Mauro Mezzetto
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

“ Summary of NuTurn”

Istituto Nazionale di Fisica Nucleare

May 8-10, 2012 - Assergi, Italy

LABORATORI NAZIONALI DEL GRAN SASSO

νTURN 2012

NEUTRINO AT THE TURNING POINT

THE NEW OPPORTUNITIES OFFERED BY A LARGE Θ_{13}.
A WORKSHOP TO EXAMINE THE EXPERIMENTAL PERSPECTIVES AND TO DISCUSS THE NEUTRINO BEAMS, THE EXPERIMENTS AND EUROPEAN SITES TO PROGRESS IN THE STUDY OF NEUTRINO OSCILLATIONS.

HTTP://NUTURN2012.LNGS.INFN.IT

International Advisory Committee

Roberto Battiston - Perugia University & INFN
Sergio Bertolucci - CERN
Fernando Ferroni - INFN
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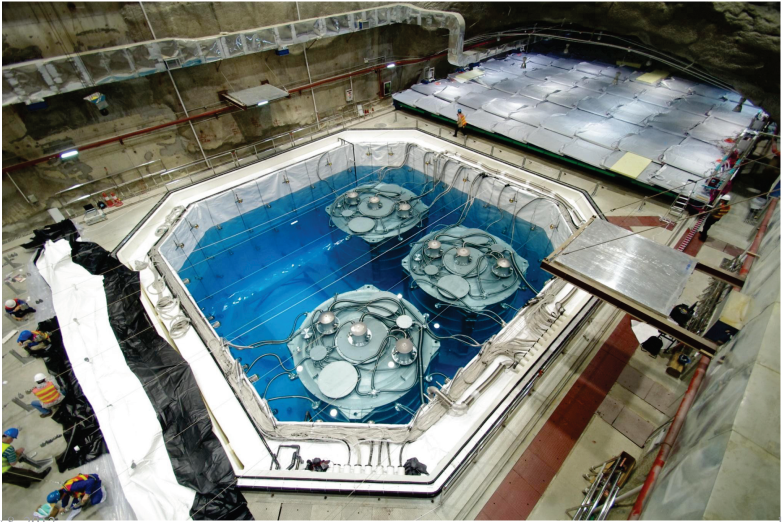
Fausto Chiarizia - *Sonia Sebastiani*
nuturn@lngs.infn.it

Two new great players in neutrino physics

Three ADs insalled in Hall 3
Physics Data Taking Started on Dec.24, 2011



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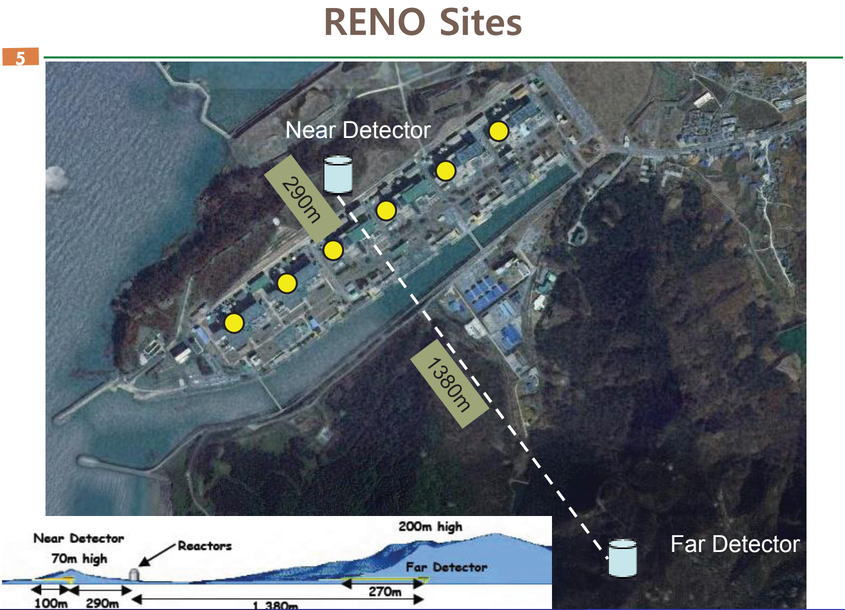
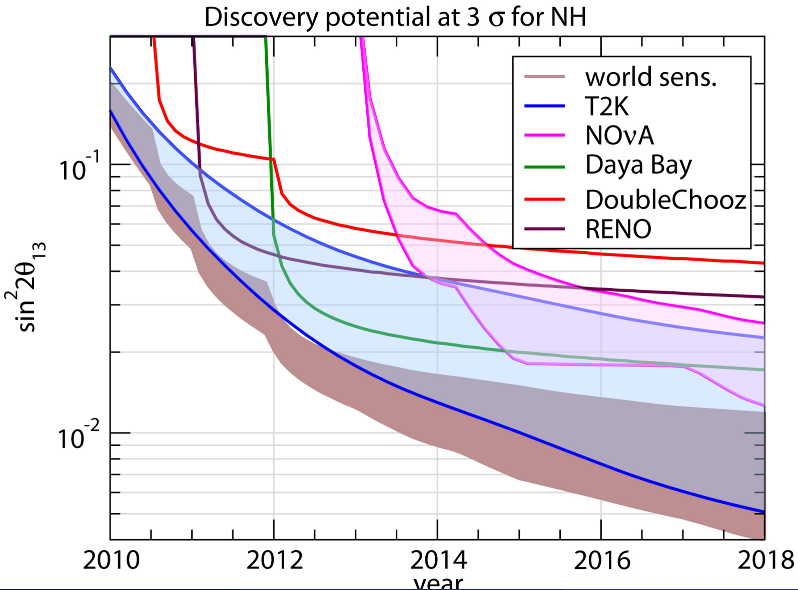

RENO Sites
5
Near Detector
290m
1380m
Far Detector
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
270m
1,380m

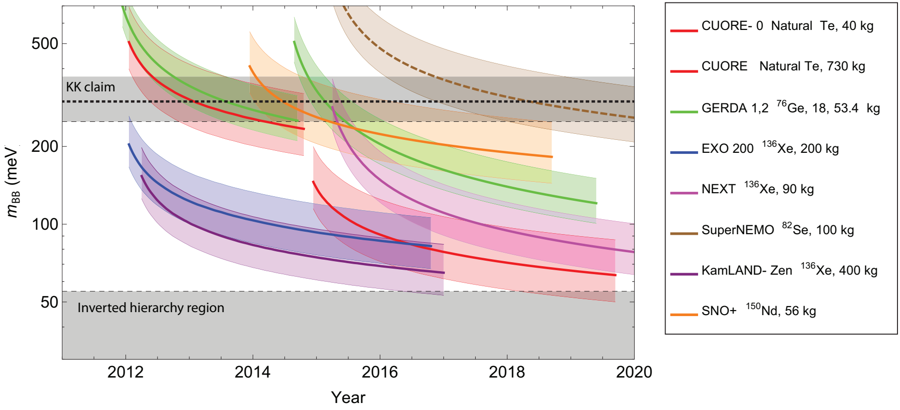
Fourteen months ago . . .

M.M. and T. Schwetz, J.Phys.G G37 (2010) 103001

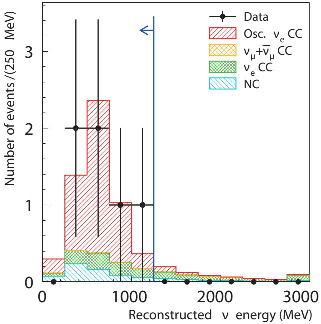


Something similar is going to happen in double beta decays

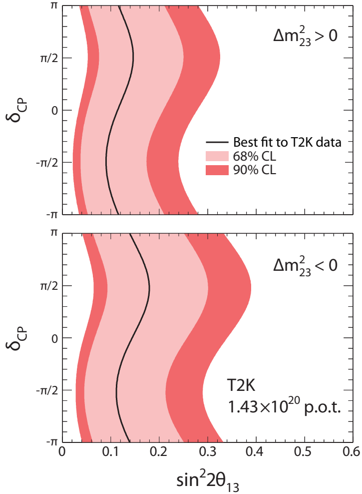
90%CL sensitivity along the time. Computed for the optimistic assumptions of J. J. Gomez-Cadenas, J. Martin-Albo, M.M., F. Monrabal and M. Sorel, Riv. Nuovo Cim. **35** (2012) 29



T2K result, PRL 107 (2011) 041801



Expected: 1.5 +/- 0.3
Measured: 6

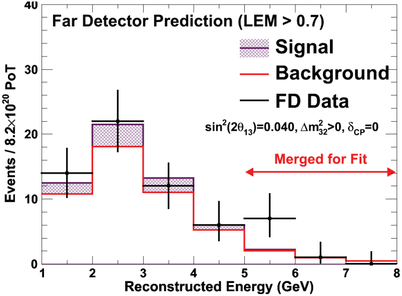


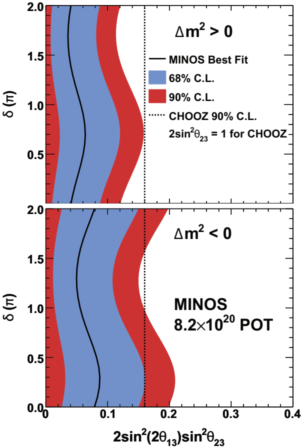
Systematic errors

Source	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}$%	$^{+5.6}_{-5.2}$%
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}$%	$^{+17.6}_{-17.5}$%

Results on appearance of electron-neutrinos with 8.2x10[20] POT

	MINOS	T2K
pot	8.2 10^{20}	1.45 10^{20}
tjoule	1.57	0.07
tjoule kton	7.85	1.57

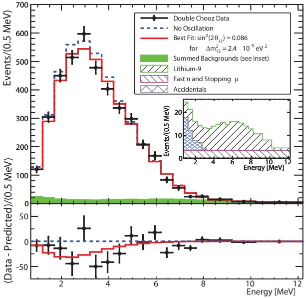




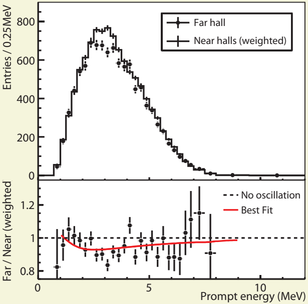
Year	pot	Expected	Detected
2009	3.1 10^{20}	27	35
2010	7.0 10^{20}	49	54
2011	8.2 10^{20}	49	62

Reactor Data

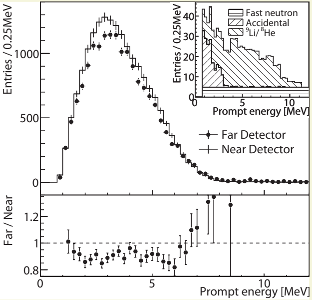
Double Chooz



Daya Bay



RENO



θ_{13} is large!

with SBL data:

$$\sin^2\theta_{13} = 0.022^{+0.0033}_{-0.0030}$$
$$\sin^2 2\theta_{13} = 0.086 \pm 0.012$$
$$\theta_{13} = (8.5^{+0.62}_{-0.61})^\circ$$

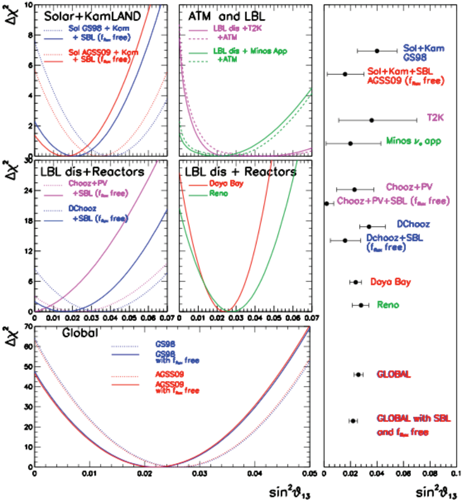
6.9σ significance

without SBL data using 2011 flux pred.:

$$\sin^2\theta_{13} = 0.026^{+0.0034}_{-0.0032}$$
$$\sin^2 2\theta_{13} = 0.101^{+0.013}_{-0.012}$$
$$\theta_{13} = (9.3 \pm 0.59)^\circ$$

8.0σ significance

Gonzalez-Garcia, Maltoni, Salvado, TS, in prep.



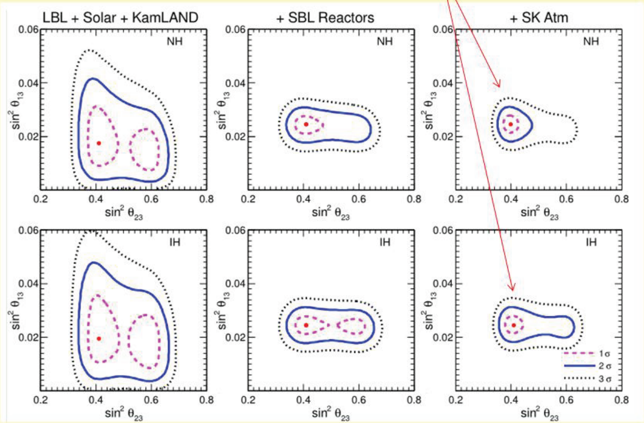
T. Schwetz 2

Global fits are providing stimulating insights

Adding SK atm data: the preference for θ_{23} in the 1st octant is corroborated

normal hierarchy

inverted hierarchy



Gianluigi Fogli

νTURN 2012, Laboratori Nazionali del Gran Sasso, May 9, 2012

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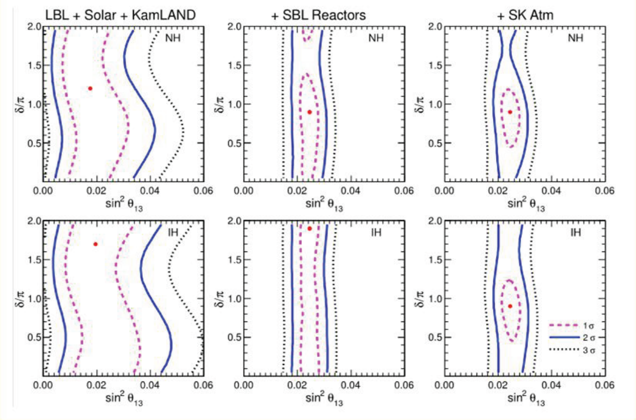
Global fits are providing stimulating insights

Adding SK atmospheric data:



We find a ~ 1σ preference for θ ~ π as in the early analysis of hep-ph/0506083.

Gianluigi Fogli vTURN 2012, Laboratori Nazionali del Gran Sasso, May 9, 2012 29

Necessary conditions to have LCPV detectable

The third necessary condition has just been fulfilled !

ν_μ-ν_e oscillations in a 3 ν scheme

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{ c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \qquad \text{matter effect} \quad (\text{CP odd})$$

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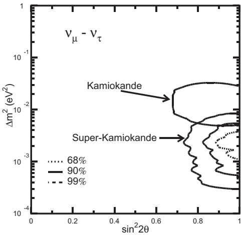
SK, PRL 81(1998) 1562 (3558 citations)



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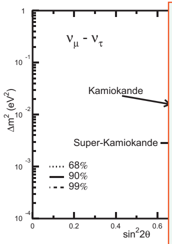
$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E}$$ CPeven

$$\mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\,\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E}$$ CPodd

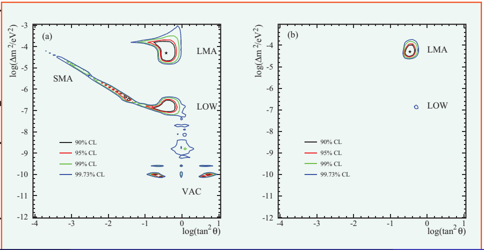
$$+ 4s_{12}^2 c_{13}^2\{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\}\sin\frac{\Delta m_{12}^2 L}{4E}$$ solar driven

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}(1-2s_{13}^2)$$ matter effect (CP odd)

SK, PRL 81(1998) 1562 (3558 citations)



SNO, PRL 89 (2002) 011302 (1934 citations)



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$$\mp\, 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+\, 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

$$\mp\, 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}$$

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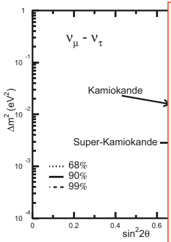
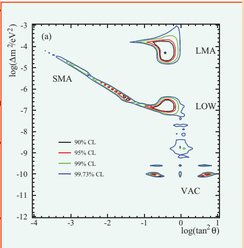
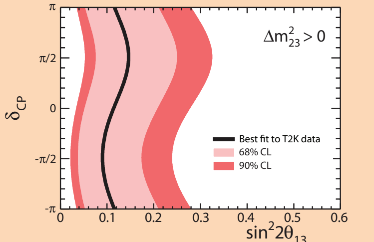


SNO, PRL 89 (2002) 01



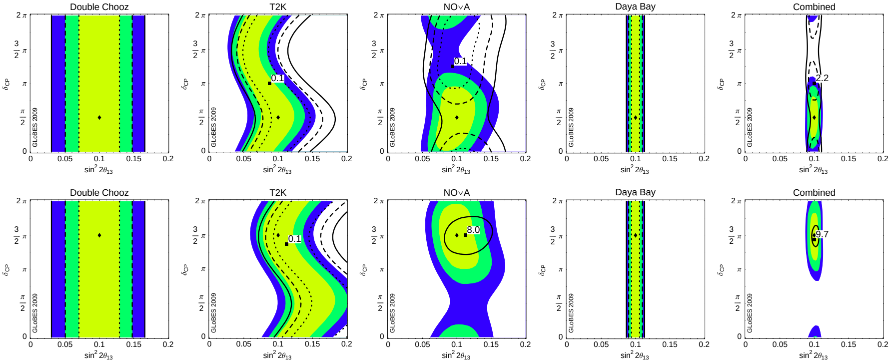
T2K, arXiv:1106.2822



Reactors vs Accelerators: 2018

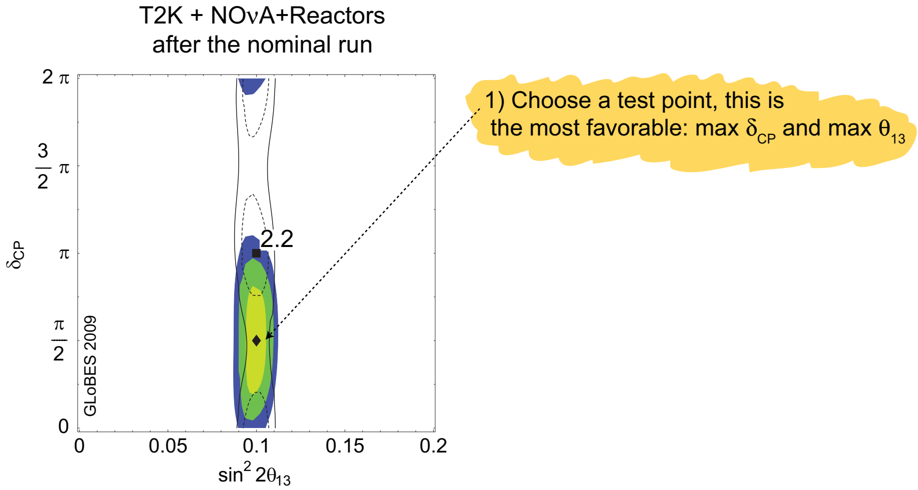
P. Huber et al., JHEP 0911:044,2009.

Fit at $\sin^2 2\theta_{13} = 0.1$ (1,2,3 σ)



Status after this generation of LBL experiments: CPV

From P. Huber et al., JHEP 0911:044,2009.



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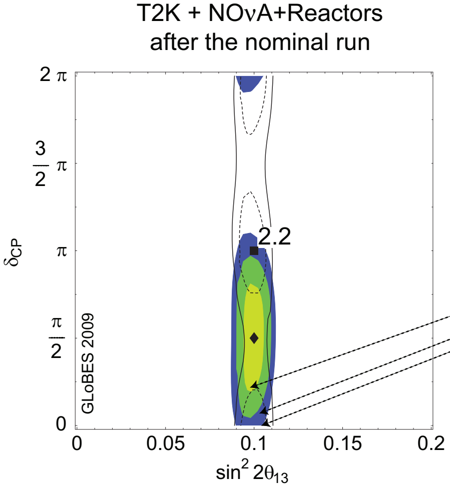
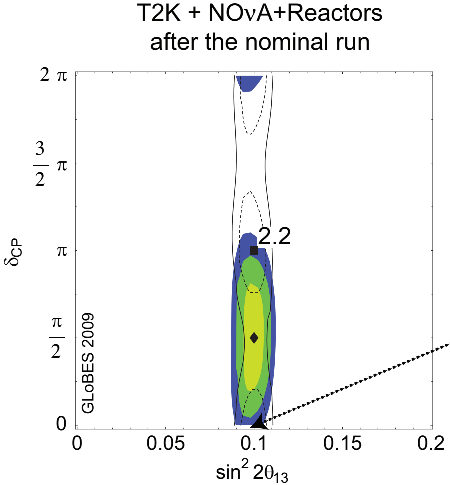


1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

Status after this generation of LBL experiments: CPV

From P. Huber et al., JHEP 0911:044,2009.



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

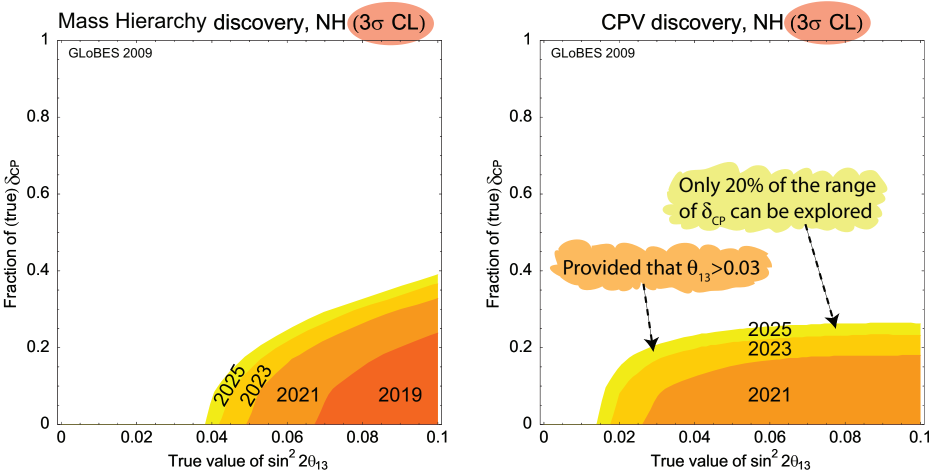
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

3) Null CP is compatible with data already at 2σ

Status after accelerator upgrades

From P. Huber et al., JHEP 0911:044,2009.

Prediction of sensitivity including a **fully optimized global run** (antineutrinos in T2K and NOνA) and **full upgrade of the accelerators**: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)



Mass Hierarchy

- NoνA + T2K
- INO
- Daya Bay II
- Pingu
- SPS to SK
- HyperKamiokande
- Laguna-LBNO Expression of interest

NOVA as hierarchy determining machine

95% CL Resolution of Mass Hierarchy (Normal Ordering)

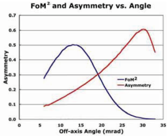
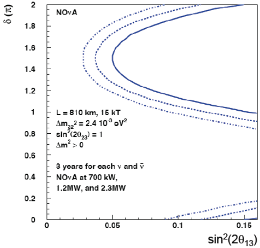
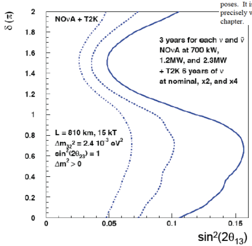


Fig. 13.4: Figure of merit squared (arbitrary units) and neutrino oscillation asymmetry due to the matter effect for $\Delta m^2 = 0.0025$ eV^2 versus off-axis angle. See text for an explanation. This figure is for illustrative purposes. It is based on a toy model and may not agree precisely with the simulation data presented in this chapter.



NOνA Only



NOνA + 6yrs T2K

Optimizing MI beam energy to solve hierarchy?

Peter Shanahan - NOvA/Fermilab   Fermilab Wine & Cheese - June 17, 2011   4

INO (Identifying the Neutrino mass Ordering)

How does the global situation improve if atmospheric data from the India-based Neutrino Observatory (INO) is combined with NOvA+T2K+reactors? Blennow, TS, 1203.3388

- *INO starts 2017 with 50kt or 100kt*
- *muon threshold of 2 GeV*
- *zenith angle region $-1 < \cos\theta < -0.1$*
- *~230 (neutrino+antineutrino) events per 50 kt yr (no osc)*
- *for energy and direction reconstruction consider "low" (15%, 15°) and "high" (10%, 10°) resolution scenario*
- *assume $\sin^2 2\theta_{13} = 0.09 \pm 0.017$*

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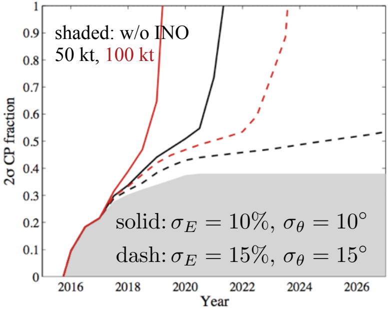
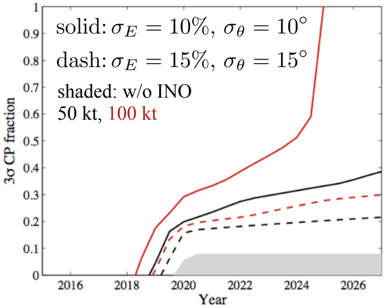
INO (Identifying the Neutrino mass Ordering)





Blennow, TS, 1203.3388

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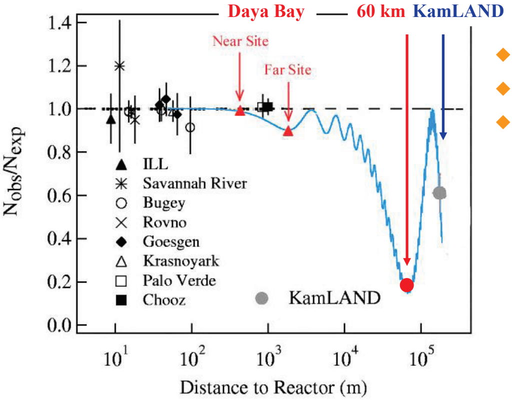
Daya Bay-II Experiment

Giant Detector located at 60 km from Daya Bay reactors, the 1st maximum of θ_{12} oscillation.



- **20 kton detector**
- **3% energy resolution**
- Rich physics possibilities
  - **Mass hierarchy**
  - **Precision measurement of 4 mixing parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Sterile neutrino**
  - **Abnormal magnetic moment**
  - **Possible CPV**

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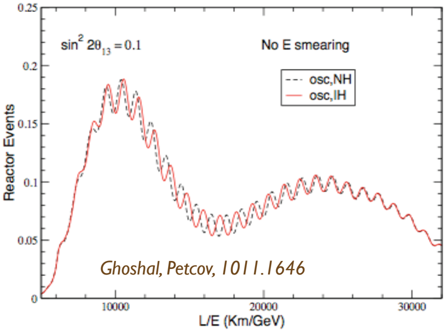
Hierarchy from a reactor experiment

Petcov, Piai, hep-ph/0112074

$\bar{\nu}_e$ disappearance at intermediate baseline (40~60 km)
interference term between solar and atmospheric oscillations



T. Schwetz

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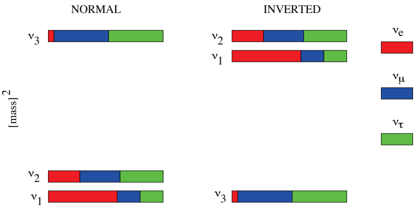
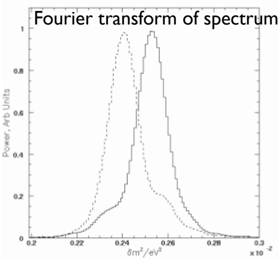
Hierarchy from a reactor experiment





Learned, Dye, Pakvasa, Svoboda, 06
Zhan, Wang, Cao, Wen, 08

- *there are two large frequencies: Δm^2_{31} and Δm^2_{32}*
- *θ_{12} is non-maximal and we know the sign of Δm^2_{21}*
- *for NH (IH) the larger (smaller) frequency dominates*

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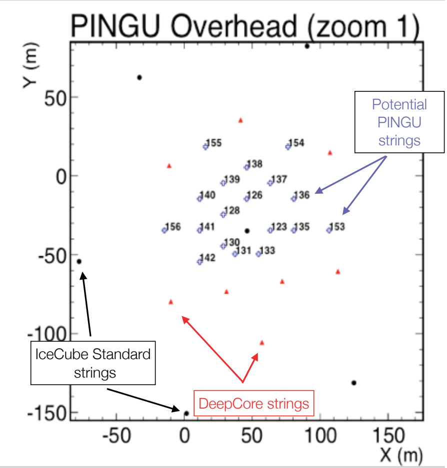
PINGU: Possible Geometry

- Add 18-20 strings into DeepCore volume
- One of many possible geometries
- R & D for future water/ice cerenkov detectors



Pingu

The mass hierarchy from the ice?

IceCube → DeepCore → ***PINGU***

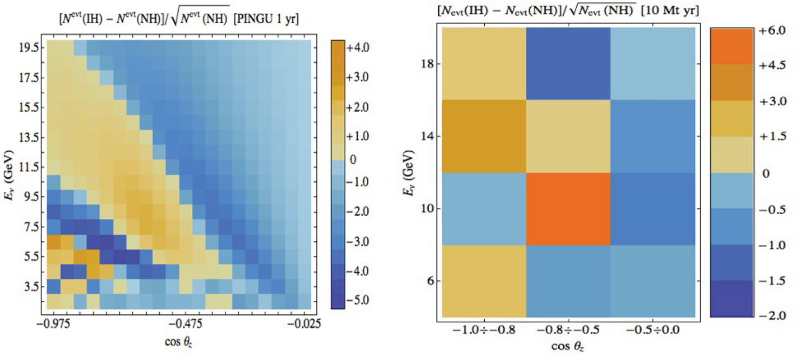
- *~20 additional strings within DeepCore*
- *lower threshold to few GeV*
- *~10 Mt effective volume*
- *construction within 1 yr, ~$25 M*

Doug Cowen, NuSky, ICTP, June 2011

T. Schwetz 27

Pingu

Mass hierarchy from PINGU



Akhmedov, Razzaque, Smirnov, in prep.

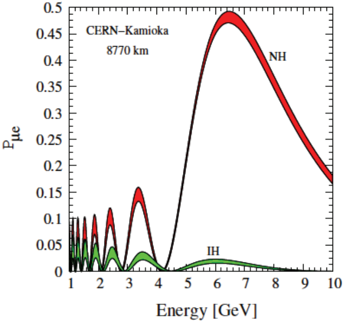
T. Schwetz 29

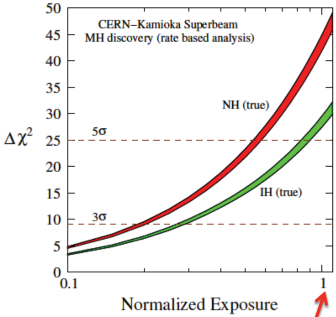
SPS to SK

Computed for 50 GeV/c proton beam. At 400 GeV/c and 700 kw apparently requires 3-5 years to have 5 sigmas

CERN-Super-K (8870 km)

Agarwalla-Hernandez April 12





Channel	CERN-Kamioka (8870 km)	
	Signal	Background
	CC-1 ring	Int+Mis-id+NC = Total
$\nu_\mu \to \nu_e$ (NH)	**44**	1+2+16=**19**
$\nu_\mu \to \nu_e$ (IH)	**2**	1+3+16=**20**
$\nu_\mu \to \nu_\mu$ (NH)	**83**	**2**
$\nu_\mu \to \nu_\mu$ (IH)	**91**	**2**

5×10^{21} pot.

May 8-10, 2012 NuTURN@

LBNO EoI: the physics reach

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- **Ultimate** long baseline oscillations measurements:
  - LBNO can measure all transitions (e/μ/tau) and determine precisely oscillation parameters. It can achieve a **5σ C.L. determination of the neutrino mass hierarchy** in a few years. In a 10 years run, it explores a **significant part of the CPV parameter space, namely 60% CPV coverage at 90%C.L.**
  - Both the local situation and the distance make it such that it can evolve into larger detector(s) and a more powerful beams (e.g HP-PS and/or NF) and thus, **offers a long term vision**. For example, with a three-fold increase in exposure, **it reaches 75% CPV coverage at 3σ C.L.**. Competitive with T2HK (even more with JPARC MR at 700kW...) and LBNE.
- **Strongly** extended sensitivity to nucleon decay in several channels. E.g. some channels with sensitivity similar to HK:

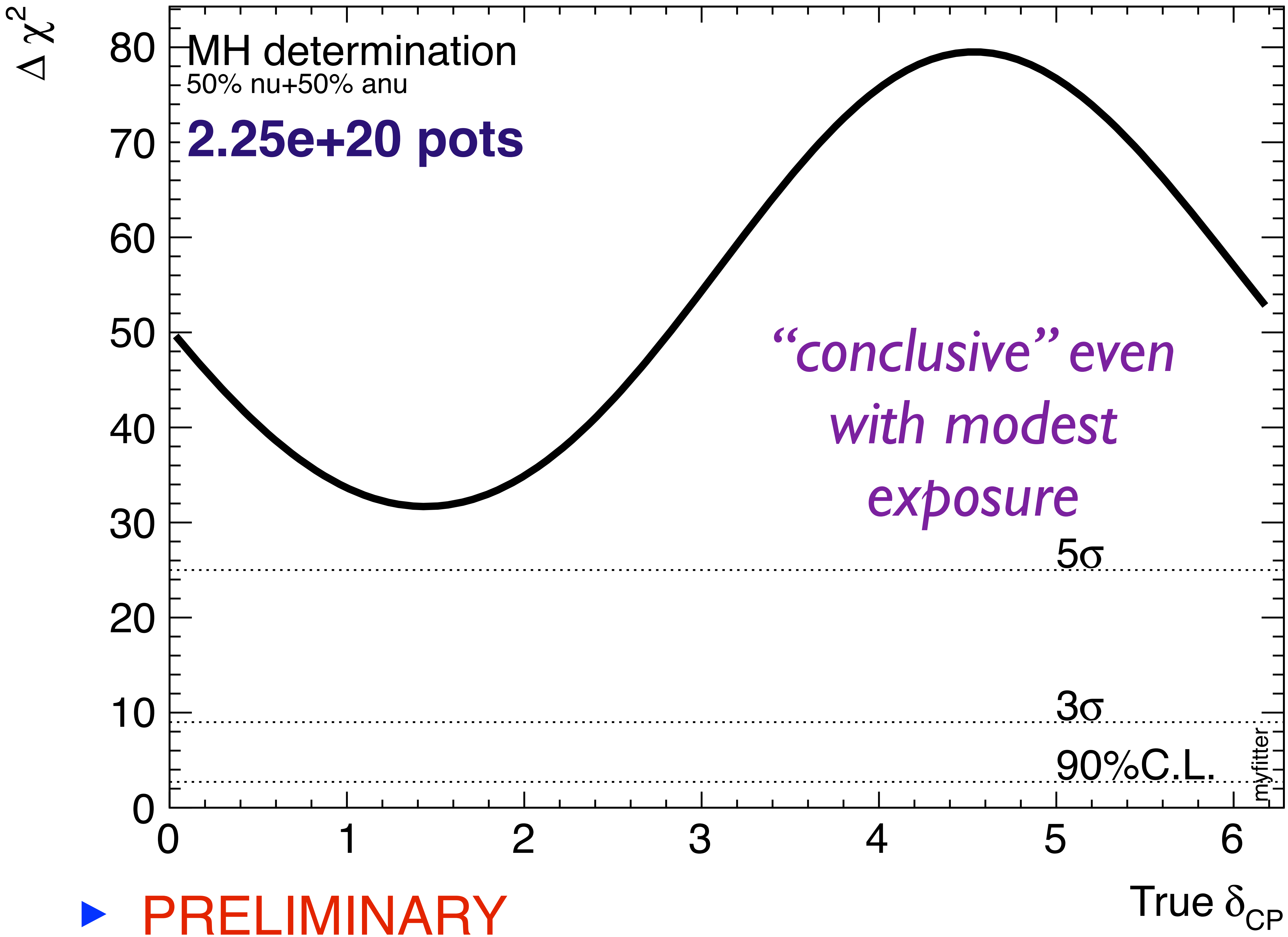
$$Br(p \to \bar{\nu} K) > 2 \times 10^{34} y (90\% C.L.) \qquad Br(n \to e^- K^+) > 2 \times 10^{34} y (90\% C.L.)$$

- **Interesting** astrophysics: LBNO acts as an nu-observatory in the 10 MeV-100 GeV range.

5600 atmospheric events/yr **relic SN, WIMP annihilation, ...**

>10000's events @ SN explosion@10kpc

MH determination

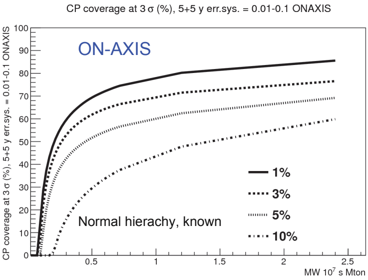


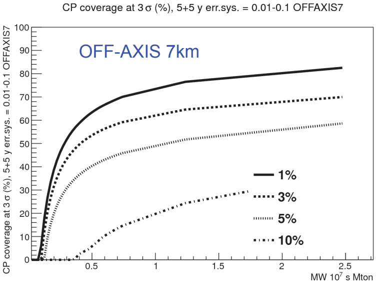
- PRELIMINARY

CP Violation

- HyperKamiokande
- Laguna-LBNO
- 50 kton at Gran Sasso
- Laguna comparisons by S. Pascoli
- CP studies by A. Longhin
- Laguna-LBNO Expression of interest

Systematics on absolute flux normalization





Very relevant effect

expected: δ induces mostly a change in normalization at L=730 km

5 % : widely used but the T2K super-beam nowadays is still above the 10% level

Crucial for the design of future experiments

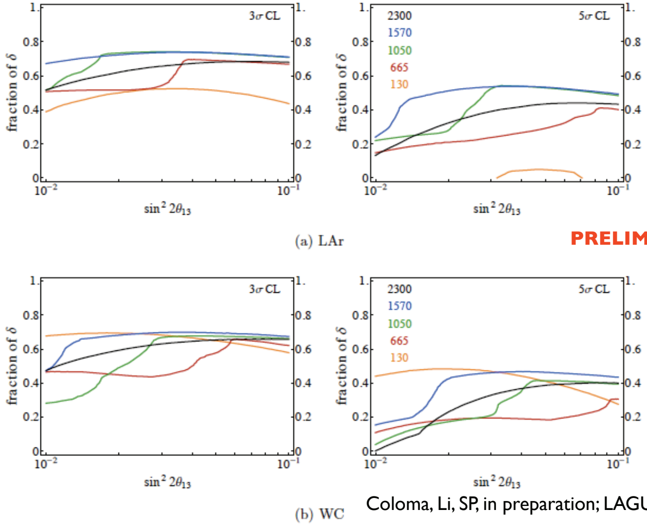
- LAr TPC already goes in this direction
- Ancillary detectors: near, on-axis far + off-axis far

Improving the systematic error pays more than brute force (boosting mass/beam)

Baseline invariance

Comparison between baselines

The determination of CPV



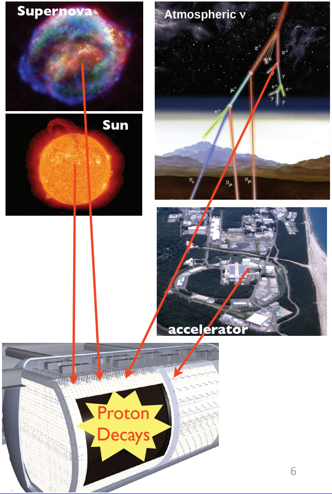
PRELIMINARY

Coloma, Li, SP, in preparation; LAGUNA-LBNO

Hyper-K WG,
arXiv:1109.3262 [hep-ex]

Multi-purpose detector, Hyper-K

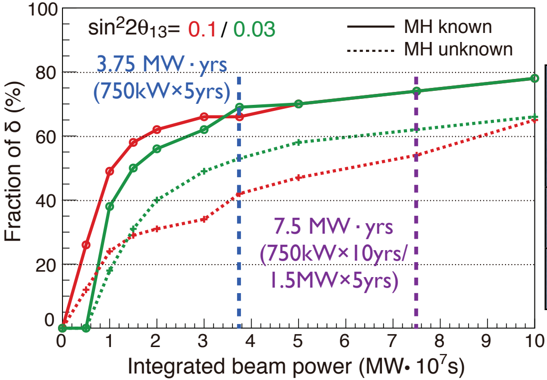
- Total (fiducial) volume is 1 (0.56) million ton
  - 25 × Super-K
- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac δ)
  - ν mass hierarchy determination($\Delta m^2_{32}>0$ or <0)
  - θ_{23} octant determination ($\theta_{23}<\pi/4$ or $>\pi/4$)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years
- Neutrinos from astrophysical objects
  - 200 ν's / day from Sun
  - 250,000 (50) ν's from Supernova @Galactic-center (Andromeda)
  - 830 ν's / 10 years Supernova relic ν
  - WIMP ν, solar flare ν, etc



6

Fraction of δ (%) for CPV discovery

Fraction of δ in % for which expected CPV (sinδ≠0) significance is >3σ



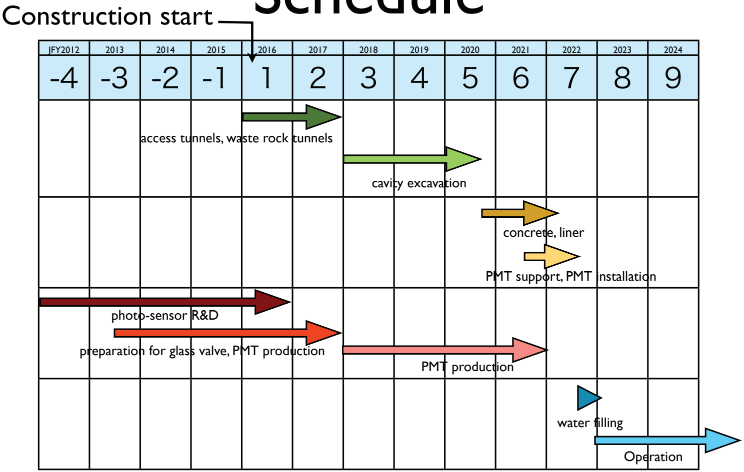
$\sin^2 2\theta_{13}=0.1$

(MW× yrs)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

- Effect of unknown mass hierarchy is limited
  - Input from atm ν and other experiments also expected for MH

Japan has a great opportunity

Schedule



assuming budget being approved from JPY2016

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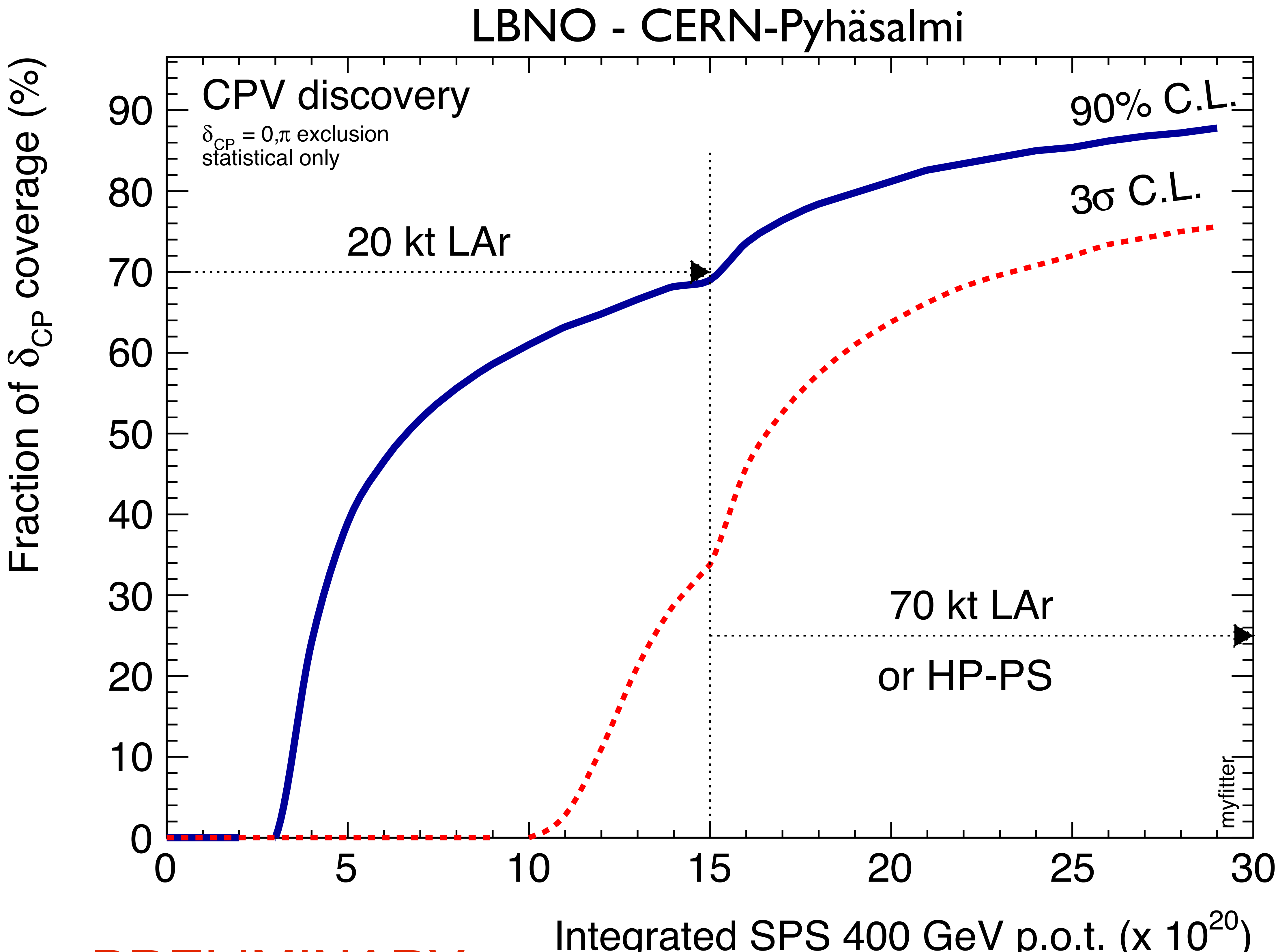
CPV discovery as function of p.o.t.



- PRELIMINARY

A realistic programme to explore CP violation in the leptonic sector

Carlo Rubbia
LNGS-Assergi, Italy
CERN, Geneva, Switzerland

The "Modular" approach

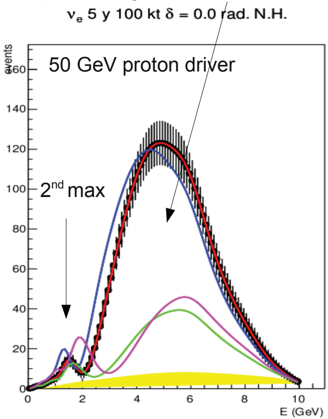
- The most naïve design would assume a single (may be ≈100 kton) LAr container of a huge size. But the dimensions of most events under study (beam-ν, cosmic ray-ν, proton decays) are of much smaller dimensions.
- For instance, the whole volume of ultra-pure LAr will be totally contaminated even by a tiny accidental leak (ppb). A spare container vessel for ≈100 kton are unrealistic.
- Fortunately increasing the size of a single container does not introduce significant physics arguments in its favour.
- A modular structure with several separate vessels, each of a few thousand tons, is to us a more realistic solution.
- A reasonable single volume unit could be of 8 x 8 m^2 cross section, a drift gap of 4 m and a length of about 60 m, corresponding to 3840 m^3 of liquid or 5370 t of LAr.
- Two units should be located side to side with 10 kt mass.

A first cost estimate, based on ICARUS know-how

- Based on the long experience with ICARUS and a firm cooperation with industries in the realization of the detectors, a relatively firm estimate of the costs may be given.
- The cost, including contingencies, based on the above list of items 1-7 is as follows:
  - Engineering design and prefabrication costs: 10 M€
  - Construction and installation of first 10 kt: 40 M€
  - Scale reduction and other 4 modules (40 kt): 120 M€
  - LAr procurement for 50 kt fiducial mass 40 M€
- Total construction cost for a 50 kt fiducial mass 210 M€
- Total with additional extension of + 20 kt 285 M€
- Excavated volume for 50 kt fiducial mass 1.25×10^5 m^3

2290 ↔ 730 km

- MH: 2290 km is superior (large matter effects), no ambiguities from MH knowledge



- CP violation: not a huge difference
- Higher coverage at 2290 at high exposures (where 2nd max starts to play a role)

νTURN, LNGS. 8-10 May 2012