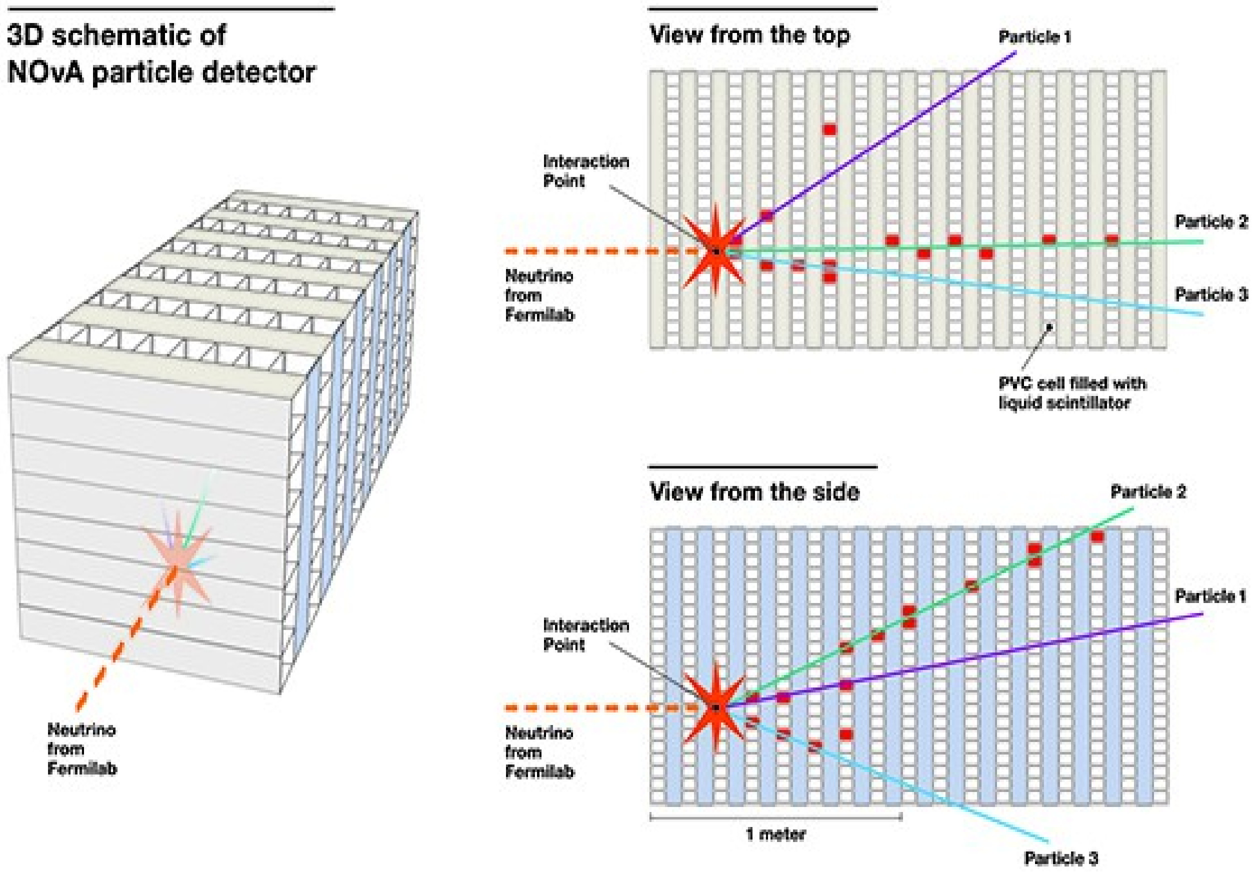
Nuovi esperimenti
Nova
Minos+

Nova


3D schematic of
NOvA particle detector
Neutrino
from
Fermilab
View from the top
Particle 1
Interaction
Point
Particle 2
Neutrino
from
Fermilab
Particle 3
PVC cell filled with
liquid scintillator
View from the side
Particle 2
Particle 1
Interaction
Point
Neutrino
from
Fermilab
1 meter
Particle 3

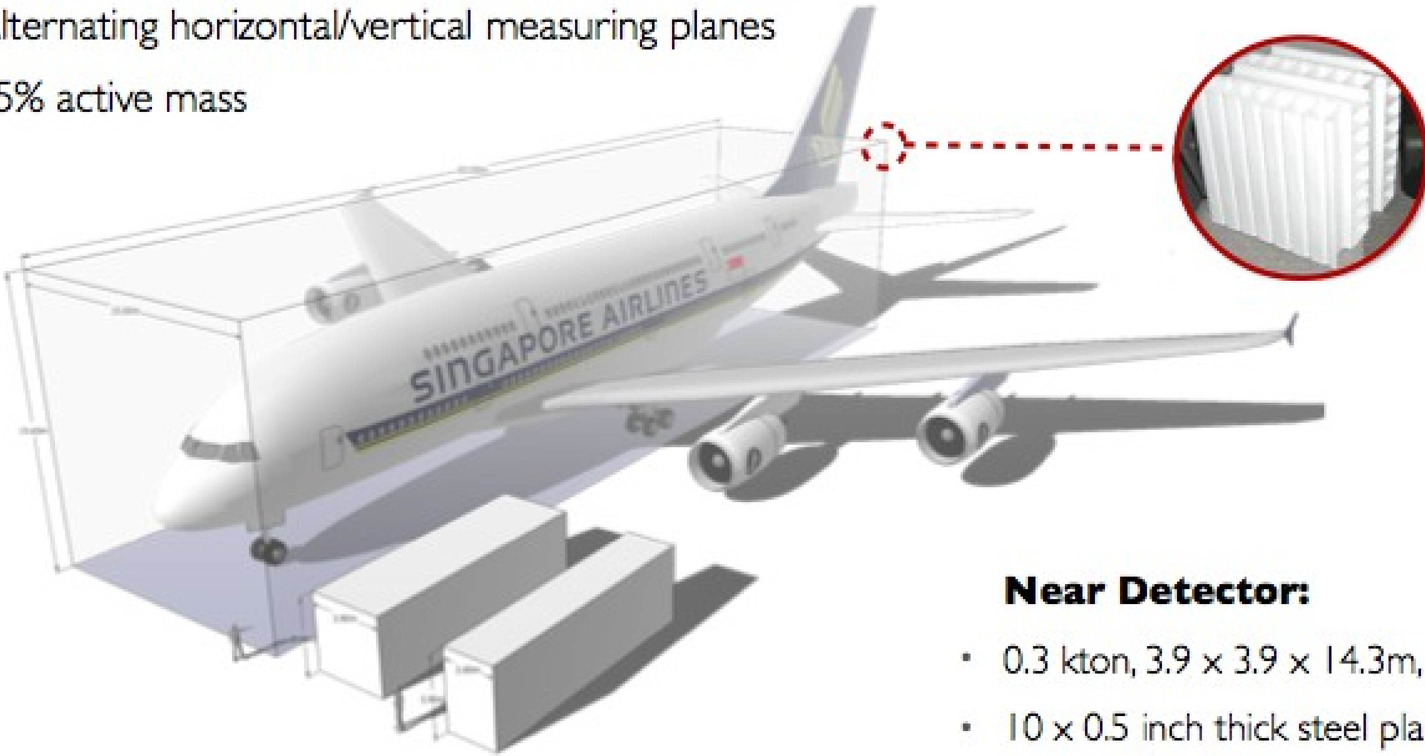
The NOvA experiment

- **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment
- Fermilab's Flagship Intensity Frontier Experiment
- 810 km baseline from Fermilab to Ash River, Minnesota
- 700 kW NuMI (Neutrinos at the Main Injector) beam
- Two functionally identical detectors, optimised for ν_e identification placed 14 mrad off the NuMI beam axis
- Physics goals:
  - Search for $\nu_\mu \rightarrow \nu_e$ transitions (with both neutrinos and antineutrinos) and measure θ_{13}
  - Resolution of the neutrino mass hierarchy
  - Search for CP violation in the neutrino sector
  - Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.
  - Determine the octant of θ_{23}

NOvA Detectors

Far Detector:

- 14 kton, 15.6 x 15.6 x 63m, 896 planes arranged in 28 blocks of 32 planes for assembly
- Alternating horizontal/vertical measuring planes
- 65% active mass

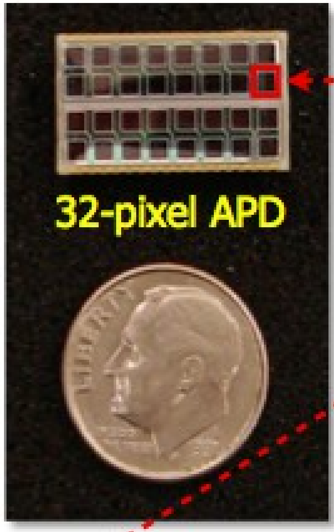


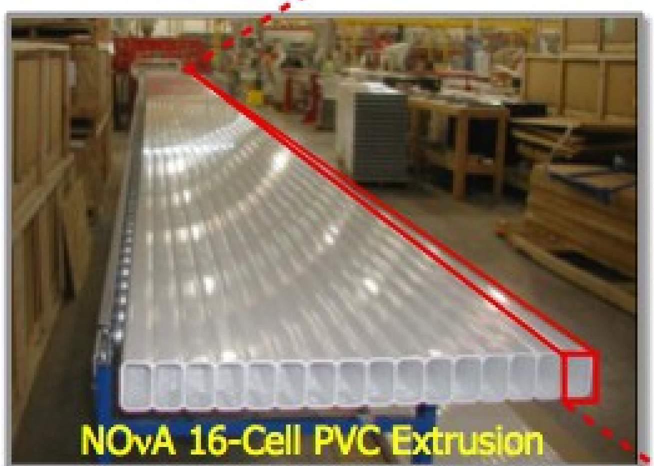
Near Detector:

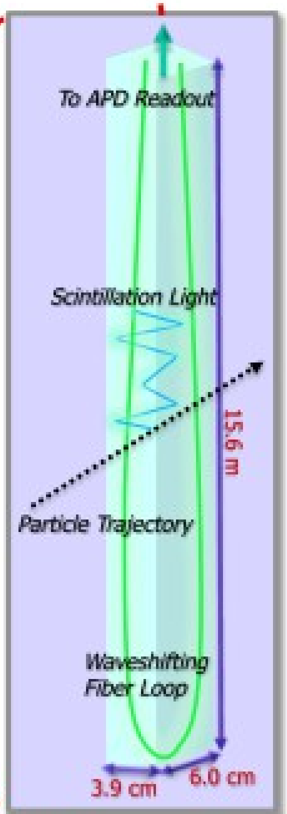
- 0.3 kton, 3.9 x 3.9 x 14.3m, 214 planes
- 10 x 0.5 inch thick steel planes as muon catcher to range out muons
- Situated 14 mrad off-axis next to MINOS ND, 105m underground

Detector Technology

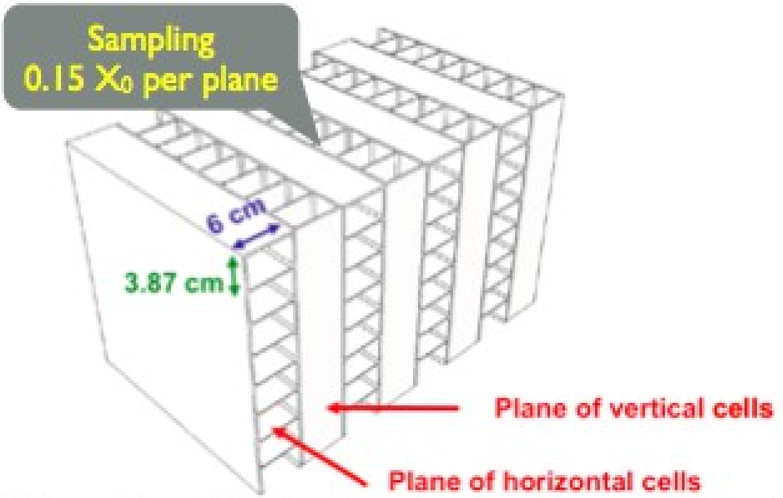
- Near and Far detectors composed of highly reflective 16-cell PVC extrusions
  - Two extrusions glued together into 32-cell module
  - 24 extrusions/plane in Far detector (384 cells/plane)
  - 344'064 cells in Far Detector
- Extrusions filled with liquid scintillator
- Each cell read out by a wavelength-shifting fiber into one pixel of a 32-pixel avalanche photodiode (APD)
- Provide a radiation length of ~ 40 cm, 2 GeV muon travels 10m !





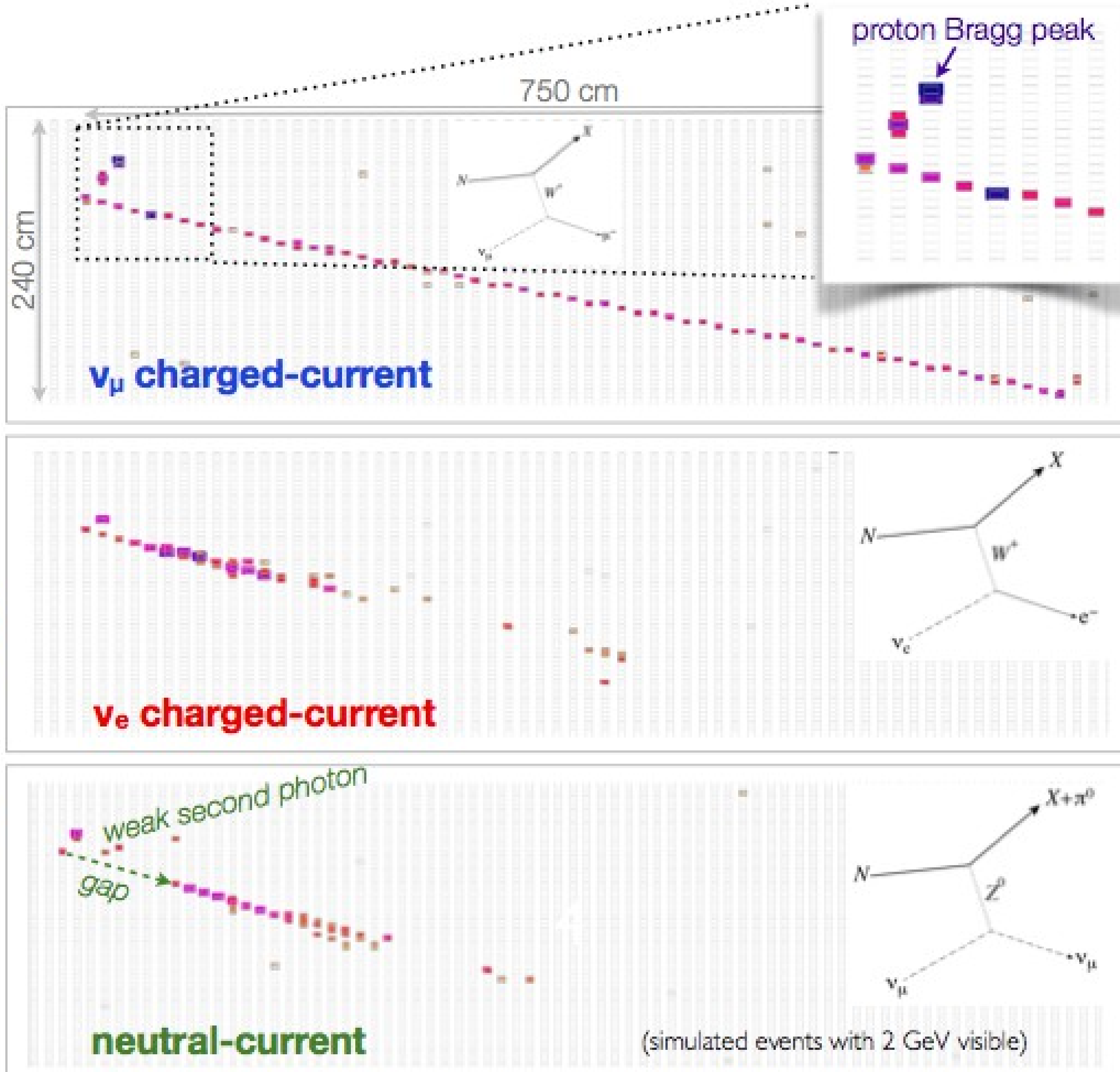


Scintillator cell with looped WLS fiber

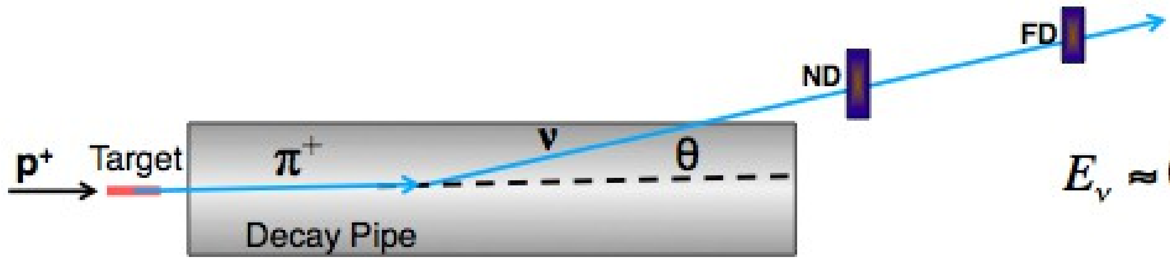


Neutrino Events

- Topologies of basic interaction channels simulated in the NOvA detectors
- Each "pixel" is a single 4 cm x 6 cm x 15 m cell of liquid scintillator
- Need >1000:1 rejection against background
- Detector challenge: Achieve large target mass (10's+ kilotons) while maintaining high granularity to avoid confusing the detection channels
- NOvA achieves ~45% efficiency for ν_e CC while limiting NC→ν_e CC fake rate to 0.1%
- X_0 = 38 cm (6 cell depths, 10 cell widths)

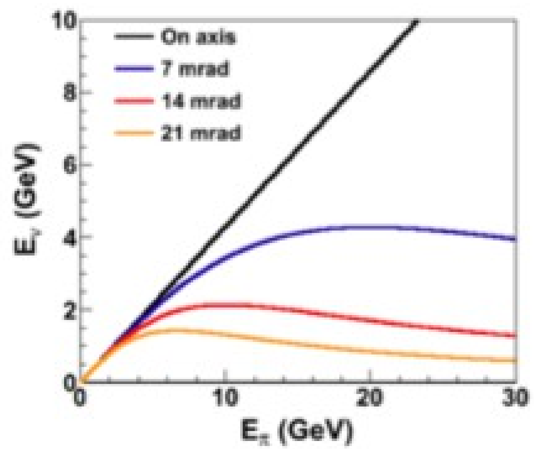


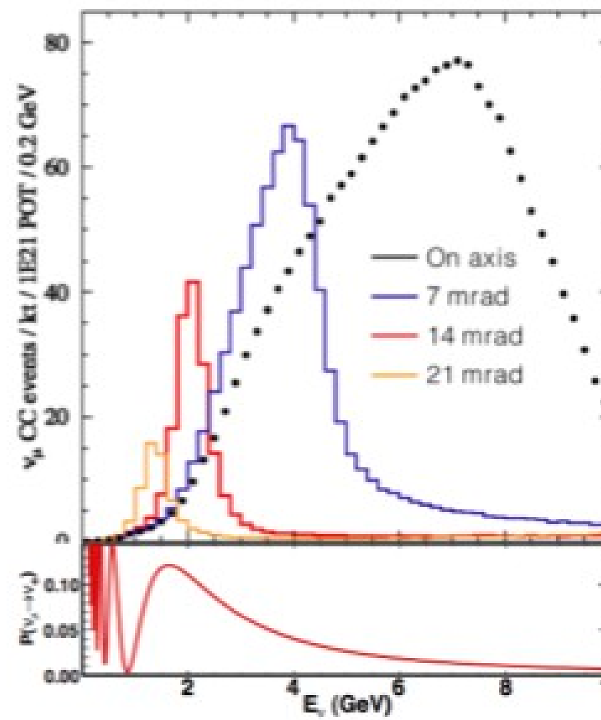
NuMI Off-axis Beam



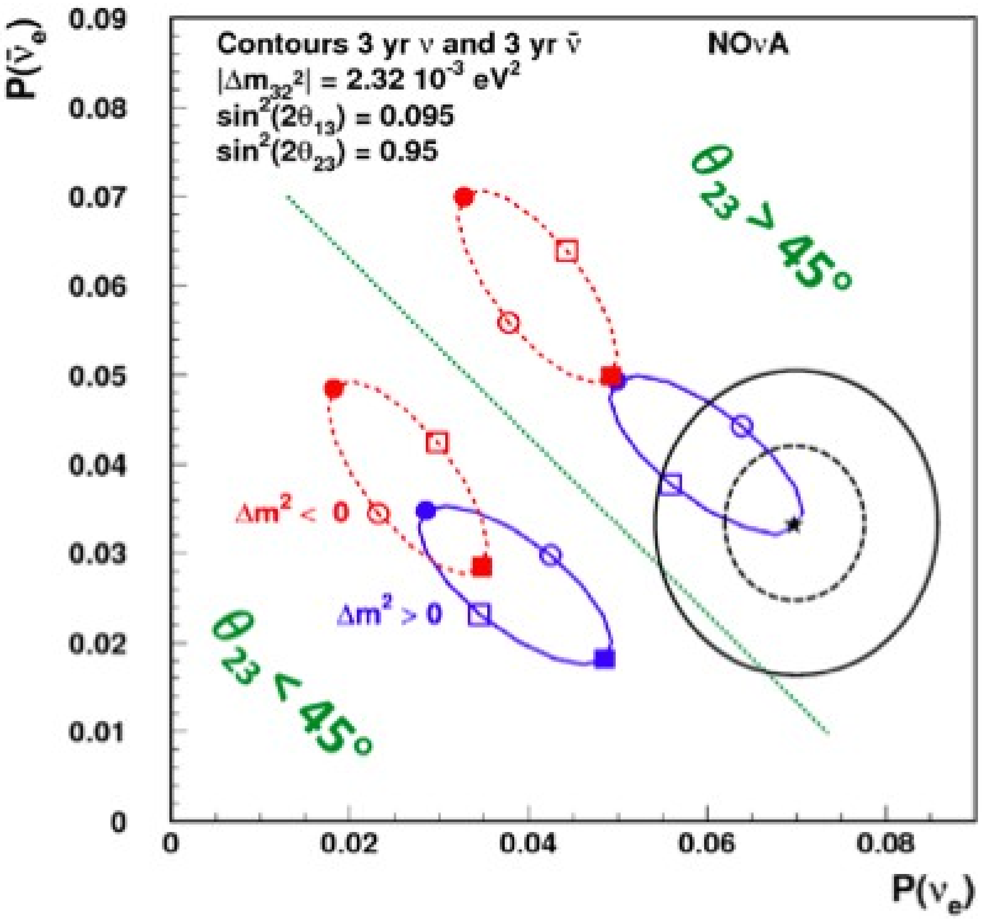
$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- Medium Energy NuMI configuration most favorable to look for $\nu_\mu \rightarrow \nu_e$ oscillations over 810 km baseline
- At 14 mrad off-axis, narrow band beam peaked at E_ν=2GeV
  - Near oscillation maximum
  - Removes high energy NC background events



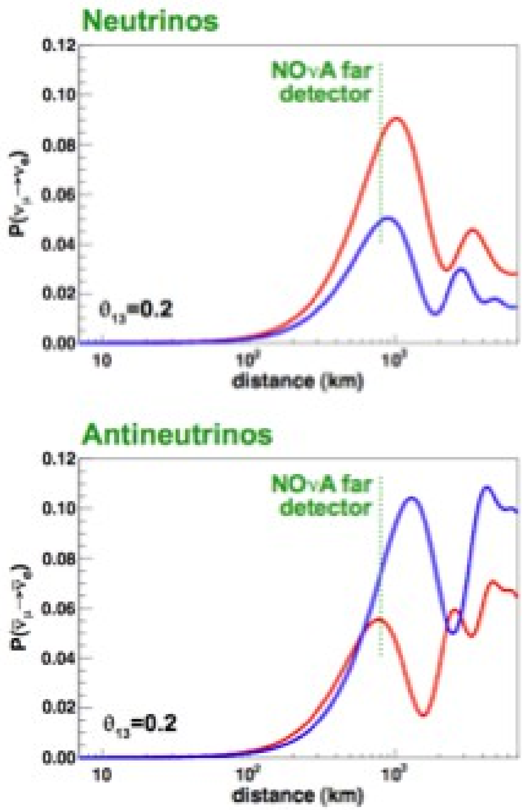


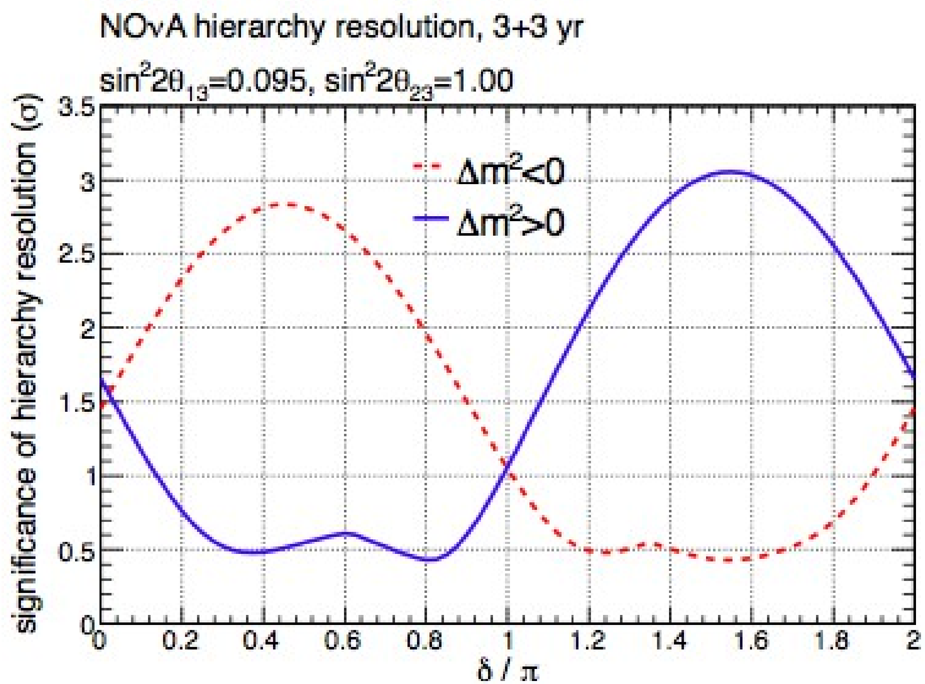
NOvA Physics



- NOvA plans to run for 3 years in neutrino and 3 years in antineutrino mode
- The strategy is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to extract mass hierarchy and first information on δ_{CP}
- Precision measurement of $\sin^2(2\theta_{23})$ from $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- If θ_{23} is non-maximal: capable of determining the octant

Mass Hierarchy

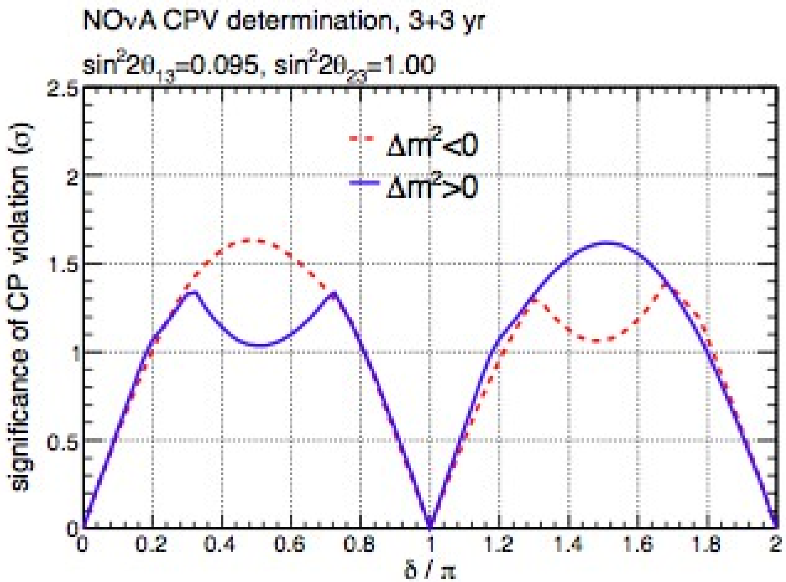


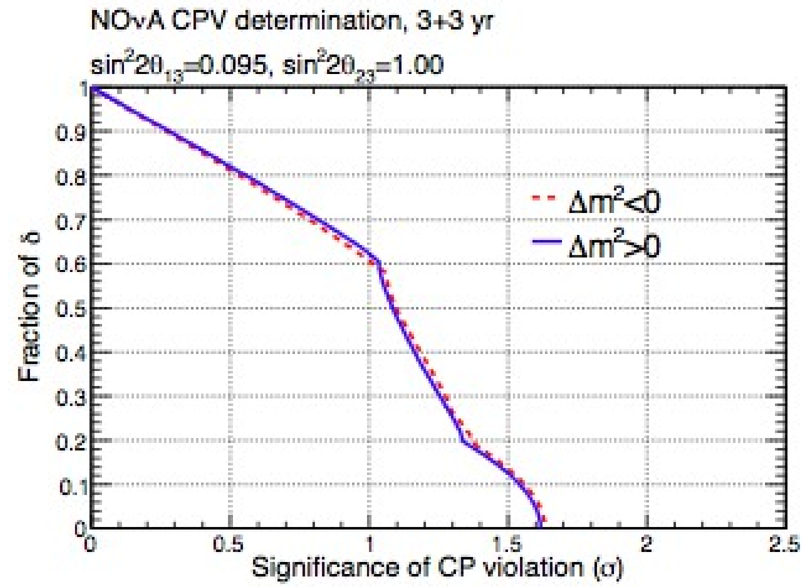


- Take advantage of large matter effects => 30% enhancement/suppression of $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ probability (11% in T2K)

- Significance of mass hierarchy resolution using energy spectrum.
- Energy fit provides improvement on the fully degenerate δCP values.

CP Violation



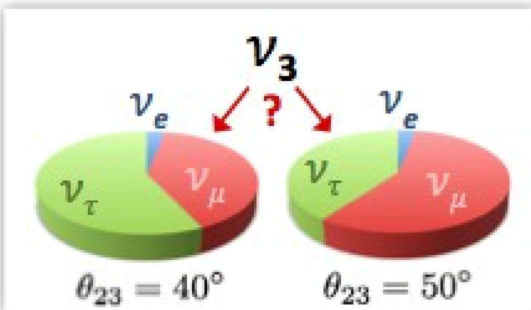


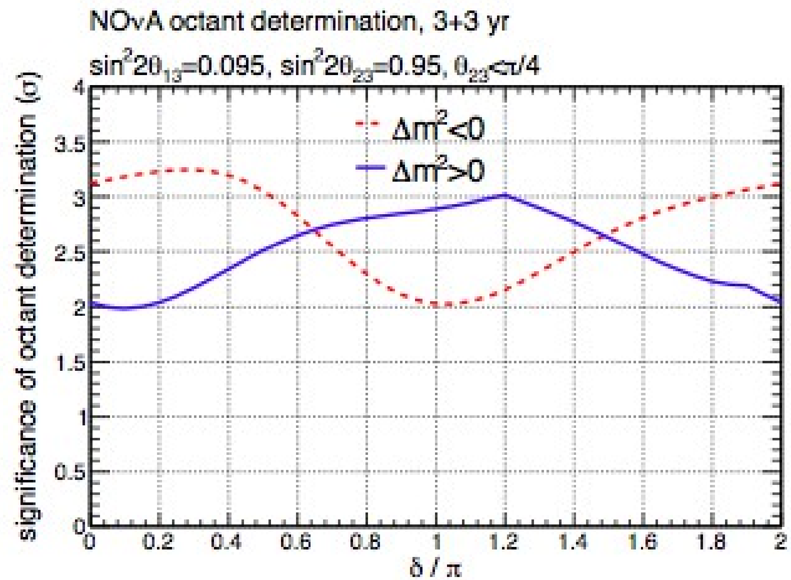
- First glimpse at δ_{CP} !!
- Significance of CP violation using energy spectrum
- Assumes that mass hierarchy is unknown
- Results from full simulation, reconstruction, selection, and analysis framework
- FD only, extrapolation methods from ND in progress

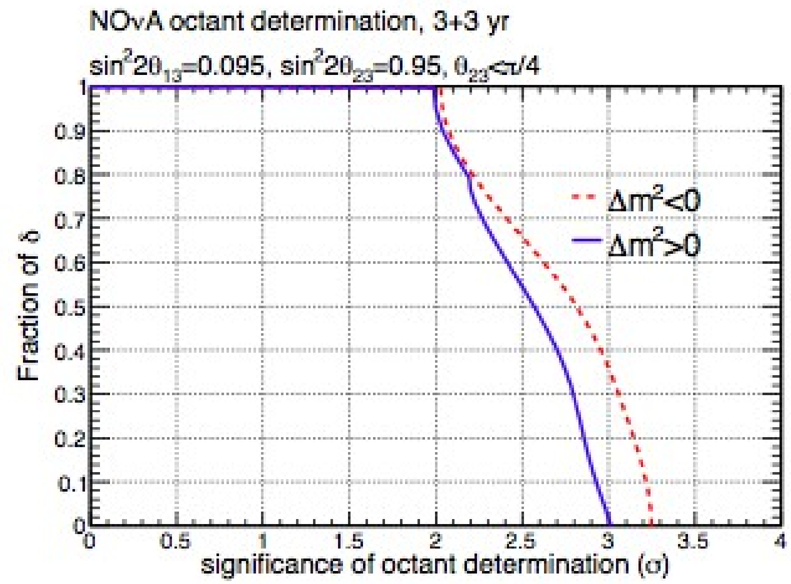
Octant Determination

$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

$\Rightarrow \theta_{23}$ octant sensitivity

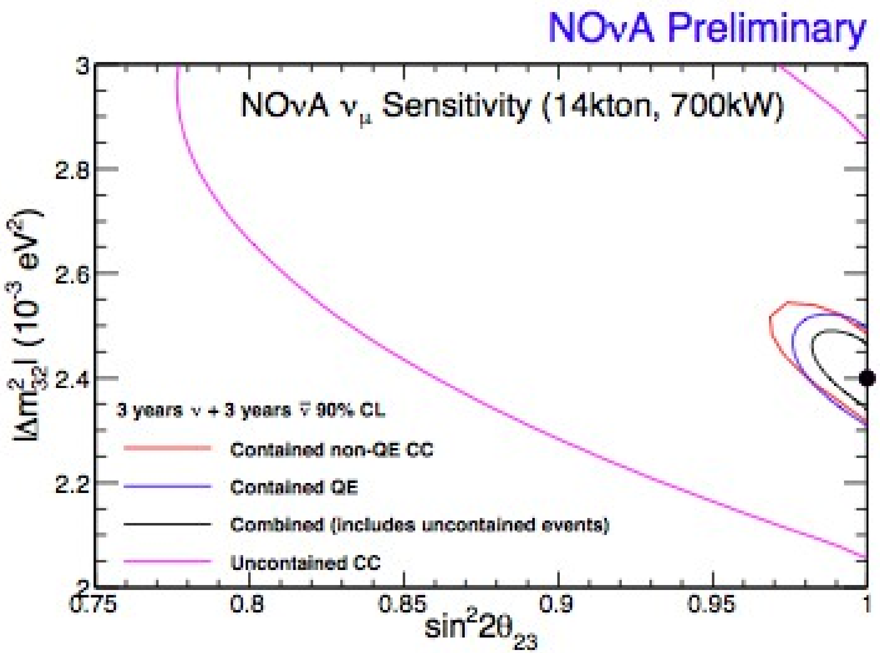


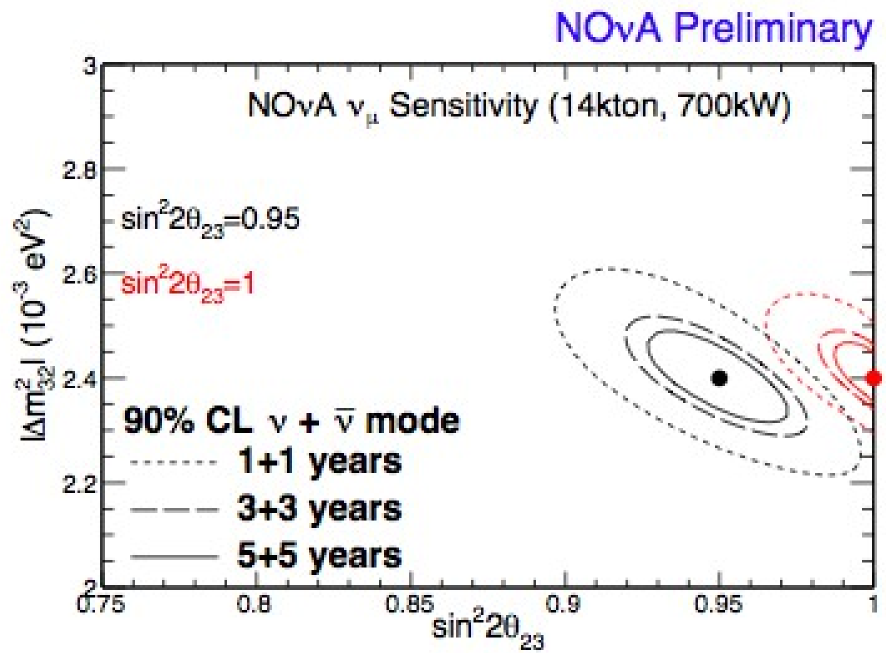




- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°, tells us whether or not ν_μ couples more strongly to ν_2 or ν_3
- Combines appearance and disappearance
- For lower octant
- Upper octant slightly better

Muon Neutrino Disappearance



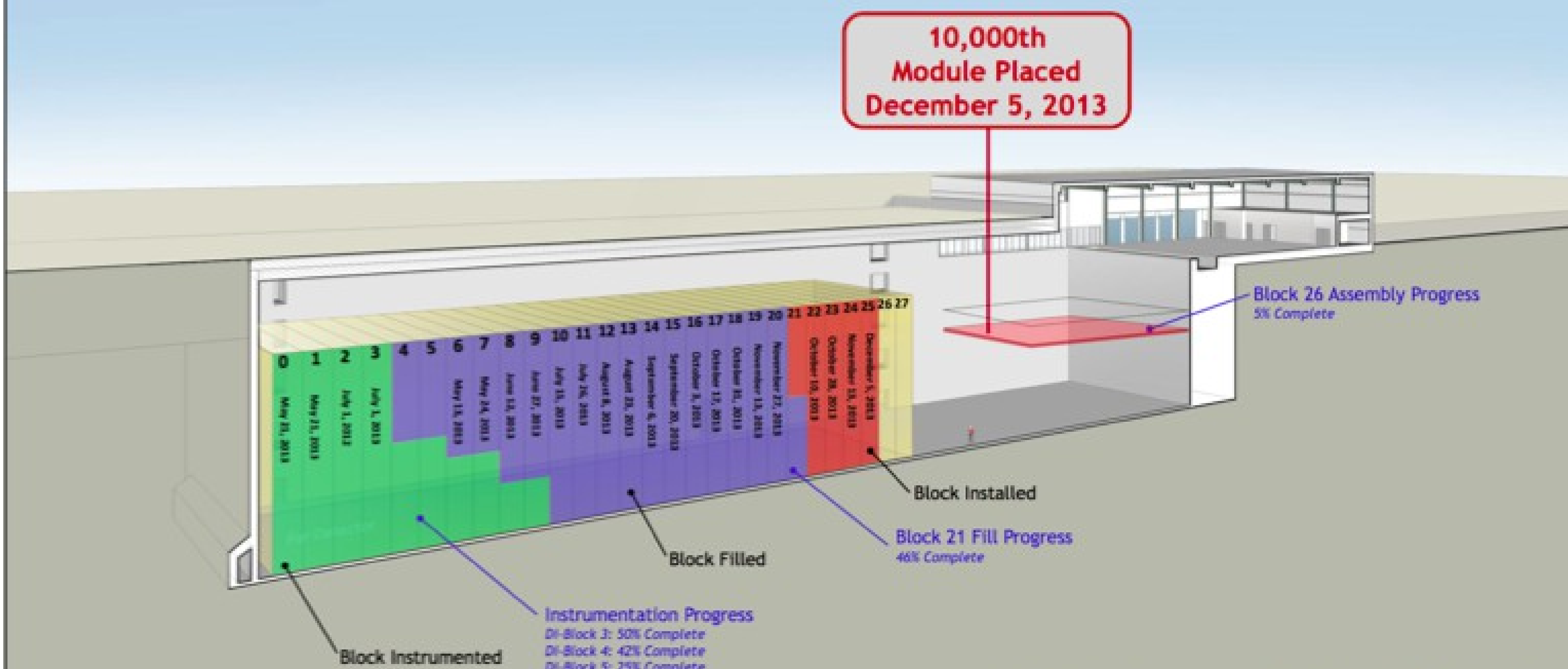


- ~80 contained + 80 uncontained muon neutrino CC events/year
- Percent level uncertainty on atmospheric mixing parameters in 3+3 years
- Exclude maximal mixing in 1+1 year at 90% if $\sin^2(2\theta_{23})$=0.95 (statistical sensitivity only)

Far Detector Construction

Far Detector

Status as of December 9th 2013



14 kilotons = 28 NOvA Blocks

26 blocks of PVC modules are assembled and installed in place

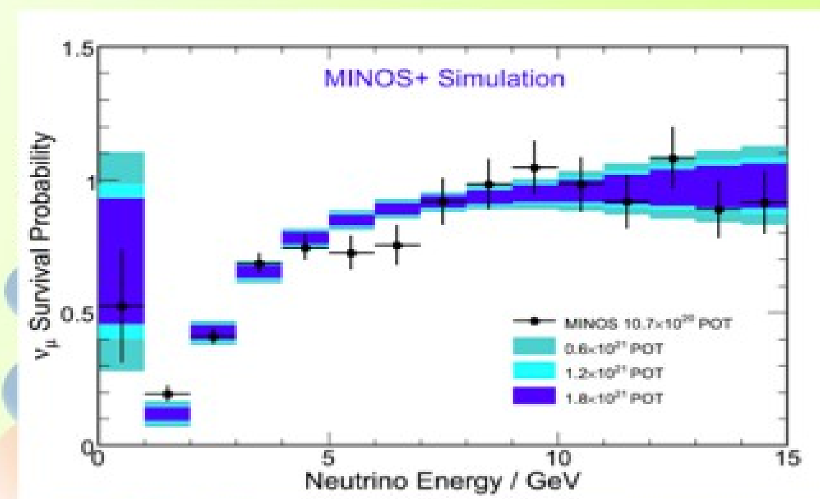
21.46 blocks are filled with liquid scintillator

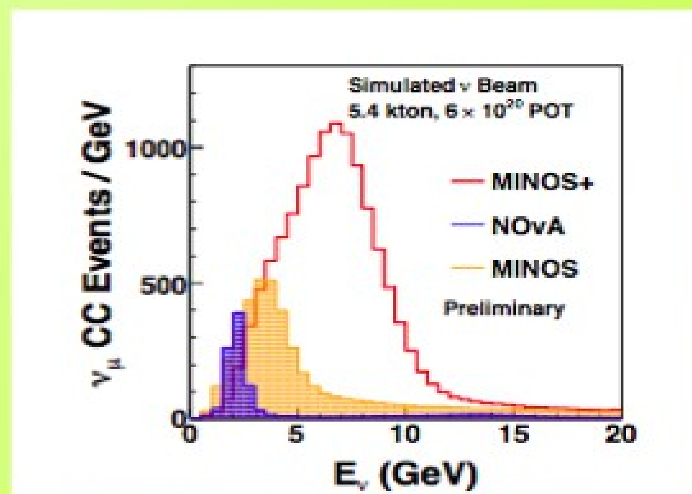
6.33 blocks are outfitted with electronics

Minos +

MINOS+

- The overarching reason to run MINOS in the NuMI-NOVA beam is to look for "non-standard" physics in a previously "unexplored" region :
  - Precision will be significantly increased (factor 60 in statistics in 3 years)
  - Where else would you look for evidence of non-3x3 effects?
    - Not at the oscillation maximum, main oscillation dominates
- 3000 events/year between 4-10 GeV near oscillation maximum

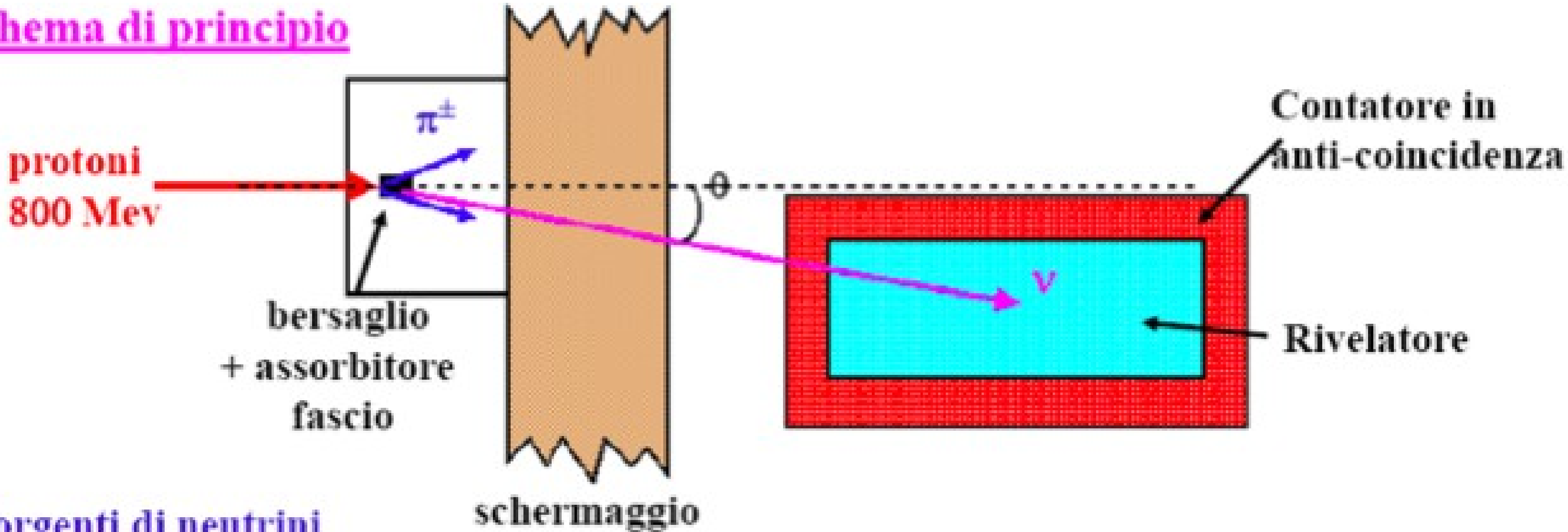




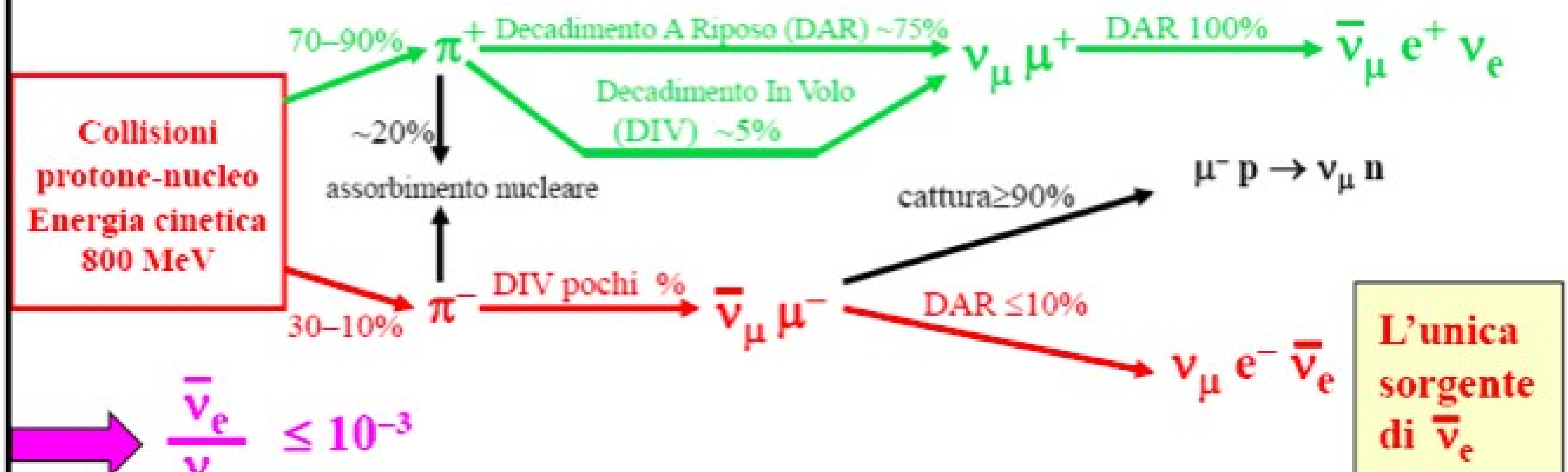
Oltre i 3 neutrini…

Esperimenti LSND e KARMEN : ricerca di oscillazioni $\bar{\nu}_\mu - \bar{\nu}_e$

Schema di principio



Sorgenti di neutrini



$$\Rightarrow \frac{\bar{\nu}_e}{\nu_e} \leq 10^{-3}$$

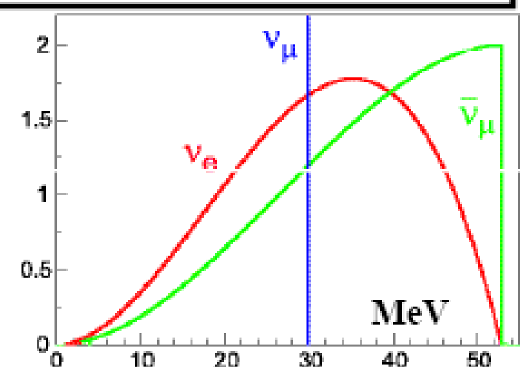
Parametri degli esperimenti LSND e KARMEN

	LSND	KARMEN
Acceleratore	Los Alamos Neutron Science Centre	Neutron Spallation Facility ISIS , R.A.L. (U.K.)
Energia cin. protoni	800 MeV	800 MeV
Corrente protoni	1000 μA	200 μA
Rivelatore	Cilindro riempito di scintillatore liquido Luce di scintillazione e luce Čerenkov	512 celle indipendenti riempite di scintillatore liquido
Massa rivelatore	167 tonn.	56 tonn.
Localizzazione evento	misura tempo PMT	dimensione cella
Distanza dalla sorgente ν	29 m	17 m
Angolo θ tra direzione fascio protoni e neutrini	11°	90°
Presa - dati	1993 – 98	1997 – 2001
Protoni su bersaglio	4.6×10^{23}	1.5×10^{23}

Spettri d'energia dei neutrini dal decadimento a riposo

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$



Esperimento LSND: evidenza di oscillazioni $\overline{\nu}_\mu - \overline{\nu}_e$

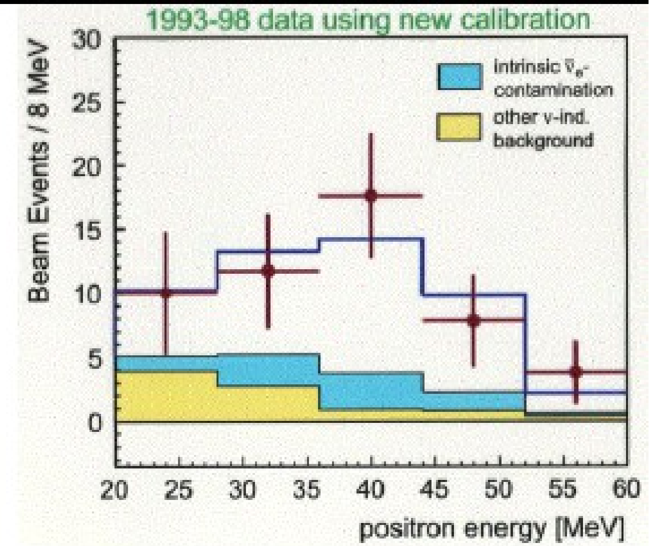
Positroni con 20 < *E* < 60 MeV

N(beam-on) – N(beam-off) = 49.1 ± 9.4 eventi

Fondo da neutrini = 16. 9 ± 2.3

Segnale $\overline{\nu}_e$ = 32.2 ± 9.4 eventi

$\mathcal{P}_{osc} = (0.264 \pm 0.067 \pm 0.045) \times 10^{-2}$

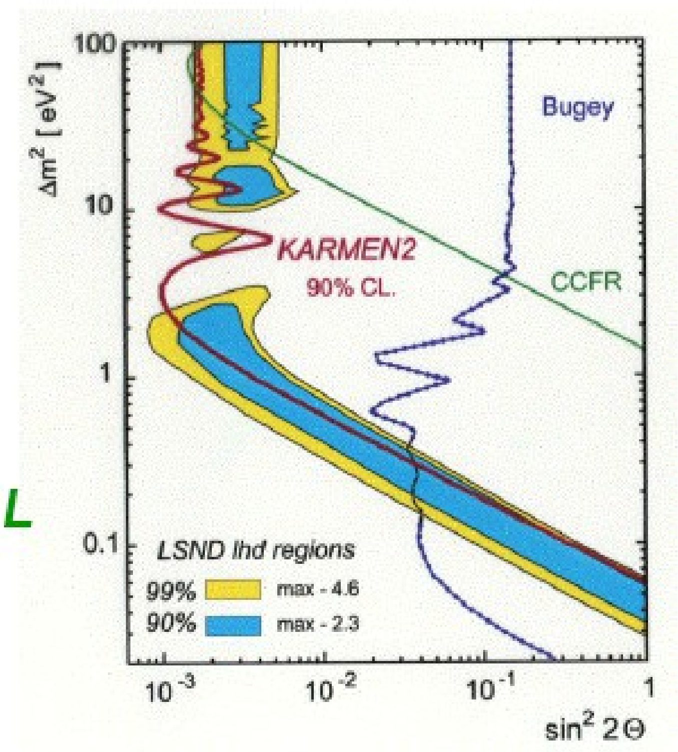


Esperimento KARMEN: nessuna evidenza di oscillazioni $\nu_\mu - \nu_e$

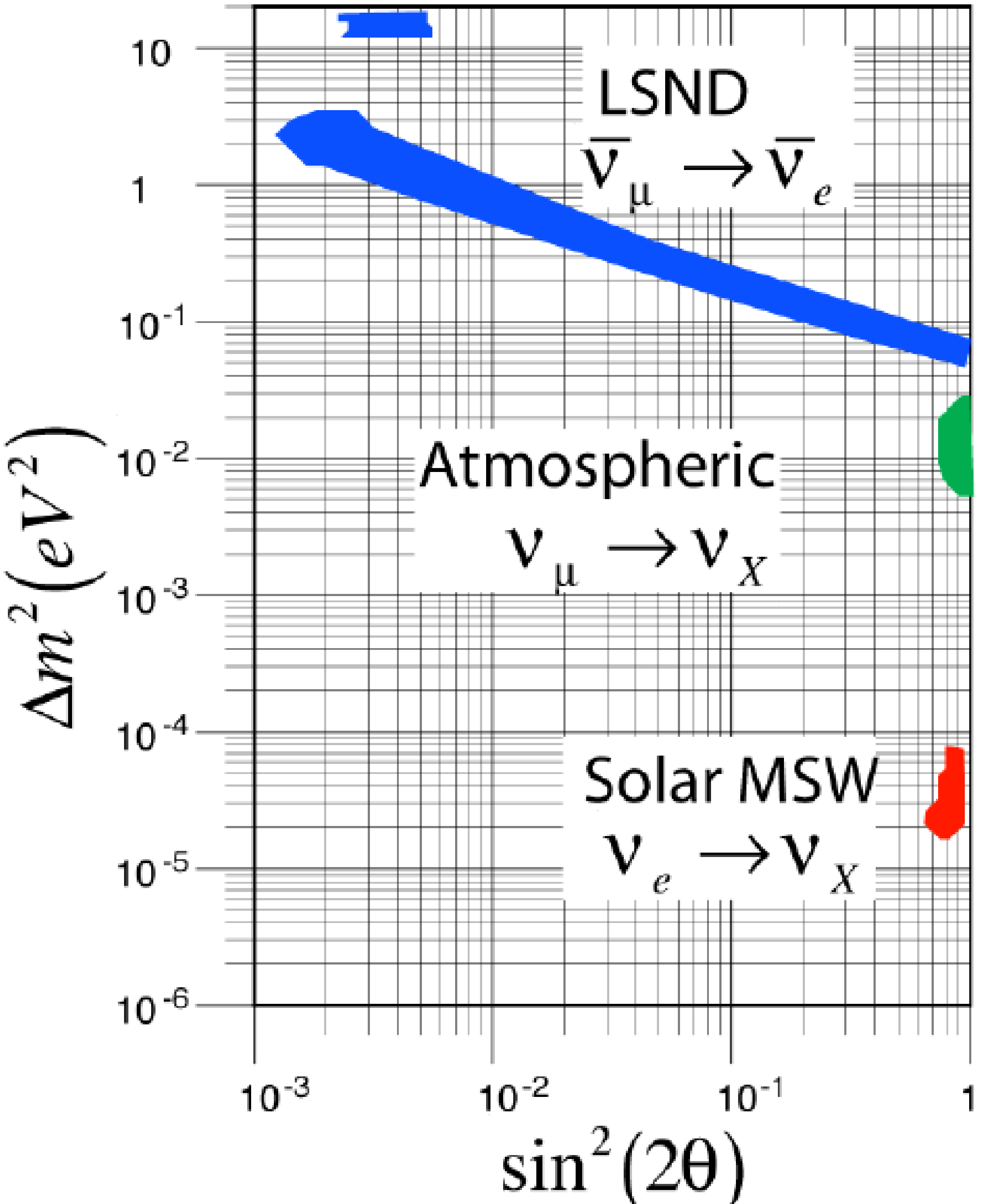
Positroni con 16 < *E* < 50 MeV selezionati : 15

Fondo previsto totale: 15.8 ± 0.5 eventi

$\mathcal{P}_{osc} < 0.085 \times 10^{-2}$ (livello conf. 90%)



Compatibilità tra KARMEN e LSND
possibile soltanto in una regione limitata
dei parametri di oscillazione perchè la distanza *L*
è diversa per i due esperimenti:
L = 29 m (LSND);
L = 17 m (KARMEN)



LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Atmospheric
$\nu_\mu \rightarrow \nu_X$
Solar MSW
$\nu_e \rightarrow \nu_X$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\Delta m^2 (eV^2)$
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta)$

Segnale di oscillazione $\bar{\nu}_\mu - \bar{\nu}_e$ in LSND : un problema serio

Definizione: $\Delta m_{ik}{}^2 = m_k{}^2 - m_i{}^2 \quad (i,k = 1, 2, 3)$

$$\Rightarrow \quad \Delta m_{12}{}^2 + \Delta m_{23}{}^2 + \Delta m_{31}{}^2 = 0$$

Segnali di oscillazione:

- **Neutrini solari:** $\Delta m_{12}{}^2 \approx 7.6 \times 10^{-5}$ eV^2
- **Neutrini atmosferici:** $\Delta m_{23}{}^2 \approx 2.5 \times 10^{-3}$ eV^2
- **LSND:** $|\Delta m_{31}{}^2| = 0.2 — 2$ eV^2

$$\Rightarrow \quad |\Delta m_{12}{}^2 + \Delta m_{23}{}^2 + \Delta m_{31}{}^2| = 0.2 — 2 \text{ eV}^2$$

L'interpretazione dei tre risultati richiede almeno quattro neutrini.

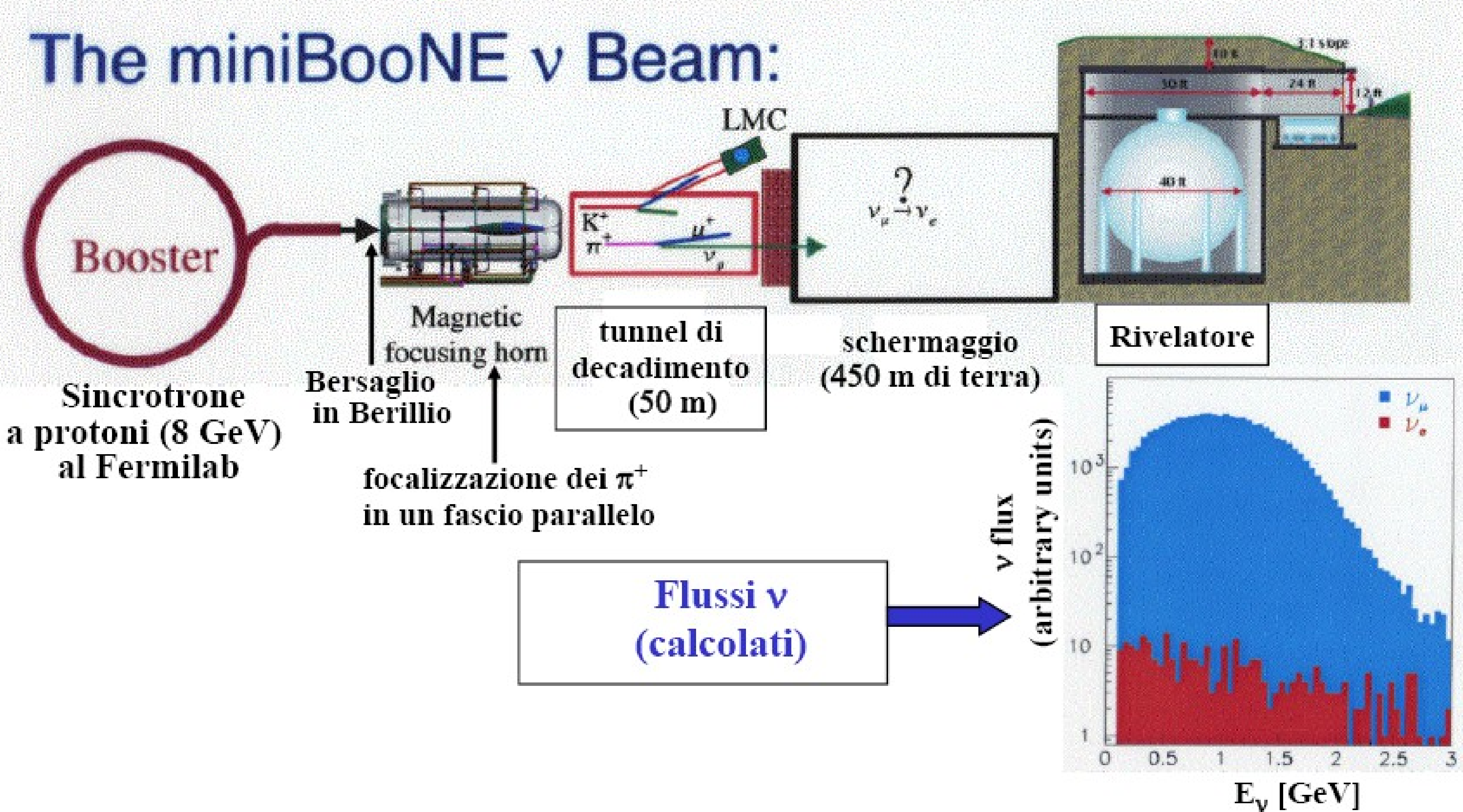
Risultati degli esperimenti LEP: numero di neutrini leggeri = 3

⇒ altri neutrini, se esistono, devono essere "sterili":
costante di accoppiamento ai bosoni W e Z = 0
⇒ nessuna interazione con la materia

MiniBooNE

Scopo: conferma del segnale LSND

- fase iniziale: ricerca di oscillazioni $\nu_\mu - \nu_e$;
- fase successiva: ricerca di oscillazioni $\overline{\nu}_\mu - \overline{\nu}_e$;
- in caso di conferma del segnale LSND, installazione di un secondo rivelatore a L diverso

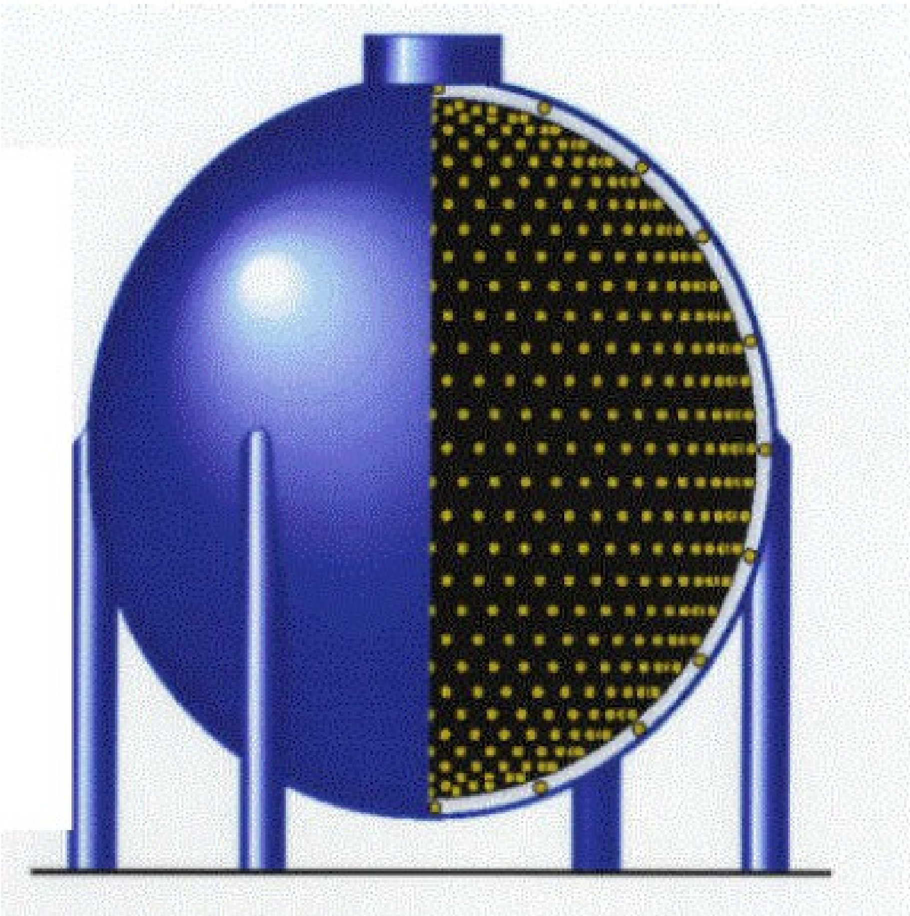


MiniBooNE/LSND Neutrino Oscillation Results

M. Sorel (IFIC - CSIC & U.Valencia)

Workshop on Beyond Three Family Neutrino Oscillations
May 3-4, 2011, LNGS (Italy)

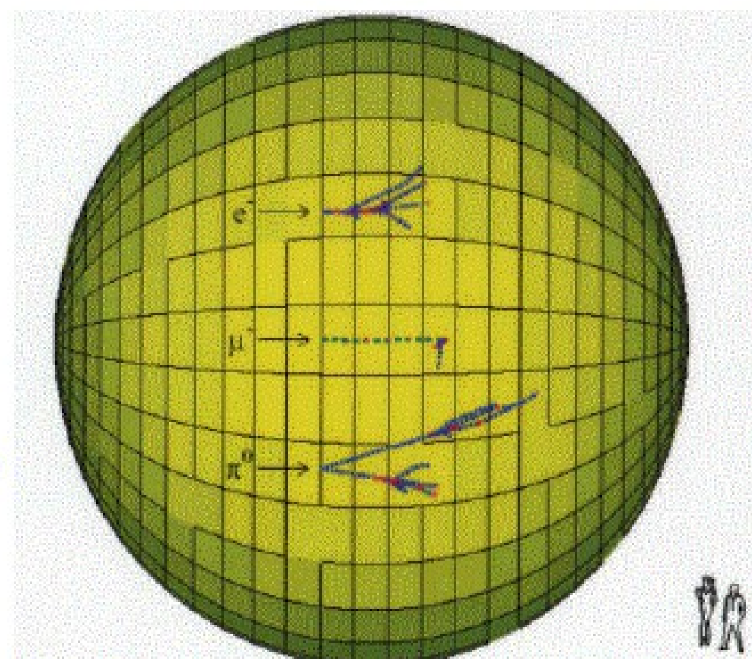
Rivelatore MiniBooNE



- Contenitore sferico, diametro 12 m
  807 tonn. olio minerale poco scintillante.
- Raccolta della luce Čerenkov (direzionale)
  e della luce da scintillazione.
- Massa fiduciale 445 tonn.
- Regione interna isolata otticamente
  (1280 fototubi, diam. 20 cm)
- Regione esterna in anticoincidenza
  (240 fototubi)

Identificazione delle particelle secondarie

basata sul comportamento diverso di elettroni, muoni, pioni e sulla configurazione degli anelli di luce Čerenkov

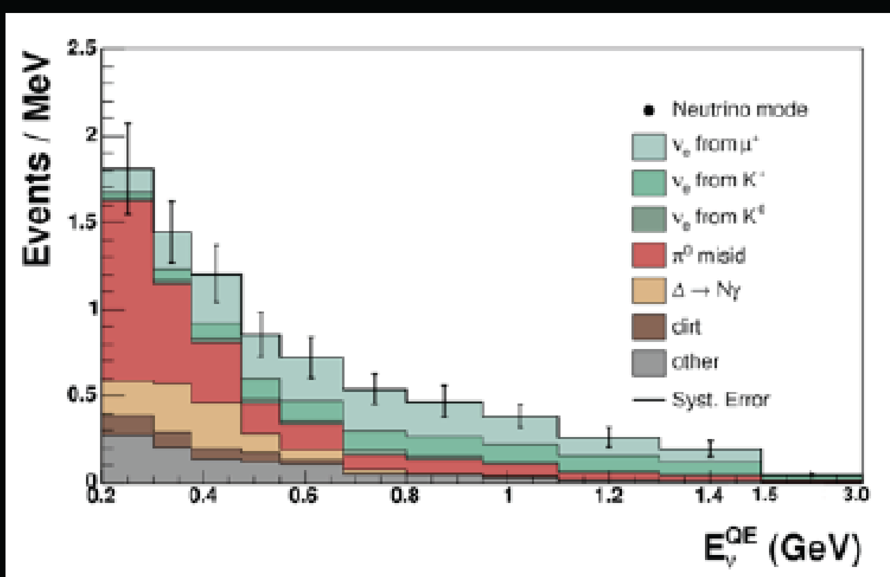


Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

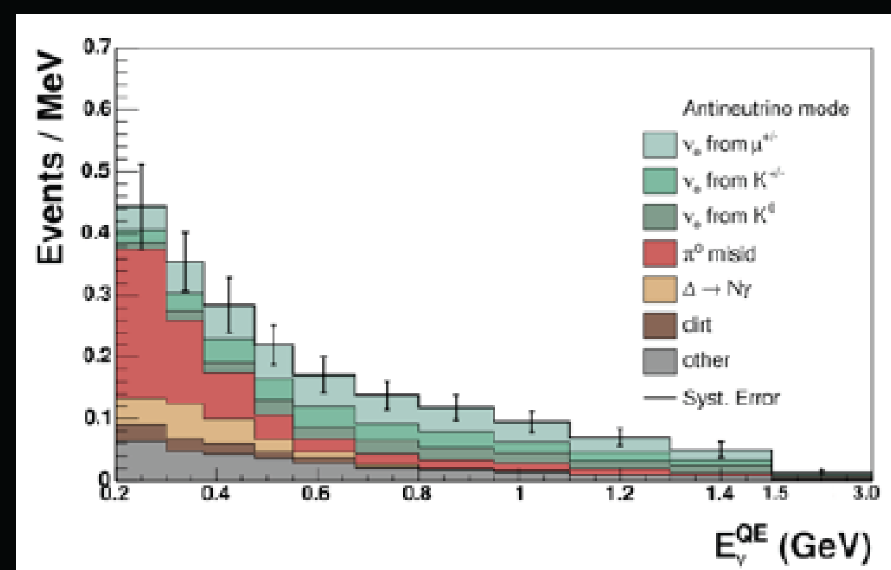
Two separate searches, one in neutrino mode and one in antineutrino mode

Look for appearance of ν_e or $\bar{\nu}_e$ events above background expectations versus energy, and see if described by a two-neutrino oscillation hypothesis

Expected background neutrino mode



Expected background antineutrino mode



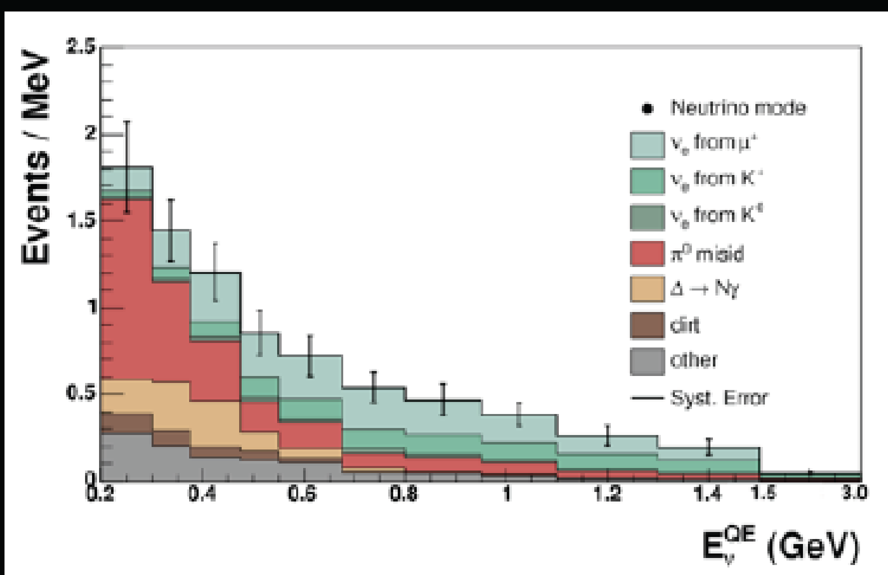
Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Two separate searches, one in neutrino mode and one in antineutrino mode

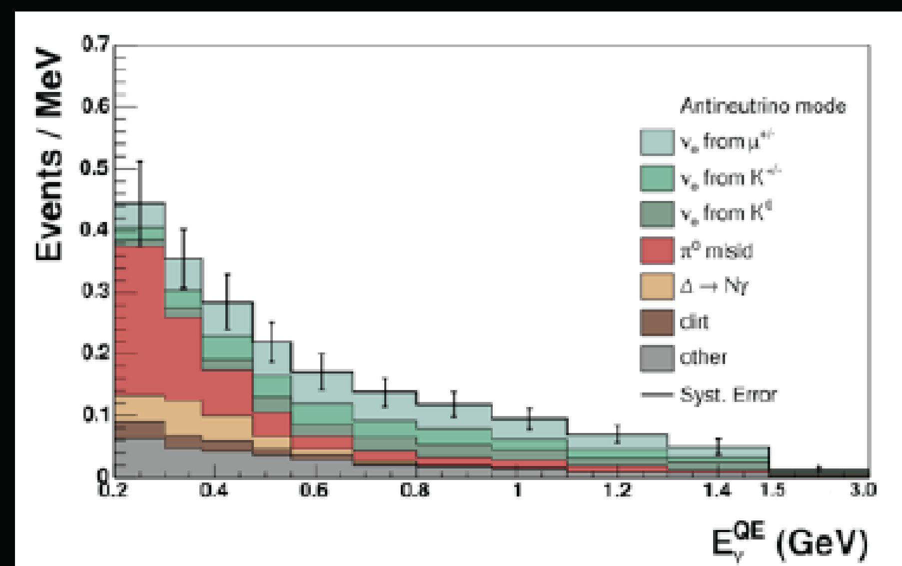
High statistics, powerful test of LSND's simplest interpretation

Lower statistics (less powerful), but direct test of LSND excess

Expected background neutrino mode



Expected background antineutrino mode



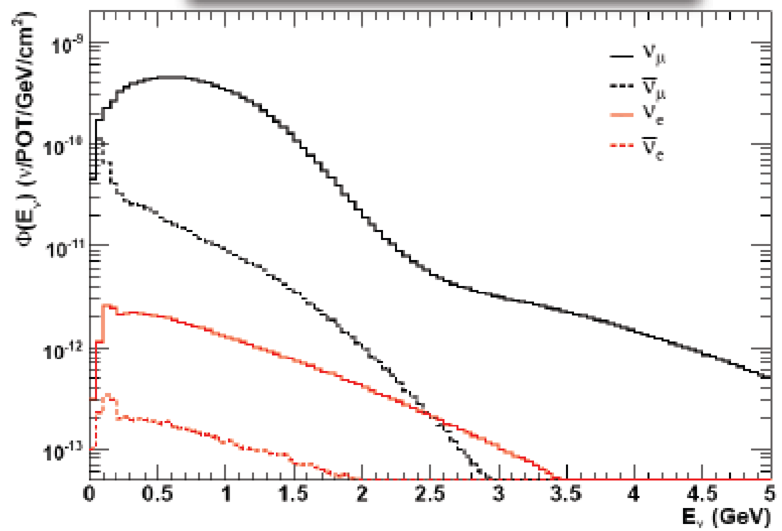
The MiniBooNE Recipe For Appearance Searches

Ingredients:

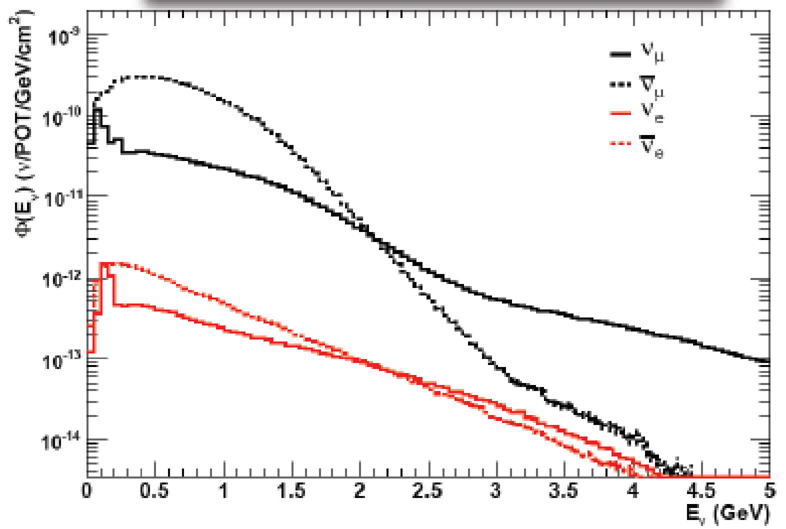
- Same L/E as LSND
- High intensity ν_μ beam with low intrinsic ν_e contamination
- Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)
- Information about neutrino energy spectrum
- Patience (& data stability)

- ☑ Same L/E as LSND
- ☑ High intensity ν_μ beam with low intrinsic ν_e contamination

Neutrino mode flux prediction



Antineutrino mode flux prediction

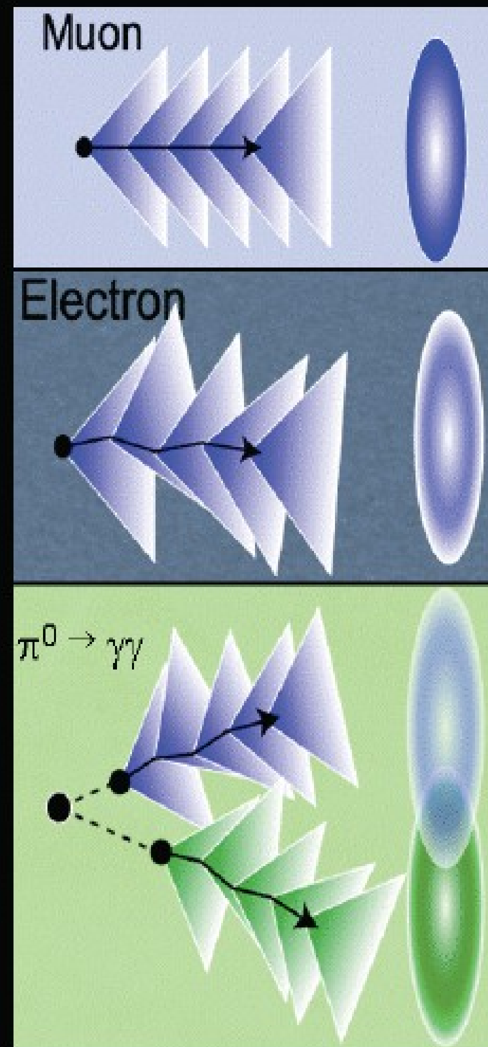


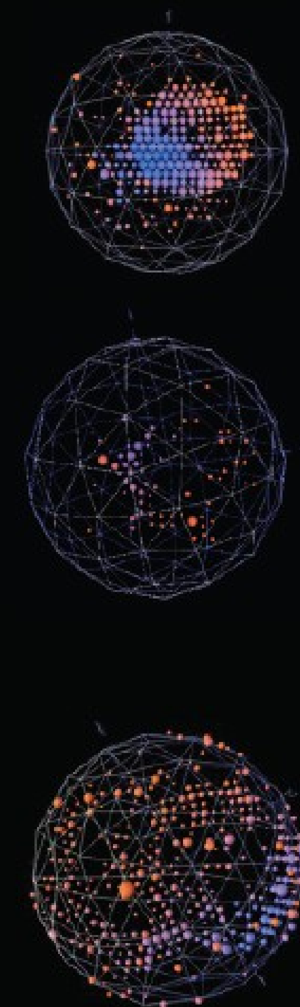
Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)

Muons:
- long tracks
- sharp Cherenkov ring
- ~80% with decay electron tag

Electrons:
- short tracks
- fuzzy Cherenkov ring
- single subevent

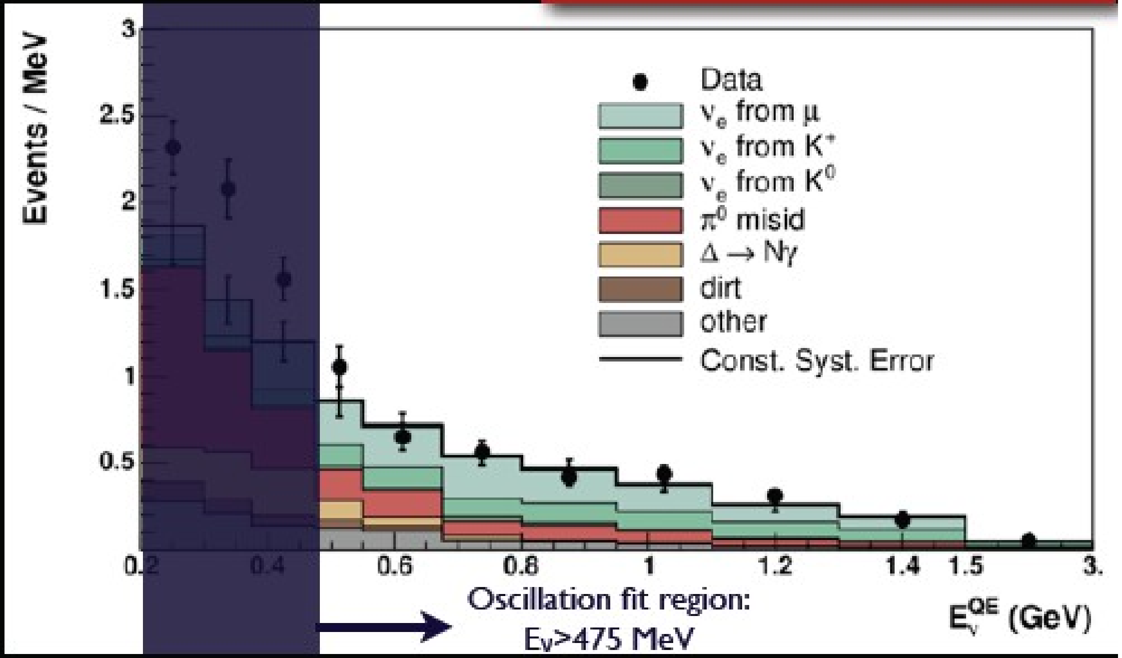
$\pi^0 \rightarrow \gamma\gamma$:
- disconnected short tracks
- typically two fuzzy rings with $m_{\gamma\gamma} \sim m_\pi$
- single subevent





Results (Oscillation Fit Region)

PRL 102, 101802 (2009), $6.46 \cdot 10^{20}$ POT



$475 < E_\nu < 1250$ MeV counts:

- 22.1 ± 35.7 excess events
- No evidence for oscillations

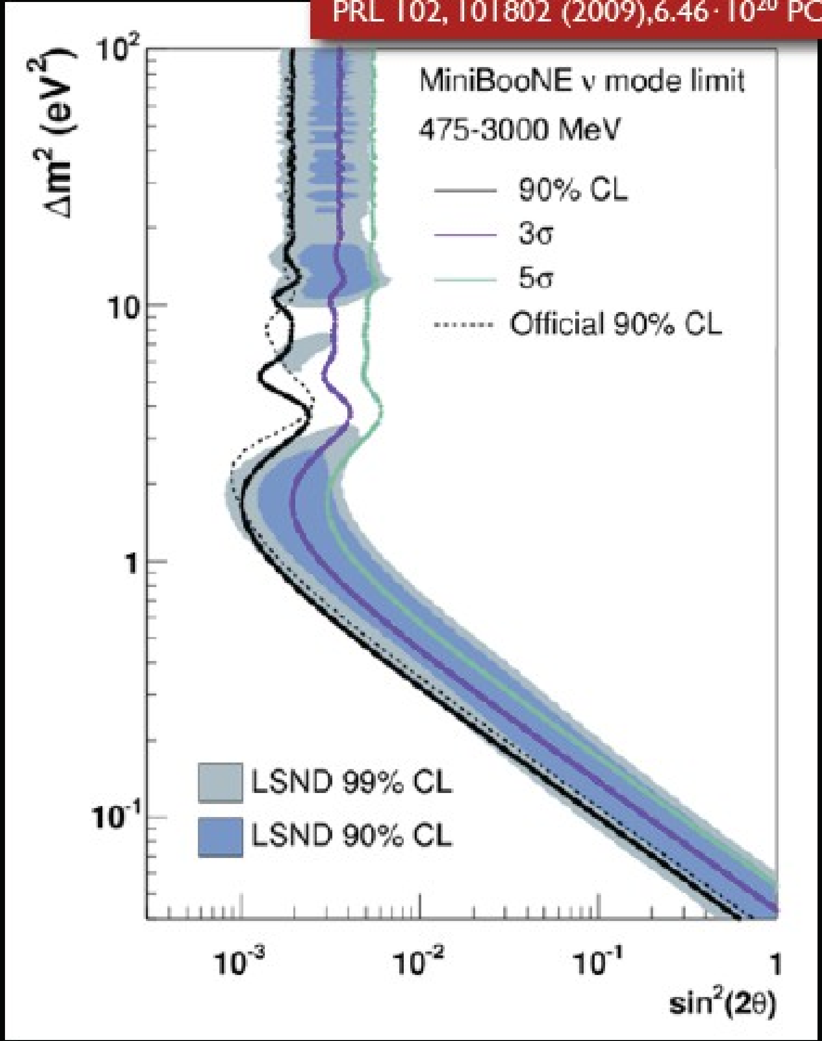
$E_\nu > 475$ MeV energy fit:

- null: χ^2/dof = 9.1/15 (87%)
- best-fit: χ^2/dof = 7.2/13 (89%)

- Assume no ν_μ/ν_e disappearance

Results (Oscillation Fit Region)

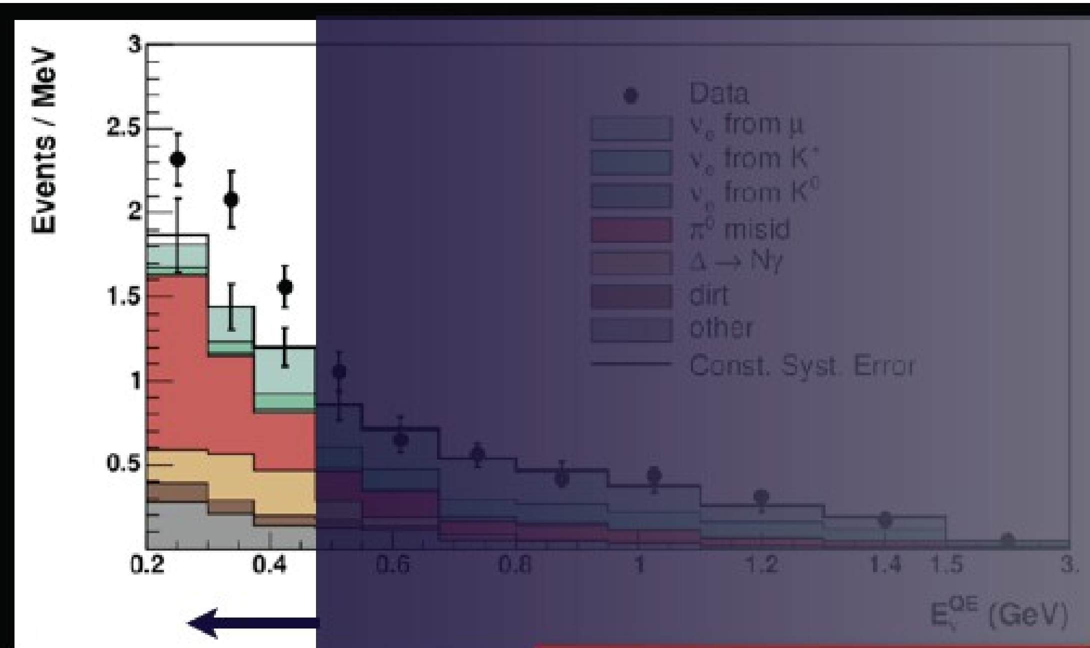
PRL 102, 101802 (2009), $6.46 \cdot 10^{20}$ POT



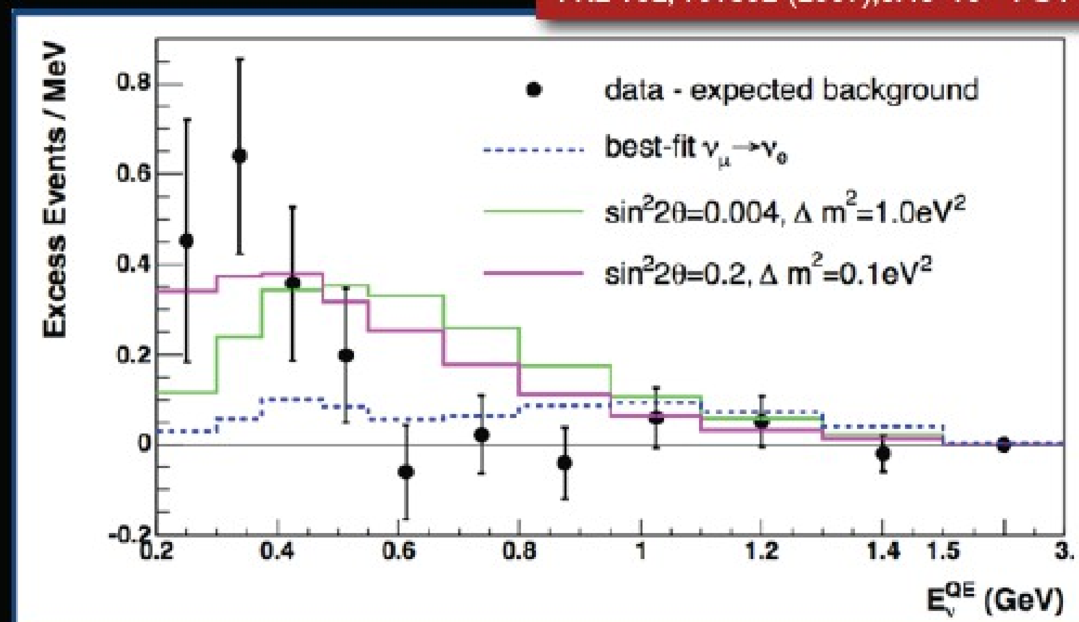
• MiniBooNE rules out the LSND two-neutrino oscillation interpretation (assuming no CP or CPT violation)

Results (Low Energies)

- 200 < E_ν < 475 MeV counts:
  - 128.8 ± 20.4 ± 38.3 excess events
  - 3.0σ significance
- Shape inconsistent with 2ν oscillations
- Excess remains unexplained

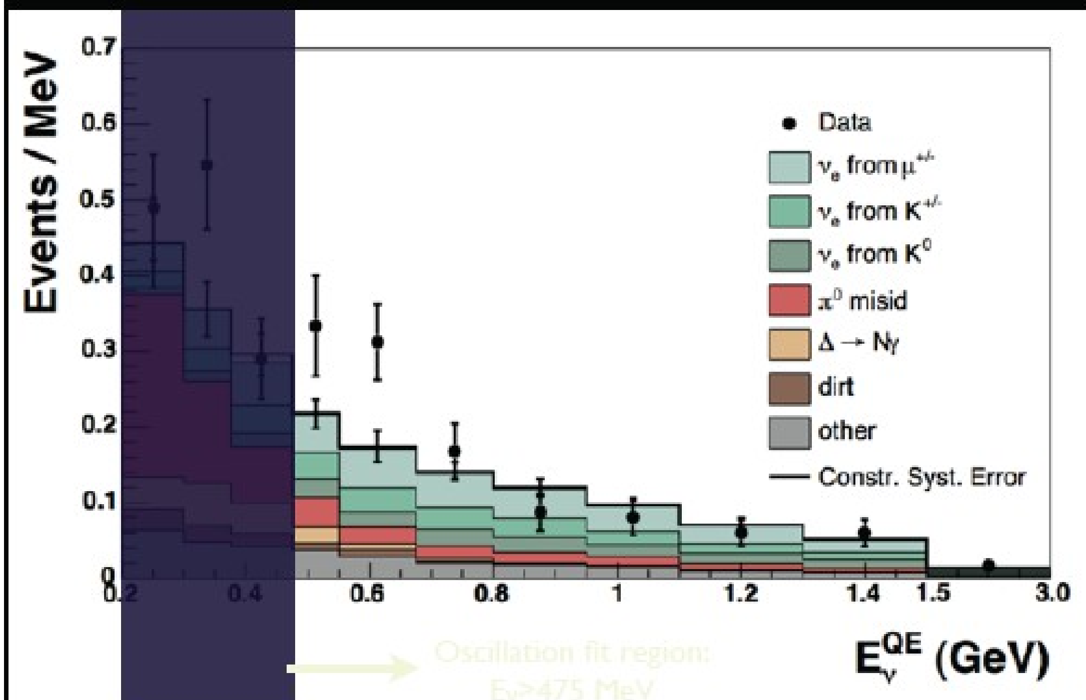


PRL 102, 101802 (2009), $6.46 \cdot 10^{20}$ POT



Anti-neutrino channel

Results



$475 < E_\nu < 1250$ MeV:

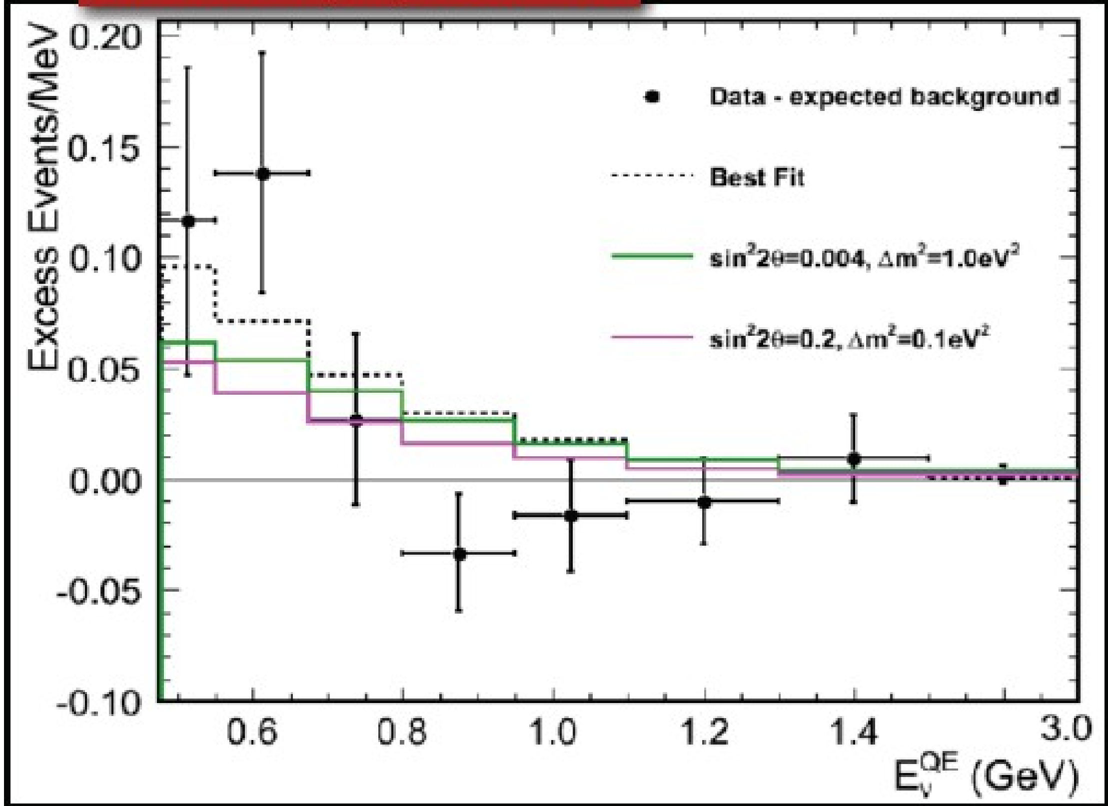
- 20.9 ± 14.0 excess events
- Consistent with LSND best fit expectation: 22 events

- Significance of excess largely in energy shape different from bgr:
  - null: χ^2/dof = 18.5/6
  - 0.5% probability for background-only hypothesis

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT

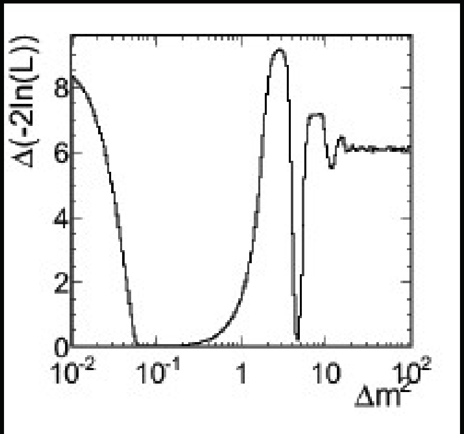
Results

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT



E-dependent fit to oscillations:

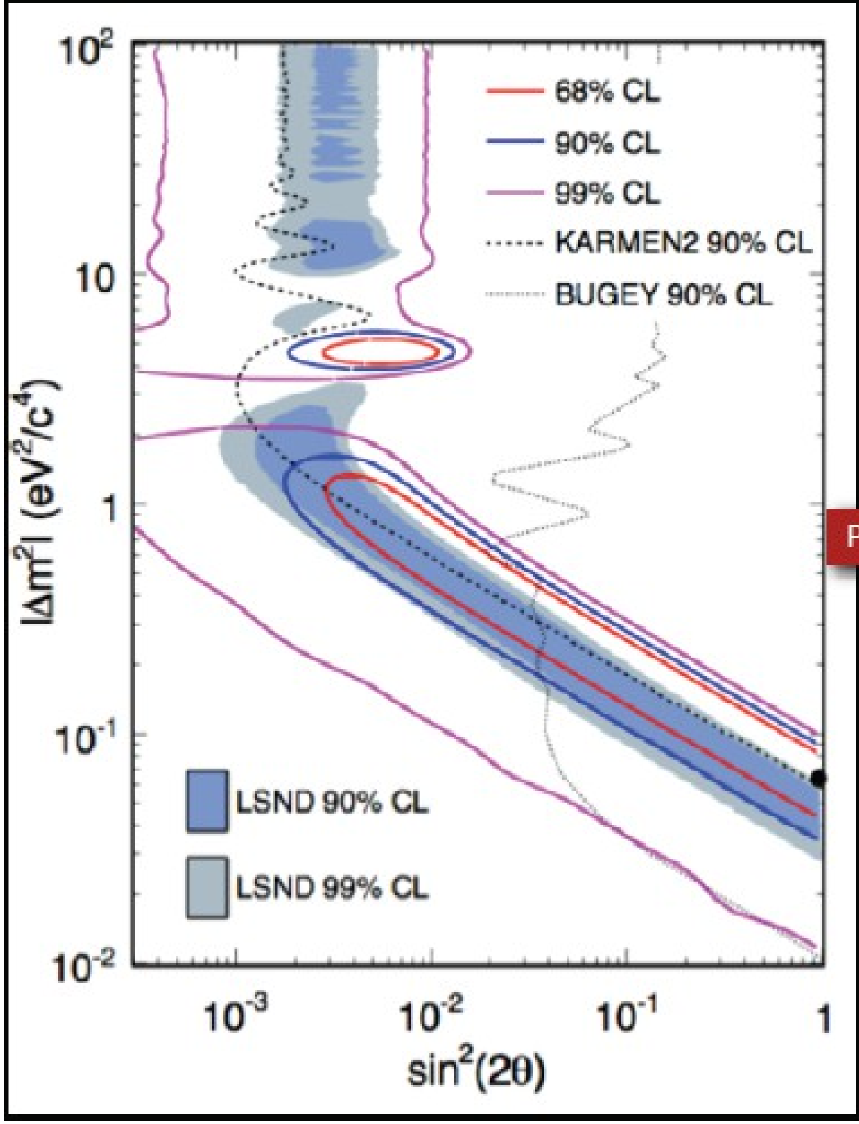
- Assume no ν_μ/ν_e disappearance
- Assume only antineutrinos oscillate
- Best fit: $(\sin^2 2\theta, \Delta m^2) = (0.96, 0.064\ eV^2)$



$475 < E_\nu < 1250$ MeV:

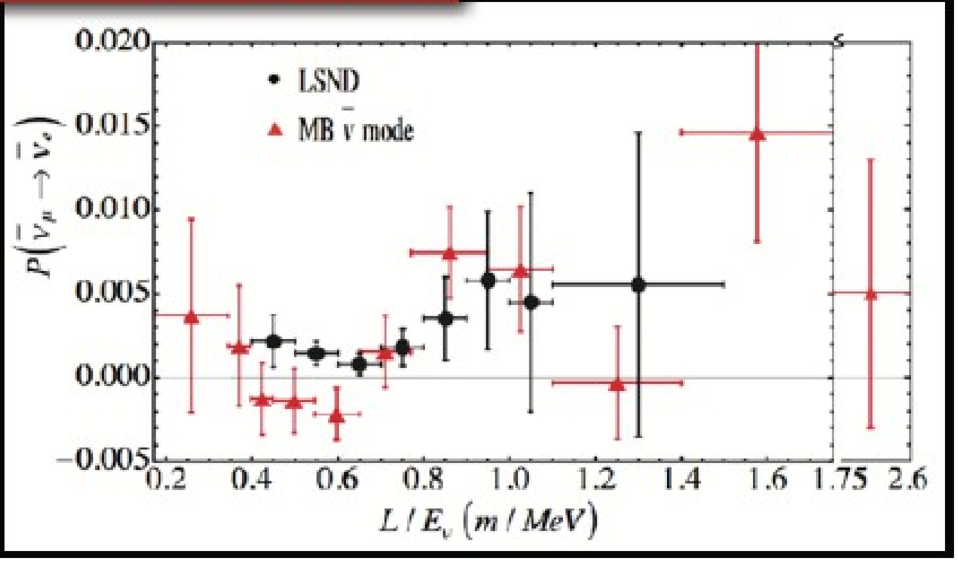
- Best fit: χ^2/dof = 8.0/4 (8.7%)
- Consistent with 2ν oscillations
- Oscillations favored over background hypothesis at 99.4% CL

Results



- Consistent with oscillation interpretation of LSND
  - Overlap in oscillation parameters allowed regions
  - Consistent L/E trend for excess-inferred oscillation probabilities

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT



Confused? Here's a Summary of MiniBooNE Appearance Claims

1. In a ν_μ beam above 475 MeV, we see no evidence for an excess of ν_e-like events

2. In a ν_μ beam below 475 MeV, we see a 3σ excess (128 + 43) of ν_e-like events that does not fit well a 2ν oscillation hypothesis

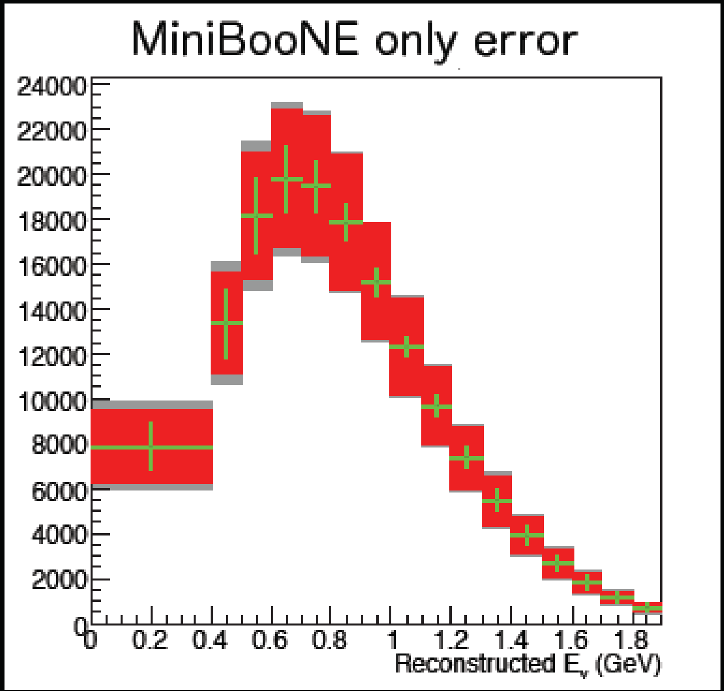
3. In a $\bar{\nu}_\mu$ beam below 475 MeV, we see (18 ± 14) events, consistent with both no excess and LSND + ν-only low-E excess. This rules out some explanations of the ν_μ beam low-E excess

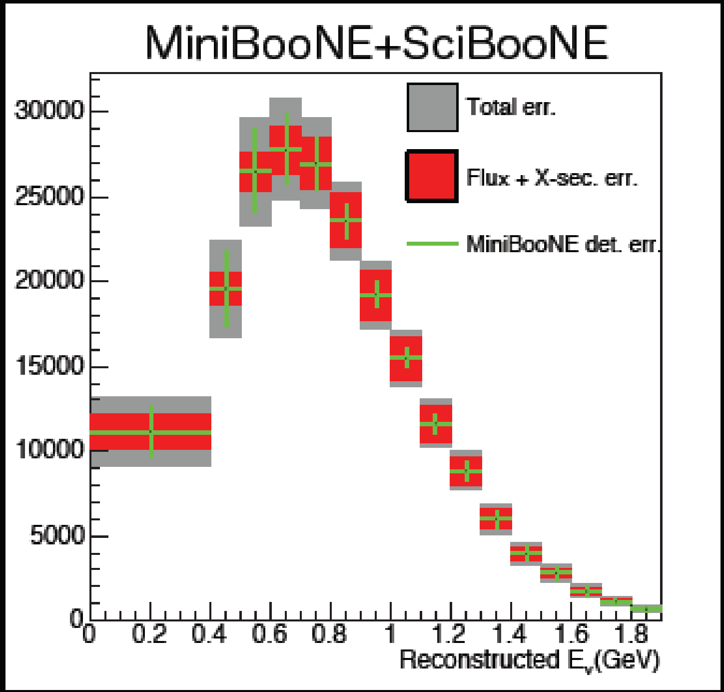
4. In a $\bar{\nu}_\mu$ beam above 475 MeV, we see an excess of events. The null hypothesis in the 475-1250 MeV region is only 0.5% probable. A 2ν fit prefers an LSND-like signal at 99.4% CL

Scomparsa (neutrini e antineutrini muonici)

New SciBooNE+MiniBooNE Results

- SciBooNE: near detector in same beam as MiniBooNE, 100m from production target
- SciBooNE ν_μ data allow to reduce flux and cross section systematic uncertainties affecting MiniBooNE ν_μ predictions to same level as detector response uncertainties:





Improvement over MiniBooNE-only analysis (2009)

New SciBooNE+MiniBooNE Results

- Use MiniBooNE neutrino mode data taken both prior to ("old") and together with ("new") SciBooNE

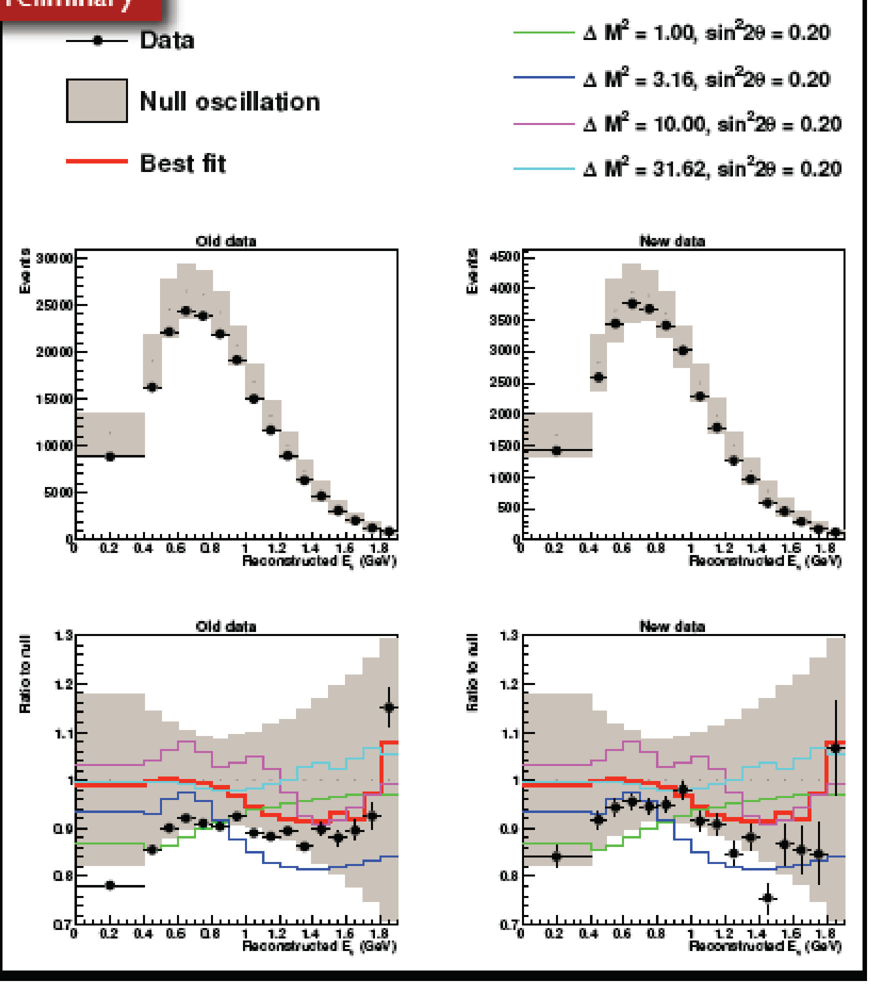
- Best fit: Δm^2=42 eV^2, $\sin^2 2\theta$=0.51

- Null: χ^2/dof = 41.5/32
- Best: χ^2/dof = 35.6/30

- $\Delta\chi^2$(observed)=5.9
- Simulations: $\Delta\chi^2$(90% CL, null)=8.4

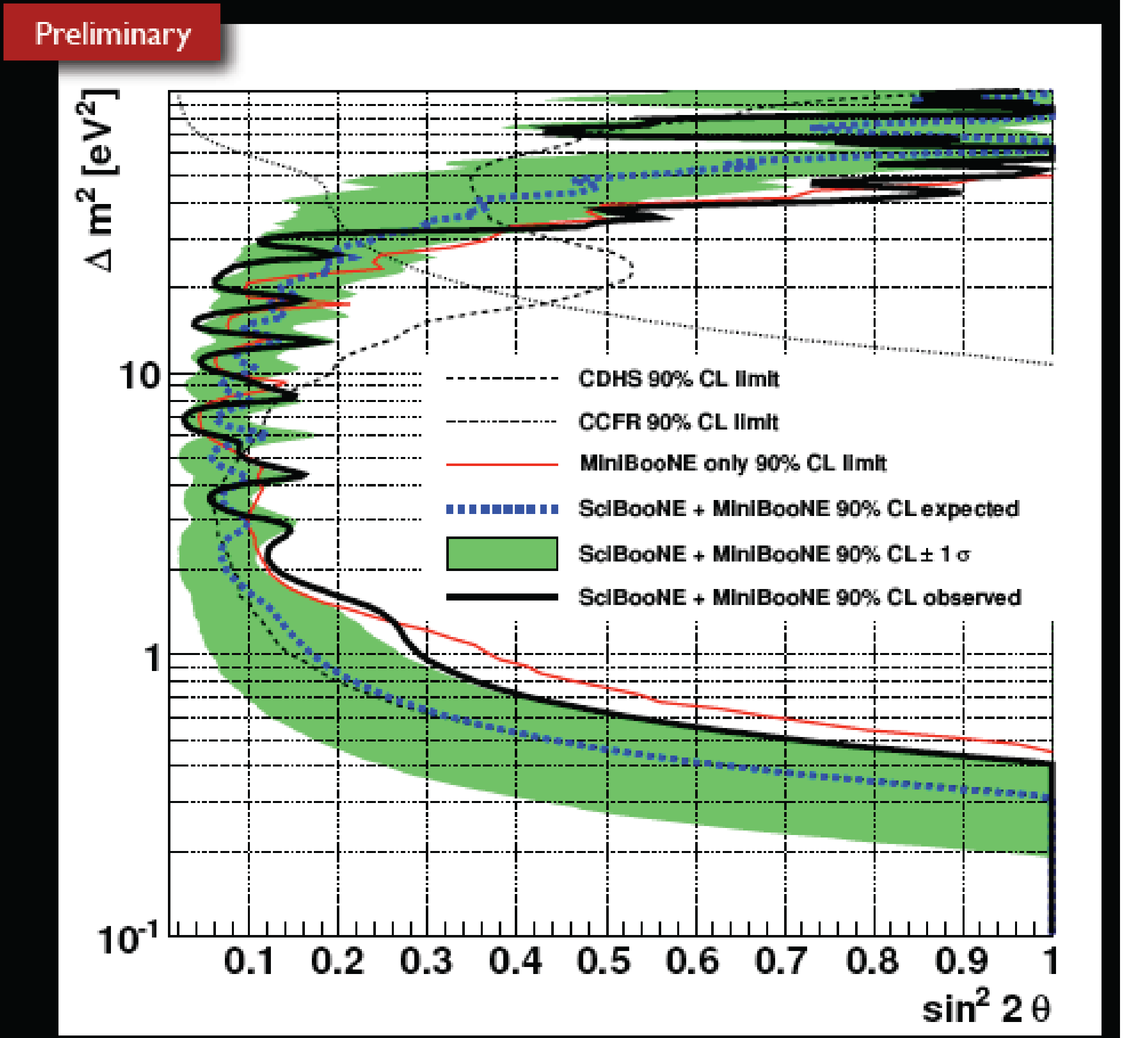
- **No significant ν_μ disappearance observed**

Preliminary



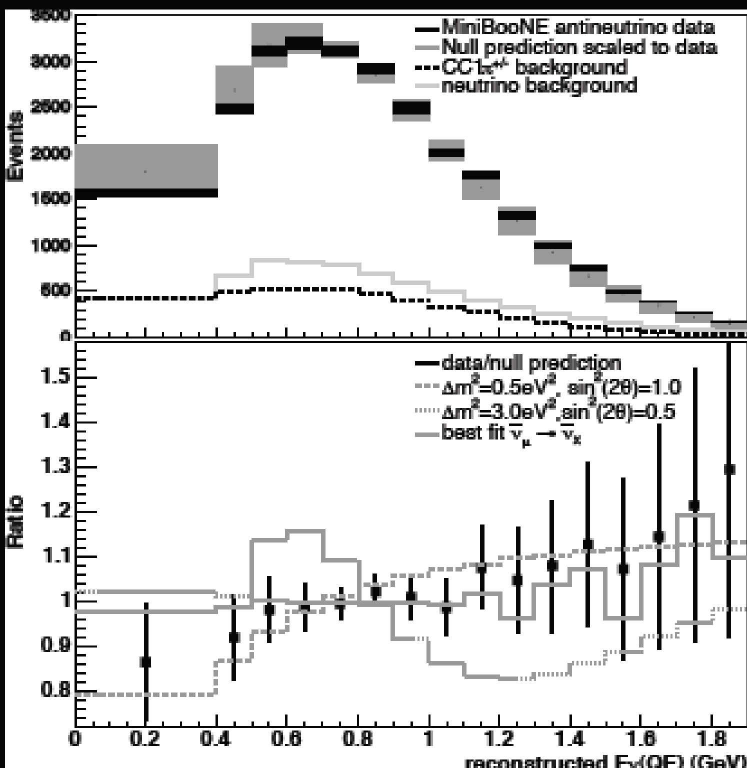
New SciBooNE+MiniBooNE Results

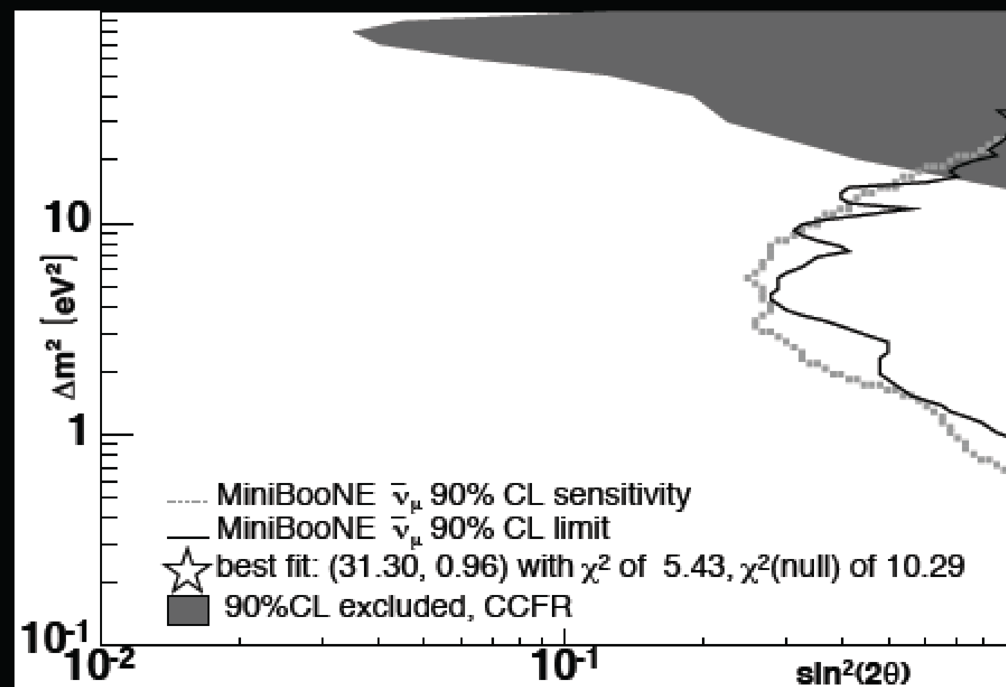
- World's strongest limit for $10 < \Delta m^2 < 30$ eV^2
- Limit weaker than sensitivity for $\Delta m^2 < 30$ eV^2 because of small data deficit observed
- Constrains sterile neutrino mixing models



MiniBooNE ν_μ Disappearance

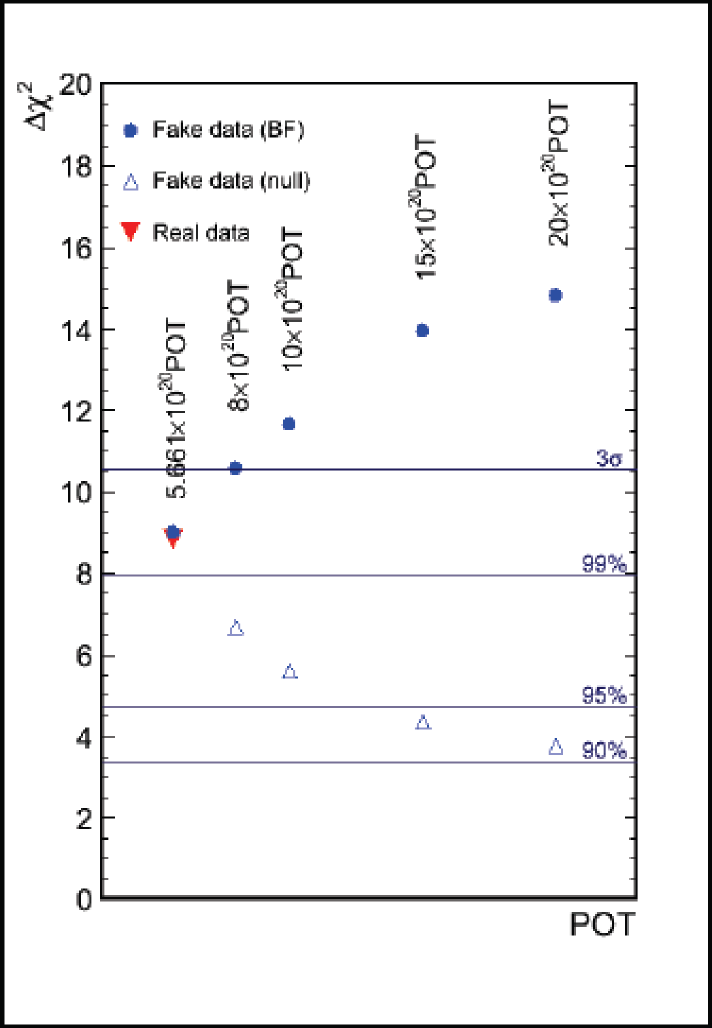
- 2009 results: no $\bar{\nu}_\mu$ disappearance observed, but limited sensitivity
- Current antineutrino mode data statistics (x3 2009 result) + SciBooNE near detector constraint will allow for a more sensitive search
- Particularly interesting now, given MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results!





PRL 103, 061802 (2009)

Conclusions:



- 15 years after first first LSND claim for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, the issue is still not settled

- At such small oscillation probabilities, not an easy measurement to make!

- MiniBooNE is exploring four oscillation channels and a large L/E range covering LSND, but no clear picture (invoking steriles or otherwise) has emerged so far

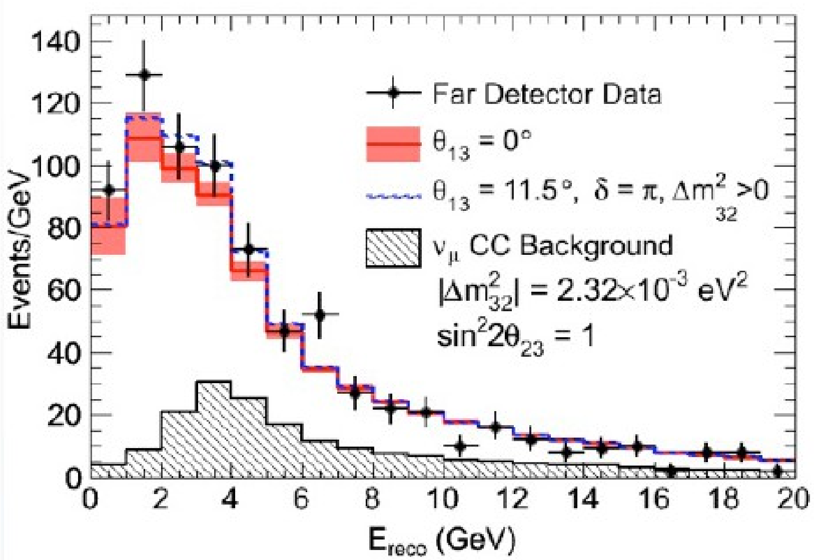
- More MiniBooNE data needed:
  - New $\bar{\nu}_\mu \to \bar{\nu}_e$ results this summer ($9 \cdot 10^{20}$ POT)
  - Continue $\bar{\nu}$ mode data-taking until March 2012 ($12 \cdot 10^{20}$ POT)
  - Plan to submit proposal this fall for 2nd identical detector at 200m

- More eperimental efforts definitely needed:
  - See talks at this workshop

- Ci sono (chiare?) indicazioni di un diverso comportamento tra neutrini ed anti-neutrini
- Le oscillazioni osservate da LSND e MiniBOONE non possono rientrare in uno schema a tre soli neutrini
- La non osservazione di un quarto neutrino leggero lascia presumere che serva includere almeno un neutrino sterile o comunque che serva ricorrere a nuova fisica

MINOS: update su neutrini sterili

Neutral Currents in the Far Detector



- Expect: **754** events
- Observe: **802** events
- No deficit of NC events

$$R = \frac{N_{data} - BG}{S_{NC}}$$

1.09 ± 0.06 (stat.) ± 0.05 (syst.)
(no ν_e appearance)

1.01 ± 0.06 (stat.) ± 0.05 (syst.)
(with ν_e appearance)

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40)\ \text{at } 90\%\ \text{C.L.}$$

no (with) ν_e appearance

Submitted to PRL, arXiv:1104.3922

Neutrini sterili

Seguiamo direttamente le slides di Pedro Machado a ICFA 2014:

https://indico.in2p3.fr/getFile.py/access?contribId=6&sessionId=1&resId=0&materialId=slides&confId=8974

e quelle di Teppei Katori a NuPhys 2013:

http://nuphys2013.iopconfs.org/IOP/media/uploaded/EVIOP/event_421/TK_SBL_131219%5B1%5D.pdf

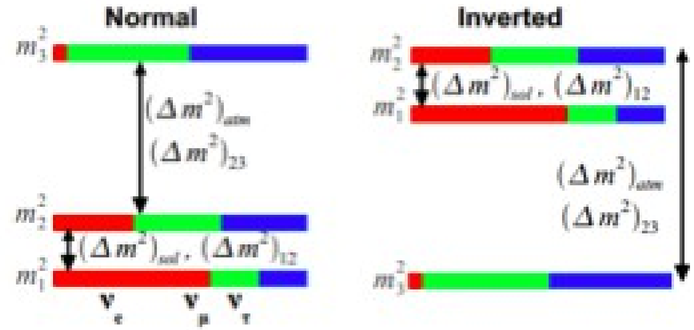
Neutrini: il futuro

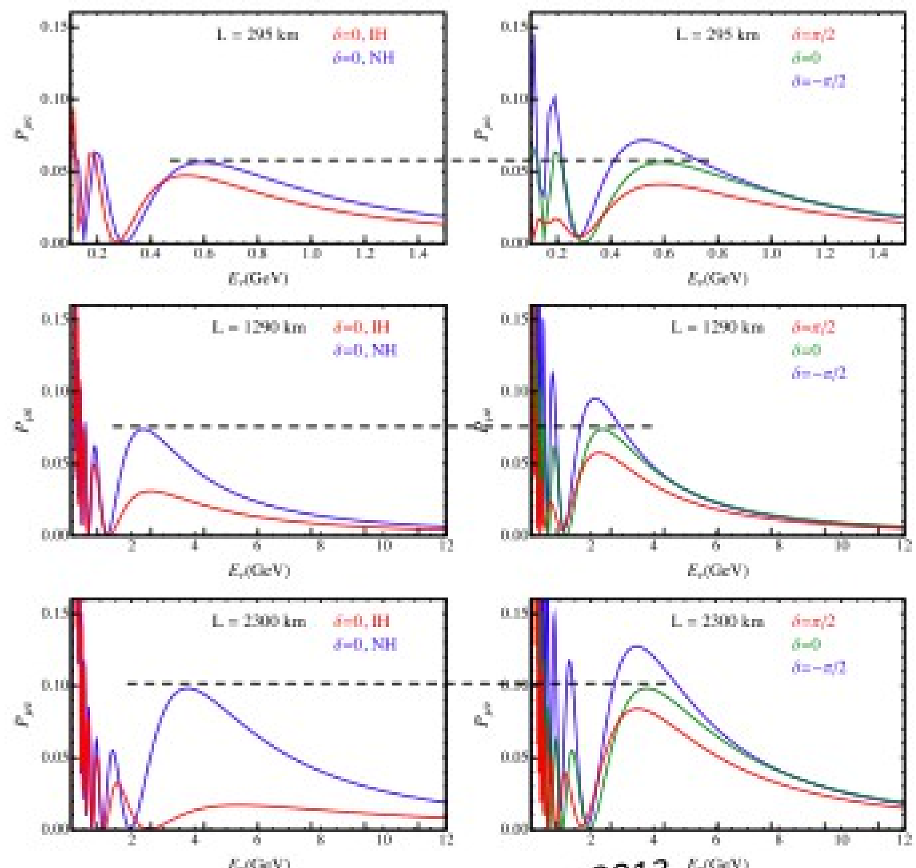
Points of consensus

- **Scientific imperative:**
  - *Programme* to measure neutrino properties with a precision sufficient to elucidate the underlying physics;
- **Key steps:**
  - Completing the picture:
    MH, CPiV, $\text{sgn}(\theta_{23} - 45^\circ)$
  - Testing the framework:
    Redundant set of measurements to over constrain SνM
- **Accelerator-based programme essential:**
  - Only means to measure all transitions precisely;
  - Conventional facilities sufficient to:
    - Determine MH, make initial search for CPiV, $\text{sgn}(\theta_{23} - 45^\circ)$
  - Novel facilities required to:
    - Test the framework:
      Neutrino Factory recognised to offer ultimate sensitivity and precision

Neutrino Mass Hierarchy

- **Large θ_{13} open doors to MH**
  - **Utilize matter effects**
    - ➢ **e-ν CC interactions in the earth modulate the oscillation probability at long baselines (LBNE, LBNO, T2HK)**





K. Long @NuFact2013

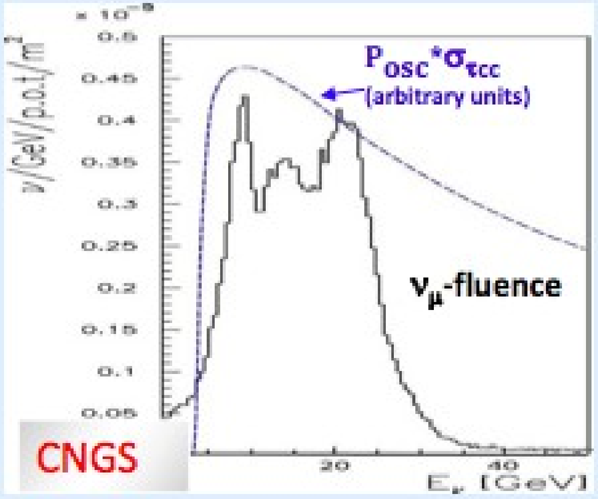
High Intensity Neutrino Beams

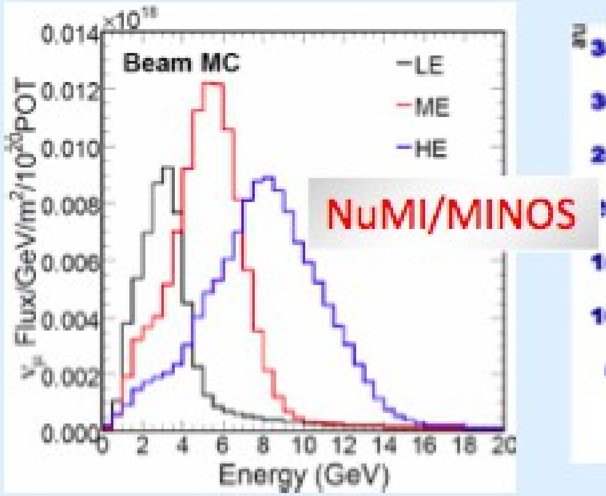
A.K.Ichiawa, Kyoto University

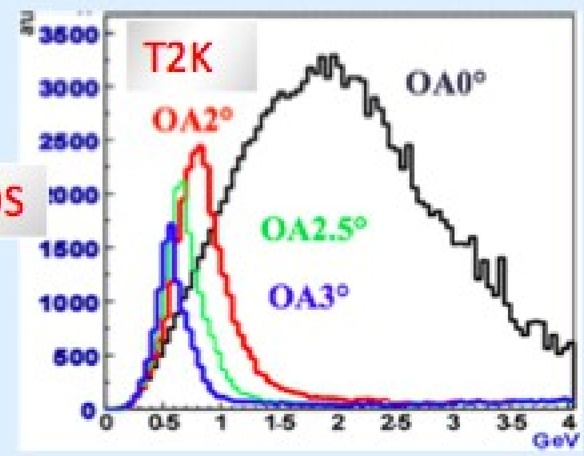
@ Neutrino 2014

Feature of Superbeam ν flux

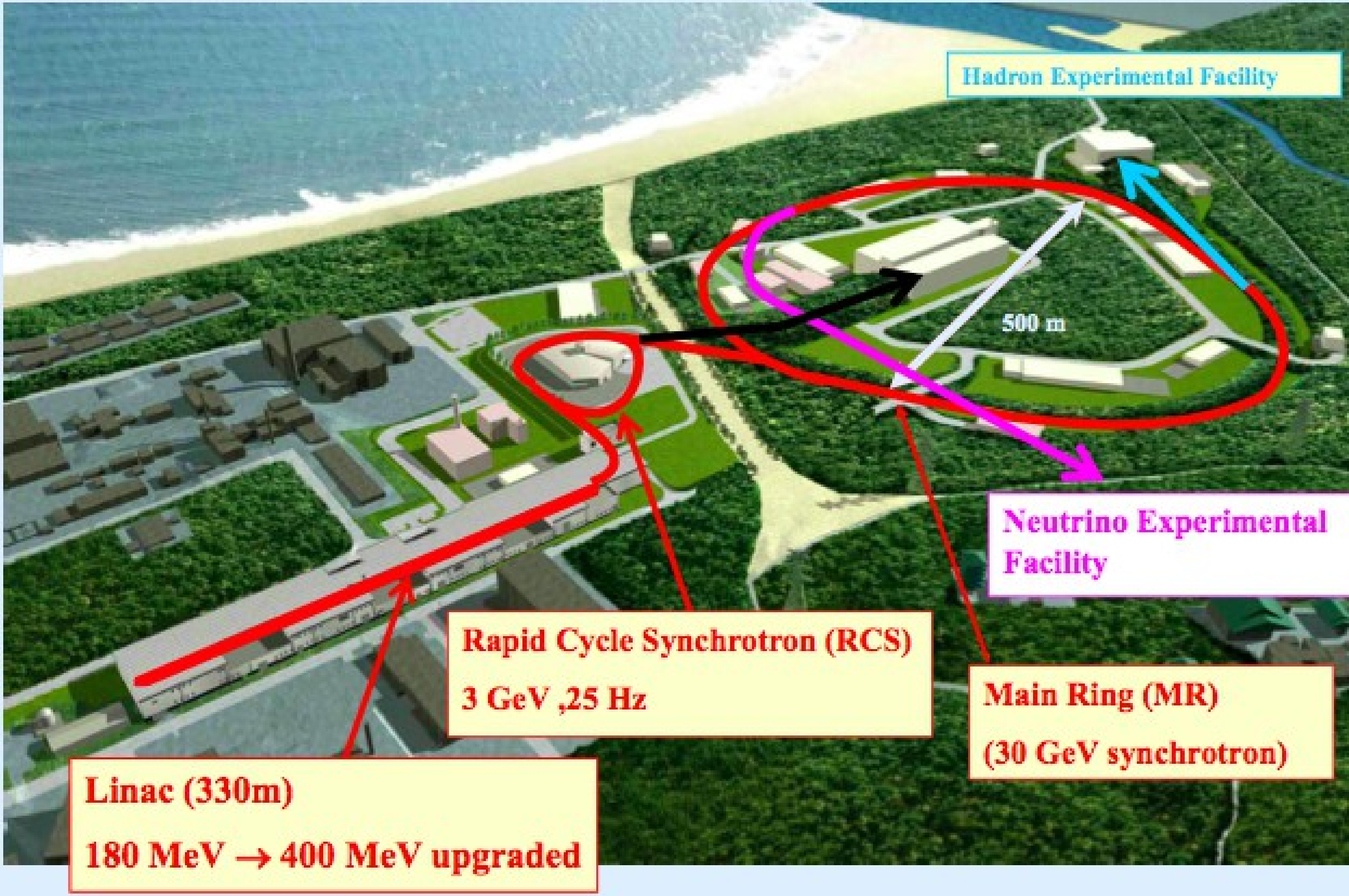
- Wide band, but can be narrowed by
  - target-horn distance (NuMI)
  - off-axis method (T2K, NOvA)
- ~10% uncertainty with p-nucleus hadron production measurement (e.g. NA61, MIPP)+beamline error
- a few % ν_e contamination from the decay of Kaons and muons
- ν beam or anti-ν beam depending on the horn current polarity
  - Yield difference is modest (~10%), but ν-nucleus cross section is different: $\sigma_\nu:\sigma_{\bar{\nu}}$=2~3:1







J-PARC


Hadron Experimental Facility
500 m
Neutrino Experimental Facility
Rapid Cycle Synchrotron (RCS)
3 GeV ,25 Hz
Main Ring (MR)
(30 GeV synchrotron)
Linac (330m)
180 MeV → 400 MeV upgraded

J-PARC power upgrade plan

JFY	2013	2014	2015	2016	2017
power(kW)	200-240	200-300	→	→	750
	Linac 180MeV→400MeV	Linac Front-end current 30mA→50mA	Main Ring rep. cycle 2.5s→1.3s w/ new Magnet Power supplies and new high Impedance RF		

- ➢ Current bottleneck

  beam loss at injection to MR

  → can't increase ppp (already world-highest)

  → go higher rep. rate → 0.75 MW

  ✓ New RF R&D completed

  ✓ Small prototype of 1 Hz PS is working.

- ➢ Long-term possibility under study

  ✓ New 8 GeV Booster

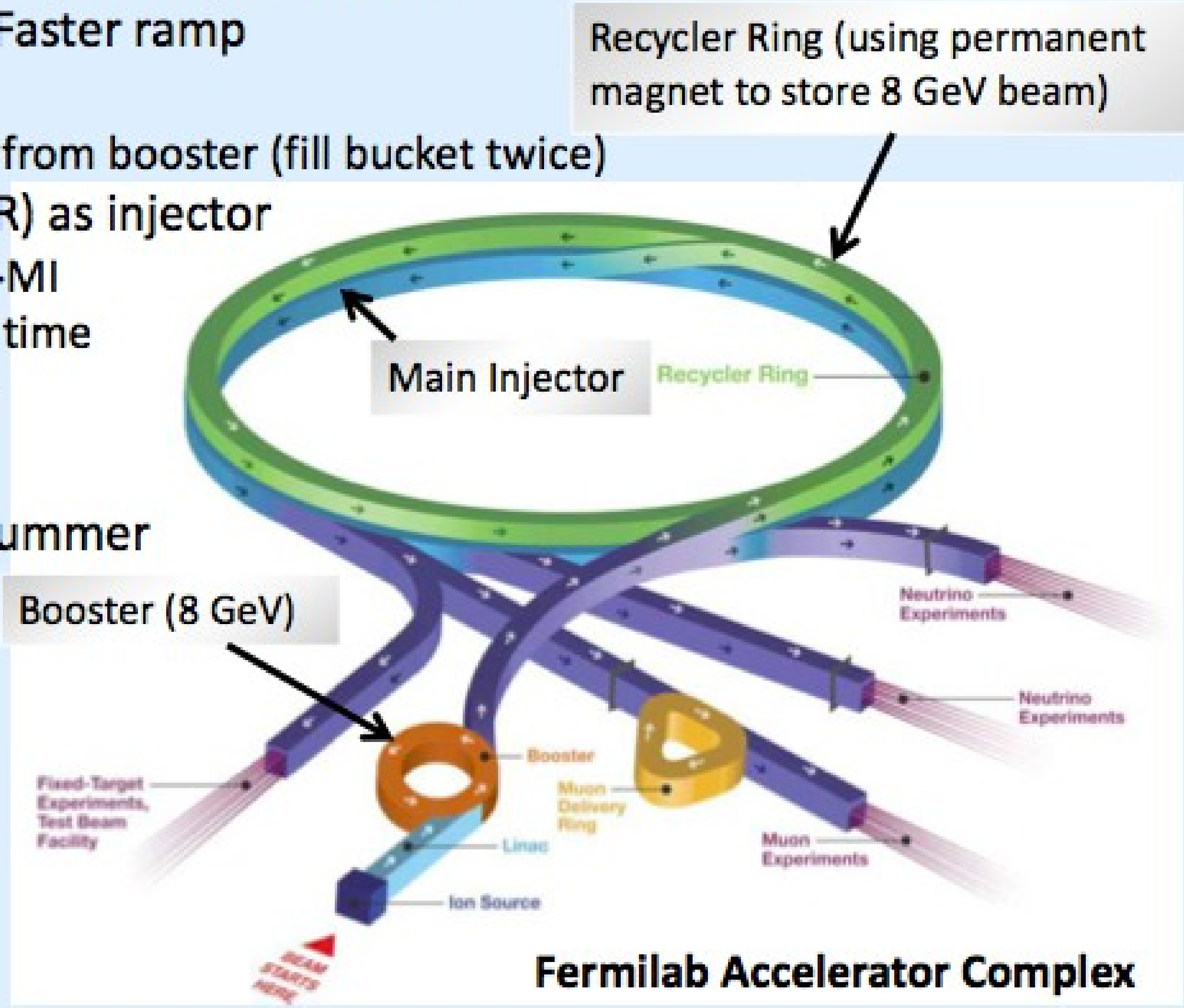
  ✓ Target > 1~3MW

New high impedance RF

FNAL power present upgrade plan

Booster is the current primary bottleneck.

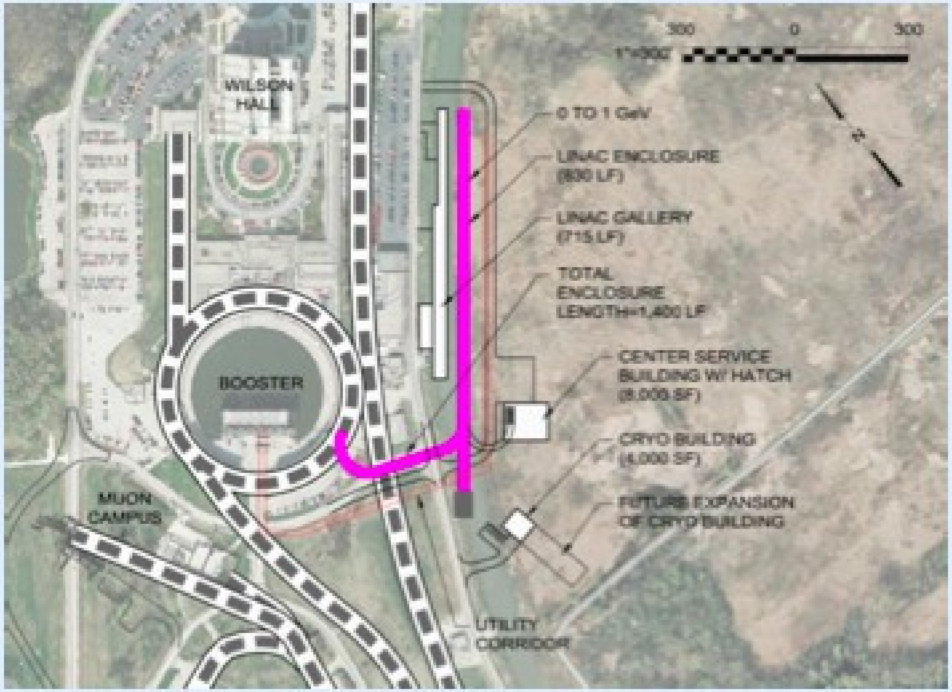
- ➢ Main Injector (MI) Faster ramp
- ➢ Slip stack
  - ✓ Put two batches from booster (fill bucket twice)
- ➢ Use recycler ring(RR) as injector
  - ✓ booster → RR →MI
  - ✓ reduce injection time
- ➢ 280 kW →350kW →450kW by the end of this summer
- ➢ 700 kW in 2015



Fermilab Accelerator Complex

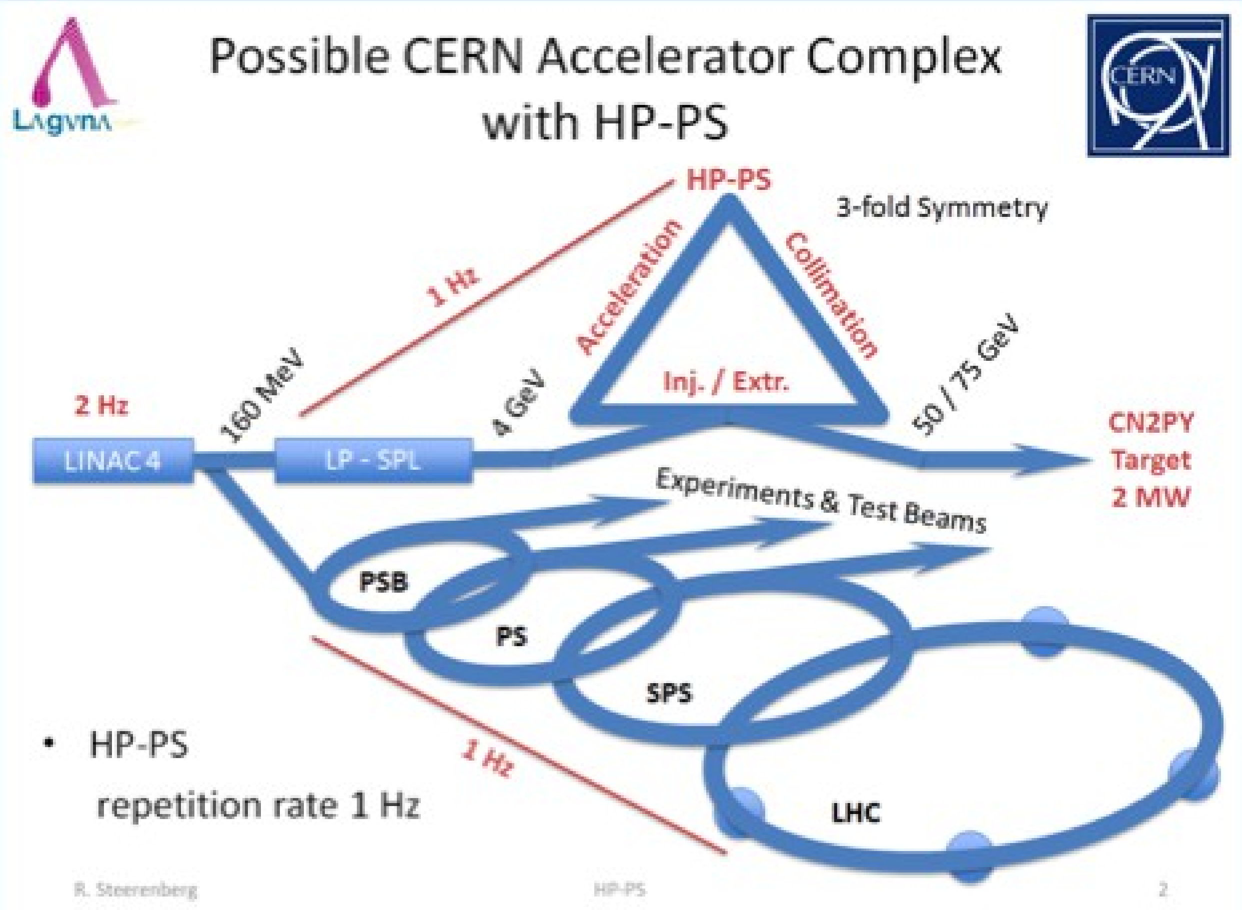
FNAL future power upgrade plan -Proton Improvement Plan(PIP) II-

- goal > 1MW (~2025)
- Linac 400 MeV →New 800 MeV super conducting pulsed linac
- Higher energy injection to Booster will reduce beam loss

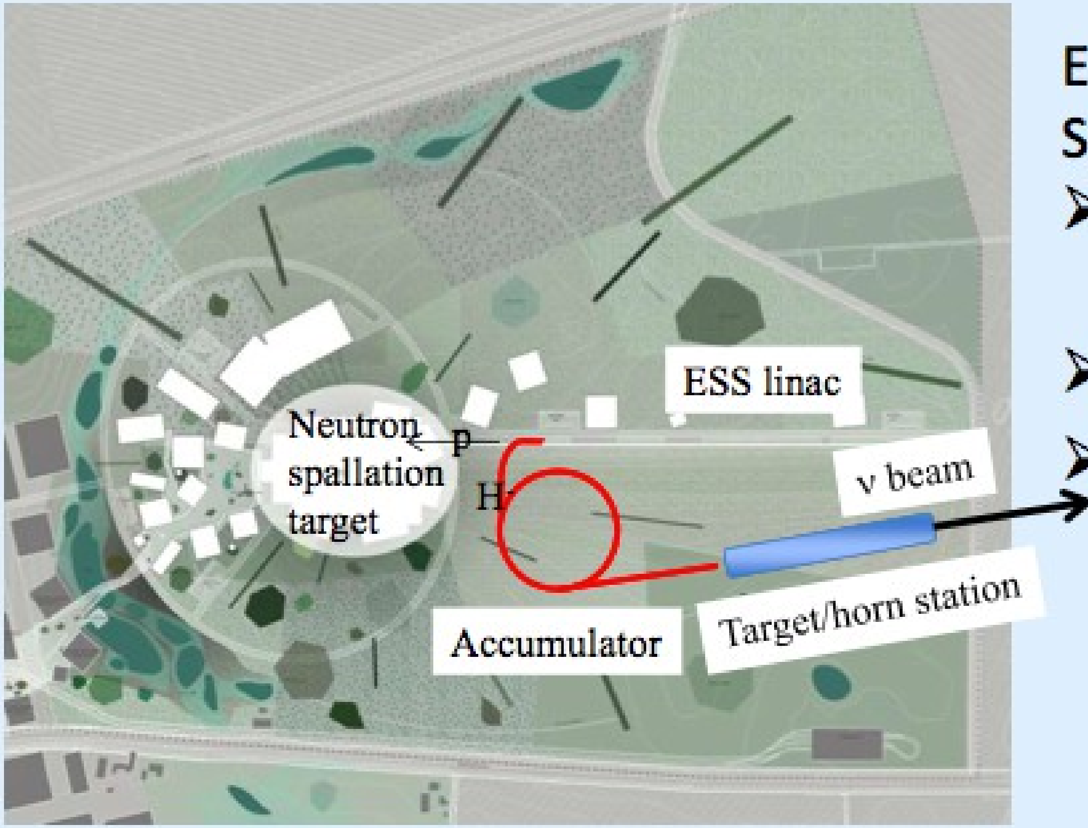


CN2PY (CERN-to-Pyhasalmi)

- Initial beam from SPS(+) 400 GeV/750 kW
- Phase II: LP-SPL(Superconducting Linac) to HP-PS 50 GeV/2 MW



ESS 2 GeV linac as proton driver for a neutrino Super Beam (proposal)



ESS: European Spallation Source in Sweden

- **2 GeV 5 MW** superconduction linac
- First beams 2019
- **Full power 2022**

Proposal

rise frequency from 14 Hz to 28 Hz.

(duty 4.0% → 8.0%, RF power 5 MW → 10MW)

Summary

	Energy	Power		
		Current	Planed	Future
J-PARC/KEK	30 GeV	~0.25MW T2K	0.75MW T2K	~2MW
FNAL	120 GeV	~0.36MW MINOS	0.7MW NOvA	~2MW
CERN	400 GeV/c	0.3MW~0.5MW OPERA/ICARUS	(0.2MW for short baseline: CENF)	0.7~2MW (CN2PY)

Achieved = < 0.5 MW

Desired > 1 MW

Need tough works to go beyond 0.5 MW

Many innovative works are necessary for power beyond ~0.7 MW

THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

Neutrino Factories

Neutrino 2014
Boston University, Boston

Paul Soler, 4 June 2014

University of Glasgow

Neutrino Factory

- Definition of a Neutrino Factory:
  - While many of the intense neutrino sources could be labelled "Neutrino Factories", the modern definition of a Neutrino Factory is that of an accelerator that produces intense neutrino beams from the decay of muons:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

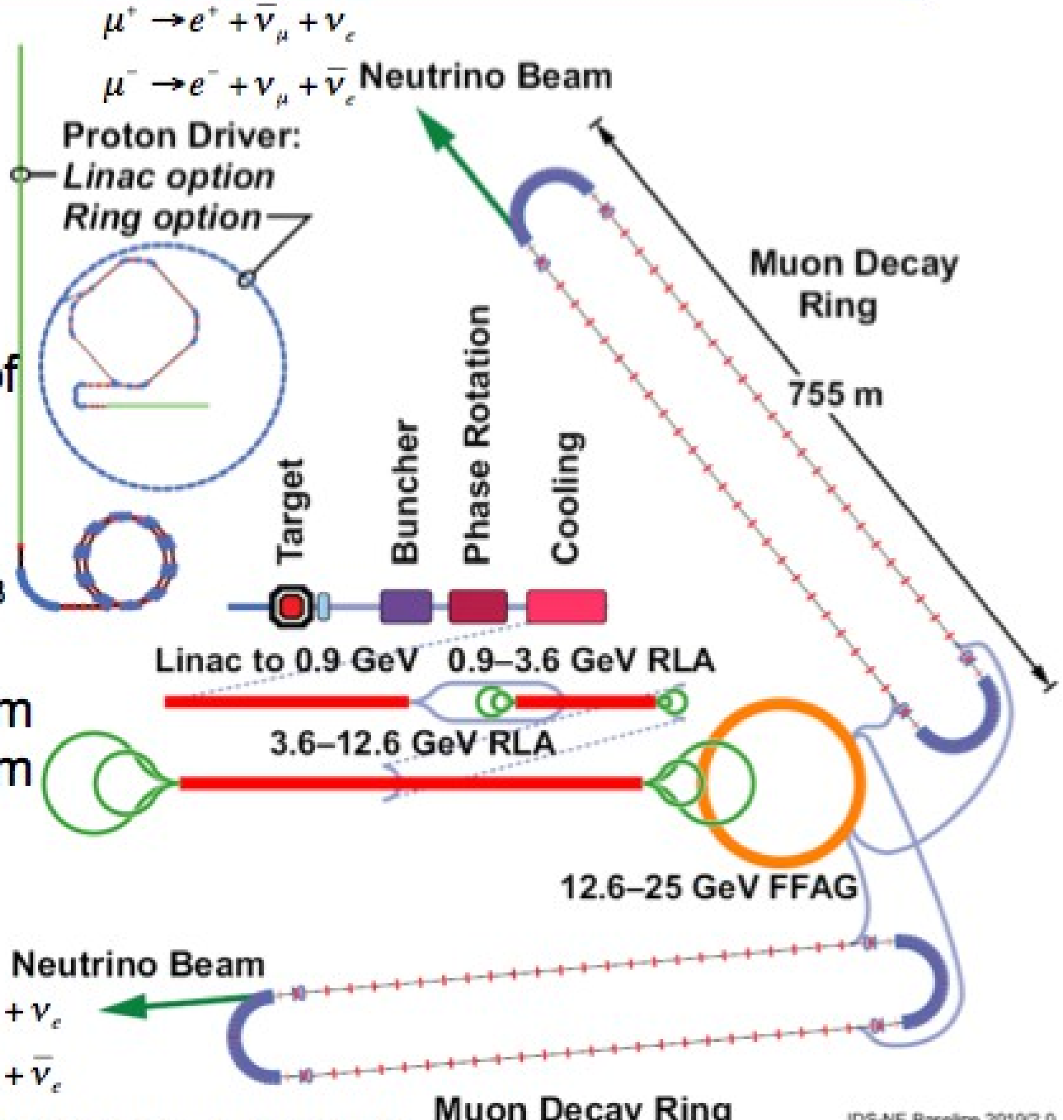
$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

  - Birth of modern neutrino factory: S. Geer: Phys Rev D57, 6989 (1998)
  - Then, came **seven** design studies: CERN (Yellow Report 99-02, 1999), Fermilab (Study I) and Brookhaven (Study II, IIa), ECFA/CERN Study (CERN-2004-002), Scoping Study (JINST 4 P07001 & T05001, 2009, Rept. Prog. Phys. 72, 2009, 106201) and …
  - International Design Study (IDS-NF): launched 2008, Reference Design Report in 2014 (Interim Design Report arXiv:1102.2402)
  - Lately: Muon Accelerator Programme in USA to stage Neutrino Factory (arXiv:1308.0494) and nuSTORM proposal (arXiv:1308.6822)

Optimisation of Neutrino Factory

- Before θ_{13} discovery, baseline design for a Neutrino Factory had two storage rings and energy was 25 GeV (v2.0)
- Optimised for small value of θ_{13}
- Two different baselines to reduce ambiguities in θ_{13} vs δ fits
- One baseline was ~4000 km and the other was ~7500 km (magic baseline).

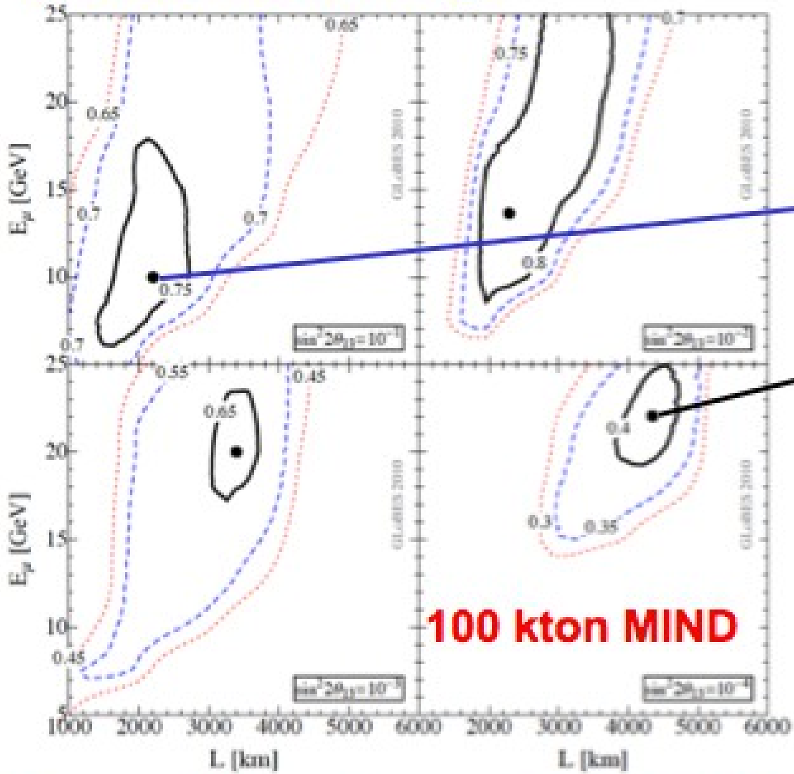
arXiv:1112.2853

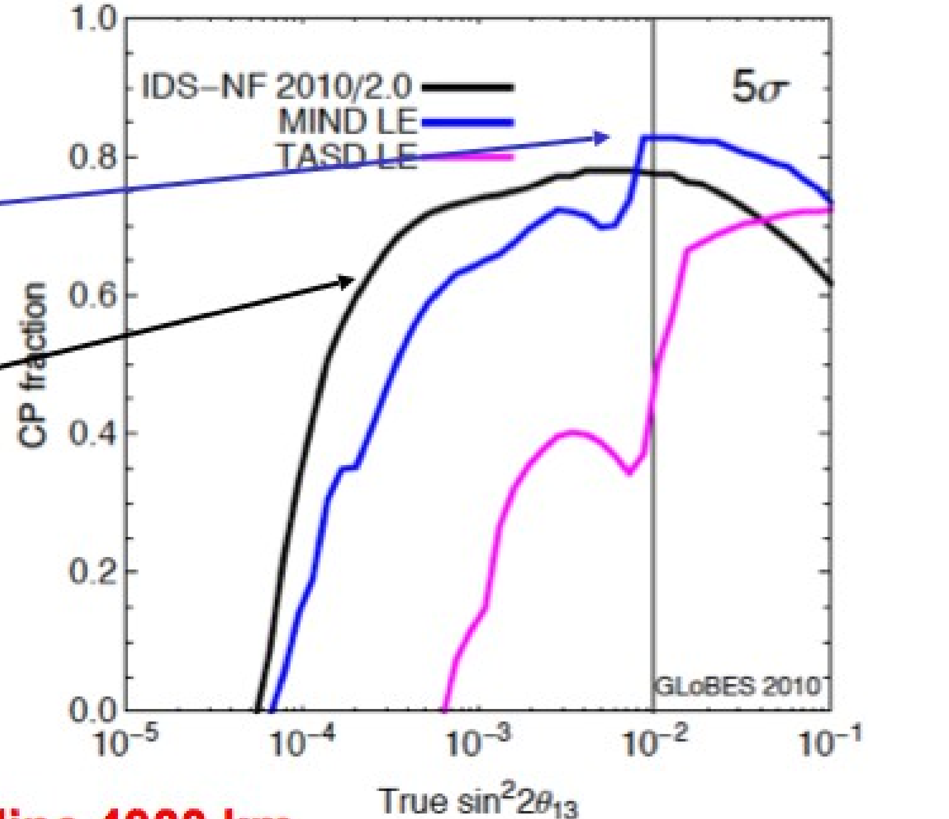


Optimisation of Neutrino Factory

- Optimisation for high θ_{13}: only one baseline

Contours of CP coverage





For small θ_{13}: Energy 25 GeV, Baseline 4000 km

For large θ_{13}: Energy 10 GeV, Baseline 2000 km, L/E ~ 200 km/GeV

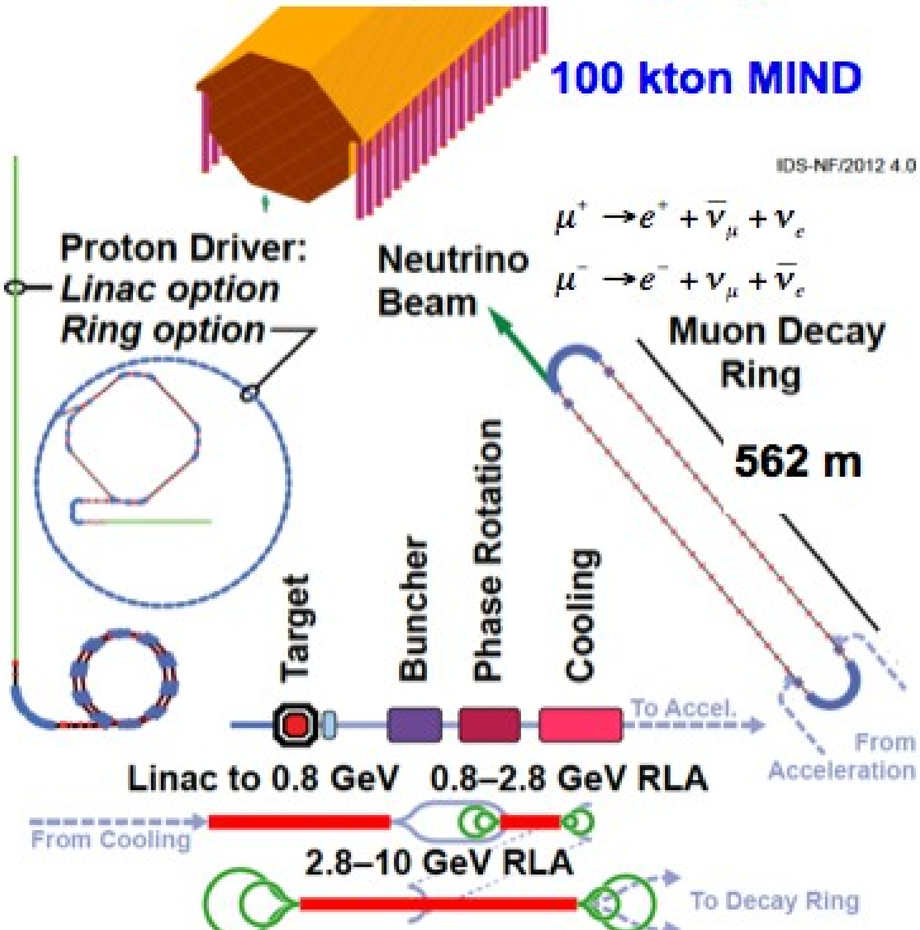
International Design Study for a Neutrino Factory

- Proton driver
  - Proton beam ~8 GeV on target
- Target, capture and decay
  - Create π, decay into μ (MERIT)
- Bunching and phase rotation
  - Reduce ΔE of bunch
- Ionization Cooling
  - Reduce transverse emittance

See M. Leonova (MICE Poster)

- Acceleration
  - 120 MeV→ 10 GeV with RLAs
  - FFAG option now not favoured
- Decay ring: 10^{21} muons/year
  - Store for ~100 turns
  - Long straight sections

IDS-NF baseline review 2012: from 25 GeV to 10 GeV muons, one storage ring with detector at 2000 km, due to large θ_{13} results

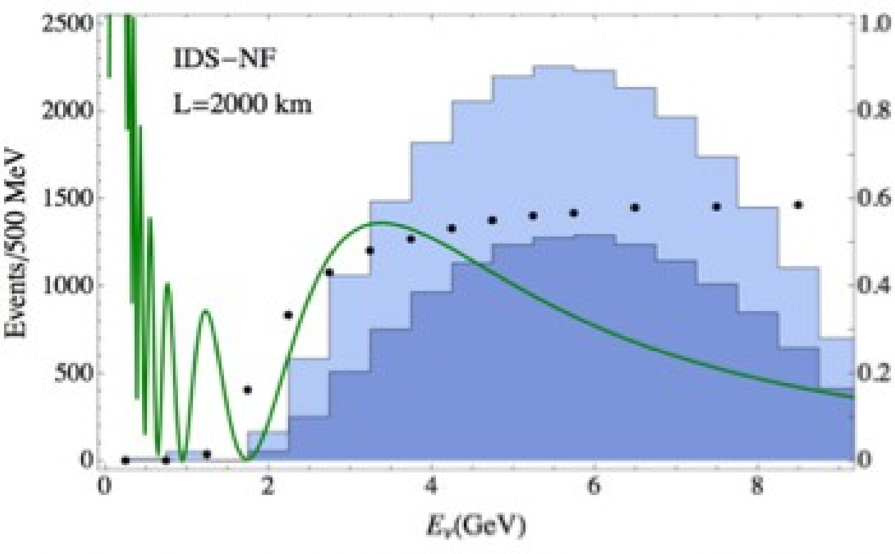


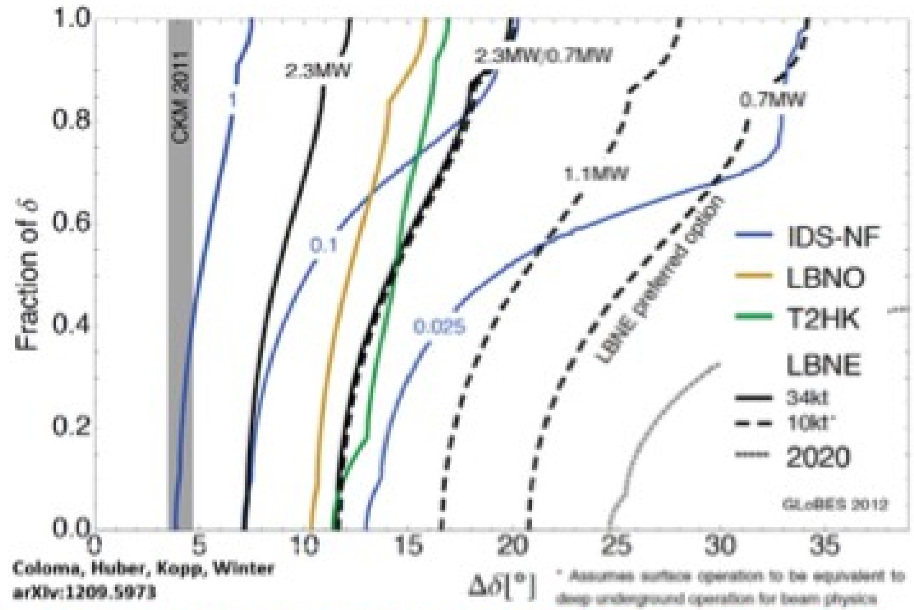
Neutrino 2014, Boston: 4 June 2014

Performance 10 GeV Neutrino Factory

- Systematic errors: 1% signal and 20% background
- Results 10 GeV Neutrino Factory, 10^{21} μ/year for 10 years with 100 kton MIND at 2000 km gives best sensitivity to CP violation
- This is the "best of all possible neutrino factories"

arXiv:1209.5973



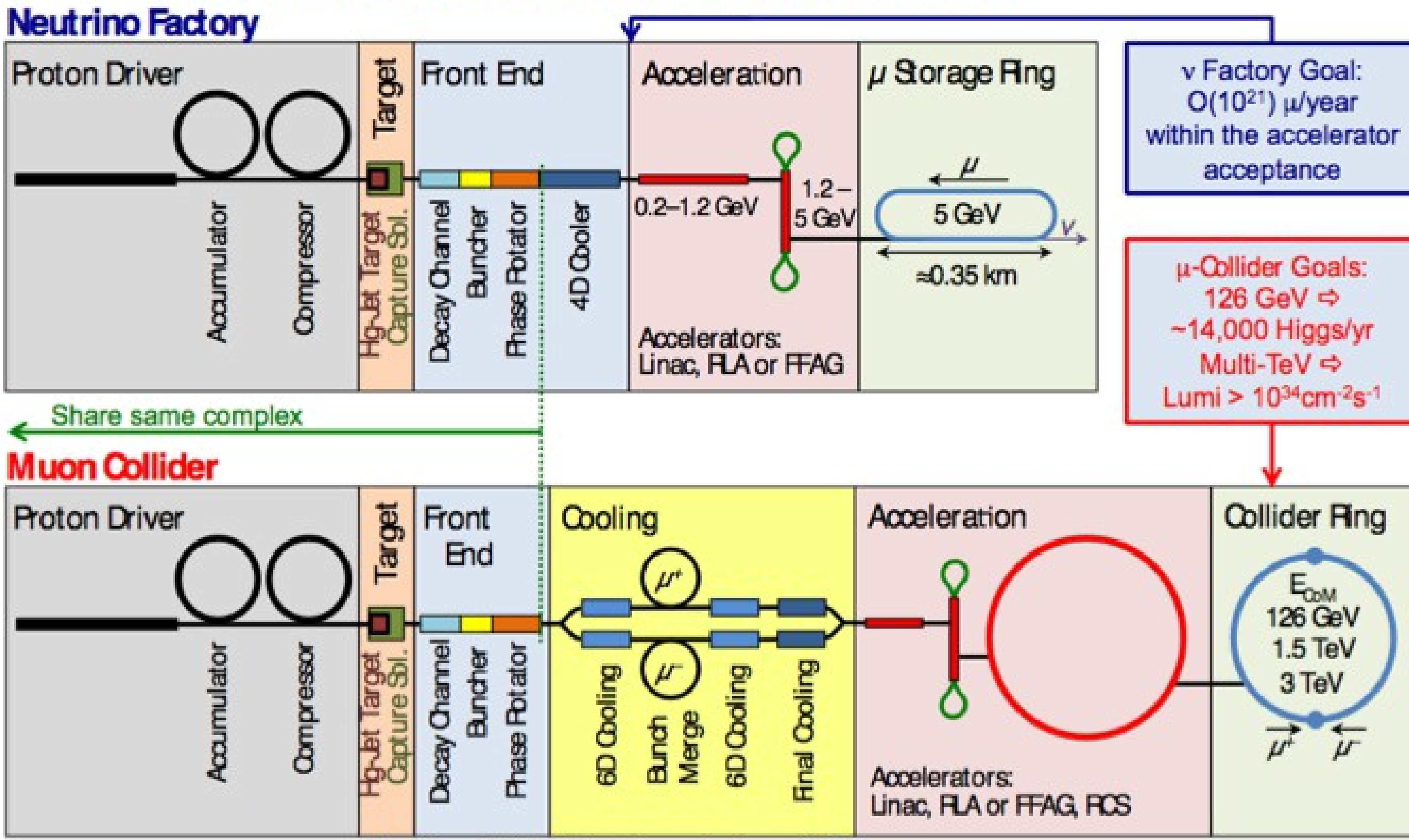


CP violation 5σ coverage is 85% (ie. 85% probability of CPV discovery!)

Muon Accelerator Staging Programme

- Synergies between NuMAX and Muon Collider components

Muon Accelrator Staging Study (MASS)



Neutrino 2014, Boston: 4 June 2014

Stage 1: nuSTORM

- nuSTORM is entry-level neutrino factory from 3.8 GeV/c muons that can be realised now without any new technology
  - Pions captured in horn, transported and stochastically injected into ring
  - 52% of pions decay to muons before first turn: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - For 10^{20} POT, we expect flash of neutrinos from 8.6×10^{18} pion decays
  - Muons within momentum acceptance (3.8 GeV ± 10%) circulate in ring.
  - Muon lifetime is 27 orbits of decay
  - For 10^{20} POT, we expect 2.6×10^{17} μ^+ that decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  - Therefore, we have hybrid beam from pion and muon decay, which allows one to perform rich physics programme of neutrino cross-section measurements and sterile neutrino search

nuSTORM posters
D. Adey, A. Bross

Neutrino 2014, Boston: 4 June 2014

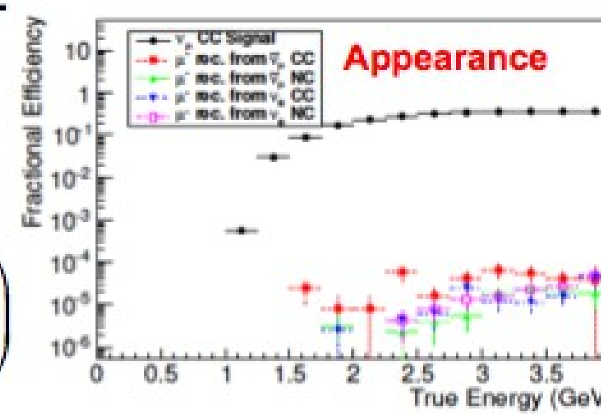
Stage 1: nuSTORM

- Sterile neutrino search in short-baseline experiment
- Far detector: 1.3 kton magnetised iron (Super BIND) at 2 km
- Magnetic field: 1.5-2.6 fed by 240 kA by STL
- Appearance and disappearance searches:

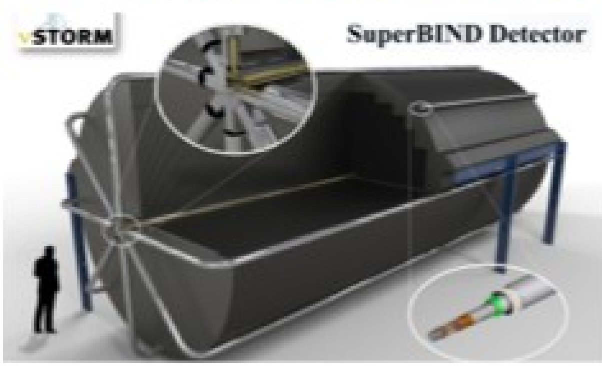
$$P_{e\mu}(x) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

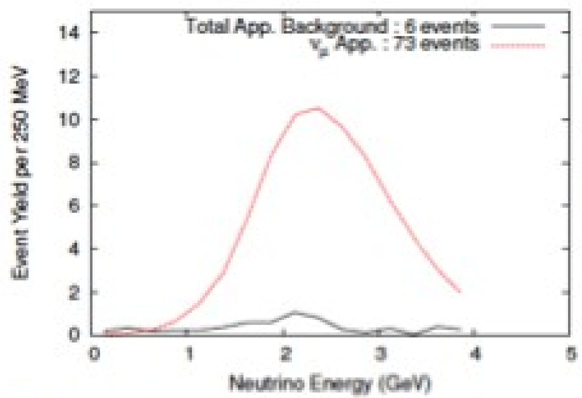
$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

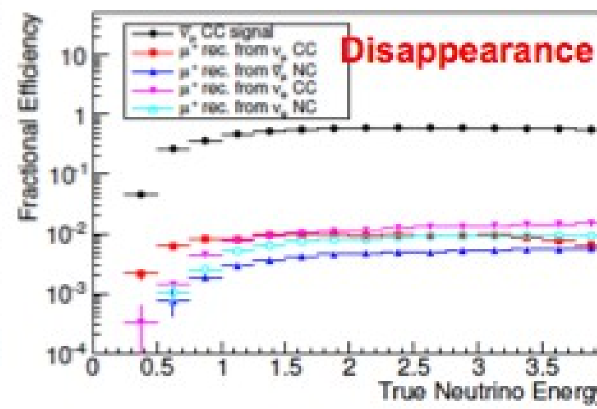
Adey et al., PRD 89 (2014) 071301



(a)Appearance efficiencies







(b)Disappearance efficiencies

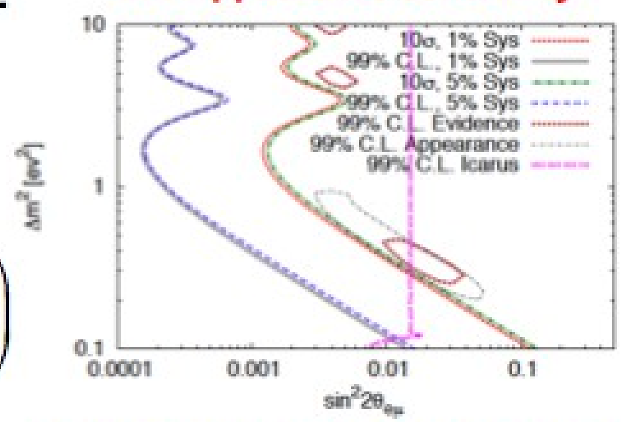
Stage 1: nuSTORM

- Sterile neutrino search in short-baseline experiment
- Far detector: 1.3 kton magnetised iron (Super BIND) at 2 km
- Magnetic field: 1.5-2.6 fed by 240 kA by STL
- Appearance and disappearance searches:

$$P_{e\mu}(x) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

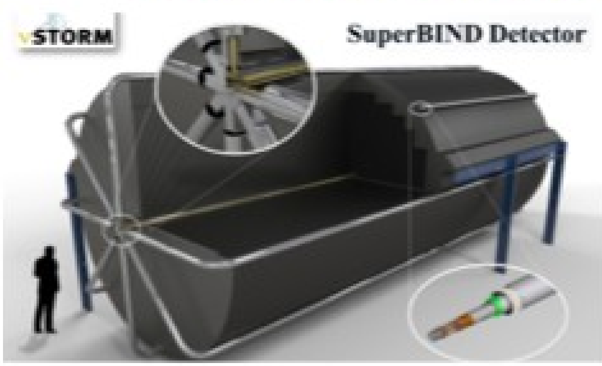
$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

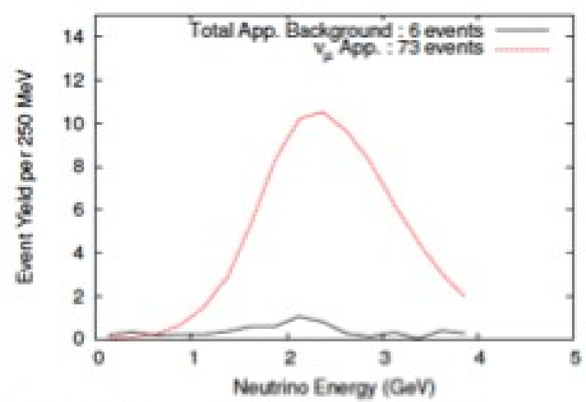
10σ Appearance sensitivity

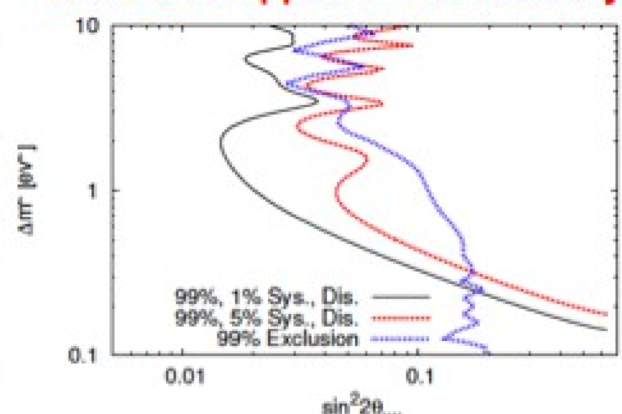


Adey et al., PRD 89 (2014) 071301

99% CL Disappearance sensitivity







Neutrino 2014, Boston: 4 June 2014

Stage 1: nuSTORM

- nuSTORM could be sited at Fermilab (also at CERN)

Near Detector Hall

Far Detector Hall (D0)

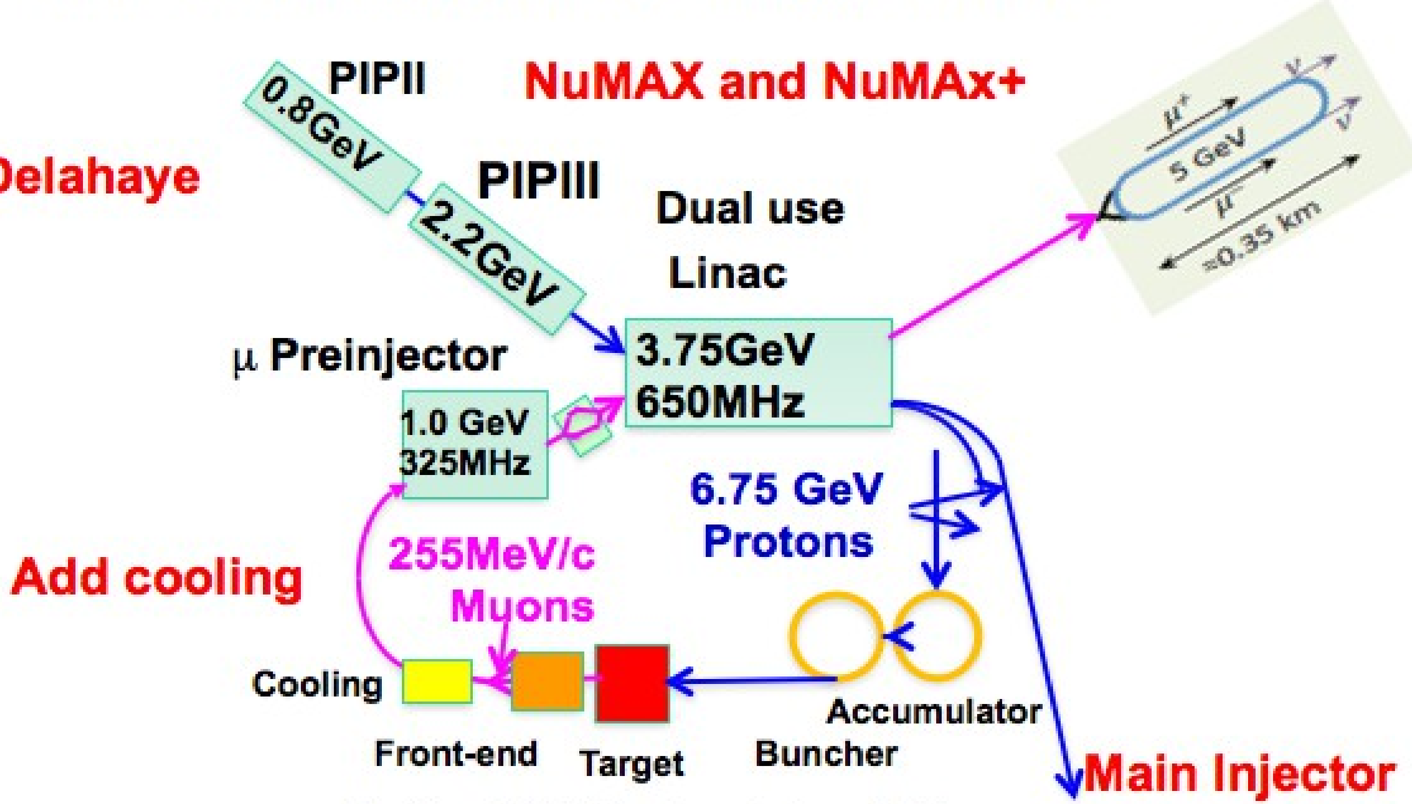
Target building

Decay ring

Stage 4: NuMAX+

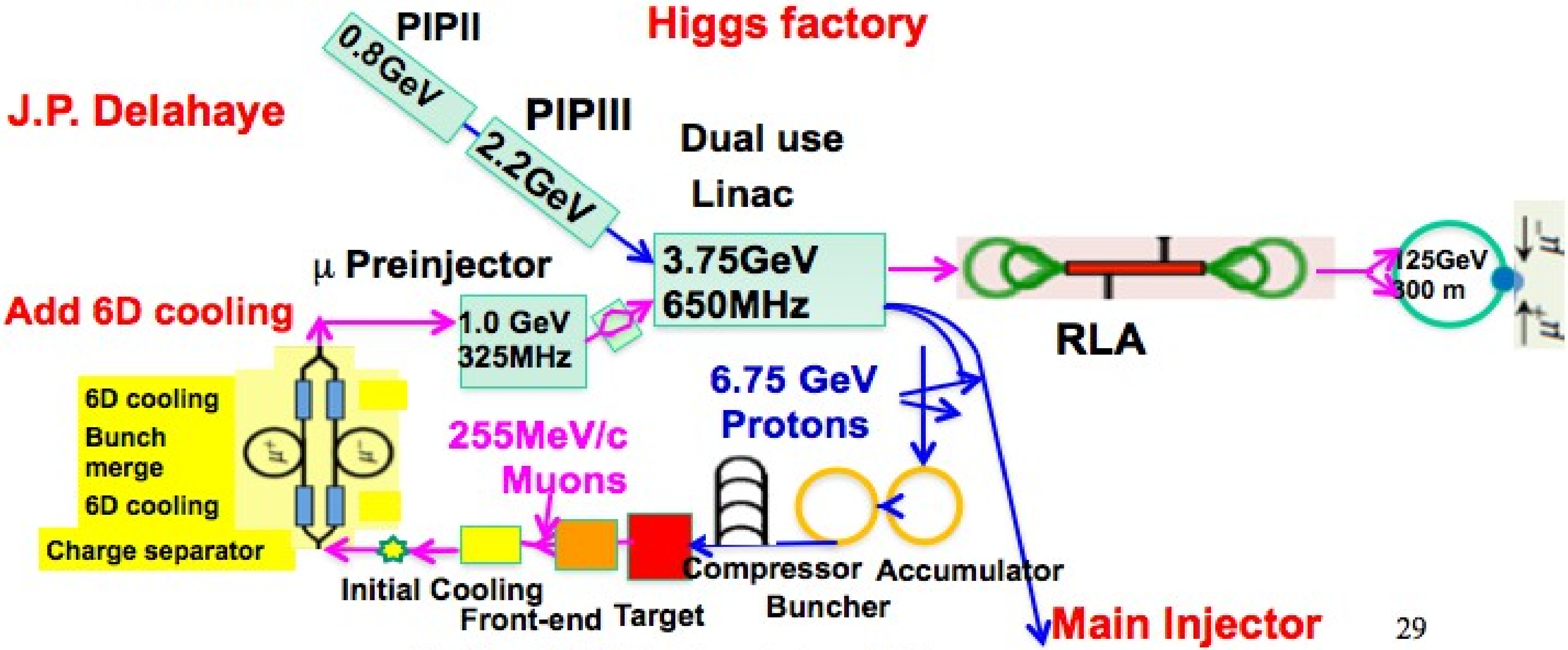
- Neutrinos from a Muon Accelerator CompleX (NuMAX+)
  - Neutrino Factory with 10^{21} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - Increased proton power and/or larger detectors

J.P. Delahaye



Stage 5: Muon Collider-Higgs Factory Option

- Higgs Factory: production of Higgs at 126 GeV CM
  - Collider capable of providing ~13,500 Higgs events per year with exquisite energy resolution: direct Higgs mass and width
  - Possible upgrade to a Top Factory with production of up to 60000 top particles per year



Conclusions

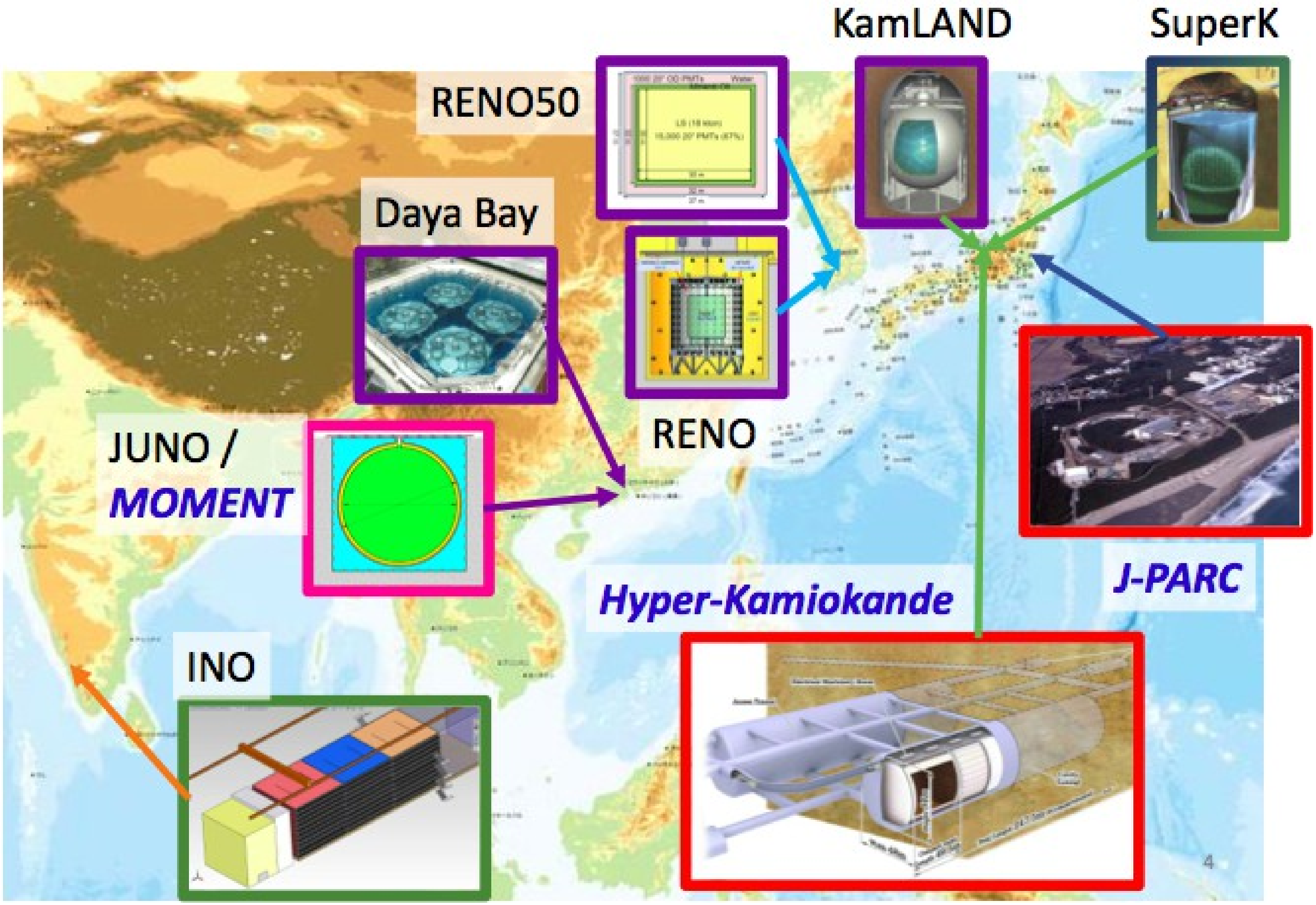
- International Design Study for a Neutrino Factory (IDS-NF) has concluded its study
  - Interim Design Report delivered March 2011
  - Reference Design Report should be published by this summer
  - It defines benchmark Neutrino Factory
  - However, expensive and very challenging so needs staging
- Staging scenario assumes:
  - Stage 1: nuSTORM for short-baseline and neutrino scattering physics
  - Stage 2: commissioning of NuMAX to SURF (no cooling)
  - Stage 3: NuMAX includes a 6D cooling stage
  - Stage 4: NUMAX+ includes full power, cooling and detector size
  - Stages 5 & 6: upgradeable to Higgs Factory or TeV-scale Muon Collider
- Neutrino Factories offer best potential for discovery of neutrino CP violation, with upgrade path towards muon colliders

Future Long-baseline Neutrino Oscillations ~ View from Asia ~

Yoshinari Hayato

(Kamioka, ICRR, UTokyo)

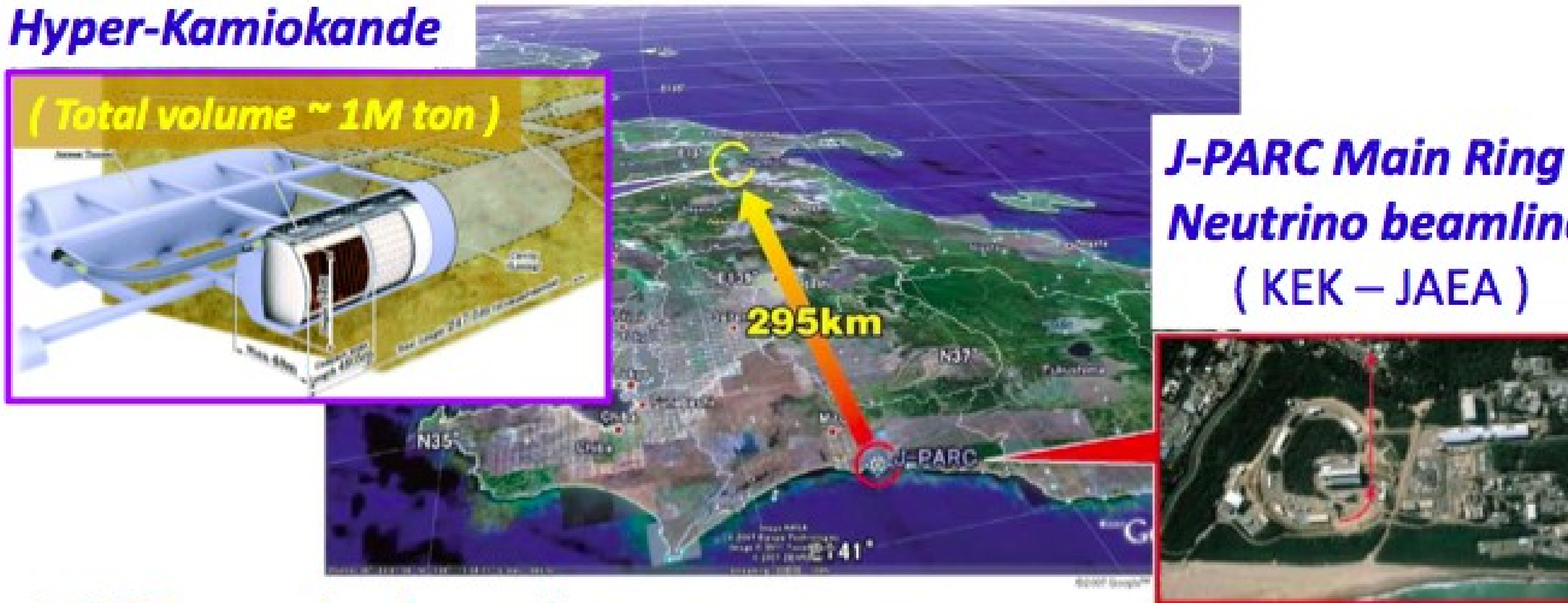
Neutrino experiments & related facilities in Asia



J-PARC neutrino beam

& Hyper-Kamiokande

Hyper-Kamiokande with J-PARC neutrino beam



J-PARC neutrino beam line

One of the most powerful beamlines in operation and further intensity upgrade (>750kW) is undergoing.

Hyper-Kamiokande

World largest water Cherenkov detector (fid. vol. 560 kt.)

Powerful combination to search for the lepton sector CP violation!

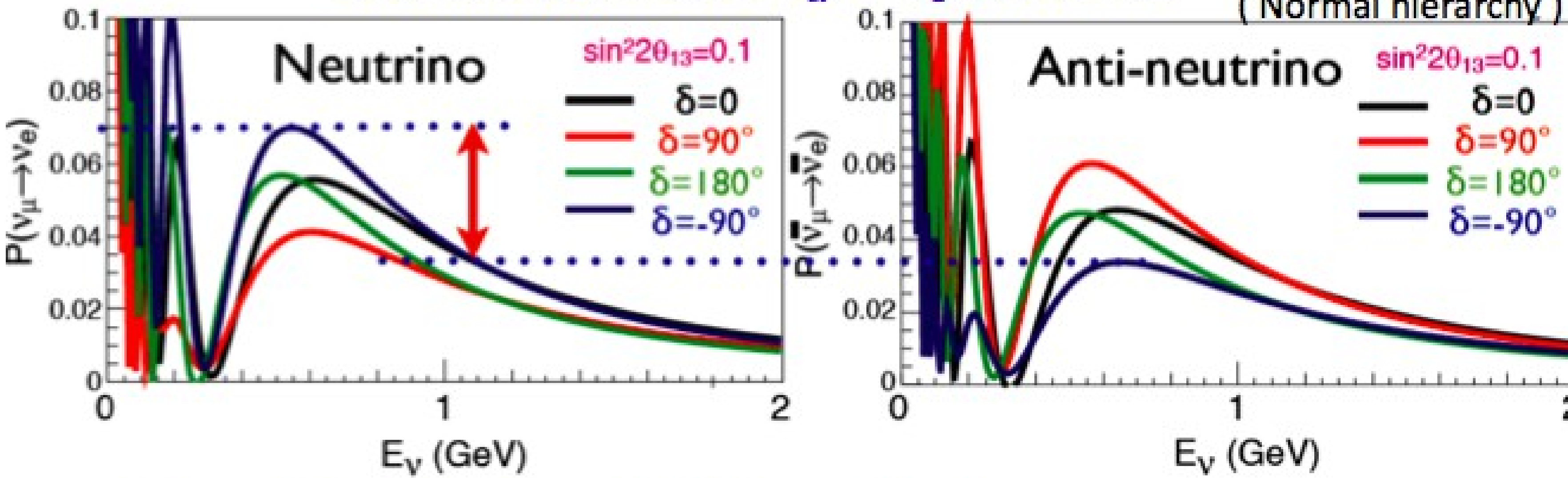
Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

CP-non conservation term in osc. prob. $\propto$ $\sin\theta_{13}\sin\delta$ ($\sin^2 2\theta_{13} \sim 0.1$)

(sign of δ for anti-neutrino is different from neutrino)

Oscillation prob. for $\nu_\mu \rightarrow \nu_e$ @ 295km

(Normal hierarchy)



→ Hyper-Kamiokande + J-PARC neutrino beam

~ 3000 ν_e & ~ 2000 $\bar{\nu}_e$ signal events are expected, when $\delta = 0$

(7.5×10^7 MW·sec)

Measurements of δ by comparing oscillations of ν and $\bar{\nu}$.

At maximum CP violation, ~25% difference from δ=0 case.

Hyper-Kamiokande

Far detector " Hyper-Kamiokande"

What is not sufficient in SK? => ~ Statistics = target mass ~

1Mton Water Cherenkov detector

HK : Fiducial volume

560 kton **~ 25 x SK**

(48m x 54m x 250m)

Photo coverage : 20%

(99,000 20 inch Photo sensors)

Maximum utilization of resources and experiences in SK

~ Use established technology for the long term operation
to achieve physics goal in timely manner.

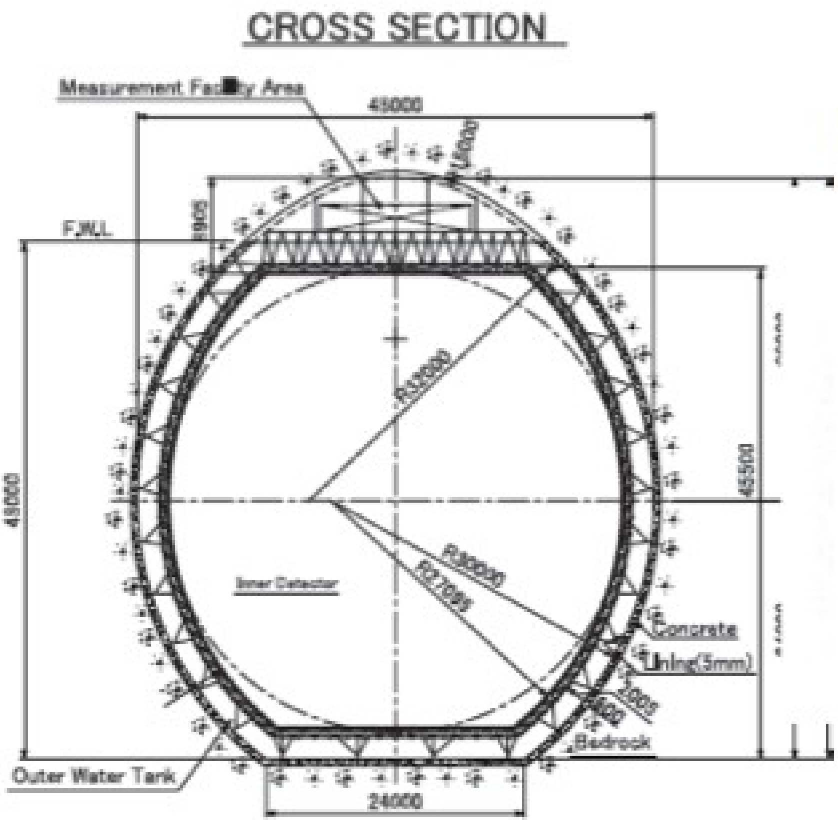
Broad science programs

1) **Accelerator neutrinos from J-PARC**
2) Atmospheric, Solar, Super Nova and cosmic neutrinos
3) Nucleon decay searches etc….

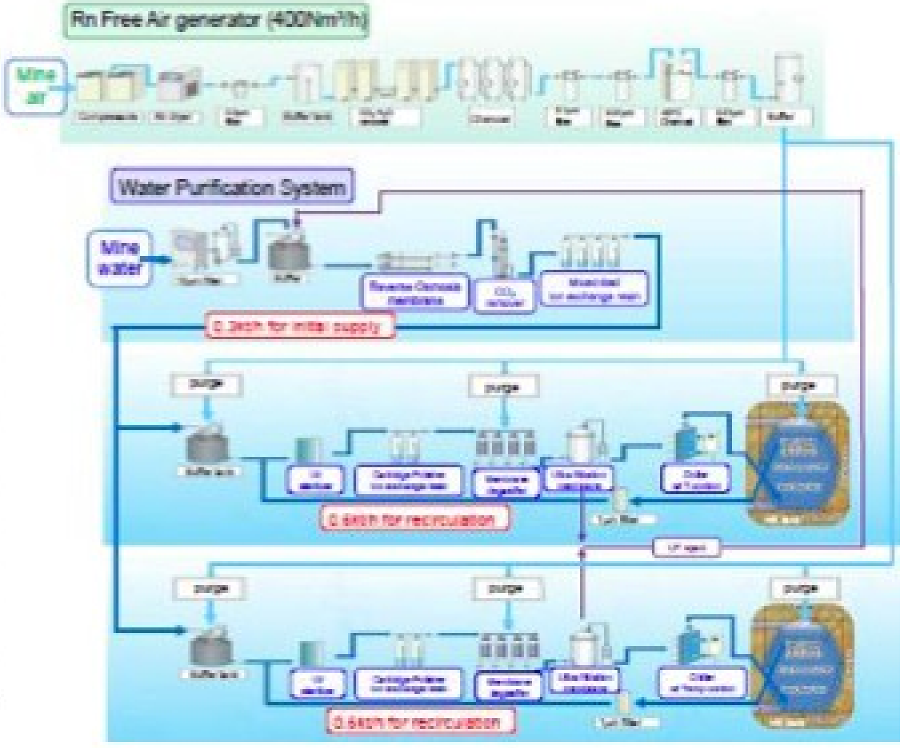
Hyper-Kamiokande detector

Design of the detector structure

Incl. PMT supports



Schematic diagram of water purification system for HK detector

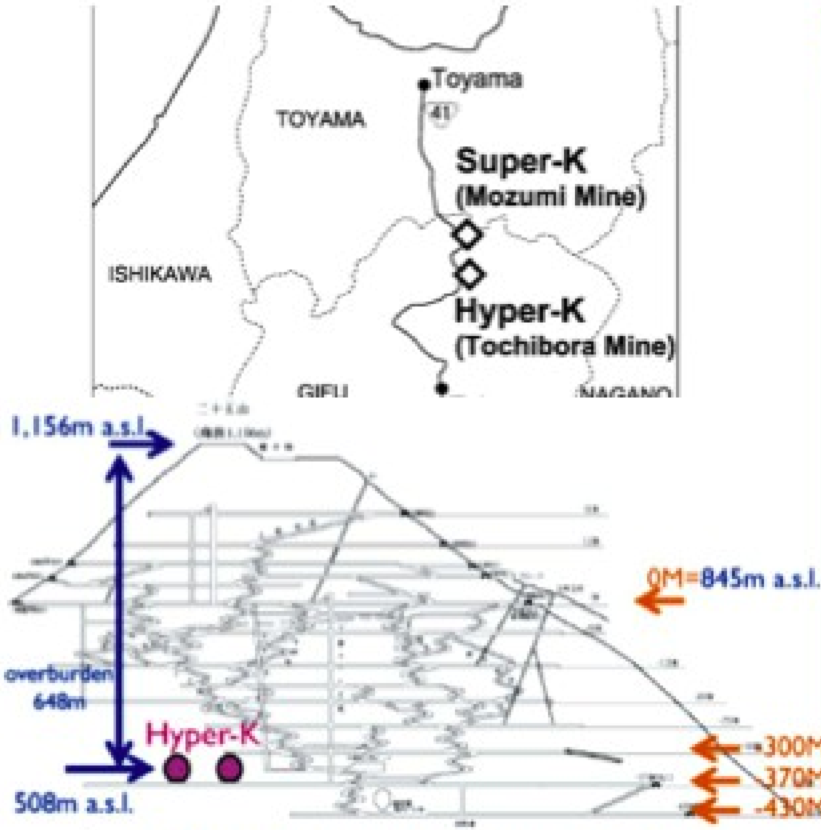


→ ***Baseline design of the detector is finished based on the past experiences in SK.***

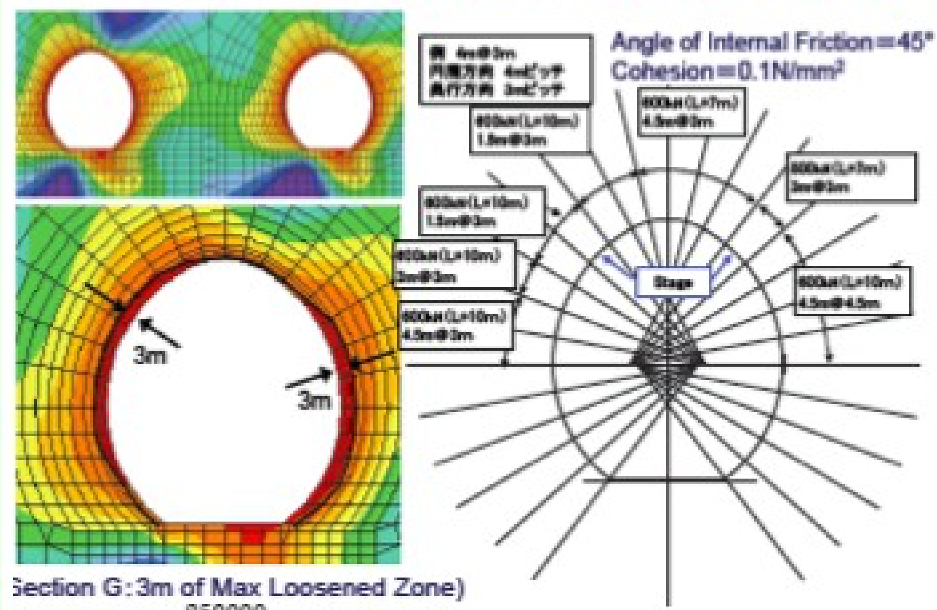
Hyper-Kamiokande detector

Is it possible to construct such gigantic detectors?

Candidate site : Tochibora mine in Kamioka



Design of the cavern and its supporting structures



➡ Based on the geological survey and analyses, the cavern and the supporting structures were designed.

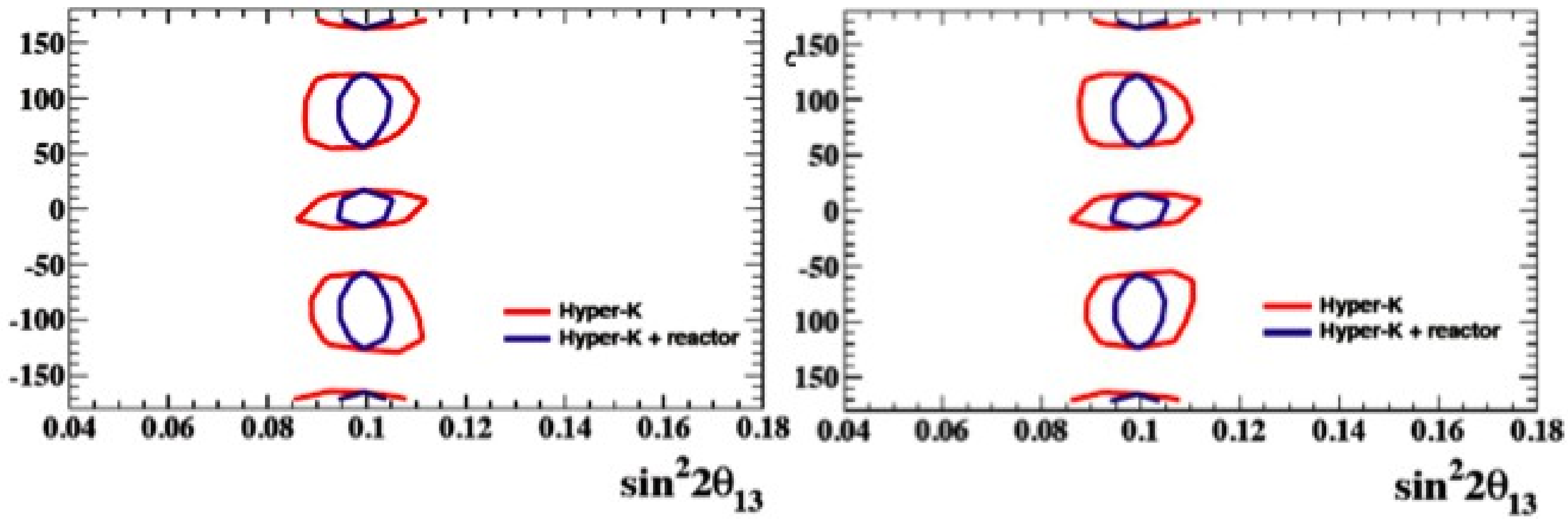
Possible to construct HK Caverns with existing technology.

Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

Use both # of observed events
and reconstructed energy spectra of ν and $\bar{\nu}$.

(@ 7.5 x 10^7 MW·sec , ν: $\bar{\nu}$ = 1 : 3)

Normal mass hierarchy *Inverted mass hierarchy*



Determination power of CP δ parameter
1σ error of δ is expected to be 8° ~ 19°.

MOMENT

~ a muon decay medium baseline neutrino facility ~

MOMENT ~ a muon decay medium baseline neutrino facility

Future accelerator based neutrino oscillation experiment in China

Intended to study CP violation in the lepton sector

Lowering the energy to largely reduce backgrounds from pion productions.

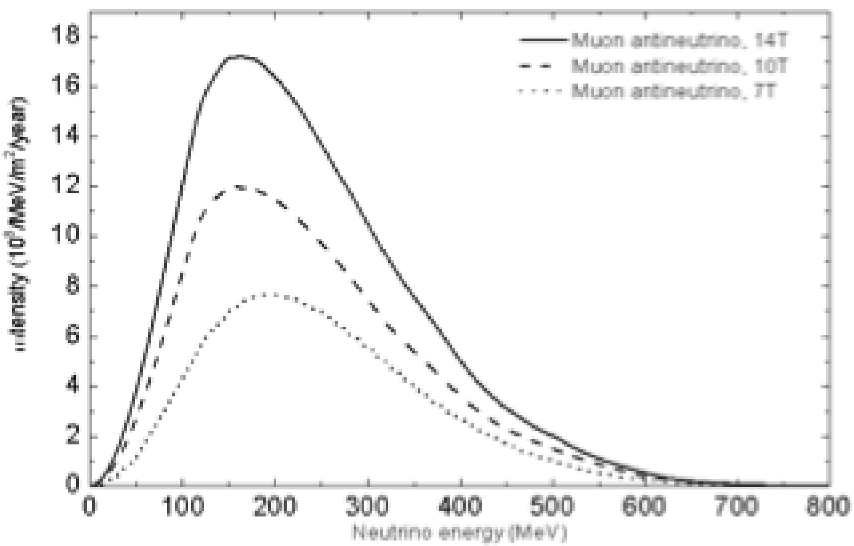
Planned **baseline is ~ 150km**

Mean beam energy is tuned **~ 240 MeV.**

Neutrino beam from **muon decays**
(Conventional neutrino beam uses ν from pion decays)

Expected neutrino flux
(Depends on the level of the pion capture field at target)

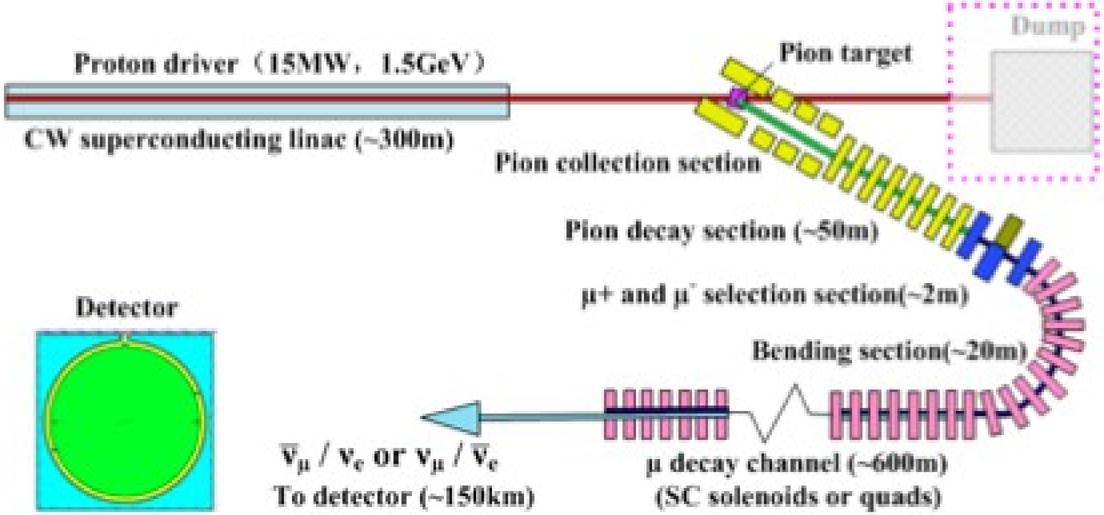
14T Field : **4.7×10^{11}** ν/m^2/year
(7T Field : 2.1×10^{11} ν/m^2/year)



MOMENT ~ a muon decay medium baseline neutrino facility

Use extremely intense proton beam (***15MW***)
from CW Superconducting LINAC

Accelerator : Use the same technology but different design for China-ADS (a funded R&D project)



Pion target

Mercury jet or fluidized tungsten powder

Detector : ** Need charge identification **

Various possibilities are considered

- Water Cherenkov detector with Gd (like GAZOOKS)
- Magnetized Iron detector (MIND)
- Magnetized liquid Argon detector

Future Long-Baseline Neutrino Oscillations: View from North America

Robert J. Wilson

Colorado State University

26th International Conference on Neutrino Physics and Astrophysics

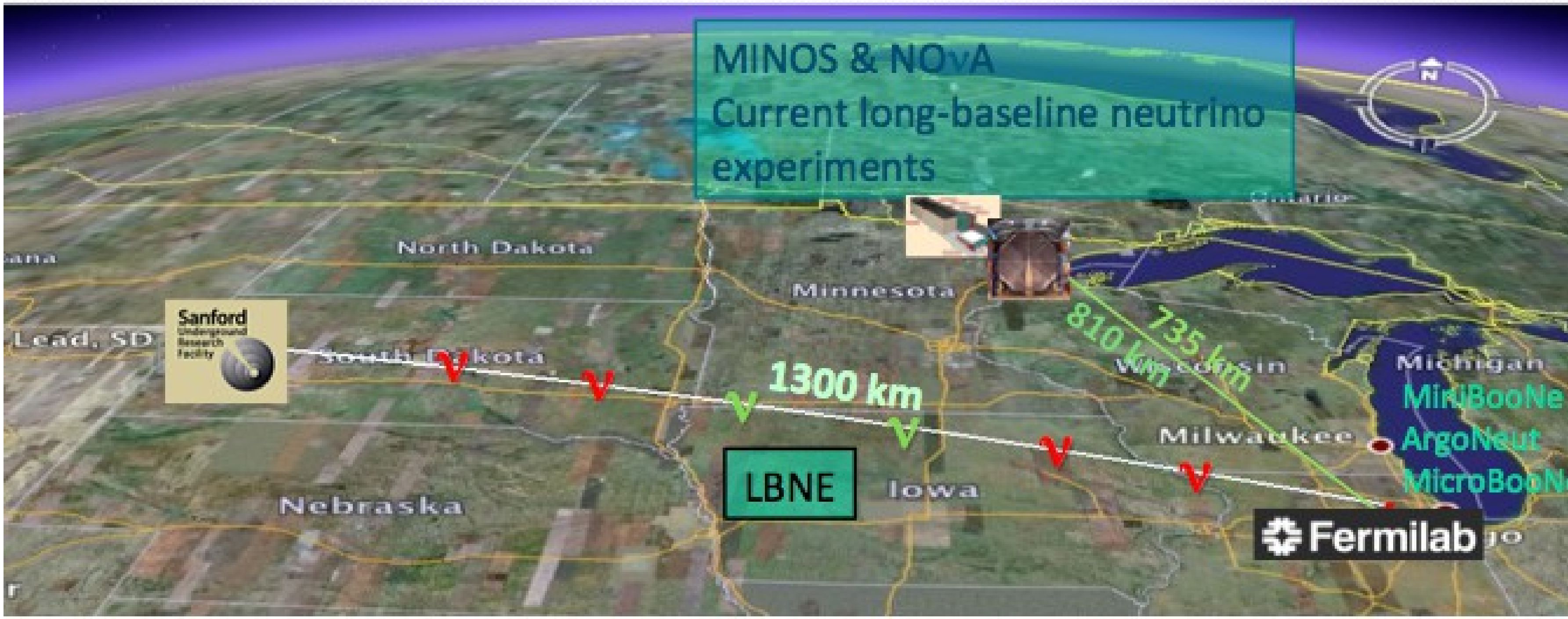
Boston, USA

June 4th, 2014

Colorado State University

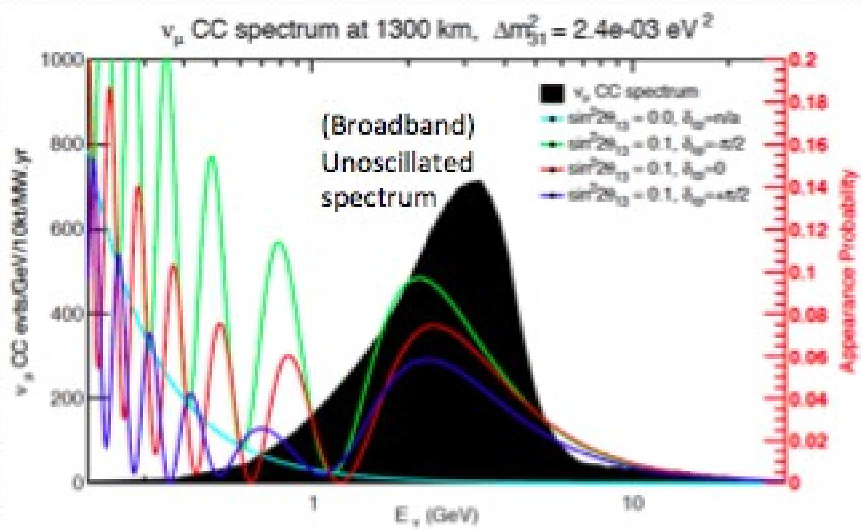
U.S. DEPARTMENT OF ENERGY

Long-Baseline Measurements



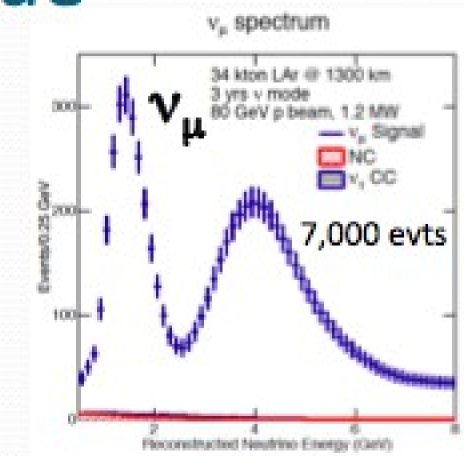
Comprehensive CP Violation, Mass Hierarchy, Non-Standard Interactions
Need Longer Baseline
and High Intensity Broadband Neutrino/Anti-Neutrino Beam

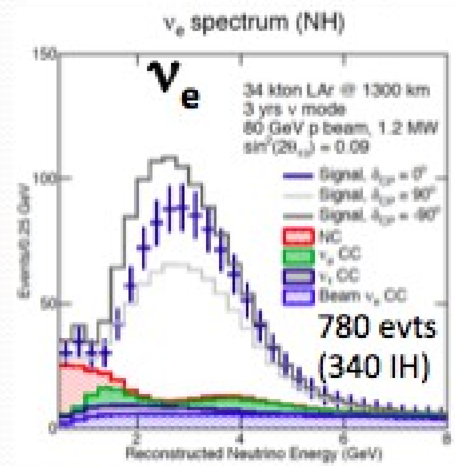
Essential Experimental Technique



disappearance

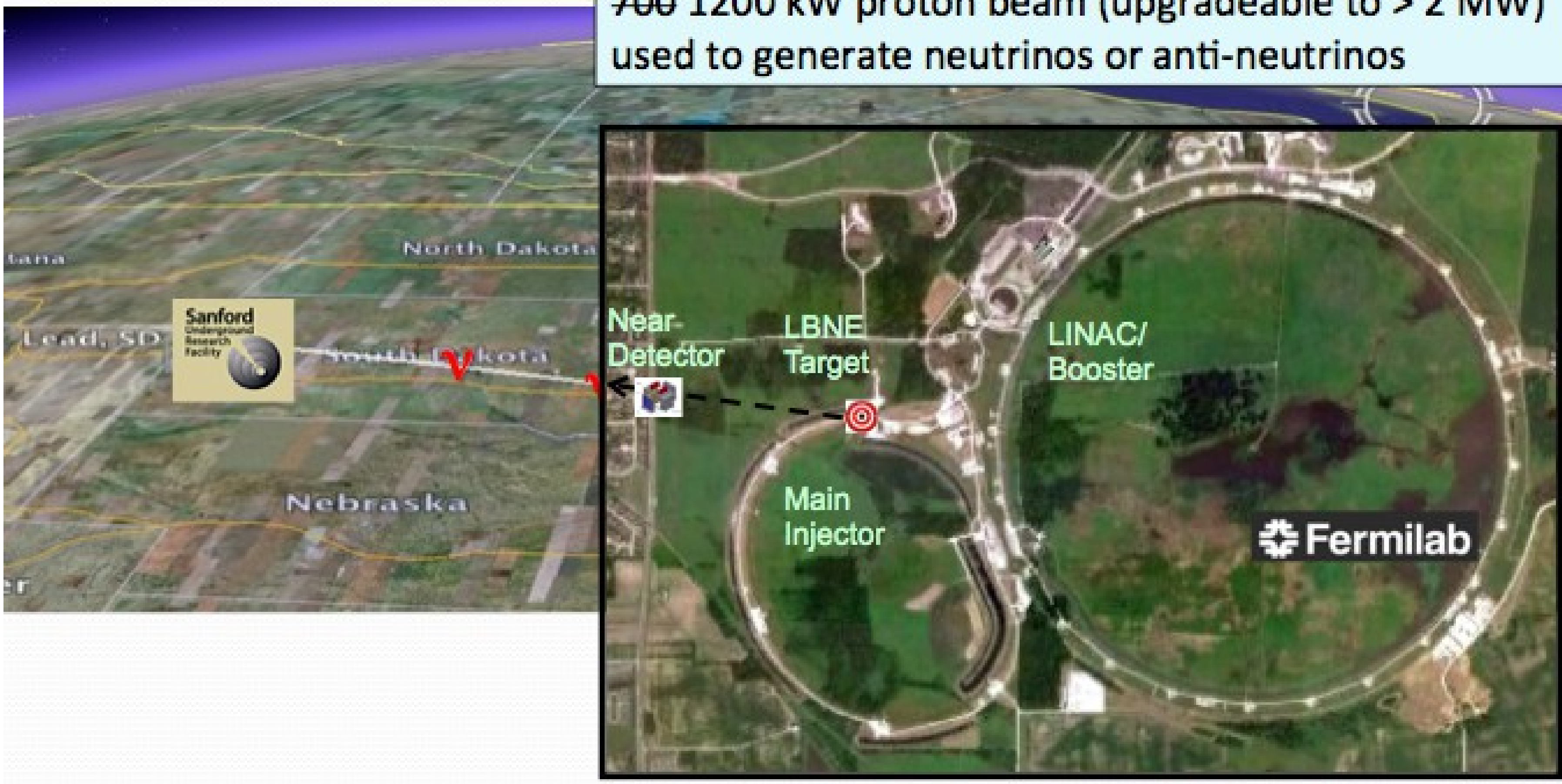
appearance



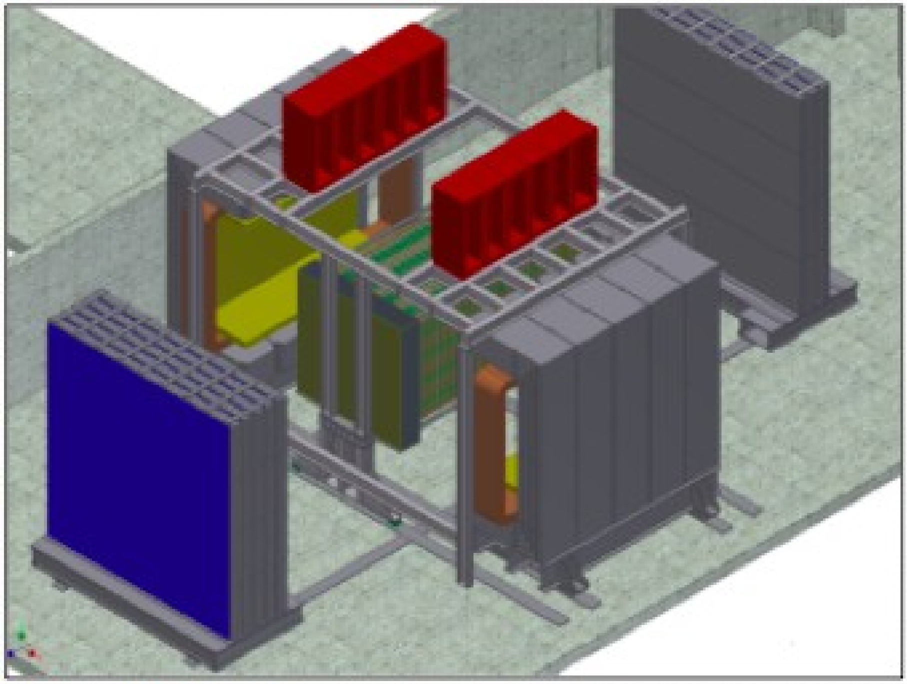


- Produce a pure ν_μ muon-neutrino beam with energy spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- **LBNE is a near optimal choice of beam and distance for sensitivity to CP violation, CP phase, neutrino mass hierarchy and other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

~~700~~ 1200 kW proton beam (upgradeable to > 2 MW) used to generate neutrinos or anti-neutrinos



Highly-Capable Near Detector System



- Fine-Grained Tracker – 460 m from target
  - Low-mass straw-tube tracker with pressurized gaseous argon target
  - Relative/absolute flux measurements
  - High precision neutrino interaction studies ~10^7 interactions/year!
  - Additional target materials possible
  - Proposal pending in India
- Muon monitor system

Poster #49 X. Tian

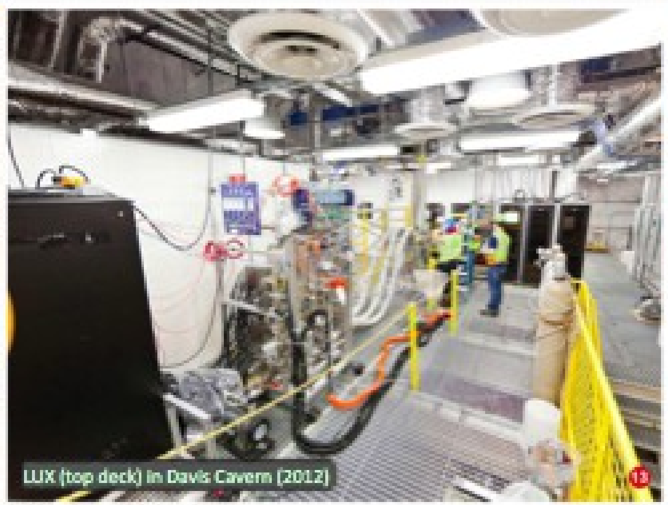
Sanford Underground Research Facility at Homestake Mine
Facilities at 4300 mwe depth


MAJORANA detector assembly room


DAVIS Cavern entrances

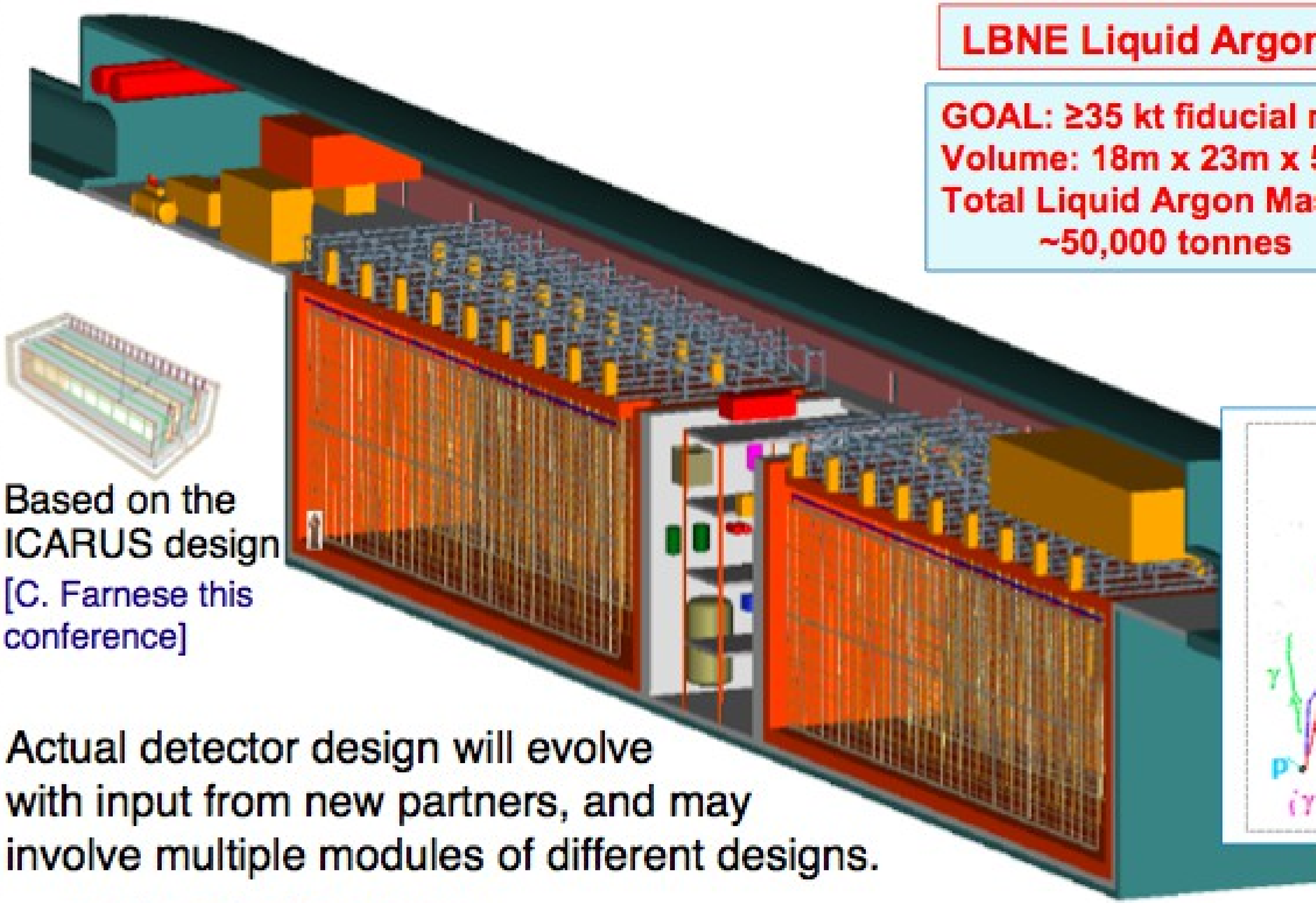

Davis Cavern entrance


MAJORANA Electroforming Laboratory


LUX (top deck) in Davis Cavern (2012)


MAJORANA Demontsrator (2012)

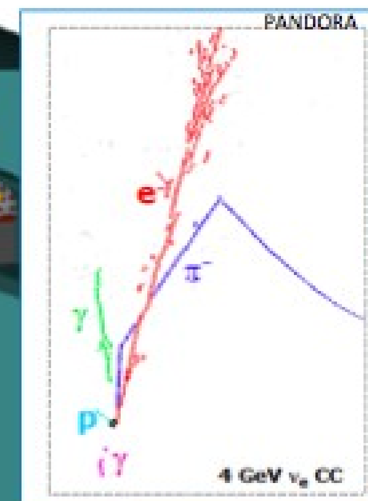
Current Far Detector Design



LBNE Liquid Argon TPC

GOAL: ≥35 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass:
~50,000 tonnes

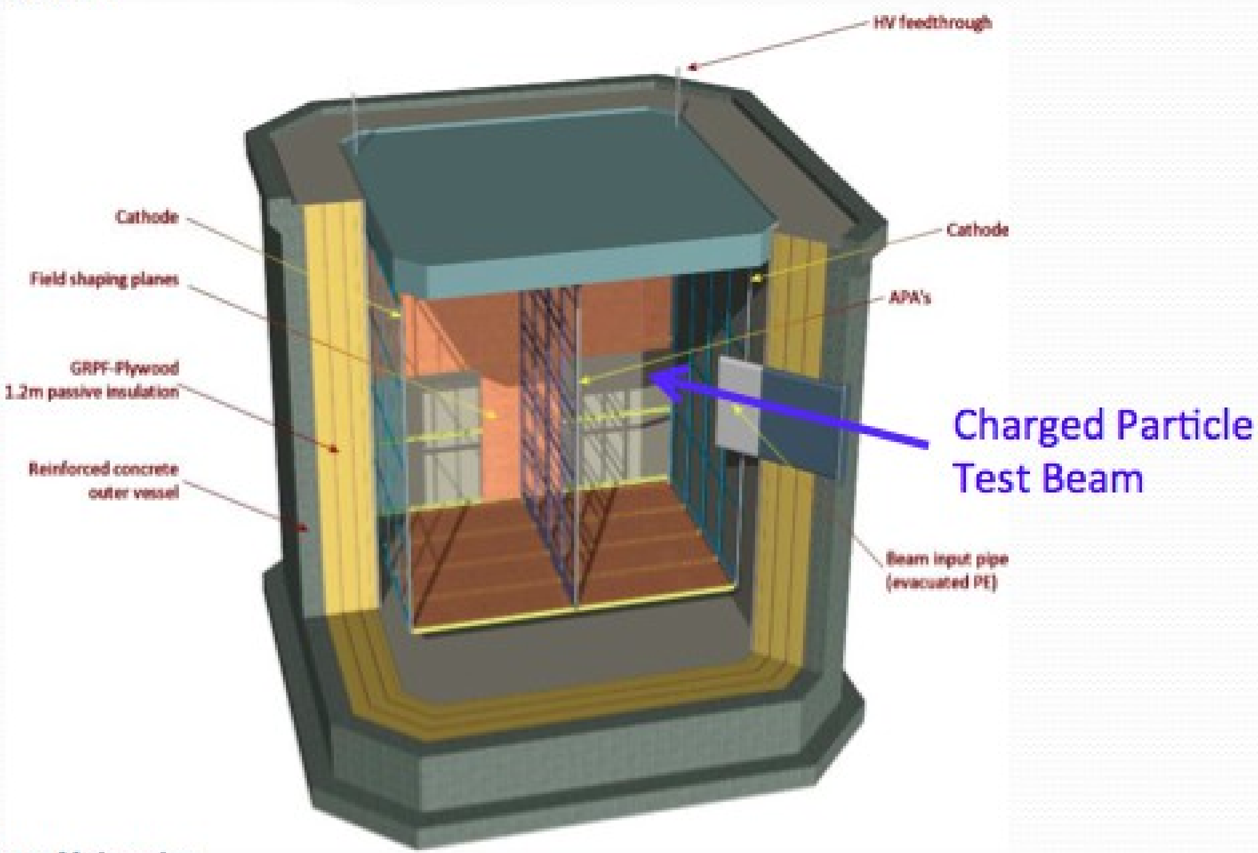
Based on the ICARUS design
[C. Farnese this conference]



Actual detector design will evolve with input from new partners, and may involve multiple modules of different designs.

Full-Scale Prototype in LBNO-DEMO Cryostat

- Together with CERN and the LBNO Collaboration, we are developing a plan to test full-scale LBNE drift cell(s) in the 8x8x8 m^3 cryostat to be built at CERN as part of WA105.



Related Activities

- LBNE Related R&D/Physics proposals
  - LARIAT – LArTPC in charged particle beam at FNAL
  - CAPTAIN – LArTPC neutron flux at LANL -> FNAL
  - LAr1-ND – LArTPC short-baseline in FNAL Booster Neutrino Beam
  - ICARUS – LArTPC short-baseline in FNAL Booster Neutrino Beam
  - NA61-US – proton target characterization
- Mt-scale Water Cherenkov
  - CHIPS – CHerenkov In mine PitS
    - Water Cherenkov in NuMI beam NOvA -- arXiv:1307.5918
    - Not recommended by P5
    - R&D with 50t prototype to be deployed this summer

Future Long Baseline Neutrino Oscillations: View from Europe

by

Thomas Patzak

PARIS DIDEROT université PARIS 7

Département Physique Paris Diderot

Since 2005 substantial financial support from EU for Design Studies (**12M€ + 5 M€ from nat.**): To pave the way for the next generation Long Baseline Neutrino Oscillation Research Facility

2008 – 2012: EUROnu: *"A High Intensity Neutrino Oscillation Facility in Europe"*

- CERN to Frejus superbeam
- Neutrino Factory
- Beta Beam with higher Q isotopes

2008 – 2011: LAGUNA: *"Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics"*

- 7 underground locations
- 3 detector technologies: LAr, LSc and WCD

2011 – 2014: LAGUNA-LBNO: *"Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations"*

- Detailed studies of 3 sites: Fréjus, Umbria and Pyhäsalmi, 130 km, 750 km and 2300 km from CERN
- Engineering design, construction and costing for LAr, LSc and WCD

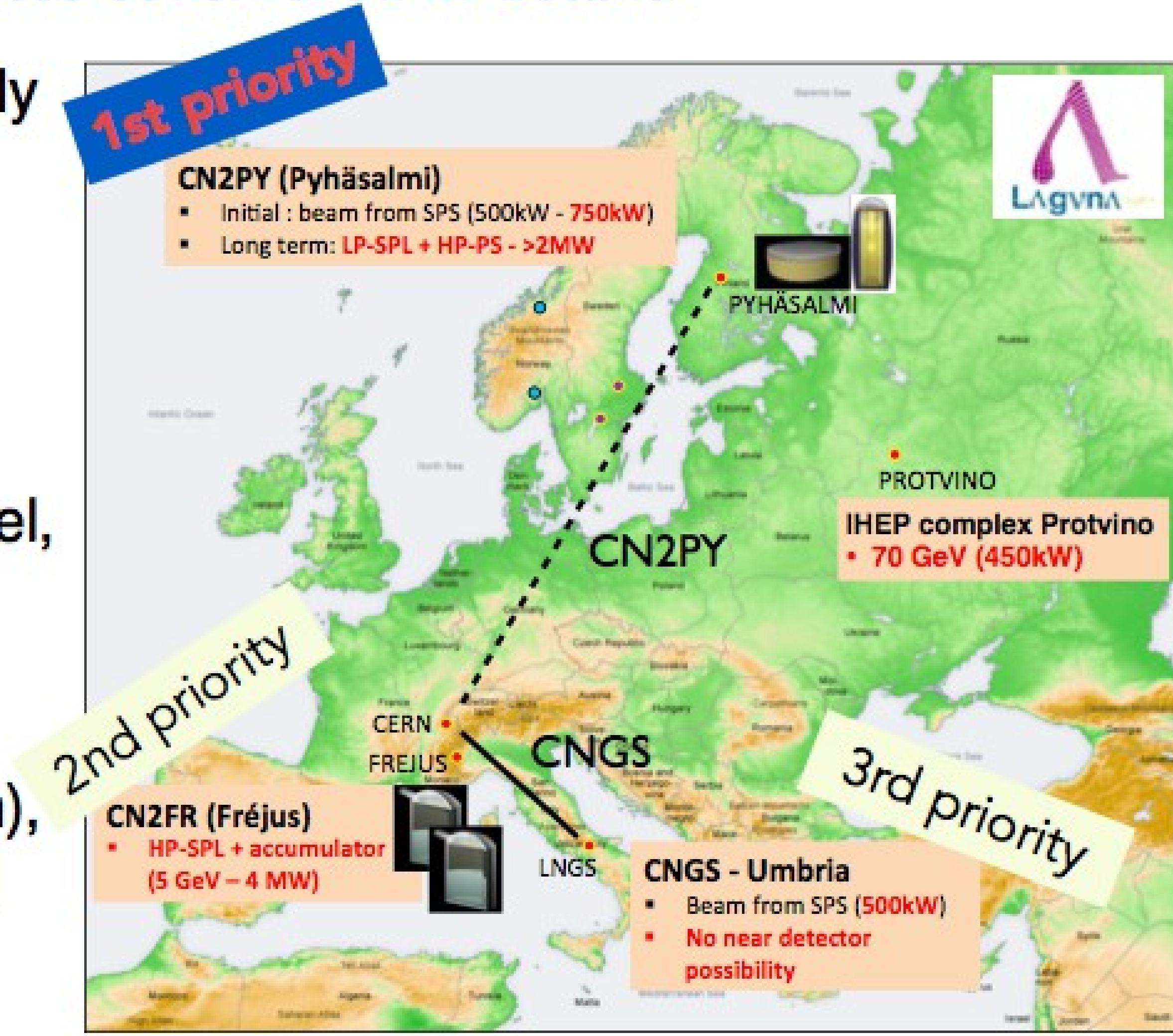
LAGUNA-LBNO: A decade of steady progress…

- **GLACIER** (Giant Liquid Argon Charge Imaging ExpeRiment, **2003**)
  - New concept of Double Phase Liquid Argon TPC for CP-violation and future deep underground detector, up to 100 kton mass (hep-ph/0402110)
- **LAGUNA DS** (FP7 Design Study **2008-2011**)
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **LAGUNA-LBNO DS** (FP7 DS Long Baseline Neutrino Oscillations, **2011-2014**)
  - ~300 members; 14 countries + CERN, 4.9 M€
  - Fully engineered detector designs for 20/50 kt DLAr, 50 kt LSc, 540 kt WCD
  - Underground Facility construction and costing (Pyhäsalmi, Fréjus and Umbria)
  - Extended site investigation at Pyhäsalmi mine
- **LBNO** (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, **June 2012**) - CERN-SPSC-2012-021 ; SPSC-EOI-007)
  - An incremental approach with high level physics starting from phase 1 (MH + LCPV + Astro)
  - ~230 authors; 51 institutions
- **WA105** (CERN experiment, **August 2013**)
  - kt-scale demonstrator for LBNO @ CERN: engineering and charged particle calibration

Site prioritisation

Several sites considered in details

- **Pyhäsalmi mine** (privately owned), 4000 m.w.e overburden, excellent infrastructure for deep underground access
- **Fréjus**, nearby road tunnel, 4800 m.w.e. overburden, horizontal access
- **Umbria** (LNGS extension), green site with horizontal access, 2000 m.w.e., CNGS off-axis beam



LAGUNA-LBNO Strategy for MH and LCPV

- Very long baseline (2300 km) to explore the L/E oscillation pattern predicted by the 3 flavor mixing paradigm over the 1st and 2nd max

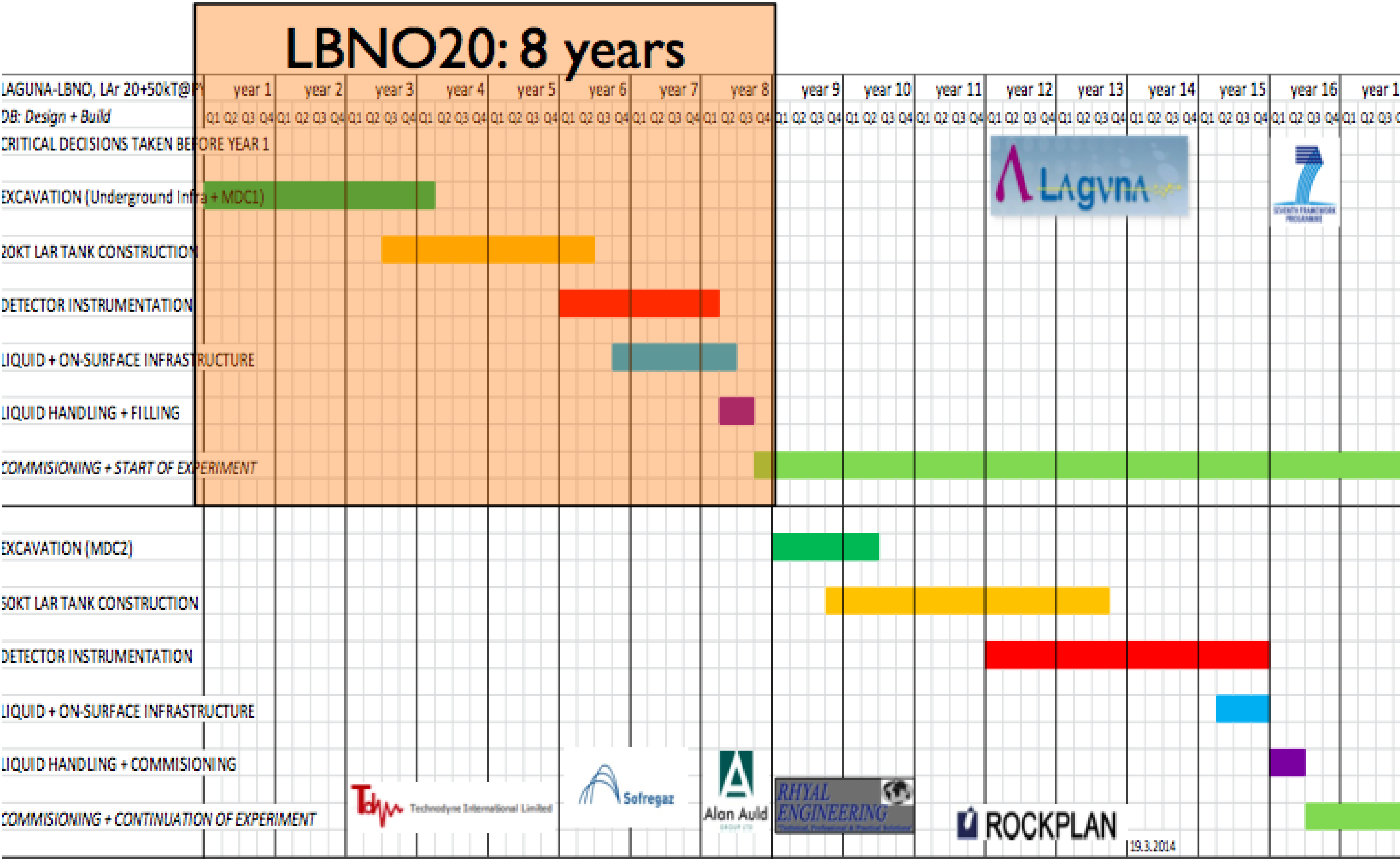
- Phased experiment to adjust the beam and detector mass with respect to the findings of phase n-1 to use resources in the most efficient way (incremental approach).

- LBNO has a fully engineered design, construction plan and costing for the underground infrastructure, the detector and the beam for all phases of the experiment.

- Phase I (LBNO20):
  - 24 kt fid. DLAr + SPS beam (750 kW, Ep = 400 GeV)
  - Guaranteed 5 σ MH determination + 46 % δ_{CP} coverage at 3 σ + p-decay + astroparticles
  - Estimated cost (detector + infrastructure + contingency): ≈ 210 M€ +/- 10%

- Phase II (LBNO70):
  - 70 kt fid. DLAr + HPPS beam (2 MW, Ep = 50 GeV) or Protvino beam
  - 80 % δ_{CP} coverage at 3 σ + p-decay + astroparticles

TECHNICAL TIMESCALE FOR CONSTRUCTION LAGUNA-LBNO 20+50KT



Recent update of the LBL physics program:

10.1007/JHEP05(2014)094

Prepared for submission to JHEP

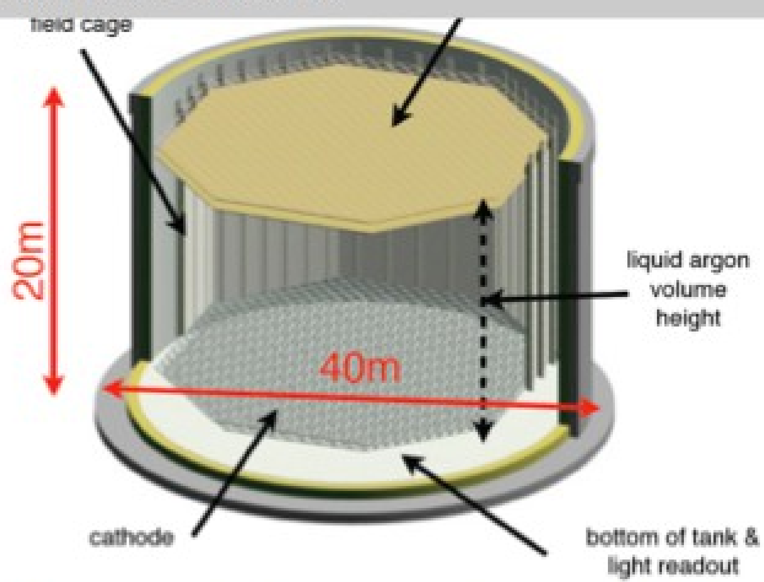
The mass-hierarchy and CP-violation discovery reach of the LBNO long-baseline neutrino experiment

S.K. Agarwalla, L. Agostino, M. Aittola, A. Alekou, B. Andrieu, D. Angus, F. Antoniou, A. Ariga, T. Ariga, R. Asfandiyarov, D. Autiero, P. Ballett, I. Bandac, D. Banerjee, G. J. Barker, G. Barr, W. Bartmann, F. Bay, V. Berardi, I. Bertram, O. Bésida, A.M. Blebea-Apostu, A. Blondel, M. Bogomilov, E. Borriello, S. Boyd, I. Brancus, A. Bravar, M. Buizza-Avanzini, F. Cafagna, M. Calin, M. Calviani, M. Campanelli, C. Cantini, O. Caretta, G. Cata-Danil, M.G. Catanesi, A. Cervera, S. Chakraborty, L. Chaussard, D. Chesneanu, F. Chipesiu, G. Christodoulou, J. Coleman, P. Crivelli, T. Davenne, J. Dawson, I. De Bonis, J. De Jong, Y. Déclais, P. Del Amo Sanchez, A. Delbart, C. Densham, F. Di Lodovico, S. Di Luise, D. Duchesneau, J. Dumarchez, I. Efthymiopoulos, A. Eliseev, S. Emery, K. Enqvist, T. Enqvist, L. Epprecht, A. Ereditato, A.N. Erykalov, T. Esanu, A.J. Finch, M.D. Fitton, D. Franco, V. Galymov, G. Gavrilov, A. Gendotti, C. Giganti, B. Goddard, J.J. Gomez, C.M. Gomoiu, Y.A. Gornushkin, P. Gorodetzky, N. Grant, A. Haesler, M.D. Haigh, T. Hasegawa, S. Haug, M. Hierholzer, J. Hissa, S. Horikawa, K. Huitu, J. Ilic, A.N. Ioannisian, A. Izmaylov, A. Jipa, K. Kainulainen, T. Kalliokoski, Y. Karadzhov, J. Kawada, M. Khabibullin, A. Khotjantsev, E. Kokko, A.N. Kopylov, L.L. Kormos, A. Korzenev, S. Kosyanenko, I. Kreslo, D. Kryn, Y. Kudenko, V. A. Kudryavtsev, J. Kumpulainen, P. Kuusiniemi, J. Lagoda, I. Lazanu, J.-M. Levy, R.P. Litchfield, K. Loo, P. Loveridge, J. Maalampi, L. Magaletti, R.M. Margineanu, J. Marteau, C. Martin-Mari, V. Matveev, K. Mavrokoridis, E. Mazzucato, N. McCauley, A. Mercadante, O. Mineev, A. Mirizzi, B. Mitrica, B. Morgan, M. Murdoch, S. Murphy, K. Mursula, S. Narita, D.A. Nesterenko, K. Nguyen, K. Nikolics, E. Noah, Yu. Novikov, H. O'Keeffe, J. Odell, A. Oprima, V. Palladino, Y. Papaphilippou, S. Pascoli, T. Patzak, D. Payne, M. Pectu, E. Pennacchio, L. Periale, H. Pessard, C. Pistillo, B. Popov, P. Przewlocki, M. Quinto, E. Radicioni, Y. Ramachers, P.N. Ratoff, M. Ravonel, M. Rayner, F. Resnati, O. Ristea, A. Robert, E. Rondio, A. Rubbia, K. Rummukainen, R. Sacco, A. Saftoiu, K. Sakashita, J. Sarkamo, F. Sato, N. Saviano, E. Scantamburlo, F. Sergiampietri, D. Sgalaberna, E. Shaposhnikova, M. Slupecki, M. Sorel, N. J. C. Spooner, A. Stahl, D. Stanca, R. Steerenberg, A.R. Sterian, P. Sterian, B. Still, S. Stoica, T. Strauss, J. Suhonen, V. Suvorov, M. Szeptycka, R. Terri, L.F. Thompson, G. Toma, A. Tonazzo, C. Touramanis, W.H. Trzaska, R. Tsenov, K. Tuominen, A. Vacheret, M. Valram, G. Vankova-Kirilova, F. Vanucci, G. Vasseur, F. Velotti, P. Velten, T. Viant, H. Vincke, A. Virtanen, A. Vorobyev, D. Wark, A. Weber, M. Weber, C. Wiebusch, J.R. Wilson, S. Wu, N. Yershov, J. Zalipska, and M. Zito.

arXiv:1312.6520v3 [hep-ph] 20 Jan 2014

Basic assumptions :

- Realistic systematics
- 2300 km baseline
- SPS 400 GeV protons – 750 kW beam
- HPPS 50 GeV protons – 2 MW beam
- Liquid Argon double phase detector GLACIER : LBNO20 -> LBNO70



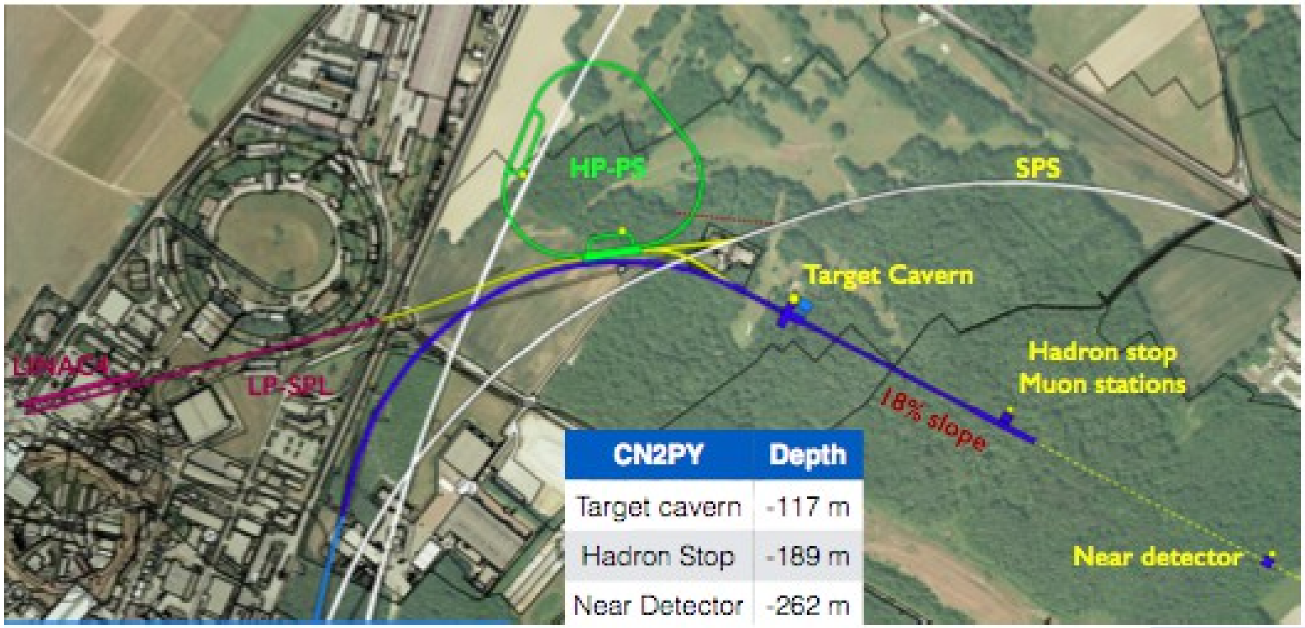
Updated beam LBNO design

Phase 1 : proton beam extracted beam from SPS

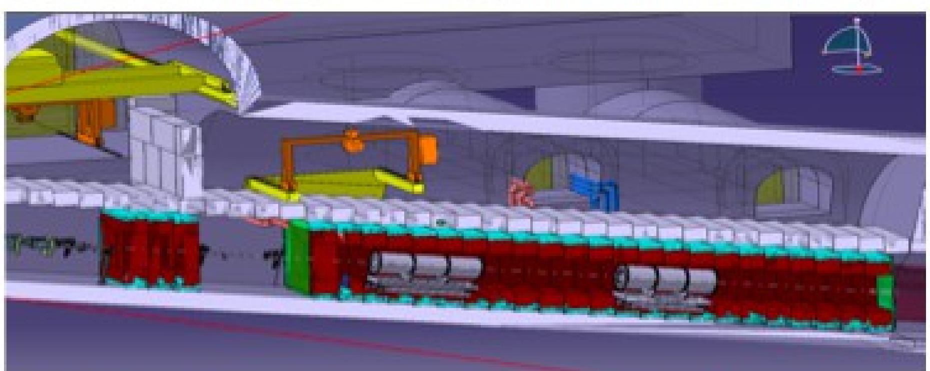
400 GeV, max 7.0 10^{13} protons every 6 sec, ~750 kW beam power, 10 μs pulse

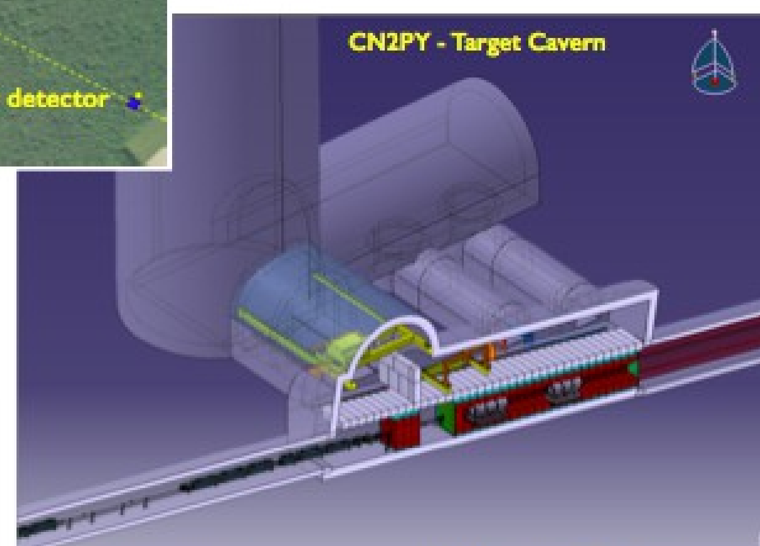
Phase 2 : use the proton beam from a new HP-PS

50 GeV, 1 Hz, 2.5 10^{14} ppp, 2 MW beam power, 4 μs pulse



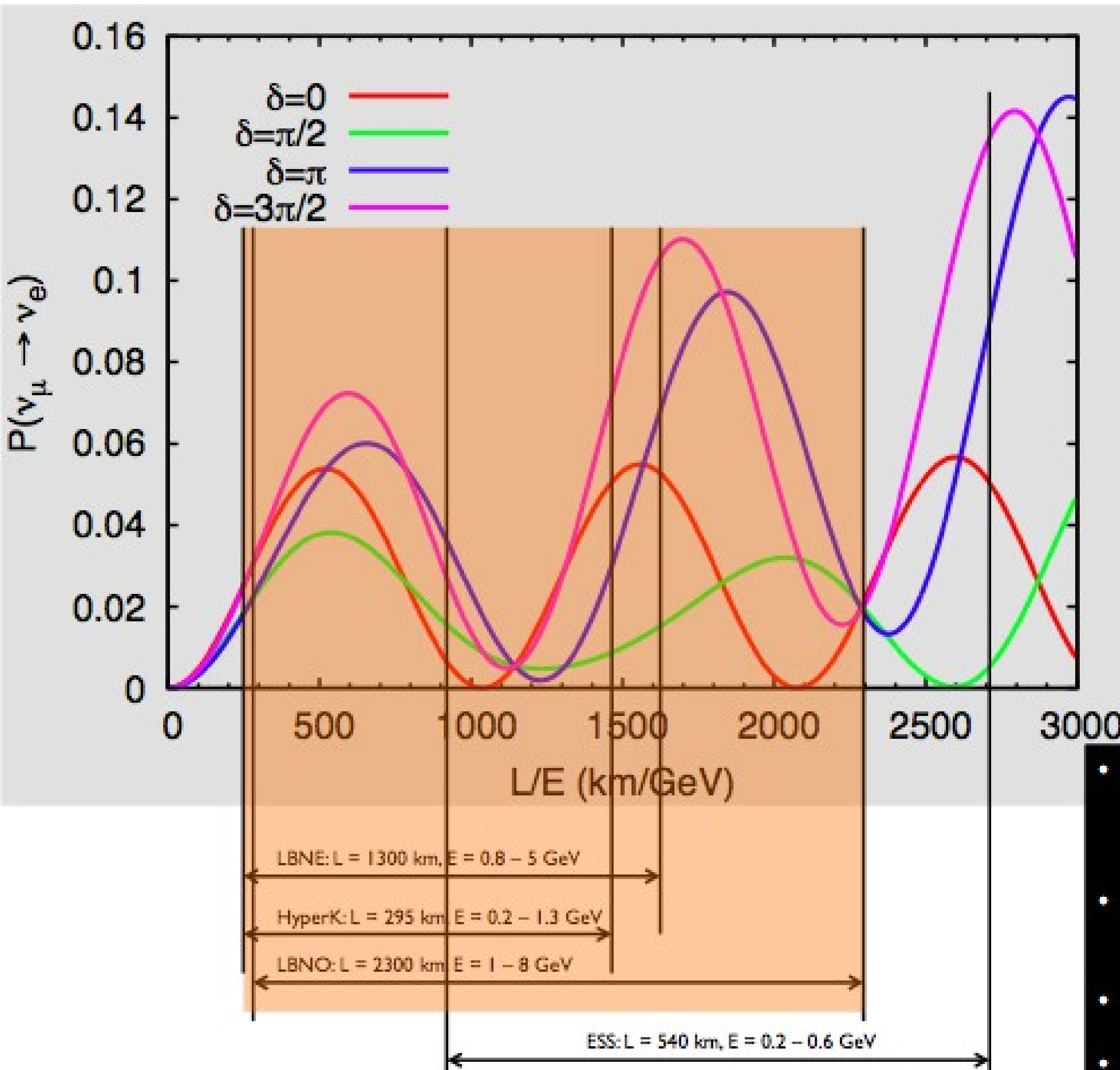
CN2PY	Depth
Target cavern	-117 m
Hadron Stop	-189 m
Near Detector	-262 m

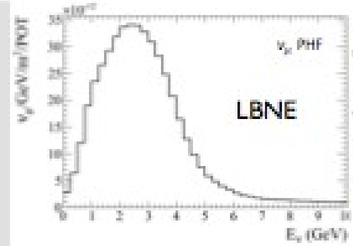


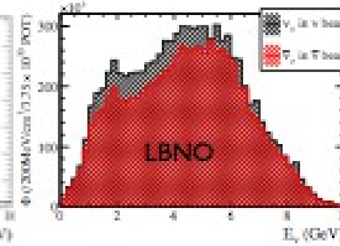


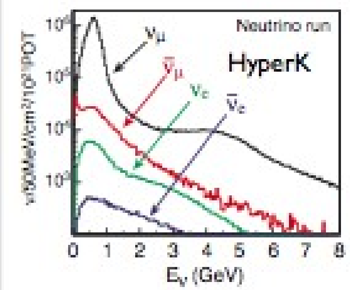
CP Violation with LBNO

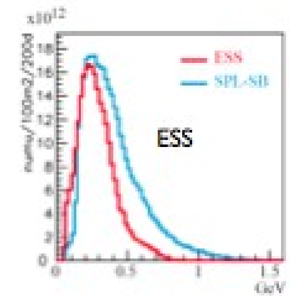
1st and 2nd maximum and the wiggles of L/E…











- CP sensitivity depends on the ability to measure the L/E behavior and the 1st and 2nd maximum and on the control of systematic errors.
- Low energies are disfavored since flux & x-section are suppressed. One need to go higher L/E.
- LBNO has better L/E coverage then LBNE and HK.
- LBNE and HK have similar coverage.

Conclusions

- After 2 consecutive DS the LBNO collaboration has a clear end-to-end path to propose an experiment capable to
  - Determine unambiguously (>5 σ) MH (no need for external input) and
  - Cover 80% of the CPV phase space at 3σ and 65 % at 5σ with realistic systematic error assumptions -> P5 requirement satisfied
  - Deep underground location:
    - Astrophysics program
    - p-decay

    } Complementary to WCD

- Full conceptual design available, developed in collaboration with industrial partners leading to: Underground facility, construction sequence, well defined costs,…
- LAGUNA-LBNO DS final report August 2014, stay tuned!
- Planned next step: construction and operation of LBNO-DEMO (WA 105)

LAGUNA-LBNO DS	WA 105	LBNO – PILOT (2.5 – 5 kt)	LBNO Phase I (LBNO20)	LBNO Phase II (LBNO70)
Site selection Full assessment of physics Full engineering costing	DLAr demonstrator Calibration Software development	Underground installation Astro particle physics	MH CPV 3 σ: 46% Proton decay Astrophysics	CPV 3 σ: 80 % Proton decay Astrophysics
2014	2018	202X	202X	203X

Non solo acceleratori…

Future Reactor Experiments

Liangjian Wen

Institute of High Energy Physics, Beijing

中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Running & Future Reactor Neutrino Exp.

θ_{13} companies

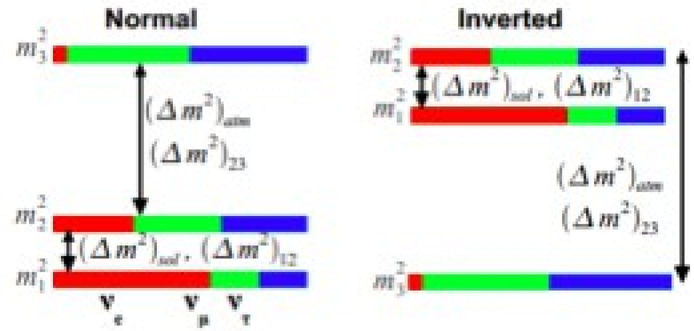
Mass Hierarchy

Sterile ν (see D. Lhuillier's talk)

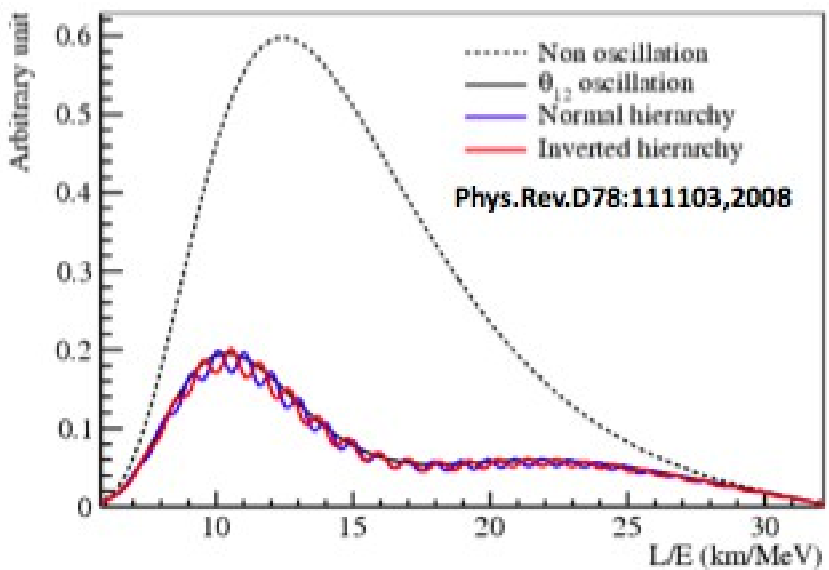
ν Scattering (see P. Barbeau's talk)

Apologies to the projects not be plotted here.

Neutrino Mass Hierarchy



- Large θ_{13} open doors to MH
  - Exploit L/E spectrum with reactors
    - ➢ Precision energy spectrum measurement (JUNO, RENO-50)
    - ➢ Look for interference between solar- and atmospheric- oscillations → relative measurement



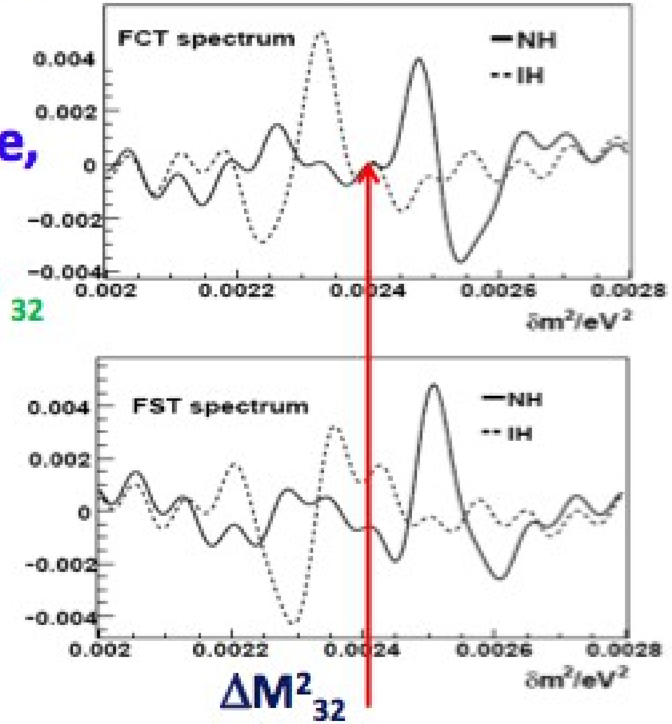
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

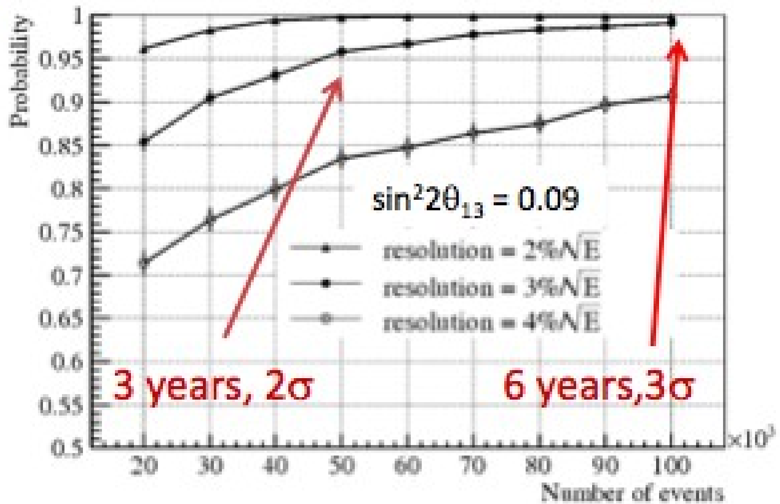
S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
...
Realistic requirements about determining MH with reactors will be discussed later

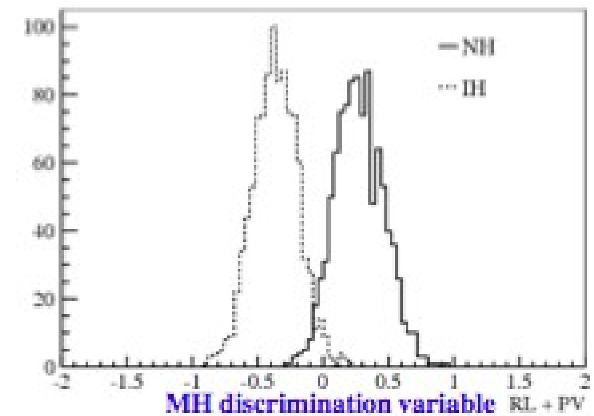
Independent on CP phase and θ_{23} (Acc. & Atm. do)
Energy Resolution is the key

Initial MH Sensitivity with FT method

- **Fourier transform enhances the visible features in ΔM^2 (oscillation frequency) regime, take ΔM^2_{32} as reference**
  - NH (IH): ΔM^2_{31} peak at the right (left) of ΔM^2_{32}
- **Distinctive features, no pre-condition of ΔM^2_{32}**







Experiment Concepts:

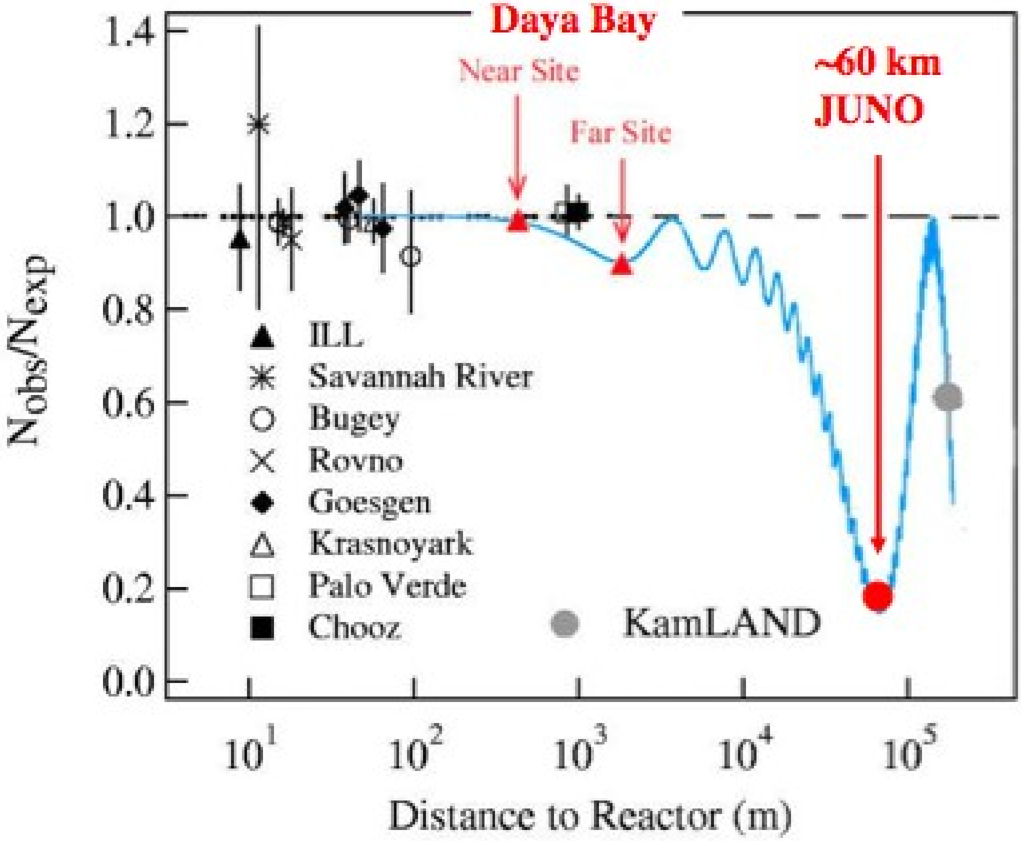
36GW reactors; 58km baseline

20 kton LS; 3%/$\sqrt{E}$ resolution;

L. Zhan et al, PRD78:111103,2008; PRD79:073007,2009

JUNO Experiment

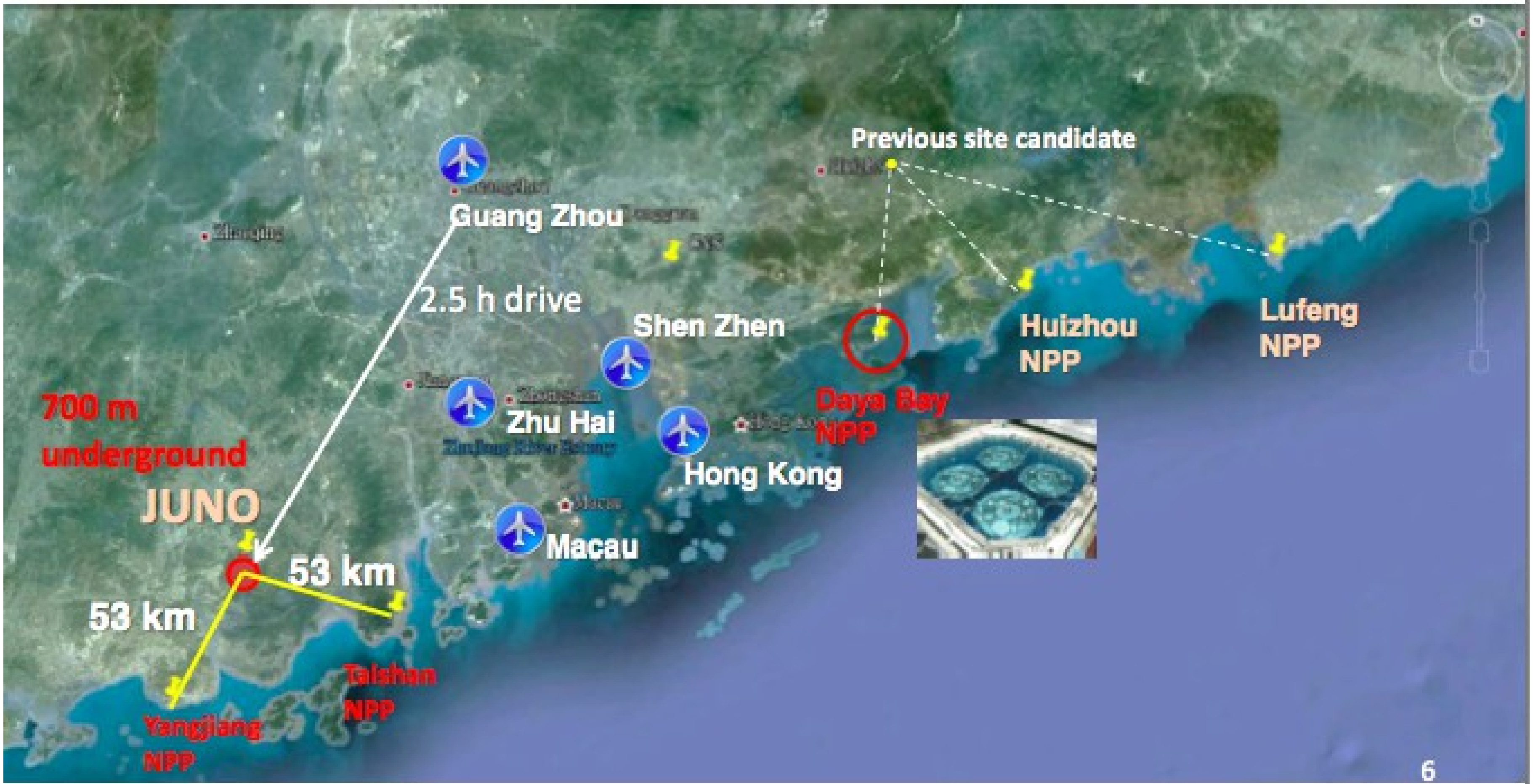
- Jiangmen Underground Neutrino Observatory (was Daya Bay II)
- Primary goals: mass hierarchy and precision meas.
  - 20 kton LS detector, $3\%/\sqrt{E}$ energy resolution
- Proposed in 2008, approved in Feb.2013. ~300M US$



- Rich Physics
  - Mass hierarchy
  - Precision measurement of mixing parameters
  - Supernova neutrinos
  - Geo-neutrinos
  - Solar neutrinos
  - Sterile neutrinos
  - Atmospheric neutrinos
  - Exotic searches

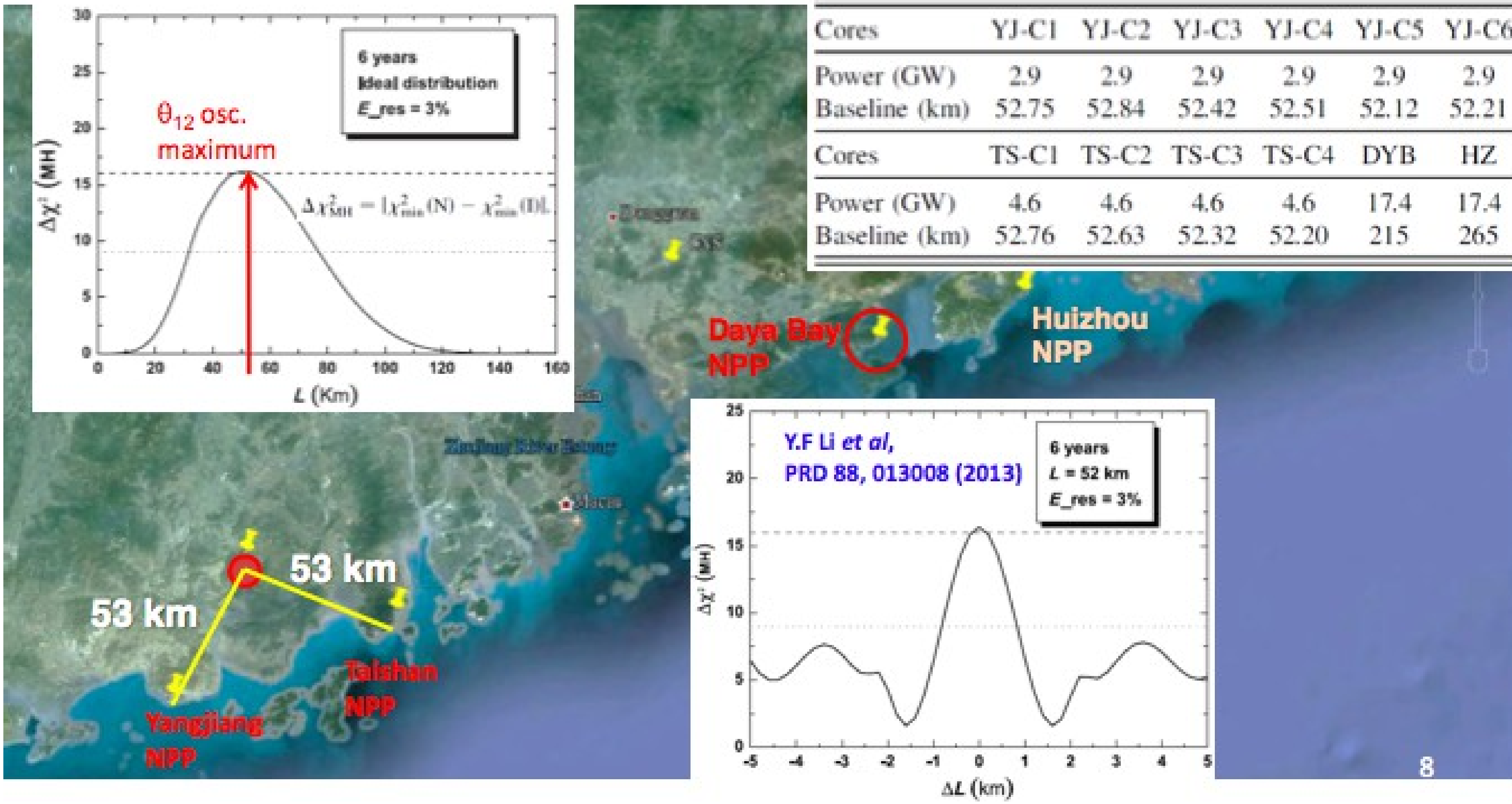
Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Optimum baseline for MH

- **Optimum at the oscillation maximum of θ_{12}**
- **Multiple reactors may cancel the oscillation structure**
  - **Baseline difference cannot be more than 500 m**



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

RENO-50

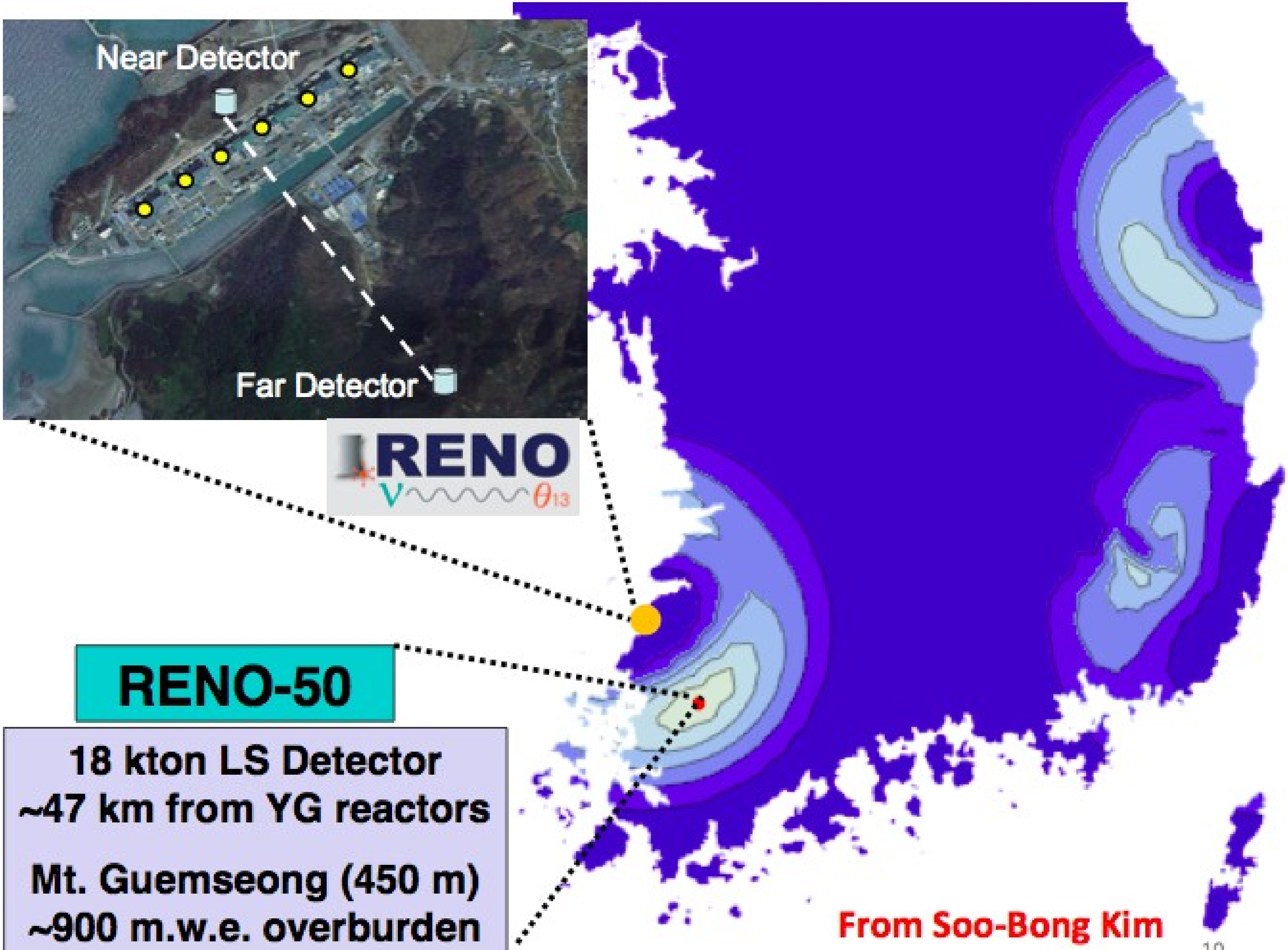
From Soo-Bong Kim

- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

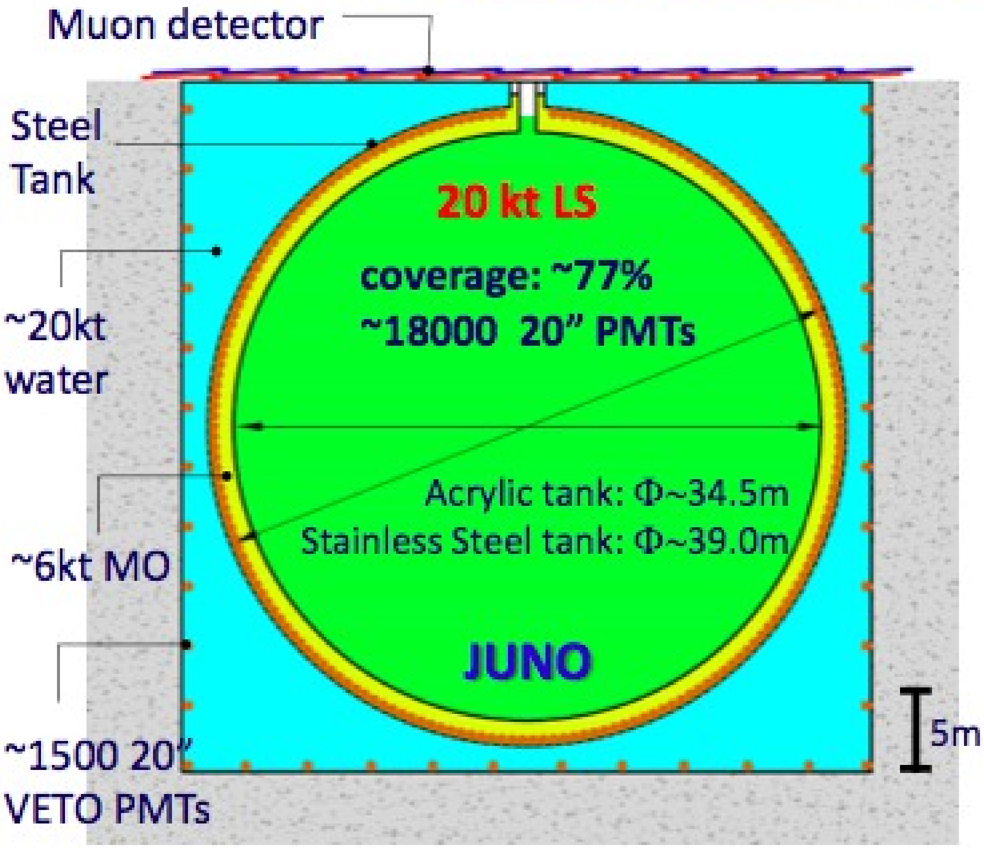
- **Goals** : - Determination of neutrino mass hierarchy
  - High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}
  - Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects

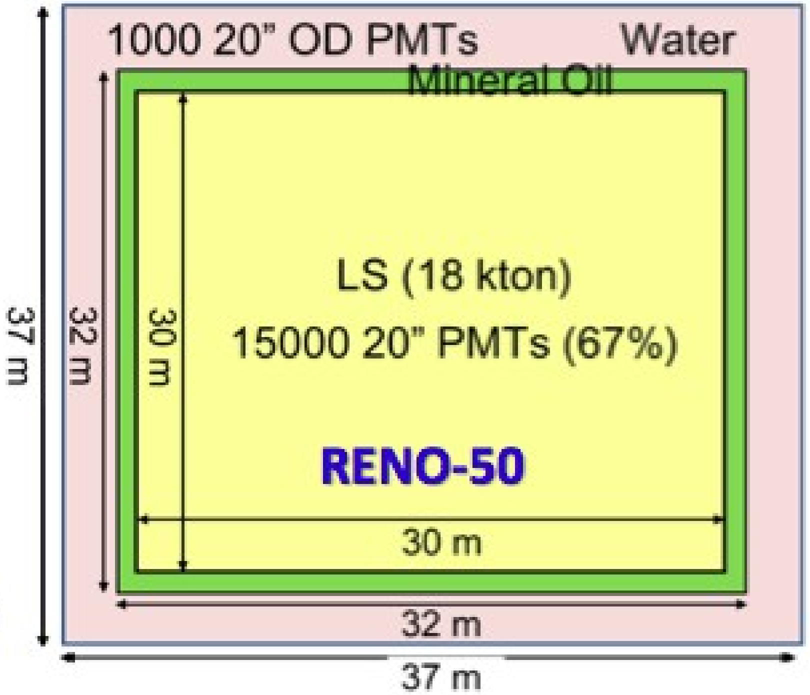
- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2014 ~ 2019 : Facility and detector construction
  2020 ~ : Operation and experiment


Near Detector
Far Detector
RENO
ν θ_{13}
RENO-50
18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
From Soo-Bong Kim

Challenge: high-precision, giant LS detector





	KamLAND	JUNO	RENO-50
LS mass	~1 kt	20 kt	18 kt
Energy Resolution	$6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV

Requirements on Energy Resolution

- **$3\%/\sqrt{E}$ energy resolution**
- **Take JUNO MC as example**
  - Based on DYB MC
  - JUNO Geometry
  - 77% photocathode coverage (KamLAND: ~34%)
  - High QE PMT, QE_{max}: 25% → 35%
  - LS attenuation length (1 m-tube measurement @ 430nm)

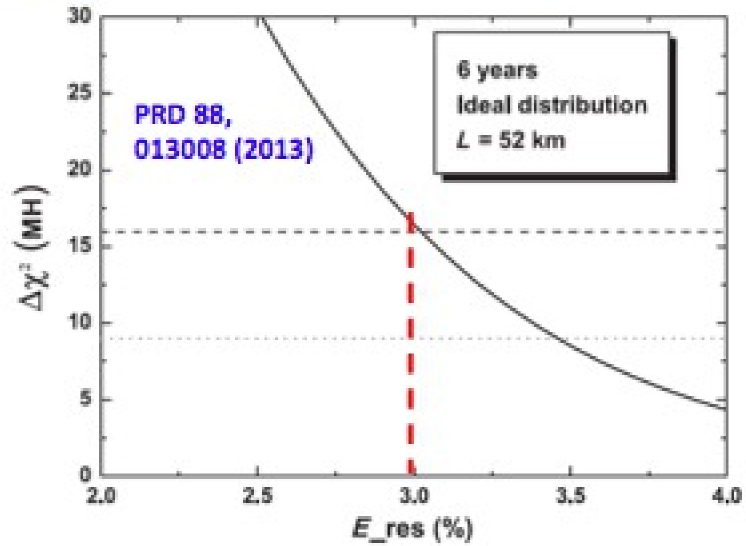
from 15 m

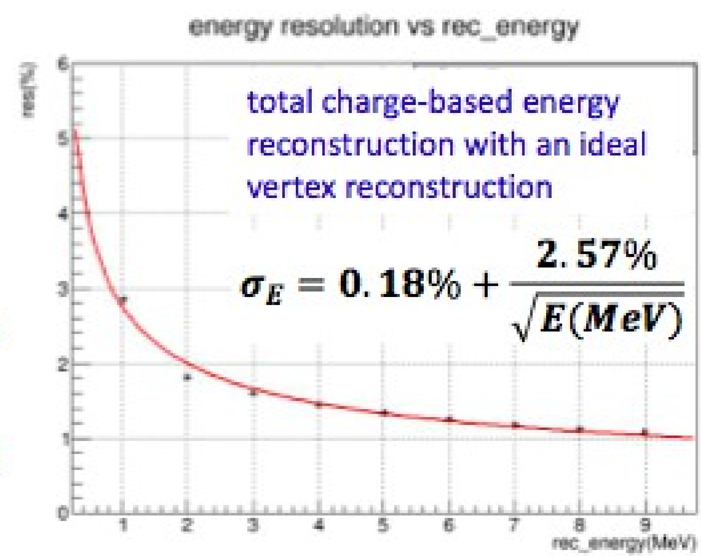
= absorption 30 m + Rayleigh scattering 30 m

to 20 m

= absorption 60 m + Rayleigh scattering 30 m

The Highlighted parameters are input to MC

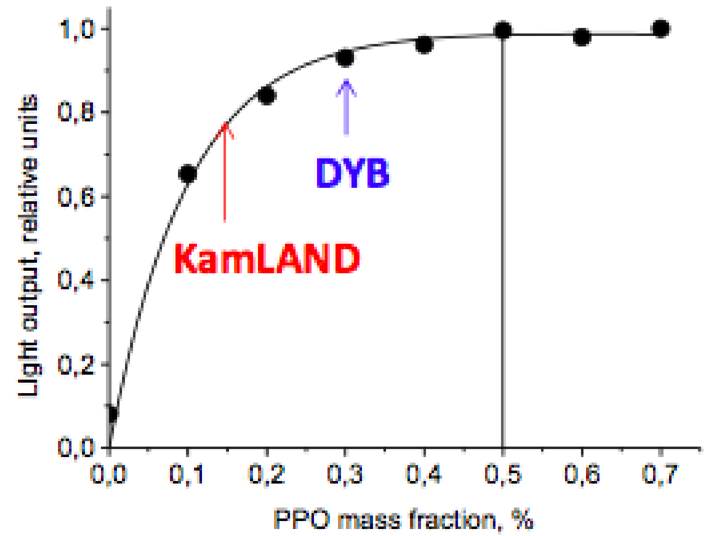




Liquid Scintillator in JUNO

- Current choice:

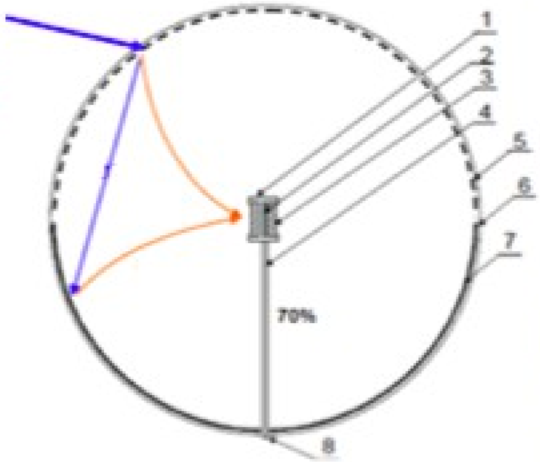
  LAB+PPO+bisMSB (no Gd-loading)
- Increase light yield
  - Optimization of fluors concentration
- Increase transparency
  - Good raw solvent LAB
    - Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc
  - Online handling/purification
    - Distillation, Filtration, Water extraction, Nitrogen stripping, …
- Reduce radioactivity
  - Less risk, since no Gd
  - Singles<3Hz (above 0.7MeV), if ^{40}K/U/Th $<10^{-15}$ g/g (preliminary)

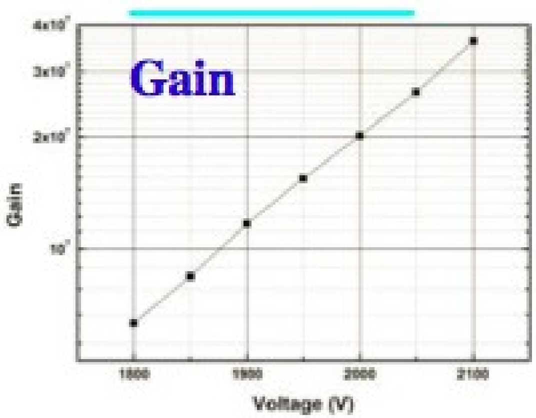


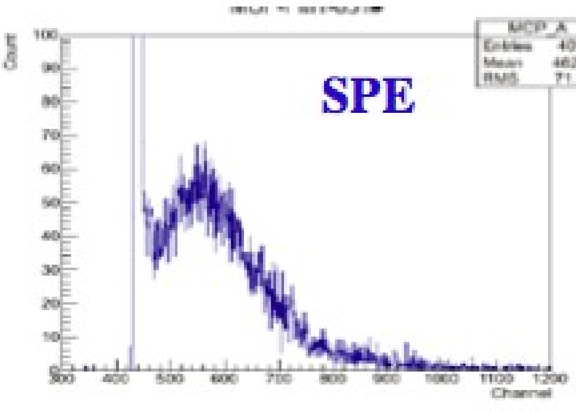
Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m
LAB from Nanjing, Raw	20 m
Al_2O_3 coloum	25 m

High QE PMT Effort in JUNO

- High QE 20" PMTs under development:
  - A new design using MCP: 4π collection
- MCP-PMT development:
  - Technical issues mostly resolved
  - Successful 8" prototypes
  - A few 20" prototypes
- Alternative options: Hamamatsu or Photonics

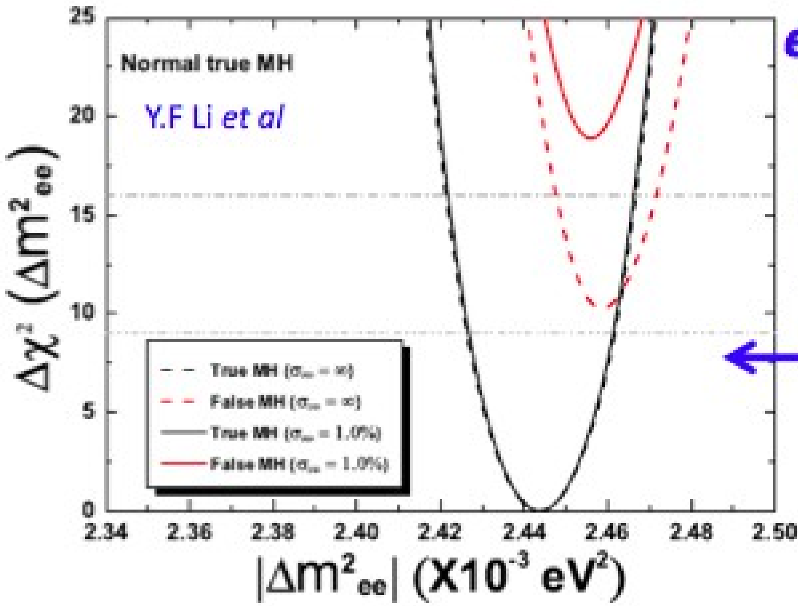






	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	~2
TTS	5.5ns	1.5 ns	3.5 ns

Sensitivity on MH and mixing parameters



e.g JUNO MH sensitivity with 6 years' data:

Ref: Y.F Li et al, PRD 88, 013008 (2013)	Relative Meas.	[a]Use absolute Δm^2
Ideal case	4σ	5σ
[b]Realistic case	3σ	4σ

[a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level
[b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

	Current	e.g JUNO
Δm^2_{12}	~3%	~0.5%
Δm^2_{23}	~4%	~0.6%
$\sin^2\theta_{12}$	~7%	~0.7%
$\sin^2\theta_{23}$	~15%	N/A
$\sin^2\theta_{13}$	~6% → ~4%	~ 15%

Probing the unitarity of U_{PMNS} to ~1%

There is nothing new to be discovered in physics. All that remains is more and more precise measurement,..
William Thompson (1900)

The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place...
F.K. Richtmeyer (1931)

S.L Glashow, arXiv:1305.5482

Everything Under the Sun

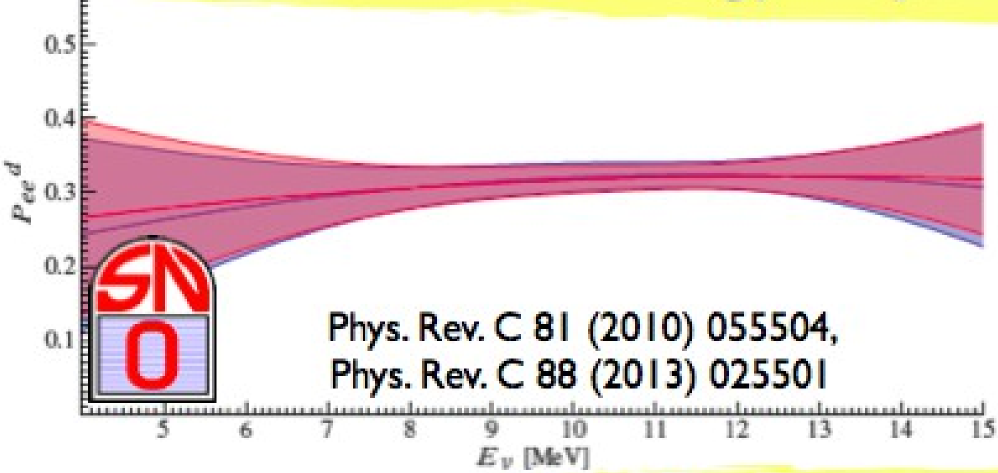
Gabriel D. Orebi Gann
Neutrino 2014, Boston
June 3rd, 2014

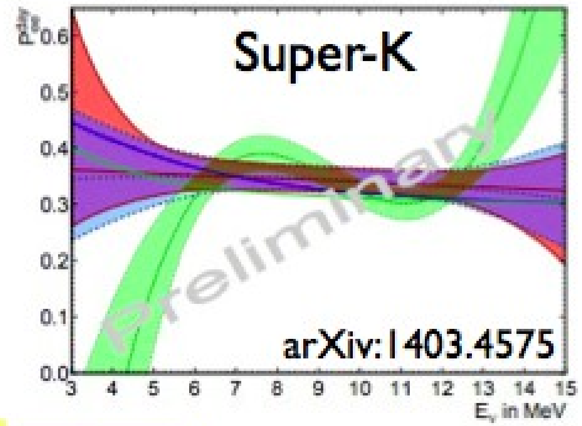
U. C. Berkeley
& LBNL

Precision Era

Low Energy Threshold Analysis

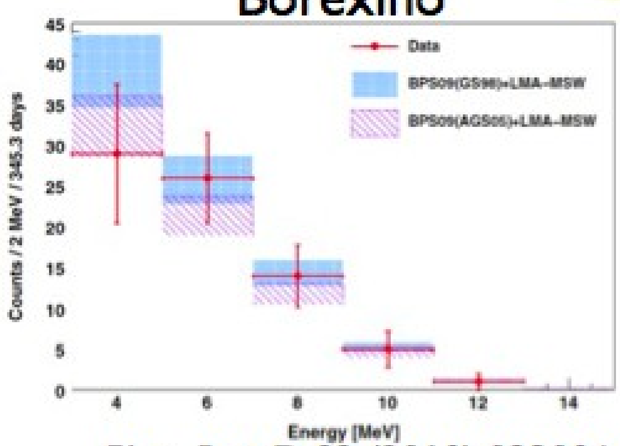
Direct Fit for Energy-Dependent Survival Probability





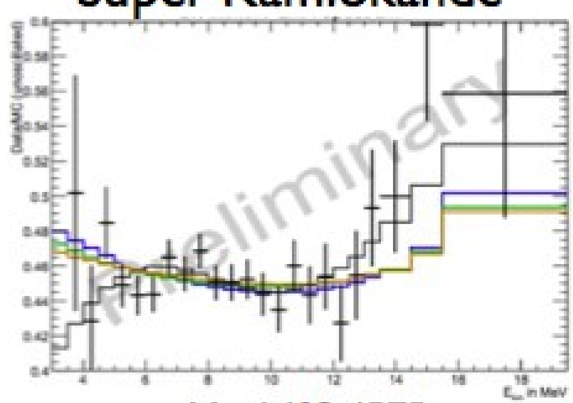
Electron recoil spectra

Borexino



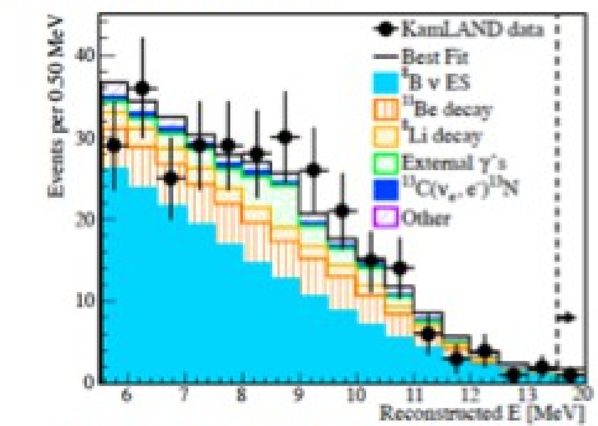
Phys. Rev. D 82 (2010) 033006

Super-Kamiokande



arXiv:1403.4575

KamLAND



Phys. Rev. C 84 (2011) 035804

Non-Standard Model Testing

Light sterile neutrino — PRD 83:113011 (2011)

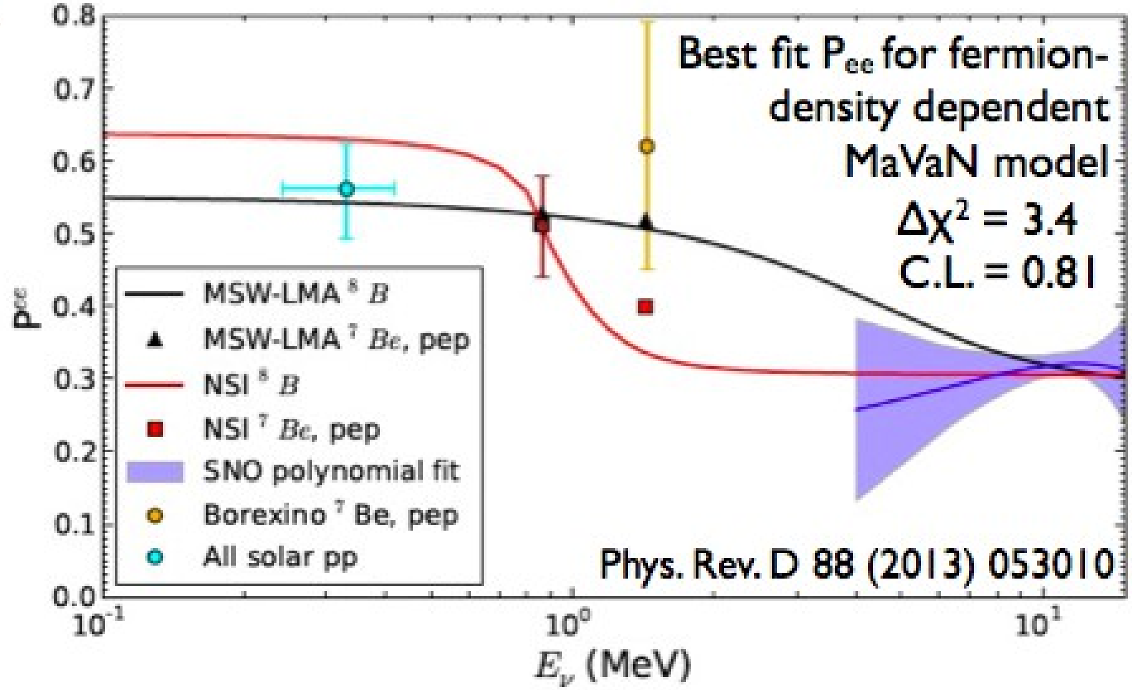
Non-standard MSW Dynamics — PRD 83:101701 (2011)

Non-Standard Models, Solar Neutrinos and Large θ_{13} — PRD 88: 053010 (2013)

- Non-standard forward scattering
- Mass-varying neutrinos
- Long-range leptonic forces
- Non-standard solar model

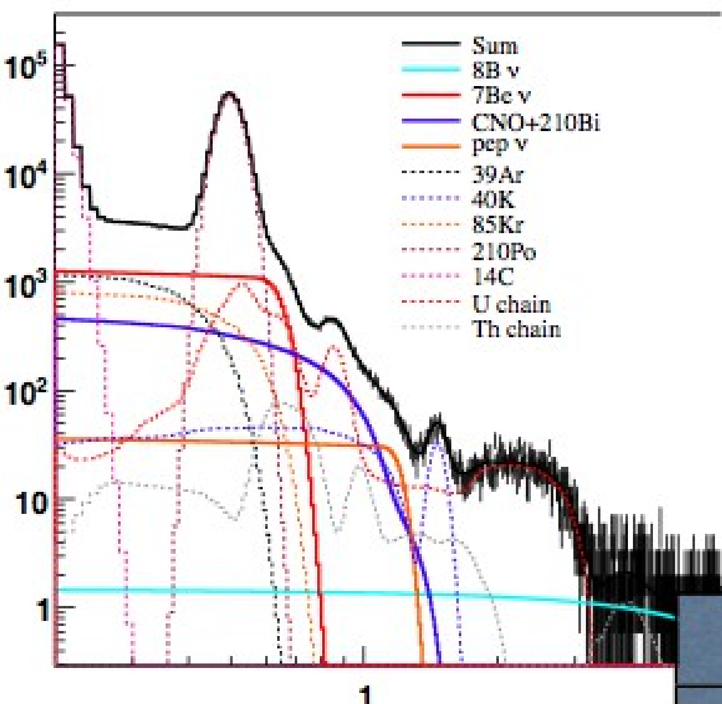
No significant effects ($< 2\sigma$)

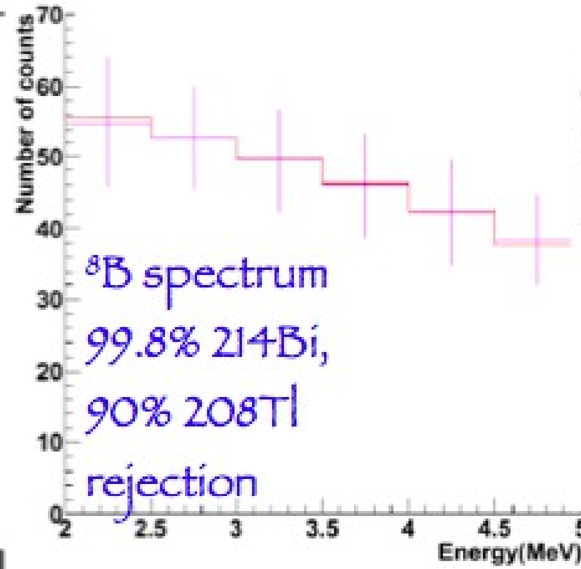
Results limited by experimental precision

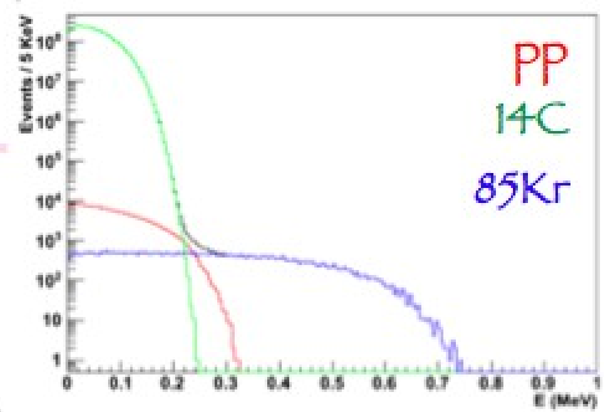


SNO+ Sensitivity

- 1 year livetime
- 50% fiducial volume (negligible external bkg)
- Assuming Borexino-level purification levels





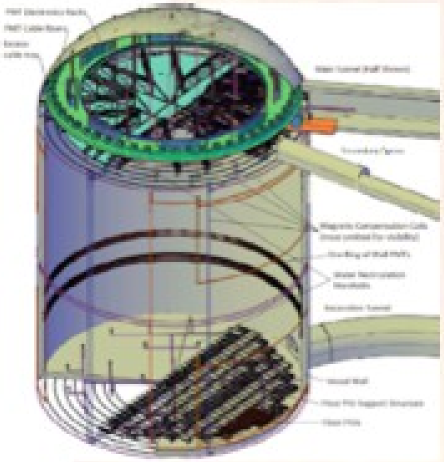


(pp dependent on ^{14}C, ^{85}Kr)
(CNO dependent on ^{210}Bi)

	pep	^{8}B	^{7}Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

"Mega-Ton" Scale

Hyper-Kamiokande



- 0.99e6 T (20* Super-K)
- 1750 mwe depth
- 115,000 8B ES / year
- 0.5% sensitivity to D-N amplitude variation
- 4σ confirmation of MSW

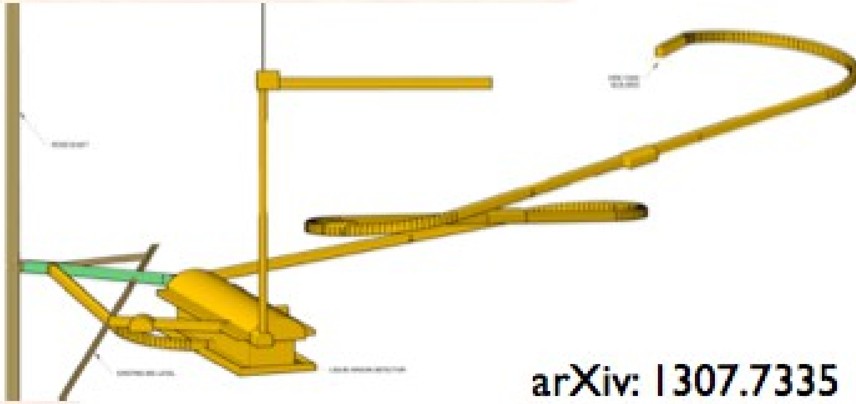
arXiv: 1309.0184

LBNF

- 40kT LAr (+ 50kT WCD?) - p5
  - CC on ^{40}Ar, E_{th} = 5MeV

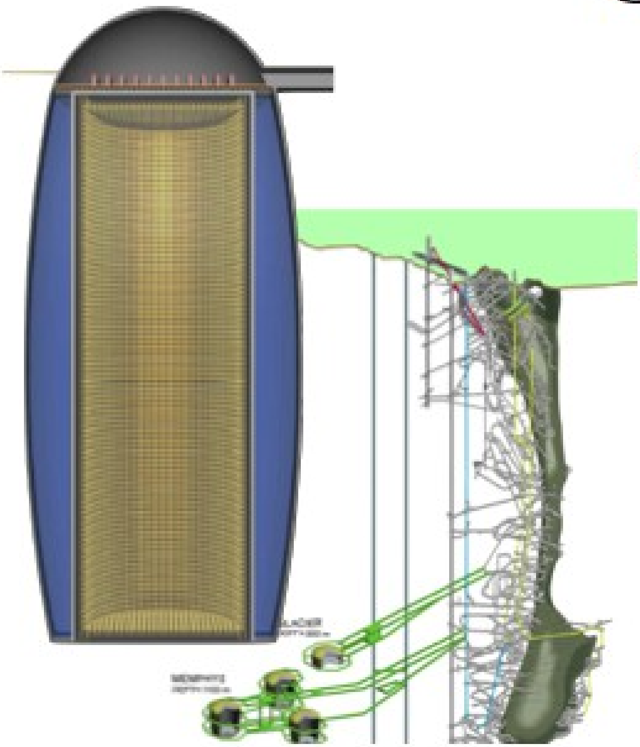
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

Transition	Rate (evts/day)
Fermi	31
Gamow-Teller	88



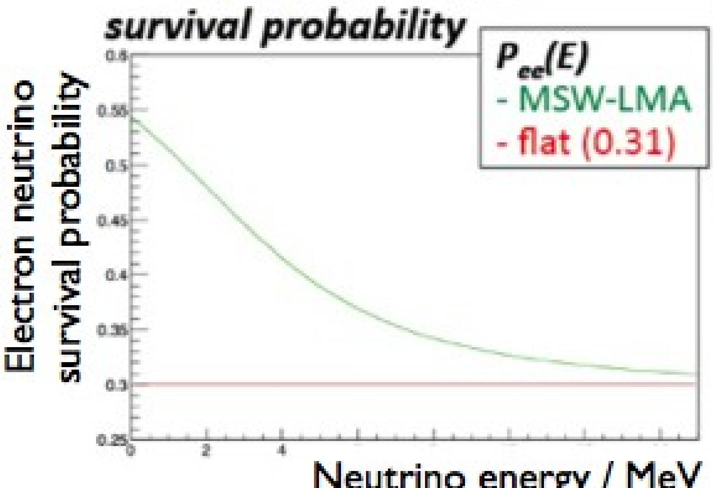
arXiv: 1307.7335

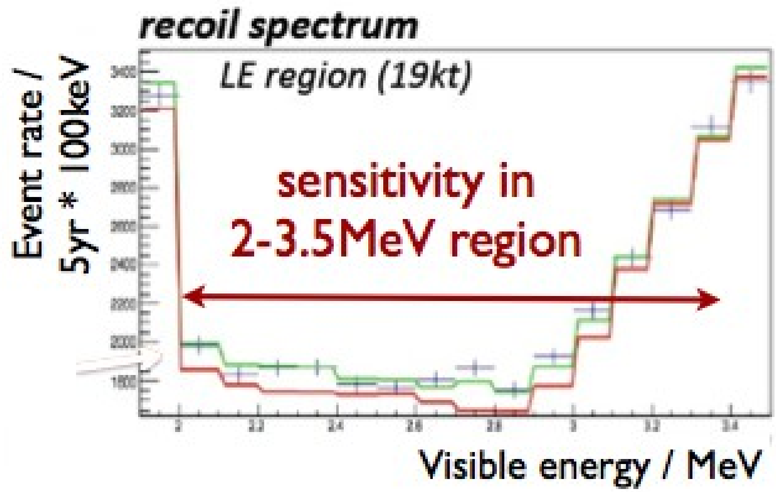
Low **E**nergy **N**eutrino **A**stronomy



Posters: Dr Bick, #84

- 50kT LS (30kT FV solar), 30% coverage
- Unprecedented statistics at low-energy
  - 3σ discovery potential for 0.1%-amplitude temporal modulations in ^{7}Be flux
  - CNO detection
  - Low-energy ^{8}B spectrum (+ CC on ^{13}C)

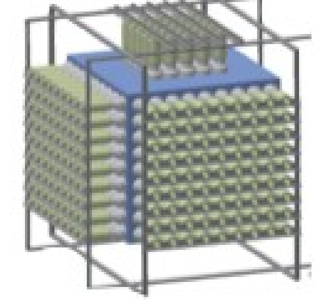




5σ after 3-5 years

M. Wurm, TAUP 2013

http://www.e15.ph.tum.de/research_and_projects/lena/

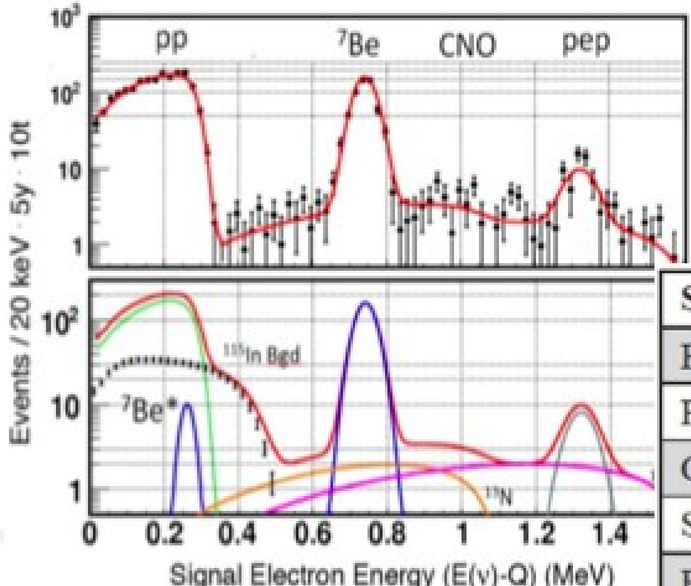


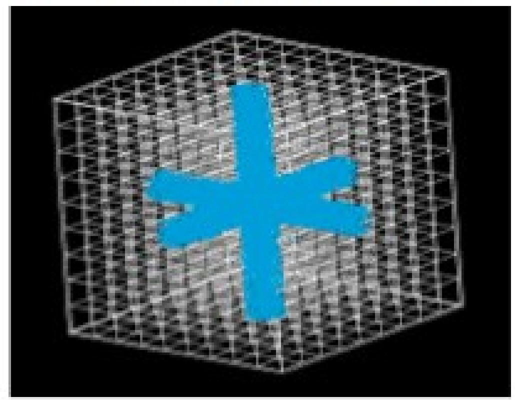
CC Detection: LENS

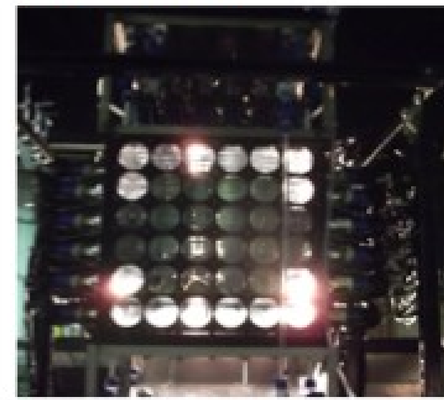
$$\nu_e + {}^{115}In \longrightarrow {}^{115}Sn^* + \beta^-$$

$$\tau = 4.76\mu s \hookrightarrow \gamma(115\text{keV}) + \gamma(497\text{keV}) + {}^{115}\text{Sn}$$

- Delayed triple coincidence helps reject ^{115}In bkg (need 10^{11} rejection)
- Q = 115keV : 95% of pp spectrum
- Segmentation helps reject ext bkgs







Source	pp	7Be	CNO* (GS98)	CNO† (AGSS09)
Flux (/cm2/s)	6.00E+10	4.70E+09	4.97E+08	3.74E+08
Flux (SNU) [Bah88]	468	116	15	11
Cross section[Rap85]	1.00E-44	2.50E-44	2.50E-44	2.50E-44
Survival probability	56	54	54	54
Rate (per ton year)	26	6.2	1.2	0.9
Rate (10 tons · 5 yr)	**1296**	**310**	**58**	**43**

Posters: Dr Yokley, #85

A "New" Idea for CC Detection

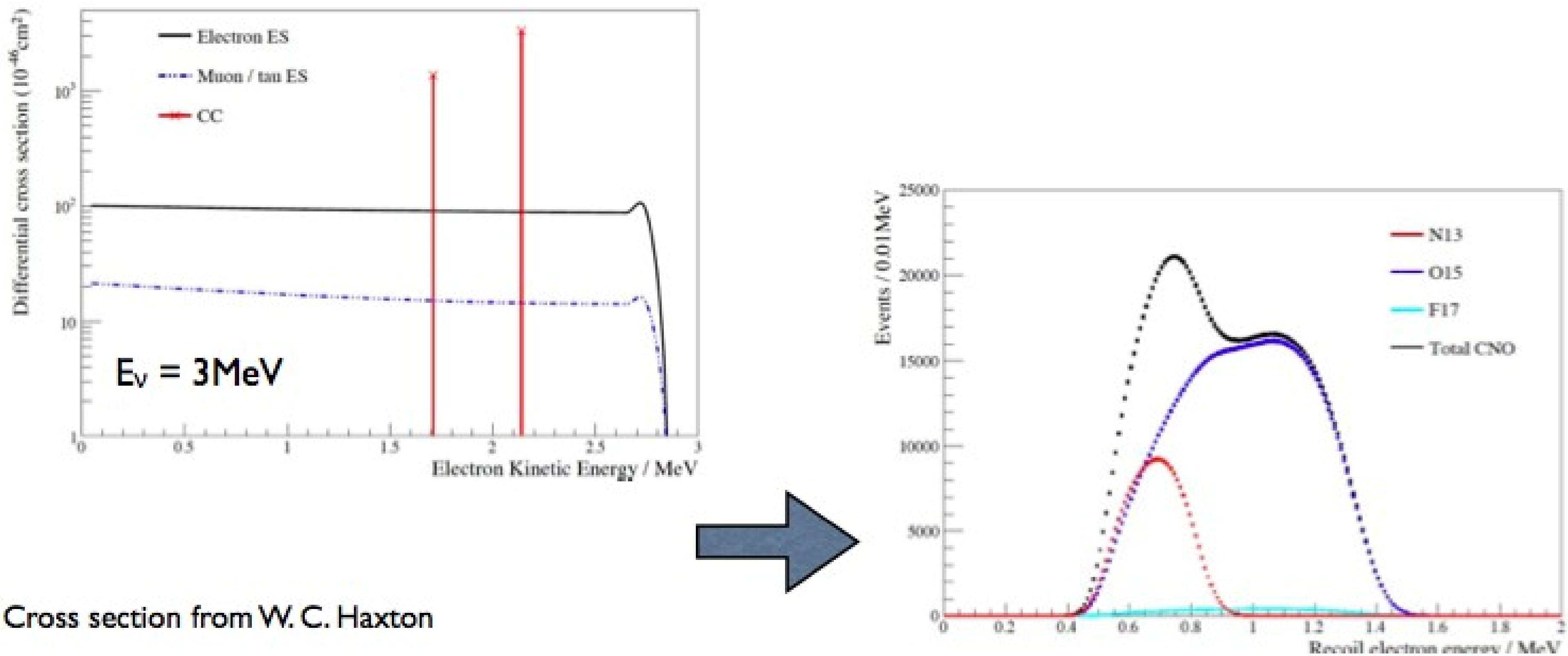
- Load large water Cherenkov detector with e.g. ^{7}Li for CC interaction

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

- Water Cherenkov ⇒ water-based LS

Phys. Rev. C 88 (2013) 065502

http://underground.physics.berkeley.edu/WbLSWorkshop.html



Cross section from W. C. Haxton

Siti di conferenze recenti

ICFA 2014: https://indico.in2p3.fr/conferenceOtherViews.py?view=standard&confId=8974

NEUTRINO 2014: http://neutrino2014.bu.edu/