Physics with High Intensity Proton Sources

Young-Kee Kim
Fermilab PAC Meeting
June 17-21, 2008
Engaging the Community in planning / developing programs,
Supporting the Community

Steering Group Process

Intensity Frontier Workshops:
Accelerator Workshop (25 institutions, 4 nations)
3 Physics Workshops w/ Fermilab UEC (80 institutions, 8 nations)
Future physics workshops – twice a year (Jan. and Jun.)

P5 Process
Tools for Particle Physics at Fermilab

- Tevatron (CDF, DZero)
- LHC (Accelerator, CMS)
- ILC R&D
- \( \mu \) Collider R&D

Energy Frontier

- SDSS,
- Pierre Auger,
- CDMS, COUPP,
- DES, SNAP R&D

Non-accelerator based

Intensity Frontier

- Main Injector Protons
  - MINOS
- NOvA
- MINERvA

Project X for Physics of Flavor

- Booster Protons
  - MiniBooNE
- SciBooNE
AIP’s Ten Top Physics Stories for 2007

• Three out of ten were from HEP:

  – The Energy Frontier: The Tevatron, in its quest to observe the Higgs boson, updated the top quark mass and observed several new types of collision events, such as those in which only a single top quark is made, and those in which a W and Z boson or two Z bosons are made simultaneously.

  – The Intensity Frontier: The MiniBooNE experiment at Fermilab solves a neutrino mystery, apparently dismissing the possibility of a fourth species of neutrino.

  – The Cosmic Frontier: Based on data recorded at the Auger Observatory, astronomers conclude that the highest energy cosmic rays come from active galactic nuclei.
P5 Roadmap for Scenario B (FY07 Level) - Fermilab

Roadmap for the Scenario with Constant level of Effort at the FY2007 Level

<table>
<thead>
<tr>
<th>Key</th>
<th>R&amp;D</th>
<th>Construction</th>
<th>Operation</th>
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<tr>
<th>1. The Energy Frontier</th>
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2.2 Precision Measurement |

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The Intensity Frontier
P5 Roadmap

Scenario B: FY07 Level

| Roadmap for the Scenario with Constant level of Effort at the FY2007 Level |
| FY07 | FY08 | FY09 | FY10 | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 2. The Intensity Frontier |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1 Neutrino Physics |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1.1 Mini and SciBOONE |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1.2 MINOS |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1.6 MINERvA |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1.7 NOvA |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1.8 Beamline to DUSEL |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.1.9 First Section Large Det |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.2 Precision Measurements |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.2.2 Mu-e Conv Expt |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.2.3 Rare K Decays |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.3 DUSEL |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2.4 High Intens Proton Sce Fermilab |      |      |      |      |      |      |      |      |      |      |      |      |      |

Scenario A: FY08 Level
Scenario C: Double the budget in 10 years
Intensity Frontier Vision at Fermilab
Aligned with P5

a phased approach with ever increasing beam intensities and ever increasing detector capabilities
Physics of Flavor

• Flavor phenomena
  – Essential to shaping physics beyond the SM.

• SM is incomplete:
  – Neutrino Masses (flavor)
    • The only new physics seen so far in the laboratory
  – Baryon Asymmetry of the Universe (flavor)
  – Dark Matter
  – Dark Energy
Neutrinos

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
Neutrinos

- Neutrino masses
  - via See-Saw mechanism, point to new physics at a very high mass scale (unification scale).

\[ m_v M = (m_{\text{quark}})^2 \]

- Baryon Asymmetry of the Universe
  - Possible scenarios as the source
    - Electroweak baryogenesis – LHC and ILC.
    - Leptogenesis – Neutrino CP violation would support it.

- The Four Measurements
  - value of \( \sin^2 2\theta_{13} \)
  - Are neutrino masses Dirac or Majorana?
  - Is the mass ordering normal or inverted?
  - CP violation
The Intensity Frontier: Present

MI beam power at 120 GeV since multi-batch slip stacking become operational

17 kW at 8 GeV for Neutrinos

250 kW at 120 GeV for Neutrinos

~$4.5 \times 10^{16}$ p/hr
The Intensity Frontier: Early Next Decade

- 16 kW at 8 GeV for Precision Measurements
- 700 kW at 120 GeV for Neutrinos
NOVA
MINOS
MINIBOONE

Neutrino Oscillation
MiniBooNE: $\nu_\mu \rightarrow \nu_e$

The LSND result requires the 4\textsuperscript{th} neutrino.

MiniBooNE ruled out the LSND result.
MINOS: $\nu_\mu \rightarrow \nu_x$, $\nu_\mu \rightarrow \nu_e$

Projected 90% Exclusion (Prelim)

- CHOOZ 90% CL
- $3.25 \times 10^{20}$ POT $\Delta m^2 > 0$ (2008, 10%)
- $3.25 \times 10^{20}$ POT $\Delta m^2 < 0$ (2008, 10%)
- $6.5 \times 10^{20}$ POT $\Delta m^2 > 0$ (+~1 year, 5%)
- $9.5 \times 10^{20}$ POT $\Delta m^2 > 0$ (+~2 years, 5%)

Best $\Delta m^2_{32}$ measurement!
Possibly an early glimpse on $\theta_{13}$

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NOvA could provide the first glimpse of the mass hierarchy for large $\theta_{13}$ - the only near term probe of hierarchy in the world.
MINERVA

SCIBOONE

Neutrino's Interactions with Matter
How do neutrinos interact with matter?

- We are entering
  - a precision era in neutrino oscillation physics.

- It requires
  - precise determination of the neutrino reaction and production cross sections.
8 GeV Proton Beam from Booster

SciBooNE

T2K

SciBooNE

K2K

Flux (normalized by area)

$E_{\nu}$ (GeV)

Entries 1200

$E_{\nu}$ (GeV)

$v$ CC QE

$v$ CC resonant $\pi$

$v$ CC coherent $\pi$

$v$ CC other

$\nu$ NC

anti-$\nu$

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Slide 20
Construction has begun
Data taking in end 2009

Pre-Minerva
(sans MiniBoone, K2K)

Post MINERvA
(stat errors only)

for MINOS, T2K, NOvA, DUSEL

MINOS

MINERvA

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Slide 21
The Intensity Frontier:

Towards DUSEL:

Neutrinos to DUSEL:

DUSEL Beamline Working Group formed to develop a conceptual plan of beamline optics / components / instrumentation, near detector hall, the beamline (beam extraction, civil construction, target area).

700 kW at 120 GeV

For Precision Measurements

16 kW at 8 GeV

Towards DUSEL
NSF’s proposed Underground Lab. DUSEL

Phase 1 Detector
Phase 2 Full Size Detector (→ Proton Decay, Supernova)

NOvA (off-axis)
MINOS (on-axis)

735 km

Phase 1: 700 kW
Phase 2: Project X (2.3 MW)
Project X: Naming Contest

Main Injector: 2 MW at 60-120 GeV for neutrinos
Recycler: up to 200 kW at 8 GeV for precision measurements

National Project with International Collaboration

8 GeV ILC - ILC LINAC + Recycler + Main Injector

High Intensity Proton Accelerator: Project X
Neutrino / Proton Decay "Massive" Detectors

Options under consideration:
～300 kt WC, ～100 kt LAr, or some combination of the two.
Fermilab supports both technologies.

- Water Cerenkov
  - Known technology

- Liquid Argon TPCs
  - Great promise (x 3-4)
LAr TPC R&D / Physics Program

Reviewed by External Review chaired by Bob Kephart.

Yale TPC
Luke & Bo

R&D

Purity, electronics development

Underground safety, cryo operation, TPC performance, reconstruction

Beam $v_e, \gamma/\pi^0$ sep.

ArgoNeuT

100-200 ton

R&D

Cold electronics, evacuation requirement, Tank construction, insulation

Low E excess, cross sections

microBooNE

R&D

Underground operation, Technical & cost scaling

$\theta_{13}$, mass hierarchy

LAr at NuMI near or Homestake

Request the PAC to make a recommendation on the MicroBooNE experiment proposal

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The $3\sigma$ Reach of the Successive Phases

$\sin^22\theta_{13}$

Mass Ordering

CP Violation

Discovery Potential for $\sin^2(2\theta_{13}) = 0$

Discovery Potential $\Delta m_{31}^2$

Discovery Potential for $\delta \neq 0$ and $(\pi/2)$

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Slide 27
Precision Measurements
Precision Meas.s: Energy – Intensity Connection

Energy Frontier Facility

The Gauge Sector
Higgs
EWSB

Intensity Frontier Facility

The Flavor Sector
Mixings, Masses,
CPV, FCNC, LFV, ...

EWSB – Flavor Intimate Relationship:
No EWSB $\rightarrow$ fermions degenerate $\rightarrow$ no visible flavor effect

Intensity Frontier can probe new physics at a scale $>>$ TeV scale.

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Phase 1 Precision Measurements

The Intensity Frontier:

For Neutrinos
700 kW at 120 GeV

For Precision Measurements
16 kW at 8 GeV
The Intensity Frontier:

Phase 2 Precision Measurements with Project X

Stretcher Possibilities:
Accumulator / Debuncher, Recycler, Tevatron

- high duty factor
- high availability
- good beam structure

8 GeV ILC-like Linac

Recycler: upto 200 kW at 8 GeV for precision measurements
Main Injector: >2 MW at 60-120 GeV for neutrinos

Machine Experiments Interface Study Group:
define and clarify beam requirements and the usage of the existing rings
Neutrinos change from one kind to another. Do charged leptons do, too?

In SM

\[ \mu^- \rightarrow W^- \rightarrow \nu_\mu \rightarrow \nu_e \rightarrow e^- \]

Virtual neutrino mixing

\( \gamma \) can be real (\( \mu \rightarrow e\gamma \)) or virtual (\( \mu + \text{neucleus} \rightarrow e + \text{neucleus} \))

Experimental reach \( \sim 10^{-13} \) (\( \mu \rightarrow e\gamma \)), \( 10^{-17} \) (\( \mu N \rightarrow eN \))

\[
Br(\mu \rightarrow e\gamma) = \left| \frac{3\alpha}{32\pi} \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}
\]
Muons: $\mu$ to $e$ Conv. ($\mu N \rightarrow eN$) in New Physics

**Supersymmetry**
- Rate $\sim 10^{-15}$
- $\Lambda_c \sim 3000$ TeV

**Compositeness**
- $|U_{\mu N}U_{e N}|^2 \sim 8 \times 10^{-13}$
- $g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$

**Leptoquark**
- $M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2}$ TeV/c$^2$

**Heavy Neutrinos**
- $\mu^-$
- $e^-$
- $q$

**Second Higgs Doublet**
- Second Higgs Doublet
- $M_{Z'} = 3000$ TeV/c$^2$

**Heavy Z'**
- Anomalous Z Coupling

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Slide 33
mu2e Muon Beam and Detector

for every incident proton
0.0025 μ-’s are stopped in
the 17 0.2 mm Al target
foils

LOI submitted
Proposal for Stage 1 Approval expected Fall 2008

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mu2e can probe $10^3 - 10^4$ TeV.
Japan-US workshops in discussion

(Japan-US Project Funds)

Japan-US MOU in progress
Other Possibilities:

depending on Budget,
Future Discoveries (e.g. LHC),
.....
Kaons: Rare Decays

Standard Model
\[
\begin{align*}
\text{Br}(K^+ \rightarrow \pi^+ \nu \nu) &= 8 \times 10^{-11} \\
\text{Br}(K_L \rightarrow \pi^0 \nu \nu) &= 3 \times 10^{-11}
\end{align*}
\]

An almost-Minimal Flavor Violation World:

Measuring small deviations from SM is important.

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Kaons: Rare Decays

Experimental focus:
Theoretically & experimentally clean – a few % uncertainty

~1,000 clean Kaon events with Project X

\( K_L \rightarrow \pi^0\nu\nu \)

Experiment Concept
Muons for g-2

- Also sensitive to physics at a high mass scale

- With higher precision, could help determine the SUSY parameters
  - \( \tan \beta \)
  - \( \text{sign}(\mu) \)
New Physics in Other Precision Measurements

- **Charms**
  - $D^0 - \bar{D}^0$ mixing

- **TeV-based Neutrinos (NuSOnG)**
  - Electroweak Precision
    - $Z'$
    - Oblique Corrections
    - Sterile Mixing
    - NuTeV Anomaly?
Project X:

Evoluitional Path to

v-Factor & n+\mu+ Collider
Evolutionary Path to $\nu$-Factory & $\mu^+\mu^-$ Collider

Project X

1. 8 GeV SC Linac
2. Recycler Main Injector

Muon Collider Test Facility

2. Muon Collider Test Facility
3. Muon Collider R&D Hall
4. Decay Cool
5. Target Phase Rot. & Bunch

Neutrino Factory

3. Pre-Accel
4. RLA (1-4 GeV)
5. 4 GeV Ring

1.5 TeV Muon Collider

4. 6D Cooling
5. Final Cooling

4. Muon Acc
5. Collider Ring

More Acc

Larger ring

Beam to DUSEL

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Slide 43
Opportunities with Project X

Neutrinos: Oscillation
(International Collaboration)

Muons
$\mu \rightarrow e$ conversion
(Phase 2)

Muons g-2

Kaons
$K^+ \rightarrow \pi^+ \nu \nu$, $K_L \rightarrow \pi^0 \nu \nu$

Antiprotons
Hyperon CP
Antihydrogen CPT

Charm
Mixing, CP

$\nu$'s
EWK

ILC

Muon Collider

Neutrino Factory

Accelerator Science

Need international coordination & collab.

Documented in Golden Book

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Intensity Frontier Vision at Fermilab
Aligned with P5

a phased approach with
ever increasing beam intensities
and ever increasing detector capabilities