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A magnetic spectrometer RICH

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Abstract

In this paper, a novel type of detector is discussed. A RICH with very long focal length (i.e. 20 m) with respect to its transverse dimensions, with a dipole magnet in the middle, can work as a magnetic spectrometer and a standard RICH at the same time. With only one detector the momentum and the velocity of a charged particle (and so its mass) can be measured. This object is intrinsically very fast and also well suited for triggering purposes.

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Keywords: RICH; PID; Magnetic spectrometer

1. Introduction

Detectors based on Cherenkov light emission have been used since long time: a charged particle with a velocity larger than the speed of light in the crossed medium emits in a cone centered on the particle trajectory with half-angle θ_c given by $\cos\theta_c = 1/n\beta$ where n is the index of refraction of the medium and β the particle velocity in units of speed of light c. The Cherenkov cone can be imaged by means of a spherical mirror onto a ring on the mirror focal plane: these detectors are called RICH [1] and have become very popular in high energy Physics experiments, both in fixed target setup or in collider mode. The radius r_c of the Cherenkov ring can be simply related to the Cherenkov angle by $r_c = f \times \theta_c$ where f is the focal length of the mirror and the approximation used is good for small angles. More recently RICH with very long focal length have been built (SELEX [2]: $f \approx 10$ m) or proposed (CKM [3] and P326 [4]: $f \approx 20$ m). If the focal length is much larger than the transverse dimensions of the detector, an evolution of the RICH concept can be envisaged: a dipole magnet can be put in the middle of the detector and, provided that the magnetic field spread is much smaller than the focal length, the RICH can work as a magnetic spectrometer. A charged particle passing through it will be deflected by the dipole magnet by an angle $\theta_{mag} = p_t/p$ where p is the particle momentum and p_t is the momentum kick given by the dipole magnet. The emitted Cherenkov light will be imaged by the mirror onto two rings with the same radius and the same position in the non-bending plane: the distance between the two rings centers will be $f \times \theta_{mag}$. In Fig. 1 this concept is shown.

The two rings can be simultaneously fitted with four parameters: the rings common radius, the center position of one of the rings (two parameters) and the distance from the other ring center. With such a fit the particle velocity (from θ_c) and the particle momentum (from θ_{mag}) can be reconstructed; the ring center position also gives the particle direction. The mass of the particle can be inferred without any external information, in contrast to usual RICH detectors. In this simple setup, the sign of the particle charge cannot be determined because no information is available to identify which of the two rings is due to the particle path before the magnet and which is after.

The performances of this novel detector, which will be named MASPRICH for short, will be discussed in the following sections going into the details of a specific example, from which expectations for other setups can be inferred.

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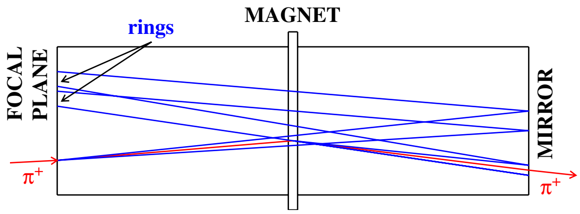

Fig. 1. Setup of a magnetic spectrometer RICH (not in scale): a charged particle (in red) is deflected by the dipole magnet; the Cherenkov light (in blue) is imaged by the mirror onto two rings on the focal plane.

2. Simulation

A simple simulation has been produced. A cylinder 20 m long with a 2.5 m diameter has been considered; a spherical mirror with 20 m focal length is put at the end of the detector (the mirror can be a mosaic of smaller pieces with the same focal length); the center of the sphere associated with the mirror is located at 1 m above the cylinder axis in the non-bending plane. A magnetic dipole is located in the middle of the cylinder: the magnetic field intensity is assumed to be longitudinally distributed with a Gaussian shape with 0.88 m standard deviation and to provide a total p_t kick of 360 MeV/c. The cylinder is filled with neon gas at atmospheric pressure and room temperature with an index of refraction such that $(n-1) = 67 \times 10^{-6}$ corresponding to a maximum θ_c of 11.6 mrad. It is assumed that the presence of the magnetic field does not change the index of refraction. A matrix of photomultipliers (PMT) is located on the mirror focal plane: the PMTs are arranged in hexagonal packing with closest distance among two PMTs of 18 mm (few thousands of PMTs are needed).

In total, 2×10^5 positively charged particles have been generated equally distributed among positrons, pions, muons and kaons. They have been uniformly generated in momentum between 10 GeV/c (close to the muon threshold) and 80 GeV/c (close to the proton threshold). They have been also uniformly generated in angle between 0 and 10 mrad with respect to the cylinder axis and between 0 and 2π in the transverse plane. Finally, the charged particle entrance point in the cylinder has been uniformly generated at a distance between 0 and 50 cm from the cylinder axis.

The light emitted by the charged particle has been generated according to the Cherenkov spectrum at an angle determined by the particle velocity and the neon dispersion curve [6]. The effect of bending in the region of high magnetic field is taken into account. The light is reflected by the mirror with 90% efficiency and properly directed towards the focal plane. The mirror is assumed to be a high quality one, with a figure of merit D_0 of 4 mm.[1] A quartz window separating the neon gas from the photodetectors is assumed with a transmission efficiency of 85%. The PMT quantum response is introduced assuming the Hamamatsu R7400-U04 [5] with a peak quantum efficiency of 20% and a quantum efficiency integrated over the light spectrum of 0.8 eV. The geometrical packing efficiency is about 90% (ratio of circle to hexagon area). The active area of the PMT is a circle of about 8 mm diameter and a truncated cone guide, to convey the light from the external 18 mm wide circle, is assumed; the collection efficiency is estimated to be 85%, assuming that 80% of the photons impinging on the truncated cone are reflected towards the PMT active area.

More than 45 photoelectrons are produced on average for a $\beta = 1$ particle, but since the same PMT can detect more than one photoelectron, the actual number of hit PMTs becomes about 40.

3. Reconstruction

The two rings are simultaneously fitted. A simple linearized and iterated χ^2 fit is performed with four free parameters. In order to remove photons emitted during the particle bending, hits with high fit residuals are removed from the fit. Fig. 2 shows the result of the fit with the reconstructed momentum and Cherenkov angle. Positrons, muons, pions and kaons are clearly visible. It is evident the good separation between positrons, muons and pions below 40 GeV/c momentum; kaons are very well separated from the others but their threshold is above 50 GeV/c momentum. Fig. 3 shows the reconstructed momentum versus the generated momentum for charged pions: it is clear the good linearity of the result.

Assuming a high quality mirror, the Cherenkov angle resolution is dominated by the PMTs granularity. If $d = 18$ mm is the distance between two close PMTs, the single hit Cherenkov angle resolution is given by $d/(4f) \approx 225\,\mu$rad where $f = 20$ m is the mirror focal length.

The second contribution is given by the neon dispersion, whose effect depends of the PMT spectrum response. With the assumed PMT the effective dispersion is $\Delta n = 1.6 \times 10^{-6}$ which corresponds to a single hit angular resolution of $\Delta n/\theta_c$ which is 140 μrad at $\beta = 1$.

The third contribution is given by the charged particle multiple scattering: 20 m of neon corresponds to about 6% of radiation length. The Cherenkov radiation is emitted uniformly along the charged particle path and on average $\frac{2}{3}$ of the path contribute to the multiple scattering, which corresponds to a single hit angular resolution of 55 μrad at $p = 35$ GeV/c.

The total Cherenkov angle resolution is roughly given by the single hit resolution divided by the square root of the number of degrees of freedom of the fit (number of hits minus number of fitted parameters).

In Fig. 4 the Cherenkov angle resolution and in Fig. 5 the momentum resolution for charged pions are shown as a function of momentum. The filled circles correspond to the case in which all the contributions to the resolution are

[1]The mirror D_0 parameter is defined as the diameter of the minimum spot produced by a point source put on the mirror center and where 95% of the light is collected.

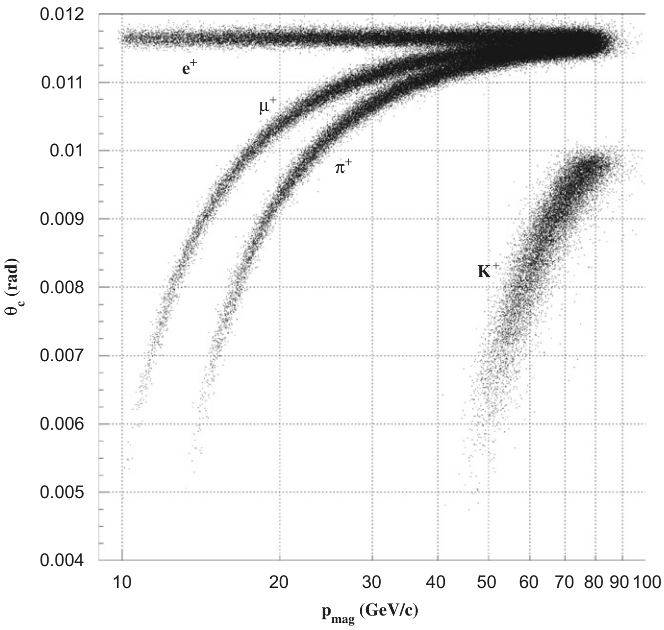

Fig. 2. Particle identification performances: the Cherenkov angle as a function of the particle momentum is shown, both simultaneously fitted by the imaged rings. The different particle contributions are indicated. Note the log scale in abscissa.

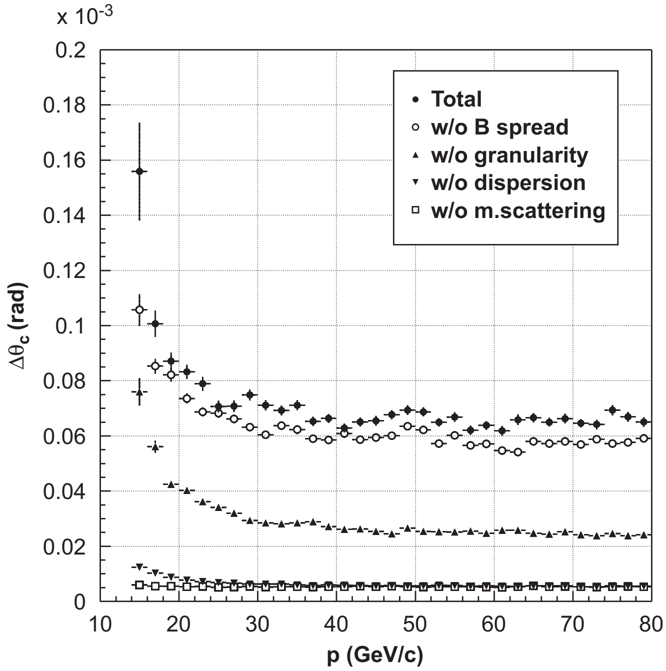

Fig. 4. Cherenkov angle resolution as a function of particle momentum for charged pions. The different contributions to the resolution are indicated (see text for explanation).

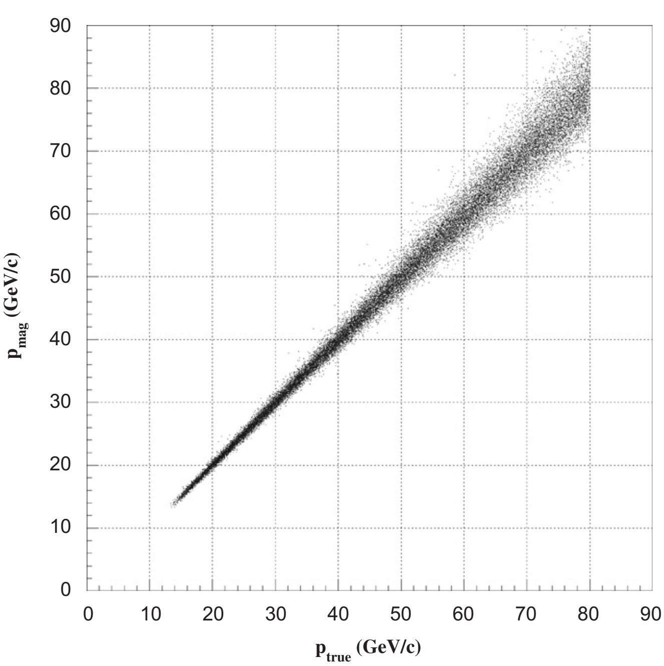

Fig. 3. Reconstructed momentum versus true momentum for charged pions (generated between 10 and 80 GeV/c momentum).

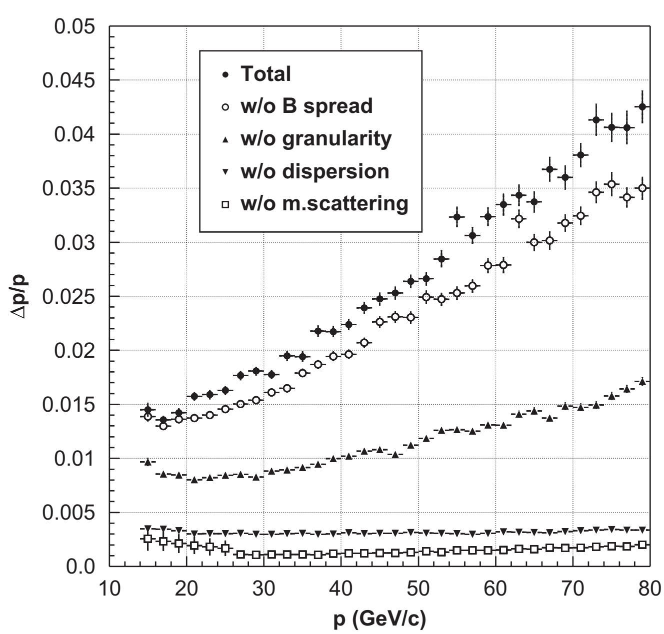

Fig. 5. Momentum resolution as a function of particle momentum for charged pions. The different contributions to the resolution are indicated (see text for explanation).

switched on; then the effect of magnetic field spread is removed (open circles); the third distribution corresponds to the case in which the PMTs granularity is also switched off; then the dispersion effect is also removed and finally also the multiple scattering contribution is neglected. What is left is due to the reconstruction algorithm and smaller resolution effects. The rise of the resolution at low momentum is due to the small number of photoelectrons close to the Cherenkov threshold. Quite remarkable is the very small dependence of the momentum resolution from the multiple scattering.

In Fig. 6 the particle identification performances of the MASPRICH detector are expressed as number of standard deviations of Cherenkov angle as a function of reconstructed

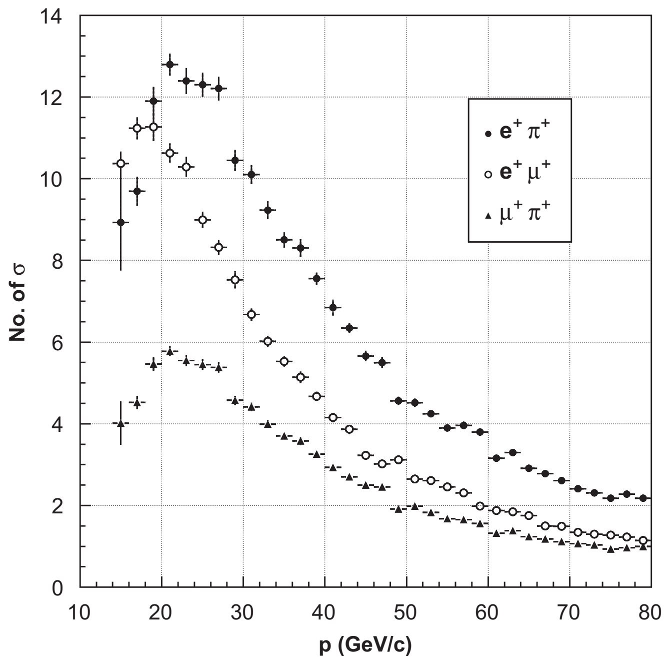

Fig. 6. Separation between different couples of particles as a function of reconstructed momentum, expressed as number of standard deviations of Cherenkov angle.

momentum: the e–μ separation is better than e–π one at low momentum because close to the threshold pions produce less photoelectrons than muons. The separation close to the threshold can be improved if also the number of photoelectrons is taken into account.

4. Fast timing and triggering

The time of arrival of Cherenkov photons, emitted by a charged particle, at the mirror focal plane is essentially the same. The change of particle trajectory after the magnet, the neon dispersion and the charged particle multiple scattering introduce small effects on the time and the dominant contribution is by far the PMT intrinsic time resolution and that due to the readout chain. With the assumed PMT, a fast (and presently available) electronics and the indicated number of hits, a total time resolution of the order of 100 ps is reasonably achievable, making the MASPRICH a very fast detector.

The MASPRICH is also well suited for triggering, thanks to its fastness. A simple hits multiplicity trigger is enough to select one charged track and also to reject multi-tracks events.

5. Conclusions

An innovative detector has been proposed named MASPRICH, able to simultaneously measure the momentum and the mass of a charged particle. A specific example has been worked out in details to understand the performances of the detector. It is clear that changing the radiating gas (and/or its pressure) good momentum resolution and particle identification can be obtained in different momentum ranges or for different types of charged particles. The detector is well suited for low multiplicity events but can sustain high event rates. The driving cost of the apparatus is clearly given by the photomultipliers, the number of which depends on the acceptance needed for the reconstructed charged particles.[2]

Acknowledgments

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[5] see ⟨http://www.hamamatsu.com/⟩.

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[2]In the example described in the text more than 4000 PMTs have been hit but in a realistic experimental setup this number can be much smaller.