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Experimental studies on medium modification of hadron mass

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The breaking of the chiral symmetry is widely accepted as a key mechanism to gerenete hadron mass. However, it is still not well established theoretically and also experimentally due to an difficulty in Quantum Chromodynamics (QCD) at a low-energy regime. Experimental studies on medium modificaion of hadron mass have been intensively performed to investigate the origin of hadron mass. Dilepton measurement can give a direct information of the medium modification of vector meson mass, since it is almost free from the final state interaction. The experimental results obtained so far are briefly reviewd. A new experiment is planned to do systematic studies on the medium modification using a high-momentum primary beam now being constructed at the J-PARC Hadron Facility. The current status is reported.

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1. Introduction

It is widely believed that the constituent quark masses are generated as a consequence of the chiral symmetry breaking. The hadron is well described as a bound state of constituent quarks, which has an extra mass of several hundred MeV inside the hadron. For example, the constituent masses of u and d quarks are of order 300 MeV whereas the current quark mass is only a few MeV. Given the fact that the pion can be understand as the Nambu-Goldstone boson associated with the chiral symmetry breaking, it would be a plausible explanation for the origin of hadron mass. However, the order parameter of the chiral symmetry is not well determined theoretically, especially for other mesons. Therefore, we need a help from the theoretical side to connect experimental observables to the origin of hadron mass. The mass of the vector meson could be modified as a consequence of the spontaneous and/or dynamical breaking of chiral symmetry. At high temperature and/or high density, chiral symmetry is sure to be restored and the properties of the hadron would be modified from those in the vacuum. The mass modification of the vector meson has been intensively studied in heavy ion collisions and also in cold nuclear matter. While a drastic change is expected at or above a critical temperature, the system evolves dynamically in heavy-ion collisions, thus making any theoretical interpretation difficult. Normal nuclear matter is a static system, where a precursor effect of chiral symmetry restoration is expected even at the normal nuclear density, as pointed out in [1, 2, 3] and many other theoretical works. In the following section, past and future experimental programs are briefly described.

2. Overview of Experimental Results

One of the experimental approaches to the origin of hadron mass is to measure properties of bound systems which have a meson inside. Partial restoration of the chiral symmetry is experimentally indicated from measurement of a deeply bound pionic atom [4], through theoretical work showing that the chiral order parameter can be translated from the pion-nucleus scattering length [5].

The other powerful tool is the dilepton measurement, which can deliver the direct information of the mother particle. Dilepton measurements to explore the modification of the hadron mass have been performed in a variety of facilities worldwide. The pioneering work was done in the CERES/NA45 experiment reporting the enhancement at the low-mass side of ρ and ω mesons in the invariant mass spectrum of e^+e^- pairs produced in Pb-Au collisions at 158 AGeV [6]. The NA60 experiment measured muon pairs in 158 AGeV In-In collisions at the CERN SPS. In that experiment all known sources and background from the observed spectrum were subtracted and the remaining signal was consistent with the broadening of the ρ meson [7], as shown in figure 1. A large low-mass enhancement was observed in the PHENIX experiment on the e^+e^- spectrum measured in $\sqrt{s} = 200$ GeV Au + Au collisions at RHIC [8], as shown in Fig. 2. Currently, none of the theoretical models employed to reproduce the data at the SPS can describe the enhancement observed by the PHENIX. This is called as "PHENIX puzzle". Recently the STAR Collaboration has reported the low-mass enhancement on the e^+e^- invariant mass spectrum, however the enhancement factor seems to be inconsistent with that measured in the PHENIX experiment [9].

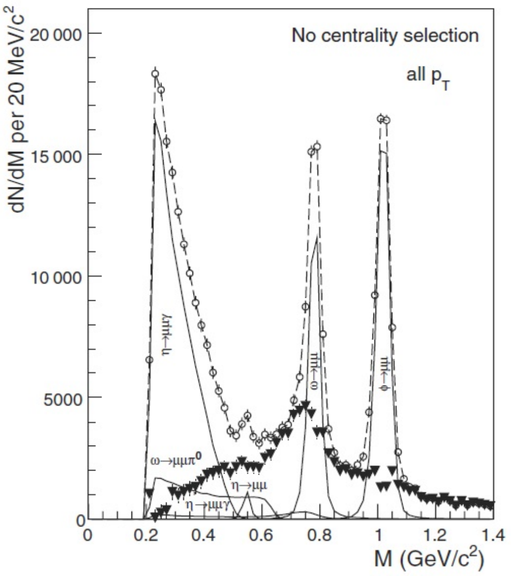

Figure 1: Invariant mass spectrum of $\mu^+\mu^-$ after subtracting the combinatorial background [7]. The remnant after subtracting all the known hadronic sources except ρ meson is indicated with thick triangles.

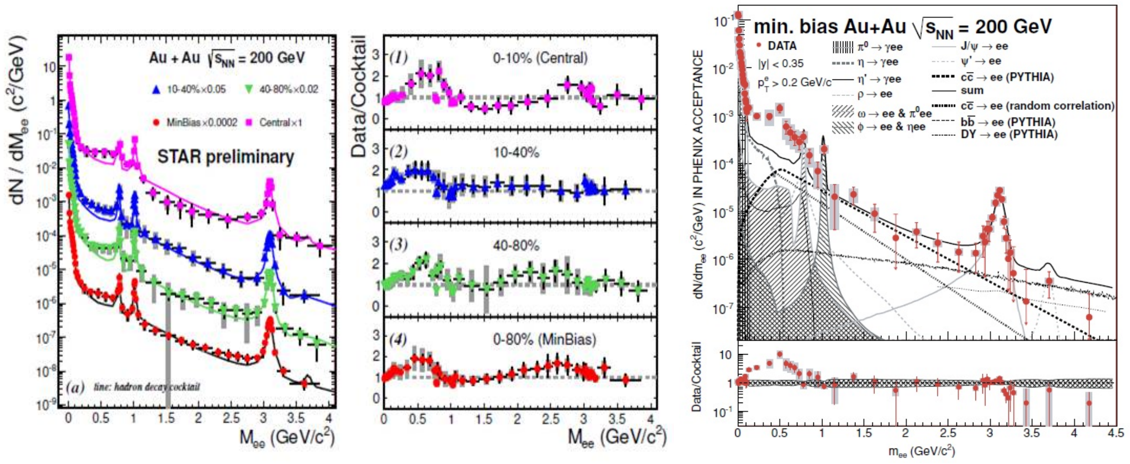

Figure 2: Left: Invariant mass spectra of e^+e^- in the STAR acceptance for Au+Au collisions at $\sqrt{NN}$ = 200 GeV for different centrality selections; Middle: Ratio of data to cocktail of STAR data. The figures are taken from the literature [9]. Right: Inclusive mass spectrum of e^+e^- pairs in the PHENIX acceptance in minimum-bias Au+Au data compared to expectations from the decays of light hadrons and correlated decays of charm, bottom, and Drell-Yan [8]. The bottom shows the ratio of data to the cocktail.

At low-energy region, dilepton measurements were performed to investigate the hadron mass modification in cold nuclear matter. The KEK-PS E325 experiment observed the modification of ρ, ω and ϕ mesons in the nuclear medium on the invariant-mass spectra of e^+e^- pairs in 12-GeV $p+A$ interactions [10, 11]. The large enhancement is observed at the low-mass side of the ρ and ω mesons with a significance of $\sim$ 10σ [10]. This enhancement can be reproduced with a model in which the mass of ρ and ω decreases by 9.2% with no width broadening. Figure 3

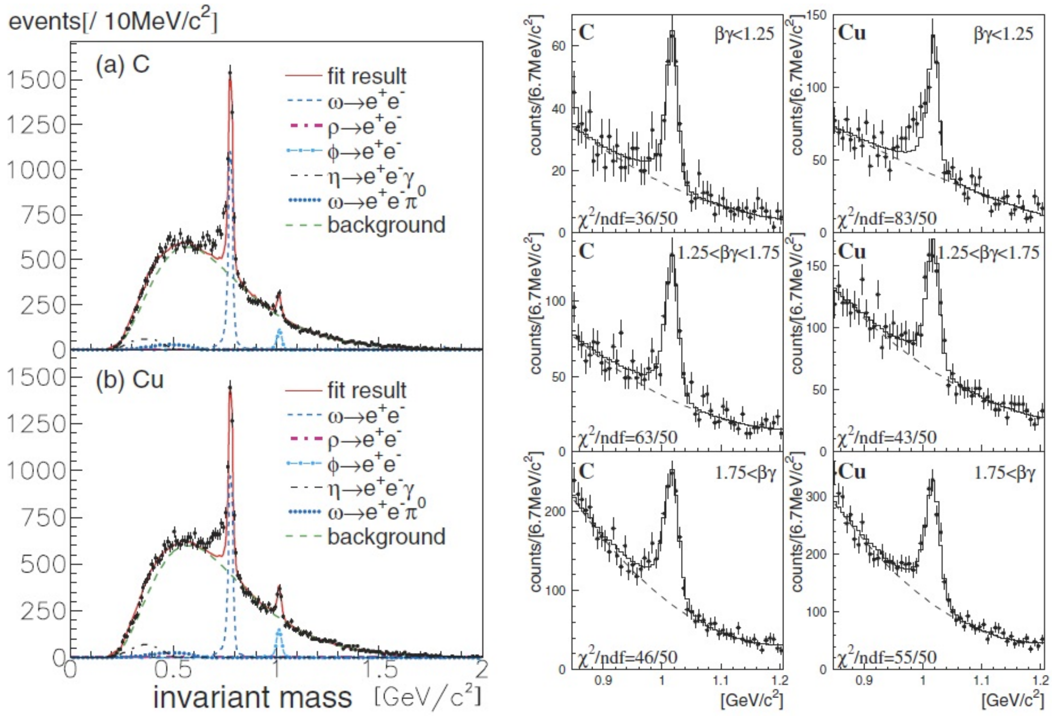

Figure 3: Left: Invariant mass spectra of e^+e^- for the (a) C and (b) Cu targets [10]. Right: Invariant mass spectra of e^+e^- with the fit results. The target and $\beta\gamma$ region are shown in each panel [11].

shows the invariant-mass spectra of e^+e^- pairs for the carbon and copper targets. Clear peaks of the in-vacuum ϕ meson are seen in all momentum regions for both sets of target data. Only in the low-momentum region of the copper target data, where the ϕ meson is expected to have a larger probability of decaying inside the nucleus, is the enhancement over the unmodified shape observed. The observed modification can be described with a model in which the mass of the ϕ meson decreases by 3.4% and the decay width broadens by 3.6 times at the normal nuclear density. The observed mass modifications of the ρ and ω meson and also the ϕ meson are consistent with the theoretical prediction based on the in-medium QCD sum rule [1].

The CBELSA/TAPS Collaboration reported a mass modification of the ω meson measured in the $\gamma + A \rightarrow \omega + X \rightarrow \pi^0\gamma + X$ reaction on a Nb target [12]. It is advantageous to use the decay channel of $\omega \rightarrow \pi^0\gamma$ since one can address the modification of ω apart from the ρ, which is always overlapped on the dilepton measurement. However, one should carefully treat the final-state interaction between the hadronic decay product and the target nucleus. The low-momentum π^0s were eliminated to reduce the effect of final-state interaction. The enhancement was explained with an 8% mass decrease in nuclei at first, but later it was found to be statistically marginal in the reanalysis [13]. From the analysis of the transparency ratio, the absorption cross section of the ω is deduced and it is converted into the additional width in the nuclei, which is thought to be increased by a factor of 30 at the normal nuclear density [14], as shown in Fig. 4.

The medium modification of ρ and ω were not observed on the invariant-mass spectrum of e^+e^- pairs produced in photoproduction measured by the CLAS Collaboration [15]. Figure 5 shows the fit result of the heaviest target data. The extracted ρ line shape is consistent with the

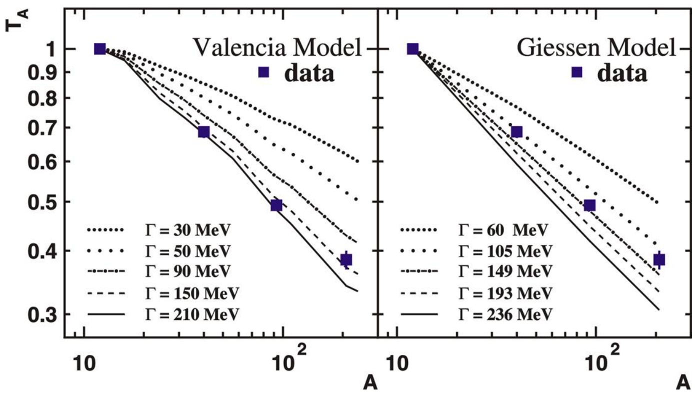

Figure 4: Measured transparency ratio in comparison with a theoretical simulation [14].

model calculation if the collisional broadening inside the target nucleus is taken into account.

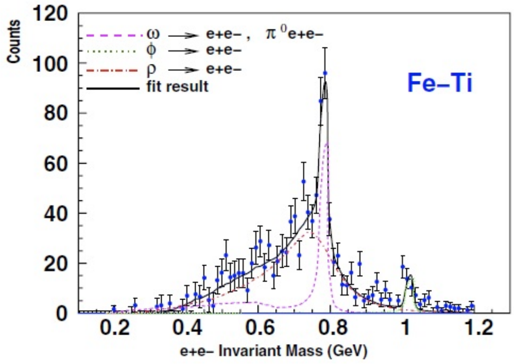

Figure 5: Invariant mass spectrum of e^+e^- pairs measured in γA reaction with Fe/Ti targets [15]. The combinatorial background is subtracted.

3. Future Experiment at J-PARC

A new experiment will be performed at the high-momentum beam line, which is expected to be constructed by the end of FY 2015 at the J-PARC Hadron Experimental Facility. The beam line can provide 30 GeV/c primary protons branched off at the middle of the switch-yard with a typical intensity of 10^{10}–10^{12} protons/pulse. The beam line is also used as a secondary beam line by inserting a production target at the switching point. The high-momentum secondary beam line will provide an opportunity to perform the spectroscopy of multi-strange particles and/or charmed baryons.

The E16 experiment aims at obtaining experimental evidence for the onset of chiral symmetry restoration in nuclear matter. The matter-size dependence of the mass modification is planned to be studied using various targets (CH_2, C, Cu, and Pb). It is crucial to use a thin target to suppress the background originating from the γ conversions and also the radiative tail associated with the bremsstrahlung in the target material. A schematic view of the spectrometer is illustrated in Fig. 6. The electrons are identified with a newly constructed spectrometer that has an acceptance

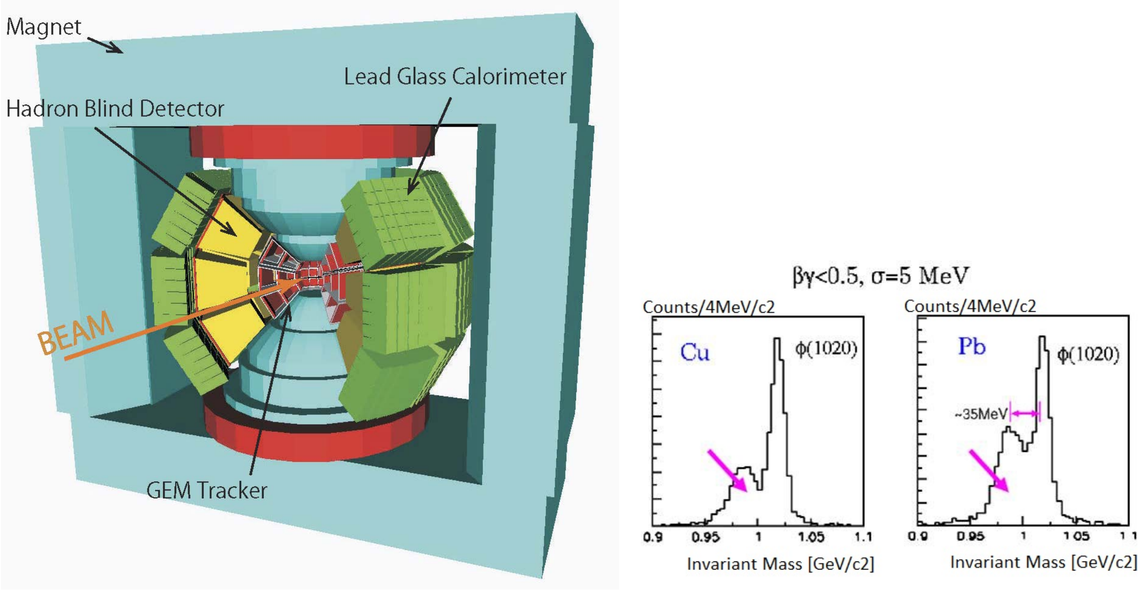

Figure 6: Left: Schematic view of the E16 Dilepton Spectrometer. Right: Expected invariant mass spectra of e^+e^- with copper and lead targets at the mass of ϕ meson.

5 times larger than that of E325. The particle trajectory is measured with the GEM tracker to realize high resolution under a high interaction rate, which is typically 10 MHz. The electron identification is performed with the Hadron Blind Detector (HBD) originally developed for the PHENIX experiment. The HBD is filled with CF_4 gas, which works as a Čerenkov radiator, and an amplification gas with a photo-cathode to amplify the photoelectrons. The photo-cathode consists of a GEM stack on top of which a CsI is evaporated. The yield of $\phi \to e^+e^-$ events is estimated to be 10^5 for each target. With these statistics, the momentum and nuclear size dependence of the ϕ meson mass can be studied systematically.

4. Summary and Outlook

The medium modification of vector meson mass has been intensively studied with dilepton measurements to investigate the origin of hadron mass. In heavy ion collisions, the large enhancements were observed at the low-mass region up to the mass of ϕ meson at the SPS and top RHIC energy. In the cold nuclear matter, the mass modification of light vector meson were observed on the dilepton spectra measured in 12 GeV/c p+A reactions, whereas it was reported that the spectral modification was not significant for mesons produced in the photo-induced reactions. The new beam line transporting high-momentum primary and/or secondary beam particles will be completed in FY 2015. The J-PARC E16 experiment will be launched soon to investigate the momentum and nuclear-mass number dependence of the mass modification. The systematic study will provide a solid understanding especially for the modification expected in the cold nuclear matter.

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