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Note on $K_s \rightarrow \mu^+\mu^-$ Search in the Neutral Hyperon Beam

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ABSTRACT

The possibility of doing a search for $K_S^\circ \to \mu^+\mu^-$ in the neutral hyperon beam is explored. It is found that the spectrometer to be used on the beam survey can be used to search down to the level of 10^{-9} to 10^{-10}, comparable to the present limit on $K_L^\circ \to \mu^+\mu^-$.

Introduction

It is the purpose of this note to explore in detail the possibility of a search for $K_S \to \mu^+\mu^-$ in the apparatus described in the main proposal for Experiment 8. A K^0 decay into a lepton pair is of intrinsic interest, and can occur through neutral leptonic currents in the weak hamiltonian, through second order weak interactions, or through a weak-electromagnetic process. The third possibility leads to the prediction of a definite lower bound for the CP conserving decay $K_2 \to \mu^+\mu^-$:

$$\frac{\Gamma(K_2 \to \mu^+\mu^-)}{\Gamma(K_2 \to \gamma\gamma)} \geq 1.1 \times 10^{-5}.$$ [1]

This argument is reliable at the ~20% level. Since the decay rate $K_L \to \gamma\gamma$ (assumed the same as $K_2 \to \gamma\gamma$) has been measured[2], one can write the lower bound as

$$\frac{\Gamma(K_2 \to \mu^+\mu^-)}{\Gamma(K_2 \to \text{all})} \geq 6.1 \times 10^{-9}.$$

The experimental upper limit is

$$\frac{\Gamma(K_2 \to \mu^+\mu^-)}{\Gamma(K_2 \to \text{all})} \leq 1.8 \times 10^{-9}$$

(90% confidence).[3] The theoretical lower bound would have corresponded to ten events, where one possible candidate was detected. This discrepancy is fairly serious if the experiment is correct and has generated a great deal of interest in the $K^0 \to 2\mu$ problem. In the K_S^0 mode, the published upper limit is

$$\frac{\Gamma(K_S \to \mu^+\mu^-)}{\Gamma(K_S \to \text{all})} \leq 7 \times 10^{-6}.$$ [4]

A reliable lower bound ratio relating $K_s \to 2\mu$ and $K_s \to \gamma\gamma$ is not possible because of unknown contributions from the large 2π intermediate state, which is of course suppressed in the K_L case.

A relation between $K_L \to 2\mu$ and $K_s \to 2\mu$ can be obtained, however, if it is assumed that the discrepancy between theoretical and experimental bounds is due to a cancellation of the $K_2 \to 2\gamma \to 2\mu$ amplitude by a CP violating K_1 amplitude. This question has been investigated by Christ and Lee[5], who find

$$10^{-5} \geq \frac{(K_s \to 2\mu)}{(K_s \to \text{all})} \geq 5 \times 10^{-7},$$

provided that the CP violating contribution is responsible for decreasing the theoretical lower bound. Very roughly, the argument stems from writing $K_L = K_2 + \varepsilon K_1$, $K_s = K_1 + \varepsilon K_2$, where $\varepsilon \sim 2 \times 10^{-3}$, and estimating $K_1 \to \mu^+\mu^-$ by saying

$$\Gamma(K_1 \to \mu^+\mu^-) \approx \varepsilon^{-2}\, \Gamma(K_2 \to \mu^+\mu^-).$$

Using the lower bound for $\Gamma(K_2 \to \mu^+\mu^-)$ and the K_s and K_L lifetimes then leads to

$$\frac{\Gamma(K_s \to \mu^+\mu^-)}{\Gamma(K_s \to \text{all})} \sim 10^{-6}.$$

If the rate is in fact this high, then the decay mode should be observed by experiments now in progress. If it is below the limits quoted earlier, then the discrepancy in the K_L decay cannot be explained by CP violation, but the $K_s \to \mu^+\mu^-$ rate remains an interesting number. For this reason the ability of the apparatus designed for the neutral hyperon beam (which is also a K_s beam) to detect this rare mode was studied using Monte-Carlo techniques. The results of this study are presented below.

Experimental Layout and Trigger Criteria

The layout is shown in Fig. 1. The spectrometer is exactly the same as

that employed in the beam survey; the only change required is to remove the photon counter and replace it with the "hadron veto" wall, a few days' operation.

The spectrometer will have an average geometric efficiency of about 60% for detecting the $K_S^o \rightarrow \mu^+\mu^-$ mode. This efficiency drops essentially to zero below 30 GeV. The mean energy of K_S^o decays observed should be about 90 GeV. They represent 5% of the total K_o, $\bar{K}_o$ flux into the beam solid angle. With 1 1/2 mm. wire spacing in the proportional chambers, this spectrometer gives a mass resolution at the K^o mass of 11 MeV (fwhm). The decay zone and all of the region up to the magnet are in vacuum; the remainder of the spectrometer is in helium.

Charged pion decays in flight set a lower limit to the trigger rate in this experiment. A 40 GeV pion has a probability of 1% of decaying somewhere in the apparatus. The key to the trigger logic is the "hadron veto", which is designed to distinguish muons from hadrons to at least the level of efficiency corresponding to the irreducible triggers from decays in flight. Hadrons of the highest energies observed in this experiment produce extremely penetrating cascades: A shower counter, at the optimum depth in the iron, is used to detect the cascade and suppress the high energy hadrons. The design is based on data from the Echo Lake calorimeter, and is discussed in Appendix B.

By the time they reach the hadron veto, the positive and negative decay products are well separated. Thus, a muon signal can be demanded from both left and right halves of the hadron veto. In addition, hard-wired logic on the proportional chambers is used to suppress triggers from neutron interactions.

Event Rates, Trigger Rates, and Running Time

Experimental planning has been based on an assumed sample of 10^{10} detectable K_S^o decays. With the configuration shown, we have estimated the number of triggers

in an experiment of that size to be of the order of 5×10^6. The sources of these triggers are summarized in the table below.

SOURCES OF TRIGGERS

Event	# detectable per 10^{10} K_S°	Millions of triggers due to:		
		π decays in flight	π decay + veto failure	2 veto failures
$K_S^\circ \to \pi^+\pi^-$	6×10^9	.6	.2	.1
$K_L^\circ \to \pi^\pm\mu^\mp\nu$	4×10^7	.3		
$\Lambda \to p\pi^-$	1×10^{11}		1.6	0.1
Neutron interactions (first chamber)	6×10^9	1.0	0.8	0.2
TOTAL		1.9	2.6	0.4
GRAND TOTAL		$\sim 5 \times 10^6$ triggers		

Using the FANC K^+ and K^- production curves from the NAL 1969 Summer Study, the most pessimistic as to K production, and a beam solid angle of 1.3×10^{-6} steradians, we estimate that 7×10^{14} protons on target are required for an experiment of this size. If the design flux of 10^{10} protons/pulse is achieved in the diffracted beam, and assuming 10^4 useful pulses per day, this experiment requires a week of actual data taking. If the intensity is lower, of course, a longer run would be necessary. If the flux is below 2×10^9, the experiment can be held at 5 weeks and a smaller sample taken, unless physics interest at that time justifies a larger search.

These flux estimates are based on forward production. Though the overall K/n ratio improves as one goes to larger production angles, we detect primarily

the portion of the K spectrum above 50 GeV. This actually drops more rapidly than neutron production. Thus, forward production is probably optimum.

Backgrounds

The major source of background in this experiment is the mode $K_S^\circ \to \pi^+\pi^-$ with both pions decaying in flight in the apparatus. Neutron interactions are eliminated entirely by insisting the event occurs well into the vacuum chamber. For any that survive this test, there are a variety of others (notably target-pointing) that will also serve. $K_L^\circ \to \pi^\pm\mu^\mp\nu$ are also eliminated handily, mainly by a cutoff on the visible energy. $\Lambda \to p\pi^-$ do not give masses in the K mass region.

Fig. 2 shows the results of a Monte-Carlo simulation of the experiment. Note that the background lies entirely below the K° mass. This feature is a benefit of the high bending power used in this spectrometer, and is explained in more detail in Appendix A. The Monte-Carlo program took into account multiple scattering (including the detailed structure of the chambers) and misalignment (assumed to be 0.1 mm.). Unless this estimate is unduly optimistic, it indicates that the experiment is capable of detecting a branching ratio as low as 10^{-9}. If the mode is not observed, the upper limit should be about as good as the results of reference 3 for the K_L° mode.

No event quality criteria have been imposed on these simulated events. As most of the events came from π-μ decays in or after the magnet, the best tests (target-pointing and vertex intersection) help very little. However, most of the high mass events come from the high energy tail of the K° spectrum; an energy cut at 140 GeV would eliminate over half of them, while sacrificing only about 5% of "real" events.

Appendix A - Effect of π-μ Decay on Mass Measurement

Although our spectrometer has somewhat poorer mass resolution than that employed in lower-energy versions of this experiment, by using a high magnetic bend it eliminates some of the difficulties with π decays in flight. This can be seen by examining the expression for effective mass in the high energy limit ($p \gg m$, $\theta \ll 1$)

$$M^2 = P_1 P_2 \theta^2 + m_1^2 (1 + \frac{P_2}{P_1}) + m_2^2 (1 + \frac{P_1}{P_2})$$

where θ is the opening angle between $\vec{P}_1$ and $\vec{P}_2$.

The relative size of the terms depends solely on the c.m. decay angle. For $K_{\pi 2}$, the last two terms contribute at least .078 GeV^2, in a 90° c.m. decay. At any other angle these terms are larger. If the event is interpreted as a two-μ decay, substitution of m_μ for m_π drops this term by at least .034 GeV^2, a drop in mass of 40 MeV. Substantial errors in momenta and angles are required to get it back up in the K° mass region.

The π-μ decay introduces two kinds of errors

(1) The momentum of the μ is lower than that of the π.

(2) The muon is given an angular "kick".

These errors are correlated in a most fortunate way. As the reader may verify for himself by expressing the first term in terms of c.m. decay angles of the two pions, a decay that occurs before the magnet ordinarily reduces this term, and never increases it sufficiently to get back to the K mass region.

More dangerous is a decay in or shortly after the magnet, which gives a false momentum reading. In the popular parallel-focus decay spectrometers, the transverse momentum introduced by the magnet is equal to the decay product momentum in the K center of mass - thus, a π-μ decay can lead to a false momentum

reading as high as $\Delta P/P = 29.6/235 = .12$. Two decays both in the direction to give high momentum values can lift the mass back into the K mass region. In our spectrometer, with a 1 GeV magnet transverse momentum, this kick can give at most a 3% error. In the most unfavorable situation, this raises the effective mass to .469 - still 6 standard deviations from the K peak.

Appendix B - Hadron Veto Design

The hadron veto wall consists of 12 slabs of iron, each 120" x 21" x 8", stacked to a total thickness of 96". It contains two complete planes of scintillation counters, one behind the entire wall and one behind the third layer. A "muon" signal consists of a coincidence between the two layers, plus the requirement that the signal in the first layer be below a preset threshold, to eliminate high energy hadrons by detecting the cascade they produce.

To predict the ability of such a device, to reject hadrons, one must know two factors

(1) the probability that a hadronic shower will penetrate deep enough to give a count in the back counter ("punch-through")

(2) the probability that the shower will give a signal below the threshold of the front counter ("mis-fire")

Data to estimate factor (2) was obtained experimentally, from data tapes from the Echo Lake Cosmic Ray calorimeter, kindly lent by Dr. John Learned. This device consisted of 1200 gm/cm^2 of iron, with scintillation counters at ten depths. It was used to observe hadronic showers in the range 70 to 600 GeV. The data shows that the shower reaches its maximum development at a depth of 350 to 450 g/cm^2, this position varying slowly with energy, and the signal at this point is about one equivalent minimum ionizing track per

GeV incident energy. We set a threshold of 10 equivalent tracks. After subtracting an energy-independent effect, the probability that the incoming hadron penetrates to the level of the counter without having its first interaction, we found the remaining "no-fire" probability scaled as $E^{-.7}$. Though the reliability of extrapolating formula below 70 GeV is questionable, it is only in the higher energy region that the count rate in the back counter becomes high enough to make the shower counter essential. The extrapolated probability of shower counter "misfire" is the top curve on Fig. 3.

To determine punch through probabilities, the Echo Lake shower development curves were extrapolated from their maximum depth (about 1200 g/cm^2 of iron) to our depth of 1900. The reliability of this extrapolation is questionable, but it agrees fairly well with the Monte-Carlo results of M. Awschalom at NAL. At great depths of iron, a point is ultimately reached where the tail of the cascade is dominated by fast muons, which range out slowly; this is why simply making the wall thicker is not the best way to obtain a 1% filter. To estimate this contribution, we noted that fast pions exist mainly in the region near the peak of the cascade. Their number is nearly proportional to primary energy, and thus their mean energy remains at about 2 to 3 GeV, changing slowly with primary energy. Decay muons from these pions have ranges comparable to the thickness of the remainder of the wall. Numerically, this crude model gives a fast muon contribution of $2 \times 10^{-4}\ E_o$, which is added to the extrapolated calorimeter curves.

The results are shown in Fig. 3. The high miss rate above 120 GeV could prove quite annoying, as there are many protons from Λ decay in this energy region. To suppress this further, further calorimeter layers can be used. A single counter 12 inches wide near the beam axis will intercept most of

the shower from hadrons above 60 GeV. The effect of one such counter at a depth of 800 g/cm^2 was included in the estimate of trigger rates.

These estimates of efficiency do not take into account correlations, which must certainly exist; for example, a late-starting cascade is also more likely to punch through. Thus, one can expect the performance of this device to be worse than these calculations imply.

Finally, the shower counters will occasionally register an electromagnetic cascade triggered by a muon. Processes that contribute to this include Bremsstrahlung, knock-ons, and direct pair production. Examining the usual Bhabba-Heitler shower theory, only showers of greater than about 1 GeV generate enough electrons to trigger the shower counter. An expression was obtained for the distance over which the shower exceeds 10 electrons, as a function of incident energy, and integrated over the cross sections for these processes given in Rossi, High Energy Particles. The results are summarized in the table below. Averaged over the entire spectrum, losses should be somewhat less than 1%, comparable to those from chamber inefficiencies.

LOSS RATE OF MUONS DUE TO ELECTROMAGNETIC CASCADES INDUCED IN SHOWER COUNTER

E_μ	Bremsstrahlung	Pair Prod.	Knock-ons	Total
10	3.9×10^{-4}	1.8×10^{-5}	1.7×10^{-4}	6×10^{-4}
30	1.2×10^{-3}	5.9×10^{-4}	2.9×10^{-4}	2.1×10^{-3}
60	1.9×10^{-3}	4.8×10^{-3}	3.2×10^{-4}	6.0×10^{-3}
100	2.7×10^{-3}	2.2×10^{-2}	3.6×10^{-4}	2.5×10^{-2}

References

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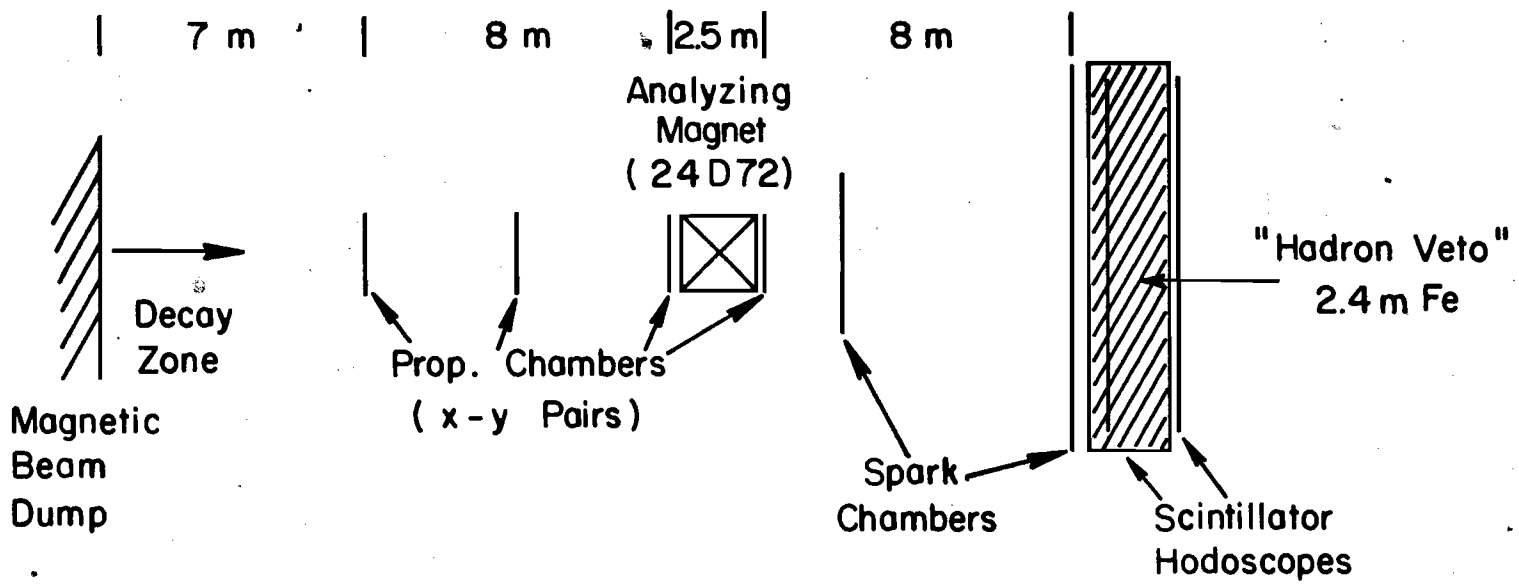
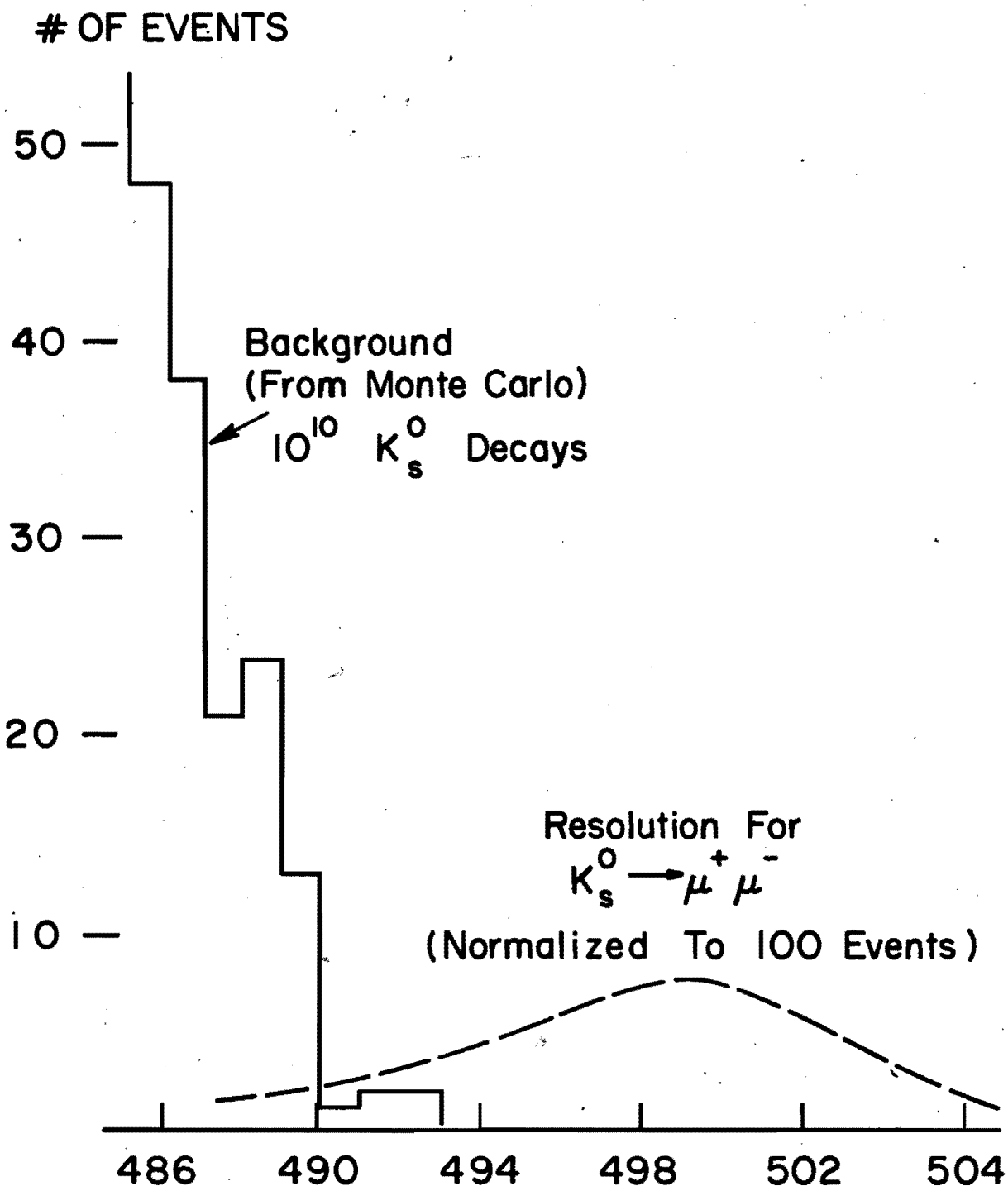
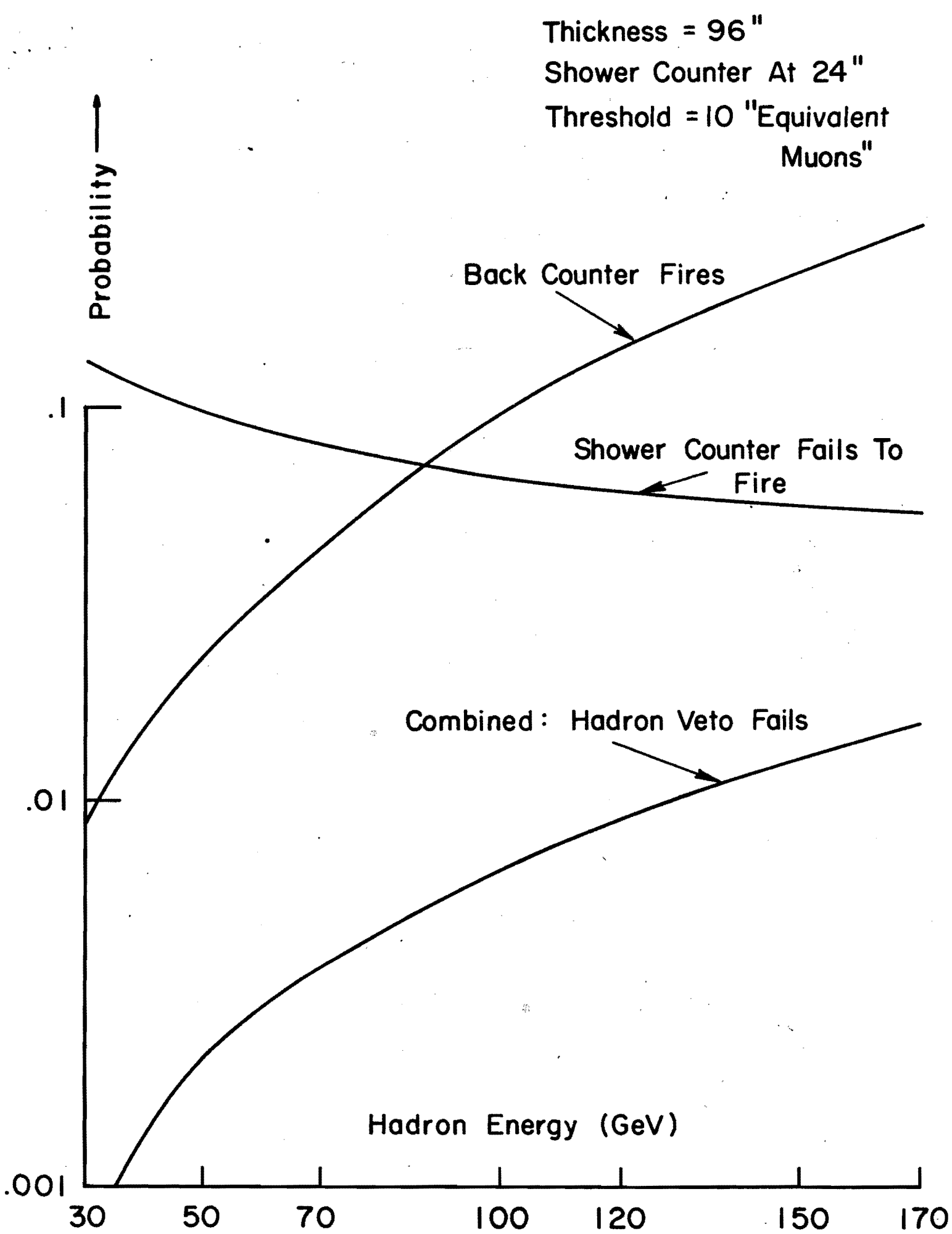
2. Banner, et al;Phys. Rev. Letters 21, 1103 (1968); and Arnold, et al; Phys. Letters 28B, 56 (1968).
3. A. Clark, et al; Phys. Rev. Letters 26, 1667 (1971).
4. B. D. Hyams, et al; Phys. Letters 29B, 521 (1969).
5. N. Christ and T. D. Lee; Phys. Rev. 4D, 209 (1971).
6. G. D. Demeester (thesis); University of Michigan, UM-HE-71-5.



TRANSVERSE DIMENSIONS EXAGGERATED 4/1


OF EVENTS
50
40
30
20
10
Background
(From Monte Carlo)
10^{10} K_s^0 Decays
Resolution For
$K_s^0 \rightarrow \mu^+ \mu^-$
(Normalized To 100 Events)
486
490
494
498
502
504


Thickness = 96"
Shower Counter At 24"
Threshold = 10 "Equivalent Muons"
Probability
Back Counter Fires
Shower Counter Fails To Fire
Combined: Hadron Veto Fails
Hadron Energy (GeV)
.1
.01
.001
30
50
70
100
120
150
170