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

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

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: $m_q < \bar{q}q >$ and $< \alpha_s/\pi G^2 >$

$< \bar{q}q >$ 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: $f_\pi^2 m_\pi^2 = (m_u + m_d) < \bar{q}q >$

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) restauration 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:

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

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

Trace anomaly:

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

Between vacuum states: energy of the vacuum. Between nucleons

$$m_N \bar{u}(p) u(p) =< N(p)|\frac{\beta}{2g} G^a_{\mu\nu} G^{a\,\mu\nu} + m\bar{q}q|N(p) >$$

contribution of light quarks (πN scattering, σ-term):$\approx$ 50 MeV,
contribution of the heavy quarks are expected to be 100-200 MeV,
gluons contribution to the mass of the proton: $\approx$ 750 MeV

Why dileptons

- measured (DLS, HADES, CERES, NA60, STAR, ALICE)
- without final state interaction
- vector mesons decay to dileptons $\rightarrow$ vector mesons in matter
- interesting results for p-nucleus (KEK) and nucleus-nucleus (SPS,RHIC,LHC) collisions

Description of heavy ion reactions

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

- The initial state is known
- The degrees of freedom are known
- Final state? Transport models give good description of the data
- thermal models?
  (J. Cleymans, H. Oeschler, K. Redlich, J.Phys.G25:281-285,1999)
  particle ratios are good, except for η, for strangness an extra, somewhat artificial parameter, even then Ξ is completely wrong
  M. Zetenyi, Gy. Wolf, Influence of anisotropic Λ/Σ creation on the Ξ multiplicity in subthreshold proton-nucleus collisions, e-Print: arXiv:1803.10573
- No global equlibrium at 0.4 AGeV central $Ru^{96}_{44} + Zr^{96}_{40}$ collisions
  FOPI, Phys.Rev.Lett. 84 (2000) 1120

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 $\leftrightarrow$ Nπ, Nη, Nσ, Nρ, Nω, $\Delta\pi$, N(1440)π, KΛ, KΣ
- 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
- $\frac{d\sigma^{X \to NR}}{dM_R} \sim A(M_R)\lambda^{0.5}(s, M_R^2, M_N^2)$

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 $F_\alpha = f_\alpha(x,p,t)A_\alpha$
  $A(p) = -2ImG^{ret} = \frac{\hat{\Gamma}}{(E^2 - \mathbf{p}^2 - m_0^2 - \mathrm{Re}\Sigma^{ret})^2 + \frac{1}{4}\hat{\Gamma}^2}$,

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

Transport equations

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

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

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

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

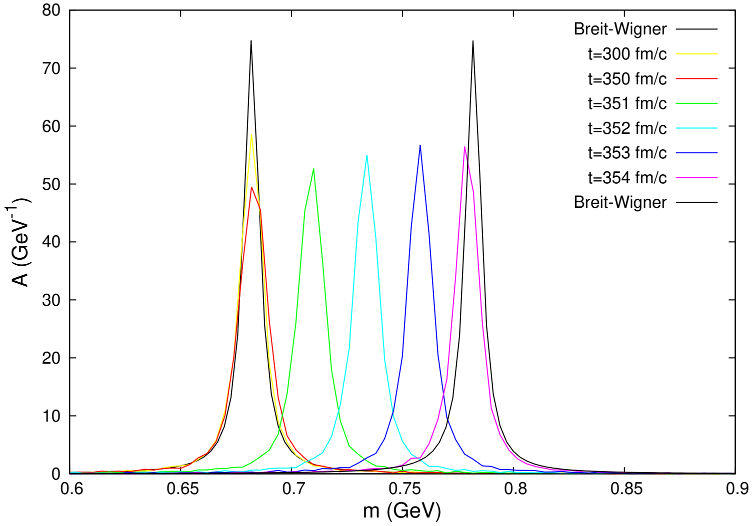
  $C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2-\vec{P}_i^2-M_0^2-Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{\partial}{\partial \epsilon_i} Im\Sigma^{ret}_{(i)} \right]$

- the last equation for homogenous system can be rewritten as

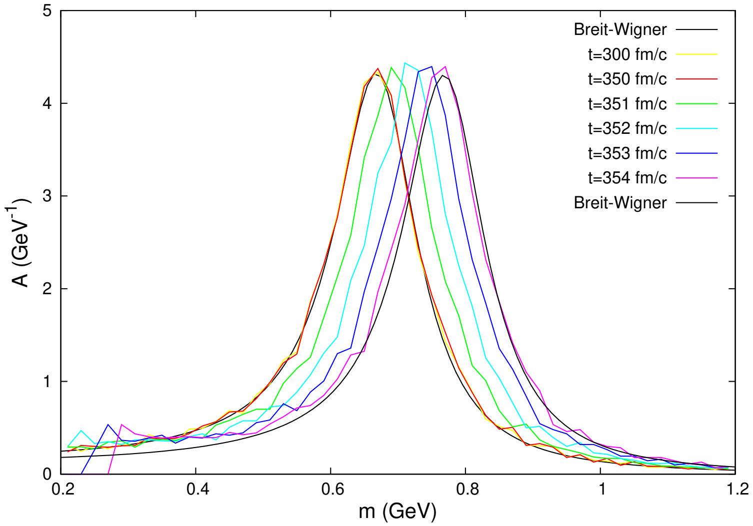
  $\frac{dM_i^2}{dt} = \frac{d(\epsilon_i^2-P_i^2)}{dt} = \frac{dRe\Sigma^{ret}_{(i)}}{dt} + \frac{M_i^2-M_0^2-Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{dIm\Sigma^{ret}_{(i)}}{dt}$

Evolution of mass distribution in a box

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



ω



ρ

Statistical Bootstrap approach

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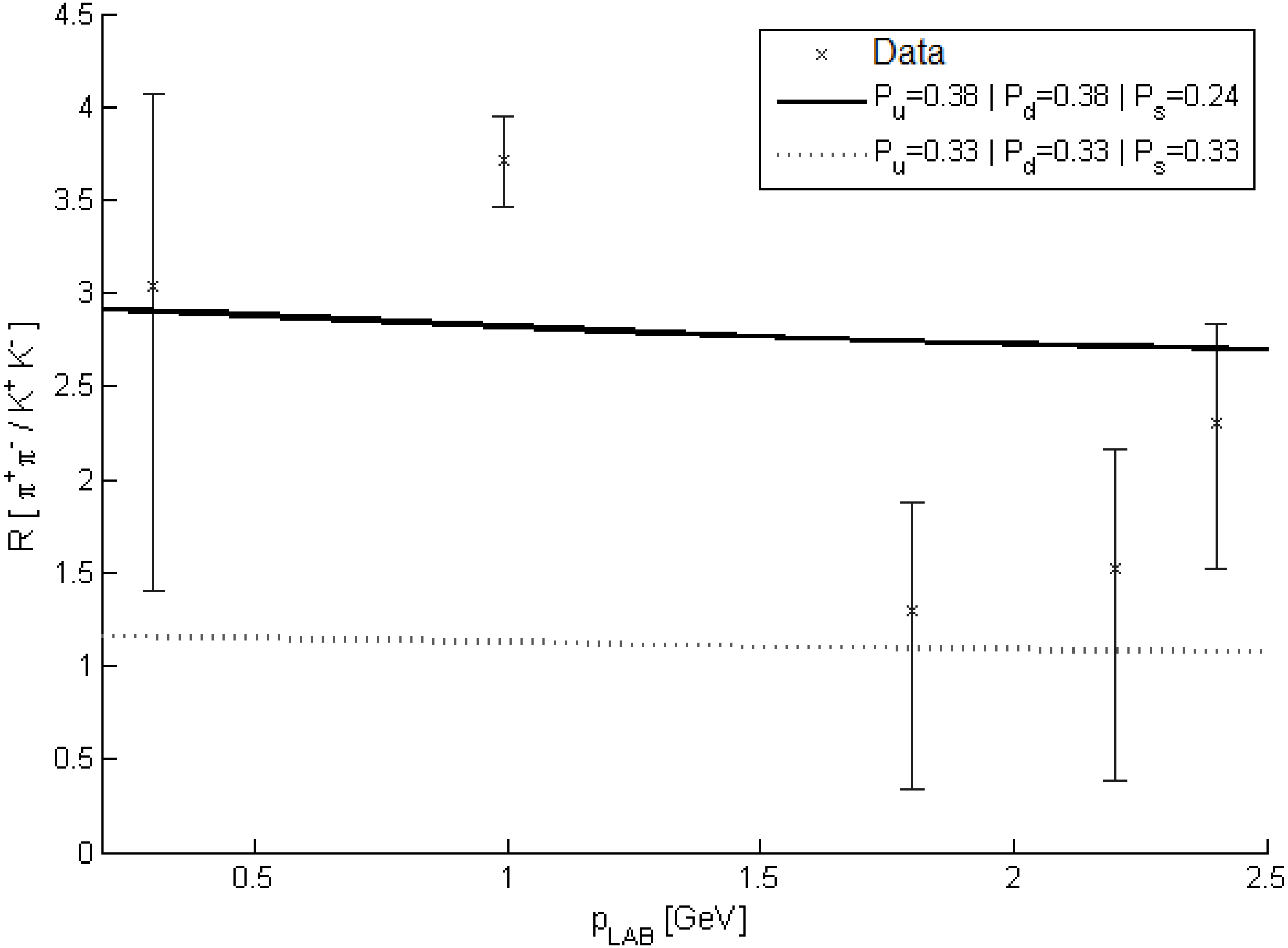
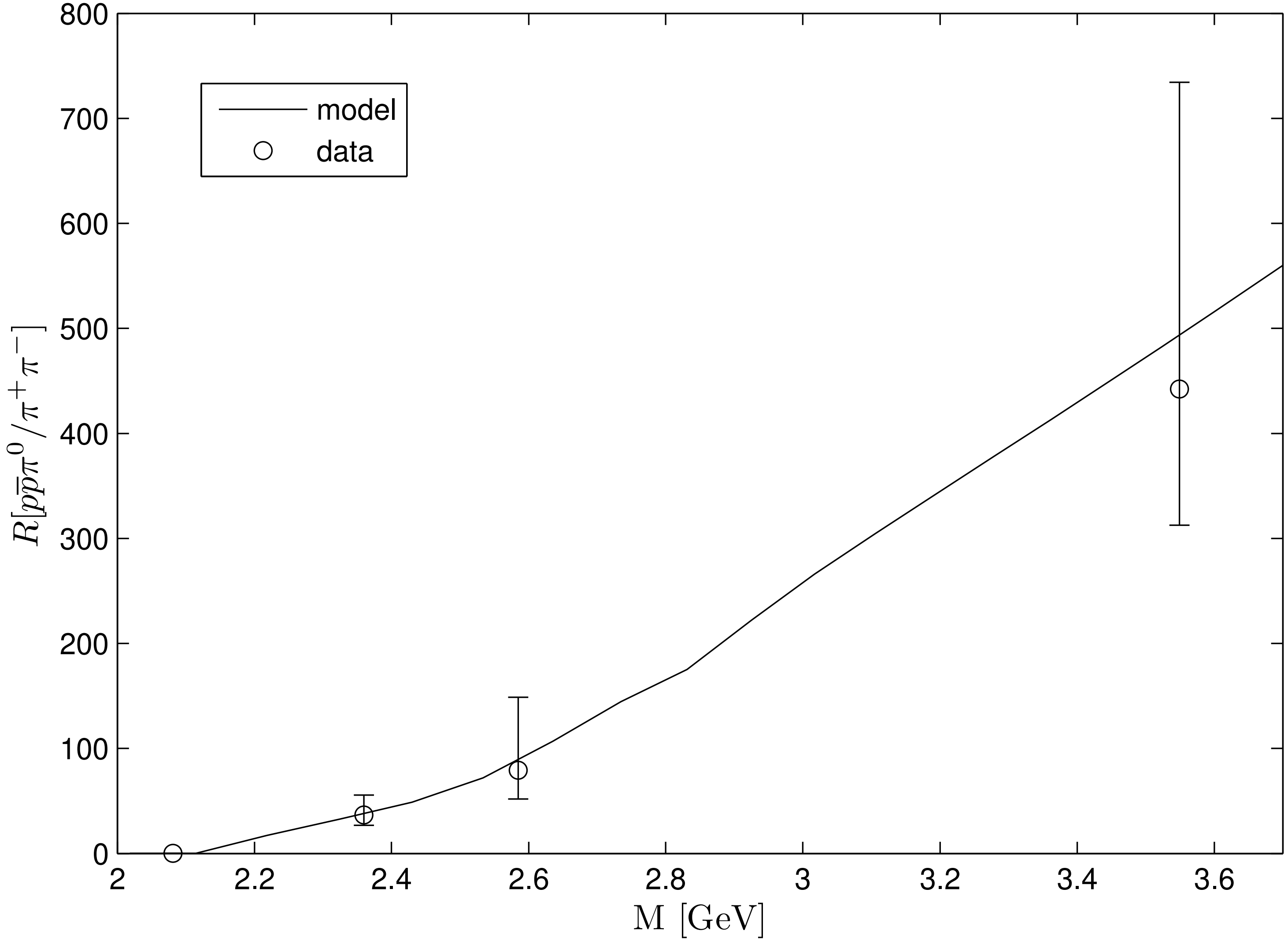
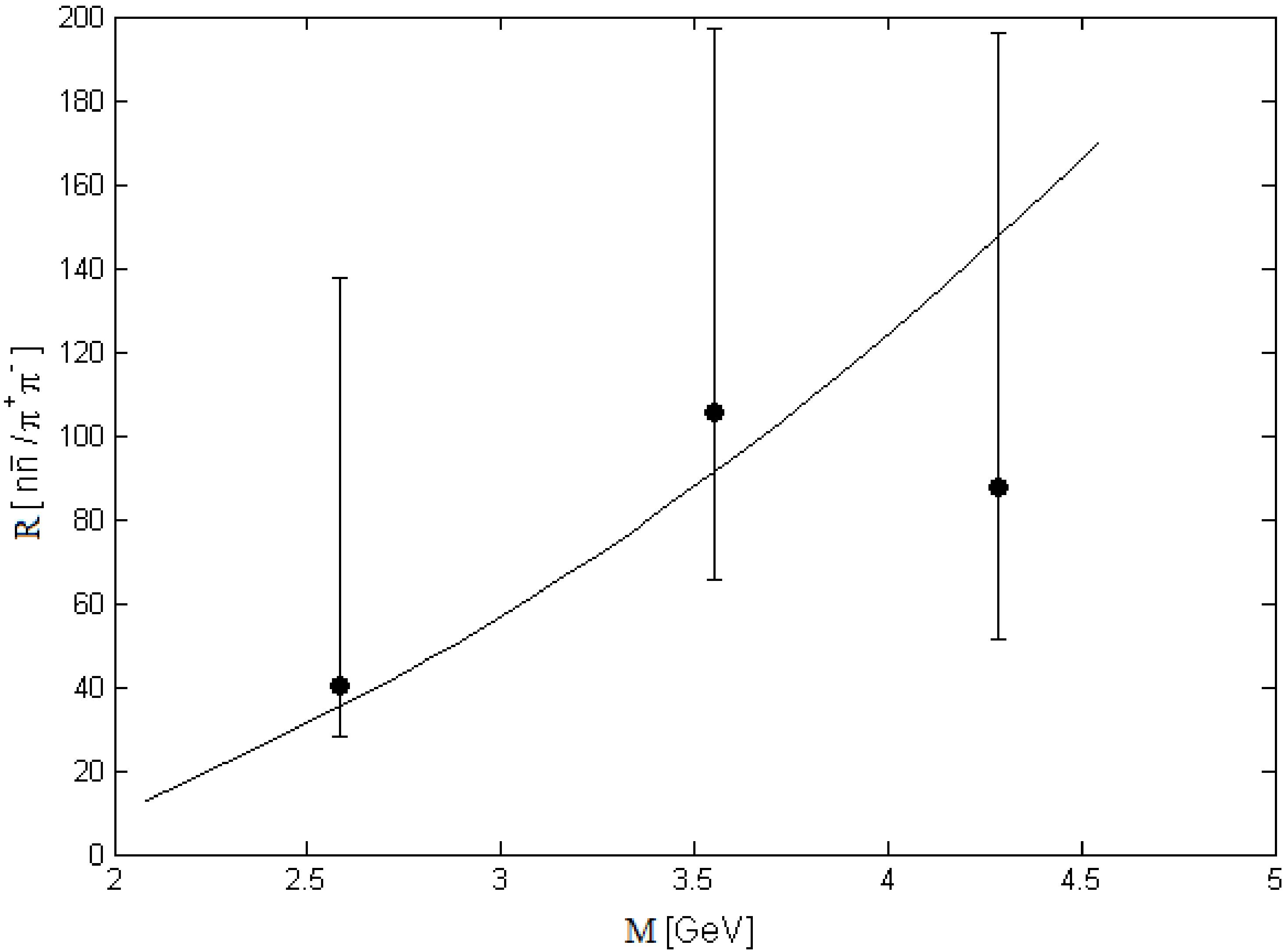
- Estimate unknown cross sections of different hadronic reactions up to a few GeV in c.m.s energy.
- Our method incorporate that during the collision a compound system, a fireball, is formed and, through possible production of subsequent fireballs, this system decays into a specific final state.
- The 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 $\rho(m)$.



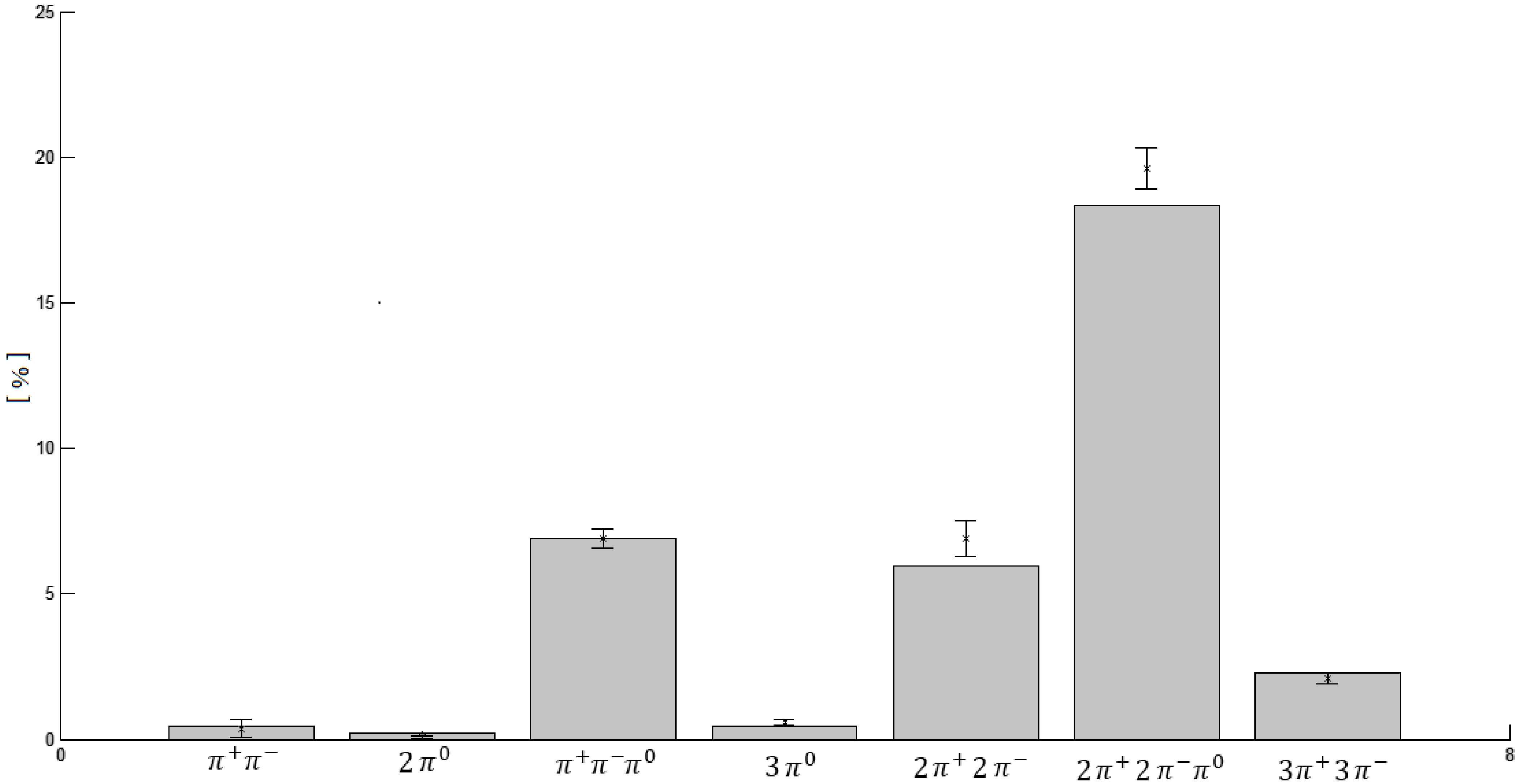
Data
P_u=0.38 | P_d=0.38 | P_s=0.24
P_u=0.33 | P_d=0.33 | P_s=0.33
R [$\pi^+\pi^-$ / K^+K^-]
p_{LAB} [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

Predictions





200
180
160
140
120
100
80
60
40
20
0
2
2.5
3
3.5
4
4.5
5
R [$n\bar{n}$ / $\pi^+\pi^-$]
M [GeV]



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

Charmonium in vacuum and in matter

- Charmonium: J/Ψ, Ψ(3686), Ψ(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

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

- 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?

$\bar{p}$A at PANDA energies

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

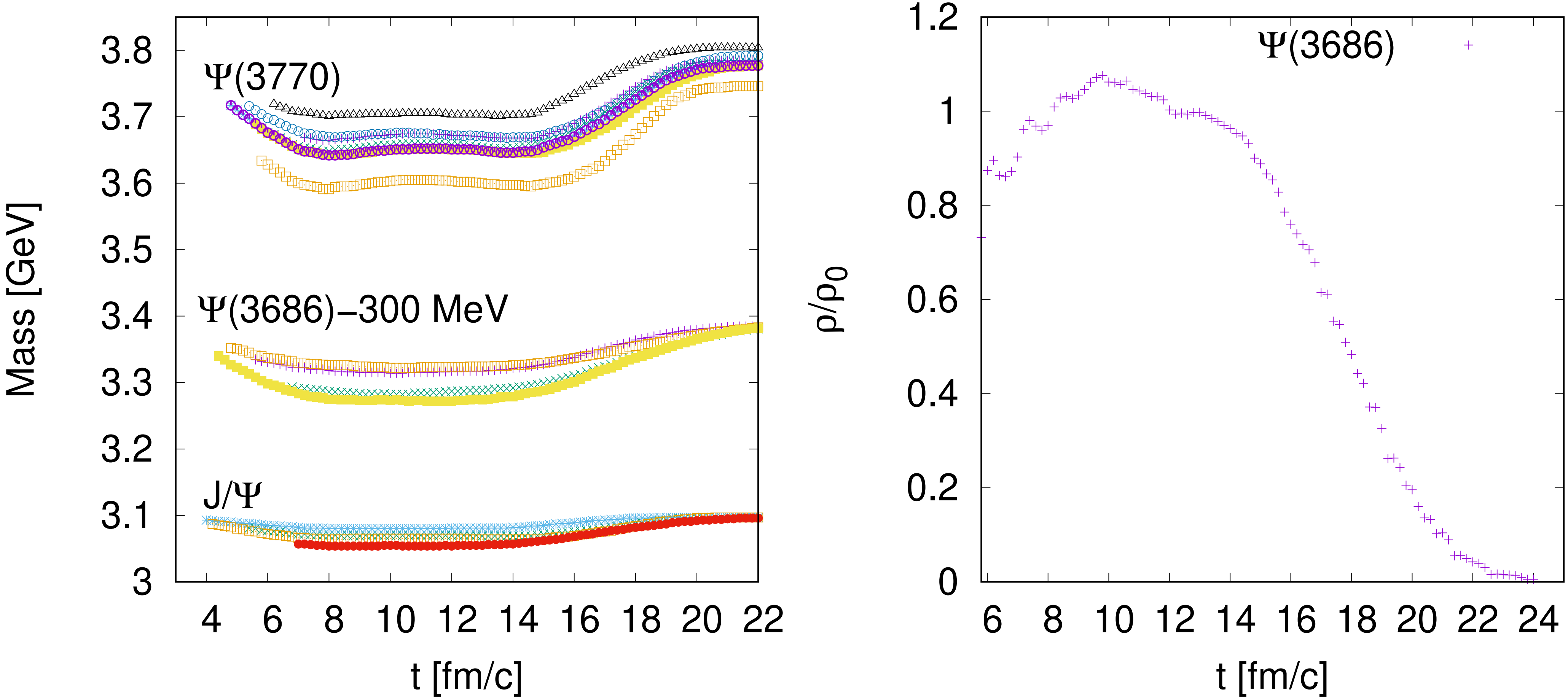
background:

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

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

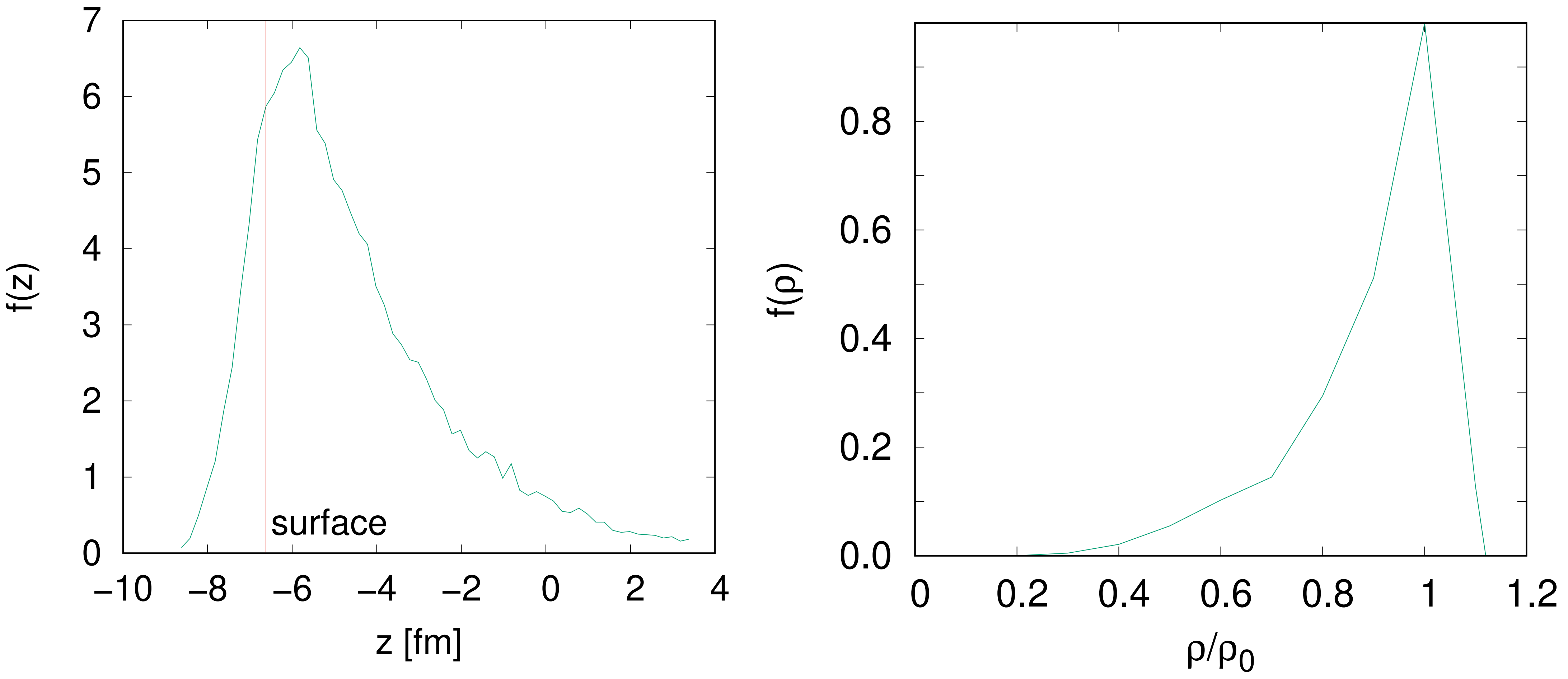
up to moderate energies the background is low

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



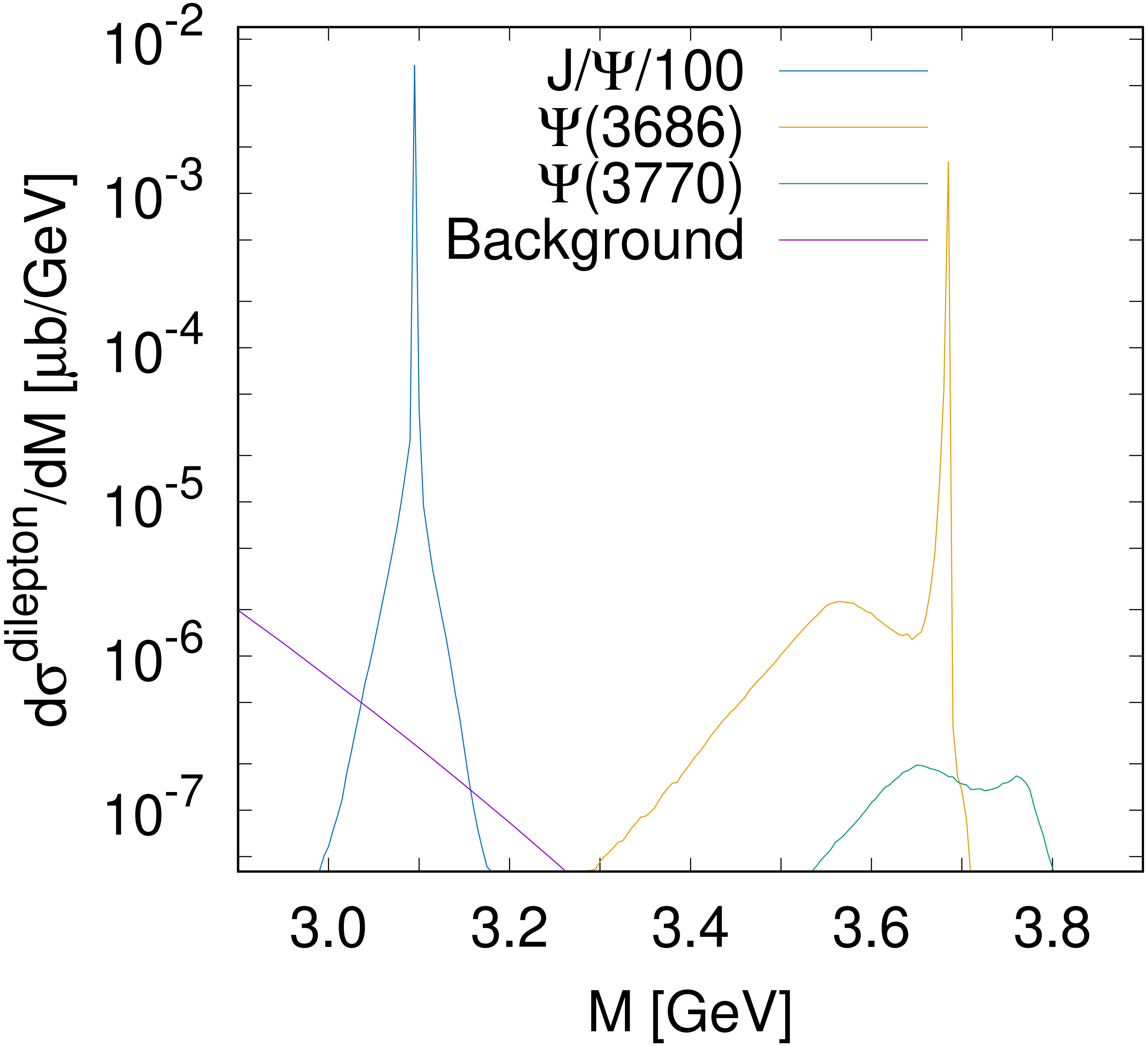
The charmonium states are created at the surface of the heavy nucleus,
travel through the dense matter (decays with some probability),
crosses the thin surface again and reaching the vacuum.
Major contribution to the dilepton channel are coming from the dense matter and from the vacuum.

Charmonium creation



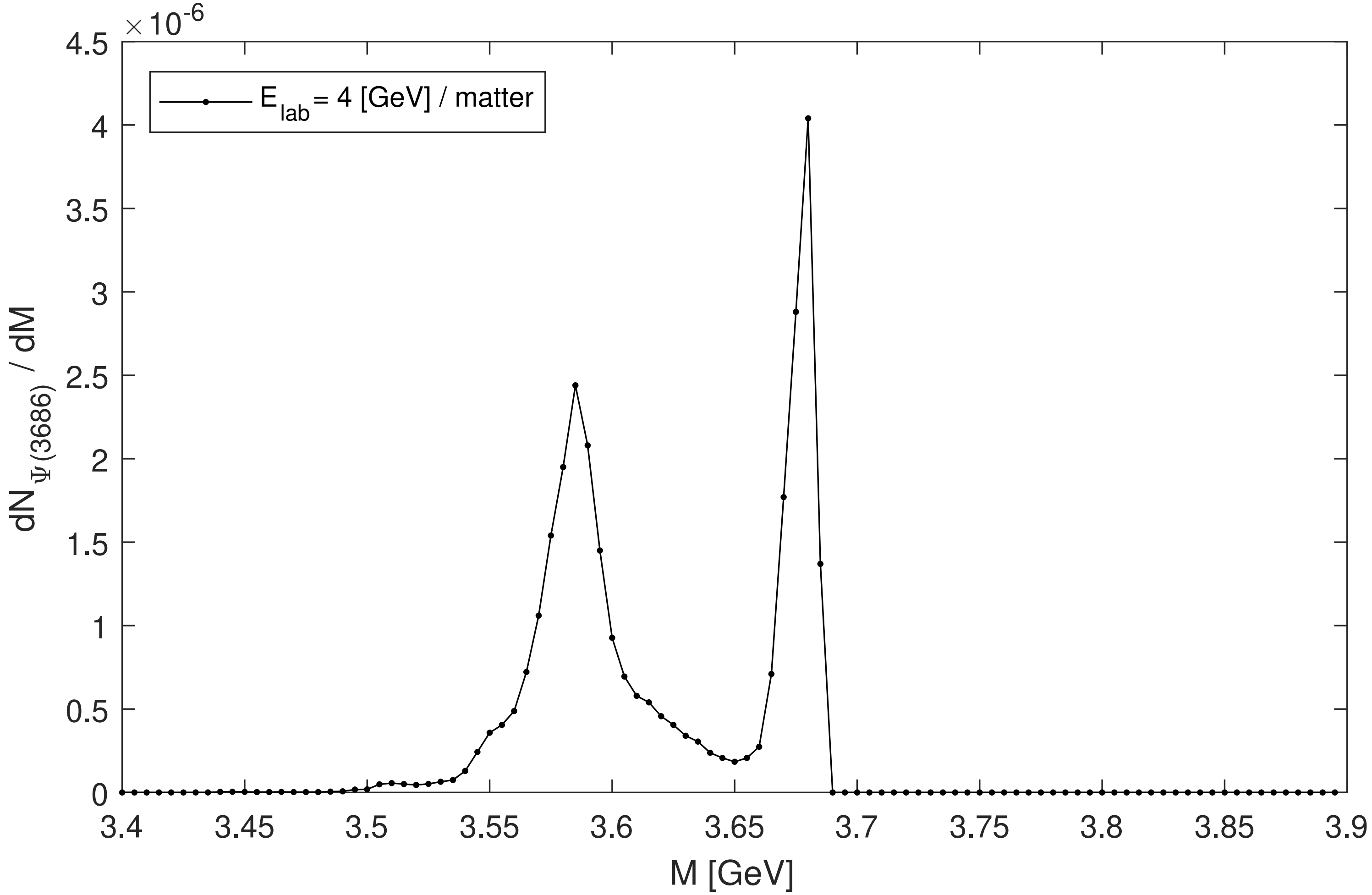
Most of the charmonium are created close to the surface of the nucleus

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



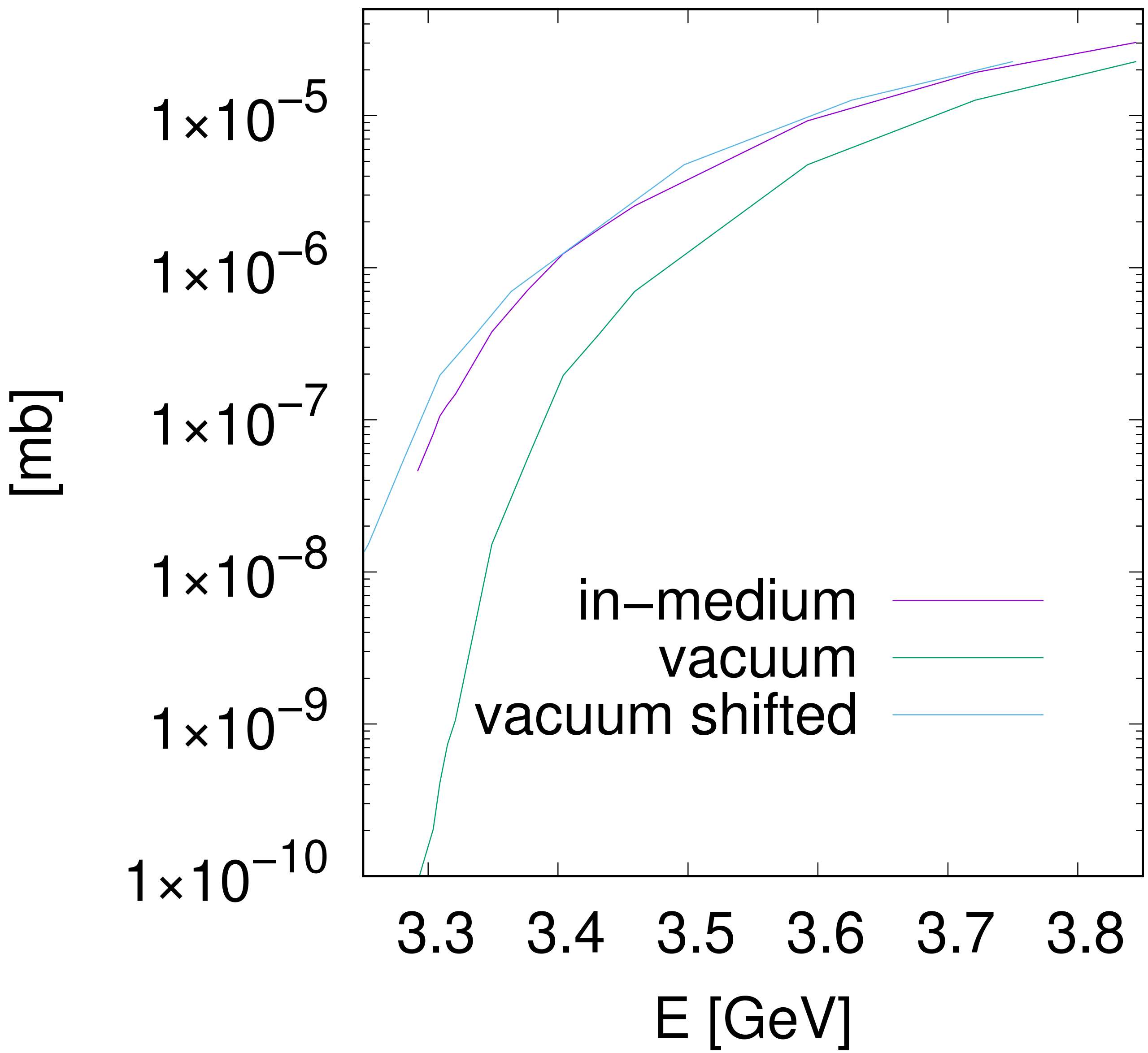
Dilepton invariant mass spectrum in central collision (0-4.5 fm, ≈ 33% of the cross section)

$\bar{p}$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



$\Psi(3686)$

- 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
- 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?

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.
- We can measure the gluon condensate in nuclear matter.