

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

eQCD, Kapaonik, Serbia, 13.03.2018.

Gy. Wolf

in collaboration with G. Balassa, P. Kovács, M. Zétényi, Wigner RCP  
Su Houn Lee, Yonsei University, Korea

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

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  $J/\psi$  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) 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

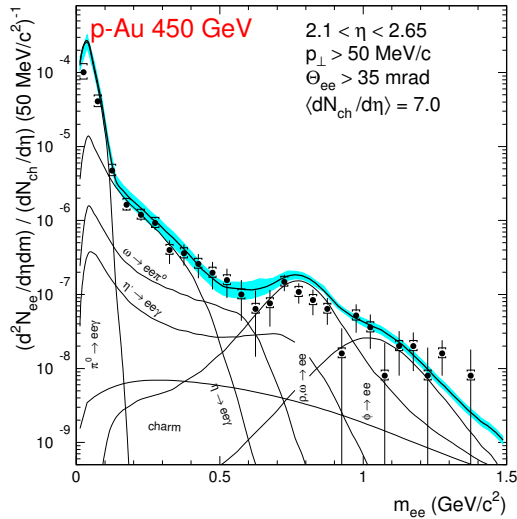
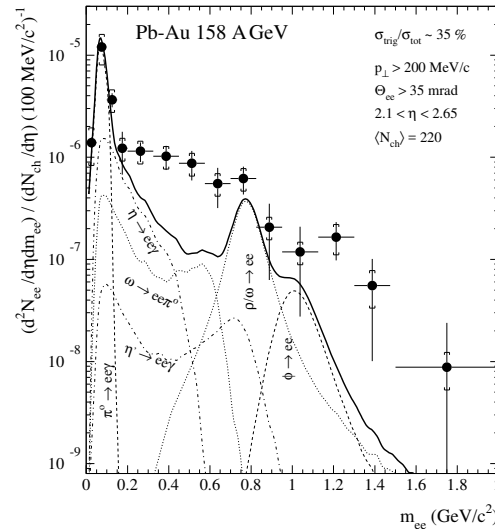
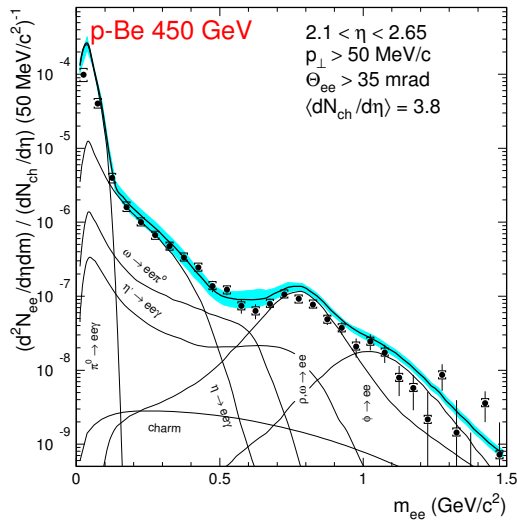
$$m_N \bar{u}(p)u(p) = \langle N(p) | \frac{\beta}{2g} G_{\mu\nu}^a G^{a \mu\nu} + m \bar{q}q | N(p) \rangle$$

contribution of light quarks can be estimated ( $\sigma$ -term):  $\approx 50$  MeV,  
contribution of the heavy quarks are expected to be small, 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 → vector mesons in matter
- much better than 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  $\eta$
- Dalitz-decay of  $\pi$ ,  $\eta$  and  $\omega$
- Dalitz-decay of baryon resonances  
Zetenyi, Wolf, Phys. Rev, C67 (2003) 044002;  
Heavy Ion Phys. 17 (2003) 27
- pn bremsstrahlung
- Drell-Yan:  $\bar{q}q \rightarrow e^+e^-$
- 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  $\eta$ , for strangeness an extra, somewhat artificial parameter, even then  $\Xi$  is completely wrong

- No global equilibrium at 0.4 AGeV central  $Ru_{44}^{96} + Zr_{40}^{96}$  collisions  
FOPI, Phys.Rev.Lett. 84 (2000) 1120

- 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 +  $\Lambda$  and  $\Sigma$  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

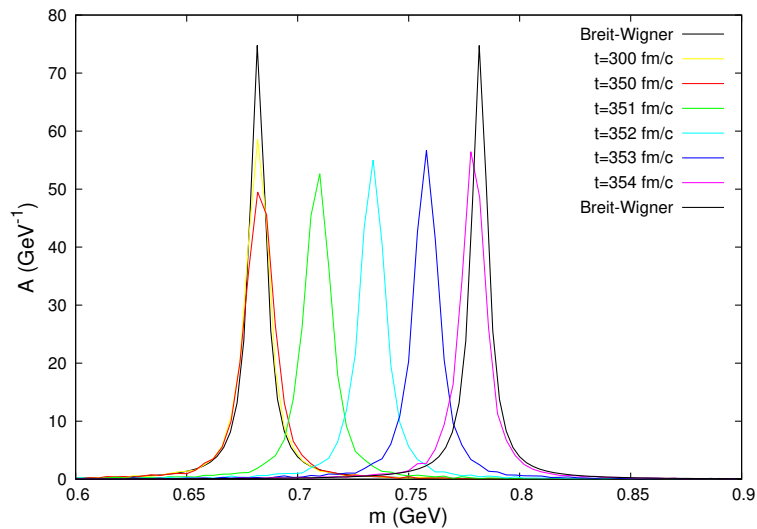
$$C_{(i)} = \frac{1}{2\epsilon_i} \left[ \frac{\partial}{\partial \epsilon_i} \text{Re}\Sigma_{(i)}^{\text{ret}} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - \text{Re}\Sigma_{(i)}^{\text{ret}}}{\text{Im}\Sigma_{(i)}^{\text{ret}}} \frac{\partial}{\partial \epsilon_i} \text{Im}\Sigma_{(i)}^{\text{ret}}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

- the last equation for homogenous system can be rewritten as

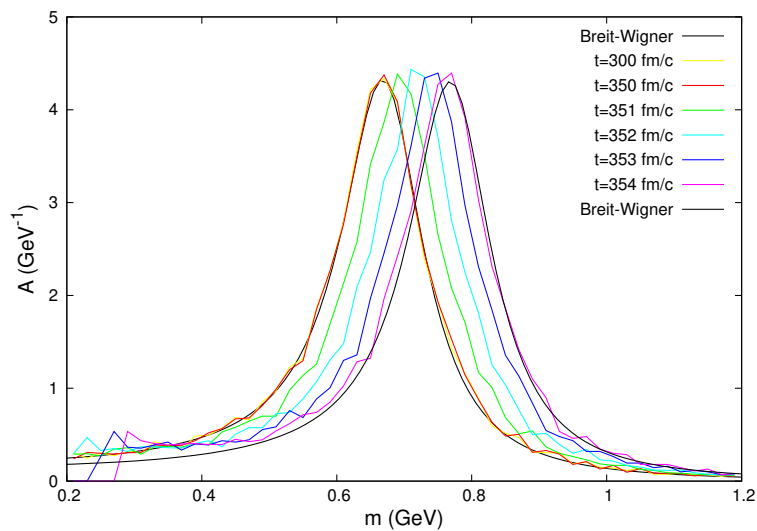
$$\frac{dM_i^2}{dt} = \frac{d(\epsilon_i^2 - P_i^2)}{dt} = \frac{d\text{Re}\Sigma_{(i)}^{\text{ret}}}{dt} + \frac{M_i^2 - M_0^2 - \text{Re}\Sigma_{(i)}^{\text{ret}}}{\text{Im}\Sigma_{(i)}^{\text{ret}}} \frac{d\text{Im}\Sigma_{(i)}^{\text{ret}}}{dt}$$

# Evolution of mass distribution in a box

the vector meson masses are shifted linearly with density, and change the density linearly from  $\rho_0$  to 0 in 4 fm/c:



$\omega$



$\rho$

# Charmonium in vacuum and in matter

- Charmonium:  $J/\Psi$ ,  $\Psi(3686)$ ,  $\Psi(3770)$ : 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?

## $\bar{p}A$ at PANDA 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 $\rho/\rho_0$

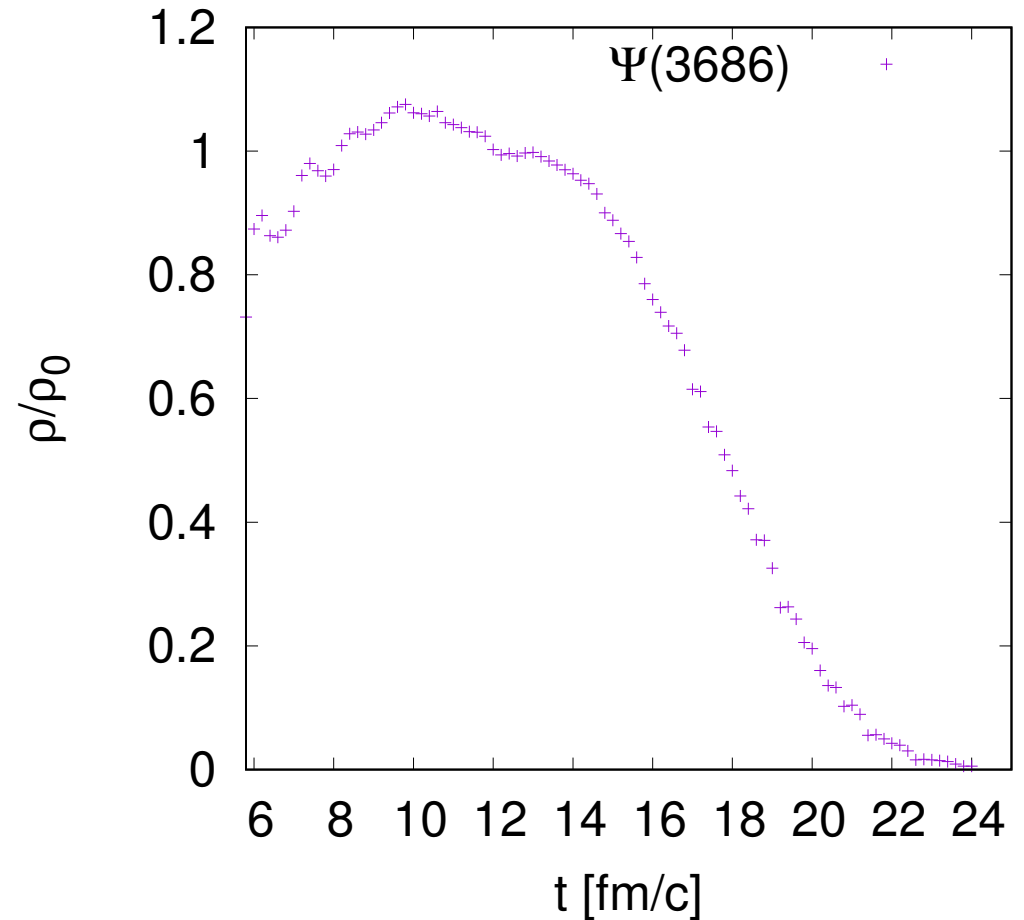
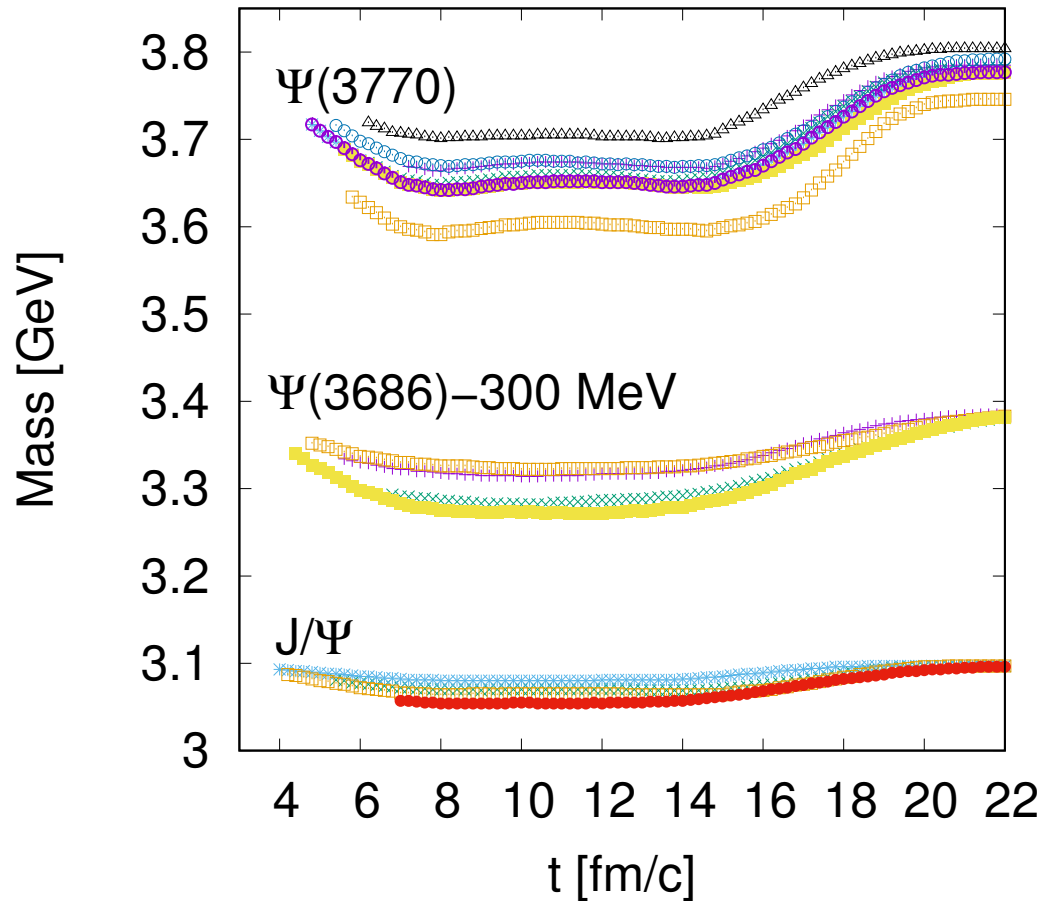
background:

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

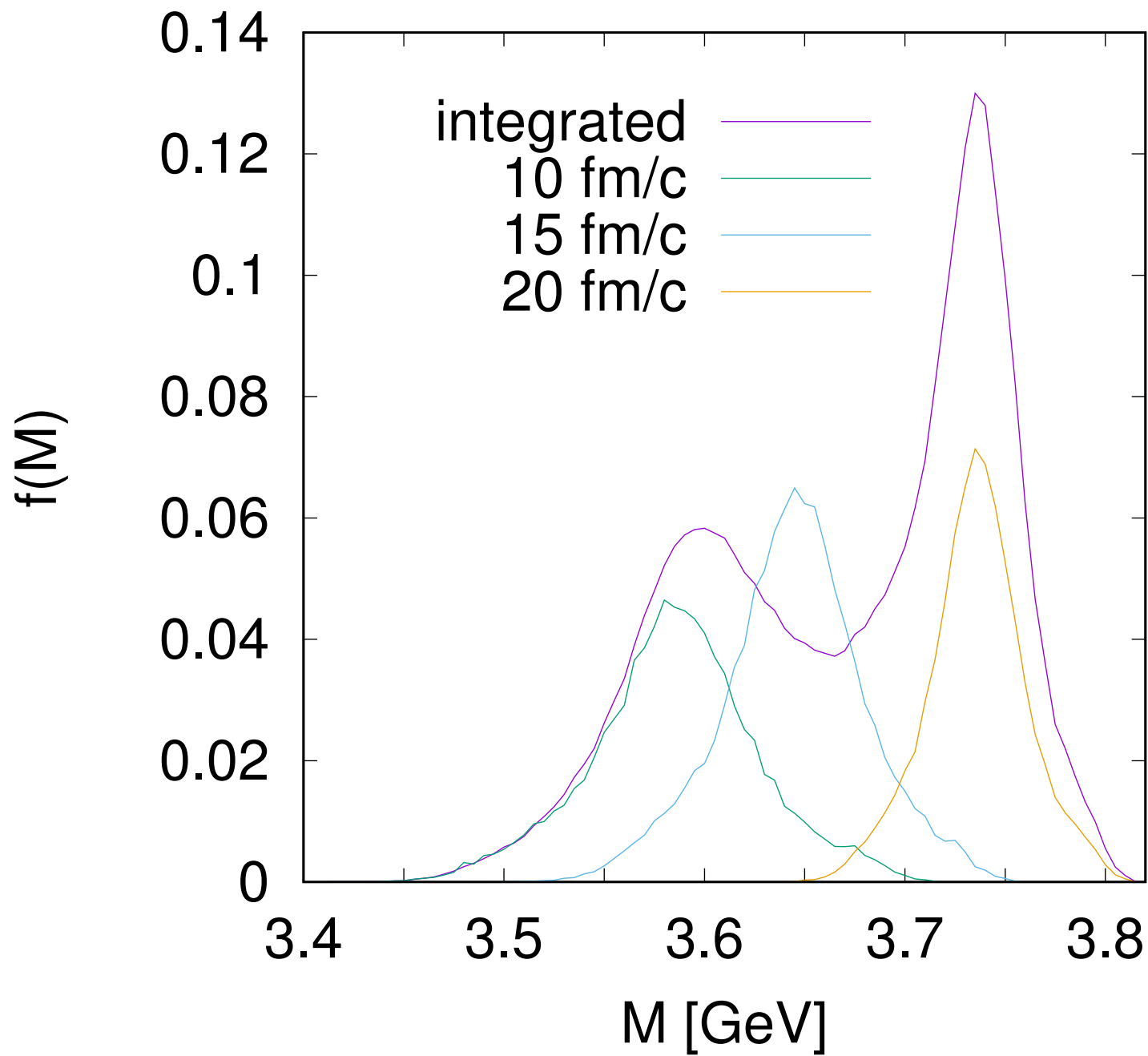


The charmonium states are created at the surface of the heavy nucleus, travel through the dense matter (decays with some probability), crosses the thin surface again and reaching the vacuum.

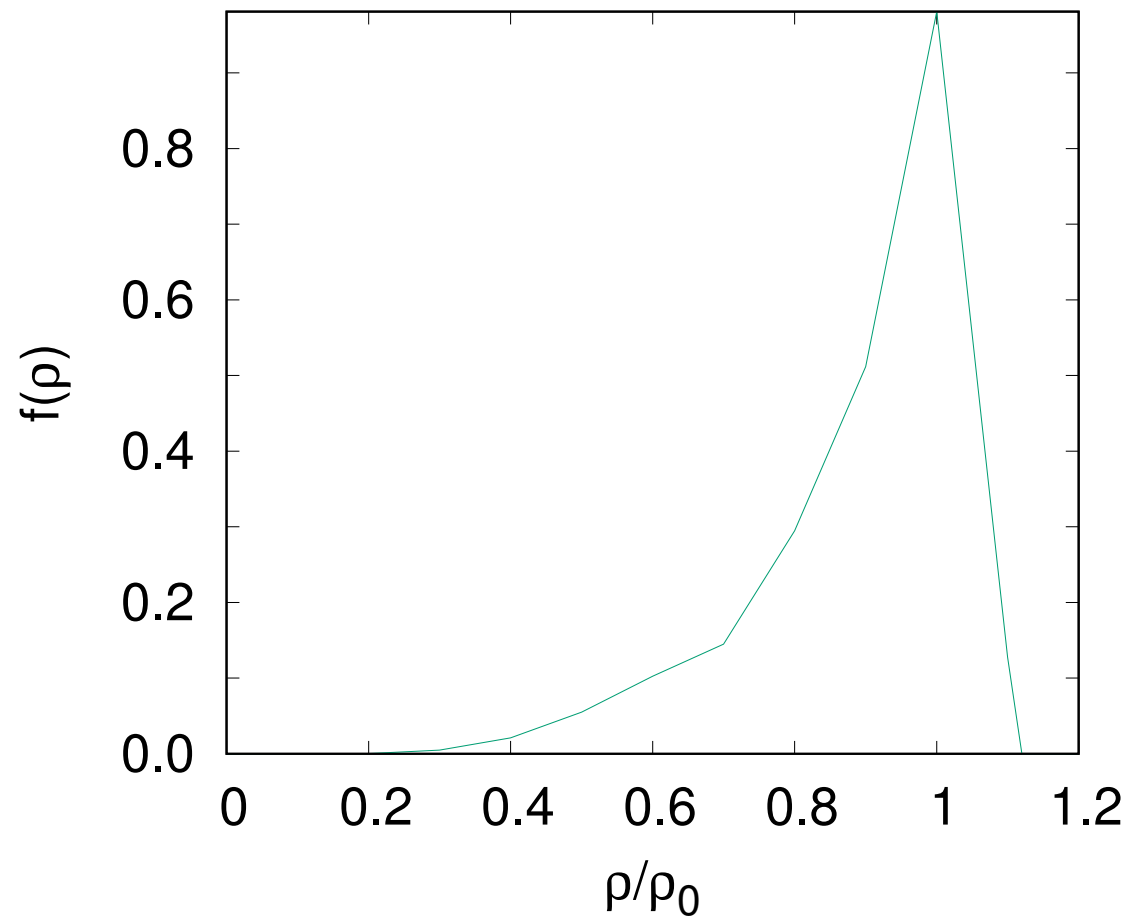
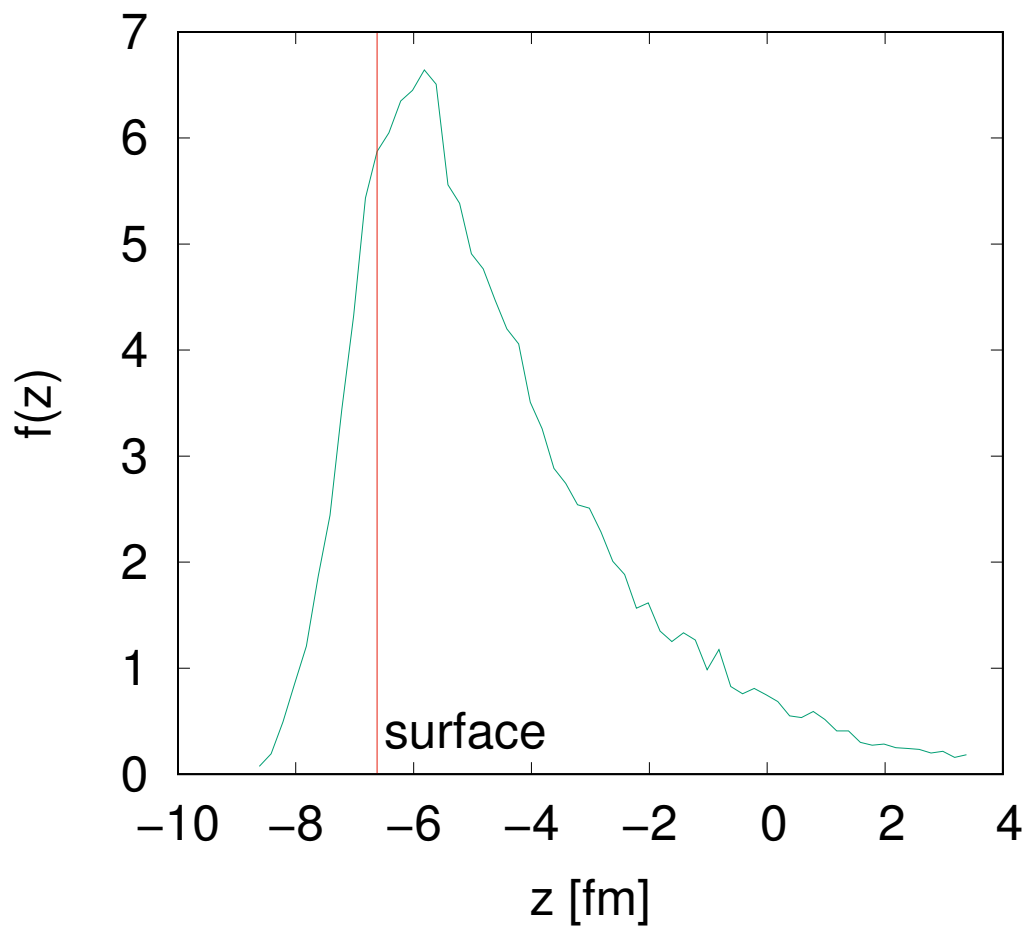
Major contribution to the dilepton channel are coming from the dense matter and from the vacuum.



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

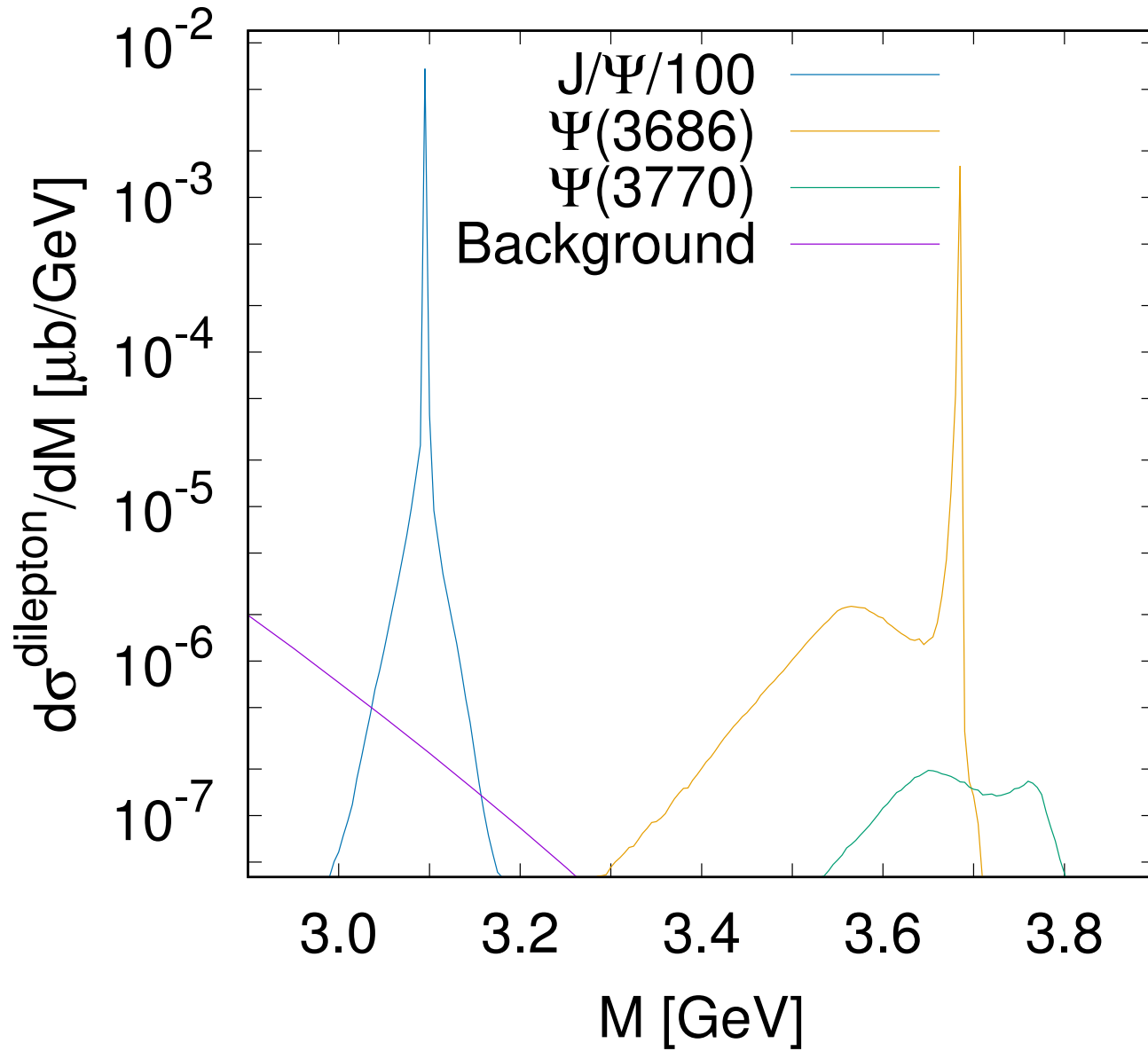


# Charmonium creation



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)

## $\Psi(3686)$

- 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.

## 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

$$\begin{aligned}\sigma(M) &= \left( \int \prod_{i=1}^n d^3 p_i R(M, p_1, \dots, p_n) \right) \times \left( \int \prod_{j=1}^m d^3 k_j w(M, k_1, \dots, k_m) \right) \\ &= \sigma_{Tot}(M) \cdot W(M)\end{aligned}$$

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

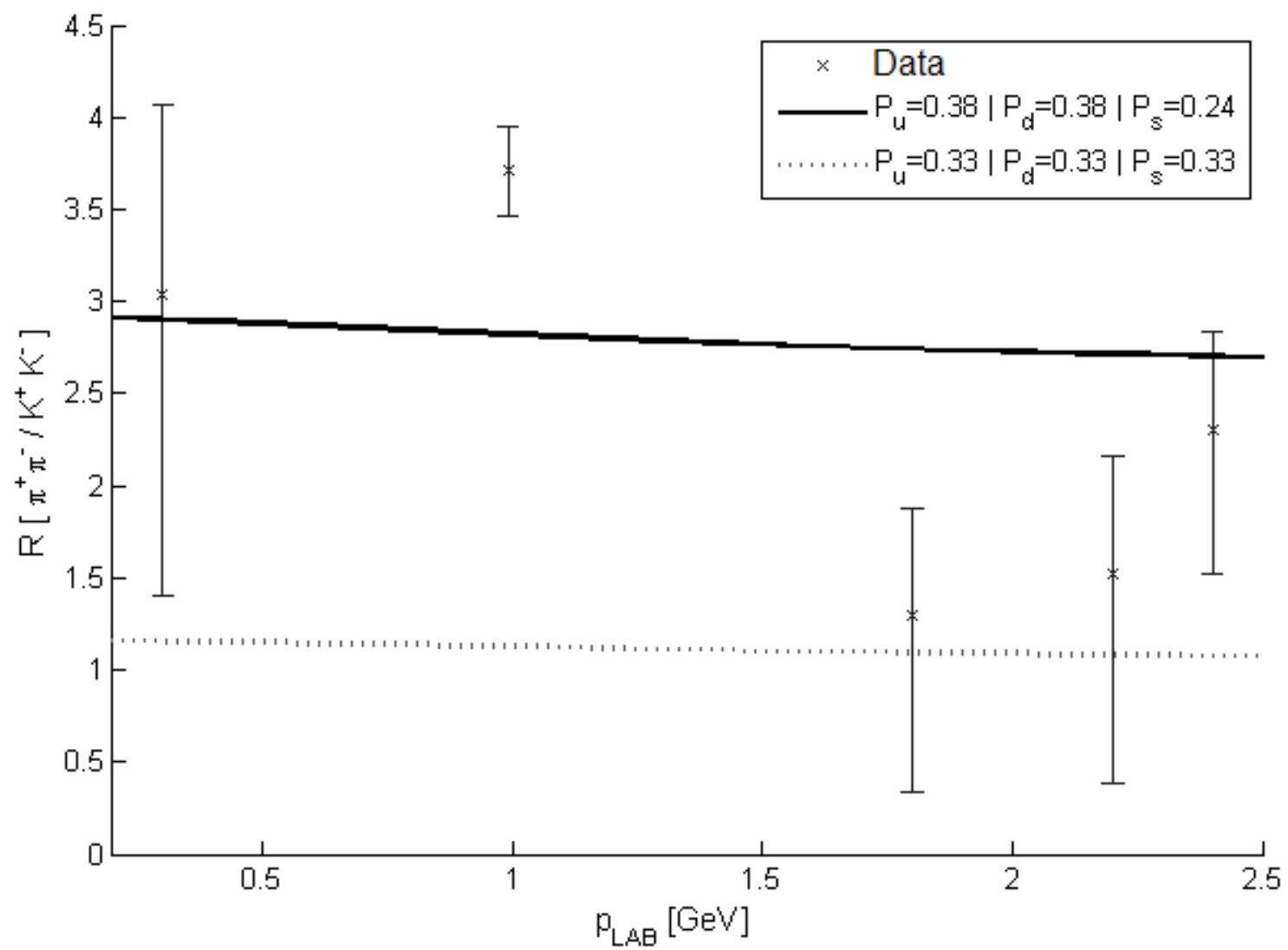
$$W_k^{n_1, \dots, n_k}(M) = N(M) P_k^{fb}(M) C_Q(M)$$

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

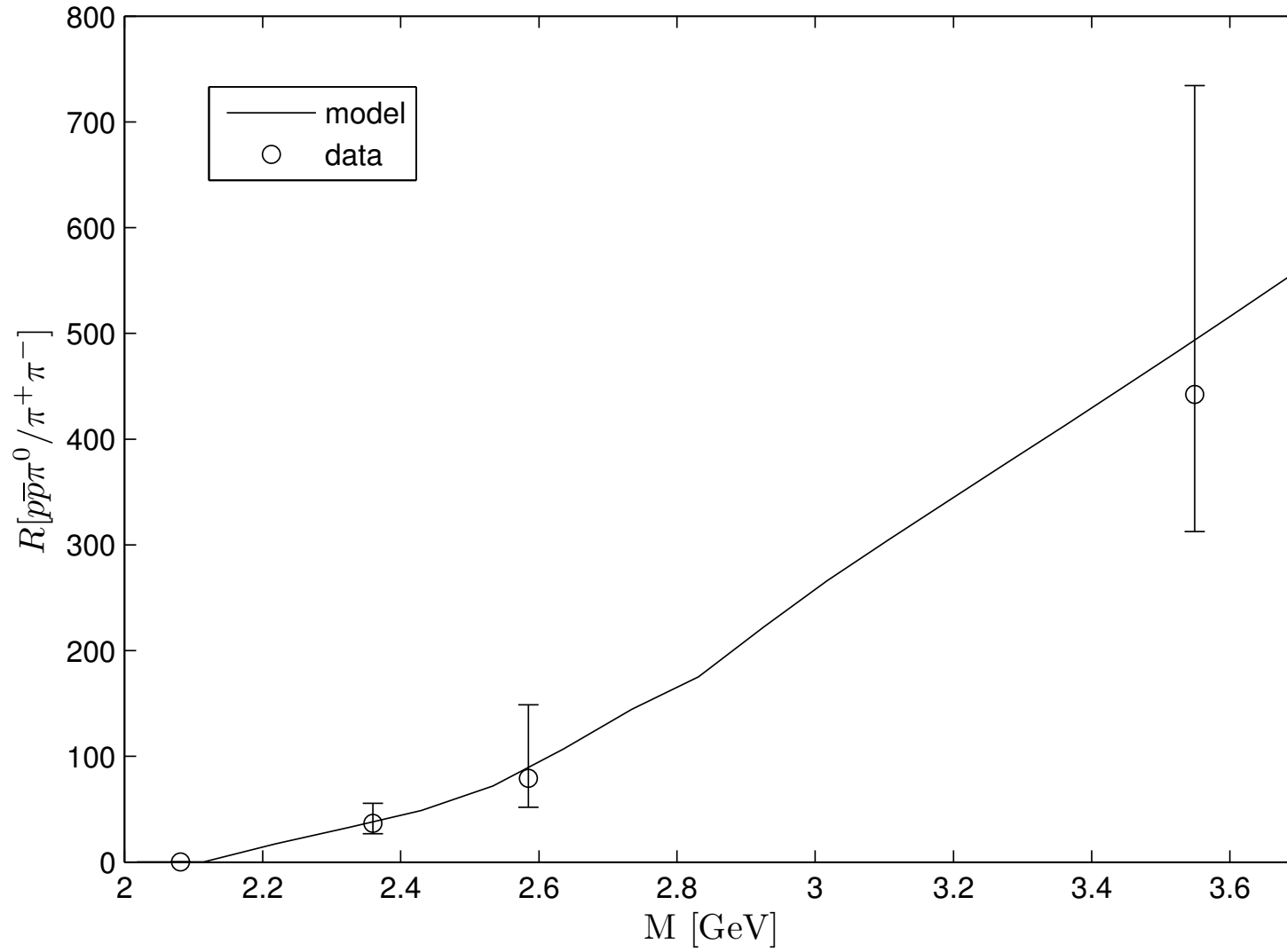
$P_k^{fb}$ : formation probability of  $k$  fireballs,  $C_Q(M)$ : the quark-combinatorical factor,  $x_i$ 's are the invariant masses of the individual fireballs,  $P_{n_i}^{H,i}(x_i)$ 's are the hadronization probabilities

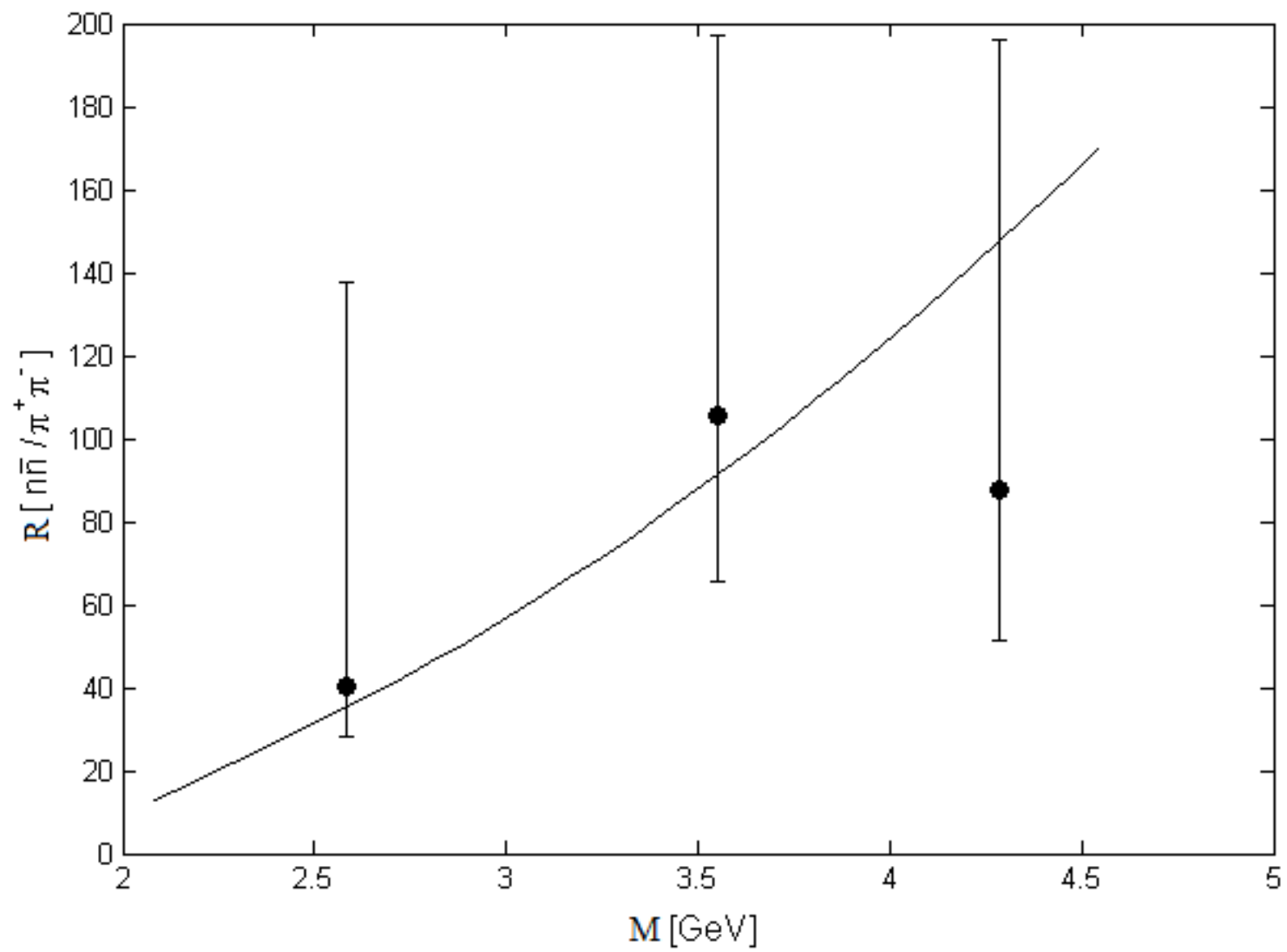
- $P_{n_i}^{H,i}(x_i)$ 's the hadronization probabilities, are the phase space factors that a fireball with energy  $(x_i)$  decays to the given hadrons
- $P_k^{fb}$  the formation probability of  $k$  fireballs are calculated in the following way: any decaying fireball randomly distribute its energy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

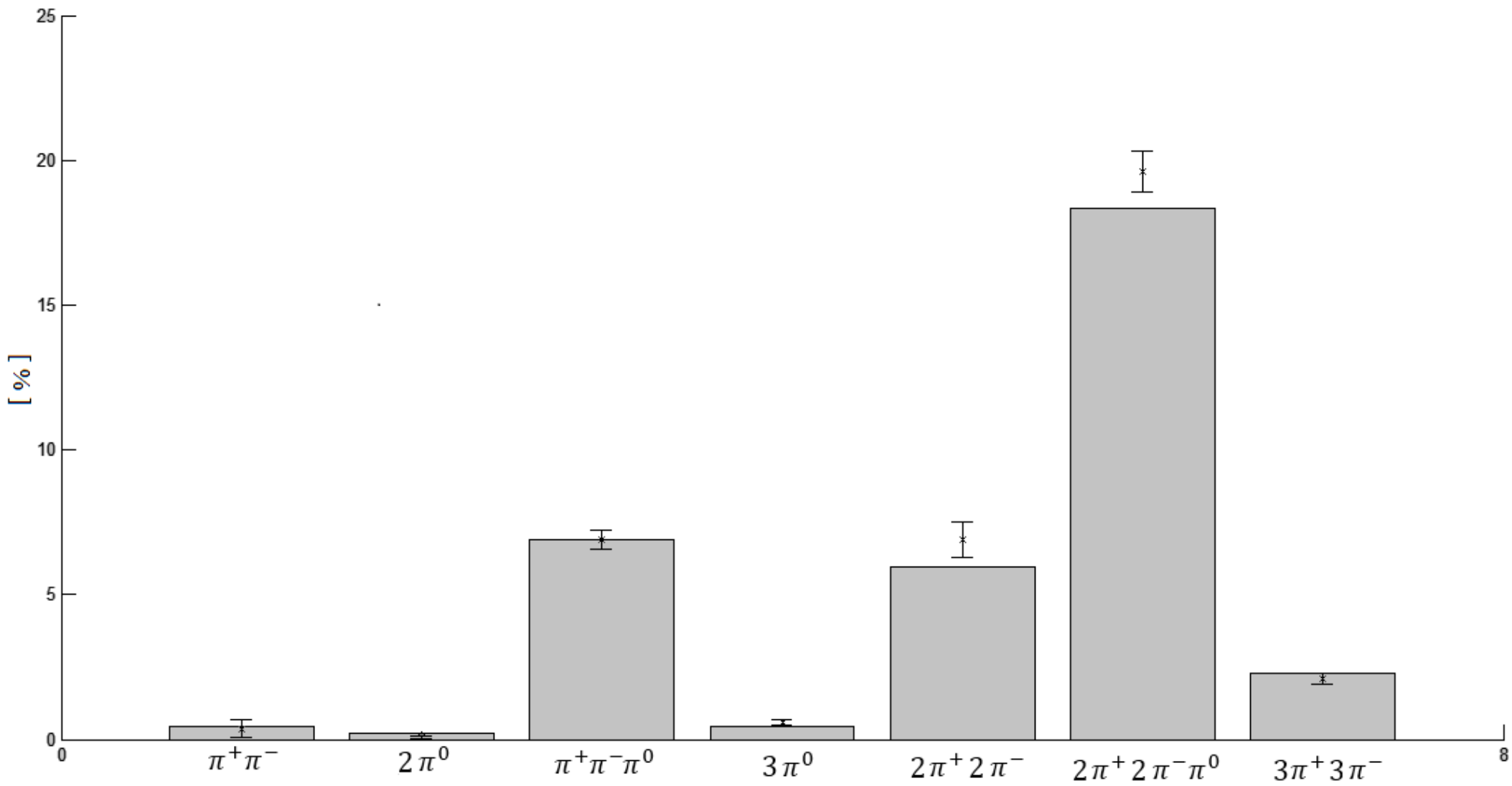




# Predictions

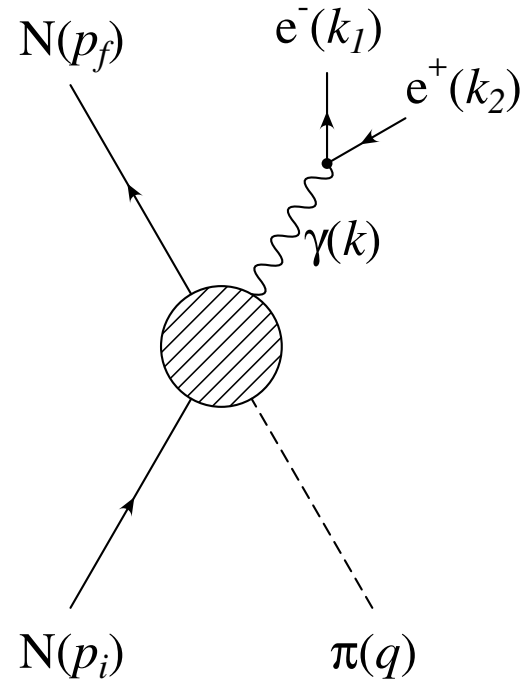




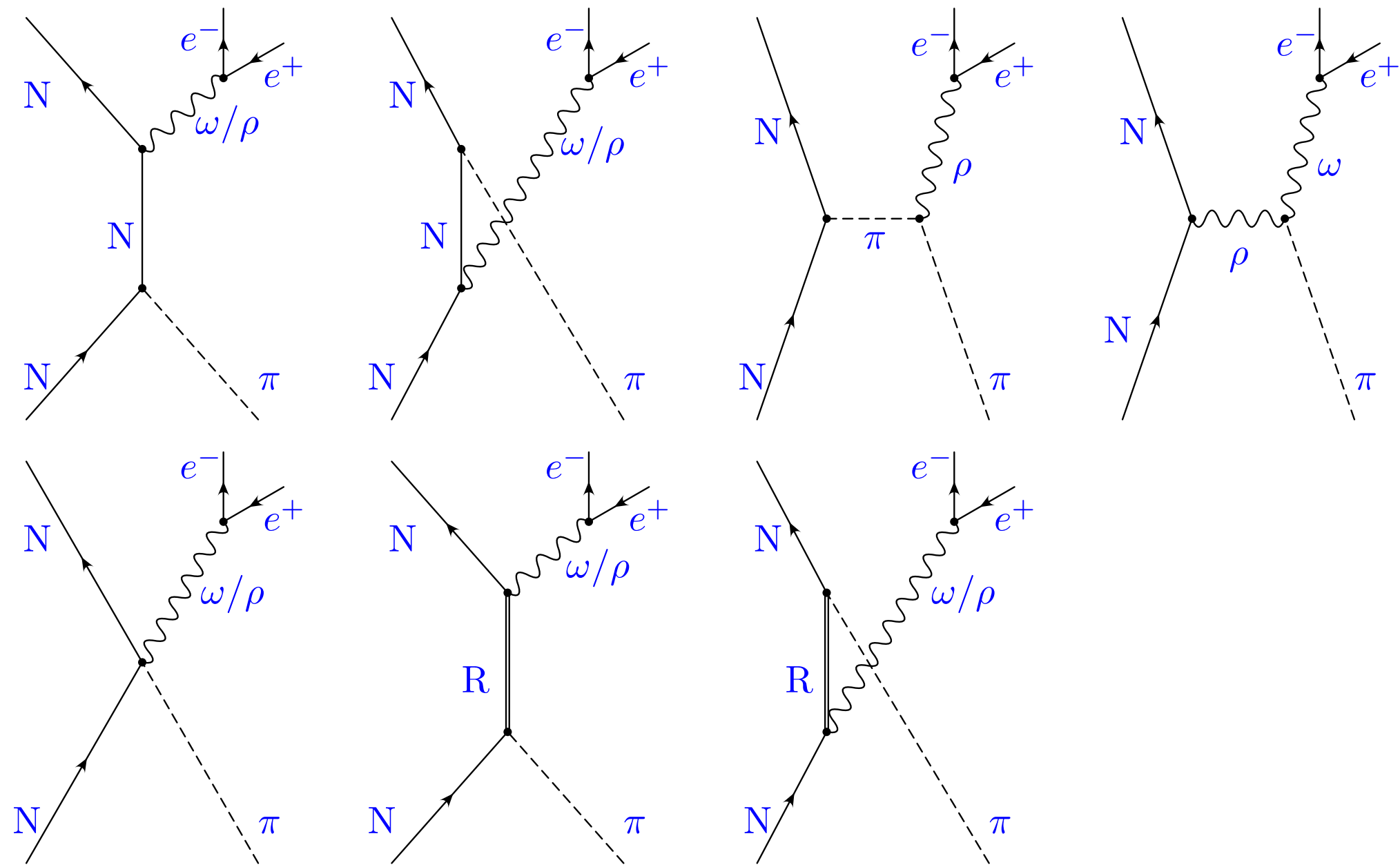


$$\pi + N \rightarrow N + e^+ e^-$$

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



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

$$\mathcal{L}_{NN\pi} = -\frac{f_{NN\pi}}{m_\pi} \bar{\psi}_N \gamma_5 \gamma^\mu \vec{\tau} \psi_N \cdot \partial_\mu \vec{\pi}.$$

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

$$\mathcal{L}_{NN\rho} = g_\rho \bar{\psi}_N \left( \vec{\rho} - \kappa_\rho \frac{\sigma_{\mu\nu}}{4m_N} \vec{\rho}^{\mu\nu} \right) \cdot \vec{\tau} \psi_N, \quad \mathcal{L}_{NN\omega} = g_\omega \bar{\psi}_N \left( \psi - \kappa_\omega \frac{\sigma_{\mu\nu}}{4m_N} \omega^{\mu\nu} \right) \psi_N.$$

$\rho_0$  couples to  $\bar{\psi}_N \tau_0 \psi_N$  so to p and to n with different signs, while  $\omega$  with the same sign

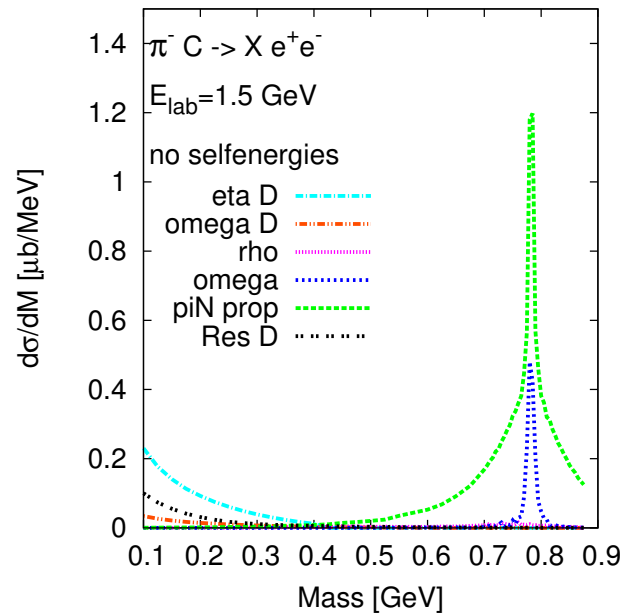
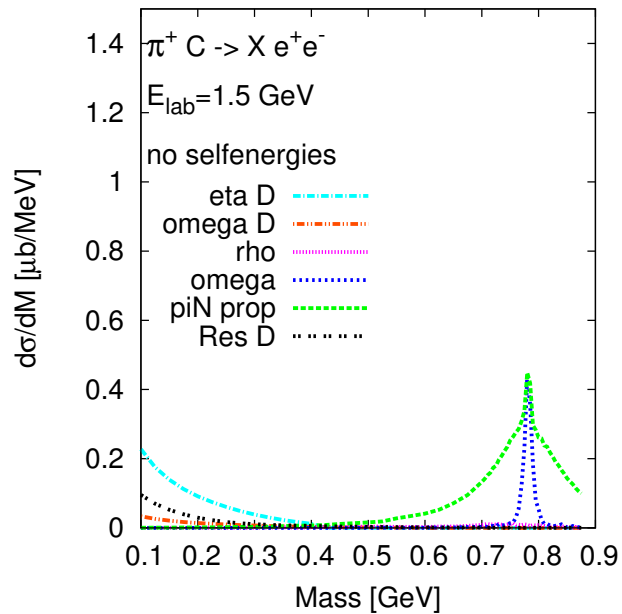
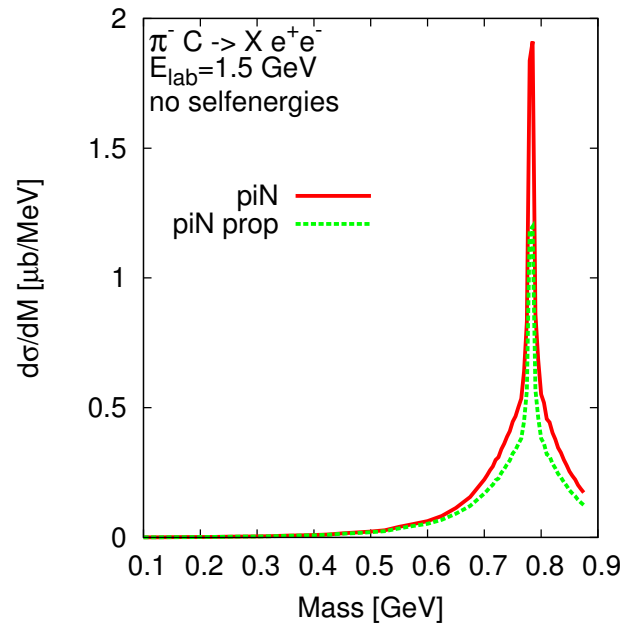
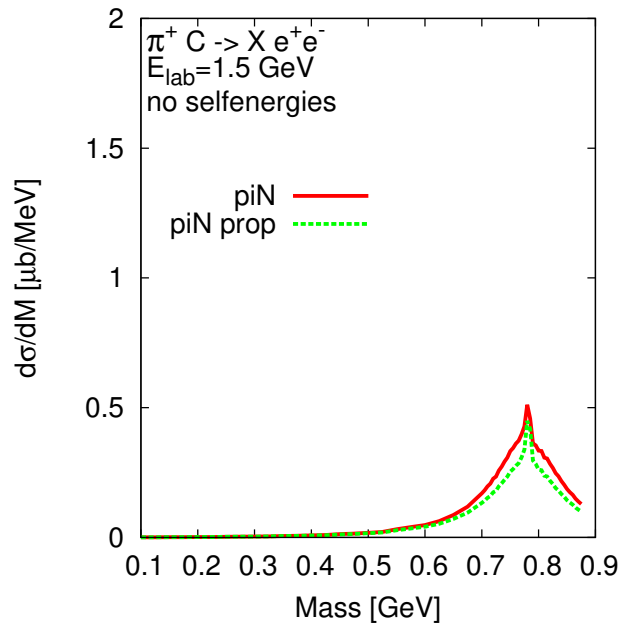
Considering  $\pi^- p \rightarrow n e^+ e^-$  and  $\pi^+ n \rightarrow p e^+ e^-$  in one channel constructive and in the other channel destructive interference

# Dileptons in pion-nucleus collisions

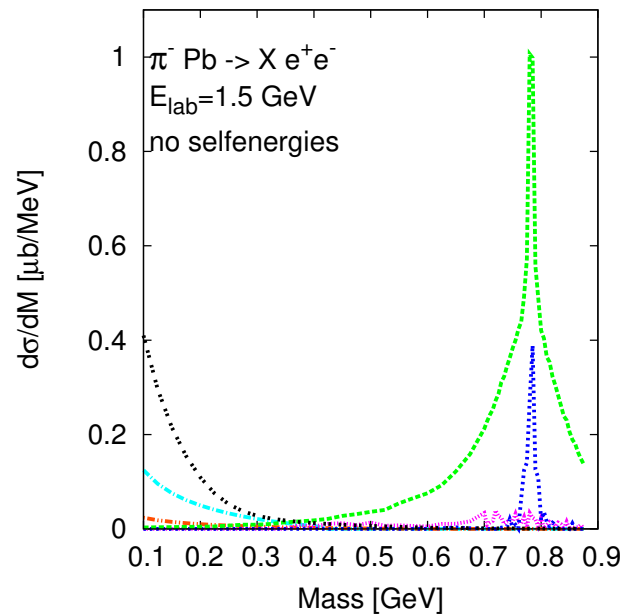
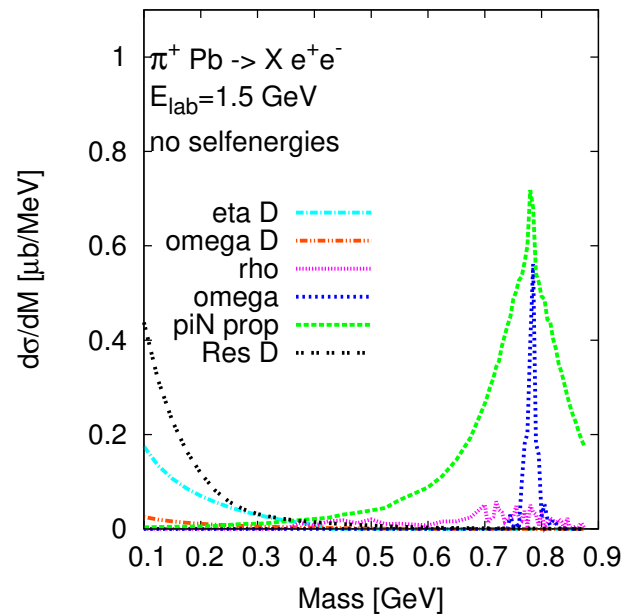
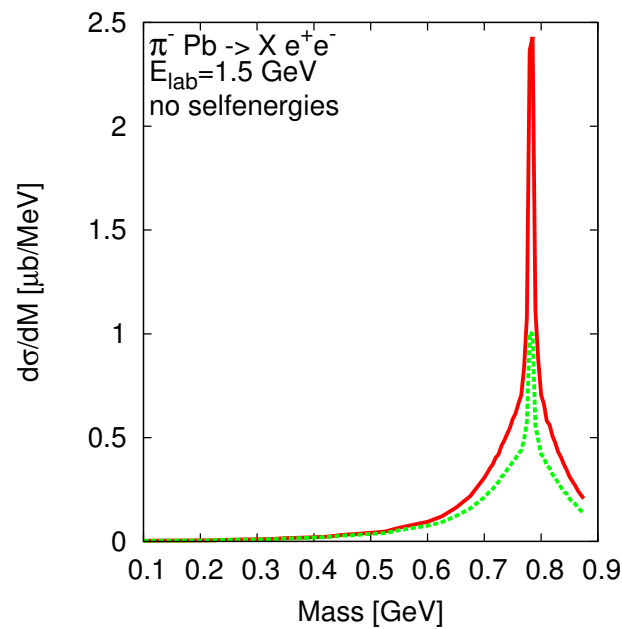
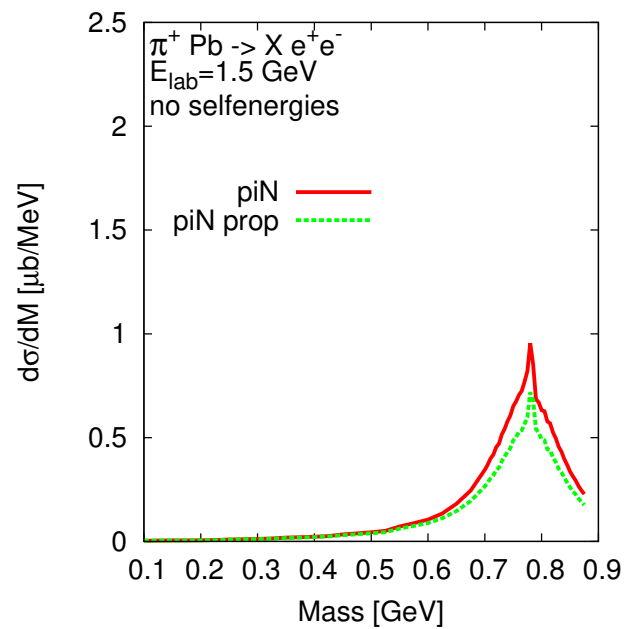
- $\frac{d\sigma}{dM} \pi^- p \rightarrow n e^+ e^- (m_\omega) \approx 4 \frac{d\sigma}{dM} \pi^+ n \rightarrow p e^+ e^- (m_\omega)$  because of the interference
- The effect is strong if cross section through  $\rho$  and  $\omega$  are similar
- coupling constants of  $\omega$  were taken from the 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  $\rho$  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  $\omega$ 's which will interfere with a  $\rho$ ?



# $\pi$ C, 1.5 GeV, no selfenergies, Preliminary results



# $\pi$ Pb, 1.5 GeV, no selfenergies, Preliminary results



# Dileptons in pion-nucleus collisions

- $\frac{\frac{d\sigma}{dM} \pi^- p \rightarrow n e^+ e^- (m_\omega)}{\frac{d\sigma}{dM} \pi^+ n \rightarrow p e^+ e^- (m_\omega)} \approx 4$
- $\frac{\frac{d\sigma}{dM} \pi^- C^{12} \rightarrow X e^+ e^- (m_\omega)}{\frac{d\sigma}{dM} \pi^+ C^{12} \rightarrow X e^+ e^- (m_\omega)} \approx 2.9$
- $\frac{\frac{d\sigma}{dM} \pi^- Pb^{207} \rightarrow X e^+ e^- (m_\omega) / N_p}{\frac{d\sigma}{dM} \pi^+ Pb^{207} \rightarrow X e^+ e^- (m_\omega) / N_n} \approx 2.0$

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:

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

$$G^{11}(1, 2) = G^T(1, 2) = \langle T(\phi(1)\phi(2)) \rangle$$

$$G^{22}(1, 2) = G^{AT}(1, 2) = \langle \tilde{T}(\phi(1)\phi(2)) \rangle$$

$$G^{21}(1, 2) = G^<(1, 2) = \langle \phi(2)\phi(1) \rangle$$

$$G^{12}(1, 2) = G^>(1, 2) = \langle \phi(1)\phi(2) \rangle$$

$$G^r(1, 2) = \theta(t_1 - t_2)(G^>(x_1, t_1; x_2, t_2) - G^<(x_1, t_1; x_2, t_2))$$

$$G^a(1, 2) = \theta(t_2 - t_1)(G^<(x_1, t_1; x_2, t_2) - G^>(x_1, t_1; x_2, t_2))$$

After some manipulation: *Kadanoff-Baym equation:*

$$(i\hbar\partial_{t_1} - H_0(1))G^<(1, 2) = \int d^3\Sigma^r(1, 3)G^<(3, 2) + \int d^3\Sigma^<(1, 3)G^a(3, 2)$$

$$(i\hbar\partial_{t_1} - H_0(1))G^r(1, 2) = \delta^4(1, 2) + \int d^3\Sigma^r(1, 3)G^r(3, 2)$$

# Wigner-transformation

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

$$r = x_1 - x_2 \quad , \quad R = x_1 + x_2$$

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  $F_\alpha = iG^<(R, P) = f_\alpha(x, p, t)A_\alpha$

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

Cassing, Juchem (2000) and Leupold (2000)

- testparticle approximation