Longbase Neutrino Physics

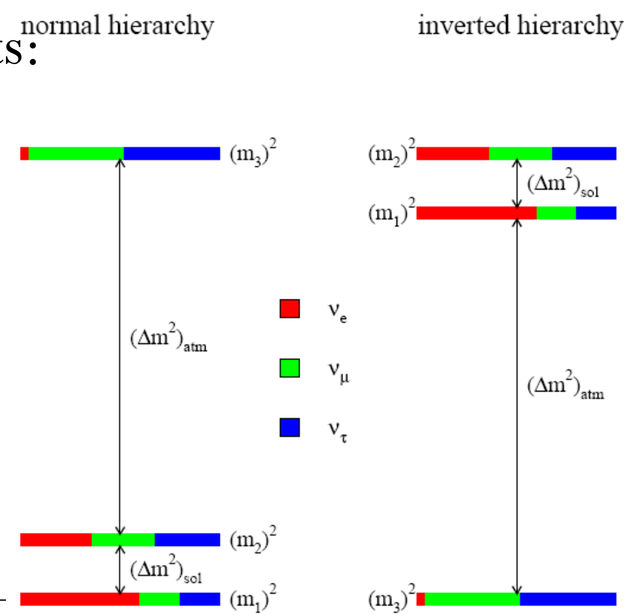
Neil McCauley
University of Liverpool
Birmingham February 2013

Neutrino mixing

- Neutrino mixing is characterised by the PMNS matrix.

$$\mathbf{U}_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \boxed{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

- Fundamental parameters of nature just like CKM
- Open questions for long baseline experiments:
  - Mass Hierarchy.
    - Either/or question.
    - Appears through matter effect.
  - CP Violating Phase δ
  - Mixing Angles θ_{13}, θ_{23} .
    - Octant of θ_{23}
    - Is θ_{23} maximal?



Oscillations and measurement

- Different oscillation channels are sensitive to different combinations of mixing parameters
  - In general we want to measure $P_{osc}(E_\nu)$

- Short Baseline Reactors: $p \sim \sin^2 2\theta_{13}$, Δm^2_{13}
  - Directly measure θ_{13}.
  - Solar term at longer baselines.

- Long Baseline: $p \sim \sin^2\theta_{23}\sin^2 2\theta_{13}$, Δm^2_{13}
  - Combination of mixing angles
  - Octant important.
- Corrections
  - Matter Term $\rightarrow$ sign of Δm^2_{13} , mass hierarchy.
  - CP Terms $\rightarrow$ CP Even and CP odd terms $\rightarrow$ CPV
  - Solar Term.

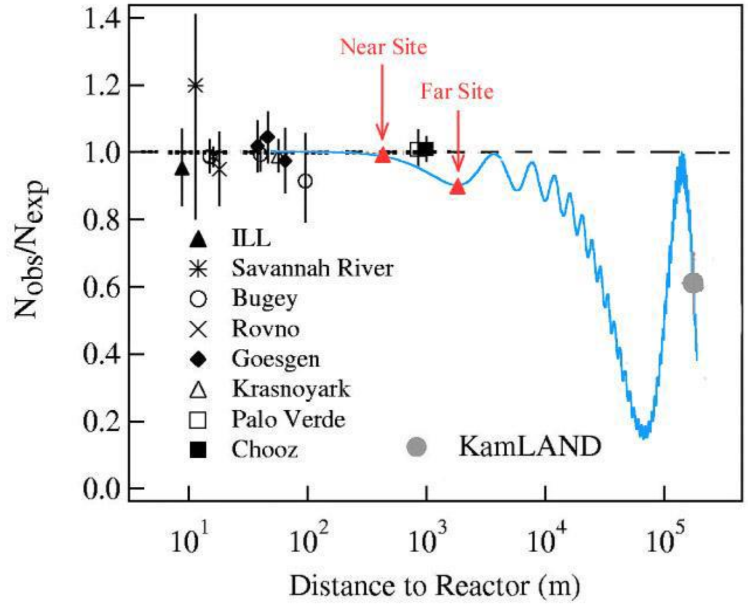
Current Status

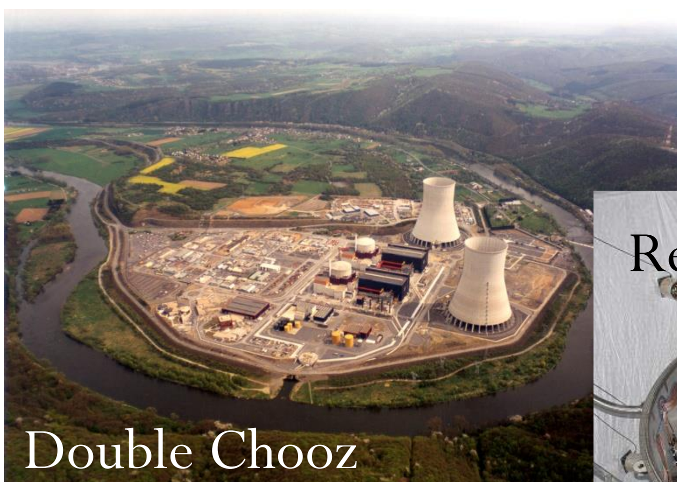
- Current programs first aim : θ_{13}
  - Gatekeeper to CP Violation and Mass Hierarchy
  - Knowledge of θ_{13} required to plan next stages of neutrino program.
  - Discovery of non-zero θ_{13} key development of the last 12 months.

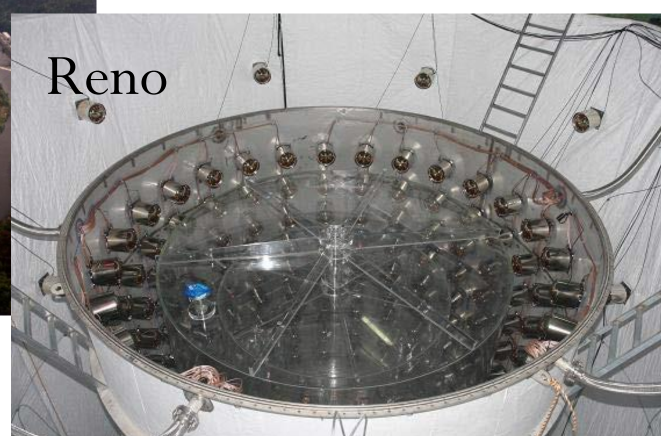
- Also aim to
  - Reduce uncertainties on other oscillation parameters
  - Start to test the 3 neutrino oscillation model

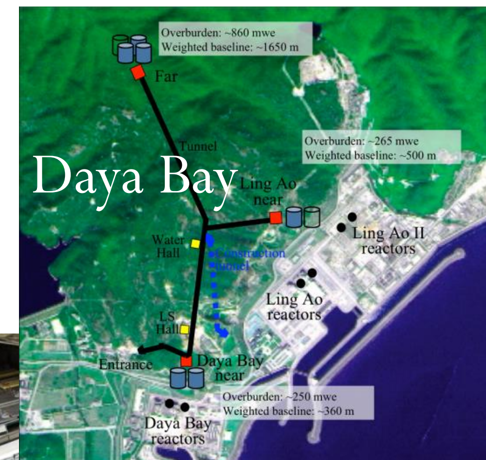
Reactor Experiments

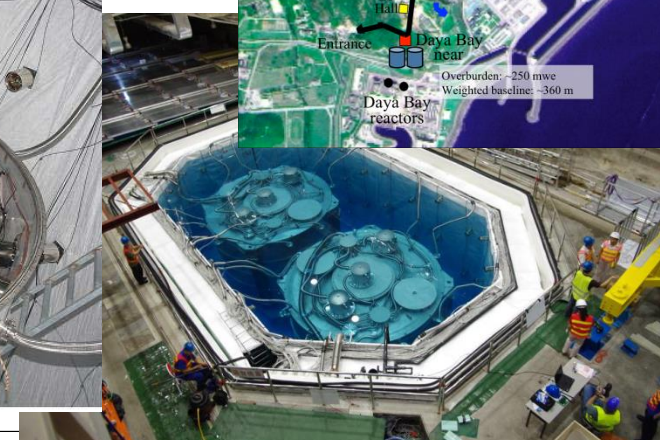
- Search for θ_{13} short baseline, disappearance mode.
  - $p(\overline{\nu}_e \rightarrow \overline{\nu}_e)$
- Clean measurement of θ_{13}, independent of other mixing parameters
  - Does require Δm^2 from long baseline experiments.





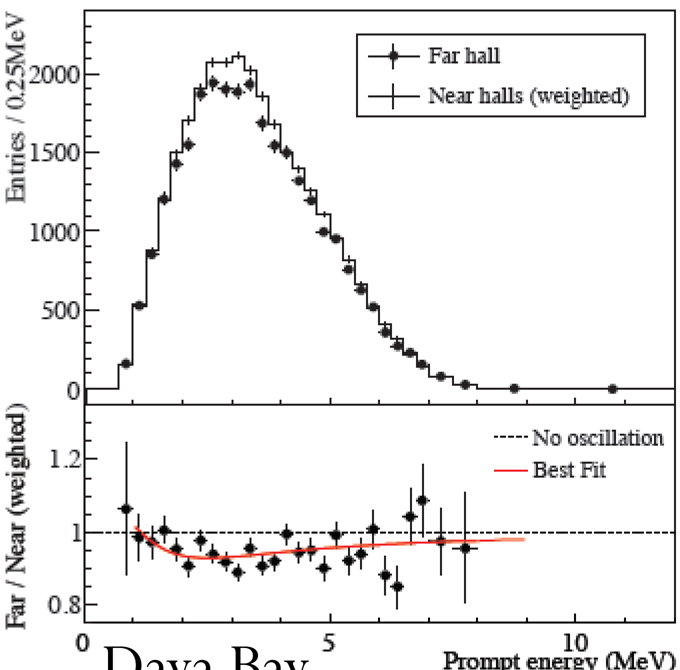




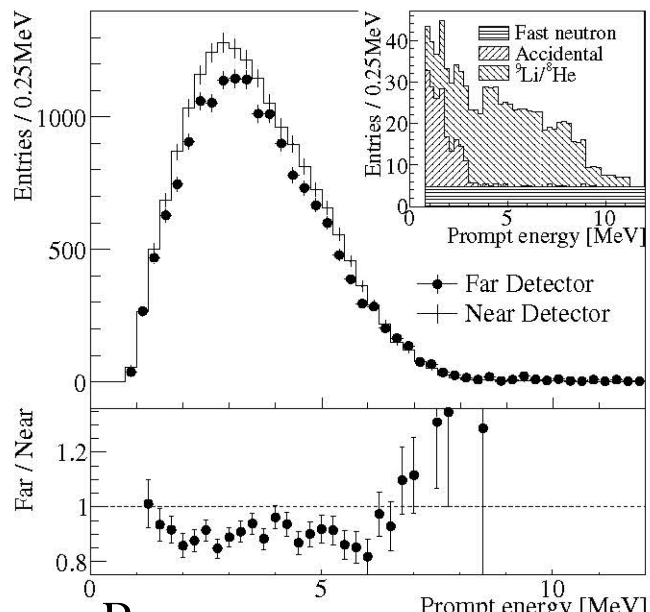


Results from Reactors

- Measurement of non-zero θ_{13}
  - Daya Bay : $\mathrm{Sin}^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst})\ 7.7\sigma$
  - Reno : $\mathrm{Sin}^2 2\theta_{13} = 0.113 \pm 0.013(\mathrm{stat}) \pm 0.019(\mathrm{syst})\ 4.9\sigma$



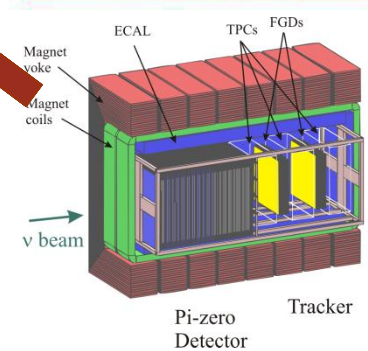
Daya Bay



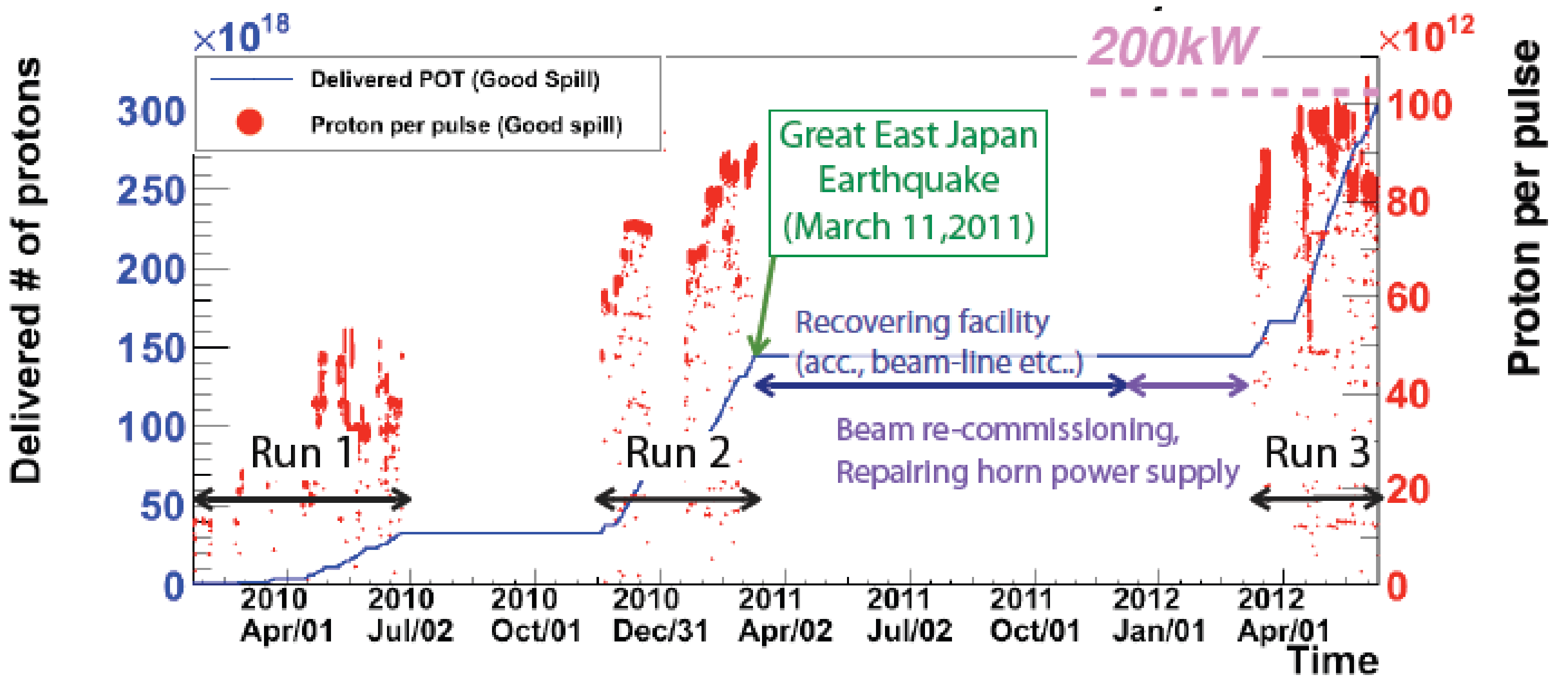
Reno

T2K Experiment

- 295km baseline
- Narrow band neutrino beam Epeak ~600 MeV
- First measurements using off-axis beam technique.



T2K Data



Run1 + 2 (2010-2011)
1.43×10^{20} p.o.t.

* ND280 Run1+2 data is used for oscillation analysis

Run3 (2012) : 1.58×10^{20} p.o.t

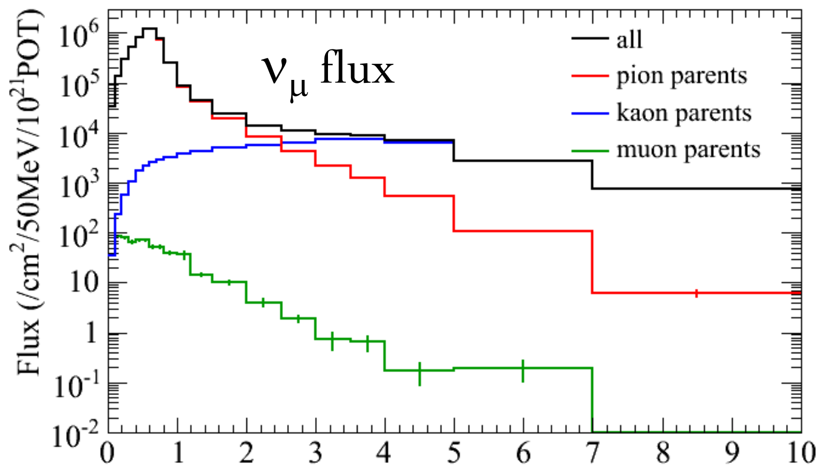
* including 0.21×10^{20} p.o.t. with 200kA horn operation (13% flux reduction at peak) (250kA horn current for nominal operation)

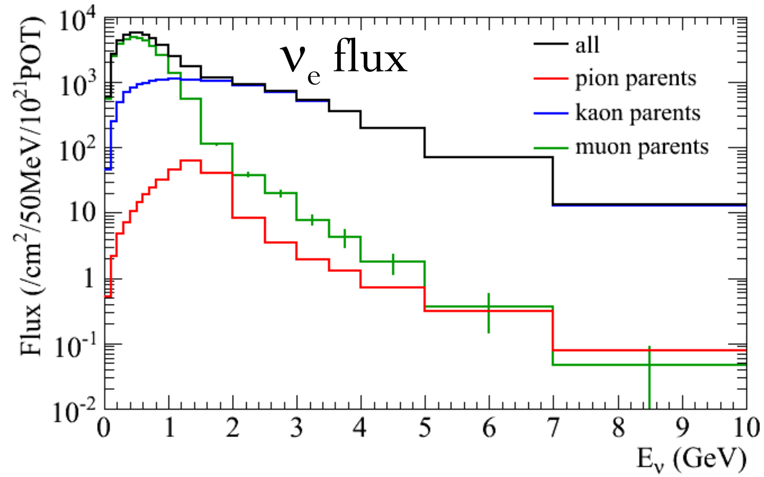
* ND280 Run3 data is checked and consistent with Run1+2

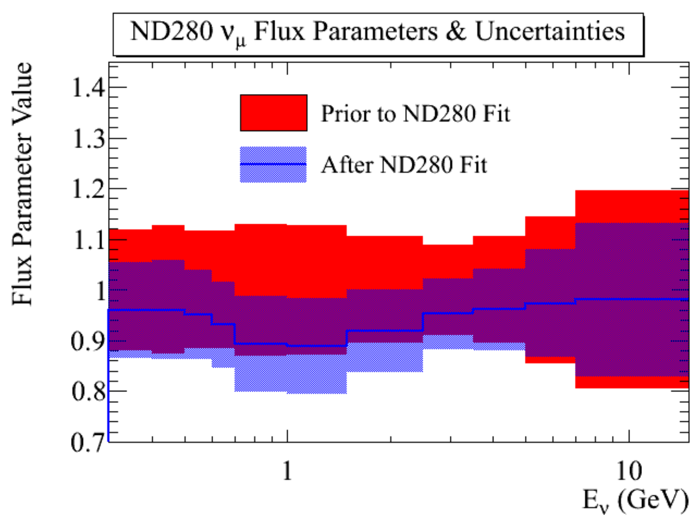
- T2K now running again and fully operational following the March 2011 earthquake.

T2K Flux

- Flux prediction from beam group
  - Includes hadron production constraints from NA61
- ν_μ interactions measured at ND280
  - Fit to reduce flux uncertainties and cross section constraints.

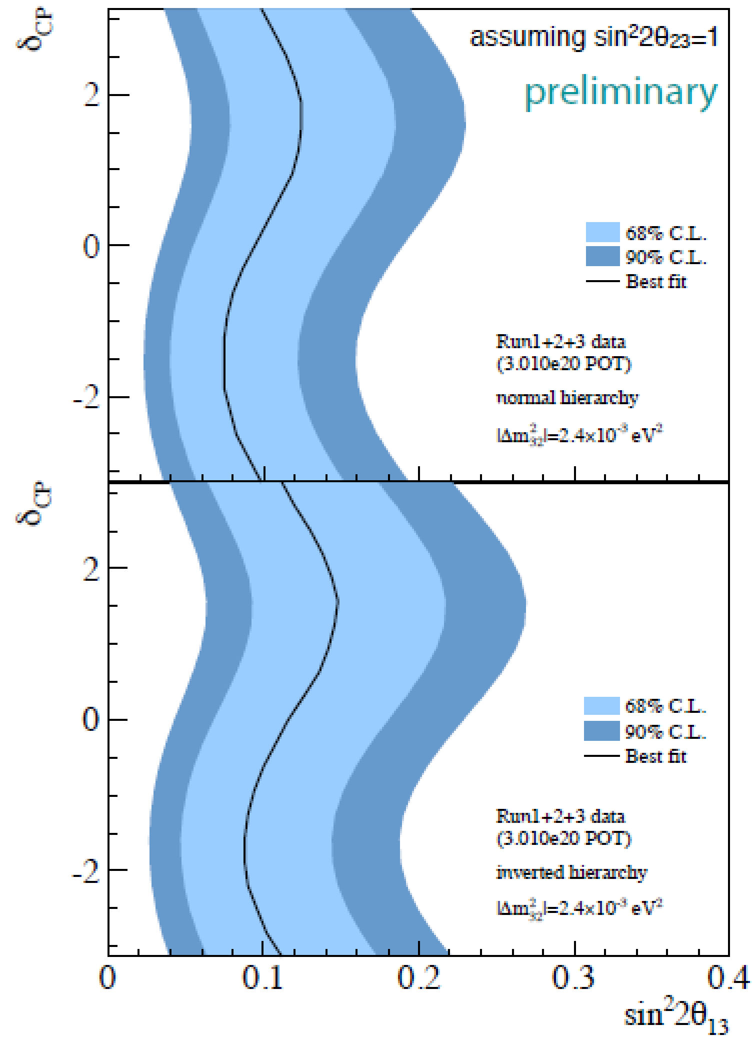


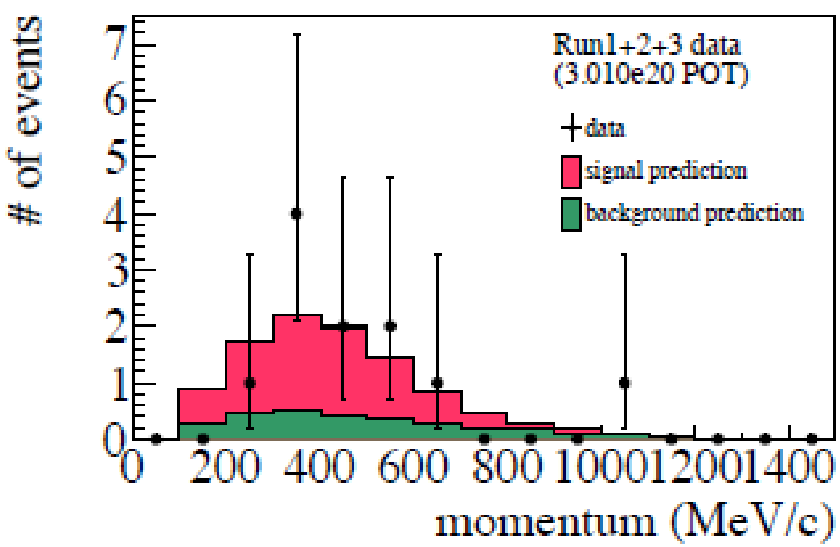


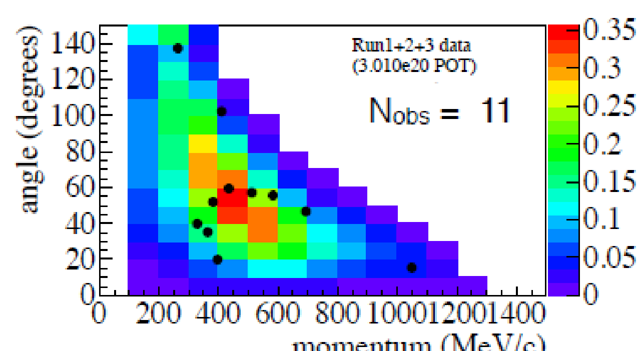


Detection of $\nu_\mu \rightarrow \nu_e$

- 11 events observed, 2.94 background expected
- Detection of θ_{13} at 3.2 σ.
- $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$
  - Normal Hierarchy, $\delta=0$

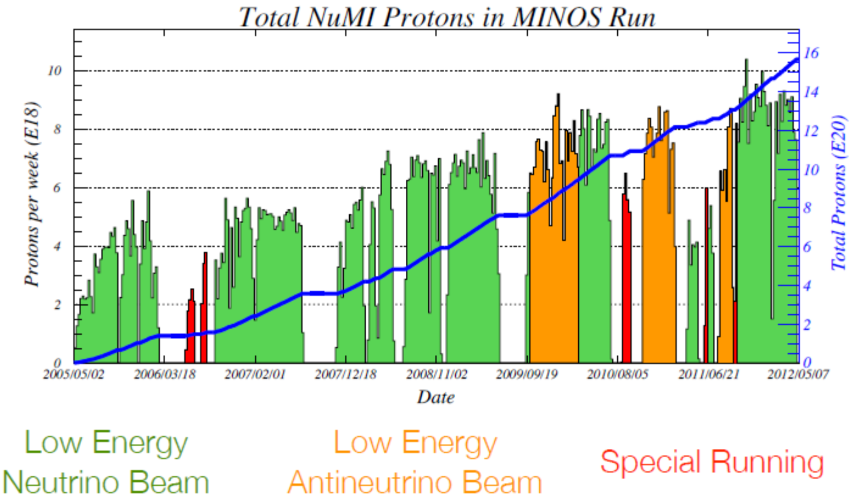


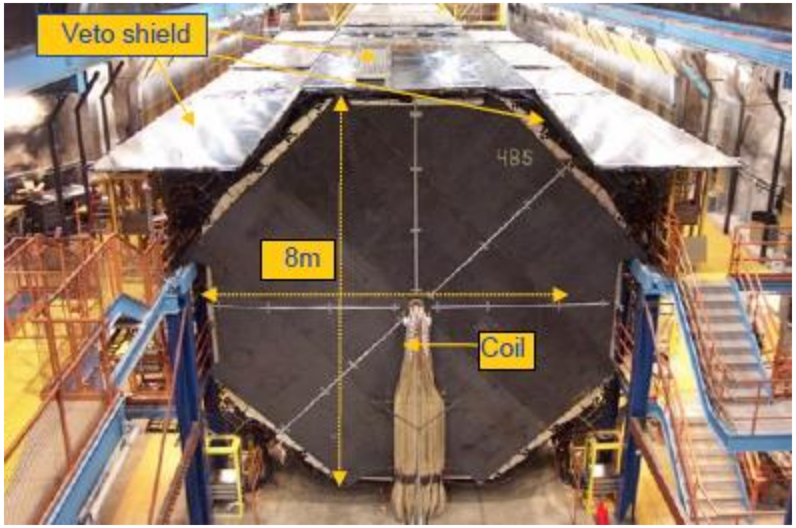




Minos

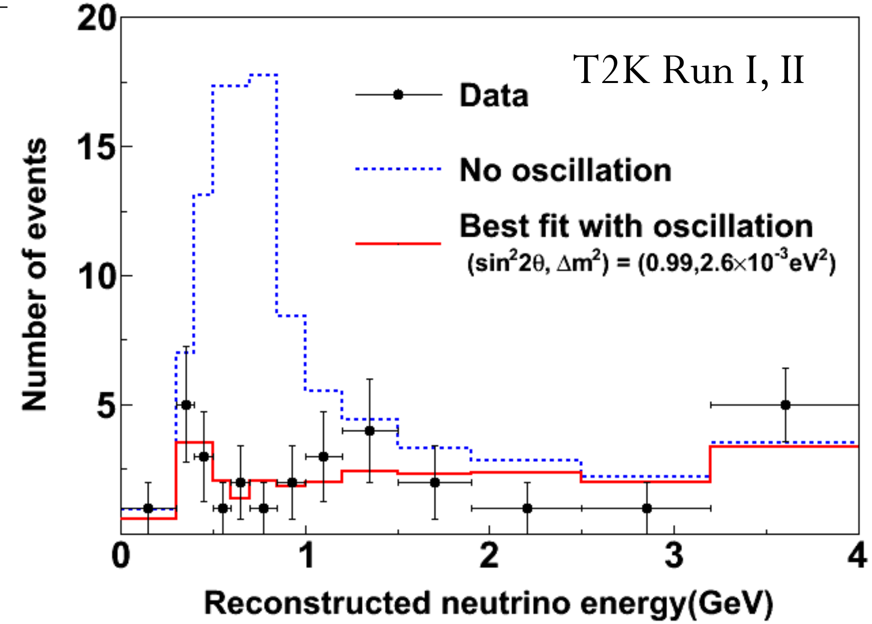
- 735 km baseline
- Uses NUMI beam in low energy configuration
  - Full dataset now collected.
- 5.4 kton magnetised iron calorimeter
  - 980 ton near detector

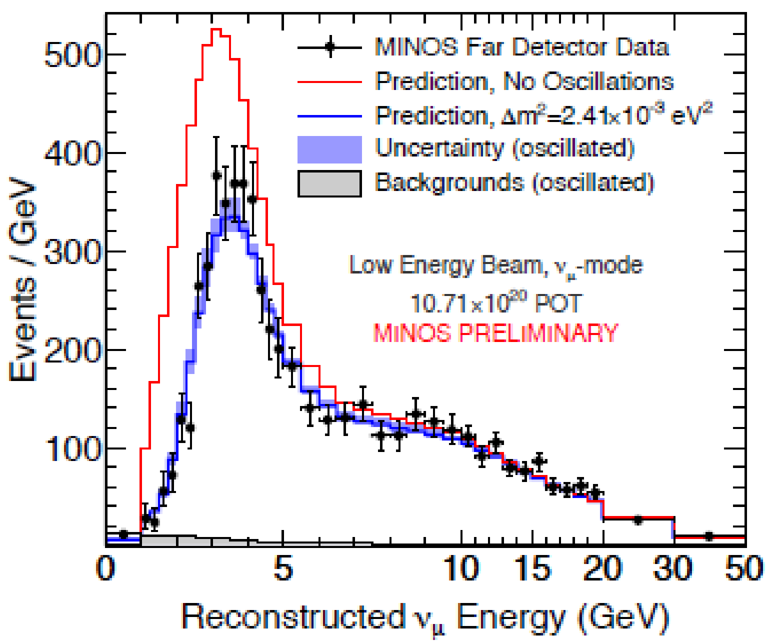


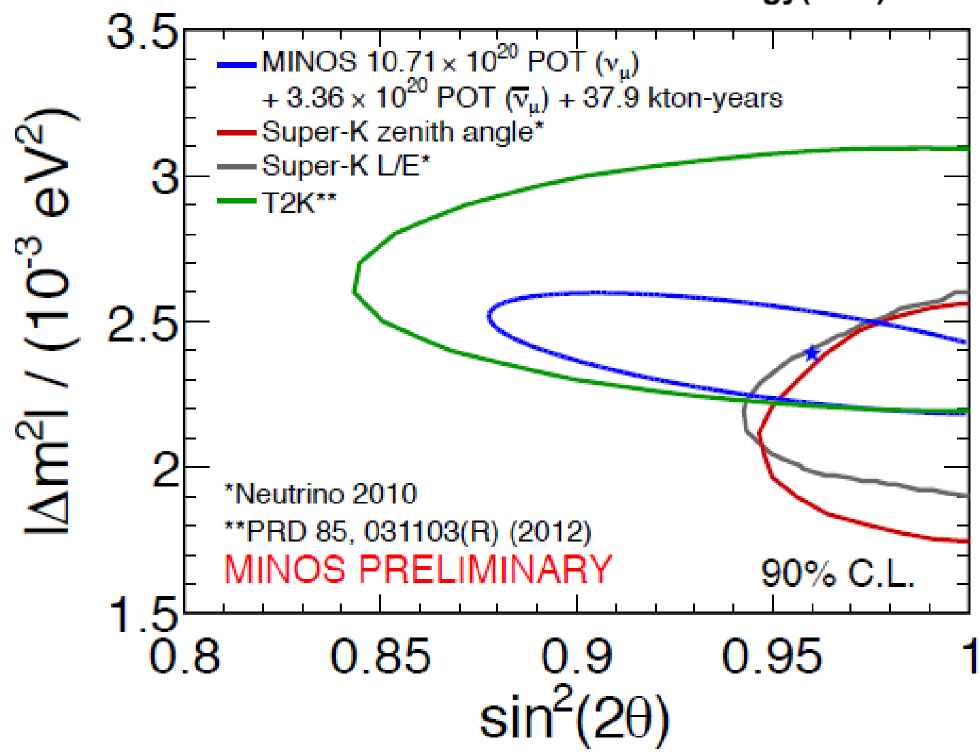


Measurements of θ_{23}

- Atmospheric neutrino results still very competitive.
- Crucial to improve measurement of θ_{23} as it appears with θ_{13} in long baseline probabilities.





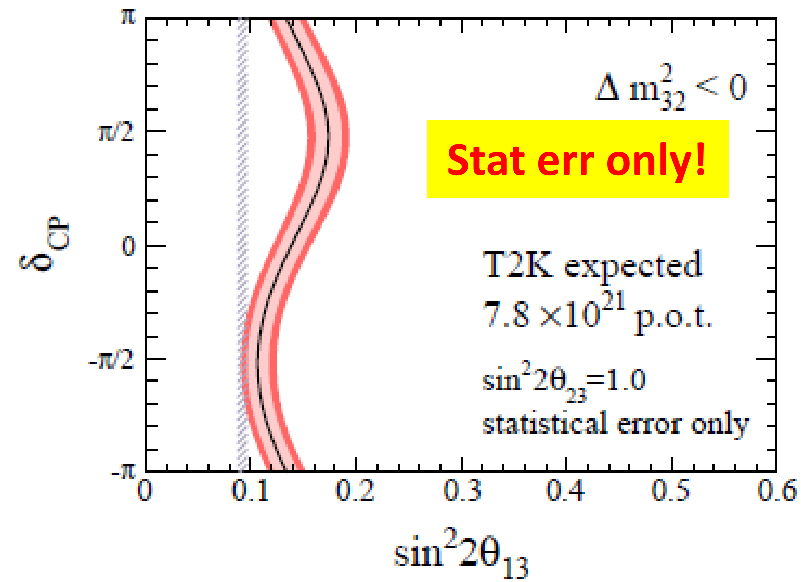


Long baseline experiments to ~2020

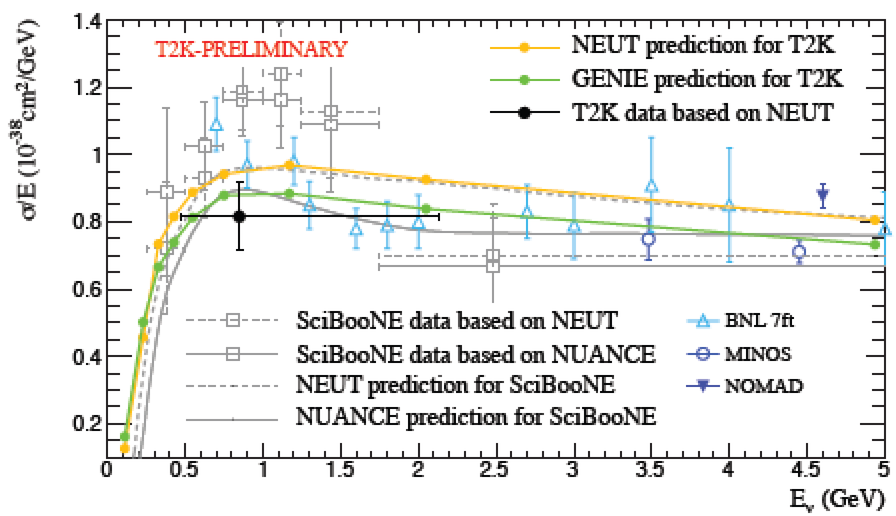
- For the next decade the neutrino community will be working to fully exploit existing neutrino beamlines:
  - JPARC-SK
  - NUMI
  - CNGS
- Improved measurements of θ_{13}, θ_{23} and Δm^2.
  - Requires reduction in systematics with better cross section measurements.
- Potential sensitivity to CP violation in some scenarios.

T2K Programme

- Plan to continue increasing beam power over the next 10 years.
  - Aim for 750kW by 2018
    - 400 MeV Linac upgrade in 2013 long shutdown (July-Dec).
  - Final target dataset 750kWx5x10^7s.
    - Current data ~ 5% of this.
- Significant reduction in error bars for θ_{13}, θ_{23} and Δm^2_{23}
- Program of cross section measurements with near detector.



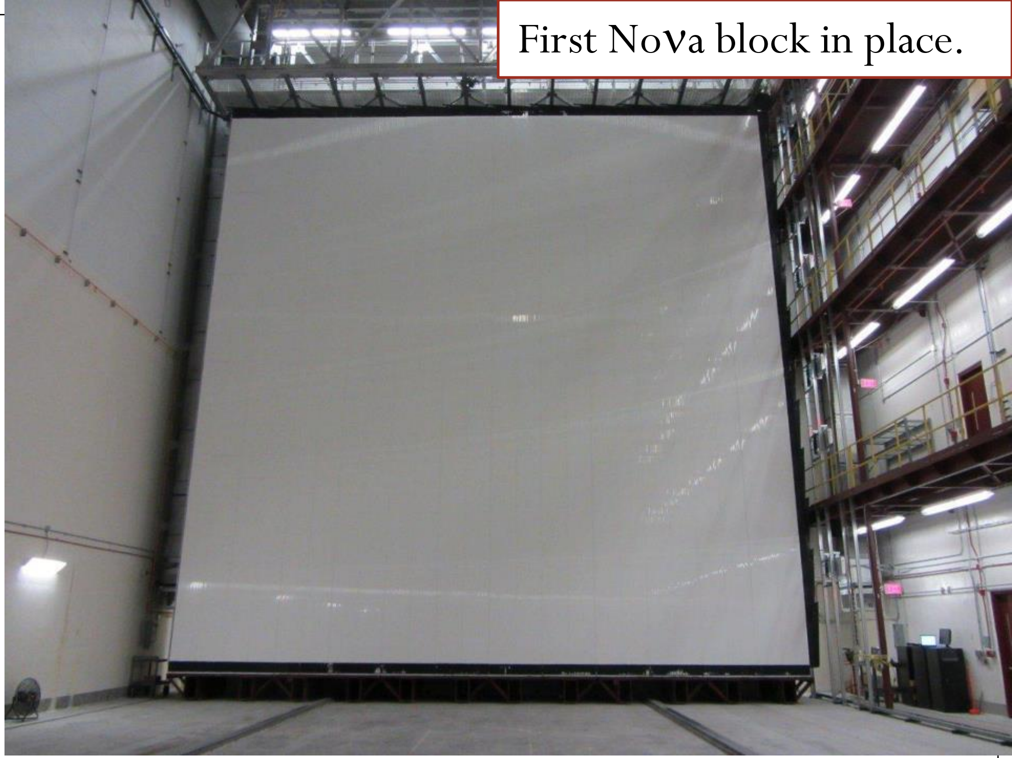
Expected beam power	May 2012	2014	2018
	190kW	300kW	750kW

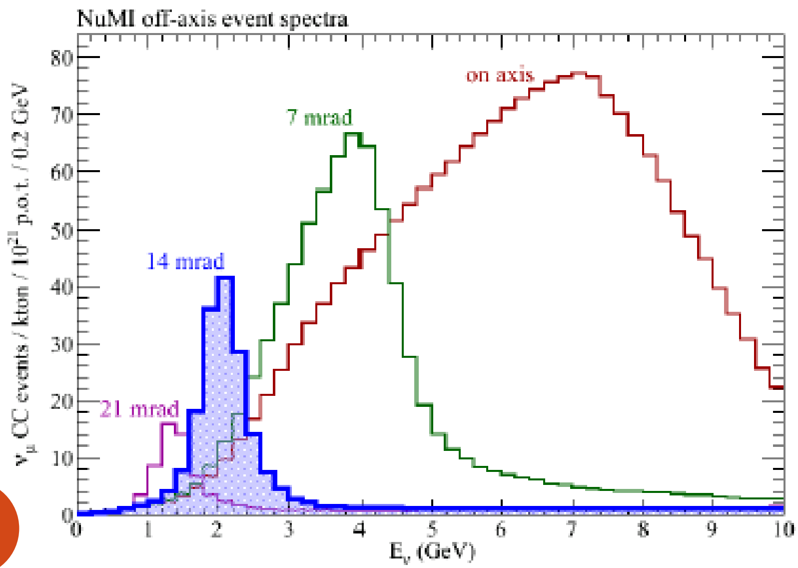


NOνA

- Continued exploitation of the NUMI beamline.
- 14 kt totally active scintillatior detector.
  - On surface.
  - Ash River Mn
- Baseline 810km
  - 14mrad off axis
- Beam power 350 kW → ~700kW

First Noνa block in place.

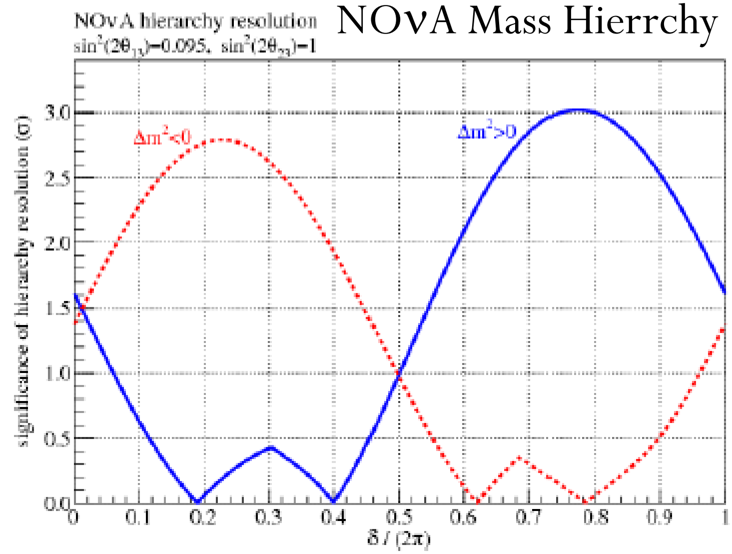




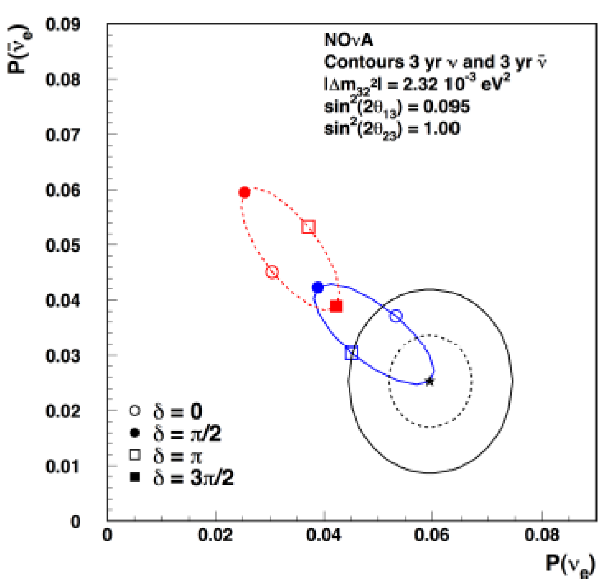
NOνA physics reach

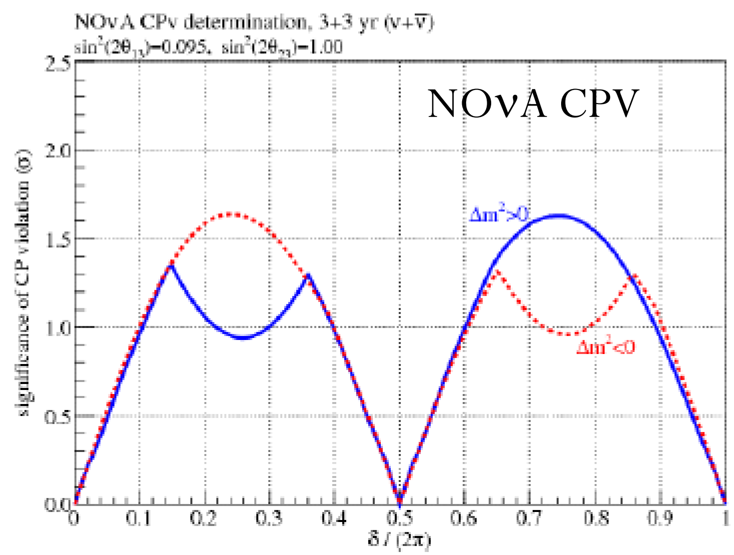
- Assume 3 yr ν/ 3 yr antiν.
- Potential for 5σ νe appearance in first year
- Investigate mass hierarchy, CPV and θ_{23} including octant in course of run.

NOνA Mass Hierrchy



1 and 2 σ Contours for Starred Point

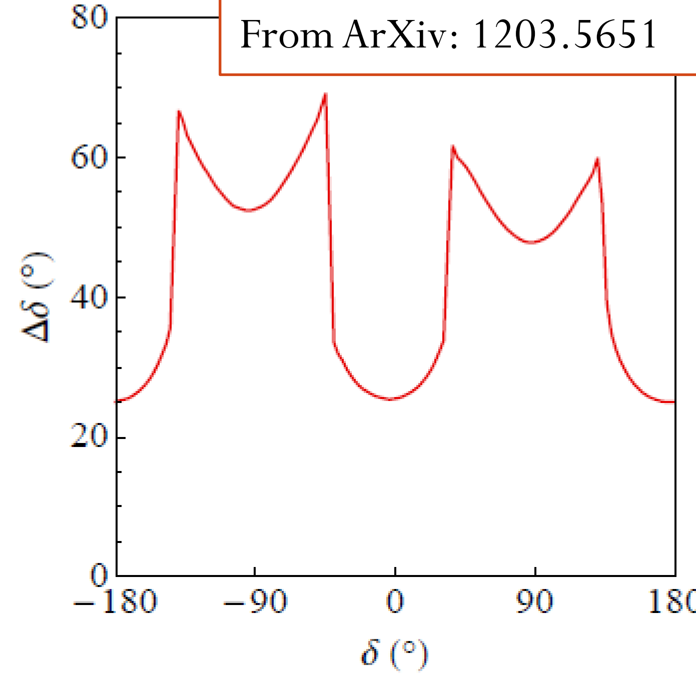




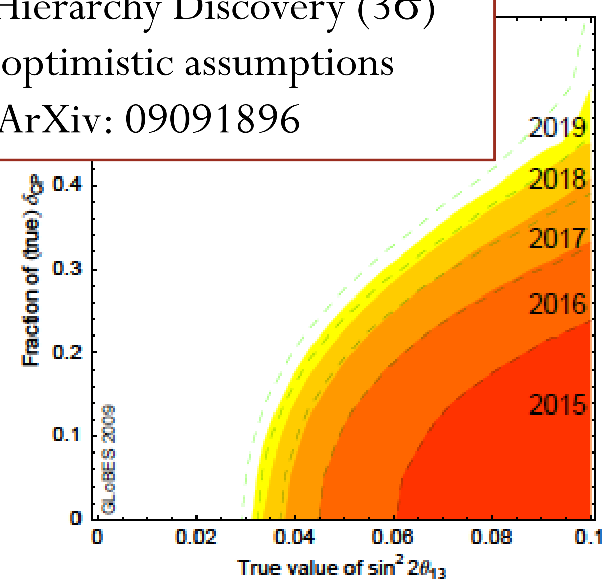
Combining Results

- In many ways T2K and NOνA complement each other.
  - Different matter effects
  - Can help resolve ambiguities in the parameters and improve sensitivity to mass hierarchy and CPV.
  - Reactor experiments also contribute.
- Health warning:
  - Global fits be necessity assume the 3 neutrino mixing model.

Potential error on δ
From ArXiv: 1203.5651



Mass Hierarchy Discovery (3σ)
Some optimistic assumptions
From ArXiv: 09091896



Future long baseline experiments

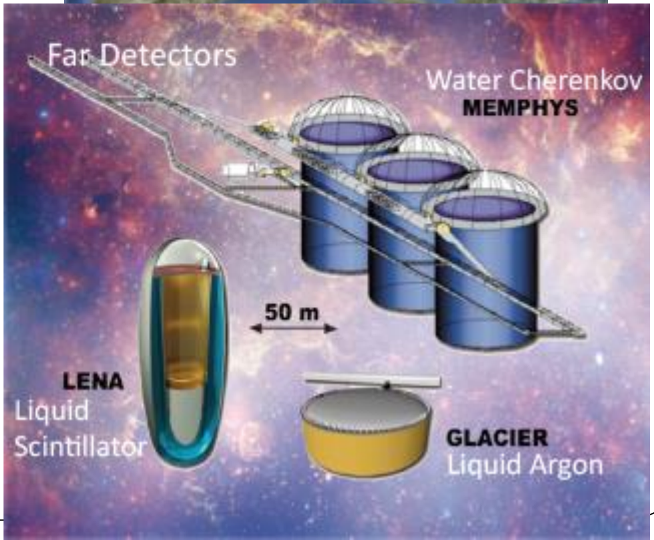
- The recent discovery of θ_{13} has crystallised the effort in the planning of the next generation of experiments.

- The following proposals are the culmination for a decade of work exploring new ideas and technologies.

- Next Generation experiments to:
  - Determine mass hierarchy, aim for 5σ precision.
  - Maximise sensitivity to CP violation.
  - Test the standard picture of 3 generation mixing.
  - Aim for a complementary broad physics program with astrophysical neutrino and proton decay measurements.

The European Option: LAGUNA-LBNO

- European design study to investigate future long baseline experiments and large underground facilities.
- LAGUNA 2008-2011
  - Detailed investigation and engineering of 7 sites across Europe
  - Detector technologies and capabilities.
  - > 1000 pages of documentation produced.
- LAGUNA-LBNO 2011 -
  - Continued investigation and planning of 3 sites for long baseline neutrino experiments.
  - Pyhäsalmi Glacier, LENA
  - Frejus : Mephys
  - Further exploitation of CNGS.



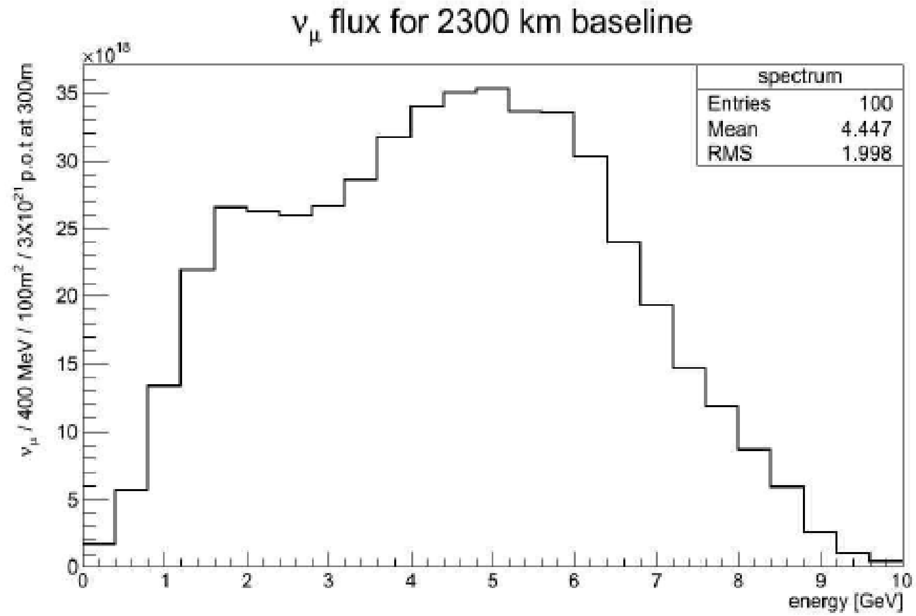
CERN-Pyhäsalmi

- Neutrino beam from SPS
  - 500kW
- Far site to host
  - 20kT double phase liquid argon TPC Glacier
  - 50kT magnetised iron calorimeter MIND.
- Resolve first and second oscillation maxima
  - Increases CP sensitivity
  - Test of oscillations
- Large distance
  - Spectacular matter effect!

2100 km from RAL, 1500 km from DESY, and 1160 km from Protvino.

The Beamline

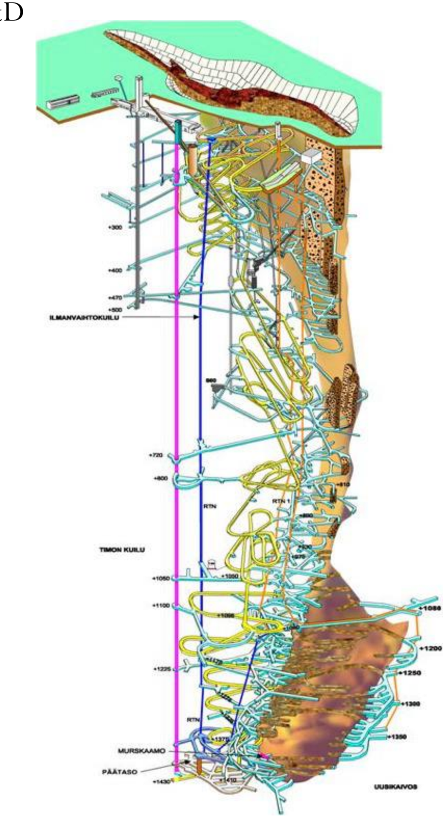
- CERN already has the most powerful neutrino beam
  - CNGS 500kW
  - Natural starting point for design
- Relatively short tunnel (300m) but 10º dip angle.
  - Target station and tunnel in NA.
- Potential improvements with upgrades for HL-LHC
  - Studies on going at CERN.
- Number of upgrade paths
  - SPS upgrades – 700 kW
  - New accelerator HP-PS 2MW



The mine at Pyhäsalmi

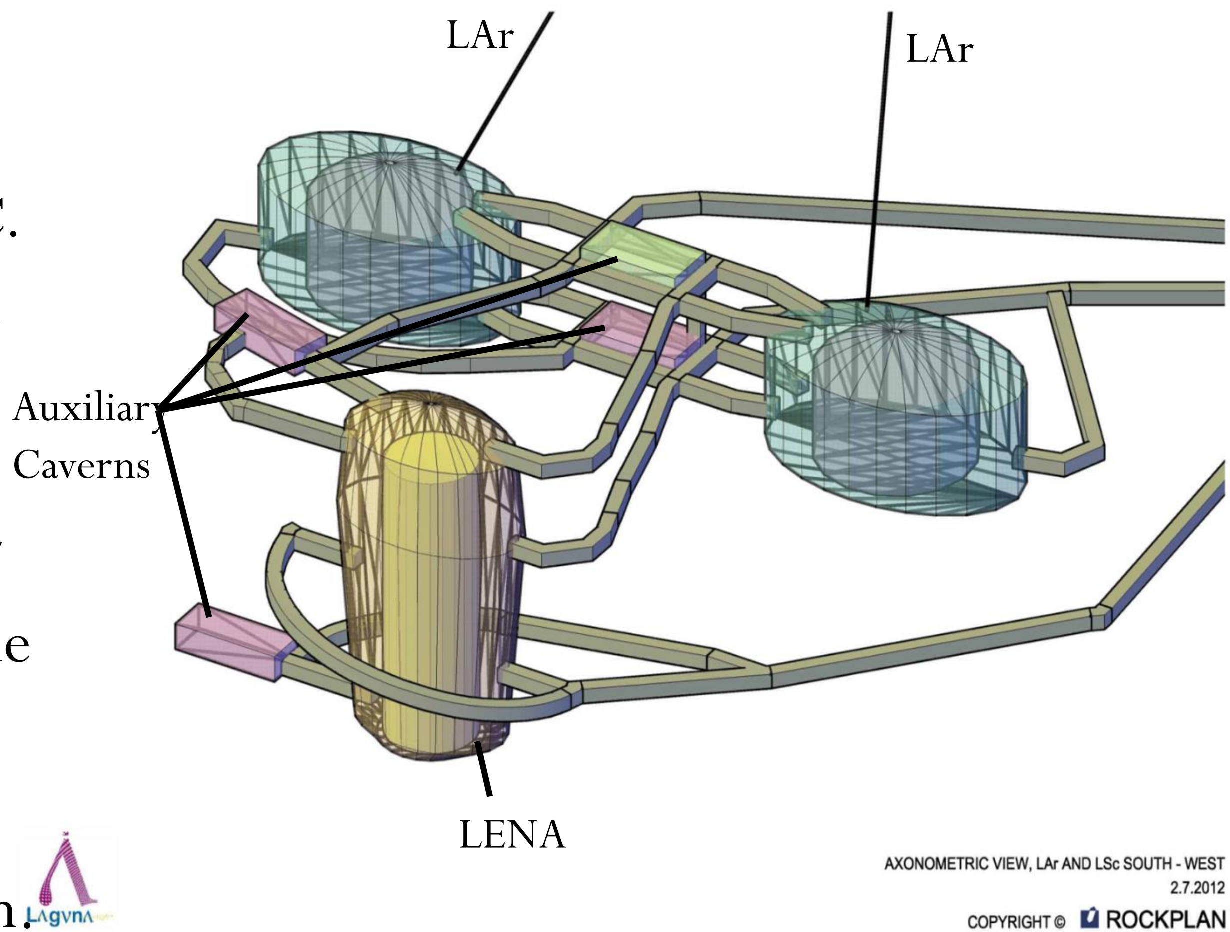
- Deepest mine in Europe
  - Depths to 1400 m possible
  - Produces Cu, Zn and FeS_2
- Currently a working mine
  - Reserves until 2018
  - Chance to take over this infrastructure
- Access underground via 11km tunnel and via shaft.
- Distance via road
  - Oulu – 165 km
  - Jyväaskylä – 180 km
  - Helsinki 450 km
- Strong support from Finland
  - €1.6 m for site investigation
  - Further high level discussions on going

250 m long tunnel and a cavern at 1400 m excavated for LAGUNA R&D



Possible Underground Layout

- Space for
  - 2x50 kton LAr TPC.
  - 50 kton magnetised iron calorimeter
  - 50 kton liquid scintillator detector
- Proposed site in mine at 1400m depth
- Area now under detailed investigation.

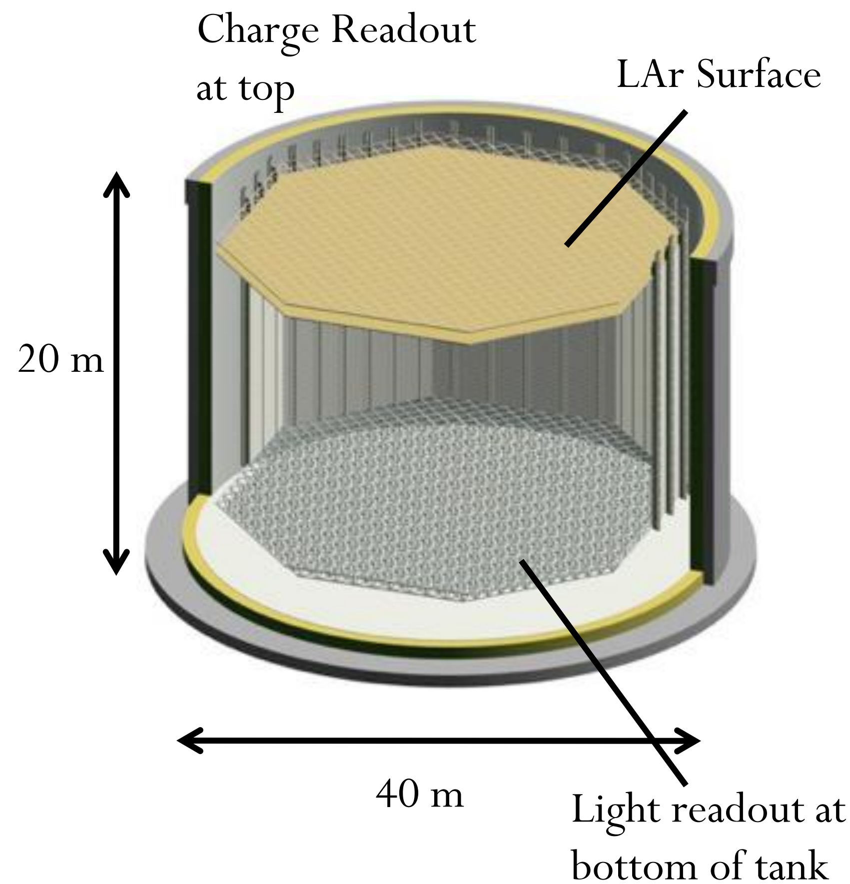


Far Detector Options

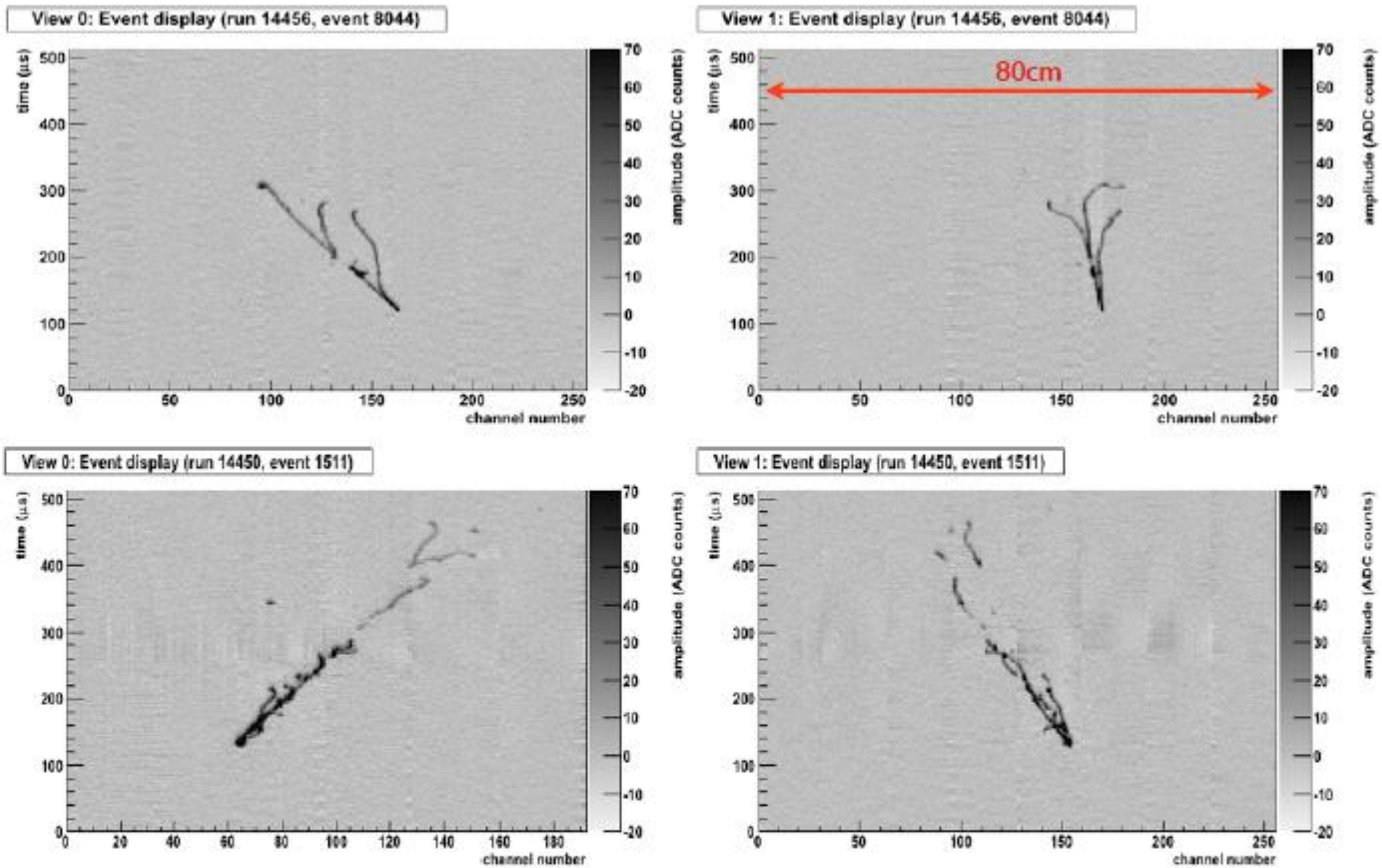
- To fully exploit the beamline the far detector must have the following capabilities:
  - Must be scalable to the large masses required.
  - Must be able to distinguish electrons and muons
  - Must be able to reconstruct many tracks at once
  - Should have excellent energy resolution.
- To achieve this we study as many possible technologies as possible
  - Combinations of detectors to give best results?
- Note water Cherenkov does not meet these criteria.

Glacier

- 20 kton double phase LAr LEM TPC.
  - Very fine grained tracking calorimeter
- Best detector for
  - Electron appearance
  - Reconstruction of multiple tracks from high multiplicity events.
- Excellent ν energy reconstruction.
- Low energy threshold for all particles



Events in LAr

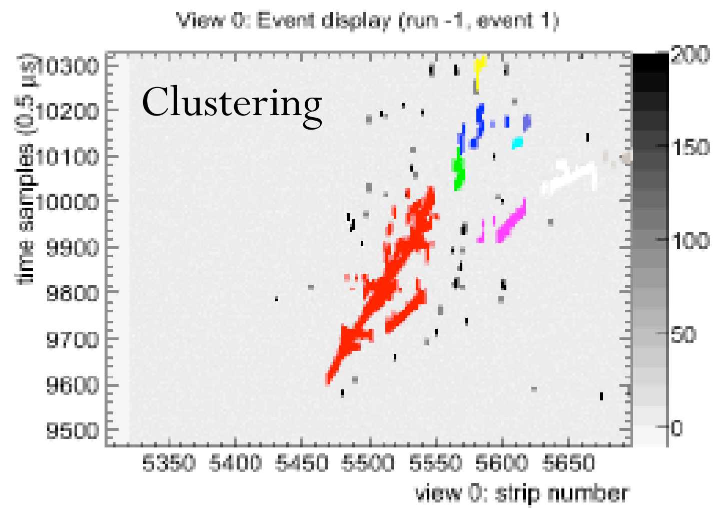


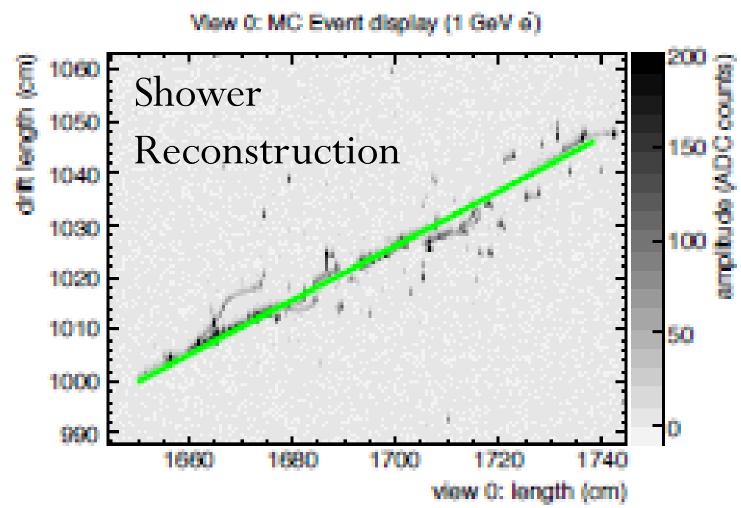
Cosmic track in 80 cm X 40 cm double phase test detector

MIP S:N >100

Reconstruction in Liquid Argon

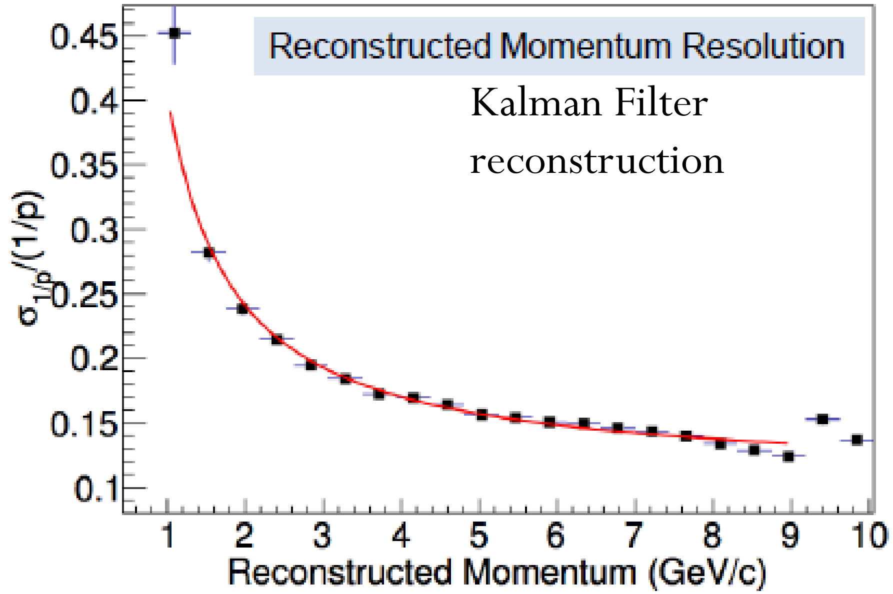
- Studies underway to simulate LAr TPC and to reconstruct the events.
- QSCAN software provides testbed for simulation and reconstruction tools.

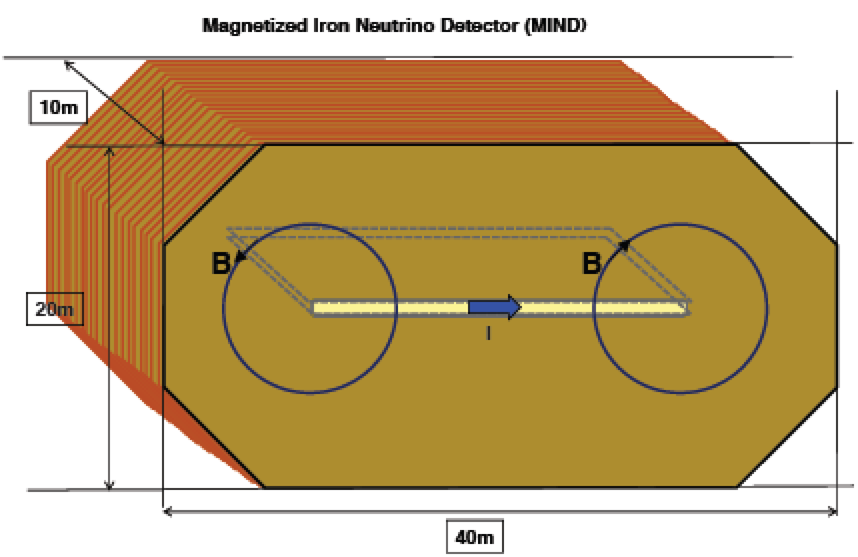




MIND

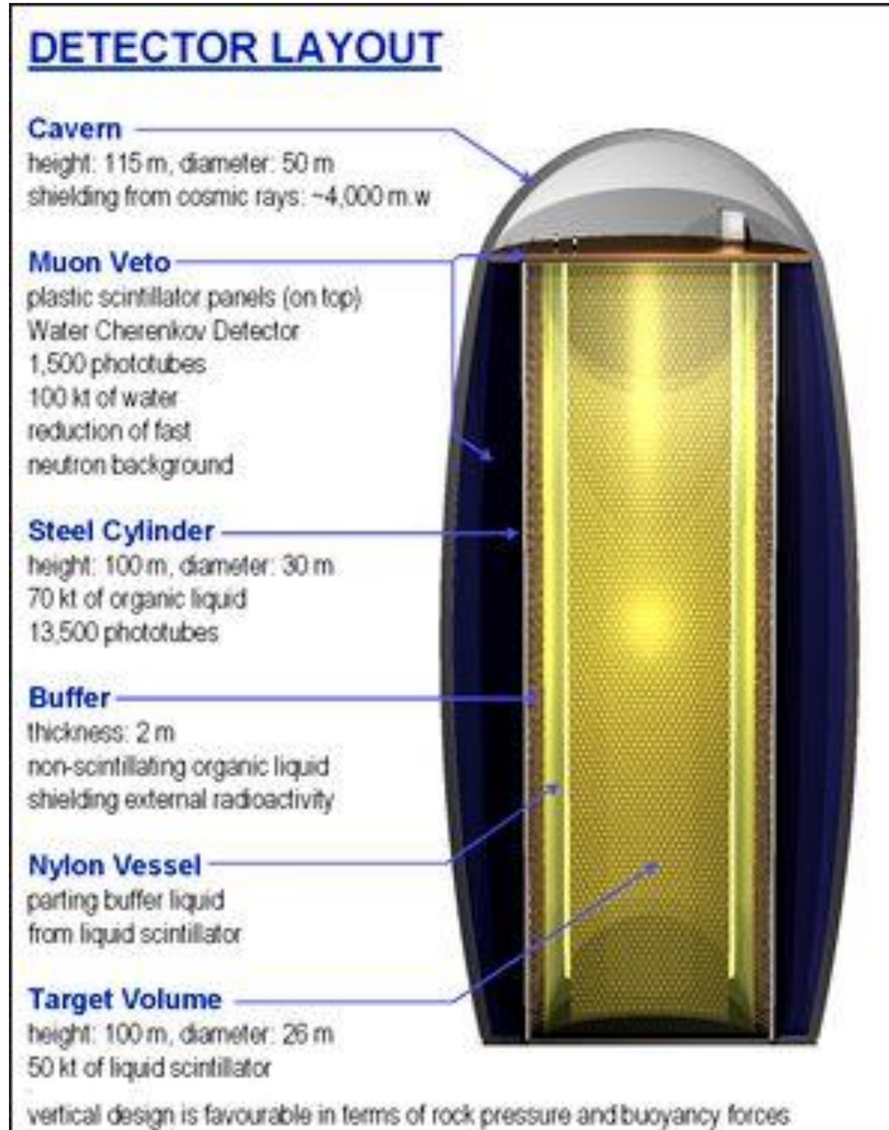
- Magnetised Iron Calorimeter
  - Similar to MINOS
  - Well proven technology
- 3cm Fe Plates, 1cm Scintillator Bars
- B= 1.5-2.5 T
- Measurement of muon momentum distribution and total neutrino energy.
- Excellent Charge determination
  - Ideal far detector for future neutrino factory.



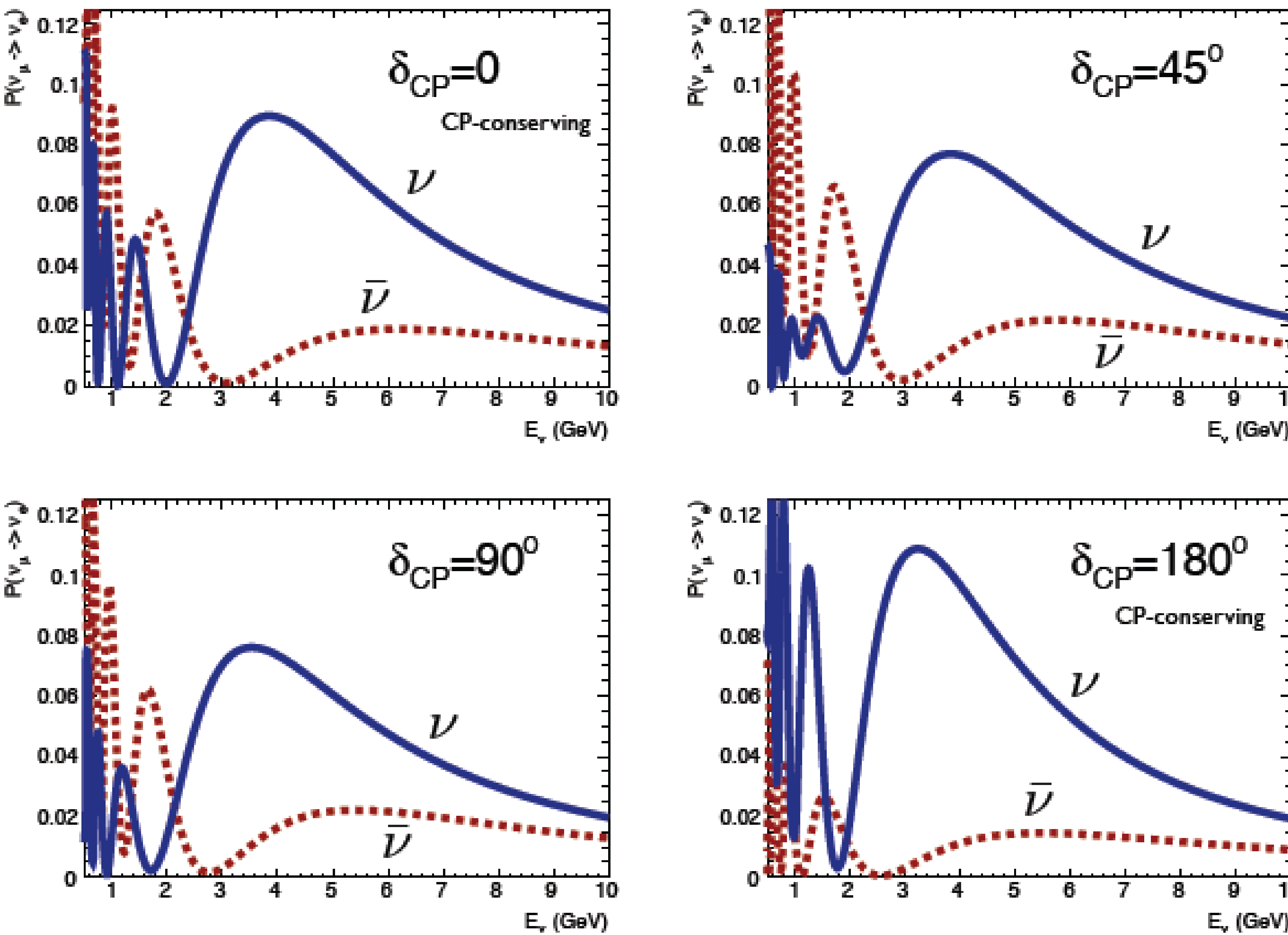


LENA

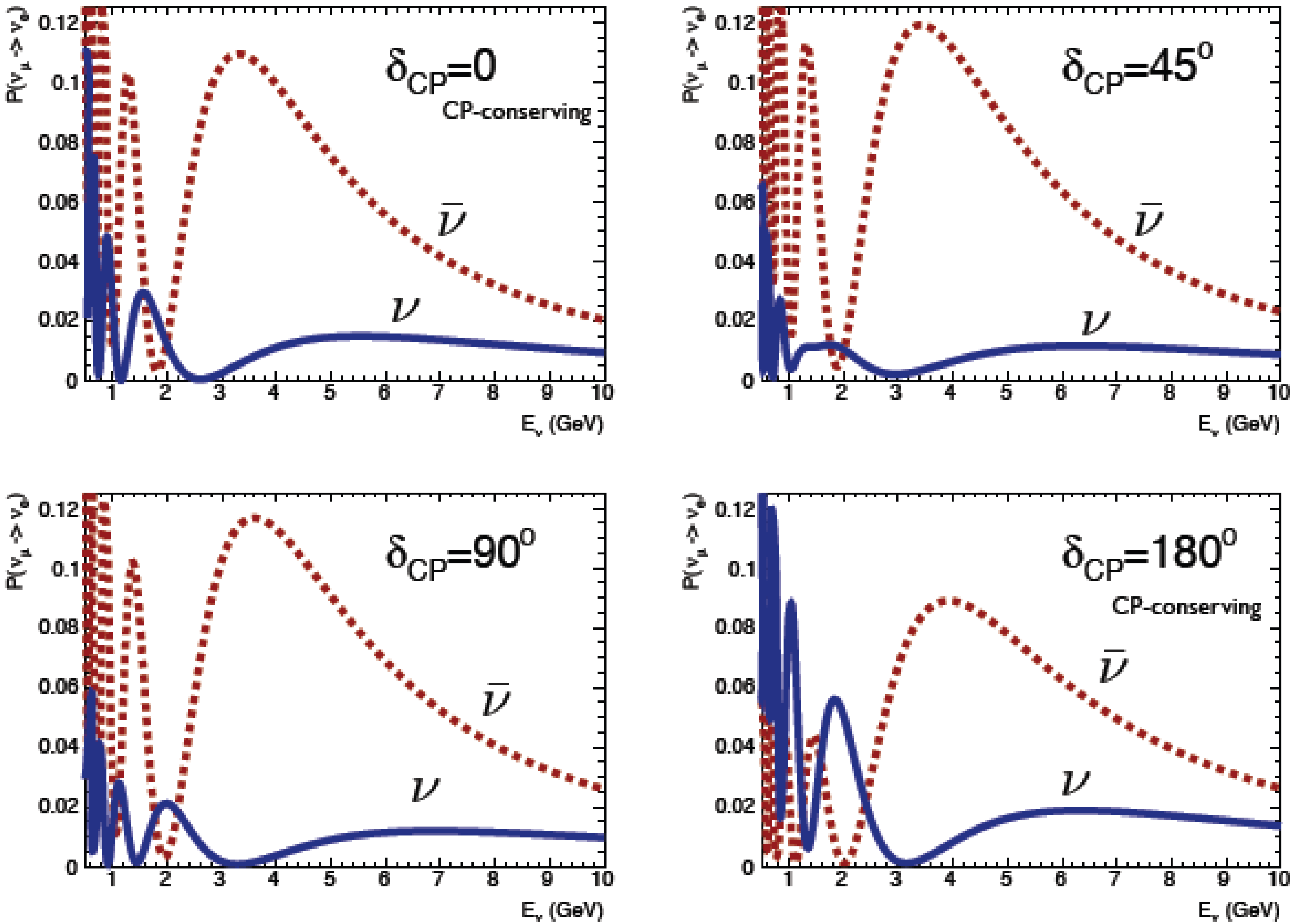
- Liquid Scintillator detector
  - Proven technology, scaled up.
- As well as beam measurements rich physics program
  - Solar neutrinos
  - Supernova neutrinos
  - Atmospheric neutrinos
  - Proton Decay
- Target : 100m high x 26m diameter
  - 50 kton
- 45000 8" PMTs



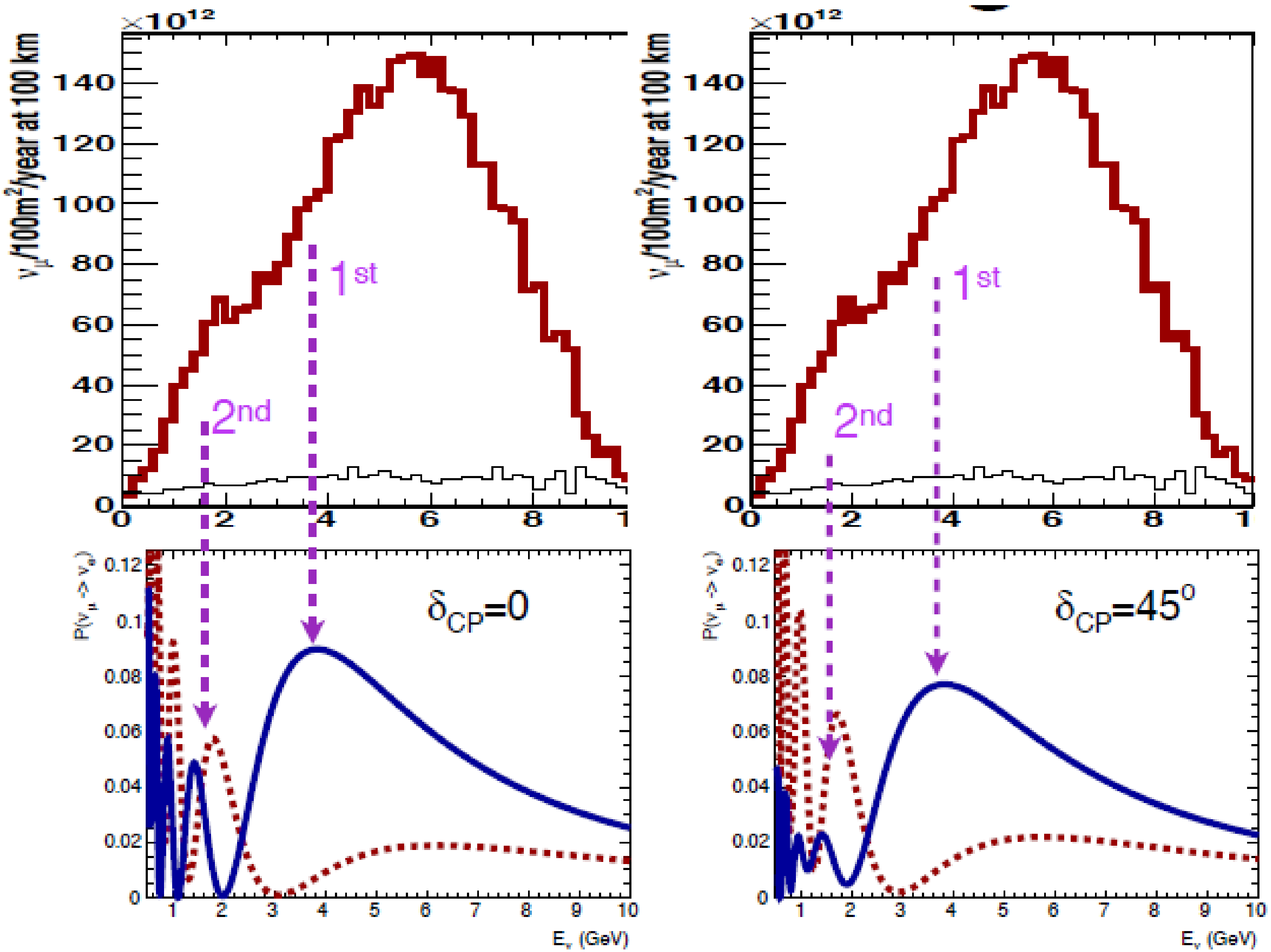
Signals at Pyhäsalmi : Normal Hierarchy



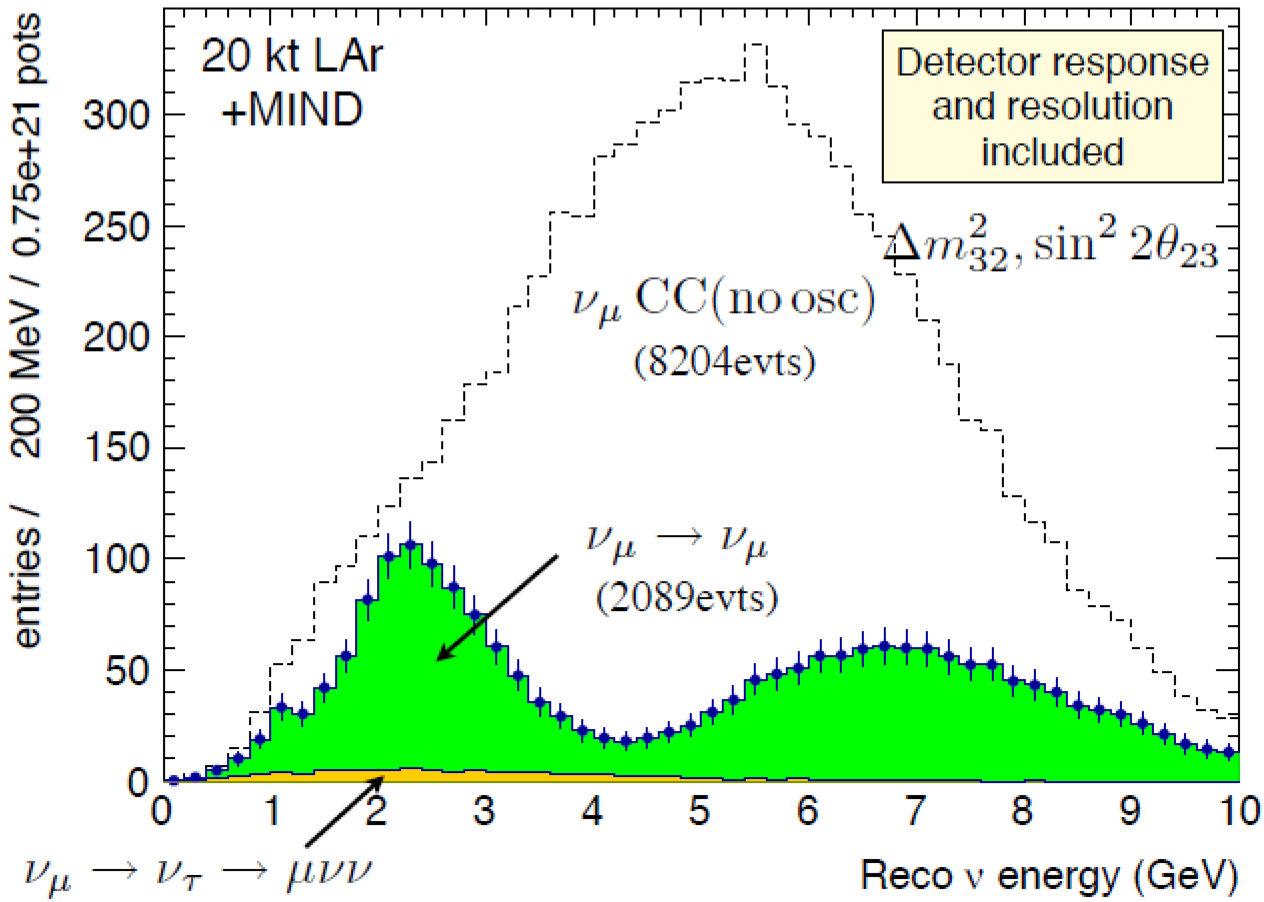
Signals at Pyhäsalmi : Inverted Hierarchy



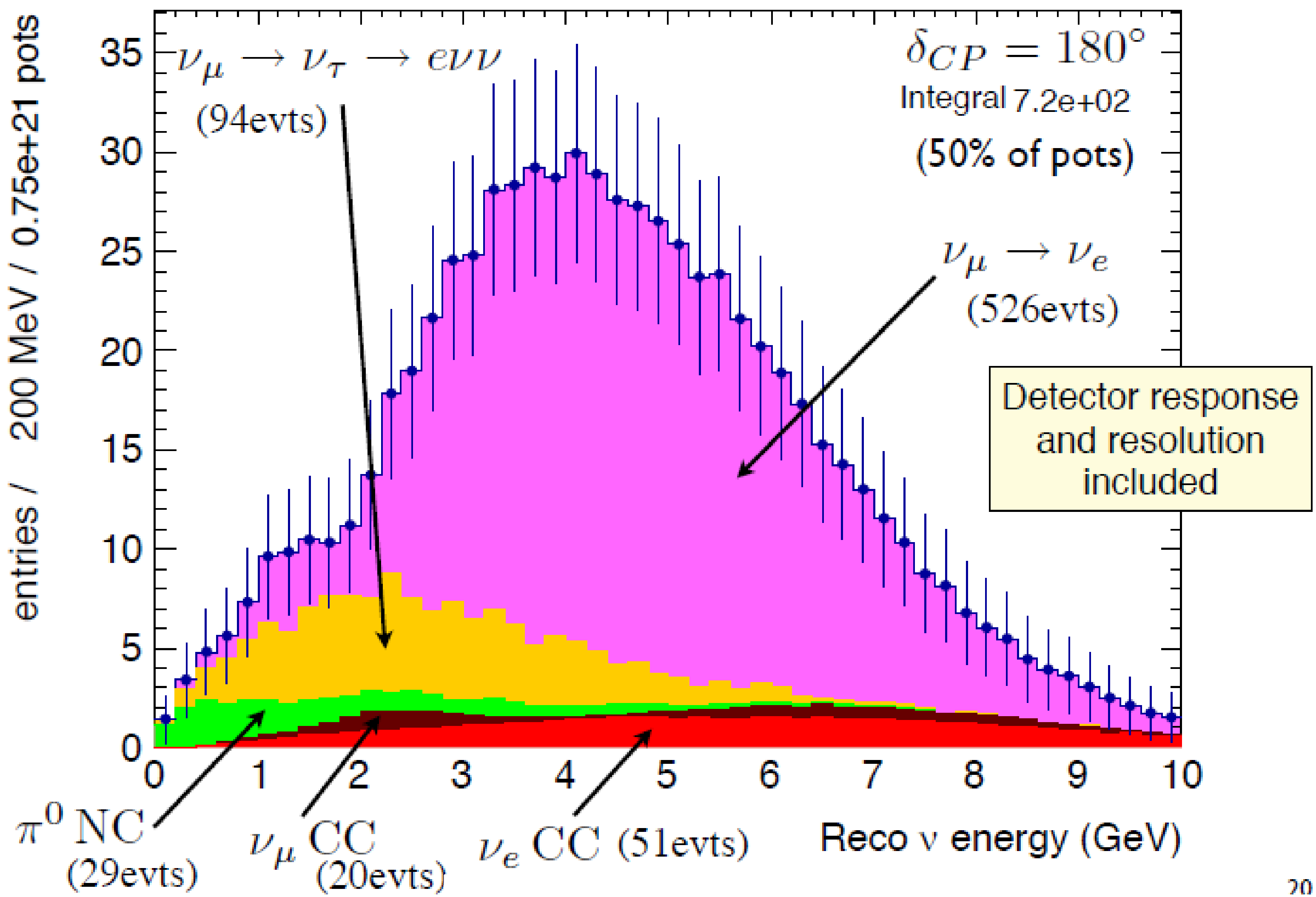
Flux Matching



Expected ν_μ sample



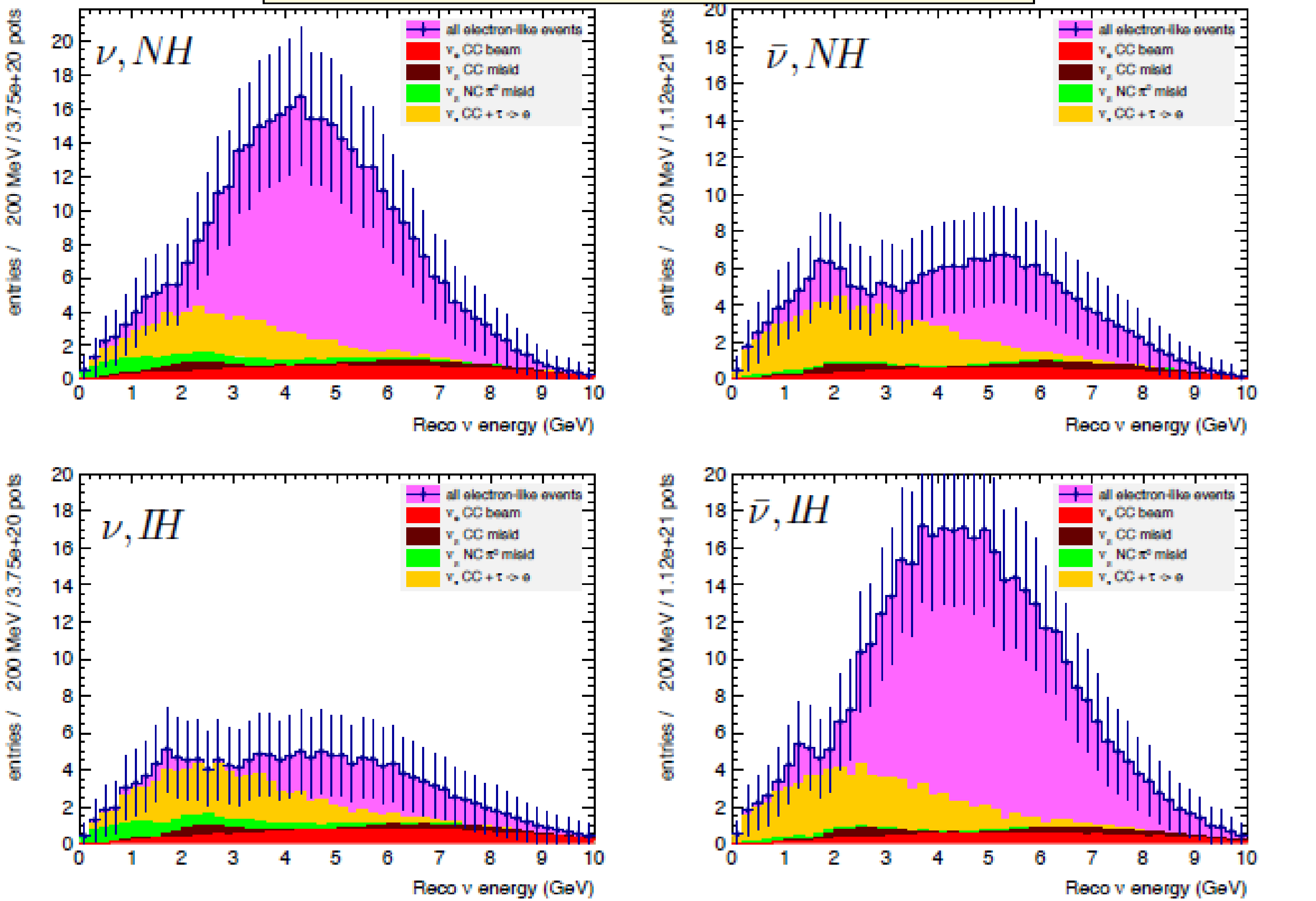
Expected ν_e sample



Determining oscillation parameters

Detector response and resolution included

Running mode:
ν/anti-ν:25%/75%

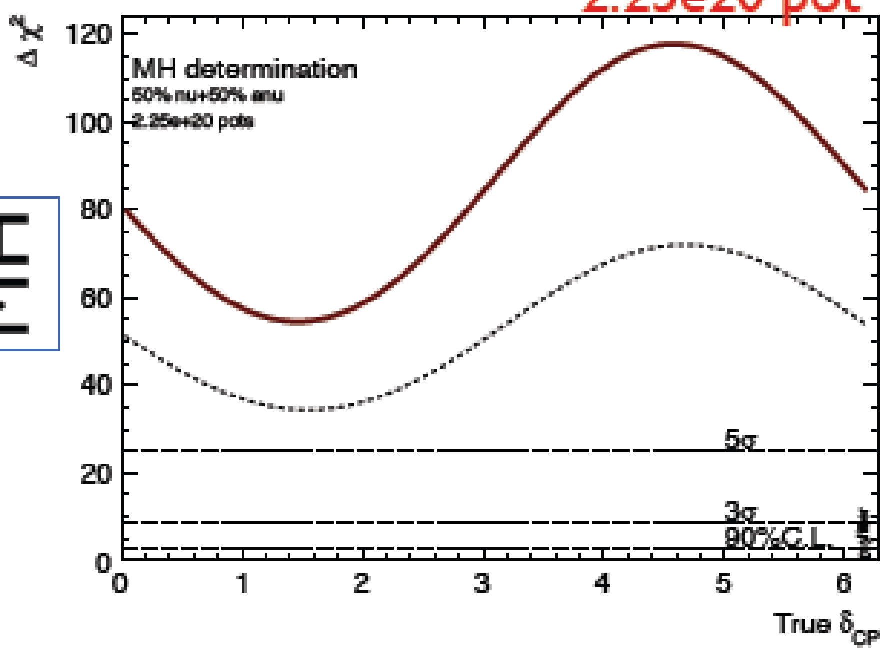


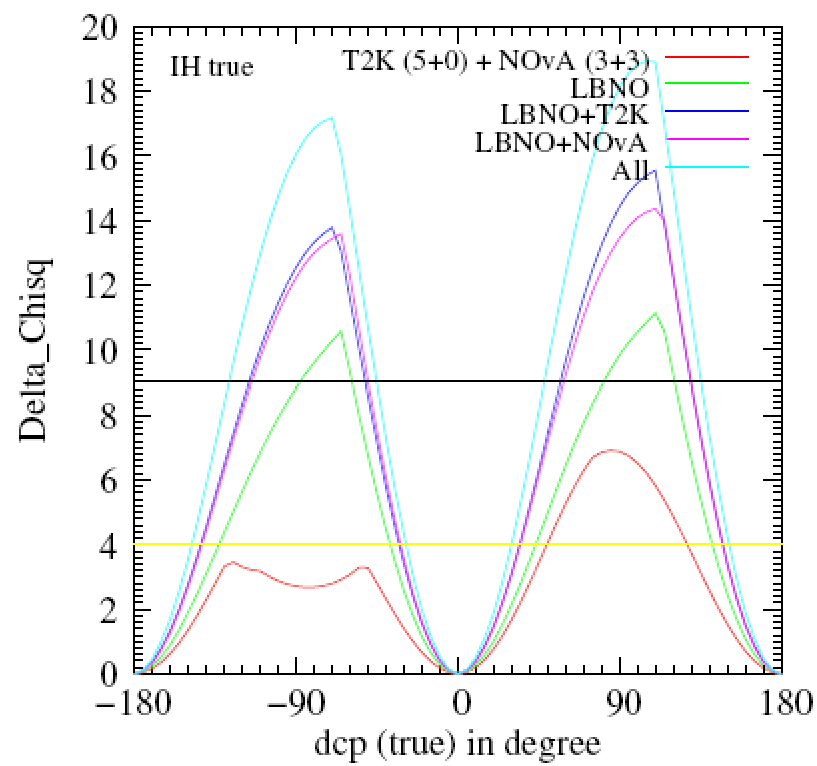
Physics reach of CERN- Pyhäsalmi

- After 10 years:
  - Full coverage of matter effect at 5σ.
  - 71% (44%) coverage of CPV at 90% (3σ).

MH

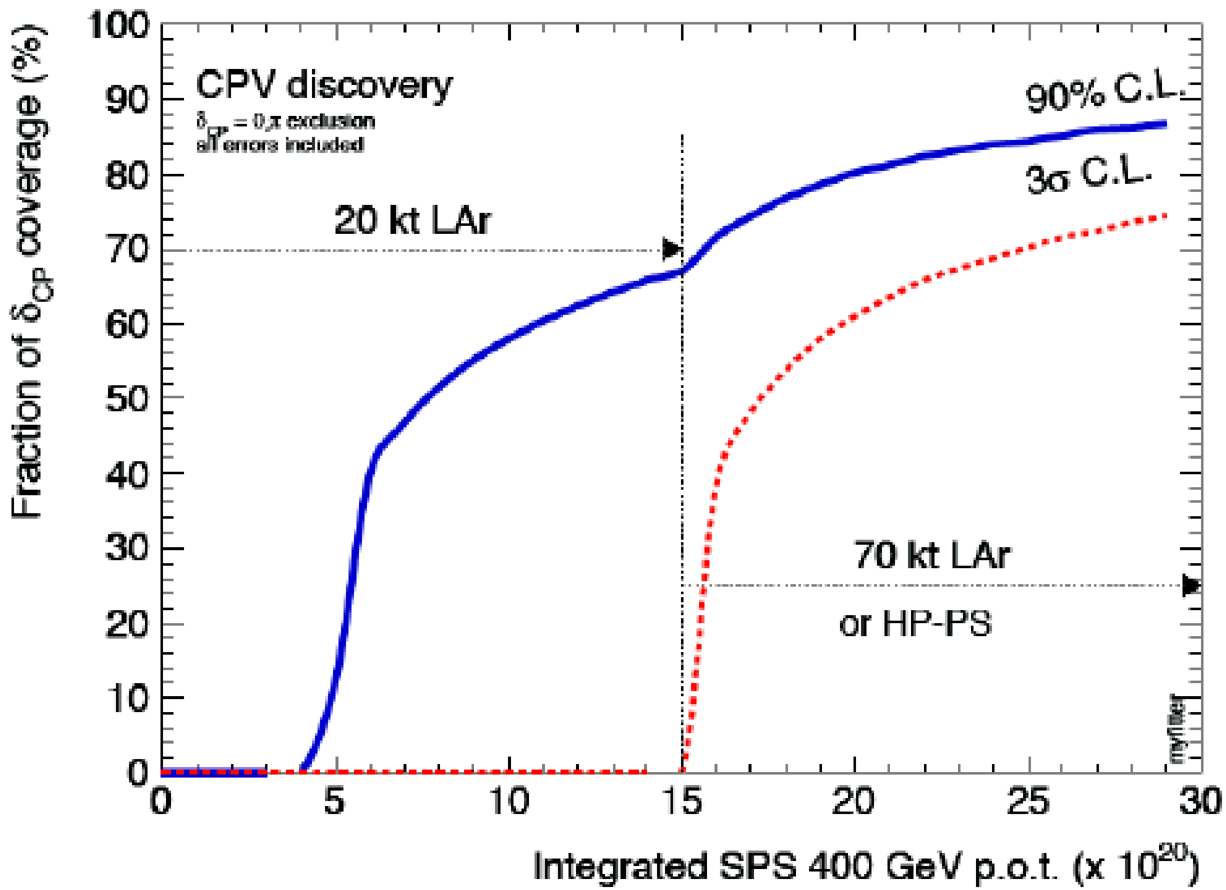
2.25e20 pot





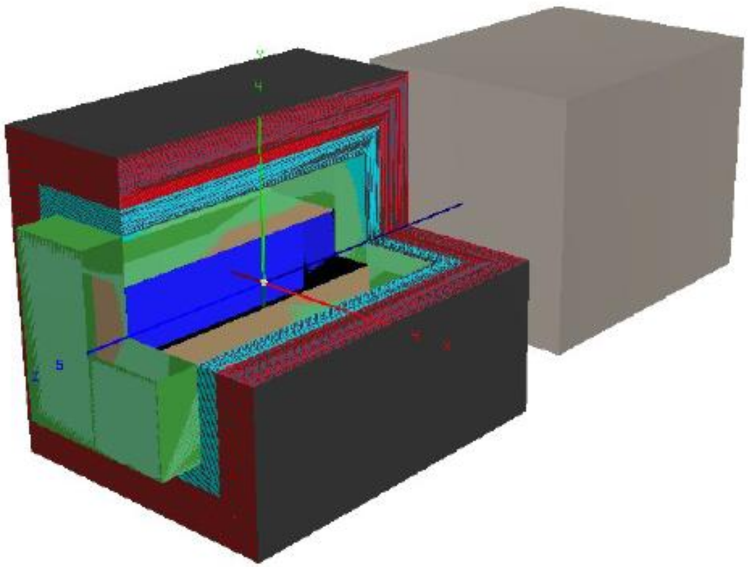
CP Coverage

Incremental approach with conventional beams



Near Detector Options

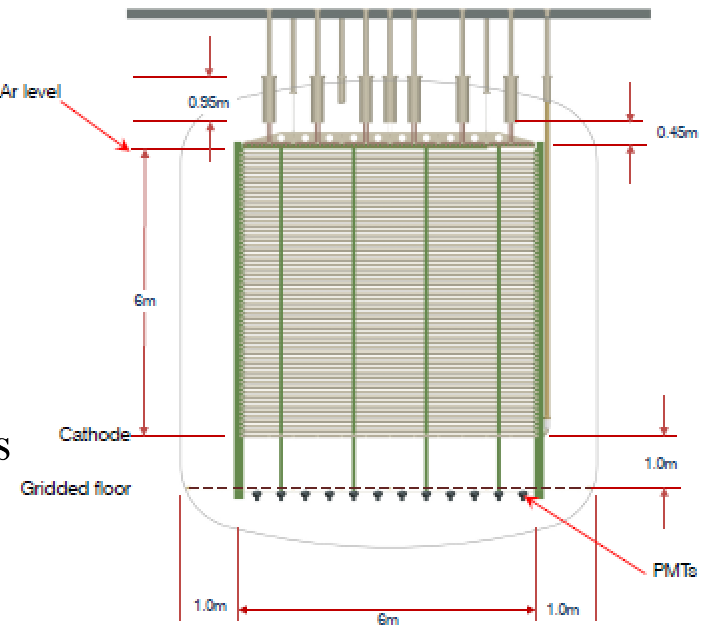
- A near detector will be required to control beam systematics and measure required cross sections.
- Can place the detector between 300m and 800m from target.
- Challenges:
  - Fully reconstruct DIS events
  - Match target materials
  - Detector Speed
- There is now a dedicated working group looking at the near detector design.



Possible Option:
High Pressure Ar TPC surrounded by scintillator with magnetic field
Followed by a magnetised iron calorimeter

The LAr testbeam program at CERN

- CERN is now planning and will start construction on a testbeam facility for liquid Argon detectors
  - Extension of existing beams in the north area
  - LAr infrastructure and detector pit provided
- Will provide
  - Charged particles from the test beam facility
  - Neutrinos from the potential short baseline program.
- Laguna liquid argon prototype will exploit this facility
  - 6x6x6 m detector
  - 300 tons of liquid Argon.
  - 5m drift
  - Ability to swap out readout
  - Full test of technology for Glacier.



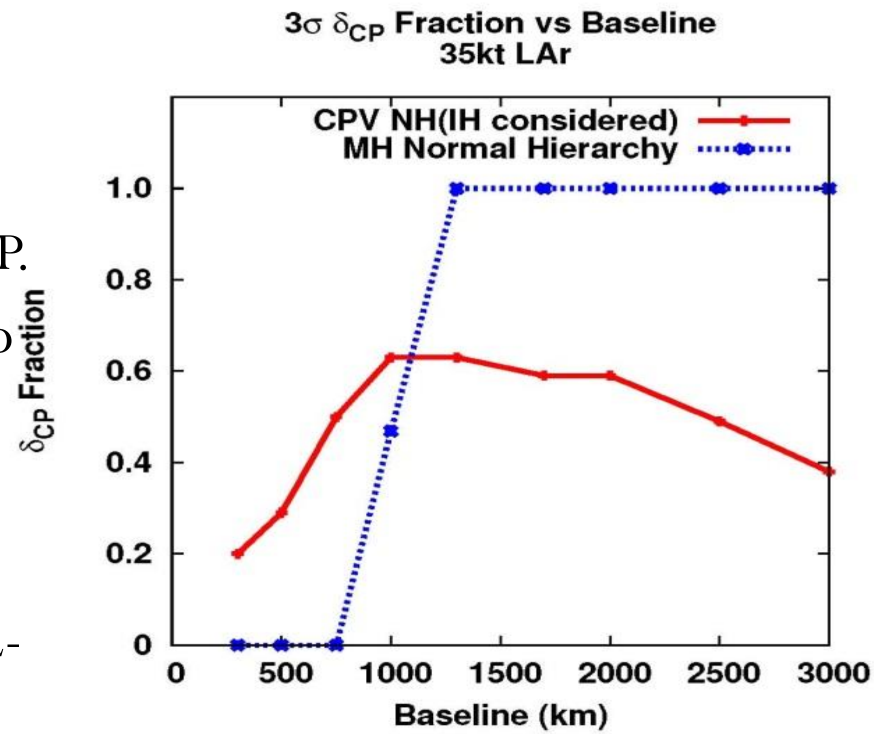
side view

Timeline for LBNO

- LAGUNA design study 2008-2011
- Start of LAGUNA – LBNO 2011
- Submission of EOI to CERN SPSC summer 2012
- Extended site investigations 2013
- End of LAGUNA LBNO 2014
- LAGUNA LAr prototype at CERN begins 2014-2016
- Critical decision 2015?
- Construction from 2016?
- Start of physics running 2023?

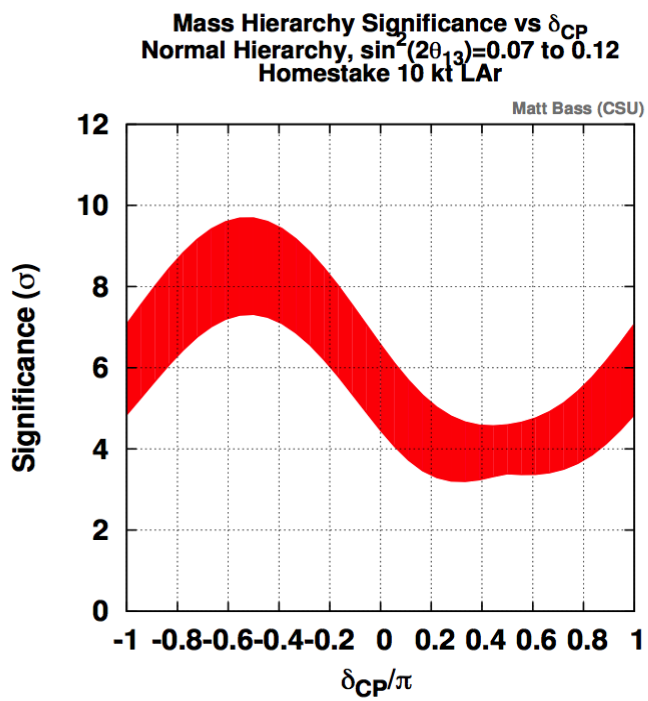
US Program : LBNE

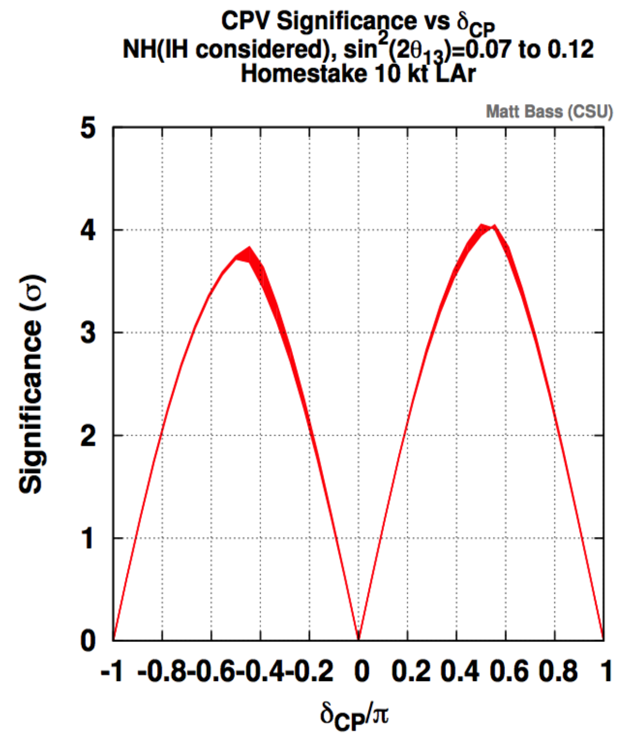
- Neutrino Beam from Fermilab to homestake
  - Baseline of 1300 km
  - Good sensitivity to matter effect and CP.
- Recently underwent reconfiguration to meet US budgetary constraints.
  - Requirements for a staged approach
- Phase 1
  - Construct upgradeable beamline FNAL-Homestake 700 kW.
  - 10 kt surface single phase LAr TPC.
  - No near detector.
- Obtained CD1 at end of 2012



Physics Reach of LBNE phase 1

- Can determine mass hierarchy at 3σ .
- Some coverage of CP violation.
- Precision measurement of other oscillation parameters.



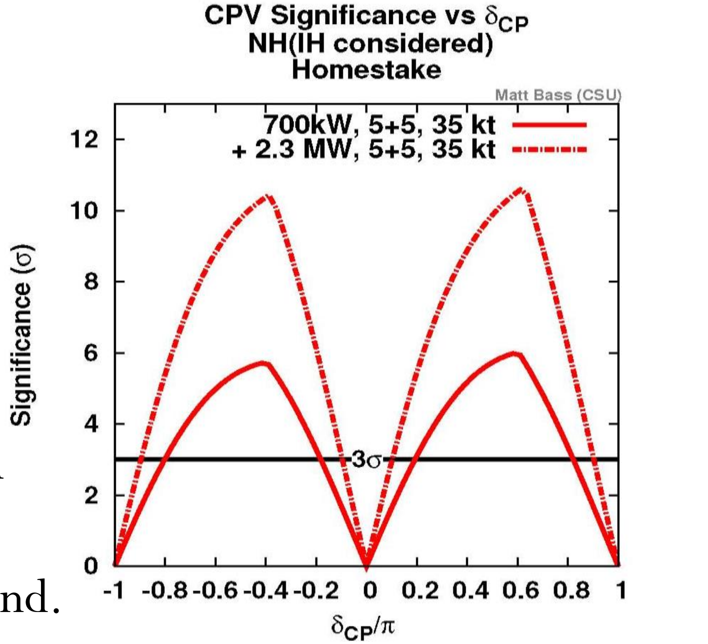


Upgrades to LBNE

- Scope for future development
  - Far Detector underground : 35kt LAr
  - Intensity : Project X
  - Improved systematics : Near Detector(s)

- There is also scope for foreign investment in phase 1.
  - 15% additional cost - far detector underground.
  - 15% additional cost - add near detector.
  - Open to contributions to any aspect of the project.

- The US is now actively looking for partners in LBNE to increase the scope of the phase 1 program.



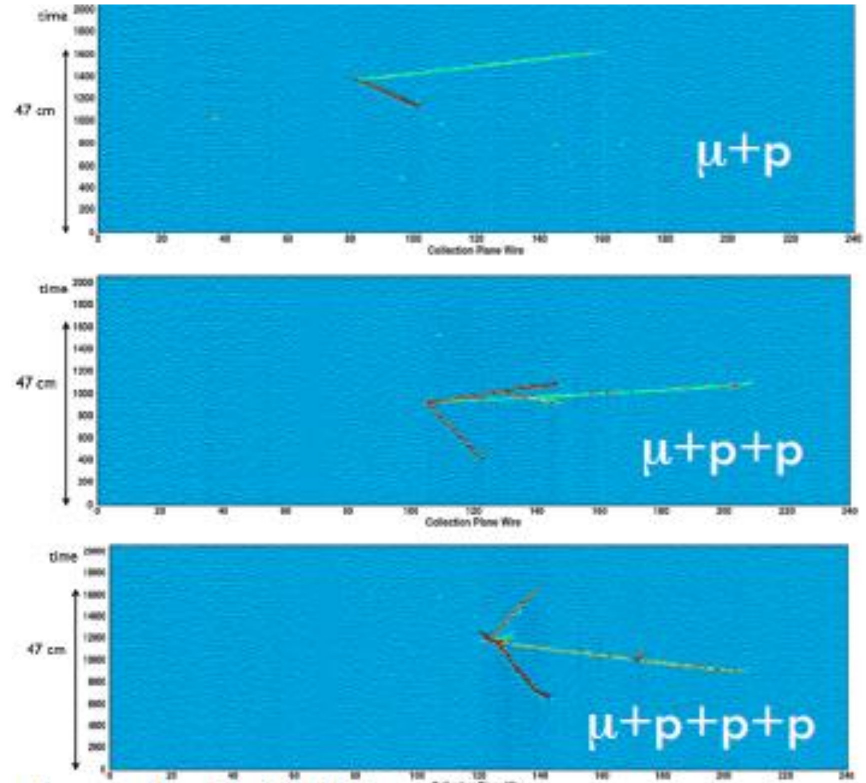
Final LBNE Configuration.

60% CP violation coverage at 3σ.

Liquid Argon R&D in the US

- Unlike European option the US are investigating single phase technology
  - Ala ICARUS

- ArgoNeut
  - 500l detector in NuMI beamline
  - Taking data
- MicroBoone
  - 150 ton detector in MiniBoone Beamline
  - Under Construction



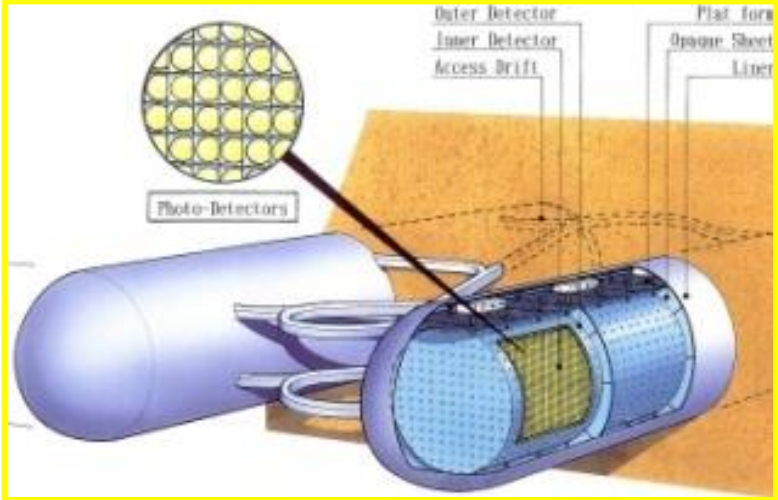
ArgoNeut data

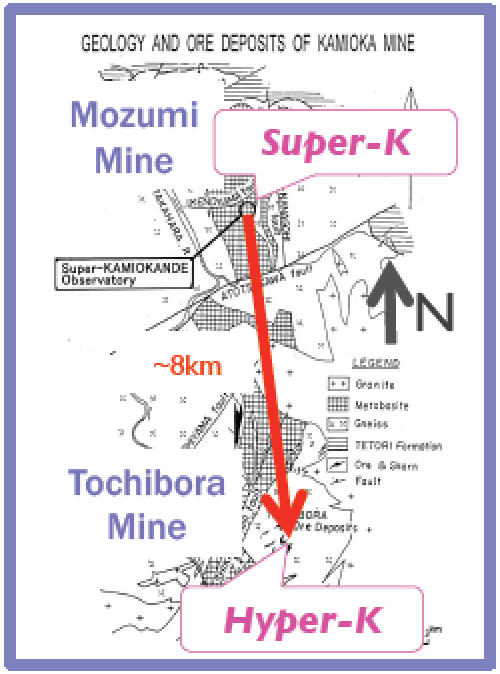
The Japanese option

- Exploit the current JPARC neutrino beam.
    - Expect 750kW by ~2020.

- Hyper-Kamiokande
    - 0.56 Mton fiducial water Cherenkov
        - ~20 x SK
    - 2 caverns
    - 99000 PMTs
        - 20% coverage
    - Aim for construction in 2018

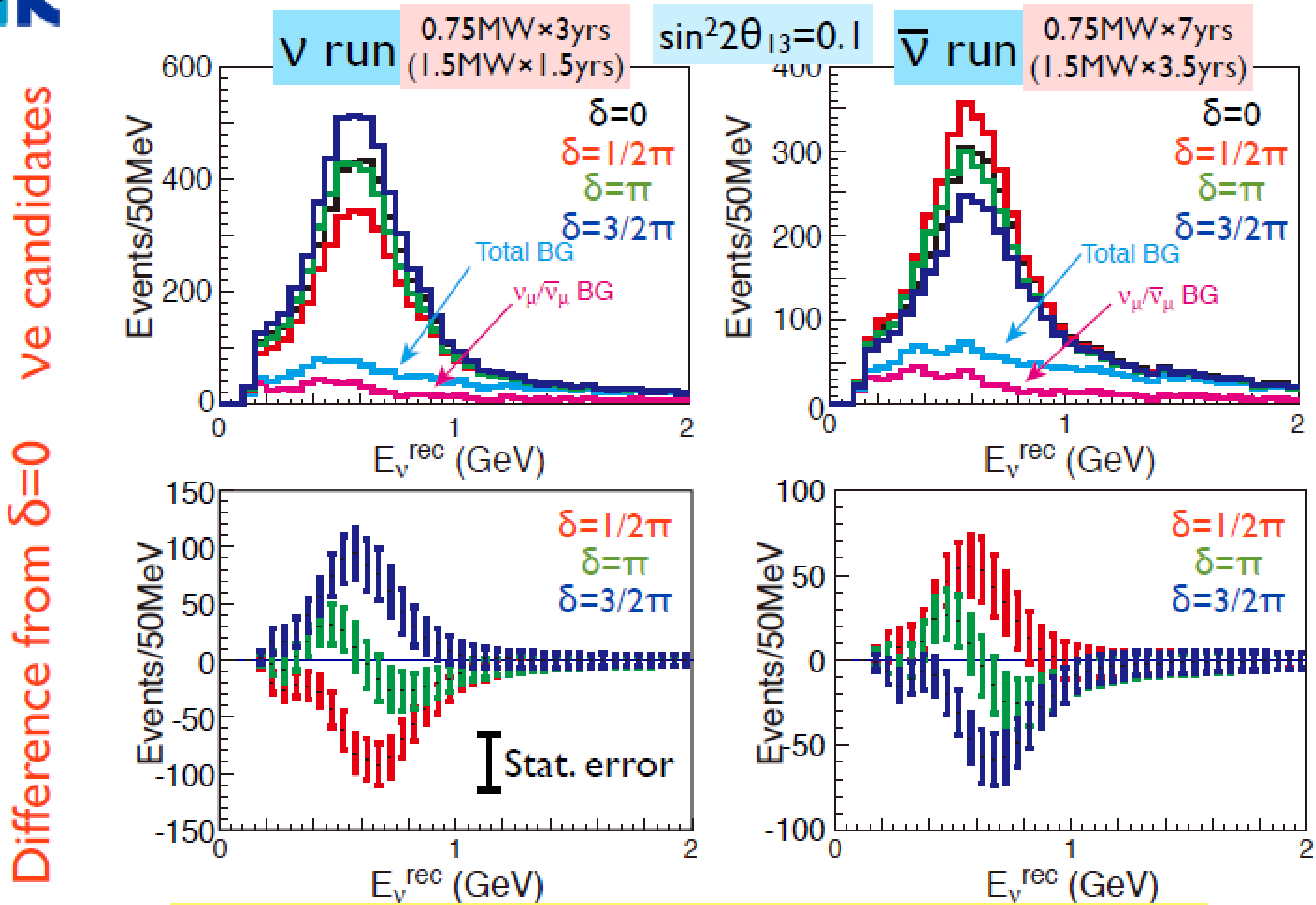
- Collaboration starting to form





Effect of δ

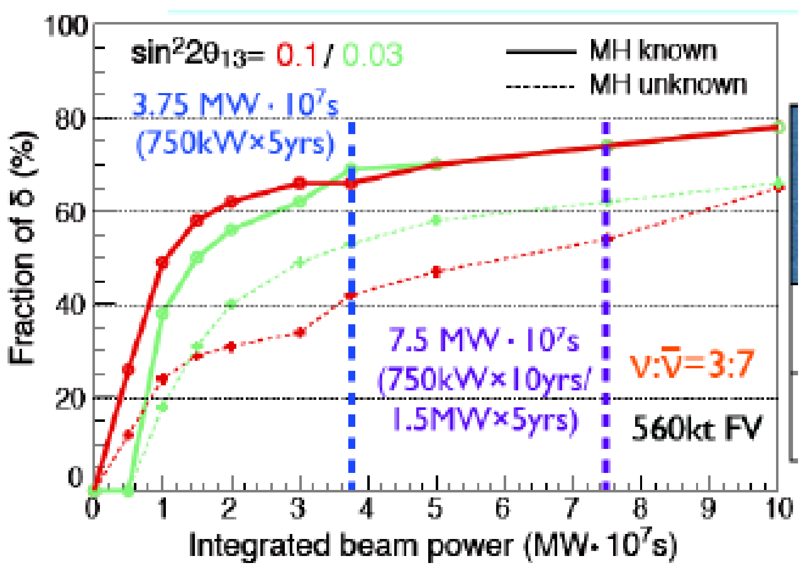
1year=10^7sec

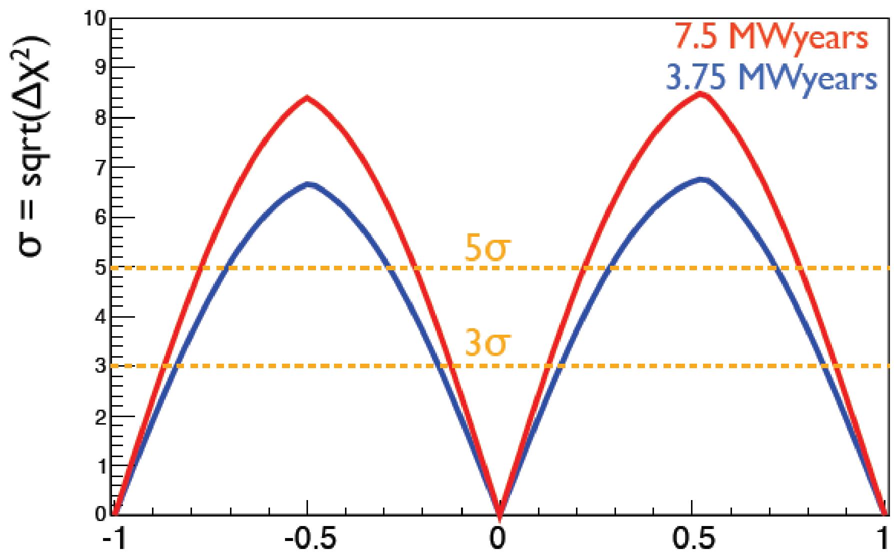


Number + shape: sensitive to all values of δ

Hyper Kamiokande Sensitivity

- Assume 3 year neutrino / 7 years anti neutrino.
  - 5% systematics
- Good sensitivity to CP
  - 77% (55%) coverage at 3 (5) sigma.
  - Aim to access to Mass Hierarchy though joint analysis with atmospheric neutrinos and other experiments.
- Rich physics program of proton decay, extraterrestrial and atmospheric neutrinos.





Other physics at Hyper-K

- Proton Decay
  - Increased sensitivity for
    - $e\pi$ >$1.3\text{x}10^{35}$ years
    - $K\nu$ >$3\text{x}10^{34}$ years
    - Many other modes possible
- Atmospheric Neutrinos
  - Major statistics increase
  - Can aim for mass hierarchy
- Supernova Neutrinos
  - Sensitive to any galactic supernova with huge statistics
  - Discovery of relic supernova neutrinos
  - ~0.5 events for a typical supernova in the local cluster
- Solar Neutrinos
  - Very high statistics for day-night asymmetry.

Comments on the long baseline program

- The discovery of large θ_{13} has condensed the options for the next generation of long baseline experiments.
- 5σ measurement of the mass hierarchy and significant regions of the CP violating phase are possible.
- Mixing measurements should be made at high precision to test the 3 neutrino mixing paradigm.
- Experiments and facilities should be designed for further extension to future experiments, should the data guide us in that direction.
- Experiments to measure neutrino cross sections and hadron production will also be required and will play a key role in these measurements.

Conclusions

- Discovery of θ_{13} signposts the next steps for long baseline neutrino experiments.
- There is an experimental program that will take us to ~2020
  - Longbase line experiments
  - Test beam program
- To allow for clear and unambiguous discoveries we need to next generation experiments
  - Need to push forward with these steps.