Neutrino Collaboration with Fermilab Present and Future

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Member – Neutrino Working Group

Indo-US Collaboration on Project-X

Interaction Meeting on Project-X, IUAC, 17-18 June, 2011

INTENSITY FRONTIER - Why Interest in Neutrinos?

- **Neutrinos: Of all the known particles, neutrinos are the most mysterious and abundant. We need to know their properties to fully understand the evolution of the Universe.**
- **Neutrino Masses and Mixing (The most important discovery of Particle Physics in last twenty years)**:
  - **Evidence of Physics Beyond the Standard Model**
  - May signal new physics at very high energies
  - A new, different and complementary window on the origin of mass
  - Provides a different window on the problem of flavor (why three (3) generations?, why mixing?, why CP violation?)
  - In some scenarios beyond the SM, Neutrinos could be an important component of the dark matter.
- Lepton number and CP-violation could be at the origin of the baryon asymmetry of the Universe.
- The discovery of small effects in neutrino physics (violation of unitarity, sterile neutrinos, non-standard interactions, CP and CPT violations) could unveil new particles and interactions.

QUESTIONS FOR THE FUTURE - IN NEUTRINO SECTOR?

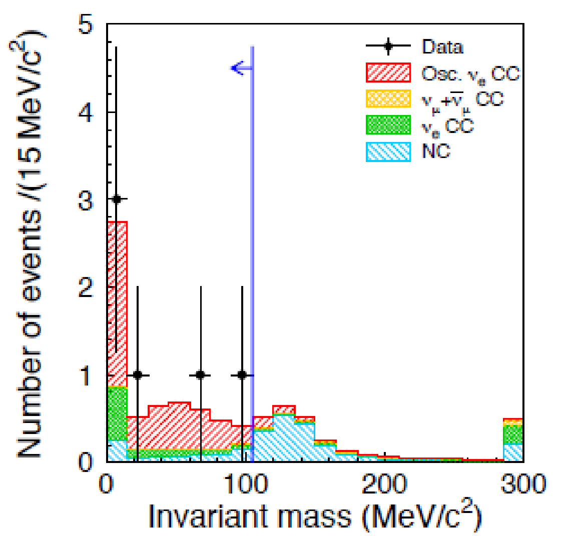
1. What is the value of θ_{13}, the mixing angle between first and third-generation neutrinos for which, so far, experiments have only established limits? The first possible indication of its large positive value came on 15.6.2011 from T2K. Determining the size of θ_{13} has critical importance not only because it is a fundamental parameter, but because its value will determine the tactics to best address many other questions in neutrino physics. MINOS, T2K, NOνA, Double-CHOOZ, Daya-Bay, RENO, LBNE

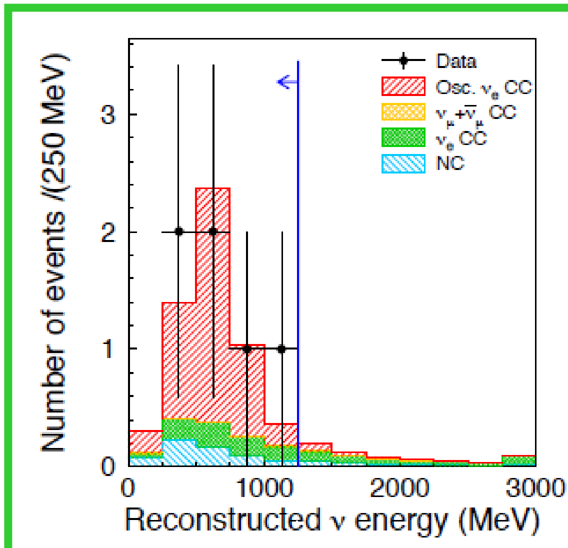
2. Do neutrino oscillation violate CP? If so, how can leptonic CP violation drive a matter-antimatter asymmetry among leptons in early universe (leptogenesis)? What is the value of the CP-violating phase, which is so far completely unknown? Is CP violation among neutrinos related to CP violation in the quark sector? LBNE

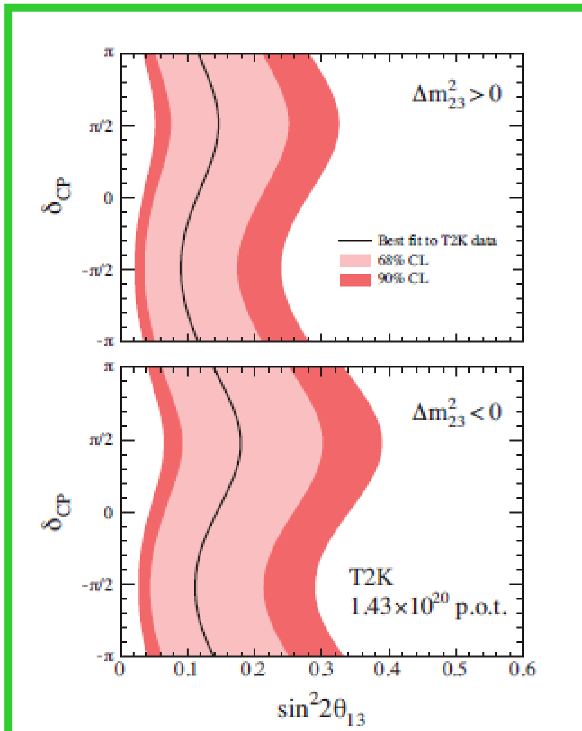
3. What are the relative masses of the three known neutrinos? Are they “normal,” analogous to the quark sector, (m3>m2>m1) or do they have a so-called “inverted” hierarchy (m2>m1>m3)? Oscillation studies currently allow either ordering. The ordering has important consequences for interpreting the results of neutrinoless double beta decay experiments and for understanding the origin and pattern of masses in a more fundamental way, restricting possible theoretical models. LBNE or INO

DOE-NSF $\longrightarrow$ HEPAP $\longrightarrow$ P5 $\longrightarrow$ Report $\longrightarrow$ 10yr Plan $\longrightarrow$ Page 34 & 35

T2K RESULT ON $\nu_\mu \rightarrow \nu_e$ OSCILLATION - 15.JUNE.2011







Number of protons on Target = 1.43×10^{20}

Expected background at FD with no oscillation = 1.5

Number of electron like events observed at FD = 6

90% C.L. interval and best fit point assuming

($\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2, $\mathrm{Sin}^2 2\theta_{23} = 1$ and $\delta_{CP} = 0$)

$0.03 < \mathrm{Sin}^2 2\theta_{13} < 0.28$ (normal) — **$\mathrm{Sin}^2 2\theta_{13} = 0.11$**

$0.04 < \mathrm{Sin}^2 2\theta_{13} < 0.34$ (inverted) — **$\mathrm{Sin}^2 2\theta_{13} = 0.14$**

QUESTIONS FOR THE FUTURE - IN NEUTRINO SECTOR?

4. Is θ_{23} maximal (45 degrees)? If so, why? Will the pattern of neutrino mixing provide insights regarding unification of the fundamental forces? Will it indicate new symmetries or new selection rules? T2K, NOνA, INO, LBNE

5. Are neutrinos their own anti-particles? Do they give rise to lepton number violation, or leptogenesis, in early universe? Do they have observable laboratory consequences such as the sought-after neutrinoless double beta decay in nuclei. CUORICINO/CUORE, NEMO3/SUPERNEMO, GERDA, EXO, SNO++, COBRA, MAJORANA etc.

6. What can we learn from observation of the intense flux of neutrinos from a supernova within our galaxy? Can we observe the neutrino remnants of supernovae that have occurred since the beginning of time. Super-K, LBNE, Ice-Cube

7. What can neutrinos tell us about new physics beyond the Standard Model such as deviation of weak mixing angle from those determined at the colliders, violation of sum rules and isospin symmetry? Are there large Δm2 oscillations as hinted by LSND and MiniBooNE experimentss? Are there non standard interactions? The find grained Near Detector for LBNE will have the capability to address these questions with unprecendented precision. Do sterile neutrinos exist? Fine-Grained Near Detector for LBNE (ex: HiResMν or a variation of it)

8. What is the absolute mass of neutrinos? Tritium (KATRIN) and $0\nu\beta\beta$ Decay

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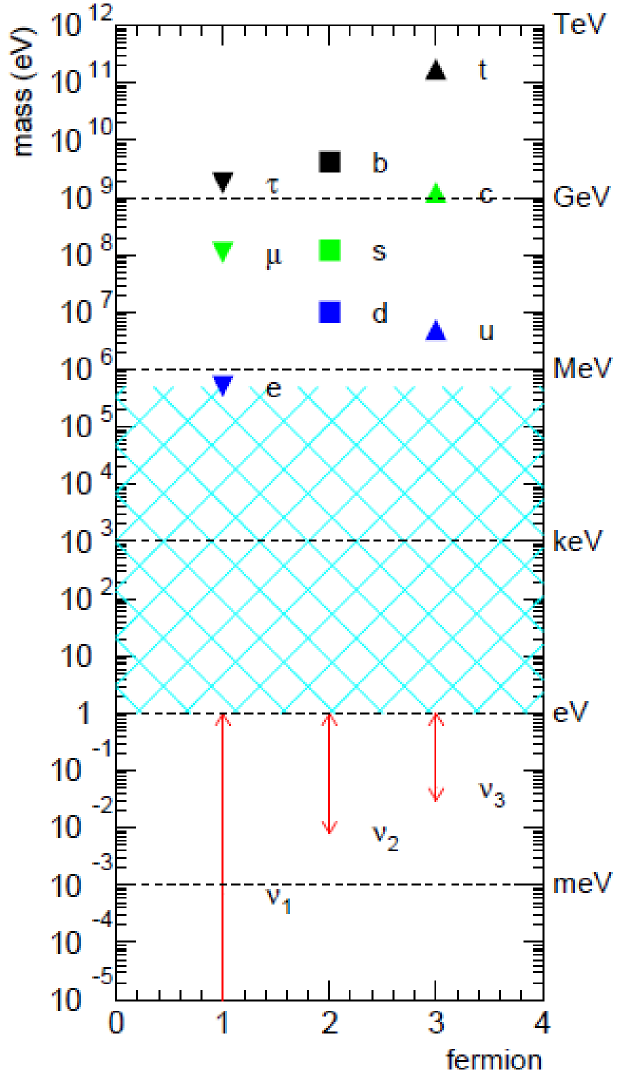
WHAT ARE NEUTRINOS TELLING US?



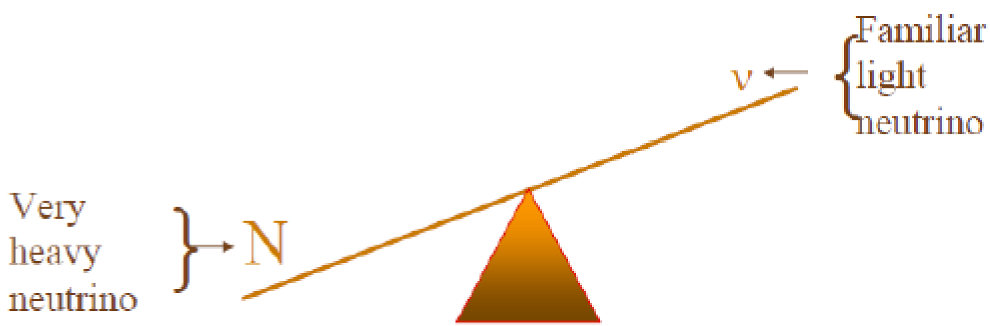
Neutrinos have tiny masses.
Not expected in the SM.

Lepton Mixing is different from quark mixing.

A complementary window on the problem of flavor.

SOMETHING ABOUT UNIFICATION?

See-Saw Mechanism



Mass (N) ~ 10^{15} GeV

The Strong, EM and Weak forces unify at ~ 10^{16} GeV

This might shed light on the physics at energy scales (unification scale?) which cannot be tested directly.

HISTORY OF COLLABORATION AT FERMILAB – MY VERSION

1. Emulsion exposure in 200 and 400 GeV beam – late 70's
2. Di-muon (DY) experiment – as individual collaborators – late 70's
3. Fixed target experiment E706 – DU – 1985 - 1992
4. Tevatron Collider D0 – DU, PU, TIFR – since late 80's, early 90's

   (Tevatron to finish operation on 30/9/2011)

Visit of US team in 2003 to discuss further collaboration:

5. Accelerator Collaboration – RRCAT, IUAC, BARC, VECC, IGCAR ~2006
6. Neutrino Collaboration – Since 2010

   Across the board on Fermilab Neutrino Experiments

   We are working on MIPP, MINOS, NOνA, LBNE [pre-Project-X (700KW beam power) and with Project-X (~2.3 MW beam power)]

   Institutions Involved - BHU, CUSAT, DU, IITG, IITH, JU, HU, PU.

MOU between INDIAN and US INSTITUTIONS

Memorandum of Understanding

between

US Universities & Accelerator Laboratories

and

Indian Universities & Accelerator Laboratories

concerning

Collaboration on R&D for Various Accelerator Physics and High Energy Physics Projects

January 9, 2006

1. Introduction

1.1 General Description

This Memorandum of Understanding (MOU) establishes a collaboration framework between various US and Indian Accelerator Laboratories and Universities, hereinafter referred to as the "Parties", to pursue coordinated R&D in areas of mutual interest pertaining to accelerator and high energy physics projects. This agreement between the Parties is made to further the objectives of any existing national and international collaborations, and shall not alter those collaborations. This MOU between the Parties is not a legal contractual obligation on the part of any of the institutions that are a party to the agreement.

1.2 Objective

The objective of this MOU is to document the terms under which work of the Parties is to be performed.

1.3 Scope

This MOU covers work to be performed by the Parties in the furtherance of the goals of the collaborations and the specific R&D tasks within the topics of collaboration.

1.4 Initial List of Participating Institutions

The following is a list of the Institutions that are a party to the collaboration. The Parties agree that after mutual consultation, they would favorably consider admitting new partner institutions from the USA and India who want to contribute towards the objective of this Agreement.

1 01/09/06

4.2 Approvals

The following concur in the terms of this Memorandum of Understanding:

Piermaria Oddone, Director, FNAL	Vinod C. Sahni, Director, RRCAT
1/9/05	March 8, 2006
Date	Date
Jonathon Dorfan, Director, SLAC	Bikash Sinha, Director, VECC
1/23/06	March 9, 2006
Date	Date
Christoph Leemann, Director, TJNAJ	Amit Roy, Director, IUAC
1/18/06	March 9, 2006.
Date	Date
Maury Tigner, Director, Newman Lab	S. Bhattacharya, Director, TIFR
	April 17, 2006
Date	Date
	S. Banerjee, Director, BARC
	March 14, 2006
Date	Date
	Deepak ~~Pental~~, Vice Chancellor, DU
	April 10, 2006
Date	Date

8 01/09/06

LETTER FROM THE FERMILAB DIRECTOR

Fermilab

Fermi National Accelerator Laboratory
P.O. Box 500 • Batavia, IL • 60510-0500
630-840-3211 (phone)
630-840-2900 (fax)

Director's Office

November 08, 2009

Prof. Brajesh Chandra Choudhary
Department of Physics & Astrophysics
University of Delhi
Delhi - 110 007, India

Prof. Sanjib Mishra
Department of Physics and Astromony
University of South Carolina
Columbia, SC- 29208

Dear Prof. Choudhary and Prof. Mishra,

Fermilab's program for the next decade includes investigation of physics at the intensity frontier while vigorously participating in energy frontier physics at LHC and the cosmic frontier. With the energy frontier moving from the Fermilab-Tevatron to the CERN-LHC, a significant fraction of our Indian collaborators will shift to LHC.

Scientists from US and Indian institutions have been collaborating on high energy physics experiments at Fermilab since 1985. Together we have made valuable contributions to the Fermilab program. Recently we have developed strong accelerator collaboration with the Indian Department of Atomic Energy laboratories. This collaboration is making considerable progress in contributing to the proposed Project-X R&D and SRF infrastructure. We have been exploring the possibilities of expanding this collaboration to the intensity frontier physics at Fermilab. I would like to seek your help, as a member of neutrino experiments at Fermilab and with ties to physics community in India, in establishing neutrino collaboration with Indian institutions.

I am requesting you to work with Shekhar Mishra, Fermilab, in developing this collaboration. While working with the management of the respective Fermilab experiments, you would serve as the Technical Project Managers for the work that would be carried by Indian institutions collaboration.

Thank you,

Sincerely,

Piermaria J. Oddone,
Laboratory Director

Fermi National Accelerator Laboratory / Kirk Road and Pine Street / P.O. Box 500 / Batavia, IL 60510 / 630.840.3000 / www.fnal.gov / fermilab@fnal.gov
Office of Science / U.S. Department of Energy / Managed by Fermi Research Alliance, LLC

MOU on ν Collaboration between Indian Institutions & FERMILAB

ADDENDUM

to the

Memorandum of Understanding

between

US Universities & Accelerator Laboratories

and

Indian Universities & Accelerator Laboratories

concerning

Collaboration on R&D for Accelerator Physics and High Energy Physics Projects

Addendum IV: "US and Indian Institutions Collaboration on Neutrino Physics, Related Experiments and Detector Development."

Nov 10, 2009

1. Authority and Limitations

Pursuant to the Memorandum of Understanding ("MOU") between the U.S. Universities & Accelerator Laboratories and Indian Universities & Accelerator Laboratories dated January 9, 2006, Fermilab and Indian Accelerator Laboratories (the "Parties") intend to undertake the work described in this Addendum IV. The Parties acknowledge that their intended work shall be consistent with the terms and conditions of the MOU, the terms and conditions of their respective contracts and programs, and subject to the availability of appropriated funds as provided to them. The Parties further acknowledge and understand that their agreement with and signature to Addendum IV does not create a legal, contractual obligation for either Party nor may form the basis of a claim for reliance thereon. The Parties agree to comport their activities under Addendum IV in conformance with all applicable U.S. and Indian laws and regulations, including those related to export control.

2. Introduction

The work detailed in this document falls within the scope of the MOU cited above. It addresses two key areas of collaboration mentioned in the main MOU. These are: (i) Neutrino Physics; and (ii) Development of Novel and Large Particle Detectors. All terms and conditions under which the work will be carried out are found within the main MOU.

The following concur on the terms of this Memorandum of Understanding Addendum:

10 Nov, 2009		11/16/09	
Dr. Amit Roy Director IUAC	Date	Dr. Piermaria Oddone Director, Fermilab	Date
Nov 10, 2009		11/13/09	
Dr. Vinod Sahni Collaboration Coordinator DAE, India	Date	Dr. Shekhar Mishra, Collaboration Coordinator, Fermilab	Date
10 Nov 2009		19. Nov. 09	
Prof. Brajesh Choudhary, Technical Project Manager University of Delhi, India	Date	Prof. Sanjib Mishra Technical Project Manager University of South Carolina, Columbia	Date

Collaborating Institutions:

1. Banaras Hindu University, Varanasi
2. Cochin University of Science & Tech., Cochin
3. University of Delhi, Delhi
4. IITG, Guwahati
5. IITH, Hyderabad
6. Jammu University, Jammu-Tawi
7. Hyderabad University, Hyderabad
8. Panjab University, Chandigarh

More Institutions have shown interest.
Others are most welcome.

A Proposal by Indian Physicists to collaborate on Neutrino Projects at Fermilb

Venktesh Singh
Banaras Hindu University, Varanasi - 221005, UP

M. R. Anantharaman, V. C. Kuriakose, Ramesh Babu Thayyullathil
Cochin University of Science and Technology, Kochi – 862022, Kerala

Brajesh Choudhary, Suresh Kumar, Samit Kumar Mandal, Smarjit Triambak
University of Delhi, Delhi – 110007

Bipul Bhuyan
Indian Institute of Technology Guwahati, Guwahati – 781039, Assam

Money expected by September.

Requested amount 12.4 crores

Bindu Bambah, Harikumar, R. Mohantha
University of Hyderabad, Hyderabad – 500046, AP

Anjan Giri
Indian Institute of Technology Hyderabad, Yeddumaalaram – 502205, AP

Baba V. K. S. Potukuchii
University of Jammu, Jammu-Tawi, J & K State, 18006

Vipin Bhatnagar, Ashok Kumar, Sandeep Sahijpal, Jasbir Singh,
Panjab University, Chandigarh – 160014

STATUS OF THE COLLABORATION

- **Strong support from Universities, DAE and DST management for this collaboration.**
- ***DST expects to approve the financial support by September 2011.***
- **Collaboration already in progress since January 2010.**
- **Five students and several faculty already involved in MIPP, MINOS and LBNE collaborations. Details to follow.**

Essential Elements of the Proposal

- **Focus of the Experimental Studies @ Fermilab**
  - **Participate in cutting edge neutrino experiments**
  - **Measurement of Neutrino Flux with MIPP** – MIPP data will be the ONLY empirical constraint on the neutrino-flux in present and future accelerator experiments and help atmospheric as well as long-baseline neutrino experiments make precision measurements
  - **Gain Experience with MINOS Detector**
    - Use 5.4KTon magnetized Fe-Scintillator calorimeter; should prove useful for future magnetized calorimeter such as ICAL at INO
    - Measure the most precise value of atmospheric mixing parameter Δm^2_{23}
    - Learn to conduct $\nu_\mu \rightarrow \nu_e$ (θ_{13}) search in a magnetized Fe calorimeter; challenge is to find a small ν_e signal among large neutral current π^0s
  - **Participate in LBNE-DUSEL Neutrino Experiment** (Beamline ~1300 Km)
    - Search θ_{13} down to $\mathrm{Sin}^2 2\theta_{13}$ = 0.003 or θ_{13} less than 2 degrees
    - Measure CP violation in the lepton sector
    - Measure Mass Hierarchy for Neutrinos
- **Focus of the Detector Developments @ Home**
  - **Create detector R&D labs at various Universities**(Gaseous Detectors, Scintillators and Scintillating Crystal based Calorimetric studies)

Major Gains that are Expected from Our Efforts

- **Training of Young Physicists: Most useful resource for domestic future high energy physics/nuclear physics programs:**
  Will prepare a cadre of young graduate students, post-doctoral fellows, and junior faculty for world class projects at home, eg, ICAL @ INO & other experiments.
- **Start EHEP Groups at New Institutions**
  Example – participation by - IIT (Hyderabad), Univ. of Hyderabad, CUSAT and others.
- **Hands on Experience at Fermilab: Will help us in:**
  - Learning design of experiments
  - Fabricating detectors - Scintillator (solid + liquid), LAr, Water Cherenkov
  - Developing auxiliary system such as DAQ & gas distribution system
  - Maintain and operate experiments
  - Data analysis
  - Opportunity to work on MINOS – a mini ICAL
- **New Detector Labs at Universities and indigenous training of future manpower**

What have we achieved in a year and half ?

- **Five students and several faculty already involved in MIPP, MINOS and LBNE collaborations.**
  - Two students working towards their Ph.D thesis on MIPP.
  - One student working towards Ph.D thesis on MINOS.
  - Two students spent considerable time (6 months to a year) analyzing MIPP data.
  - One more student to start Ph.D work soon at Fermilab
  - One faculty visited for a year as prestigious International Fellow.
  - At present two faculty at Fermilab working on LBNE.

- **We have presented results, talks and posters at**
  - MIPP poster at NuFact 2010
  - MIPP poster at Fermilab annual users meet, 2011
  - MIPP poster to be presented at Lepton Photon 2011
  - MINOS talk at APS meeting in CA, 2011
  - MINOS poster at Fermilab annual users meeting.
  - LBNE talk at NuFact 2010 and NuHorizon 2011
  - Have written scientific notes for MIPP, MINOS and LBNE

Why partcipate in LBNE and LBNE-ND?

Inspiration from the DAE/DST management – participate if:

- **The program is Physics Rich**
  - ✓ **Compelling Neutrino Physics**
  - ✓ **Physics of Near Detector**
    - ❖ **Participation by Experimentalists / Engineers**
    - ❖ **Exploration by theorists due to richness of the program**

- **Indian contribution should be significant and should have DAE-DST ownership**
  - ✓ **Design, built, and operate Magnet + ECal + Muon system, or Magnet + ECal, or Magnet + Muon system**

- **Contribution should have synergy with interest and expertise in India and with INO program**
  - ✓ **Expertise exists in magnet design, scintillator (for ECal and/or muon) and RPC (muon) detectors and SiPM (Ecal) readout**
  - ✓ **Complements INO physics program**

Near Detector Concept and Physics?

1. Use of "identical small detector" at the near site is insufficient for future LBL experiments. Due to scale impossible to have identical ND and FD. What should be the aim of an ideal ND? It should provide:
   - ✓ Flux of ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ at ND and FD as function of E_ν and θ_ν
   - ✓ Absolute neutrino energy (E_ν) scale
   - ✓ Measurement of neutrino induced π^0, π^+, π^-, p, $K^\pm$ flux in NC and CC interactions - backgrounds to oscillation signal
   - ✓ Difference between neutrino and anti-neutrino interactions for both electron and muon flavor
   - ✓ The LBNE-ND aims to provide precise constraints on the systematic errors affecting the ν oscillations physics – ultimate calibration of the Far Detector

2. Discovery Potential - Sum-rules, iso-spin physics, searches (sterile neutrinos etc.)
3. A whole bunch of very precise measurement
4. Over 75 different topics/papers/thesis (next-page)

PHYSICS POTENTIAL with HiResMν?

APPENDIX A: Physics Potential of HiResMν

Below we enumerate some physics topics which can be studied with the proposed experiment and can be the subject of PhD theses. The list is not complete. It is intended to illustrate the outstanding physics potential of HiResMν; the many theses it will engender.

About NuMI and Service to LBLν

1: The energy scale and relative flux of ν_μ Flux in NuMI

2: The $\overline{\nu}_\mu$ relative to ν_μ as a function of E_ν in NuMI

3: Relative abundance of ν_e and $\overline{\nu}_e$ -vs- ν_μ and $\overline{\nu}_\mu$ in NuMI

4: An empirical parametrization of K^0_L yield in NuMI using the $\overline{\nu}_e$ data

5: Redundancy check on the MIPP π^+, K^+, π^-, K^-, and K^0_L yields in NuMI using the ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$ induced charged current interactions

Neutral-Pion Production in ν-Interactions

6: Coherent and single π^0 production in ν-induced neutral current interactions

7: Multiplicity and energy distribution π^0 production in neutral current and charged current processes as a function of hadronic energy

8: The cross section of π^0 production as a function of X_F and P_T in the ν-CC interactions

Charged-Pion & Kaon and Proton & Neutron Production in ν-Interactions

9: Coherent and single π^+ production in ν-induced charged current interactions

10: Coherent and single π^- production in $\overline{\nu}$-induced charged current interactions

11: Charged π/K/Proton production in the the neutral current and chaged current interactions as a function of hadronic energy

12: The cross section of $\pi^{\pm}/K^{\pm}$/proton production as a function of X_F and P_T in the ν-CC interactions

13: Measurement of neutron production via charge-exchange process in the CC and NC interactions

Neutrino-Electron Scattering

14: Measurement of inverse muon decay and absolute normalization of the NuMI flux above $E_\nu > 11$ GeV with $\lesssim 1\%$ precision

15: Search for the lepton violating $\overline{\nu}_\mu - e^-$ CC interaction

16: The ν_μ-e^- and $\overline{\nu}_\mu$-e^- neutral current interaction and determination of $\sin^2\theta_W$

17: Measurement of the chiral couplings, g_L and g_R using the ν_μ-e^- and $\overline{\nu}_\mu$-e^- neutral current interactions

ν-Nucleon Neutral Current Scattering

18: Measurement of neutral current to charged current ratio, R^ν, as a function of hadronic energy in the range $0.25 \leq E_{Had} \leq 20$ GeV

19: Measurement of neutral current to charged current ratio, R^ν and $R^{\overline{\nu}}$, for $E_{Had} \geq 3$ GeV and determination of the electroweak parameters $\sin^2\theta_W$ and ρ.

Non-Scaling Charged and Neutral Current Processes

20: Measurement of ν_μ quasi-elastic CC interaction

21: Measurement of $\overline{\nu}_\mu$ quasi-elastic CC interaction

22: Determination of M_A from the QE cross section and the shape of the kinematic variables (Q^2, Y_{Bj}, etc.)

23: Measurement of the axial form-factor of the nucleon from quasi-elastic interactions

24: Measurement of ν_μ induced resonance processes

25: Measurement of $\overline{\nu}_\mu$ induced resonance processes

26: Measurement of resonant form-factors and structure functions

27: Study of the transition between scaling and non-scaling processes

28: Constraints on the Fermi-motion of the nucleons using the 2-track topology of neutrino quasi-elastic interactions

29: Coherent ρ^+ production in ν-induced charged current interactions

30: Neutral Current elastic scattering on proton $\nu(\overline{\nu}_\mu)p \to \nu(\overline{\nu}_\mu)p$

31: Measurement of the strange quark contribution to the nucleon spin ΔS

32: Determination of the weak mixing angle from NC elastic scattering off protons

Inclusive Charged Current Processes

33: Measurement of the inclusive ν_μ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

34: Measurement of the inclusive $\overline{\nu}_\mu$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

35: Measurement of the inclusive ν_e and $\overline{\nu}_e$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

36: Measurement of the differential ν_μ charged current cross-section as a function of x_{Bj}, y_{Bj} and E_ν.

37: Measurement of the differential $\overline{\nu}_\mu$ charged current cross-section as a function of x_{Bj}, y_{Bj} and E_ν.

38: Determination of xF_3 and F_2 structure functions in ν_μ charged current interactions and the QCD evolution

39: Determination of xF_3 and F_2 structure functions in $\overline{\nu}_\mu$ charged current interactions and the QCD evolution

40: Measurement of the longitudinal structure function, F_L, in ν_μ and $\overline{\nu}_\mu$ charged current interactions and test of QCD

41: Determination of the gluon structure function, bound-state and higher twist effects

42: Precise tests of sum-rules in QPM/QCD

43: Measurement of ν_μ and $\overline{\nu}_\mu$ charged current differential cross-section at large-x_{Bj} and -y_{Bj}

44: Measurement of scaled momentum, rapidity, sphericity and thrust in (anti)neutrino charged current interactions

45: Search for rapidity gap in neutrino charged current interactions.

46: Verification of quark-hadron duality in (anti)neutrino interactions

47: Verification of the PCAC hypothesis at low momentum transfer

48: Determination of the behavior of $R = \sigma_L/\sigma_T$ at low momentum transfer

Nuclear Effects

49: Measurement of nuclear effects on F_2 in (anti)neutrino scattering from ratios of Pb,Fe and C targets

50: Measurement of nuclear effects on xF_3 in (anti)neutrino scattering from ratios of Pb,Fe and C targets

51: Study of (anti)shadowing in neutrino and antineutrino interactions and impact of axial-vector current

52: Measurement of axial form-factors for the bound nucleons from quasi-elastic interactions on Pb, Fe and C

53: Measurement of hadron multiplicities and kinematics as a function of the atomic number

Semi-Exclusive and Exclusive Processes

54: Measurement of charmed hadron production via dilepton ($\mu^-\mu^+$, and μ^-e^+) processes

55: Determination of the nucleon strange sea using the (anti)neutrino charm production and QCD evolution

56: Measurement of J/ψ production in neutral current interactions

57: Measurement of K^0_S, Λ and $\overline{\Lambda}$ production in neutrino CC processes

of K^0_S, Λ and $\overline{\Lambda}$ production in antineutrino CC processes

of K^0_S, Λ and $\overline{\Lambda}$ production in (anti)neutrino NC processes

60: Measurement of exclusive strange hadron and hyperon production in (anti)neutrino charged and neutral current

61: Measurement of the Λ and $\overline{\Lambda}$ polarization in neutrino charged current interactions

62: Measurement of the Λ and $\overline{\Lambda}$ polarization in antineutrino charged current interactions

63: Measurement of the Λ and $\overline{\Lambda}$ polarization in (anti)neutrino neutral current interactions

64: Inclusive production of rho0(770), f0(980) and f2(1270) mesons in (anti)neutrino charged current interactions

65: Measurement of backward going protons and pions in neutrino CC interactions and constraints on nuclear processes

66: D*+ production in neutrino charged current interactions

67: Determination of the D^0, D^+, D_s, Λ_c production fractions in (anti)neutrino interactions

68: Production of K*(892)+- vector mesons and their spin alignment in neutrino interactions

Search for New Physics and Exotic Phenomena

69: Search for heavy neutrinos using electronic, muonic and hadronic decays

70: Search for eV (pseudo)scalar penetrating particles

71: Search for the exotic Theta+ resonance in the neutrino charged current interactions

72: Search for heavy neutrinos mixing with tau neutrinos

73: Search for an anomalous gauge boson in pi0 decays at the 120 GeV p-NuMI target

74: Search for anomaly mediated neutrino induced photons

75: Search for the magnetic moment of neutrinos

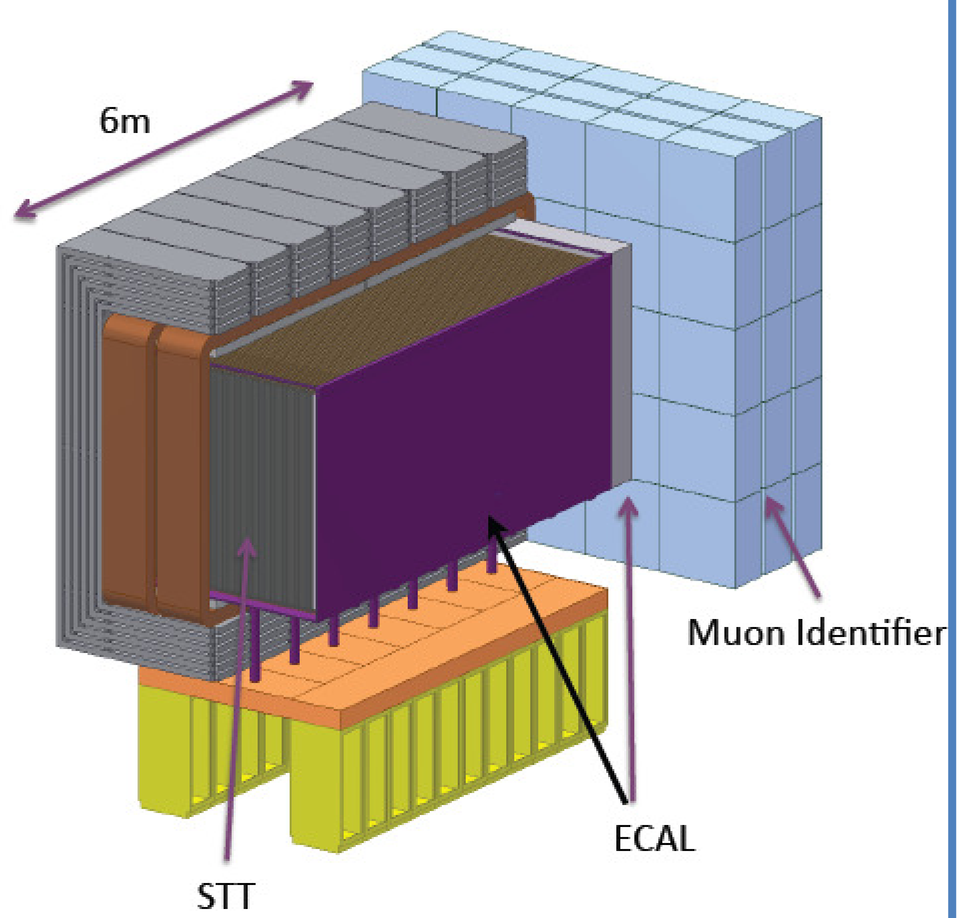
76: A test of ν_μ-ν_e universality down to 10^{-4} level

77: A test of ν_μ-ν_e coupling down to 10^{-3} level

- *77 HiResMnu Topics listed*
- *Many topics are pertinent to oscillation physics*
- *Some non-oscillation topics might lead to discovery*
- *Topics mentioned will have the the highest sensitivity/precision todate*

Near Detector Concepts for LBNE

OPTION ONE - STRAW TUBE TRACKER (STT) – Best performance out of all



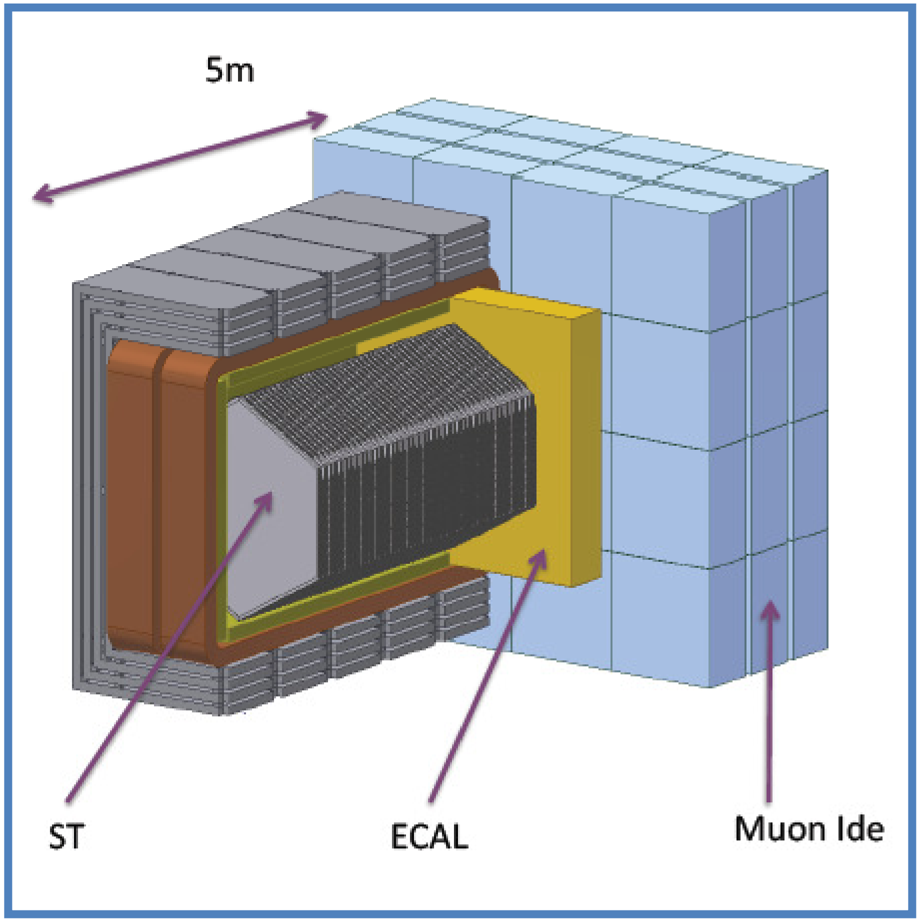
- 4m X 4m X 7m STT (7 tons, density = 0.1 gm/cm^3)
- 4π ECAL
- Dipole Field (0.4T)
- Muon-detection (RPC) in Dipole and downstream

- ✓ Transition radiation – distinguished $e^{\pm}$, and γ thus distinguishing ν_e, $\bar{\nu}_e$, and π^0
- ✓ dE/dX – separates p, $\pi^{\pm}$, $K^{\pm}$
- ✓ Muon + Magnet - $\mu^{\pm}$
- ✓ H_2O and D_2O Target (~X5 FD stat.) $\rightarrow$ WC-FD
- ✓ QE-Proton ID $\rightarrow$ Absolute Flux measurement
- ✓ Pressurized Ar-Target (~X5 FD stat) $\rightarrow$ LAr-FD

Scientifically Richest and Most ambitious

Near Detector Concepts for LBNE

OPTION TWO – SCINTILLATOR TRACKER (ST)
Works only for Water Cherenkov Far Detector

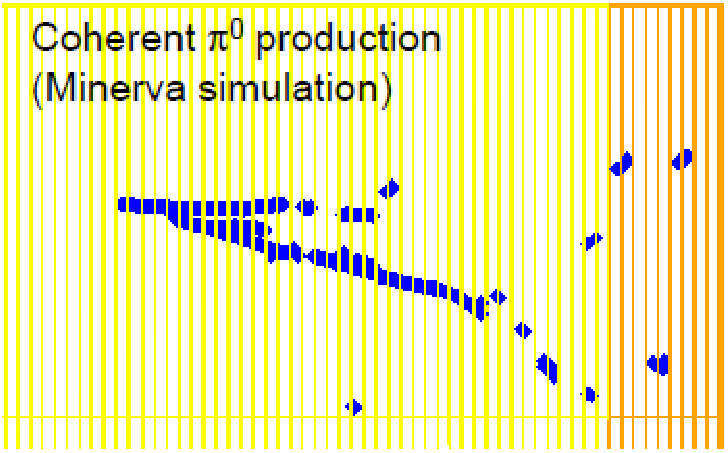


- 3m X 3m X 5m Sci-Tracker (7 tons, density = 1.0 gm/cm^3)
- 4π ECAL
- Dipole Field (0.4T)
- Muon-detection (RPC) in Dipole and downstream

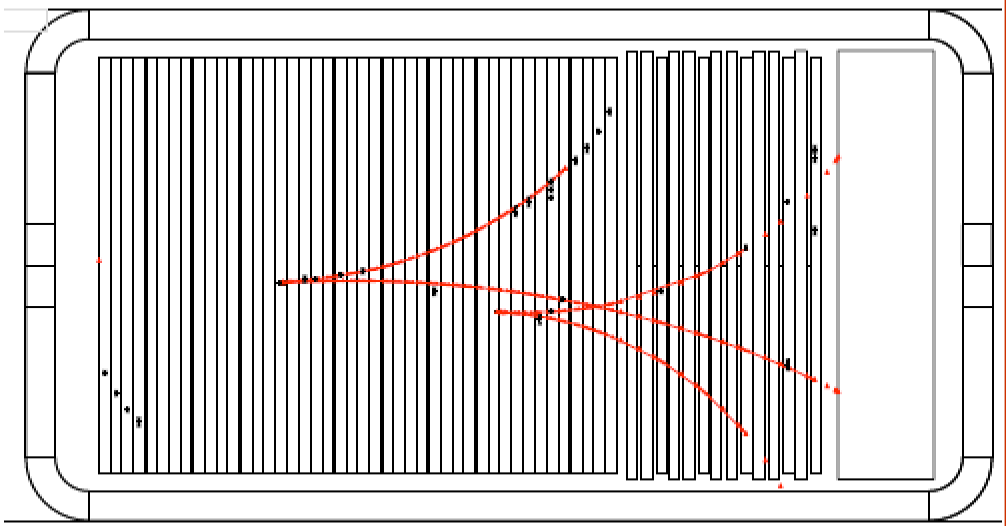
✓ Muon + Magnet - $\mu^{\pm}$

✓ H_2O Target (~X5 FD stat.) $\rightarrow$ WC-FD

COHERENT PI-ZERO (π^0) PRODUCTION



NOMAD DATA

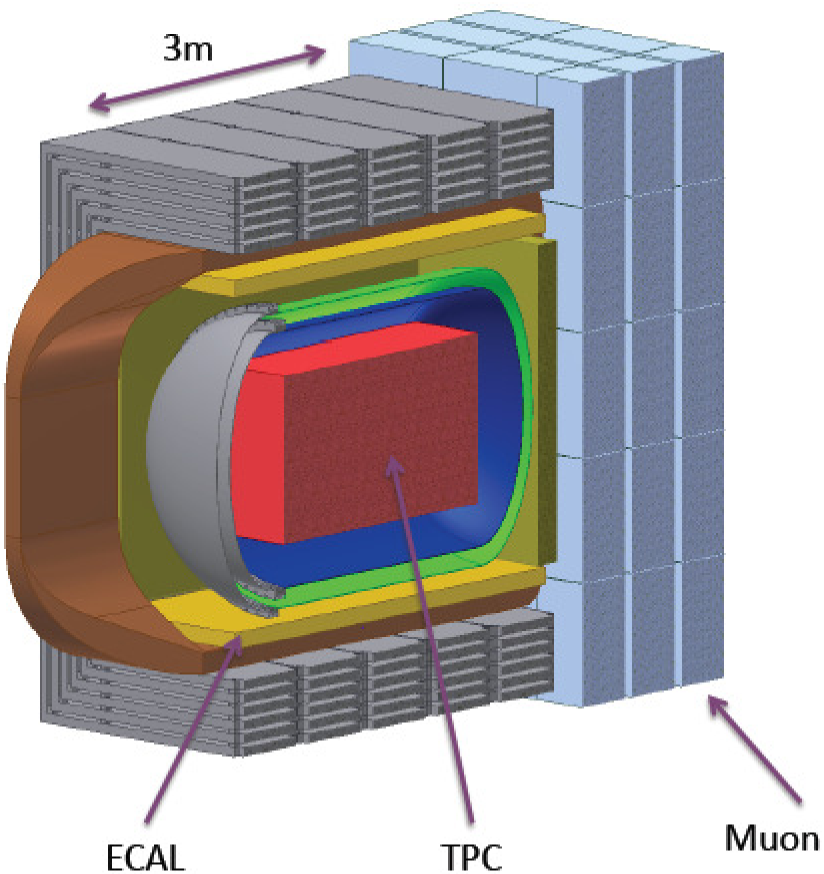


- **MINERVA SIMULATION:**
- **A Scintillator-Tracker**
- **Million Dollar Question – What is the RESOLUTION in scintillator?**

- ✓ **NOMAD DATA**
- ✓ **$\pi^0 \rightarrow \gamma\gamma \rightarrow e^{\pm}e^{\pm}$ is clearly visible.**
- ✓ **STT will have 12 times more hits. One can reconstruct $e^{\pm}$, γ, and thus π^0.**
- ✓ **Measurement of π^0 in NC and CC via $\gamma\gamma$ in tracker. π^0 is the largest background to $\bar{\nu}_e$ appearance.**
- ✓ **Measure beam ν_e and $\bar{\nu}_e$. A must if there are large Δm^2 (~ 1 eV^2) oscillation a la LSND or MiniBooNE.**
- ✓ **Measure absolute flux.**

Near Detector Concepts for LBNE

OPTION THREE – LAr TPC Tracker (TPCT)



- **1.8m X 1.8m X 3m LAr (13 tons)**
- **4π ECAL**
- **Dipole Field (0.4T)**
- **Muon-detection (RPC) in Dipole and downstream**

✓ **LAr-FD**

OPTION FOUR is similar to OPTION THREE – but much larger LAr TPCT ~100 tons

Why a B-Field?

1. **Constrain E_ν flux.**
2. **ND must measure the full range of E_ν and θ_ν else the sensitivity of FD will be compromised.**
3. **For LBNE, the maximal sensitivity for δ_{CP} is at E_ν = 1.5 GeV.**
4. **STT will be able to distinguish μ^+ and μ^- down to 0.3 GeV.**

Also the ND must measure and identify leptons (largely μ's) at large angles.

Must measure the difference in ν_e and $\bar{\nu}_e$ interactions which might fake a "δ_{CP}" in the range 0.5-1.0 GeV

SUMMARY – ND must have a magnetic field.

ν_μ - QE Sensitivity Calculation

1. Precision determination of ν_μ - QE requires proton tracking.
2. Example of a ν-interaction in a high resolution ND as a calibration of FD. Need proton-tracking & resolution to point to the H_2O and D_2O vertex.
3. QE in H_2O and D_2O will provide an absolute-flux measurement.
4. μ^-,p provide an "*in situ*" constraint on the Fermi-motion and hence on the E_ν scale.
5. QE interactions dominant in low-Eν. Need accurate parameterization of QE.
6. So – ND must track and ID QE-protons.

Figure 14: A ν_μ-QE candidate in NOMAD

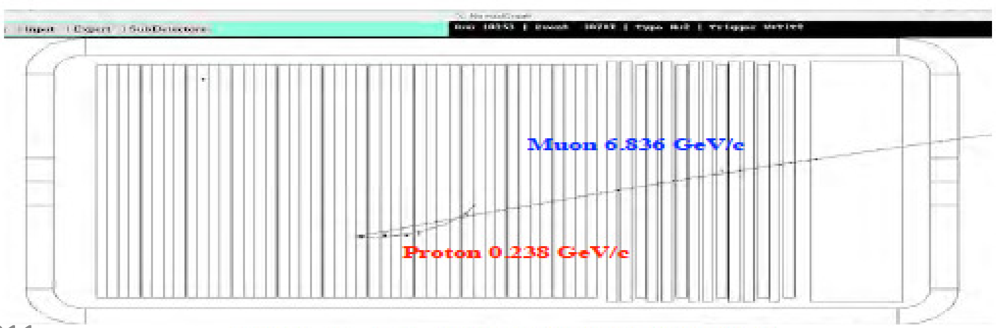


Figure 15: A ν_μ-QE candidate in NOMAD

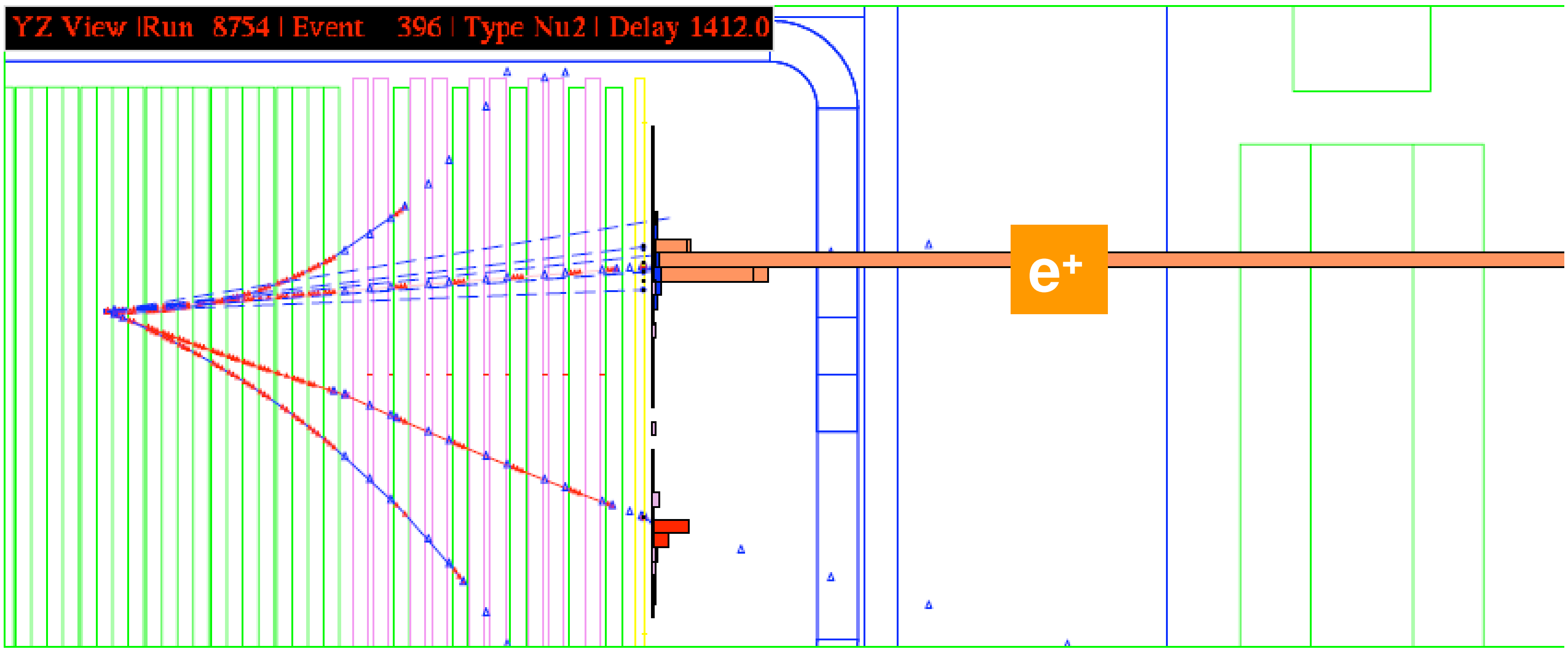
Use NOMAD data/MC as calibration.

STT will have X6 more points for protons.

Such low proton momentum quite common at LBNE.

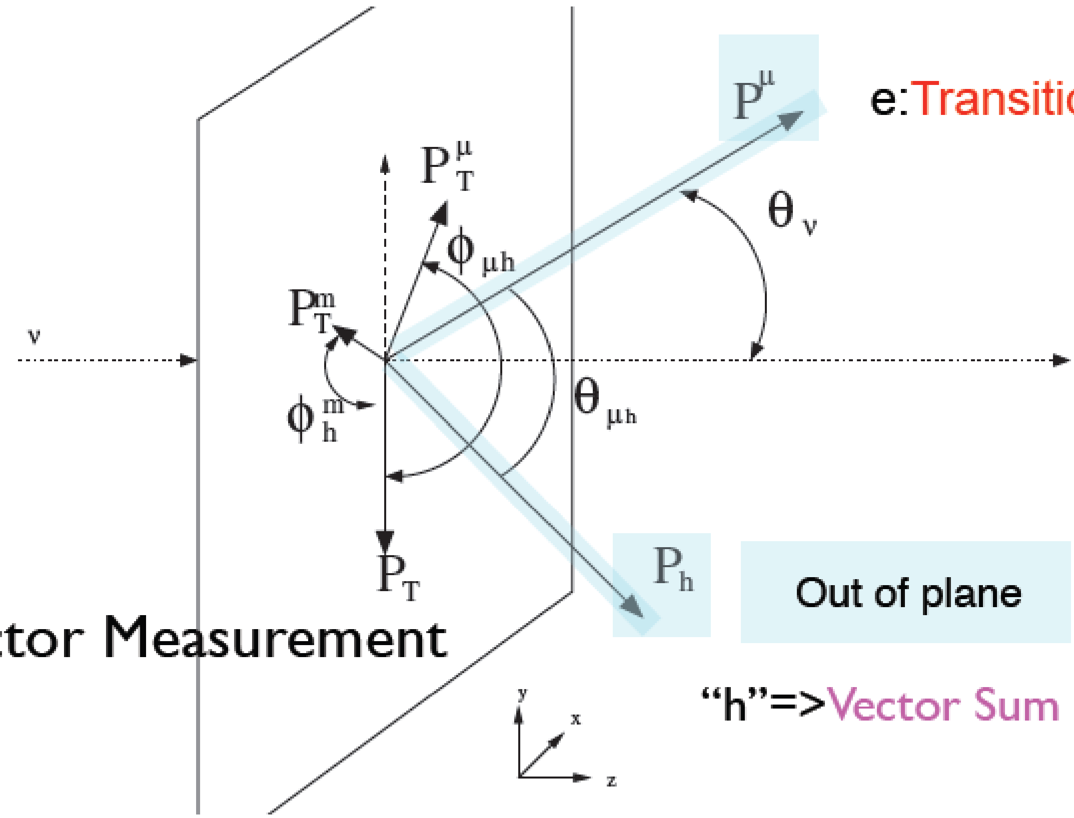
A $\bar{\nu}$e CC Candidate in NOMAD

The most difficult of neutrino species to identify



- ✓ X12 higher sampling in STT (HIresMν)
- ✓ X 4π calorimetric and μ coverage
- ✓ ECAL is critical for ν_e, $\bar{\nu}_e$, and π^0 reconstruction.
- ✓ $\bar{\nu}_e$ most difficult to reconstruct in any neutrino experiment. Only ~0.2% of ν_μ CC events.

KINEMATICS IN STT DETECTOR

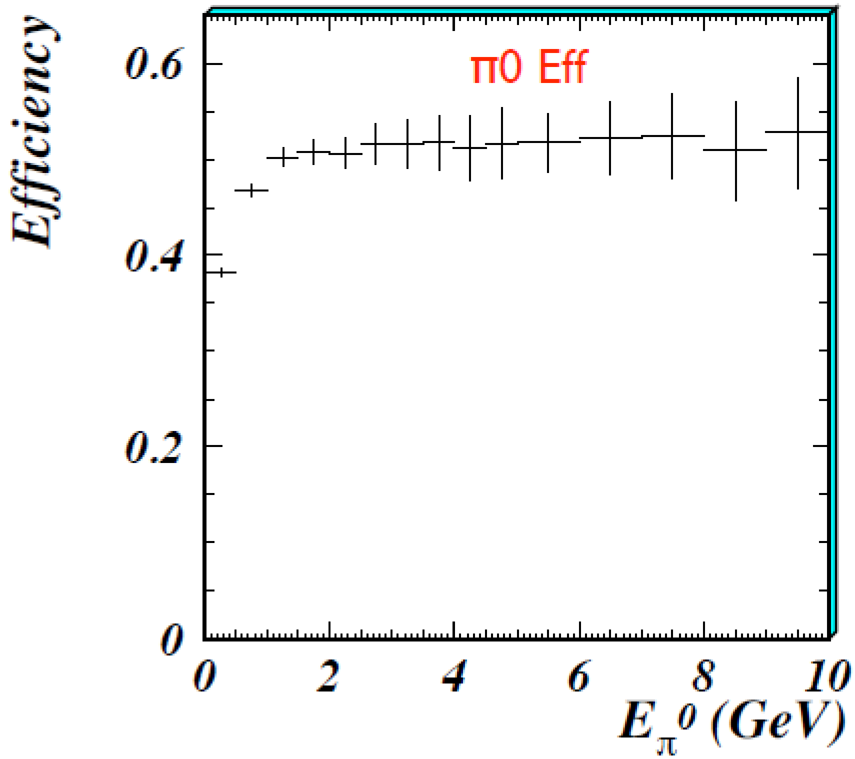


⇛ Pt-Vector Measurement

"h"=>Vector Sum of Tracks

1. Allows to reconstruct P_t^{μ} and P_h in a plane ⊥ to the neutrino direction. Neutrino is parallel to the detector.
2. One can measure missing P_t vector.
3. In ideal CC case it will be zero. For NC case – large missing P_t.
4. Allows to classify and understand the event. Only STT can do it.

Why ECAL is critical for LBNE ND?



- ✓ Clean π^0 and γ-signature in STT.
- ✓ ν-NC and CC $\rightarrow \pi^0 \rightarrow \gamma\gamma$. 50% of the γ will convert into $e^\pm$ in the STT, away from the primary vertex. We focus on these.
- ✓ γ-identification. $e^\pm$ ID: TR – using kinematic cut: Mass, opening angle.
- ✓ At least one converted γ in STT. Another γ in the downstream or side ECAL.

Conclusion $\rightarrow \pi^0$ is very well constrained in CC and NC.

Measurement of the RATIO $\Re_{e\mu}$?

- Search/Impact of large Δm^2 oscillations. If these exists then the assumption that flux at ND is unoscillated is false.
- Independent analysis of ν-data and $\bar{\nu}$-data due to possible differences between MiniBooNE/LSND results.
  - ✓ Need a detector which can identify e^+ and e^-.
- Measure the ratio between the observed ν_e ($\bar{\nu}_e$) CC events and the observed ν_μ ($\bar{\nu}_\mu$) CC events as a function of L/E_ν:

$$\mathcal{R}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \nu_e N \rightarrow e^- X}{\#\ of\ \nu_\mu N \rightarrow \mu^- X}(L/(E\nu))$$

$$\bar{\mathcal{R}}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \bar{\nu}_e N \rightarrow e^+ X}{\#\ of\ \bar{\nu}_\mu N \rightarrow \mu^+ X}(L/(E\nu))$$

- Compare the measured ratios $\Re_{e\mu}(L/E_\nu)$ and $\Re_{e\mu}(L/E_\nu)$ with the predictions from the ν-flux determination assuming no oscillations
- Same analysis technique used in NOMAD to search for $\nu_\mu \rightarrow \nu_e$ oscillations
- MiniBooNE effect is at 1% level. LSND measurement at 0.1% level.

HiResMν or STT – Such Rich Physics

Measurement	STT	Sci+μDet	LAr	LArB	LArB+Sci+μDet	LAr+STT
In Situ Flux Measurements for LBL:						
$\nu e^- \rightarrow \nu e^-$	Yes	No	Yes	No	No	Yes
$\nu_\mu e^- \rightarrow \mu^- \nu_e$	Yes	Yes	No	Yes	Yes	Yes
$\nu_\mu n \rightarrow \mu^- p$ at $Q^2 = 0$	Yes	Yes	No	No	Yes	Yes
Low-ν_0 method	Yes	Yes	No	Yes	Yes	Yes
ν_e and $\bar{\nu}_e$ CC	Yes	No	No	Yes	Yes	Yes
Background Measurements for LBL:						
NC cross sections	Yes	Yes	No	Yes	Yes	Yes
π^0/γ in NC and CC	Yes	Yes	Yes	Yes	Yes	Yes
μ decays of $\pi^\pm, K^\pm$	Yes	No	No	Yes	Yes	Yes
(Semi)-Exclusive processes	Yes	Yes	Yes	Yes	Yes	Yes
Precision Measurements of Neutrino Interactions:						
$\sin^2\theta_W$ ν N DIS	Yes	No	No	No	No	Yes
$\sin^2\theta_W$ νe	Yes	No	Yes	No	No	Yes
Δs	Yes	Yes	Yes	Yes	Yes	Yes
νMSM neutral leptons	Yes	Yes	Yes	Yes	Yes	Yes
High Δm^2 oscillations	Yes	No	No	Yes	Yes	Yes
Adler sum rule	Yes	No	No	No	No	Yes
$D/(p+n)$	Yes	No	No	No	No	Yes
Nucleon structure	Yes	Yes	Yes	Yes	Yes	Yes
Nuclear effects	Yes	Yes	Yes	Yes	Yes	Yes

TABLE XXVIII: Summary of measurements that can be performed by different ND reference configurations.

Summary page from the Short-Baseline Physics Report: Roberto Petti

ELECTROMAGNETIC CALORIMETER

1. **Composed of Scintillator (5m x 25mm x 10mm) and Pb-sheets (1.75mm) in X & Y views. WLS/Clear fibre and Silicon Photo-Multiplier readout on both sides. Possibility of co-extrusion of scintillator and fibre. Reduces cost.**
2. **4π coverage surrounding STT, embedded in the magnet.**
3. **Magnet and ECAL designs linked with each other.**

4. ***A most important sub-detector of the LBNE-ND.***

5. **Downstream ECAL – One module**
   - ✓ **18 X_0 → 58 layers (29 in X and 29 in Y) → ~ 50cm in Z**
6. **Barrel ECAL – Four modules (To p/Bottom and Left/Right)**
   - ✓ **10 X_0 → 32 layers (16 in X and 16 in Y**
7. **Upstream ECAL – One Module**
   - ✓ **10 X_0 → 32 layers (16 in X and 16 in Y)**

Photon position precision in X and Y of 0.3mm.
More precise the γ position more precise is π^0.

COST ESTIMATE & SUPPORT REQUESTED

In India technical expertise exists in:

- ❖ **Scintillation Detector + Si PM → necessary for LBNE Calorimeter**
- ❖ **RPC → necessary for the Muon system, and**
- ❖ **Magnet fabrication (through Indian industry)**

Estimated cost of various components of the LBNE ND:

- ➢ **STT = $ 23.5 M**
- ➢ **ECAL = $ 18.6 M**
- ➢ **Dipole Magnet = $ 22.5 M**
- ➢ **Muon Detector = $ 8.6M**

- ✓ **Magnet + ECAL + Muon = $50M**
- ✓ **Magnet + ECAL only = $40M**
- ✓ **Magnet + Muon only = $30M**

To make a significant contribution to, and claim ownership in, the LBNE –project, need $50M (Rs. 250 crores).

THANKS TO OUR COLLEAGUES

The details of this presentation was prepared in active consultation with

- ✓ **Prof. Sanjib Mishra – Member Neutrino Working group**
- ✓ **Dr. Bill Louis – Manager Level 2, LBNE-ND**
- ✓ **Dr. Christopher Mauger – Manager Level 3, LBNE-ND**
- ✓ **Dr. David Lee**

with overall comments from
Jim Strait – Project Manager – LBNE Experiment.

THANKS TO ALL OF THEM.

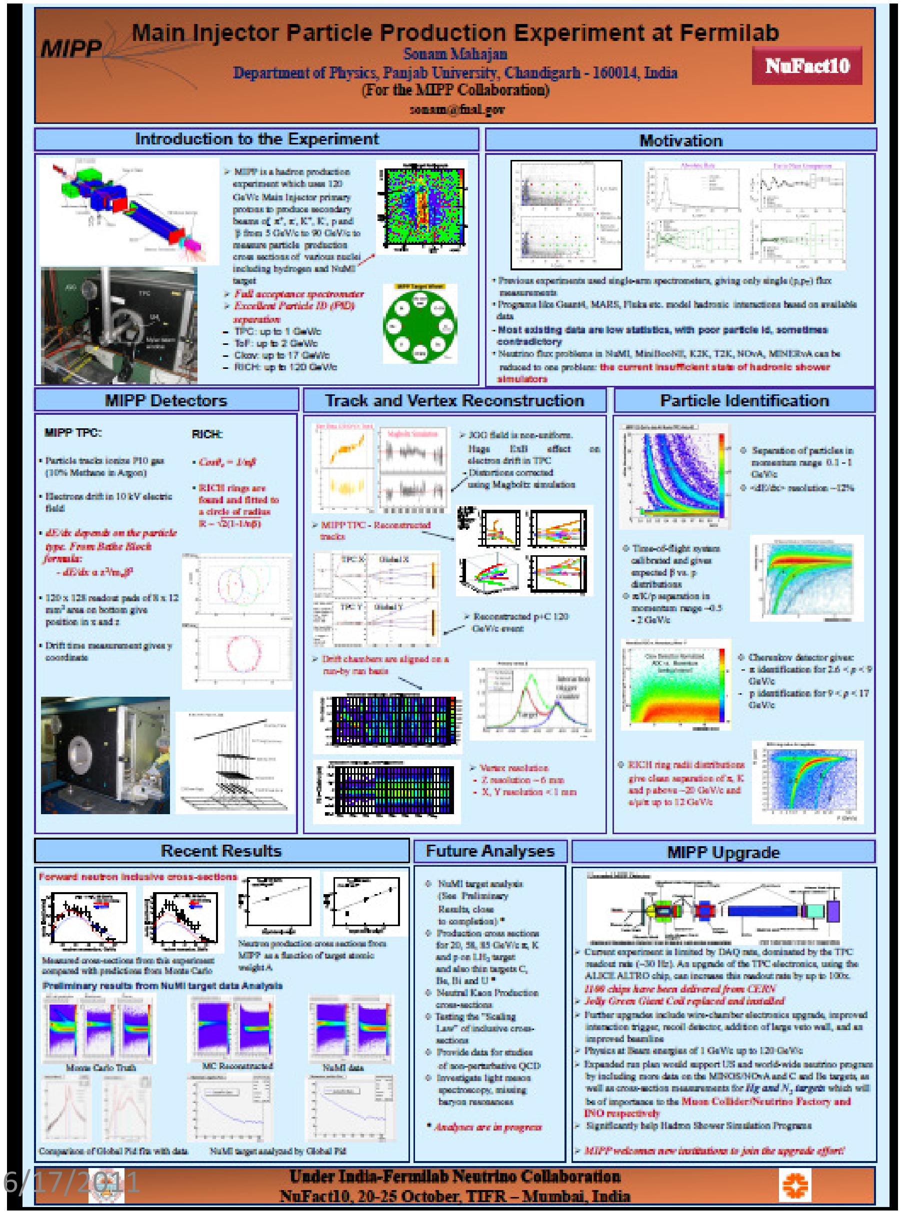
Summary and Conclusions

- India – Fermilab neutrino collaboration is progressing well.
- Students and faculty are already working on MIPP, MINOS and LBNE – at present fully supported by Fermilab resources.
- We have a proposal with the DST for support for next 3 years. Approved by DAE-DST apex committee. Funding expected soon.

- **The present proposal aims towards working on compelling neutrino and new physics for next couple of decades.**
- **Will train and generate manpower towards future scientific projects in India (students, postdocs, faculties, engineers).**
- **Complementary and synergetic to our indigenous efforts.**
- **Indian industry can play major role in detector building**
- **To further strengthen the collaboration we must participate in a big way.**
- **To make a significant contribution to the experiment, and claim ownership in, LBNE-project need support of \$50M (Rs 250 crores).**

THANK YOU

What have we achieved in a year and half ?



Sonam Mahajan – Ph.D student, PU

Advisor: Vipin Bhatnagar, PU
Co-advisor: Brajesh Choudhary, DU

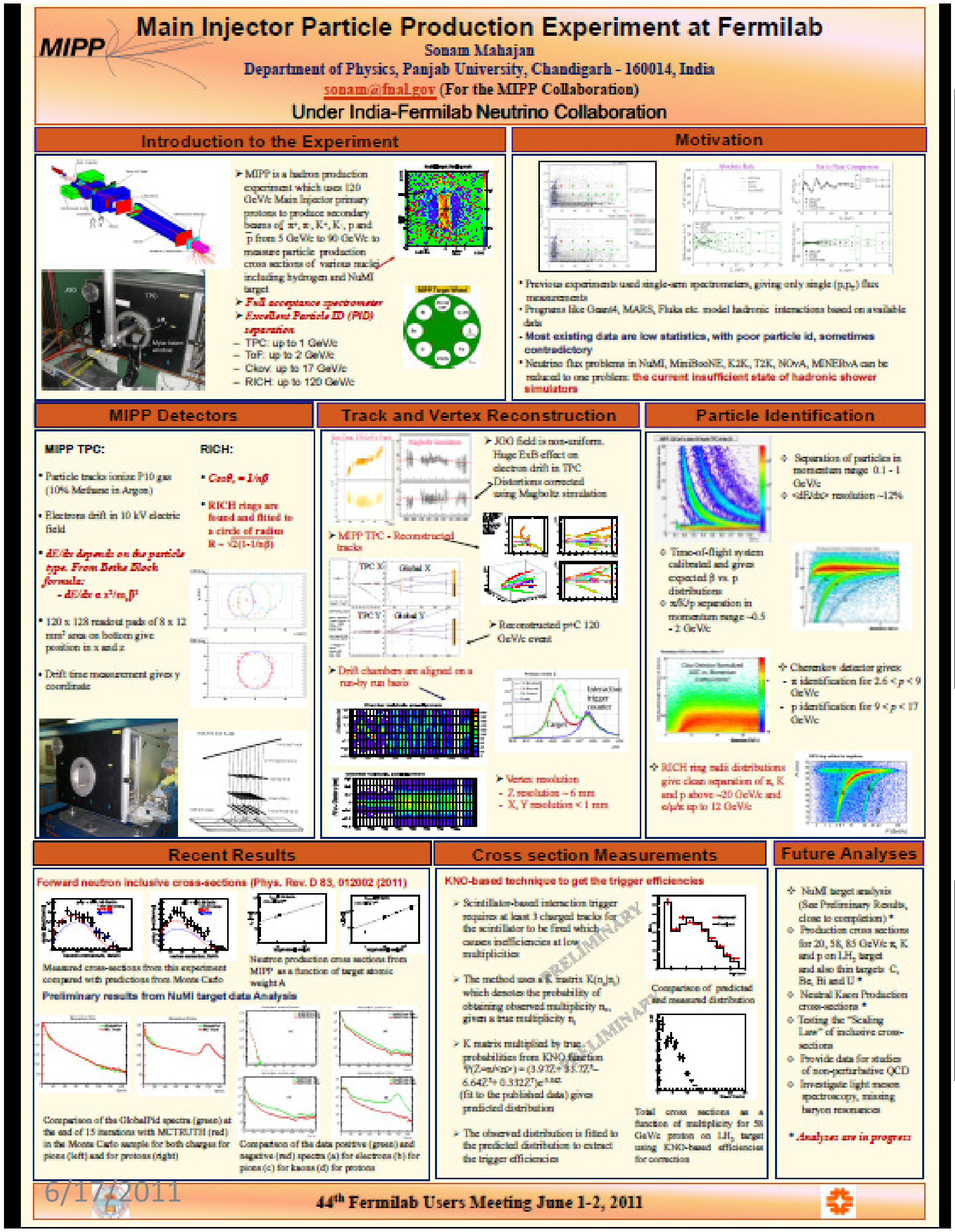
Currently working on data for interaction of 58 GeV proton on LH2.

1. Track multiplicity study.
2. Scintillator based trigger efficiency as a function of multiplicity, track momentum for 58 GeV proton on LH2, Bismuth, & Carbon targets and 120 GeV proton on Be and Carbon targets
3. Study of elastic, inelastic x-section using DPMJET
4. KNO scaling, etc. etc.

Presented a poster on behalf of the collaboration at NuFact10.

Very encouraging response.

What have we achieved in a year and half?



Sonam Mahajan – Ph.D student, PU

Advisor: Vipin Bhatnagar, PU
Co-advisor: Brajesh Choudhary, DU

Presented a poster on behalf of the MINOS collaboration at Fermilab's annual users meeting.

Very encouraging response.

Further work to appear as poster at Lepton Photon 2011 to be held at TIFR, Mumbai, 22-27 August, 2011.

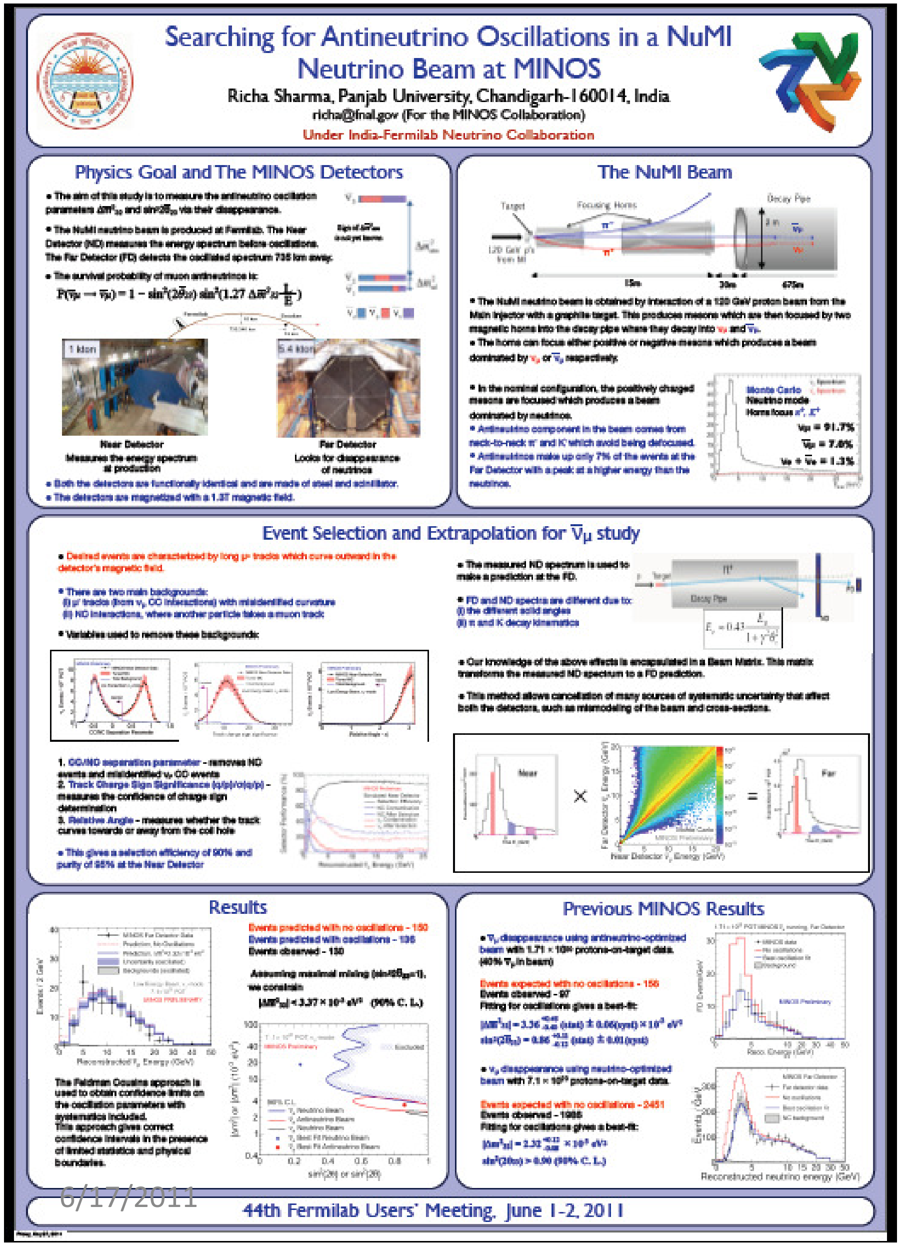
What have we achieved in a year and half?

Richa Sharma – Ph.D student, PU
Advisor: Vipin Bhatnagar, PU, Co-advisor: Brajesh Choudhary, DU

Working on charge current analysis with anti-neutrino data at MINOS.
Gave a talk at APS April meeting at Anaheim, CA from April 30 – May 3, 2011.

MINOS has previously reported the results of $\bar{\nu}_\mu$ disappearance from a direct observation of muon antineutrinos. The antineutrinos studied for this purpose are taken from two types of beam configurations: (a) Forward Horn Current (FHC), optimized for ν_μ selection where the $\bar{\nu}_\mu$ content is 7% of the neutrino beam, and (b) Reverse Horn Current (RHC), optimized for $\bar{\nu}_\mu$ selection where the $\bar{\nu}_\mu$ content is 40% of the beam. The previous analyses were based on 3.2e20 protons on the NuMI target in FHC configuration and 1.7e20 protons on target in RHC configuration. These analyses make a precise measurement of the oscillation parameters $\Delta\bar{m}^2_{23}$ and $sin^2 2\bar{\theta}_{23}$ and also constrain the fraction of ν_μ that oscillate to $\bar{\nu}_\mu$. In the present analysis we have an FHC $\bar{\nu}_\mu$ data sample with 7.1e20 protons on target which will be used to improve the previous measurements. This talk summarizes the agreement between data and simulation in the Near Detector at Fermilab.

What have we achieved in a year and half?



Richa Sharma – Ph.D student, PU

Advisor: Vipin Bhatnagar, PU
Co-advisor: Brajesh Choudhary, DU

Presented a poster on behalf of the MINOS collaboration at Fermilab's annual users meeting.

Very encouraging response.

What have we achieved in a year and half?

Amandeep Singh – Ph.D student, PU
Advisor: Ashok Kumar, PU.

Working towards his Ph.D thesis on MIPP. At present working on Ks analysis.

Arun Kumar Soma – Ph.D student, BHU
Advisor: Venktesh Singh, BHU.

Participated in MIPP data analysis for six months. Work to appear in paper.

Sourav Tarafdar – Ph.D student, BHU
Advisor: Venktesh Singh, BHU.

Participating in MIPP data analysis for one year. Work to appear in paper.

Navaneeth Poomthottathil - Ph.D student, CUSAT
Advisor - Ramesh BabuThayyullathil

Recently joined. Getting started with basics of EHEP, Neutrino Physics, HEP related detectors etc. Hope to be in Fermilab by beginning of 2012.

What have we achieved in a year and half?

LBNE Document # 916, Version 2
July 9, 2010

Simulation of the Cosmic Muon flux at the Homestake Mine.

Bipul Bhuyan
Department of Physics
Indian Institute of Technology Guwahati, India

Abstract

Simulated results on the cosmic ray muon flux at the 4850 level in the Homestake mine has been presented. The expected cosmic ray muon flux is 4.63×10^{-9} Hz/cm^2 at the 4850 level which corresponds to an integrated muon flux of 1459 μ / m^2 / year. The flux distrubution as a function of the muon energy as well as the zenith angle has also been presented.

1

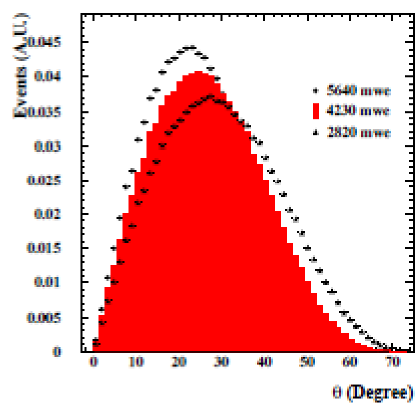


Figure 5: Zenith angle distributions for Cosmic Muon flux at the depth of 5640 m.w.e, 4230 m.w.e and 2820 m.w.e.

What have we achieved in a year and half?

LBNE : Physics Reach & Status

Brajesh Choudhary
University of Delhi, Delhi
On behalf of LBNE Collaboration

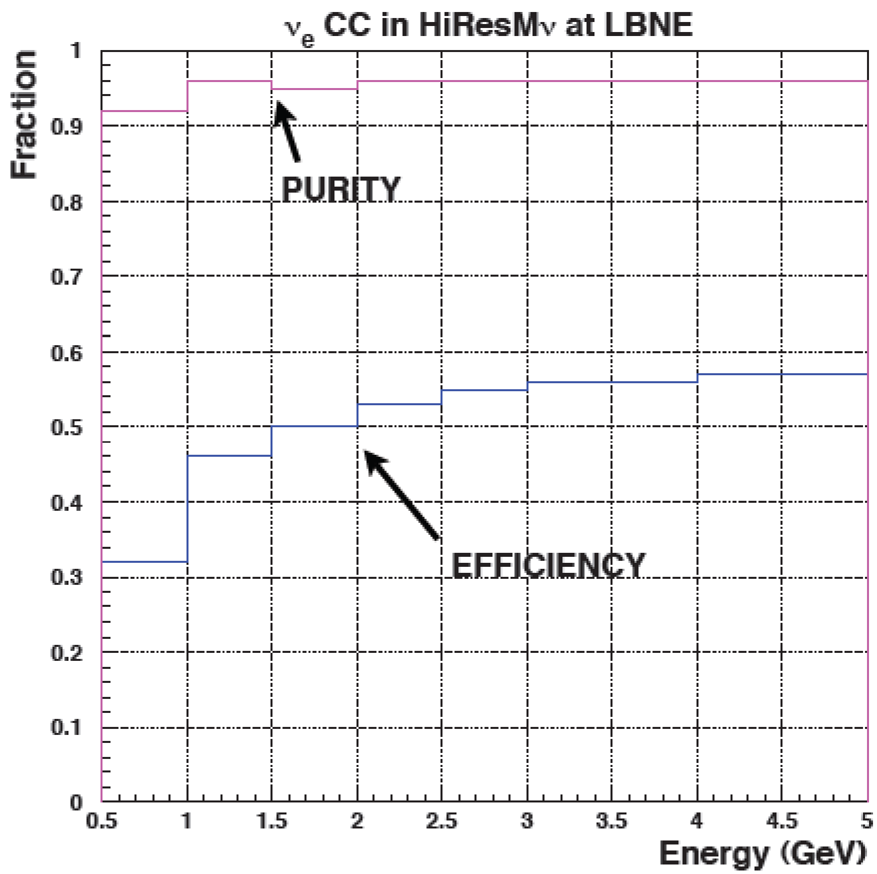
12th International Workshop on Neutrino Factories, Superbeams and Beta Beams
20-25 October, 2010,
TIFR-Mumbai, India

Current Status & Deliverables Over Next 3 Years

- **Current Status**
  - Since January 2010 – 4+1 Ph.D students & 4 faculty have visited Fermilab.
  - Three (2+1) Ph.D student (stationed at Fermilab) are working towards thesis on MIPP (2 students) and MINOS (1 student) respectively. One more to follow soon.
  - One faculty was awarded a prestigious International fellowship.

- **With the present funding - Expected Deliverables till 2014**
  - Establish detector R&D labs at Delhi, Panjab and Banaras.
  - Establish simulation center at IIT(G), DU and PU.
  - New groups at CUSAT, HU, JU and IIT(H) - to launch multi-faceted activities at four institutions.
  - Senior Ph.D students to work on neutrino physics at Fermilab.
  - We expect 3 students to write thesis on MIPP.
  - We expect 2 students to write thesis on MINOS.
  - Other students to write thesis on MINOS, MINOS+, NOνA & LBNE.
  - With time we will ramp up participation of students as well as faculty.
  - Later we will work on NOνA and LBNE.
  - Participate in the design of LBNE near detector.

IDENTIFICATION OF ν_e CC INTERACTIONS



- *The HiResMν detector can distinguish electrons from positrons in STT*
  - $\Longrightarrow$ *Reconstruction of the e's as bending tracks NOT showers*
- *Electron identification against charged hadrons from both TR and dE/dx*
  - $\Longrightarrow$ *TR π rejection of 10^{-3} for $\varepsilon \sim 90\%$*
- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject non-prompt backgrounds (π^0 in ν_μ CC and NC)*
  - $\Longrightarrow$ *On average $\varepsilon =$ 55% and $\eta =$ 99% for ν_e CC at LBNE*

VeBar-CC Sensitivity:

If we keep the signal efficiency at ~55%, then purity is about 95%

Absolute Flux using ν-e Elastic NC Scattering

- Using the Weak Mixing Angle (0.238) at Q~0.1 GeV (known to ≤1% precision)

⇒ $\sigma(\nu_x e\text{-NC})$ known ⇒ Absolute-$\phi(\nu_x)$

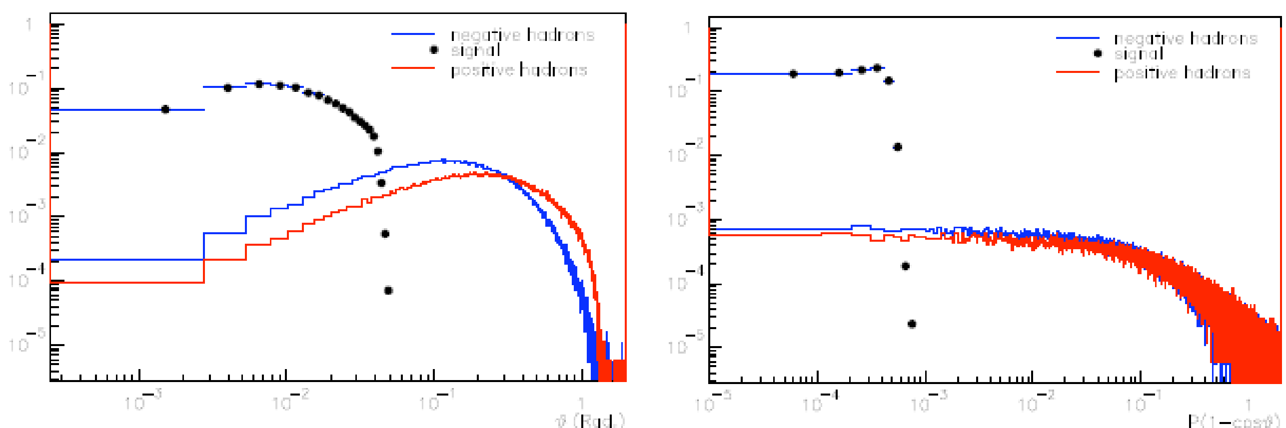
- ν-e ➠ Signal: Single, forward e-

Background: NC induced π_0 ➠ γ ➠ e- (e+ invisible): charge-symmetric

- Two-step Analysis: ✵Electron-ID:TR ✵Kinematic cut: ζ=Pe(1-cosΘe)

Simulation of charged hadron background.

(use LBNE Flux)



θ $\qquad$ $\zeta \ (\equiv P_e(1-\cos\theta))$

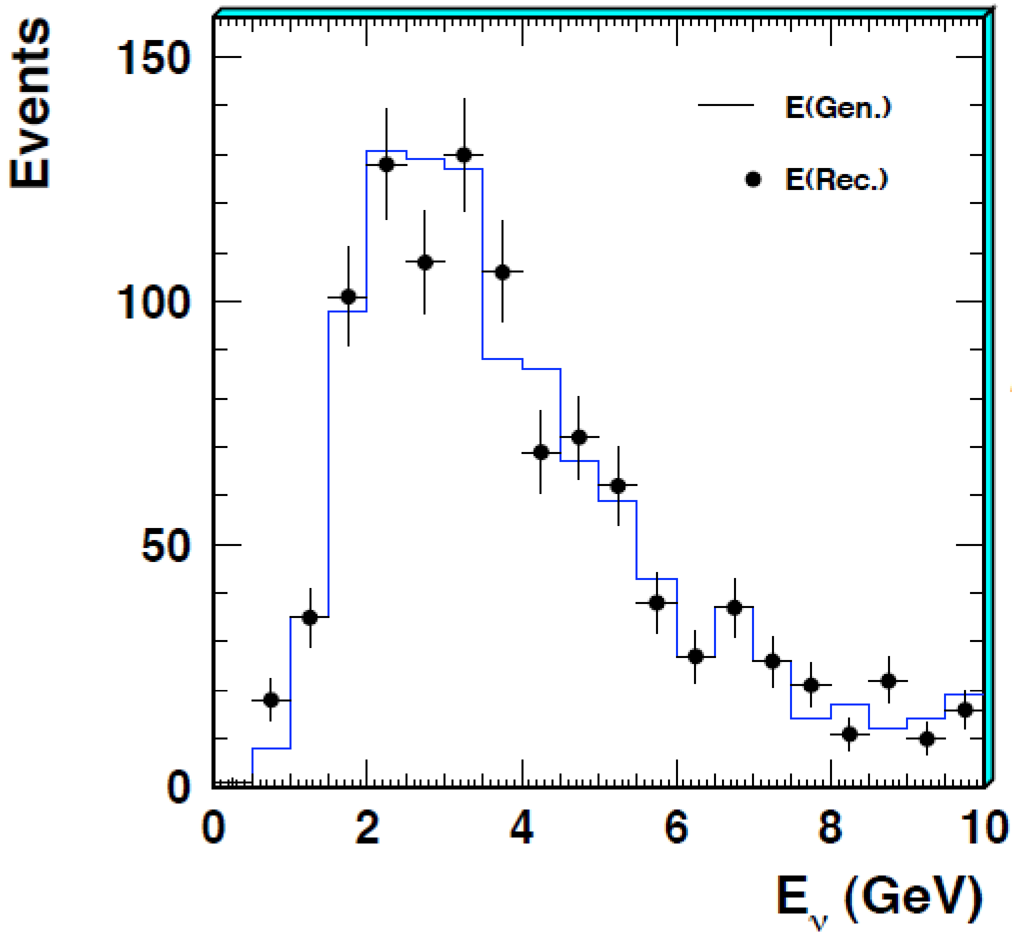
Background charge symmetric & benign

Eff➢64%
Bkg➢ ≤10**(-6) ⇚ Measured

⇚ Conclusion

Absolute Flux using ν-e Elastic Scattering

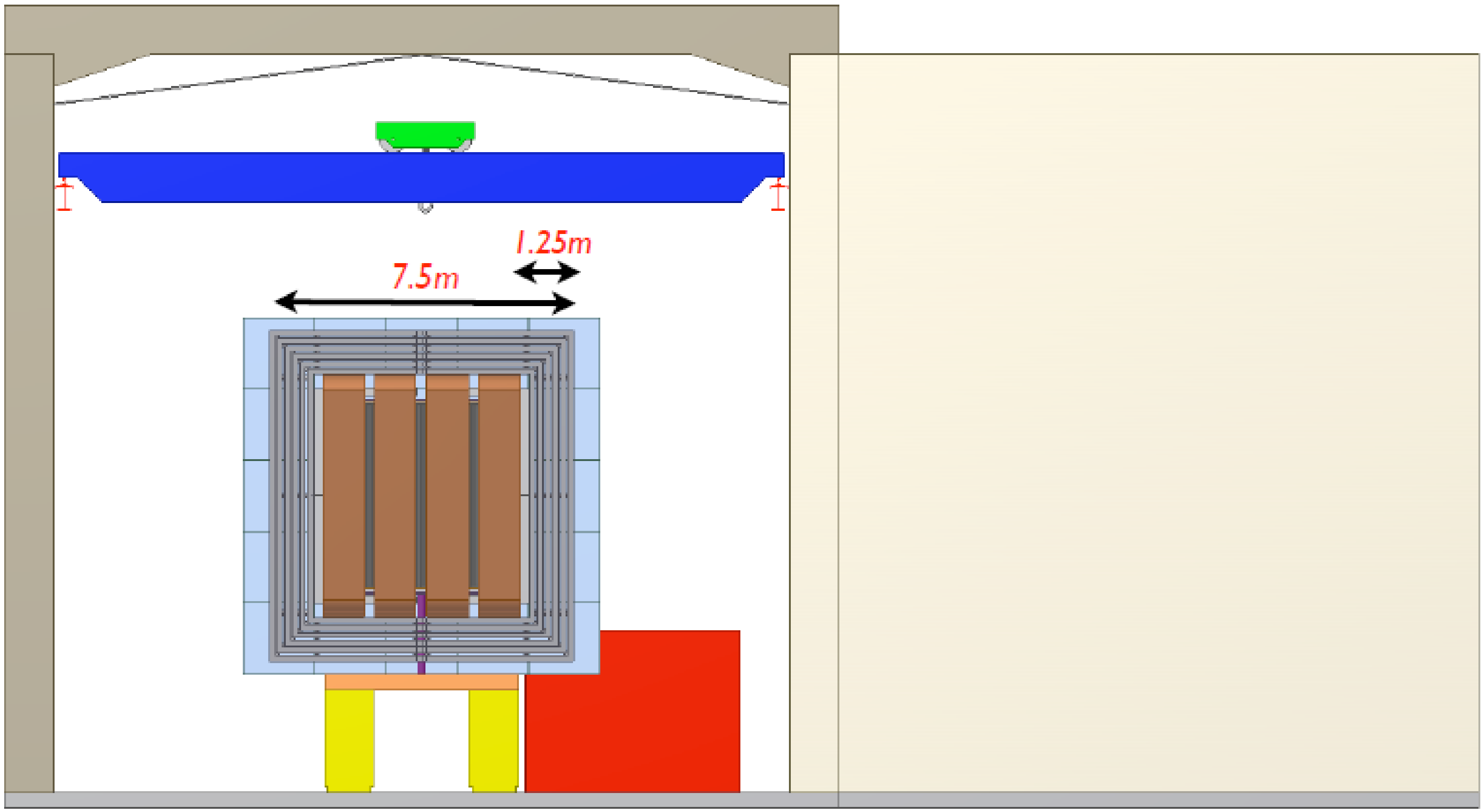
- Shape of Enu using (Ee, θe):
- The precision on relative ν-flux (shape) is worse than in that determined using Low-ν0 technique

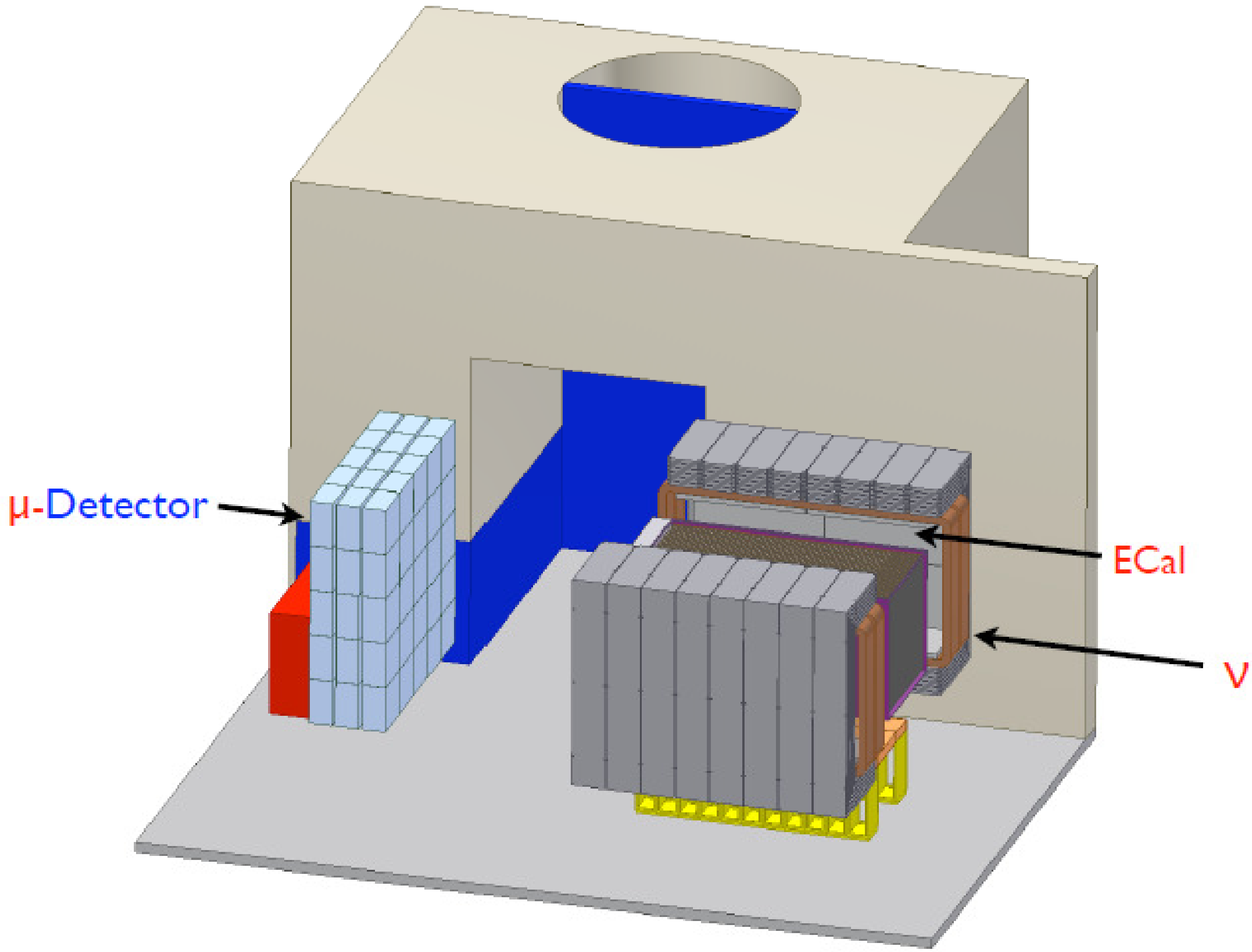


1<Enu<4 => 1000 events
700kW; 3Yr Nu-Run

⇛ *ND will provide ~3% precision on Absolute-ν_μ*

Front View: Dipole Magnet in ND Hall




μ-Detector
ECal
ν