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
Many generations of Accelerators created with higher and higher energy and intensity beams.

Ernest Lawrence (1901 - 1958)

Tevatron: $\times 10^4$ bigger, $\times 10^6$ higher energy
Intense neutrino beams

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

~2000 Scientists

"Fermilab: Present and Future", Young-Kee Kim, ANL Colloquium, Jan. 6, 2010
top quark

Gluons

(proton mass = \( \bullet = \sim 1\text{GeV/c}^2 \))
• Present theory (Standard Model) is a remarkable intellectual construction

• Particle experiments ever done fits in the framework

• But huge questions remain unanswered.

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

Higgs yet to be discovered
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?
History of the Universe

Create particles/antiparticles that existed \(~0.001\) ns after Big Bang.
- Direct: Tevatron, LHC, ....
- Indirect: \(\nu\)'s, Rare Processes, ...

Unification, New Symmetry
Towards simple, elegant, complete theory

E = mc\(^2\)

How did the universe come to be?
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.
HERA

Electromagnetic Force
Weak Nuclear Force
Strong Nuclear Force
Gravitation

Electroweak Unification
Grand Unification
Planck Scale
Big Bang

Higher energy [GeV], Shorter distance
Stronger force

9 "Fermilab: Present and Future", Young-Kee Kim, ANL Colloquium, Jan. 6, 2010
The Standard Model fails to unify the strong and electroweak forces.
But details count!
Precision measurements are crucial.
Early discovery at LHC

LHC could discover strongly coupled SUSY

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?
Intensity: Large effects in kaon decay rates

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

New Physics: $K_L \rightarrow \pi^0 \bar{\nu} \nu$
Nothing

LHC

Lots

Only handle on the next energy scale

Intensity Frontier

Determine/verify structure of new physics. Anything beyond?
Intensity Frontier: Neutrinos

- Recent Discoveries
  - produced much excitement.
  - the only new physics seen so far in the lab.

- Behave so different from other particles
  - Mass, Oscillation pattern, $\nu = \bar{\nu}$ possibility

- A Matter-Dominate Universe
  - Require Matter-Antimatter Asymmetry (CP Violation)
  - Quarks can not explain. Maybe the leptons can.

- Unification
  - $\nu$ mass, mixing point toward new symmetries (unification)

- Cosmic Connection
  - $\sim 10^9$ neutrinos / nucleon or electron in the Universe.
  - Neutrino mass affects large scale structure.
The neutrino spectrum: unknowns

\[ \text{(Mass)}^2 \]

\[ \Delta m^2 \]

\[ \theta_{13} \]

Normal

\[ \Delta m^2 \]

\[ \text{Inverted} \]

\[ \Delta m^2 \]

\[ \theta_{13} \]

Mass Hierarchy
Matter – Antimatter Asymmetry Phase $\delta$

$v = \bar{v}$ ?
Particle Physics at the Three Frontiers

Endorsed by the US Particle Physics Community
Particle Physics

- Global enterprise
- Many laboratories have changed missions. A few principle particle physics laboratories in the world
- Important and healthy to maintain expertise, long term stability, and support in all three regions, and to engage the worldwide community
- More coordination and collaboration
US Particle Physics Today

• National Laboratories
  - Fermilab
    - Single mission – particle physics
  - Other laboratories: ANL, BNL, LANL, LBNL, SNAL, …
    - Multi missions including particle physics
    - Particle physics is not the primary mission

• Universities

• We need to maintain expertise and uniqueness in laboratories and universities
Fermilab Programs at Three Frontiers (Now)

Hadron Colliders:
- Tevatron
- LHC

Neutrinos

http://www.fnal.gov/pub/science/frontiers/

Dark Matter,
Dark Energy,
UHE Particles from Space
Fermilab Programs at Three Frontiers (Future)

Hadron Colliders:
- LHC
- Project X:
  - Neutrinos
  - Rare Processes
  - Precision Meas.s
  - Nuclear Physics

Lepton Colliders:
- Sub-TeV: ILC
- Multi-TeV: $\mu$ Collider (CLIC)

Dark Matter,
Dark Energy,
UHE Particles from Space

http://www.fnal.gov/pub/science/frontiers/
Cosmic Frontier: Dark Matter

Underground experiments may detect Dark Matter candidates.

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

~10 keV nuclear recoil

Cosmic Frontier

Accelerators can produce dark matter in the laboratory and understand exactly what it is.
Dark Matter Searches – Underground Detectors

NSF’s proposed Underground Lab. DUSEL

~1 ton
Technology:
CDMS
COUPP
LAr TPC

MINOS
735 km
MiniBooNE
SciBooNE
MicroBooNE
MINERvA

COUPP
60 kg / 30 liter

CDMS
Low temp. Ge / Si crystals

4 kg → 15 kg → 100 kg

World’s Best Limits
CDMS (4 kg) Results

Calibration

Ionization yield = \( E_{\text{charge}} / E_{\text{phonon}} \)

Data

0.8 ± 0.2 background expected
90% CL Limit: Present and Future

- CDMS II Current (2 years)
- 15kg @ Soudan (2 years)
- 100kg @ SNOLAB (2 years)
- 1.5T @ DUSEL (3 years)
1. **SDSS (Sloan Digital Sky Survey)**
   - 2.5 meter telescope in New Mexico
   - Ranks as the facility with the highest impact in astronomy for the 3rd year in a row.
   - Power spectrum of galaxies constrain dark energy density parameter.

2. **DES (Dark Energy Survey)**
   - 4 meter telescope in Chile
   - DES Camera under construction

3. **JDEM (Joint Dark Energy Mission)**
   - Space telescope
   - Fermilab Goal: Science Operation Center
Auger Observatory studies ultra-high energy cosmic rays.

- Cosmic rays with $E > 57,000,000$ TeV
- Active Galactic Nuclei
Energy and Intensity Frontiers

Energy-Intensity Integrated Program

Today: operates Tevatron & highest power $\nu$ beams

Future: continue to have the integrated plan
Progress: the Tevatron

Total Integrated Luminosity
7.5 fb⁻¹


~100 publications / year, ~60 Ph.D.s / year
Plan to run through FY2011: 7.5 fb⁻¹ (now) → 12 fb⁻¹
### Physics at the Tevatron

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Total Inelastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>mb</td>
<td>jets (qq, qg, gg)</td>
</tr>
<tr>
<td>µb</td>
<td>b̅b</td>
</tr>
<tr>
<td>nb</td>
<td>W</td>
</tr>
<tr>
<td>pb</td>
<td>Z</td>
</tr>
<tr>
<td>fb</td>
<td>tt</td>
</tr>
<tr>
<td></td>
<td>WH, ZH</td>
</tr>
<tr>
<td></td>
<td>Higgs</td>
</tr>
<tr>
<td></td>
<td>Light SUSY, ....</td>
</tr>
</tbody>
</table>

- **Higgs Mass [GeV/c^2]**
  - 100
  - 120
  - 140
  - 160
  - 180
  - 200

**Observed so far**

- Bs mixing, φP, ....
- WZ
- Single Top
- ZZ

**Cross Section**

- mb
- µb
- nb
- pb
- fb

**Higgs Mass [GeV/c^2]**
The Tevatron Predicts Higgs Mass via Quantum Corrections

\[ m_H = 87^{+35}_{-26} \text{ GeV} \quad (m_{\text{top}} = 173.1 \pm 1.3 \text{ GeV}) \]

Favors “light” Higgs in the range where Tevatron has good potential.
Observations: rare SM processes

Diboson production: more luminosity allows access to smaller cross sections
The Higgs Search

• The SM Higgs (if it exists) is being produced NOW at the Tevatron! We have enough energy
  • Just not that often & it’s buried in “backgrounds”
  • It’s a story of luminosity, passion, persistence and luck
  • We know how to look for it and we are in fact closing in!

• Over the last years, there’s been a dramatic infusion of people, effort and ideas, aimed at finding the Higgs
Tevatron Run II Preliminary, $L=2.0-5.4\, fb^{-1}$

95% CL Limit/SM

- LEP Exclusion
- Tevatron Exclusion

Expected
- $\pm 1\sigma$ Expected
- $\pm 2\sigma$ Expected

$10$

$1$

$100\ 110\ 120\ 130\ 140\ 150\ 160\ 170\ 180\ 190\ 200$

$m_H (GeV/c^2)$

SM=1

November 6, 2009
Fermilab and LHC:
Accelerator and Detector Design/Engineering/Construction and Upgrades

LHC IR quadrupoles

LHC upgrade
3.4m Nb3Sn prototype

CMS Detectors
Calorimeter
Muon Chamber
Silicon Tracker

CMS Pixel Detector

Fermilab: US CMS Host Lab; the only US CMS Lab
Remote Operation Center (ROC):
Detector Commissioning and Monitoring
Accelerator Monitoring
CERN Night = FNAL Day

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 good as being at CERN.
Requires critical mass (~100 Fermilab + University Scientists at Fermilab).
Supporting the LHC Community

CERN-Fermilab Hadron Collider Physics Summer School

<table>
<thead>
<tr>
<th>1st</th>
<th>Fermilab</th>
<th>August 9-18, 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>CERN</td>
<td>June 6-15, 2007</td>
</tr>
<tr>
<td>3rd</td>
<td>Fermilab</td>
<td>August 12-22, 2008</td>
</tr>
<tr>
<td>4th</td>
<td>CERN</td>
<td>June 8-17, 2009</td>
</tr>
<tr>
<td>5th</td>
<td>Fermilab</td>
<td>Summer 2010</td>
</tr>
</tbody>
</table>

3rd School at Fermilab

Graduate Students and Postdocs from around the world
International Neutrino Summer School

Merging various neutrino schools into one coherent school
Rotating in three regions

<table>
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<tr>
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<th>July 6-18, 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>KEK</td>
<td>2010</td>
</tr>
<tr>
<td>3rd</td>
<td>Europe</td>
<td>2011</td>
</tr>
</tbody>
</table>

1st School at Fermilab

Graduate Students and Postdocs from around the world
The Intensity Frontier: Neutrinos

260 kW 120 GeV MI protons
& 8 kW 8 GeV Booster protons
run simultaneously with the Tevatron

8 GeV Booster

120 GeV Main Injector

Neutrino beam from 8 GeV Booster

MiniBooNE: Excludes “4th gen.” ν
Low Eng Excess in ν, Now running anti-ν

SciBooNE: ν – Matter Interactions

MicroBooNE: 170 ton LAr TPC
Neutrino beam from 120 GeV MI

Global fit:
\( \theta_{13} = 0 \) disfavored by ~2\( \sigma \)
Central value \( \sin^2 2\theta_{13} = 0.08 \)

Best \( \Delta m^2_{23} \)
\( \theta_{13} ? \)

MINERvA: Ops. w/ Partial Det. (2009)
\( \nu \) – Matter Interactions
NOvA: Data Taking in FY12-13

- $\theta_{13}$
- Mass Ordering:
  - the only near term project in the world sensitive to mass ordering
- improved precision: 2-3
- ...

MINERvA: Ops. w/ Full Det.(2010)

$\nu$ – Matter Interactions
Muon to e Conversion ($\mu N \rightarrow eN$)

Muon $g-2$, $K^+ \rightarrow \pi^+ \nu\nu$ (1000 events) under consideration
Project X: intense proton accelerator

http://www.fnal.gov/pub/pub/projectx/

- The intensity frontier answers fundamental questions
- Project X is the key
- Project X can lead us back to the energy frontier
Evolution of Project X: 3 Simultaneous Beams

- 3 GeV protons, 2 MW CW (continuous pulses at 325 MHz)
  - Rare processes + precision measurements
  - Flexible time patterns + pulse intensities
- 8 GeV protons, 20 – 200 kW: rare processes + precision measurements
- 60 – 120 GeV protons, 2 MW (to Homestake) for neutrinos

Diagram:
- 3 GeV, 0.7 mA CW Linac (SCRF)
- 3 → 8 GeV RCS or Linac
- Recycler/Main Injector 120 GeV
  - Neutrinos (2 MW)
  - Nuclear (0.5 MW)
  - Kaons (0.5 MW)
  - Muons (0.5 MW)
  - (1.0 MW)
Fermilab: Present and Future, Young-Kee Kim, ANL Colloquium, Jan. 6, 2010

NSF’s proposed Underground Lab. DUSEL

Iron mine at Soudan

MINOS (Far Det.)

Project X: ~2 MW

Combination of WC and LAr

~100 kton Liquid Ar TPC (event from ArgoNeuT)

~300 kton Water Cerenkov (Super K)

MINOS (Far Det.)

SciBooNE

MiniBooNE

MINERvA

MicroBooNE

NOvA

MiniBooNE

SciBooNE

MINOS

NOvA

MINERvA

MicroBooNE

Matter – Antimatter Asymmetry with Neutrinos

Proton Decay

Supernovae Neutrinos
The Intensity Frontier: Fermilab → DUSEL Option

Existing + Potential Underground Labs

excluding the big cavern

4850 Level Conceptual Layout

"Fermilab: Present and Future", Young-Kee Kim, ANL Colloquium, Jan. 6, 2010
Mu2e can probe $\sim 10^4$ TeV
A path back to the energy frontier?

Lepton colliders beyond LHC

- **ILC Enough**
  - $E < 1$ TeV
  - By far the easiest!

- **ILC not enough**
  - $E > 1$ TeV
  - **or**

- **CLIC**
- **or**

- **Muon collider**
International Linear Collider (ILC)
Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

Muon Cooling
Reduce the transverse motion of the muons and create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Located 100 meters underground. Muons live long enough to make about 1000 turns.

4 TeV
ILC/Project X technology
Project X upgrade

http://www.fnal.gov/pub/muonCollider/
Muon collider functional layout

Color indicates degree of needed R&D (difficulty) and demonstration
System Test Facility with beams

ILC / Project X / Muon Collider technology at Fermilab
Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.
Evolution of $\nu$ Program: Neutrino Factory

- Muon Colliders & Neutrino Factories require similar, & potentially identical, muon sources:

(a) Neutrino Factory

(b) Muon Collider
Project X

- Would be a fantastic machine at the intensity frontier for neutrino physics, kaon physics, muon physics, and nuclear physics

- Would develop and exercise the technologies to position the US to host a global facility at the energy frontier (or contribute to one elsewhere)
  - ILC and muon collider
US Strategy

Energy Frontier

Intensity Frontier

Tevatron → Project X → (LHC)

protons

technology injector

ILC / µ Collider

Detector Synergy:

- NuMI
  - (260kW)
  - Booster
    - MINOS
    - SciBooNE
    - ArgoNeuT
- NuMI
  - (700kW)
- 2 MW (120GeV) for ν
  + 2 MW (3 GeV) + 200 kW (8 GeV)

ν Factory

- Project X
- Kitami (K+ (K0/KL, K+) II)
- EDM (µ, Λ, Σ+)
- Nuclear Physics

Intensity Frontier

Energy Frontier

- Mu2e
- Mu2e II
- µ g-2
- µ g-2 II
- K+
- (K0/KL, K+) II

ν Factory
Closing Remarks

• **Compelling Questions in Particle Physics**
  - Require three interrelated frontiers
    - The Energy Frontier
    - The Intensity Frontier
    - The Cosmic Frontier

• **Fermilab: Current and Future**
  - A balanced program at 3 interrelated frontiers
  - Project X (intense proton source)
    - Intensity Frontier Facility (broad physics program)
    - A path back to the Energy Frontier
      - ILC technology
      - Front end of a muon collider (and/or $\nu$ factory),
        Acceleration technology for a muon collider
and some luck

Higgs reach with continued analysis improvement

running through FY09 (red) FY11 (blue)
Evolution of Project X: 3 Simultaneous Beams

- 2 MW CW (continuous pulses at 325 MHz) 2-3 GeV protons
  rare processes and precision measurements
  flexible time patterns and pulse intensities
- 20 – 200 kW 8 GeV protons
  rare processes and precision measurements
- 2 MW 60 – 120 GeV protons (to Homestake) for neutrinos
Flexible bunch format

- Variable H⁻ ion source provides current 1 to 10 mA DC
- Variable bunch formats:
  1. Ion source at 1 mA, no beam chopping: $1.9 \times 10^7$ protons per bunch at 325 MHz rate
  2. Ion source at 10 mA, 90% beam chopping: $1.9 \times 10^8$ protons per bunch at 32.5 MHz rate (1 mA ave current)
  3. Bunch-by-bunch chopping example (ion source at 4.7 mA), chopping and rf splitting for 3 experiments

Transverse kick at rf splitter
(81 MHz, similar to crab cavity)
Other applications

• Nuclear Physics
  - Can drive an ISOL target for Nuclear Physics applications. Totally complementary program for nuclear EDMs and fundamental experiments on atomic traps just with ISOL target

• Muon Spin Rotation
  - Currently done in Rikken, PSI and TRIUMF
  - Would produce the most intense muon beams available, including, polarization and monochromatization
Muon experiments

- Next generation $\mu \rightarrow e$ conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- $\mu \rightarrow 3e$
- Next generation (g-2) if motivated by theory, next round, LHC
- Other:
  - $\mu$ edm.
  - $\mu^+e^- \rightarrow \mu^-e^+$
  - $\mu^-A \rightarrow \mu^+A'$
- Systematic study of radiative $\mu$ capture on nuclei.
Evolution of $\nu$ Program: Neutrino Factory

- If $\sin^2 2\theta_{13}$ is small
  - Choose a NF energy of 25 GeV & a very long baseline (e.g. ~3000km) – up to ~ x100 improvement in sensitivity compared to a superbeam

- If $\theta_{13}$ is large (> .005)
  - A 4 GeV NF aimed at Homestake gives clean reach into CP violation, mass hierarchy and any unusual features
Multi-TeV Lepton Colliders

- **Muon Collider Approach: Fermilab’s Focus**
  - Based on a secondary beam: we have experience basing colliders on antiprotons. For μ’s we must do it in 20 msec.
  - Advantages: narrow energy spread (no beamstrahlung) and small physical footprint (no synchrotron radiation)
  - No new methods of acceleration, but new method of deceleration!: muon cooling

- **CLIC Approach: CERN’s Focus**
  - Advantages: stable particles, polarization
  - Two-beam accelerator scheme

- **Physics/detector**
  - ILC-CLIC-Muon Collider Synergy
The $3\sigma$ reach (2 MW, 100 kton LAr TPC)

<table>
<thead>
<tr>
<th>$\sin^22\theta_{13}$</th>
<th>Mass Hierarchy</th>
<th>CP Violation</th>
</tr>
</thead>
</table>

NOvA

Project X $\rightarrow$ DUSEL

"Fermilab: Present and Future", Young-Kee Kim, ANL Colloquium, Jan. 6, 2010