E = mc^2
Opening Windows on the World

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What is the world made of?
What holds the world together?
Where did we come from?

the smallest things in the world
interactions (forces) between them
the Universe’s past, present, and future

Particle Physics: physics where small and big things meet, inner and outer space meet
Accelerators are powerful tools for Particle Physics!

Tevatron, Fermilab, Chicago, USA
2 TeV proton-antiproton collider
Operating since 1985

KEKb, KEK, Tsukuba, Japan
10 GeV e⁻e⁺ collider
Operating since 1999

Neutrino beams

LHC, CERN, Geneva, Switzerland
7→14 TeV proton-proton collider
Expect to start operations late 2009
Accelerators are **Powerful Microscopes.**

They make high energy particle beams that allow us to see small things.

\[ \lambda = \frac{h}{p} \]

seen by low energy beam (poorer resolution)

seen by high energy beam (better resolution)
Accelerators are also *Time Machines* because they make particles last seen in the earliest moments of the universe.
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Particle and anti-particle annihilate.

\[ E = mc^2 \]
Accelerators are also **Time Machines**

because they make particles last seen in the earliest moments of the universe.

\[ E = Mc^2 \]

- particle beam
- intensity

\[ m_v \leftrightarrow M_N \]
Many generations of Accelerators created with higher and higher energy and intensity beams

1929

~2000 Scientists
Fermilab experiments using accelerators
> 2 publications every week
~2 Ph.D.s every week

Ernest Lawrence (1901 - 1958)

Tevatron: $x_{10^4}$ bigger, $x_{10^6}$ higher energy
Intense neutrino beams
With advances in accelerators, we discovered many surprises.

The field of Particle Physics has been tremendously successful in creating and establishing "Standard Model of Particle Physics" answering "what the universe is made of" and "how it works"
Scientific Drivers

- Present theory (Standard Model) is a remarkable intellectual construction.

- Every particle experiment ever done (except neutrino expt.s) fits in the framework.

- But huge questions remain unanswered.

- New physics is required to answer:
  - e.g. Supersymmetric extension of SM, extra dimensions, ....

\( H \) (Higgs) yet to be discovered.
What is the universe made of?

~90 years ago ~60 years ago ~40 years ago Present

atom
electron

10^{-19} \text{ m} \sim 1 \text{ TeV}

1 \quad 10,000

1 \quad 10

1 \quad 100,000

of human hair

proton

down quark

neutron

up quark
down quark

Rutherford
Everything is made of electrons, up quarks and down quarks.

Are they the smallest things?
What holds the world together?
Beginnings of Unification

Gravitational Force
Issac Newton (1642 - 1727)

Electromagnetic Force
James Clerk Maxwell (1831 - 1879)
Unification of Gravity and Electromagnetism?

Einstein tried to unify electromagnetism and gravity but he failed.
Radioactive decays

Enrico Fermi (1901 - 1954)

Radioactive decay: $n \to p + e^- + \bar{\nu}_e$

Uuud

Strong Force

Weak Force

1 fm = $10^{-15}$ m

Holding proton, nucleus

Gluons
Dream of Unification continues!

We believe that there is an underlying simplicity behind vast phenomena in nature.

*Do all the forces become one?*
At high energy, do forces start to behave the same as if there is just one force, not several forces?

*Extra hidden dimensions in space?*
Particle Physics & Cosmology Questions from Astrophysical Observations
Everything is made of electrons, up quarks and down quarks.

Everything that we can see

Galaxies are held together by mass far bigger (x5) than all stars combined.

Dark Matter - What is it?
Where did we come from?

How did we get here?
Where are we going?

Understanding our Universe!
Create particles & antiparticles that existed ~0.001 ns after Big Bang:
- Tevatron
- LHC

Where did all antimatter go?
Not only is the Universe expanding, it is Accelerating!!

Where does energy come from? Dark Energy
What is the world made of?
What holds the world together?
Where did we come from?
1. What is the origin of mass for fundamental particles?
2. Why are there so many kinds of particles?
3. Do all the forces become one?
4. Are there extra dimensions of space?
5. What are neutrinos telling us?
6. What happened to the antimatter?
7. What is dark matter?
8. How can we solve the mystery of dark energy?
9. How did the universe come to be?
10. Are there undiscovered principles of nature: new symmetries, new physical laws?
E = m_X c^2
A herd of American bison, symbolizing Fermilab’s presence on the frontiers of particle physics and the connection to its prairie origins.

6,800-acre park-like site
2008 Nobel Prize in Physics

Nambu (Univ. of Chicago)
Kobayashi (KEK) – Maskawa (Kyoto Univ.)

for “Mechanism of Symmetry Breaking”
The Energy Frontier: “Tevatron”
The Intensity Frontier: Neutrino Beams
Origin of Mass:
There might be something (new particle?!) in the universe that gives mass to particles.

Nothing in the universe

Something in the universe

Higgs Particles:

Electron → mass

Z, W Boson →

Top Quark →

Mass

∞

coupling strength to Higgs
Tevatron: Improve Higgs Mass Pred. via Quantum Corrections

1 GeV = 1 GeV / c² ~ proton mass

MW and Mtop measurements favor light Higgs < ~180 GeV
LEP2 direct searches – excluded Higgs < 114 GeV at 95% CL
Favored Higgs mass range (114 – 180 GeV) is great for the Tevatron!
Physics at the Tevatron

Observed so far

- Total Inelastic jets (qq, qg, gg)
- bb
- W
- Z
- tt

WZ, Single Top, ZZ

WH, ZF, Higgs

Light SUSY, ....

Higgs Mass [GeV/c^2]

100 120 140 160 180 200
Tevatron: Improve Higgs Mass Pred. via Quantum Corrections
LHC: Designed to discover Higgs with $M_{\text{higgs}} = 100 \sim 800$ GeV

![Graph showing $M_{\text{top}}$ versus $M_W$](image1)

- $M_{\text{top}}$: Tevatron
- $M_W$: Tevatron + LEP2

![Graph showing $M_{\gamma\gamma}$ versus $M_{\text{higgs}}$](image2)

- 130 GeV Higgs
Tevatron: Improve Higgs Mass Pred. via Quantum Corrections

LHC: Designed to discover Higgs with $M_{\text{higgs}} = 100 \sim 800$ GeV

Tevatron: favors $< \sim 180$ GeV, excludes 160-170 GeV, continues to improve

Will Tevatron’s Higgs prediction agree with what LHC sees?
Fermilab and LHC

US CMS Host Lab; the only US CMS Lab
- CMS Tier-1 Computing Center
- LHC Physics Center
- Support US CMS Community

To make being at Fermilab as productive as being at CERN.
Requires critical mass (~100 Fermilab + University Scientists at Fermilab).
If we discover a “Higgs-like” particle, is it alone responsible for giving mass to W, Z, fermions?

Experimenters must precisely measure the properties of the Higgs particle without invoking theoretical assumptions.
Hadron Collider (Tevatron / LHC):

Lepton Collider (ILC, CLIC, Muon Collider):
LHC (pp) Results

< 1 TeV
ILC (e^+e^-) Enough

By far the easiest!

or

> 1 TeV
ILC not Enough

or

CLIC (e^+e^-)

or

Muon collider (µ^+µ^-)

Lepton colliders beyond LHC
Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

pp 2 TeV
Tevatron

μ+μ− 4 TeV

LHC
d=8.4km
pp 14 TeV

e+e− ~1 TeV

ILC
l=30km

e+e− 3 TeV

VLHC
d=74km

CLIC
l=50km
The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Dark Energy – Scalar Field
Could give a handle on dark energy(scalar field)?

If discovered, the Higgs is a very powerful probe of new physics.
1. SDSS (Sloan Digital Sky Survey)
   - 2.5 m telescope in New Mexico
   - Power spectrum of galaxies constrain dark energy density parameter
   - Ranks as the facility with the highest impact in astronomy for the 3rd year in a row.

2. DES (Dark Energy Survey)
   - 4 m telescope in Chile (Construction)

3. JDEM (Joint Dark Energy Mission)
   - Space telescope (Proposed)
   - Fermilab’s goal: run Science Ops. Center.
LHC discovers strongly coupled SUSY

Interplay: Energy Frontier ↔ Intensity Frontier

A host of new particles: fit roughly some masses, make assumption on couplings
The Intensity Frontier can probe new physics at a scale >> TeV.

Muon to electron conversion: $\mu N \rightarrow eN$

Neutrinos change from one kind to another. Do charged leptons do, too?
Mu2e Experiment: $\mu$ to e Conversion ($\mu N \rightarrow e N$)
Large effects in kaon decay rates

SM: $K_L \rightarrow \pi^0 \nu \bar{\nu}$

New Physics: $K_L \rightarrow \pi^0 \nu \bar{\nu}$
We want to believe that there was just one force after the Big Bang.

As the universe cooled down, the single force split into the four that we know today.
Electromagnetic Force
Weak Nuclear Force
Strong Nuclear Force
Gravitation

HERA:
Stronger force

Higher energy [GeV], Shorter distance
The Standard Model fails to unify the strong and electroweak forces.
But details count! Precision measurements are crucial.
The enigmatic neutrinos are among the most abundant of the tiny particles that make up our universe. To understand the universe, must understand neutrinos.

Behavior is so different from other particles.

Opening a “new” window:
Unification, Matter-Antimatter Asymmetry

\[ m_{\nu} M = (m_{\text{quark}})^2 \]
matter – antimatter asymmetry in neutrinos
Proton decay
Supernovae neutrinos
Project X (Proposed)
National Project with International Collaboration

• Fantastic machine at intensity frontier for $\nu$, $\mu$, kaon beams
• Would develop technologies to position US to host a global facility at the energy frontier (ILC and muon collider)
Unifying gravity to the other 3 forces

→ **extra hidden dimensions in space** beyond the 3 we sense daily.

Too small to observe?

Some models predict large extra dimensions:
large enough to observe up to multi TeV scale.

LHC may discover extra dimensions.
A lepton collider can identify size, shape, # of extra dimensions.
Dark Matter

Underground experiments may detect Dark Matter candidates.

WIMP (~200 km/s, ~100 GeV)

~10 keV nuclear recoil

Cosmic Frontier
Dark Matter Searches – **Underground Detectors**

**Homestake**
- 0.5~1 ton
- Technology: CDMS, COUPP, LAr TPC

**Soudan**
- 735 km
- 1300 km

**CDMS**
- Low temp. Ge / Si crystals

**COUPP**
- Room temp. CF$_3$I Bubble Chamber

**World’s Best Limits**
- 2 kg / 1 liter
- 4 kg
Dark Matter

Underground experiments may detect Dark Matter candidates.

WIMP (~200 km/s, ~100 GeV)

~10 keV nuclear recoil

Cosmic Frontier

Energy Frontier

Intensity Frontier

Accelerators can produce dark matter in the laboratory and understand exactly what it is.
Particles Tell Stories!

The discovery of a new particle is often the opening chapter revealing unexpected features of our universe.

Particles are messengers telling a profound story about nature and laws of nature in microscopic world.

The role of physicists is to find the particles and to listen to their stories.
Discovering a new particle is Exciting!

Top quark event recorded early 90’s

We have been listening to the story that top quarks are telling us:
The top mass told us about the Higgs mass.
Story is consistent with our understanding of the standard model.
We keep searching for a story we have not heard before.
Discovering “laws of nature” is even more Exciting!!

Hope in the next ~5 years we will discover Higgs and listen very carefully to Higgs.
What are neutrinos telling us?
What are muons telling us?
What are kaons telling us?
This will open windows for discovering new laws of nature.

This saga continues….
There might be supersymmetric partners, dark matter, another force carrier, large extra dimensions, …… for other new laws of nature.

Whatever is out there, this is our best opportunity to find it’s story!
The Tevatron Predicts Higgs Mass via Quantum Corrections

Favors Higgs mass range (114 – 180 GeV) at 95% CL. In this range, Tevatron has good potential.
Higgs at LHC and Tevatron

Low Mass Higgs
(LHC: $H \rightarrow \gamma\gamma, \tau\tau$) vs. (Tevatron: $H \rightarrow bb$)

160 – 170 GeV
Excluded by Tevatron (3-4 fb$^{-1}$)

LHC 130 GeV Higgs

$M_{Higgs}$ [GeV] vs. $M_{\gamma\gamma}$ [GeV]
ILC can observe Higgs no matter how it decays!

\[ e^+ e^- \rightarrow Z + \text{Higgs} \]

\[ \downarrow \quad \downarrow \]

2 b’s invisible

Unique ability for model-independent tests of Higgs couplings to other particles
Tevatron Sensitivity on Standard Model Higgs

Sensitivity Projection: Region Favored by $M_{\text{top}}^{\text{Tevatron}}, M_{W}^{\text{Tevatron+LEP}}, \ldots$

Excluded by $M_{top}^{\text{Tevatron}}, M_{W}^{\text{Tevatron+LEP}}, \ldots$

Excluded by LEP

Higgs Mass (GeV/c^2)

Year 2009

Year 2011

95% CL

90% CL

$H \rightarrow b \bar{b}$

Excluded by Tevatron (3-4 fb$^{-1}$)

$H \rightarrow W^+W^-$

Update the results with 5 fb$^{-1}$ data soon
Interplay: LHC ↔ Intensity Frontier

- nothing
- LHC
- Lots

Only handle on the next energy scale

Intensity Frontier

Determine/verify structure of new physics. Anything beyond?