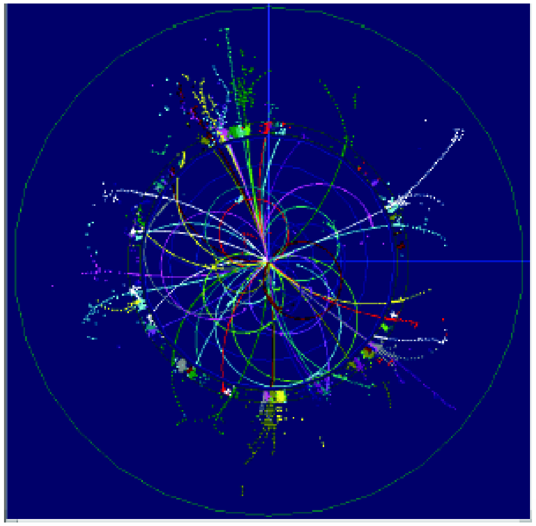
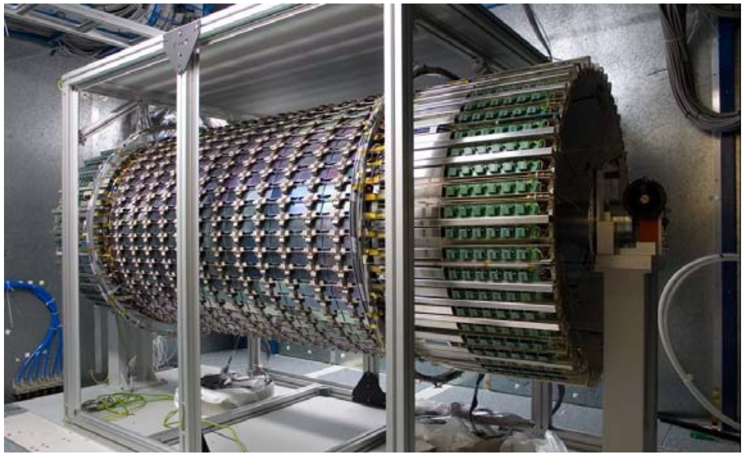
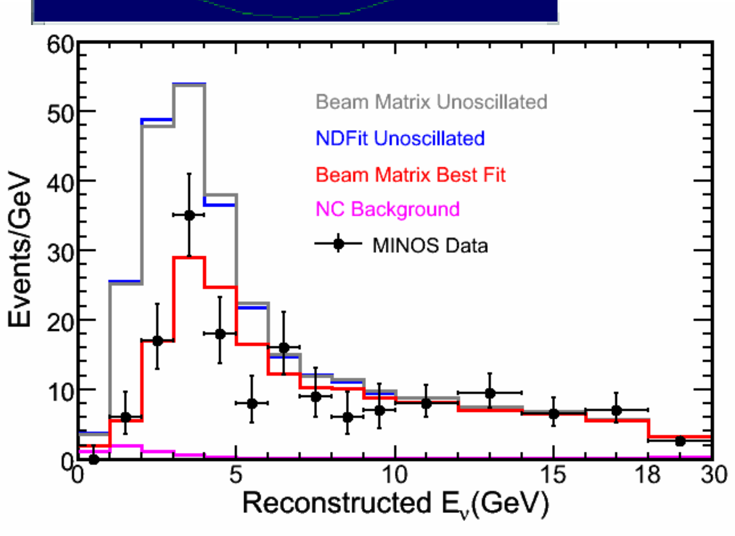
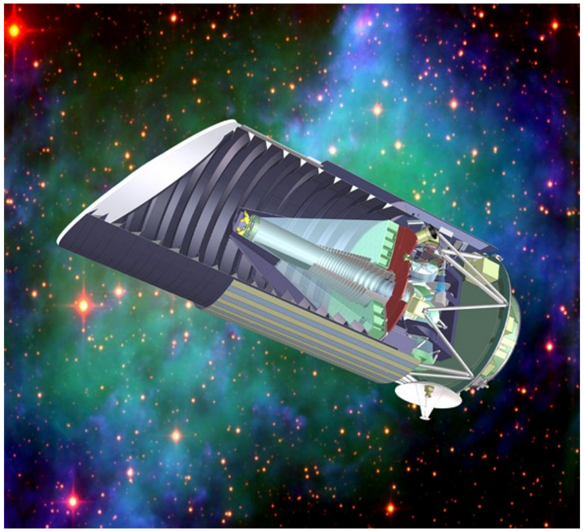
P5 Report: The Particle Physics Roadmap
October 2006









P5 Members

Abe Seiden (UCSC) Chair
Hiroaki Aihara (University of Tokyo)
Andy Albrecht (UCDavis)
Jim Alexander (Cornell)
Daniela Bortoletto (Purdue)
Claudio Campagnari (UCSB)
Marcela Carena (FNAL)
William Carithers (LBNL)
Dan Green (FNAL)
JoAnne Hewett (SLAC)
Boris Kayser (FNAL)
Karl Jakobs (University of Freiburg)
Ann Nelson (U. of Washington)
Harrison Prosper (Florida State U.)
Tor Raubenheimer (SLAC)
Steve Ritz (NASA)
Michael Schmidt (Yale)
Mel Shochet (U. of Chicago) (Ex-Officio)
Harry Weerts (ANL)
Stanley Wojcicki (Stanford U.)

The Roadmap

P5 is charged to maintain the U.S. Particle Physics Roadmap for the more costly projects of our field. In this report we have constructed a new Roadmap. It includes specific recommendations for project construction and R&D toward major projects for the next five years and recommendations for review dates for projects that we anticipate being ready for construction early in the next decade. These along with ongoing projects and those whose construction is nearing completion form the new Roadmap. In constructing a Roadmap we have used input from the EPP2010 report, the NuSAG report, and the DETF report.

Items not on Roadmap

The Roadmap concerns mostly larger scale efforts. There is of course more to the program than this. In particular, we strongly value a number of smaller projects, the development of new initiatives and associated R&D, collaboration on projects abroad, and accelerator R&D. We also do not explicitly mention the critical work in theoretical physics. Adequate support for the University Program, which includes approximately 100 universities nationally is required for the success of the activities within the program and on the Roadmap.

Outline of Report

The P5 report covers the following topics: a discussion of the major science-opportunities (Chapter III); discussion of potential projects, their costs, and assumptions regarding government agency budgets (Chapter IV); planning guidelines which follow from the science and budget projections (Chapter V); explicit recommendations for construction and reviews (Chapter VI); additional recommendations on projects and directions in the various research areas (Chapter VII); and a more extensive discussion of the various opportunities within the experimental program (Chapter VIII). I've included material from all the sections here.

Budget Assumptions

To arrive at a roadmap we need to make assumptions about budgets. In the case of the DOE, a five year funding profile in the document called “Office of Science 5-year Budget Plan: FY2007-FY2011” submitted by the DOE to Congress in early March of 2006 as part of the FY07 budget submission gives us a concrete budget plan to work with. The numbers in this plan were as follows:

FY07	FY08	FY09	FY10	FY11
$775M	$785M	$810M	$890M	$975M

In addition, the closing of PEP-II at the end of FY08 and the Tevatron at the end of FY09 (the exact date for the Tevatron to still be reviewed by P5 next year), as foreseen in the most recent P5 planning, should allow funds to flow to exciting new projects. The recuperation of funds presently used for these programs is a crucial assumption in our planning. We assume that budgets grow by 3% per year after FY11, a roughly “flat” budget in then year dollars assuming an annual inflation rate of 3%. We use these numbers in planning our roadmap. We call this our base budget plan.

Budget Assumptions

An alternative budget would assume a 7% annual increase resulting in a doubling of the HEP budget over 10 years. The numbers for the DOE in such a plan, through FY11, would be:

FY07	FY08	FY09	FY10	FY11
$775M	$829M	$877M	$950M	$1016M

We use these numbers to examine what might be possible in a plan that doubles funding over a 10 year period, as might be appropriate for a renewed emphasis on the physical sciences and their importance to the country's economic health.

Budget Assumptions

The NSF budget plan for EPP is less specific than that of the DOE but the NSF has a number of important objectives. There is a commitment to reserve at least 50% of the budget for university individual investigator support. There is a commitment for $18 million/year for the centrally managed LHC Research Program. There is a commitment to advance the case for the Deep Underground Science and Engineering Laboratory (DUSEL) as an MREFC project with more than half of the funding to go to the initial suite of experiments located at DUSEL. DUSEL operations would be supported, beginning the last year of construction, under reasonable assumptions of budget growth. Significant funding would be provided for R&D for DUSEL and the initial suite of experiments over the next few years.

Science Questions

- The question of mass:
  How do elementary particles acquire their mass?
  How is the electroweak symmetry broken?
  Does the Higgs boson –postulated within the Standard Model- exist?
- The question of undiscovered principles of nature:
  Are there new quantum dimensions corresponding to Supersymmetry?
  Are there hidden additional dimensions of space and time?
  Are there new forces of nature?
- The question of the dark universe:
  What is the dark matter in the universe?
  What is the nature of dark energy?
- The question of unification:
  Is there a universal interaction from which all known fundamental forces, including gravity, can be derived?
- The question of flavor:
  Why are there three families of matter?
  Why are the neutrino masses so small?
  What is the origin of CP violation?

Science Opportunities

We have grouped the major science opportunities into five categories, which we list below.

1) The energy frontier projects: LHC-ILC. These have enormous discovery potential, including the possibility to discover new symmetries, new physical laws, extra dimensions of space-time, an understanding of dark matter, and improve our understanding of the nature of the vacuum and the origin of mass. The experiments at the LHC will start data taking in FY08. The ILC is under development as an International Project with strong U.S. participation.

Science Opportunities

2) A program to understand the nature of dark matter, which has been manifest to date only through astrophysical measurements. Primary efforts from the particle physics community, which are complementary to the work in astrophysics, involve laboratory programs to produce dark matter at the LHC and then analyze its properties in detail at the ILC, experiments aimed at direct detection of cosmic dark matter through scattering in materials, and measurement of particles produced by cosmic dark matter annihilation. This field has many innovative techniques in a development phase and DUSEL could provide a location for a large-scale dark matter scattering experiment.

Science Opportunities

3) A program to understand the nature of dark energy, which accelerates the expansion of the universe. Unlike most phenomena, dark energy can only be studied through astronomical observations at the present time; therefore the large-scale projects from the particle physics community involve interagency collaborations with the astronomy program at the NSF (toward an earth based telescope) or NASA (toward a space based telescope). The program envisions smaller (called Stage III) projects that could start data collection by the end of the decade and an ambitious earth based survey telescope and novel space based dark energy mission (called Stage IV projects).

Science Opportunities

4) Neutrino science investigations using neutrino-less double beta decay, reactor and accelerator neutrino oscillation experiments, and neutrinos from sources in space. The experiments have a broad agenda: to study the neutrino mass spectrum and mixing parameters, to determine whether neutrinos are their own antiparticles, and to study objects that act as high energy accelerators in space. A topic of particular importance is CP violation in this sector since neutrinos may have played an important role in generating the asymmetry between the quantity of matter and antimatter that we observe in the universe.

Science Opportunities

5) Precision measurements involving charged leptons or quarks. The study of these fermion systems has historically provided much of the information embodied in the Standard Model. Rare processes sensitive to potential new physics provide tests for and constraints on processes beyond the Standard Model. Such measurements could add valuable information required to understand discoveries at the energy frontier. Potentially interesting processes include measurements of the muon g-2, μ to e conversion, rare decays visible in a very high luminosity B experiment, and rare K decays using kaon beams.

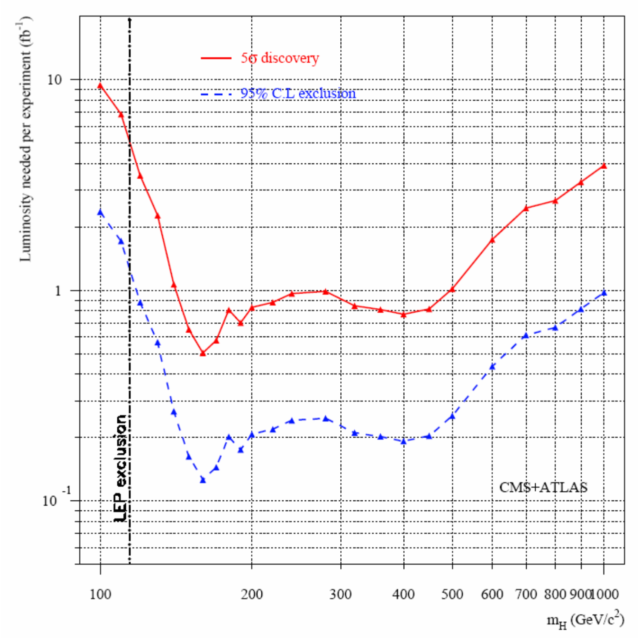
Physics at the Energy Frontier

Over the last 50 years particle physics has achieved a remarkable understanding of the constituents of matter and the underlying dynamics describing the interactions between them. This was possible through a complementary and vigorous experimental program at various accelerator based facilities around the world, a continued increase in the available energy at the frontier, improvements in detector technology, and a steady improvement in understanding the fundamental theory. This effort has resulted in the Standard Model (SM), which is based on symmetries that we know are broken as revealed by the different behavior of the weak and electromagnetic forces. We have not yet observed how these symmetries are broken, however, many of the options open new vistas beyond the SM. To understand how the symmetries of the SM are broken we have to explore energy regimes that are beyond our current experimental reach. Fortunately general arguments and data taken to date indicate that the next step in energy will reveal key missing elements of our physics picture.

Physics at the Energy Frontier

The simplest picture for the breaking of the SM symmetries involves a number of scalar fields. In this picture the lowest energy state of the universe has all of space-time filled by a field, called the Higgs field, which through interactions with the other particles generates their mass and mixings. Since particle properties (for example the electron mass) appear to be the same everywhere in the universe this field must exist everywhere, which is what we think of as the vacuum. Extensions to the simplest picture, for example in the case of additional symmetries as in Supersymmetry, can result in a number of scalar fields contributing to the vacuum. Fortunately, in all of these pictures, the Higgs field gives rise to new scalar particles (called Higgs bosons or Higgs particles) that can be produced in the laboratory. These particles have properties that reflect the mechanism by which the vacuum is generated. Using indirect measurements to date, the simplest Higgs picture would have detectable Higgs bosons at a mass near 100 GeV, while theory predicts that it is not heavier than roughly 1 TeV. From general arguments, new physics associated with the Higgs mechanism, such as Supersymmetry or extra dimensions of space, should set in at masses not larger than 1 TeV.

Physics at the Energy Frontier



The prospects for discovering a Standard Model Higgs boson in initial LHC running, as a function of its mass, combining the capabilities of ATLAS and CMS. [Ref: J.-J.Blaising, A.De Reock, J.Ellis, F.Gianotti, P.Janot, L.Rolandi and D.Schlatter, "Potential LHC contributions to Europe's future strategy at the high-energy frontier", contribution to the CERN Council Strategy Group workshop, Zeuthen, May 2006.]

With $5fb^{-1}$ of data the LHC Supersymmetry reach is likely to be > 1.5 TeV.

The Energy Frontier: LHC-ILC

The LHC is a proton-proton collider with a center-of-mass energy of 14 TeV. Such a large collision energy is required in order to reach energies in the TeV range for the collisions of the elementary building blocks within the proton. In parallel, high-energy physicists throughout the world have been constructing components for two large general-purpose detectors, ATLAS and CMS. Given the high collision energy, the LHC will be an exploratory machine into the TeV energy range. It will definitively answer the question of the existence of the Higgs particle and of TeV-scale Supersymmetry.

The Energy Frontier: LHC-ILC

The ILC is a proposed e^+e^- linear collider, designed for physics in concert with the LHC. It would consist of two roughly 20 km linear accelerators, which would collide electrons and positrons at their intersection with initially tunable collision energies up 0.5 TeV, upgradeable to 1.0 TeV. Since the electron is a fundamental particle, the full collision energy of the ILC would be available to study new phenomena. The beams can also be polarized, adding resolving power to the subsequent analysis of the collisions. These machine properties result in a clean experimental environment and a complete knowledge of the quantum state of the collision. This removes theoretical or experimental ambiguities or model dependency in analysing the data.

The Energy Frontier: LHC-ILC

The unique ILC capabilities allow for the identification of the new particles observed at the LHC and the discovery of the underlying theory that gives rise to them. In the possible theoretical scenarios before us today, experiments at the ILC will be able to answer questions such as: does the Higgs have the correct properties to give the measured mass to all particles? Are there additional components to the Higgs boson that would give rise to new physics? Are the partner particles discovered at the LHC associated with Supersymmetry or extra dimensions or something else? How many extra dimensions are there, what is their size and shape, and where do the elementary particles reside within them? What is the mass, spin, and couplings of the dark matter particle? Do they account for the thermal relic density of dark matter in the universe as determined by astrophysical observations?

Realizing the ILC

The scientists proposing the ILC have striven to make it a truly international project from its inception, with the goal that the ILC would be designed, funded, managed, and operated as a fully international scientific project. At this time, the design studies are being lead by the ILC Global Design Effort team, which includes 63 scientists and engineers from around the world. This team has agreed on the baseline configuration for the particle collider and is developing an international reference design with sample sites and cost estimates for Europe, North America, and Asia.

Realizing the ILC

At present, the GDE is focusing the efforts of hundreds of accelerator scientists, engineers, and particle physicists in North America, Europe and Asia on the design of the ILC. The goal is to produce an ILC Reference Design Report (RDR) to be released in early 2007 and an ILC Technical Design Report (TDR) in 2009-2010. This time scale matches well the expected date for first major physics results from the LHC. To insure that the ILC R&D maximally supports the GDE design effort, the GDE is providing global guidance for the program, setting priorities, and identifying gaps in the program. The GDE R&D Board has created a number of task forces aimed at clarifying some of the most important topics.

Realizing the ILC

The linear collider R&D program is supported regionally by the major high-energy physics laboratories throughout the world. The largest fraction of the R&D program is focused on the superconducting (SC) cavities and cryomodules needed in the main linac. In Europe, activities are centered at DESY and the TESLA Test Facility. In Asia, the R&D is centered at KEK where a new linac test facility is being constructed with locally produced SC cavities. In the U.S. the SC cavity R&D is distributed between ANL, Jefferson Lab, and Cornell University, while the cryomodule design is being done at Fermilab; all of these activities have the goal of constructing an RF unit, the basic building block of the main linac, at Fermilab.

Realizing the ILC

Other laboratories around the world are supporting other crucial elements of the R&D program: the rf power sources are being developed at SLAC and KEK; the fundamental mode couplers are being developed at Orsay, KEK, and SLAC; elements of the positron source are being developed in the UK, ANL, LLNL, and SLAC; the damping ring components are being studied at many laboratories including INFN Frascati, KEK, Cornell, ANL, LBNL, and SLAC; and the beam delivery system components are being developed in the UK, KEK, BNL, and SLAC.

Realizing the ILC

The physics questions that the ILC will address require detector capabilities that are beyond the performance of current detectors. To achieve these advances a well-orchestrated detector R&D program is needed. Such a program has been realized in Europe where it is addressing some of the R&D areas that need attention. In the U.S. such a coherent program, including universities and laboratories and centrally managed, is only partially in place. The U.S. efforts on ILC detector R&D are lagging both in terms of funding and manpower. Given that the U.S. wants to play a leading role in the ILC, this problem needs to be addressed and a well-defined U.S. ILC detector program with sufficient funding should be realized.

Dark Matter

The nature and origin of dark matter (DM) is one of the most important questions of science today. While astrophysical observations indicate that it exists we do not know what it is. We do know that it is not ordinary matter. In this sense, dark matter provides the first and most robust evidence for physics beyond the Standard Model (SM) of particle physics. Thus, the detection and study of dark matter must be one of the priorities of particle physics.

Dark Matter

A large number of astrophysical observations provide strong evidence that roughly 23% of the energy density of the universe consists of dark matter, whose presence is inferred only from its gravitational influences. Furthermore, observations of the small-scale structure of the universe demand that dark matter particles are non-relativistic – this is referred to as “cold” dark matter.

Dark Matter

The Standard Model provides no viable candidate for cold dark matter. Theoretical particle physics extensions to this model provide many candidates for dark matter particles, and the best-motivated ones are:

1. Axions: these particles were postulated to solve the problem of the absence of CP-violation in the strong interactions. They would have very small interaction cross-sections for the strong and weak interactions. Their masses should be extremely small, in the range 10^{-6} to 10^{-3} eV.
2. WIMPs: these “weakly-interacting massive particles” should have masses on the order of the electroweak scale, and would interact weakly, similar to the interactions expected for a heavy neutrino. WIMP candidates arise in models of electroweak symmetry breaking.

Dark Matter

There are three avenues for observing dark matter in terrestrial experiments:

1. Direct detection: WIMPs scatter elastically off of atomic nuclei whose recoil can be observed in specially designed apparatus. Axions interact with photons in a highly sensitive resonant cavity.
2. Indirect detection: WIMPs in the cosmos annihilate and the products of that interaction (high-energy photons, leptons, neutrinos, or even hadrons) are observed.
3. High-energy colliders: WIMPs are produced directly in the collisions of hadrons (Tevatron and LHC) or electrons (ILC). The Tevatron or the LHC will find evidence for dark matter particles through apparent missing energy in events with jets, leptons and/or photons. The ILC will allow precise measurements of the WIMP mass, and of the properties of other new particles. This will allow theorists to compute the relic dark matter density, at least within a given model, and relate it to astrophysical measurements.

Direct Detection of Dark Matter

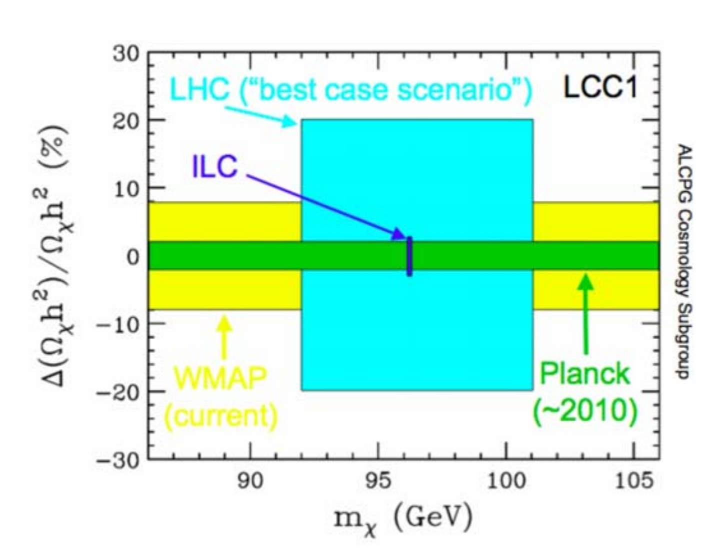
Experiments searching for axionic cold dark matter are important since they have no counterparts in accelerator based experiments, and are likely to be the only way axions will be observed if they exist. The ADMX experiment offers essentially unique capabilities and any signal would be a triumph not only for revealing the nature of dark matter but also for understanding the strong CP problem. Coverage of the full range of plausible parameter space poses serious technological challenges, but the first order of magnitude is within reach and plans for the second order of magnitude are taking shape.

Direct Detection of Dark Matter

The leading experiments for WIMP detection, at the present time, use large Ge or Si crystalline masses cooled to sub-Kelvin temperatures. A primary example of these cryogenic detectors is CDMS, installed in the Soudan mine. It has produced limits on cross sections for WIMP detection between about 10^{-42} cm^2/nucleon and 10^{-43} cm^2/nucleon. The goal of the next phase of the experiment is a sensitivity increase of about a factor of 100.

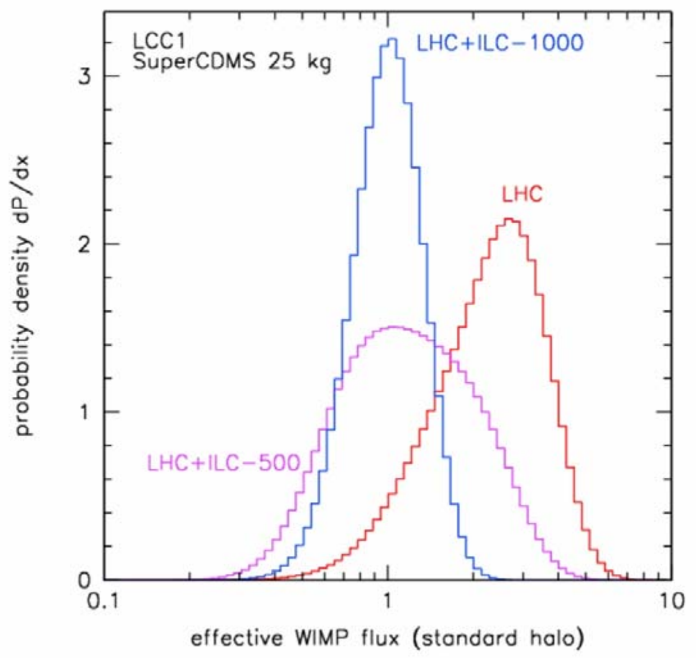
Newer approaches use detectors based on large volumes of liquified noble gases, which are in the proof-of-principle phase, but rapidly developing. The aim is to scale these to ton or multi-ton detectors. The eventual goal is to reach limits of 10^{-46} cm^2/nucleon, if WIMPs have not already seen with larger cross sections. R&D for such detectors should be strongly supported. The DMSAG will provide much useful guidance for an optimum program.

Dark Matter-Global Comparisons



Accuracy in the dark matter relic abundance determination using measurements possible at the LHC and the ILC, respectively, for the supersymmetric benchmark scenario LCC1. Also shown by the light (yellow) and dark (green) horizontal bands are the measurements from WMAP and prospective Planck. Figure from a study by the ALCPG Cosmology Subgroup.

Dark Matter-Local Comparison



Effective WIMP fluxes inferred on the basis of the combination of data from SuperCDMS and the collider experiments. Here, “effective WIMP flux” means the ratio of the local flux to that expected in a reference halo model. Two versions of the ILC are shown, at 500 GeV and 1 TeV. [ref. E. Baltz, M. Battaglia, M. Peskin and T. Wizansky, hep-ph/0602187].

Dark Energy

Over the last several years observations of distant supernovae, galaxies and clusters of galaxies, and the cosmic microwave background, have provided strong evidence that the cosmic expansion of our universe is accelerating. The data are consistent with a standard cosmological paradigm augmented by the postulate that 70% of the universe is composed of a mysterious "dark energy" that drives the acceleration. Dark energy challenges our understanding of fundamental physics; different ideas have been put forth but none of them are wholly satisfactory. Further observations are required to learn more about this phenomenon.

Dark Energy

The dark energy is described by an equation of state that is different from all the other components of the universe (baryons and electrons, photons, neutrinos, and dark matter). The goals of a dark energy observational program may be reached through measurement of the expansion history of the universe and through measurement of the growth rate of structures in the universe. All of these measurements of dark energy properties can be expressed in terms of the equation of state at different redshifts. If the expansion is due instead to a failure of general relativity, this could be revealed by finding discrepancies between the equation of state inferred from different types of data.

Dark Energy

The proposed observational program focuses on four techniques, which allow especially good tests of the nature of the dark energy. They are:

1) Baryon acoustic oscillations as observed in large-scale surveys of the spatial distribution of galaxies.
2) Galaxy cluster surveys, which measure the spatial density and distribution of galaxy clusters.
3) Supernova surveys using Type 1a supernovae as standard candles to determine the luminosity distance versus redshift, which is directly affected by the dark energy.
4) Weak lensing surveys, which measure the distortion of background images due to bending of light as it passes by galaxies or clusters of galaxies.

Dark Energy

Many of these techniques are rather new. The most incisive future measurements of dark energy will employ a number of techniques whose varying strengths and sensitivities, including different systematic uncertainties, will provide the greatest opportunity to reveal the nature of dark energy. The current program to probe the nature of dark energy is staged, thus allowing time to develop new ideas and new measurement techniques. Following the DETF, the different stages are: Stage I, which represents projects completed; Stage II, ongoing projects; Stage III near-term, medium-cost projects, which combine a number of the techniques mentioned earlier; and ambitious Stage IV projects that are more costly.

Dark Energy

My rough assessment of the expected errors for the different stages:

Eq. Of State:	Now	Distant Past
Stage III	4%	30%
Stage IV	1-2%	10-20%

Stage III and IV are needed to really establish the history of Dark Energy and make the comparisons that will test for alternative explanations.

Dark Energy

The U.S. particle physics community has played a leading role in three major dark energy initiatives: the Dark Energy Survey (DES), the SuperNova/Acceleration Probe (SNAP), and the Large Synoptic Survey Telescope (LSST). The first one is a Stage III project; the last two are Stage IV projects.

Dark Energy

The DES project is U.S. led and has collaborators from the U.K. and Spain. It is land based and proposes to develop a new 520 megapixel wide-field camera, to be mounted on the existing 4m Blanco Telescope in Chile. Photometric redshifts up to $z = 1.1$ should be obtained. The program plans to use all four observational techniques discussed earlier. The survey observations could start in 2009 and a five-year observational program is being planned.

Dark Energy

The SNAP program has been planned as a joint DOE-NASA effort. It is one of several proposals submitted in response to the NASA-DOE Joint Dark Energy Mission (JDEM) space based initiative, but the only one with significant involvement by the U.S. high-energy physics community. It is a natural follow up to the pioneering Supernova Cosmology Project that provided one of the initial evidences for an accelerating universe. SNAP will focus on two principal observational techniques: study of the redshifts and luminosities for Type 1a supernovae and observations of weak gravitational lensing. There has been interest expressed in possible collaboration by scientists in both Russia and France.

Dark Energy

Recently, there have been further developments regarding JDEM. On August 3, 2006, NASA announced that it had selected three proposals for advanced mission concept study for JDEM. In addition to SNAP, NASA also selected the ADEPT and Destiny proposals. The decision on selection of a specific proposal would most likely be made in two years, after completion of the studies.

Dark Energy

Even though NASA is proceeding with the initial JDEM steps, it is not yet committed to follow through with this program. There are several other missions that will compete for funding and launching opportunities: the gravitational wave detector LISA, the X-ray observatory Constellation-X, the Cosmic Inflation Probe and the Black Hole Finder. Accordingly, there is some interest among the SNAP proponents to investigate the possibility to proceed with the project without NASA involvement. Clearly that would require utilizing launching facilities outside of U.S. and hence a significantly enlarged international collaboration. The decision to go forward in the near-term with one of the five possible NASA projects is expected in about one year. If JDEM is selected it could begin construction in FY09 with a launch as early as 2013.

Dark Energy

LSST is the third dark energy initiative with significant contributions from the U.S. high-energy physics community. The expectation is that the project would be funded jointly by the NSF and the DOE with some additional private funds. LSST is a ground based Stage IV effort. It would use a newly constructed 8.4 m telescope, sited at Cerro Pachon in Chile. LSST would be a survey instrument, able to reach galaxies up to a redshift of z = 3. LSST would study dark energy through baryon oscillations, supernovae, and weak lensing techniques. The expected first light is in 2013, first science observations in 2014.

Neutrino Science

Under consideration are three types of experiments that have been proposed to address a number of the most pressing questions regarding neutrinos:

1. Reactor neutrino experiments. These experiments seek to observe the disappearance of low energy electron antineutrinos from a reactor on their way to detectors placed at a distance of order 1 km. They are uniquely sensitive to $\sin^2 2\theta_{13}$.
2. Accelerator neutrino experiments. These experiments use the oscillation signals over longer baselines. They are sensitive not only to θ_{13}, but also to the atmospheric mixing angle θ_{23}, to whether the neutrino mass spectrum is normal or inverted, and to whether neutrino oscillation violates CP. The quantities that will actually be measured by accelerator experiments will typically involve several underlying neutrino properties at once. These properties will then have to be sorted out. This would clearly be facilitated by a clean measurement of θ_{13} by a reactor experiment.
3. Neutrino-less double beta decay experiments. The observation of this process, at any nonzero level, would establish that neutrinos are their own antiparticles.

Reactor Neutrino Experiments

Nuclear reactors are a copious source of $\bar{\nu}_e$. Planned experiments are expected to be sensitive to the probability of disappearance down to about the 1% level. Since they search for a small disappearance probability, the sensitivity of reactor experiments is typically limited by systematic effects. The current most stringent limit is $\sin^2 2\theta_{13} < 0.12$, established by the CHOOZ experiment in France. This experiment used a single detector. All new planned experiments include two or more similar liquid scintillator detectors, placed near and far from the reactors. By taking ratios of event counts in the near and far detectors, the systematic uncertainties are substantially reduced.

Reactor Neutrino Experiments

The upgraded CHOOZ experiment (Double CHOOZ, or DCHOOZ) will be the first new experiment to come on line. Operations with one detector could start as early as 2007, with a second detector added by the end of 2008. DCHOOZ will reach a $\sin^2 2\theta_{13}$ sensitivity of 0.07 in one year with a single detector and 0.02-0.03 with three years of running and both detectors. Thus DCHOOZ will provide an early indication on the size of $\sin^2 2\theta_{13}$.

Reactor Neutrino Experiments

The Daya-Bay project is a collaboration of Chinese and U.S. physicists. The reactor complex consists of two reactors at the Daya Bay site and two more at the nearby Ling Ao site, with two more reactors planned there. Daya Bay is a more ambitious experiment than DCHOOZ. Its goal is to reach a $\sin^2 2\theta_{13}$ sensitivity of order 0.01 in three years of running. The better sensitivity of Daya-Bay with respect to DCHOOZ is due to the higher power of the reactors, and thus the higher neutrino flux, and a larger detector volume.

Reactor Neutrino Experiments

The Daya Bay collaboration plans to deploy six detectors at four different locations: a site near the Daya Bay reactors, a site near the Ling Ao reactors, a site at an intermediate distance from both sets of reactors, and a far site. A plan, not yet fully worked out, for swapping detectors between sites to reduce systematic errors is an important ingredient of the project. The cost of the project is not well known at this time, however, the majority of the cost would be borne by China.

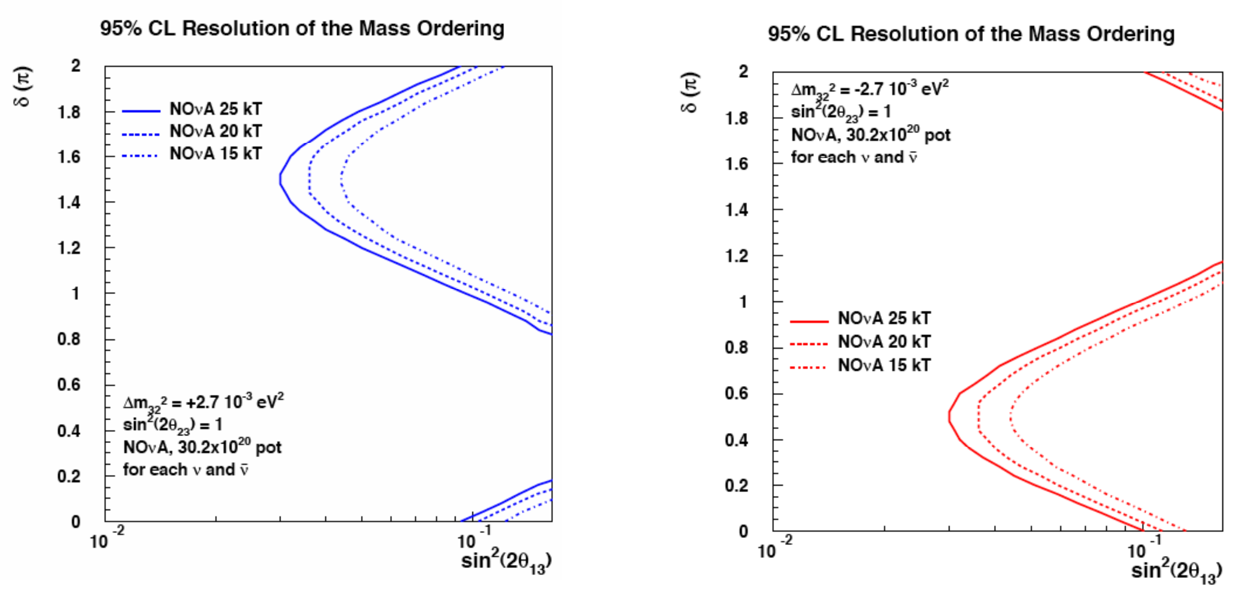
Accelerator Neutrino Experiments

The NuMI Off-Axis ν_e Appearance Experiment (NOνA) is a long-baseline experiment whose primary science objective is the use of $\nu_\mu \rightarrow \nu_e$ oscillations to answer the neutrino mass hierarchy question: is the neutrino mass spectrum normal (*i.e.*, quark-like) or inverted? NOνA leverages the existing NuMI facility infrastructure at Fermilab. Because of the long baseline available (810 km), for L/E fixed near the oscillation maximum, the beam energy is relatively large, around 2 GeV. The large energy, together with the capability of running both neutrino and antineutrino beams, gives NOνA unique experimental access to matter effects and hence the mass hierarchy.

Accelerator Neutrino Experiments

A new off-axis neutrino beam is also currently under construction in Japan, to be directed at the existing Super-Kamiokande detector. The primary science objective of this experiment, known as T2K, is to measure $\sin^2(2\theta_{13})$. Because of the shorter baseline (and lower beam energy), and because antineutrinos will not be an option in the new facility, T2K will not be able to determine the mass hierarchy or establish CP violation.

Accelerator Neutrino Experiments



The regions of parameter space for which NOνA Phase 1 can determine the mass hierarchy for normal (left plot) and inverted (right plot) hierarchy. Currently, we know that sin2(2θ_{13}) is less than 0.12.

Accelerator Neutrino Experiments

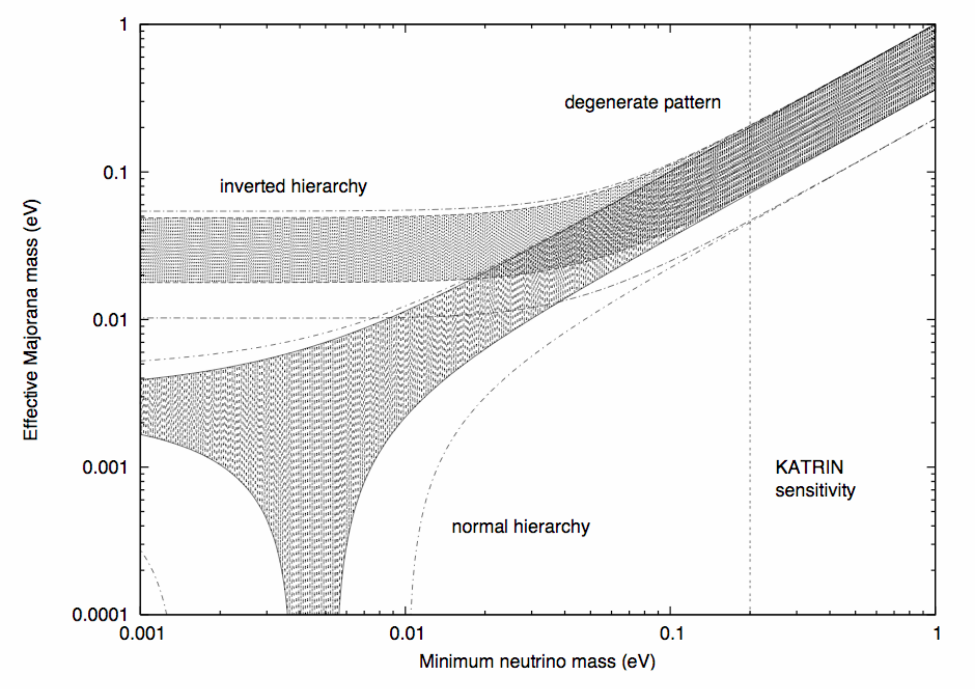
$\sin^2(2\theta_{13})$, hierarchy	$\delta=0$	$\delta=\pi/2$	$\delta=\pi$	$\delta=3\pi/2$
0.02, normal	26 (8.5)	13 (11)	23 (7.5)	36 (4.3)
0.12, normal	141 (46)	111 (54)	134 (43)	164 (36)
0.02, inverted	14 (11)	6.8 (17)	17 (13)	24 (7.0)
0.12, inverted	83 (66)	65 (80)	89 (69)	107 (55)

Numbers of neutrino- (antineutrino-) induced events in NOνA phase I, on top of a background of 12 (7.4) events, for representative values of the relevant mixing parameters. Source: NOνA collaboration.

Neutrino-less Double Beta Decay

At present the only feasible way to determine whether neutrinos are Majorana particles (that is, they are their own antiparticles) is through searching for neutrino-less double beta decay using unstable nuclei. The rate is proportional to the square of the ``effective neutrino mass'', which involves the neutrino masses and mixing parameters. For Majorana neutrinos, an inverted hierarchy, and no light sterile neutrinos, m_{eff} is at least 0.01 eV. NuSAG has identified this value as a worthwhile, if challenging, goal. There are a large number of experiments, using a diversity of techniques, that have proposed future stages with sensitivity to the inverted hierarchy region. Three of these were selected by NuSAG to have highest funding priority. These are CUORE, EXO, and Majorana. The U.S. particle physics community has been mainly involved in developing EXO.

Neutrino-less Double Beta Decay



The relation between the effective Majorana mass and the mass of the lightest mass eigenstate. The shaded areas indicate the allowed effective Majorana mass values using the best-fit oscillation parameters. The dot-dash lines indicate how the allowed regions grow when the 95% CL uncertainties in the oscillation parameters are taken into account. The sensitivity of the planned KATRIN β-decay experiment is also shown. Source: NuSAG report 1 (2005).

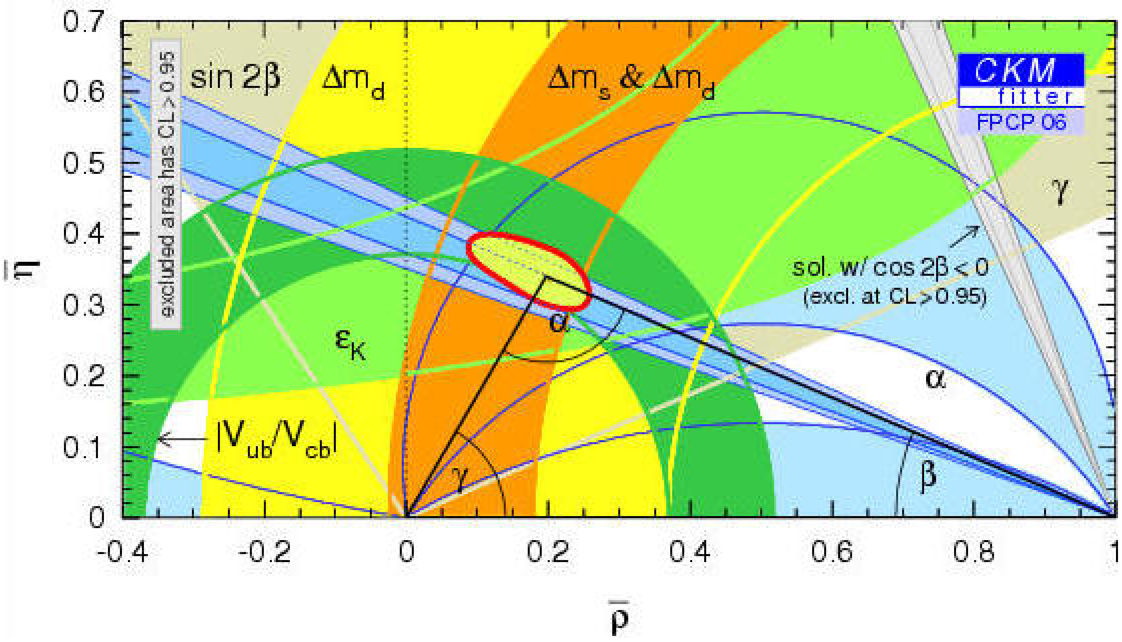
DUSEL

In response to community expressions of interest in the establishment of a U.S. underground facility for physics and other sciences, the National Science Foundation is considering the creation of a Deep Underground Science and Engineering Laboratory (DUSEL). A multi-step planning and evaluation process is underway, with the goal of a construction start in 2010. DUSEL would consist initially of a laboratory containing experiments that would include a large-scale dark matter direct detection experiment, a large-scale neutrino-less double beta decay probe, and a third physics experiment such as one on solar neutrinos or one measuring nuclear reaction rates under very low background conditions. It would also encompass R&D on a megaton-scale proton-decay and neutrino detector, and on a large cavern that could house such a detector. The cavern R&D could embrace modest exploratory excavation. Thus DUSEL would enable several important science projects.

Longer-Term Neutrino Oscillation Program

Strategies for going beyond Phase 1 of both NOνA and T2K to a stage with considerable sensitivity to CP violation are being explored for the timeframe beyond 2015. In the U.S., this exploration is being carried out by the Workshop on Long Baseline Neutrino Experiments. The findings of the Workshop on Long Baseline Neutrino Experiments will be considered in the international context by the Neutrino Scientific Assessment Group (NuSAG) later this year. In addition, plans for the future will certainly be influenced by shorter-term experimental findings. The ultimate neutrino facility may be a Neutrino Factory based on a storage ring for muons whose daughter neutrinos form a very intense, and effectively flavor-pure, beam. The Neutrino Factory, Beta Beams, and related facilities are the focus of an International Scoping Study.

Precision Measurements for Charged Leptons and Quarks



Precision Measurements for Charged Leptons and Quarks

There are several measurements (g-2 of the muon and B hadronic penguin decays) that show discrepancies at the 1-2.5σ level. Example below, muon g-2. Numbers are from the 2006 Particle Data Group compilation.

Contributions to a_μ (in units of 10^{-11})

E821	116 592 080 ± 54 ± 33
SM QED	116 584 719 ± 0.1 ± 0.4
SM EW	154 ± 1 ± 2
SM hadronic $(VP)_{e+e-}$	6 963 ± 62 ± 35
SM hadronic $(VP)_\tau$	7 110 ± 51 ± 28
Three loop (VP)	-98 ±1
SM hadronic (LBL)	120 ± 35
SM Total $_{e+e-}$	116 591 858 ± 72 ± 35 ± 3

Planning Guidelines

In order to arrive at recommendations, we have articulated a number of planning guidelines. We summarize the key points here. They have been developed with the recent recommendations of the EPP2010 committee in mind, the goal of capitalizing on the major science opportunities before us, and the specific numbers in our base budget plan.

1) The LHC program is our most important near term project given its broad science agenda and potential for discovery. It will be important to support the physics analysis, computing, maintenance and operations, upgrade R&D and necessary travel to make the U.S. LHC program a success. The level of support for this program should not be allowed to erode through inflation.
2) Our highest priority for investments toward the future is the ILC based on our present understanding of its potential for breakthrough science. We need to participate vigorously in the international R&D program for this machine as well as accomplish the preparatory work required if the U.S. is to bid to host this accelerator.

Planning Guidelines

3) Investments in a phased program to study dark matter, dark energy, and neutrino interactions are essential for answering some of the most interesting science questions. This will allow complementary discoveries to those expected at the LHC or the ILC. A phased program will allow time for progress in our understanding of the physics as well as the development of additional techniques for making the key measurements.
4) In making a plan, we have arrived at a budget split for new investments of about 60% toward the ILC and 40% toward the new projects in dark matter, dark energy, and neutrinos through 2012. The budget plan expresses our priority for developing the ILC but also allows significant progress in the other areas. We feel that the investments in dark matter, dark energy, and neutrino science in our plan are the minimum for a healthy program.
5) Recommendations for construction starts on the longer-term elements of the Roadmap should be made toward the end of this decade by a new P5 panel, after thorough review of new physics results from the LHC and other experiments.

Recommendations for Construction and Reviews

To provide recommendations for major construction and R&D activities we have grouped the projects under consideration into several broad categories, with different degrees of priority for each group. We list groupings below in priority order. They are based on our set of planning guidelines. The activities are meant to mainly fit into a five-year timeline.

Recommendations for Construction and Reviews

1. The highest priority group involves the investigations at the energy frontier. These are the full range of activities for the LHC program and the R&D for the ILC.
2. The second group includes the near-term program in dark matter and dark energy, as well as measurement of the third neutrino-mixing angle. This grouping includes the three small experiments: DES, the 25 kg CDMS experiment, and the Daya Bay reactor experiment. Also in this group is the support for the LSST and SNAP, to bring these to the "Preliminary Design Review Stage" in the case of the NSF and "CD2 Stage" in the case of the DOE over a two to three year time frame. We recommend that the DOE work with NASA to ensure that a dark energy space mission can be carried out and that the three potential approaches to the mission have been properly evaluated. The final item in this group is the R&D funding for DUSEL, along with support by the NSF and the DOE for R&D for both a large dark matter and neutrino-less double beta decay experiment.
3. The next item is the construction of the NOνA experiment at Fermilab along with a program of modest machine improvements.
4. The final item is the construction of the muon g-2 experiment at BNL.

Recommendations for Construction and Reviews

Matching the costs of these projects to our budget scenarios, we find that the first three groupings can be carried out in the base budget plan. This includes near term projects as well as R&D investments for highly capable future projects, satisfying the most important science goals presented earlier.

Note, however, that the ILC R&D ramp up profile, chosen to match the 60% of new investment goal expressed in our planning guidelines, and the NOνA construction schedule must both be slowed with respect to the most aggressive proposals, if the costs are to be matched to the assumed annual budgets.

Recommendations for Construction and Reviews

The budget that would double support over a decade would have a very significant science impact by allowing added support for the Stage IV dark energy experiments. The preparatory work for these could be completed in a more timely way, while we also pursue the other important areas in our first two groupings. In addition, the ILC R&D could be pursued more vigorously. In this scenario the muon g-2 experiment could be considered for construction.

Recommendations for Construction and Reviews

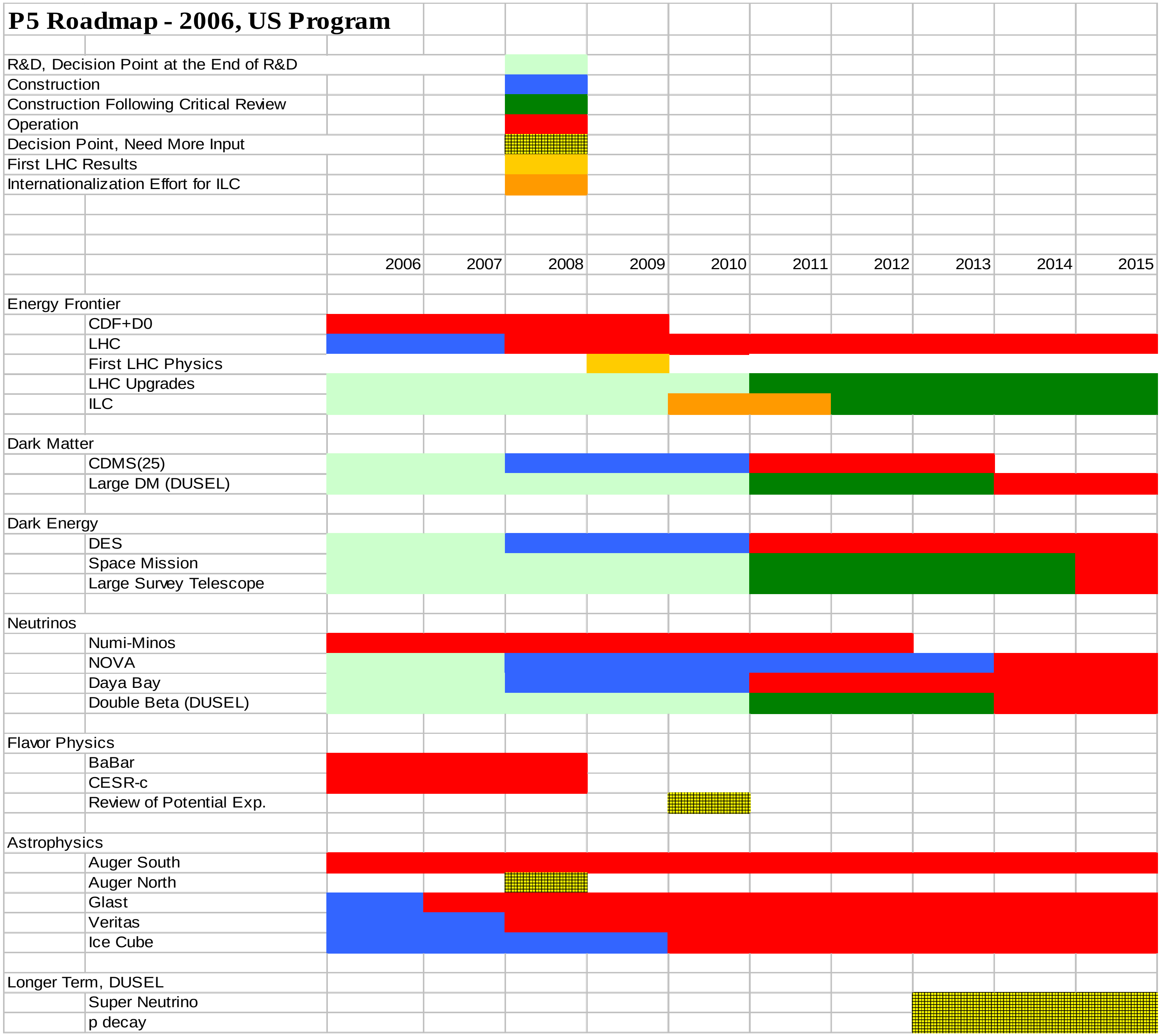
We recommend a review by P5 toward the end of this decade to look at projects that could start construction early in the next decade. The base budget plan would allow a significant number of these to move forward to construction. The review should take into account new physics results, especially those from the LHC, results on R&D for new projects, budget and cost projections at the time, and the status of interagency agreements and MREFC plans. We list some of the areas to be examined.

1. The ILC, including a possible U.S. bid to host, and the steps needed at the governmental level for internationalization.
2. The LHC Upgrades, required for an order of magnitude luminosity increase at the LHC.
3. DUSEL and the large experiments to search for dark matter and neutrino-less double beta decay.
4. The Stage IV dark energy experiments, a large survey telescope and a dark energy space mission. Interagency agreements are crucial to these projects, which could start construction soon after review.
5. An evaluation of the status of flavor physics and the importance of further experiments across a number of possibilities such as the muon g-2, μ to e conversion, a very high luminosity B experiment, and rare K decays.

Recommendations for Construction and Reviews

We anticipate that a separate review by P5 will be required to look at the best directions for further experiments in neutrino physics. Much work is ongoing internationally in this area with an optimum program dependent on measurements to be made by the next generation of neutrino experiments as well as results from ongoing R&D. A second important physics area that might be included in this review would be an ambitious proton decay experiment.   These two projects could be the major second phase of experiments for DUSEL. The physics results over the next five to ten years will determine the best date and best set of areas to look at in such a review.

P5 Roadmap - 2006, US Program



R&D, Decision Point at the End of R&D	░
Construction	🟦
Construction Following Critical Review	🟩
Operation	🟥
Decision Point, Need More Input	▨
First LHC Results	🟨
Internationalization Effort for ILC	🟧

		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Energy Frontier											
	CDF+D0	🟥	🟥	🟥	🟥						
	LHC	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	First LHC Physics				🟨						
	LHC Upgrades	░	░	░	░	░	🟩	🟩	🟩	🟩	🟩
	ILC	░	░	░	░	🟧	🟧	🟩	🟩	🟩	🟩
Dark Matter											
	CDMS(25)	░	░	🟦	🟦	🟦	🟥	🟥	🟥		
	Large DM (DUSEL)	░	░	░	░	░	🟩	🟩	🟩	🟥	🟥
Dark Energy											
	DES	░	░	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥
	Space Mission	░	░	░	░	░	🟩	🟩	🟩	🟩	🟥
	Large Survey Telescope	░	░	░	░	░	🟩	🟩	🟩	🟩	🟥
Neutrinos											
	Numi-Minos	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
	NOVA	░	░	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥
	Daya Bay	░	░	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥
	Double Beta (DUSEL)	░	░	░	░	░	🟩	🟩	🟩	🟥	🟥
Flavor Physics											
	BaBar	🟥	🟥	🟥							
	CESR-c	🟥	🟥	🟥							
	Review of Potential Exp.					▨					
Astrophysics											
	Auger South	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Auger North			▨							
	Glast	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Veritas	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Ice Cube	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥
Longer Term, DUSEL											
	Super Neutrino								▨	▨	▨
	p decay								▨	▨	▨