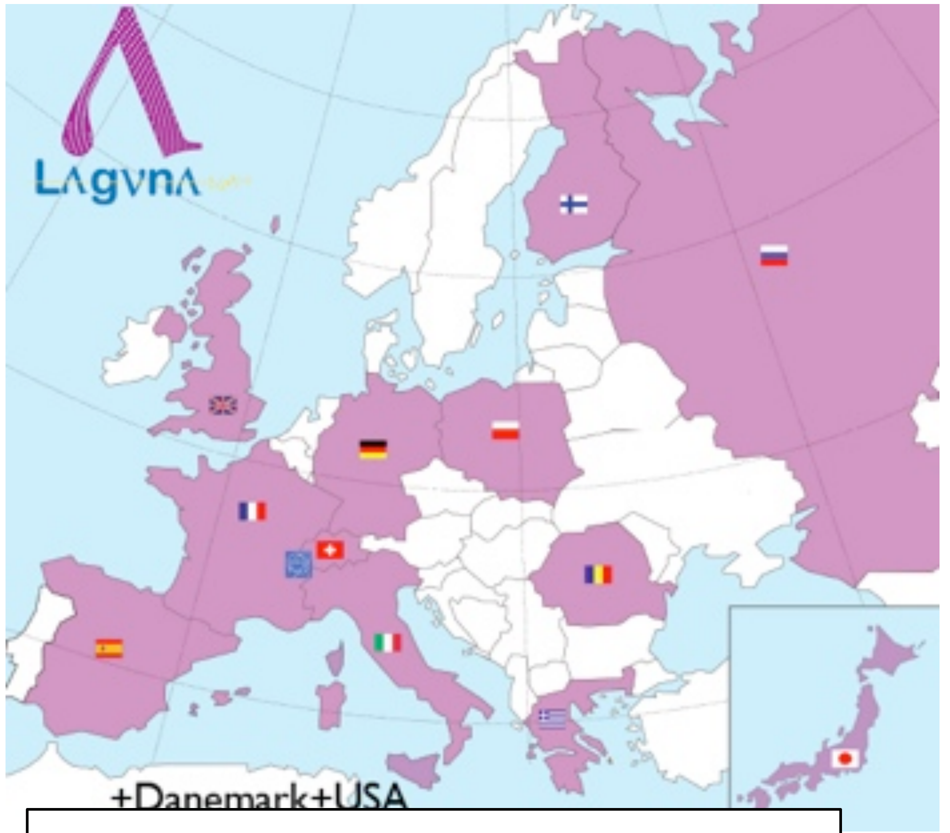
# *LAGUNA and LBNO: Towards the next generation neutrino observatory in Europe*

Thomas Patzak

# LAGUNA/LBNO consortium

**Large Apparatus for Grand Unification and Neutrino Astrophysics**
**and**
**Long Baseline Neutrino Oscillations**

- **LAGUNA DS** (FP7 Design Study 2008-2011)
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **LAGUNA-LBNO DS** (FP7 DS Long Baseline Neutrino Oscillations, 2011-2014)
  - ~300 members; 14 countries + CERN
  - Down selection of sites & detectors
- **LBNO** (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, June 2012)
  - An incremental approach, based on the findings of LAGUNA
  - ~230 authors; 51 institutions
  - CERN-SPSC-2012-021 ; SPSC-EOI-007, under review

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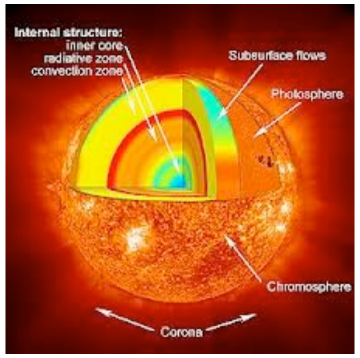
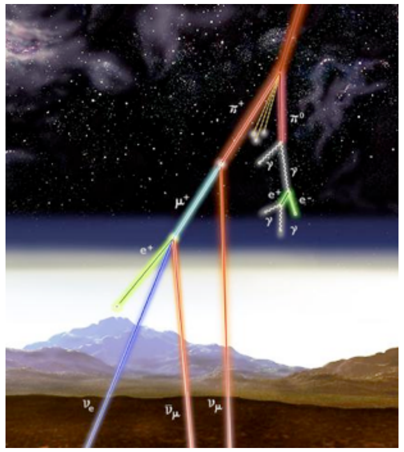
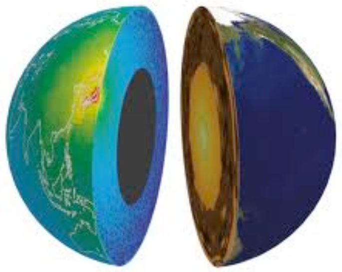
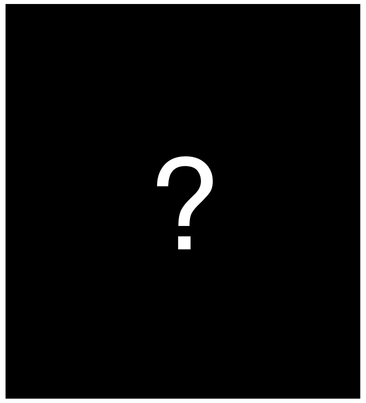
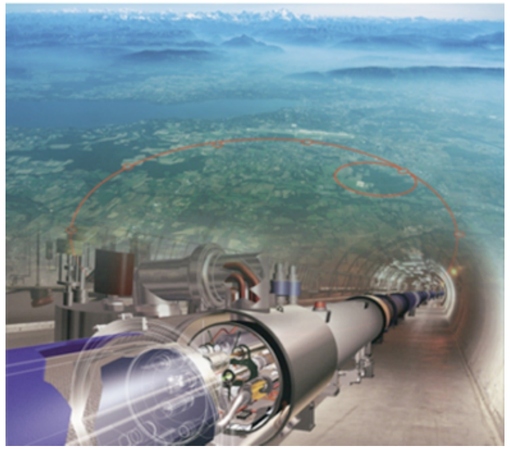






# LAGUNA Physics:

1. Accelerator based:
   - $\delta_{CP}$
   - Mass Hierarchy
   - MSNP precision
   - 3 ν or 3+n ?

large $\theta_{13}$

2. Non-Accelerator based:
   - Proton decay

3. Neutrino Astronomy:
   - Supernova neutrinos
   - Diffuse Supernova Neutrinos (DSN)
   - Solar Neutrinos
   - Atmospheric Neutrinos
   - Geo Neutrinos

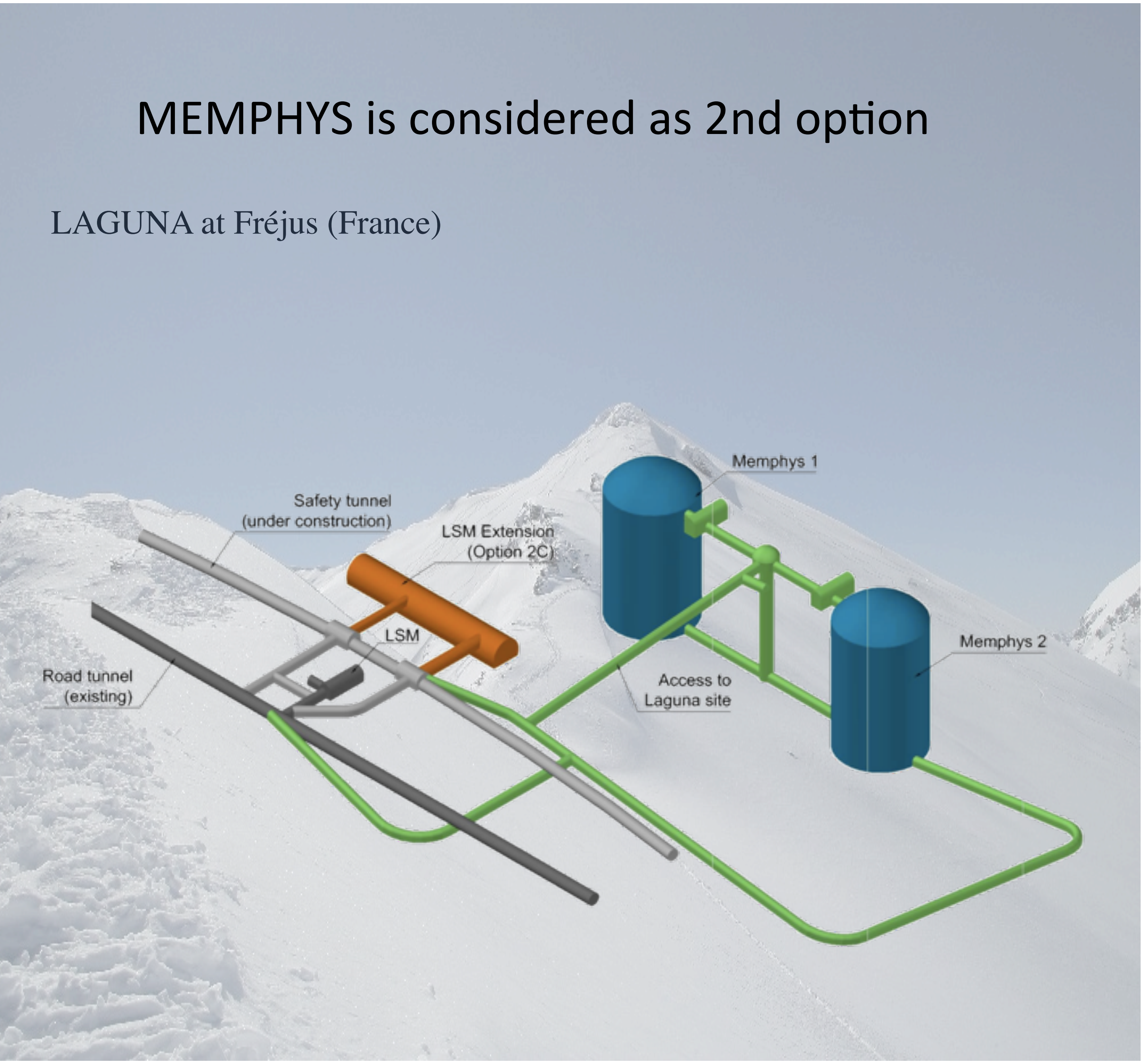
4. Dark Matter

Even after the crowning discovery of the Higgs at CERN July 4th 2012, Neutrino physics is the only experimental proof for physics beyond the standard model (BSM)

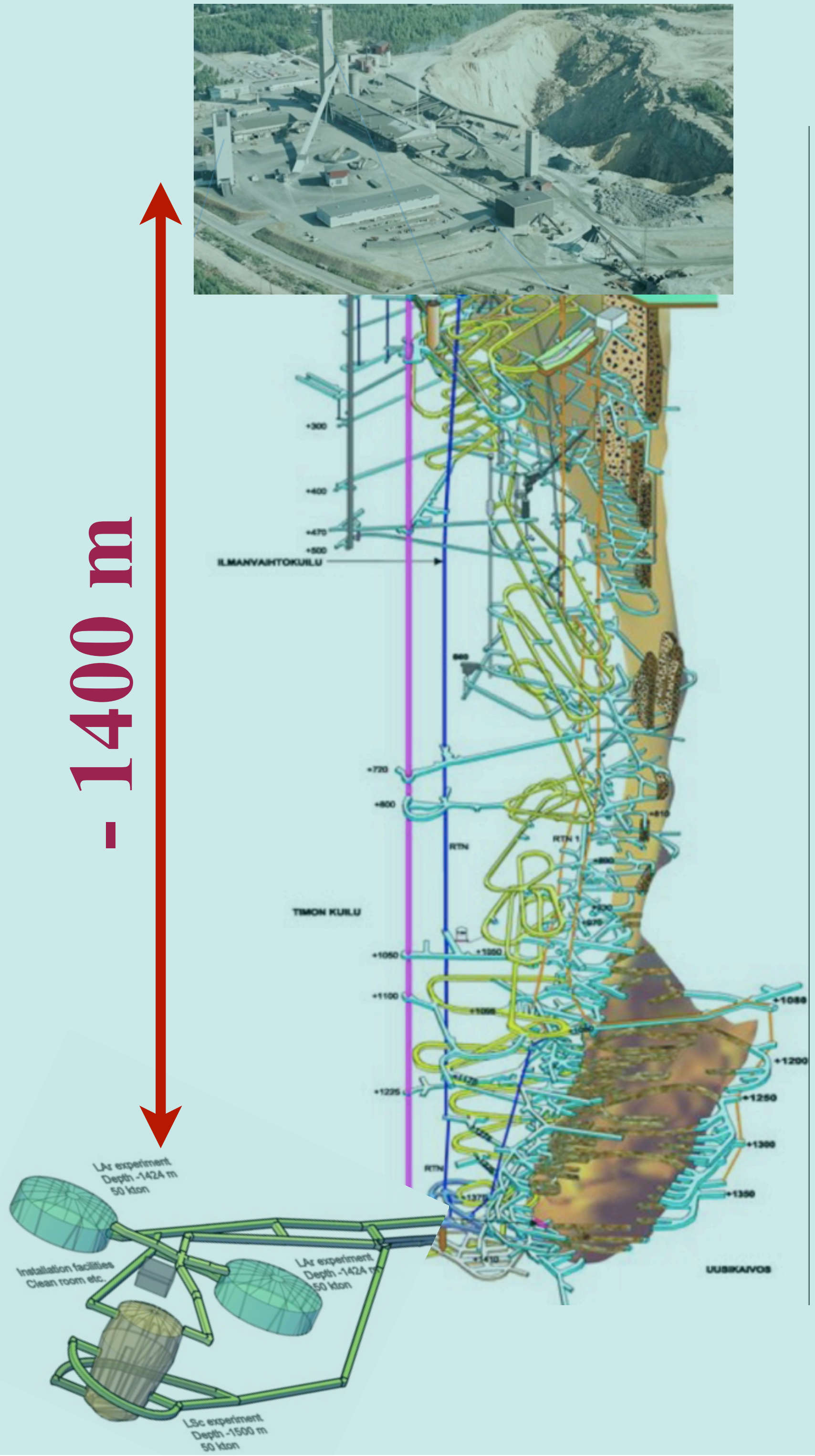
# *LAGUNA-LBNO - Cite specific investigations:*

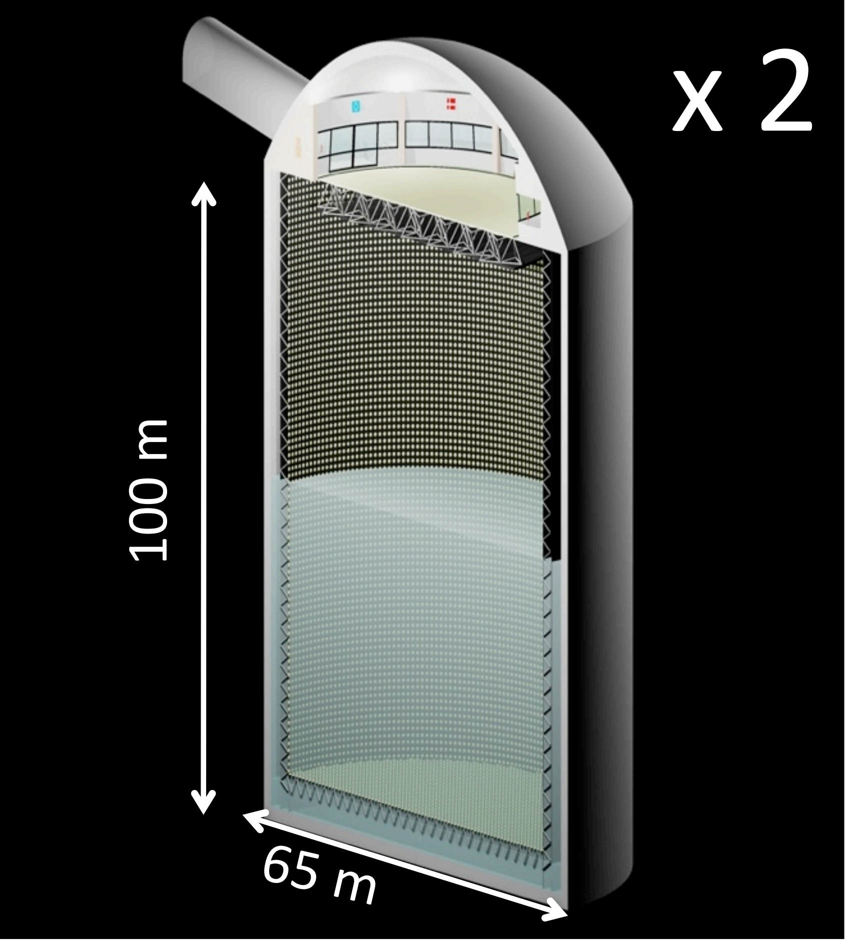
1. Shortest baseline (130 km), CERN -> Fréjus: no matter effects; clean measurement of LCPV
2. Longest baseline (2300 km), CERN -> Pyhäsalmi: matter effect; mass hierarchy, LCPV
   - Facility Construction Plan and Costing (WP2)
   - Lifetime Operation (WP3)
   - Baseline Neutrino Beams from CERN (WP4)
   - Science and Impact on Detector Design (WP5)

MEMPHYS is considered as 2nd option




## 1st Option: LAr + LSc @ Pyhäsalmi
## SPSC-EOI-007

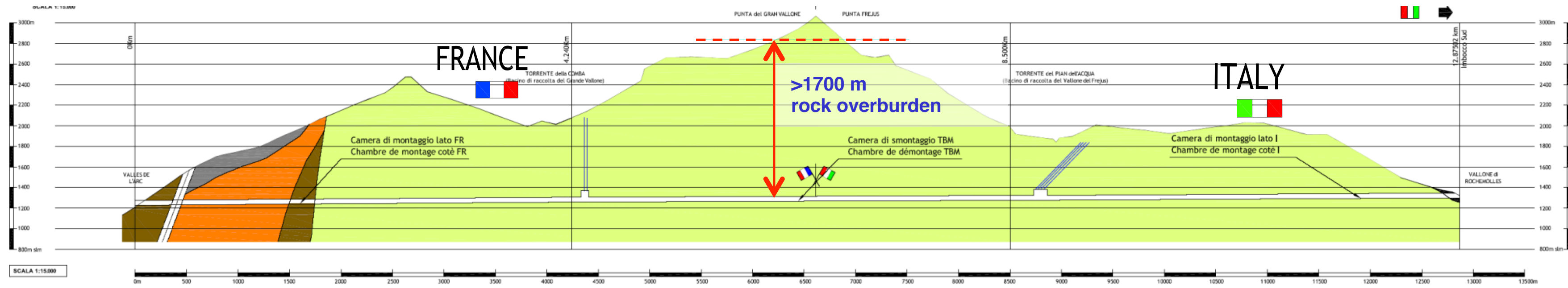





# MEMPHYS (MEgatonMassPHYSics)

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

Longitudinal section (Road tunnel)

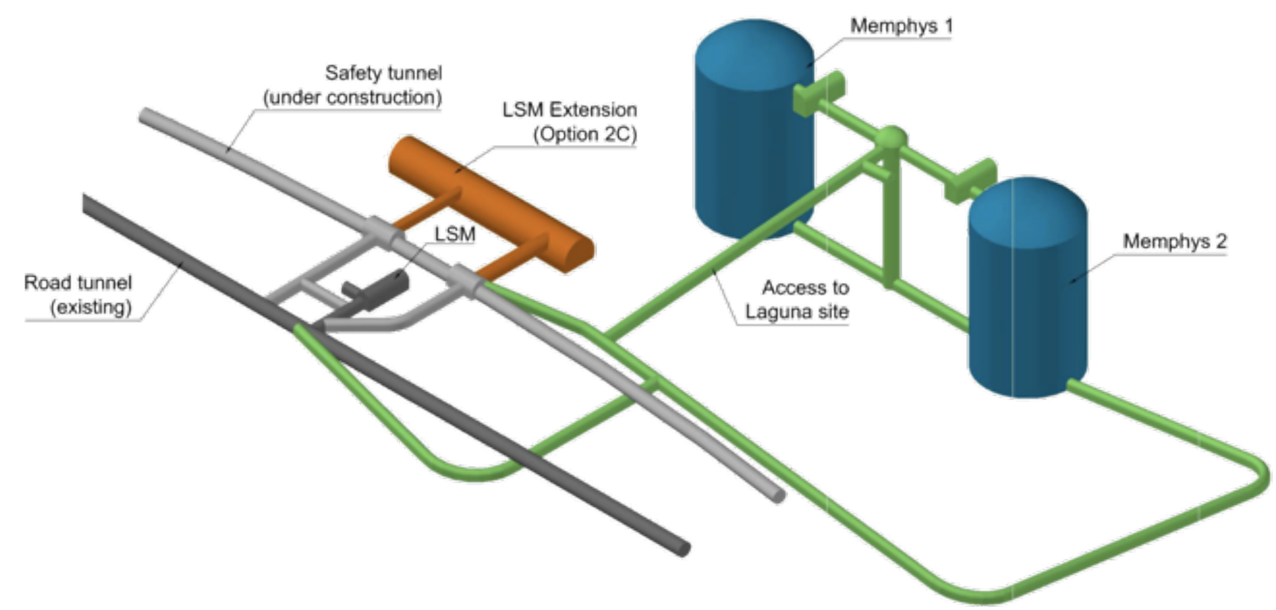



6,6 km | 6,2 km

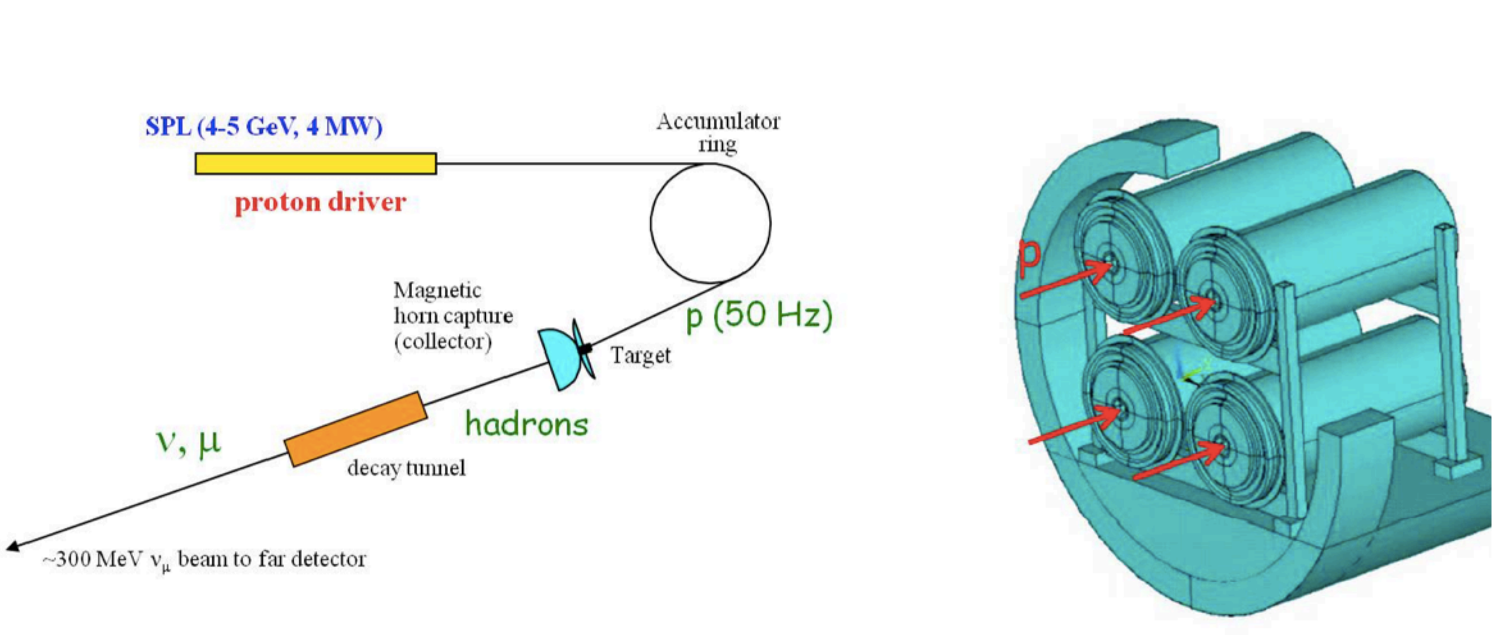
12.8 km

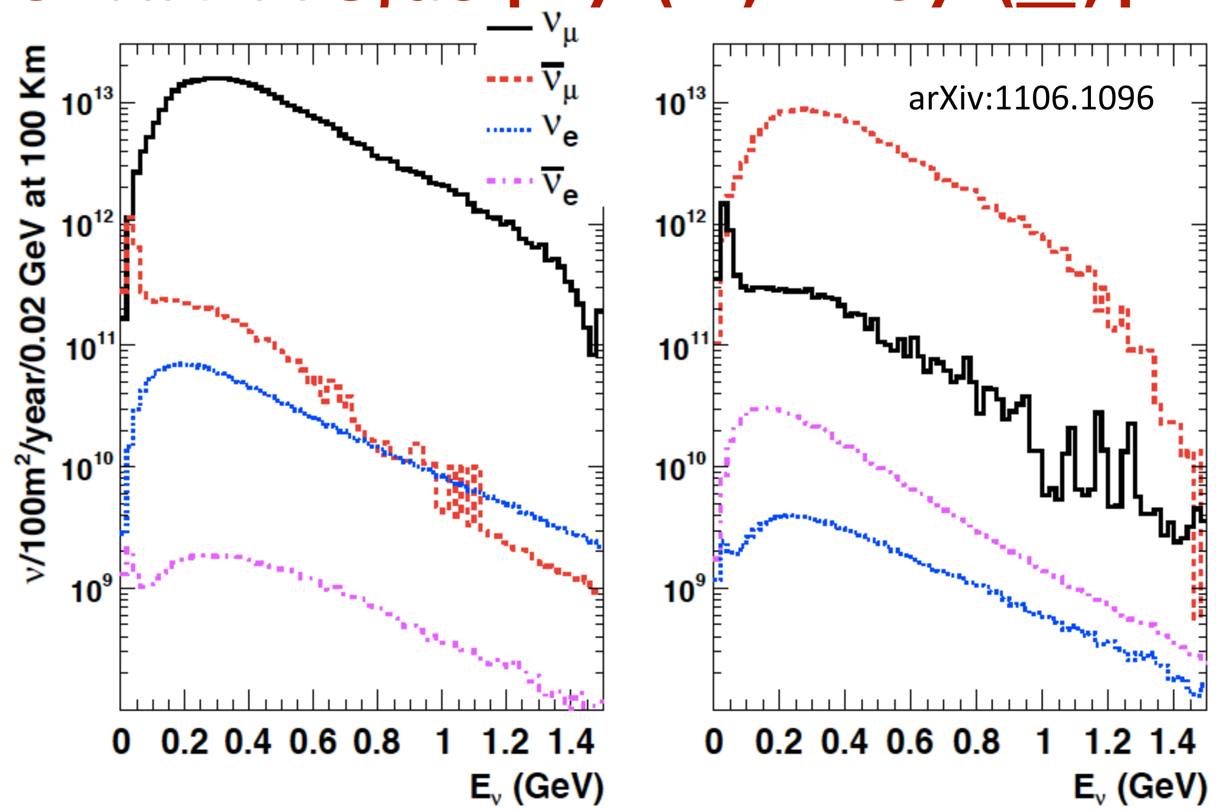
http://www.apc.univ-paris7.fr/APC_CS/Experiences/MEMPHYS/

- Water Cherenkov
  - well proven technology
  - each tank is 6.6 x SK --> mild extrapolation only!
- total fiducial mass: 500 kt
- 2 cylindrical modules 65 x 100 m
  - size limited by light attenuation length (λ~80m) and pressure on PMTs
  - readout : ~140000 12” PMTs, 30% geom. cover
  - R&D on readout electronics and DAQ + detailed study on excavation @Fréjus existing & ongoing

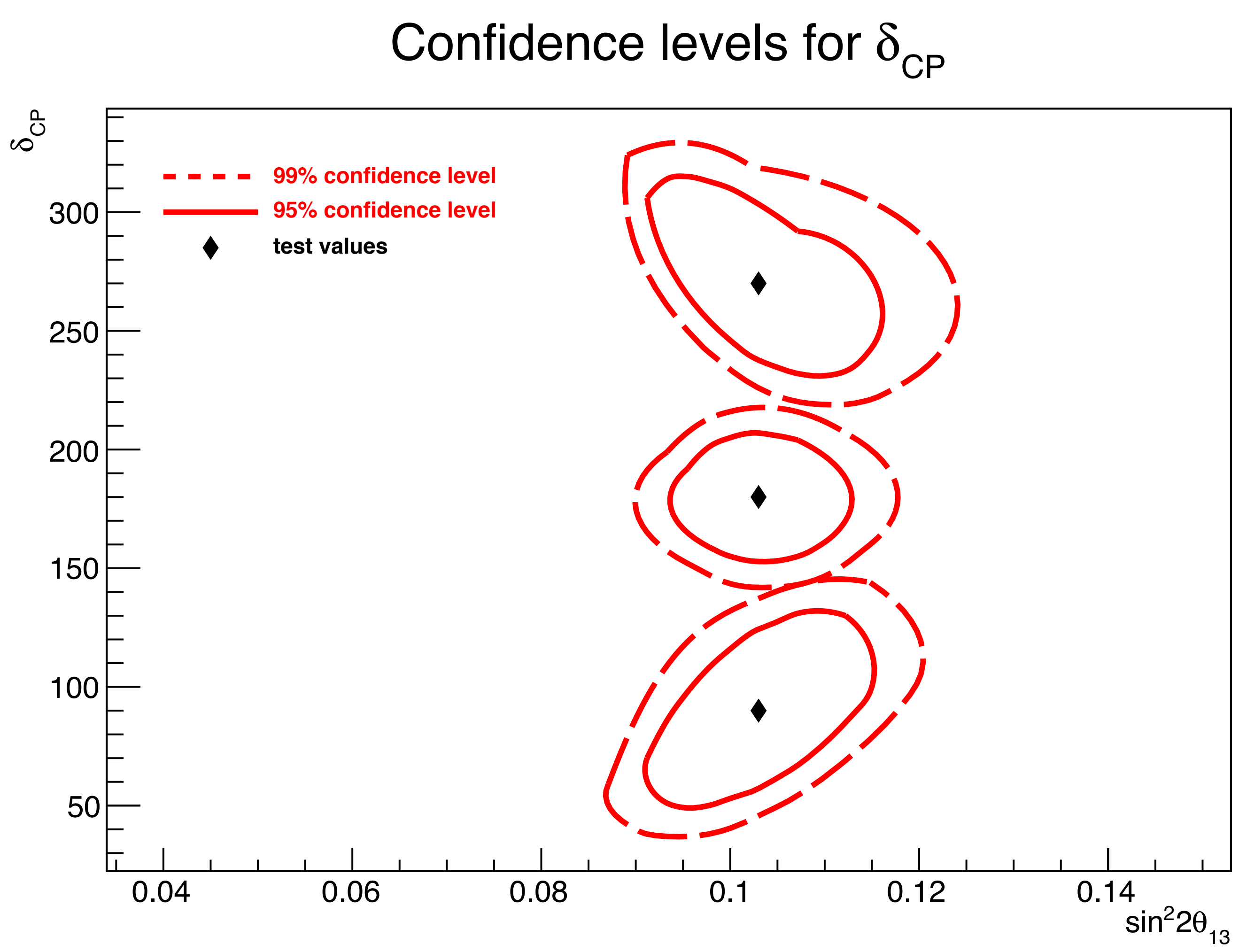


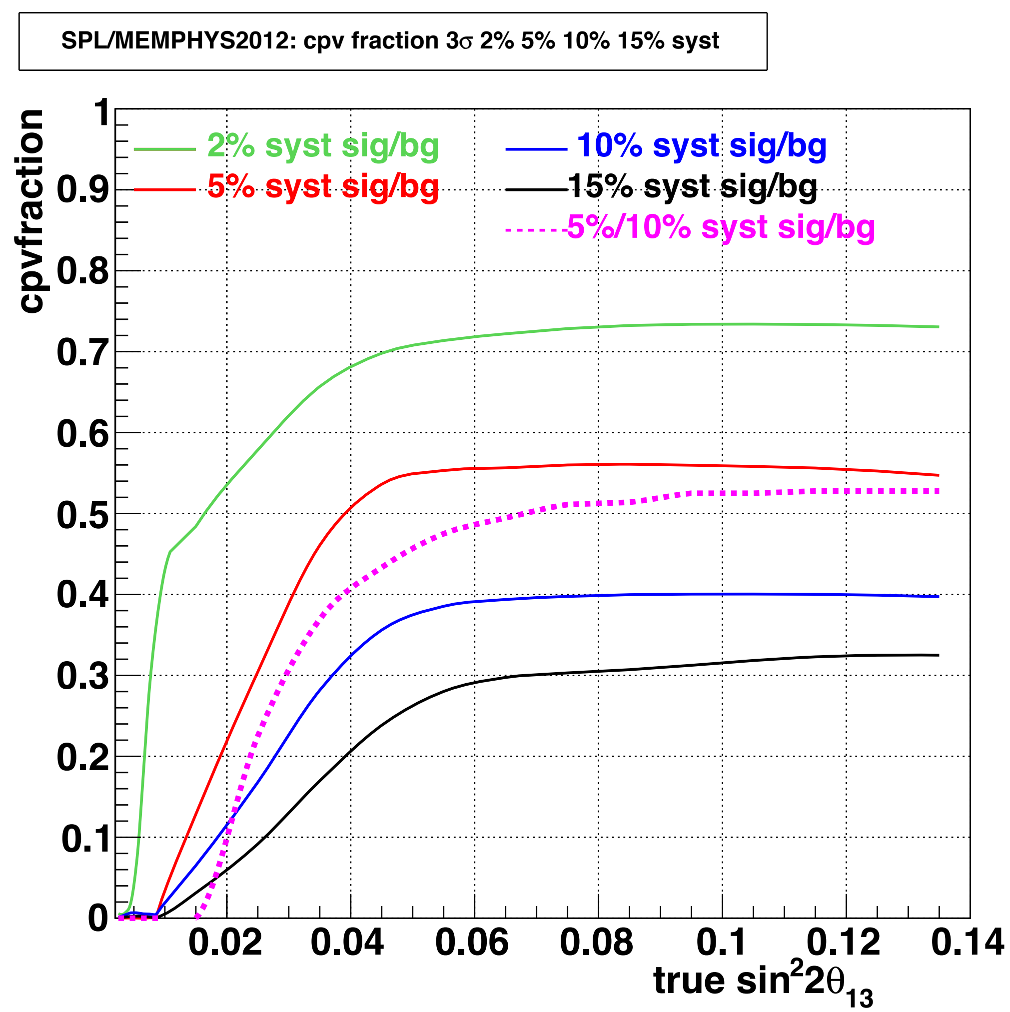
# LCPV with MEMPHYS and SPL beam CERN-Frejus [2y (ν) + 8y (ν̅)]




**5.6 x 10²² p.o.t./y with 4 MW x 10⁷ s at 4.5 GeV**

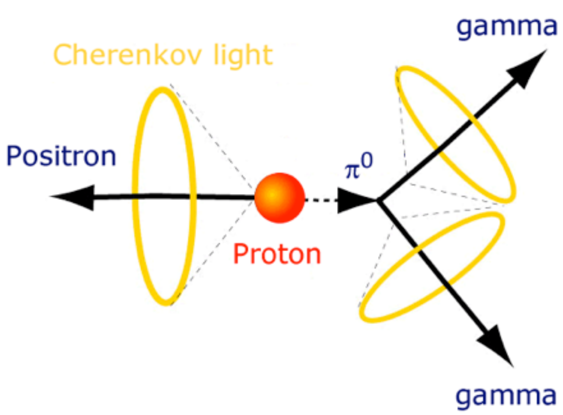



JCAP 1301 (2013) 024

# MEMPHYS non-accelerator Physics

## Proton Decay



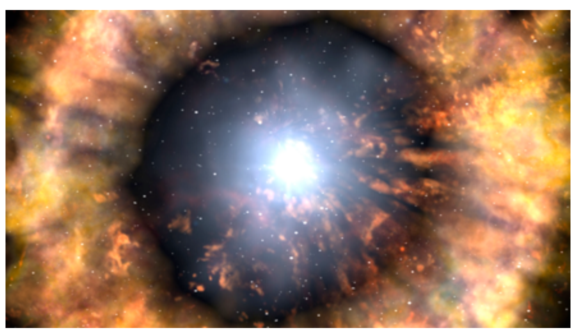

| Model | Decay Modes | Predictions |
|---|---|---|
| Georgi-Glashow | - | ruled out |
| Type II-$SU(5)$ | all | $\tau_p < 2 \times 10^{36}$ yr |
| Type III-$SU(5)$ | $p \to \pi^0 e^+$ | $\approx 10^{35-36}$ yr |
| Adjoint $SU(5)$ | $p \to \pi^0 e^+$<br>$p \to K^+ \bar{\nu}$<br>$p \to \pi^+ \bar{\nu}$ | $\tau_{e^+\pi^0} < 10^{35}$ yr<br>$\tau_{K^+\bar{\nu}} < 9 \times 10^{36}$ yr<br>$\tau_{\pi^+\bar{\nu}} < 3 \times 10^{35}$ 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:

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

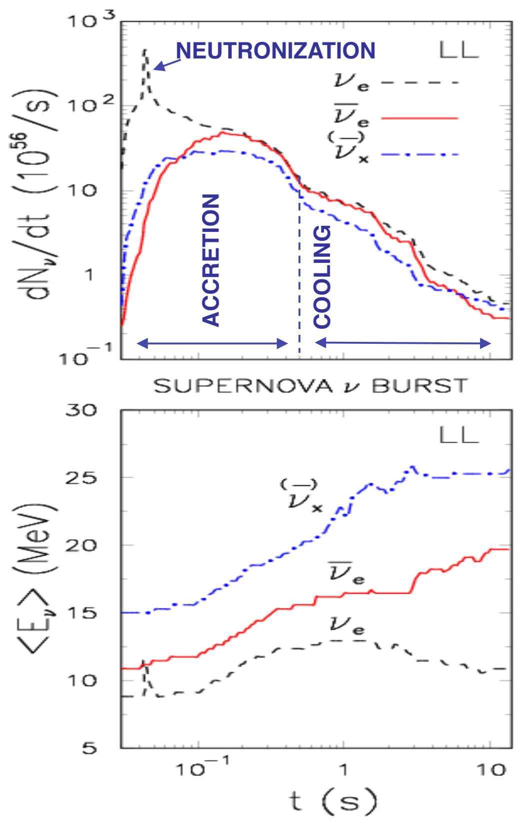
$p \to \bar{\nu} K^+$: ~ $2.4 \times 10^{34}$ y at 90% C.L.

## Supernova

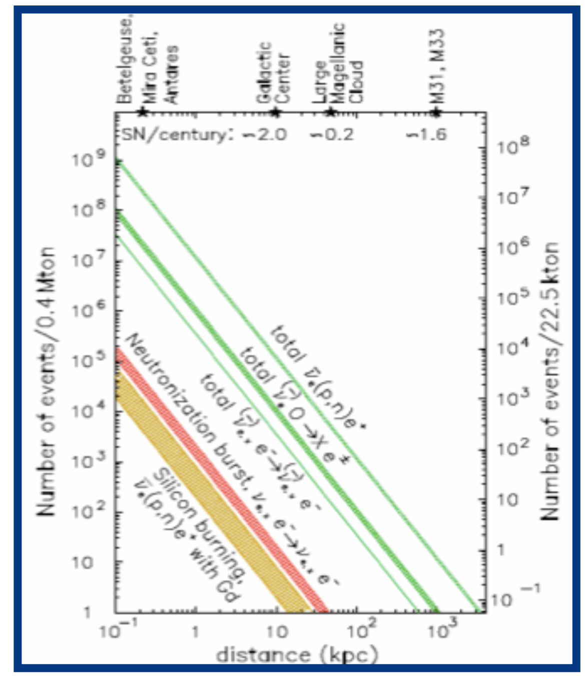


**Galactic SN**: Huge statistics

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




Fogli et al., hep-ph/0412046



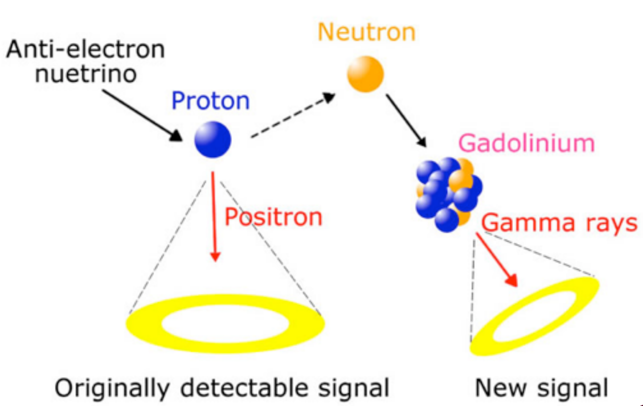

For a galactic Supernova @ 10 kpc:

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

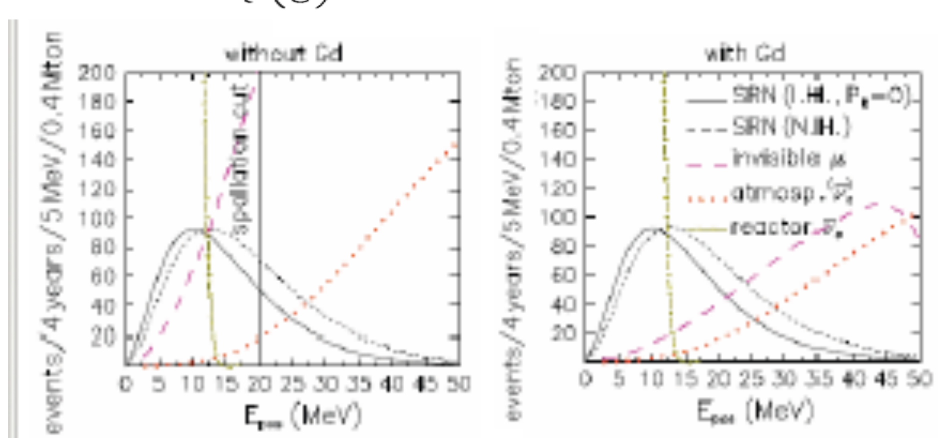
ES: ~ $1.2 \times 10^3$ e

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

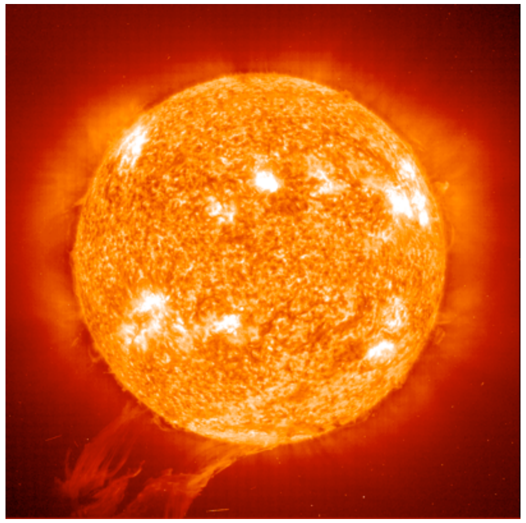
# MEMPHYS non-accelerator Physics

Reactor Neutrinos

1 MEMPHYS tank with Gd 250 kt fiducial @ Fréjus:

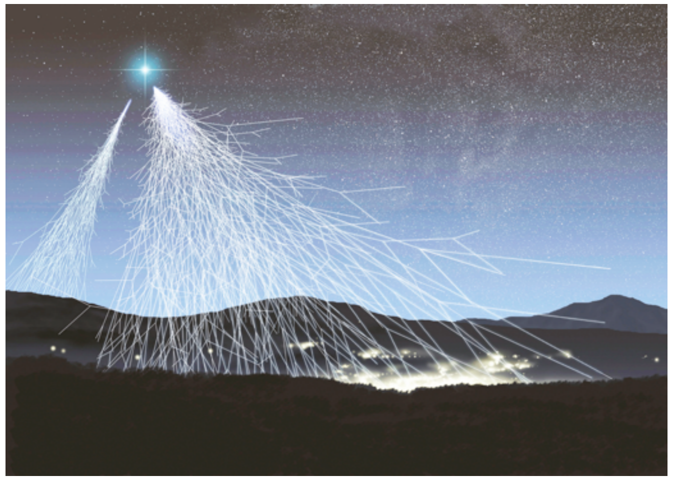
~ $2.7 \times 10^4$ per year

Solar Neutrinos



ES $\nu_{8B}$ ~ $1.3 \times 10^6$ per year

Atmospheric Neutrinos



~ $4.8 \times 10^4$ per year

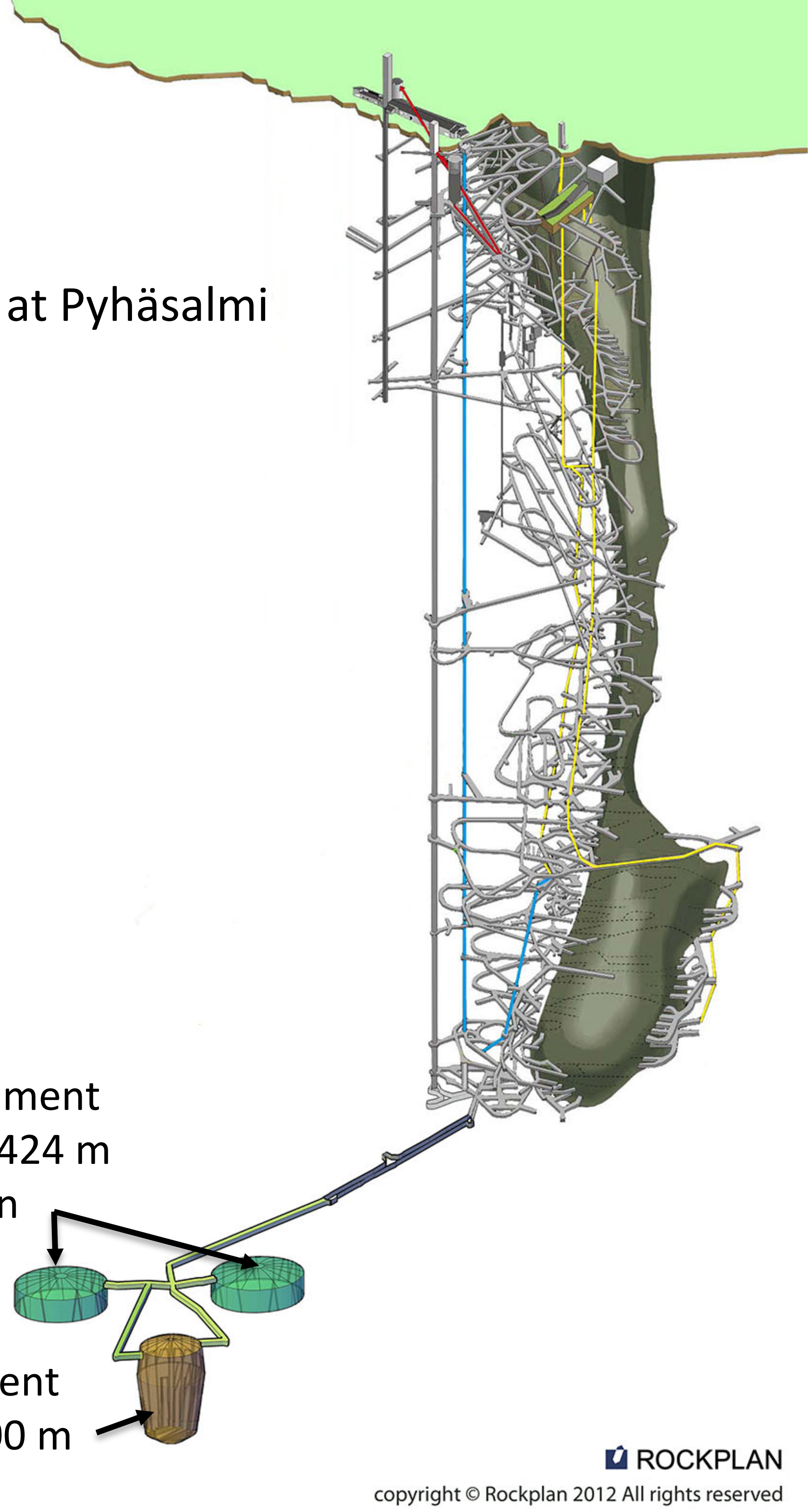
# Water Cherenkov is a well known technology

## 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
- Need a new accelerator - Super Beam (4MW)
- Need at least 1 cylinder with 250 kt fid. mass
- Need €€€€

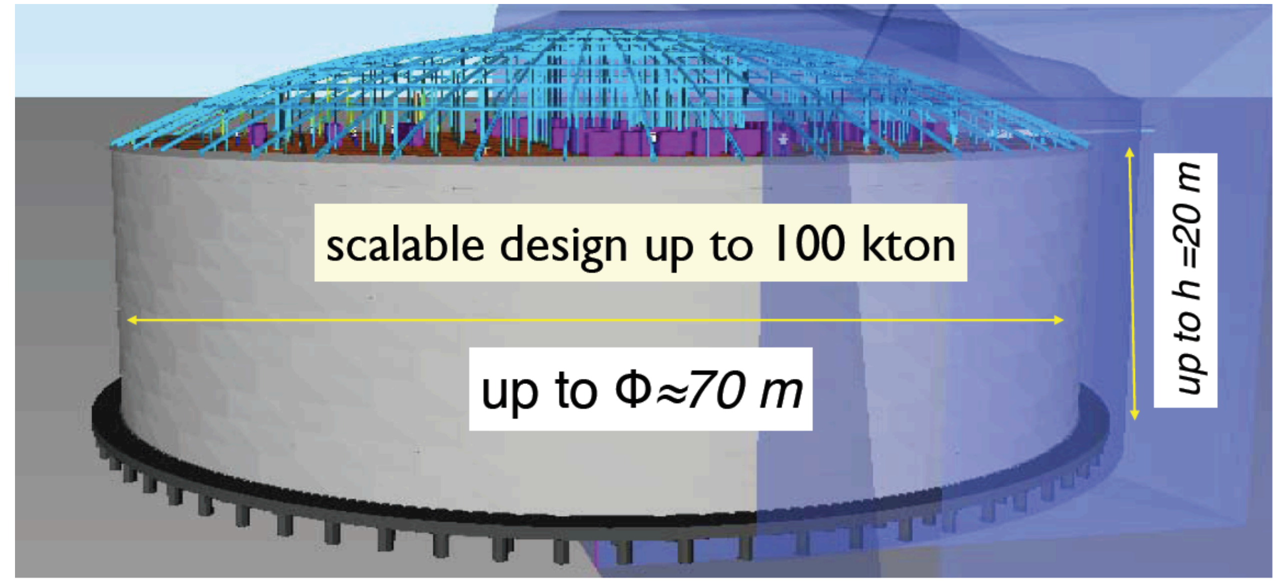
- The LAGUNA-LBNO collaboration decided to put this option in 2nd priority
- The costs, possible implementation and physics potential will be fully studied within the LAGUNA-LBNO program until 2014

LAGUNA at Pyhäsalmi
Finland

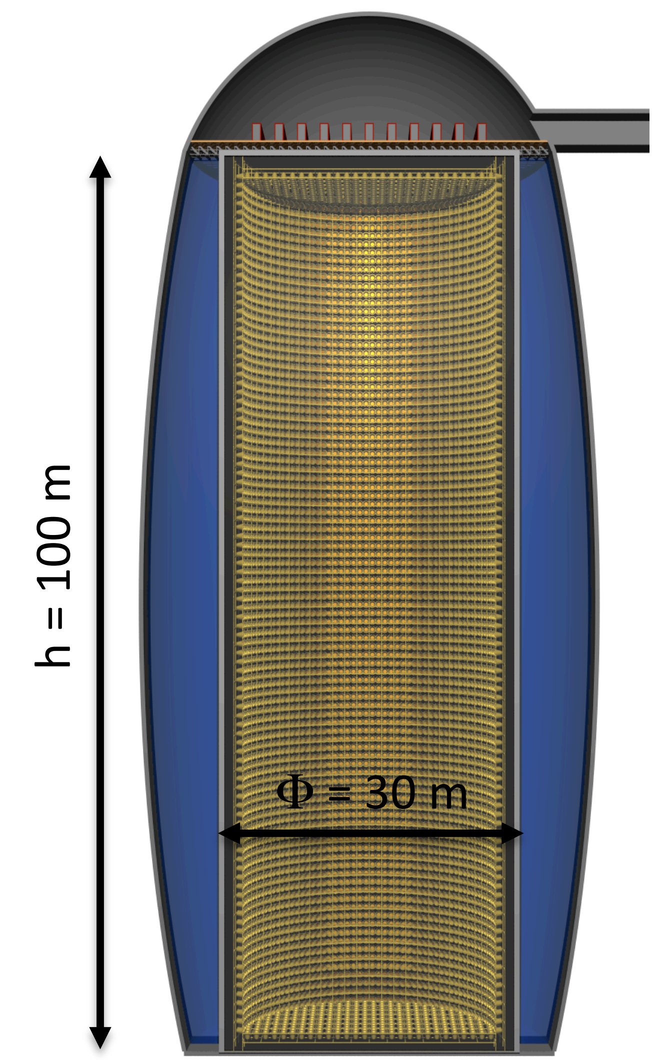



LAr experiment
Depth = 1424 m
2 x 50 kton

LSc experiment
Depth = 1500 m
50 kton

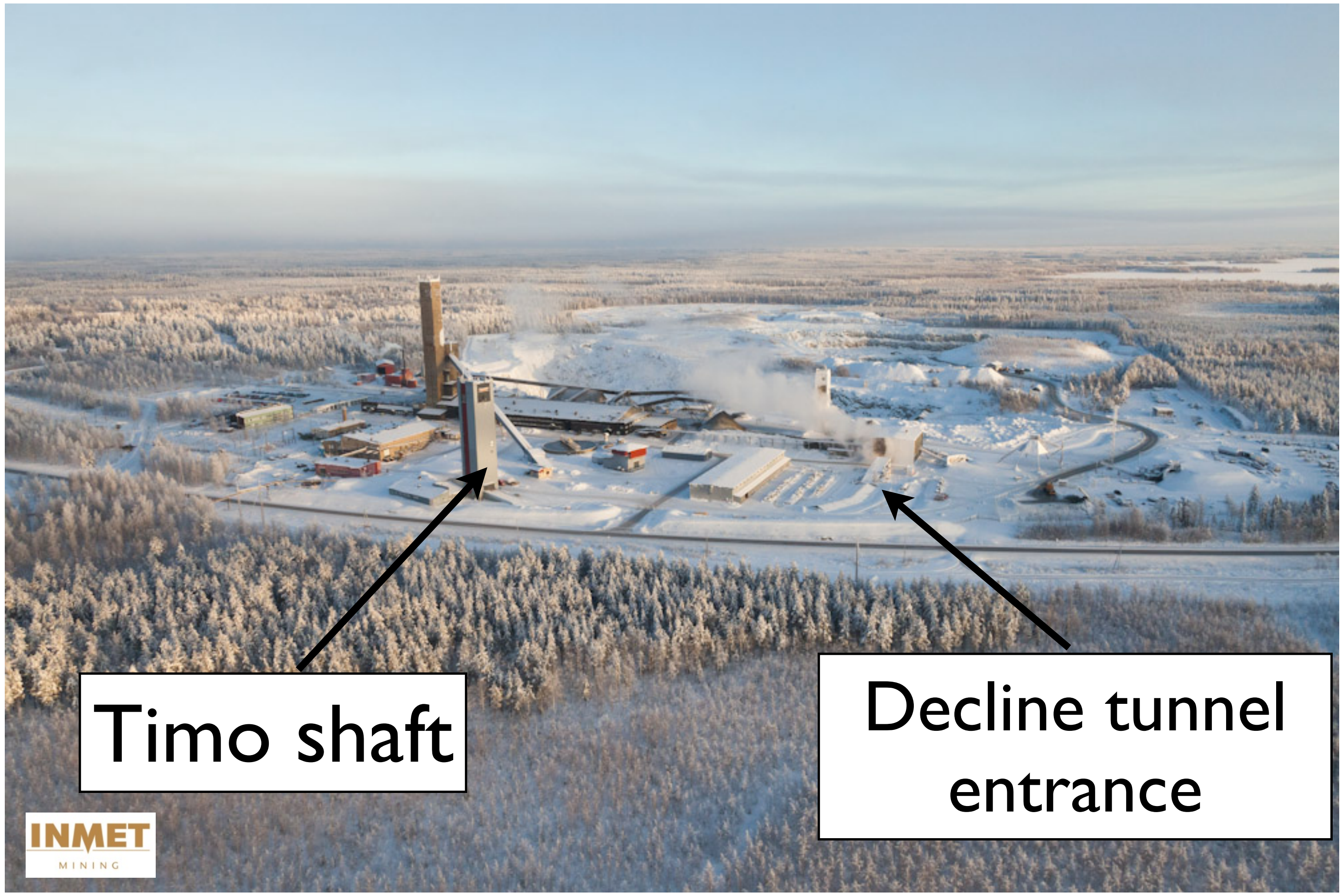



GLACIER



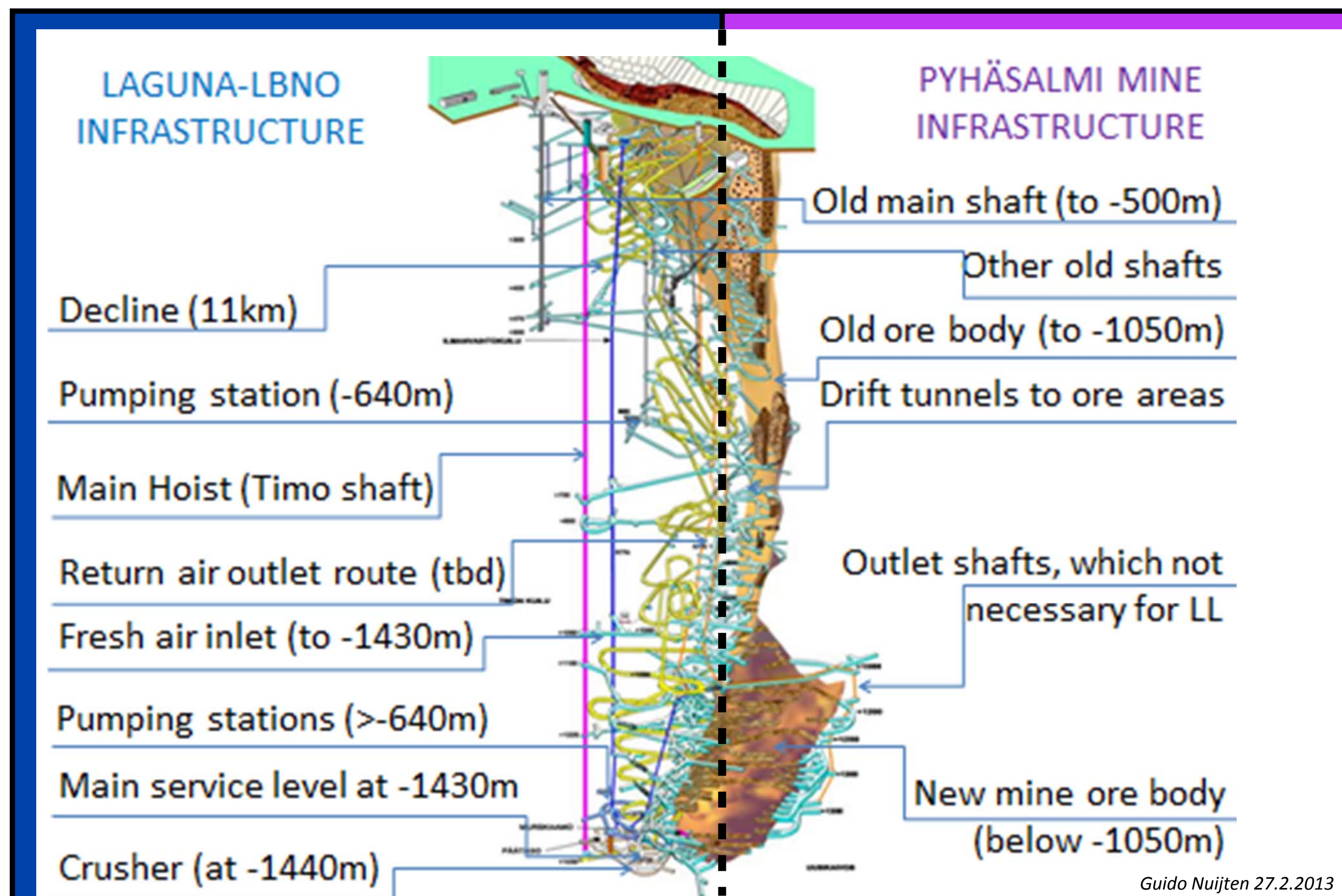

LENA

# (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.
  - 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

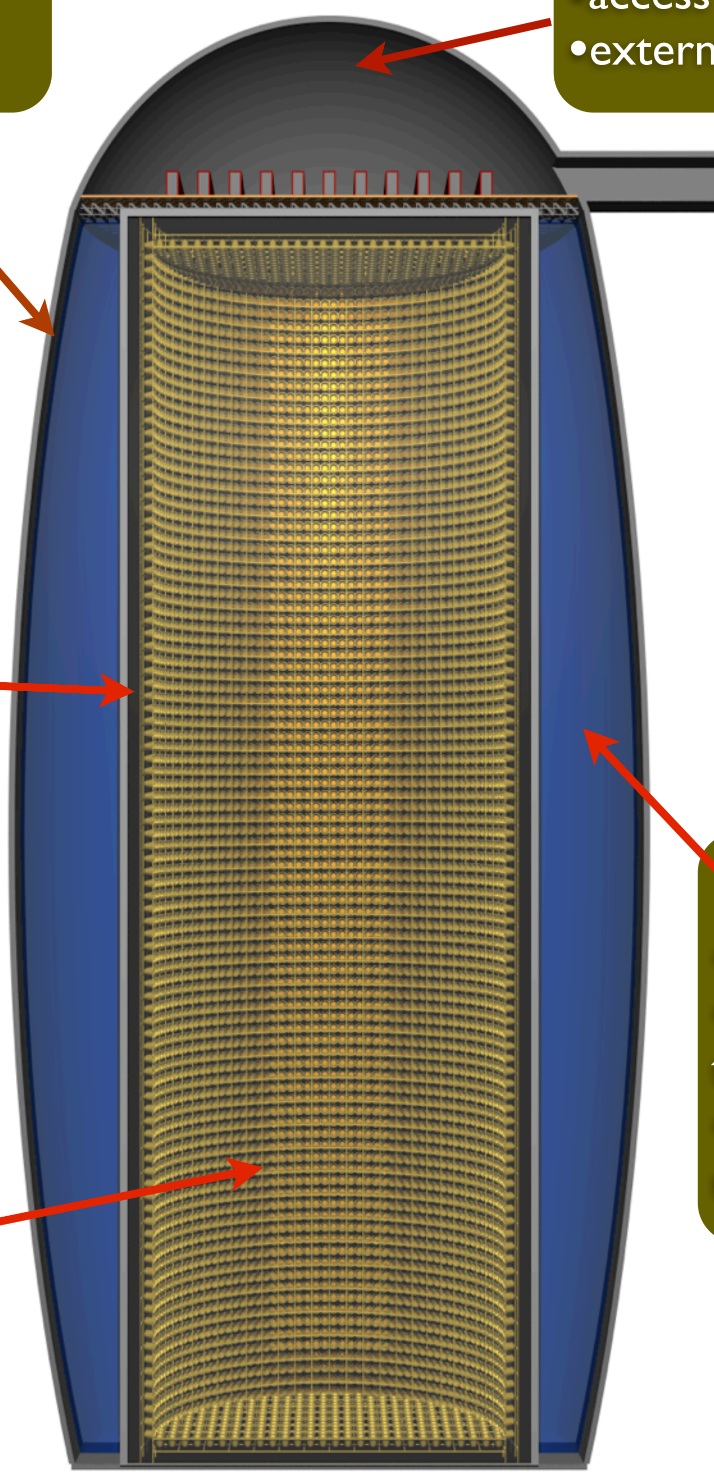

Cafeteria, meeting room and sauna at 1400 m below ground


Mobile phones work and internet available also at 1400 m

# LENA:

<u>Egg shaped cavern</u>
- Height = 120 m
- Ø ≃ 36 m

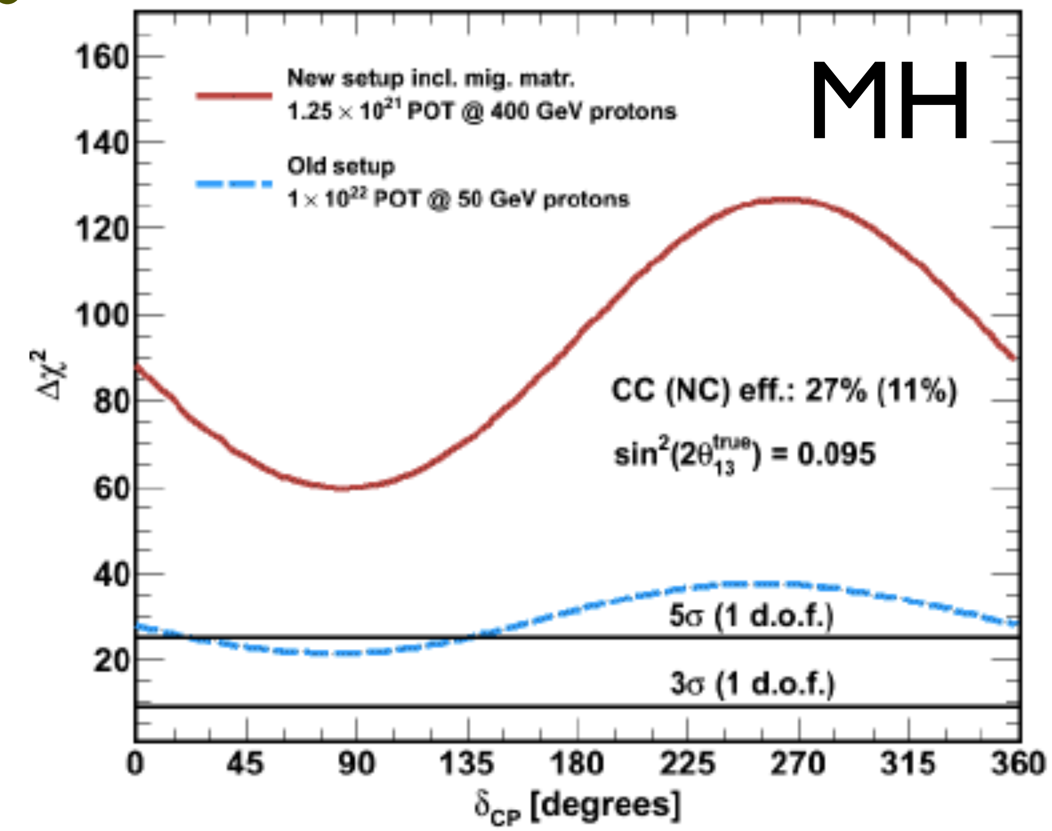
<u>Top Cavern</u>
- access to top deck
- external muon veto

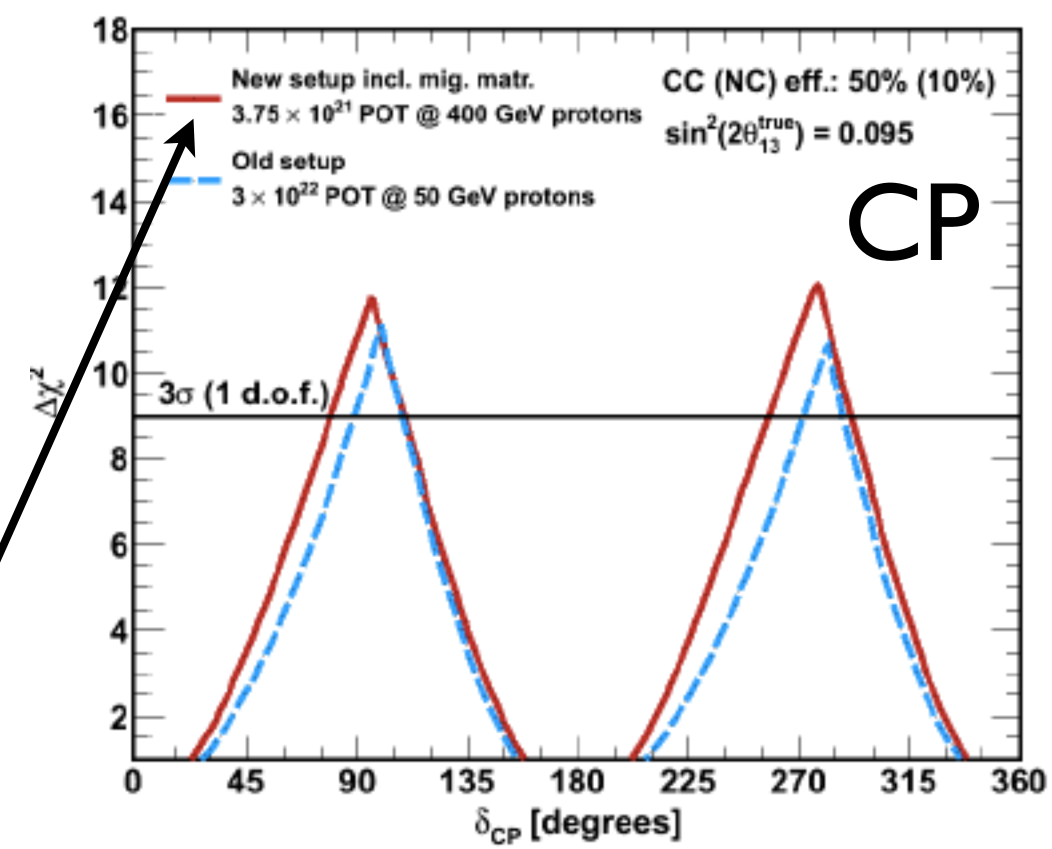


<u>Detector Tank</u>
- concrete wall cylinder
- Height = 100 m
- Ø = 30 m
- ≃ 32000 12”

<u>Water-filled cavern</u>
- ~ 2000 12” PMT
- veto for inclined muon tracks
- shielding for fast neutrons

<u>Target</u>
50 kt scintillator




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

# Strategy

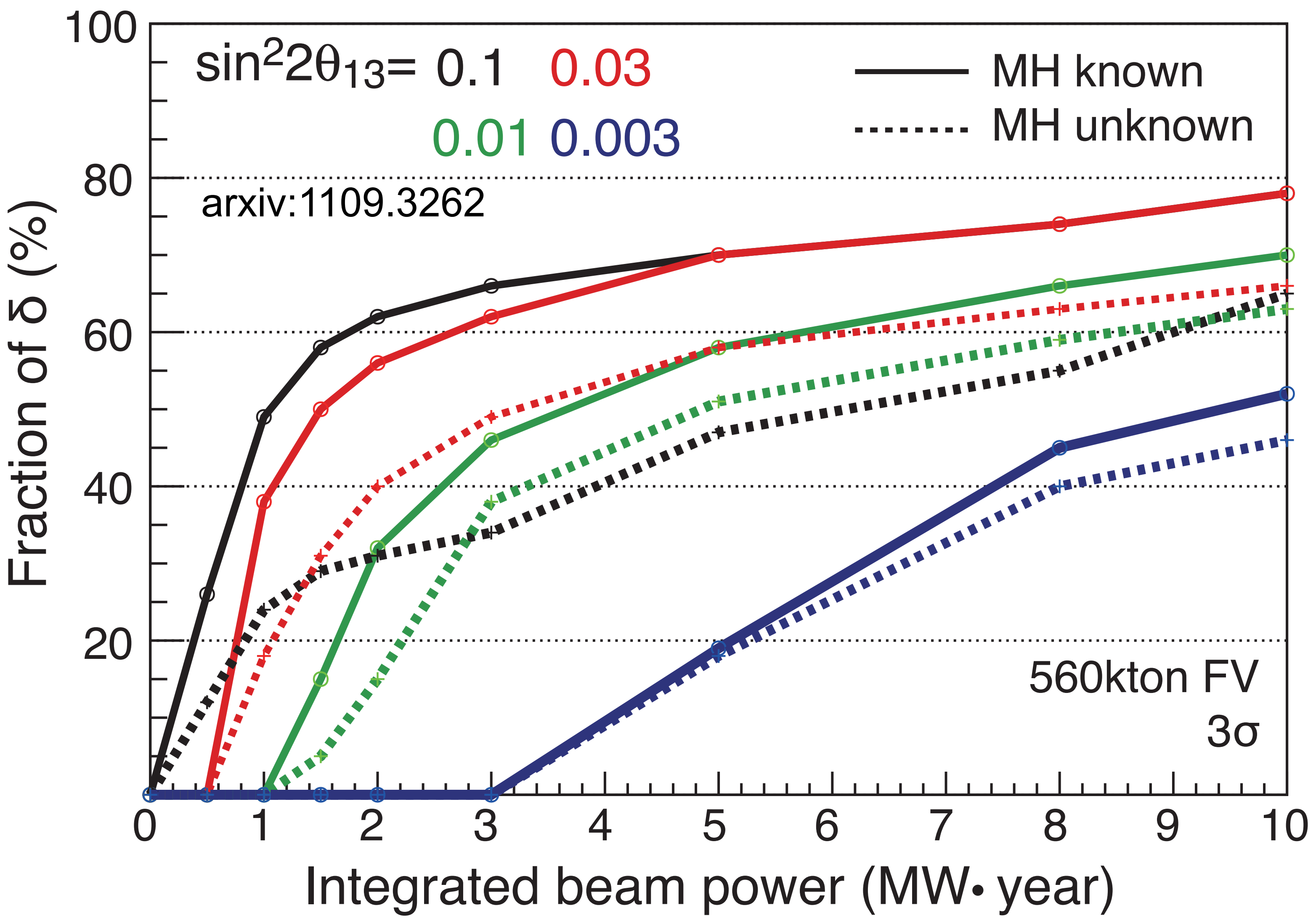
- Based on the findings from LAGUNA and LAGUNA-LBNO the collaboration decided to put forward a concrete proposal for the future neutrino observatory in 2012, EoI 007 to CERN.
- We have compared 7 locations in Europe and conducted precise estimations on the costs of the facility, of the detector and of the beam.
- We compared the physics potential of all possible combinations - detector - location - beam.
- **The conclusion is to propose a neutrino observatory with a clear long-term strategy in a deep underground location at the longest baseline proposed, 2300 km, compatible with:**
  - a full astro-particle program and
  - an incremental long-baseline program with a competitive 1st stage 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.

# Strategy (2)

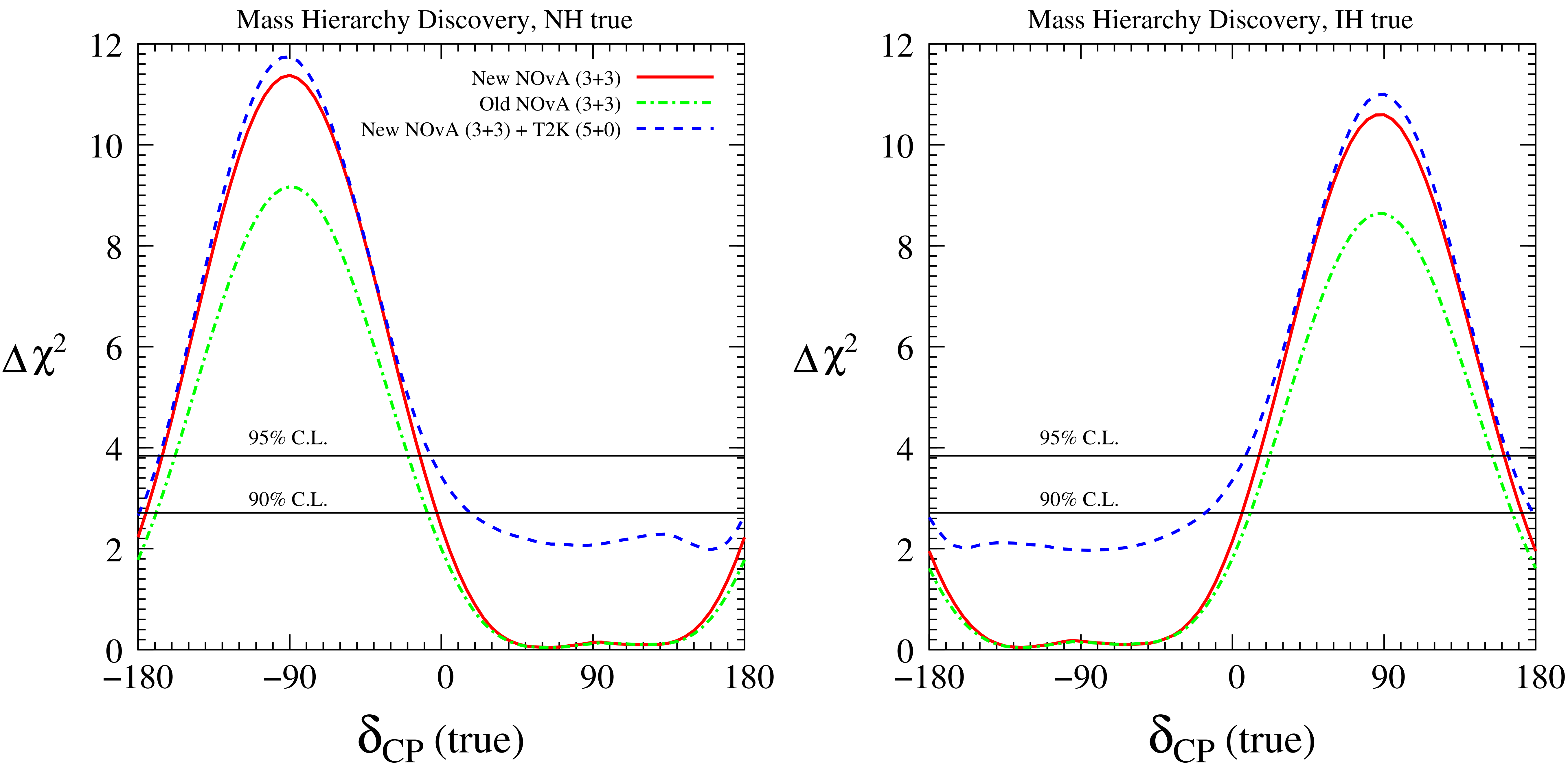
## Determination of the mass hierarchy is indispensable to perform CPV searches, e.g. HK:

- 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.



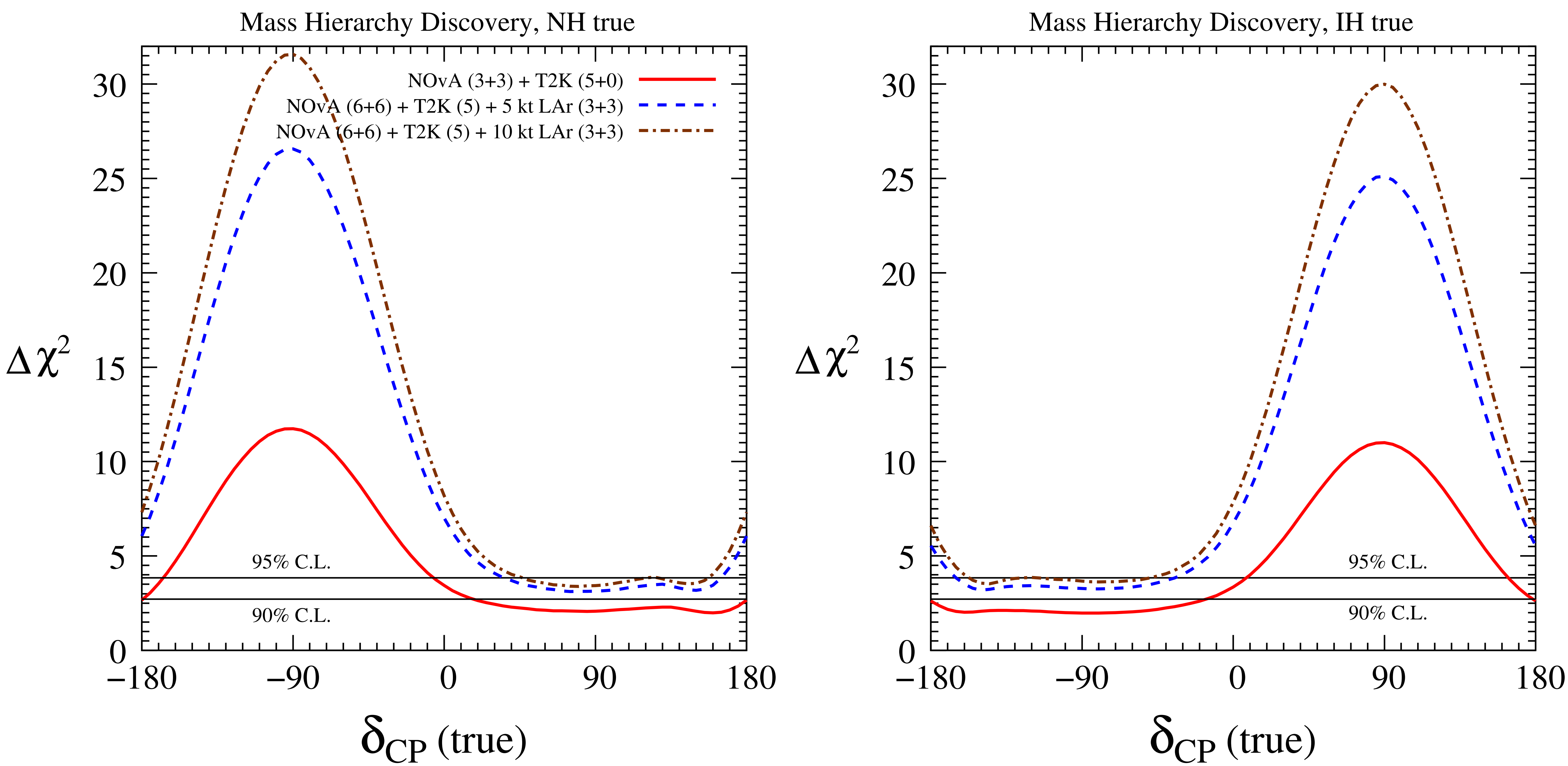
# What can we learn from T2K and NOVA ?




**Agarwalla *et al.*, arXiv: 1208.3644**

# Can only cover ≈ half of the phase space at 3δ

# Add a TPC on the surface at Ash River...

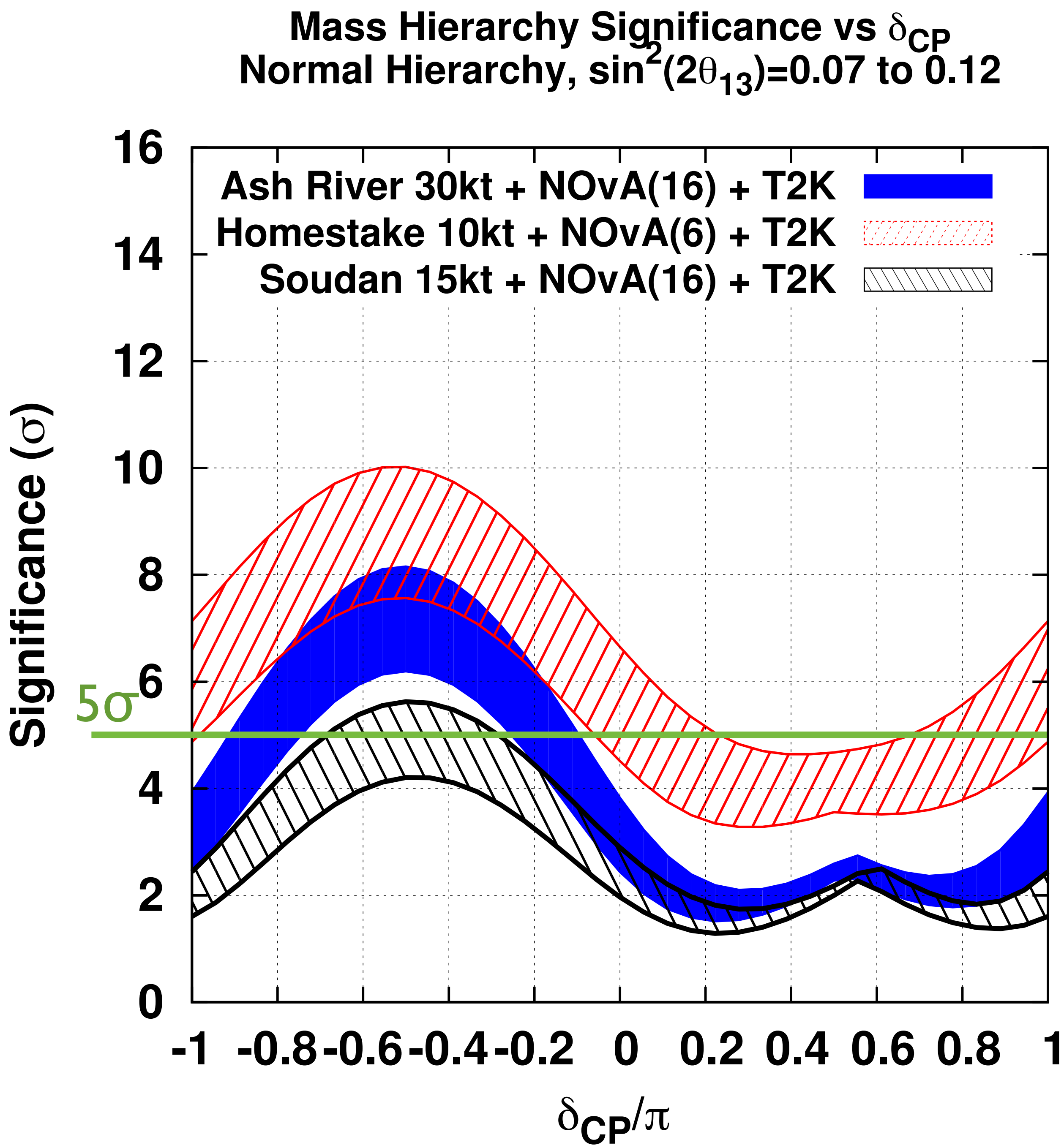


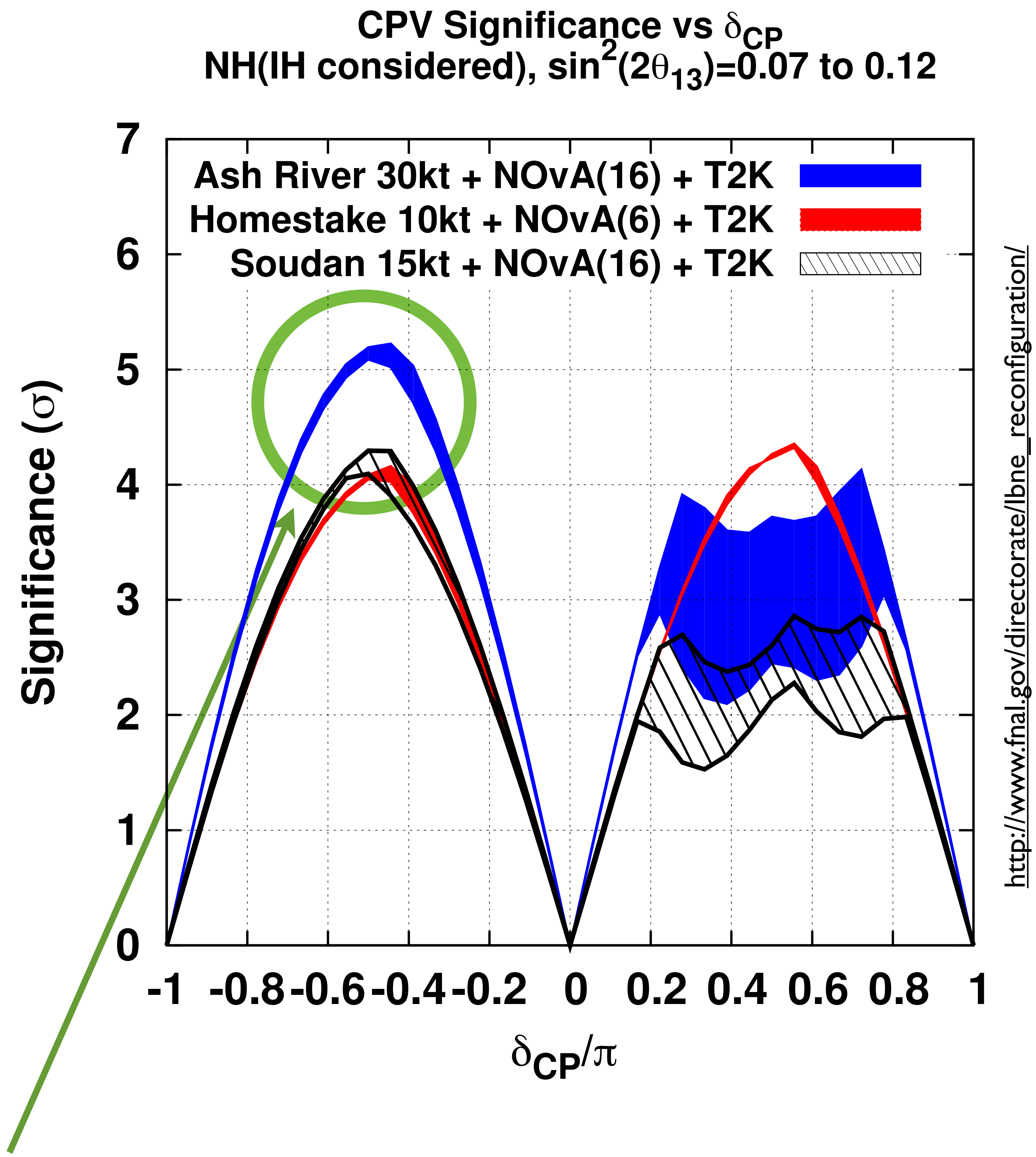

**Agarwalla *et al.*, arXiv: 1208.3644**

**Still only half the phase space!**

# Need long base line > 1000 km to measure MH

## LBNE: 10 years @ 700kW




Be aware: Ash River has the best CPV sensitivity when MH is determined ! The displayed sensitivities come mostly from parameter fitting around 1st maximum

# 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 ascertaining their L/E dependence.

# Towards a real experiment: SPSC-EoI-007: «Expression of Interest for a very long baseline neutrino oscillation experiment (LBNO)»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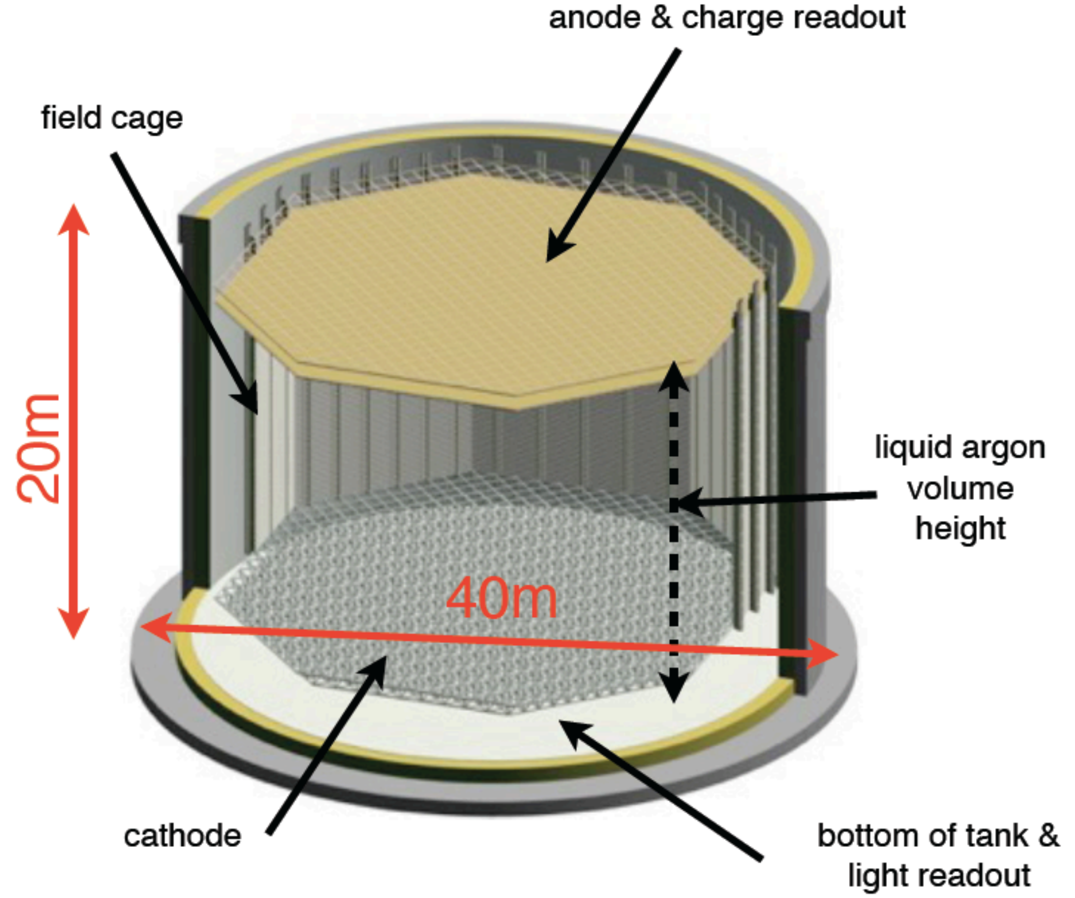
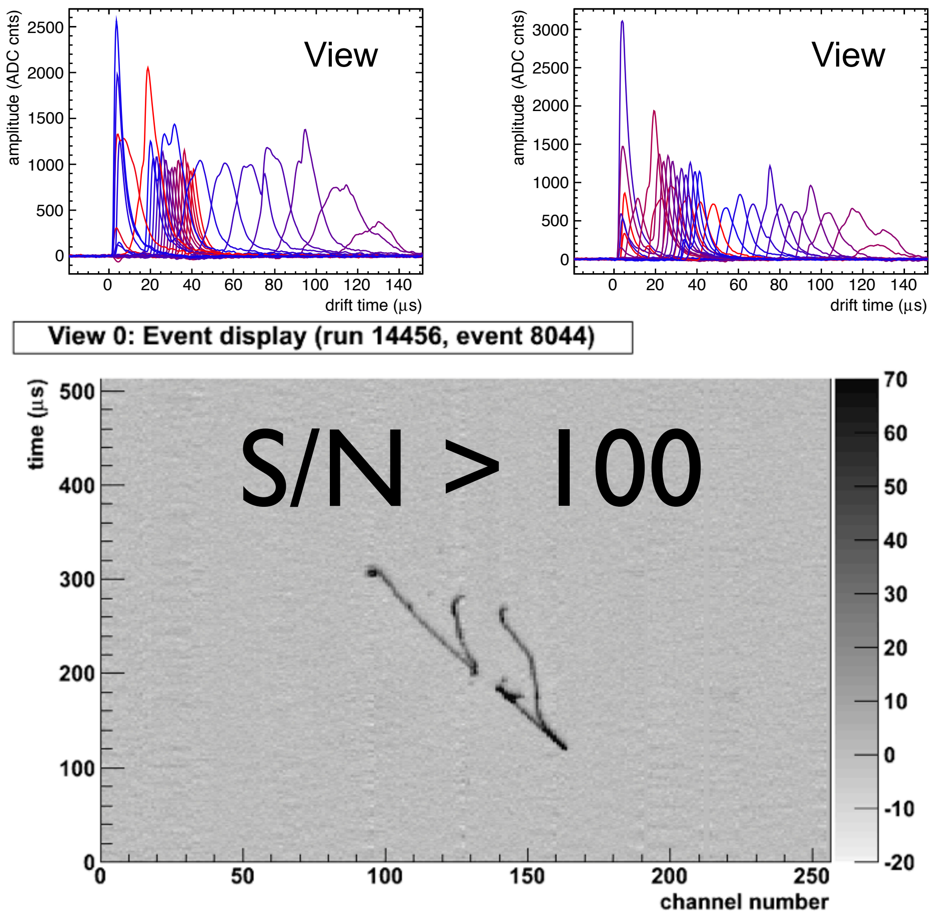
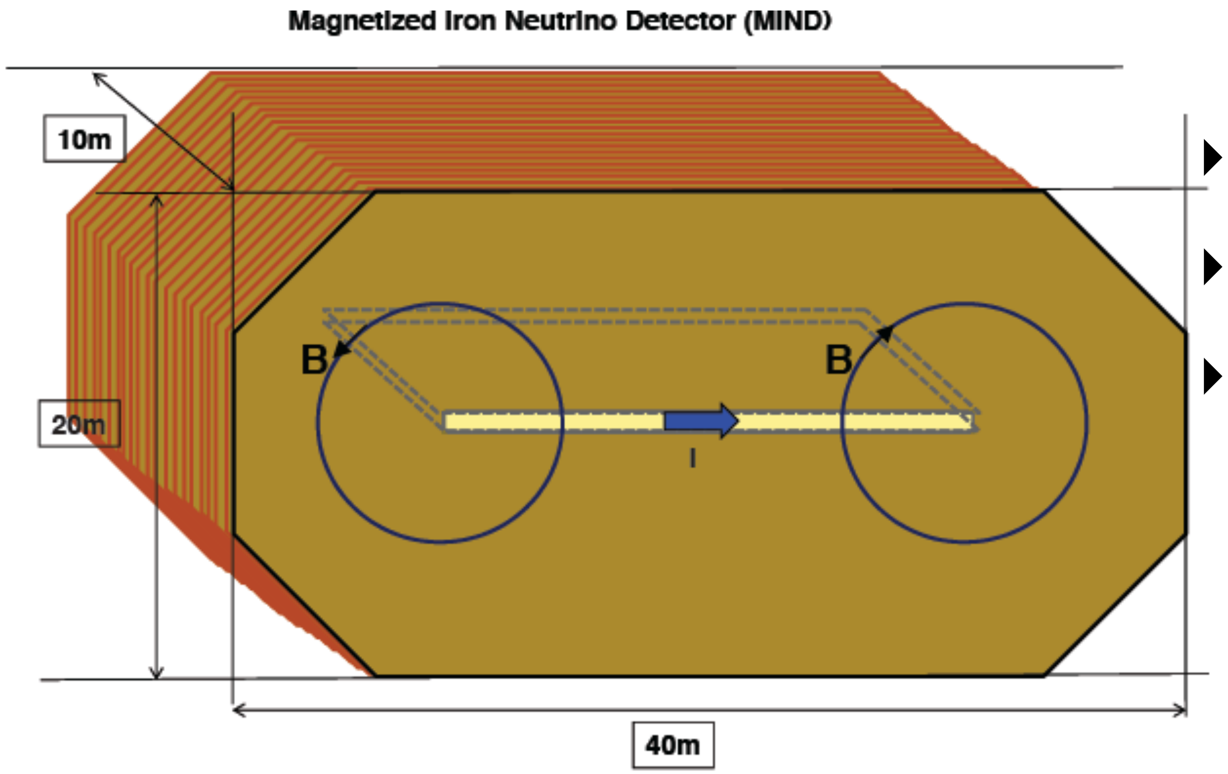
# Stage I: 20 kt LAr with 700 kW SPS



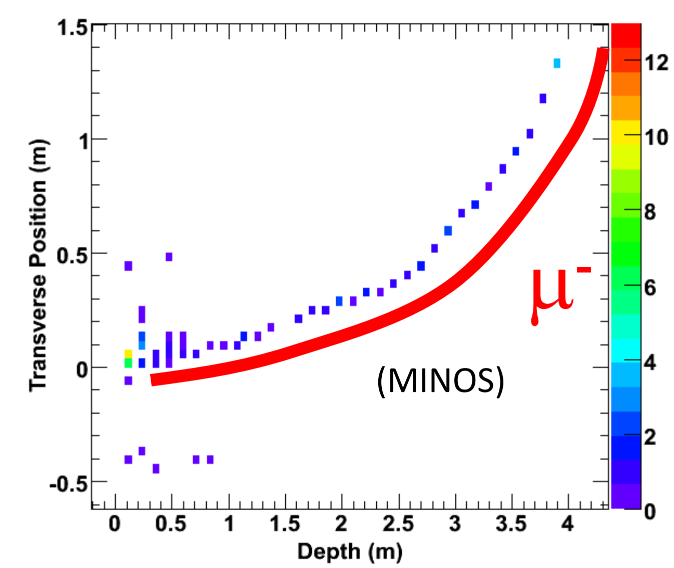




# 35kton MIND magnetised iron with scintillator slabs (MINOS-like)

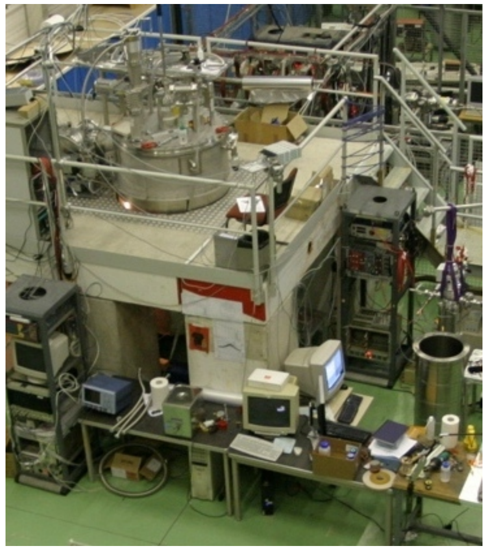



- 3cm Fe plates,
- 1cm scintillator bars,
- B=1.5-2.5 T

## $\nu_\mu$ Charged Current



# LAr detector prototyping efforts

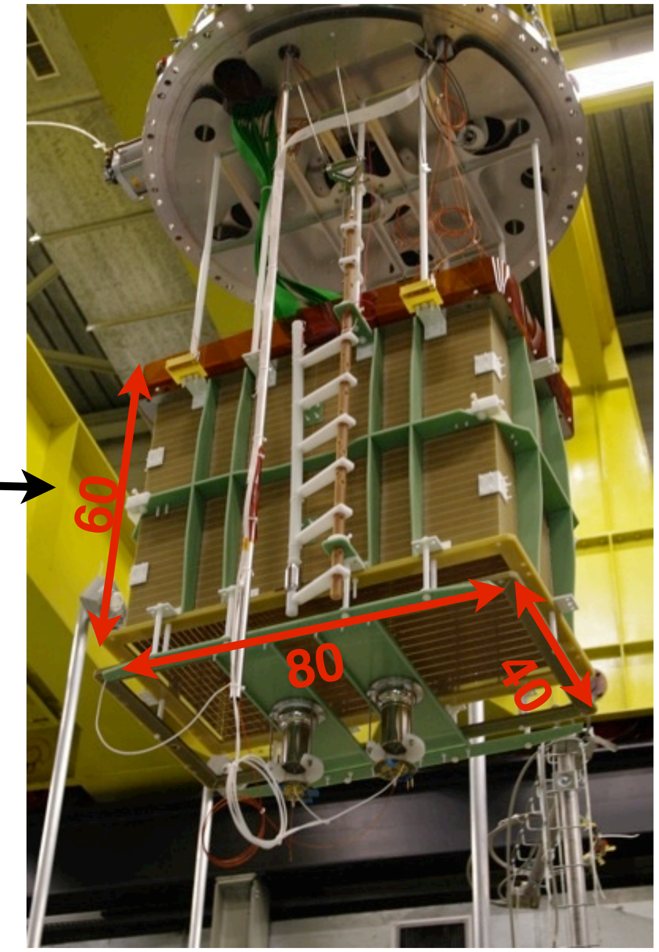


(1) ArDM-1t @ CERN

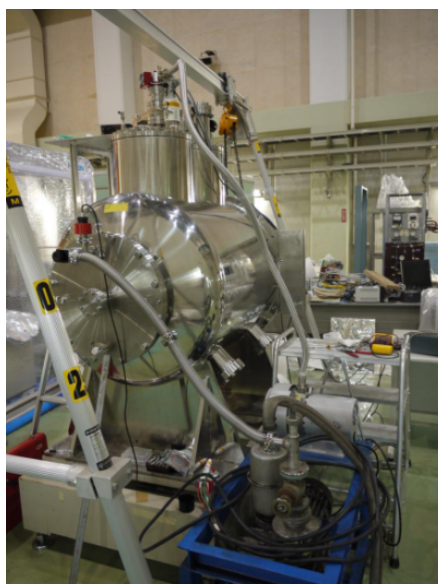
**J.Phys.Conf.Ser. 39 (2006) 129-132**

World's first double phase liquid argon
LEM-TPC successfully operated

40x80cm2
**JINST 7 (2012) P08026**




Courtesy A. Rubbia



(2) J-PARC T32 J-PARC

**J.Phys.Conf.Ser. 308 (2011) 012008**

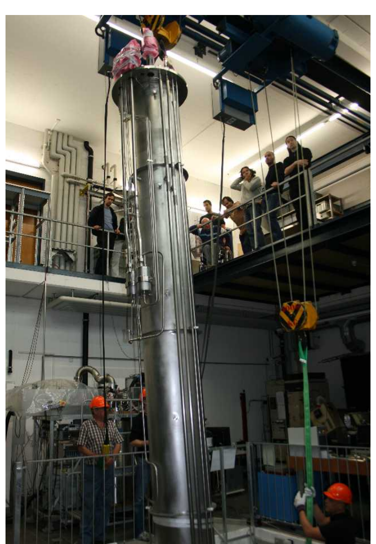
0.4 ton LAr TPC

World's largest sample of charged particles
events ever collected

(4) 10T @ CERN

**J.Phys.Conf.Ser. 308 (2011) 012024**

Purity by flushing w/o evacuation



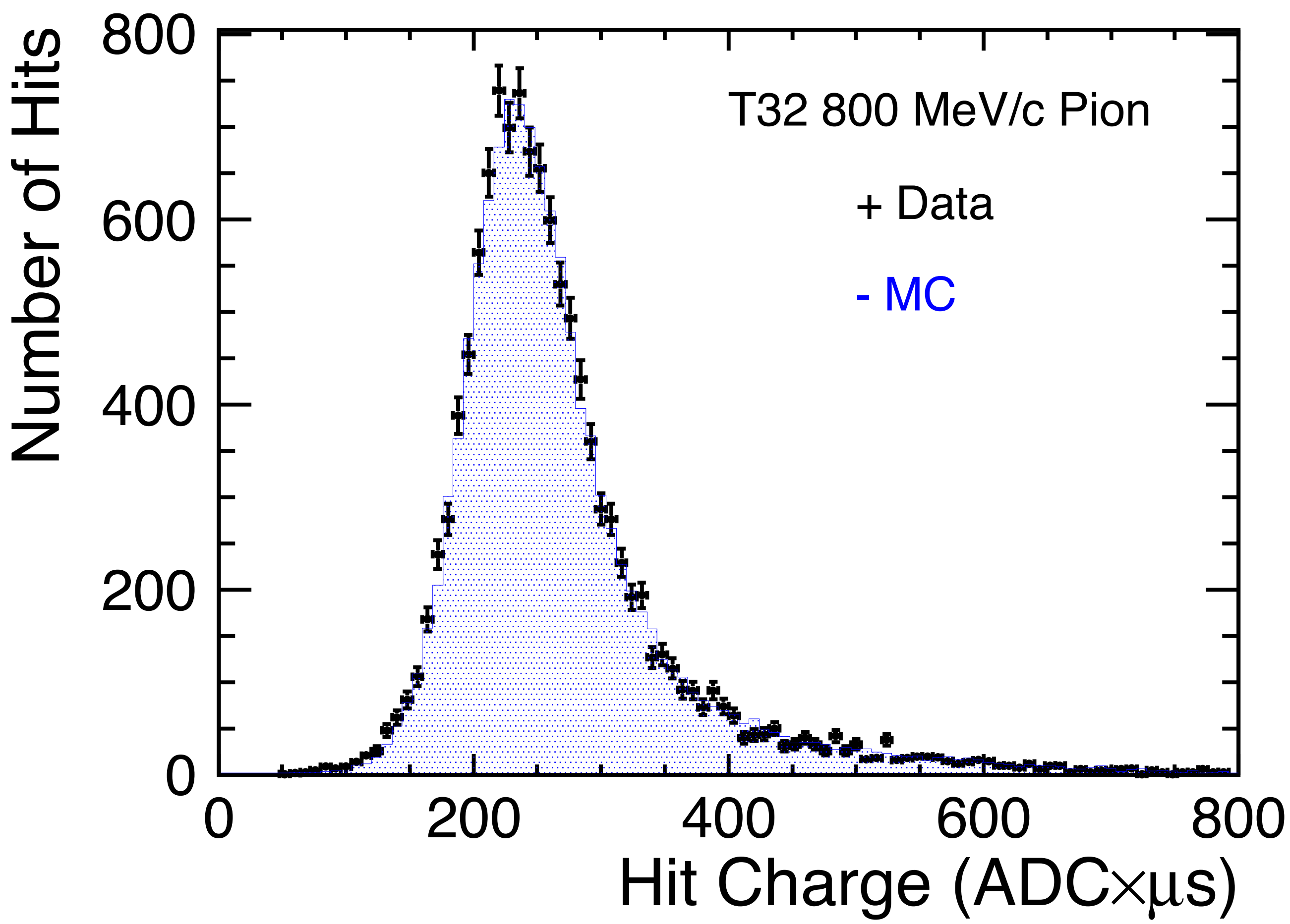
(3) ArgonTube @ Bern

**Nucl.Phys.Proc.Suppl. 139 (2005) 301-310**

Aim to demonstrate world's longest
electron drift path

# LAr R&D: Tracking performance

JPARC T32 exposed to K1.1BR tagged beam




J.Phys.Conf.Ser. 308 (2011) 012008

## Data well described by:

**Birks Law**

$$Q = A \frac{Q_0}{1+(k/\varepsilon)\times(dE/dx)\times(1/\rho)}$$

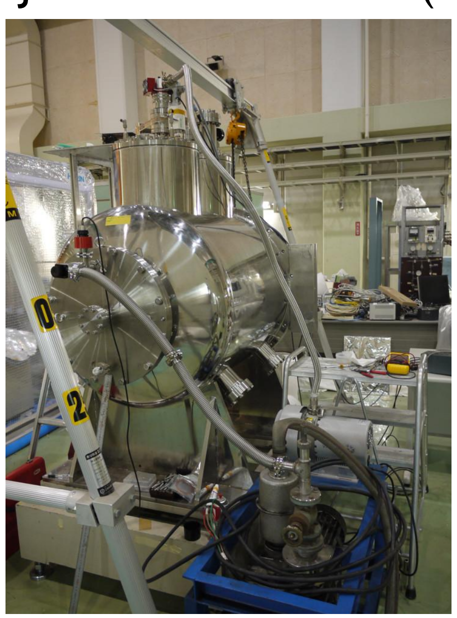
Raw charge ($Q_0$); Observable charge ($Q$)

$$A = 0.8$$

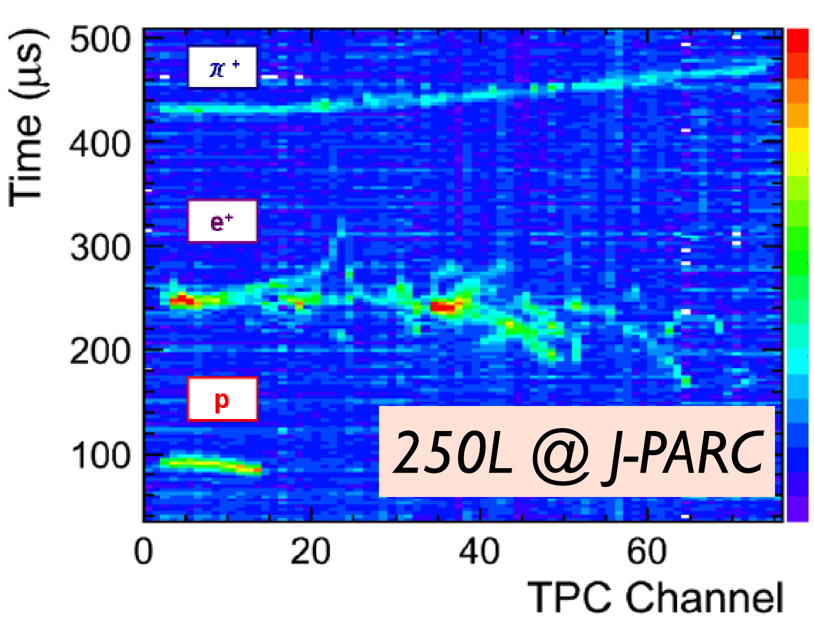
$$k = 0.0486\ \mathrm{kV/cm}\,\frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

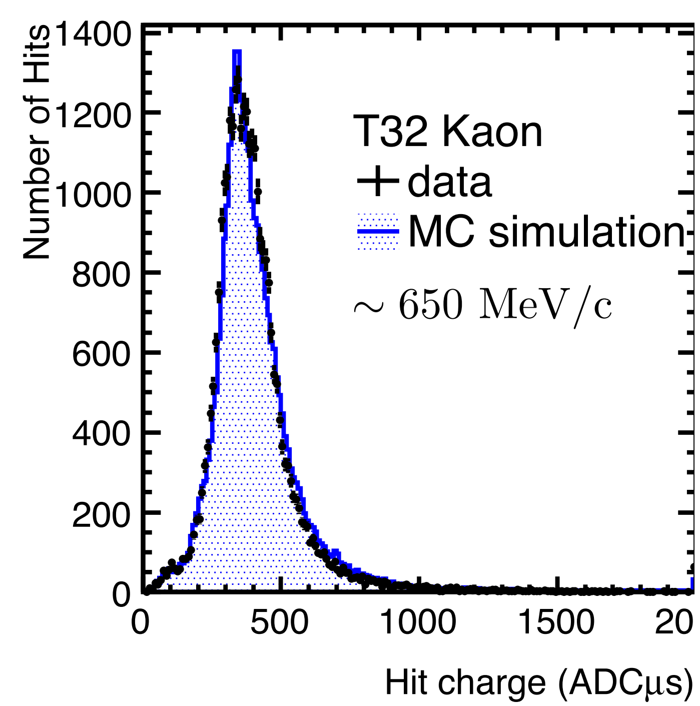
NIM A 523, 275 (2004)

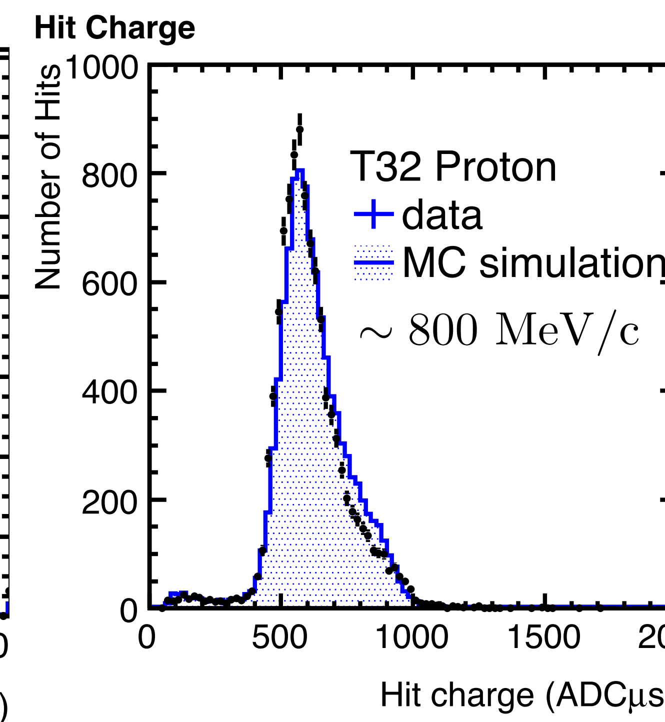
J-PARC T32 chamber (ETHZ-KEK-Iwate-Waseda)



Courtesy T. Maruyama



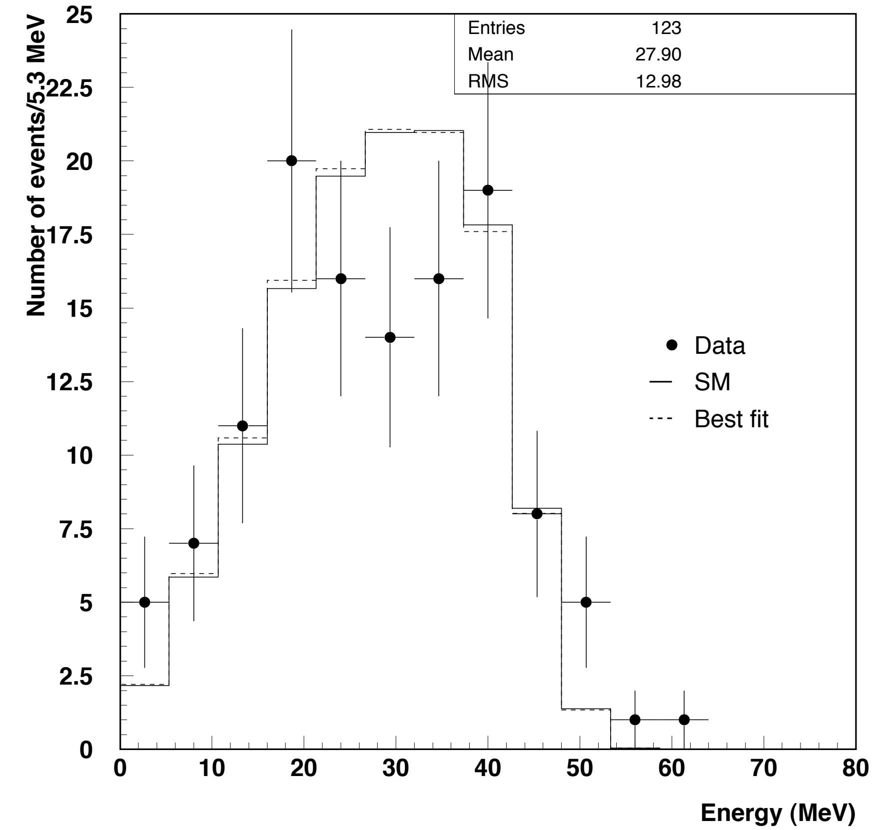

Courtesy A. Rubbia

## Good understand of tracking

# LAr R&D: Calorimetric performance

Michel electrons form stopping muon decay sample

$$\frac{\sigma_e}{E} \simeq \frac{11\%}{\sqrt{E(\mathrm{MeV})}} \oplus 4\%$$




Eur. Phys. J. C33, 233 (2004)

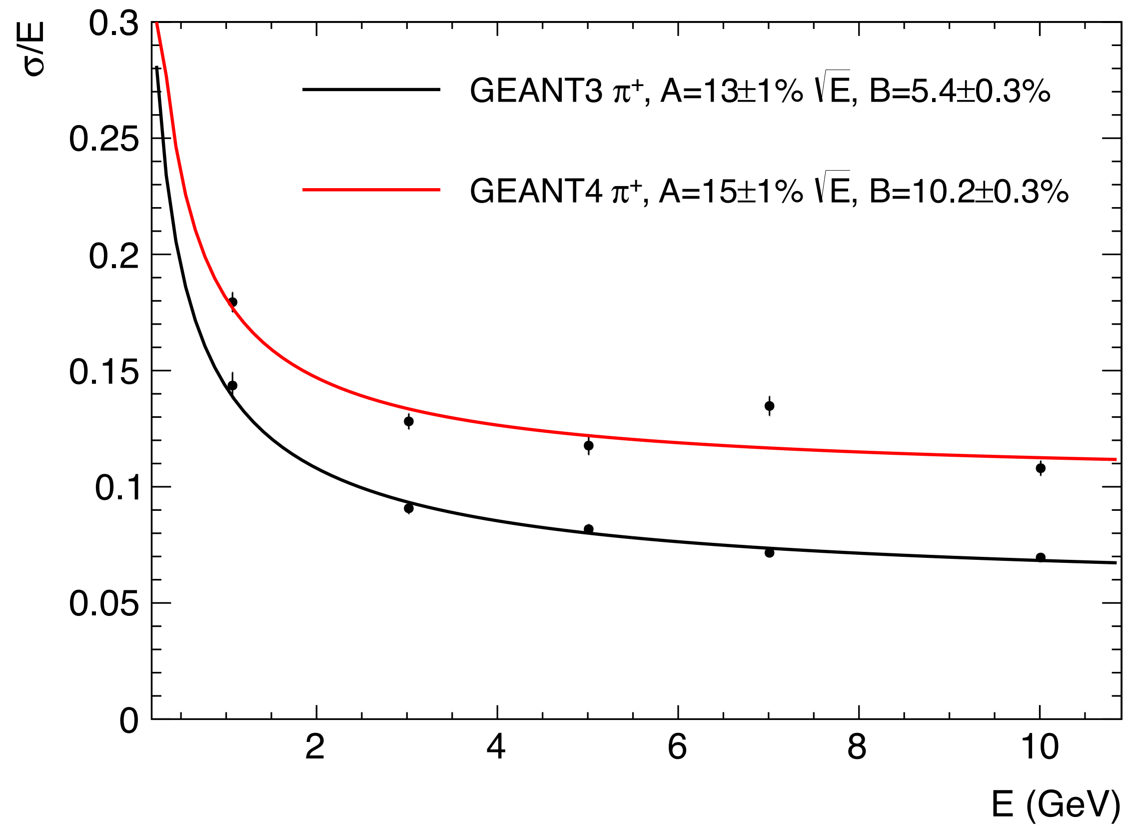
MC simulations at higher energies:

$$\frac{\sigma_{em}^{MC}}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus 1\%$$

$$\frac{\sigma_{had}^{MC}}{E} \simeq \frac{15\%}{\sqrt{E}} \oplus 10\%$$

↑ needs to be confirmed by experimental data

G3 and G4 comparison

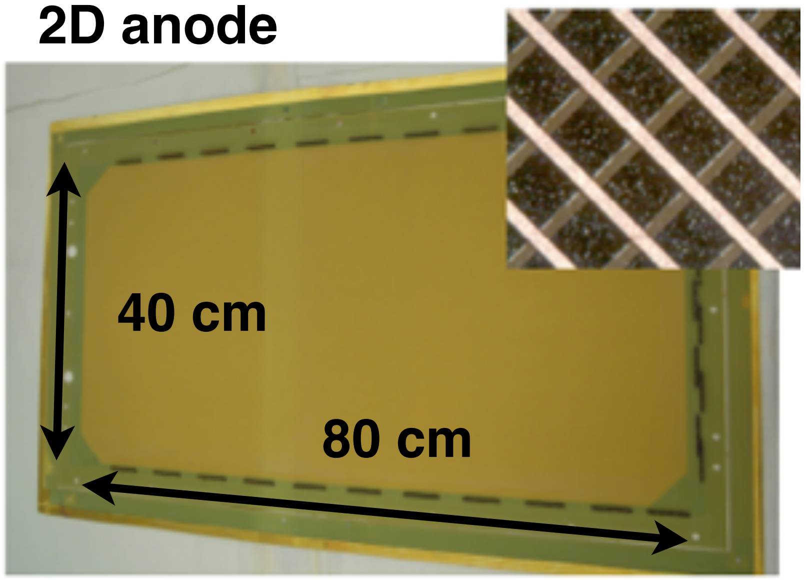



Courtesy A. Rubbia

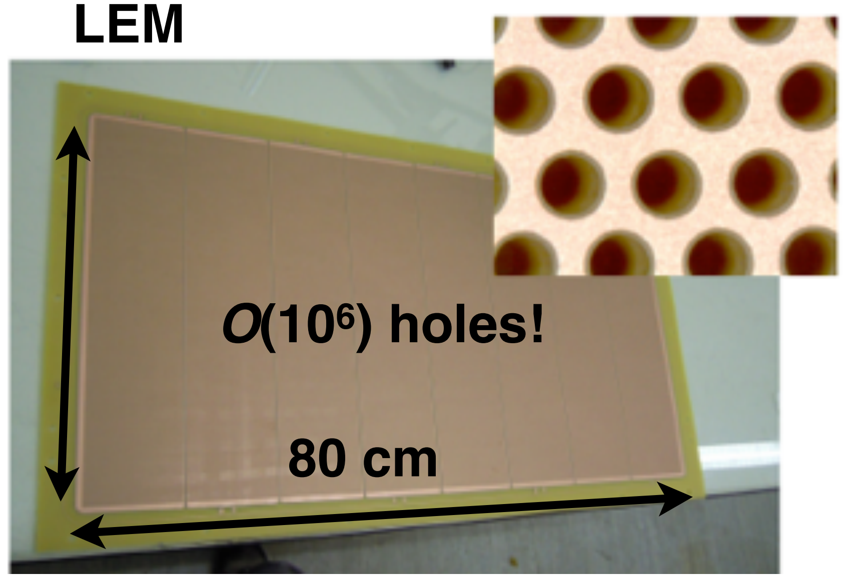
# LAr-LEM TPC@CERN: Production of a 40x80 cm$^2$ charge readout sandwich

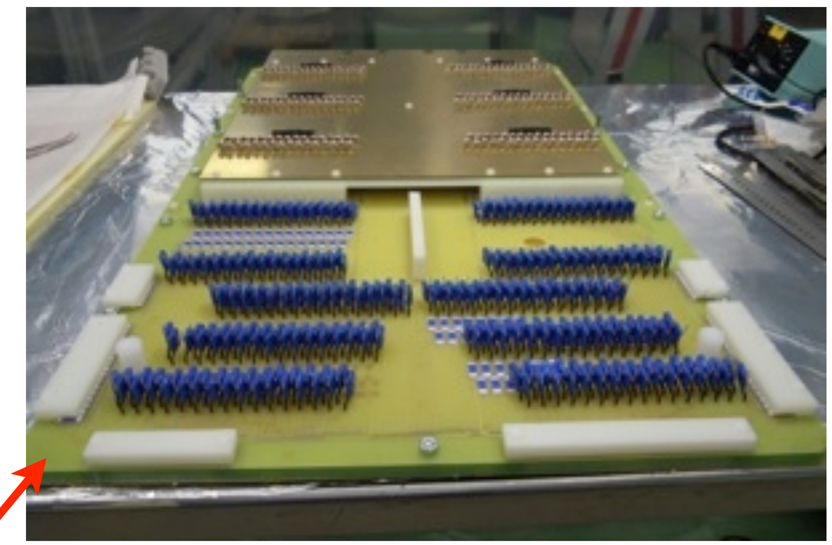
- After successful test of LEM and 2D anode in the 3L setup we designed and produced a 40x80 cm$^2$ charge readout for a new 250L LAr LEM-TPC (production and assembling finished by summer 2011)
- The ArDM cryostat @CERN was used for a first test of the new charge readout system

**2D anode**



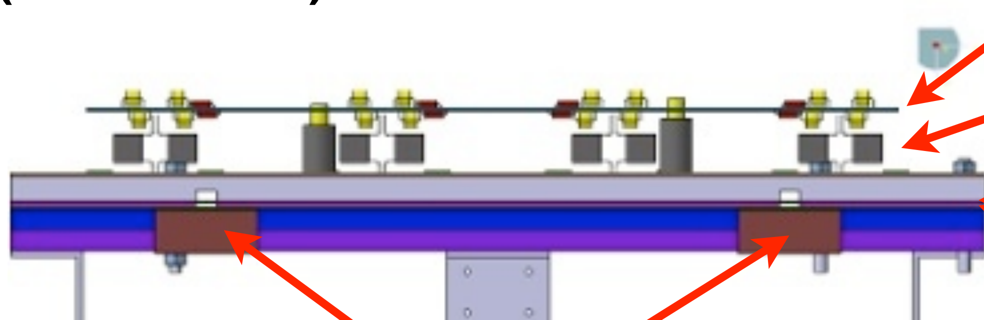

**LEM**



- Manufacturer: CERN TS/DEM group and ELTOS company (Italy)
- Largest LEM/THGEM and 2D readout ever produced!!!

**Design of a compact, robust and scalable readout cassette ("sandwich")**



signal coll. plane

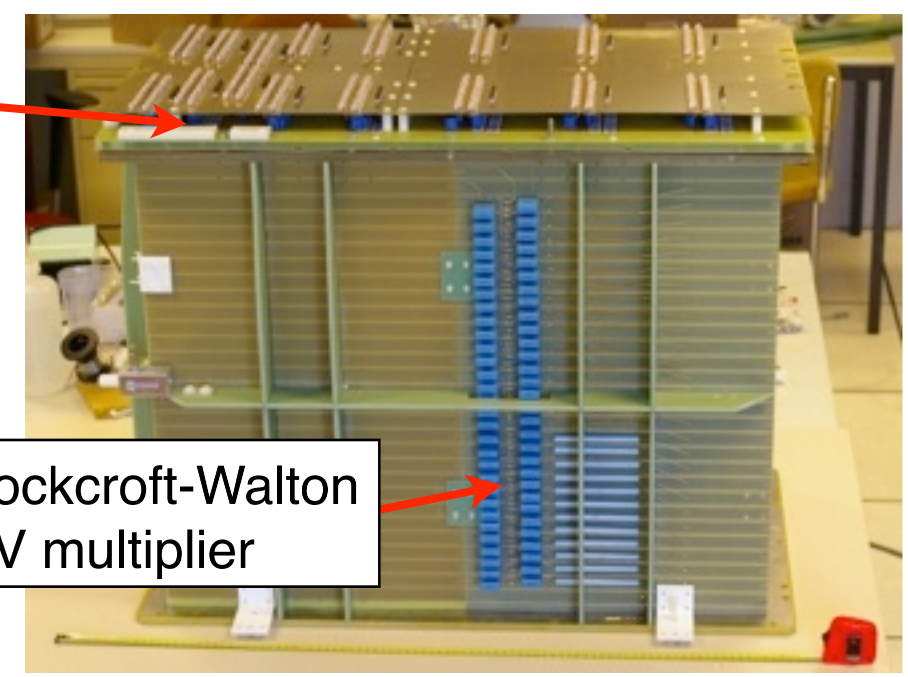
HV decoupling capacitors

2D anode

LEM

2 extr. grids

capacitive level meters



Cockcroft-Walton HV multiplier

Courtesy A. Rubbia

# MIND: Magnetized Iron Neutrino Detector

- Measurement of charge and momentum of muons coming from interactions in the LAr detector

- Independent physics program:
  - Precise measurement of the $\nu_\mu$ disappearance channel and atmospheric parameters
  - Search for sterile neutrinos by disappearance in the neutral current channel
  - Measurement of the tau appearance in the $\tau \rightarrow \mu$ channel

# The neutrino beam and upgrades

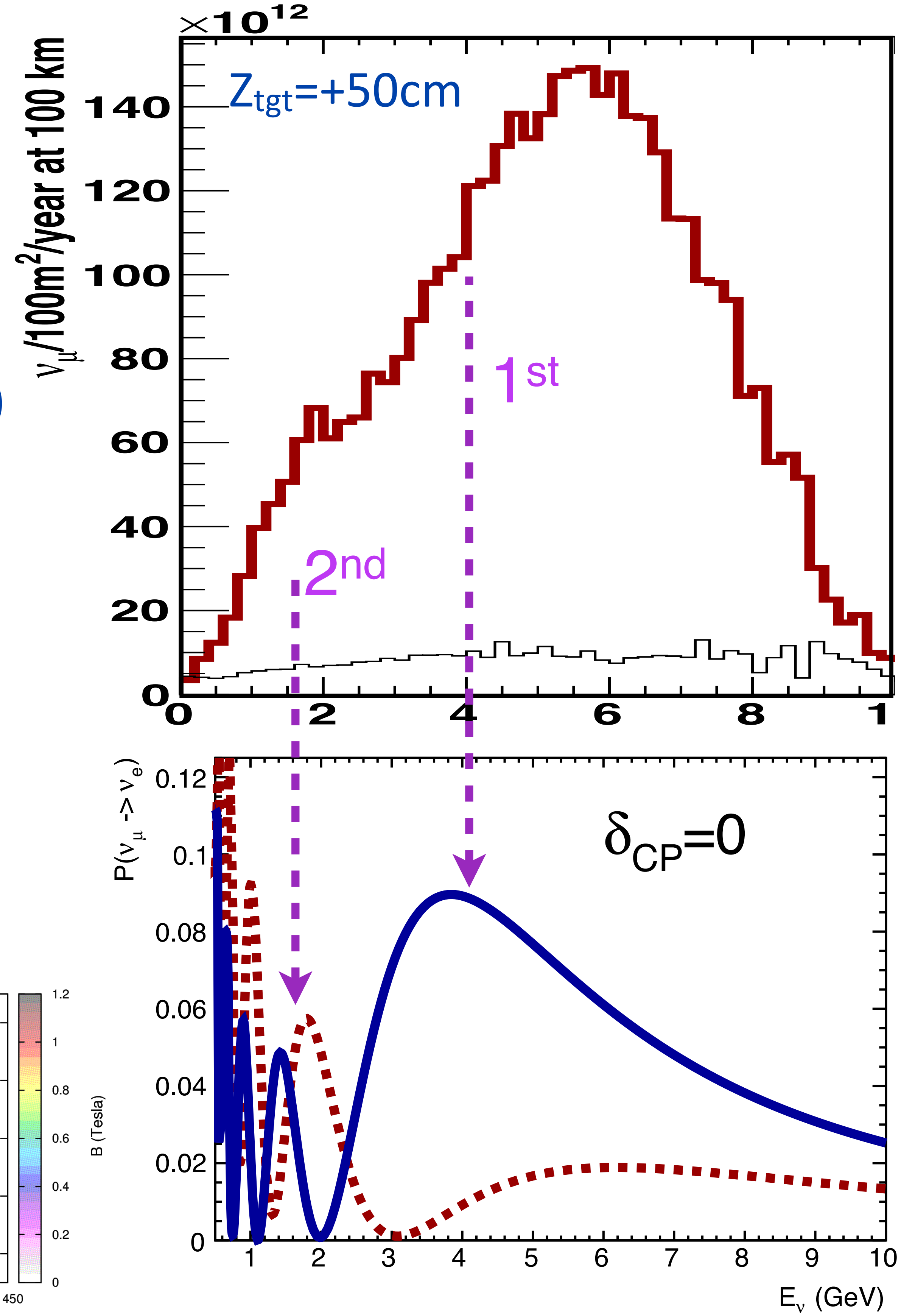
- **CN2PY horn focused neutrino beam towards Pyhäsalmi**
  - Starting point is SPS and CNGS operation (achieved 420kW)
  - Design optimised target and horn focusing systems.
  - Afford relatively short decay tunnel ≈300m, but 10deg dip angle
  - Near detector station to achieve target systematic errors
  - Consider dedicated set of hadron-production measurements

- **Benefit from improved performance of SPS+injectors for LHC-HL; consider further options to upgrade power of SPS:**
  - SPS intensity is upgraded to **7e13 ppp @ 400 GeV** (6 s cycle).
  - Yearly integrated pot = **(0.8–1.3)x 1e20 pot / yr**
  - Total integrated (12 years) = **(1–1.5)x 1e21 pot**
  - Range corresponds to sharing 60–85%
  - Studies ongoing within CERN acc. team

- **Upgrade path (three long term options):**
  - **SPS upgrades (800 GeV) → 2 MW**
  - **New HP-PS accelerator (50 GeV) → 2 MW**
  - **NF storage ring**

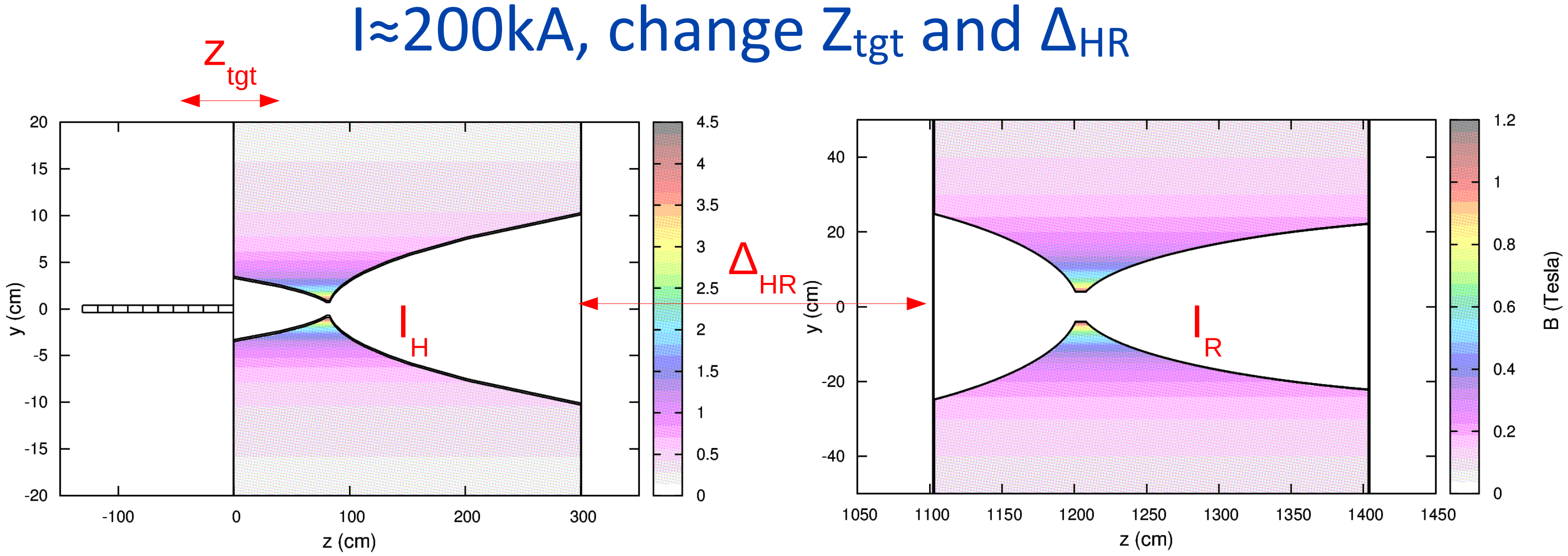
# LBNO baseline beam design

- Conventional beam, horn focused
- Medium energy to cover at $E_\nu \approx 4$ GeV (1st max) and $E_\nu \approx 1.5$ GeV (2nd max)
- Wide band covering 1st and 2nd maximum
- Small tail at high energy
- Positive and negative focus (ν and anti-ν modes)
- High beam power (initially 700 kW then 2MW)
- Angle 10deg dip angle (distance = 2300km)
- Muon monitors
- Magnetised near neutrino detector

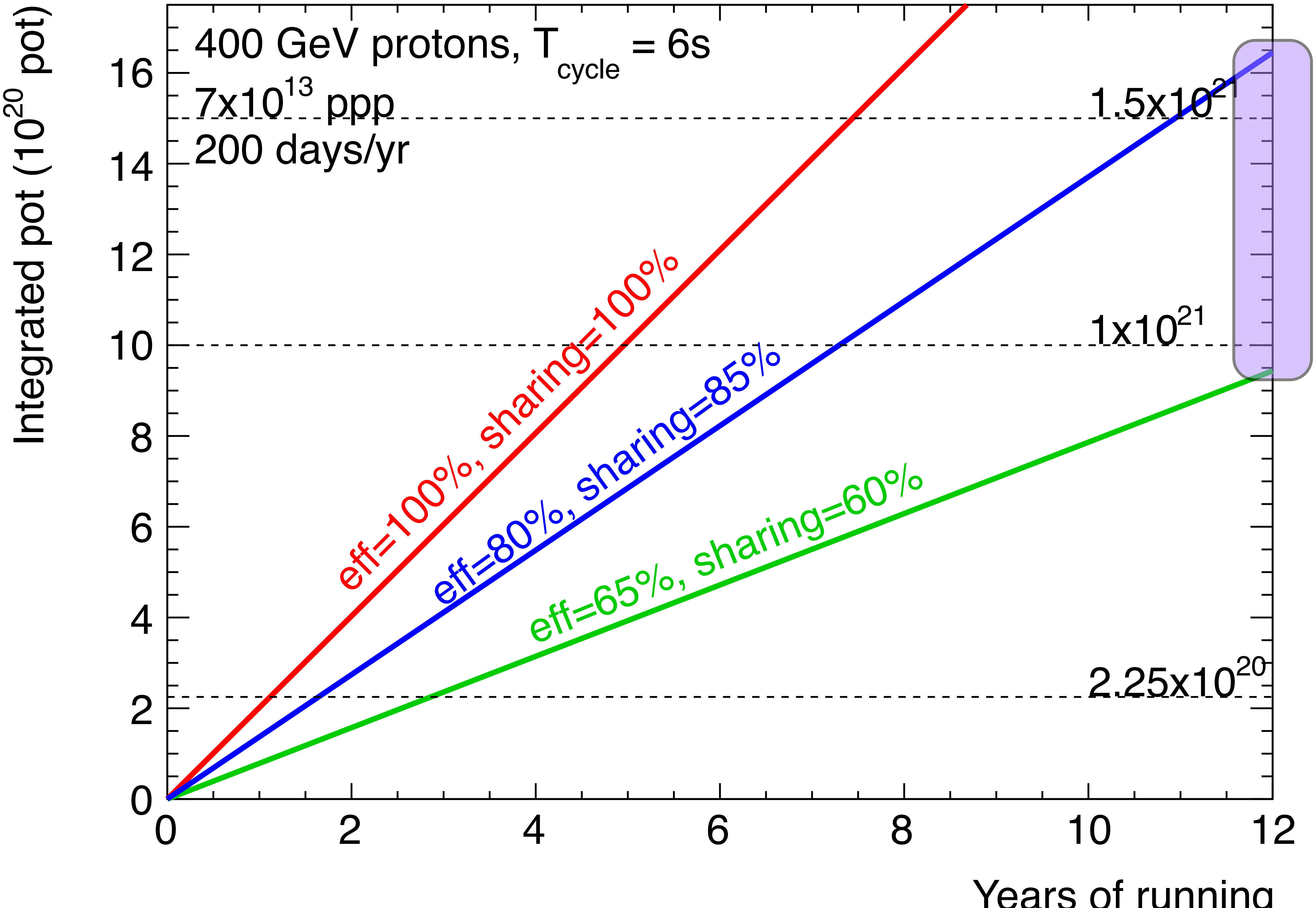



## Focusing optimisation (preliminary)

Graphite target (r=4mm), Horn shapes fixed, I≈200kA, change $Z_{tgt}$ and $\Delta_{HR}$



# Total integrated p.o.t.



# LBNO Strategy on Mass Hierarchy and $\delta_{CP}$ (1)

## Incremental approach:

- $1^{st}$ 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

- $2^{nd}$ 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

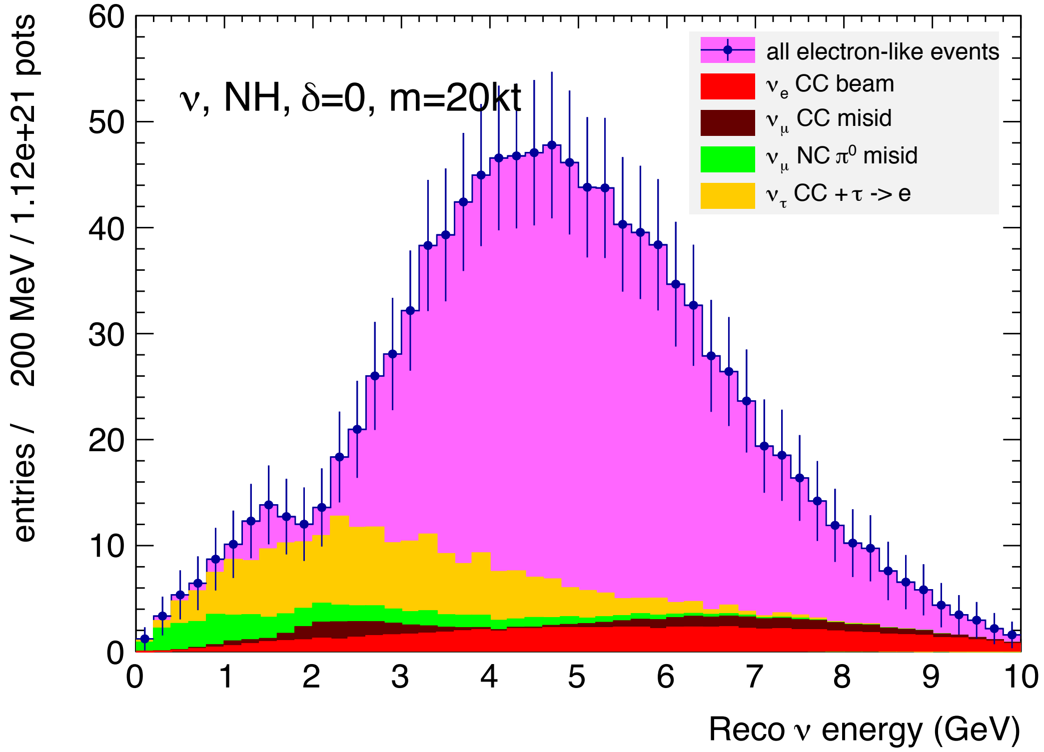
## Measurement of the energy dependence of the oscillation probabilities ranging from the $1^{st}$ to the $2^{nd}$ maximum (L/E behavior)

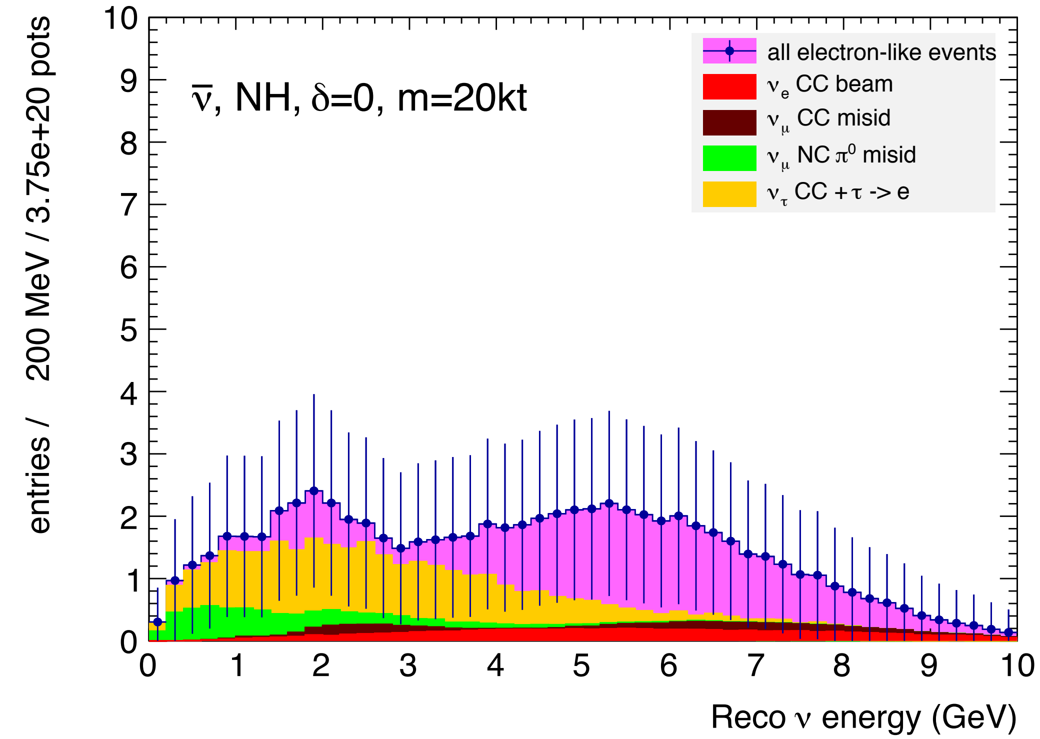
# Neutrino + anti-Neutrino running to distinguish NH from IH

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

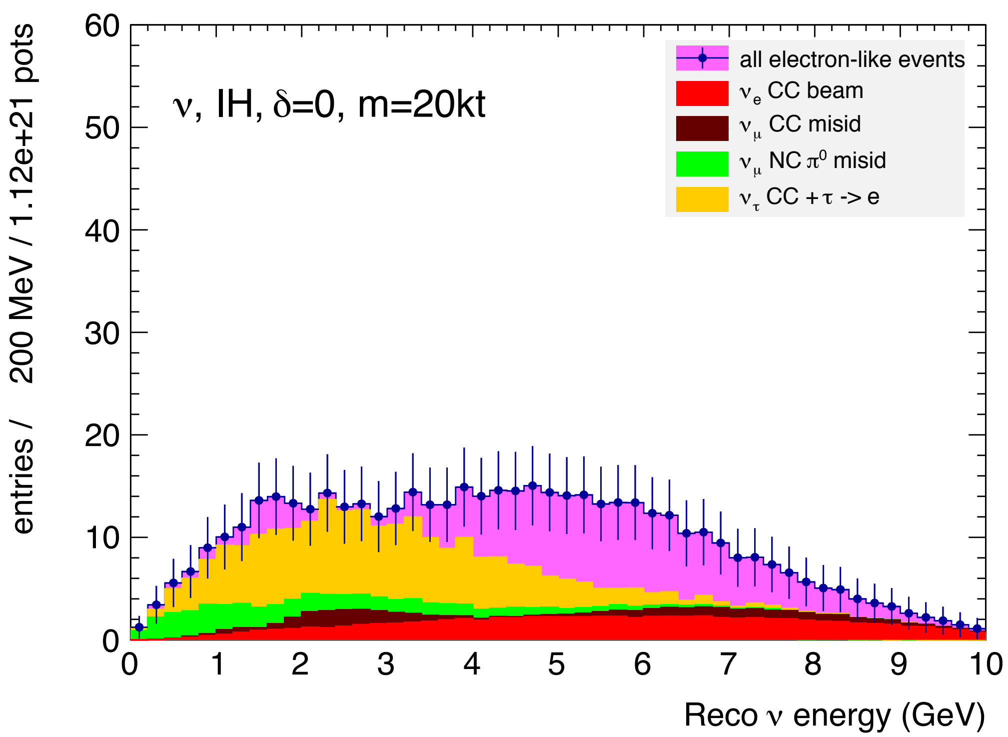
## Neutrinos | anti-Neutrinos

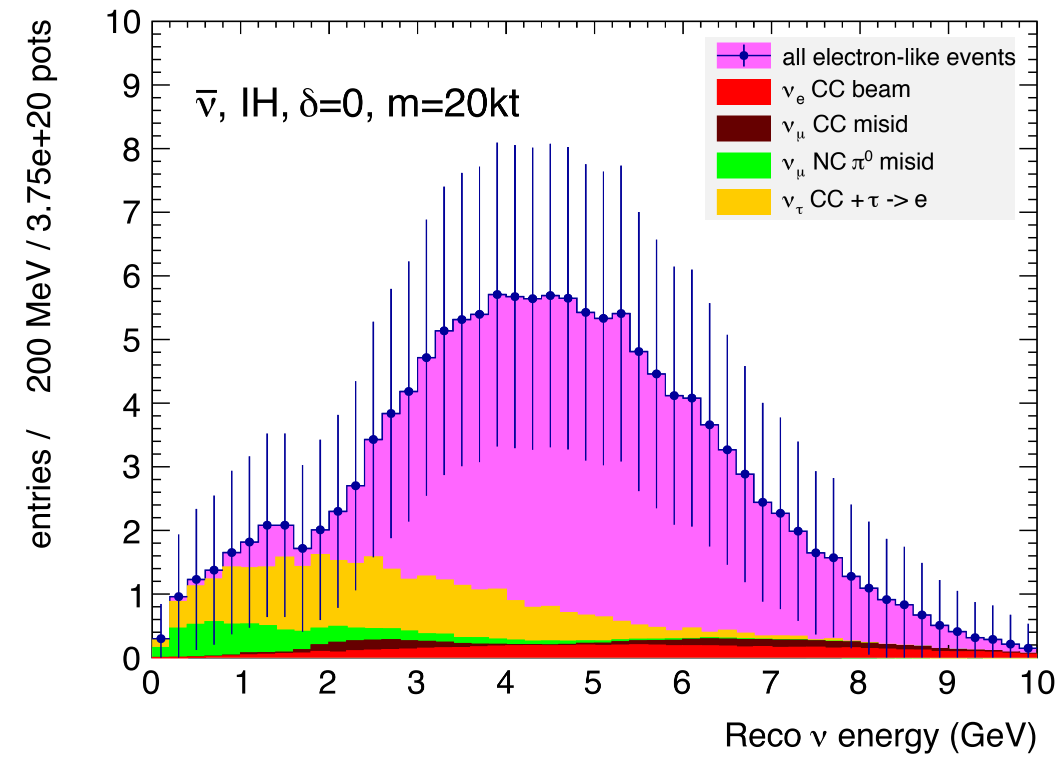
NH




IH

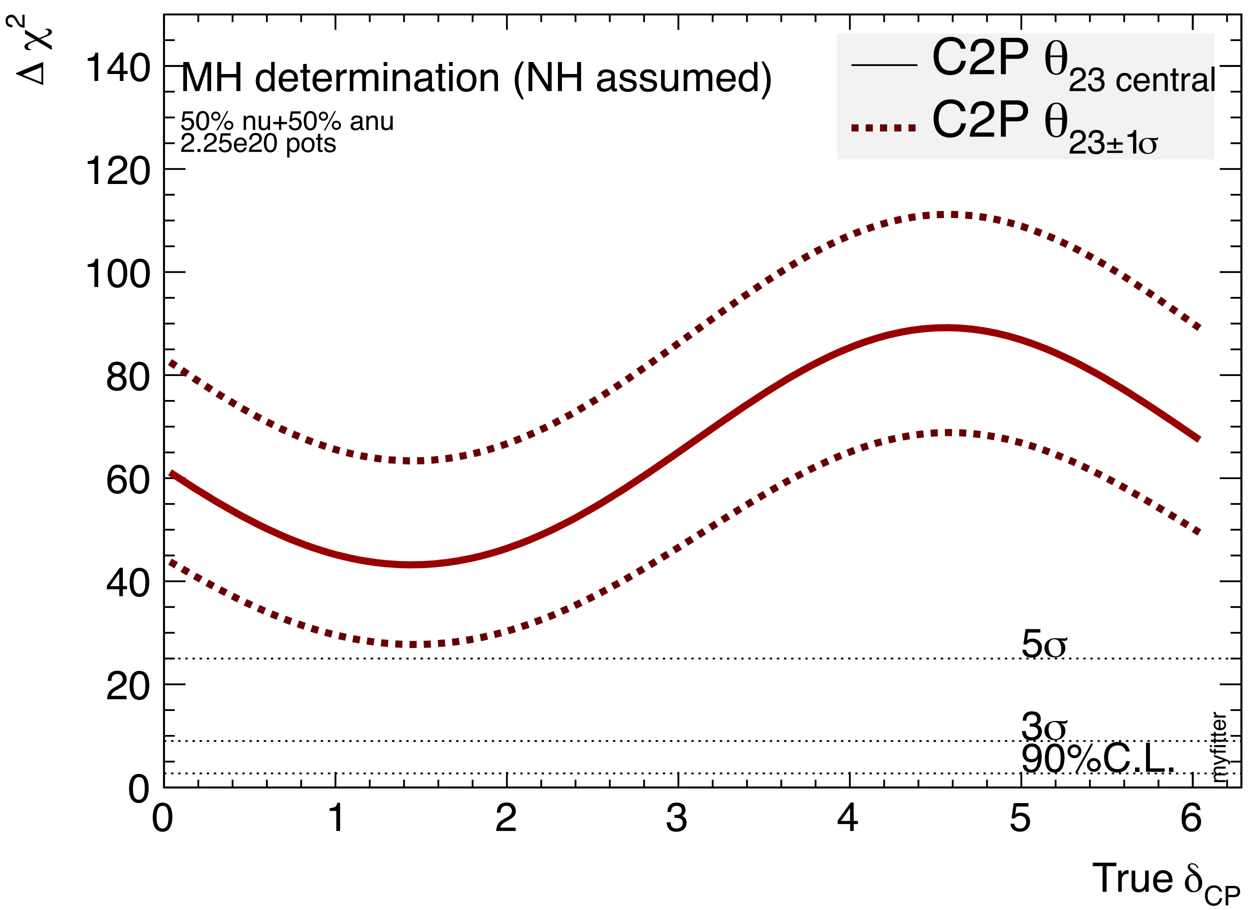


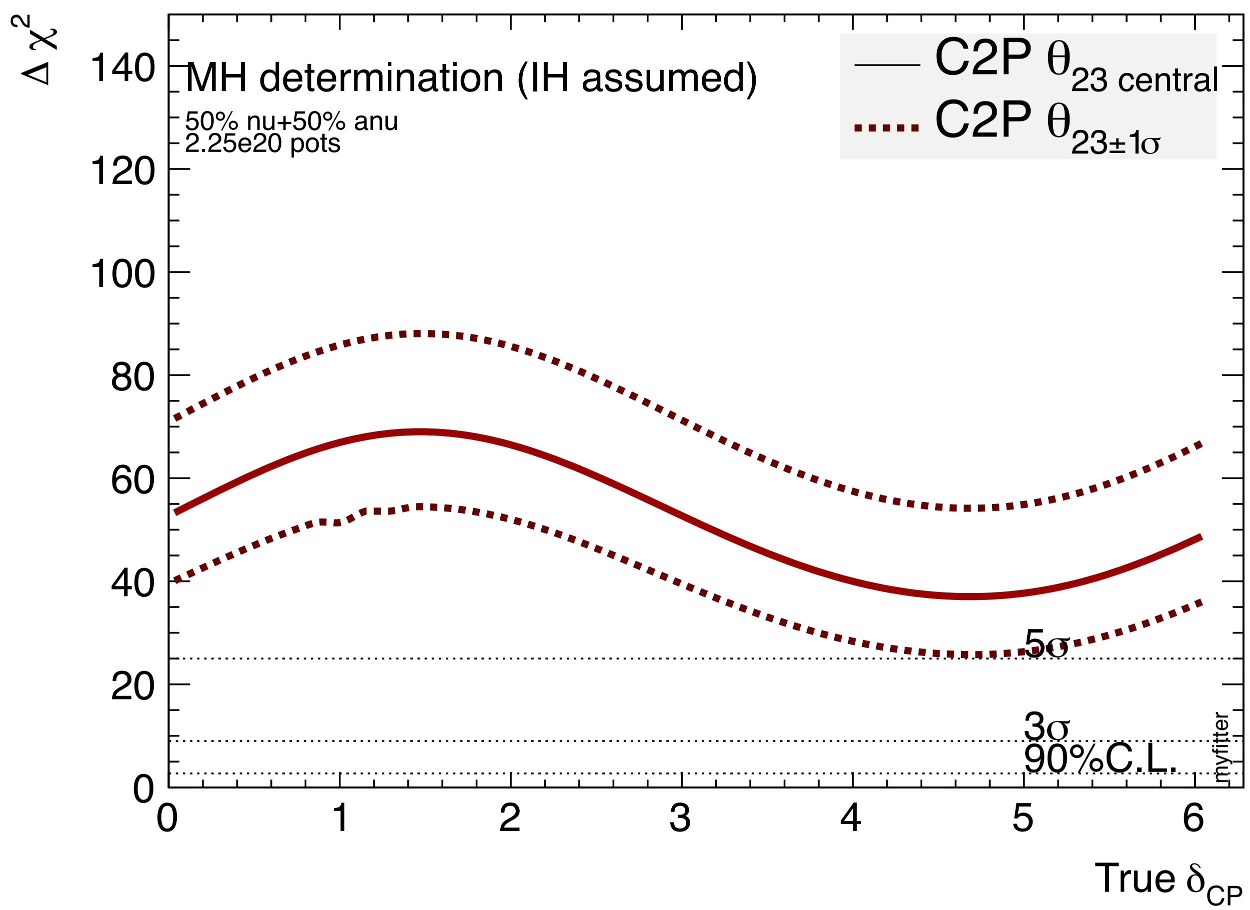



# LBNO Strategy on Mass Hierarchy and $\delta_{CP}$ (2)

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

LBNO will provide a > 5σ direct determination of MH <u>independent</u> of the values of $\theta_{23}$ & $\delta_{CP}$ in ≈ **2 years** of running

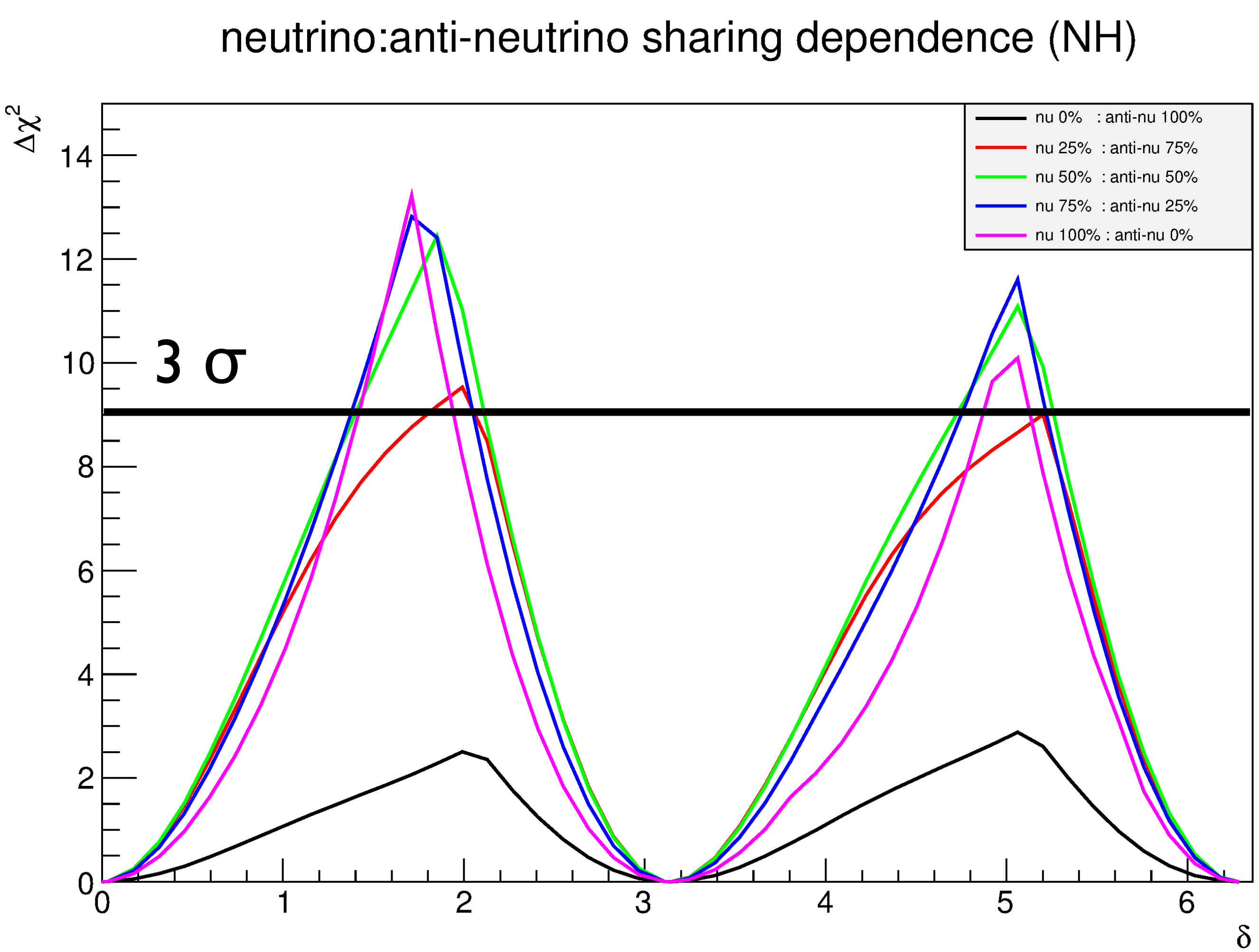


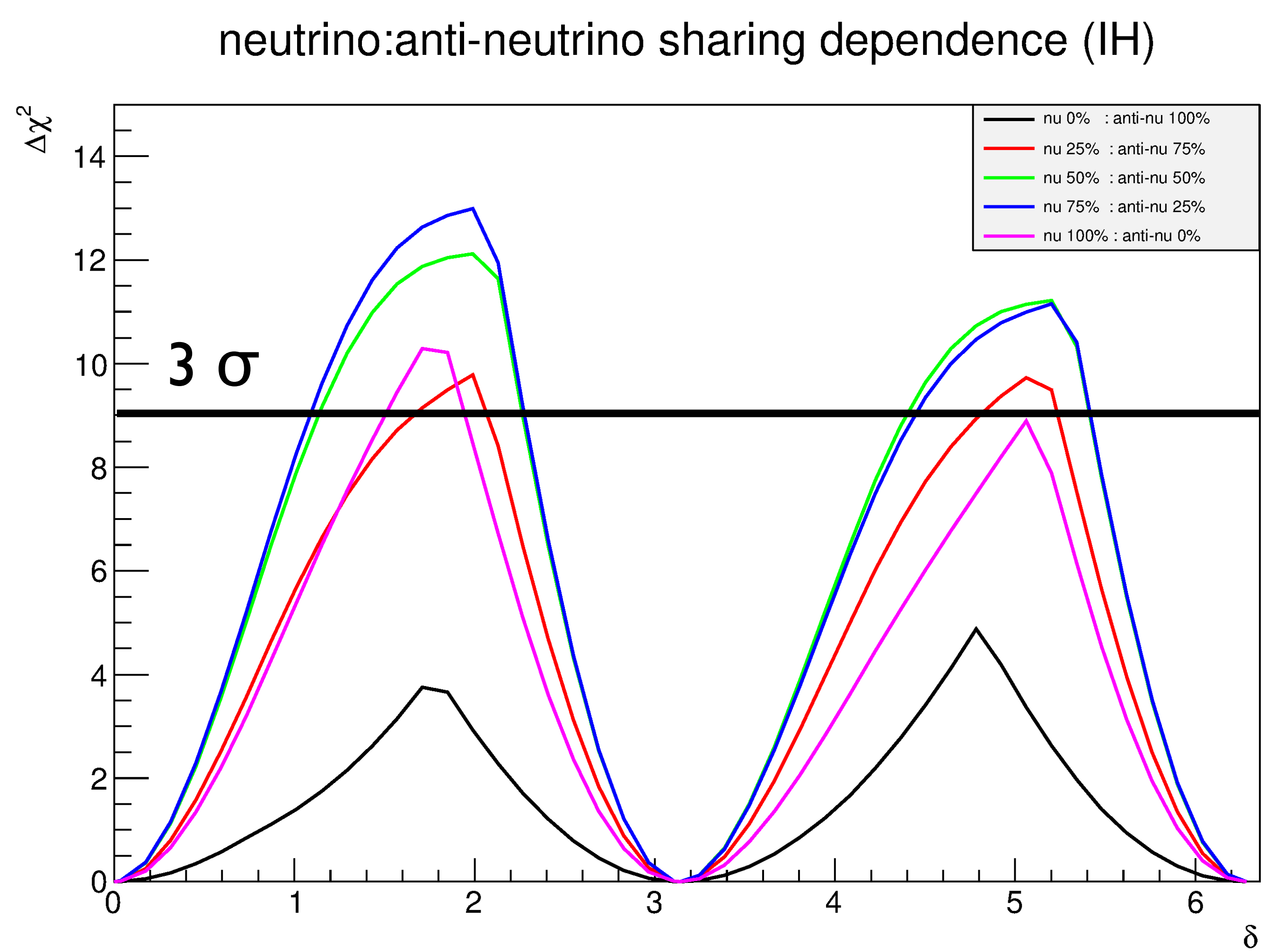




Other methods proposed (atmospheric neutrinos, reactors) do not provide such a level of sensitivity and could be prone to irreducible systematic errors

# LBNO Strategy on Mass Hierarchy and $\delta_{CP}$ (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 $\delta_{CP}$

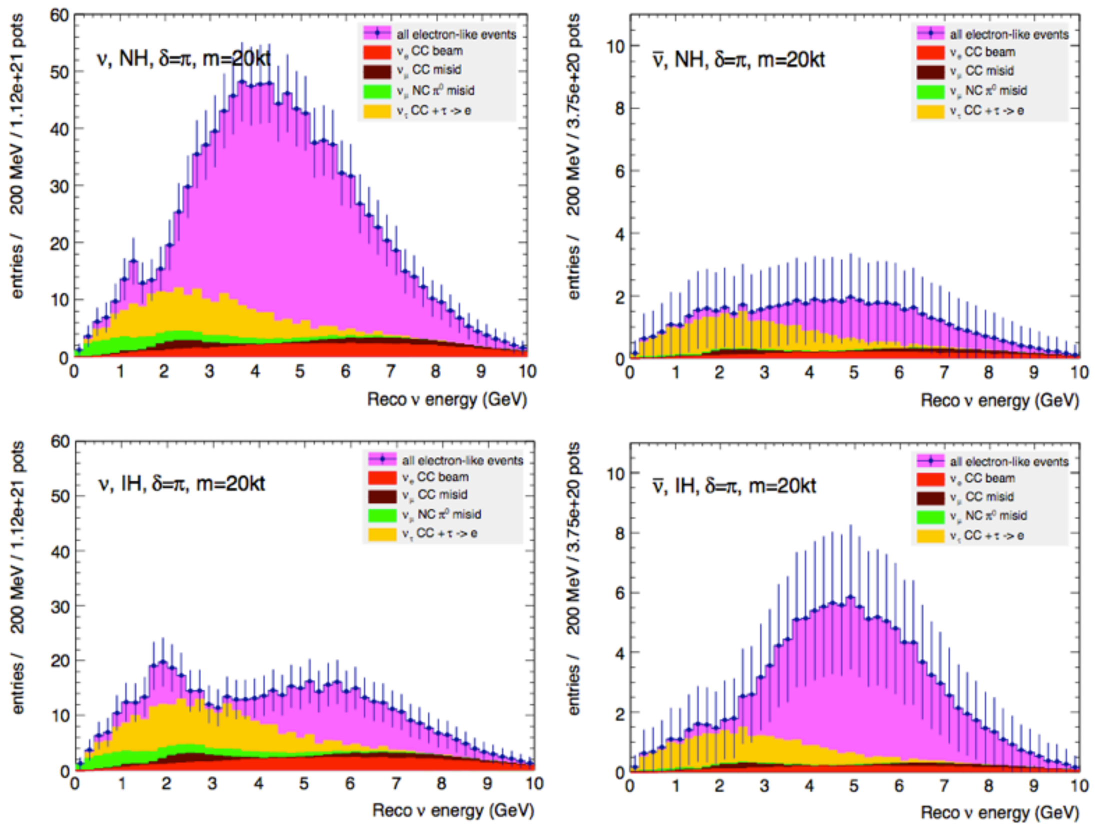


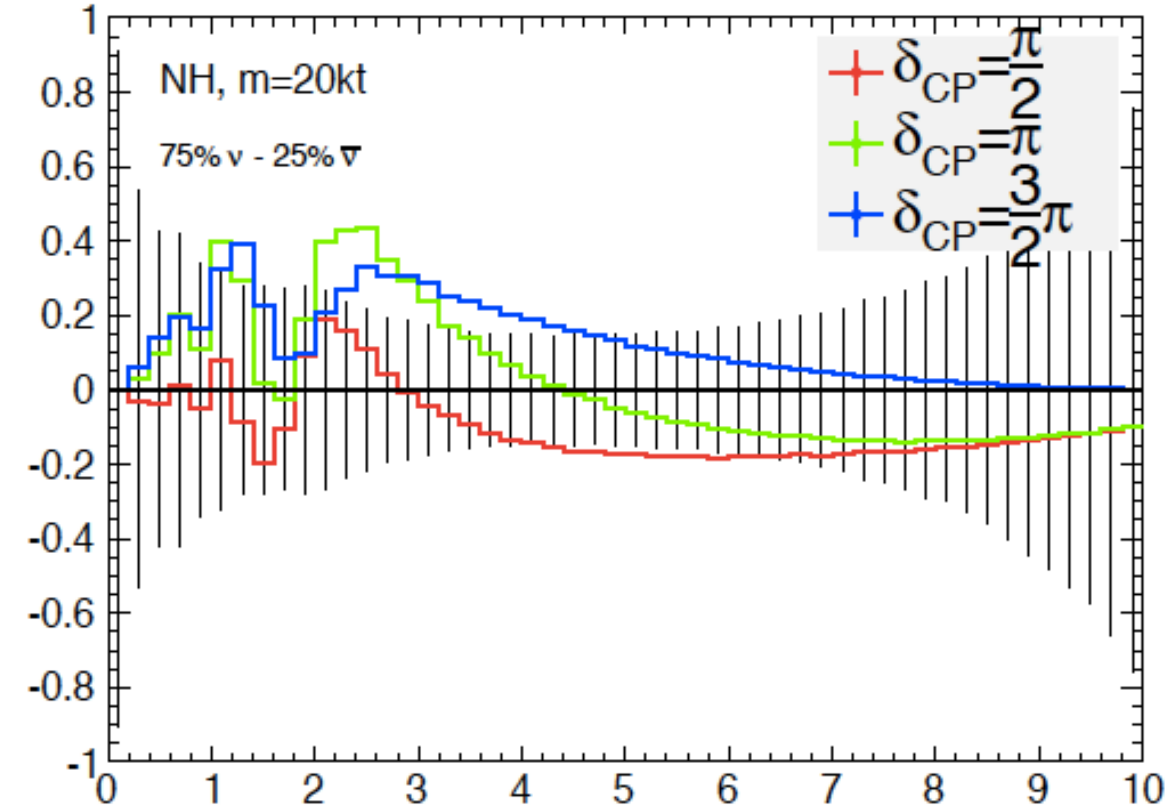



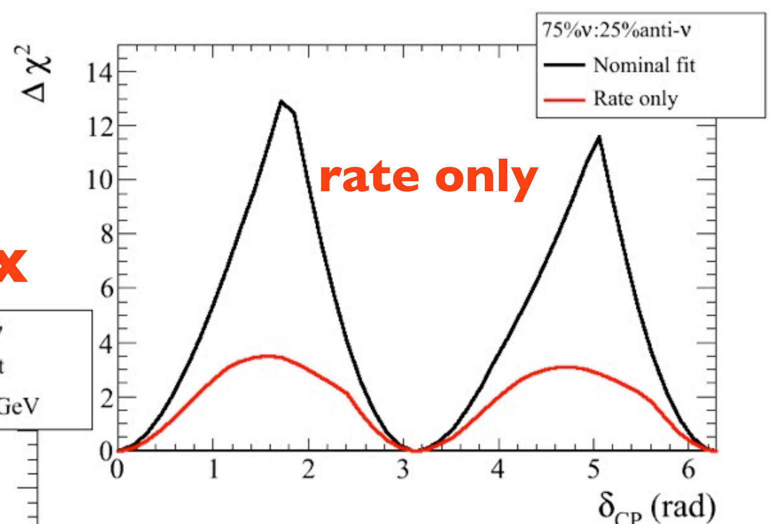

# Design value: 75 % ν - 25 % anti-ν

# LBNO Strategy on Mass Hierarchy and $\delta_{CP}$ (4)

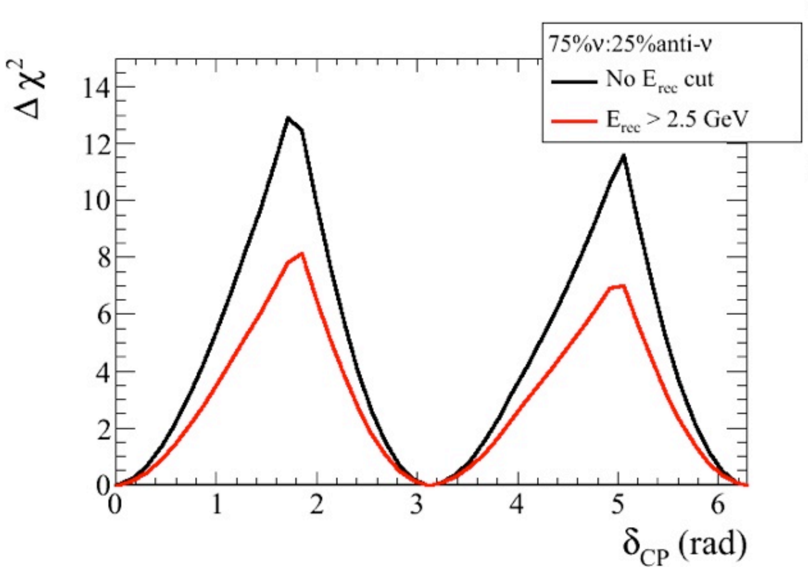
## Use all spectral information: Rate & Shape for energy range 1st - 2nd max

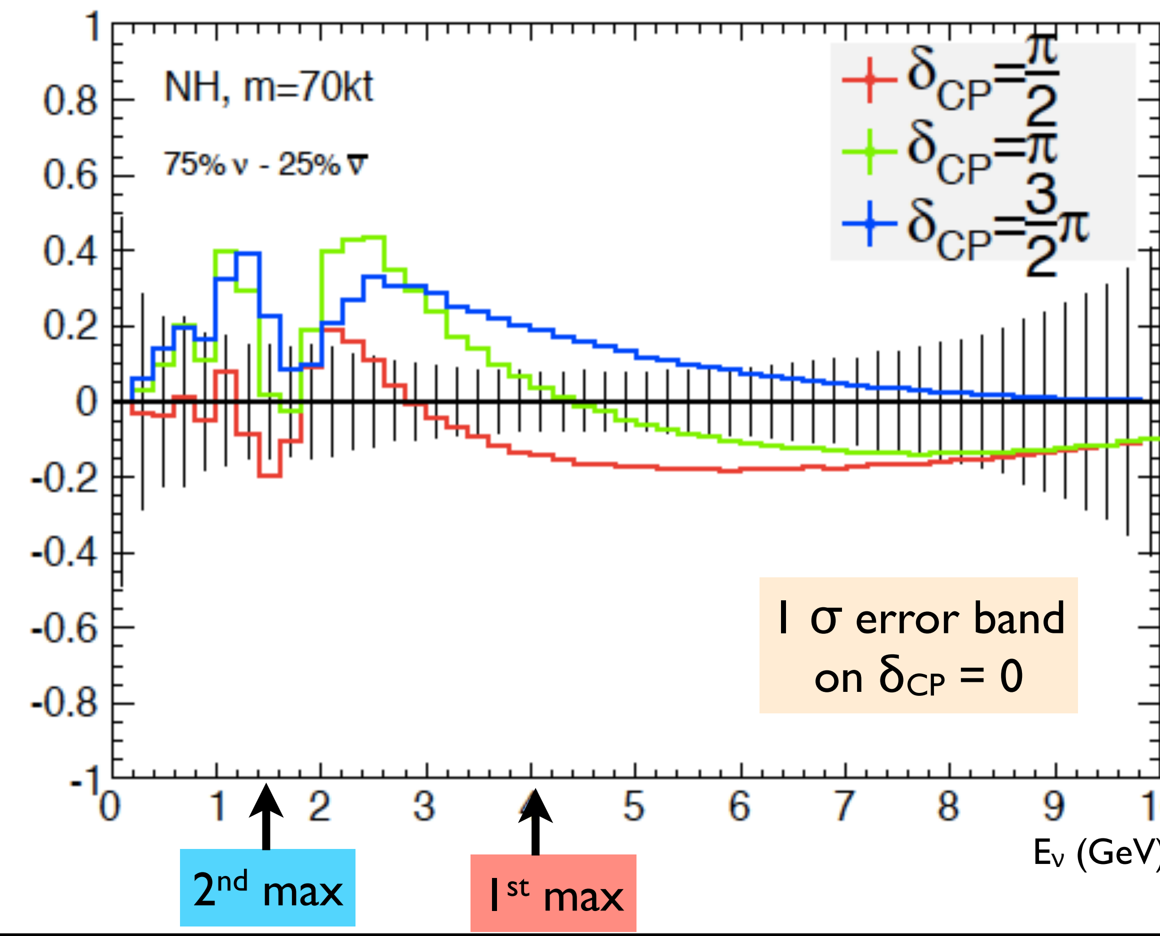


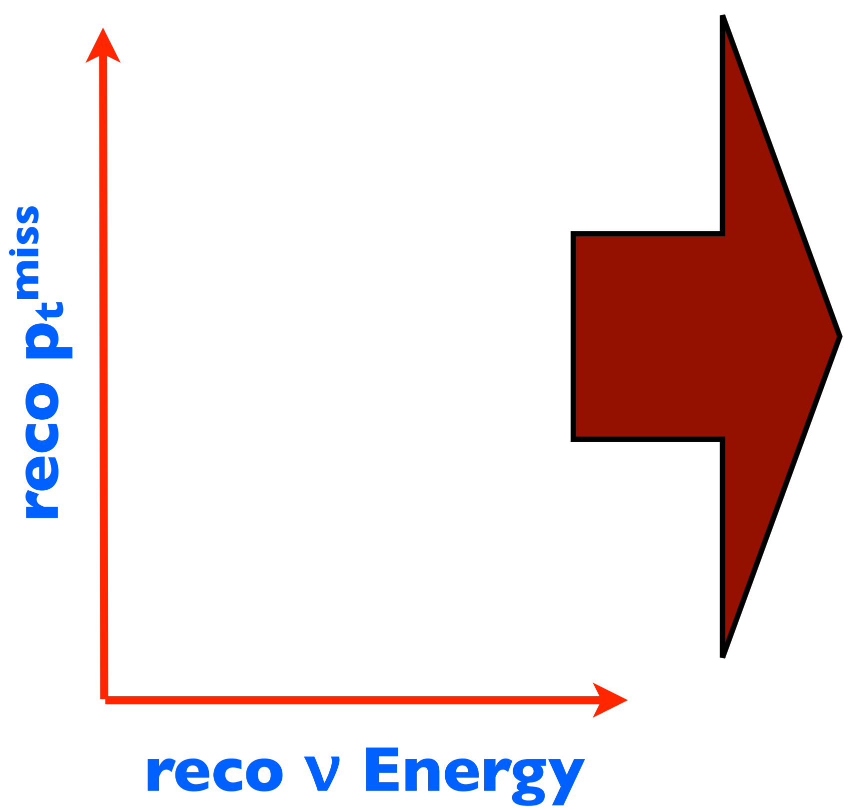



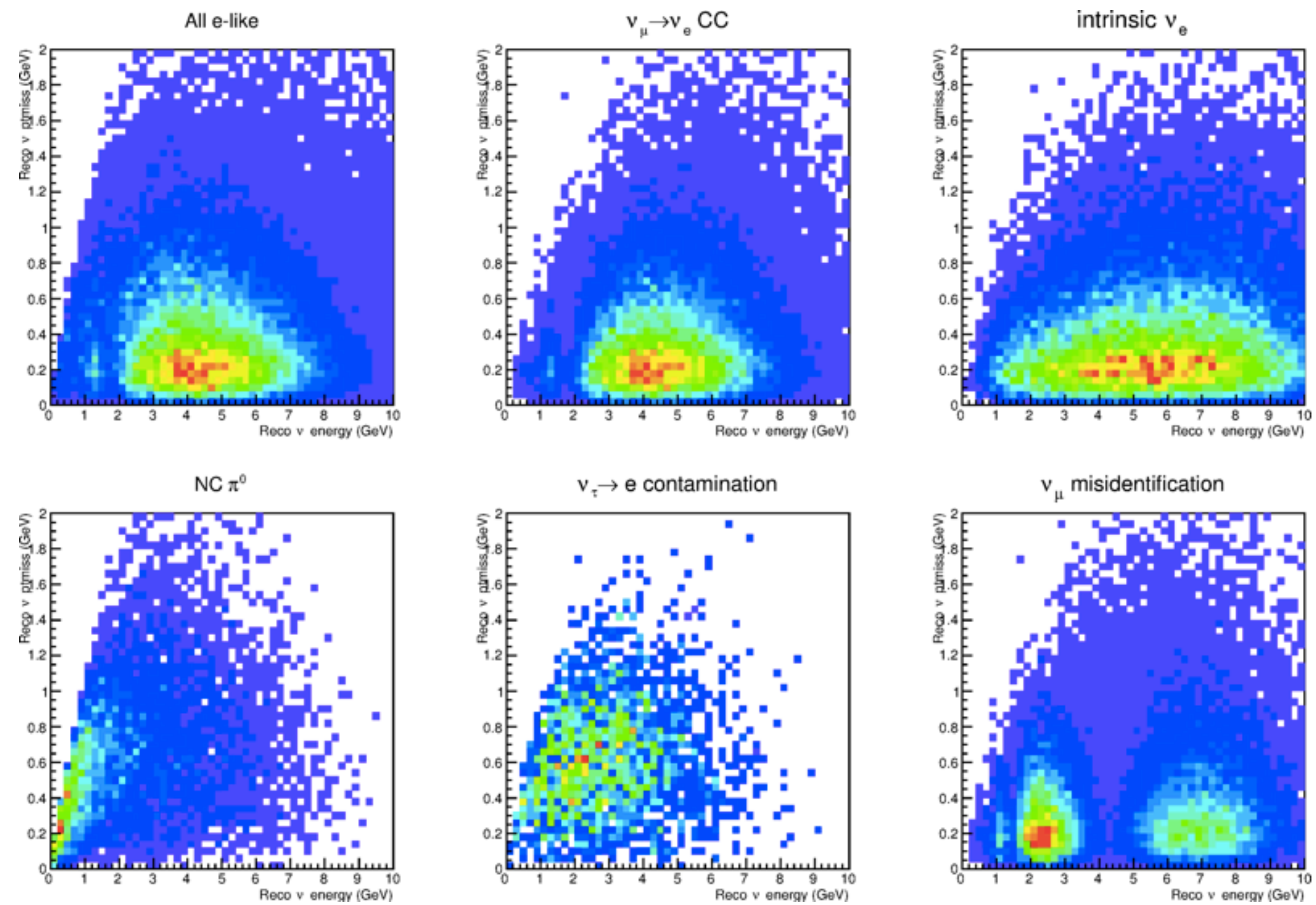

**w/ and w/o 2nd max**



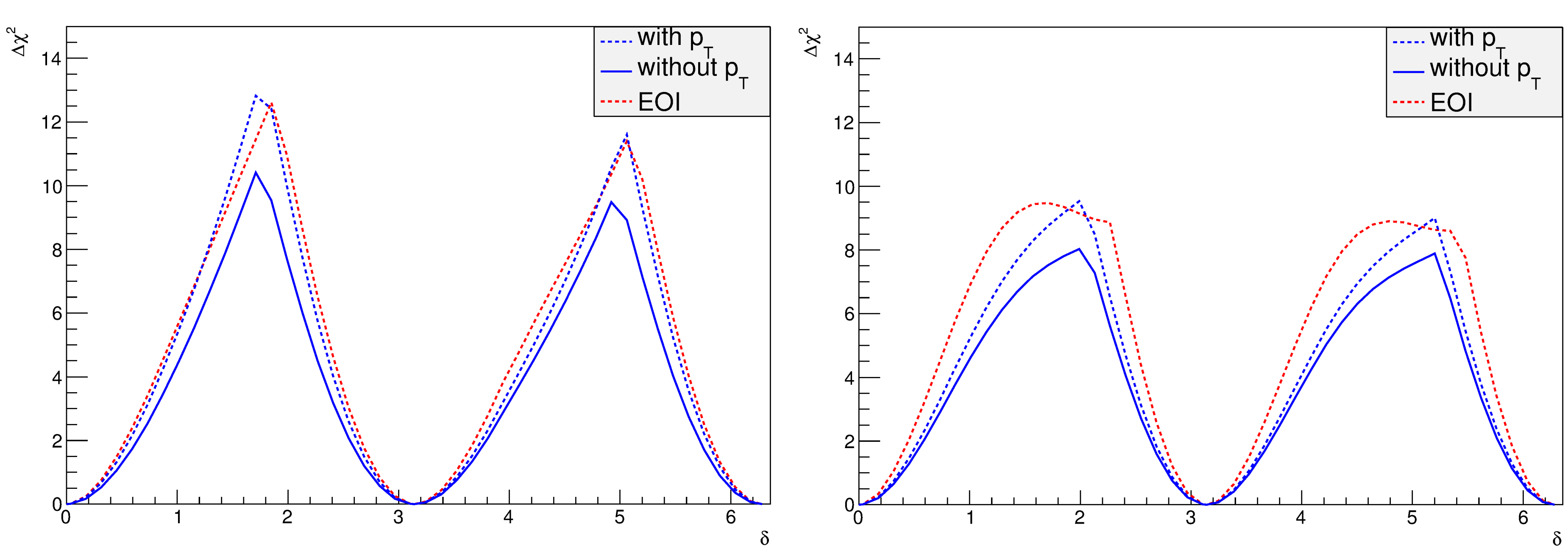
# Use all event information: Particle ID, Energy and kinematics ($p_t$)




75% neutrino : 25% anti-neutrino

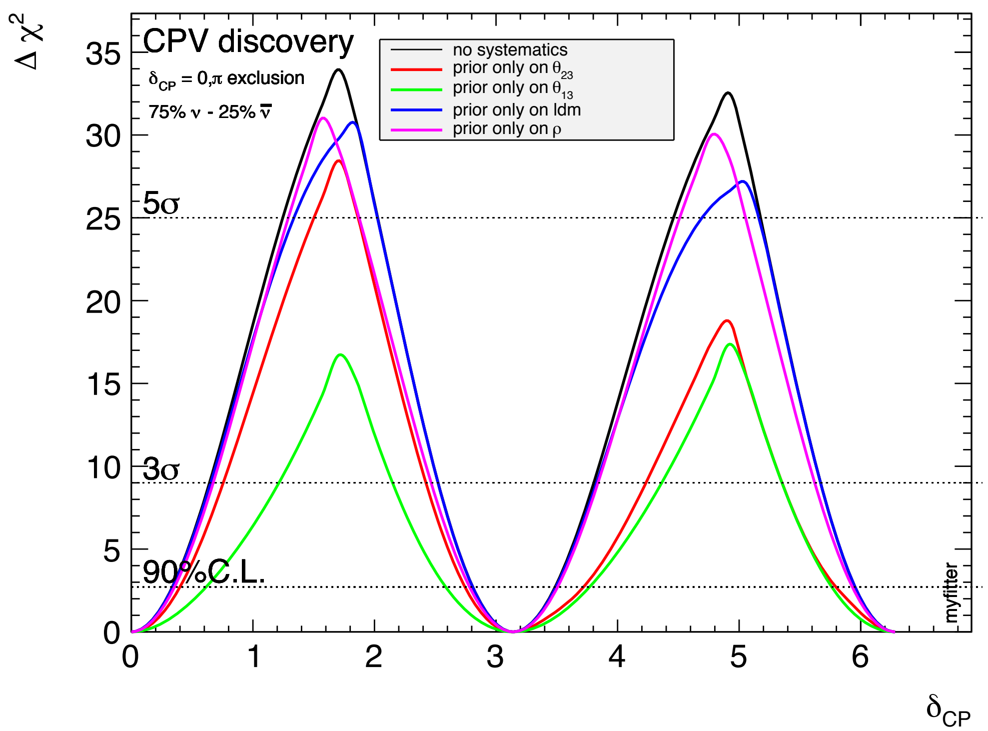
25% neutrino : 75% anti-neutrino



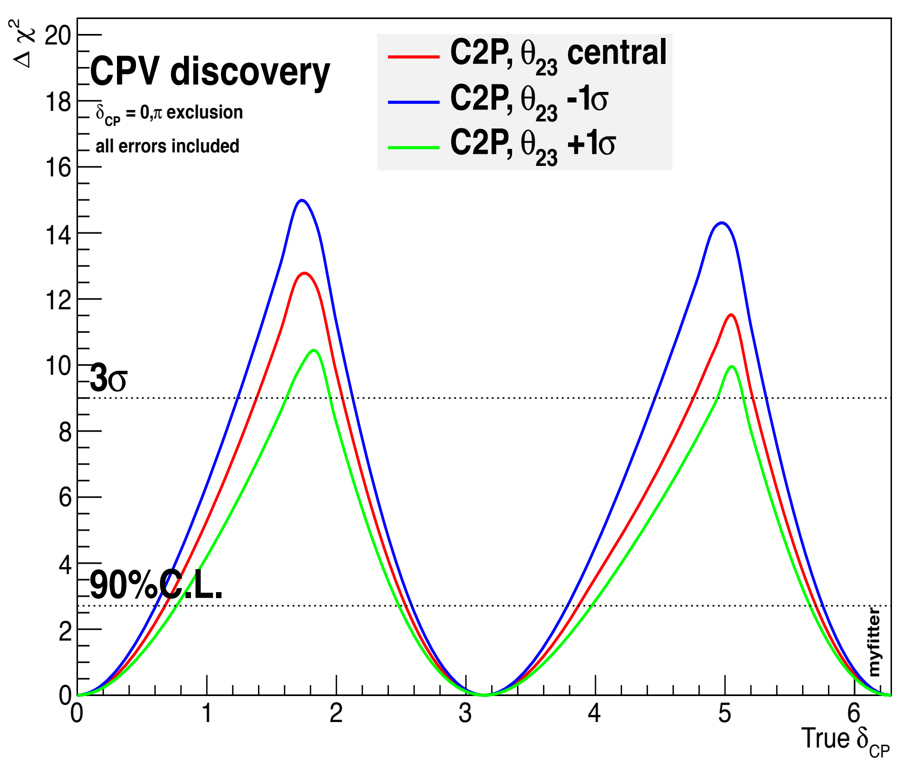
# LBNO Strategy on Mass Hierarchy and $\delta_{CP}$ (5)

## Use best knowledge on systematics and oscillation parameters

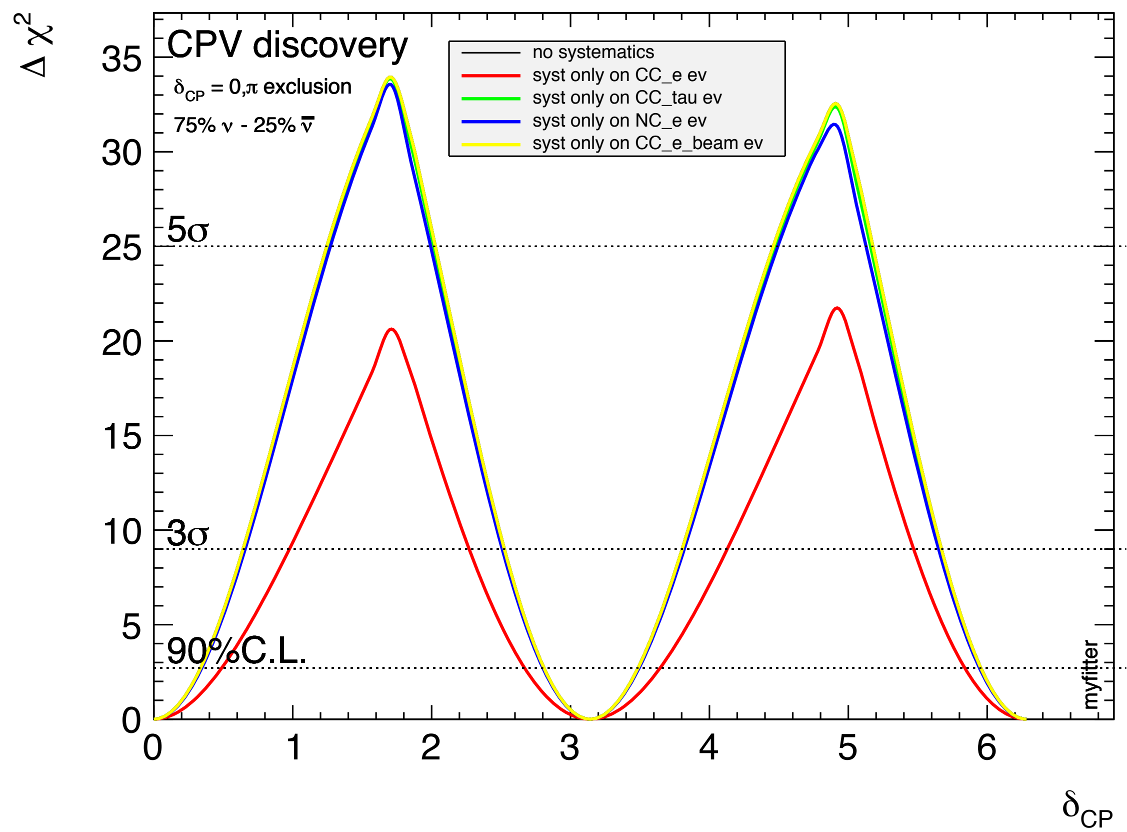
### oscillation parameters




Effect of $\theta_{23}$



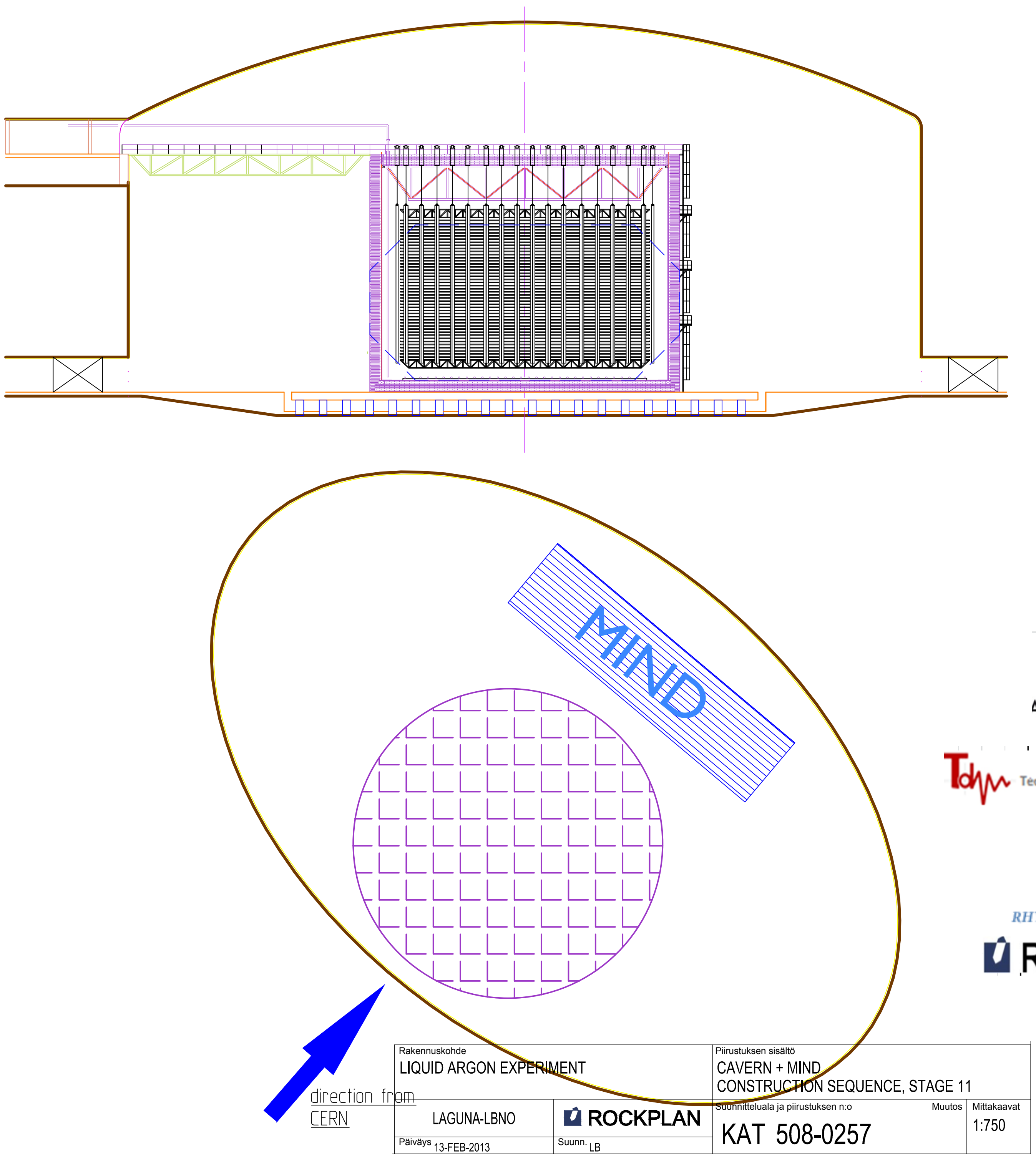

### Systematics



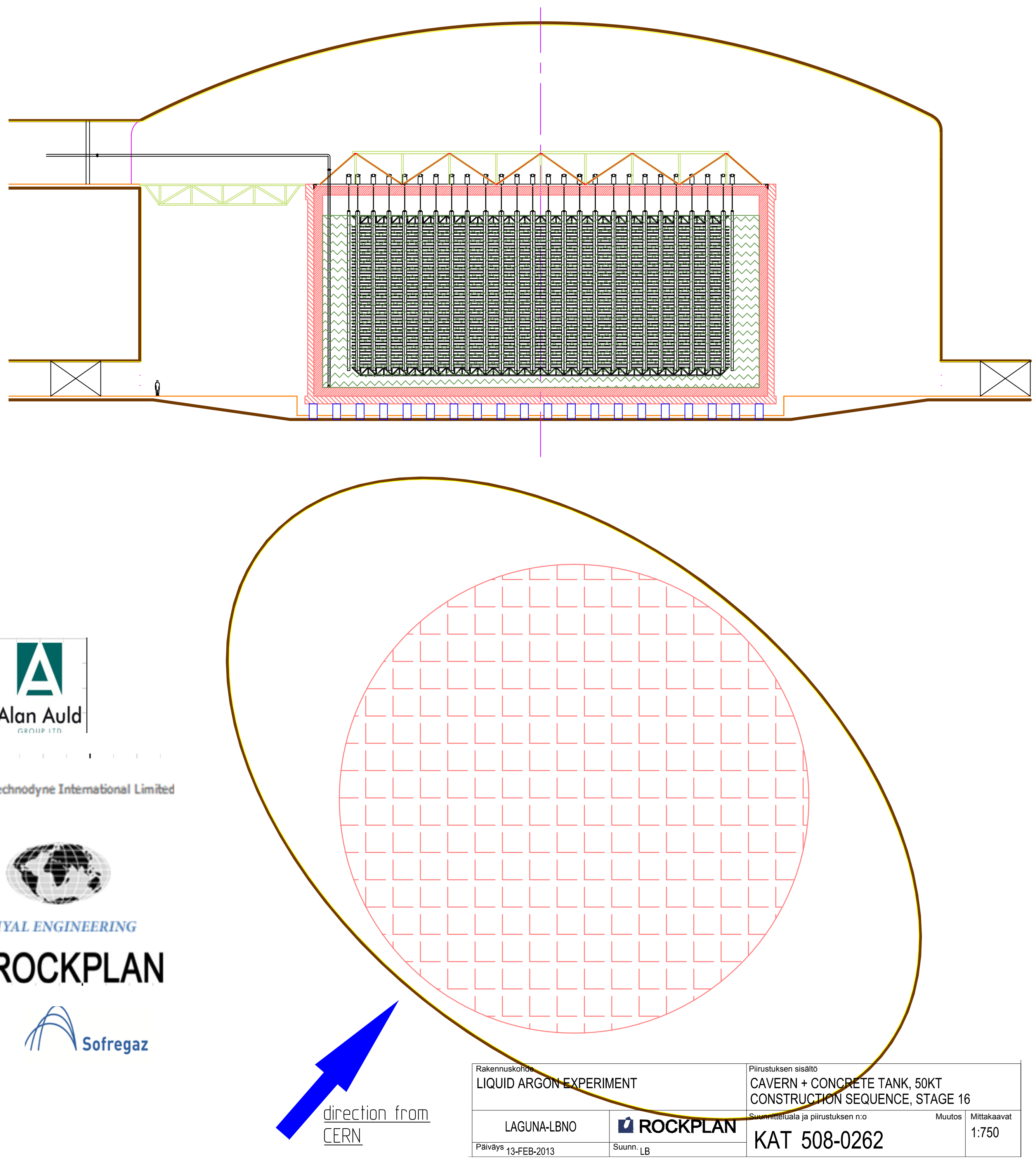

**The most important oscillation parameters are $\theta_{23}$ and $\theta_{13}$ and the most important systematics is the knowledge of the absolute rate of $\nu_e$ CC events.**

# LBNO caverns layout

| 20kton LAr + 35 kton MIND | 50kton LAr |
|---|---|

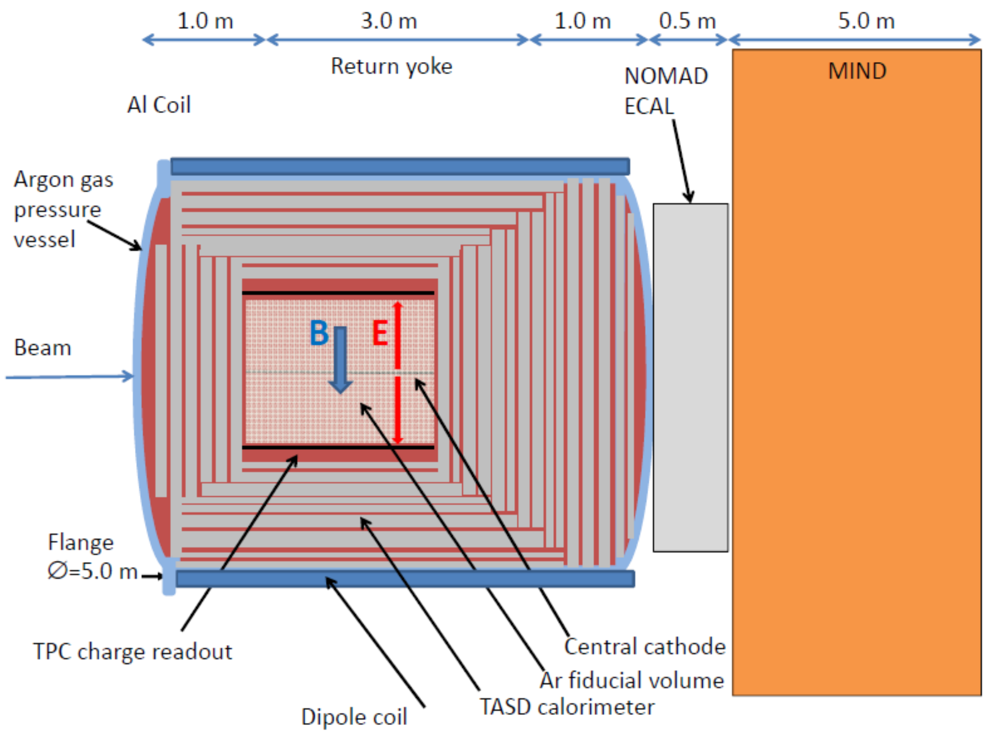



Alan Auld
Technodyne International Limited
RHYAL ENGINEERING
ROCKPLAN
Sofregaz

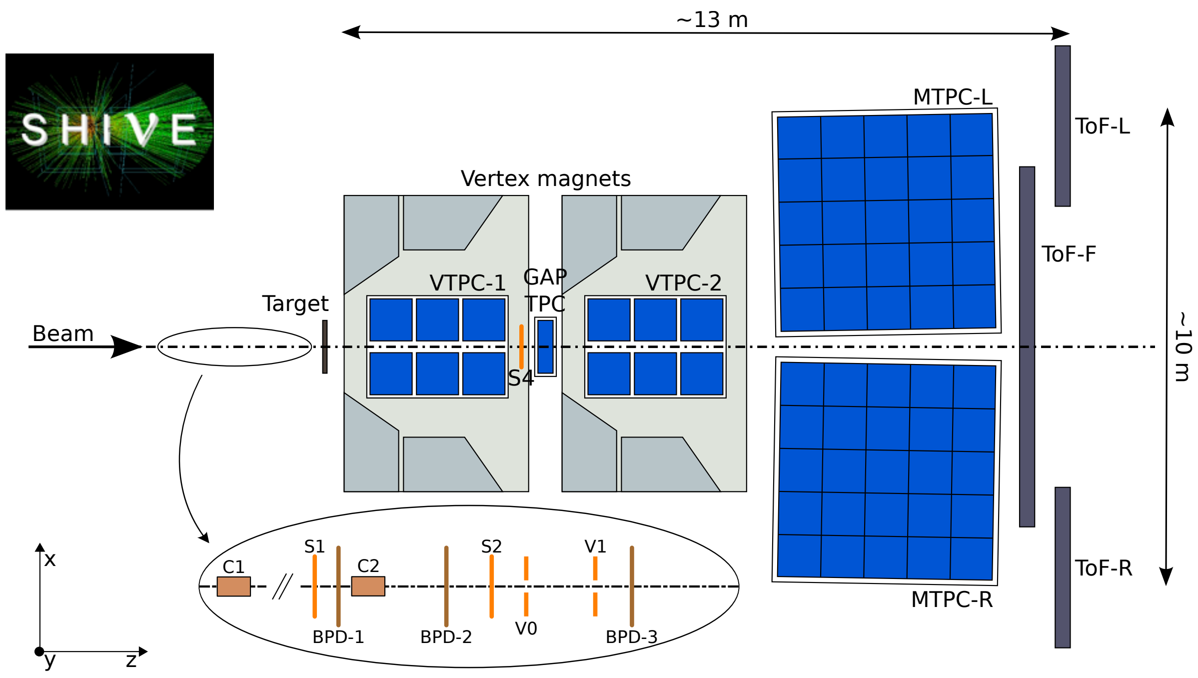


# Near detector and hadro-production

- **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 @ 7e13 ppp 400 GeV
- 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 upgrade needed for 400 GeV incident protons

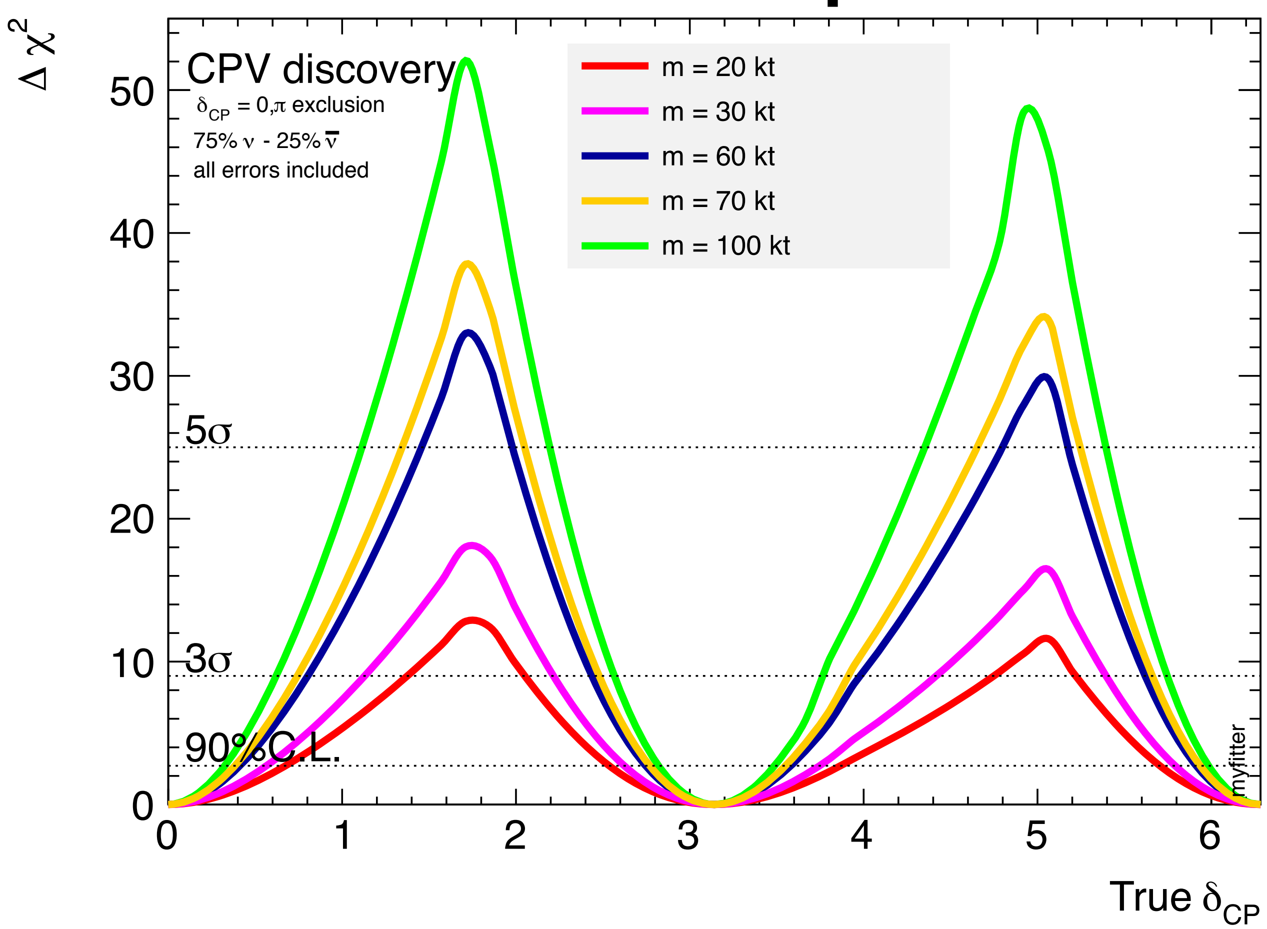
- Precision neutrino cross-section measurements: e.g. MINERVA, T2K-ND280, also nuSTORM

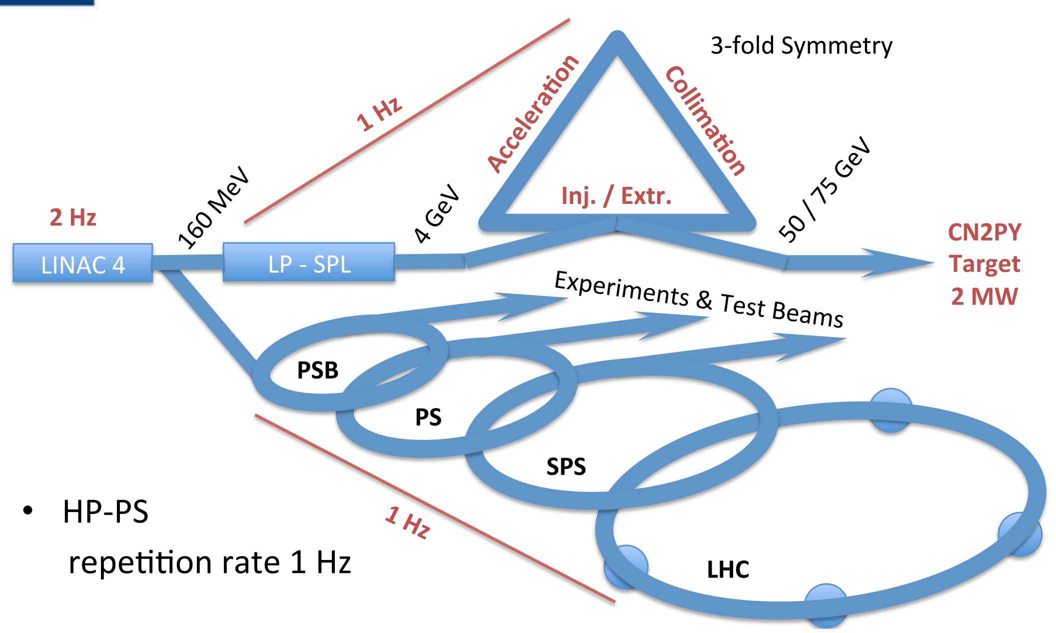
# LBNO Strategy on Mass Hierarchy and $\delta_{CP}$ (6)

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

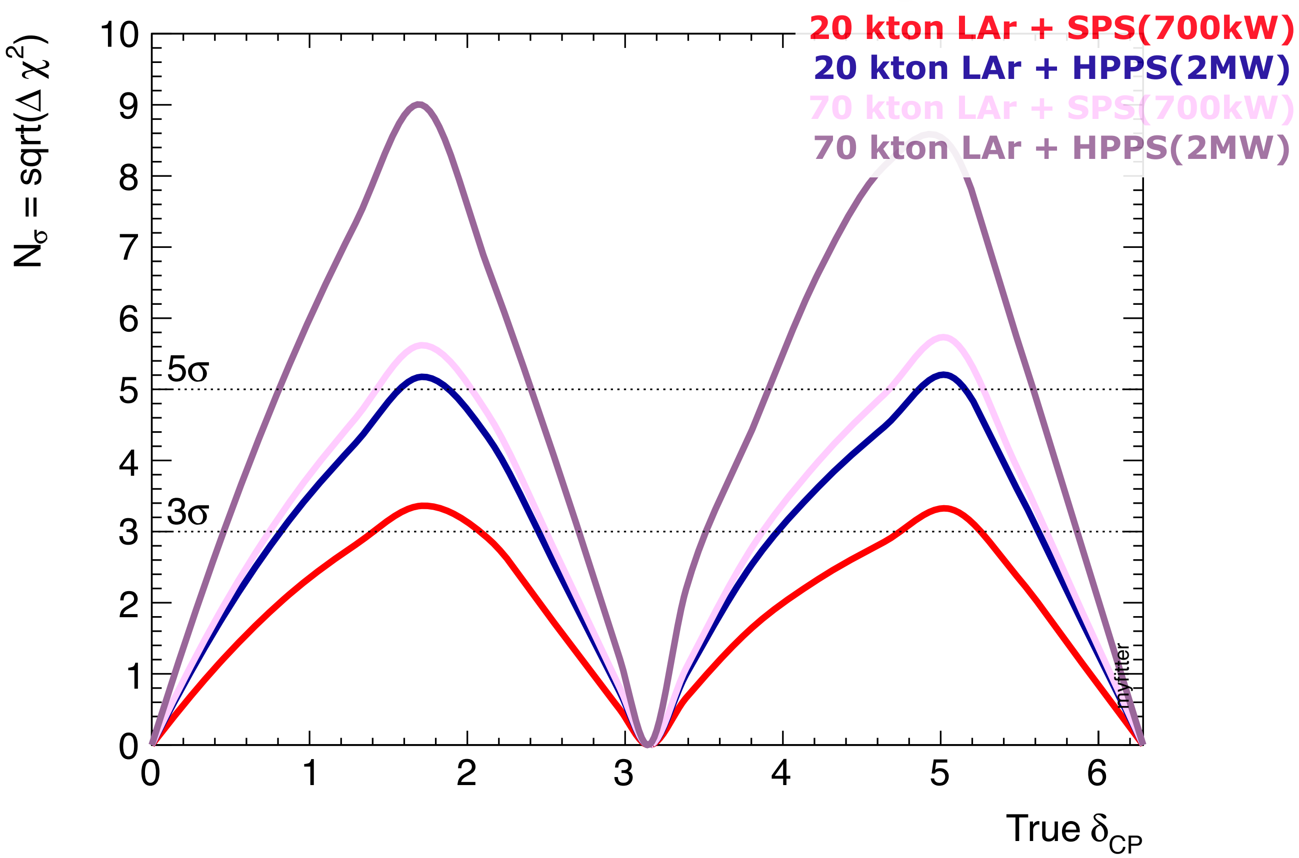
### High power HP-PS study

1.5 x $10^{21}$ p.o.t.



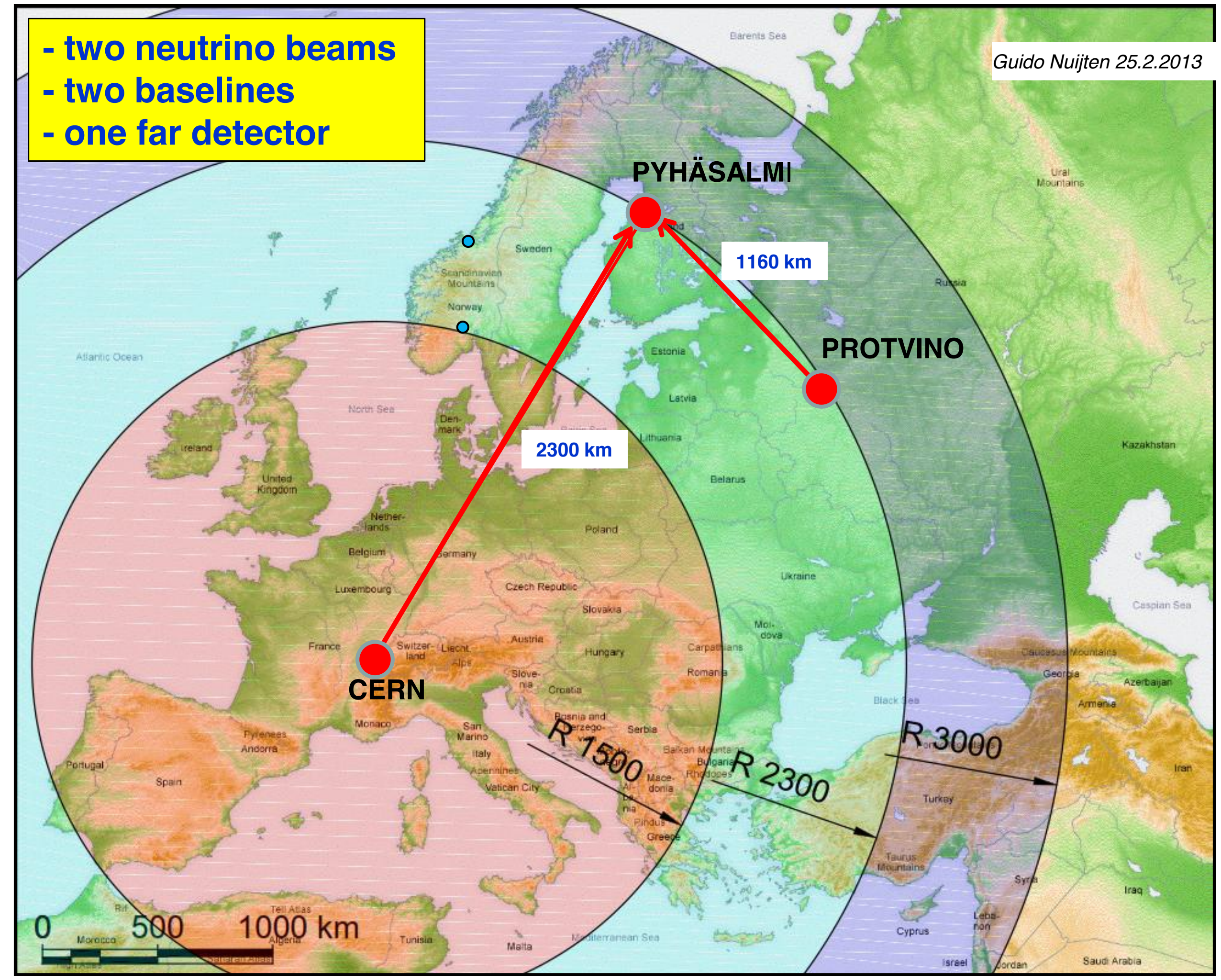




- HP-PS
  repetition rate 1 Hz



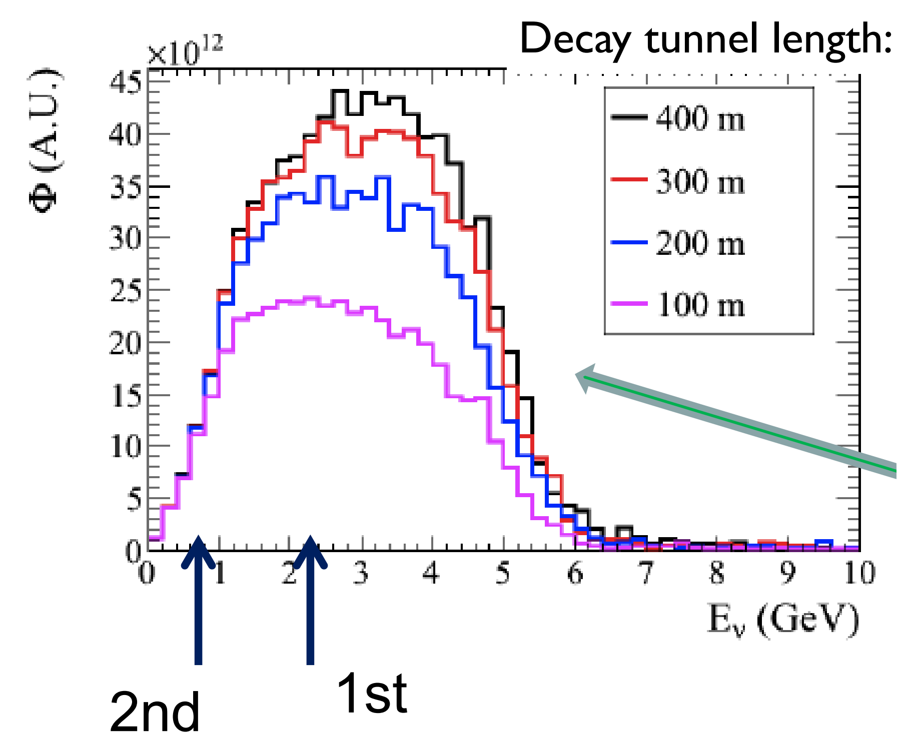
# Possibility of neutrinos from Protvino

PRELIMINARY


## Desired parameters for neutrino beam:

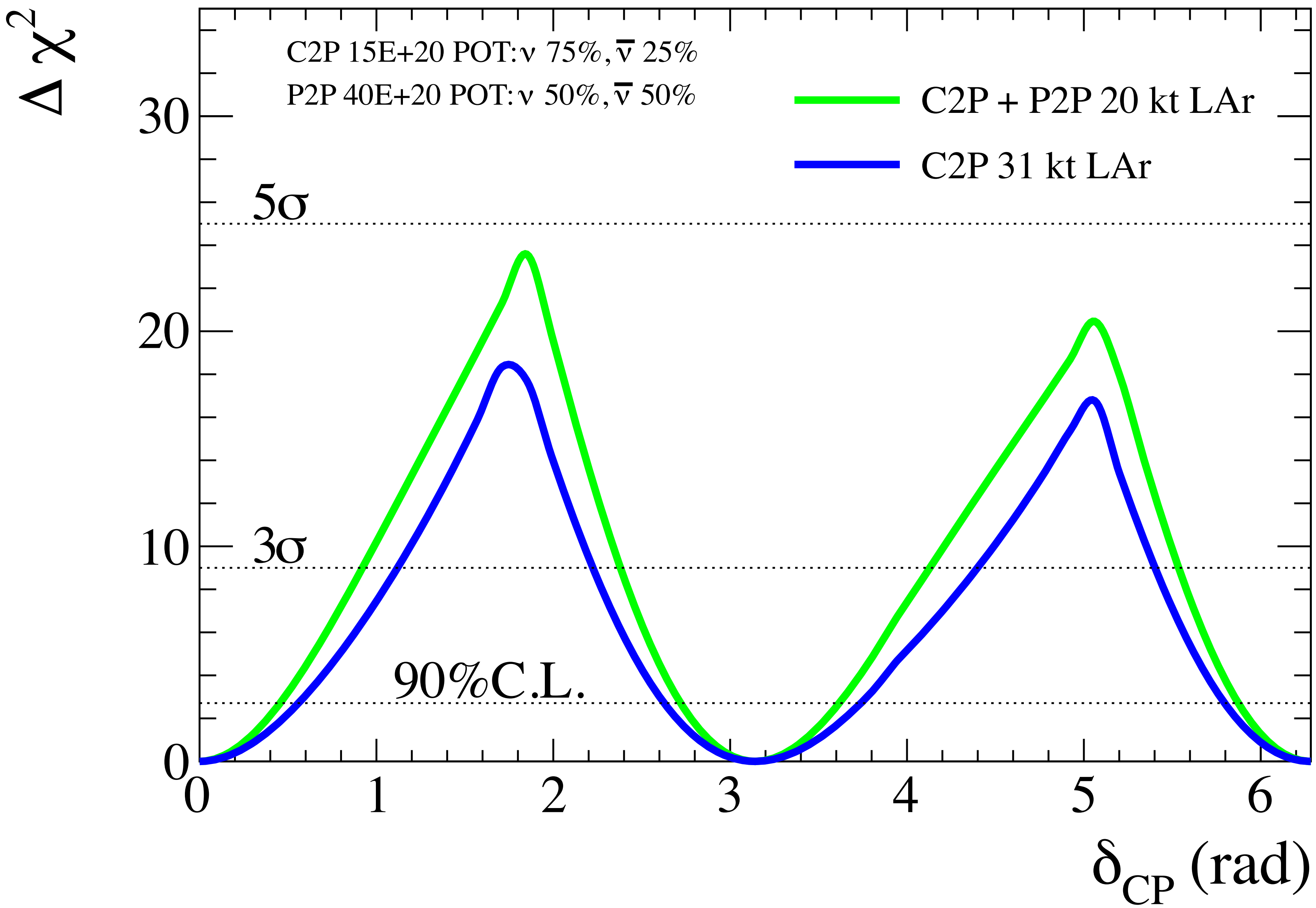
| | |
|---|---|
| Proton energy | 70 GeV |
| Repetition rate | 0.2 Hz |
| Intensity | $2.2 \times 10^{14}$ ppp |
| Power | 450 kW |
| Neutrino channel | 200-300 m |
| Angle to Pyhäsalmi | 5.2 deg |
| Distance to ND | 500 - 750 m |
| ND depth (at 500m) | 46 m |




**≈2000 $\nu_\mu$ CC / 20 kton / year (no osc.)**

**C2P+P2P sensitivity under study**

# CPV sensitivity is better for an experiment with two different baselines compared to increased detector mass or beam power of a unique baseline!

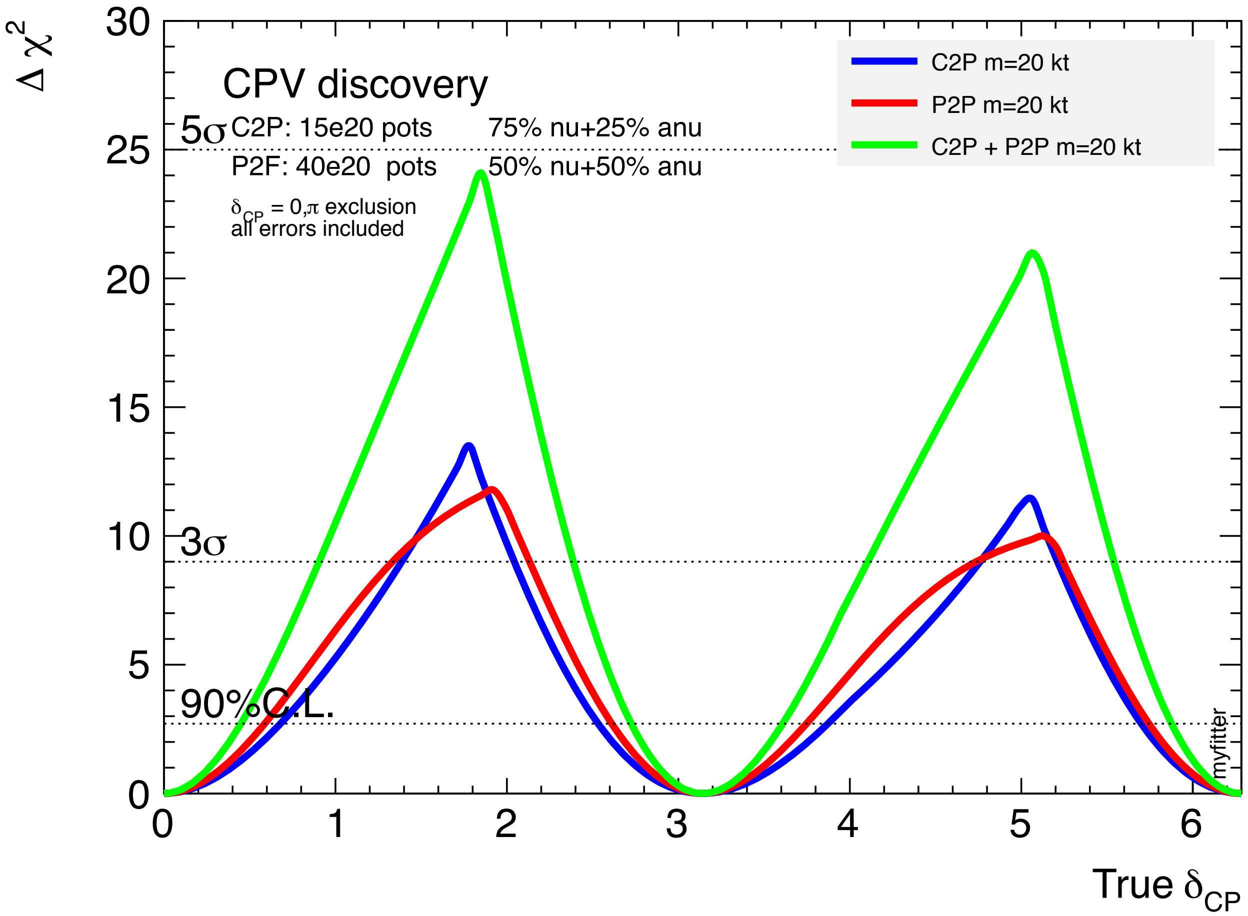



31 kt is the mass equivalent of a single detector for the statistics of the two beams

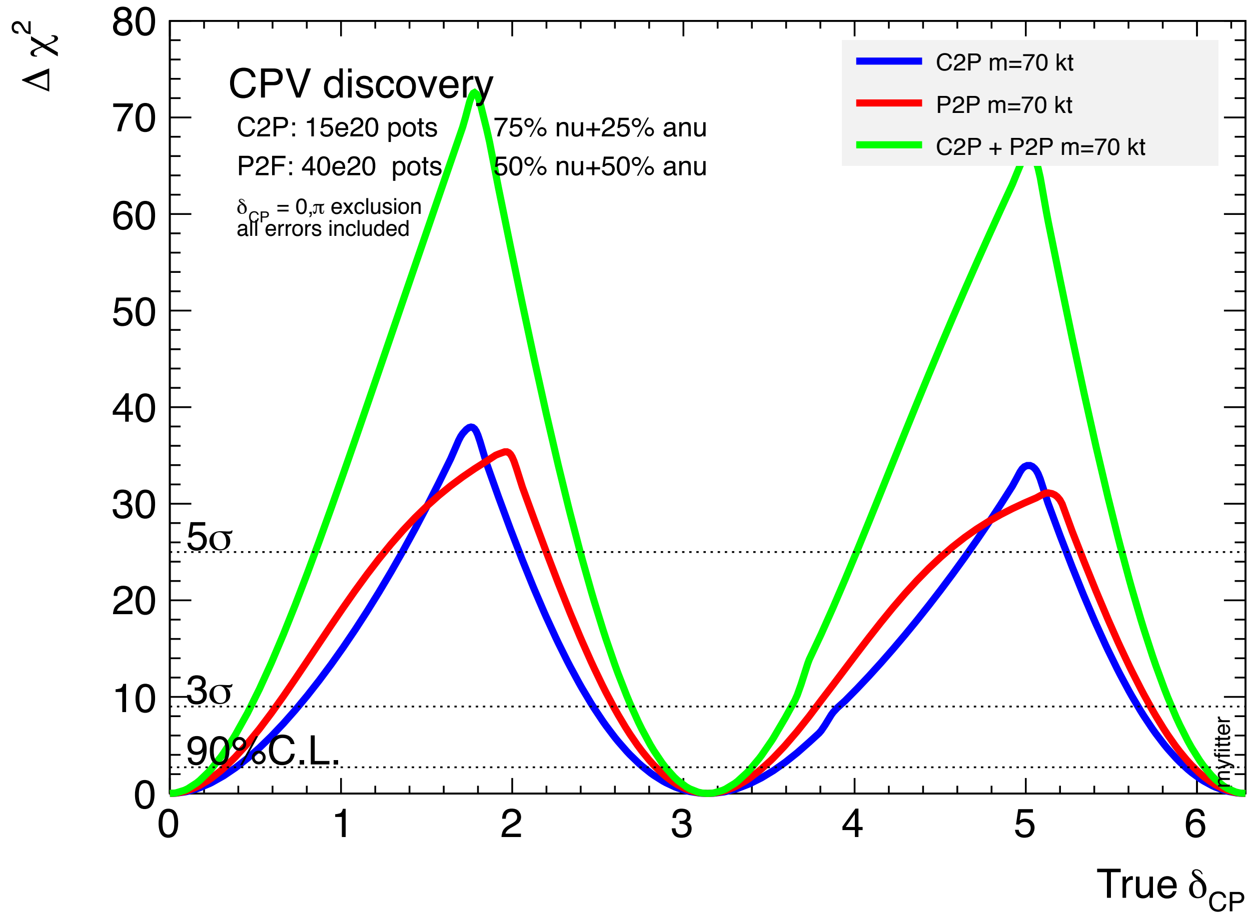
LBNO with Protvino beam

# LBNO with 2nd beam from Protvino

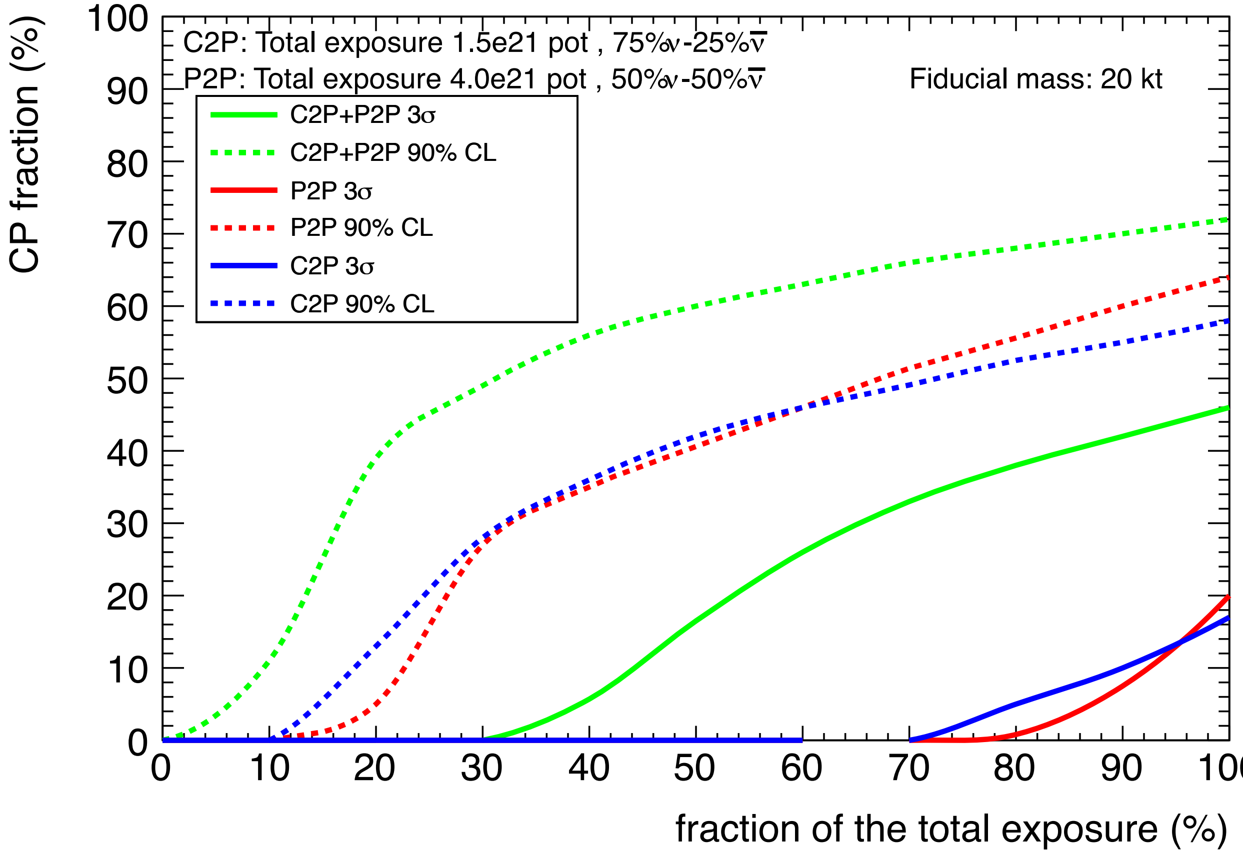
## 20 kt LAr

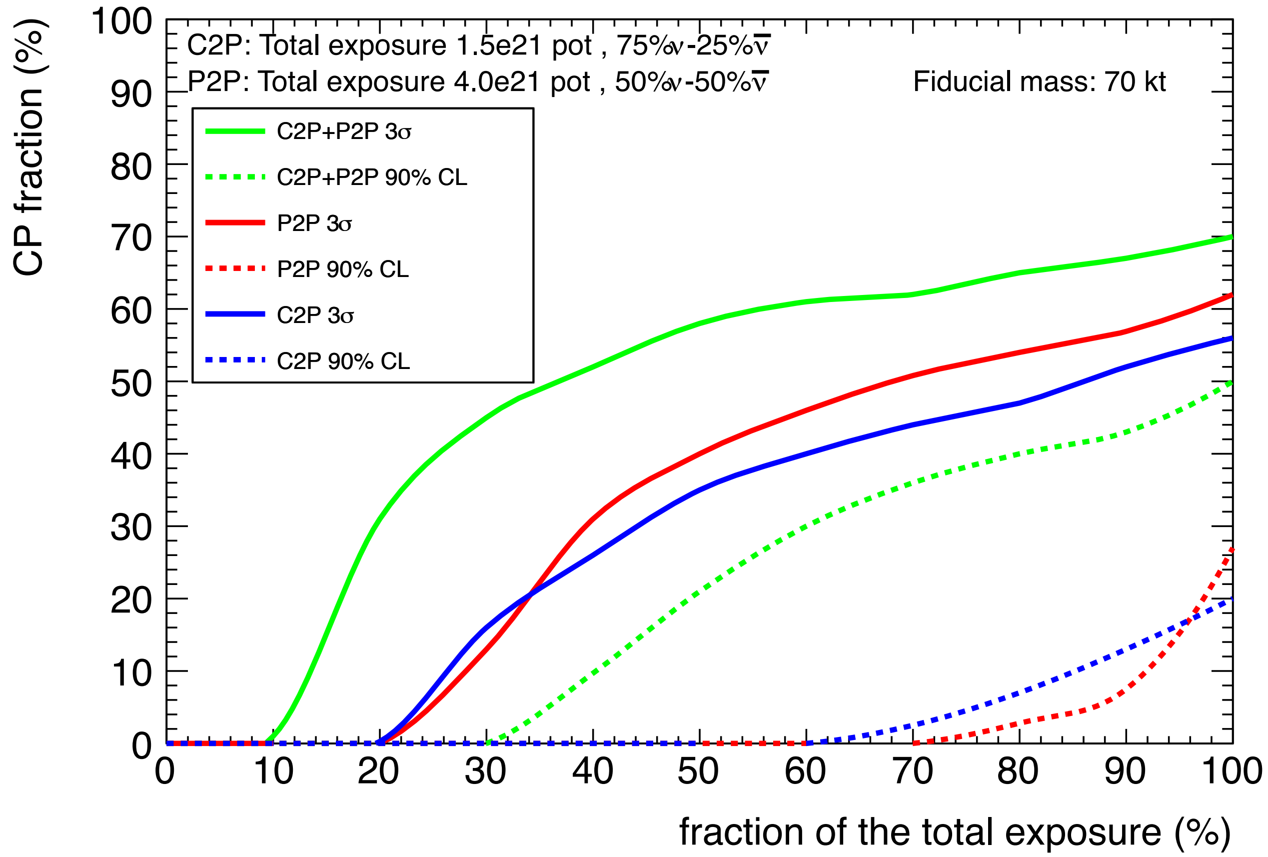



## 70 kt LAr



# LBNO with 2nd beam from Protvino

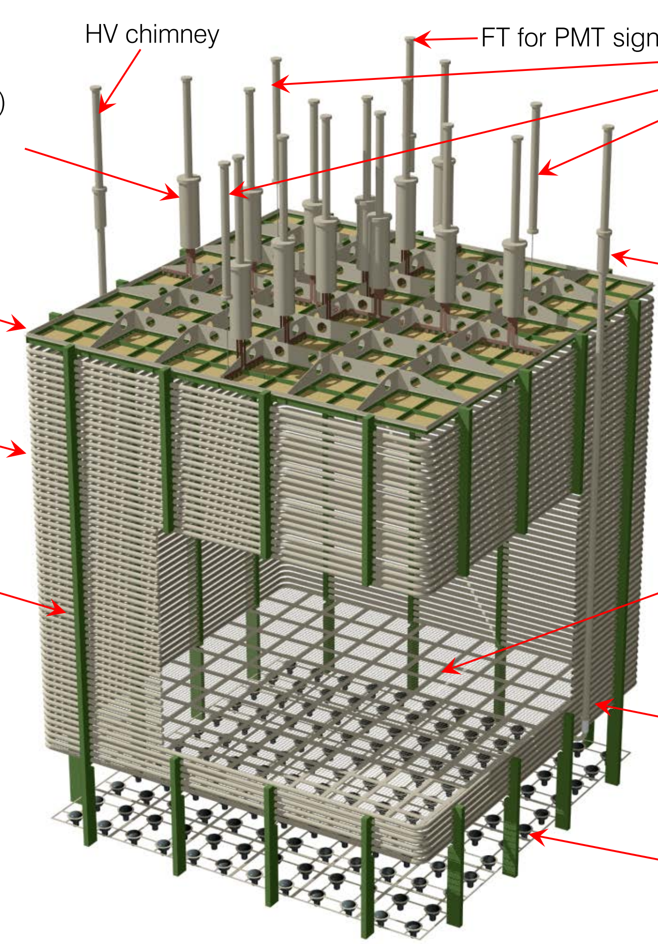


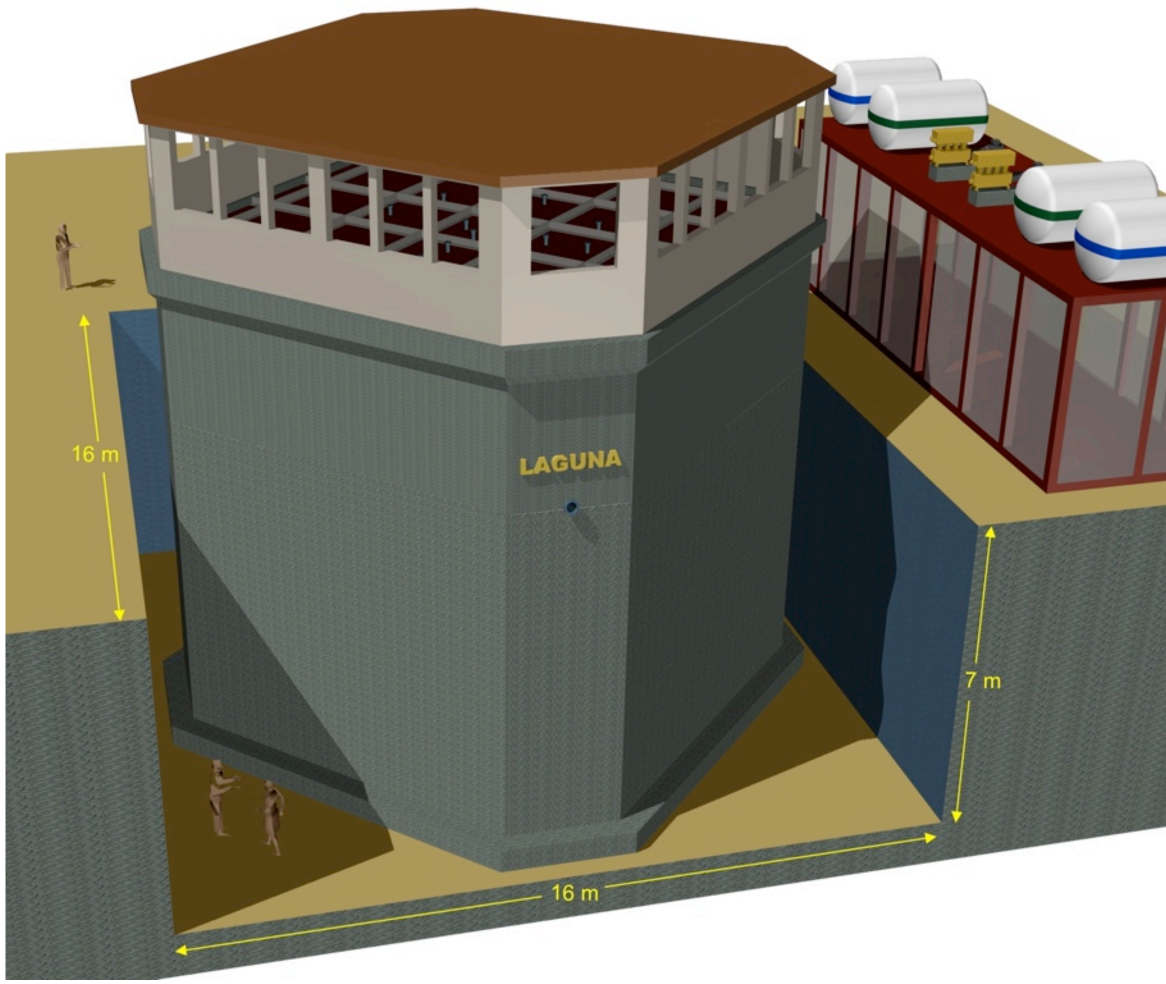




**Sensitivity to CP-violation, in terms of the fraction of δ can be excluded, as a function of the total exposure**

# 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**



# Conclusions

- **Next generation Neutrino Physics will come from new, large scale underground detectors**
- **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 LAr + 700 kW SPS**
- **Outstanding Physics Potential:**

**1. Accelerator based:**
- **Mass Hierarchy > 5 $\delta$ all phase space**
- **$\delta_{CP}$**
- **MSNP precision --> 3 $\nu$ or 3+n ?**

**2. Non-Accelerator based:**
- **Proton decay: Significantly** extended sensitivity to nucleon decay in many channels. **Br(p → anti-$\nu$ 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)**

- **R&D efforts show promising prospects, with a focus now shifting to larger scale demonstrators (as suggested by CERN SPSC). Far and near detectors engineering has started. Detailed technical investigations are being pursued at the Pyhäsalmi mine. Detailed cost estimates for construction are being developed.**
- **Need more collaborators, more support from the community, local governments, funding agencies and CERN. The project is OPEN and is still being defined. In particular, we are open to interested groups wanting to join the 6x6x6m3 prototype effort.**

# Acknowledgements


- FP7 Research Infrastructure "Design Studies" LAGUNA (Grant Agreement No. 212343 FP7-INFRA-2007-1) and LAGUNA-LBNO (Grant Agreement No. 284518 FP7-INFRA-2011-1)
- We are grateful to the CERN Management for supporting the LAGUNA-LBNO design study.
- We thank the CERN staff participating in LAGUNA-LBNO, in particular M.Benedikt, M.Calviani, I.Efthymiopoulos, A.Ferrari, R.Garoby, F.Gerigk, B.Goddard, A.Kosmicki, J.Osborne, Y.Papaphilippou, R.Principe, L.Rossi, E.Shaposhnikova and R.Steerenberg.
- We thank the HP-PS design study team J. Alabau, A. Alekou, F.Antoniou, M.Benedikt, B.Goddard, A.Lachaize, C.Lazardis, Y.Papaphilippou, A.Parfenova, R.Steerenberg.
- We thank André Rubbia for providing lots of transparencies.

# LAGUNA - LBNO...


**Thank you for your attention !**

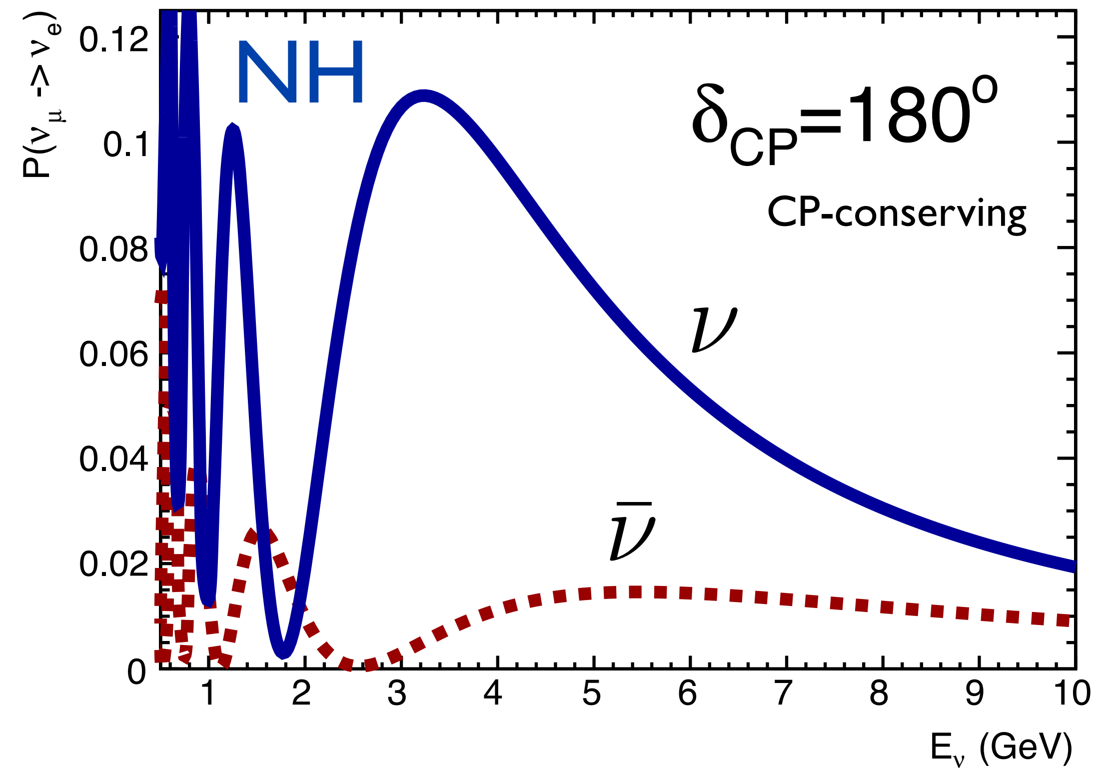
# Back-up slides

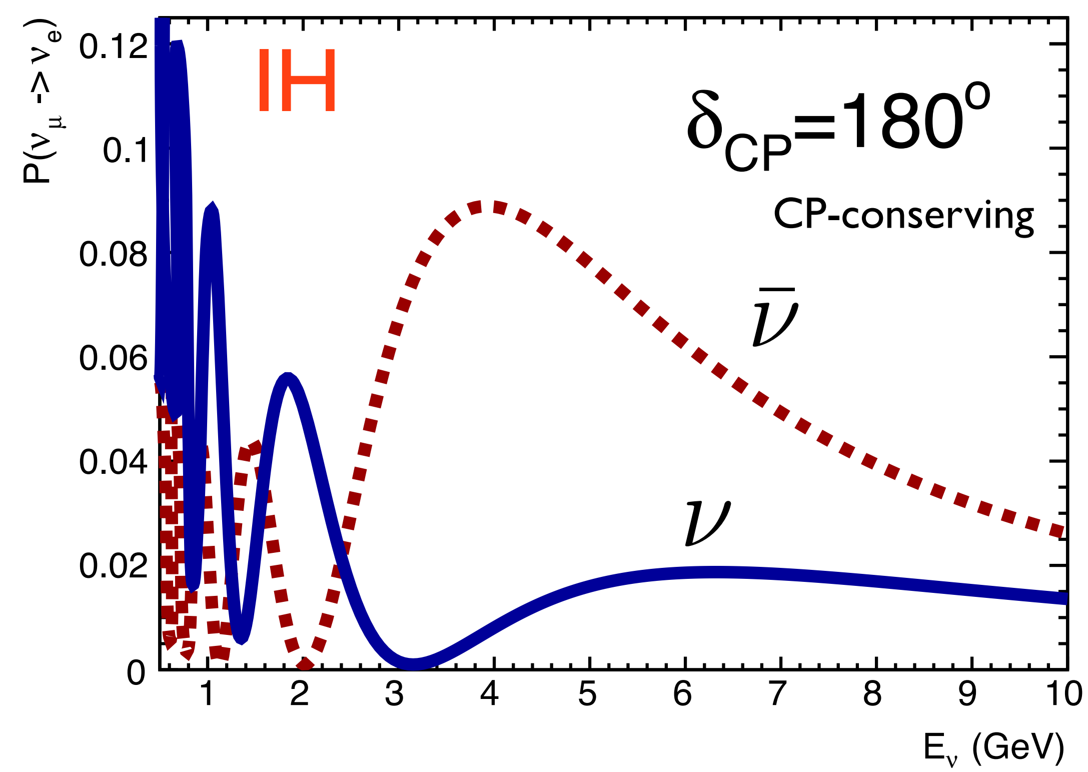
# Reaching very long baselines

- ★ **"Zoom effect"**: 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.
- ★ **Decoupling of MH and CPV:** 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)!
- ★ **Ultimate upgrade possibilities:** make a step towards the NF

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

L=2300 km




→ very clear signature !

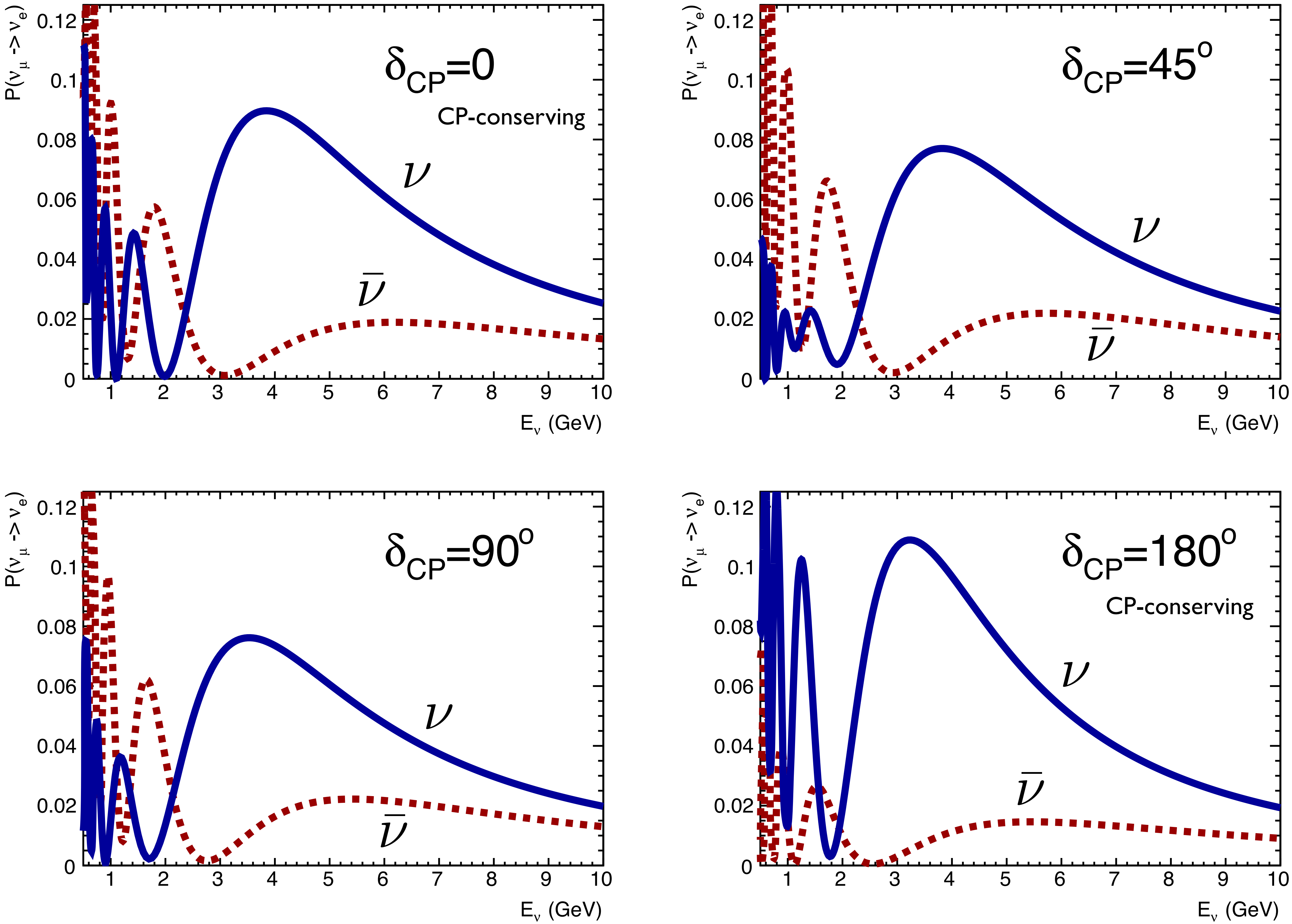
# An incremental approach

- **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

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

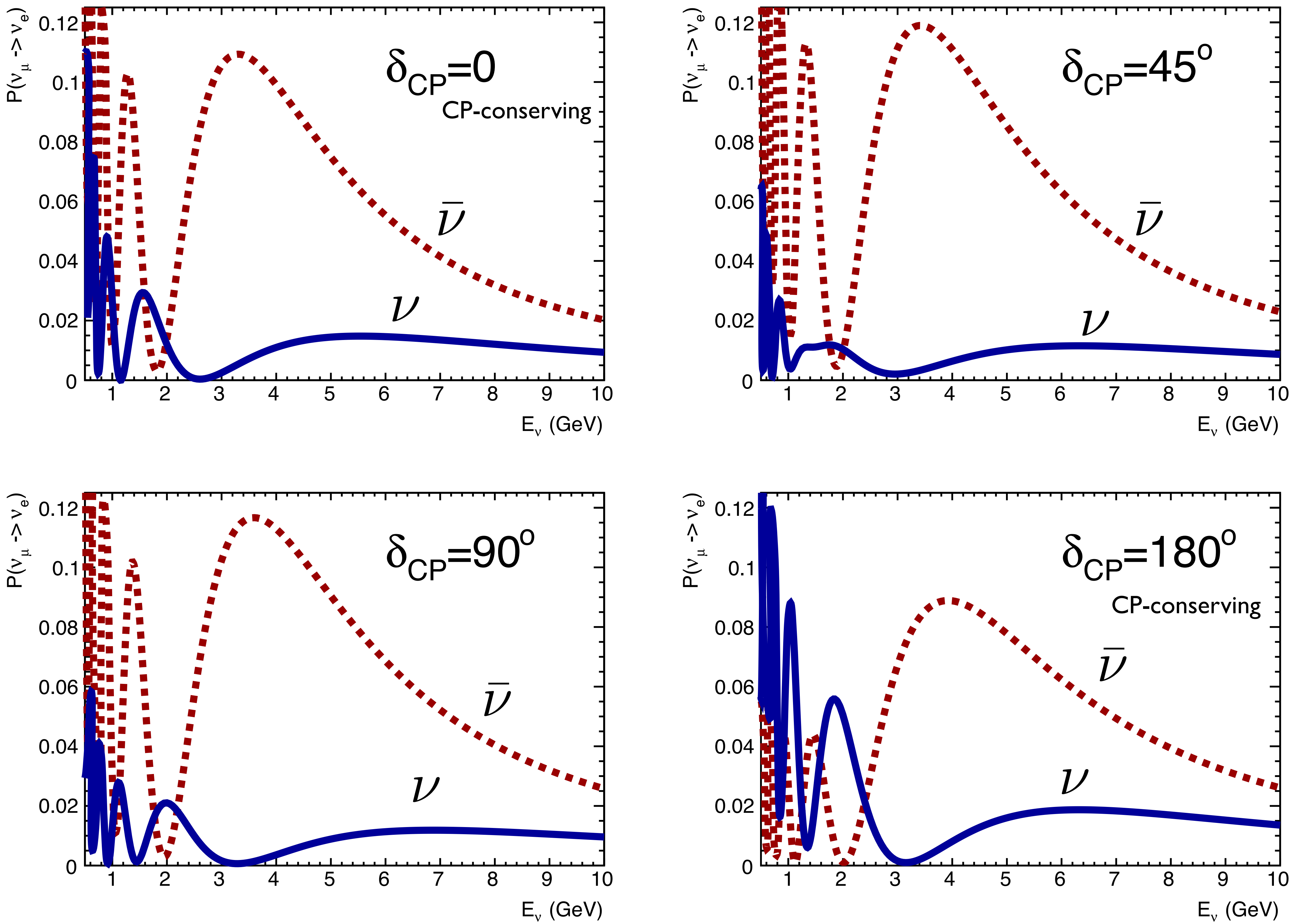


# LBNO: CP+matter effects in $\nu_\mu \rightarrow \nu_e$

★Inverted mass hierarchy

L=2300 km

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

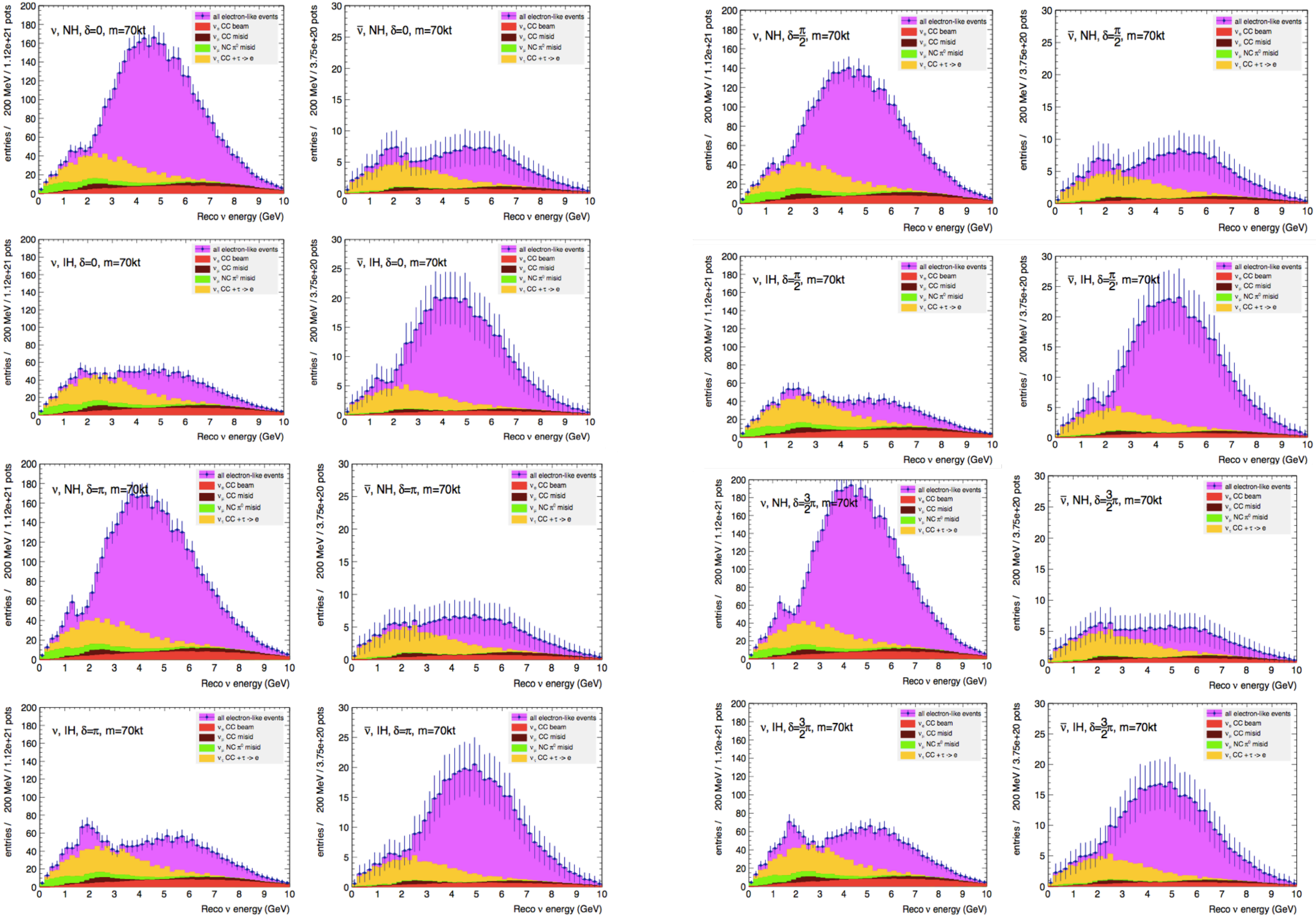


# Timeline

| LAGUNA-LBNO, LAr 20kT@PYHÄSALMI | year 1 | | | | year 2 | | | | year 3 | | | | year 4 | | | | year 5 | | | | year 6 | | | | year 7 | | | | year 8 | | | | year 9 | | | | year 10 | | | | year 11 | | | | year 12 | | | | year 13 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| CRITICAL DECISIONS TAKEN BEFORE YEAR 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -PM: contracts & site preparation | X | X | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| PILOT WORKS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -excavation (pilot cavern + shaft) | | | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -auxiliary infrastructure | | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - construction (floor + 1 kT tank) | | | | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - detector (transport from CERN) | | | | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - detector (installation) | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - liquid handling (filling 1 kT LAr) | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - start + testing of experiment (1 kT LAr) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| EXCAVATION (1 LAr stand alone) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -main detector cavern no. 1 | | | | | | | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -auxiliary infrastructure | | | | | | | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 20KT LAR TANK CONSTRUCTION | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -foundation (floor + columns) | | | | | | | | | | | | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -off site preparation works | | | | | | | | | | | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -20kT tank & roof + water test | | | | | | | | | | | | | | | | | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -chemical cleaning | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| DETECTOR INSTRUMENTATION | *Note: to be finalized with D3.1 works* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - PMT fabrication + transport to site | | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| -detector (light+charge readout) | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | |
| - cabling, electronics & testing | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| -close of tank + perlite | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | |
| LIQUID + ON-SURFACE INFRASTRUCTURE | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - On-surface computer centre, offices etc. | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | |
| - On-surface purification & storage plants | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| -underground liquid infrastructure | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | |
| LIQUID HANDLING + COMMISIONING | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - filling with LAr | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | | | | | | | | | | | | | | | | | | | | |
| START OF EXPERIMENT | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| - 20kT final testing and calibration | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X | | | | | | | | | | | | | | | | |

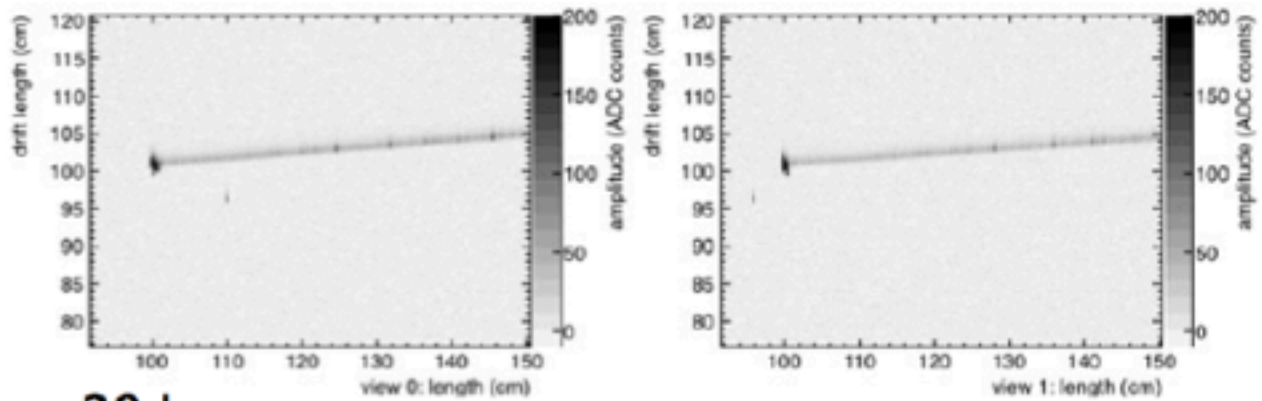
# More on $\delta_{CP}$:

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



# Comparing liquid vs gas argon

liquid Ar




Ar gas 20 bar