LAGUNA-LBNO Perspectives for Neutrino Mass Hierarchy Measurement

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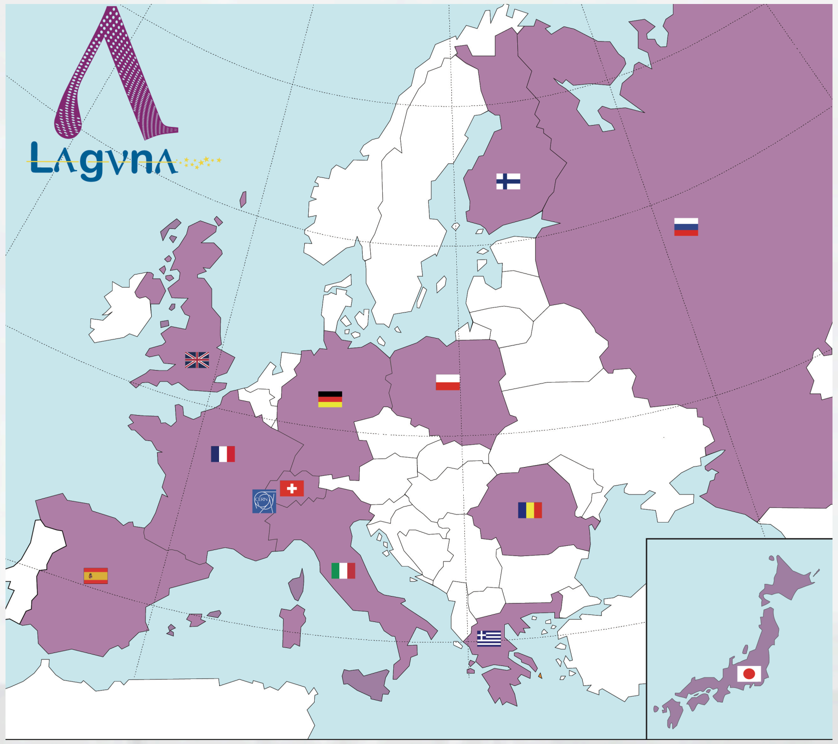
APC Laboratory, Paris

ORCA Workshop

Paris, April 17th 2013

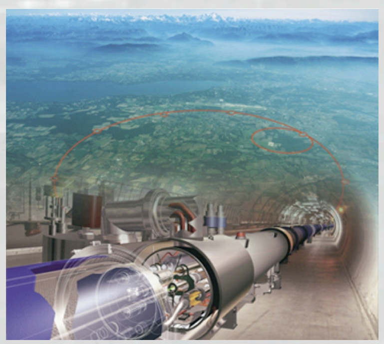


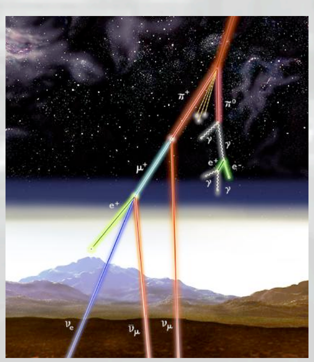
LAGUNA-LBNO: Large Apparatus for Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations

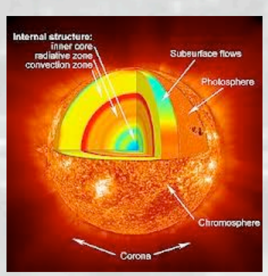
LAGUNA-LBNO consortium = 13 countries, 45 institutions, ~300 members

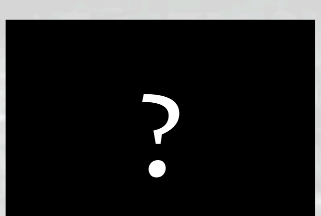
FP7 DS: 2011 - 2014; 4.9 M€

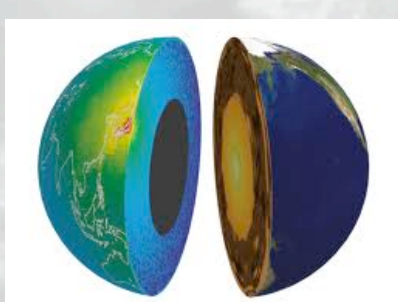
LAGUNA-LBNO Physics:











1. Accelerator based:

- **Mass Hierarchy**
- δ_{CP}
- MSNP precision
- 3 ν or 3+n ?

large θ_{13}

2. Non-Accelerator based:

- Proton decay

3. Neutrino Astronomy:

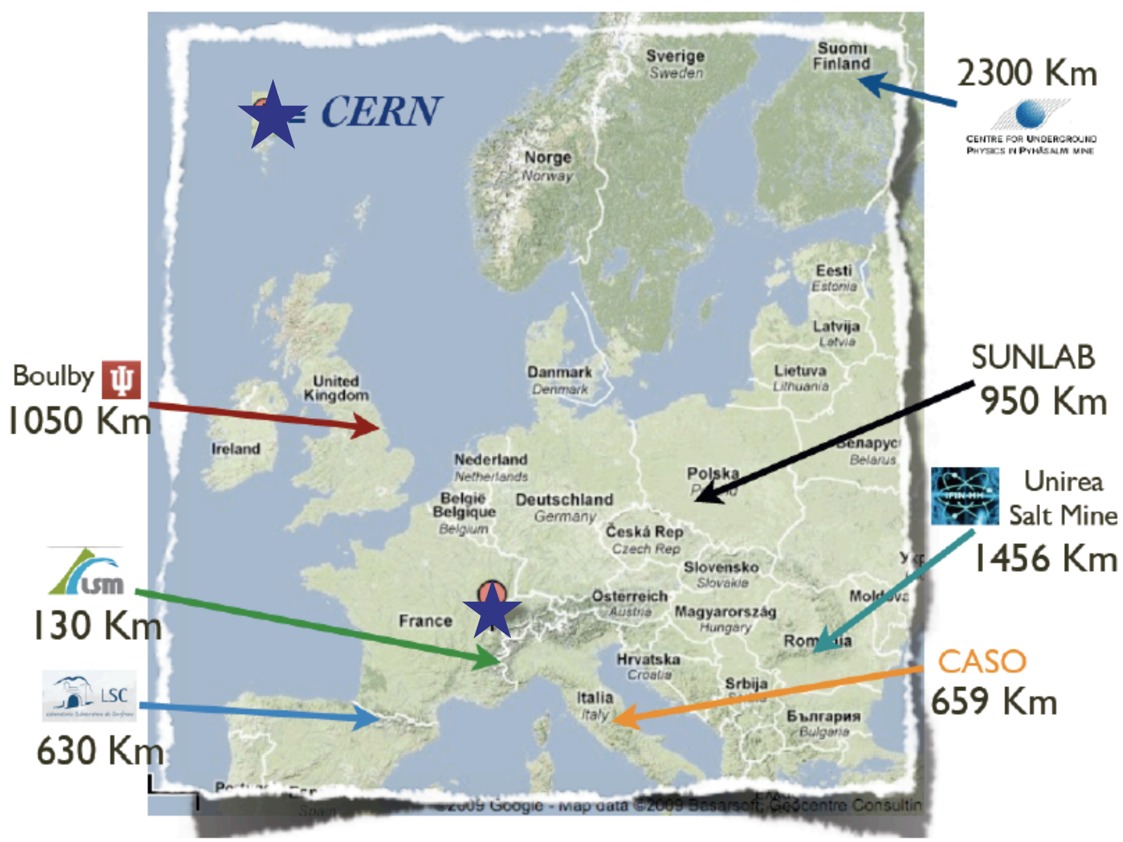
- Supernova neutrinos
- Diffuse Supernova Neutrinos
- Solar Neutrinos
- Atmospheric Neutrinos
- Geo Neutrinos

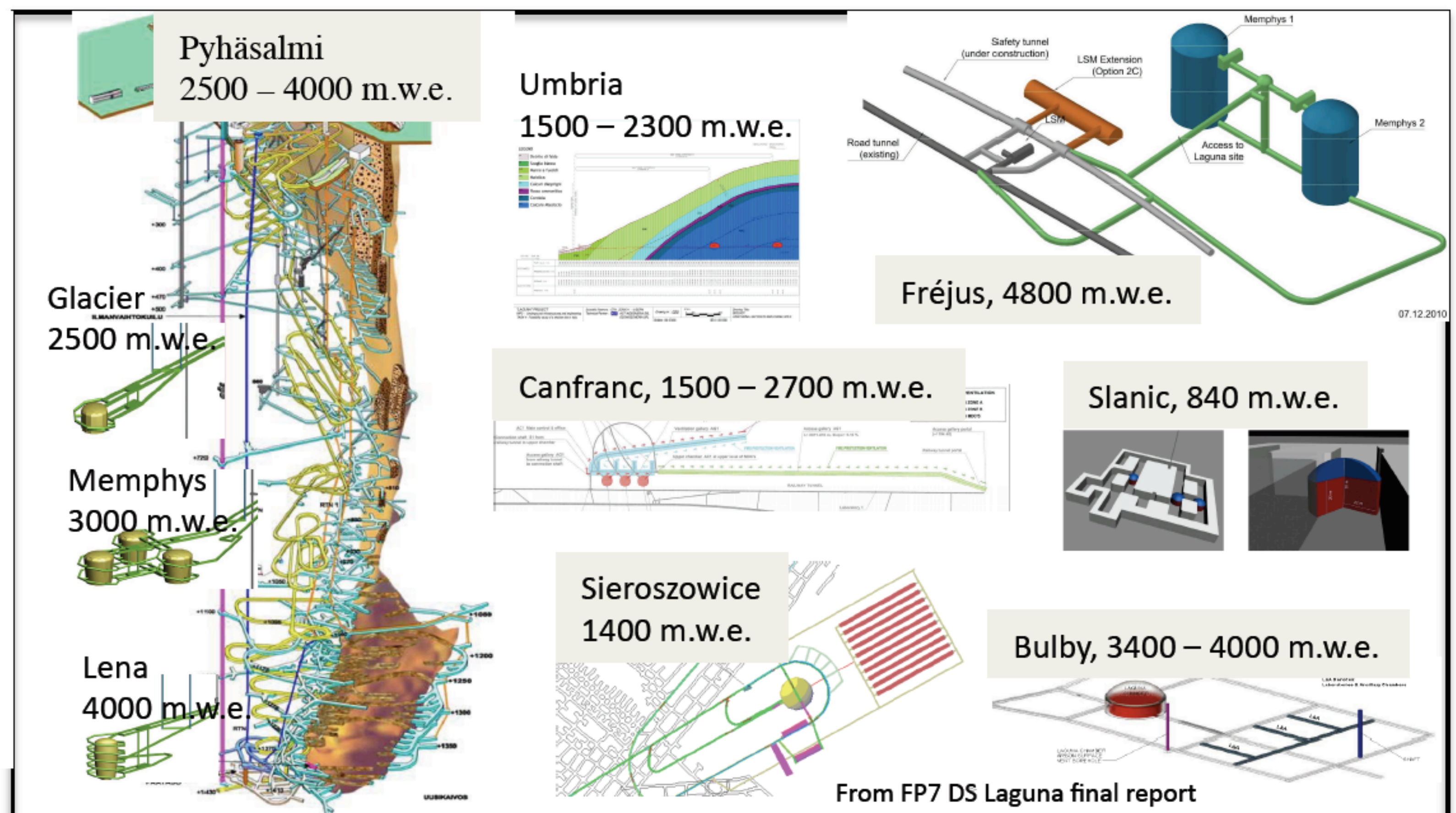
4. Dark Matter

LAGUNA (2008 - 2011):

~ 100 members; EU funding 1,7 M€

- ✓ LAGUNA => very comprehensive evaluation of all sites, construction and costs
- ✓ LAGUNA => baselines from 130 km to 2300 km available in Europe = advantage
- ✓ LAGUNA => allowed to form a strong community in Europe (> 100 physicists and Ing.)
- ✓ LAGUNA => showed the need to evaluate constraints and costs for the detector options





New program: LAGUNA-LBNO, Start September 2011 – End September 2014

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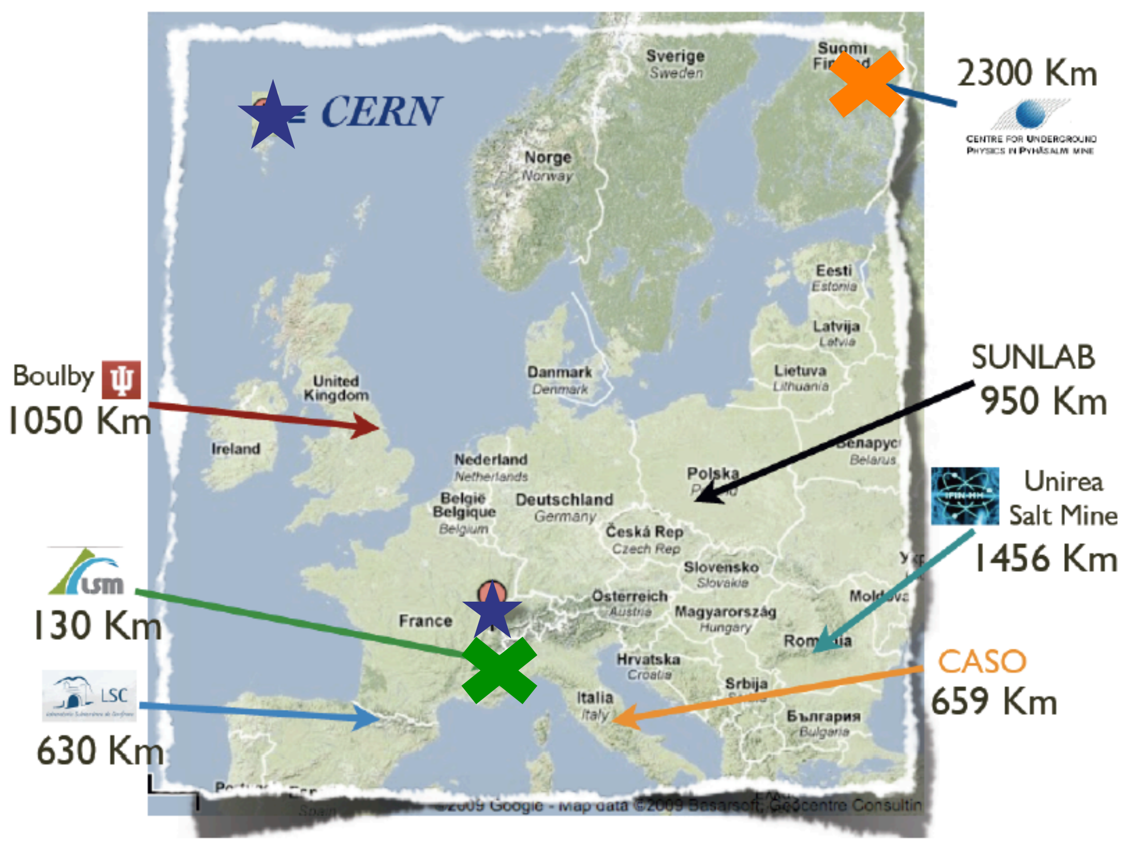
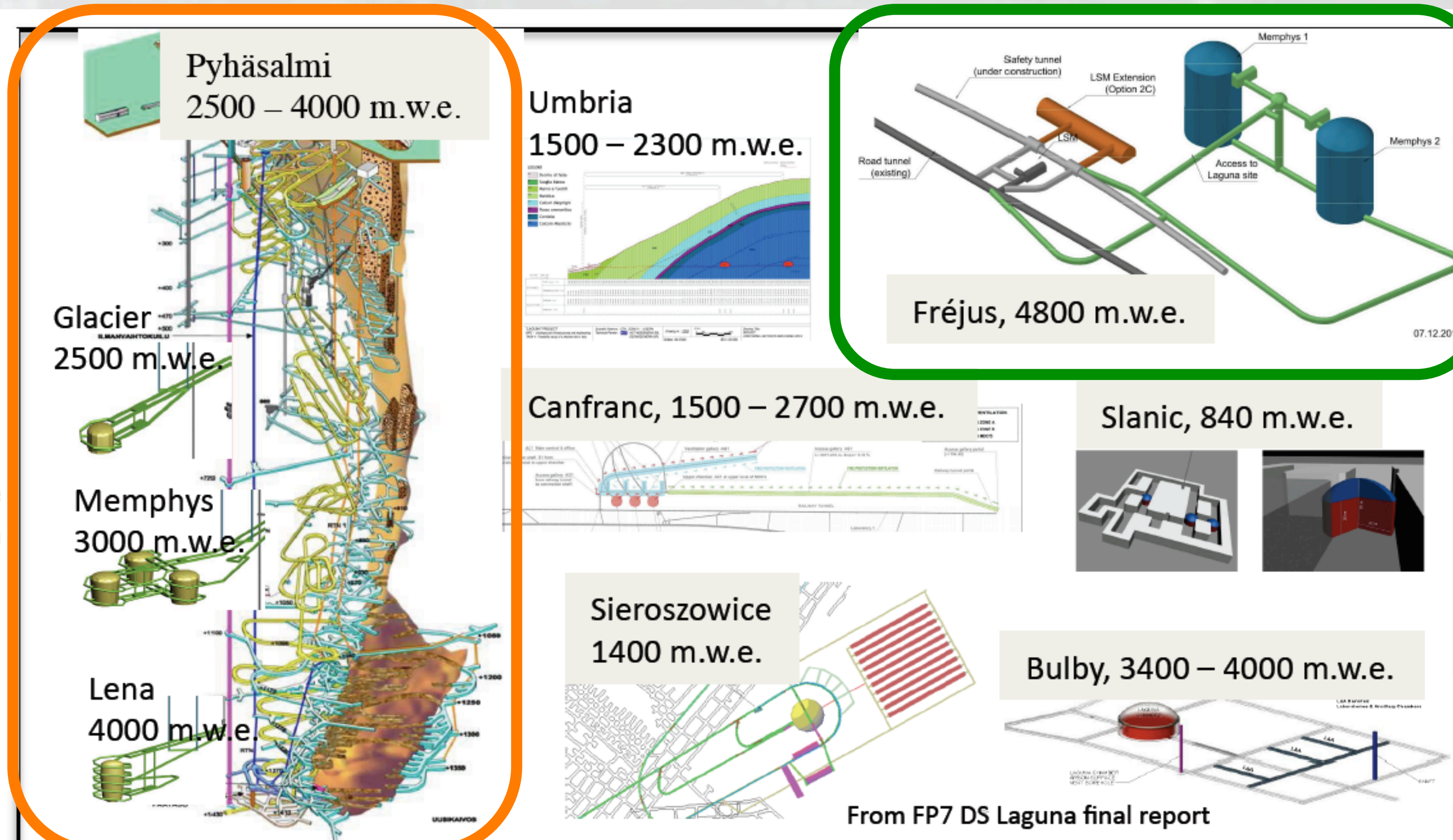
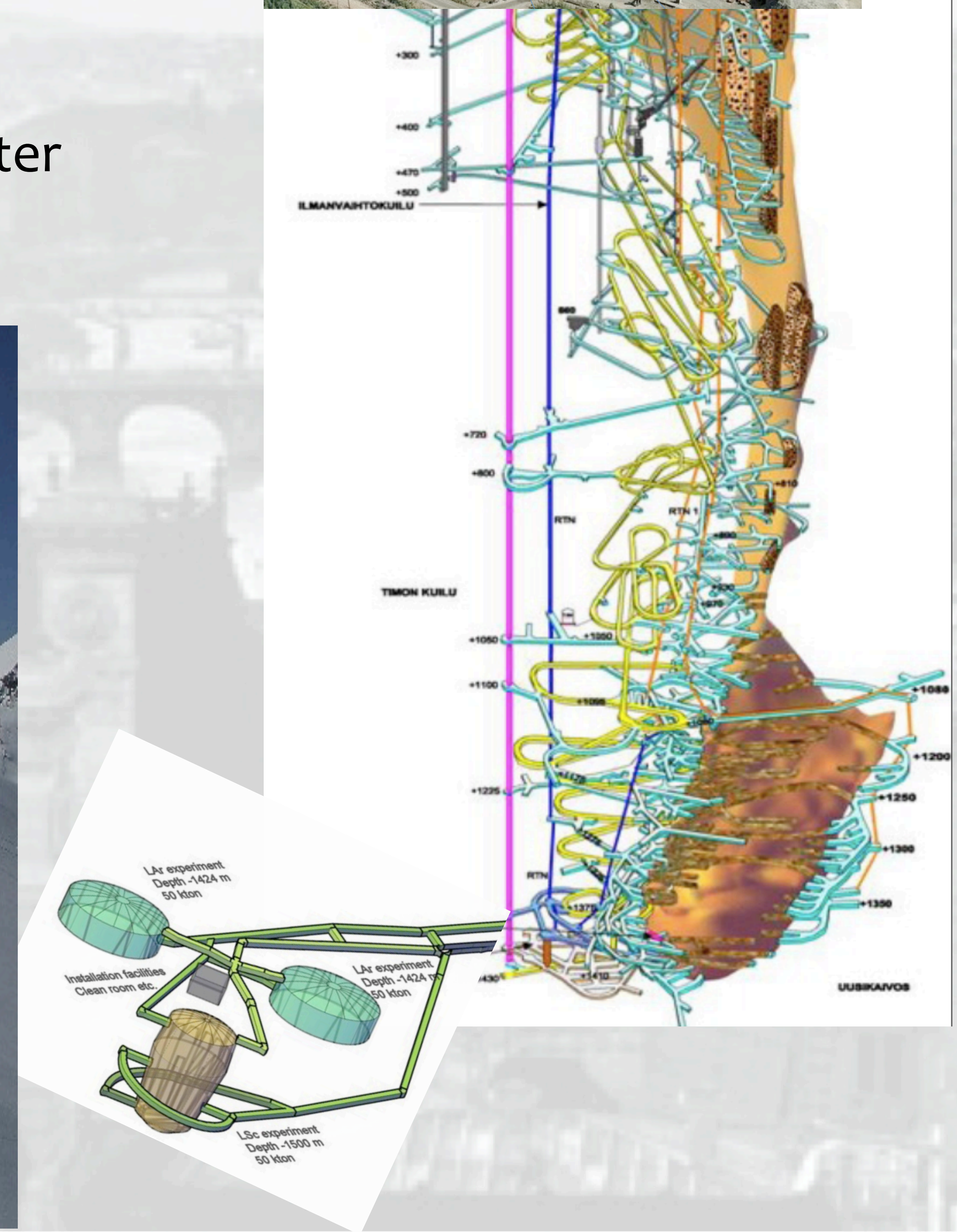




New program: LAGUNA-LBNO, Start September 2011 – End September 2014

LAGUNA-LBNO (2011 - 2014)

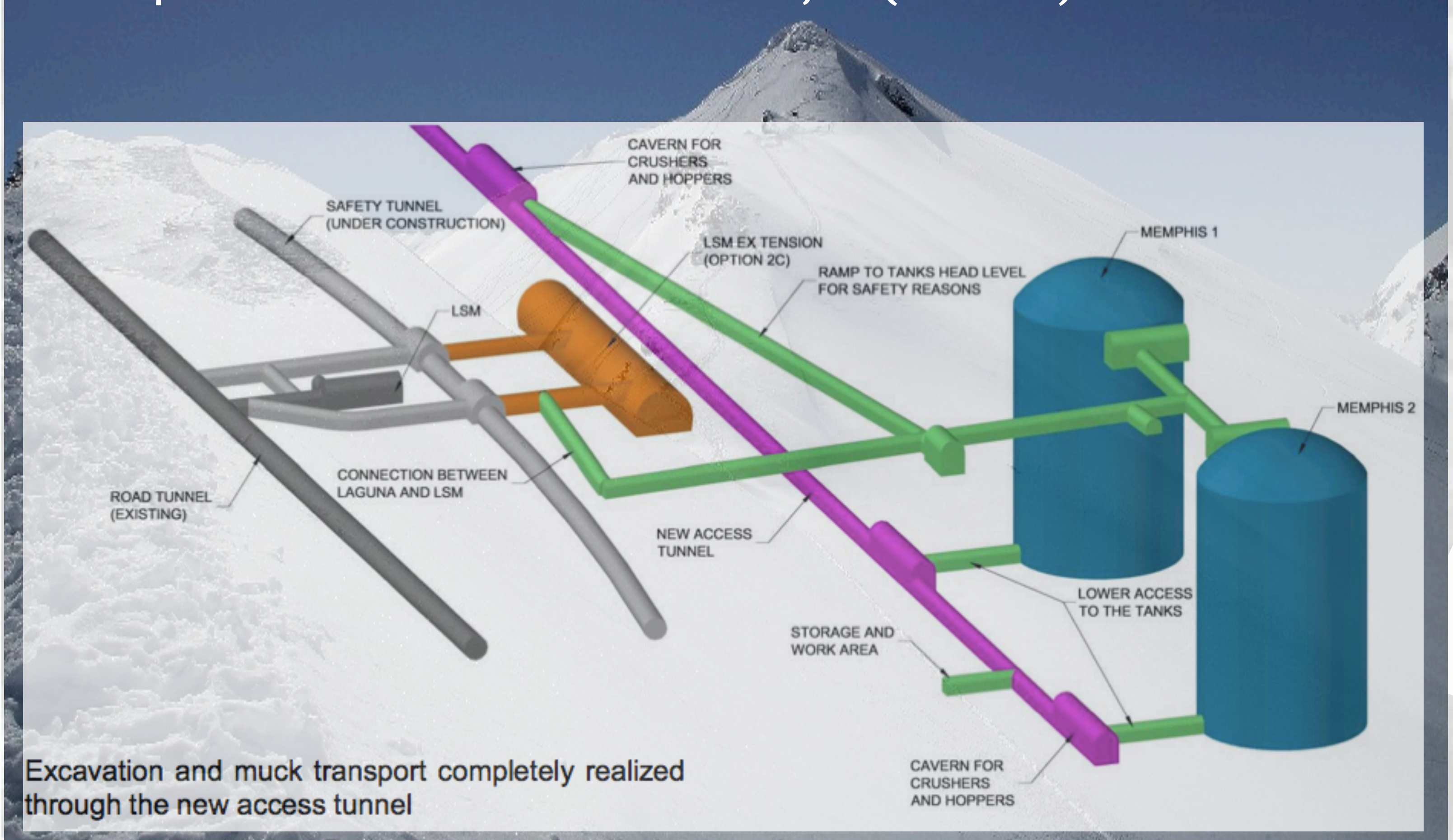
1st option: LAGUNA-LBNO at Pyhäsalmi (Finland)

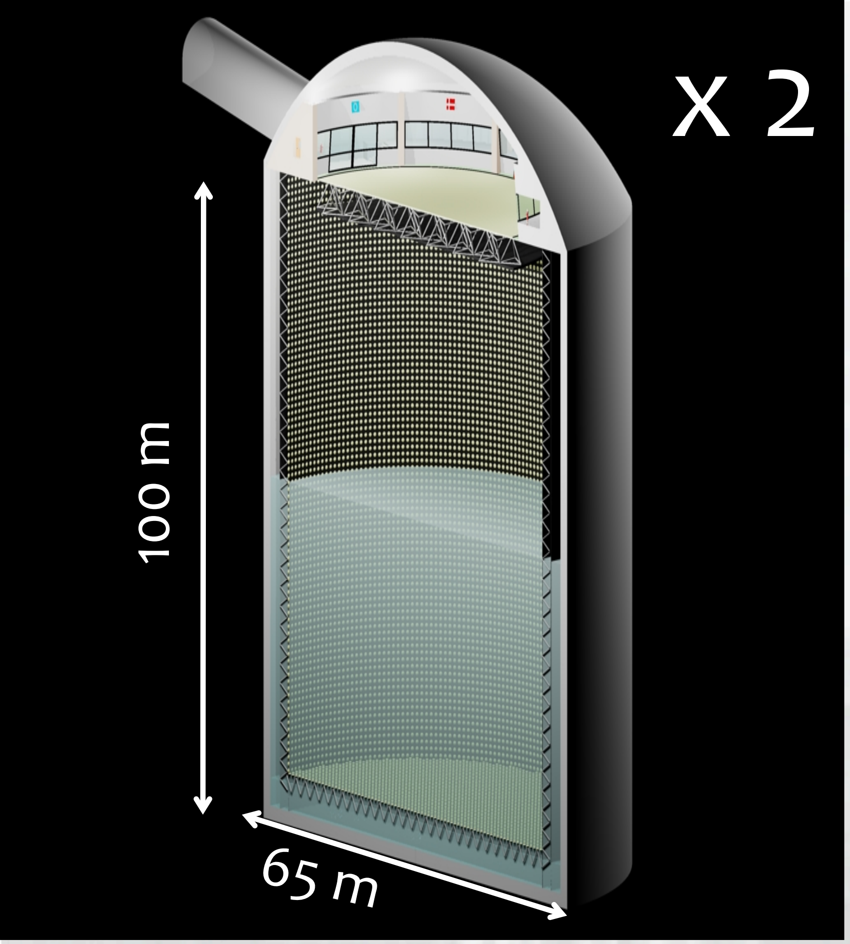


EOI for a very long baseline neutrino oscillation experiment
CERN-SPSC-2012-021; SPSC-EOI-007

1. **Longest baseline (2300 km),** CERN -> Pyhäsalmi: matter effect; mass hierarchy, LCPV
2. Shortest baseline (130 km), CERN -> Fréjus: no matter effects; clean measurement of LCPV

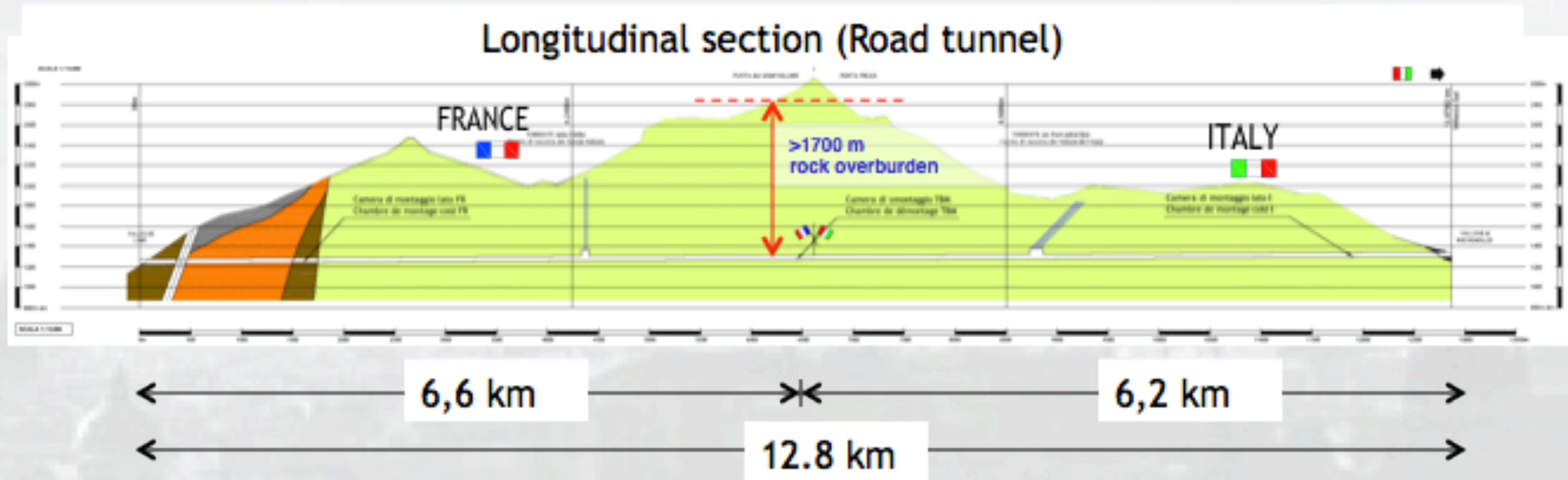
2nd option: LAGUNA-LBNO at Fréjus (France)





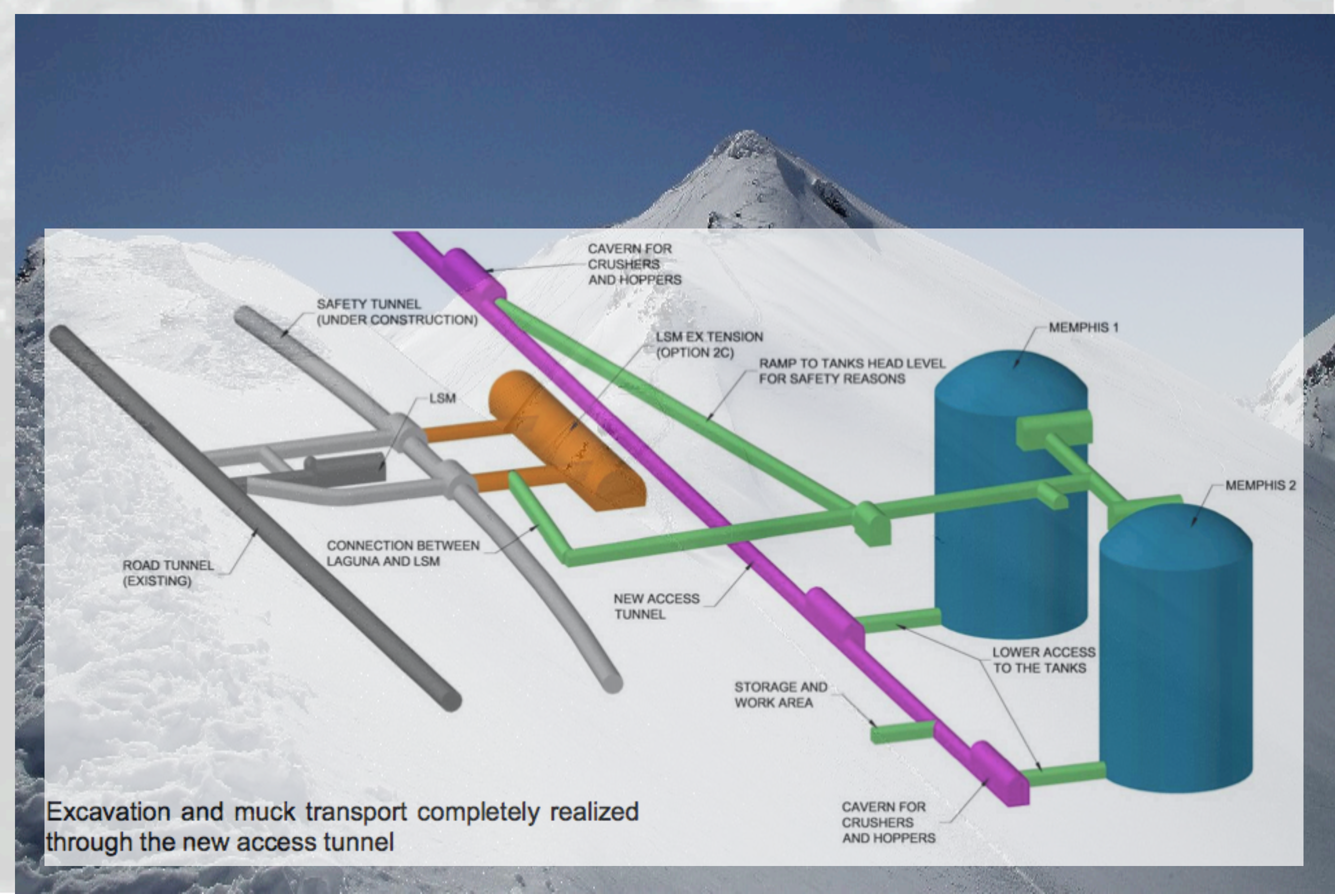
MEMPHYS (MEgatonMassPHYSics)

130 km from CERN, 4800 m.w.e.



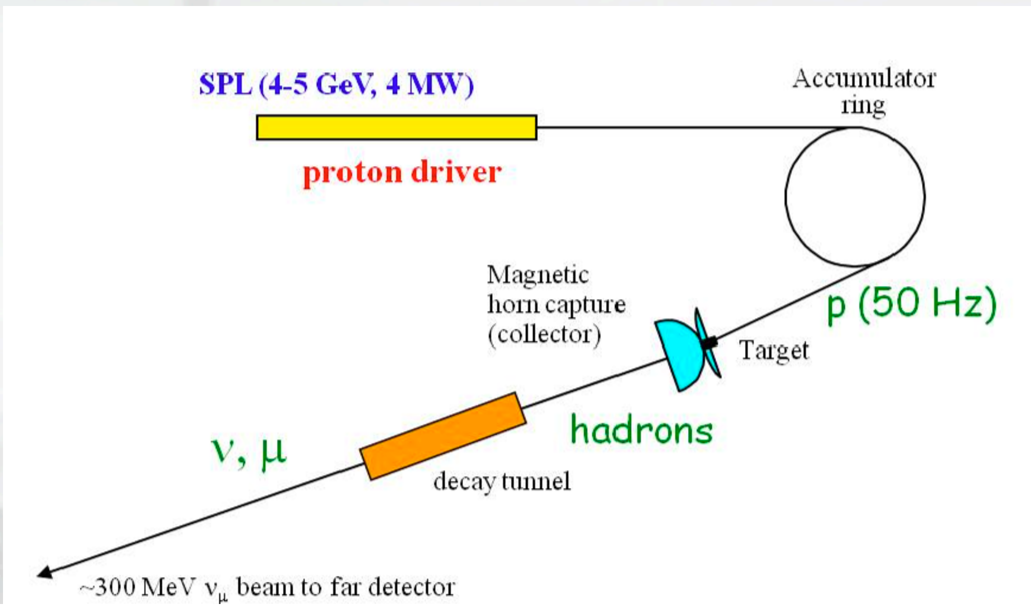
http://www.apc.univ-paris7.fr/APC_CS/Experiences/MEMPHYS/

- **Water Cherenkov**
  - well proven technology
  - each tank is 7 x SK --> mild extrapolation only!
- **total fiducial mass: 500 kt**
- **2 cylindrical modules 65 x 100 m**
  - size limited by light attenuation length (λ~100m) and pressure on PMTs
  - readout : ~130000 12" PMTs, 20% geom. cover
  - R&D on readout electronics and DAQ + detailed study on excavation @Fréjus existing & ongoing

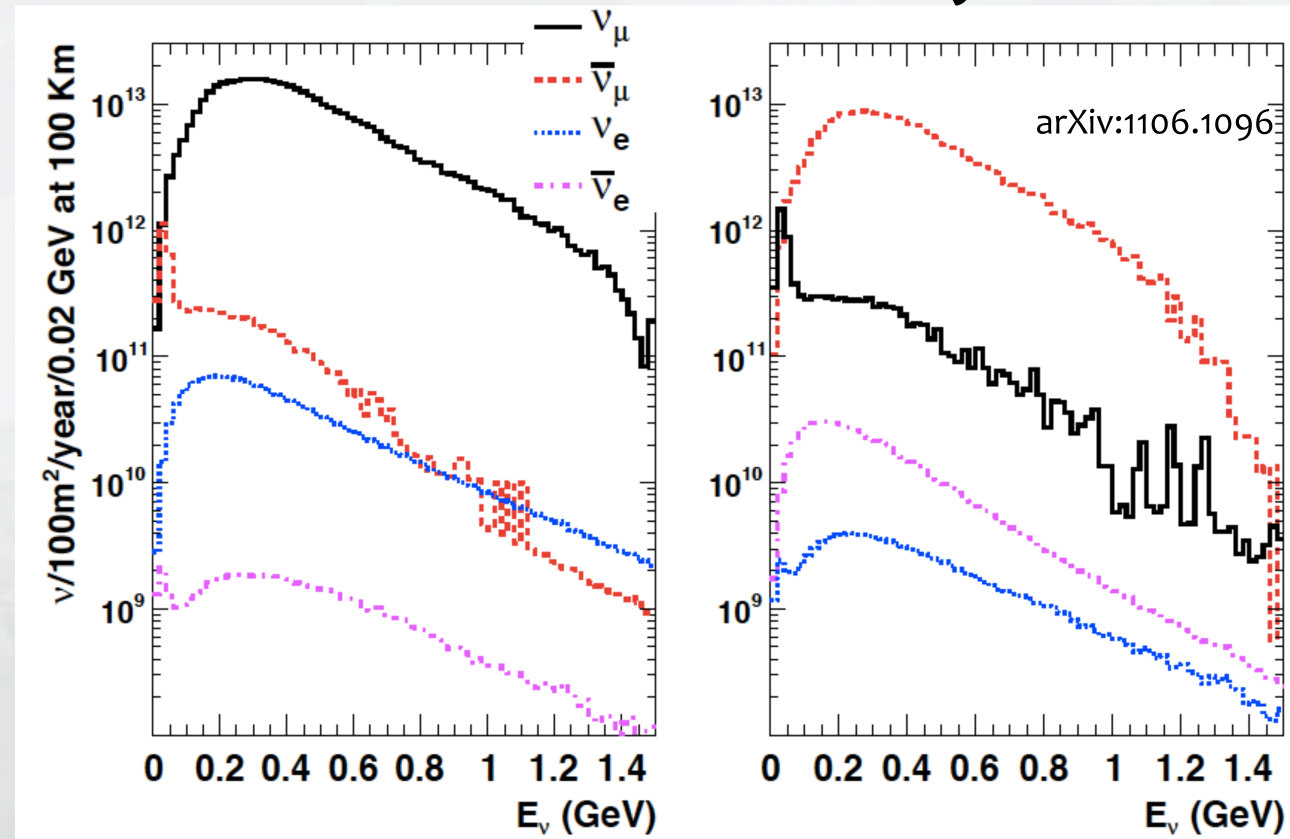


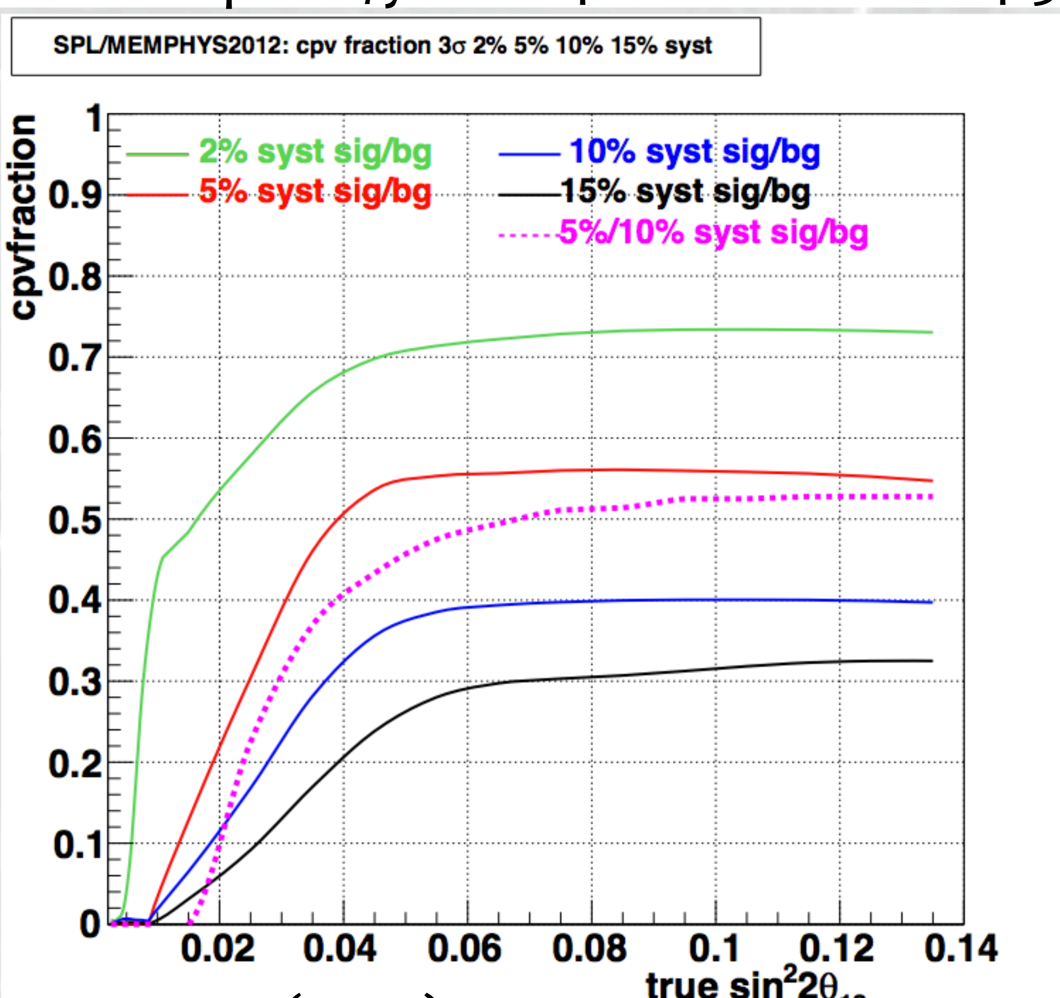
MEMPHYS Potential and SPL beam CERN-Frejus

[2y (ν) + 8y ($\bar{\nu}$)]

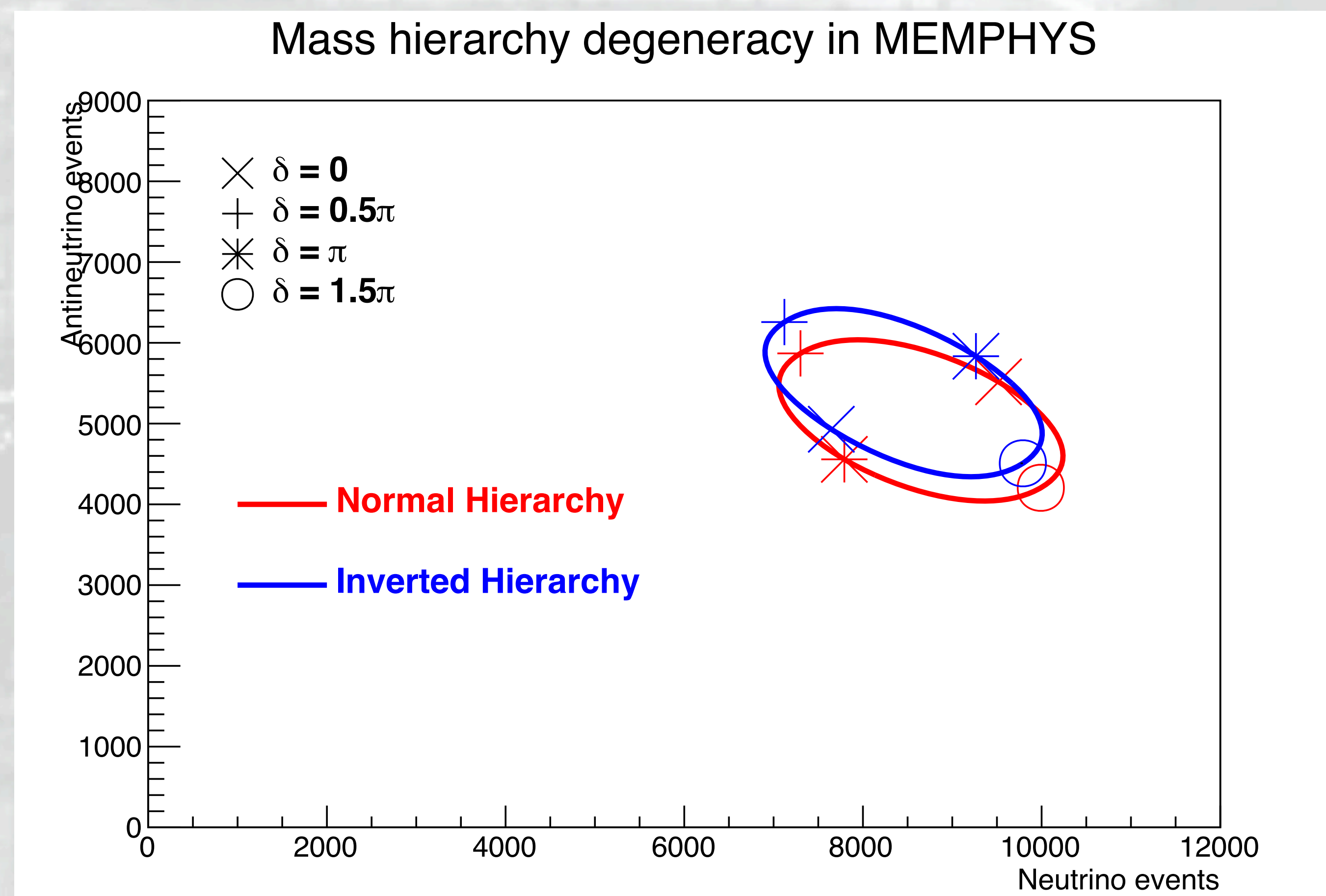


5.6 x 10^{22} p.o.t./y with 4 MW x 10^7 s at 4.5 GeV





JCAP 1301 (2013) 024



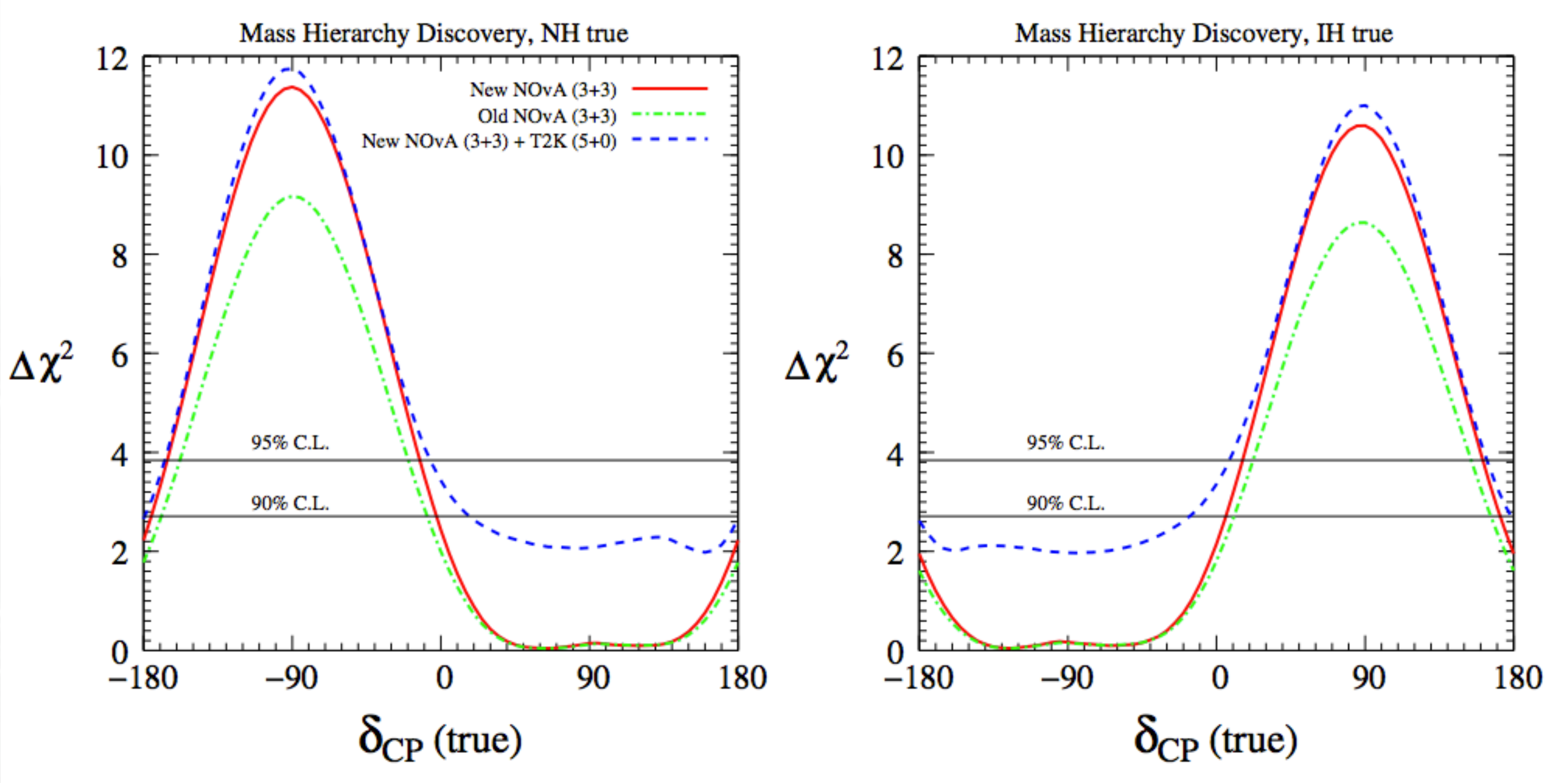
Water Cherenkov is a well known technology

But

- Event reconstruction is limited to single prong QECC
  - Therefore the beam energy is about 0.1 to 1 GeV
    - This calls for short baseline
- No sensitivity to the MH due to the short distance
- Need a new accelerator - Super Beam (4MW)
- Need at least 1 cylinder with 250 kt fid. mass
- Need €€€€

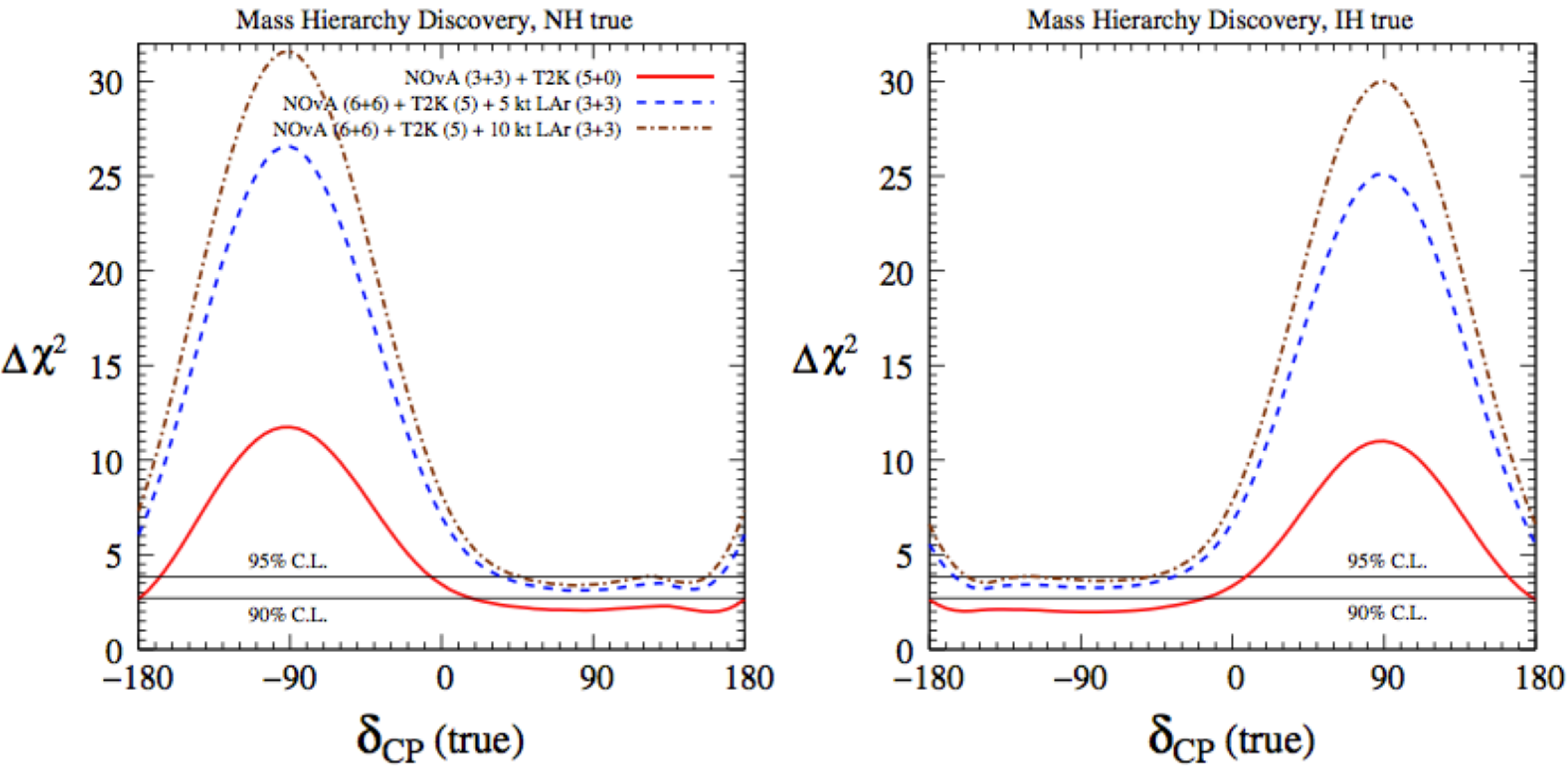
- The LAGUNA-LBNO collaboration decided to put this option in 2nd priority (fully studied within the LAGUNA-LBNO program until 2014)
- Another more powerful solution is needed

What can we learn from T2K (295km) and NOVA (810km) ?



Can only cover ≈ half of the phase space at <3σ

Adding a TPC on the surface at Ash River (810km)…

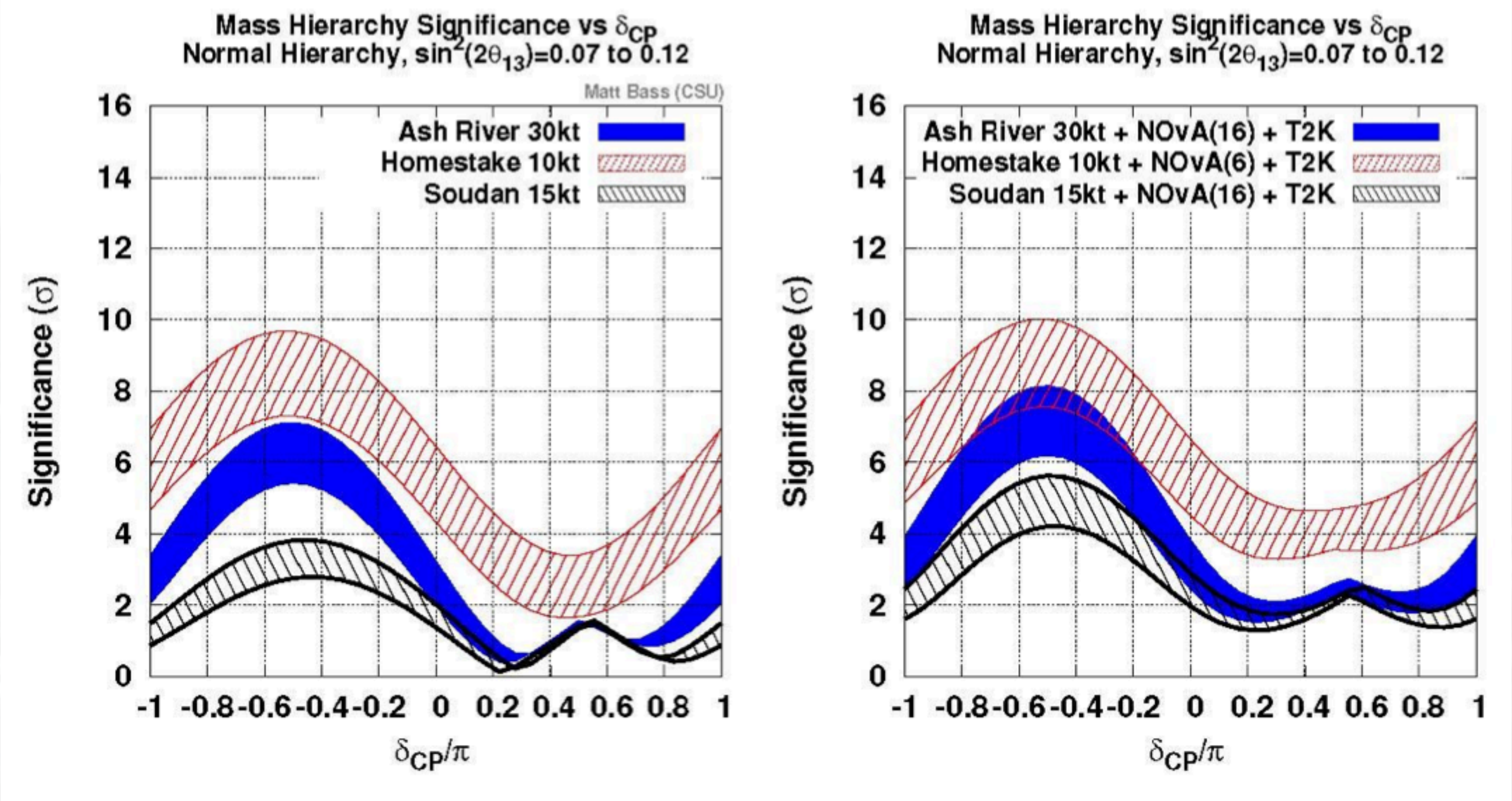


Still only half the phase space!

Need long base line > 1000 km to measure MH

LBNE: 10 years @ 700kW

http://www.fnal.gov/directorate/lbne_reconfiguration/

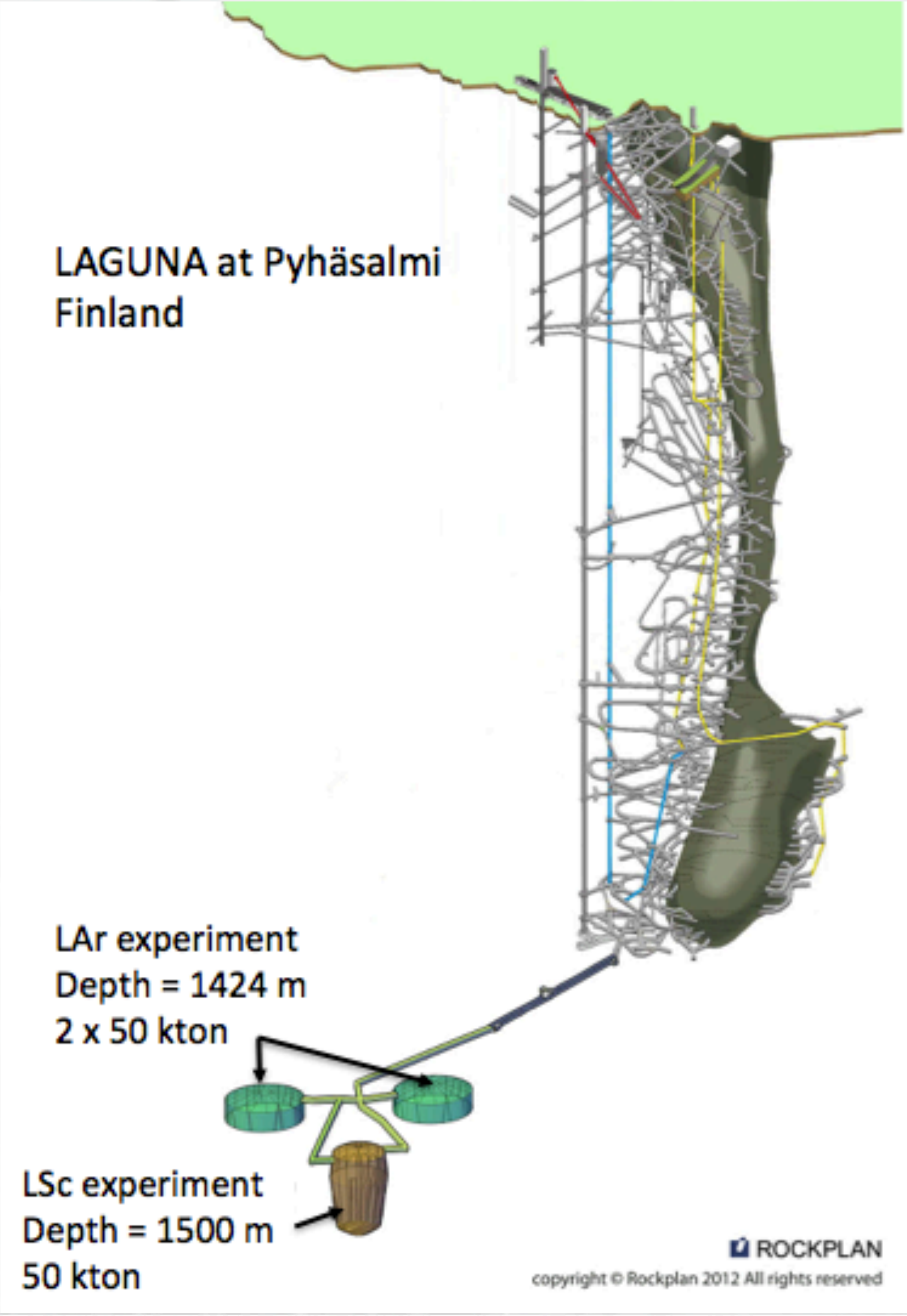


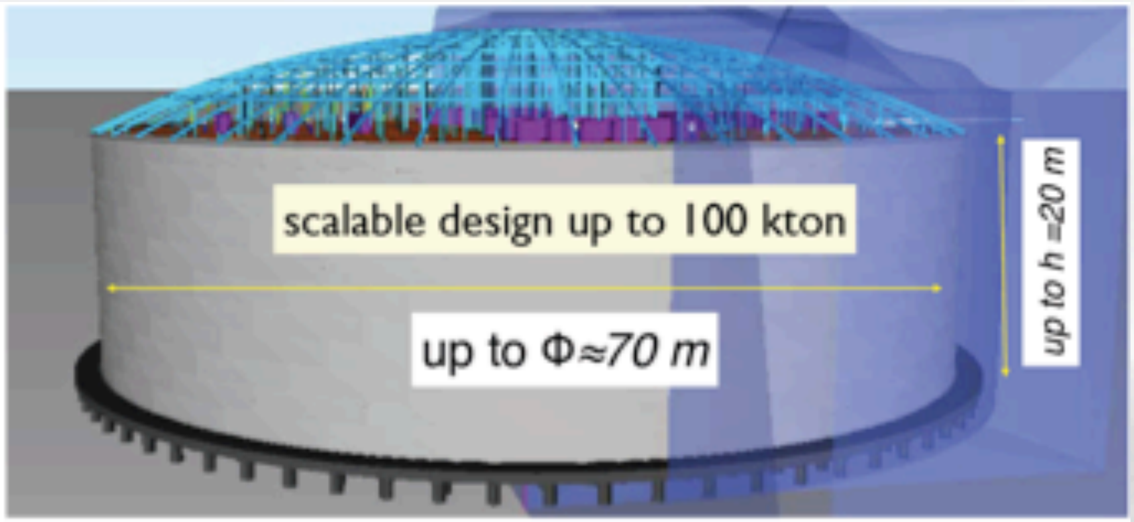
- Long time running,
- Big dependence on δ_{CP} value,
- Needed combination with other experiments!

Final remarks on the MH strategy:

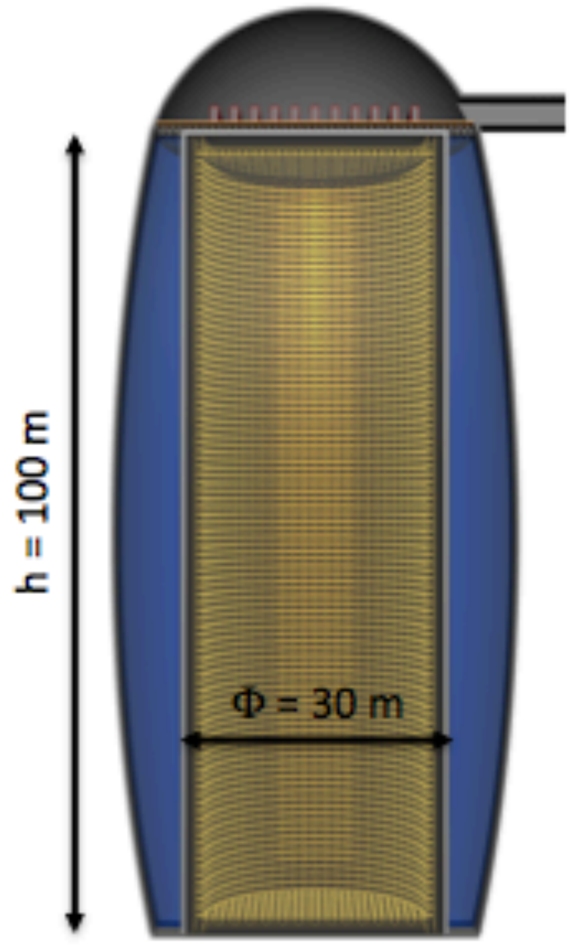
- To measure MH on the > 5σ level one need to go to very long baselines, ~ **1000 km gives not enough MSW** to measure the full phase space.
- Global fits of many experiments can guide and help the research but cannot replace the **measurement of a dedicated experiment.**
- **LBNO aims at exploring and resolve the mass hierarchy and the CP-phase problem by observing clear signatures and determining their L/E dependence**

LAGUNA-LBNO Desiderata





GLACIER



LENA

LAGUNA-LBNO Strategy

- **Incremental approach:**

  - **1st stage:**
    - ➡ «conventional» beam based on 400 GeV protons from the SPS **700 kW**
    - ➡ total 1.5 x 10^{21} PoT (**10 - 12 years**)
    - ➡ **20 kt LAr** detector and **35 kt iron/scintillator** detector

  - **2nd stage: upgrade detector to 70 kt and / or the beam power to 2 MW**

- **Measure all transitions:**
  - Appearance: $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$
  - Disappearance: $\nu_\mu \rightarrow \nu_\mu$
  - neutral currents

- **Neutrino and anti-Neutrino beams**

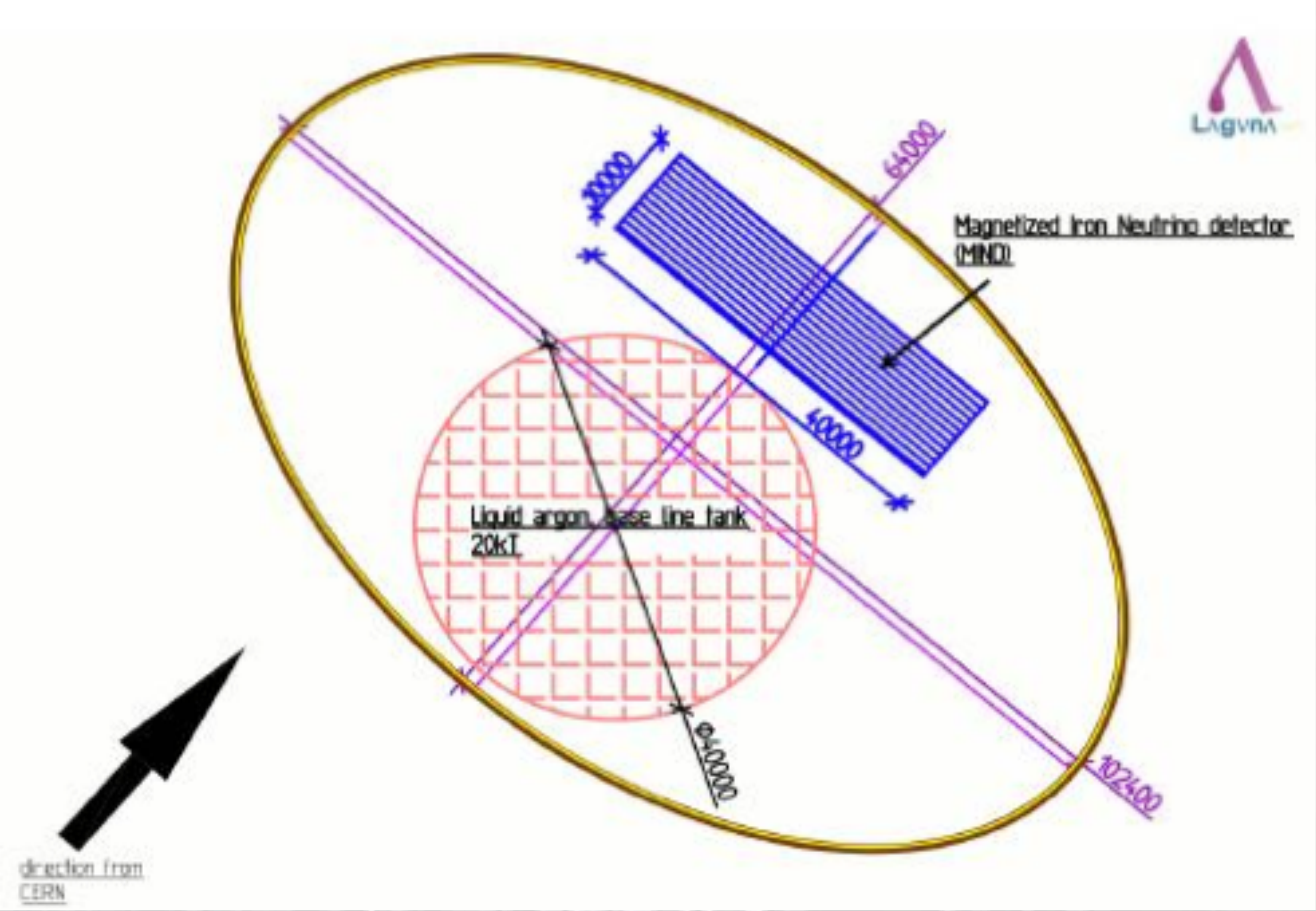
- **L/E behavior**: measurement of the energy dependence of the oscillation probabilities ranging from the 1st to the 2nd maximum

- **+ non accelerator physics**

Far Detectors

Requirements:

- Fiducial mass of at least **20kt in first phase** (c.f. SuperK 22.5kt)
- Fine granularity reconstruction for **electron neutrino appearance** reconstruction and multi-prong events (e.g. high energy DIS events)
- Efficient over a broad energy range 0.5GeV<E<10GeV with $\sigma_E/E \sim 10\%$ to observe **L/E spectrum**

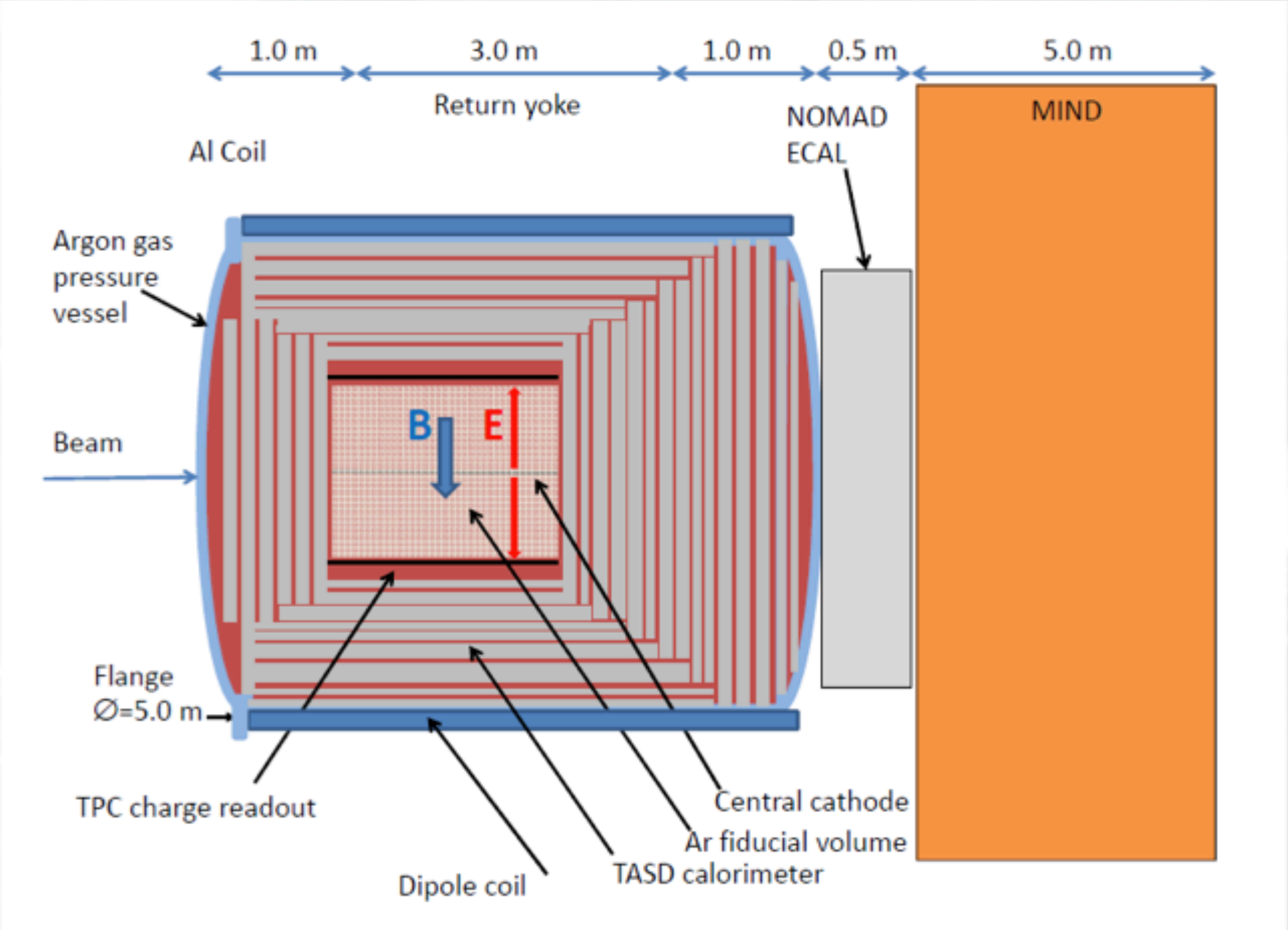


Reference Design:
Double phase Liquid argon TPC (**GLACIER**) in conjunction with a magnetised iron detector (**MIND**)

Near detector

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,...

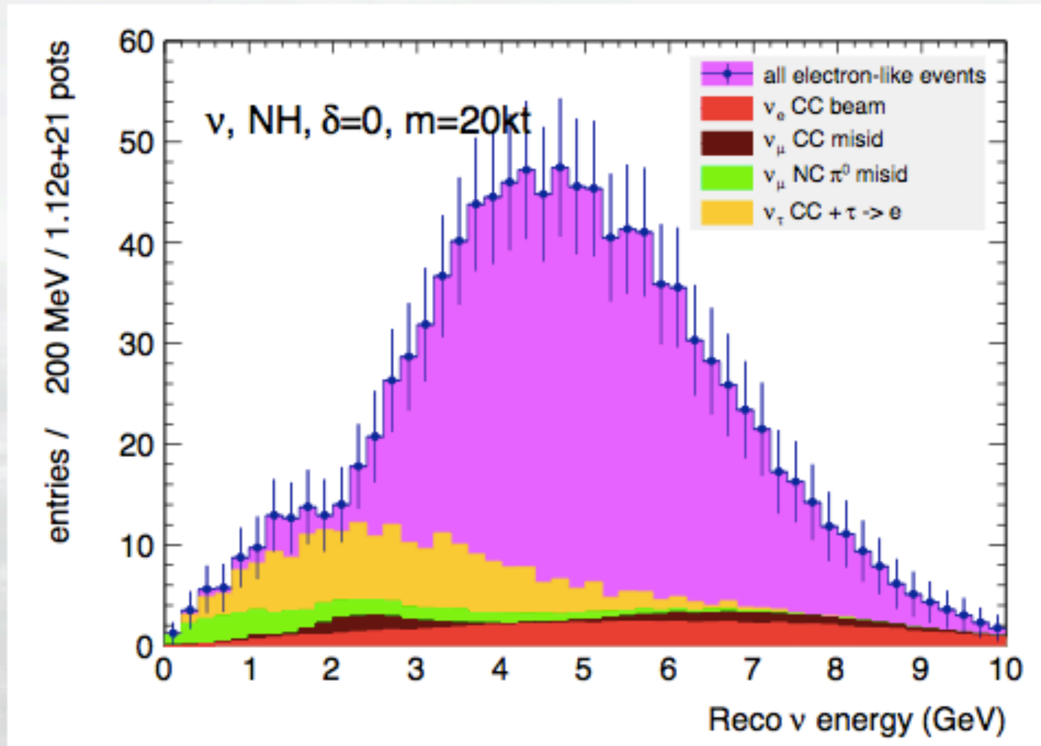


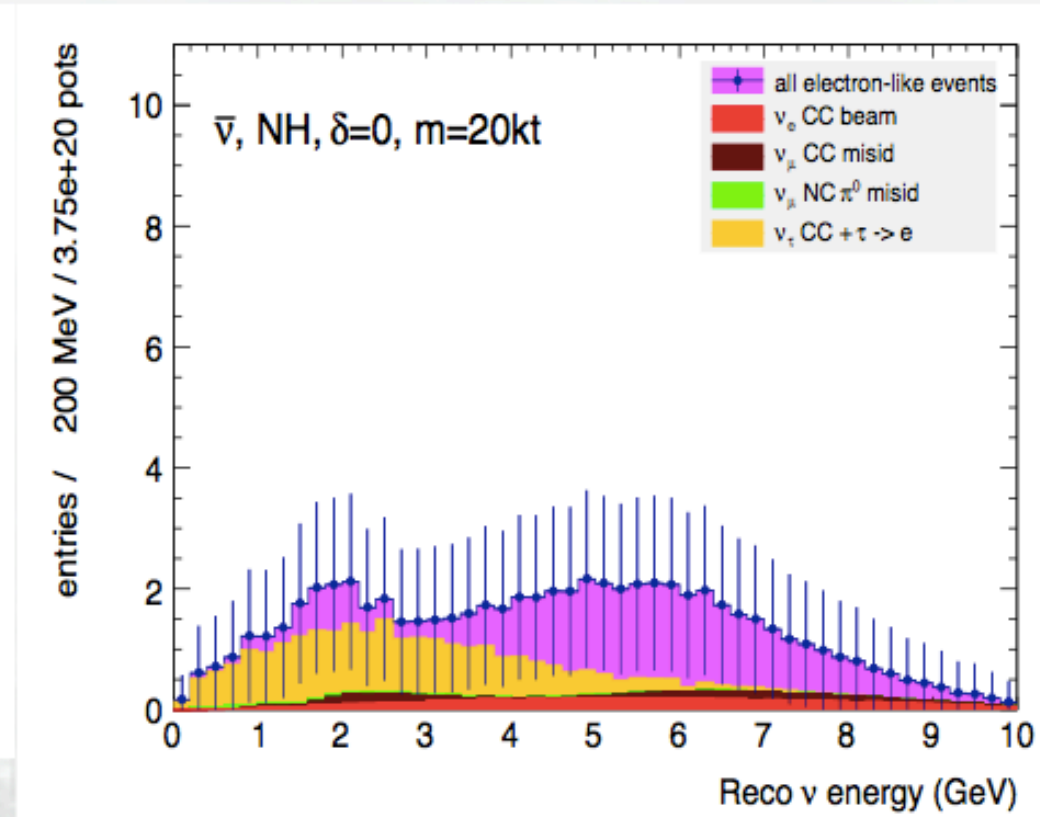
- Concept: 20 bar gas argon-mixture TPC (2.4 m × 2.4 m × 3 m) surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 600 kg argon mass in TPC
- 0.2 event/spill @ $7e^{13}$ ppp 400 GeV
- O(100'000) events/year

ν + anti-ν running to distinguish NH from IH

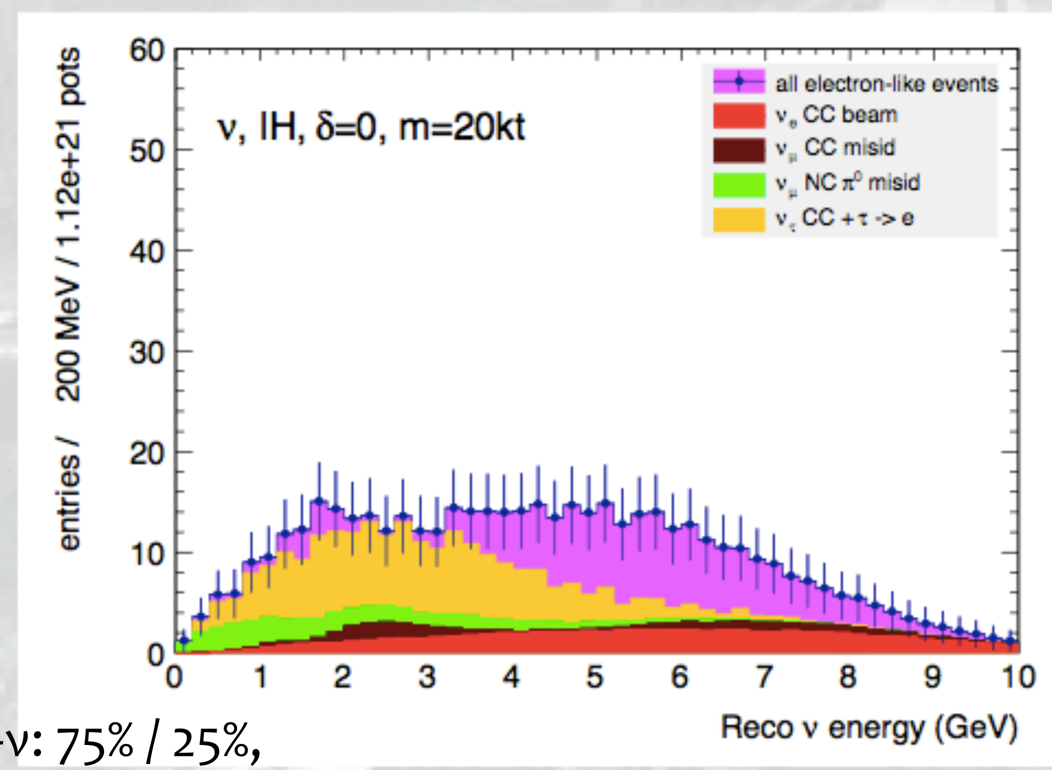
Neutrinos | anti-Neutrinos

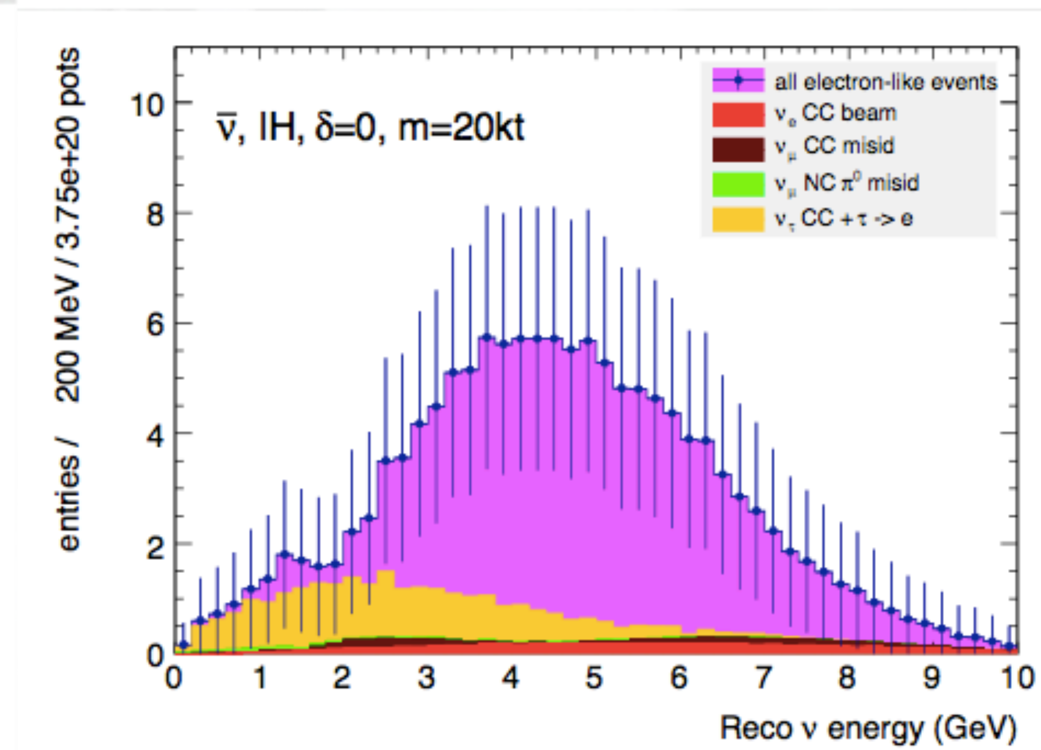
NH





IH



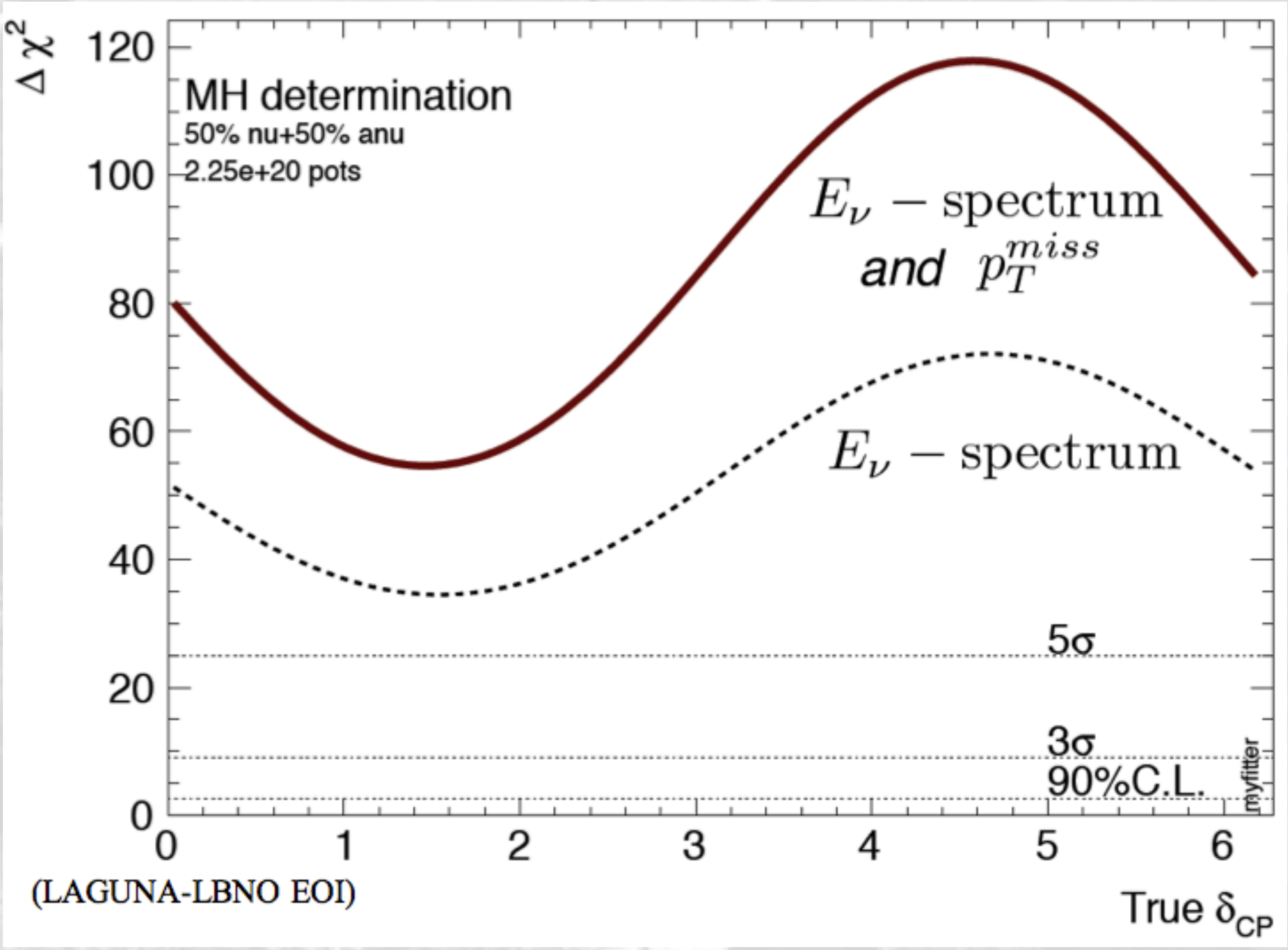


- 20 kt fid. mass LAr
- Running mode: ν/anti-ν: 75% / 25%,
- Detector response and resolution included

LBNO Mass Hierarchy Sensitivity

LBNO will provide a

- **> 5σ direct determination of MH**
- **independent from the values of θ_{23} & δ_{CP}**
- **in ≈ 2 years of running**



Extracting MH from global fits can not replace a direct 5σ measurement from an experiment!

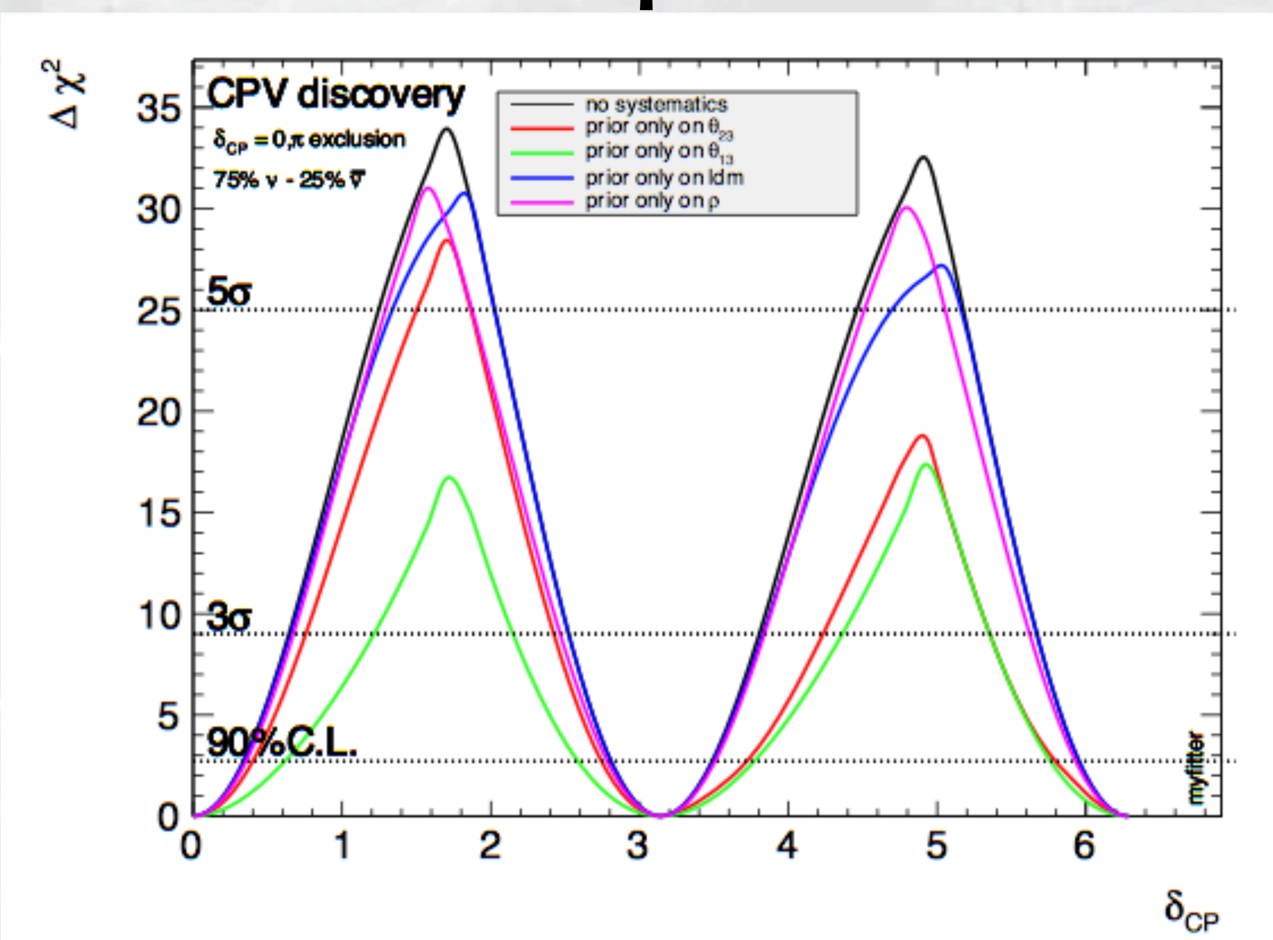
50% ν, 50% anti-ν
2.25 x 10^{20} pot ~ 2y

LBNO 1st phase: δ_{CP} Discovery

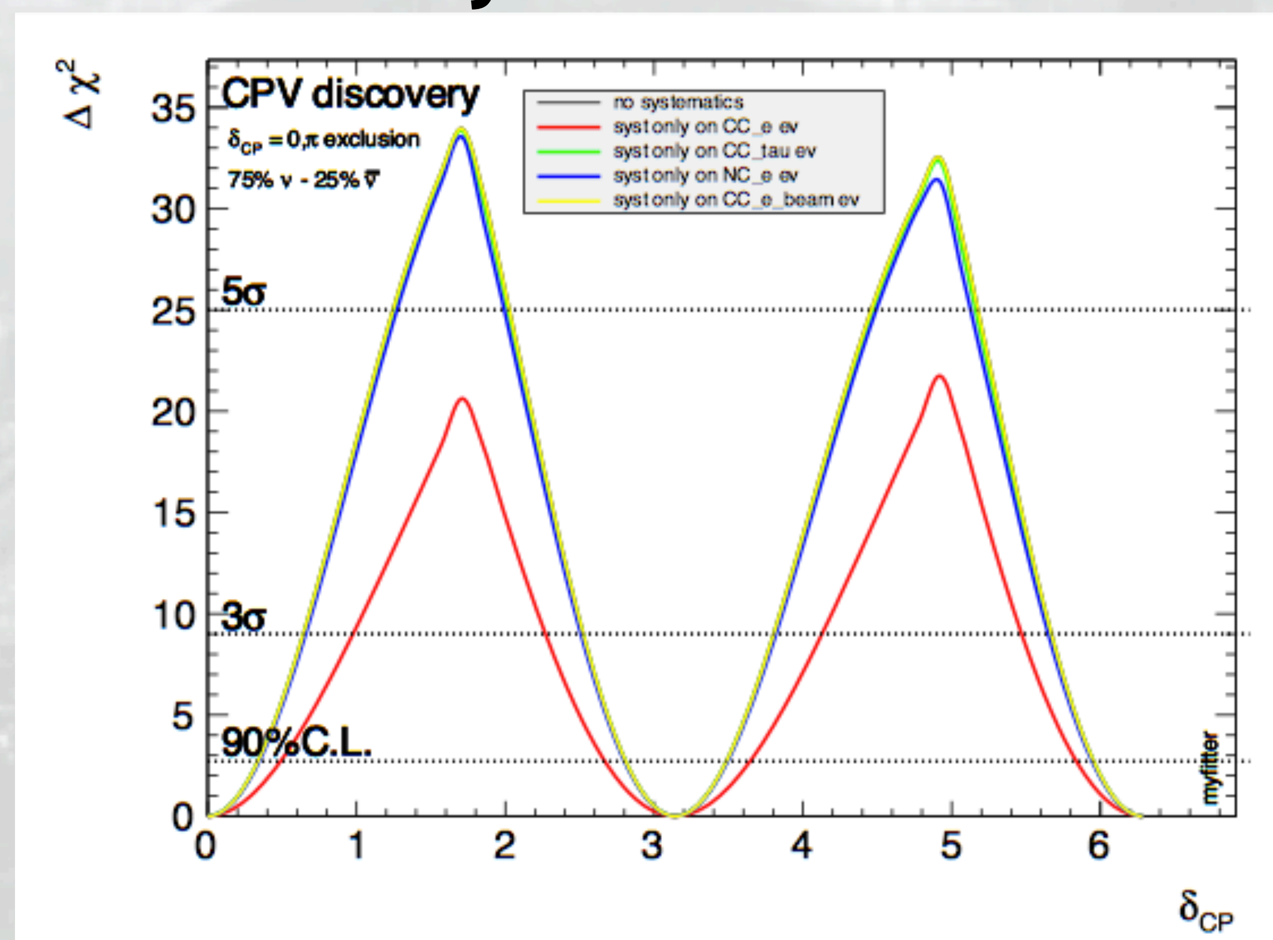
Once MH determined run for 8 to 10 years with optimized sharing of neutrinos / anti-neutrinos to **cover the most possible phase space in δ_{CP}**

Use best knowledge on systematics and oscillation parameters

Oscillation parameters



Systematics

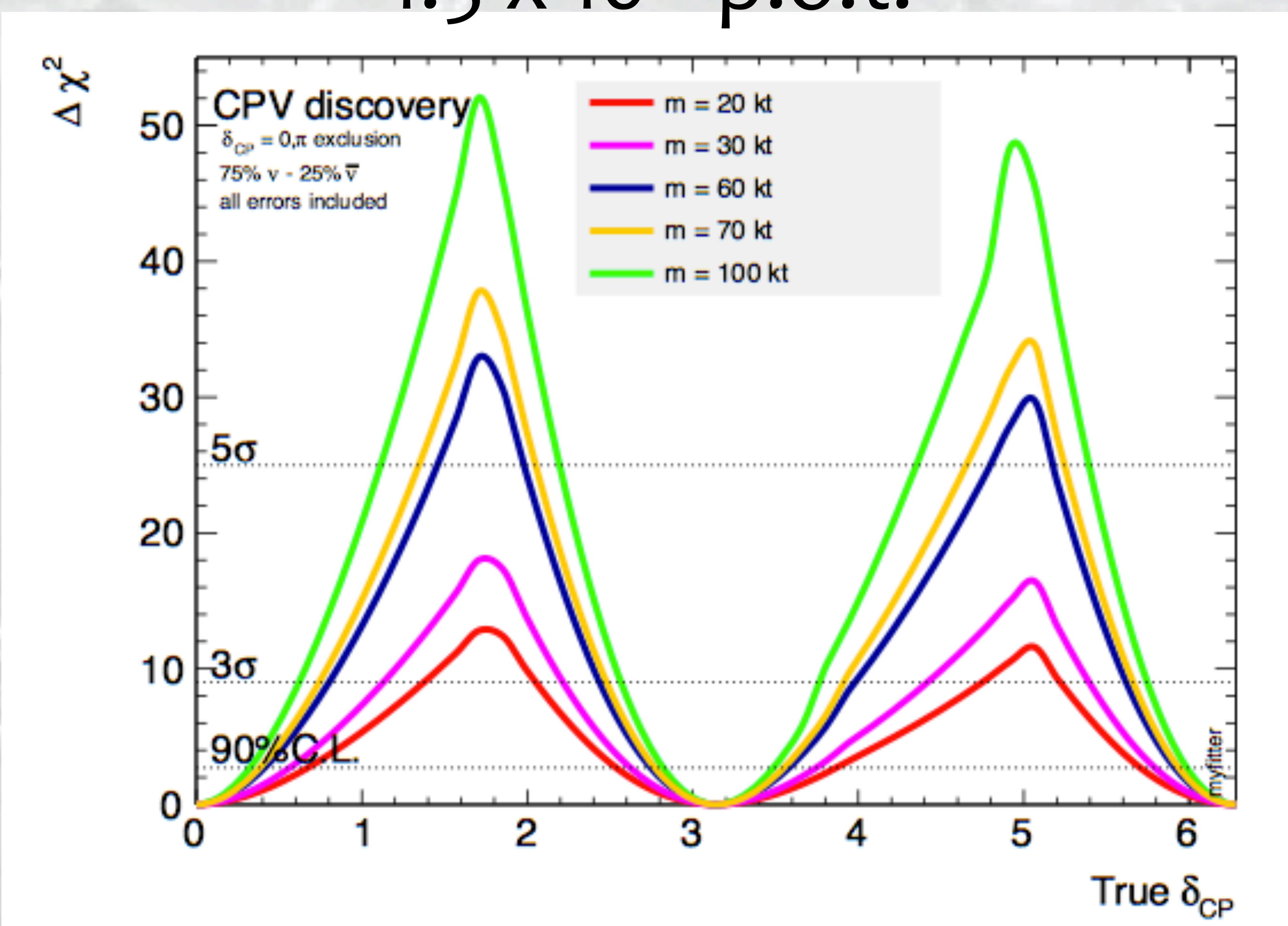


- The most important oscillation parameters are θ_{23} and θ_{13}
- the most important systematics is the knowledge of the absolute rate of ν_e CC events

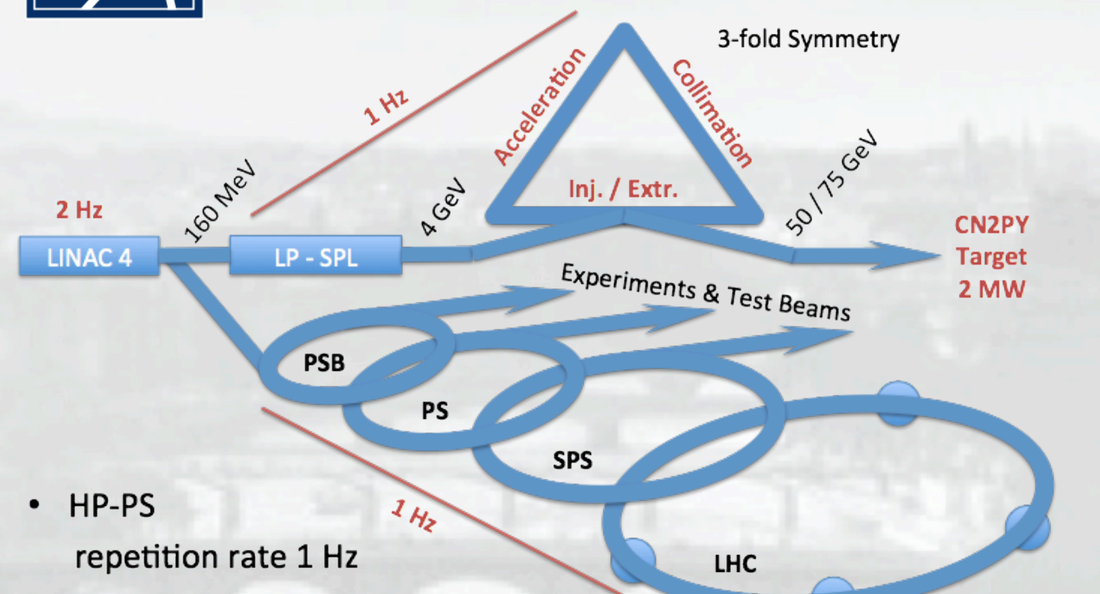
LBNO 2nd phase: δ_{CP} Discovery

Go to stage II to measure 5σ CPV:
Increase mass and/or beam power

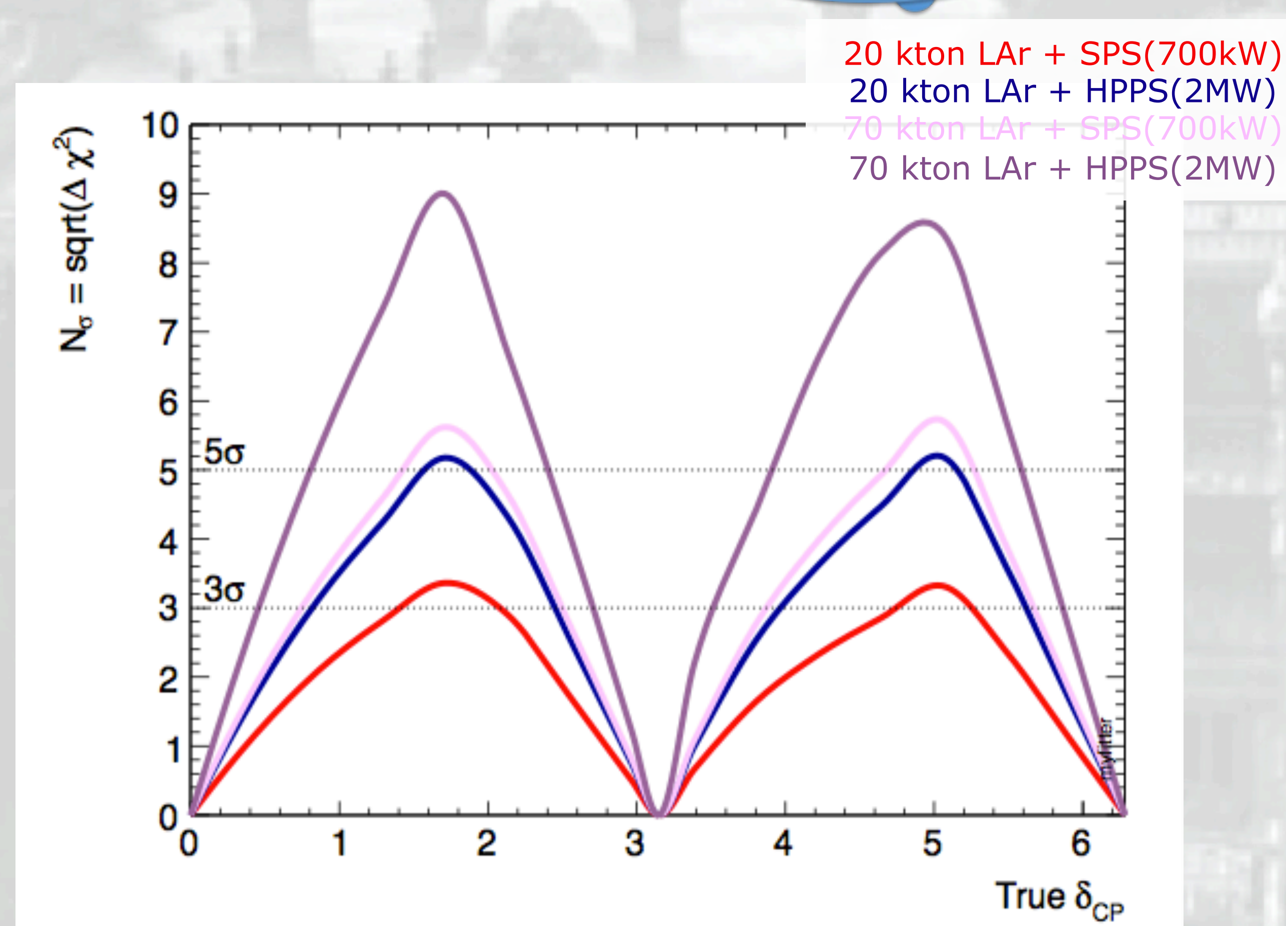
1.5×10^{21} p.o.t.



High power HP-PS study



- HP-PS
  repetition rate 1 Hz



Conclusions

- LAGUNA/LBNO is a project with a very rich and interesting physics program with **fundamental discovery potential.**
- The LAGUNA-LBNO collaboration decided to propose **stage I** of 20kt LAr + 700 kW SPS at 2300km of baseline
- Outstanding Physics Potential:

1. Accelerator based:
- **Mass Hierarchy > 5 σ all phase space in 2y**
- δ_{CP}
- MSNP precision --> 3 ν or 3+n ?

2. Non-Accelerator based:
- Proton decay: Significantly extended sensitivity to nucleon decay in many channels.

  Br(p → anti-ν K) > 2 × 10^{34}y (90%C.L.)

  Br(n → e K^{+}) > 2 × 10^{34}y (90%C.L.)

3. Neutrino Astronomy:
- Supernova neutrinos >10000’s events @ SN explosion@10kpc
- Diffuse Supernova Neutrinos (DSN)
- Neutrinos from DM annihilation
- Atmospheric Neutrinos (5600 events/y)

Milestones - Timescale

LAGUNA Design Study funded for site studies:	**2008-2011**
Categorize the sites and down-select:	**Sept. 2010**
Start of LAGUNA-LBNO	**2011**
Submission of LBNO EoI to CERN	**2012**
End of LAGUNA-LBNO DS: technical designs, layouts, liquids handling&storage, safety, ...	**2014**
Critical decision	**2015 ?**
Excavation-construction (incremental):	**2016-2021 ?**
Phase 1 LBL physics start:	**2023 ?**
Phase 2 incremental step implementation:	**>2025 ?**

Towards a real experiment: SPSC-EoI-007: «Expression of Interest for a very long baseline neutrino oscillation experiment (LBNO)»

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Back-up slides

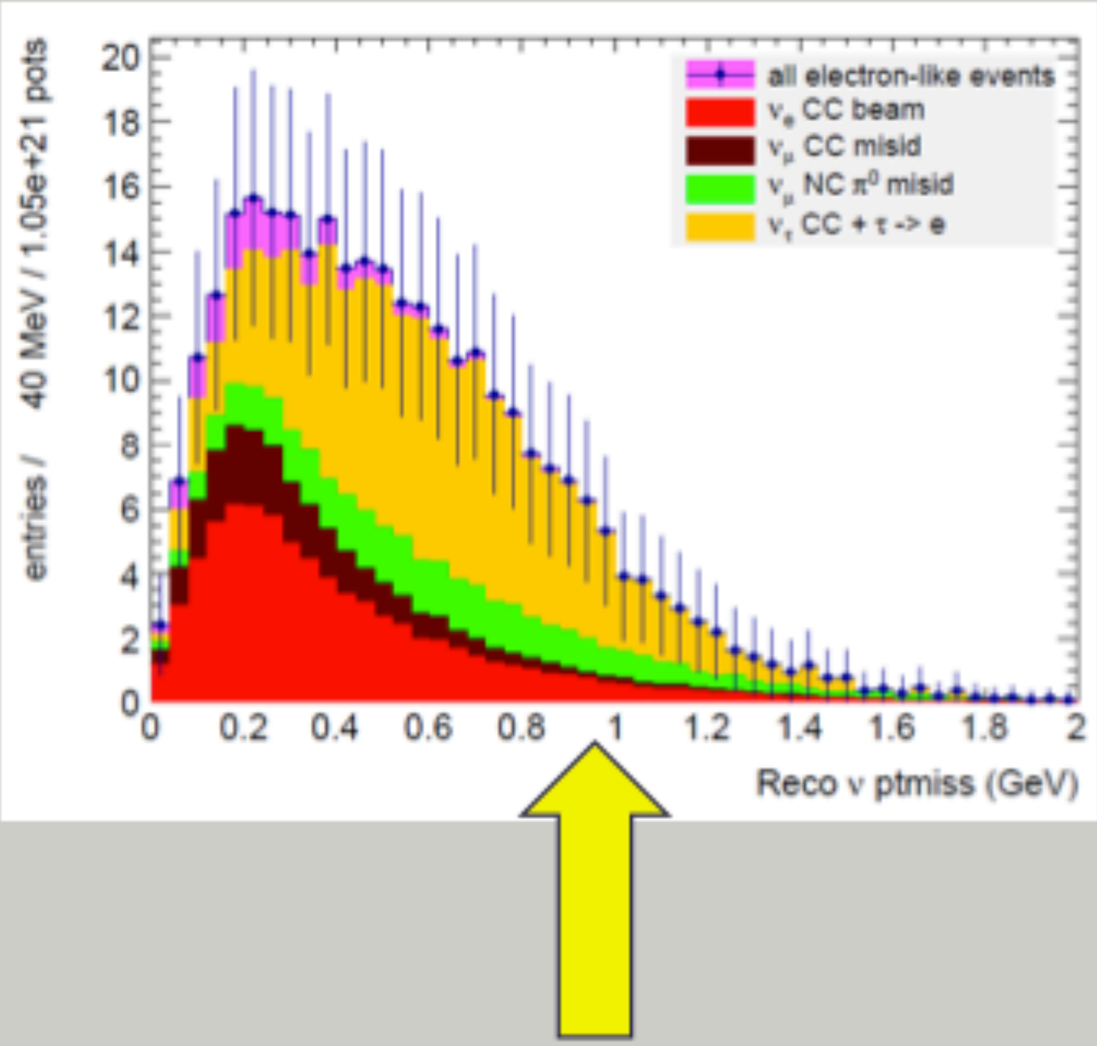
Mass Hierarchy Sensitivity Fit

- Make χ^2 fit to `expected' ν+anti-ν energy distributions for a choice of MH, using model with opposite choice of MH and marginalising over all oscillation parameters (Gaussian)

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	±4%

- Systematics accounted for (correlated bin-to-bin for flux and cross section uncertainties)

Name	MH determination Error (1σ)
Bin-to-bin correlated:	
Signal normalization (f_{sig})	±5%
Beam electron contamination normalization ($f_{\nu_e CC}$)	±5%
Tau normalization ($f_{\nu_\tau CC}$)	±50%
ν NC and ν_μ CC background ($f_{\nu NC}$)	±10%
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	±5%
Bin-to-bin uncorrelated	±5%



- Extend to include simultaneous fit to missing transverse momentum to better constrain tau background

LAGUNA-LBNO Strategy

- Based on the findings from LAGUNA and LAGUNA-LBNO → concrete proposal for the future neutrino observatory in 2012, EoI 007 to CERN.
- Comparison of 7 locations in Europe with precise estimations on the costs of the facility, of the detector and of the beam.
- Comparison of the physics potential of all possible combinations - detector - location - beam.
- **Conclusion: propose a neutrino observatory with a clear long-term strategy in a deep underground location (4km w.e.) at the longest baseline proposed, 2300 km, compatible with:**
  - a full **astro-particle program** and
  - an **incremental long-baseline program**, guaranteeing high level physics performance from the beginning.
  - Stage 1 is based on a **20 kt fid. LAr detector (double phase) and a conventional beam from the CERN SPS of 700 kW.**
  - If the findings from stage 1 require, the detector and the beam will be upgraded to 70 kt and 2 MW.
  - The location of the infrastructure is perfectly adapted to a neutrino factory, allowing the ultimate measurements in the accelerator neutrino field.

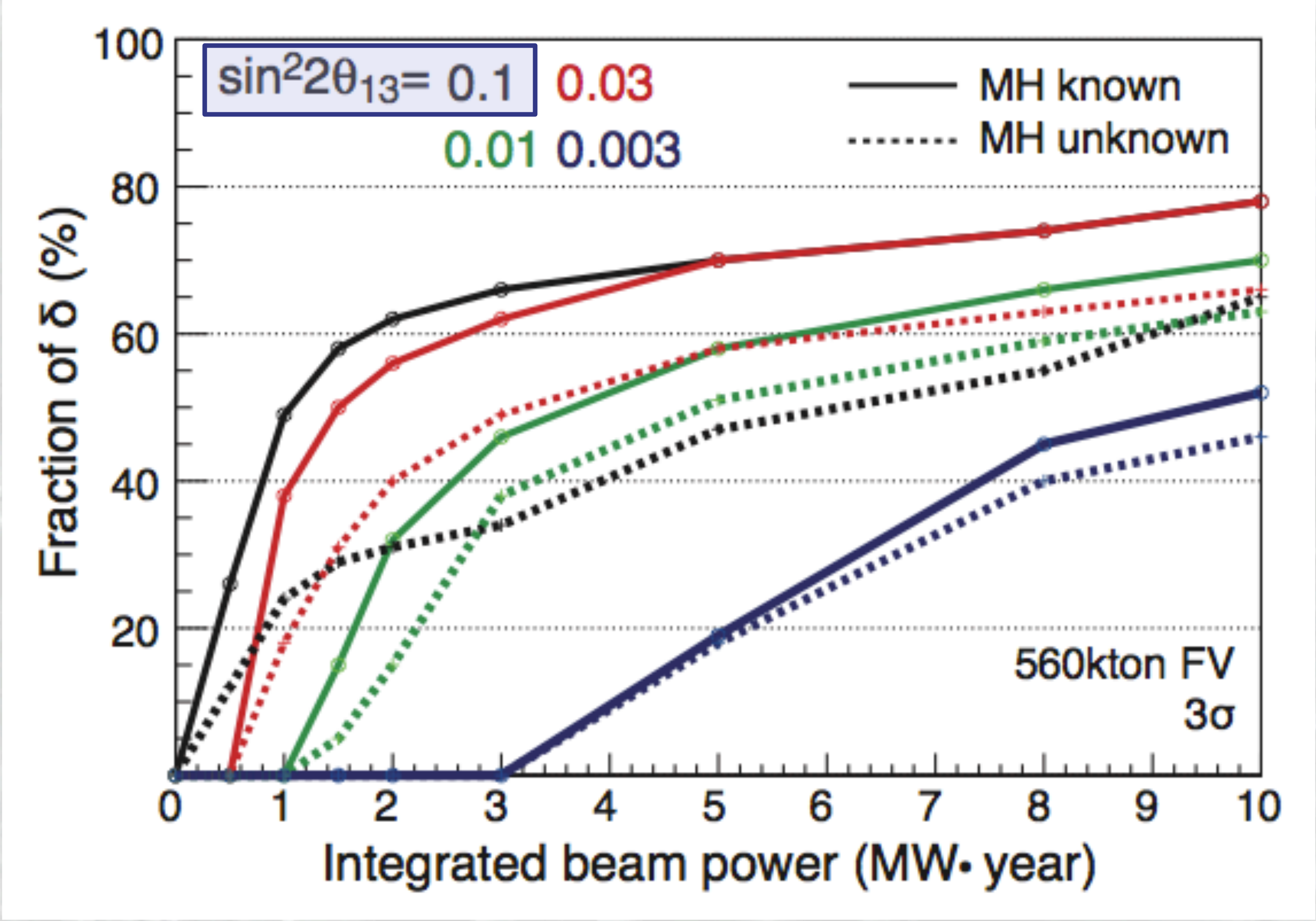
What can we learn from HyperKamiokande?

Determination of the mass hierarchy is indispensable to perform CPV searches, e.g. HyperKamiokande in Japan:

- 3 MW×years (note: >10 years at present JPARC MR power)
  MH known: 65% coverage → MH unknown: 35% coverage

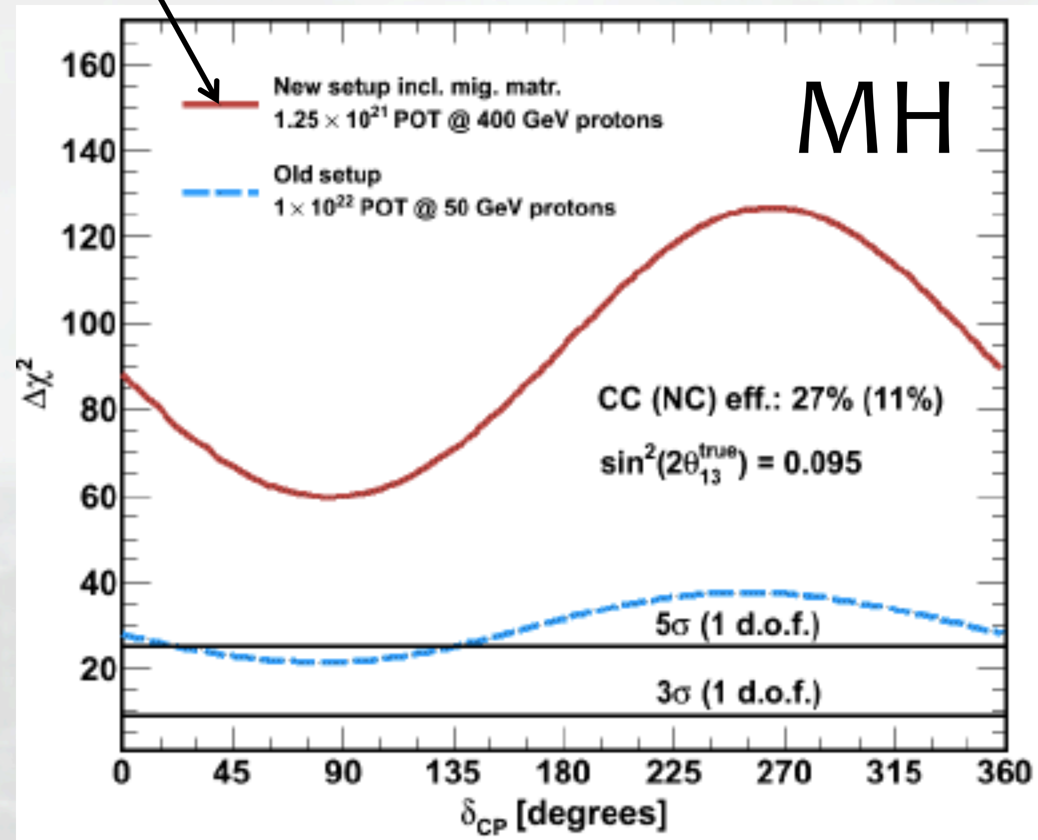
- 10 MW×years needed to reach 65% coverage if MH unknown! rather unlikely within present JPARC projections.

arxiv:1109.3262



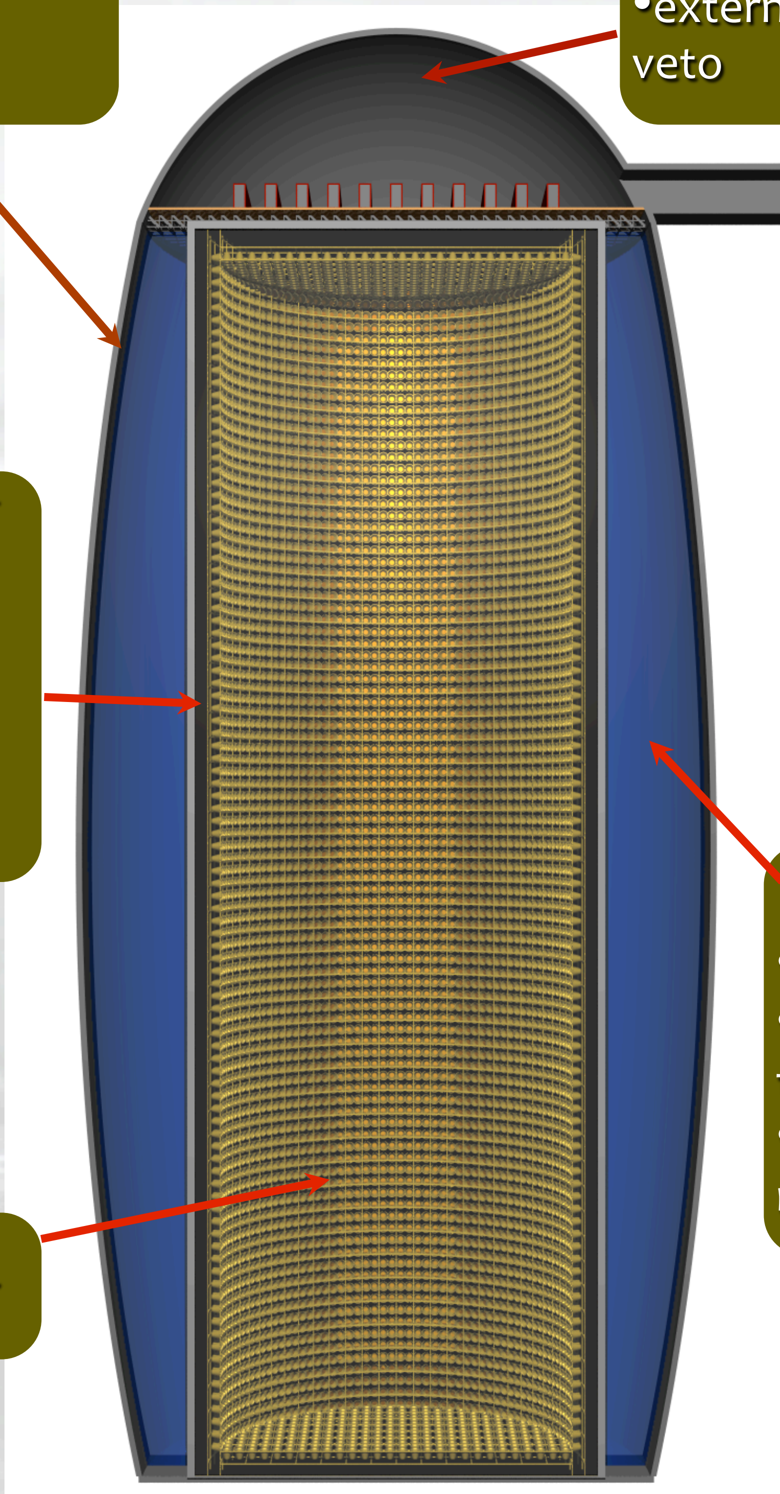
LENA:

Attention, this is 8y with the envisaged 700 kW SPS beam!



Egg shaped cavern
- Height = 120 m
- Ø ≈ 36 m

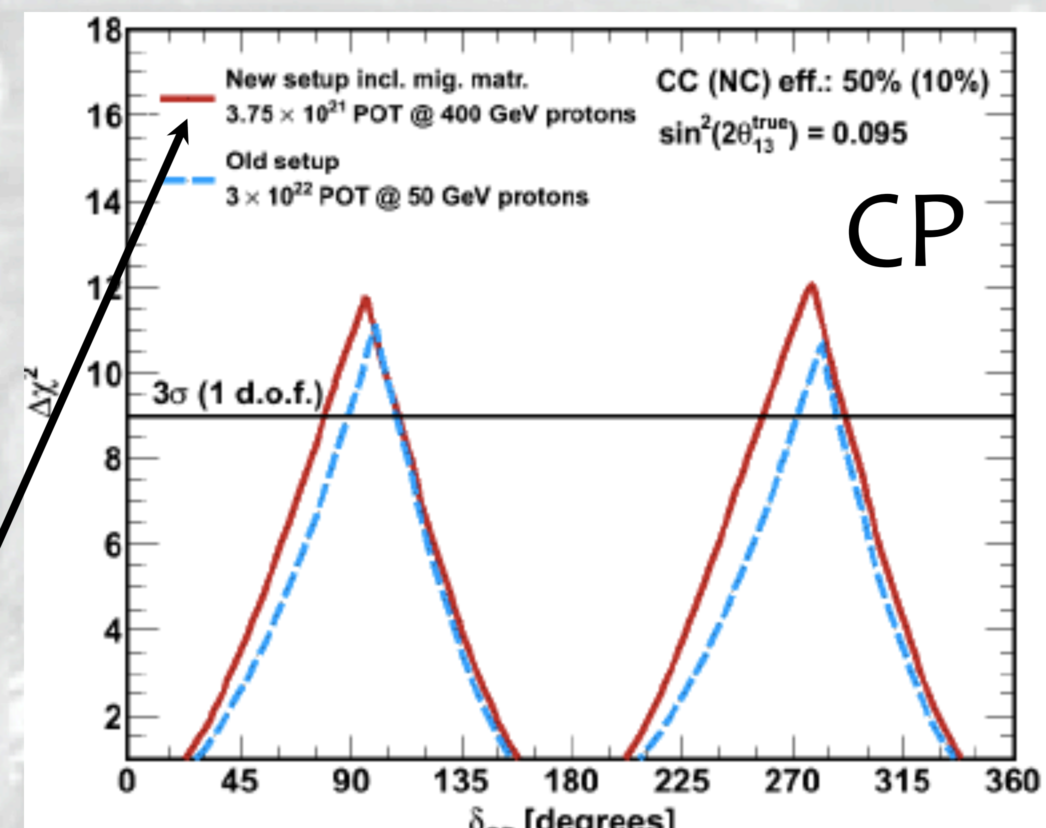
Top Cavern
- access to top deck
- external muon veto



Detector Tank
- concrete wall cylinder
- Height = 100 m
- Ø = 30 m
- ≈ 32000 12'' PMT

Water-filled cavern
- ~ 2000 12'' PMT
- veto for inclined muon tracks
- shielding for fast neutrons

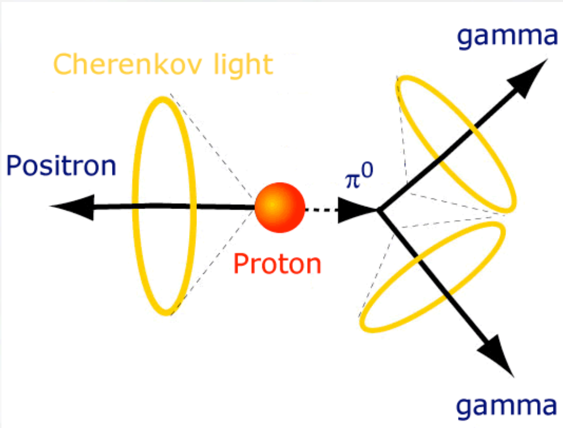
Target
50 kt scintillator



Attention, this is 20-24y with the envisaged 700 kW SPS beam!

MEMPHYS non-accelerator Physics

Proton Decay



Model	Decay Modes	Predictions
Georgi-Glashow	-	ruled out
Type II-$SU(5)$	all	$\tau_p < 2 \times 10^{36}$ yr
Type III-$SU(5)$	$p \to \pi^0 e^+$	$\approx 10^{35-36}$ yr
Adjoint $SU(5)$	$p \to \pi^0 e^+$ $p \to K^+ \bar{\nu}$ $p \to \pi^+ \bar{\nu}$	$\tau_{e^+\pi^0} < 10^{35}$ yr $\tau_{K^+\bar{\nu}} < 9 \times 10^{36}$ yr $\tau_{\pi^+\bar{\nu}} < 3 \times 10^{35}$ yr
Non-SUSY $SO(10)$	$p \to e^+ \pi^0$	$\approx 10^{33-38}$ yr
Minimal SUSY $SU(5)$	$p \to \bar{\nu} K^+$	$\approx 10^{32-34}$ yr
SUSY $SO(10)$	$p \to \bar{\nu} K^+$	$\approx 10^{33-36}$ yr

WCD 10 years, 500 kt fiducial:

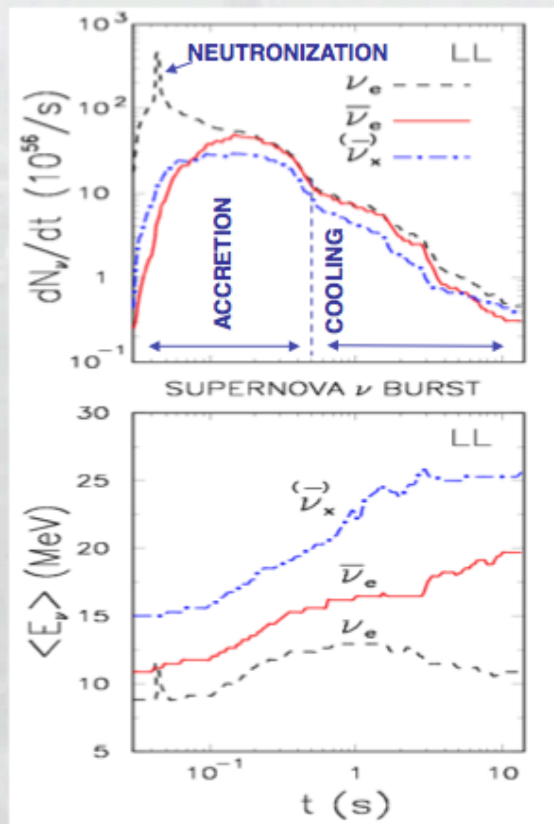
$p \to e^+\pi^0$: ~1.2 x 10^{35} y at 90% C.L.

$p \to \bar{\nu} K^+$: ~ 2.4 x 10^{34} y at 90% C.L.

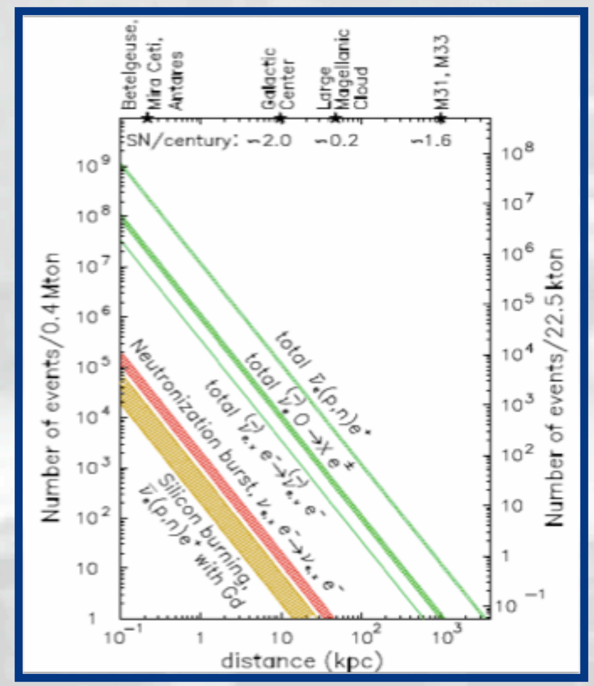
Supernova

Galactic SN: Huge statistics

- SN explosion mechanism: shock waves, neutronization burst
- Neutrino production parameters: rate, spectra
- Neutrino properties



Fogli et al., hep-ph/0412046



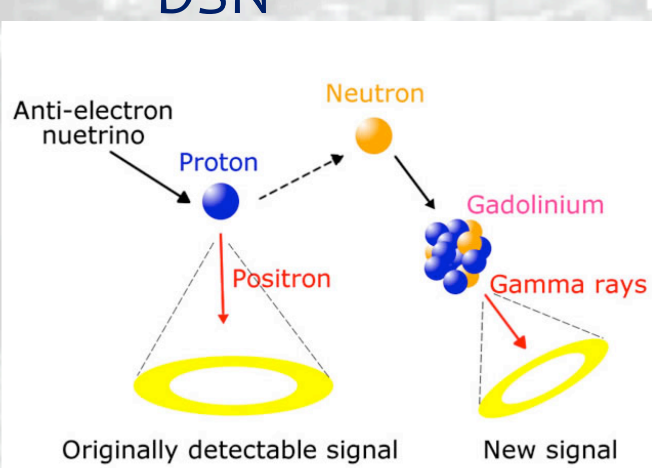
For a galactic Supernova @ 10 kpc:

CC: ~ 2.5 x 10^5 $\bar{\nu}_e$

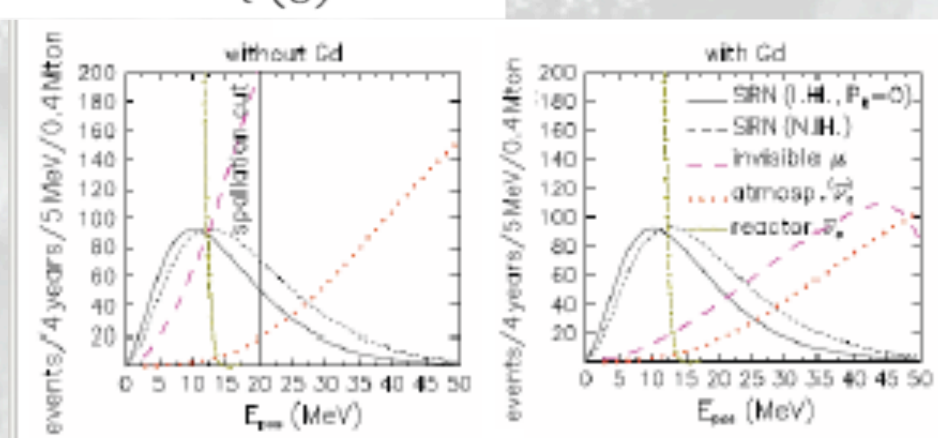
ES: ~ 1.2 x 10^3 e

O 10 events @ 1 Mpc

DSN



M. Nakahata



GADZOOKS! Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004

For 1 tank with Gd (250 kt):

S/B (5y) = (52 - 132) / 57

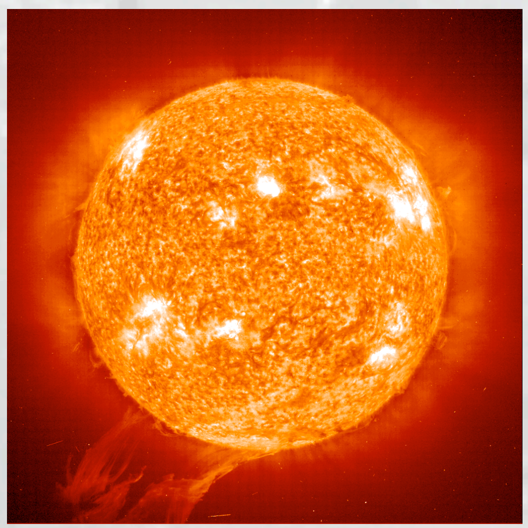
MEMPHYS non-accelerator Physics

Reactor Neutrinos

1 MEMPHYS tank with Gd 250 kt fiducial @ Fréjus:

~ 2.7×10^4 per year

Solar Neutrinos

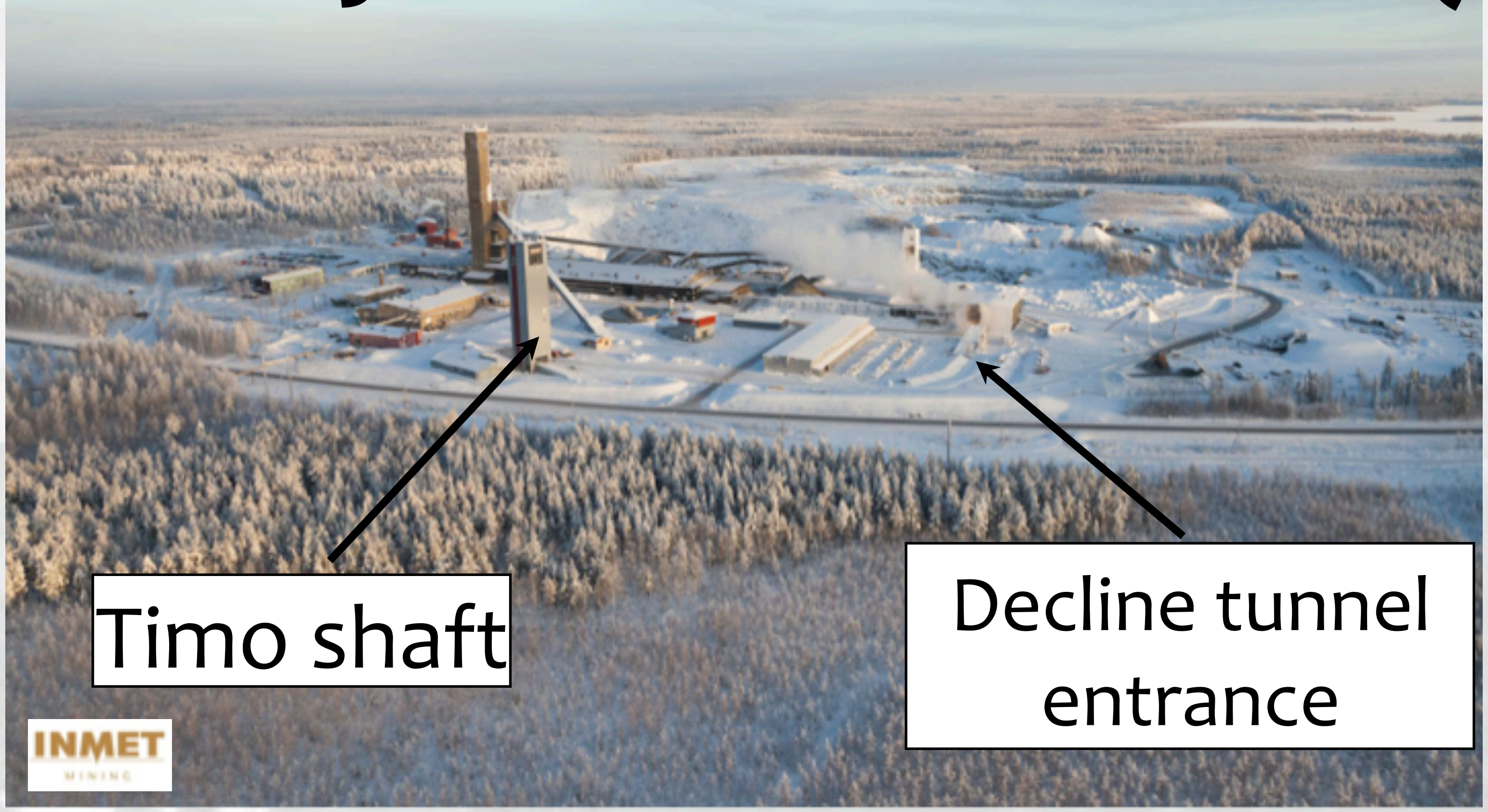


ES ν_{8B} ~ 1.3×10^6 per year

Atmospheric Neutrinos

~ 4.8×10^4 per year

Pyhäsalmi mine (Inmet/PM Oy)



★ Underground mining activities foreseen to stop in 2018. On-surface activities will continue afterwards. The mining company has never expressed an intention to benefit from LAGUNA, so some of the mine-related cost concerns that have been uttered are unfounded.

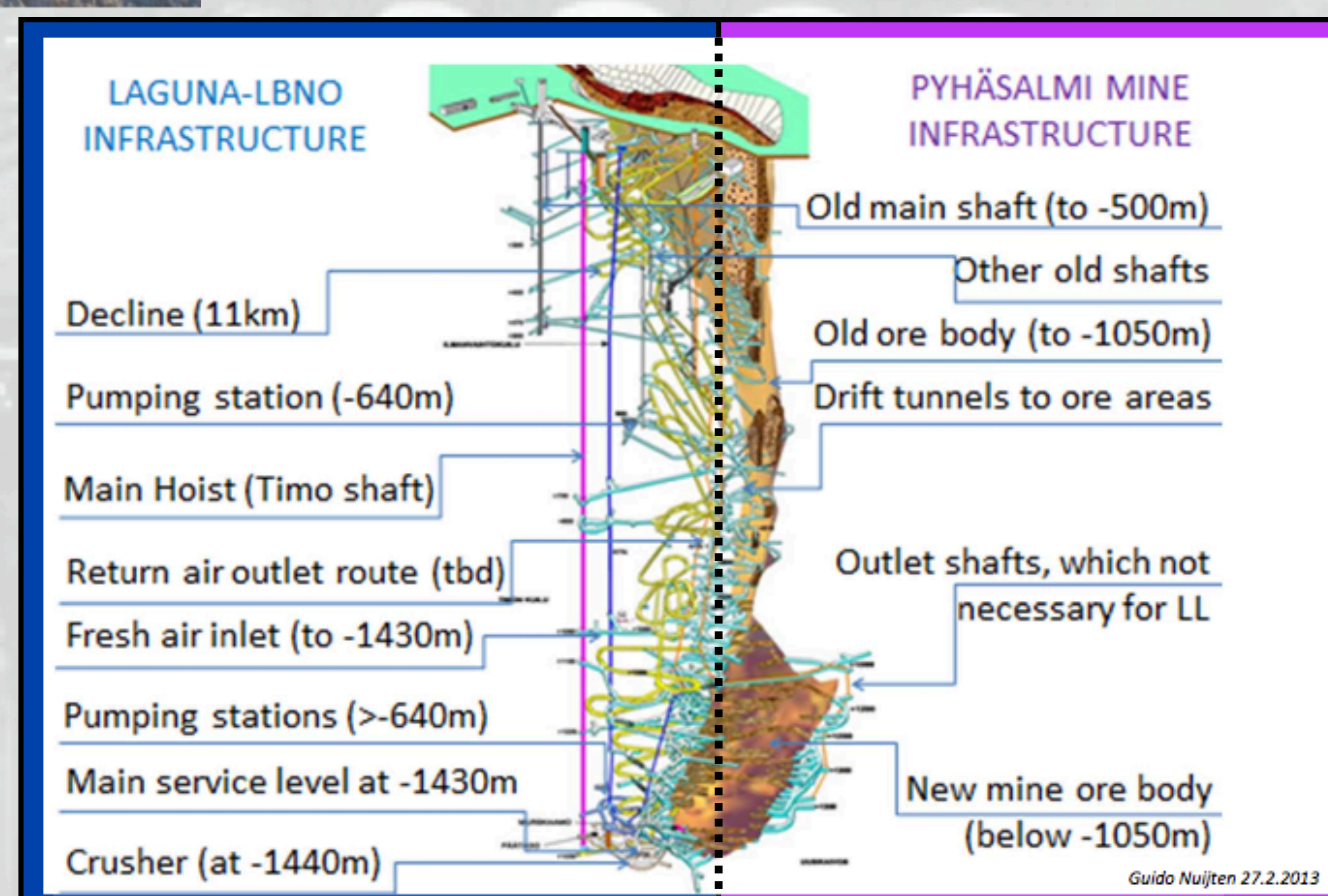
★ An **extended site investigation** is in progress in the location where LAGUNA caverns would be excavated (funded by Finland+mine). So far 750m of rock have been drilled. Results expected in 2014.

★ Only those parts that are necessary for LAGUNA/LBNO during construction and operation would be transferred to the new entity.

G. Barker, NuMass2013, Milan

- The decline (length about 11km)
- The main hoist (Timo shaft, from surface to -1440m)
- The fresh air inlet shaft (from surface to -1440m)
- An return air outlet route
- Pumping stations (the main pump at -640m and the pumps on deeper levels down to -1440m)
- The Main service level at – 1410m
- The crusher at -1440m

★ Yearly operational costs for LAGUNA are found to be similar to those for MINOS in the Soudan mine.



This pump alone takes all the water from 645 m to the surface

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

Cafeteria, meeting room and sauna at 1400 m below ground

Mobile phones work and internet available also at 1400 m

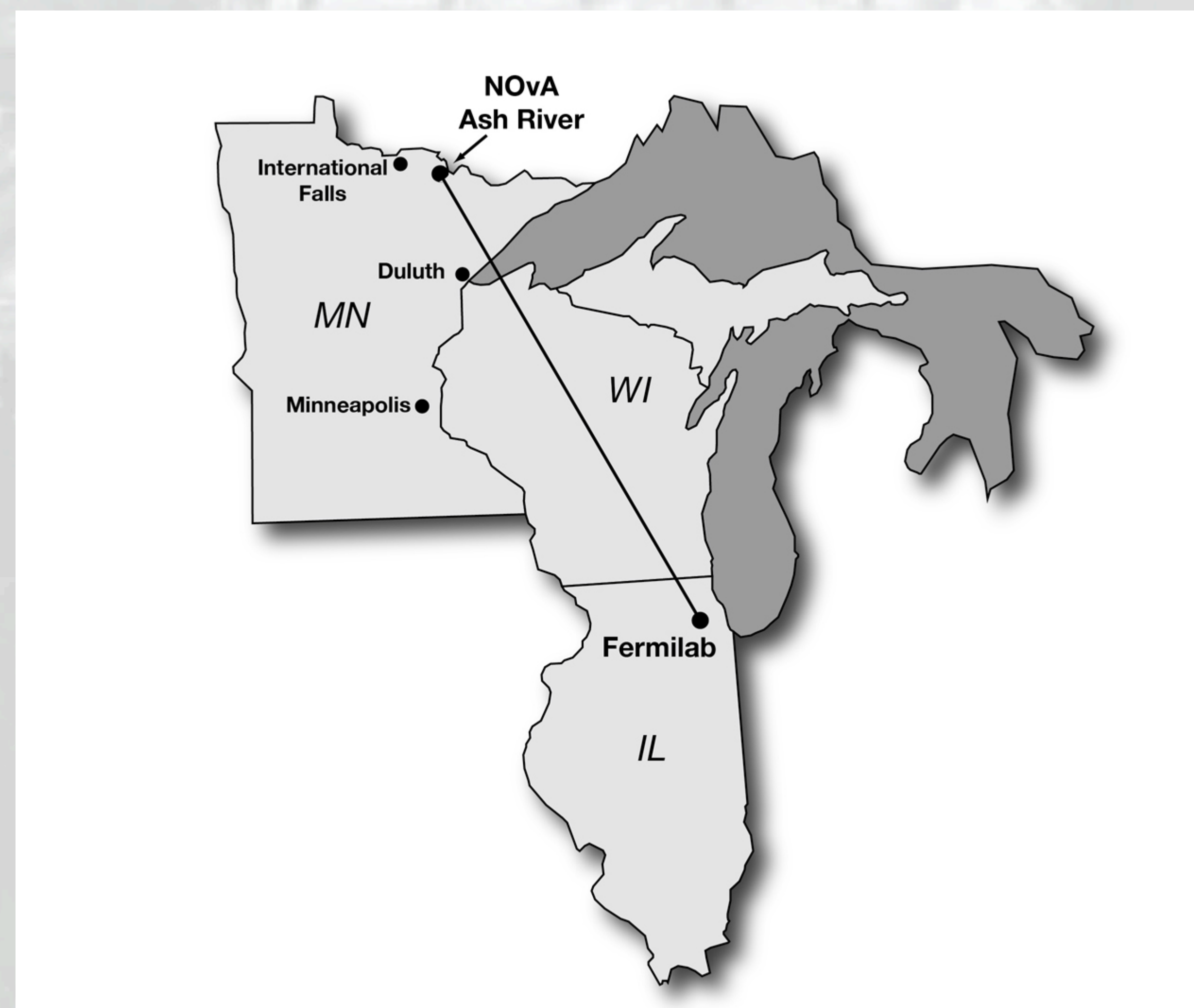
Already running experiments: NOVA and T2K

From Tokai To Kamioka

- L=295km, <E>=0.7GeV
- **Near detector off-axis (2-3°, 280m):** ND280, TPC
- **Far detector off-axis (295km):** Super-Kamiokande (50kt), Water Cherenkov
- JPARC beam: currently 200kW ramping up to 700kW (<2019)

NOVA:

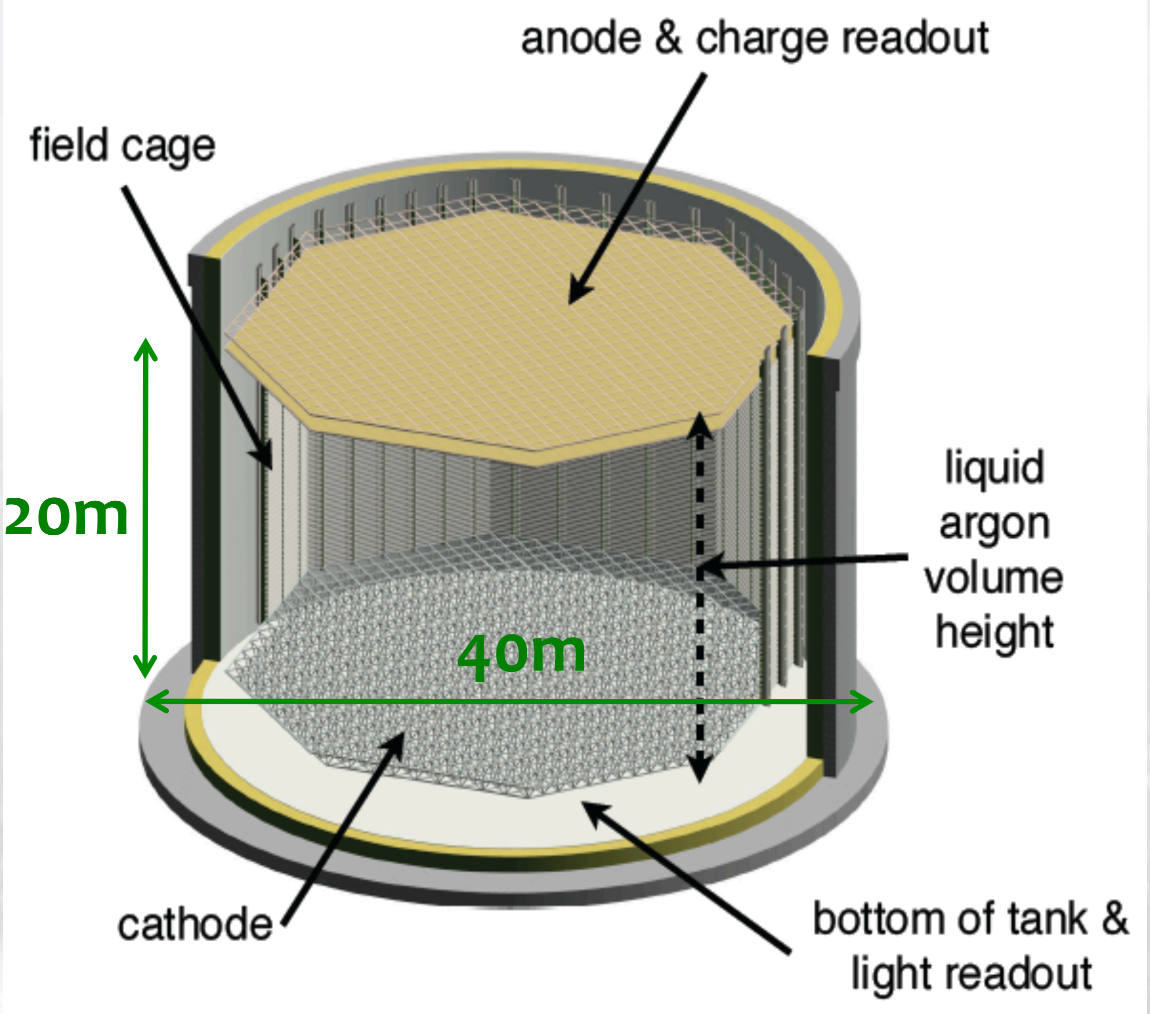
- L=810 km, <E>=2 GeV
- **Near detector off-axis (~1°, 250m):** ~ 200tons of liquid scintillator
- **Far detector off-axis (~1°, 810km):** ~ 15ktons of liquid scintillator
- NUMI beam re-starts May 2013 @ 700 kW (6 months ramp-up)



Far Detectors

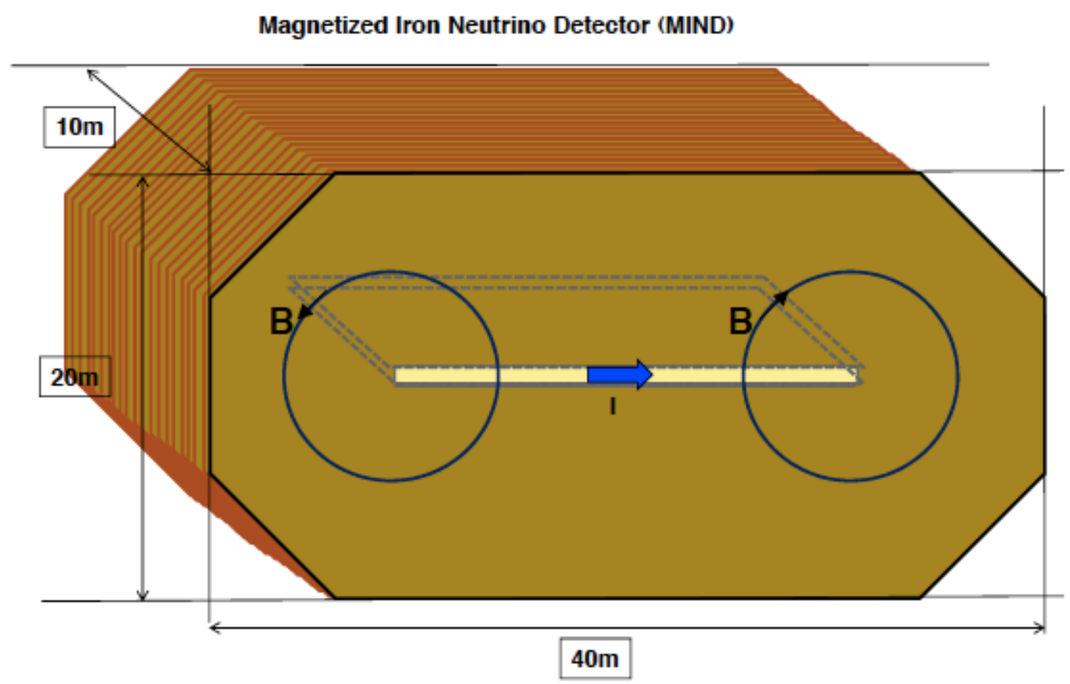
20 kt double-phase LAr LEM TPC (GLACIER): the best for electron appearance measurements

- Very fine grain tracking-calorimeter
- Can reconstruct multi-prong topologies down to low energy thresholds
- Excellent energy resolution across broad energy spectrum – ideal for spectrum measurement
- π_0 background almost negligible



35kt magnetised muon detector (MIND): conventional, well-proven, detector for muon CC and NC

- 3cm Fe plates, 1cm scintillator bars, B=1.5-2.5T
- Muon/mip momentum and charge determination for ν/anti-ν discrimination and neutrino energy measurement



Reaching very long baselines

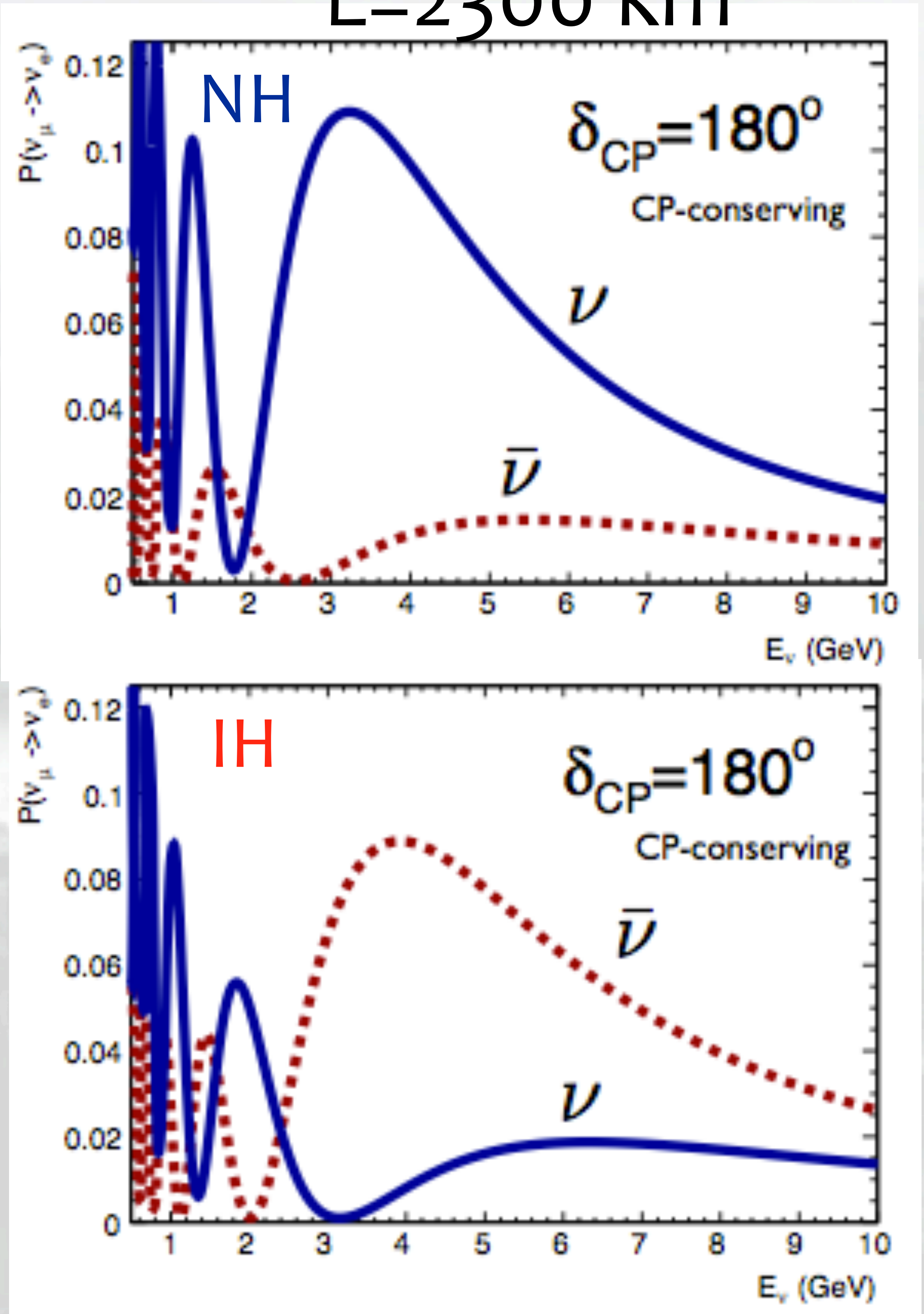
- <u>"Zoom effect"</u>: The L/E dependence can be observed in an "expanded" scale at large L
  ➠ Measure the full spectral information for unambiguous sensitivity and a direct proof of the observed phenomenon.

- <u>Decoupling of MH and CPV:</u> at medium and short baselines, the absence of knowledge of MH can completely compromise the efforts to discover CPV. A guaranteed & conclusive sensitivity to MH with existing beam power and initial mass requires a very long baseline.
  ➠ Opt for a guaranteed MH measurement in two years of running, not relying on the success of other experiments to give necessary inputs. After MH fixed, optimise the running for CP (this depends on NH/IH)!

- <u>Ultimate upgrade possibilities:</u> make a step towards the NF

→ now is the time to move to very long baselines !!

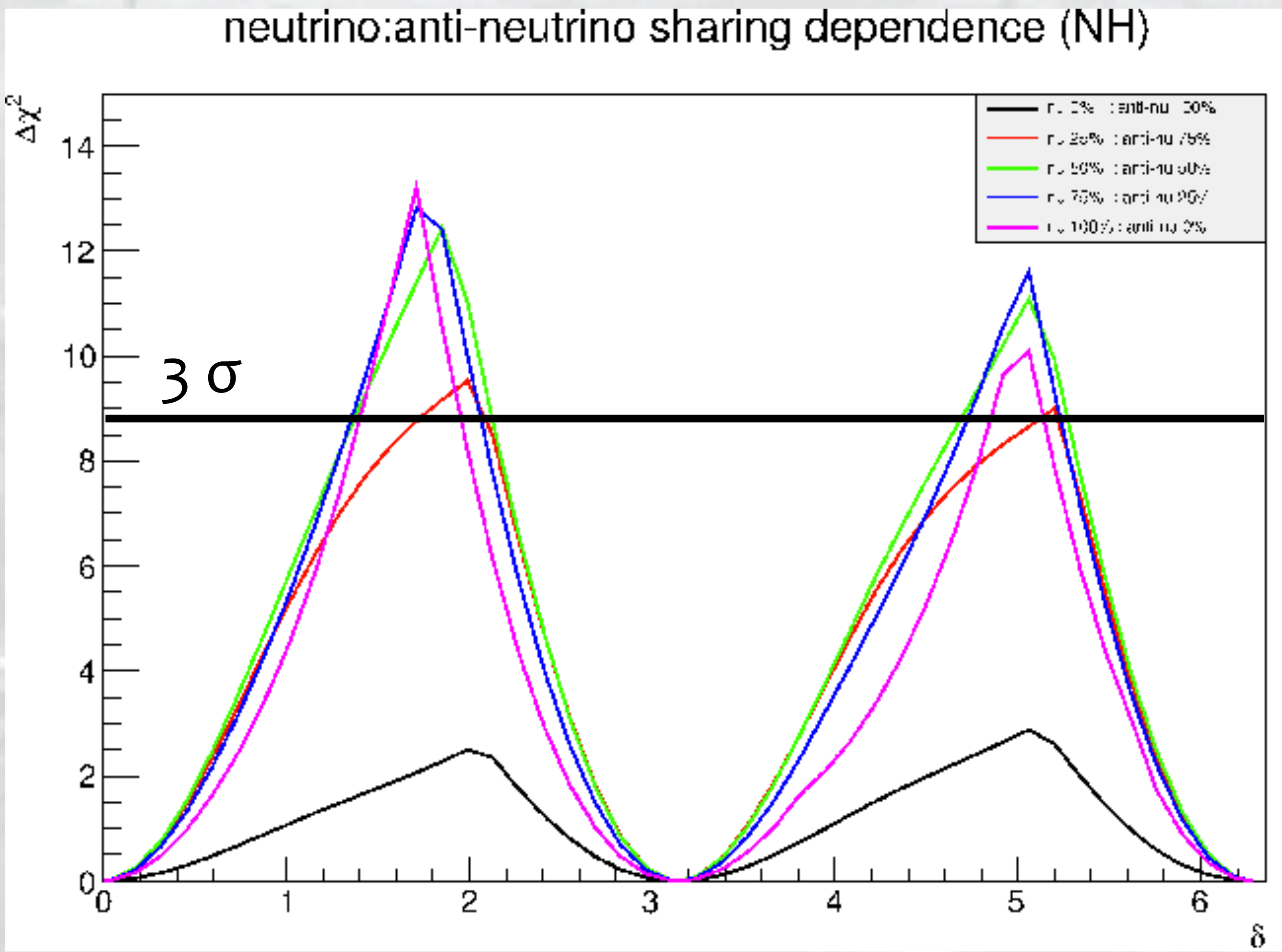
L=2300 km

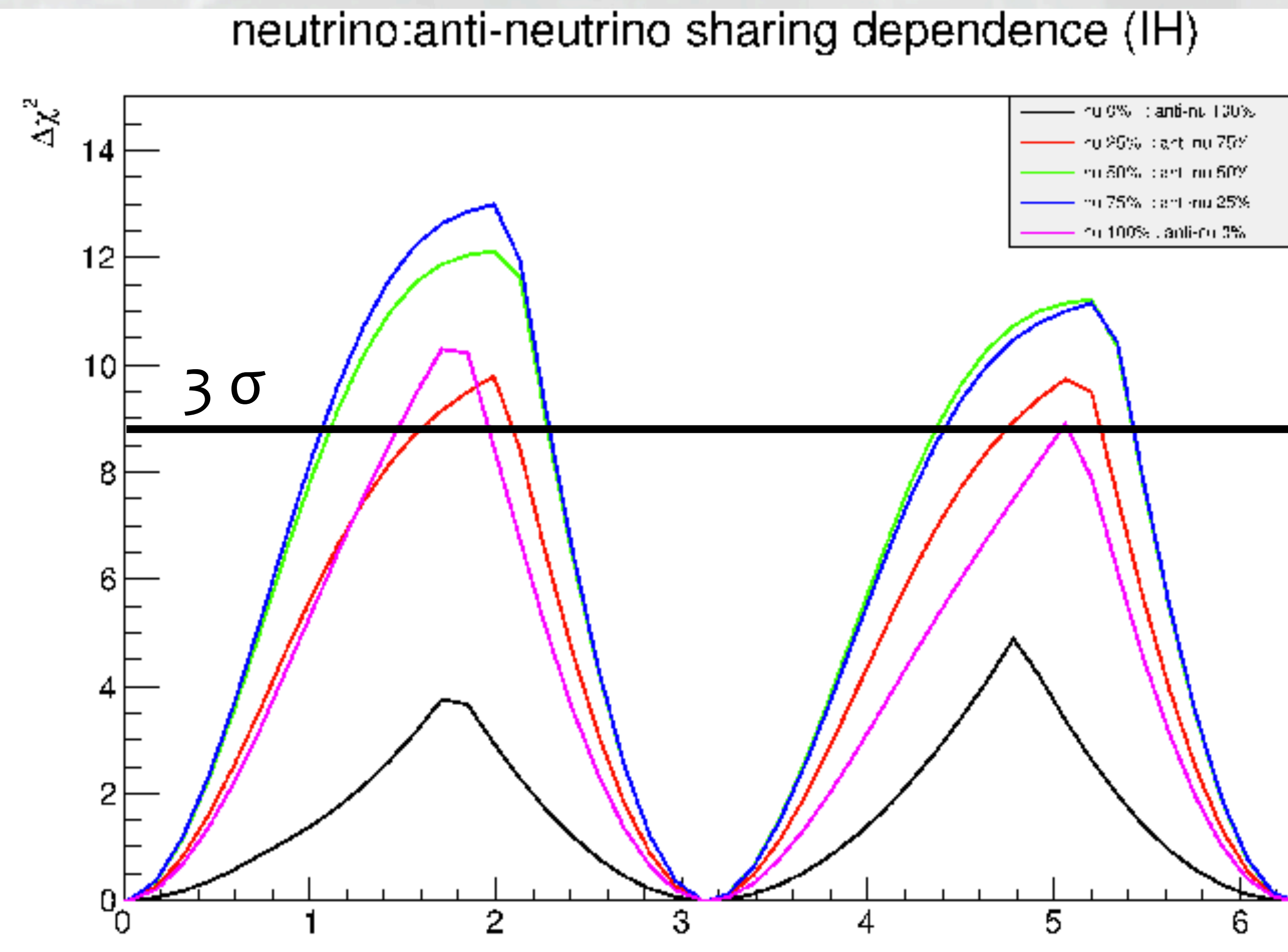


→ very clear signature !

LBNO Strategy on Mass Hierarchy and δ_{CP} (3)

Once MH determined run for 8 to 10 years with optimized sharing of neutrinos / anti-neutrinos to **cover the most possible phase space in δ_{CP}**

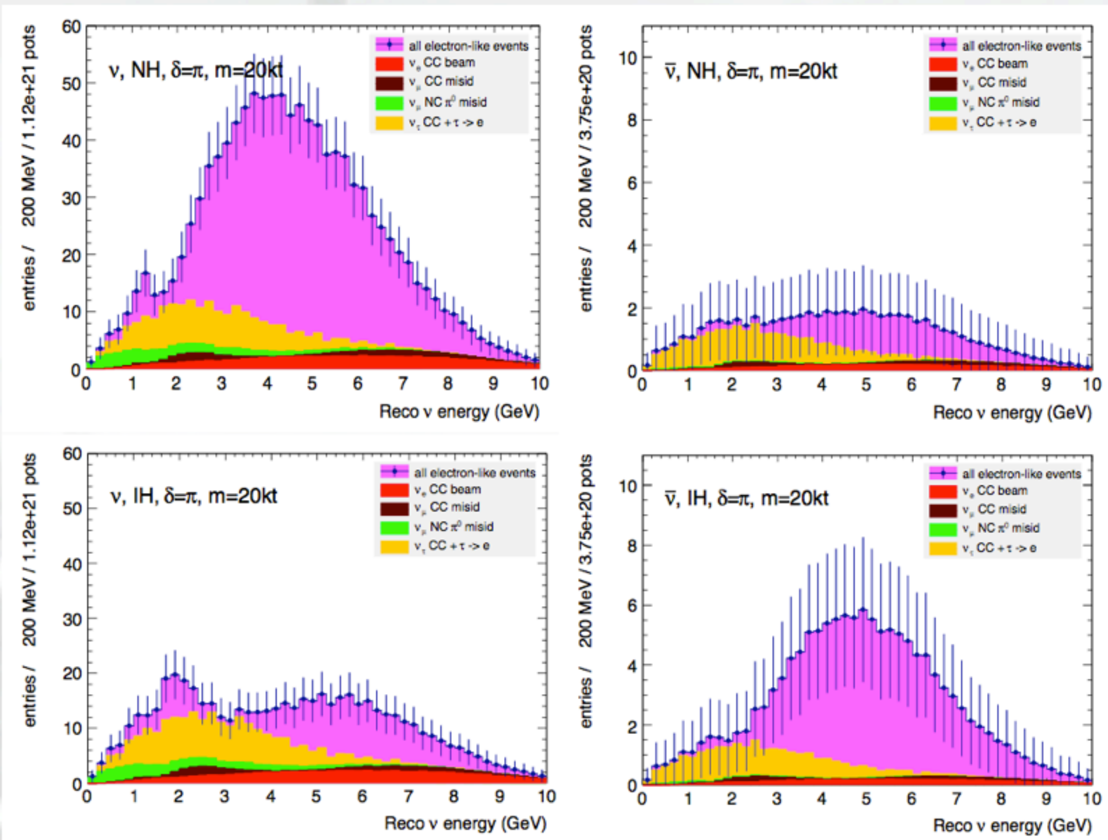


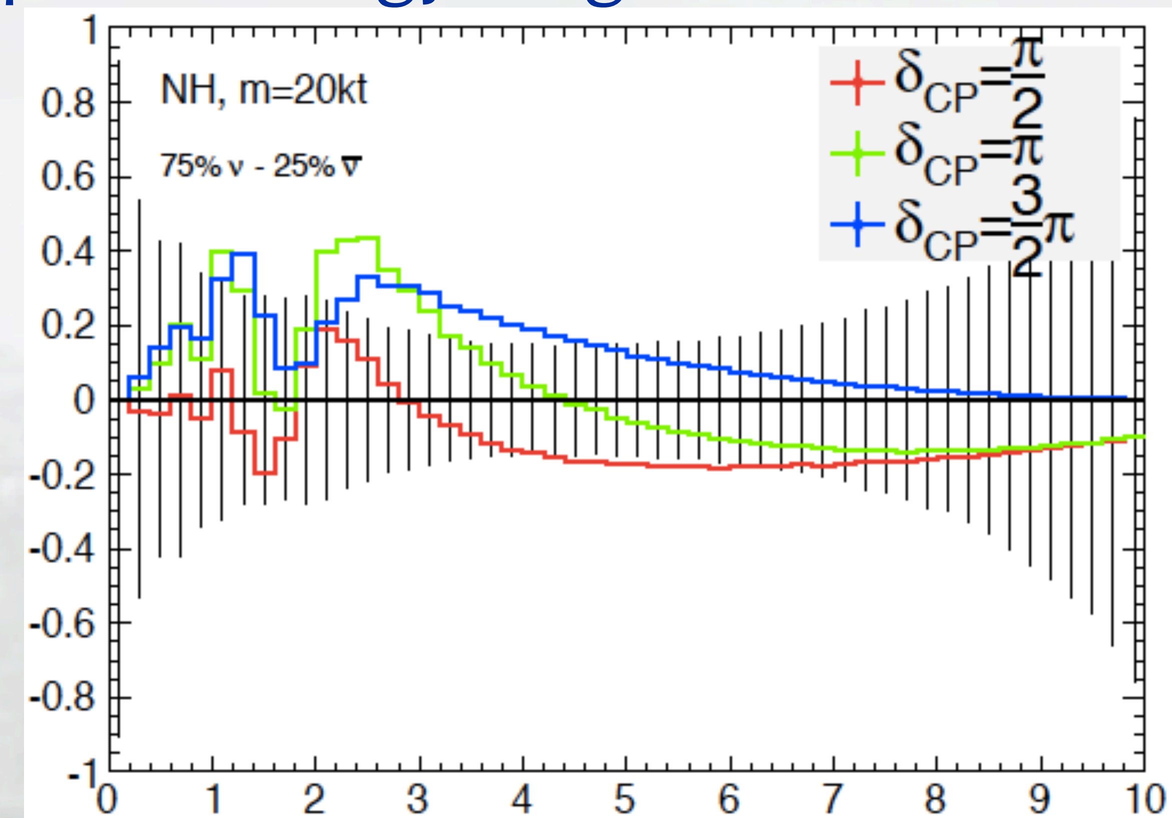


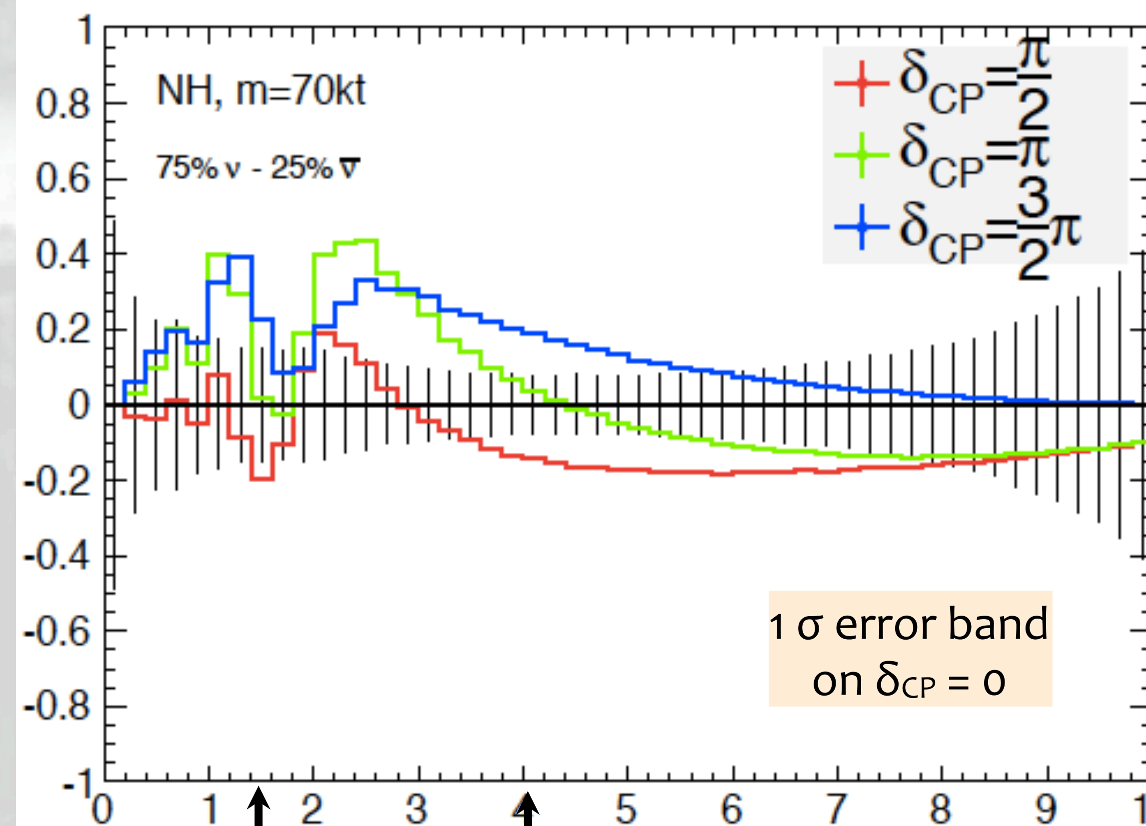
Design value: 75 % ν - 25 % anti-ν

LBNO Strategy on Mass Hierarchy and δ_{CP} (4)

Use all spectral information: Rate & Shape for energy range 1st - 2nd max

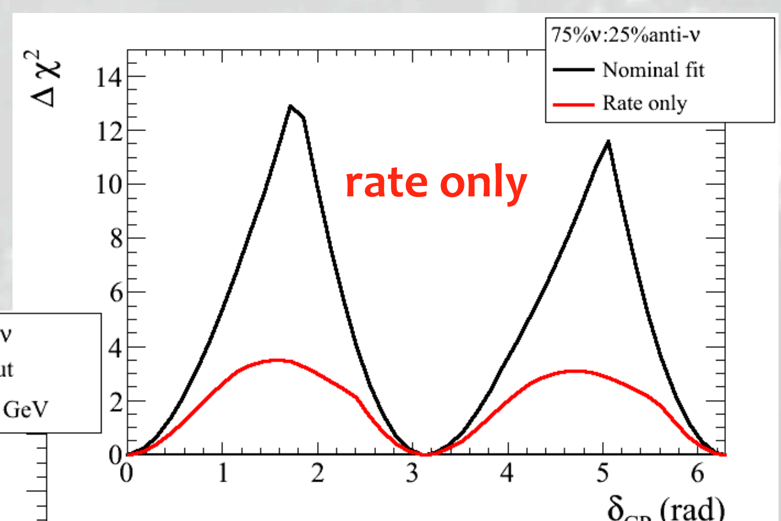




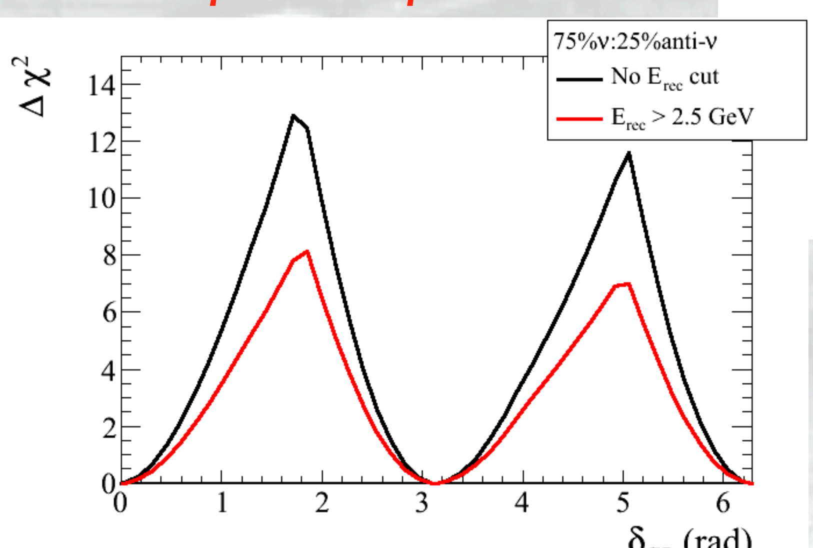


2nd max

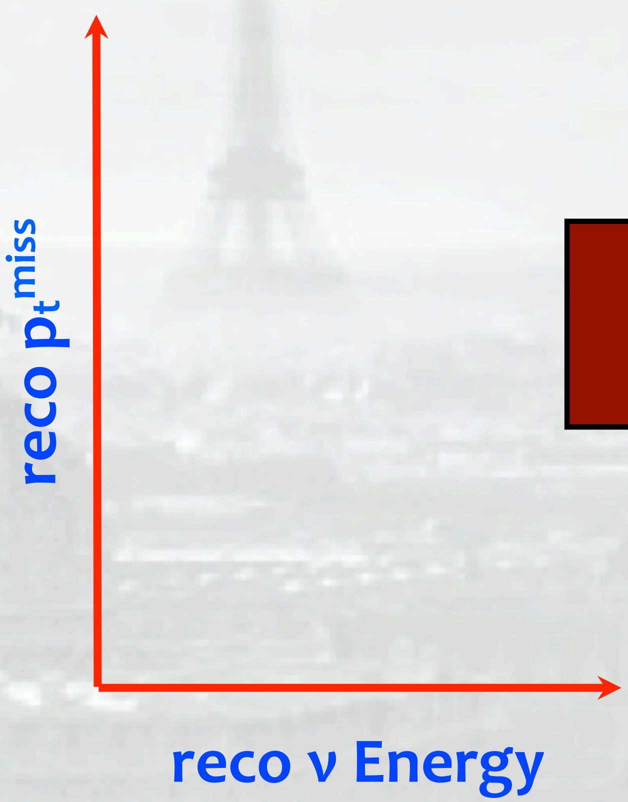
1st max

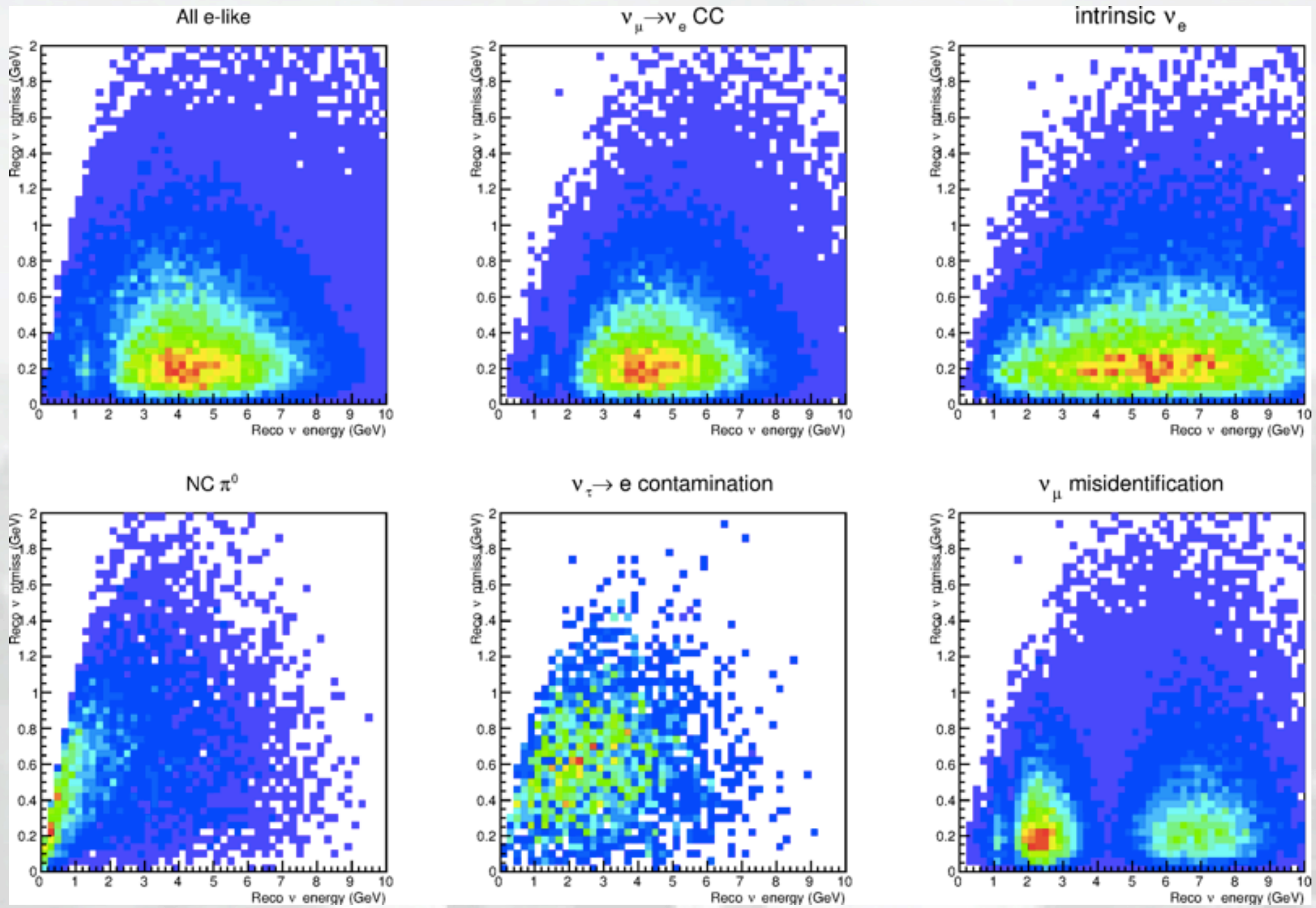


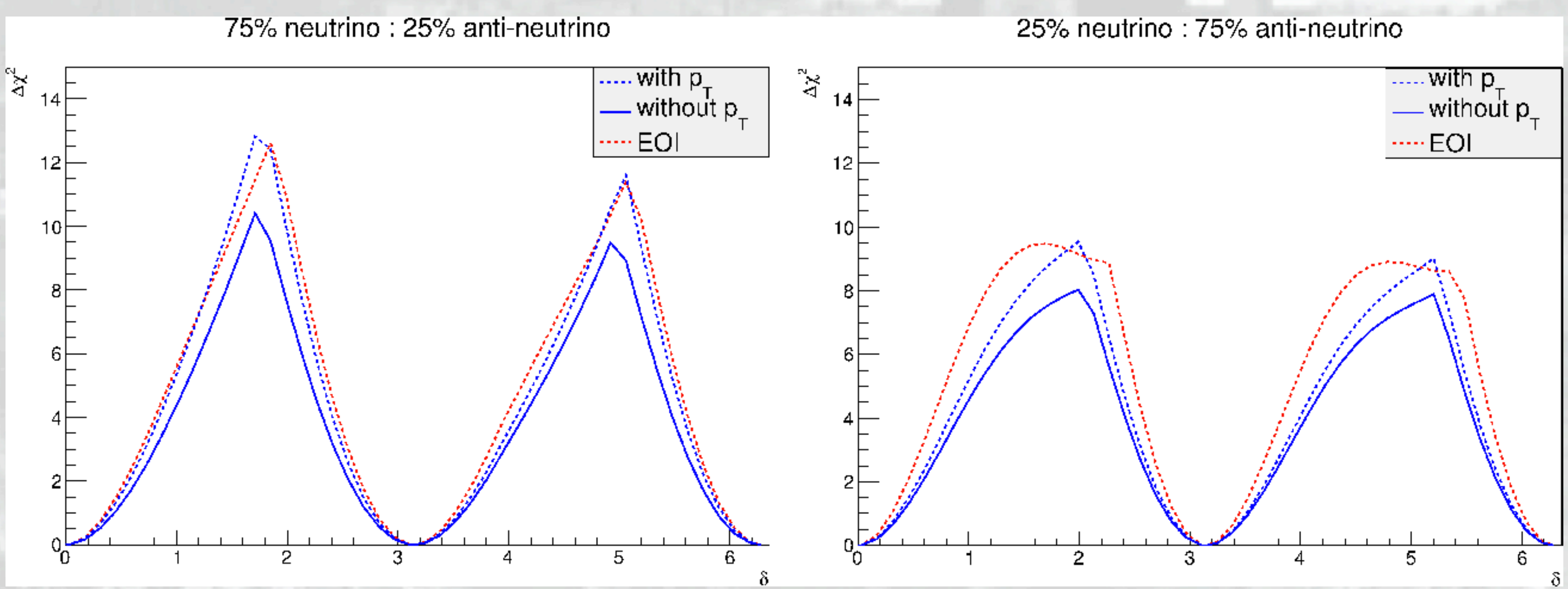
w/ and w/o 2nd max



Use all event information: Particle ID, Energy and kinematics (p_t)







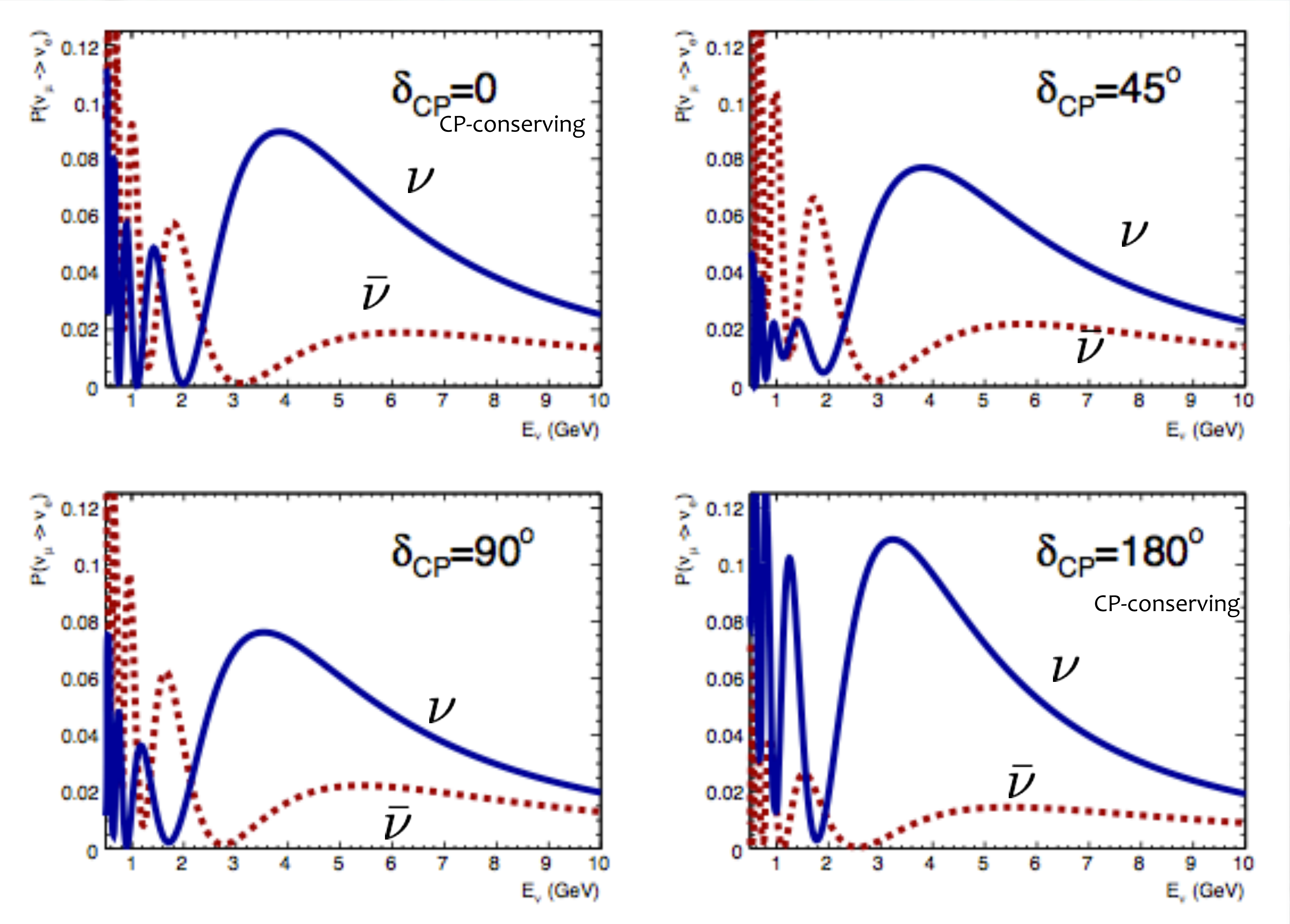
An incremental approach

- Subleading effects: The CP-violation measurement requires the measurement of the oscillation probabilities with high precision.
- Exposure: Compared to present generation "discovery" experiment, the next generation will require precision, hence more than ten-fold increase in statistics and an improved knowledge of systematics. This will require very large exposures (where exposure = mass x beam integrated intensity expressed e.g. in kton * GeV * pots) and improved far detector technologies.
- What is the right far detector mass? 10 kton seems definitely too small (half SuperK!). 20 kton might be better, but maybe not even enough. Since 2003, we have been considering the GLACIER concept "up to 100 kton".
- What is the "right" exposure ? We do not know. The larger exposure, the better the coverage in CP. On the other hand, Nature might be kind to us (just as she was for the other oscillation parameters!!) and CPV of neutrinos might be a large effect !
- An incremental approach: We advocate an initial LAr mass of 20kton to be complemented by a 50 kton in a second phase, each with significant physics reach and chances to find CPV. Before considering this approach, we have successfully addressed the critical issues of the the scalability of the detector design and its cost-effectiveness.

LBNO: CP+matter effects in $\nu_\mu \rightarrow \nu_e$

★Normal mass hierarchy L=2300 km

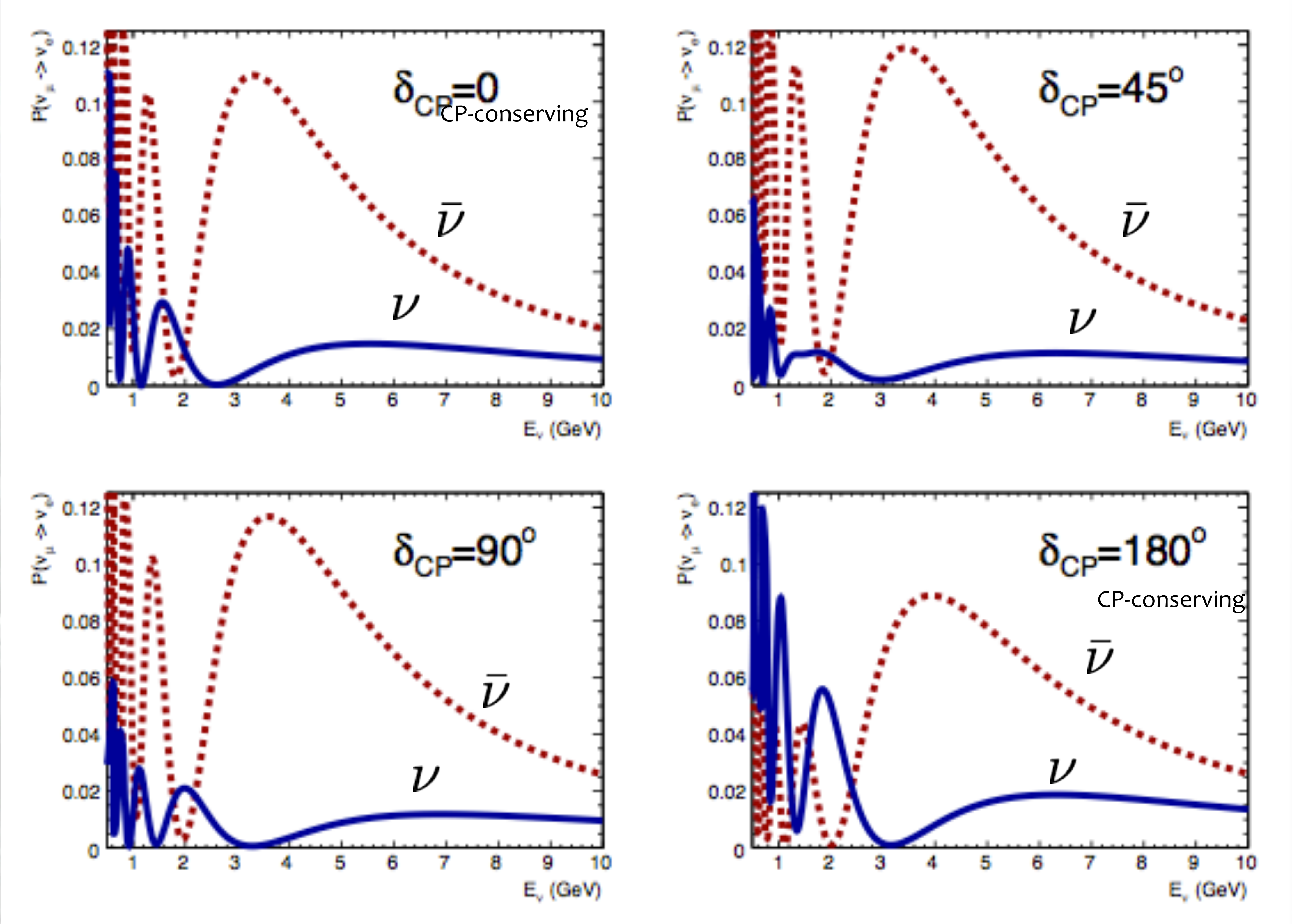
$\sin^2(2\theta_{13}) = 0.09$



LBNO: CP+matter effects in $\nu_\mu \rightarrow \nu_e$

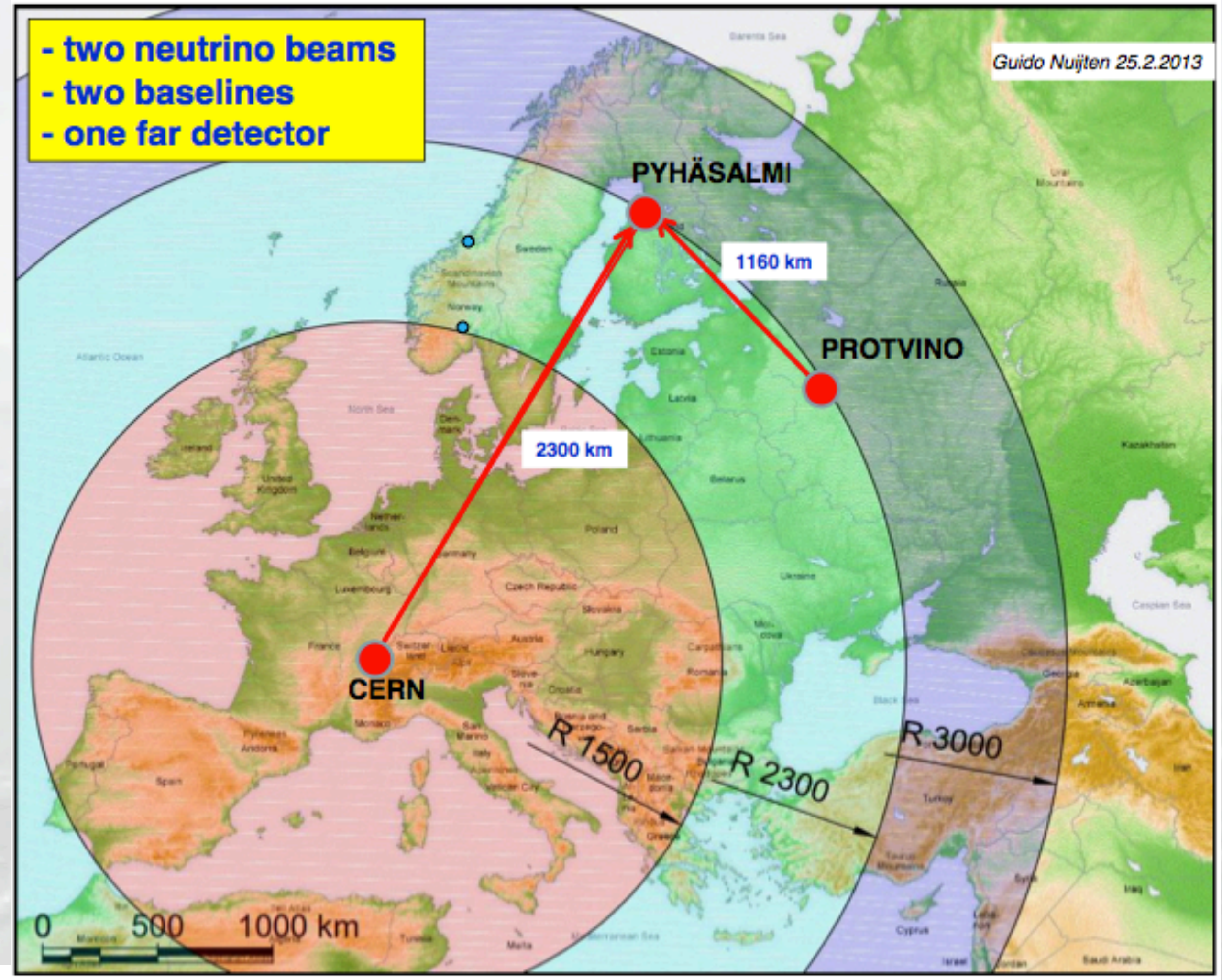
★Inverted mass hierarchy L=2300 km

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



Possibility of neutrinos from Protvino

PRELIMINARY

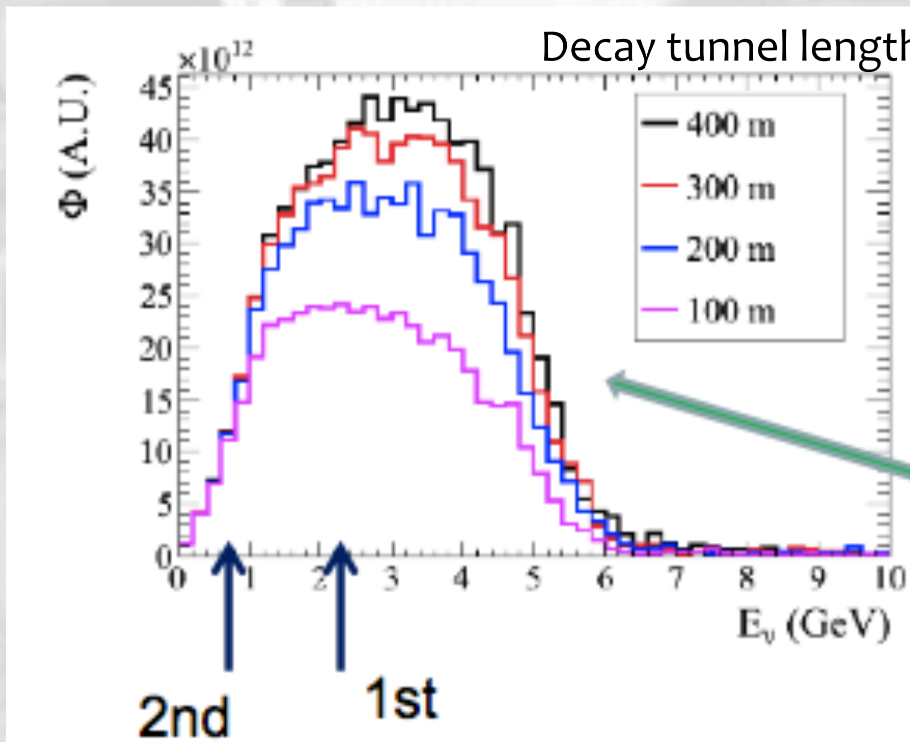


Desired parameters for neutrino beam:

Proton energy	70 GeV
Repetition rate	0.2 Hz
Intensity	2.2x10^{14} ppp
Power	450 kW
Neutrino channel	200-300 m
Angle to Pyhäsalmi	5.2 deg
Distance to ND	500 - 750 m
ND depth (at 500m)	46 m

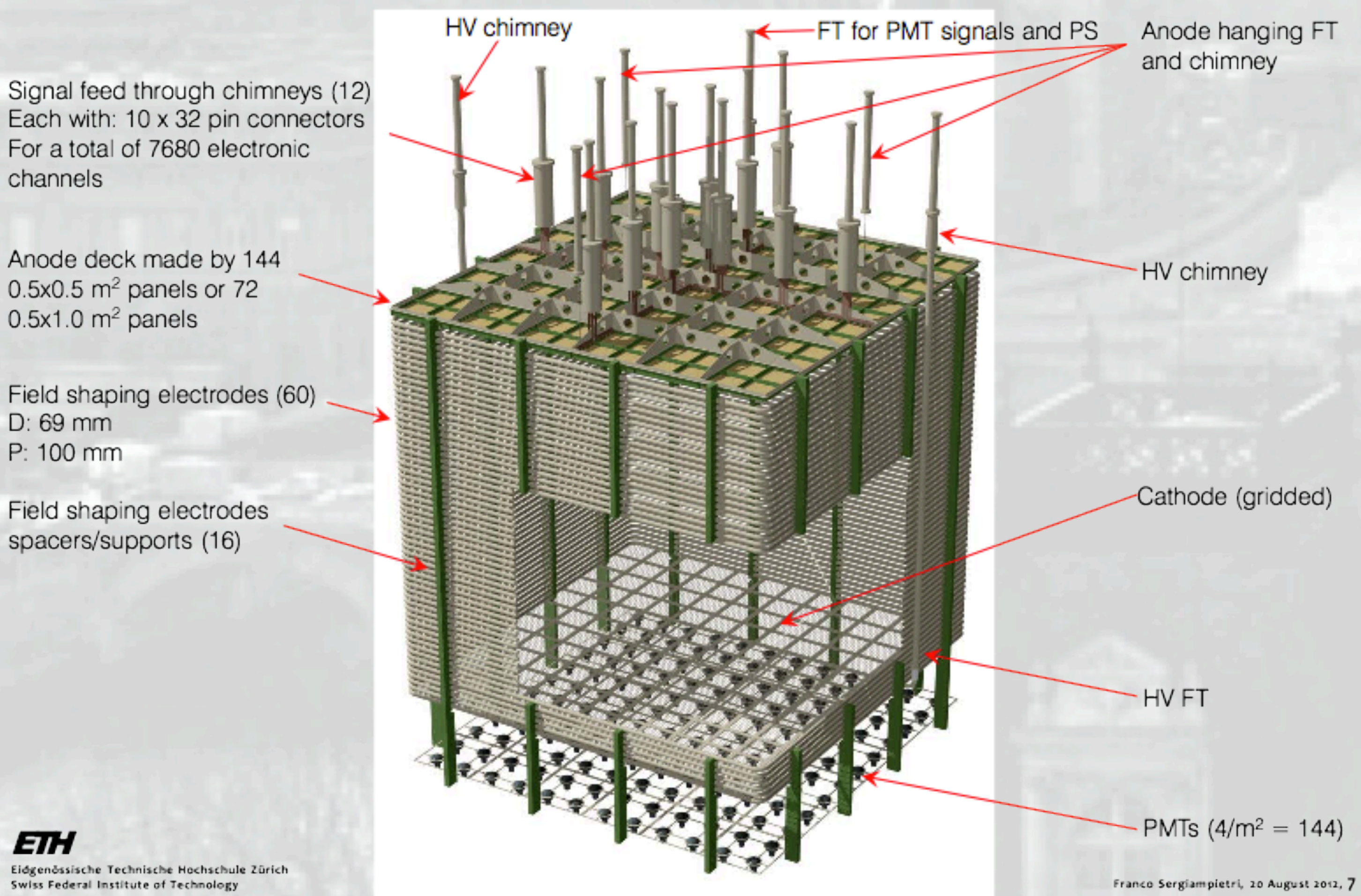
≈2000 νμ CC / 20 kton / year (no osc.)

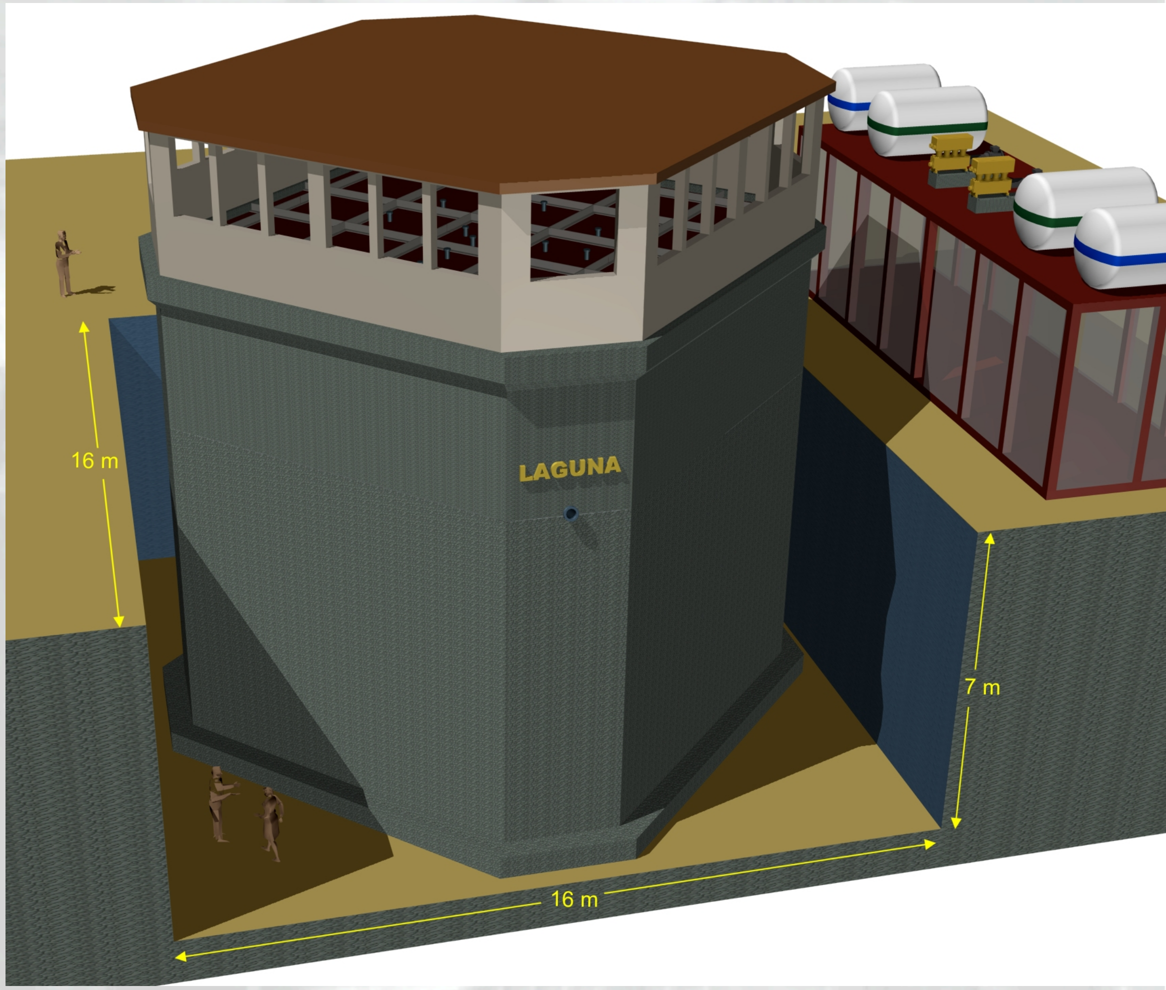
C2P+P2P sensitivity under study



A large scale demonstrator ?

- Consider a **6x6x6 = 216 m³ active volume detector** to be constructed and operated as a prototype of the far detector double-phase TPC
- Charged test beams to collect the large controlled data set allowing **electromagnetic** and **hadronic calorimetry** and general **detector performance** (PID, …) to be measured, **simulation and reconstruction** to be improved and validated
- Considering detector to be positioned in the CERN North Area (EHN1 building ?)
- Opportunities offered by the CENF neutrino beam under study
- **Technical proposal to CERN SPSC in preparation**





More on δ_{CP}:

Running mode: ν/anti-ν: 75% / 25%, 70 kt fid. mass LAr, Detector response and resolution included