Mass shift of charmonium states in heavy ion collisions

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OUTLINE

- Motivation
- BUU transport
- Results: charmonium mass shift in pbar-Au collisions at 6 GeV

- Boltzman-Uehling-Uhlenbeck (BUU) transport to simulate the non-equilibrium dynamics of heavy ion collisions
- The degrees of freedom : hadrons (mesons, baryons + resonances)
- Hadrons with heavier quarks are also important e.g. charmonium, bottomonium,…
- In medium effects -> self energy plays an important role.
- The mass of the charmonium states can change significantly due to nuclear effects -> it may be possible to examine the mass shifts from the dilepton spectra -> information about the gluon condensate -> QCD vacuum

Charmonium in matter

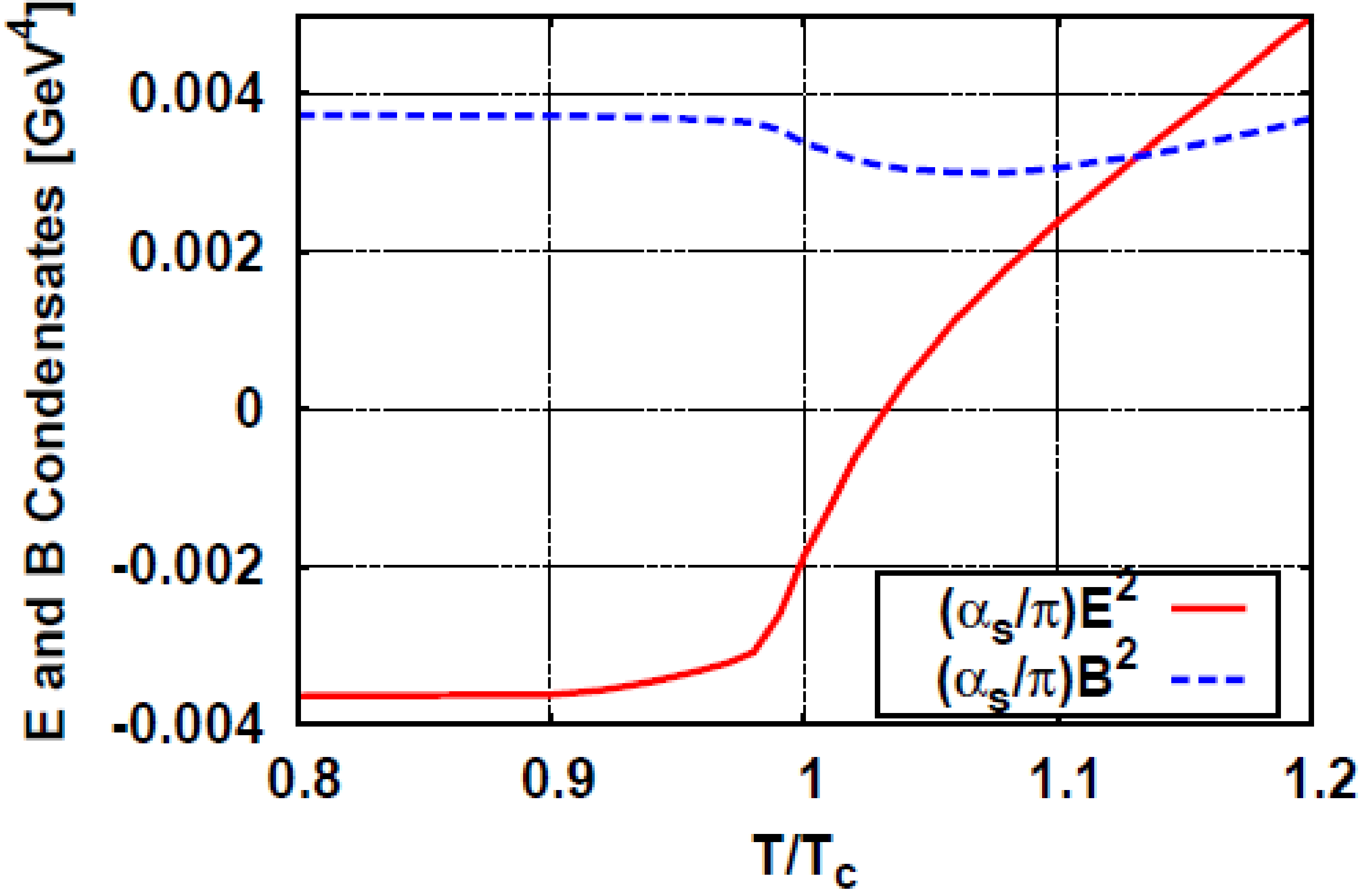
- $c\bar{c}$ is a dipole in color electric field -> mass shift due to second order Stark-effect (NRQCD **Phys.Rev. D79 (2009) 011501**)

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

Ψ – Coulomb wave function, $\epsilon = 2m_c - m_\Psi$ is the binding energy.

- $D\bar{D}$ loops also contribute to the self energy + D meson gets a mass shift due to the Stark effect.
- Width changes due to collisional broadening.

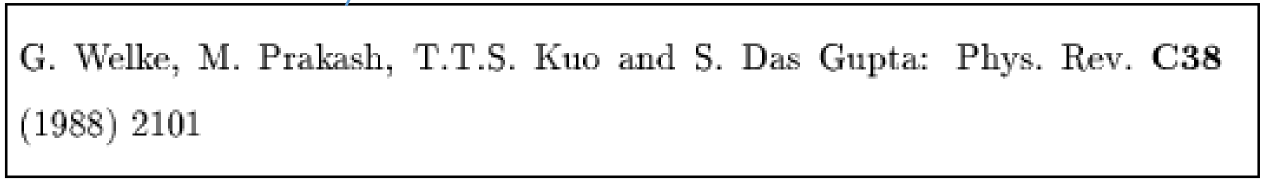
Phys.Rev. D79 (2009) 011501



Kinetic theory

- Starting point -> Boltzmann-Ühling-Uhlenbeck equation
- $\frac{\partial F}{\partial t} + \frac{\partial H}{\partial p}\frac{\partial F}{\partial x} - \frac{\partial H}{\partial x}\frac{\partial F}{\partial p} = C$ $\qquad H = \sqrt{\left(m + U(p,x)\right)^2 + p^2}$
- Momentum dependent mean-field potential:

$$U(x,p) = A\frac{n}{n_0} + B\left(\frac{n}{n_0}\right)^{\tau} + C\frac{2}{n_0}\int \frac{d^3p'}{(2\pi)^3}\left(\frac{f_N(x,p')}{1 + \left(\frac{p-p'}{\Lambda}\right)^2}\right)$$



G. Welke, M. Prakash, T.T.S. Kuo and S. Das Gupta: Phys. Rev. **C38** (1988) 2101

Mass of the scalar meson -> YUKAWA type interaction

- Test-particle method: $F = \sum \delta^{(3)}\left(x - x_i(t)\right)\delta^{(4)}\left(p - p_i(t)\right)$
- Collision term couples the equations
- Off-shell transport is more complicated (propagate the spectral functions -> energy conservation?)

- Problems when the particle spectral function is not δ-like
  - Width change
  - Mass shift

They are changing their shapes during evolution.

- This is ok if the particles have very long lifetime and weakly interact with the sorroundings.
- Inadequate for short-lived (broad resonance states) of high collision rate (->collisional broadening)
- Simple on-shell -> not regaining the vacuum mass !!
- We have to put the self energy information (especially the imaginary part ~ spectral function) into the equations of motion!

Equations of motion

- $\frac{dx}{dt} = \frac{1}{1-C}\frac{1}{2E}\left(2p + \nabla_p Re\Sigma^R + \frac{m^2-m_0^2-Re\Sigma^R}{\Gamma}\nabla_p\Gamma\right)$
- $\frac{dp}{dt} = -\frac{1}{1-C}\frac{1}{2E}\left(\nabla_x Re\,\Sigma^R + \frac{m^2-m_0^2-Re\Sigma^R}{\Gamma}\nabla_x\Gamma\right)$
- $\frac{dE}{dt} = \frac{1}{1-C}\frac{1}{2E}\left(\partial_t Re\,\Sigma^R + \frac{m^2-m_0^2-Re\Sigma^R}{\Gamma}\partial_t\Gamma\right)$

Where $C = \frac{1}{2E}\left(\partial_E Re\,\Sigma^R + \frac{m^2-m_0^2-Re\Sigma^R}{\Gamma}\partial_E\Gamma\right)$ is a renormalization factor, and $\Sigma^{\mathrm{R}} = \Sigma^{\mathrm{R}}(n, E, p)$.

Density depenedent self energy

$$\frac{dm^2}{dt} = \frac{1}{1-C}\left(\frac{d}{dt}Re\Sigma^R + \frac{m^2 - m_0^2 - Re\Sigma^R}{\Gamma}\frac{d}{dt}\Gamma\right)$$

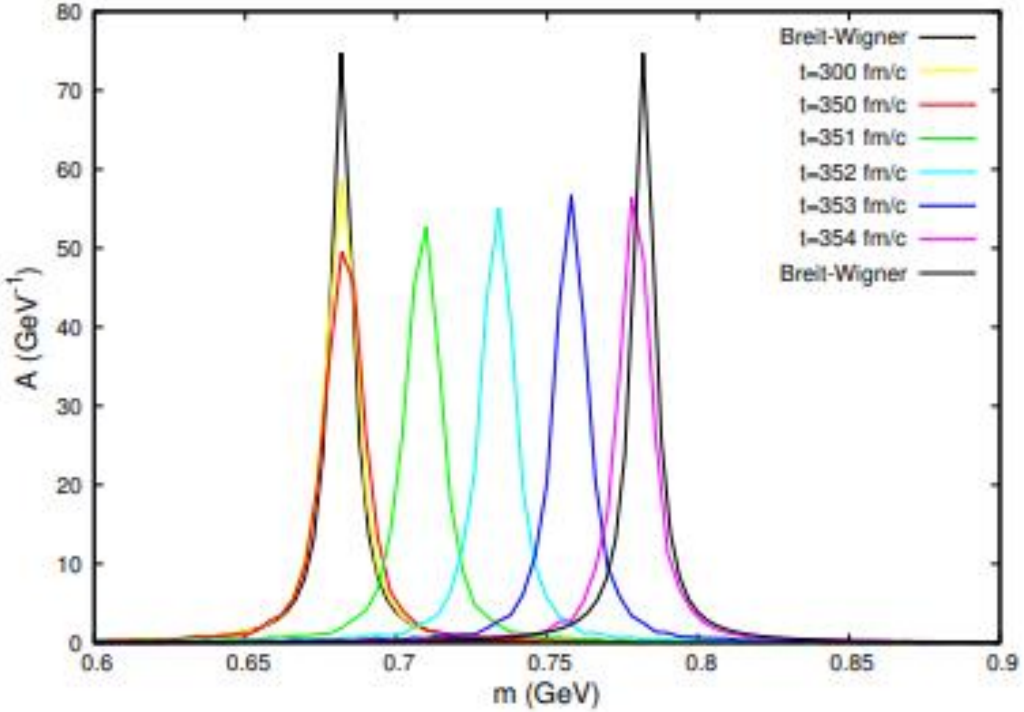
- Form of the self-energy (Ansatz):

$$Re\Sigma_V^R = 2m_V \Delta m_V \frac{n}{n_0}$$

$$Im\Sigma_V^R = m_V \left(\Gamma_V^{vac} + \frac{n\sigma_V v}{\sqrt{1-v^2}} \right)$$

- Assumption: the self energy varies “slowly”.
- The mass shift is proportional to the density of the surrounding matter !
- From the mass shift equation -> the vacuum mass is recovered at the end of the collision !
- Energy conserving method (apart from numerical artifacts).

Evoulution of $A_\rho(m,t)$ and $A_\omega(m,t)$



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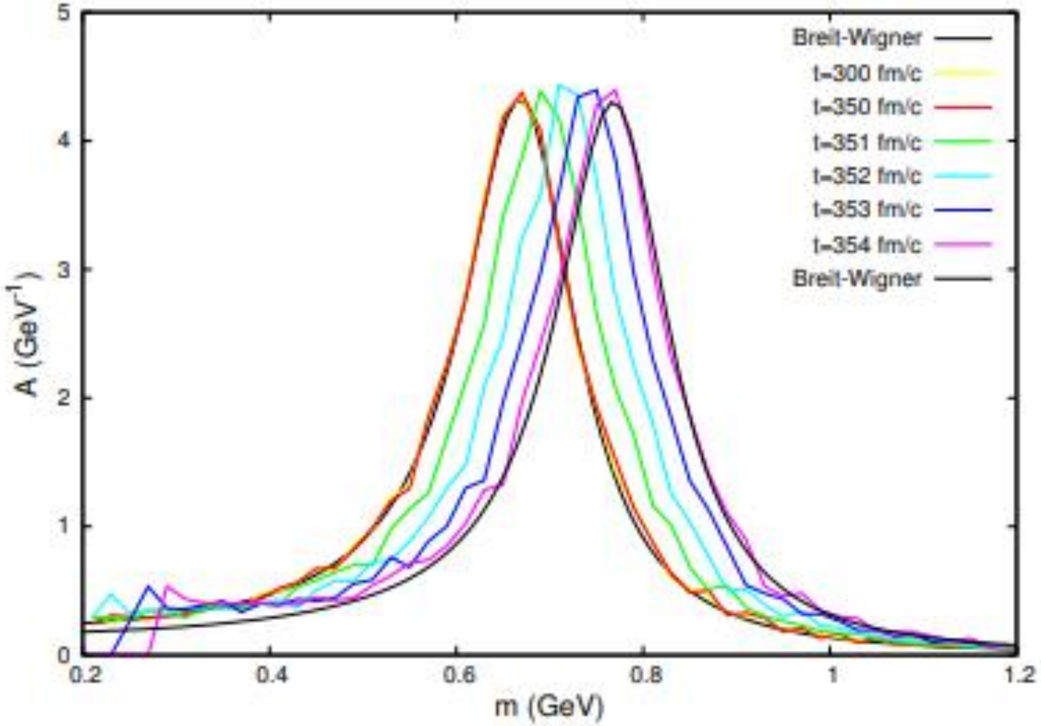
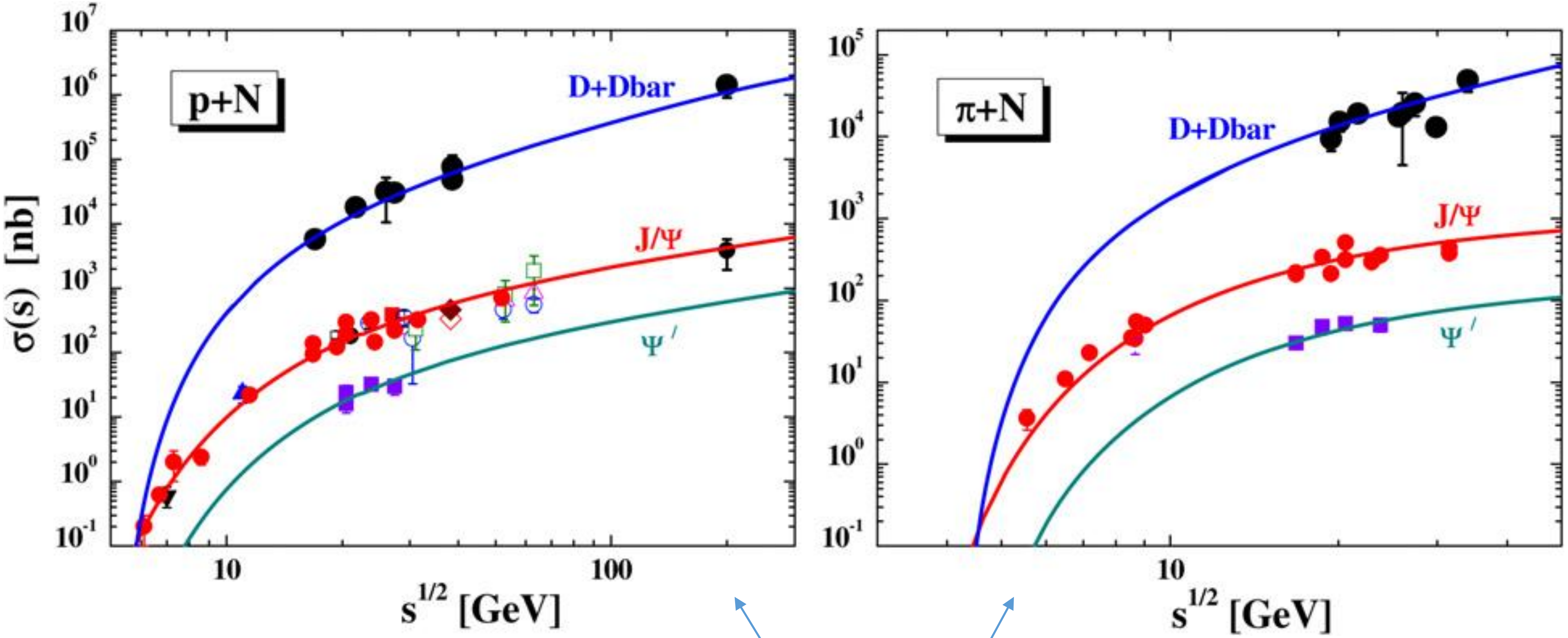


ρ

Collision term

- 24 baryon resonances + Λ and Σ baryons
- $\pi, \eta, \sigma, \rho, \omega, K$
- Now also : J/Ψ, $\Psi(3686), \Psi(3770)$
- Collision term:
  - $NN \leftrightarrow NR$
  - $NN \leftrightarrow \Delta\Delta$
  - $R \rightarrow N\pi, N\eta, N\sigma, N\rho, N\omega, \Delta\pi, N(1440)\pi, K\Lambda, K\Sigma$
- New cross sections:
  - $p\bar{p} \rightarrow J/\Psi\,\pi^0$, $\boldsymbol{\Psi(3686)\pi^0}$, $\Psi(3770)\pi^0$
  - $\pi^- p \ \rightarrow n\,J/\Psi$, **n** $\boldsymbol{\Psi(3686)}$, n $\Psi(3770)$
  - $p\bar{p} \rightarrow D^0\overline{D^0}$, D^+D^-
  - $pp \rightarrow ppJ/\Psi + X$
  - J/Ψ absorption on N

Charm cross sections

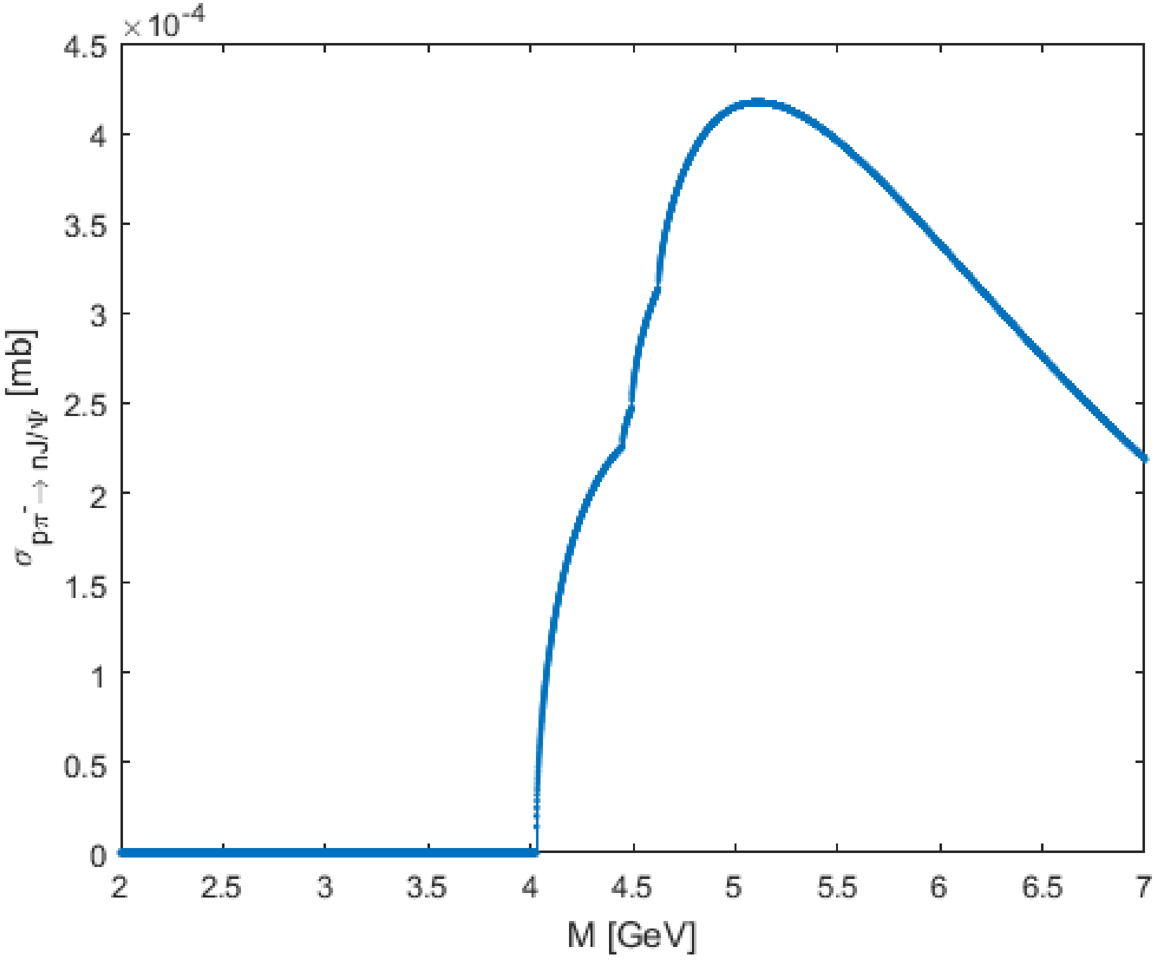


$\sigma_{NN \rightarrow X + J/\Psi}$

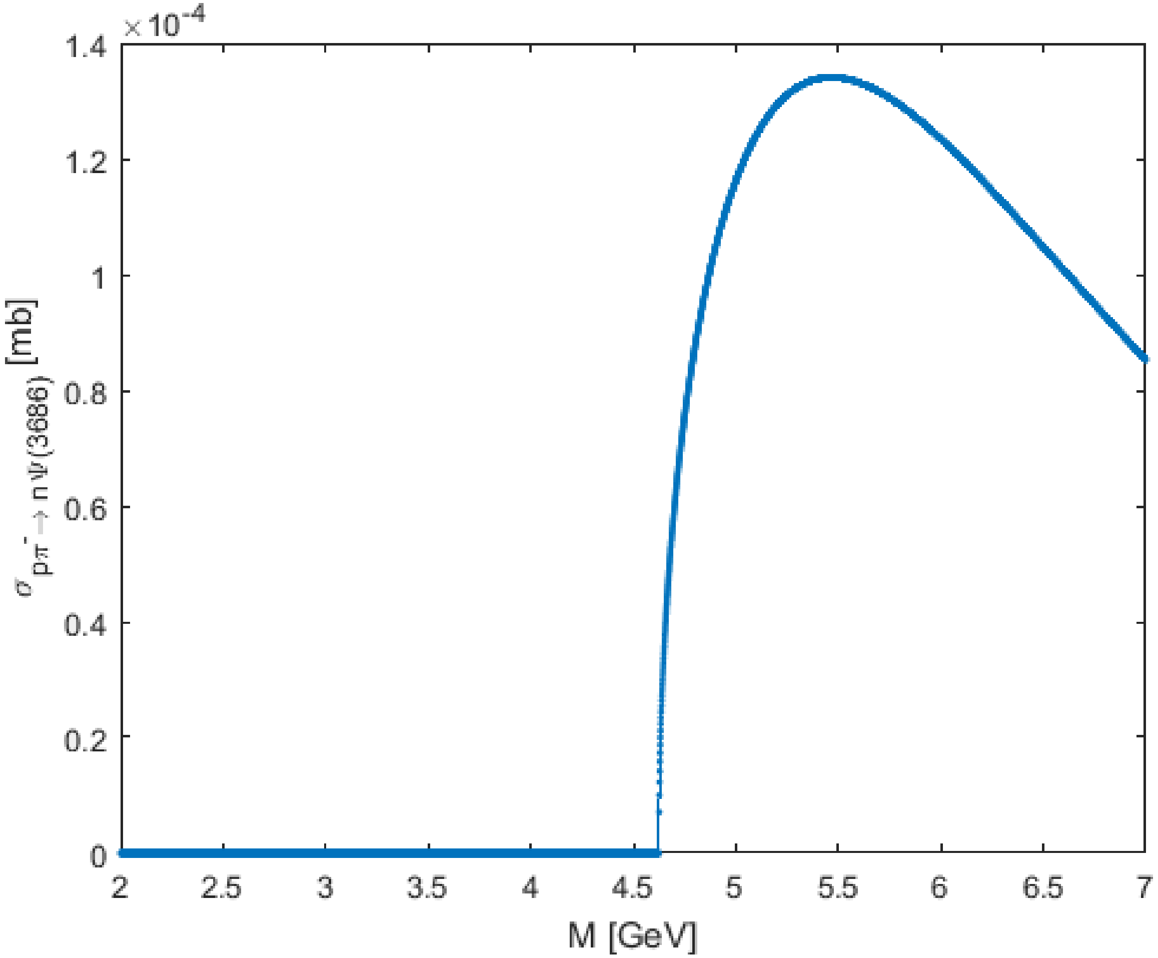
$\sigma_{\pi N \rightarrow X + J/\Psi}$

Nuclear Physics A 786 (2007) 183–200

$\sigma_{p\pi^- \to nJ/\Psi}$



$\sigma_{p\pi^- \to n\Psi(3686)}$

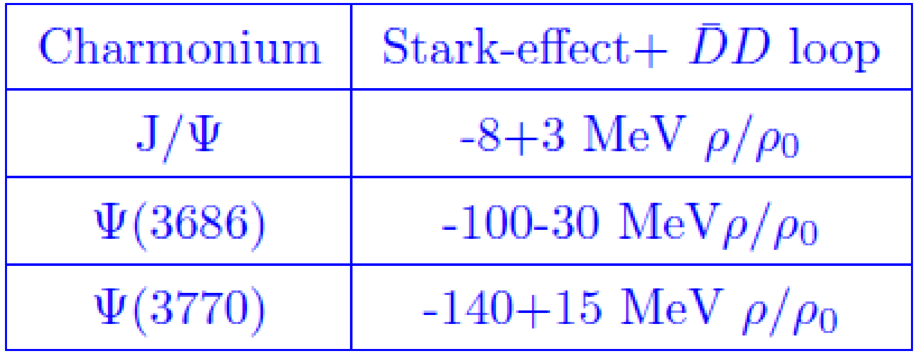


Simulation method

- Initalize particles (on-shell / off-shell)
- Propagate particles in matter (self energy changes if the density changes -> spectral function will change) according to EOM.
- Hadronic collisions:
  - Geometric picture
  - Broadening (self energy changes -> spectral function changes)
  - Particle production (e.g. JPSI)
  - Particle annihilation
- Pauli blocking (phase space occupation examination)

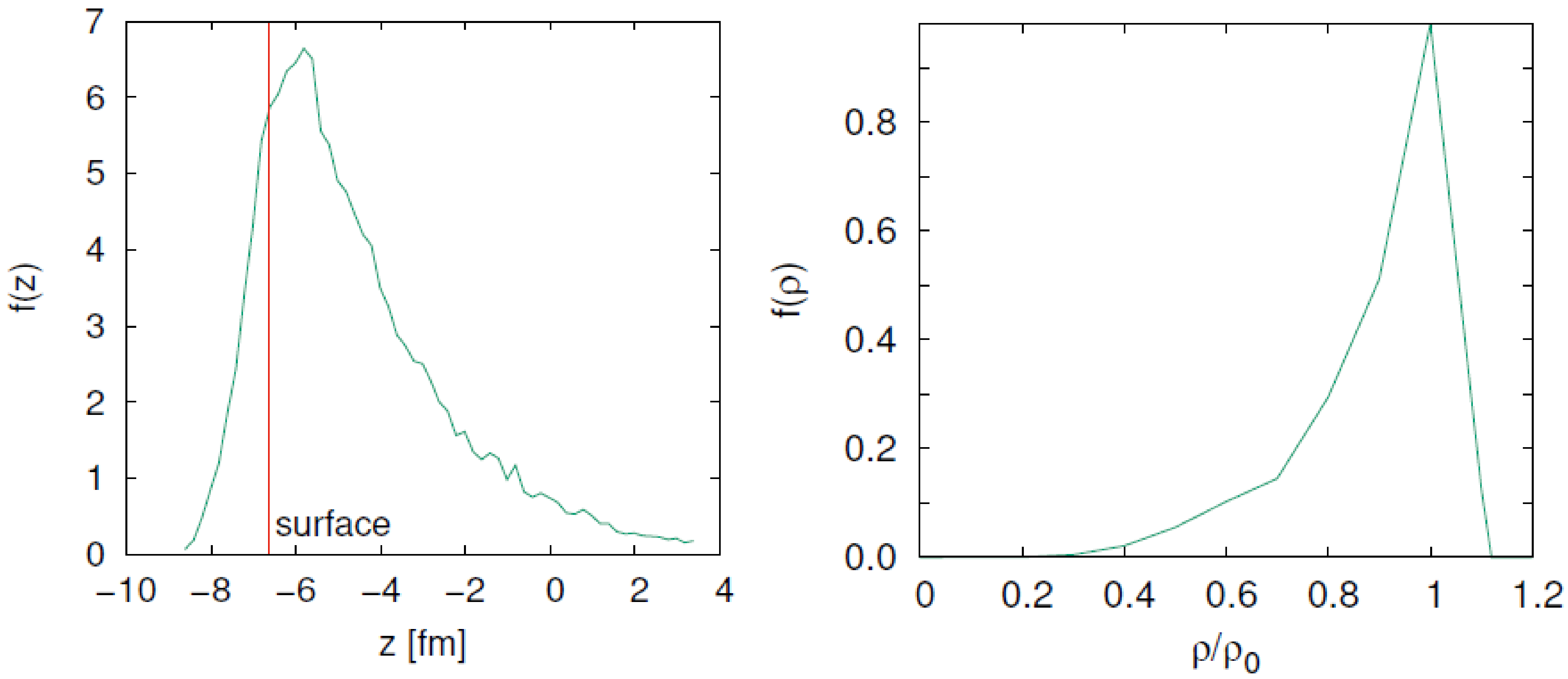
Charmonium mass shift

- From the dilepton spectrum we will be able to see the mass shift of some of the charmonium states (in theory at least)
- Background:
  - Drell-Yan
  - Open-charm e.g. weak decay of D meson pairs ($c \rightarrow s + e + \overline{\nu_e}$) so from two D mesons we get a dilepton pair ($D \rightarrow K e \overline{\nu_e}$)
  - For now it seems like up to few GeV the background is low.
- We examined $\bar{p}Au$ collisions at 6 GeV
- The calculated mass shifts (input):



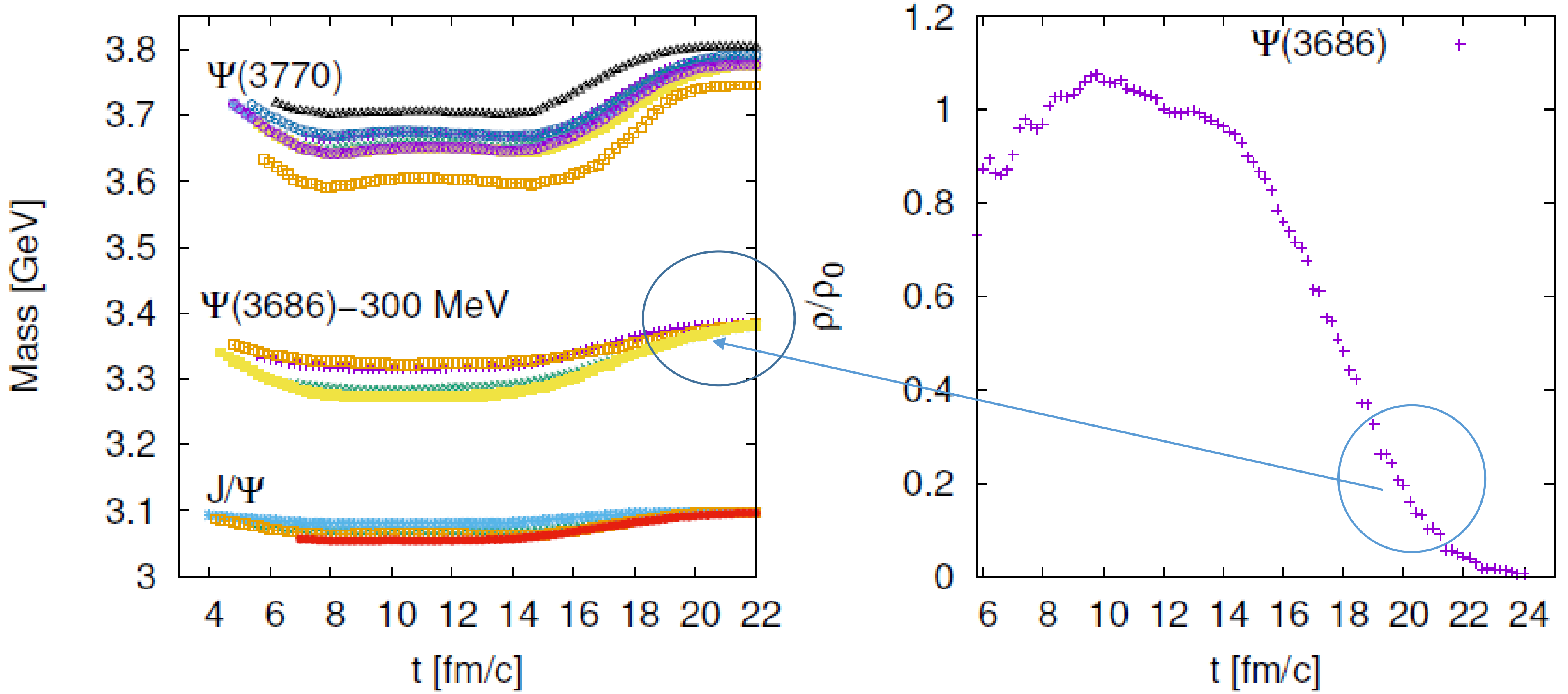
Charmonium	Stark-effect+ $\bar{D}D$ loop
J/Ψ	-8+3 MeV ρ/ρ_0
Ψ(3686)	-100-30 MeVρ/ρ_0
Ψ(3770)	-140+15 MeV ρ/ρ_0

Where do they created?



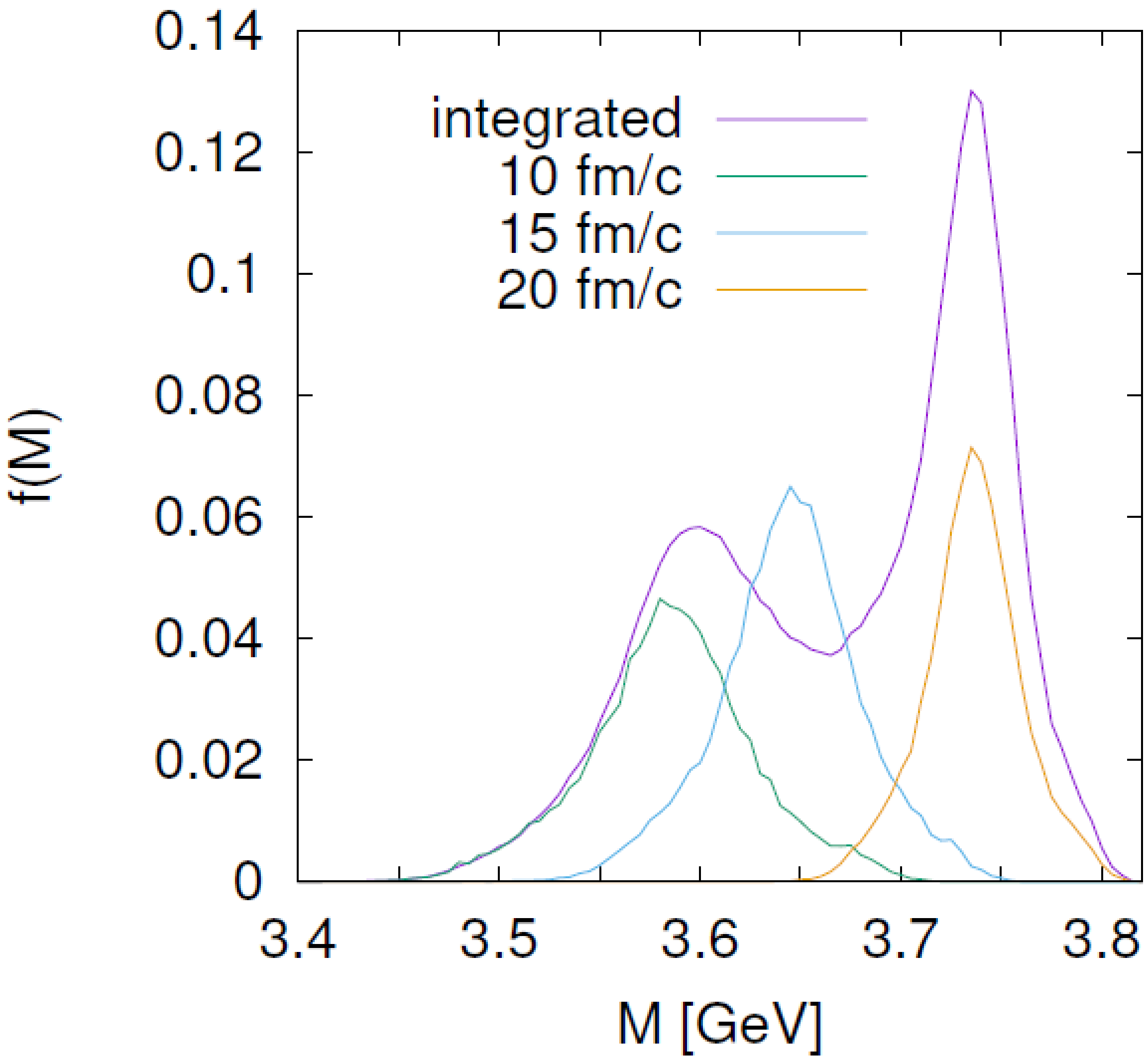
Most of the antiprotons annihilate at the surface of the target -> the charmonium is also created here -> it can probe the matter during its evolution with its decay to dileptons.

Time evoulution of masses and density



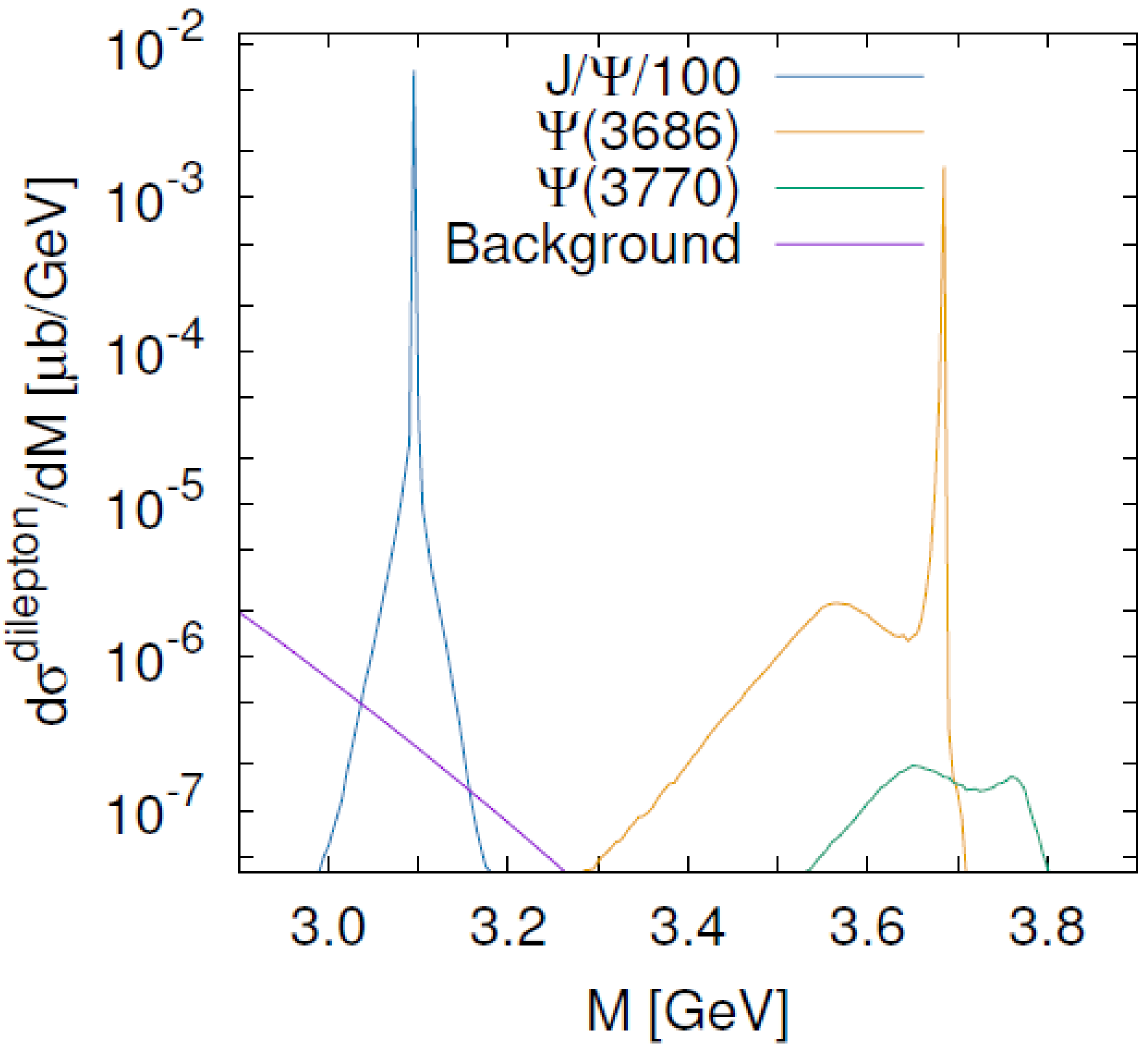
- The charmonium regains its vacuum values at the end of the collision.
- There is a sharp transition from the dense matter to vacuum ~[14-18]fm/c -> we have to see two peaks at the end.

- The transition region is thin -> most of the dileptons come from the dense matter or from the vacuum -> we should see some separation in the spectrum.
- Time evolution of the mass spectra ($\Psi(3770)$).
- The integrated spectrum shows the two peak structure.



- Dilepton invariant mass spectrum from BUU.
- The J/Ψ mass shift is too low to see anything interesting.
- The $\Psi(3770)$ vacuum width overlaps with the shifted spectrum.
- Possible candidate: $\Psi(3686)$
- The mass shift corresponds to $\rho \approx 0.9\rho_0$
- **Method**:

1. Measure peak distance -> get the mass shift at $\rho \approx 0.9\rho_0$
2. From the mass shift we can obtain the gluon condensate at $\rho \approx 0.9\rho_0$



Summary

- We use Non-equilibrium off-shell transport to simulate heavy ion collisions.
- We developed a “semi-statistical” method based on the Bootstrap model to calculate unknown cross sections.
- We examined the mass shift of the charmonium states in nuclear matter.
- The most probable candidate to measure the mass shift therefore the gluon condensate is the $\Psi(3686)$ state.
- Future:
  - Find the “best” energy range to see the two peak structure (or only the shifted peak at the beginning)
  - Develop further the statistical model (elastic scattering, many body collisions)
  - Put many body collisions into the simulation (hard task…geometrical picture is not really good -> effective models/Regge-method/crossing symmetry)