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Hadron Collisions at TeV Energies

R.N. Cahn

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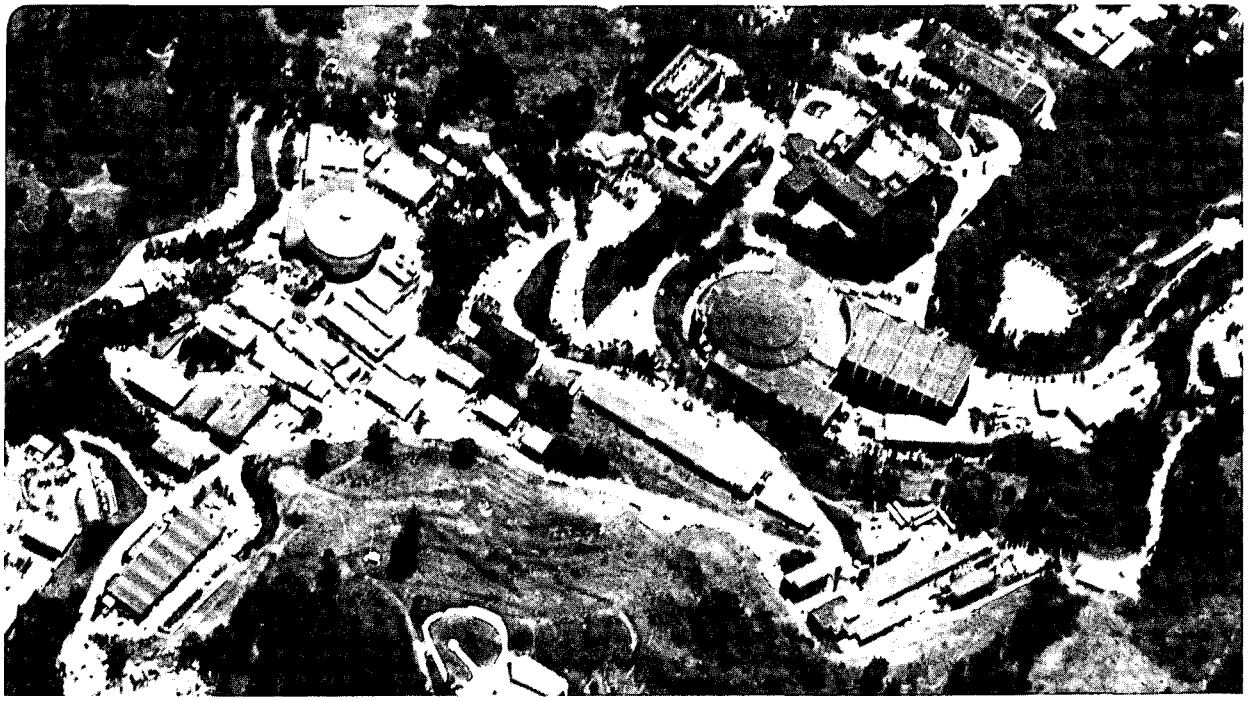

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HADRON COLLISIONS AT TEV ENERGIES *

Robert N. Cahn

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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If there is one equation of modern physics that has been assimilated into mass culture it is $E = mc^2$. We all know that Einstein's relation means that matter can be turned into energy and indeed the very small amounts of matter thus transformed in nuclear reactions can produce enormous amounts of energy. For the particle physicist, however, the equation is most interesting when applied in the opposite direction. From excess energy, new matter can be created. So pervasive is this concept that we usually state the masses of elementary particles in terms of energy. Thus we say that a proton has a mass of about 940 million electron volts or MeV.

Since just after World War II, particle physicists have constructed accelerators reaching higher and higher energies. This has enabled them to create new particles of greater and greater mass. Indeed, so many particles were discovered that Enrico Fermi is said to have remarked "Young man, if I could remember the names of these particles, I would have been a botanist." On a pragmatic level, particle physicists dealt with this proliferation by establishing a group that keeps track of all the new particles and their properties and issues ever two years an updated booklet that is supposed to fit in one's pocket, containing the most important facts. The abbreviated particle summary is 60 pages long. A more fundamental response has been to find patterns that explain these particles and their properties.

The continuing goal of particle physics is to find patterns and explanations for patterns among the particles we discover. The search has led to investigations at higher and higher energies and to shorter and shorter time spans. Particles that decay in a thousandth of a millionth of a second are regarded as long-lived. Of course we don't encounter such particles in our daily routine, but in the subatomic world they are the rule rather than the exception. Indeed, the Particle Data Booklet section on "Stable Particles" includes particles whose lifetimes are 10^{-17}s and in the extreme, the W and Z bosons of recent fame with lifetimes 10^{-25}s. Generally, particles decay into lighter particles unless there is some very good reason for them not to. The electron does not decay because there is no lighter particle that carries electric charge and so far

as we know electric charge is conserved, that is, it is preserved in all processes.

Despite the arcane nature of high energy physics research, it maintains a strong hold on the public imagination. The speed with which new scientific concepts become part of the common culture is a reflection both of the importance of science and technology to our society and to the continuing interest, widely shared, in the fundamental nature of physical reality. The existence atoms was not even established one hundred years ago, and the essence of the atomic model with its tiny nucleus surrounded by electrons was not discovered until 1911. Even more remarkably, the neutron, which accounts for more than half of the matter of which we and the world around us are made, was not found until 1932. Yet the fundamentals of the atom with a nucleus made of protons and neutrons, surrounded by a cloud of electrons, are now taught in schoolrooms throughout the world.

The discoveries of particle physics are being assimilated even more rapidly today. Newspapers and magazines carry stories of quarks and W bosons. In the movie *Roxanne*, Daryl Hannah, cast as a stereotypical, beautiful blonde astrophysicist, announced to Steve Martin that b and t quarks are the most common of the six quarks. This surely set a record for the absorption of new physical discoveries into popular culture because the b quark was discovered in 1977, and the t quark has yet to be found!

If particle physics doesn't perhaps have the glamour of Hollywood, it does have a glamour of its own. This glamour has enabled it to attract many of the most outstanding students of science worldwide and made it a thoroughly international enterprise. Major accelerators are being built and operated in the United States, West Germany, Switzerland, Japan, China, and the Soviet Union. Even more important, the work in each of these laboratories involves collaborations of researchers from around the world. No group has a monopoly on discovery. The fundamentals of particle physics were laid down by people like Hideki Yukawa, Enrico Fermi, Richard Feynman, Murray Gell-Mann, C. N. Yang, and T. D. Lee. A major achievement of the discipline has been to formulate a theory that successfully explains electromagnetic and weak

interactions. This theory was based on the work of many, including the Dutch physicist G. 't Hooft and the Korean-American B. W. Lee. It culminated in the award of a Nobel Prize to Sheldon Glashow, Steven Weinberg, and Abdus Salam, two American Jews and a Pakistani Moslem. The desire for an understanding of the fundamental nature of matter is shared by humankind throughout the world and amply demonstrates the contributions that diverse cultures can make.

There is an unfortunate tendency to emphasize the theoretical achievements of particle physics over the experimental ones. This is a hard error to avoid because a successful theory summarizes succinctly the results of the experiments. But the truth is that there are lots of theories but few that survive the test of experiment. The great success of the model of particle interactions now embraced by physicists was established in a series of superb experiments. In fact, there are no important data that conflict with this model.

The model of Glashow, Weinberg, and Salam goes by the unassuming title "The Standard Model." The primary roles are played by two sorts of particles. The first are the quarks and the leptons. The leptons include the electron and the electron-type neutrino, and in addition, two more analogous pairs, the muon and muon-type neutrino, and the tau-lepton and its neutrino. The second are the gauge particles. These include the photon, the W and Z bosons, and the gluons. The photon carries the electromagnetic interaction and is manifested as light. The gluon carries the strong force, which binds the quarks together. The W is responsible for beta decay. That's it: quarks, leptons, the photon, W, Z, and gluons. Almost. There is a little bit more that we shall speak of later.

Six quarks, six leptons, and four kinds of gauge particles. A tidy description and one whose complete mathematical elaboration is good enough to describe all the data we have so far. Is it time to quit? Are there no more questions? The fact is that this picture raises many new questions and in fact they are questions much more interesting than the ones we worried about back in the old days, when I was a student in the early 1970s. Actually a few of the questions

have been around for a long time, but when they were originally posed they didn't really sound like scientific questions. When the muon, which seems to be just a heavier version of the electron was discovered, I. I. Rabi is said to have asked: "Who ordered that?" We can't address the question in that form, but we can ask why are there three pairs of leptons and three pairs of quarks. Or are there in fact more left to be discovered.

The model is tidy, but not tidy enough for the taste of most particle physicists because we can't explain why there are the quarks and leptons we observe, nor why they have the masses they do. We don't even know whether the neutrinos have masses or not and the experiments are contradictory on this point. Why are there three basic forces: gravity (about which I shall say little), strong interactions that bind the quarks into protons and nucleons, and the electroweak interactions responsible for electricity, magnetism, and weak interactions. Are there more fundamental forces or more fundamental particles? Are the quarks and leptons truly fundamental or are they too composed of still more primitive objects?

In order to answer these questions we need more clues and these can only come from new experiments. If we are to look more deeply inside matter, we must have a more powerful microscope and accelerators are the microscopes of particle physics. The higher the energy of the machine, the smaller the structures that can be examined. This is clearest at machines where high energy photons are used to probe matter. The higher the energy of the photon, the shorter is its wavelength. The shorter its wavelength, the smaller the structure it can discern. The same principle holds true when particles other than photons are used. The highest energy machines available today are the proton-antiproton collider at CERN in Geneva and a similar machine located at Fermilab, outside Chicago. At CERN beams of particles with an energy of 310 thousand million electron volts - GeV - collide against each other. At Fermilab the energy is 800 GeV per beam.

In principle, this makes 620 GeV or 1600 GeV available to be turned into matter at the two machines. In fact this does not happen. The reason is that a

proton with an energy, say, of 800 GeV acts like a bundle of smaller particles, quarks, antiquarks, and gluons and the energy is shared among them. The most interesting collisions occur when one of these constituents collides nearly head-on with a constituent from a particle in the opposite beam. Since each constituent carries only a fraction of the 800 GeV, the total energy available in this collision of constituents is much less than 1600 GeV.

The machine at CERN was constructed primarily to observe the W and Z bosons, whose masses had been predicted to be about 80 - 90 GeV. The most energetic constituents inside the proton are quarks and those in the antiproton are antiquarks. When a quark and an antiquark collide they may produce a W or Z if their total energy is just right. With the beams initially at 270 GeV each, the W or Z could be produced if both the quark and antiquark carried about one-sixth the energy of the beam. About one event in ten million produces a W or Z boson at CERN.

How can the Ws or Zs be observed? Ultimately, most techniques for observing elementary particles depend on the effect that a swiftly moving charged particle has when passing through matter. The charged particle collides with electrons in the material and knocks them out of the atom to which they are attached, leaving behind an ion. The liberated electrons can be sensed by attracting them to a positive voltage. This same principle can be applied in a great variety of ways and it is possible to construct detectors that are sensitive to particular kinds of particles.

If a prototypical detector is examined from the inside out, there are usually four major layers. In the first, the charged particles paths are measured by sensing the trail of electrons left behind by the ionization process. Neutral particles like the neutron and photon cannot be measured in this section. The next section is called the electromagnetic calorimeter, that is, it measures electromagnetic energy. This energy is deposited preferentially by electrons and photons, but other particles too can be detected. The third division is the hadronic calorimeter. This measures the energy of most of the particles other than the electrons and photons. Finally there is a muon detector. Energetic

muons are especially hard to stop and they pass right through the first three divisions, leaving a track in the first division and only a small signal in the two calorimeters. Even more evasive are the neutrinos. These pass right through the whole detector without being affected. In fact, this makes it possible to detect very energetic neutrinos that are moving transverse to the beam. If we see the energy of many particles moving to the left, we know they must be balanced by something moving to the right. If nothing is visible in the detector, we suspect there were neutrinos moving to the right unobserved.

What does a W or Z look like in a detector? That depends on what the W or Z turns into. In fact, the W or Z lives only 10^{-25} seconds on average, before turning into some other particles. The Z for example can turn into an electron and an antielectron, that is a positron. This happens about 3% of the time. More often, the Z turns into a quark and antiquark. However, we never see a single quark or antiquark. This is because the gluons that bind quarks and antiquarks are so powerful that a quark can never entirely escape the grasp of the gluons. A quark and an antiquark produced by a decaying Z ultimately show up as a multitude of hadrons, strongly interacting particles made of quarks and antiquarks bound together by gluons.

When a Z decays into a quark and an antiquark, the ultimate effect then is that there are two jets of hadrons that shoot out along the directions of the original quark and antiquark. These jets are easily visible in the detector. Sometimes the Z decays into a pair of muons. These are seen in the muon detector. The last possibility, which occurs about 20% of the time, is that the Z decays into a pair of neutrinos. When this happens, no signal is observed in the detector.

Now this makes it sound pretty easy to find a Z boson. In fact it is not so easy because the decay into a quark and an antiquark is not a very useful signal. The reason is very simple. There are other processes that occur, and much more frequently, that look just the same. Sometime a constituent of the proton collides with one from the antiproton and doesn't produce anything in particular but simply bounces off. One parton goes one way and one another.

These partons again turn into jets of hadrons and these look just like the jets produced by a decaying Z. Now we might hope to distinguish them by measuring the energies of the jets to see whether they really came from a Z, but it turns out that there are so many jets produced simply by ordinary collisions that they overwhelm the jets from Zs. Fortunately it is very hard to make an electron-positron pair appear with just the right energy to have come from a Z so when we see such a pair we can be pretty sure it really did come from a Z. The same is true for a pair of muons.

The detection of a W follows a similar pattern. Most of the time a W decays into a quark and an antiquark, which turn into jets of hadrons. They are lost in the vast number of events having two jets that are not the result of W or Z decay. About 8% of the time the W decays into an electron and a neutrino. Often the electron can be detected because it is moving transverse to the beam direction, the direction along which most of the produced particles go. The neutrino balances the electron's transverse momentum by going in the opposite direction. Now while the electron is detected by the electromagnetic calorimeter, the neutrino simply passes through the detector without a trace. But it is easy to deduce that the neutrino was there because the electron's momentum must be balanced by something. These events are very characteristic and demonstrate that it is important that the detector have no holes so that the absence of the balancing particle be a reliable signal that a neutrino was produced.

All of this has already been accomplished at hadron colliders. What are the goals of future research at the CERN and Fermilab machines, and what can we look forward to at future high energy hadron colliders? First we had better make good *Roxanne's* claim by finding the t quark. In fact, we are all pretty sure it is being produced already at CERN and Fermilab. Why then can't we find it? To understand this, we must look more at the process of beta decay.

A very simple beta decay is the decay of a neutron. If a neutron is free rather than in a nucleus, it has a lifetime of about 1000 seconds. It decays into

a proton, an electron and an antineutrino. The way we think of the decay, though, is slightly different. The neutron tries to decay into a proton and a W boson. It can't really do this because the neutron has a mass of 939.5 MeV and the proton has a mass of 938.3 MeV. There is just 1.2 MeV left over, which is certainly not enough to make a W, which has a mass of 83,000 MeV. However, quantum mechanics works a little like Israeli bank accounts. You are always allowed a little overdraft. So we borrow 83,000 MeV to make the W, but of course we do have to pay it back. To do this, the W turns into an electron and a neutrino, whose combined energy is just the 1.2 MeV that was available.

The t quark will undergo beta decay itself. If its mass is less than the mass of a b quark plus the mass of a W, the process will be the virtual one just described. Thus the final products will sometimes be a b quark, an electron, and a neutrino. The b quark will produce a jet of hadrons. Indeed, at very high energies we will usually be dealing not with individual hadrons. The real quanta that the detectors will able to find will be jets, muons, isolated electrons, neutrinos, and perhaps isolated photons. Events will be interpreted not in terms of pions or baryons, but in terms of quarks, gluons, Ws and Zs. These will be the quanta of interest. Moreover, generally, only particles with large transverse momentum will be accessible. The rest will be lost in a flood of low transverse momentum debris.

To find the t quark then, we look for a charged lepton and a jet and a neutrino in the form a missing transverse momentum. In addition, we can insist on finding evidence for an accompanying $\bar{t}$ or $\bar{b}$. The latter would arise from the decay of a W into $t\bar{b}$. Unfortunately there are other processes that yield similar-looking events.

We know there is a t quark. The most interesting discoveries will be those that are mere speculations now or are not even imagined. It is possible that there are additional quarks and leptons. They might simply be too massive to have been produced. However, if the same pattern that has repeated itself three times occurs again, there will be one charge 2/3 quark, one charge

$-1/3$ quark, one charge -1 lepton and one neutral lepton, together with their respective antiparticles. Now the known neutrinos are all very light, so it is natural to suspect the next neutrino would be light. But then it could be produced in the decay of the Z into two neutrinos. Now the addition of new possibilities for the Z decay would just make it decay faster and this can be measured, albeit indirectly, at the new collider at Stanford. We can assume that within two or three years, either at Stanford or at an analogous electron–positron machine being built at CERN, it will be determined whether there are more than three neutrinos and thus whether there are additional families of matter particles like the three already known. If a new neutrino shows up, it will be the job of the hadron colliders to search for the other fermions in the family.

More dramatic than the discovery of another family of matter particles would be the observation of a new force particle, a new gauge boson. A hadron collider like the SSC or LHC would be ideal for searching for such an object. The SSC would dwarf even the 27 km ring being completed at CERN. Seven sites in the United States are being considered for the construction of the 90 km ring. Just as with the observation of the Z at CERN, the technique for finding a new gauge boson would be to look for an electron-positron pair or a pair of muons. By measuring the energies of the two particles and the angle between them it is possible to deduce the mass of the system from which they came. If there were another particle like the Z there would be many events all of which indicated the same mass. Estimates show that if there were a new Z boson with a mass less than about 6 TeV it could be found at the SSC. This is an extraordinary range, 70 times the highest mass elementary particle thus far known.

An extra Z would profoundly affect our view of particle interactions. Each gauge boson is associated with a symmetry. The photon is associated with the symmetry of electromagnetic gauge invariance whose consequence is the conservation of electric charge. The gluons are associated with an "color" $SU(3)$ symmetry. Unlike the "flavor" $SU(3)$ symmetry that relates the various

particles, the color symmetry is exact. The W and Z bosons are associated with a symmetry as well.

Initially in the standard model of electroweak interactions there is a rotation symmetry, not in real space but in an abstract internal space. Since we can rotate about the x, y, or z axes, this really provides three separate symmetries. In addition, there is a fourth symmetry, distinct from the three internal rotational symmetries. Every symmetry is connected with a massless gauge boson like the photon, so initially the W^+, W^-, Z, and photon are all massless.

This symmetry is broken spontaneously, that is, it turns out that the energy of the universe can be decreased if it takes on a configuration that does not have the full symmetry. A ferromagnet must point in some direction even though the interactions inside a ferromagnet have no preference for any particular spatial direction. The overall universe must in the same way pick a direction in the internal rotational space. This reduces the number of symmetry operations. A sphere has a full rotational symmetry - three degrees of freedom - but if we put lines of latitude on it, only the rotations about the axis through the north and south poles remain.

A primary goal of the SSC would be the investigation of the mechanism by which the large symmetry with four massless gauge particles is broken down to the symmetry with just a massless photon. In the simplest model of this mechanism there is just one direct manifestation: the existence of a Higgs boson.

It turns out that a heavy Higgs boson can be made in two ways. In the first, two gluons collide and make a t quark and an anti t quark, which subsequently collide themselves to make the Higgs boson. In the second, quarks make two W bosons, which subsequently collide to make the Higgs boson. Making the Higgs boson is the easy part. The hard part is to find it afterwards. If the Higgs boson is more massive than two Z bosons, it will often decay into such a pair. It is then possible to look for the Z bosons in the usual way, by observing the electrons or muons, possibly by finding one Z decaying into electrons or

muons, and the other into neutrinos, which leave the tell-tale sign of one-sided events.

The challenge of the search for the Higgs boson is enormous. We might be looking for just fifty events of the sort described produced in one year. The total number of events produced in the same year would be 10^{15}, about one hundred million every second. To sort out the events and find the interesting ones will be a difficult and essential task. It appears that the SSC could find a Higgs boson with a mass up to 700 GeV or possibly more.

As exotic as the search for the Higgs boson may sound, it actually represents the most conservative prospect for particle physics. One popular alternative has not one Higgs boson, but five, of which two carry charge and three are neutral. While this sounds far less economical than the minimal model with just one Higgs boson, it is required if the world is supersymmetric.

While the word *supersymmetry* may sound like it was invented by an ad agency, it actually represents a subtle and profound idea. Quantum mechanics divides all particles into two classes, the fermions with half-integral spin and the bosons with integral spin. The quarks and leptons are fermions. The gauge particles are bosons. Supersymmetry connects the two classes. For every fermion there is an associated boson. In fact, the bosons and fermions that have been observed are not associated with each other by supersymmetry. None of the supersymmetric particles has yet been found. Now this makes some people skeptical about the whole proposition, but it could be that these partners are too heavy to have been observed yet.

The key to discovering supersymmetry is again the trick of looking for missing transverse momentum. Of the yet-to-be-discovered supersymmetric particles there will be a lightest one and it will, like the neutrino, escape from the detector. The events with supersymmetric particles may also be signalled by the presence of W or Z bosons.

At a new hadron collider it would be possible to search deeper inside the quarks and leptons to see whether there is another more fundamental level of

matter. After all, it does not seem very fundamental to have so many quarks and leptons. Perhaps they could be built of fewer constituents. One sign of this would be a deviation from the prediction for the number of hadronic jets produced with very high energy. The scattering law for quarks is quite analogous to the law discovered by Ernest Rutherford in 1911. He analyzed the data of Hans Geiger and Ernest Marsden that showed that alpha particles from a radioactive source were frequently deflected through a large angle when directed on a thin metal foil. Rutherford showed this could be understood if inside the atom there were a tiny nucleus. The structure of the nucleus itself could only be seen once higher energy projectiles were available. The SSC will allow us to look inside the quark up to a scale of about 40 TeV, corresponding to a distance of 5×10^{-19} cm.

We can speculate on what will be found at the new colliders, but the record of particle physicists is poor in this regard. Nature is usually more inventive and wonderful than anything we can imagine in advance. The international collaborations that will explore this new level of physical reality will demonstrate man's ability to understand and master his environment. They will continue the half century of particle physics that has shown what can be accomplished by international co-operation in pursuit of goals that are shared by peoples around the world.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720