# Charmonium masses in antiproton-nucleus reaction

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- Motivation
- Transport
- Bootstrap approach
- $\bar{p}$A reaction (PANDA)
- Summary

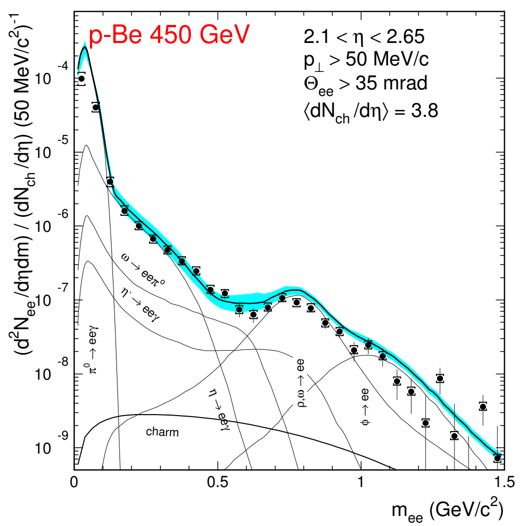
# Gluon condensate in matter

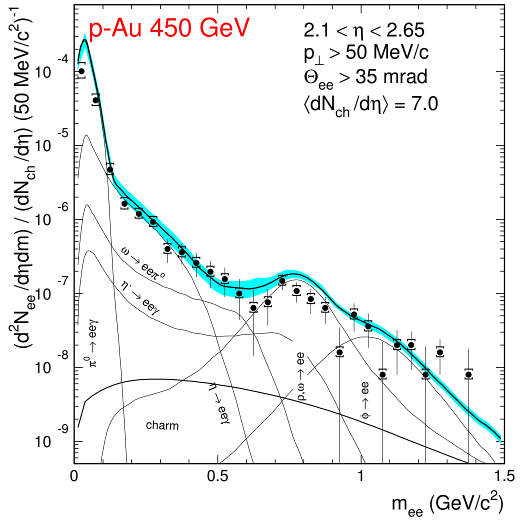
- In QCD the condensates like $m_q < \bar{q}q >$ quark condensate and $< \alpha_s/\pi G^2 >$ gluon condensate are fundamental quantities
- They are known in vacuum, in matter only the first correction terms linear in density or quadratic in temperature are known
- the masses of hadrons made of light quarks changes mainly due to the (partial) restauration of chiral symmetry (its order parameter $m_q < \bar{q}q >_\rho$), those made of heavy quarks are sensitive on the changes of gluon condensate
- measuring the charmonium masses in matter may tell us what is the gluon condensate in matter

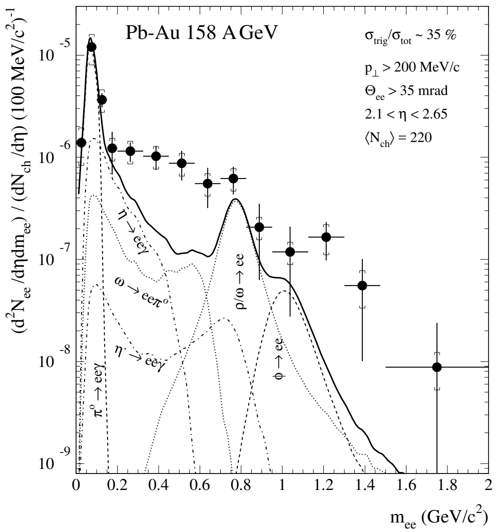
## Why dileptons

- measured (DLS, HADES, CERES, NA60, STAR, ALICE)
- without final state interaction
- vector mesons decay to dileptons $\rightarrow$ vector mesons in matter
- much better then photons:
  mass can be used to distinguish between the different sources
- interesting results for p-nucleus (KEK) and nucleus-nucleus (SPS,RHIC,LHC) collisions

# CERES data




G. Agakichiev *et al.*
Eur. Phys. J. C4 (1998) 231

G. Agakichiev *et al.*
Phys. Lett. B422 (1998) 405

# Dilepton production in NN

- Direct decay of vector mesons and $\eta$
- Dalitz-decay of $\pi$, $\eta$ and $\omega$
- Dalitz-decay of baryon resonances
  Zetenyi, Wolf, Phys. Rev, C67 (2003) 044002;
  Heavy Ion Phys. 17 (2003) 27
- pn bremsstrahlung not negligible
- Drell-Yan
- Open charm
- Charmonium decay

# BUU

- Boltzmann-Ühling-Uhlenbeck equation

$$\frac{\partial F}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial F}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial F}{\partial \mathbf{p}} = \mathcal{C}, \quad H = \sqrt{(m_0 + U(\mathbf{p},\mathbf{x}))^2 + \mathbf{p}^2}$$

- potential: momentum dependent, soft: K=215 MeV

  $U^{nr} = A\frac{n}{n_0} + B\left(\frac{n}{n_0}\right)^\tau + C\frac{2}{n_0}\int\frac{d^3p'}{(2\pi)^3}\frac{f_N(x,p')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2},$

  S. Teis, W. Cassing, M. Effenberger, A. Hombach, U. Mosel, Gy. Wolf, Z. Phys. A359 (1997) 297-304,

  Gy. Wolf et al., Phys.Atom.Nucl. 75 (2012) 718-720

- testparticle method

  $F = \sum_{i=1}^{N_{test}} \delta^{(3)}(\mathbf{x} - \mathbf{x}_i(t))\delta^{(4)}(p - p_i(t)).$

# Collision term

- NN $\leftrightarrow$ NR, NN $\leftrightarrow$ $\Delta\Delta$
- baryon resonance can decay via 9 channels
  R $\leftrightarrow$ N$\pi$, N$\eta$, N$\sigma$, N$\rho$, N$\omega$, $\Delta\pi$, N(1440)$\pi$, K$\Lambda$, K$\Sigma$
- 24 baryon resonances + $\Lambda$ and $\Sigma$ baryons
  $\pi, \eta, \sigma, \rho, \omega$ and kaons
- $\pi\pi \leftrightarrow \rho$, $\pi\pi \leftrightarrow \sigma$, $\pi\rho \leftrightarrow \omega$
- for resonances: energy dependent with
- $\frac{d\sigma^{X \to NR}}{dM_R} \sim A(M_R)\lambda^{0.5}(s, M_R^2, M_N^2)$

## Spectral equilibration

- medium effects on the spectrum of hadrons (vector mesons)
- how they get on-shell (energy-momentum conservation)
- Field theoretical method (Kadanoff-Baym equation)
  B. Schenke, C. Greiner, Phys.Rev.C73:034909,2006
- Off-shell transport
  W. Cassing, S. Juchem, Nucl.Phys. A672 (2000) 417
  S. Leupold, Nucl.Phys. A672 (2000) 475
- Spectral equilibration: Markov or memory effect

# Off-shell transport

- Kadanoff-Baym equation for retarded Green-function
  Wigner-transformation, gradient expansion
- transport equation for $F_\alpha = f_\alpha(x,p,t)A_\alpha$
  $A(p) = -2ImG^{ret} = \frac{\hat{\Gamma}}{(E^2-\mathbf{p}^2-m_0^2-\mathrm{Re}\Sigma^{ret})^2+\frac{1}{4}\hat{\Gamma}^2}$,

  W. Cassing, S. Juchem, Nucl.Phys. A672 (2000) 417
  S. Leupold, Nucl.Phys. A672 (2000) 475
- testparticle approximation

# Transport equations

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

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

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

- where $C_{(i)}$ renormalization factor

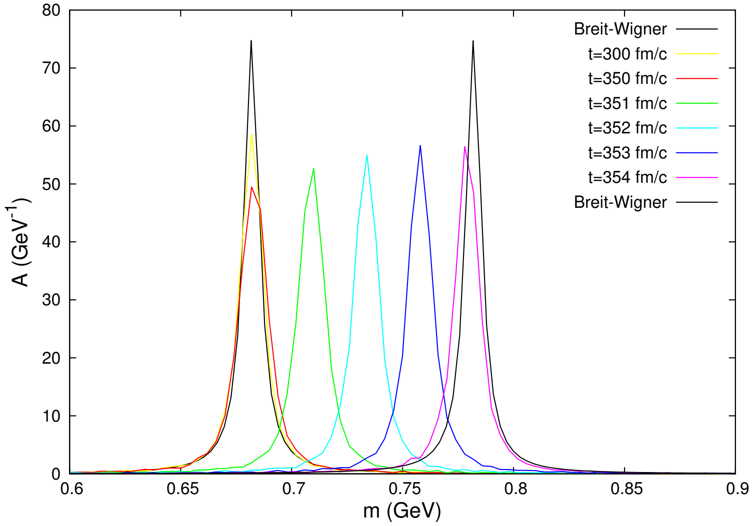
$$C_{(i)} = \frac{1}{2\epsilon_i} \left[ \frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{\partial}{\partial \epsilon_i} Im\Sigma^{ret}_{(i)} \right]$$

- the last equation for homogenous system can be rewritten as

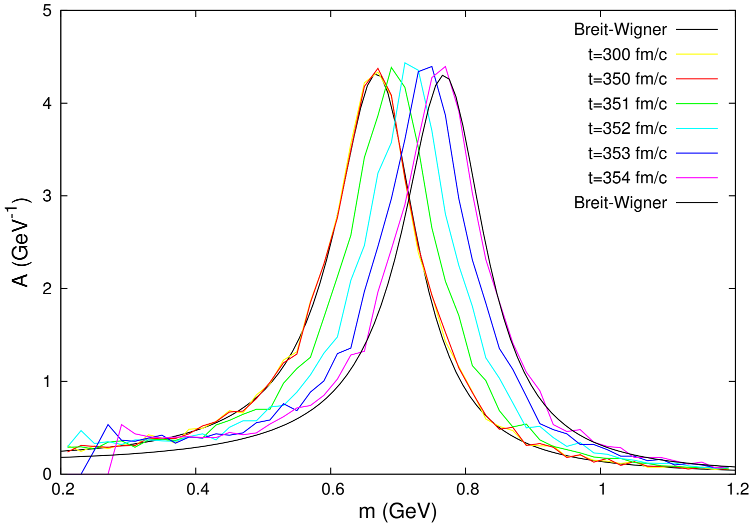
$$\frac{dM_i^2}{dt} = \frac{d(\epsilon_i^2 - P_i^2)}{dt} = \frac{dRe\Sigma^{ret}_{(i)}}{dt} + \frac{M_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{dIm\Sigma^{ret}_{(i)}}{dt}$$

# Evolution of mass distribution in a box

the vector meson masses are shifted linearly with density, and change the density linearly from $\rho_0$ to 0 in 4 fm/c:




$\omega$




$\rho$

## Statistical Bootstrap approach

Balassa, Kovács, Wolf, EPJA in press

- Estimate unknown cross sections of different hadronic reactions up to a few GeV in c.m.s energy.
- Our method incorporate that during the collision a compound system, a fireball, is formed and, through possible production of subsequent fireballs, this system decays into a specific final state.
- The probability of the resulting final state can be calculated from the corresponding phase space, the quark content of the final state, the density of states $\rho(m)$.

# Model

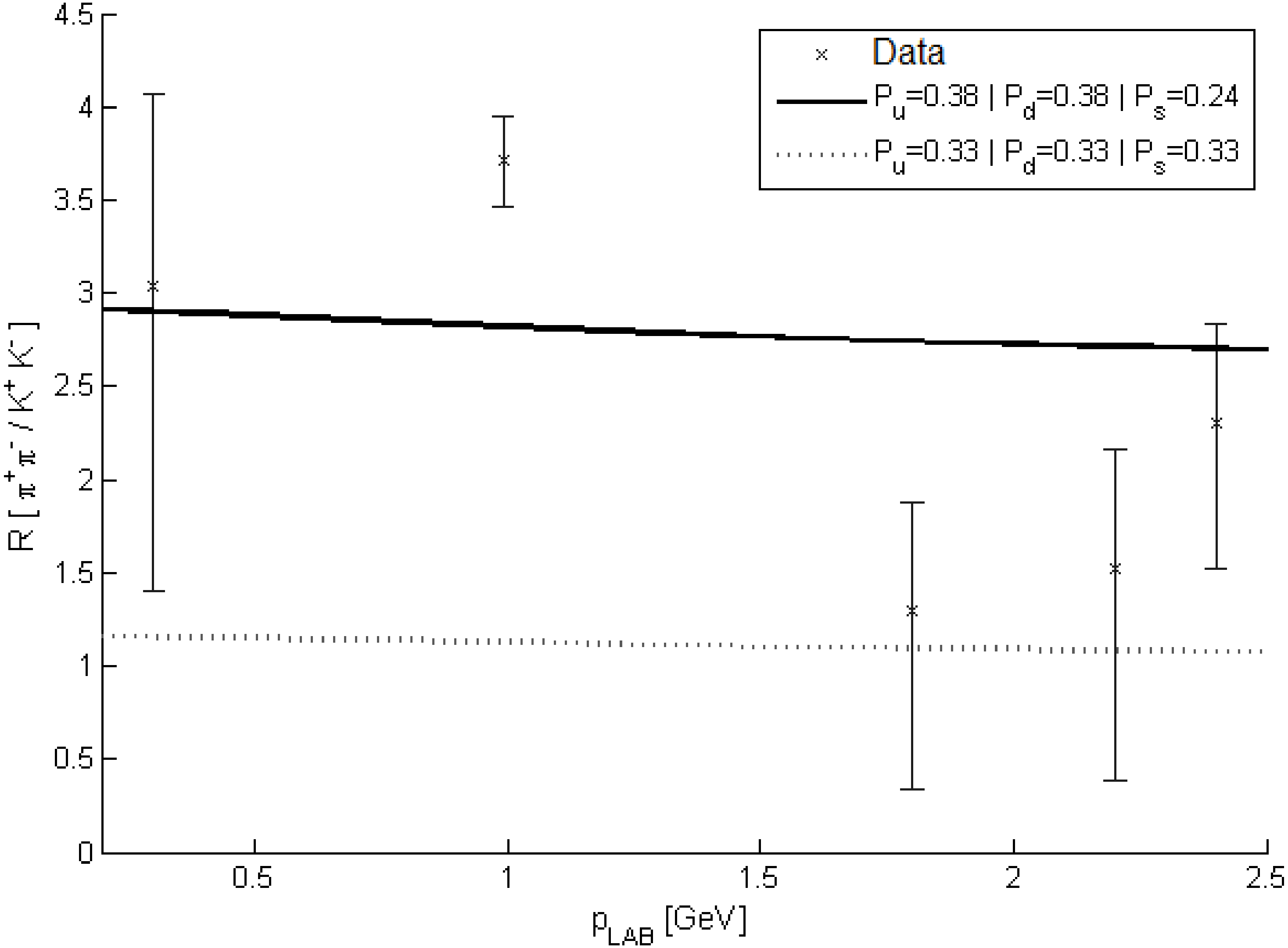
$$\sigma(M) = \left(\int \prod_{i=1}^{n} d^3p_i R(M, p_1, \ldots, p_n)\right) \times \left(\int \prod_{j=1}^{m} d^3k_j w(M, k_1, \ldots, k_m)\right)$$
$$= \sigma_{Tot}(M) \cdot W(M)$$

$$\sigma_{p\pi^- \to n\pi^+\pi^-} \equiv \frac{W_{n\pi^+\pi^-}}{W_{p\pi^-}} \frac{\sigma^{Tot}_{p\pi^-}}{\sigma^{Tot}_{p\pi^-}} \sigma_{p\pi^- \to p\pi^-} = \frac{W_{n\pi^+\pi^-}}{W_{p\pi^-}} \sigma_{p\pi^- \to p\pi^-}$$

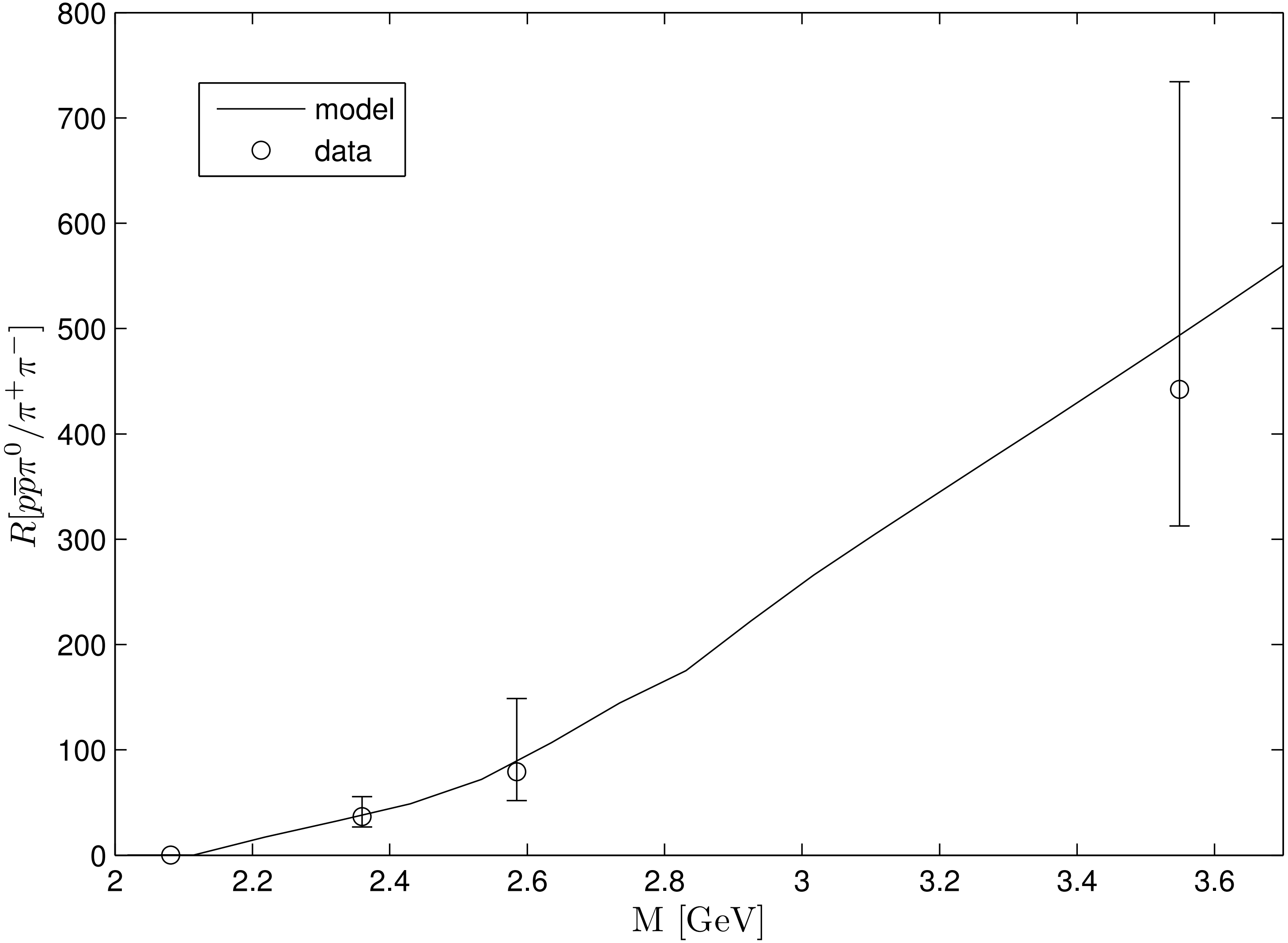
$$W_k^{n_1,\ldots,n_k}(M) = N(M) P_k^{fb}(M) C_Q(M)$$
$$\int_{x_{1,min}}^{x_{1,max}} \cdots \int_{x_{k,min}}^{x_{k,max}} \prod_{i=1}^{k} dx_i P_{n_1}^{H,1}(x_1) P_{n_2}^{H,2}(x_2) \cdots P_{n_k}^{H,k}(x_k) \delta\left(\sum_{i=1}^{k} x_i - M\right)$$

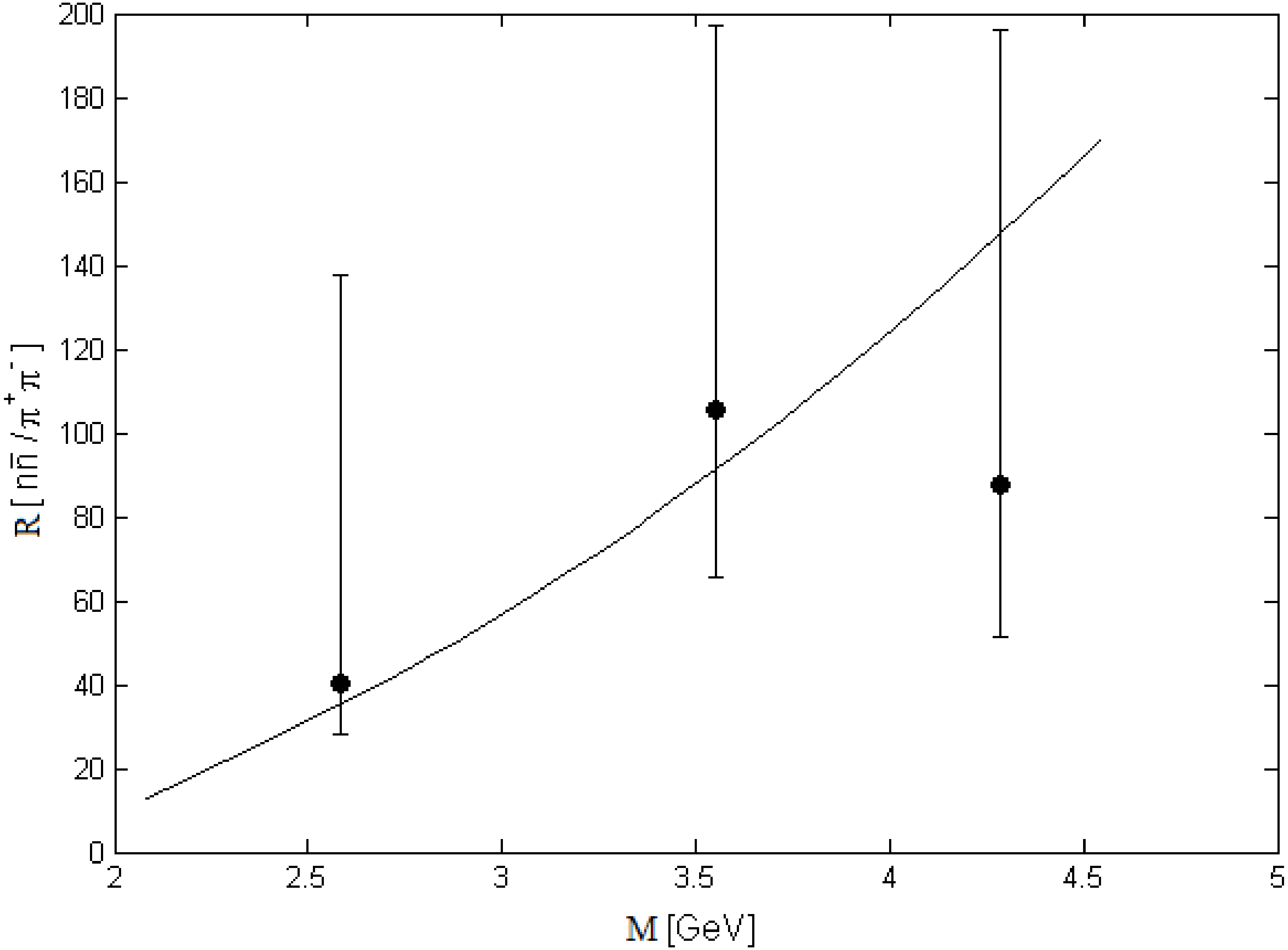
$P_k^{fb}$: formation probability of $k$ fireballs, $C_Q(M)$: the quark-combinatorical factor, $x_i$'s are the invariant masses of the individual fireballs, $P_{n_i}^{H,i}(x_i)$'s are the hadronization probabilities

- $P^{H,i}_{n_i}(x_i)$'s the hadronization probabilities, are the phase space factors that a fireball with energy $(x_i)$ decays to the given hadrons
- $P^{fb}_k$ the formation probability of $k$ fireballs are calculated in the following way: any decaying fireball randomly distribute its energy between the daughter fireballs requiring that the daughters's energy is higher than the minimal energy of a fireball: $2m_\pi$ (otherwise they cannot hadronize).
- the quark combinatorical factor consists of combinatorical factors multiplied with quark creation probabilties, the energy independent creation probabilities are fitted to data $P_u = P_d = 0.38, P_s = 0.24, P_c = 3.52 \cdot 10^{-5}$.

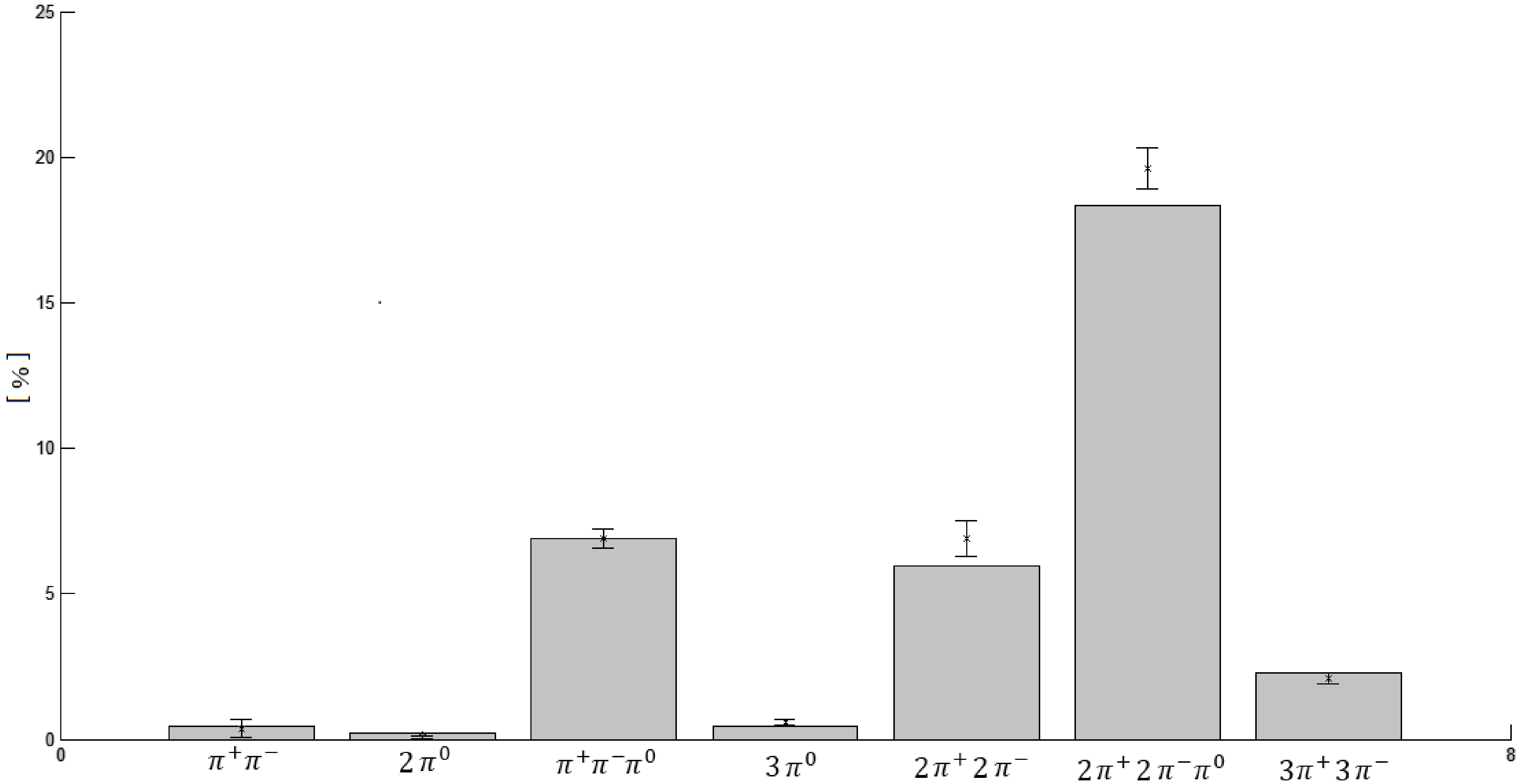

Data
$P_u$=0.38 | $P_d$=0.38 | $P_s$=0.24
$P_u$=0.33 | $P_d$=0.33 | $P_s$=0.33
R [ $\pi^+\pi^-$ / $K^+K^-$ ]
$p_{LAB}$ [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

# Predictions





200
180
160
140
120
100
80
60
40
20
0
2
2.5
3
3.5
4
4.5
5
R [ nn̄ /π⁺π⁻ ]
M [GeV]



25
20
15
10
5
0
[ % ]
0
$\pi^+\pi^-$
$2\pi^0$
$\pi^+\pi^-\pi^0$
$3\pi^0$
$2\pi^+2\pi^-$
$2\pi^+2\pi^-\pi^0$
$3\pi^+3\pi^-$
8

# $\bar{p}$A at PANDA energies

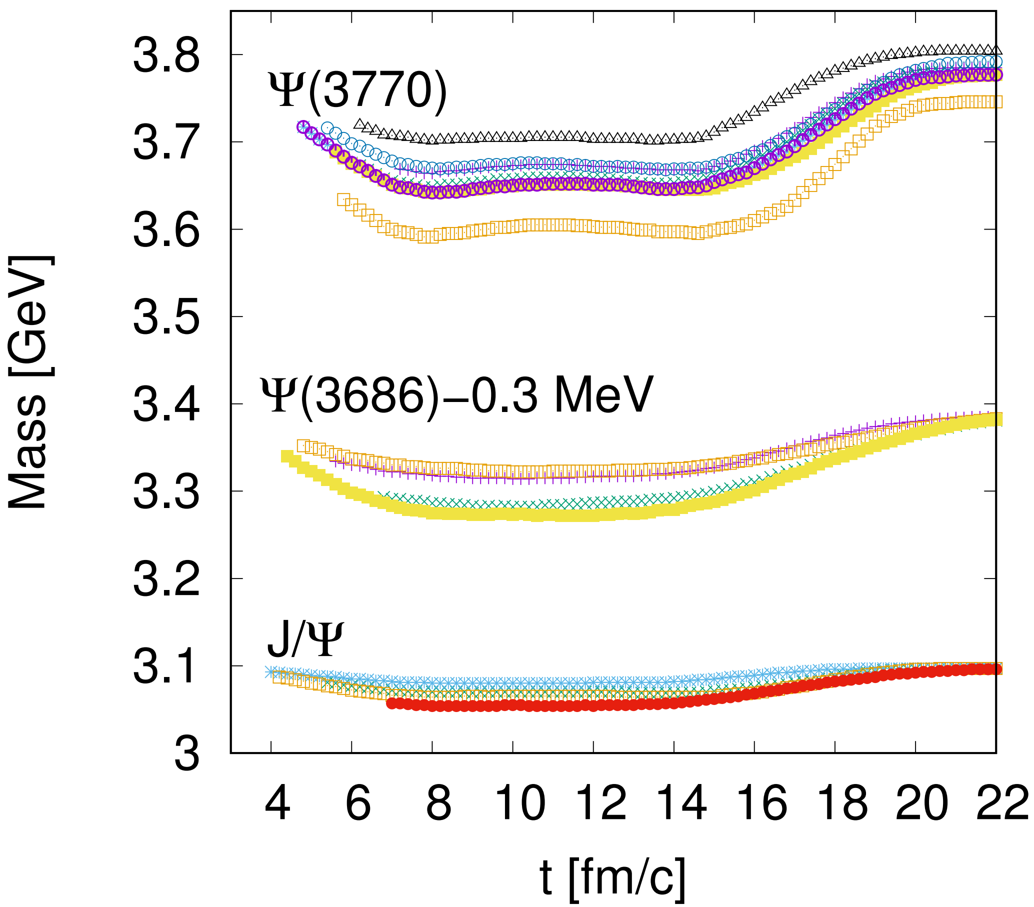
- J/Ψ, Ψ(3686), Ψ(3770)
- gluon condensate is reduced in matter (at $\rho_0$ by 6%)
  → charmonium mass is reduced via the second order Stark-effect
- mass shift linearly depends on density:
  S.H. Lee, C.M. Ko Phys. Rev. C67 (2003) 038202

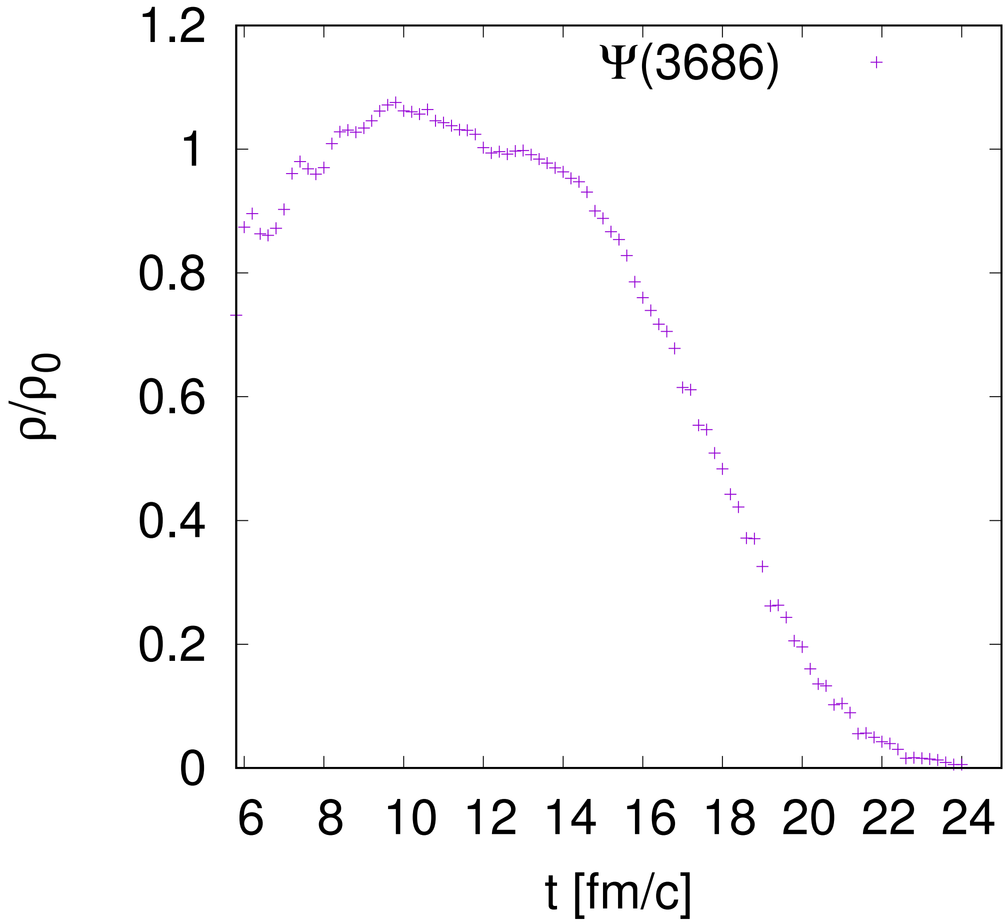
$$\Delta m_\psi = -\frac{\rho_N}{18 m_N} \int dk^2 \left| \frac{\partial \psi(k)}{\partial k} \right|^2 \frac{k}{k^2/m_c + \epsilon} \left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle_N \qquad \epsilon = 2m_c - m_\Psi$$

| Charmonium | Mass shift | width |
|---|---|---|
| J/Ψ | -15 MeV $\rho/\rho_0$ | $\Gamma_0$+coll. broadening |
| Ψ(3686) | -100 MeV$\rho/\rho_0$ | $\Gamma_0$+coll. broadening |
| Ψ(3770) | -140 MeV $\rho/\rho_0$ | $\Gamma_0$+coll. broadening |

- dilepton branching ratio in matter?

# Time evolution of masses and density at $\bar{p}$Au 8 GeV/c

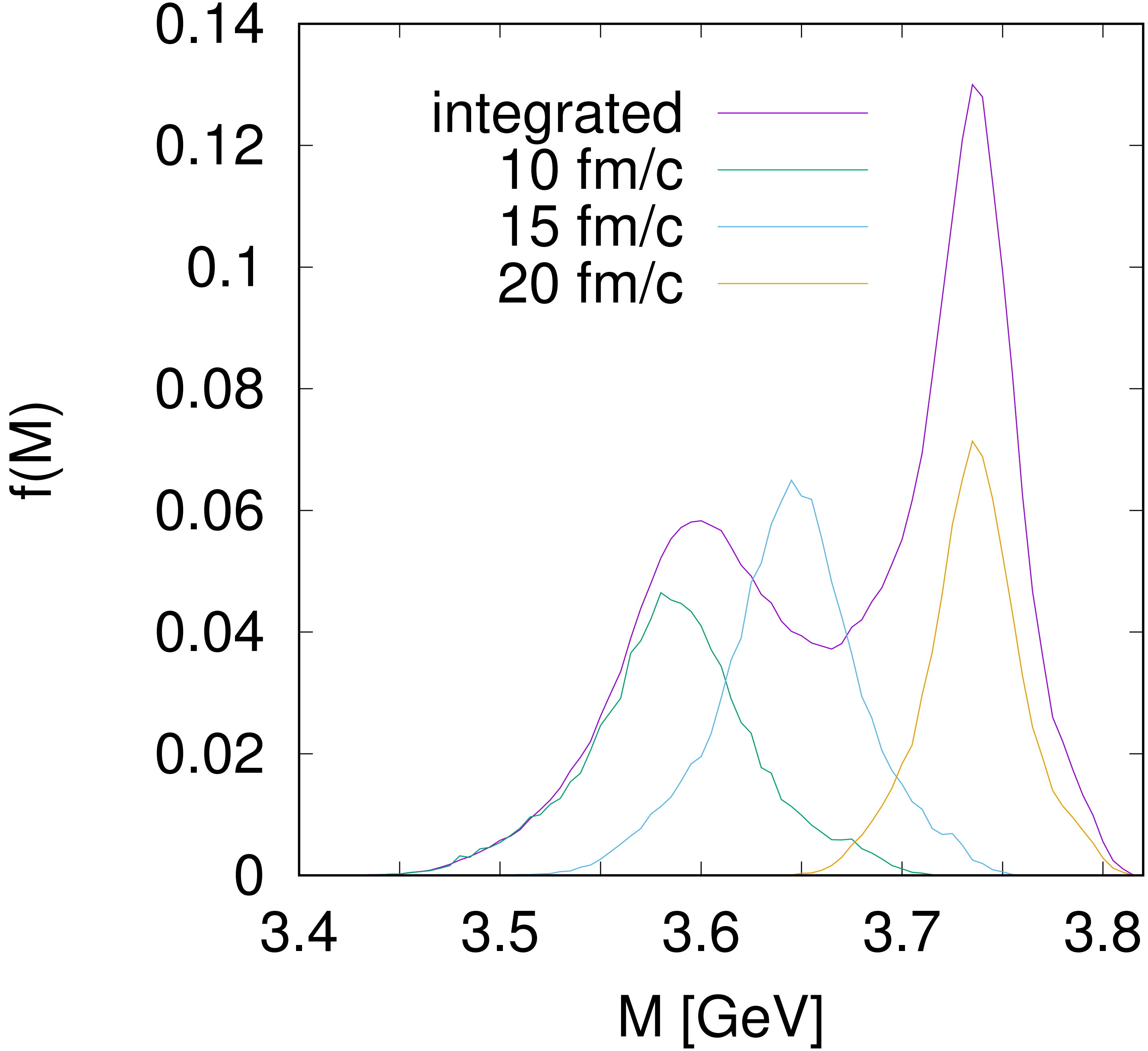


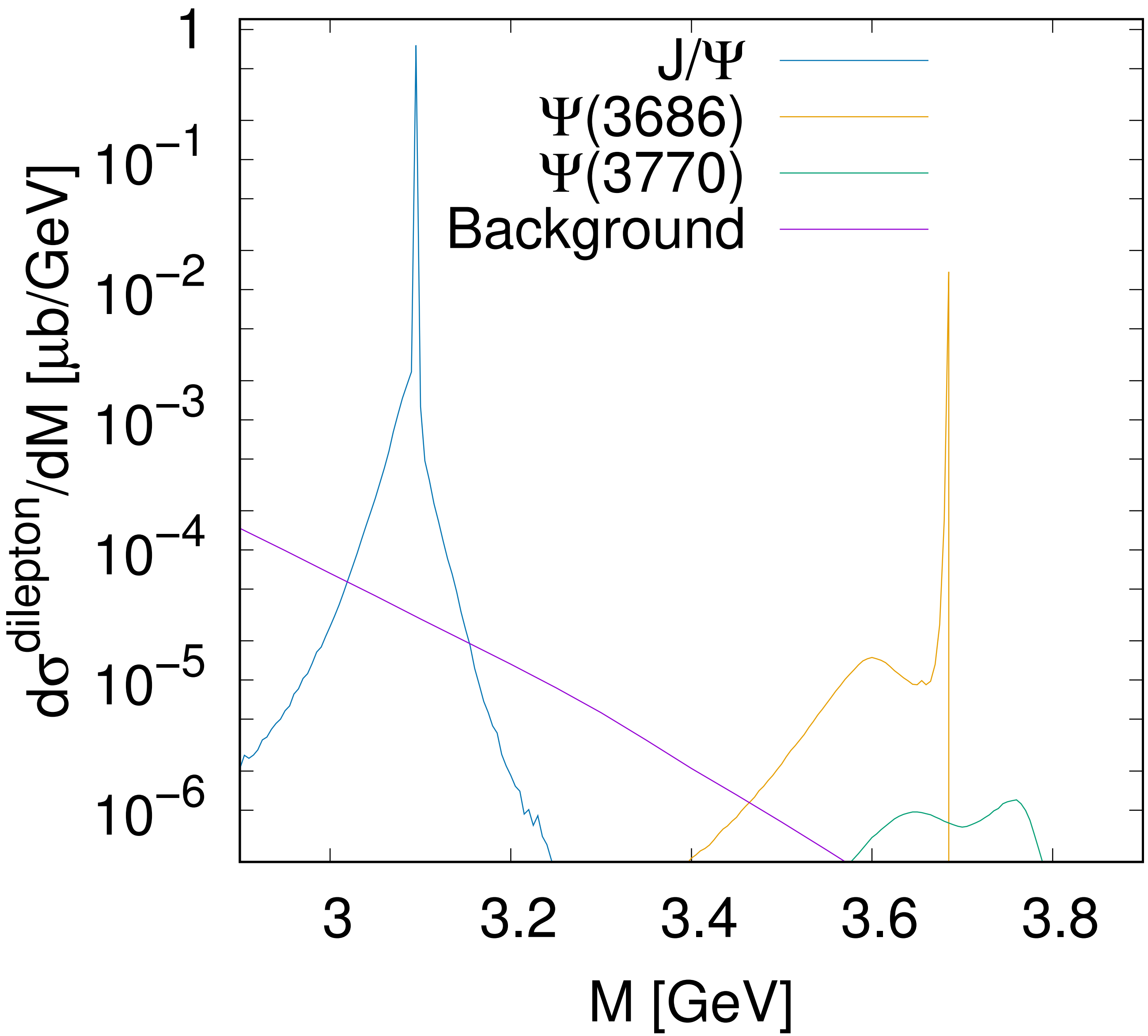

The charmonium states are created at the surface of the heavy nucleus, travel through the dense matter (decays with some probability), crosses the thin surface again and reaching the vacuum.

Major contribution to the dilepton channel are coming from the dense matter and from the vacuum.

# Time evolution of mass spectra, $\bar{p}$Au at 8 GeV/c



## $\bar{p}$Au at 8 GeV




Dilepton invariant mass spectrum in central collision (0-4.5 fm, ≈ 33% of the cross section)

## $\Psi(3686)$

- The distance between the peaks corresponds to a mass shift at $\rho \approx 0.9\rho_0$
- qualitatively the same picture if increase or reduce the mass shift by factor of 2
- measuring the peak distance, we obtain the mass shift at $\rho \approx 0.9\rho_0$
- measuring the mass shift, we obtain the gluon condensate at $\rho \approx 0.9\rho_0$
- the same picture at 6 and at 10 GeV

# Summary

- We developed a bootstrap approach to calculate unknown cross sections. For known channels it fits the experimental data
- Dilepton production in $\bar{p}$A provides us the possibility to study charmonium spectral function in matter
- measure the gluon condensate in nuclear matter.