A Twenty Year
Roadmap for Particle Physics

Report on HEPAP Sub-Panel

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UCLA
December 5, 2001

Caveats

1. Presentation represents collective work of numerous people (much borrowed). Some obligatory material.
2. Talk and emphasis being given by one person.
3. Little on accelerator details.
4. Planning for future is ongoing.

Subpanel Membership

Jonathan Bagger - Johns Hopkins University (Co-Chair)
Barry Barish - California Institute of Technology (Co-Chair)

Paul Avery - University of Florida
Janet Conrad - Columbia University
Persis Drell - Cornell University
Glennys Farrar - New York University
Larry Gladney - Univ of Pennsylvania
Don Hartill - Cornell University
Norbert Holtkamp - Oak Ridge National Lab
George Kalmus - Rutherford Appleton Lab
Rocky Kolb - Fermilab
Joseph Lykken - Fermilab
William Marciano - Brookhaven Natl Lab
John Marriner - Fermilab
Jay Marx - Lawrence Berkeley National Lab
Kevin McFarland - University of Rochester
Hitoshi Murayama - Univ of Calif, Berkeley
Yorikiyo Nagashima - Osaka University
Rene Ong - Univ of Calif, Los Angeles
Tor Raubenheimer - SLAC
Abraham Seiden - Univ of Calif, Santa Cruz
Melvyn Shochet - University of Chicago
William Willis - Columbia University
Fred Gilman (Ex-Officio) - Carnegie Mellon
Glen Crawford (Executive Secretary) - DOE

The Subpanel's Approach

- **We opened up our process and consulted broadly !!**
  - We offered the community many opportunities for input.
    - Held Public Town Meetings.
    - Invited private meetings at Snowmass by signup.
    - Posed questions to the community.
    - Received > 100 individual letters.
    - Heard from major figures in the field.
  - We solicited input broadly from government officials.
    - Consulted extensively with NSF & DOE HEP.
    - Consulted with OMB, State Department, and Congressional staff.
  - We consulted the U.S. laboratory directors throughout our process.
  - We received direct presentations and follow ups on major proposed initiatives for the future.

Our Process

- Subpanel Meetings
  - Gaithersburg, Maryland, March 28-29, 2001
  - Brookhaven National Laboratory, April 19-20, 2001
  - Stanford Linear Accelerator Center, May 23-24, 2001
  - Fermi National Accelerator Laboratory, June 11-12, 2001
  - Snowmass, July 1-3, 2001 and
  - Snowmass, July 17-20, 2001
  - Washington, D.C., August 16-18, 2001
  - Santa Fe, September 9-14, 2001 (Final Meeting)
- Presentations and background materials for all open sessions were posted on our website. The plenary sessions and town meetings were webcast.

Our Steps Toward Recommendations

- <u>The Science</u> *Our first goal was to answer the questions:*
  - What is the scope of our field?
  - What are the important recent accomplishments?
  - What is the status of the field?
  - What are the prospects for our science?
  - What new projects can reach these goals?
  - What do they require? (R&D, time scale, budgets, international collaborations and/or non-U.S. projects)

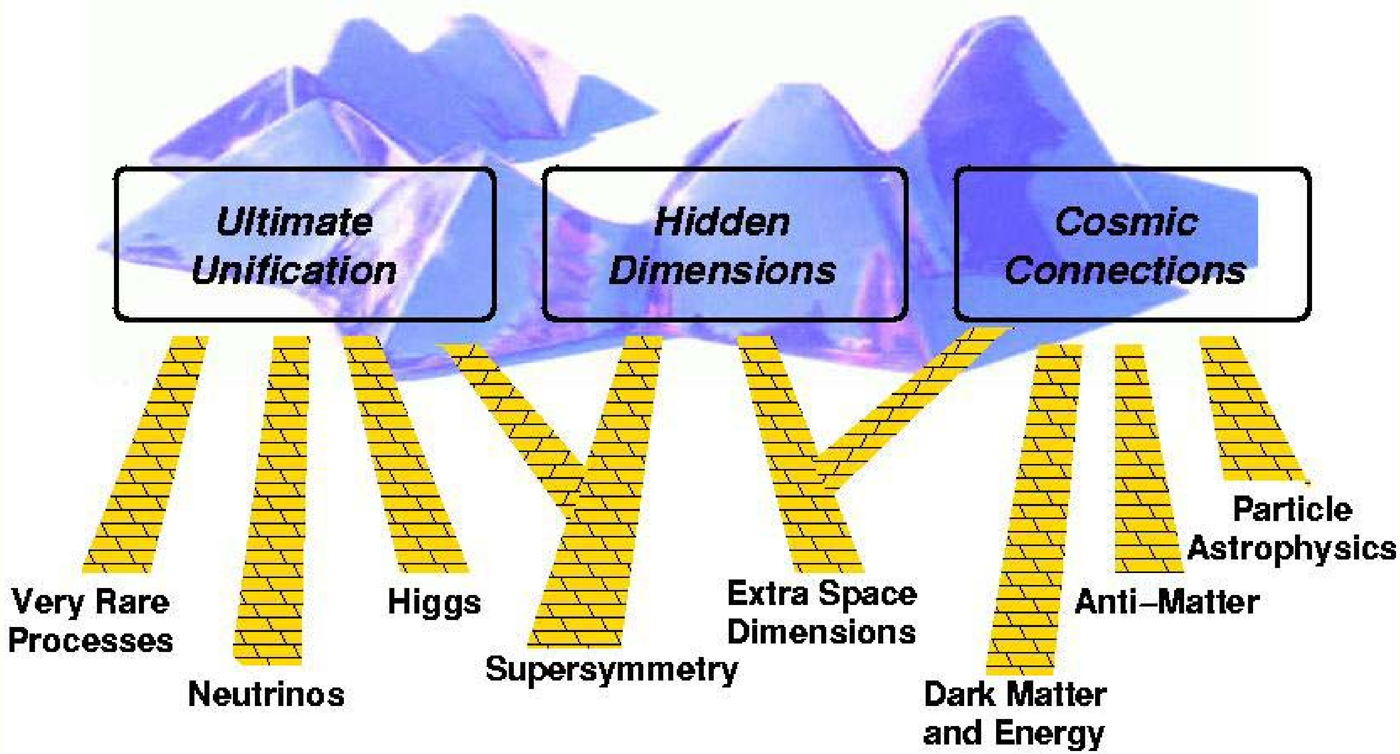
Our field is defined by the scientific questions we ask, not by the tools we use.

Recommendations

Five Recommendations:

1. Endorsement of broad scientific goals – U.S. should remain a leader in particle physics.
2. Formulation of a 20 year Roadmap for field.
3. First major project – e^+e^- Linear Collider.
4. The U.S. should try to host the Linear Collider.
5. We must invest in near-term and long-term R & D.

Matter, Energy, Space and Time



Paths to the Goals of Particle Physics

From each of these goals flows a diverse research program that will be carried out in partnership with society, and with colleagues across the globe.

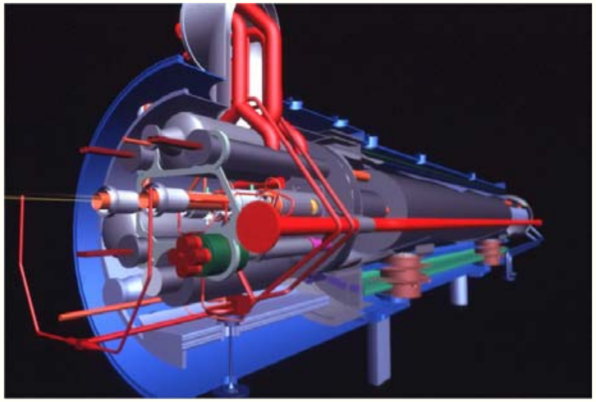
Recommendation #1

We recommend that the U.S. take steps to remain a world leader in the vital and exciting field of particle physics, through a broad program of research focused on the frontiers of matter, energy, space and time.

The U.S. has achieved its leadership position through the generous support of the American people. We renew and reaffirm our commitment to return full value for the considerable investment made by our fellow citizens. This includes, but is not limited to, sharing our intellectual insights through education and outreach, providing highly trained scientific and technical manpower to help drive the economy, and developing new technologies that foster the health, wealth and security of society at large.

The Particle Physics Roadmap

- We have many tools at our disposal from forefront accelerators to satellites in space to experiments deep underground.



Accelerator
LHC Magnet

Space

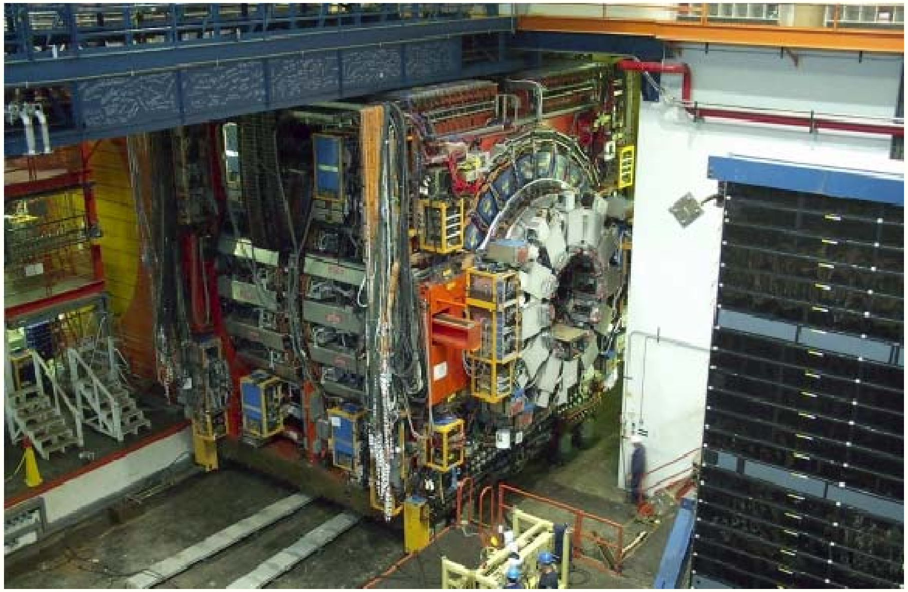
The Soudan Mine
MINOS

Our science requires forefront accelerators at the energy and luminosity frontiers. It also requires innovative experiments in space, underground, and away from accelerators.

The Particle Physics Roadmap

- Major Elements of the Roadmap by Topic
  - The Existing and Near-Term Program
  - The Energy Frontier
  - Theoretical Physics
  - Lepton Flavor Physics
  - Quark Flavor Physics
  - Very Rare Processes
  - Cosmology and Particle Physics
  - High-Energy Particle-Astrophysics

The roadmap lists the physics opportunities that we can see over the next twenty years. However, not all the avenues will be pursued, either here or abroad. The roadmap provides the basis for the difficult choices that will have to be made.

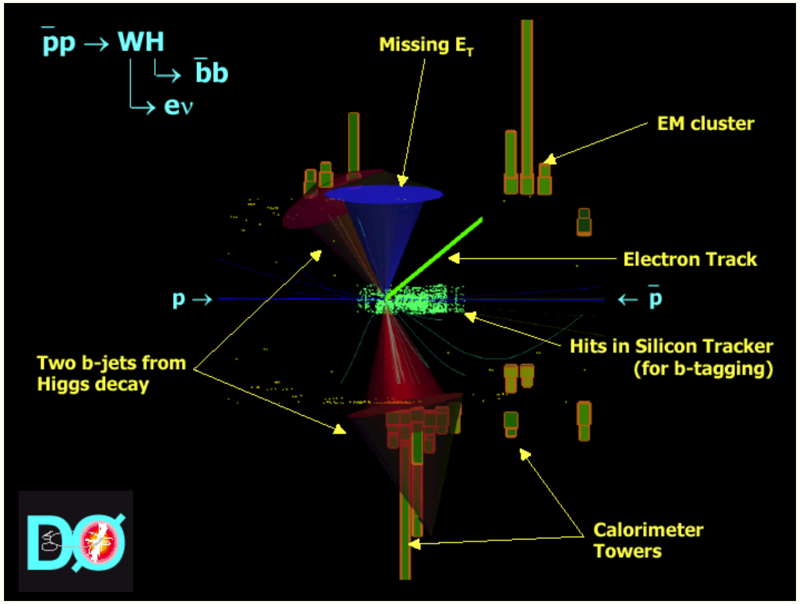


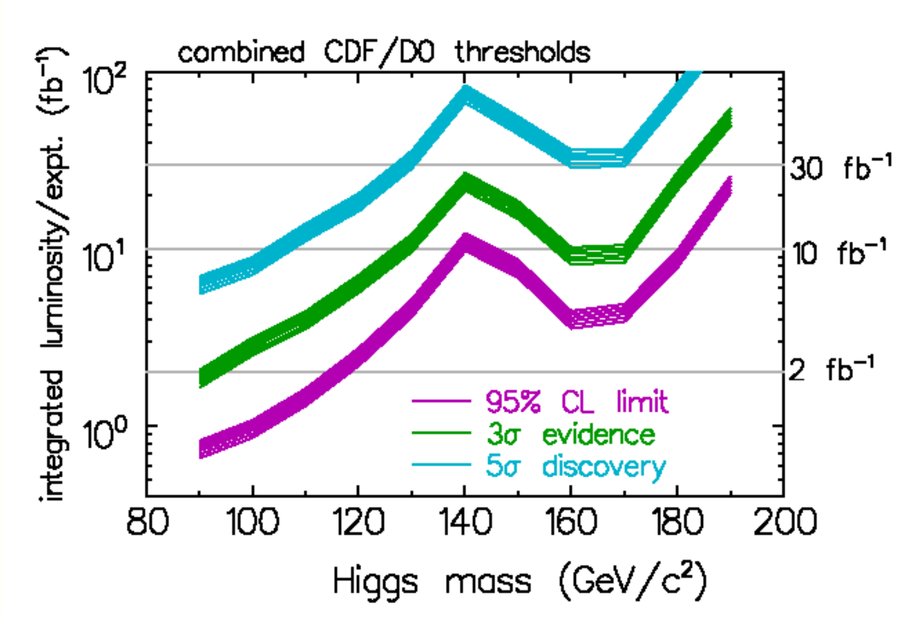
The Particle Physics Roadmap

Existing and Near-Term Program

Fermilab Run 2:

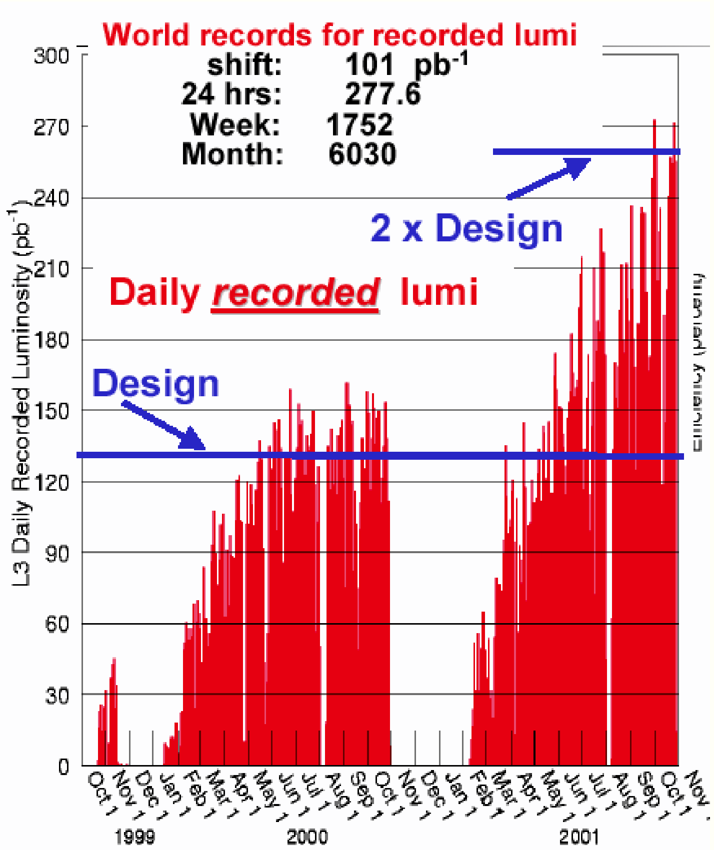
Pursuit of the Higgs





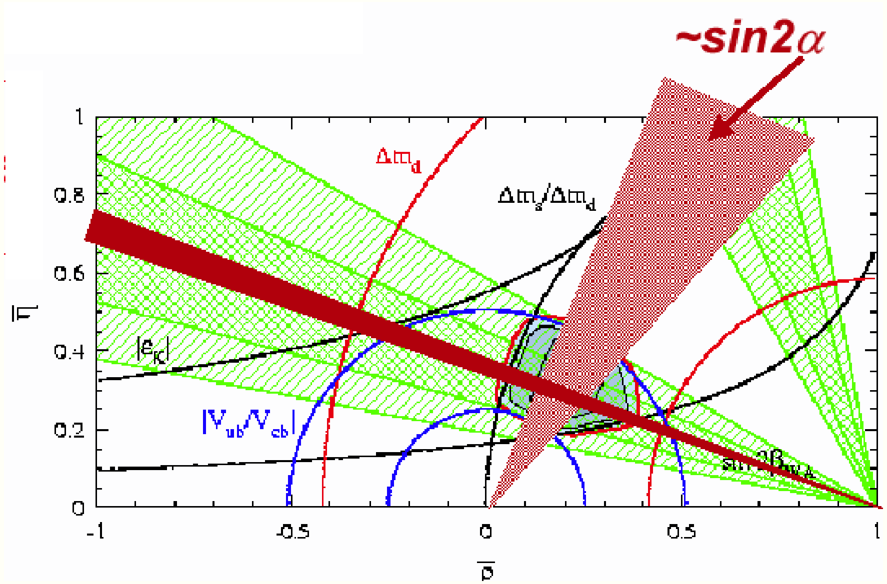
The Particle Physics Roadmap

Existing and Near-Term Program



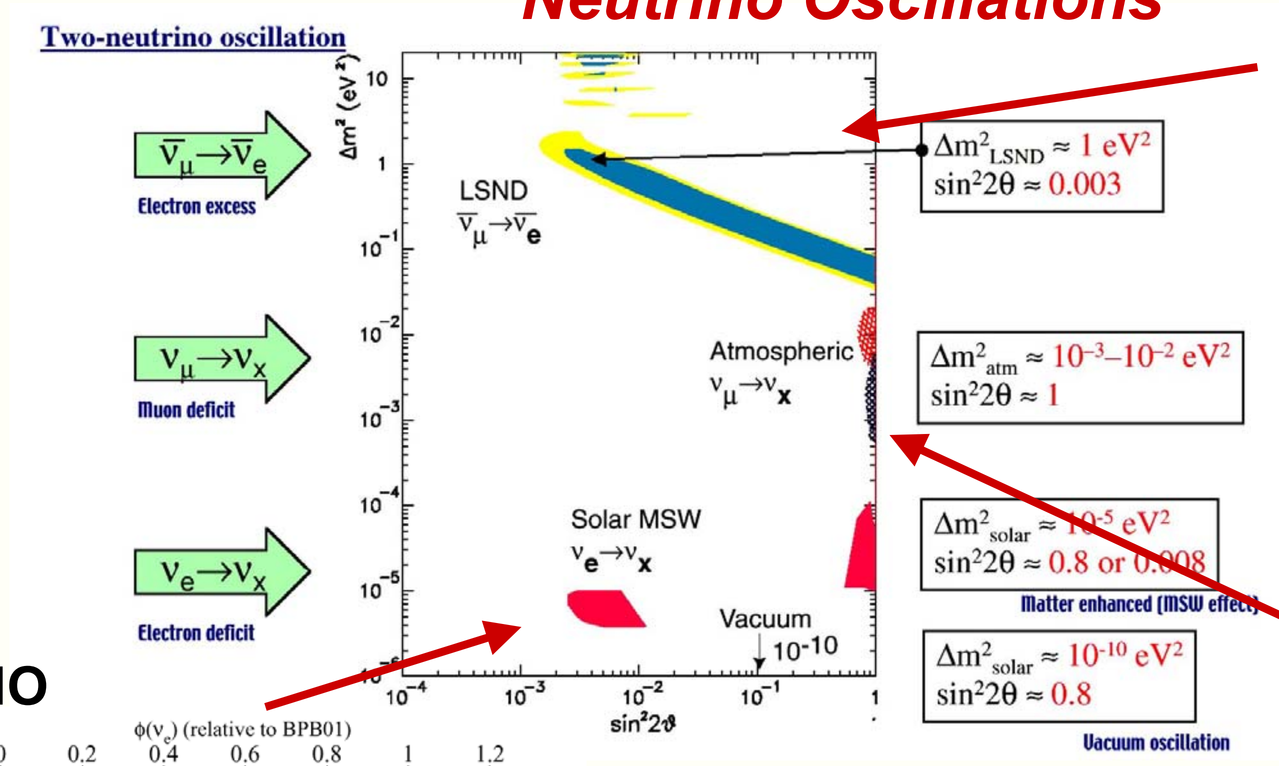
BaBar Next 5 years ~ 500 fb^{-1}

Precision measurement of sin2α, sin2β, as well as CKM elements….



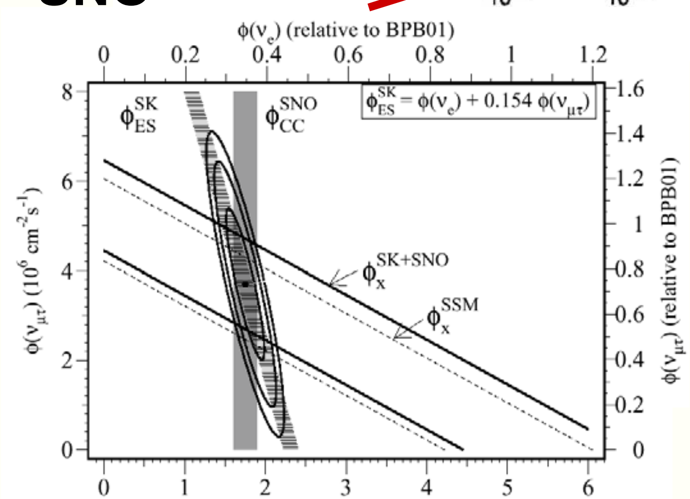
Recent Steps

Neutrino Oscillations

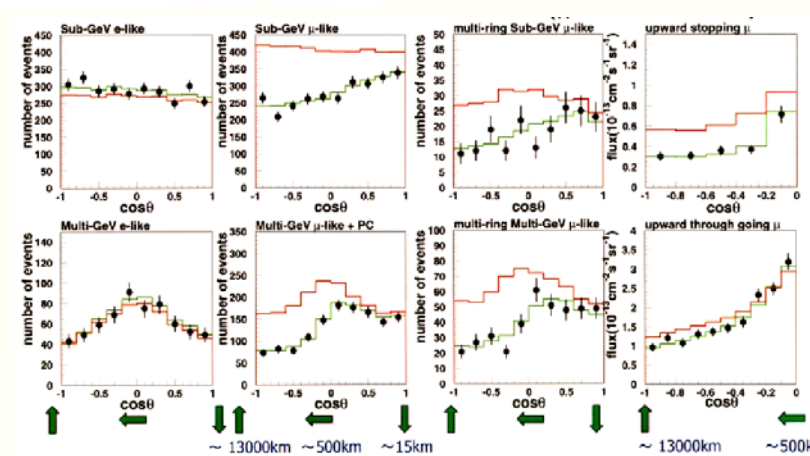


MiniBooNE

SNO



SuperK

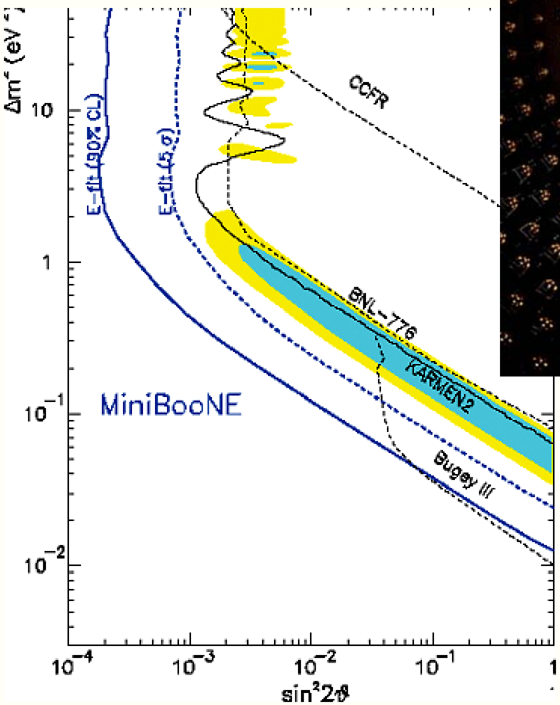


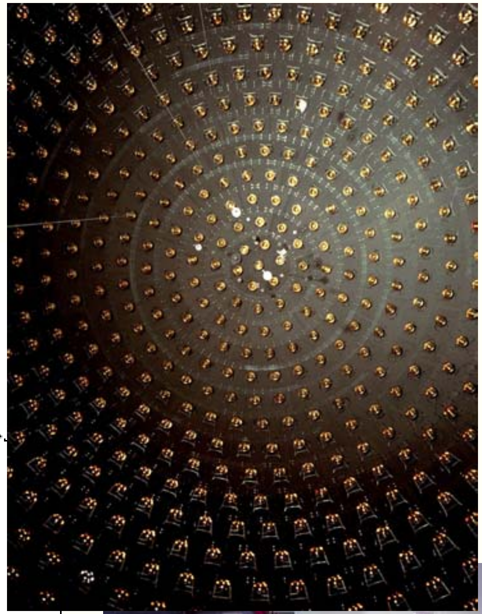
The Particle Physics Roadmap

Existing and Near-Term Program

MiniBooNE

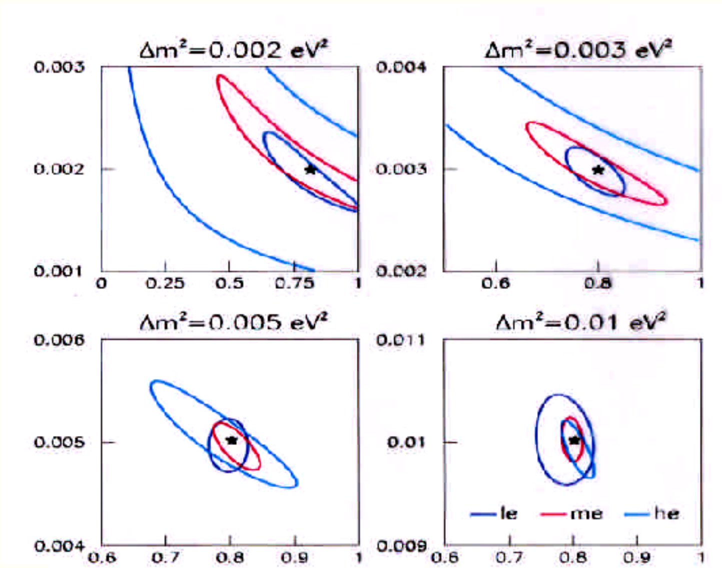
Refute or confirm LSND





MINOS

Atmospheric ν parameters



The Particle Physics Roadmap

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  - The Existing and Near-Term Program
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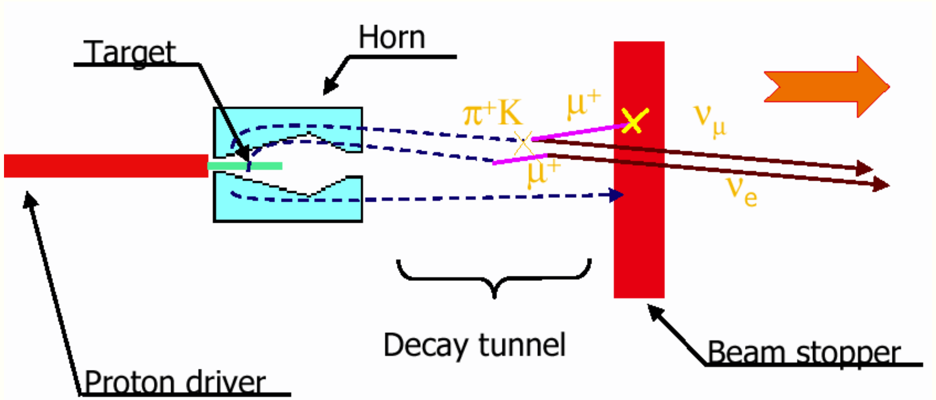
Lepton Flavor Physics

Neutrinos

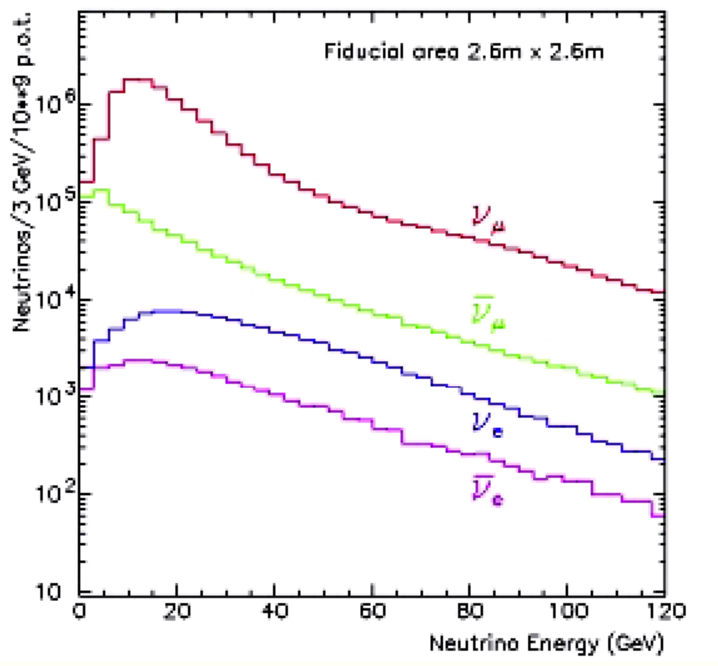
Superbeam

Conventional Beam
Intense Proton Driver



Proton driver – 1 – 4 MW
Neutrino Energy – GeVs

(optimum energy / detector distance ??)

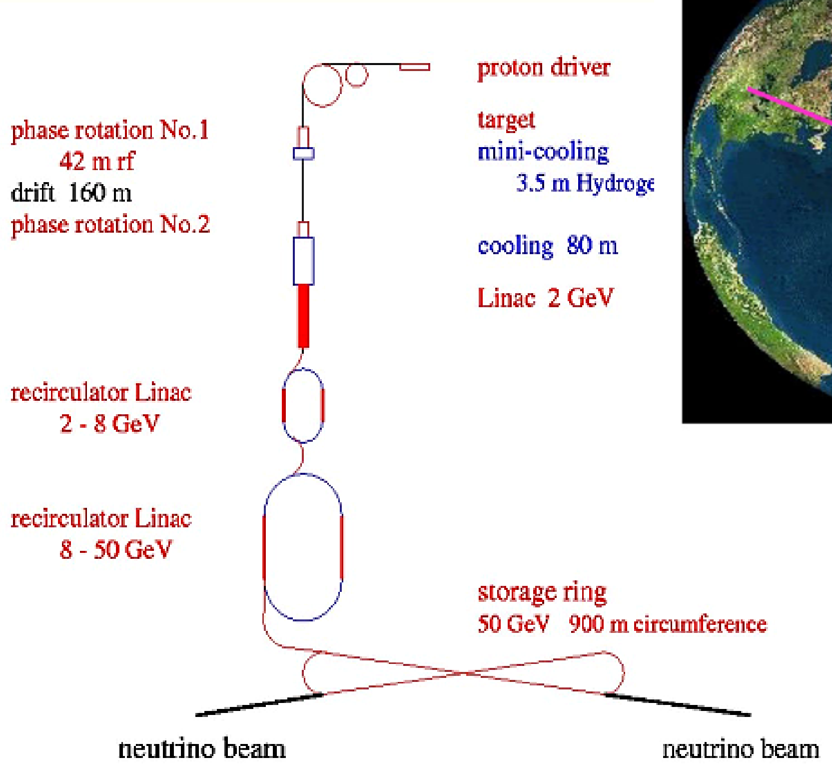


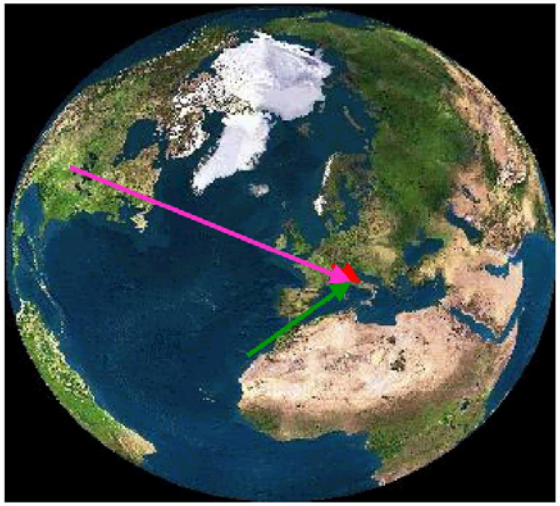
- **Factor 10–100 beyond MINOS**
- **Accurate parameters**
  - **$s_{23} \sim 10^{-2}$, $s_{13} \sim 5 \times 10^{-3}$**
- **Poor sensitivity to δ**

Lepton Flavor Physics

Neutrinos

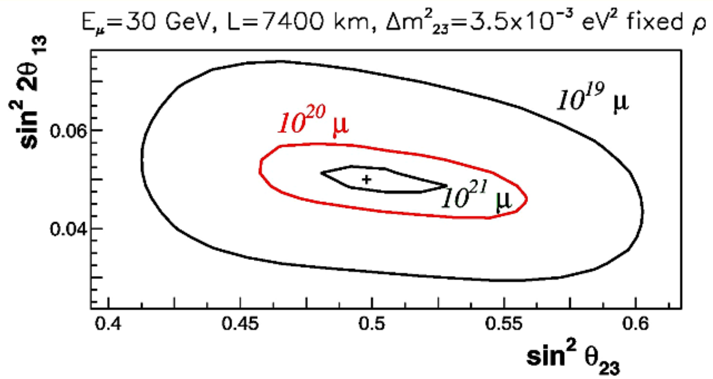
Neutrino Factory
Muon Collider





Example:
7400 km baseline

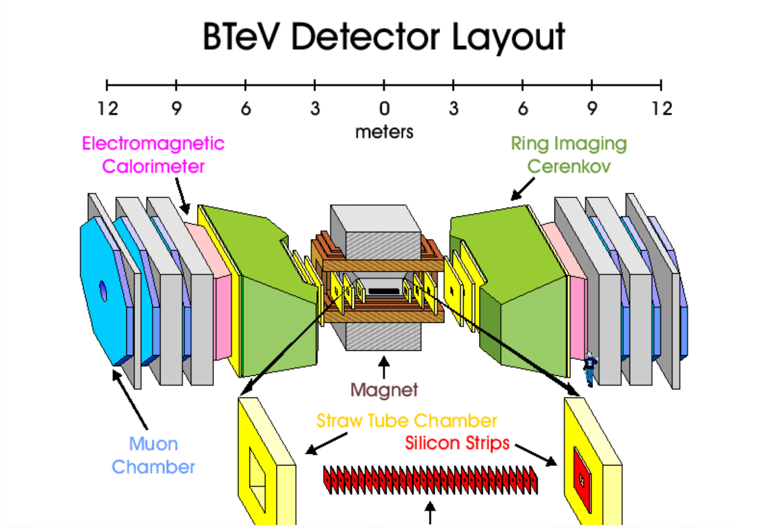
Fermilab → Gran Sasso
"world project"

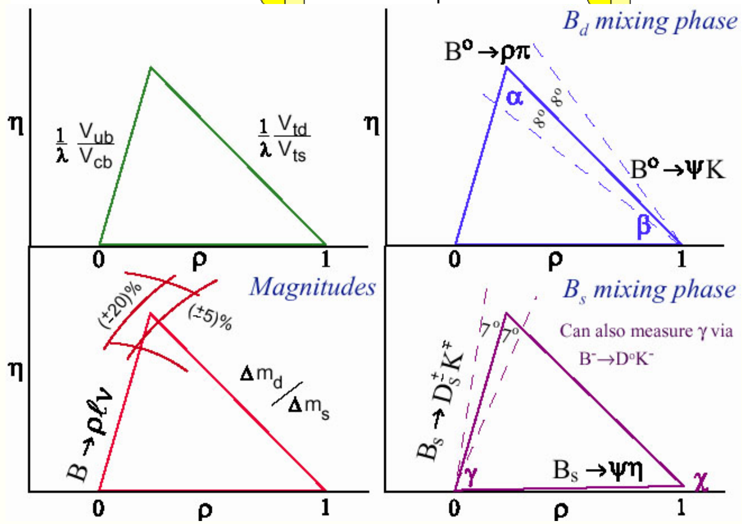


neutrino beams
select ν_μ's or anti ν_μ's

- **Accurately determine mixing matrix**
- **Measure CP violation in ν sector?**
  Depends on θ_{13}??

The Particle Physics Roadmap
Quark Flavor Physics



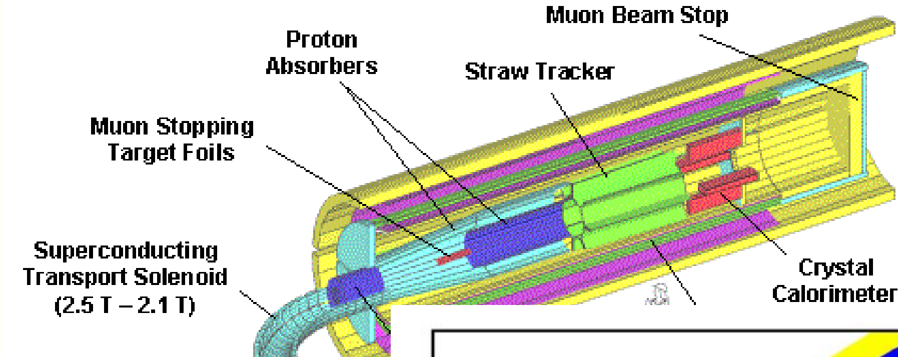


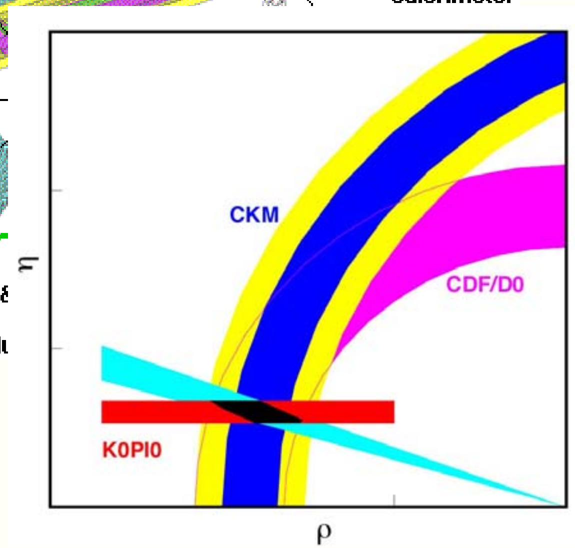
- **Quark mass, mixing, CP violation, using strange, charm and bottom hadrons….**

- **Precision measurements to challenge the Standard Model.**

CLEO-c, BTeV, SuperBaBar ….

The Particle Physics Roadmap





Very Rare Processes

- Some very rare processes probe CP violation in the strange quark system.
- Lepton flavor violation and proton decay are consequences of grand unification!

$K^0 \to \pi^0 \nu\nu \qquad K^+ \to \pi^+ \nu\nu,$

$\mu \to e\, \gamma \qquad p \to K^+ \nu$

CKM, K0PI0, MECO ….

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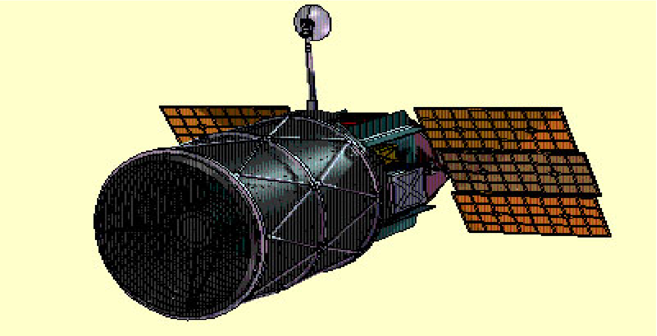
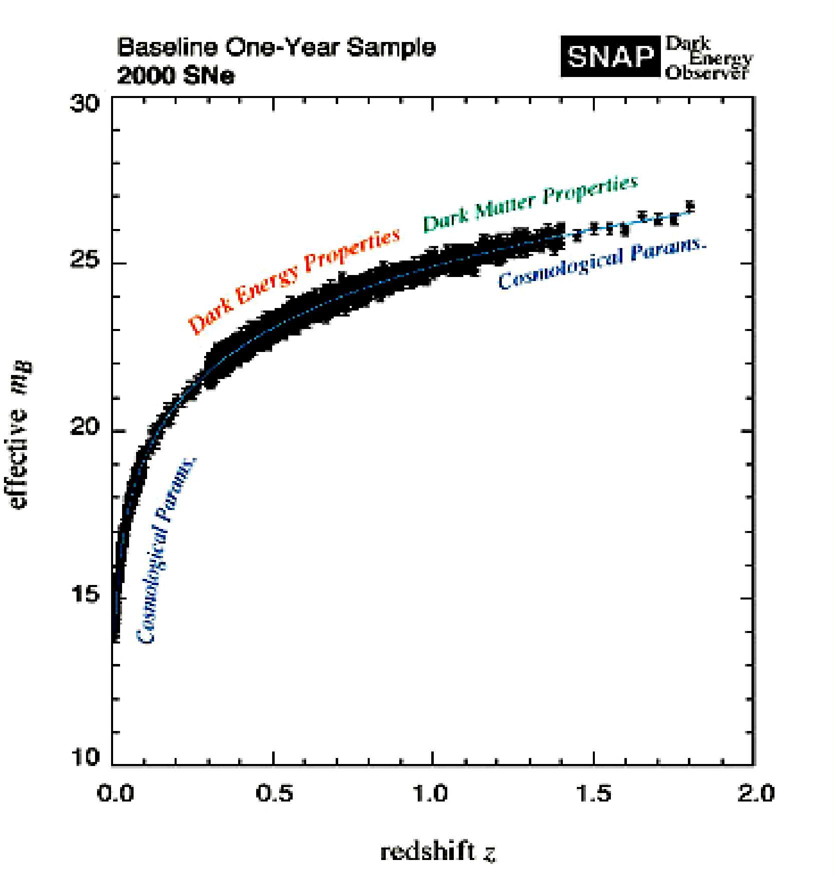
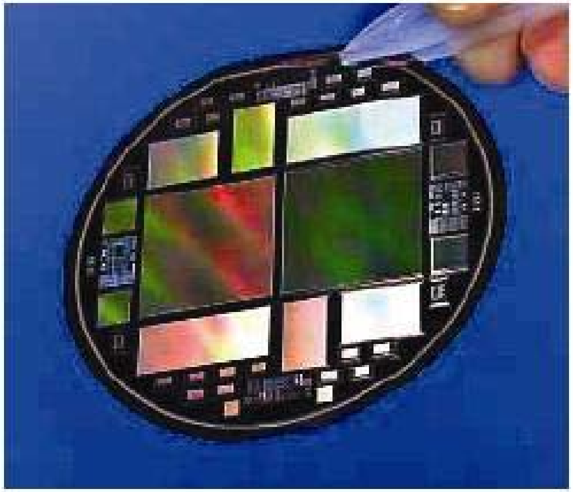
Cosmology and Particle Physics

Dark Energy





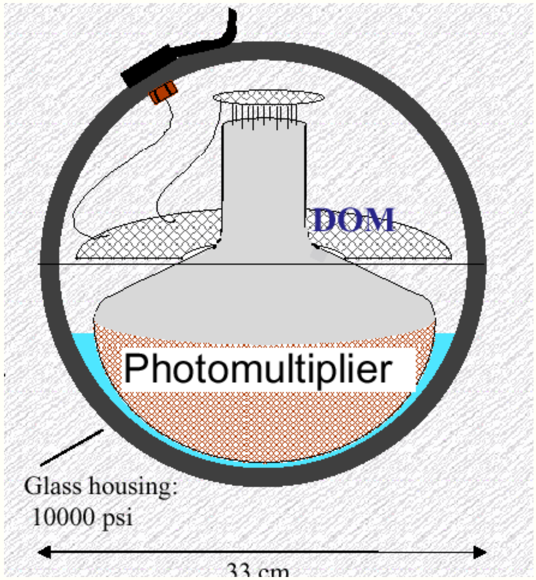


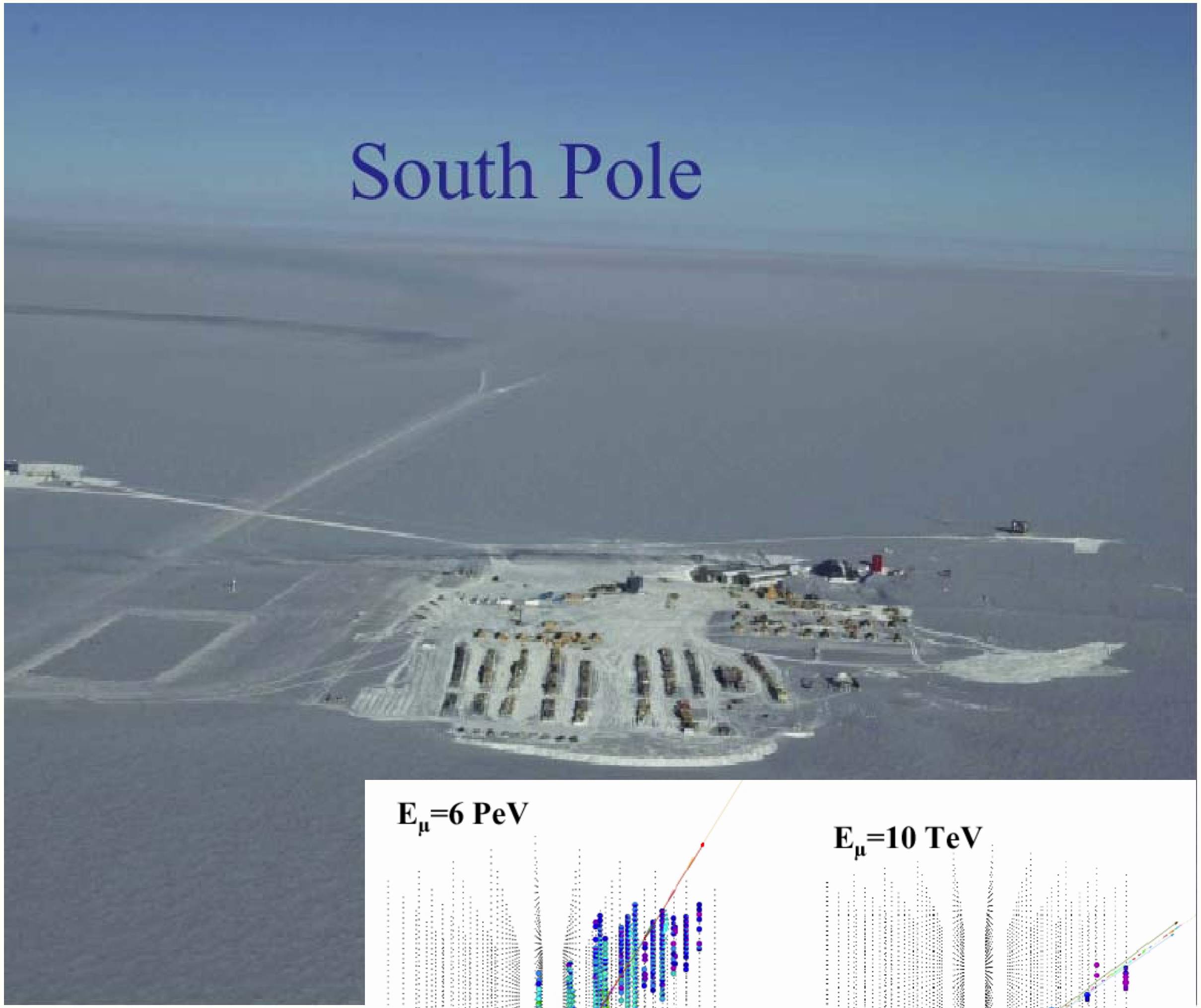
The SNAP Dark Energy Detector. SNAP requires R&D to develop a detector with one billion CCD's.

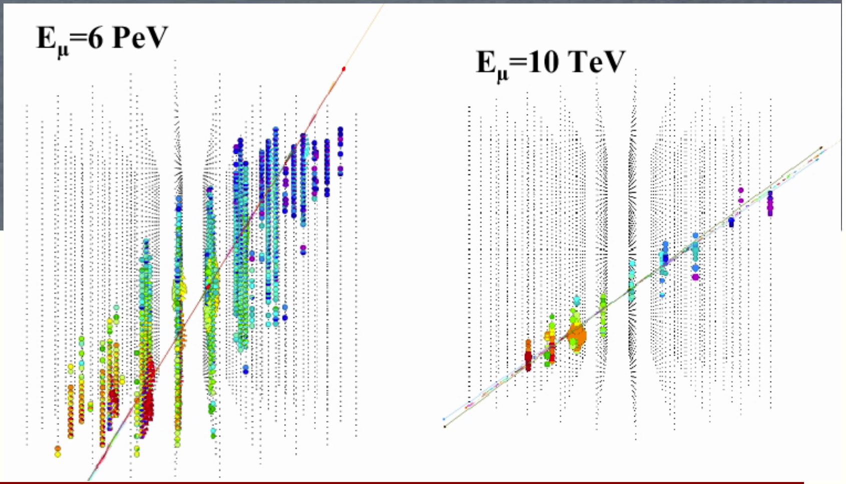
IceCube

The Detector

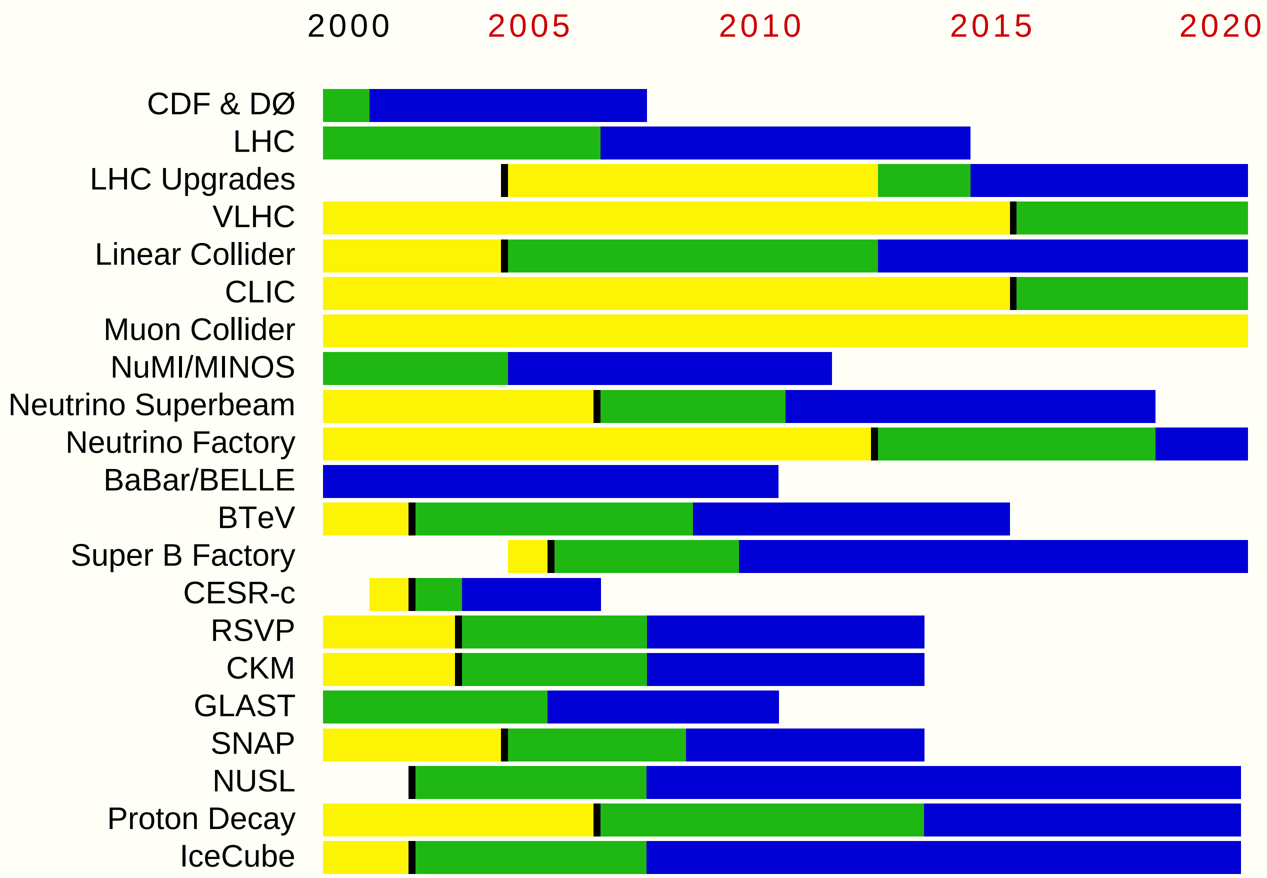
Depth: 1400-2400m
80 strings
4980 phototubes







The Particle Physics Roadmap



Not all projects illustrated on the roadmap can be pursued.

Setting Priorities and Making Choices

- **We recommend the creation of a Prioritization Panel for mid-scale projects.**
  - **Medium scale projects (total costs between $50M and $500M) make up a major part of the U.S. program.**
  - **They must be evaluated in competition with each other, considering the science, the resources and the global program.**
  - **We expect a robust program of these projects.**

Prioritization is central to our plan for a diverse, aggressive program of particle physics, and to an optimal program of scientific investigation.

Setting Priorities and Making Choices

- **Guidelines for P5**
  - **Medium-scale projects must be evaluated in competition with each other, in the context of the overall constraints and goals of our field.**
  - **The panel will be to advise HEPAP and the agencies on the prioritization of these projects.**
  - **The panel will weigh scientific impact, resource allocation, and programmatic issues.**

P5 will optimize the program choices and present them forcefully for funding. It will ensure a diverse and balanced program, well-matched to our scientific goals.

Recommendation #2

We recommend a twenty-year roadmap for our field to chart our steps on the frontiers of matter, energy, space and time. The map will evolve with time to reflect new scientific opportunities, as well as developments within the international community. It will drive our choice of the next major facility and allow us to craft a balanced program to maximize scientific opportunity.

We recommend a new mechanism to update the roadmap and set priorities across the program. We understand that this will require hard choices to select which projects to begin and which to phase out. Factors that must be considered include the potential scientific payoff, cost and technical feasibility, balance and diversity, and the way any proposed new initiative fits into the global structure of the field.

Investing for the Future

Accelerator R&D

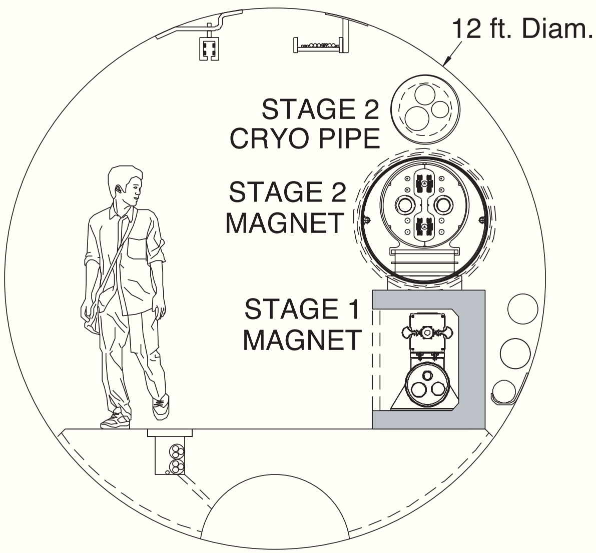
- **Advances in particle physics depend critically on developing more powerful particle accelerators.**
- **It is imperative for the U.S. to participate broadly in the global accelerator R&D program.**
- **Accelerator R&D has important impacts elsewhere in science and technology.**

We give high priority to accelerator R&D because it is absolutely critical to the future of our field.

Investing for the Future

Accelerator R&D --VLHC

- A **linear collider** is the highest priority in this report. R&D toward that facility must be increased significantly.
- A **very large hadron collider (VLHC)** is a long-range objective for our field.



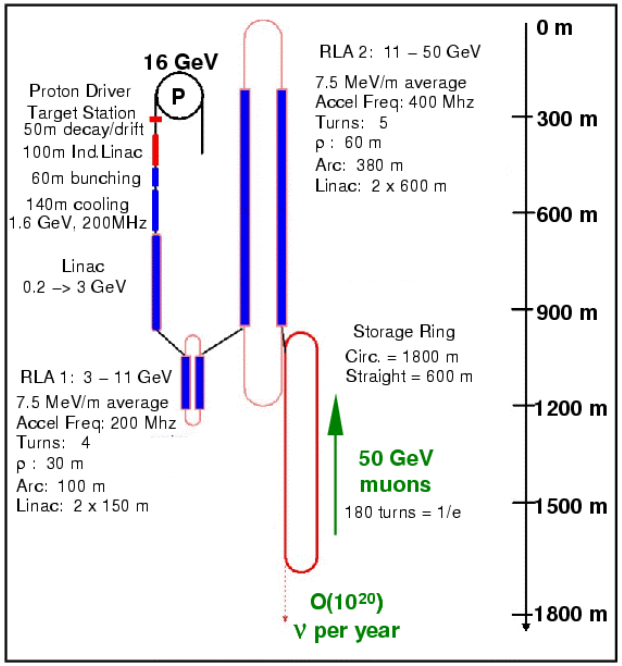
Concept for a VLHC

- We strongly support R&D toward such a machine at about the current level of effort.
- High-field magnet research is particularly important.
- An international collaboration should be formed as early as possible.

Investing for the Future

Accelerator R&D – Muon Collider/Neutrino Factory

- We support the neutrino source as the primary goal of the muon collaboration.
- We recommend continued R&D near the present level.
- The level of effort is well below what is required to make an aggressive attack toward a neutrino factory.
- International collaboration on the essential muon cooling experiment is very important.



Recommendation #5

We recommend that vigorous long-term R&D aimed toward future high-energy accelerators be carried out at high priority within our program. It is also important to continue our development of particle detectors and information technology. These investments are valuable for their broader benefits and crucial to the long-range future of our field.

The Particle Physics Roadmap

- **Major Elements of the Roadmap by Topic**
  - The Existing and Near-Term Program
  - The Energy Frontier
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  - Lepton Flavor Physics
  - Quark Flavor Physics
  - Very Rare Processes
  - Cosmology and Particle Physics
  - High-Energy Particle-Astrophysics

The Linear Collider

The Next Step: The TeV Scale

- Exploration of the TeV scale will begin, but not end, with the CERN LHC.
- There is now a worldwide consensus that:
  - The LHC and a linear collider are both essential to discover and understand the new physics at the TeV scale.
  - A coherent approach, exploiting the strengths of both machines, will maximize the scientific contributions of each.

The centerpiece of our roadmap is the thorough exploration of the TeV scale.

The Linear Collider

Why a Linear Collider?

- **The linear collider accelerates electrons and positrons, structureless particles that interact through precisely calculable weak and electromagnetic interactions.**
- **A linear collider can:**
  - **Determine the spins and quantum numbers of new particles.**
  - **Measure cross sections and branching ratios.**
  - **Carry out precision measurements and expose crucial details of new physics.**

Physics program endorsed by the Asian and European Committees for Future Accelerators, by the U.S. high-energy physics community during the 2001 Snowmass workshop, and by this subpanel.

The Linear Collider
500 GeV: The First Step

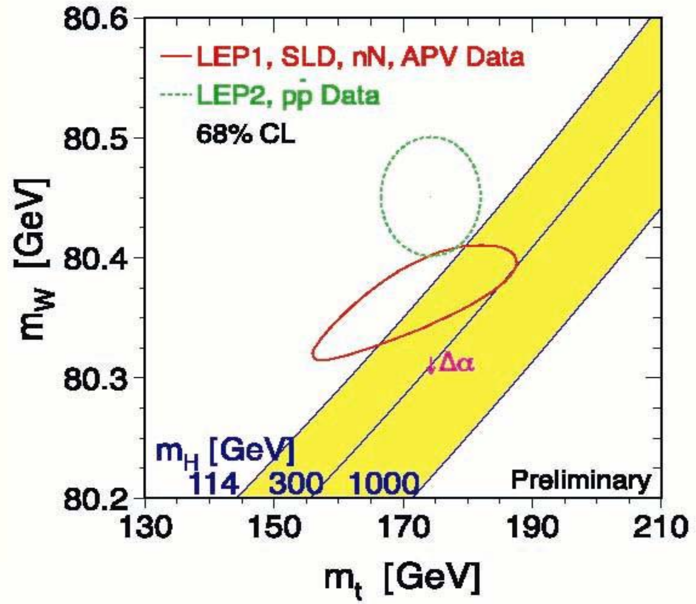
- **The case for starting at 500 GeV builds on the success of the Standard Model.**
  - **We know there must be new physics, and we know where to look.**
- **On general grounds, we know that new physics must appear by the TeV scale.**
- **The new physics is likely to include a Higgs.**
  - **The Higgs is a fundamental spin-zero particle – a new force, a radical departure from anything we have seen before.**

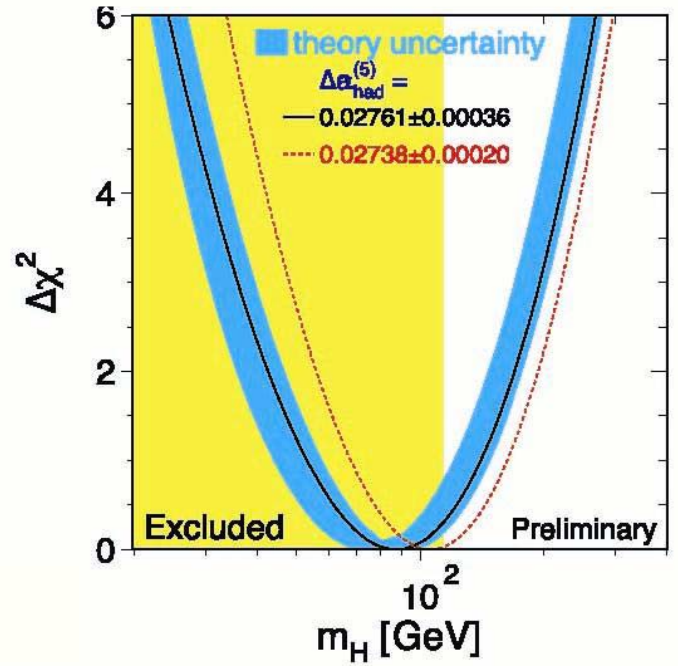
The Linear Collider

Standard Model Fit

In fact, fits to the Standard Model prefer a Higgs boson mass of less than 200 GeV.

Such a light Higgs boson is well within reach of a 500 GeV linear collider.





The Linear Collider

Measurements at 500 GeV

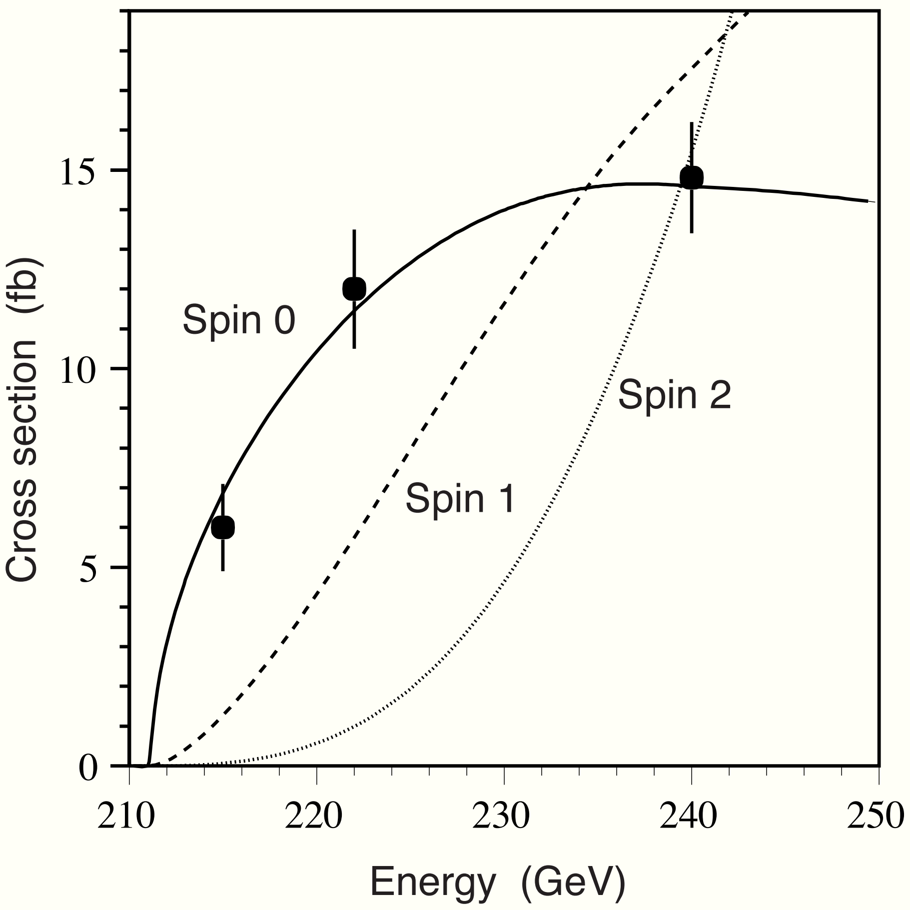
- **Experiments at the LHC are likely to discover the Higgs.**
- **But a linear collider answers crucial questions:**
  - **Does the Higgs have spin zero, as required?**
  - **Does it generate masses for the *W* and *Z*, and for the quarks and leptons?**
  - **Does the Higgs generate its own mass?**

The Linear Collider

Spin Measurement

The LHC can determine the spin of a Higgs if its decay into *ZZ* has sufficient rate. But the linear collider can measure the spin of any Higgs it can produce.

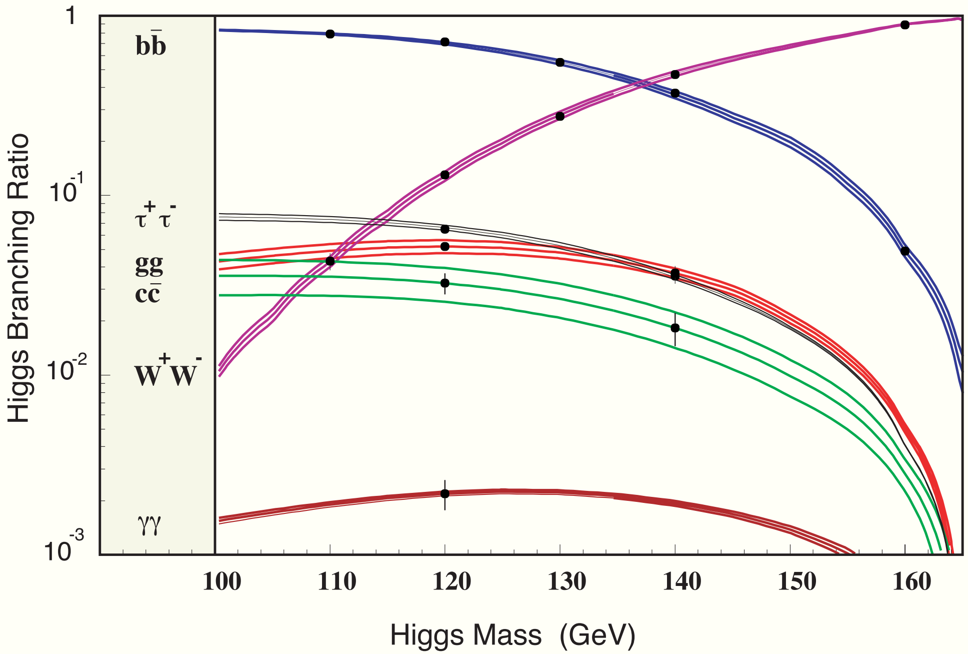
The process $e^+e^- \to HZ$ can be used to measure the spin of a 120 GeV Higgs particle. The error bars are based on 20 fb^{-1} of luminosity at each point.



The Linear Collider

Branching Fraction Measurement

The LHC will measure *ratios* of Higgs couplings. The linear collider, working with the LHC, can determine the *magnitudes* of these couplings very precisely.



The figure shows estimated measurements of the Higgs branching fractions, assuming a 120 GeV Higgs, and 500 fb^{-1} of integrated luminosity.

The Linear Collider

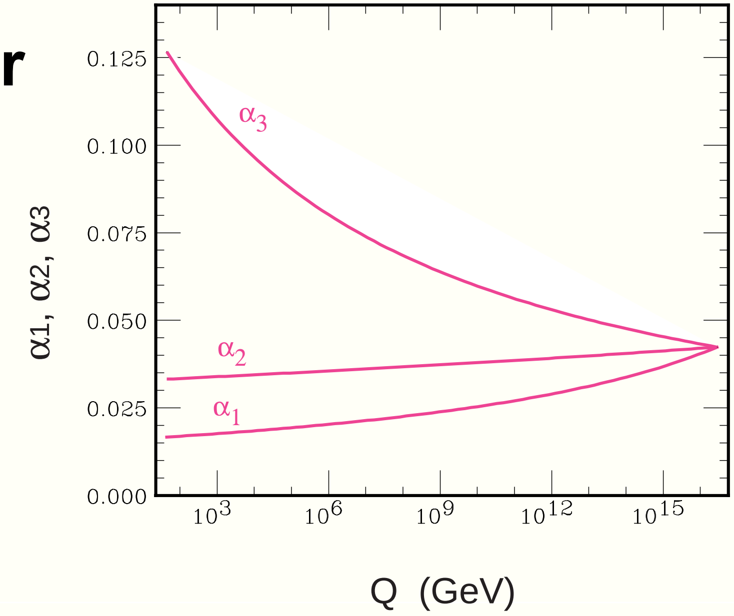
800-1000 GeV: The Essential Next Step

- **At 500 GeV we expect to be able to study the Higgs.**
  - **But our goals – ultimate unification, hidden dimensions, and cosmic connections – all point to other new physics at the TeV scale.**
- **If there is a Higgs, we need to know why it is there.**
  - **The Higgs is so different from the other particles, there must be more to the story.**
- **We have many ideas – but which, if any, is right?**
  - **We won't know without fully exploring the TeV scale.**

The Linear Collider

New Quantum Dimensions

- **There are already hints that quantum dimensions permit the electroweak force to unify with the strong nuclear force.**
  - **Protons are unstable and eventually decay.**
- **Supersymmetry unifies matter with forces.**
  - **Every known particle has a supersymmetric partner, waiting to be discovered at the TeV scale.**



The Linear Collider

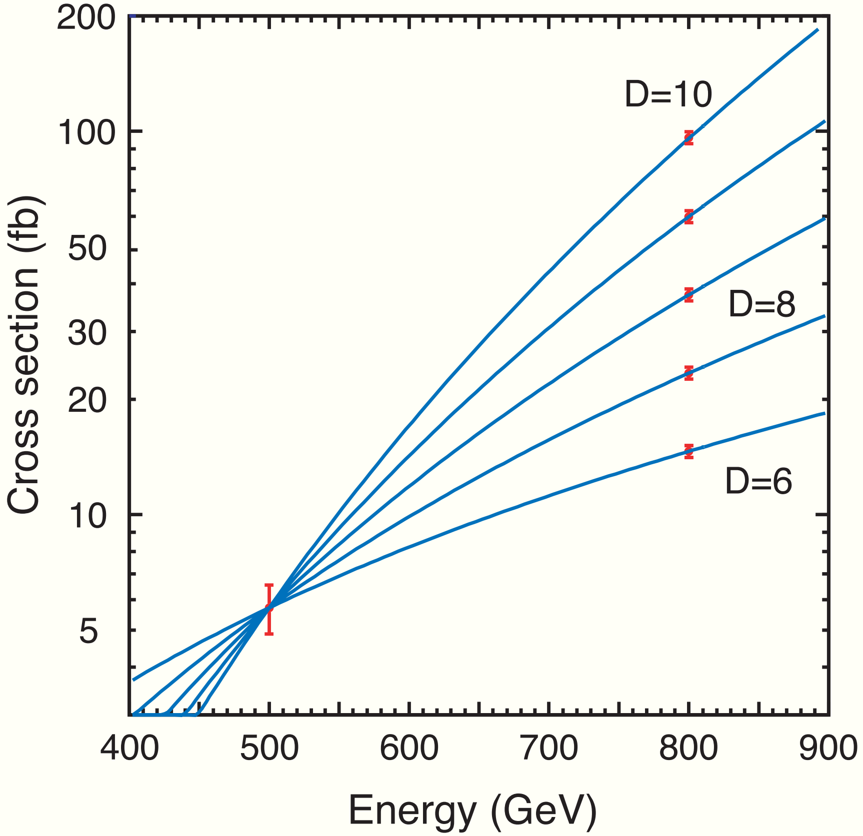
Testing Supersymmetry

- **To test supersymmetry, we need to measure the superparticle spins and couplings. Do the spins differ by 1/2? Are the couplings correct?**
  - **All the superparticle masses and couplings can be precisely measured at a high-energy linear collider, provided they can be produced. Precision measurements are crucial.**
  - **Some superparticles should be in range of a 500 GeV machine; exploration of the full spectrum requires at least 800-1000 GeV.**

The Linear Collider

New Spacetime Dimensions

- Other theoretical explanations of electroweak unification involve new hidden spatial dimensions.
- Particles moving in these dimensions induce observable effects at the TeV scale.
- The LHC can find hidden dimensions; the linear collider can map their nature, shapes and sizes.
  - If gravitons travel extra dimensions, the linear collider can demonstrate that they have spin two.
  - Even if the hidden dimensions are not directly accessible, precision measurements at the linear collider can detect for their indirect effects on TeV physics.



The Linear Collider

Measuring The Number of Dimensions

New space-time dimensions can be mapped by studying the emission of gravitons into the extra dimensions, together with a photon or jets emitted into the normal dimensions.

The figure shows the cross section needed to produce extra-dimensional gravitons in association with ordinary photons. Measurements at different beam energies can determine the number and size of the extra dimensions.

The Linear Collider

Finding Dark Matter

- **What is the dark matter that pervades the universe?**
  - **Many models of TeV physics contain new particles that could fit the bill.**
  - **The dark matter might be neutralinos, stable neutral superparticles predicted by supersymmetry.**
- **Measurements at the linear collider will allow us to develop a predictive theory of this dark matter.**
  - **These measurements would push our detailed knowledge of the early universe back to a trillionth of a second after the Big Bang.**

The Linear Collider

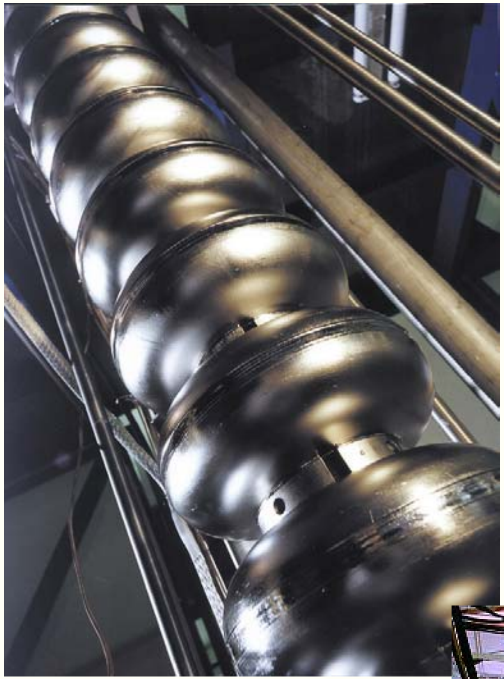
Science-Driven Requirements

- **A linear collider with a maximum energy near 1 TeV is well matched to our goal of exploring the TeV energy scale.**
  - There is a strong argument for starting linear collider operation at about 500 GeV.
  - After a rich, multiyear program at 500 GeV, we will raise the collider's energy to complete our exploration of the TeV scale and take full advantage of our large investment in the machine.
  - We anticipate equally exciting discoveries at these higher energies.

The Linear Collider

Technologies

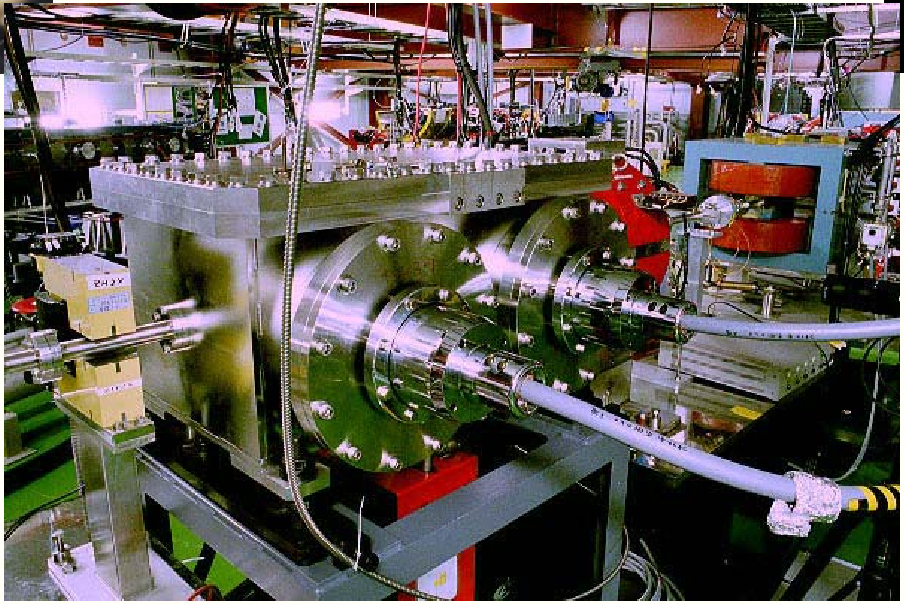
- The international accelerator community now firmly believes that a TeV-scale linear collider can be successfully built at an acceptable cost with the correct science-driven capabilities.
- This is a result of an intensive R&D period, where there has been a strong level of international cooperation and communication.



TESLA
Superconducting Cavity

NLC
High Power
Klystron

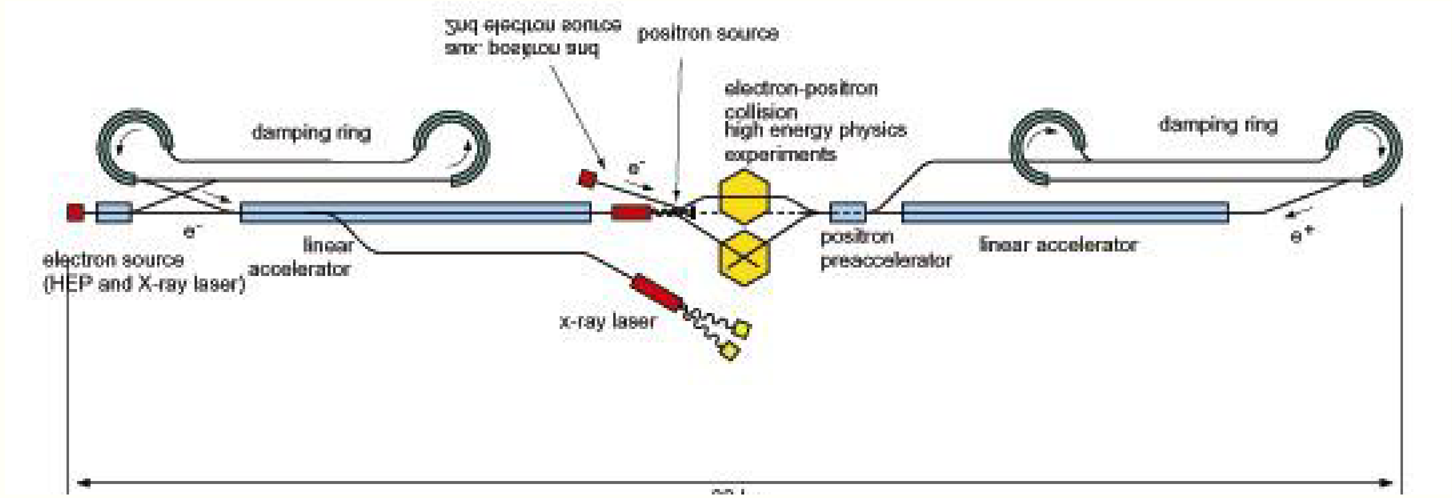
JLC
Accelerator
Test Facility



The Linear Collider

Technologies

- **TESLA Design**
  - A 33-kilometer electron-positron linear collider based on superconducting technology.
  - In addition to its colliding beam capabilities, the TESLA proposal includes an X-ray laser facility.
  - The TESLA Technical Design Report (March 2001) was submitted to the German Scientific Council.



The Linear Collider

R&D Programs

- Making the Technology Choice for the Linear Collider
  - The International Committee for Future Accelerators (ICFA) is doing a technical assessment of the two competing technologies.
    - A report from ICFA's study should be available within a year.
  - The international collaboration that will build the linear collider must decide on the optimum technology.
    - That decision must be based on sufficient R&D so that all relevant issues have been addressed in enough detail to support the decision.
  - For the case of a U.S.-hosted machine, we recommend developing a process for making this decision as early as possible, to focus the development work on the technology to be employed.

Recommendation #3

We recommend that the highest priority of the U.S. program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world. This facility is the next major step in the field and should be designed, built and operated as a fully international effort.

We also recommend that the U.S. take a leadership position in forming the international collaboration needed to develop a final design, build and operate this machine. The U.S. participation should be undertaken as a partnership between DOE and NSF, with the full involvement of the entire particle physics community. We urge the immediate creation of a steering group to coordinate all U.S. efforts toward a linear collider.

The Linear Collider

The Case for Hosting in the U.S.

- **A healthy worldwide physics program requires a distribution of major facilities around the globe.**
  - At present, the LHC is being constructed in Europe, and the JHF, a major high intensity proton facility, is underway in Japan.
- **Past investments in accelerator facilities have enormously enriched our society.**
  - History shows that accelerator facilities provide important platforms for major advances in physics and technology.
  - The linear collider would attract some of the brightest scientists from around the world to the U.S.

The Linear Collider

Constructing the Linear Collider

If the linear collider is sited in the United States, we envision financing it through a combination of investments from non-U.S.collaborators, the use of existing infrastructure and human resources within the U.S. program, and increased support to the U.S. particle physics program.

- **International investment is essential for a project of this scale.**
  - **All partners must feel ownership, so full internationalization must begin at the start of the project and cover all its aspects and stages.**
  - **This means that initial steps toward internationalization should begin immediately, independent of the final location of the facility.**

The Linear Collider

Constructing the Linear Collider

- A significant fraction of the linear collider must be financed from the existing U.S. high-energy physics program.
  - If a linear collider is built in the U.S, the site should be at or near an existing high-energy physics laboratory, to take full advantage of existing resources.
  - At existing laboratories, we foresee a natural realignment of accelerator physicists, technicians, engineers, and particle physicists as the linear collider project ramps up and other activities fulfill their scientific objectives.
- We believe that a bold new initiative like the linear collider merits new funding from the U.S. government.
  - We envision that the host country, in this case the U.S., would contribute about two-thirds of the cost of the project, including redirection.

The Linear Collider

Organizational Issues

A number of issues need to be resolved. These include reaching final agreement on the technical design for the machine, working toward the definition of an optimized experimental program, conducting negotiations in the political sphere to arrange an international collaboration to build the facility.

The formation of an international organization under scientific leadership is necessary to complete the linear collider design and to initiate the collaborations for its physics use. As a first step, we recommend formation of a U.S. Linear Collider Steering Committee.

Recommendation #4

We recommend that the U.S. prepare to bid to host the linear collider, in a facility that is international from the inception, with a broad mandate in fundamental physics research and accelerator development. We believe that the intellectual, educational, and societal benefits make this a wise investment of our nation’s resources.

We envision financing the linear collider through a combination of international partnership, use of existing resources, and incremental project support. If it is built in the U.S., the linear collider should be sited to take full advantage of the resources and infrastructure available at SLAC and Fermilab.

HEPAP Subpanel

What's next?

- We need, as a community, to embrace a vision for the future of our field.
- As a unified community, we need to share this vision to those in other branches of physics and in other fields of science.
- We believe that the plan presented here is very ambitious, but offers great rewards.

Provide your input to the sub-panel:

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