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

Elméleti Tea, Wigner FK, 26.01.2018.

Gy. Wolf

in collaboration with G. Balassa, P. Kovács, M. Zétényi, Wigner RCP

Su Houng Lee, Yonsei University, Korea

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

Gy. Wolf, G. Balassa, P. Kovács, M. Zétényi, S.H. Lee, Act. Phys. Pol. B10 (2017) 1177, arxiv:1711.10372

arXiv:1712.06537, submitted to Phys. Lett. B

The QCD vacuum

condensates: the most important ones: $m_q < \bar{q}q >$ and $< \alpha_s/\pi G^2 >$

Quark condensate: order parameter of the restauration of the spontaneous chiral symmetry breaking

plays fundamental role in the phenomenology of strong interaction

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 can be estimated (pion-nucleon sigma term): ≈ 50 MeV, contribution of the heavy quarks are expected to be small, gluons contribute to $80 - 90\%$ the mass of the proton: ≈ 750 MeV

Gluon condensate in matter

- Quark and gluon condensates are known in vacuum, in matter only the first nonvanishing derivatives: first in density and second in temperature are known

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

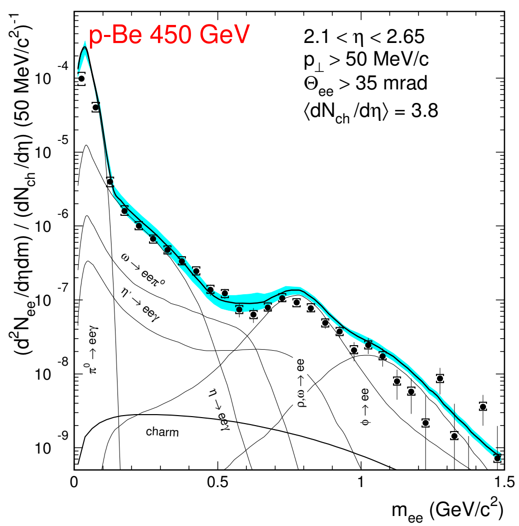
$$< T|O|T >=< 0|O|0 > + \int d^3p/p_0 f_\pi(p,T) < \pi(p)|O|\pi(p) >$$

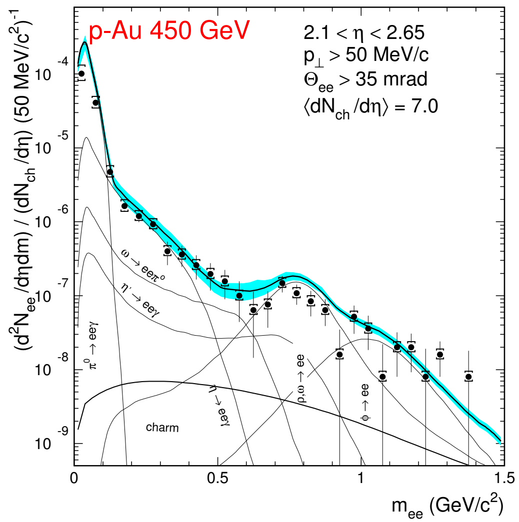
- the masses of hadrons made of light quarks changes mainly due to the (partial) restauration of chiral symmetry (its order parameter $m_q < \bar{q}q >_\rho$)
- hadrons made of heavy quarks are sensitive on the changes of gluon condensate
- measuring the charmonium masses in matter may tell us what is the gluon condensate in matter

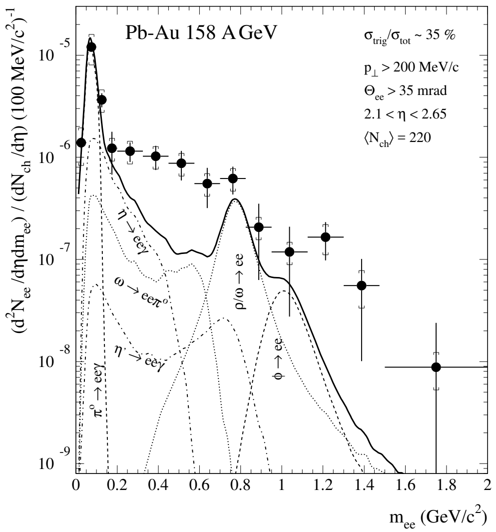
Why dileptons

- measured (DLS, HADES, CERES, NA60, STAR, ALICE)
- without final state interaction
- vector mesons decay to dileptons → vector mesons in matter
- much better then photons:
  spectrum is measurable, 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 elementary reactions

- Direct decay of vector mesons and η
- Dalitz-decay of π, η and ω
- Dalitz-decay of baryon resonances
  Zetenyi, Wolf, Phys. Rev, C67 (2003) 044002;
  Heavy Ion Phys. 17 (2003) 27
- pn bremsstrahlung
- Drell-Yan: $\bar{q}q \to e^+e^-$
- Open charm $(\bar{q}c) + (\bar{c}q)$ (weak decay of c and $\bar{c}$)
- Charmonium $(\bar{c}c)$ decay

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 compltetely wrong
- No global equlibrium at 0.4 AGeV central $Ru_{44}^{96} + Zr_{40}^{96}$ 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
- $\frac{d\sigma^{X\to NR}}{dM_R} \sim A(M_R)\lambda^{0.5}(s, M_R^2, M_N^2)$

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

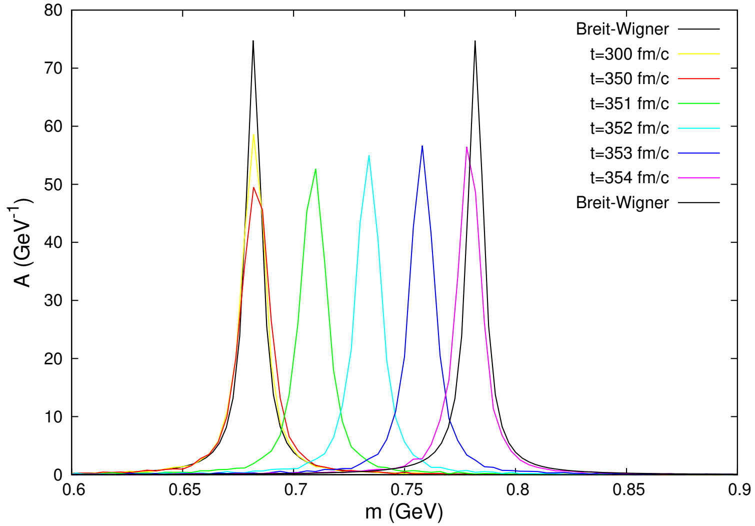
  $C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial\epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2-\vec{P}_i^2-M_0^2-Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{\partial}{\partial\epsilon_i} Im\Sigma^{ret}_{(i)} \right]$

- the last equation for homogenous system can be rewritten as

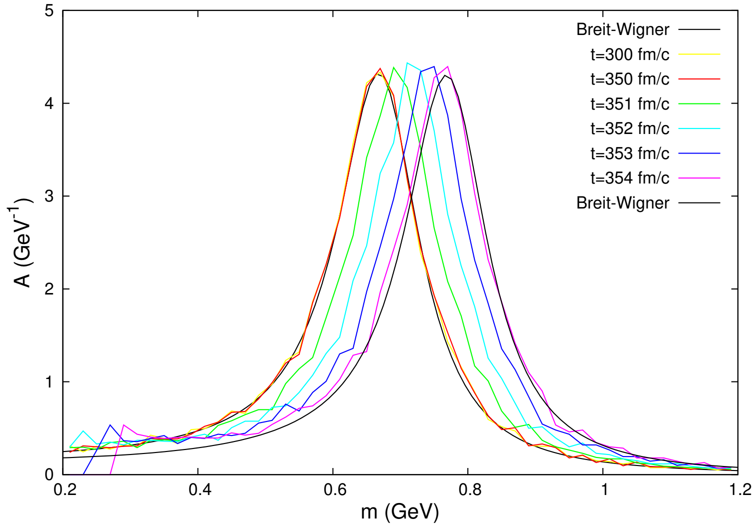
  $\frac{dM_i^2}{dt} = \frac{d(\epsilon_i^2-P_i^2)}{dt} = \frac{dRe\Sigma^{ret}_{(i)}}{dt} + \frac{M_i^2-M_0^2-Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{dIm\Sigma^{ret}_{(i)}}{dt}$

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

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

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

$$= \sigma_{Tot}(M) \cdot W(M)$$

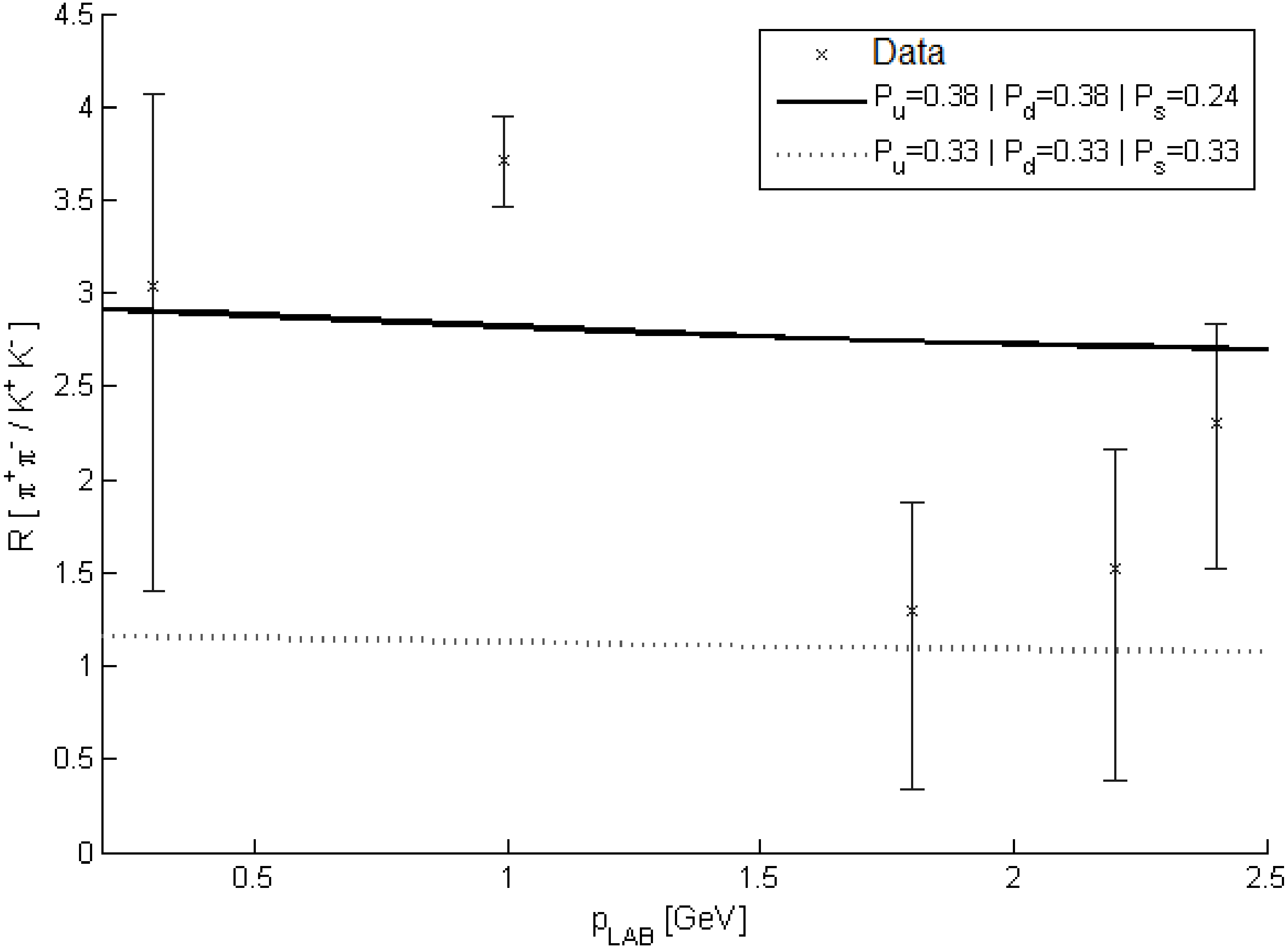
$$\sigma_{p\pi^- \to n\pi^+\pi^-} \equiv \frac{W_{n\pi^+\pi^-}}{W_{p\pi^-}} \frac{\sigma^{Tot}_{p\pi^-}}{\sigma^{Tot}_{p\pi^-}} \sigma_{p\pi^- \to p\pi^-} = \frac{W_{n\pi^+\pi^-}}{W_{p\pi^-}} \sigma_{p\pi^- \to p\pi^-}$$

$$W_k^{n_1,\ldots,n_k}(M) = N(M) P_k^{fb}(M) C_Q(M)$$

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

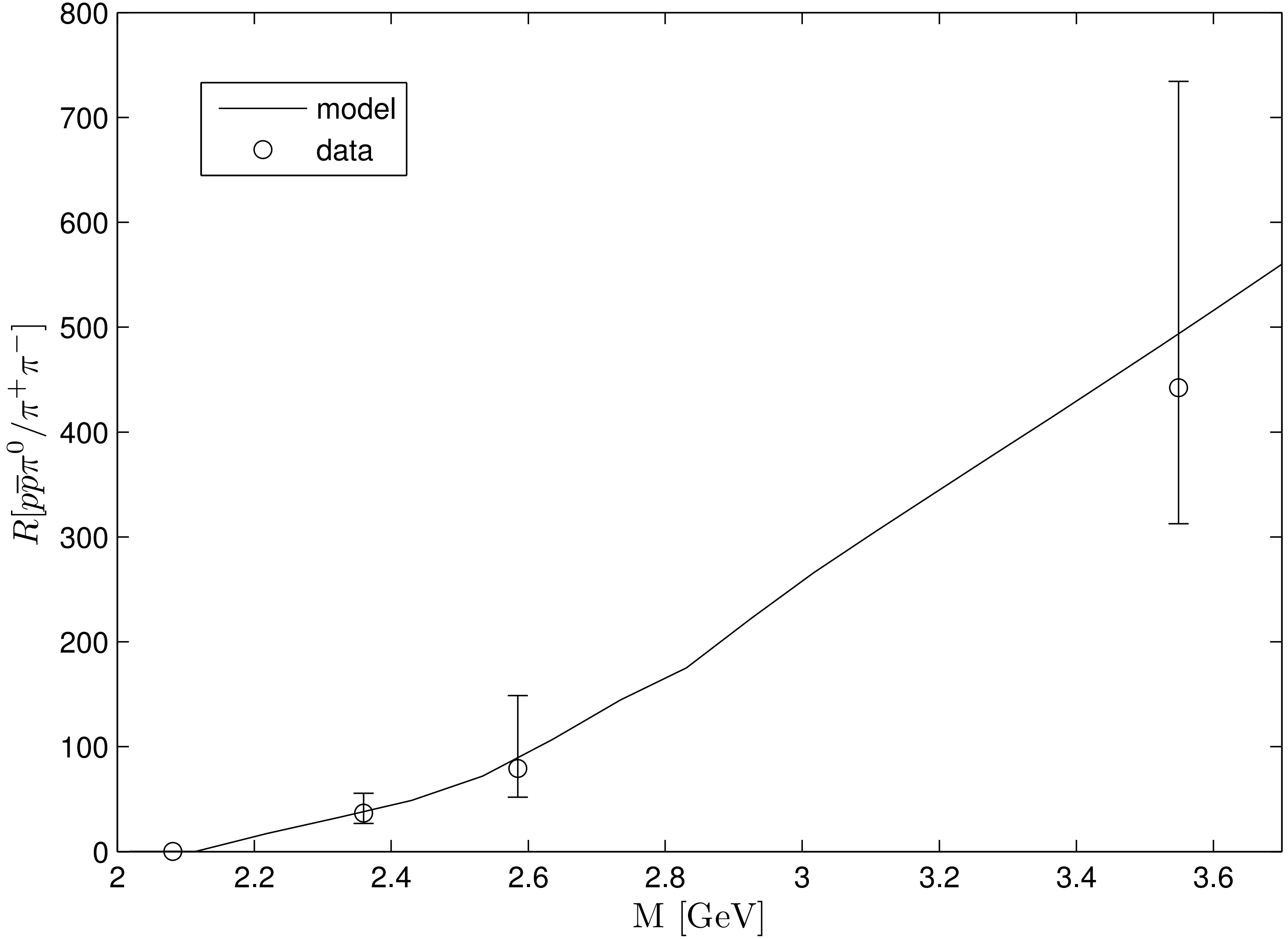
P_k^{fb}: formation probability of k fireballs, $C_Q(M)$: the quark-combinatorical factor, x_i's are the invariant masses of the individual fireballs, $P_{n_i}^{H,i}(x_i)$'s are the hadronization probabilities

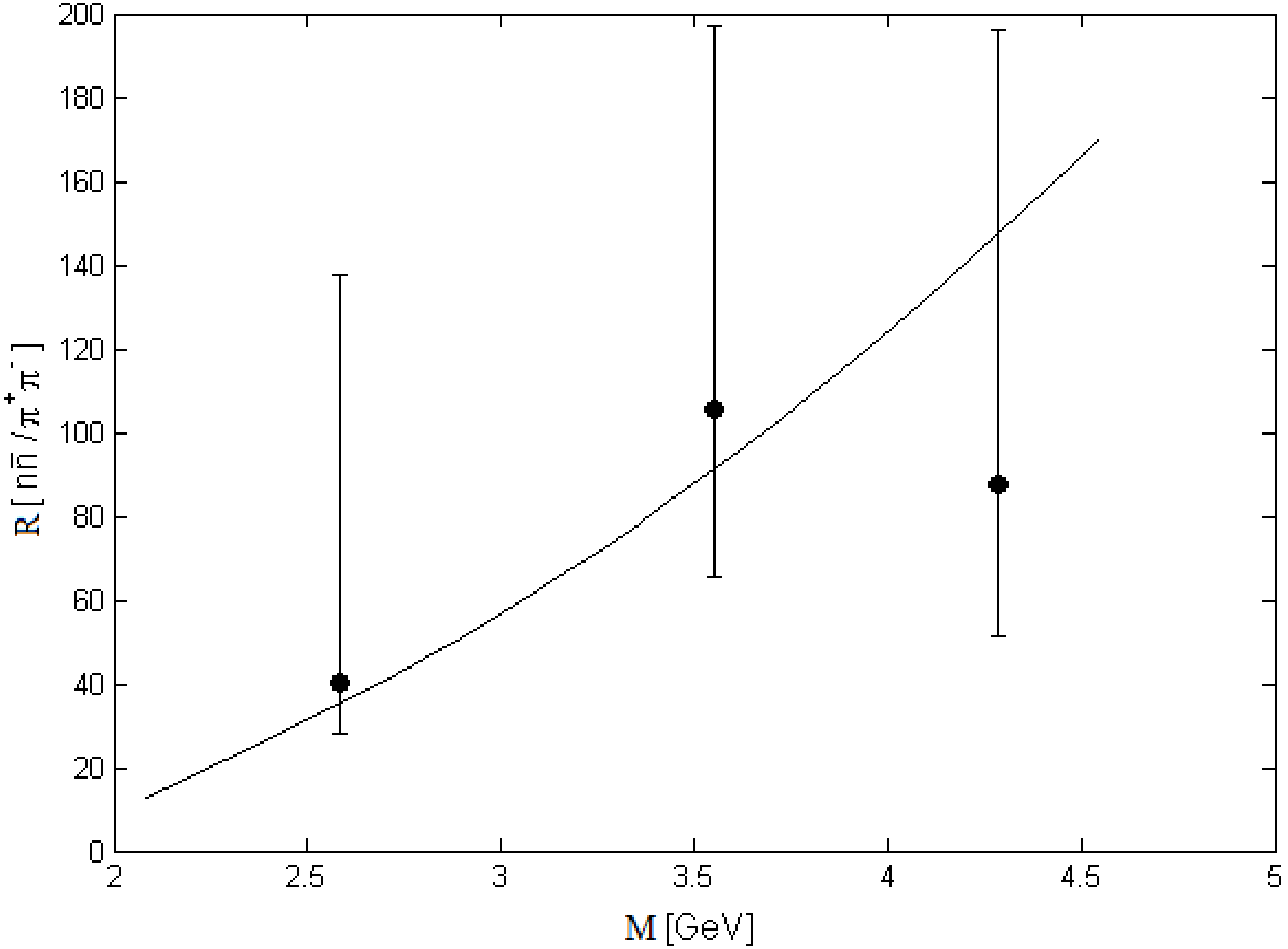
- $P_{n_i}^{H,i}(x_i)$'s the hadronization probabilities, are the phase space factors that a fireball with energy (x_i) decays to the given hadrons
- P_k^{fb} the formation probability of k fireballs are calculated in the following way: any decaying fireball randomly distribute its energy between the 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 $P_u = P_d = 0.38, P_s = 0.24, P_c = 3.52 \cdot 10^{-5}$.



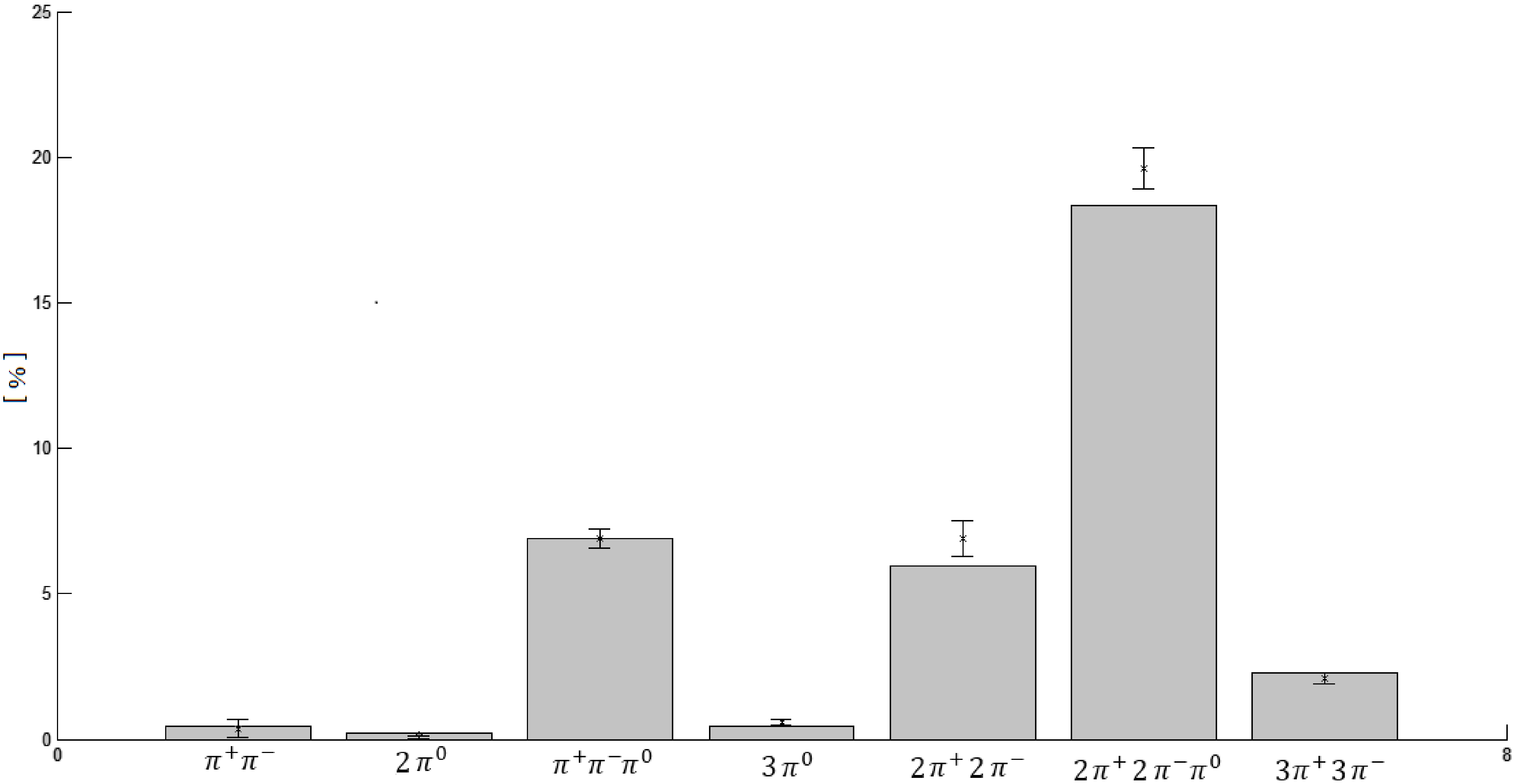
Data
P_u=0.38 | P_d=0.38 | P_s=0.24
P_u=0.33 | P_d=0.33 | P_s=0.33
R [π+π- / K+ K-]
p_LAB [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0.5
1
1.5
2
2.5

Predictions





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



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, $\Psi(3686)$, $\Psi(3770)$: 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

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

- 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

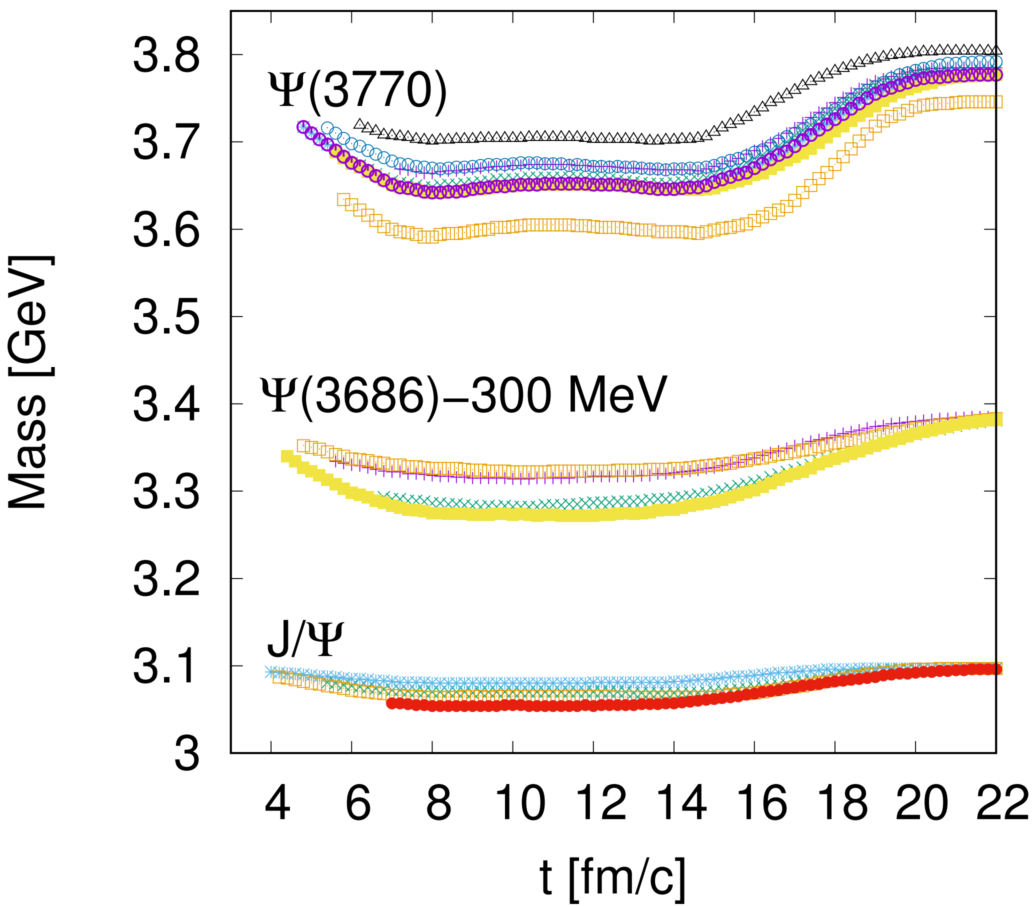
background:

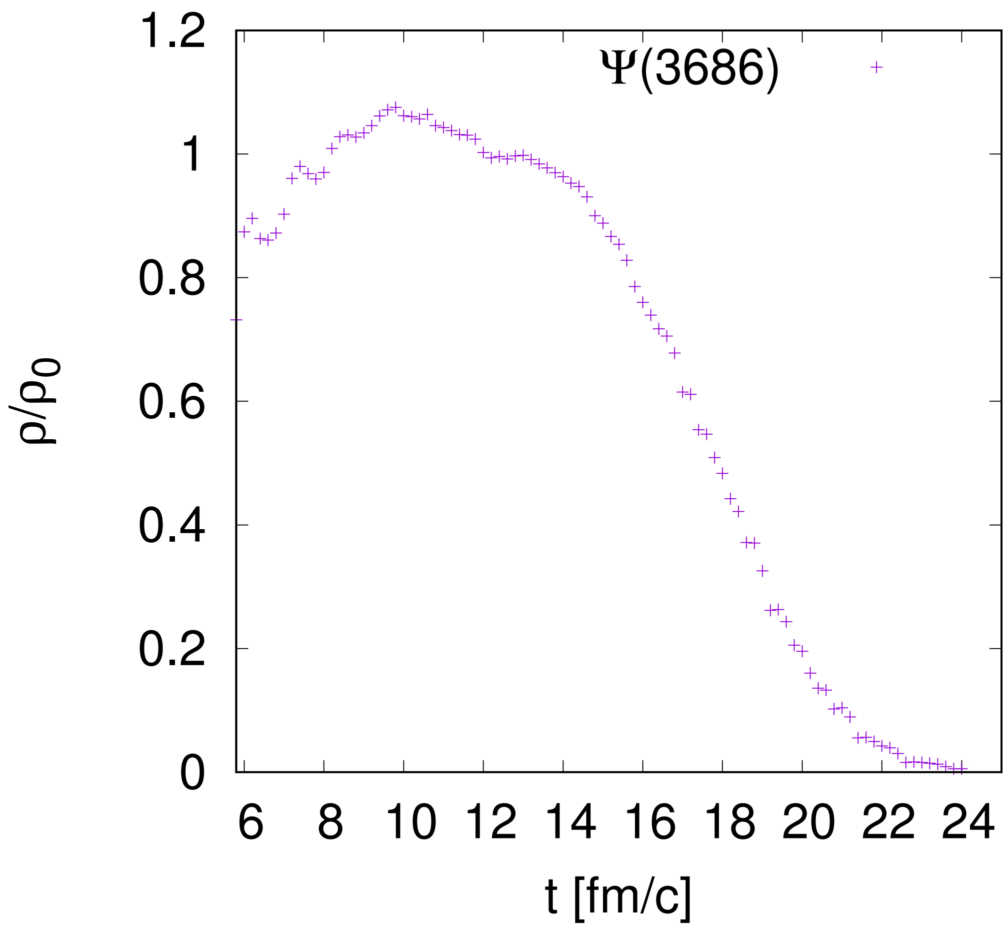
Drell-Yan: small number of energetic hadron-hadron collisions

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

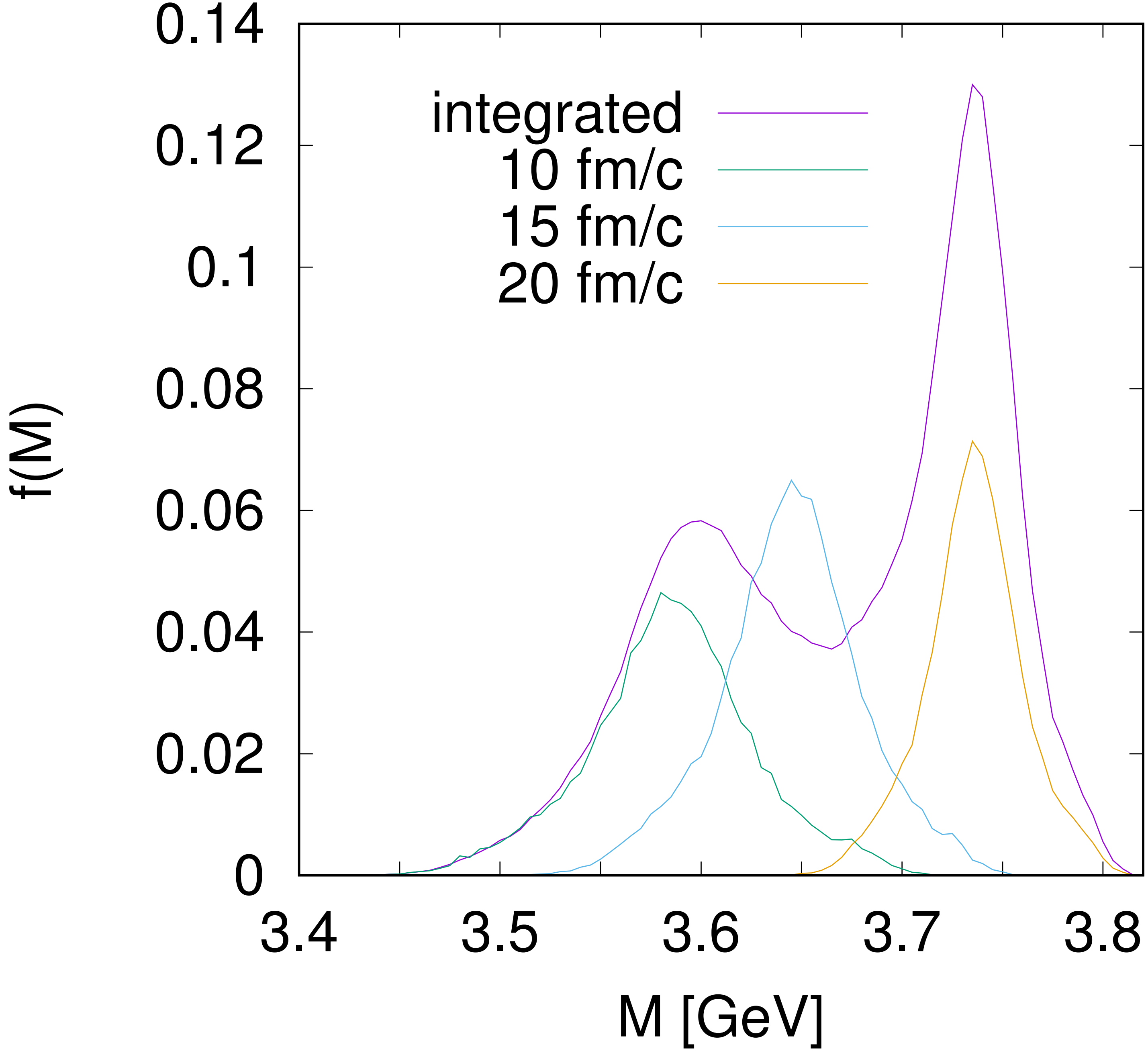
Time evolution of masses and density at $\bar{p}$Au 6 GeV/c



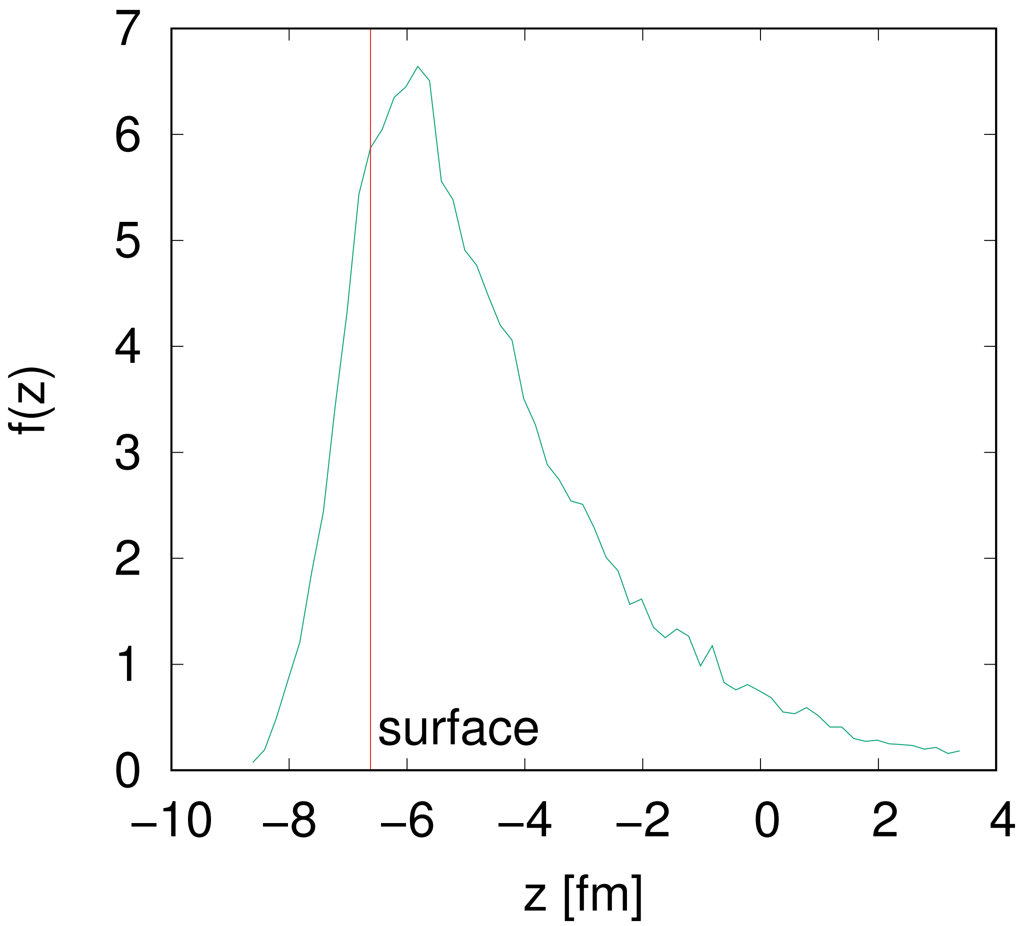


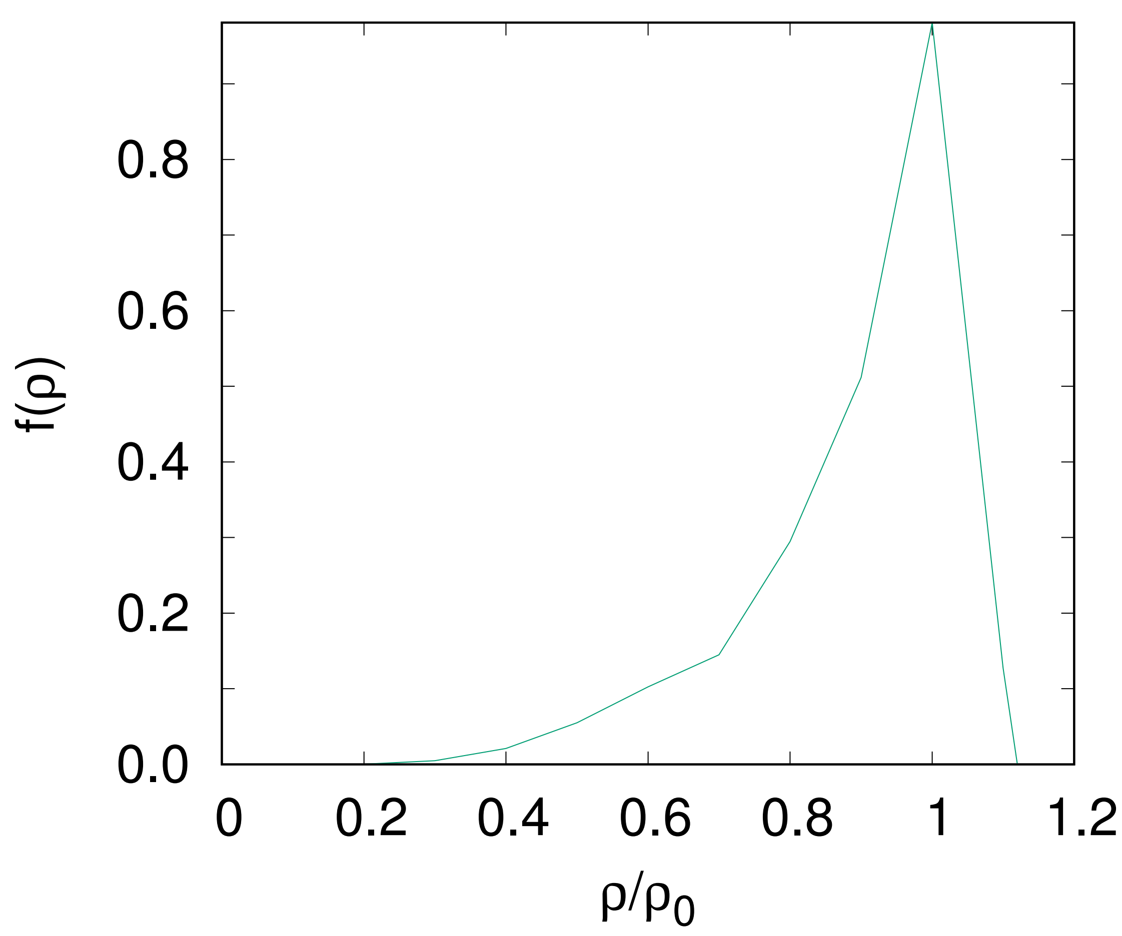
The charmonium states are created at the surface of the heavy nucleus,
travel through the dense matter (decays with some probability),
crosses the thin surface again and reaching the vacuum.
Major contribution to the dilepton channel are coming from the dense matter and from the vacuum.

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



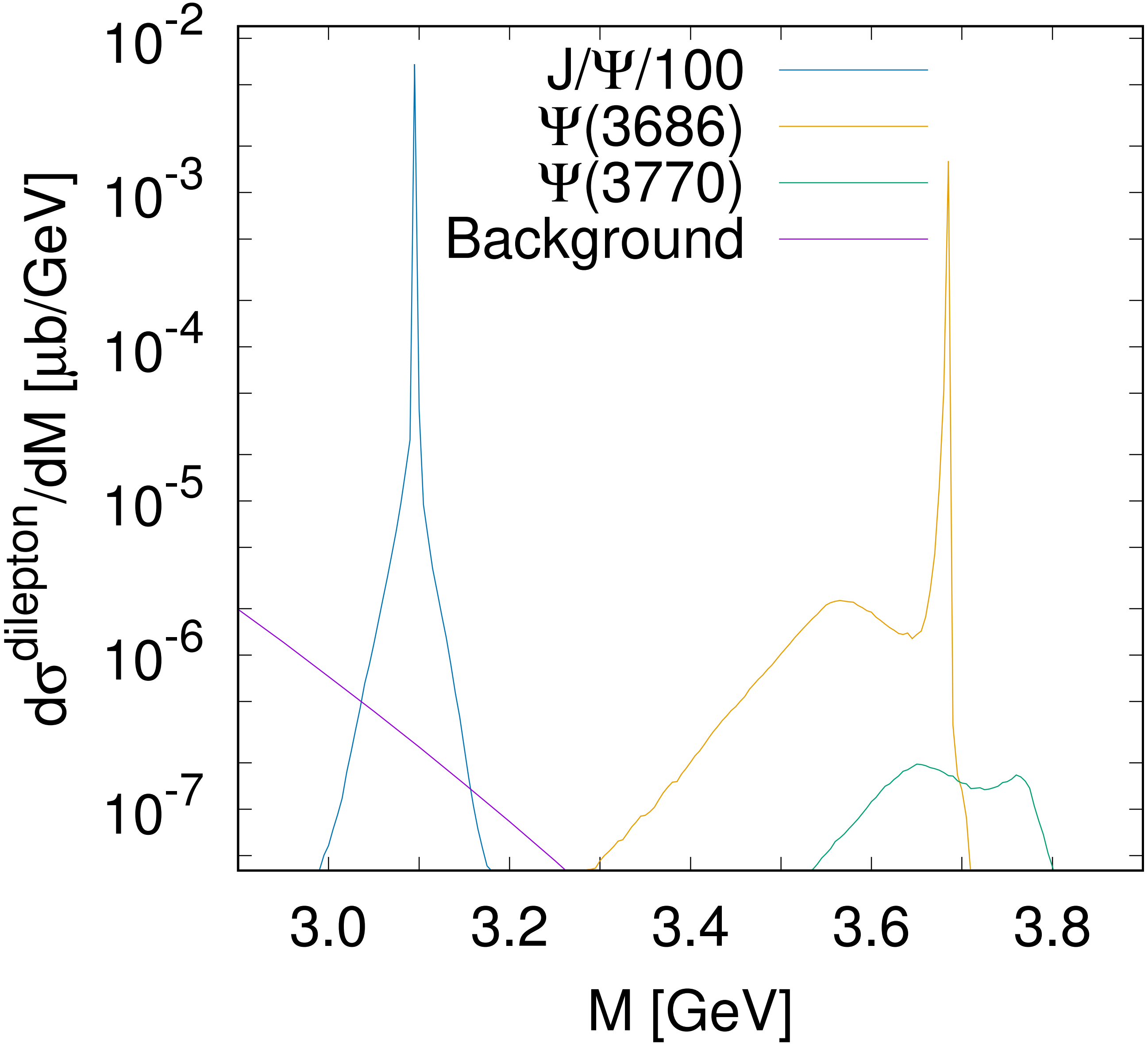
Charmonium creation





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

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



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

$\Psi(3686)$

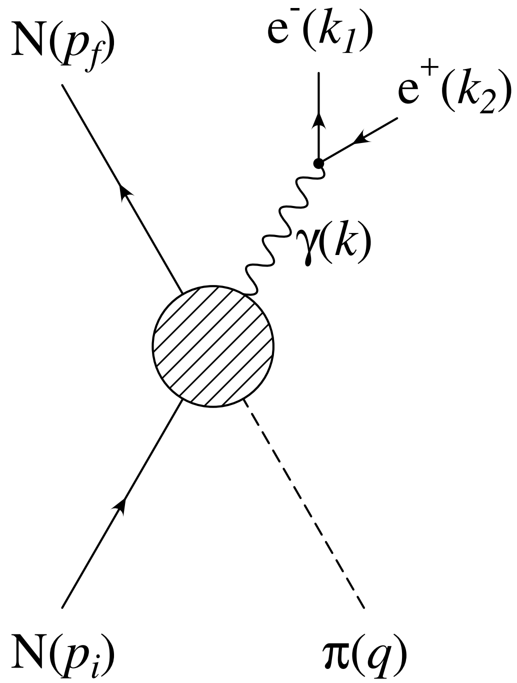
- The distance between the peaks corresponds to a mass shift at $\rho \approx 0.9\rho_0$
- qualitatively the same picture if increase or reduce the mass shift by factor of 2
- measuring the peak distance, we obtain the mass shift at $\rho \approx 0.9\rho_0$
- measuring the mass shift, we obtain the gluon condensate at $\rho \approx 0.9\rho_0$
- the same picture at 6-10 GeV
- key points: cross sections are not, background is several magnitude less than the signal
- em. width
- absorption cross section of $\bar{p}N$

Summary

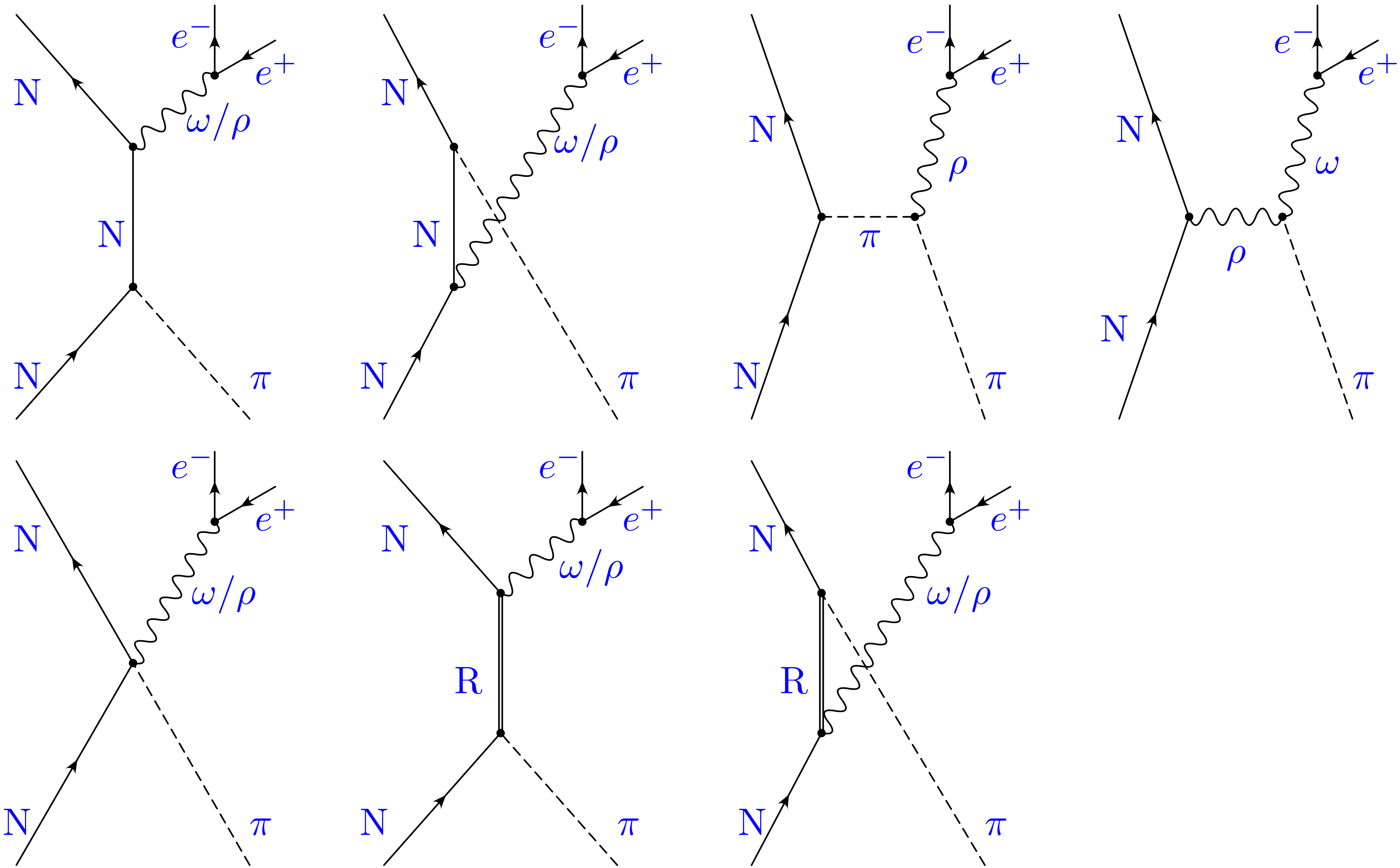
- We developed a bootstrap approach to calculate unknown cross sections. For known channels it fits the experimental data
- Dilepton production in $\bar{p}$A provides us the possibility to study charmonium spectral function in matter.
- We can measure the gluon condensate in nuclear matter.

$\pi + N \to N + e^+e^-$

- Coupled-channel approaches
  K-matrix: Post-Mosel
  Bethe-Salpeter: Lutz-Wolf-Friman
- Effective field theory:
  Zétényi, Wolf,
  Phys. Rev. C86 (2012) 065209



Feynman diagrams for $\pi + N \to N + e^+e^-$



Effective Field Theory for $\pi + N \to N + e^+e^-$

$$\mathcal{L}_{\mathcal{NN}\pi} = -\frac{\mathrm{f_{NN\pi}}}{\mathrm{m}_\pi}\overline{\psi}_{\mathcal{N}}\gamma_5\gamma^\mu\vec{\tau}\psi_{\mathcal{N}}\cdot\partial_\mu\vec{\pi}.$$

$$\mathcal{L}_{\omega\rho\pi} = \frac{\mathrm{g}_{\omega\rho\pi}}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\omega_\nu\mathrm{Tr}\left((\partial_\alpha\vec{\rho_\beta}\cdot\vec{\tau})(\vec{\pi}\cdot\vec{\tau})\right)$$

$$\mathcal{L}_{\mathcal{NN}\rho} = \mathrm{g}_\rho\overline{\psi}_{\mathrm{N}}\left(\vec{\not{\rho}} - \kappa_\rho\frac{\sigma_{\mu\nu}}{4\mathrm{m_N}}\vec{\rho}^{\mu\nu}\right)\cdot\vec{\tau}\psi_{\mathrm{N}}, \quad \mathcal{L}_{\mathcal{NN}\omega} = \mathrm{g}_\omega\overline{\psi}_{\mathrm{N}}\left(\not{\omega} - \kappa_\omega\frac{\sigma_{\mu\nu}}{4\mathrm{m_N}}\omega^{\mu\nu}\right)\psi_{\mathrm{N}}.$$

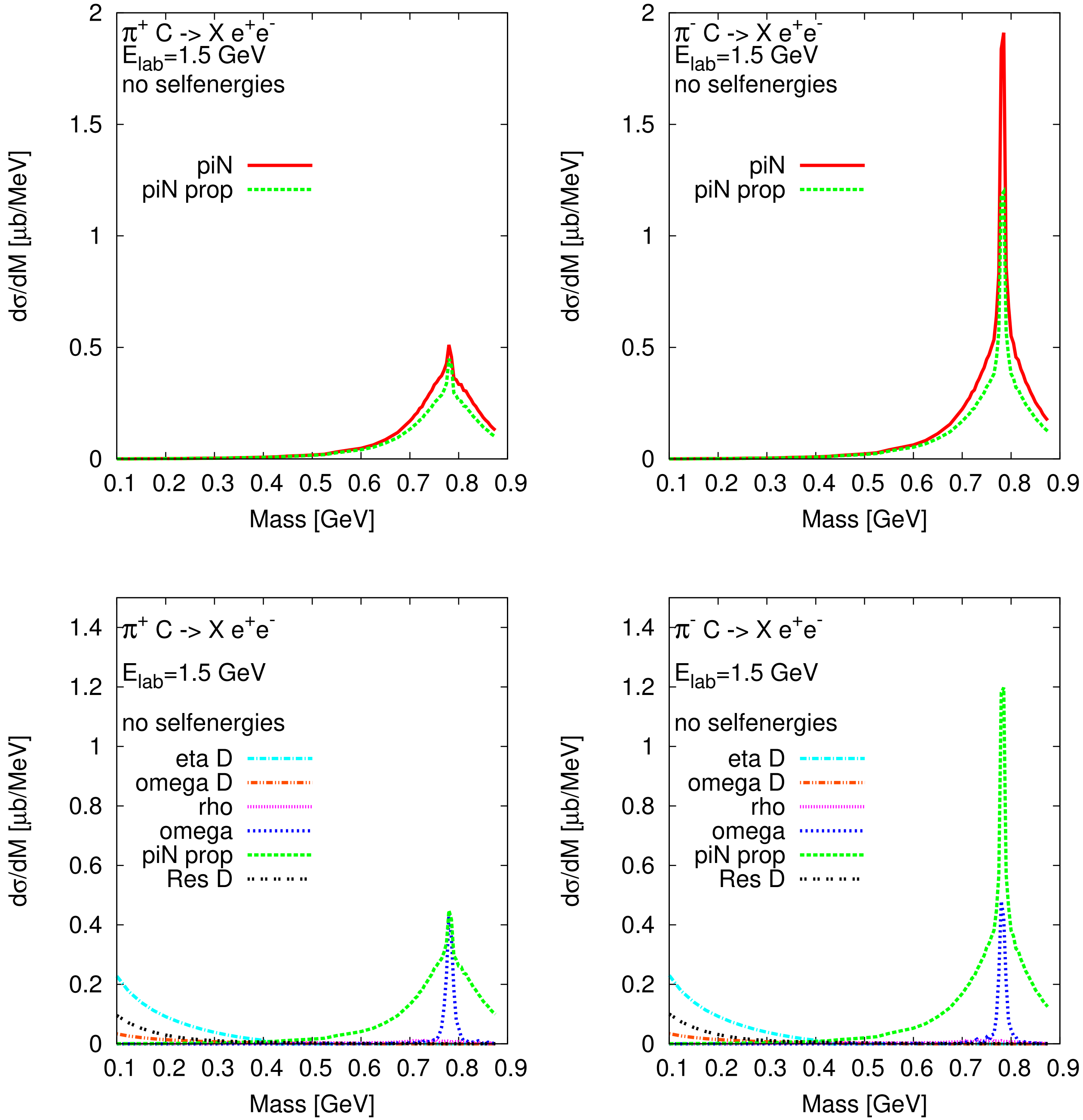
ρ_0 couples to $\bar{\psi}_N\tau_0\psi_N$ so to p and to n with different signs, while ω with the same sign

Considering $\pi^- p \to ne^+e^-$ and $\pi^+ n \to pe^+e^-$ in one channel constructive and in the other channel destructive interference

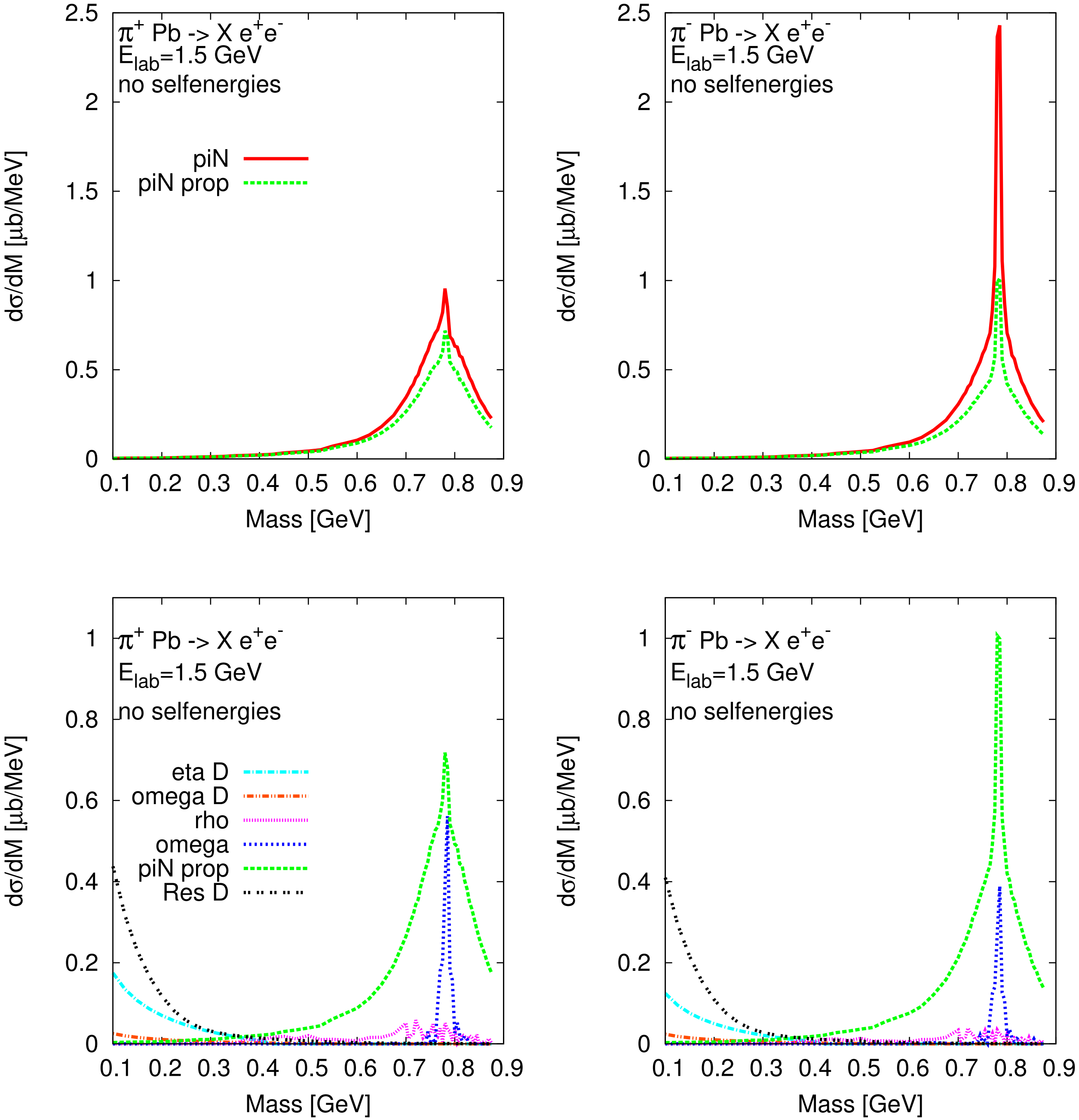
Dileptons in pion-nucleus collisions

- $\frac{\frac{d\sigma}{dM}^{\pi^- p \to n e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ n \to p e^+ e^-}(m_\omega)} \approx 4$ because of the interference
- The effect is strong if cross secton through ρ and ω are similar
- coupling constants of ω were taken from the literature, we plan to make our fit
- The same problem was studied in M.F.M. Lutz, B. Friman, M. Soyeur, Nucl. Phys. A713 (2003) 97 and A.I. Titov, B Kämpfer, EPJ A 12 (2001) 217. They had smaller ρ cross section, so the effect was strong at lower $\sqrt{s}$
- How much of this coherence survive in a nucleus?
- In a nucleus coherence is lost if one of the vector meson collides
- Quantum measurement: collisional broadening for those ω's which will interfere with a ρ?

π C, 1.5 GeV, no selfenergies, Preliminary results



π Pb, 1.5 GeV, no selfenergies, Preliminary results



Dileptons in pion-nucleus collisions

- $$\frac{\frac{d\sigma}{dM}^{\pi^- p \to n e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ n \to p e^+ e^-}(m_\omega)} \approx 4$$
  $$\frac{\frac{d\sigma}{dM}^{\pi^- C^{12} \to X e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ C^{12} \to X e^+ e^-}(m_\omega)} \approx 2.9$$
  $$\frac{\frac{d\sigma}{dM}^{\pi^- Pb^{207} \to X e^+ e^-}(m_\omega)/N_p}{\frac{d\sigma}{dM}^{\pi^+ Pb^{207} \to X e^+ e^-}(m_\omega)/N_n} \approx 2.0$$
  In case of complete decoherence these ratios should be 1.
- Experimentally the decoherence can be observed in strongly interacting matter.
- Is an interference with its pair a measurement? Collisional broadening?

Kadanoff-Baym Equation

Schwinger-Dyson equation:

$$G = G_0 + G_0 \Sigma G$$

$$\begin{aligned}
G^{11}(1,2) &= G^{T}(1,2) = \langle T(\phi(1)\phi(2))\rangle \\
G^{22}(1,2) &= G^{AT}(1,2) = \langle \tilde{T}(\phi(1)\phi(2))\rangle \\
G^{21}(1,2) &= G^{<}(1,2) = \langle \phi(2)\phi(1)\rangle \\
G^{12}(1,2) &= G^{>}(1,2) = \langle \phi(1)\phi(2)\rangle \\
G^{r}(1,2) &= \theta(t1 - t2)(G^{>}(x1,t1;x2,t2) - G^{<}(x1,t1;x2,t2)) \\
G^{a}(1,2) &= \theta(t2 - t1)(G^{<}(x1,t1;x2,t2) - G^{>}(x1,t1;x2,t2))
\end{aligned}$$

After some manipulation: *Kadanoff-Baym equation*:

$$\begin{aligned}
(i\hbar\partial_{t1} - H_0(1))G^{<}(1,2) &= \int d3\, \Sigma^{r}(1,3)G^{<}(3,2) + \int d3\, \Sigma^{<}(1,3)G^{a}(3,2) \\
(i\hbar\partial_{t1} - H_0(1))G^{r}(1,2) &= \delta^{4}(1,2) + \int d3\, \Sigma^{r}(1,3)G^{r}(3,2)
\end{aligned}$$

Wigner-transformation

- Retarded propagator is not a distribution function
- Wigner transform:

$$r = x1 - x2 \qquad , \qquad R = x1 + x2$$

R (center of mass) dependence of propagators and selfenergies are weaker than the r dependence

$$G^r(R,P) = \int d^4r \, G^r(X+r, X-r)$$

- Gradient expansion in r. Neglect all terms with more than one derivative in R
- transport equation for $F_\alpha = iG^<(R,P) = f_\alpha(x,p,t)A_\alpha$
  $A(p) = -2ImG^r = \frac{\hat{\Gamma}}{(E^2 - \mathbf{p}^2 - m_0^2 - \mathrm{Re}\Sigma^r)^2 + \frac{1}{4}\hat{\Gamma}^2}$,

  Cassing, Juchem (2000) and Leupold (2000)
- testparticle approximation