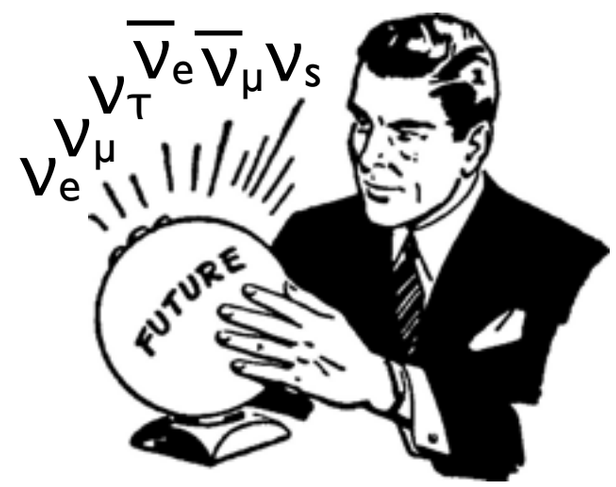
HEP 2013
Stockholm
18-24 July 2013
( info@eps-hep2013.eu )

# Neutrino programme: the future

*where and how many?*





## André Rubbia (ETH Zürich)


Special ECFA session: Particle Physics after the European Strategy Update


ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



EPS-HEP 2013, Stockholm, Sweden, July 18-24th, 2013

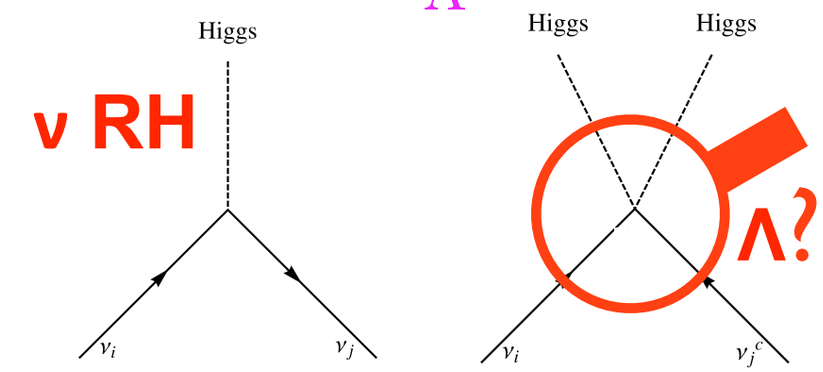

LAGUNA

v2

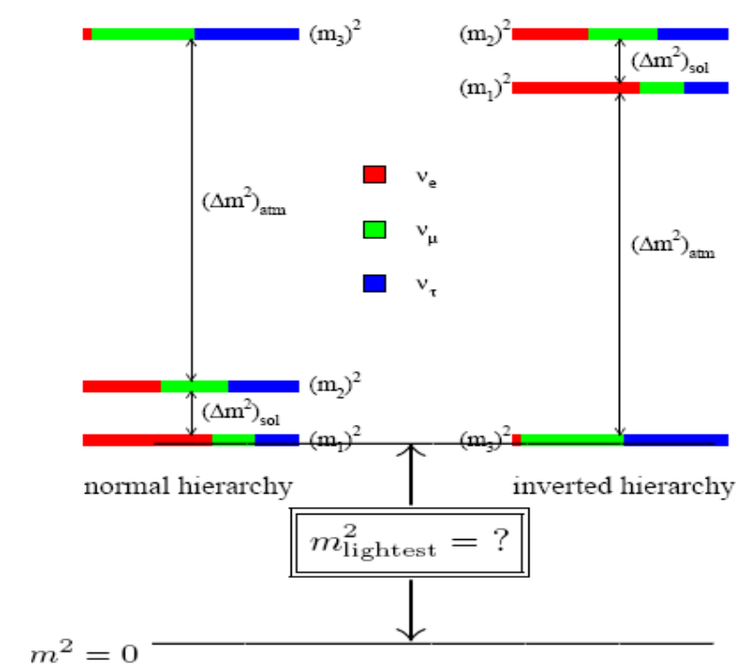
# Neutrinos at the frontier

- **Neutrinos play a fundamental and special role in particle physics, astrophysics and cosmology**
- **Neutrino masses** → presently the <u>only</u> evidence of new physics beyond the SM – additional d.o.f. <u>must</u> exist: either **ν RH** and/or **new scale Λ** (>> TeV ?)
- **A window to questions related to a deeper description of physics and to the evolution of the Universe:**
  - Why are neutrino masses so small ?
    Why is the mixing matrix so different than the one of quarks? What does this picture suggest ?
  - **How is the hierarchy of the ν mass eigenstates ?**
  - Which is the absolute mass of the lightest state ?
  - Are neutrinos Majorana particles ?
  - **P, CP, CPT are fundamental symmetries. "P is maximally violated by neutrinos but CP is saved" (W. Pauli). Is CP violated by neutrinos as well or is it a special feature of quarks ?**
  - Are there sterile states and is there mixing … ?

$$\underbrace{Y^{ij}\Psi_L^i\Psi_R^j\phi}_{-\mathcal{L}_{\rm Dirac}} + \underbrace{\frac{g^{ij}}{\Lambda}\Psi_L^i\Psi_L^{T,j}\phi\phi^T}_{-\mathcal{L}_{\rm Majorana}}$$



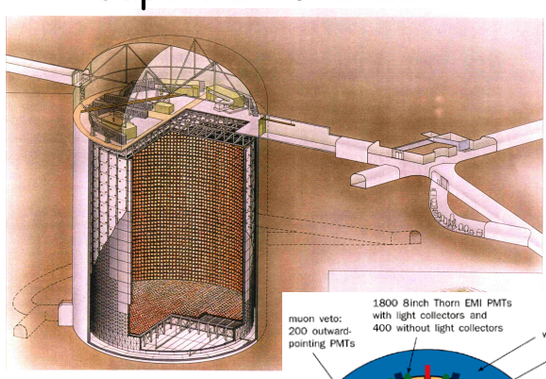

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

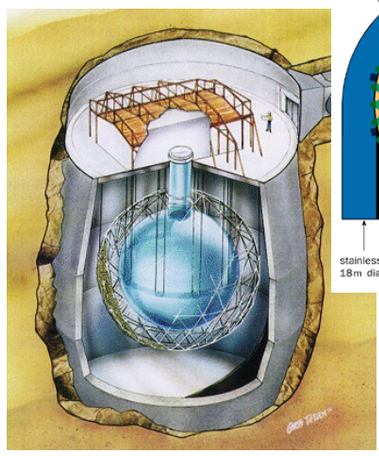


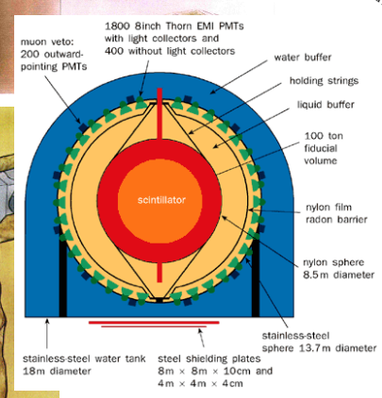
# The past and present

- **A rich and varied experimental neutrino oscillations programme:**
  A decade of revolutionary experiments have unravelled a new flavour sector

SuperKamiokande



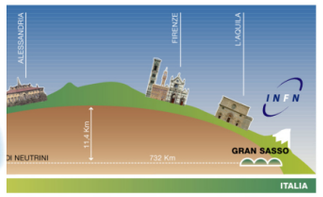





SNO

Borexino

MINOS, Opera

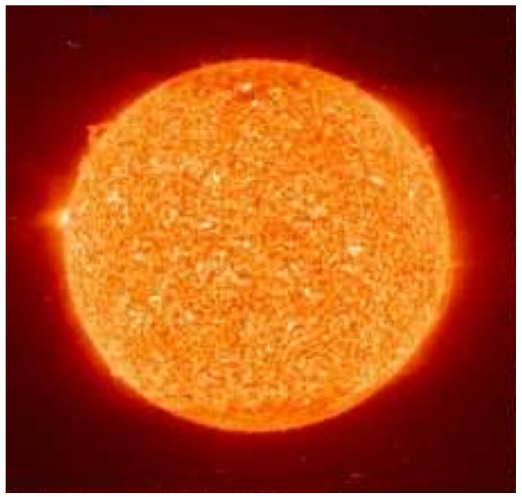

...and more

- **Equally fundamental but not discussed here due to lack of time:**
  - **Experiments at end-point of single beta decays aimed at measuring the absolute neutrino mass (KATRIN) and new searches for neutrino-less double beta decays to test Majorana nature of neutrinos (CUORE, EXO, GERDA, Kamland-Zen, Majorana, NEMO, NEXT, SNO+, ...)**
  - **Cosmological observations yielding information on neutrino properties**

# Global data on neutrino oscillations

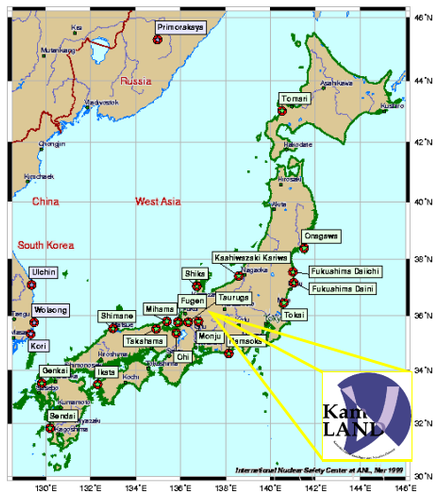
from various neutrino sources and
vastly different energy and distance scales:

sun



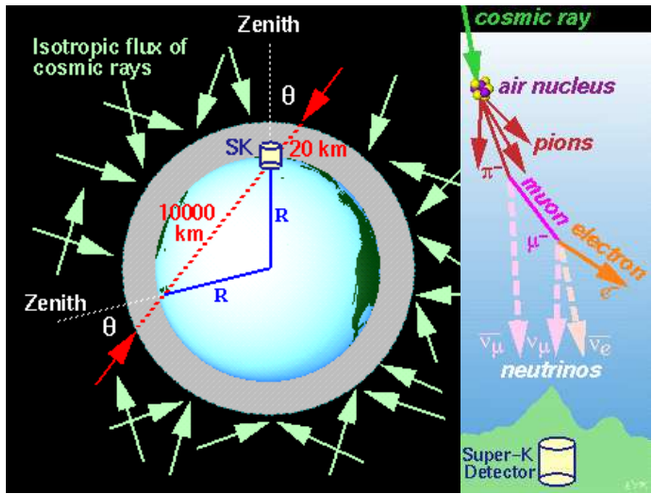
Homestake,SAGE,GALLEX
SuperK, SNO, Borexino

reactors




KamLAND, CHOOZ

atmosphere




SuperKamiokande

accelerators

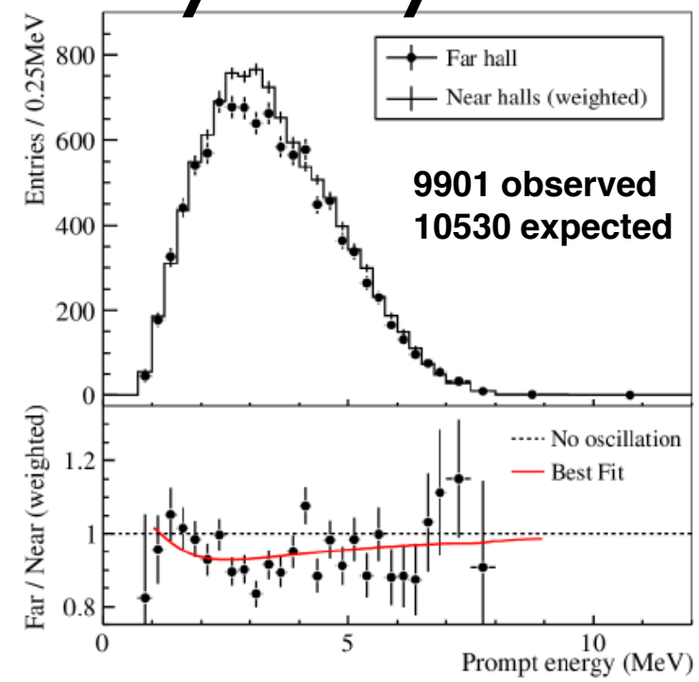

K2K, MINOS, T2K

- global data fits nicely with the 3 neutrinos from the SM
- a few "anomalies" at 2-3 $\sigma$: LSND, MiniBooNE, reactor anomaly,
  - *Sterile* states conceivable, would imply PMNS matrix non-unitary

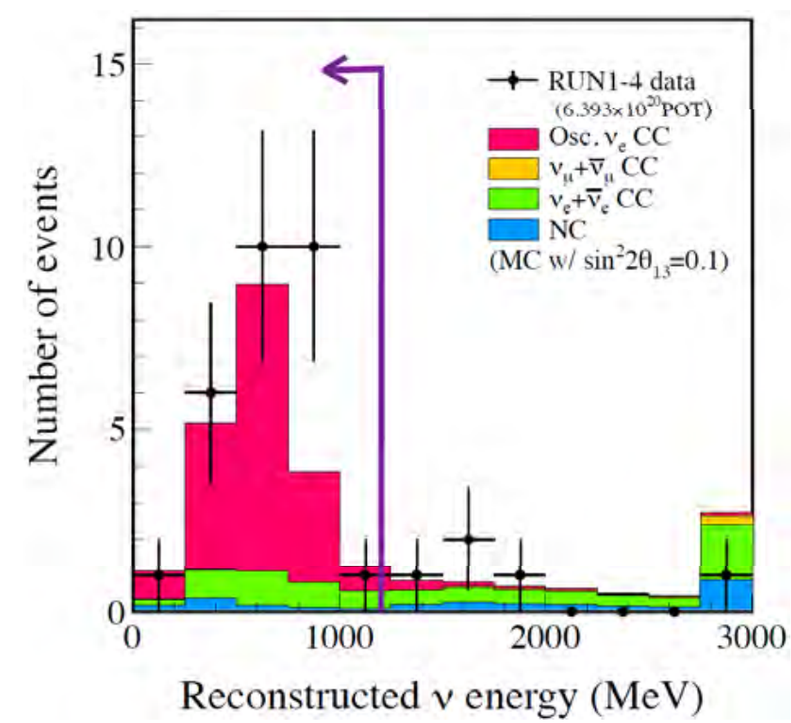
# Discovery of $\Theta_{13}$: a turning point

- **$\nu\mu \rightarrow \nu e$ oscillations and $\Theta_{13}$**
  - **June 2011**: First result from T2K off-axis beam experiment ($\nu\mu \rightarrow \nu e$ appearance)
    6 events observed, 1.5 events background → 2.5σ for non-zero $\Theta_{13}$
  - **March 2012**: Daya Bay reactor anti-neutrinos $\bar{\nu}e \rightarrow \bar{\nu}x$ ($\bar{\nu}e$ disappearance) → 5.2σ exclusion of no oscillation hypothesis. Also Double Chooz and RENO.
  - **July 2013**: **T2K reports 28 candidate events for electron appearance with 4.64±0.53 events background** → 7.5σ discovery of appearance of new flavour in neutrino oscillations
- NOvA at Ash River is completing construction and beam is expected with a partial detector in the coming weeks. We look forward to a successful startup !
- **We entered in a new era → With large $\Theta_{13}$ the next steps are accessible with conventional neutrino beams, and CPV & MH become the new goals!**

Daya Bay result

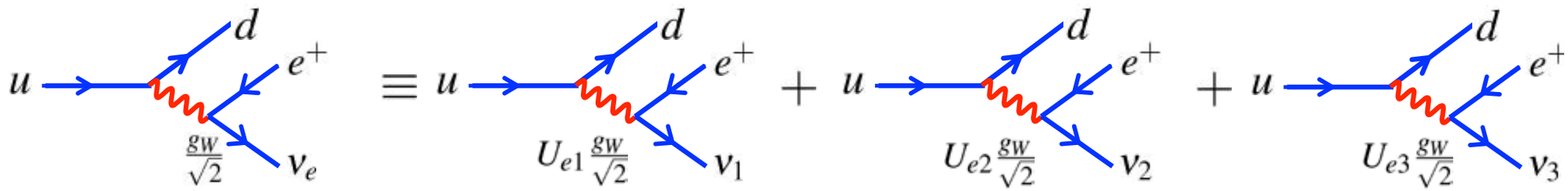



T2K 2013 result



# The 3νSM paradigm: where we are today

- Weak eigenstates are coherent superposition of the fundamental mass eigenstates:




★ **The 3x3 Unitary matrix $U$ is known as the Pontecorvo-Maki-Nakagawa-Sakata matrix, usually abbreviated PMNS**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

http://www.nu-fit.org: arXiv:1209.3023

Not updated with latest results!

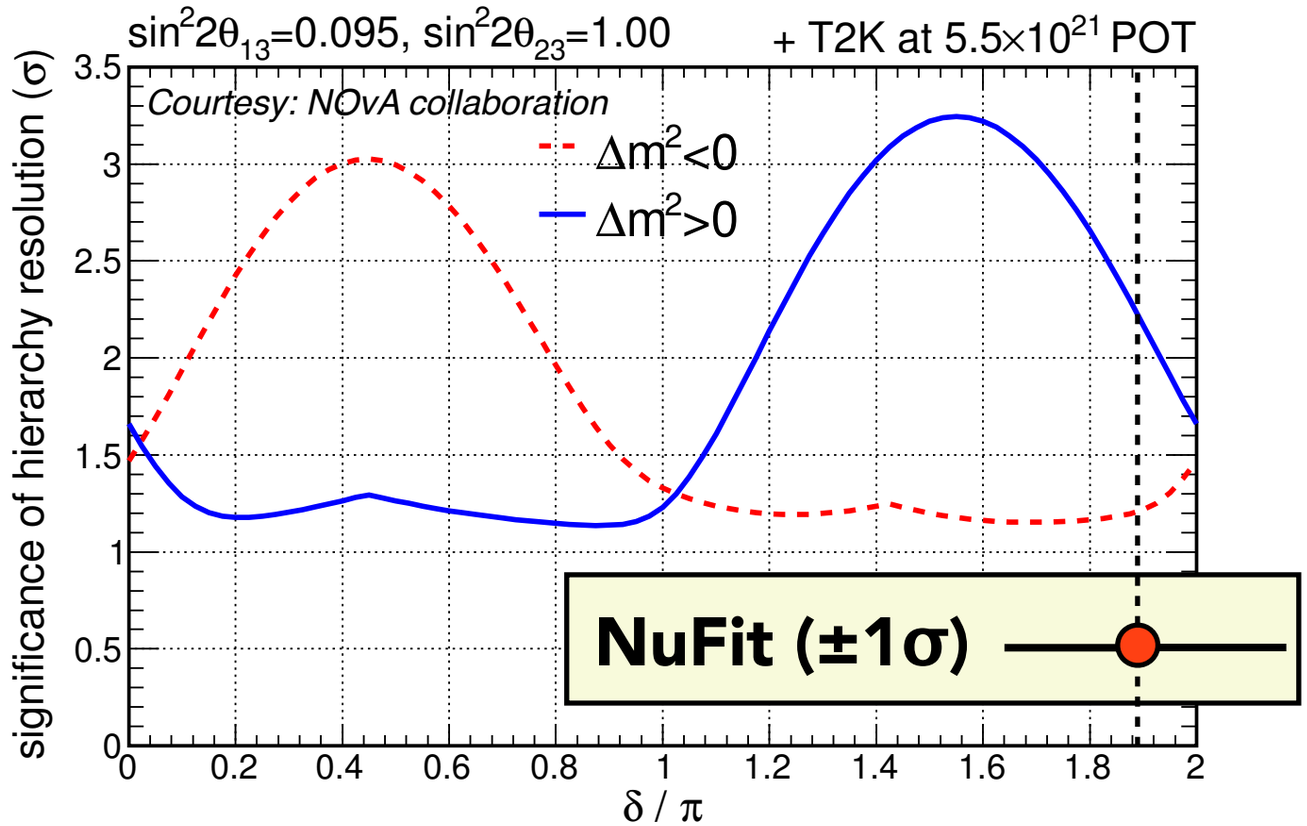
| | Fluxes + RSBL | |
|---|---|---|
| | bfp $\pm 1\sigma$ | $3\sigma$ range |
| $\sin^2\theta_{12}$ | $0.306^{+0.012}_{-0.012}$ | $0.271 \to 0.346$ |
| $\theta_{12}/^\circ$ | $33.57^{+0.77}_{-0.75}$ | $31.38 \to 36.01$ |
| $\sin^2\theta_{23}$ | $0.437^{+0.061}_{-0.031}$ | $0.357 \to 0.654$ |
| $\theta_{23}/^\circ$ | $41.4^{+3.5}_{-1.8}$ | $36.7 \to 54.0$ |
| $\sin^2\theta_{13}$ | $0.0231^{+0.0023}_{-0.0022}$ | $0.0161 \to 0.0299$ |
| $\theta_{13}/^\circ$ | $8.75^{+0.42}_{-0.44}$ | $7.29 \to 9.96$ |
| $\delta_{CP}/^\circ$ | $341^{+58}_{-46}$ | $0 \to 360$ |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.45^{+0.19}_{-0.16}$ | $6.98 \to 8.05$ |
| $\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N) | $+2.421^{+0.022}_{-0.023}$ | $+2.248 \to +2.612$ |
| $\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I) | $-2.410^{+0.062}_{-0.063}$ | $-2.603 \to -2.226$ |

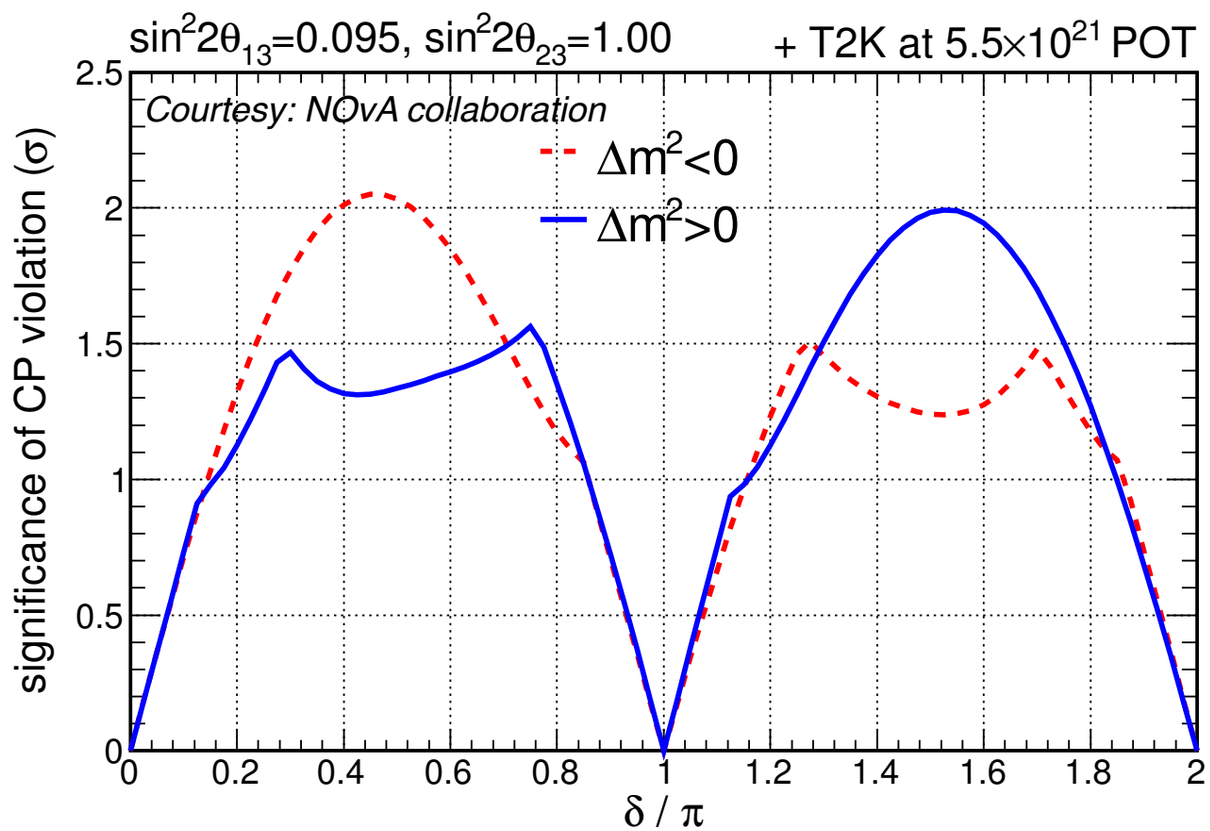
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{“Atmospheric”}} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“Solar”}}$$

**Dominates:** “Atmospheric” “subleading” “Solar”

- **Pre-EPS-HEP2013 precision on parameters: $\delta(\theta_{12})\approx 2\%$, $\delta(\theta_{23})\approx 8\%$, $\delta(\theta_{13})\approx 5\%$, $\delta(\Delta m^2_{21})\approx 3\%$, $\delta(\Delta m^2_{31})\approx 1\%$(NH)-$3\%$(IH)**
- **All values of CP-phase δ are allowed at 3σ C.L.**
- **No hints for neutrino mass hierarchy (MH)**
- **Both NH and IH solutions are allowed**
- Caveat: Global fits deliver the best adjustment to the existing data, but cannot prove the models. They cannot replace new direct experimental tests.

# T2K and NOvA: the future until ≈2020




Mass hierarchy determination:

- combined fit NOvA (6 years of nominal running) + T2K pot projection
- exploiting bigger matter effect (≈30%) at 830km(NOvA) comparing to 295km(T2K)
- strongly depends on true value of $\delta_{CP}$ and on true hierarchy (NH/IH)
- **>50% phase-space unreachable**

CP-violation discovery:

- combined fit NOvA (6 years of nominal running) + T2K pot projection
- **in the best case a 2σ hint**
- affected by uncertainty of MH

**⇒New experiments needed beyond 2020 !**

# How to test CPV in neutrino sector?

- If PMNS matrix is complex, then neutrino and antineutrinos will behave differently in their flavour oscillations. CP and T will be violated (CPT conserved). This excludes disappearance channels (e.g. $\nu_e \to \nu_e$).

  → **Main channel of investigation: the appearance channel $\nu_\mu \to \nu_e$**

- **Neutrino/antineutrino difference:** $P(\nu_\mu \to \nu_e; E) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e; E)$

  ➡ Sensitive to any origin (in principle not only induced by $\delta_{CP}$)

- **Energy dependence of oscillation probability, independently for neutrinos and antineutrinos:**

$$P(\nu_\mu \to \nu_e; L) \simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \left\{1 + \frac{a}{\delta m_{31}^2} \cdot 2(1 - 2s_{13}^2)\right\} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$
$$+ c_{13}^2 s_{13} s_{23} \left\{-\frac{aL}{E} s_{13} s_{23}(1 - 2s_{13}^2) + \frac{\delta m_{21}^2 L}{E} s_{12}(-s_{13} s_{23} s_{12} + c_\delta c_{23} c_{12})\right\} \sin \frac{\delta m_{31}^2 L}{2E}$$
$$- 4\frac{\delta m_{21}^2 L}{2E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$

$$a \equiv 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm^{-3}}} \frac{E}{\mathrm{GeV}}$$

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*Matter terms∼a*

*CP-even*

*L/E dependence*

*CP-odd∼sin$\delta_{CP}$*

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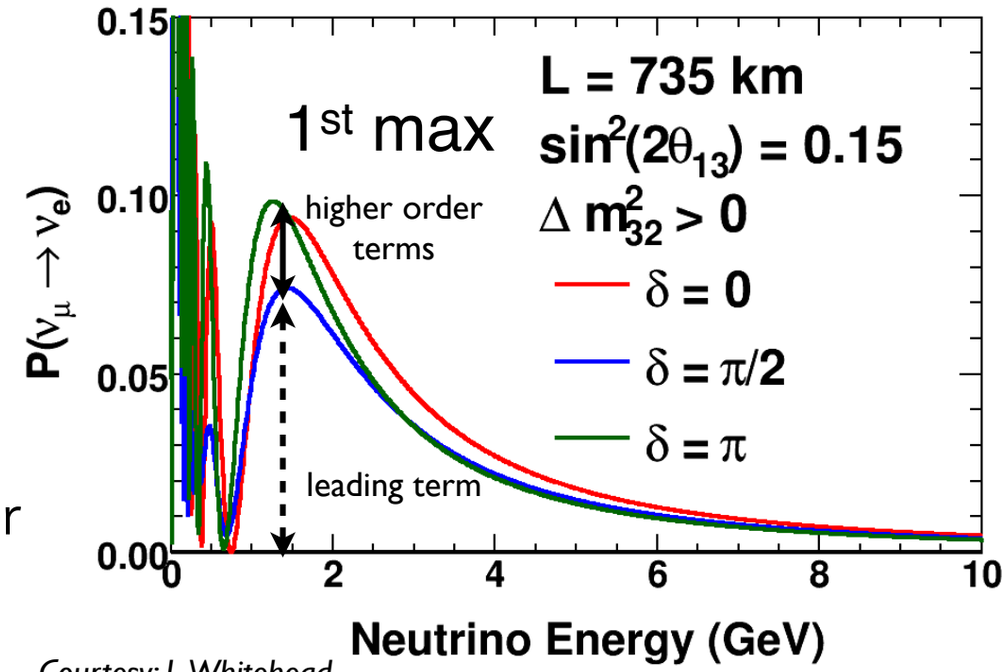
➡ Direct test of $\delta_{CP}$ origin of CPV and of matter terms

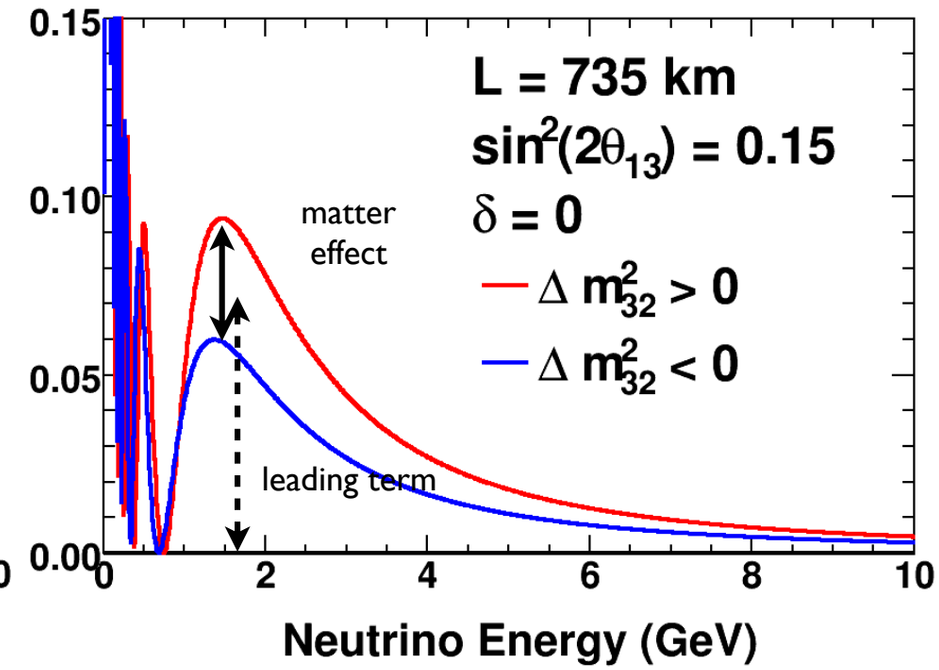
# Matter effects and CPV degeneracy

Matter effects in Earth mimic CP violation as they affect neutrinos and antineutrinos differently
→ They have to be accurately <u>measured</u> and subtracted in order to look for CP

δ dependence




mass hierarchy dependence



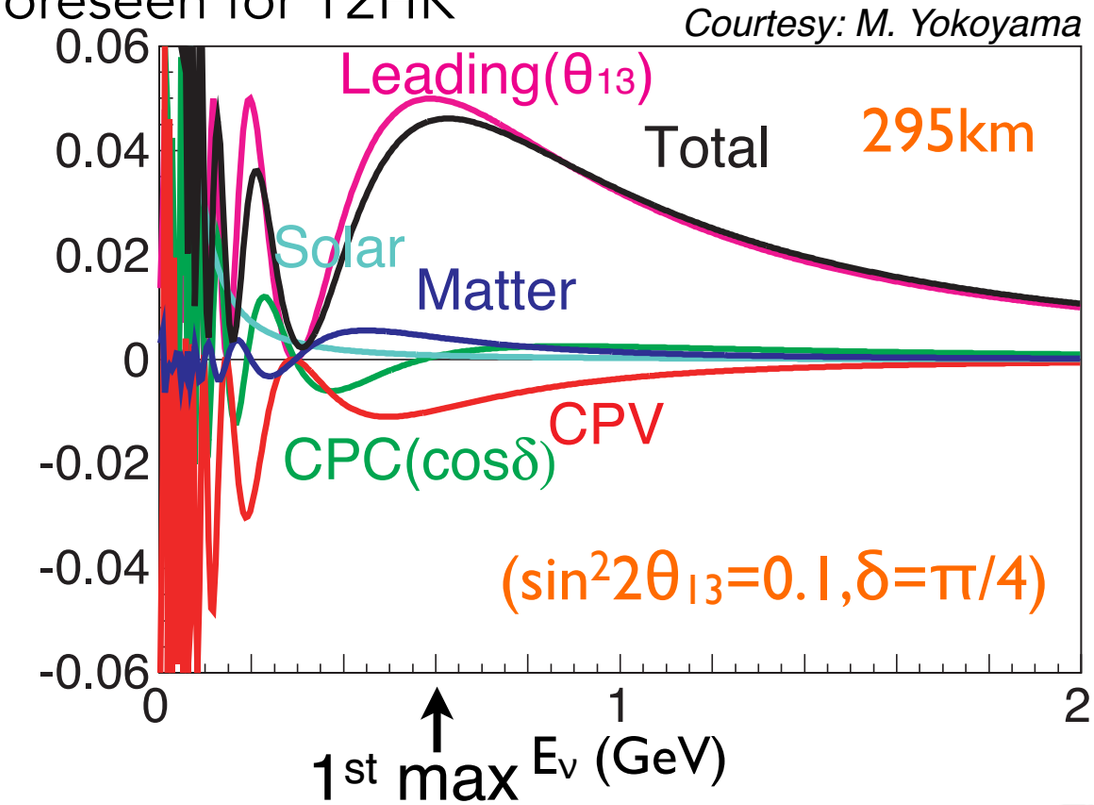

*Courtesy: L.Whitehead*

**<u>Example</u>**: 295 km baseline such as T2K and foreseen for T2HK

Leading term $\propto \sin^2 2\theta_{13}$
CPV term $\propto \sin 2\theta_{13}$
Matter effect $\propto \sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$
signal ↑, CP asymmetry ↓
matter/CP ↑

*Courtesy: M. Yokoyama*



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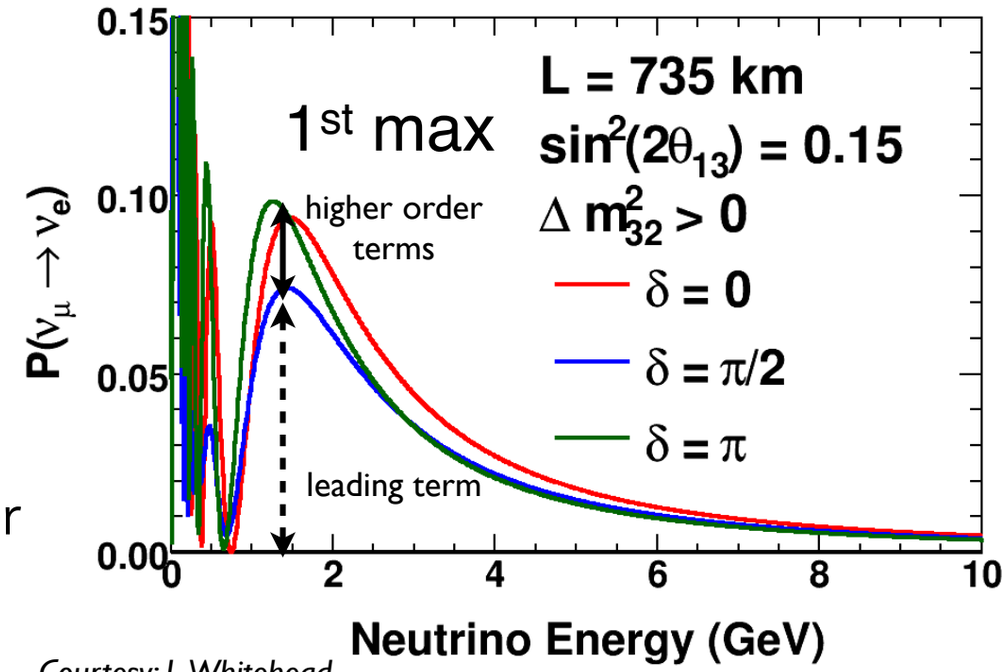
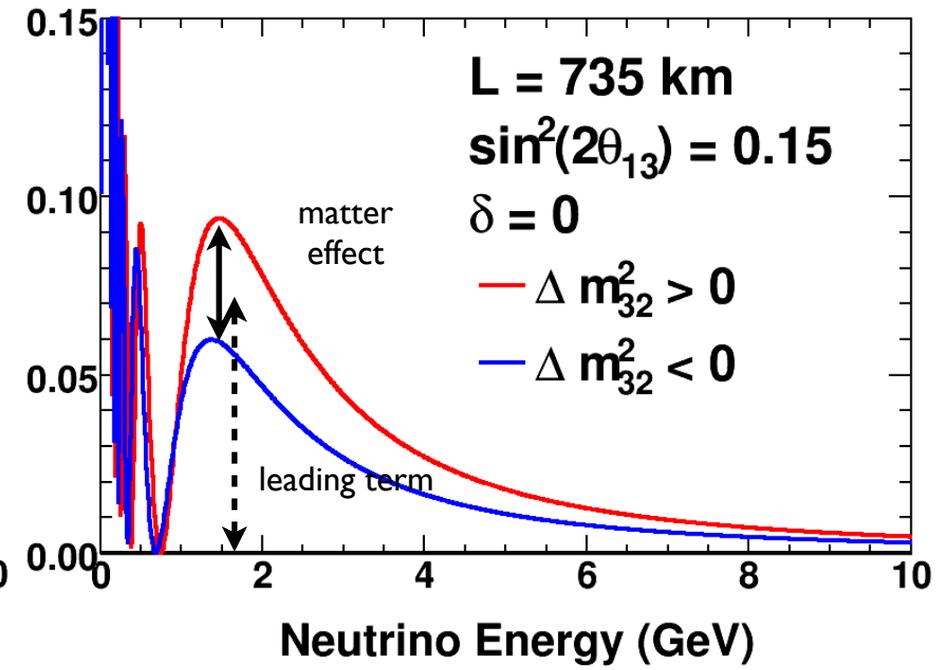



mass hierarchy dependence

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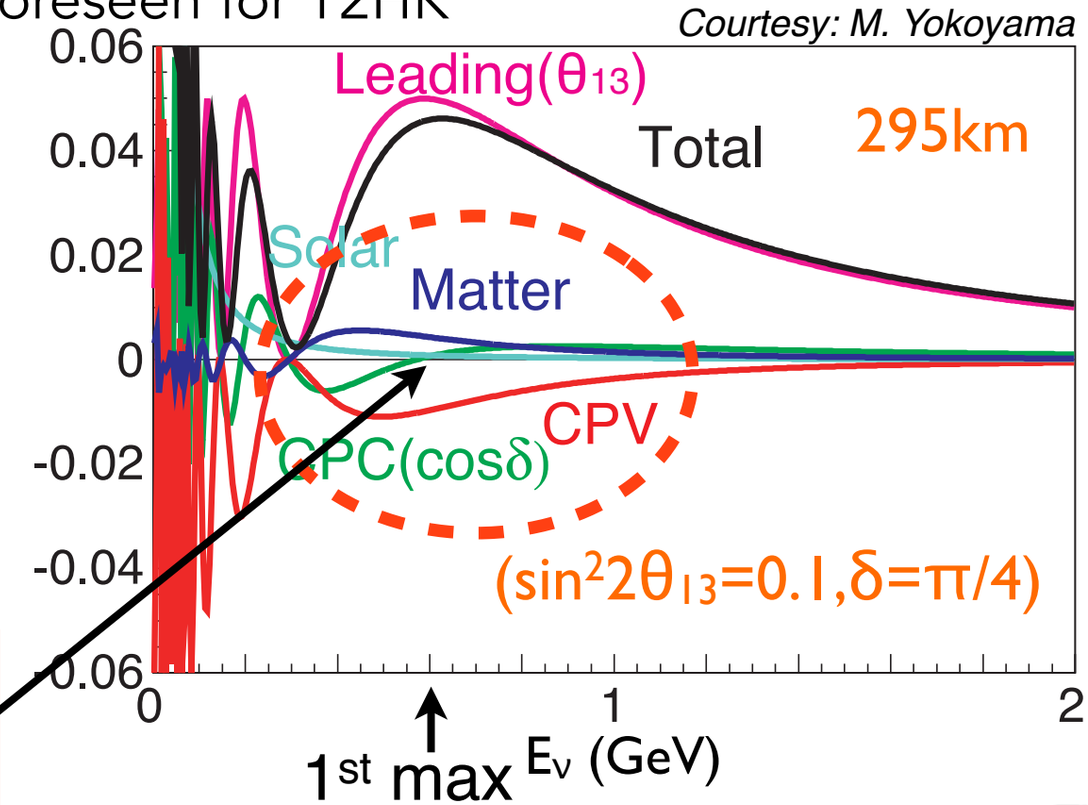



**Matter effects and CPV asymmetries are of the same order !**

# Enhanced CP effect at 2nd maximum

- **Matter- and pure CP-terms are disentangled by their different L/E dependence and by the growing CP effect with L/E:**

$$\mathcal{A} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

$$16\frac{a}{\delta m^2_{31}}\sin^2\frac{\delta m^2_{31}L}{4E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

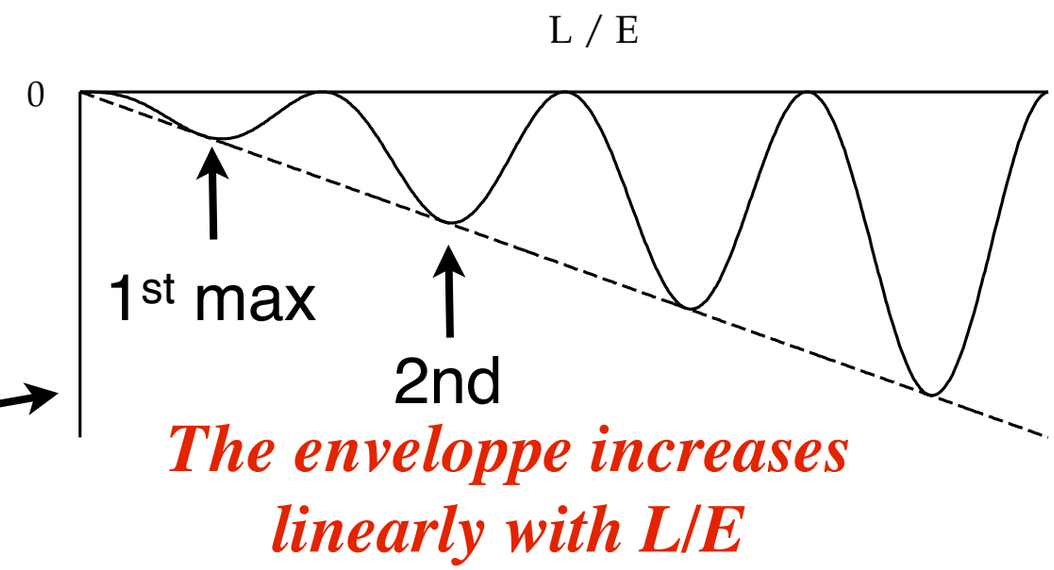
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

$$-8\frac{\delta m^2_{21}L}{2E}\sin^2\frac{\delta m^2_{31}L}{4E}s_\delta c^2_{13}s_{13}c_{23}s_{23}c_{12}s_{12}$$

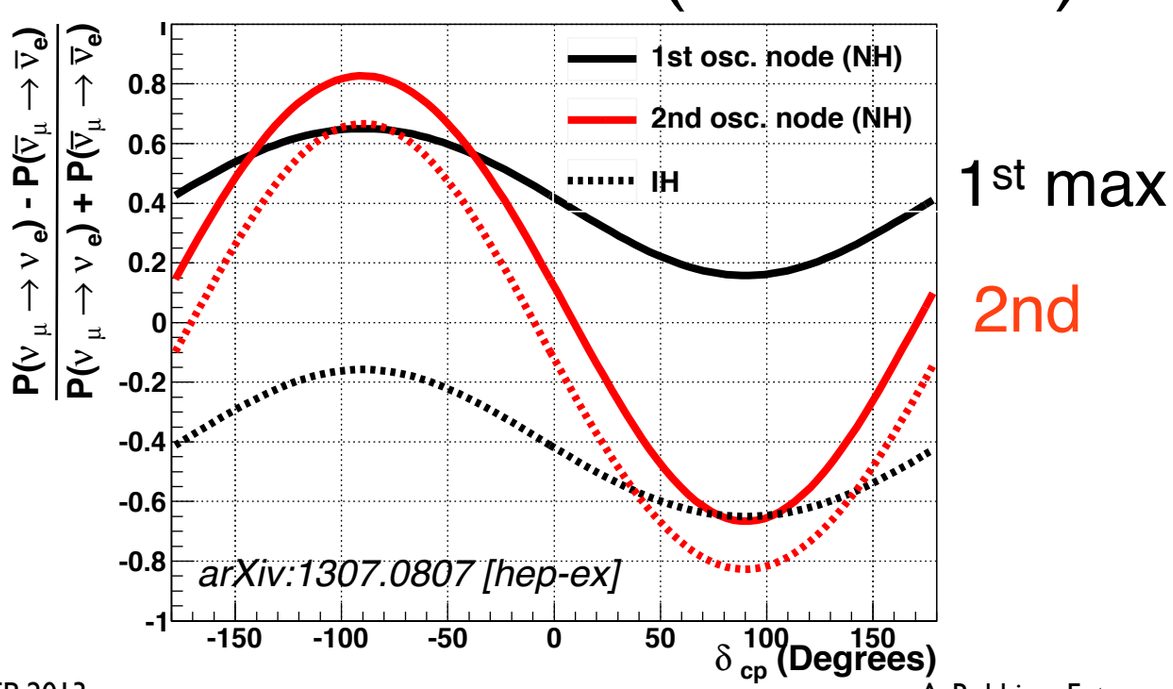
***Matter terms***

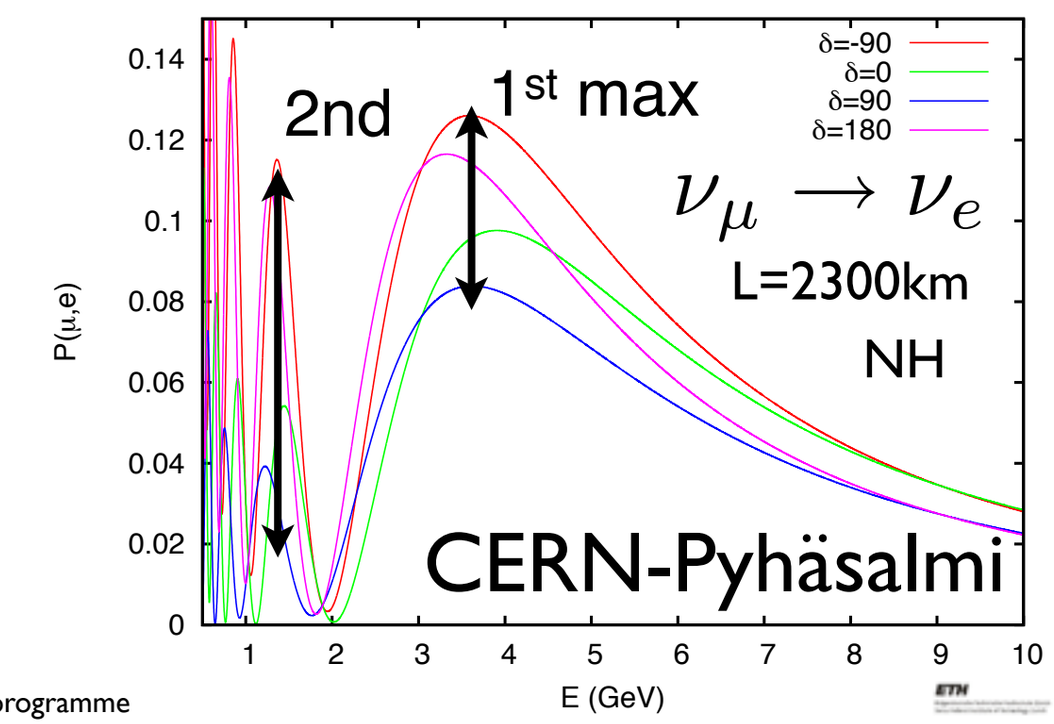
***Pure CP-term***

$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}$$




FNAL-Homestake (L=1300km)



# Worldwide interest in LBL ν oscillations

- **Japan: T2K approved with Phase II as option (April 2004)**
  - Beyond T2K, an upgrade of JPARC beam to multi-megawatt power and new far detector (JPARC neutrino beam used by T2K is already MW-capable).
- **Astro Particle Physics European Committee (ApPEC, 2007)**
  - We recommend that a new large European infrastructure is put forward as a future international multi-purpose facility for improved studies of proton decay and of low- energy neutrinos from astrophysical origin (…) should also address the underground infrastructure and the possibility of an eventual detection of future accelerator neutrino beams.
- **US particle physics project prioritization panel (US P5, 2008)**
  - The P5-panel recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technologies for a large multipurpose neutrino and proton decay detector.
- **China (2012)**
  - Implementation of 2$^{nd}$ phase Daya Bay II (JUNO) for precision neutrino oscillation parameter measurements and MH determination.
- **Korea (2012)**
  - Considering 2$^{nd}$ phase with RENO-50 for precision neutrino oscillation parameter measurements and MH determination.
- **CERN European Strategy (2013)**
  - Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

# More specifically in Europe...

- **LAGUNA DS** (FP7 Design Study 2008-2011)
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **EUROν DS** (FP7 DS High Intensity Neutrino Beams, 2008-2012)
  - Superbeam (HP-SPL), Betabeam and Neutrino Factory
- **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, CERN-SPSC-EOI-007)
  - Consensus towards full long baseline physics + full astroparticle as mandatory physics drivers
  - An incremental approach with clear phase 1 physics goals and well-defined upgrade plan
  - ~230 authors; 51 institutions
  - CERN-SPSC-2012-021 ; SPSC-EOI-007, under review by SPS Committee

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

# LBNO (CERN SPSC-EOI-007)

http://cdsweb.cern.ch/record/1457543

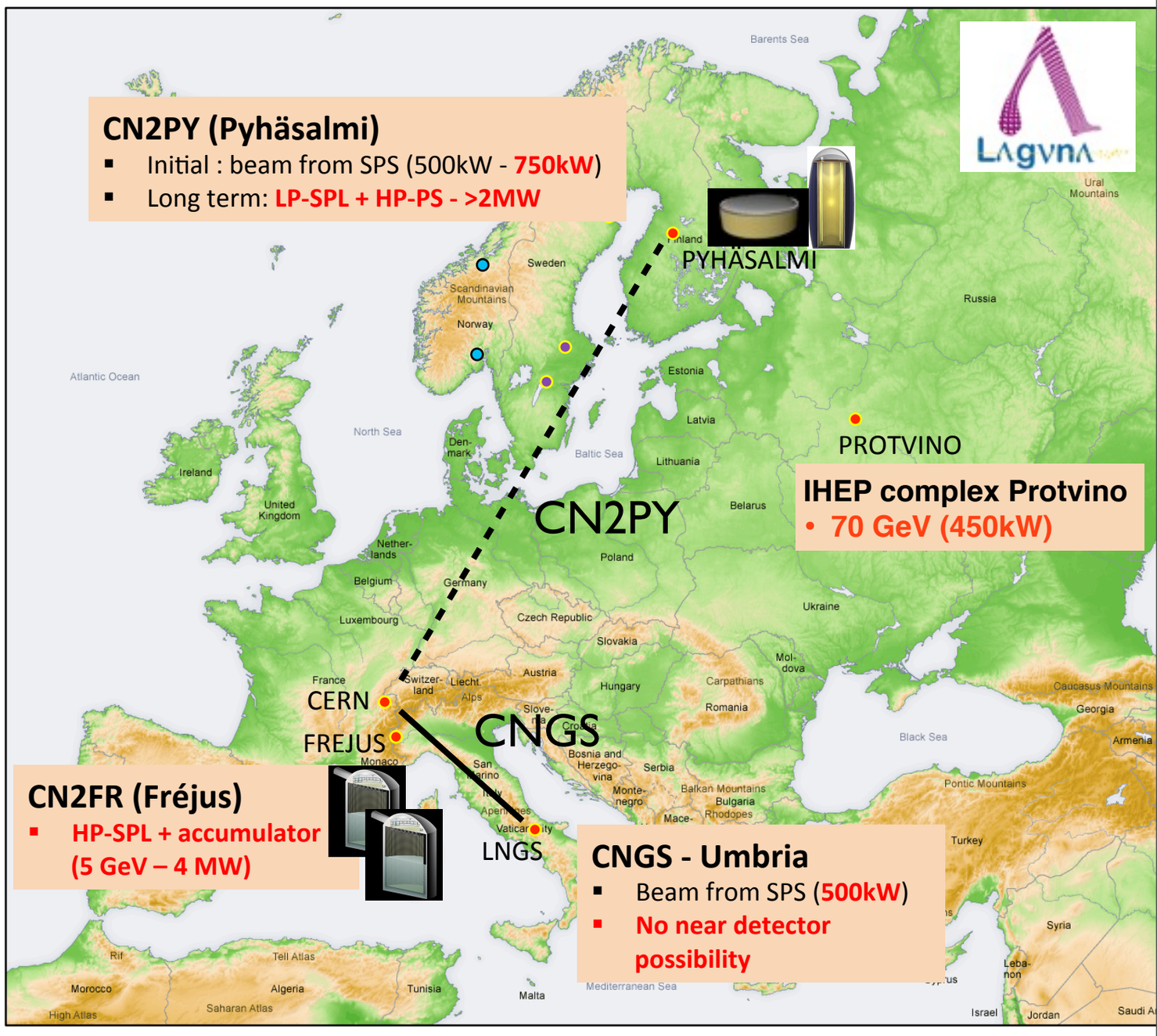
- **In June 2012, an enlarged LAGUNA-LBNO Consortium has put forward an Expression of Interested to CERN, focused on neutrino Mass Hierarchy determination and CPV discovery coupled to a full astrophysics programme at the Pyhäsalmi (Finland) site**
  - Based on the findings of several design studies – LAGUNA/LAGUNA-LBNO and EUROν.
  - Supported by rock, civil, detector engineering designs and many years of detector R&D
- **An incremental long-baseline program with a competitive 1st stage guaranteeing high level physics performance from the beginning.**
  - LBNO Stage 1 is based on a 20 kt fid. LAr detector (double phase) and a conventional beam from the CERN SPS of 700 kW at 2300 km.
  - If the findings from Stage 1 require, the detector and the beam will be upgraded to 70 kton mass and 2 MW proton power.
  - The costs, possible implementation schemes and physics potentials will be further studied until the end of 2014.
- **Initial positive feedback from SPSC (108$^{th}$ minutes, January 2013)**
  - **The SPSC supports the physics case and recognises its timely relevance in the rapidly evolving neutrino physics landscape.**
  - **SPSC notes that the Finnish Government could not commit to host LAGUNA-LBNO in the proposed Pyhäsalmi site**
  - **SPSC supports double phase LAr TPC as promising technique for future LBL**
  - **SPSC encourages LBNO to proceed with necessary R&D for validation of double phase LAr TPC on large scale**

# LAGUNA-LBNO: sites overview

## Three far sites considered in details

arXiv:1003.1921 [hep-ph]

- **Option 1: Pyhäsalmi mine** (privately owned), 4000 m.w.e overburden, excellent infrastructure for deep underground access
- **Option 2: Fréjus**, nearby road tunnel, 4800 m.w.e. overburden, horizontal access
- **Option 3: Umbria** (LNGS extension), green site with horizontal access, 2000 m.w.e., CNGS off-axis beam
- **Protons and beams:**
  - Design of new CERN conventional neutrino beam to Finland (CN2PY) Baseline = 2300 km
  - Upgrades of CERN SPS to 700kW
  - New CERN HP-PS (2MW@50 GeV)
  - Recently: assessment of a new conventional beam coupled to accelerator upgrade at Protvino, Russia (OMEGA project) – Baseline = 1160 km



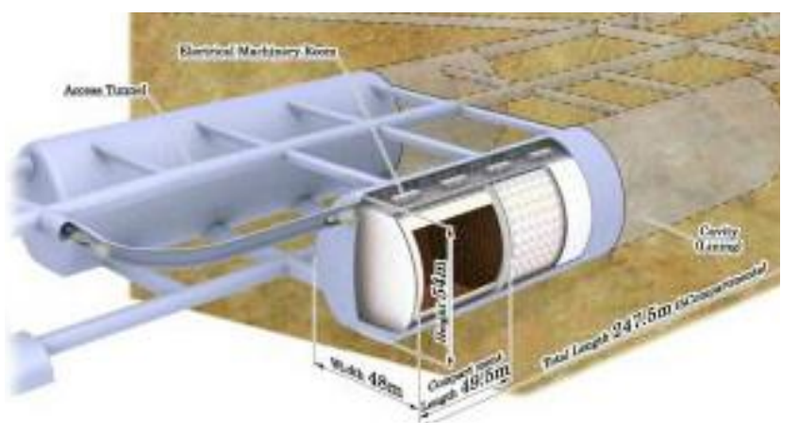

- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

# Water Cerenkov detector approach

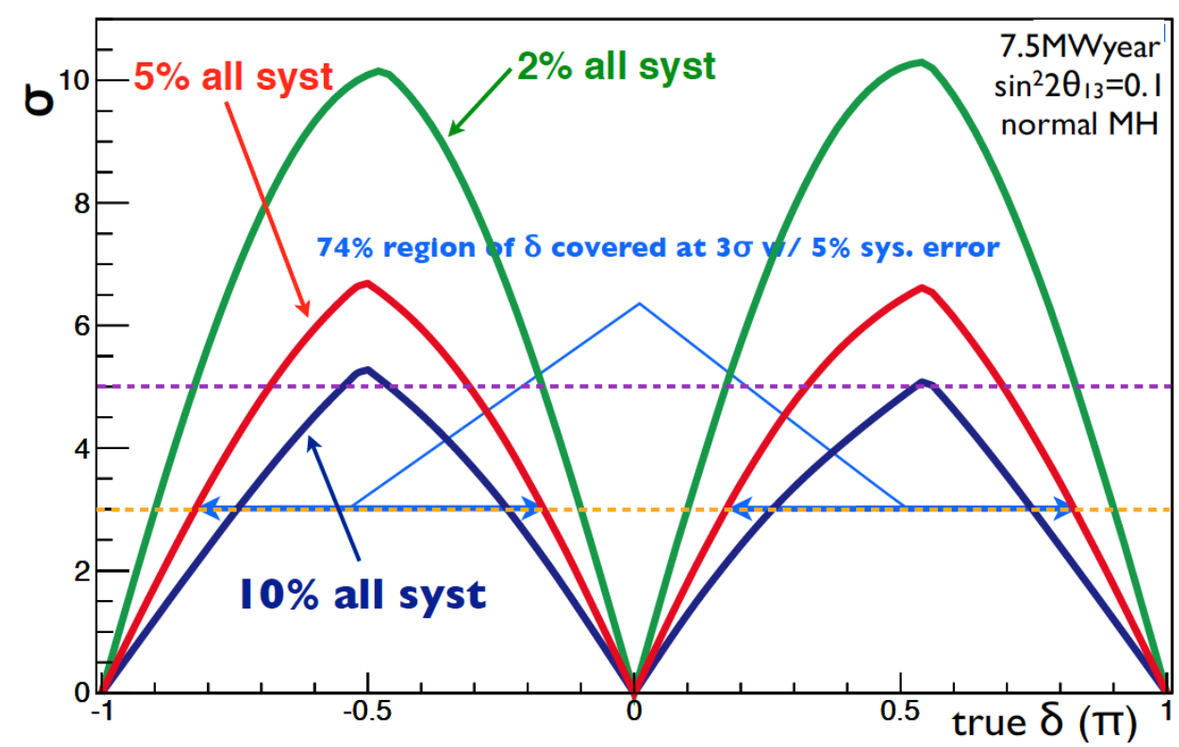
- Studied in LAGUNA as a possible option (MEMPHYS) for what concerns the technical implementation, physics performance and costing
  - Large water Cerenkov detector O(0.5 Mton), 140k 12'' PMT
  - Low energy narrow beam (0.1-1 GeV) → just single ring in QE events
  - New super-beam needed ~O(MW) 4MW SPL beam
  - CERN-Fréjus 130km → no mass hierarchy determination
  - Counting only experiment on neutrinos-antineutrinos asymmetry

LAGUNA-LBNO classified MEMPHYS as 2nd priority

## HyperKamiokande project in Japan (extrapolation 25x SK)



| | |
|---|---|
| Total Volume | 0.99 Megaton |
| Inner Volume | 0.74 Mton |
| Fiducial Volume | 0.56 Mton (0.056 Mton × 10 compartments) |
| Outer Volume | 0.2 Megaton |
| Photo-sensors | 99,000 20''Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8''Φ PMTs for Outer Det. |




**74% (55%) CP coverage 3σ if MH known (unknown) with 5% syst. and 10 years at 750 kW**

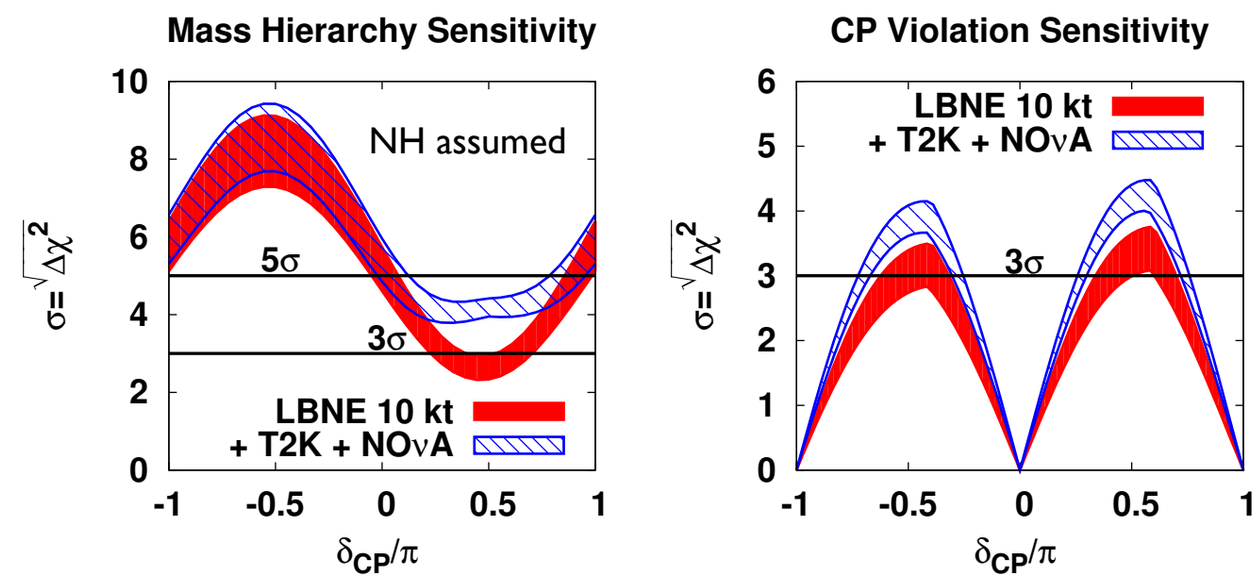
# Liquid Argon detector approach

LAGUNA-LBNO classified as 1st priority

- Main option in LAGUNA-LBNO:
  - Initial (double phase) liquid argon TPC 20kton and upgrade plan
  - High energy (>1 GeV) beam, all final states accessible
  - L/E pattern and second oscillation maximum
  - Long baseline (>1000 km) → mass hierarchy measurement (2300km for LBNO from CERN to Pyhäsalmi) and CPV with 1st and 2nd maximum

## LBNE10 project in USA

- First phase >2023 (~900 M$ CD-1 baseline): 700 kW beam from FNAL to Homestake, 1300 km → too short to guarantee MH discovery → 10 kton LAr on surface → limited physics capabilities and operation risks
- No near detector
- Further potential stages: underground far detector 35 kton, 2.3 MW beam (Project X)
- Sensitivity only from first oscillation max. → needs small syst. errors O(1%) to reach CPV discovery



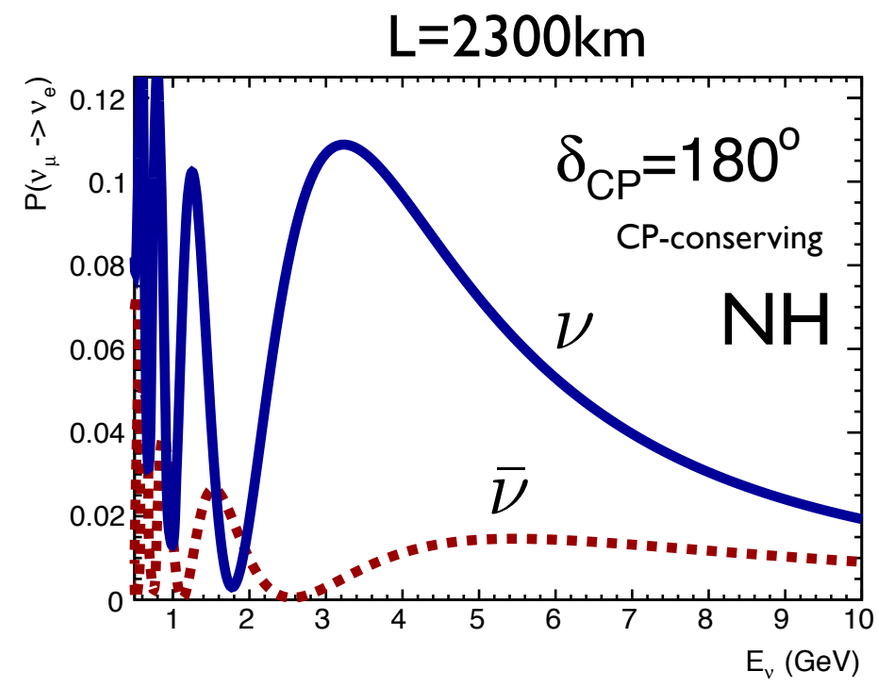

**Can resolve MH with $\geq 5/4\sigma$ for 50%/all $\delta_{cp}$ combined**

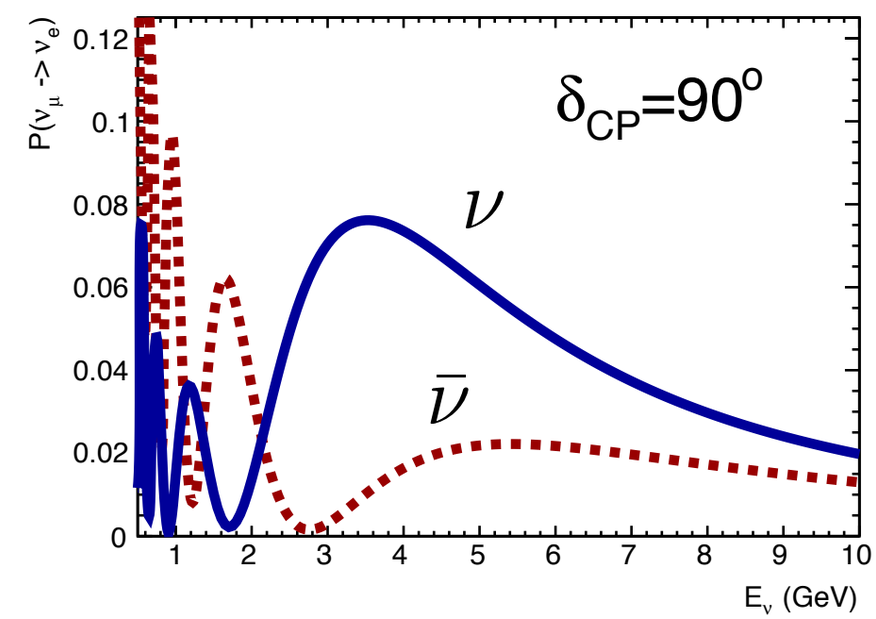
**Can resolve CPV with $\geq 3\sigma$ for 45% $\delta_{cp}$ combined**

*Assumes 1%/5% signal/background normalization uncertainties. Disappearance and appearance modes are combined, all 3-flavor parameters included with constraints based on uncertainties from current global fits. $\theta_{13}$ constraint using Daya Bay systematics only uncertainty.* *Courtesy: M. Bishai*

# LBNO main physics goals

- **Long baseline neutrino oscillations at 2300km**
  - $\nu\mu \rightarrow \nu e$ & $\nu\mu \rightarrow \nu\tau$ & $\nu\mu \rightarrow \nu\mu$ & $\nu$NC
  - Direct measurement of the energy dependence (L/E behaviour) induced by matter effects and CP-phase terms, independently for $\nu$ and anti-$\nu$, by direct measurement of event spectrum, in particular covering 1st and 2nd oscillation maxima
  - Mass hierarchy determination at >5$\sigma$ C.L. in first two years of running
  - CP-phase measurement in initial phase and CPV "discovery" ($\Rightarrow$ 5$\sigma$ C.L.) with upgrade to increase statistical importance of 2$^{nd}$ maximum
  - Test of three generation mixing paradigm



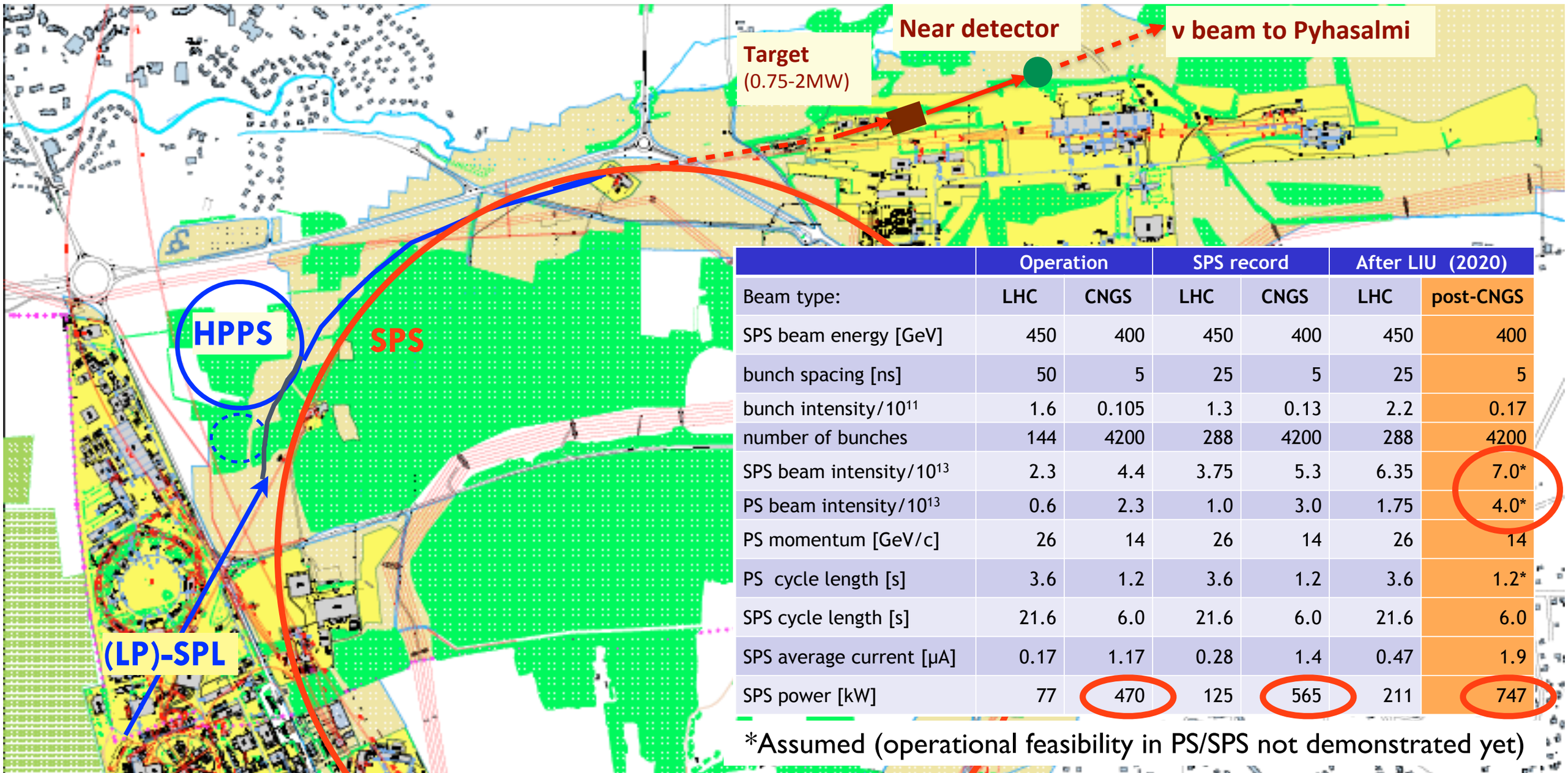




- **A full astrophysics programme**
  - Nucleon decays (direct GUT evidence)
  - Atmospheric neutrino detection with complementary oscillation measurements and Earth spectroscopy
  - Astrophysical neutrino detection
  - Searches for new sources of low-energy neutrinos

# The CN2PY beam

- **Phase 1** : use the proton beam extracted beam from SPS
- **400 GeV**, max 7.0 $10^{13}$ protons every 6 sec, **750 kW** nominal beam power, 10 μs pulse
- Yearly integrated pot = (8–13)e19 pot / yr depending on "sharing" with other fixed target programmes.

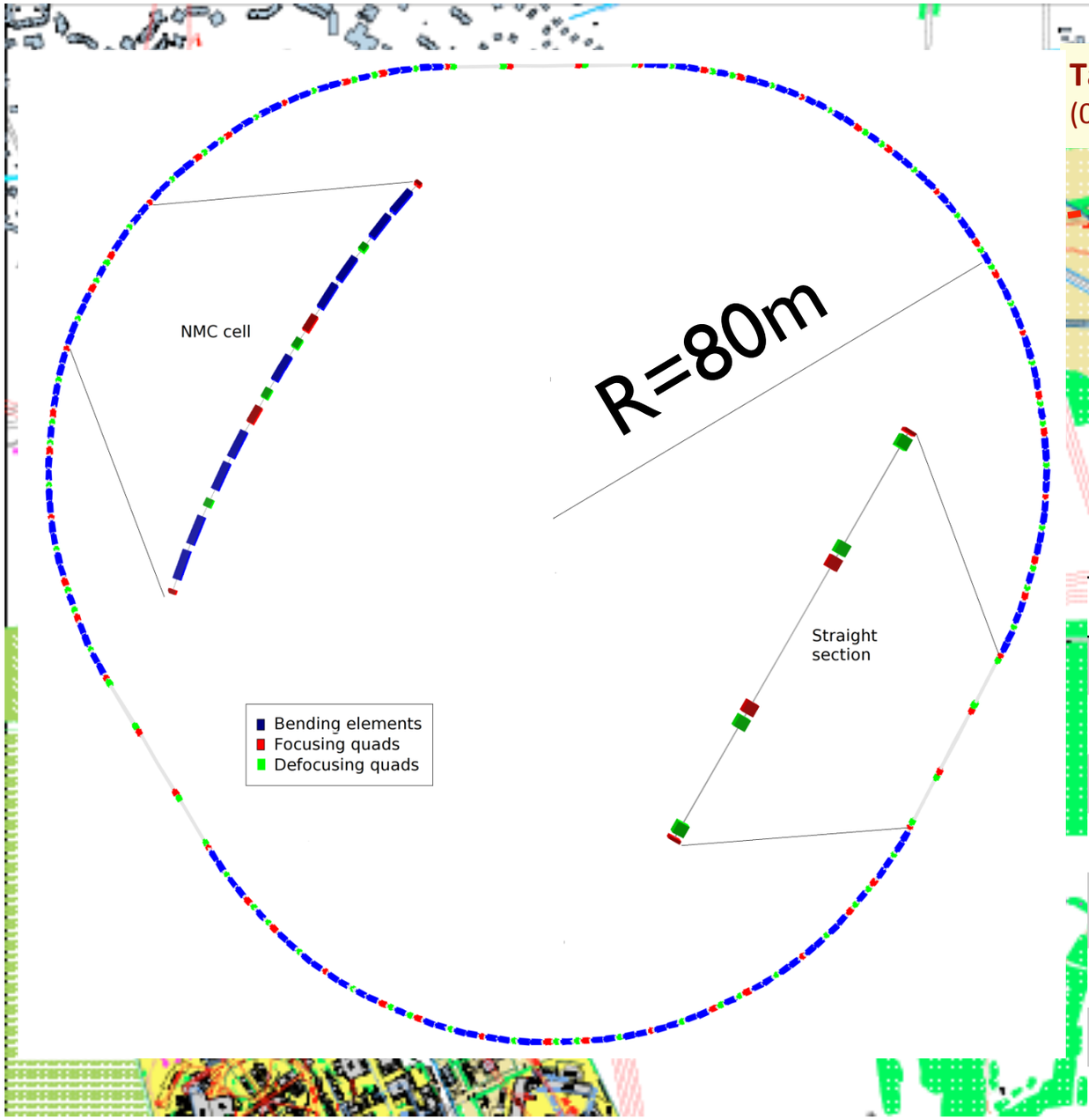
- **Phase 2** : use the proton beam from the new HP-PS
- **50**(70) GeV, 1 Hz, 2.5e14 ppp, **2 MW** nominal beam power, 4 μs pulse

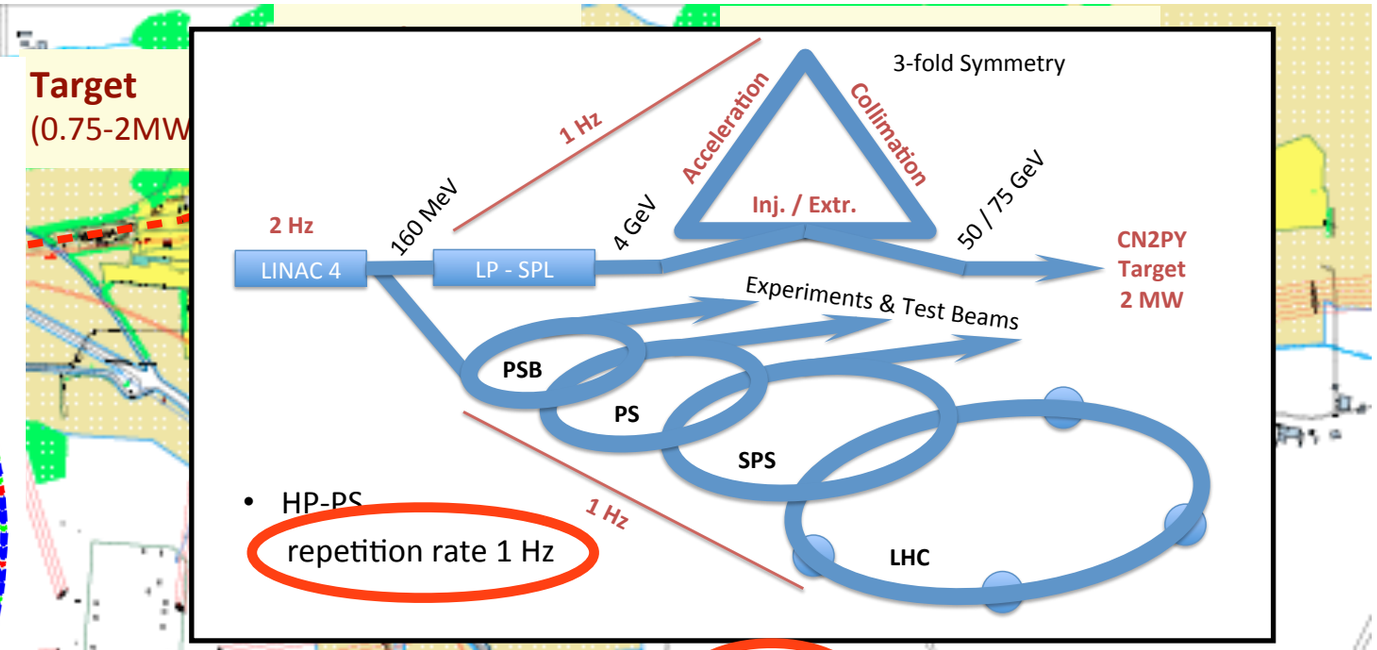



| | Operation | | SPS record | | After LIU (2020) | |
|---|---|---|---|---|---|---|
| Beam type: | LHC | CNGS | LHC | CNGS | LHC | post-CNGS |
| SPS beam energy [GeV] | 450 | 400 | 450 | 400 | 450 | 400 |
| bunch spacing [ns] | 50 | 5 | 25 | 5 | 25 | 5 |
| bunch intensity/$10^{11}$ | 1.6 | 0.105 | 1.3 | 0.13 | 2.2 | 0.17 |
| number of bunches | 144 | 4200 | 288 | 4200 | 288 | 4200 |
| SPS beam intensity/$10^{13}$ | 2.3 | 4.4 | 3.75 | 5.3 | 6.35 | 7.0* |
| PS beam intensity/$10^{13}$ | 0.6 | 2.3 | 1.0 | 3.0 | 1.75 | 4.0* |
| PS momentum [GeV/c] | 26 | 14 | 26 | 14 | 26 | 14 |
| PS cycle length [s] | 3.6 | 1.2 | 3.6 | 1.2 | 3.6 | 1.2* |
| SPS cycle length [s] | 21.6 | 6.0 | 21.6 | 6.0 | 21.6 | 6.0 |
| SPS average current [μA] | 0.17 | 1.17 | 0.28 | 1.4 | 0.47 | 1.9 |
| SPS power [kW] | 77 | 470 | 125 | 565 | 211 | 747 |

*Assumed (operational feasibility in PS/SPS not demonstrated yet)

# High power HP-PS study



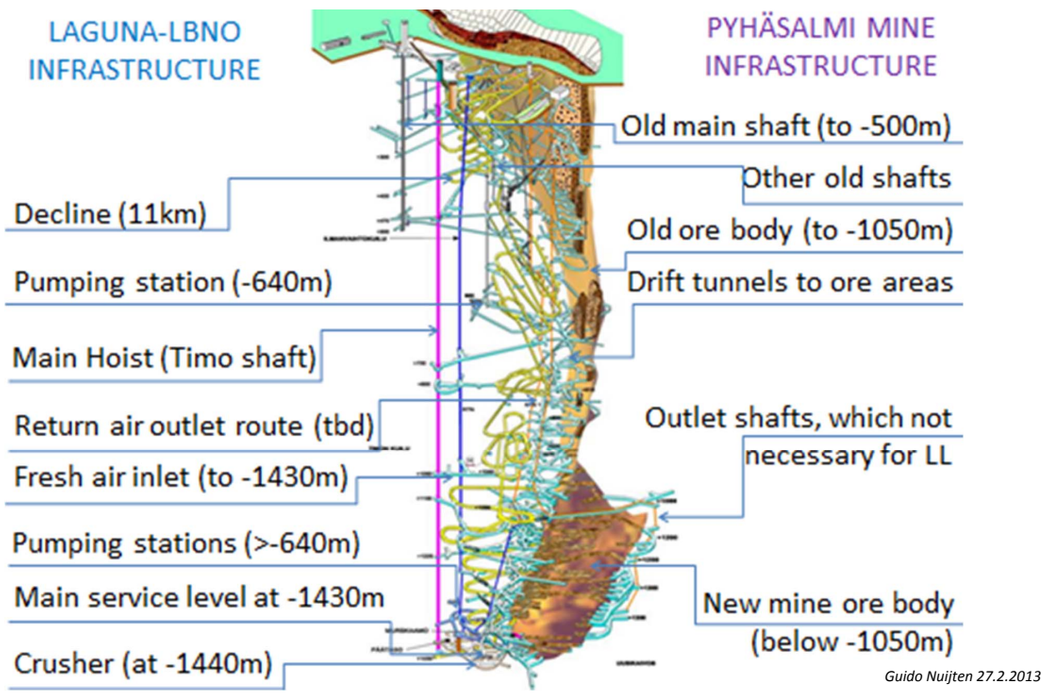



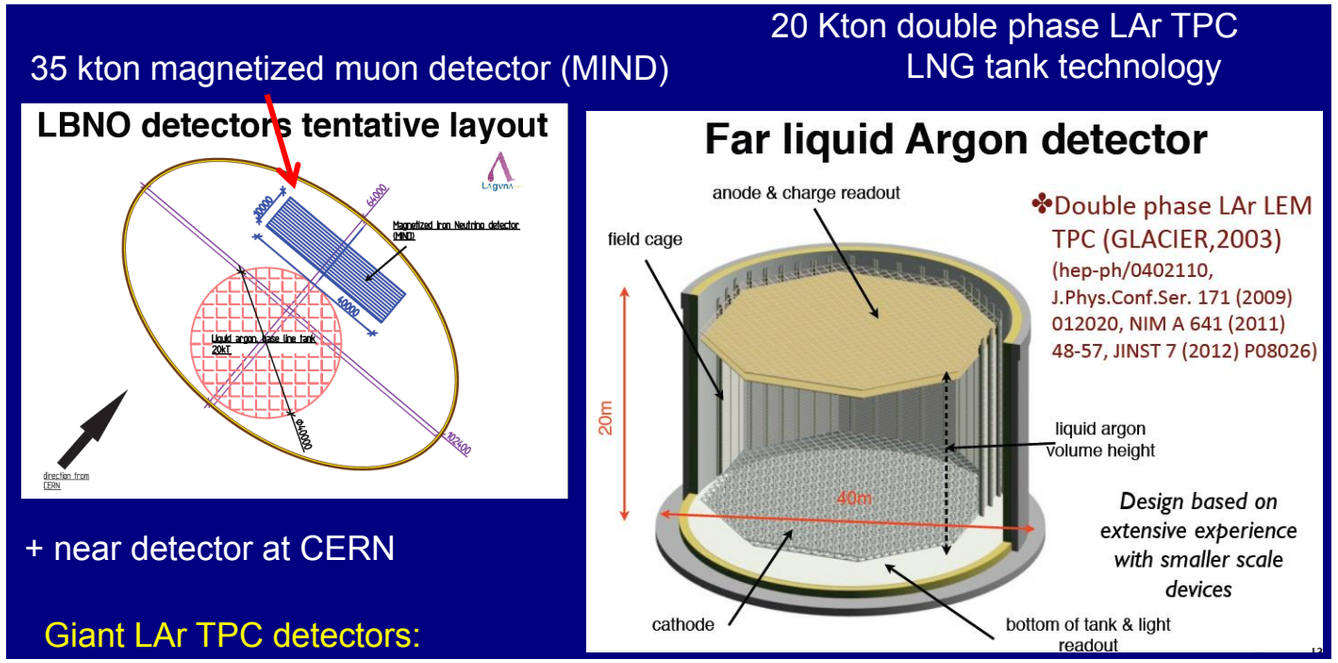

| Parameter | 50 GeV | 75 GeV | Units |
|---|---|---|---|
| Inj. / Extr. Kinetic Energy | 4 / 50 | 4 / 75 | [GeV] |
| Beam power | 2 | | [MW] |
| Repetition rate | 1 | | [Hz] |
| $f_{rev}$ / $f_{RF}$ @ inj. | 0.248 / 38.97 | | [MHz] |
| RF harmonic | 157 | | - |
| $f_{rev}$ / $f_{RF}$ @ extr. | 0.255 / 40.08 | 0.255 / 40.09 | [MHz] |
| Bunch spacing @ extr. | 25 | | [ns] |
| Total beam intensity | $2.5 \times 10^{14}$ | $1.7 \times 10^{14}$ | - |
| Number of bunches | 147 | | - |
| Intensity per bunch | $1.7 \times 10^{12}$ | $1.25 \times 10^{12}$ | - |
| Main dipole field inj. / extr. | 0.17 / 2.1 | 0.17 / 3.13 | [T] |
| Ramp time | 500 | 500 | [ms] |
| Dipole field rate dB/dt (acc. ramp) | 3.9 | 5.9 | [T/s] |

- Basic design well underway and main parameters available
- Optics design well advanced
- Injection and extraction concepts are available
- Basic ideas about accelerating RF system
- Basic ideas about collimation
- Consolidate optics and establish set of requirements for different magnet families.
- Design of magnet foreseen.

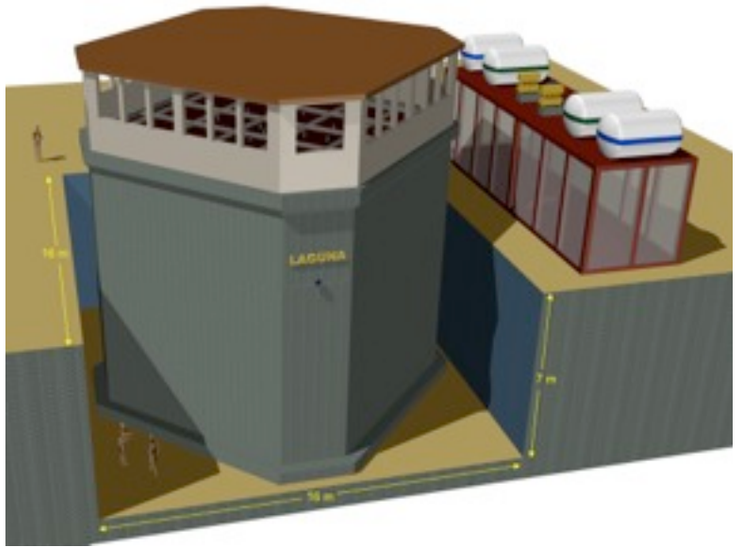
# LBNO far site and detectors

- The LAGUNA LBNO collaboration is in the most advanced state for what concerns all technical implementation and site studies, costing and prototyping.
- The Pyhäsalmi site is extremely convenient (baseline, infrastructures, depth, excavation aspects). An extended site investigation is progressing well (750 m drilled) →Discussions will continue with Finland in order to define its real contribution, after some initial misunderstanding. Alternative sites in Scandinavia are been looked into.




- **Next milestone: Large-scale LBNO detectors prototyping at CERN, with priority emphasis on a large double-phase LAr demonstrator, using charged-particle test beams (2014-2017).**

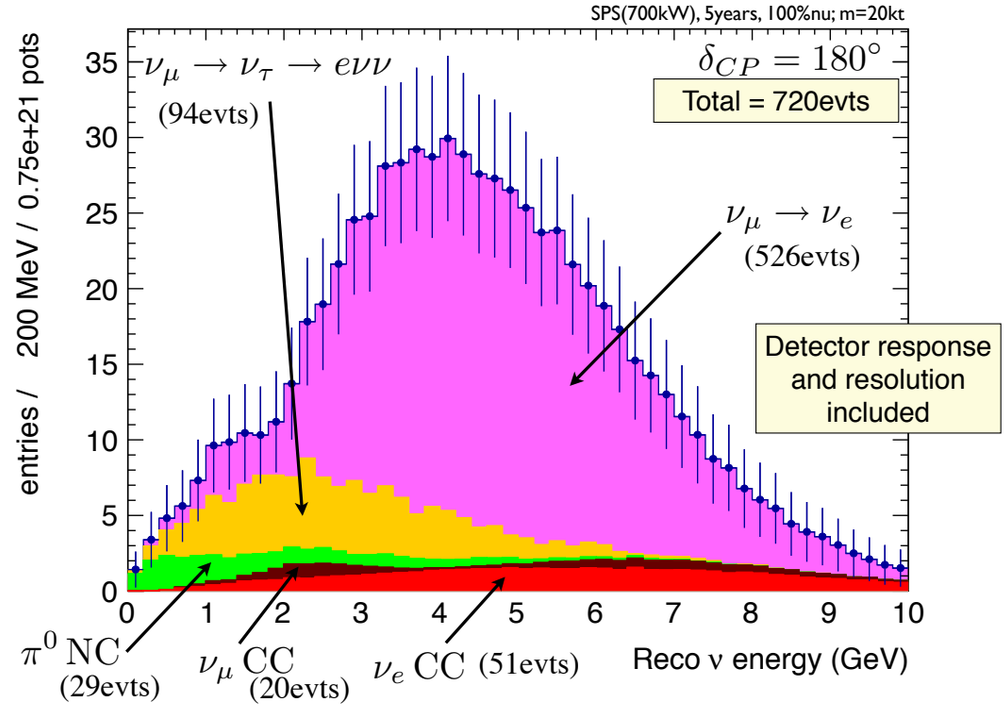


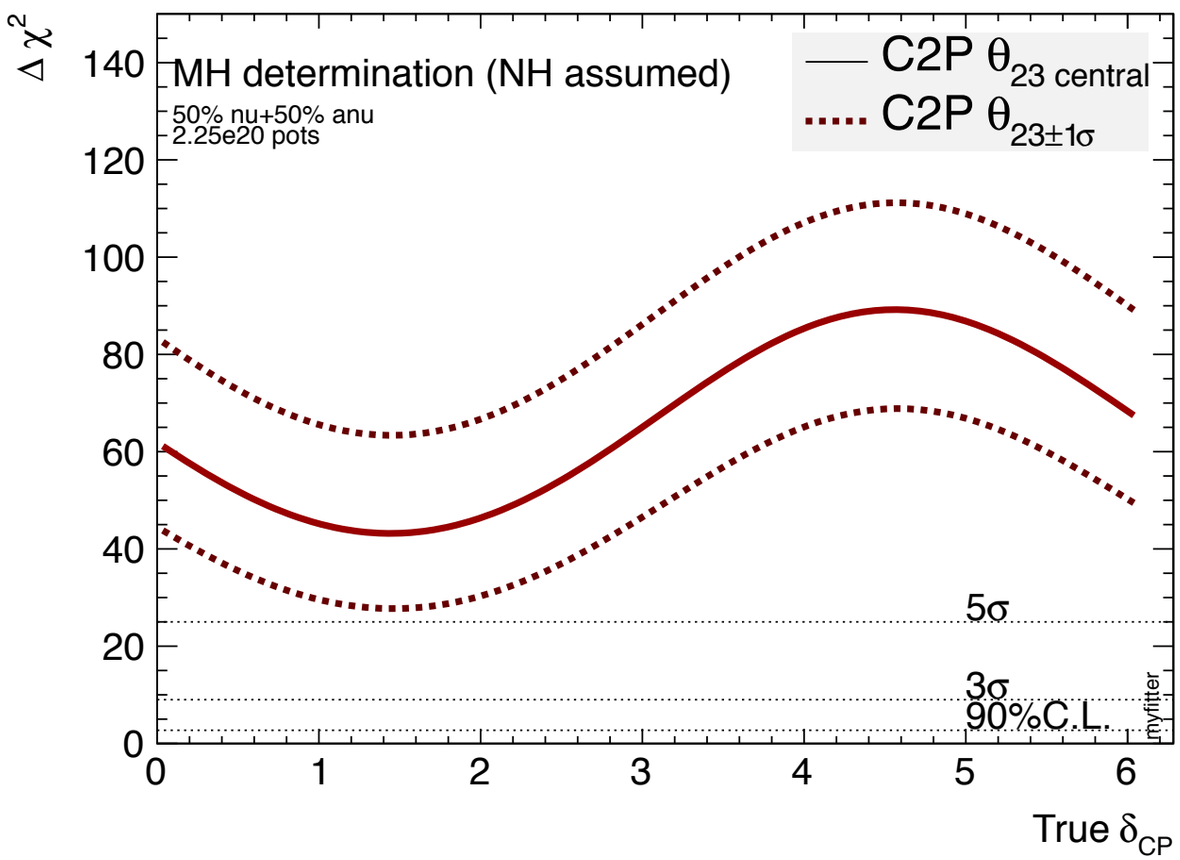
# LBNO unambiguous MH determination

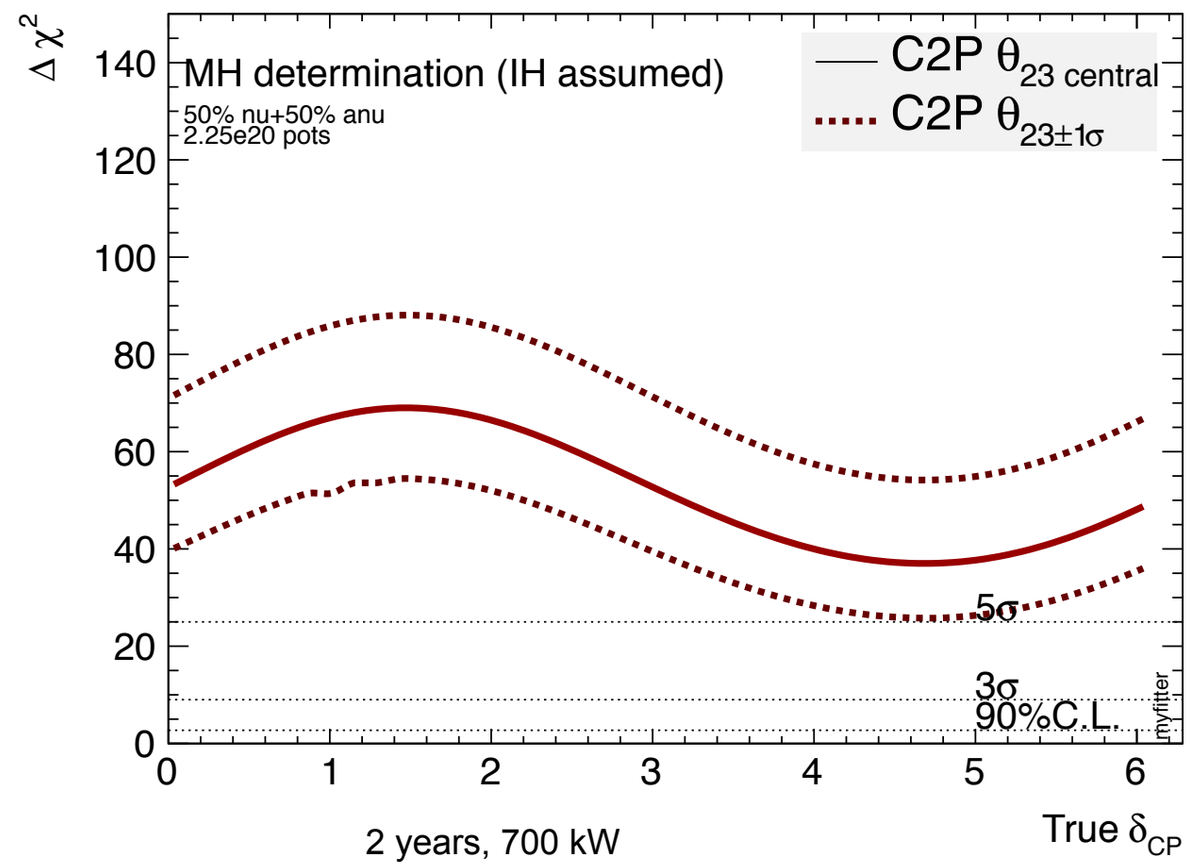
Unique setup in the world to test matter effects in neutrino propagation!

L/E shape + nu/nubar by changing horn polarity

Provide a >5σ direct determination of MH independent of the values of $\theta_{23}$ & $\delta_{CP}$ in ≈2 years of running



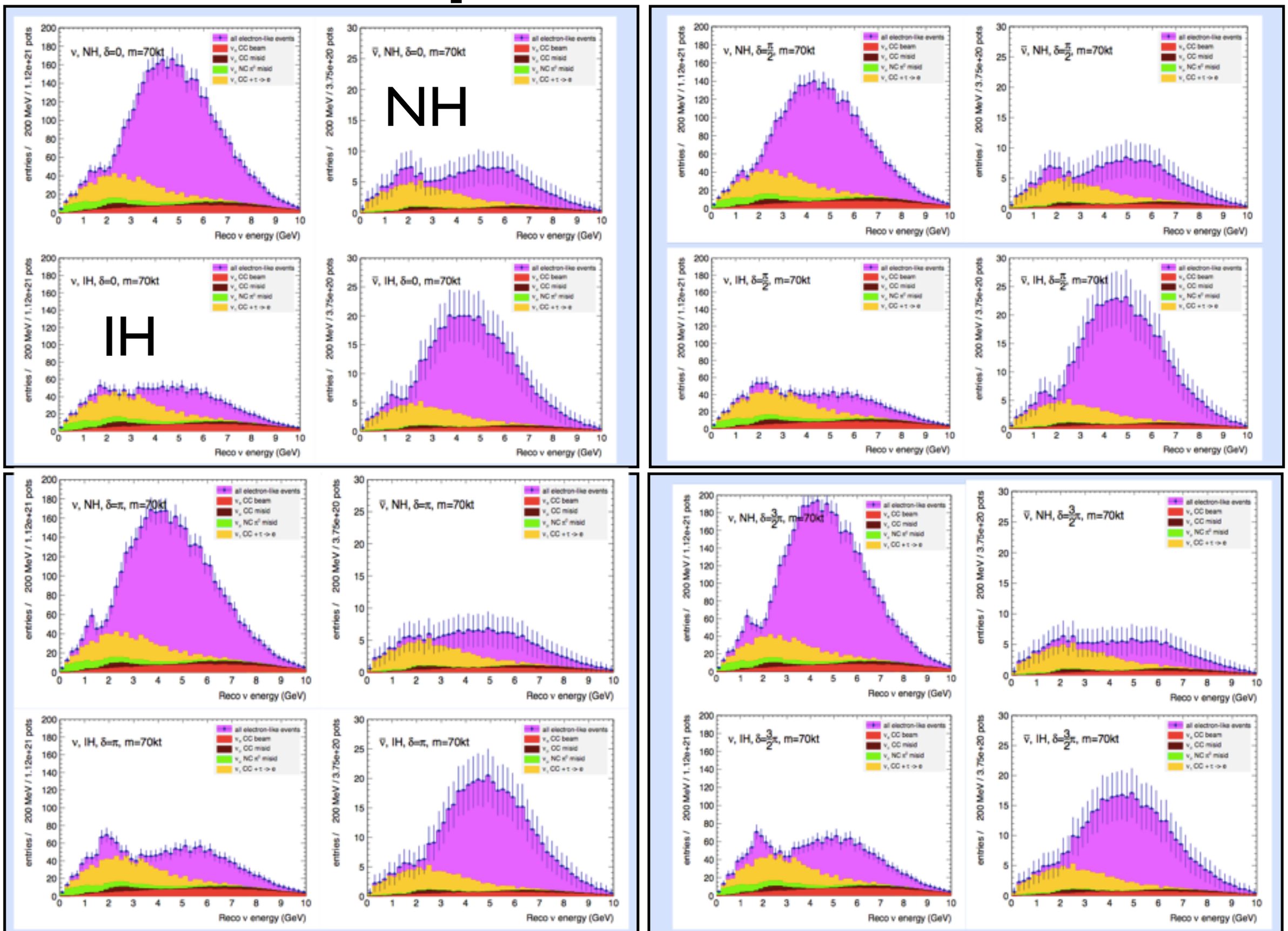




2 years, 700 kW
- $2.25\times10^{20}$ pot
- 50% nu, 50% nubar

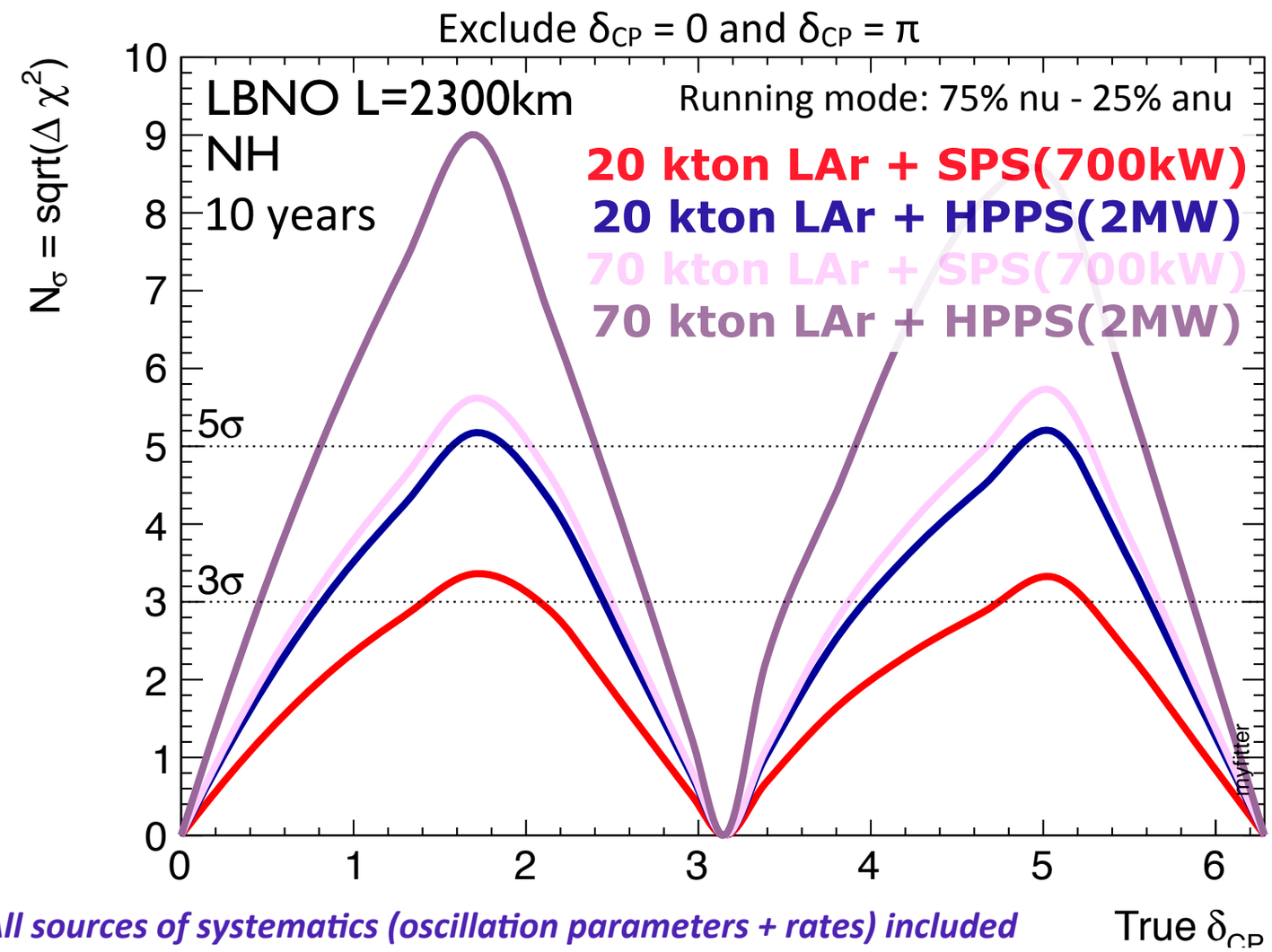
Startup in 2023, MH >5σ in 2025

# $\delta_{CP}$ & MH dependence

SPS(700kW), 10y, 75%nu-25%antinu; m=70kt



# LBNO sensitivity to CP violation

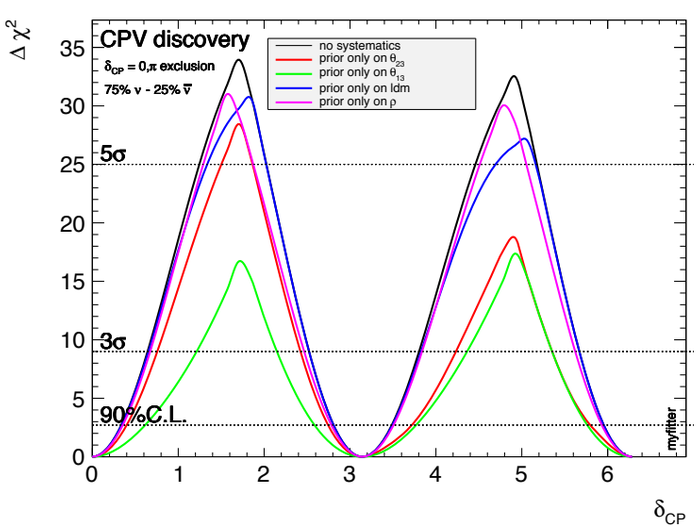


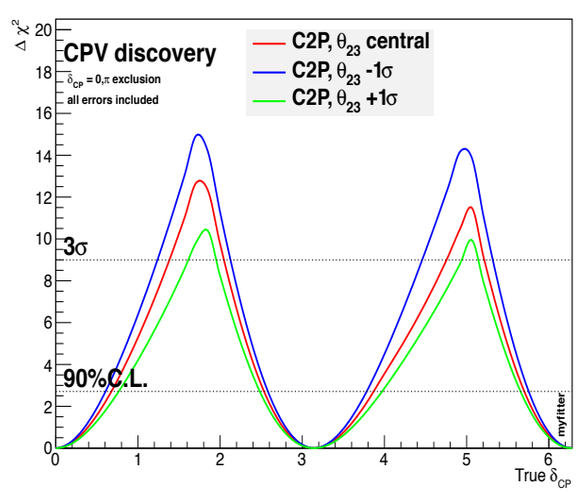

| Name | Value | Error (1σ) |
|---|---|---|
| L (km) | 2300 | exact |
| $\Delta m^2_{21}$ eV$^2$ | 7.60E-05 | exact |
| $\lvert \Delta m^2_{32} \rvert$ eV$^2$ | 2.40E-03 | ±4% |
| $\sin^2\theta_{12}$ | 0.30 | exact |
| $\sin^2 2\theta_{13}$ | 0.09 | ±10% |
| $\sin^2\theta_{23}$ | 0.50 | ±10% |
| <ρ> | 3.2 g/cm3 | ±4% |

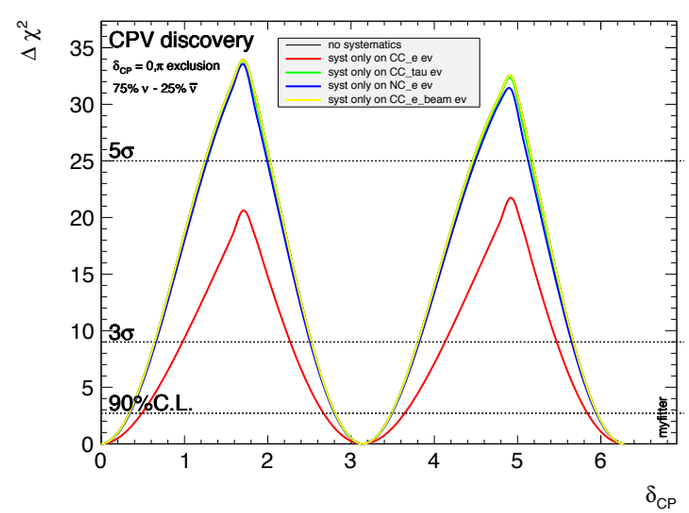
| Name | MH determination Error (1$\sigma$) | CP determination Error (1$\sigma$) |
|---|---|---|
| Bin-to-bin correlated: | | |
| Signal normalization ($f_{sig}$) | ±5% | ±5% |
| Beam electron contamination normalization ($f_{\nu_e CC}$) | ±5% | ±5% |
| Tau normalization ($f_{\nu_\tau CC}$) | ±50% | ±20% |
| $\nu$ NC and $\nu_\mu$ CC background ($f_{\nu_{NC}}$) | ±10% | ±10% |
| Relative norm. of "+" and "-" horn polarity ($f_{+/-}$) | ±5% | ±5% |
| Bin-to-bin uncorrelated | ±5% | ±5% |

*All sources of systematics (oscillation parameters + rates) included*

Several detailed studies and discussions with SPSC concerning role of systematic errors:

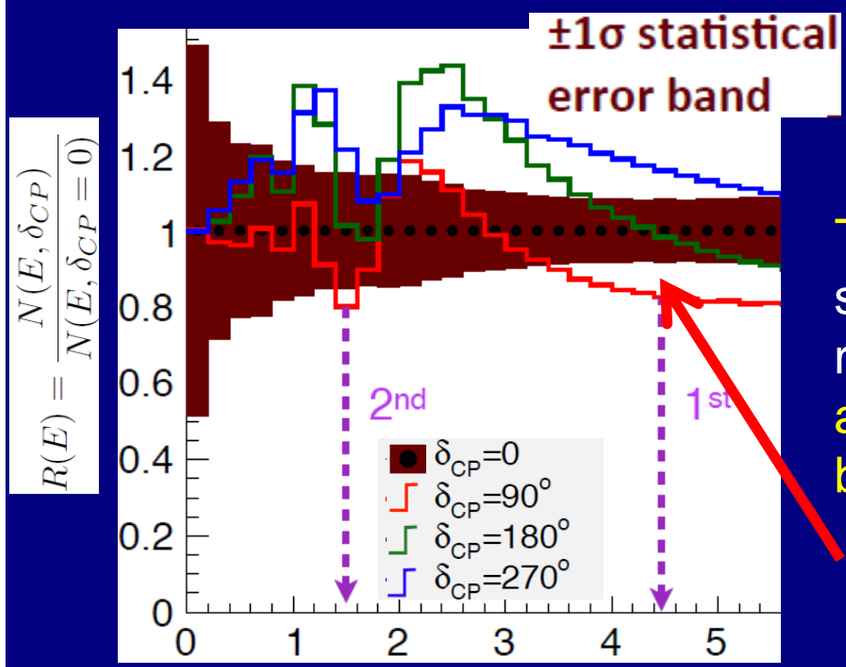


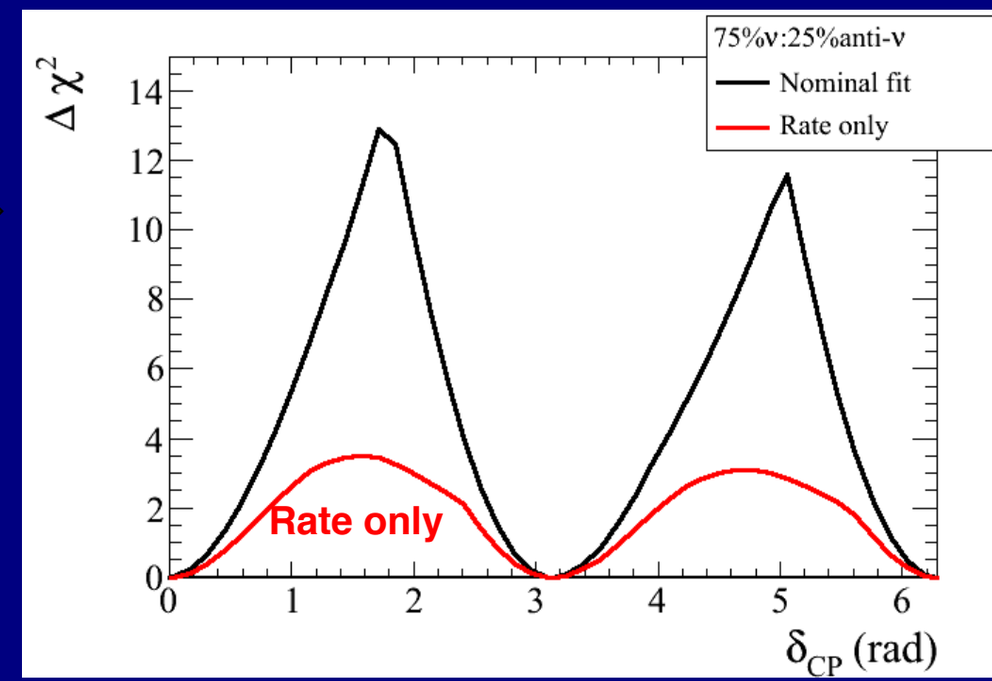



# A world of useful information and full test of the 3 neutrinos paradigm !

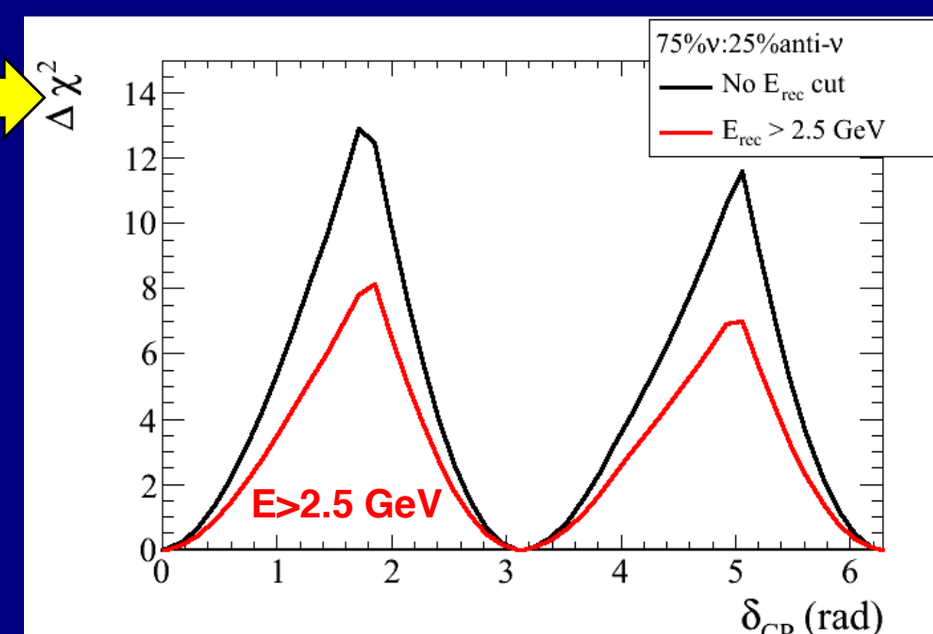
Measurement of L/E pattern independently for nu and nubar for the first and second maxima vs a counting experiment

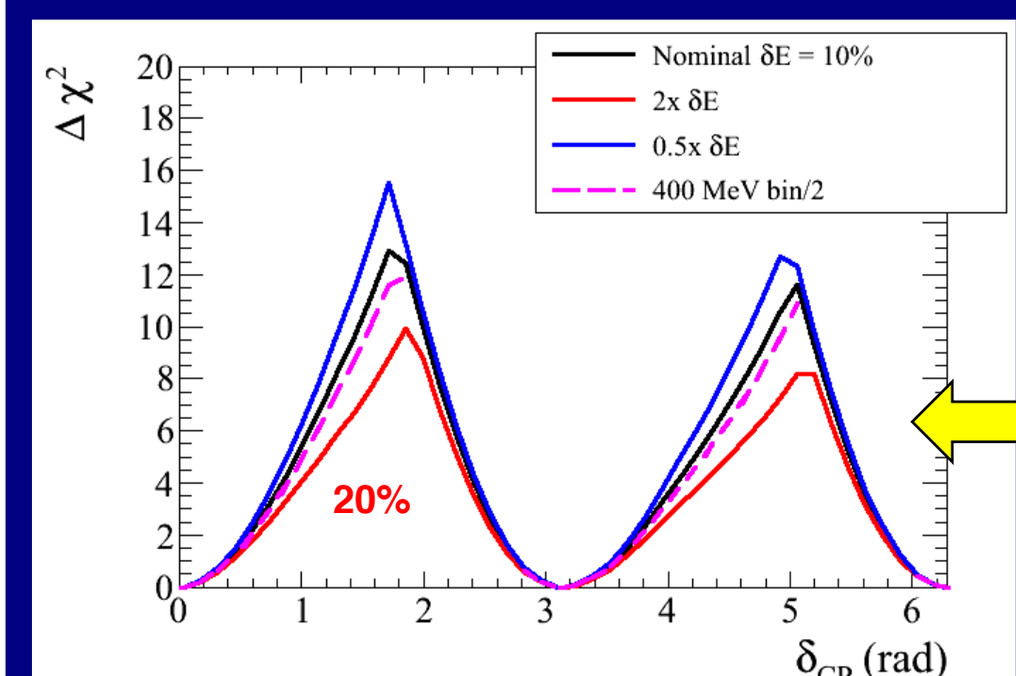



The importance of the second maximum: rather rich CP-dependent features are present at energies below the first maximum

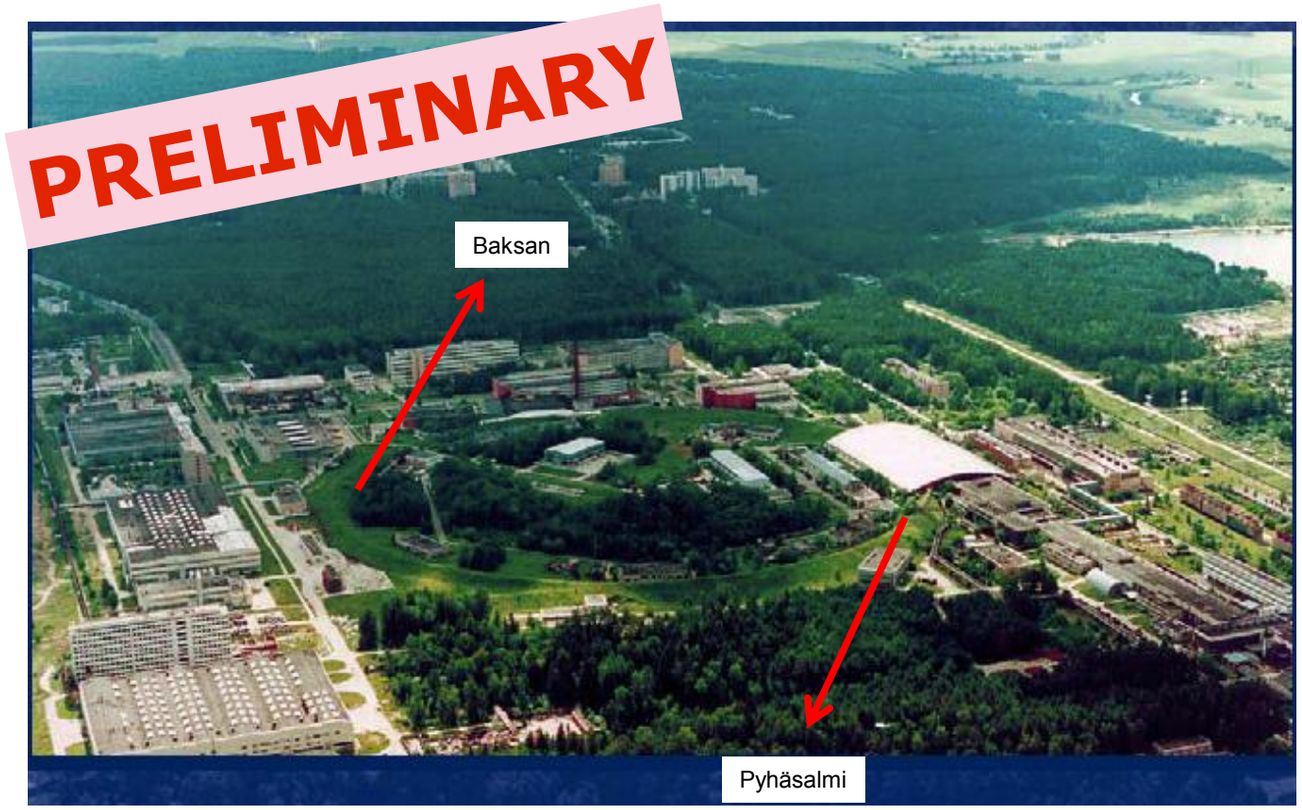
Flatter "rate dominated" region larger syst. effects related to normalization

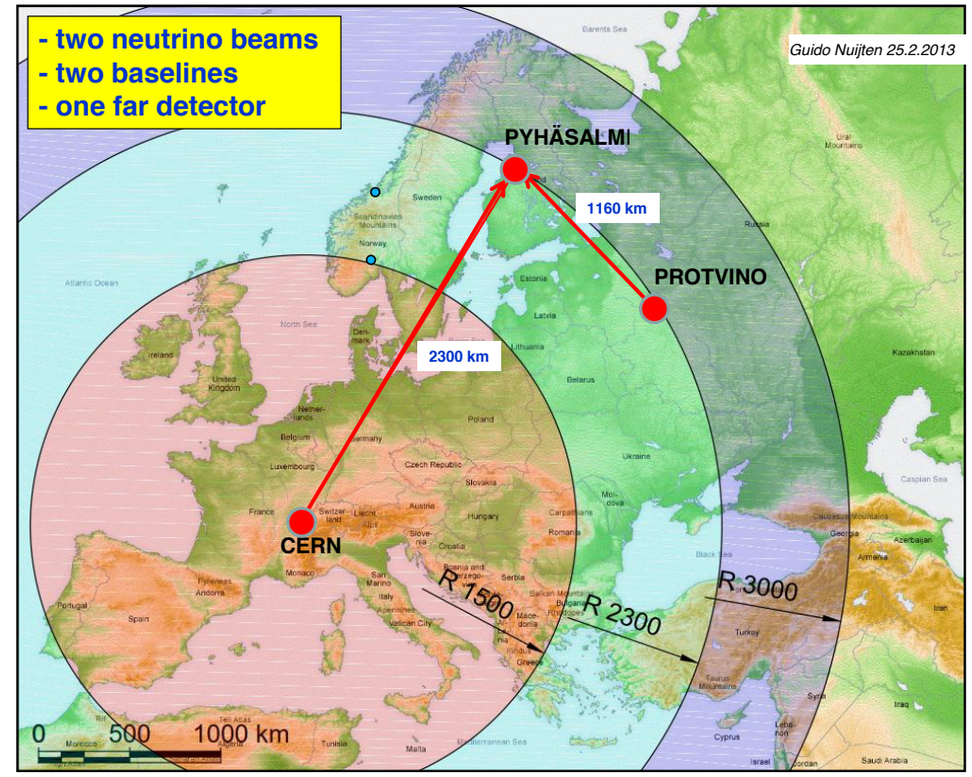



The importance of energy resolution 10% vs 20%

# Possibility of neutrinos from Protvino

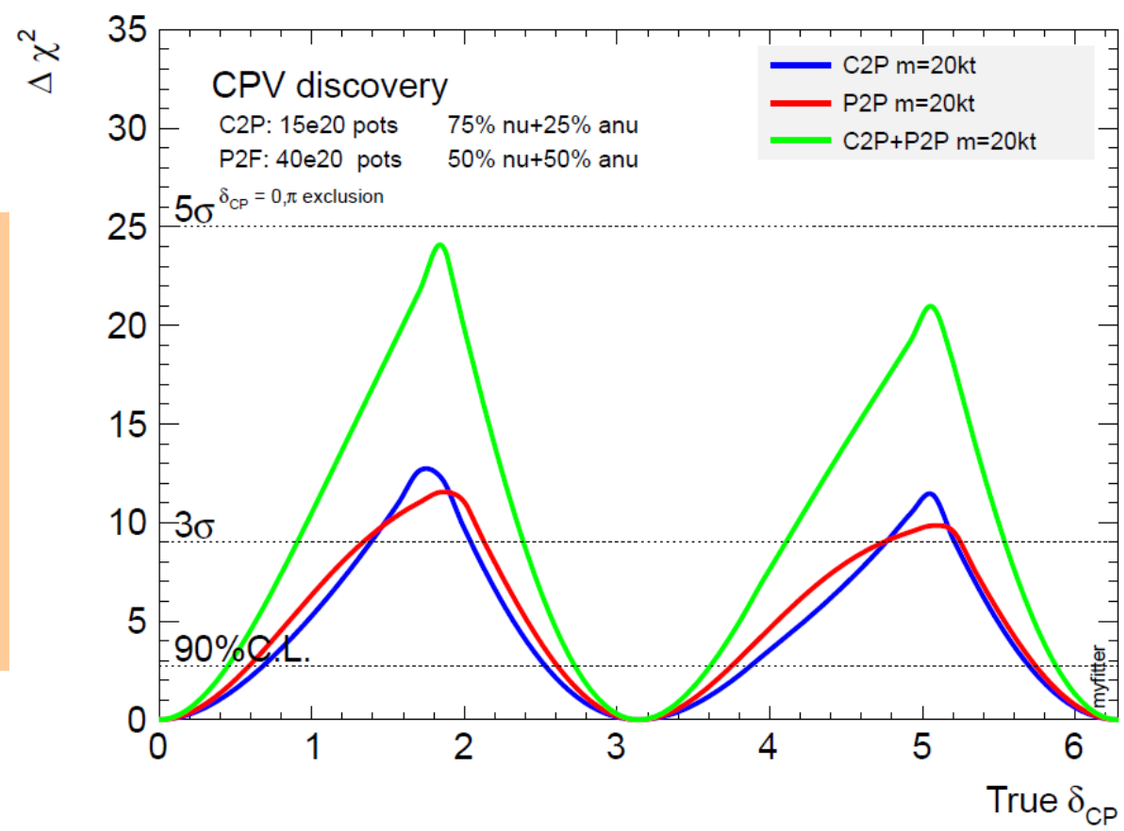



## Desired parameters for neutrino beam:

| | |
|---|---|
| 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 |

**≈1800 $\nu\mu$ CC / 20 kton / year (no osc.)**



# Towards worldwide coordination

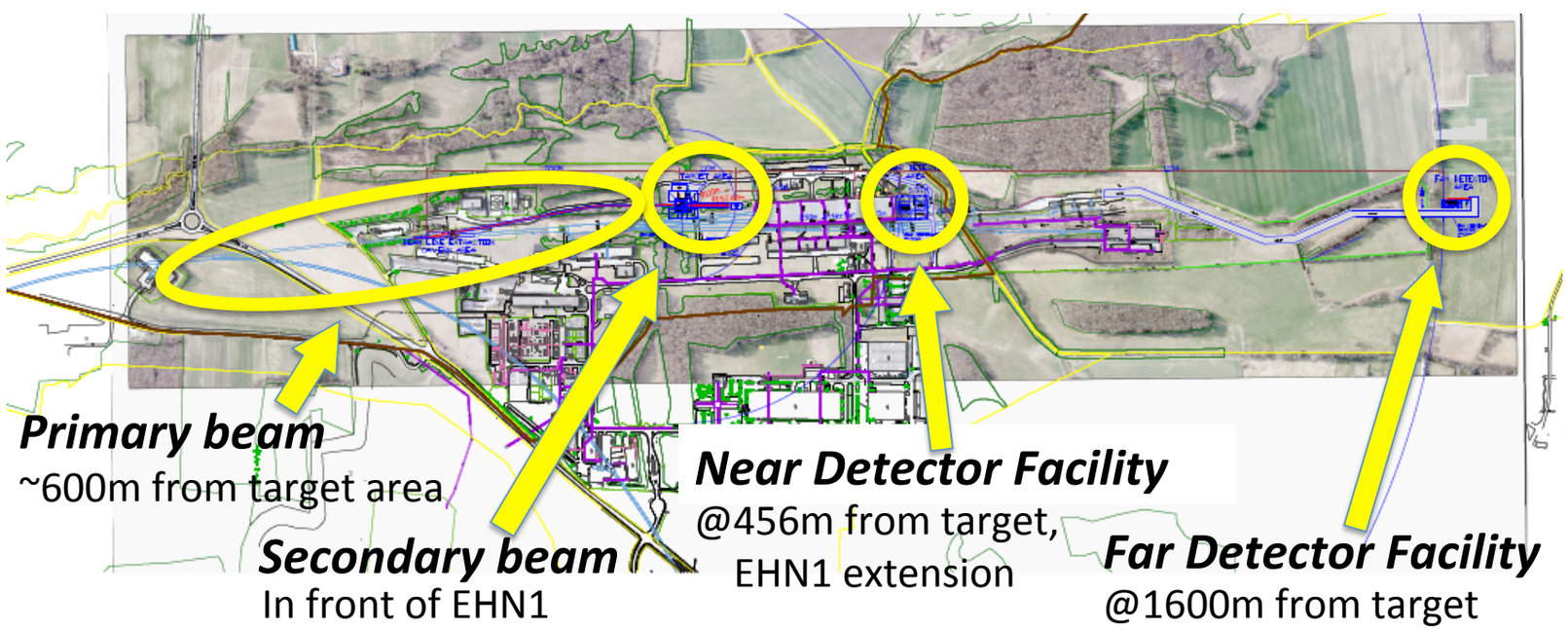
- **The US is inviting the world neutrino community to exploit the substantial investment planned by the DOE Project Baseline CD-1 scope (LBNE10), consisting of a well-designed and developed plan including:**
  - A high-power proton source and neutrino beam at Fermilab
  - A 10kton on-surface far LAr detector, 1300 km from Fermilab
- **Additional international funding commitments should be secured sufficiently prior to "CD-2" in order to refine the Project Baseline scope (LBNE10) to include opportunities such as:**
  - a near detector complex at FNAL
  - an underground location at SURF for the far detector
- **However, staging the Far Detector is impractical, and a detector at the surface is not a step towards a larger underground detector:**
  - LBNE must implement a viable plan for an underground detector by CD-2
- **A key issue is to understand how non-DOE funds can reach the desired level to make a world deep-underground facility for neutrino physics, astrophysics, and searches for non-conservation of baryon number at Homestake**
  - Multilateral agreement ? International resources board ?
  - CERN to propose ways to implement an effective platform for ν research <u>outside</u> CERN ?

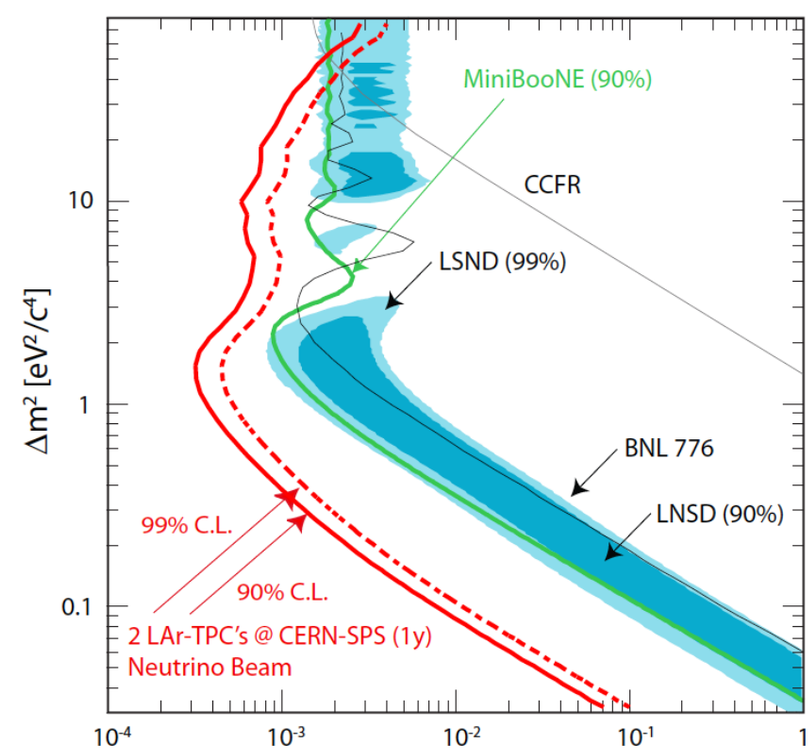
# Joining forces in LBNE/LBNO ?

- Formal discussions between LBNE and LBNO collaborations have started with the goal to see if forces could be joined for the best interest of science.
- **Several questions of different nature will be addressed, such as for example:**
  - **Physics**: while LBNO chose 2300km baseline, it is very likely that a US-based program will be constrained to 1300km. Can the entire set of measurements considered in LBNO be addressed at the shorter baseline? how complementary is it to other efforts worldwide, i.e. 300 km envisioned by T2HK ?
  - **Technical**: LBNE and LBNO have adopted largely different designs for the LAr detectors. The choices for their underground layouts are also vastly different. Is there a mutual technical understanding of the risks associated with either ? LBNO considered 20 kton LAr as initial mass (size of existing SuperKamiokande and minimum mass for the non-accelerator physics programme). What is the largest mass conceivable at Homestake in Phase 1 and at what cost ?
  - **R&D**: a large effort is needed to extrapolate existing LAr TPCs to the required size. Are the R&D plans of LBNE and LBNO coherent and well coordinated, such as to make maximum efficient use of existing infrastructure in the US and in Europe ? can a common R&D path put in place ?
- etc… **Next LBNE/LBNO joint task force meeting Monday July 22nd …**

# CENF - CERN Neutrino Facility

- **Triggered by ICARUS/NESSiE (SPSC-P347) for the search of sterile neutrinos at CERN. SPSC-P347 proposes an ambitious plan: (1) two LAr+muon detectors (near and far); (2) a challenging tight timescale (start 2016) and (3) an investment cost O(100MCHF).**
- The scientific opportunities of CENF have been considered and carefully reviewed by committees, and compared to the ongoing short baseline program at FNAL and with planned measurements at MeV energies (reactors, sources, etc…).
- **The present status is:**
  - High risk that the proposed programme will not address the presently existing LSND/MiniBooNE anomalies with the required >5σ C.L. to elucidate the sterile neutrino problem.
  - The necessity of a CENF neutrino beam for future long baseline neutrino projects has not yet been quantified.
  - The timescale for realisation (likely beyond LHC LS2) and the required resources are in conflict with a significant involvement in LBL experiments.



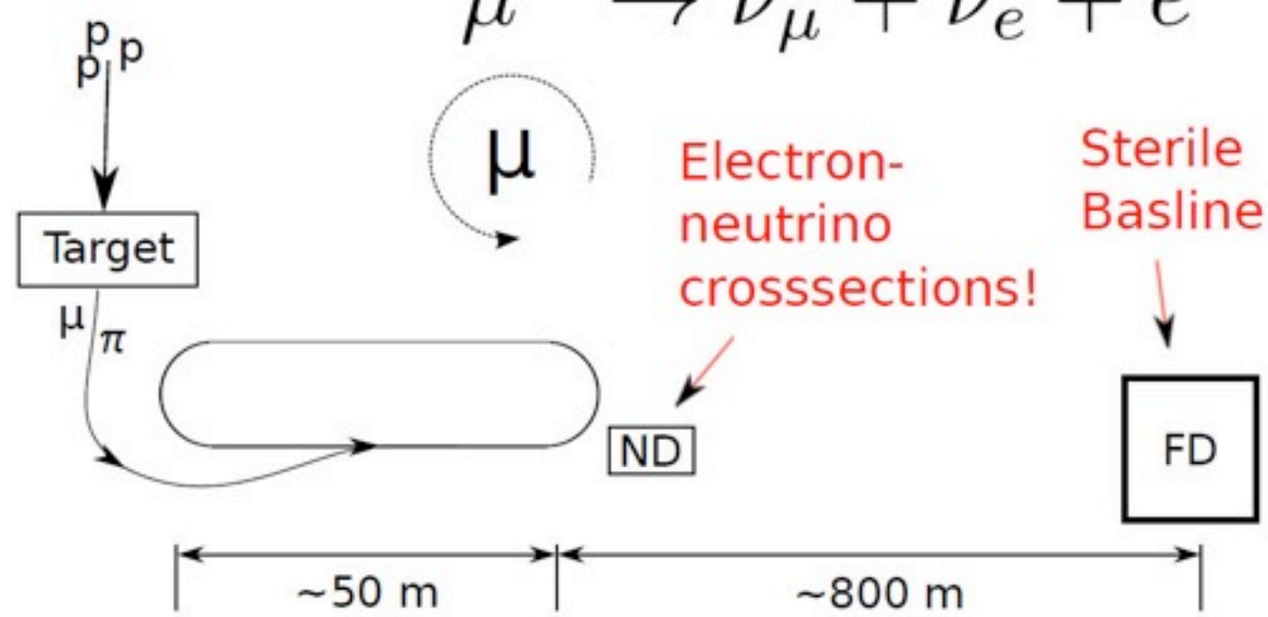



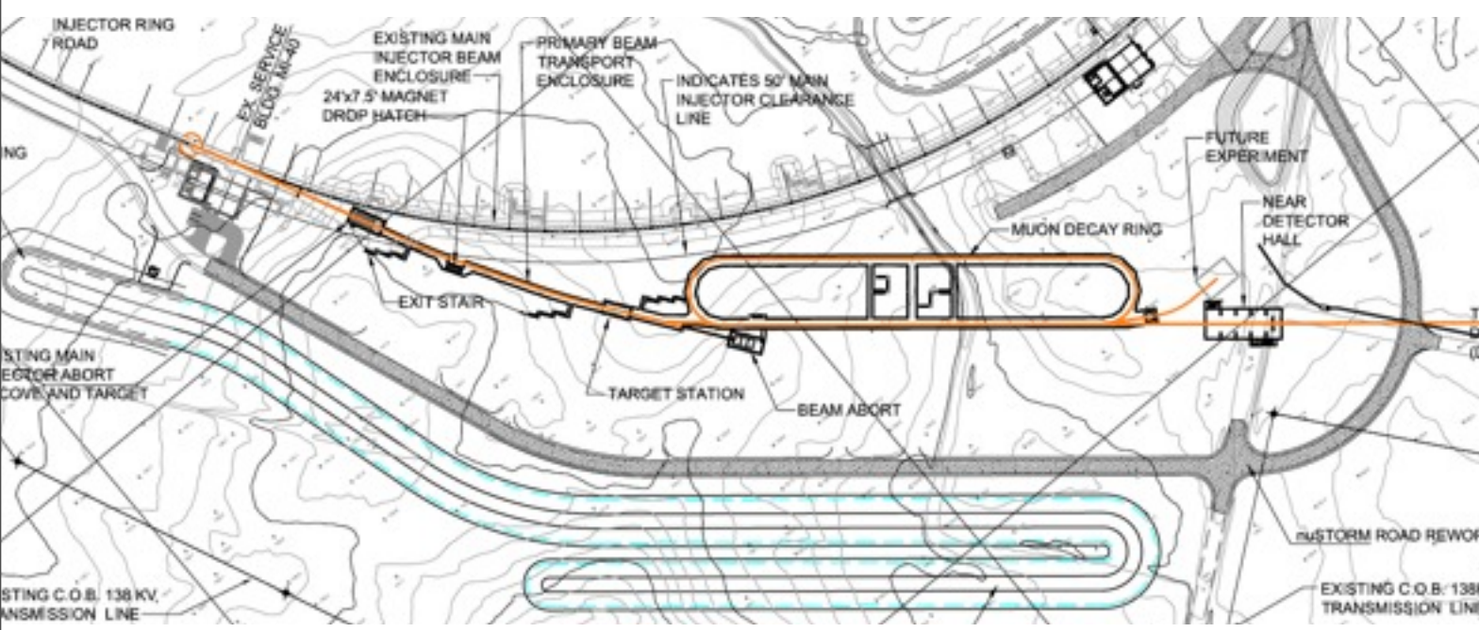
# νSTORM - ν's from μ storage ring

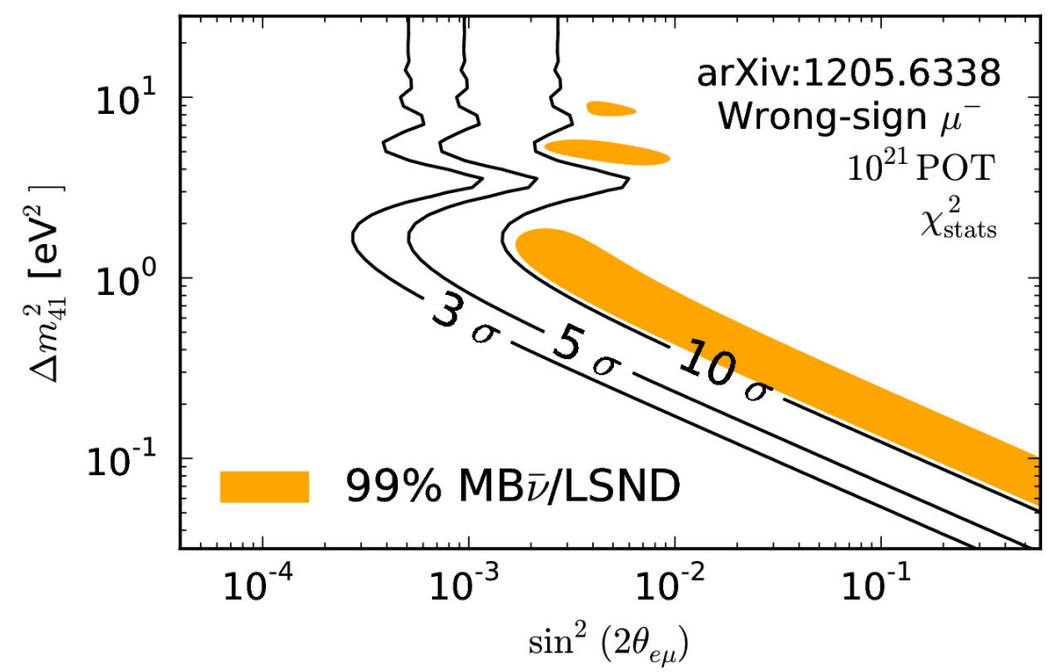
- Neutrinos from Stored Muons (old idea but never realised!)
- Strongly revived interest in the combination of
  - a clear resolution of the short-baseline neutrino anomalies with >>5σ C.L.
  - the precise measurements of the electron neutrino cross-sections needed for LBL experiments,
  - and the synergy with neutrino-factory technology.
- **FNAL PAC stage-1 approval in June 2013. To be reviewed by US HEPAP P5 in the future (≈300M$ project).**
- **LOI submitted at CERN in June 2013, under review.**

**Well-understood neutrino source:**

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$



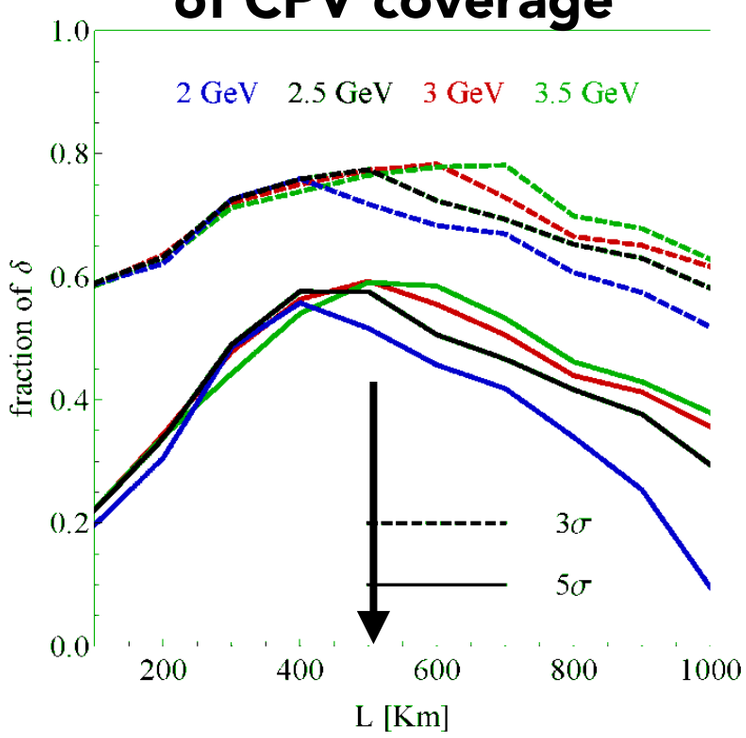



# The EUROSB concept

- The European Spallation Source (ESS), which is being built in Lund, will have a 5 MW 2.5 GeV superconducting linac
- First beams 2019, Full operation 2025
- **Idea: Double linac power to 10MW (+accumulator ring) to deliver in addition 5MW to a neutrino target to produce extremely intense beam with an average neutrino energy ≈300 MeV (Estimated additional cost for ν beam: 400M€)**
- A MEMPHYS 540kton Water Cerenkov detector at Garpenberg mine (L=540 km).


**Preliminary estimate of CPV coverage**




- Unique opportunity to develop MW-class very low-energy neutrino beam and understand operational issues (highly challenging!)
- Low energy beam poorly focused and cross-sections very low, so sensitivity limited by statistics (at present level of understanding of systematic errors)
- Synergy with LAGUNA/LBNO for the far site (CERN-Garpenberg≈1700km and Protvino-Garpenberg≈1300km) and detector

# Outlook on neutrinos

**FNAL:**
"neutrinos are flagship program"

**CERN ESG:**
"long baseline neutrinos are in high-priority large-scale scientific activities"

**Japanese roadmap:**
"T2HK 2nd priority just after ILC"

- **Worldwide consensus on the fundamental necessity of a rich neutrino programme, aimed among others at CPV discovery.**
- A master-plan must be developed to gather the needed resources from all regions, necessary to accomplish a truly comprehensive and highly successful CPV violation discovery programme.
- **The choice of the location(s) or the kind of experiment(s) should continue to be primarily of scientific and technical nature.**
- **High-power accelerators, new neutrino beams, and liquid argon detector technology, are areas where R&D resources are needed now.**

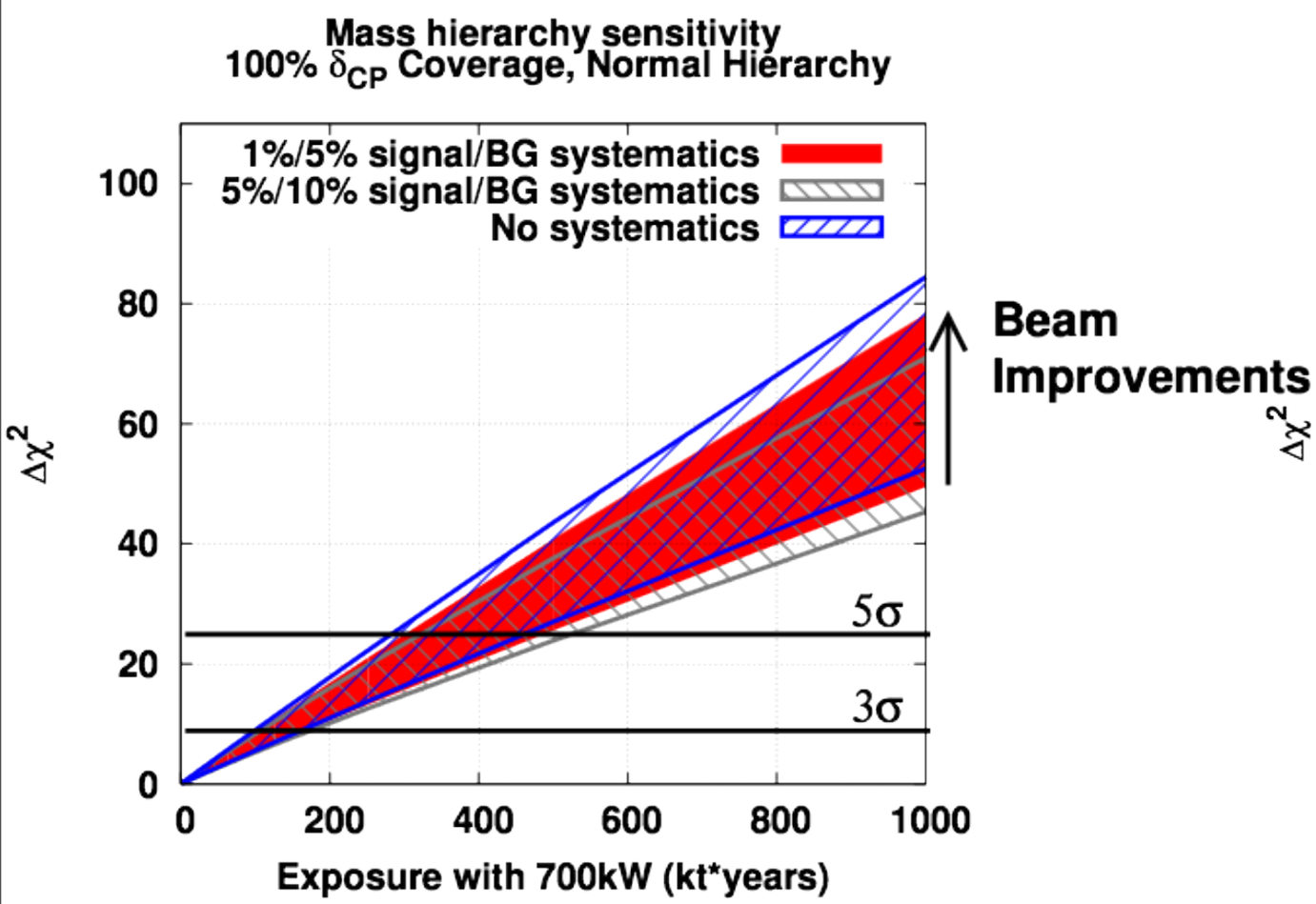

Thank you for your attention !

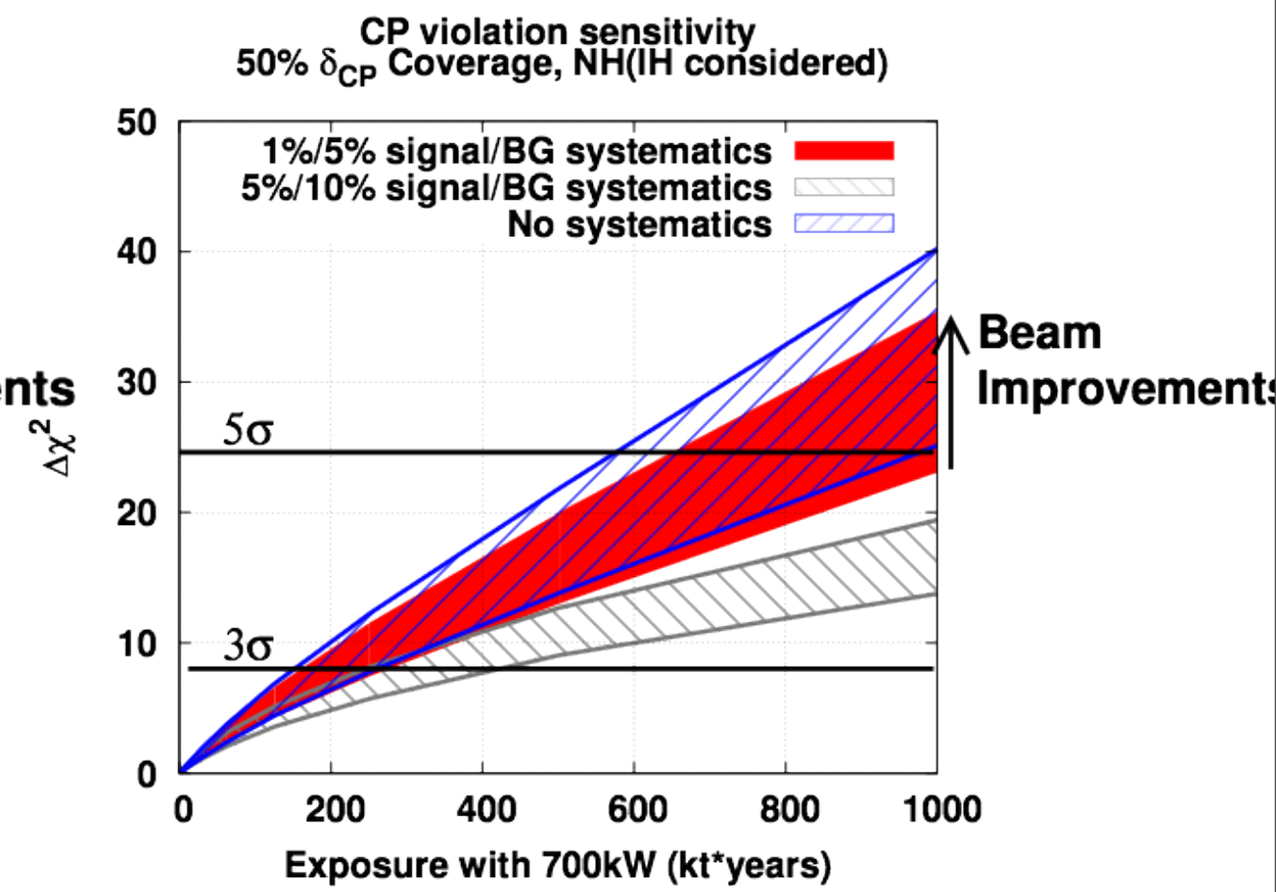
# Backup slides

Courtesy PvZ

# LBNE phase-2 sensitivity

34 kton LBNE + Project X

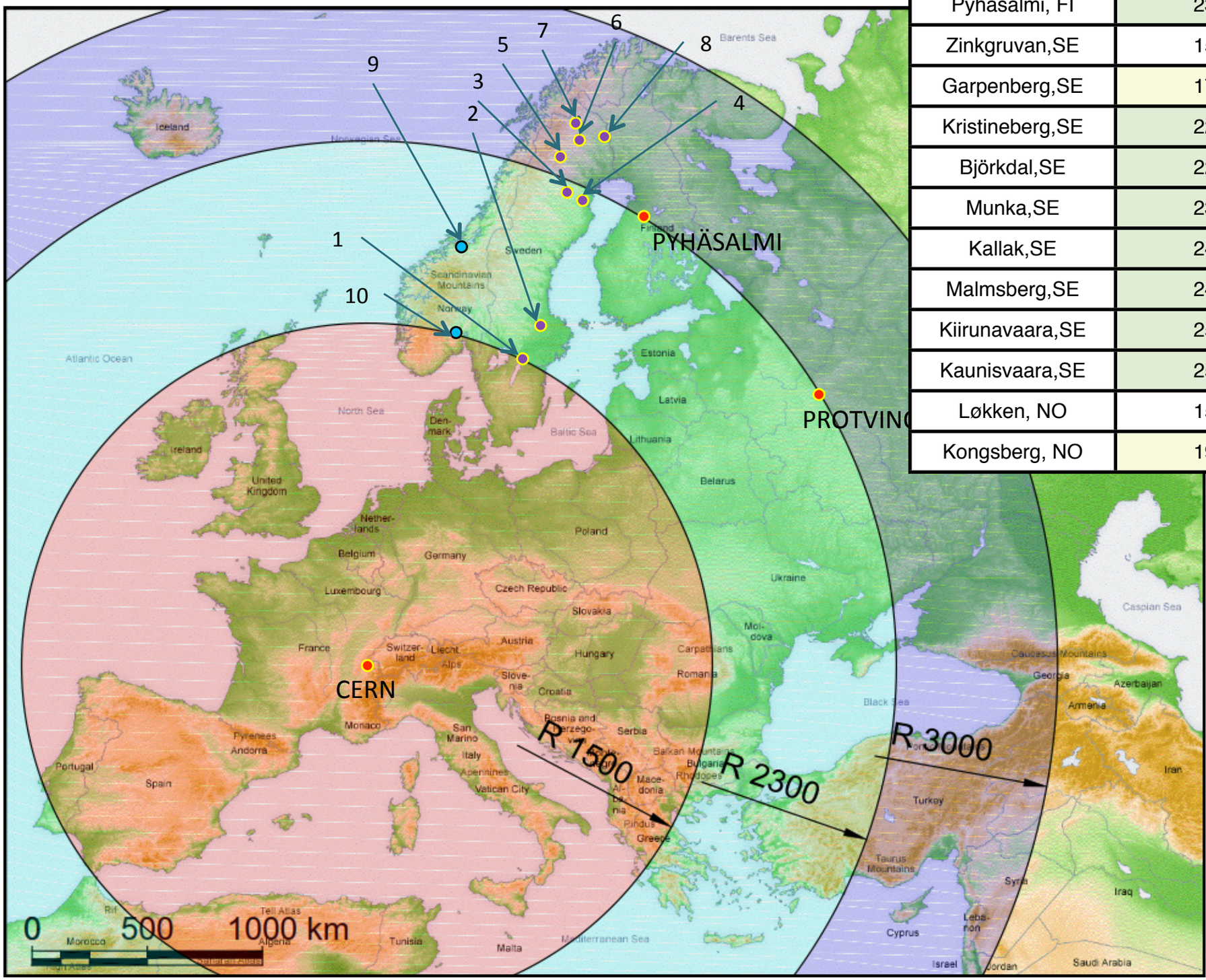



Needs systematic error of 1%/5% to reach 5σ C.L. CPV even in case of phase 2 exposure (1 Mt x year) !
(or go to longer baseline to recover 2nd max sensitivity!)

# A first look at nearby mines...

- LAGUNA/LBNO retains Pyhäsalmi as its **first choice** for far site



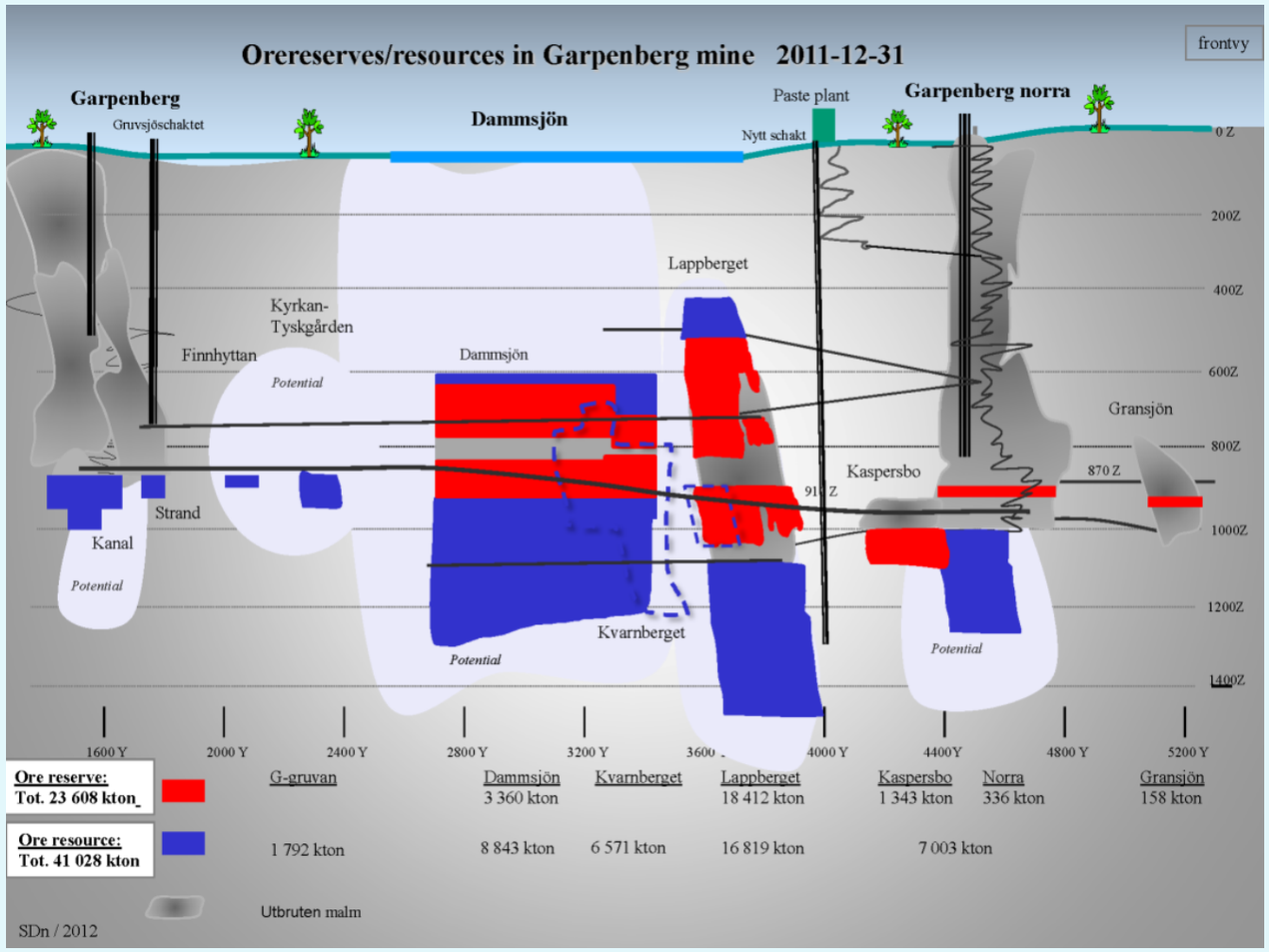

| Location | Baseline from CERN (km) | Baseline from Protvino (km) | Baseline from ESS (km) |
|---|---|---|---|
| Pyhäsalmi, FI | 2300 | 1160 | 1140 |
| Zinkgruvan,SE | 1530 | 1420 | 360 |
| Garpenberg,SE | 1730 | 1300 | 540 |
| Kristineberg,SE | 2230 | 1530 | 1080 |
| Björkdal,SE | 2270 | 1450 | 1100 |
| Munka,SE | 2310 | 1620 | 1160 |
| Kallak,SE | 2400 | 1700 | 1260 |
| Malmsberg,SE | 2480 | 1620 | 1320 |
| Kiirunavaara,SE | 2530 | 1700 | 1380 |
| Kaunisvaara,SE | 2552 | 1580 | 1390 |
| Løkken, NO | 1536 | 1740 | 500 |
| Kongsberg, NO | 1900 | 1800 | 840 |

- The concerns that the Finnish government expressed are obviously serious, one cannot exclude that other sites with similar advantages need to be found.
- There are several mines nearby.
- See also talk by Tord Ekelof (next talk)

# Garpenberg Mine

Distance from ESS Lund **540 km**

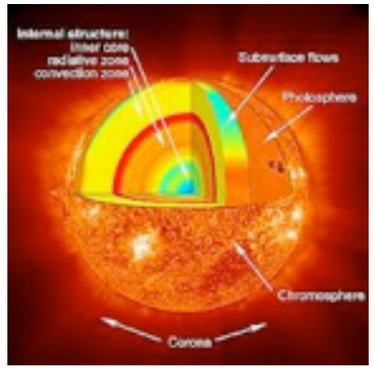
Depth 1232 m
Truck access tunnels
Two ore hoist shafts

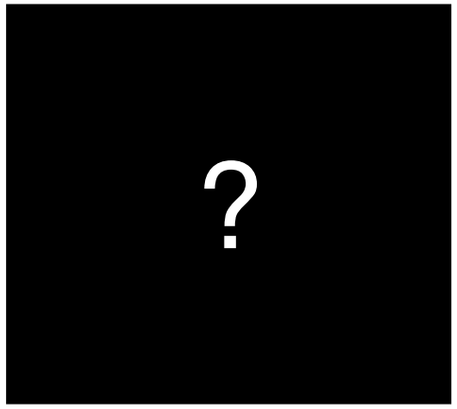

A new ore hoist schaft is planned to be ready i 3 years, leaving the two ex shafts existing free for other uses

# Goal: LAGUNA underground observatory

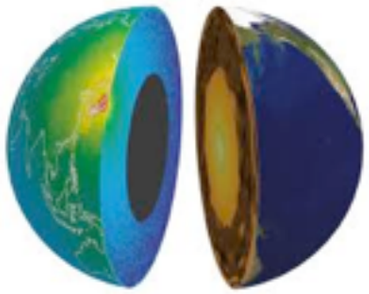
Supernova




Sun

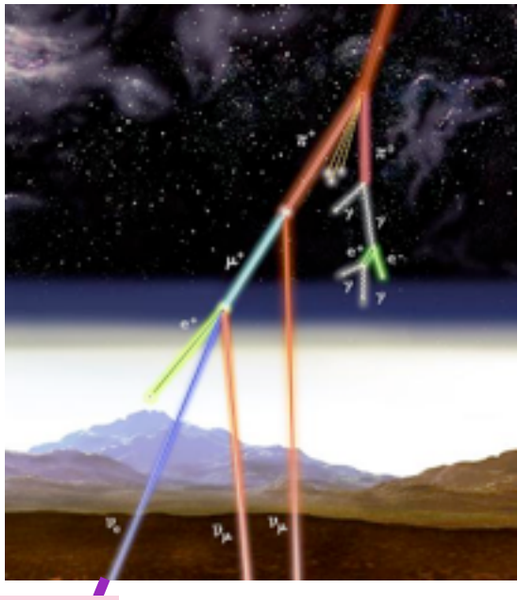



Unknown ?



Earth

Atmosphere



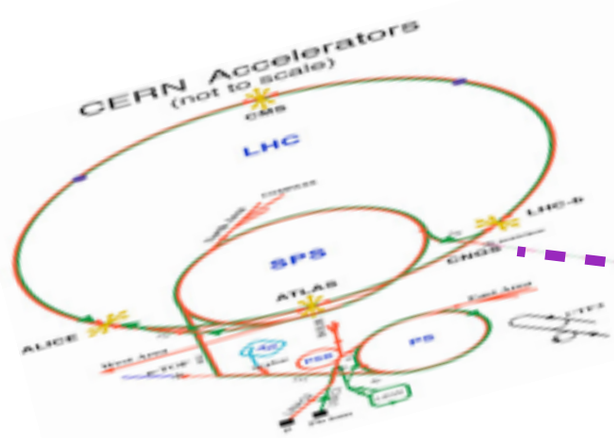
Neutrinos from MeV to 10's GeV

Reactors

Neutrino oscillations → MH, CPV, precision

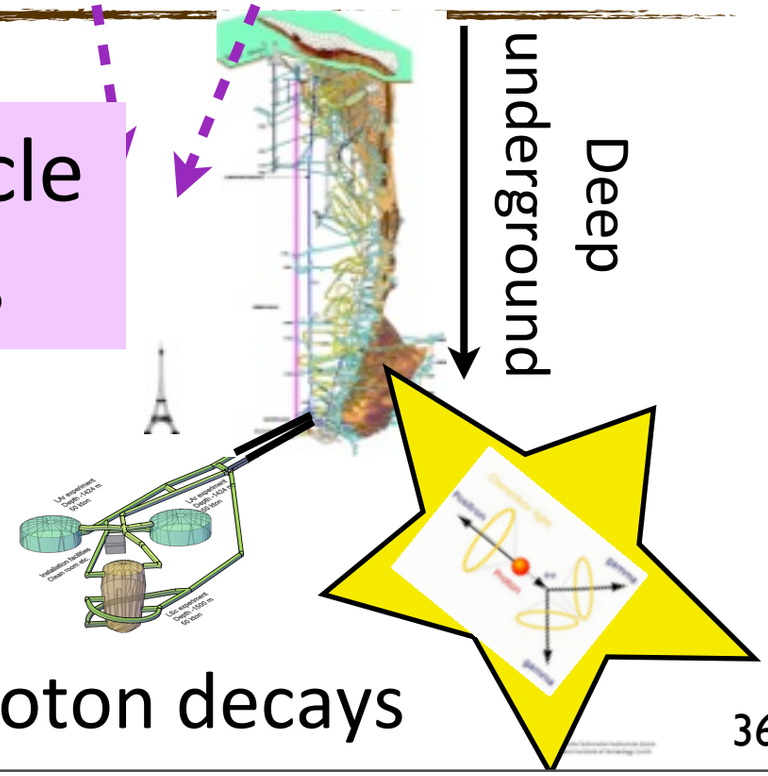
Proton lifetime

Address questions of particle and astroparticle physics



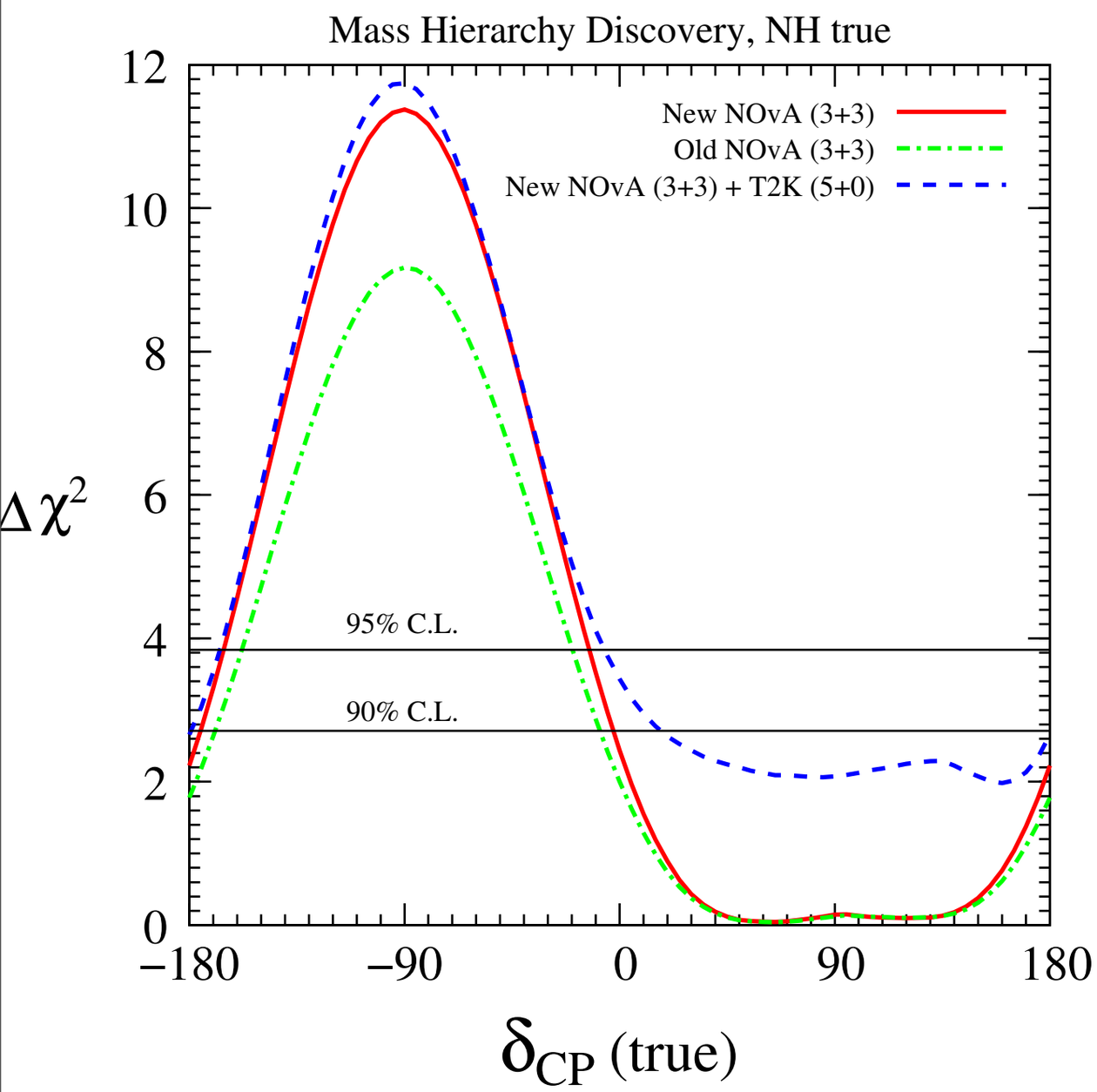

Accelerators

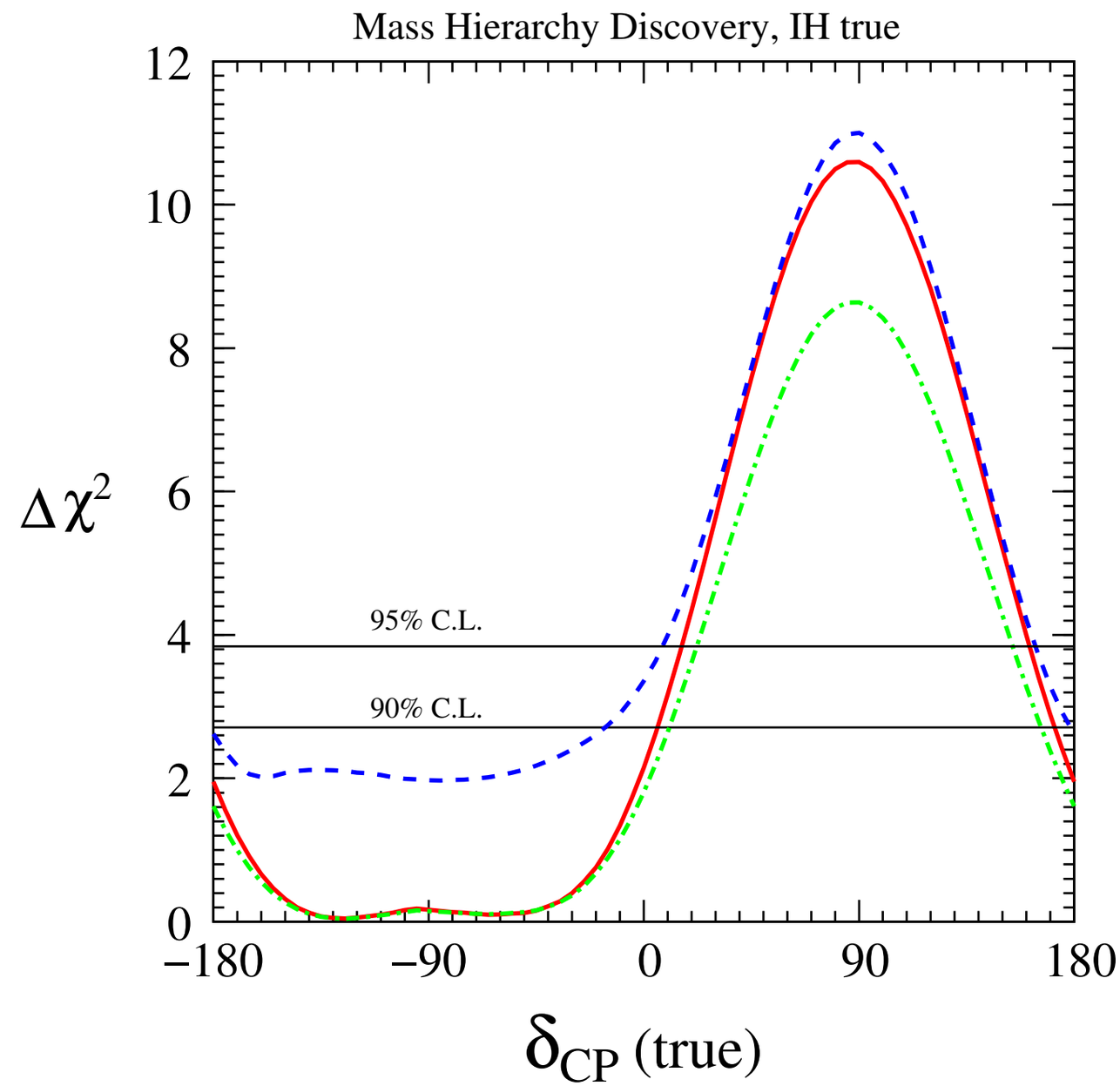
Terrestrial baseline




Proton decays

# What can we learn from T2K and NOVA ?




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

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

# LAGUNA-LBNO organisation

EC FP7 GA no 284518

http://laguna.ethz.ch:8080/Plone/deliverables

**Institution Board**

**Executive Board**

WP1: Management, Project Steering

**LAGUNA-LBNO Executive Board:**
Alain Blondel (UniGe)
Ilias Efthymiopoulos (CERN)
Takuya Hasegawa (KEK)
Yuri Kudenko (INR)
Guido Nuijten (Rockplan, Helsinki)
Lothar Oberauer (TUM)
Thomas Patzak (APC, Paris)
Silvia Pascoli (Durham)
Federico Petrolo (ETH Zürich)
André Rubbia (ETH Zürich)
Chris Thompson (Alan Auld Engineering)
Wladyslaw Trzaska (Jyväskyla)
Alfons Weber (Oxford)
Marco Zito (CEA)

**Technical Board**

**Scientific Board**

WP2: Underground Facility Construction, Plan and Costing

– Cavern and underground facility design
– Tank design
– Costing
– Risk assessment

WP3: Detector Lifetime Operation

– Detector instrumentation
– Installation
– Liquid Handling
– Costing
– Risk assessment

WP4: Long Baseline Neutrino Beams, Accelerators, Near Detector

– Primary and secondary beam line design and layout
– HP-PS conceptual design
– Near Detector
– Costing

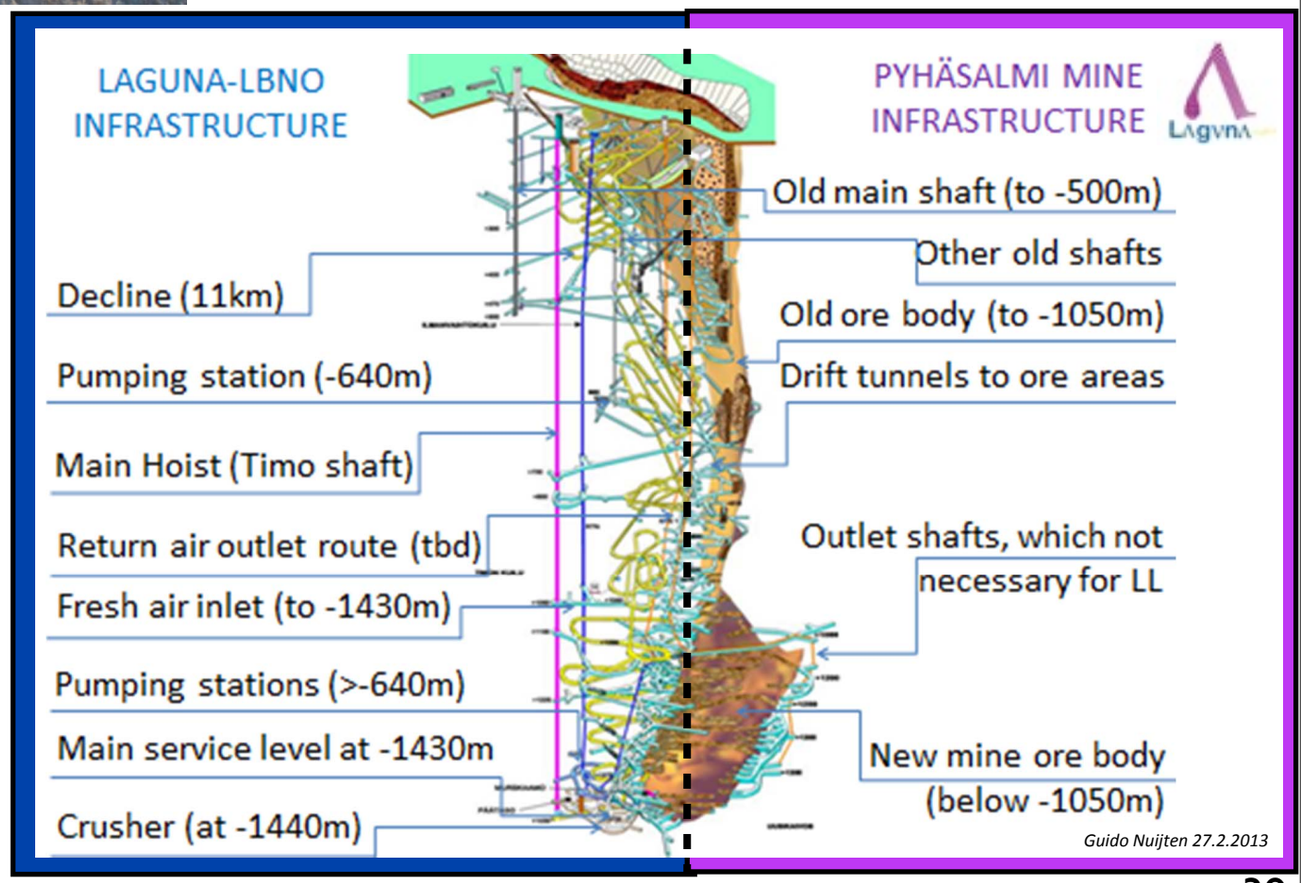
WP5: Science and Impact on Detector Design

– WCD, LAr, LSc simulation
– Unified physics performance assessment
– SPSC task force
– Protvino task force

# Pyhäsalmi mine (Inmet/PM Oy)


- Inmet Mining Corporation acquired by First Quantum Minerals Ltd (March 2013)
- Underground mining activities lifetime estimated until 2019. On-surface activities would continue afterwards.
- **Extended site investigation**
  - Assess rock where LAGUNA caverns would be excavated
  - So far 750m drilled. Final report expected in 2014.

- Only those parts that are necessary for LAGUNA/ LBNO during construction and operation would be transferred to the LAGUNA lab's 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.

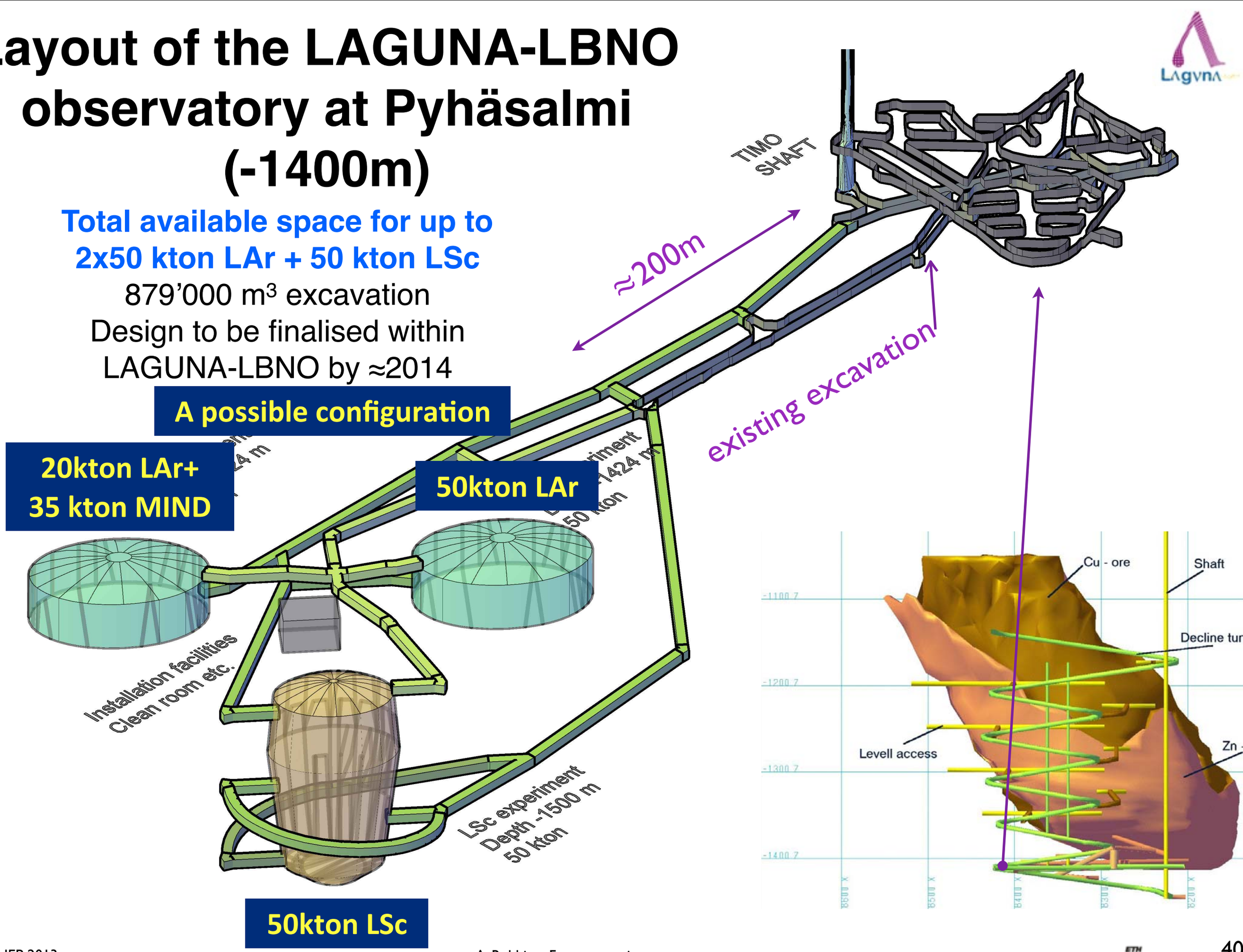


# Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)

**Total available space for up to 2x50 kton LAr + 50 kton LSc**

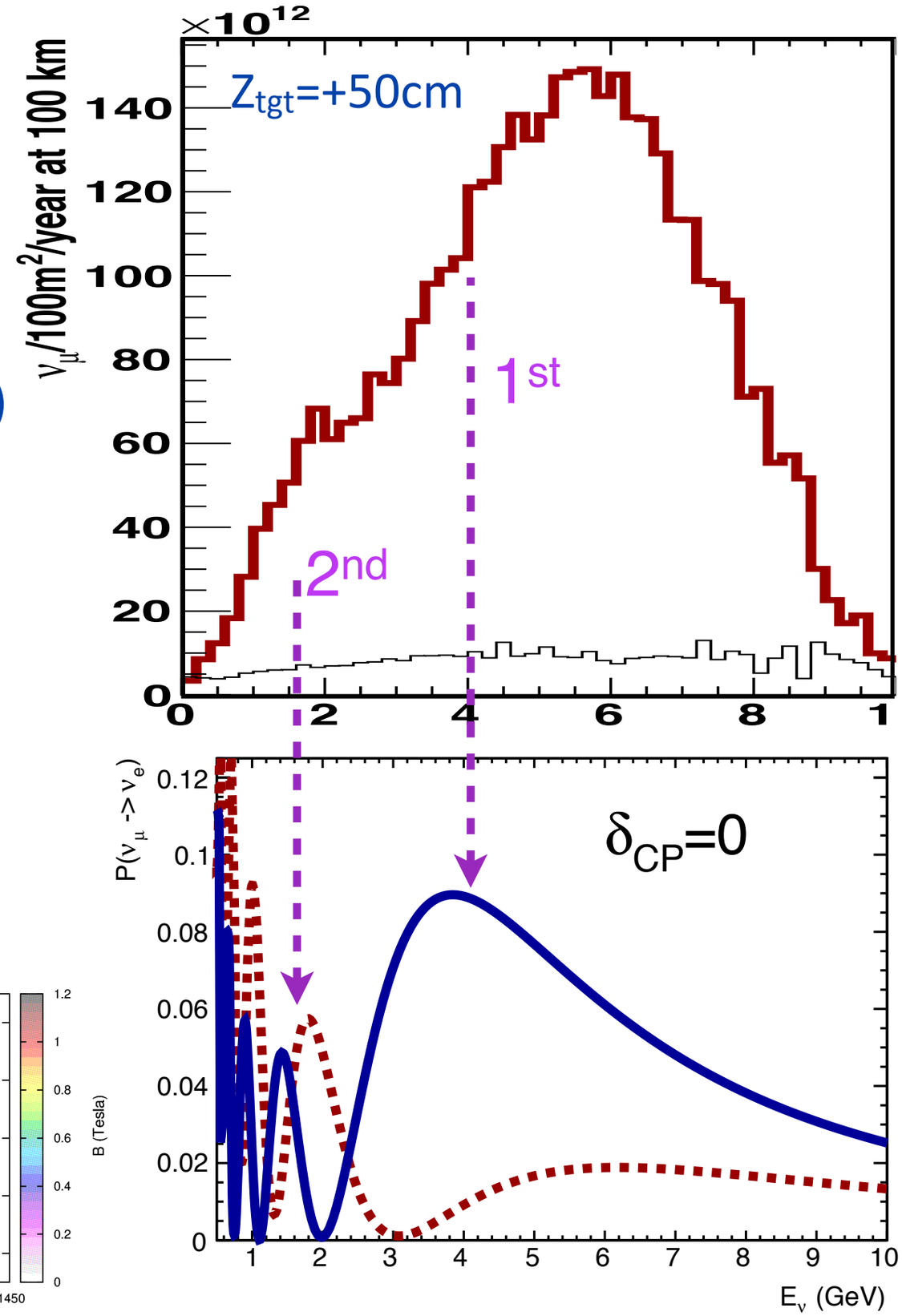
879'000 m³ excavation

Design to be finalised within LAGUNA-LBNO by ≈2014



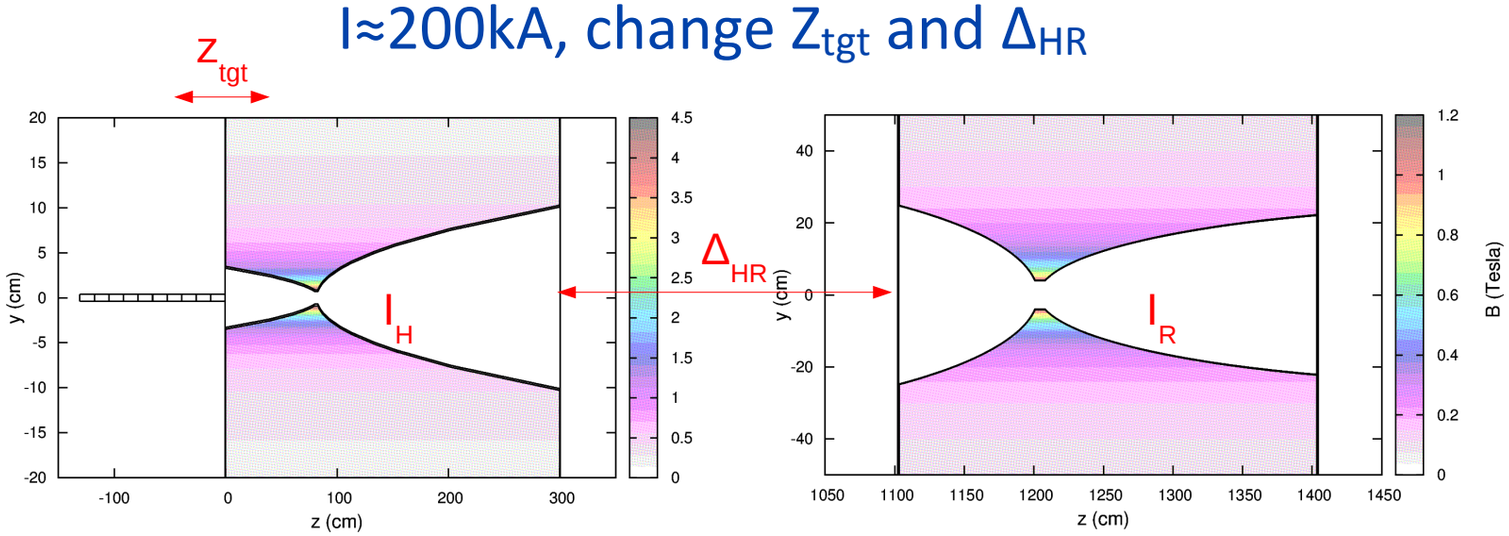
# LBNO baseline beam optimisation

- 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 $\Delta_{HR}$



# LBNO sensitivity for MH&CPV

- Include impact of systematic uncertainties in sensitivity computations

Oscillation parameters:

| Name | Value | Error (1σ) |
|---|---|---|
| L (km) | 2300 | exact |
| $\Delta m^2_{21}$ eV$^2$ | 7.60E-05 | exact |
| $\lvert \Delta m^2_{32} \rvert$ eV$^2$ | 2.40E-03 | ±4% |
| $\sin^2\theta_{12}$ | 0.30 | exact |
| $\sin^2 2\theta_{13}$ | 0.09 | ±10% |
| $\sin^2\theta_{23}$ | 0.50 | ±10% |
| <ρ> | 3.2 g/cm3 | ±4% |

*Oscillation values & errors from http://www.nu-fit.org*

$$\chi^2 = \sum_i (N_i - n_i)^2 / \mathrm{N_i} + \sum_j f_j^2 / \sigma^2_{f_j}$$

True rate (all sys parameter fixed to default values)

Systematic terms and their priors

$$n = \left(1 \pm \frac{f_\pm}{2}\right)\left((1+f_{sig})n_{sig} + (1+f_{NC})n_{NC} + (1+f_{\nu_e})n_{\nu_e} + (1+f_{\nu_\tau})n_{\nu_\tau}\right)$$

Syst. error on rates in bins of energy

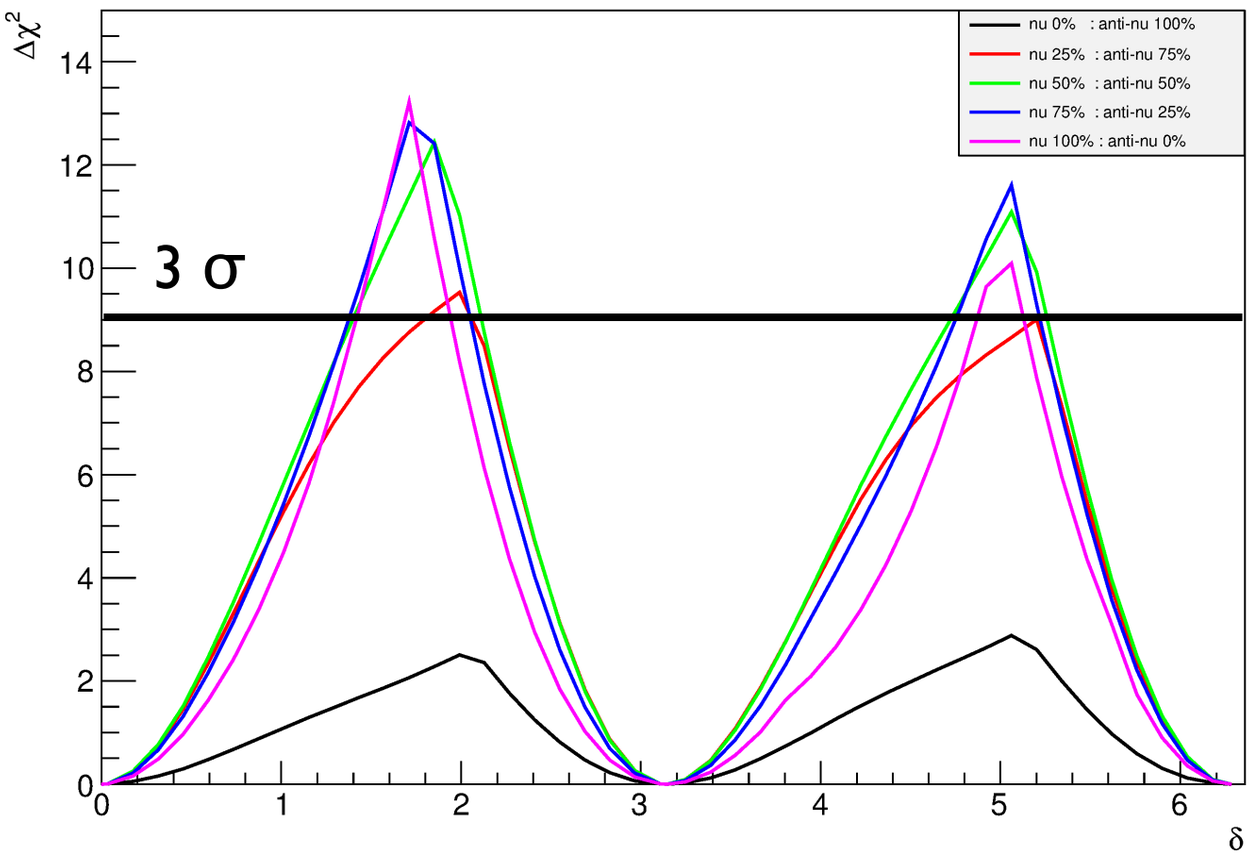
| Name | MH determination Error ($1\sigma$) | CP determination Error ($1\sigma$) |
|---|---|---|
| Bin-to-bin correlated: | | |
| Signal normalization ($f_{sig}$) | ±5% | ±5% |
| Beam electron contamination normalization ($f_{\nu_e CC}$) | ±5% | ±5% |
| Tau normalization ($f_{\nu_\tau CC}$) | ±50% | ±20% |
| $\nu$ NC and $\nu_\mu$ CC background ($f_{\nu_{NC}}$) | ±10% | ±10% |
| Relative norm. of "+" and "-" horn polarity ($f_{+/-}$) | ±5% | ±5% |
| Bin-to-bin uncorrelated | ±5% | ±5% |

# Sharing between nu vs antinu's

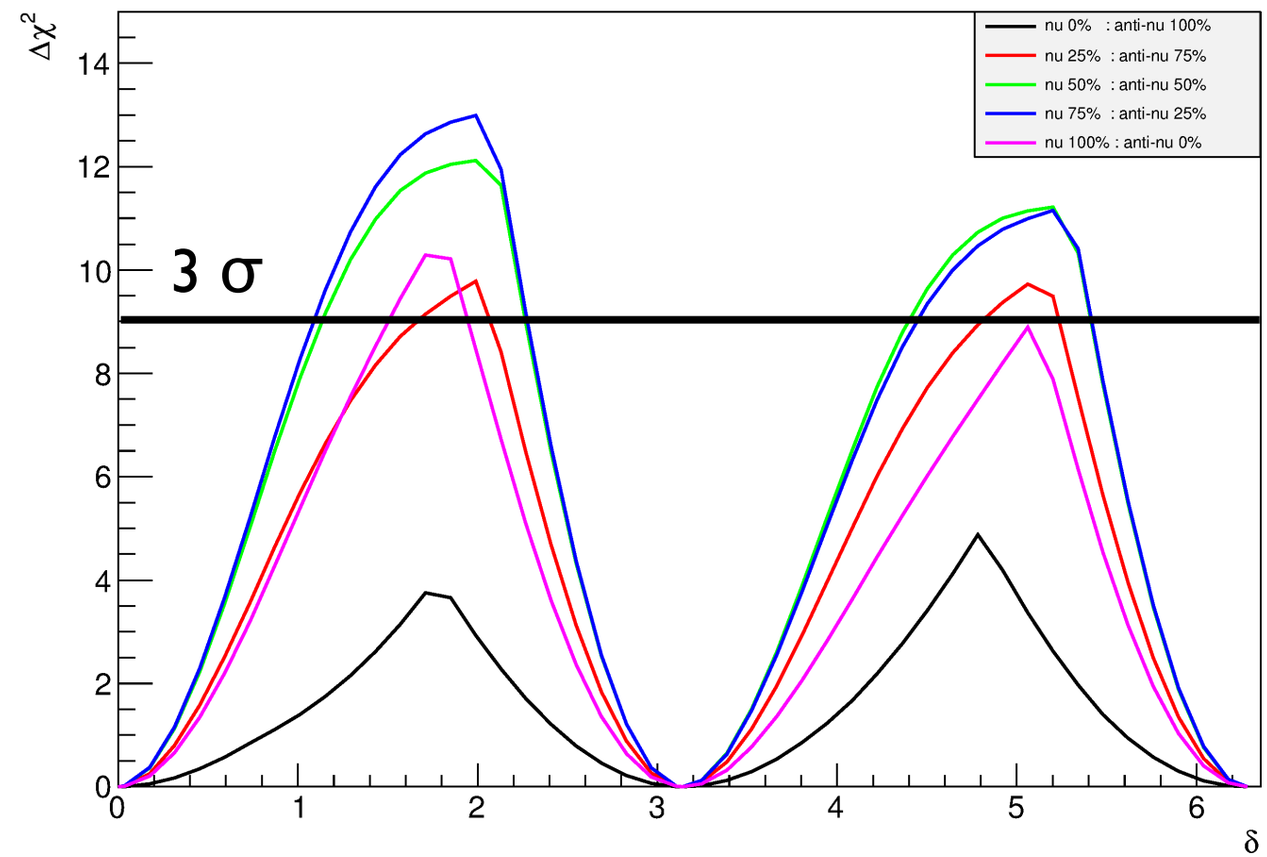
**After MH determined in 2 years, run for ≈10 years with optimised sharing of neutrinos / anti-neutrinos to cover the most possible phase space in $\delta_{CP}$**

LBNO L=2300km, 20 kton, 10 years

neutrino:anti-neutrino sharing dependence (NH)

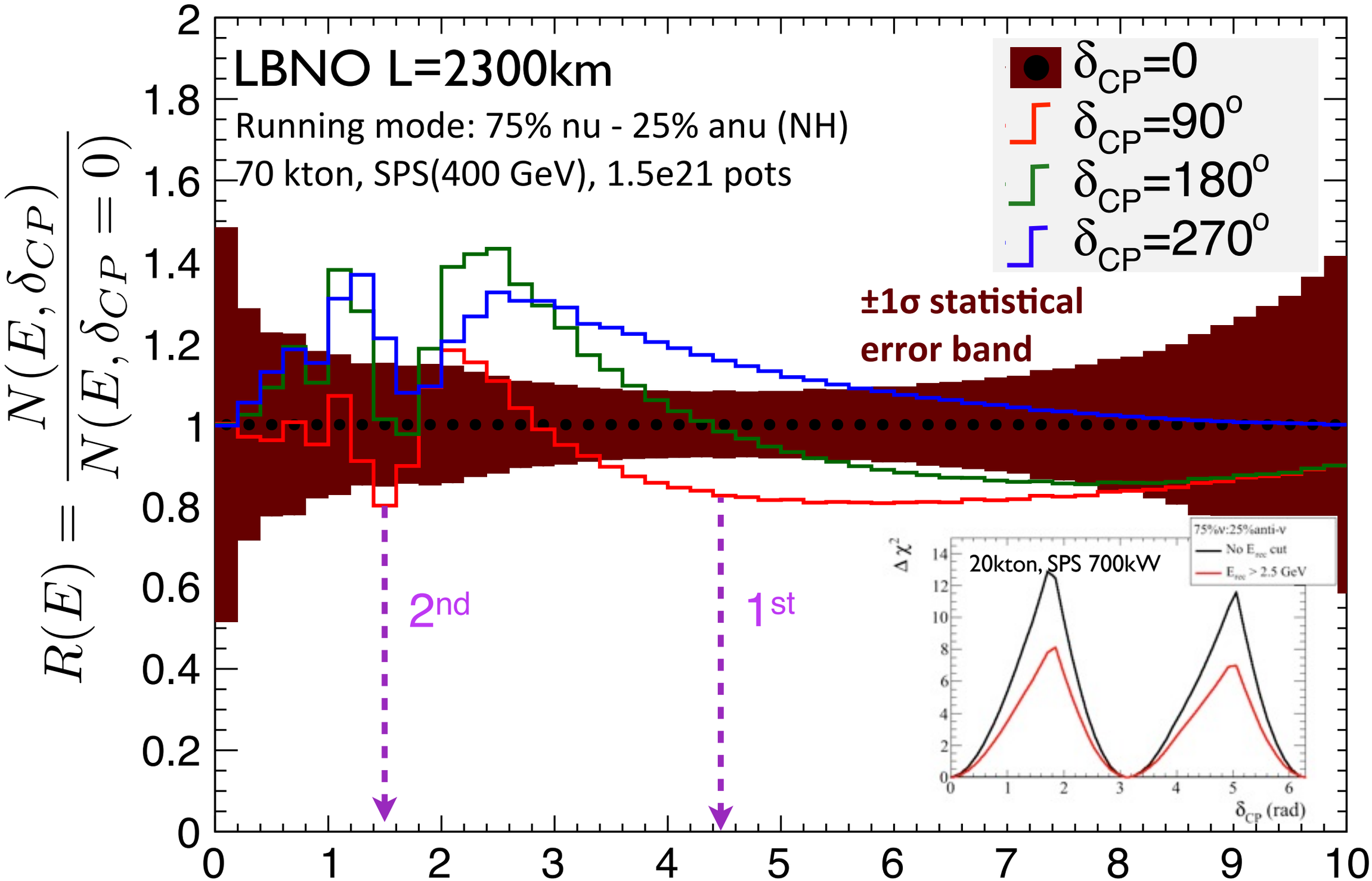



neutrino:anti-neutrino sharing dependence (IH)




**Design value: 75 % ν - 25 % anti-ν**

# Sensitivity to CPV: importance of 2nd max

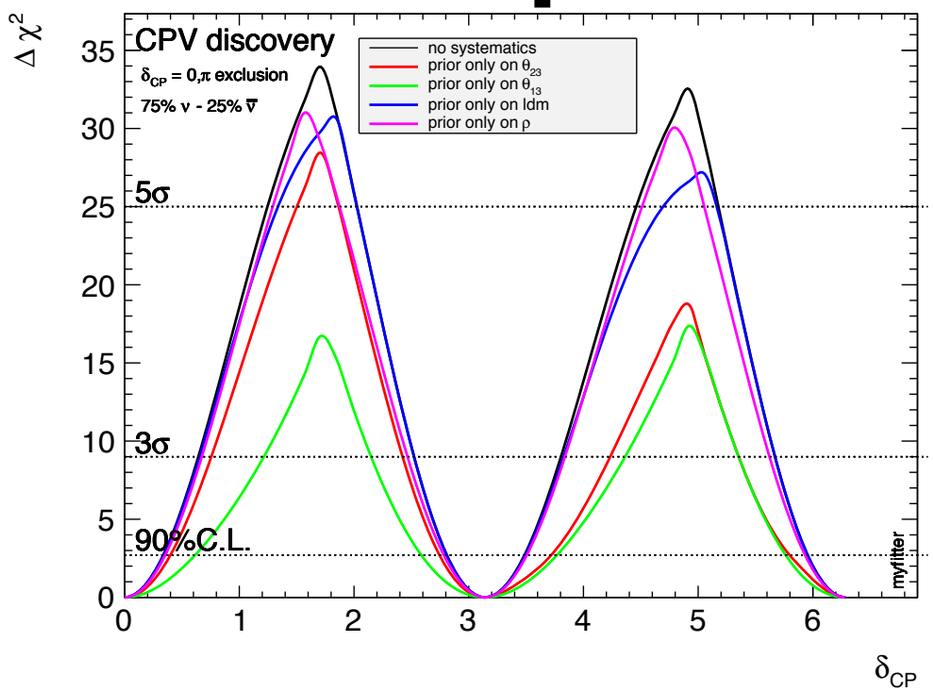



*The 1st maximum, although statistically significant, is rather featureless*

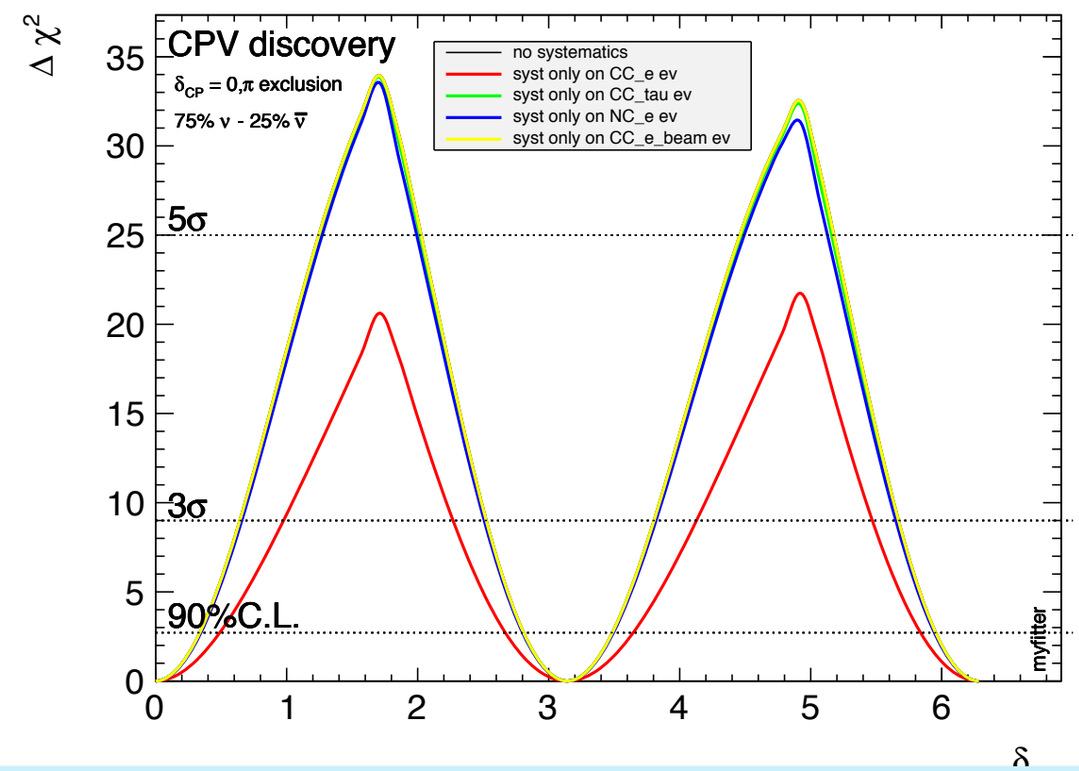
# Effect of systematic errors

LBNO L=2300km, 20 kton, 10 years

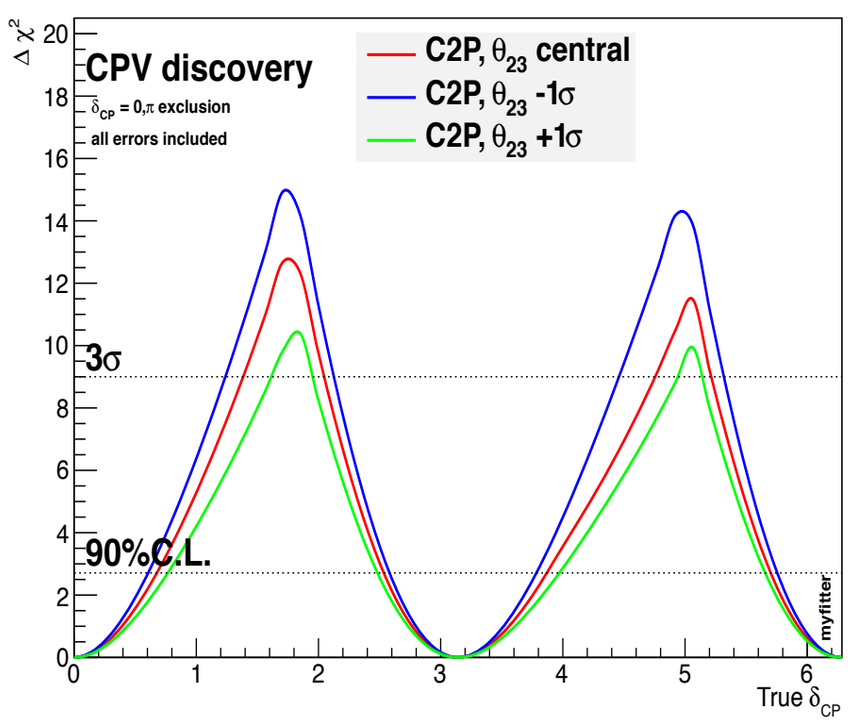
## Oscillation parameters




## Detector related




Effect of $\theta_{23}$

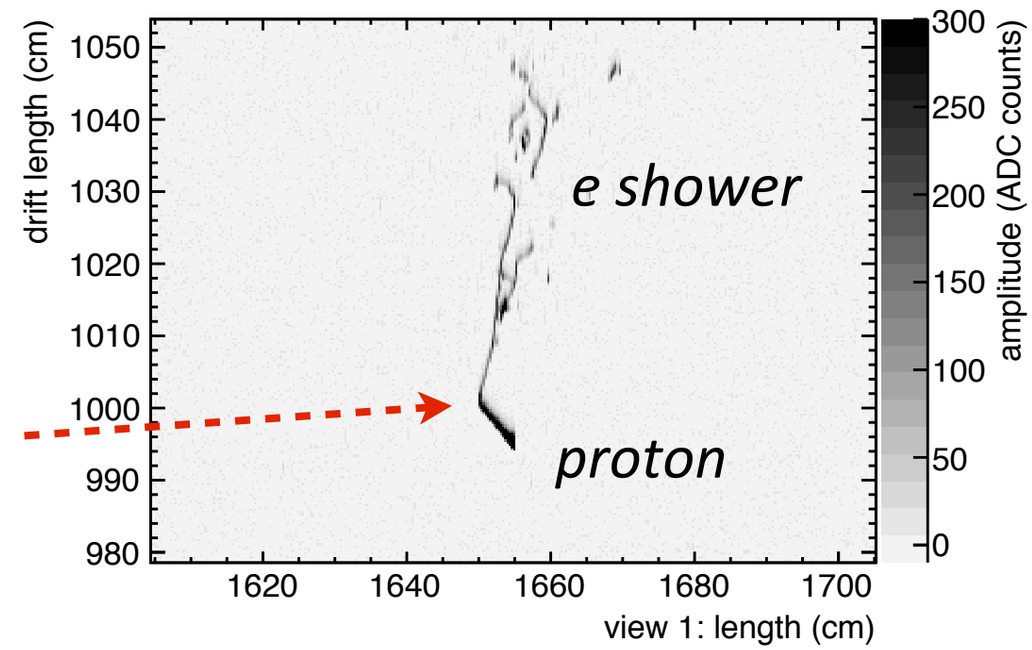



**Without systematic errors, the 20 kton would reach 5sigma CPV in 10 years The most important oscillation parameters are $\theta_{23}$ and $\theta_{13}$ and the most important systematics is the knowledge of the absolute rate of $\nu_e$ CC events.**

# Atmospheric neutrinos

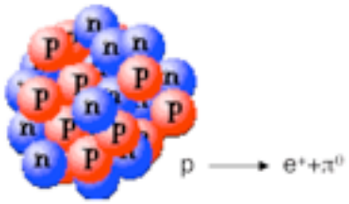
| Mode | Events/20kt/yr |
|---|---|
| $\nu_e$CC | 1440 |
| $\bar{\nu}_e$CC | 310 |
| $\nu_\mu$CC | 2440(w/o osc) |
| $\bar{\nu}_\mu$CC | 680(w/o osc) |
| $\nu$NC | 640 |

**MC:** $\nu_e$CC




- **Neutrino oscillation physics complementary to long baseline beam**
- Clean $\nu_e$ & $\nu_\mu$ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 $\nu_\tau$ CC / year)

# Proton decay sensitivity




## For a 20kton exposure of 10 years (200 kton×year)

JHEP 0704 (2007) 041

| Mode | Lifetime (90%C.L.) |
|---|---|
| $p \to \nu K^+$ | **$>3\times10^{34}$ yrs** |
| $p \to e^+\gamma$, $p \to \mu^+\gamma$ | **$>3\times10^{34}$ yrs** |
| $p \to \mu^-\pi^+K^+$ | **$>3\times10^{34}$ yrs** |
| $n \to e^-K^+$ | **$>3\times10^{34}$ yrs** |
| $p \to \mu^+K^0$, $p \to e^+K^0$ | $>1\times10^{34}$ yrs |
| $p \to e^+\pi^0$ | $>1\times10^{34}$ yrs |
| $p \to \mu^+\pi^0$ | $>0.8\times10^{34}$ yrs |
| $n \to e^+\pi^-$ | $>0.8\times10^{34}$ yrs |

Expect ≈linear sensitivity improvement with exposure until 1000 kton×year

# Supernova detection channels

JCAP 0310 (2003) 009
JCAP 0408 (2004) 001

**For 20 kton and a SN explosion at the distance of 5 kpc:**

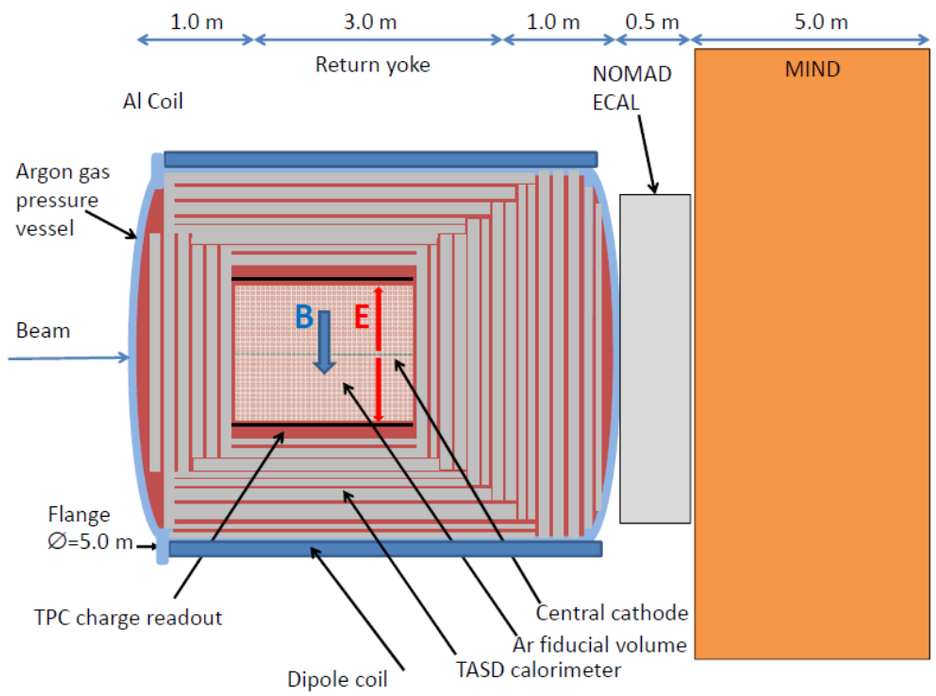
$$\langle E_{\nu_e} \rangle = 11 MeV, \langle E_{\bar{\nu}_e} \rangle = 16 MeV, \langle E_{\nu_x} \rangle = \langle E_{\bar{\nu}_x} \rangle = 25 MeV$$

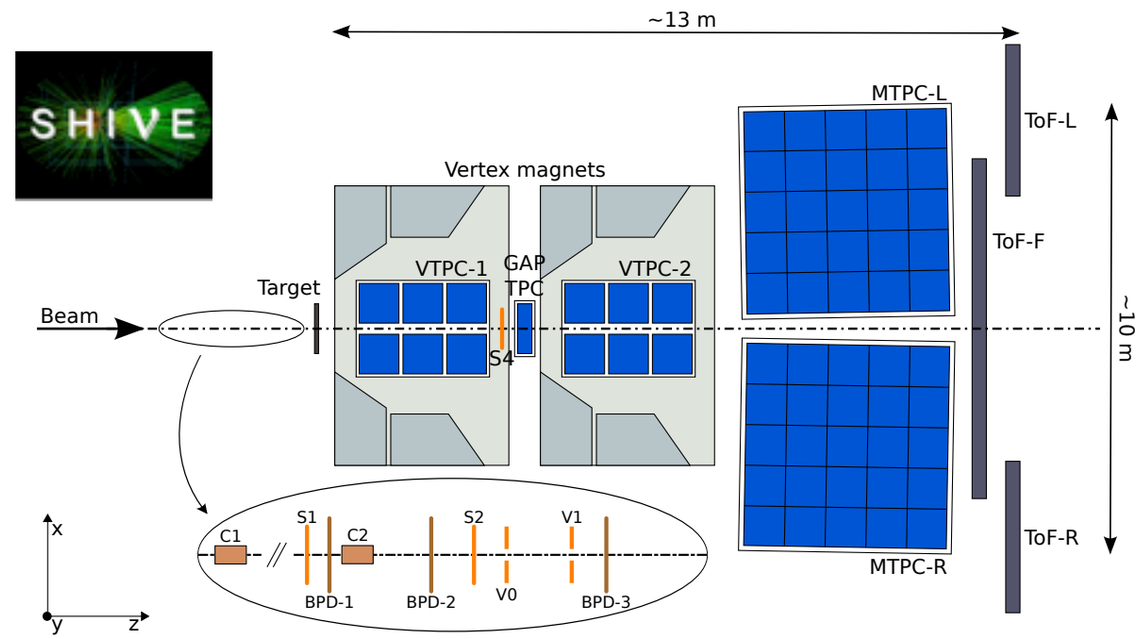
| | | **Events:** |
|---|---|---|
| $\nu_e \; {}^{40}Ar \rightarrow e^- \; {}^{40}K^*$ | ($E_\nu$ > 1.5 MeV) | ≈23820 |
| $\bar{\nu}_e \; {}^{40}Ar \rightarrow e^+ \; {}^{40}Cl^*$ | ($E_\nu$ > 7.48 MeV) | ≈2420 |
| $\nu_x \; {}^{40}Ar \rightarrow \nu_x + \; {}^{40}Ar^*$ | | ≈30440 |
| $\nu_x \; e^- \rightarrow \nu_x \; e^-$ | | ≈1330 |

- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Combined analysis of all reaction modes
- Neutrino mass via TOF

# LBNO near detector and hadroproduction

- **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,...**



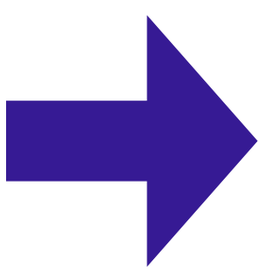

- Concept: 20 bar gas argon-mixture TPC (2.4 m × 2.4 m × 3 m) surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 600 kg argon mass in TPC
- 0.2 event/spill @ 7e13 ppp 400 GeV
- O(100'000) events/year

- 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 far detectors requirements

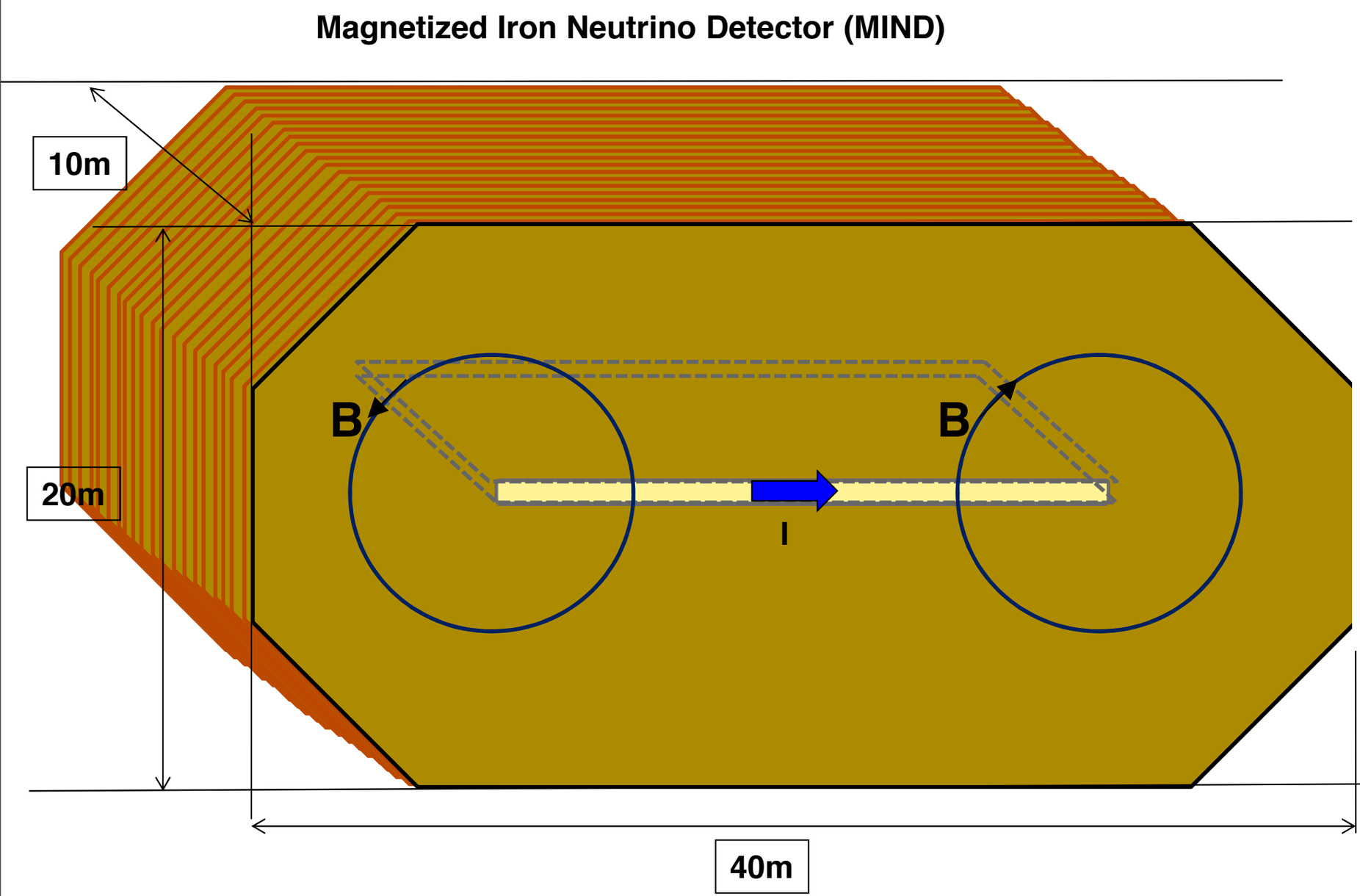
- **Detect electron&tau appearance and muon disappearance + NC**
- Fiducial mass at least equal to that of SuperK (>20kton)
- Clean neutrino detection in the energy range $0.5<E_\nu<10$ GeV (→ multi-prong events, not only QE)
- Fine granularity for clean $\nu_\mu \rightarrow \nu_e$ appearance signal
- Neutrino energy resolution $\Delta E_\nu/E_\nu < 10\%$ to observe L/E
- Full kinematical reconstruction, e.g. for $\nu_\mu \rightarrow \nu_\tau$
- $4\pi$ acceptance for all tracks and neutrals
- Charge and momentum determination for muons, to e.g. study $\nu_\mu/\overline{\nu_\mu}$ in both horn configurations

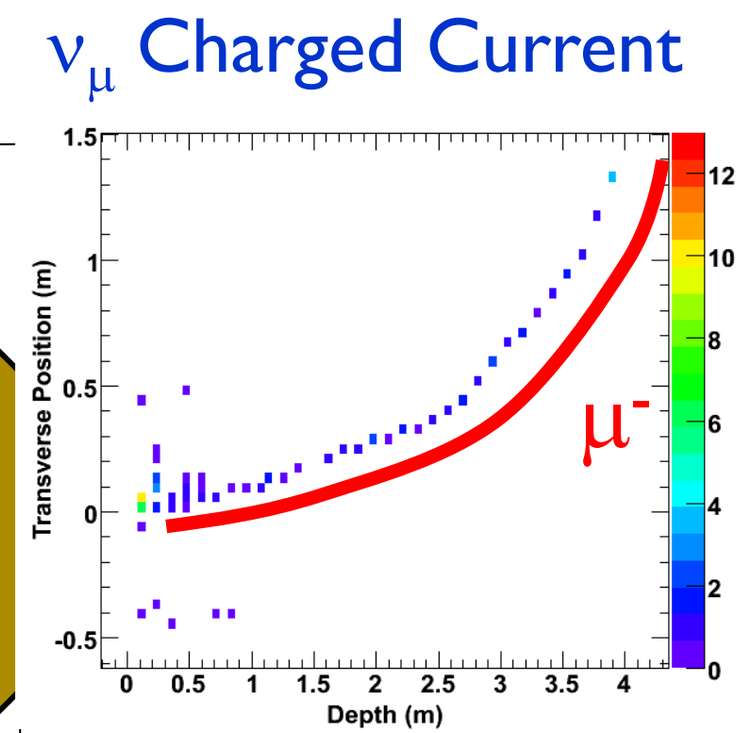


**❖Liquid argon TPC complemented by magnetized iron detector (MIND).**

# LBNO far muon detector concept

35kton MIND magnetised iron with scintillator slabs (MINOS-like, reference IDS-NF)



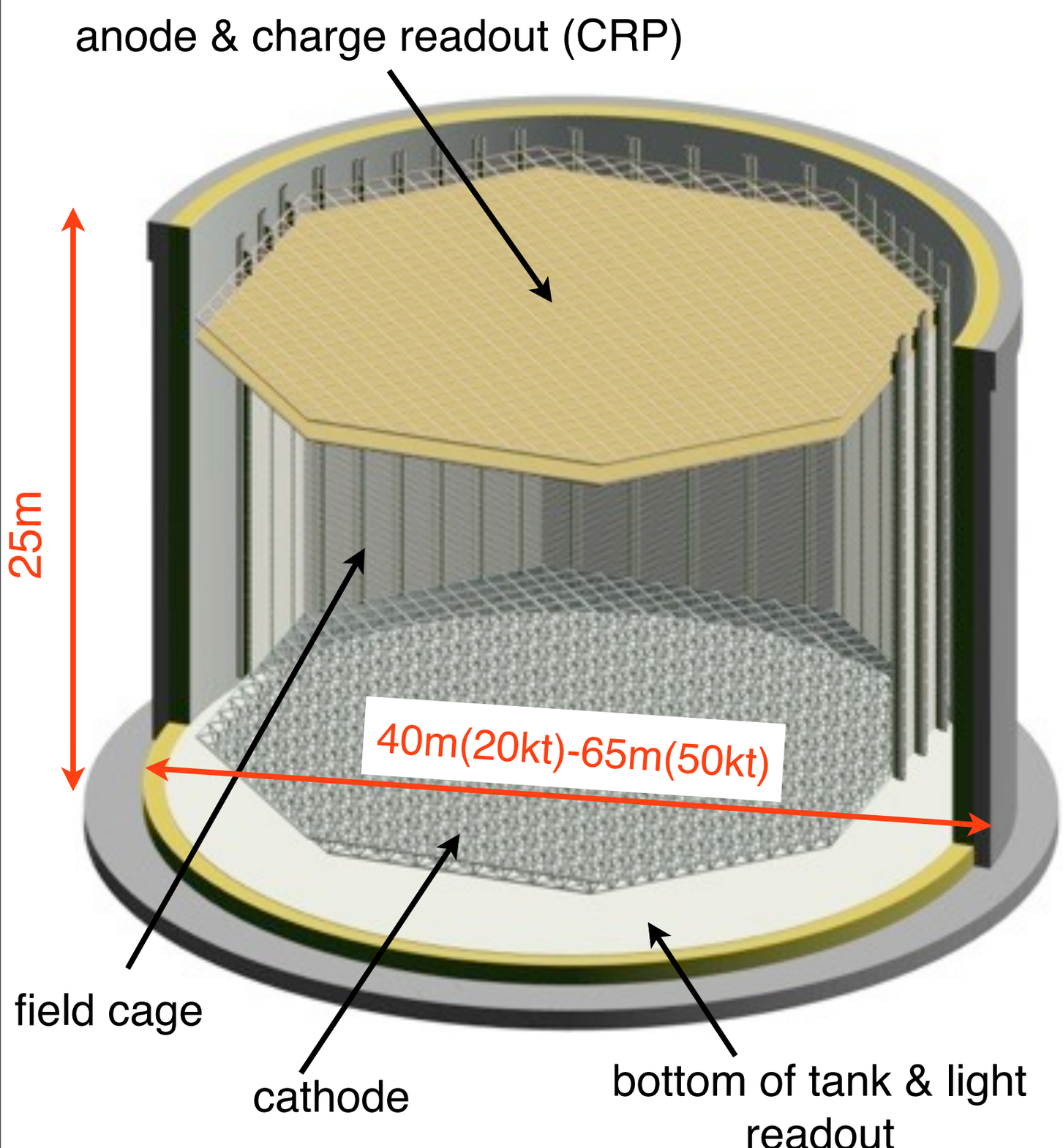




MINOS

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

# LBNO far liquid Argon detector

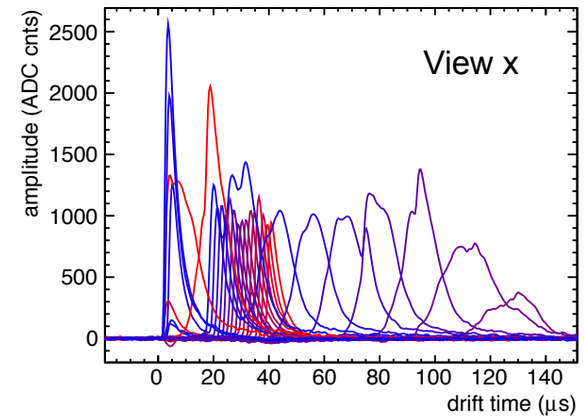
## ✤Double phase LAr LEM TPC

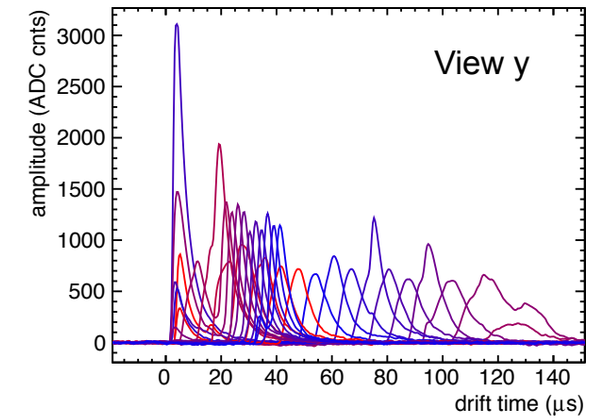


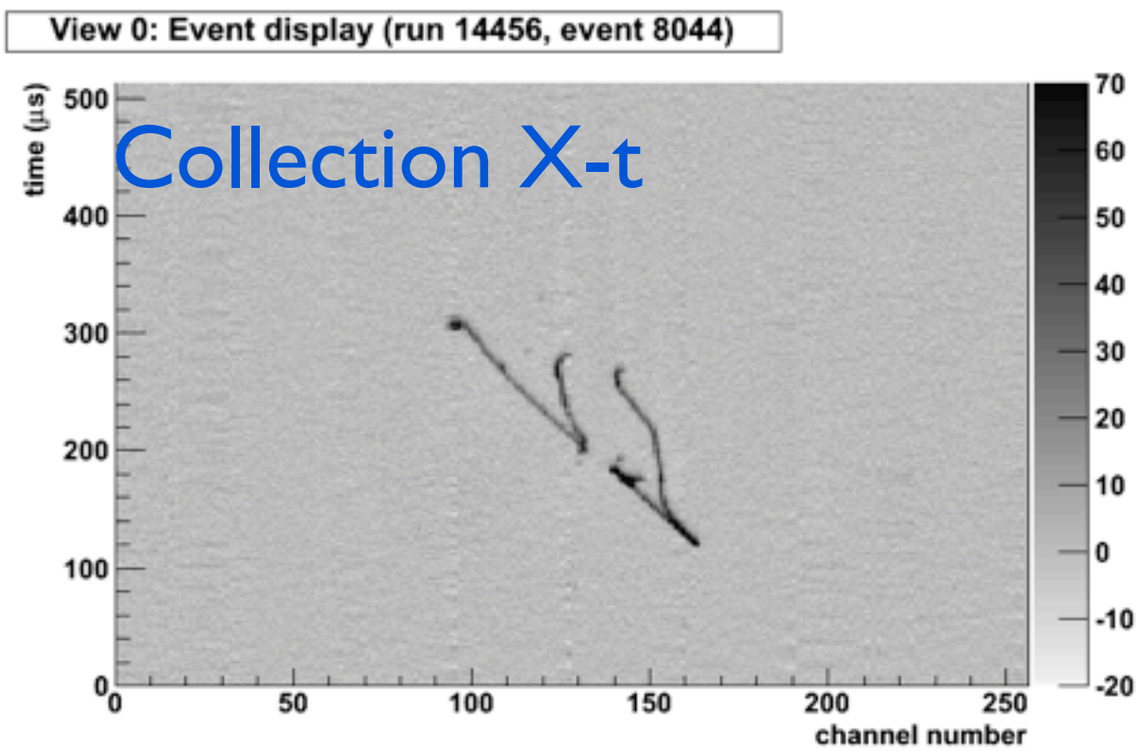

| | | 20 KT | 50 KT | 100 KT |
|---|---|---|---|---|
| Liquid argon density at 1.2 bar | [T/m³] | 1.38346 | | |
| Liquid argon volume height | [m] | 22 | | |
| Active liquid argon height | [m] | 20 | | |
| Pressure on the bottom due to LAr | [T/m²] | 30.4 (≡ 0.3 MPa ≡ 3 bar) | | |
| Inner vessel diameter | [m] | 37 | 55 | 76 |
| Inner vessel base surface | [m²] | 1075.2 | 2375.8 | 4536.5 |
| Liquid argon volume | [m³] | 23654.6 | 52268.2 | 99802.1 |
| Total liquid argon mass | [T] | 32525.6 | 71869.8 | 137229.9 |
| Active LAr area (percentage) | [m²] | 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 |

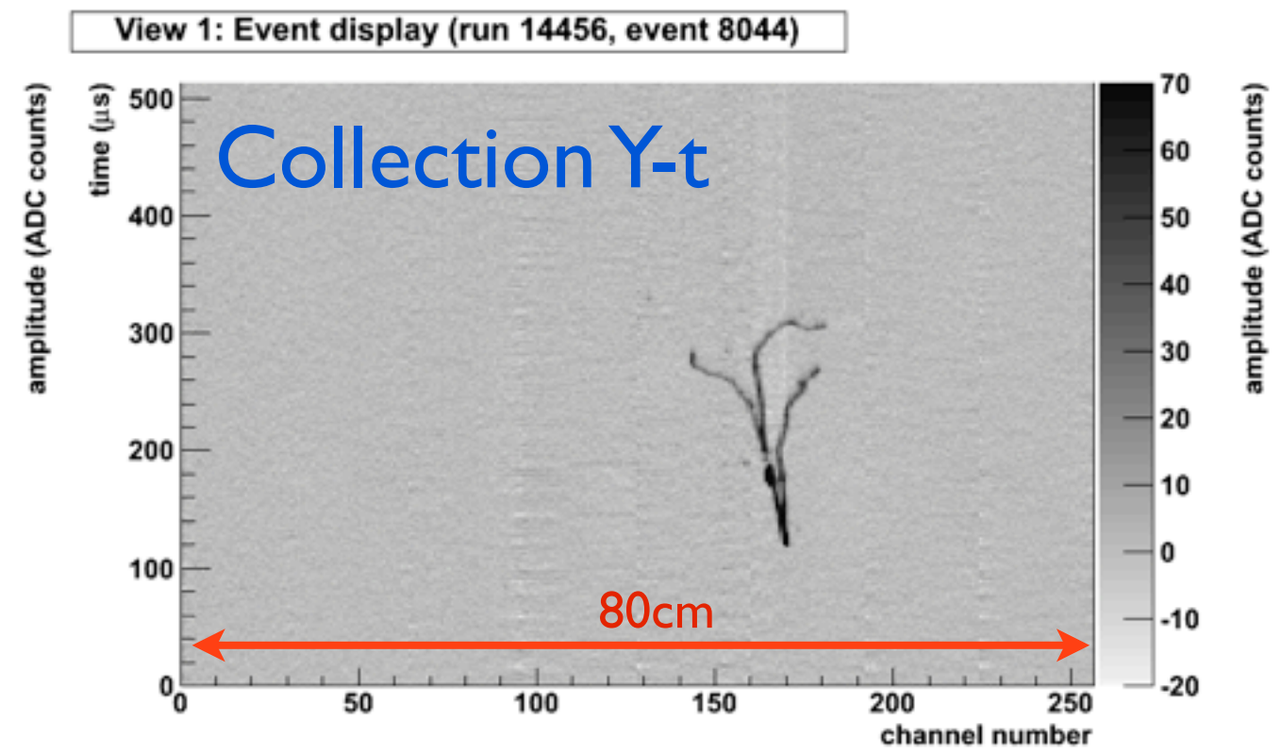
# LBNO far liquid Argon detector

- Double phase LAr LEM TPC
  (GLACIER hep-ph/0402110; J.Phys.Conf.Ser. 171 (2009) 012020; NIM A 641 (2011) 48-57; JINST 7 (2012) P08026; 2013 JINST 8 P04012)




Gain demonstrated up to 90
Optimal gain for neutrino physics operation ≈ 10 - 20
Much better S/N and imaging performance than single phase
Low threshold (≈100 keV with S/N = 10)
Both views in collection mode (50%-50% charge sharing) avoid induction planes

# Summary

- LAGUNA/LBNO design study has made significant progress at designing and optimising a next generation deep underground neutrino observatory.
- LBNO has been put forward to CERN with unique physics potentials, including astro-particle physics and proton decay search. It is conceived as an incremental approach starting with an underground LAr detector, a clear stage 1 physics goal and well-defined upgrade plan, in order to reach a CPV discovery and possibly up to 70 kton mass.
- We are now proposing a demonstrator for the double phase LAr technology at a relevant scale (216m$^3$).
- The LAGUNA/LBNO consortium plans to finalise its findings and submit its reports by the end of 2014.

# LBNO Expression of Interest


A. Stahl,[1] C. Wiebusch,[1] A. M. Guler,[2] M. Kamiscioglu,[2] R. Sever,[2] A.U. Yilmazer,[3] C. Gunes,[3] D. Yilmaz,[3] P. Del Amo Sanchez,[4] D. Duchesneau,[4] H. Pessard,[4] E. Marcoulaki,[5] I. A. Papazoglou,[5] V. Berardi,[6] F. Cafagna,[6] M.G. Catanesi,[6] L. Magaletti,[6] A. Mercadante,[6] M. Quinto,[6] E. Radicioni,[6] A. Ereditato,[7] I. Kreslo,[7] C. Pistillo,[7] M. Weber,[7] A. Ariga,[7] T. Ariga,[7] T. Strauss,[7] M. Hierholzer,[7] J. Kawada,[7] C. Hsu,[7] S. Haug,[7] A. Jipa,[8] I. Lazanu,[8] A. Cardini,[9] A. Lai,[9] R. Oldeman,[10] M. Thomson,[11] A. Blake,[11] M. Prest,[12] A. Auld,[13] J. Elliot,[13] J. Lumbard,[13] C. Thompson,[13] Y.A. Gornushkin,[14] S. Pascoli,[15] R. Collins,[16] M. Haworth,[16] J. Thompson,[16] G. Bencivenni,[17] D. Domenici,[17] A. Longhin,[17] A. Blondel,[18] A. Bravar,[18] F. Dufour,[18] Y. Karadzhov,[18] A. Korzenev,[18] E. Noah,[18] M. Ravonel,[18] M. Rayner,[18] R. Asfandiyarov,[18] A. Haesler,[18] C. Martin,[18] E. Scantamburlo,[18] F. Cadoux,[18] R. Bayes,[19] F.J.P. Soler,[19] L. Aalto-Setälä,[20] K. Enqvist,[20] K. Huitu,[20] K. Rummukainen,[20] G. Nuijten,[21] K.J. Eskola,[22] K. Kainulainen,[22] T. Kalliokoski,[22] J. Kumpulainen,[22] K. Loo,[22] J. Maalampi,[22] M. Manninen,[22] I. Moore,[22] J. Suhonen,[22] W.H. Trzaska,[22] K. Tuominen,[22] A. Virtanen,[22] I. Bertram,[23] A. Finch,[23] N. Grant,[23] L.L. Kormos,[23] P. Ratoff,[23] G. Christodoulou,[24] J. Coleman,[24] C. Touramanis,[24] K. Mavrokoridis,[24] M. Murdoch,[24] N. McCauley,[24] D. Payne,[24] P. Jonsson,[25] A. Kaboth,[25] K. Long,[25] M. Malek,[25] M. Scott,[25] Y. Uchida,[25] M.O. Wascko,[25] F. Di Lodovico,[26] J.R. Wilson,[26] B. Still,[26] R. Sacco,[26] R. Terri,[26] M. Campanelli,[27] R. Nichol,[27] J. Thomas,[27] A. Izmaylov,[28] M. Khabibullin,[28] A. Khotjantsev,[28] Y. Kudenko,[28] V. Matveev,[28] O. Mineev,[28] N. Yershov,[28] V. Palladino,[29] J. Evans,[30] S. Söldner-Rembold,[30] U.K. Yang,[30] M. Bonesini,[31] T. Pihlajaniemi,[32] M. Weckström,[32] K. Mursula,[32] T. Enqvist,[32] P. Kuusiniemi,[32] T. Räihä,[32] J. Sarkamo,[32] M. Slupecki,[32] J. Hissa,[32] E. Kokko,[32] M. Aittola,[32] G. Barr,[33] M.D. Haigh,[33] J. de Jong,[33] H. O'Keeffe,[33] A. Vacheret,[33] A. Weber,[33,34] G. Galvanin,[35] M. Temussi,[35] O. Caretta,[34] T. Davenne,[34] C. Densham,[34] J. Ilic,[34] P. Loveridge,[34] J. Odell,[34] D. Wark,[34] A. Robert,[36] B. Andrieu,[36] B. Popov,[36,14] C. Giganti,[36] J.-M. Levy,[36] J. Dumarchez,[36] M. Buizza-Avanzini,[37] A. Cabrera,[37] J. Dawson,[37] D. Franco,[37] D. Kryn,[37] M. Obolensky,[37] T. Patzak,[37] A. Tonazzo,[37] F. Vanucci,[37] D. Orestano,[38] B. Di Micco,[38] L. Tortora,[39] O. Bésida,[40] A. Delbart,[40] S. Emery,[40] V. Galymov,[40] E. Mazzucato,[40] G. Vasseur,[40] M. Zito,[40] V.A. Kudryavtsev,[41] L.F. Thompson,[41] R. Tsenov,[42] D. Kolev,[42] I. Rusinov,[42] M. Bogomilov,[42] G. Vankova,[42] R. Matev,[42] A. Vorobyev,[43] Yu. Novikov,[43] S. Kosyanenko,[43] V. Suvorov,[43] G. Gavrilov,[43] E. Baussan,[44] M. Dracos,[44] C. Jollet,[44] A. Meregaglia,[44] E. Vallazza,[45] S.K. Agarwalla,[46] T. Li,[46] D. Autiero,[47] L. Chaussard,[47] Y. Déclais,[47] J. Marteau,[47] E. Pennacchio,[47] E. Rondio,[48] J. Lagoda,[48] J. Zalipska,[48] P. Przewlocki,[48] K. Grzelak,[49] G. J. Barker,[50] S. Boyd,[50] P.F. Harrison,[50] R.P. Litchfield,[50] Y. Ramachers,[50] A. Badertscher,[51] A. Curioni,[51] U. Degunda,[51] L. Epprecht,[51] A. Gendotti,[51] L. Knecht,[51] S. DiLuise,[51] S. Horikawa,[51] D. Lussi,[51] S. Murphy,[51] G. Natterer,[51] F. Petrolo,[51] L. Periale,[51] A. Rubbia,[51,*] F. Sergiampietri,[51] and T. Viant[51]

1. III. Physikalisches Institut, RWTH Aachen, Aachen, Germany
2. Middle East Technical University (METU), Ankara, Turkey
3. Ankara University, Ankara, Turkey
4. LAPP, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
5. Institute of Nuclear Technology-Radiation Protection, National Centre for Scientific Research "Demokritos", Athens, Greece
6. INFN and Dipartimento interateneo di Fisica di Bari, Bari, Italy
7. University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), Bern, Switzerland
8. Faculty of Physics, University of Bucharest, Bucharest, Romania
9. INFN Sezione di Cagliari, Cagliari, Italy
10. INFN Sezione di Cagliari and Università di Cagliari, Cagliari, Italy
11. University of Cambridge, Cambridge, United Kingdom
12. Universita' dell'Insubria, sede di Como/ INFN Milano Bicocca, Como, Italy
13. Alan Auld Engineering, Doncaster, United Kingdom
14. Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
15. Institute for Particle Physics Phenomenology, Durham University, United Kingdom
16. Technodyne International Limited, Eastleigh, Hampshire, United Kingdom
17. INFN Laboratori Nazionali di Frascati, Frascati, Italy
18. University of Geneva, Section de Physique, DPNC, Geneva, Switzerland
19. University of Glasgow, Glasgow, United Kingdom
20. University of Helsinki, Helsinki, Finland
21. Rockplan Ltd., Helsinki, Finland
22. Department of Physics, University of Jyväskylä, Finland
23. Physics Department, Lancaster University, Lancaster, United Kingdom
24. University of Liverpool, Department of Physics, Liverpool, United Kingdom
25. Imperial College, London, United Kingdom
26. Queen Mary University of London, School of Physics, London, United Kingdom
27. Dept. of Physics and Astronomy, University College London, London, United Kingdom
28. Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
29. INFN Sezione di Napoli and Università di Napoli, Dipartimento di Fisica, Napoli, Italy
30. University of Manchester, Manchester, United Kingdom
31. INFN Milano Bicocca, Milano, Italy
32. University of Oulu, Oulu, Finland
33. Oxford University, Department of Physics, Oxford, United Kingdom
34. STFC, Rutherford Appleton Laboratory, Harwell Oxford, United Kingdom
35. AGT Ingegneria S.r.l., Perugia, Italy
36. UPMC, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Paris, France
37. APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité Paris, France
38. Università and INFN Roma Tre, Roma, Italy
39. INFN Roma Tre, Roma, Italy
40. IRFU, CEA Saclay, Gif-sur-Yvette, France
41. University of Sheffield, Department of Physics and Astronomy, Sheffield, United Kingdom
42. Department of Atomic Physics, Faculty of Physics, St.Kliment Ohridski University of Sofia, Sofia, Bulgaria
43. Petersburg Nuclear Physics Institute (PNPI), St-Petersburg, Russia
44. IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
45. INFN Trieste, Trieste, Italy
46. IFIC (CSIC & University of Valencia), Valencia, Spain
47. Université de Lyon, Université Claude Bernard Lyon 1, IPN Lyon (IN2P3), Villeurbanne, France
48. National Centre for Nuclear Research (NCBJ), Warsaw, Poland
49. Institute of Experimental Physics, Warsaw University (IFD UW), Warsaw, Poland
50. University of Warwick, Department of Physics, Coventry, United Kingdom
51. ETH Zurich, Institute for Particle Physics, Zurich, Switzerland

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- 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.
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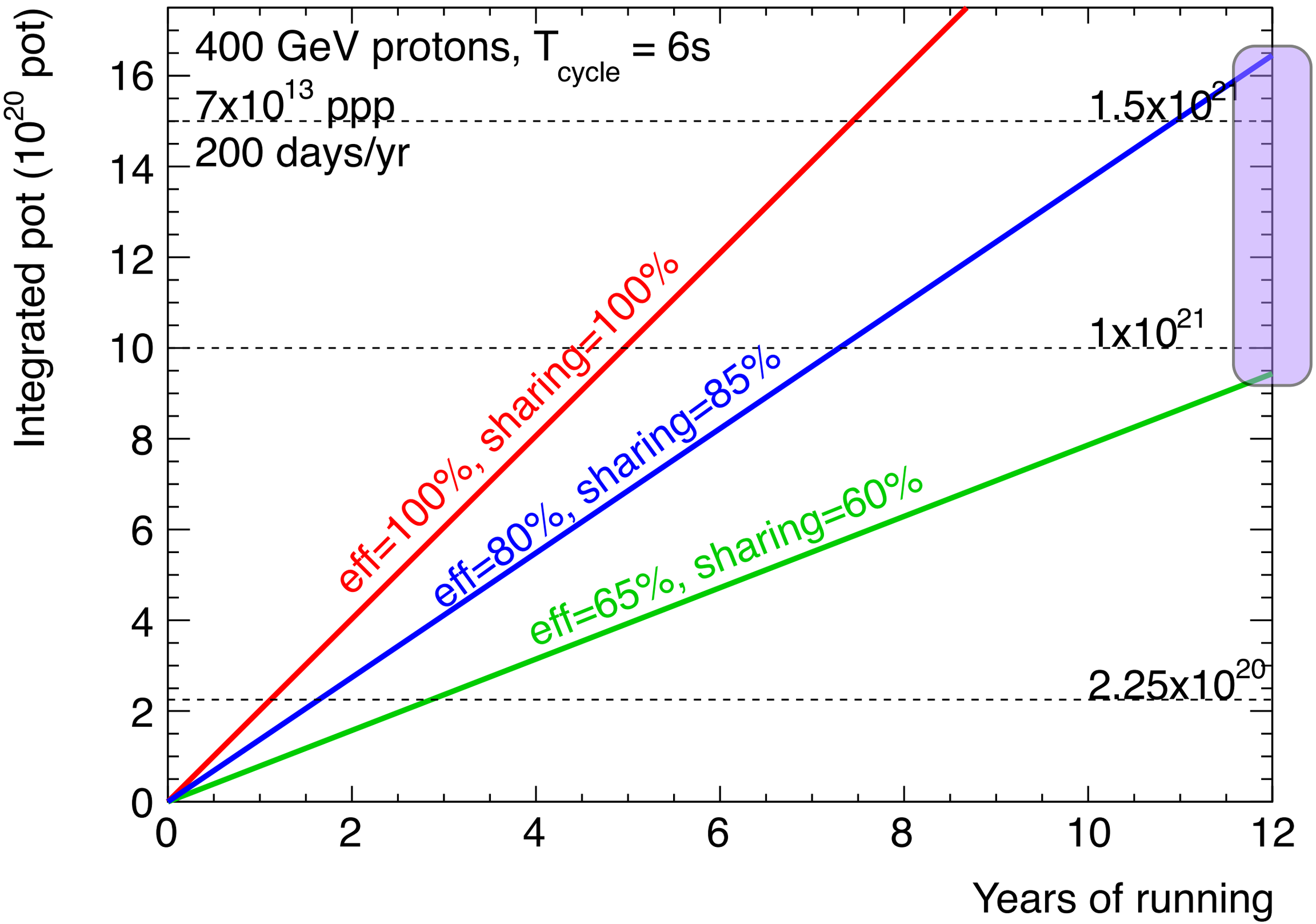
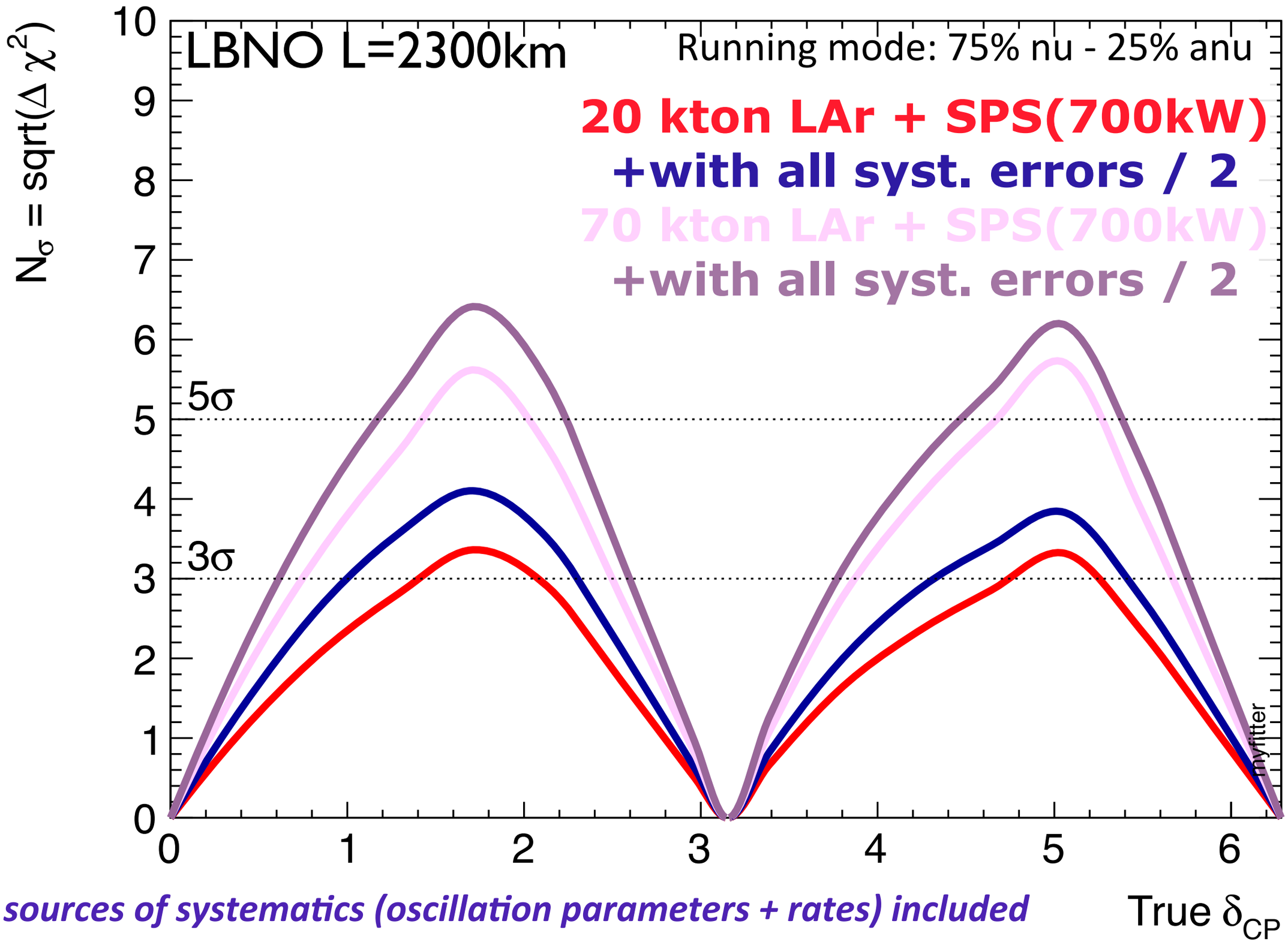
- The contributions of Anselmo Cervera are also recognized.

# Total integrated p.o.t.



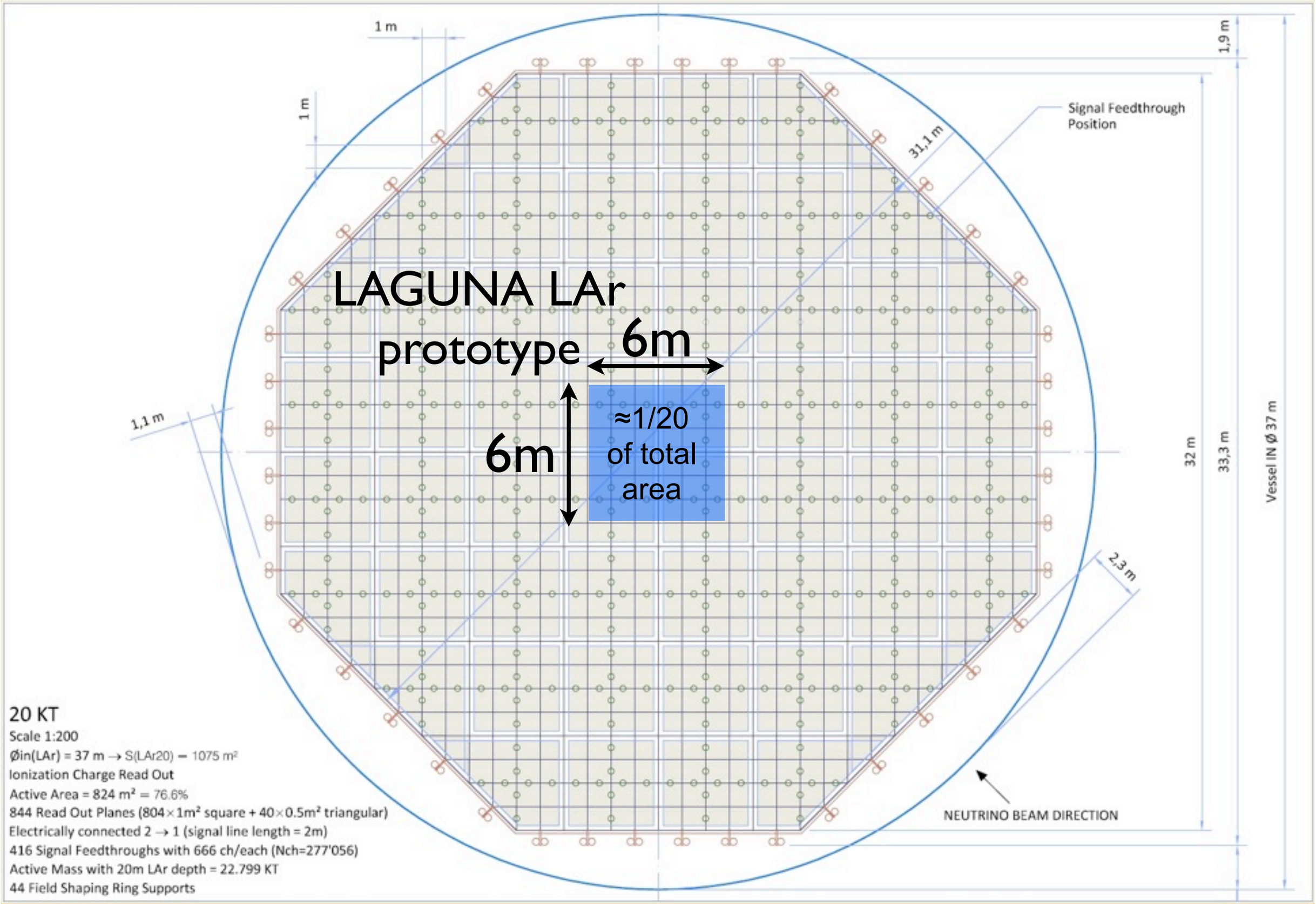
# Sensitivity to CP violation:

Exclude $\delta_{CP} = 0$ and $\delta_{CP} = \pi$



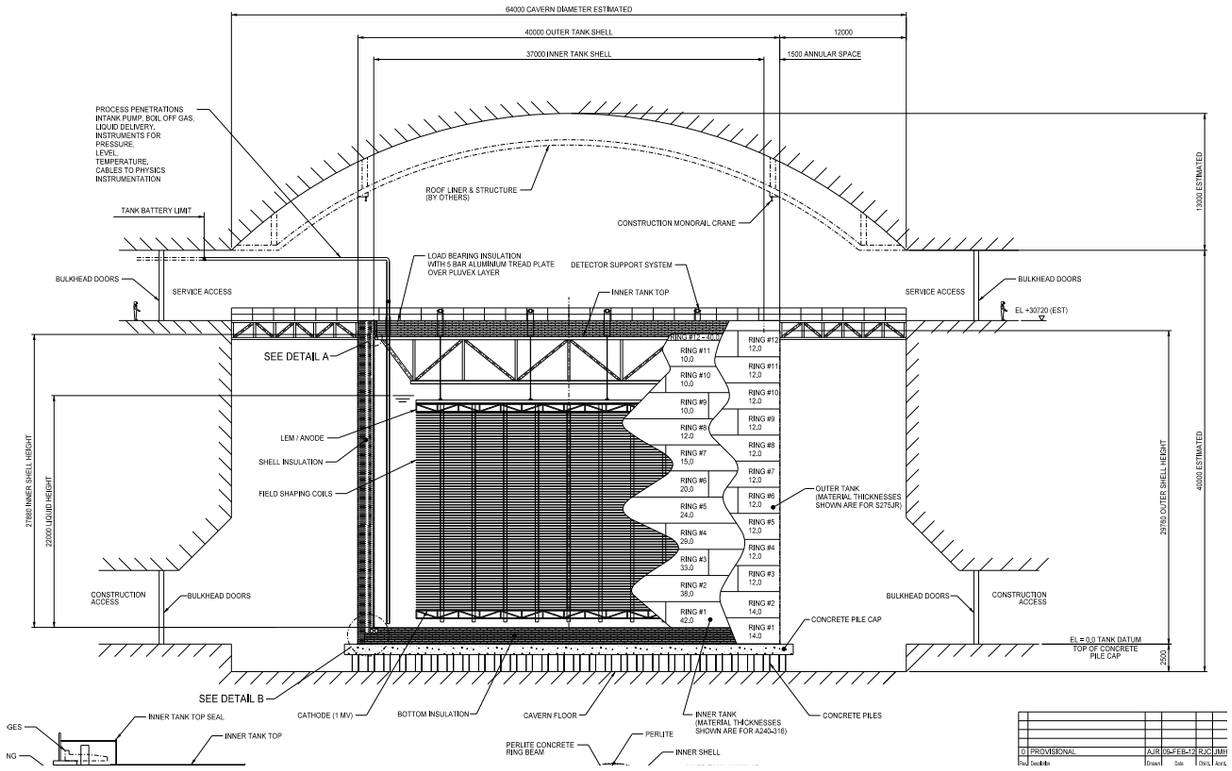

*All sources of systematics (oscillation parameters + rates) included*

# LAGUNA 6x6x6 m³ prototype compared to 20kton

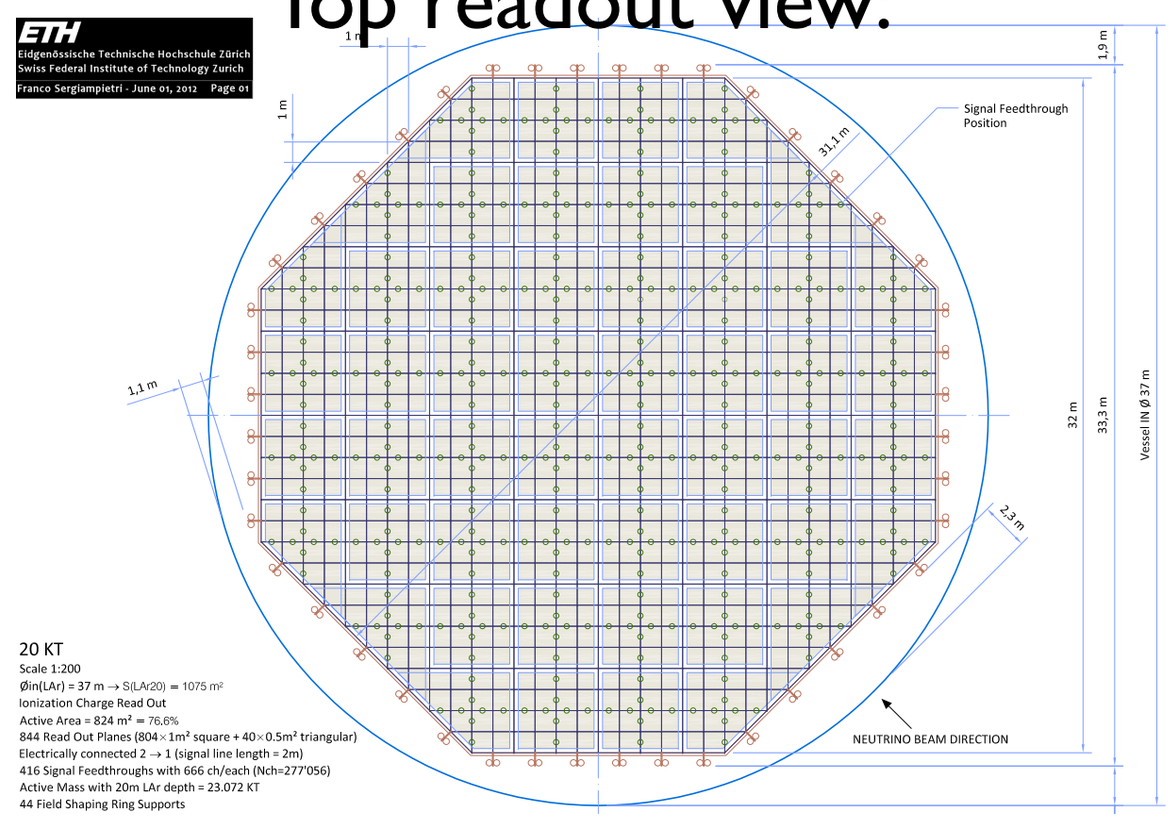


# LAr detector design

- GLACIER concept unchanged since 2003: Simple, scalable detector design, from one up to 100 kton (hep-ph/0402110)
- Single module non-evacuable cryo-tank based on industrial LNG technology
  - industrial conceptual design (Technodyne, AAE, Ryhal engineering, TGE, GTT)
  - two tank options: 9% Ni-steel or membrane (detailed comparison up to costing of assembly in underground cavern)
  - three volumes: 20, 50 and 100 kton
- Liquid filling, purification, and boiloff recondensation
  - industrial conceptual design for liquid argon process (Sofregaz), 70kW total cooling power @ 87 K
  - purity < 10 ppt $O_2$ equivalent
- Charge readout (e.g. 20 kton fid.)
  - 23'072 kton active, 824 $m^2$ active area
  - 844 readout planes, 277'056 channels total
  - 20 m drift
- Light readout (trigger)
  - 804 8" PMT (e.g. Hamamatsu R5912-02MOD) WLS coated placed below cathode

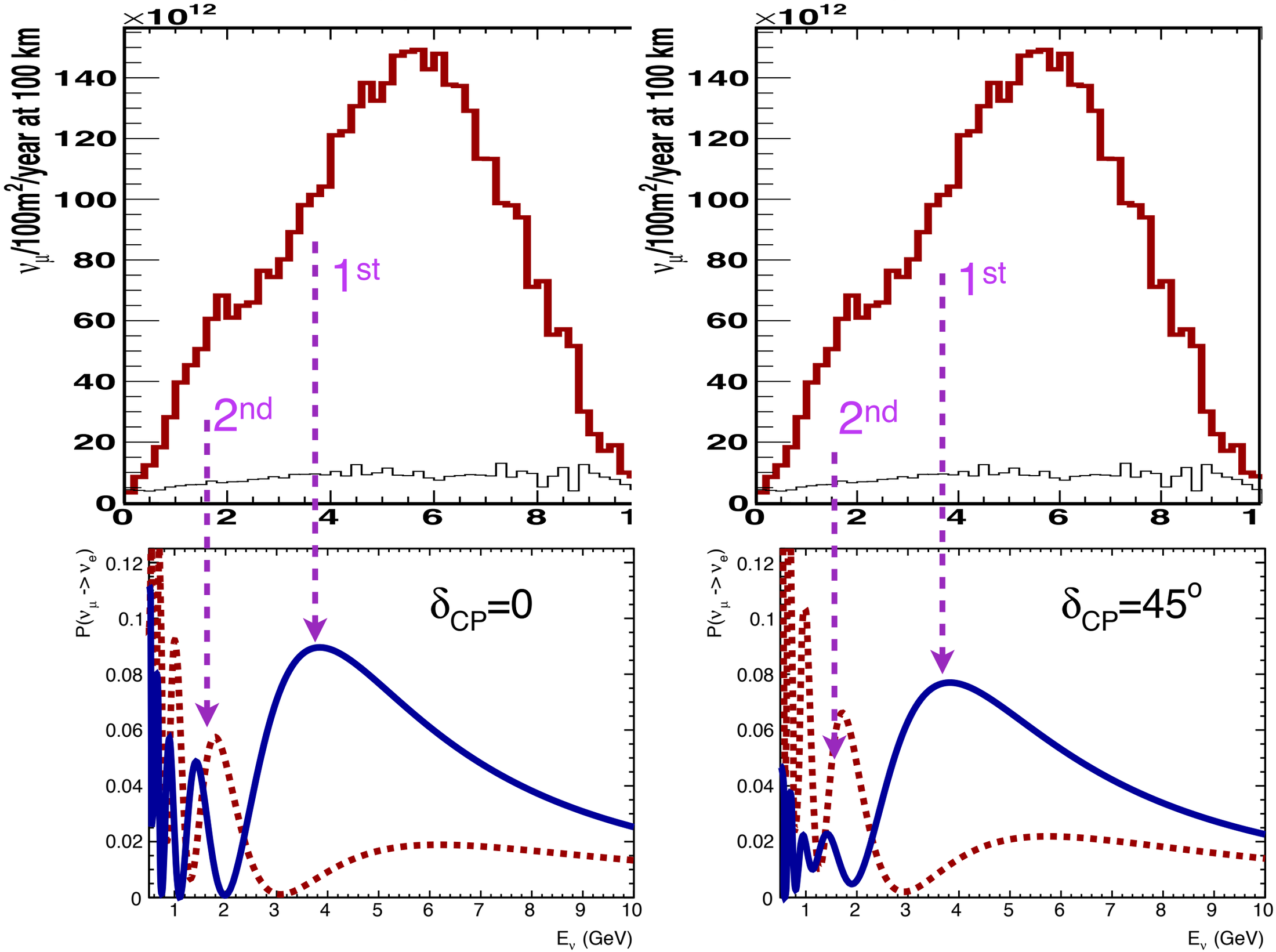



## Top readout view:

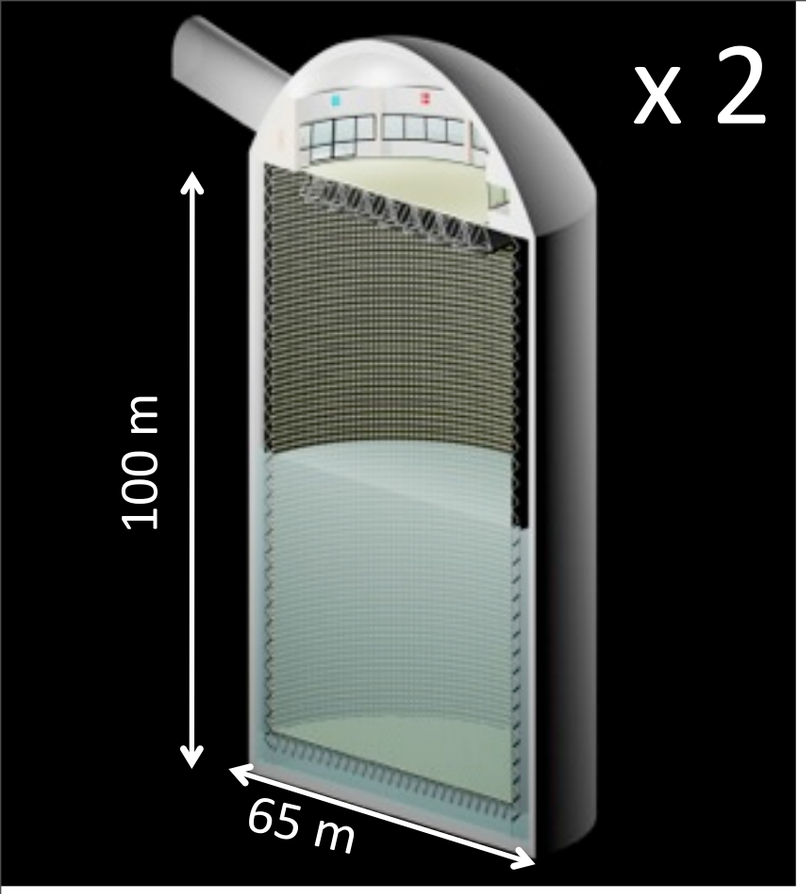


# Flux optimisation

Maximize two conditions: (1) event rate at first maximum and (2) ratio of 2nd/1st maximum flux



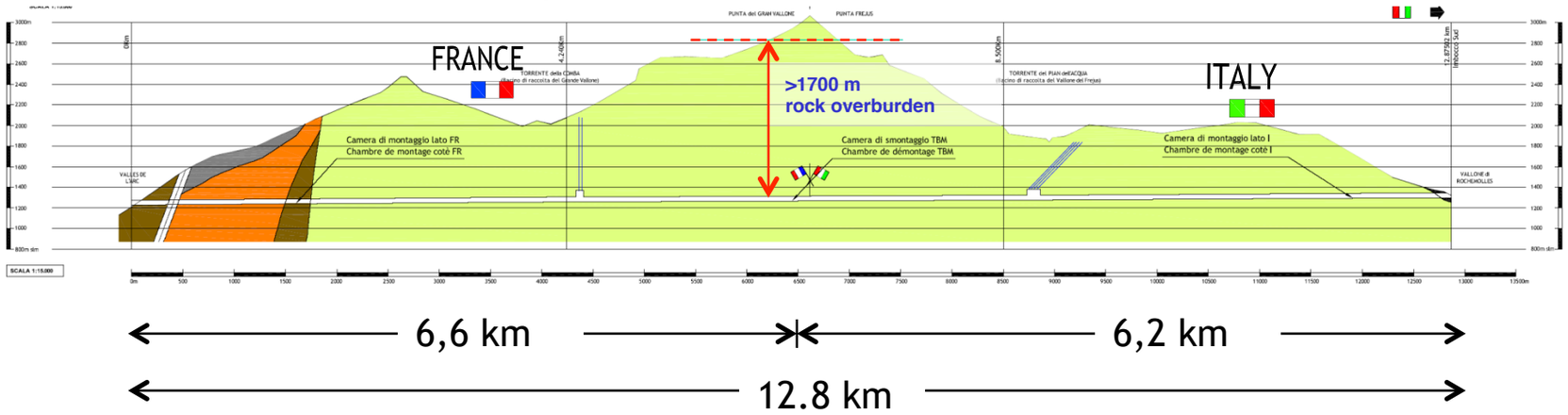

LAGUNA-LBNO, work in progress




# MEMPHYS (MEgatonMassPHYSics)

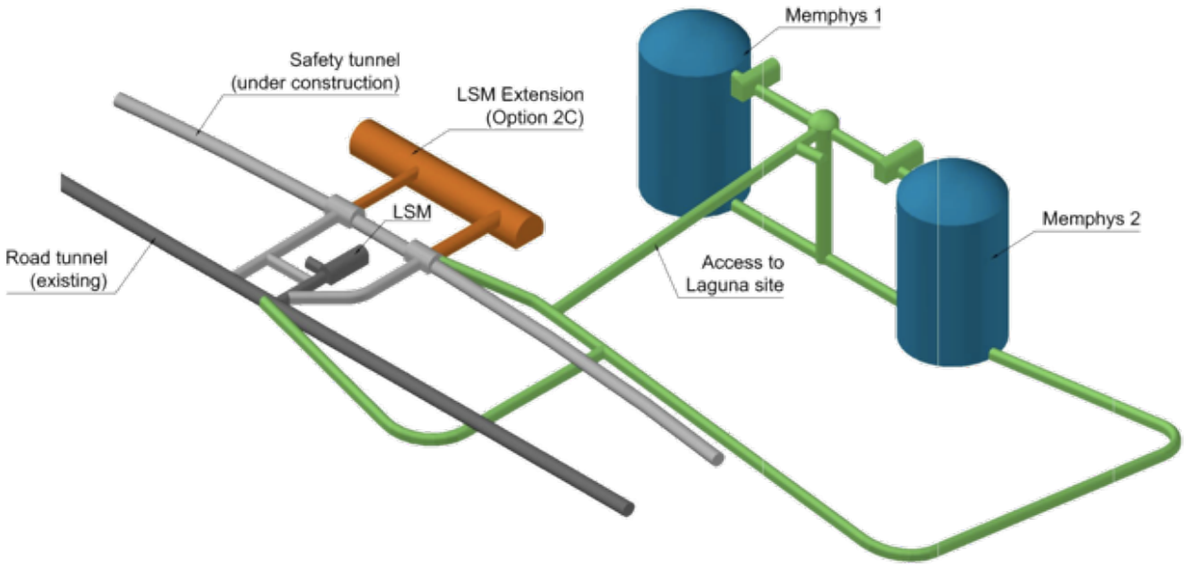
**130 km from CERN, 4800 m.w.e.**

Longitudinal section (Road tunnel)

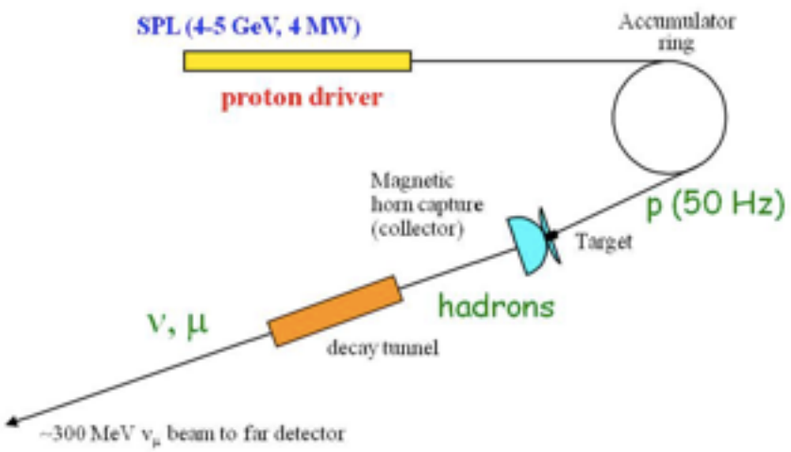


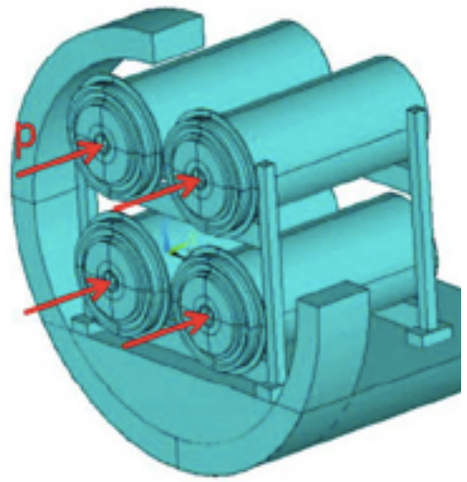

http://www.apc.univ-paris7.fr/APC_CS/Experiences/MEMPHYS/

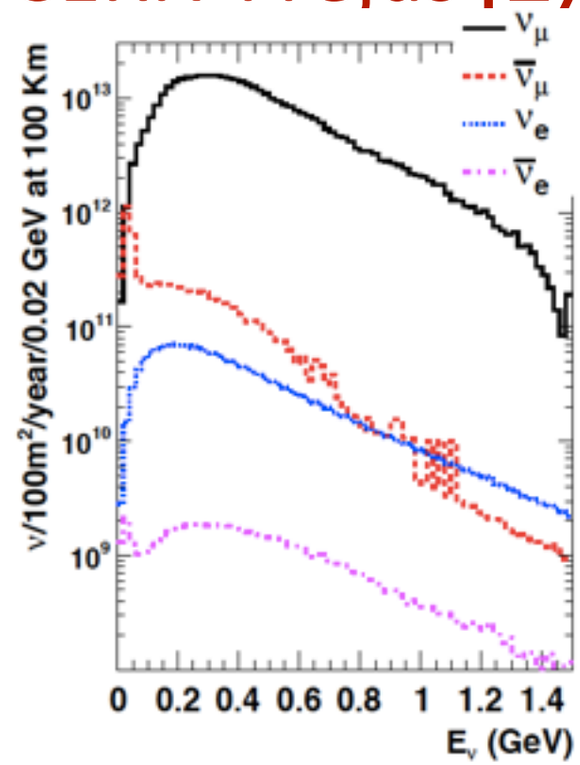
- Water Cherenkov
  - well proven technology
  - each tank is 6.6 x SK --> mild extrapolation only
- total fiducial mass: 500 kt
- 2 cylindrical modules 65 x 100 m
  - size limited by light attenuation length (λ~80m) and pressure on PMTs
  - readout : ~140000 12” PMTs, 30% geom. cover
  - R&D on readout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

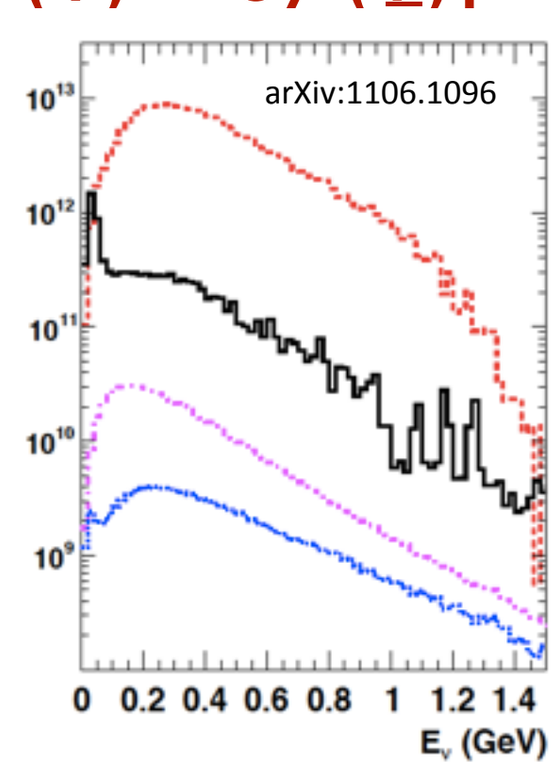


# LCPV with MEMPHYS and SPL beam CERN-Frejus [2y (ν) + 8y (ν̲)]



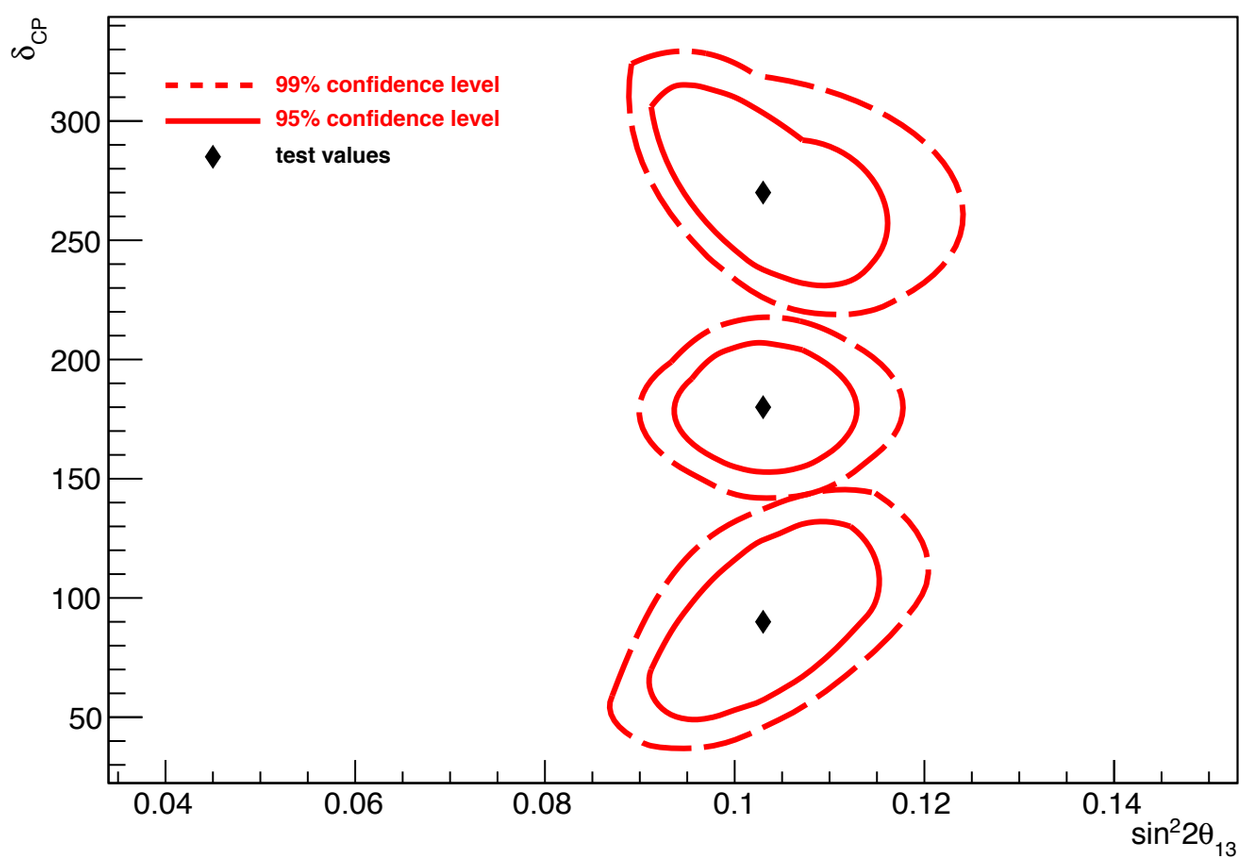



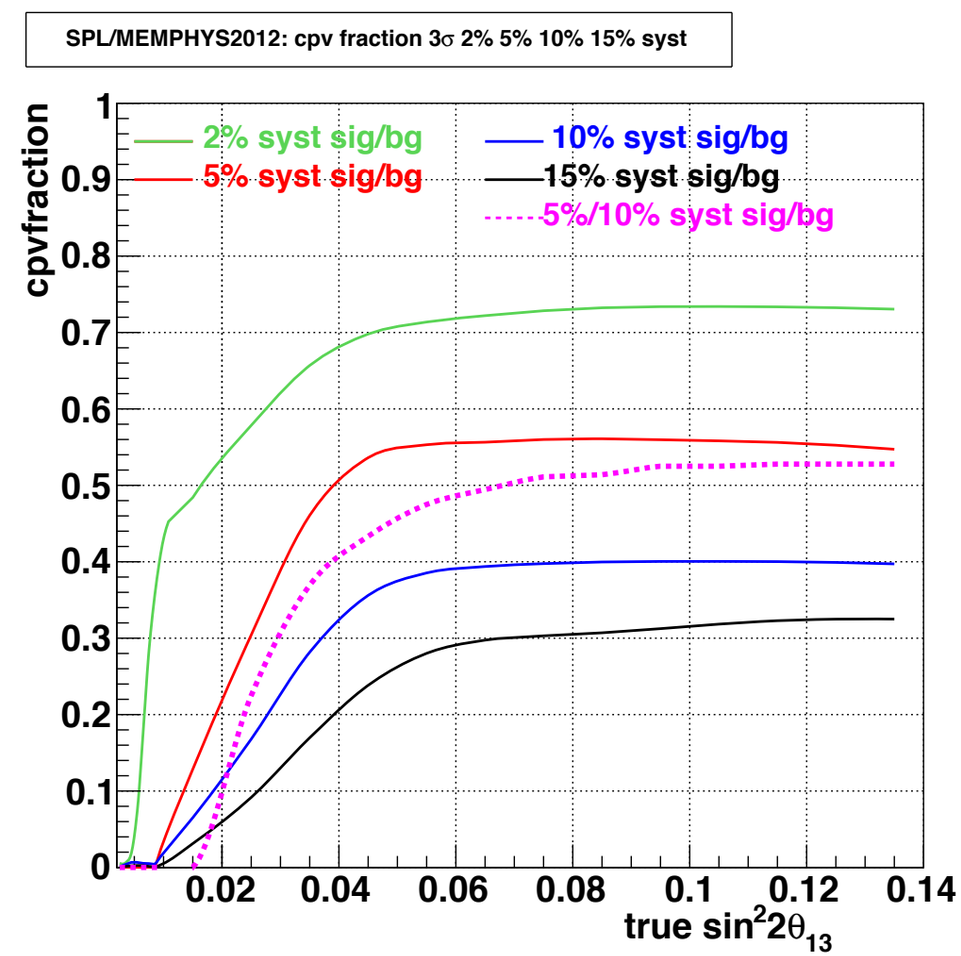




**5.6 x $10^{22}$ p.o.t./y with 4 MW x $10^7$ s at 4.5 GeV**

Confidence levels for $\delta_{CP}$

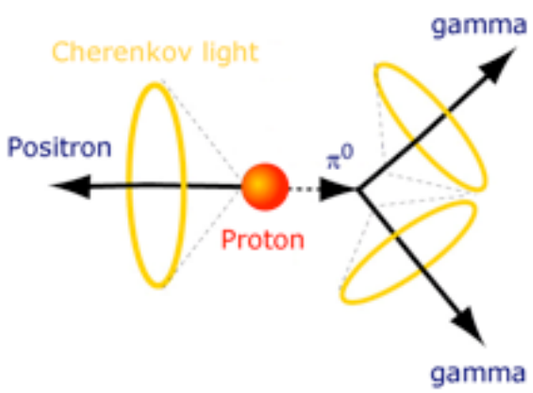



JCAP 1301 (2013) 024

# MEMPHYS non-accelerator Physics

## Proton Decay



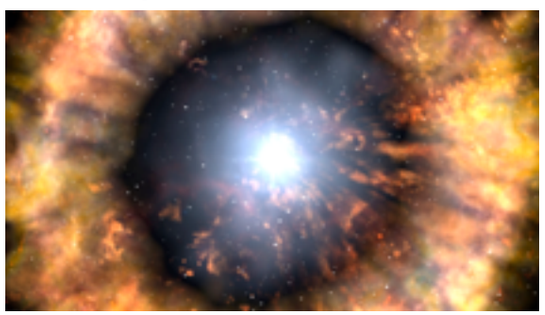

| Model | Decay Modes | Predictions |
|---|---|---|
| Georgi-Glashow | - | ruled out |
| Type II-$SU(5)$ | all | $\tau_p < 2 \times 10^{36}$ yr |
| Type III-$SU(5)$ | $p \to \pi^0 e^+$ | $\approx 10^{35-36}$ yr |
| Adjoint $SU(5)$ | $p \to \pi^0 e^+$<br>$p \to K^+ \bar{\nu}$<br>$p \to \pi^+ \bar{\nu}$ | $\tau_{e^+\pi^0} < 10^{35}$ 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 --> $e^+\pi^0$: ~1.2 x $10^{35}$ y at 90% C.L.

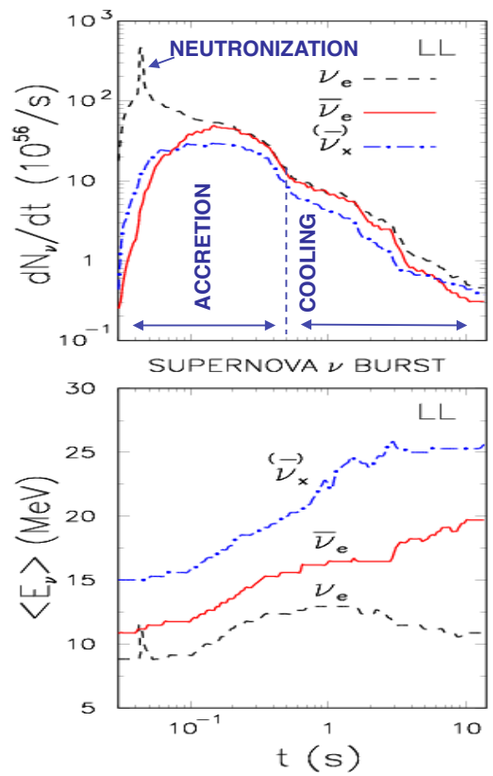
p --> $\bar{\nu}$ $K^+$: ~ 2.4 x $10^{34}$ y at 90% C.L.

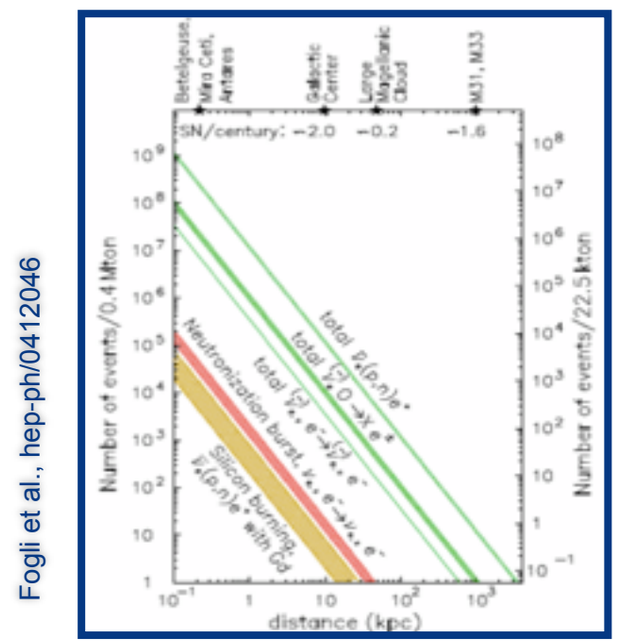
## Supernova



**Galactic SN**: Huge statistics

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




Fogli et al., hep-ph/0412046

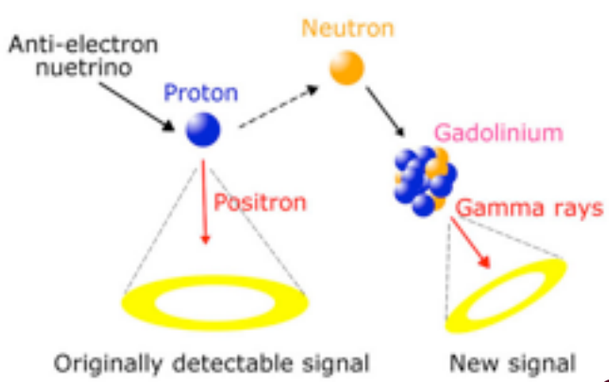
For a galactic Supernova @ 10 kpc:

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

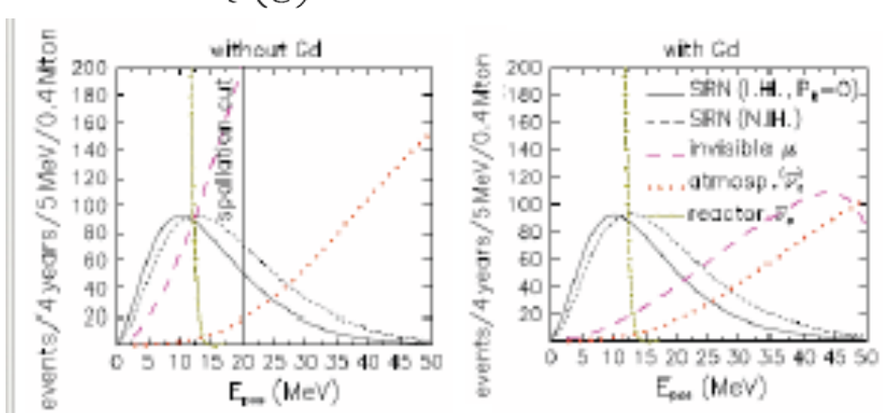
ES: ~ 1.2 x $10^3$ e

O 10 events @ 1 Mpc

## DSN




M. Nakahata

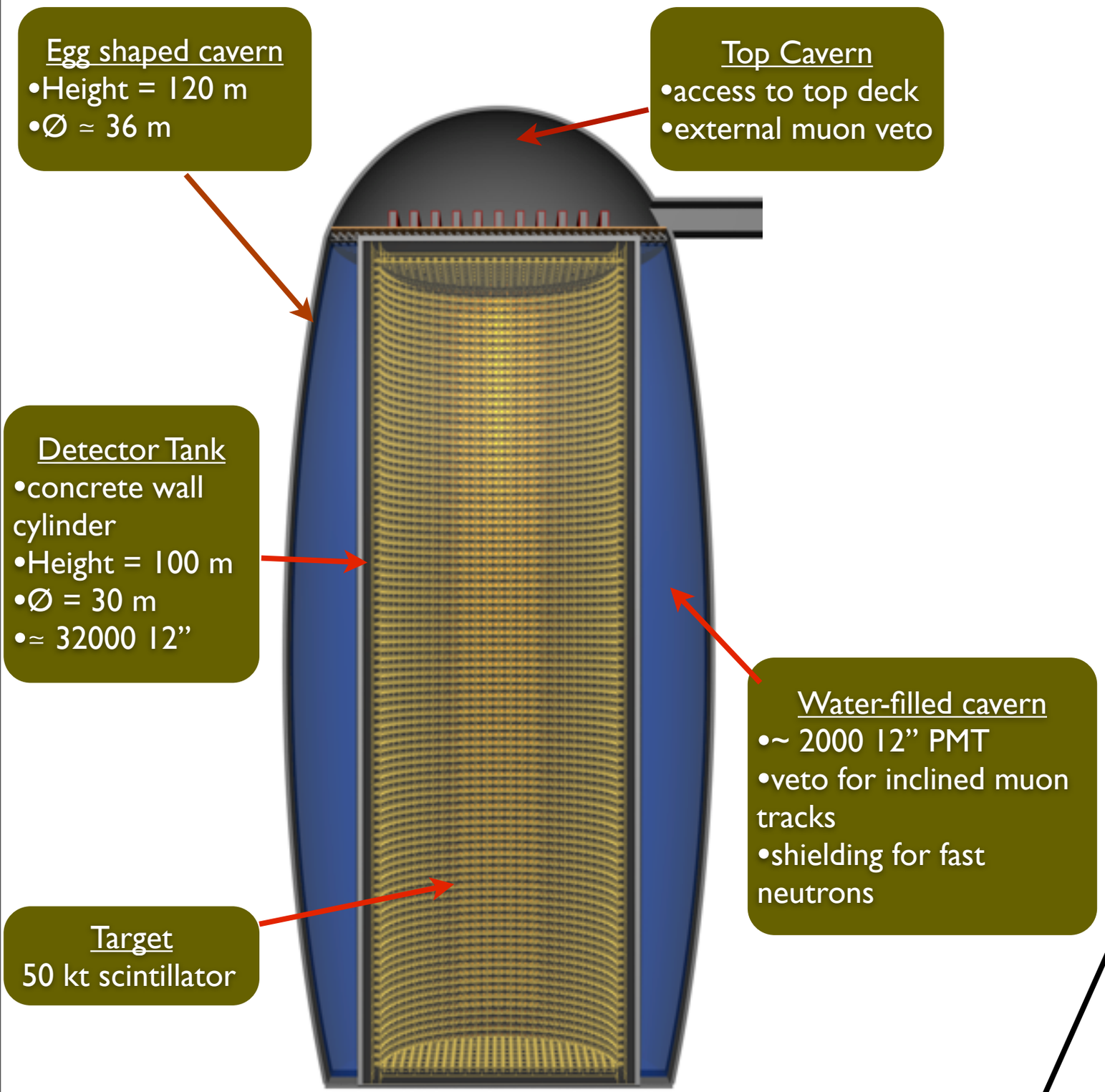


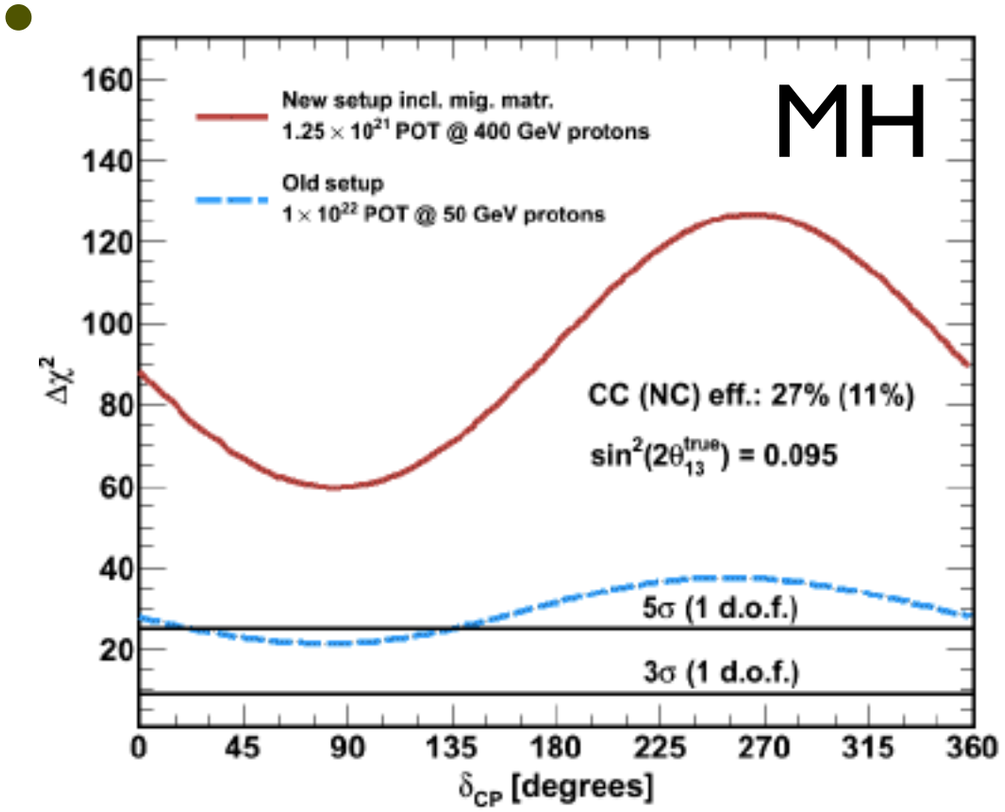

GADZOOKS Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004

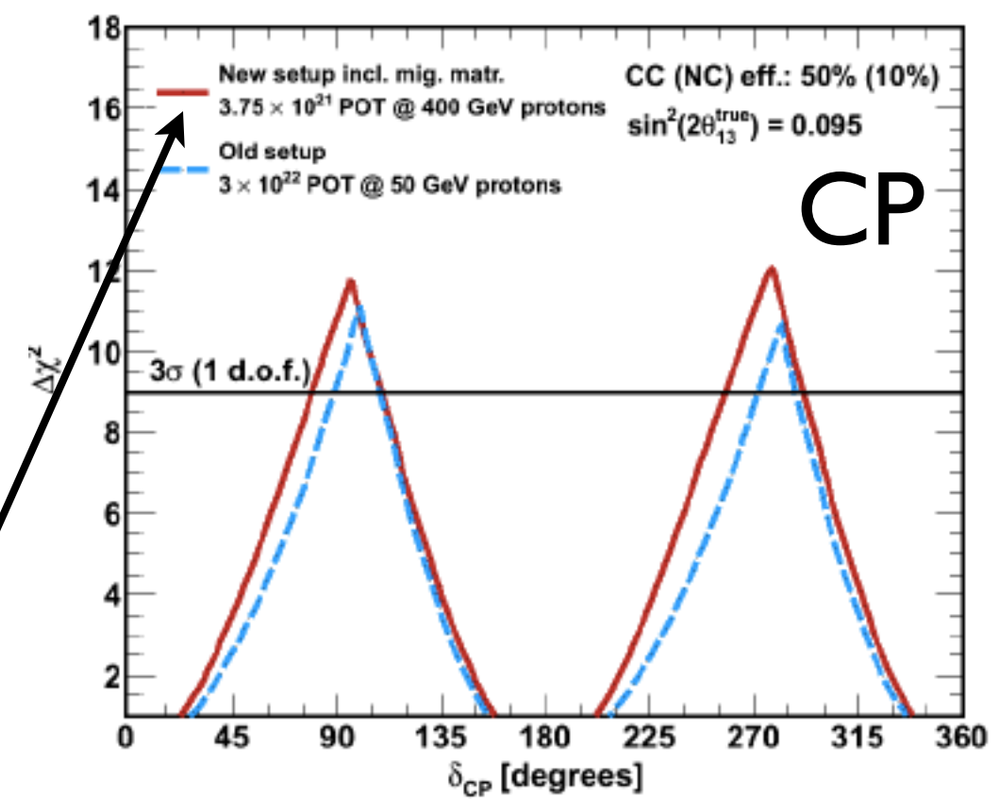
For 1 tank with Gd (250 kt):

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

# LENA:




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