

Charmonium ($\bar{c}c$) mass in antiproton-nucleus reactions, how the in-medium gluon condensate can be measured

EMMI Hadron Physics Seminar at GSI, 04.07.2018.

Gy. Wolf

MTA Wigner RCP

- Motivation
- Transport
- $\bar{p}A$ reaction (PANDA) and πA reaction

Gy. Wolf, G. Balassa, P. Kovács, M. Zétényi, S.H. Lee,

Act. Phys. Pol. B10 (2017) 1177, arxiv:1711.10372

Phys. Lett. B780 (2018) 25, arXiv:1712.06537

The QCD vacuum

condensates: the most important ones: $m_q \langle \bar{q}q \rangle$ and $\langle \alpha_s/\pi G^2 \rangle$
 $\langle \bar{q}q \rangle$ order parameter of the spontaneous chiral symmetry breaking
plays fundamental role in the phenomenology of strong interaction

How to determine them:

Gell-Man-Oakes-Renner relation: $f_\pi^2 m_\pi^2 = (m_u + m_d) \langle \bar{q}q \rangle$

QCD sum rules: fitting many meson masses (gluon condensate can be determined from J/ψ mass)

It gives a consistent picture for meson masses in terms of condensates.

In matter: the masses of hadrons made of light quarks changes mainly due to the (partial) restoration of chiral symmetry

hadrons 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

Gluon condensate in matter

Quark and gluon condensates are known in vacuum, in matter:

$$\langle n.m. | O | n.m. \rangle = \langle 0 | O | 0 \rangle + \int d^3p/p_0 f_N(p, \mu) \langle N | O | N \rangle$$

we need to know $\langle N | \bar{q}q | N \rangle$ and $\langle N | \alpha_s G^2 | N \rangle$

Trace anomaly:

$$T_\mu^{QCD \mu} = \frac{\beta}{2g} G_{\mu\nu}^a G^{a \mu\nu} + m \bar{q}q$$

Between vacuum states: energy of the vacuum. Between nucleons

$$m_N \bar{u}(p)u(p) = \langle N(p) | \frac{\beta}{2g} G_{\mu\nu}^a G^{a \mu\nu} + m \bar{q}q | N(p) \rangle$$

contribution of light quarks (πN scattering, σ -term): ≈ 50 MeV,

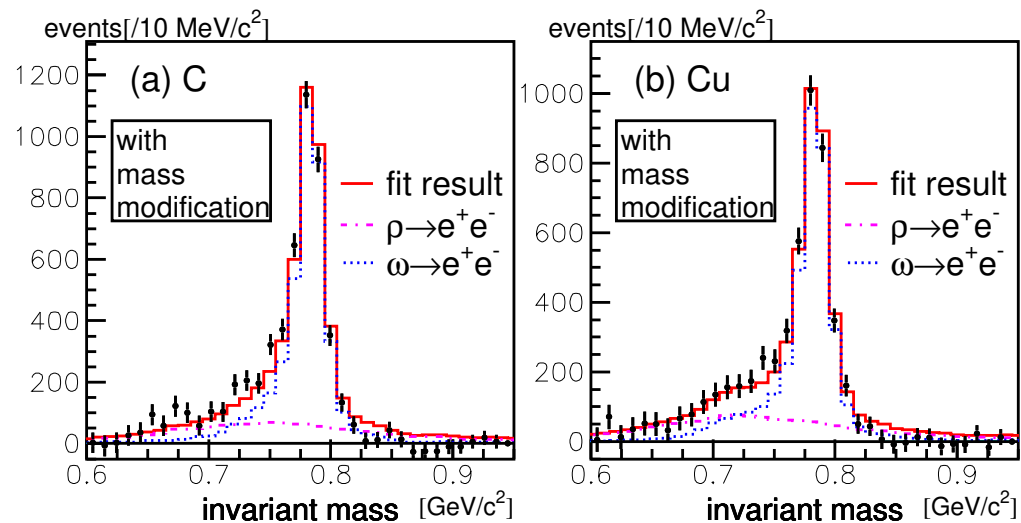
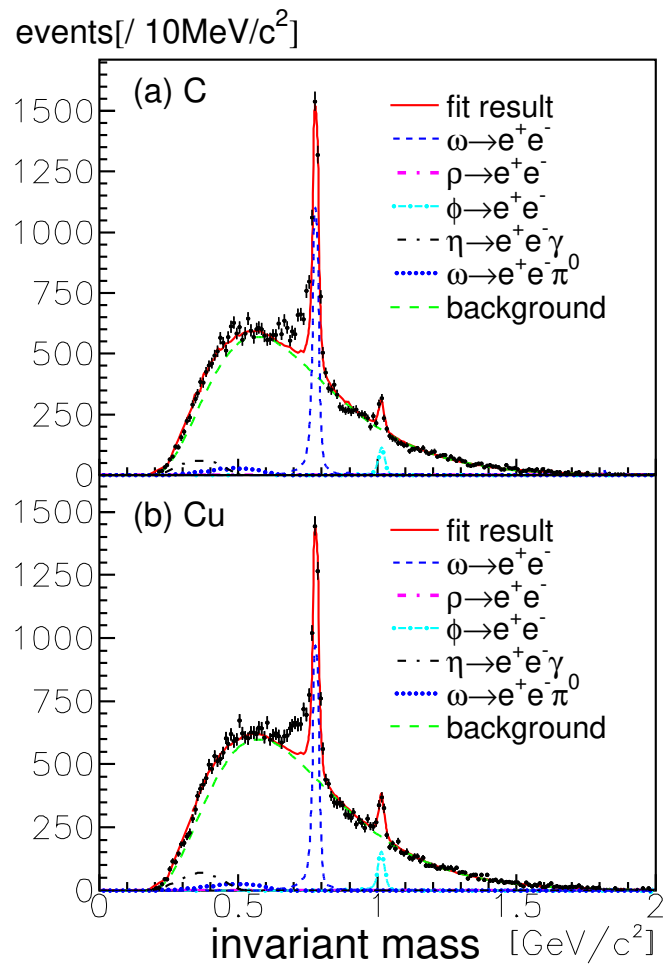
contribution of the heavy quarks are expected to be 100-200 MeV,

gluons contribution to the mass of the proton: ≈ 750 MeV

Why dileptons

- without final state interaction
 - vector mesons decay to dileptons → vector mesons in matter
 - interesting results for p-nucleus (KEK) and nucleus-nucleus (SPS,RHIC,LHC) collisions
- almost all direct or indirect indication for in-medium modification of hadrons are observed in the dileptonic decay channel
- (some exceptions: TAPS/ELSA: $\omega \rightarrow \pi\gamma$,
PHENIX: very indirect: η' from Bose-Einstein correlation for π 's, and mesonic atoms)

KEK E325 12 GeV pA data ρ and ω



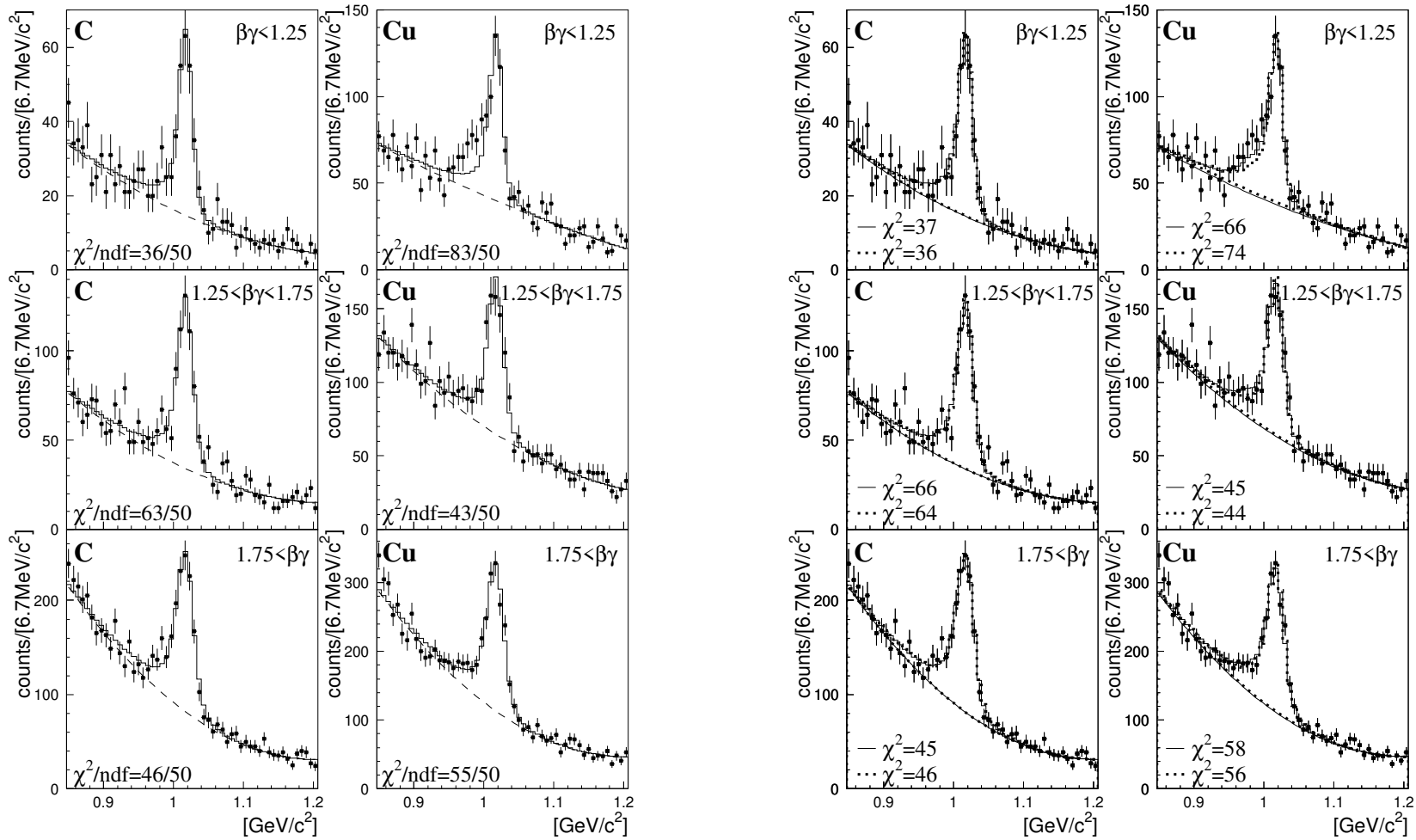
$$m(\rho)/m(0) = 1 - 0.09(\rho/\rho_0)$$

no broadening

M. Naruki *et al.*

Phys. Rev. Lett. 96 (2006) 092301

KEK E325 12 GeV pA data for ϕ



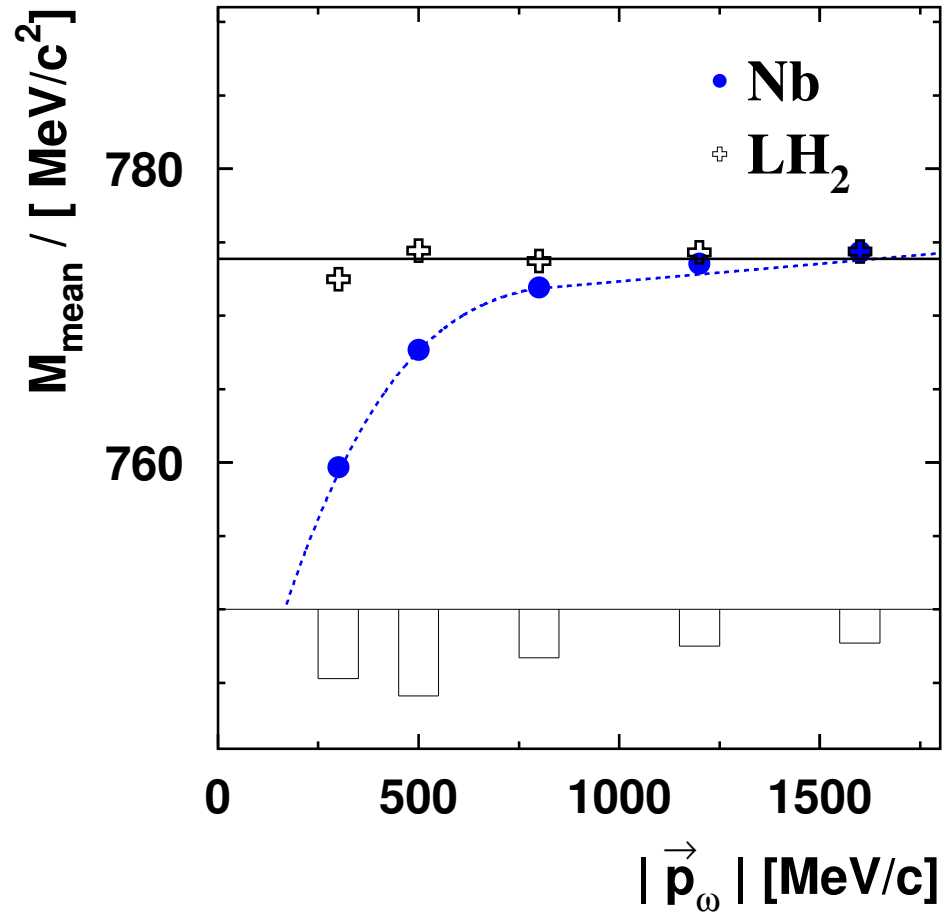
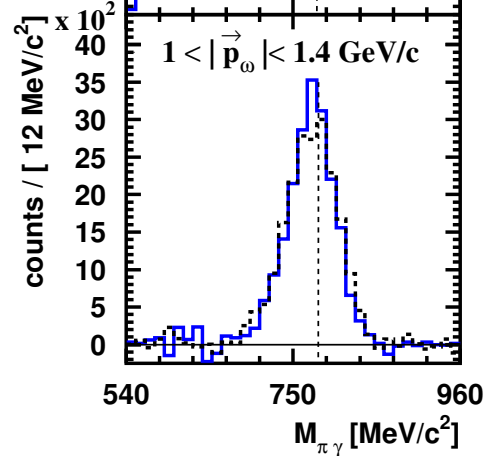
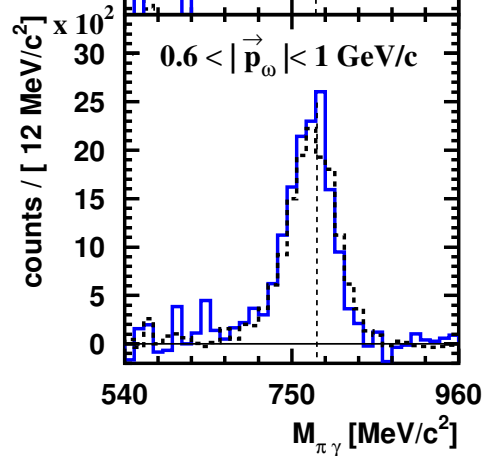
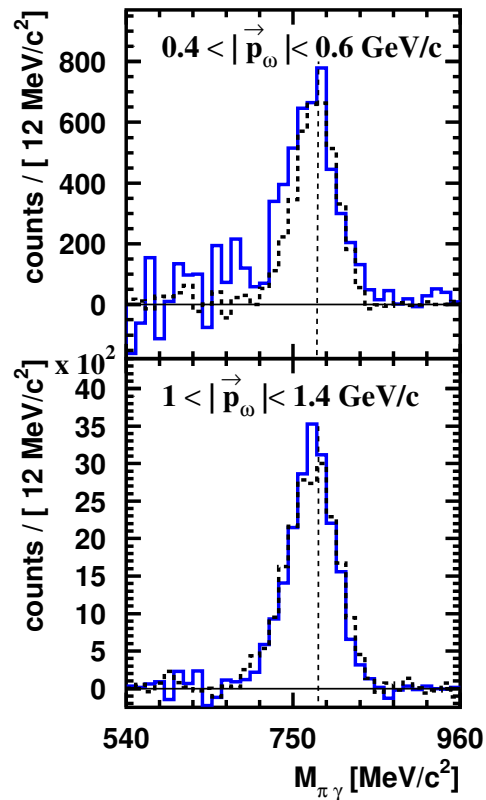
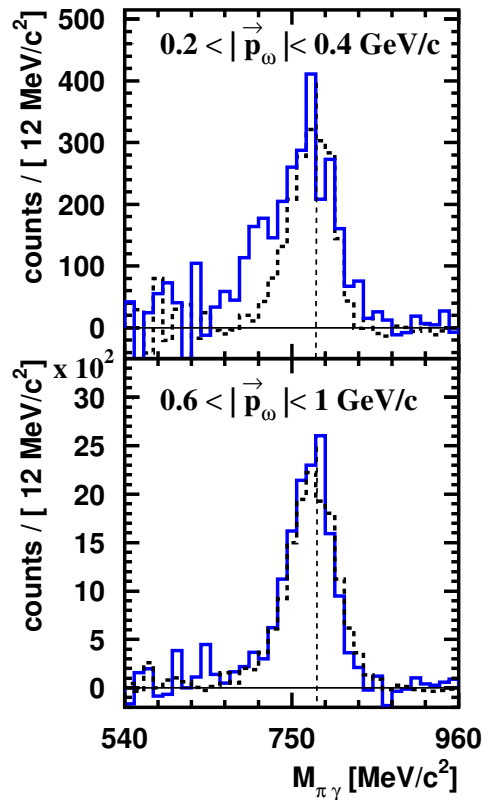
$$m(\rho)/m(0) = 1 - 0.033(\rho/\rho_0)$$

$$\Gamma(\rho)/\Gamma(0) = 3.6(\rho/\rho_0)$$

R. Muto *et al.*

Phys. Rev. Lett. 98 (2007) 042501

TAPS/ELSA data for $\gamma A \rightarrow \omega X$



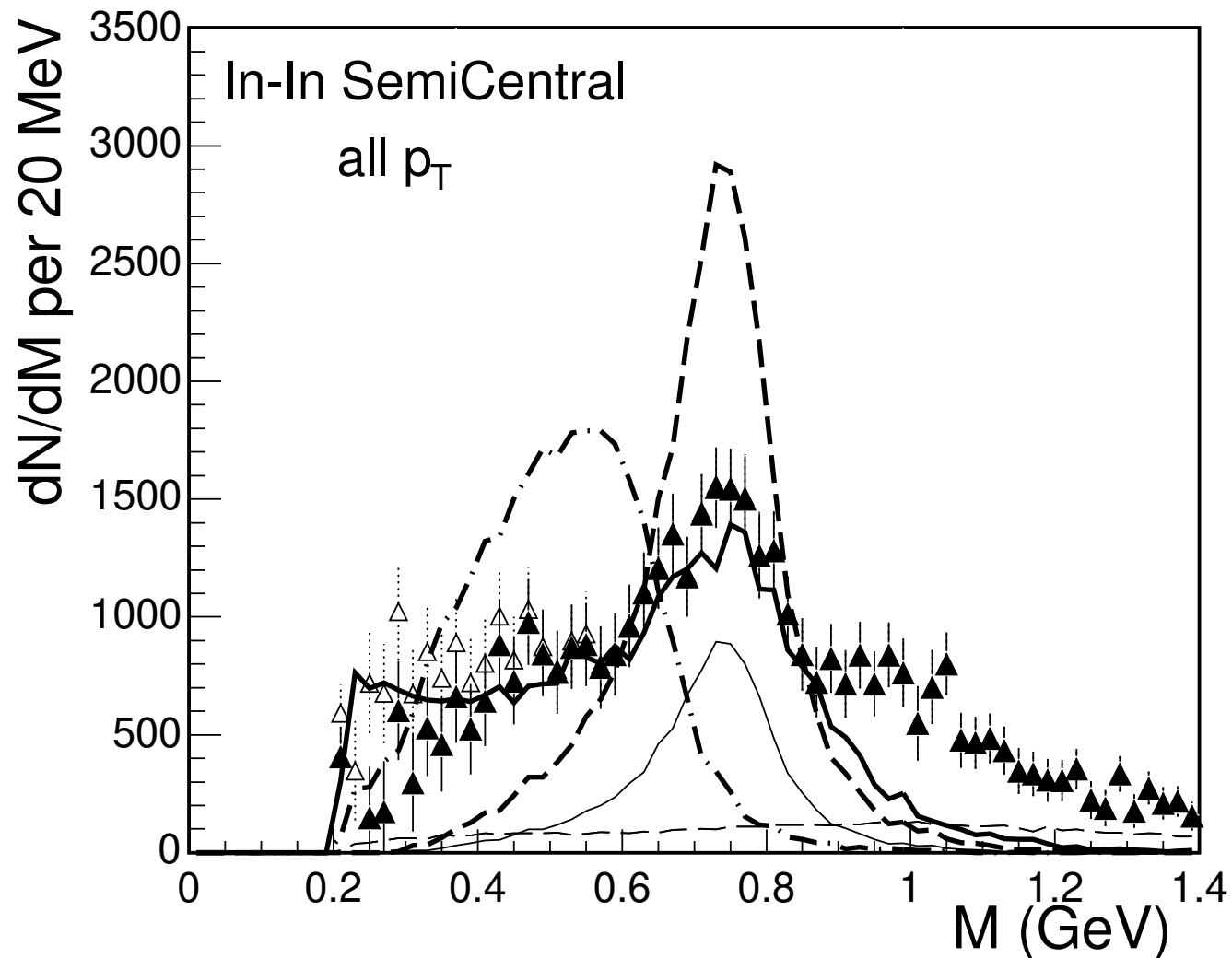
$$m(\rho)/m(0) = 1 - 0.14(\rho/\rho_0), \quad \bar{\rho} = 0.6\rho_0$$

$$\Gamma_{res} = 55 \text{ MeV}$$

D. Trnka *et al.*

Phys. Rev. Lett. 94 (2005) 192303

NA60 data for ρ



thick solid line: ρ -broadening
due to hadronic reactions
R. Rapp, J. Wambach
Adv. Nucl. Phys. 25, 1

S. Damjanovic *et al.*
Eur.Phys.J.C49:235-241,2007

Description of heavy ion reactions: BuBUU transport model

Energy range: 0.1-10 GeV bombarding energies (SIS,CBM,PANDA,NICA)

- The initial state is known
- The degrees of freedom are known
- Transport models give good description of the data

Some recent Publications:

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

Gy. Wolf, M. Zetenyi, Dilepton and ϕ meson production in elementary and nuclear collisions at the NICA fixed-target experiment, Eur.Phys.J. A52 (2016) no.8, 258

M. Zetenyi, Gy. Wolf, Influence of anisotropic Λ/Σ creation on the Ξ multiplicity in subthreshold proton-nucleus collisions, e-Print: arXiv:1803.10573

- 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

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

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 + Λ and Σ 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
- $\frac{d\sigma^{X \rightarrow NR}}{dM_R} \sim A(M_R) \lambda^{0.5}(s, M_R^2, M_N^2)$

Unknown cross sections: Statistical bootstrap:

G. Balassa, P. Kovács, Gy. Wolf, Eur. Phys. J. A54 (2018) 25,

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 $F_\alpha = f_\alpha(x, p, t)A_\alpha$

$$A(p) = -2ImG^{ret} = \frac{\hat{\Gamma}}{(E^2 - \mathbf{p}^2 - m_0^2 - \text{Re}\Sigma^{ret})^2 + \frac{1}{4}\hat{\Gamma}^2},$$

W. Cassing, S. Juchem, Nucl.Phys. A672 (2000) 417

S. Leupold, Nucl.Phys. A672 (2000) 475

- testparticle approximation

Transport equations

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

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

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

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

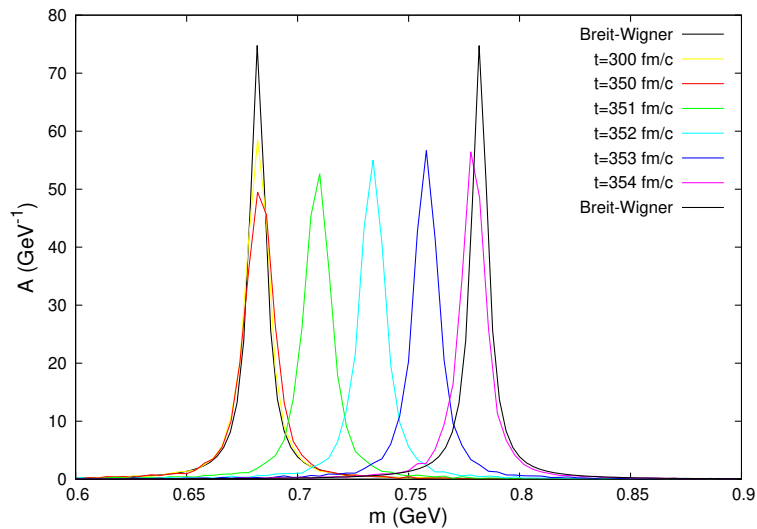
$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} \text{Re}\Sigma_{(i)}^{\text{ret}} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - \text{Re}\Sigma_{(i)}^{\text{ret}}}{\text{Im}\Sigma_{(i)}^{\text{ret}}} \frac{\partial}{\partial \epsilon_i} \text{Im}\Sigma_{(i)}^{\text{ret}}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

- the last equation for homogenous system can be rewritten as

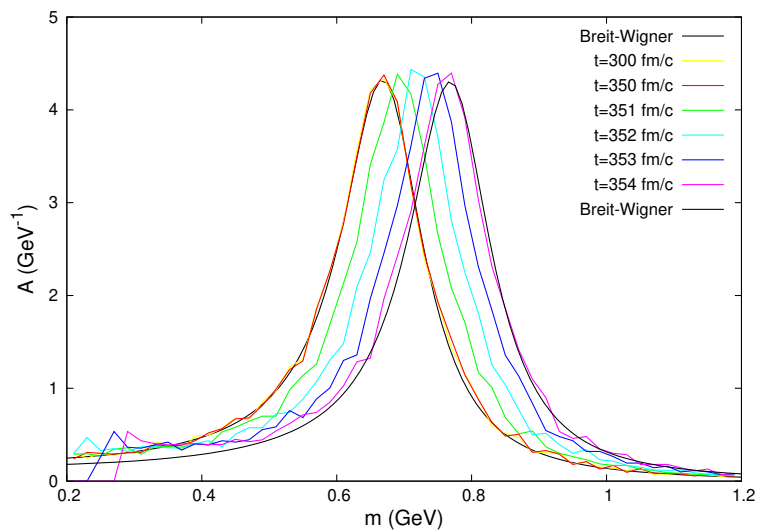
$$\frac{dM_i^2}{dt} = \frac{d(\epsilon_i^2 - P_i^2)}{dt} = \frac{d\text{Re}\Sigma_{(i)}^{\text{ret}}}{dt} + \frac{M_i^2 - M_0^2 - \text{Re}\Sigma_{(i)}^{\text{ret}}}{\text{Im}\Sigma_{(i)}^{\text{ret}}} \frac{d\text{Im}\Sigma_{(i)}^{\text{ret}}}{dt}$$

Evolution of mass distribution in a box

the vector meson masses are shifted linearly with density, and change the density linearly from ρ_0 to 0 in 4 fm/c:



ω

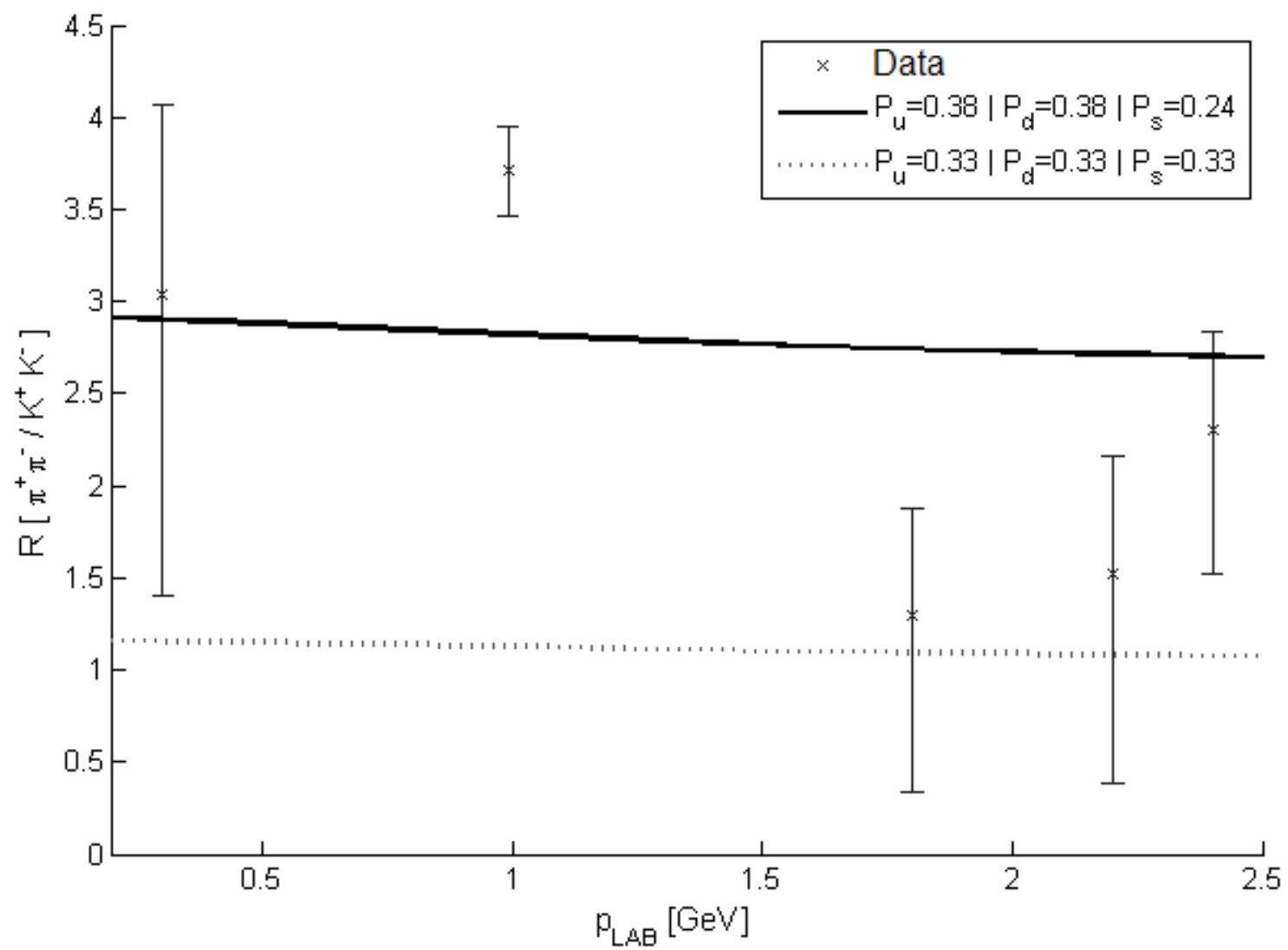


ρ

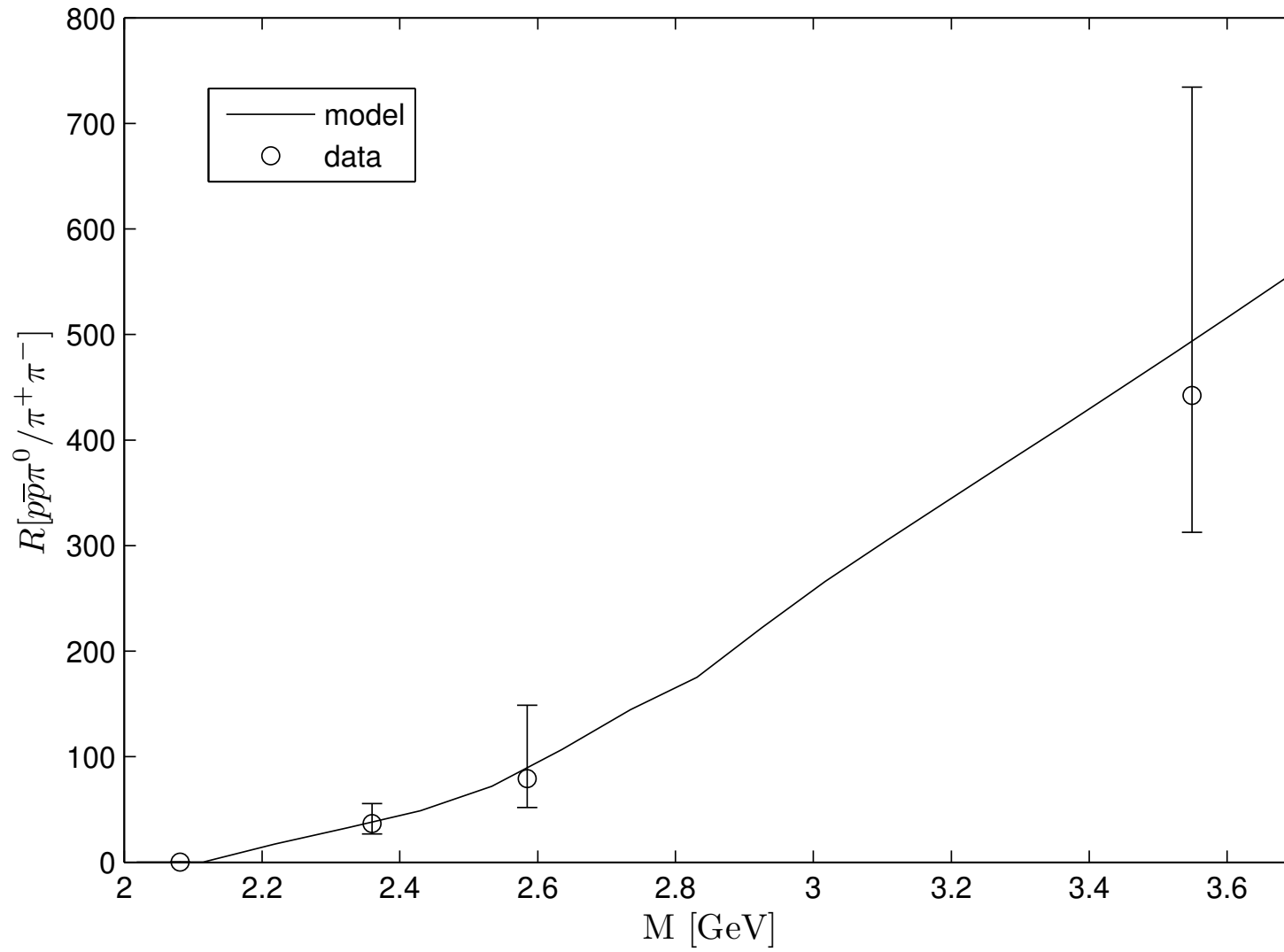
Statistical Bootstrap approach

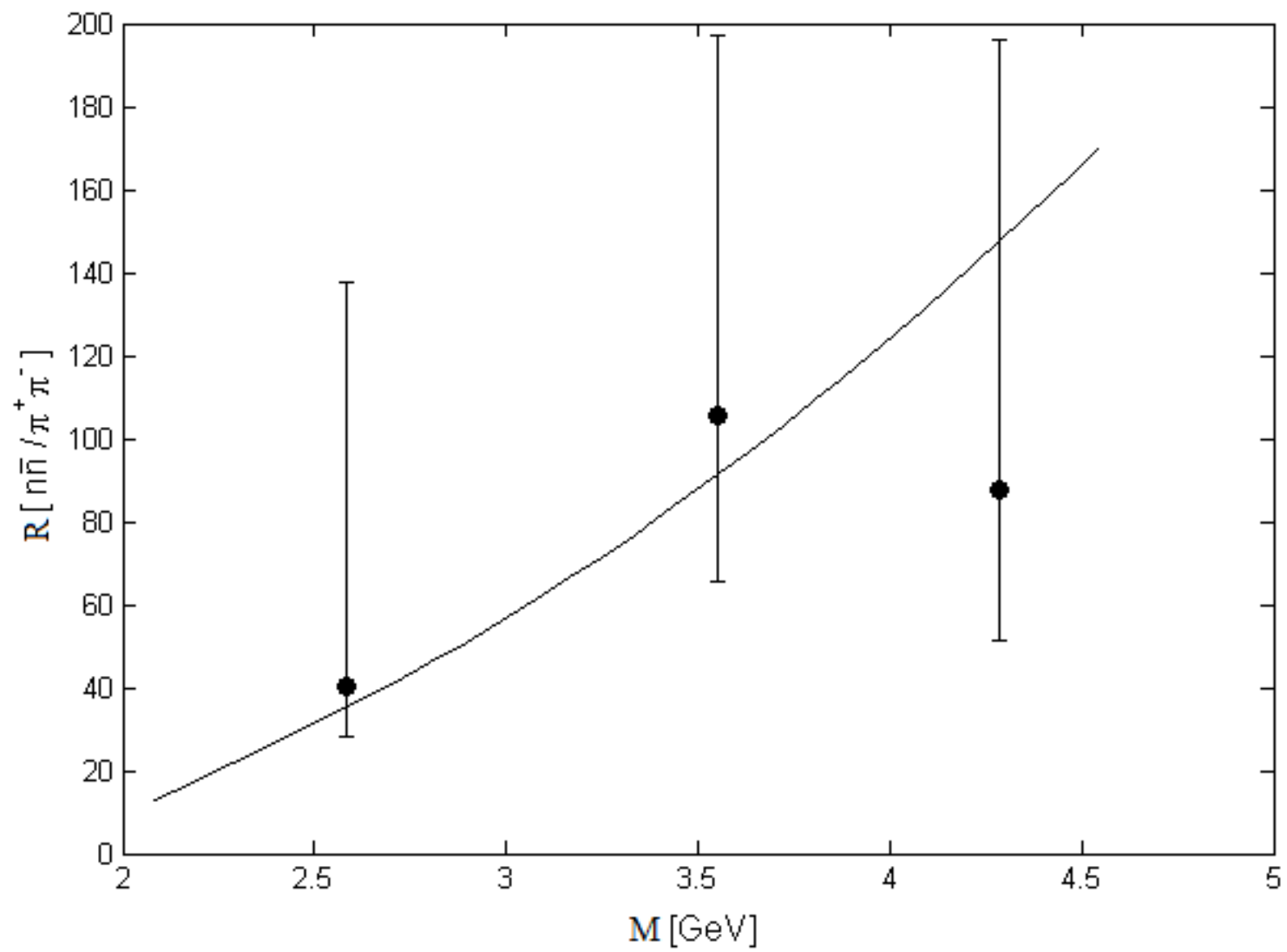
G. Balassa, P. Kovács, Gy. Wolf, Eur. Phys. J. A54 (2018) 25

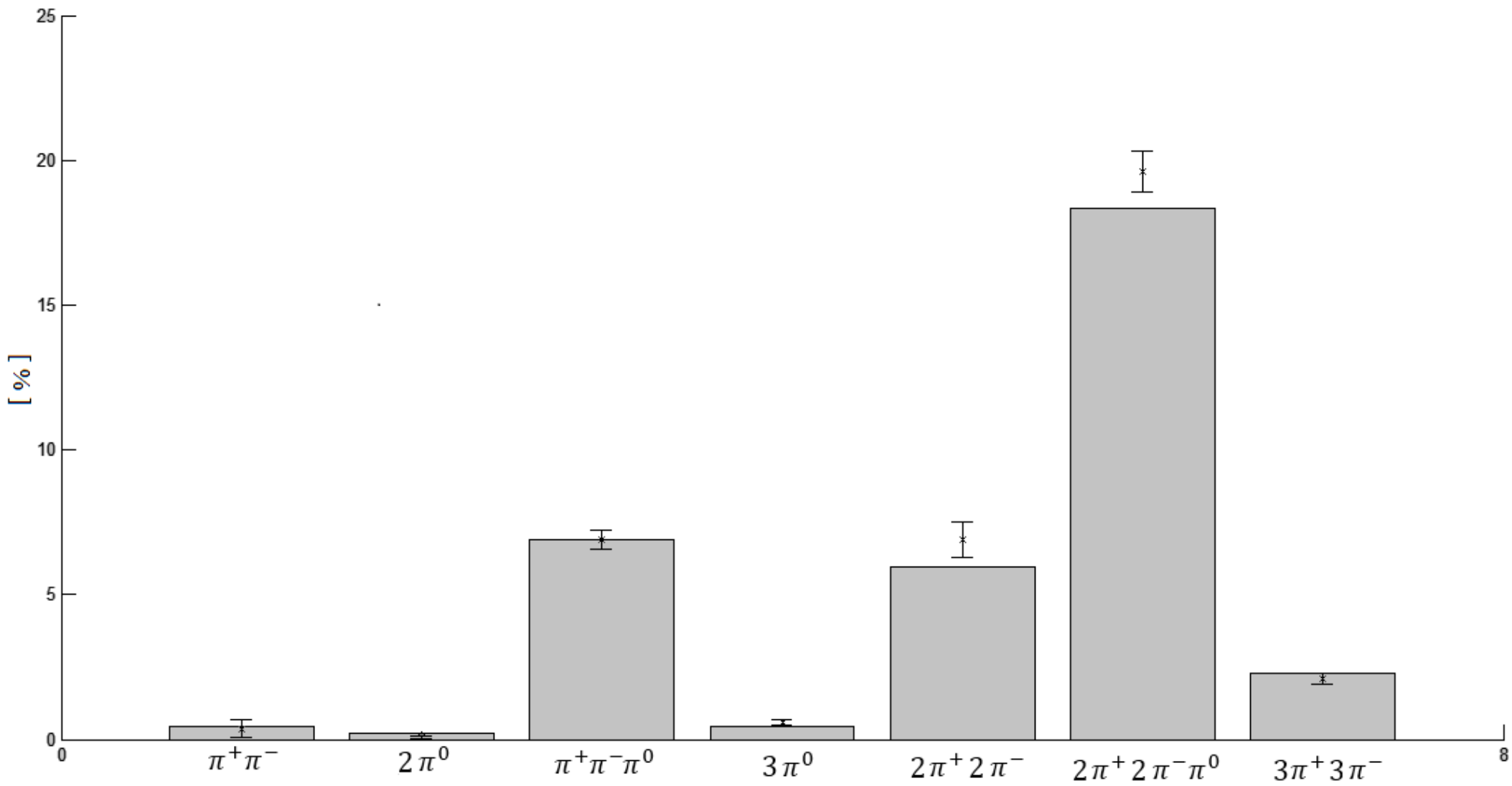
- Estimate unknown cross sections of different hadronic reactions up to a few GeV in c.m.s energy.
- Our method incorporate that during the collision a compound system, a fireball, is formed and, through possible production of subsequent fireballs, this system decays into a specific final state.
- The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



Predictions







Charmonium in vacuum and in matter

- Charmonium: J/Ψ , $\Psi(3686)$, $\Psi(3770)$: colour dipoles in colour-electric field
- $\bar{D}(\bar{c}q)D(\bar{q}c)$ loops contribute to the charmonium selfenergies
- in matter the energy of the colour dipole is modified due to the modification of the gluon condensate **second order Stark-effect**
S.H. Lee, C.M. Ko Phys. Rev. C67 (2003) 038202

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

- the effect of the $\bar{D}D$ loop modified, because the mass of D mesons also modified due to the change of the quark condensate
- The width of the charmonium increases due to the collisional broadening
- dilepton branching ratio in matter?
due to collisional broadening $\Gamma_{med}^{tot} \gg \Gamma_{vac}^{tot}$. What is Γ_{med}^{em} ? Br_{med}^{em} ?

$\bar{p}A$ at PANDA energies

Charmonium	Stark-effect+ $\bar{D}D$ loop
J/ Ψ	-8+3 MeV ρ/ρ_0
$\Psi(3686)$	-100-30 MeV ρ/ρ_0
$\Psi(3770)$	-140+15 MeV ρ/ρ_0

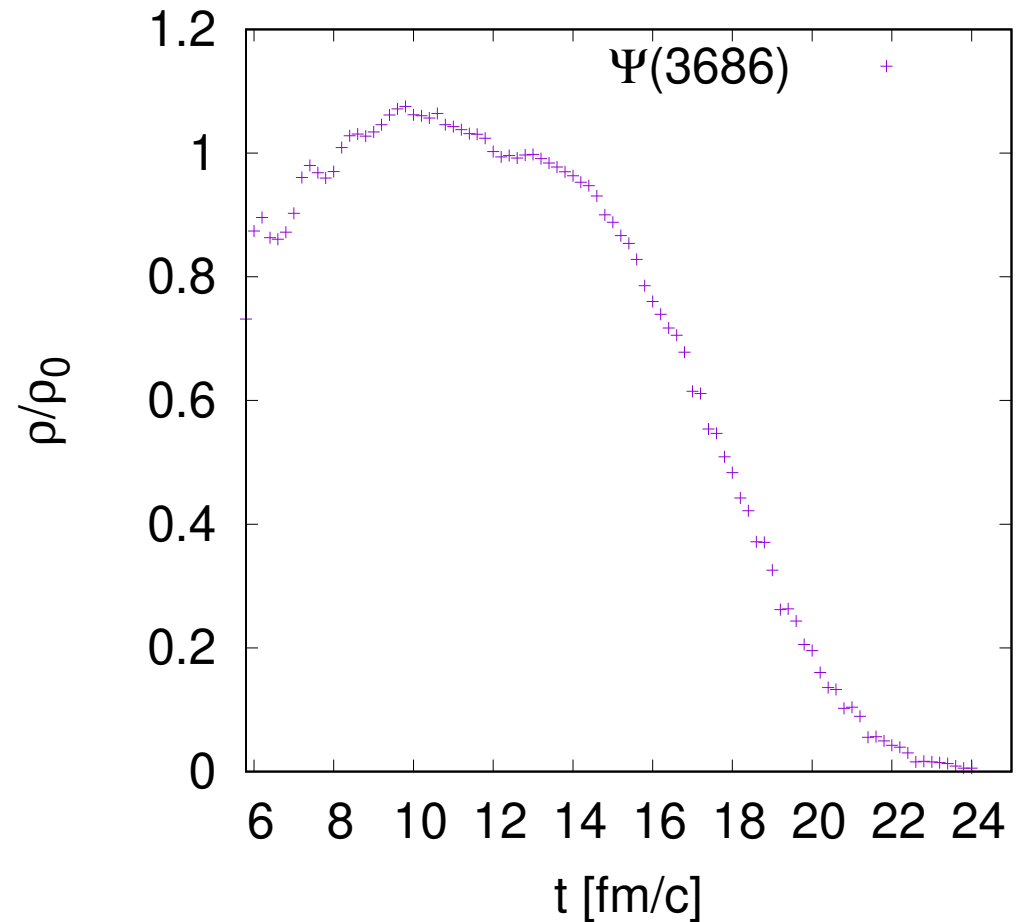
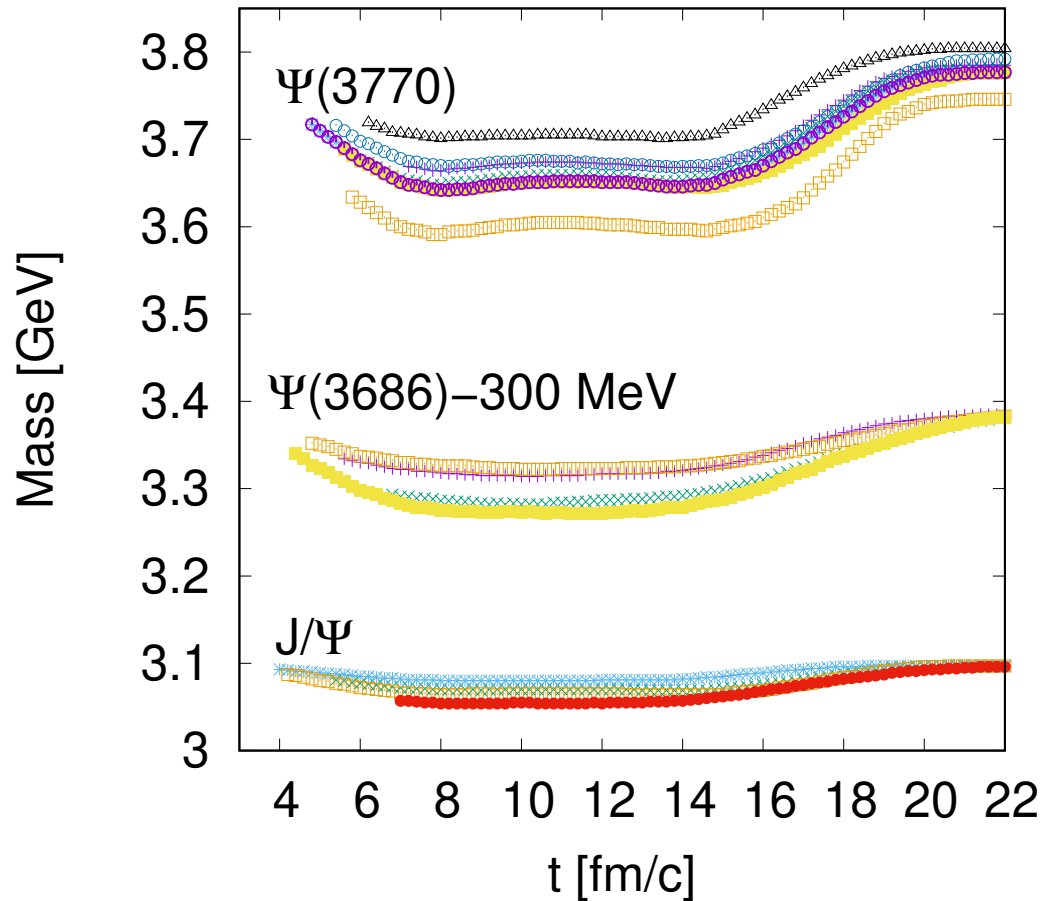
background:

Drell-Yan: small number of energetic hadron-hadron collisions

$\bar{D}D$ decay: c quark decays weakly to s quark, $D \rightarrow Ke\bar{\nu}_e$ and similarly for \bar{D} , close to the threshold due to the production of two kaons the available energy for dileptons are strongly reduced

up to moderate energies the background is low

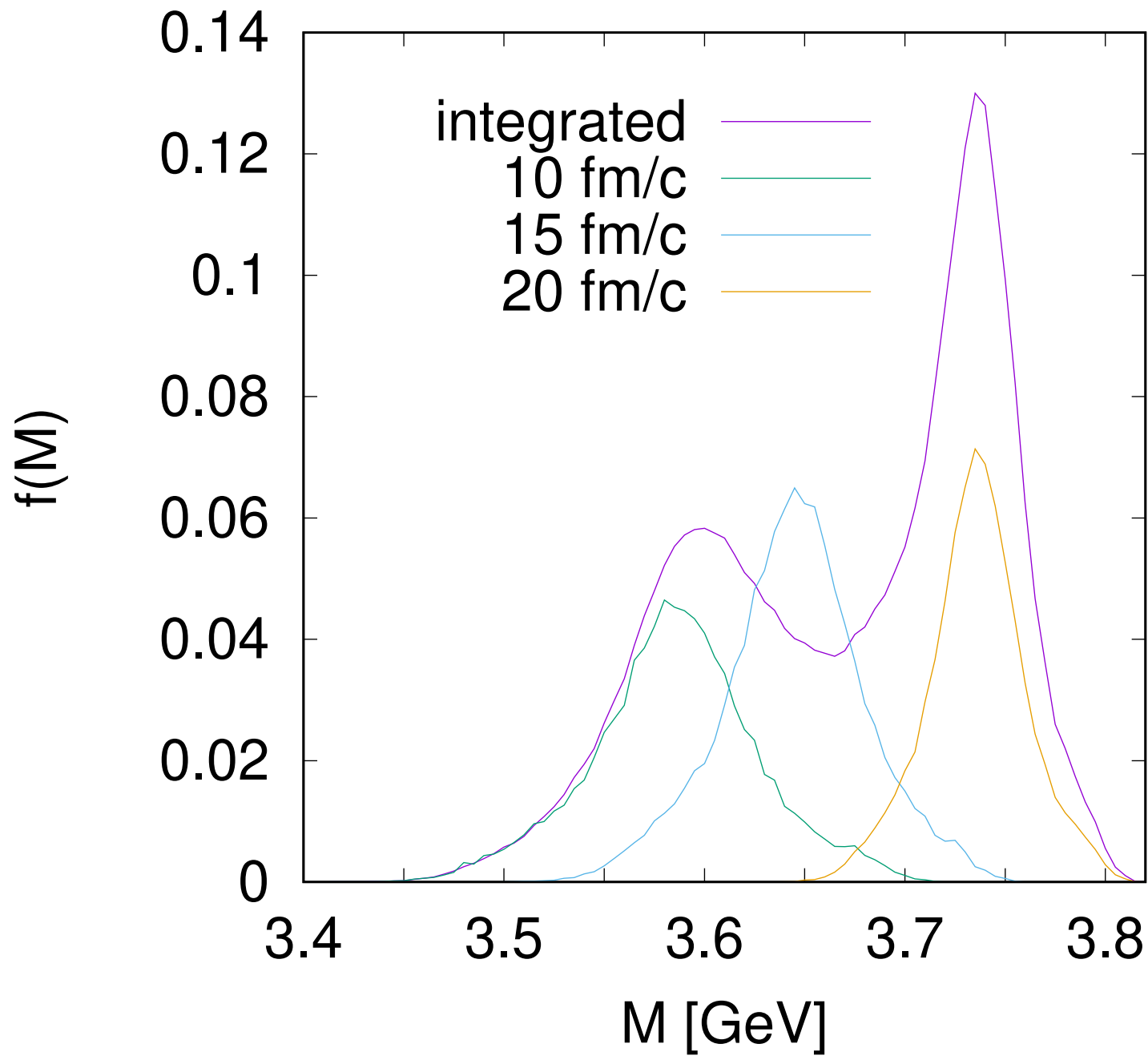
Time evolution of masses and density at $\bar{p}\text{Au}$ 6 GeV/c



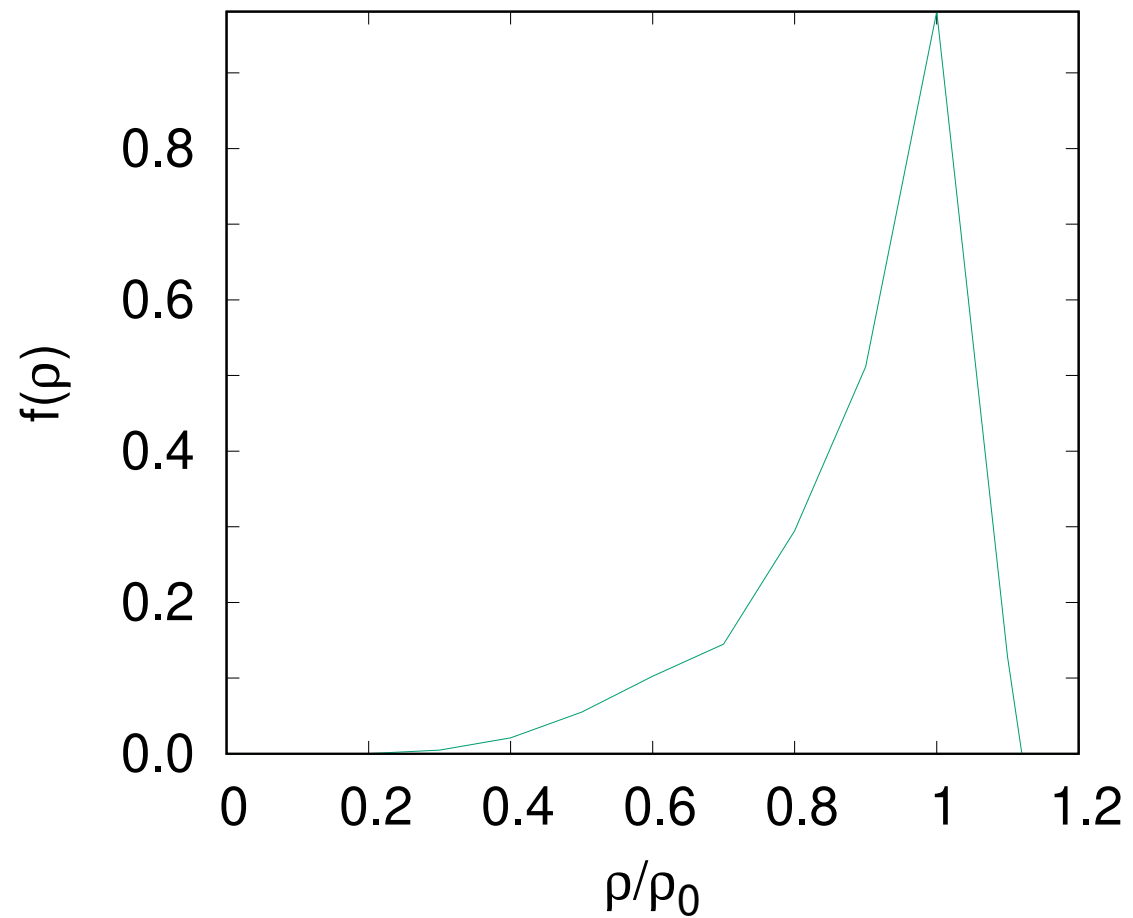
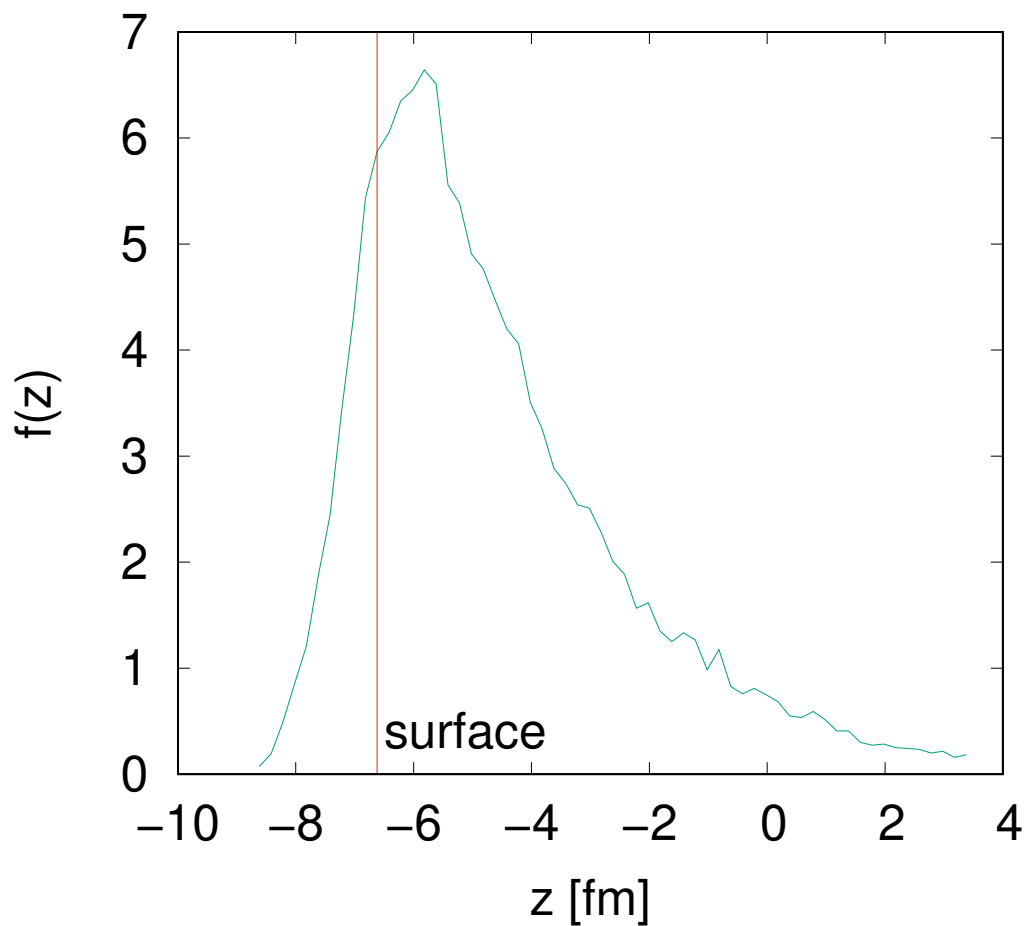
The charmonium states are created at the surface of the heavy nucleus, travel through the dense matter (decays with some probability), crosses the thin surface again and reaching the vacuum.

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

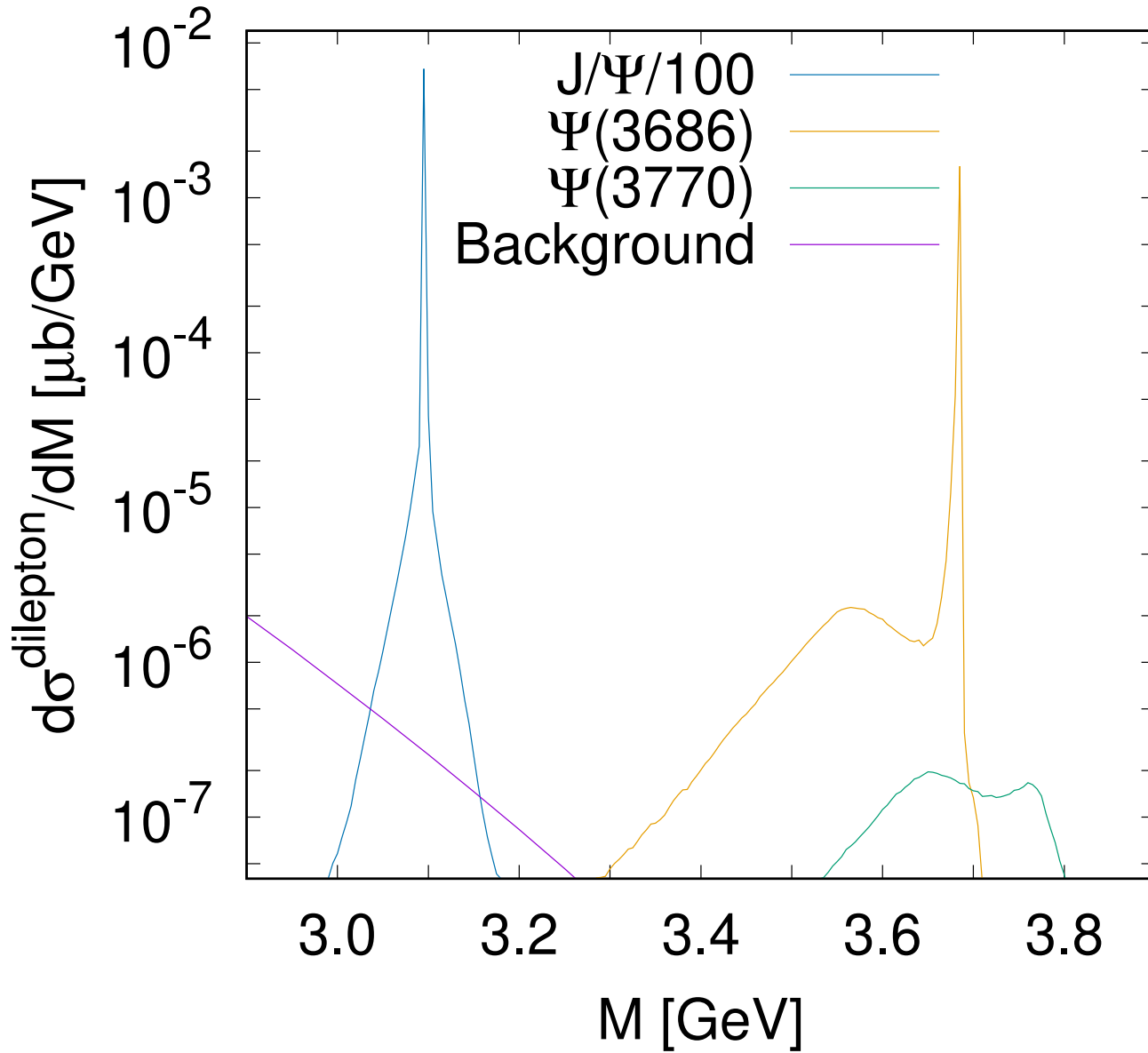


Charmonium creation



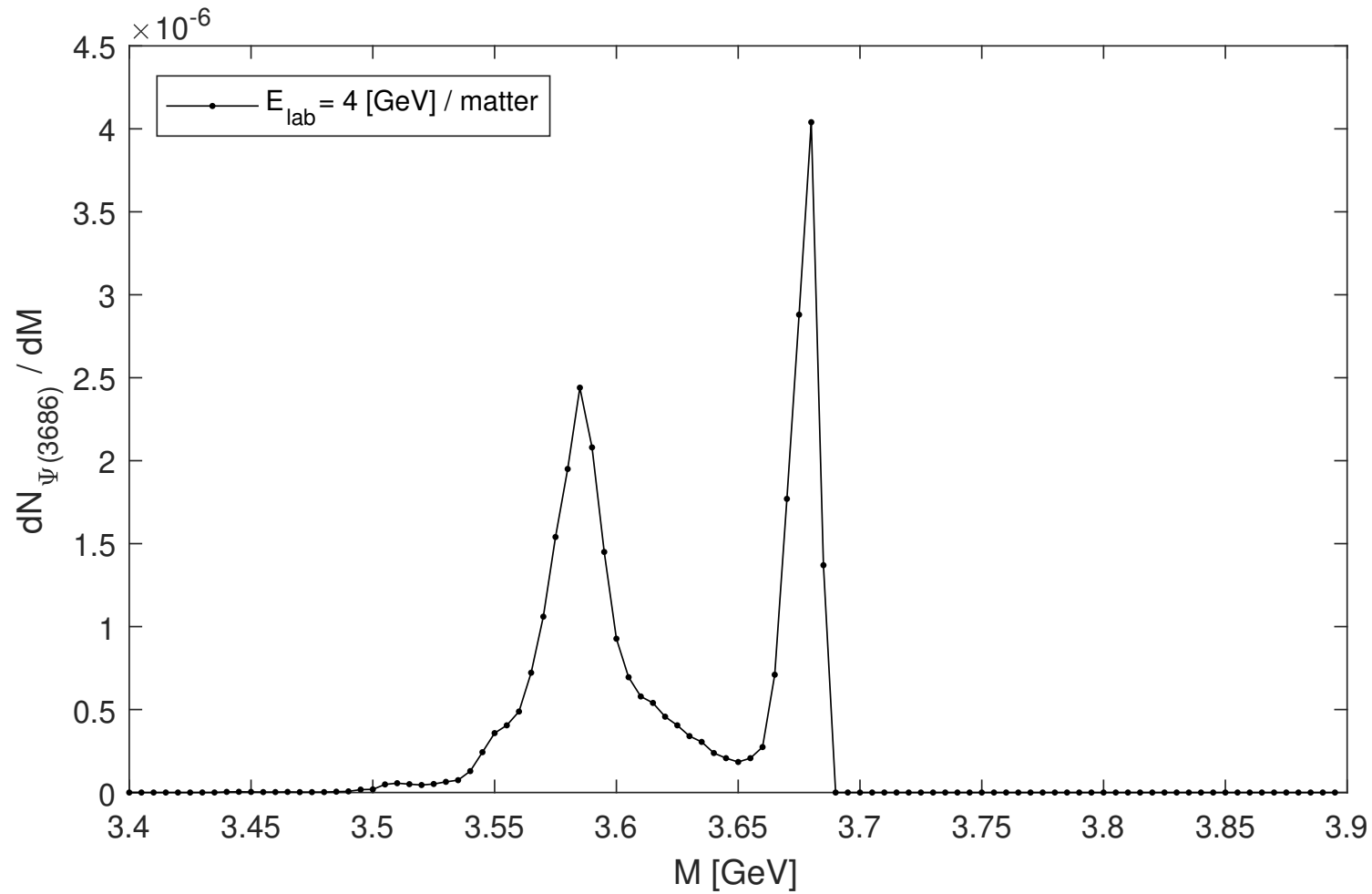
Most of the charmonium are created close to the surface of the nucleus

$\bar{p}\text{Au}$ at 6 GeV/c



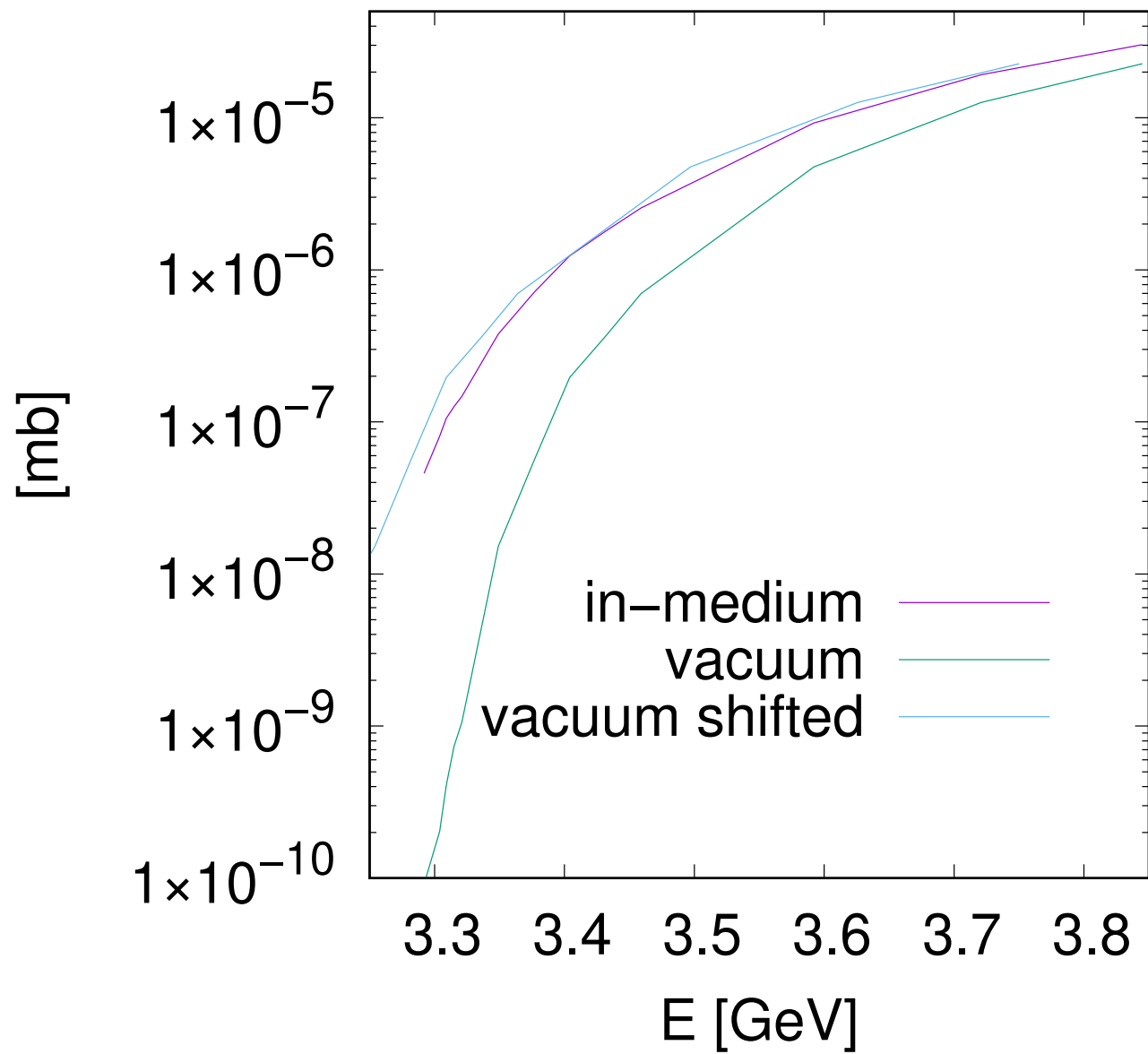
Dilepton invariant mass spectrum in central collision (0-4.5 fm, $\approx 33\%$ of the cross section)

$\bar{p}\text{Au}$ at 4 GeV/c

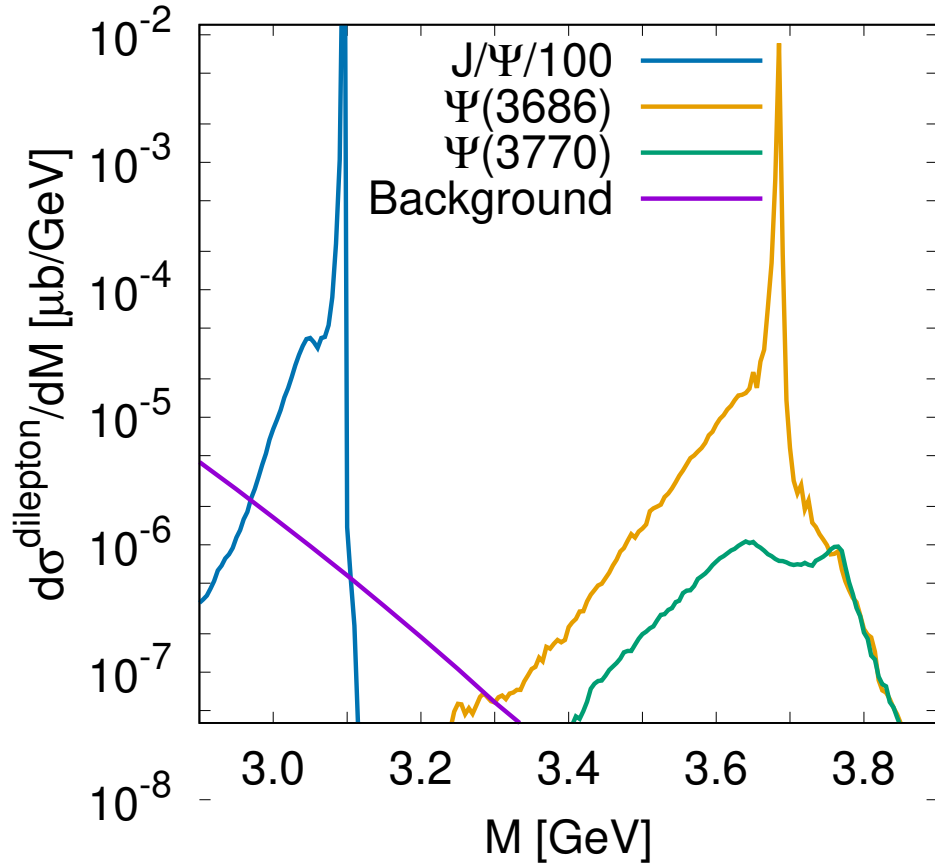


Just above threshold, the charmonium is very slow, spend more time in matter.

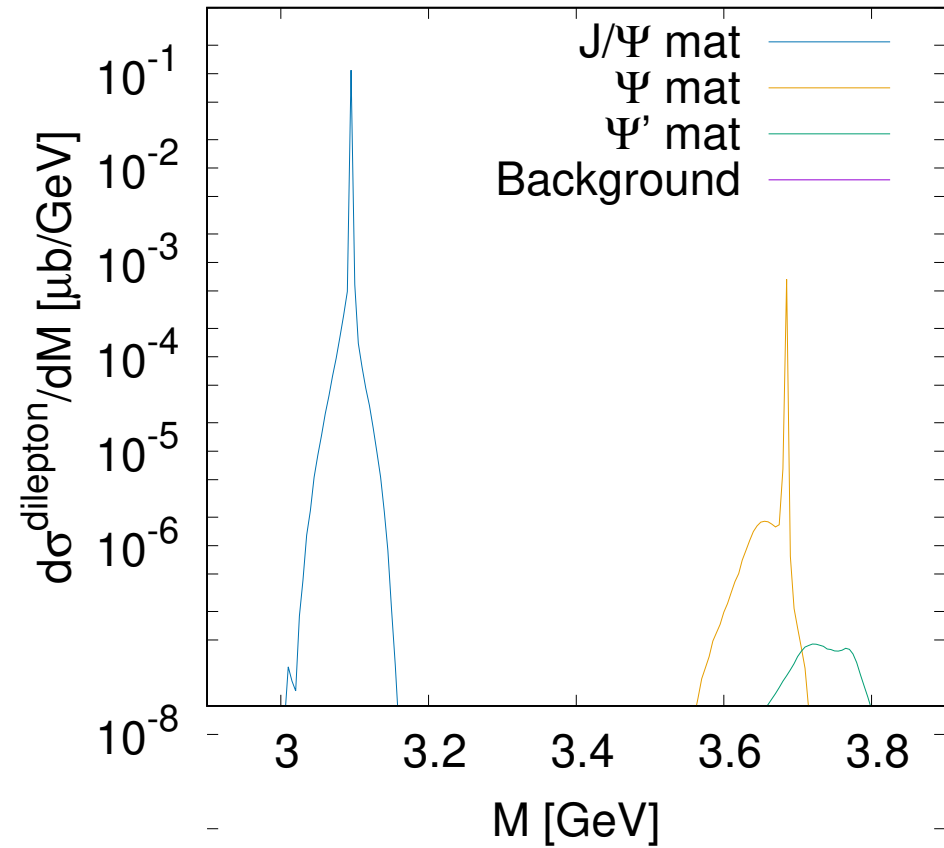
$\Psi(3686)$ excitation function in \bar{p} Au reactions



Playing with the mass shift



mass shift 50 MeV

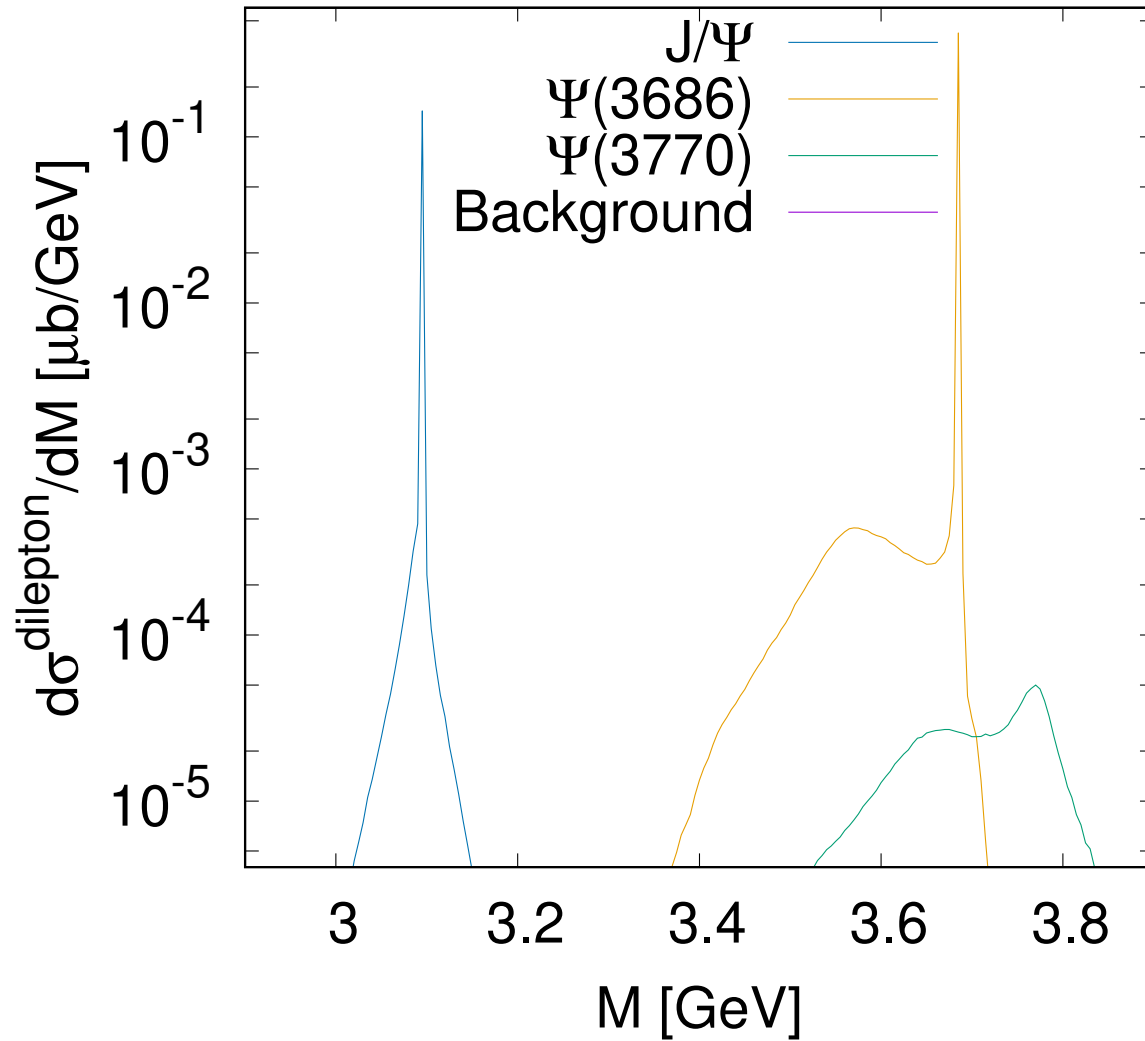


mass shift 60 MeV

$\Psi(3686)$

- 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 6-10 GeV
- measuring the $JP/\Psi, \Psi(3686)$ states allow to determine their mass shift if it is > 60 MeV
- key points: cross sections are not, background is several magnitude less than the signal
- em. width
- absorption cross section of $\bar{p}N$
- can the error of the experimental mass resolution from the vacuum peak overshadow the smaller, in-medium peak?

π Au at 12 GeV/c



Pion beam is similarly good as antiproton, having more or less the same advantages as antiprotons.

Summary

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