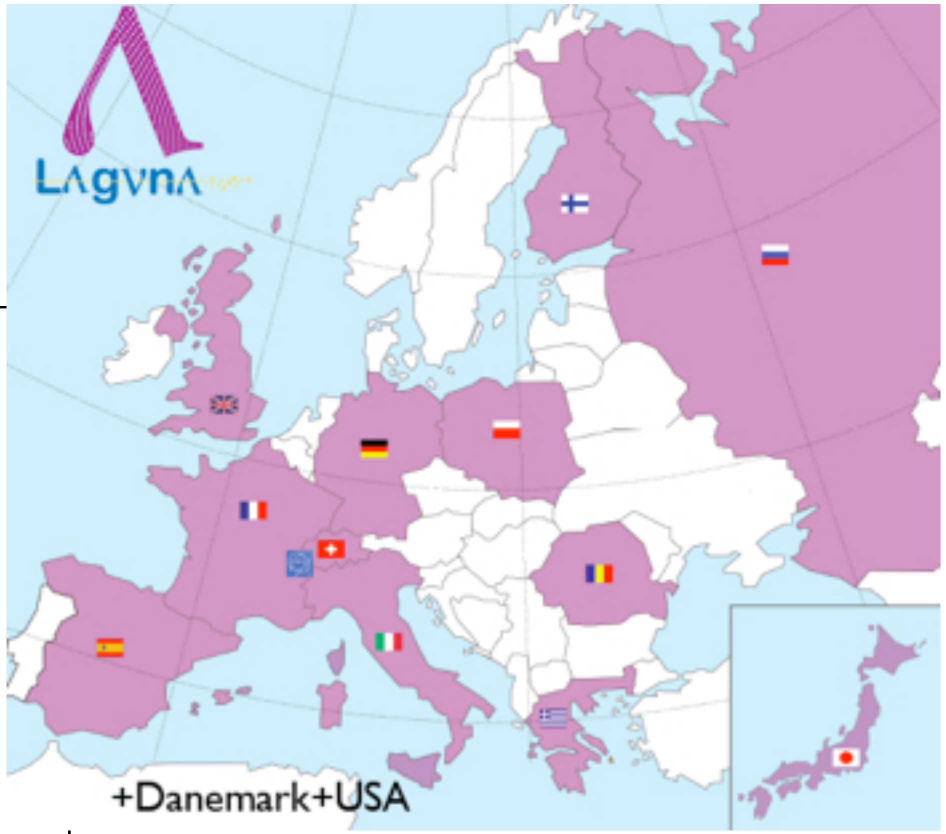
LAGUNA and LBNO: Towards the next generation neutrino observatory in Europe

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, 1.7 M€
  – 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, 4.9 M€
  – 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 -> WA105 Large scale prototype at CERN

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

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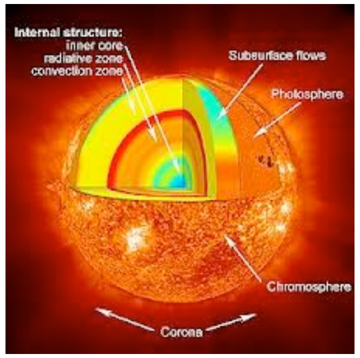
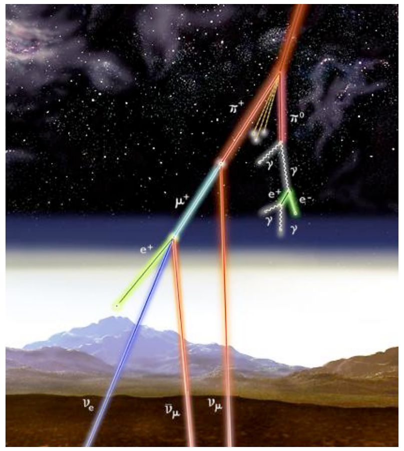
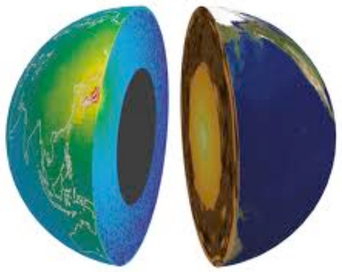
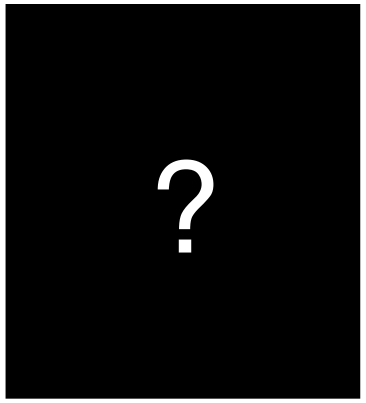
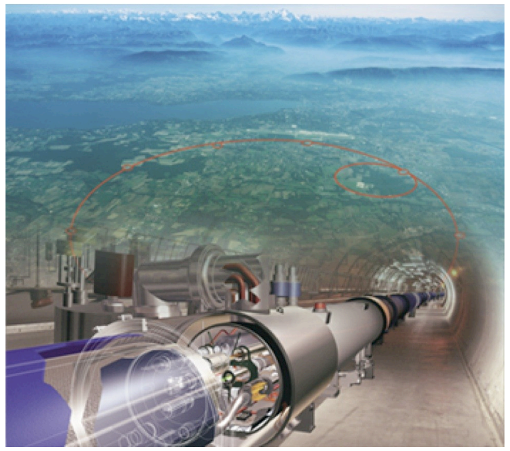




LAGUNA Physics:

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

large θ_{13}

2. Non-Accelerator based:
   - Proton decay

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

4. Dark Matter

The highly important discovery of the Higgs at CERN July 4th 2012 has crowned the SM,
Neutrino physics provides us with surprises!

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.

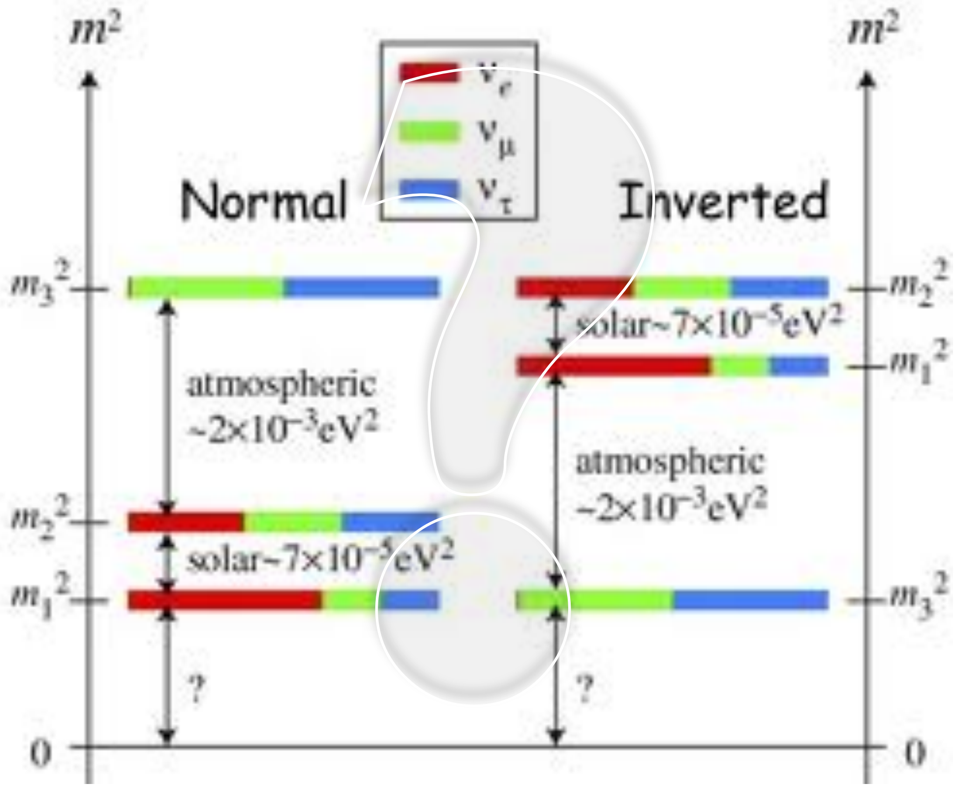
- We compared the physics potential of all possible combinations - detector - location - beam.

- **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
  - Competitive nucleon decay measurements wrt SK and
  - An incremental long-baseline program with a competitive 1st stage guaranteeing high level physics performance from the beginning. (e.g. MH at 5 σ CL with ~100% power in ~5years)
  - 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.

Mass Hierarchy is a fundamental measurement:



- MH is a **prerequisite** to study leptonic CPV
- Scenarios for lepto-genesis
- Hints for theory development (GUT models)
- Feasibility and interpretation of $0\nu\beta\beta$ experiments
- Interpretation of HDM from cosmology in terms of ν masses

LBNO strategy on MH:

- To guarantee the measure MH on the > 5 σ level one need to go to very long baselines > 2000 km.
- MH should be settled early in the exp. to optimize the ν / $\overline{\nu}$ ratio to maximize CP sensitivity.
- The **median 5 σ sensitivity** (p = 0.5) for LBNO is reached within 2 years of running.
- The **guaranteed 5 σ sensitivity** (p ~ 1) for LBNO is reached within 5 years of running.
- 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.

Mass Hierarchy with LBNO

In neutrino physics we have a long history of few σ anomalies, hints and excesses…

- <u>Sterile neutrino:</u>
  - ➢ We got the reactor anomaly, the Gallium anomaly, the LSND excess, the MinibooNE excess/anomaly
  - ➢ All with 2 – 3 σ and the problem is still not solved
  - ➢ This calls for a conclusive 5 σ experiment → ν-STORM?

- <u>Mass Hierarchy:</u>
  - ➢ Many 2 σ, 3 σ maybe 4 σ experiments proposed using atm-ν's (e.g.: INO, PINGU/ORCA) or reactor-ν's (e.g.: JUNO,RENO-50).
  - ➢ Very sensitive to assumptions on the detector performance, small changes lead to vanish the projected CL reach.
  - ➢ The reach of future long baseline experiments depend on the knowledge of oscillation priors and systematics.
  - ➢ Is 1% for systematics realistic / achievable ?
  - ➢ No experiment is sheltered from an underestimated systematic error!
  - ➢ All physics potentials are evaluated using the median experiment P = 0.5, so 50% of the exp. will not reach the projected CL!
  - ➢ The sum of all these few sigma experiments does not give a conclusive answer to the MH problem.
  - ➢ **<u>This calls for a conclusive and guaranteed 5 σ experiment = LBNO!</u>**

- Today we are **not** in a situation that we do not know how to do such an experiment, with LBNO we have a concrete, well studied proposal on the table since 2012.

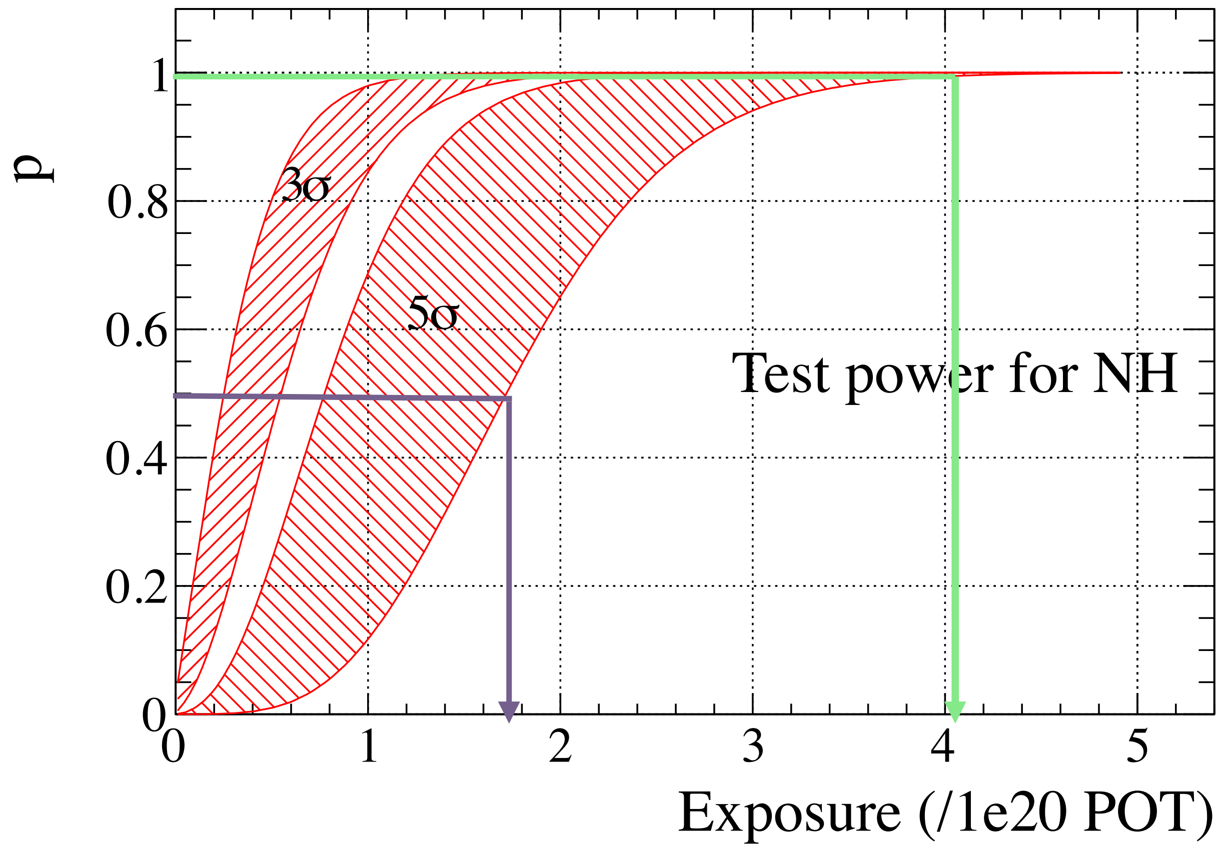
- The power of LBNO comes from the baseline of 2300 km and the possibility to switch beam polarity allowing to determine the MH at > 5 σ over the whole phase space with sufficient « margin » with respect to systematics and knowledge on oscillation priors.

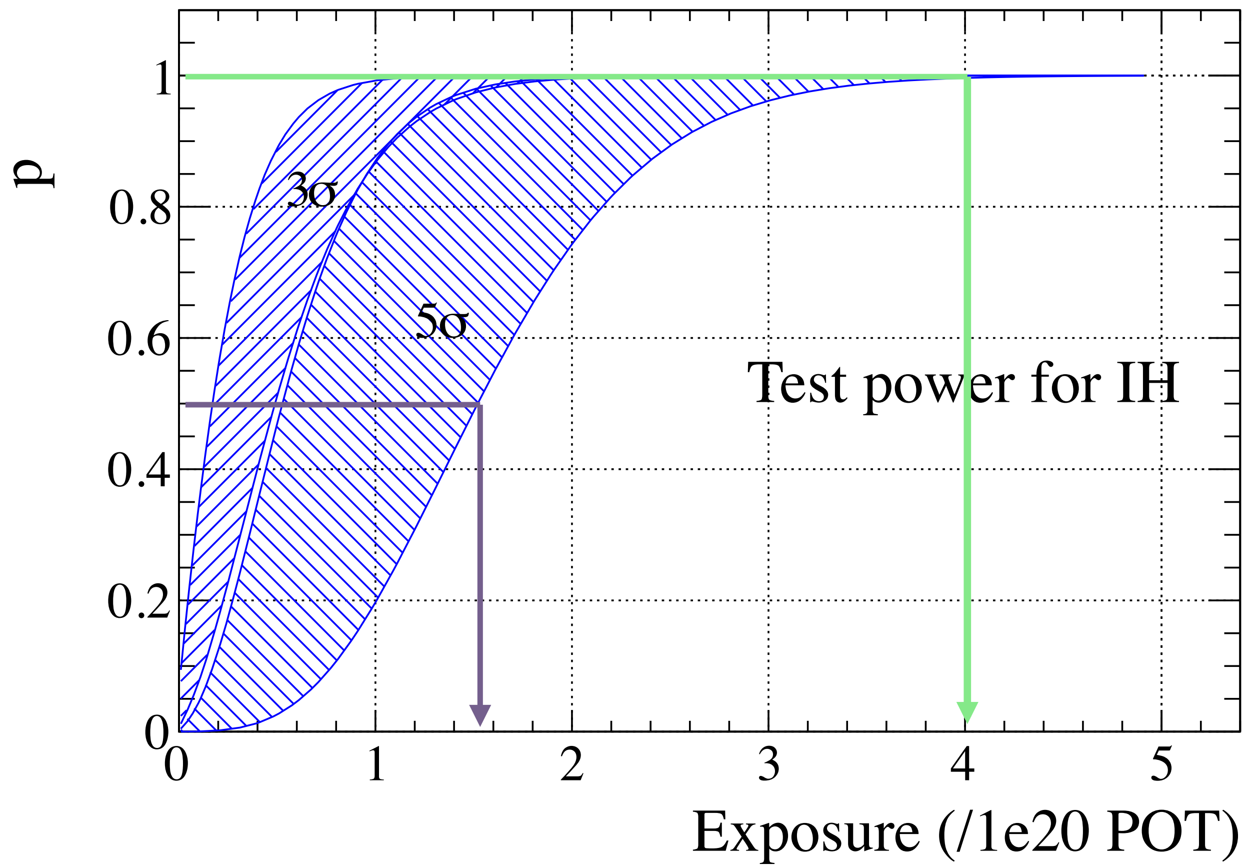
In order to convince the community we need more than one experiment measuring the same parameters with a completely different method and detector technology!

MH sensitivity and unique power of LBNO

- Power vs exposure for all values of δ_{CP} (shaded bands)

arXiv:1312.6520





p = 0.5 => "Median experiment"
50% chance not to achieve the projected CL.

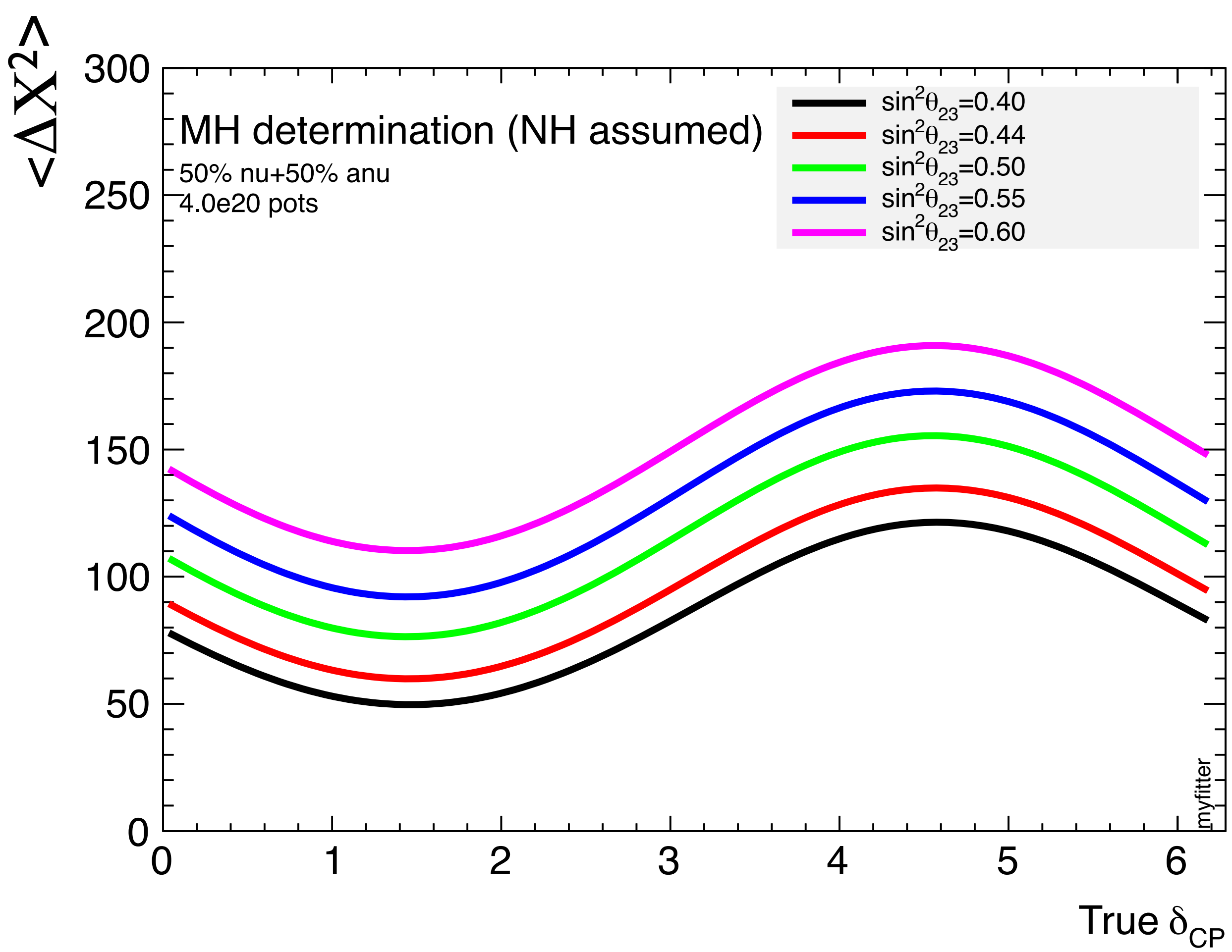
One should not bet on marginal physics reach!

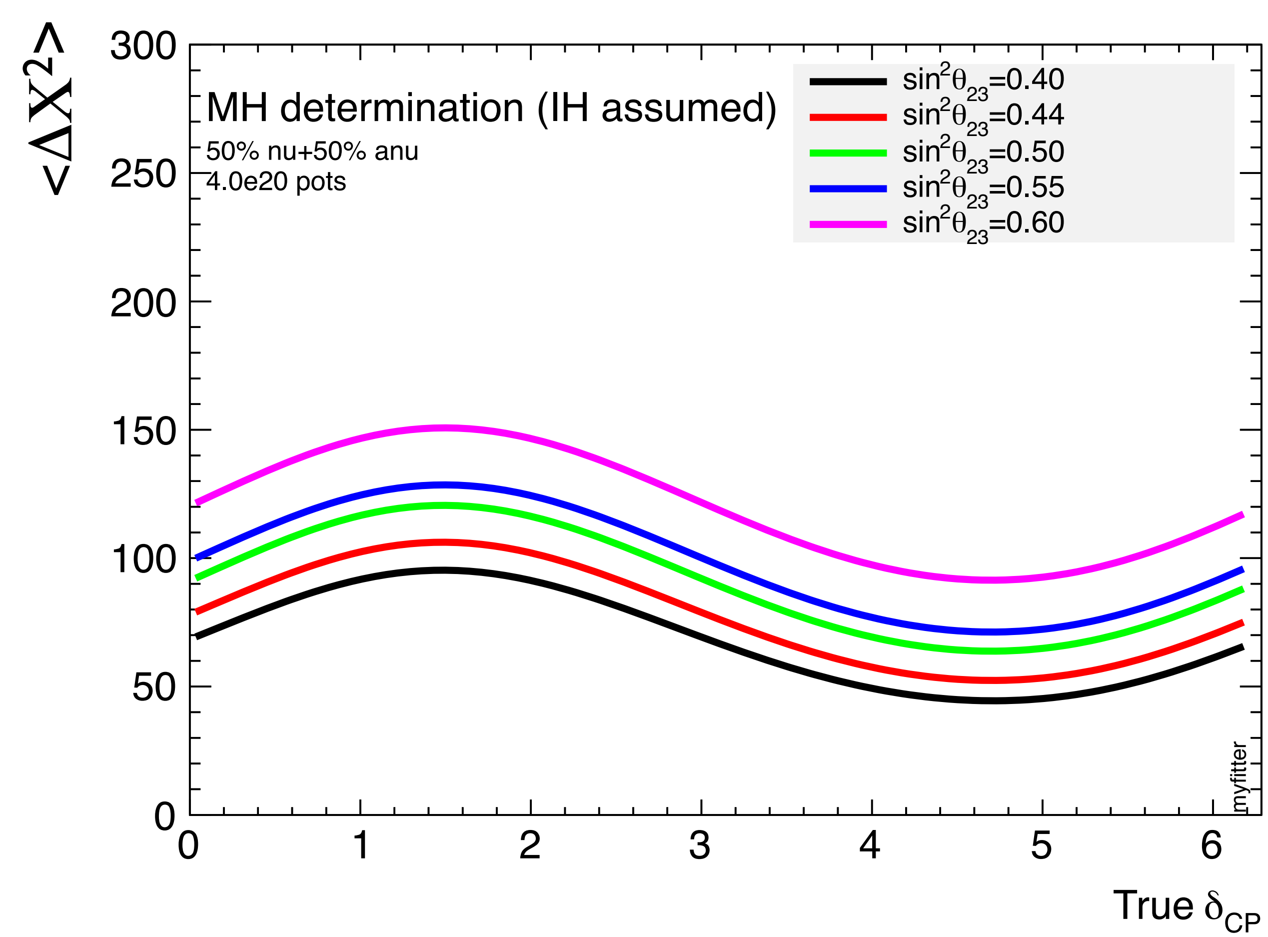
p ~1 => "Full power experiment"
~ 100% chance to achieve the projected CL!

THE LBNO CHOICE TO QUOTE SENSITIVITY

LBNO Strategy on Mass Hierarchy

Mean value of the mass hierarchy test statistic as a function of true δ_{CP} and the value of $\sin^2\Theta_{23}$ for an exposure of 4×10^{20} pots (or about 5 years of running at the SPS) and LBNO 20 kton LAr double phase detector.





CP Violation with LBNO

- **Measure δ_{CP} by measuring the energy dependence of the neutrino spectrum (L/E behavior) and the 2nd maximum, this is highly complementary to the HK proposal which measures only the ratio at the first maximum.**

- 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

- Incremental approach of LBNO:

  - **Phase 1:**

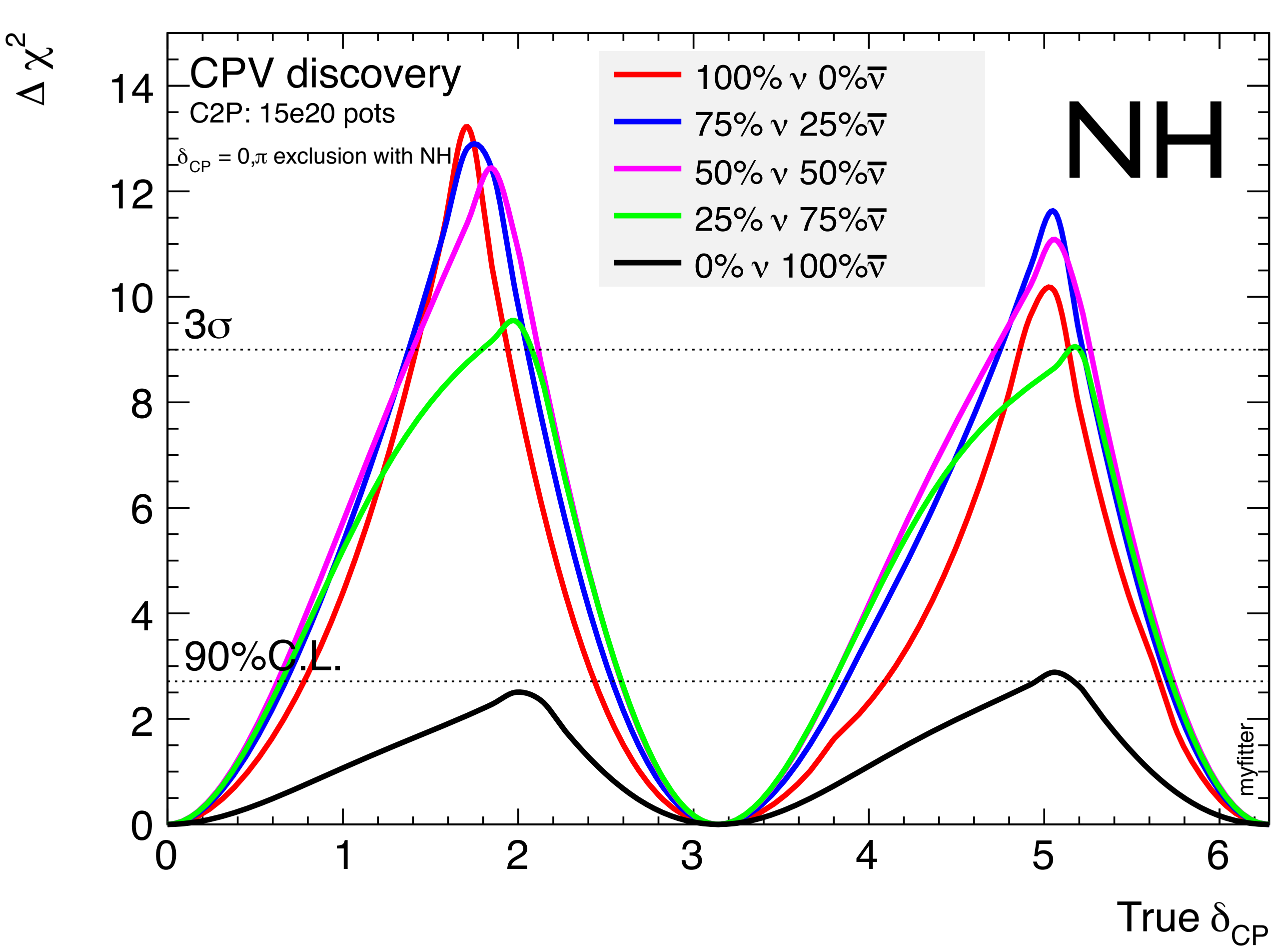
    - Conventional beam based on 400 GeV protons from the SPS 700 kW
    - Total 1.5 x 10^{21} PoT (10 - 12 years)
    - 20 kt LAr double phase detector
    - This determines MH at > 5σ within 4 – 5 years.
    - The knowledge of MH allows to adjust the ν / $\bar{\nu}$ ratio to maximize CP sensitivity.
    - Adjust beam to 2nd max to enhance CPV sensitivity

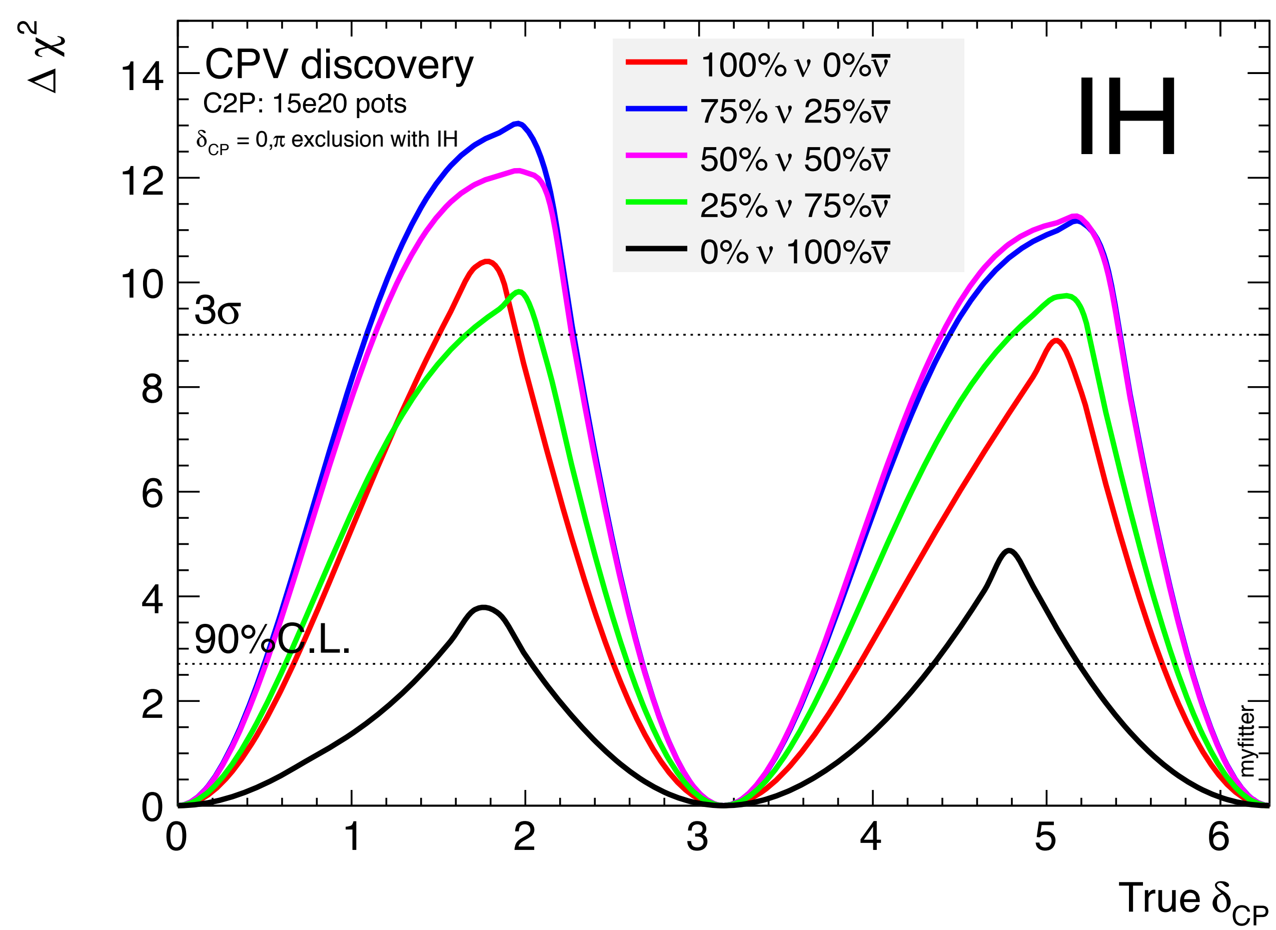
  - **Phase 2:**

    - Upgrade detector to 70 kt and / or the beam power to 2 MW
    - WBB to fully explore L/E and the 2nd maximum.
    - This allows CPV discovery at > 5σ level

LBNO Strategy on δ_{CP}

Once MH determined run for 5 more years with optimized sharing of neutrinos / anti-neutrinos to cover the most possible phase space in δ_{CP}

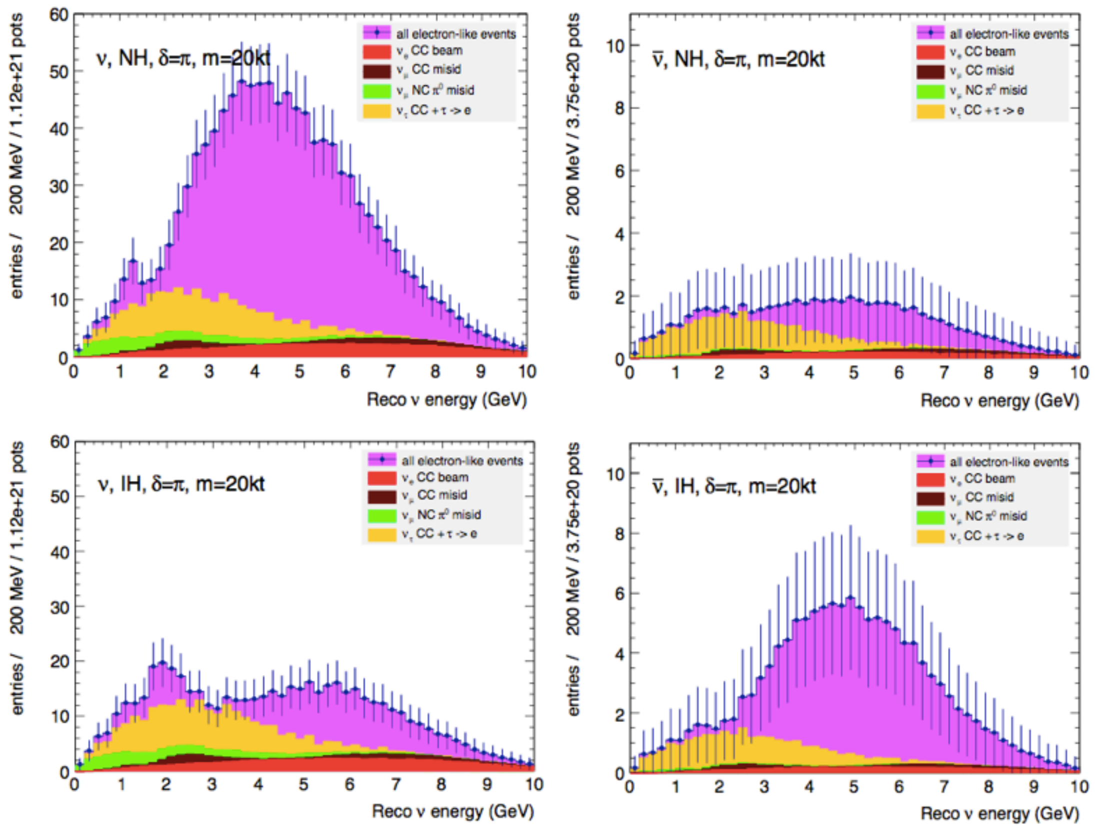


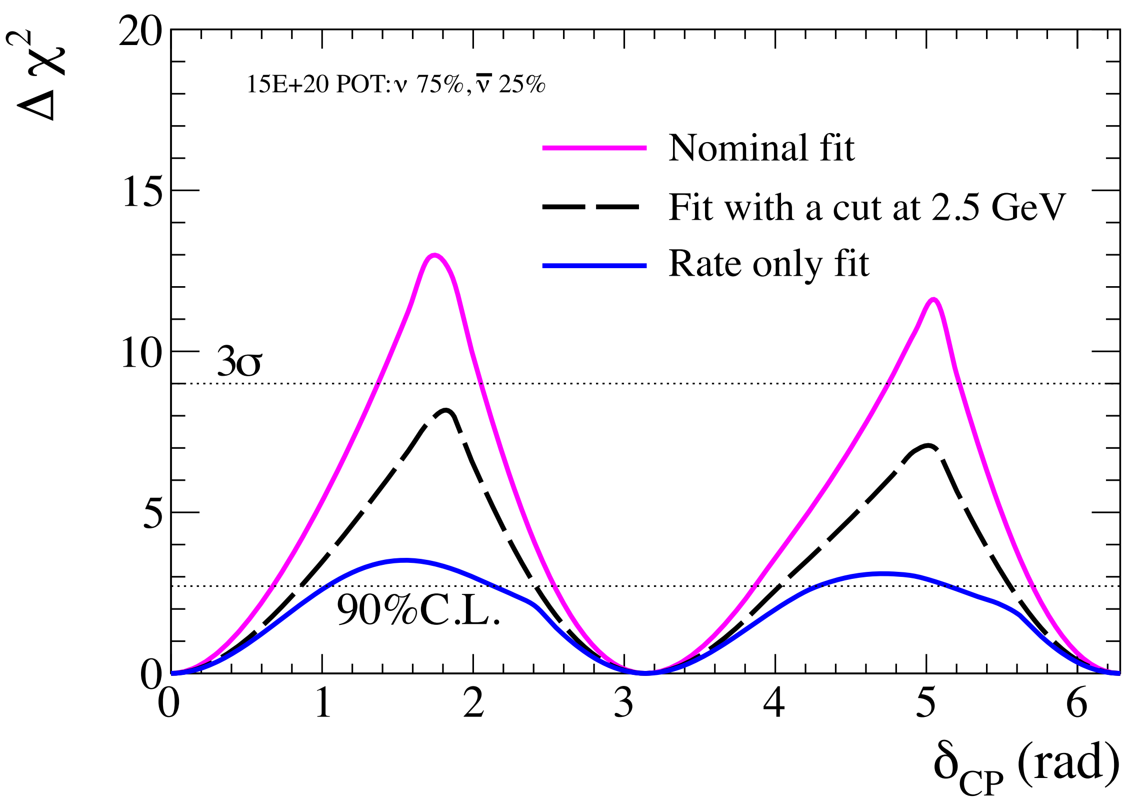


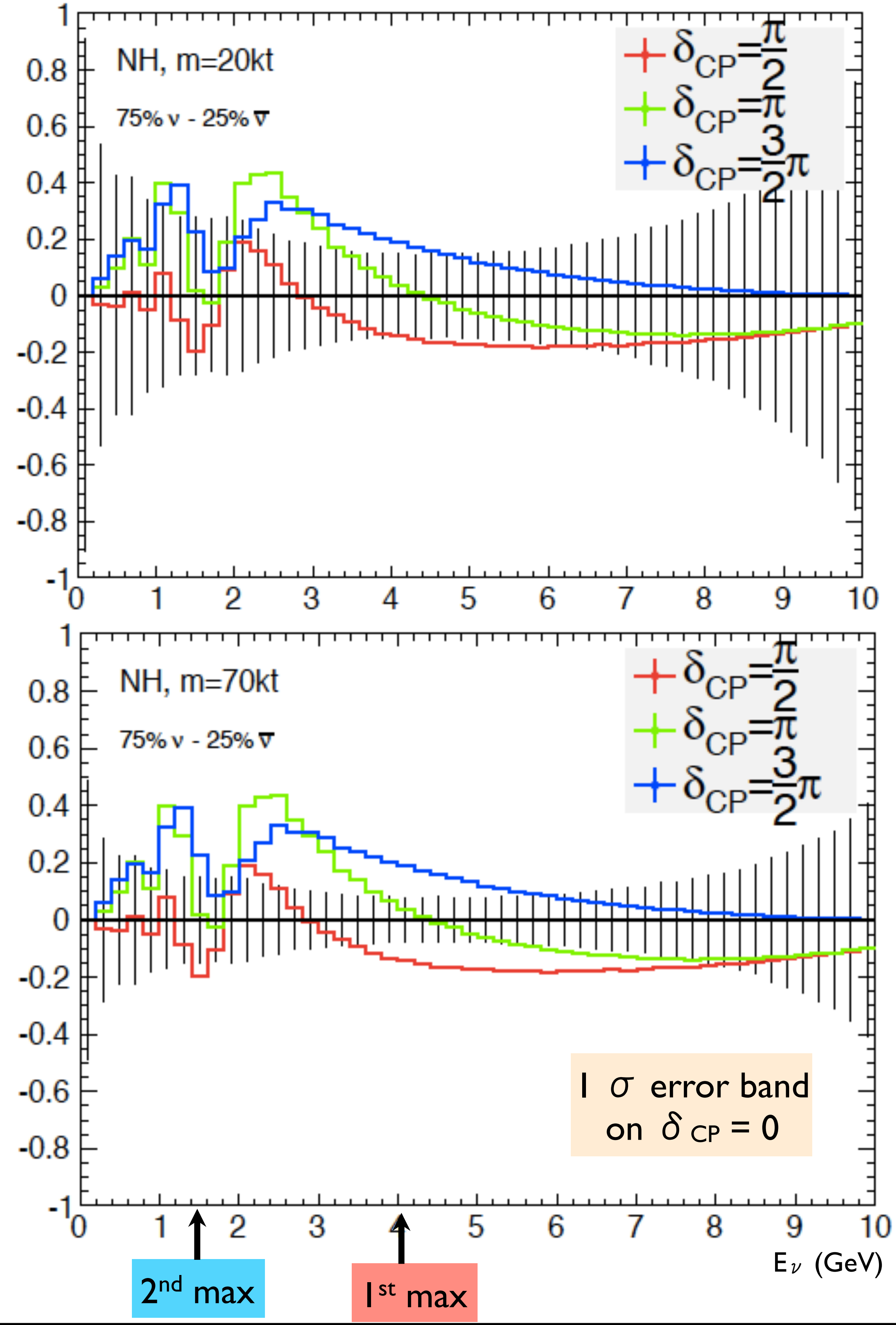
Design value: 75 % ν - 25 % anti-ν

LBNO Strategy on δ_{CP}

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

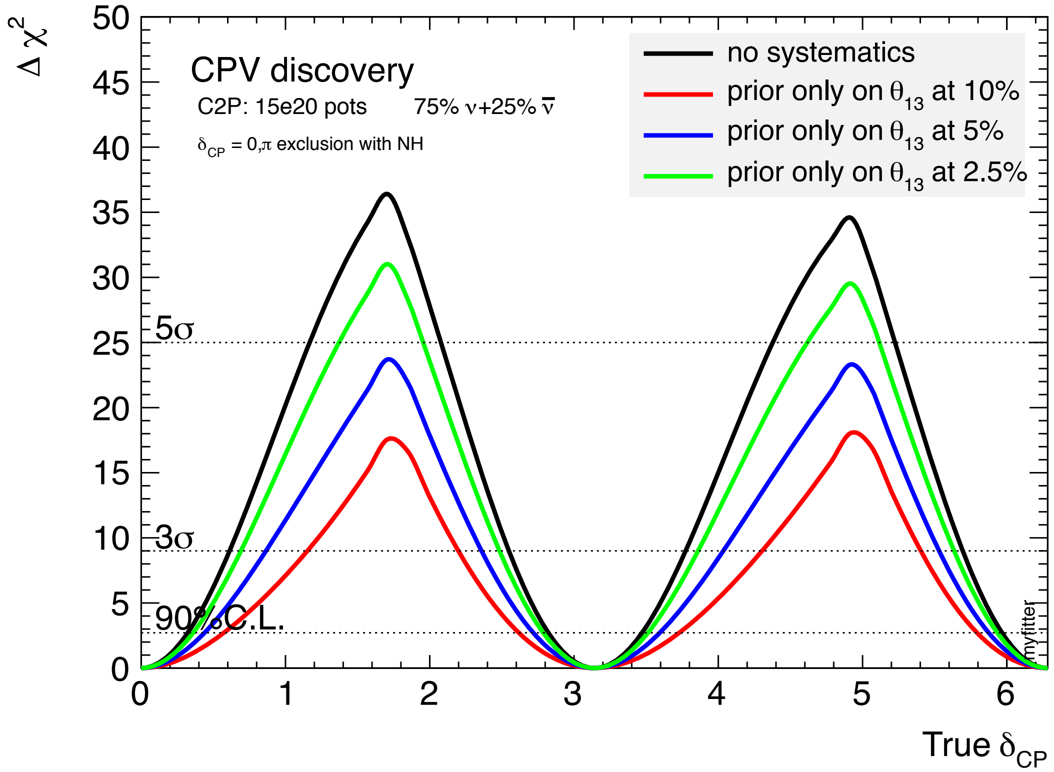


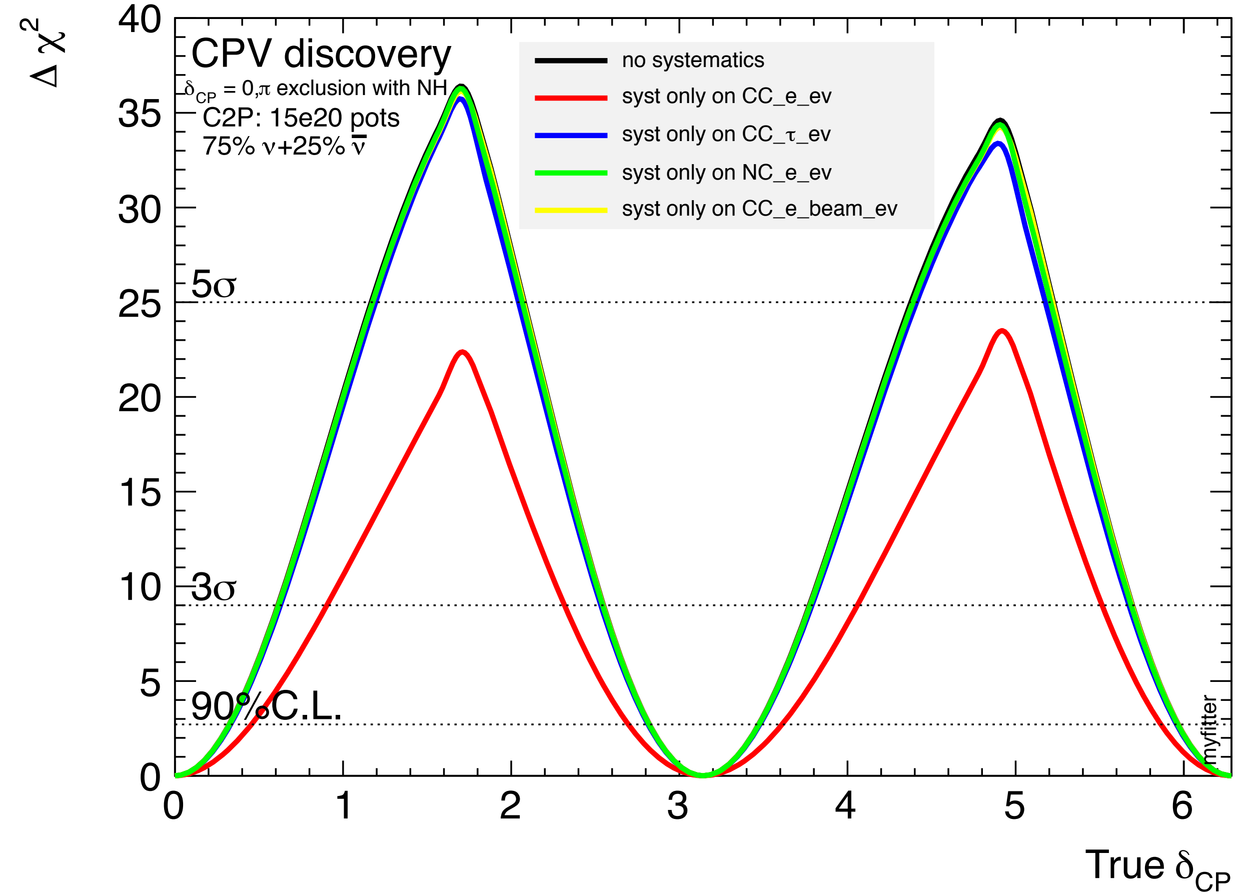


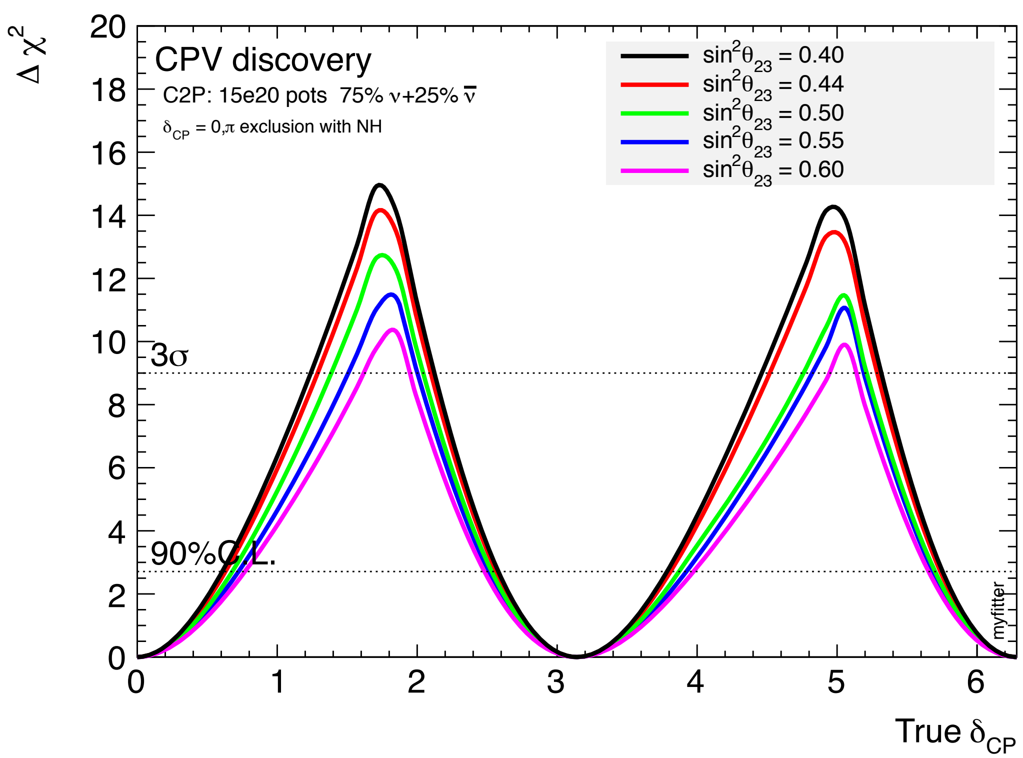


LBNO Strategy on δ_{CP}

Use best knowledge and realistic assumptions on systematics and oscillation parameters

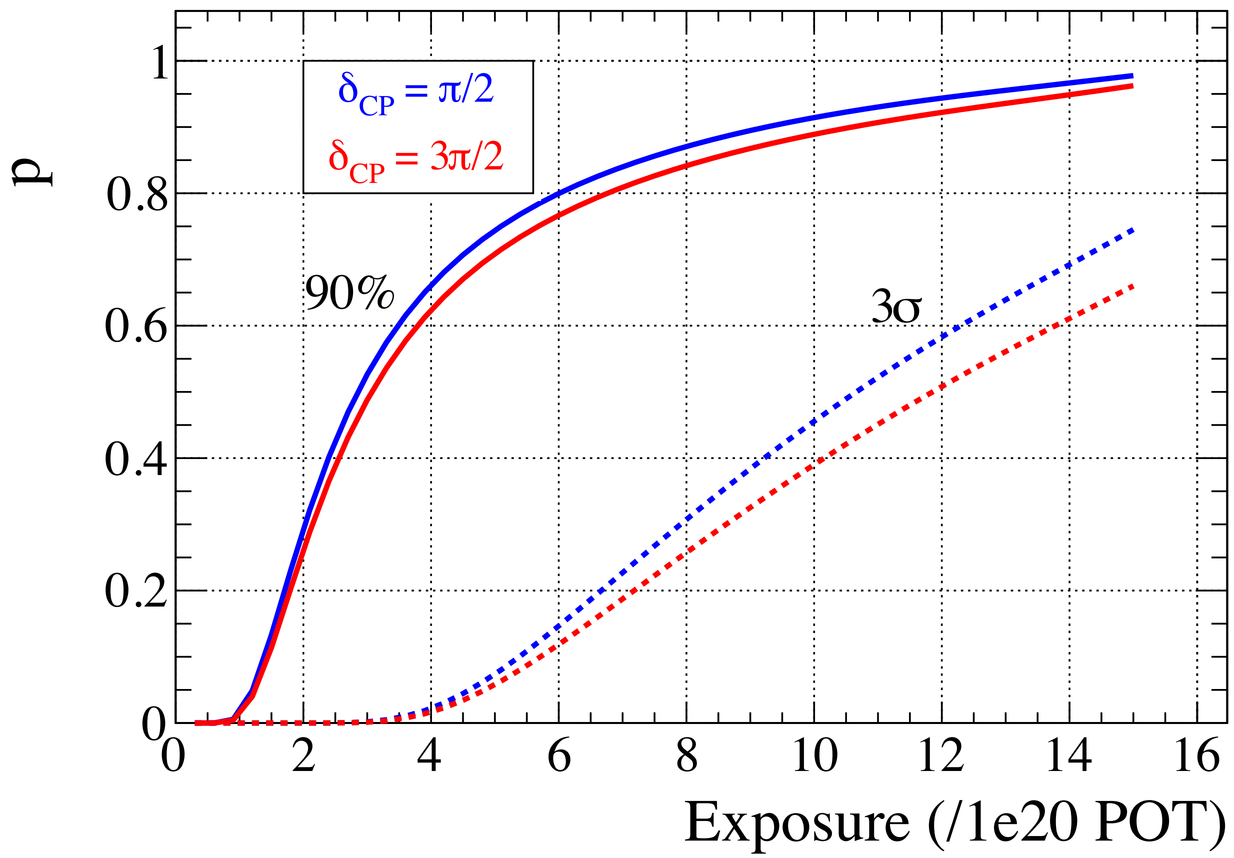






The most important oscillation parameters are θ_{23} and θ_{13} and the most important systematics is the knowledge of the absolute rate of ν_e CC events.

Best knowledge and **realistic** assumptions on oscillation parameters and systematics…



Name	Value	error (1σ)	error (%)
L	2300 km	exact	exact
Δm^2_{21}	7.6×10^{-5} eV^2	exact	exact
$\lvert\Delta m^2_{31}\rvert \times 10^{-3}$ eV^2	2.420	± 0.091	± 3.75 %
$\sin^2\theta_{12}$	0.31	exact	exact
$\sin^2 2\theta_{13}$	0.10	± 0.01	$\pm 10\%$
$\sin^2\theta_{23}$	0.440	± 0.044	$\pm 10\%$
ιverage density of traversed matter (ρ)	3.20 g/cm^3	± 0.13	$\pm 4\%$

ɜ **5**: Assumptions on the values of the oscillation parameters and their uncertainties.

Name	Value	error (1σ)
Signal normalization (f_{sig})	1	$\pm 5\%$
Beam electron contamination normalization (f_{ν_e})	1	$\pm 5\%$
Tau normalization (f_{ν_τ})	1	$\pm 20\% - \pm 50\%$
ν NC and ν_μ CC background (f_{NC})	1	$\pm 10\%$

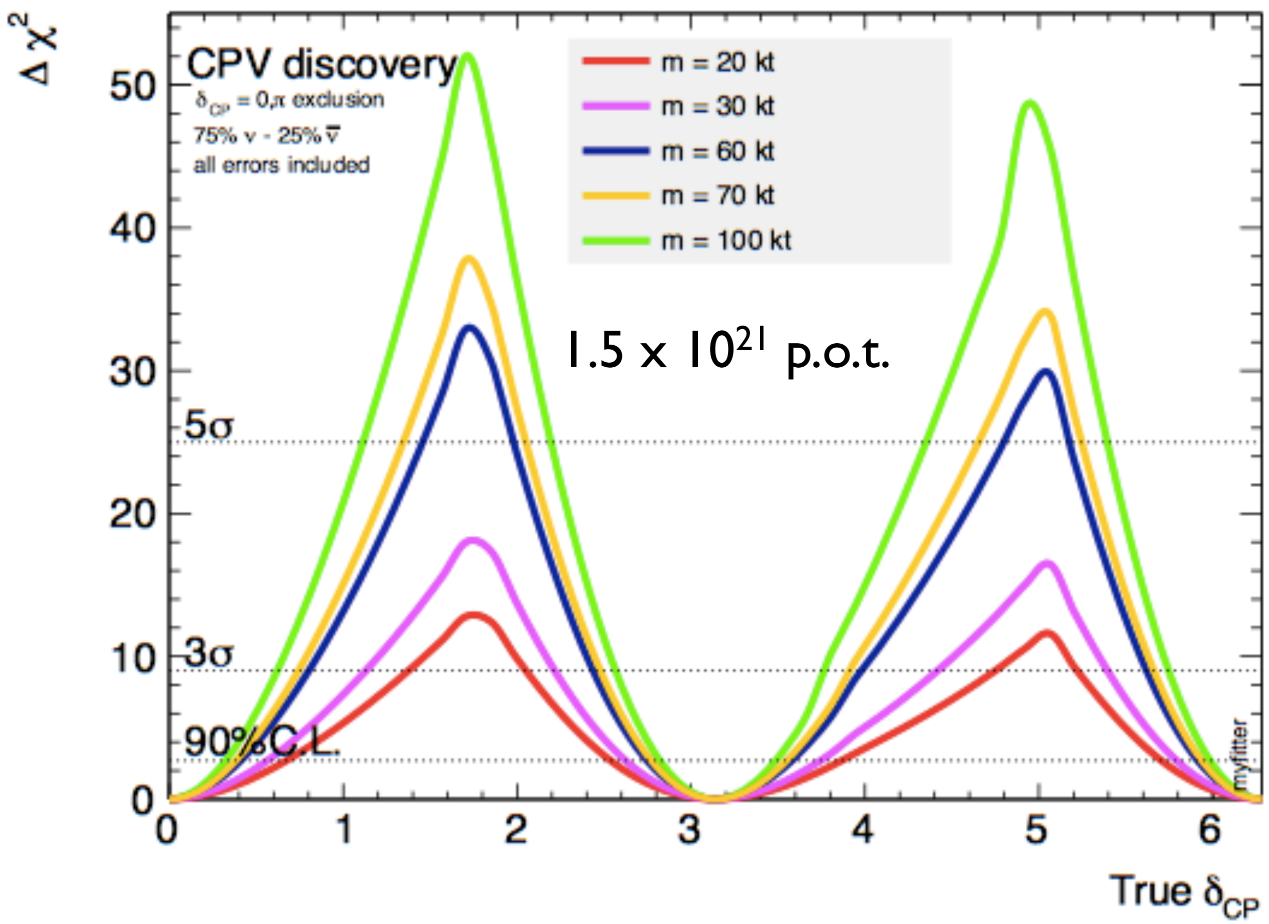
ɜ **6**: Assumptions on event normalization uncertainties (bin-to-bin correlated errors).

- As show before statistically LBNO Phase I can reach 5σ on CPV.
- Current knowledge and conservative assumptions on systematics allow a 3 σ measurement of CPV with LBNO phase I
- The baseline of 2300 km allows the measurement of the 2nd max, less sensitive to systematic effects.

For all details see our paper: arXiv:1312.6520

LBNO Strategy on δ_{CP}

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



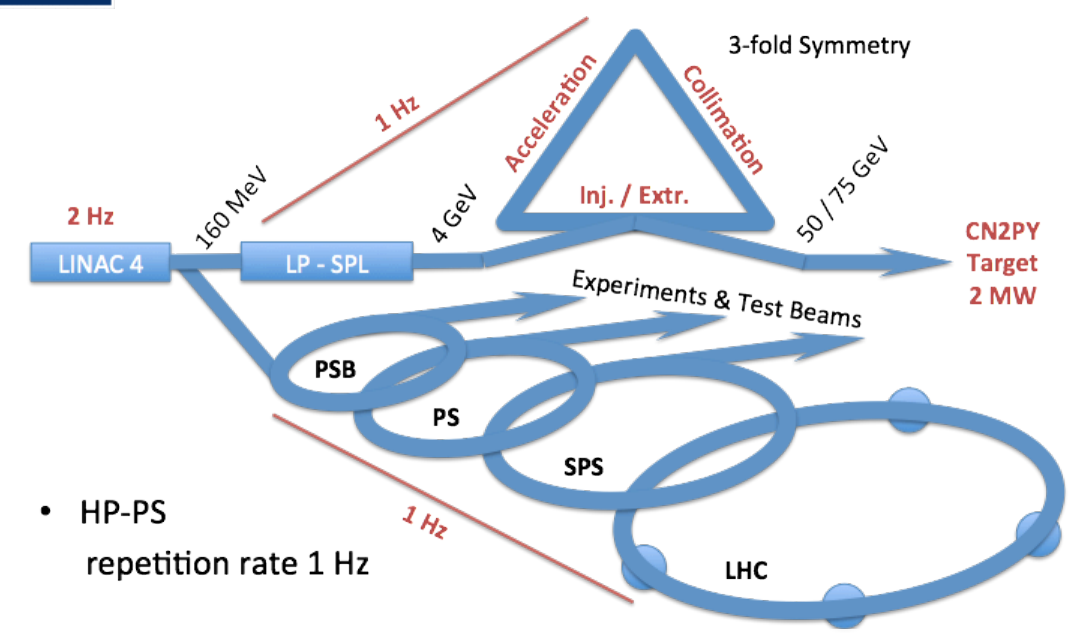
Name	Value	error (1σ)	error (%)
L	2300 km	exact	exact
Δm^2_{21}	$7.6 \times 10^{-5}\ eV^2$	exact	exact
$\lvert\Delta m^2_{31}\rvert \times 10^{-3}\ eV^2$	2.420	±0.091	±3.75 %
$\sin^2\theta_{12}$	0.31	exact	exact
$\sin^2 2\theta_{13}$	0.10	±0.01	±10%
$\sin^2\theta_{23}$	0.440	±0.044	±10%
Average density of traversed matter (ρ)	3.20 g/cm^3	±0.13	±4%

Table 5: Assumptions on the values of the oscillation parameters and their uncertainties.

Name	Value	error (1σ)
Signal normalization (f_{sig})	1	±5%
Beam electron contamination normalization (f_{ν_e})	1	±5%
Tau normalization (f_{ν_τ})	1	±20% – ±50%
ν NC and ν_μ CC background (f_{NC})	1	±10%

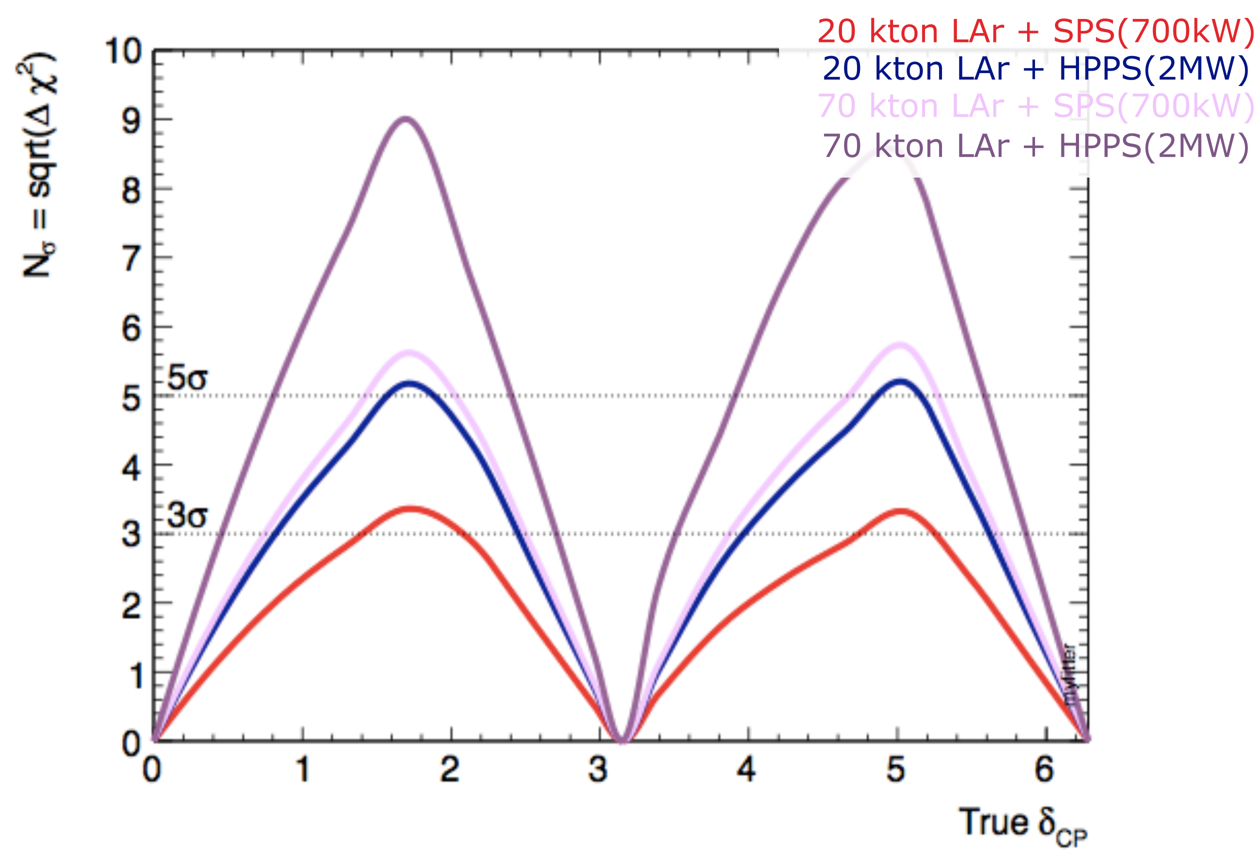
Table 6: Assumptions on event normalization uncertainties (bin-to-bin correlated errors).

High power HP-PS study

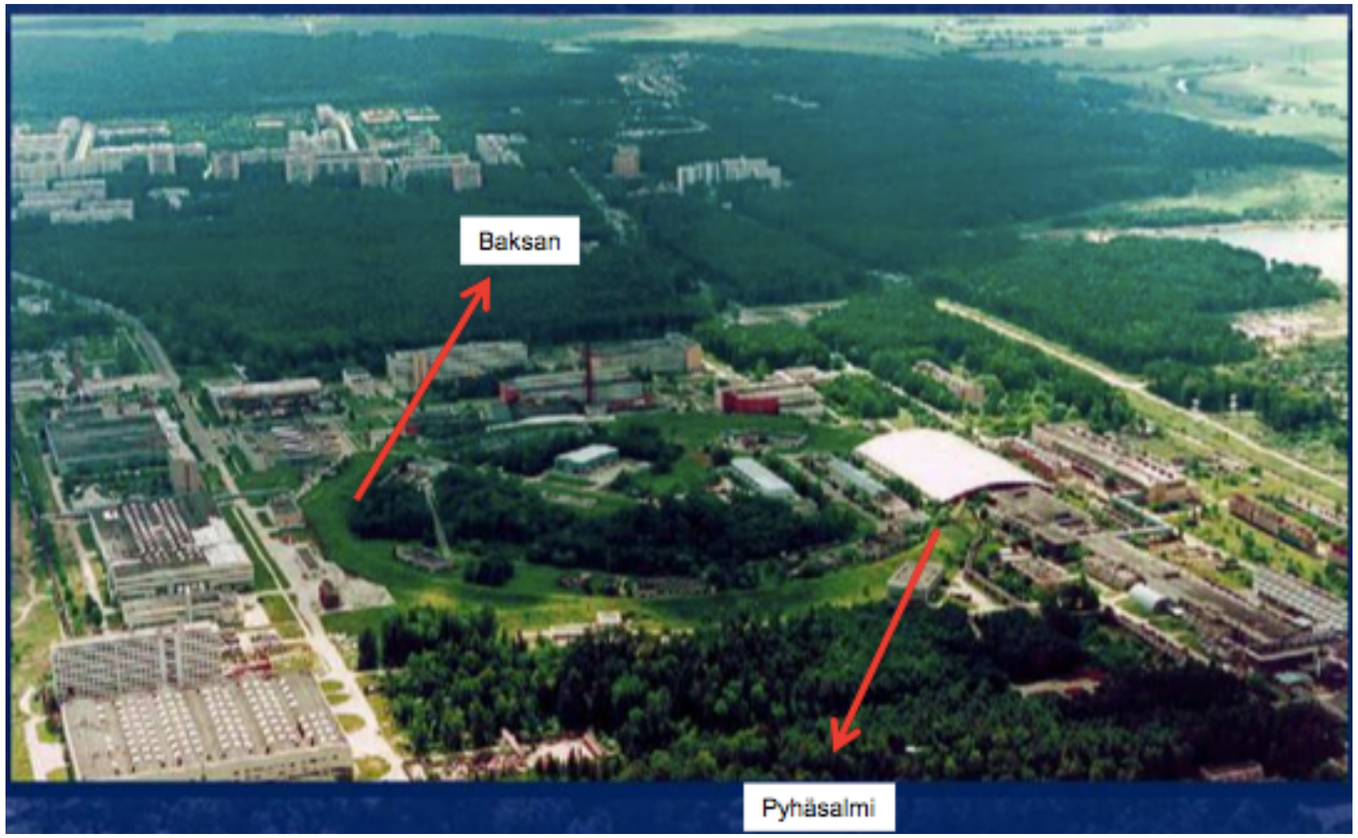


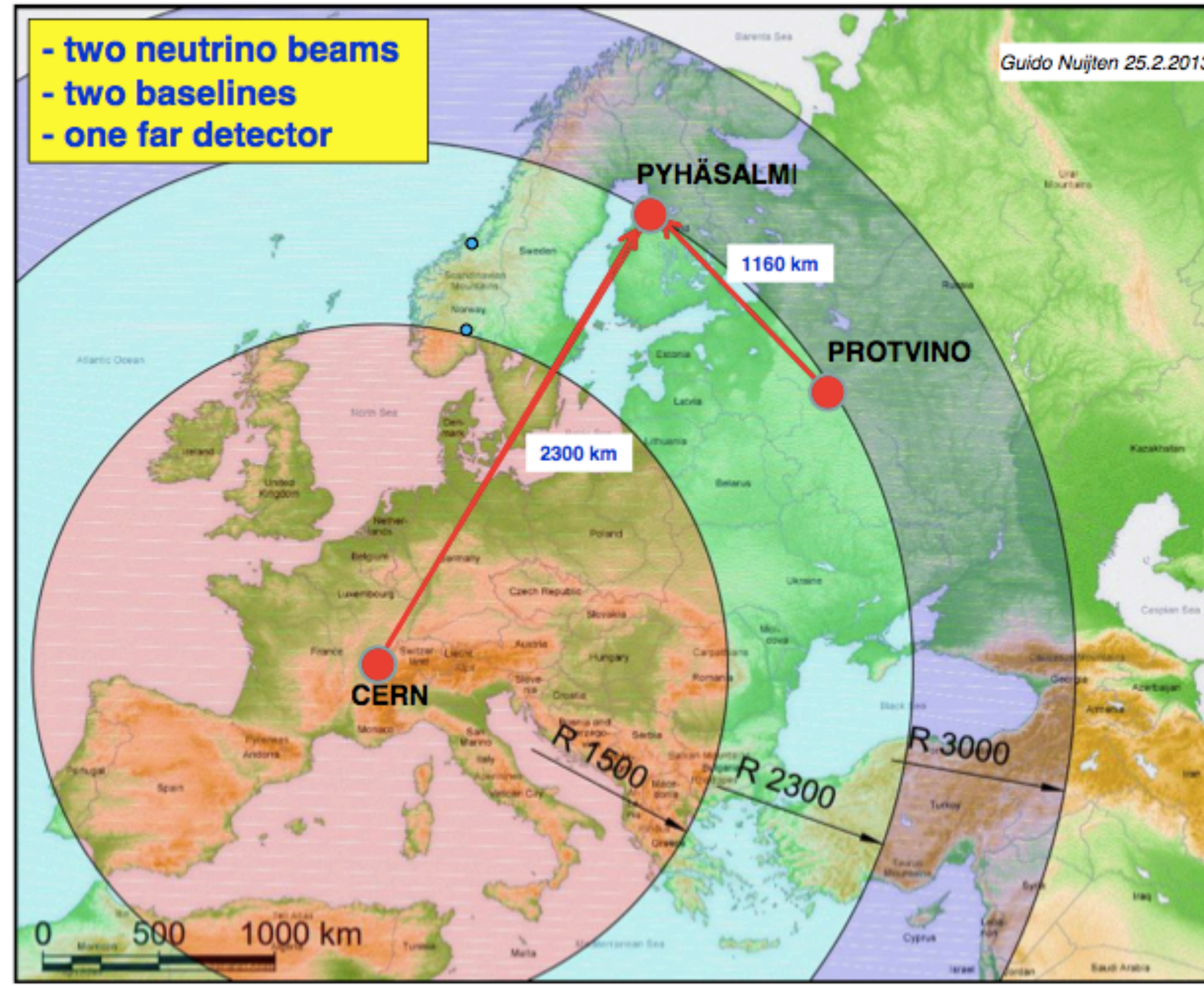
- HP-PS
  repetition rate 1 Hz

See talk by Roland Garoby this afternoon!



Possibility of neutrinos from Protvino



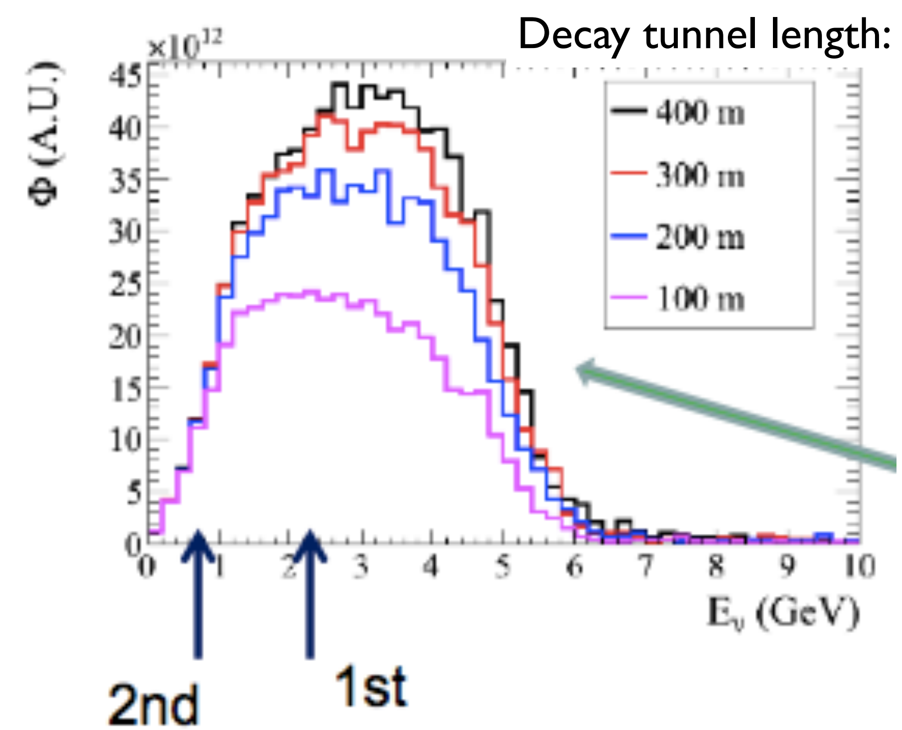


Desired parameters for neutrino beam:

Proton energy	70 GeV
Repetition rate	0.2 Hz
Intensity	2.2×10^{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

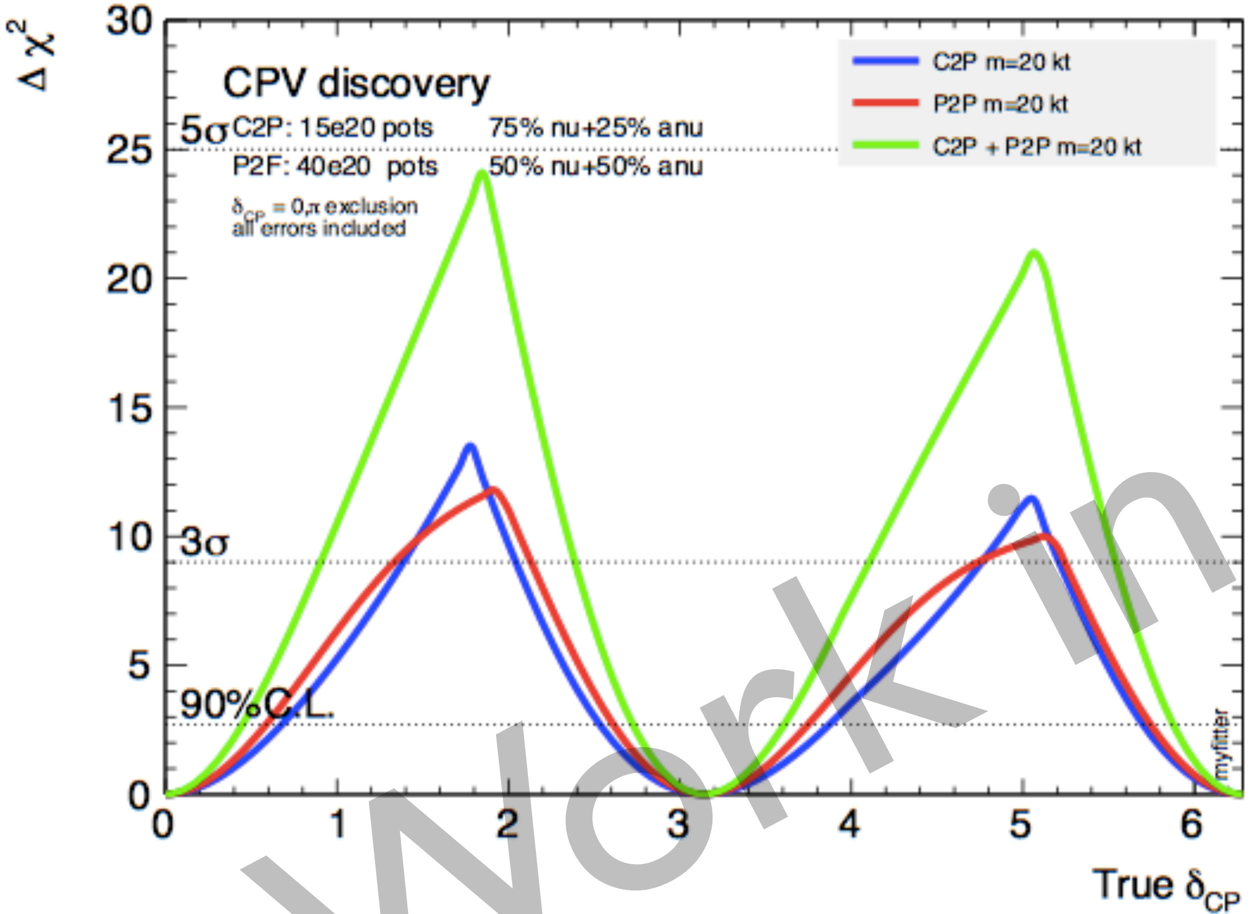
≈2000 $\nu\mu$ CC / 20 kton / year (no osc.)

C2P+P2P sensitivity under study

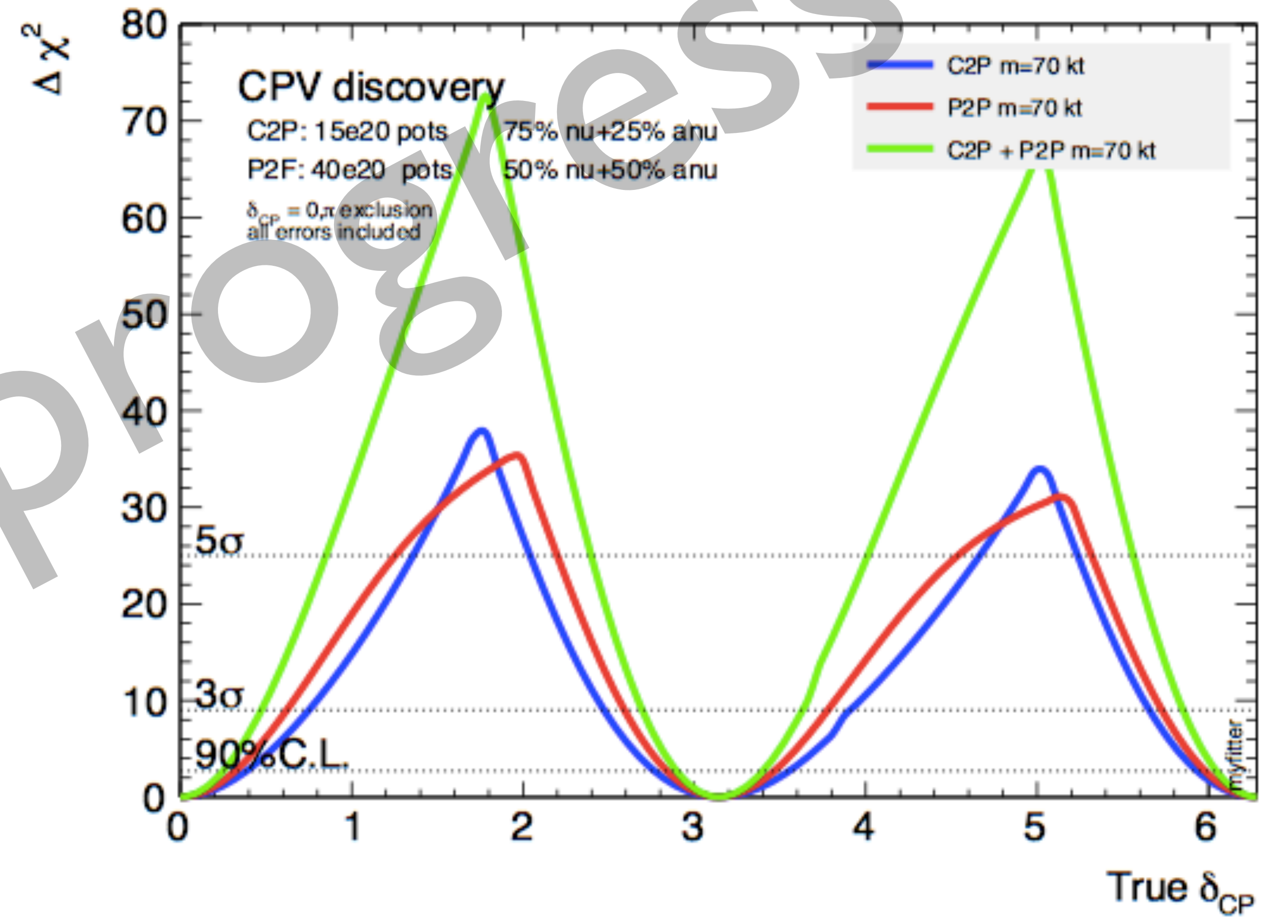


LBNO with 2nd beam from Protvino

20 kt LAr

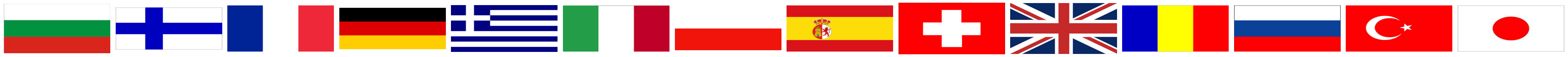


70 kt LAr



Work in progress

LBNO an International Collaboration



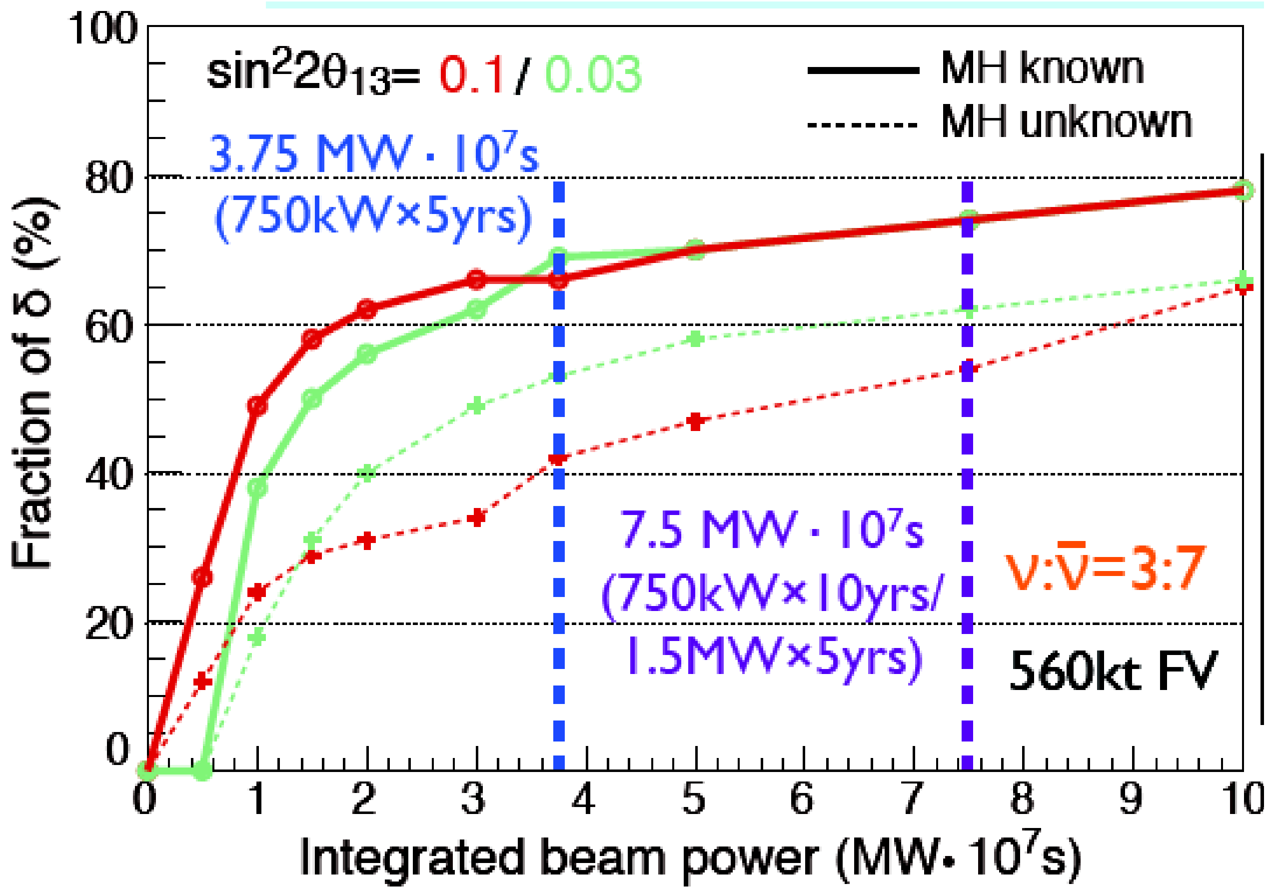
The LAGUNA/LBNO collaboration has more than 200 members and includes institutions from nine CERN member states (Bulgaria, Finland, France, Germany, Greece, Italy, Poland, Spain, Switzerland, and the UK), as well as one candidate for accession to CERN (Romania) and two CERN observers (Russia, Turkey) and Japan (KEK).
- The LBNO collaboration is nearing completion of an EU-funded design study, and the detailed engineering and full costing of LBNO Pilot, Phase 1(20kton LAr) and Phase 2 (70kton) at Pyhäsalmi will be delivered in June 2014.

<u>Status of discussions between LBNE and LBNO:</u>

- The scientific goals and chosen detector technology of LBNE and LBNO are very similar. Leadership of both LBNE and LBNO have agreed that working together towards our common goals would be mutually beneficial.
- A task force to investigate joining forces between LBNE and LBNO, which has 5 members from each Executive Committee, meets every ~2 weeks.
- A Joint Physics Task Force is carrying out a careful comparison of analyses and developing a common understanding of science strategy.
  - As of today we agree on:
    - ✓ Oscillation priors and systematics have a huge impact on the scientific output
    - ✓ MH is a prerequisite for CP
    - ✓ Measuring of L/E and the 2nd max is very important
  - We disagree on:
    - ❖ What are the realistic assumptions on priors and systematics
    - ❖ To evaluate the potential of the experiment as median (LBNE) or full power (LBNO)
    - ❖ The baseline
    - ❖ The synergy with HK and the need for more than one experiment
- LBNO plans a program of development of their far detector, in particular the two-phase readout technology, including a 6 m^3 prototype in a 8 m^3 cryostat that would be a proof of principle that a large scale detector can be built. This will be carried out at CERN under the newly approved WA105 project and is expected to be completed around 2017.
- LBNE and LBNO are discussing initial collaboration that would be centered on detector development under WA105, including common LAr technology, comparison of single- and double-phase readout, and use of the large cryostat for prototyping LBNE as well as LBNO detectors.

Synergy of LBNO with HyperKamiokande

- HK measures δ_{CP} from the neutrino/anti-neutrino asymmetry at the 1st max. This is not sufficient to prove the full 3 neutrino mixing schema.
- HK δ_{CP} sensitivity is highly dependent on the knowledge of MH



- The baseline of 2300 km for the LBNO experiment will provide an unambiguous determination of MH
- The baseline of 2300 km + WBB allows the measurement of the L/E behavior and the 1st and 2nd max.
- The effect of δ_{CP} is larger at the 2nd max. and systematics are less critical.
- The baseline of 2300 km requires higher neutrino energies where X-sections are better known.
- Independent cross check with two different detector technologies.

Conclusions

- The LBNO collaboration has put a real proposal on the table since 2012.
- LBNO is the only proposed experiment which can guarantee a 5σ measurement of MH

- The early determination of MH is crucial to:
  - Tune the beam for the CPV measurement and
  - Provide the long awaited input to the community

- LBNO and LBNE look similar but LBNO has clearly the better scientific potential even with conservative assumptions.
- LBNO has a clear strategy with a phased program with priority on MH in the 1st phase

- LBNO has real synergy and complementary to HK by:
  - Providing MH
  - Measuring CP in a different way using L/E and the 2nd max
  - The deployment of a fine-grained LAr detector is sensible only if one can make complementary measurements with respect to a statistically outnumbering detector like HK.

- LBNO will provide a very detailed, reliable and competitive costing by June 2014.
- The 2300 km baseline of LBNO is perfect for the ultimate neutrino factory.

The End

Optimistic assumptions lead to better CP coverage, but how can we know???

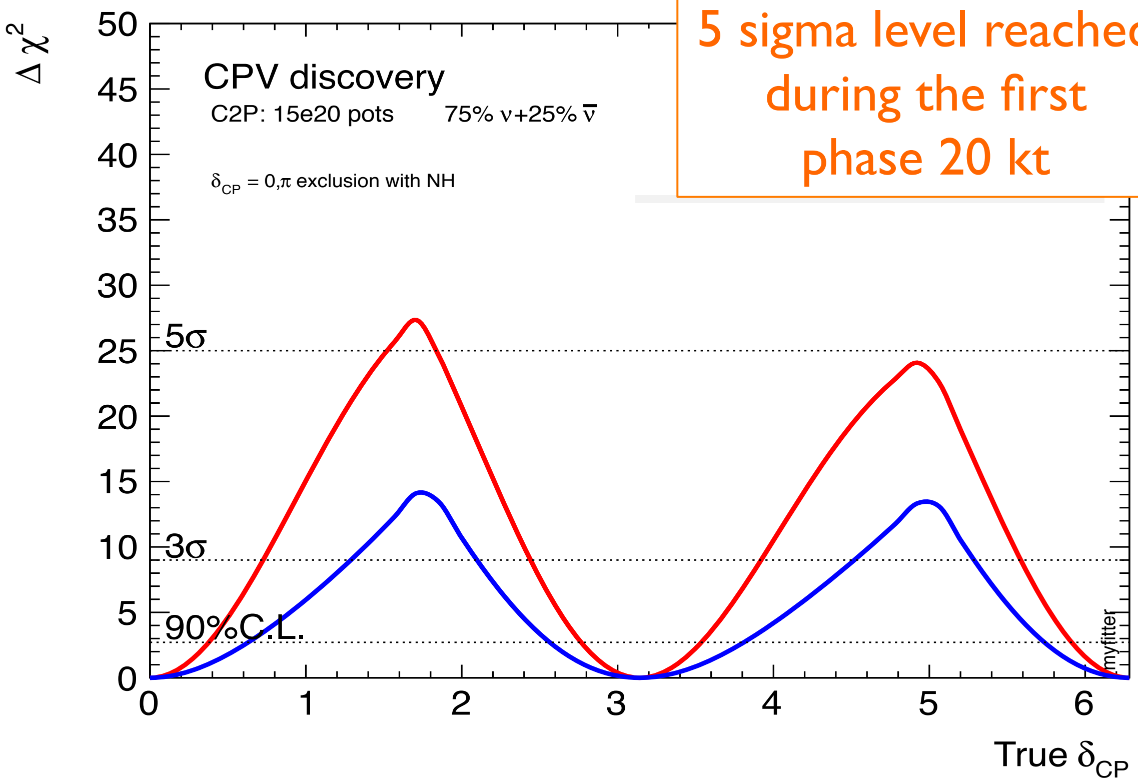
Curves are simulated for 20 kt and 1.5e21 POT at 2300 km

-LBNO conservative assumptions

-LBNO optimistic assumptions

Name	Value	error (1σ)	error (%)
L	2300 km	exact	exact
Δm^2_{21}	$7.6 \times 10^{-5}\ eV^2$	exact	exact
$\lvert\Delta m^2_{32}\rvert \times 10^{-3}\ eV^2$	2.42	± 0.09	± 3.72 %
$sin^2\theta_{12}$	0.31	exact	exact
$sin^2 2\theta_{13}$	0.10	± 0.01	$\pm 10\%$ 3%
$sin^2\theta_{23}$	0.44 0.38	± 0.04	$\pm 9\%$
Average density of traversed matter (ρ)	$3.20\ g/cm^3$ $2.8\ g/cm^3$	$\pm 0.$[illegible]	$\pm 4\%$

Name	Value	error (1σ)
Signal normalization (f_{sig})	1	$\pm 5\%$ $\pm 1\%$
Beam electron contamination normalization (f_{ν_e})	1	$\pm 5\%$
~~Tau normalization (f_{ν_τ})~~	1	~~$\pm 20\% - \pm 50\%$ $\pm 5\%$~~
ν NC and ν_μ CC background (f_{NC})	1	$\pm 10\%$ $\pm 5\%$



5 sigma level reached during the first phase 20 kt

Name conventions:

Values as in the SPSC paper = CONSERVATIVE VALUES

Values with red modifications = OPTIMISTIC VALUES

The most important differences are:

-The value of θ_{23} Fogli et al. arXiv:1205.5254v3 (ours: Gonzales et al. arXiv:1209.3023)

-Error on sin^22 θ_{13}

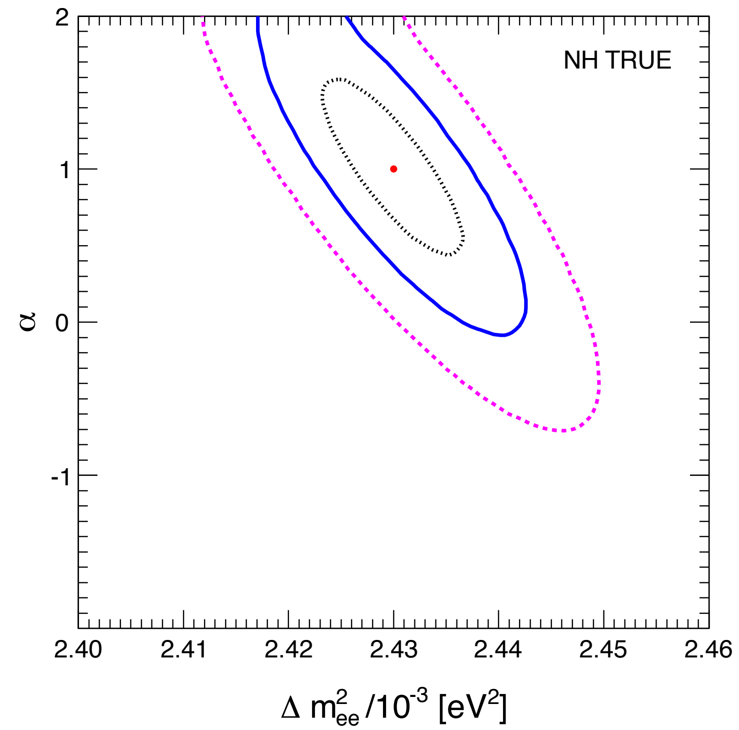
-Systematics on signal and background

Can other experiments measure MH convincingly? **NO !**

Reactor experiments:

e.g. JUNO: 2 σ if systematics are extremely well controlled.

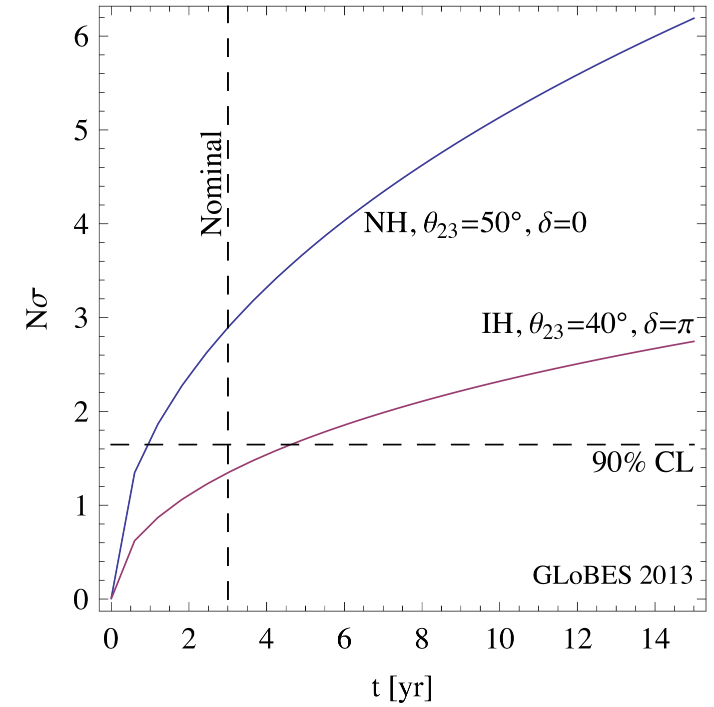
F. Capozzi et al. arXiv:1309.1638v1



Atmospheric Neutrinos:

e.g. PINGU very sensitive to oscillation priors, the hierarchy nature has chosen and the value of δ_{CP}

W.Winter, [arXiv:1305.5539]



- NON of the proposed experiments or any combination of them is able to claim the discovery of the **fundamental** parameter - the mass hierarchy!
- The only way to discover the MH is a very long baseline accelerator experiment.
- In view of the high level funding needed for such experiment the new facility has to **guarantee** the 5 σ discovery over the whole phase space for both solutions (NH and IH) and in depended of being lucky or unlucky with statistical fluctuations.
- The community needs this input therefore, such experiment has to be done within a reasonable time scale of 10 to 15 years from now.