Proposal for a Hadron Blind Detector for PHENIX

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A Hadron Blind Detector (HBD) is proposed as upgrade of the PHENIX detector at RHIC, BNL. The HBD will allow the measurement of low-mass $e^+e^-$ pairs from the decay of the light vector mesons $\rho$, $\omega$, $\phi$ and the low-mass continuum in Au-Au collisions at energies up to $\sqrt{s_{NN}} = 200$ GeV. From MC simulations and general considerations, the HBD has to identify electrons with very high efficiency (> 90%), double hit recognition better than 90%, moderate pion rejection factor of $\sim 200$ and radiation budget of the order of 1% of a radiation length. The first choice under study is a windowless Cherenkov detector, operated with pure $CF_4$, in a special proximity focus configuration with a CsI photocathode and a multistage GEM amplification element.

1. Introduction

The PHENIX experiment at RHIC, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, is specially designed to measure electrons, muons, photons, neutral mesons and identified charged hadrons in ultrarelativistic heavy-ion collisions. With this broad spectrum of observables PHENIX is able to study in detail the collision dynamics and in particular the earliest stages where the new state of matter, known as the Quark-Gluon plasma (QGP) is expected to be formed.

The layout of the PHENIX detector \textsuperscript{11} is shown in Fig. \textsuperscript{1}. It consists of two central spectrometer arms, each one covering 90° in azimuth and $|\eta| < 0.35$ and two forward muon spectrometers with full azimuthal coverage in the pseudorapidity range $1.2 < |\eta| < 2.2$. The central arm detectors are located outside an axially symmetric magnetic field provided by a central magnet. The detectors include a high resolution tracking system consisting of drift chambers, pad chambers, and time-expansion chambers. Together with a high resolution time-of-flight hodoscope, electromagnetic calorimeters, and a gas-filled ring imaging Cherenkov counter, the central arms provide excellent hadron, electron, and photon identification capabilities over a wide range of transverse momenta. The presently achieved particle momentum resolution is $\delta p/p = 0.8\% \oplus 1.0\% p$ GeV/c, close to the design value of $\delta p/p = 0.6\% \oplus 0.3\% p$ GeV/c.

Figure 1. View of the PHENIX detector.

For global event characterization, the setup includes a silicon vertex detector, two zero-degree calorimeters sensitive to neutrons emitted along the beam axis, and a set of beam-beam counters to determine the reference for time-of-flight mea-
measurements and vertex determination. The data acquisition system is capable of archiving 60 MB/s which corresponds to about 400 minimum bias Au-Au events per second.

The present set-up of the PHENIX detector does not allow a good measurement of low-mass electron pairs with \( m_{e^+e^-} \leq 1 \text{GeV}/c^2 \). Tracks with momentum \( p \leq 200 \text{MeV} \) cannot leave the magnetic field region. Thus, very often for the pairs originating from \( \gamma \) conversions and \( \pi^0 \) Dalitz decays only one of the partners is detected. This leads to a huge combinatorial background that increases quadratically with the number of charged tracks \( N_{ch} \). At the high multiplicities of RHIC, this makes signal detection extremely difficult. For example, first PHENIX results show, in agreement with Monte Carlo studies, that even with a large single electron \( p_t \) cut of 300 \( \text{MeV}/c \), the \( \phi \) meson measurement has a signal to background ratio, \( S/B \), of about 1/20 [2] and at lower invariant masses \( m_{e^+e^-} \approx 400 \text{MeV}/c^2 \), \( S/B \approx 1/100 \).

A proposal for an upgrade of the PHENIX detector to dramatically improve the performance in the measurement of low-mass \( e^+e^- \) pairs is presently under study. The upgrade has two main elements: the installation of a second coil, foreseen in the original PHENIX design, to generate an almost field-free region extending up to \( \sim 60 \text{ cm} \) in the radial direction and an additional detector in that region to recognize, and provide the necessary rejection of, Dalitz and conversion tracks.

In this paper, we limit the discussion to a possible realization of this additional detector. We present the detector concept, expected performance and benefits. We then describe the current R&D program to address a number of issues and questions raised.

2. General Concept of the Upgrade

The basic idea of the proposed upgrade exploits the fact that the opening angle of electron pairs from \( \gamma \) conversions and \( \pi^0 \) Dalitz decays is small compared to the pairs from light vector mesons. In a field-free region this angle is preserved and by applying an opening angle cut one can reject more than 90% of the conversions and \( \pi^0 \) Dalitz decays, while conserving most of the signal.

Monte Carlo studies at the principle level [3], with an additional detector in the zero field region, assuming perfect spatial resolution and perfect electron identification give a \( S/B \) ratio of \( \sim 10 \) at the \( \phi \) meson mass region with an opening angle cut of \( \sim 180 \text{ mrad} \). The simulations show that the background tracks remaining after such cut are close to the boundaries of the fiducial acceptance. Therefore adding a veto area to the inner detector further improves the \( S/B \) ratio. For example, increasing the acceptance in the azimuthal direction from \( 90^\circ \) to \( 120^\circ \) and from \( |\eta| \leq 0.35 \) to \( |\eta| \leq 0.50 \) in pseudo-rapidity allows us to reach a \( S/B \) ratio of about 25 [3].

At this level of rejection, the quality of the low-mass \( e^+e^- \) pair measurement will not any longer be limited by the combinatorial background of conversions and \( \pi^0 \) Dalitz decays but rather by the background originating from semi-leptonic decays of charmed mesons. Reducing this latter source is beyond the scope of the proposed upgrade. Current crude estimates of the \( S/B \) including the charm background give a \( S/B \approx 1 \).

3. Hadron Blind Detector

The results of the simulations and general considerations allow us to determine the inner detector specifications: electron identification with an efficiency \( > 90\% \) including double hit recognition; a moderate \( \pi \) rejection factor as low as 100-200; the detector must fit within the radial distance \( 20 \leq r \leq 70 \text{ cm} \); the detector should cover a slightly larger acceptance (veto area) than the central arms; a radiation budget of the order of 1% of a radiation length.

The requirements on electron identification limit the choice to a Cherenkov type detector. After careful consideration of relevant options (configuration, radiator gas, window, detector gas, photocathode, amplifying element, readout scheme) our first choice is an HBD (Hadron Blind Detector) in the following configuration: a Cherenkov detector operated with pure \( CF_4 \) (or a \( CF_4 \) based mixture) both as radiator and detector gas, in a special windowless proximity focus.
geometry, with a CsI photocathode, multistage GEM (Gas Electron Multiplier) as detector element and pad readout.

In this configuration, Cherenkov photons from an electron passing through the radiator are directly collected on the CsI photocathode, evaporated onto the first GEM, forming a circular blob, not a ring as in a RICH detector.

The location of the HBD in the PHENIX detector is shown in Fig. 2 and a possible layout of the readout element is shown in Fig. 3.

Figure 2. The HBD location in the PHENIX detector.

Figure 3. Layout of the readout element of the HBD.

This scheme exhibits a number of very attractive features. The use of a windowless detector with CF₄ results in a very broad bandwidth between the CsI threshold of ~6eV up to the CF₄ cut-off of ~11.5eV and a large figure of merit $N_0 \sim 940\text{cm}^{-1}$ ($N_0 = \int Q.E. \, dE$). After including losses incurred by the optical transparency of the entrance mesh (10%) and the photocathode (25%) a very large number of detected photoelectrons, $N_{pe} = 40$, is expected in a 50 cm long radiator. This large number of photoelectrons ensures a very high electron efficiency. The "reflective" photocathode scheme makes the CsI totally screened from photons produced in the avalanche. The mesh before the first GEM is needed to ensure a zero field above the photocathode, which is best for electron extraction in the "reflective" mode. Since the pattern produced by the detector is a circular blob (maximum radius of 1.8 cm in a 50 cm long radiator) there is no a priori need to detect single photo-electrons as in a RICH detector. This has the double benefit of low-granularity (the pad size can be comparable to the blob size) and a relatively low gain operation (since a pad will collect a relatively large primary charge).

4. Expected Performance of the HBD

4.1. Occupancy and event rate

The occupancy and interaction rate expected at the HBD are very modest. With a charged particle density $dN_{ch}/d\eta = 650$ in central Au-Au collisions at $\sqrt{s_{NN}} = 200\text{GeV}$ the largest detector occupancy is calculated to be 0.02 charged particles/$\text{cm}^2$. The expected interaction rate is 1400 Hz at the design RHIC luminosity.

4.2. Scintillation of CF₄

CF₄ is known to scintillate and its scintillation properties were studied by several groups. The main feature of the scintillation spectrum is a line at 163 nm where the CsI is sensitive.

Since scintillation occurs uniformly in 4\pi whereas the Cherenkov light is emitted in a very narrow cone a considerable reduction of the scintillation background can be achieved by installing shades. With a simple simulation, the scintillation background over the size of a blob is found to be 4 photo-electrons. Adding radial shades close to the photocathode, 5 cm high and with 5 cm spacing in both directions, reduces the back-
ground by a factor of three while reducing the Cherenkov photons by less than 10%.

4.3. Detector response to electrons and hadrons

The detector performance for a few options with $CF_4$-based gases is shown in Table 1 (More options are considered in [3]).

The table shows the estimated response to electrons and hadrons. The response to electrons is characterized by the number of detected photoelectrons $N_{pe}$, the maximum radius of the blob $R_{blob}$ and the double hit recognition $DHR$. $DHR$ is the probability to resolve two electrons with zero opening angle using amplitude analysis, and accepting 5% misidentification of single electrons as double hits.

The response to hadrons is characterized by the number of electrons $N_e$ produced by a hadron within the size of a blob. It may be uniformly spread over the whole detector area as in the case of scintillation (G) or localized (L) in one pad when it results from ionization. For the latter we have assumed that the relevant ionization path-length for a particle traversing the first GEM is only the distance above its surface corresponding to a half of the hole pitch ($\sim 100\mu m$) where the electric field collects the primary ionization inside the holes.

The last column of Table 1 shows an estimate of the $\pi$ rejection factor that can be achieved. It is defined as the number of incident pions divided by the number of $\pi$ producing a signal above the lowest 5% of a single electron signal.

5. R&D Program and plans

Among the options listed in Table 1 the simplest and most attractive is the first one. It gives around 40 photoelectrons per electron. It has excellent $DHR$ and very high $\pi$ rejection. Recently the operation of a detector consisting of CsI photocathode, three stages of GEM in pure $CF_4$ has been demonstrated [10]. It gives some support that the proposed configuration of the HBD can be realized. We consider this as our prime choice and the other options in the table and others listed in [3] are alternatives to cure possible problems which may arise. Indeed there are a number of issues and questions which need to be investigated in a comprehensive R&D program which has recently started.

The main goal of the R&D program is to demonstrate the feasibility of the proposed Hadron Blind Detector configuration. The specific issues to be investigated are:

◊ Further studies of the $CF_4$ scintillation. We plan to measure the scintillation signal produced by a MIP in the laboratory using cosmic muons. From our current estimates the scintillation background is negligible. However, if needed it could be substantially reduced by installing shades. Detailed simulations will be needed to optimize the shade configuration.

◊ Study of aging effects on the GEMs elements and the CsI photocathode in pure $CF_4$ atmosphere. This is one of the most critical issues. The CsI QE degrades with a high dose of accumulated charge [11]. From published numbers [11], this does not seem to represent a problem. The total charge expected to be accumulated on the CsI over 10 years of continuous operation of the detector at design luminosity is well below 1mC/cm$^2$ (even assuming 100% ion feedback). However, aging in the presence of $CF_4$ might be more severe and needs to be studied. The biggest concern is the aggressivity of $CF_4$ with some materials and HF which can be formed by chemical reactions of $CF_4$ with water.

◊ Optimize the detector configuration: 2-3 GEMs or 2 GEMs + MWPC. One of the most important requirements is a stable operation of the detector without sparking at a high enough gain to ensure the required electron identification.

◊ Detector granularity needs to be studied and optimized. This is an important design parameter affecting occupancy, hit pile-up, $DHR$ and last but not least cost. Our first option here is to detect the blob in hexagonal pads of size comparable to the blob size. This ensures as much charge as possible in one pad, a low gas gain factor in the detector and low granularity.

◊ Study and optimize the HBD response to electrons versus hadrons. This is one of the most important features of the proposed detector. The electric field above the first GEM plays a crucial
Table 1
The detector performance for different configurations and gas choices.

| Radiator gas | $\gamma_{th}$ | Shades | $N_{pe\ per\ e^\pm}$ | $R_{blob\ [cm]}$ | DHR[%] | $N_e\ G/L$ | $\pi$ rejection |
|--------------|----------------|--------|------------------------|------------------|--------|------------|----------------|
| $CF_4$       | 28             | No     | 40                     | 1.8              | >90    | 4/1        | $>10^4$        |
| $CF_4$       | 28             | Yes    | 35                     | 1.8              | >90    | 1/1        | $>10^4$        |
| $CF_4/Ne\ 50/50$ | ≈ 40  | No     | 30                     | 1.3              | ≈ 90   | 2/1        | $\approx 10^4$ |
| $CF_4/Ne\ 10/90$ | ≈ 70  | No     | 20                     | 1.0              | ≈ 70   | 1/1        | 350            |

role here [7]. It affects the collection of photoelectrons released from the $CsI$ and also the collected primary charge from the passage of a hadron.

♦ Define the specifications and develop the front-end electronics. Analog information will be needed to recognize single and double hits. The specifications are closely linked to other parameters of the system, like the pad size, the expected signal amplitude and shape.

♦ Study the influence of residual magnetic field on the pattern recognition. The second coil largely compensates the magnetic field created by the main coil. However this does not result in a fully field-free region. Some residual field will be present and its influence on the pattern recognition has to be studied.

♦ Monte Carlo simulations. There is a broad program of simulations that have to be performed: (i) include the HBD in a full Monte Carlo simulation to study and optimize its response. (ii) How much material can be tolerated before the HBD? (iii) More realistic simulations of the HBD and its impact in rejecting the combinatorial background, including all sources of electrons ($\gamma$ conversions, Dalitz decays, resonance decays and semi-leptonic decays of open charm).

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