Particle Physics and Fermilab

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21st Century Questions in Particle Physics

- Origin of mass for elementary particles?
- Where did all antimatter go?
- What do neutrinos tell us?
- Do charged leptons oscillate?
- Why three families of quarks and leptons?
- Do all forces become one?
- Extra dimensions?
- Will protons ever decay?
- Supersymmetry or other new symmetries?
- What is dark matter?
- What is dark energy?
How do we make progress?

Go to:

Highest energies
Shortest distances
Earliest moments of the Universe

Reveal laws of nature: ~complete and ~elegant

Answer the questions and understand our origin
Tools for the Future

The Energy Frontier
- Origin of Mass

The Intensity Frontier
- Matter/Antimatter Asymmetry
- Neutrino Physics
- Proton Decay

The Cosmic Frontier
- Dark Matter
- Origin of Universe
- Unification of Forces
- New Physics Beyond the Standard Model
- Cosmic Particles
- Dark Energy
$E = Mc^2$

Energy Frontier

Particle $E$

Anti-particle
Discover the nature of massive known & **NEW** particles indirectly by intense beams of charged leptons and quarks.

**Quantum Fluctuation**

- **Top**
- **W, Z**
- **NEW**

![Uncertainty Principle](image)

\[ E = M c^2 \approx 10^4 \text{ TeV} \]
Intensity Frontier

Probe even more massive NEW particles by intense neutrino beams

\[ E = Mc^2 \approx 10^{12} \text{ TeV} \]

\[ m_\nu \times m_N \sim (m_{\text{quark}})^2 \]
Experimental reach (model dependent)

Intensity Frontier
- Proton Decays
- Neutrinos
- Charged Leptons
- Quarks

Energy Frontier
- LHC
- Tevatron

Indirectly
Directly
Connection

Time since the Big Bang
$10^{-11} \text{ s} = 0.01 \text{ ns}$

more complete
more elegant theory
Cosmic Frontier at Fermilab

Dark Matter Detector

Detector

CDMS

DarkSide

COUPP

Detectors in underground facilities

Dark Energy Camera

570-Megapixel digital camera

Fermilab

Chile

DES
Cosmic Frontier at Fermilab

Exploring Highest Cosmic Ray Particles (Auger)

Exploring Quantum Space-time (Fermilab Holometer)
Energy Frontier at Fermilab

Fermilab

CERN

LHC

pp: 7 TeV \rightarrow 14 TeV

Tevatron

pp: 2 TeV

Remote Control Room at Fermilab

LHC

pp: 7 TeV \rightarrow 14 TeV

Lepton Collider (ILC, Muon Collider)

Hadron Collider

(energy decision)
Excluded by direct searches at 95%CL

Results still coming out from Tevatron

Higgs \rightarrow 2\text{ photos at LHC}
Higgs \rightarrow 2\text{ bottom quarks at Tevatron}
Stay tuned this year!
Intensity Frontier at Fermilab

SCRF Test Facility

Muon Test Facility

Neutron cancer center

Main Injector

Recycler

neutrino beams

muon beams

testbeam

proton beam
Neutrinos: known unknowns

\[ v = \bar{v} \] ?

Matter – Antimatter Asymmetry

unknown unknowns
Exploring unknown unknowns in neutrino oscillation

Machado, Nunokawa, Funchal

Extra Dimension

$E_\nu$ (GeV)
Intensity Frontier at Fermilab: Neutrinos

MINERvA
MiniBooNE
MINOS (far)
MINOS (near)
Operating since 2005 (350 kW)

NOvA (far)
under construction
Online 2013 (700 kW)

LBNE under development
700 kW $\rightarrow$ 2.3 MW (Project X)
1300 km

Operating since 2005 (350 kW)

MINOS (near)
MINERvA
NOvA
Near detector

Proton decay
Supernovae neutrinos

Goal: operating in 2020s
Intensity Frontier at Fermilab
(muon program: this decade)
Intensity Frontier at Fermilab: Muon Campus (this decade)
Anomalous magnetic moment

\[ a_\mu = (g-2)/2 \sim 0.001 \]

uncertainty \( \sim 10^{-10} \)

Intensity Frontier at Fermilab: muon g-2
Intensity Frontier at Fermilab: $\mu \rightarrow e$ conversion

- Negligible rate in the SM: $< 10^{-54}$

- Measurable rate with new physics contributions: $\sim 10^{-15}$

[Diagrams of Loops and Contact Terms showing processes like Supersymmetry, Heavy Neutrinos, Two Higgs Doublets, Compositeness, Leptoquarks, and New Heavy Bosons / Anomalous Couplings]
Intensity Frontier at Fermilab: $\mu \rightarrow e$ conversion

Conversion of a muon into an electron in the field of a nucleus:

$\mu \rightarrow e$

Mu2e experimental rate sensitivity: $10^{-16} - 10^{-17}$

Mu2e has discovery sensitivity to many new physics models
Intensity Frontier at Fermilab
Kaon beam (if an opportunity arises)

$K^+ \rightarrow \pi^+ \nu \nu$ rate in SM $\sim 10^{-10}$
will be the world’s most powerful (> 5 MW) and flexible (162 MHz) proton source

will make the world’s most powerful beams of neutrinos, muons, kaons and nuclei to explore new physics in unprecedented breadth and depth

will establish a versatile technical foundation for future accelerators
Project X: Low-energy Program

Highest-intensity proton accelerator in the world

Proposed Experimental Areas
Muon Conversion Experiment

1. Proton beam
2. Capture solenoid
3. Transfer solenoid
4. FFAG ring
5. Detector solenoid
K^+ \rightarrow \pi^+\nu\bar{\nu} Experiment

1. Beam
2. Cerenkov counter
3. Magnet
4. Gamma veto
5. Target
6. Drift chamber
7. Beam veto
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ Experiment

1. $K_L$ beam
2. Photon veto
3. Photon calorimeter
4. Beam photon veto
Electric Dipole Moment Search

1. $^{225}$Ra oven
2. Zeeman slower
3. Magneto-optical trap
4. Optical dipole trap
5. EDM probe
Nuclear Energy Station Concept

Proton Beam

Isotope production – $^{239}$Pu, $^{60}$Co

Stations
- Materials - temperature control
- ADS - lead or lead-bismuth loop
- HTGR - graphite, He loop
- SFR - sodium fast reactor loop
- LWR - Zr, water loop
- MSR - molten salt loop
- Fusion - lithium loop
- Other - Cold neutron - liquid He

Spallation Target
Project X: High-energy Program

More beam for high-intensity neutrino experiments

Neutrinos to LBNE

Transfer into Main Injector & Recycler

8 GeV Pulsed Proton Beam
The Project X and the big questions

Origin of mass for elementary particles?

Why is matter dominant?

Why is matter dominant?

What do neutrinos tell us?

Do charged leptons oscillate?

Why three families of quarks and leptons?

Do the forces unify?

Will protons every decay?

Supersymmetry or other new symmetries?

Extra dimensions?

What is dark matter?

What is dark energy?
Muon Beamline & Neutrino Factory

Highest-intensity muon and neutrino source in the world
Muon Collider
The first collider of this kind
Project X and Lepton Collider Development Facilities at Fermilab
Accelerator System Test / Research Facility
Illinois Accelerator Research Center

Construction of IARC (2011 – 2013)
Groundbreaking on Dec. 16, 2011

CDF Assembly / Collision Hall

New building

Accelerator: science, technology, education, partnerships with industry
Project X and Accelerator Driven Subcritical Reactor
Nuclear waste transmutation / Energy sources

10MW Accelerator
20 MW electrical

1550 MW Thermal Power

600 MW Electrical Power

Energy extraction with efficiency $\eta \ (\sim 40\%)$
Fermilab Program

- **NuMI (120 GeV):** 350 kW
  - Booster (8 GeV): 35 kW
- **NuMI (120 GeV):** 700 kW
  - Booster (8 GeV): 80 kW
- **Project X:**
  - >2MW @ 120 GeV
  - 3MW @ 3 GeV
  - 150 kW @ 8 GeV
- **Neutrino Factory**
- **LHC Tevatron**
- **LHC Upgrades in luminosity and energy**
- **Lepton Colliders**
- **Dark Matter, Dark Energy, Ultra High Energy Cosmic Particles**

**Accelerator/Detector/Computing Technology Development**
Vision of Fermilab

- Fermilab is going after the most exciting questions in particle physics, questions about the nature and future of our universe.

- Fermilab continues to operate most of its existing accelerators with enhanced capabilities and next generation experiments (2010s)

- Fermilab will build new accelerators and experiments for the future (2020s and beyond)