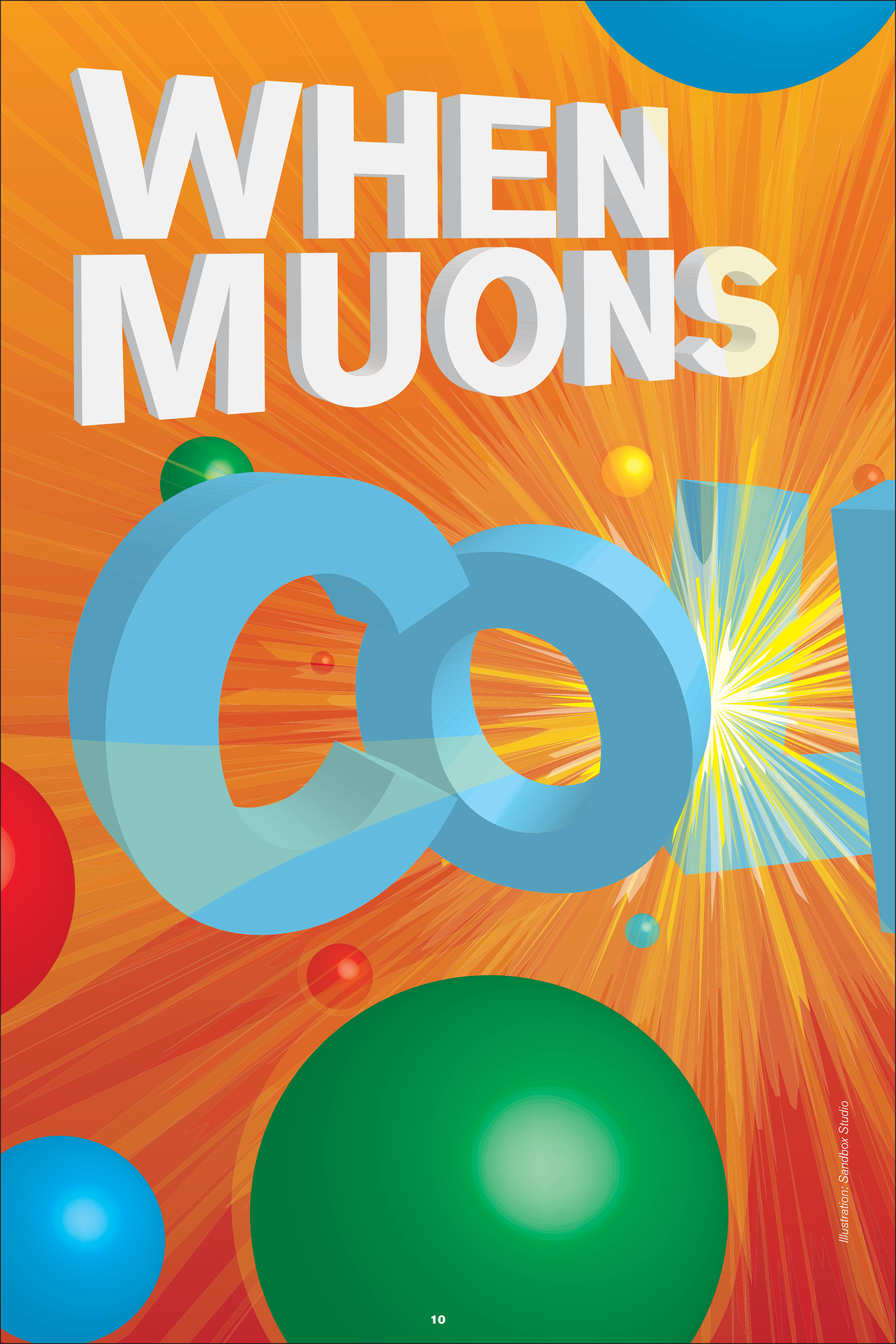


Illustration: Sandbox Studio

A new type of particle collider known as a muon collider–considered a wild idea a decade ago–is winning over skeptics as scientists find solutions to the machine's many technological challenges. By Leah Hesla

When Fermilab physicist Steve Geer agreed to perform a calculation as part of a muon collider task force 10 years ago, he imagined he would show that the collider's technical challenges were too difficult to be solved and move on to other matters. But as he delved further into the problem, he realized that the obstacles he had envisioned could in principle be overcome.

"I started as a skeptic," he says. "But the more I studied it, I realized it might be a solvable problem."

A muon collider—a machine that currently exists only in computer simulation—is a relative newcomer to the world of particle accelerators. At the moment, the reception from the particle physics community to this first-of-its-kind particle smasher is "polite," says Fermilab physicist Alan Bross.

Politeness will suffice for now: research and development on the machine are gearing up thanks to funding from the US Department of Energy. In August, a DOE review panel supported the launch of the Muon Accelerator Program, or MAP, an international initiative led by Fermilab. Scientists hope the program will receive about $15 million per year over seven years to examine the collider's feasibility and cost effectiveness.

Mutable muons

As with any new high-energy physics project, the muon collider has its share of skeptics who voice doubts about its projected R&D timeline or its cans of engineering worms. But Bross, a member of the MAP management council, assures the physics community that "we're not raving lunatics."

Muons—heavy cousins of the electron—have tragically short lifetimes: they decay after about two millionths of a second. Yet these blink-and-you-miss-them muons may help particle scientists find answers to some of the universe's most nagging questions.

Accelerator scientists are accustomed to arranging collisions between electrons or protons. Since these particles don't decay, they can travel around a circular accelerator for days or weeks. Muons, in contrast, don't leave much time for acceleration and manipulation. Still, it's an obstacle scientists believe they can overcome.

"It's doable," says Vladimir Shiltsev, director of Fermilab's Accelerator Physics Center.

A muon collider would accelerate two beams of muons in opposite directions around a 6-kilometer-circumference underground ring. Those beams would collide head-on at close to the speed of light. Scientists would mine the collision aftermath to look for dark matter, supersymmetric particles, signs of extra spatial dimensions, and other subatomic phenomena.

Getting to the point where a muon-muon collision is in principle achievable means being able to produce and manipulate a beam of muons, and that's no small challenge.

Avoiding a subatomic mess

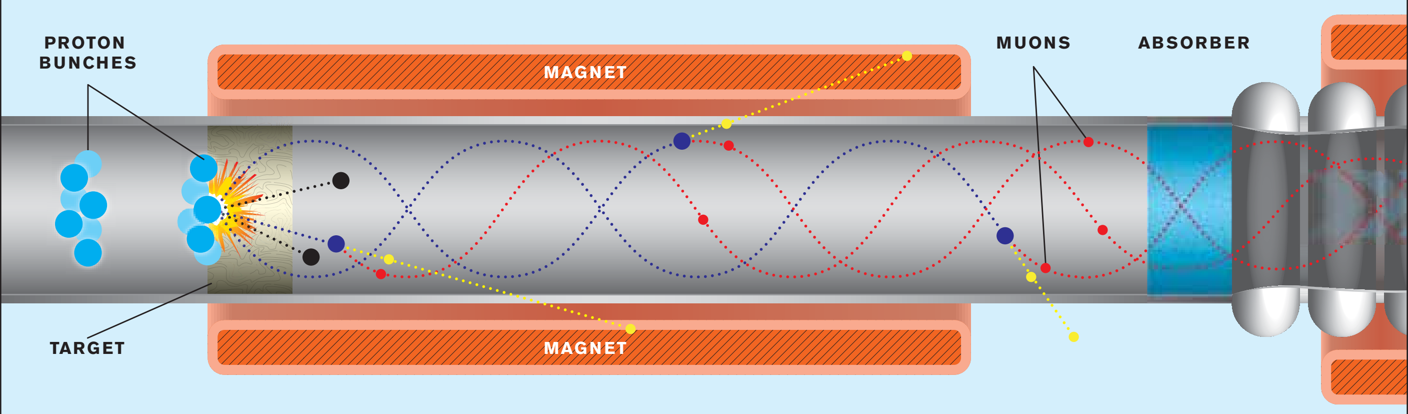
The Large Hadron Collider in Europe, which started operations in 2009, is a proton-proton collider with a circumference of 27 kilometers. Scientists think of the LHC as a universal particle physics discovery machine. It scans a wide range of energies to look for the elusive Higgs boson and other particles, the way a birdwatcher would walk through a forest and look for a particular bird. But once he's located the bird in a treetop and wants to get a close look, the naked eye won't cut it. He'll want a pair of binoculars to better study the bird's plumage and behavior.

A muon collider would be a particle physicist's set of binoculars. It would zoom in on a narrow region of energy to uncover the physics phenomena that the LHC can't reveal on its own. It would provide a clear, unobstructed view of the subatomic world.

"The beauty of a muon collider is that the collision events are clean," says Shiltsev.

Clean events arise because muons are indivisible. Unlike protons, which contain quarks and gluons, muons have no component parts. Two colliding protons are like two high-velocity bags of trash meeting in mid-air: the pieces of garbage inside the bags, not the two bags themselves, are doing the colliding. The difficulty then lies in sorting through the mess each collision creates and tracing which bottle cap triggered the trajectory of which candy wrapper.

With muons, there is no garbage. Being a muon



Slow beam

is uncomplicated. When two colliding muons have opposite charges—one positive, one negative—they annihilate, and all their energy goes into making new matter. In contrast, when the LHC accelerates protons, it's really the quarks and gluons inside the protons that are colliding, and each component carries only a fraction of the total proton energy.

"The actual collisions you see at the LHC in general have something like a tenth of the energy" of the full proton-proton collision, says Bob Palmer of Brookhaven National Laboratory, who has led previous incarnations of the muon collider collaboration.

Muons vs. electrons

The muon collider faces some competition. The familiar electron, another collision candidate, is also indivisible and produces clean collisions as well. But the lightweight electron is harder to accelerate along a curved path than heavier particles, such as muons and protons. An electron, whose mass is 1/200th that of a muon, easily radiates its energy away when it follows the curve of a circular accelerator at high speed.

A muon would better retain its energy, even as it zooms around a 6-kilometer circle thousands of times at close to the speed of light. Those multiple trips around the track would allow muons to reach high collision energies, higher than those of quark-quark and quark-gluon collisions produced at the LHC.

Scientists can overcome the electron's radiation problem by designing electron colliders that are straight and tens of kilometers long. Right now, the physics community contemplates two possible options. One is the International Linear Collider, a proposed 30-kilometer-long electron-positron collider. In 2012, scientists and engineers will deliver the detailed drawings and plans for the ILC. Although the ILC option is the furthest along in R&D, its cost, estimated at $15 billion to $20 billion, gives scientists and would-be funders pause.

The other option is CERN's Compact Linear Collider, which would be about 15 to 20 kilometers longer than the ILC. Scientists hope that CLIC can reach much higher energies than the ILC by using a different acceleration technology. It will be another year or so before scientists will have figured out whether the CLIC concept is feasible. But the length of the proposed machine—about 50 kilometers—could make CLIC extremely expensive.

Which one of these three collider designs will be nominated as the LHC's precision counterpart depends in great part on the discoveries that the LHC will make in the next several years. They will determine how high a collision energy an electron or muon collider must achieve.

Particles live at different energy scales, measured in TeV, or Tera-electronvolts. Thanks to Fermilab's Tevatron collider and generations of particle accelerators before it, scientists know which particles live at which energies—up to a certain energy level. Beyond that point, the energy realm is unexplored territory, and scientists think there is a bonanza of particles waiting to be unearthed.

Results from the LHC, a machine that could reveal particles as heavy as a few TeV, will tell scientists where to go digging. Right now, they're wondering whether the LHC's most interesting discoveries will be at less than half a TeV.

"If the answer is 'yes,' then the International Linear Collider is the way to go," Shiltsev says. "If the answer is 'no,' then there will be a choice between CLIC and the muon collider."

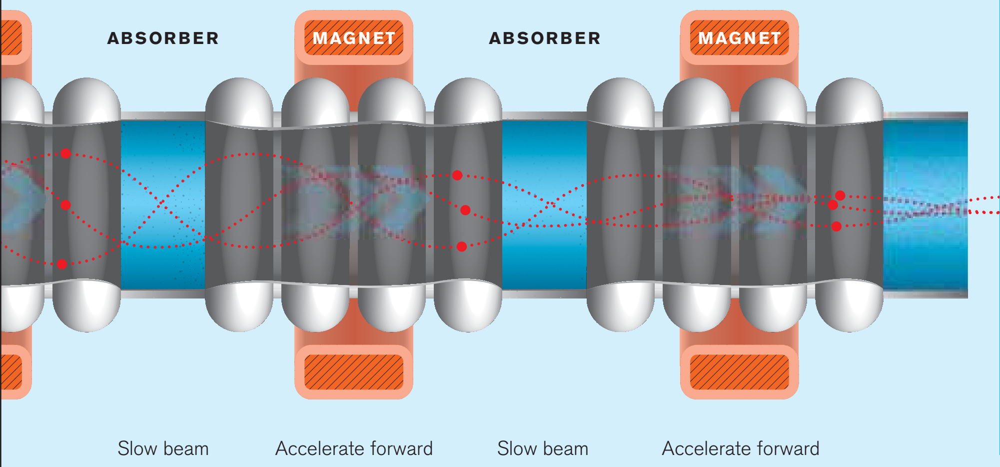
CLIC could reach energies of up to 3 TeV. Scientists developing the muon collider are aiming for energies up to 4 TeV, about the energy of the most powerful quark-quark collisions at the LHC.

Higher energies typically lead to higher costs. But the compact size of a circular muon collider has the potential to be cheaper than the ILC or CLIC.

"The muon collider is quite tiny for the same energy as the LHC," Palmer says. "It would easily fit on the Fermilab site. It would even fit on the Brookhaven site."

The challenge

To make the muon collider a real contender as the next particle collider, scientists will have to show that the machine can attain a good deal of something called luminosity.



Making a muon beam
Scientists create large numbers of muons by steering an intense proton beam into a target made of a dense liquid such as mercury. A set of magnets gets the resulting muons moving in the right direction. The challenge is to corral the muons into dense beams. Physicists are developing a technique known as ionization cooling. It tames muons by sending them through a series of magnets and absorbers filled with gas. The gas slows the muons and absorbs their energy while the magnetic fields confine the muons and narrow the beam. Acceleration devices then propel the muons forward. This process is repeated many times until the muon beam is almost laser-like.

Luminosity is a measure of how many collision events your machine can produce per second. To increase the chances of seeing interesting events, colliders must have as much luminosity as possible. To achieve that, you need lots of particles traveling through your accelerator, and you need them to be contained in compact, dense packets, called bunches.

Loose bunches of particles cannot effectively collide. It would be similar to throwing two handfuls of rice at each other from far away and hoping a few grains hit each other.

Wrangling ephemeral muons to form tight bunches and speed around a ring is tougher than herding cats. To create those bunches, particles have to be corralled, or cooled, as the process is called in physics. For the muon collider, successful cooling is the single greatest engineering challenge facing scientists, and they will have to draw on bold ingenuity to get it done.

In nature, muons come to us from cosmic rays. For a muon accelerator, scientists would create muons by smashing protons into a dense liquid such as mercury. Muons born from these human-made collisions are an unruly bunch, flying every which-way with every which-energy.

"It's been described as a pumpkin-sized beam," Geer says. "You can't put that immediately into an accelerator."

Two experiments—MuCool at Fermilab and the Muon Ionization Cooling Experiment at the Rutherford-Appleton Laboratory in Oxfordshire, England—are dedicated to advancing techniques for muon cooling.

The aim is to shrink a pumpkin-sized beam into a millionth of its volume in two millionths of a second, well before the muons decay into electrons and neutrinos.

"We do beam cooling all the time with beams of other particles," Geer says. "But the present techniques take far longer than a couple of microseconds. We need a new technique that takes a very short period of time."

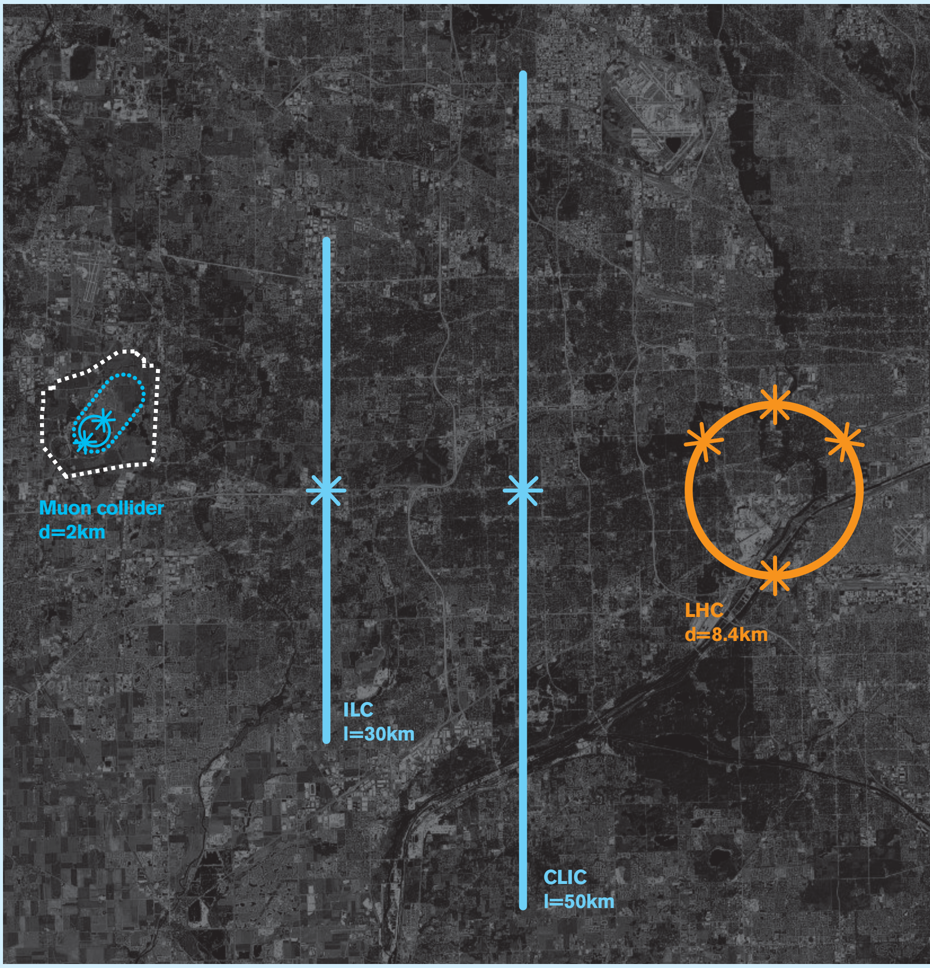
One of the techniques under consideration looks particularly promising: ionization cooling. It tames muons by sending them through a series of magnets and containers filled with liquid hydrogen, for example. As the muons repeatedly collide with the hydrogen, it absorbs the muons' frenetic energy while the magnetic fields confine the particles and narrow the beam. Acceleration devices then propel the compressed beam of muons forward. This process is repeated until the muon beam is almost laser-like, ready for injection into the main accelerator.

Although cooling is only one of the big hurdles scientists face, the muon collider community is rather optimistic that it can overcome all engineering challenges.

"We are right on the cusp of knowing how to solve the problems that we've been talking about for so long," Palmer says. "And now, we're getting to the point where we see how the thing is actually possible."

Proposed particle colliders
Particle physicists are considering three types of particle colliders for reaching higher collision energies. Their relative sizes are shown at right, with the Large Hadron Collider for comparison. A 4-TeV muon collider would be only a couple of kilometers in diameter and fit on the Fermilab site, but it still faces many engineering challenges. The well-advanced design of the International Linear Collider, which would make electrons and positrons collide at 0.5 TeV, calls for a 30-kilometer-long machine. Also under consideration is a 3-TeV electron-positron collider known as the Compact Linear Collider, or CLIC. If technically feasible, it would be about 50 kilometers long. In comparison, the Large Hadron Collider in operation at the European laboratory CERN has a circumference of 27 kilometers and is more than eight kilometers in diameter.

Images: Sandbox Studio



First stage: Project X

Taking into consideration the decades it takes to plan and build a large particle accelerator, high-energy physicists hope to keep pace with the LHC and choose between an electron and muon collider in the next several years.

"One of the enormous potential strengths of the muon collider is that you can imagine a stageable program," says Geer. "You can start Project X here at Fermilab, build a muon facility, build a neutrino factory, and you end up with a muon collider. There's a rich array of possibilities."

Project X is a proposed high-intensity proton accelerator at Fermilab. Its main purpose is to provide an intense proton beam for a number of kaon, muon, neutrino, and nuclear physics experiments. Ultimately, the Project X accelerator could serve as the front end of a muon collider and deliver an abundance of protons, the raw material for producing muons.

The next stage would be a muon facility that cools and accelerates the muons produced by Project X. This would allow for the construction of a neutrino factory, an official component of the Muon Accelerator Program. In a neutrino factory, an intense beam of muons would circle in a storage ring until the particles decay into electrons and neutrinos, ghost-like particles that might explain the evolution of the early universe and the abundance of matter over antimatter.

"On the way to building a muon collider, we will have a great opportunity to build a neutrino factory," says Bross.

As its name indicates, a neutrino factory would provide physicists with a plentiful supply of the hard-to-catch neutrinos.

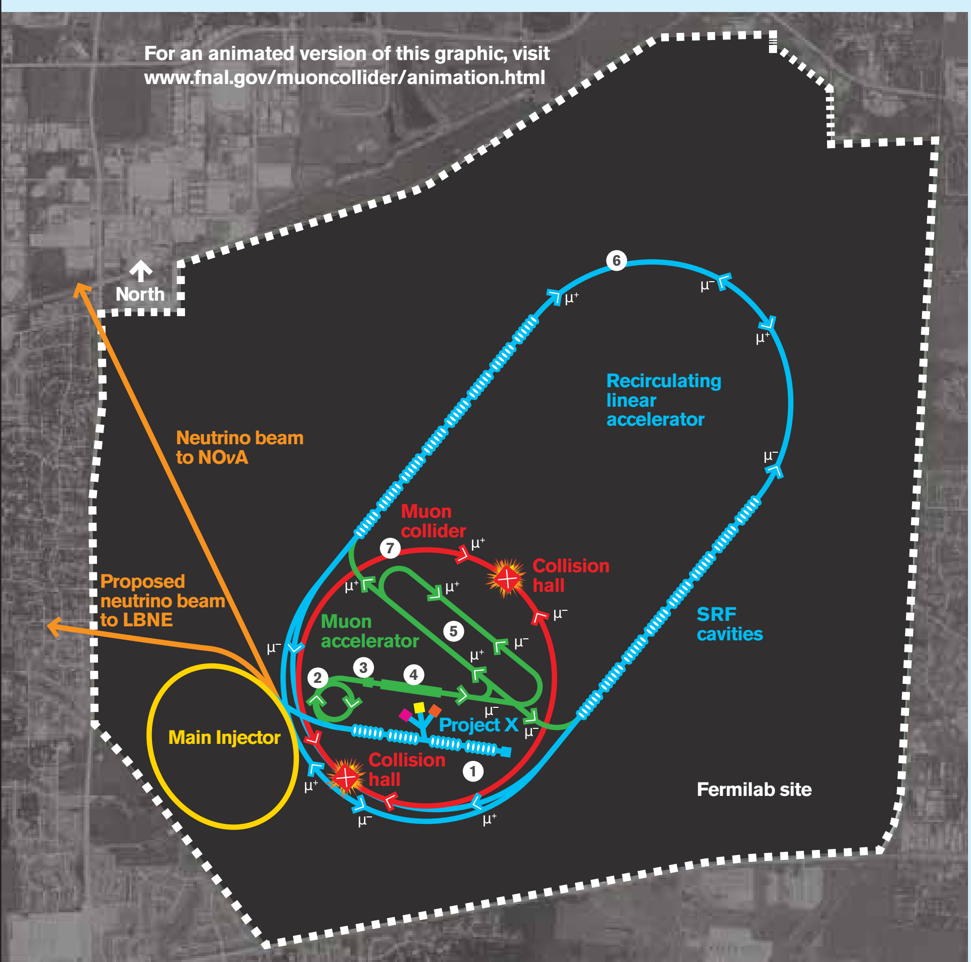
"Each muon creates two neutrinos for science," says British physicist Ken Long, chair of the International Design Study for the Neutrino Factory. "The muon collider and neutrino factory are a marriage made in heaven."

The last stage would be the construction of the muon collider ring, which would send two beams of muons in opposite directions and make them collide. It would be built while earlier stages of the accelerator complex were already providing the physics community with scientific programs that could be continued with or without the collider itself.

This staged approach to the muon collider—a machine that seemed an unlikely possibility only 10 years ago—is now an idea that physicists and funding agencies deem worth investigating.

At the moment, the muon collider may still be trailing the electron colliders in R&D efforts. But if scientists succeed, it will be "one heck of a machine, which is why the idea hasn't died in the forty-plus years it's been around," says Shiltsev.

"At some moment years away, we hope to be at the level where we can, with a light heart, say that we believe we can build this muon collider," he says. "It will be a superb machine for high-energy particle physics."



Expansion of the Fermilab accelerator complex: conceptual layout

1 Project X
Accelerate protons to 8 GeV using superconducting radio-frequency (SRF) cavities. Protons would be used for low-energy experiments and sent into the existing Main Injector to create high-intensity neutrino beams.

2 Compressor ring
Reduce size of beam before it hits target.

3 Muon production target
Smash protons into target material, generating muons with energies of about 200 MeV.

4 Muon capture and cooling
Capture, bunch, and cool muons to create a tight beam.

5 Initial muon acceleration
In a dozen turns, accelerate muons to 20 GeV. These muons could power a neutrino factory.

6 Recirculating linear accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF cavities.

7 Muon collider
Bring positively and negatively charged muons into collision at two locations 100 meters underground.