LBNE

Long-Baseline Neutrino Experiment

Bob Wilson, Vaia Papadimitriou, Jim Strait

for the LBNE Collaboration

P5 Open Meeting

Fermilab

3rd November 2013

Colorado State University

U.S. DEPARTMENT OF ENERGY

Overview

Bob Wilson – Co-Spokesperson

- LBNE Science Objectives and Anticipated Results

Vaia Papadimitriou – LBNE Beamline Manager

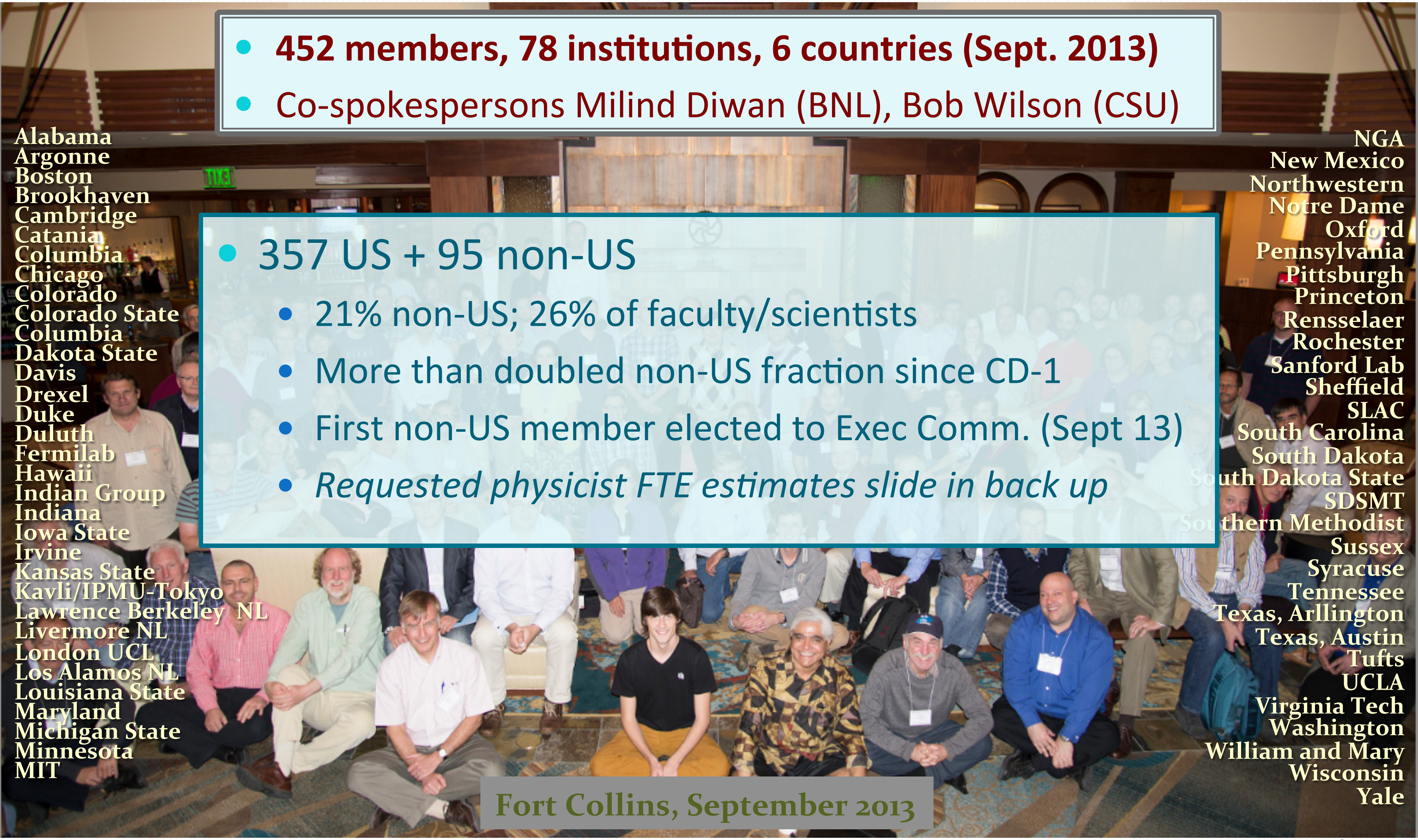
- LBNE Beamline Planning and Options

Jim Strait – Project Director

- LBNE Project Scope, Cost, Schedule and International Participation

LBNE Science Collaboration

- **452 members, 78 institutions, 6 countries (Sept. 2013)**
- Co-spokespersons Milind Diwan (BNL), Bob Wilson (CSU)



- 357 US + 95 non-US
  - 21% non-US; 26% of faculty/scientists
  - More than doubled non-US fraction since CD-1
  - First non-US member elected to Exec Comm. (Sept 13)
  - *Requested physicist FTE estimates slide in back up*

Alabama
Argonne
Boston
Brookhaven
Cambridge
Catania
Columbia
Chicago
Colorado
Colorado State
Columbia
Dakota State
Davis
Drexel
Duke
Duluth
Fermilab
Hawaii
Indian Group
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lawrence Berkeley NL
Livermore NL
London UCL
Los Alamos NL
Louisiana State
Maryland
Michigan State
Minnesota
MIT

NGA
New Mexico
Northwestern
Notre Dame
Oxford
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arllington
Texas, Austin
Tufts
UCLA
Virginia Tech
Washington
William and Mary
Wisconsin
Yale

Fort Collins, September 2013

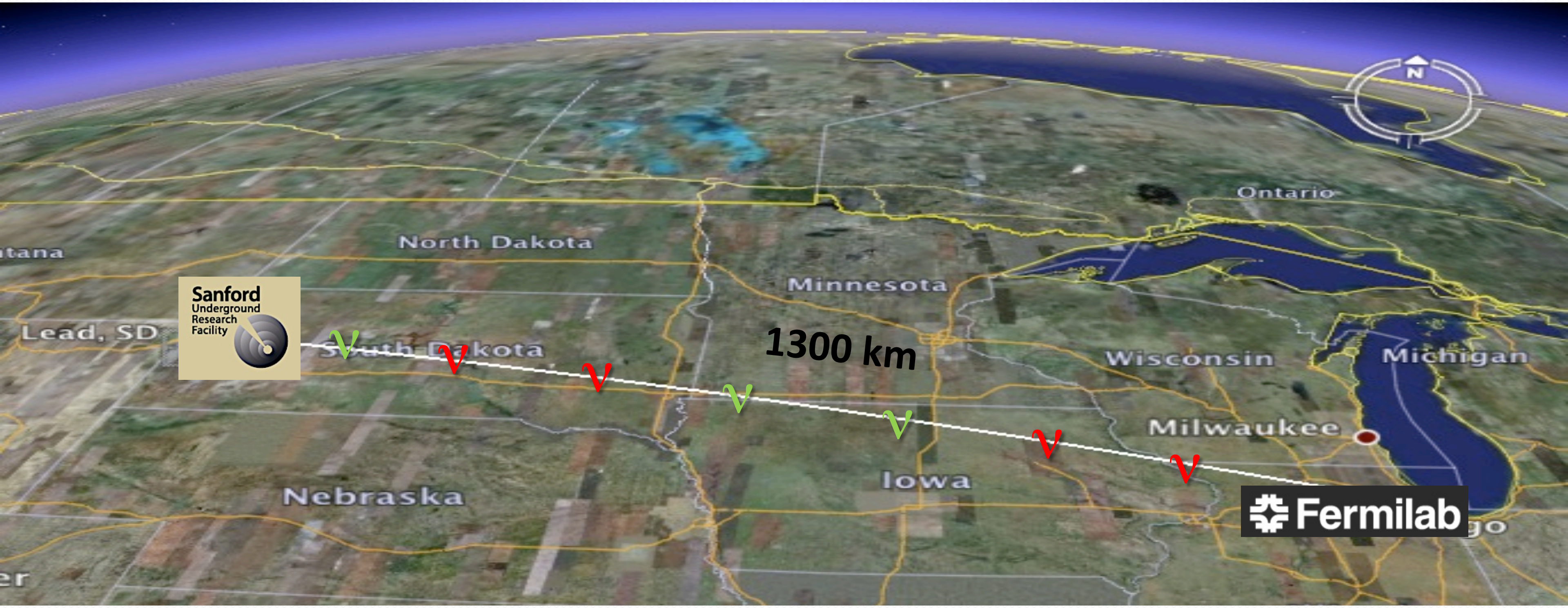
Primary Scientific Objectives

- **CP Violation in neutrino sector**
- CP Phase measurement
- Neutrino Mass Hierarchy determination
- Testing Three Neutrino-Flavor Paradigm
  - Non-Standard neutrino interactions
  - Sterile Neutrinos
- Neutrino interaction measurements
- Supernova Burst Neutrinos
- Nucleon Decay measurement

What we know…

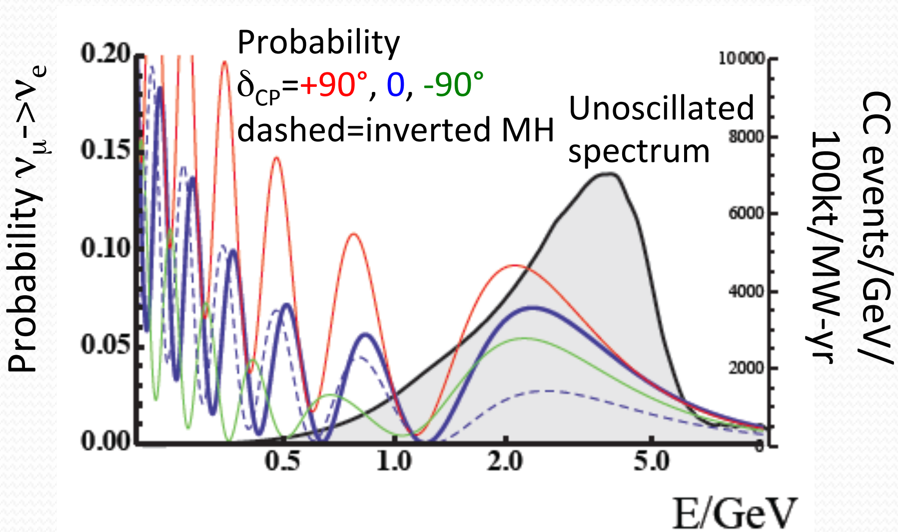
- Magnitudes of Δm_{31}^2, Δm_{21}^2, θ_{12} are well-measured (few %)
- θ_{23} is large, possibly maximal – measurement ~20%
- **θ_{13} is well-measured and <u>large</u> enough so event rates are sufficient for CP and MH measurements**
  - Barely 18 months ago we were still afraid it was zero!
- Matter induced asymmetry is large (~40% for LBNE) and separable from CP asymmetry at appropriately chosen neutrino energy and baseline
- **We can accurately predict the events rates for unknown CP phase angles and mass hierarchy in the three-flavor model**

Long-Baseline Measurements & Oscillation Parameter Sensitivities



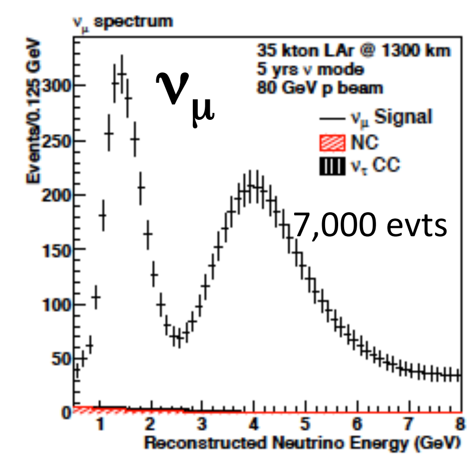
- Far Detector mass assumptions: 10 kt -> 35 kt
- Proton beam power assumptions: 700 kW -> 1.2 MW -> 2.3 MW
- Exposure: Detector Mass x Beam Power x Time

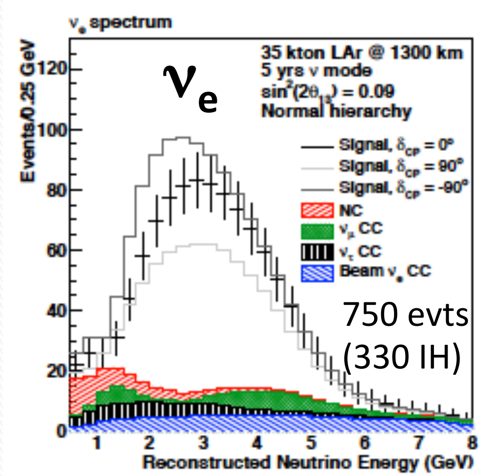
Essential Experimental Technique



disappearance

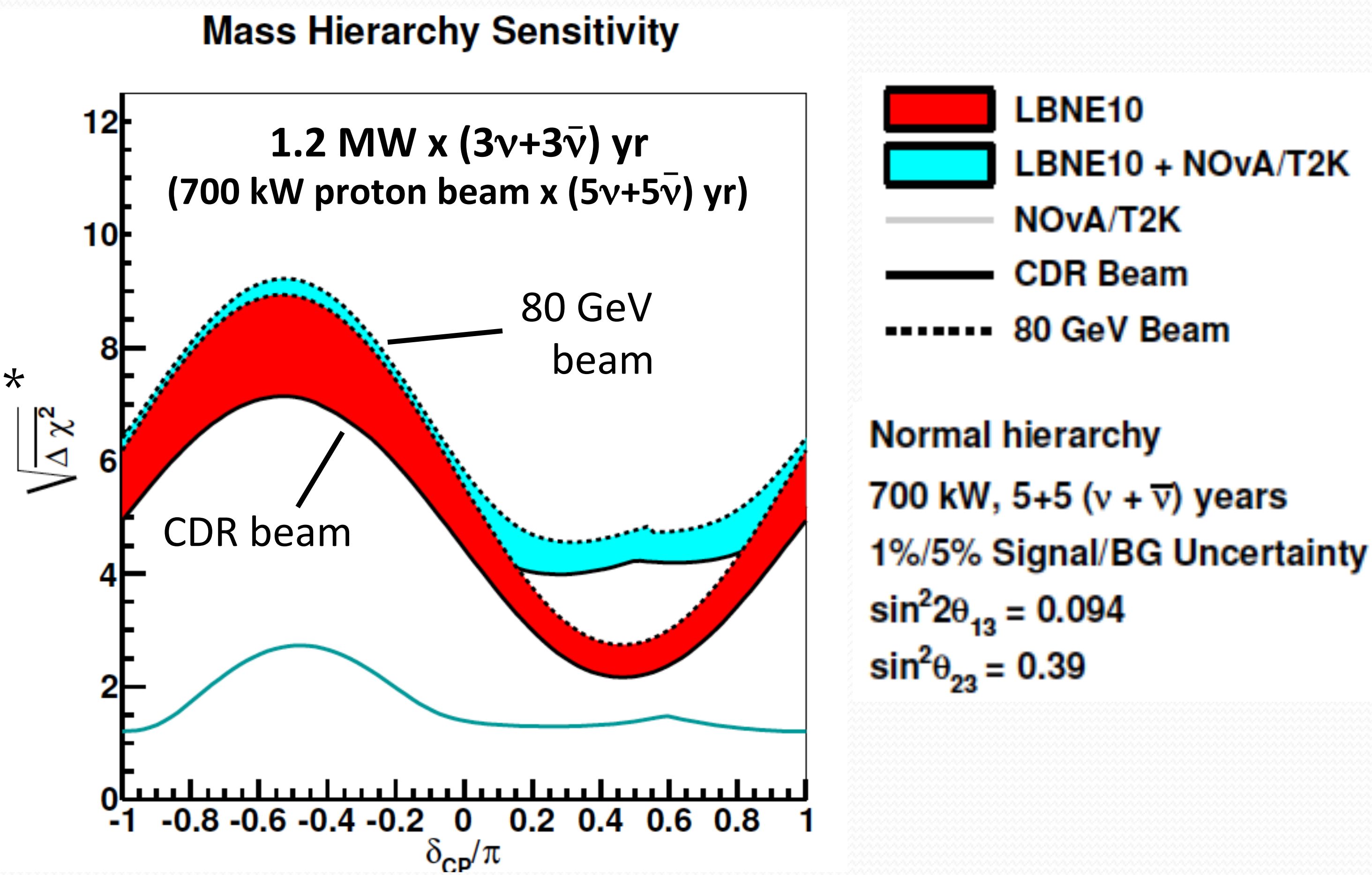
appearance





- Produce a pure ν_μ muon-neutrino beam with energy spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- **LBNE is a near optimal choice of beam and distance for sensitivity to CP violation, CP phase, neutrino mass hierarchy and other oscillation parameters in same experiment**

MH Sensitivity – 10 kt Far Detector



* For binary MH choice this does not correspond to C.L. of Gaussian σ

- LBNE 10 kt does much better than current/near term long-baseline experiments
- T2K+NOvA results help significantly if δ_{CP} at worst value

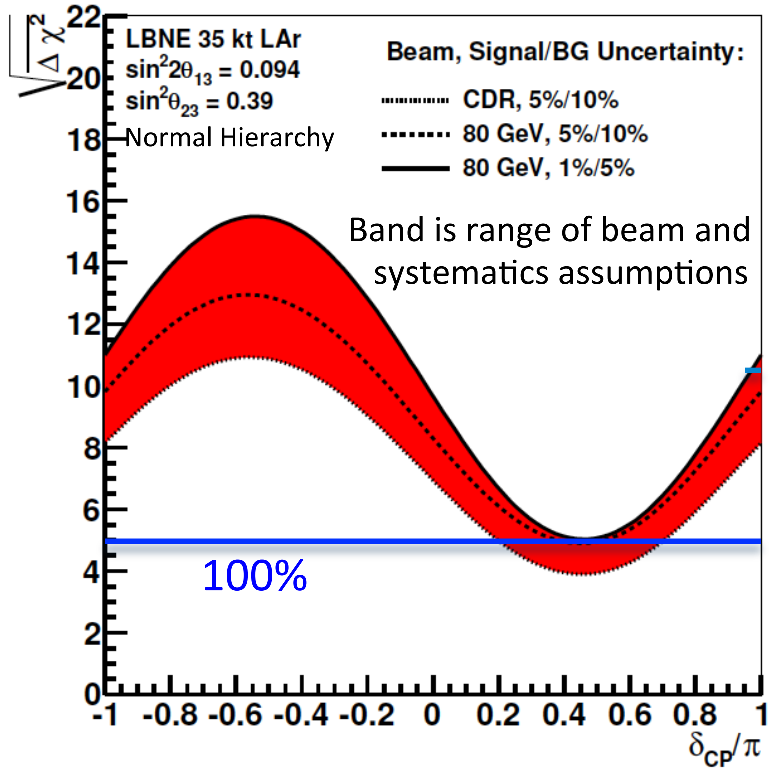
MH & CPV – 35 kt

Exposure 245 kt.MW.yr

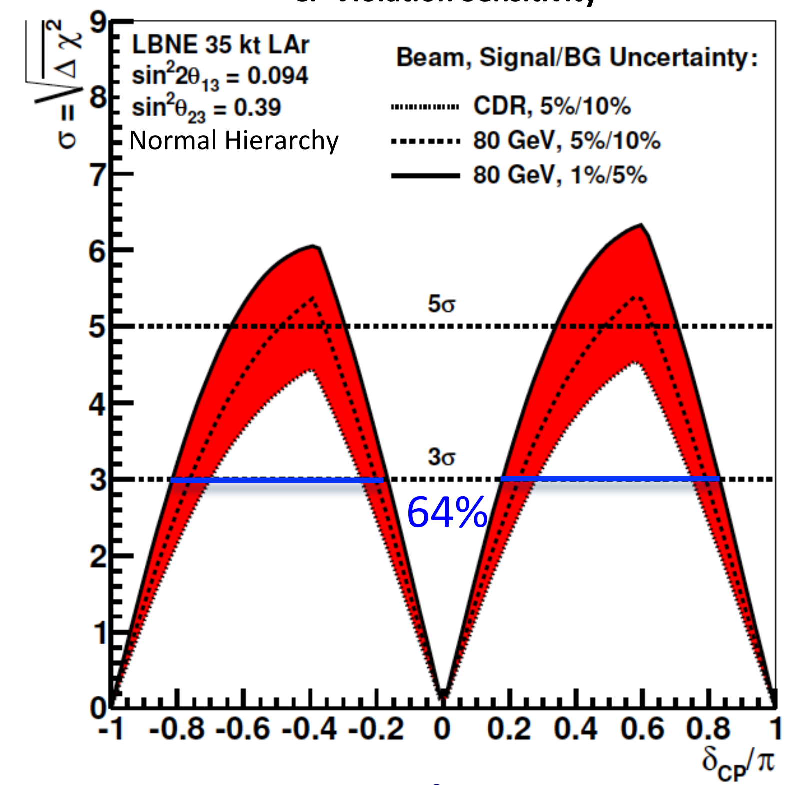
1.2 MW x (3ν+3ν̄) yr (700 kW x (5ν+5ν̄) yr)

or 20 kt at 1.2 MW x (5ν+5ν̄) yr

Mass Hierarchy Sensitivity

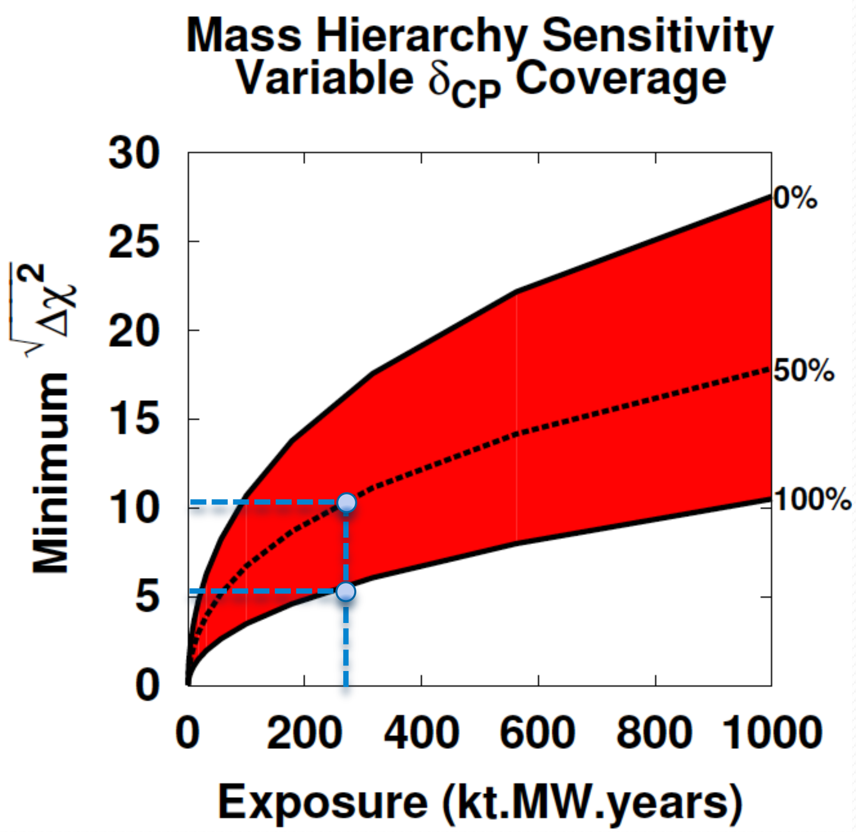


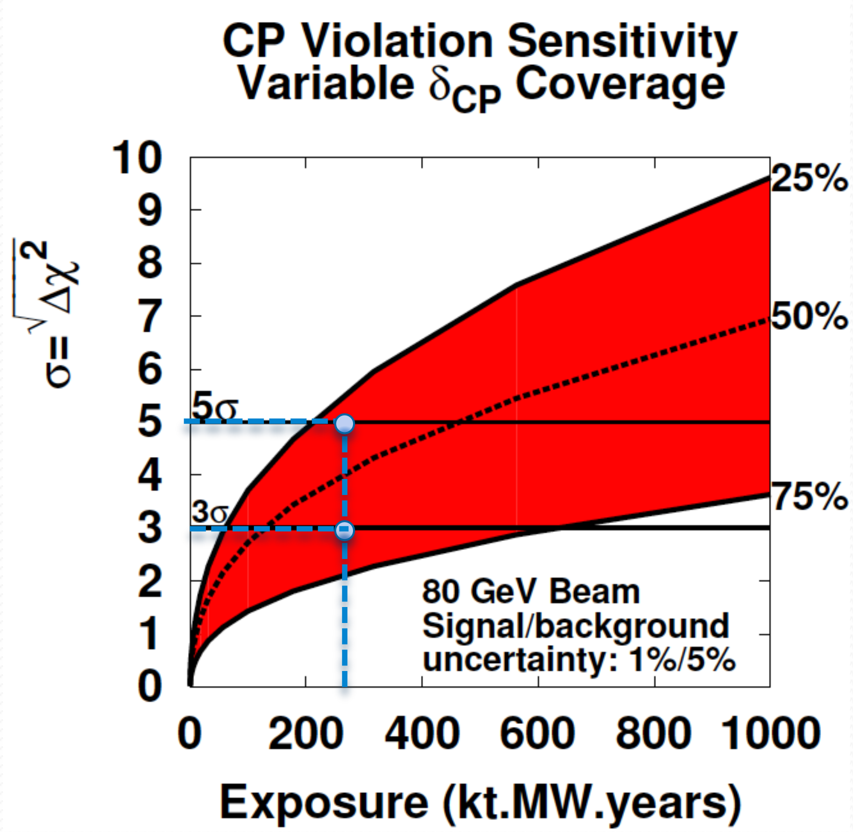
CP Violation Sensitivity



- Mass hierarchy is very well determined over most of δ_{CP} range
  - **Indep. 2-3 σ cross-check from atmospherics in LBNE and from other expts**
- CPV > 3σ over most of range and > 5σ for maximal CPV

MH & CPV Sensitivity vs. Exposure



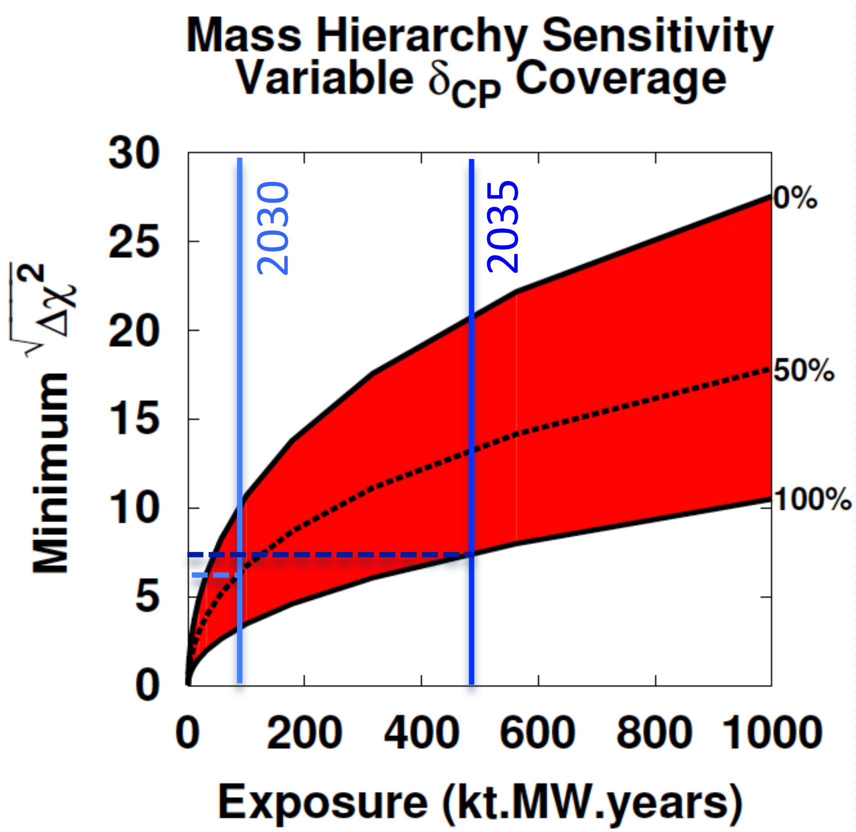


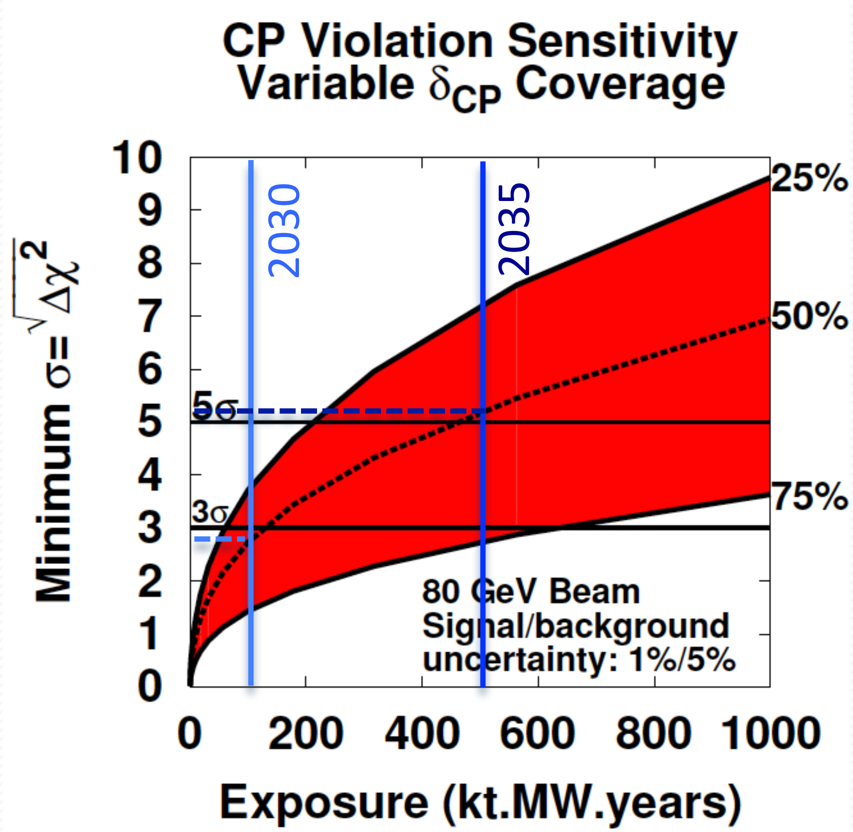
- Plot of minimum level of significance $\sqrt{\Delta\chi^2}$ for fraction δ_{CP} coverage, i.e. much of the range is significantly above this value

Detector Mass/Beam Power Scenario

- Plausible timeline
- 2025
  Detector mass: 15 kt (fid.)
  Proton beam power: 1200 kW
- 2030
  Exposure: 90 kt.MW.yr
  Add 20 kt = 35 kt
  Proton beam power: 2300 kW
- 2035
  Exposure: 490 kt.MW.yr

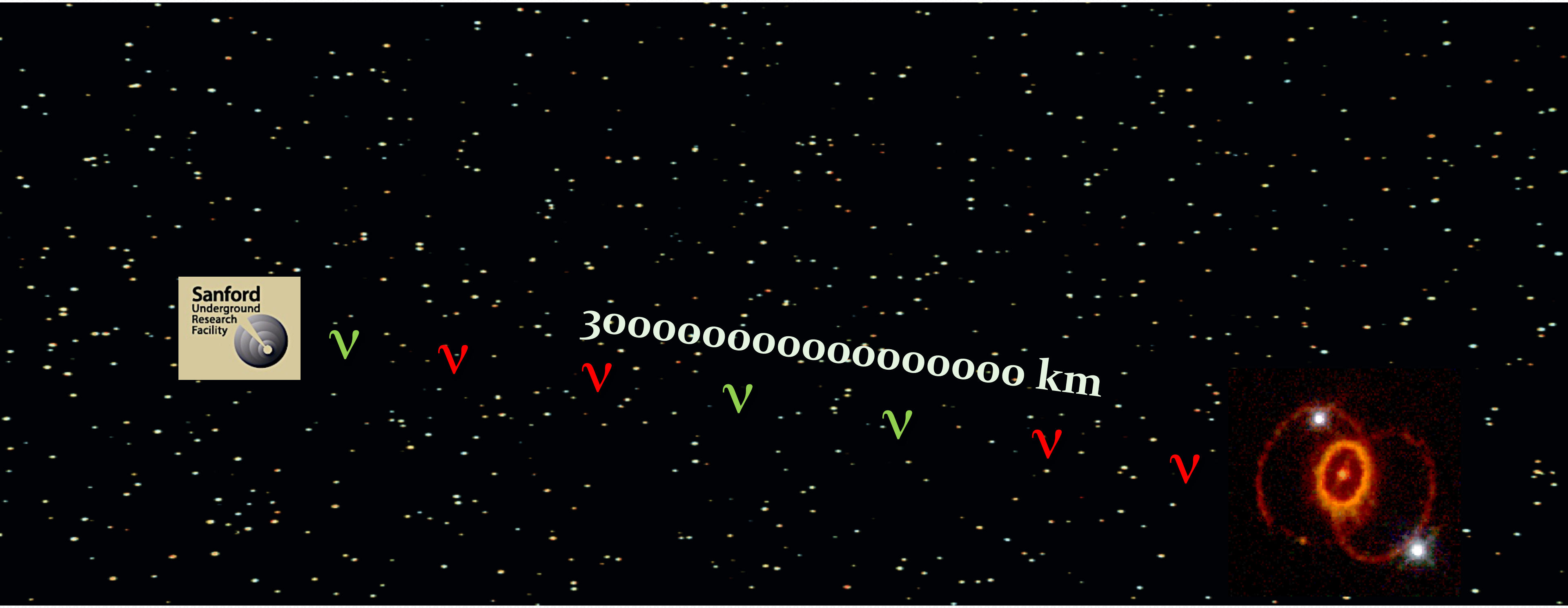
Detector/Beam Scenario
5 yr@15kt/1.2MW + 5 yr@35kt/2.3MW





- For MH minimum $\sqrt{\Delta\chi^2} > 5$ for 50% of δ_{CP} by 2030, 100% by 2035
- For CPV $\sigma \approx 3$ for 50% of δ_{CP} by 2030, $\approx 5\sigma$ for 50% by 2035

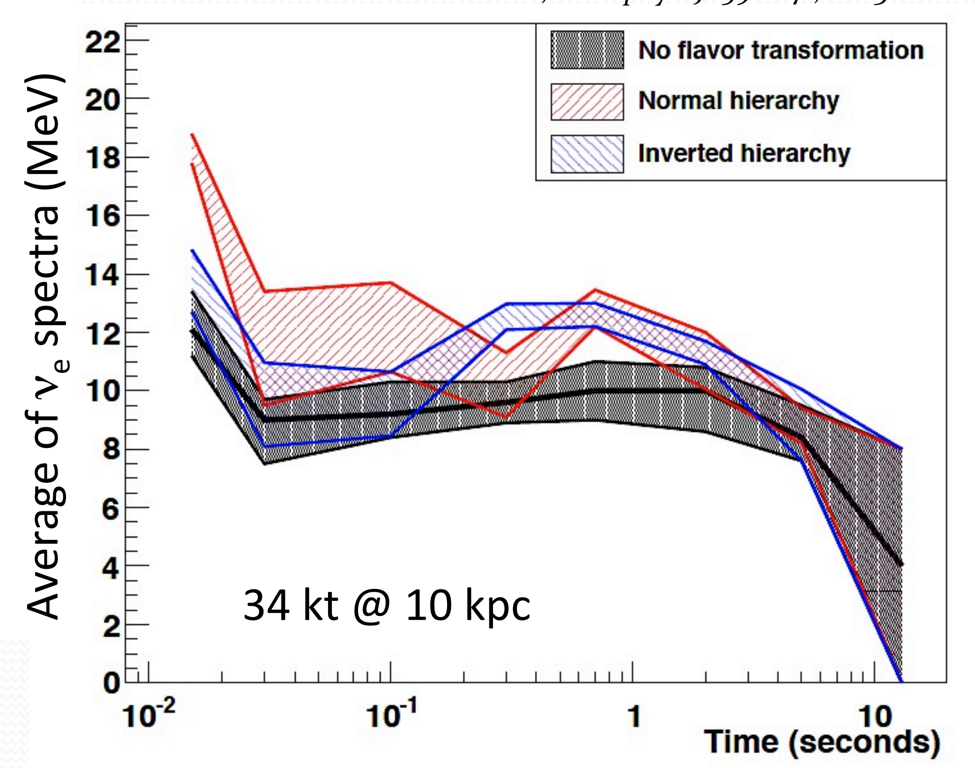
Supernova Burst Neutrinos



- When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into ν's
- SN at galactic core (10 kpc) $\Rightarrow$ several thousand interactions in 35 kt LArTPC in tens of seconds

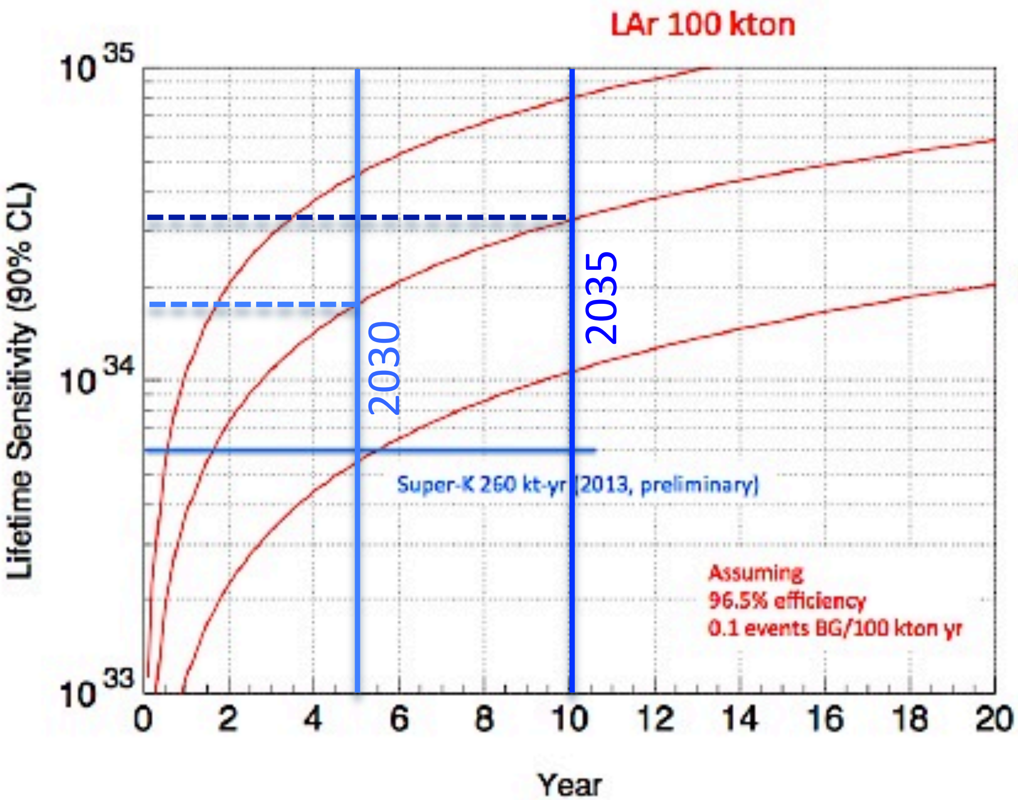
SNOwGLoBES-Smeared Spectrum

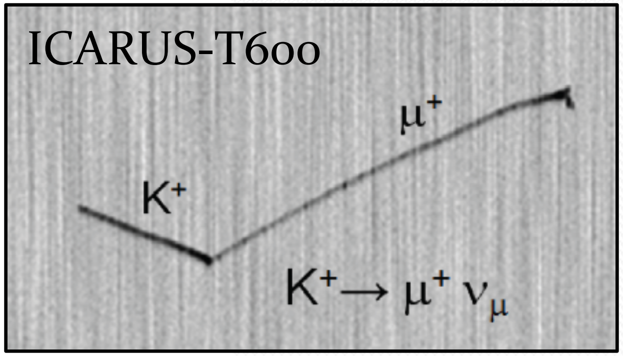
Fluxes with collective oscillations from J. Cherry, A. Friedland and H. Duan based on Keil et al. model, *Astrophys. J.* 590:871, 2003



- Time evolution of ν_e spectra provides information on MH assumptions
- Just one example of richness of time information
- LArTPC will provide detailed information complementary to SK

Proton Decay





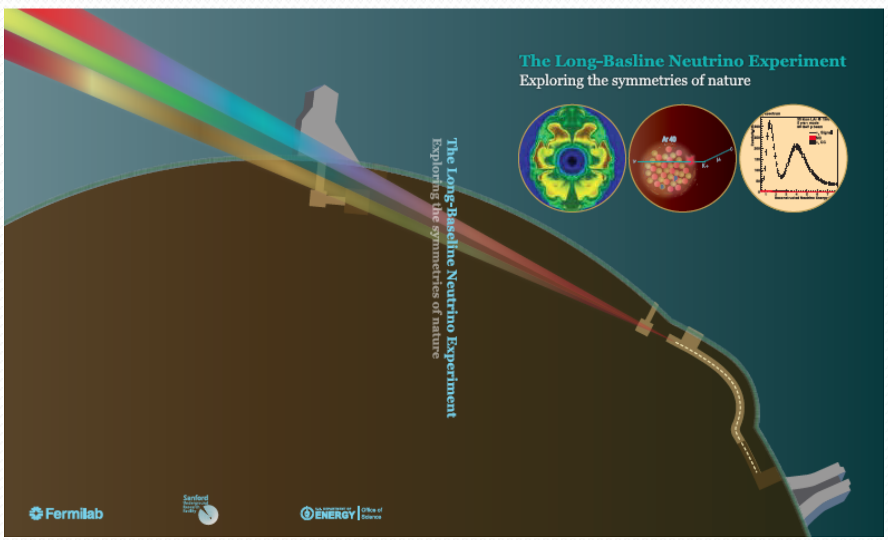
Decay Mode	Water Cherenkov Efficiency	Water Cherenkov Background	Liquid Argon TPC Efficiency	Liquid Argon TPC Background
$p \to \nu K^+$	19%	4	97%	1
$p \to \mu^+ K^0$	10%	8	47%	< 2
$p \to \mu^- \pi^+ K^+$			97%	1
$n \to e^- K^+$	10%	3	96%	< 2
$n \to e^+ \pi^-$	19%	2	44%	0.8

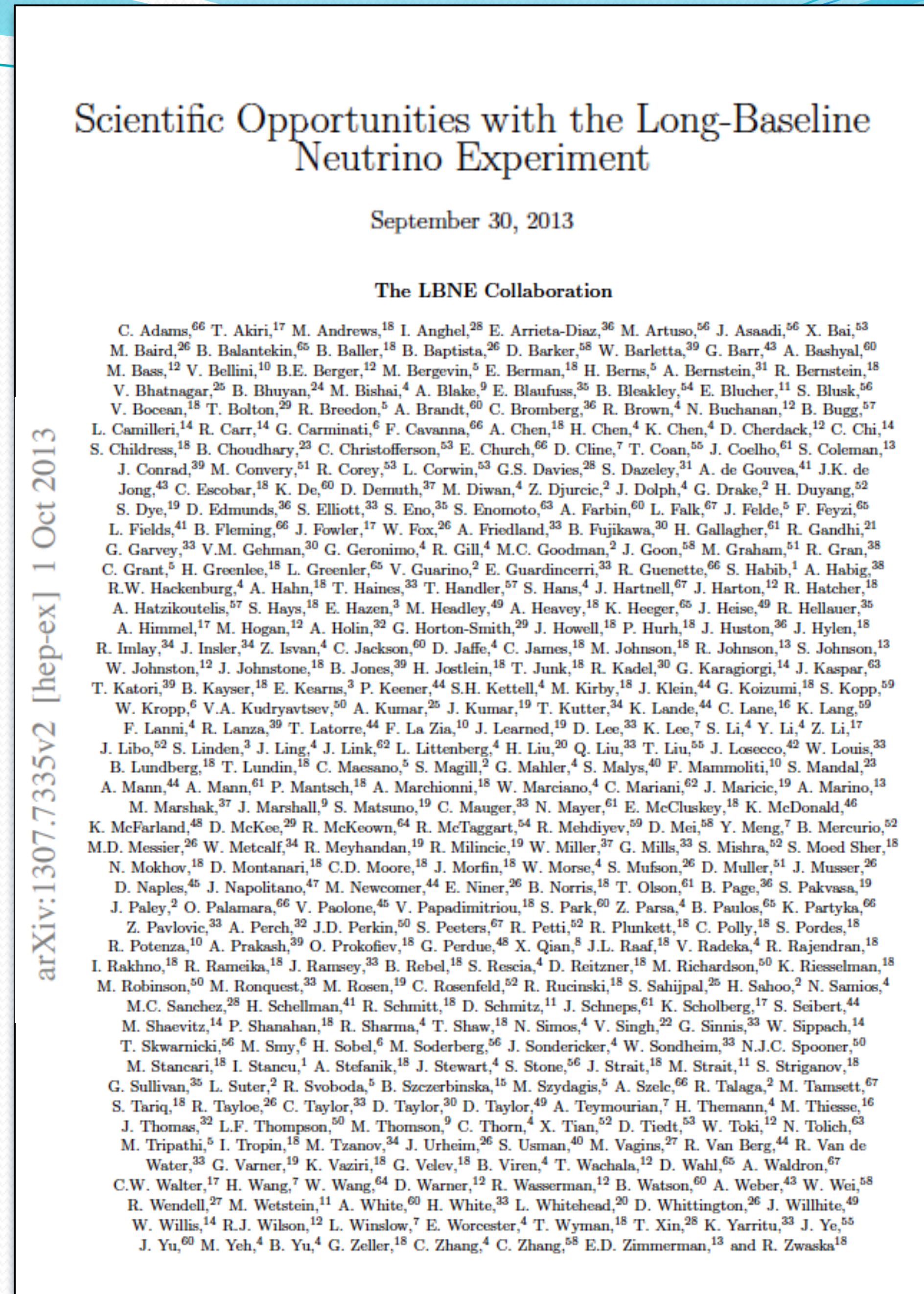
events per Mt.yr

- LAr TPC high efficiency/low background for kaon modes
- Essential if signal is in lifetime sensitivity range
- Especially interesting if SUSY discovered at LHC

More Details:

- Snowmass detailed-whitepaper arXiv:1307.7335
- Content update and printed "book" this fall





arXiv:1307.7335v2 [hep-ex] 1 Oct 2013

Scientific Opportunities with the Long-Baseline Neutrino Experiment

September 30, 2013

The LBNE Collaboration

C. Adams,[66] T. Akiri,[17] M. Andrews,[18] I. Anghel,[28] E. Arrieta-Diaz,[36] M. Artuso,[56] J. Asaadi,[56] X. Bai,[53] M. Baird,[26] B. Balantekin,[65] B. Baller,[18] B. Baptista,[26] D. Barker,[58] W. Barletta,[39] G. Barr,[43] A. Bashyal,[60] M. Bass,[12] V. Bellini,[10] B.E. Berger,[12] M. Bergevin,[5] E. Berman,[18] H. Berns,[5] A. Bernstein,[31] R. Bernstein,[18] V. Bhatnagar,[25] B. Bhuyan,[24] M. Bishai,[4] A. Blake,[9] E. Blaufuss,[35] B. Bleakley,[54] E. Blucher,[11] S. Blusk,[56] V. Bocean,[18] T. Bolton,[29] R. Breedon,[5] A. Brandt,[60] C. Bromberg,[36] R. Brown,[4] N. Buchanan,[12] B. Bugg,[57] L. Camilleri,[14] R. Carr,[14] G. Carminati,[6] F. Cavanna,[66] A. Chen,[18] H. Chen,[4] K. Chen,[4] D. Cherdack,[12] C. Chi,[14] S. Childress,[18] B. Choudhary,[23] C. Christofferson,[53] E. Church,[66] D. Cline,[7] T. Coan,[55] J. Coelho,[61] S. Coleman,[13] J. Conrad,[39] M. Convery,[51] R. Corey,[53] L. Corwin,[53] G.S. Davies,[28] S. 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Hurh,[18] J. Huston,[36] J. Hylen,[18] R. Imlay,[34] J. Insler,[34] Z. Isvan,[4] C. Jackson,[60] D. Jaffe,[4] C. James,[18] M. Johnson,[18] R. Johnson,[13] S. Johnson,[13] W. Johnston,[12] J. Johnstone,[18] B. Jones,[39] H. Jostlein,[18] T. Junk,[18] R. Kadel,[30] G. Karagiorgi,[14] J. Kaspar,[63] T. Katori,[39] B. Kayser,[18] E. Kearns,[3] P. Keener,[44] S.H. Kettell,[4] M. Kirby,[18] J. Klein,[44] G. Koizumi,[18] S. Kopp,[59] W. Kropp,[6] V.A. Kudryavtsev,[50] A. Kumar,[25] J. Kumar,[19] T. Kutter,[34] K. Lande,[44] C. Lane,[16] K. Lang,[59] F. Lanni,[4] R. Lanza,[39] T. Latorre,[44] F. La Zia,[10] J. Learned,[19] D. Lee,[33] K. Lee,[7] S. Li,[4] Y. Li,[4] Z. Li,[17] J. Libo,[52] S. Linden,[3] J. Ling,[4] J. Link,[62] L. Littenberg,[4] H. Liu,[20] Q. Liu,[33] T. Liu,[55] J. Losecco,[42] W. Louis,[33] B. Lundberg,[18] T. Lundin,[18] C. Maesano,[5] S. Magill,[2] G. Mahler,[4] S. Malys,[40] F. Mammoliti,[10] S. Mandal,[23] A. Mann,[44] A. Mann,[61] P. Mantsch,[18] A. Marchionni,[18] W. 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Qian,[8] J.L. Raaf,[18] V. Radeka,[4] R. Rajendran,[18] I. Rakhno,[18] R. Rameika,[18] J. Ramsey,[33] B. Rebel,[18] S. Rescia,[4] D. Reitzner,[18] M. Richardson,[50] K. Riesselman,[18] M. Robinson,[50] M. Ronquest,[33] M. Rosen,[19] C. Rosenfeld,[52] R. Rucinski,[18] S. Sahijpal,[25] H. Sahoo,[2] N. Samios,[4] M.C. Sanchez,[28] H. Schellman,[41] R. Schmitt,[18] D. Schmitz,[11] J. Schneps,[61] K. Scholberg,[17] S. Seibert,[44] M. Shaevitz,[14] P. Shanahan,[18] R. Sharma,[4] T. Shaw,[18] N. Simos,[4] V. Singh,[22] G. Sinnis,[33] W. Sippach,[14] T. Skwarnicki,[56] M. Smy,[6] H. Sobel,[6] M. Soderberg,[56] J. Sondericker,[4] W. Sondheim,[33] N.J.C. Spooner,[50] M. Stancari,[18] I. Stancu,[1] A. Stefanik,[18] J. Stewart,[4] S. Stone,[56] J. Strait,[18] M. Strait,[11] S. Striganov,[18] G. Sullivan,[35] L. Suter,[2] R. Svoboda,[5] B. Szczerbinska,[15] M. Szydagis,[5] A. Szelc,[66] R. Talaga,[2] M. Tamsett,[67] S. Tariq,[18] R. Tayloe,[26] C. Taylor,[33] D. Taylor,[30] D. Taylor,[49] A. Teymourian,[7] H. Themann,[4] M. Thiesse,[16] J. Thomas,[32] L.F. Thompson,[50] M. Thomson,[9] C. Thorn,[4] X. Tian,[52] D. Tiedt,[53] W. Toki,[12] N. Tolich,[63] M. Tripathi,[5] I. Tropin,[18] M. Tzanov,[34] J. Urheim,[26] S. Usman,[40] M. Vagins,[27] R. Van Berg,[44] R. Van de Water,[33] G. Varner,[19] K. Vaziri,[18] G. Velev,[18] B. Viren,[4] T. Wachala,[12] D. Wahl,[65] A. Waldron,[67] C.W. Walter,[17] H. Wang,[7] W. Wang,[64] D. Warner,[12] R. Wasserman,[12] B. Watson,[60] A. Weber,[43] W. Wei,[58] R. Wendell,[27] M. Wetstein,[11] A. White,[60] H. White,[33] L. Whitehead,[20] D. Whittington,[26] J. Willhite,[49] W. Willis,[14] R.J. Wilson,[12] L. Winslow,[7] E. Worcester,[4] T. Wyman,[18] T. Xin,[28] K. Yarritu,[33] J. Ye,[55] J. Yu,[60] M. Yeh,[4] B. Yu,[4] G. Zeller,[18] C. Zhang,[4] C. Zhang,[58] E.D. Zimmerman,[13] and R. Zwaska[18]

Community support for LBNE – Snowmass

Planning the Future of U.S. Particle Physics

Report of the 2013 Community Summer Study

Conveners: M. Bardeen, W. Barletta, L. Bauerdick, R. Brock, D. Cronin-Hennessy, M. Demarteau, M. Dine, J. L. Feng, M. Gilchriese, S. Gottlieb, J. L. Hewett, R. Lipton, H. Nicholson, M. E. Peskin, S. Ritz, H. Weerts

Division of Particles and Fields Officers in 2013: J. L. Rosner (chair and corresponding author), I. Shipsey (chair-elect), N. Hadley (vice-chair), P. Ramond (past chair)

Editorial Committee: R. H. Bernstein, N. Graf, P. McBride, M. E. Peskin, J. L. Rosner, N. Varelas, K. Yurkewicz

The Long-Baseline Neutrino Experiment (LBNE) will measure the mass hierarchy and is uniquely positioned to determine whether leptons violate CP. Future multi-megawatt beams aimed at LBNE, such as those from Project X at Fermilab, would enable studies of CP violation in neutrino oscillations with conclusive accuracy. An underground LBNE detector would also permit the study of atmospheric neutrinos, proton decay, and precision measurement of any galactic supernova explosion. This represents a vibrant global program with the U.S. as host.

Neutrinos

arXiv:1310.4340

Conveners: A. de Gouvêa[50], K. Pitts[32], K. Scholberg[26], G.P. Zeller[27]

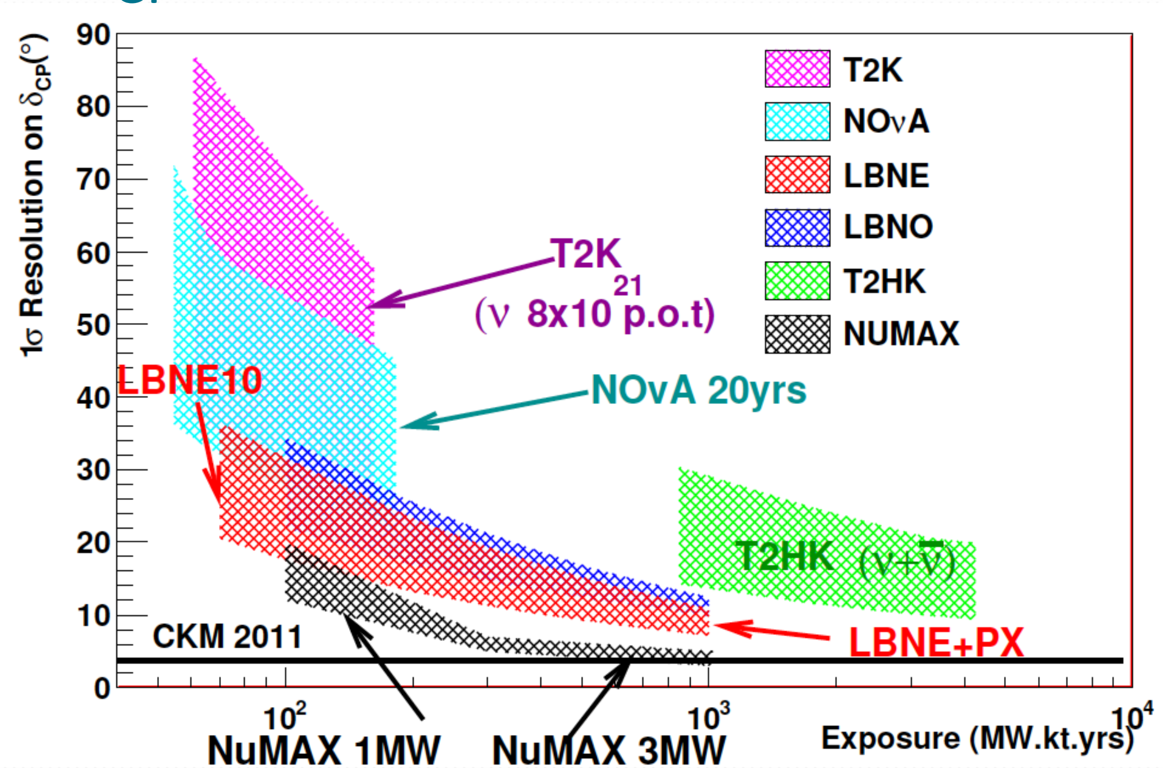
Subgroup Conveners: J. Alonso[46], A. Bernstein[41], M. Bishai[8], S. Elliott[42], K. Heeger[78], K. Hoffman[43], P. Huber[74], L.J. Kaufman[35], B. Kayser[27], J. Link[74], C. Lunardini[4], B. Monreal[15], J.G. Morfin[27], H. Robertson[75], R. Tayloe[35], N. Tolich[75]

LBNE plays a central role in the future U.S. program,

Proposed CPV/MH Experiments

- **T2HK** (Tokai-to-HyperKamiokande) *Shiozawa-san talk next*
  - Shorter baseline (295 km) + atmospheric nu's – focus on CPV
  - LOI to be submitted May 2014
- **LAGUNA/LBNO** (Large Apparatus studying Grand Unification, Neutrino Astrophysics/Long-Baseline Neutrino Oscillations)
  - Longer baseline (2300 km) – initial emphasis on MH
  - EOI submitted June 2012 (SPSC-EOI-007)
  - *Discussing joining forces with LBNE*
- **PINGU** (Precision IceCube Next Generation Upgrade)
  - Atmospheric neutrinos with spread of baselines – focus on MH
  - Whitepaper: Completion 2018, 3σ possible by 2020
- **JUNO** (Jiangmen Underground Neutrino Observatory) *Y. Wang talk*
  - Reactor neutrinos – MH independent of CP phase
  - Approved – data taking ~2020, 3 yrs to 2σ, 6 yrs to 3σ

δ_{CP} Resolution vs. Exposure



- Wide-band, long-baseline experiments achieve higher precision with less exposure than off-axis and shorter baselines (T2K, NOvA, T2HK)
- This calculation assumes MH is known
- Very long baseline has difficulty seeing explicit CP violation
- MH information from other experiments would accelerate CPV progress

International Collaboration

- **International partnership is essential**
- Past year: Detailed interactions with a number of potential non-US partners, both physics groups and funding agencies
- **Significant collaboration with several major partners has developed**
  - Very brief summary to follow
  - More details in back up slides

International Collaborators

- India (5 institutions)
  - Many Fermilab interactions with Indian agencies (DPR, DAE)
  - Proposal for highly-capable near neutrino detector is pending
- UK (9 institutions)
  - Meetings with funding agency (STFC) CEO J. Womersley and other officials
  - SOI on Long-Baseline Physics with a 60% emphasis on LBNE + Fermilab LAr program reviewed positively; invited to submit a 3-year "preparatory phase for LBNE" proposal in early 2014
- Italy (7 institutions - ICARUS)
  - LBNE discussions with INFN officials; communication between INFN president F. Ferroni, FNAL director N. Lockyer, senator C. Rubbia
  - Have received INFN support to participate in LBNE development

International Collaborators

- Brazil (5 institutions)
  - LBNE meeting with Brito Cruz, Scientific Director of Sao Paulo funding agency FAPESP (who also met with Energy Secretary Moniz in August)
  - R&D proposal to FAPESP on Photon System and Physics Studies planned for Dec. 2013; federal govt. call for proposals next spring

International Collaboration Discussions

- LAGUNA/LBNO
  - Collaboration developing long-baseline/underground science experiment for Europe; ~300 members, 13 countries; EU FP7 Framework funding through Sept. 2014
  - Task force to investigate joining forces (5 members from each Executive Committee); meets every ~2 weeks
    - Joint Physics Task Force formed – careful comparison of analyses, common understanding of science goals
    - Joint R&D efforts under discussion – WA105 project at CERN
- CERN
  - European Strategy statement on participation in long-baseline
  - Establishing two neutrino-related projects
  - Frequent communication with CERN neutrino program coordinator Marzio Nessi
  - Letter from DOE; communication between CERN DG and Fermilab director

International Collaboration Discussions

- Italy
  - Several senior INFN members of NESSiE collaboration attended LBNE Sept. 2013 collaboration meeting as observers
  - Near-term interest in neutrino-detector R&D and short-baseline experiment at CERN or Fermilab
- Russia
  - At visit to Fermilab by INR director V. Matveev, LBNE was added to the MOU between the two labs
  - Preliminary discussions with JINR (Dubna); LBNE Near Detector-related collaboration beginning between JINR and U. Panjab
- Japan
  - Japan-US Committee for Cooperation in High Energy Physics - Neutrino Task Force for coordination of proposals in areas of joint interest in accelerator, detector and physics development

LBNE Science Summary

- LBNE will determine neutrino mass hierarchy independently
  - Input from other experiments will serve to accelerate progress towards CP violation determination
- LBNE will probe CP and non-standard interactions to a precision far beyond current experiments
- LBNE will also have a rich program of precision measurements of neutrino interactions
- LBNE will probe physics only accessible to very large detectors
  - Proton decay (GUTs); Supernova burst neutrinos
- **LBNE is a cost and time effective approach to the science**
  - **There is substantial and growing international interest that will enable its full potential**

Back Up

LBNE Collaboration Details

Physicist FTE Estimates

- Based on current collaboration list and estimates of level of effort
  - University faculty counted as 1 fte if on no other experiments
  - Just attending meetings – 0.05 fte
  - Below we show Total (US) fte

- Current: 70 (58) fte
  - Fac./Sci.: 44 (37); pdoc.: 16 (14); stud.: 10 (7)
  - New groups not ramped up yet
- (Redirected) effort during project phase: 210 (160) fte
  - If no increase in # of people but effort increases to 0.5 or 0.75 for significant fraction of faculty
  - Fac./Sci: 120 (87); pdoc.: 65 (52); stud.: 35 (30)
- Expect growth towards CD-4/data: 370 (120) fte
  - Fac./Sci: 200 (130); pdoc.: 100 (80); stud.: 70 (40)
- Anticipate ultimate LBNE collaboration of 600-700 scientists
  - T2K has ~500 collaborators, 56 institutions

LBNE Collaboration - Detail

	Faculty	Postdocs	Students	Engineers	Unknown	TOTAL
Brazil	8	1	-	-	-	9
India	8		-	-	-	8
Italy	27	10	-	-	-	37
Japan	1		-	-	-	1
UK	27	5	4	4	-	40
US	206	64	37	44	6	357
TOTAL	277	80	41	48	6	452
Non-US	71	16	4	4	0	95
Fraction non-US	26%	20%	10%	8%	0%	21%

Building an International Collaboration

International Collaboration - INDIA

- Benefited from existing India Institutions Fermilab Collaboration (IIFC) -> IIFC-nuP (Neutrino Physics)
- Four of these institutions are LBNE members
- Proposal for highly-capable near neutrino detector is pending
- Very close collaboration with short-baseline/ND physics group and with ND project

- IIFCnuP meeting in Mumbai next week, followed by visits to VECC (Kolkata) and Panjab University (Chandigarh)

International Collaboration - UK

- Several institutions are charter LBNE members and long-time Fermilab neutrino program collaborators
- 2012-13 Discussions with other UK physicists and STFC* CEO J. Womersley and other officials; LBNE session with large fraction of UK neutrino community before Institute of Physics conference last spring
- <u>Four new institutions joined LBNE Sept. 2013 (nine total)</u>
- Statement of Interest (SOI) on Long-Baseline physics with a 60% emphasis on LBNE + Fermilab LAr program submitted to STFC, Sept. 2013 has successful review
- Invited to submit a 3-year "preparatory phase for LBNE" proposal early 2014

*STFC=Science and Technology Facilities Council

International Collaboration - ITALY

- ICARUS/INFN Groups
  - Discussions led to joint workshop in Padua, spring 2013
  - Seven INFN groups led by C. Rubbia joined LBNE Sept. 2013
  - World LArTPC experts - many potential areas for contributions
  - Discussions with senior INFN officials; communication between INFN president and FNAL director
  - They have received INFN support to participate in LBNE

International Collaboration – BRAZIL

- Several institutions are long time Fermilab neutrino program collaborators (MINOS, Auger)
- Four visits to Brazil by LBNE leadership; LBNE information session at equivalent of APS/DPF annual meeting
- LBNE leadership met with Scientific Director of Sao Paolo funding agency FAPESP (who also met with Energy Secretary Moniz in August)
- <u>Five institutions joined LBNE Sept. 2013</u>
- Actively involved in Photon Detector system; developing R&D proposals

International Collaboration - ITALY

- NESSiE/INFN groups
  - Six INFN groups from the NESSiE collaboration have expressed interest in LBNE
  - Multiple phone discussions; several senior members attended LBNE Sept. 2013 collaboration meeting as observers
  - Near-term interest in neutrino-detector R&D and short-baseline experiment at CERN or Fermilab

International Collaboration – LAGUNA/LBNO

- Collaboration developing long-baseline/underground science experiment for Europe
  - ~300 members, 13 countries
  - EU FP7 Framework funding through Sept. 2014
- We have established a task force to investigate joining forces (5 members from each collaboration Executive Committee)
  - meets every ~2 weeks; numerous meetings of individuals in various locales (Snowmass, conferences etc.)
- Joint Physics Task Force formed – careful comparison of analyses, common understanding of science goals
- Joint R&D efforts under discussion – WA105 project established at CERN

International Collaboration - CERN

- Comments from CERN DG yesterday
- CERN establishing neutrino-related projects
  - ICARUS+NESSiE proposal (WA104)
  - LAGUNA/LBNO proposal (WA105)
- Frequent communication with CERN neutrino program coordinator Marzio Nessi (attended Snowmass)
- Neutrino program “town hall” meeting planned Nov. 2013

International Collaboration

- RUSSIA
  - After visit to Fermilab by INR director V. Matveev, LBNE was added to the MOU between the two labs
  - Preliminary discussions with JINR (Dubna); JINR scientists visited Fermilab this fall; LBNE Near Detector-related collaboration beginning between JINR and U. Panjab
- JAPAN
  - Japan-US Committee for Cooperation in High Energy Physics - Neutrino Task Force
    - coordination of proposals in areas of joint interest in accelerator, detector and physics development
- Preliminary discussions initiated with others in the Americas, Asia and Europe

Current Neutrino & Related Experiments

Current ν FNAL Experiments

- MINERvA (65-80 collaborators/23 institutions*)
  - Neutrino cross sections (various nuclei)
  - Approved 8E20 POT nu + anti-nu; 2010-12, 2013-19? (to end of NovA run?)
- MicroBooNE (113 collaborators/19 institutions*)
  - Low energy excess; neutrino cross sections on Ar
  - Approved 6.6E20 POT nu; 2013-2016 (anti-nu to follow?)
- MINOS+/MINOS (124 collaborators/32 institutions*)
  - Non-3-flavor, NSI, θ_{23}, Δm^2
  - Approved for 2013-2016
- NOvA (147 collaborators/36 institutions*)
  - ν_e appearance, ν_μ disappearance -> Mass Hierarchy, CP Violation
  - Approved 3.6E21 POT; 3-year nu + 3-year anti-nu 2013-19/20

- **All complementary/synergistic with LBNE in various ways**
  - **Cross sections; hints at MH and CPV**

*http://intensityfrontier.fnal.gov/breadth

Current FNAL ν Experiments - Physicists

Note: A previous posting of this talk had some incorrect information.

Related Off-Shore Experiments

- T2K (SK) (~ 500 collaborators, 56 institutions, 11 countries)
  - Long-baseline neutrino osc. params; neutrino cross sections (C, $H_2 0$, other)
  - Significant US participation (incl. ~18 are in LBNE)
  - 7.8E21 POT Run 2010-19?

- NA61 (CERN)
  - Hadron production; T2K, LBNE (and other Fermilab) neutrino beam understanding
  - US groups recently joined
  - LBNE-related run 2015 (analysis through 2018)

Current & Proposed Mass Hierarchy Measurement Experiments

Mass Hierarchy Measurement Experiments

- **Long-Baseline Accelerator Experiments**: Method - compare electron neutrino appearance rates to rates at different distances or to anti-electron neutrino appearance.
  - Experiments with limited data already: MINOS, OPERA, T2K
  - Experiments with more data in the next 5 years: T2K **, NOvA **, MINOS+
  - Future experiments or proposals: LBNE, LBNO, Hyper-Kamiokande
- **Atmospheric Neutrino Experiments:** Method - measure atmospheric numu and nue well enough to find small differences in rates and angular distributions sensitive to matter effects. numu event sensitivity comes from disappearance and benefits from charge id. nue event sensitivity comes from appearance.
  - Experiments with limited data already: Super-Kamiokande, MINOS
  - Experiments with more data in the next 5 years: Super-Kamiokande **, MINOS+, IceCube/Deep Core
  - Future Experiments or proposals: INO **, PINGU **, ORCA
- **Reactor Neutrino Experiments:** Method - Compare reactor disappearance at a distance sensitive to the difference between the 32 and 31 contributions.
  - Future Experiments or proposals: JUNO **, RENO50

** Experiments with potential sensitivity before LBNE

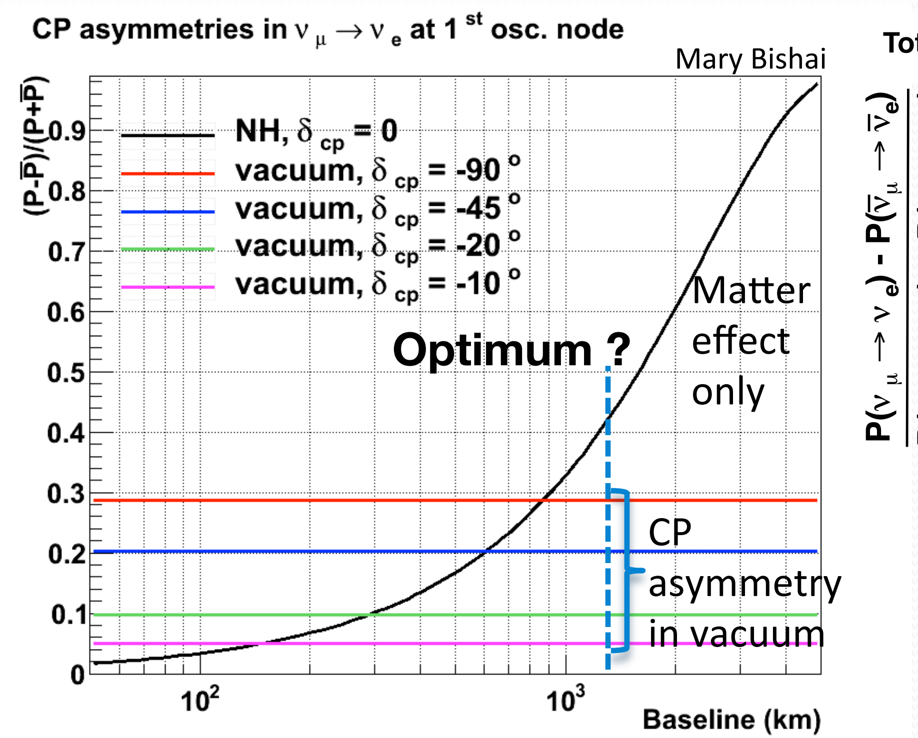
Mass Hierarchy Experiments

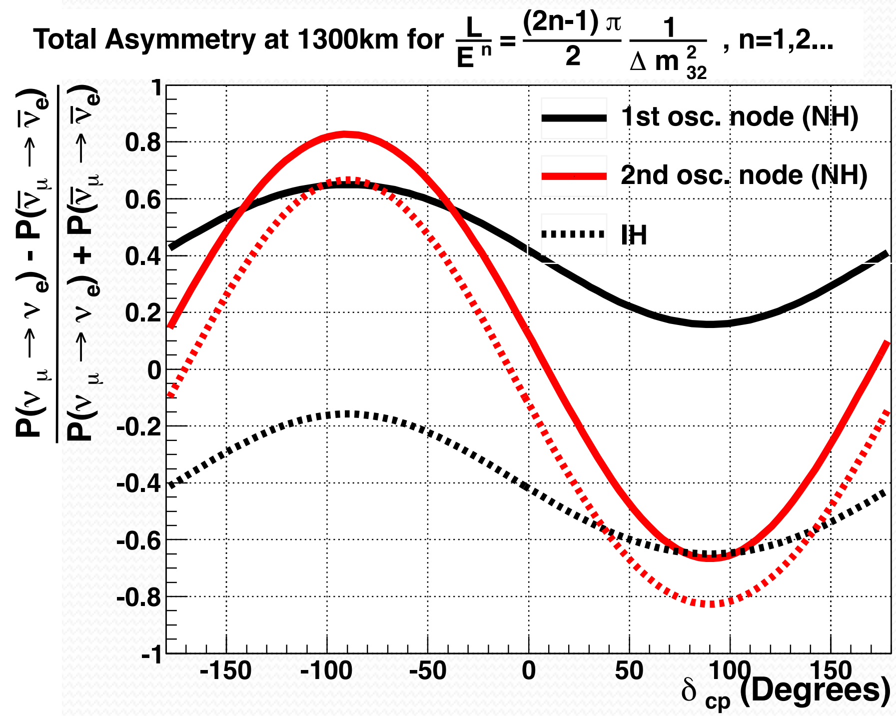
- **Supernova Neutrino Experiments:** Method - if a neutrino burst is seen, look for evidence of a spectrum swap in the nue or nuebars.
  - Experiments that could see a Supernova in the next 5 years if there is one: Super-Kamiokande, LVD, Borexino, SNO+, IceCube, NOvA
- **Cosmology:** Method - measure the sum of the neutrino masses, which has a minimum of 55 meV for the normal hierarchy and 105 meV for the inverted hierarchy. A measurement below 105 meV would indicate the normal hierarchy, but this cannot distinguish between the inverted hierarchy and a degenerate normal hierarchy.
  - Experiments that will take data in the next 5 years: Planck **, Orthers - most measurements involve fitting many results.
- **Neutrinoless Double Beta decay and direct mass**: Method - these do not measure the hierarchy, but a positive signal in either would indicate the inverted hierarchy or degenerate normal hierarchy and rule out the non-degenerate normal hierarchy.
  - Experiments that will take data in the next 5 years and beyond: KATRIN, EXO, CUORE, GERDA, Majorana, Super-NEMO, etc.

** Experiments with potential sensitivity before LBNE

Additional Science Slides

Why 1300 km: Baseline Optimization





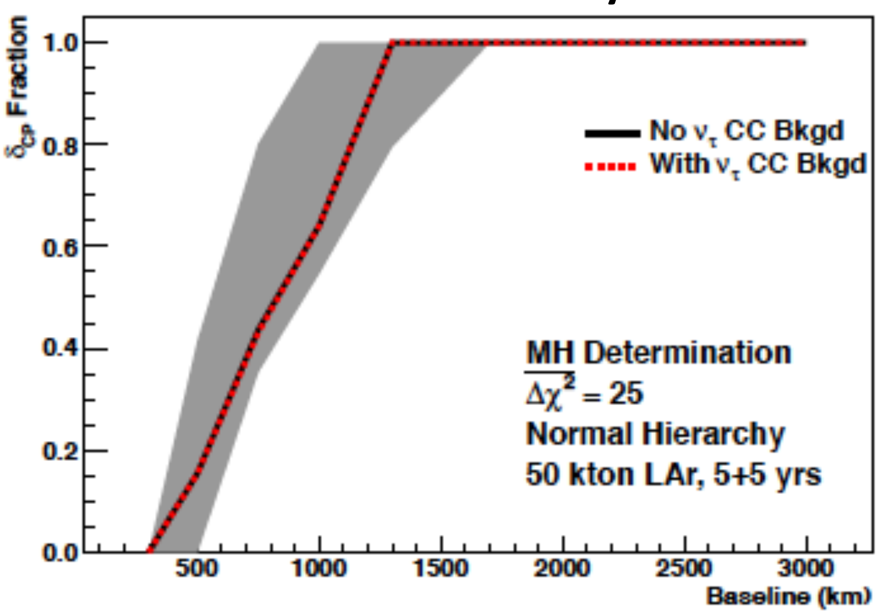
- ✧ Optimum is achieved when the asymmetry due to the matter effect is larger than the largest CP effect, but does not saturate the total asymmetry.
- ✧ At the first maximum at the optimum baseline there is no degeneracy.

Baseline Optimization

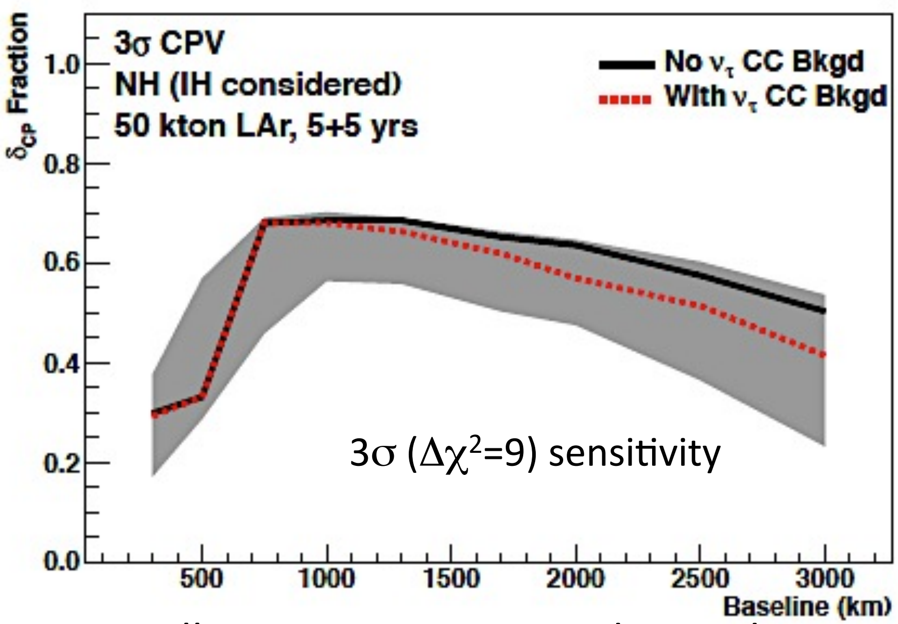
Extracted from "Baseline optimization for the measurement of CP violation and mass hierarchy in a long-baseline neutrino oscillation experiment" L. Whitehead et al. submitted to arXiv.

Note: This baseline study used a 50 kt LArTPC for the far detector fiducial mass (LBNE specific plots typically show 10kt - 34kt)

Mass Hierarchy



CP Violation



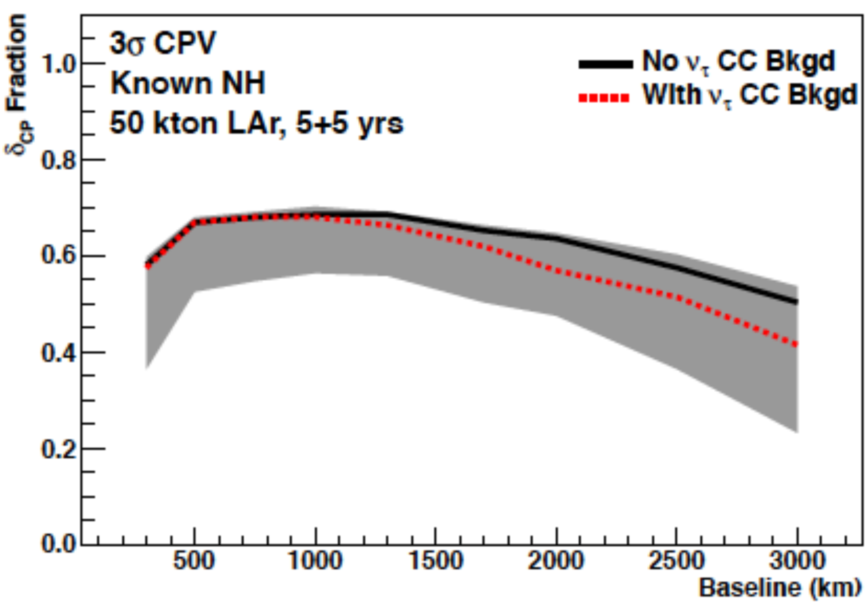
Shaded bands show range due to uncertainty in oscillation parameters and considers both octant solutions for θ_{23}

δ_{CP} resolution shows a similar behavior to CPV with shallow minimum ~1000 km

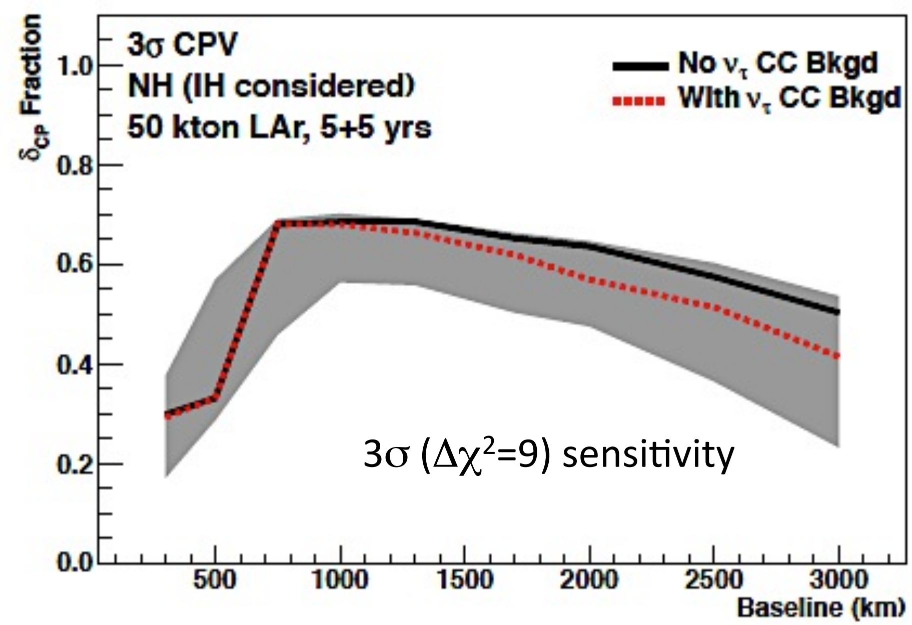
Baseline Optimization – Know MH

Extracted from "Baseline optimization for the measurement of CP violation and mass hierarchy in a long-baseline neutrino oscillation experiment" L. Whitehead et al. submitted to arXiv.

CP Violation – <u>Known</u> MH



CP Violation – MH Unknown



Shaded bands show range due to uncertainty in oscillation parameters and considers both octant solutions for θ_{23}

LBNE Beam Assumptions

- **Conceptual Design Report (CDR) Beam:**
  - Ep = 120 GeV, 700kW   Nominal 6 x 10^{20} pot/yr
  - Graphite target 96cm long
  - Target -35cm from Horn 1
  - NuMI horns, 6.6m apart, 200kA
  - Decay pipe dxl = 4x200m, air filled
- **80 GeV Beam:**
  - Ep = 80 GeV, 700 kW   Nominal 9 x 10^{20} pot/yr
  - Be target 85cm long
  - Target -25cm from Horn 1
  - NuMI horns, 6.6m apart, 230kA
  - Decay pipe dxl = 6x250m, evacuated

- 80 GeV Beam gives 50% more flux at 1st and 2nd nodes.

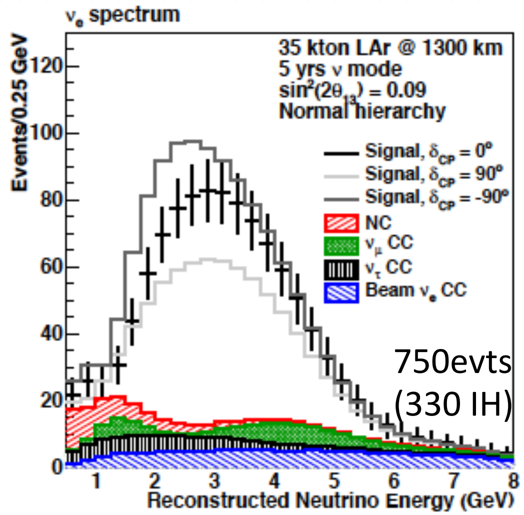
LBNE FD Performance Assumptions

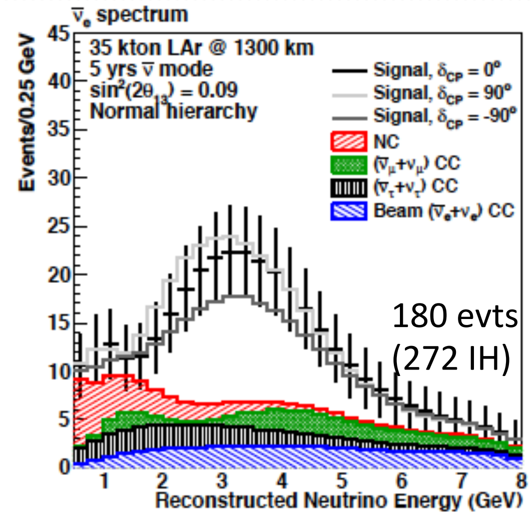
Parameter	Range of Values	Value Used for LBNE Sensitivities
For ν_e CC appearance studies		
ν_e CC efficiency	70-95%	80%
ν_μ NC mis-identification rate	0.4-2.0%	1%
ν_μ CC mis-identification rate	0.5-2.0%	1%
Other background	0%	0%
Signal normalization error	1-5%	1-5%
Background normalization error	2-15%	5-15%
For ν_μ CC disappearance studies		
ν_μ CC efficiency	80-95%	85%
ν_μ NC mis-identification rate	0.5–10%	0.5%
Other background	0%	0%
Signal normalization error	1-10%	5–10%
Background normalization error	2-20%	10-20%
For ν NC disappearance studies		
ν NC efficiency	70-95%	90%
ν_μ CC mis-identification rate	2-10%	10%
ν_e CC mis-identification rate	1-10%	10%
Other background	0%	0%
Signal normalization error	1-5%	under study
Background normalization error	2-10%	under study
Neutrino energy resolutions		
ν_e CC energy resolution	$15\%/\sqrt{E(GeV)}$	$15\%/\sqrt{E(GeV)}$
ν_μ CC energy resolution	$20\%/\sqrt{E(GeV)}$	$20\%/\sqrt{E(GeV)}$
E_{ν_e} scale uncertainty	under study	under study
E_{ν_μ} scale uncertainty	1-5%	2%

LBNE 35 kt Far Detector Spectra

Appearance

$\nu_\mu \rightarrow \nu_e$

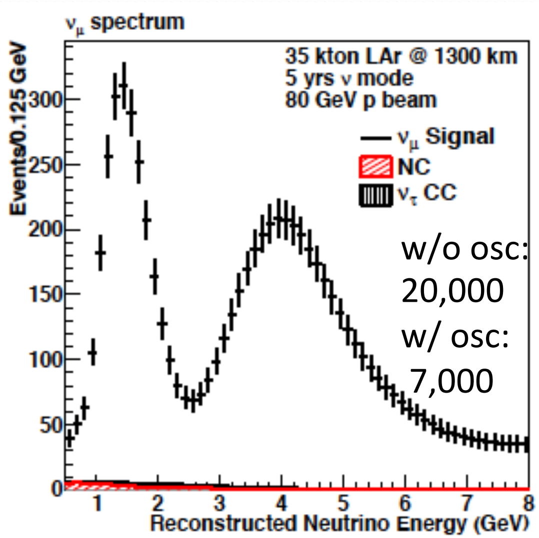


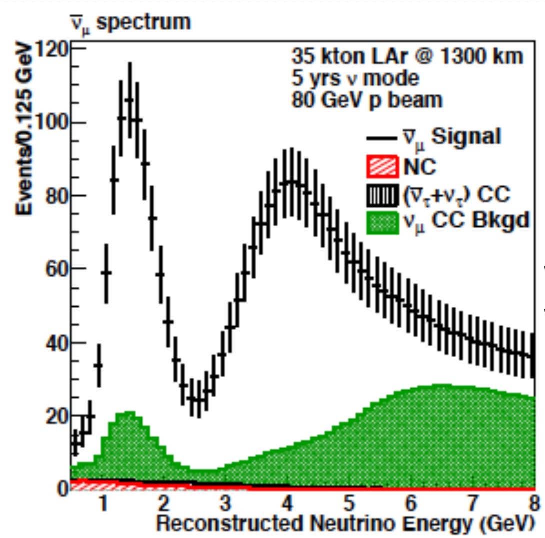


ν (5 yrs) $\quad$ **$\bar{\nu}$ (5 yrs)**

Disappearance

$\nu_\mu \rightarrow \nu_\mu$

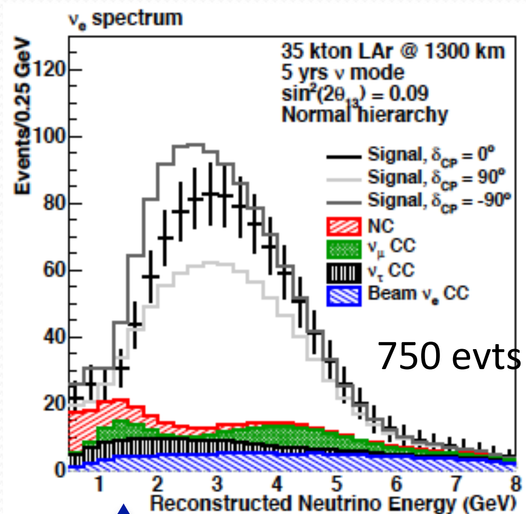


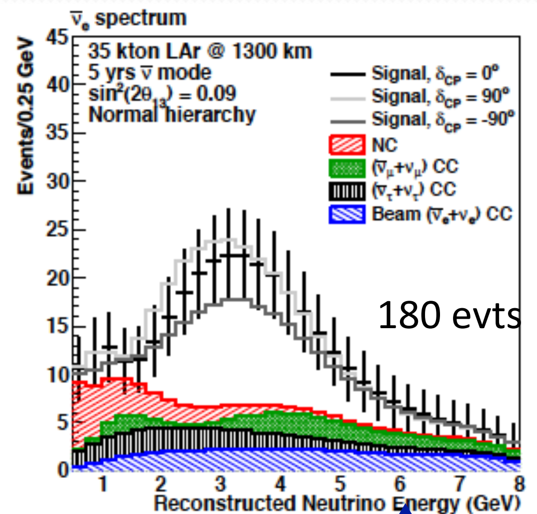


w/o osc: 6,700
w/ osc: 2,200

LBNE Spectra-Mass Hierarchy

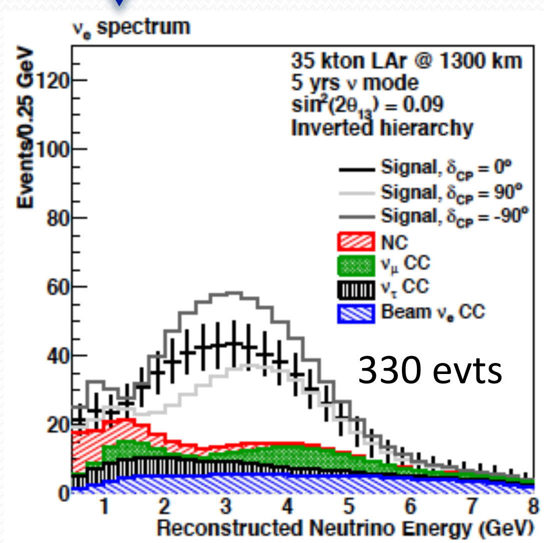
Normal

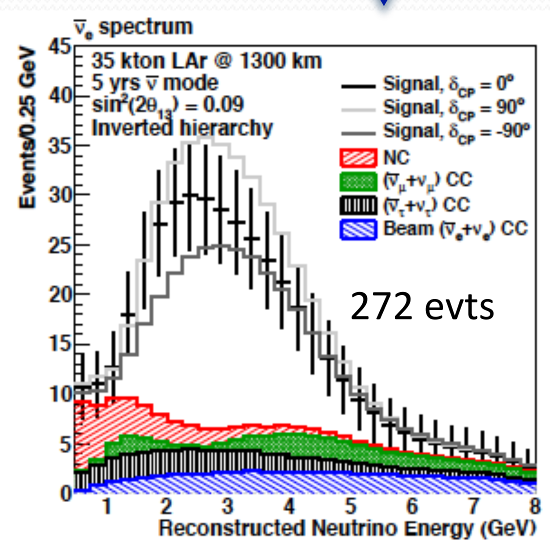




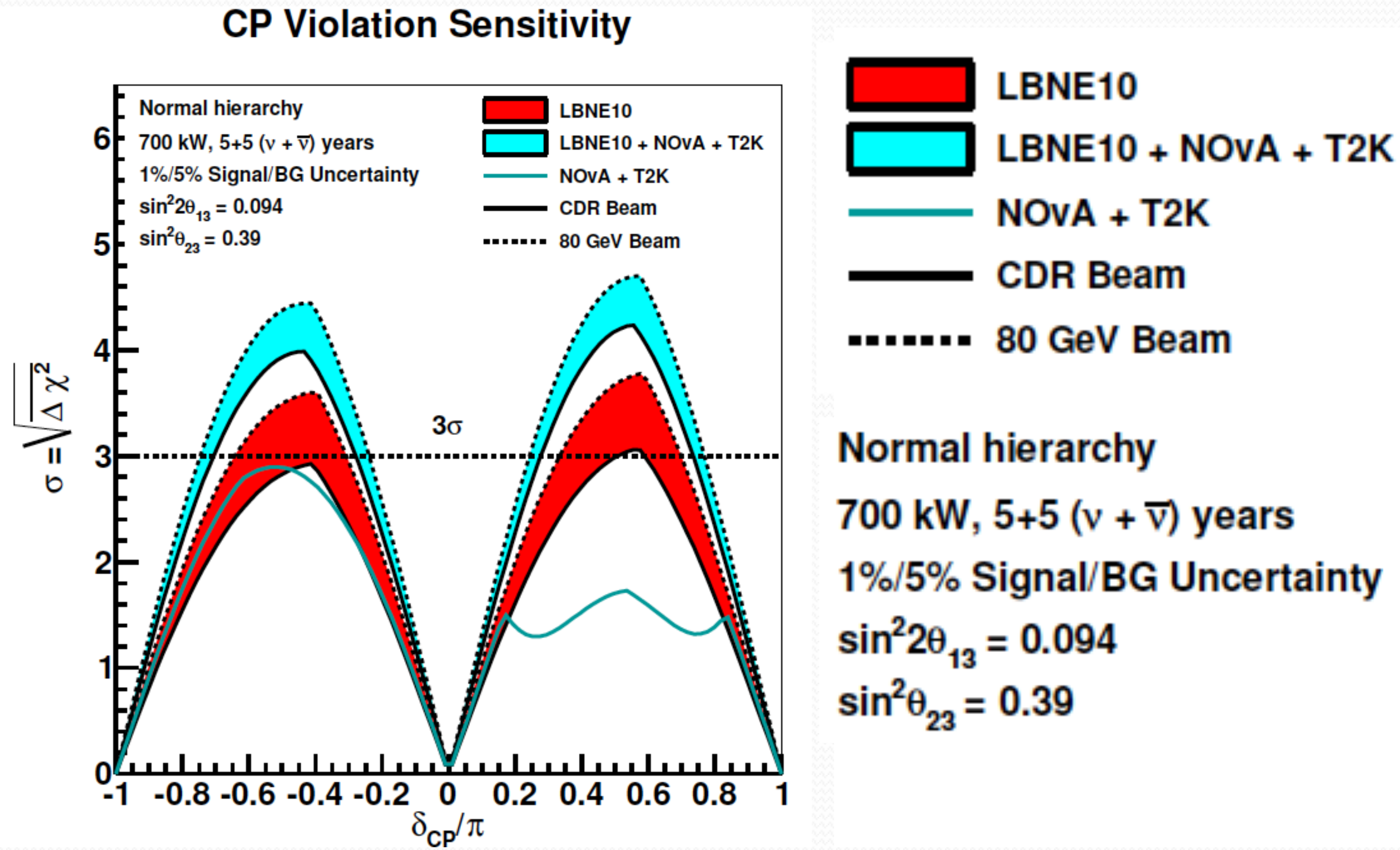
Difference due to mass ordering

Inverted



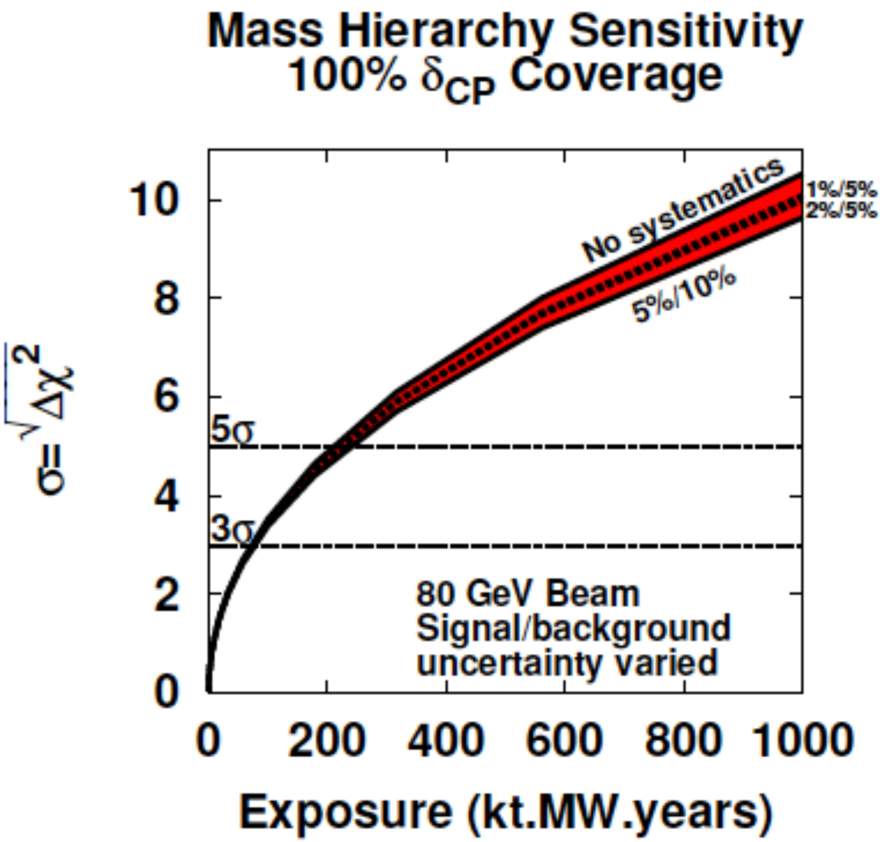


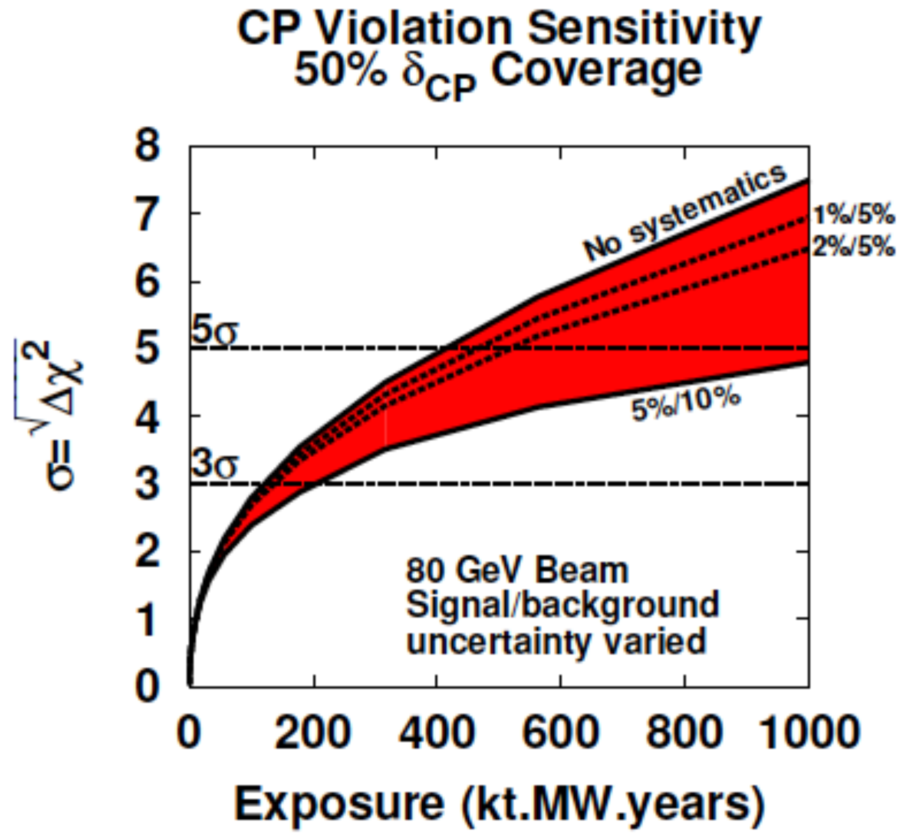
CP Violation Sensitivity – 10 kt Far Detector



- LBNE 10 kt does much better than current/near term experiments
- Exposures up to ~100 kt.MW.yr benefit from T2K+NOvA data

Impact of Normalization Uncertainties

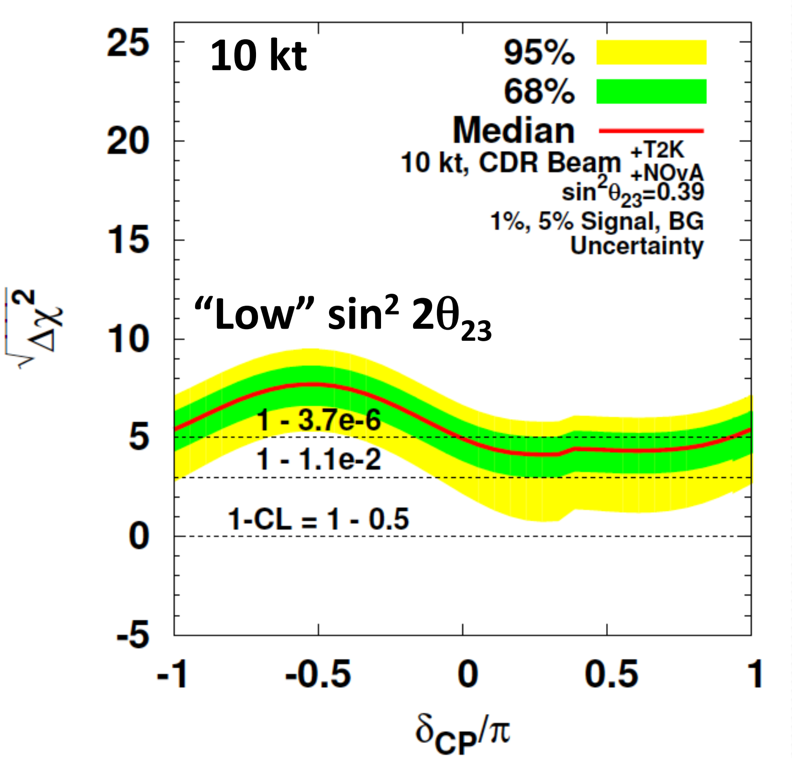


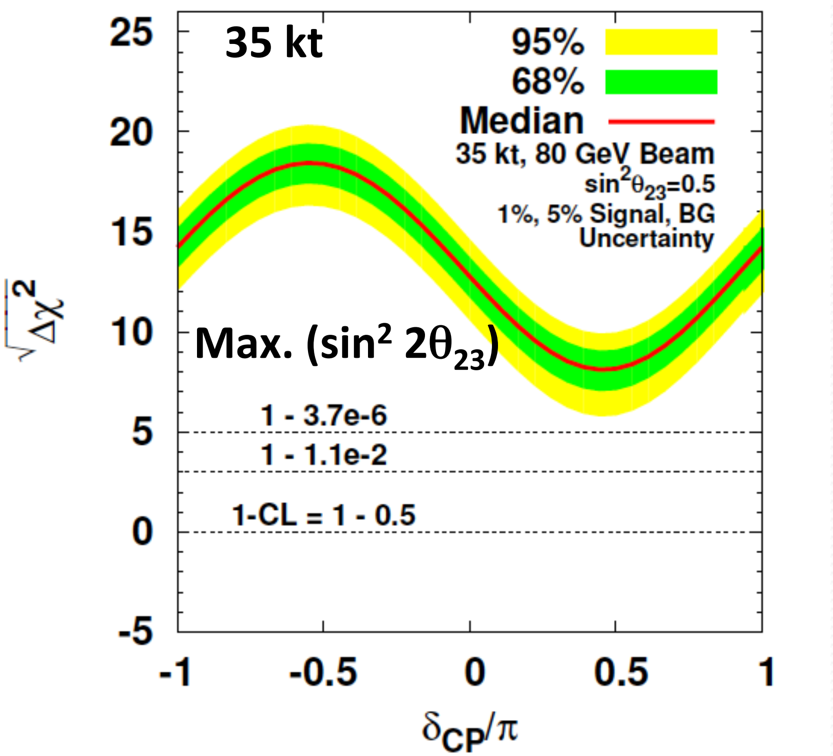


- MH relatively insensitive
- Good systematics control needed beyond ~200 kt.MW.yr for CPV
- MINOS has better than 5%/10%

Comment on Mass Hierarchy Statistics

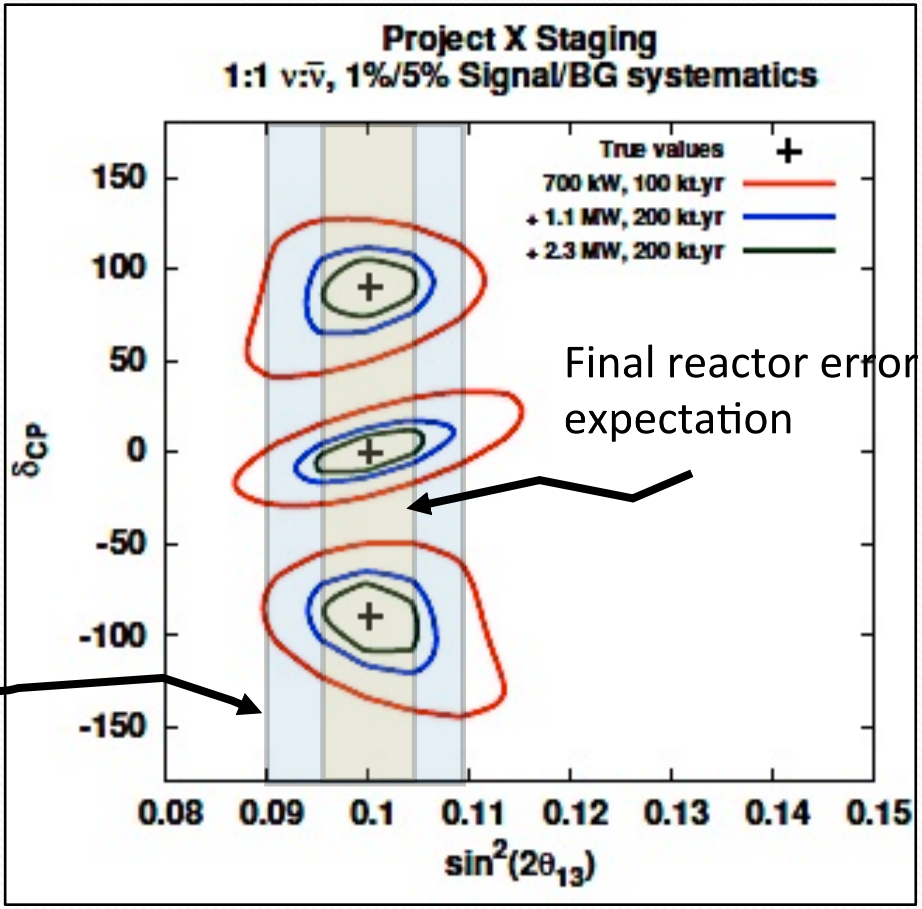
- For MH sensitivity most experiments have been using $\sigma = \sqrt{\Delta\chi^2}$ as a test statistic. Qian et al. pointed out that for a binary choice of unknown parameter, such as MH, the credible interval for this statistic does not correspond to the Gaussian confidence level





- Show in the plots: Statistical fluctuations mean that some fraction of experiments will not have the median sensitivity – this is indicated by the bands above. If a measurement is made the it will have the credible interval indicated

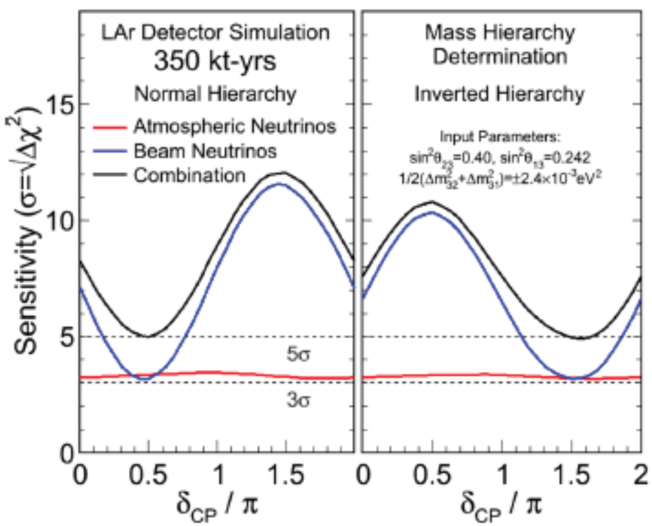
LBNE + Proton Power Increase

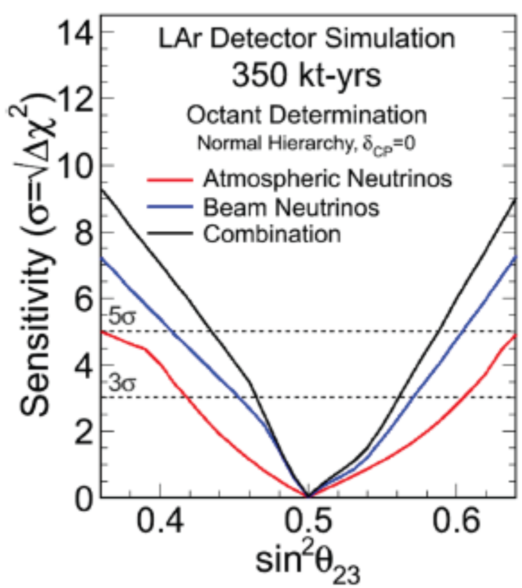


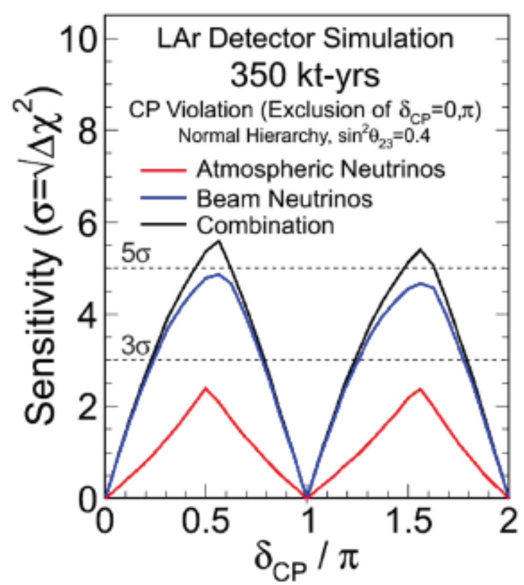
Final reactor error expectation

Current reactor error

Atmospheric Neutrinos







Signal and Background Normalization

Table 5–3: Precisions achievable from in situ ν_μ and ν_e flux measurements in the fine-grained high resolution ND with different techniques.

Flavor	Technique	Relative abundance	Absolute normalization	Relative flux $\Phi(E_\nu)$	Detector requirements
ν_μ	$\nu_\mu e^- \to \nu_\mu e^-$	1.00	2.5%	$\sim 5\%$	e ID θ_e Resolution e^-/e^+ Separation
ν_μ	$\nu_\mu e^- \to \mu^- \nu_e$	1.00	3%		μ ID θ_μ Resolution 2-Track (μ+X) Resolution μ energy scale
ν_μ	$\nu_\mu n \to \mu^- p$ $Q^2 \to 0$	1.00	$3-5\%$	$5-10\%$	D target p Angular & Energy resolution Back-Subtraction
$\bar{\nu}_\mu$	$\bar{\nu}_\mu p \to \mu^+ n$ $Q^2 \to 0$	0.70	5%	10%	H target Back-Subtraction
ν_μ	Low-ν_0	1.00		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
$\bar{\nu}_\mu$	Low-ν_0	0.70		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
$\nu_e/\bar{\nu}_e$	Low-ν_0	0.01	1-3%	2.0%	e^-/e^+ Separation (K^0_L)