Assessment of Progress towards HEP Long-term Goals High Energy Physics Advisory Panel December 22, 2006

The Office of Management and Budget requested in 2004 that the Department of Energy, Office of Science, Office of High Energy Physics (HEP) develop a set of long-term goals in Scientific Advancement to which the HEP program is committed. These goals (attached) are meant to be representative of the important priorities of the program, are not meant to be comprehensive, and are not necessarily goals of individual experiments in the field. Recent changes in the OMB PART evaluation system now require the definition of an additional level of achievement that corresponds to making good progress towards meeting each goal. We have added this performance measure in a column labeled “Good Performance”.

HEPAP has now been asked to assess progress towards the long-term goals. To aid in the evaluation of the field’s progress, DOE Office of Science developed a set of milestones that, if reached by 2008, would indicate that we are on track to meet the long-term Scientific Advancement goals. Where appropriate, we refer to these milestones in the following assessment.

We believe that this set of long-term Scientific Advancement goals is appropriate now. Some of the six have already been achieved in part, and nearly all are likely to be achieved in the 10-year timeframe. An appropriate time to set new goals is probably in 2008, when the funding plan for new proposals will be clearer.

Discover or rule out the Standard Model Higgs particle, thought to be responsible for generating mass of elementary particles.

A long-term goal of the HEP program is to discover or rule out the Standard Model Higgs particle and, if it is exists, to measure its decays into a variety of final states. This goal is part of the larger goal of understanding the origins of electroweak symmetry breaking and of particle masses.

In its simplest form, the gauge theory that describes the weak and electromagnetic forces predicts that both the photon and the W and Z bosons are initially massless as a consequence of a symmetry, $SU(2)\times U(1)$. This symmetry is spontaneously broken, and the W and Z bosons acquire mass; in this model, a massless spin-zero (scalar) boson is predicted. Peter Higgs showed how a theory with a massless gauge particle (such as the photon) and a scalar particle can become a theory of a massive vector particle. This mechanism makes it possible for the W and Z to acquire mass by coupling to a scalar field, leading to at least one massive scalar boson, the Higgs particle. The scalar Higgs field, which exists everywhere, also couples to all other particles (quarks and leptons), thereby generating masses for these particles, the values depending on the unknown coupling to each of the particles. Due to its role in electroweak symmetry breaking, the Higgs mass is thought to be of the same order as the mass of the W and Z, i.e. 100 GeV/c^2. Verifying the existence of the Higgs particle is essential to verifying the Standard Model of particle physics.

The precise mass of the Higgs particle is not predicted by the Standard Model; however, the Standard Model does predict certain relationships among the Higgs mass, top quark mass, and other measurable parameters. The expected mass range also depends on whether or not supersymmetry (described below) is realized in nature. Fits to current data predict a Higgs mass near the lower bound of 114.6 GeV/c^2 set by direct searches at LEP, and rule out at 95% confidence level a purely Standard Model explanation for a Higgs mass above about 200 GeV/c^2. Supersymmetric extensions of the Standard Model allow a Higgs with essentially Standard Model properties for masses up to approximately 1 TeV/c^2. Both the dominant decay modes and the production mechanism of the Higgs depend strongly on the value of its mass; hence the relative promise for discovering the Higgs in different decay modes varies with both the Higgs mass and the collider energy.

The Higgs boson, if it exists and has a sufficiently small mass, will be detected in hadron collider experiments, in data from the ATLAS and CMS experiments at the LHC and the CDF and D0 experiments at the Tevatron. All searches for the Higgs are strongly limited by its small production cross sections and by large backgrounds that mimic the experimental signature. Nevertheless detailed studies by two Tevatron Run II study groups have projected that the Tevatron experiments, each with 8 fb^{-1} of data (enough collisions to produce 8 events for a production cross section of 1 femtobarn), could detect Standard Model Higgs particles with mass up to about 185 GeV/c^2. The current data sample is about 1.8 fb^{-1}, increasing by roughly 0.03 fb^{-1} per week, and the experiments record the data with an efficiency of 80-95%. Hence, a low-mass Higgs should be seen at Fermilab. Reaching the long-term goal for Higgs detection over a larger mass range and measuring its properties will require the LHC experiments.

It is uncertain whether CDF and D0 analyses with larger data sets can match the sensitivity projections of the Run II study groups. At the Tevatron the best Standard Model Higgs discovery channels are Higgs produced in association with a W or Z boson, with the W or Z decaying to leptons and the Higgs decaying to either two b-jets (in the lower third of the mass window) or two Ws. The search reach is strongly affected by the detector performance for b-tagging and measuring jets, as well as efficiencies, acceptances and backgrounds for the particles that make up the signal.

At the summer 2006 conferences CDF and D0 presented Higgs boson search results based on combined multi-channel data sets with between 0.3 and 1 fb^{-1}. Projecting the current detector and analysis performance from these results to 2 fb^{-1}, the collaborations find that they would fall about a factor of ten short of the sensitivity needed to find a low-mass Standard Model Higgs. Compared to the study projections, the largest difficulty in practice has proved to be the performance for b-tagging and measuring jets. New techniques involving neural nets for b-tagging and using tracker information for jet-energy measurement are being implemented now, and are likely to lead to large improvements. In addition, larger data sets now make it possible to calibrate on events with Z bosons decaying to b-jets. D0 presented a complete list of projected Higgs search improvements, including those mentioned above. From this they estimate that it will require 3 fb^{-1} of data to achieve sensitivity to a 115 GeV Standard Model Higgs, just above the lower mass limit from LEP experiments. A DOE milestone of beginning to explore the mass region up to 115 GeV/c^2 in 2008 is likely to be achieved, perhaps with a publication delayed by a year.

The long-term HEP goals for the Higgs boson are to discover or rule out the Standard Model Higgs and, if it is discovered, to determine its mass to within a few percent and measure its couplings to several final states. These goals are likely to be achieved within ten years. Assuming it is not found at the Tevatron, the most optimistic projection is that the discovery of the Higgs boson at the LHC is assured for the entire mass range with as little as 5 fb^{-1} of analyzed, multi-channel data per experiment once the detectors and backgrounds have been well understood. Since the LHC is designed to deliver 40 fb^{-1} per year, accelerator performance is not a major worry. Numerous studies have shown that if the detector performance is up to expectations, the Higgs will be discovered if it exists and has a mass less than 1 TeV/c^2. As with any major advance in accelerators and detectors, performance of the ATLAS and CMS detectors for Higgs searches is of some concern. Actual detector performance is difficult to predict in the high energy and high luminosity environment of the LHC. Fortunately, more than one production channel and several decay modes are relevant for a light Higgs; this provides the experiments with some insurance against worse-than-expected performance in a single channel.

The long-term prospect for achieving this long-term Scientific Advancement goal is excellent. The Tevatron is now on track to deliver the necessary luminosity for D0 and CDF to explore the low mass region, and the experimenters are working to devise the tools necessary to do the difficult analysis. The LHC is on track to deliver the required luminosity to explore the full Standard Model Higgs mass range with good sensitivity.

Measure properties and interactions of the heaviest known particle (the top quark) in order to understand its particular role in the Standard Model.

The long-term goal for top physics is to measure the mass and other properties and interactions of the top quark, the heaviest known elementary particle. Because the top quark mass is of the same order of magnitude as the electroweak symmetry breaking scale, it may have some special role in particle physics. The electroweak couplings of the top quark to gauge bosons and other quarks are predicted in the Standard Model. Hence, measuring its properties and couplings with high precision is a good way to search for evidence of hypothesized new phenomena that would cause deviations from these predictions.

At the Tevatron and at LHC, these particles are produced either as top – anti-top pairs (t-tbar production) or together with a particle containing a b quark (single top production). Pair production is more copious and has smaller Standard Model backgrounds; it is thus the preferred mode to measure precisely the top quark mass and to search for rare decay modes. Single top production, for which first evidence has now been seen by the D0 experiment, would allow the direct extraction of the Standard Model parameter V_{tb} (the strength of the coupling of the W boson to t and b quarks) and allow a new test of unitarity in the quark mixing matrix.

The CDF and D0 collaborations have already analyzed large data samples of t-tbar events from approximately 1 fb^{-1} of data per experiment. Using novel analysis techniques that reduce the dominant systematic errors, they have produced a combined measurement of the top quark mass given by $m_t = 171.4 \pm 2.1$ GeV. This measurement meets the long-term goal of determining the top quark mass to a precision of ± 3 GeV/c^2.

The remaining goal is to measure top quark couplings to other quarks with a precision of about 10%. The couplings of the top quark to down or strange quarks (characterized by the parameters V_{td} and V_{ts}) can be measured through indirect processes as described below. To measure the parameter V_{tb}, it is necessary to measure the cross section for single top production, which occurs through a virtual W boson being produced and decaying to a t and anti-b quark pair. The Standard Model predicts that the parameter V_{tb} is very close to one.

Very recently, the D0 collaboration announced the first evidence of single top production using 0.9 fb^{-1} of data. Their signal corresponds to a 3.4 standard deviation significance. Using these data, they have shown that V_{tb} is in the range $0.68 < V_{tb} < 1.0$ at 95% confidence level. An earlier analysis of a smaller data set by CDF did not see a signal. Based on both the recent D0 result and the earlier CDF analysis, it is expected that a data sample of 4-8 fb^{-1} will allow the extraction of V_{tb} with a statistical error below 10%. This is consistent with the projected data sample for D0 and CDF through the end of the Fermilab Tevatron running; hence the long-term goal is likely to be reached with these data.

At the LHC, single top production will occur at a much higher rate and the backgrounds will also be larger and the experimental environment more challenging. The ATLAS and CMS collaborations estimate that they can eventually measure V_{tb} to an accuracy of about 5% within the timescale of the long-term goals. These estimates will have a much higher confidence level after the relevant backgrounds and detector performance are evaluated with real LHC data in 2008.

Measurements of couplings to other quarks rely on indirect processes: decays of mesons containing b quarks that proceed through virtual intermediate states containing a top quark. In the case of V_{td}, the most precise measurement comes from the difference in mass of the two mesons made from b and d quark anti-quark pairs (Δm_d). The value of V_{td} obtained in this way is $V_{td} = 0.0074 \pm 0.0008$, which nearly meets the long-term goal. The uncertainty is dominated by theoretical uncertainty and is expected to improve. The third parameter, V_{ts}, is determined from measurements of mixing in the decays of meson with b quarks to particles containing strange quarks. The value is $V_{ts} = 0.041 \pm 0.003$, which meets the long-term goal.

Nearly all of the long-term goals have been met, and good progress is being made towards the last of the goals, the measurement of V_{tb}.

Measure the matter-antimatter asymmetry in many particle decay modes with high precision.

A long-term goal of the HEP program is to measure the matter-antimatter asymmetry in many particle decay modes with high precision. This goal can be achieved at the B-factory experiments, BaBar at PEP-II and Belle at KEK-B, and good progress is being made towards that goal. Additional information will come from the Tevatron program, in particular for particles containing both b and s quarks.

Our understanding of particle physics includes the concept that for every particle in the universe, there is an anti-particle with equal mass yet opposite properties such as charge. We believe that particles and antiparticles existed in equal quantities at the time of the Big Bang, yet today the universe consists dominantly of particles, with hardly any antiparticles. For the Universe to evolve from particle anti-particle equality at the time of the Big Bang to the current matter anti-matter asymmetry requires violation of a property called CP symmetry. CP (charge-conjugation parity) symmetry states that the Universe would look the same if particles were exchanged for antiparticles and all space coordinates were inverted. CP symmetry is mostly respected; CP violation has been observed in nature only at a very tiny rate, too small to account for the matter anti-matter asymmetry. This presents a problem for the Standard Model, and further tests of CP symmetry in other modes are important to search for new physics that could contribute to explaining the matter anti-matter asymmetry. These tests require extremely precise measurements of the relative decay rates of particles and anti-particles into specific final states, tests that are best done at the BaBar and Belle experiments.

The specific long-terms goals are to measure the matter anti-matter asymmetry in the most sensitive modes to a precision of 4% and to measure it in many (15) other modes to a precision of 10%. The DOE established milestones towards achieving this goal: collect a large data set with detectors working well and announce new results by 2008. Through the end of the 2006 run, PEP-II delivered a total integrated luminosity of 410 fb^{-1} and BaBar recorded 391 fb^{-1} of data. The performance by the PEP-II accelerator far exceeds the design luminosity of the original proposal. The BaBar collaboration submitted 114 paper contributions to the 2006 ICHEP meeting and gave 26 presentations. This performance by BaBar more than meets the milestone. At this meeting, BaBar reported a measurement of $\sin(2\beta)$ (the parameter that quantifies the matter anti-matter asymmetry) using ψK final states with a precision of 5%. The combined average with Belle yields a world-wide accuracy of 3.8% in this channel; this measurement meets the first of the long-term goals. Nine other $b \rightarrow s$ penguin channels that are used to measure $\sin(2\beta)$ have been measured. All are currently statistically limited, with the best precision at BaBar being ~20% in the $\eta' K_s$ channel. It is expected that an accumulated luminosity of 1000 fb^{-1} will result in more than 20 modes being measured, with 10% precision in at least 15 of them. Additionally, the Tevatron experiments expect to measure a number of B_s decay modes, with 10% asymmetry measurements in some of them.

One of the long-term goals is met, and excellent progress has been made towards the other.

Confirm the existence of new supersymmetric (SUSY) particles, or rule out the minimal SUSY "Standard Model" of new physics.

A long-term goal of the HEP program is to confirm the existence of supersymmetric particles, or rule out the minimal supersymmetric standard model (MSSM) of new physics at the weak scale. This goal can be achieved at the ATLAS and CMS experiments at the LHC and the CDF and D0 experiments at the Tevatron. Because processes involving virtual supersymmetric particles can affect particle decays, e.g. of b-mesons, the BaBar and Belle experiments will constrain some models of supersymmetry.

The description of physical laws are independent of the coordinate system in which they are tested, in particular, independent of whether two such coordinate systems are displaced, rotated, or moving with constant velocity with respect to each other. This property is captured in the Poincare symmetry group. Supersymmetry is an extension of the Poincare symmetry to include symmetry with respect to transforming all integer spin particles (bosons) into half integer spin particles (fermions); this requires the existence of a fermion for every boson and vice-versa. In its unbroken form, all particle properties, including mass, of the superparticles are identical to those of their Standard Model partners except that their spin differs by a half-unit. The model with the minimum additional set of particles and new types of interactions is called the minimal supersymmetric model (MSSM). It accommodates most models of supersymmetry breaking and predicts a well described superparticle phenomenology at colliders. Supersymmetric particles at this scale also provide dark matter candidates, and allow for unification of the forces at very high energies.

Since superparticles have not yet been observed we know that supersymmetry (if it is realized in nature) is broken, with most supersymmetric particles necessarily heavier than their Standard Model partners. There are numerous theoretical models that describe supersymmetry breaking and they each predict a mass spectrum for the superparticles. Most naturally, the superparticles must exist at the electroweak scale.

The production cross sections for quark and gluon superparticles are large at the Tevatron and LHC, but their detection is difficult due to copious and complicated backgrounds. The production cross sections for leptonic and electroweak gauge superparticles are small at the Tevatron and LHC, but their signatures contain charged leptons, making them easier to observe above the background. Standard Model background processes and detector effects must be modeled and understood well before a positive signal for supersymmetry can be claimed.

It is predicted that 1 fb^{-1} of data at the Tevatron would contain at least100 detected events for either quark and gluon superparticles with mass up to 370 GeV/c^2 or electroweak gauge superparticles with mass up to 135 GeV/c^2. At the 2006 ICHEP conference, the CDF and D0 collaborations reported results at 95% CL for superparticle searches in three models of supersymmetry breaking based on analyses employing between 0.35 and 1.1 fb^{-1} of data. Depending on the mode of supersymmetry breaking, the measurements correspond to lower limits on the masses of the superpartners of the gauge bosons in the range 127-220 GeV/c^2. The bounds on the quark superpartners vary from 240-325 GeV/c^2. These recent results extend by 50 GeV/c^2 earlier bounds from Tevatron Run I and LEP II data, consistent with the DOE milestones towards the long-term goal. Further accumulation of luminosity at the Tevatron in the range of 4-8 fb^{-1} is expected to result in an additional 50-75 GeV/c^2 search reach for superparticles.

In addition, data from the B-factory experiments, Babar and Belle, have reached a level of precision where they can search for effects from supersymmetry by indirect means. The potential loop-level contribution of supersymmetry to the rare decay $B \to X_s\gamma$, combined with the precision measurement of this inclusive branching ratio at the B-factories, excludes many supersymmetric models. In addition, the rate observed for the leptonic decay $B \to \tau\nu$ by Belle excludes a large region of parameter space in the Higgs sector of supersymmetry, regardless of the specific supersymmetric breaking scenario.

Reaching the long-term goal will require the LHC with the ATLAS and CMS experiments. Both ATLAS and CMS have already assembled and tested the major components of their detectors and the final systems should be ready for commissioning by early 2008. The installation of the LHC accelerator has been proceeding smoothly and a pilot run is planned for November 2007. The LHC is scheduled to begin operations with collision energies of 14 TeV in 2008 and a physics run is planned for ATLAS and CMS during the summer of 2008. Each detector is anticipated to accumulate about 1 fb^{-1} of data during that time. A data set of this size will be ample for the collaborations to calibrate their detectors and understand the Standard Model background processes that contribute to a missing energy signature of supersymmetric particle production.

The production cross section for quark and gluon superparticles is enormous at the LHC. For example, once the detectors and backgrounds are well understood, a 5 standard deviation discovery for superparticles is possible for masses up to 1(1.5)TeV/c^2 with 0.1(1.0) fb^{-1} of data in the gravity-mediated MSSM. Eventually, quark and gluon superparticles can be discovered up to 2.5 TeV/c^2 when the LHC is operating at design luminosity of 100 fb^{-1} per year. If superparticles are discovered below 1 TeV/c^2, there will be enough statistics to observe various superparticle decay channels, and ATLAS and CMS studies have shown that superparticle masses can be measured to an accuracy of a few percent. The long range goals of confirming the existence of new superparticles or excluding MSSM at the weak scale are thus likely to be met within the 10 year timeframe, and the LHC project is meeting milestones necessary to achieve this goal.

Determine the pattern of the neutrino masses and the details of their mixing parameters.

Until about 15 years ago, nearly all available information on neutrinos was consistent with the hypothesis that they were massless. If they were massless, each type of neutrino (electron, muon, or tau), once produced, would maintain its identity. If neutrinos have mass, then they could oscillate from one type to another as they traveled from their place of production to the detectors. The amount of oscillation depends on mixing angles and the difference in the squares of the neutrino masses, and on experimental parameters such as the neutrino energy and the distance from the source to the detector. With three neutrino species, three mixing angles are needed to describe the pattern of mixing and only two independent mass-differences are possible. These neutrino mixing parameters are captured in a mass-mixing matrix similar in form to the CKM matrix that describes quark mixing.

Information on the possibility of massive neutrinos and their mixing can be obtained from studies of neutrinos from the sun, from decays of particles produced in cosmic ray showers in the atmosphere, and from reactor- and accelerator-produced beams of neutrinos. The first evidence was from the pioneering experiment of Ray Davis and collaborators, who detected a deficit of neutrinos coming from the sun. This could be explained by many things, among them oscillation of the electron neutrinos produced in the sun to some other neutrino species (since the detector was only sensitive to electron neutrinos) or a lack of understanding of the solar model. Later experiments, including SNO, eventually proved the Davis experiment to be correct. Oscillations were also detected in the atmospheric neutrino signal, by the Kamioka and IMB experiments, and these have been confirmed by other experiments, the best being the SuperKamiokande experiment. They all pointed to two different oscillation modes, characterized by two different scales for the mass differences and by two mixing angles, both large. Additionally, a single experiment, LSND at Los Alamos, published evidence for oscillations with a third mass-difference scale. If all experiments are correct, explaining the LSND result would require the existence of a fourth, non-standard neutrino.

In the past few years, a nearly consistent picture of neutrino masses and mixing has developed. A number of measurements of solar and atmospheric neutrino mixing have been made and the mixing first seen in atmospheric measurements has been confirmed with accelerator produced neutrino beams. Two of the three mixing angles have been measured with some precision, and all but one experiment are consistent with two mass differences, which have also been measured with some precision. Further ideas for improved measurements of the mixing parameters, matter effects, and the possibility of CP violation in the neutrino sector have also evolved.

The long-term Scientific Advancement goals in this field involve additional confirmation of and improvements to the mixing measurements, including measurements of the third mixing angle, for which only an upper limit is currently known, and clarifying the unconfirmed LSND measurement. We address the goals individually below.

Confirm or refute present evidence for additional neutrino species.

The LSND experiment at Los Alamos published evidence for oscillations between muon and electron anti-neutrinos. Their result was not confirmed (or definitively ruled out) by the KARMEN experiment. This result, if correct, is not consistent with a simple picture of three neutrino species that mix as described by a mixing matrix. Explaining the result would require at least the existence of a fourth neutrino with non-standard interactions. Non-standard interactions are required since both precise measurements of the Z boson width and cosmological bounds limit the number of standard neutrino species to three.

The MiniBooNe experiment at Fermilab was designed to check this result. The MiniBooNe collaboration has now finished their approved data taking, with sufficient data to confirm or refute the LSND result as projected from the original proposal. They have reported at conferences that they will cover the allowed LSND parameter space with approximately 3 standard deviation sensitivity with the current analysis techniques. This is somewhat less than what is generally accepted as definitive confirmation of such a potentially important result. They currently have no approved additional data taking planned, and are working to improve their analysis to meet the long-term goal. In the event that the analysis is not improved, additional data taking, and perhaps improvements to the beam or detector would be needed to meet the long-term goal.

Confirm or rule out the current picture of atmospheric neutrino oscillations.

The convincing evidence for the existence of neutrino oscillations observed in the atmospheric neutrino experiments (primarily the SuperKamiokande experiment, but also others) has now been convincingly and independently confirmed by two accelerator based experiments, K2K in Japan and MINOS at Fermilab, so this long-term goal has been met.

Measure the atmospheric mass difference ΔM^2_{23} to 15% (full width at 90% CL).

The MINOS experiment at Fermilab was designed to measure precisely the parameters of the atmospheric oscillation signal. They have now published results from the first significant data set; the current result is $\Delta M^2_{23} = (2.74^{+0.44}_{-0.26}) \times 10^{-3}\ eV^2$ or about a 40% full width at 90% confidence level (CL). This result was base on a delivered proton flux of 1.3×10^{20} protons on the NuMI target with a peak (average) beam power of 0.29 (0.17) MW. This meets the milestone set by the DOE for both accelerator performance and physics results towards the long-term Scientific Advancement goal. Projecting this performance to a total delivered proton flux of 7.5×10^{20} protons gives a 90% CL full width uncertainty of 15%. Many of the systematic uncertainties that contribute to the current total uncertainty should improve with more data. It is expected that the long-term goal of 15% will be reached before 2014.

Measure a non-zero value for the small neutrino mixing parameter $\sin^2(2\theta_{13})$, or else constrain it to be less than 0.06 (90% CL).

The current limit on this parameter comes from the CHOOZ reactor experiment and is $\sin^2(2\theta_{13}) \leq 0.12$. An upgraded version of this experiment, the Double CHOOZ experiment in France, should start taking data in 2007 with one detector and in 2008 or 2009 with two detectors. The use of two detectors will allow systematic uncertainties to be reduced, and the experiment should reach a sensitivity of $\sin^2(2\theta_{13})$ ~0.06 by 2009 or soon thereafter. This would satisfy the long-term Scientific Advancement goal well before 2014. Further improvement in sensitivity will come from the Daya Bay experiment that is planning to start data taking by 2010, and expecting to reach a sensitivity of $\sin^2(2\theta_{13})$ ~0.01 by 2014. Additional sensitivity, in particular to matter effects, will come from the T2K experiment in Japan and the Nova experiment at Fermilab on approximately the same time scale. This long-term goal is likely to be exceeded.

With one possible exception, progress towards all the long-term Scientific Advancement goals in the area of neutrino physics is excellent.

Directly discover or rule out new particles that could explain the cosmological "dark matter."

The last few years have seen a remarkable advance in our understanding of the large scale structure of the Universe. We now believe the energy density in the Universe to be due only in very small part (a few percent) to standard baryonic matter of the type that makes up stars and planets. Much more (of order 25 percent) is thought to be due to so-called dark matter, matter that has interaction cross sections with photons or standard matter sufficiently small that it is not easily detected. Most recently, compelling evidence has been given that the largest part of the energy density is due to *dark energy*, which could be due to a cosmological constant as in Einstein's theory of general relativity or to some dynamical entity, as proposed in a number of theoretical speculations.

From the particle physics perspective, dark matter candidates with properties consistent with those inferred from cosmological measurements have been proposed. They include weakly interacting massive particles (WIMPs), the most commonly discussed being neutral supersymmetric particles, and particles called axions, a consequence of a proposed solution to what is called the strong CP problem.

Searches for WIMPs that could explain cosmological dark matter come in two broad categories: non-accelerator searches for interactions of dark matter particles themselves in sensitive, deep underground, usually cryogenic detectors; and high energy collider accelerator searches for particles that have properties (mass, lifetime, charge) that are consistent with necessary properties of dark matter particles. A convincing case for a specific dark matter particle requires showing that dark matter particles exist (i.e. successful searches of the first type) and measuring properties consistent with the observed interactions of the dark matter candidate in the direct detection. A theoretically attractive dark matter candidate particle is the lightest supersymmetric particle if it is neutral.

There are many non-accelerator, direct detection searches, using a variety of techniques. The leading experiment at this time is CDMS operated in the Soudan mine. It uses an array of crystal detectors cooled to below 1 Kelvin. Current results from CDMS with a 2 kg detector mass set an upper limit on the cross-section of massive (~ 100 GeV/c^2) dark matter particles of 1.6×10^{-43} cm^2 per nucleon. This limit depends to some extent on cosmological assumptions, e.g. the degree to which the dark matter particles are concentrated at various distance scales. Their next run, with 5 kg detector mass, is expected to reach a cross-section limit of 1-5 $\times 10^{-44}$ cm^2 per nucleon in the next two years, indicating good progress towards the long-term goal and meeting a short-term DOE milestone.

The CDMS collaboration is proposing a follow-on experiment, Super CDMS, with a phased sequence of upgrades increasing the detector mass to 25 kg, 150 kg, and eventually 1000 kg, promising to reach a sensitivity of 10^{-46} cm^2 per nucleon. The first phase with a 25 kg detector, if approved, would be taking data in the 2010-2012 timeframe, with an expected cross-section limit of 10^{-45} cm^2 per nucleon. This cross section limit would test a significant fraction of the many current theoretical models for dark matter particles; hence CDMS would meet the long-term Scientific Advancement goal.

Other promising techniques for meeting this goal on a similar time scale also exist, although they have not yet been thoroughly tested. They primarily consist of cryogenic liquid detectors in either a single phase (liquid) or two phase (liquid and gas) detector. These techniques promise good background rejection and a more cost-effective way to scale to larger masses. Relatively small (< 10 kg) detectors have been tested and proposals exist for larger detectors (in the 100-1000 kg range). If these techniques prove successful, they could provide results on a similar (or even quicker) timescale compared with the Super CDMS devices. Additional measurements, for example of the nuclear size dependence of the cross section, would provide additional constraints on possible identities (e.g. neutralinos) of the candidate particles.

While the detection of dark matter candidate interactions in non-accelerator experiments would be a hugely important step, the full understanding of particles that constitute dark matter will come from the detection of these particles at high energy colliders. The measurement of their properties such as mass, spin, interaction cross-sections, etc., will allow a confident confirmation that these particles indeed constitute the dark matter observed in cosmological measurements. With the upcoming Tevatron runs in the next few years and the turn on of the LHC in 2008, supersymmetric or some other kind of new heavy particles should be discovered or ruled out by 2014. Depending on the properties of the detected particles and the results of the direct detection experiments, a full detailed understanding of the properties of these new particles may well require the International Linear Collider, which would operate well after 2014.

The second distinct type of dark matter candidate is the axion. These particles would be much less massive (10^{-6} to 10^{-3} eV/c^2) but many more would have been produced in the Big Bang. Theory predicts that they could account for all the dark matter if their mass is in the range 10^{-6} to 10^{-5} eV/c^2, and would make some contribution to dark matter over a wider mass range. The ADMX experiment at Livermore is currently searching for axions. It is based on detecting radio frequency photons that are resonantly produced by axion interactions in a strong magnetic field. The experiment has scanned part of the relevant mass range with one technique and is funded to modify the experiment for a Phase 1 upgrade that would explore the mass region from 10^{-6} to 10^{-5} eV/c^2 with sensitivity to a significant fraction of the axion models. A second, currently unfunded upgrade would increase the sensitivity in this mass range by about an order of magnitude and extend the mass range up to 10^{-4} eV/c^2. The first phase upgrade will be completed within a few years, while the second phase will depend on R&D and additional funding.

Progress towards all the long-term Scientific Advancement goals in the area of understanding the particle physics and cosmology of dark matter is very good.

HEP Long-term Goals

The following indicators establish specific long-term (10 year) goals in Scientific Advancement to which the HEP program is committed. They do not necessarily represent the research goals of individual experiments in the field. These goals correspond very roughly to current research priorities, but are meant to be representative of the program, not comprehensive. The definitions of "success" and "minimally effective" for each broad goal establish the metrics by which progress of the field as a whole can be measured.

HEP Long-term Goal	*"Success"*	*"Good Performance"*	*"Minimally Effective"*
Measure the properties and interactions of the heaviest known particle (the top quark) in order to understand its particular role in the Standard Model.	Measure the top quark mass to +/- 3 GeV and its couplings to other quarks with a precision of ~10% or better.	Measure the top quark mass to +/- 3 GeV and its couplings to other quarks with a precision of ~15% or better.	Measure the top quark mass to +/- 4 GeV and its couplings to other quarks with a precision of 15% or better.
Measure the matter-antimatter asymmetry in many particle decay modes with high precision.	Measure the matter-antimatter asymmetry in the primary ($B \rightarrow J/\psi K$) modes to an overall relative precision of 4% and the time-integrated asymmetry in at least 15 additional modes to an absolute precision of <10%.	Measure the matter-antimatter asymmetry in the primary ($B \rightarrow J/\psi K$) modes to an overall relative precision of 4% and the time-integrated asymmetry in at least 10 additional modes to an absolute precision of <10%.	Measure the matter-antimatter asymmetry in the primary modes to an overall relative precision of 7% and the time-integrated asymmetry in at least 10 additional modes to an absolute precision of <15%.

HEP Long-term Goal	***"Success"***	***"Good Performance"***	***"Minimally Effective"***
Discover or rule out the Standard Model Higgs particle, thought to be responsible for generating mass of elementary particles.	Discover (>5σ) or rule out (>95% CL) a new particle consistent with the Standard Model Higgs from a mass of 114 GeV, up to a mass of 800 GeV. If discovered, measure the mass of the Standard Model Higgs with a precision of a few percent or better. Measure other properties of the Higgs (e.g., couplings) using several final states.	Discover (>5σ) or rule out (>95% CL) a new particle consistent with the Standard Model Higgs from a mass of 114 GeV, up to a mass of 800 GeV. If discovered, measure the mass of the Standard Model Higgs with a precision of 10 percent or better.	Discover (>5σ) or rule out (>95% CL) a new particle consistent with the Standard Model Higgs from a mass of 114 GeV, up to a mass of 800 GeV.
Determine the pattern of the neutrino masses and the details of their mixing parameters.	Confirm or refute present evidence for additional neutrino species. Confirm or rule out the current picture of atmospheric neutrino oscillations. If confirmed, measure the atmospheric mass difference $(\Delta m)^2$ to 15% (full width at 90% CL); and measure a non-zero value for the small neutrino mixing parameter $(\sin^2(2\theta_{13}))$, or else constrain it to be less than 0.06 (90% CL, ignoring CP and matter effects)	Confirm or refute present evidence for additional neutrino species. Confirm or rule out the current picture of atmospheric neutrino oscillations. If confirmed, measure the atmospheric mass difference $(\Delta m)^2$ to 25% (full width at 90% CL); and measure a non-zero value for the small neutrino mixing parameter $(\sin^2(22_{13}))$, or else constrain it to be less than 0.10 (90% CL, ignoring CP and matter effects).	Measure atmospheric neutrino mass difference $(\Delta m)^2$ to 25% using accelerator neutrino beams. Improve current limits on neutrino oscillations.

HEP Long-term Goal	***"Success"***	***"Good Performance"***	***"Minimally Effective"***
Confirm the existence of new supersymmetric (SUSY) particles, or rule out the minimal SUSY "Standard Model" of new physics.	Extend supersymmetric quark and/or gluon searches to 2 TeV in a large class of SUSY models. For masses below 1 TeV, measure their decays into several channels and determine masses of SUSY particles produced in those decays.	Extend supersymmetric quark and/or gluon searches to 1.5 TeV in a large class of SUSY models. For masses below 0.7 TeV, measure their decays into several channels and determine masses of SUSY particles produced in those decays.	Extend supersymmetric quark and/or gluon searches to 1.5 TeV for some SUSY models (i.e. mSugra and similar models).
Directly discover, or rule out, new particles which could explain the cosmological "dark matter".	Discover (>5σ) the particle responsible for dark matter, or rule out (95% CL) many current candidates for particle dark matter (e.g., neutralinos in many SUSY models).	Rule out (90% CL) new particle(s) consistent with cosmological dark matter with a nuclear interaction cross-section larger than .10^{-45} cm^2.	Rule out (90% CL) new particle(s) consistent with cosmological dark matter with a nuclear interaction cross-section larger than 10^{-44} cm^2.