What we can learn from proton induced Charmonium production

Physics opportunities with proton beams at SIS100
6-9 Febr. 2024, Wuppertal.

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in collaboration with G. Balassa, Wigner RCP
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- Motivation
- Transport
- hadron($\bar{p}$, π,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, B11 (2018) 531
Phys. Lett. B780 (2018) 25, arXiv:1712.06537

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

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

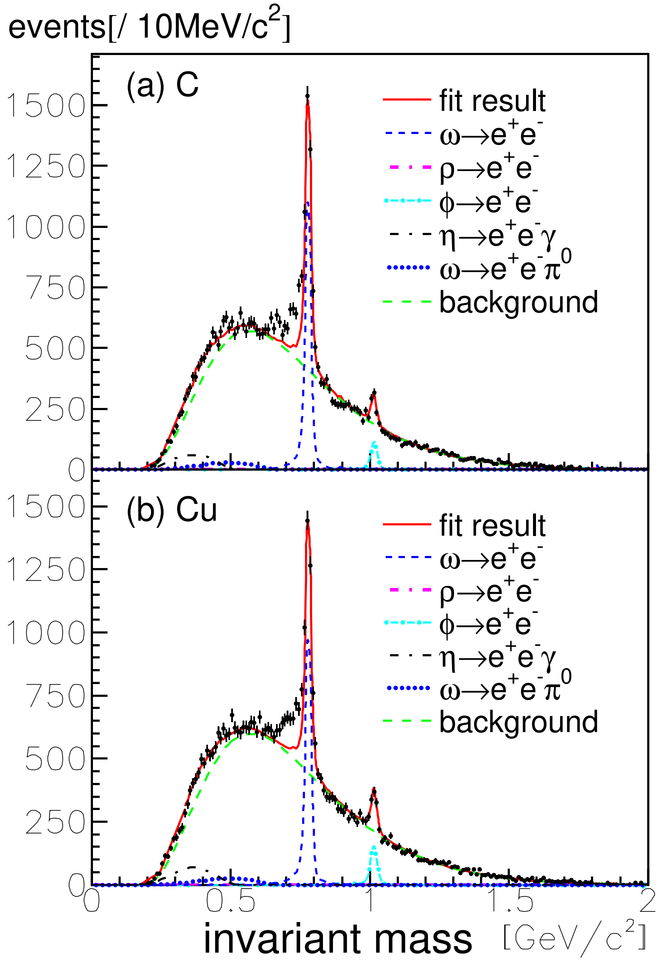
contribution of light quarks (πN scattering, σ-term):$\approx$ 50 MeV,

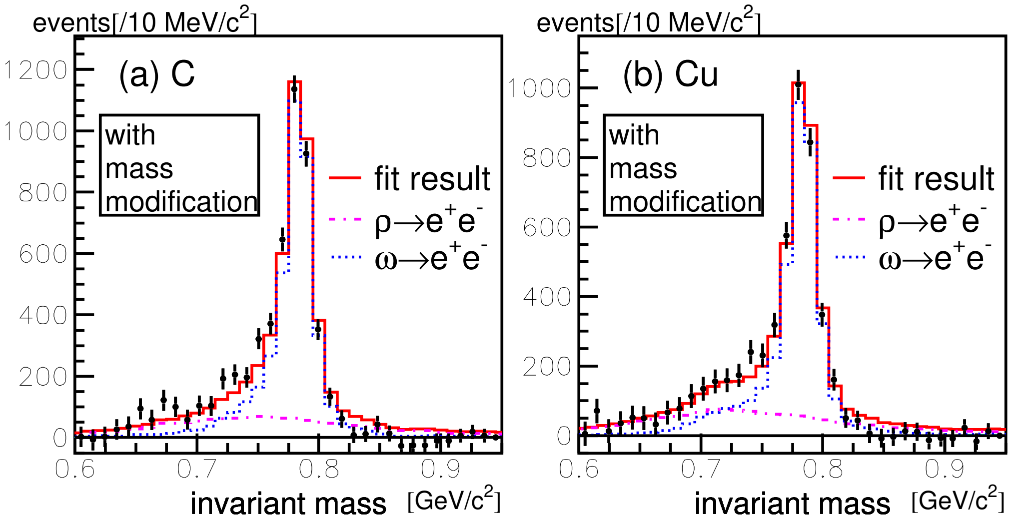
gluons contribution to the mass of the proton: $\approx$ 750 MeV

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 he dileptonic decay channel
  (some exceptions: TAPS/ELSA: $\omega \to \pi\gamma$, and mesonic atoms)

KEK E325 12 GeV pA data ρ and ω



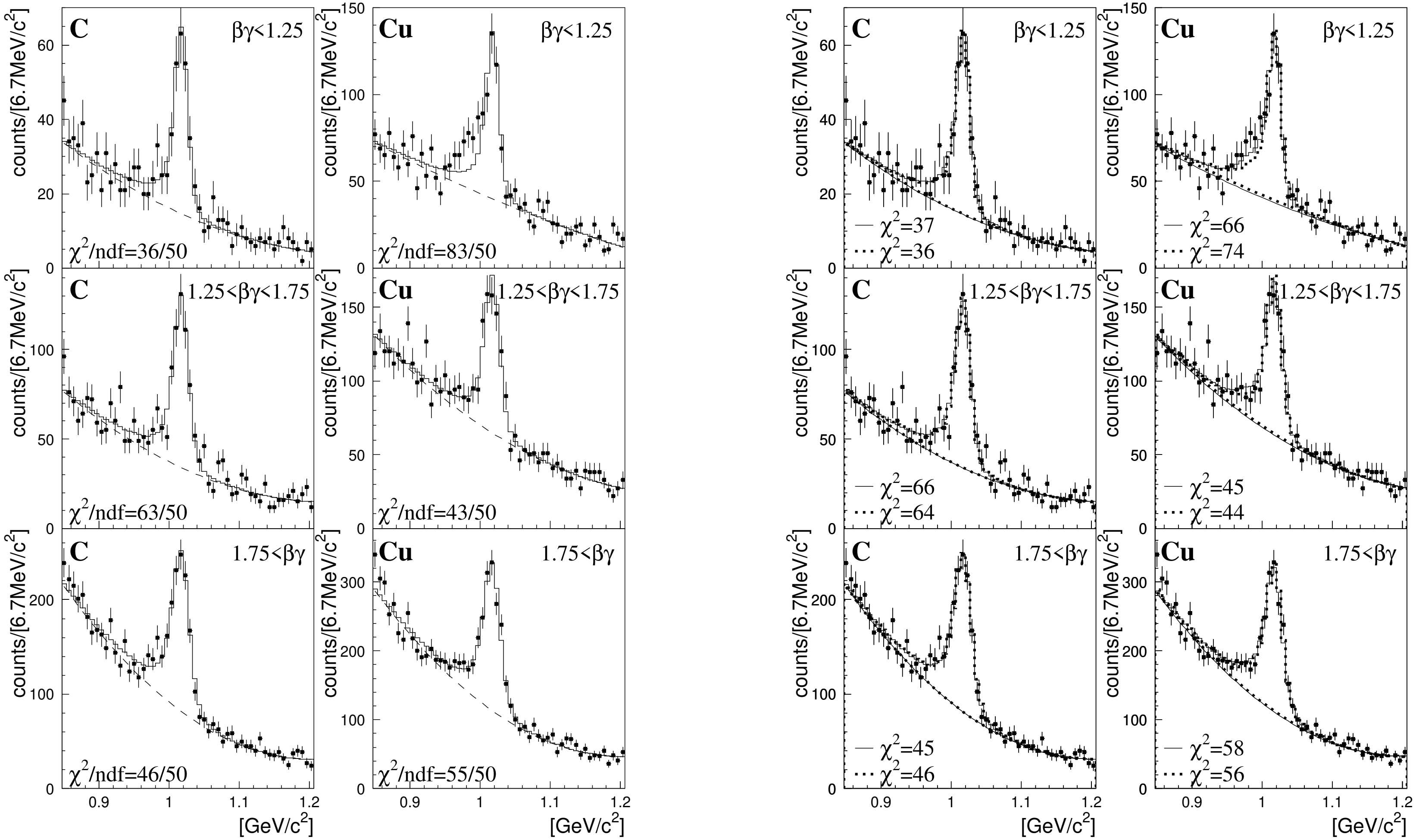


$$m(\rho)/m(0) = 1 - 0.09(\rho/\rho_0)$$

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

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

  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

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

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 Γ^{em}_{med}? Br^{em}_{med}?

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

collisional broadening at ρ_0: 15 MeV, 26 MeV and 26 MeV (cross sections were fitted to charmonium suppression at SPS)

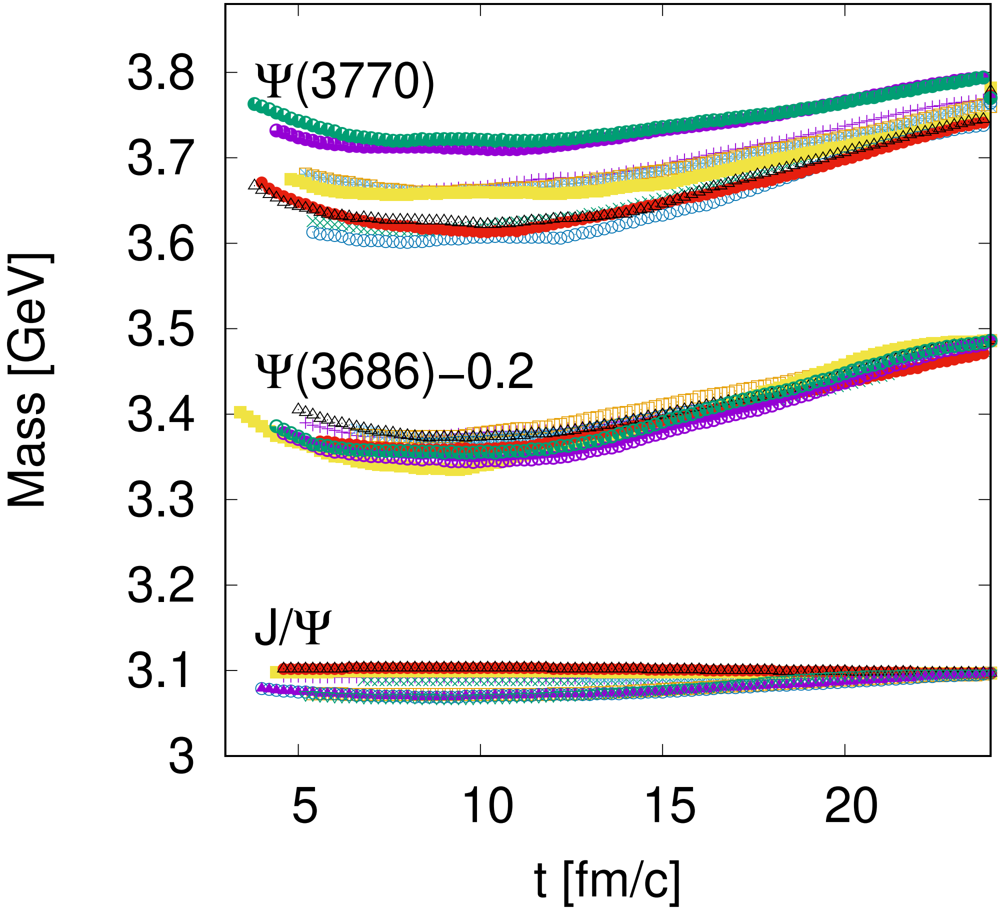
background:

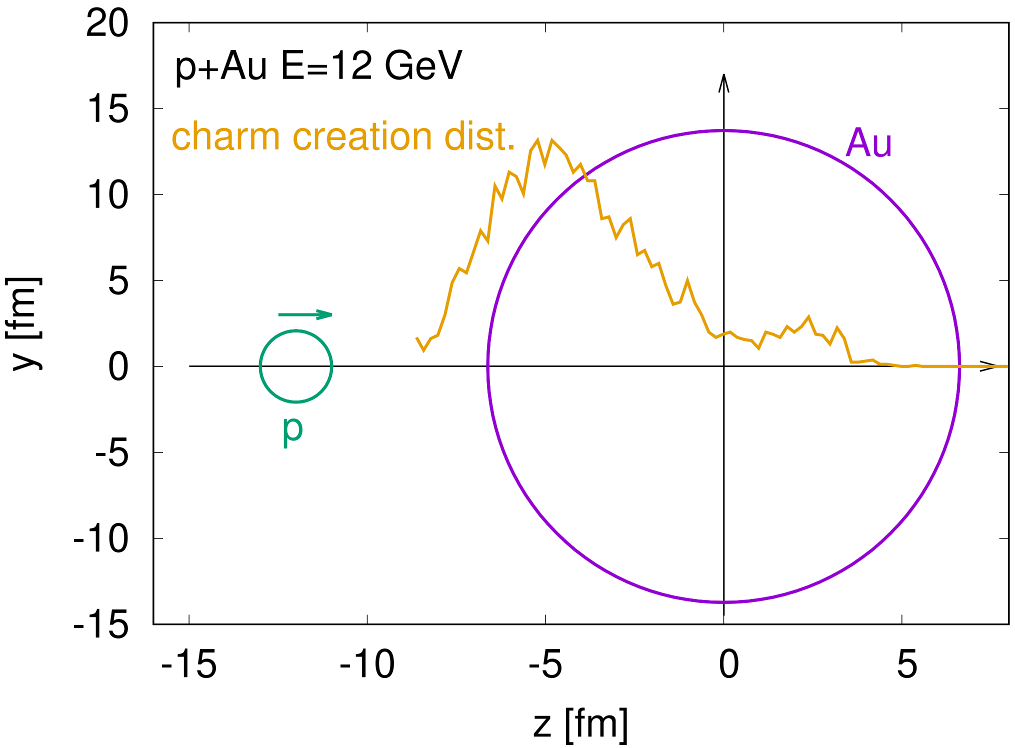
Drell-Yan: small number of energetic hadron-hadron collisions

$\bar{D}D$ decay: c quark decays weakly to s quark, $D \rightarrow Ke\bar{\nu}_e$ 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 ($<$ 7 GeV for $\bar{p}$, $<$ 12 GeV for π, $<$ 15 GeV for p) the background is low

Time evolution of masses and pos. of creation in p+Au 12GeV





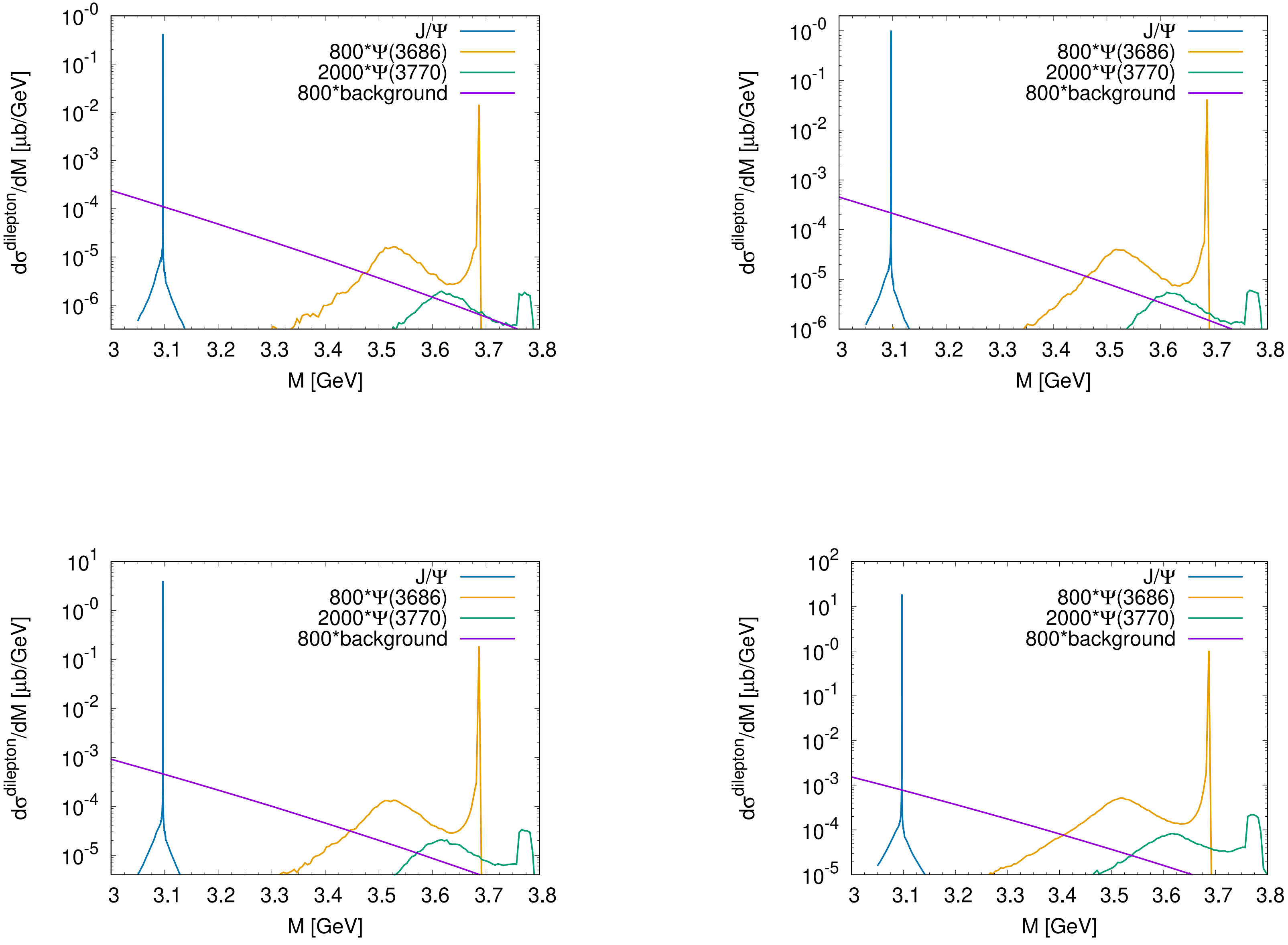
The charmonium states are created at the surface of the heavy nucleus,

travel through the dense matter (decays with some probability),

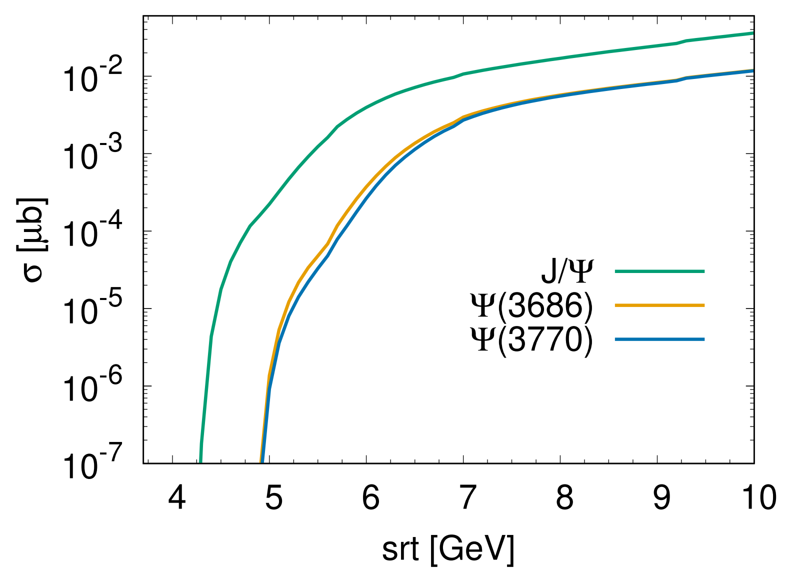
crosses the thin surface again and reaching the vacuum.

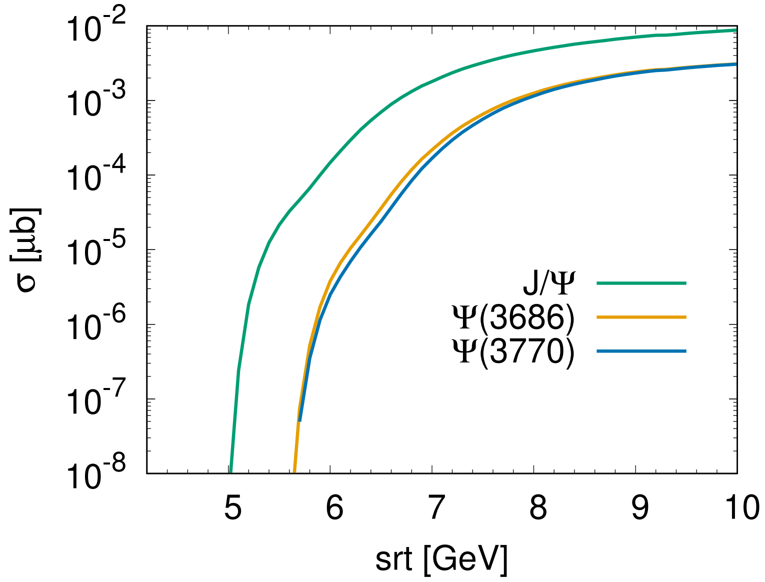
Major contribution to the dilepton channel are coming from the dense matter and from the vacuum. $t_{\rho>0.8} \approx 9$ fm, $t_{0.8>\rho>0.2} \approx 4$ fm.

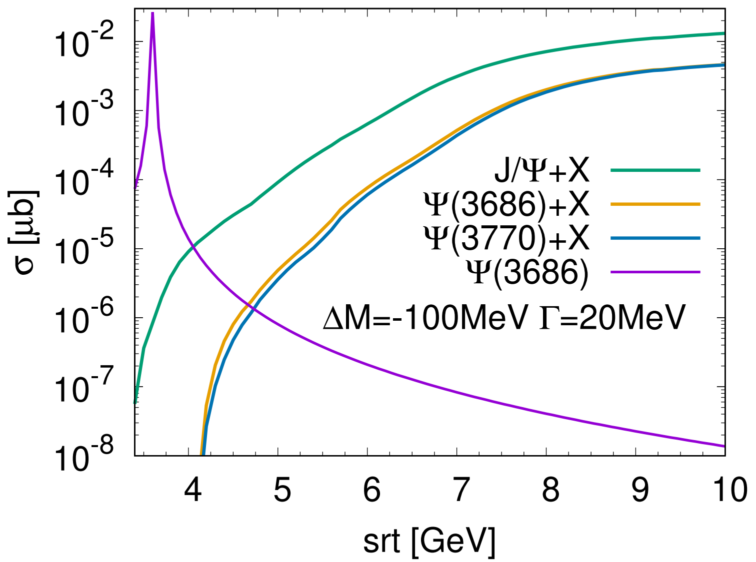
pAu at 9, 10, 12, 15 GeV

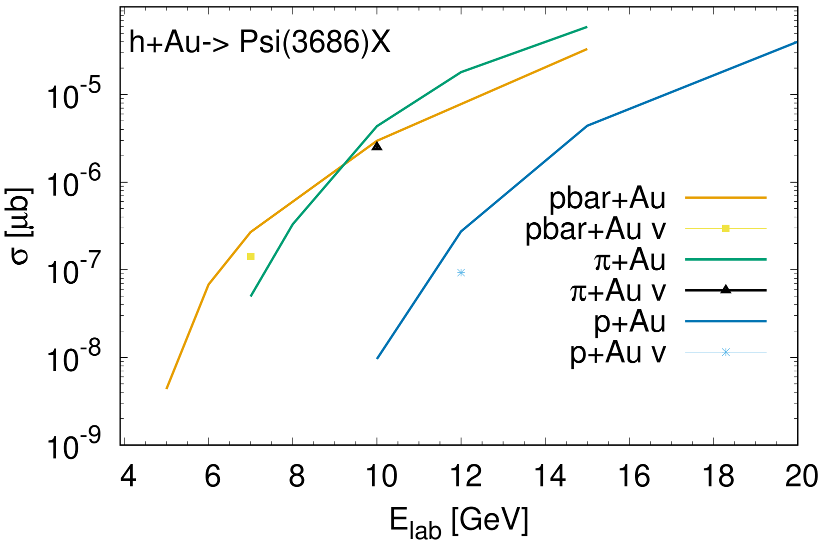


Cross sections


π p -> Charm + X

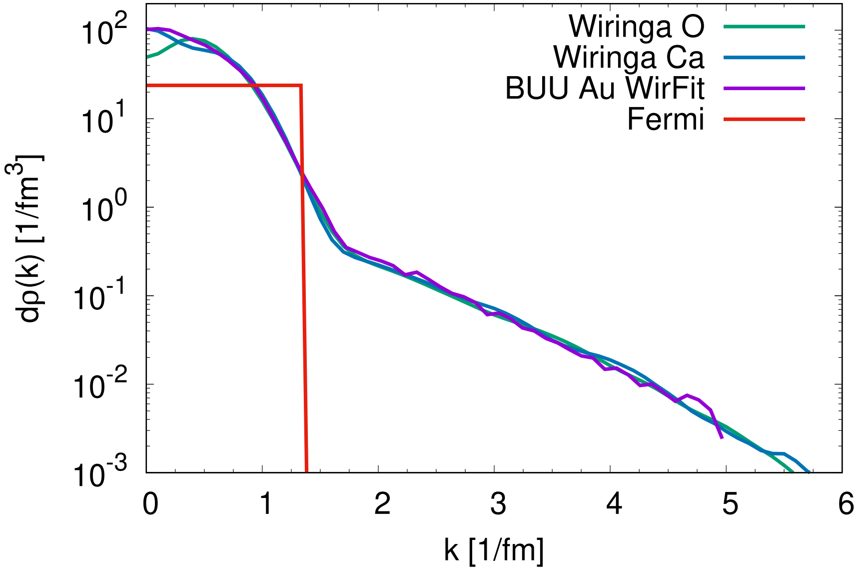

pp -> pp Charm


pbar p -> Charm X

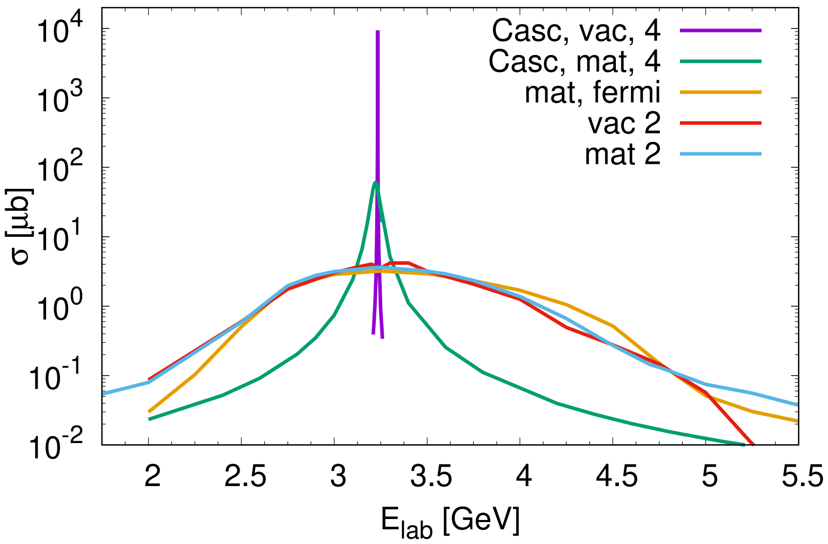


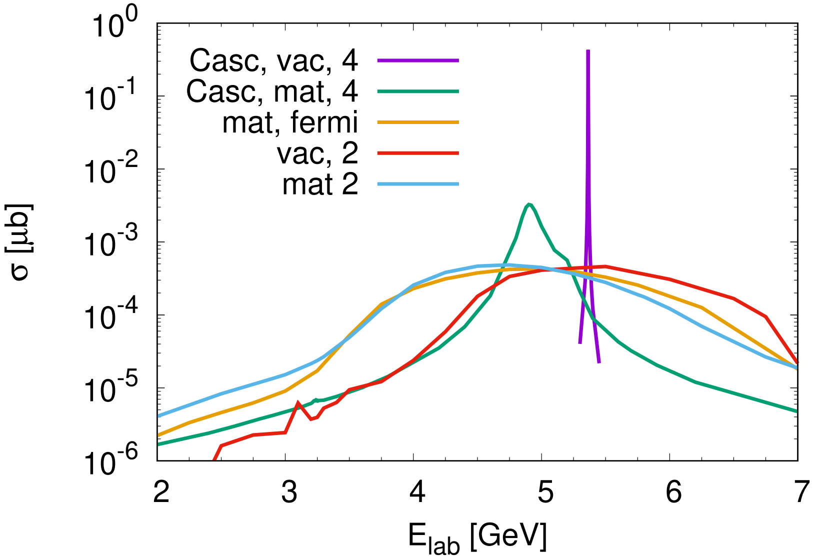
Balassa, Wolf, Eur. Phys.J. A56(2020) 237

Excitation functions

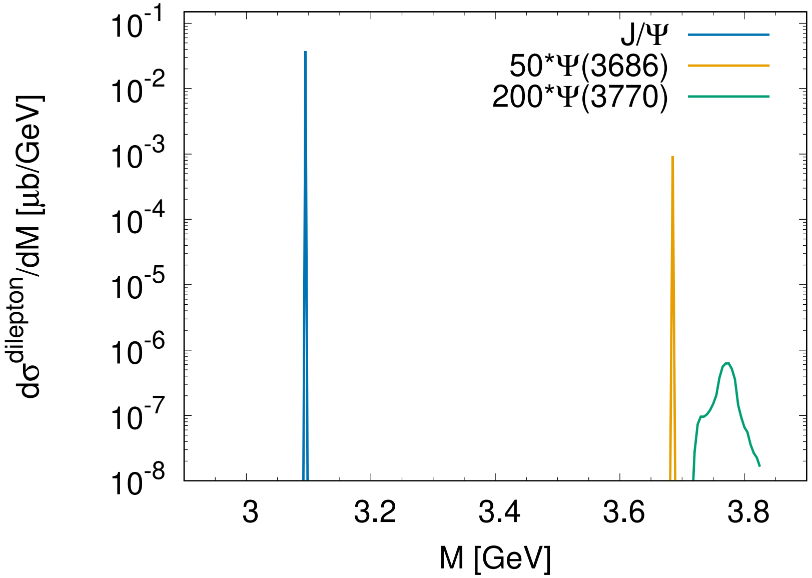


Initial momentum distribution
with short range correlation

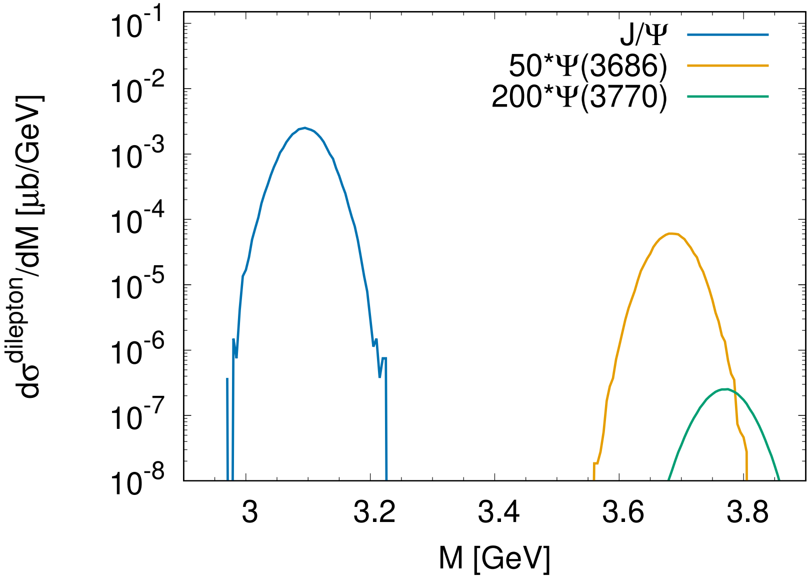




p Au at 12 GeV



J/Ψ
50*Ψ(3686)
200*Ψ(3770)
$d\sigma^{dilepton}/dM$ [μb/GeV]
M [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
3
3.2
3.4
3.6
3.8



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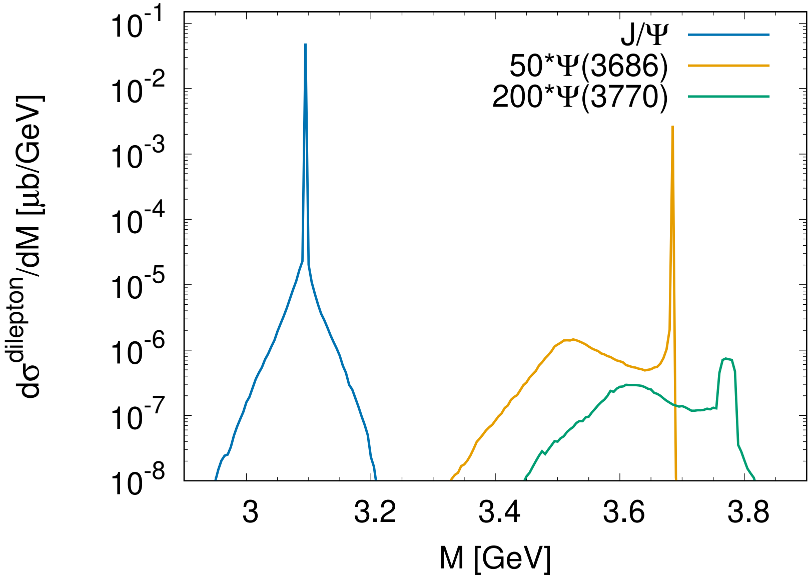
3.6
3.8



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10^{-5}
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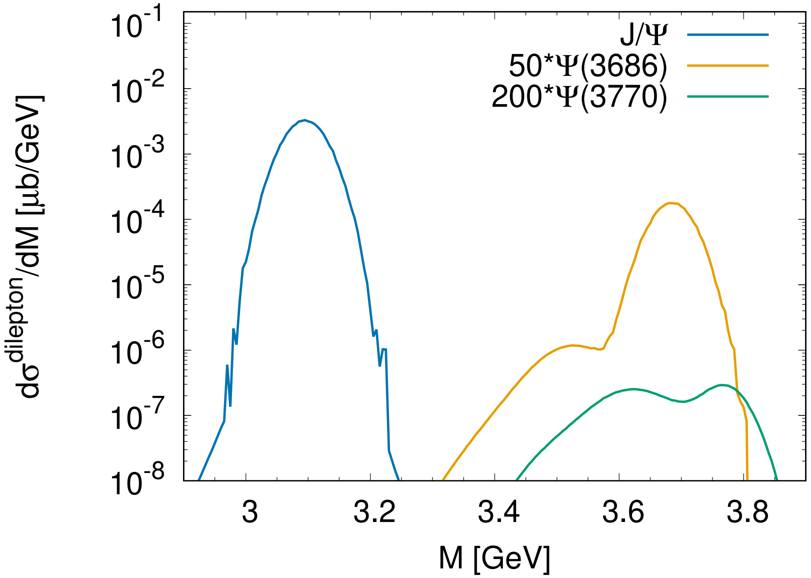
10^{-7}
10^{-8}
3
3.2
3.4
3.6
3.8



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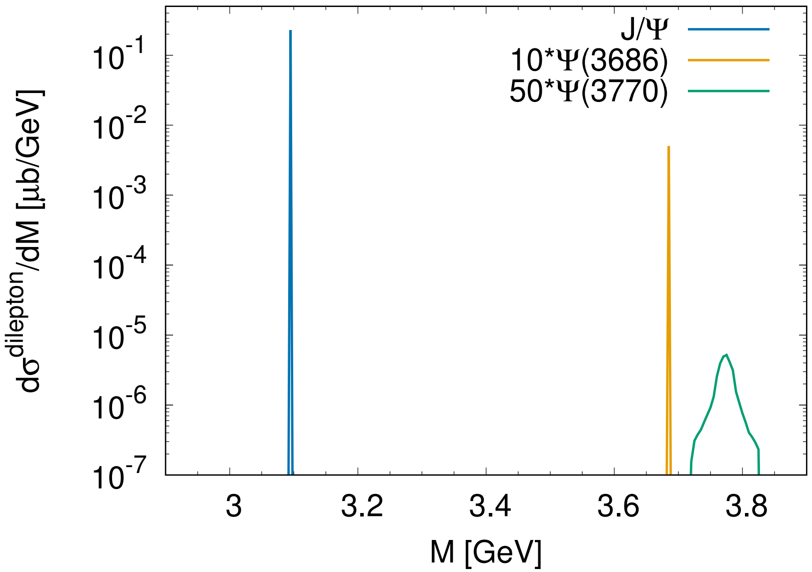
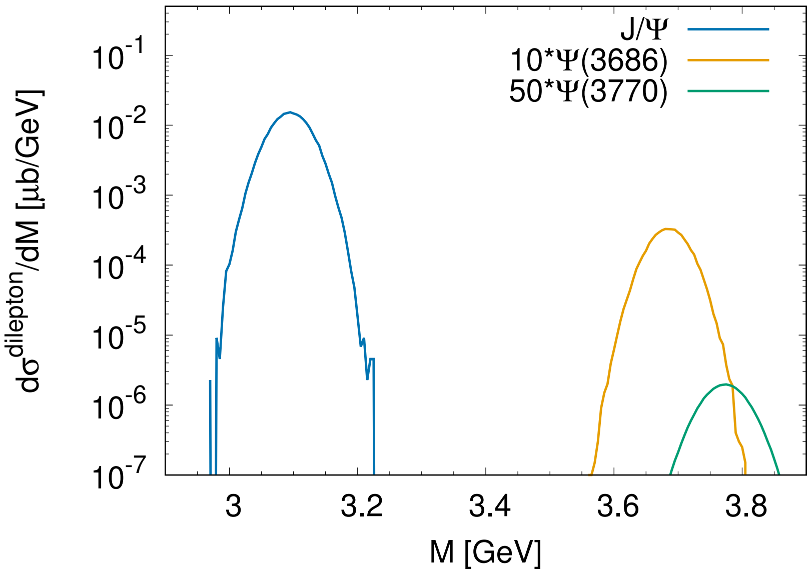
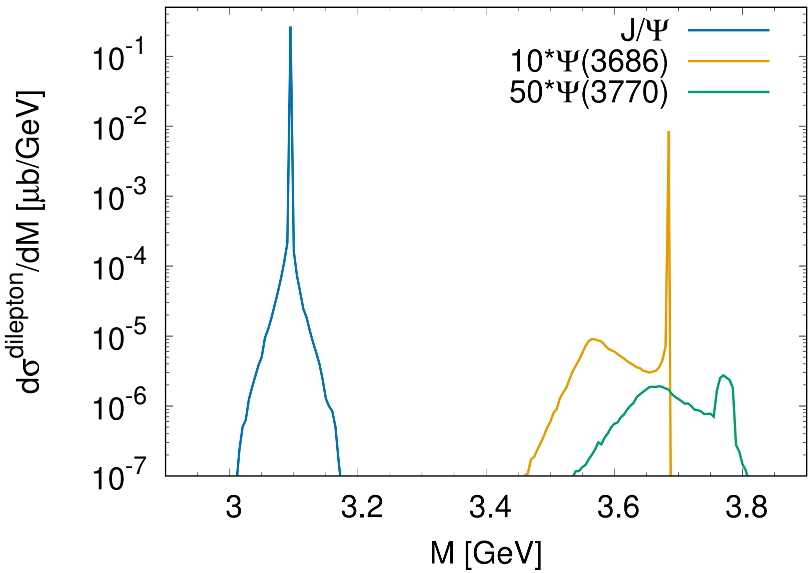
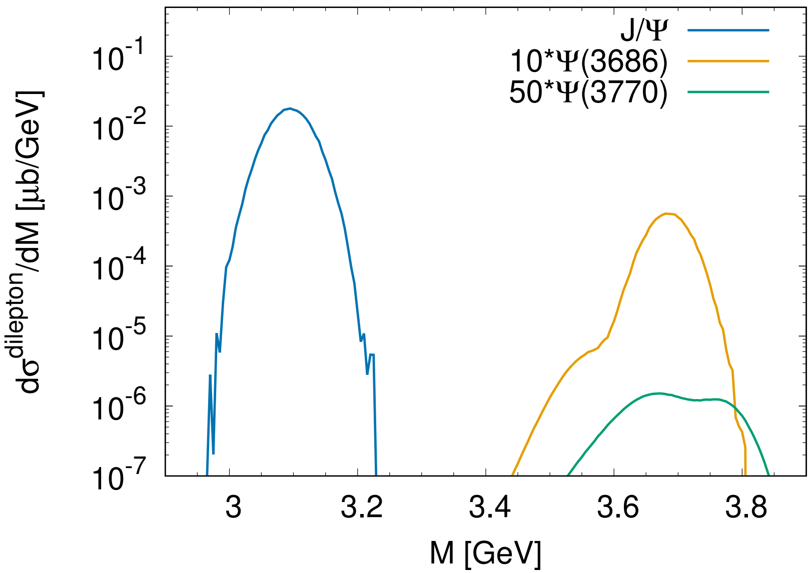
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
3
3.2
3.4
3.6
3.8

πAu at 10 GeV

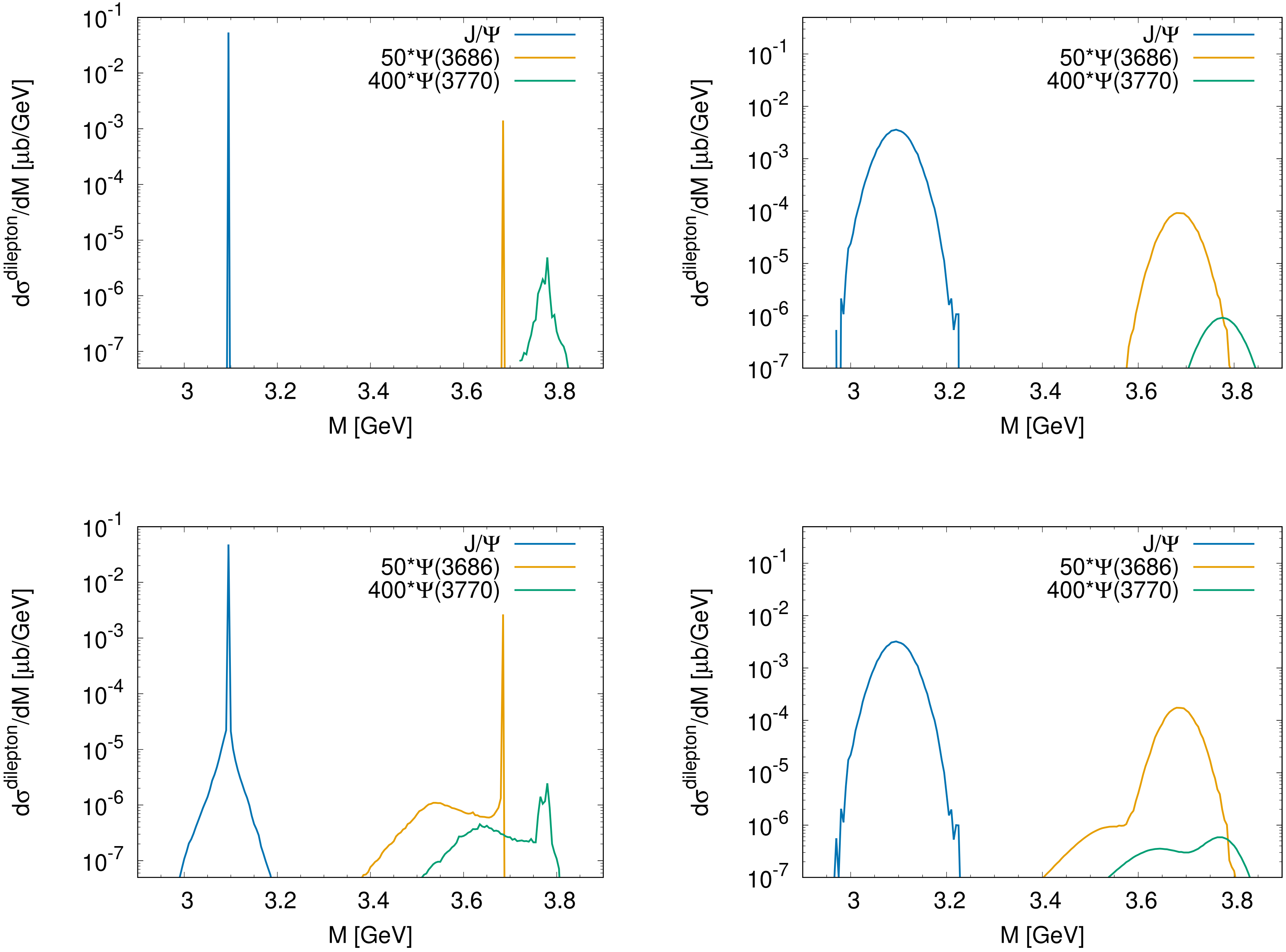








$\bar{p}$Au at 7 GeV



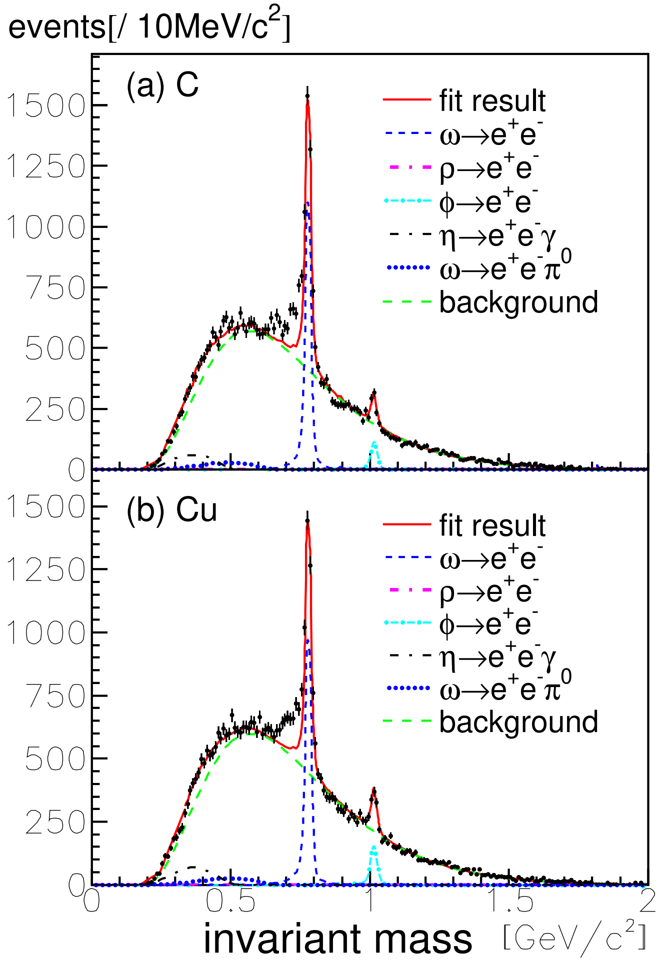
$\Psi(3686)$

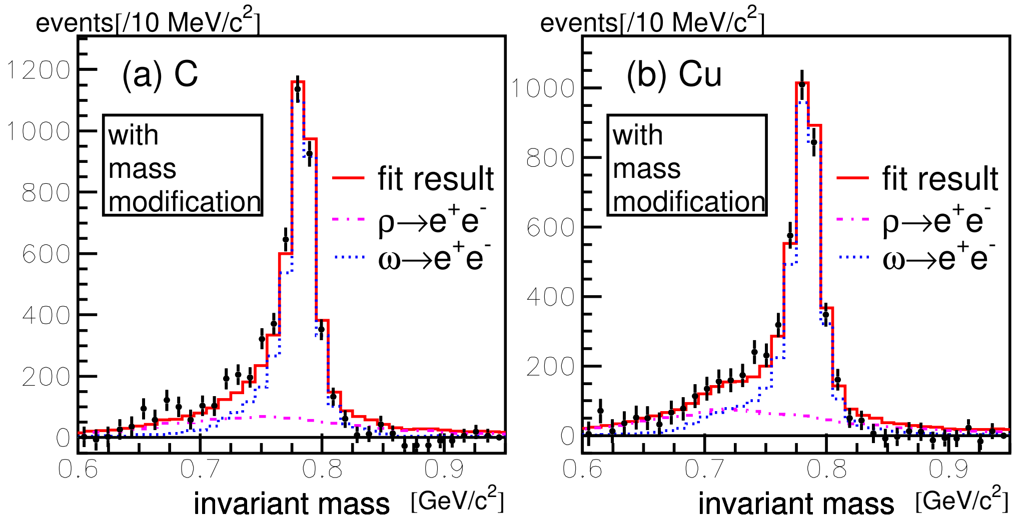
- The distance between the peaks corresponds to a mass shift at $\rho \approx 0.9\rho_0$
- qualitatively the same picture if increase or reduce the mass shift by factor of 2
- measuring the peak distance, we obtain the mass shift at $\rho \approx 0.9\rho_0$
- measuring the mass shift, we obtain the gluon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





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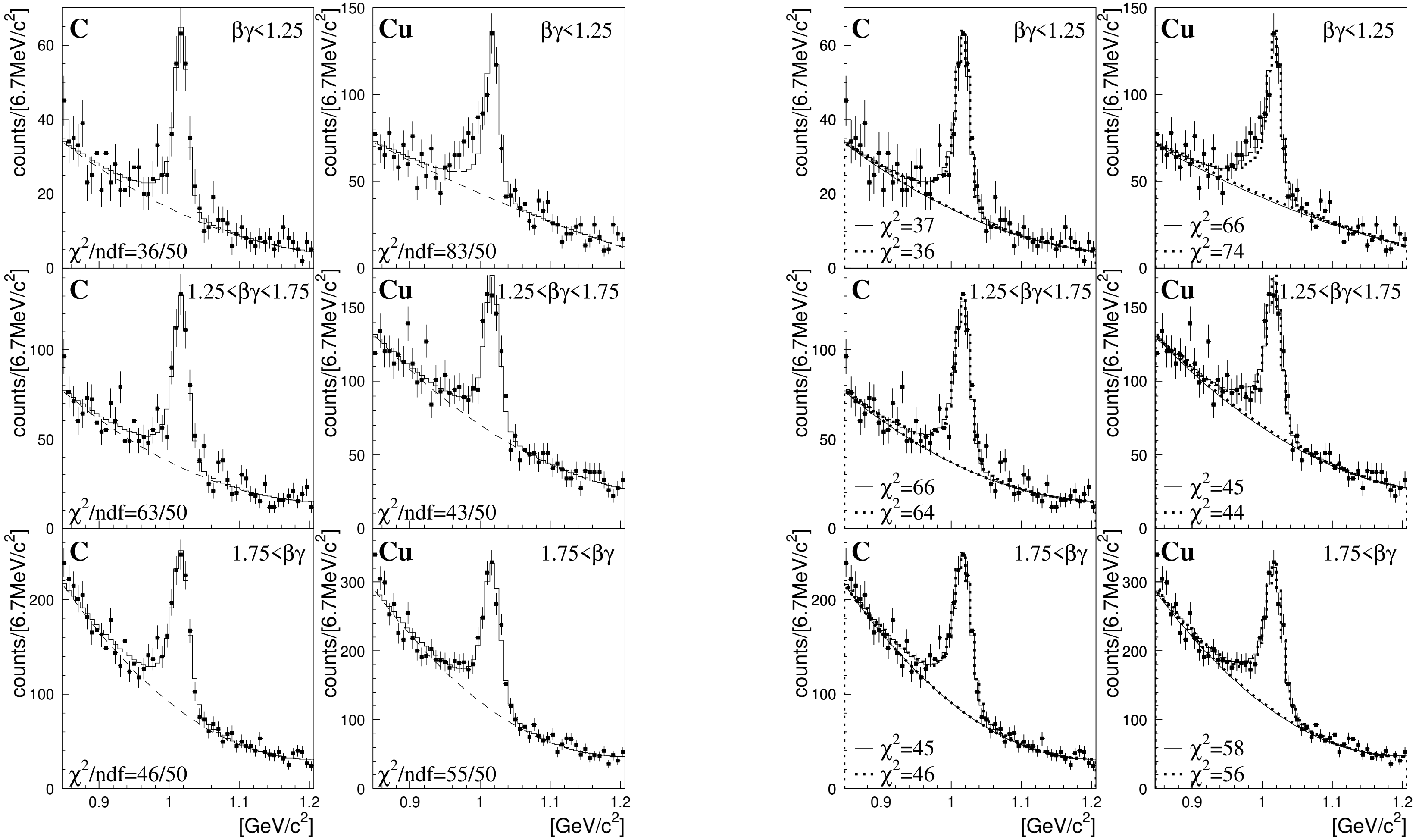
M. Naruki *et al.*

Phys. Rev. Lett. 96 (2006) 092301

KEK E325 12 GeV pA data for ϕ



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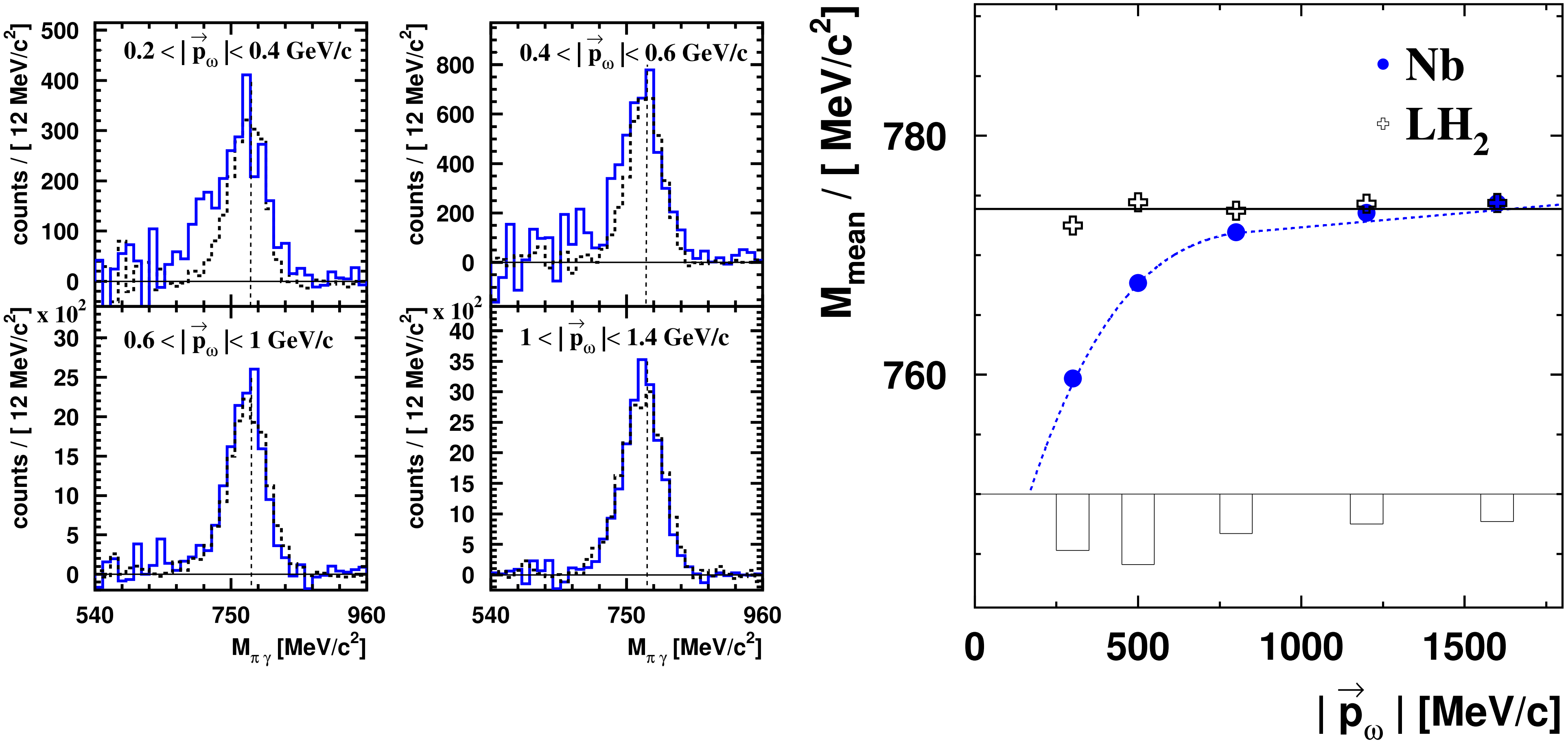
$$\Gamma(\rho)/\Gamma(0) = 3.6(\rho/\rho_0)$$

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

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



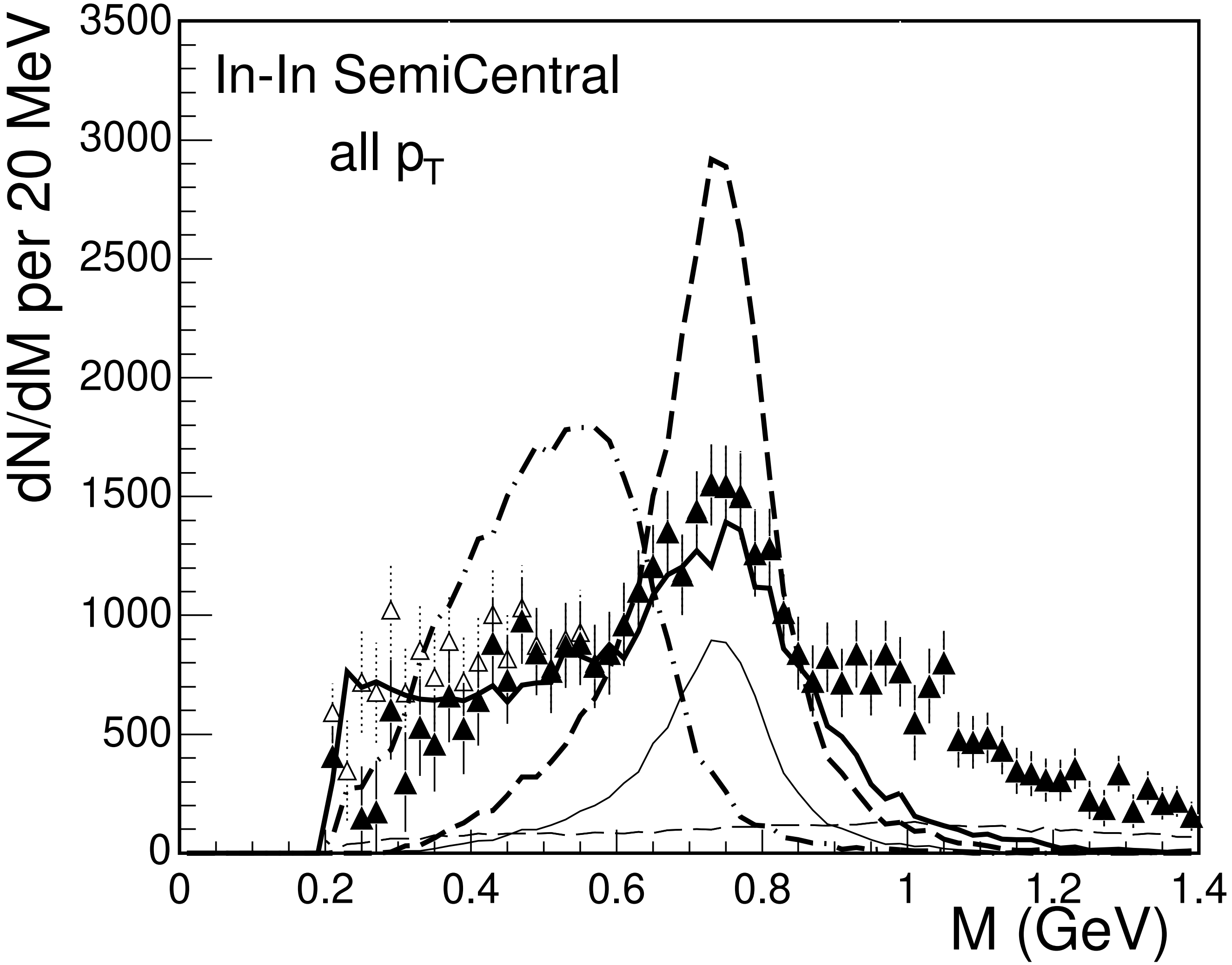
$$m(\rho)/m(0) = 1 - 0.14(\rho/\rho_0), \quad \bar{\rho} = 0.6\rho/_0$$

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

D. Trnka *et al.*

Phys. Rev. Lett. 94 (2005) 192303

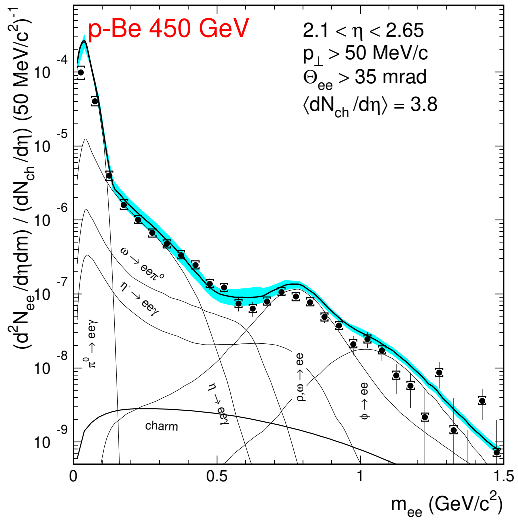
NA60 data for ρ

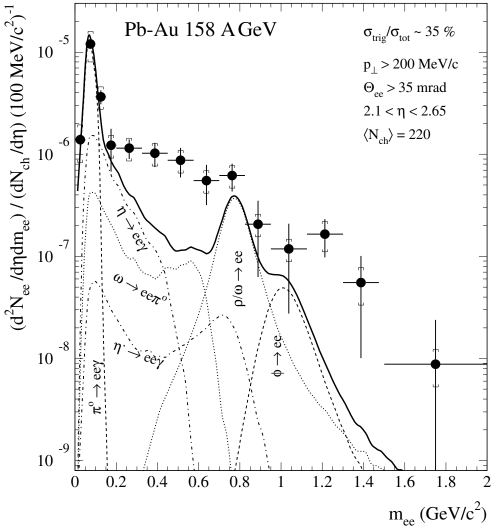


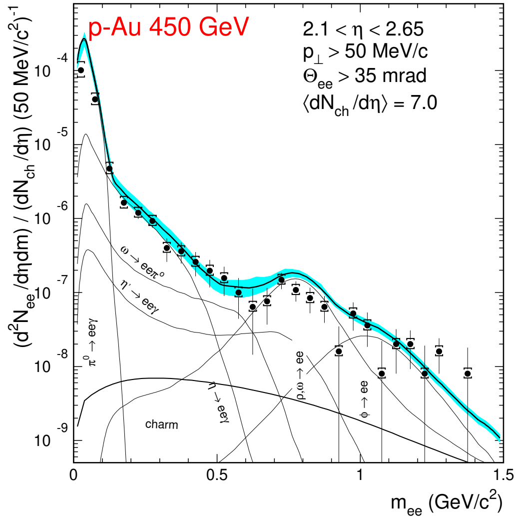
thick solid line: ρ-broadening
due to hadronic reactions
R. Rapp, J. Wambach
Adv. Nucl. Phys. 25, 1

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

CERES data







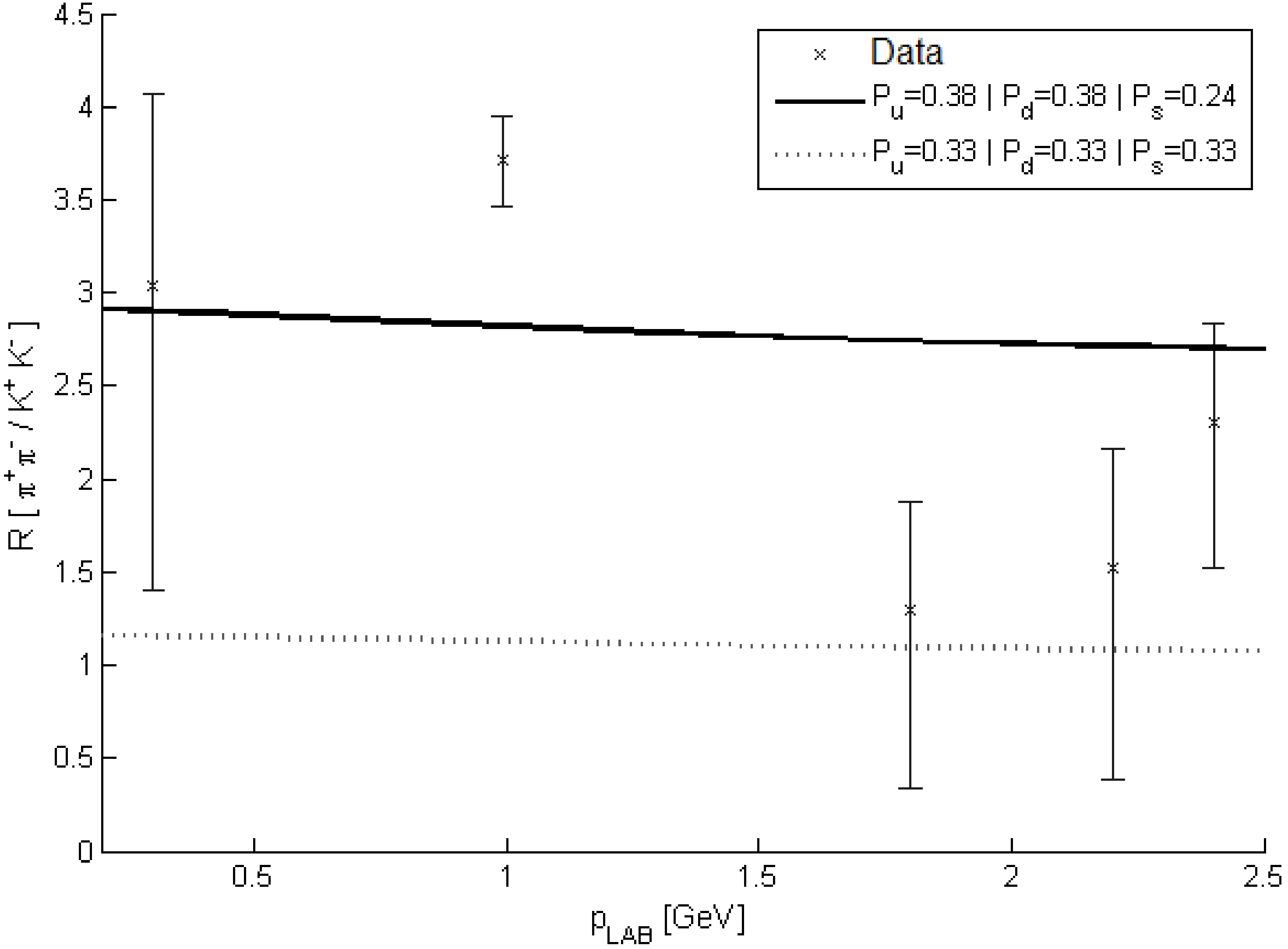
G. Agakichiev *et al.*
Eur. Phys. J. C4 (1998) 231

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

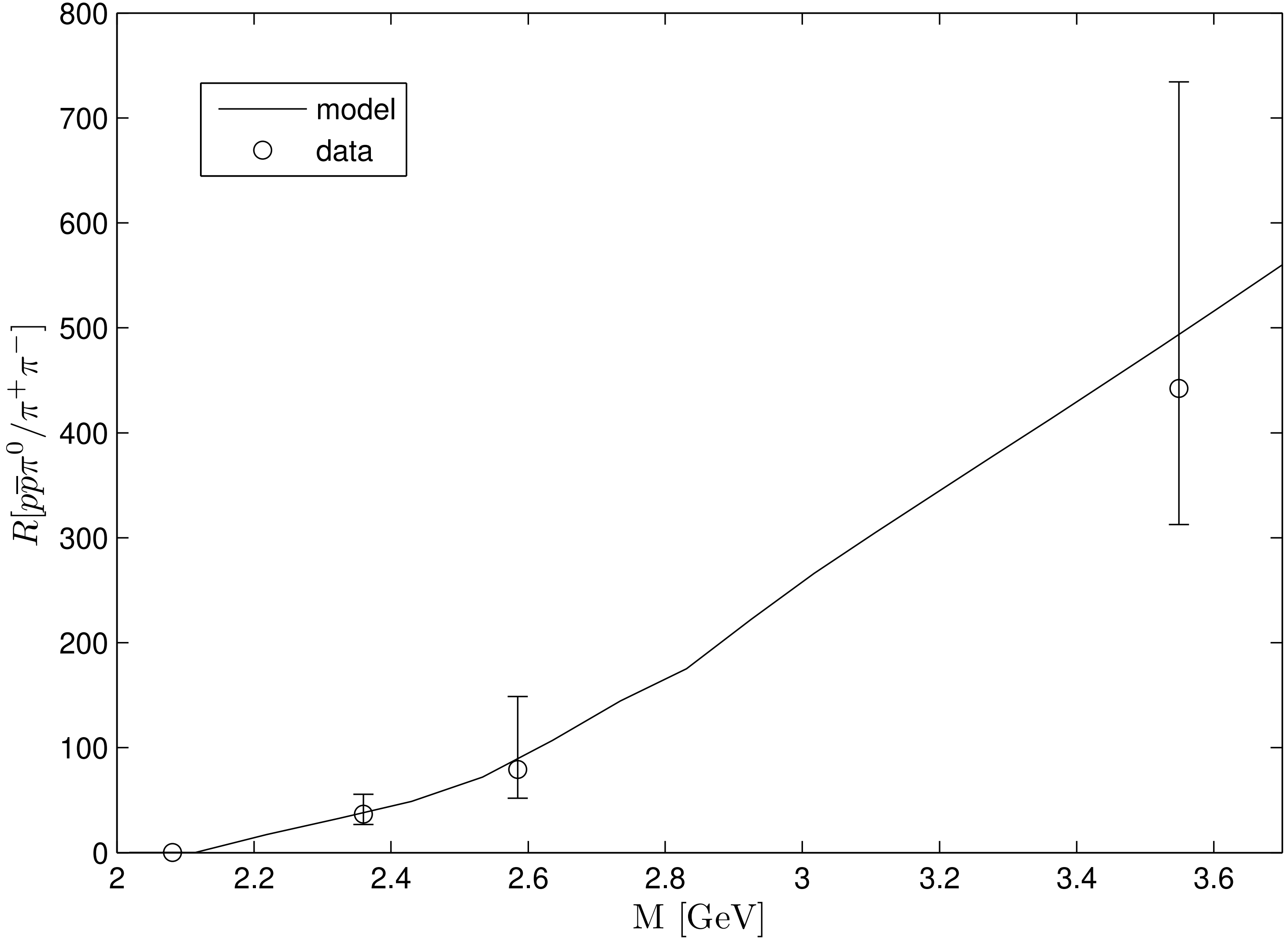
Statistical Bootstrap approach

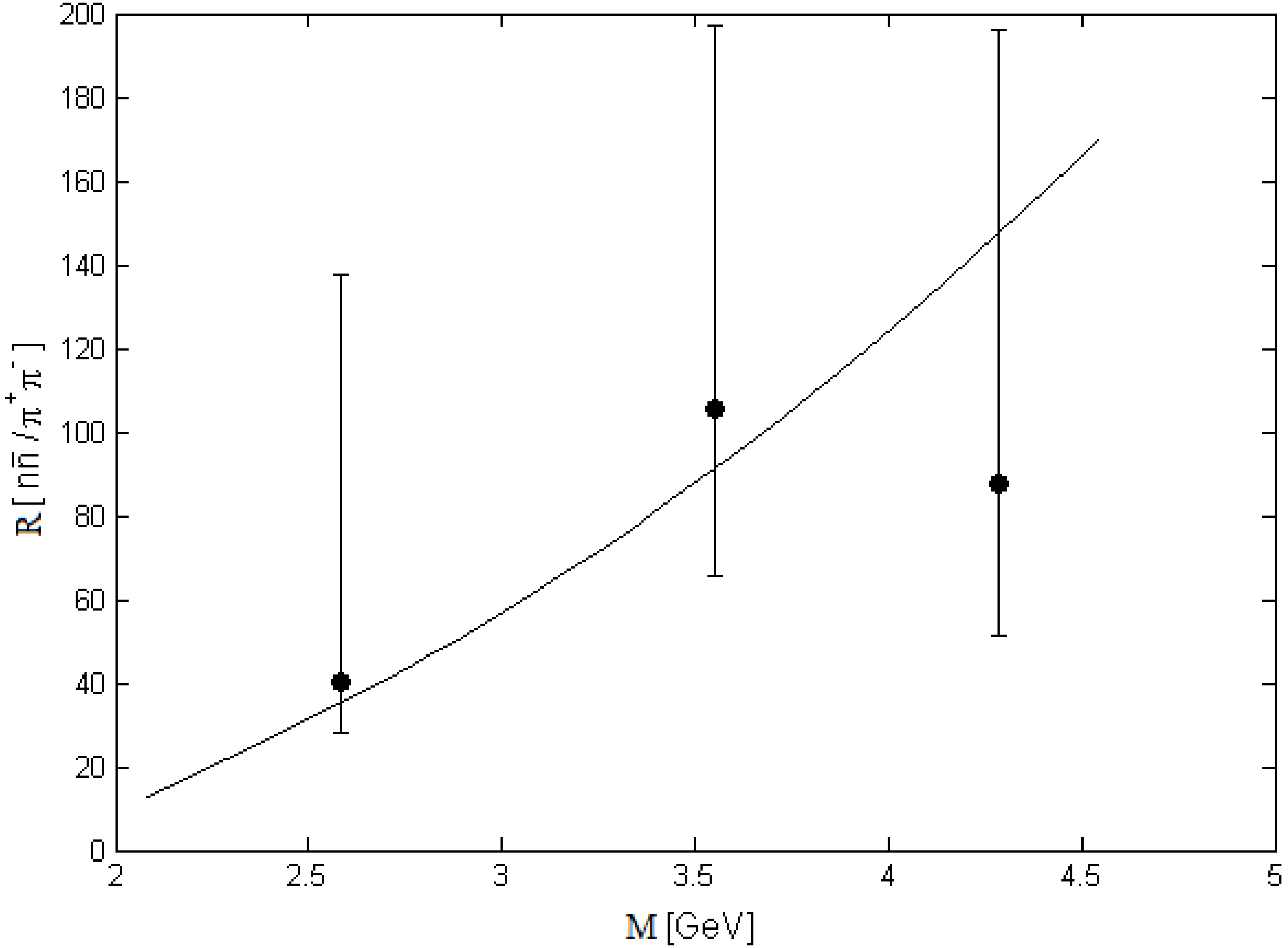
G. Balassa, P. Kovács, Gy. Wolf, Eur. Phys. J. A54 (2018) 25

- 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 $\rho(m)$.

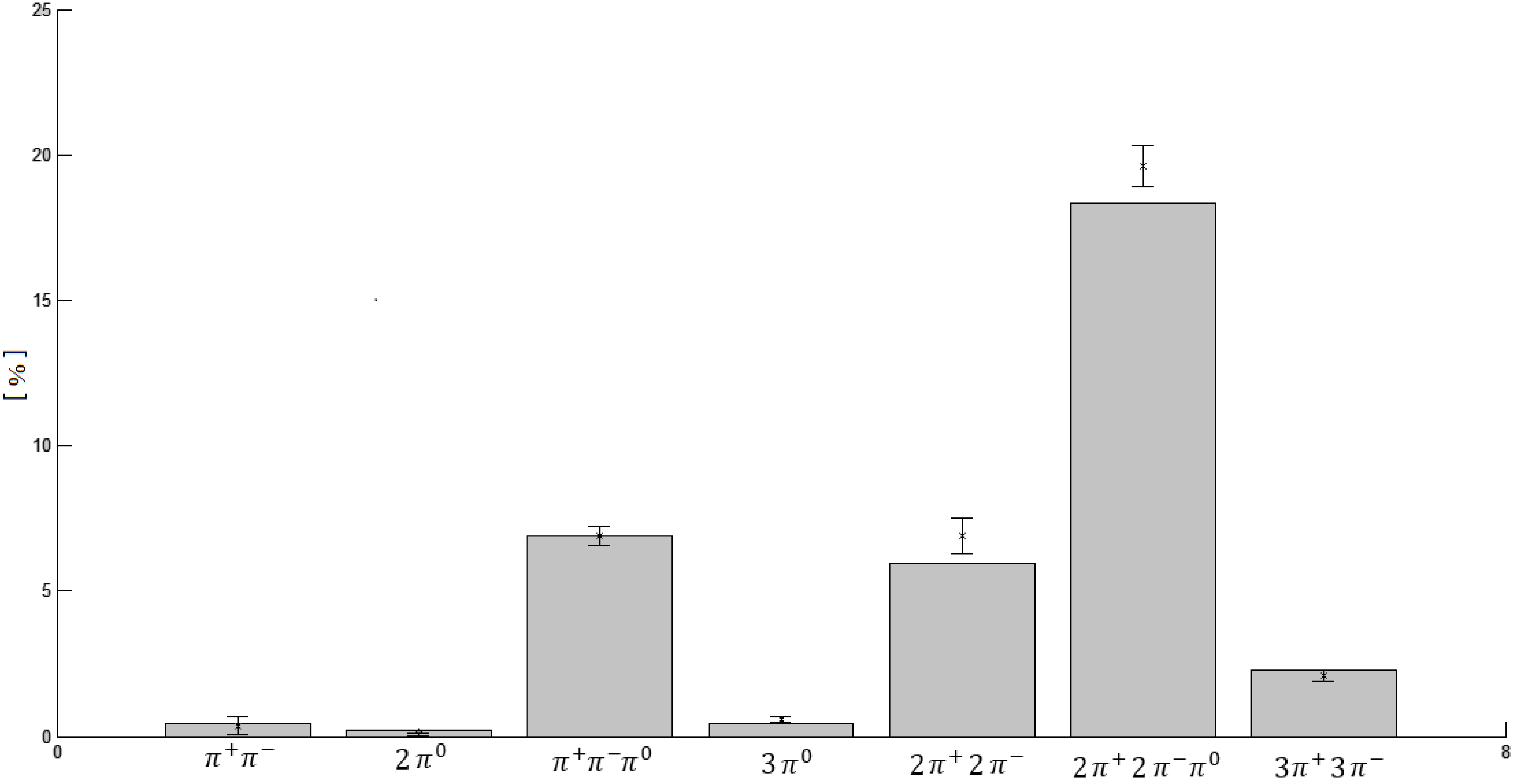

Data
P_u=0.38 | P_d=0.38 | P_s=0.24
P_u=0.33 | P_d=0.33 | P_s=0.33
$R\ [\ \pi^+\pi^-\ /\ K^+K^-\ ]$
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
p_{LAB} [GeV]

Predictions





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


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