Status of LBNO Project

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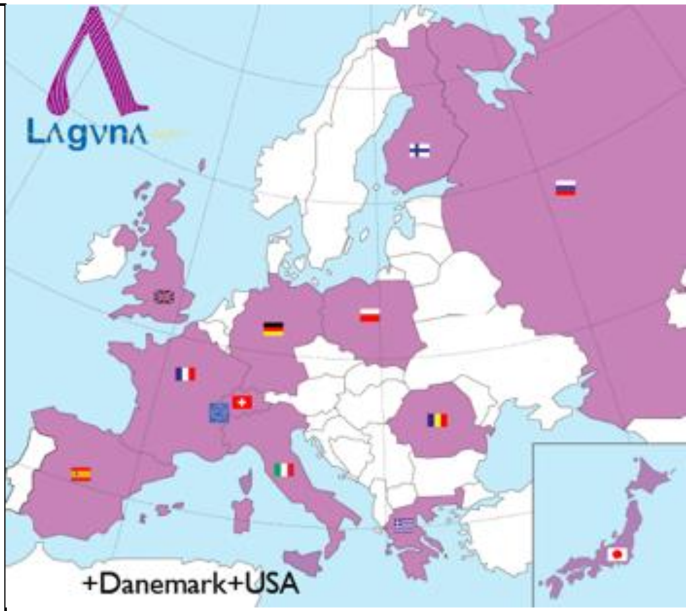
GDR NEUTRINO, June 2014

LAGUNA/LBNO consortium

- 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 SPS EoI for a very long baseline neutrino oscillation experiment, June 2012, SPSC-EOI-007)
  – ~230 authors, 51 institutions



Steering group:

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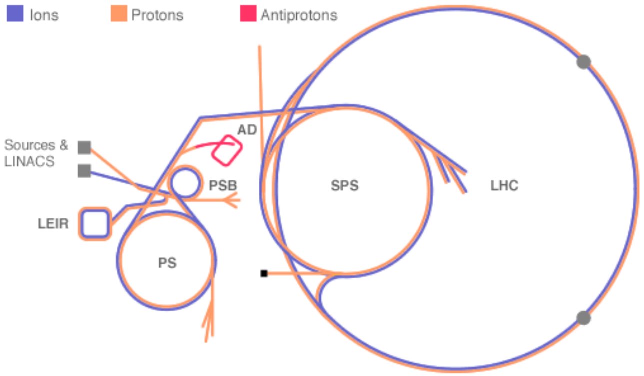
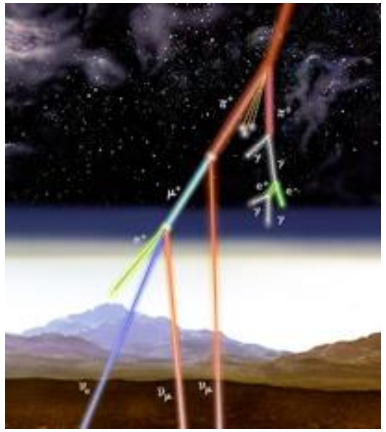
Marco Zito (CEA)

Scientific goals of LBNO

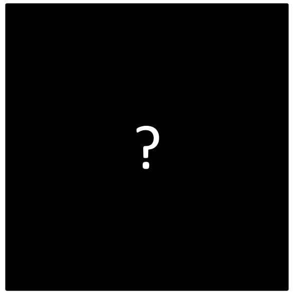
Accelerator



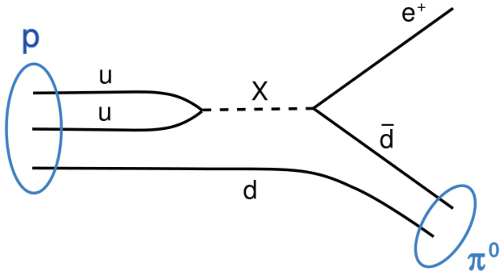
Atmosphere



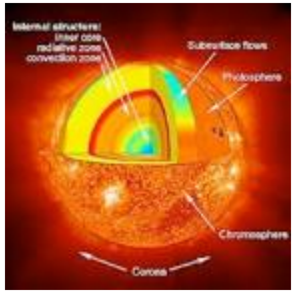
Dark matter



Nucleon decay



Sun



Supernova

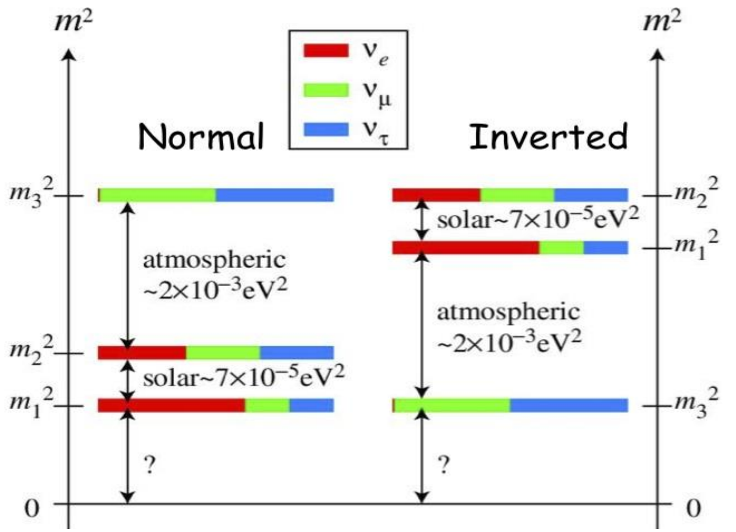
Deep underground observatory:

- Observations of neutrinos from MeV to 10's GeV
- Neutrino oscillations
  - MH, CPV, precision measurements of PMNS
- Proton lifetime

ν physics LBL: two big questions

1. Hierarchy of neutrino masses

- Crucial to resolving leptonic CPV
- Understanding origin of ν mass
- Input to $0\nu\beta\beta$-decay experiments



2. Leptonic CP violation

$$U_{PMNS} = U_{\theta_{23}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} U_{\theta_{12}}$$

If $\delta \neq 0, \pi$ ➔ CP violation in lepton sector

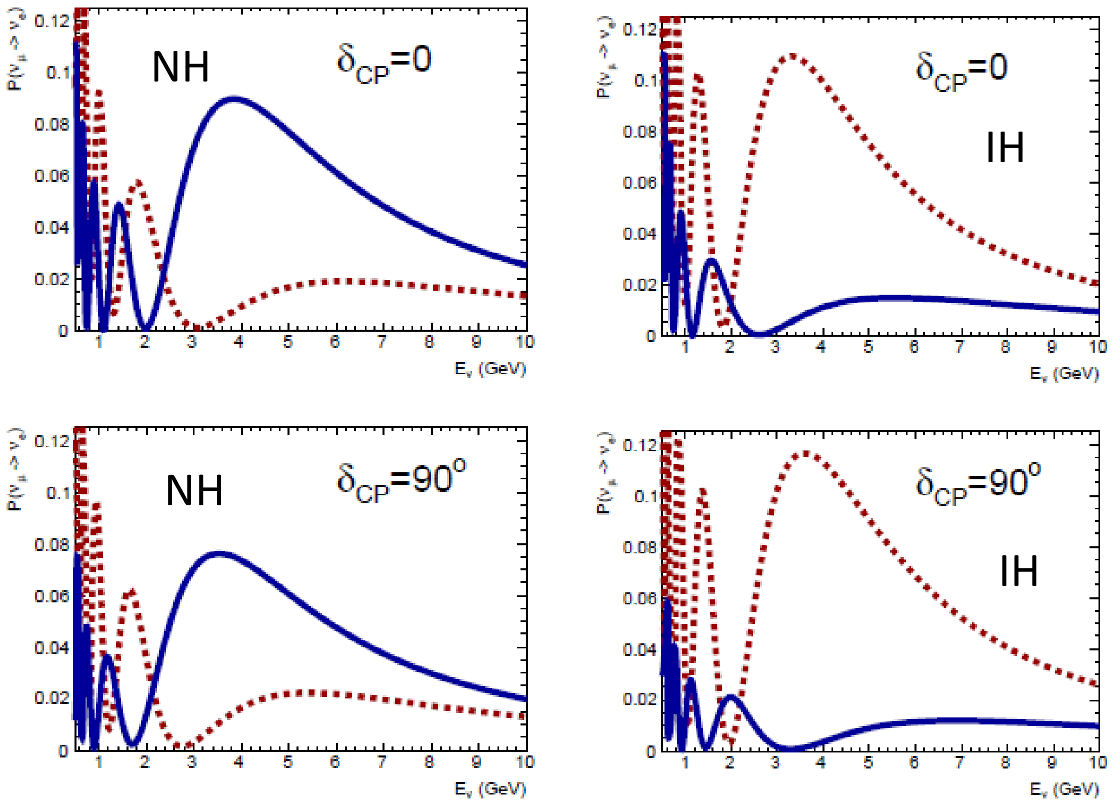
Connection with Leptogenesis?

Both questions can be addressed with conventional accelerator neutrino beams by studying $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

Resolving MH & CPV

$P_{\mu e}$ @ 2300 km

$\bar{P}_{\mu e}$ @ 2300 km



MH scenarios can be clearly distinguished due to suppression of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ($\nu_\mu \rightarrow \nu_e$) oscillations for NH (IH) over large distances

Strategy:

Wide band beam + LAr TPC and very long baseline → measure L/E behaviour over 1st + 2nd oscillation maxima

- Clear determination of MH
- Measurement of CPV
- Verification of 3-neutrino mixing paradigm

The LBNO strategy

Neutrino beam from CERN to Pyhäsalmi, Finland: CN2PY

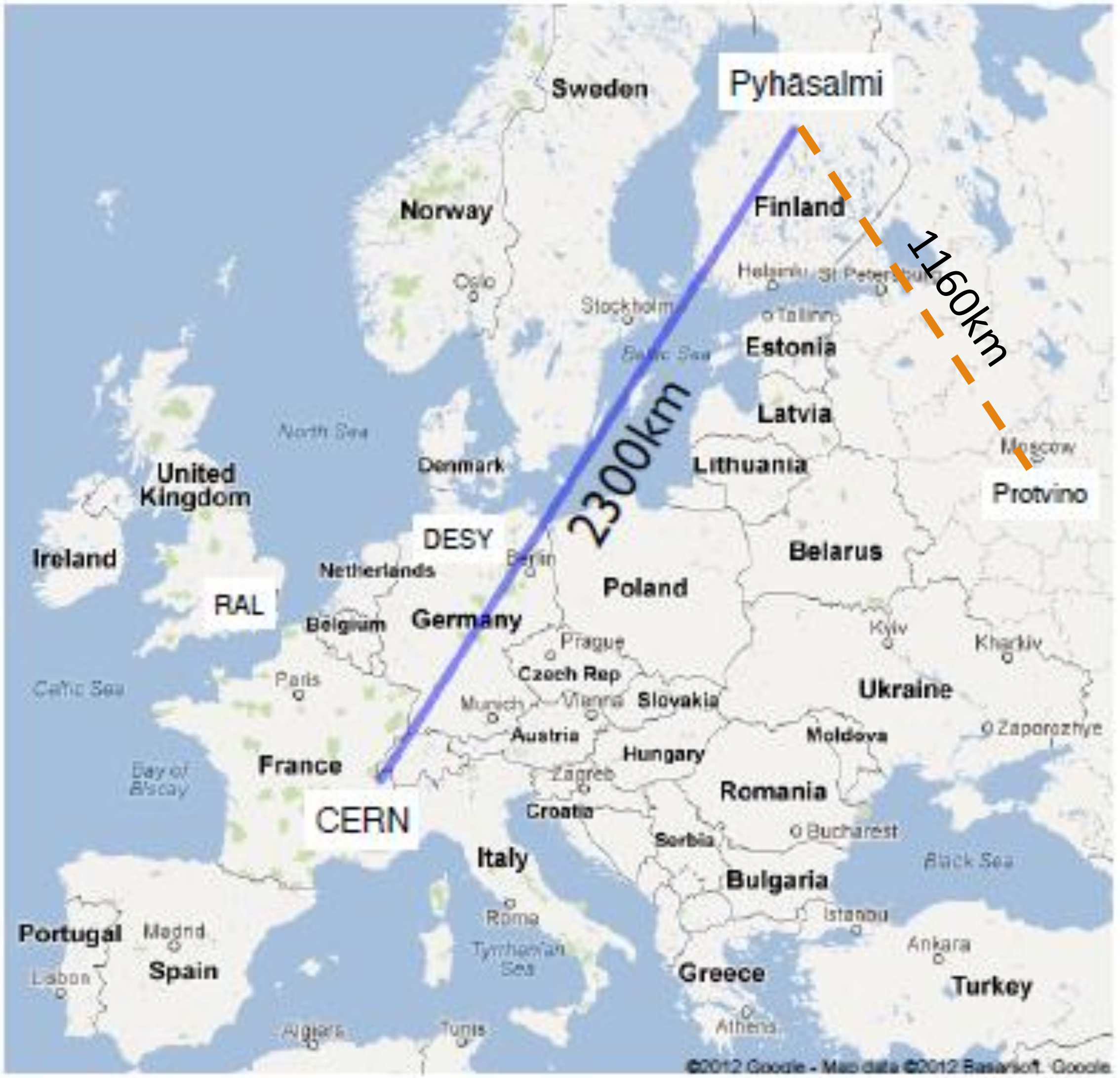
Staged approach

Phase I:

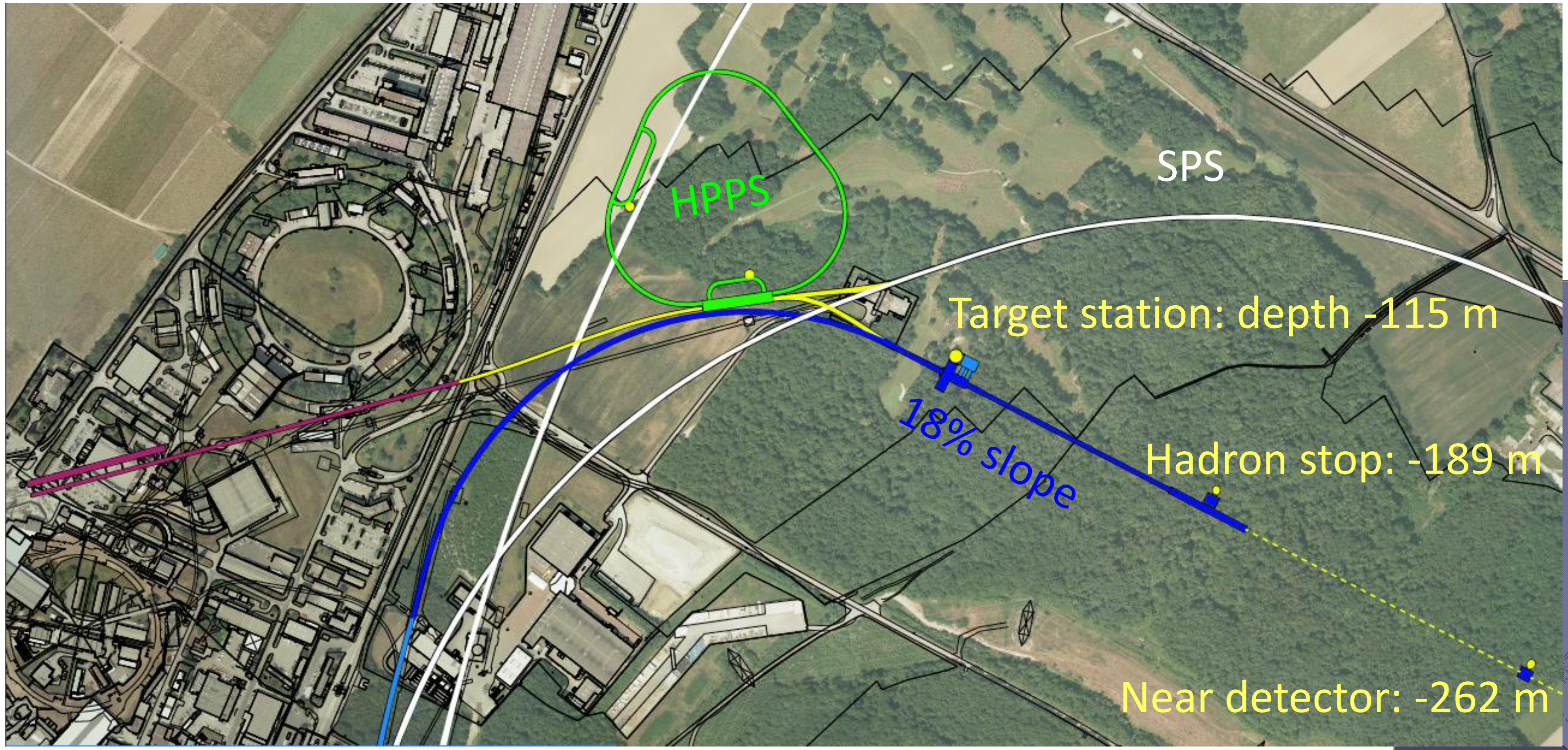
- 24 kton fiducial volume double-phase liquid argon (DLAr) + SPS beam (Ep = 400 GeV, 750 kW)
- Determination of neutrino MH
- Sensitivity to CP Violation (cover 46% of δ_{CP} space at 3σ)
- Nucleon decay (e.g., order of magnitude improvement in $p \rightarrow \nu K$ channel) + neutrino astronomy
- Estimated cost (excavation + detector + infrastructure + contingency) : $\approx$**210 M€ ± 10%**

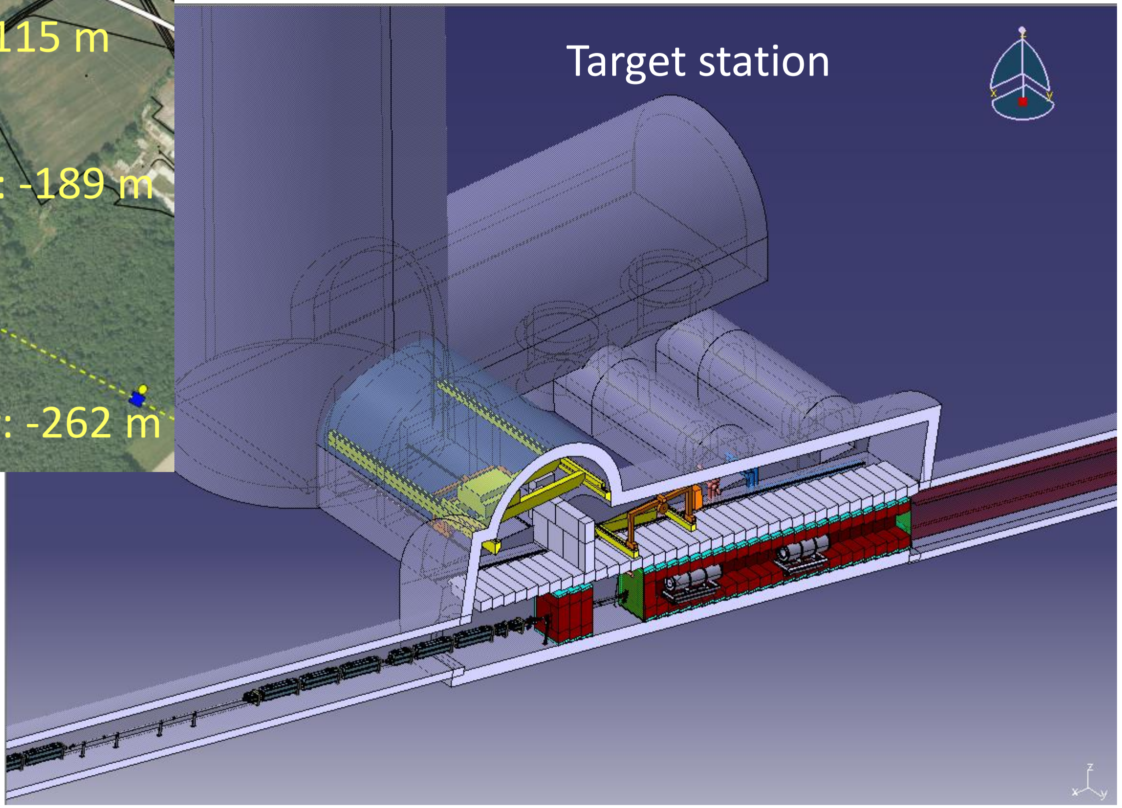
Phase II:

- 70 kton fid. DLAr + HPPS beam (Ep = 50 GeV, 2MW) or 2nd ν beam from Protvino (Ep = 70 GeV, need ~450kW)
- 80% δ_{CP} coverage at 3σ + nucleon decay + neutrino astronomy



Updated LBNO beam design





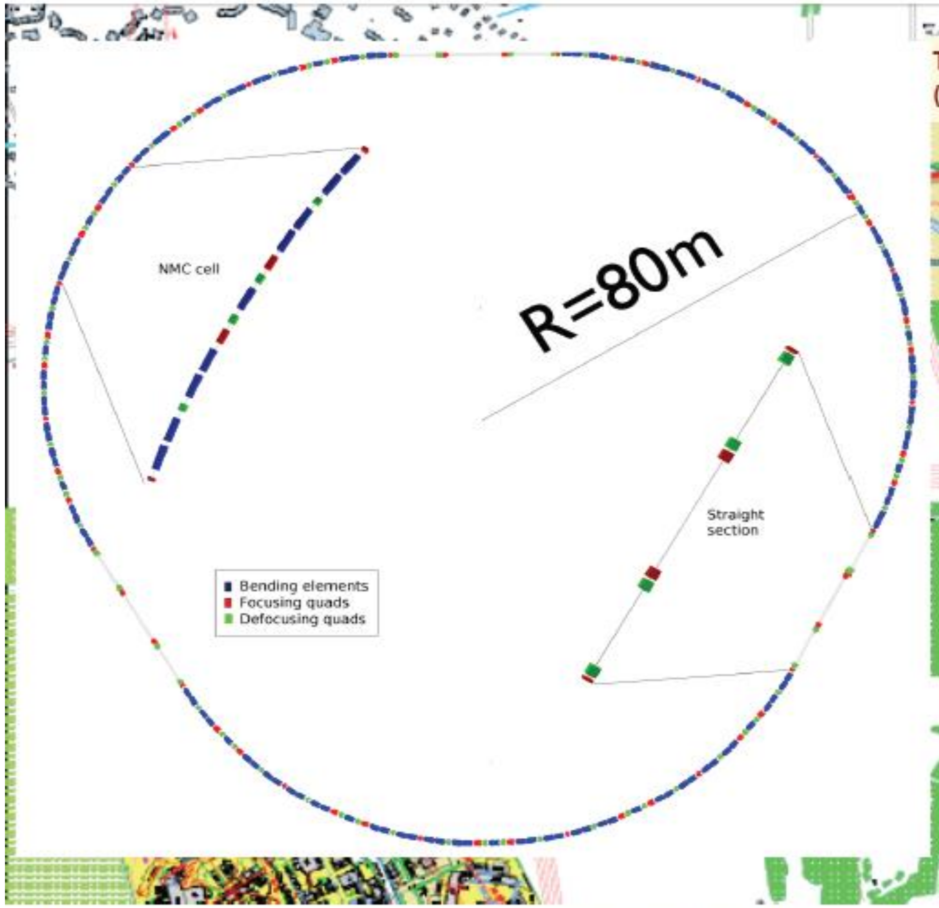
Phase I: proton beam from SPS

400 GeV, max 7E+13 protons every 6 sec, ~750 kW beam power

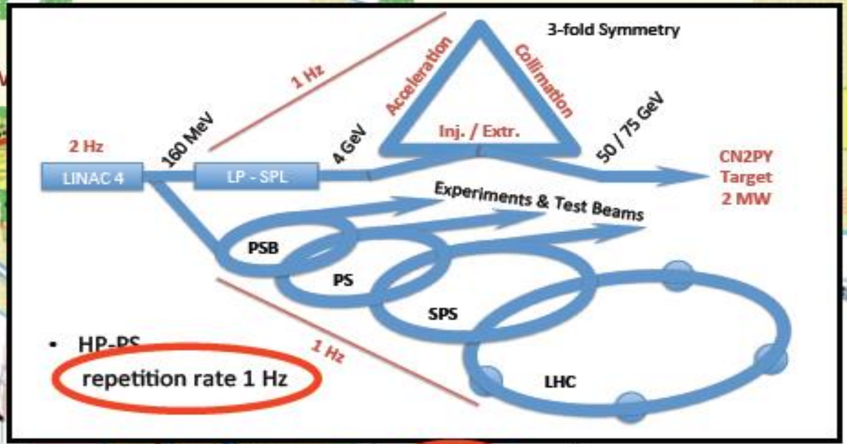
Phase II: proton beam from a new HPPS

50 GeV, 1Hz, 2.5E+14 protons per pulse, 2MW beam power

High power HP-PS study



Target (0.75-2MW



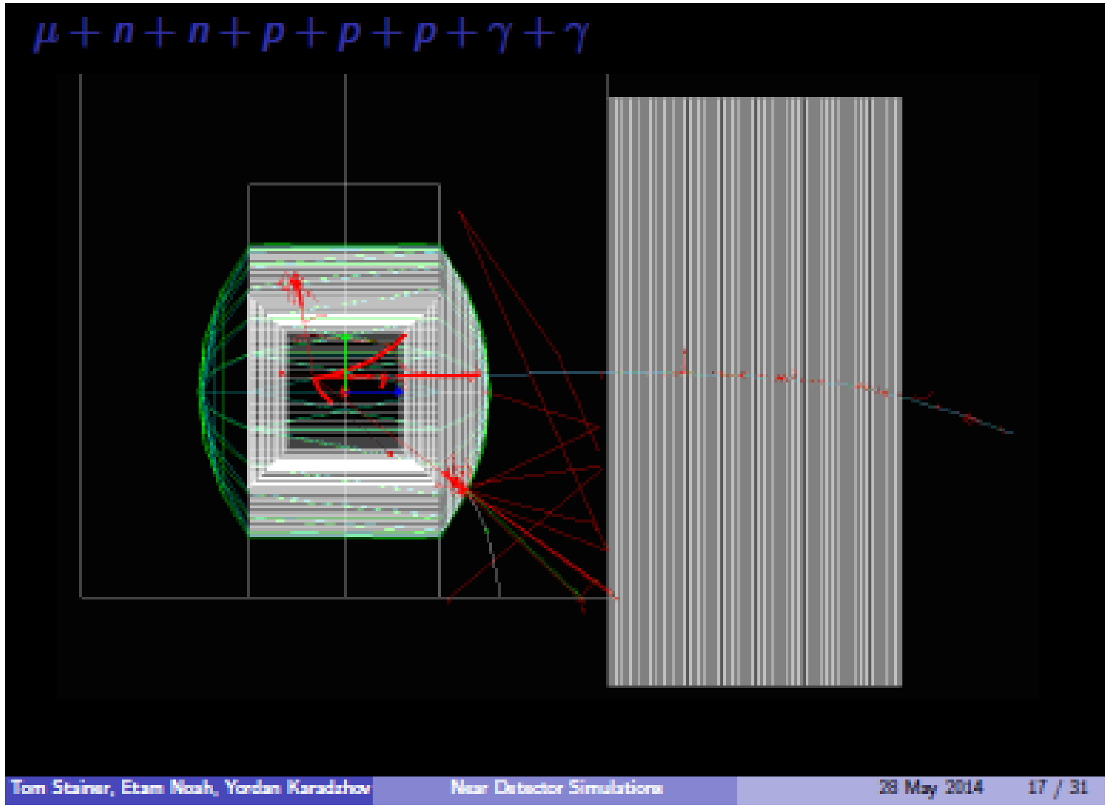
Parameter	50 GeV	75 GeV	Units
Inj. / Extr. Kinetic Energy	4 / 50	4 / 75	[GeV]
Beam power	2		[MW]
Repetition rate	1		[Hz]
f_{rev}	0.248 / 38.97		[MHz]
RF harmonic	157		-
f_{rev}	0.255 / 40.08	0.255 / 40.09	[MHz]
Bunch spacing @ extr.	25		[ns]
Total beam intensity	2.5 x 10	1.7x10	-
Number of bunches	147		-
Intensity per bunch	1.7x10	1.25x10	-
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 near detector

The goal: systematic uncertainties for signal and background need to be below ±5%, possibly at the level of 3% ➔ tight control of fluxes, cross sections, efficiencies …

Hadron-production measurements (NA61 upgraded to 400 GeV protons) + near detector are essential



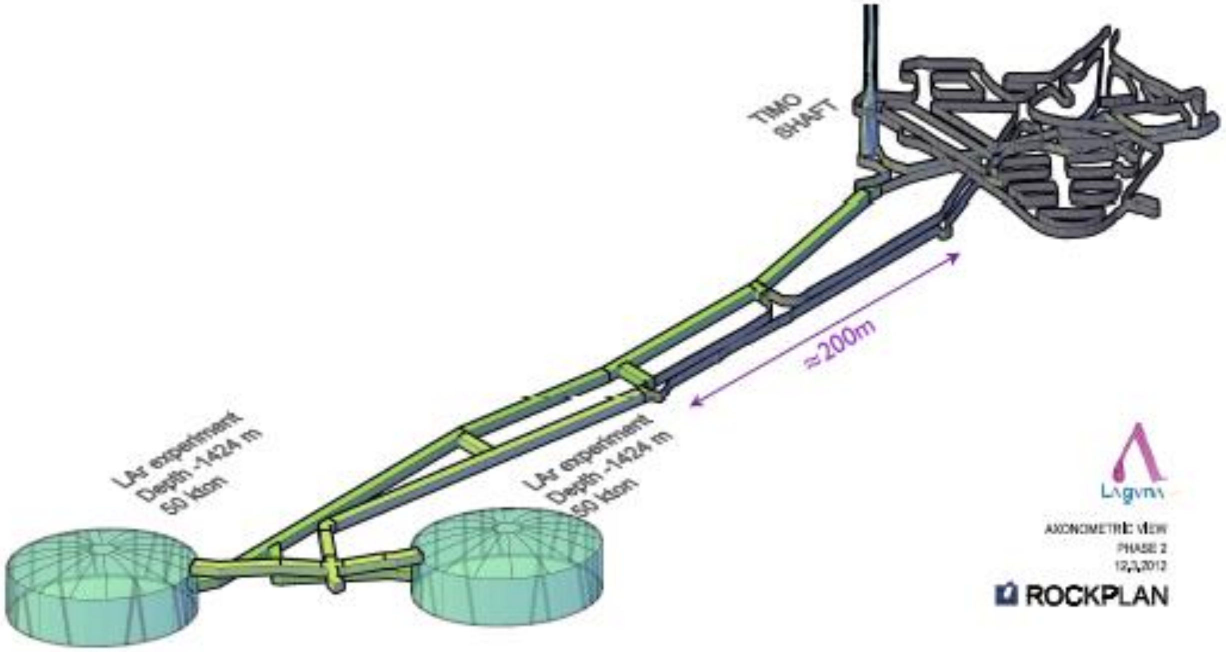
Concept:

- High pressure gas Ar-mixture TPC
    - p = 20 bar, 2 x 2 x 2 m^3
- Scintillator bar tracker surrounding the TPC
- TPC + tracker embedded in an instrumented magnet with a field of 0.5T

- 300 kg of argon mass in TPC
- 0.1 event/spill @ 7E+13 400 GeV ppp
- O(50,000) events/year

Constrain flux x cross section parameters
Precision cross-section measurements

The far detector location



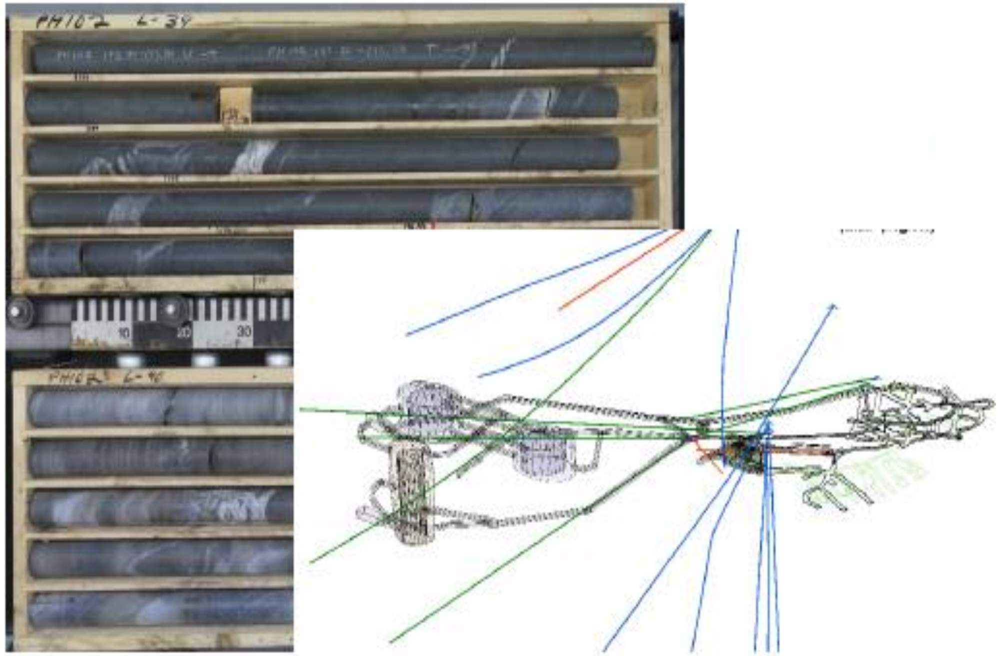
Deep underground location: -1400 m
24 kton LAr detector (Phase 1)
24 + 50 kton LAr detectors (Phase 2)

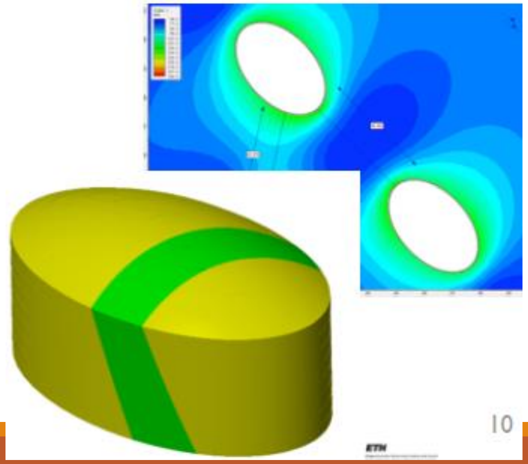
Pyhäsalmi site investigation (2013-2014)

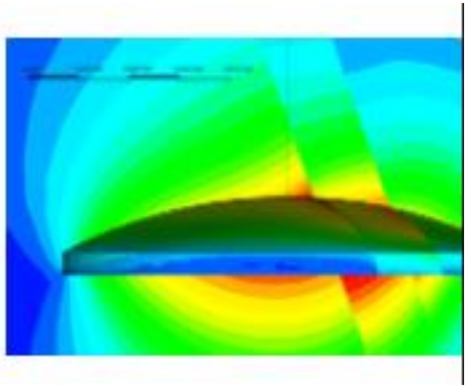
Extensive field work:

- Rock sampling and drilling ~2km of drilling)
- Core logging
- Laboratory tests
- Rock mechanical modelling
- Stress measurements

Accurate modelling of the geological environment 🡐 basis for accurate rock mechanical calculations

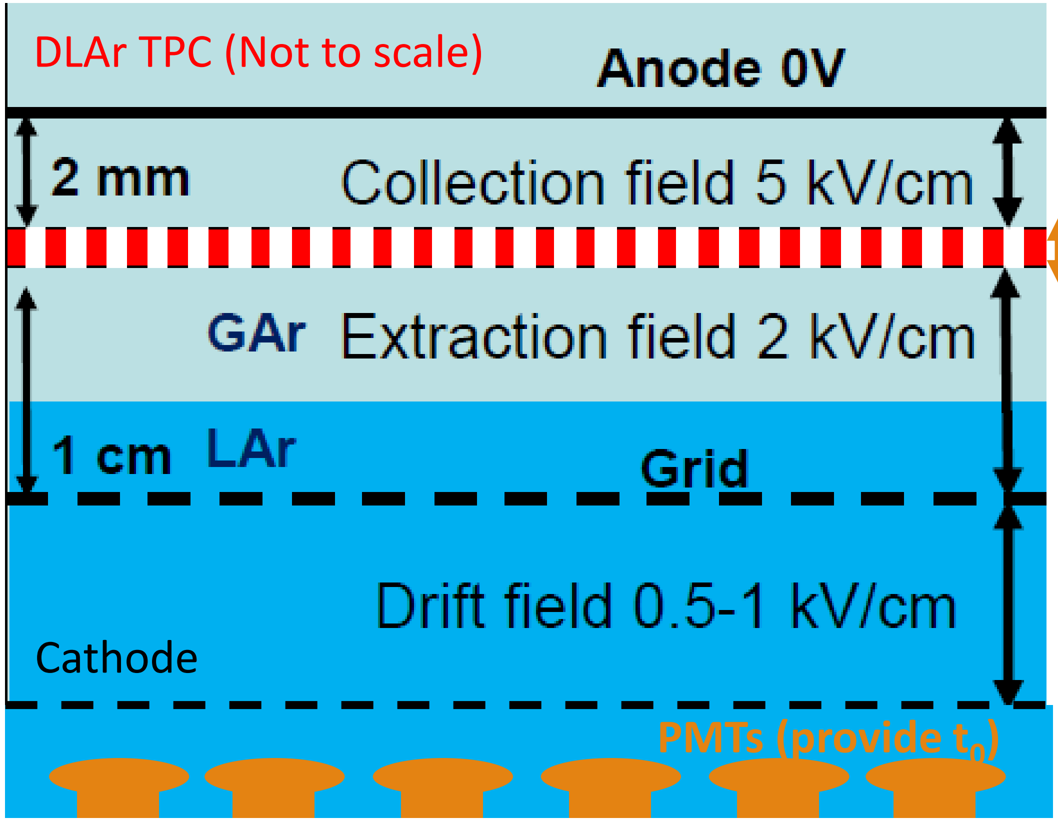




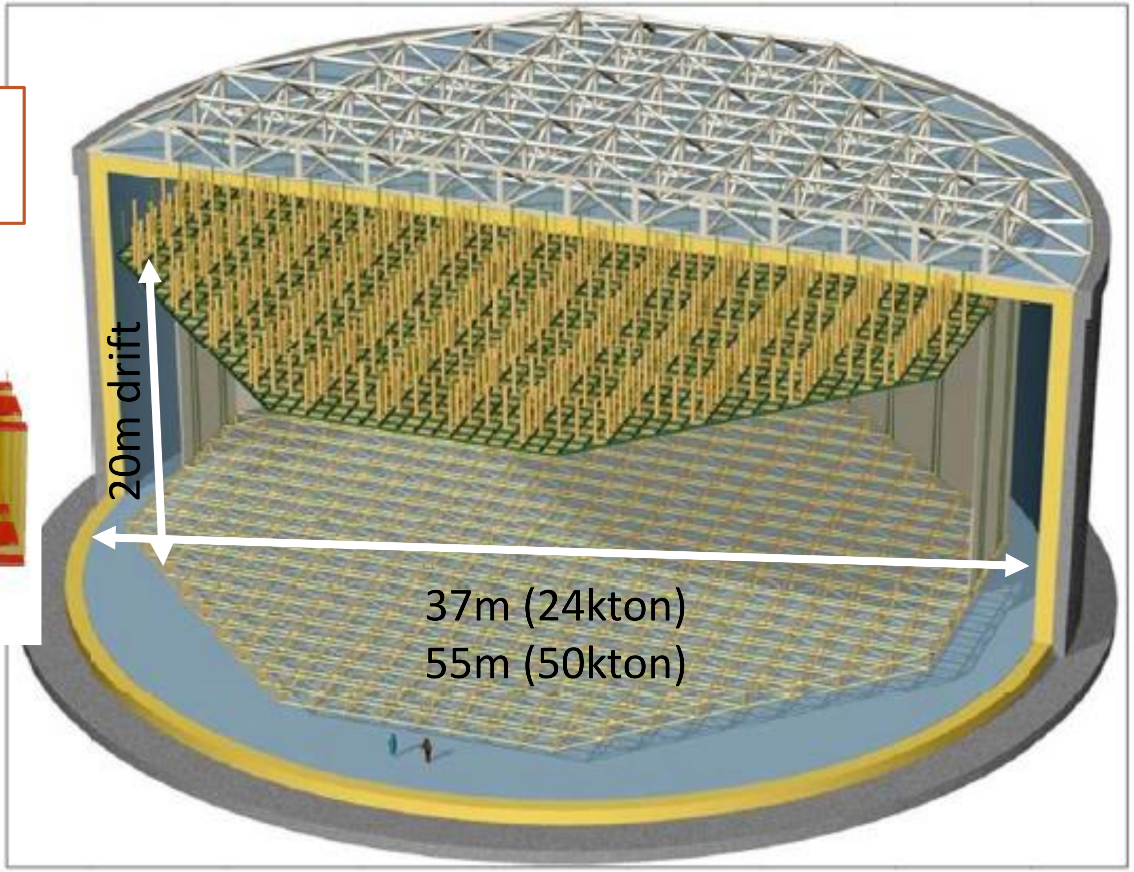


Caverns can be constructed with existing technology

The far detector: double-phase LAr



GLACIER: **G**iant **L**iquid **A**rgon **C**harge **I**maging exp**ER**iment

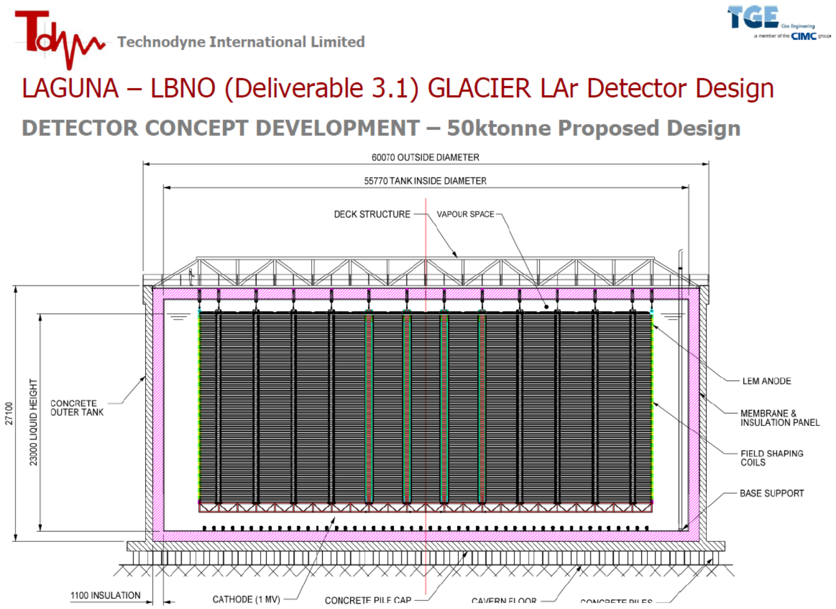


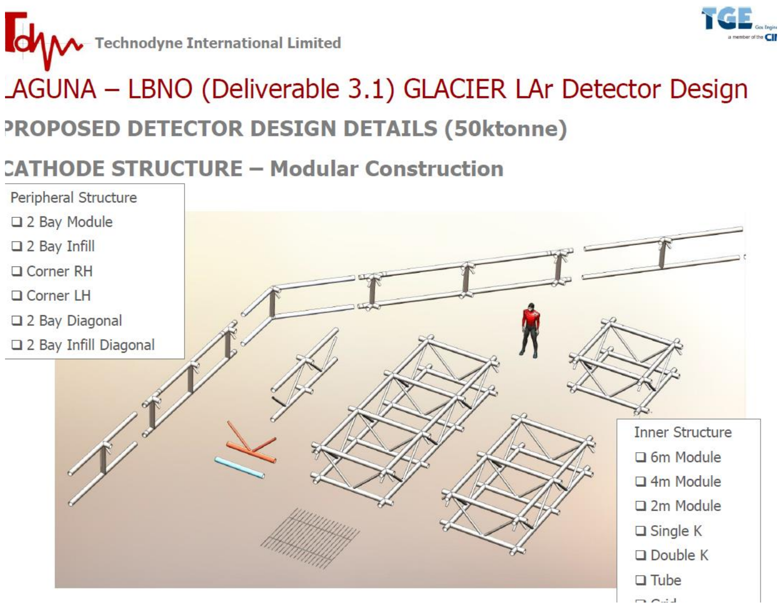
Large detector → long drift distances

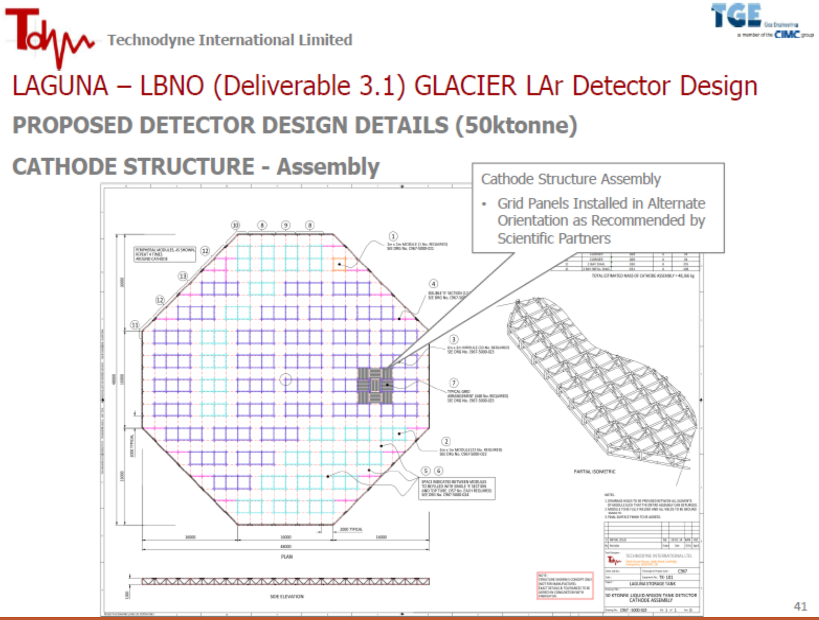
Double-phase detector to improve S/N

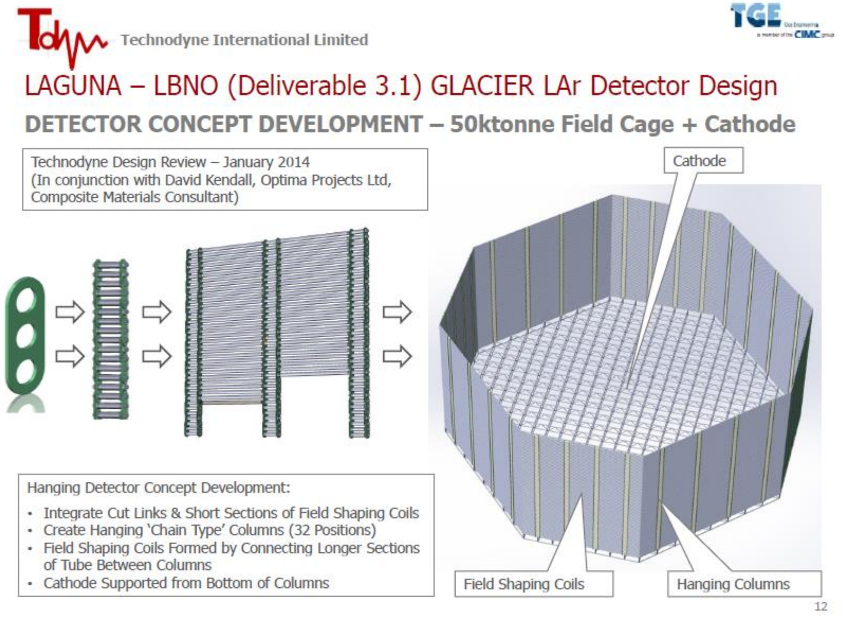
Amplification of ionization electrons in the gas phase

LAGUNA-LBNO DS → Full conceptual detector design

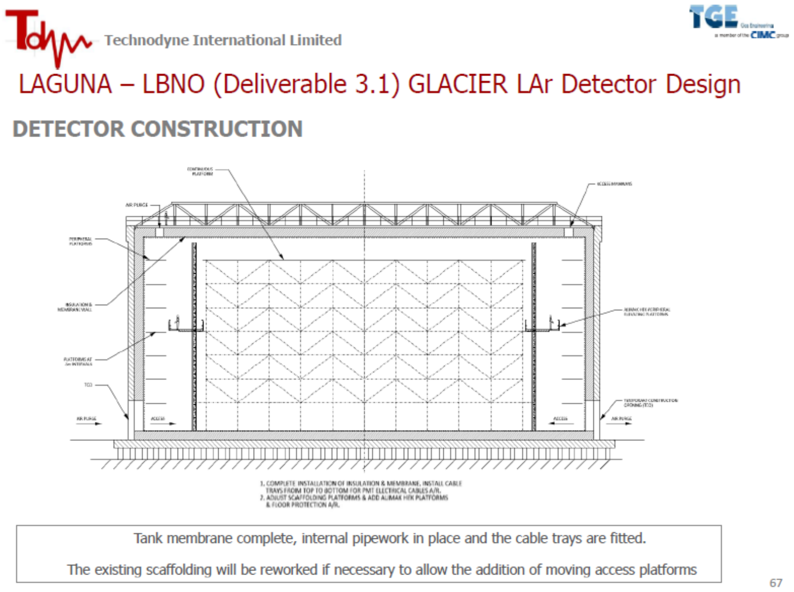


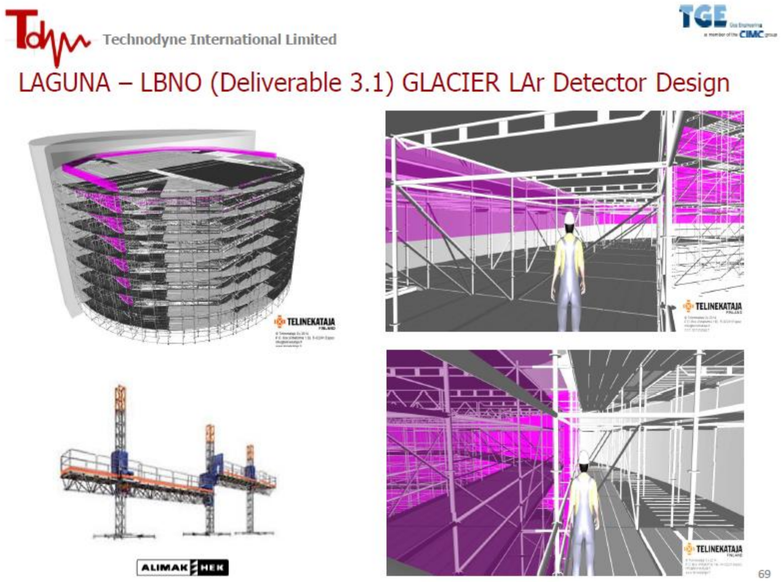


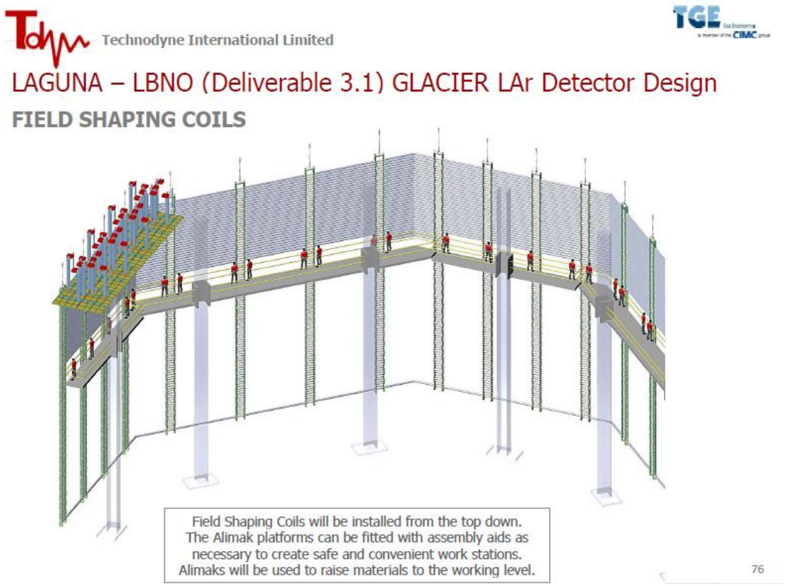


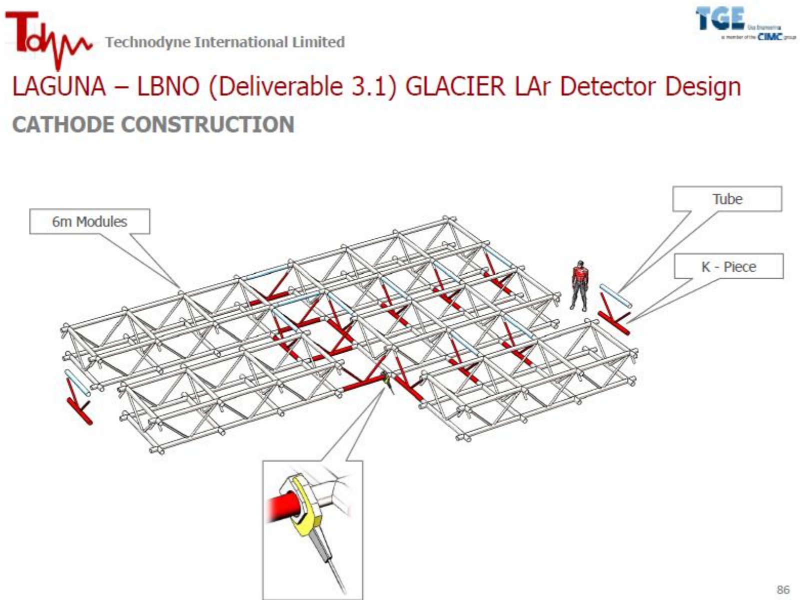


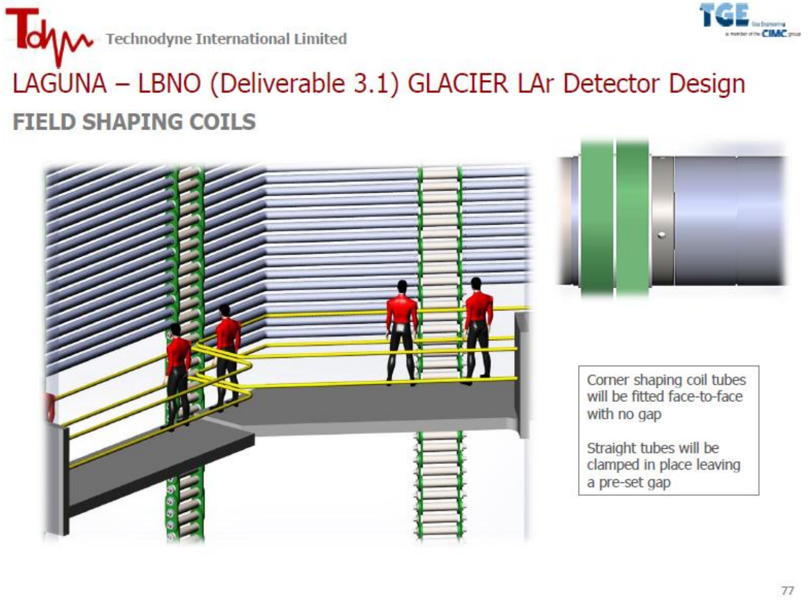
LAGUNA-LBNO DS → Underground construction sequence



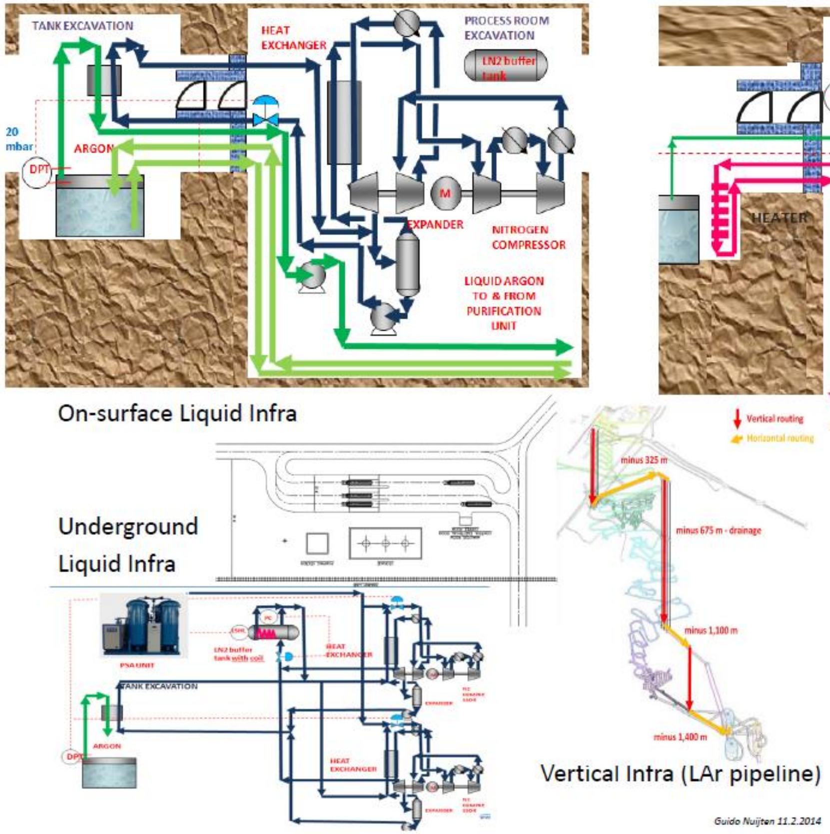


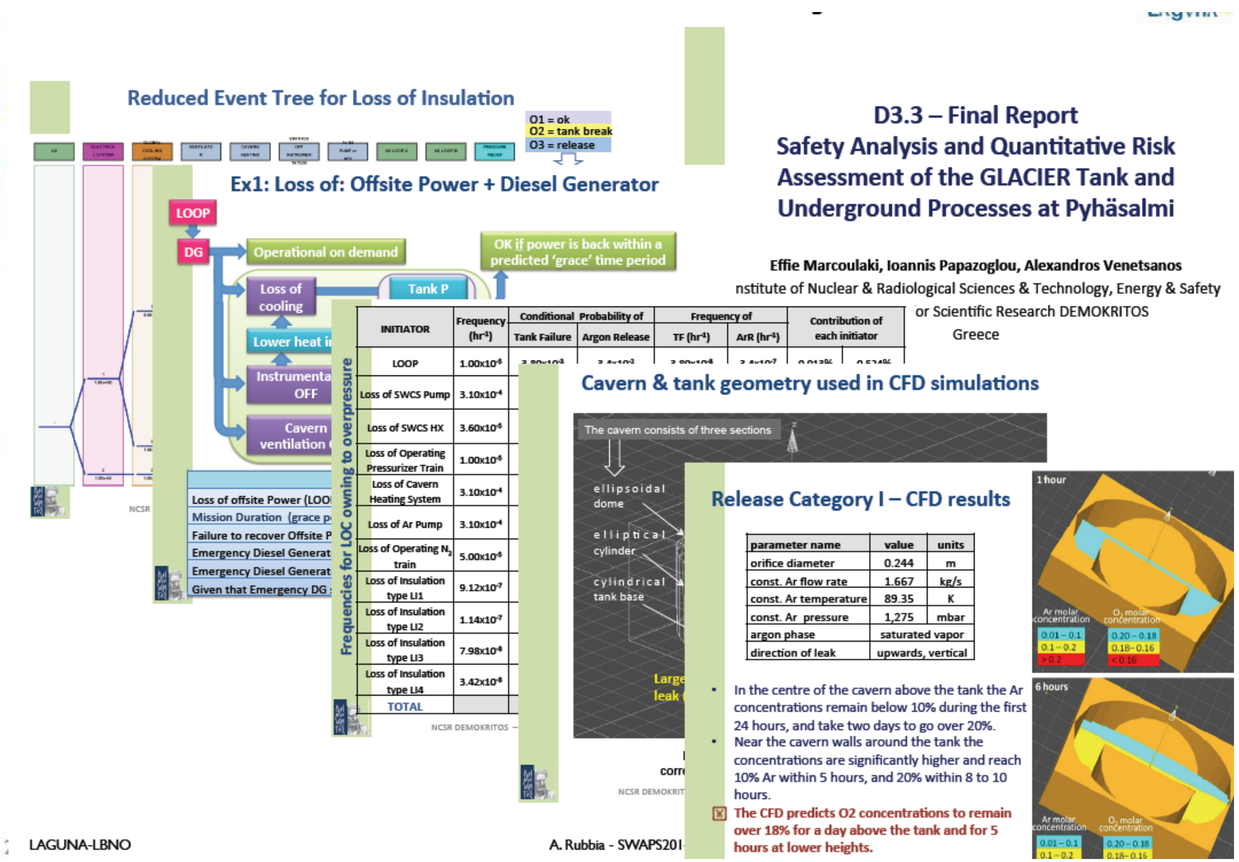




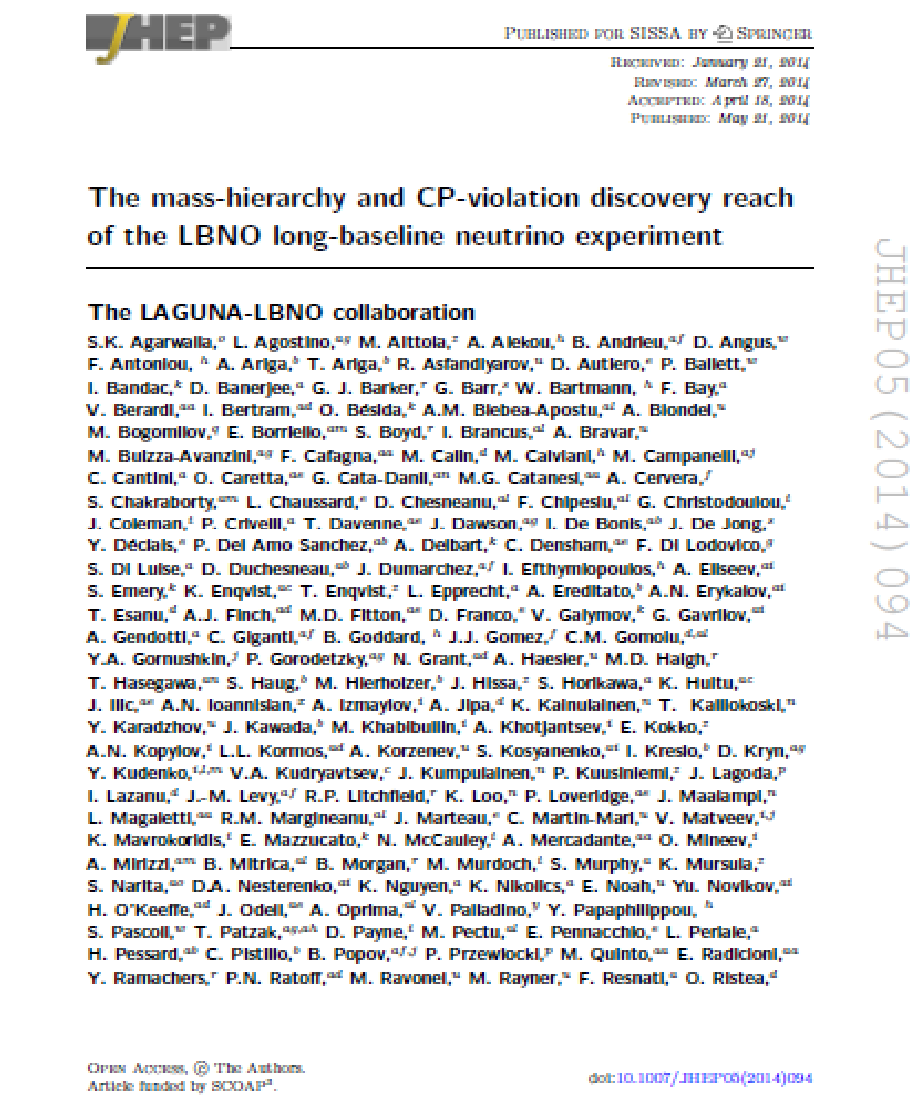


Process design & detailed risk analysis





Recent updates to the LBNO physics program



JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: January 21, 2014
REVISED: March 27, 2014
ACCEPTED: April 18, 2014
PUBLISHED: May 21, 2014

The mass-hierarchy and CP-violation discovery reach of the LBNO long-baseline neutrino experiment

The LAGUNA-LBNO collaboration

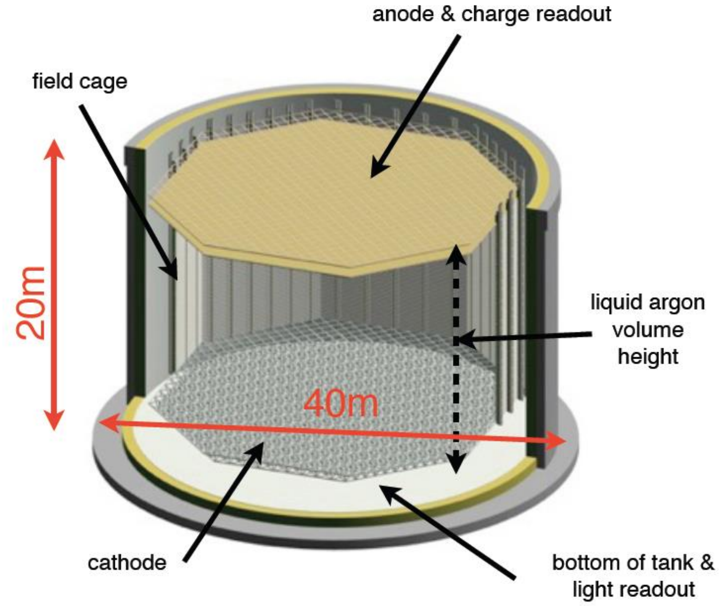
S.K. Agarwalla, L. Agostino, M. Aittola, A. Alekou, B. Andrieu, D. Angus, F. Antoniou, A. Ariga, T. Ariga, R. Asfandiyarov, D. Autiero, P. Ballett, I. Bandac, D. Banerjee, G. J. Barker, G. Barr, W. Bartmann, F. Bay, V. Berardi, I. Bertram, O. Bésida, A.M. Blebea-Apostu, A. Blondel, M. Bogomilov, E. Borriello, S. Boyd, I. Brancus, A. Bravar, M. Buizza-Avanzini, F. Cafagna, M. Calin, M. Calviani, M. Campanelli, C. Cantini, O. Caretta, G. Cata-Danil, M.G. Catanesi, A. Cervera, S. Chakraborty, L. Chaussard, D. Chesneanu, F. Chipesiu, G. Christodoulou, J. Coleman, P. Crivelli, T. Davenne, J. Dawson, I. De Bonis, J. De Jong, Y. Déclais, P. Del Amo Sanchez, A. Delbart, C. Densham, F. Di Lodovico, S. Di Luise, D. Duchesneau, J. Dumarchez, I. Efthymiopoulos, A. Eliseev, S. Emery, K. Enqvist, T. Enqvist, L. Epprecht, A. Ereditato, A.N. Erykalov, T. Esanu, A.J. Finch, M.D. Fitton, D. Franco, V. Galymov, G. Gavrilov, A. Gendotti, C. Giganti, B. Goddard, J.J. Gomez, C.M. Gomoiu, Y.A. Gornushkin, P. Gorodetzky, N. Grant, A. Haesler, M.D. Haigh, T. Hasegawa, S. Haug, M. Hierholzer, J. Hissa, S. Horikawa, K. Huitu, J. Ilic, A.N. Ioannisian, A. Izmaylov, A. Jipa, K. Kainulainen, T. Kalliokoski, Y. Karadzhov, J. Kawada, M. Khabibullin, A. Khotjantsev, E. Kokko, A.N. Kopylov, L.L. Kormos, A. Korzenev, S. Kosyanenko, I. Kreslo, D. Kryn, Y. Kudenko, V.A. Kudryavtsev, J. Kumpulainen, P. Kuusiniemi, J. Lagoda, I. Lazanu, J.-M. Levy, R.P. Litchfield, K. Loo, P. Loveridge, J. Maalampi, L. Magaletti, R.M. Margineanu, J. Marteau, C. Martin-Mari, V. Matveev, K. Mavrokoridis, E. Mazzucato, N. McCauley, A. Mercadante, O. Mineev, A. Mirizzi, B. Mitrica, B. Morgan, M. Murdoch, S. Murphy, K. Mursula, S. Narita, D.A. Nesterenko, K. Nguyen, K. Nikolics, E. Noah, Yu. Novikov, H. O'Keeffe, J. Odell, A. Oprima, V. Palladino, Y. Papaphilippou, S. Pascoli, T. Patzak, D. Payne, M. Pectu, E. Pennacchio, L. Periale, H. Pessard, C. Pistillo, B. Popov, P. Przewlocki, M. Quinto, E. Radicioni, Y. Ramachers, P.N. Ratoff, M. Ravonel, M. Rayner, F. Resnati, O. Ristea,

doi:10.1007/JHEP05(2014)094

JHEP05(2014)094

Basic assumptions:

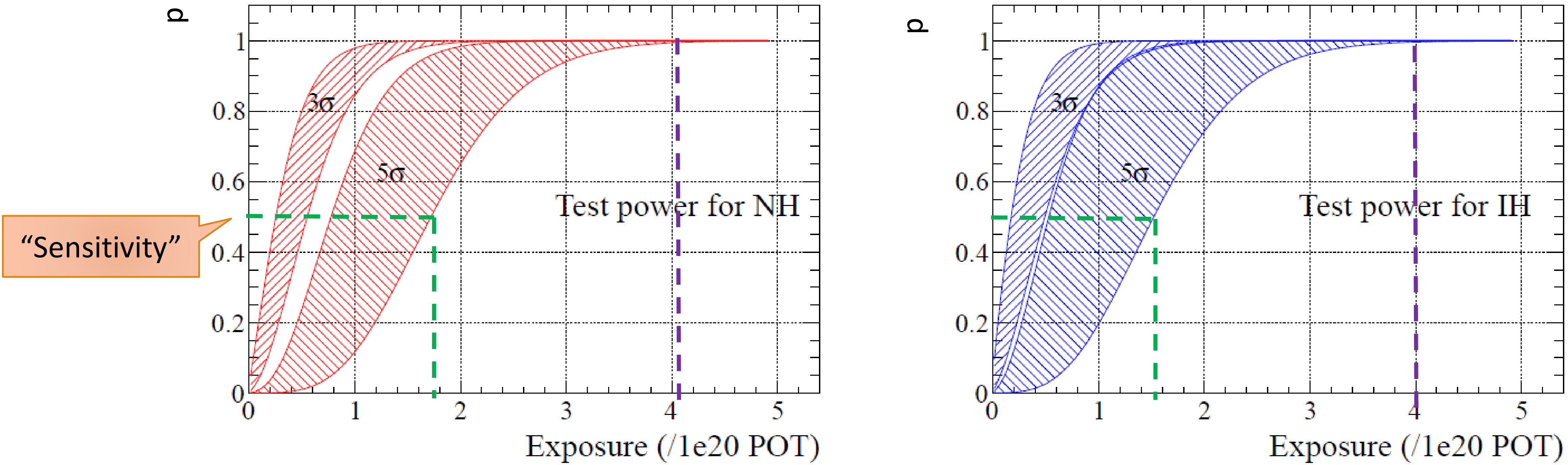
- Realistic systematics
- SPS 400 GeV protons – 750 kW beam
- HPPS 50 GeV protons – 2 MW beam
- Liquid argon double-phase detector: GLACIER
  - 24kton and 70 detector options



LBNO power to determine MH

Statistical power (probability to correctly reject false hypothesis) for MH determination vs exposure in LBNO Phase I (24kton LAr)

10.007/JHEP05 (2014) 094



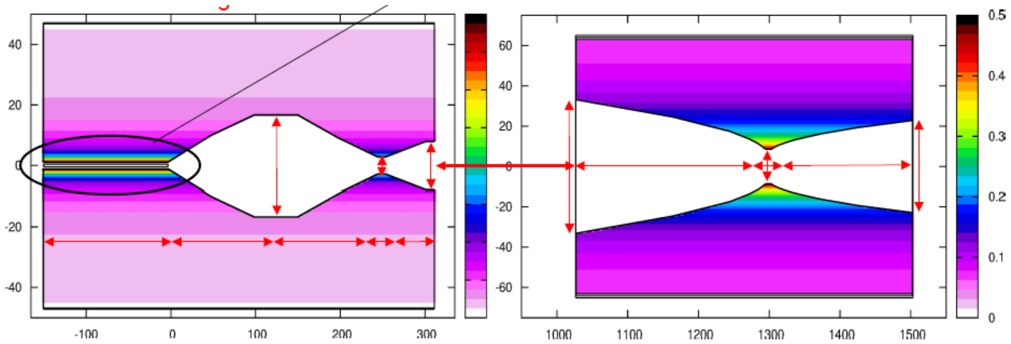
Typically sensitivity is defined at p=0.5 → 50% chance NOT to achieve projected CL

LBNO, independently of δ_{CP} value, can do MH determination at 5σ level as fast as ~2y

And it is essentially guaranteed ($p \approx 1$) within 4-5y of running (50% ν & 50% $\bar{\nu}$)

Beam optimization for δ_{CP} measurement

Parameter	Symbol	Unit	Allowed range
target radius	r_{tgt}	mm	4-15
circulating current in horn	I_H	kA	150-300
horn length 1st part	h1_l1	cm	80-200
horn length 2nd part	h1_l2	cm	150-250
horn length 3st part	h1_l3	cm	80-150
horn length 4st part	h1_l4	cm	1-10
horn length 5st part	h1_l5	cm	5-20
horn large inner radius	h1_r2	cm	7-40
horn neck radius	h1_r3	cm	2-15
horn exit radius	h1_r4	cm	3-20
reflector position	d_{HR}	m	1-20
circulating current in reflector	I_R	kA	100-250
reflector length 1st part	h2_l1	cm	50-300
reflector length 2nd part	h2_l2	cm	50-300
reflector neck length	h2_l3	cm	3-20
reflector 1st ell large radius	h2_r1	cm	10-40
reflector 2nd ell large radius	h2_r2	cm	10-40
reflector neck radius	h2_r3	cm	2-10



18 parameters to describe the system of target & horns

Each parameter is allowed to vary within a given range, that is defined by demanding physically reasonable values

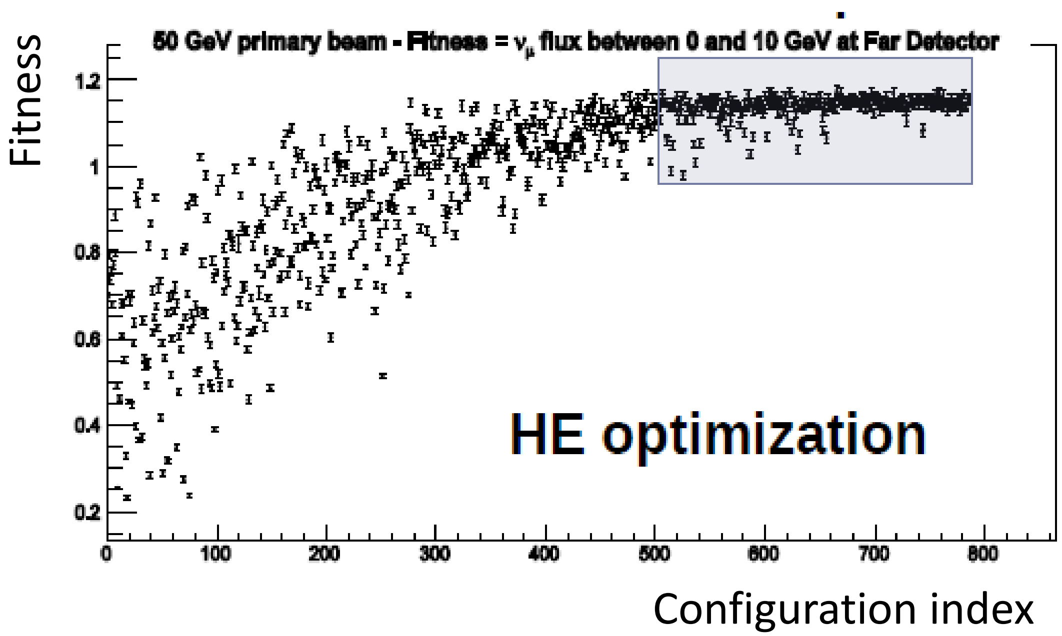
To find optimal solution use Genetic Algorithm*

- FLUKA simulation generate flux for a given parameter set (configuration)
- Assign a fitness quantity(ies) to each configuration
- Select best configuration and "breed" them in order to step through parameter space

*Implementation in DEAP "**D**istributed **E**volution **A**lgorithms for **P**ython" (Fortin et al, Journal of Machine Learning Research 13: 2171-2175) https://code.google.com/p/deap/

Beam optimization for δ_{CP} measurement

Convergence to optimal parameter values



Each point is a result of full simulation for a given parameter set

18 parameters to describe the system of target & horns

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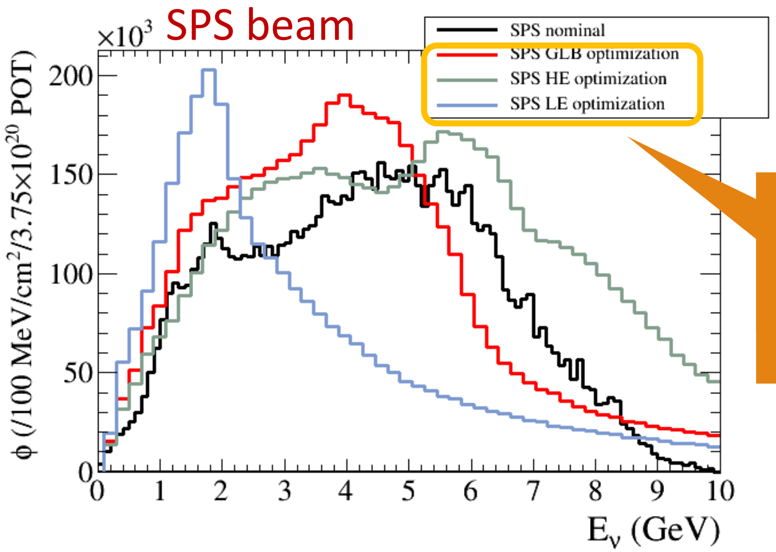
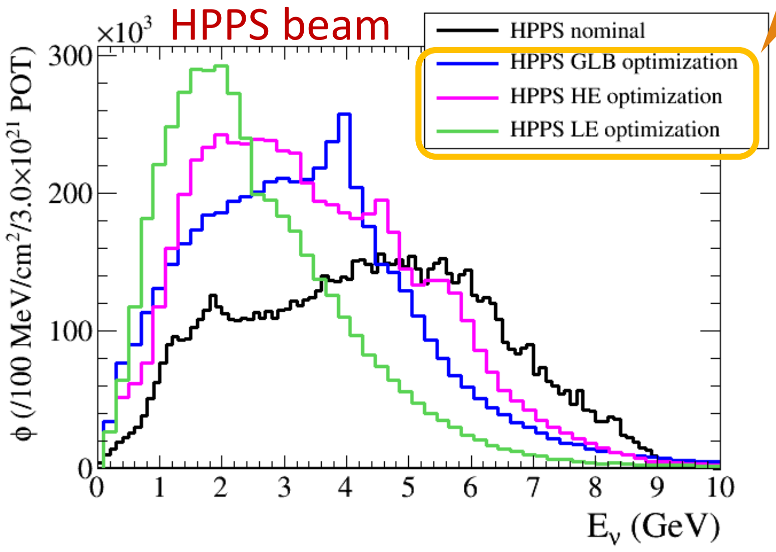
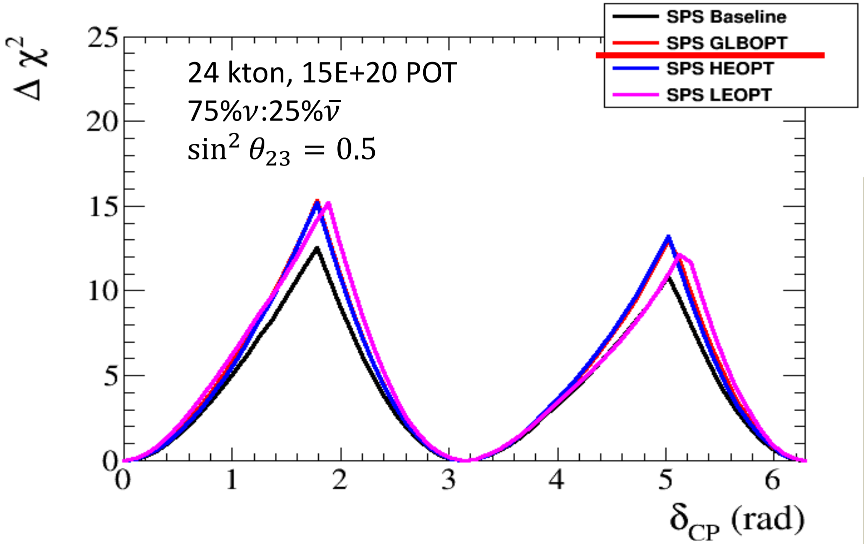
Different fitness criteria → different beams

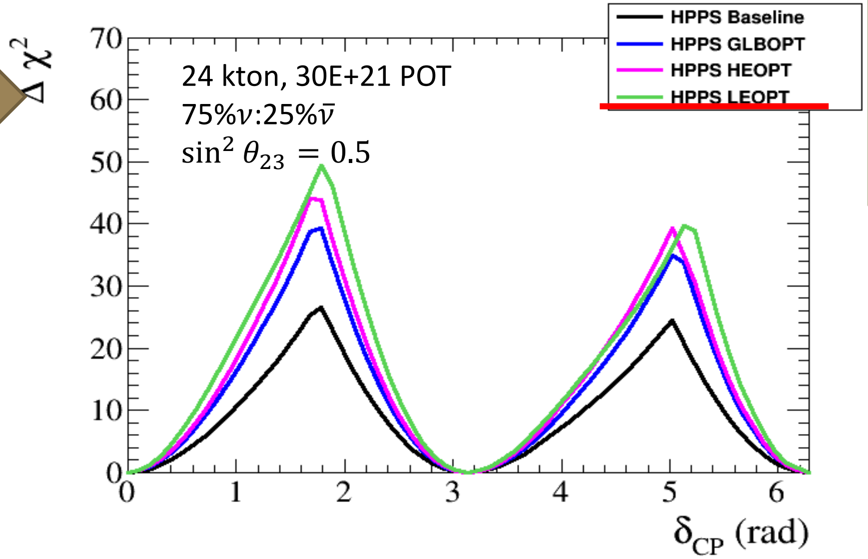




Different fitness criteria → explore different energy spectra

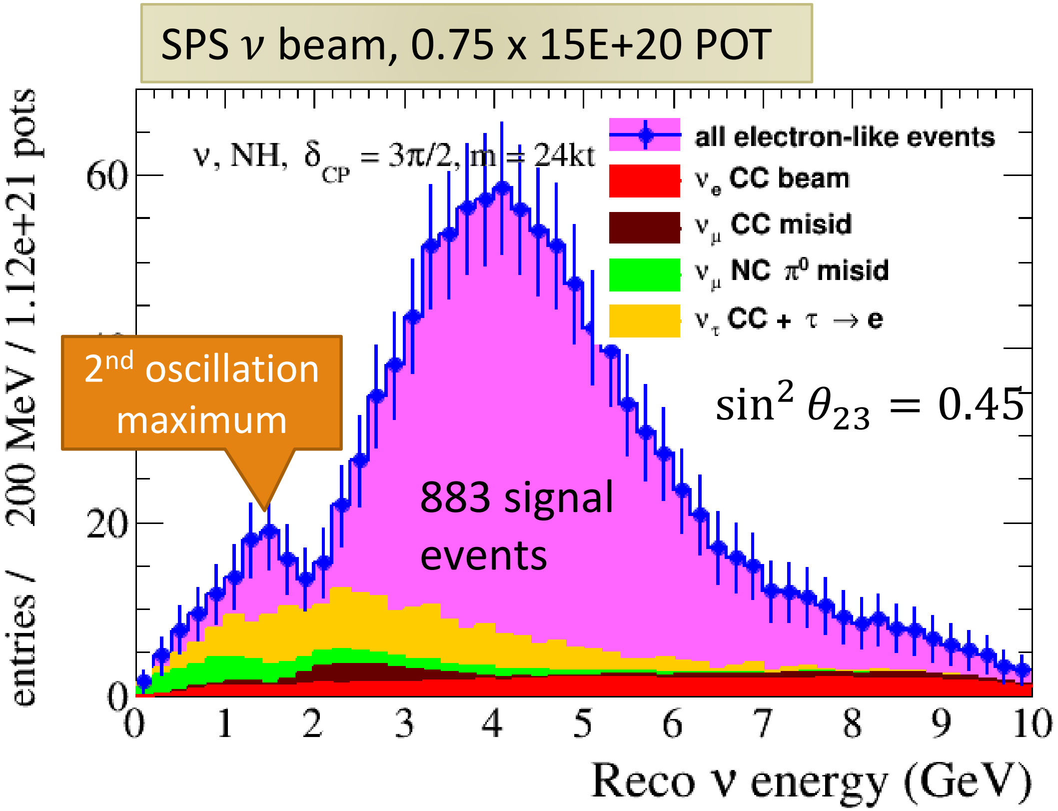
Run through LBNO analysis

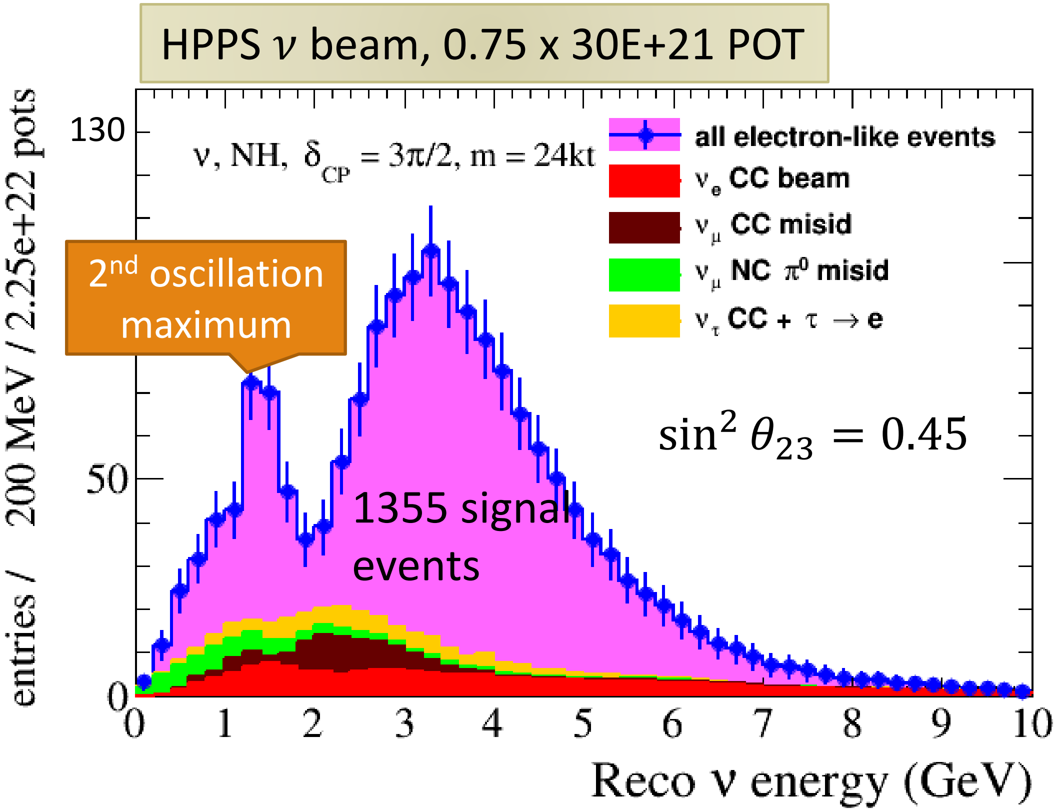




Finally select configuration with best sensitivity to CPV

Examples of event spectra

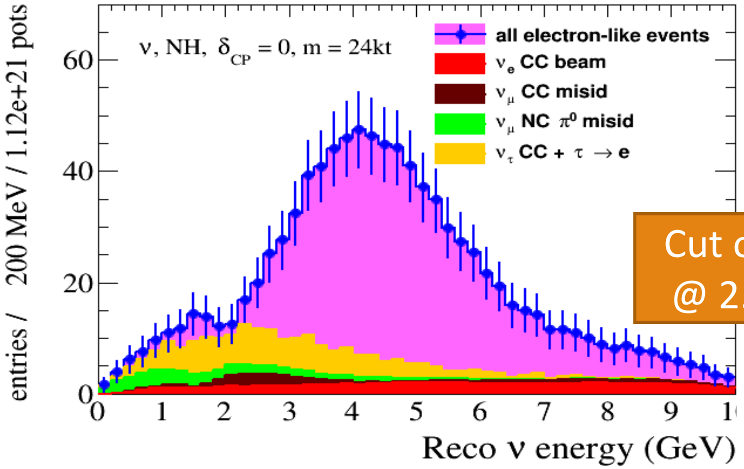




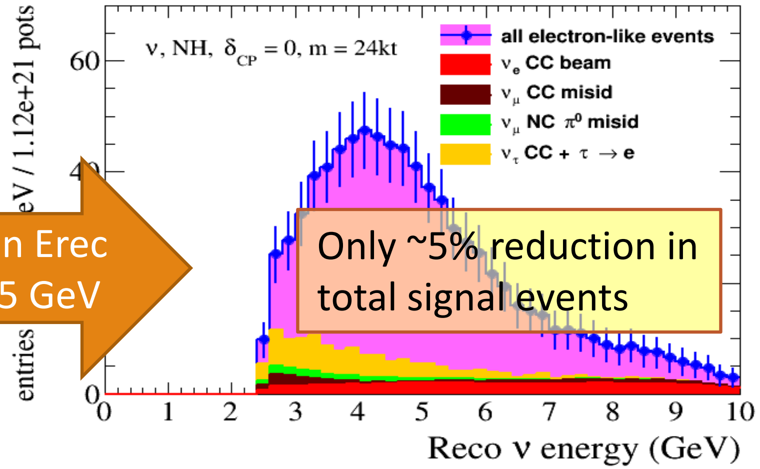
- Not a significant difference in total number of events b/w SPS and HPPS options
  - The beam power is a factor ~3 larger for HPPS
- With 50 GeV proton beam (HPPS) can give more preference to 2nd maximum
- A lot of information in the 2nd maximum for the L/E analysis

Power of the 2nd maximum

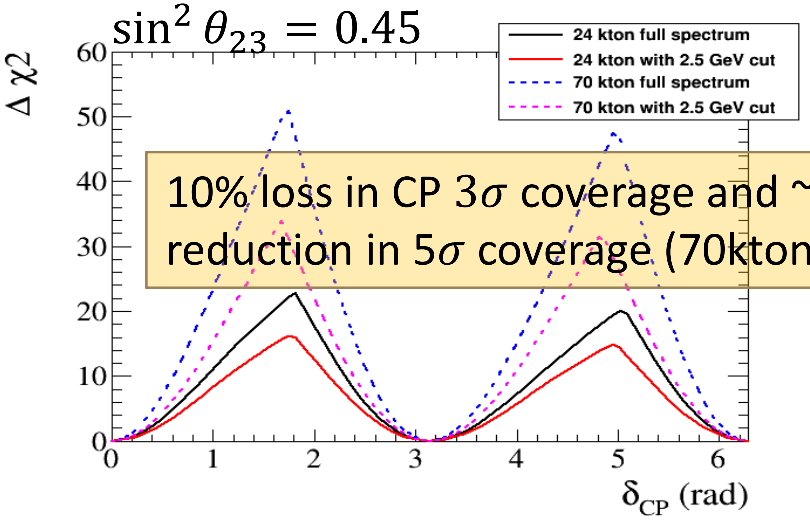
SPS beam, 15E+20 POT



Cut on Erec @ 2.5 GeV

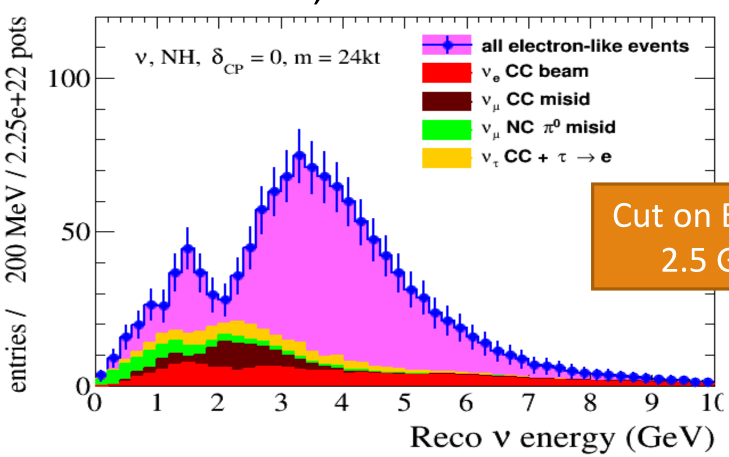


Only ~5% reduction in total signal events

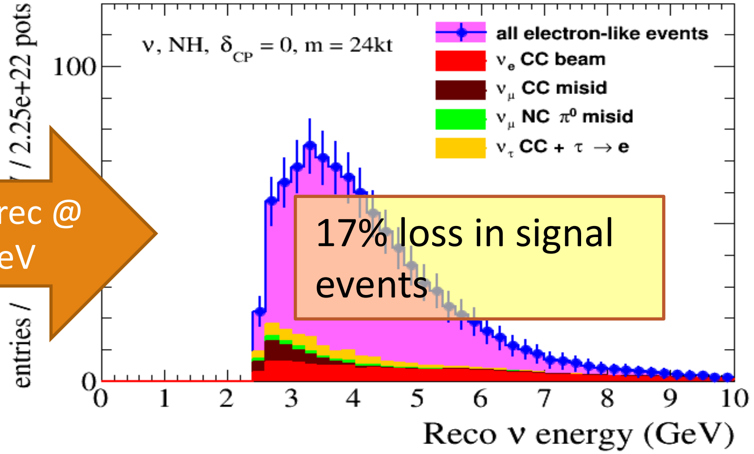


10% loss in CP 3σ coverage and ~x2 reduction in 5σ coverage (70kton)

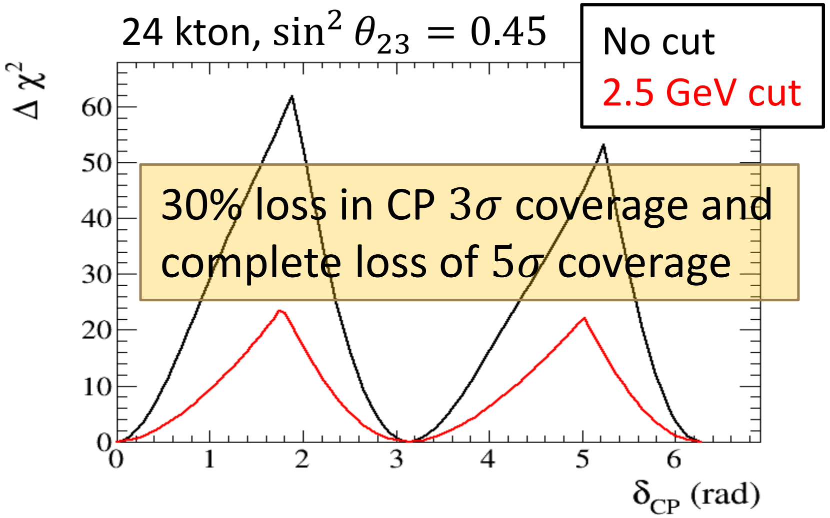
HPPS beam, 30E+21 POT



Cut on Erec @ 2.5 GeV



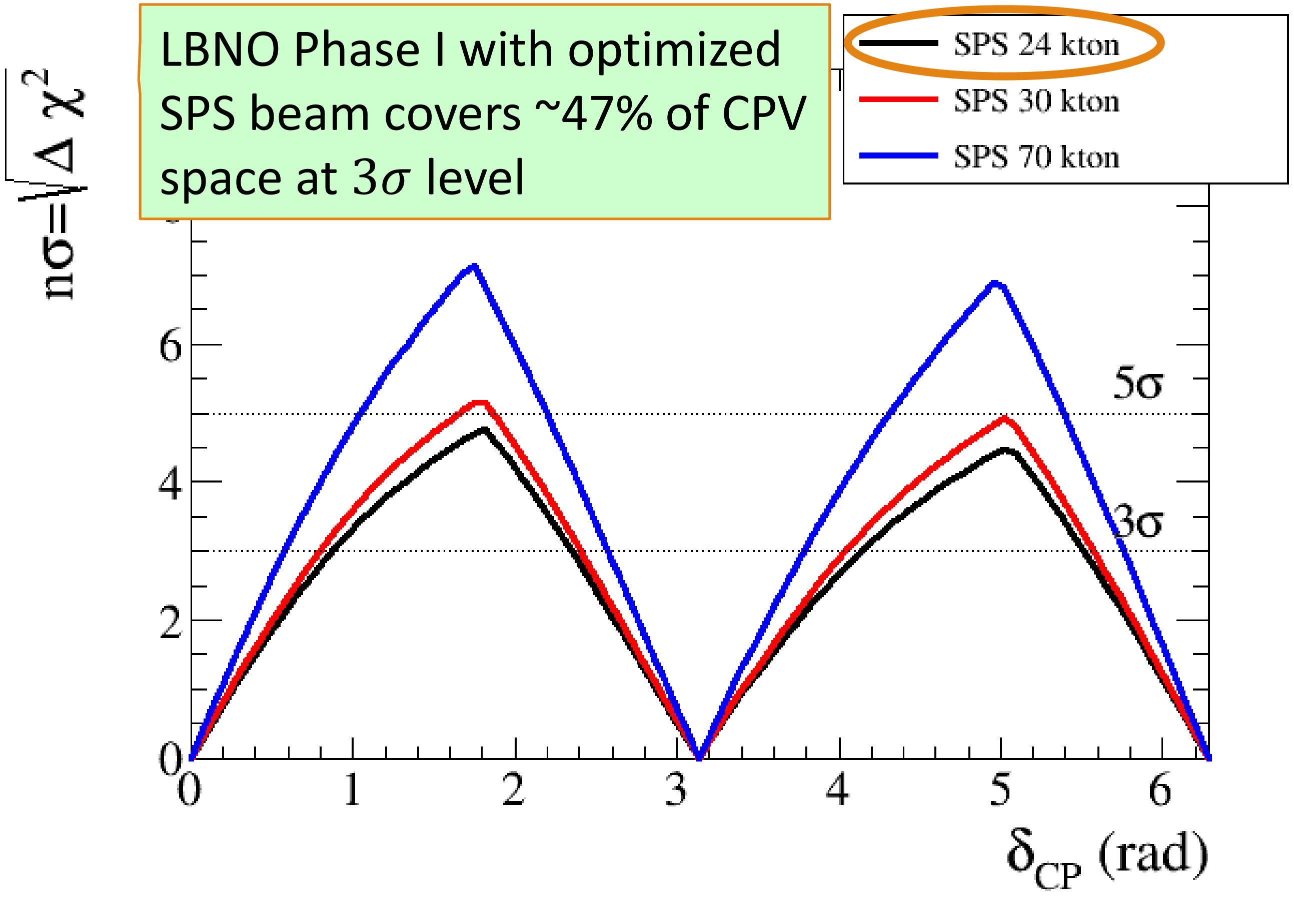
17% loss in signal events



30% loss in CP 3σ coverage and complete loss of 5σ coverage

LBNO sensitivity to CP Violation: SPS beam

LBNO Phase I with optimized SPS beam covers ~47% of CPV space at 3σ level



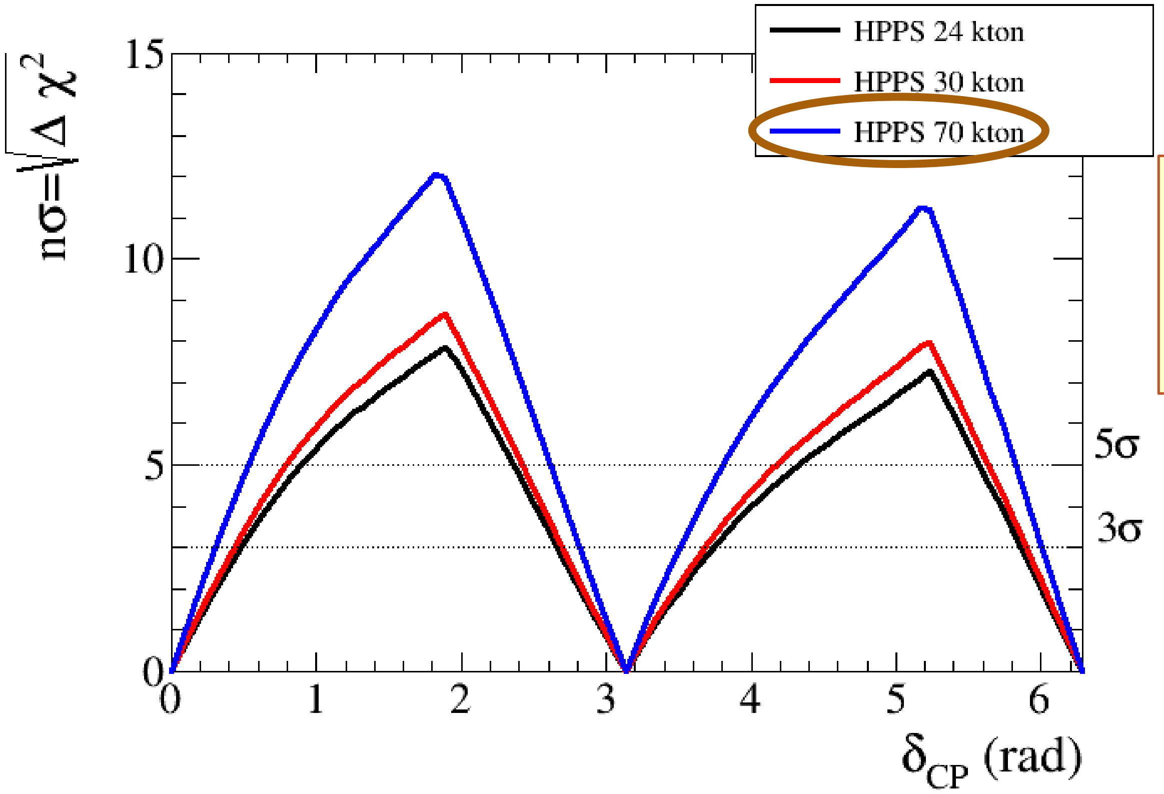
Input assumptions

Parameter	Value	Error
Signal normalization	1	3%
Intrinsic beam ν_e	1	5%
Tau background	1	20%
ν_μ CC & NC backgrounds	1	10%

Parameter	Value	Error
L	2300 km	exact
Δm^2_{21}	7.45×10^{-5}eV²	Fixed
Δm^2_{31}	2.50×10^{-3}eV²	2%
$\sin^2\theta_{12}$	0.306	Fixed
$\sin^2\theta_{23}$	0.45	5%
$\sin^2 2\theta_{13}$	0.09	3%
ρ	3.2 g/cm³	4%

Can reach a coverage of 63% at 3σ and 36% at 5σ level with just an increase in the detector mass to 70kton ← no beam improvements

LBNO sensitivity to CP Violation: HPPS beam



Ultimately, with addition of an HPPS, can reach a coverage of 80% at 3σ and 65% at 5σ level

➔ Satisfies the P5 requirement

An alternative possibility (currently under detailed study) is to use a neutrino beam from Protvino instead of HPPS to achieve similar levels of sensitivity

R&D towards large liquid argon detector

Some technical challenges:

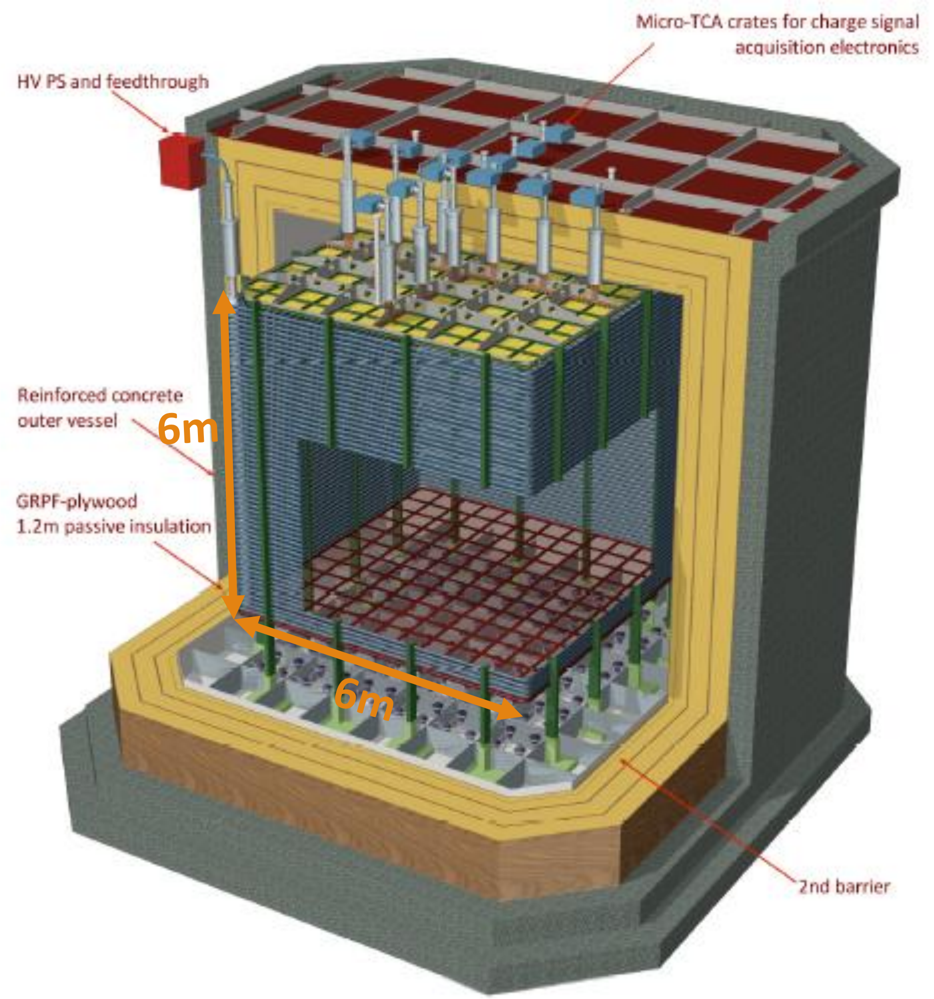
- Tank construction technique for a non-evacuated detector
- Purification system
- Long drifts
- HV system
- Double-phase charge readout
- Readout electronics

Some physics challenges:

- Energy resolution
- Particle identification
- Automated event reconstruction

To meet physics goals we need total systematics below 5% level!

LBNO-Demo



CERN WA105 (SPS-TDR-004-2014):
6 x 6 x 6 m3 (0.3 kton) active area double-phase LAr detector

- Development and proof-checking of industrial solutions for large scale LAr detector
- Controlled data set with charged particle beams (0.2 – 20 GeV/c):
  - Develop and validate event reconstruction algorithms
  - Study electromagnetic and hadronic calorimetry
  - Characterize particle identification & general detector performance

The demonstrator is a critical step towards realizing an O(10kton) scale LAr detector

Summary

LBNO program follows a phased approach with interesting results delivered at each stage

Attractive accelerator ν program:

- Unambiguous determination of the MH
- Coverage of 80% of δ_{CP} parameter space at 3σ level and 65% at 5σ

Deep underground location:

- Nucleon decay searches
- Neutrino astrophysics

Full conceptual design for such deep underground facility has been developed

- LAGUNA-LBNO DS final report in August 2014 → stay tuned

Next planned step: LBNO-Demo (WA 105)

Extra

Analysis method & systematics

Joint fit for appearance and disappearance signals:

$$\chi^2 = \chi^2_{\text{appear}} + \chi^2_{\text{disa}} + \chi^2_{\text{syst}}.$$

For $\nu_\mu \rightarrow \nu_e$ channel, fit 2D distributions in $E_\nu^{rec} - p_T^{miss}$:

$$\begin{aligned} n_e(E_\nu^{rec}, p_T^{miss}; \mathbf{o}, \mathbf{f}) &= f_{sig} n_{e-sig}(E_\nu^{rec}, p_T^{miss}; \mathbf{o}) \\ &+ f_{\nu_e} n_{\nu_e}(E_\nu^{rec}, p_T^{miss}; \mathbf{o}) + f_{\nu_\tau} n_{e,\nu_\tau}(E_\nu^{rec}, p_T^{miss}; \mathbf{o}) \\ &+ f_{NC}(n_{NC\pi^0}(E_\nu^{rec}, p_T^{miss}; \mathbf{o}) + n_{mis-\nu_\mu}(E_\nu^{rec}, p_T^{miss}; \mathbf{o})) \end{aligned}$$

Prior constraints on the nuisance parameters are introduced via typical Gaussian constraint terms:

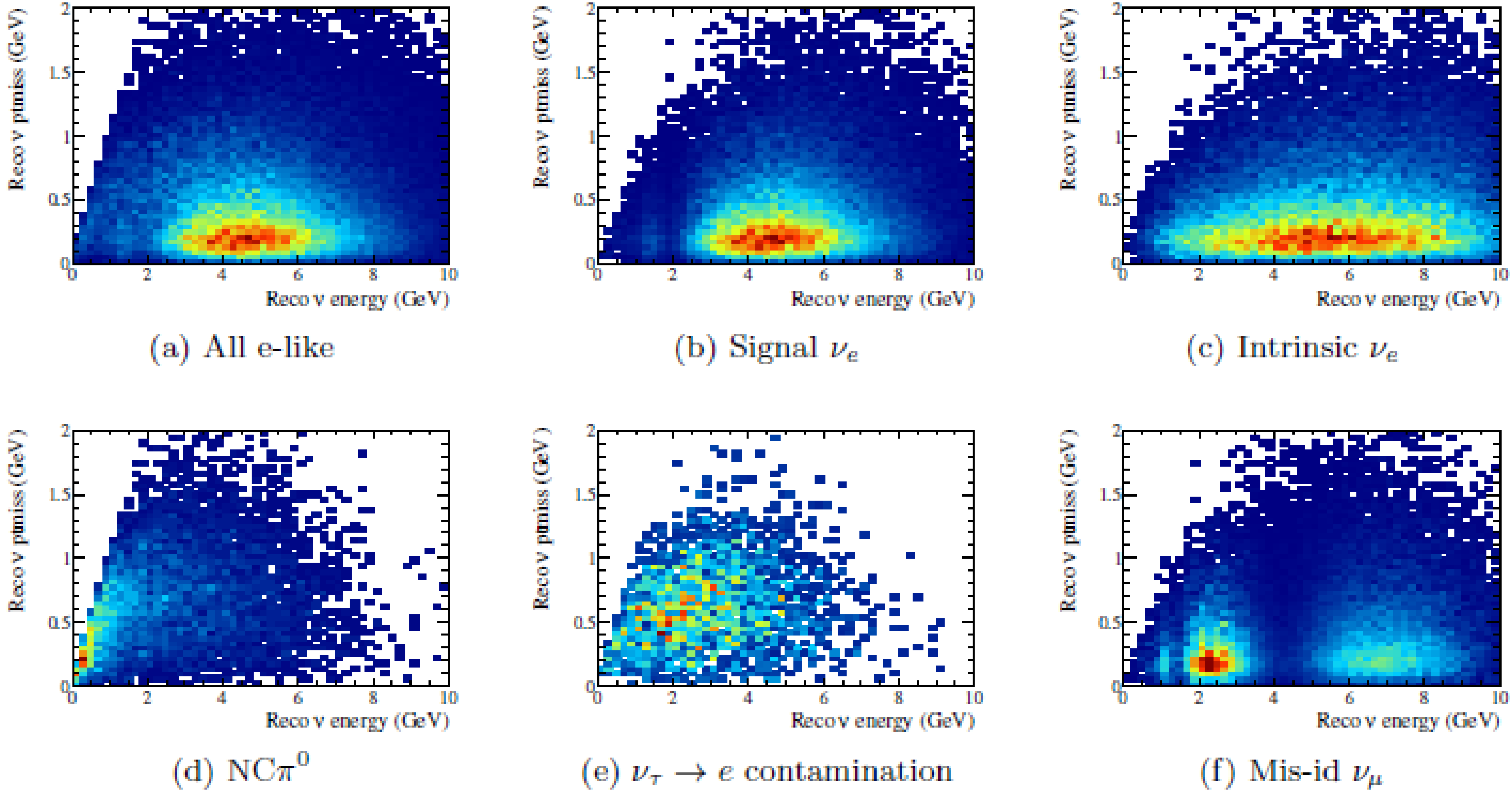
$$\chi^2_{\text{syst}} = \sum_i \frac{(a_{0,i} - a_i)^2}{\sigma^2_{a_i}}$$

Input assumptions

Parameter	Value	Error
Signal normalization	1	3%
Intrinsic beam ν_e	1	5%
Tau background	1	20% (50% for MH)
ν_μ CC & NC backgrounds	1	10%

Parameter	Value	Error
L	2300 km	exact
Δm^2_{21}	7.45×10^{-5}eV²	Fixed
Δm^2_{31}	2.50×10^{-3}eV²	2%
$\sin^2\theta_{12}$	0.306	Fixed
$\sin^2\theta_{23}$	0.45	5%
$\sin^2 2\theta_{13}$	0.09	3%
ρ	3.2 g/cm³	4%

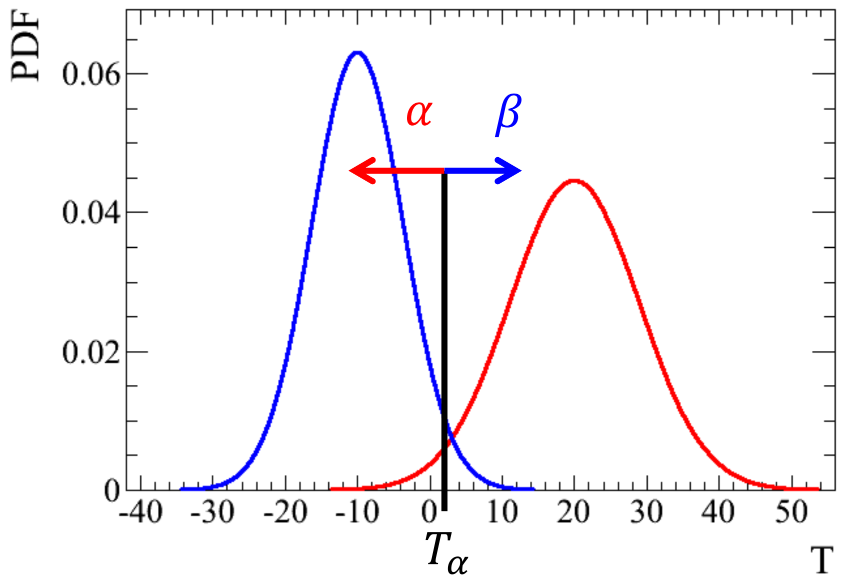
Example 2D distribution



No cuts at the moment other than 10 GeV on Ereco→ Can reduce backgrounds in the future by exploiting differences in various phase-space topologies for signal/background events

Test statistic for MH

Distribution of T assuming NH is true
Distribution of T assuming IH is true



$$T = \Delta\chi^2 = \chi^2_{IH} - \chi^2_{NH}$$

$\chi^2_{IH}(\chi^2_{NH}) - \chi^2$ minimized with respect to nuisance parameters under IH (NH) hypothesis

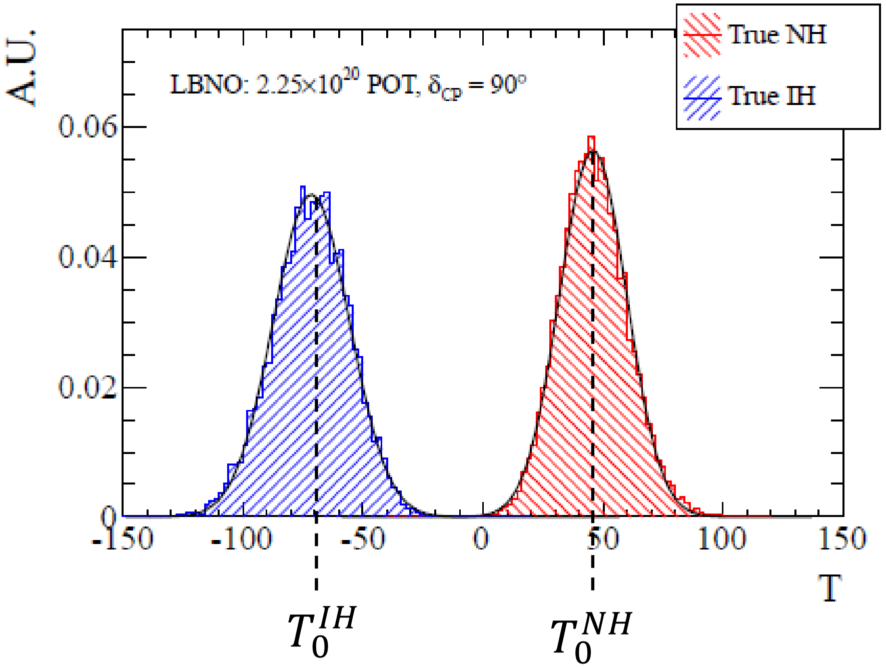
$$\alpha = \int_{-\infty}^{T_\alpha} f(T|NH)dT$$

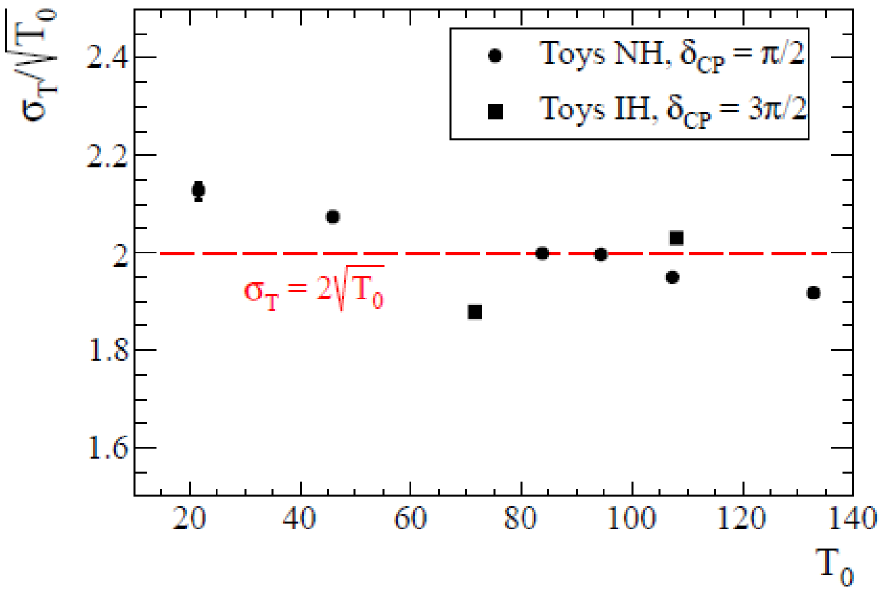
CL = 1 - α

Probability for type II error: pick hypothesis NH even though IH is correct

$$\beta = \int_{T_\alpha}^{\infty} f(T|IH)dT$$

Properties of f(T)



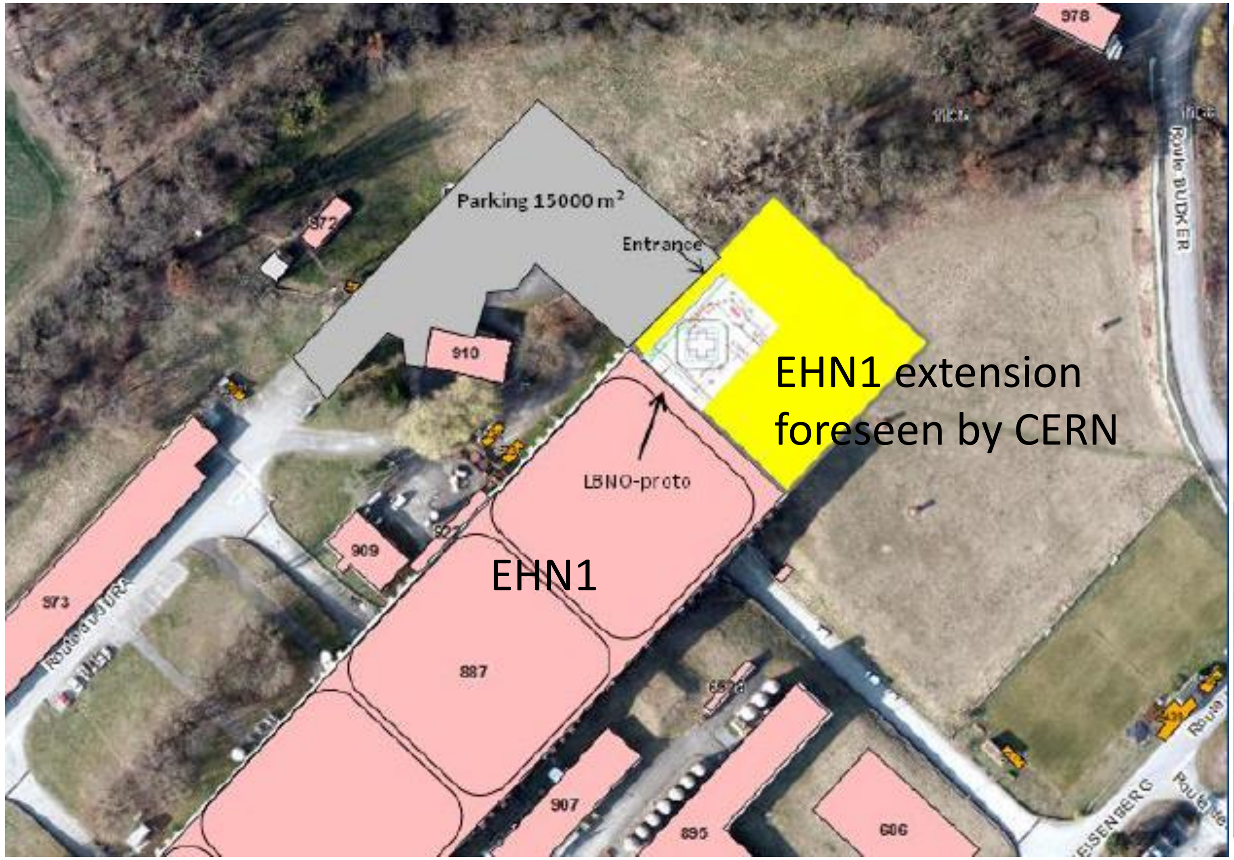


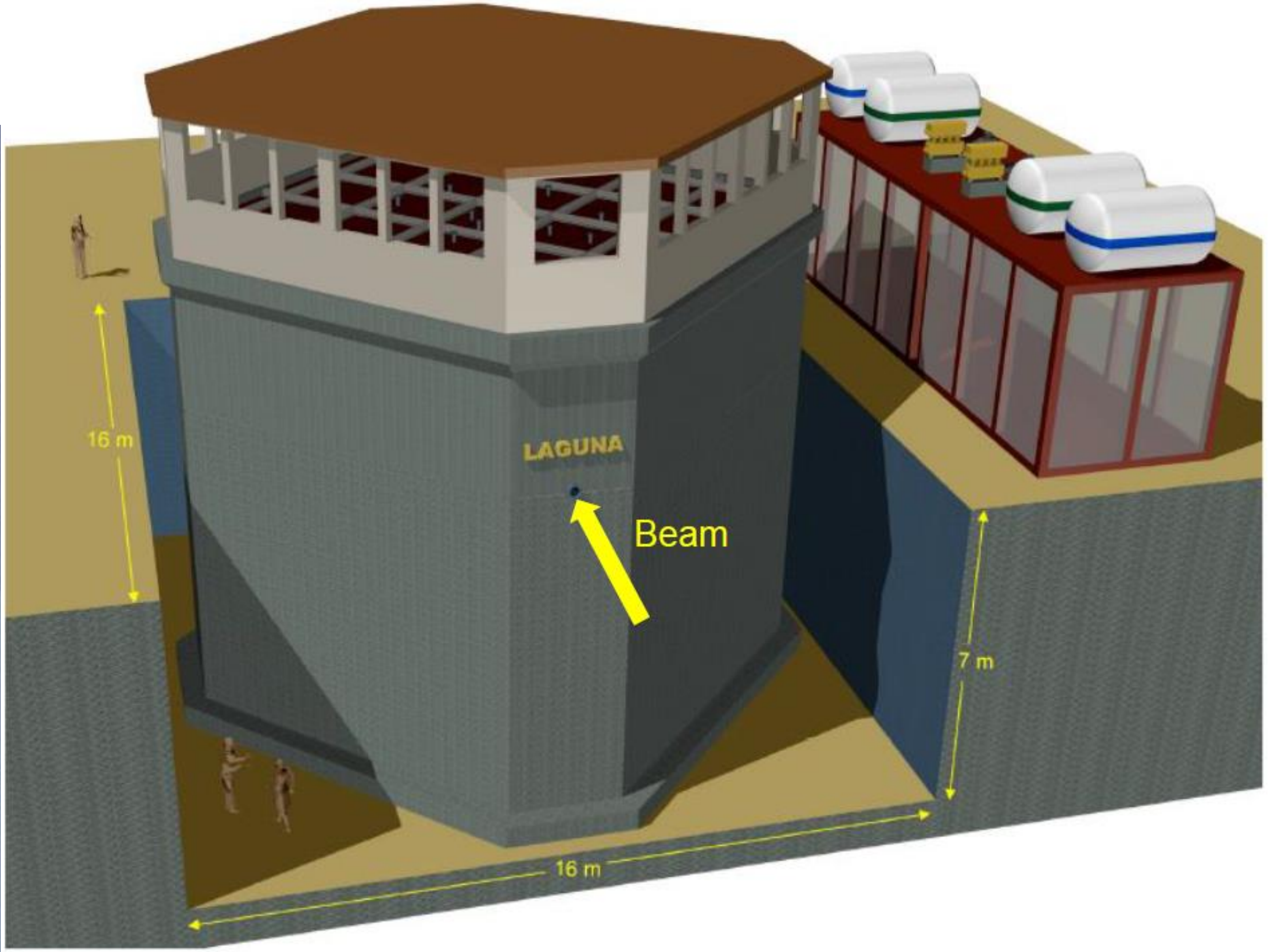
- The separation between two peaks increases with exposure
- A phenomenological approximation for f(T)

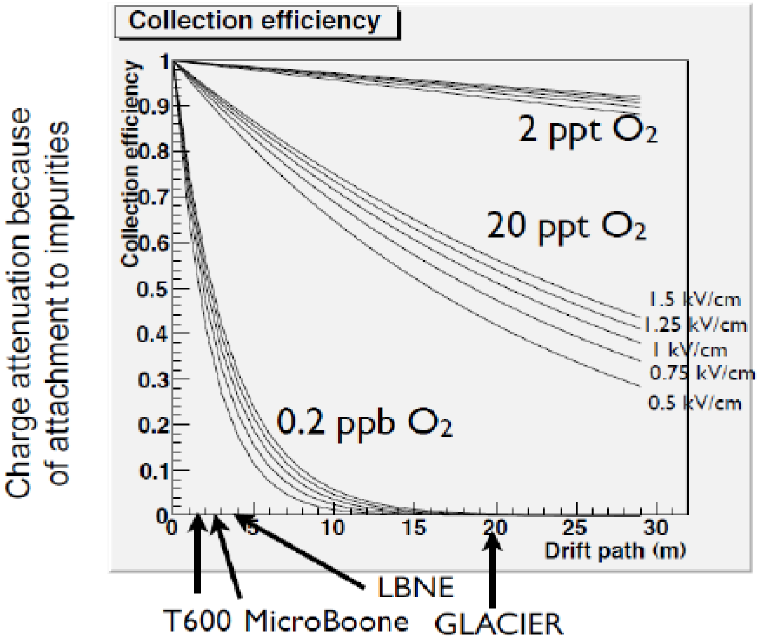
$$f(T) = \mathcal{N}(T_0, 2\sqrt{T_0})$$ ←Qian et al., hep-ph/1210.3651

- This approximation is used after checking with toy MC for LBNO for some fraction of exposures / δ_{CP} values

LBNO-Demo general overview







Drift fields E=0.5,0.75,1,1.25,1.5 kV/cm