Mesons in medium

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- Motivation
- Transport
- πA $\rightarrow Xe^{+}e^{-}$ reaction, $\rho - \omega$ interference (JPARC?)
- charmonium in hadron($\bar{p}, \pi$,p)A reaction (PANDA, JPARC?)

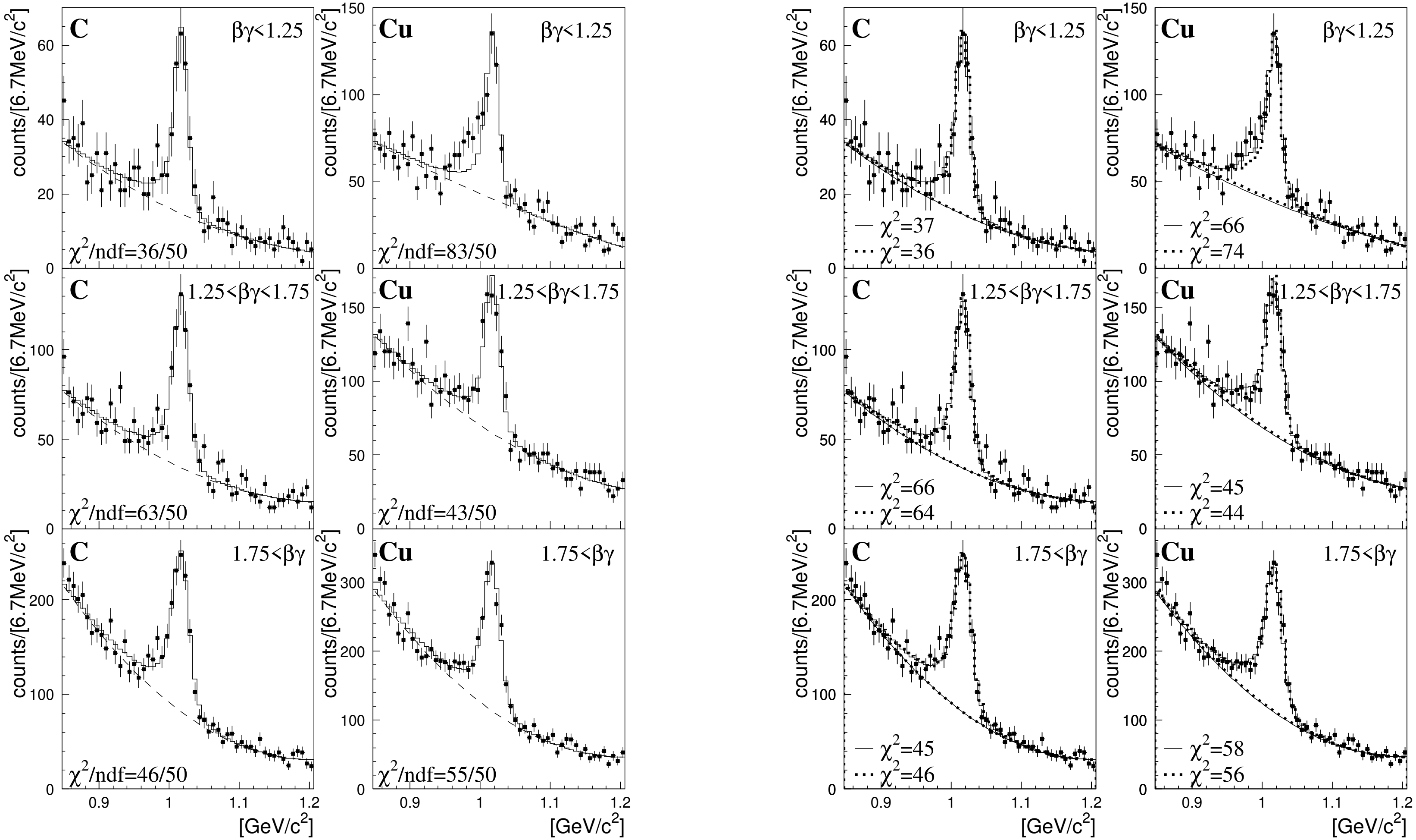
Why dileptons

- 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

  almost all direct or indirect indication for in-medium modification of hadrons are observed in he dileptonic decay channel

  (some exceptions: TAPS/ELSA: $\omega \rightarrow \pi\gamma$, and mesonic atoms)

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

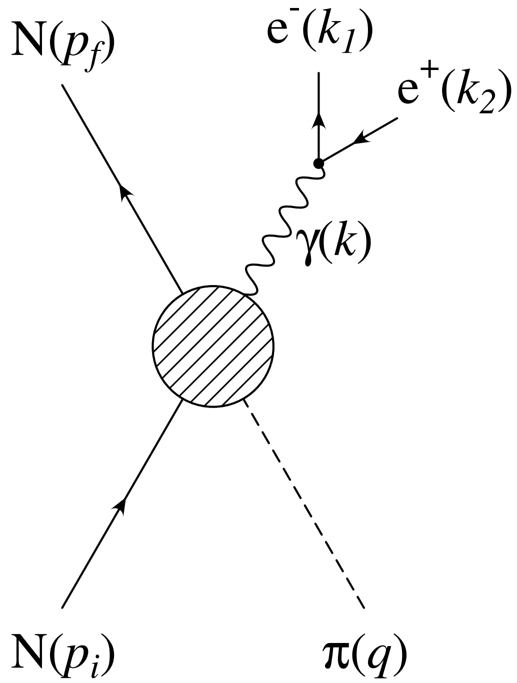
  $C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial\epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2-\vec{P}_i^2-M_0^2-Re\Sigma^{ret}_{(i)}}{Im\Sigma^{ret}_{(i)}} \frac{\partial}{\partial\epsilon_i} Im\Sigma^{ret}_{(i)} \right]$

- the last equation for homogenous system can be rewritten as

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

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

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



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

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

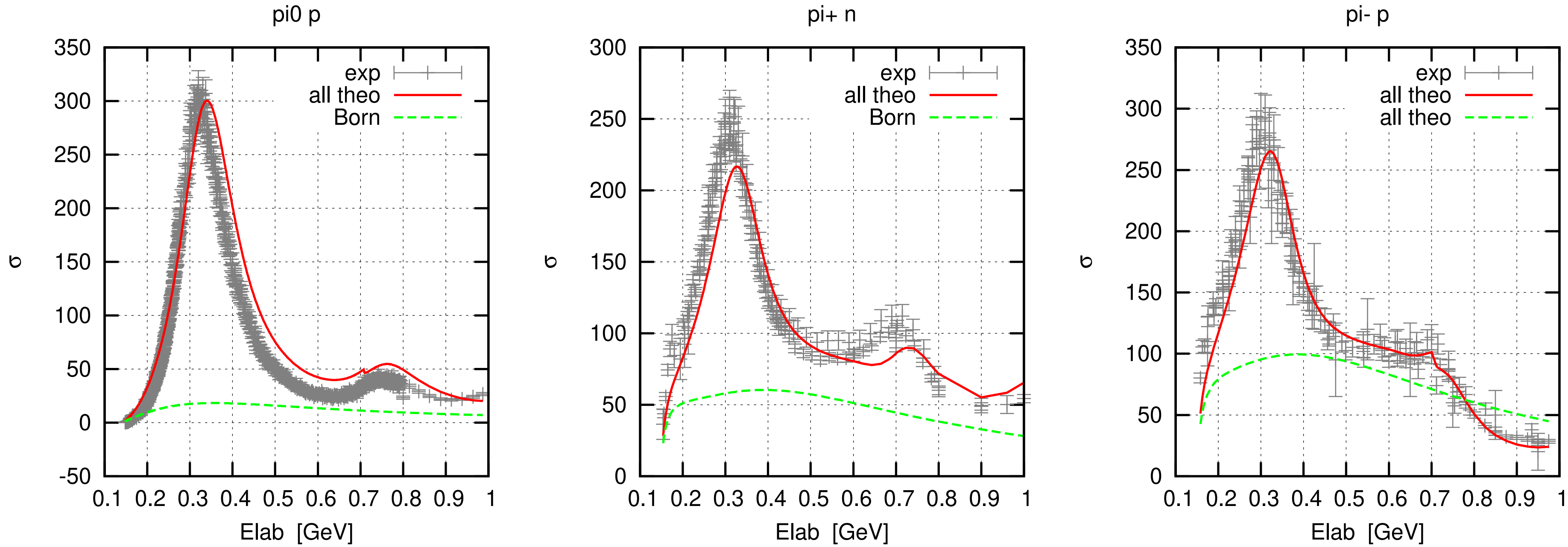
$$\mathcal{L}_{\omega\rho\pi} = \frac{\mathrm{g}_{\omega\rho\pi}}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\omega_\nu\mathrm{Tr}\left((\partial_\alpha\vec{\rho_\beta}\cdot\vec{\tau})(\vec{\pi}\cdot\vec{\tau})\right)$$

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

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

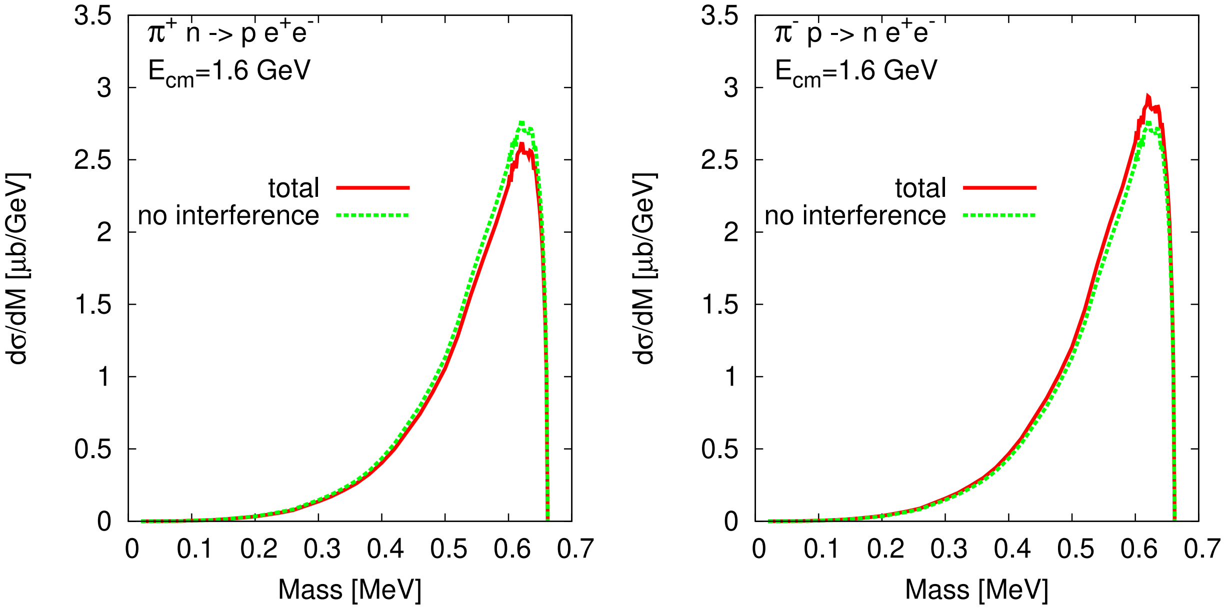
Total cross section of pion photoproduction



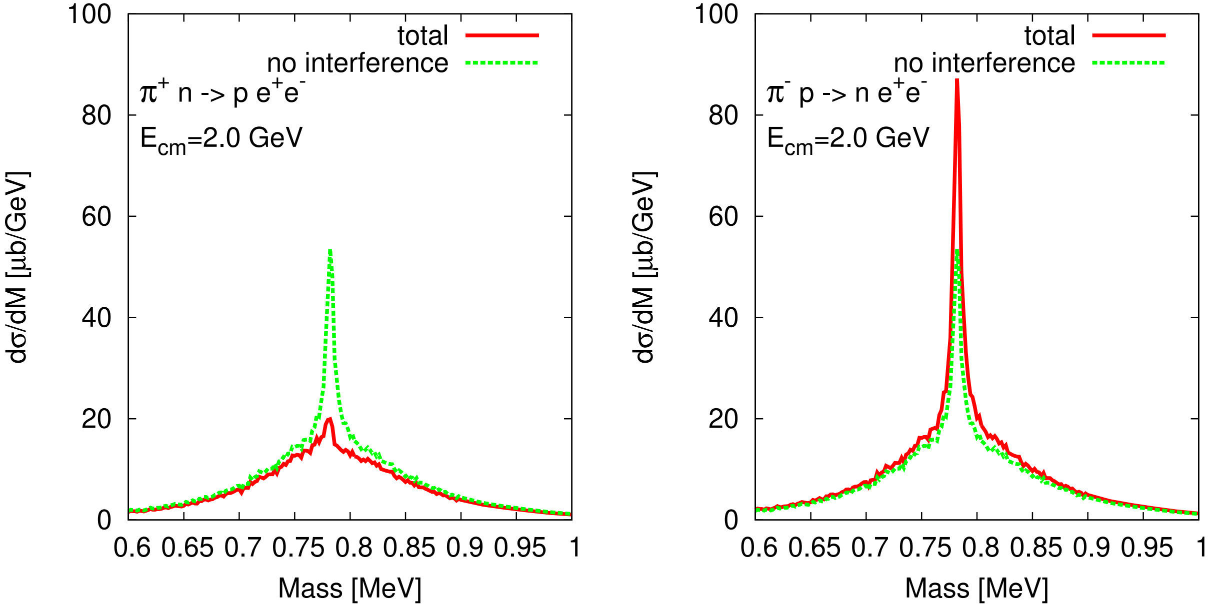
RNπ and RNρ from measured partial decay widths, RNγ is fitted

Dilepton production in πN reaction

below ω threshold



abowe ω threshold



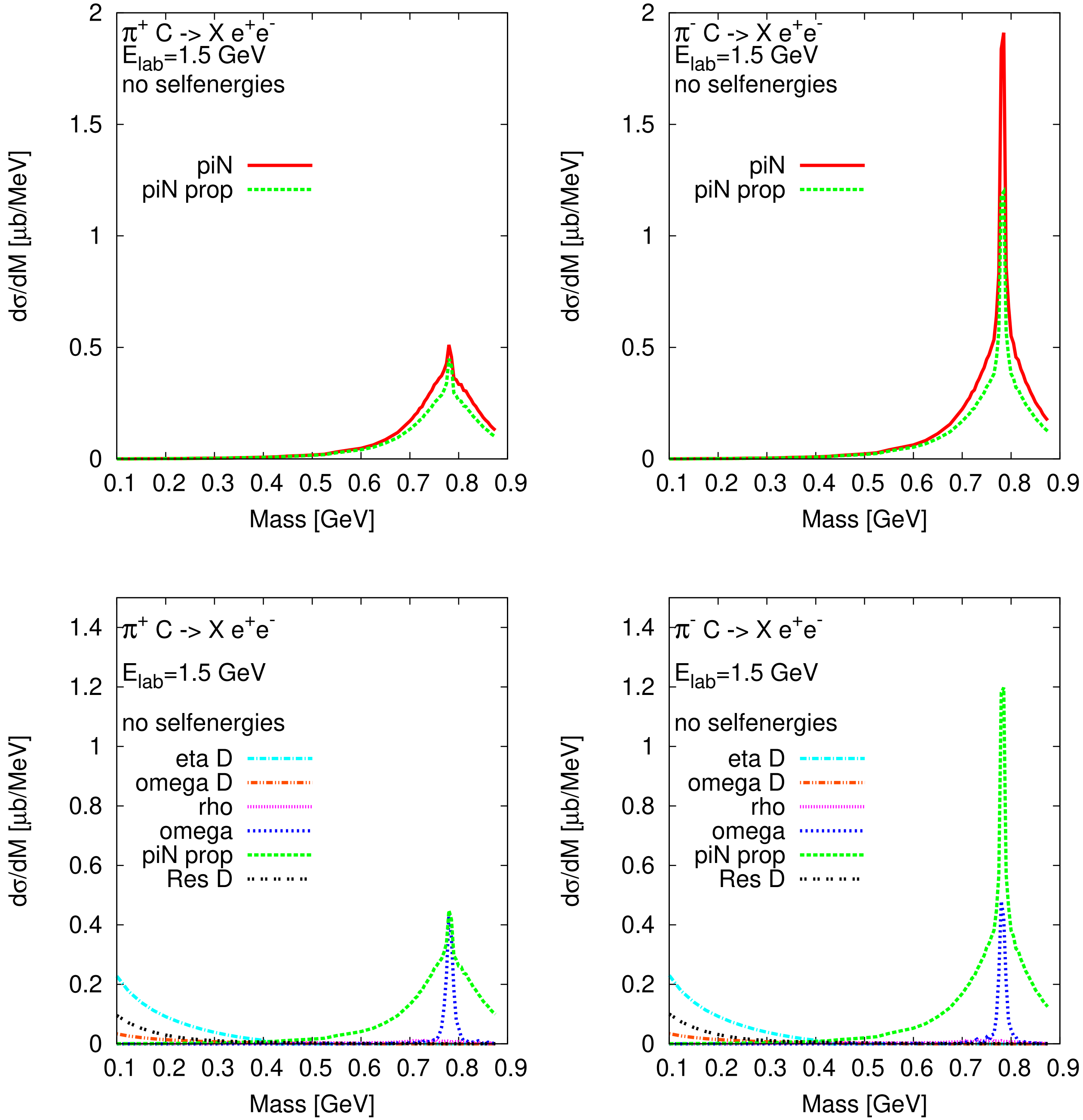
Dileptons in pion-nucleus collisions

- $\frac{\frac{d\sigma}{dM}^{\pi^- p \to n e^+ e^-}(m_\omega)}{\frac{d\sigma}{dM}^{\pi^+ n \to p e^+ e^-}(m_\omega)} \approx 4$ 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?

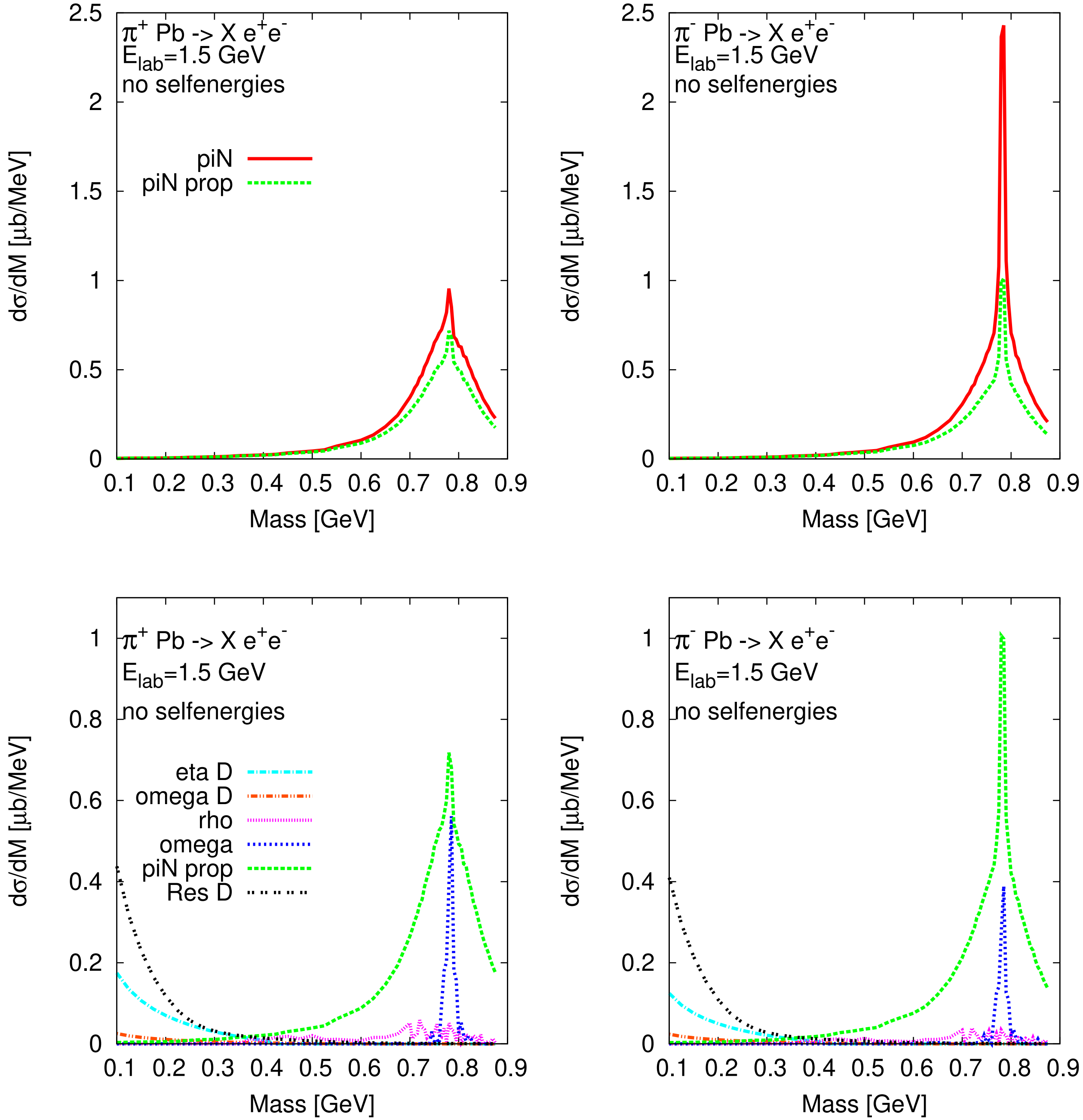
Simulation of π A collisions

- Same as usually except for $\pi N \to N e^+ e^-$
- in case of a πN collision several “doublets” are created.
  (The original π and N do not change their state.)
  A doublet consists of 2 perturbative particles ρ and ω with their cross sections and the “cross section” of the interference term. ρ and ω are created with the same position, momentum and mass.
- They propagate, decay and can be absorbed. The interference term contribute only if none of them collide or is absorbed.
- Propagation: perturbative ρ’s and ω’s propagate in the surounding medium
- Absorption: ρ’s and ω’s can be absorbed by a nucleon

π C, 1.5 GeV, no selfenergies



π Pb, 1.5 GeV, no selfenergies



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?

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

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?
  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)

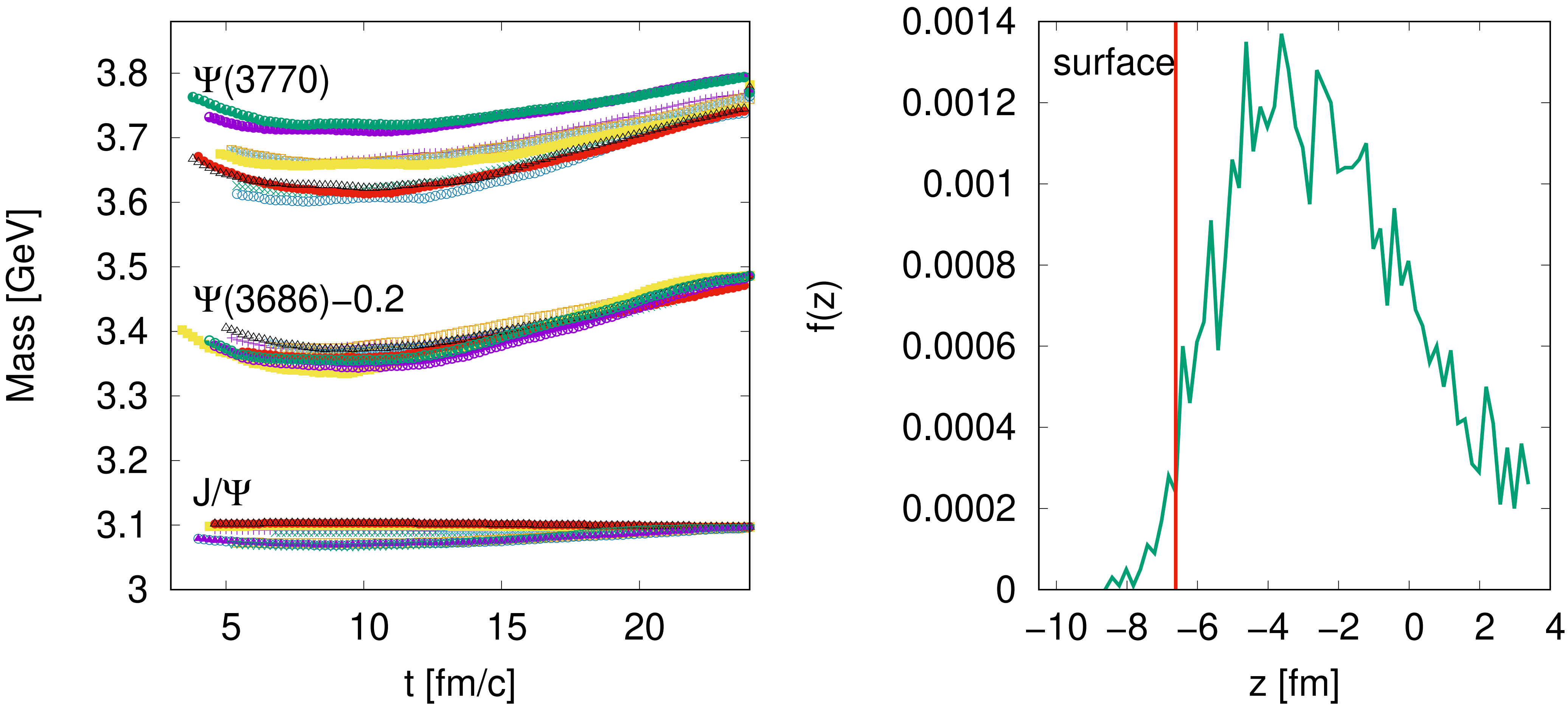
background:

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

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

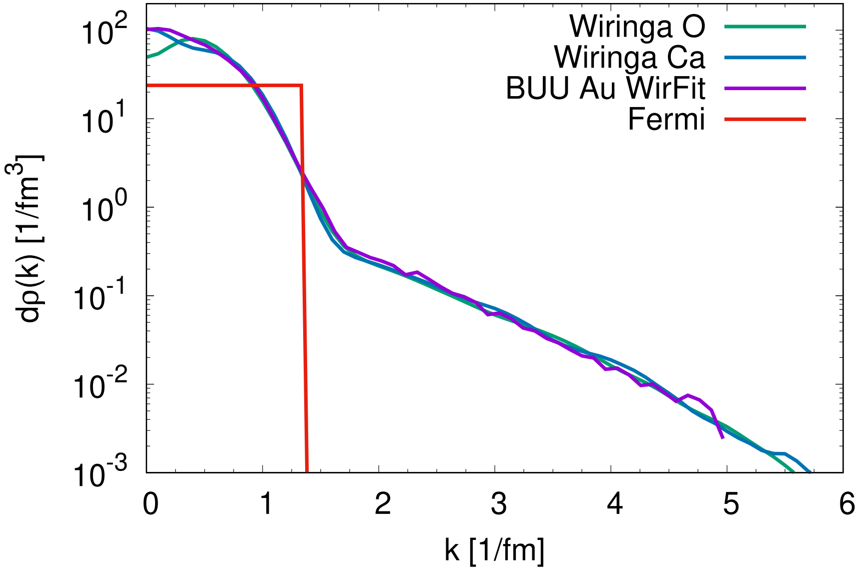
up to moderate energies ($<$ 7 GeV for $\bar{p}$, $<$ 12 GeV for π, $<$ 15 GeV for p) the background is low

Time evolution of masses and pos. of creation in πAu 6.5 GeV



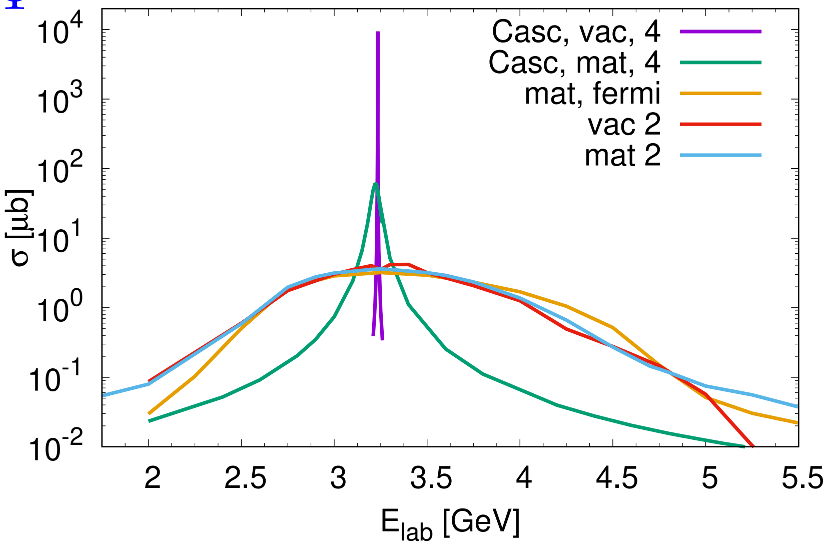
The charmonium states are created at the surface of the heavy nucleus,
travel through the dense matter (decays with some probability),
crosses the thin surface again and reaching the vacuum.
Major contribution to the dilepton channel are coming from the dense matter and from the vacuum. $t_{\rho>0.8}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

Excitation functions

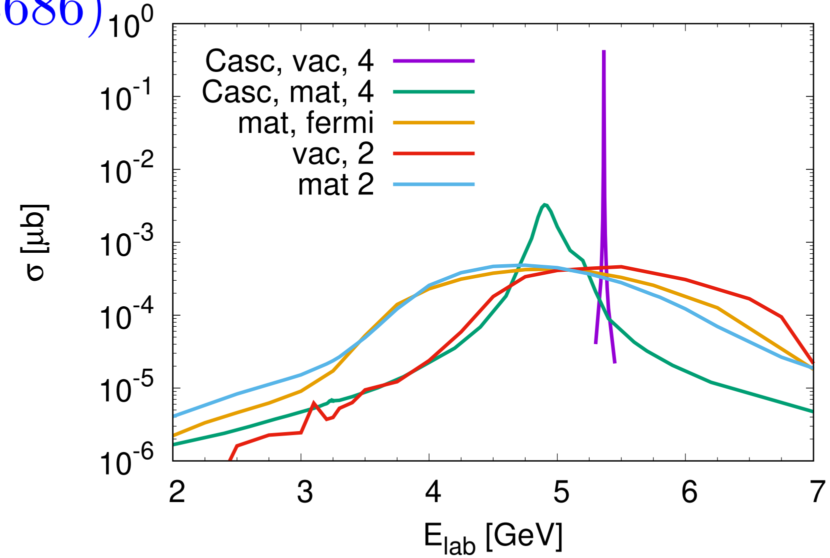


Initial momentum distribution
with short range correlation

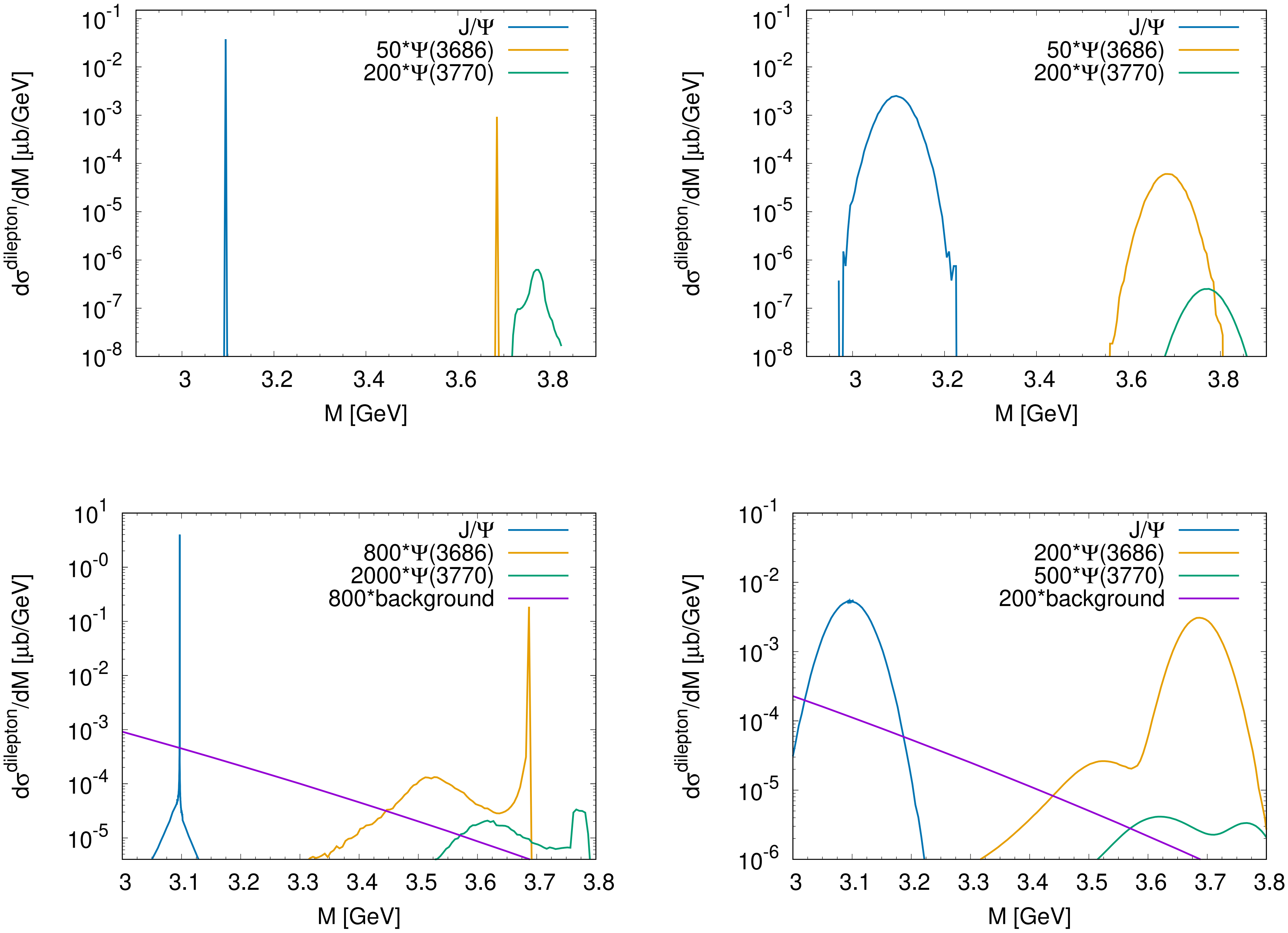
J/Ψ



$\Psi(3686)$



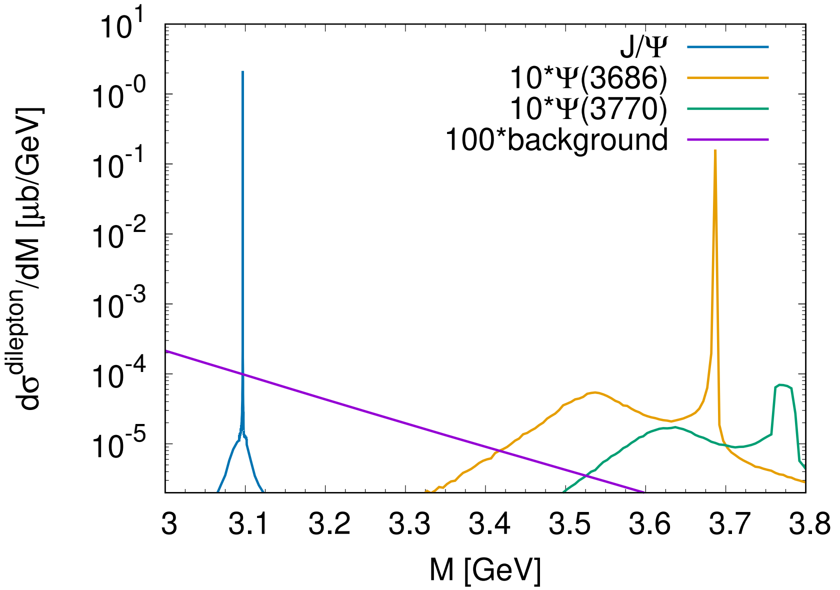
p Au at 12 GeV

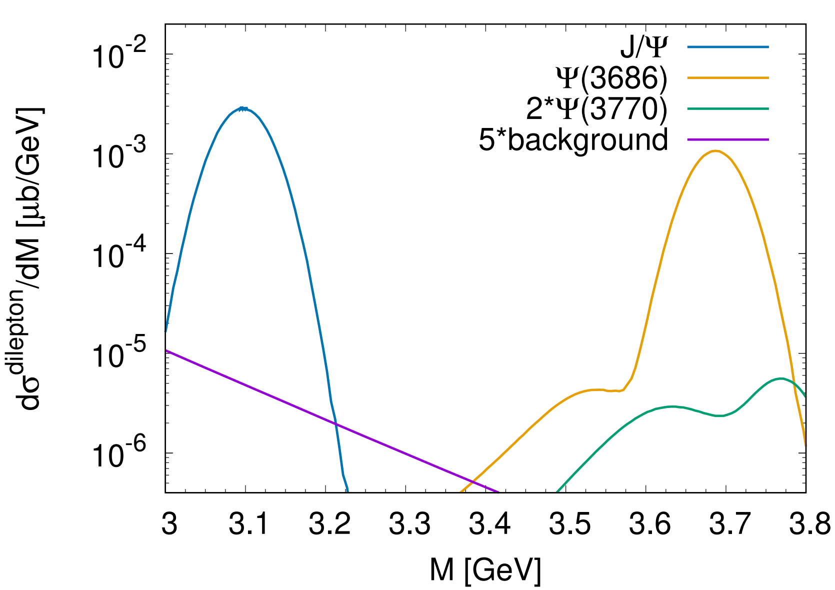


J/Ψ
50*Ψ(3686)
200*Ψ(3770)
800*Ψ(3686)
2000*Ψ(3770)
800*background
200*Ψ(3686)
500*Ψ(3770)
200*background
dσ^dilepton/dM [μb/GeV]
M [GeV]

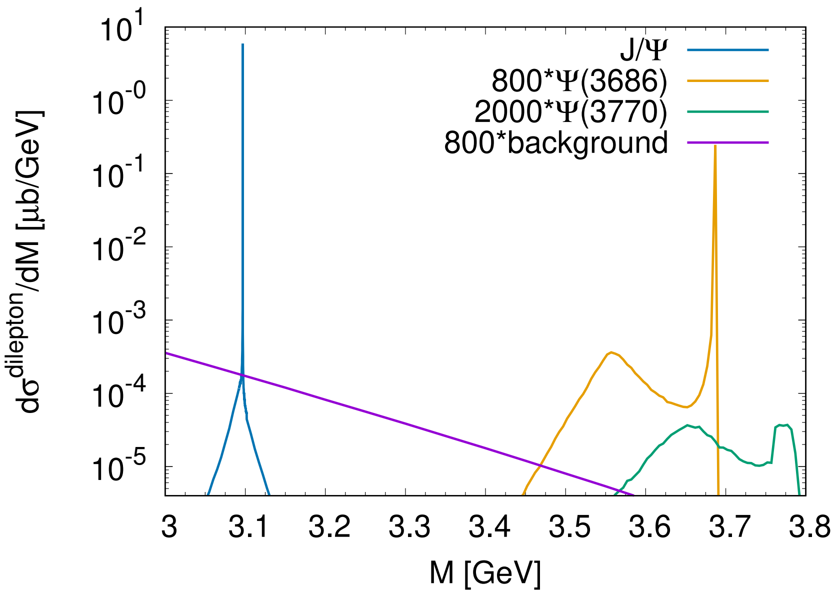
$\bar{p}$ and πAu

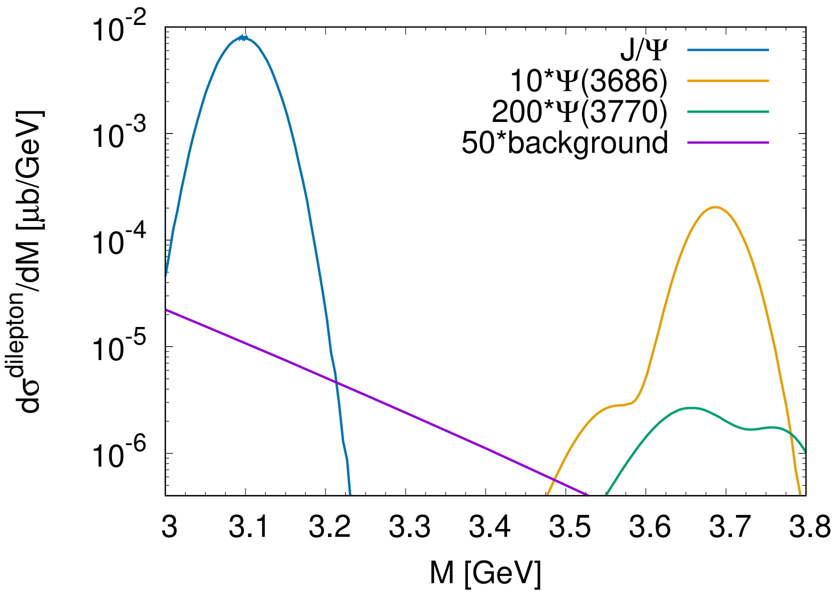
$\bar{p}$Au at 6 GeV





πAu at 9 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 over-shadow the smaller, in-medium peak?

Summary

- Experimentally the decoherence can be observed in strongly interacting matter.
- Is an interference with its pair a measurement? Collisional broadening?
- 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.