Science & Technology Facilities Council
Rutherford Appleton Laboratory

Oxford Physics

CP Violation with Laguna-LBNO

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LAGUNA

Content

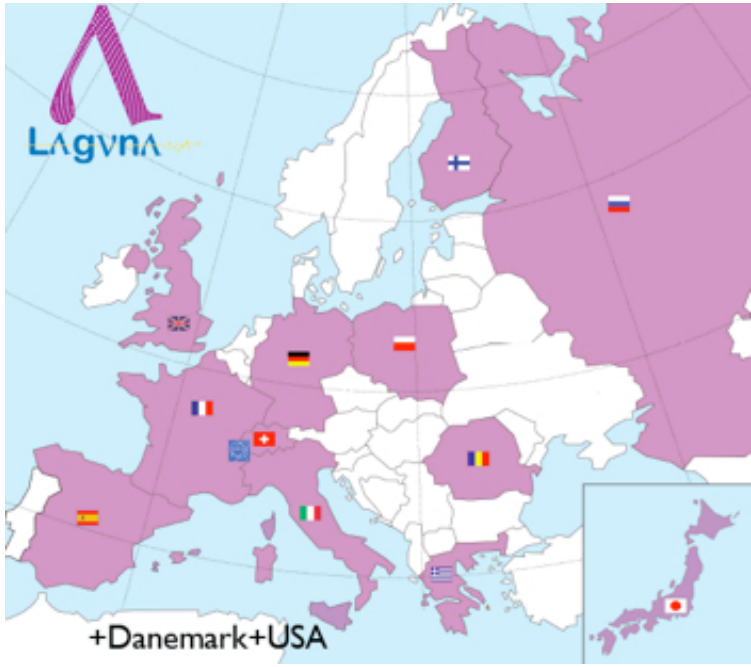
- Introduction
- Detector Options
  - Water Cherenkov Detector
  - Liquid Scintillator
  - Liquid Argon Detectors
- How to measure CPV and MH
- The effect of systematics
- Summary & Conclusion

LAGUNA-LBNO

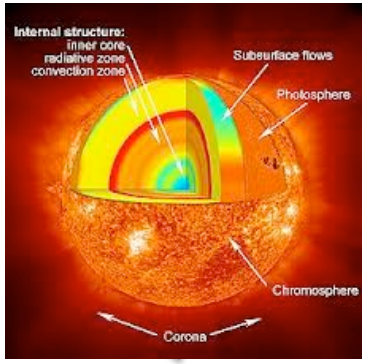
NuInt 2012

Large **A**pparatus for **G**rand **U**nification and
Neutrino **A**strophysics
Long **B**aseline **N**eutrino **O**scillations

- **LAGUNA DS** (FP7)
  - 2008 – 2011
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **LAGUNA-LBNO**
  - 2011 – 2014
  - ~300 members; 14 countries, >40 Institutions
  - Down selection of sites & detectors



Physics



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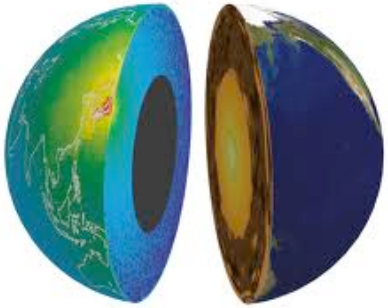
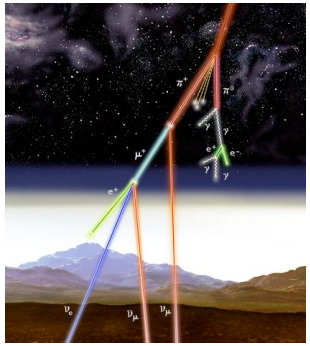
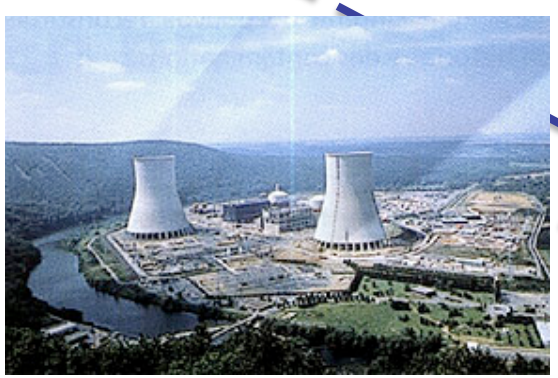
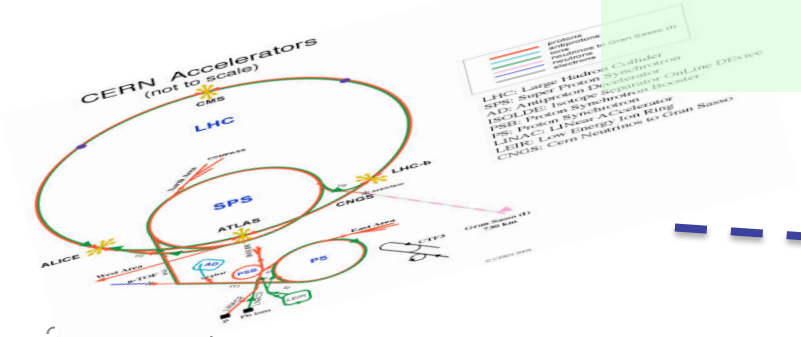
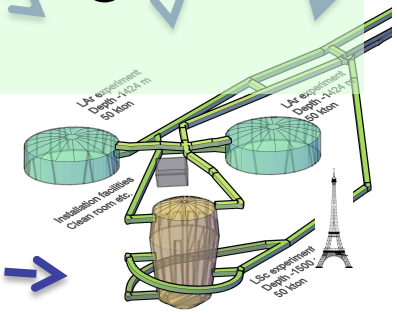


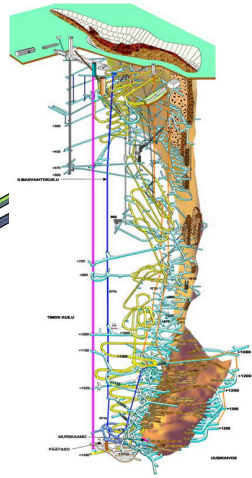




Neutrinos from MeV ➔ GeV
Particle Physics ⇔ Astroparticle
Neutrino Oscillations (MH, CPV)
Proton decay
Atmospheric-, SN- & geo-neutrinos

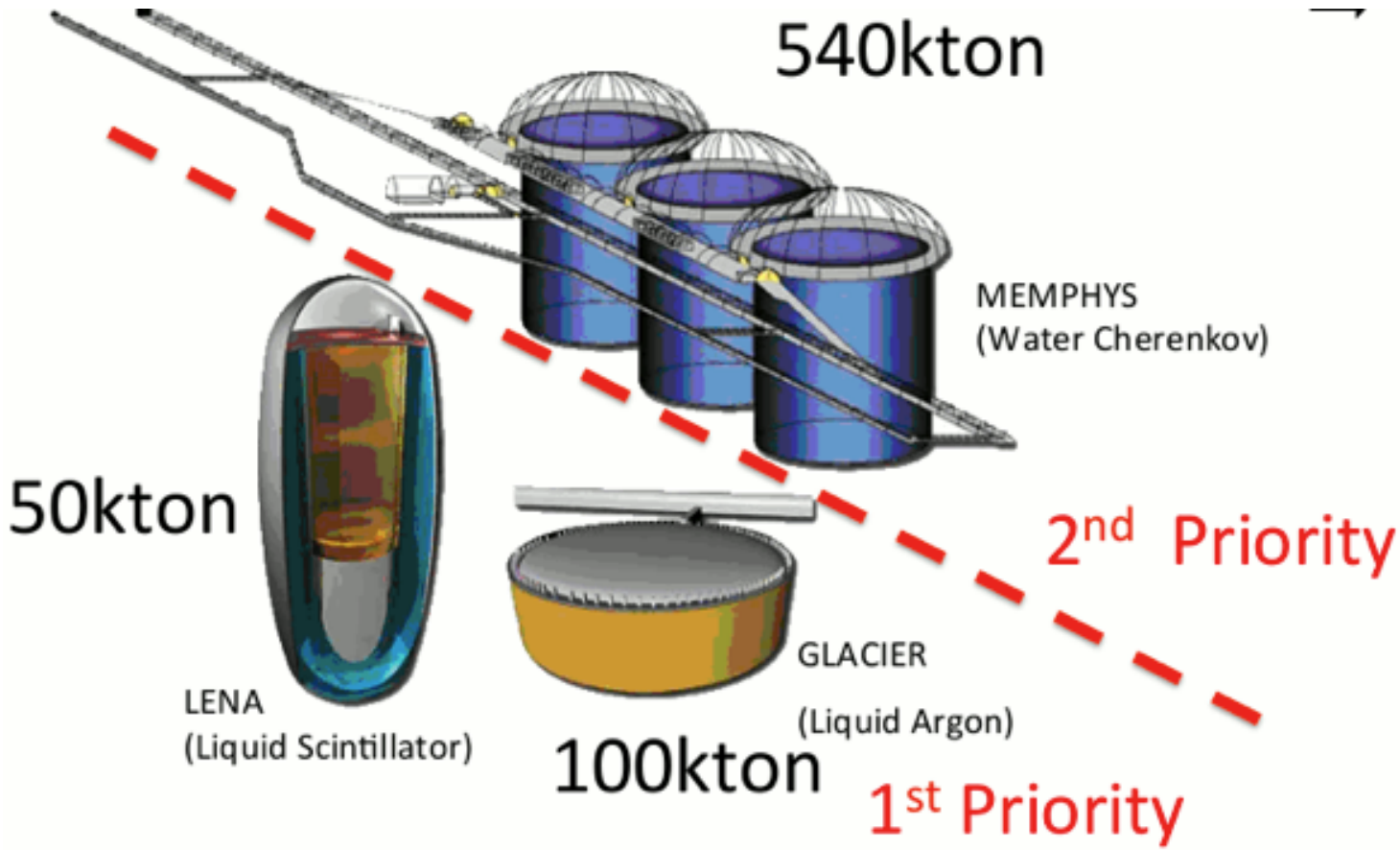






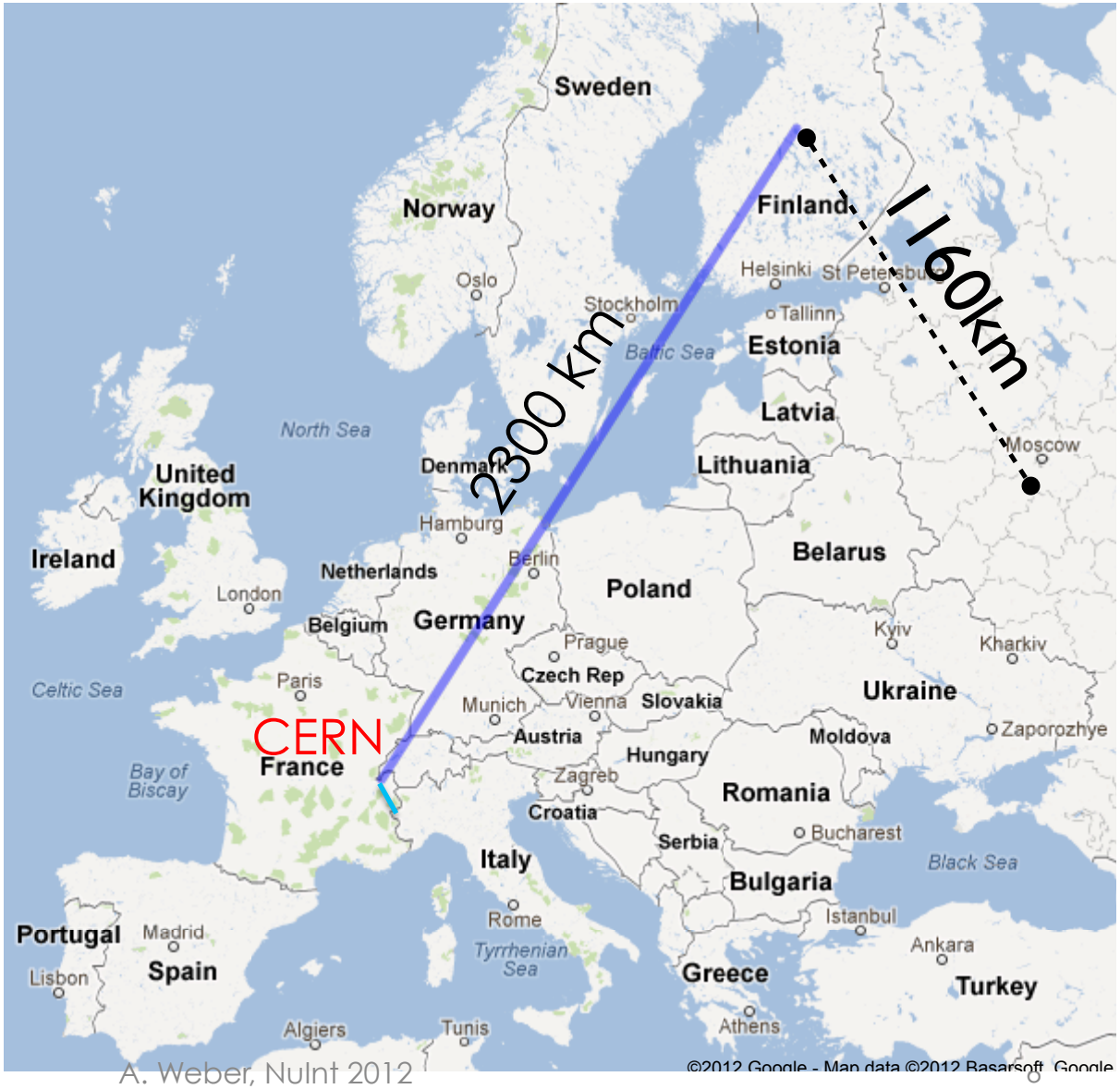
Detector Options

- Prioritisation for neutrino oscillations in light of large θ_{13}
  - 2300 km baseline: Liquid Scintillator/Argon
  - 130 km baseline: Water-Cerenkov



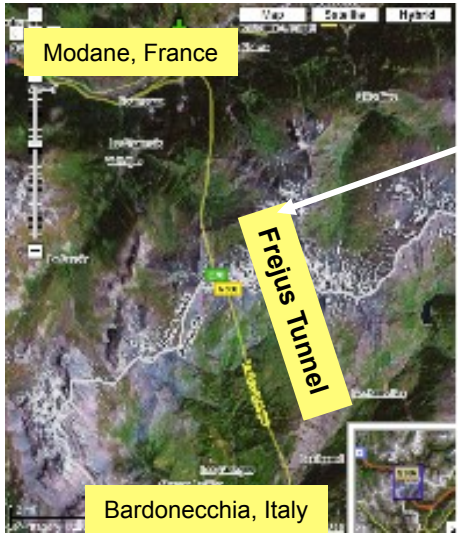
Several Sites

- Primary site
  - Pyhäsalmi
  - Traditional high energy broadband neutrino (super-) beam
- Secondary site
  - Frejus
  - Beta beam at low energy



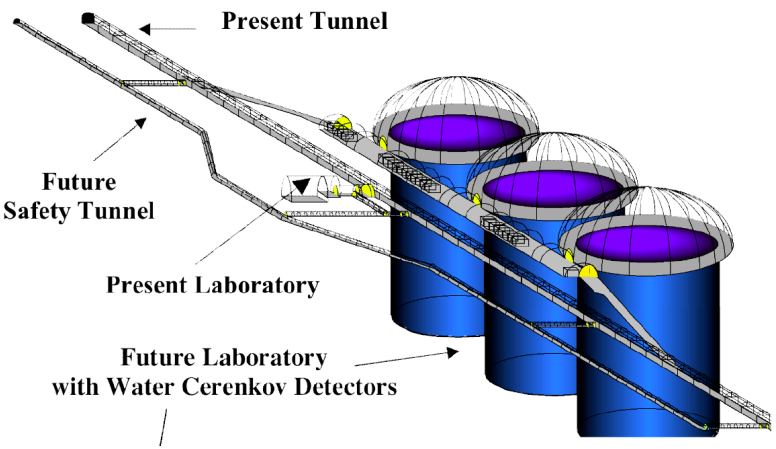
WCD

- Optimised for low energy neutrinos
  - beta-/super-beam facility at CERN



Laboratoire Souterrain de Modane

4800 m.w.e.



Megaton Mass PHYSics @Fréjus

- Water Cherenkov ("cheap and stable")
- Total fiducial mass: 440 kt
- Baseline:

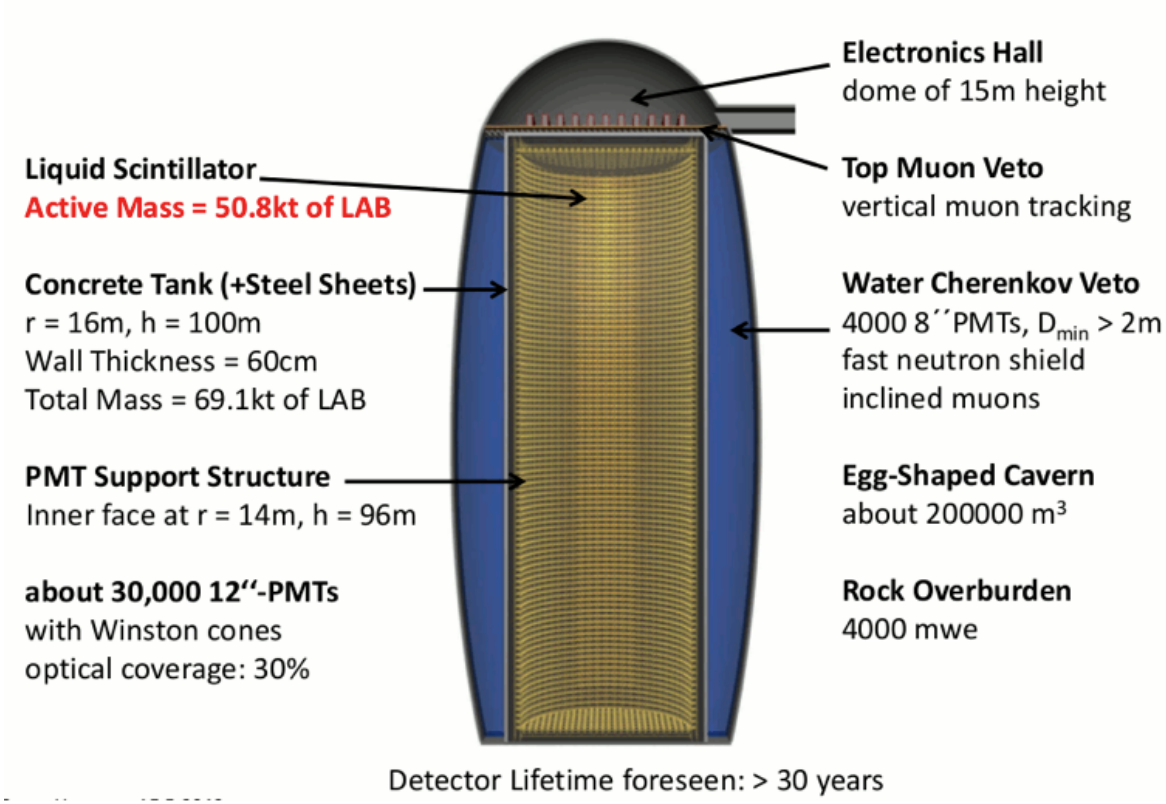
  3 Cylindrical modules 65x65 m
  - Size limited by light attenuation length (λ~80m) and pressure on PMTs
  - Readout: 12" PMTs, 30% geom. cover (#PEs =40%cov. with 20" PMTs)
- PMT R&D + detailed study on excavation existing & ongoing

http://www.apc.univ-paris7.fr/APC_CS/Experiences/MEMPHYS/

arXiv: hep-ex/0607026

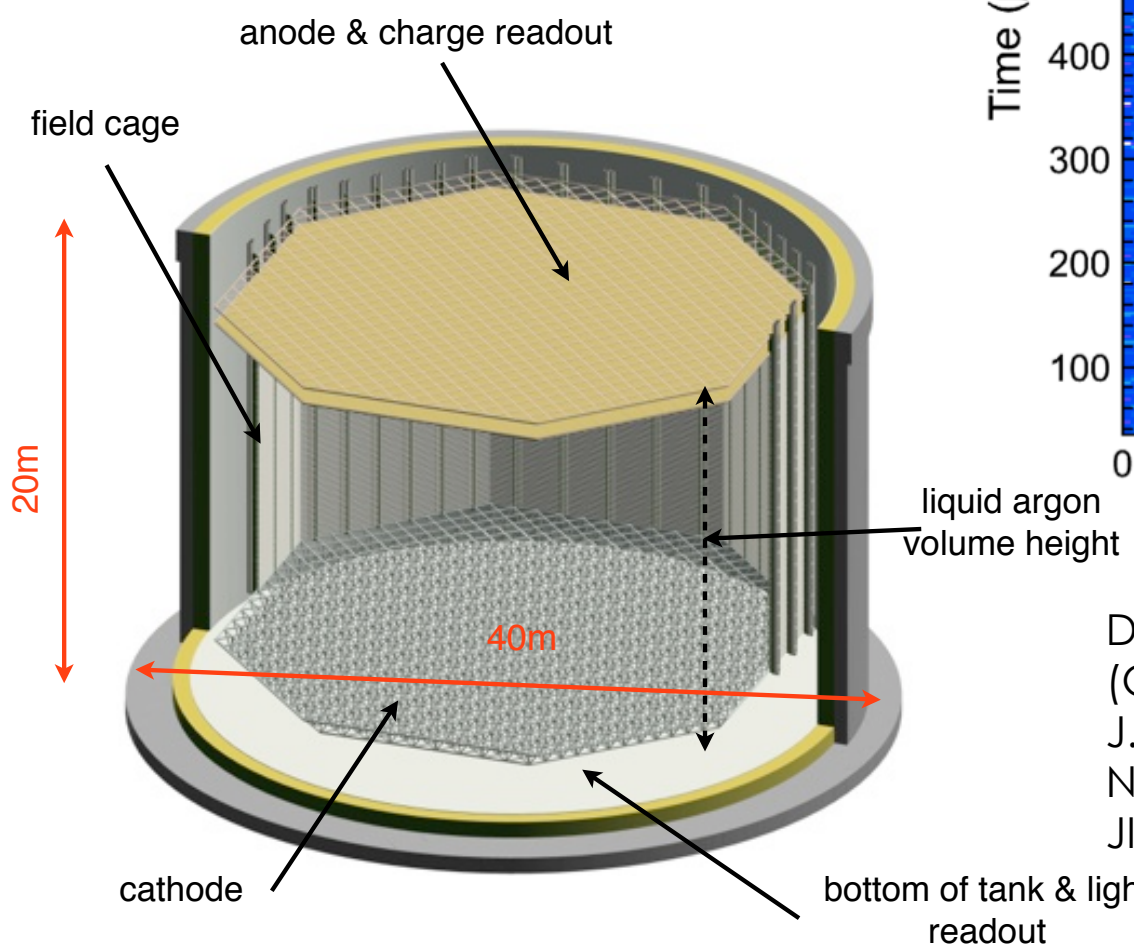
Contact: Th. Patzak (APC)

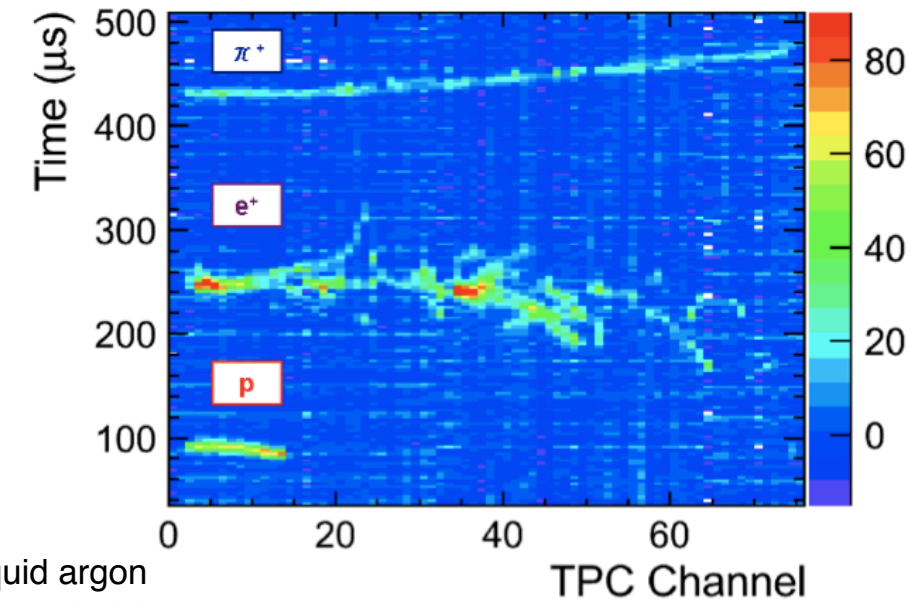
LSc- LENA



- Rich physics program (MeV ➔ GeV)
  - Solar-, geo-, SN-, reactor- neutrinos
  - Dark matter, proton decay
  - Work on GeV event tracking on-going

LAr-GLACIER





Double phase LAr LEM TPC (GLACIER,2003) (hep-ph/0402110, J.Phys.Conf.Ser. 171 (2009) 012020, NIM A 641 (2011) 48-57, JINST 7 (2012) P08026)

2-Phase Readout

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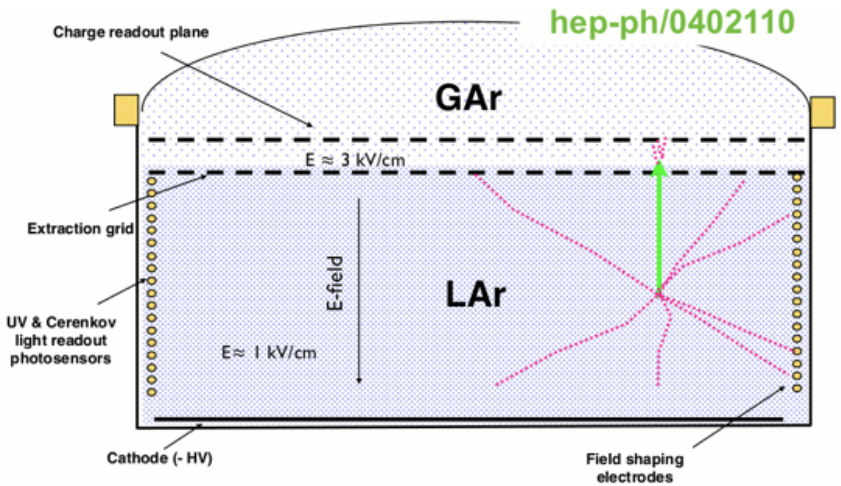
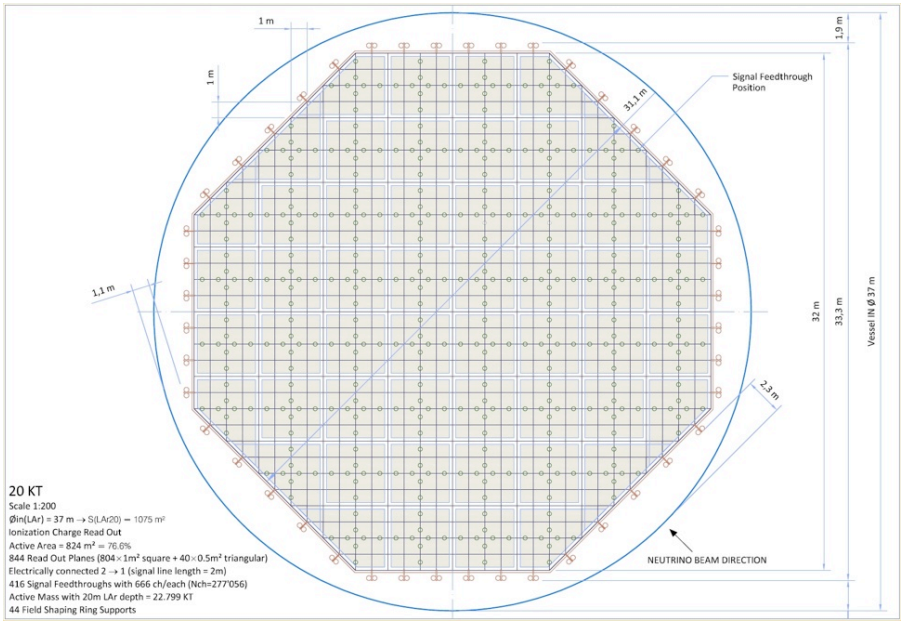
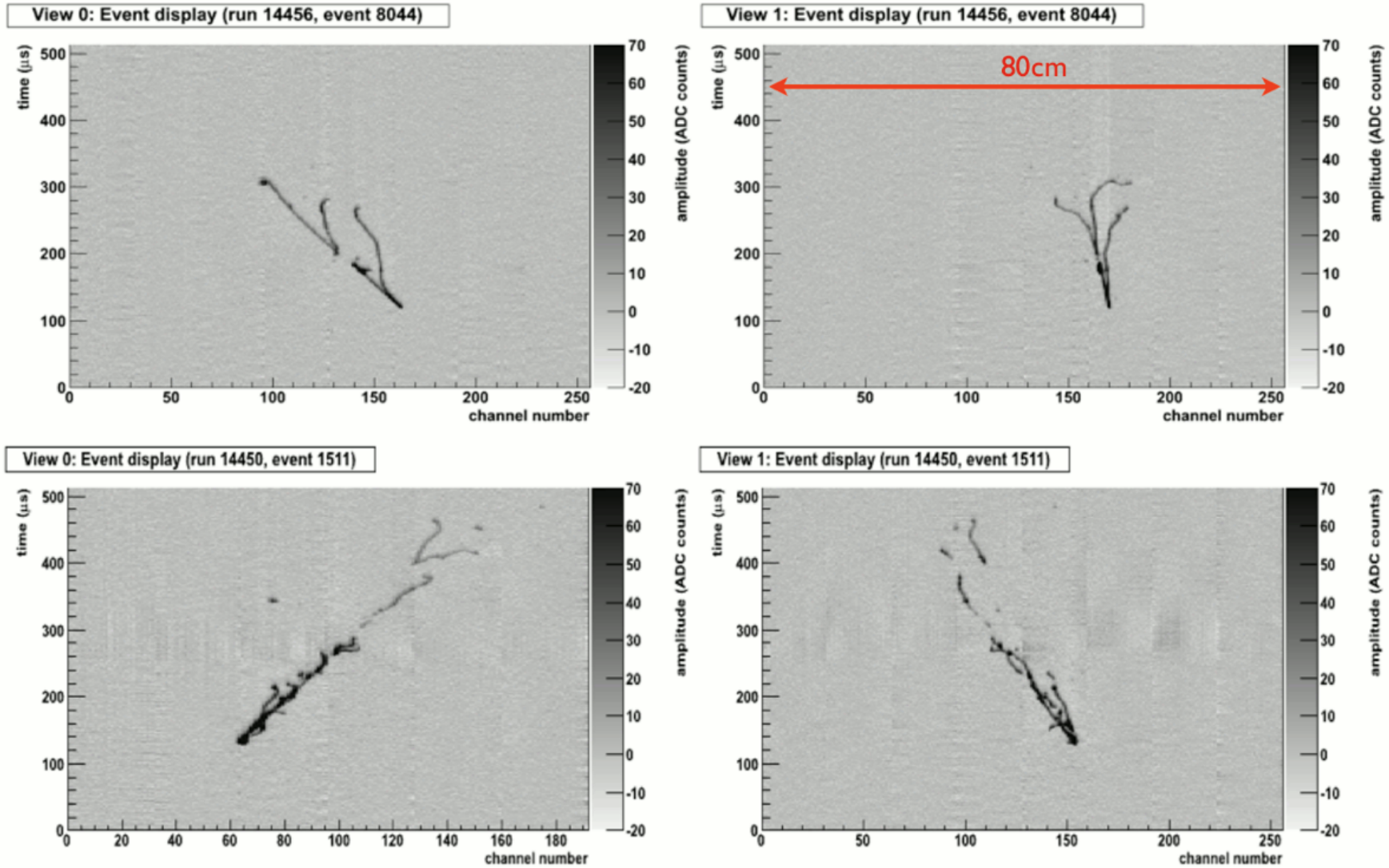
		20 KT	50 KT	100 KT
Liquid argon density at 1.2 bar	[T/m^3]	1.38346		
Liquid argon volume height	[m]	22		
Active liquid argon height	[m]	20		
Pressure on the bottom due to LAr	[T/m^2]	30.4 (≡ 0.3 MPa ≡ 3 bar)		
Inner vessel diameter	[m]	37	55	76
Inner vessel base surface	[m^2]	1075.2	2375.8	4536.5
Liquid argon volume	[m^3]	23654.6	52268.2	99802.1
Total liquid argon mass	[T]	32525.6	71869.8	137229.9
Active LAr area (percentage)	[m^2]	824 (76.6%)	1854 (78%)	3634 (80.1%)
Active (instrumented) mass	[KT]	22.799	51.299	100.550
Charge readout square panels (1m×1m)		804	1824	3596
Charge readout triangular panels (1m×1m)		40	60	72
Number of signal feedthroughs (666 channels/FT)		416	1028	1872
Number of readout channels		277056	660672	1246752
Number of PMT (area for 1 PMT)		804 (1m×1m)	1288 (1.2m×1.2m)	909 (2m×2m)
Number of field shaping electrode supports (with suspension SS ropes linked to the outer deck)		44	64	92





Cosmic Rays in 2-Phase



Expression of Interest

NuInt 2012

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VLBL neutrino oscillation experiment

CERN-SPSC-2012-012; SPSC-EOI-007

Submitted Jun 2012

Incremental approach based on Laguna findings

NPB2012 A. Rubbia – LAGUNA-LBNO 11

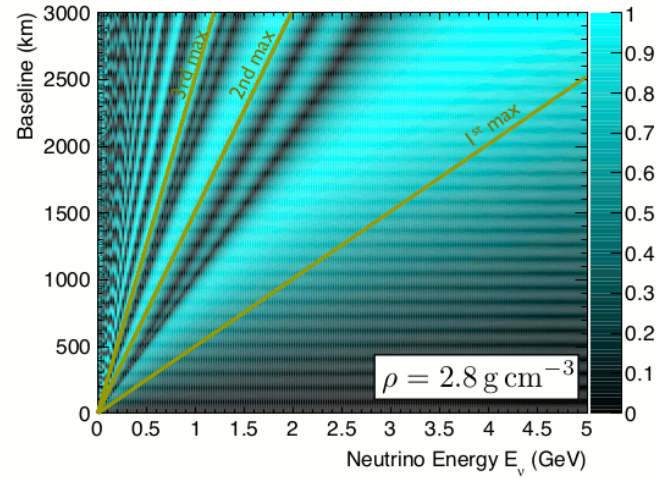
Tuesday, September 25, 12 11

Experimental Requirements

NuInt 2012

- Beam
  - Exploit long baseline pattern
  - L/E analysis of 1st and 2nd oscillation maxima
  - WBB 0.5-8 GeV
- Detector
  - Large mass
  - Fine sampling for BG rejection
  - Possible added magnetized muon detector

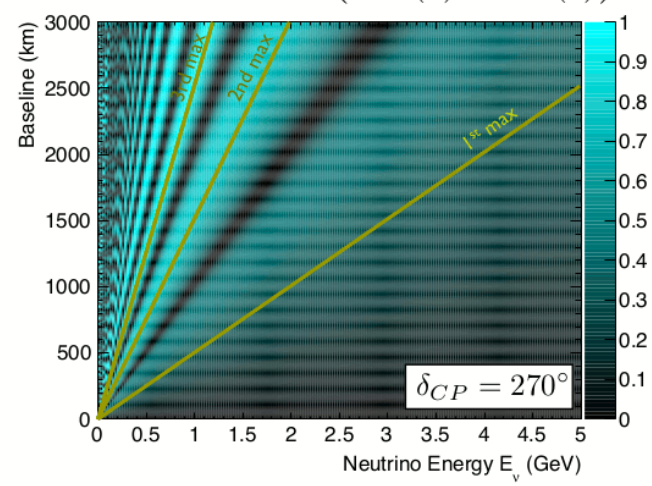
$$\mathcal{A}_{CP}(\rho) \equiv abs\left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$



$$\mathcal{A}_{CP}^{vac}(\delta_{CP}) \equiv abs\left(\frac{P^{vac}(\nu) - P^{vac}(\bar{\nu})}{P^{vac}(\nu) + P^{vac}(\bar{\nu})}\right)$$

$\sin^2(2\theta_{13}) = 0.09$

Normal mass hierarchy



Appearance Signal NH

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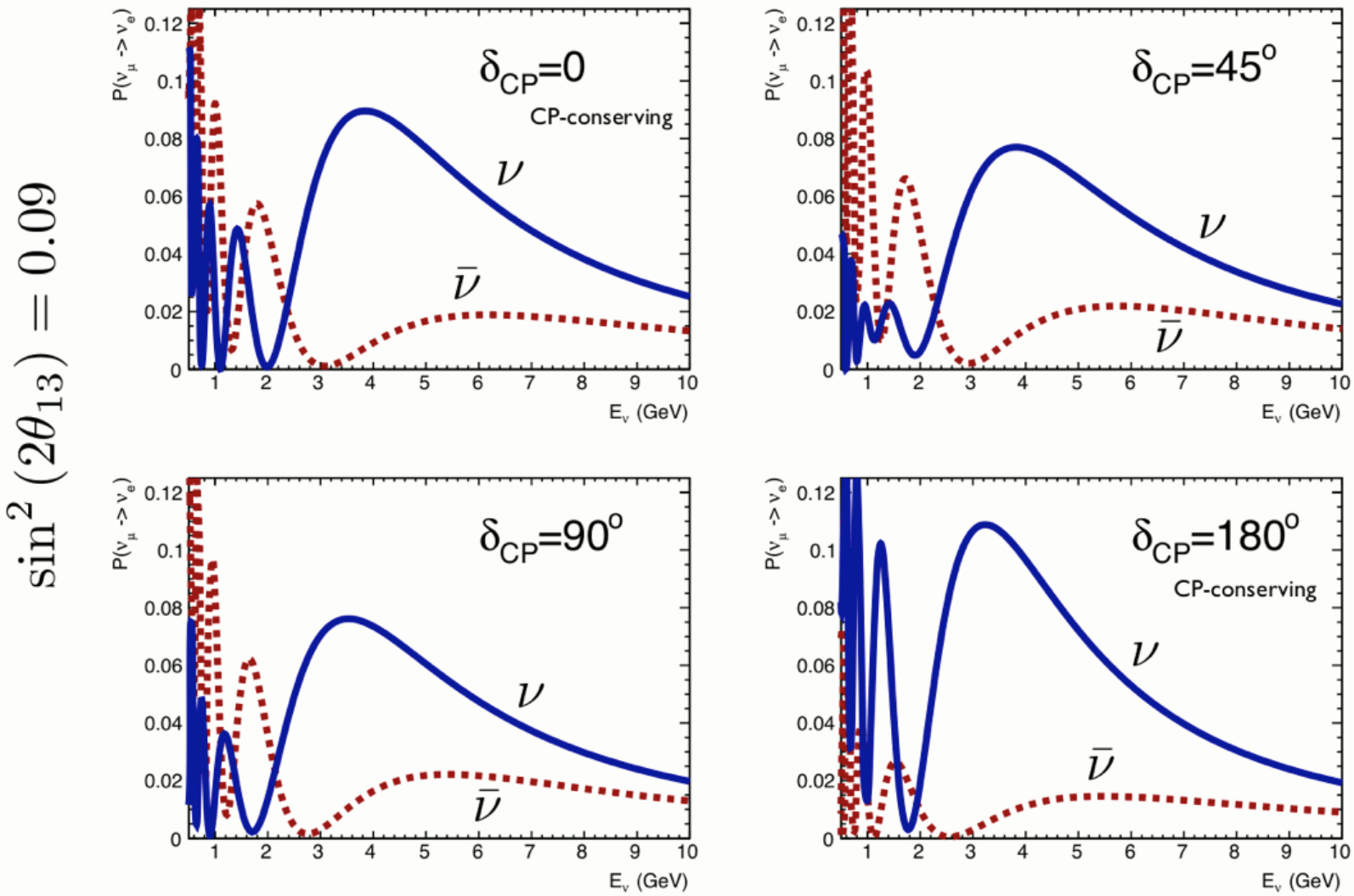
★Normal mass hierarchy

L=2300 km



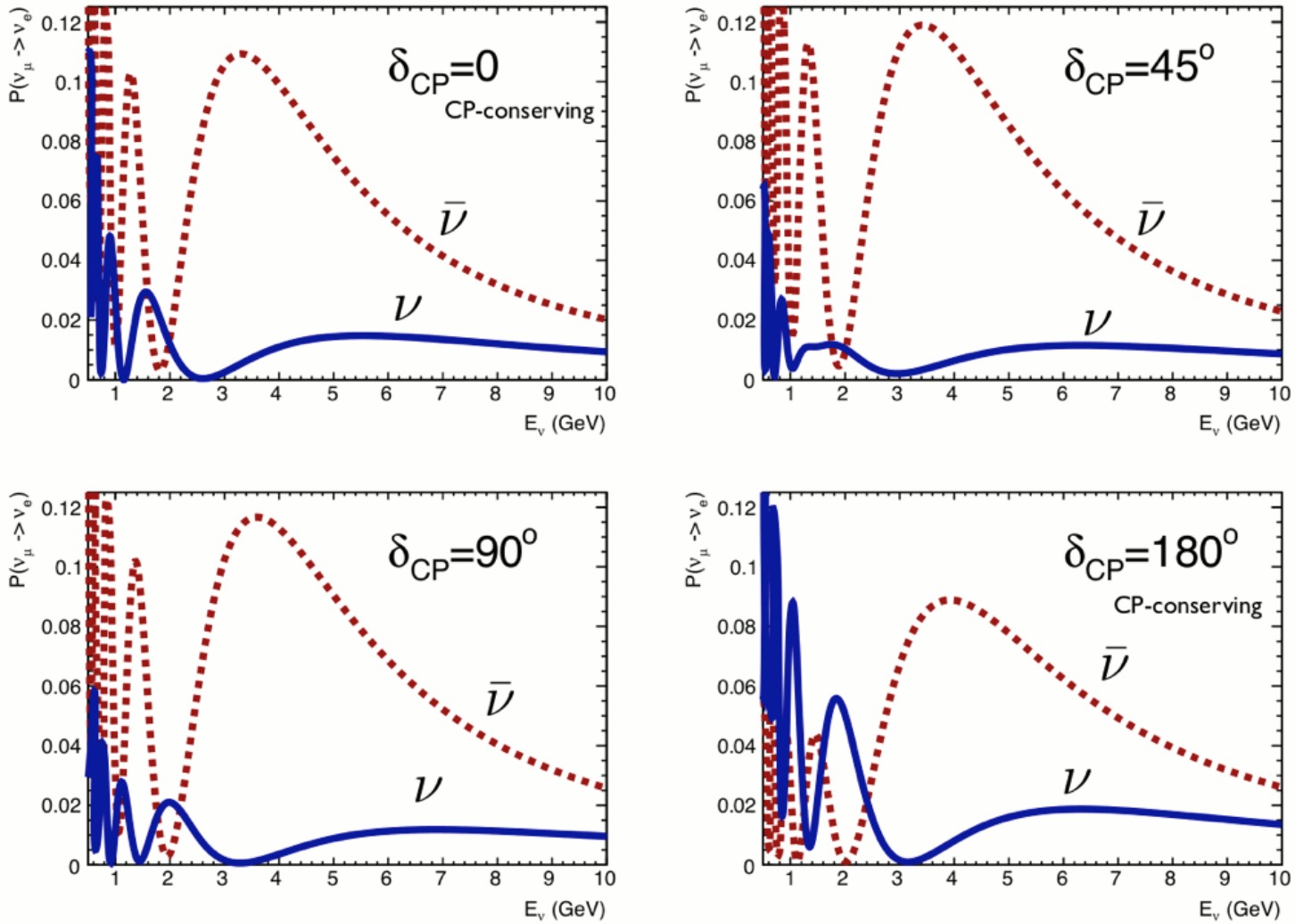
Appearance Signal IH

NuInt 2012

★Inverted mass hierarchy

L=2300 km

$\sin^2(2\theta_{13}) = 0.09$



Beam Parameters

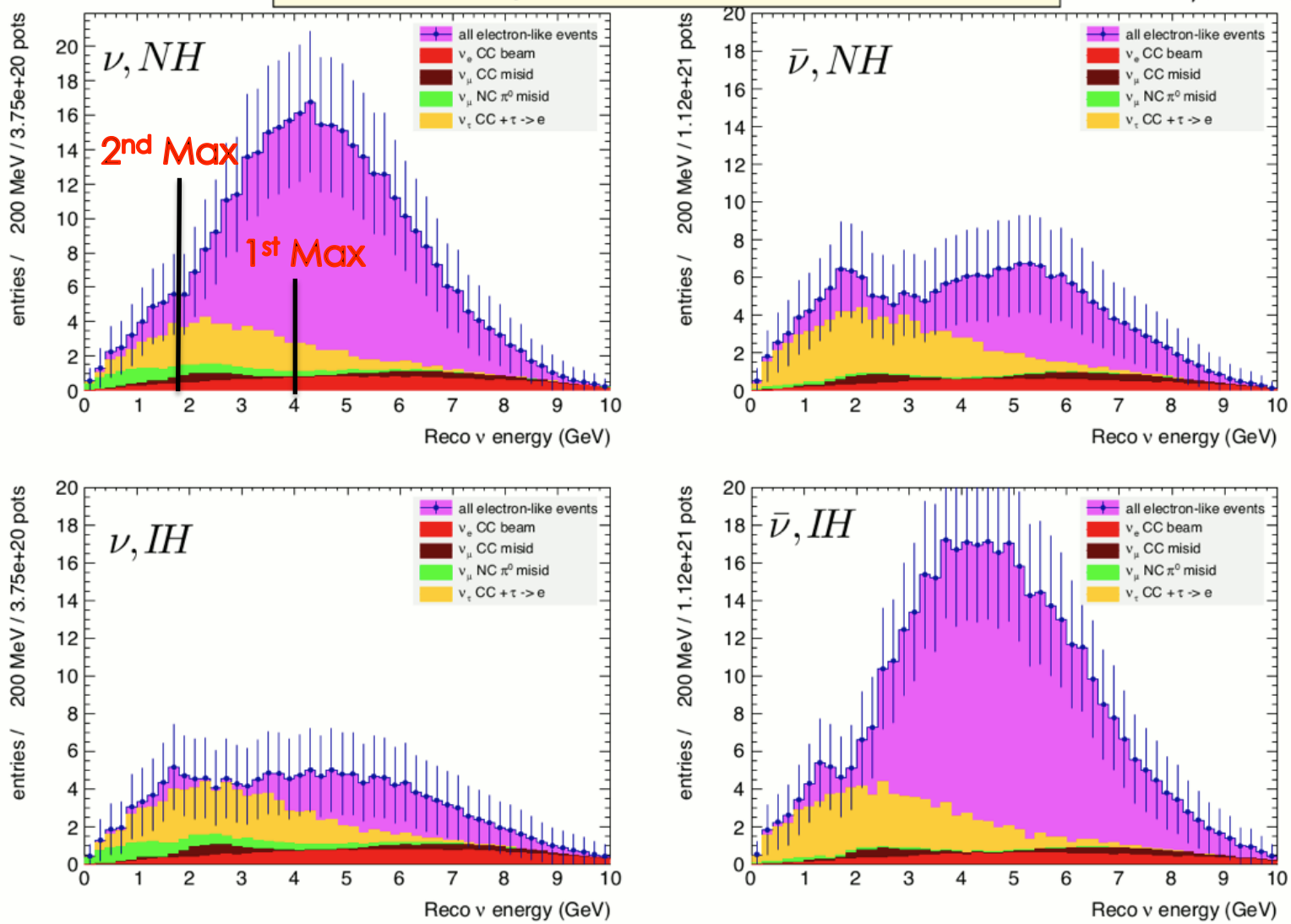
- Medium Energy
  - Oscillation @ 1.5-5 GeV
- High beam power
  - initially 700 kW
- Point to Pyhäsalmi
  - 2300 km and 10° downwards
- Muon monitor & near detector
- Initially
  - From SPS
    7×10^{13} ppp @ 400 GeV (6s cycle) ⇔ 1×10^{20} PoT/y
  - Later
    upgrade to high power PS

Signal

NuInt 2012

Detector response and resolution included

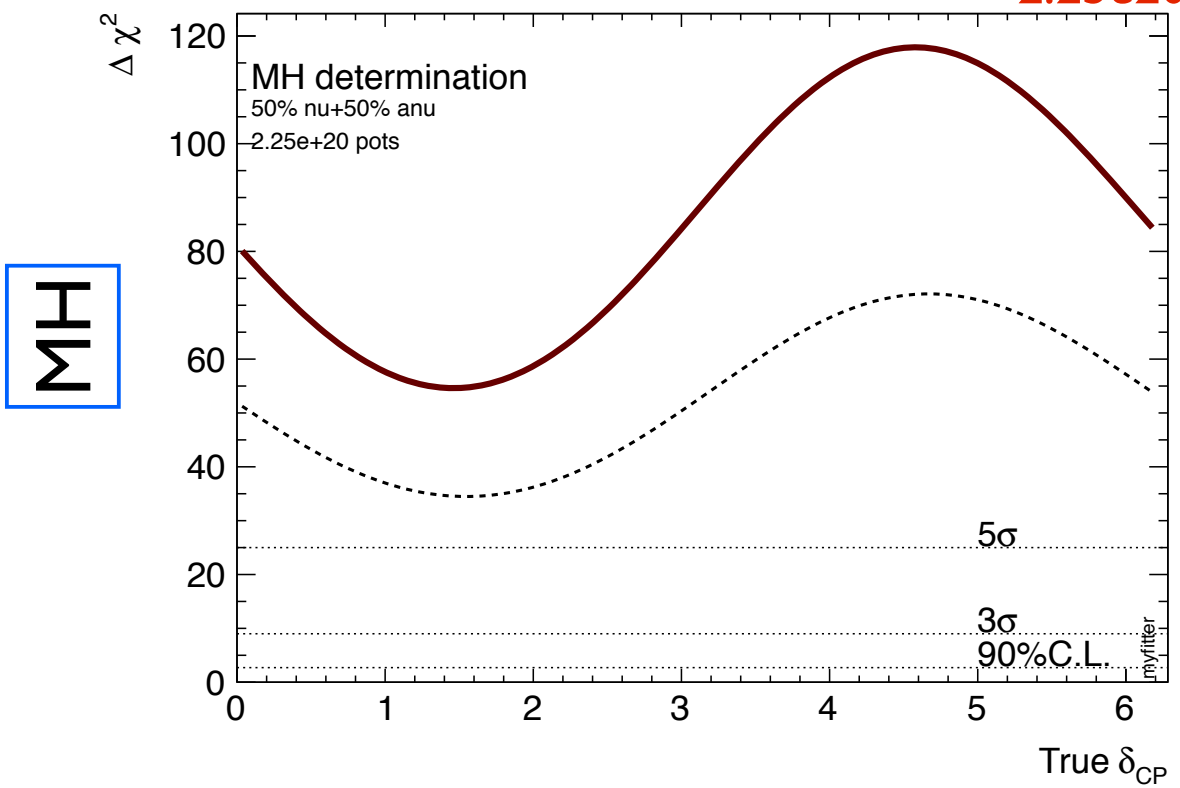
Running mode:
ν/anti-ν:25%/75%



Mass Hierarchy

NuInt 2012

2.25e20 pot

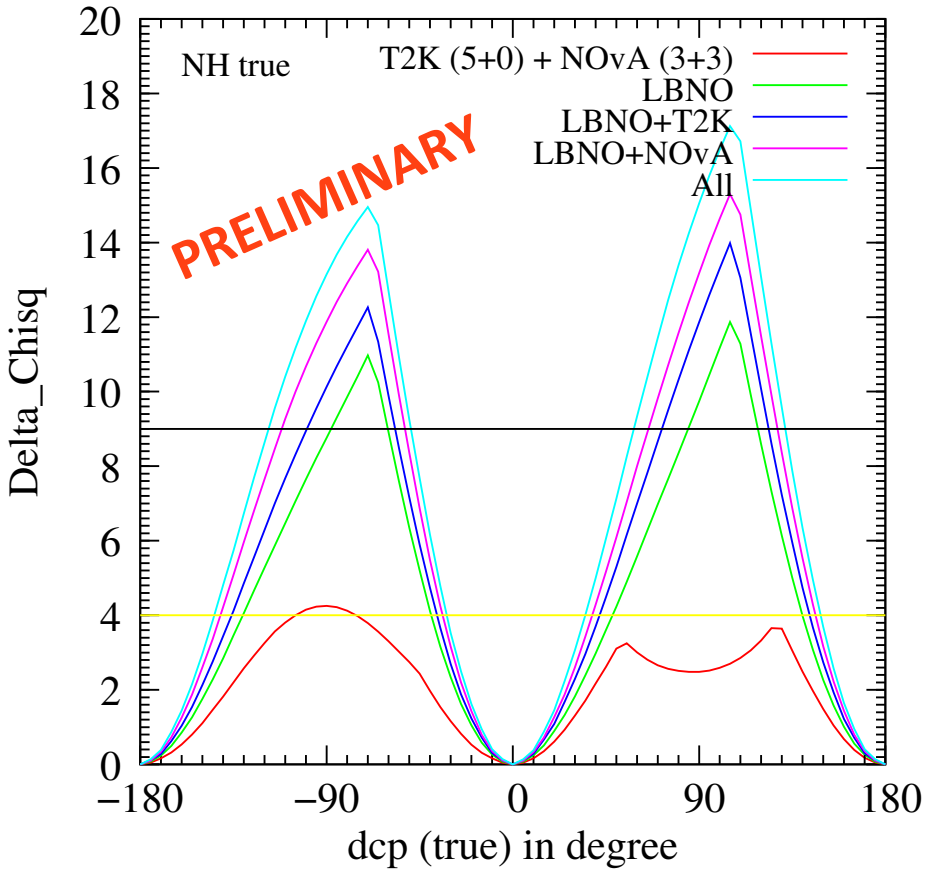


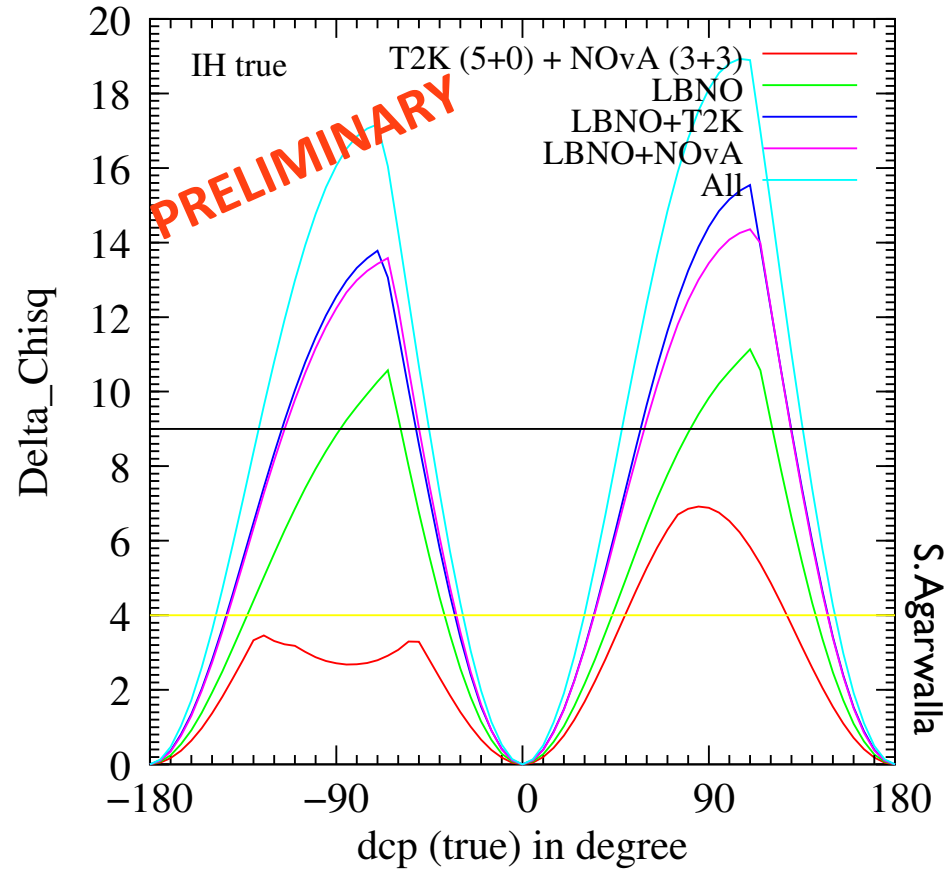
Provide a >5σ direct determination of MH for all values of δ_{CP} within 2.5 years of running

CP Sensitivity

NuInt 2012

Sensitivity combining T2K(295km), NOvA(810km) and LBNO(2300km)

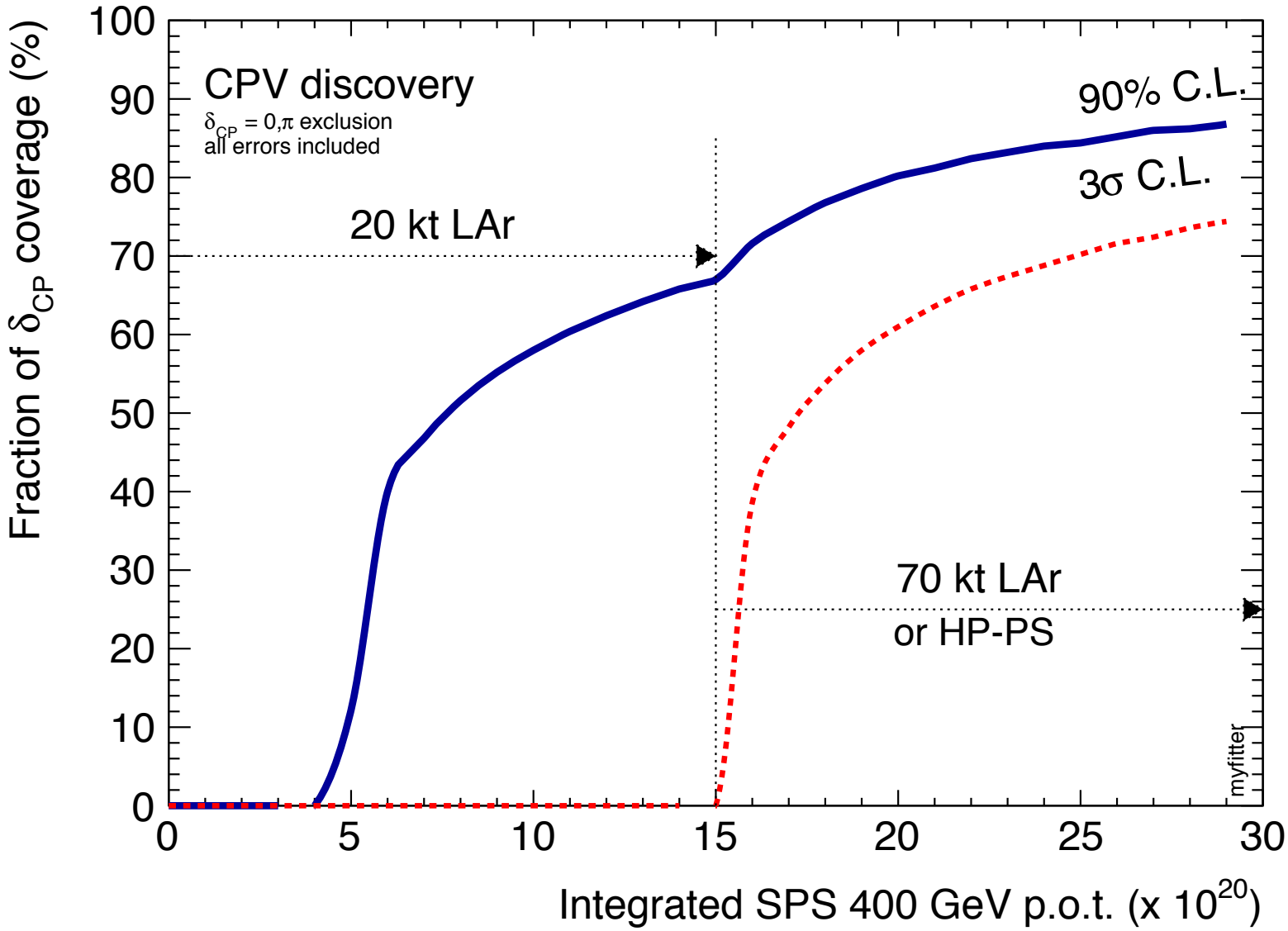




S.Agarwalla

The power of combining several different baselines L:
LBNO 20kton(5+5) + T2K(5+0) + NOvA(3+3) ≈ 40-45% CPV at >3σ C.L.

Incremental Approach



Systematics

- We estimate the significance C.L. with a chi2sq method, with which we can
  1) exclude the opposite mass hierarchy and
  2) exclude δ_{CP} = 0 or π (CPV)
- Minimize chi2sq w.r.t to the known 3-flavor oscillations and the nuisance parameters using Gaussian constraints

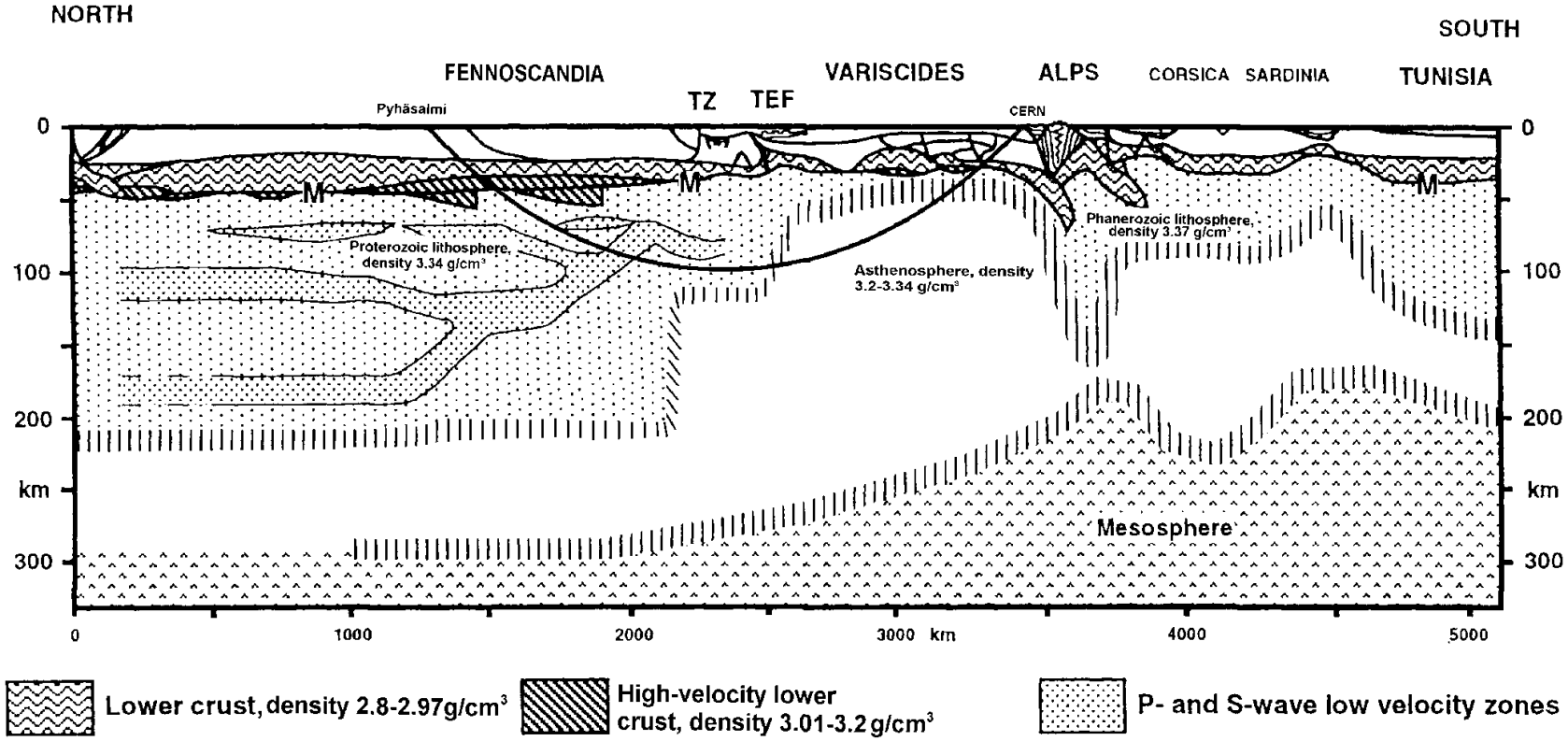
Name	Value	Error (1σ)
L	2300 km	exact
Δm^2_{21}	7.6×10^{-5} eV^2	exact
$\lvert\Delta m^2_{32}\rvert \times10^{-3}$ eV^2	2.40	±0.09
$\sin^2\theta_{12}$	0.31	exact
$\sin^2 2\theta_{13}$	0.10	±0.02
$\sin^2\theta_{23}$	0.50	±0.06
Average density of traversed matter (ρ)	3.2 g/cm^3	$\pm4\%$

Control of systematic errors will be fundamental

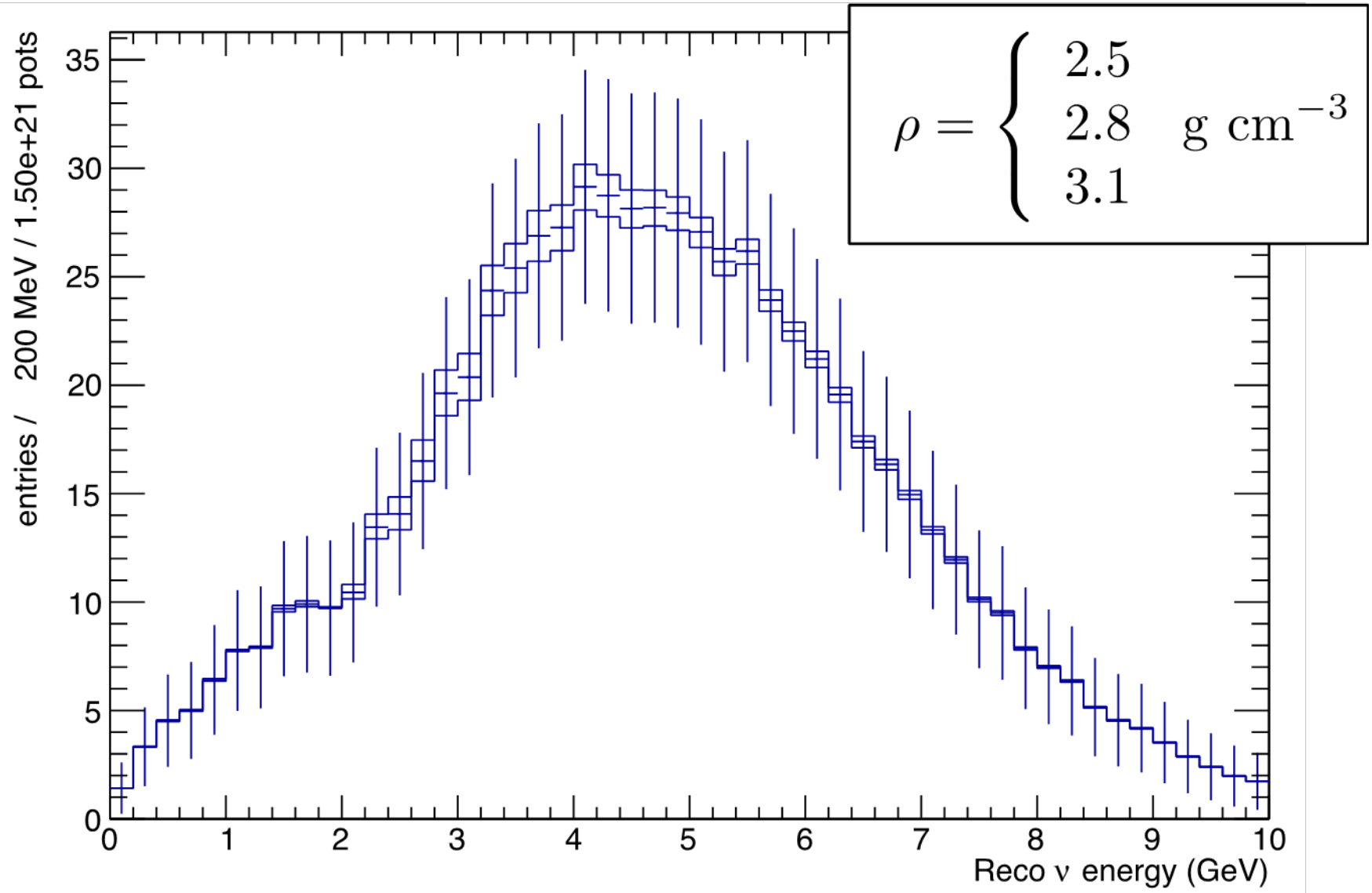
Name	MH determination	CP determination
	Error (1σ)	Error (1σ)
Bin-to-bin correlated:		
Signal normalization (f_{sig})	$\pm5\%$	$\pm5\%$
Beam electron contamination normalization ($f_{\nu_e CC}$)	$\pm5\%$	$\pm5\%$
Tau normalization ($f_{\nu_\tau CC}$)	$\pm50\%$	$\pm20\%$
ν NC and ν_μ CC background ($f_{\nu_{NC}}$)	$\pm10\%$	$\pm10\%$
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	$\pm5\%$	$\pm5\%$
Bin-to-bin uncorrelated	$\pm5\%$	$\pm5\%$

Conservative errors

Matter Effects



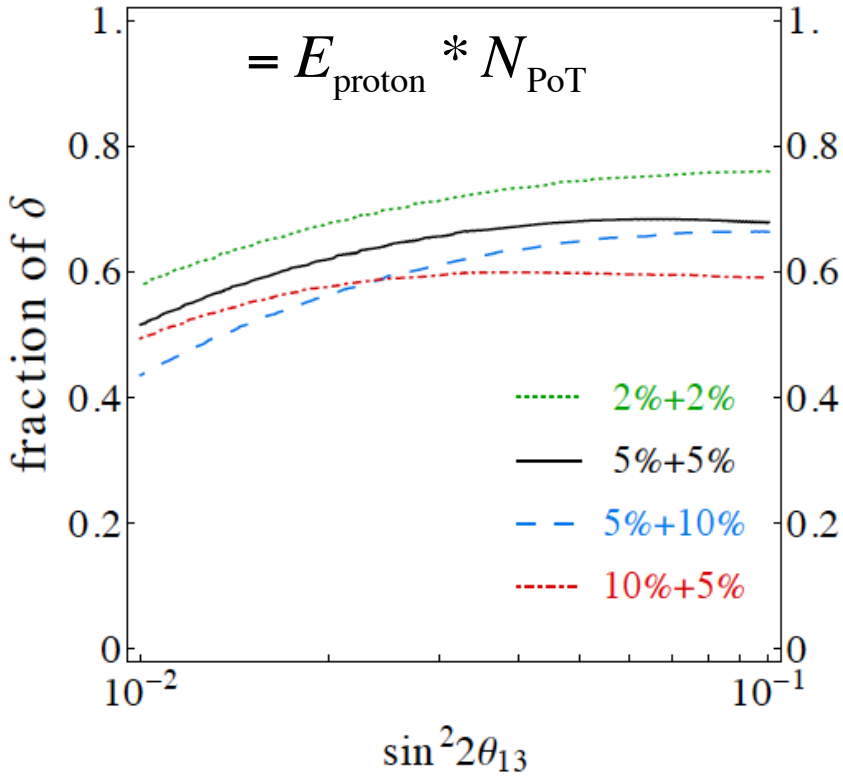
Matter Effects



Effect of Uncertainty

NuInt 2012

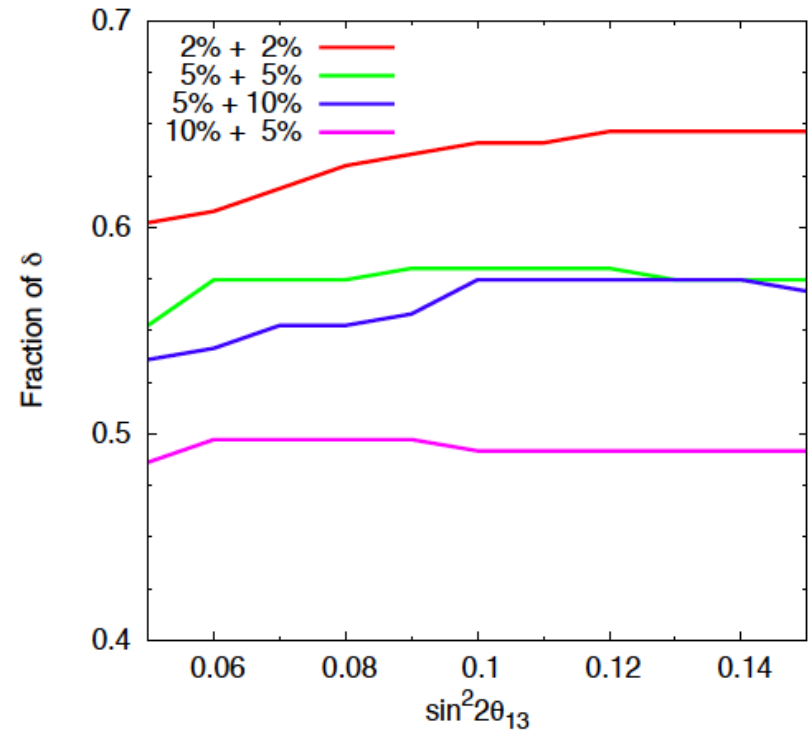
150×10^{22} GeV total, 100 kt:



P. Coloma, T. Li, S. Pascoli, [1206.4038].

CP fraction ranges from $\sim 60\% - 75\%$.

50×10^{22} GeV total, 100 kt:

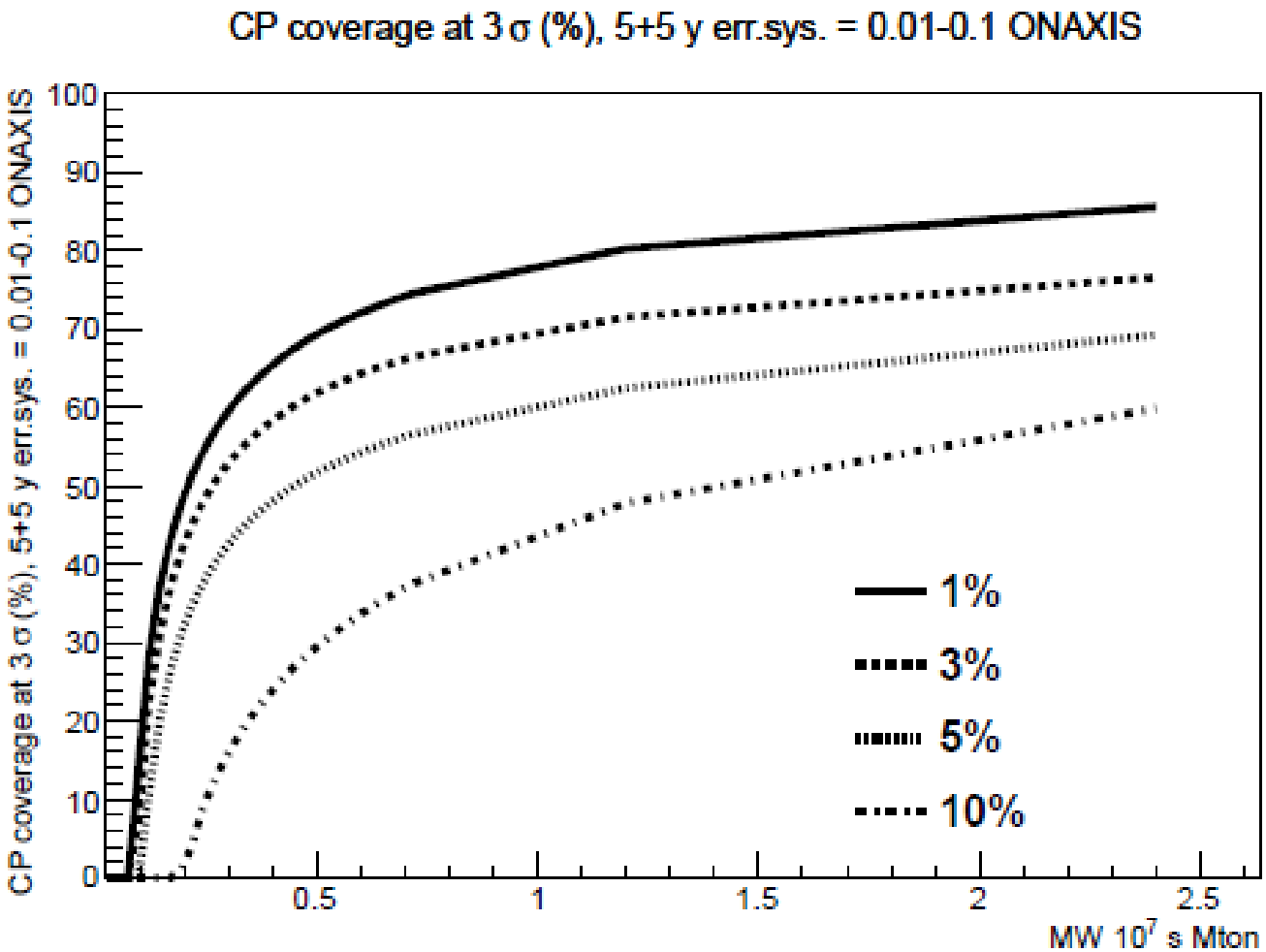


P. Coloma, T. Li, S. Pascoli.

CP fraction ranges from $\sim 48\% - 65\%$.

Effect of Systematics (II)

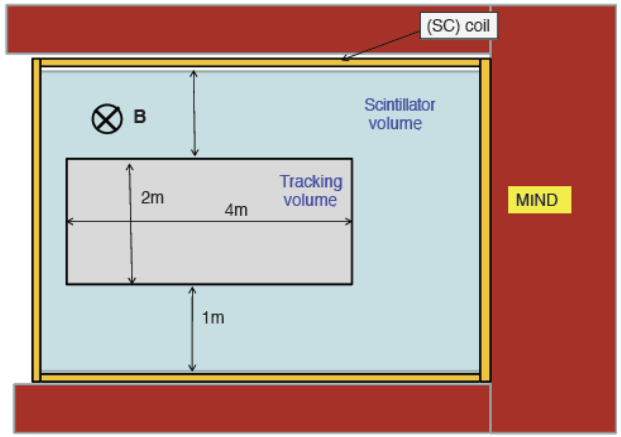
- From Dusini et al. (arXiv:1209.7010)

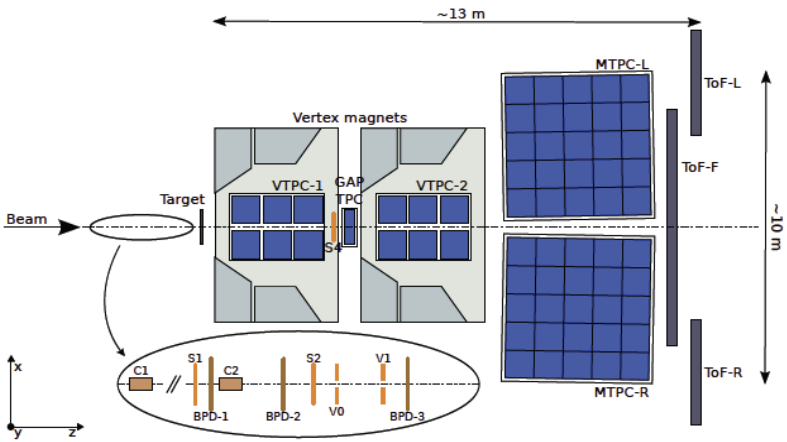


Near Detector & Hadron Production Experiment

NuInt 2012

- Aim: systematic errors for signal and backgrounds in the far detectors below ±5% possibly at the level of ±2% ⇒ control of fluxes, cross-sections, efficiencies,...





- Concept: 10 bar gas argon-mixture TPC surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 270 kg argon mass, of which ≈100 kg fiducial
- 0.2 event/spill @ 700 kW
- O(100'000) events/year

- It is widely recognized that hadro-production measurements with thin or replica target are really crucial for precision neutrino experiments (eg. K2K, T2K, MINOS).
- CERN NA61 acceptance study for 400 GeV incident protons

- Precision neutrino cross-section measurements: e.g. MINERVA, T2K-ND280, also nuSTORM (FNAL LoI)

Summary & Conclusion

- Hunt for the MH and CPV requires
  - Intense beams
  - Large detectors
  - Good control of systematics
- Next generation of experiments
  - Cross section uncertainties O(<5%)
    - Neutrinos and anti-neutrinos
    - Electron- and muon-neutrinos
  - ND important
    - Limited use for electron cross sections
  - Hadron production experiments
- Large effort in theory and experiments is needed