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

Zimányi school, Budapest, 04.12.2018.

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MTA Wigner RCP

- Motivation
- Transport
- hadron($\bar{p}, \pi$,p)A reaction (PANDA, JPARC?)

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
Act. Phys. Pol. B11 (2018) 531

# 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/$\psi$ 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 ($\pi$N scattering, $\sigma$-term):$\approx$ 50 MeV,

gluons contribution to the mass of the proton: $\approx$ 750 MeV

# BUU

- $$\frac{\partial F}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial F}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial F}{\partial \mathbf{p}} = \mathcal{C}, \quad H = \sqrt{(m_0 + U(\mathbf{p},\mathbf{x}))^2 + \mathbf{p}^2}$$
- potential: momentum dependent, soft: K=215 MeV
  $$U^{nr} = A\frac{n}{n_0} + B\left(\frac{n}{n_0}\right)^{\tau} + C\frac{2}{n_0}\int \frac{d^3p'}{(2\pi)^3}\frac{f_N(x,p')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2},$$
- testparticle method
  $$F = \sum_{i=1}^{N_{test}} \delta^{(3)}(\mathbf{x} - \mathbf{x}_i(t))\delta^{(4)}(p - p_i(t)).$$
- Unknown cross sections: Statistical bootstrap:
  G. Balassa, P. Kovács, Gy. Wolf, Eur. Phys. J. A54 (2018) 25,

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

Gy. Wolf, M. Zetenyi, Eur.Phys.J. A52 (2016) 258

M. Zetenyi, Gy. Wolf, Phys.Lett. B785 (2018) 226

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

  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

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

# 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?
  due to collisional broadening $\Gamma^{tot}_{med} >> \Gamma^{tot}_{vac}$. What is $\Gamma^{em}_{med}$? $Br^{em}_{med}$?

# hadron($\bar{p}$, $\pi$,p) A around charmonium threshold energies

| Charmonium | Stark-effect+ $\bar{D}D$ loop |
|---|---|
| J/$\Psi$ | -8+3 MeV $\rho/\rho_0$ |
| $\Psi$(3686) | -100-30 MeV$\rho/\rho_0$ |
| $\Psi$(3770) | -140+15 MeV $\rho/\rho_0$ |

collisional broadening at $\rho_0$: 15 MeV, 26 MeV and 26 MeV (cross sections were fitted to charmonium suppression at SPS)

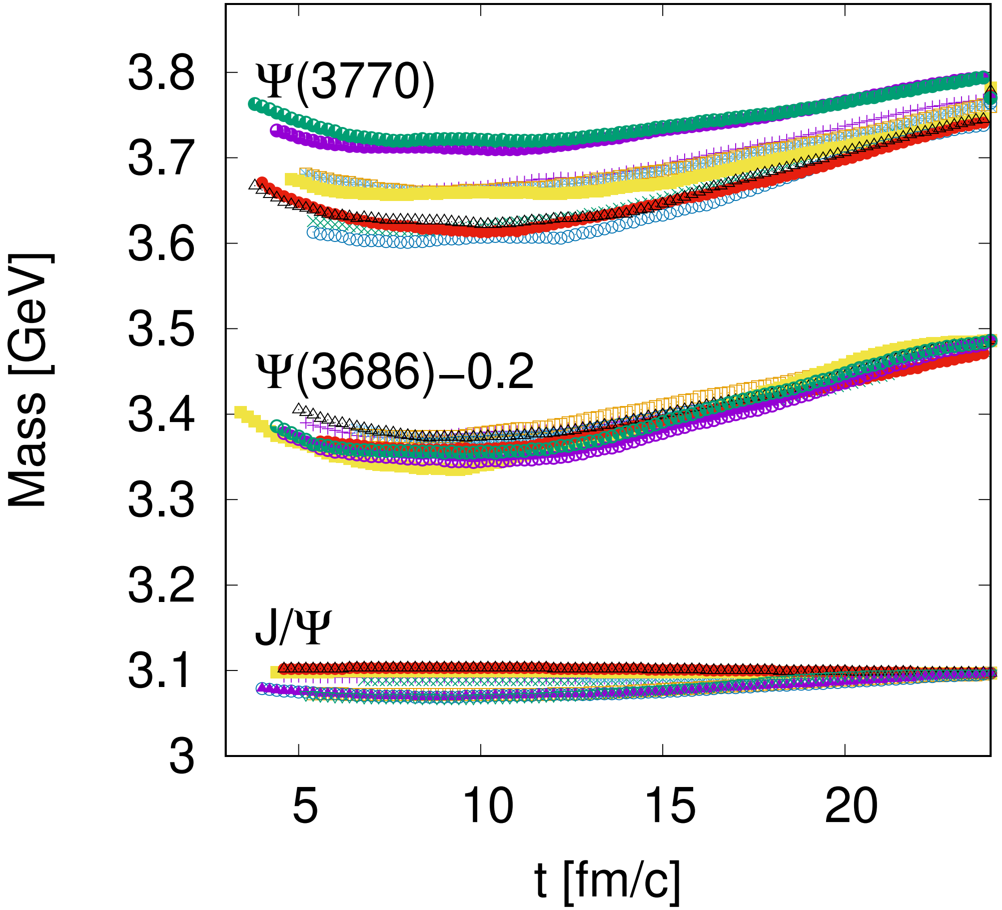
background:

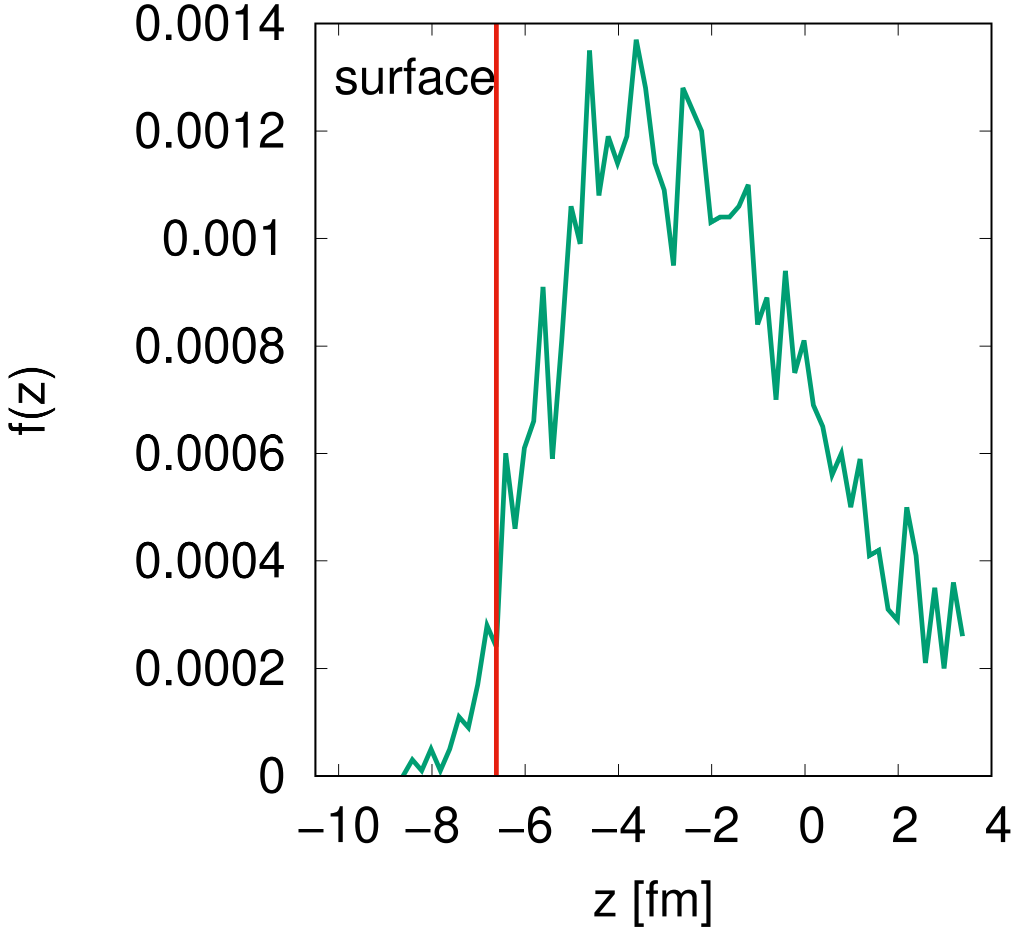
Drell-Yan: small number of energetic hadron-hadron collisions

$\bar{D}D$ decay: c quark decays weakly to s quark, $D \to Ke\bar{\nu}_e$ 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

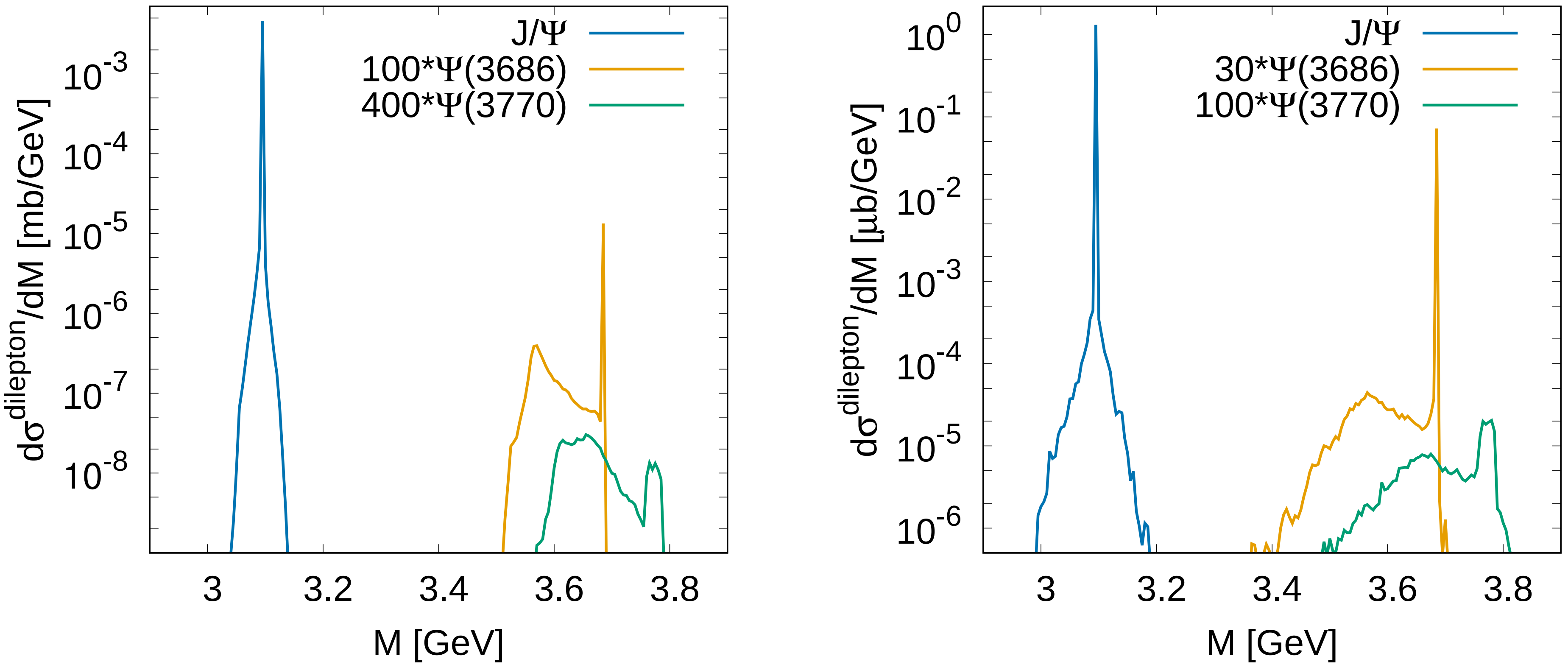
# Time evolution of masses and pos. of creation in $\pi$Au 6.5 GeV



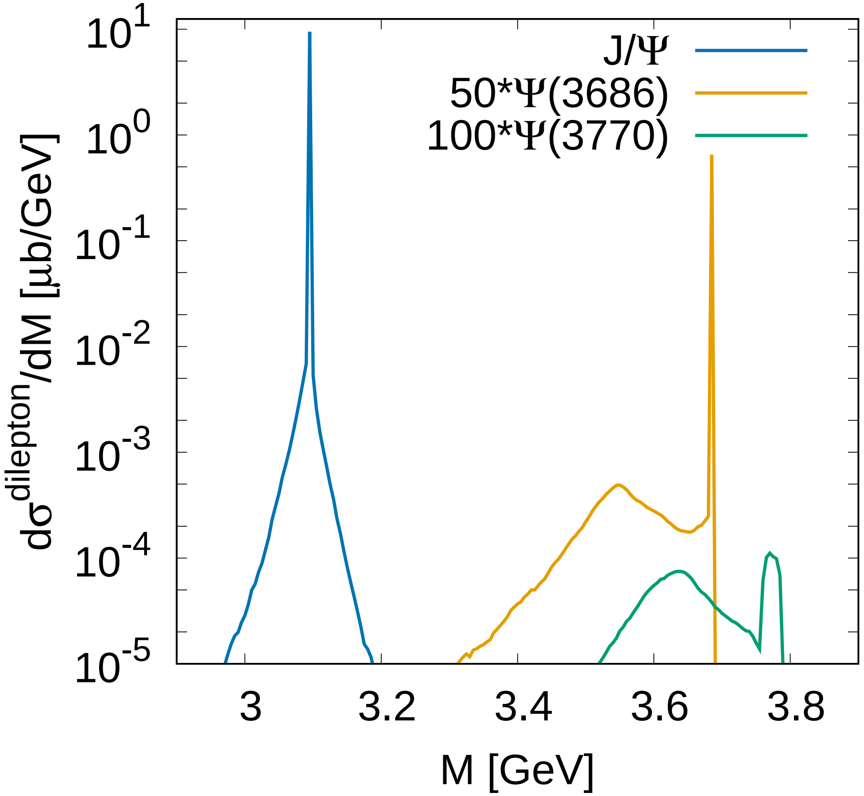



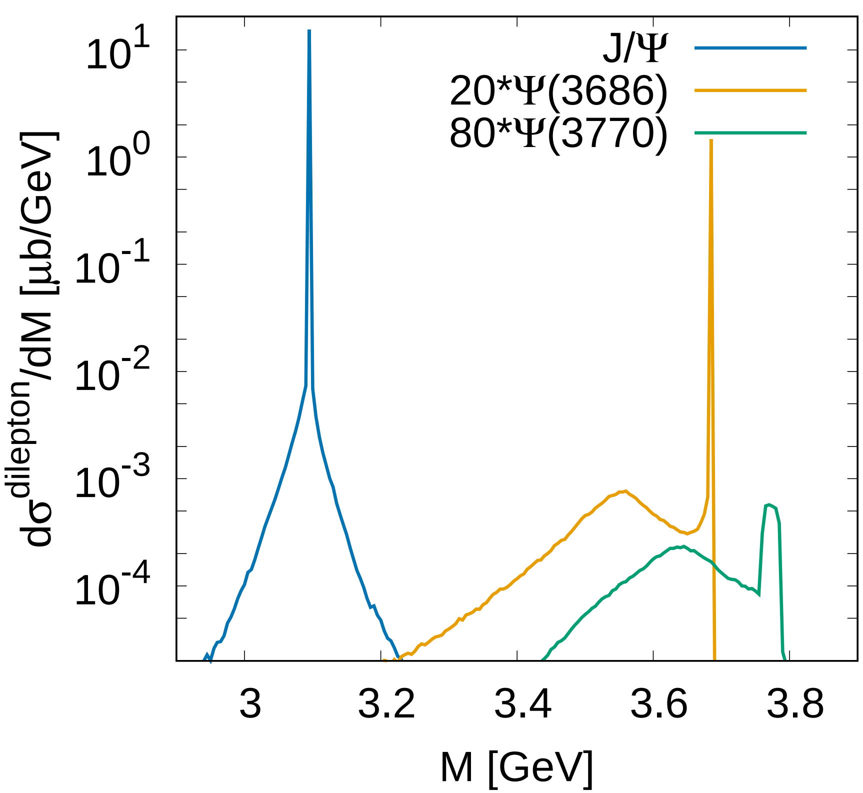

The charmonium states are created at the surface of the heavy nucleus,
travel through the dense matter (decays with some probability),
crosses the thin surface again and reaching the vacuum.
Major contribution to the dilepton channel are coming from the dense matter and from the vacuum. $t_{\rho>0.8} \approx 9$ fm, $t_{0.8>\rho>0.2} \approx 4$ fm.

# $\pi$Au at 6 GeV, pAu at 15 GeV

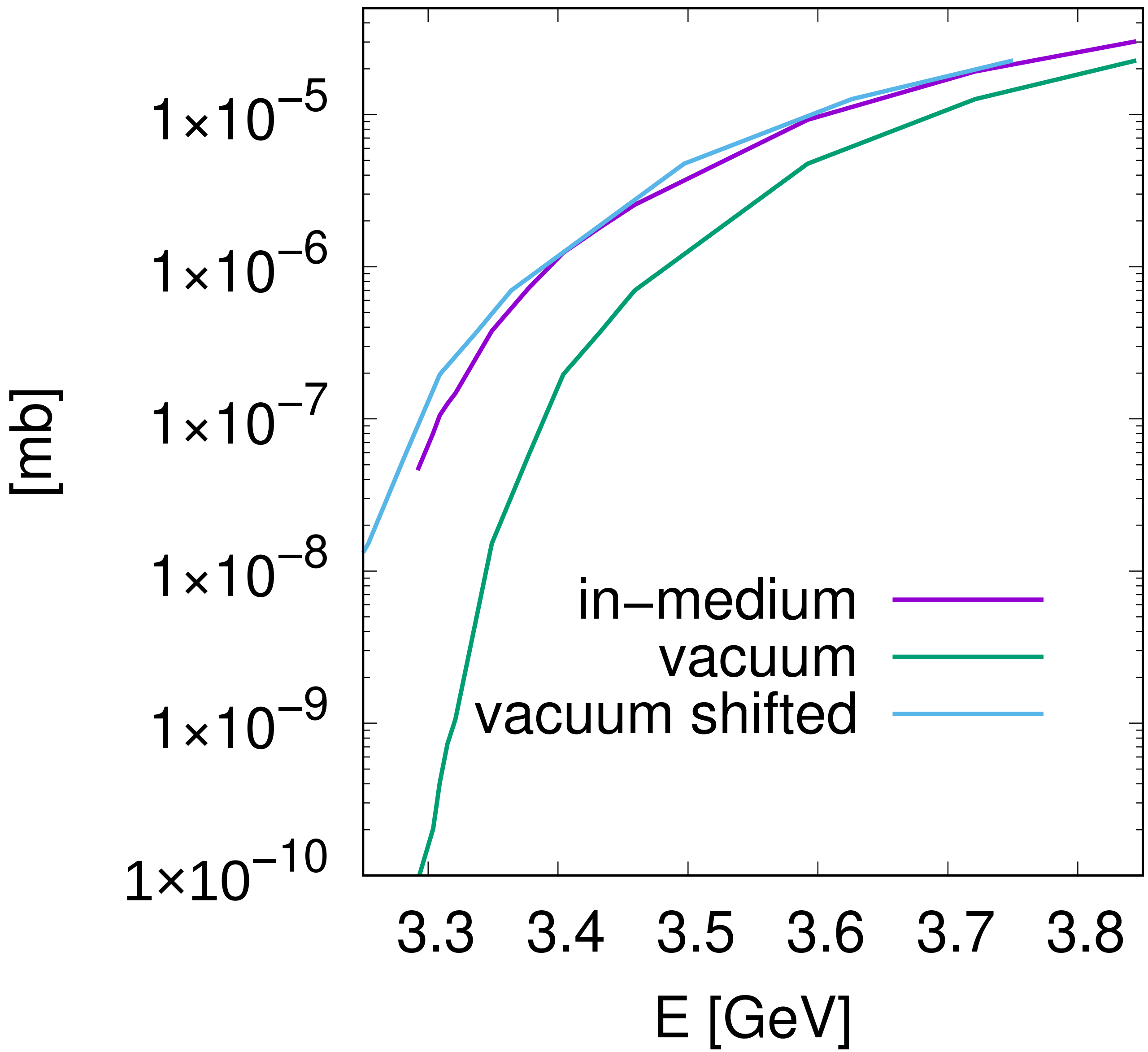


# $\bar{p}$Au at 5, 8 GeV

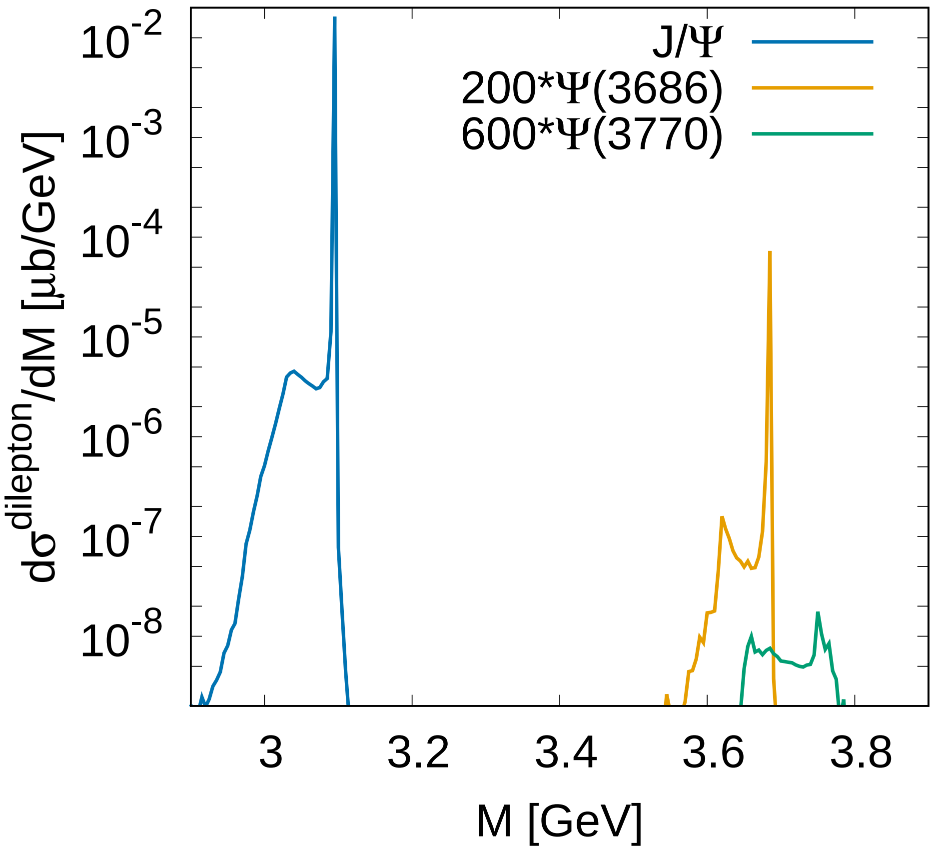


# $\Psi(3686)$ excitation function in $\bar{p}$Au reactions

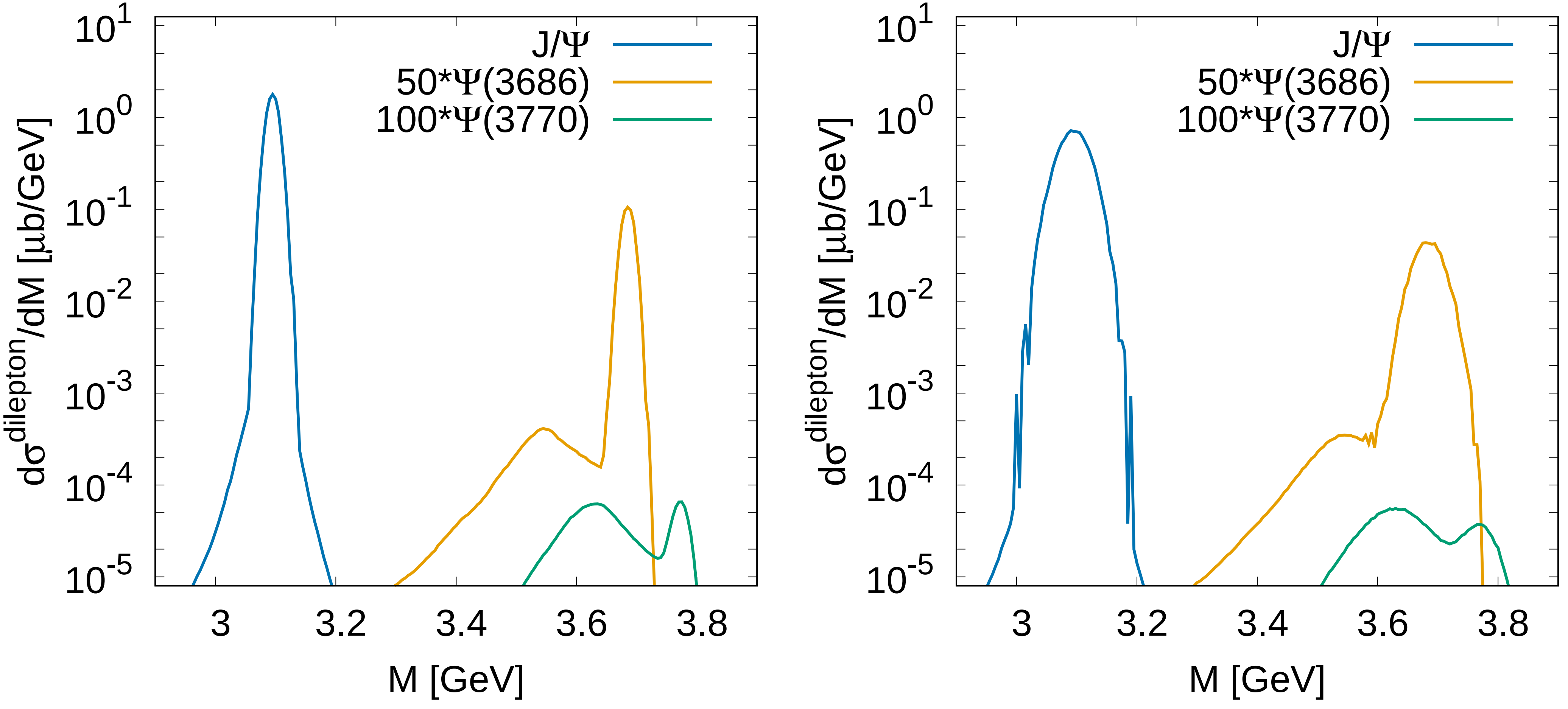


# Playing with the mass shift




pAu E=9 GeV, mass shift 50 MeV

# Detector resolution in $\bar{p}$Au 5.0 GeV




The influence of the detector resolution, left: 0.02 MeV, right 0.05 MeV.

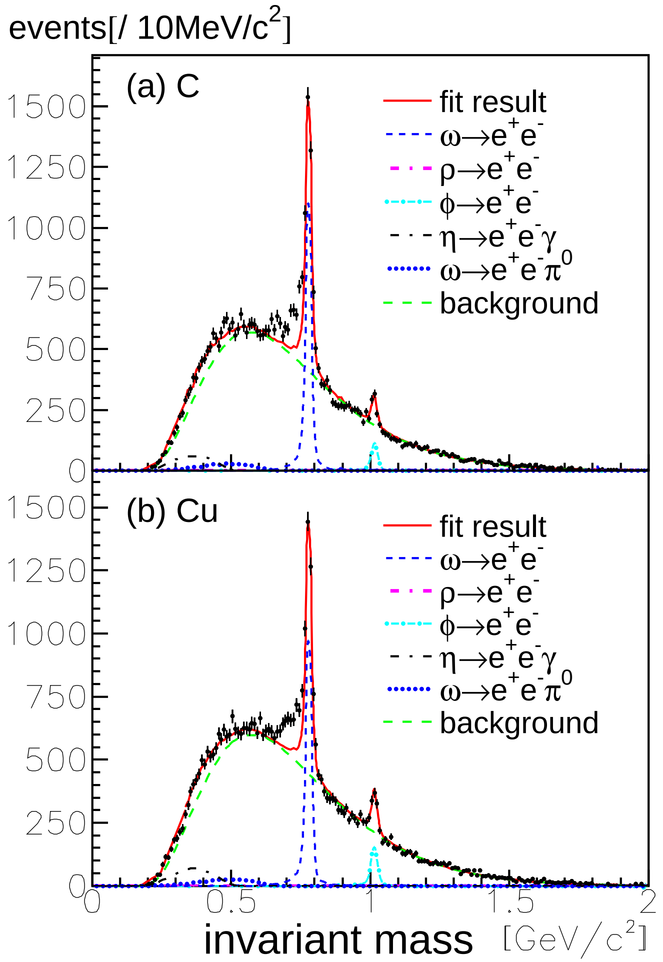
# $\Psi(3686)$

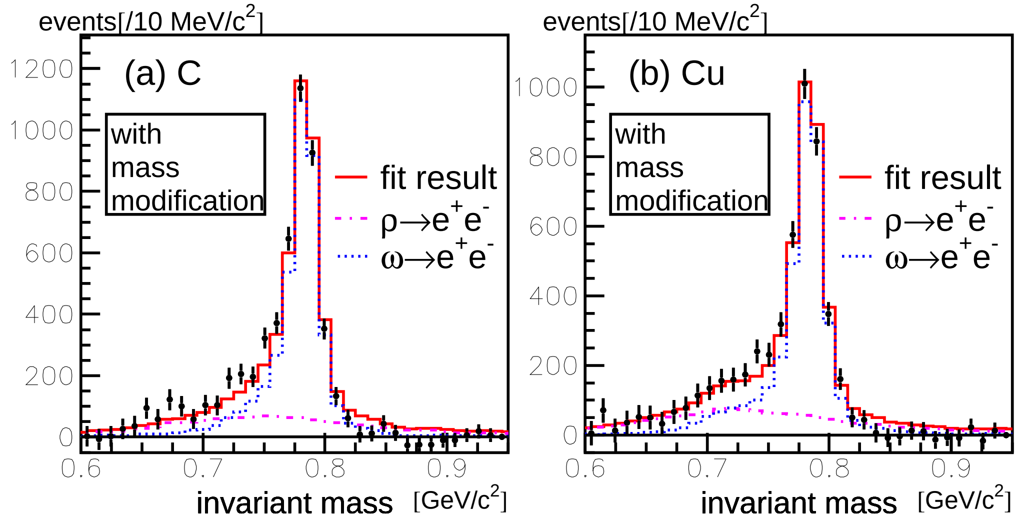
- The distance between the peaks corresponds to a mass shift at $\rho \approx 0.9\rho_0$
- qualitatively the same picture if increase or reduce the mass shift by factor of 2
- measuring the peak distance, we obtain the mass shift at $\rho \approx 0.9\rho_0$
- measuring the mass shift, we obtain the gluon condensate at $\rho \approx 0.9\rho_0$
- the same picture in $\bar{p}, \pi$, p at and above thresholds
- 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 sections 25 mb (40 mb for p)
- can the error of the experimental mass resolution from the vacuum peak overshadow the smaller, in-medium peak?

## Summary

- Dilepton production in hadron-A provides us the possibility to study charmonium mass shift in matter. In all systems we found in-medium spikes for $\Psi(3686)$.
- We can measure the gluon condensate in nuclear matter.

# KEK E325 12 GeV pA data $\rho$ and $\omega$



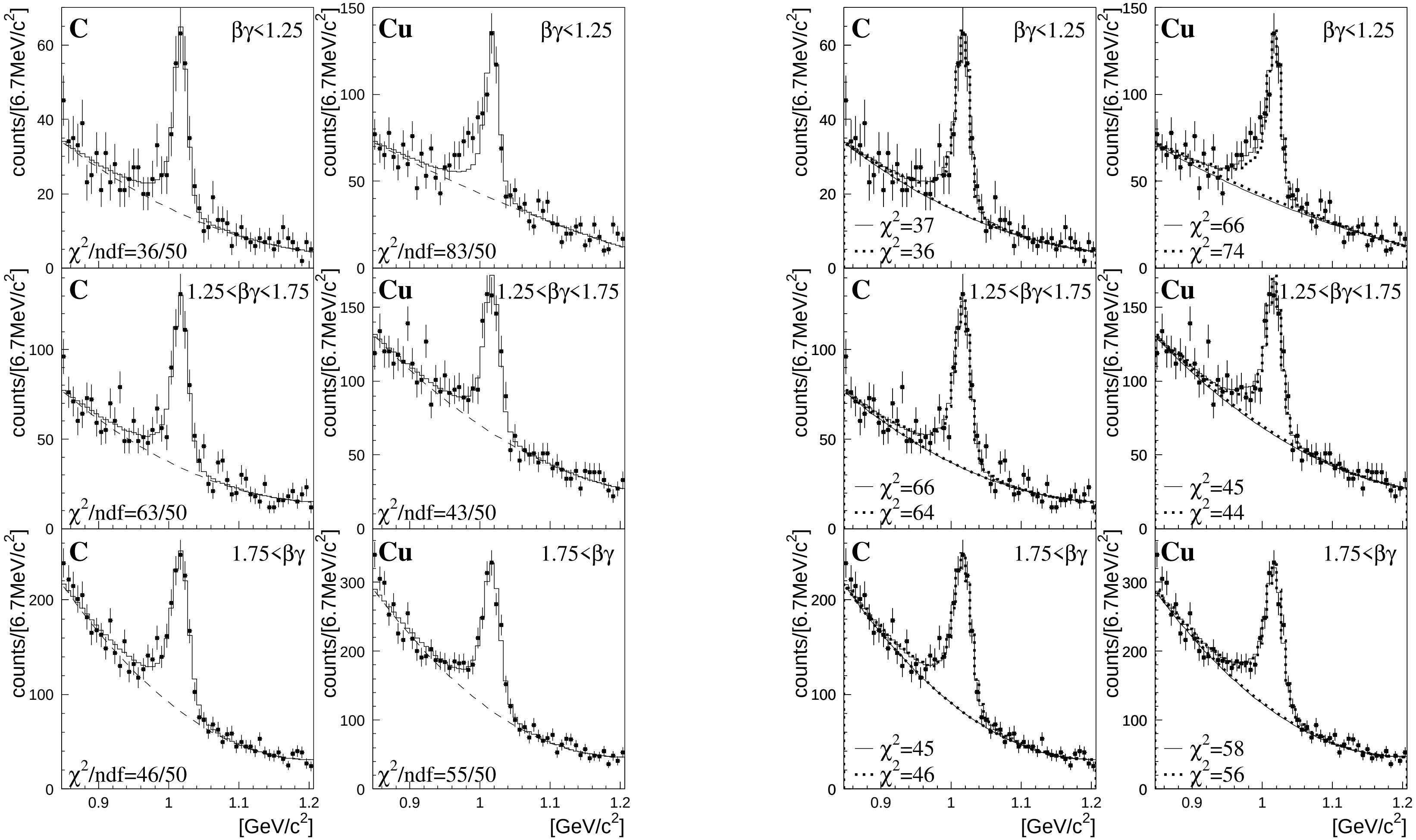




$$m(\rho)/m(0) = 1 - 0.09(\rho/\rho_0)$$

no broadening

M. Naruki *et al.*
Phys. Rev. Lett. 96 (2006) 092301

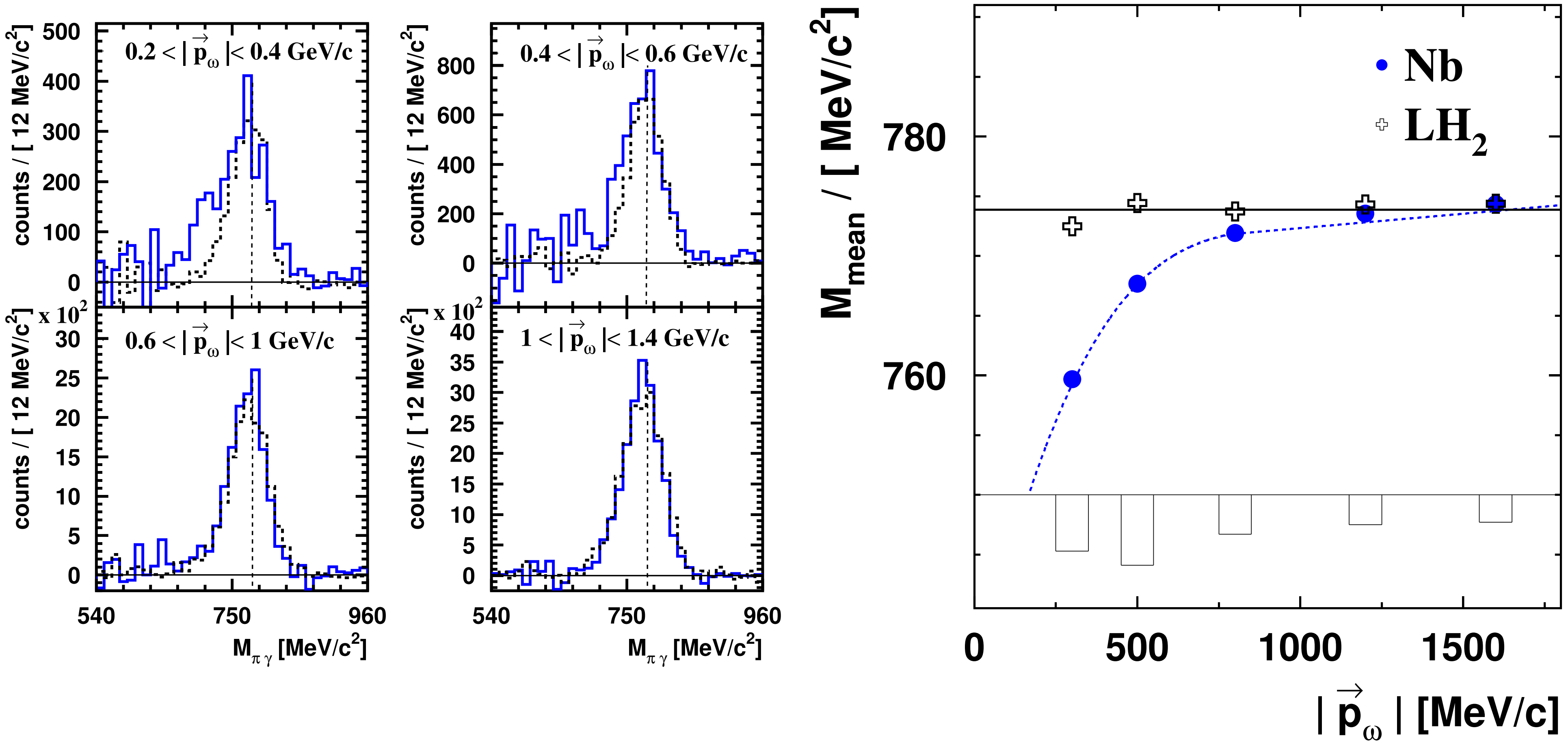
# KEK E325 12 GeV pA data for $\phi$




$$m(\rho)/m(0) = 1 - 0.033(\rho/\rho_0)$$
$$\Gamma(\rho)/\Gamma(0) = 3.6(\rho/\rho_0)$$

R. Muto *et al.*
Phys. Rev. Lett. 98 (2007) 042501

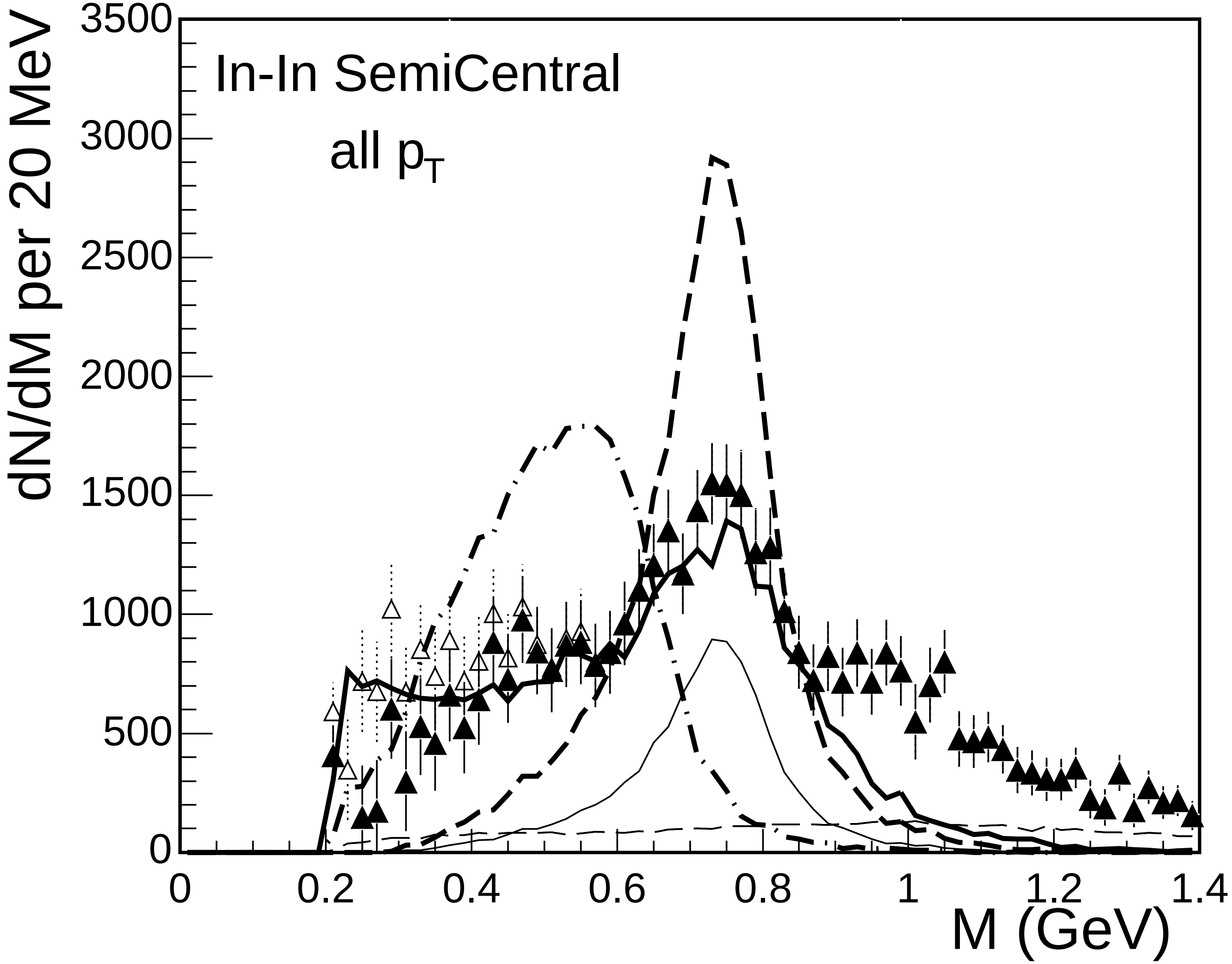
# TAPS/ELSA data for $\gamma A \to \omega X$




$m(\rho)/m(0) = 1 - 0.14(\rho/\rho_0), \quad \bar{\rho} = 0.6\rho/_0$
$\Gamma_{res} = 55MeV$

D. Trnka *et al.*
Phys. Rev. Lett. 94 (2005) 192303

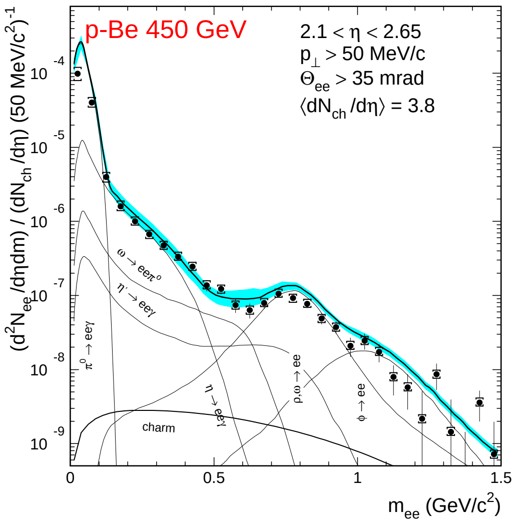
# NA60 data for $\rho$

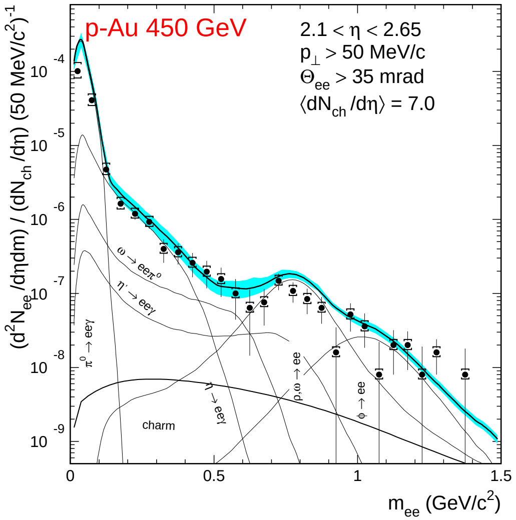


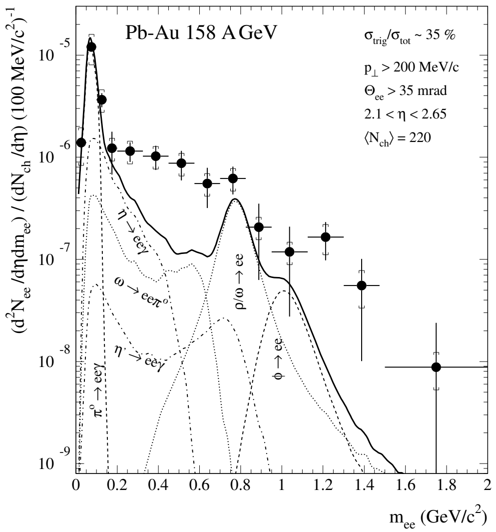

thick solid line: $\rho$-broadening due to hadronic reactions
R. Rapp, J. Wambach
Adv. Nucl. Phys. 25, 1

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

# CERES data



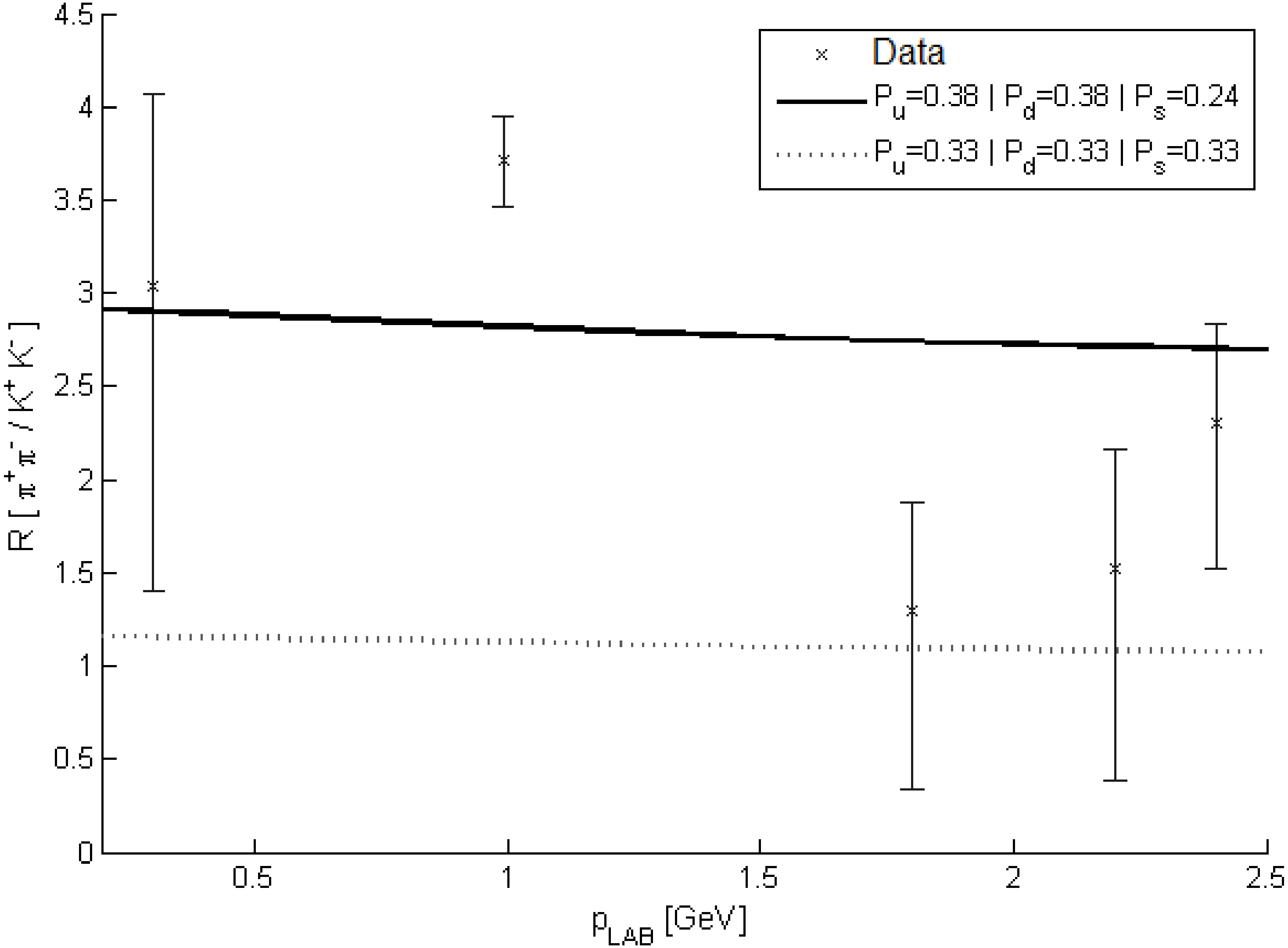

G. Agakichiev *et al.*
Eur. Phys. J. C4 (1998) 231

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

## Statistical Bootstrap approach

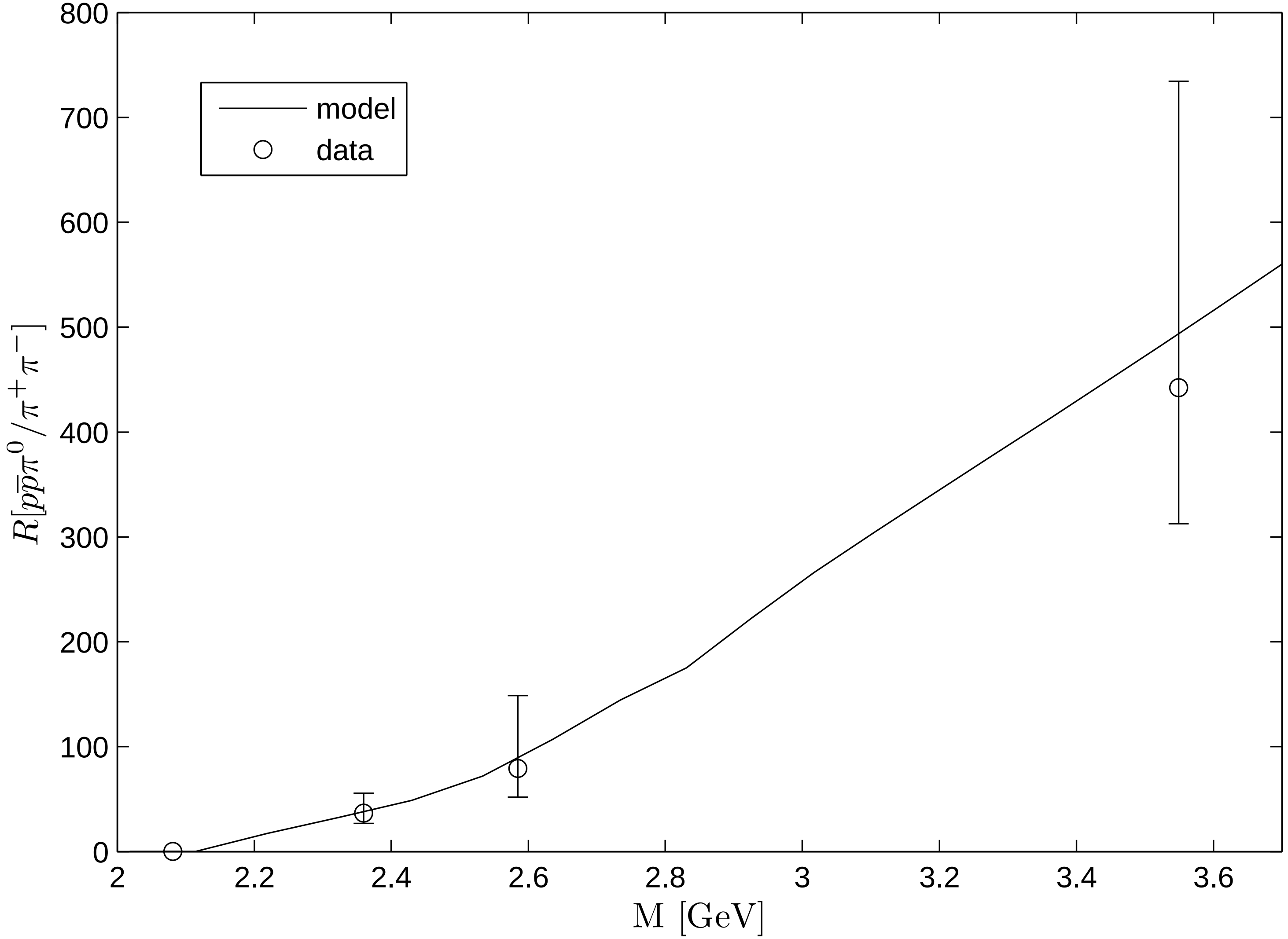
G. Balassa, P. Kovács, Gy. Wolf, Eur. Phys. J. A54 (2018) 25

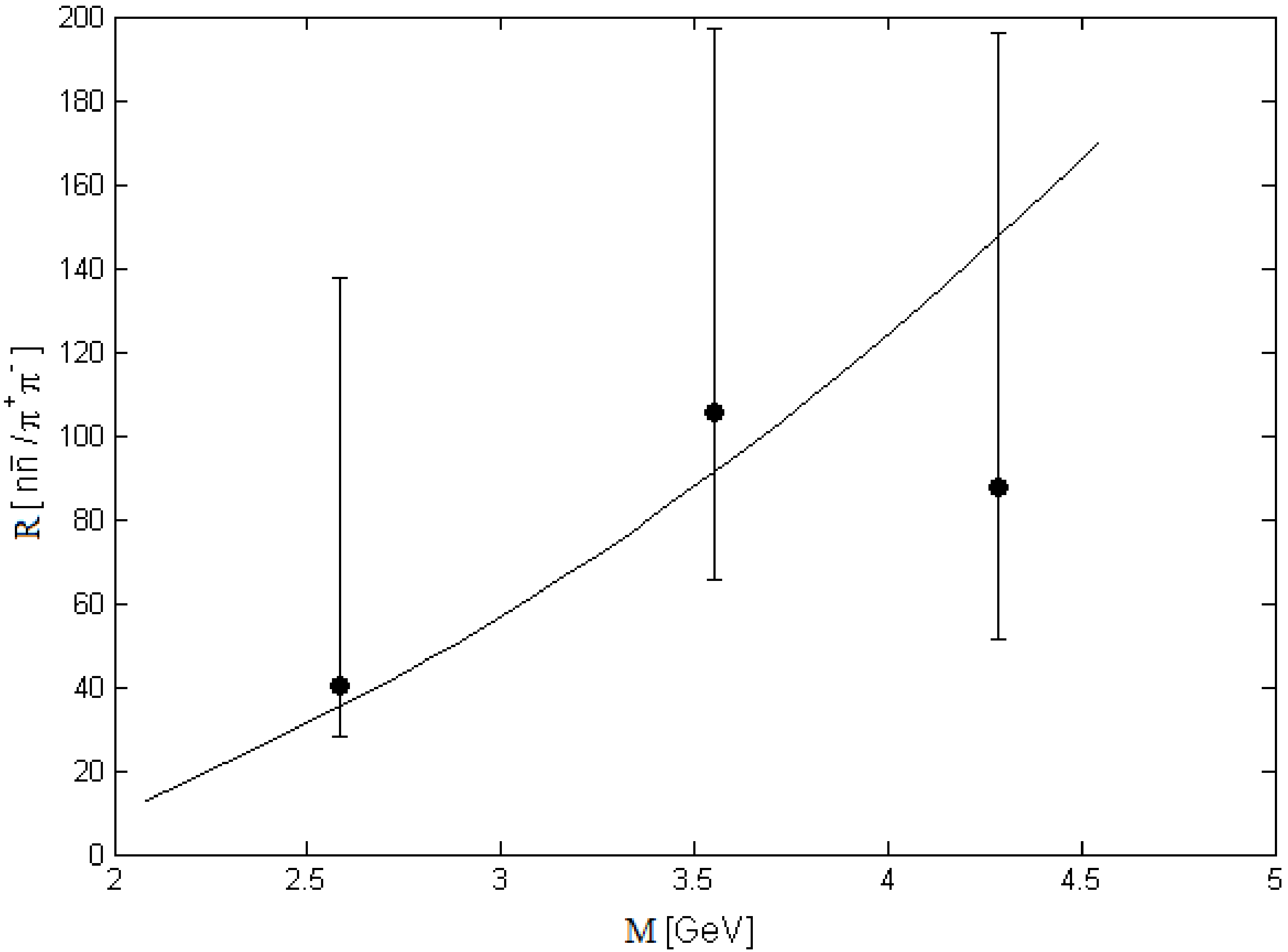
- Estimate unknown cross sections of different hadronic reactions up to a few GeV in c.m.s energy.
- Our method incorporate that during the collision a compound system, a fireball, is formed and, through possible production of subsequent fireballs, this system decays into a specific final state.
- The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



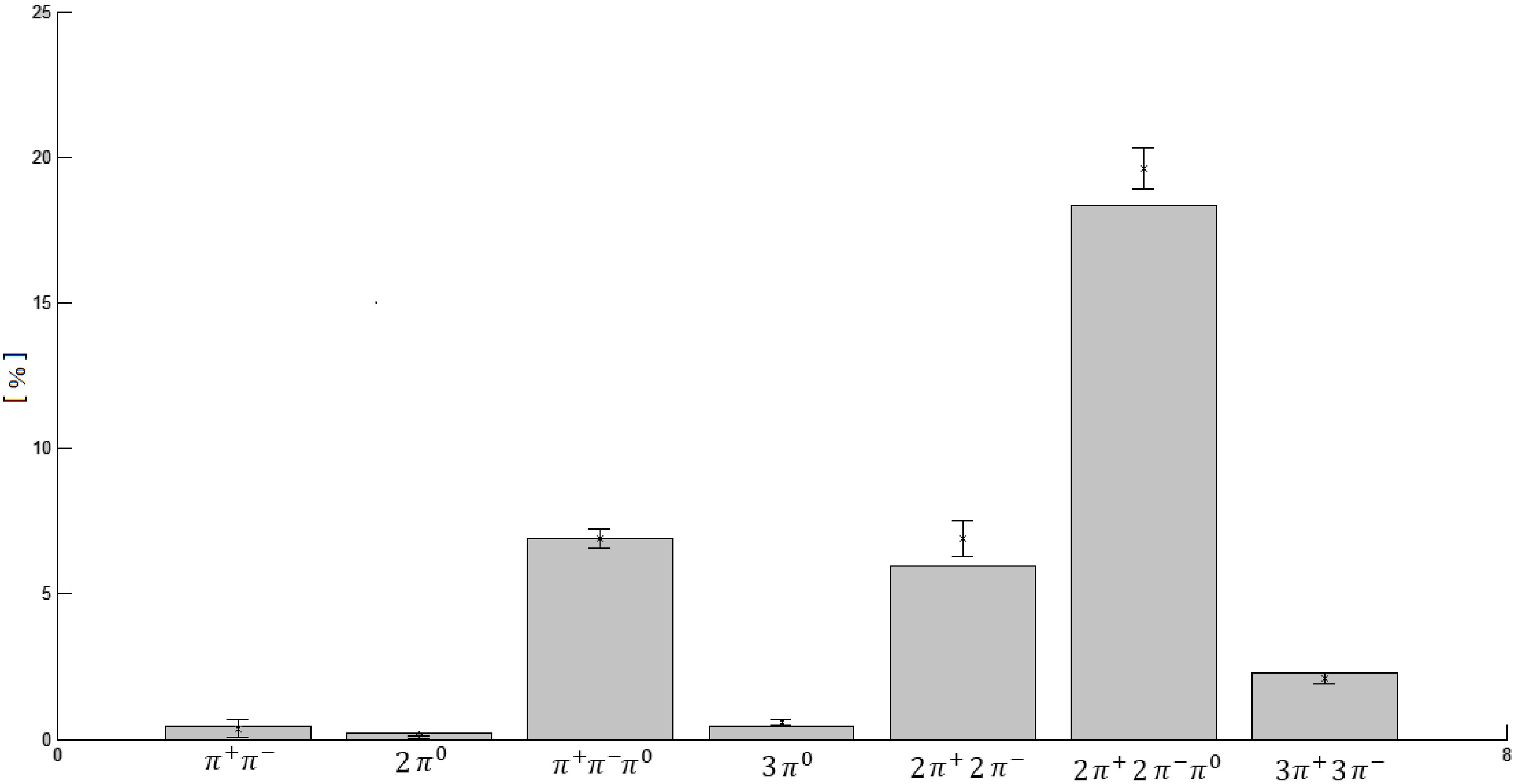
Data
P_u=0.38 | P_d=0.38 | P_s=0.24
P_u=0.33 | P_d=0.33 | P_s=0.33
R [ π+π- / K+ K- ]
p_LAB [GeV]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5

# 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
$\pi^+\pi^-$
$2\pi^0$
$\pi^+\pi^-\pi^0$
$3\pi^0$
$2\pi^+2\pi^-$
$2\pi^+2\pi^-\pi^0$
$3\pi^+3\pi^-$