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THE HADRON-BLIND DETECTOR

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Abstract

The development of highly efficient solid photocathodes, compatible with high-gain gaseous detectors, has opened the possibility to build threshold Cherenkov counters with a good hadron rejection, with a minimum amount of matter, and a time resolution of the order of the nanosecond. We discuss the properties of a hadron-blind detector, with a granularity of a few millimetres. The study of the background sources shows that a rejection power of the order of 99% can be achieved for high-energy hadrons. It permits instantaneous multihadron rejection and, combined to a fast electromagnetic calorimeter, can ensure on-line electron selection, even when they are produced close to hadronic jets. It could permit the operation of lepton-tracking detectors in a magnetic field, in very high hadronic backgrounds.

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1 INTRODUCTION

An efficient identification of electrons or muons is important in particle physics. Experimentation in a high-energy hadron collider often relies on lepton detection for the signature of new physics. The search for the neutral boson, Higgs, in future colliders, the Large Hadron Collider (LHC) or the Superconducting Super Collider (SSC), requires excellent lepton identification, associated with a good momentum measurement, especially in the low mass range [1].

In the B-meson system, CP-violation studies seem to be a challenge for present and future hadron machines [2], because of high $b\bar{b}$ production, which makes these machines good candidates for B-meson factories. Interesting decay channels (i.e. $B \rightarrow K_S^0 \psi$) and B tracking require good lepton identification and detection [3]. Top-quark search also requires lepton identification, since it relies on lepton or multilepton studies. In addition, a great improvement is expected if a non-isolated lepton of relatively low p_T is identified inside a jet often coming from a b quark [4].

The extremely high rates and multiplicities foreseen with the future hadron colliders make the tracking and momentum measurement by an internal magnet very difficult and have led to the conception of experiments [5] where all hadrons are absorbed by an adequate thickness of material, with only energetic muons emerging and giving the signature of an interesting channel, i.e. the decay of the Higgs. In addition, muon-momentum measurement requires a high-cost external magnetic spectrometer and an important surface of muon detectors [6]. This is a way to escape the problem connected with the huge rates and multiplicities, which strongly limit the choice of detectors and require a drastic improvement in their present capabilities.

We present here an instrument where the approach to the problem is different. It is insensitive to the majority of the hadrons produced in the collisions but fully sensitive to relativistic electrons. It is almost massless, with a nanosecond time resolution and a high granularity. It can be combined with high-resolution electromagnetic calorimeters, without degrading the quality of the information carried by the particle going through the detector. Such a selective detector constitutes also an efficient tracking device inside an internal magnetic field, allowing lepton momentum to be measured comfortably, since the major part of the hadrons are invisible. It relies on recent progress on high-efficiency photocathodes [7] compatible with high-gain gaseous detectors, working at atmospheric pressure with nanosecond time resolution [8, 9]*).

2 PRINCIPLE OF THE HADRON-BLIND DETECTOR (HBD)

The electrons to be detected produce Cherenkov photons in a gas radiator (Fig. 1) of such a thickness that the detection of the photons leads to full efficiency for a relativistic electron signature. The photons are transmitted, through a thin grid of about 90% transparency, to a gaseous detector fitted with a photocathode of, for instance, CsI covered with adsorbed tetrakis (dimethylamine) ethylene (TMAE). It has been observed that an efficiency close to 40% is obtained in a photon wavelength range $\lambda < 190$ nm. The results, which contradicted older measurements [10] by a factor of 2, have been confirmed by recent experiments [11]. The development of such solid photocathodes is still the subject of active research.

With a Cherenkov radiator of 1 m thickness of He + 1% CH₄, at atmospheric pressure, the number of photons produced by a relativistic electron is 10. They are focused

*) These recent developments have been done in the frame of the LAA project, at CERN.

into a narrow cone of an angular aperture of 8 mrad, thus leading to a maximum spread at the exit grid of 8 mm.

The gaseous detector consists of a parallel-plate multiplication gap of 4 mm. It has been shown that gains up to 10^6 can be reached under these conditions without sparking or feedback problems, thus permitting the easy detection of single photoelectrons. With the high quantum efficiency of these photocathodes, in the wavelength range of 140 nm to 190 nm to which the gas is fully transparent, we expect 3 photoelectrons to be extracted.

The efficiency of the detector for hadrons is dependent on two factors:

- i) The production of photons by hadrons depends on their mass

$$p_{th} = \frac{m}{\sqrt{2(n-1)}} ,$$

where n denotes the refractive index of the gaseous radiator and p_{th} is the momentum threshold.

For the gas chosen as an example, the pion threshold is at 17 GeV. However, a discrimination level can be set at an even higher value, i.e. 25 GeV/c. For a collider such as the LHC, Monte Carlo calculations show that, in the volume of a detector in the central region covering a pseudorapidity $|\eta| < 2$, the rate reduction is 10^4 .

- ii) The charged particles liberate ionization electrons in the gas. It is fairly easy to eliminate all ions from the Cherenkov radiator itself and prevent them from reaching the amplifying gap, which has, however, a limited thickness with a small probability of liberation of ionization electrons.

The thickness is reduced to a minimum by two factors. The experimental development of avalanches from electrons liberated at the photocathodes limits the region contributing to the pulses to a few hundred microns near the cathode. A time resolution of 0.5 ns (FWHM) has been obtained in the parallel-plate gaseous detector, with a CsI photocathode, at large gains, and an initial pulse of 3,000 photon electrons. A time resolution of 0.3 ns (FWHM) has been obtained with 10 photoelectrons in counter filled with 10 mb of methane [12]. For the same value of the gain the time resolution should be governed by the collision mean free path of the first electron starting the avalanche, irrespective of the pressure. We thus consider that the goal of 2 ns time resolution for the detector is realistic. This corresponds to a drift length of 100 to 200 μm and we believe that only electrons liberated in a gas of this thickness will contribute to the parasitic pulses if we can reach this resolution time in operating conditions. This will contribute to a reduction by two orders of magnitude in the load of charged particles giving rise to avalanches. The number of ionization electrons initiating an avalanche is equal to the ratio of the secondary to the primary ionization coefficient in the gases, i.e. 2 to 3 in general. This is less important when the number of photoelectrons produced by a good event is close to 10.

Another possible approach to the detector is a more conventional multiwire proportional chamber (MWPC) with pad-array readout. It has been shown that a high pad efficiency of 99% with a long detector plateau for single electrons can be obtained with a very small distance (350 μm) between the cathode (pad arrays) and anode wires [9]. Such a structure is easily obtained by putting ceramic spacers between the cathode and the wire plane. The small, 350 μm , gap also reduces the direct ionization to a small level.

- iii) The charged particles produce secondary electrons from the photocathode. Studies on secondary electrons ejected from metals by 10 GeV electrons have shown [13] a

production yield of about 5%. For CsI we may expect a value larger by a factor of about 5. It may thus be the main source of noise in our detector. The majority of ejected electrons are of very low energy, i.e. they have no chance of ionizing the gas, and we will have to deal with a background of pulses generated by a single electron. This is why it is essential to have a large photoelectric efficiency and deal with good events producing an initial number of electrons that can be eliminated by the threshold in the electronics, such as 5 to 10.

With the photocathodes deposited on 5 mm $\times$ 5 mm pads a good granularity is reached. The fact that only a threshold is required for the trigger electronics permits full benefit to be obtained from the time resolution of the detector.

The total mass of the detector is small and it can be coupled to preshower counters of the same granularity and electromagnetic calorimeters of high resolution. For instance, the BaF₂ calorimeters coupled to gaseous detectors equipped with the same type of photocathodes are ideally matched to the HBD with the same time resolution, and an energy resolution of the order of 1% [14].

After this description of the principle of the HBD, we will consider, in more detail, the factors permitting a choice of the detector length, and of the energy threshold for the hadrons, to better adapt the detector to the various applications which can be foreseen.

3 ADJUSTMENT OF THE HADRON-DETECTION THRESHOLD – DISCUSSION OF THE GAS RADIATOR

The nature and pressure of the gas radiator permit a control of the hadron-detection threshold. The limiting factor is the necessity of having enough photoelectrons for a full efficiency of the relativistic electrons.

Table 1 gives the value of the index of refraction of some gases under consideration, the Cherenkov momentum threshold p_{thr} at NTP, the energy loss (dE/dX) per metre of track, and the number of primary N_{pr} electrons created by a minimum-ionizing particle and T_{cut} is the light transmission cut-off.

Table 1
Physical properties of some candidate gases.
The optical constants are taken in the visible range.

Gas	$(n-1) \times 10^6$	P_{thr} (GeV)	dE/dX (eV/mm)	N_{pr} (mm ⁻¹)	T_{cut} (eV)
H ₂	140	8.37	37	0.52	12
He	35	16.73	34.3	0.59	12
Ne	67	12.09	155	1.2	10
Ar	283	5.88	268	2.94	10
CH ₄	444	4.7	172.8	1.6	8.8

Considering that we need 3 photoelectrons for an efficiency close to unity and that the best efficiency so far observed with a CsI-TMAE photocathode is close to 40%, we see that, taking into account the accepted hadron threshold, we have a choice of gases and pressures depending on the length we accept for the radiator.

If we go to pressures lower than 1 atm we do not expect a degradation of the time resolution if we work at the same gain, since all photoelectrons are ejected from the cathode plane, and it is the width of the time gate that will determine the rate of the parasitic pulses produced by the direct ionization of the detector gas. We can, for instance, envisage detectors of only 20 cm length, with a Cherenkov radiator mainly made of CH_4 , if we accept a hadron threshold at about 5 GeV. This could permit the use of a multilayer detector for electron tracking in a magnetic field. Some experiments are at present considering such an approach [15]. The calculations show that a threshold of 5 GeV still reduces the counting rate by 10^3 . In many cases the optimum choice of the gas corresponds to a threshold where the physical reduction of the hadron counting rate is brought to the same level or an order of magnitude lower than the counting rate due to the direct ionization of the gas in the counter. We can thus see that the optimum gas for the first application we have foreseen could be $\text{He} + \text{Ar} + \text{CH}_4$, with a thickness of only 30 cm.

4 APPLICATIONS OF THE HBD

4.1 Electron identification with a HBD and a fast calorimeter

Since the hadrons contribute to about 1% of the pulses recorded by the HBD, because of direct ionization in the gas and secondary emission from the photocathode, it is in general necessary to foresee additional detectors along the trajectories for a more restricted signature of electrons.

With a HBD coupled to a fast electromagnetic calorimeter great pion rejection can be obtained. It has been demonstrated that such a calorimeter is able to reject pions with a power of 10^4 for electrons of energy greater than 10 GeV [16].

However, for real hadronic events an important limitation comes from charged tracks pointing to an electromagnetic shower and faking an electron [17]. The high hadronic rejection of the HBD, even in very narrow jets, and its good spatial resolution, should reduce this effect to an acceptable level.

As already pointed out, the recent research on scintillators coupled to the same type of photocathodes as the one permitting the new approach to threshold Cherenkov counters leads to electromagnetic calorimeters well suited to these problems. The BaF_2 crystals permit a granularity, in the preshowering stage, of the same value as the CsI pads.

Research on new crystals, such as MgF_3K [10], shows that it is possible to obtain 10 photoelectrons from a crystal of a few millimetres thickness, thus opening the way for a detector permitting the separation of single electrons from double electrons, which may be the main source of contamination due to the Dalitz pairs from π^0 and signing dense jets producing a large energy loss in this electromagnetic calorimeter. The crystals present adequate resistance to the radiation existing near high-luminosity machines. Indeed, more research is still needed to determine if the preliminary results can lead to reliable detectors. The time resolution of these detectors is in the nanosecond region.

Finally, the very good energy resolution should permit an important background rejection in the detection of narrow states.

It is clear that for many problems the HBD can be useful. It has the advantage over conventional methods, such as the ones based on transition radiation, of much less matter and a much faster response. The contribution to the first-level trigger can also be considered. Another important advantage over a transition radiation detector (TRD) is the high rejection of double or triple pions, even in the case where they hit the same pad,

i.e. a high rejection of jets.

4.2 A very selective magnetic spectrometer

Another application of the HBD is its use as a tracking device inside a magnetic-field spectrometer. In that case, because of the momentum threshold of the BHD, the low-momentum charged particles are not seen by the detector and only high-momentum particles are selected. This should enormously facilitate the pattern-recognition problem in high-multiplicity LHC or SSC events and make possible the use of the cheap internal magnetic field spectrometer, which is considered as marginal in a conventional detector design, because of the high multiplicity and the pile-up problems.

Figure 2 illustrates a model of a tracking system, composed of 10 HBDs of 20 cm length. Each individual detector is filled with pure CH_4 at atmospheric pressure and has a $4 \times 4 \text{ mm}^2$ pad-array readout. With CH_4 the effective energy loss of a minimum-ionizing particles inside the small gap is higher than with He, but it is still low, corresponding to about one primary electron per incident particle. The expected signal is about 9 electrons per relativistic incident particle. Setting the discrimination level on the output signal at the equivalent level of 4 electrons, the efficiency of the detector remains high $\sim 95\%$ —whilst the probability of a background signal, including Landau fluctuations, is very small—of the order of a few per cent.

To evaluate the expected spatial resolutions with $4 \text{ cm} \times 4 \text{ cm}$ pads, we extrapolate the experimental results of Ref. [9]. The obtained resolution (r.m.s.) is better than the expected $s/\sqrt{12}$, where s is the pad dimension. The improvement is due to the ‘digital’ determination of the affected pads. In our case, using digital determination, the expected resolution is of the order of 1 mm per photoelectron and we have about 9 photoelectrons created per charged particle.

For pions the momentum threshold is now 5 GeV, but it can shift to 7 GeV, by adjusting the discrimination level.

Let us now consider a real LHC detector, in the central region covering a pseudorapidity range of $|\eta| < 2$, inside a magnetic field of $\sim 2 \text{ T}$ created, for simplicity, by a solenoid. This is the general concept of a selective magnetic spectrometer, since the detector is blind to low p_T hadrons, and a few high-momentum particles surviving this cut-off are measured with good accuracy

$$\frac{\sigma(p)}{p} = \sqrt{\frac{720}{N+5}} \frac{\sigma(x) p}{0.3BL^2}$$

where $\sigma(x) = 1 \text{ mm}$ is the spatial resolution of the detector, $N = 10$ is the number of measurements, $B = 2 \text{ T}$ is the magnetic field, $L = 2 \text{ m}$ is the total length, and p is the momentum (in GeV/c) of the charged particle. The expected resolution is

$$\frac{\sigma(p)}{p} = 0.27\% \times p ,$$

which gives a precision of only 27% at 100 GeV. However, with a magnet like the one proposed in Ref. [15] ($BL^2 = 18$) and an optimum arrangement of the detectors, another factor of 4 can be gained.

It is also possible to consider in the single-gap parallel-plate amplification mode having the anode grid made of wires with 1 mm spacing, parallel to the magnetic field. With a readout from every wire the cluster centroid could give a resolution of the order

of half the wire spacing. This would lead to another gain in resolution by a factor of 2 and a very fast response. This would lead to a comfortable resolution of about 3.5% at 100 GeV.

Taking into account the hadron production in the central part of a LHC detector, with a momentum above the imposed threshold, only 1% of the hadrons survive this cut-off. Most of them are produced from high- p_T jet events, since the major part of hadrons from minimum-bias events are below the cut-off. Therefore the effective multiplicity seen by the HBD system is very low and, even considering pile-up of many minimum-bias events to a given jet even, only few particles survive the momentum cut-off.

This is well illustrated in Fig. 3. The first event (a) is a generated minimum-bias event as it look in a conventional tracking spectrometer. The same event as it is seen by the HBD is shown in Fig. 3b. Events were generated through PYTHIA [18] and, for the tracking inside the magnetic field, the standard simulation program GEANT3 [19] was used. For the event generation the mass of the neutral Higgs boson was fixed at 300 GeV, as well as the top-quark mass at 130 GeV. The same comparison is shown in Fig. 4 for a Higgs event $pp \rightarrow H + X \rightarrow \mu^+ \mu^- \mu^+ \mu^- + X$.

It appears that the improvement of the event pattern is great when a system of HBD trackers is used. We point out that, as expected, the effect of the momentum threshold (5 GeV in this study) is very efficient in the central region, where a detector should be placed, i.e. $|\eta| < 2$, which eliminates the contribution of the forward-backward radiations to the counting. A few pile-up minimum-bias events, superimposed on the interesting event, should not degrade the pattern in the central region, where the contribution of minimum-bias events is small: low-momenta pions do not survive the momentum cut-off and only a few accidental electrons can be added to the good event. Furthermore, a requirement for primary vertex matching of these particles should reject a great part of them. This is one of the great advantages of this tracking: with conventional systems, the pile-up of many minimum-bias events results in a strong degradation of the event pattern.

The single-muon production rate, seen by the detector, is of the order of 10^5 Hz at the full luminosity of the LHC, dominated by $b\bar{b}$ production. This constitutes an excellent sample for studies of CP violation with B mesons, in high-rate hadronic machines such as the LHC and SSC.

At the same time, the sample is enriched by about a factor of 100, for lower energy electrons surviving the Cherenkov threshold. Such an electron sample is perhaps desirable at machines of lower luminosity, such as the Tevatron, for B-meson tagging.

5 CONCLUSION

The development of new photocathodes compatible with fast gaseous detectors permits, among other applications, envisaging a new generation of gaseous threshold counters with a nanosecond time resolution and a fast response compatible with the conditions at high-luminosity machines.

By permitting an efficient signature of electrons among large rates or large densities of hadron fluxes, several fundamental modern research problems can be addressed, such as the signature of Higgs decays.

These counters can be precious auxiliaries in combination with various sorts of calorimeters, or used as lepton-tracking counters in magnetic fields.

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Figures captions

Fig. 1 Schematic of a single cell of a HBD. A charged particle (e^-) produces Cherenkov light in a $\text{He} + \text{CH}_4$ gas radiator; photoelectrons are created on the pad photocathode, then extracted, amplified and collected on the anode grid.

Fig. 2 A tracking device composed of 10 HBDs. Each single detector has a 20 cm CH_4 gas radiator. The Cherenkov light produced by a charged particle is globally detected, by the pad-array photocathode, as a space point.

Fig. 3 Pile-up of 10 (PYTHIA-LHC)-generated minimum-bias events. Charged particles are deflected by a magnetic field of 1 Tesla, parallel to the z direction. The diameter of the solenoid is taken to be 4 m, with a length of 4 m.

a) The event seen by a conventional tracking device. Left: longitudinal (xz) view of the event. Right: transverse (xy) view of the same event.

b) The same event, seen by a HBD tracking device.

Fig. 4 A PYTHIA-generated Higgs-LHC event decaying into four muons (dashed lines). The comparison made here is the same as in Fig. 3.

Fig. 1

Fig. 2

Fig. 3

a)

b)

Fig. 4