PHYSICAL REVIEW C **75**, 051902(R) (2007)

Production of ω mesons at large transverse momenta in $p+p$ and $d+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX experiment at RHIC has measured the invariant cross section for ω-meson production at midrapidity in the transverse momentum range $2.5 < p_T < 9.25$ GeV/c in $p+p$ and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Measurements in two decay channels ($\omega \rightarrow \pi^0\pi^+\pi^-$ and $\omega \rightarrow \pi^0\gamma$) yield consistent results, and the reconstructed ω mass agrees with the accepted value within the p_T range of the measurements. The ω/π^0 ratio is found to be $0.85 \pm 0.05^{\text{stat}} \pm 0.09^{\text{sys}}$ in $p+p$ and $0.94 \pm 0.08^{\text{stat}} \pm 0.12^{\text{sys}}$ in d+Au collisions, independent of p_T. The nuclear modification factor R_{dA}^{ω} is $1.03 \pm 0.12^{\text{stat}} \pm 0.21^{\text{sys}}$ and $0.83 \pm 0.21^{\text{stat}} \pm 0.17^{\text{sys}}$ in minimum bias and central (0–20%) d+Au collisions, respectively.

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Cross sections at large transverse momentum (p_T) for products of "hard" pointlike processes (e.g., inclusive hadrons, jets, direct γ's, and heavy flavor) in high-energy hadron collisions are well described in perturbative quantum chromodynamics (pQCD) [1]. As a result they are considered to be well-calibrated probes of small-distance QCD phenomena. When going from $p+p$ to p(or d)+A and $A+A$ collisions, deviations from cross-section scaling with respect to the number of binary $N+N$ collisions provide information on cold nuclear matter effects such as initial state energy loss [2], shadowing [3] and hot nuclear matter effects such as in-medium energy loss [4], increasing importance of production via recombination [5], and modifications to the QCD vacuum [6].

Production of ω mesons at high-p_T is especially interesting. The ω and π^0 are vector and pseudoscalar mesons, respectively. The ω/π^0 ratio carries information about probabilities of corresponding spin states to be produced in hadronization. Furthermore, ω mesons can be used as a probe of the nuclear medium since a significant fraction of them produced in $A+A$ or $p(d)+A$ collisions will decay inside the produced medium ($c\tau = 23.8$ fm) possibly leading to changes of the mass and/or width of the ω with respect to their values in vacuum.

The PHENIX [7] experiment at RHIC has a unique capability to measure both neutral and charged products of $A+A$ and $p+p$ collisions at very high event rates. The two central arm spectrometers each cover 90° in azimuth and ± 0.35 in pseudorapidity. The electromagnetic calorimeter (EMCal), with energy resolution $\sigma/E = 8.1\%/\sqrt{E(\mathrm{GeV})} \oplus 2.1\%$, is used to reconstruct γ's and π^0's. For charged-particle reconstruction two layers of pad chambers provide 3D pattern recognition and fake track rejection, and a drift chamber gives momentum resolution $\sigma/p_\mathrm{T} = 0.7\%\sqrt{p_\mathrm{T}(\mathrm{GeV}/c)} \oplus 1.1\%$. Beam-beam counters (BBC) are used to provide minimum bias trigger and to determine the collision vertex. The minimum bias trigger cross sections measured by the BBC are 23.0 ± 2.2 mb in $p+p$ [8] and 1.99 ± 0.10 b in $d+$Au [9] collisions. In $d+$Au collisions the BBC are also used to separate events into centrality classes as explained in Ref. [10]. High p_T online triggers are implemented by adding together amplitudes in 4×4 adjacent EMCal towers and comparing them to a threshold of 1.4 GeV in $p+p$ and 2.4 GeV in $d+$Au. The trigger could be fired by one or more photons coming from ω-decay final states, including 3γ or $2\pi 2\gamma$.

The data was collected by the PHENIX experiment during RHIC Run3. After selecting good runs and cutting on the collision vertex ($|z| < 30$ cm) we analyzed approximately 4.6×10^7 and 2.1×10^7 high p_T trigger events, corresponding to a total integrated luminosity of 0.22 pb^{-1} and 1.5 nb^{-1} in the $p+p$ and $d+$Au collision systems, respectively.

Although ω mesons are relatively abundant in high-energy hadronic collisions ($\omega/\pi^0 \approx 1$ at high p_T), their measurement is challenging due to the multiparticle final states of the main decay channels and the combinatorial background associated with their reconstruction.

The procedure used to measure $\omega \to \pi^0\pi^+\pi^-$ is the same as used to measure $\eta \to \pi^0\pi^+\pi^-$ [10]. In case of ω one needs to account for a wider peak and different phase-space density of the three-body decay [11,12]. The analysis procedure for the photonic decay mode, $\omega \to \pi^0\gamma \to 3\gamma$, is very similar to earlier PHENIX measurements of other mesons with photonic decay modes, $\pi^0, \eta \to 2\gamma$ [8,13,14]. For both ω-decay modes studied the first step is to reconstruct π^0 candidates by combining photon pairs and applying a p_T-dependent cut around the mass of the π^0. The root-mean-square of the π^0 peak varies with p_T from 8 to 13 MeV/c^2. Candidates (which include combinatorial background) are combined with a third photon for $\omega \to \pi^0\gamma$ or with two unidentified charged tracks (assumed to be π mesons) for $\omega \to \pi^0\pi^+\pi^-$. Raw yields are extracted by fitting the p_T slices of the invariant mass distribution as in the insert panel in Fig. 1. The signal to background ratio (S/B) of $\pi^0\pi^+\pi^-$ decay channel is 1:7 at low p_T and grows with p_T to 1:1 in $p+p$ collisions. In $d+$Au collisions it starts at 1:20 and grows with p_T to 1:2. For the $\pi^0\gamma$ channel S/B is 1.5–2 times worse. Corrections for acceptance, trigger efficiency, and analysis cuts are described in detail in Ref. [10]. Further details about the analysis procedures can be found in Ref. [15].

We classify systematic error sources as type A (point-to-point uncorrelated, which can move each point independently), type B (point-to-point correlated, which can move points coherently, but potentially by different relative amounts), and type C (global, which move all points by the same relative amount). These errors are summarized in Table I for the different decay modes and collision systems. Major contributors include signal extraction (type A), online high-p_T trigger efficiency (type B) and the total cross-section measurement (type C). The uncertainty on the signal extraction, which is the dominant source of systematic error, is relatively large due to the fact that correlations in the triggered sample rendered background subtraction via event mixing impossible, and therefore the unknown shape of the underlying background had to be accounted for in the peak fit. This error is estimated based on variation of analysis cuts and fitting procedures [10].

Figure 1 shows the invariant cross sections for ω production in $p+p$, minimum bias $d+$Au, and central (0–20%) $d+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV, as a function of p_T. The p_T range ($2.5 < p_T < 9.25$ GeV/c) is limited by statistics at high p_T and by decreasing detector acceptance and trigger efficiency at low p_T. The results for the two decay modes, which involve different kinematics, detector acceptance, and efficiency corrections, agree very well.

Figure 2 shows the results for the ratio of vector to pseudoscalar meson production (ω/π^0) in $d+$Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. For the denominator we

TABLE I. Systematic errors for the ω production cross section for the two decay channels and the two collision systems analyzed. Error types are described in the text. Values with a range indicate variation of the systematic error over the p_T range of the measurement.

Type	$\omega \to \pi^0\pi^+\pi^-$		$\omega \to \pi^0\gamma$	
	$p+p$	$d+$Au	$p+p$	$d+$Au
A	7–20%	10–15%	25–40%	10%
B	8–10%	11–14%	5.8–9.2%	7.4–11%
C	11%	9.4%	13%	11%

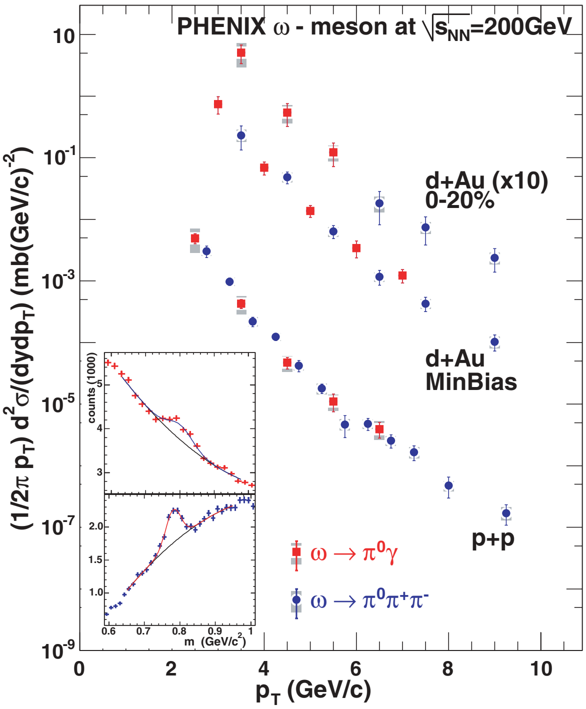

FIG. 1. (Color online) Invariant cross section of ω production in $p+p$ and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured in $\omega \to \pi^0\pi^+\pi^-$ and $\omega \to \pi^0\gamma$ decay channels. Bars and boxes represent statistical and systematic errors, respectively. Fits to invariant mass distributions of (top) $\pi^0\gamma$ and (bottom) $\pi^0\pi^+\pi^-$ are shown in the insert.

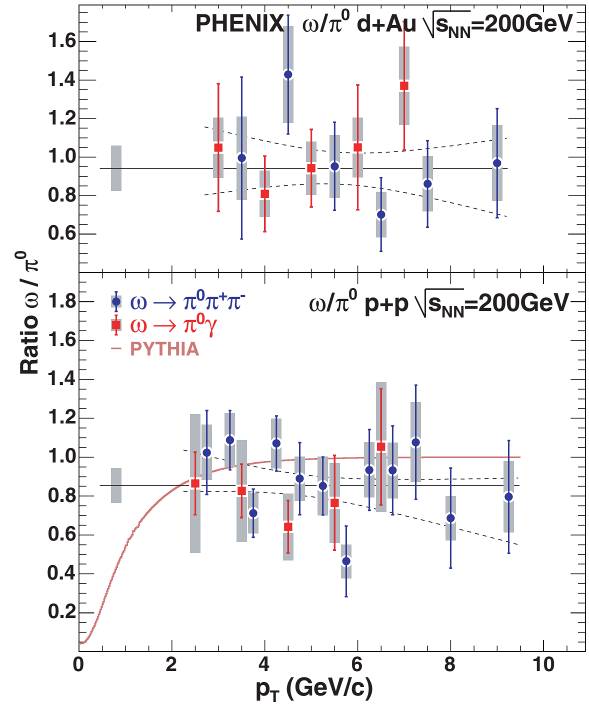

FIG. 2. (Color online) Measured ω/π^0 vs p_T in (upper panel) d+Au and (lower panel) $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Straight lines show fits to a constant for each collision system. The boxes at the left edge of the constant fit lines show the systematic error on the data averaged over p_T. Dashed lines show values within 1σ of the best linear fits to the data. The PYTHIA prediction [17] for $p+p$ collisions at $\sqrt{s} = 200$ GeV is shown with a solid curve in the bottom panel.

use inclusive π^0 yields measured by PHENIX [8,16]. The ratios in both systems are consistent with no p_T dependence over the measured range. Fits to a constant yield $\omega/\pi^0 = 0.85 \pm 0.05^{\text{stat}} \pm 0.09^{\text{sys}}$ and $0.94 \pm 0.08^{\text{stat}} \pm 0.12^{\text{sys}}$, in $p+p$ and d+Au collisions, respectively. Fits assuming linear p_T dependence have slopes consistent with zero. Figure 2 also shows that for $p_T > 3$ GeV/c PYTHIA [17] predicts constant behavior for the ω/π^0 ratio.

The R-806 experiment measured ω/π^0 in $p+p$ collisions at $\sqrt{s} = 62$ GeV [18] and found this ratio to be 0.87 ± 0.17 over $3.5 < p_T < 7$ GeV/c. The E706 experiment measured ω/π^0 in π^-+Be collisions at $\sqrt{s_{\pi N}} = 31$ GeV [19] and found values consistent with the results presented in this Rapid Communication. The ω/π^0 ratios measured in hadronic interactions by three experiments at three different energies between 31 and 200 GeV, are the same within the errors.

Several LEP experiments [20–22] have measured ω production in $e^+ + e^-$ collisions at $\sqrt{s} = 91.2$ GeV and presented results as a function of $x_p = 2p_\omega/\sqrt{s}$. This is not a well-defined quantity in hadronic interactions. However, one can compare the ω/π^0 ratio at large values of p_T and x_p. Following the procedure for handling LEP data described in Ref. [10] one finds that for $x_p > 0.5$, the largest value for which statistically significant LEP data is available, the ratio has grown to approximately 0.7, close to the measurements in hadronic interactions.

Figure 3 shows the nuclear modification factor R_{dA}^{ω}, defined as the ratio between the ω meson yields in d+Au and $p+p$ interactions scaled by the number of binary collisions in d+Au, for minimum bias and central (0–20%) d+Au events. The precise definition of R_{dA} and the procedure to determine centrality in d+Au is given in sections IV.B and III.C in Ref. [10]. We find R_{dA}^{ω} to be $1.03 \pm 0.12^{\text{stat}} \pm 0.21^{\text{sys}}$ for minimum bias and $0.83\pm0.21^{\text{stat}}\pm0.17^{\text{sys}}$ for central events, independent of p_T. R_{dA} values for two other neutral mesons (π^0 and η) measured by PHENIX [10,16] are also shown in Fig. 3. In all cases PHENIX observes that R_{dA} is close to one for $p_T > 2$ GeV/c and flat out to the highest p_T. Similar behavior is seen in preliminary analyses of K and ϕ mesons [15,23].

Recent publications suggest that modifications to the ω mass can be observed even in cold matter by studying not only the electron decay channel [24,25], but also hadronic channels [26]. For the hadronic decay modes presented here PHENIX lacks acceptance at low p_T where the effect is expected to be the most prominent. However, we have excellent mass resolution (20–25 MeV/c^2) for the mixed neutral-charged particle decay mode. Figure 4 shows extracted values for the ω mass as a function of p_T. In the p_T range of the measurement we observe no modification of the ω mass in either collision system we measure. For $p_T > 3$ GeV/c the mass of the ω meson in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV is consistent with the PDG [27] value within 7 MeV/c^2 at the 95% confidence level.

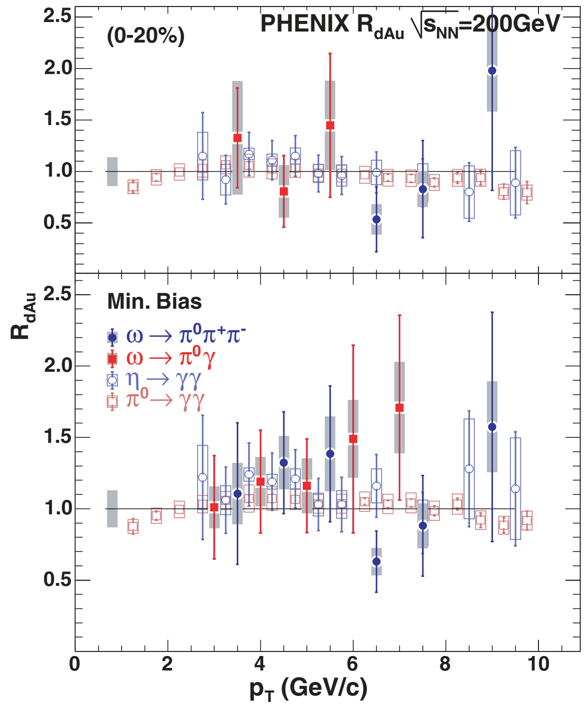

FIG. 3. (Color online) Measured R_{dA} vs p_T for neutral mesons in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for (upper panel) 0–20% central and (lower panel) minimum bias. Values for π^0's and η's are from [10,16]. For reference a line is plotted at $R_{dA} = 1$. The scaling systematic error is shown as a box on the left.

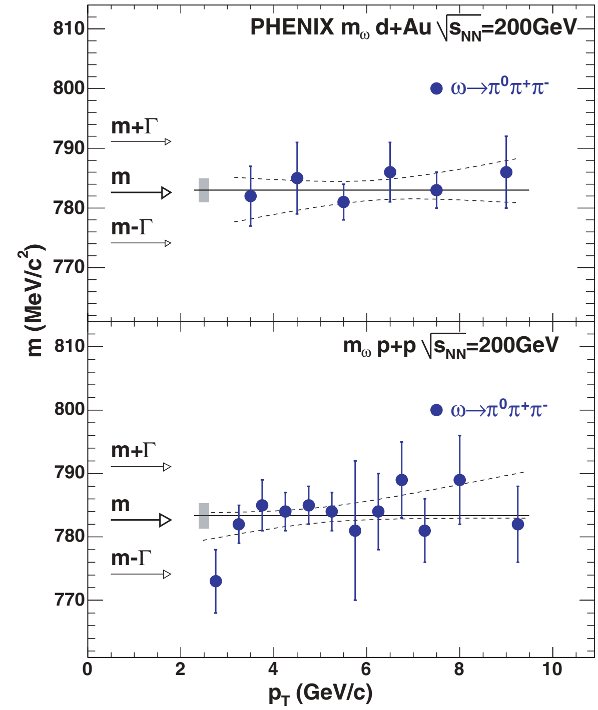

FIG. 4. (Color online) Reconstructed ω mass measured in the $\pi^0\pi^+\pi^-$ decay channel vs p_T in d+Au (upper panel) and p+p (lower panel) collisions at $\sqrt{s_{NN}} = 200$ GeV. Error bars show statistical errors. Straight lines show fits of the data to a constant. Dashed lines show values within 1σ of the best linear fit to the data. The systematic error on the fit values are shown with boxes on the left. PDG values for ω meson mass (m) and width (Γ) are shown with arrows on the left [27].

In summary we have presented the first measurement of ω production in p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The production cross section is measured in two different decay modes with consistent results. The ω/π^0 ratio in p+p collisions is found to be $0.85 \pm 0.05^{\text{stat}} \pm 0.09^{\text{sys}}$ and $0.94 \pm 0.08^{\text{stat}} \pm 0.12^{\text{sys}}$ in d+Au over the measured p_T range. This agrees with previous measurements in hadronic collisions at lower $\sqrt{s}$. The nuclear modification factor for ω production in d+Au collisions is consistent with 1 and p_T independent for $p_T > 2$ GeV/c, consistent with other meson measurements. No modifications to the ω mass were observed in p+p or d+Au collisions. In p+p collisions the mass is consistent with the PDG [27] value within 7 MeV/c^2 at the 95% confidence level. The ω meson is also interesting as a probe of the hot nuclear medium created in A+A collisions. This measurement will serve as an excellent baseline for measurements of ω production in A+A in various decay channels.

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