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Charged kaon mass measurement using the Cherenkov effect

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ABSTRACT

The two most recent and precise measurements of the charged kaon mass use X-rays from kaonic atoms and report uncertainties of 14 and 22 ppm yet differ from each other by 122 ppm. We describe the possibility of an independent mass measurement using the measurement of Cherenkov light from a narrow-band beam of kaons, pions, and protons. This technique was demonstrated using data taken opportunistically by the Main Injector Particle Production experiment at Fermi National Accelerator Laboratory which recorded beams of protons, kaons, and pions ranging in momentum from +37 to +63 GeV/c. The measured value is $491.3\pm1.7\,\text{MeV}/c^2$, which is within 1.4σ of the world average. An improvement of two orders of magnitude in precision would make this technique useful for resolving the ambiguity in the X-ray data and may be achievable in a dedicated experiment.

1. Introduction

The charged kaon mass is an important input in determining the CKM matrix element V_{us} from measurements of the branching ratio of $K^+\rightarrow\pi^0 e^+\nu$. The value of the charged kaon mass reported by the Particle Data Group is $493.677\,\text{MeV}/c^2$ with an uncertainty of 26 parts per million (ppm) [1]. This value is a weighted average of six measurements but is dominated by the two most recent and precise measurements from Denisov [2] and Gall [3] which measure X-ray energies from kaonic atoms. While these measurements report uncertainties of 14 and 22 ppm they differ by 122 ppm (4.6σ). In this article we explore one possibility to resolve this discrepancy using an independent technique for measuring the charged kaon mass based on the Cherenkov effect. The well known pion and proton masses are used as references. The technique is demonstrated using data taken opportunistically using the Ring Imaging Cherenkov (RICH) sub-detector of the Main Injector Particle Production (MIPP) experiment at Fermilab [4].

2. Measurement concept

Cherenkov light is emitted when a relativistic charged particle of mass m, momentum p, and speed $\beta=1/\sqrt{1+(m/p)^2}$ travels

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through a radiator volume of index of refraction n with $\beta > 1/n$. (As is customary in high energy physics we work in units in which the speed of light, c, is 1.) Neglecting dispersive effects for the moment, the light is emitted in a cone at an angle θ given by $\cos\theta = 1/\beta n$ [5,6] which is approximately

$$\theta = \sqrt{2\left(1-\frac{1}{n\beta}\right)} \tag{1}$$

for small angles. Now, consider two particles i and j with identical momenta p but different masses m_i, m_j and speeds β_i, β_j. They will emit Cherenkov light at angles θ_i, θ_j which are related by the expression

$$\beta_i\theta_i^2 - \beta_j\theta_j^2 = 2(\beta_i - \beta_j). \tag{2}$$

In the relativistic limit $p \gg m$, $\beta \approx 1 - m^2/2p^2$. This, when combined with Eq. (2), gives

$$\theta_i^2 - \theta_j^2 = \frac{m_j^2 - m_i^2}{p^2} \tag{3}$$

where we have neglected the small difference between $\beta\theta$ and θ. If the particles i and j are pions, protons, and kaons, we have two independent angle-squared differences that can be measured

$$\theta_\pi^2 - \theta_K^2 = \frac{m_K^2 - m_\pi^2}{p^2} \quad \text{and} \quad \theta_\pi^2 - \theta_p^2 = \frac{m_p^2 - m_\pi^2}{p^2}. \tag{4}$$

Using these, the kaon mass is given by

$$m_K^2 = m_\pi^2 + \Delta_{p\pi}\frac{\theta_\pi^2 - \theta_K^2}{\theta_\pi^2 - \theta_p^2}, \tag{5}$$

where $\Delta_{p\pi} \equiv m_p^2 - m_\pi^2$. Notice that for a monochromatic beam in the absence of dispersion the index of refraction n and momenta p drop out. The kaon mass can be determined, in principle, through measurements of the pion and proton masses and the Cherenkov angles of the three particles. The proton and pion masses are known to 0.9 and 2.5 ppm, respectively, and will not be the limiting factors in the experiment.

Using Eq. (5) we can estimate the uncertainty in m_K^2 measured using this method as

$$\sigma_{m_K^2}^2 = \sigma_{m_\pi^2}^2 + \left(\frac{\theta_\pi^2 - \theta_K^2}{\theta_\pi^2 - \theta_p^2}\right)^2 \sigma_{\Delta_{p\pi}}^2 + 4p^4\left[\theta_\pi^2 \frac{\Delta_{pK}^2}{\Delta_{p\pi}^2}\sigma_{\theta_\pi}^2 + \theta_K^2\sigma_{\theta_K}^2 + \theta_p^2\frac{\Delta_{K\pi}^2}{\Delta_{p\pi}^2}\sigma_{\theta_p}^2\right]. \tag{6}$$

The first two terms are due to the uncertainties in the pion and proton masses and are small. The third term grows with momentum and suggests that it is best to conduct the measurement at as low a momentum as possible where the differences in the Cherenkov angles are largest, while staying above proton threshold.

In a RICH detector, the angle θ can be determined on a track-by-track basis from the pattern of Cherenkov photons recorded. However, the light for a single ring will be distributed about the central angle θ due to the variation of the index of refraction of the radiator medium over the wavelengths at which Cherenkov photons are produced. This gives as contribution to the uncertainty in the average angle θ determined from a single track of

$$\sigma_{\theta_i}'^2 = \frac{1}{N_h}\left(\frac{1}{\theta_i n^2 \beta_i}\right)^2 \delta_n^2 \tag{7}$$

where δ_n is the amount of dispersion over the photomultiplier tube (PMT) wavelength acceptance and N_h is the number of PMT hits in the ring.

In a beamline, particles will be accepted if their momentum lies in a narrow window about some central value p. The finite size of this momentum acceptance window introduces an additional uncertainty in the average angle measured from a single track. Averaging over N_r rings, the momentum spread contributes an uncertainty

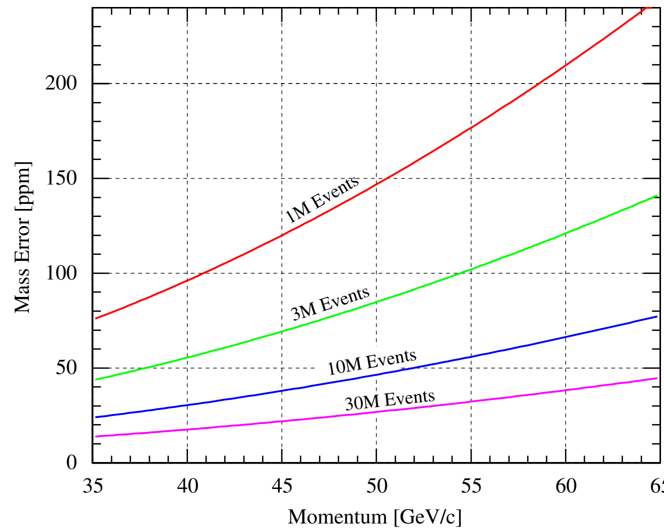

Fig. 1. Expected statistical uncertainty for kaon mass measurement.

$$\sigma_{\theta_i}^2 = \frac{1}{N_r}\left[\sigma_{\theta_i}'^2 + \left(\frac{m_i^2\beta_i}{\theta_i n p^2}\right)^2(\sigma_p/p)^2\right] \tag{8}$$

to the measurement of θ, where σ_p is the spread in the beam particle momenta about their central value. We take the specific case of an experiment using CO_2 as the radiator ($n = 1.00045$, $\delta_n = 3 \times 10^{-5}$) and a beam of central momentum 40 GeV/c with a width of $\sigma_p/p = 0.01$. Under these assumptions, σ_{θ_i} values are in good agreement with observed widths of ring radius distributions. This gives a statistical uncertainty in the kaon mass of

$$\frac{\sigma_{m_K}^2}{m_K^2} = 0.6^2 + 0.9^2 + \frac{31.0^2}{N_\pi} + \frac{44.1^2}{N_K} + \frac{18.1^2}{N_p}\ [\text{ppm}]^2 \tag{9}$$

where the first term results from uncertainties in the pion mass, the second from uncertainties in the proton mass, and the final three terms result from uncertainties in the angles θ_π, θ_K, and θ_p with N_π, N_K, and N_p being the number of millions of pion, kaon, and proton rings recorded. Using Eq. (9) we find that the uncertainty is minimized if 32% of the data is collected using protons, 23% using pions, and 45% using kaons. This result is only weakly dependent on momentum as shown in Fig. 1 which plots the expected statistical precision of the charged kaon mass as a function of momentum choice and total number of rings recorded. With 10 million rings at 40 GeV/c, we expect a statistical precision of 30 ppm using this technique.

3. RICH detector overview

The RICH detector used by MIPP was built by the SELEX Collaboration [7] for use in that experiment. We summarize here only the most important features of the detector as deployed for the MIPP experiment and refer the reader to Refs. [8–11] for details.

The geometry of the RICH counter is shown in Fig. 2. The detector was constructed from a low carbon cylindrical steel vessel 10.22 m in length and 93 in. in diameter with a wall thickness of $\frac{1}{2}$ in. The ends were sealed with 1.5 in. thick aluminum flanges that were cut out to hold thin beam windows at each end and a photomultiplier tube holder plate at the upstream end.