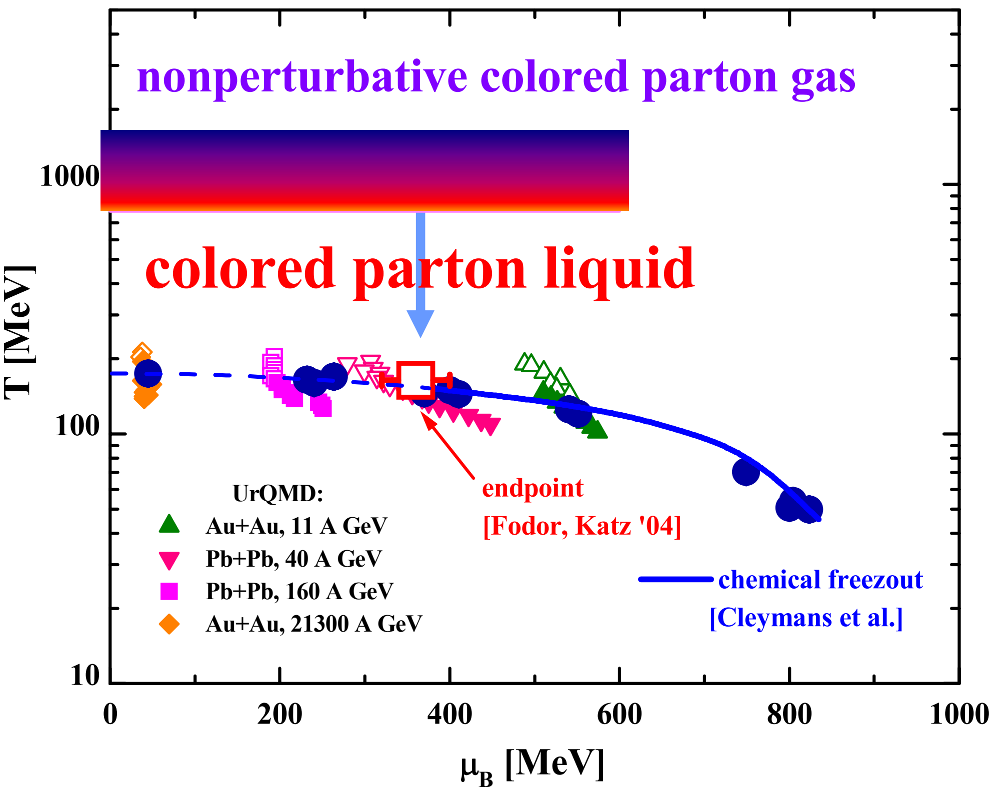
**The Quark-Gluon-Plasma is there!**
**But what are the properties of this phase ?!**

**State of the art 2005:**
**QGP is a strongly interacting and almost ideal „color liquid“ !**
**PRL 94 (2005) 172301**

**FAIR is a good place to study the tri-critical point !**

**Open charm and charmonia qualify as probes for the new medium !**

**New phase diagram of QCD**



# Thanks to the coauthors

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Andrej Kostyuk

Andre Peshier

Horst Stöcker

Kai Gallmeister

Nu Xu

**HSD & UrQMD Collaboration**

HSD, UrQMD - open codes:

http://www.th.physik.uni-frankfurt.de/~brat/hsd.html

http://www.th.physik.uni-frankfurt.de/~urqmd.html