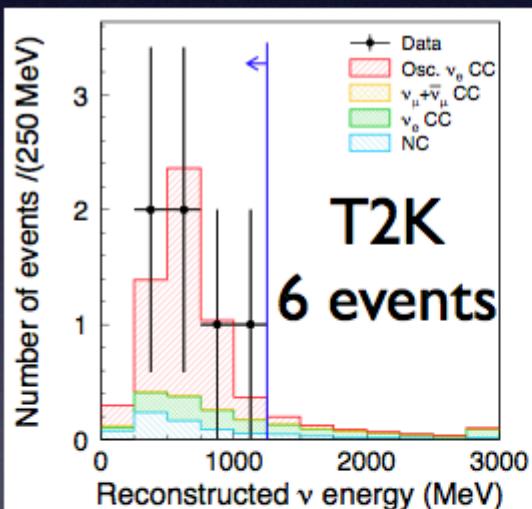


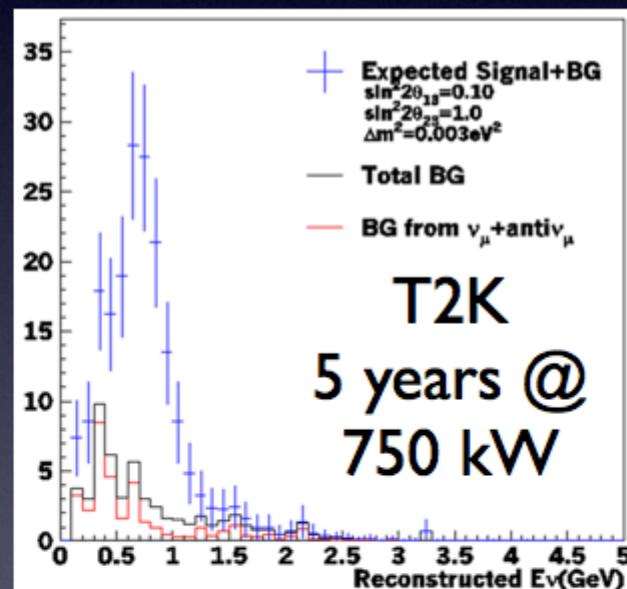


Long Baseline Neutrino Oscillation Experiments

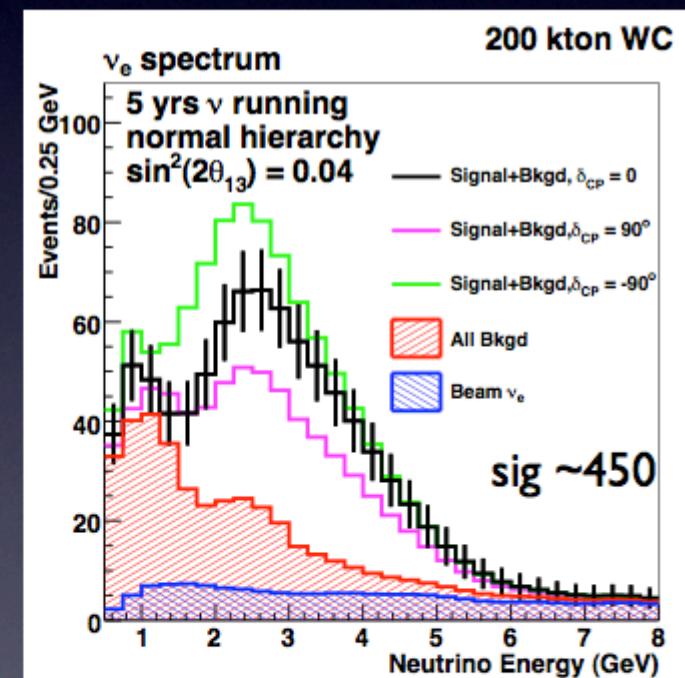
André Rubbia (ETH Zurich)



2011



≈ 2018



> 2025

Several decades of long baseline experiments

- 1st generation: K2K/T2K, MINOS, OPERA
➡ 250 km - 730 km, 1.8-22.5 kton

2-3 sector
(2000-2010)

- 2nd generation: T2K, (MINOS), NOvA
➡ 300 km - 830 km, 750 kW, 5-22.5 kton

I-3 sector
(2010-2020)

- 3rd generation: upgraded JPARC, LAGUNA-LBNO, LBNE
conventional MW-class superbeam
➡ 600 - 2500 km ? 100-1000 kton detectors ?

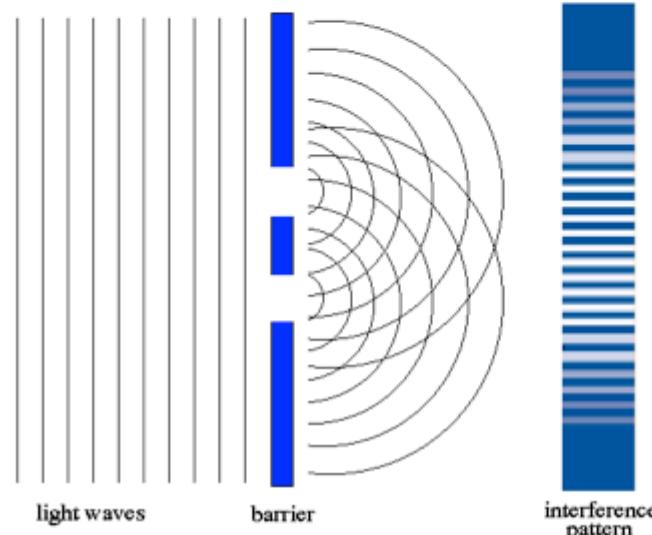
δ_{CP} sector ?
(2020-2030)

- 4th generation: next generation ν beams (NF)
➡ 3000-7000 km ? 100 kton magnetized ?

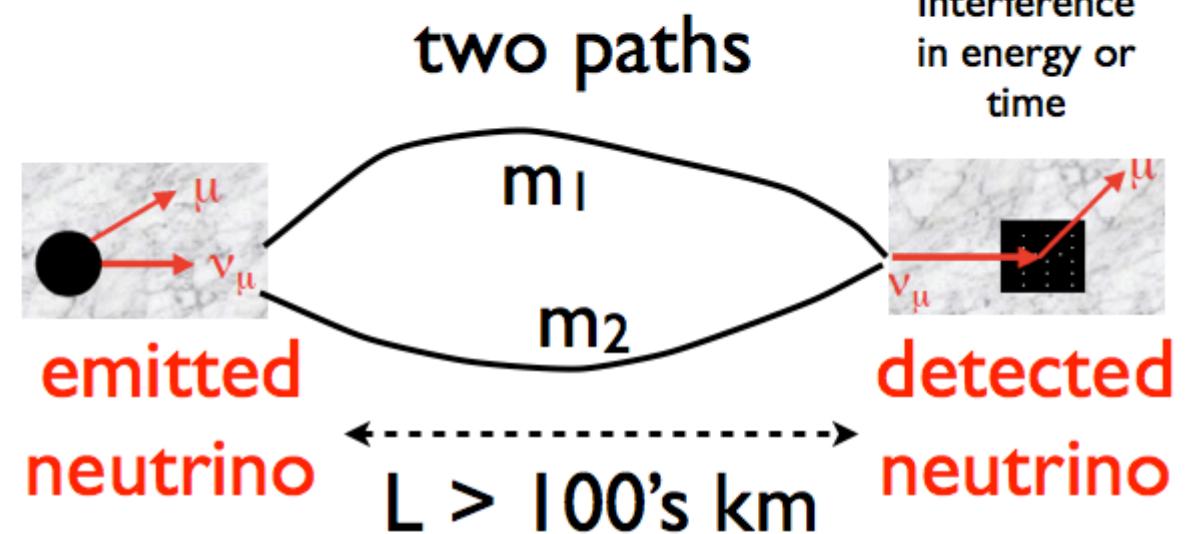
precision era ?
(2030-?)

Oscillation experiments represent a new kind of interferometry test

Interference

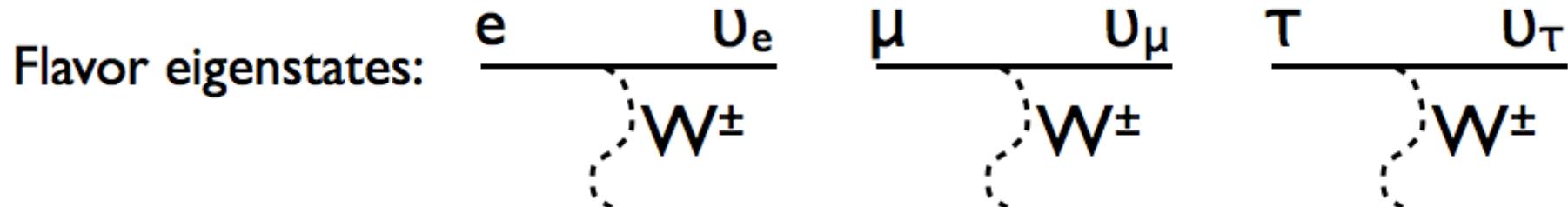


Courtesy: M. Diwan



- Just as classic optical or quantum mechanical interferometry has led to new precision, neutrino interferometry measures extremely small mass differences or interactions.
- “Any” perturbation along the path changes the neutrino interference pattern at the far detector \Rightarrow powerful window to new physics !
- Measurement can be sensitive to new unknown phenomena !

Three-neutrino flavor oscillations



Mass eigenstates: U_1, U_2, U_3

Mixing: $|\nu_l\rangle = \sum_{i=1}^3 U_{li} |\nu_i\rangle$ PMNS matrix

Standard parameterization:

2-3 sector

1-3 sector

1-2 sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor oscillations:

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\frac{\Delta m_{ij}^2 L}{4E})$$

$$+ 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\frac{\Delta m_{ij}^2 L}{4E})$$

Phenomenology of 3-neutrino oscillations

Current knowledge of parameters ➔

$$\Delta m_{21}^2 \quad (7.65^{+0.23}_{-0.20}) \cdot 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{12} \quad 0.304^{+0.022}_{-0.016}$$

SNO, KamLAND

$$|\Delta m_{31}^2| \quad (2.40^{+0.12}_{-0.11}) \cdot 10^{-3} \text{ eV}^2$$

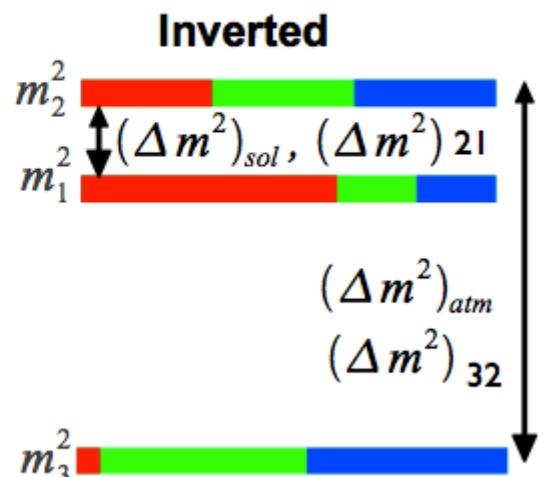
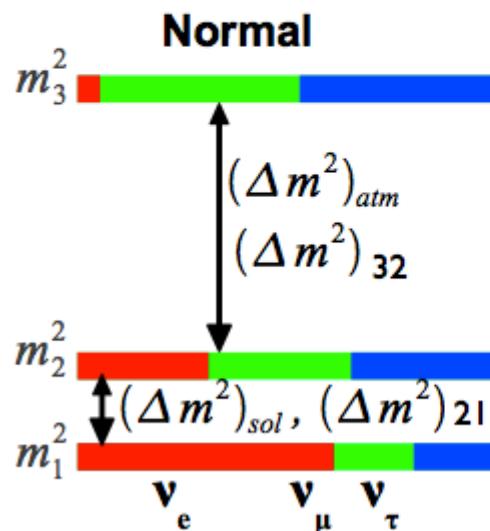
$$\sin^2 \theta_{23} \quad 0.50^{+0.07}_{-0.06}$$

SK, K2K, MINOS

$$\sin^2 2\theta_{13} \quad 0.084 \pm 0.028$$

T2K,...

Main open questions ➔



- $\sin^2 2\theta_{13} \approx 0.1$?
- CP-violation $\delta \neq 0$?
- Mass hierarchy
 $\Delta m_{31}^2 > 0$?, $\Delta m_{31}^2 < 0$?
- How precisely do we want to know the parameters ?

Theoretical input - tri-bimaximal mixing

Tri-bimaximal mixing

Harrison, Perkins, Scott, PLB 2002, hep-ph/0202074

$$\sin^2 \theta_{12} = 1/3, \quad \sin^2 \theta_{23} = 1/2, \quad \sin^2 \theta_{13} = 0$$

$$U = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Parameterize deviations

King arXiv:0710.0530

$$s_{13} = \frac{r}{\sqrt{2}}, \quad s_{12} = \frac{1}{\sqrt{3}}(1 + s), \quad s_{23} = \frac{1}{\sqrt{2}}(1 + a)$$

$$0.07 < r < 0.21, \quad -0.05 < s < 0.003, \quad -0.09 < a < 0.04$$

r = reactor

s = solar

a = atmospheric

Present data is essentially consistent with $r,s,a=0$

→ tri-bimaximal so need to measure r,s,a to “%‐level” ?

The BIG picture - ultimate goals

- τ appearance
- $\theta_{13} \neq 0$ at $>5\sigma$ significance
- Precision measurements $\Delta m_{23}^2 \pm \delta \Delta m_{23}^2$, $\theta_{23} \pm ??$
(maximal?), $\theta_{13} \pm ??$
- Mass hierarchy $\Delta m_{23}^2 > 0$?, $\Delta m_{23}^2 < 0$?
- CP-violation $\delta \neq 0, \pi$ at $>2,3,5\sigma$ significance, $\delta \pm ??$
- Unitarity of PMNS matrix
- Understand the ν -mixing parameters: tri-bimaximal ?
- Understand differences between the quark and lepton sectors
- Even more physics beyond the SM in neutrino sector ??

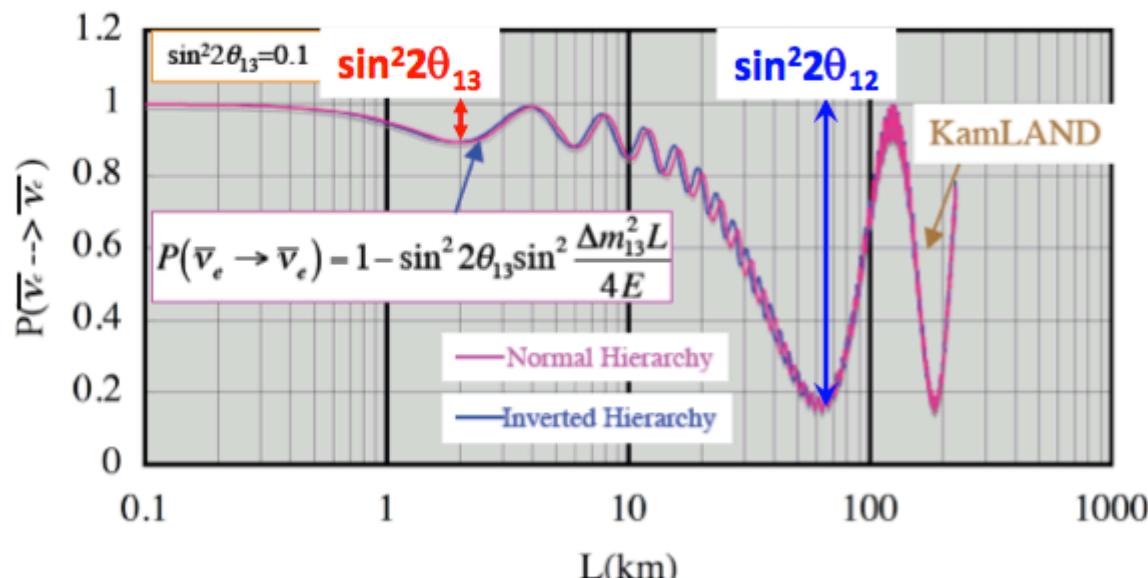
Appearance vs disappearance

ν_e appearance in a ν_μ beam (accelerator neutrinos):

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) + \text{higher order } f(\delta_{CP}, \theta_{12}) + \text{matter effects}$$

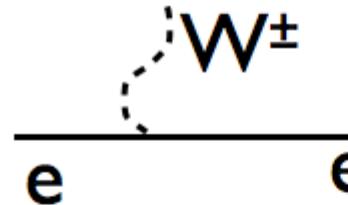
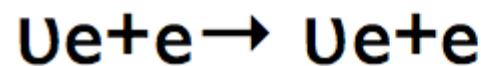
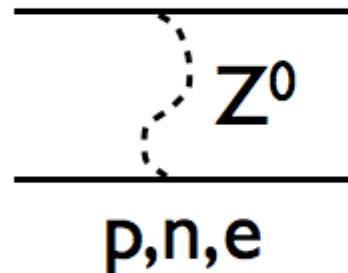
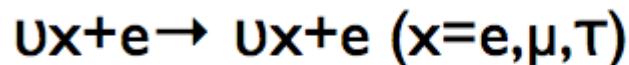
$\bar{\nu}_e$ disappearance probability (reactor neutrinos):

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$



- limited by systematics
- no information on δ_{CP} or mass hierarchy

Matter effects

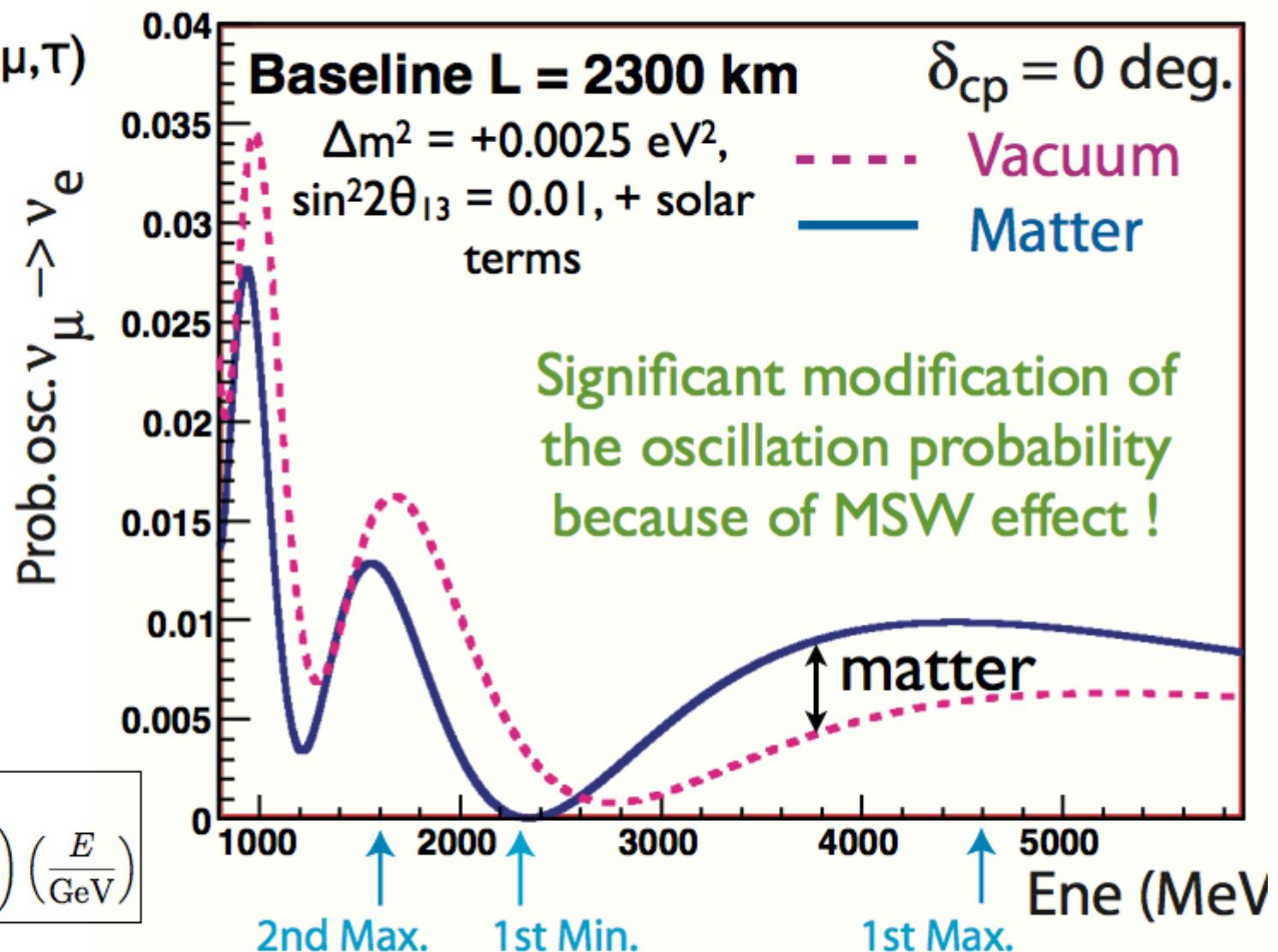


Effective potential:

$$\begin{aligned} A &\equiv 2\sqrt{2}G_F N_e E \\ &\approx 7,56 \cdot 10^{-5} \text{ eV}^2 \left(\frac{\rho}{\text{g/cm}^3} \right) \left(\frac{E}{\text{GeV}} \right) \end{aligned}$$

Grows quadratically with distances:

$$P_m(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_m \sin^2 \left(\frac{\Delta M^2 L}{4E} \right) \propto L^2$$

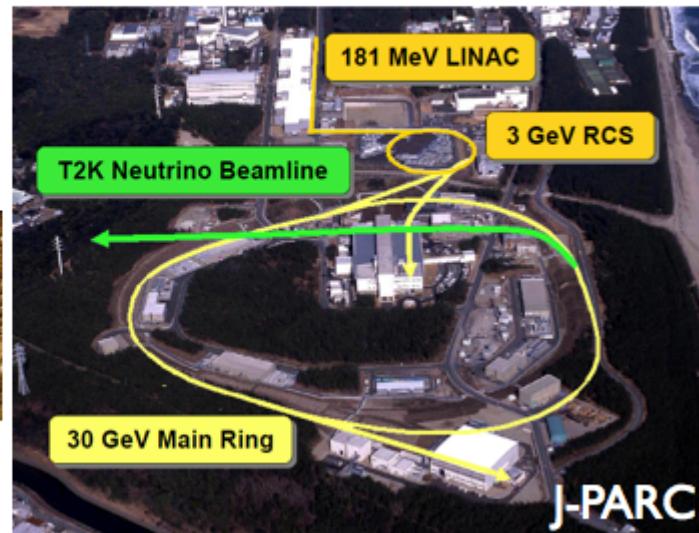
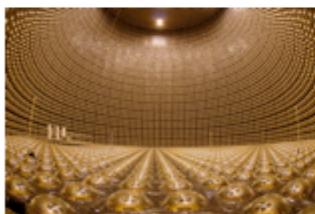


T2K and NOvA

L=830km

L=295km

Kamioka



- Ran from Jan 2010 till March 2011
- Presently stopped; restart foreseen in 2012
- Current beam power 145 kW (goal 750kW)
- Muon disappearance result released at this conference
- Electron appearance result published (90% C.L.):

$0.03 < \sin^2 2\theta_{13} < 0.28$ (best fit 0.11) normal

$0.04 < \sin^2 2\theta_{13} < 0.34$ (best fit 0.14) inverted

Aim: sensitivity $\sin^2 2\theta_{13} > 0.006$ @ 90% C.L. for $\delta_{CP}=0$



June 4, 2011

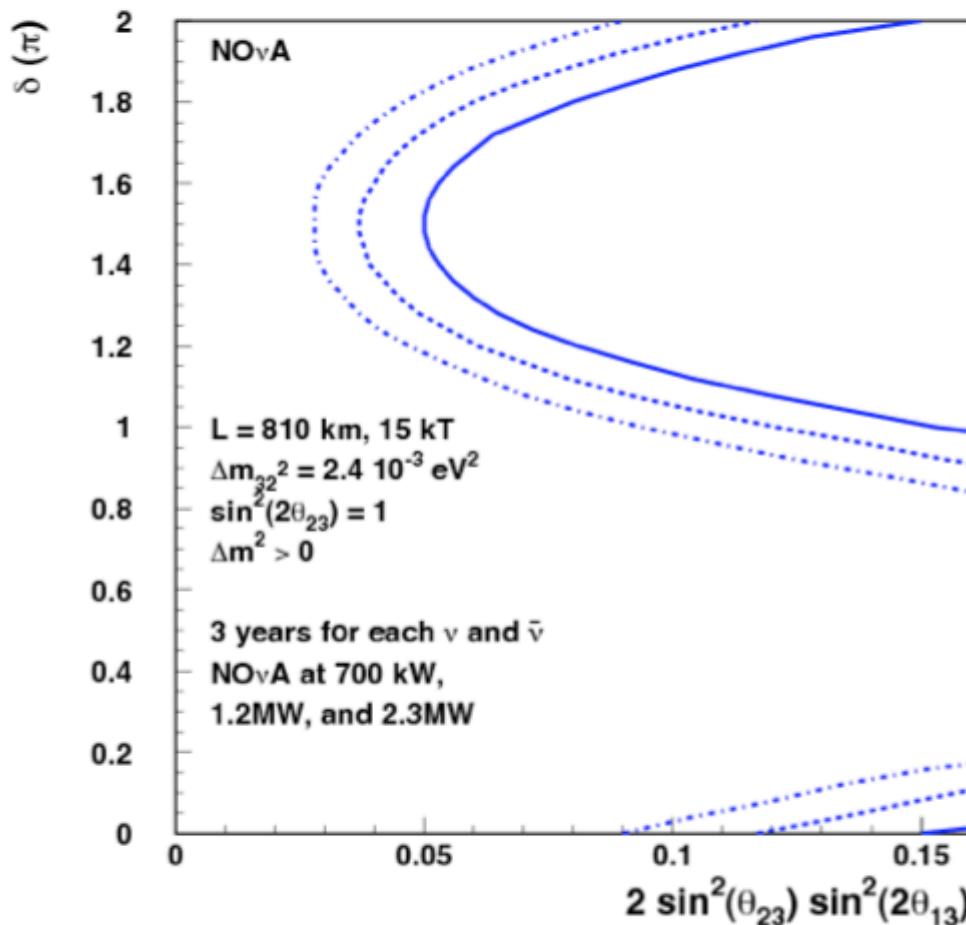
- Far detector under construction
- Start foreseen in fall 2013
- Beam power 750 kW (after upgrade)
- Baseline L=830 km gives some matter effect sensitivity
- Consider neutrino + antineutrino runs

Aim: sensitivity $\sin^2 2\theta_{13} > 0.007$
@ 90% C.L. for $\delta_{CP}=0$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) + \text{higher order } f(\delta_{CP}, \theta_{12})$$

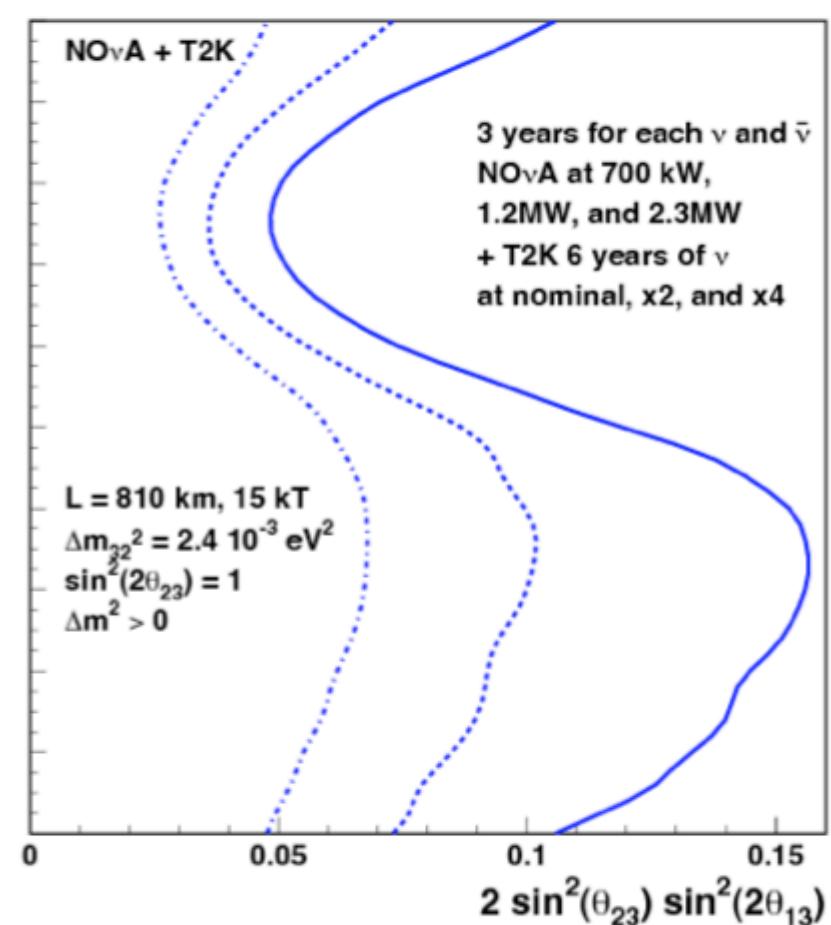
NOvA mass hierarchy resolution

95% CL Resolution of the Mass Ordering



Compare NOvA's neutrinos to NOvA's anti-neutrinos

95% CL Resolution of the Mass Ordering

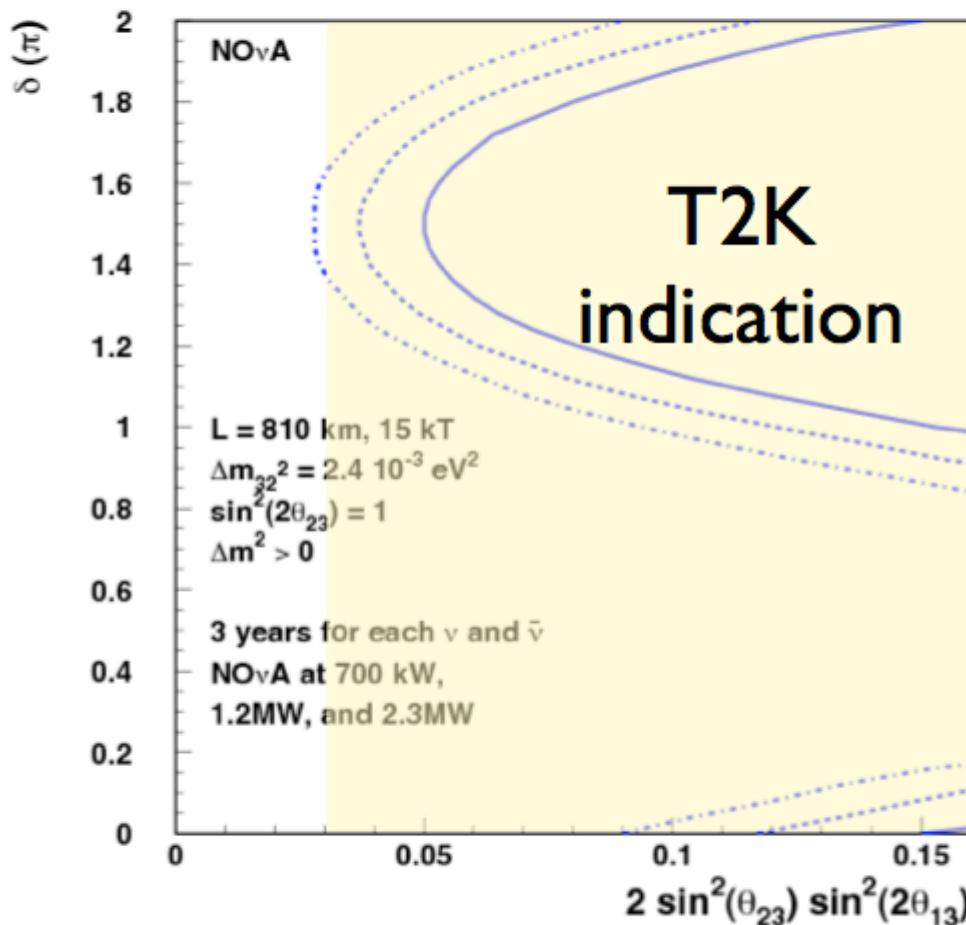


Compare NOvA's neutrinos w/ matter effect to T2K's neutrinos ~w/o matter effect

Courtesy: NOvA collaboration

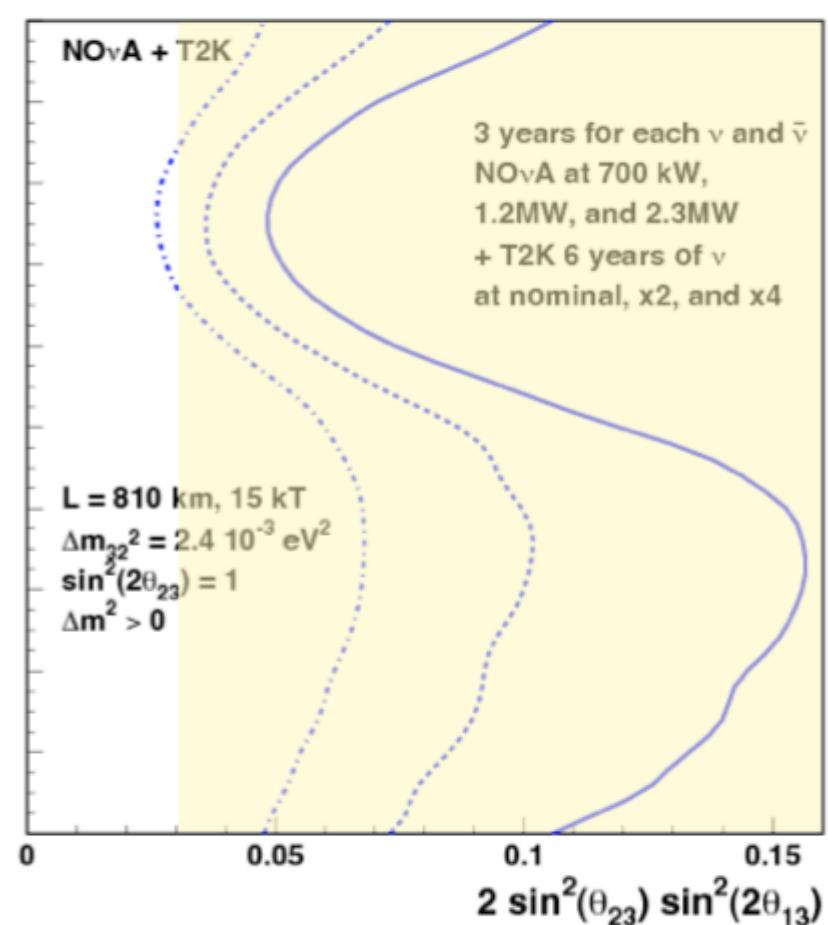
NOvA mass hierarchy resolution

95% CL Resolution of the Mass Ordering



Compare NOvA's neutrinos to NOvA's anti-neutrinos

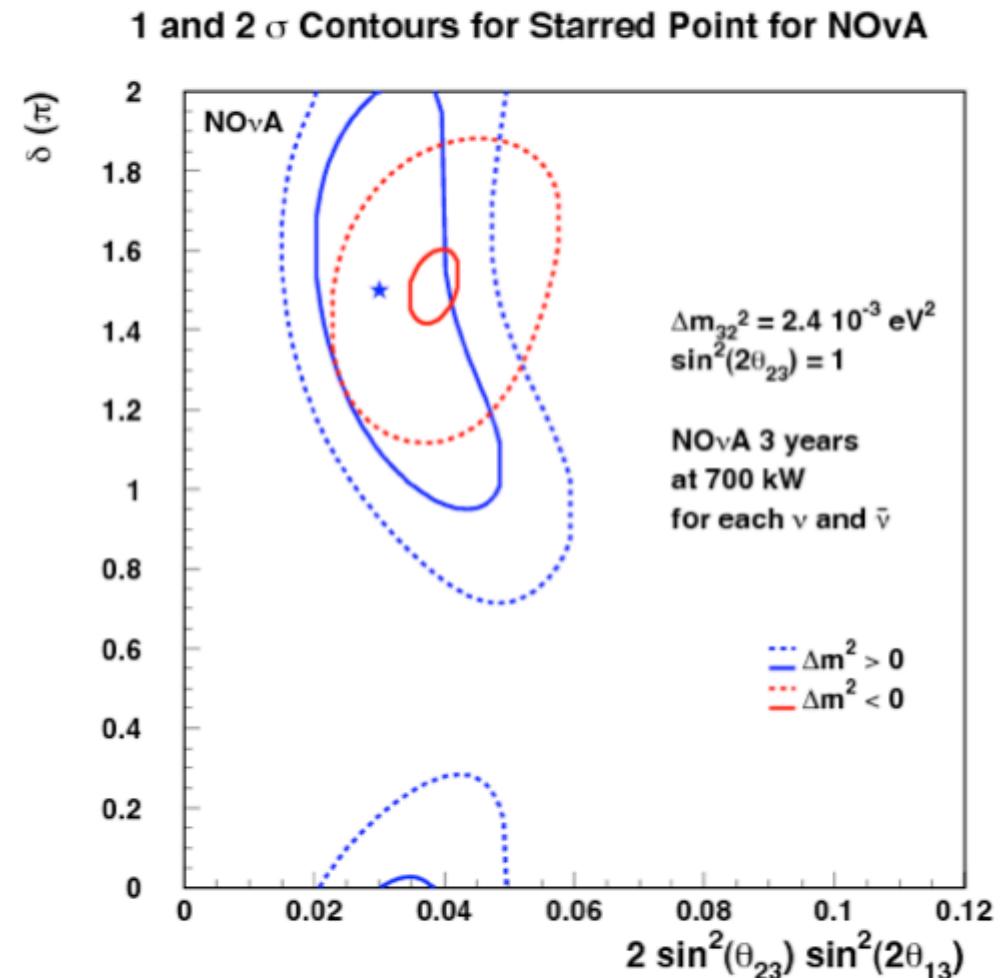
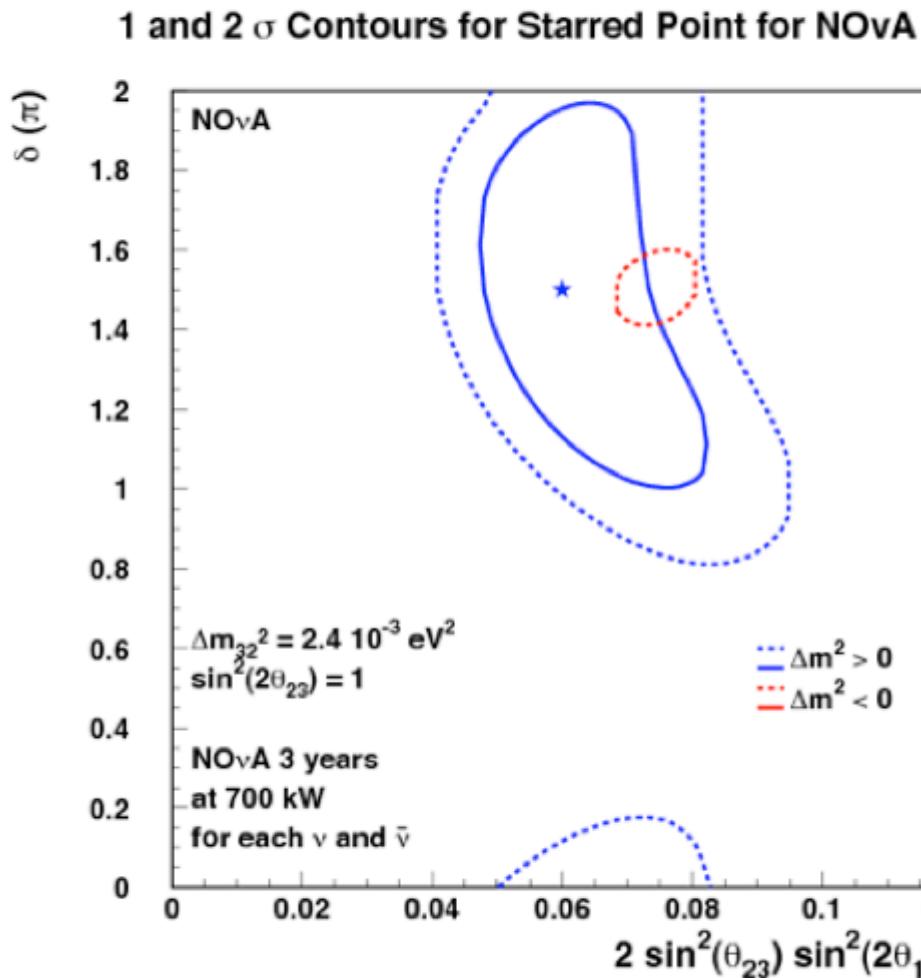
95% CL Resolution of the Mass Ordering



Compare NOvA's neutrinos w/ matter effect to T2K's neutrinos ~w/o matter effect

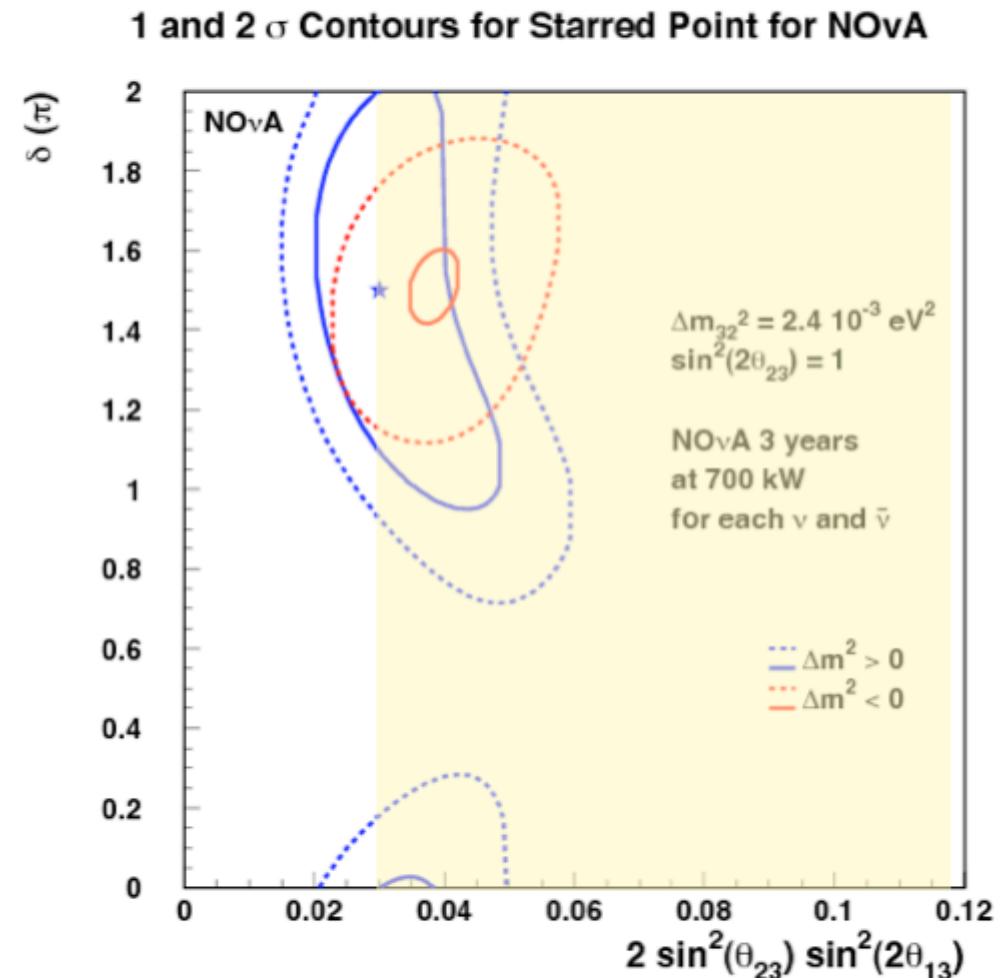
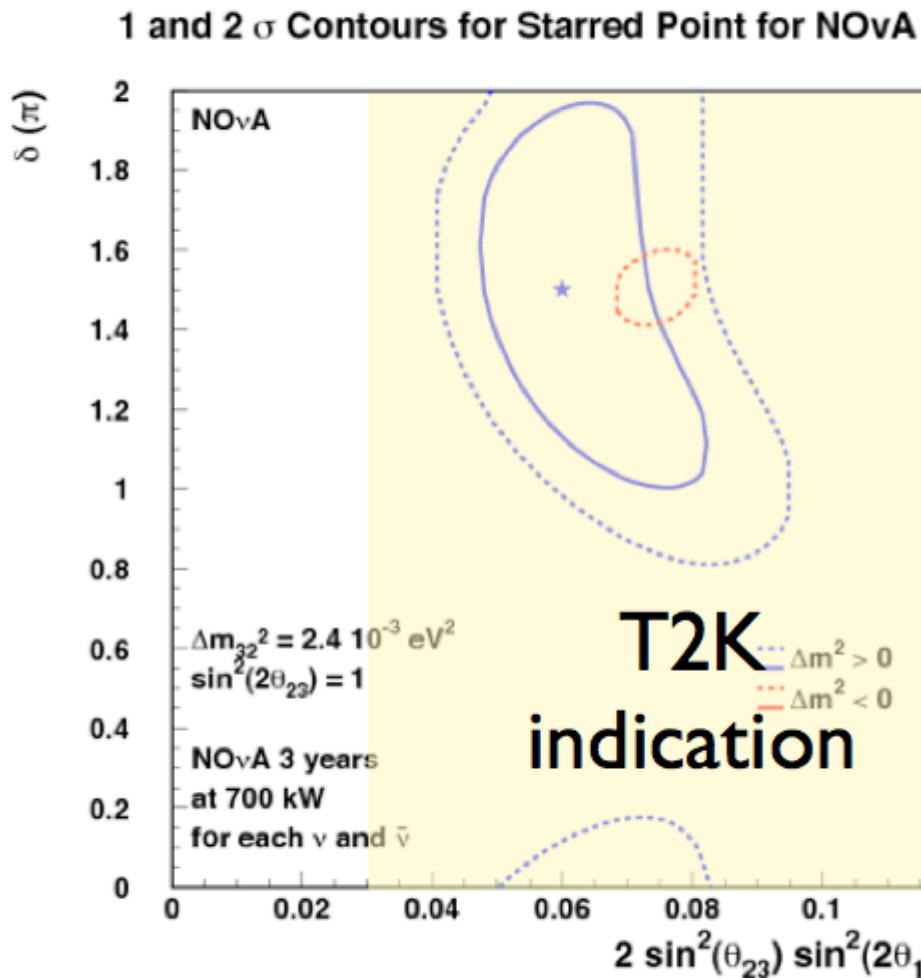
Courtesy: NOvA collaboration

NOvA CP-violation search



Courtesy: NOvA collaboration

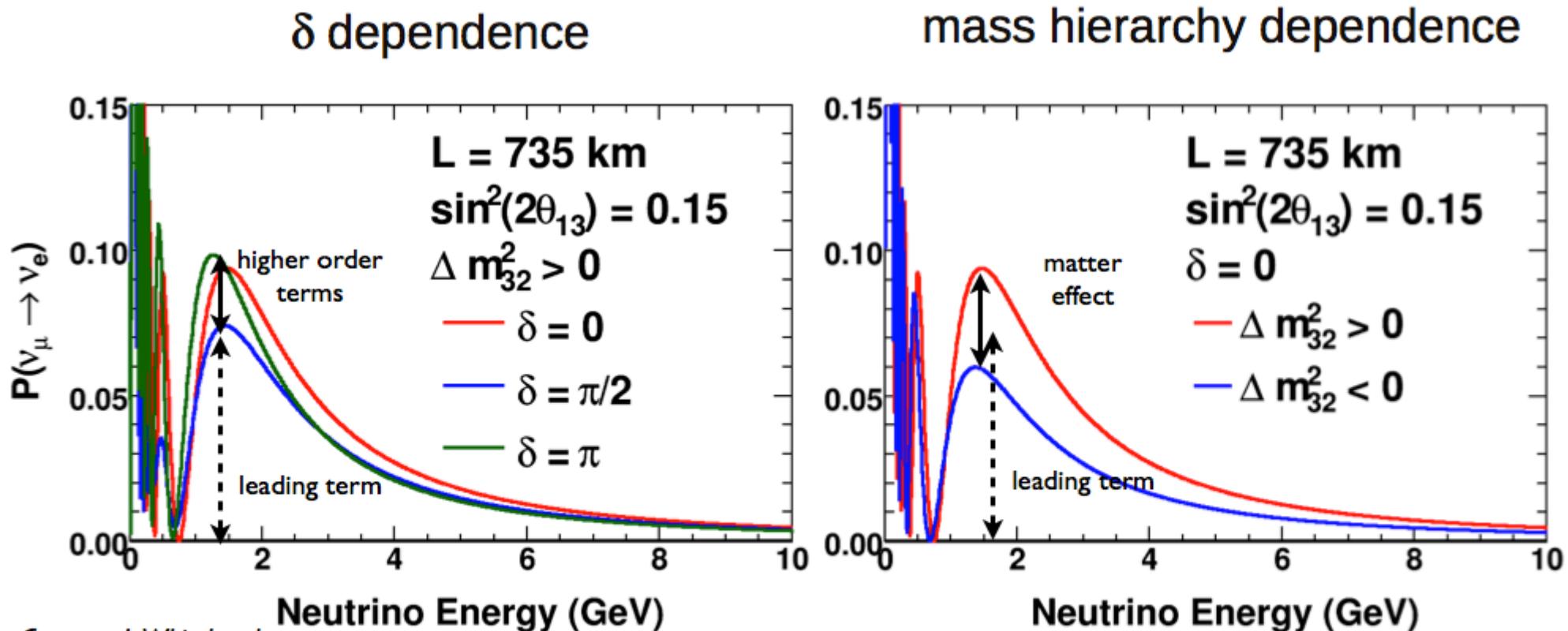
NOvA CP-violation search



Courtesy: NOvA collaboration

Beyond T2K and NOvA: Measure the higher order terms !

Next step: ν_e appearance in a ν_μ beam with high precision to test higher order terms that depend on δ_{CP} and determine the matter effects
→ Measure energy-binned probability with rel. error < O(5%)



Courtesy: L. Whitehead

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

quadratic dep. on θ_{13}
matter effect $\sim E$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta)$$

~ 7500 km
magic bln

$$+ \alpha \frac{8J_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)$$

~ 2540 km
magic bln

$$+ \alpha \frac{8I_{CP}}{\hat{A}(1 - \hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)$$

solar

$$+ \alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

term
linear dep. on θ_{13}

$$J_{CP} = 1/8 \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2, \quad \Delta = \Delta m_{31}^2 L / 4E$$

CP asymmetry grows as
 θ_{13} becomes smaller !

$$\hat{A} = 2VE / \Delta m_{31}^2 \approx (E_\nu / \text{GeV})/11 \text{ For Earth's crust.}$$

Potential 3rd generation experiments

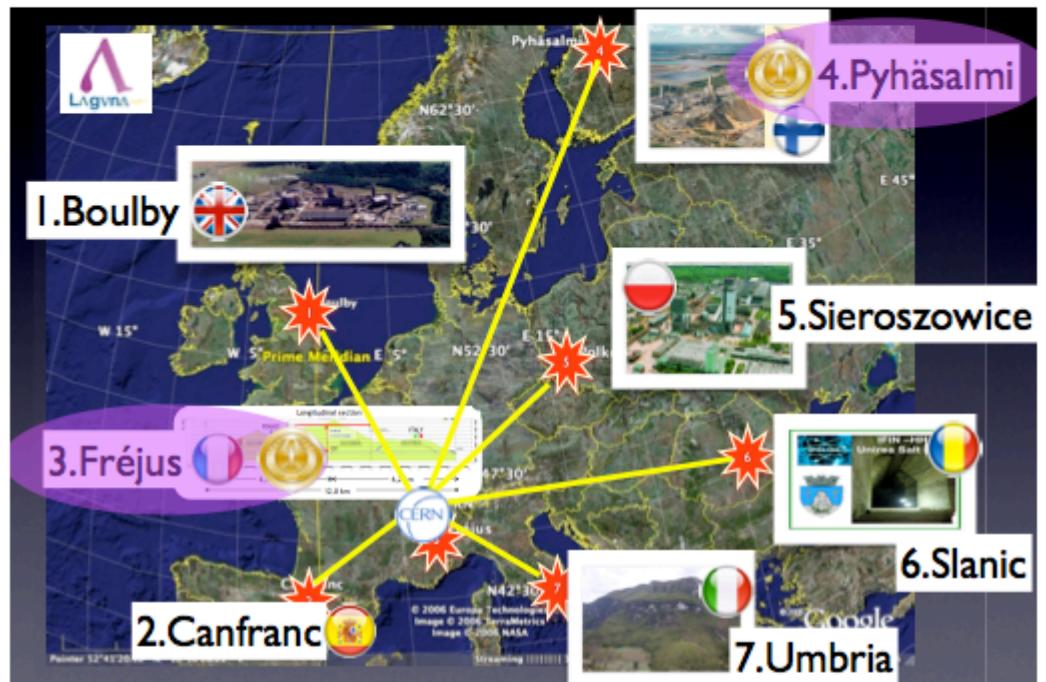
- **Giant detectors**
 - Water Cerenkov 300-500 kton
 - Liquid Argon TPC 100 kton
 - Liquid Scintillator 50 kton
 - **High proton beam intensities**
 - FNAL: 750 kW → 2 MW, 120 GeV MI protons
 - CERN: 400-700 kW, 400 GeV SPS → 2 MW 30-50 GeV HP-PS
 - J-PARC: 140-750 kW, 30 GeV MR → 1.66 MW
 - CERN : 4MW @ 5 GeV SPL
 - **Conventional beams with Long Neutrino Flight Paths**
 - **Being Pursued worldwide**
 - LAGUNA (EU), Future @ J-PARC (Japan), LBNE (USA)
 - Where will they be realized ? one or two sites / technologies ?
- at least $\times 10$ statistics
compared to T2K or
NOvA*

In USA

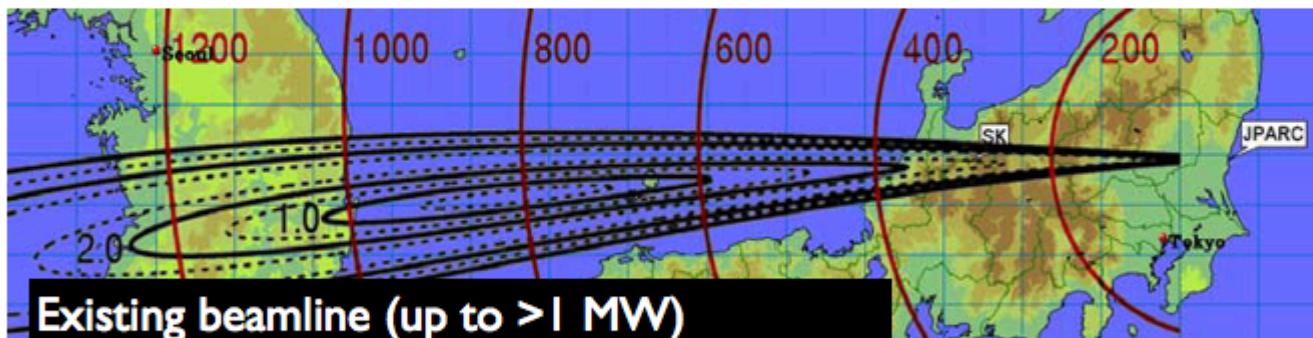


Requires new beam (LBNE)
Requires new far site detector
(LBNE/DUSEL ?)

In Europe (since 2005)



In Japan (since 2008):



Existing beamline (up to >1 MW)
Requires upgraded MR proton accelerator
Requires new far detector

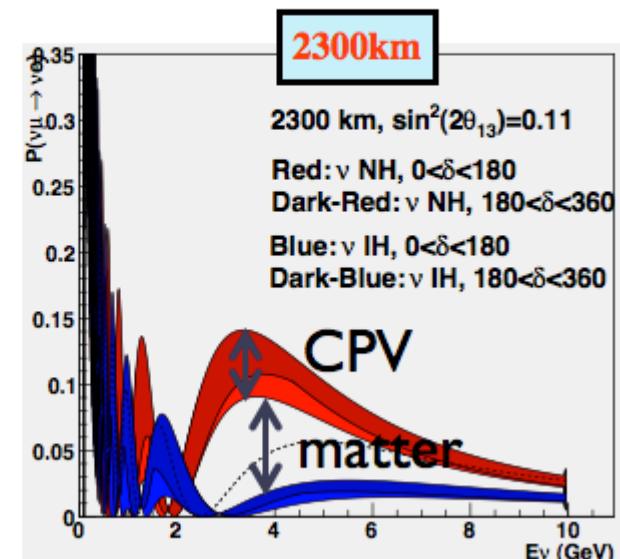
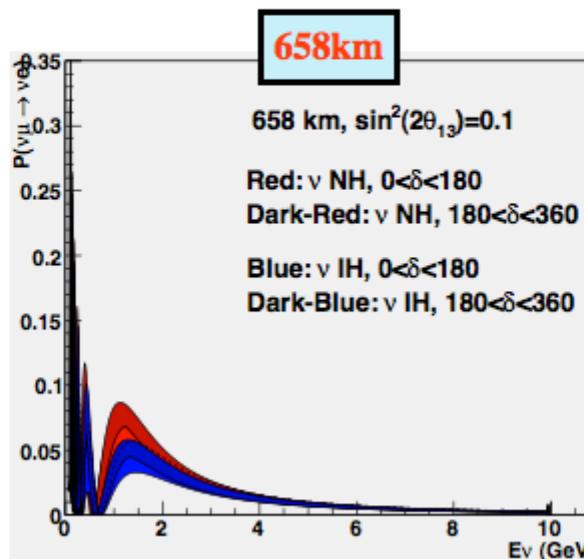
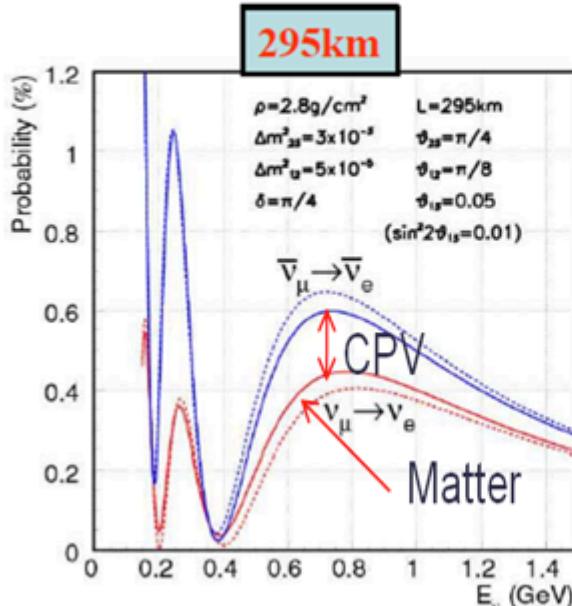
Requires new far site detector
(LAGUNA + LAGUNA-LBNO)
Requires new beam
(LAGUNA-LBNO)

EU, Japan, US world tour

	Proton driver	Baseline L	Detector / Fiducial mass	Method
LAGUNA Fréjus	CERN SPL 4MW	130 km	WC 440kt (MEMPHYS) (*)	$\nu/\bar{\nu}$ asymmetry
J-PARC- Kamioka	J-PARC MR (1.66MW)	295 km	WC 600kt (HyperK)	$\nu/\bar{\nu}$ asymmetry
J-PARC- Okinoshima	J-PARC MR (1.66MW)	658 km	LAr 100 kt	WBB
LBNE	FNAL MI 750kW (2.3MW ProjectX)	1300 km	WC 200kt or LAr 34kt	WBB
LAGUNA Slanic (**)	CERN SPS 700kW (1.6MW HP-PS)	1570 km	LAr 100 kt	WBB
LAGUNA Pyhäsalmi	CERN SPS 700kW (1.6MW HP-PS)	2300 km	LAr 100 kt (*)	WBB

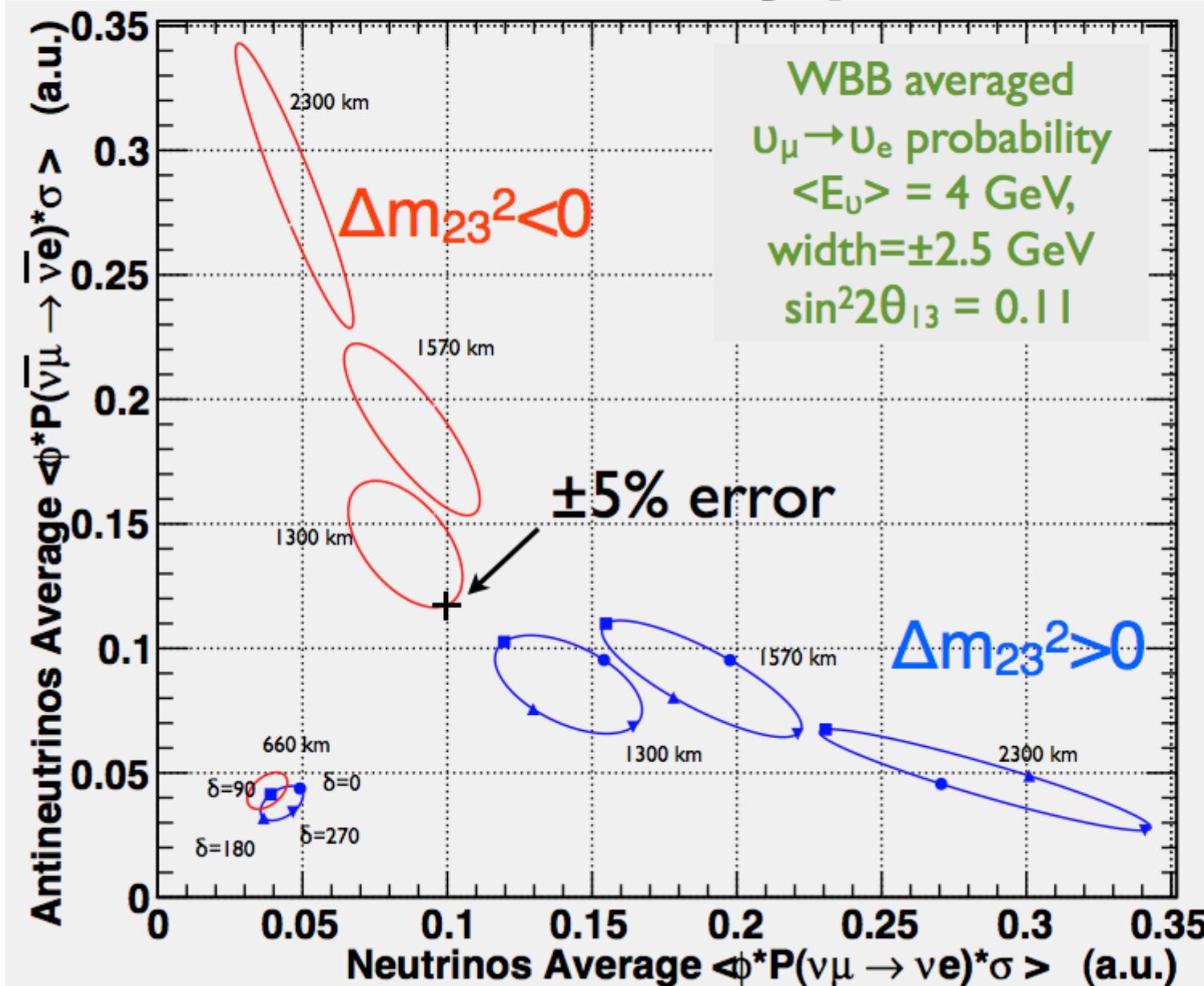
(*) physics reach of LENA option under investigation in LAGUNA - not considered here
 (**) site provides only shallow depth - lower priority

Measuring higher order terms



- Two main modes of investigation (or a combination of both)
 - ★ ν_e Appearance Energy Spectrum Shape in Wide Band Beam (WBB) at fixed L
 - ▶ Peak position and height for 1st, 2nd maximum and minimum
 - ▶ Sensitive to all the non-vanishing δ including 180°
 - ▶ Investigate CP phase with ν run only, but need WBB
 - ▶ Need very good energy resolution and low background systematics
 - ★ Difference between ν_e and $\bar{\nu}_e$ Appearance Behaviors (CP asymmetry)
 - ▶ Also in Narrow Band Beam (off-axis)
 - ▶ Need both beam polarities with similar statistics to study effect
 - ▶ Need good control of systematic errors between neutrino & antineutrino run

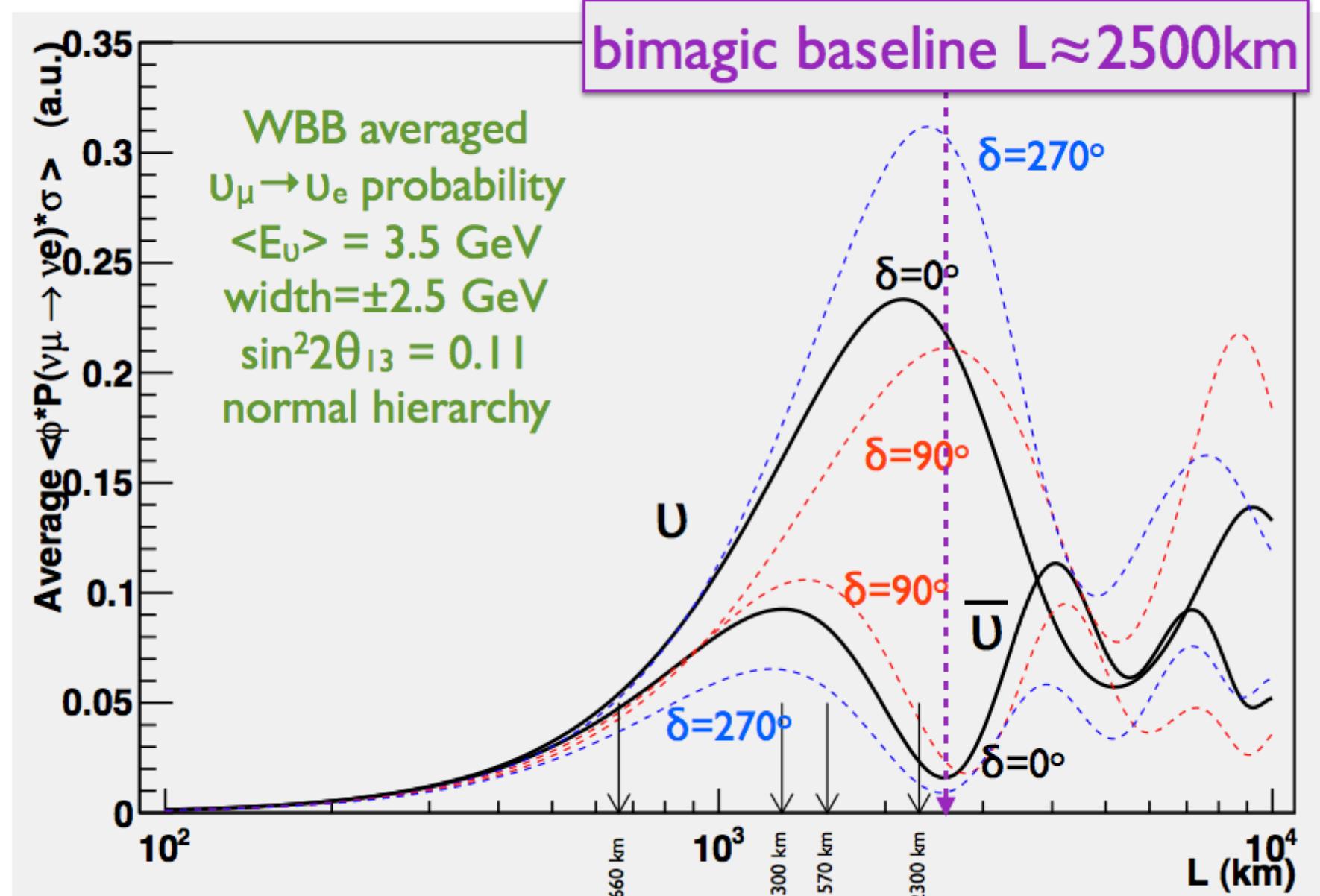
Simultaneous solution to CP and mass hierarchy problems



Longer baselines
are better to
determine mass
hierarchy.

And the two
ellipses are better
separated, which
provides an
unambiguous δ_{CP}
determination

Baseline consideration



The optimal baselines are in the range 1300-2500 km

Staged plans towards high power proton beam facilities

Courtesy: I. Efthymiopoulos

Now → Foreseen upgrades → Major upgrades

JPARC

T2K
(300km)
- 0.15MW operation in 2011



T2K
(300km)
- expected 0.75MW gradually ~2014



T2HK (300km)
Okinoshima(658km)
- expected 1.66MW operation, by >2014

FNAL

NUMI/MINOS
(730km)
- 0.3MW sustained operation



NUMI/NOVA
(810km off-axis)
- 0.75MW upgrade (~2013)



LBNE/DUSEL
(1300 km)
- 2MW operation requires Project-X

CERN

CNGS
(730km)
- 0.3MW sustained operation, 0.5MW if no beam sharing

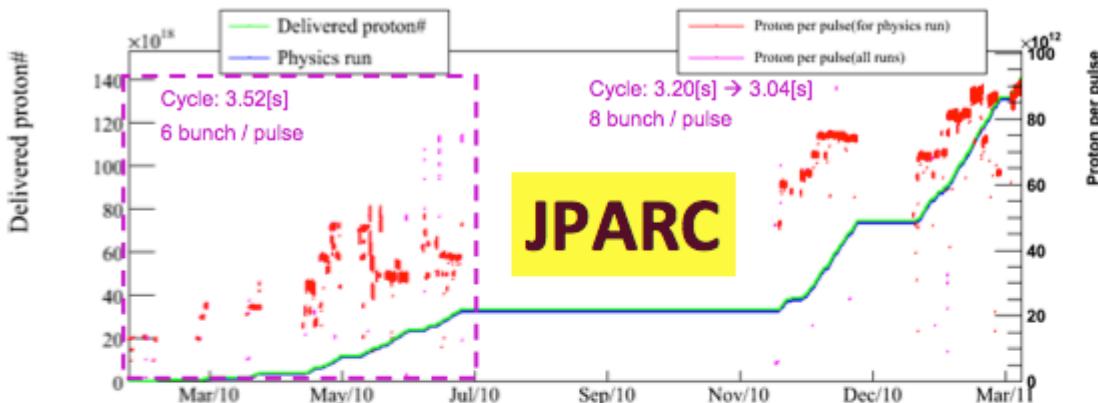


CNGS+ (730km) or CN2PY (2300km)
- 0.75MW "ultimate", requires SPS and injector upgrade

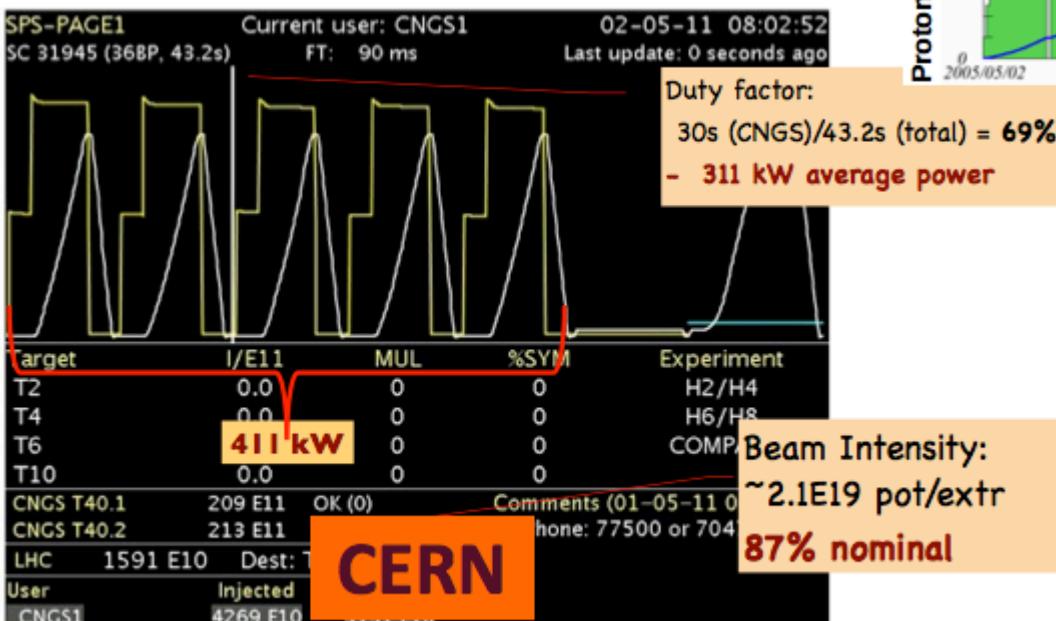


CN2PY(2300km)
CN2FR(130km)
- 2MW operation requires LP-SPL+HPPS, or HP-SPL+Accumulator (4MW)

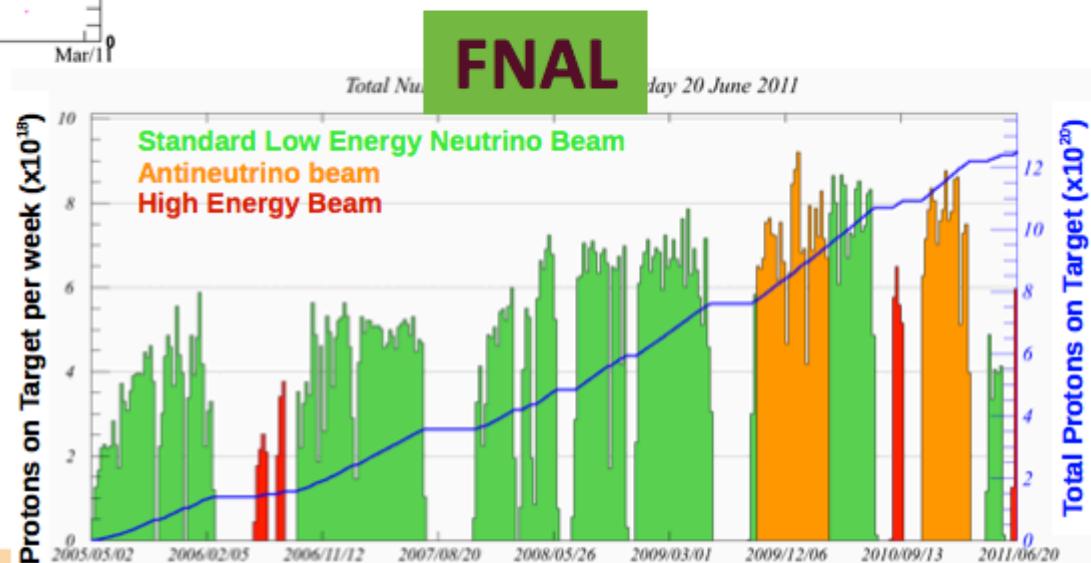
Real life examples



- **145 kW beam power**
- **1.45×10^{20} p.o.t @ 30 GeV** accumulated so far
- MR intensity presently limited by losses at injection



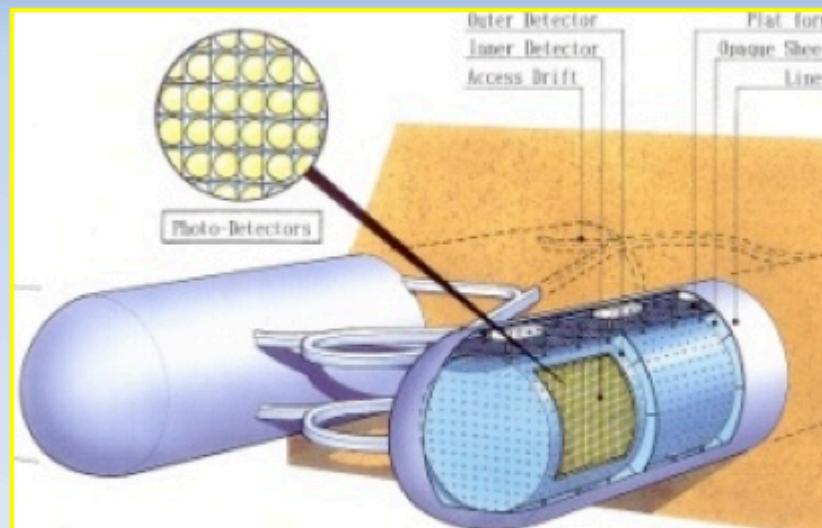
A. Rubbia



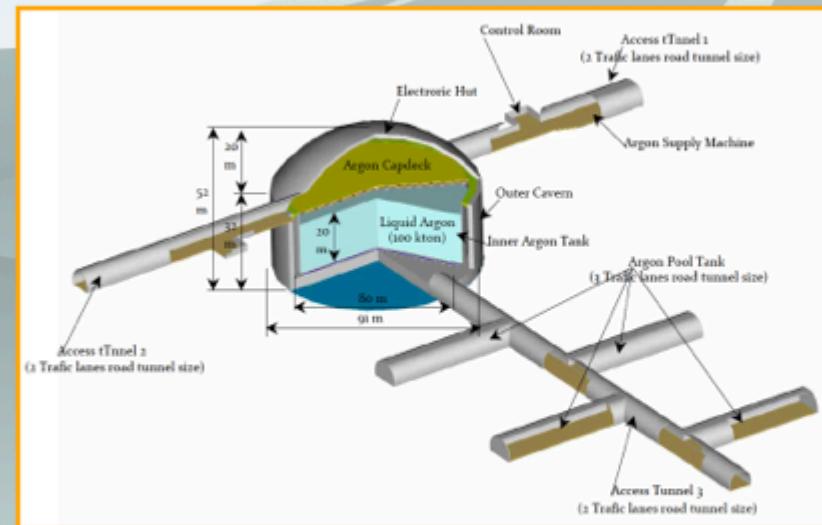
- **300 kW beam power**
- **12.5×10^{20} p.o.t @ 120 GeV** accumulated so far

- **311 kW average beam power**
- **1.5×10^{20} p.o.t @ 400 GeV** accumulated so far
- Integrated intensity limited by shared mode of operation

Kamioka L=295km OA=2.5deg

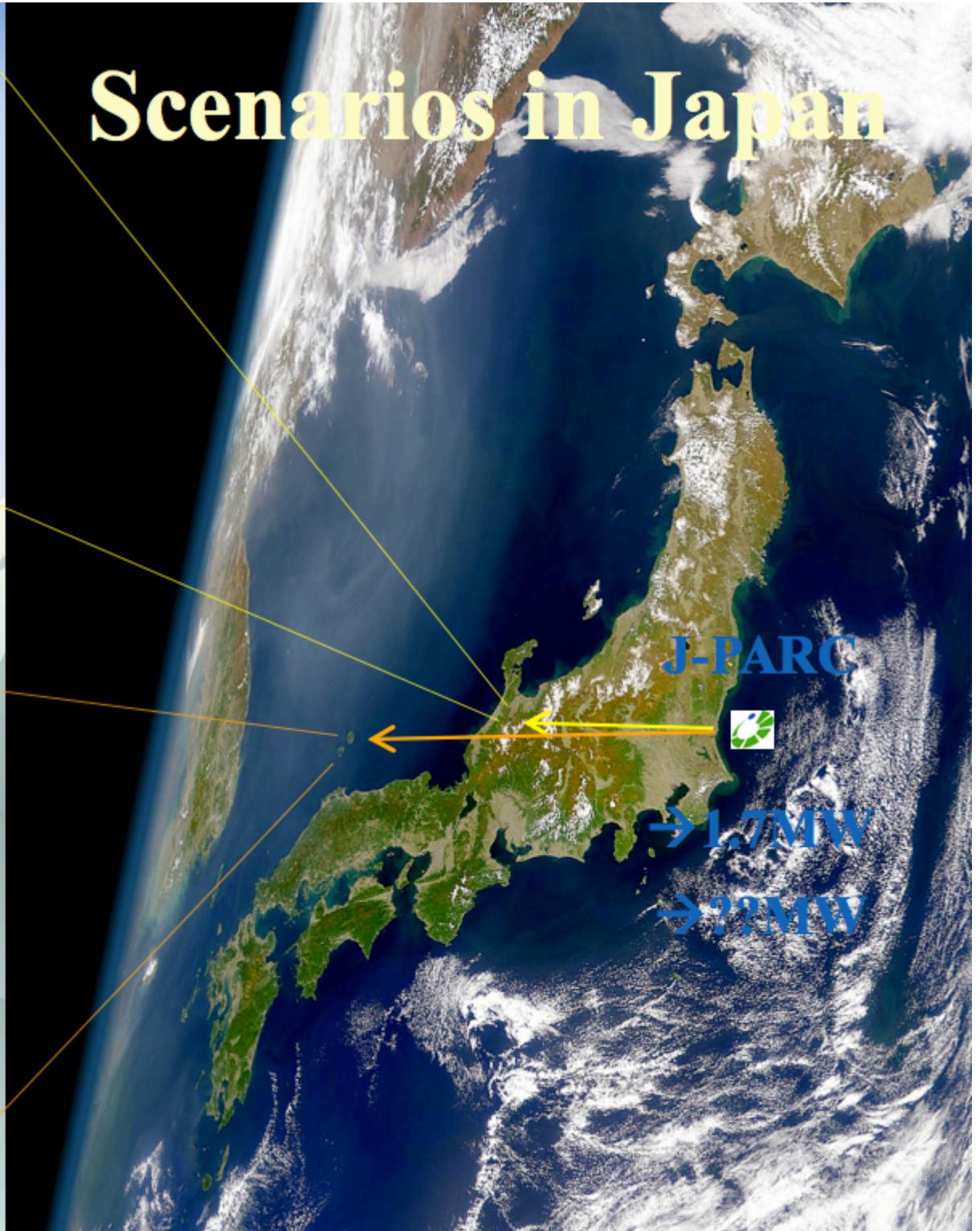


Okinoshima L=658km OA=0.78deg
Almost On-Axis

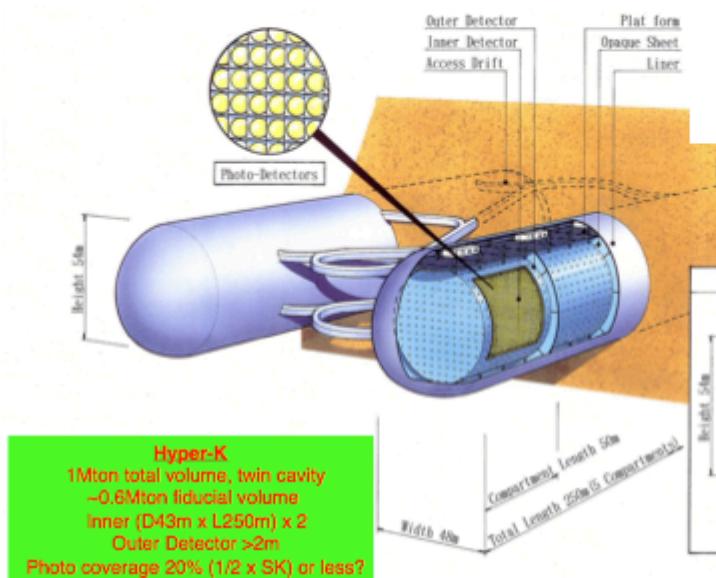


P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111

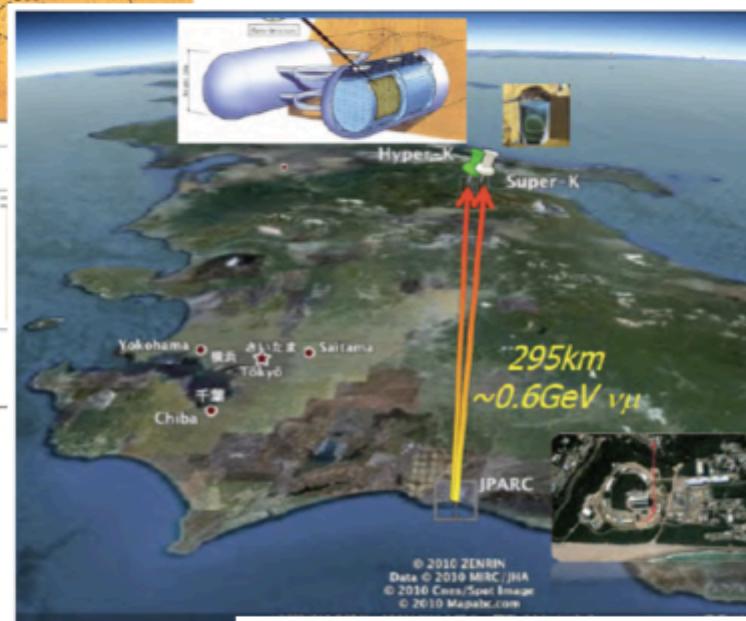
Scenarios in Japan



Upgraded J-PARC + Hyperkamiokande



- ◆ 8km south from Super-K
- ◆ same T2K beam off-axis angle
- ◆ 2.6km horizontal drive from entrance
- ◆ under the peak of Nijuugo-yama
- ◆ 648m of rock or 1,750 m.w.e. overburden

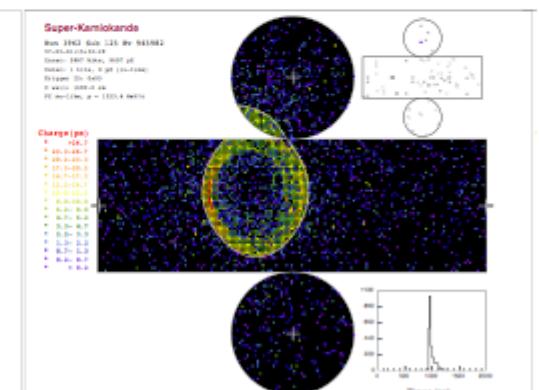
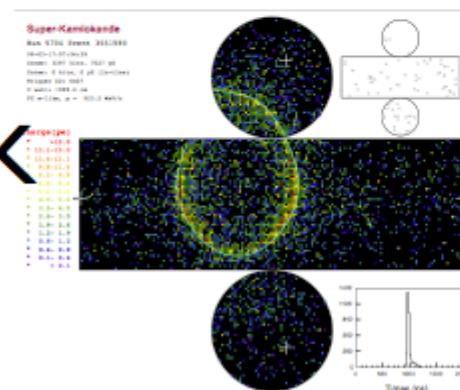


Courtesy: M. Shiozawa



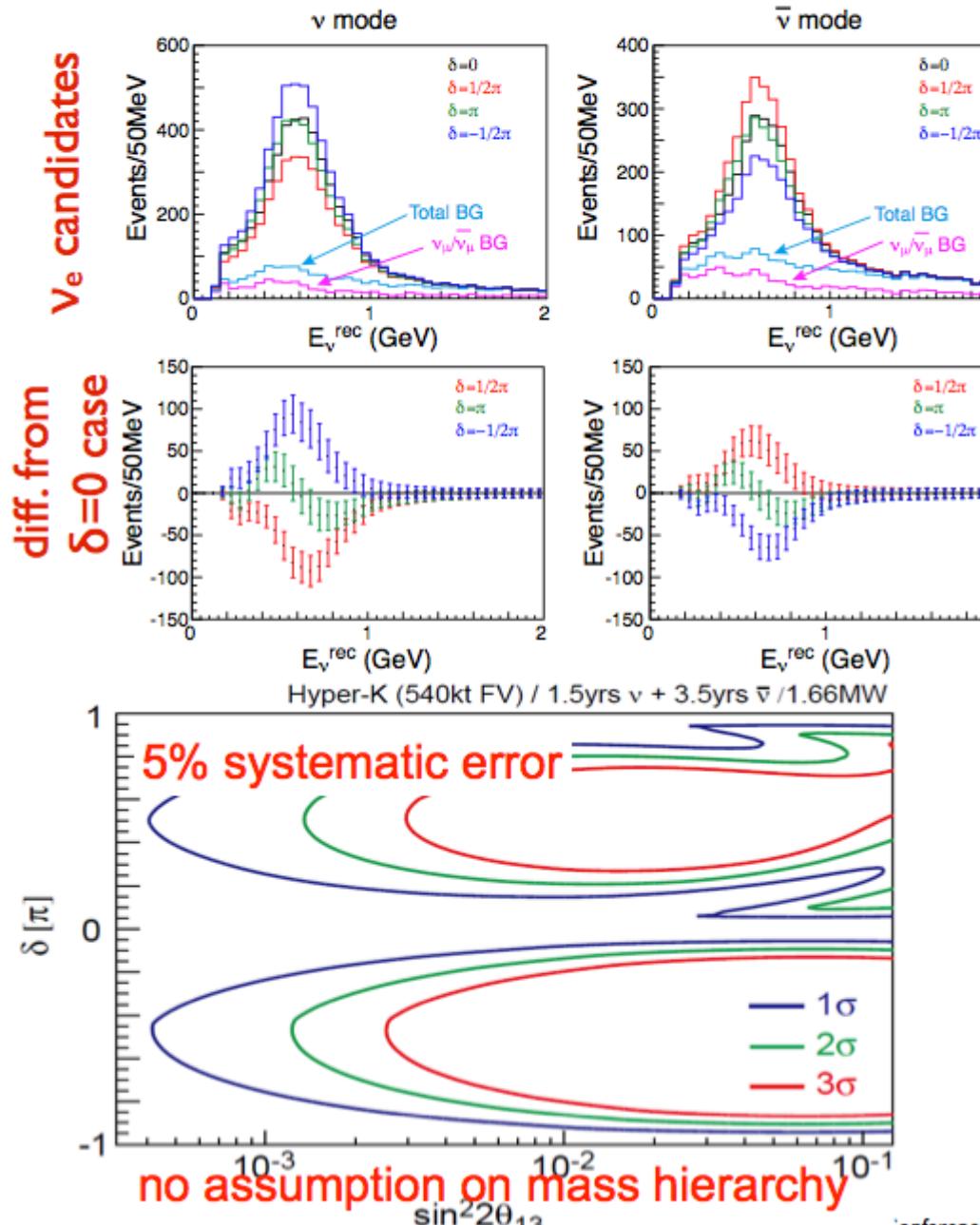
Excellent performance especially for
low energy w/ low multiplicity
Cherenkov threshold
Energy reconstruction assuming CCQE
Efficient for low energy
Good PID (μ/e)
Established analysis
**Good at low E (<1GeV)
narrow band beam**
Match with low energy off-axis beam

SuperK
MC:



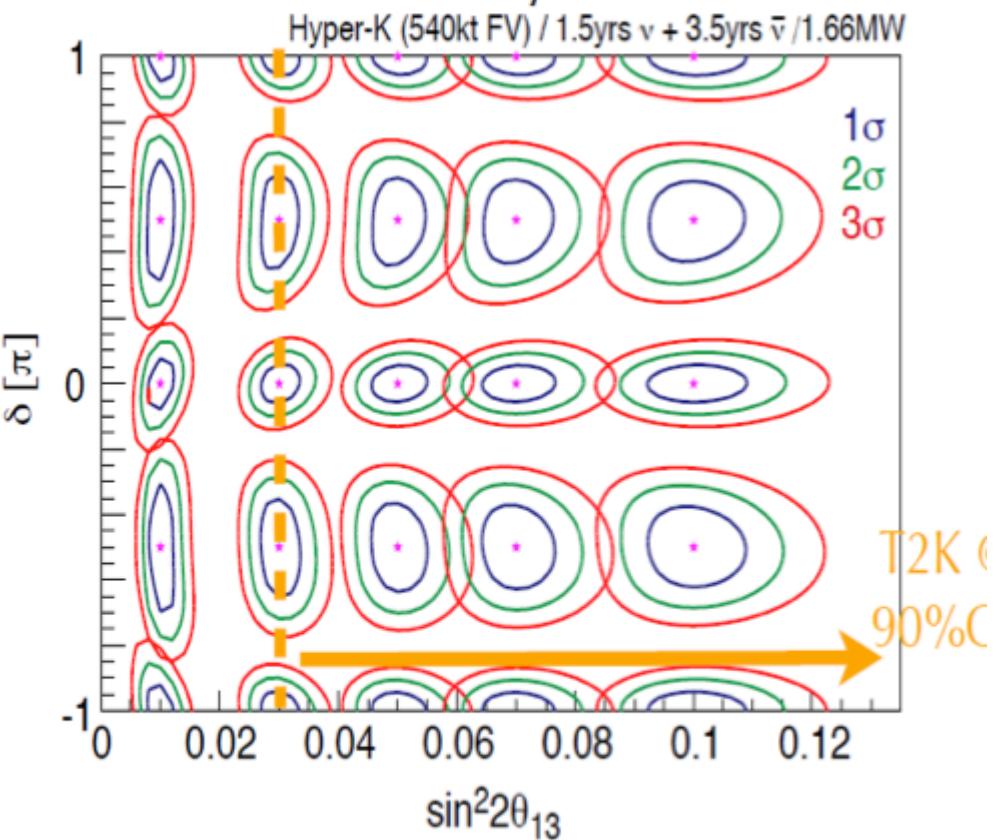
J-PARC + HK physics performance

1.5 yr ν + 3.5 yrs $\bar{\nu}$ @ 1.66 MW



Very good chance to detect CPV & have potential on sign(Δm_{23}) with atm ν
Becomes more difficult for large θ_{13}
Challenge: reach a systematic error <5%

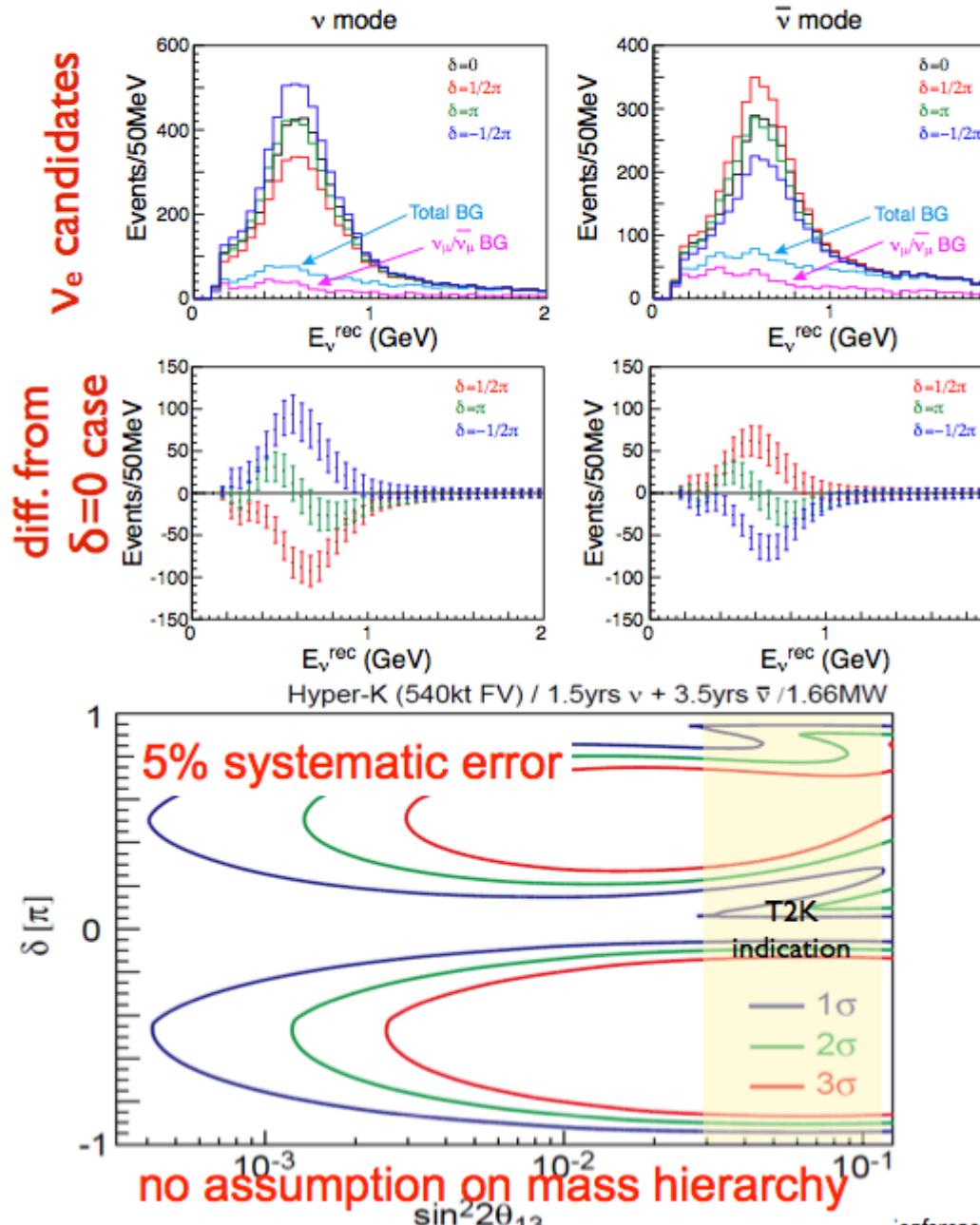
Sensitivity on δ_{CP}



Courtesy: M. Shiozawa

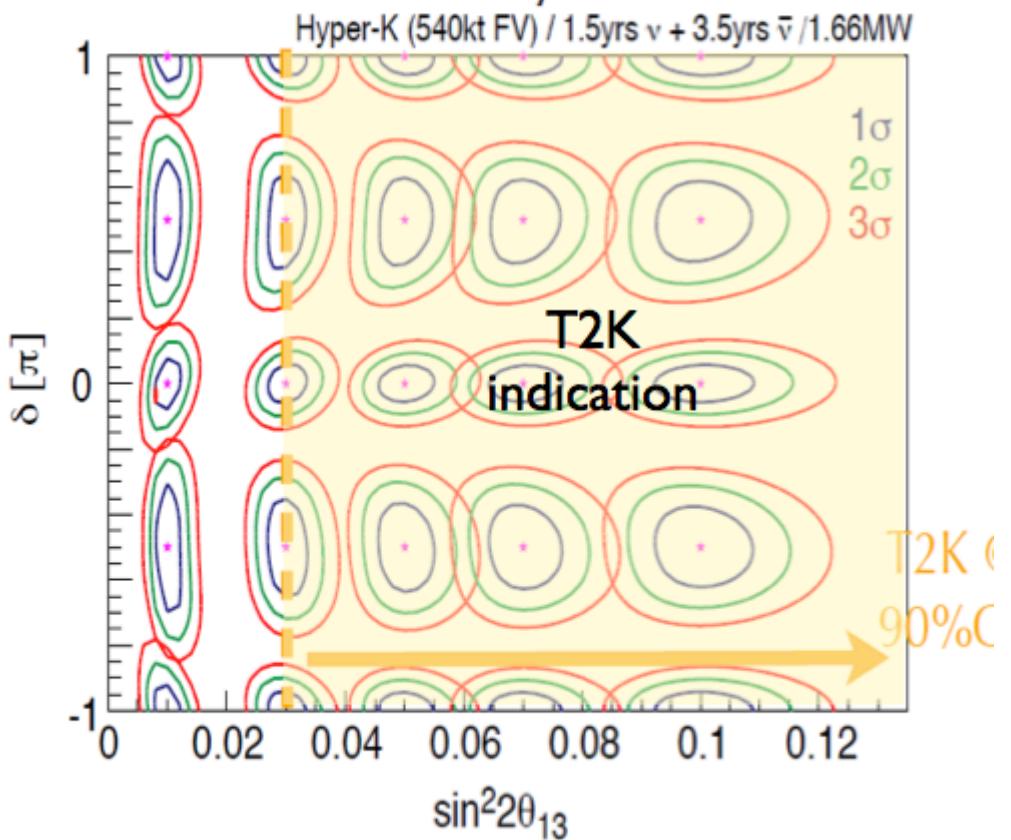
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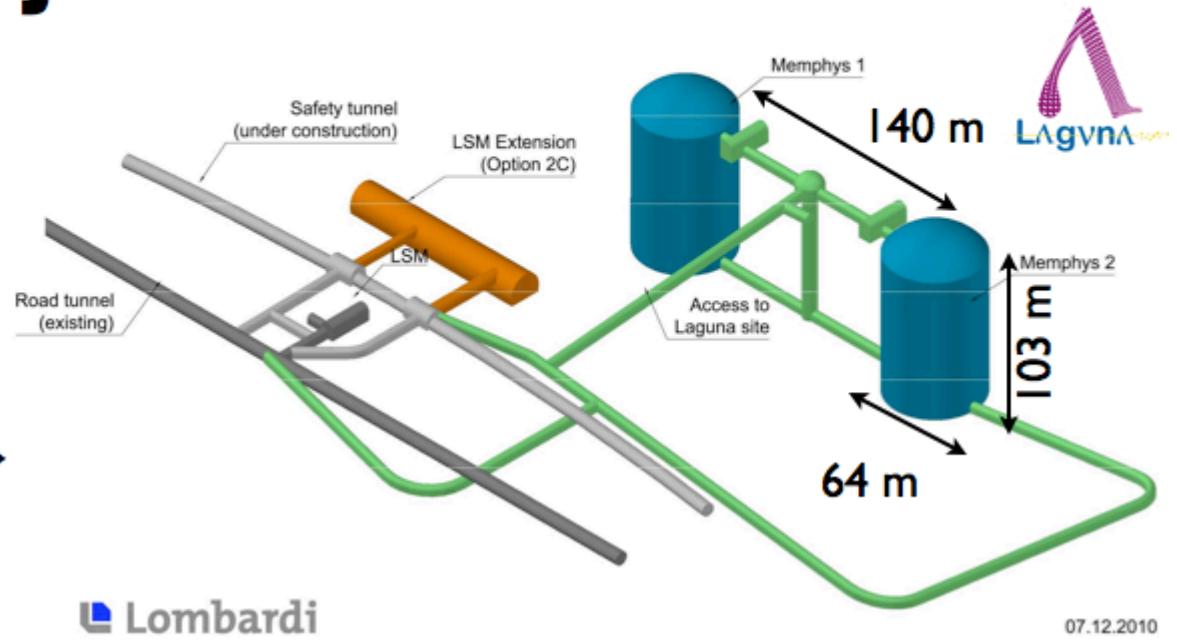
Sensitivity on δ_{CP}



Courtesy: M. Shiozawa

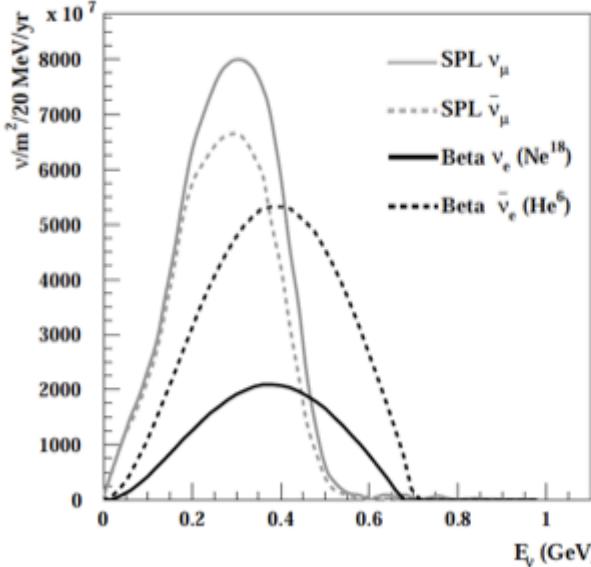
LAGUNA Fréjus w/ MEMPHYS

Water Cerenkov detector,
2 independent modules,
 $330'000 \text{ m}^3$ each
220'000 8-10" PMTs
 $\approx 500 \text{ kton}$ fiducial mass



CERN-Fréjus offers a very short baseline
not considered elsewhere in the world →
unique physics opportunities in Europe
Envision a beta-beam to complement SB

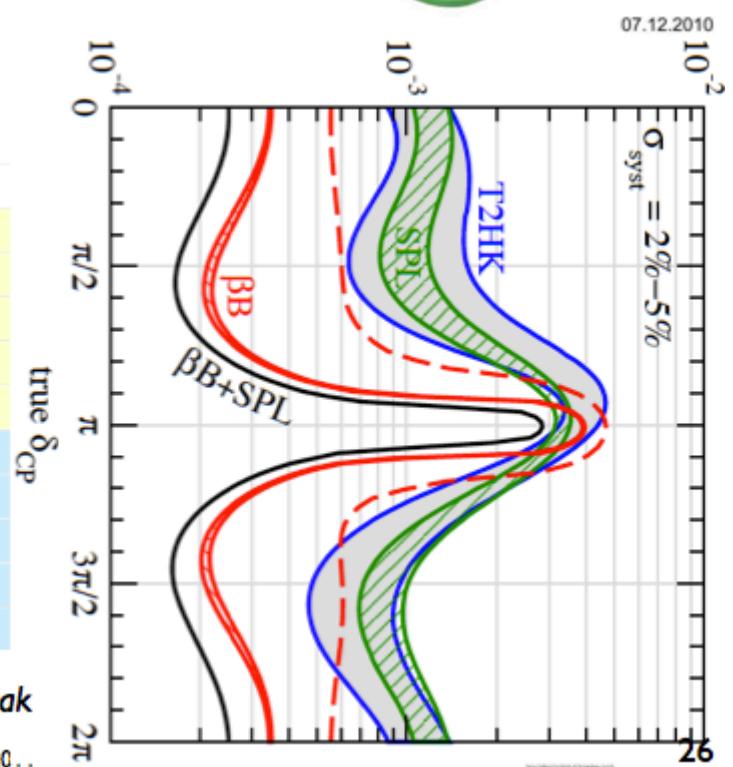
CERN SPL 5 GeV 4MW



2 yr v + 8 yrs v-bar @ 4 MW

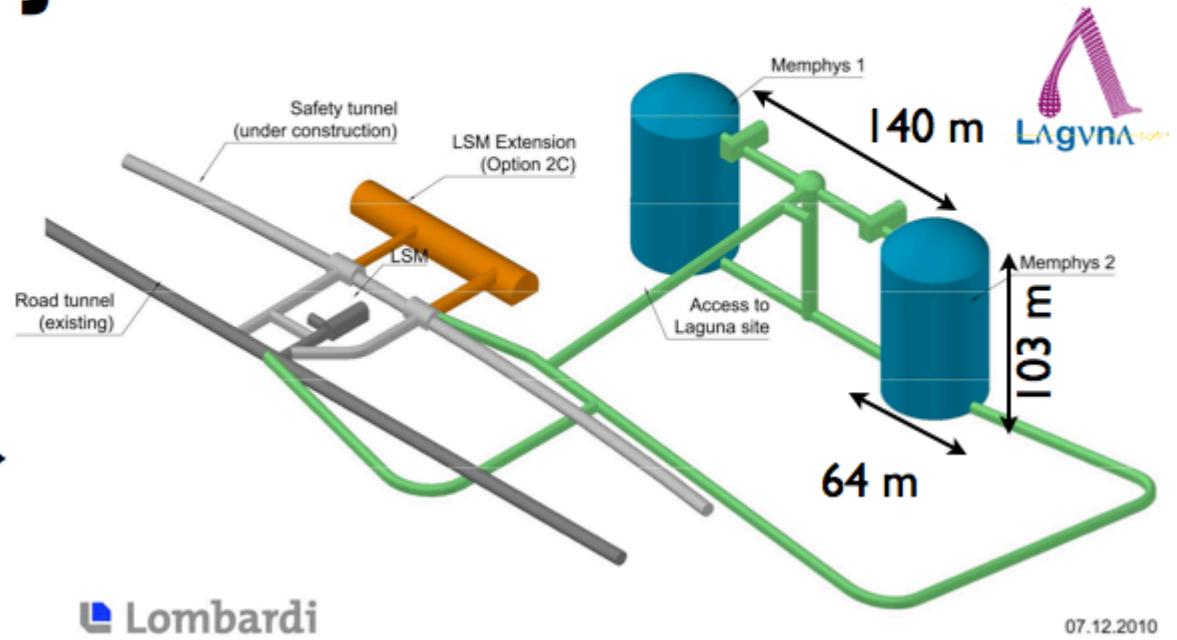
	BB		SB	
	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$
Appearance v				
Bkgd	143	28	622	51
$\sin^2 2\theta_{13} = 0$				
10^{-3}	76	88	105	14
10^{-2}	326	365	423	137
Appearance v-bar				
Bkgd	157	31	640	57
$\sin^2 2\theta_{13} = 0$				
10^{-3}	83	12	102	146
10^{-2}	351	126	376	516

Courtesy: T. Patzak



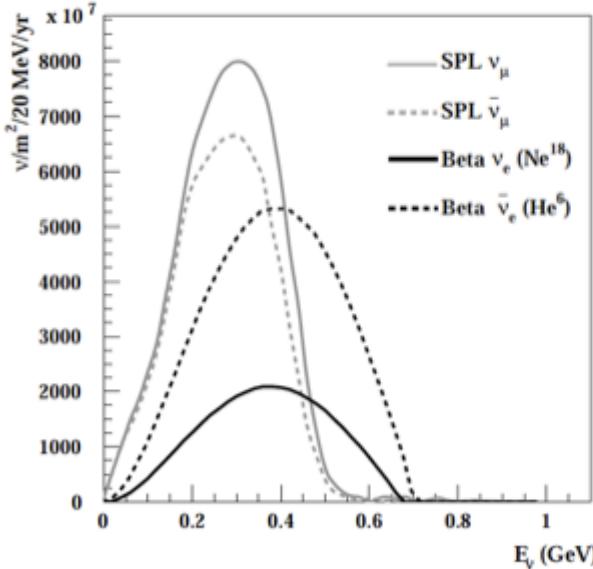
LAGUNA Fréjus w/ MEMPHYS

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 $330'000 \text{ m}^3$ each
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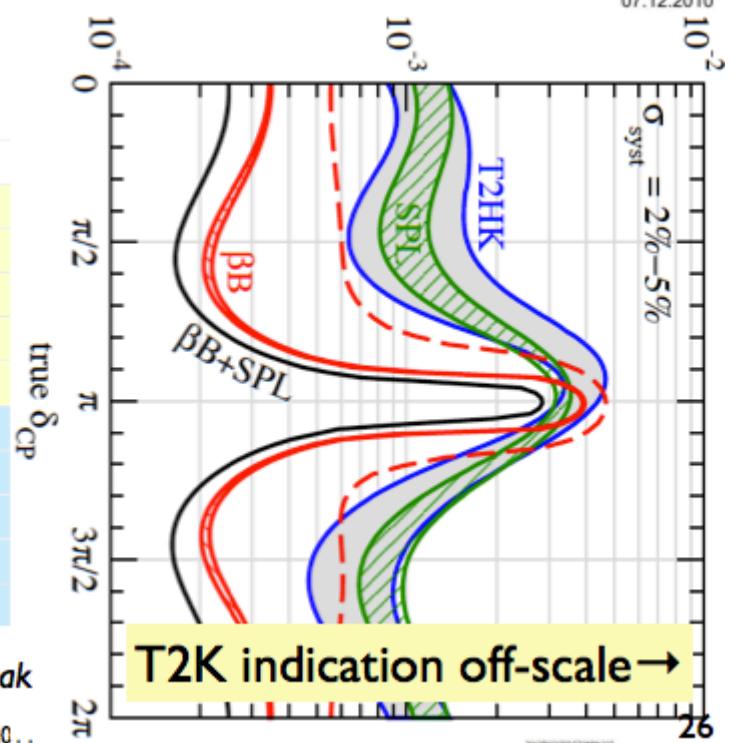
CERN SPL 5 GeV 4MW



2 yr ν + 8 yrs $\bar{\nu}$ @ 4 MW

	BB		SB	
	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$
Appearance ν				
Bkgd	143	28	622	51
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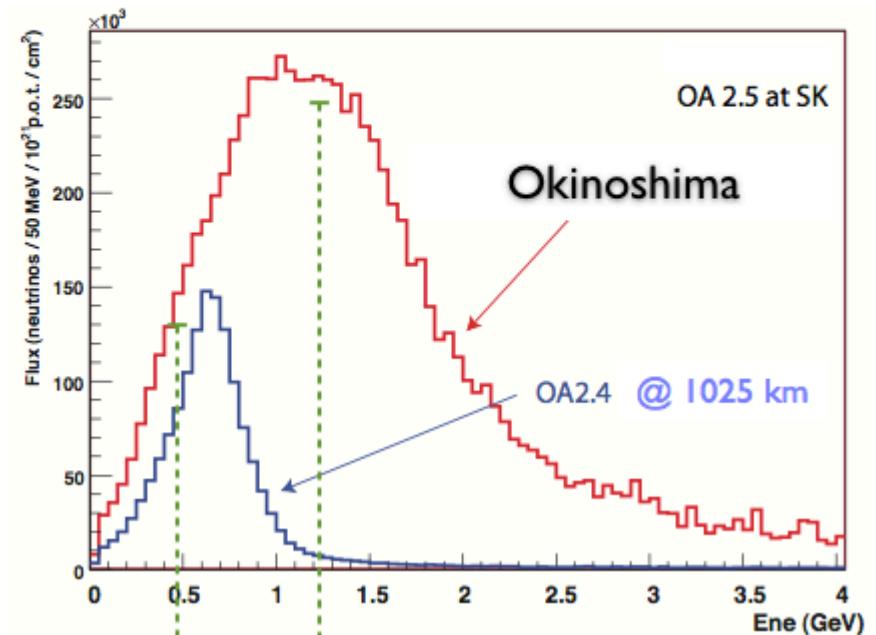
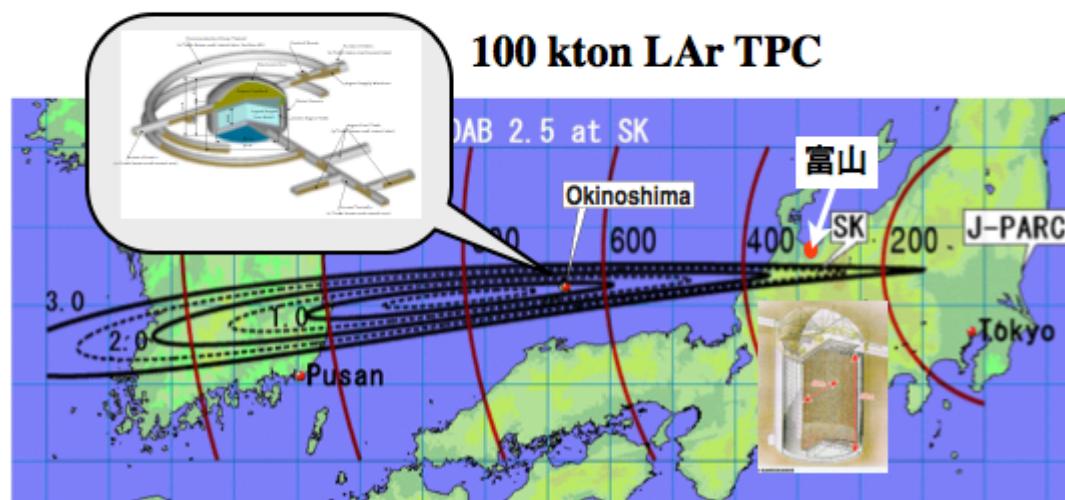
Courtesy: T. Patzak



J-PARC to Okinoshima

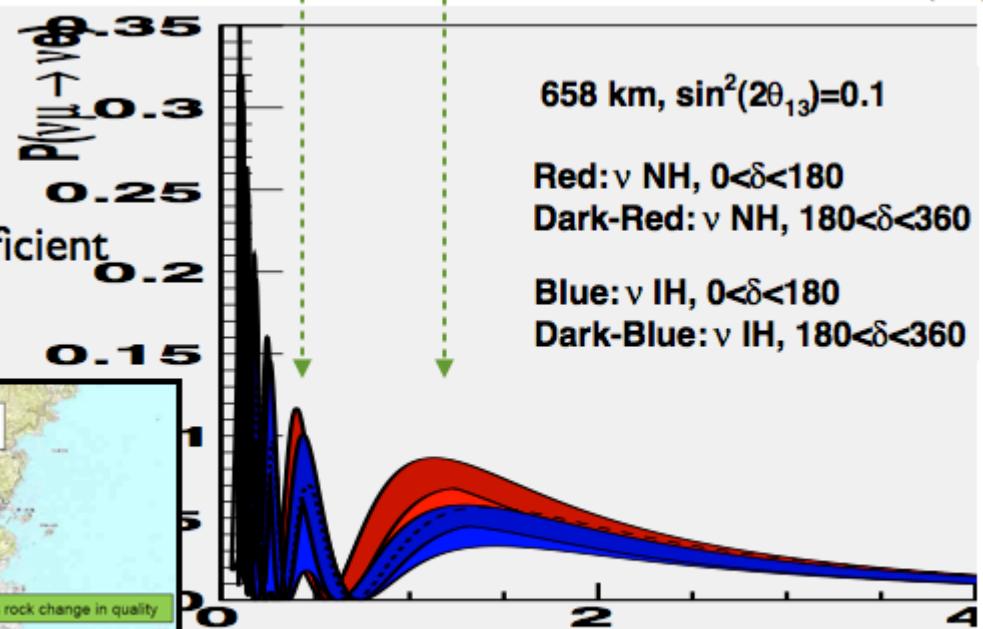
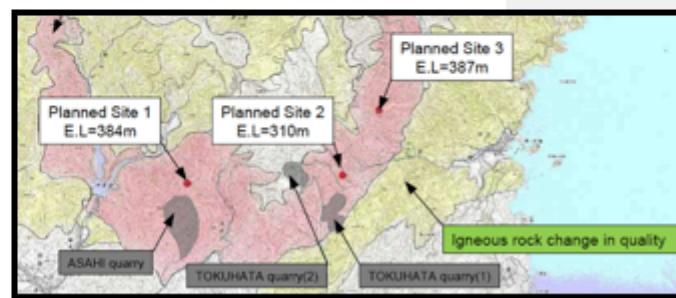
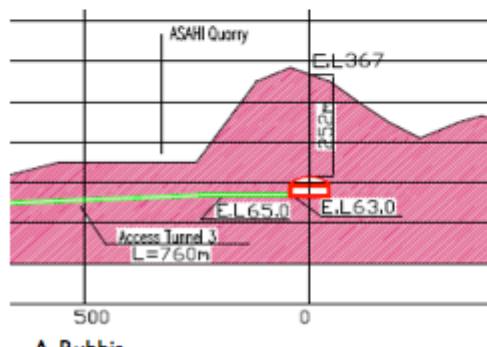
arXiv:0804.2111 [hep-ph] (2008)

P32 proposal (LAr TPC R&D) approved by J-PARC PAC



Okinoshima prestudy :

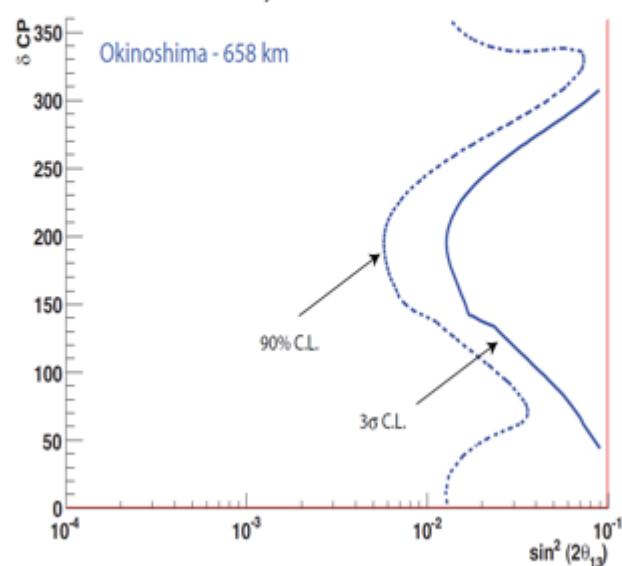
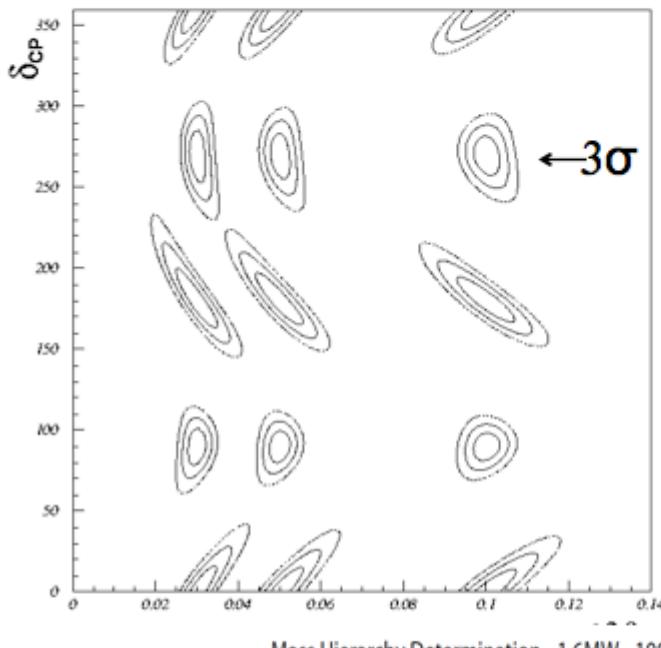
- three best candidate sites on Okinoshima
- bed rock adequate for large cavern
- infrastructure (road, port, electrical power, ...) sufficient
- liquid argon procurement possible via ferries



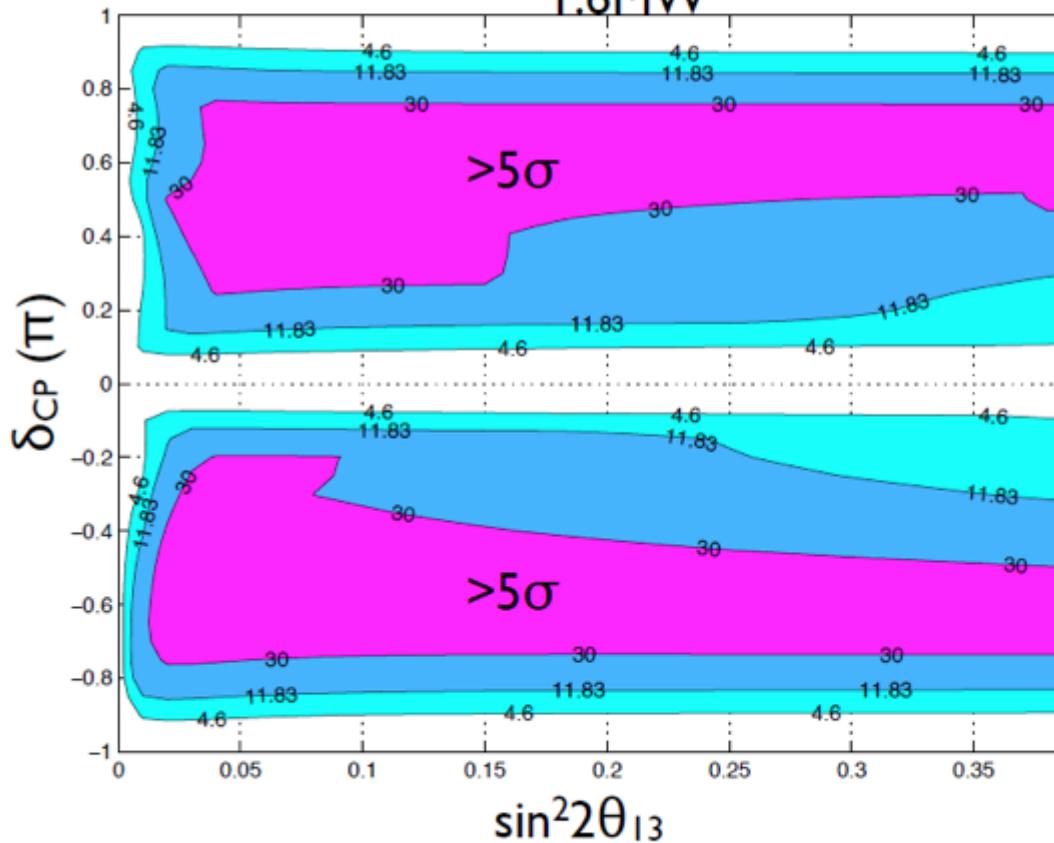
Okinoshima Neutrino event rate and experimental sensitivity

Events in 100 kton, 658 km, 5 years @ 1.66 MW

No Osc.	ν_μ CC	ν_e CC	ν_μ CC	ν_e CC
5 years	82000	750	1460	35



GLACIER 100 kt @ Okinoshima, 5+5 years $\nu + \text{anti}\nu$
1.6MW



“CP-discovery” is defined as the ability to exclude $\delta_{CP} = 0, \pi$ at the given C.L.

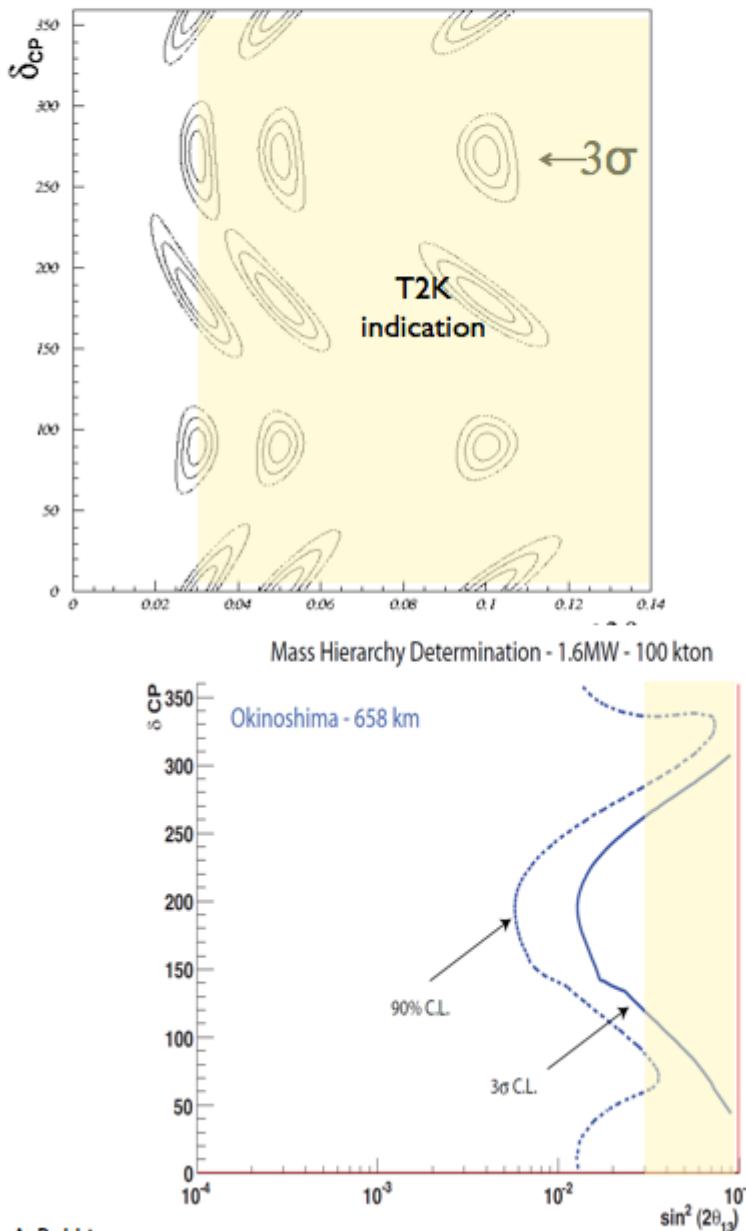
CP-discovery (mass hierarchy **not** known)

A. Rubbia, 18/61

Okinoshima Neutrino event rate and experimental sensitivity

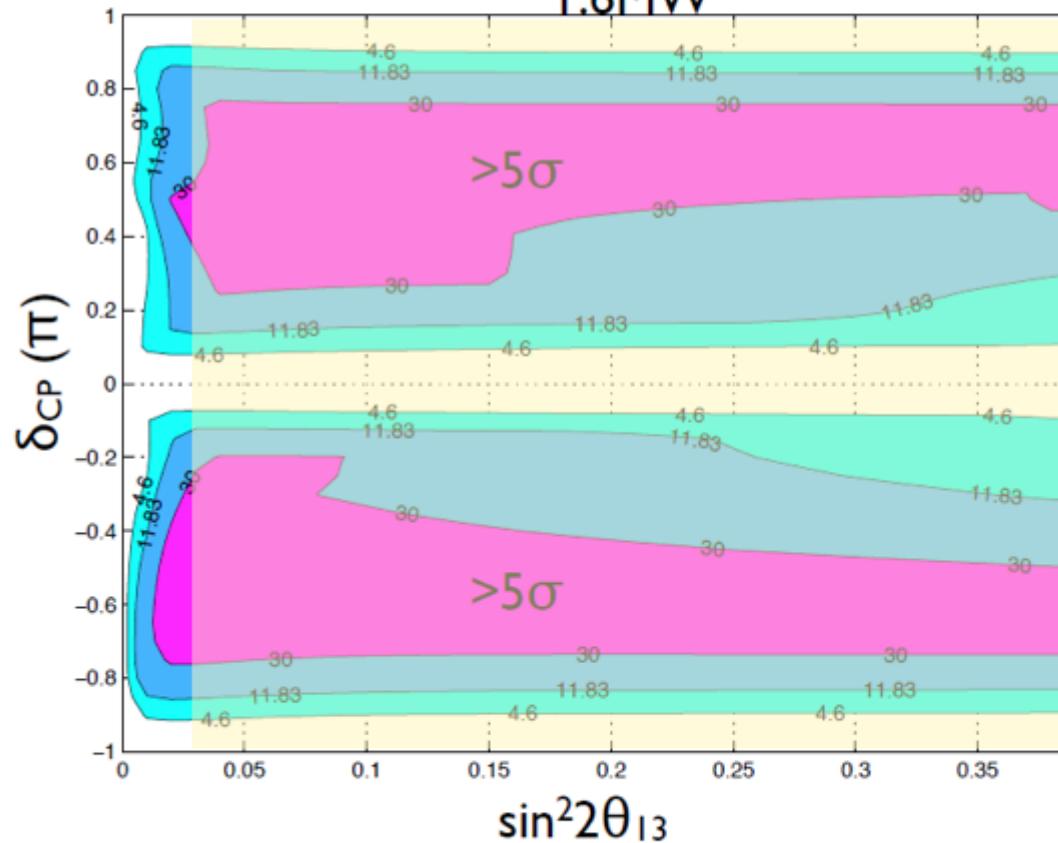
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CP-discovery (mass hierarchy **not** known)
A. Rubbia, 18/61

LAGUNA Pyhäsalmi w/ GLACIER



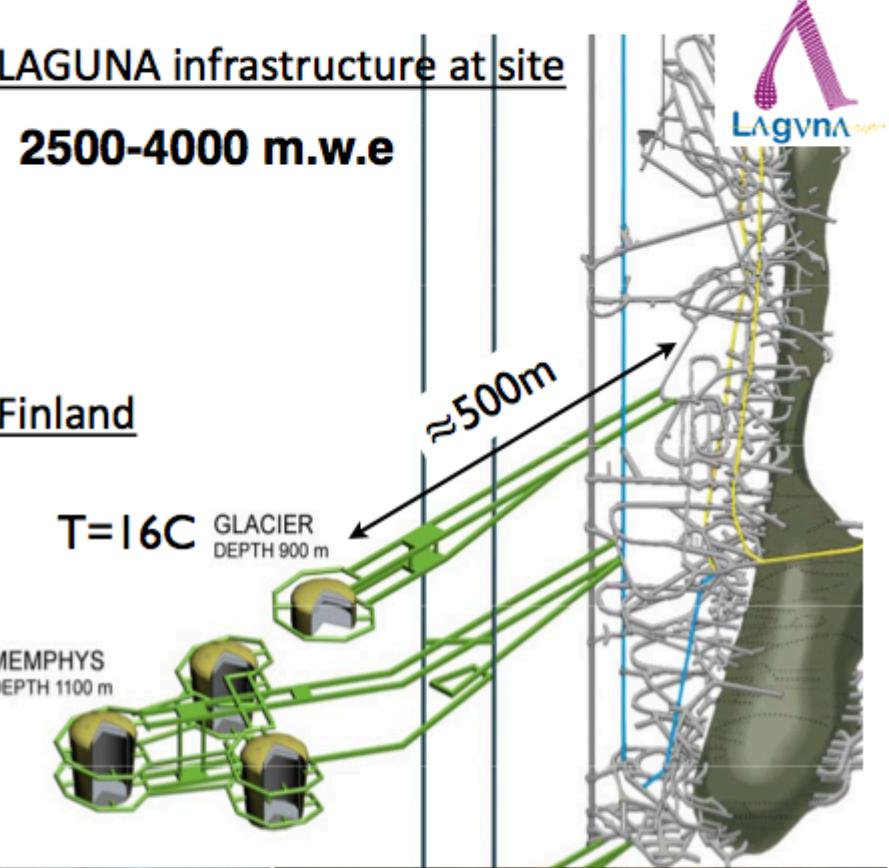
LAGUNA infrastructure at site

2500-4000 m.w.e

Finland

T=16C GLACIER DEPTH 900 m

MEMPHYS DEPTH 1100 m



Main aspects of the infrastructure

- existing working mine with very high standards
- existing decline tunnel access to deepest level
- excellent excavation strategy
- efficient rock disposal
- no disturbance with hosting site
- sufficient fresh air inlet
- effective outlet of return air
- safety
- supply routes for construction
- storage of material
- quality control of material at the vicinity
- supply route (pipe lines) for liquids



Cafeteria, meeting room and sauna at 1400 m below ground



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

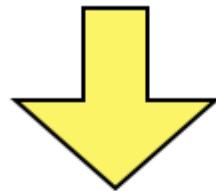
CERN new conventional beams option



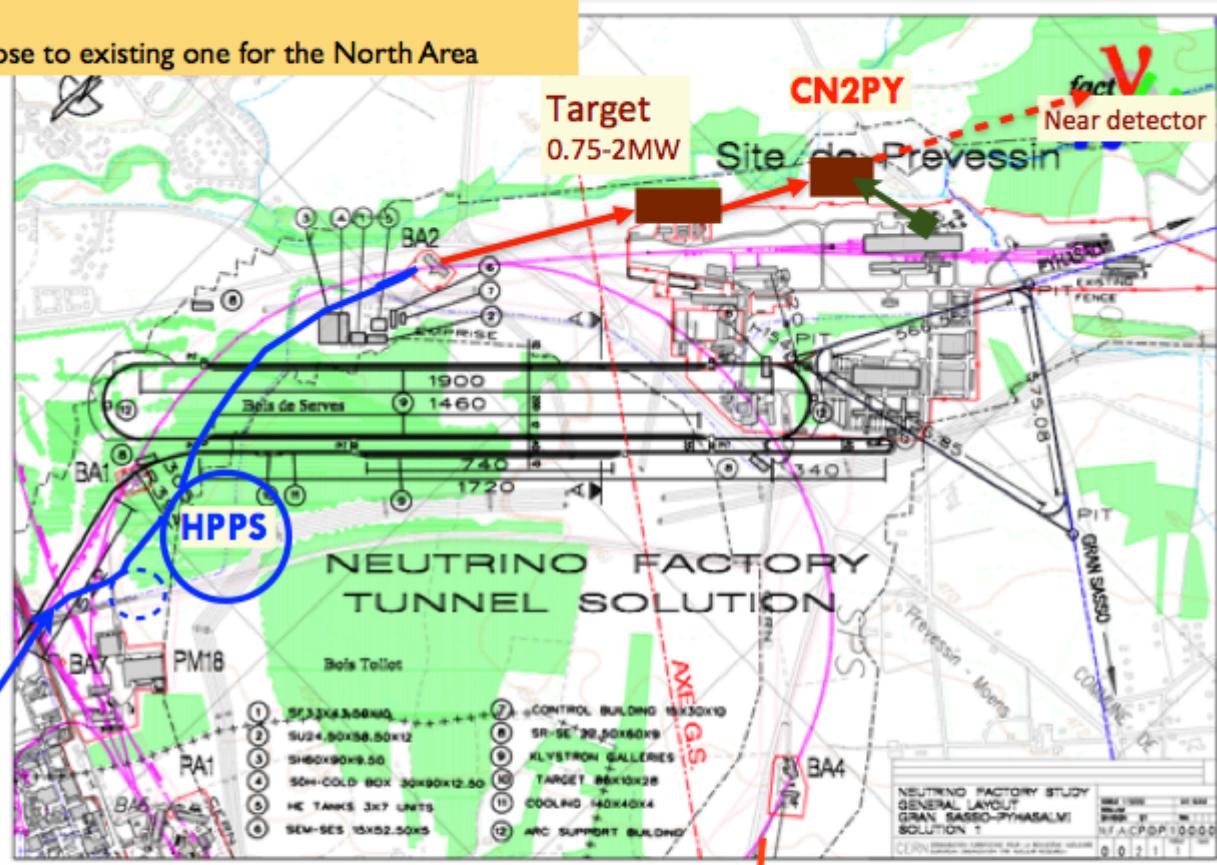
Option B:

Target station close to existing one for the North Area

- Feasibility of new beams approved by CERN study (LAGUNA-LBNO/2011-2014)
- New beam facility accepts protons from 400 GeV SPS and eventual new 50 GeV HP-PS
- Will produce conceptual design reports within 2014



(LP)-SPL

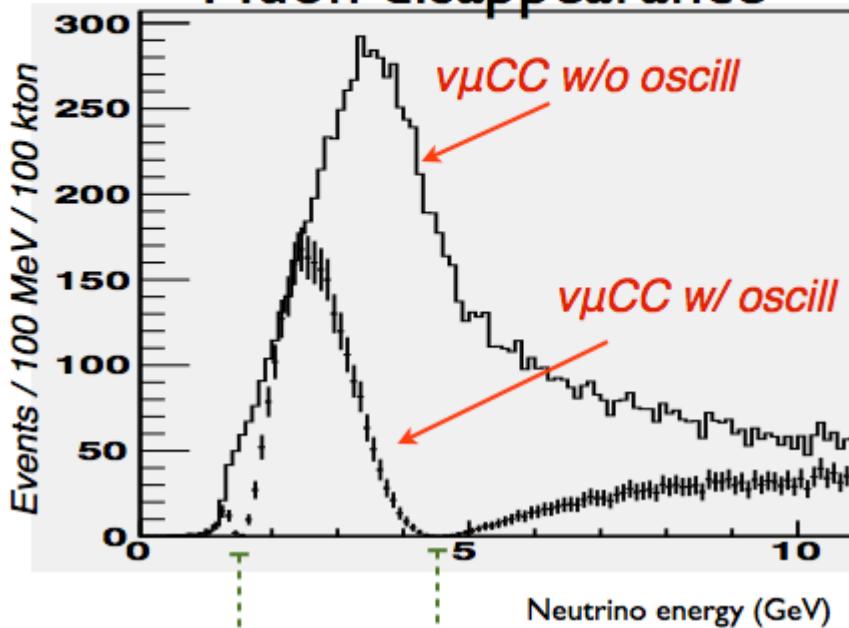


LAGUNA-LBNO:

- **Task 4.1** Study of impact of CERN SPS accelerator intensity upgrade to neutrino beams
- **Task 4.2** Feasibility of intensity upgrade of CNGS facility
- **Task 4.3** Conceptual design of the CN2PY neutrino beam
- **Task 4.4** Feasibility study of a 30-50 GeV high power PS
- **Task 4.5** Definition of the accelerators and beamlines layout at CERN
- **Task 4.6** Study of the Magnetic Configuration for the LAGUNA detector
- **Task 4.7** Definition of near detector requirements and development of conceptual design

LAGUNA Pyhäsalmi experimental sensitivity

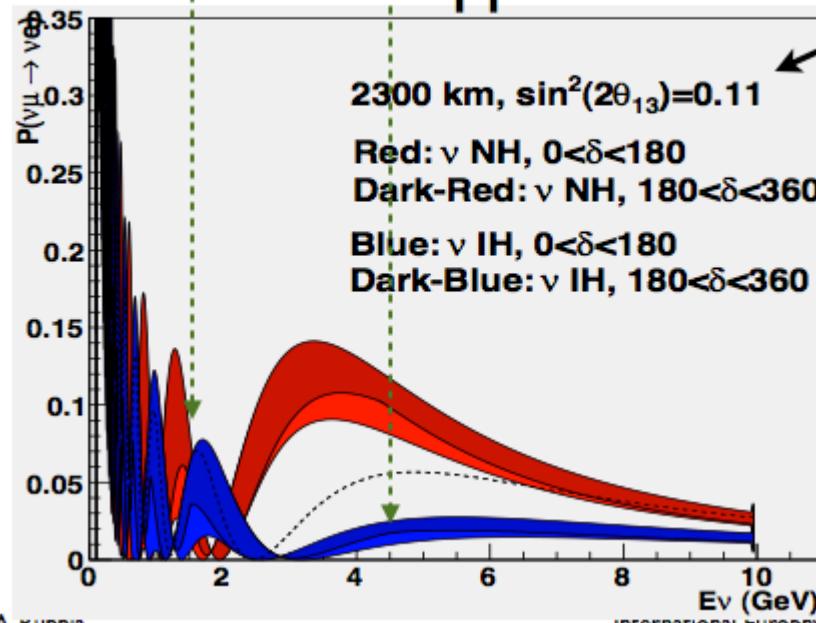
Muon disappearance



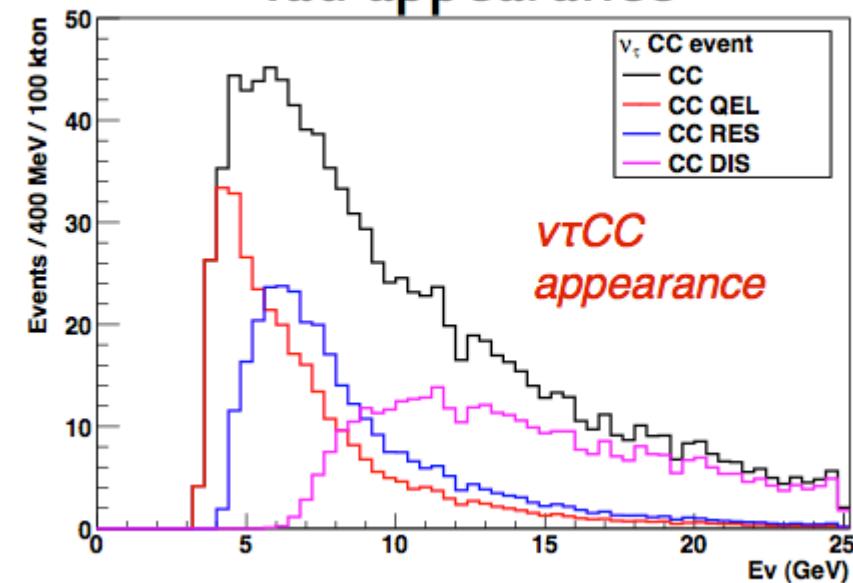
Event rates: CERN SPS 400 GeV
5 years @ 9.4×10^{19} pots/year

Distance/OA	Neutrino horn polarity $\sin^2 2\theta_{23} = 1.0, \sin^2 2\theta_{13} = 0.1$			
	$\nu_\mu CC$	$\nu_e CC$	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Pyhäsalmi 2300 km 0.25 deg	17152	250	880	1018

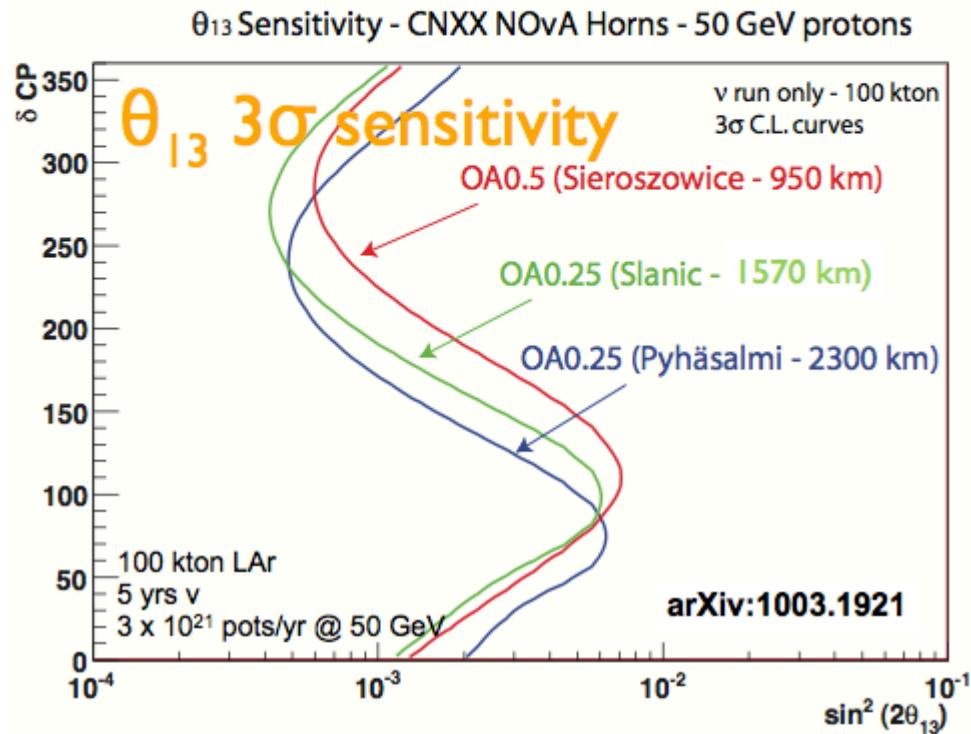
Electron appearance



Tau appearance

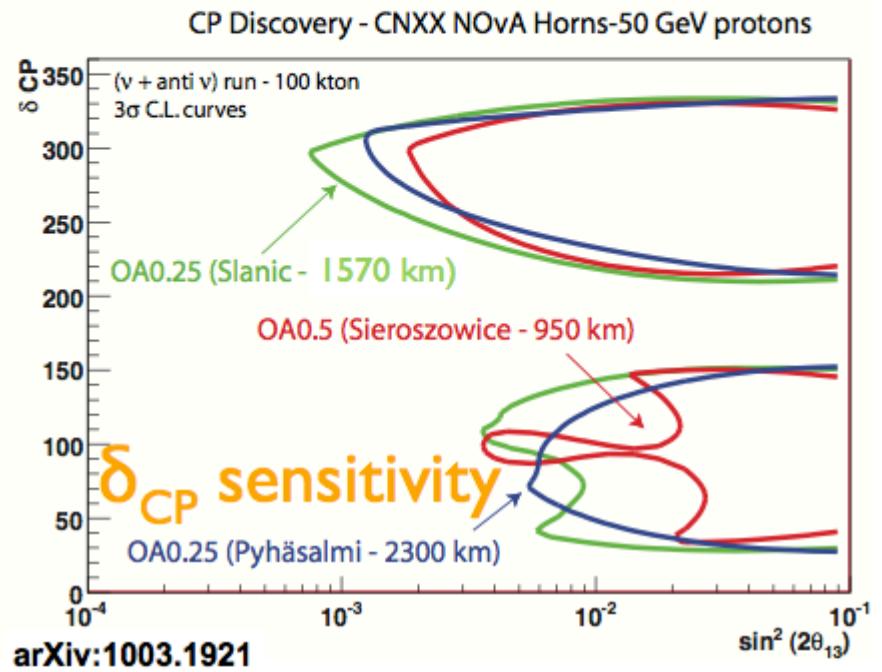


LAGUNA Pyhäsalmi experimental sensitivity

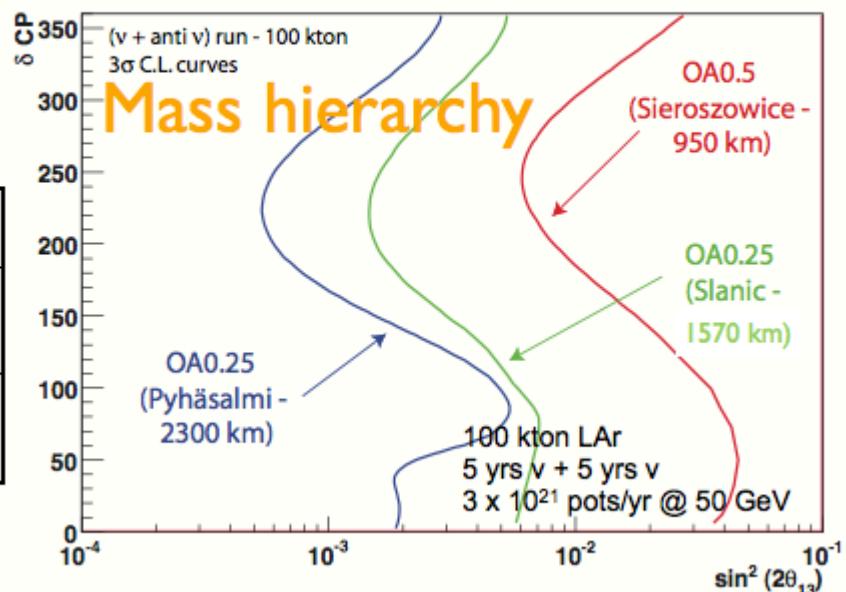


Event rate per year: 50 GeV HP-PS,
 3×10^{21} pots/yr, 1.6 MW

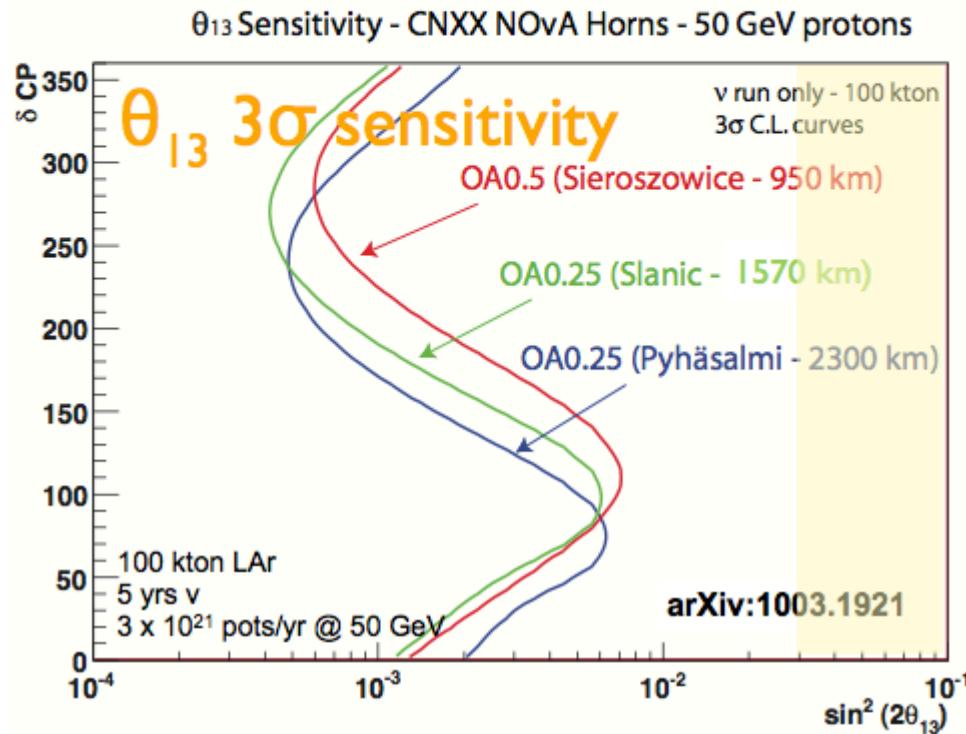
No Osc.	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
positive horn 1 year	17257	110	203	7
negative horn 1 year	471	16	7577	32



Mass Hierarchy Exclusion - CNXX NOvA Horns-50 GeV protons

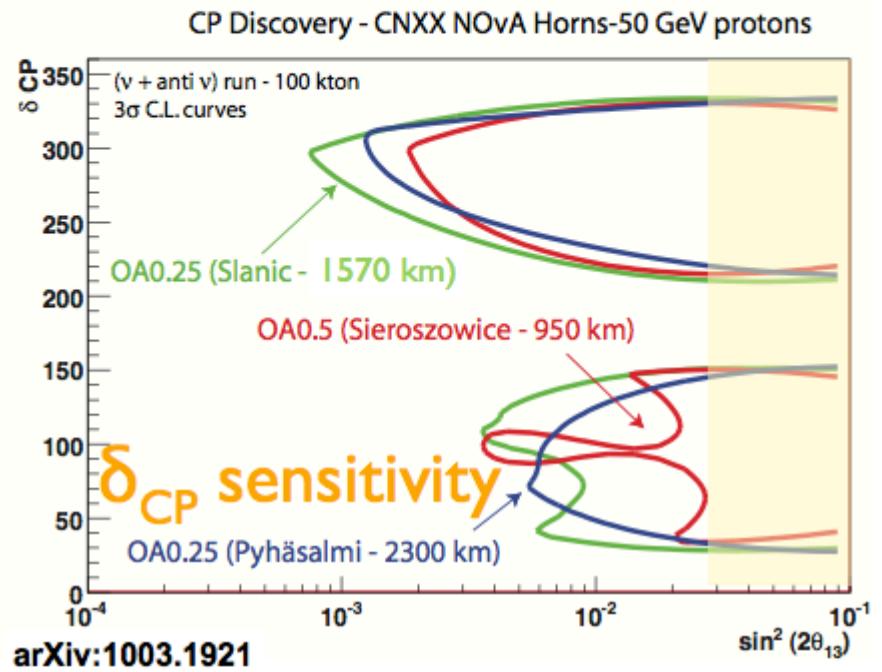


LAGUNA Pyhäsalmi experimental sensitivity

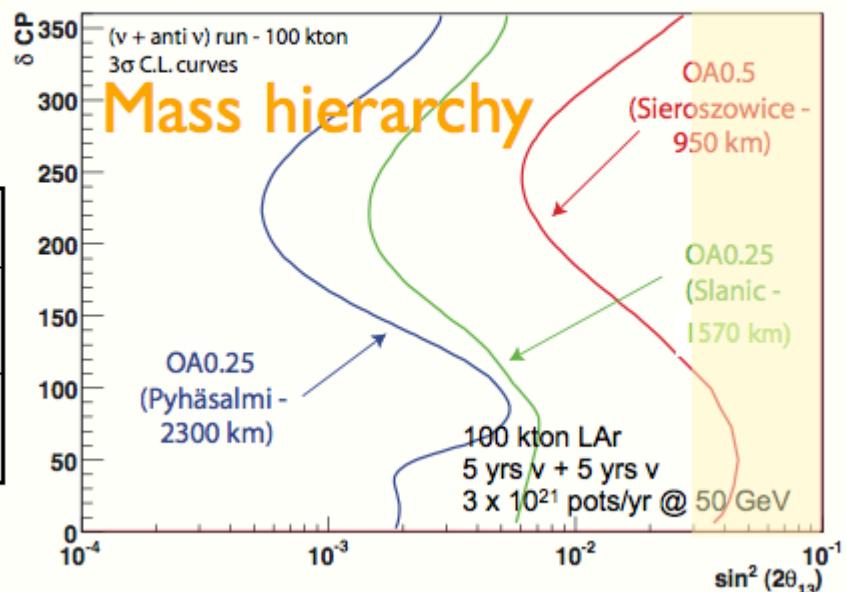


Event rate per year: 50 GeV HP-PS,
3 x 10²¹ pots/yr, 1.6 MW

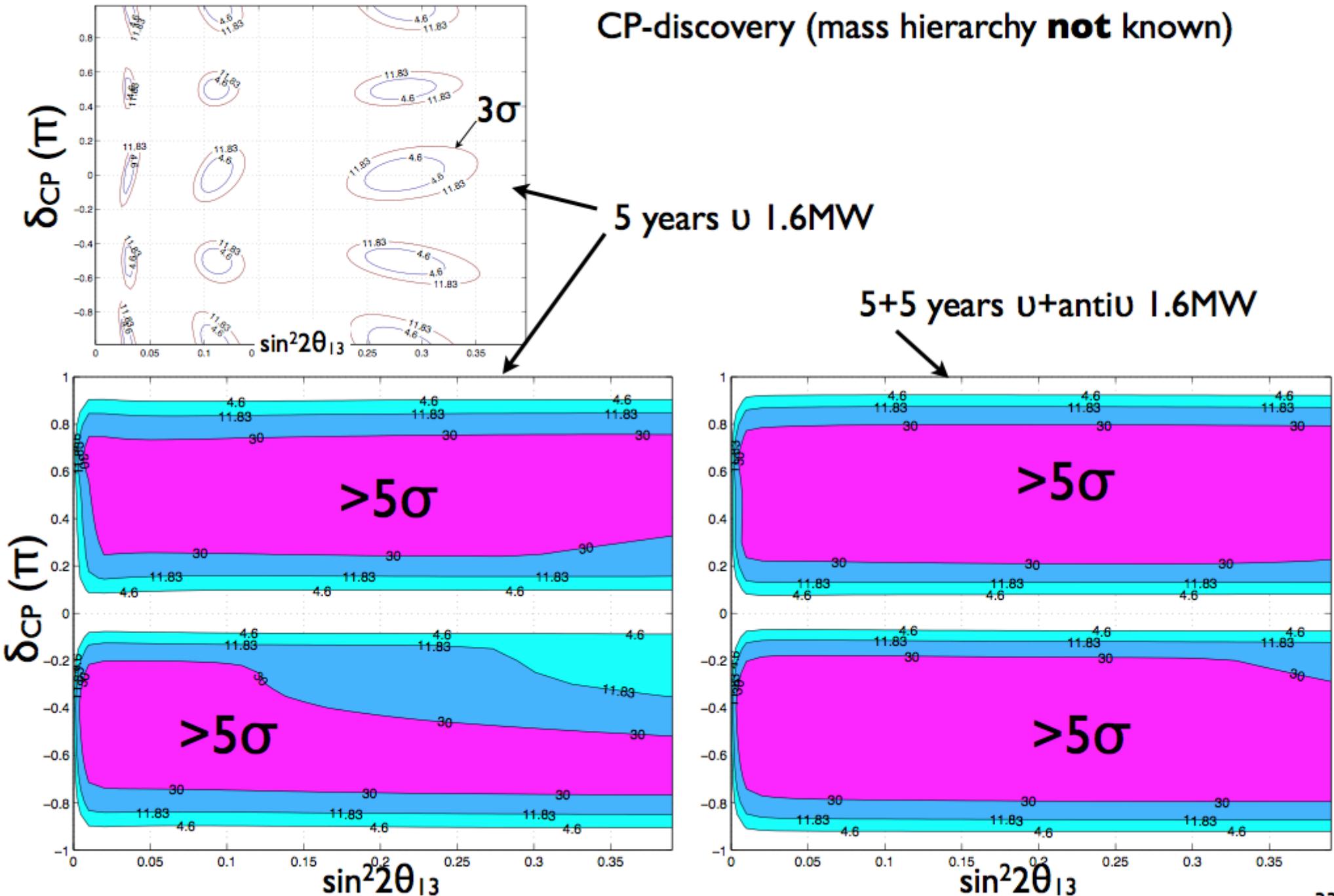
No Osc.	v_μ CC	v_e CC	\bar{v}_μ CC	\bar{v}_e CC
positive horn 1 year	17257	110	203	7
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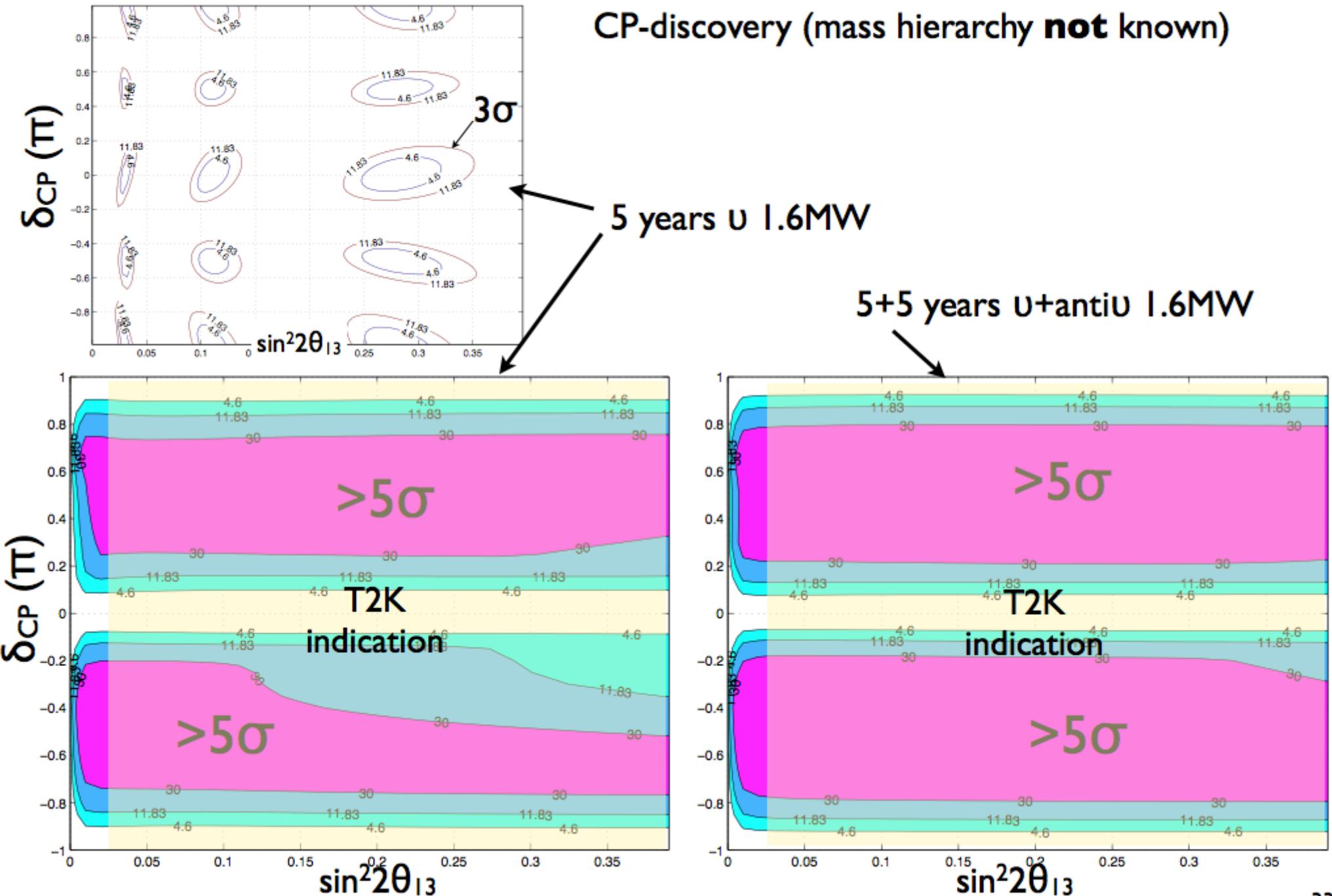
Mass Hierarchy Exclusion - CNXX NOvA Horns-50 GeV protons



LAGUNA Pyhäsalmi experimental sensitivity



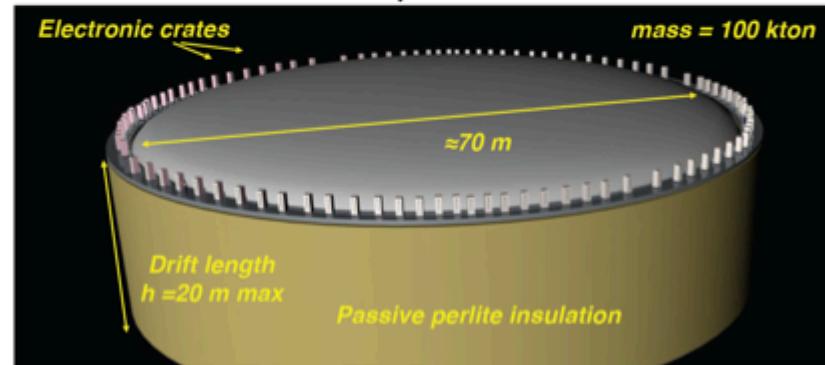
LAGUNA Pyhäsalmi experimental sensitivity



Giant Liquid Argon Detector (KEK-ETHZ)

Giant Liquid Argon Charge Imaging ExpeRiment

A scalable detector with a non-evacuable dewar and ionization charge detection with amplification



Single module non-evacuable cryo-tank based on industrial LNG technology

Cylindrical shape with excellent surface / volume ratio

Simple, scalable detector design, possibly up to 100 kton

A. Rubbia hep-ph/0402110
Venice, Nov 2003

Extremely high performance
“Electronic Bubble Chamber”
3D tracking of all charged particle from
very low energy threshold

Precise resolution of ~mm

Fully active homogeneous 4π detector
(as WC)

Good PID w/ dE/dx , π^0 rejection

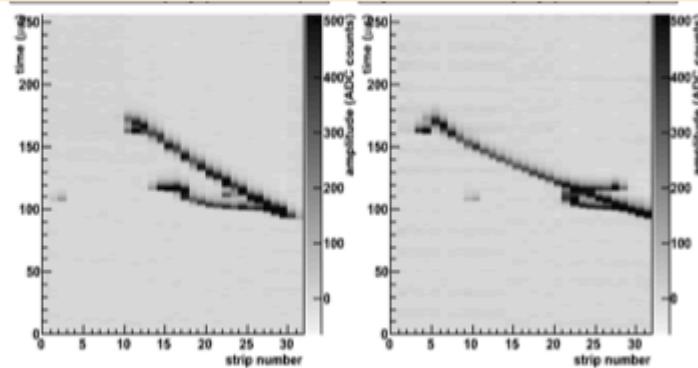
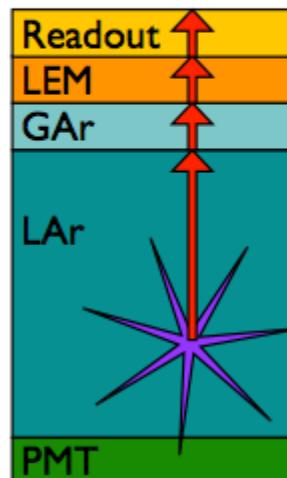
Double phase w/ Gas amplification

<10 ppt purity needed

LEM readout ($\sim 10^6$ ch)

600ton detector realized and working

Double phase charge readout w/ adjustable gain

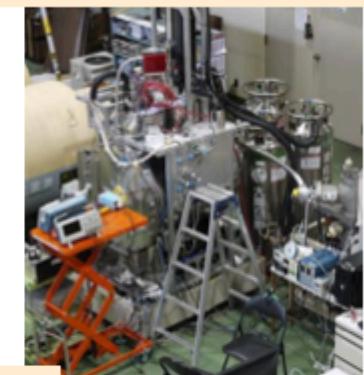


Much improved S/N (>100) compared
to single-phase LAr operation (≈ 15)

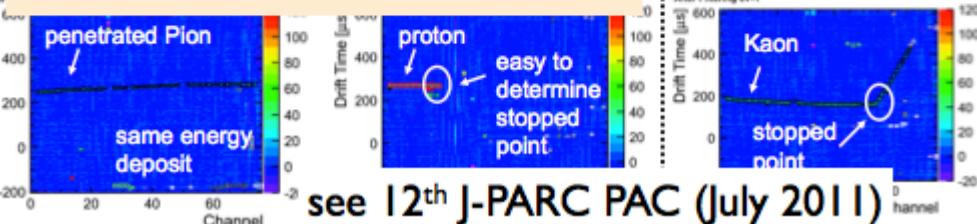
ArDM-1ton (CERN RE18 Collab)



Test beam at J-PARC (T32 Collaboration)



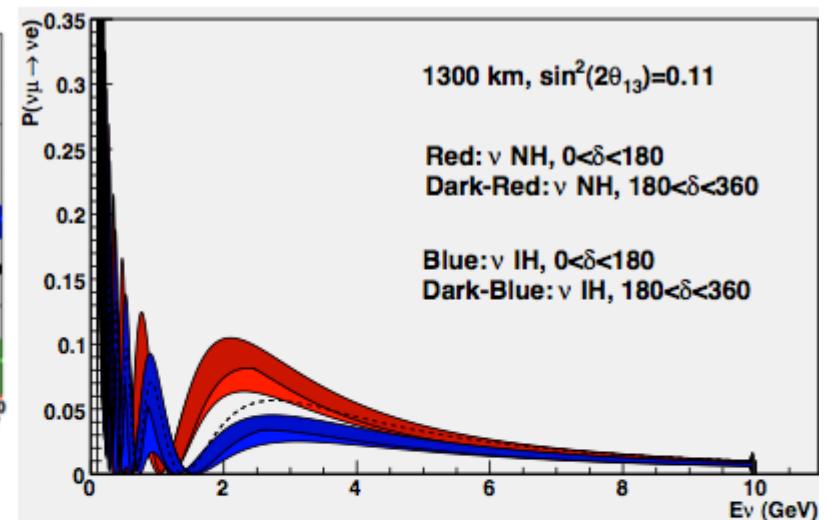
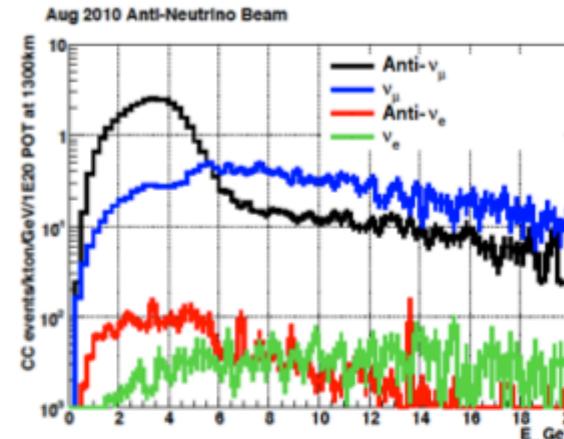
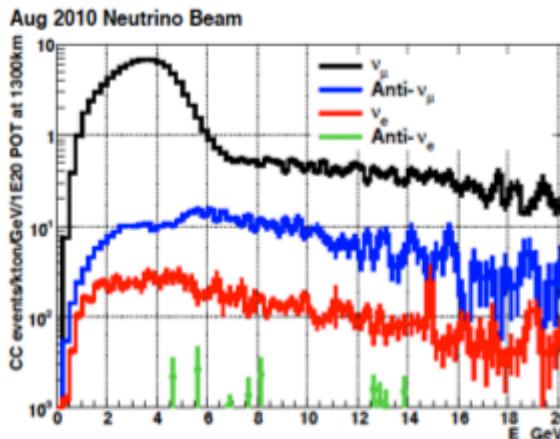
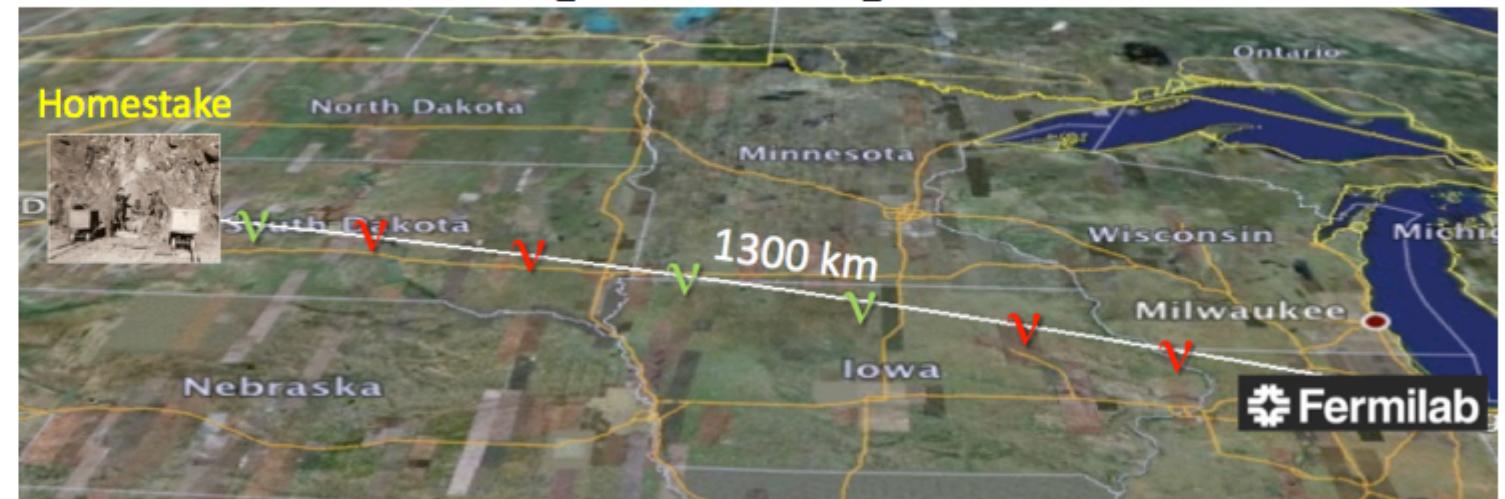
Automatic reconstruction software



see 12th J-PARC PAC (July 2011)

LBNE (USA)

- Collaboration:
~300 physicists
and engineers, 55
institutions
- CD-0 in Jan 2011
- Two far detector
options WC+LAr



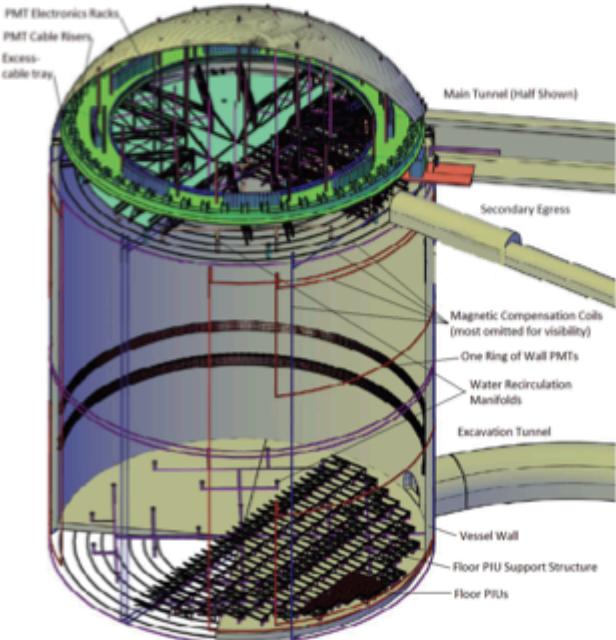
Oscillation CC rates/(100 kT.MW.yr):

$$\nu \text{ beam}, \Delta m_{31}^2 = +2.5 \times 10^{-3} \text{ eV}^2, \delta_{CP} = 0, \sin^2 2\theta_{13} = 0.04$$

Beam Tune	ν_μ	ν_μ OSC	ν_e beam	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Low-Energy (LE)	29K	11K	260	560	140

LBNE two detector options

Water Cerenkov Counter



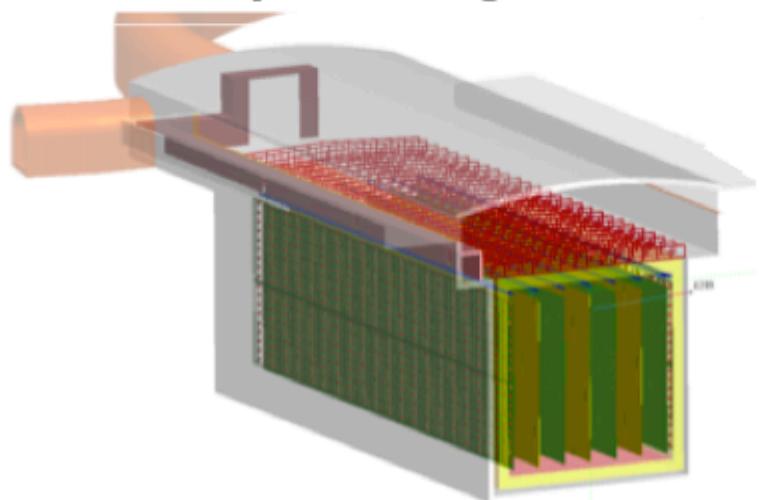
Main Detector Components

- Large Cavern
- Water Vessel
- Ultra-pure water system
- PMTs with Electronics
- 2 sizes under consideration:
150 kt or 200 kt fiducial mass
(7-9 x SuperK)
- **PMT + light collectors give photon detection efficiency equivalent to SuperK II**

- The "blue ribbon" panel has completed its report – it is quite favorable, and we are promised a clear decision by DOE as to what extent they will use the Homestake site – not only for LBNE but for all the "underground" science experiments. This decision needs to be made in time for FY13 budget request, **by end of this summer**.
- A decision on which technology to pursue (water or liquid argon) will be made as soon as possible – delayed due to NSF and DUSEL uncertainty. **Collaboration would like to pursue both** – but probably too expensive without **significant international participation**.

Courtesy: B. Svoboda

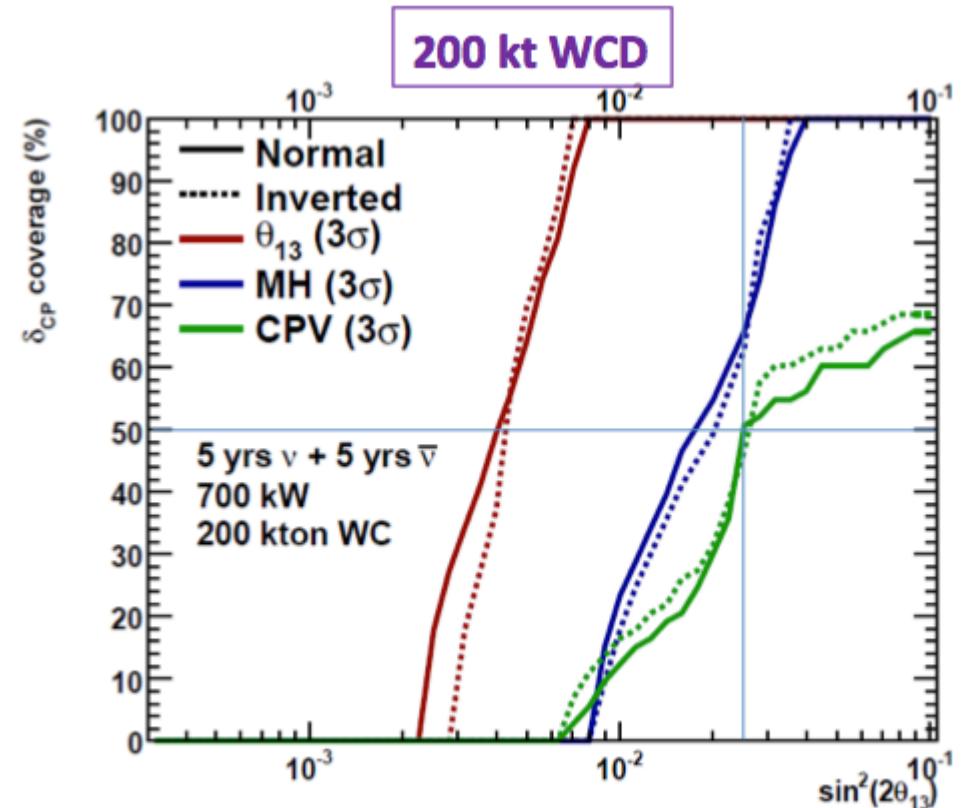
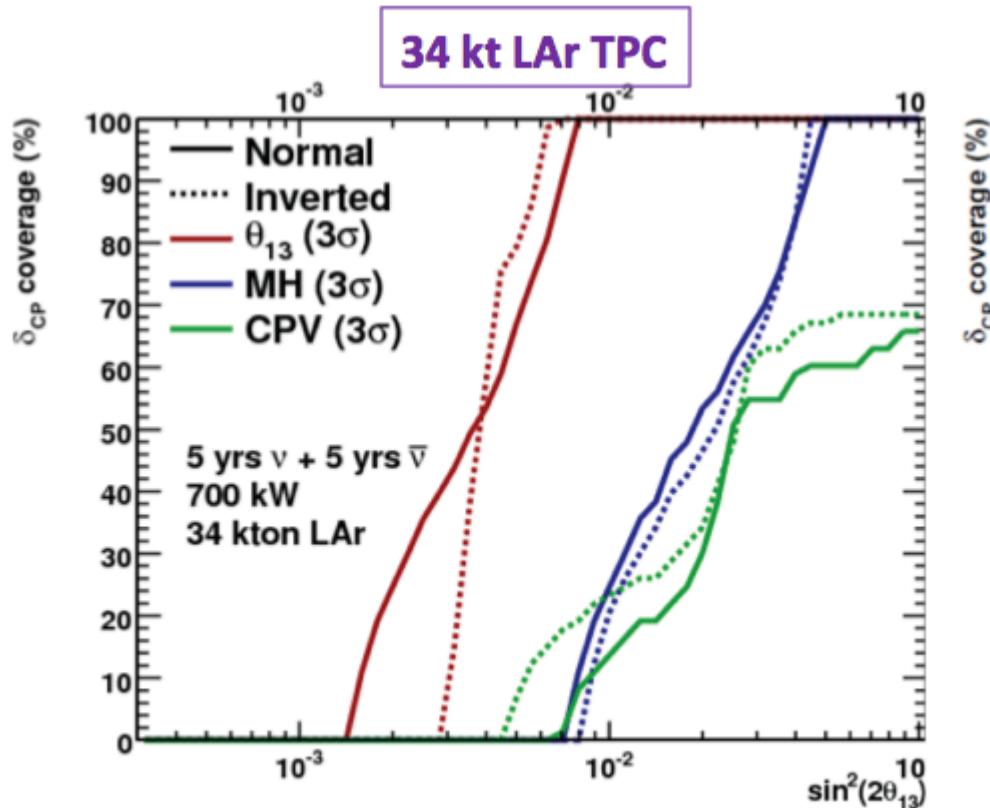
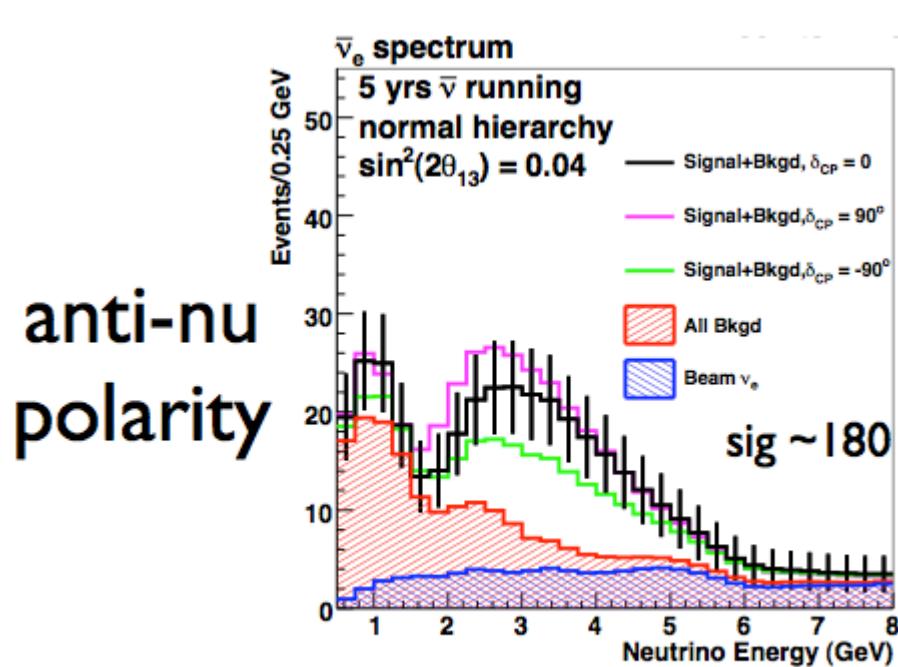
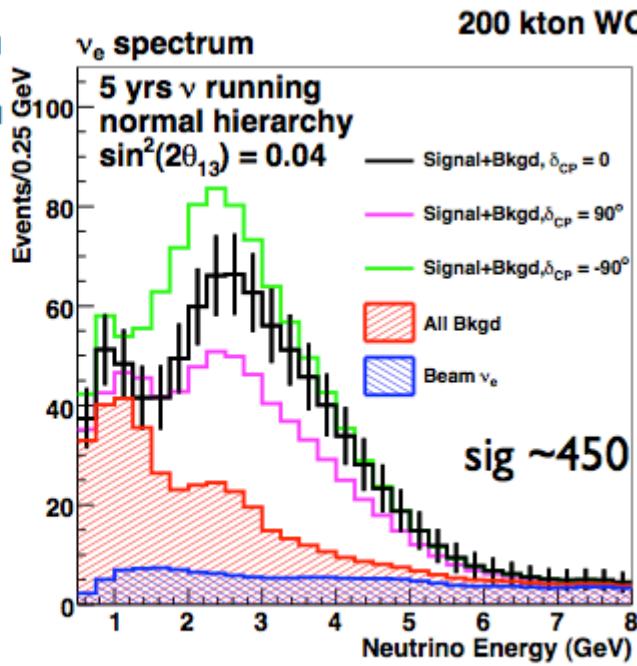
Liquid Argon



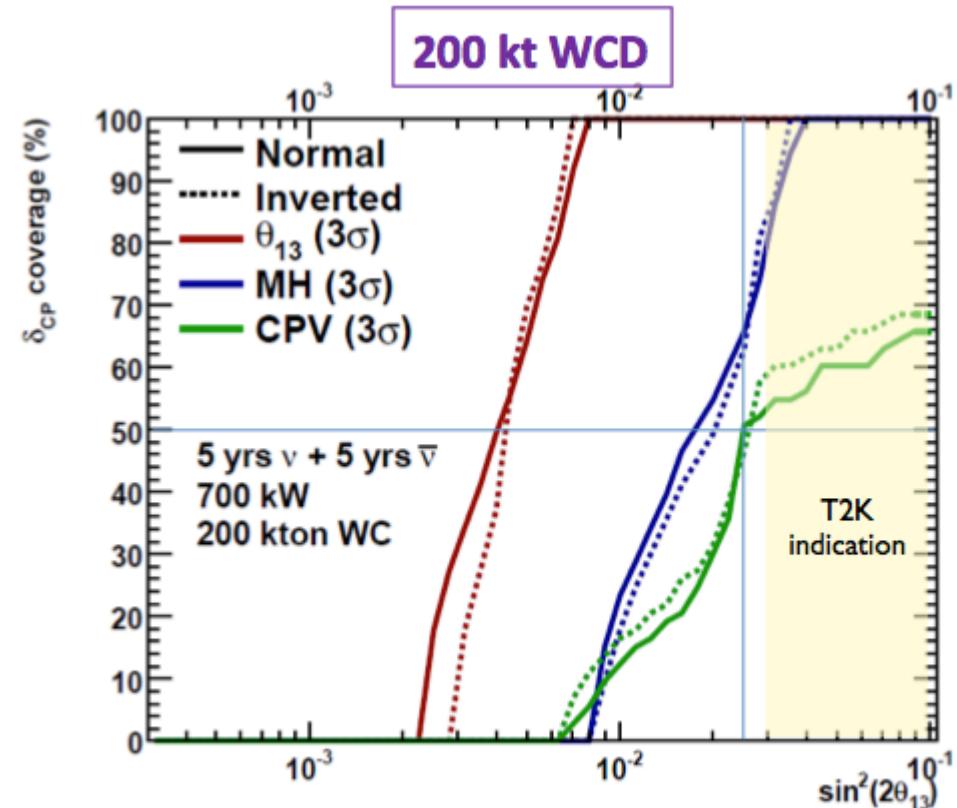
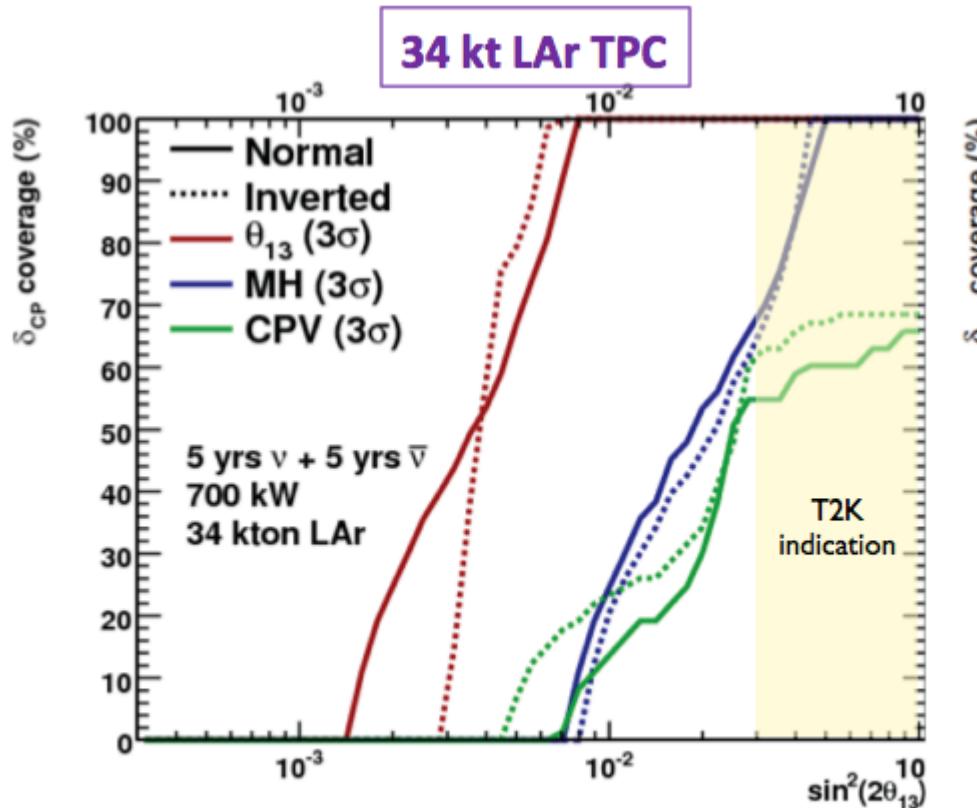
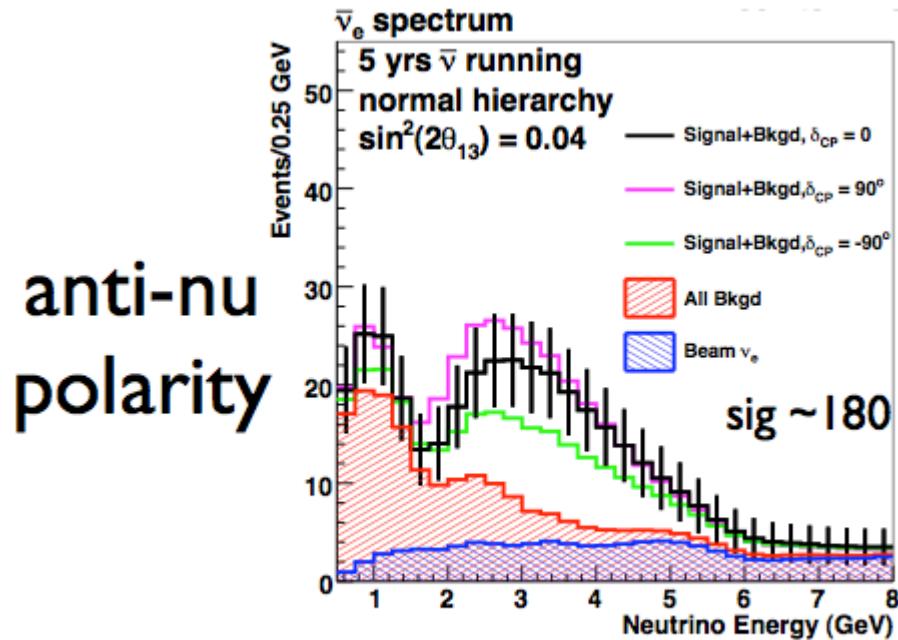
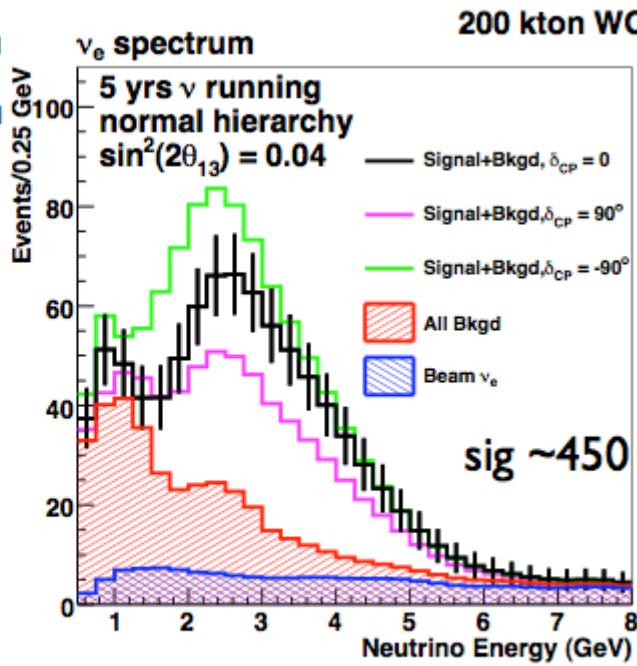
LBNE LAr development builds on world-wide R&D program
LBNE-specific prototyping program includes:

- 3 x 3 m² membrane cryostat wall panel – testing in progress
- 3 x 3 x 3 m³ membrane cryostat prototype
 - Understand cryostat technology
 - Verify purity in this cryostat
 - Preliminary design complete; operational in 2012
- kton-scale full engineering prototype
 - Full engineering prototype of complete detector system
 - Leverage DZero infrastructure to minimize construction cost and time, and operating cost.
 - Early planning stage; schedule depends on funding, but could be operational in 2014.
- **DOE panel estimate – ~five years of R&D required.**
- **It would make sense to have a common international program on this.**

nu
polarity



nu
polarity



Summary – so, what we need ?

- An intense (>1 MW) broad band (0-5 GeV) beam with some tunability. Spectrum should cover 1st maximum, and also 2nd maximum at lower energies.
- Baseline of 1300 to 2500 km to have large matter effects (any new physics is expected to be related to matter-like effects).
- Giant underground detectors ($\sim 100\text{kt}$ of efficient mass) capable of clean identification of electron neutrino events, covering the GeVs range of the beam.
- More than one order of magnitude statistical power increase compared to T2K/NOvA, and reduced and systematic errors.
- Perhaps foresee upgrades, to beam power and detector mass.

Also, non-accelerator physics

- These giant underground detectors will in addition cover a very rich astroparticle physics programme:
 - proton decay
 - atmospheric neutrinos
 - supernovae collapse neutrinos
 - unknown sources of astrophysical neutrinos (e.g. DM annihilation)
 - solar neutrinos
 - geo-neutrinos
 - etc.

Conclusions

- World-wide interest for next generation long-baseline based on the conventional neutrino beam technology, with longer baselines to address CP-violation and mass hierarchy, as the next step beyond T2K/NOvA.
- Physics case is strongly reinforced by recent evidence for $\sin^2 2\theta_{13} > 0.01$ in T2K and MINOS.
- As a community, we should aim at realizing two complementary projects (but many challenges ahead).
- Worldwide coordination is surely necessary.
- The LAGUNA consortium (EU, Japan, Russia) will consider a staged approach.



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