The Physics Opportunities and Technical Challenges of a Muon Collider *

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January 24, 1994

Abstract

We describe the physics oppportunities and technical challenges of a muon collider as a tool for exploring high energy physics phenomena.

*Paper submitted to Columbia University of New York in partial fulfillment of the requirements for a Doctorate of Philosophy.
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1 Introduction

The continued success of the standard model (SM) of elementary particle physics has gradually but fundamentally altered the character of experimental high energy physics in the past decade or so. Ever more precise, expensive and time-consuming experiments continue to agree with the predictions of the SM, and the only really good chance for new discoveries appears to be by searching at energies higher than previously attained (in the TeV energy range).

The high energy frontier also has its problems, as emphasized by the cancellation of the SSC accelerator. Colliding beam facilities tend to be very large, technically challenging and expensive.

The SSC and the proposed Large Hadron Collider (LHC) at CERN were designed to collide protons. Proton collisions have two main drawbacks:

- Protons are complex composite particles. The hard scattering interactions that could produce new high mass particles actually occur between the quark and gluon constituents of the proton, and each constituent particle carries only a fraction of the proton momentum. This lowers the actual collision energy and means that interactions occur at a range of center of mass (CoM) energies and rest frames. The mass reach of hadron colliders for discovering new particles is diluted by this, by a factor of roughly 10 to 20.

- The strongly interacting protons produce enormous numbers of uninteresting
background particles from soft collisions. This tends to obscure the rare interesting processes and causes serious radiation and event triggering problems for the particle detectors.

The problems of hadron colliders are avoided by colliding electrons (and positrons). However, electrons have severe problems with synchrotron radiation which are specifically related to their light mass ($M_e = 0.511$ MeV):

- The energy loss per revolution from synchrotron radiation for a charged particle in a circular cyclotron accelerator of radius $R$ is given by

$$\Delta E(\text{MeV}) = 8.85 \times 10^{-2}[E(\text{GeV})]^4 \frac{1}{R(\text{meters})}$$ (1)

This loss must be compensated for by using radio-frequency cavities to accelerate the beam. This quickly becomes prohibitive as the electron energy is increased. The most powerful cyclotron accelerator for electrons will probably be the LEP-II accelerator at the CERN laboratory in Switzerland, which will come on-line in the next few years. The 27 kilometer ring will provide $e^+e^-$ collisions at CoM energies of 170 GeV. The only practical way of colliding electrons at energies higher than this is using single-pass collisions from pairs of opposed linear accelerators.

- Even linear electron colliders have the serious problem of “beamstrahlung” at the collision point. In future planned $e^+e^-$ colliders the magnetic fields generated from the intersection of high density electron and positron beams will
reach thousands of Teslas, inducing the particles to emit intense synchrotron radiation. This lowers and spreads out the CoM energies of the collisions, and also creates a serious background of photons in the detector. In addition, the photons can interact with either individual electrons or the macroscopic electromagnetic field of the oncoming beam to produce low energy electron pairs, which also form an experimental background. Pair production becomes a prohibitive background when the critical synchrotron radiation energy of the magnetic fields (equation 14.85 of Jackson\textsuperscript{1}) approaches the electron beam energy.

The above problems and the multi-billion dollar expense of proposed $e^+e^-$ and proton colliders have provoked a pessimism in the high energy physics community about the experimental future of the field. Nevertheless, the importance of further experimental progress to the advancement of the field cannot be overstated. To quote Harvard theorist Sidney R. Coleman\textsuperscript{2} “Experiment is the source of imagination. All the philosophers in the world thinking for thousands of years couldn’t come up with quantum mechanics”. This impasse underlines the importance of novel accelerator technologies. In the opinion of well known experimental physicist Samuel C. Ting\textsuperscript{2} “We need revolutionary ideas in accelerator design more than we need theory. Most universities do not have an accelerator course. Without such a course, and an infusion of new ideas, the field will die.”

One idea that shows promise is to avoid the synchrotron radiation problems of electrons by using muons instead. These “fat electrons” have 200 times the mass of
electrons ($M_\mu = 105.66$ MeV, c.f. with 0.511 MeV for electrons) and, in keeping with the idea of lepton universality, have otherwise nearly identical physics properties. They can be produced copiously by impinging proton beams on a target to produce pions and then letting the pions decay to muons. The one very serious drawback of muons is that they are unstable, decaying with a rest-frame lifetime of 2.2 $\mu$s into electrons and neutrinos:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu.$$  

(2)

This fact means that muon colliders must do everything very fast. The muons must be collected, “cooled” into small dense bunches, accelerated and collided before a significant fraction of them decay.

2 Physics Opportunities at the High Energy Frontier

The top quark and the Higgs boson are the two undiscovered elementary particles required to complete the original (and simplest) version of the SM – sometimes called the Minimal Standard Model (MSM). Experiments have set lower limits on the masses of the top quark and the Higgs particle of $M_{\text{top}} \simeq 130$ GeV\cite{3} and $M_{\text{Higgs}} = 48$ GeV\cite{4}, respectively, while the consistency of the MSM requires $M_{\text{top}}$ to be below about 250 GeV and $M_{\text{Higgs}}$ to be below $\sim 1$ TeV. This means that a muon collider could be used to discover and/or study the properties of either of these.

The Fermilab Tevatron $p\bar{p}$ collider, operating at either 900 GeV or 1 TeV, appears to have a reasonable chance of discovering the top quark in the next few years, and
it will almost certainly be discovered if and when the LHC starts taking data around the turn of the century. However, hadron colliders will probably only to be able to determine \( M_{\text{top}} \) to within about 5 GeV. The cleaner experimental conditions in lepton colliders could improve this to better than 1 GeV, and provide better tests of QCD predictions for top quark decays.

The Higgs boson is a much more difficult experimental target because of its low production cross section. The dominant production modes for lepton colliders are shown in figures 1a–d and the production modes for hadron colliders are shown in figures 2a and 2b.

The cross section contributions at lepton colliders from figures 1a and 1b are shown in figure 3. Note that the higher order process of 1b actually rises with increasing CoM energy, and this is the main Higgs production mechanism for TeV scale lepton colliders. The cross section for figure 1c is smaller than 1b because of the smaller NC coupling and \( M_Z > M_W \), and so it hasn’t been considered seriously in the lepton collider studies I have seen. (I am not sure how much smaller – it is reduced by a factor of about seven at the HERA ep collider and I would guess a similar or smaller reduction at a higher energy lepton collider.) However, it appears to give a much cleaner signature for the Higgs particle than the corresponding W -fusion process because \( M_{\text{Higgs}} \) can be reconstructed from the outgoing leptons and the known beam energies. Figure 1d is enhanced for \( \mu^+\mu^- \) colliders relative to \( e^+e^- \) colliders by a factor of \( (M_\mu/M_e)^2 \simeq 40,000 \). It makes an insignificant contribution for electron
Figure 1: The dominant Higgs production mechanisms for lepton colliders.
Figure 2: The dominant Higgs production mechanisms for hadron colliders.
colliders but for $\mu^+\mu^-$ colliders and $M_{\text{Higgs}} \lesssim 200$ GeV there is a significant Higgs production resonance at $E_{CM} = M_{\text{Higgs}}$. Once the Higgs has been discovered a “Higgs factory” muon collider could be built to sit on this resonance.

The Higgs decays preferentially to the heaviest particle–antiparticle pair lighter than $M_{\text{Higgs}}$. At the lighter end of the expected mass range for $M_{\text{Higgs}}$ the decay to $b\bar{b}$ pairs is favored, while heavier Higgs can decay to $t\bar{t}$ or $W$ and $Z$ bosons. Hadron colliders have such enormous background problems for most of these decays that the Higgs must be searched for in less common decay modes.

Another topic in the MSM that lepton colliders will be particularly useful for studying is the triple and quartic gauge boson couplings: $WW\gamma$, $WWZ$, $WWW$, $WWWW$,
\(WWZZ, WW\gamma\gamma\) and \(WWZ\gamma\). The anticipated observation of these couplings at LEP-II will provide the first experimental verification of the non-abelian nature of the standard model, and they can be studied with greater precision at higher energy lepton colliders.

The MSM is known to be only a good phenomenological theory that becomes inconsistent at experimentally inaccessible energy scales. The verification of the MSM at the next generation of colliders is only the most conservative scenario, and many physicists think that there is a good chance that exotic new processes will be revealed. This might take the form of extra Higgs particles, missing energy from the new particles predicted in various “supersymmetric” theories, or something even more unexpected. These exciting possibilities provide some of the main motivation for building new accelerators.

3 Luminosity, and Ionization Cooling of Muons

The production of high mass particles is expected to be a very rare process, requiring enormous collision rates – this is motivated by the observation that point-like cross sections fall as the inverse square of the center of momentum (CoM) energy. For example, the production of \(e^+e^-\) pairs in muon collisions is given by

\[
\sigma(\mu^+\mu^- \rightarrow e^+e^-) \equiv \frac{1}{R} = \frac{4\pi\alpha^3}{3s} = \frac{87 \text{ fbarn}}{E_{\text{CM}}^2 (\text{TeV}^2)},
\]

(3)

The number of events produced at an accelerator is given by the product of the cross section for that process, \(\sigma\), and the luminosity of the accelerator, \(\mathcal{L}\), integrated
over its running time

\[
\text{number of events} = \sigma \int \mathcal{L} dt.
\]

(4)

Design luminosities for the next generation of planned accelerations are typically \( \mathcal{L} = 10^{33} - 10^{34} \text{cm}^{-2}\text{sec}^{-1} \). For a canonical year of \( 10^7 \) seconds this corresponds to an integrated luminosity of \( \sigma \int \mathcal{L} dt = 10 - 100 \text{ inverse fbarn} \). (So equation (3) predicts that a muon collider with 1 TeV CoM energy and \( \mathcal{L} = 10^{34} \text{cm}^{-2}\text{sec}^{-1} \) would produce around 10,000 electron pairs in a year’s running.)

The luminosity of an accelerator is given by

\[
\mathcal{L} = \frac{N^2 f}{A},
\]

(5)

where \( N \) is the number of \( \mu^+ \) or \( \mu^- \) in a bunch (assumed equal), \( f \) is the frequency of collisions and \( A \) is the (effective) cross-sectional area of the beams at the collision point. The primary goal of accelerator design is deliver as large an \( \mathcal{L} \) as possible at the specified energy.

The cross-sectional area, \( A \), is minimized by designing a magnet lattice to focus strongly at the collision point and by minimizing the phase space volume of the particle bunches so that they will come to a good focus at the collision point. The phase space volume, \( PS \), of the beam can be written as a 6-dimensional product of the beam spread in coordinate and momentum space

\[
PS = \Delta x \Delta p_x \Delta y \Delta p_y \Delta z \Delta p_z.
\]

(6)

The \( PS \) of the particle bunch is conserved in any interactions with macroscopic
external electromagnetic fields, including the time-dependent fields applied during
the acceleration and storage of the bunch in the accelerator. The product of the
momentum spread and the spatial spread in each dimension is usually also separately
conserved (with a few caveats), but momentum spread is easily traded for spatial
spread by focusing or defocusing the bunch. However, $PS$ does tend to increase due
to the following effects

1. The bunch tends to be pushed apart by its own charge – the “space-charge”
effect. This tendency must be opposed by longitudinal and transverse focusing
in the accelerator.

2. Disruptions of the bunches can be induced by (e.g.) interaction of the beam charge
with accelerator elements (particularly r.f. cavities). While in principle this
may not increase the true phase space volume the practical effect is to cause
“filamentation” of the bunch so that it acts as though it is occupying a larger
phase space volume.

Since producing muons from pion decays gives very large values of $PS$ it is nec-
essary to cool the muons considerably before acceleration.

Muons can be cooled by a very simple method known as ionization cooling. The
concept is illustrated in figure 4a. A bunch of muons is passed through a slab of
material to reduce the muon energies. This reduces the transverse momentum spread
by a factor equal to the fractional energy loss. The momentum in the direction of the
beam is also reduced, but this can then be restored by accelerating the bunch in r.f.
cavities. The net effect is that the bunch ends up with the same energy but a lower transverse momentum spread. A variation is shown in figure 4b. A wedge of matter is placed in a dispersive region of the magnet lattice where the high energy muons are displaced from lower energy muons. The higher energy muons pass through more material than the lower energy ones and lose more energy. The original mean energy is then restored with an r.f. cavity, and this time the longitudinal momentum spread of the beam has been reduced.

This cooling mechanism is unique to muons. Electrons and hadrons such as protons would interact in the cooling material, and the only other heavy lepton – the tau – decays far too quickly for cooling or acceleration.

There are two heating mechanisms that compete with the cooling process:

- The transverse momentum spread of the beam is increased by multiple coulomb scattering (MCS)

\[ \frac{d(\Delta p_{x,y})^2}{dz} = \frac{1}{L_R} (13.6 \text{ MeV}/c)^2, \] (7)

where \( L_R \) is the radiation length of the material.

- The longitudinal momentum spread is increased by energy straggling

\[ \frac{d(\Delta p_z)^2}{dz} = \frac{dE}{dz} I, \] (8)

where \( I \) is the mean energy exchange (\( \sim 12Z \text{ eV} \)), the additional energy losses from hard single scatters have been neglected and the approximation \( p_z \simeq E \) is used.
Figure 4: Ionization cooling of muons.
Cooling is optimized by

1. Using a low Z material such as beryllium to maximize the energy loss per radiation length and reduce the energy straggling. (Beryllium has an energy loss of 105 MeV per radiation length, compared with only 7.2 MeV for lead.)

2. Focusing the muons into a tight bunch at the material to blow up the longitudinal and transverse momentum spreads to large values which can be effectively reduced by cooling.

3. Using low energy beams so that the fractional energy loss per radiation length is maximized. The energy cannot be below about 0.3 GeV because below this the muons are no longer relativistic minimum-ionizing particles and the energy spread of the bunch increases quickly when passed through material.

An interesting idea that unfortunately probably won’t work is to use crystals to cool the beam even further. Certain axes of crystals tend to channel charged particles and hold them while they lose energy – giving cooling without MCS. Large, high quality crystals of silicon, germanium and tungsten have been grown and used for extensive studies of particle channeling, and bent crystals have been used to steer particle beams. Unfortunately, the solid angle for capturing particles is very small (∼milliradians at 50 MeV, falling as $1/\sqrt{E}$ citeChen crystal) and the particles dechannel over characteristic lengths of centimeters at 10 GeV, rising in proportion to the beam energy. This appears to be too small by about two orders of magnitude
for net cooling.

Beam cooling at a muon accelerator would be expected to consist of some tens of slabs of beryllium or some other low Z material inside a lattice of magnets and accelerating structures to transport the beam and manipulate its distribution in phase space.

4 Conceptual Design of a Muon Collider

The idea of muon storage rings has probably been around since the 1960’s or earlier, and muon colliders have been seriously discussed at least as early as 1980[7]. A conceptual design of a muon collider is shown in figure 5[8]. This section discusses each of the components of the accelerator.

The requirement of colliding bunches containing $10^{11} - 10^{12}$ muons means that the hadron accelerator must deliver $10^{13} - 10^{14}$ protons into the target at a rate of 10 Hz or higher. This is more than any existing accelerator, but this technology has been studied in detail for the planned meson factories KAON and PILAC. The KAON design calls for bunches of $6 \cdot 10^{13}$ 30 GeV protons at a rate of 10 Hz.

Possible modifications to the KAON design that might be improvements for a muon collider are

- The muon collider needs both charges of muons, while protons produce predominantly $\mu^+$ (from $\pi^+$). This could be solved by using deuterium ions instead of protons.
Figure 5: Conceptual design of a muon collider.
• There is no need to be above the energy threshold for kaon production, and nucleon (proton or neutron) kinetic energies as low as 700 MeV produce pions copiously\cite{9}. This would be cheaper, would decrease the decay length of the pions and would decrease the energy flux onto the production target. It would also open up the speculative possibility of using an induction linac instead of a storage ring for accelerating the protons/deuterium ions. (Induction linacs can produce accelerating gradients in excess of 1 MeV/m and reach good efficiencies of better than 50\% for short, intense particle bunches\cite{10} – which sounds ideal for a muon collider.)

The thermal shock on the target is a difficult design problem. A bunch of $10^{14}$ 1 GeV protons delivers 6000 joules onto the target spot in a nanosecond timescale, some fraction of which will go into shock heating of the target. This load is repeated 10 times or more every second. This must be handled by maintaining a large spot size and intensive cooling of the target. A more exotic option which has already been tested at accelerators is using a liquid jet target of either water or a molten metal.

A schematic diagram of the pion collection and decay channel is shown in figure 6. One speculative alternative is to use a long ($\sim 50 – 100$ m) solenoidal magnet with a large aperture. The transverse momenta of the pions coming off the production target range up to around 300 MeV/c. Almost all of these pions would be confined in spiral orbits by an iron solenoidal magnet with a 2 Tesla field and 50 cm aperture radius, or by a superconducting magnet with a 6 Tesla field and a 20 cm aperture radius.
Figure 6: A schematic diagram of the beam-line elements used for pion collection and decay to muons.
The pions would decay to muons inside the magnet, and the positive and negative muons could be separated by including an additional transverse magnetic field. This idea would be much more practical if r.f. acceleration could be provided inside the magnet (I have no idea whether this is possible). In this case the acceptance could be a large fraction of unity for both $\mu^+$ and $\mu^-$.

The acceleration of the muons must proceed relatively quickly to avoid losing too big a fraction to decays. The average accelerating gradient required is several MeV/m, which is easily within today’s technology since the SLC electron linac currently operates with an average gradient of 20 MeV/m. A simple numerical integration finds that when muons are accelerated from 300 MeV to 2 TeV at a constant gradient of 5 (or 10, or 20) MeV/m the fraction surviving is 74% (or 85%, or 93%).

Figure 5 uses a linac to accelerate the muon beams. This is likely to be a very expensive option – almost half the cost of a $e^+e^-$ linear collider just for acceleration. Bob Palmer suggests using instead a recirculation linac, as shown in figure 7. The particles pass through each of the superconducting linacs several times over, and are transported between the linacs by the bending magnets in the recirculation loops. The motivation for this design is that r.f. accelerating cavities are very expensive, so it is cheaper to use the same cavities several times per bunch. This design is basically a higher energy copy of the existing CEBAF $e^+e^-$ accelerator, which also uses superconducting r.f. cavities.

After acceleration the $\mu^+$ and $\mu^-$ bunches are injected into the collider rings in
Figure 7: Conceptual diagram of a recirculating linac accelerator structure.
opposing directions. Since muons are heavy enough that synchrotron radiation is not a problem their beam transport properties are similar to protons. For example, 1 TeV muons would require a ring of radius about 1 km, being the same energy as the protons in the Fermilab Tevatron accelerator. The decay length of the muons in the ring is given by

$$\text{decay length} = 6233 \, \text{km} \cdot E_\mu \, (\text{TeV})$$.

(9)

This means that the number of muons in a bunch decays by a factor of $1/e$ in about 1000 turns – independent of energy.

One advantage for muon colliders over hadron colliders is that the storage time required is only milliseconds rather than hours, so the requirements on beam stability are much less demanding. Palmer suggests using an “isochronous” ring, with few r.f. cavities to compress the bunch length.

5 Detector Design Issues

The particle detectors at the interaction point would be expected to be similar to those at other high energy colliders, with particle tracking in a magnetized space surrounding the interaction point and with calorimeters enclosing this region. (One difference might be a greater emphasis on the precise determination of muon momenta.)

The backgrounds emanating from the vertex itself would be expected to much smaller than for hadron colliders, and probably smaller than at TeV energy electron colliders. However, the decay of the muons to electrons will still lead to serious
backgrounds at the detectors. For 2 TeV muons approximately one in \(10^7\) will decay per meter, so a bunch of \(10^{12}\) muons will produce about \(10^5\) electrons per meter with an average energy of about \(2/3\) TeV. All of these electrons will eventually hit the beam pipe somewhere in the ring, initiating electromagnetic showers. This leads to two types of backgrounds

1. The electromagnetic showers from electrons striking the final focus magnets close to the interaction point can leak into the detector.

2. Electromagnetic showers anywhere along the straight sections before the interaction point will occasionally produce a muon pair. This is suppressed relative to \(e^+e^-\) pair production by a factor of \((M_\mu/M_e)^2 = 40,000\), but the muons can pass through any shielding placed in front of the detector.

These backgrounds must be suppressed by a combination of shielding and design of the final focus magnets, and the detector must have enough electronic channels of tracking and calorimetry to be able to correct for the remaining background.

A reasonable design for the beam-line\[^1\text{2}\] might include a final focus region consisting of iron quadrupole magnets many meters long with a conical aperture decreasing from several cm at the entrance to about 1 mm at the end closest to the interaction point. Much of the remaining 1–2 meters distance to the interaction point might have a small aperture surrounded by a tungsten shield. The thickness of the tungsten would be determined by a compromise between the background suppression and the loss of angular acceptance into the detector. Such tungsten shields have also been dis-
cussed for TeV scale $e^+e^-$ colliders, blocking up to 10 degrees of angular acceptance about the beam-pipe.

6 Spin-off Physics Opportunities at a Muon Collider Facility

A muon collider facility would provide for much useful physics research apart from muon collisions. Further physics topics include

- spallation neutron experiments
- neutrino physics
- muon fixed target physics.

The short intense bunches of deuterium ions used for creating the pions are also ideal for producing neutrons, and designs for spallation neutron sources include just such a beam\cite{13}. The neutrons could either be collected from the primary proton target or from the beam dump downstream of the target. Neutrons are somewhat complementary to x-rays as important probes for condensed matter experiments, and the interest in neutron sources is illustrated by the plans to build the Advanced Neutron Source in the U.S.A. at a cost of over 1 billion dollars.

Muon decays in the accelerator straight sections around the interaction points would provide a neutrino source unique in its intensity and composition. Each cycle of the muon bunch would produce sub-nanosecond bursts of roughly $10^7 \nu_\mu$’s and $\bar{\nu}_e$’s (or $\bar{\nu}_\mu$’s and $\nu_e$’s for the $\mu^+$ bunch traveling in the opposite direction). These
would have an average energy of around 1/3 the muon beam energy, and would have an angular divergence of only about $1/\gamma_\mu \sim 0.1$ mr or the angular spread in the muon directions along the straight section (whichever is larger). This would allow substantial improvements in both precise measurements and searches for exotic physics processes in neutrino-nucleon scattering. For example, the large neutrino-induced event samples could substantially improve current measurements of nucleon structure functions and weak mixing angle measurements from neutrino-nucleon scattering, and the purity of the beam and the 50% component of electron neutrinos would allow unprecedented sensitivities in detector-based searches for neutrino oscillations (a topic which is currently popular). In fact, the neutrino beam would be strong enough to be a radiation hazard, and it is likely that human habitation would have to be forbidden along a line extending out from the accelerator straight sections.

### 7 Feasibility and Cost

| parameter                        | muon I     | muon II    |
|----------------------------------|------------|------------|
| luminosity (cm$^{-2}$s$^{-1}$)   | $1.3 \times 10^{34}$ | $4 \times 10^{34}$ |
| beam energy (TeV)                | 2          | 2          |
| proton frequency (Hz)            | 10         | 30         |
| protons/bunch                    | $6 \times 10^{13}$ | $2 \times 10^{14}$ |
| muons/bunch                      | $4 \times 10^{11}$ | $1 \times 10^{12}$ |
| phase space (MeV$^3$ mm$^3$)     | $1.0 \times 10^5$ | $0.8 \times 10^5$ |

Table 1: Parameter choices for a muon collider [11].

The parameters of two conceptual designs for a muon collider by Palmer [11] are given in table 1. Achieving the design luminosities given by Palmer would make such
Muon colliders extremely attractive for exploring the TeV energy scale. It should be stressed that a lot of work will be required before one can estimate with any confidence what are reasonable design parameters for a muon collider.

Palmer also provided an “order of magnitude” cost estimate for a 4 TeV CoM muon collider, with the caveat that it was an extremely crude estimate which should not be taken seriously. He obtained the proton source cost (0.5 billion) using the KAON cost estimates, the linac cost (1.0 billion) using estimates for the Next Linear Collider $e^+e^-$ machine and the tunnel and magnet cost (0.2 billion + 0.9 billion) by scaling to the SSC. Adding 0.5 billion dollars for the facility and 0.3 billion for the muon cooling gives a very tentative estimate for a total cost of 3.4 billion dollars. This is certainly a very hefty price tag, but it is competitive with and probably cheaper than the competing technologies, and the price would be less for a lower CoM energy.

8 Summary

Muon colliders show great promise for exploring the high energy frontier in elementary particle physics. However, it will take a lot of detailed study to determine whether they are actually feasible or are just another good idea that won’t quite work.
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