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Physics with Low Energy Hadrons

Gaston Guttierez

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Laurence Littenberg

Brookhaven National Laboratory, Physics Department
Upton, New York 11973

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Gaston Guttierez[(a)], Laurence Littenberg[(b)]

(a) *Fermi National Accelerator Laboratory*
Batavia, IL 60510

(b) *Brookhaven National Laboratory*
Physics Department,
Upton NY, 11973, USA

Abstract. The prospects for low energy hadron physics at the front end of a muon collider are discussed.

I INTRODUCTION

The front end of a muon collider as conceived for the purposes of this workshop, is pretty close to the classical idea of a kaon factory. For example, the late lamented KAON [1] was to have been a $30\,GeV$, $100\mu A$ machine. This is to be compared with $16\,GeV$, $60\mu A$ for the machine under discussion. Table 1 shows how this facilities compares with other sources extant, under construction or proposed.

TABLE 1. Front end of the muon collider compared with other multi-GeV fixed target proton sources. 'TP' means trillion protons.

Machine:	AGS	AGS'	FMI	JHF	FMCFE
$p(GeV/c)$:	25	25	120	50	16
Duty factor:	0.33	0.27	0.33	0.16	0.90
TP/sec:	20	30	10	60	400
average forward K_L:	$1.3\ 10^9$	$2\ 10^9$	10^9	$3.8\ 10^9$	$25\ 10^9$
2 body acceptance:	.02	.02	.10	.04	.013
"K_L sensitivity":	26	40	100	150	325
K^+ stop:	12	18	8	47	210

AGS' is the expected performance of the AGS in 2000. FMI and JHF indicate the design parameters of the Fermilab Main Injector and the Japan Hadron Facility 50 GeV PS. Most of the entries are obvious, but there are a few slightly obscure measures of usefulness. The average forward K_L are the number of expected K_L per second in a 'typical' modern 0^o beam. Where possible this is guided by actual experience at similar energy facilities. Similar remarks apply to the two body acceptance entries, although these particular numbers may be slightly unfair to the lower energy accelerators. The K_L sensitivity row is simply the rescaled product of the two rows above it. These numbers give some idea of the relative reach of the accelerators for studying two-body K_L decays. The last row gives a relative measure of the stopping K^+ intensity possible, assuming the use of a 0^o separated beam. None of the entries in the table have any account of subtleties like background rejection, but they give a rough idea of the situation. The front end of a muon collider has the potential to push certain experiments beyond what can be done, even at the most intense facilities now being planned. Of course one has to do a lot of work to establish whether this is true for any particular experimental target.

II HADRON PHYSICS

'Hadron physics' covers a lot of ground, from subjects deep in the bosom of nuclear physics to ones still generally classified as particle physics. However the line is always shifting monotonically so that more and more of this area is considered nuclear. The fact that it is generally on the border between these two fields has led to problems. Unlike political entities where border territories are jealously competed for, in physics, the border enclaves tend to suffer from neglect. This has led to a lot of people being dispossessed. Gregg Franklin [2] gave an excellent summary of a number of these topics, so we can afford to give most of them short shrift in this report. In our working group we had talks by Kam Seth and Hal Spinka. The former noted that there's about an order of magnitude advantage of the FMC front end over the AGS for K^- and $\bar{p}$ production below about $5\,GeV/c$. This is quite inspiring to workers in hadron physics. A very interesting use for such enhanced flux was advocated by Hal Spinka.

A Polarized anti-protons

Spinka reported on an idea for making and exploiting a polarized anti-proton beam. It is based on the observation that $\mathcal{O}(1\,GeV/c)$ anti-protons elastically scattered off protons at finite angle are observed to be polarized, at levels up to 50% [3]! However most of the cross section is at small t, where the polarization is rather smaller. Nonetheless quite respectable polarizations can be achieved in this way. Figure 1 shows a conceptual drawing of such a polarized $\bar{p}$ beam.

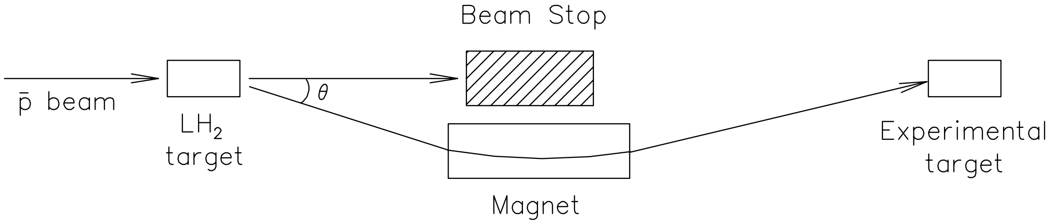

FIGURE 1. Polarized proton beam.

The spin of the $\bar{p}$ will be perpendicular to the scattering plane, and the magnetic field direction is such that it does not precess. To maximize the flux, Spinka envisioned a toroidal geometry with the acceptance centered around $-t \sim 0.12\, GeV/c$. He made a Monte Carlo simulation trying to stick to practical (but not fully optimized) design parameters. For incoming $\bar{p}$'s with $\Delta p/p = \pm 5\%$, spot size $= \pm 1$ cm, and divergence $= \pm 5$ mr, a 10 cm liquid hydrogen target, and defining good events as those with a trajectory passing within ± 2 cm of the beam radius and ± 5 cm in z at the experimental target, he found an $\bar{p}$ intensity of 2×10^{-4} per incident $\bar{p}$. The average polarization was 20%. This is clearly one of the programs that could benefit from the full intensity of the FMC front end. Using $375 TP$ of $16 GeV/c$ protons, one should be able to make on the order of $50,000$ polarized $\bar{p}$'s/second in this way.

There is quite an extensive menu of physics that could be done with such a facility. There are five $\bar{N}N$ elastic amplitudes and two isospin states; ≥ 20 spin parameters must be measured at each angle and energy for a full amplitude determination. Using a polarized proton target, one could measure P, C_{NN}, C_{SS}, C_{LL}, and C_{SL} for $\bar{p}p \rightarrow \bar{p}p$ and $\bar{p}p \rightarrow \bar{n}n$. Using quasielastic scattering from a polarized deuterium target, one could measure these same quantities for $\bar{p}n \rightarrow \bar{p}n$. Other measurements that could be made simultaneously are $\Delta\sigma_L(\bar{p}p)$ and $\Delta\sigma_T(\bar{p}p)$ for $\bar{p} \rightarrow \pi^+\pi^-, K^+K^-$ and other reactions.

Other areas where high-quality antiproton beams would be welcome are the study of $\bar{p}$ forward scattering parameters, and the time-like form-factor of protons.

B Proton-induced reactions

Kam Seth showed us data from tests of QCD scaling laws, where the ratio of $\frac{d\sigma}{dt}$ was divided by the expected s^{10} factor. The ratio exhibits fascinating oscillations when plotted against $ln(s)$. This is said to be related to the phenomenon of color transparency, another possible target of studies at the FMC front end. Both these kinds of studies were dropped rather than completed by high energy physicists in the past. The problems they addressed were not really solved, but were victims of an insufficiently long attention span.

Another subject discussed by Seth was parity non-conservation in polarized pp interactions. This is allowed by interference between strong and weak interactions, but is predicted to be very small: $|A_L| \equiv |(\overrightarrow{\sigma} - \overleftarrow{\sigma})/(\overrightarrow{\sigma} + \overleftarrow{\sigma})| \approx 10^{-7}$. This is indeed found to be the case at low energy, but there is one high energy ($6\,GeV/c$) measurement from Argonne [4] which gives $A_L = (26.5 \pm 6.0 \pm 3.6) \times 10^{-7}$. Obviously confirmation is needed, and indeed the entire range above $1\,GeV/c$ should be mapped out. This is an example of a very provocative result that has not been followed up.

C Spectroscopy

Both Seth and Spinka talked about spectroscopy. There has been renewed interest in baryon spectroscopy, mainly because of the advent of new facilities, CLAS at TJNAF and the Crystal Ball at the AGS. The latter program will very probably end in 1999, largely closing the door to the use of hadronic probes in this area. Since the use of hadronic and leptonic probes are complementary, this represents a difficulty for the field, and the loss of a good opportunity. The baryon spectrum needs to be better nailed down. Very basic problems have to be addressed. These include the effective degrees of freedom (3 quarks? quark-diquark?...), how the gluon degrees of freedom are exhibited in the baryon spectrum, the presence or absence of exotic baryons, and the origin of the apparent clustering of baryon states.

Spinka recommended a long program based on two detectors. One would specialize in all-neutral states and the other would have large solid angle acceptance with momentum analysis for charged particles. The latter might include neutrals detection at some level. Ideally, the program would include polarized target measurements. For the most part, this program does not require a large fraction of the flux available at the FMC front end.

Seth discussed meson resonances. He mentioned the recent observation of a candidate for an exotic meson at BNL [5]. There are also of course candidates for glueballs. No type of candidate is exactly where the theorists would like it, but they are probably not out of reach of revisions to the theory. However even assuming theory embraces these objects, there is still a raft of other predicted objects to be found. These include glueballs of higher mass and spin, and strangeonium hybrids in the $2\,GeV$ region that would be relatively narrow. All could profitably be studied at the FMC front end, and for the most part using only a small fraction of the available protons.

D Some General Comments on Hadronic Physics

There's something about this area that makes high energy physicists uncomfortable; maybe it reminds us of unfinished business that we dropped in the rush to the frontier. The more patient intermediate energy types are happy to clean up after us, if only we give them the chance.

Although it is clear there are subjects in this area that require the full intensity of the FMC front end, most can make a lot of progress using only a small fraction of this flux. It's more a matter of having good beamlines and detectors and reliable running time. In other words, they mainly need a home.

III K DECAYS

Certainly one of the most compelling area of physics that could be addressed by a machine with the parameters under discussion is K decay, although this may not be true by the time it is actually built. Most of the discussion in our working group concerned this area.

A $K \to \pi\nu\bar{\nu}$

The most interesting subject in K decays these days is the pursuit of the GIM-suppressed flavor-changing neutral current processes $K \to \pi\nu\bar{\nu}$. In these decays short distance effects are not tiny corrections to a large leading order term, but totally dominate the rate. Long distance contributions are negligible [6], and hadronic matrix elements can be calculated to $\sim 1\%$ accuracy from the rate of the common $Ke3$ decay [7]. In the Standard Model, the amplitudes are dominated by terms proportional to V_{td} [8], a crucial quantity not easy to measure. The charged mode is sensitive to $|V_{td}|$. A next-to-leading-logarithmic order calculation of QCD corrections has been done [9], and it is known that $B(K^+ \to \pi^+\nu\bar{\nu})$ can give $|V_{td}|$ to 5%, assuming that other SM quantities such as m_t are tied down. Under broad assumptions [10], the neutral mode is essentially a pure CP-violating transition, with a completely negligible indirect (ϵ) component [11]. Unlike the charged mode, there is essentially no charm contribution. A measurement of its rate would yield an unambiguous determination of η, modulo m_t, etc. Combining measurements of the neutral and charged rates determines the unitary angle β, independent of data from the B system [12]. Figure 2 show the relationship between the unitarity triangle and the two kaon FCNC rates. The current ranges of prediction for $B(K^+ \to \pi^+\nu\bar{\nu})$ and $B(K_L \to \pi^0\nu\bar{\nu})$ are is $(0.6 - 1.5) \times 10^{-10}$ and $(1 - 3) \times 10^{-11}$ respectively. The uncertainty in each case is given almost entirely by lack of knowledge of the input parameters. These decays compare very well in theoretical cleanliness with those measurements in the B system that have been widely advocated for determining the angles of the unitarity triangle

Besides measuring the magnitude and phase of V_{td} with unique "cleanliness", and with systematics completely different from those of B experiments, it has lately been emphasized that to understand the effects of possible new physics beyond the Standard Model in the B system, it will be essential to measure $K \to \pi\nu\bar{\nu}$ [10,13] as well.

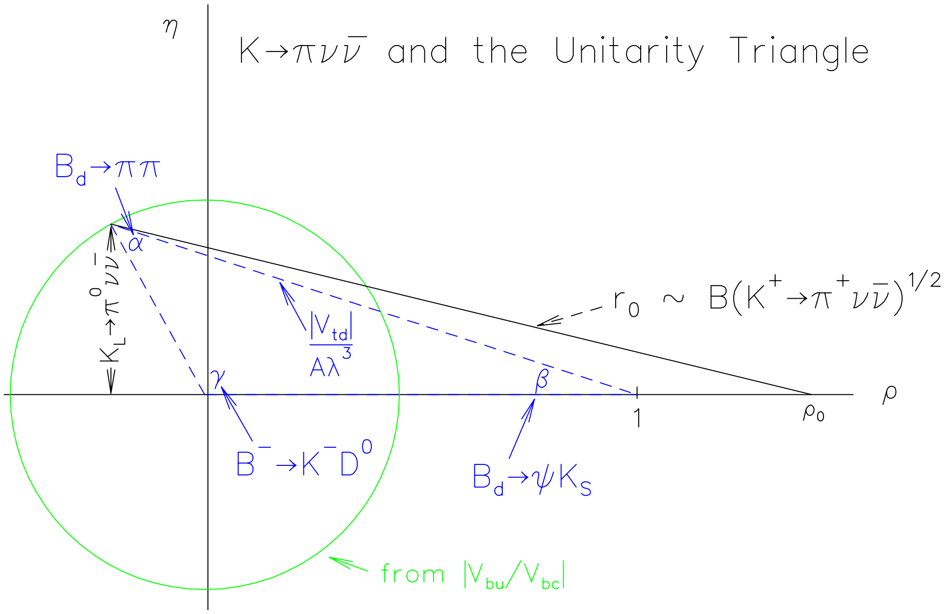

FIGURE 2. Diagram illustrating the relationship of the charged and neutral FCNC kaon decay $K \to \pi\nu\bar{\nu}$ rates to the unitarity triangle. The height of the triangle is proportional to $B(K_L \to \pi^0\nu\bar{\nu}$.

1 *Experimental status and prospects of $K \to \pi\nu\bar{\nu}$*

For more than ten years, the E787 collaboration at the AGS has been pursuing $K^+ \to \pi^+\nu\bar{\nu}$, using a solenoidal magnetic spectrometer in a stopping K^+ beam. This group recently published evidence for the first observation of this decay [14]. The corresponding branching ratio was $(4.2^{+9.7}_{-3.5}) \times 10^{-10}$, consistent with the above-mentioned SM range. E787 has collected data corresponding to about 2.5 times that of the sample containing the first event, and plans to continue to run at least through 1999. This should allow the observation of a few events at the Standard Model level. Beyond this, a proposal for continuing the study of $K^+ \to \pi^+\nu\bar{\nu}$ into the AGS-2000 era is being prepared [15]. The intention is to collect $15-20$ events at the SM level. Work is also in progress on a proposal to study this decay in an in-flight geometry at the Fermilab Main Injector [16].

There have as yet been no dedicated searches for $K_L \to \pi^0\nu\bar{\nu}$, but the KTeV group at Fermilab has recently reported a preliminary result from a special one-day run in a configuration customized for this decay [17]: $B(K_L \to \pi^0\nu\bar{\nu}) < 1.8 \times 10^{-6}$ at 90% *c.l.* This group expects to reach the level of a few times 10^{-8} by 1999 [18]. Thereafter, they plan to reconfigure and upgrade their apparatus for working at the Main Injector. They have an Expression of Interest for an experiment aimed at collecting several tens of $K_L \to \pi^0\nu\bar{\nu}$ events [19]. There is also an approved AGS proposal [20] for an experiment scoped to collect $\sim$ 70 events, which will be discussed below. In addition, there is an approved proposal to search for this decay at KEK [21]

2 $K^+ \to \pi^+ \nu \bar{\nu}$ at the front end of the FMC

Fig 3 shows the apparatus [22] of AGS Experiment 787, a solenoidal spectrometer situated in a $\sim$ 700 MeV/c separated K^+ beam. About 7×10^6 K^+ per AGS spill enter the detector, accompanied by about 2×10^6 pions and muons. The beam strikes a BeO degrader and approximately one quarter of the K^+ penetrate it unscathed and stop in a highly segmented scintillating fiber target. After a $2\,ns$ delay, the detector becomes sensitive to unaccompanied pions exiting the target transversely. These are momentum analyzed by a small, low-mass drift chamber immersed in a $1\,T$ magnetic field, and penetrate a cylindrical array of scintillators and straw chambers ("range stack"), in which they come to rest. The range stack scintillators are read out at both ends by photomultipliers instrumented with 500 MHz, 8-bit transient digitizers. These are used to detect the characteristic $\pi \to \mu \to e$ decay chain. This distinguishes pions very effectively from muons which lack the first step in the chain. An important design principle of the experiment was the minimization of "dead" material, allowing the use of the comparison of range, momentum, and kinetic energy as a powerful means of particle identification. The kinematic and life-cycle methods of particle identification can be used in turn to establish each other's rejection power. Excellent muon rejection power is needed because a major background to $K^+ \to \pi^+ \nu \bar{\nu}$ is $K^+ \to \mu^+ \nu$, whose rate is almost ten orders of magnitude larger than that of the signal.

Surrounding the range stack is a cylindrical array of lead-scintillator shower counters (the "barrel veto") and plugging the upstream and downstream ends of the detector are pure CsI endcap photon vetoes. In addition there are a number of supplementary vetoes in the beam direction. These complete a hermeticity that achieves a 10^6 rejection of π^0's. This is necessary since a second major background to $K^+ \to \pi^+ \nu \bar{\nu}$ is $K^+ \to \pi^+ \pi^0$. The background-rejection power of the experiment has proved quite adequate to reach the Standard Model level of sensitivity.

The main limitation on the experiment is instantaneous detector rate. This leads to both random veto losses and eventually to problems with background rejection. However to the extent that additional protons are available, one can make an immediate gain in sensitivity/hour through increasing the duty factor of the AGS (currently 44%), by extending the flat-top (currently 1.6 seconds every 3.6 seconds). The sensitivity of the experiment increases proportionately, and no improvement in detector performance is required. One can also reduce the momentum of the beam, so that more of the incident K^+ actually decay in the target. This fraction is currently only about 25%. Since the detector rates are proportional to the flux of K^+ impinging on the BeO degrader, but the sensitivity is proportional to the flux of K^+ penetrating it and stopping in the target, this will clearly help. Both increasing the duty factor and reducing the beam momentum require using more of the AGS protons. However, since the experiment uses only about 25% of the presently available proton flux, and the AGS intensity is expected to rise over the next couple of years, significant advances seem quite possible.

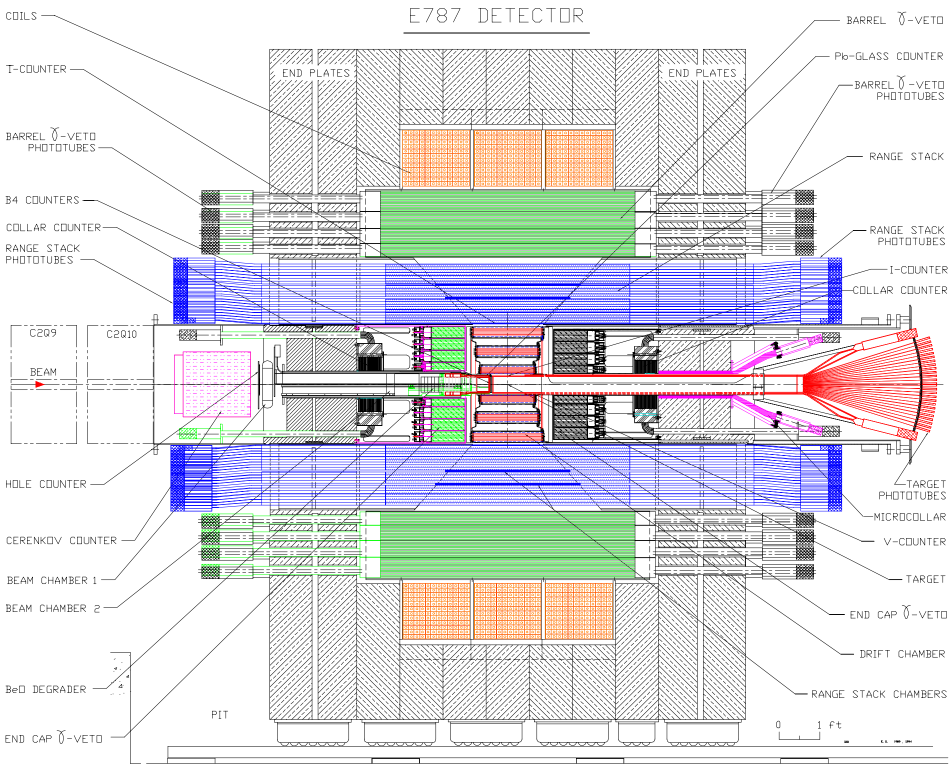

FIGURE 3. E787 detector, mounted in a 1-T solenoid. A ~ 700 MeV/c K^+ beam enters from the left, slows down in a BeO degrader and stops in a highly-segmented scintillating fiber target. Decay π^+ are momentum analyzed by a cylindrical drift chamber and stop in an array of scintillation counters and straw chambers. A barrel lead-scintillator array and CsI (pure) endcaps complete an hermetic photon veto.

Now as mentioned above, there are other improvements under study for the AGS-2000 time scale. All would be applicable to the front end of the First Muon Collider. We should say at the outset that for a low energy forward beam like that of E787, very little K^+ flux is lost in reducing the primary proton energy from the AGS's current $24\,GeV/c$ to the $16\,GeV/c$ of the FMC front end. Table 2 shows a list of possible expedients that could be applied to push the stopping K^+ technique at a higher intensity machine. The units of primary proton intensity shown are TP, *i.e.* trillion protons. The AGS provides a total of about $60\,TP$ per cycle at the moment, we assume that the front end of the First Muon Collider will provide $375\,TP/second$. The potential increase in flux is more than a factor 20, since the AGS pulses only once every 3.6 seconds, whereas the new machine would be practically DC. Note that in Table 2, not quite all the available protons are used.

TABLE 2. $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ from E787 to FMC front end

	sensitivity/year	protons required
How we think we're doing lately:	2×10^{-10}	$15\,TP/cycle$
Max spill, double year (to 30wks):	6×10^{-11}	$50\,TP/cycle$
Reduce beam p, use $\pi\nu\bar{\nu}2$:	2×10^{-11}	$100\,TP/cycle$
Go to MCFE (d.f. $0.73 \Rightarrow 0.9$):	1.7×10^{-11}	$25\,TP/\mathrm{sec}$
Further reduce beam p:	1.3×10^{-11}	$50\,TP/\mathrm{sec}$
Drop e from $\pi \Rightarrow \mu \Rightarrow e$:	9.5×10^{-12}	$50\,TP/\mathrm{sec}$
30 weeks ⇒ 45 weeks/year:	6.4×10^{-12}	$50\,TP/\mathrm{sec}$
Speed up vetoes:	3.2×10^{-12}	$100\,TP/\mathrm{sec}$
Reduce Δp, increase geom. acc.:	2.5×10^{-12}	$300\,TP/\mathrm{sec}$
Better beam/tgt instrumentation:	1.6×10^{-12}	$300\,TP/\mathrm{sec}$
Improved stopping cntr technology:	1.0×10^{-12}	$300\,TP/\mathrm{sec}$

Table 2 starts from E787's best guess as to current sensitivity per running year, which is optimistically taken to be 15 weeks long. The second line is the result of running twice as long, and of extending the spill by a large factor (improving the duty factor). The latter costs more than a factor 3 in proton current. The third line assumes that one reduces the beam momentum from the present 700 MeV/c to about 550 MeV/c, and also that one can exploit a large region of phase space that we have not yet accessed. This region corresponds to π^+ with momentum below that of the π^+ from the $K^+ \rightarrow \pi^+\pi^0$ background reaction (*i.e.* $p < 205/ > MeV/c$). This possibility is under study at the moment. If successful, it would allow one to collect about 5 Standard Model events per year, which is the goal of the AGS-2000 initiative. Going to the next line, one enters the world of the front end of the First Muon Collider. One immediately gets a small but significant improvement from the increased duty factor. The availability of so many more protons tempts one to further reduce the beam momentum, to get another small factor. Then, one can try to to drop the electron requirement from the $\pi \rightarrow \mu \rightarrow e$ decay chain criterion. This reduces the cut and deadtime losses significantly, but it requires a compensating improvement in the kinematic rejection of $K^+ \rightarrow \mu^+\nu$ events by about a factor 10. It is thought this can be obtained by upgrading the drift chamber. The next line assumes that one can run for 45 weeks/year at the front end of the First Muon Collider. Why not, since this is a virtual machine? At this point, one is collecting about 15 events/year assuming the central value of the Standard Model predicted range of branching ratio is correct. To make further progress, it is necessary to make major improvements to the detector. Note that one gets pretty far without this!

The next factor of two comes from speeding up the veto counters by a factor two. This would be achieved by replacing the current veto counter technology, and improving the electronics. The time resolution of the present vetoes is not state of the art, so this can certainly be accomplished if the resources are made available. Once the veto gates can be cut in half, one can turn up the wick by a factor two. The next small factor comes from reducing the beam momentum spread by a factor three (one has to compensate for this by increased proton flux), and reconfiguring the apparatus to have better geometrical acceptance. The last two factors come from improving the beam and target instrumentation (whose space and time resolutions could certainly be improved), thus reducing random veto and cut losses, and finally, replacing the present stopping counter technology by something faster, brighter and more granular. This brings one to 10^{-12}/event or $\sim$ 100 SM events/year, which is about as far as any technique so far proposed, and probably about as far as one needs to go until present theoretical uncertainties are reduced.

In our session there was a talk by Bob Tschirhart on the CKM initiative [16]. This is a possible FMI experiment in which $K^+ \to \pi^+\nu\bar{\nu}$ is studied in flight using a $22.8\,GeV/c$ RF separated beam. This technique turns out to be highly optimized for the high energy regime, and so is not directly adaptable to the FMC front end. However it is quite relevant to the subject at hand because the sensitivity goal of CKM is very similar to that on the bottom line of Table 2. This if CKM is successfully completed in a timely fashion, it may not make sense to pursue $K^+ \to \pi^+\nu\bar{\nu}$ at the FMC front end by the incremental technique described above. The virtue of that technique is that it is rather well understood. However if the state of the art at the point the FMC front end is ready as moved beyond 10^{-12}, a more aggressive (and imaginative) approach will have to be undertaken. This assumes that advances in theory make higher precision worthwhile.

3 $K_L \to \pi^0\nu\bar{\nu}$ at the front end of the FMC

Fig. 4 shows a conceptual drawing of a detector [20] proposed to search for $K_L \to \pi^0\nu\bar{\nu}$ at AGS-2000. It is assumed that when the RHIC collider comes online, the AGS will be free at least 20 hours a day for fixed target experiments. At that point, the available proton flux is expected to be 10^{14} per acceleration cycle. Using about half the available flux, in 80 weeks of running time, on the order of 70 $K^0 \to \pi^0\nu\bar{\nu}$ events could be recorded with a background contamination of less than 10 events. This would allow a precision on η of $< 10\%$ (modulo uncertainty in $|V_{cb}|$).

The principles of the experiment are as follows. First, the neutral beam is extracted at quite a large angle ($\sim 45^o$) so that both the neutron and kaon momentum spectra are quite soft. This minimizes the flux of neutrons that can produce π^0's through interactions with vacuum windows or residual gas. To further suppress background from this source, a vacuum of 10^{-7} Torr must be maintained throughout the beam region. Second, the beam is made highly asymmetric and very carefully collimated. Third, the AGS proton beam is microbunched on extraction with a period of $\sim 40\,ns$. The bunch width is $\leq$ 200 ps, allowing time-of-flight measurement to determine the neutral kaon's momentum. With this time bunching technique, the massless and other fast debris from the primary target interaction arrive at the detector before the kaons of interest, and so can be vetoed. Fourth, the detector incorporates active pre-radiators that measure the direction of the photons from the $K_L \to \pi^0 \nu\bar{\nu}$ decay. In conjunction with a high resolution calorimeter, this allows one to fully reconstruct the π^0, independent of any assumptions about the beam. Combined with the beam timing information, this allows one to transform the π^0 into the K_L center of mass. Pi-zeros from the major background to $K_L \to \pi^0 \nu\bar{\nu}$, $K_L \to \pi^0\pi^0$, have a unique energy in this system and so can be recognized. The fifth major requirement is hermetic photon vetoing. Extrapolating from photon vetoing performance achieved in E787, it is estimated that an average single γ rejection of $10^4 : 1$ is possible.

The independent kinematic and photon vetoing of $K_L \to \pi^0\pi^0$ background allow the power of each technique to be measured. This kind of redundancy is essential in measuring a rare decay mode with such a poor signature. With proper kinematic and vetoing selection, it should be possible to suppress the $K_L \to \pi^0\pi^0$ background to $\leq 10\%$ of the signal.

Other potential backgrounds are $K_L \to \gamma\gamma$, $K_L \to \pi^- e^+ \nu$, with the e^+ annihilating and the π^- undergoing charge exchange before they are detected, $\Lambda \to \pi^0 n$, and accidentals. These backgrounds have been calculated to contribute to less than 1 event each after 80 weeks of AGS 2000 running time.

Intensive simulation, design, prototype, and beam test work are underway on E926. However since the experiment is not yet built, much less run, any extrapolation to the front end of the First Muon Collider must be far more cautious than in the case of E787. Table 3 shows a possible progression.

TABLE 3. $K_L \to \pi^0 \nu\bar{\nu}$ from E787 to FMC front end

	sensitivity/year	protons required
Nominal estimate of E926:	1.2×10^{-12}	$50\,TP/cycle$
MCFE: Comfort factors/d.f.=0.9:	1×10^{-12}	$50\,TP/sec$
Longer beam		
Filter		
Tune angle/aperture		
Shorter decay volume, smaller beam:	5×10^{-13}	$200\,TP/sec$
Better time response, double rate:	3×10^{-13}	$375\,TP/sec$

There would be an immediate small factor as one exploited the 90% duty factor of the First Muon Collider front end. It would probably be wise to use the next factor of beam on what are labeled “comfort factors” in Table 3. These include a longer beam line for better time resolution and collimation, a

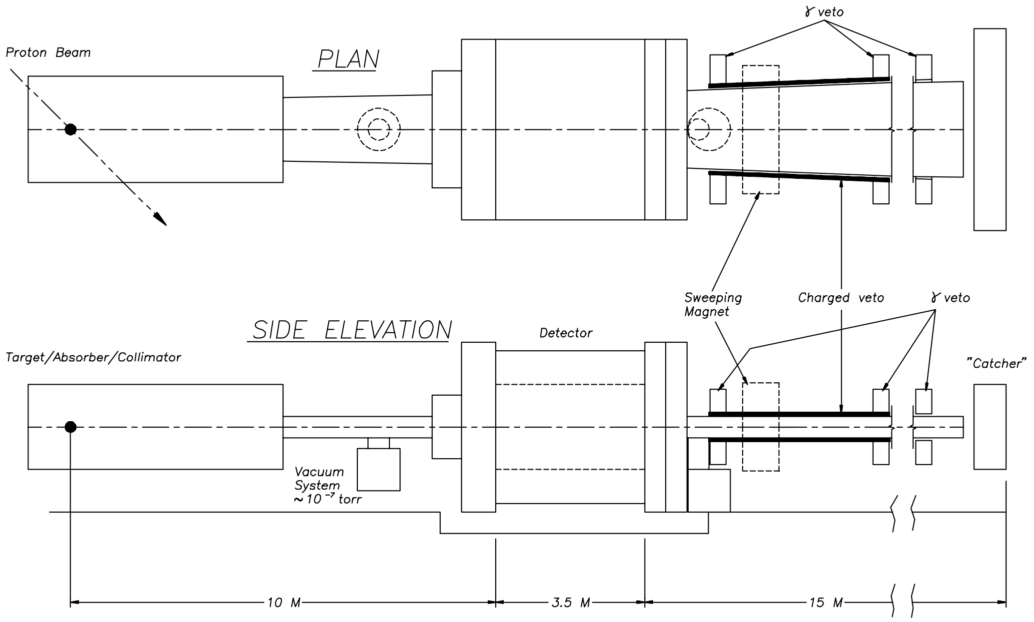

FIGURE 4. Schematic of the proposed 926 detector.

filter to differentially attenuate neutrons and very low energy kaons, and some scope for adjusting the production angle and aperture of the beam. One could then use additional flux by shortening the decay volume, thereby increasing the acceptance of the detector. Finally, if money were no object, faster photon detectors could be deployed so that more beam could be accommodated. This results in a rate of about 70 SM events per year. In a few years of running, in principle η could be determined to about 3%.

B CPT

Another experiment being considered for the Main Injection goes under the acronym 'CPT' [23]. Its primary purpose is to improve the current sensitivity to possible CPT-violation in the K system by a factor large enough to make it sensitive to Planck-scale effects. In particular they seek to measure the phase difference between η_{+-} and ϵ, and evaluate the Bell-Steinberger relation [24]. In addition they will measure CP-violation in $K^0 \to 3\pi$ decay and improve the CP-violation measurements in $K^0 \to \pi^+\pi^-\gamma$. They will also study rare K_S decays. Table 4 is a summary of their goals, compared to current data.

Figure 5 shows the proposed layout. The CPT experiment would share the RF separated K^+ beam with the CKM experiment mentioned above. They would run the beam, set at $25\,GeV/c$ and containing 2×10^8 K^+/pulse, into a W target where K^0's would be produced via charge exchange reactions. The resulting K^0 spectrum peaks at about $15\,GeV/c$. The beam passes through

TABLE 4. Summary of principle measurements of CPT.

	existing data	CPT experiment
ϕ_{+-}	$\pm 1^o$	$\pm 0.02^o$
Imx	$\pm 2.6 \times 10^{-2}$	$\pm 5 \times 10^{-4}$
$Im\eta_{+-0}$	$\pm 1.7 \times 10^{-2}$	$\pm 4 \times 10^{-4}$
$Im\eta_{000}$	$\pm 3 \times 10^{-1}$	$\pm 2 \times 10^{-3}$
$\lvert\eta_{+-}\rvert$	$\pm 1\%$	$\pm 0.1\%$
$\lvert\eta_{+-\gamma}\rvert$	$\pm 3\%$	$\pm 0.1\%$
$B(K_S \to \pi^0 e^+ e^-)$	$< 3.9 \times 10^{-7}$	$\sim 10^{-10}$

a 1.3m long hyperon magnet to remove charged particles and approximately 2000 K_L and 5000 K_S decays/pulse occur in a $14m$ decay tank. The decays are analyzed in a simple dipole spectrometer augmented by an electromagnetic calorimeter and muon detectors.

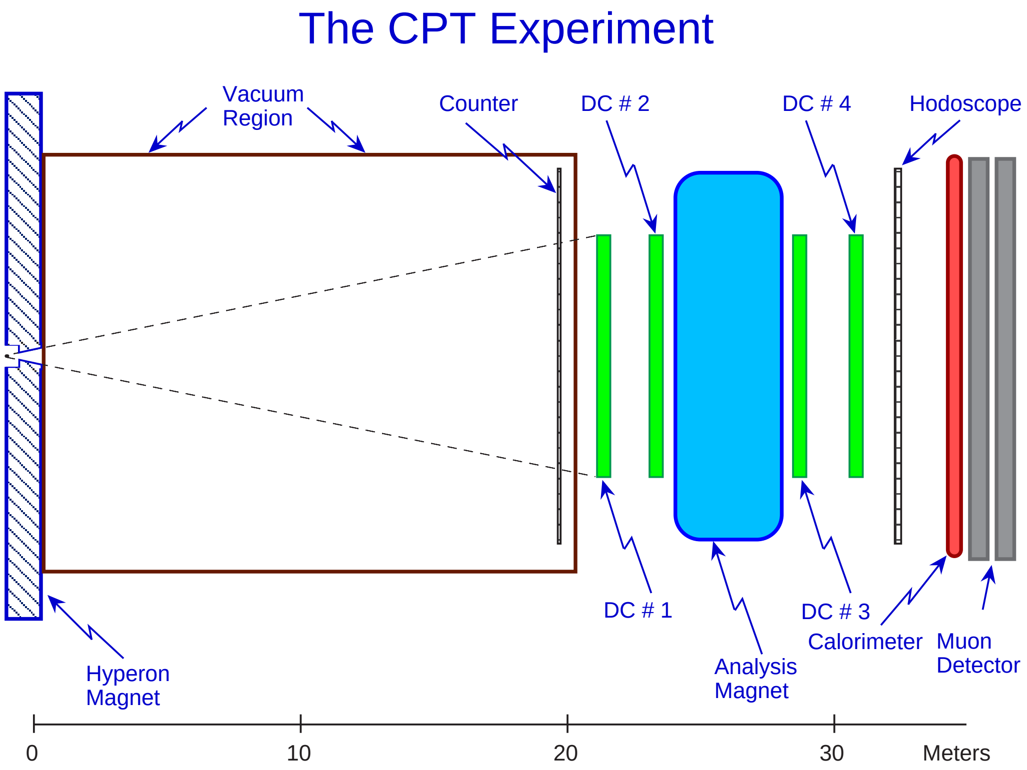

FIGURE 5. Schematic of the CPT detector.

Steve Schnetzer gave a presentation of CPT and discussed the possibility the experiment might be adapted to FMC front-end conditions. Unlike the cases of the other FMI kaon proposals, the answer for CPT is a qualified 'yes'. A certain fraction of the physics targets might remain accessible. Certainly the number of available K^+ is greater at the latter machine. Roughly speaking, the forward cross-section for $16\,GeV/c$ protons to produce K^+ of say $10\,GeV/c$ is about 1/12 of that for $120\,GeV/c$ protons to produce K^+ of $25\,GeV/c$. This is almost completely compensated by the greater charge exchange cross section at the lower energy. However the K_S decay loss is also greater at lower energies. Putting all the factors together, there is an optimum at $p_K \sim 6\,GeV/c$ where the relative number of K_S decays per incident primary protons is $\sim 80\%$ of that at the FMI. Since there are 40× more protons at the FMC front end, a good deal of the physics menu could be further advanced there. There are exceptions, however, such as η_{000}, where the poorer acceptance and photon definition of the lower energy incarnation are bound to hurt.

C Probing symmetry violations through μ polarization in K decay

1 T-violating μ^+ polarization in $K\mu3$ decay

The need for CP-violation in addition to that given by the SM in order to explain the observed baryon asymmetry of the universe [25] motivates investigating low-energy 'windows' where such effects are cleanly identifiable. The CKM model gives virtually no T-violating (out-of-decay-plane) polarization in $K^+ \to \pi^0\mu^+\nu$, allowing such a window. Moreover a number of popular attempts to go beyond the Standard Model predict a finite polarization at a level that is experimentally accessible [26].

If T is conserved, the $f_+(q^2)$ and $f_-(q^2)$ form factors that multiply the $(p_K + p_\pi)$ and $(p_K - p_\pi)$ terms respectively in the $K\ell3$ amplitude are relatively real. Therefore T violation is characterized by the size of the imaginary part of their ratio $Im\xi \equiv Im(f_-/f_+)$. This quantity is in turn approximately proportional to the component of polarization transverse to the $K\mu3$ decay plane, $\wp_T = (0.2 - 0.3)\,Im\xi$ depending on the phase space sampled.

Experiment 246 at KEK represents a new technique in the study of T-violating μ^+ polarization in $K\mu3$. It looks promising, but it has not quite proved itself yet. A second approach [27], being advocated for the AGS is to instead optimize the technique of most previous experiments of this type [28]. This was described by Hong Ma in his talk to our session [29]. Fig. 6 shows the layout of the proposed experiment. The source of K^+ is a $2\,GeV/c$ separated beam, a facility quite well suited to the FMC font end. Other improvements with respect to previous experiments include larger acceptance, more nearly complete reconstruction of the decays, finer polarimeter segmentation, and graphite, instead of aluminum, as polarimeter absorbing material. A beam of $\sim 2 \times 10^7$ K^+'s/pulse impinges on a decay tank in which about 5×10^6 decay. π^0 photons are detected in a "shashlyk" calorimeter and μ^+'s penetrate the calorimeter and are tracked into the polarimeter where they stop. When the muons decay, their daughter electrons are tracked through at least two segments of the cylindrically symmetric polarimeter. One is looking for differences in the rates clockwise-going and counter-clockwise-going muon decays. In this case, there are 96 segments as compared to 32 in Ref. [28]. To properly align the the decay plane with the detector, K^+ decays where the π^0 is directed along the beam and the μ^+ approximately perpendicular it in the K^+ center of mass are selected by the trigger. There is no spectrometer magnet, but a ~ 70 G solenoidal field is imposed on the polarimeter to precess the muons. The polarity of this field is reversed every AGS pulse. This technique is very effective in controlling systematic errors. The analyzing power of the polarimeter is calculated to be $\mathcal{O}(30\%)$ which is a large improvement over that of Ref. [28]. The expected statistical sensitivity of the experiment is $\sigma_{\wp_T} = \pm 0.00013$ in about 2000 hours of running. This corresponds to an uncertainty of roughly 7×10^{-4} in $Im\xi$. Systematic errors must be held below this level.

An order of magnitude greater $2\,GeV/c$ K^+ flux would be available at the FMC front end. About a factor 5 higher singles rates could be accommodated by the proposed apparatus. Perhaps the sensitivity of the experiment could be pushed even further by optimizing the beam. It might be necessary to further segment the polarimeter and make some other apparatus improvements to facilitate tighter control on systematics. Conservatively, one should be able to improve the proposed AGS measurement five-fold, which will yield $\sigma_{\wp_T} = \pm 0.000025$, a very worthwhile level indeed.

2 Polarization effects in $K^+ \to \pi^+\mu^+\mu^-$

Top-quark loops very similar to those which make $K \to \pi\nu\bar{\nu}$ sensitive to V_{td} occur in $K^+ \to \pi^+\mu^+\mu^-$ as well. However in the latter decay these are overwhelmed by much larger photon exchange effects. The calculation of the branching ratio and decay distribution is an interesting exercise in chiral perturbation theory, but not very revealing of short distance effects. However in the muon polarization such effects are not obscured, and there has been quite a bit of theoretical work on both SM effects and possible non-SM effects in this decay [30].

In the SM there is a parity-violating longetudinal polarization of the μ^+ that is sensitive to the CKM parameter ρ and that can be almost as large as 1% [31]. In principle ρ can be determined to $\sim \pm 0.06$ by such a measurement. This is however, quite an experimental challenge. The reaction $K^+ \to \pi^+\mu^+\mu^-$ has only recently been discovered by E787 at BNL [33], with a branching ratio of $(5.0 \pm 0.4 \pm 0.7 \pm 0.6) \times 10^{-8}$. To achieve a $\sim 20\%$ measurement of the μ^+ polarization asymmetry would require at least 8×10^7 events (there are presently about 600 in the world), or a single event sensitivity of about 5×10^{-15}. For an apparatus with 1% acceptance (including K^+ decay probability), which would not be easy, one needs to produce 1.5×10^{17} K^+. If one could

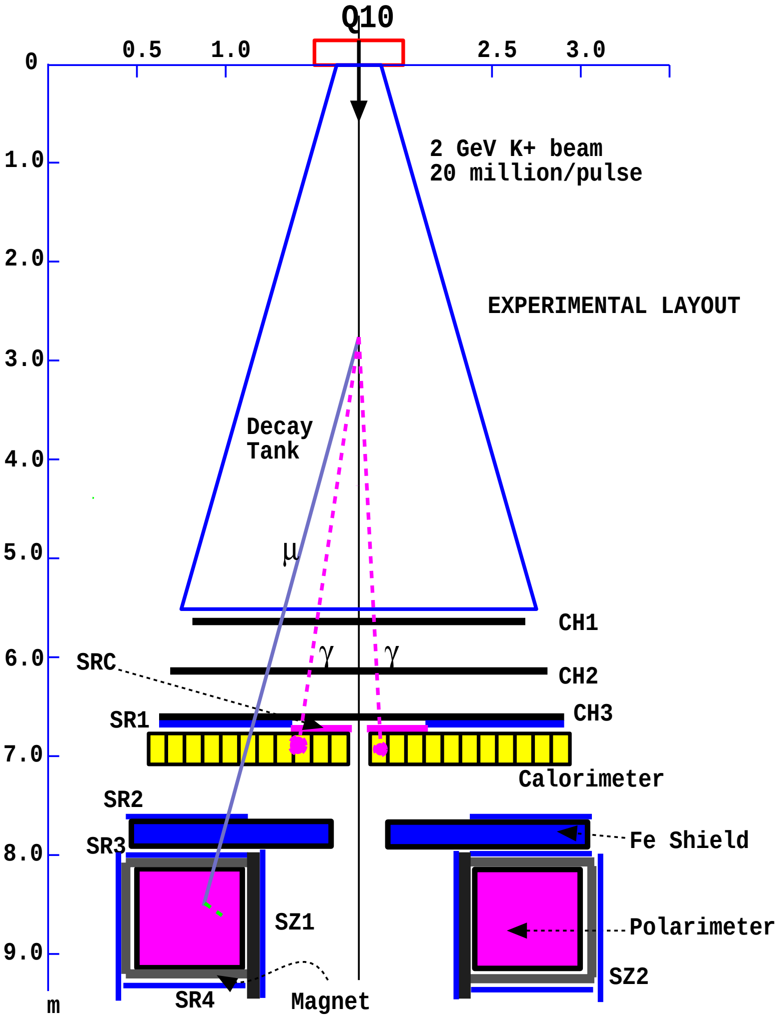

FIGURE 6. Schematic of the proposed 923 detector with a $K\mu3$ event superimposed.

run for a few years, one would need a beam of $\sim 5 \times 10^9$ K^+/sec. Such a beam is in fact possible, using the entire flux of the FMC front end. This is an experiment that might be a good match for the machine under discussion, given the probably timescale.

If this measurement seems insufficiently difficult, note that a measurement of the two-spin correlation between the μ^+ and the μ^-, is sensitive to CKM η [32], as well as non-SM CP-violating effects.

IV CONCLUSION

There's plenty of potential for interesting physics measurements at the front end of a muon collider. If it were completed tomorrow, there's no question it would be heavily subscribed and produce a raft of important results. However whether it is worth exploiting will be very subject to the vicissitudes of history and politics. Where would one be starting from? What other facilities are available? Also, in order for people to make the large commitment necessary to do these experiments, they would need to have some assurance that the machine would be available for this kind of work for an extended period. One can't expect users to come in, work for two years on extremely complex experimental programs, then pack up and go home because the muon collider needs the protons. Also, any sharing of the protons with the collider would immediately dilute the advantage factors of Table 1.

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