Low-mass dielectron production at RHIC using the PHENIX detector.

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Abstract

A hadron blind detector (HBD) has been constructed and installed in the PHENIX experiment. The detector is presently undergoing commissioning and preparation for the forthcoming RHIC run. The HBD will allow the measurement of electron-positron pairs from the decay of the light vector mesons ($\rho$, $\omega$ and $\phi$) and the low-mass pair continuum in $Au + Au$ collisions at energies up to $\sqrt{s_{NN}} = 200$ GeV.

In this report I give an update on the construction, assembly and commissioning of the final HBD. I describe the detailed Monte Carlo simulation based on GEANT that is being developed for the HBD and present results gained in the full-scale HBD prototype beam test. I also present results of the analysis of the $\phi$ meson production in the $K^+K^-$ decay channel in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

1 Introduction

The properties of the new state of matter discovered at the Relativistic Heavy Ion Collider (RHIC) can be investigated by studying the production of low-mass dielectron pairs. An enhancement of low-mass dileptons over the hadronic cocktail was seen in Pb+Au collisions at 158 AGeV by CERES [1, 2, 3] and in In+In collisions at 158 AGeV by NA60 [4, 5] at CERN SPS. This enhancement has been interpreted as thermal radiation from a high density hadron gas, emitted through pion annihilation mediated by a $\rho$ meson which might undergo in-medium modification [6, 7]. Theoretical calculations show that the enhancement should also persist at RHIC energies [8]. PHENIX is one out of four experiments (BRAHMS, PHENIX, PHOBOS and STAR) associated with the heavy-ion program at the RHIC [9]. PHENIX is a large multipurpose detector optimized to measure electromagnetic probes as well as hadrons [10]. However, the measurement of low-mass electron pairs is practically impossible due to a very low signal/background ratio in the mass range of interest. To extend the capability for the measurement of low-mass dielectron pairs in PHENIX, a Hadron Blind Detector (HBD) has been developed [12, 13].

2 The PHENIX detector

The layout of the PHENIX detector is shown in Fig. 1. The PHENIX detector comprises four spectrometer arms. The two central arms (East and West) are instrumented to detect electrons, photons and charged hadrons. They cover $|\eta| < 0.35$ in rapidity and $90^\circ$ in azimuthal angle. The two forward arms (North and South) are instrumented to detect muons. They have full azimuthal coverage for $1.2 < |\eta| < 2.4$. There are three magnets in PHENIX: the Central Magnet provides an axial magnetic field for the Central Arms while the Muon Magnets produce a radial field for the Muon Arms. A set of inner coils in the
central magnet, installed for Run-4, allows to cancel the magnetic field in the vertex region up to a radial distance of \( \sim 60 \) cm. The Central arms contain a tracking system consisting of Drift Chambers (DC) and Pad Chambers (PC) \([11]\). There are two types of Electro-Magnetic Calorimeters (EMCal), one made of lead-glass (PbGl) and the other made of lead and scintillator material (PbSc), for measuring the energy of electrons and photons. There is also a Ring-Imaging Čerenkov Counter (RICH) for electron identification and a Time-Of-Flight detector (TOF) and Aerogel Čerenkov Counter (ACC) for charged hadron identification. These subsystems, together with the initial time information measured in the Beam-Beam Counters (BBC) are capable to identify hadrons, electrons and photons over a large momentum range. The Zero Degree Calorimeters (ZDC) and the BBC are dedicated subsystems that determine the collision vertex and event centrality and also provide the minimum bias interaction trigger.

### 3 Development of the HBD for PHENIX

#### 3.1 The HBD concept

The HBD is a windowless Čerenkov detector operated with pure CF\(_4\): a 50 cm long radiator connected to a triple GEM detector \([14]\) (see Fig. 2) with a cesium iodide (CsI) film evaporated on the top surface of the first GEM in a proximity focus configuration. The avalanche charge from the GEM stack is read out in a pad plane with hexagonal pads having a size similar to the size of the Čerenkov blob. The HBD’s primary purpose is to tag electrons originating from \(\gamma\) conversions and \(\pi^0\) Dalitz decays in the field free region surrounding the collision vertex. Since the opening angle of the pairs from these sources is small as compared to those from light vector mesons and it is preserved in the absence of magnetic field, they can be easily identified in the HBD, based on the blob amplitude.
which will be twice the blob amplitude produced by a single electron and the blob size which will be considerably large than for single electron. A significant R&D program was carried out to develop the various components of this detector that has now been completed [15, 16, 17].

3.2 Construction

Vessel construction The HBD vessel was designed and built by our group at the Weizmann Institute. The HBD has two identical arms (see exploded view of one arm in Fig. 3), each one covering 135° in azimuth and $|\eta| < 0.45$. This larger acceptance as compared to the one of the central arms provides a generous veto area helping to reject close pairs in which one of the tracks is outside of the PHENIX acceptance [13]. Each arm is formed by ten panels glued together and to a pair of thin FR4 frames that provide rigidity to the detector vessel and two side panels, attached to the FR4 frames with plastic screws. The panels consist of a 19 mm thick honeycomb core (a 13 mm thick honeycomb is used for the side panels) and a pair of 0.25 mm thick FR4 sheets glued to it from both sides. The detector entrance window is made of 127 µm thick mylar foil coated with 100 nm aluminum. The window is placed between two FR4 supports bolted to each other with an 0-ring seal allowing easy replacement of the window if needed. One of the window supports is glued into the vessel. Among the eight smaller back panels the central six are equipped with two triple GEM photon detector modules on the inside, and connected to the Front End Electronics (FEE) board attached to the outer surface of the detector. The other two back panels are used for the detector services: gas in/out, high voltage distribution circuits, high voltage feed-through, UV transparent windows. The detector anode is made of 50 µm thick Kapton foil with 1152 hexagonal pads printed on one side and short signal traces on the other side (pads and traces are made of 5 µm thick copper), in one single piece ($140 \times 63 \ cm^2$). It also serves as an additional gas seal. Plated through holes connect the pads to the signal traces.

Special tooling and jigs were developed and used during all phases of the construction to meet the tight mechanical tolerance of all subcomponents of the order of 0.1 mm and to achieve 0.5 mm clearance between adjacent photon detector modules. No mechanical problems were found during the vessel construction and detector assembly.

Special attention was paid to minimization of the material budget, to keep the multiple scattering to a minimum and to reduce the amount of conversions in the PHENIX central arm acceptance. With this design each box weights $\sim 5$ kg. Adding all accessories results in a total weight of less then 10 kg. The total radiation length within the central arm acceptance is calculated to be 3.34%. The contribution of the 50 cm CF$_4$ gas is 0.54%, the vessel and the electronics constitute 0.92% and 1.88%, respectively.

One important requirement was the gas tightness of the box. Oxygen and water vapour
Figure 2: Triple GEM detector configuration in the reverse bias mode (left) and in the forward bias mode (right).

absorb Čerenkov photons on their way through the radiator reducing the overall photoelectron yield. Every 10 ppm of either oxygen or water result in a loss of approximately 1 photoelectron in the 50 cm radiator length. Also, water speeds up the CsI photo-cathodes aging rate. The measured leak rate for both arms of the detector was at the level of 0.1 cc/min, which is a very good result for a total volume of 311 liters.

**Triple GEM detectors** Each triple GEM module consists of one gold plated GEM with a cesium iodide (CsI) film evaporated on its top surface and two standard GEMs below. A 90% transparent stainless steel mesh 1.5 mm above the stack can be biased by a positive or negative voltage with respect to the upper GEM. Depending on the drift field direction, charge produced by ionizing particles in the gap between the mesh and the GEM stack can either be collected by the upper GEM (forward bias), or repelled from it (reverse bias). The mesh and the three GEMs are mounted on FR4 fiberglass frames. The frames have a width of 5 mm and a thickness of 1.5 mm that defines the inter-gap distance. Since the fiberglass frame is narrow and rather flexible, special tooling was developed to stretch the GEM foils and mesh and glue them onto the frames. To prevent sagitta of the mesh and foils the frames have a cross-like 0.3 mm wide support. The three GEM foils and the mesh are stacked together and attached to the detector vessel by 8 pins. The pins are located at the corners and the middle of the frame and maintain the frames undeformed under tension. With this GEM support design, the resulting total dead area within the central arm acceptance is calculated to be 6%.

All GEMs were produced at CERN. The standard GEM foil 22×27 cm$^2$ in size is made of 50 µm thick Kapton, with 5 µm copper cladding on both sides. The gold plated GEM foil has additional thin layers of nickel and gold on top of the copper layer. The gold coating prevents chemical interaction between CsI and copper, the nickel layer provides good adhesion of the gold layer. The GEMs are chemically pierced with 80 µm holes which are separated 150 µm apart. One of the GEM surfaces is divided into 28 segments
to reduce the capacitance and energy stored in case of discharge.

The GEM foils assembly, test and gain mapping were done at Weizmann Institute. All operations with the GEMs were performed either in a clean room (better than Class 100) or in a stainless steel test box. First, the foils were mechanically stretched on a special stretching device and then, while stretched, they were glued to the FR4 frame with epoxy. When the epoxy was cured, all excesses of Kapton foil were cut out, and a 20 MΩ SMD resistor was soldered to each HV segment. Quality control of the foil (measurement of the leakage current through the GEM) was performed at every step of the GEM preparation before framing, after framing and also after soldering the resistors. GEMs that passed the initial test in the clean room were individually measured up to 520 V in CF₄ atmosphere requiring the leakage current to be below 5 nA. Finally, a gain mapping of the GEMs was done in Ar/CO₂ with a ⁵⁵Fe X-ray source to measure the gas-gain variation across the foil, and the results were stored in a database. The last two tests were done in a stainless steel test box and success of these tests ensured that the GEM holds the necessary operating voltage and provided information about the gas-gain uniformity. Forty eight standard GEMs and twenty four gold plated GEMs combined in triplets in order to give the lowest possible gain variation for all modules were selected to be assembled in the detector. The resulting gain spread was found to be between 5% and 20% in all 24 modules.

**HBD photo-cathodes and electronics**  
The photo-cathodes for the HBD were produced at Stony Brook University [18] using a high vacuum evaporator system. The quantum efficiency of the photo-cathode was measured in situ inside the evaporator over the entire area of the GEM using a remote controlled movable UV light source and current monitor. All the produced photo-cathodes have the quantum efficiency as high as in the R&D. 

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Figure 3: Exploded view of the HBD detector. One side cover is removed for clarity.
3 DEVELOPMENT OF THE HBD FOR PHENIX

The HBD is equipped with hybrid preamps developed by the Instrumentation Division at BNL. This type of preamp produces a differential signal in the range from 0 to ±1 V that is delivered to a receiver and front end module (FEM). The FEM contains a 12 bit, 65 MHz flash-ADC for each channel which digitizes the signal and sends the data via an optical G-Link to the PHENIX data acquisition system. The FEM and all digital electronics were designed and constructed by Nevis Laboratories.

3.3 Commissioning

Both detector arms are now installed and detector commissioning is underway. The HBD gas system is ready, including the CF$_4$ gas recirculation system. The CF$_4$ gas transparency monitor is installed. Several measurements of the relative quantum efficiency of the CsI were performed and did not show any evidence of photo-cathodes degradation. Readout electronics were delivered, and are operational. HBD data can be taken in stand-alone mode or in conjunction with the rest of PHENIX. Pedestal runs are done routinely. In order to reduce the data size of a single event, a zero suppression algorithm is implemented. Pedestal values for every channel can be stored in memory on the receiver board and subtracted from the incoming data. The data from channels with amplitude below a preset threshold then get suppressed from the output data stream. In order for the zero suppression procedure to work properly, it must be assured that the stored pedestal data used for subtraction is very close to the pedestal values at the time of data taking. The test of the zero suppression algorithm and pedestal stability is ongoing. The sigma values of the pedestals give a good estimate of the noise in the HBD readout electronics. The noise level is found to be $\sim 1\sigma$, which corresponds to $\sim 0.37$ primary electrons at a gain of $10^4$ (estimated as the square-root of the variance of the pedestal values over $\sim 10000$ events).

3.4 Status of the HBD software

Much work is ongoing on the software front to address the detector operation, monitoring, data reconstruction:

- HBD Monte-Carlo simulation
- HBD pattern recognition and tracking software
- HBD event display and online monitoring software
- software for the HV power supplies control
- set of applications for the monitoring of HBD HV status

Detector simulation programs are an important tool during the design phase to develop a detector with optimal parameters. When the final detector is taking data the simulations become important for understanding the data. In PHENIX the standard simulation package is called PISA and it is based on the GEANT3 [20] package. The output of the PISA
package gives information about the hits in each subsystem in 3D space. The pattern recognition is done in several stages. First it is done independently in every subsystem capable of stand-alone pattern recognition. In the second stage the hits found in each subsystem are associated to track candidates, defined by the PHENIX tracking detectors (DC, PC1).

The final HBD design has been integrated into PISA, as shown in Fig. 4. Almost every detail is included in the detector description. However, some simplifications are used in the materials which are not active detecting elements or are outside the fiducial PHENIX acceptance. The HBD pattern recognition algorithm and tracking have been implemented into the PHENIX reconstruction software. Now it is undergoing testing and optimization.

Visualization of single events is necessary for online monitoring purposes as well as for fast checking of the validity of the reconstruction software and simulation algorithms. The HBD event display has been developed and is routinely used during the development stage of pattern recognition, clustering and other algorithms. It is also being implemented now in the HBD online monitoring package.

The LeCroy 1458 high voltage mainframe, equipped with six LeCroy 1471N 8-channel units, is used to provide the high voltage to each tipple GEM detector module. The HV control software allows to feed independently each HBD module (operation of group of modules is also possible), to monitor the status of the detector modules in real time and to store a snapshot of the LeCroy parameters for all detector modules in a database. A set of programs to look at the data stored in the HBD high voltage database has been prepared. This allows to monitor and optimize the HV system conditioning process.
3 DEVELOPMENT OF THE HBD FOR PHENIX

3.5 Beam test of the HBD full-scale prototype

A full-scale prototype of the HBD was built to test and optimize the construction procedures. It was made out of the same materials, with size and shape similar to the final detector. The prototype was equipped with one 24×25 cm$^2$ detector module and instrumented with a readout plane and electronics as foreseen for the HBD. The test of the full-scale prototype under beam conditions (200 GeV $p + p$ collisions) was done at Brookhaven National Laboratory during the Run-6 of the RHIC [19]. The prototype was installed in the same location where the West arm of the final HBD is supposed to sit. The magnetic field in the Central arm of PHENIX was switched off during the runs dedicated to HBD studies, except two runs that were taken with the “plus-minus” magnetic field configuration. Also a special trigger was set up to increase the electron sample in the prototype active area. The PHENIX DAQ system was used for data taking, so information from all other subsystems was stored in parallel with information from the HBD. All through the test, the detector was under CF$_4$ flow. The HBD was read out routinely at different voltages across GEM foils without any problem. A set of pulser runs were also taken for calibration to determine pedestal levels of the electronics as well as sigmas of the noise distributions. As can be seen from the left panel of Fig. 5 the noise of the prototype electronics does not follow a Gaussian distribution. The origin of this noise distribution shape is unknown, but it could be due to grounding loops or imperfect shielding of the detector. The problem seems to be solved in the final detector (see right panel of Fig. 5).

![Figure 5](image)

Figure 5: Distribution of the ADC baseline values (one channel) after pedestal subtraction for the prototype (left) and for the final HBD (right). The distributions are fitted with Gaussian function and fits are shown in black.

Prototype data analysis Valid tracks reconstructed in the central arm were confirmed by the matching of the projected and associated hit informations at the EMCal and PC3. Electrons were selected by demanding a minimum energy of the associated cluster in the EMCal ($E > 0.5$ GeV) and at least one associated PMT hit in the RICH. Hadrons were selected by demanding the opposite conditions, namely a maximum energy of the
associated cluster in the EMCal ($E < 0.5$ GeV) and zero associated PMT hits in the RICH. A pad hit with an amplitude greater than $4\sigma$ of its noise distribution if found reasonably close (within $\sim 5$ cm) to the central track projection onto the HBD plane was tagged as the center of the HBD cluster associated to this track. Pads, adjacent to the center of the cluster, were added to this cluster if their amplitude was greater than $2\sigma$ of the noise distribution.

**Results** Charge distribution of clusters produced by particles identified as hadrons measured in forward bias mode (black points) and reverse bias modes (red points) are shown in Fig. 6. The left panel shows charge distributions measured at gain of $\sim 2500$ and the right panel shows the same at gain of $\sim 6600$. The forward bias spectrum is well reproduced by a Landau distribution (shown by a blue line) of the energy loss of a minimum ionizing particle. The reverse bias mode shows a strong suppression of the direct ionization signal, as expected.

Figure 6: Cluster charge distribution for minimum ionizing particles obtained in reverse bias mode (red) and in forward bias mode (black) at gain $\sim 2500$ (right) and gain $\sim 6600$ (left).

Figure 7: Cluster charge distribution (left) and cluster size distribution (right) for identified electrons and hadrons obtained in reverse bias mode.
A comparison of the cluster charge and cluster size distributions produced by hadrons and electrons measured in the reverse bias mode is shown in Fig. 7. The electrons in this analysis are identified by the RICH and EMCal subsystems of PHENIX only. From the distributions in Fig. 7 one sees that hadrons can be effectively rejected by an amplitude cut at around 100 ADC channels together with a size cut requiring more than one pad fired.

4 Data analysis

I have performed studies of the $\phi$ meson production via the $K^+K^-$ decay channel in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV using the Run-4 data. The main goal was to obtain the $\phi$ meson transverse mass distribution, its invariant yield and inverse slope parameters. The steps undertaken in this analysis include detailed data quality assurance studies, tuning of calibration parameters, single particle and particle pair cuts evaluation, combinatorial background estimation, signal extraction, Monte Carlo simulation to correct raw $\phi$ yield for acceptance effects, reconstruction efficiency and multiplicity effects, correction to account for run-by-run detector performance variations and evaluation of systematic errors.

In Run-4, the inner and outer coils were operated in the ++ and −− configurations \cite{21} (both outer and inner coil sets were energized to have fields adding). The final number of analyzed events is 409 M minimum bias triggers, 183 M for the ++ magnetic field configuration and 226 M for the −− case.

The kaons in PHENIX can be identified using the TOF wall and the EMCal (PbSc) detector. The performed analysis is restricted to the kaons identified by the TOF system only. Since there is no way to distinguish kaons from $\phi$ decay from other kaons, all kaon tracks from each event passing the track selection requirements are paired to form the like and unlike-sign invariant mass distributions. The $\phi$ signal thus sits on a large combinatorial background. This background is determined by a mixed event technique in which the kaons ($K^+$ and $K^-$) from one event are combined with the kaons from the next 20 events provided that all events are within the same centrality and vertex classes. The invariant mass distribution for the mixed-event sample constructed in this way reproduces the shape of the combinatorial background. The mixed event spectrum is then normalized to the measured $2\sqrt{N_{++}N_{--}}$ \cite{22}, where $N_{++}$ and $N_{--}$ represent the measured integrals of like sign yields. The measured and normalized mixed unlike minimum bias spectra, and the subtraction of the two for the ++ and for the −− magnetic field configurations are shown in Fig. 8. The $\phi$ meson yield is obtained by summing the bin contents in the mass window $m = 1.008 - 1.032$ GeV/c$^2$. Let us denote $\mathcal{F}G(m,m_t)$ - the invariant mass ($m$) distribution constructed using real pairs for a given $m_T$ bin, $\mathcal{B}G(m,m_t)$ - the
corresponding one for mixed pairs and $\alpha$ the mixed event normalization factor, then the raw $\phi$ yield in a given $m_T$ bin is:

$$N_{\phi}^\text{raw}(m_T) = \int_{1.008}^{1.032} F_G(m, m_T) dm - \alpha \int_{1.008}^{1.032} B G(m, m_T) dm$$  \hspace{1cm} (4.1)

The invariant $\phi$ meson yield in each $m_T$ bin is given by:

$$\frac{1}{2\pi m_T} \frac{d^2N}{dm_T dy} = \frac{N_{\phi}^\text{raw}(m_T) \cdot CF(m_T)}{2\pi m_T \cdot N_{\text{events}} \cdot \varepsilon_{\text{emb}} \cdot \varepsilon_{\text{rbr}} \cdot BR \cdot \Delta m_T},$$  \hspace{1cm} (4.2)

where $CF(m_T)$ is the correction factor to account for detector acceptance and reconstruction efficiency, $\varepsilon_{\text{emb}}$ is the pair embedding efficiency which accounts for the reconstruction losses due to detector occupancy, $N_{\text{events}}$ is the number of analyzed events, $\varepsilon_{\text{rbr}}$ is the efficiency due to variations in the detector performance from run to run, $\Delta m_T$ is the bin size and $BR$ is the $\phi \rightarrow K^+K^-$ branching ratio which is equal to 0.491.

The $CF(m_T)$ was determined using single particle Monte Carlo simulations. About 50 million single $\phi$ mesons were generated with an exponential transverse momentum distribution, decayed into $K^+$ and $K^-$, and then propagated through the PHENIX detector simulation and reconstruction chain. The resulting output was analyzed in exactly the same way as the data and the ratio of the generated $\phi$ yield to the reconstructed one in a given $m_T$ bin gives the $CF(m_T)$ for that $m_T$ bin.

Fig. 9 shows the $\phi$ meson transverse mass spectra in minimum bias and in five cen-
trality bins, 0-10%, 10-20%, 20-40%, 40-60% and 60-94%. For each centrality bin the $dN/dy$ and the inverse slope $T$ are obtained by fitting the invariant transverse mass distribution of the $\phi$ meson yield with the exponential function given by

$$ \frac{1}{2\pi m_T} \frac{d^2N}{dm_T dy} = \frac{dN/dy}{2\pi T (T+M_\phi)} e^{-(m_T-M_\phi)/T}, $$

where $M_\phi$ is the PDG value of the $\phi$ mesons’ mass, 1.019 GeV/$c^2$. The results are summarized in Table 1.

The preliminary results of this analysis, combined with the results of $\phi \to K^+ K^-$ analysis done at Vanderbilt University, were presented at the Quark Matter 2005 conference [23].

Table 1: Summary of $dN/dy$ and $T$ for minimum bias and different centralities.

<table>
<thead>
<tr>
<th></th>
<th>$dN/dy$</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB (0-94%)</td>
<td>0.907 ± 0.070 (stat) ± 0.145 (syst)</td>
<td>0.396 ± 0.009 (stat) ± 0.024 (syst)</td>
</tr>
<tr>
<td>0 - 10%</td>
<td>3.235 ± 0.503 (stat) ± 0.614 (syst)</td>
<td>0.384 ± 0.016 (stat) ± 0.035 (syst)</td>
</tr>
<tr>
<td>10 - 20%</td>
<td>2.153 ± 0.302 (stat) ± 0.344 (syst)</td>
<td>0.394 ± 0.015 (stat) ± 0.026 (syst)</td>
</tr>
<tr>
<td>20 - 40%</td>
<td>1.105 ± 0.093 (stat) ± 0.154 (syst)</td>
<td>0.414 ± 0.009 (stat) ± 0.017 (syst)</td>
</tr>
<tr>
<td>40 - 60%</td>
<td>0.506 ± 0.052 (stat) ± 0.076 (syst)</td>
<td>0.391 ± 0.012 (stat) ± 0.012 (syst)</td>
</tr>
<tr>
<td>60 - 94%</td>
<td>0.077 ± 0.013 (stat) ± 0.010 (syst)</td>
<td>0.377 ± 0.020 (stat) ± 0.008 (syst)</td>
</tr>
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</table>

Figure 9: The invariant $m_T$ spectra of the $\phi$ meson in minimum bias events and in five different centrality bins.

5 Plans

I plan to continue my work on the HBD commissioning and HBD related software development including analysis of the data taking during the forthcoming HBD commissioning
run. I will also continue the studies of the $\phi$ meson production in the $K^+ K^-$ decay channel in $Au + Au$ and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

References


[20] GEANT, Detector Description and Simulation Tool, CERN Program Library Long Writeup W5013.

