PHY313 - CEI544
The Mystery of Matter
From Quarks to the Cosmos
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Peter Paul
Office Physics D-143
www.physics.sunysb.edu PHY313
Eleventh Homework Set, due April 28, 2005

1. Describe briefly the differences between Fermions and Bosons.

2. Explain what Gauge symmetry stipulates.

3. By whom, when and where was the mechanism invented that can give mass to the elementary particles?

4. What particles does the Large Hadron Collider (LHC) accelerate and to what energy. Where is it being built?

5. Give at least one scientific goal for the LHC.

6. What are the supersymmetric partners of quarks and gluons?
The mass of the Higgs Particle

Particles can interact with heavy particles that are hidden in the vacuum. In this example the 5-GeV $B^0$ meson feels the presence of the 90 GeV $W^\pm$ particles. These virtual particles affect the energy of the real particle. In turn from the energy of the real particle we can deduce approximately the mass of the virtual particle.
Evolution of Gauge Couplings (reciprocals)

Standard Model

Supersymmetry
Running Couplings

Forces Merge at High Energies

Strength of Force

Energy in GeV

Peter P.
How does SUSY change the strength of forces?

- The strength of the force is affected by the Gauge bosons. By introducing additional gauge bosons and by changing the Boson masses, the slope of the interaction strength as a function of energy changes.
Proposed next generation facilities

- A number of new, powerful and expensive facilities are under construction or being proposed to address these and other issues.
- We will discuss here three or four of them:
  - The Large Hadron Collider under construction at CERN. It is under construction.
  - The International Linear Collider. It is in a discussion and design phase as a World Facility
  - Long Baseline neutrino experiments. It is in the planning stage.
  - Large underground detectors for proton decay and neutrino-less double beta decay.
The need for new high energy facilities

- Exploration of the remaining mysteries of the fundamental aspects of Nature requires increasingly higher energies. This is because…
- The Higgs process for the creation of mass indicates one or more massive particles with a mass of at least 115 GeV.
- SUSY requires a complementary group of new particles with masses between \( \sim 200 \text{ GeV} \) and 1 TeV.
- Speculative heavy Boson explaining CP violation would also have a mass beyond 500 GeV.
- Creation of high mass requires high beam energies! This leads to expensive accelerators.
International Linear Collider

• A precision “microscope” for probing the nature of any particle found in the region between 500 and 1,000 GeV with very high energy resolution.
• An electron-positron collider of c.m. energy up to 1.2 TeV.
• Very large (~33 km) and very expensive: $6 to 12 Billion.

• Mission: To make precision measurements on any new particles, such as Higgs candidates or supersymmetric s-particles, discovered by the LHC, to make sure that they really are what we believe they are.
• As such it is not a discovery machine but a verification machine.
• Only one such facility in the world: Where should it be?
  – In the US at Fermilab
  – In Japan at the KEK Laboratory
Electron beams bring in energy more efficiently

- elementary particles
- well-defined energy, angular momentum
- uses its full energy
- can produce particles democratically
- can capture nearly full information
Why linear instead of circular?

• An energetic electron or positron beam moving on a circular (or even curved) path emits EM radiation.
• The intensity of this radiation increases with the 4th power of the beam energy.
• At high beam energies this is very intense X-ray radiation, which is used in many Synchrotron Radiation Facilities around the world.
• However, in a high-energy accelerator this energy must be replaced to maintain the energy of the beam. This energy loss makes circular electron accelerators above \( \sim 1 \text{ GeV} \) impractical.
Synchrotron Radiation

- Synchrotron radiation is emitted continuously as the electrons bend around the ring. The loss of the energy radiated off needs to be replaced.
- The loss increases with the fourth power of the beam energy. At some energy it becomes impractical and very expensive to add the energy back in to keep the beam on track.
- The linear accelerator is the only answer.
A practical concept

- electron position collider at 0.5-1 TeV
- about 20 miles long
- super-high-tech: nanometer beams
Fermilab as possible ILC site

Fermi National Accelerator Laboratory, ~60 miles west of Chicago would be the preferred site for the ILC in the U.S.
How can we probe the Higgs with the ILC?

- An important Higgs production process is $e^+e^- \rightarrow Z + \text{Higgs}$

- There are many possible final states, depending on how the Z and Higgs decay

Examples are:

- $e^+e^- \rightarrow Z + \text{Higgs} \ \rightarrow bb$
  $\downarrow \mu^+\mu^-$

- $e^+e^- \rightarrow Z + \text{Higgs} \ \rightarrow \text{invisible final states}$
  $\downarrow \mu^+\mu^-$
The decay of the Higgs
This is what you might see

ILC Simulation for $e^+e^- \rightarrow Z + \text{Higgs}$ with $Z \rightarrow 2 \text{ b-quarks and Higgs} \rightarrow \text{invisible}$
ILC produces clean signals for new particles

**Recoil Technique**

In $e^+e^- \rightarrow Z + \text{Anything}$

- ‘Anything’ corresponds to a system recoiling against the $Z$
- The mass of this system is determined solely by kinematics and conservation of energy!
  - because we see everything else, we know what is escaping!

Peak in Recoil Mass corresponds to 120 GeV Higgs!

**ILC Detector Simulation of W-Superpartner Production**

**Heavy Z-like Bosons appear as resonance-peak at LHC**

LHC determines mass of new Z-like boson to few percent
Should we build the ILC?

**Pro’s:**
- It will provide precision data and clean events on any new particles that the LHC discovers.
- It reaches the same mass scale as the LHC with much less beam energy and it produces clean signals.
- It will provide a cutting edge High Energy Facility for U.S. science.
- It will be a driver for technology

**Con’s**
- It is very costly. It will put a lot of science money into one basket.
- It is restricted, for technical reasons, to energies below $\sim 1$ TeV. What of the LHC discovers nothing new between 500 GeV and 1 TeV?
- The U.S. could let another country take a lead and tag along, just as we did with the LHC, getting much of the science at a faction of the cost (maybe 30%).
Long Baseline Neutrino Studies

- We know from solar and atmospheric neutrinos that neutrinos morph from one flavor into another, from a $\mu$-neutrino into an e-neutrino etc. But the data are limited by the limited numbers of neutrinos and the low energies that are available.

- Neutrinos are special because of their definite Helicity: Neutrinos are left-handed, antineutrinos are right-handed.

- **They may provide insight or even be the driving force behind the large CP violation.**

- Neutrino Factories for the production of muon neutrinos will be ready in 2008 in Japan, and could be available later at BNL.
Mixing neutrino flavors

- We know of 3 neutrino generations or flavors:
  - Electron neutrino: call it #1
  - Muon neutrino: call it #2
  - Tau neutrino; call it #3

- They can all have different masses
  - $m(1)$; $m(2)$; $m(3)$

- We do not know which one is heavier and which one is lighter.
- Oscillation experiments can determine the differences of $m^2$ but no absolute numbers.

- For example,
  $$\Delta m^2(12) = m(2)^2 - m(1)^2$$

- The mass of the electron neutrino is $< 5\text{eV}$. A new experiment (Katrin) will bring that down to a limit of $0.2\text{ eV}$

- We know that $m(12)^2$ is between $0.03$ and $0.1\text{eV}$

- Assuming that $m(2) > m(1)$, this gives $m(2) \sim 1\text{ eV}$
The basic equations simplified

• If I start with muon neutrinos and wish to observe their change into electron neutrinos, the probability is given by

\[ P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 \left\{ \frac{1.27 \cdot (m_{\nu\mu}^2 - m_{\nu e}^2) \cdot L}{E_\nu} \right\} \]

\[ \Delta m_{32}^2 = (1.6 - 4.0) \cdot 10^{-3} \text{eV}^2 \]
\[ \Delta m_{21}^2 = (3 - 10) \cdot 10^{-5} \text{eV}^2 \]

• Only the \textit{difference} of the \(m^2\)'s enters, not the masses themselves!
• L is the travel distance for the neutrinos from the production place to the detector.
• \(E = \) energy of the neutrino, which does not change significantly during the transformation.
• If we want the bracket to be large \(L/E_\nu\), must be large.
• If \(E_\nu \approx 1 \text{GeV}\) for ease of detection, then the travel distance L should be between 1000 and 2000 miles!
The Physicist’s equations

Oscillation Probabilities when 

\[ \Delta m_{12}^2 \ll \Delta m_{23}^2 \approx \Delta m_{13}^2 \]

\[ \Delta m_{ij}^2 = m_j^2 - m_i^2 \]

\( \mathbf{v}_\mu \) disappearance

\[ P_{\nu_\mu \to \nu_\mu} \approx 1 - \cos^4 \theta_{13} \cdot \sin^2 2 \theta_{23} \cdot \sin^2 \left( 1.27 \frac{\Delta m_{23}^2 L}{E_\nu} \right) \]

\( \mathbf{v}_e \) appearance

\[ P_{\nu_\mu \to \nu_e} \approx \sin^2 \theta_{23} \cdot \sin^2 \theta_{13} \cdot \sin^2 \left( 1.27 \frac{\Delta m_{13}^2 L}{E_\nu} \right) \]

\( \delta \): \( CP \) in \( \nu_e \) appearance

\[ A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2 \theta_{12}}{\sin \theta_{13}} \cdot \sin \delta \]
The Japanese T2K proposal

Combination of very powerful production accelerator and a huge Water Cerenkov detector (in stage II) will produce good data in ~ 5 years.

However: The distance is relatively short
Can the detector differentiate between $\nu_\mu$ and $\nu_e$?

- The answer is yes.
How to know the Number of neutrinos sent

- Muon monitors @ ~140m
  - spill-by-spill monitoring of π–beam direction/intensity
- First Front detector @ 280m
  - 0 degree definition
  - \( E_\nu, \pi^0 \) production to ~10%
- Second Front Detector @ ~2km
  - Ultimate systematics
- Far detector @ 295km
  - Super-Kamiokande (50kt)

Neutrino spectra at diff. dist

- 1.5km
- 295km
- 0.28km

dominant syst. in K2K
Physics Goals of the Very Long Baseline Neutrino Program

We introduce a plan to provide the following goals in a single facility:

- precise determination of the oscillation parameters $\Delta m_{32}^2$ and $\sin^2 2\theta_{23}$
- detection of the oscillation of $\nu_\mu \to \nu_e$ and measurement of $\sin^2 2\theta_{13}$
- a measurement of $\Delta m_{21}^2 \sin^2 2\theta_{12}$ in a $\nu_\mu \to \nu_e$ appearance mode can be made even if the value of $\theta_{13}$ is zero
- verification of matter enhancement and the sign of $\Delta m_{32}^2$
- determination of the CP-violation parameter $\delta_{CP}$ in the neutrino sector

The use of a single neutrino super beam source and half-megaton neutrino detector will optimize the efficiency and cost-effectiveness of a full program of neutrino measurements. If the value of $\sin^2 2\theta_{13}$ happens to be larger than $\sim 0.01$, then all the parameters, including CP-violation can be determined in the VLB program presented here. If not, anti-neutrino running can be done
Advantages of a Very Long Baseline

- neutrino oscillations result from the factor $\sin^2(\Delta m^2_{32} L / 4E)$ modulating the $\nu$ flux for each flavor (here $\nu_\mu$ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a very long baseline actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the $\Delta m^2_{32}$ to be precisely measured by a wavelength rather than an amplitude (reducing systematic errors)
The BNL to Homestake/Henderson Mine Proposal

1 MW beam power
5 Years running
2000 miles
cost ~$300 Million for beam

\[ \sin^2 2\theta_{23} = 1.0 \]
\[ \Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]

1 MW 0.5 MT 5yr

- No oscillations: 13290 evts
- With oscillations: 6538 evts
- Bckg in oscillated signal: 1211 evts

Reconstructed $\nu$ Energy (GeV)
The T2K Neutrino detectors
SuperTankers of Neutrino Physics:

Ring Imaging Water Cherenkov Detectors

Massive Active Volume for
Atmospheric $\nu$ Interactions
Solar $\nu$ Interactions
Relic Supernova $\nu$
Nucleon Decay Signals

Tank of Water (all Active)

Measure light direction
U.S. Long baseline geography

- Homestake Mine in South Dakota and Henderson Mine in Colorado are 6000 to 8000 feet deep mines that have the right distance to the neutrino sources.
The BNL source of neutrinos

AGS Target Power Upgrade to 1 MW

- the AGS Upgrade together with the 1.0 MW Super Neutrino Beam has an estimated cost of $369M FY03 (TEC) dollars
Send neutrinos through the Earth
The Next Big Thing: UNO

Proposed by Prof. C.K. Jung of Stony Brook

640,000 tons of Water
60,000 light sensors

Twenty Times Bigger than Super-Kamiokande
A Deep Underground Laboratory

The Henderson Mine

- Owned by Climax Molybdenum Company, a subsidiary of Phelps Dodge Corporation
- Established in 1970's
  - A modern mine developed under strict environmental regulation and self imposed high standards
- One of the 10 largest underground hard rock mines operating in the world w/ a vast infrastructure
- Mine Product: Molybdenum (Moly) ore
- Mining Method: Panel Caving (Block Caving)
- Mining Capacity: ~40,000 - 50,000 ton/day
  - Actual operation: ~20,000 - 30,000 ton/day
    ⇒ under-utilized infrastructure
- Expected Mine Life: another ~20 years

Figure 1. Underground laboratories currently in use for physics.
Biggest Moly Mine and largest Underground Lab: together?

- Existing tailing site and all necessary environmental permits
- Henderson 2000 modernization project: ~$150M

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Go deep under a mountain
The mass of the universe

• Since the inflationary period the universe is expanding uniformly and is cooling.
• If the mass in the universe is large enough, eventually the thermal explosion force will be overcome by the gravitational forces between all the mass, and the universe will begin to contract back. This universe is “closed”.
• If the mass is too small, the universe may expand forever: This universe is open.
• The critical parameter is called $\Omega$
  - $\Omega < 1$ closed Universe; $\Omega = 1$ critical; $\Omega > 1$ open Universe
• Amazingly, $\Omega \sim 1$. Just at the borderline
• Cosmic Microwave Background Experiment shows that energy is distributed quite uniformly.
The mass of the universe

The Mass Composition of the Universe

- Unknown neutrino mass
- Neutrinos 0.5%
- Luminous Stars/Galaxies 0.5%
- Remaining all Baryonic Matter 3.0%
- Dark Matter 26.0%
- Unknown nature of matter
- Dark Energy 70.0%

Completely unknown origin

Our current best estimates!

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Dark Matter

- Dark Matter is matter that is not “visible” to experiment in any part of the electromagnetic range, either infrared, optical X-ray or gamma-ray
The matter is not so uniformly distributed
Twelfths Homework, due May 5, 2005

• Why does an electron-positron collider have more useful energy for the production of new particles than a proton-proton collider of the same energy.

1. How far does a muon neutrino flying with the speed of light generally have to travel for it to change into an electron neutrino?

2. What high-energy physics reaction is used to produce muon neutrinos?

3. Why is it not practical to accelerate electron in a circular accelerator at high energies?

4. List one scientific goal of the International Linear Collider?

5. Which ones of the four fundamental forces converge with equal interaction strength at $10^{16}$ GeV? At what energy do all four forces converge (hint: remember first lecture!).