# Forward/backward $J/\psi \to \mu\mu$ production in Cu+Au collisions at PHENIX

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**Abstract.** RHIC is a versatile machine which has the unique capability to collide different nuclei. One new system recently explored is that of Cu on Au at 200 GeV. One of the first PHENIX measurements made in these collisions was that of forward and backward $J/\psi$ production, where the production mechanism for $J/\psi$ is believed to be dominated by gluon-fusion interactions. Resultant yields from such interactions can be modified in both cold and hot nuclear matter, where the asymmetric nature of the initial state of this collision system may give rise to a systematic difference in forward and backward particle production. In these proceedings, we present our latest studies and compare the resulting distributions to those from earlier heavy-ion collision systems.

## 1. Introduction

During the 2012 RHIC run, the flexibility of the RHIC accelerator was enacted to collide ions of asymmetric size (Cu on Au), allowing the exploration of the unique phase space created in such collisions. For very central collisions, the smaller radius Cu is entirely swallowed by the larger gold nucleus. For off-center (mid peripheral) collisions, the differing radii form naturally odd harmonics along with the expected even harmoincs ($v_2$) which occur in symmetric systems. In *core* and *corona* type models, these Cu+Au collisions lead to a large left/right asymmetry (largest corona on the Au-side). Aside from the transverse asymmetries, a longitudinal asymmetry exists in terms of the forward/backward momenta. The larger Au nucleus, for a given collision, contributes more participants than the Cu nucleus, which may play a role in forward (Cu-going) and backward (Au-going) particle production. The previous asymmetric system collided ($d$+Au) probed the role of cold nuclear matter, particle production in the absence of the hot, dense Quark-Gluon Plasma (QGP). For this new system, QGP effects are very much at the fore in terms of particle production and modification.

For this new type of collision system, PHENIX earmarked several analyses for fast-track evaluation of the collision dynamics. The soft sector focused on the azimuthal dependence on particle production, see [1], whereas the hard sector was studied via the measurement of forward/backward $J/\psi$ yields. The production of $J/\psi$ is a hard collision product and is dominated by gluon fusion. It was theorized [2] that this loosely bound charmonium state may not survive the hot, dense matter created in the collision of large nuclei, resulting in a suppression relative to the expected production from $p$+$p$ collisions. Observance of this suppression was heralded as an initial signature for QGP formation. However, in $d$+Au collisions, it is observed that, even in the absence of the hot, dense QGP, the yields of $J/\psi$ are significantly modified [3].

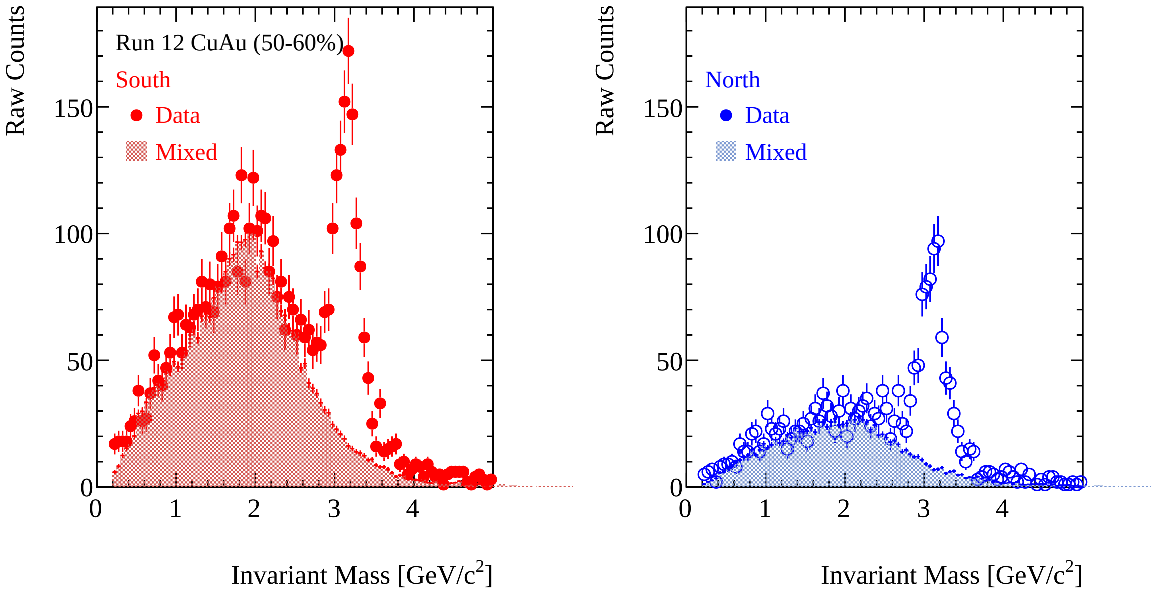


**Figure 1.** Raw di-$\mu$ spectrum from mid-peripheral (50-60% central) Cu+Au collisions. The left panel shows raw signal (including combinatorial background) data from the South-arm (Au-going) muon-candidate pairs. The left panel shows pairs from the North (Cu-going) spectrometer. The shaded area represents the (combinatorial) background, determined from event-mixing (see text).

It is then difficult to disentangle the complex interplay between cold ($d$+Au) and hot (A+A) collisional modification simply with two systems. Measurements of the modification in a smaller system, Cu+Cu [4], are found to be commensurate with the Au+Au system, leading to the conclusion that further variables are needed to disentangle all the effects. The Cu+Au system becomes a favorable source owing to its natural asymmetries in both the forward/backward and side/side regions.

There are an array of effects in both hot and cold nuclear matter which can contribute to the modification of the spectra. In cold nuclear matter (often referred to as CNM), nuclear modification to the parton distribution functions lead to a suppression of low-$x$ gluons (known as the "shadowing region") and a compensatory enhancement of large-$x$ gluons ("anti-shadowing region"). Further effects also measured in light-meson and baryon production include the Cronin effect, due to multiple partonic scatterings and energy loss/break-up in the nucleus. Once the initial-state (CNM) modification has occurred, the hot nuclear matter (or final state effects) further change the measured yields of $J/\psi$s, predominantly due to color screening.

The current interpretation of the results from RHIC, and the LHC, require both cold- and hot-nuclear matter effects, although the true relative contribution is difficult to disentangle. Colliding different systems, at the same energy, provides additional insight into the relative importance of such mechanisms.

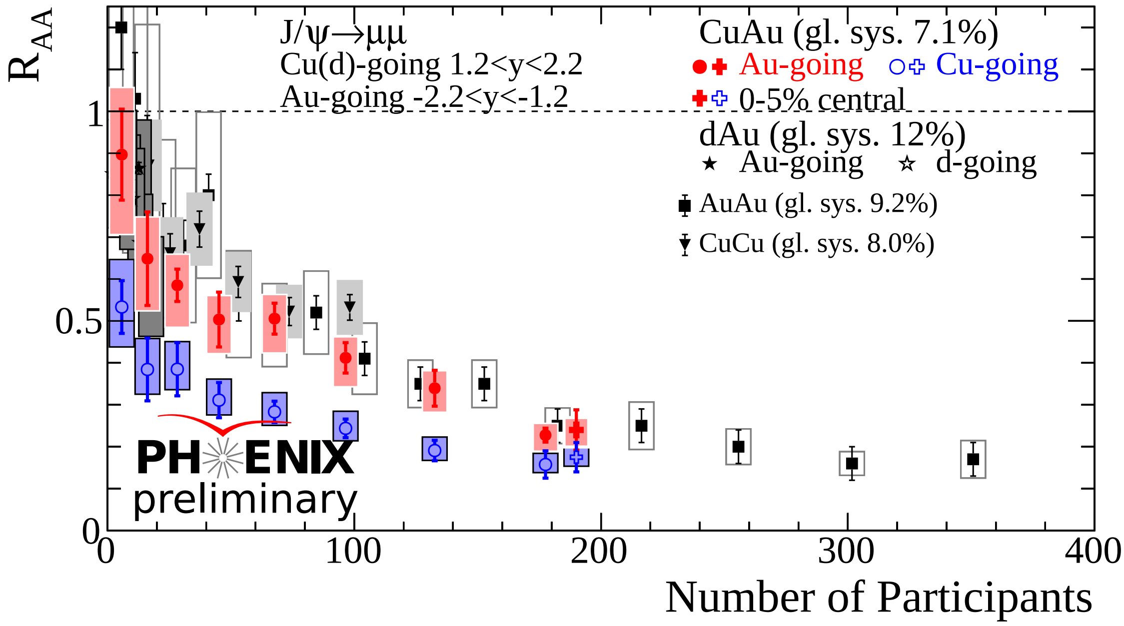


**Figure 2.** Comparison of the nuclear modification factor found in Cu+Au collisions (red and blue) to Au+Au (square symbols), Cu+Cu (triangles), and $d$+Au (stars) data. The red depict the $R_{AA}$ in the Au-going direction, the blue show the Cu-going data. The cross-symbol shows the top 5% of collision cross-section in which the Cu-nucleus is completed swallowed by the Au-nucleus.

## 2. $J/\psi$ measurement

The PHENIX experiment has three spectrometers for measuring charmonia: the central arm spectrometer with tracking and electromagnetic calorimetery, not discussed in these proceedings, and forward (north) and backward (south) muon spectrometers. These muon spectrometers are similarly constructed with a tracker inside of a magnetic field, followed by a muon identifier. The muon identifier is several layers of iron, inter-spaced with Iorocci tubes for read-out. A particle is identified as a muon if it completely penetrates the muon identifier. To reduce the number of hadrons into the muon-tracker, additional hadronic absorber material was added after RHIC Run 9. Hadrons which are identified as muons are strongly suppressed and contribute to the combinatoric background.

Further reduction of the non-muon backgrounds is made through several track-quality residual variables. The reconstruction of tracks in the muon system is broken into two broad pieces, a momentum-determining track in the tracker and a muon-identifying road in the muon-identifier. From the tracker, the track-$\chi^2$ measures the closeness of the found track to that expected in the spectrometer assuming no multiple-scattering. Roads formed in the muon-identifier can be up to four planes "deep"; hadronic candidates are more likely to fail to penetrate through all planes and therefore requiring "deep" roads signals a likely muon candidate. Matching the road and track portions also reduces hadronic backgrounds as the larger multiple scattering for hadrons causes a mis-match in joining the road, both in actual spatial position and the slope between the two pieces.

For the first time in heavy-ion collisions, the data-rate from RHIC exceeded the PHENIX ability to collect all the data. All muon-arm triggers were retained, as well as other rare triggers

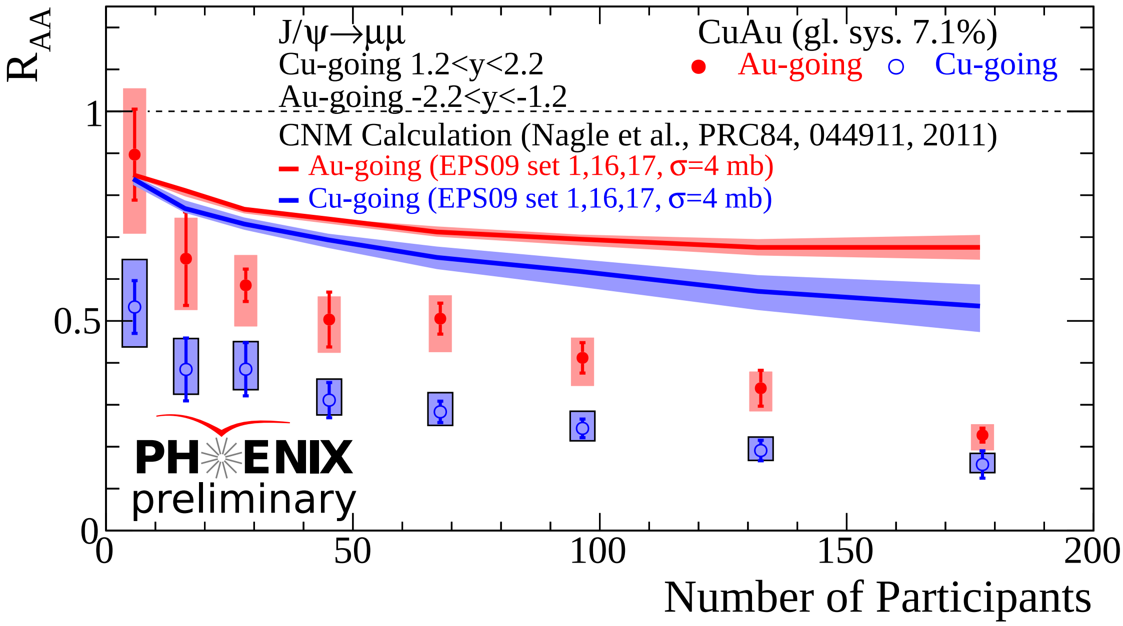


**Figure 3.** Comparison between the nuclear modification factor found in Cu+Au collisions (red and blue symbols) and a model (lines) which describes cold-nuclear effects, see text for a description. The red (blue) lines represent this models cold nuclear matter component of the Au- (Cu-)going data.

for other analyses, however only a fraction of minimum bias data were collected. The dataset analyzed comprises of about 12 billion minimum bias events sampled, from which over 25 K $J/\psi$s were found.

The data were divided into ten centrality classes, based on the energy signals in the Beam-Beam-Counters (BBCs). In addition to the requirements of track quality, the event vertex was required to be within 10 cm of the nominal interaction position in PHENIX.

Figure 1 shows the measured dimuon-pairs, after the subtraction of the non-correlated background. The background subtraction was formed via a mixing of candidate tracks from two separate events, which necessarily breaks all correlations. The signal peak is fit using a double-Gaussian form (which is found to best describe the lower-background $p+p$ data) to extract the final yields. The raw yields are corrected for detector inefficiencies via the embedding of simulated tracks into real minimum bias events.

## 3. Results

To show the relative suppression of the $A+B$ data, the nuclear modification factor, $R_{AB}$ was formed as in Eqn. 1. This ratio compares the yield in $A+B$ collisions to that expected from $p+p$ collisions, where the expected scaling factor between the two systems is the number of binary collisions ($N_{coll}$).

$$R_{AB} = \frac{1}{N_{coll}} \frac{Yield\ in\ A+B}{Yield\ in\ p+p} \tag{1}$$

The measured $R_{AA}$ in Cu+Au collisions are shown in Fig. 2, and compared to $d$+Au, Cu+Cu,

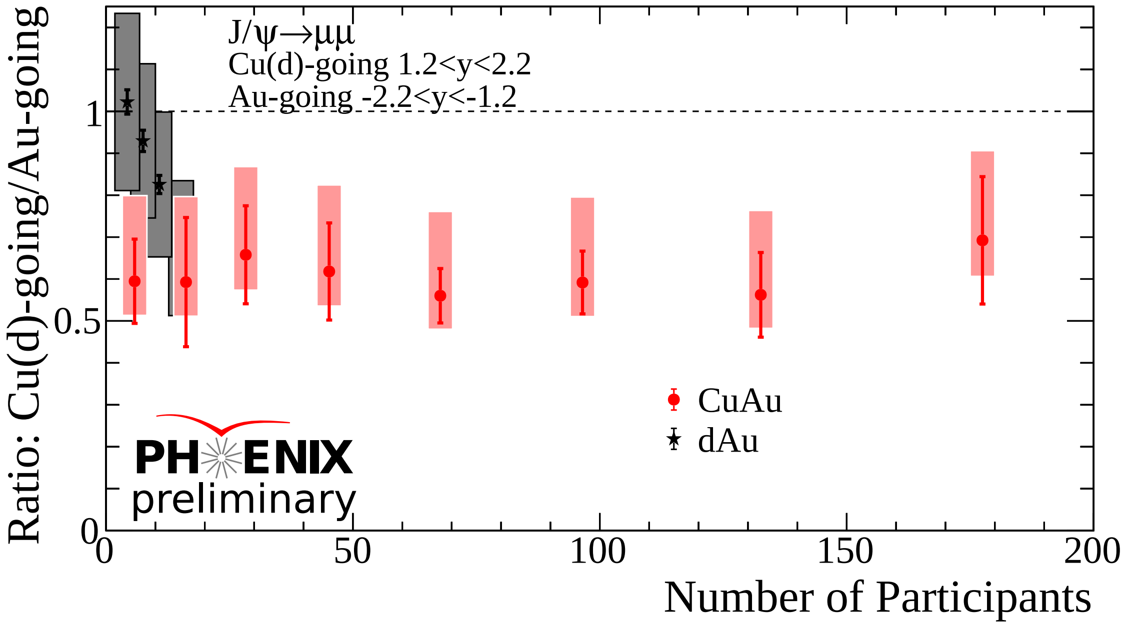


**Figure 4.** Ratio of the $J/\psi$ yield from forward (Cu-going) to backward (Au-going) rapidities. The grey stars represent the same ratio in $d$+Au collisions.

and Au+Au collision data. Here, the red symbols depict the Au-going (backward) data, where the low-$x$ gluon comes from the Cu-nucleus, and the blue show the Cu-going (forward) data. Cu+Au data are presented in 10% centrality slices (circles), except for the most central point, which shows a 0-5% central bin and represents events where the Cu nucleus is wholly swallowed by the Au nucleus. As is evident, the backward nuclear modification is found to be the same as for Cu+Cu and Au+Au data, whereas a stronger modification of the forward-going $J/\psi$s is seen.

The role of cold-nuclear matter was explored using a model of the data where the initial parton distributions are modified using the EPS09 data sets [6], coupled with a nuclear break-up cross-section of the $J/\psi$. This model [7] was tuned to the $d$+Au data where a break-up cross-section of 4 mb was found. Assuming that this model can be used in $A+B$ collisions as an estimator of the initial state modification, the same break-up cross-section was applied to the Cu+Au system. The result is shown in Fig. 3. A difference between forward and backward $J/\psi$ is expected already due to CNM. The additional suppression, assuming this model represents the full underlying suppression, must be due to final-state effects of the QGP.

To further study this, Fig. 4, shows the ratio of $J/\psi$ yields in the forward (Cu-going) region to the backward (Au-going) region. This ratio is surprisingly found to be independent of centrality and provides a challenge to theories trying to model the data.

## 4. Summary

In summary, we have measured the number of $J/\psi$s in the Cu+Au collision system and compared the forward (Cu-going) and backward (Au-going) yields. The production relative to that expected from $p$+$p$ collisions is found to be suppressed, similarly to Au+Au and Cu+Cu data. The suppression found in the forward direction is larger than that in the backward direction.

Using a model of cold nuclear matter effects, which described well the $d$+Au data, shows an expected difference forward and backward, although this does not account for all the suppression observed; the remainder due, presumably, to QGP-effects.

## References

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