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MULTI-CHANNEL MEASUREMENTS OF LIGHT VECTOR MESONS AT PHENIX

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The PHENIX experiment at RHIC is uniquely suitable for systematic studies of light vector mesons, whose mass states are considered as a sensitive probe of partial chiral symmetry restoration and as a signature of deconfined partonic state of matter. Their challengingly small signal to background ratios in multi body decay channels in heavy ion collisions have been extensively attacked. Significant improvements have been recently achieved of signal extraction techniques. The final results on yields, transverse momentum spectra, and possibly mass states of light vector mesons including ϕ and ω are well in the near future prospects.

1. Light Vector Mesons in High Energy Nucleus Collisions

1.1. *Physics background and history*

Mass states of light vector mesons are considered to be sensitive probes of partial chiral symmetry restoration theoretically expected in high temperature and/or baryon densities. Some of the experimental results at CERN SPS and KEK PS are explained as onsets of the phenomenon.[1,2] In high energy heavy ion collisions, their modifications have been looked for also as a signature of deconfined partonic state of matter. Systematic comparison among results from different regions in the QCD phase diagram and via different channels will provide critical information for study of partial chiral symmetry restoration and hence of the origin of mass of hadrons.

1.2. *What are "mesons in non-hadronic phase"?*

A frequently asked question on measurement of possible mass modification of light vector mesons in "deconfined partonic matter" is: what do we really see by looking at hadrons in non-hadronic phase? Even above the phase boundary between confinement and deconfinement, quarks may form bound states which should be interpreted as precursors of hadrons. The recent discovery in lattice QCD that J/Ψ remains as a prominent peak up to about 1.6 times the critical temperature is a numerical support of the picture.[3] Their mass states may however be modified from those in vacuum and of special interest to understand the properties and origins of mass of hadrons.

2. Experimental Approach

2.1. *PHENIX at RHIC: the right tool*

The high capabilities of the PHENIX experiment to measure leptons and photons as well as hadrons, along with the high integrated luminosities achieved by the RHIC accelerator, make the experiment uniquely suitable for systematic studies on properties of light vector mesons at high energy densities, hopefully including above the QCD phase transition. In addition to historically popular di-lepton decay channels such as e^+e^-, various other channels such as $\pi^0\gamma$ have been paid attention and are under extensive studies. Another important feature of RHIC is its versatility. Comparison among collision systems from p+p to Au+Au provides a vital systematics, with baseline measurements in p+p and d+Au collisions with the same apparatus as in Au+Au.

2.2. *Multiple species in multiple decay channels*

PHENIX is capable of measurements of multiple species of light vector mesons in multiple decay channels into leptons, photons and hadrons. For instance ϕ mesons are measured in hadronic (K^+K^-) and leptonic (e^+e^-) channels, and ω mesons in hadronic ($\pi^0\pi^+\pi^-$), radiative ($\pi^0\gamma$) and leptonic (e^+e^-) channels. The systematic measurements in multiple decay channels are vital to understand the properties of the light vector mesons in the created matter, as the different channels are to probe the matter in different ways and to different extents due to the unequal degrees of penetration in the final hadronic states. Measurements in multiple channels have another advantage in kinematic coverage. The coverage of transverse momentum of ω mesons provided by two of the decay channels is demonstrated in Fig. 1. The combined wide coverage of transverse momentum provides an additional axis in systematics, which is the probability for the mesons to decay in the matter.

3. Recent Experimental Highlights

3.1. *Measurements of ω mesons in Au+Au collisions*

The largest data sample at RHIC on Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV has been from the Run 4 in 2003-2004, with the integrated luminosity of $\sim 240\ \mu\text{b}^{-1}$. With the data sample, production of ω mesons in Au+Au collisions has been studied in PHENIX both in e^+e^- and $\pi^0\gamma$ decay channels.[4–6] As a reference, that in p+p and d+Au collisions has also been analyzed in $\pi^0\pi^+\pi^-$ and $\pi^0\gamma$ channels.[5–7] Figure 2 shows the invariant production cross section of ω mesons in Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV, scaled with the number of binary nucleon-nucleon collisions.

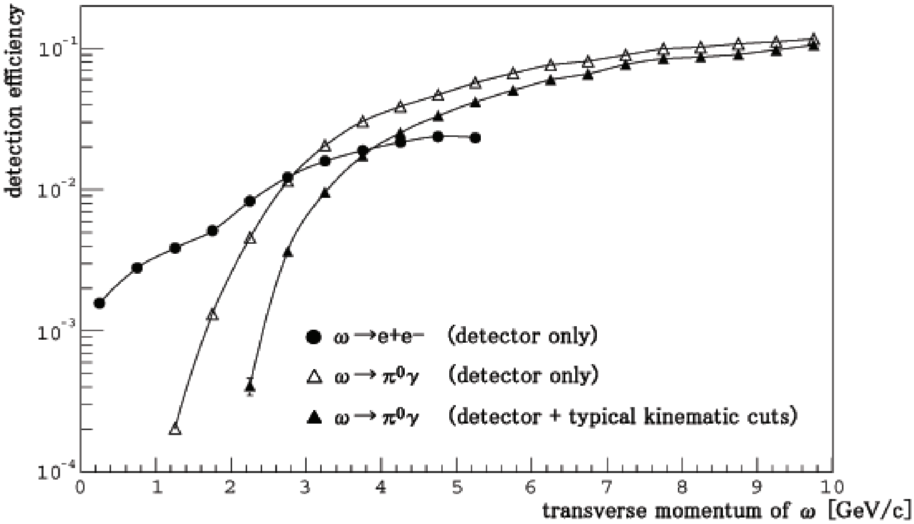

Fig. 1. Acceptance of PHENIX experiment for ω mesons in e^+e^- and $\pi^0\gamma$ decay channels.

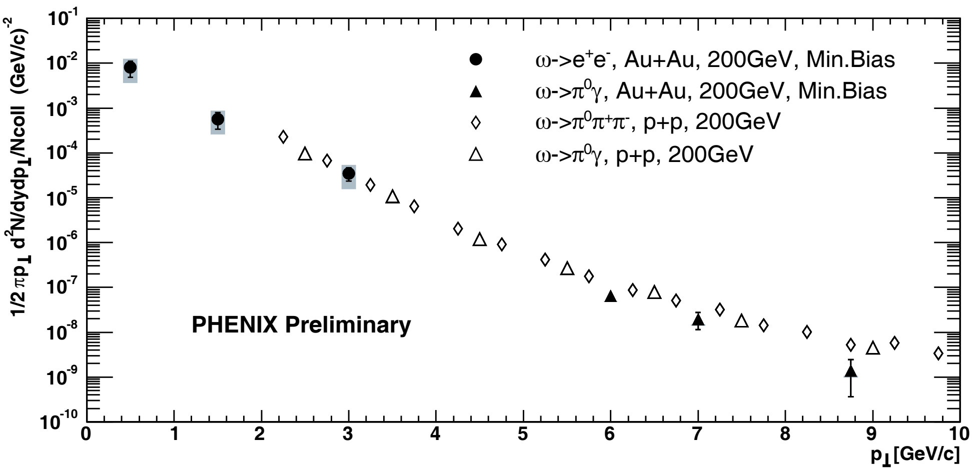

Fig. 2. Invariant production cross section of ω mesons in Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV, scaled with the number of binary nucleon-nucleon collisions.

3.2. *Challenges and progress in $Au + Au$ analysis*

The largest challenge in measurements of light vector mesons in heavy ion collisions is their small signal to background (S/B) ratios due to huge combinatorial backgrounds in multi body decays (see Fig. 3, left). As an example, with the statistics so far accumulated at PHENIX, measurement of ϕ and ω mesons in Au+Au collisions in e^+e^- decay channel has marginal statistical significance (see Fig. 3, right). A

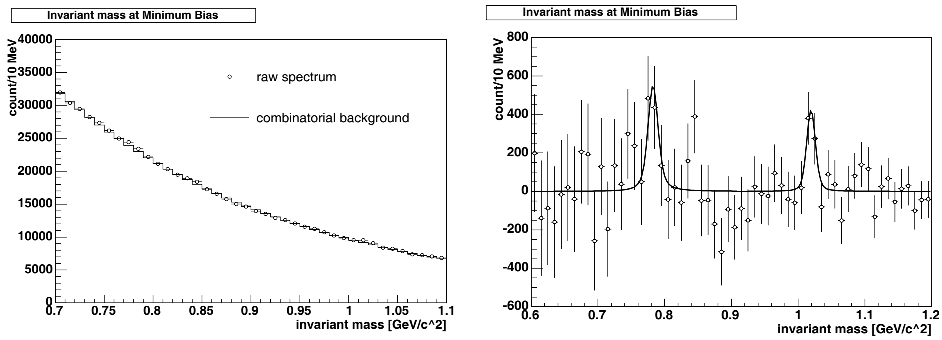

Fig. 3. Invariant mass spectra of e^+e^- in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Left panel: before background subtraction. Right panel: after evaluation and subtraction of combinatorial background.

number of key techniques are hence developed in evaluation and subtraction of the combinatorial background to extract the signal.[4]

In parallel to the improved background subtraction techniques, kinematic selection on the decay products is another effective approach to maximize the statistical significance of the signal, i.e. $S/\sqrt{S+B}$. This approach is especially important in channels with more than two decay products, e.g. radiative and hadronic decay channels of ω mesons, due to the even worse combinatorial background situations. In $\pi^0\gamma$ decay channel of ω mesons, the kinematic selections on decay products which have been found most effective include the minimum transverse momentum of the decay π^0 and the minimum energy of the third (which is not via the π^0) γ. The tightness of π^0 identification, based on the invariant mass reconstructed from $\gamma\gamma$ pairs, is found to have a less but non-zero impact. The selection criteria have been optimized as a function of the transverse momentum of finally reconstructed ω meson, based on simulation studies of efficiency for the signals and evaluation of combinatorial background from the real data.[8] The effect of optimization on the statistical significance of the signal is demonstrated in Fig. 4.

With the optimized kinematic selections in $\pi^0\gamma$ decay channel of ω mesons in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the expected peak significance in the PHENIX run 4 data sample has been significantly improved to the level of $3 \sim 4\ \sigma$ for ω's with transverse momentum above 5 GeV/c, as shown in Fig. 5, assuming no suppression or enhancement of ω mesons relative to production in p+p collisions.

The significant improvements in signal extraction techniques open a possibility to acquire further information on yields, transverse momentum spectra and possibly mass states of ω mesons, with a higher precision and in wider systematics both in kinematics and collision centrality. The techniques are also applicable to ϕ mesons and to different data sets, e.g. with lighter collision systems and/or lower collision energies.

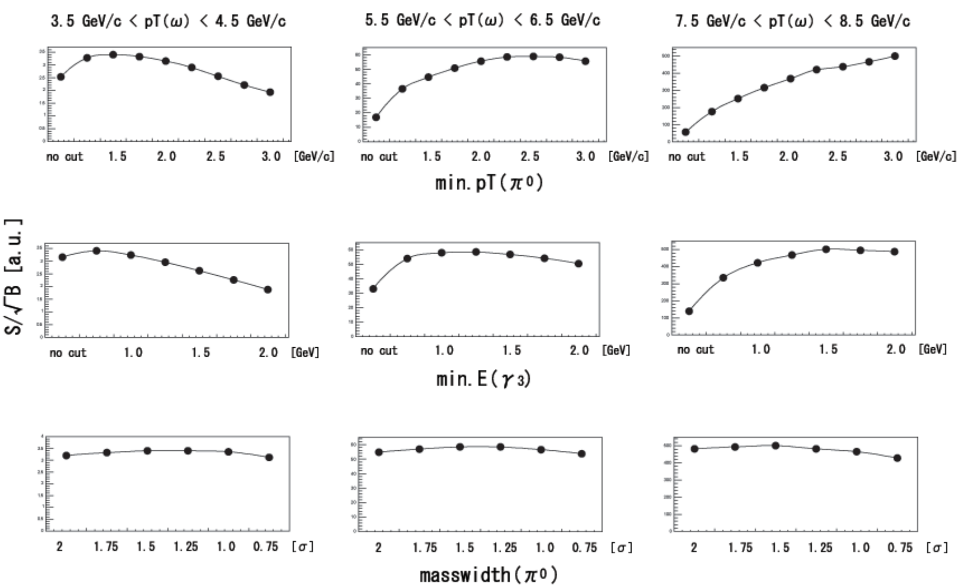

Fig. 4. Effect of kinematic selection on decay products on the statistical significance of the signal ($S/\sqrt{S+B}$) in $\pi^0\gamma$ decay channel of ω mesons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Top panels: as a function of minimum transverse momentum of decay π^0. Middle panels: as a function of minimum energy of third γ. Bottom panels: as a function of tightness of decay π^0 identification.

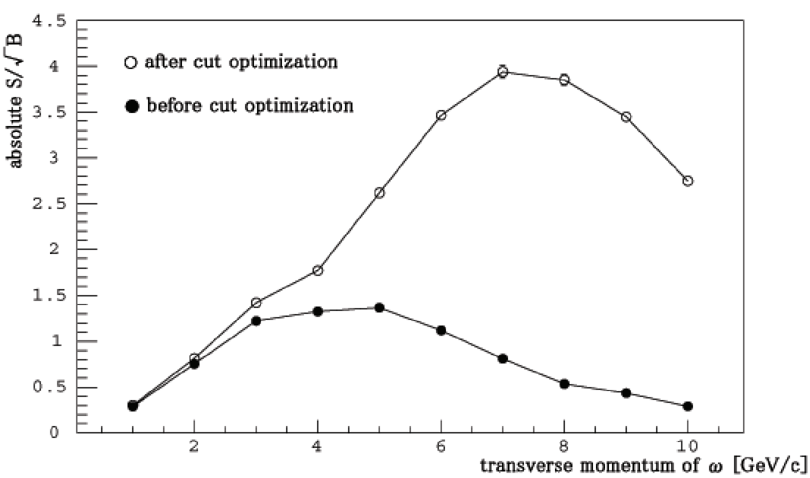

Fig. 5. Expected significance of ω signal in $\pi^0\gamma$ decay channel in minimum bias Au+Au collisions with the Run 4 statistics. See text for details.

4. Summary

The PHENIX experiment at RHIC is uniquely suitable for systematic studies of light vector mesons, whose mass states are expected as a sensitive key clue to study partial chiral symmetry restoration and hence the origin of mass of hadrons, and as a signature of deconfined partonic state of matter. Analysis of the largest data sample of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, taken in 2003–2004, is ever in progress, where the challengingly small signal to background ratios in multi body decay channels of light vector mesons have been extensively attacked. Significant improvements have been recently achieved of signal extraction techniques both in e^+e^- and $\pi^0\gamma$ decay channels of ω mesons. The final results on yields, transverse momentum spectra, and possibly mass states of light vector mesons including ϕ and ω are well in the near future prospects of PHENIX.

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