



# Status of LBNO Project

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INSTITUT DE PHYSIQUE NUCLÉAIRE DE LYON

GDR NEUTRINO, June 2014

# LAGUNA/LBNO consortium

- **LAGUNA DS** (FP7 Design Study 2008-2011)

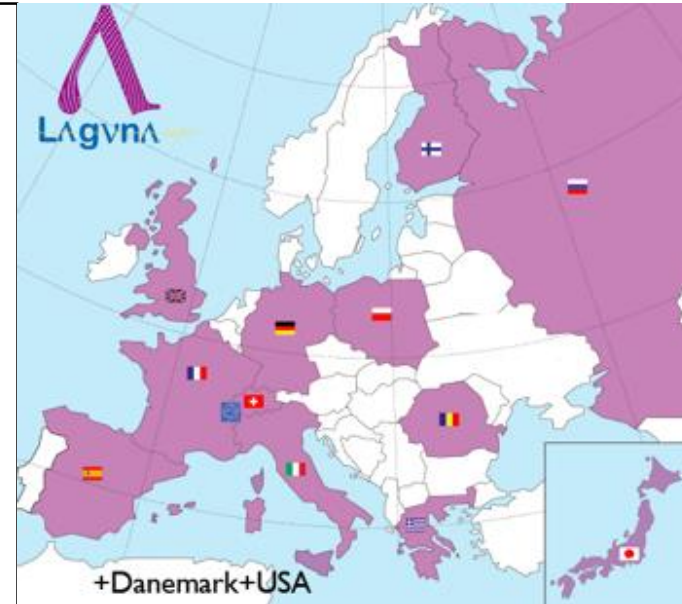
- ~100 members; 10 countries, 1.7 M€
- 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)

- **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

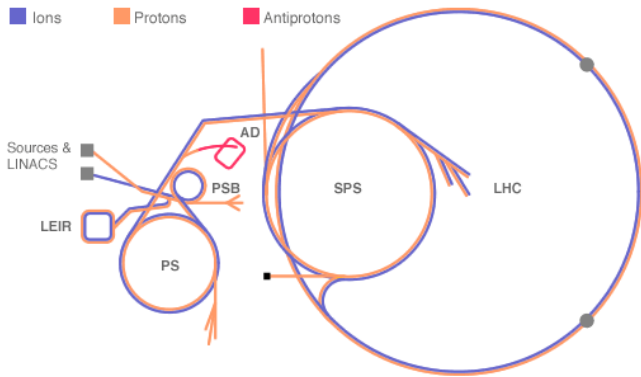


**Steering group:**

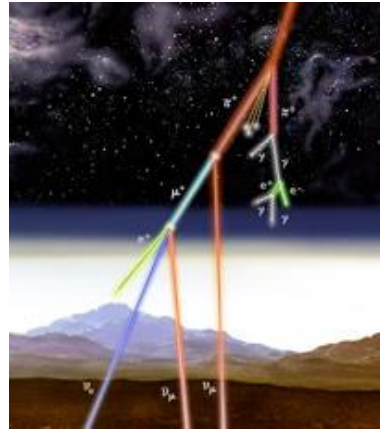
- Alain Blondel (UniGe)
- Ilias Efthymiopoulos (CERN)
- Takuya Hasegawa (KEK)
- Yuri Kudenko (INR)
- Guido Nuijten (Rockplan, Helsinki)
- Lothar Oberauer (TUM)
- Thomas Patzak (APC, Paris)
- Silvia Pascoli (Durham)
- Federico Petrollo (ETH Zürich)
- André Rubbia (ETH Zürich)
- Wladyslaw Trzaska (Jyväskylä)
- Alfons Weber (Oxford)
- Marco Zito (CEA)

# Scientific goals of LBNO

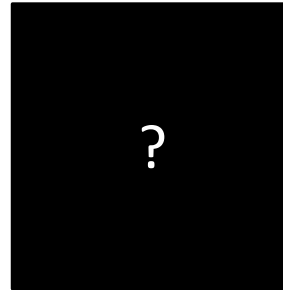
## Accelerator



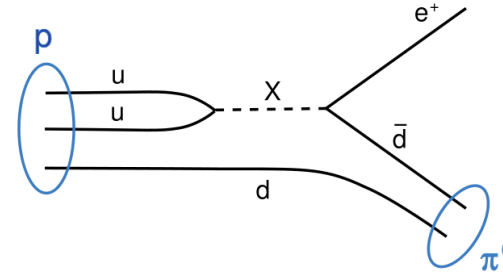
## Atmosphere



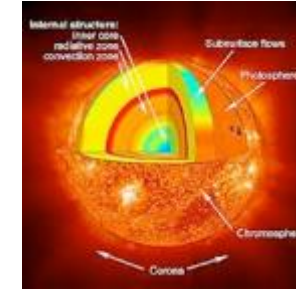
## Dark matter



## Nucleon decay



## Sun



## Supernova



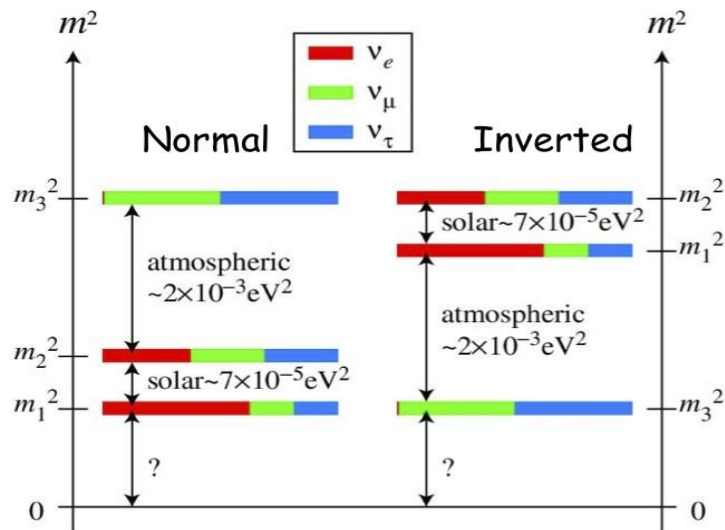
Deep underground observatory:

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

# $\nu$ physics LBL: two big questions

## 1. Hierarchy of neutrino masses

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



## 2. Leptonic CP violation

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

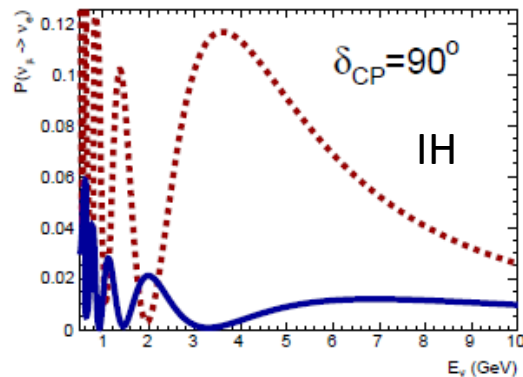
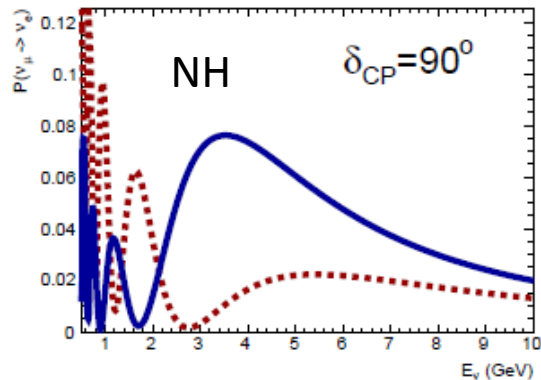
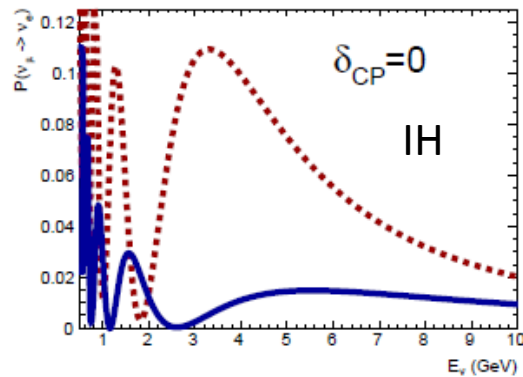
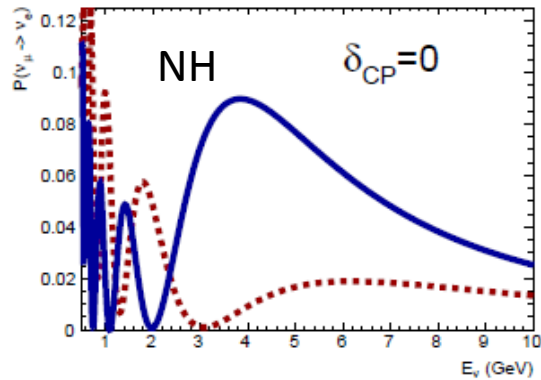
If  $\delta \neq 0, \pi \rightarrow$  CP violation in lepton sector

Connection with Leptogenesis?

Both questions can be addressed with conventional accelerator neutrino beams by studying  $\nu_\mu \rightarrow \nu_e$  &  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  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  $\rightarrow$  measure L/E behaviour over 1<sup>st</sup> + 2<sup>nd</sup> 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

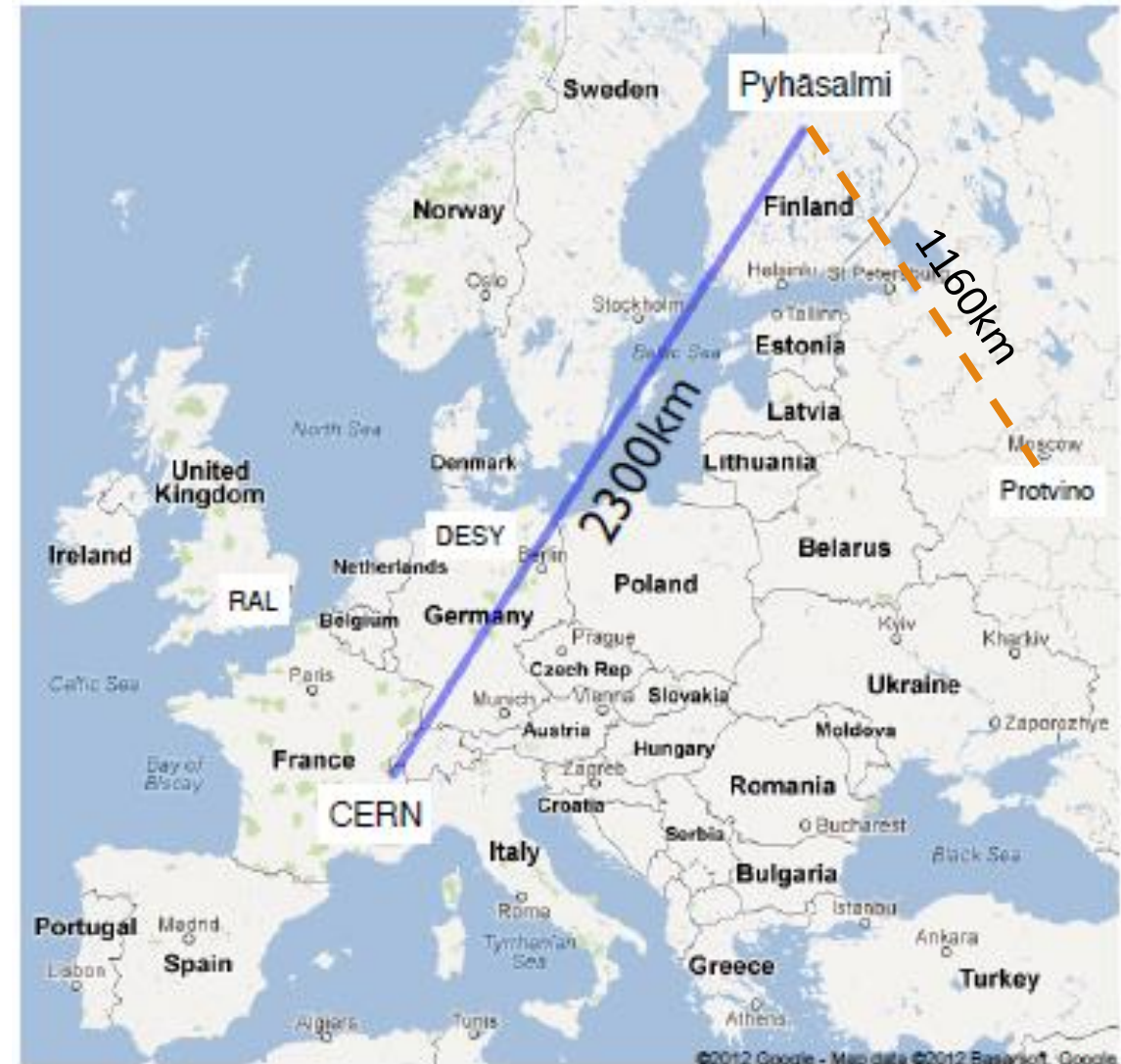
Staged approach

Phase I:

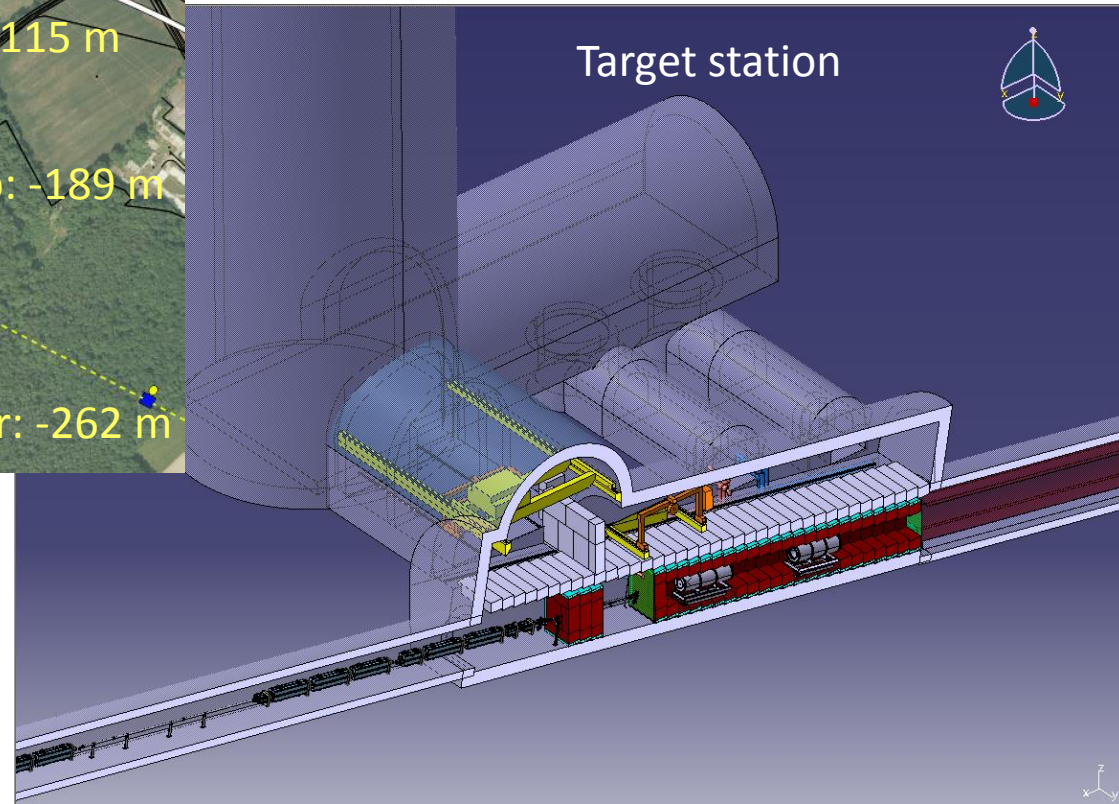
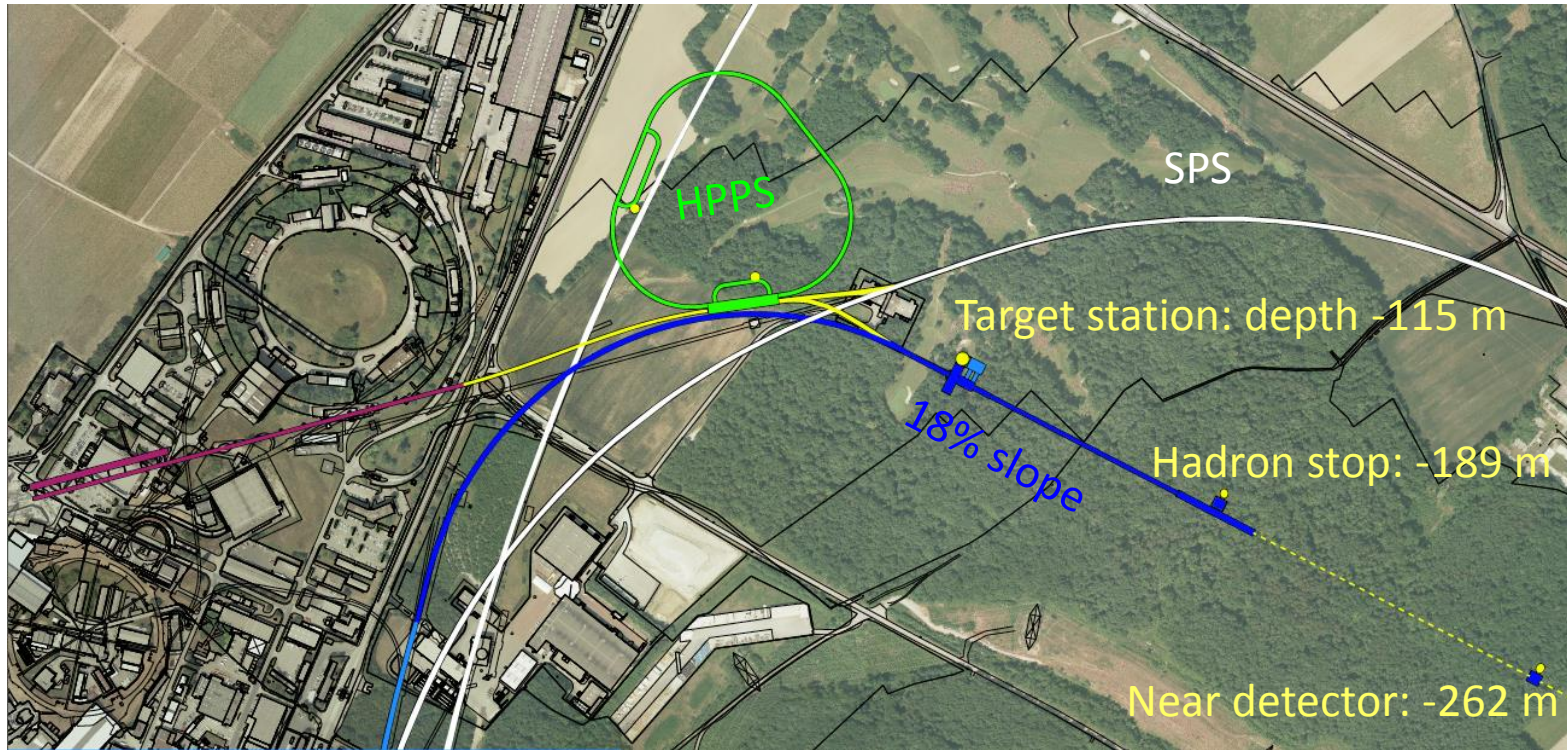
- 24 kton fiducial volume double-phase liquid argon (DLAr) + SPS beam ( $E_p = 400 \text{ GeV}$ , 750 kW)
- Determination of neutrino MH
- Sensitivity to CP Violation (cover 46% of  $\delta_{CP}$  space at  $3\sigma$ )
- Nucleon decay (e.g., order of magnitude improvement in  $p \rightarrow \nu K$  channel)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

Phase II:

- 70 kton fid. DLAr + HPPS beam ( $E_p = 50 \text{ GeV}$ , 2MW) or 2<sup>nd</sup>  $\nu$  beam from Protvino ( $E_p = 70 \text{ GeV}$ , need  $\sim 450 \text{ kW}$ )
- 80%  $\delta_{CP}$  coverage at  $3\sigma$  + nucleon decay + neutrino astronomy



# Updated LBNO beam design



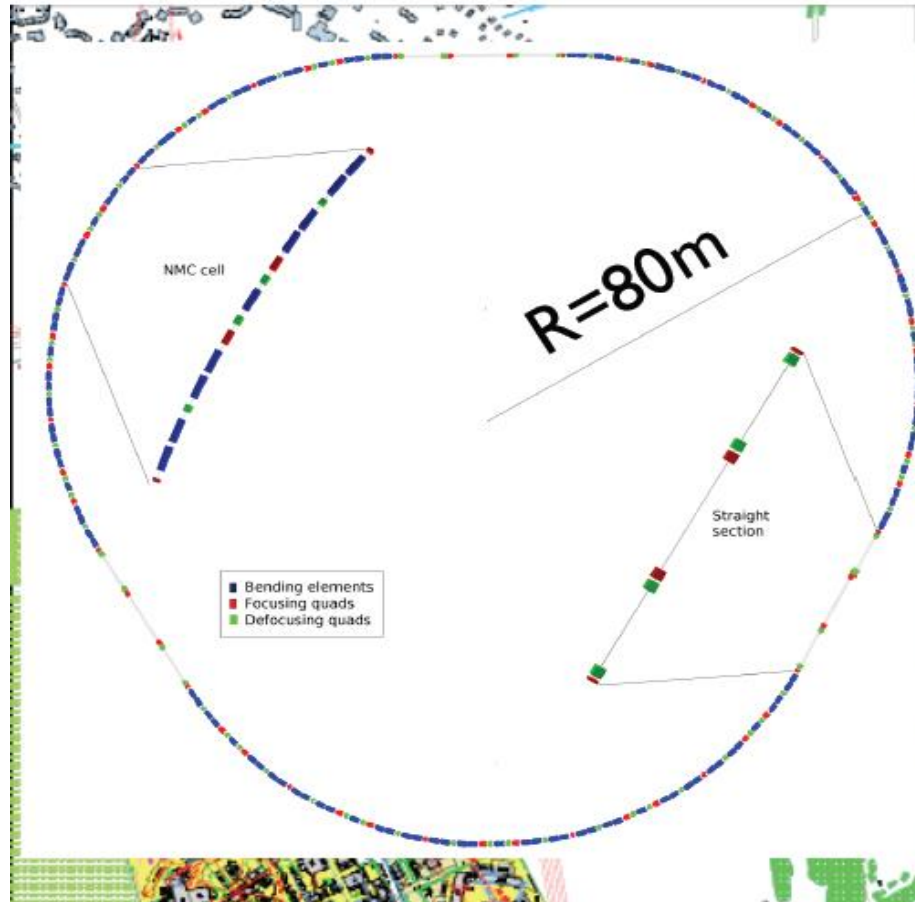
## Phase I: proton beam from SPS

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

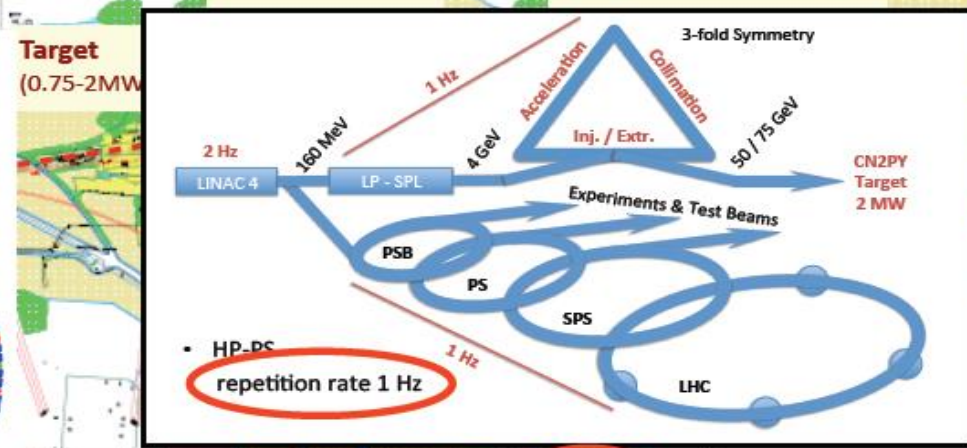
## Phase II: proton beam from a new HPPS

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

# High power HP-PS study



- 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.



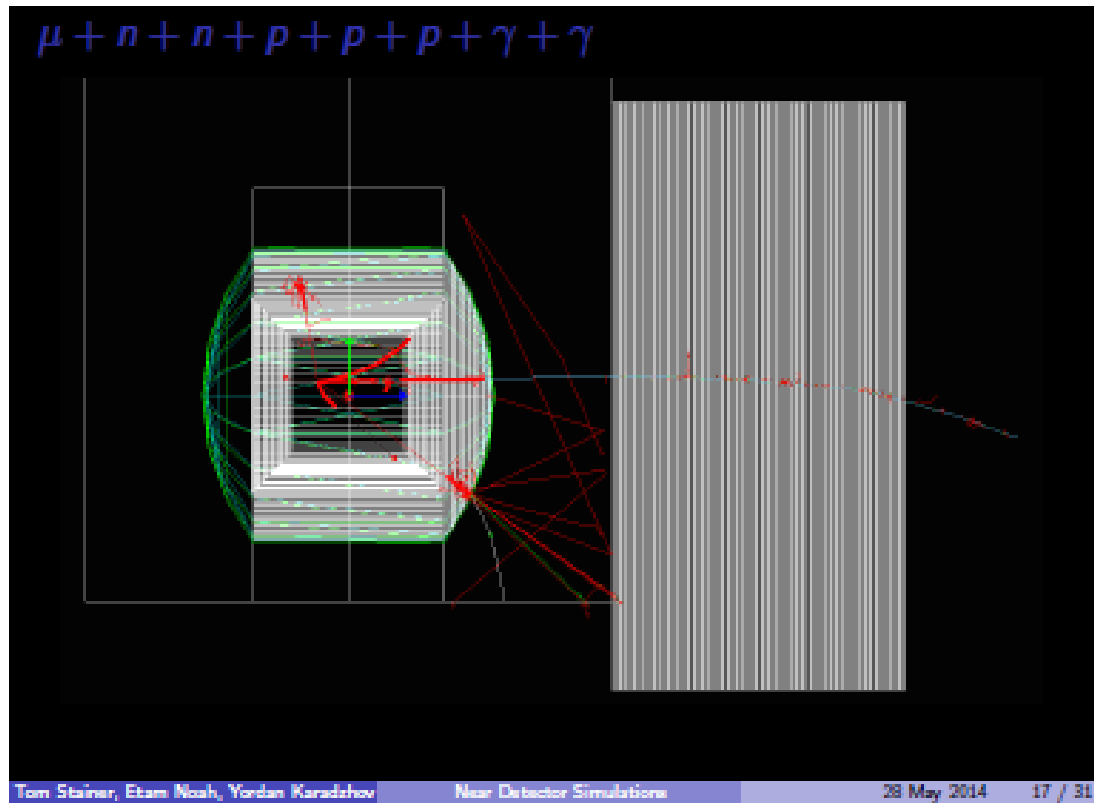
Parameter	50 GeV	75 GeV	Units
Inj. / Extr. Kinetic Energy	4 / 50	4 / 75	[GeV]
Beam power	2		[MW]
Repetition rate	1		[Hz]
$f_{rev}$	0.248 / 38.97		[MHz]
RF harmonic	157		-
$f_{rev}$	0.255 / 40.08	0.255 / 40.09	[MHz]
Bunch spacing @ extr.	25		[ns]
Total beam intensity	$2.5 \times 10^{11}$	$1.7 \times 10^{11}$	-
Number of bunches	147		-
Intensity per bunch	$1.7 \times 10^6$	$1.25 \times 10^6$	-
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]



# LBNO near detector

The goal: systematic uncertainties for signal and background need to be **below  $\pm 5\%$** , 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

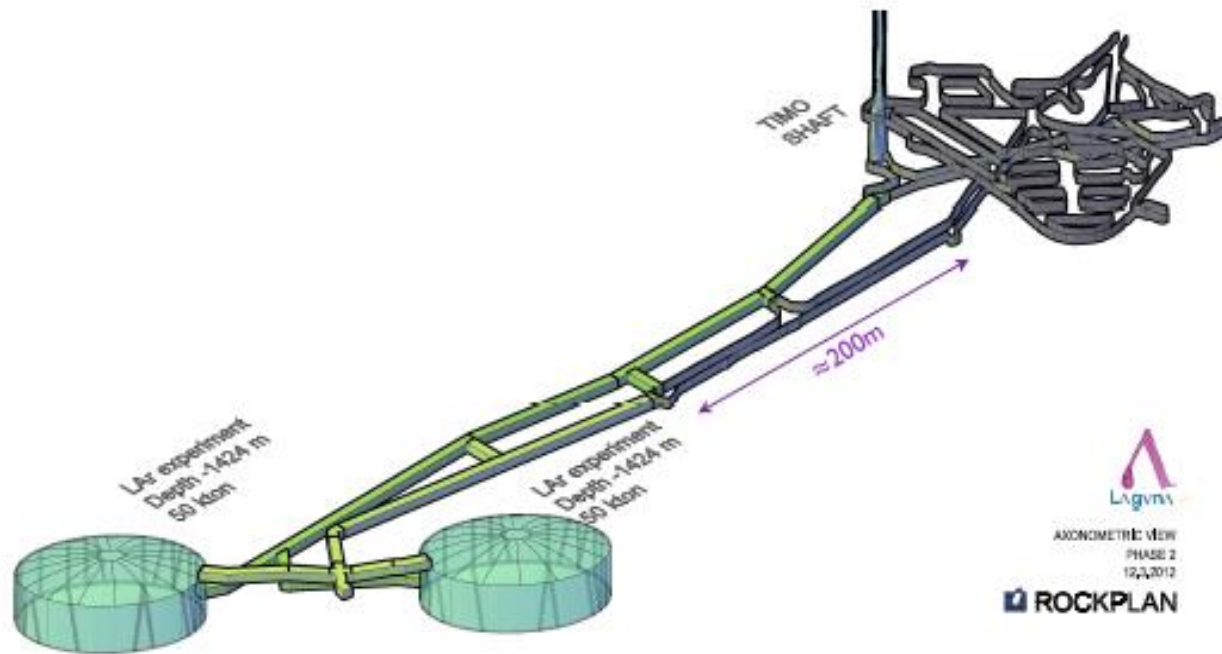


Concept:

- High pressure gas Ar-mixture TPC
  - $p = 20$  bar,  $2 \times 2 \times 2$  m<sup>3</sup>
- 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)



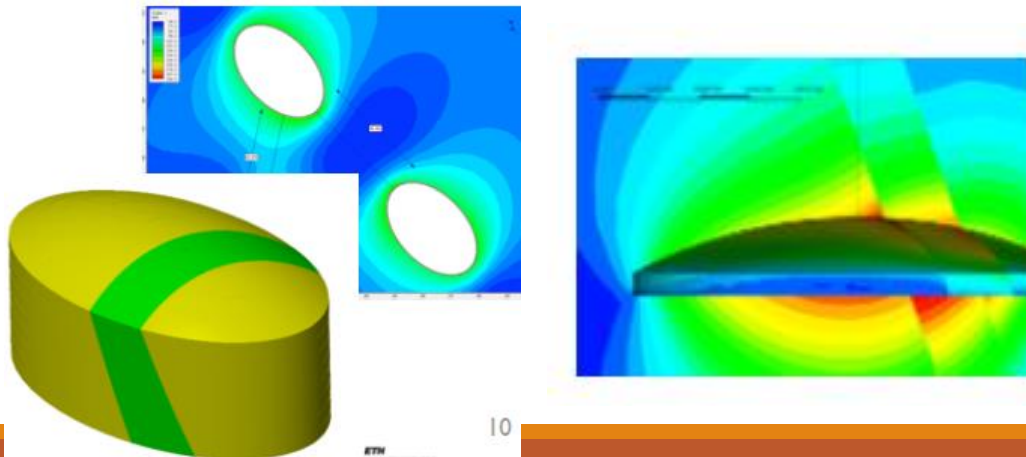
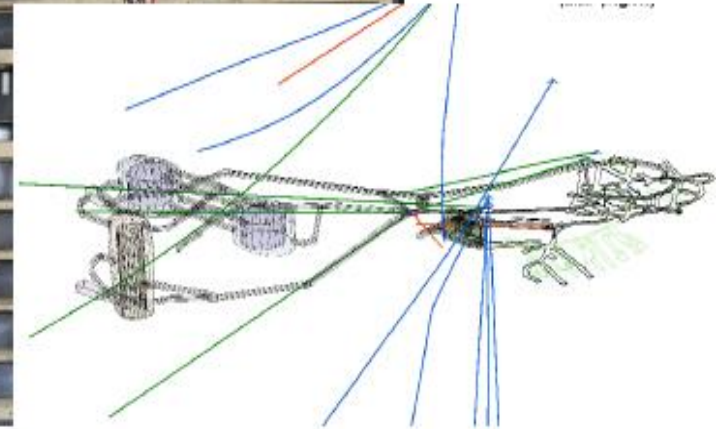
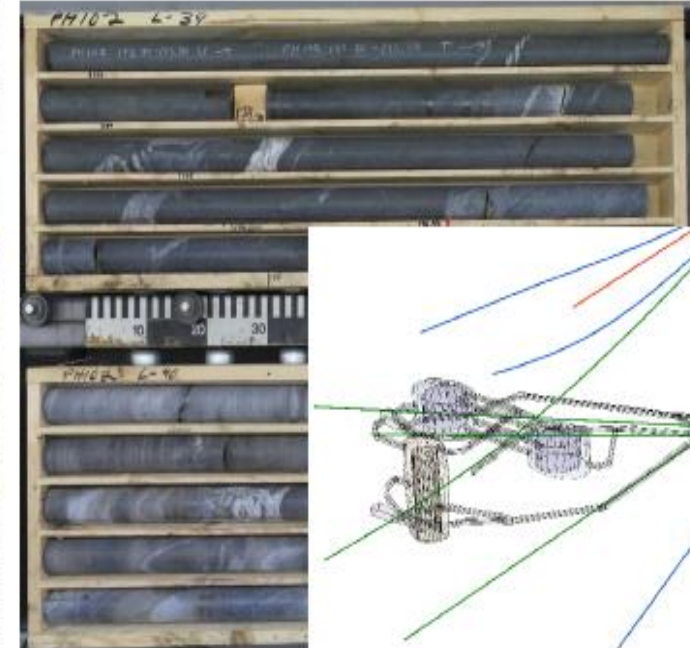
# Pyhäsalmi site investigation (2013-2014)

## Extensive field work:

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

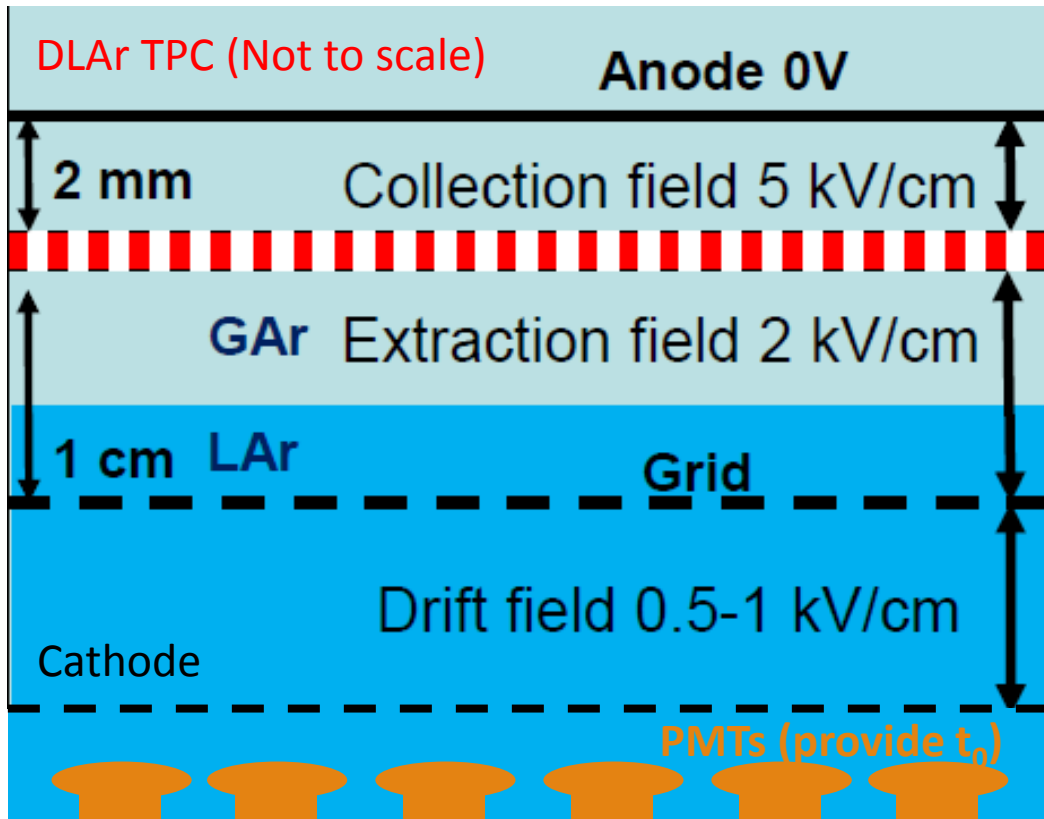


Accurate modelling of the geological environment ← basis for accurate rock mechanical calculations

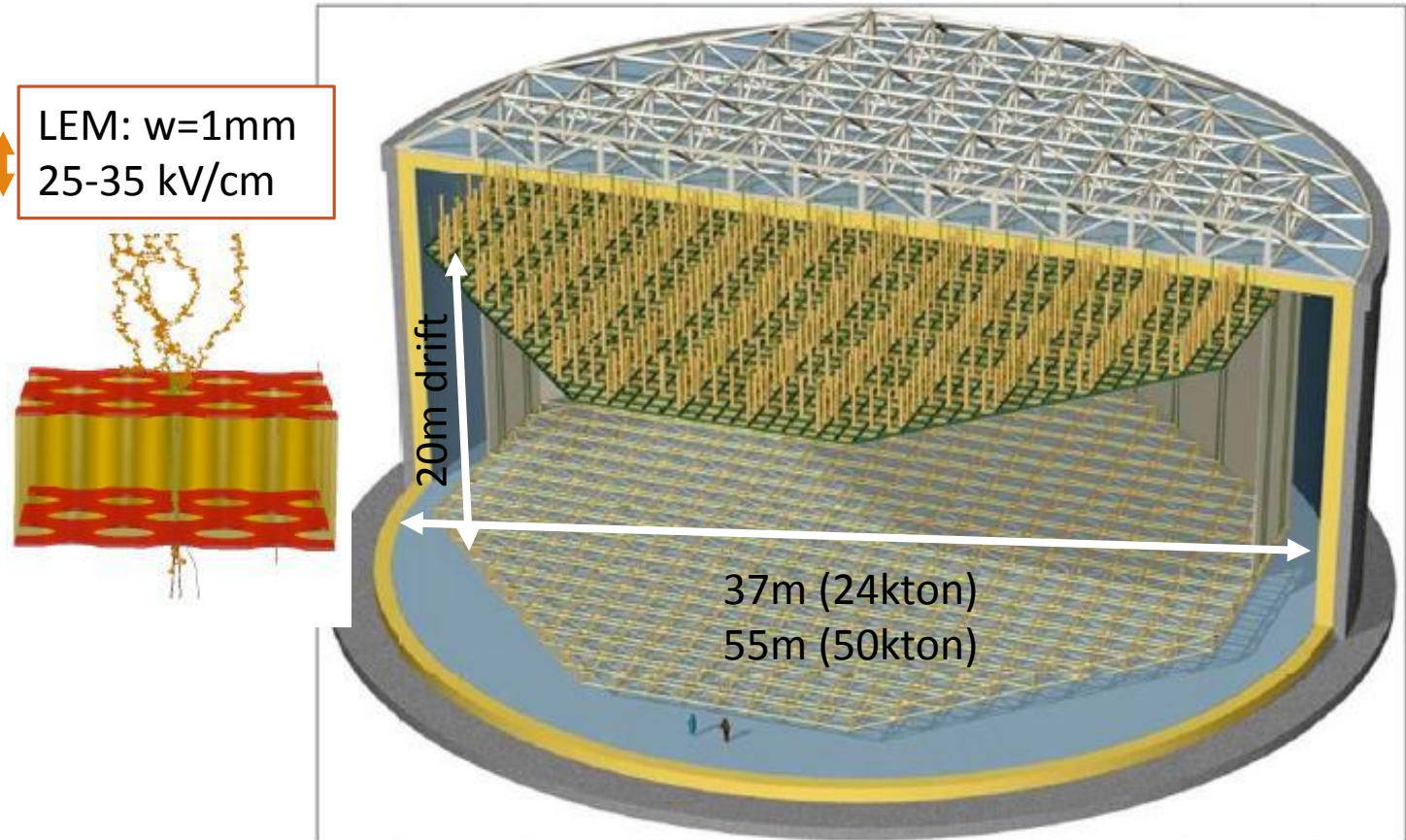


Caverns can be constructed with existing technology

# The far detector: double-phase LAr

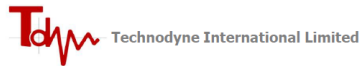


GLACIER: Giant Liquid Argon Charge Imaging expERiment

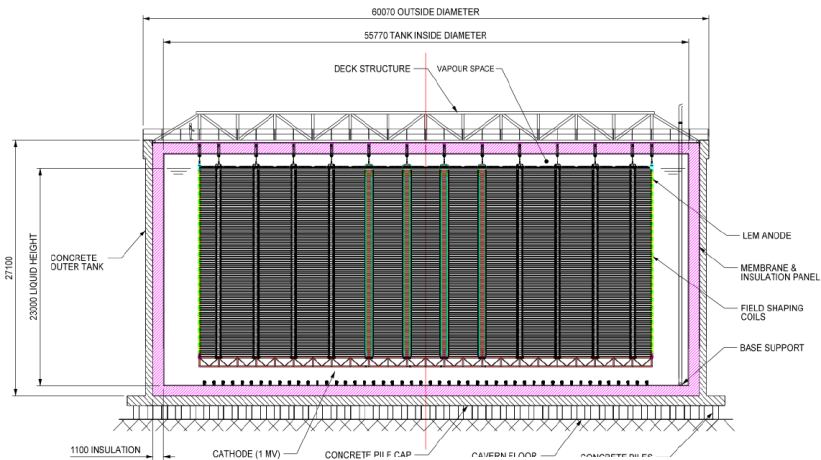


Large detector  $\rightarrow$  long drift distances  
Double-phase detector to improve S/N  
Amplification of ionization electrons in the gas phase

# LAGUNA-LBNO DS → Full conceptual detector design



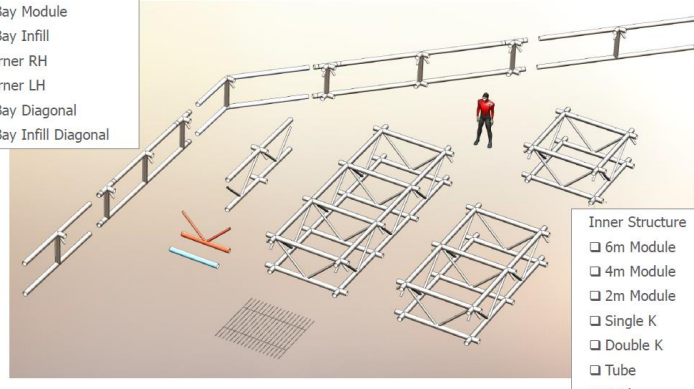
LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design  
DETECTOR CONCEPT DEVELOPMENT – 50ktonne Proposed Design



LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design  
PROPOSED DETECTOR DESIGN DETAILS (50ktonne)

## CATHODE STRUCTURE – Modular Construction

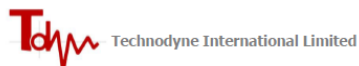
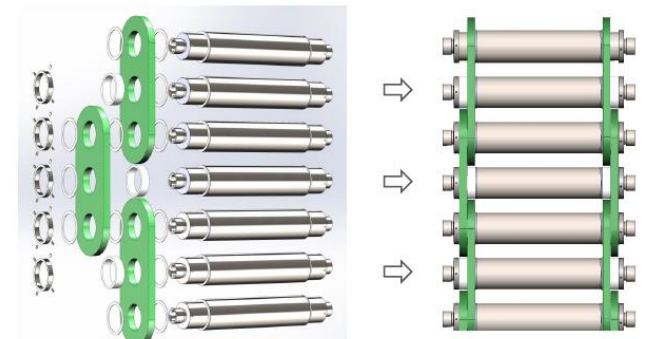
- Peripheral Structure
- 2 Bay Module
  - 2 Bay Infill
  - Corner RH
  - Corner LH
  - 2 Bay Diagonal
  - 2 Bay Infill Diagonal



LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design  
PROPOSED DETECTOR DESIGN DETAILS (50ktonne)

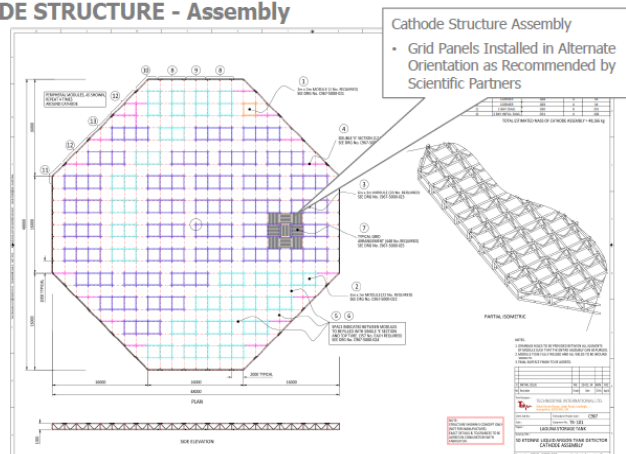
## HANGING COLUMNS – Link Pins & Links Assembly

- Link Pins & Links Assembled in Clean Room Environment
- All Parts Cleaned Prior to Assembly



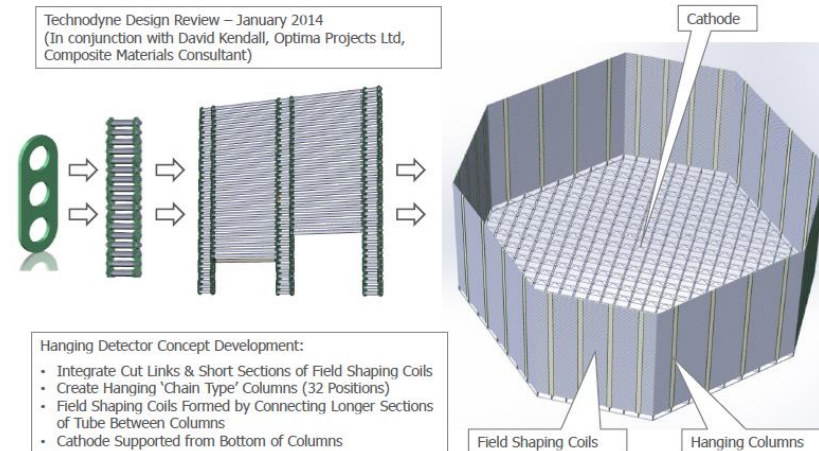
LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design  
PROPOSED DETECTOR DESIGN DETAILS (50ktonne)

## CATHODE STRUCTURE - Assembly



LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design  
DETECTOR CONCEPT DEVELOPMENT – 50ktonne Field Cage + Cathode

Technodyne Design Review – January 2014  
(In conjunction with David Kendall, Optima Projects Ltd, Composite Materials Consultant)



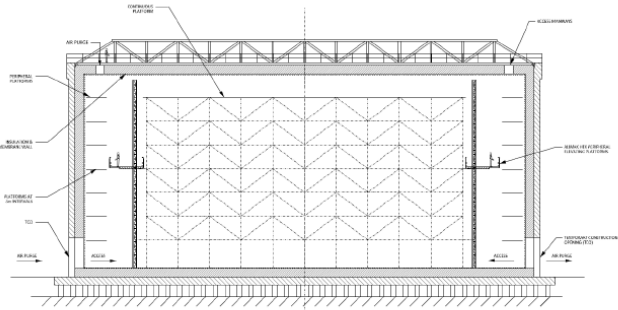
- Hanging Detector Concept Development:
- Integrate Cut Links & Short Sections of Field Shaping Coils
  - Create Hanging "Chain Type" Columns (32 Positions)
  - Field Shaping Coils Formed by Connecting Longer Sections of Tube Between Columns
  - Cathode Supported from Bottom of Columns

# LAGUNA-LBNO DS → Underground construction sequence

Tdym Technodyne International Limited

TGE a member of the CIMAC group

## LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design DETECTOR CONSTRUCTION



1. COMPLETE INSTALLATION OF INSULATION & SHEATHING. INSTALL CABLE TRAYS FROM TOP TO BOTTOM FOR THE ELECTRICAL CABLES.
2. ADJUST SCAFFOLDING PLATFORMS & ADD ALIMAK FOR PLATFORMS & FLOOR PROTECTION AIN.

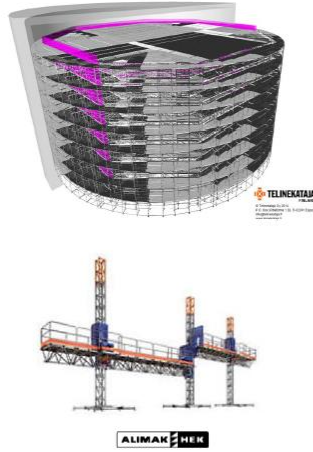
Tank membrane complete, internal pipework in place and the cable trays are fitted.  
The existing scaffolding will be reworked if necessary to allow the addition of moving access platforms

67

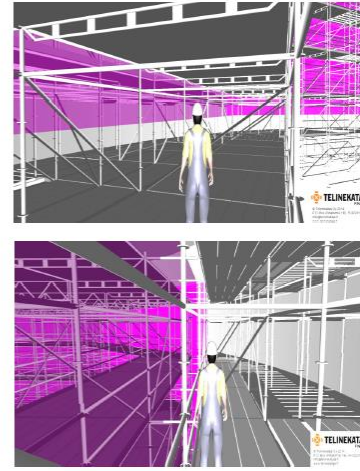
Tdym Technodyne International Limited

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## LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design



ALIMAK

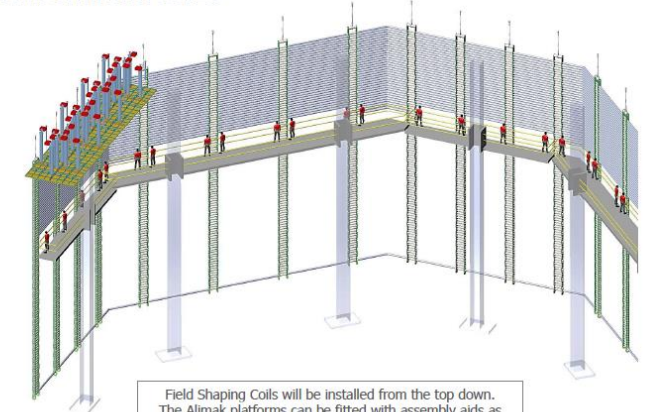


69

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## LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design FIELD SHAPING COILS



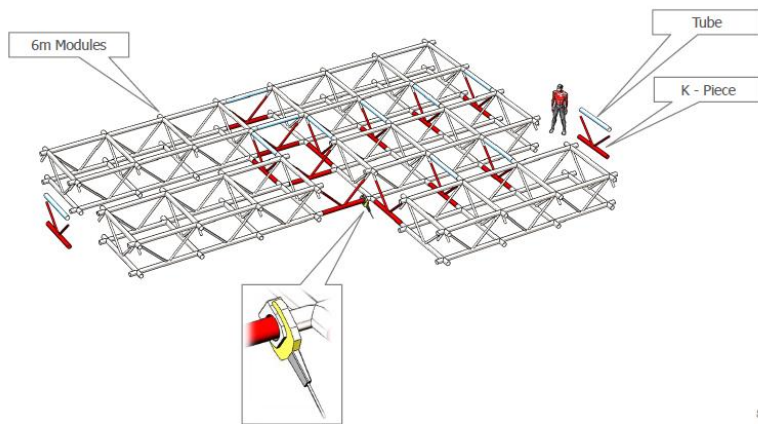
Field Shaping Coils will be installed from the top down. The Alimak platforms can be fitted with assembly aids as necessary to create safe and convenient work stations. Alimaks will be used to raise materials to the working level.

76

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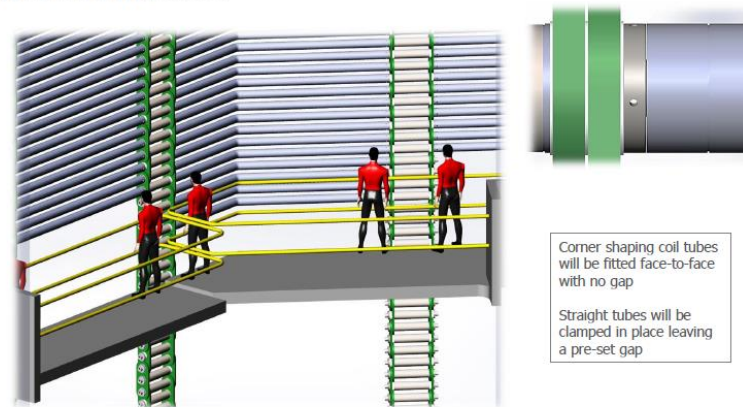
## LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design CATHODE CONSTRUCTION



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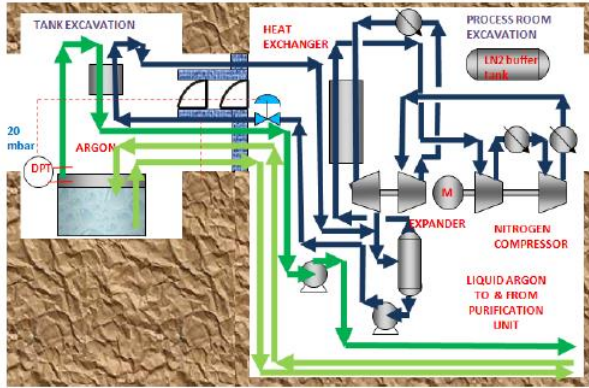
## LAGUNA – LBNO (Deliverable 3.1) GLACIER LAr Detector Design FIELD SHAPING COILS



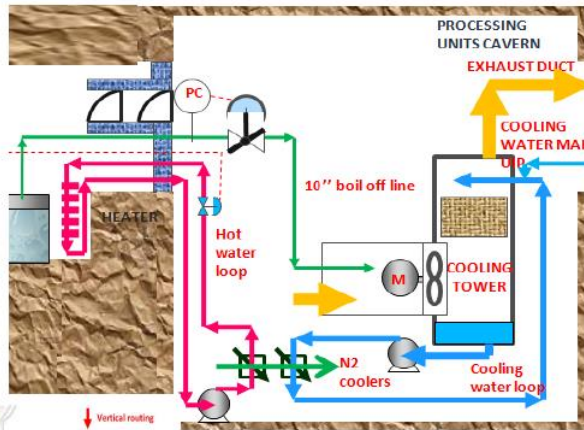
Corner shaping coil tubes will be fitted face-to-face with no gap  
Straight tubes will be clamped in place leaving a pre-set gap

77

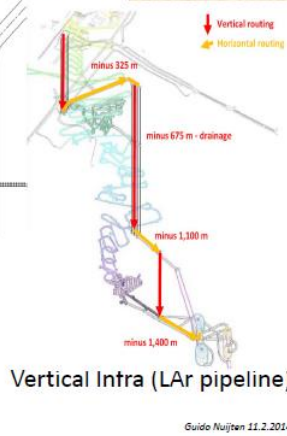
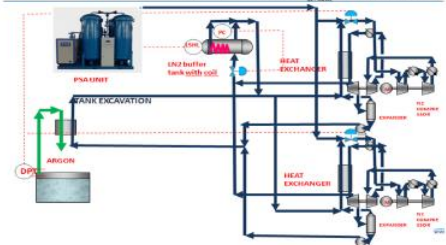
# Process design & detailed risk analysis



On-surface Liquid Infra



Underground Liquid Infra



Vertical Intra (LAr pipeline)

Guido Nuijten 11.2.2014



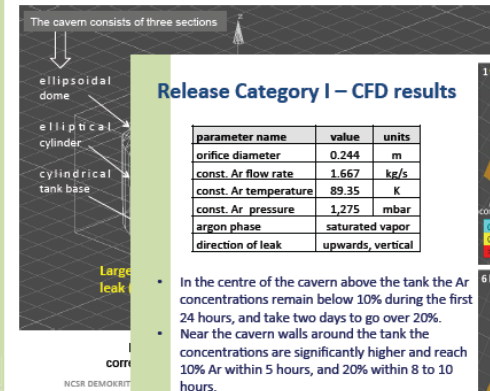
Ex1: Loss of: Offsite Power + Diesel Generator

INITIATOR	Frequency (hr <sup>-1</sup> )	Conditional Probability of Tank Failure	Probability of Argon Release	Frequency of Tank Failure (hr <sup>-1</sup> )	Frequency of ArR (hr <sup>-1</sup> )	Contribution of each initiator
LOOP	1.00x10 <sup>4</sup>	3.00x10 <sup>-3</sup>	3.40x10 <sup>-3</sup>	3.00x10 <sup>-1</sup>	3.40x10 <sup>-1</sup>	0.13%
Loss of SWCS Pump	3.10x10 <sup>4</sup>					0.13%
Loss of SWCS HX	3.60x10 <sup>4</sup>					0.13%
Loss of Operating Pressurizer Train	1.00x10 <sup>4</sup>					0.13%
Loss of Cavern Heating System	3.10x10 <sup>4</sup>					0.13%
Loss of Ar Pump	3.10x10 <sup>4</sup>					0.13%
Loss of Operating N <sub>2</sub> train	5.00x10 <sup>4</sup>					0.13%
Loss of insulation type LI1	9.12x10 <sup>7</sup>					0.13%
Loss of insulation type LI2	1.14x10 <sup>7</sup>					0.13%
Loss of insulation type LI3	7.98x10 <sup>4</sup>					0.13%
Loss of insulation type LI4	3.42x10 <sup>4</sup>					0.13%
TOTAL						0.13%

## D3.3 – Final Report Safety Analysis and Quantitative Risk Assessment of the GLACIER Tank and Underground Processes at Pyhäsalmi

Effie Marcoulaki, Ioannis Papazoglou, Alexandros Venetsanos  
Institute of Nuclear & Radiological Sciences & Technology, Energy & Safety or Scientific Research DEMOKRITOS  
Greece

### Cavern & tank geometry used in CFD simulations

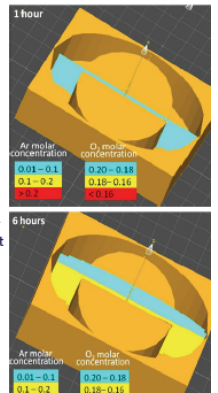


### Release Category I – CFD results

parameter name	value	units
orifice diameter	0.244	m
const. Ar flow rate	1.667	kg/s
const. Ar temperature	89.35	K
const. Ar pressure	1,275	mbar
argon phase	saturated vapor	
direction of leak	upwards, vertical	

- In the centre of the cavern above the tank the Ar concentrations remain below 10% during the first 24 hours, and take two days to go over 20%.
- Near the cavern walls around the tank the concentrations are significantly higher and reach 10% Ar within 5 hours, and 20% within 8 to 10 hours.

The CFD predicts O<sub>2</sub> concentrations to remain over 18% for a day above the tank and for 5 hours at lower heights.



# Recent updates to the LBNO physics program



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

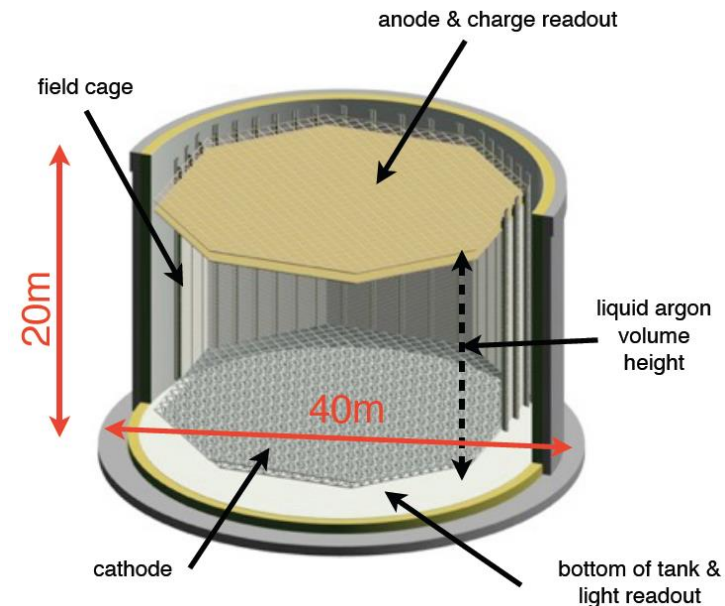
### The LAGUNA-LBNO collaboration

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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

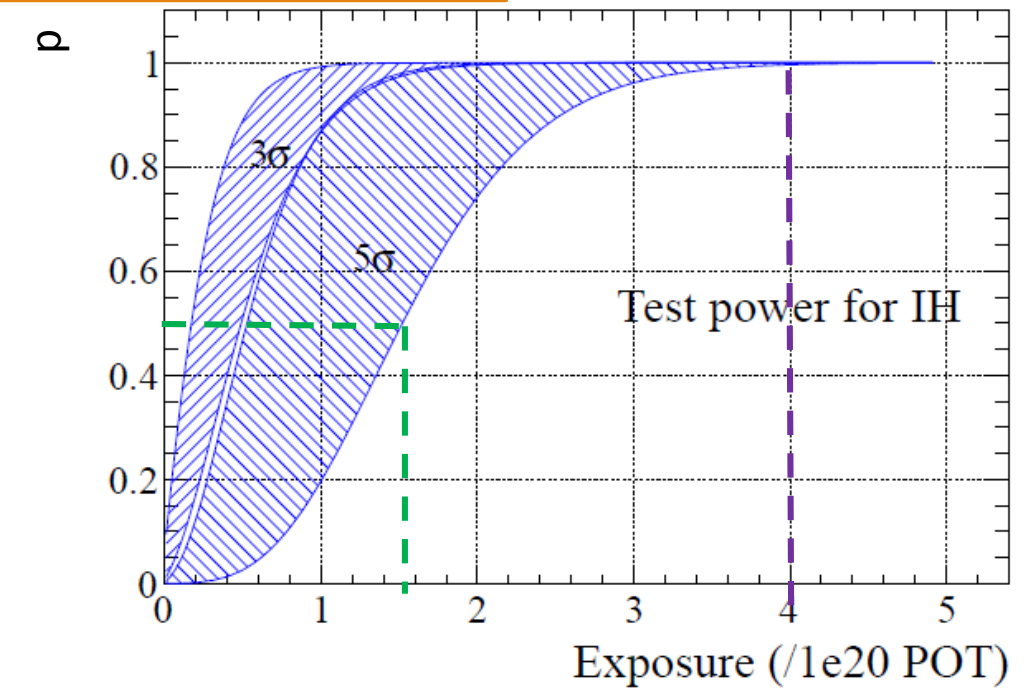
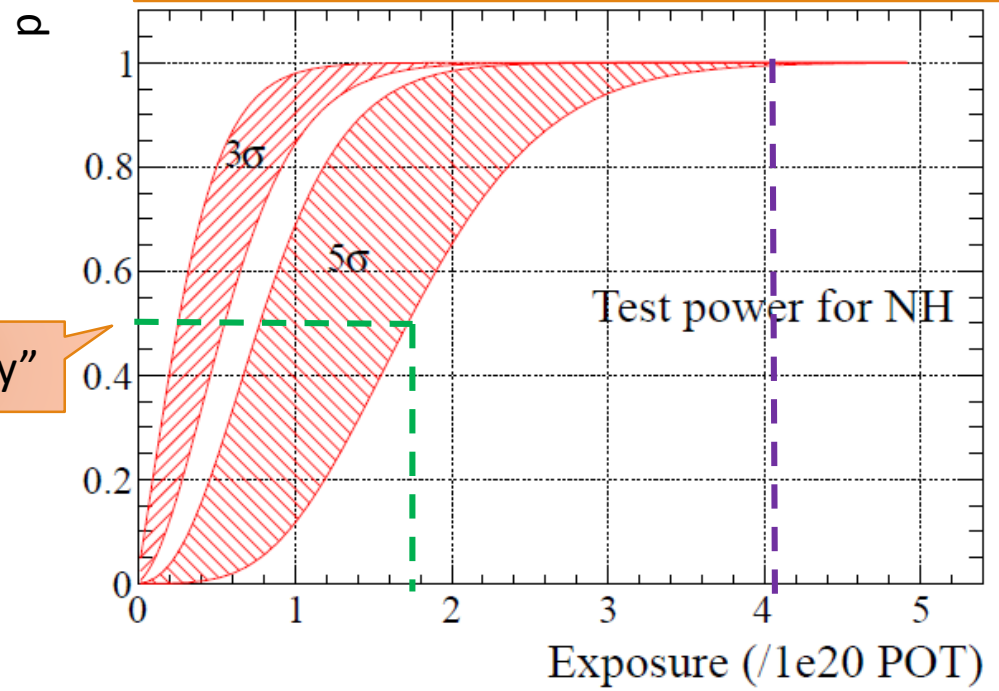




# LBNO power to determine MH

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

10.007/JHEP05 (2014) 094



“Sensitivity”

Typically sensitivity is defined at  $p=0.5 \rightarrow$  50% chance NOT to achieve projected CL LBNO, independently of  $\delta_{CP}$  value, can do MH determination at  $5\sigma$  level as fast as  $\sim 2y$   
**And it is essentially guaranteed ( $p \approx 1$ ) within 4-5y of running (50%  $\nu$  & 50%  $\bar{\nu}$ )**

# Beam optimization for $\delta_{CP}$ measurement

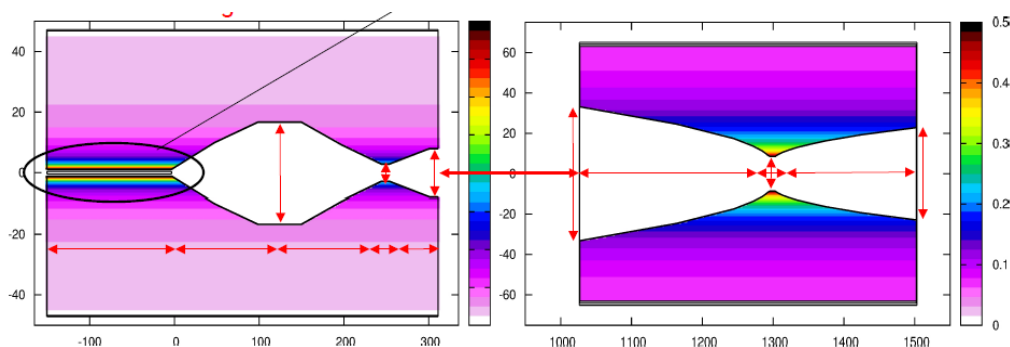
Parameter	Symbol	Unit	Allowed range
target radius	$r_{tgt}$	mm	4-15
circulating current in horn	$I_H$	kA	150-300
horn length 1st part	h1_l1	cm	80-200
horn length 2nd part	h1_l2	cm	150-250
horn length 3rd part	h1_l3	cm	80-150
horn length 4th part	h1_l4	cm	1-10
horn length 5th part	h1_l5	cm	5-20
horn large 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\*

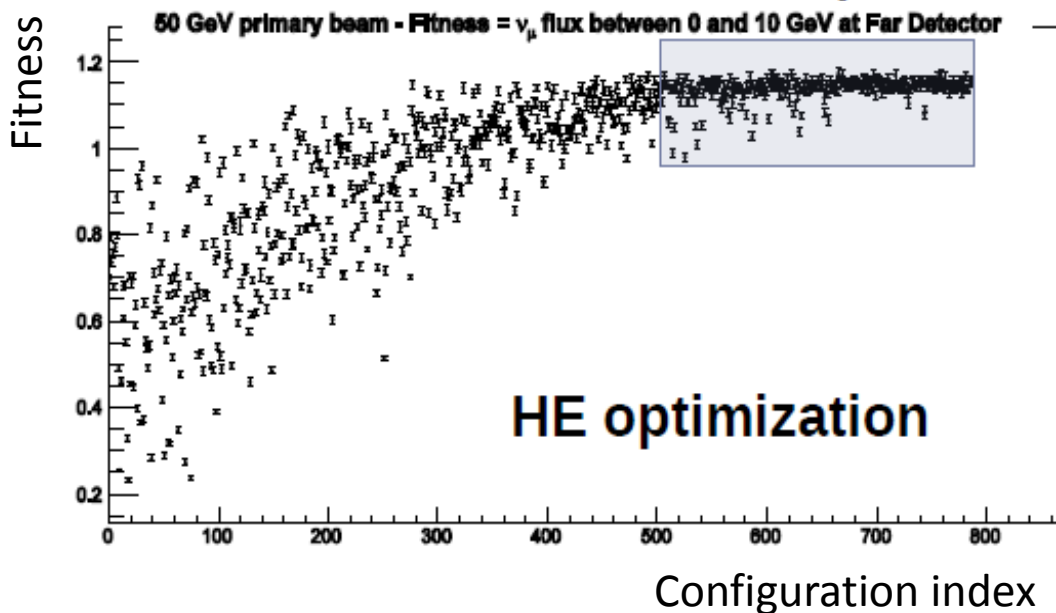
- FLUKA simulation generate flux for a given parameter set (configuration)
- Assign a fitness quantity(ies) to each configuration
- Select best configuration and “breed” them in order to step through parameter space



\*Implementation in DEAP “Distributed Evolution Algorithms for Python” (Fortin et al, Journal of Machine Learning Research 13: 2171-2175) <https://code.google.com/p/deap/>

# Beam optimization for $\delta_{CP}$ 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

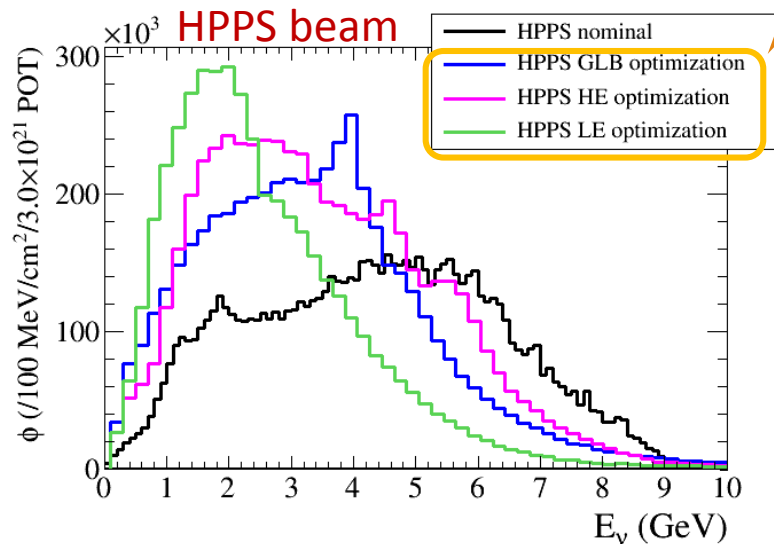
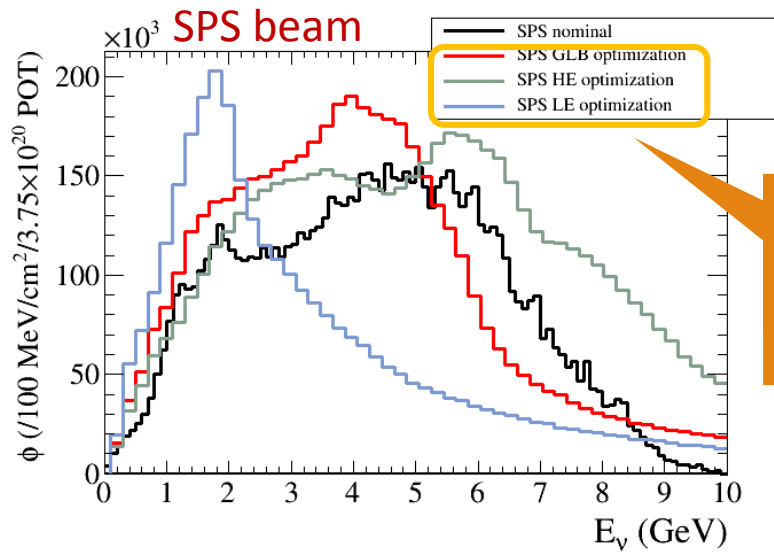
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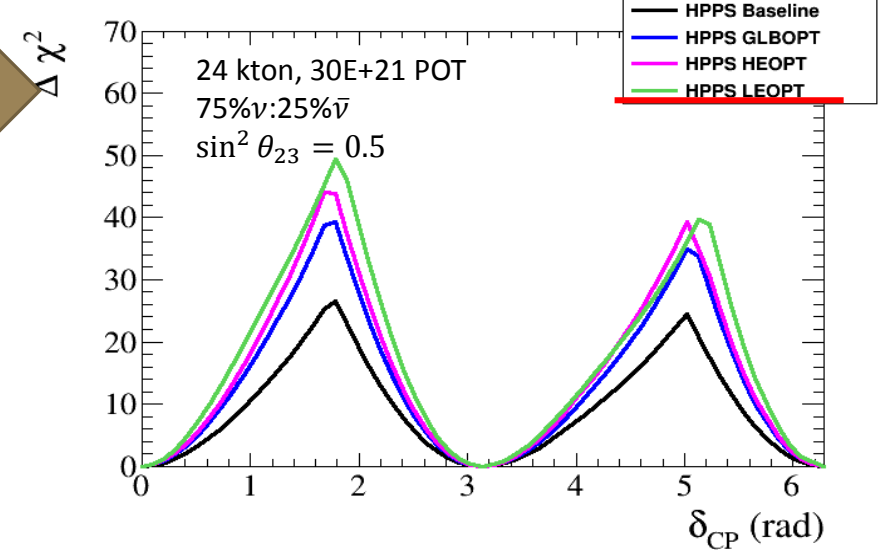
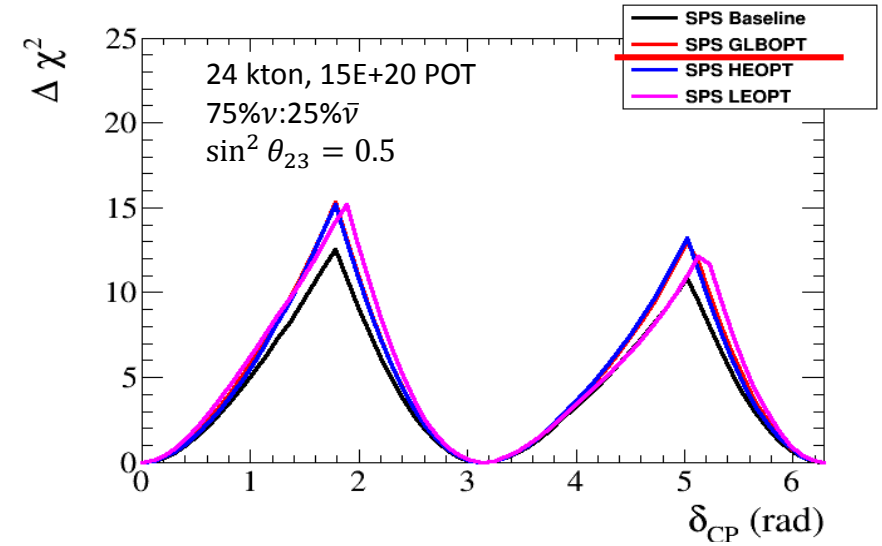
\*Implementation in DEAP “Distributed Evolution Algorithms for Python” (Fortin et al, Journal of Machine Learning Research 13: 2171-2175) <https://code.google.com/p/deap/>

# Different fitness criteria $\rightarrow$ different beams



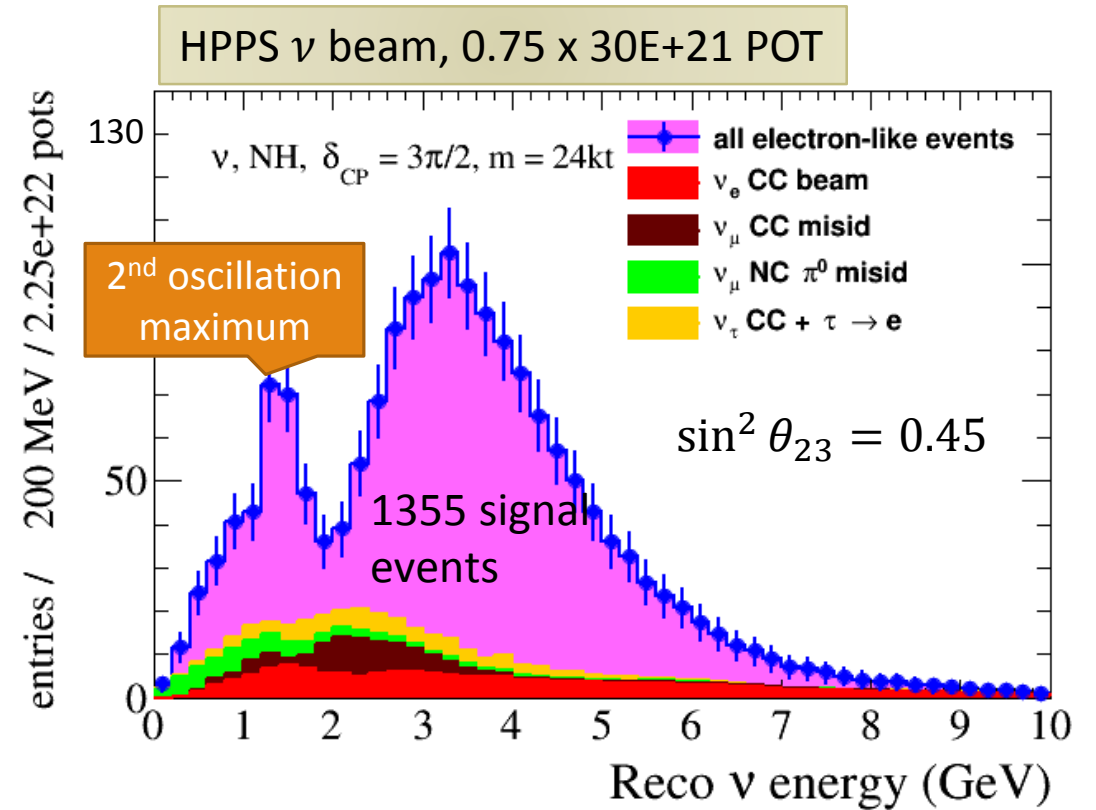
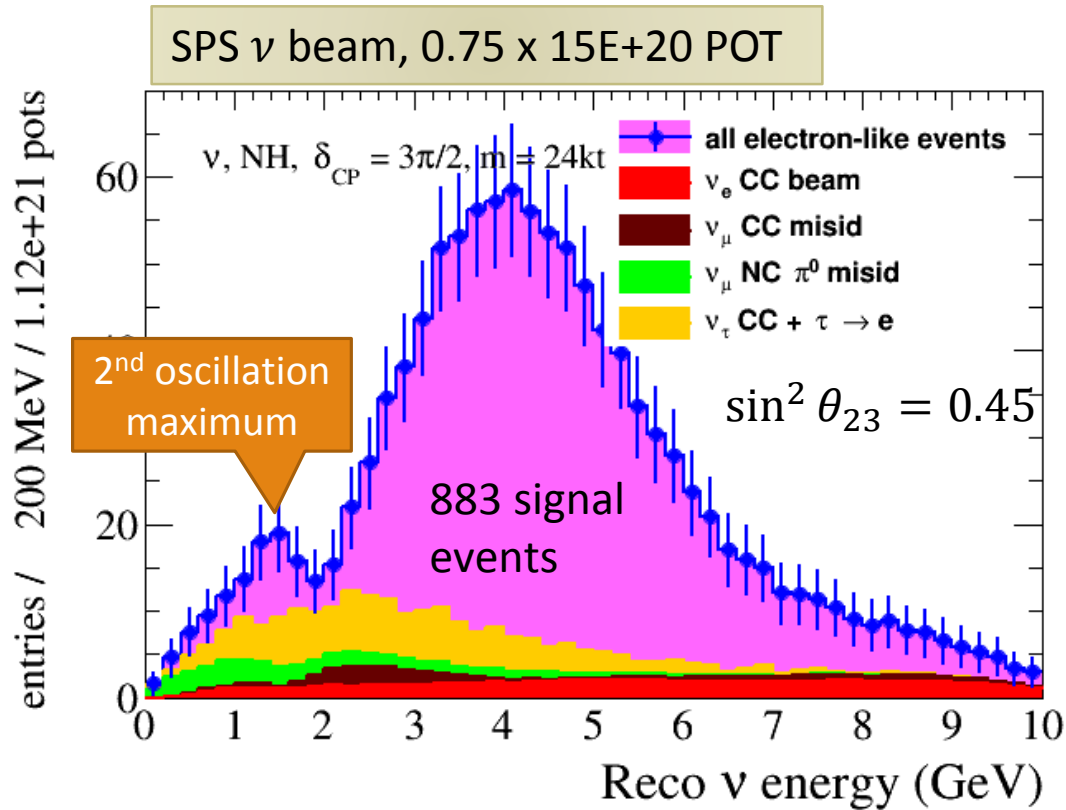
Different fitness criteria  $\rightarrow$  explore different energy spectra

Run through LBNO analysis



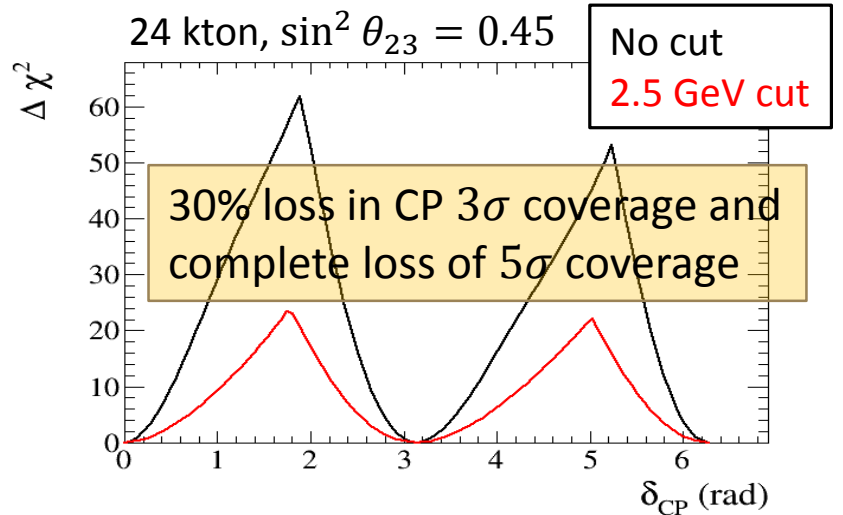
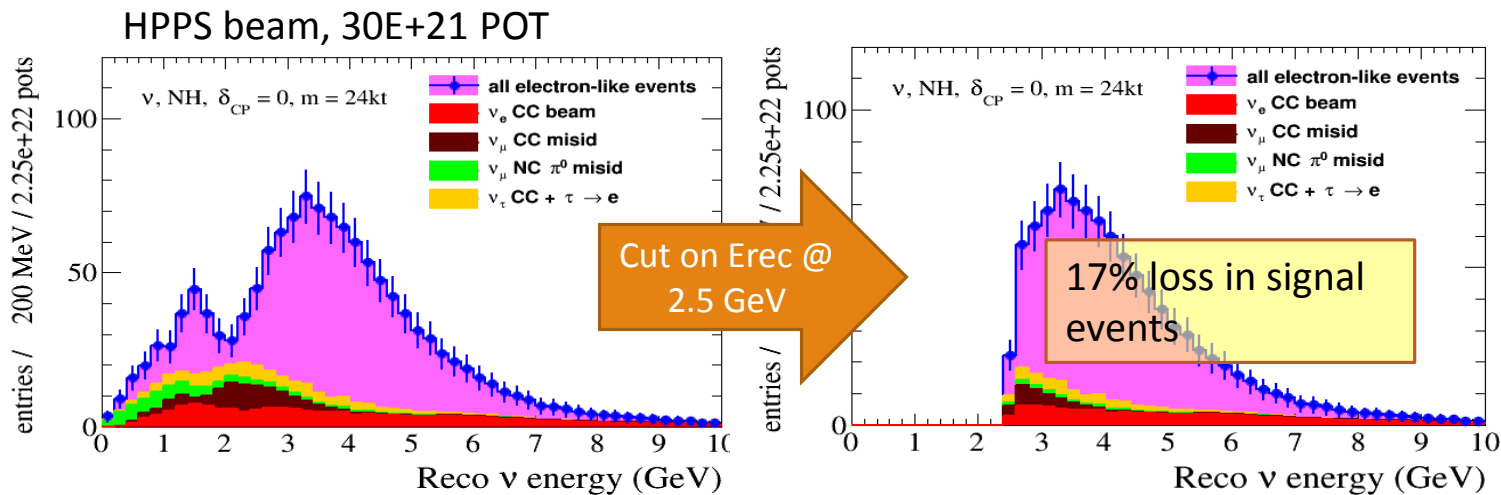
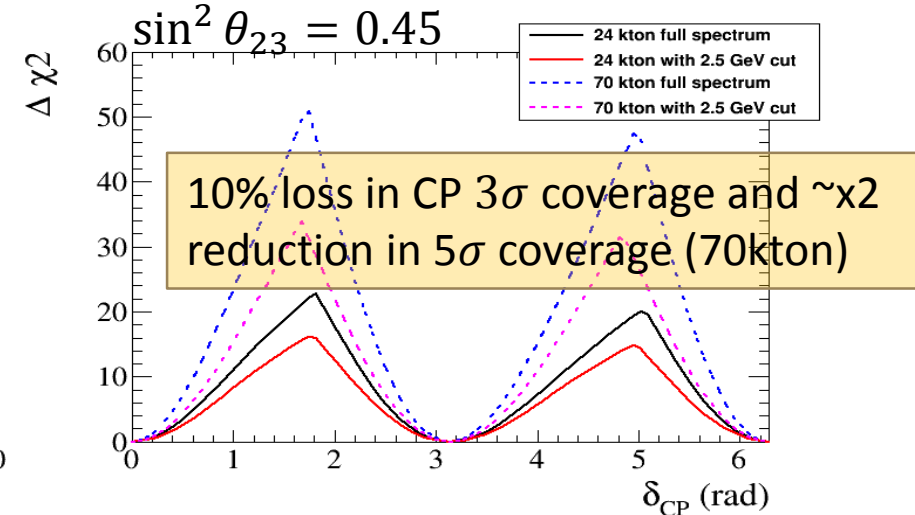
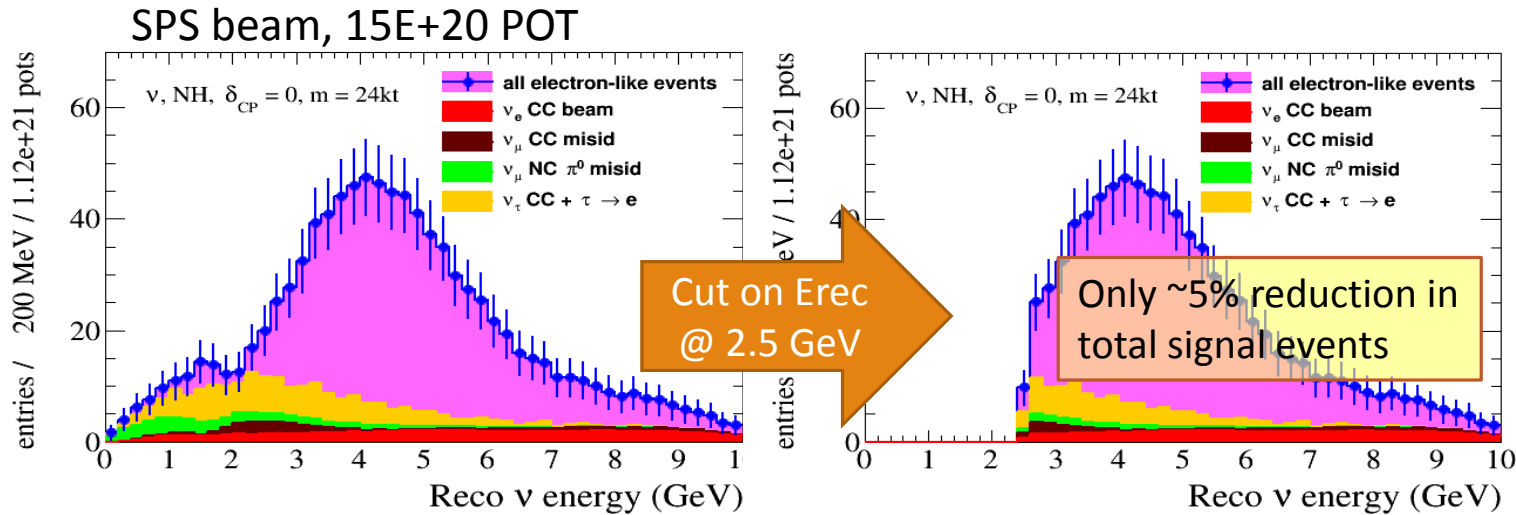
Finally select configuration with best sensitivity to CPV

# Examples of event spectra

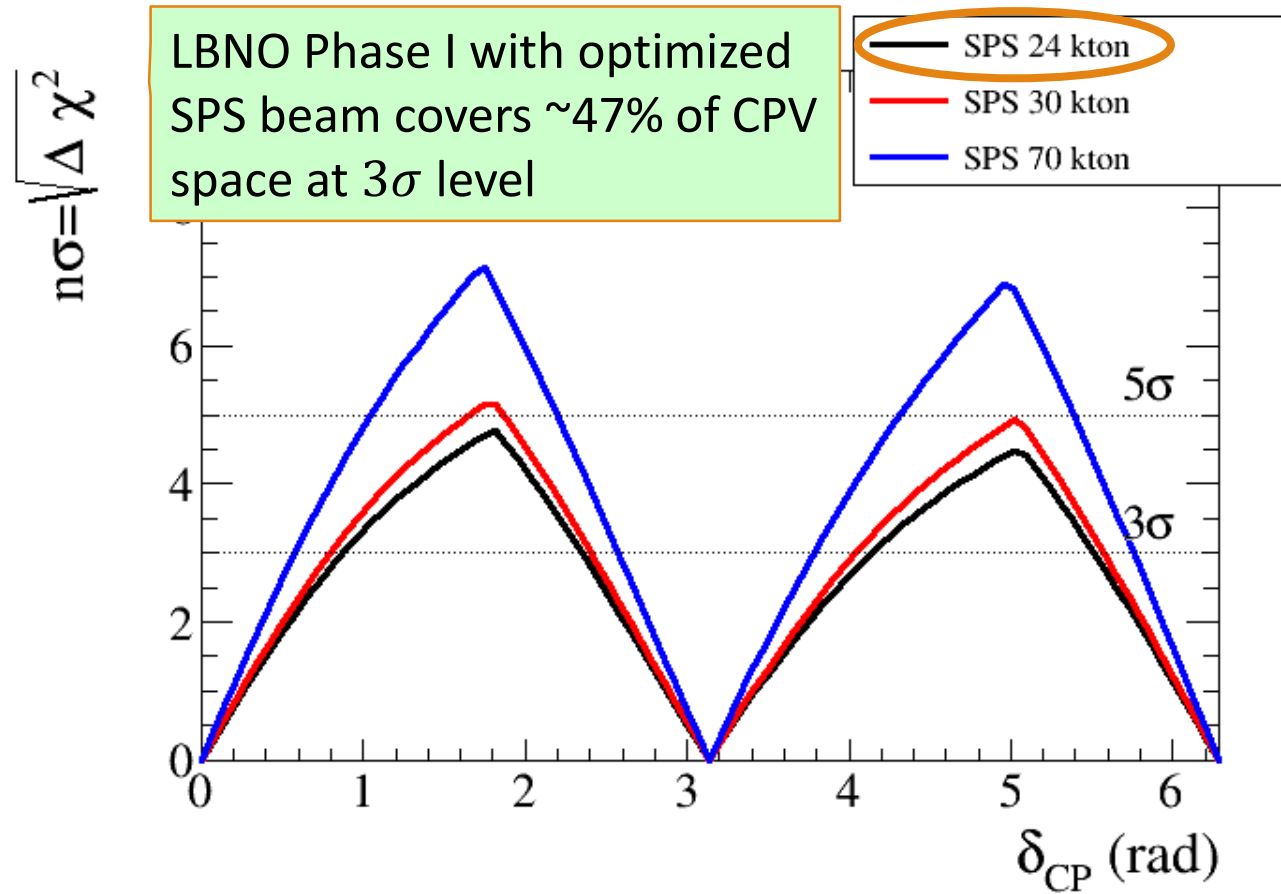


- Not a significant difference in total number of events b/w SPS and HPPS options
  - The beam power is a factor  $\sim 3$  larger for HPPS
- With 50 GeV proton beam (HPPS) can give more preference to 2<sup>nd</sup> maximum
- A lot of information in the 2<sup>nd</sup> maximum for the L/E analysis

# Power of the 2<sup>nd</sup> maximum



# LBNO sensitivity to CP Violation: SPS beam



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

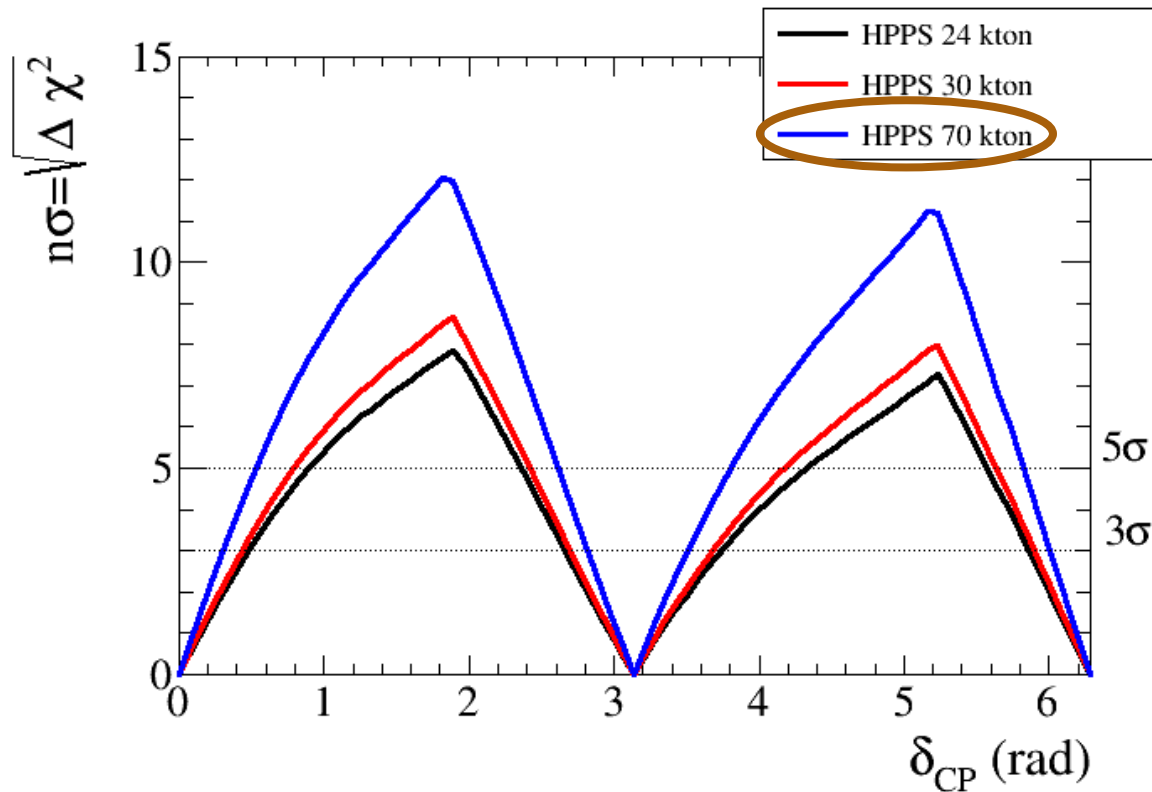
## Input assumptions

Parameter	Value	Error
Signal normalization	1	3%
Intrinsic beam $\nu_e$	1	5%
Tau background	1	20%
$\nu_\mu$ CC & NC backgrounds	1	10%

Parameter	Value	Error
L	2300 km	exact
$\Delta m_{21}^2$	$7.45 \times 10^{-5} \text{eV}^2$	Fixed
$\Delta m_{31}^2$	$2.50 \times 10^{-3} \text{eV}^2$	2%
$\sin^2 \theta_{12}$	0.306	Fixed
$\sin^2 \theta_{23}$	0.45	5%
$\sin^2 2\theta_{13}$	0.09	3%
$\rho$	$3.2 \text{g/cm}^3$	4%

Can reach a coverage of 63% at  $3\sigma$  and 36% at  $5\sigma$  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  $3\sigma$**  and **65% at  $5\sigma$**  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


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## Some technical challenges:

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

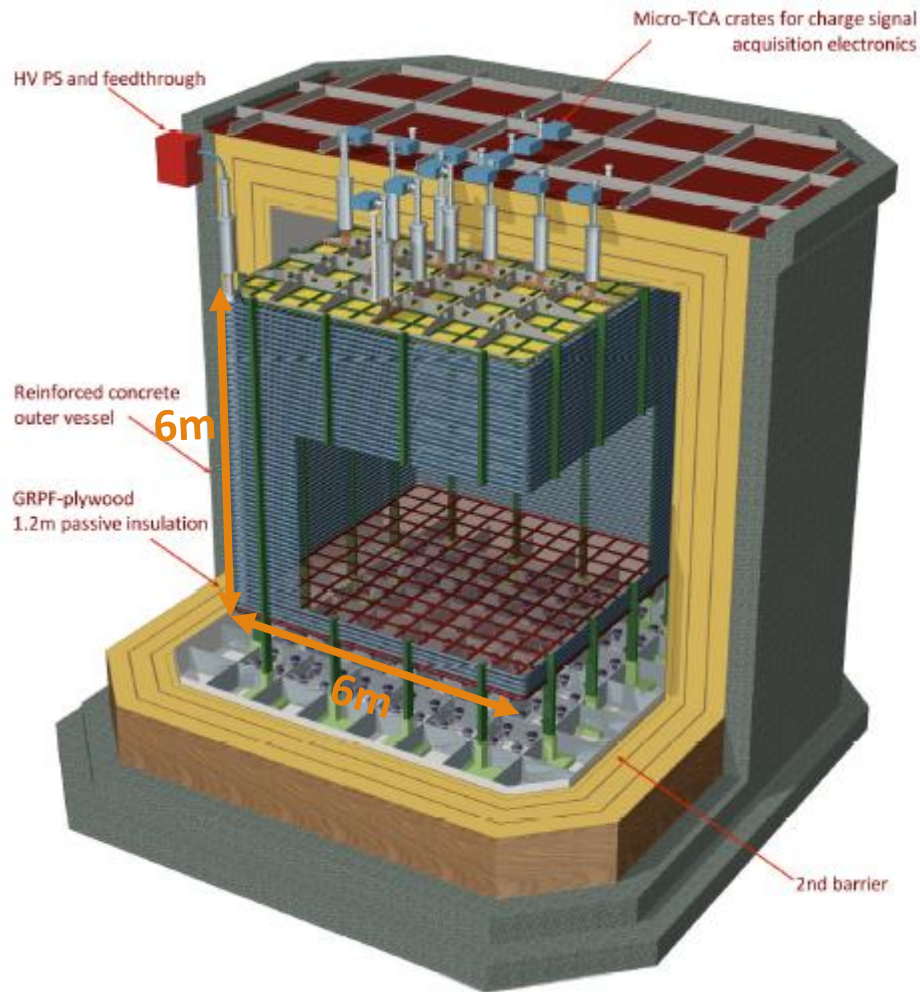
## Some physics challenges:

- 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 m<sup>3</sup> (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

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

Attractive accelerator  $\nu$  program:

- Unambiguous determination of the MH
- Coverage of 80% of  $\delta_{CP}$  parameter space at  $3\sigma$  level and 65% at  $5\sigma$

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:

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

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

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

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

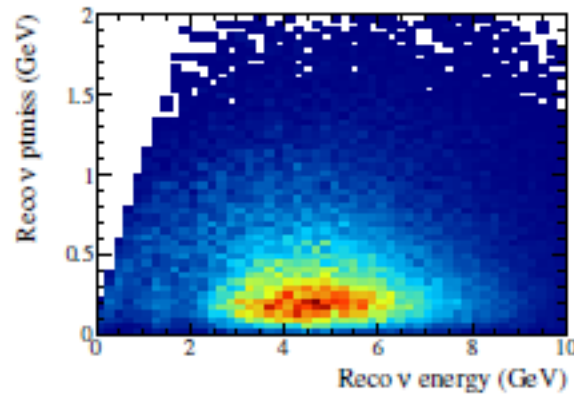
$$\chi_{\text{syst}}^2 = \sum_i \frac{(a_{0,i} - a_i)^2}{\sigma_{a_i}^2}$$

## Input assumptions

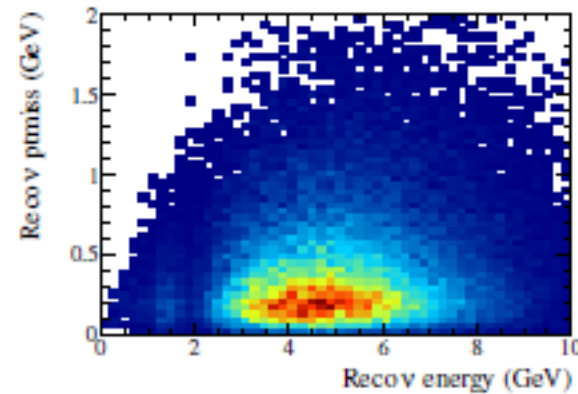
Parameter	Value	Error
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$\rho$	3.2 g/cm <sup>3</sup>	4%

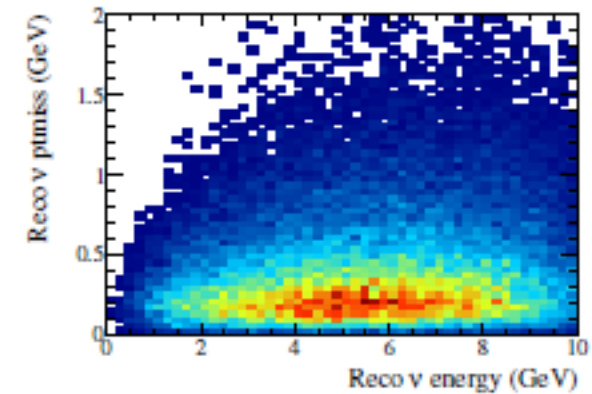
# Example 2D distribution



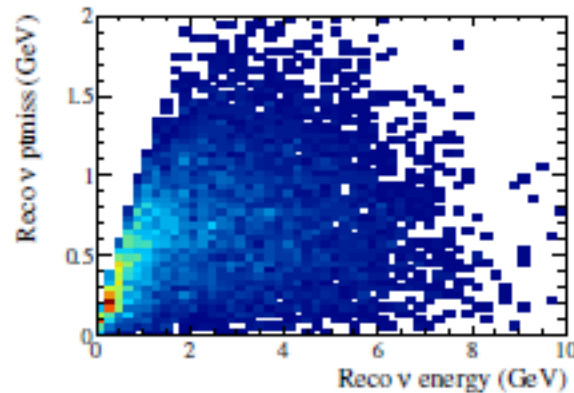
(a) All e-like



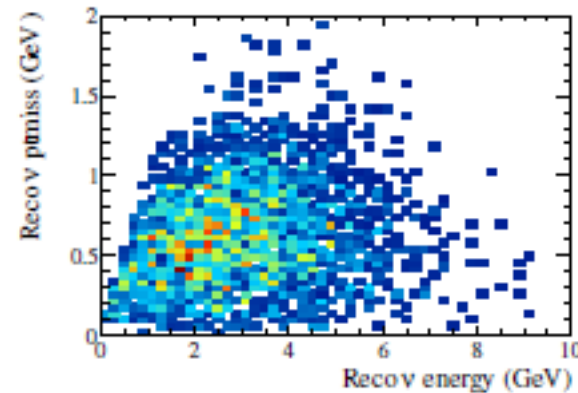
(b) Signal  $\nu_e$



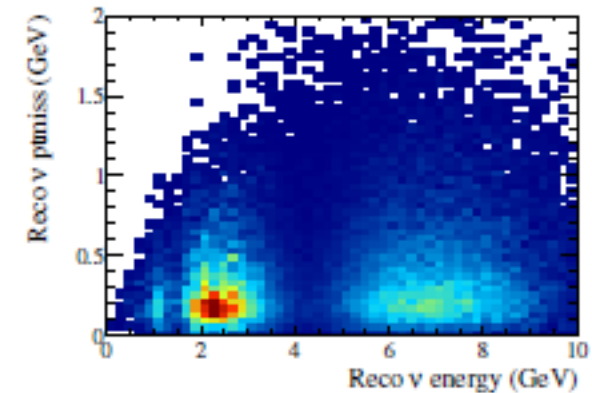
(c) Intrinsic  $\nu_e$



(d)  $NC\pi^0$



(e)  $\nu_\tau \rightarrow e$  contamination

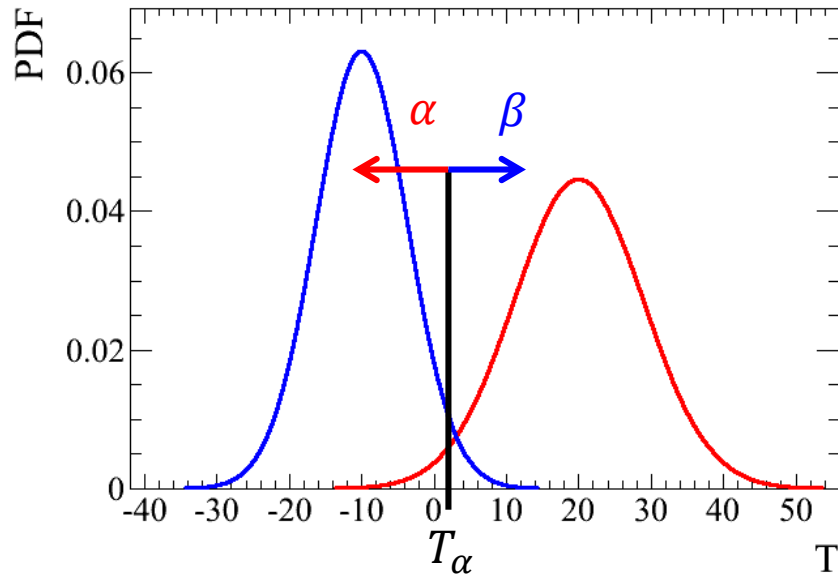


(f) Mis-id  $\nu_\mu$

No cuts at the moment other than 10 GeV on E reco  $\rightarrow$  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



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

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

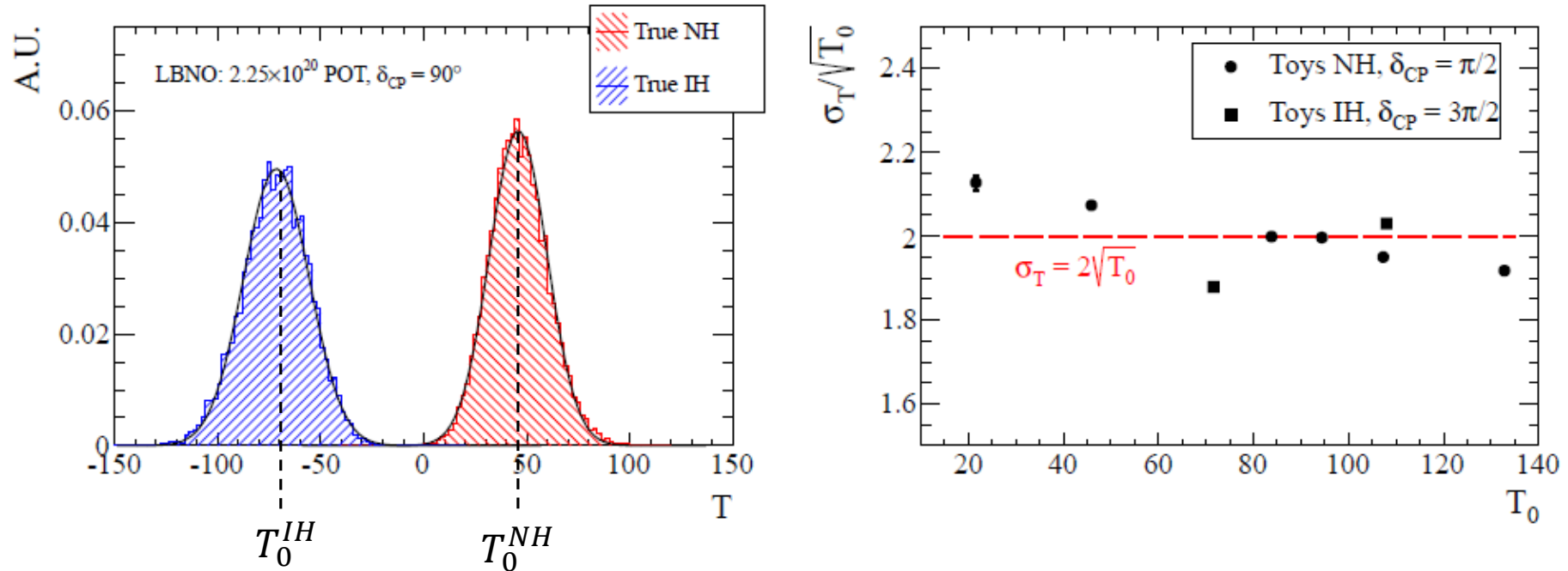
$$\alpha = \int_{-\infty}^{T_\alpha} f(T|NH) dT$$

CL = 1 -  $\alpha$

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

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

# Properties of $f(T)$



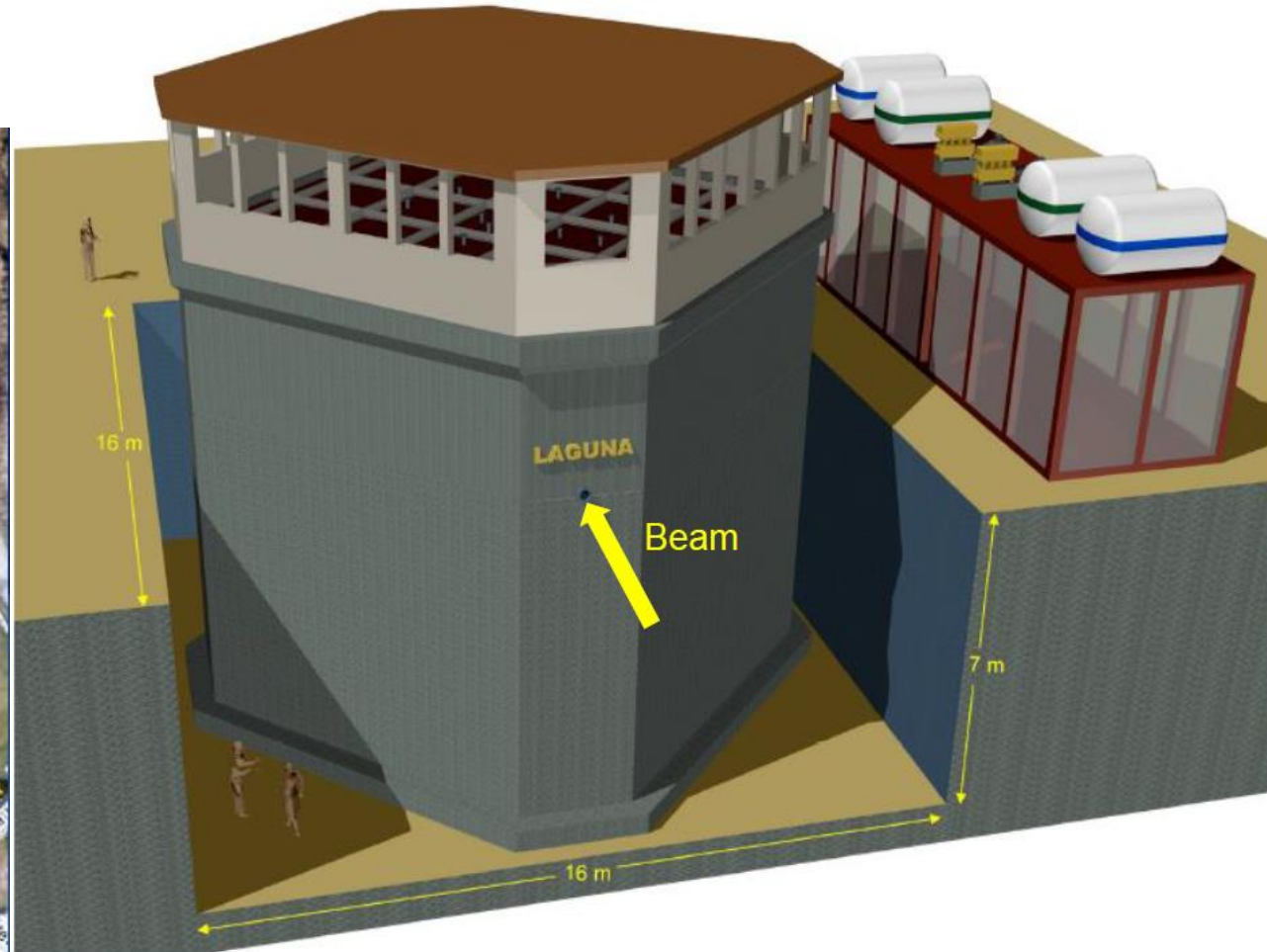
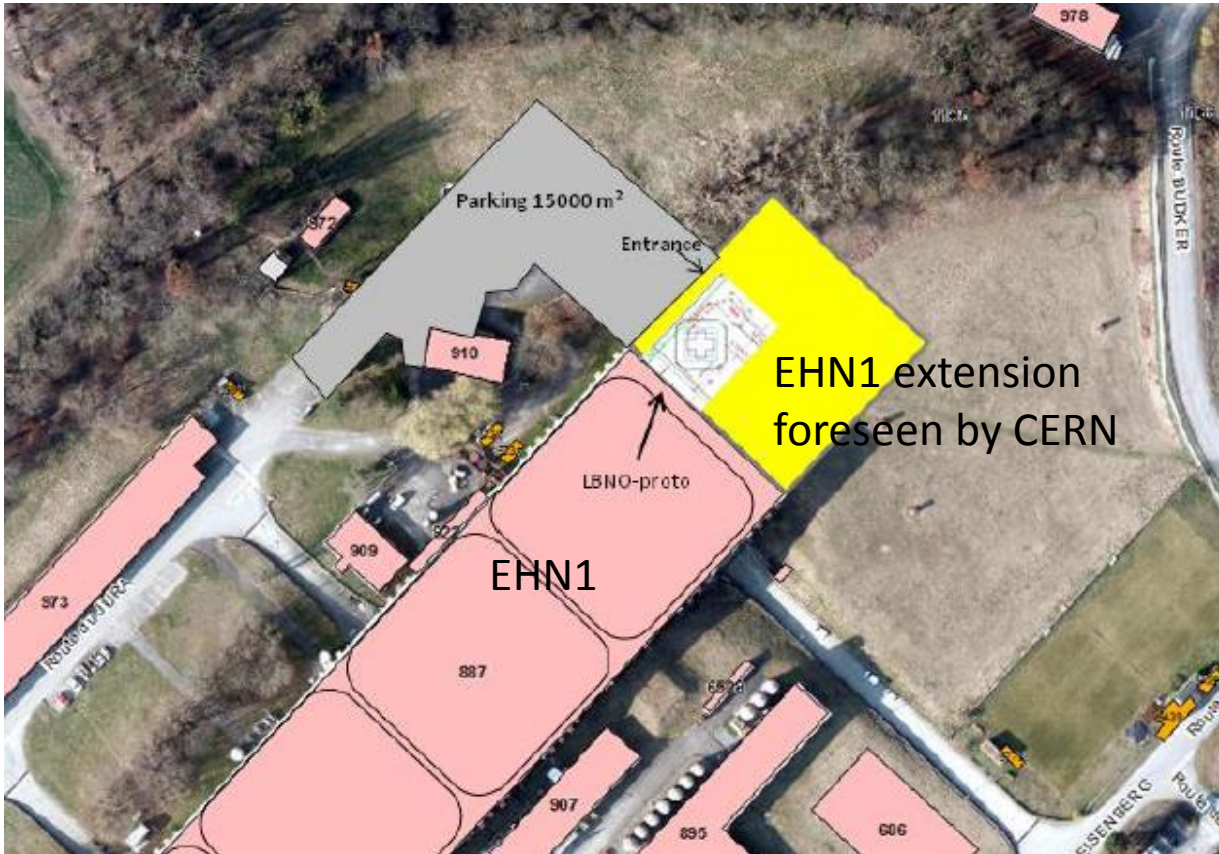
- The separation between two peaks increases with exposure
- A phenomenological approximation for  $f(T)$

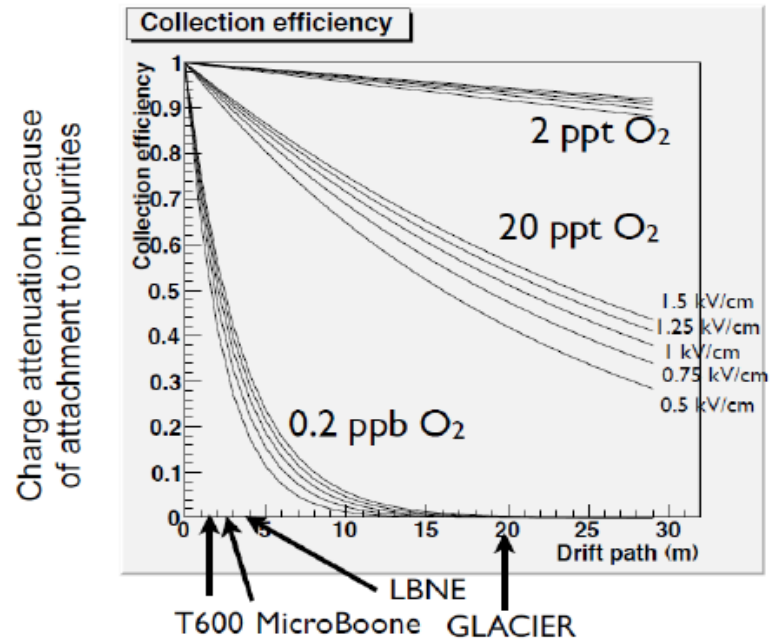
$$f(T) = \mathcal{N}(T_0, 2\sqrt{T_0}) \leftarrow \text{Qian et al., hep-ph/1210.3651}$$

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



# LBNO-Demo general overview





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

