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Measurement of the ϕ-meson production in the relativistic heavy ion collisions with the PHENIX detector at RHIC

A. Milov(*) for the PHENIX Collaboration
Weizmann Institute of Science - Rehovot, 76100, Israel

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Summary. — This proceeding gives the most complete review of the measurements of the ϕ-meson production in relativistic heavy ion and proton-proton collisions performed by the PHENIX experiment at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. The measurements of the ϕ-meson are consistent in the analysis of various decay modes, using different techniques. The results show expected similarities when analyzed in Au + Au and Cu + Cu collision systems for the corresponding centrality classes. In other systems PHENIX observes not only the difference between the suppression of ϕ-meson and the proton, reflecting generally different behavior between mesons and baryons, but also a significant difference in suppression of different mesons. These results are hard to explain due to the mass or quark content of the ϕ-meson.

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1. – Introduction

The ϕ meson is considered among the most interesting probes of the Quark Gluon Plasma (sQGP) created in the Relativistic Heavy Ion (RHI) Collisions. ϕ mesons are copiously produced in RHI collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ and have both hadronic and leptonic decay modes. The ϕ-meson is a $s\bar{s}$ state and therefore provides a direct way to study strangeness content of the collisions and understand its contribution to the phenomenon of high-p_T suppression in RHI collisions. Among the unique properties that allow studying the mechanism of particle production using ϕ-mesons is its mass which is slightly higher than the mass of the lightest baryon. This feature gives a possibility to untangle the mass-related effects from the number of quark-related effects in the particle production in RHI collisions.

(*) E-mail: alexander.milov@weizmann.ac.il

TABLE I. – *Physics runs, accumulated statistics and analyzed decay modes.*

Run	Year	Species	$\sqrt{s_{NN}}$ (GeV)	$\int Ldt$	N_{sampled}		ref.
2	2001/2002	Au + Au	200	$24\,\mu\text{b}^{-1}$	170M	K^+K^-, e^+e^-	[2]
3	2002/2003	d + Au	200	$2.74\,\text{nb}^{-1}$	5.5B	K^+K^-	[3]
		p + p	200	$0.35\,\text{pb}^{-1}$	6.6B	K^+K^-	[4]
4	2003/2004	Au + Au	200	$241\,\mu\text{b}^{-1}$	1.5B	K^+K^-, e^+e^-	[5-7]
		Au + Au	62.4	$9\,\mu\text{b}^{-1}$	58M	K^+K^-	[8]
5	2005	Cu + Cu	200	$3\,\text{nb}^{-1}$	8.6B	K^+K^-	[9]
		Cu + Cu	62.4	$0.19\,\text{nb}^{-1}$	0.4B	K^+K^-	[8]
		p + p	200	$3.8\,\text{pb}^{-1}$	85B	K^+K^-, e^+e^-	[9]
8	2008	d + Au	200	$80\,\text{nb}^{-1}$	160B	$\mu^+\mu^-$	[10]

Another unique feature of the ϕ meson is a small mass difference between the particle and the mass of two K mesons to which it decays. That makes it a sensitive probe of the medium induced effects. Under such conditions the ϕ meson measured decay rate in K^+K^- channel [1] may differ from its vacuum value.

The existing information on the ϕ-meson production in RHI is still incomplete and sometimes controversial. Recent results by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) present a systematic studies of the ϕ-meson production in p + p, d + Au, Cu + Cu and Au + Au collision systems at RHIC energies of $\sqrt{s_{NN}} = 62$ and 200 GeV. The measurements of the differential invariant is performed using K^+K^-, e^+e^- and $\mu^+\mu^-$ channels and reach the p_T of 7 GeV/c.

2. – Data analysis

Results presented in this proceeding are based on measurements performed by the PHENIX experiment in several physics runs summarized in table I. The analysis was done in hadronic and leptonic decay modes using several analysis techniques. Some results have been previously published in references listed in table I. These publications also contain a detailed description of the analysis procedures. Here we only focus on some of the distinct features of these analyses.

Measurement of the spectral distribution in K^+K^- mode was done by reconstructing the invariant mass distributions in separate p_T bins. Examples of mass distributions reconstructed in several decay modes are shown in fig. 1. The combinatorial background was partially removed by mixed event technique and then by fitting the mass distribution by a sum of a parabolic function for the background and a convolution of the Breight-Wigner and Gaussian function for the signal. The parabolic component of the fit was subtracted from the data and the sums of the bins in the region $\pm 6 \times$ r.m.s. around the center of ϕ peak were taken as the raw yield of the ϕ-meson. In e^+e^- mode random combinatorial background was fully subtracted using the mixed event technique explained in details in [11]. For the $\mu^+\mu^-$ mode the background subtraction was also done using the mixed event technique based on a different principle.

The raw yields were then corrected for the geometric acceptance, reconstruction efficiency, analysis cuts. Where such was relevant the yields were also corrected for the trigger efficiency.

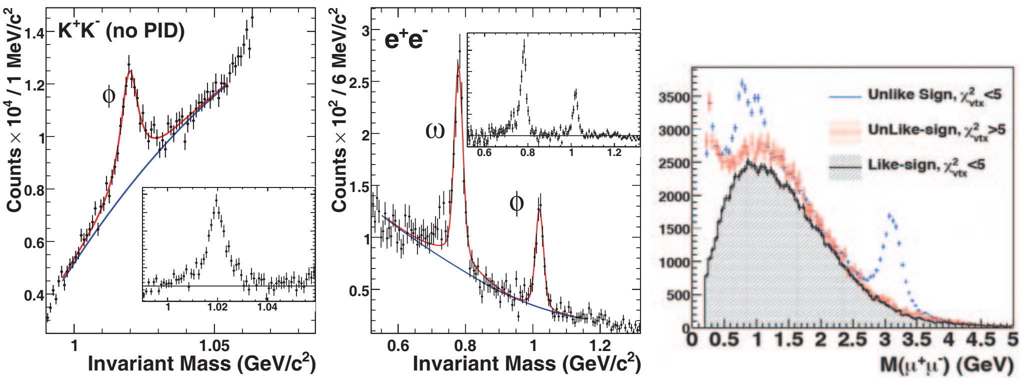

Fig. 1. – Invariant mass pair distribution for K^+K^- [9] (left) e^+e^- [9] (centre) and $\mu^+\mu^-$ (right) pairs showing the signal with the background and the estimated backgrounds.

In the analysis of the early data of the K^+K^- decay mode both K mesons were identified using PHENIX Time-of-Flight system [12] or PHENIX calorimeters timing capabilities [13]. Full particle identification greatly reduces combinatorial background, however also reduces the kinematic range in where the ϕ-meson can be measured due to limited momentum range of particle identification and detector coverage. Therefore in the analysis of the Run 4 and successive in addition to the full K identification the particle identification requirement was lifted for one or both tracks. As a result of that the measurement was extended to a transverse momentum p_T of 7 GeV/c. Different techniques were compared to each other in the overlapping region confirming the consistency of the measurement. The comparison is shown in fig. 2.

The combinatorial background subtraction in the e^+e^- decay mode measurement is described in [9, 11]. The mixed event techniques allow removing absolutely normalized

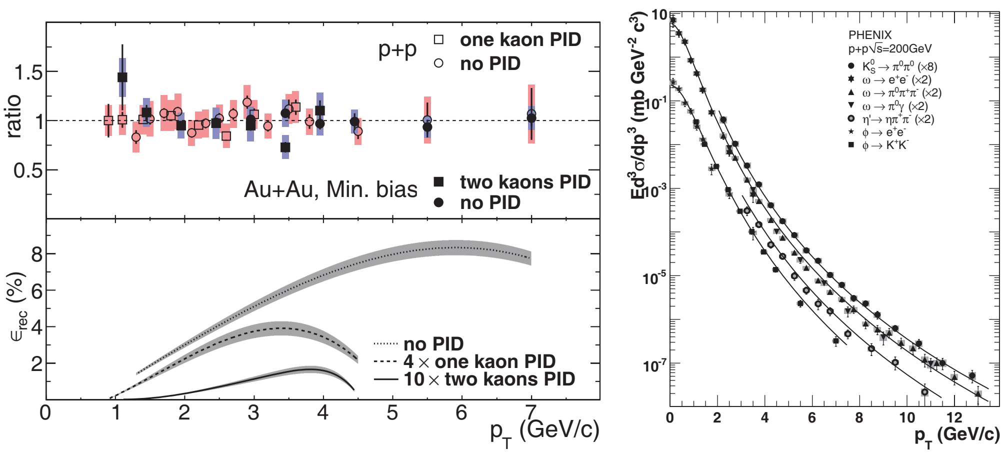

Fig. 2. – The left panel shows the PHENIX reconstruction efficiency for the ϕ-meson measurement in K^+K^- mode for three different cases (lower panel) and the comparison of the fully corrected spectra divided by a common fit (upper panel) [5]. The right panel shows the consistency of ϕ-meson measurement in K^+K^- and e^+e^- decay modes [9].

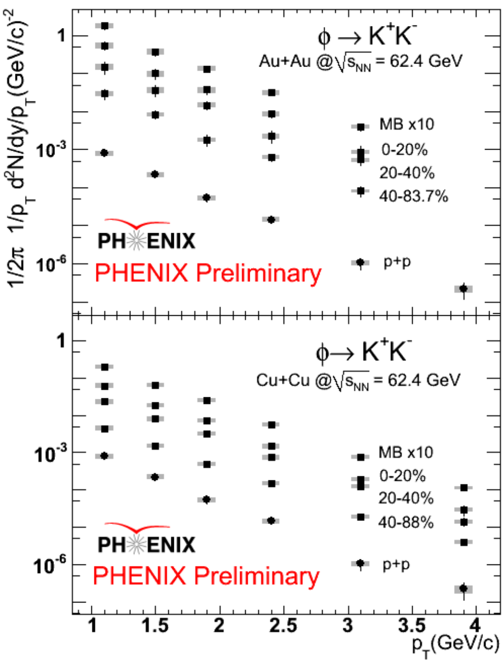

Fig. 3. – Upper panel shows the ϕ-meson spectra measured in centrality bins at $\sqrt{s_{NN}} = 62.4\,\text{GeV}$ in Au + Au systems using K^+K^- decay channel. The lower panel shows the same for Cu + Cu system.

background contribution by reconstructing the shape of the background with electrons randomly picked from different events with similar topology and normalizing it using statistics accumulated in the like- and unlike-sign pairs. In the novel PHENIX analysis of the $\mu^+\mu^-$ decay mode the background is dominated by the $\mu^+\mu^-$ mesons coming from the in-flight decays of $\pi^{\pm}$. The background was subtracted based on the data driven approach using tracks with poor pointing to the primary event vertex.

3. – Results

PHENIX result of the ϕ-meson measurements in p + p collisions in e^+e^- and K^+K^- decay modes is shown in the right panel of fig. 2. The measurements in both modes are consistent with each other. Measuring the e^+e^- decay channel in p + p collisions at $\sqrt{s} = 200\,\text{GeV}$ allows reconstructing the ϕ-meson. It gives a possibility to directly measure the absolute yields and $\langle p_T \rangle$ of the ϕ-meson. The integrated cross-section of the ϕ-meson production at mid-rapidity is measured to be $\mathrm{d}\sigma^{\phi}/\mathrm{d}y = 0.432 \pm 0.031^{\text{stat}} \pm 0.051^{\text{syst}}\,\text{mb}$. The mean transverse momentum $\langle p_T^{\phi} \rangle = 0.752 \pm 0.032^{\text{stat}} \pm 0.014^{\text{syst}}\,\text{GeV}/c$ [9]. One can note that recent statistical model calculation [14] applied to the p + p system accurately describes yields of most particles measured at full RHIC energy, but it underpredicts the ϕ-meson cross-section by approximately 25%.

The panels of fig. 3 show the PHENIX preliminary results on ϕ-meson measurement in Au + Au and Cu + Cu at $\sqrt{s_{NN}} = 62.4\,\text{GeV}$, respectively. Figure 4 shows the results measured in d + Au at $\sqrt{s_{NN}} = 200\,\text{GeV}$ in e^+e^- decay mode.

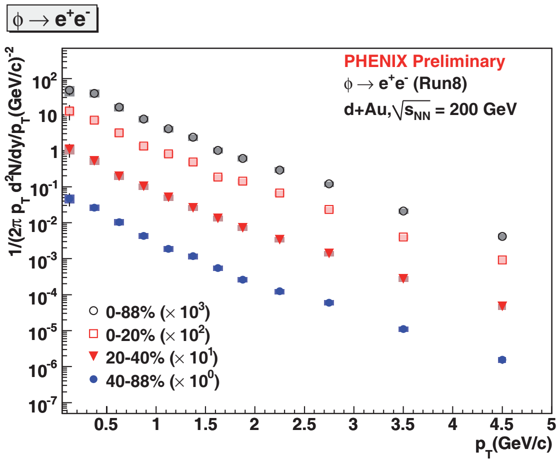

Fig. 4. – e^+e^- decay channel measurement in $\mathrm{d+Au}$ system at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$.

Figure 5 presents a complete set of measurements by the PHENIX experiment at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ in all collisions systems in K^+K^- decay channel [5].

Based on the measurements presented in figs. 3 and 5 the comparison made for centrality bins with approximately the same number of participants N_{part} demonstrates that the spectral distributions of ϕ in different systems at the same energy are consistent with each other. The second-order effects related to the shape of the nucleon overlap region do not play an important role in the integrated yield of ϕ-meson production. We also observe a good agreement between the measurement of ϕ at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ in $\mathrm{d+Au}$ system for the Minimum Bias and the most central centrality bins measured in e^+e^- (fig. 4) and K^+K^- (fig. 5 right) decay modes.

Limited range of the measurements at low p_T makes the calculations of the integrated yields difficult. Implying further assumptions about the spectral shape one can conclude that the integrated yields divided by the N_{part} show a steady growth from lighter collision systems to heavier and also with centrality [15]. Relative increase of the ϕ production from $\mathrm{p+p}$ to the most central $\mathrm{Au+Au}$ collisions reaches approximately a factor of 3 at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. This is consistent with the measurements performed by the STAR experiment [16,17], however, a discrepancy in the measurement of $\mathrm{d}N/\mathrm{d}p_T$ in the overlap region, especially in $\mathrm{Au+Au}$ collisions still remains unresolved between the two experiments [5]. At $\sqrt{s_{NN}} = 62\,\mathrm{GeV}$ the absolute yield also increases with centrality, but in the absence of the $\mathrm{p+p}$ measurement at the same energy it is more difficult to quantify.

Nuclear modification factor R_{dA} for the $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ is shown in the left panel of fig. 6. The results are shown for the most central and for peripheral events. Compared to preliminary PHENIX results [15] these data are of a much higher quality and exclude a possible growth of the ϕ-meson R_{dA} with p_T in the central event sample, admissible by larger errors in preliminary measurements.

Figure 6 demonstrates the difference in the suppression pattern not only between mesons and baryons but also between different mesons. The lower right panel presenting peripheral $\mathrm{d+Au}$ results shows that the R_{dA} of ϕ- and π^0-mesons and the proton are consistent with 1. In the most central $\mathrm{d+Au}$ events the proton R_{dA} increases with p_T

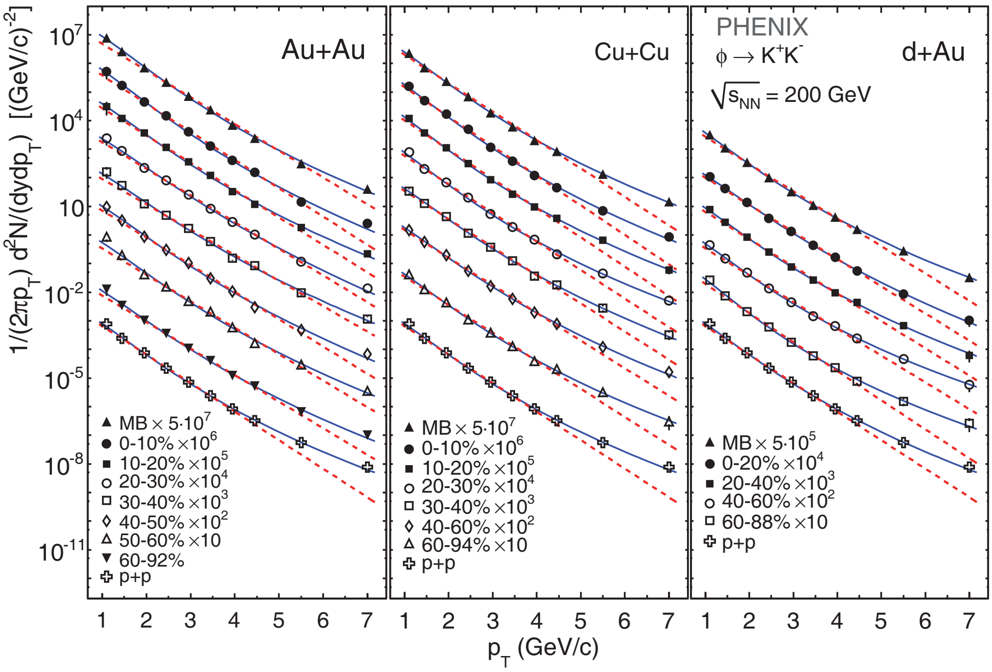

Fig. 5. – The three panels from left to right show the spectra of the ϕ-meson measured in Au + Au, Cu + Cu and d + Au collisions systems in K^+K^- decay mode at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [5]. The p + p results are added as the lower set of points to each plot. The lines are the best fits to the exponential function (dashed) and Tsallis function (solid).

and the R_{dA} of ϕ-meson and of π^0-meson remain very close to each other and do not show significant p_T dependence as is seen for the baryons. This shows a difference between mesons and baryons behavior and argues that the mass of the particle does not play a major role in the suppression mechanism in d + Au collisions.

Difference between mesons and baryons becomes more evident in heavy nuclei collisions. In the most peripheral centrality class shown in the left lower panel of fig. 6 proton and the two mesons have different p_T dependence of the R_{AA}. The difference remains at all centralities as it becomes clear from the upper panel of the same figure, presenting the most central event sample. Left panel of fig. 6 also demonstrates that the R_{AA} of ϕ- and π^0-meson in Au + Au evolve differently with centrality. This was not seen in d + Au collisions. In all three centrality classes shown in the figure the magnitude of R_{AA} of ϕ-meson is consistently higher than the R_{AA} measured for π^0. This was also observed in the Cu + Cu collisions at the same energy, where the magnitude of the R_{AA} was found to be the same as in Au + Au collisions for the centrality classes with similar N_{part}.

In the most central events, shown in the top panel of fig. 6 the R_{AA} of ϕ-meson is almost twice higher compared to π^0 R_{AA} in the intermediate p_T region of 2–5 GeV/c. At higher p_T the measurement suffers from large statistical uncertainty. This precludes from giving a definite answer to a question whether at higher p_T all mesons show some "universal" suppression level.

In the lower p_T region between 1–2 GeV/c the K-meson shows the same magnitude of suppression as ϕ-meson, suggesting that the presence of the s-quark plays an important

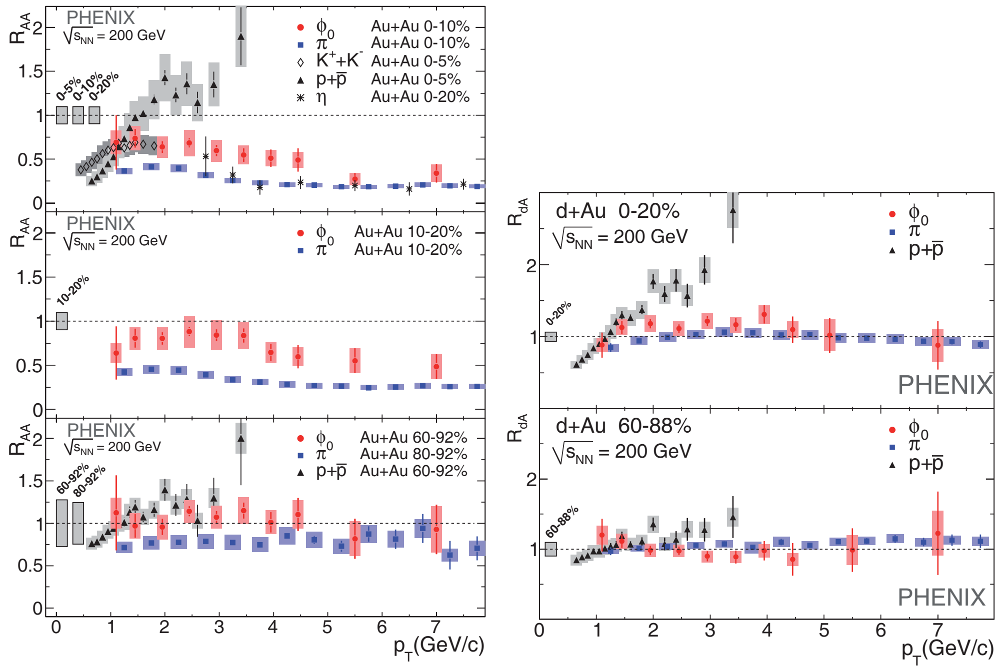

Fig. 6. – Nuclear modification factor R_{dA} (left) and R_{AA} (right) measured by PHENIX at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [5]. The results for ϕ are compared with the results measured for other particles.

role in the suppression mechanism. The p_T region where the currently existing data overlaps between these two particles does not exceed $1\,\mathrm{GeV}/c$, which makes it impossible to give an answer to the question whether the R_{dA} of ϕ- and K-meson is identical or not. An extension of the p_T range of the measurements for ϕ- and K-meson would help to understand the role of the s-quark in the suppression mechanism. It would also be important to make a measurement of a particle not containing s-quarks, such as the ω-meson which would be a control measurement for this study.

In order to further understand whether the s-quark changes the magnitude of measured R_{AA} one needs to consider other mesons containing s-quarks. One of them is the η-meson also shown in the top panel of fig 6. This particle has approximately 50% strange quark content [18], similar to K-meson and it shows the same magnitude of the R_{AA} as the π^0-meson which has no strange quark.

Figure 6 demonstrates that the nature of the hadron suppression mechanism in RHI collisions is not well understood. Existing data clearly points to the fact that the number of quarks plays a more important role in high-p_T suppression compared to the particle mass. At the same time a recent measurement of ϕ-meson shows significant differences in nuclear modification factor compared to lighter mesons. The particle mass or particle quark content can explain the difference in R_{AA} observed between the data.

PHENIX preliminary results on the suppression of the light mesons in d + Au collisions measured in $\mu^+\mu^-$ channel are shown in fig. 7.

The results show no suppression of measured resonances in Au-going side, but in deuteron direction the magnitude of suppression (R_{CP}) is different for different particles.

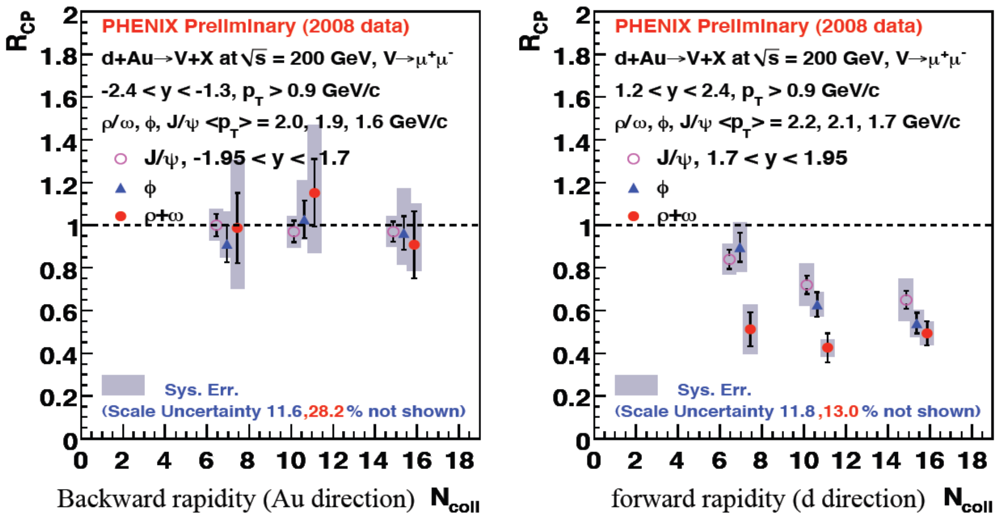

Fig. 7. – Nuclear modification factor (R_{CP}) of light vector mesons and J/ψ in gold-going (left) and deuteron-going (right) directions measured by PHENIX at $\sqrt{s_{NN}} = 200\,\text{GeV}$ in $\mu^+\mu^-$ decay channel.

It must be mentioned that the p_T region where the particles are reconstructed is different for different mesons. The J/ψ is measured starting with zero momentum, but $\langle p_T\rangle$ of ρ/ω and ϕ in these measurements are above $2\,\text{GeV}/c$, therefore the difference in the results might be even larger than shown in the plot. These new results suggest that the suppression in d + Au collisions might be sensitive to the particle quark content, or the effect might be due to the different production mechanisms for these particles.

4. – Conclusions

The PHENIX experiment at the Relativistic Heavy Ion Collider has performed systematic measurements of ϕ-meson production in the K^+K^-, e^+e^-, and $\mu^+\mu^-$ decay channel in a wide rapidity range in p + p, d + Au, Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}}$ of 63 and 200 GeV. Results are presented on the ϕ invariant yield and the nuclear modification factor R_{AA} for Au + Au and Cu + Cu, and R_{dA} for d + Au collisions, studied as a function of transverse momentum ($1 < p_T < 7\,\text{GeV}/c$) and centrality. In central and mid-central Au + Au collisions, the R_{AA} of ϕ-meson exhibits a suppression relative to expectations from binary scaled p + p results. The amount of suppression is smaller than that of the π^0 and the η in the intermediate p_T range (2–5 GeV/c), whereas at higher p_T the ϕ, π^0 and η show similar suppression. The baryon (protons and anti-protons) excess observed in central Au + Au collisions at intermediate p_T is not observed for the ϕ-meson despite the similar mass of the proton and the ϕ. This suggests that the excess is linked to the number of constituent quarks rather than the hadron mass. The difference gradually disappears with decreasing centrality and for peripheral collisions the R_{AA} values for both particles are consistent with binary scaling. Cu + Cu collisions show the same yield and suppression as Au + Au collisions for the same number of N_{part}. The R_{dA} of ϕ shows no significant evidence for cold nuclear effects within uncertainties. Recent PHENIX preliminary results on the meson suppression in d + Au events show that the ϕ-meson is suppressed at forward rapidity.

Largely the interest to measure the ϕ meson in RHI collision is because it provides a tool to study the history of the sQGP evolution beginning from the very early stages. That is possible due to its short lifetime and the presence of the di-lepton decay mode. To address this area of research the PHENIX experiment at RHIC underwent an upgrade with the Hadron Blind Detector [19] which allows to isolate the resonance signal from the excessive background coming from the Dalitz decays of light species such as π^0 and η mesons as well as from the conversions of their secondary photons. The data from the PHENIX physics run in the upgraded configuration is being currently analyzed.

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