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Workshop on Physics at the First Muon Collider and Front–End of a Muon Collider: A Brief Summary

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Abstract. In November 1997 a workshop was held at Fermilab to explore the physics potential of the first muon collider, and the physics potential of the accelerator complex at the "front–end" of the collider. An extensive physics program emerged from the workshop. This paper attempts to summarize this physics program and identify the main conclusions from the workshop.

INTRODUCTION

Over the last couple of years a significant effort has been devoted to exploring the feasibility of designing a high–luminosity high–energy muon collider. This effort has been motivated by the theoretical prejudice that there is new physics beyond the Standard Model (SM) at the TeV energy scale, and that a multi–TeV lepton–lepton collider will be needed to make precision measurements at this new scale. An attractive feature of the muon collider concept is that muon colliders appear to be "stagable" with each stage offering a unique cutting edge physics program. Hence, the path towards a multi-TeV muon collider might be via one or more cheaper "demonstration" stages, each making a significant contribution to our understanding of particle physics. Candidate demonstration stages are (i) part or all of the "front–end" accelerator complex, (ii) a Z^0 factory offering at least an order of magnitude more Z^0s than LEP, (iii) a Higgs factory designed to produce Higgs-like particles in the s-channel if $m_H < 2m_W$, (iv) a WW factory ($\sqrt{s} = 2m_W$), (v) a $t\bar{t}$ factory ($\sqrt{s} = 2m_t$), (vi) a SUSY factory if supersymmetric states are found at LEP2, TEV33, or the LHC, or (vii) a Techni–factory, if Technicolor states are observed.

The Workshop on Physics at the First Muon Collider and Front–end of a Muon Collider was held at Fermilab from 6–9 November 1997. The goal of the

TABLE 1. Operational parameters of an upgraded Fermilab proton source for a Muon Collider. The right–most column shows parameters for the fully upgraded source, and the other columns for possible intermediate steps in the upgrade.

	Step 1	Step 1	Step 2	Step 3
Linac (operating at 15 Hz)	Scenario 1	Scenario 2		
Kinetic Energy (MeV)	400	1000	1000	1000
Pulse Length (μs)	0.75	0.75	0.75	0.75
H^- per pulse	1×10^{13}	1.5×10^{13}	2.5×10^{13}	1×10^{14}
Pre–Booster (operating at 15 Hz)				
Extraction Kinetic Energy (GeV)				4.5
Momentum Spread (95% FW)				0.5%
Circumference (m)				180.6
Protons per bunch				5×10^{13}
Number of bunches				2
Extracted bunch length (ns)				21
Transverse Emittance (mm–mr)				200π
Longitudinal Emittance (eV-sec)				1.8
Booster (operating at 15 Hz)				
Extraction Kinetic Energy (GeV)	16	8	16	16
Momentum Spread (95% FW)	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	1.2%
Circumference (m)	474.2	474.2	474.2	474.2
Protons per bunch	1.2×10^{11}	1.8×10^{11}	3×10^{11}	5×10^{13}
Number of bunches	84	84	84	2
Extracted bunch length (ns)	4.9	4.9	4.9	2.3
Transverse Emittance (mm–mr)	50π	30π	50π	240π
Longitudinal Emittance (eV-sec)	2.2	1.8	1.8	4.0

workshop was to explore the physics potential of each of the various options for the first muon collider (FMC), including the physics that could be pursued at the accelerator complex at the "front–end" of the collider. The accelerator parameters assumed for the workshop were based on recent studies of how the facilities at Fermilab might evolve towards a high-energy muon collider. A summary of these parameters can be found in Tables 1–3. Figure 1 shows in a schematic how the FMC might fit within the existing accelerator complex at Fermilab.

FRONT–END PARAMETERS AND PHYSICS

The "Front-End" of a muon collider consists of:

(a) A high-intensity proton source. We will assume that the proton source accelerates protons to 16 GeV/c, is cycling at 15 Hz, and produces 2 proton bunches per cycle, each containing 5×10^{13} particles. These parameters are based on the Fermilab summer study summarized in Ref. [1]. This upgrade to the existing proton source at Fermilab would require upgrading the 400 MeV Linac to a 1 GeV Linac, moving the 8 GeV Booster to a new location to overcome radiation limitations, upgrading the Booster energy to 16 GeV, and finally, adding a 4.5 GeV Pre-Booster to enable

TABLE 2. Parameters of muon bunches downstream of the ionization cooling channel.

	Narrow σ_p	Broad σ_p
muons per bunch	5×10^{12}	5×10^{12}
μ^+ bunches per cycle	1	1
μ^- bunches per cycle	1	1
Momentum (MeV/c)	200	200
σ_p/p	5%	10%
Bunch length (cm)	1.5	10
Normalized $\epsilon_\perp$ (mm–mr)	200π	60π
Repetition rate (Hz)	15	15
μ^+ per year (10^7 secs)	7.5×10^{20}	7.5×10^{20}

the protons to be compressed into short ($\sim$ 2 ns) long bunches. The upgrade is in principle stagable. Plausible staging steps and the associated proton source parameters are summarized in Table 1.

(b) A pion production and collection system, followed by a pion decay channel. Each incident proton bunch interacts in a target to produce $\sim 3\times10^{13}$ charged pions of each sign. The $\pi^\pm$ are confined within a high field solenoid co-axial with the beam direction. At the end of a 20 m long decay channel consisting of a 7 Tesla solenoid with a radius of 25 cm each incident proton results in about 0.2 muons of each charge. If in each accelerator cycle the first incident proton bunch is used to make and collect μ^+s, and the second bunch used for μ^-s, there will be about 10^{13} muons of each charge available at the end of the decay channel per cycle.

(c) A muon cooling channel. The muons exiting the decay channel populate a very diffuse 6–dimensional phase–space. The diffuse muon cloud must be cooled using a new fast cooling technique to form an intense beam before most of the muons have decayed. The cooling method proposed for the muon collider is ionization cooling [2]. Table 2 summarizes the properties of the muons at the end of the cooling channel. Note that the phase–space occupied by the muons can be optimized either to maximize the luminosity of the collider, or alternatively to minimize the beam energy spread at the expense of luminosity. At the end of the cooling channel each muon bunch is expected to contain about 5×10^{12} muons with a momentum of order 200 MeV/c.

(d) A muon acceleration system. A series of recirculating linear accelerators (RLAs) to accelerate the muons up to the colliding beam energy. Each RLA consists of two Linacs connected together by two arcs. Three RLAs with the operational parameters summarized in Table 3 would be able to accelerate the muons up to 250 GeV.

The front–end accelerator complex could be used for a variety of fixed target type physics. Note that the new Fermilab Main Injector can accept a factor

TABLE 3. Recirculating linear accelerator parameters.

	RLA 1	RLA 2	RLA 3
Input Energy (GeV)	1.0	9.6	70
Output Energy (GeV)	9.6	70	250
No. of turns	9	11	12
Linac Length (m)	100	300	533.3
Arc Length (m)	30	175	520
Bunch Length (ps)	158	43	19
Revolution Time (μs)	0.9	3.1	7.0
Decay Losses	9.0%	5.2%	2.4%
Initial muons per bunch	5×10^{12}	4.6×10^{12}	4.3×10^{12}
μ^+ bunches per sec	15	15	15

of $\sim$ 5 more protons per cycle than can be provided by the existing Fermilab proton source. Hence, an upgraded proton source of the type required for a muon collider would directly benefit the foreseen FNAL MI program. In addition, a muon collider front–end offers many other possibilities, some of them quite unique. Four working groups were convened in the workshop to considered the range of possibilities. The main conclusions from these groups are listed in the sub–sections below.

Low Energy Hadron Physics

The proton source required for the FMC would allow a continuation of low and intermediate energy kaon physics with intensities a factor of 20 more than presently available at the AGS, and a factor of a few greater than foreseen at the FNAL MI, an upgraded AGS, or the proposed KEK JHF. Rare kaon decays and precision kaon CP and CPT studies can provide windows on physics beyond the SM and are likely to remain of interest well into the future. As an example consider the rare decays $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$. Precise measurements of these decay modes would enable a precise determination of V_{td} and the CP violation parameter η. The first $K^+ \rightarrow \pi^+\nu\bar{\nu}$ event has recently been reported by the BNL E787 collaboration. The decay $K_L \rightarrow \pi^0\nu\bar{\nu}$ has not yet been observed. Future experiments at the AGS and at the FNAL MI may yield a few of these rare K^+ and K_L decays per year. It has been estimated [3] that at the muon collider proton source of order 100 events per year could be observed in each mode. However, this kaon physics program would require the addition of a stretcher ring to the FMC proton source. Other interesting kaon experiments that might be pursued include muon transverse polarization in $K^+ \rightarrow \pi^0\mu^+\nu_\mu$ or $K^+ \rightarrow \mu^+\nu_\mu\gamma$, spin–spin correlations in $K^+ \rightarrow \pi^+\mu^+\mu^-$, and polarization effects in $K^+ \rightarrow \mu^+\mu^-$. Finally, in addition to the kaon physics program there are many other interesting low energy hadron physics experiments that, although they don't require the full potential of future high intensity proton sources, never-the-less are looking for a home. It is therefore likely that the proton source at the FMC would support a healthy low energy hadron physics program.

Neutrino Physics

Conventional neutrino beams are made by allowing pions and kaons to decay in a decay channel. This produces a ν_μ beam with a small ν_e component from $K^+ \rightarrow e^+\pi^0\nu_e$ decays, and if the primary proton beam energy is sufficient, a small ν_τ component from D_S decays. The uncertainties on the fluxes and flavor content of the resulting neutrino beam introduce significant systematic uncertainties for many neutrino experiments. A muon collider accelerator complex offers the very attractive possibility of making intense neutrino beams using a muon decay channel. The resulting beam would have a precisely calculable flux and, for μ^- decays, would be a mixture of 50% ν_μ and 50% $\bar{\nu}_e$. This would provide a uniquely "clean" tool for neutrino physics.

The characteristics of the neutrino pulses downstream of the RLAs are summarized in Table 4. The resulting "accidental" neutrino beam 600 m downstream of RLA3 is sufficiently intense to produce [4] 7.5×10^5 events per year in a 1 m long 10 cm radius liquid hydrogen target ! Indeed, the neutrino beam intensity downstream of RLA3 is about a factor of 1000 greater than the intensity of existing neutrino beams. These high neutrino fluxes would enable compact highly instrumented detectors to be used with active fine-grained targets, micro–vertexing, and good particle identification ... a "quantum leap" in the design of neutrino detectors ! It has been proposed [5] to optimize the neutrino physics potential at a muon collider accelerator complex by building muon storage rings with straight sections pointing in the desired direction. Low energy storage rings could be built for long–baseline neutrino oscillation experiments with the plane of the storage ring tilted downwards so that the neutrino beam traverses the Earth. The neutrino beam intensity from a 20 GeV/c muon storage ring is sufficient to produce hundreds of CC events per year in a 10 kT detector on the other side of the Earth [5]. Neutrino beams at the front end of a muon collider would clearly enable significant improvements in the sensitivity of experiments searching for, and perhaps eventually measuring, neutrino flavor oscillations. For example, for large mixing angles, values of Δm^2 approaching 10^{-5} eV^2 might be observable for ν_e–ν_μ oscillations, and 10^{-4} eV^2 for ν_e–ν_τ oscillations [5]. Finally, it has been pointed out [6] that if neutrino oscillations are observed, the fluxes and characteristics of the neutrino beams at the front end of the muon collider would facilitate very interesting tests of Lorentz invariance, CPT invariance, and the equivalence principle.

TABLE 4. Neutrino beam pulses from the straight sections of the Recirculating Linacs.

	1	2	3	4	5	6	7	8	9	10	11	12
RLA 1												
E_μ(start) (GeV)	1.0	1.96	2.92	3.88	4.84	5.8	6.76	7.72	8.68	9.64		
E_μ(end) (GeV)	1.48	2.44	3.4	4.36	5.32	6.28	7.24	8.2	9.16			
$< E_\mu >$ (GeV)	1.24	2.2	3.16	4.12	5.08	6.04	7.0	7.96	8.92			
$\gamma c\tau$ (km)	7.72	13.7	19.7	25.7	31.7	37.8	43.8	49.6	55.7			
$f_{decay} = 100m/\gamma c\tau(\%)$	1.3	0.73	0.51	0.39	0.32	0.26	0.23	0.20	0.18			
N_{decay}/bunch ($\times 10^{10}$)	6.5	3.7	2.6	2.0	1.6	1.3	1.2	1.0	0.9			
N_{decay}/year ($\times 10^{18}$)	9.8	5.5	3.8	2.9	2.4	2.0	1.7	1.5	1.4			
RLA 2												
E_μ(start) (GeV)	9.6	15.1	20.6	26.1	31.6	37.1	42.6	48.1	53.6	59.1	64.6	70.1
E_μ(end) (GeV)	12.4	17.9	29.4	28.9	34.4	39.9	45.4	50.9	56.4	61.9	67.4	
$< E_\mu >$ (GeV)	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0	60.5	66.0	
$\gamma c\tau$ (km)	68.7	100	140	170	210	240	270	310	340	380	410	
$f_{decay} = 300m/\gamma c\tau(\%)$	0.44	0.30	0.21	0.18	0.14	0.13	0.11	0.097	0.088	0.079	0.073	
N_{decay}/bunch ($\times 10^{10}$)	2.0	1.4	0.97	0.83	0.64	0.60	0.51	0.45	0.40	0.36	0.34	
N_{decay}/year ($\times 10^{18}$)	3.0	2.1	1.5	1.2	0.96	0.90	0.77	0.68	0.60	0.54	0.51	
RLA 3												
E_μ(start) (GeV)	70	85	100	115	130	145	160	175	190	205	220	235
E_μ(end) (GeV)	77.5	92.5	108	123	138	153	168	183	198	213	228	243
$< E_\mu >$ (GeV)	73.8	88.8	104	119	134	149	164	179	194	209	224	239
$\gamma c\tau$ (km)	460	550	650	740	840	930	1000	1100	1200	1300	1400	1500
$f_{decay} = 533m/\gamma c\tau(\%)$	0.12	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
N_{decay}/bunch ($\times 10^{10}$)	0.52	0.42	0.35	0.31	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15
N_{decay}/year ($\times 10^{18}$)	0.78	0.63	0.53	0.46	0.41	0.37	0.34	0.31	0.28	0.26	0.25	0.23

Deep Inelastic Scattering

Deep inelastic scattering measurements at a muon collider facility could be pursued at fixed target experiments using intense muon and neutrino beams, or at a μp collider if the muon collider ring was located near a proton storage ring (Fig. 1). At the workshop there was little enthusiasm for the fixed target muon option. However, there was extensive enthusiasm for exploiting the intense neutrino beams, using light targets in general and liquid hydrogen targets in particular. This would enable the proton structure function to be measured directly without the need for nuclear corrections. In addition, Shiltsev [7] has calculated the parameters of a μp collider using 1 TeV protons stored in the Tevatron and 250 GeV muons stored in a muon-collider type ring. The average luminosity of this machine would be $\sim 10^{33}\ cm^{-2}s^{-1}$. A 10 fb^{-1} data sample would contain 10^6 events with $Q^2 > 5000$ GeV^2 [4] (the present ZEUS sample, which corresponds to 34 nb^{-1}, contains 326 events with $Q^2 > 5000$ GeV^2), and would allow the discovery of leptoquarks with standard couplings up to 800 GeV/c^2. Hence, the deep inelastic scattering group at the workshop concluded that the high-Q^2 physics at a 200 GeV $\times$ 1 TeV μp collider would be very interesting. However, due to a large background [8] flux in the forward muon direction, it is suspected that small angle scattering measurements would be difficult, and hence the low–x physics program would be limited.

Slow/Stopped Muon Physics

Current low energy muon beam facilities produce typically 10^7–10^8 μ per second. The muon source at a muon collider would provide muon beams with intensities approaching 10^{14} μ per second (Table 2). A small fraction of the available muons could be used to support a broad range of low energy muon experiments. However, it should be noted that in general the bunch structure at a muon collider accelerator facility is not ideal for low energy muon experiments that tend to require either a DC muon beam to minimize instantaneous rates, or a CW beam with $\sim 2\mu$s between bunches. Hence, either experiments have to be designed to match the bunch structure in Table 2, or the muon source has to be designed so that it can also provide DC and/or CW muon beams. Neither of these options is straightforward, and both deserve detailed study.

Perhaps the best motivated particle physics experiments using low energy muons are searches for muon–number violation in rare muon decays ($\mu \to e\gamma$, $\mu \to eee$), muonium–antimuonium oscillation, or $\mu \to e$ conversion. The detection of muon number non-conservation would be a spectacular signal for physics beyond the SM. Many extensions to the SM predict lepton flavor violation at levels that may be detectable in the next few years. As an example consider $\mu \to e$ conversion, for which the current experimental bound is $< 7 \times 10^{-13}$. Ongoing experiments are expected to improve the sensitivity by a factor of about 3. In the longer term a recently approved BNL experiment proposes to achieve a sensitivity of 10^{-16}. Several models of physics beyond the SM predict signals at this level. For example, due to slepton and gaugino mixing, some supersymmetry (SUSY) models predict $\mu \to e$ conversion at rates that would be observable. At the front end of a muon collider it may be possible [9] to achieve a sensitivity of 10^{-18}–10^{-19} !

Finally, there are many other muon experiments that might be profitably pursued at the front end of a muon collider. Some examples are (i) precision measurements (muon anomalous magnetic moment, muon electric dipole moment, muon lifetime, muonium hyperfine splitting, etc), (ii) ν_μ mass constraints, (iii) searches for parity and CP violation in muonic atoms, (iv) condensed matter physics using μSR, and (v) μ^- catalized fusion research.

THE FIRST MUON COLLIDER

The workshop parameters for the FMC are shown in Table 5. Note that the assumptions that went into computing the luminosities were somewhat conservative. To obtain a more aggressive but still reasonable set of goals for the FMC these luminosities can be multiplied by a factor of three. In addition

TABLE 5. Parameters for (going from left to right) a narrowband low–energy, broadband low–energy, medium–energy, top factory, and higher–energy FMC.

$\sqrt{s}$	100	100	200	350	500
σ_p/p	3×10^{-5}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Muons per bunch	3×10^{12}	3×10^{12}	2×10^{12}	2×10^{12}	2×10^{12}
Number of bunches	1	1	2	2	2
Repetition rate (Hz)	15	15	15	15	15
Norm. $\epsilon_\perp$ (mm-mr)	297π	85π	67π	56π	50π
Collider circum. (m)	380	380	700	864	1000
f_{rev} (Hz)	7.9×10^5	7.9×10^5	4.3×10^5	3.5×10^5	3.0×10^5
turns/lifetime	820	820	890	1260	1560
$\beta^\star$ (cm)	13	4	3	2.6	2.3
σ_z (cm)	13	4	3	2.6	2.3
σ_r (μm)	286	85	47	30	22
L_{peak} $(cm^{-2}s^{-1})$	6×10^{32}	7×10^{33}	6×10^{33}	1×10^{34}	2×10^{34}
L_{av} $(cm^{-2}s^{-1})$	5×10^{30}	6×10^{31}	1×10^{32}	3×10^{32}	7×10^{32}

to specific conclusions that emerged from the workshop for each physics sub–topic, there were also some more general conclusions:

(i) The luminosities in Table 5 are at the threshold of physics interest. A factor of 3–or–more luminosity would be very desirable, and should be the goal of the FMC design. With this increase in luminosity there seems to be a tremendous potential physics program.

(ii) Initial studies [10] show that the absolute energy calibration of the FMC could be at the level of $\delta E/E \sim 10^{-5}$, with a beam energy spread $\sigma_p/p \sim 3\times10^{-5}$. This would give the FMC a unique capability as a precision tool to scan and measure the parameters of any resonant states produced in the s–channel.

(iii) It is unclear with what precision the luminosity can be measured at a muon collider. Precise measurements of muon Bhabha scattering may not be possible because of the large backgrounds induced by showering high–energy electrons from muon decay, and the necessity of having shielding cones of 10°–20° half–angle in the forward/backward directions. More work needs to be done on understanding how best to measure the luminosity, and how well it needs to be measured.

(iv) Significant muon polarization would increase the physics potential of the FMC.

Higgs Physics

Current theoretical prejudice suggests that if one or more Higgs bosons exists, the lightest Higgs boson has a mass $m_h < 150$ GeV/c^2. If this is true, the FMC could be designed to be an s–channel Higgs factory. This would be a unique tool for studying the Higgs boson. Consider a specific example. Suppose a Higgs boson has been observed at TEV33 with a mass m_h = 110 GeV/c^2, which is then confirmed and pinned down at the LHC with a precision σ_m = 0.1 MeV/c^2. It has been shown [11] that if the FMC beam energy spread is 0.003% (2 MeV), and the luminosity is a factor of 3 greater than in Table 5, it will take 1 operational year (10^7 secs) to make a first rough scan to determine m_h to 2 MeV/c^2. A precise 3 point scan, taking 3 years, would then determine m_h to $\sim$ 0.1 MeV/c^2. If the width $\Gamma_h = 3$ MeV, it would be determined with a precision $\Delta\Gamma_h/\Gamma_h$ = 16%. At the same time the dominant decay channels would be measured with good precision (3% for $\sigma.B(b\bar{b})$ and 15% for $\sigma.B(WW)$). This "tour de force" in Higgs measurements is a unique capability amongst all currently imagined futuristic colliders. Not only is the width measurement sufficiently precise to distinguish between a SM and MSSM Higgs boson over a large region of SUSY parameter space, but from the ratio of branching ratios B(WW)/B($b\bar{b}$) one should be able to infer the presence of a heavy Higgs (A^0) up to masses $M_A \sim$ 400 GeV/c^2. At a higher energy muon collider the direct discovery and measurement of the A^0 would then be possible in the s–channel for a large region of SUSY parameter space.

WW and Z^0 Physics

The LEP era of Z^0–pole physics is over. It is likely that the 2.8σ discrepancy between the $\sin^2\theta_W$ values determined from the SLD left–right asymmetry measurement and from the LEP forward–backward asymmetry measurements will remain. A muon collider Z^0 factory producing 10^8 Z^0 events per year would push beyond the statistical reach of LEP by an order of magnitude. This would require a luminosity of 2×10^{32} cm^{-2} s^{-1}, consistent with a factor of 3 more than in Table 5. A Z^0 factory with this capability might be of interest if there was no known Higgs, SUSY, Technicolor, or other type of new particle to scan and measure in the s–channel. In this case it may become important to resolve the $\sin^2\theta_W$ discrepancy using an FMC with polarized muon beams, and obtain further experimental guidance from precision FMC Z^0 measurements. Anticipated precisions for the various Z^0 measurements at the FMC are discussed in [11]. Ultimately the precision with which m_W is known may limit the sensitivity to new physics obtained from the overall consistency of the measured SM parameters. In this case an FMC with $\sqrt{s} \sim 2m_W + 0.5$ GeV may be desirable to obtain a precision $\delta m_W \sim 6$ MeV/c^2 for an integrated luminosity of 100 pb^{-1}.

SUSY Searches and Measurements

In supersymmetric extensions to the SM each fermion (boson) has a boson (fermion) superpartner. SUSY is broken by introducing soft masses and couplings that do not result in quadratic divergences. In the MSSM, this scheme results in over 100 SUSY-breaking parameters. Hence, if SUSY has something to do with electroweak symmetry breaking there are many SUSY particles to discover, and a large number of measurements at a variety of high energy colliders will be required to pin down the model dependent details. Although much of the SUSY phenomenology is model dependent, the prediction that the lightest Higgs boson has a mass $m_h < 150$ GeV/c^2 is more general. A muon collider Higgs factory would play a unique role in providing precise measurements of the lightest Higgs boson properties. Furthermore, finding the MSSM heavier Higgs particles (H^0 and A^0) may not be easy in futuristic e^+e^- or high energy hadron colliders. Hence, once the parameters of the lightest Higgs boson have been precisely determined, a muon collider at higher energies scanning in the region of the heavier Higgs bosons might make a crucial contribution to our understanding of the details of the emerging underlying SUSY theory.

Muon colliders can also contribute to unraveling the SUSY zoo in other ways. For example, fine tuning arguments in mSUGRA models suggest the lightest chargino is lighter than 200 GeV/c^2, in which case this chargino may well be discovered at TEV33. The energy of the FMC could then be chosen to pair produce charginos, a process that proceeds at lowest order via s–channel production with an intermediate γ, Z, or H, and via t–channel muon–sneutrino exchange. The amplitudes from these diagrams interfere destructively, and the threshold dependence of the cross-section at a muon collider is sensitive to the mass of the muon sneutrino up to masses of a few hundred GeV/c^2. Other t–channel sparticle exchanges in sparticle pair production process at a muon collider are also of interest, and can probe for example the presence of heavy squarks via t–channel enhancements. Finally, it is likely that of the many sparticles, at least some would have masses in the TeV range, and hence ultimately a multi-TeV muon collider would be required. A more detailed discussion of the strength of the muon collider physics program in a SUSY world can be found in Ref. [12].

Strong Dynamics

Although supersymmetry is very appealing, we may not be living in a SUSY–world. Technicolor is perhaps the most actively pursued alternative to a SUSY solution to electroweak symmetry breaking. Modern technicolor models predict narrow neutral technihadrons (π_T, ρ_T, and ω_T) which would appear as spectacular narrow resonances at an FMC with $\sqrt{s} = 100$–200 GeV and beam energy spread $\sigma_E/E < 10^{-4}$. For example, technipions are expected to couple to $\mu^+\mu^-$ with a strength proportional to m_μ. Furthermore the technipion coupling is enhanced with respect to the equivalent Higgs boson coupling. Hence, an FMC at the appropriate energy would be a superb technipion factory. Modern technicolor ideas also suggest that eventually there will be a compelling need for a multi-TeV muon collider to search for a TeV-scale Z', and to search for and measure higher mass techni–particles. A more detailed discussion of the strong dynamics physics potential of muon colliders can be found in Ref. [13].

Top Factory

The shape of the $\mu^+\mu^- \rightarrow t\bar{t}$ cross–section over the threshold region is sensitive to $m_t, \Gamma_t, V_{tb}, m_h$, and α_s. A precise scan over the threshold region can therefore be used to improve our knowledge of some or all of these parameters. These measurements could also be performed at an e^+e^- collider. However, with a smaller beam energy spread and less initial state radiation, for a given integrated luminosity the measurements at a muon collider would be more precise. As an example, if we assume a factor of 3 more luminosity than in Table 5, a 1 year scan would determine m_t with a precision of 200 MeV/c^2, and a 10 year scan would improve the mass determination to 70 MeV/c^2. Further discussion of the top-factory physics at a muon collider can be found in Ref. [14].

CONCLUSIONS

The development of high luminosity muon colliders is motivated primarily by the desire to build a multi-TeV lepton collider. However, before achieving this goal it will probably be necessary to advance along the learning curve by first constructing and operating a more modest facility. The workshop has demonstrated that there are world class cutting edge physics programs that could be pursued at both the front end of a muon collider and at a "low" energy FMC. We do not yet know whether a muon collider is technically feasible, but given the amount of interest in the muon collider and its front end that was manifest at the workshop, and the strength of the physics program that could be pursued at a muon collider facility, I believe that there is a compelling case to vigorously pursue a muon collider R&D program.

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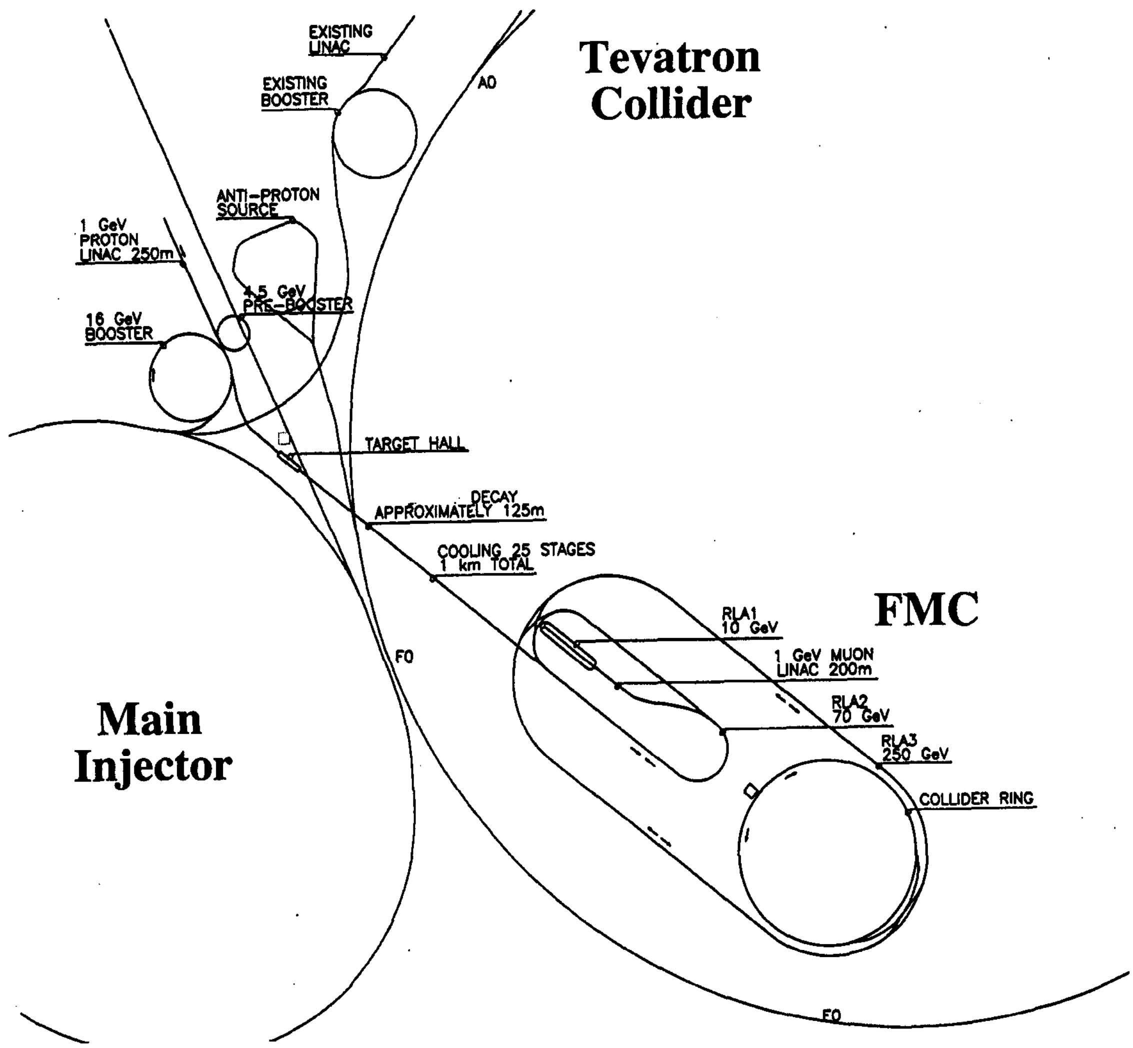

FIGURE 1. Schematic showing a plausible location for the First Muon Collider at Fermilab.