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# Can BNL-Style Studies of $K \rightarrow \pi \nu \bar{\nu}$ be pushed at the FEMC?

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**Abstract.** Techniques developed for studying  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  at the Brookhaven National Laboratory Alternating Gradient Synchrotron are briefly described. The applicability of these approaches at the front end of the First Muon Collider is assessed.

## I THEORETICAL MOTIVATION

It has long been appreciated [1] that the flavor-changing neutral current processes  $K \rightarrow \pi \nu \bar{\nu}$  are uniquely clean probes of short distance physics in  $K$  decays. Long distance contributions are tiny [2], and the hadronic matrix elements are given to  $\sim 1\%$  accuracy by the rate of the common  $Ke3$  decay [3]. In the Standard Model, the amplitudes are dominated by terms proportional to  $V_{td}$  [4], offering unique access to this elusive quantity. The charged mode is sensitive to the modulus of  $V_{td}$ . Now that a next-to-leading-logarithmic order calculation of QCD corrections has been done [5], its rate gives  $|V_{td}|$  to 5%, modulo knowledge of other SM parameter such as  $m_t$ . The neutral mode is essentially a pure CP-violating transition, with only a negligible indirect ( $\epsilon$ ) component [6]. It is even cleaner from a theoretical point of view than the charged mode. A measurement of its rate would yield an unambiguous determination of  $\eta$ , given knowledge of  $|V_{cb}|$  (the rate is actually proportional to  $[Im(V_{ts}^* V_{td})]^2$ ). The "true" theoretical uncertainty is only  $\sim 1\%$ . Combining measurements of the neutral and charged rates determines the unitary angle  $\beta$ , independent of the  $B$  system [7]. Figure 1 illustrates the relationship between the unitarity triangle and the two kaon FCNC rates. The current ranges of prediction for  $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  and  $B(K_L \rightarrow \pi^0 \nu \bar{\nu})$  are  $(0.6-1.5) \times 10^{-10}$  and  $(1-3) \times 10^{-11}$  respectively. The magnitudes of these ranges are almost entirely due to uncertainty in the input parameters such as  $|V_{cb}|$  and  $|V_{td}|$ . These decays

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compare favorably in theoretical cleanliness with  $B$  system measurements that have been proposed for determining the angles of the unitarity triangle

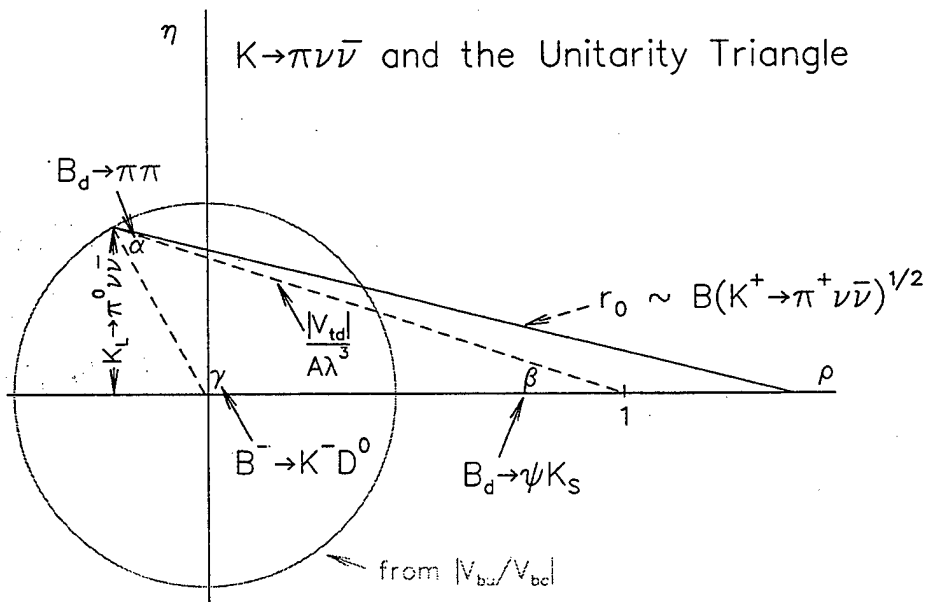


FIGURE 1. Diagram of the relationship of the charged and neutral FCNC kaon decay  $K \rightarrow \pi \nu \bar{\nu}$  rates to the unitarity triangle.

Beyond this, it has lately become clear that to understand the possible effects of new physics beyond the Standard Model in the  $B$  system, it will be essential to have these  $K$  measurements [8]

## II EXPERIMENTAL STATUS AND PROSPECTS

For more than ten years, the E787 collaboration at the AGS has been pursuing  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ , using a solenoidal magnetic spectrometer in a stopping  $K^+$  beam. This group recently published evidence for the first observation of this decay [9]. 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  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  into the AGS-2000 era is being prepared [10]. 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 [11].

There have as yet been no dedicated searches for  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ , 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 [12]:  $B(K_L \rightarrow$

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$\pi^0\nu\bar{\nu}$ )  $< 1.8 \times 10^{-6}$  at 90% *c.l.* This group expects to reach the level of a few times  $10^{-8}$  by 1999 [13]. 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  $K_L \rightarrow \pi^0\nu\bar{\nu}$  events [14]. There is also an approved AGS proposal [15] 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 [16]

### III $K^+ \rightarrow \pi^+\nu\bar{\nu}$ AT THE FRONT END OF THE FMC

Fig 2 shows the apparatus [17] of AGS Experiment 787, a solenoidal spectrometer situated at the end of a  $\sim 700$  MeV/c separated  $K^+$  beam. About  $7 \times 10^6$   $K^+$  per AGS spill enter the detector, accompanied by about  $2 \times 10^6$  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  $\sim 2$  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 1T 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  $\pi \rightarrow \mu \rightarrow e$  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  $K^+ \rightarrow \pi^+\nu\bar{\nu}$  is  $K^+ \rightarrow \mu^+\nu$ .

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  $\pi^0$ 's. This is necessary since a second major background to  $K^+ \rightarrow \pi^+\nu\bar{\nu}$  is  $K^+ \rightarrow \pi^+\pi^0$ . 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). This increases the sensitivity of the experiment

proportionately, without requiring any improvement in detector performance. Another expedient is to reduce the momentum of the beam, so that a higher fraction of the incident  $K^+$  actually stop and decay usefully in the target. This fraction is currently only about 25%. Since the detector rates are proportional to the  $K^+$  striking the BeO degrader used to slow the beam, and the sensitivity is proportional to the  $K^+$  penetrating the degrader and stopping in the target, one can clearly win in this way. Increasing the duty factor and reducing the beam momentum both require expending more of the AGS protons. Since the experiment uses only about 25% of the presently available flux, and the total AGS intensity is expected to rise over the next couple of years, significant advances seem quite possible.

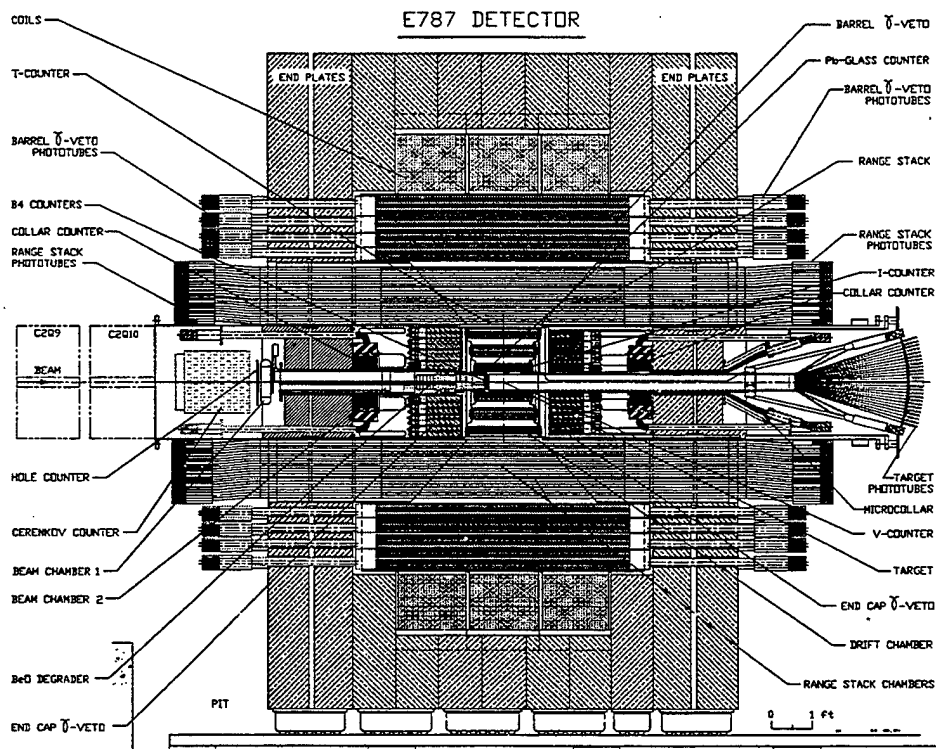


FIGURE 2. E787 detector, built into a 1-T solenoid. A  $\sim 700$  MeV/c  $K^+$  beam enters from the left, slows down in a BeO degrader and stops in a highly-segmented scintillating fiber target. Decay  $\pi^+$  are momentum analyzed by a cylindrical drift chamber and range out in an array of scintillation 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. I 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 1 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, and the front end of the First Muon Collider is supposed to 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 1, not quite all the available protons are used.

**TABLE 1.**  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  from E787 to FMC front end

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

Table 1 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  $\pi^+$  with momentum below that of the  $\pi^+$  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 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 relatively minor upgrades to 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 a combination of replacement of veto counter technology, and improvements to 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 possibly about as far as one needs to go until present theoretical uncertainties are reduced.

#### IV $K_L \rightarrow \pi^0 \nu \bar{\nu}$ AT THE FRONT END OF THE FMC

Fig. 3 shows a conceptual drawing of a detector [15] proposed to search for  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  at AGS-2000. It is assumed that upon the startup of the RHIC collider, the AGS will be free at least 20 hours a day for fixed target proton experiments. At that point, the available flux is expected to be  $10^{14}$  protons per acceleration cycle. Using about half the available flux, it is estimated that in 80 weeks of running time, on the order of 70  $K^0 \rightarrow \pi^0 \nu \bar{\nu}$  events could be recorded with a background contamination of less than 10 events. This would yield a precision on  $\eta$  of  $< 10\%$  (modulo uncertainty in  $|V_{cb}|$ ). The techniques for obtaining the required sensitivity and background rejection are as follows. First the neutral beam is extracted at a very wide angle ( $\sim 45^\circ$ ) to soften both the neutron and kaon momentum spectra. This minimizes the flux of neutrons above  $\pi^0$  production threshold that can produce background by interacting with vacuum windows or residual gas. To further suppress background from the latter, a vacuum of  $10^{-7}$  Torr must be maintained throughout the beam region. Second, the proton beam from the AGS is bunched on extraction with a time microstructure of period  $\sim 40$  ns. The rms bunch width is  $\leq 200$  ps to allow time of flight measurement to determine the neutral kaon's momentum to a few percent. The soft kaon spectrum ( $\bar{p} \sim 750$  MeV/c) is necessary for this to work. Also, 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 distinguished from the decay products of the latter. Third, the detector incorporates active shower pre-converters that allow measurement of the direction of the  $\pi^0$  photons coming from the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay. In conjunction with a high resolution scintillating fiber calorimeter, this allows one to fully reconstruct the  $\pi^0$ , independent of any assumptions about the beam. Finally, combining this with the beam timing information, one can transform the  $\pi^0$  into the  $K_L$  center of mass. The last major requirement is hermetic photon vetoing. Extrapolating from photon vetoing performance measured in E787, it is estimated that an average single  $\gamma$  rejection of  $10^4 : 1$  can be achieved. The main expected background to  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  is the 300-million-fold more frequent  $K_L \rightarrow \pi^0 \pi^0$  decay ( $K_{\pi 2}$ ). These events become background when two of the four final state photons are missed. If the two missed photons are from the decay of the same  $\pi^0$  ("even" case), then the detected pair will reconstruct properly to a  $\pi^0$  meson. The energy of this reconstructed  $\pi^0$ , in the rest frame of the  $K_L$ , will equal 248.84 MeV/c (modulo the resolution). If the two detected photons each originate from a different  $\pi^0$  ("odd" case), then they will not, in general, reconstruct to a  $\pi^0$  mass. In addition, the  $K_{\pi 2}$  events which evade the photon veto tend to have rather small values of missing energy and missing mass compared to signal events. Therefore, with proper kinematic cuts, one is able to suppress the  $K_{\pi 2}$  background to  $\leq 10\%$  of the signal.

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

The E926 proposal received scientific approval by the AGS PAC in October, 1996. Intensive simulation, design, prototype, and beam test work is underway.

Since E926 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 2 shows a possible progression.

TABLE 2.  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  from E787 to FMC front end

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

There would be an immediate small factor as one exploited the 90% duty

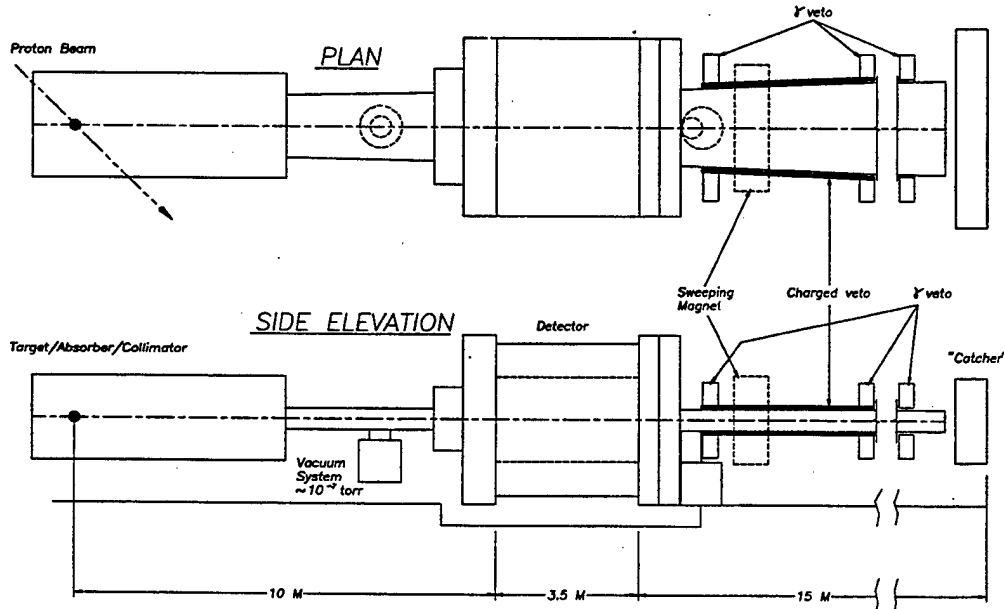


FIGURE 3. Schematic of the proposed 926 detector.

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 2. These include a longer beam line for better time resolution and collimation, a 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  $\eta$  could be determined to about 3%.

## V CONCLUSION

Techniques for exploiting high-intensity low energy kaon beams have been developed at Brookhaven for the study of  $K \rightarrow \pi^+ \nu \bar{\nu}$ . These emphasize measurement of all possible kinematic quantities, redundant methods of background rejection, hermetic photon vetoing and the use of deadtimeless electronics. Extending these techniques, the sensitivity achievable for both charged and neutral  $K \rightarrow \pi \nu \bar{\nu}$  at the front end of the First Muon Collider is excellent. The theoretical motivation for doing such searches is likely to remain very strong. The main open question is whether these branching ratios will not be already well-measured at other facilities, such as Japanese Hadron Facility or the Fermilab Main Injector, by the time the front end of the FMC

opens for business.

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