MUON STORAGE RINGS*

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Muon storage rings are reviewed in an introductory manner. The physics opportunities are exciting. The technical difficulties are considerable, but can be spread over three step scenario. First a neutrino factory would make definitive experiments on neutrino oscillations; then several generations of precision muon colliders could explore the spectrum of particles associated with electroweak symmetry breaking or supersymmetry; finally high energy lepton collisions could be envisaged.

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1. Introduction

The concept of muon colliders was introduced by Budker [1, 2], and developed further by Skrinsky *et al.* [3–10] and Neuffer [11–14]. The study of muon collider design has been underway in the U.S. since 1992, and, through a considerable amount of ingenuity and novel ideas, has led to a plausible design philosophy and sets of parameters for muon colliders. The Muon Collider Collaboration became a formal entity in May of 1997. It comprises more than 100 physicists from 20 institutions, with a small contribution by three CERN accelerator physicists. The goal of the collaboration is to complete within a few years the R&D needed to determine whether a muon collider is technically feasible, and, if it is, to design the First Muon Collider [15].

On this side of the Atlantic, the European community is blessed by the existence of a solid and ambitious project, LHC, able to explore effectively parton-parton centre-of-mass energies up to 1–2 TeV. Future options for CERN beyond the LHC, investigated in [16], include the muon collider as an interesting possibility. Because the muon collider is so original, in both its accelerator physics aspects and its physics capabilities, it seemed necessary

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to study it in more detail. A prospective study group, encouraged by ECFA, began its investigations in June 1998, and is presently producing a detailed report [17].

The physics programme is extremely rich and the accelerator challenges would be considerable, if addressed all at the same time for trying to build right-away a high energy collider. Following also the physics questions of today, the european study group has proposed a **three-step scenario**, with machines of gradually increasing technical difficulty, each step being justified on physics grounds in its own right.

1. *Neutrino factory*

This first step involves a high-intensity proton source, a first design of a muon collector, acceleration to an energy of about 20 GeV, and a muon storage ring for neutrino production. These neutrino beams are unique in intensity and quality, allowing definitive experiments in neutrino oscillations and neutrino-nucleon scattering. The intense muon source also opens opportunities in muon physics.

2. *Precision muon colliders*

A generation of muon colliders with centre-of-mass energy in the range $\sqrt{s}$=100–1000 GeV can be envisaged, once the important question of **muon cooling** has been answered, so as to allow high luminosities to be obtained. These machines are very compact and attractive. Muon colliders can do all the physics of lepton colliders in this energy range, but they offer more. Their superior energy resolution and calibration, as well as the direct muon coupling to the Higgs boson(s), make them a tool of choice for precision studies of new particles in this mass range, if the LHC should reveal their existence.

3. *The high-energy frontier*

The maximum energy that one can envisage for muon colliders using the existing CERN infrastructure is about 7 TeV in the centre of mass. This involves a more or less straightforward extrapolation of the design of the lower-energy colliders, and again offers the physics potential of a electron-positron collider, though with superior energy resolution and some possible advantages associated with flavour-non-universal couplings. At energies above 3 TeV, and with the present designs, the radiation induced by neutrinos at the locations where they emerge from the earth is too severe. Therefore, in the present state of understanding, the high-energy step is limited there. For the moment, progress could come from better-quality muon beams, or careful arrangements of the site and of the locations of straight sections.

The development over time of these three steps would offer an extremely rich programme of physics experiments for many years, and allow for the continuous improvement of the various technologies necessary to handle high-intensity muon beams.

2. Overview of muon machines

The overall sketch of a muon machine is represented in Fig. 1, taken from the 1996 snowmass study [18]. Its main elements are the following.

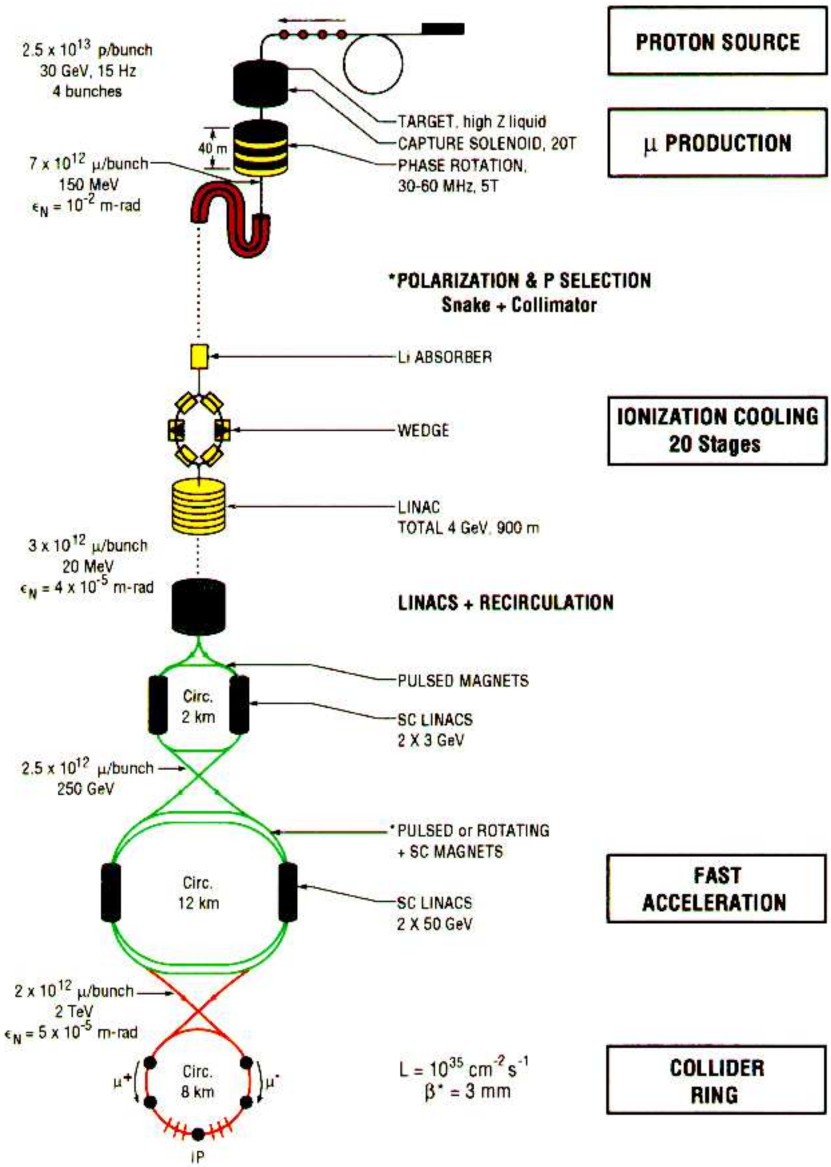

Fig. 1. General sketch of a muon collider

2.1. Muon source

Muons are produced from the decay of pions. To produce a large number of these, a high intensity proton driver is needed. The number of pions produced per proton in a dense target is more or less proportional to proton beam energy, so at the end the total number of pions is proportional to the proton beam power. The proton energy is a parameter that can be used to maximise the capture efficiency of pions and their decay muons in reasonable time buckets necessary for their acceleration in an RF system. The beam power that is discussed now ranges from 4 to 20 MW, 10^{15} to 6. 10^{16} protons per second, imposing extremely strong design constraints on the target.

The american designs typically call for protons of 8–32 GeV produced by synchrotrons. This imposes a time structure of one bunch of muons every 15 Hz. At CERN, one is presently investigating the possibility to operate with a very high intensity linac at lower energy. This allows a higher repetition rate, up to 350 MHz (the frequency of LEP cavities) or more. This high frequency imposes a bunching system at a later stage, at least for muon colliders, and the low energy might make cature much more difficult. These are open problems at the moment.

2.2. Muon collection

The greater abundance of pions, and their decay muons, is in the energy range of a few hundred MeV, with transverse momenta of the same order of magnitude. They can be trapped if a strong solenoidal field is appplied. Solenoids providing up to 20 Tesla are considered around the target [19]. In this case a diameter of 10 cm would be sufficient to trap all pions of transverse momentum below 150 MeV. The pions trapped this way decay into muons in typically 50 meters, and the decay muons have very similar velocities.

Unfortunately the produced muons have a large spectrum of longitudinal velocities and quicly spread out in space. It is necessary at this point to envisage a trapping in time (or longitudinal velocities), by a system called "bunch rotation". This is typically an accelerating device which will slow down the faster particles and accelerate the slower ones, reducing the longitudinal momentum spectrum from a bite of 200–500 MeV down to 350$\pm$10 MeV. The design of this section is critical for the overal performance of the system. It must also be imbedded in a strong magnetic field, the coexistence of which with RF cavities (especially superconducting ones) is delicate.

2.3. Muon cooling

Once the muons are collected in a reasonable range of longitudinal momenta one can start to try to make them into a small bunch, *i.e.* to reduce the transverse momentum. This can be done by *ionisation cooling*. The principle is similar to radiation damping in a circular electron storage ring. Particles loose energy due to

— synchrotron radiation in the arcs of an electron ring

— energy loss in ionisation material for muons

and this reduces their momentum in all three space directions. RF cavities then give the same amount of energy back, but of course this increases only the longitudinal momentum, so that the net effect is to reduce the transverse momentum.

This is the principle, but dE/dx is accompanied with multiple scattering, which itself creates transverse momentum, and straggling, which creates again energy spread. These effects are minimized if the dE/dx material is located at places with strong focusing, *i.e.* high magnetic field, which is seen again to play a very important role.

Best cooling is provided at small energies, probably just above minimum ionization at about 300 MeV. It involves a sequence of strong magnetic fields and strong accelerating cavities. The decay lifetime of the muon (2.2 μ s, $c\tau$=660 m) imposes these strong fields, as the process must take place quickly. Systems involving long drift spaces, such as damping rings, lead to poor performance. More cooling is obtained by using more such elements and stronger magnetic fields.

At this point a beam of muons is available at 200–300 MeV, with hopefully a few 10^{14} muons per second, is available. Much more cooling is required for muon colliders, where the luminosity is inversely proportionnal to the beam size, than for the neutrino factory storage ring, where transverse momenta have to be compared with the 30 MeV transverse momentum in muon decay.

2.4. Energy cooling

Further reduction in energy spread can be obtained by dE/dx. If muons of different energies can be separated in space (in a magnetic spectrometer, for instance) then their energy spread can be reduced by having them go through variable amounts of material, the higher energy particles losing more energy and the lower energy particles losing less energy. It has been calculated that energy spread as low as 3 10^{-5} could be achieved this way for 50 GeV muon beams. This is an important feature of the Higgs factories.

2.5. Muon acceleration

Here again, acceleration must be very fast, although the dilated muon decay time helps more and more. At least the first stages must be done in linear accelerating structures, possibly with recycling as in CEBAF. The CERN group envisages steps of 5 GeV followed by a series of arcs, so that four steps lead to a 20 GeV muon beam. Although it is probably the most expensive part in the

2.6. Muon storage

Storage of the muons in the storage rings is a non-issue at low repetition rates, since the preceeding bunch has competely decayed by the time the next one comes. The low repetition rate (10–1000 Hz) is the only possible scenario for muon colliders. At high repetition rate, possible for a neutrino factory ring, this is no longer the case; then *(i)* several bunches of muons must cohabitate in the storage ring; or even *(ii)* stacking might be required.

2.7. Layout on the CERN site

A possible layout of a muon complex on the CERN site is shown in figure 2. It seems that the three scenarios would fit on the CERN site with only a reasonable amount of civil engeneering.

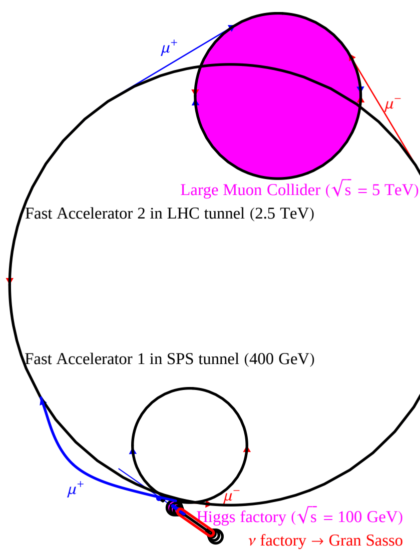

Fig. 2. Possible layout of a muon complex on the CERN site.

3. Neutrino factory

The layout of a Neutrino factory is given in Fig. 3. Muons are stored in a ring with long straight sections, so that most of the decays happen on the straight sections, 40% in each direction. A pioneering study was performed by Geer [20].

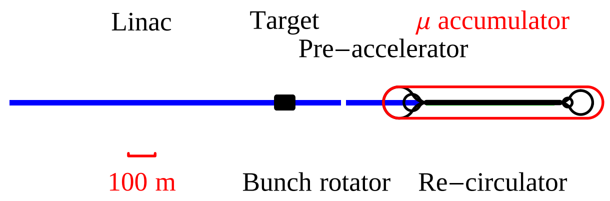

Fig. 3. Possible layout of a neutrino factory based on a muon ring.

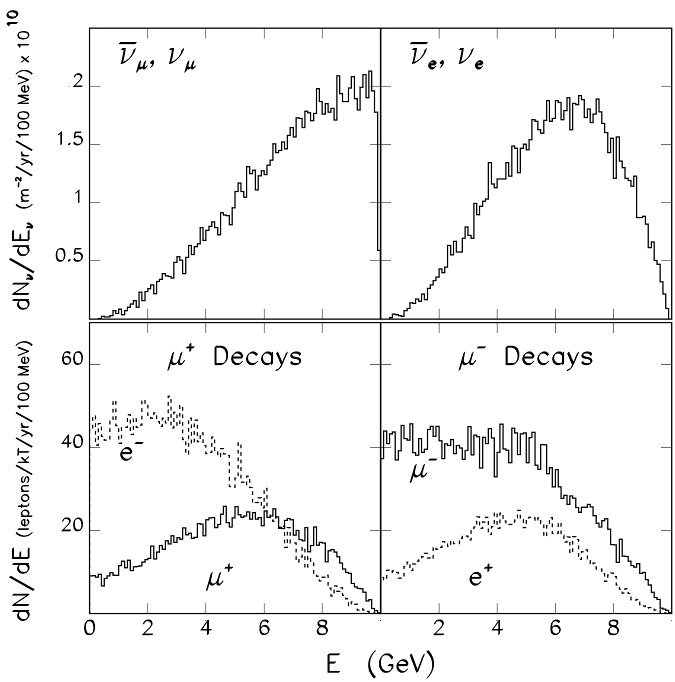

Fig. 4. Neutrino fluxes at 730 km from an Neutrino factory, and lepton spectra in neutrino interactions for a 10 GeV muon beam.

With a beam of few 10^{14} muons per second one gets twice as many neutrinos from muon decay:

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

or the charge symmetric combination for a μ^- beam. The flux is calculable exactly, and peaks at the muon momentum, as shown in figure 4. The intensity in muon neutrinos produced by a 30 GeV muon ring would be similar to 100 times that of the NUMI or NGS beams.

The existence of electron neutrinos is a unique feature of these neutrino beams from muon decay. The electron neutrinos have a different leptonic charge from the muon neutrinos.

3.1. Neutrino oscillations

High intensity, tunable energy, extremely well known spectrum, the symmetry between μ^- and μ^+, and the existence of electron neutrinos with a different leptonic charge from the muon neutrinos are the main advantages of these neutrino beams. They should allow definitive experiments to determine the coefficients of the neutrino mixing matrix, a physics programme that is likely to keep us busy for the next 20–30 years.

Oscillations can be observed by the appearance of leptons of wrong sign and flavour. Assuming a μ^+ driven neutrino beam the appearance of neutrino interactions with
— high energy μ^- signals $\nu_e \to \nu_\mu$ oscillation;
— high energy τ^- signals $\nu_e \to \nu_\tau$ oscillation;
— high energy e^+ signals $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation;
— high energy τ^+ signals $\bar{\nu}_\mu \to \bar{\nu}_\tau$ oscillation.

The analysis of three family mixing $\nu_1, \nu_2, \nu_3 \leftrightarrow \nu_e, \nu_\mu, \nu_\tau$ and resulting oscillations has been performed by, among others, De Rujúla *et al.* [21], with emphasis on the region of mixing angles and mass diffferences indicated by recent results on solar neutrinos and atmospheric neutrinos. Accelerator experiments with baselines commensurate with the earth are sensitive to the large mass difference oscillations. They depend on three parameters:

1) the large mass difference $\Delta m^2_{13} \simeq \Delta m^2_{23}$ since Δm^2_{12}, which governs solar neutrino oscillations is presumably very small;

2) the mixing angle between the heavy states ν_2, ν_3, θ_{23}, to which atmospheric neutrino oscillations are presently sensitive;

3) the mixing angle between the light and heavy states ν_1, ν_3, θ_{23}, which can be uniquely probed by $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ oscillations.

These authors have imagined a neutrino factory with 2×10^{20} decays of $E_\mu = 20$ GeV μ^-'s and a 10 kt detector situated in the Gran Sasso Laboratory. The detector is assumed to identify and measure the charge and momentum of muons — not of electrons. The sensitivity reach, given

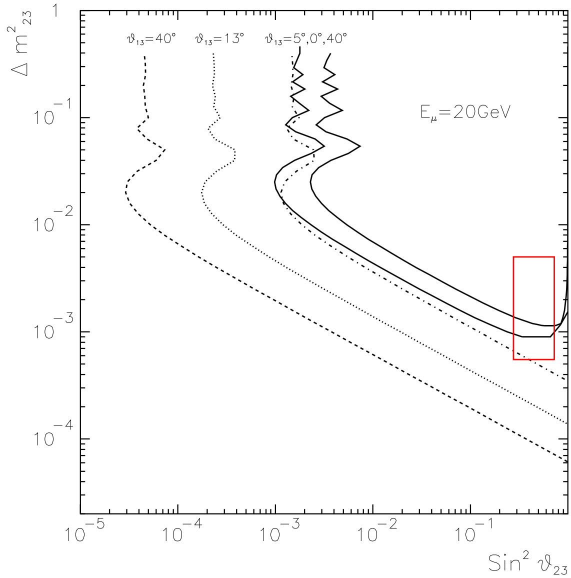

Fig. 5. Sensitivity reach in the plane $[\sin^2\theta_{23}, \Delta m^2_{23}]$ at 90% confidence, for our reference set-up, a μ^--decay beam and $L = 732$ km. Matter effects are taken into account. The discontinuous lines correspond to the appearance observable $N[\mu^+]$ (at $\theta_{13} = 40, 13, 5^0$) and the full lines correspond to the disappearance observable N_μ at $\theta_{13} = 0, 40^0$. The rectangle is the approximate domain allowed by SuperK data.

in Fig. 5, and Fig. 6, show clearly that a precision measurement could be made of these three parameters.

In principle, a 3×3 mixing matrix could have a complex phase, leading to the possibility of CP or T violation. This is also discussed in [21]. Because of neutrino oscillations in matter, which is not charge symmetric, the CP asymmetry

$$A_{\rm CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)}$$

is non zero even in absence of a phase in the mixing matrix. However the T-odd asymmetry,

$$A_{\rm T} = \frac{P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_{\rm e})}{P(\nu_e \to \nu_\mu) + P(\nu_\mu \to \nu_{\rm e})}$$

is cleaner since a non sero value is an unambiguous signal for a phase in the mixing matrix. The estimates in [21] indicate that the effect could be marginally seen, at a statistical level of two standard deviations. With more

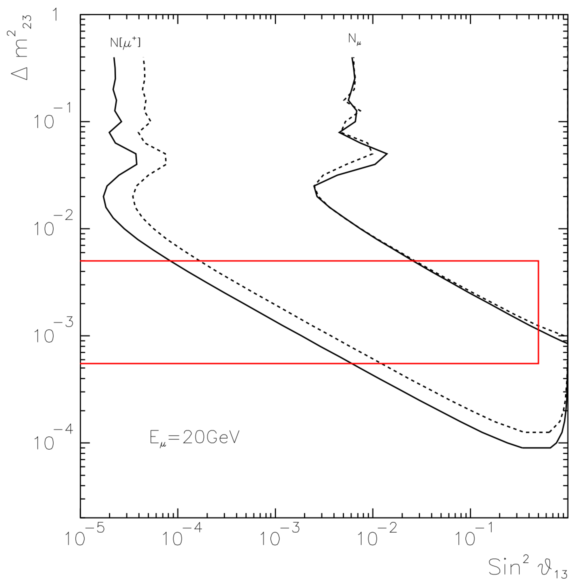

Fig. 6. Sensitivity reach in the plane $[\sin^2\theta_{13}, \Delta m^2_{23}]$, at 90% confidence, for the same conditions as in Fig. 5. The continuous (dashed) lines correspond to $\theta_{23} = 45^0\,(30^0)$. The lines covering the most (least) ground are for the appearance (disappearance) observable $N[\mu^+]$ (N_μ). The rectangular domain is the approximate region allowed by SuperK data.

tons, more flux more techniques, the effect might be measurable. This is completely unique to the neutrino factory and will certainly be the source of much work.

3.2. Other neutrino applications of the neutrino factory

As discussed in [17], the neutrino beams are also available at a very short distance, with high intensities concentrated in a small spot, a few centimeters if one brings a detector in the vicinity of the end of the straight section where muons decay. Statistics so far available in very massive neutrino detectors would become available for small target experiments. This should open the possibility of so far unfeasible experiments, neutrino experiments having targets which so far were reserved to muon or electron scattering experiments. Here are a few of the ideas that come to mind: high granularity silicon telescope targets for a detailed study of charm production; polarised hydrogen or deuterium targets for study of the spin structure functions; thin heavy targets for precision studies of nuclear effects; precision measurement of NC/CC ratio.

3.3. Physics with stopped muons

The availability of an unprecedented flux of low-energy muons at the exit of the muon cooler would open opportunities for muon physics in its own right [22].

Violations of lepton flavour conservation, already indicated by the neutrino oscillations, are expected at some level in muon physics. They also arise from slepton loops in supersymmetry as soon as sleptons have a non-degenerate spectrum [23].

The physics of this programme could cover experiments such as

- search for $\mu \to e\gamma$ and $\mu \to eee$ decays;
- search for the lepton flavour violating muon conversion $\mu N \to eN$;
- improved measurements of muon properties: muon lifetime, gyromagnetic anomaly $g_\mu - 2$, Michel parameters, and electric dipole moment;
- study of muonic atoms and of muon capture.

Other possible applications of low-energy muons, such as catalysed muon fusion, would also be worth investigating.

4. Precision muon colliders

Taking advantage of the experience gained running intense muon and neutrino factories, the community could envisage the construction of muon colliders, starting with intermediate energy colliders of limited dimensions aimed at precision measurements. It is impossible at this moment to define the exact parameters and goals of these precision machines, since they will depend to a large extent on the physics panorama. Should a light Higgs boson (up to $M_H = 140$ GeV) be discovered at LEP, Tevatron or LHC, the study of its properties at a muon collider would be ideal, and readiness to design and build that machine will be precious. The heavier Higgses H and A of supersymmetry would offer a natural scale as well, should they exist.

4.1. Machine parameters

Parameters of the muon colliders are given in Table 4.1, from Ref. [15]. They correspond to the specific choices of the proton source, a 16 GeV synchrotron operating at 15 Hz. With respect to the muon beam of a neutrino factory, the muon collider differs by three important elements.

- Both μ^+ and μ^- must be used at the same time, preferably in equal or nearly equal numbers. Production of a large number of π^- has led the authors of Ref. [15] to envisage their production by rather high energy protons on heavy targets. A possible alternative, which would be an interesting line of study, would be to use deutons or alpha particles as projectiles, ensuring isospin symmetry by construction, and avoiding the need of high energy protons and/or heavy targets. This might have practical advantages for the design of the driver and of the target. The lower energy beams produce as many or even more pions per unit of driving beam power, and in a more restricted phase space. However, the feasibility of efficient particle collection at these low momenta remains to be demonstrated.

- The muon beams must have a small emmittance. This requires cooling to a much larger extent than for the neutrino beam application. Ionization cooling is considered the most likely method. It involves a succession of dE/dX light material absorbers imbedded in strong focusing magnetic fields and of accelerating RF sections. Althought cooling rests on the rather well-known properties of muon interactions with matter, the feasibility and performance of an actual implementation remain to be demonstrated.

- The muon beams must have a large bunch population to ensure adequate luminosity. This requires accumulating particles in a few bunches, hence the relatively low repetition rate. The comparison of the repetition rate to the muon lifetime (see Table I) shows that, especially for the low energy muon colliders, their is a large amount of freedom in the repetition rate, from a few Hz up to almost 1 KHz for a 100 GeV centre-of-mass collider.

At least for the first colliders, the size is rather limited, as can be seen in Fig. 7

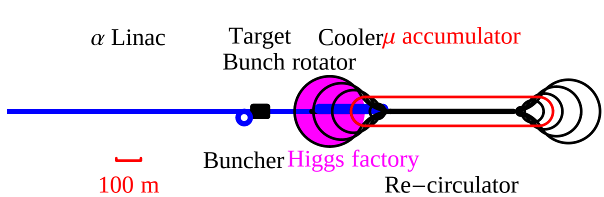

Fig. 7. Possible layout of the first Precision Muon Collider together with the neutrino factory.

A very important quality of the muon collider is the possibility of exchange between transverse and longitudinal emmitance, leading to reduced energy spread. This can be achieved by introducing an absorber of adequately designed variable thickness in a dispersive section. This leads to a possibly very small energy spread, a precious quality for study of narrow resonances, and a mandatory property for the possible operation with polarised beams. Of course this is achieved at the expense of luminosity (see Table I).

TABLE I

Baseline parameters for high- and low-energy muon colliders. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year $= 10^7$ s. From the muon collider collaboration [15].

CoM energy (TeV)	3	0.4	0.1		
p energy (GeV)	16	16	16		
p's/bunch	$2.5\ 10^{13}$	$2.5\ 10^{13}$	$5\ 10^{13}$		
Bunches/fill	4	4	2		
Rep. rate (Hz)	15	15	15		
$1/\tau_\mu$ (Hz)	32	240	960		
p power (MW)	4	4	4		
μ/bunch	$2\ 10^{12}$	$2\ 10^{12}$	$4\ 10^{12}$		
μ power (MW)	28	4	1		
Wall power (MW)	204	120	81		
Collider circum. (m)	6000	1000	350		
$\langle B \rangle$ (T)	5.2	4.7	3		
$\sigma E/E(\%)$	0.16	0.14	0.12	0.01	0.003
ϵ_n (π mm-mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
$n_{\rm turns}^{\rm effective}$	785	700	450	450	450
Luminosity (cm^{-2}/s)	$7\ 10^{34}$	10^{33}	$1.2\ 10^{32}$	$2.2\ 10^{31}$	10^{31}
Higgs/year			1900	4000	3900

4.2. Overview of physics capabilities

In general a muon collider can do everything that an e^+e^- collider could do.

On the negative side for the muon collider, one finds the difficulty to provide the very high luminosity. This is essentially constrained by the proton power on the target, by the capability one has to cool the beams further, and finally by the eventual possibility to circumvent the beam-beam tune shift. The figures given above represent the present understanding of the muon collider performance and are typically a factor 10 or more lower than the corresponding ones for electron colliders. An improvement would clearly be welcome! In addition, the operating range of a muon collider is rather narrower than that of an electron linear collider: In addition to the usual scaling law in E^2, the luminosity of a muon collider for a given circumference of the collider ring increases linearly with muon energy, due to the dilatation of muon lifetime, leading to a scaling law in E^3. One is led to envisage more than one precision machine, for example one Higgs and Z factory, then one for top threshold or heavy higgses,*etc*... Much of the infrastructure should remain the same, though.

Muon colliders offer, on the other hand, two major advantages with respect to the electron colliders.

The first one is the almost infinitely precise knowledge of the beam energy spectrum. This is discussed in more detail in Refs. [24, 25]. Muon are unavoidably polarised in pion decay, and a polarisation of about 20% remains when they are injected in the storage ring. The spin precession frequency can then be used as a measure of the muon beam energy. The electron spectrum in muon decay depends on the muon polarisation and can be used on a turn-by-turn basis to monitor the muon spin precession. An example of such a measurement is given in Fig. 8, which shows the number of high energy electrons oscillating from turn to turn. Statistics are almost infinite and precision very high. The oscillation amplitude is a measure of the beam polarisation, its frequency a measure of the beam energy, and is decrease with time, a measure of energy spread. Analyses of such spectra show that for a 50 GeV beam with a beam energy spread of $\sigma_E/E = 10^{-3}$ and 20% polarisation, these parameters can be determined for *each muon fill* with a statistical precision of:
$\Delta E/E = 2\ 10^{-6}$, ($\Delta E = 100$ KeV) for the energy
$\Delta(\sigma_E)/E = 2\ 10^{-6}$ for the relative energy spread
$\Delta P = 3\ 10^{-4}$ for the polarisation itself.
For a beam energy spread of $\sigma_E/E = 3\ 10^{-5}$ these numbers become:
$\Delta E/E = 10^{-7}$, ($\Delta E = 5$ KeV) for the energy
$\Delta(\sigma_E)/E = 5\ 10^{-7}$ for the relative energy spread
10^{-4} for the polarisation itself.

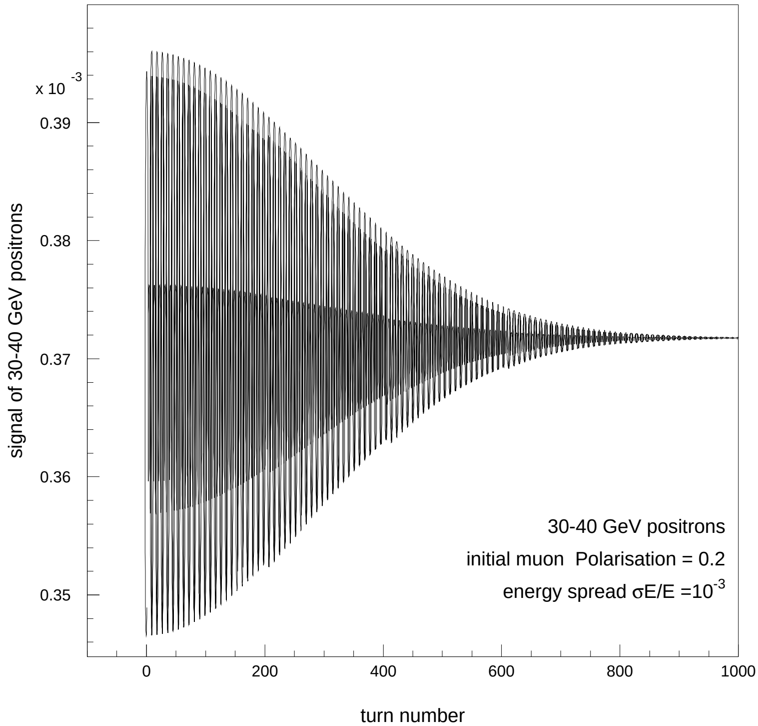

Fig. 8. Oscillation with turn number in a muon collider fill of the number of electrons in the energy range 30-40 GeV for 50 GeV muons (normalised to the total number of muon decays during the given turn). The oscillation amplitude is a measure of the beam polarisation, its frequency a measure of the beam energy, and is decrease with time, a measure of energy spread.

This is a determining factor in the study of thresholds and narrow resonances, which are used to make precise measurements of particle masses, widths and cross-sections, from which couplings to the muon can be derived. In contrast, electron linear colliders are faced with the serious problem of beamsstrahlung, a phenomenon which not only induces a loss of center-of-mass energy resolution, but is difficult to monitor precisely. To take an example, the present TESLA design leads to an average energy loss of between 1 and 3% with a corresponding energy spread. This energy spread dilutes thresholds and resonances. The shift of several GeV in center-of-mass energy has an intrinsic uncertainty that can be hoped to be reduced to the level of a few % of its value, still several tens of MeV, which will limit intrinsically all measurements of particle masses and widths. Consequently a muon collider could measure precisely (a few MeV) the W mass, the top threshold, as well as the thresholds for new pair produced particles. It could also re-measure very precisely the Z boson width and, thanks to the availability of beam polarization for both e^+ and e^-, the left-right asymmetry A_{LR}.

The other highlight of physics with muon colliders is the well known fact that the Higgs boson(s) couple to muons with a strength proportional to the muon mass squared, leading to usable cross-section for $\mu^+\mu^- \to H$, as long as the lightest Higgs mass lies below the W pair threshold. Such a scan has been studied by *e.g.* Murray [26], and is shown in figure 9. The precision achievable on the Higgs boson parameters is
0.1 MeV on m_h;
0.5 MeV on Γ_h;
less than a percent on the peak cross-section $\sigma(\mu\mu \to b\bar{b})$.

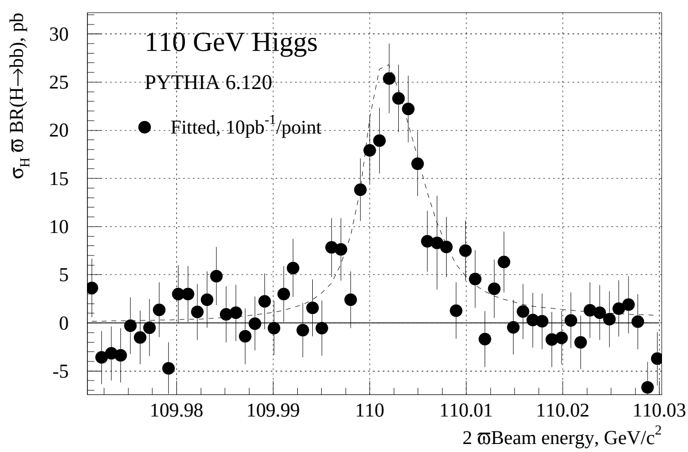

Fig. 9. The production cross-section for pairs of b-quarks from a 110 GeV$/c^2$ Higgs Boson as a function of beam energy. Dots are fitted MC corresponding to 10 pb^{-1} of events, and the continuous line is the simulated cross-section. The line-shape is given by PYTHIA 6.120 and no spread in the beam energy is allowed for.

The fact that the Higgs mass(es) and width(s) could be measured with a precision of a few hundreds of KeV is probably extremely important, although the full impact may not have been realized yet. It appears from the investigations that have been performed so far, that, in the few scenarios considered, it reduces the available parameter phase space by several orders of magnitude [27]. If they are ever made, these measurements could well have a similar historical importance as the precise measurements of the Z line shape at LEP. This is true of the Standard Model case with one Higgs boson, and would become truly fascinating if there were two more Higgses, possibly of different CP quantum numbers and interfering [28], as in most Higgs doublet models, in particular in Supersymmetry. The spectacular signature of these heavy Higgses is shown in Fig. 10. This physics would be amazing (if these particles are ever to exist) in particular if squarks were produced in the decay of these Higgses [29], allowing a clear separation between the CP-odd and CP-even state.

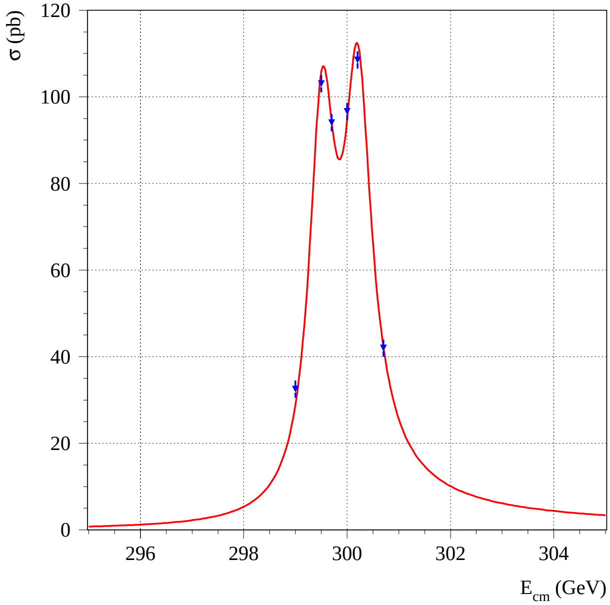

Fig. 10. Production cross section of H and A *via* $\mu^+\mu^- \to H, A \to b\bar{b}$ as a function of the centre-of-mass energy for $m_A = 300$ GeV and $\tan\beta = 10$, with a centre-of-mass energy relative spread of 3.10^{-5}. The triangles with error bars represent a simulated six energy point scan, with 25 pb^{-1} per point.

Finally, the muons are simply different from electrons, and would couple to different partners if those existed, allowing powerful searches for excited muons or scalar muon-partners.

This brief overview underlines the complementarity between electron and muon colliders, and the extent of the loss to the physics community, should muon colliders not be built.

5. The high energy frontier

Increasing the energy of muon colliders is essentially an economic, rather than technological, challenge. As shown in Fig. 2, a collider of centre-of-mass energy of at least 5 TeV could fit in the CERN site. The major constraint here comes from neutrino radiation hazard.

At first it might seem surprising that the major radiation issue in a complex that involves 10^{15} to $6.\ 10^{16}$ proton interactions and 10^{14} muon

decays per second would be caused by neutrinos. A quick examination of the scaling laws of interactions of the neutrinos produced by muon decays in the collider ring leads, however to this conclusion:
1. The neutrino cross-section increases like E;
2. The number of particles produced in a neutrino collision and subsequent showering thereof in matter also increases like E;
3. The neutrino beam opening angle, thus the lateral extension of the area hit by the beam of neutrinos, is inversely proportional to energy.

Thus radiation increases as E^3. For the muon collider parameters given in table 4.1, radiation exceeds the CERN allowed limit for radiation outside of its territory for a centre-of-mass energy of 3–4 TeV. This problem is clearly somewhat remote in the far future, and much remains to be learned about the operation of muon colliders. Nevertheless, the improvements point to more or better cooling and clever arrangement of the site with respect to the environment.

6. Conclusions

The line of facilities using muon beams seems extremely interesting, providing a very rich physics programme for many years. The European particle physics community must take this option very seriously. Detailed simulations and design become necessary, in the absence of which the feasibility and competitiveness of muon storage rings and colliders cannot be ascertained.

A series of ECFA-sponsored workshops will now take place to undertake the detailed work that is necessary to design and evaluate more completely such a project, with initial emphasis on the Neutrino Factory. The design and even the construction of this line of machines could involve competences that are available in different laboratories throughout Europe. A dedicated collaboration involving European laboratories is necessary in order to go further, and could become extremely effective.

It is a pleasure to thank all my colleagues from the american muon collaboration and from the ECFA prospective study group for enjoyable and fruitful (for me) collaboration. I want to thank our hosts from Cracow for their exceptional hospitality and friendliness, and hope very much to come back to Cracow soon.

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