Future Long Baseline Neutrino Oscillations: View from Europe

by

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Since 2005 substantial financial support from EU for Design Studies (**12M€ + 5 M€ from nat.**): To pave the way for the next generation Long Baseline Neutrino Oscillation Research Facility

2008 – 2012: EUROnu: *"A High Intensity Neutrino Oscillation Facility in Europe"*

- CERN to Frejus superbeam
- Neutrino Factory
- Beta Beam with higher Q isotopes

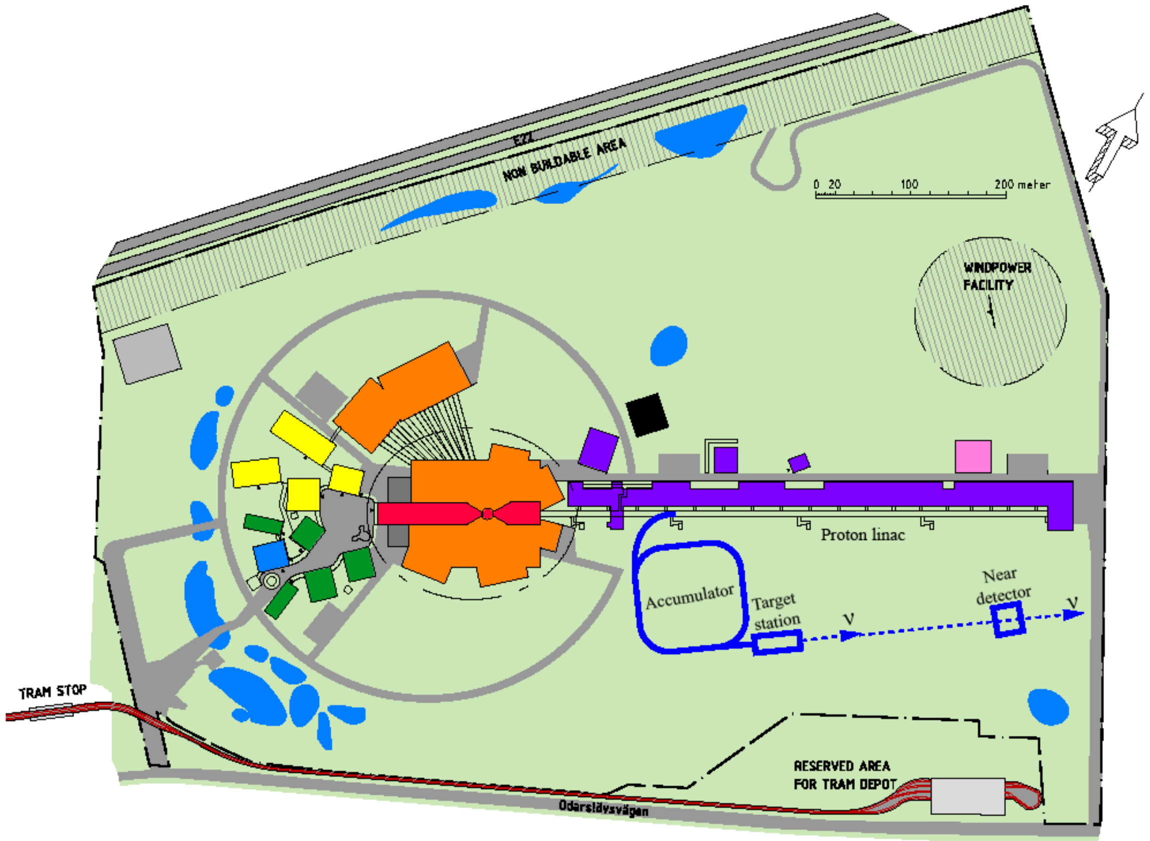
2008 – 2011: LAGUNA: *"Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics"*

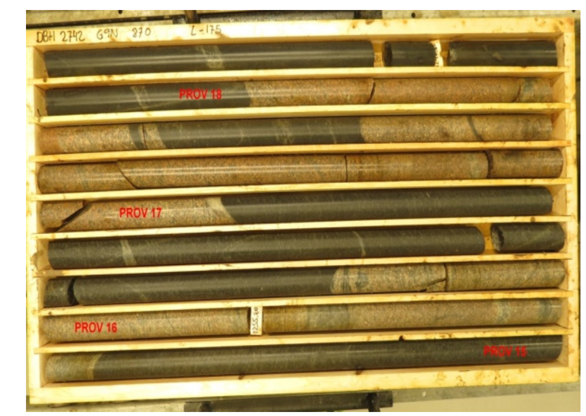
- 7 underground locations
- 3 detector technologies: LAr, LSc and WCD

2011 – 2014: LAGUNA-LBNO: *"Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations"*

- Detailed studies of 3 sites: Fréjus, Umbria and Pyhäsalmi, 130 km, 750 km and 2300 km from CERN
- Engineering design, construction and costing for LAr, LSc and WCD

Recent Idea: A Superbeam from ESS for leptonic CPV search





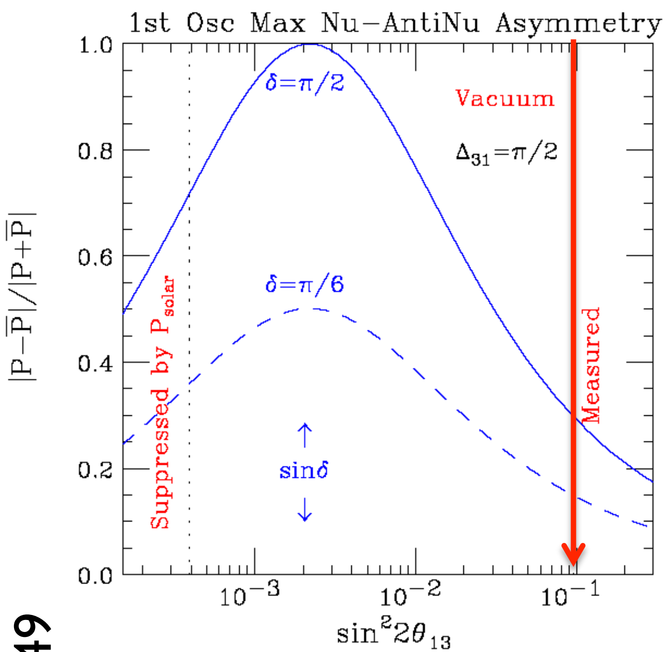
- The ESS will be a copious source of spallation neutrons
- 5 MW average beam power in the linac
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 4% duty cycle
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
- **>2.7x10^{23} p.o.t/year**
- **Doubling pulse frequency → 10 MW of which 5 MW for neutrino beam**

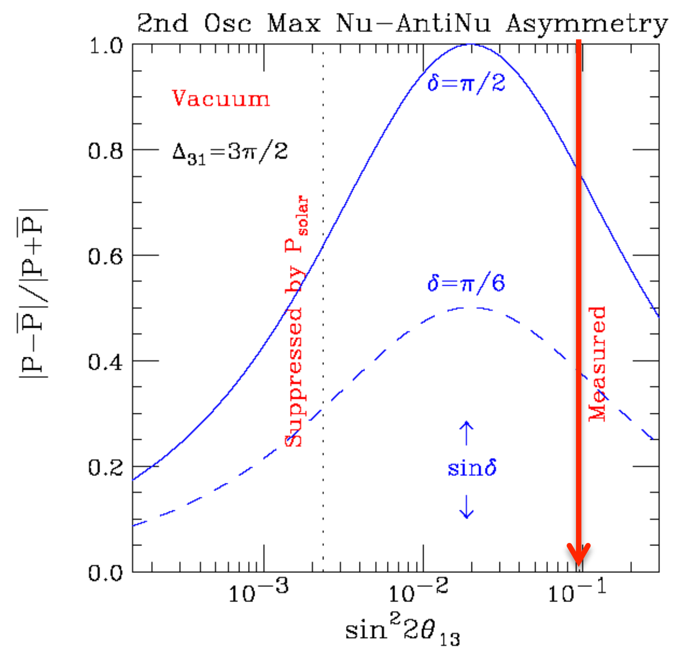
- Several mines for locating the underground MEMPHYS type Megaton Water Cherenkov Detector available in Scandinavia
- **Garpenberg Mine:**
  - **540 km from Lund**
  - **currently being investigated**
  - **1232 m depth**
  - **Truck access tunnels, two ore hoist shafts**

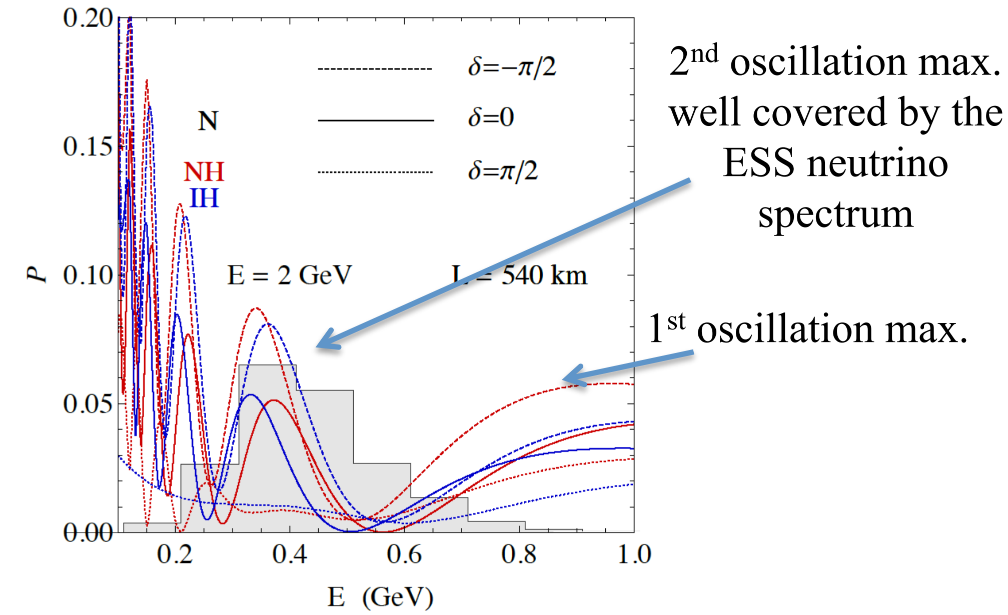
Next step: Submission of DS (2015 – 2018?)

Courtesy Tord Ekelöf

Superbeam from ESS towards a 550 kt Water Cherenkov detector at the 2nd oscillation maximum



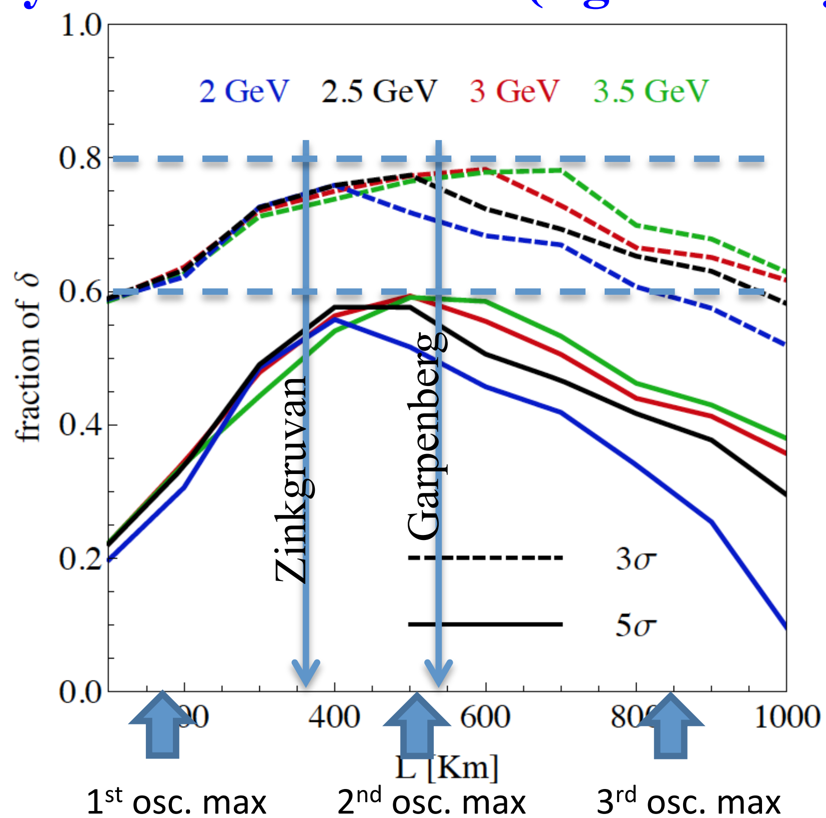




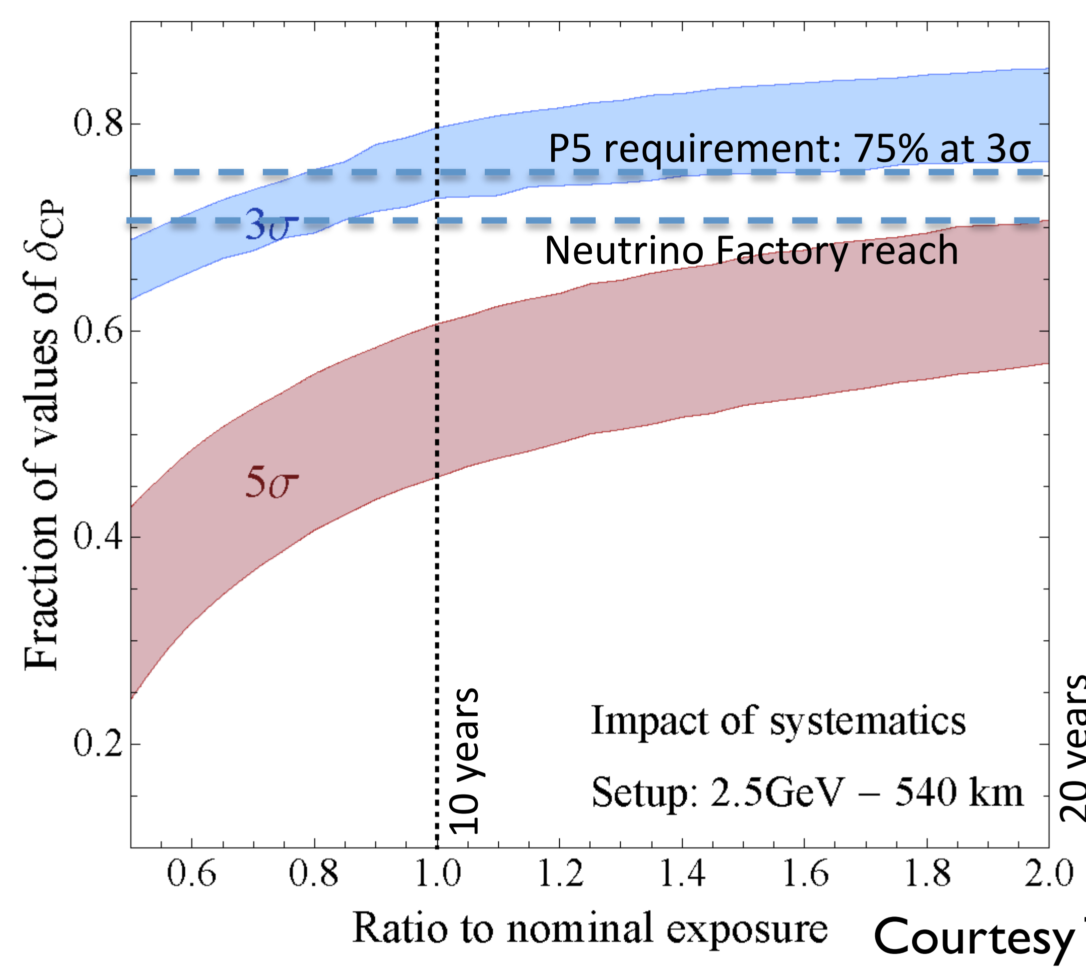
Nuclear Physics, Section B (2014), pp. 127-149

Baseline optimization

- Zinkgruvan is better for 2 GeV
- Garpenberg is better for > 2.5 GeV
- **Syst. errors: 5%/10%(signal/backg.)**



for ESSnuSB systematic errors see 1209.5973 [hep-ph] (lower limit "default" case, upper limit "optimistic" case)

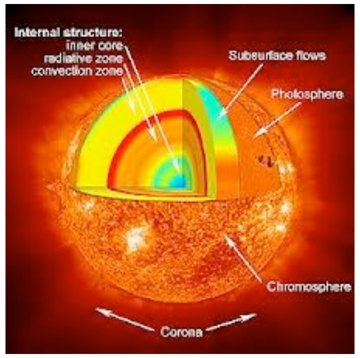


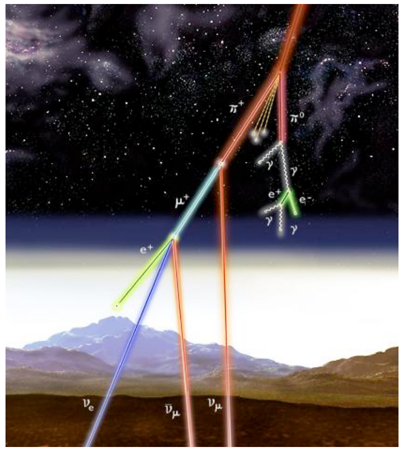
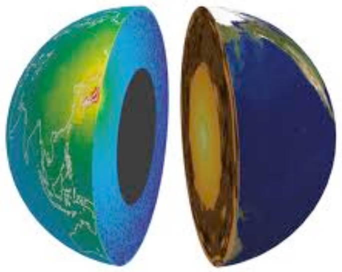
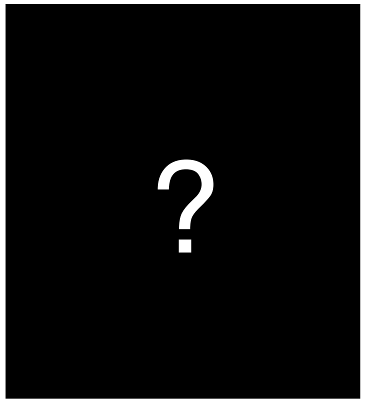
Poster M. Dracos & T. EKelöf (ID 127)

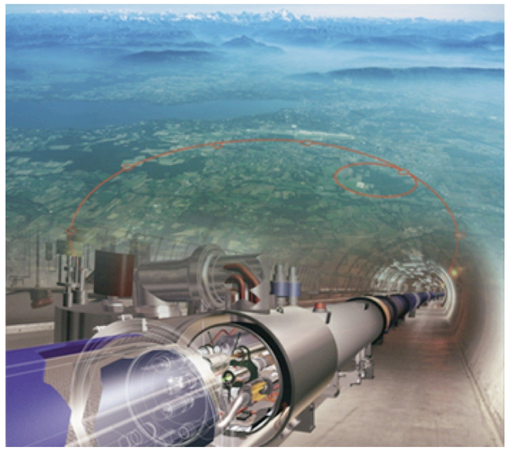
Courtesy Tord Ekelöf

LAGUNA-LBNO: A decade of steady progress…

- **GLACIER** (Giant Liquid Argon Charge Imaging ExpeRiment, **2003**)
  - New concept of Double Phase Liquid Argon TPC for CP-violation and future deep underground detector, up to 100 kton mass (hep-ph/0402110)
- **LAGUNA DS** (FP7 Design Study **2008-2011**)
  - ~100 members; 10 countries
  - 3 detector technologies ⊗ 7 sites, different baselines (130 → 2300km)
- **LAGUNA-LBNO DS** (FP7 DS Long Baseline Neutrino Oscillations, **2011-2014**)
  - ~300 members; 14 countries + CERN, 4.9 M€
  - Fully engineered detector designs for 20/50 kt DLAr, 50 kt LSc, 540 kt WCD
  - Underground Facility construction and costing (Pyhäsalmi, Fréjus and Umbria)
  - Extended site investigation at Pyhäsalmi mine
- **LBNO** (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, **June 2012**) - CERN-SPSC-2012-021 ; SPSC-EOI-007)
  - An incremental approach with high level physics starting from phase 1 (MH + LCPV + Astro)
  - ~230 authors; 51 institutions
- **WA105** (CERN experiment, **August 2013**)
  - kt-scale demonstrator for LBNO @ CERN: engineering and charged particle calibration



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

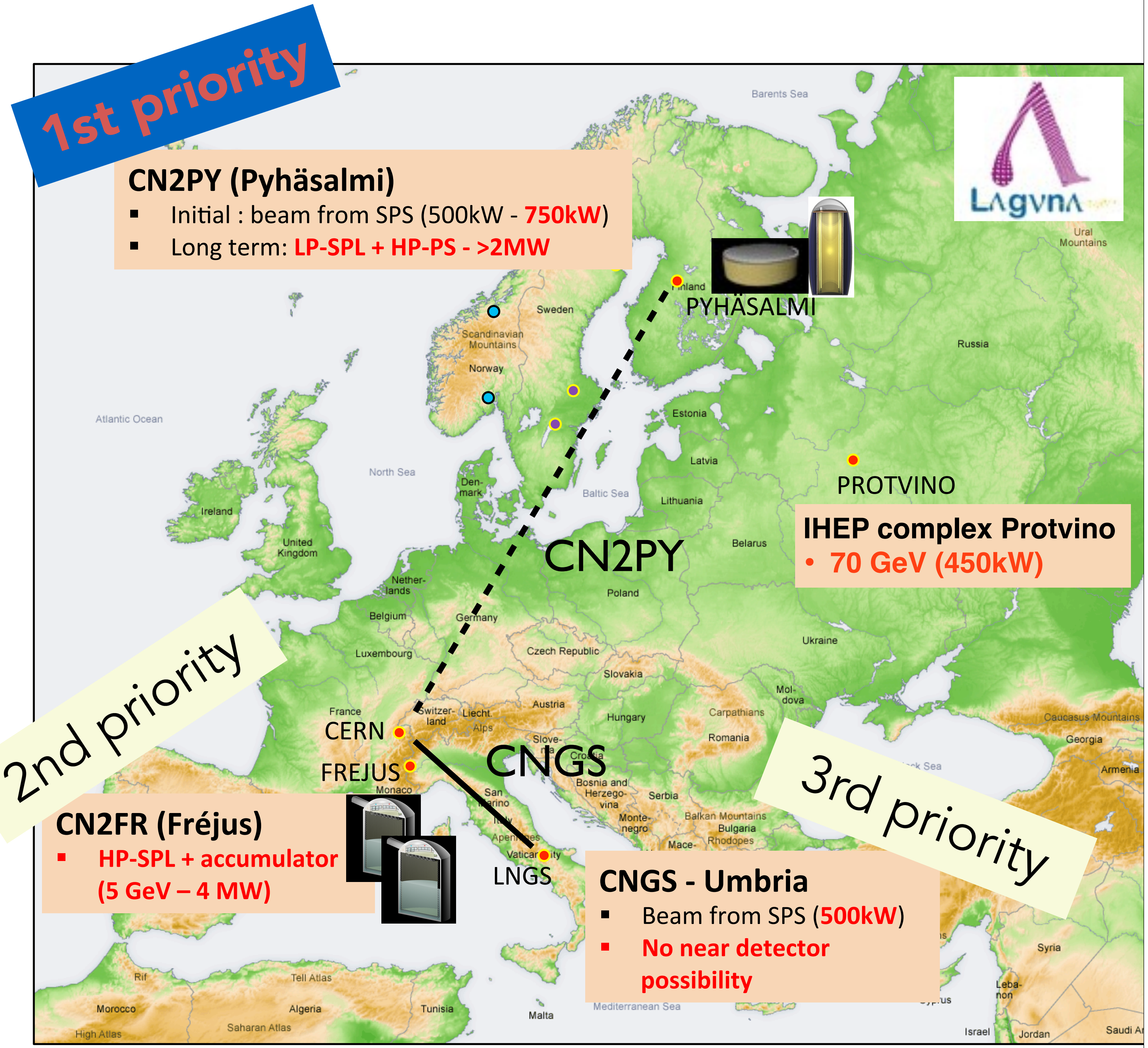
4. Dark Matter:
   - Indirect from WIMP annihilation is the sun

Neutrino physics provides us with surprises beyond the SM!

Site prioritisation

Several sites considered in details

- **Pyhäsalmi mine** (privately owned), 4000 m.w.e overburden, excellent infrastructure for deep underground access
- **Fréjus**, nearby road tunnel, 4800 m.w.e. overburden, horizontal access
- **Umbria** (LNGS extension), green site with horizontal access, 2000 m.w.e., CNGS off-axis beam



LAGUNA-LBNO Strategy for MH and LCPV

- Very long baseline (2300 km) to explore the L/E oscillation pattern predicted by the 3 flavor mixing paradigm over the 1st and 2nd max

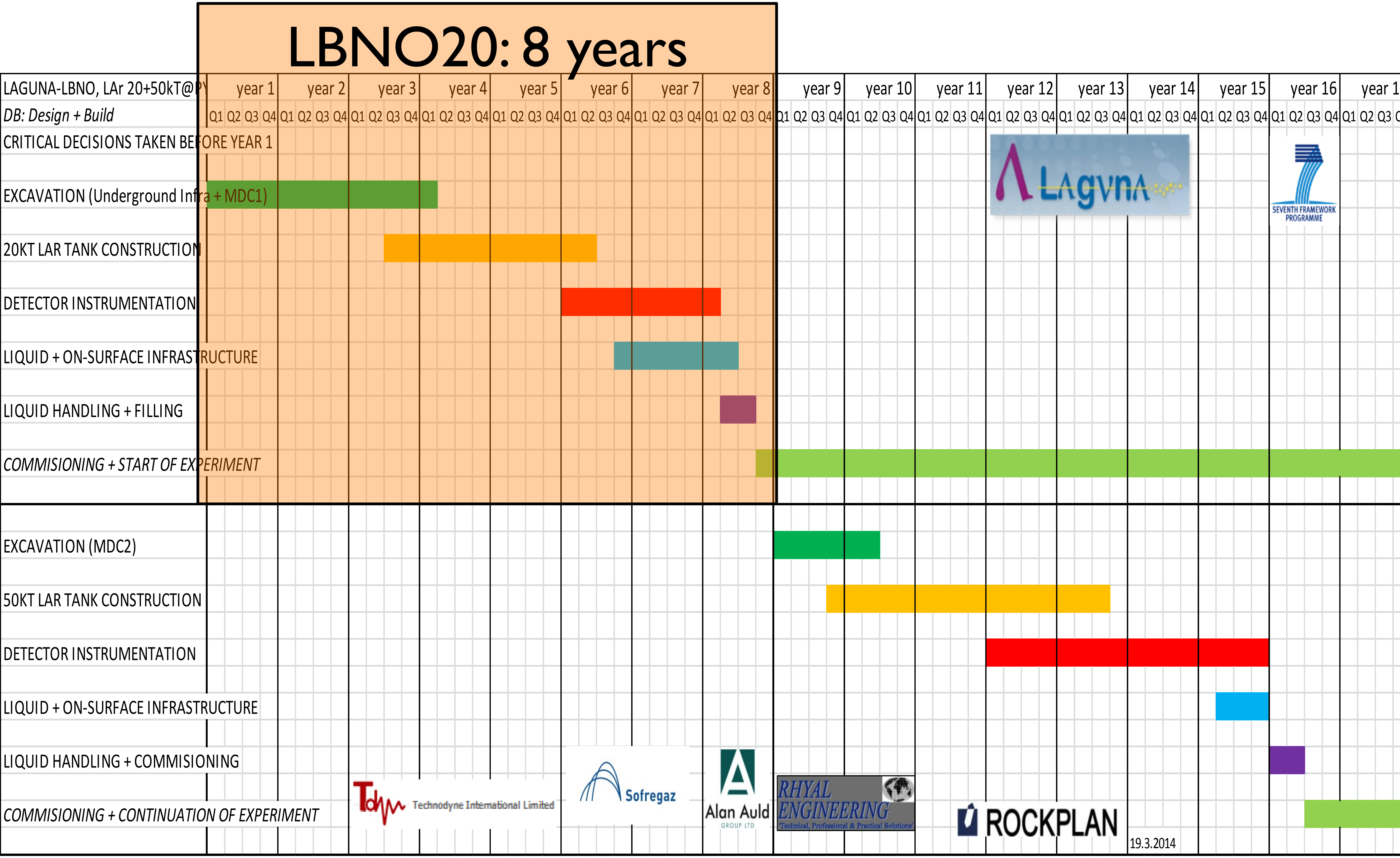
- Phased experiment to adjust the beam and detector mass with respect to the findings of phase n-1 to use resources in the most efficient way (incremental approach).

- LBNO has a fully engineered design, construction plan and costing for the underground infrastructure, the detector and the beam for all phases of the experiment.

- Phase I (LBNO20):
  - 24 kt fid. DLAr + SPS beam (750 kW, Ep = 400 GeV)
  - Guaranteed 5 σ MH determination + 46 % δ_{CP} coverage at 3 σ + p-decay + astroparticles
  - Estimated cost (detector + infrastructure + contingency): ≈ 210 M€ +/- 10%

- Phase II (LBNO70):
  - 70 kt fid. DLAr + HPPS beam (2 MW, Ep = 50 GeV) or Protvino beam
  - 80 % δ_{CP} coverage at 3 σ + p-decay + astroparticles

TECHNICAL TIMESCALE FOR CONSTRUCTION LAGUNA-LBNO 20+50KT



Recent update of the LBL physics program:

10.1007/JHEP05(2014)094

Prepared for submission to JHEP

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

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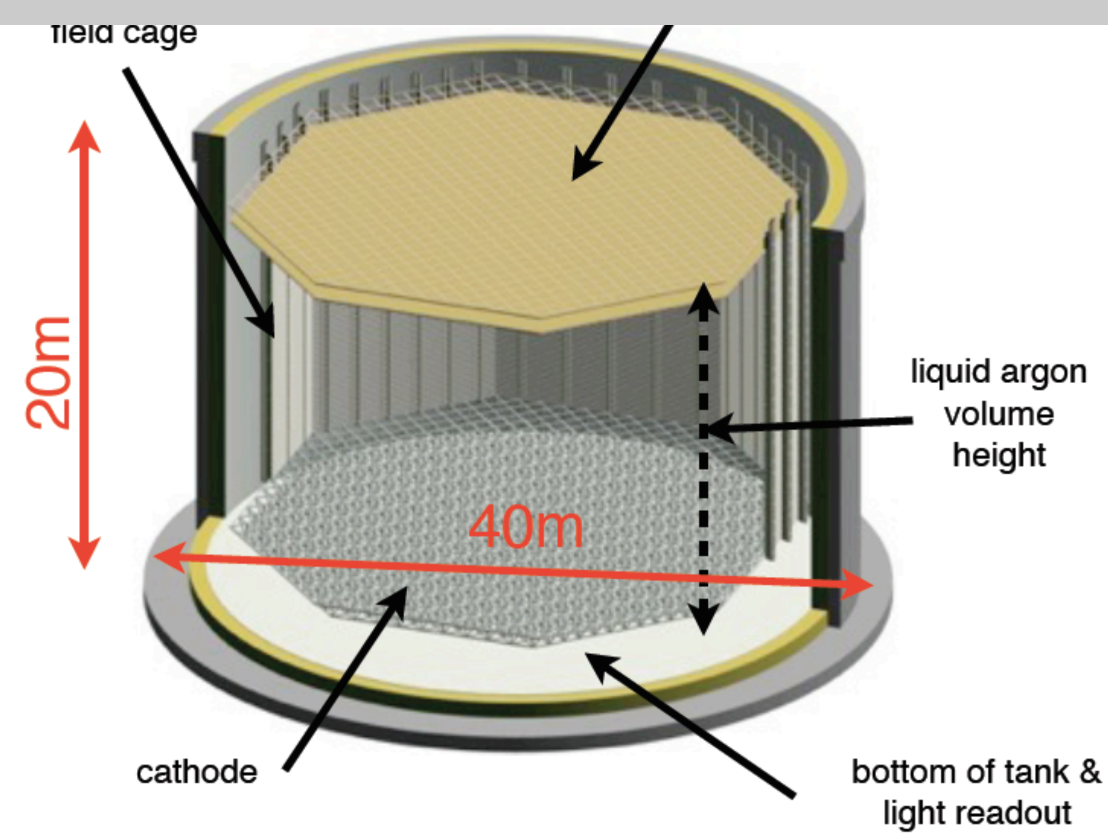
Basic assumptions :

- Realistic systematics
- 2300 km baseline
- SPS 400 GeV protons – 750 kW beam
- HPPS 50 GeV protons – 2 MW beam
- Liquid Argon double phase detector GLACIER :
  LBNO20 -> LBNO70



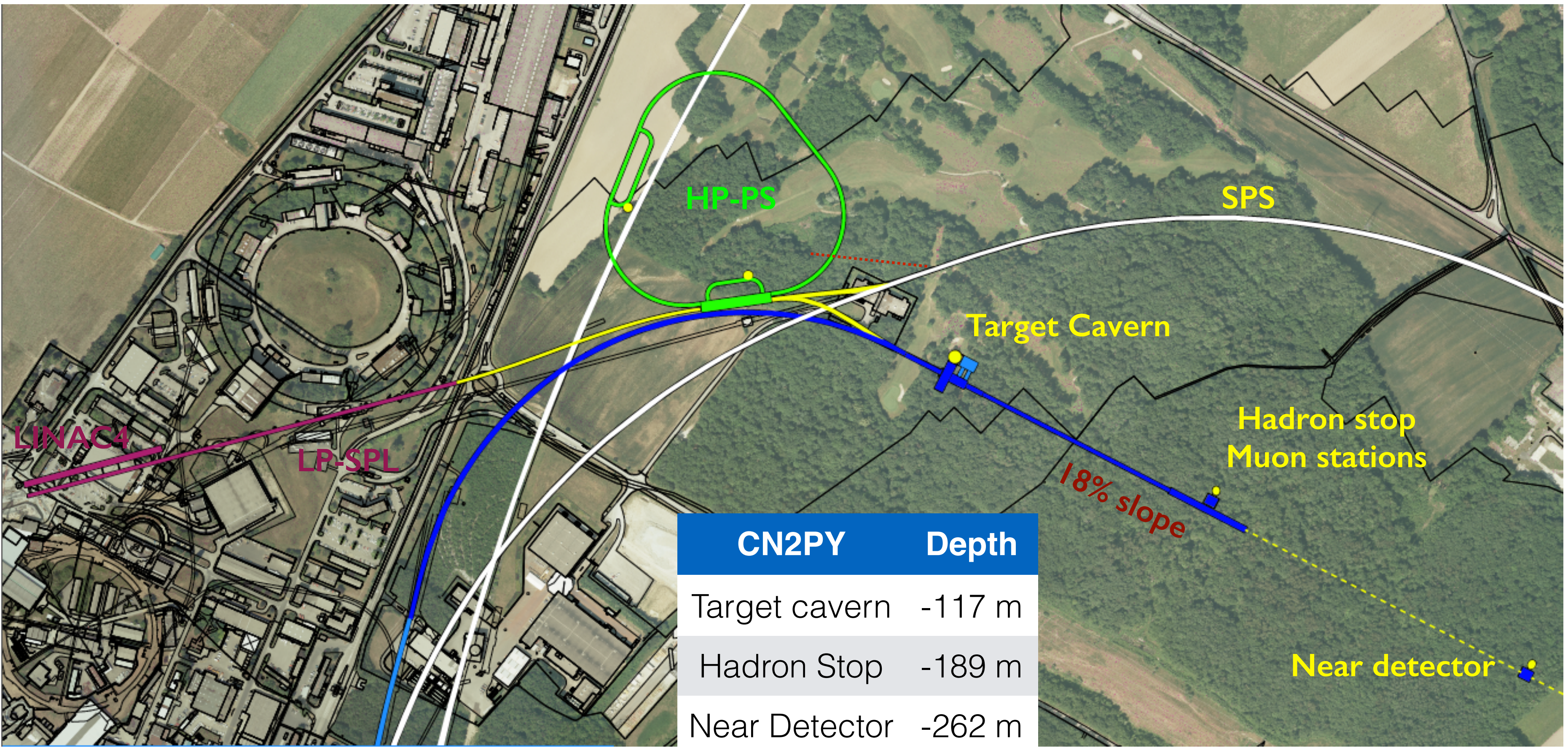
Updated beam LBNO design

Phase 1 : proton beam extracted beam from SPS

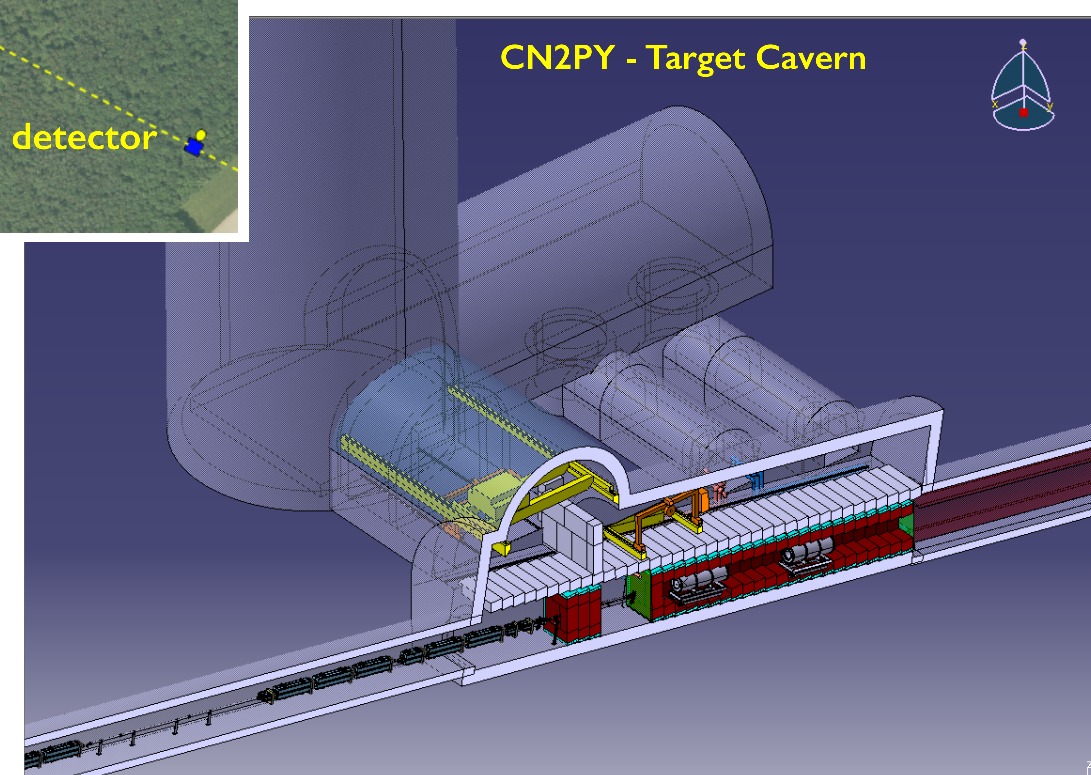
400 GeV, max 7.0 10^{13} protons every 6 sec, ~750 kW beam power, 10 μs pulse

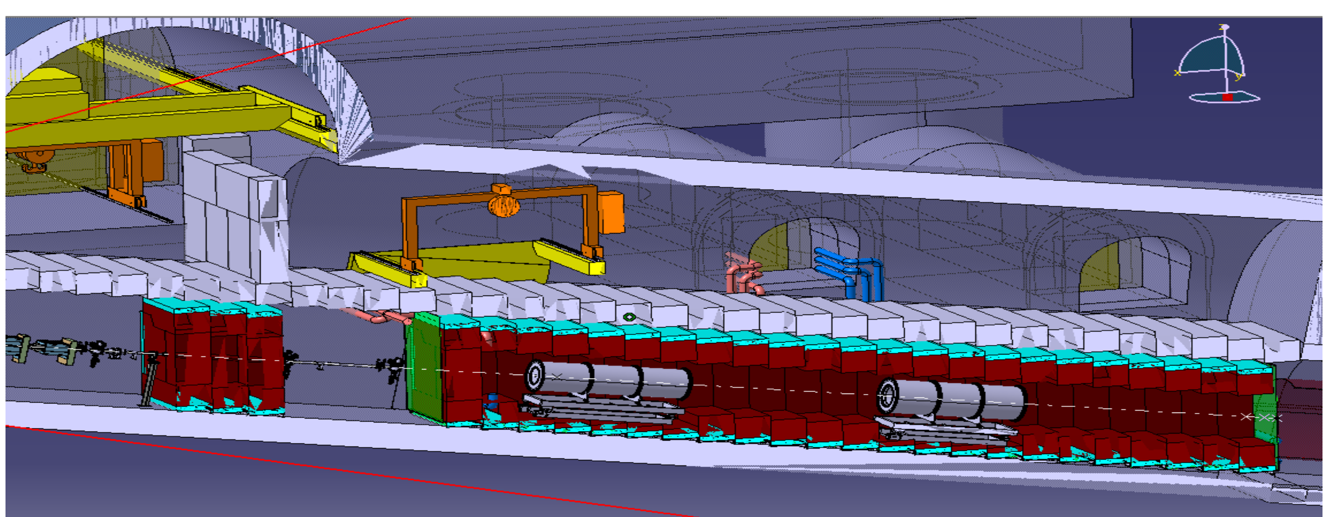
Phase 2 : use the proton beam from a new HP-PS

50 GeV, 1 Hz, 2.5 10^{14} ppp, 2 MW beam power, 4 μs pulse

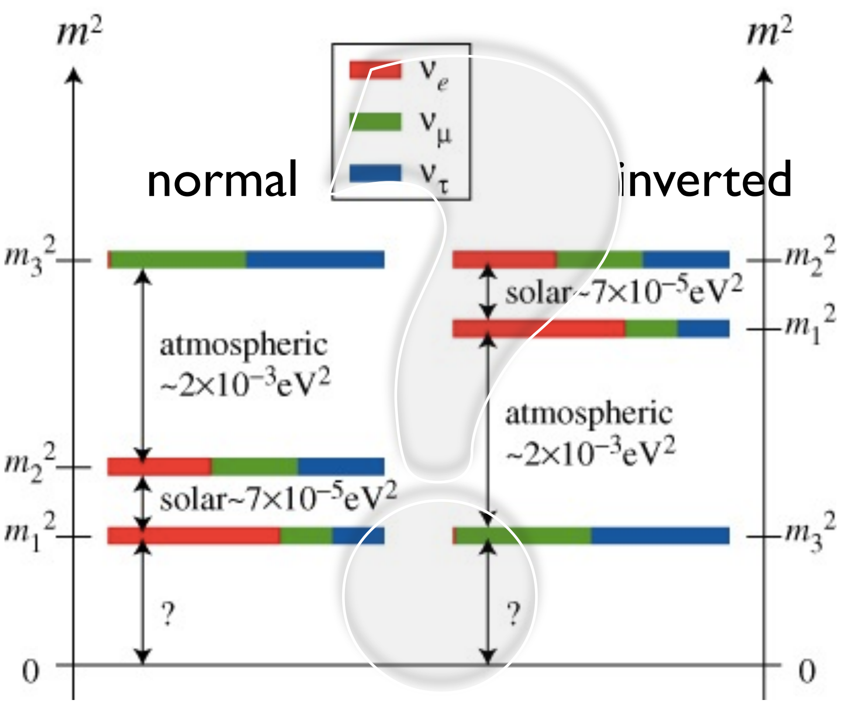


CN2PY	Depth
Target cavern	-117 m
Hadron Stop	-189 m
Near Detector	-262 m





Mass Hierarchy is a fundamental measurement



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

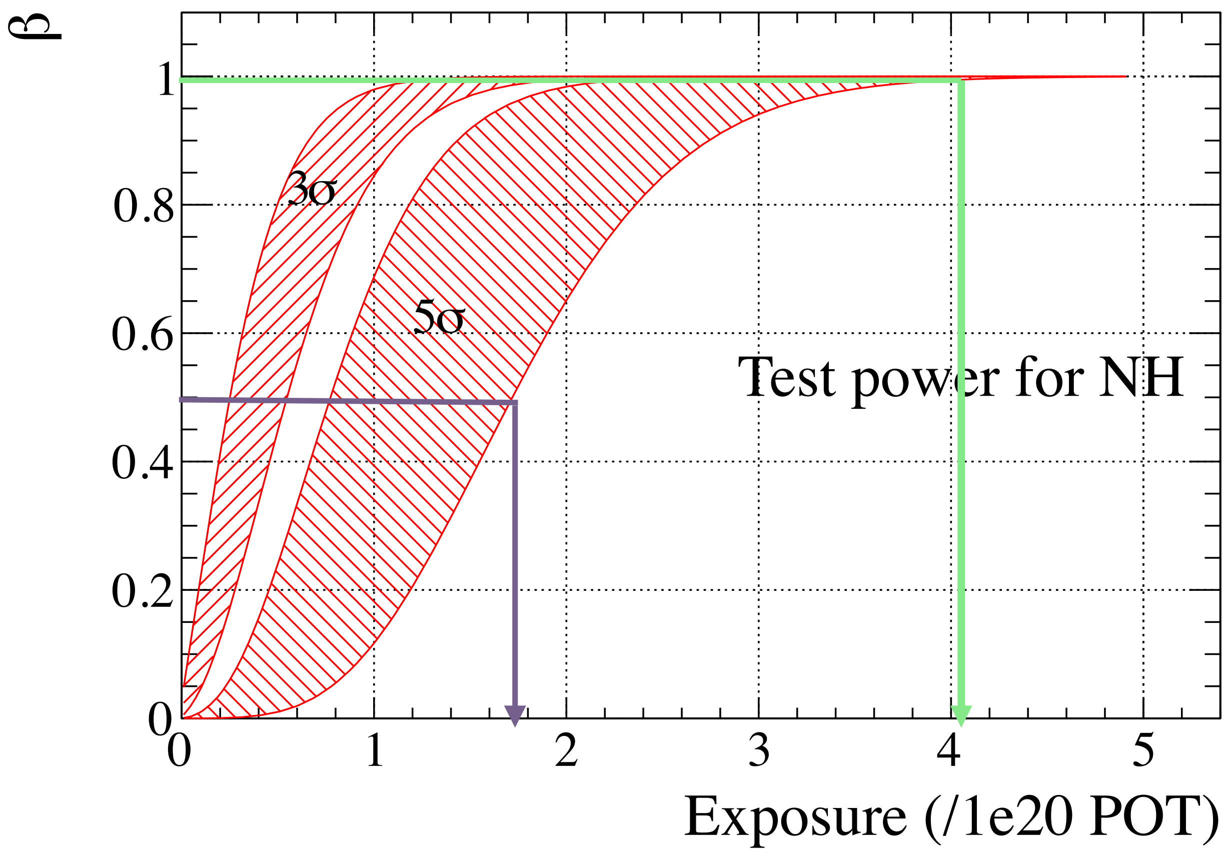
LBNO strategy on MH:

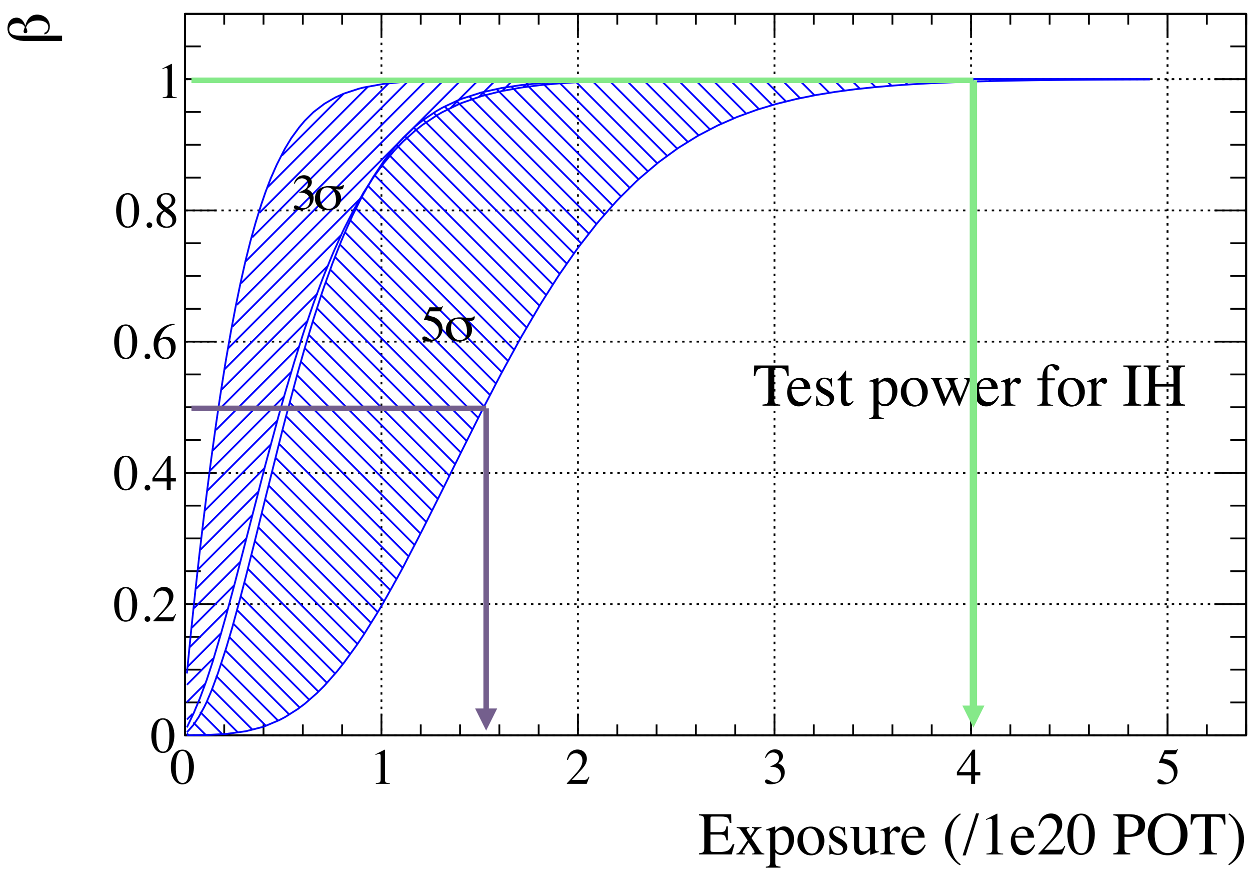
10.1007/JHEP05(2014)094

- To guarantee the measure MH on the > 5 σ level one need to go to very long baselines > 2000 km.
- Accelerator based -> most direct and least systematic prone method (change horn polarity)
- MH should be settled early in the exp. to optimize the ν / $\bar{\nu}$ 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 4-5 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.

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!

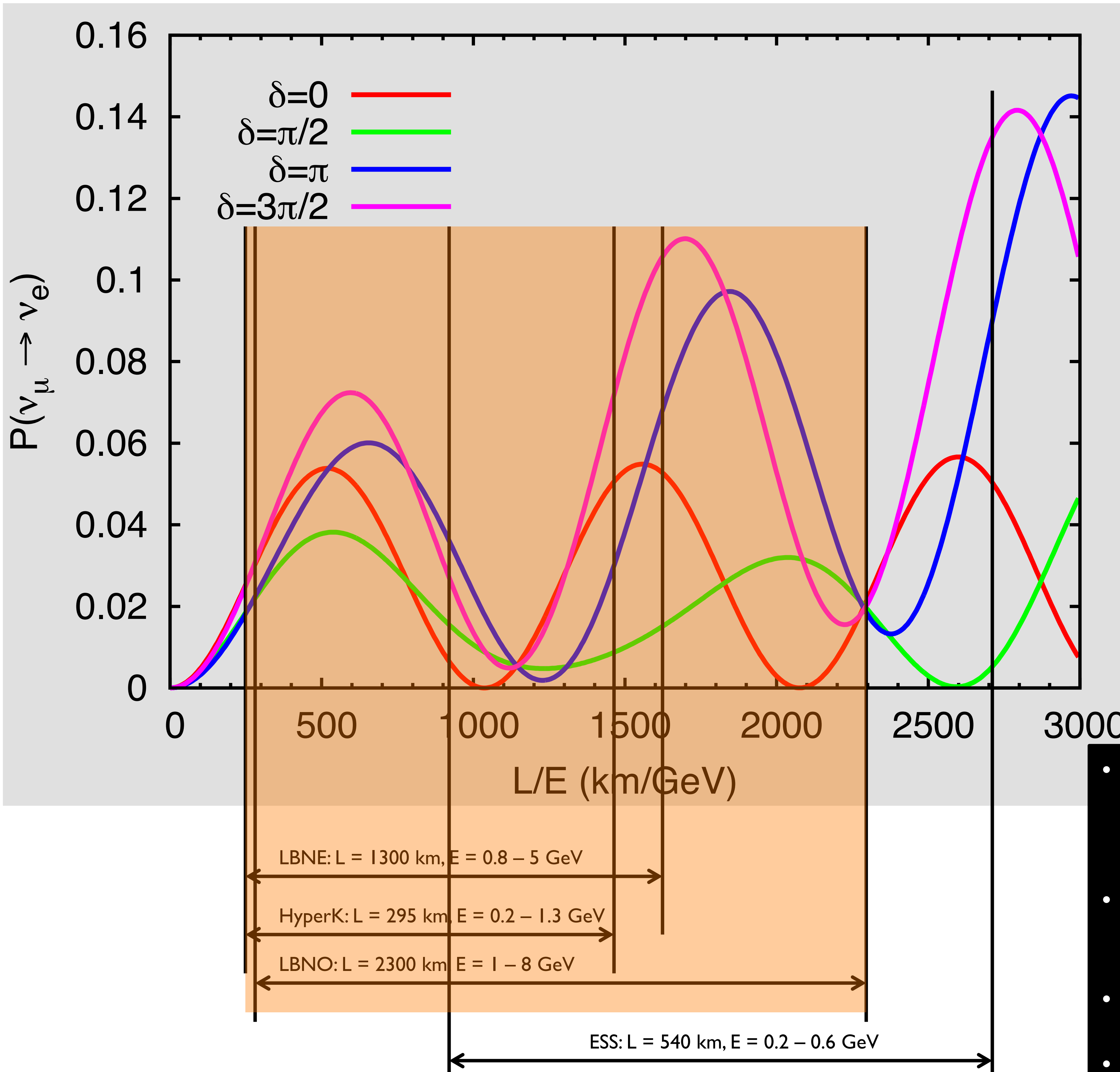
p ~1 => "Full power experiment"
~ 100% chance to achieve the projected CL!

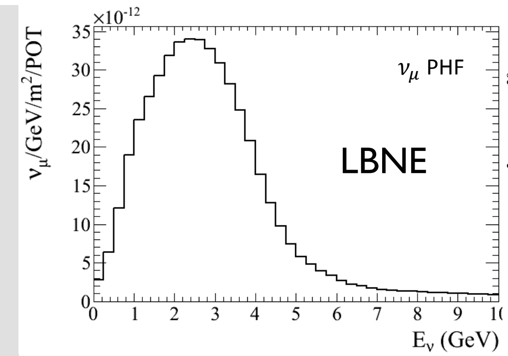
THE LBNO CHOICE TO QUOTE SENSITIVITY

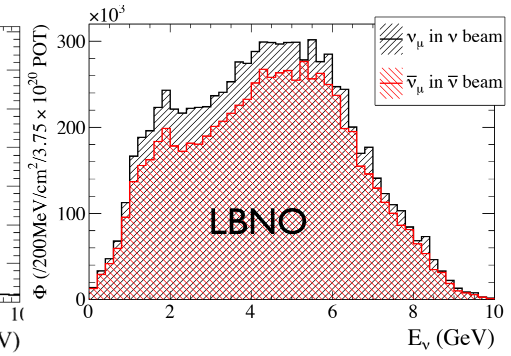
LBNO20 (Phase I of LBNO) discovers MH in ≈ 2 y

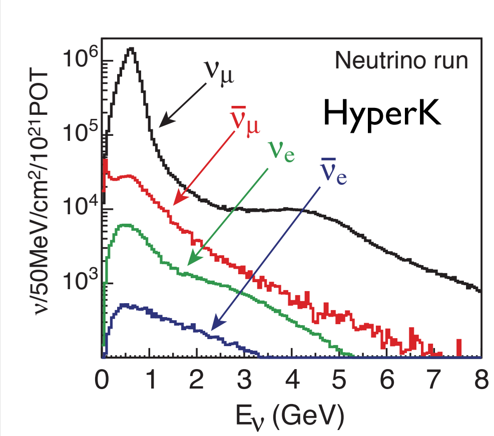
CP Violation with LBNO

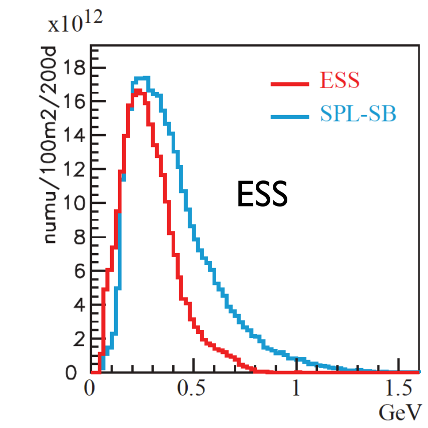
I[st] and 2[nd] maximum and the wiggles of L/E…









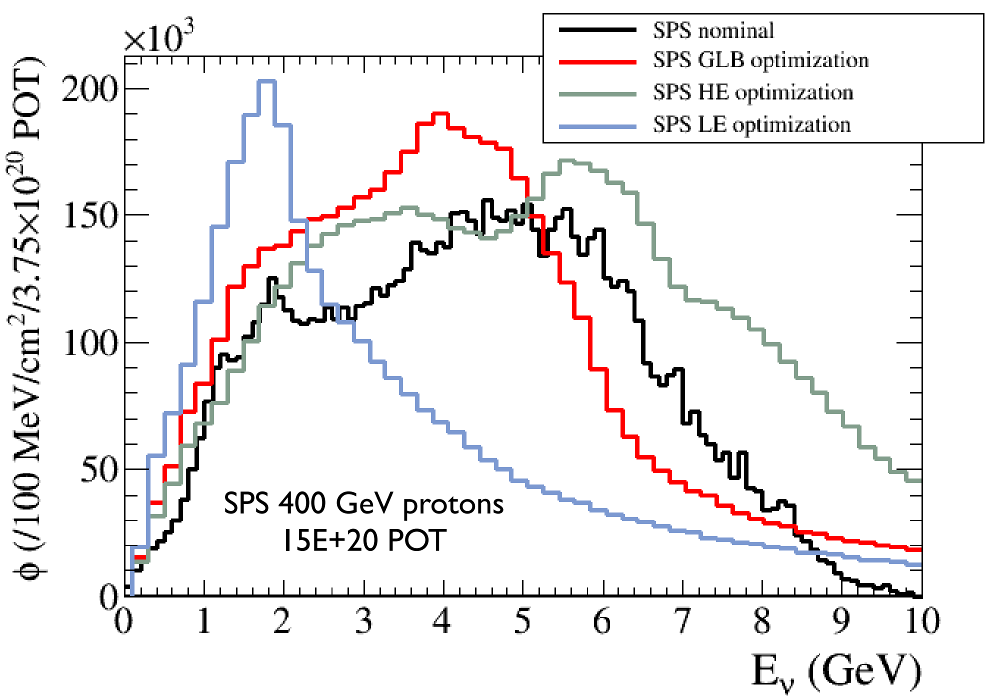


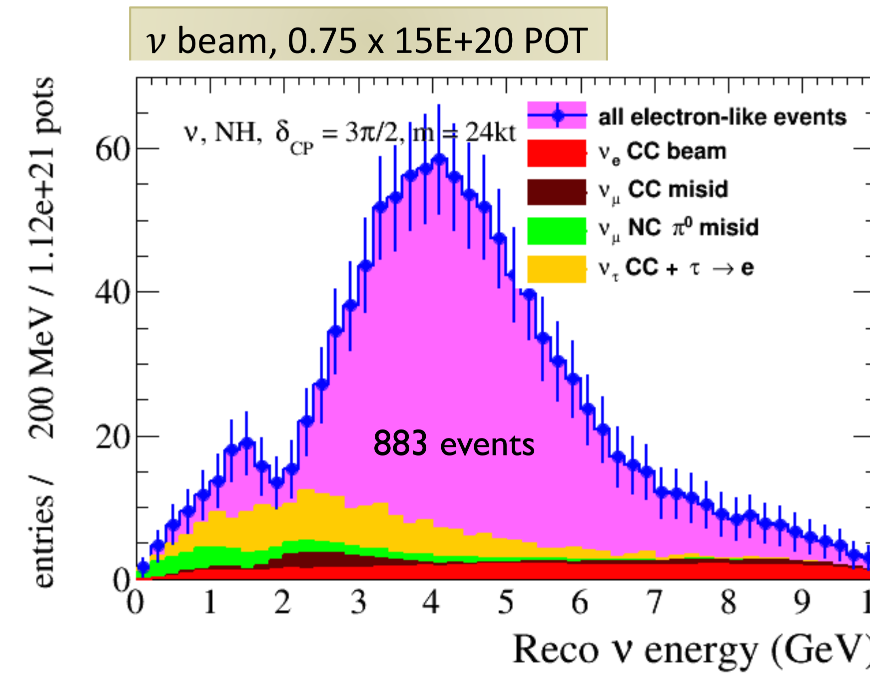
- CP sensitivity depends on the ability to measure the L/E behavior and the I[st] and 2[nd] maximum and on the control of systematic errors.
- Low energies are disfavored since flux & x-section are suppressed. One need to go higher L/E.
- LBNO has better L/E coverage then LBNE and HK.
- LBNE and HK have similar coverage.

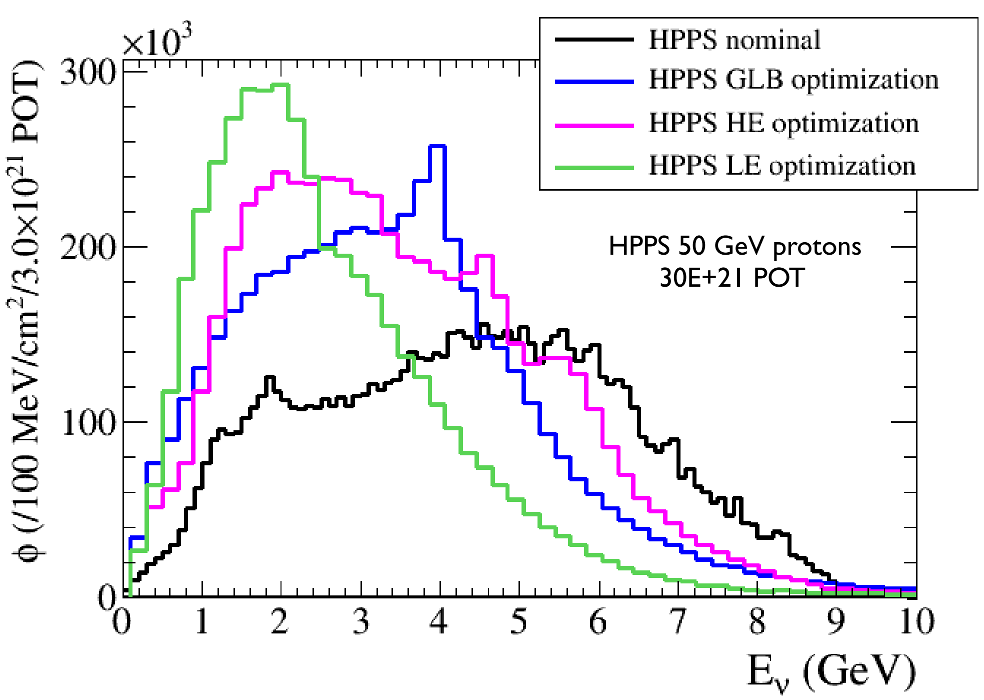
CP Violation with LBNO

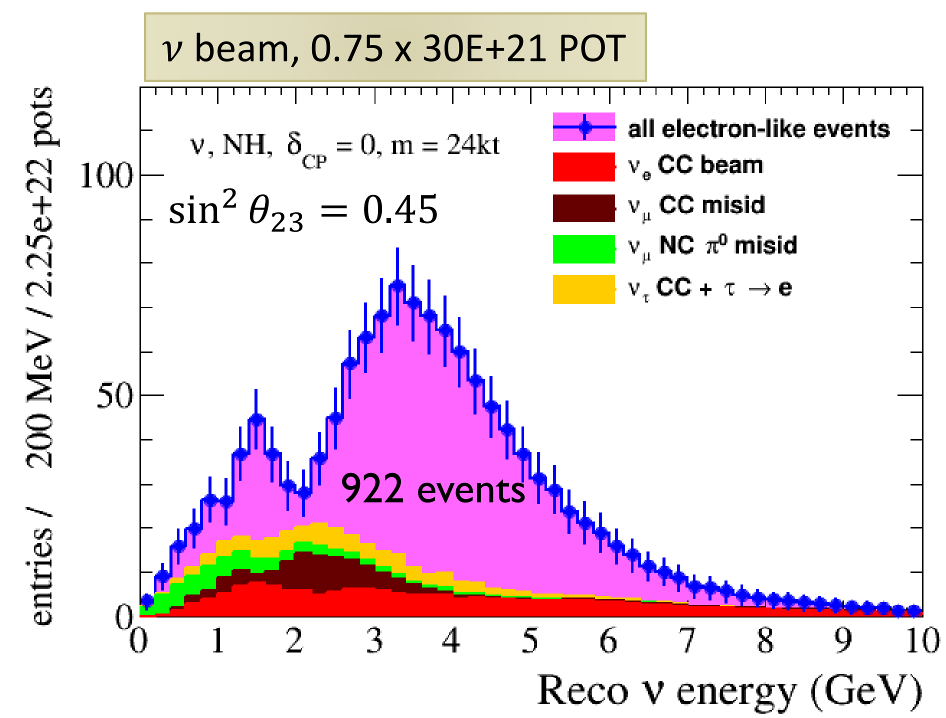
Measure δ_{CP} by measuring the energy dependence of the neutrino spectrum, the **L/E behavior**, and the **2nd maximum**, this is fully complementary to the HK proposal which measures the asymmetry between nu and anti-nu oscillation probabilities at the first maximum.

Continuous effort to optimize the beam to enhance the CPV coverage of the experiment:









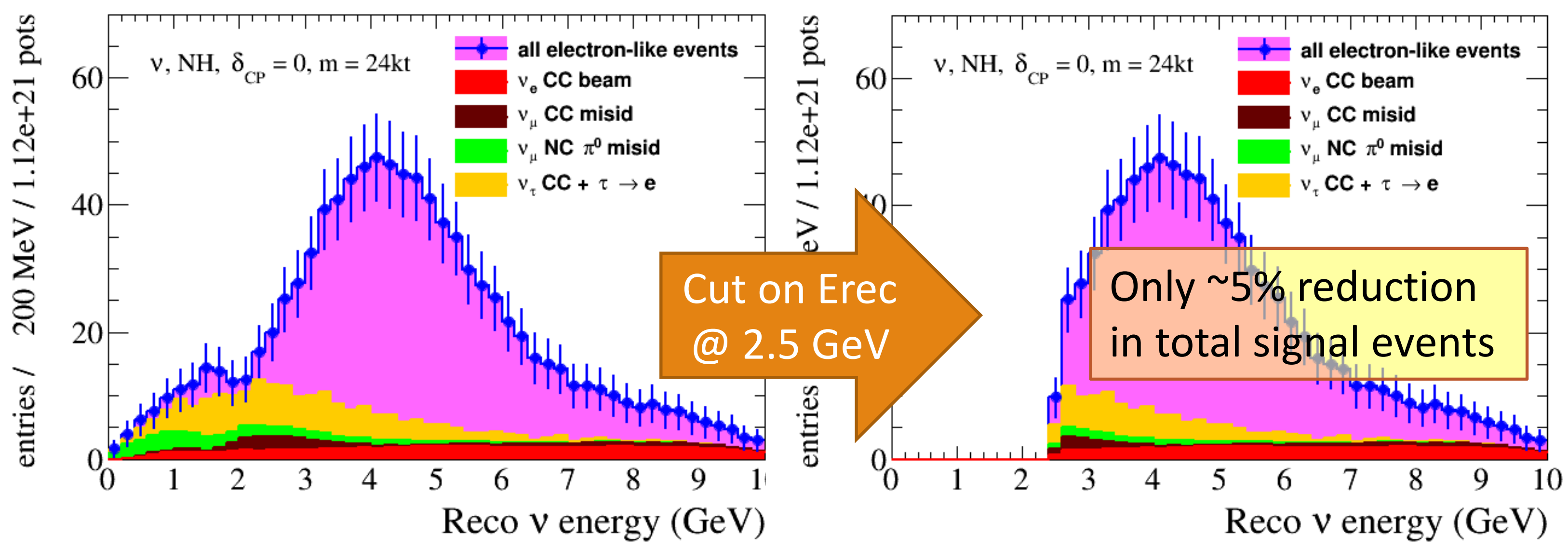
Poster L.Agostino (ID 47)

Best CPV coverage is obtained for "SPS GLB" and "HPPS LEOPT"

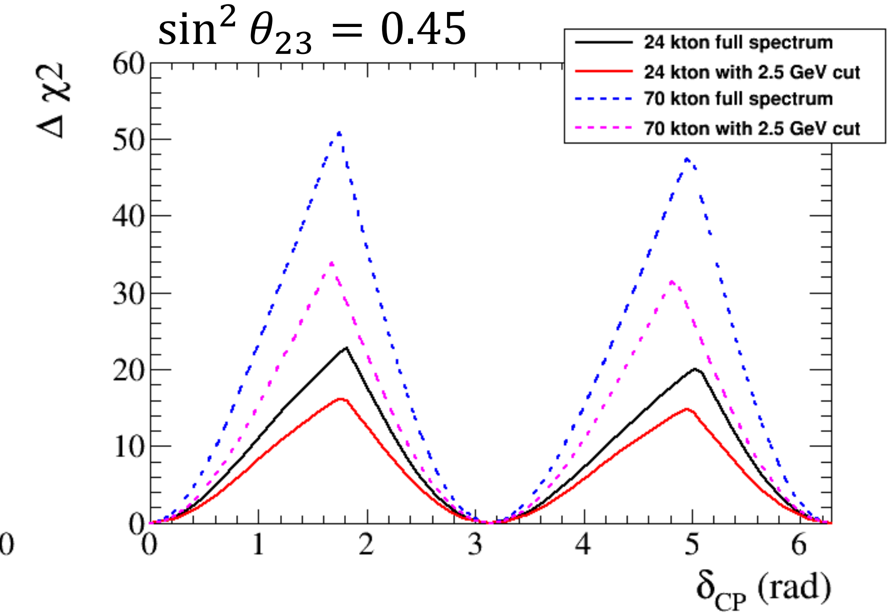
CP Violation with LBNO

The power of the 2nd maximum and L/E:

SPS beam, 15E+20 POT

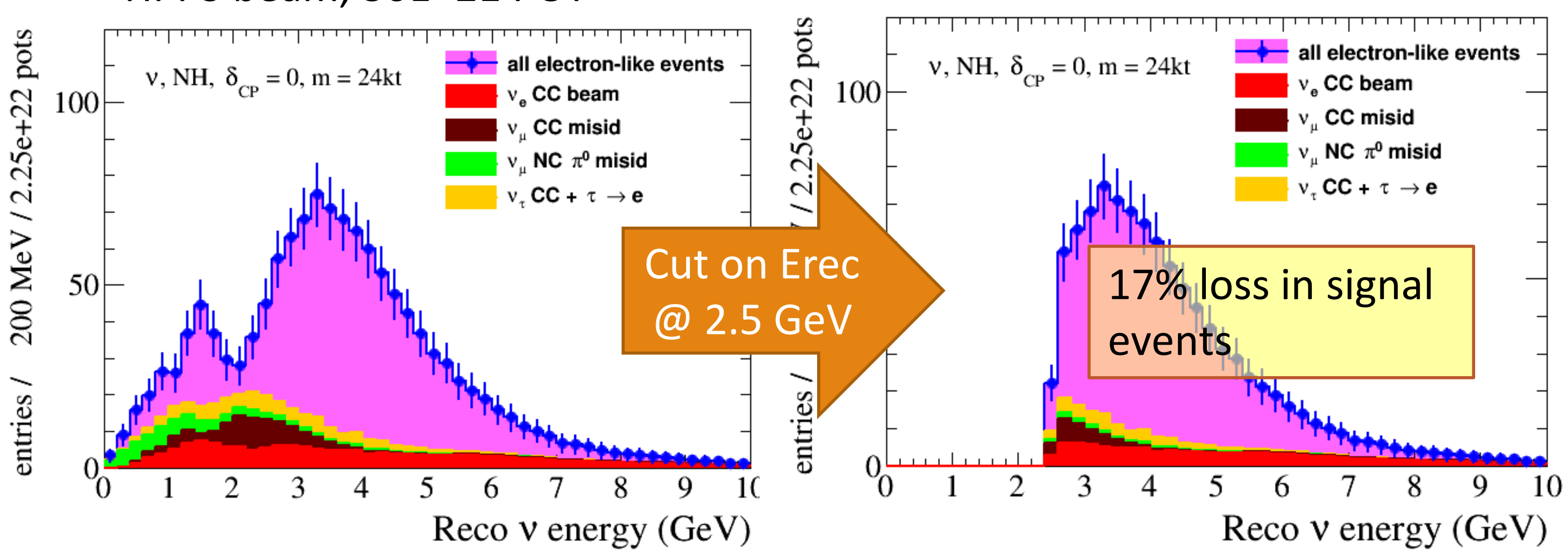


$\sin^2\theta_{23} = 0.45$

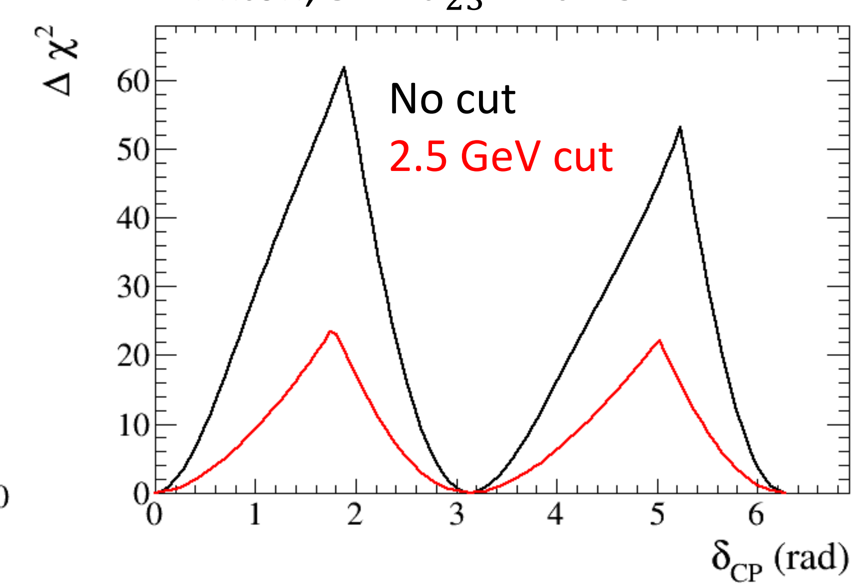


10 % loss in CP coverage

HPPS beam, 30E+21 POT



24 kton, $\sin^2\theta_{23} = 0.45$



Dramatic effect in the HPPS beam! Loss of 30 % coverage at 3 σ and 100% at 5 σ

CP Violation with LBNO

Assumed values and errors for oscillation parameters and systematics

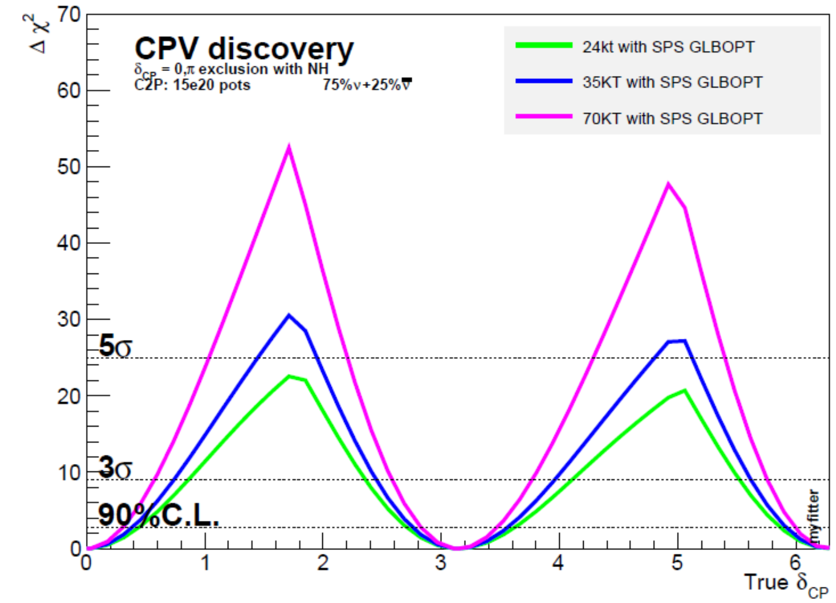
Parameter	Value	Error
L	2300 km	exact
Δm^2_{21}	7.45×10^{-5} eV^2	fixed
Δm^2_{31}	2.42×10^{-3} eV^2	2 %
$\sin^2\theta_{12}$	0.306	fixed
$\sin^2\theta_{23}$	0.446	5 %
$\sin^2 2\theta_{13}$	0.09	3 %
ρ	3.20 g/cm^3	4 %

www.nu-fit.org

After TAUP 2013

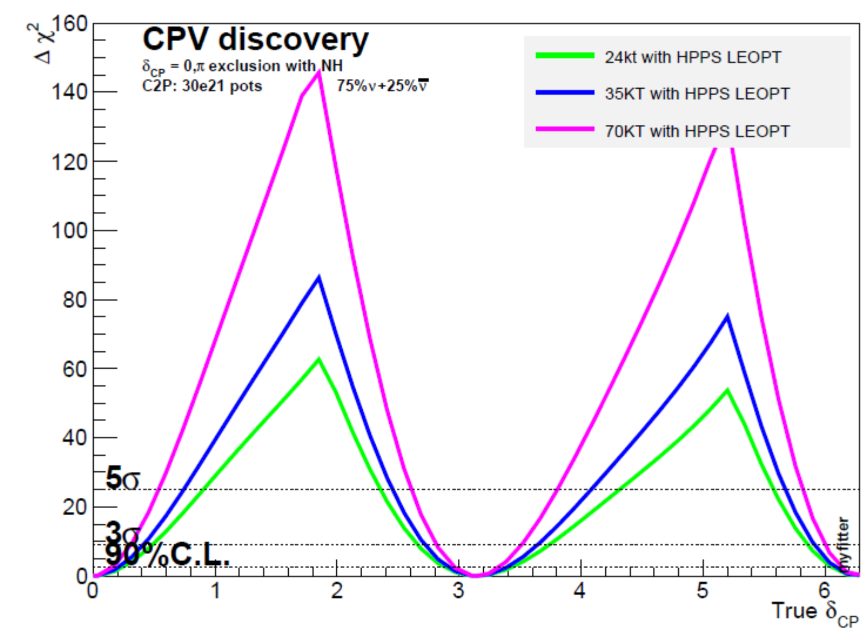
Parameter	Value	Error
Signal normalization (f_{sig})	1	3 %
Beam electron contamination normalization ($f_{\nu e}$)	1	5 %
Tau normalization ($f_{\nu\tau}$)	1	20 %
ν NC and ν_μ CC background (f_{NC})	1	10 %

LBNO Phase I (24 kt) with Optimized SPS beam: Covers 47 % CPV space at 3 σ



Remark: Similar results are obtained with LBNO @ Garpenberg

LBNO Phase II (70kt) with Optimized HPPS beam: Covers 80 % CPV space at 3 σ



Remark: Alternatively an additional beam from Protvino instead of HPPS

LAGUNA-LBNO TB SUMMARY OF WORK

IN TOTAL 3000 PAGES: Release August 2014

Huge amount of work has been accomplished:

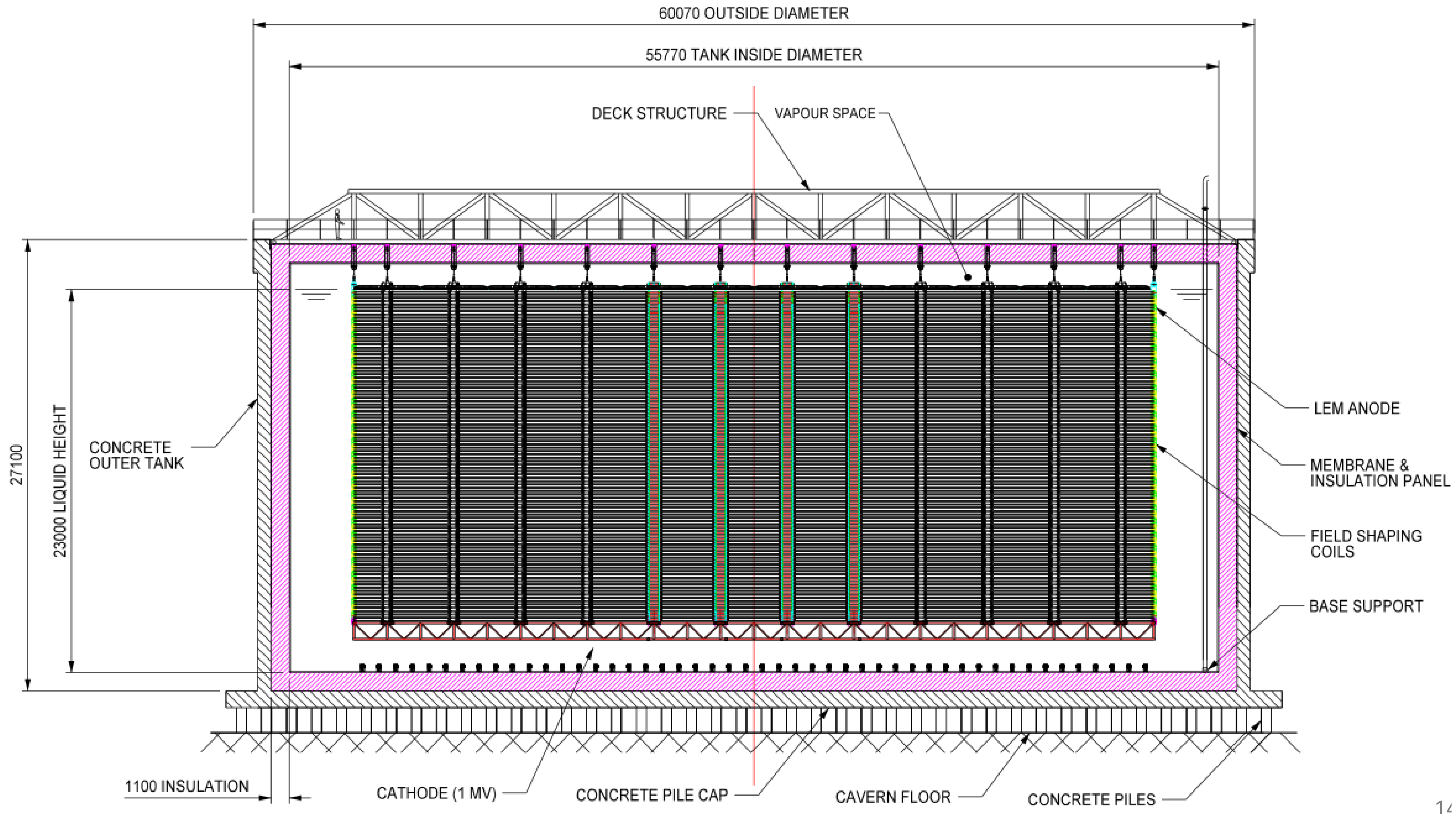
1400 person-months: all sites visited

Mobile phones work and internet available also at 1400 m

250 m long tunnel and a cavern at 1400m excavated for LAGUNA R&D

Engineering done by world class industrial partners

From the LAGUNA-LBNO DS we have **highly detailed** detector and process engineering designs, construction sequence, risk analysis, Infrastructure design and costing



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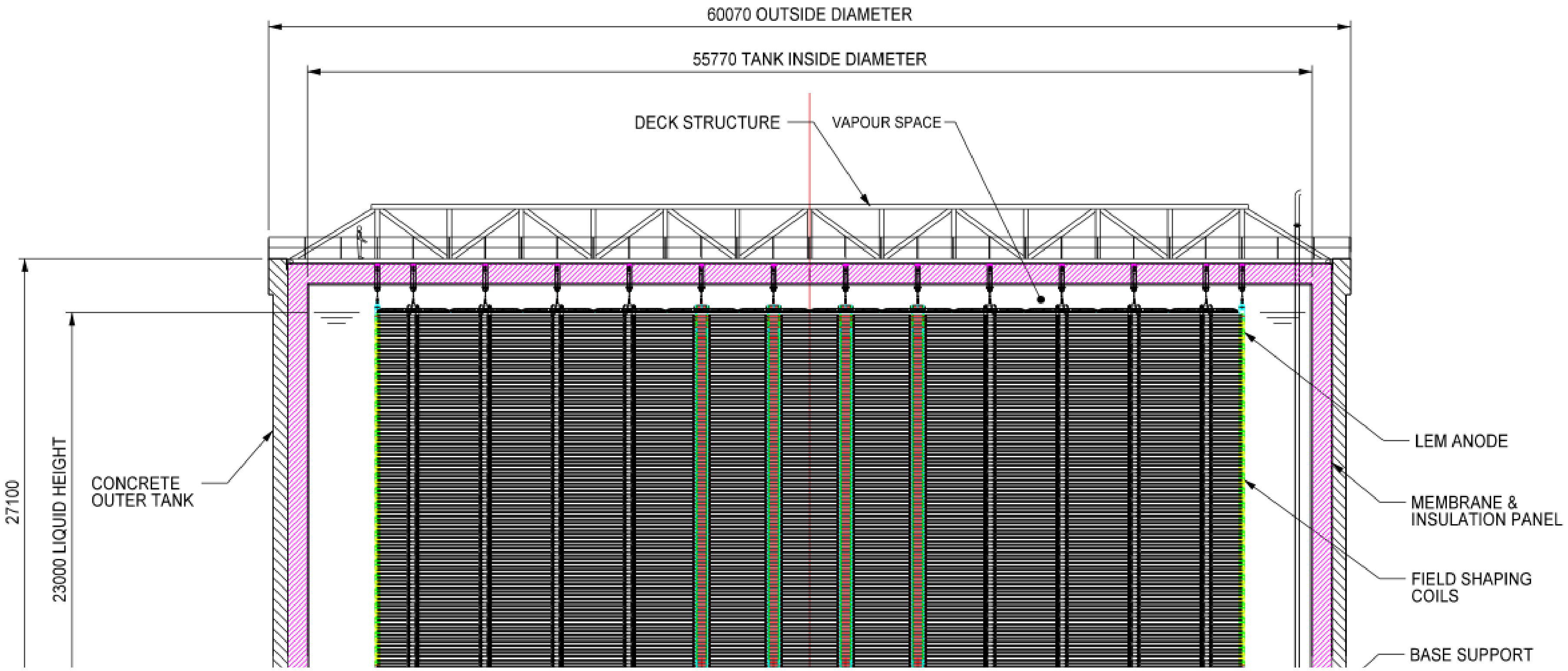
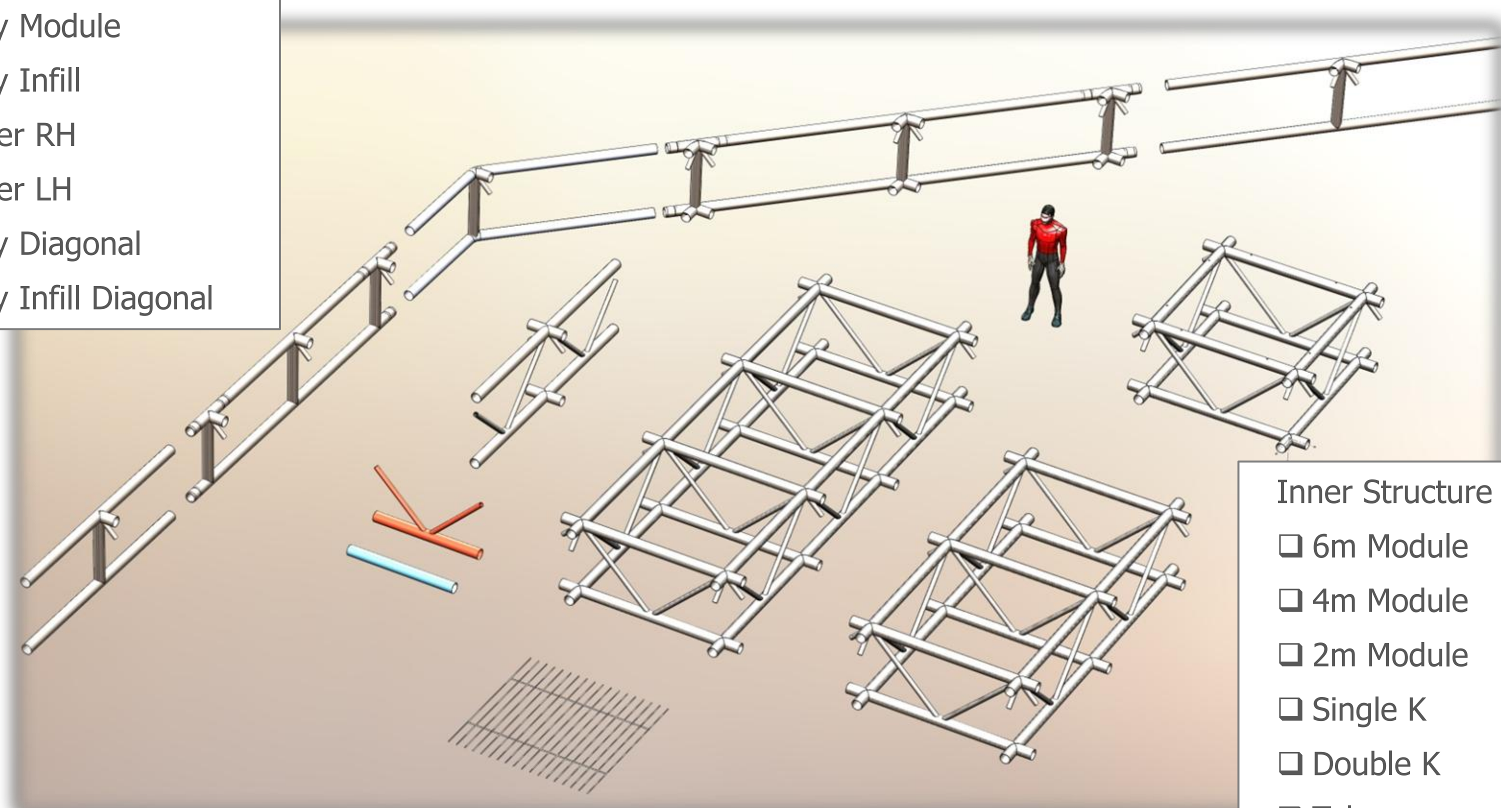


Peripheral Structure

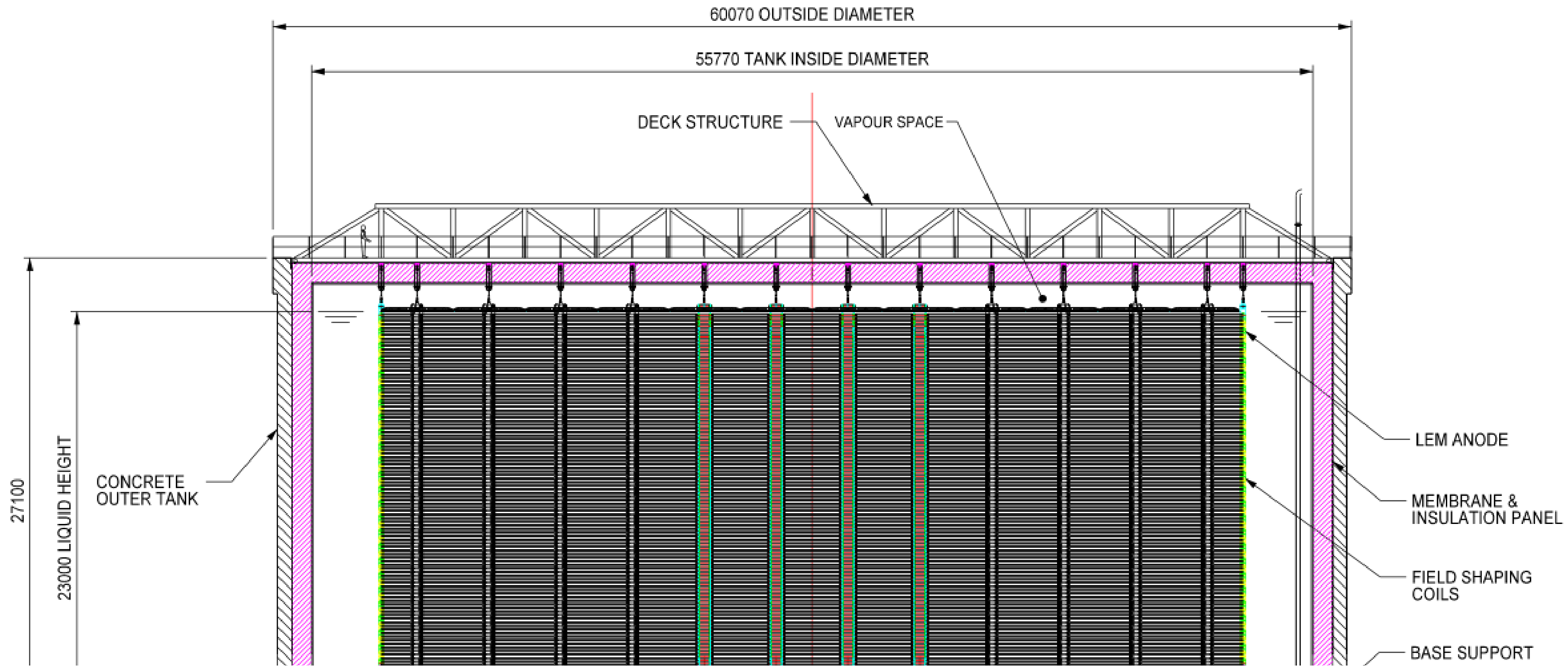
- 2 Bay Module
- 2 Bay Infill
- Corner RH
- Corner LH
- 2 Bay Diagonal
- 2 Bay Infill Diagonal



Inner Structure

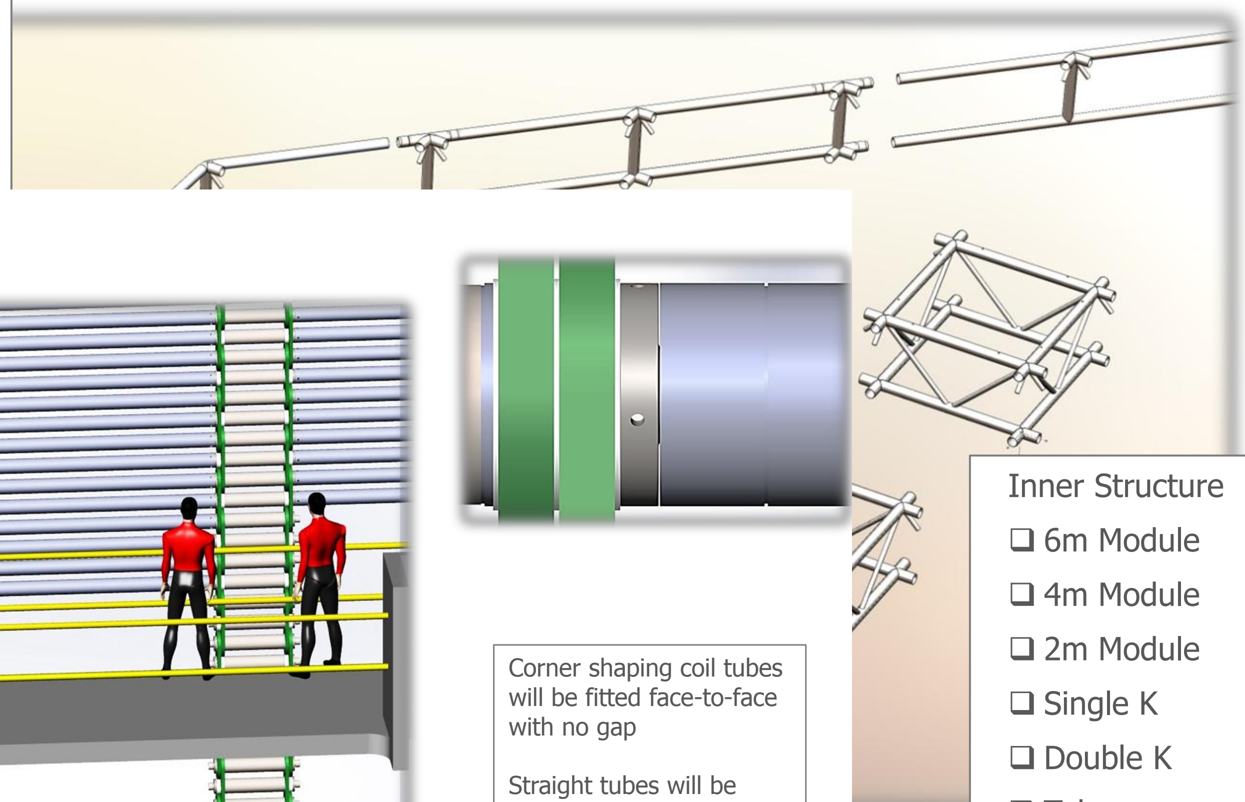
- 6m Module
- 4m Module
- 2m Module
- Single K
- Double K
- Tube
- Grid

From the LAGUNA-LBNO DS we have **highly detailed** detector and process engineering designs, construction sequence, risk analysis, Infrastructure design and costing

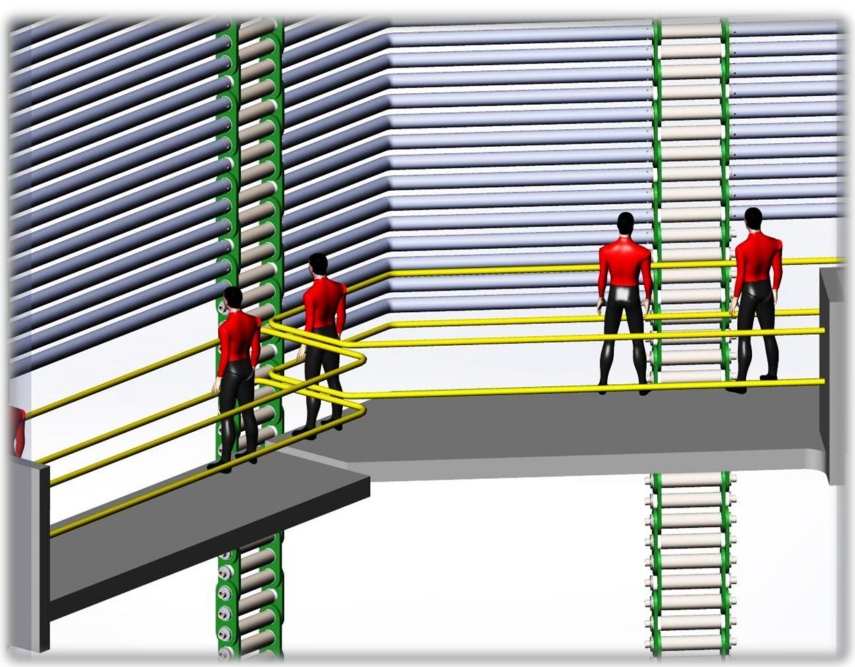


Peripheral Structure

- ❑ 2 Bay Module
- ❑ 2 Bay Infill
- ❑ Corner RH
- ❑ Corner LH



FIELD SHAPING COILS



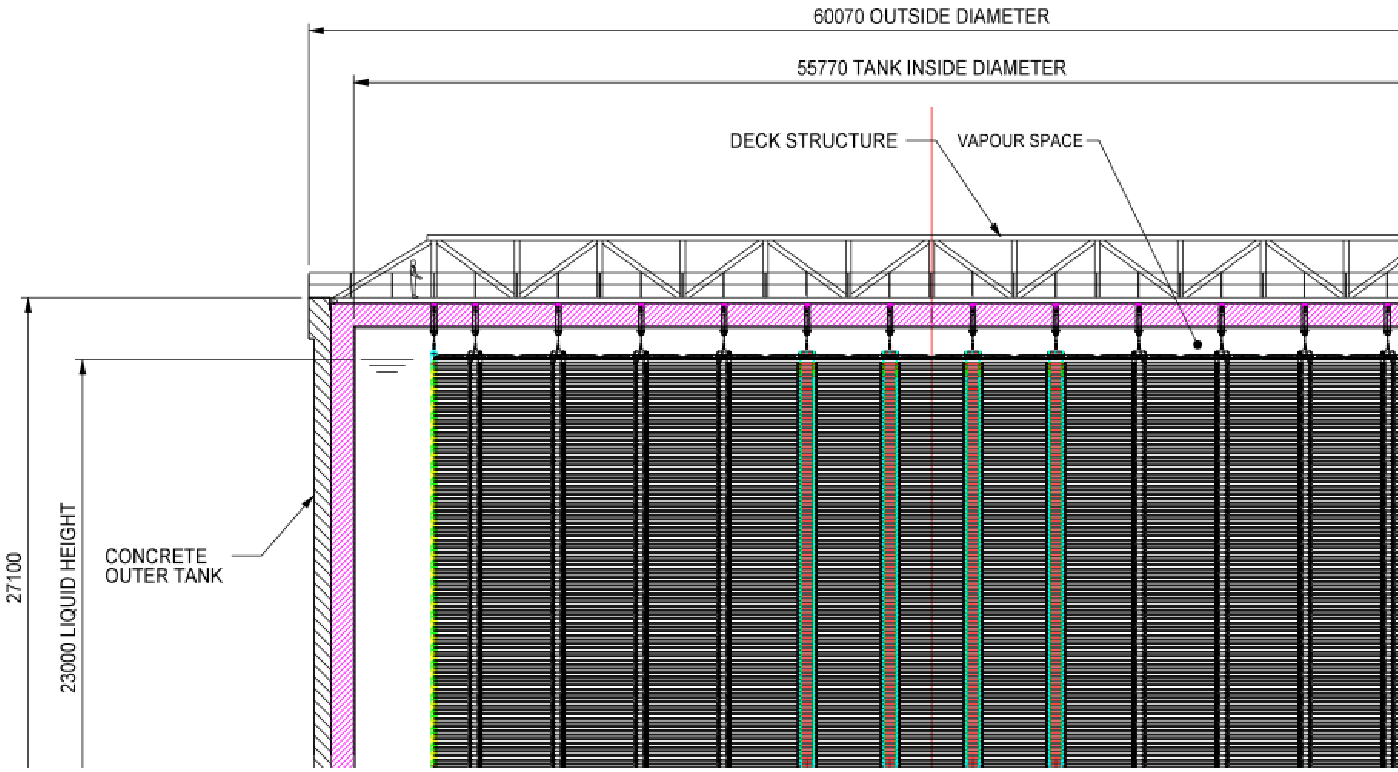
Corner shaping coil tubes will be fitted face-to-face with no gap

Straight tubes will be clamped in place leaving a pre-set gap

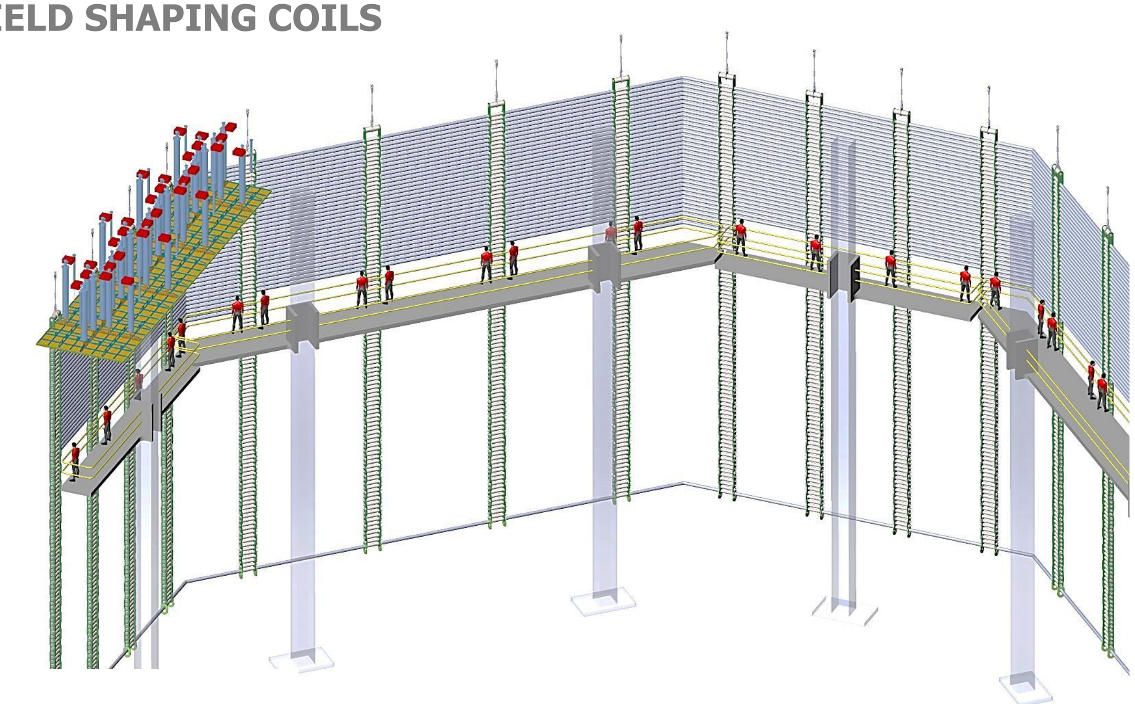
Inner Structure

- ❑ 6m Module
- ❑ 4m Module
- ❑ 2m Module
- ❑ Single K
- ❑ Double K
- ❑ Tube
- ❑ Grid

From the LAGUNA-LBNO DS we have **highly detailed** detector and process engineering designs, construction sequence, risk analysis, Infrastructure design and costing

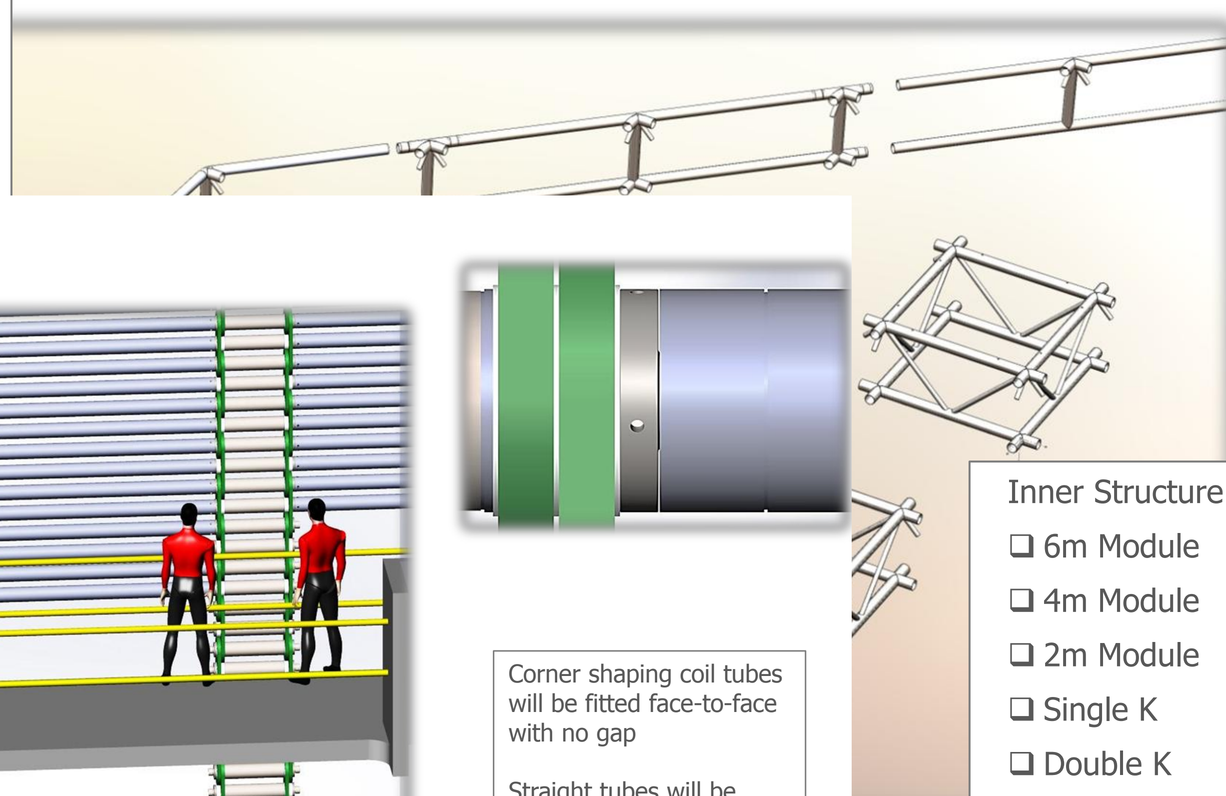


FIELD SHAPING COILS

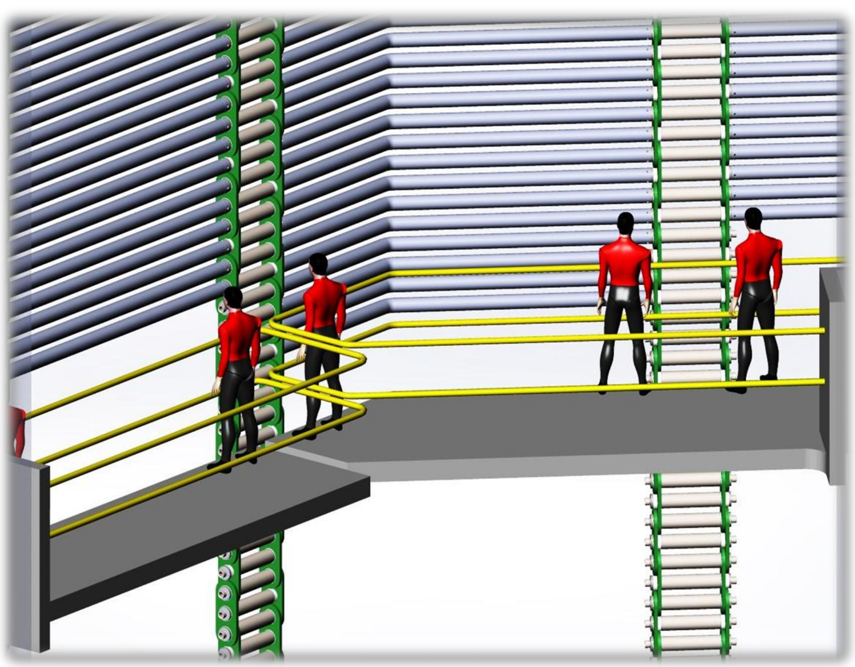


ield Shaping Coils will be installed from the top down.
ne Alimak platforms can be fitted with assembly aids as
ecessary to create safe and convenient work stations.
naks will be used to raise materials to the working level.

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



FIELD SHAPING COILS



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Inner Structure
- ❑ 6m Module
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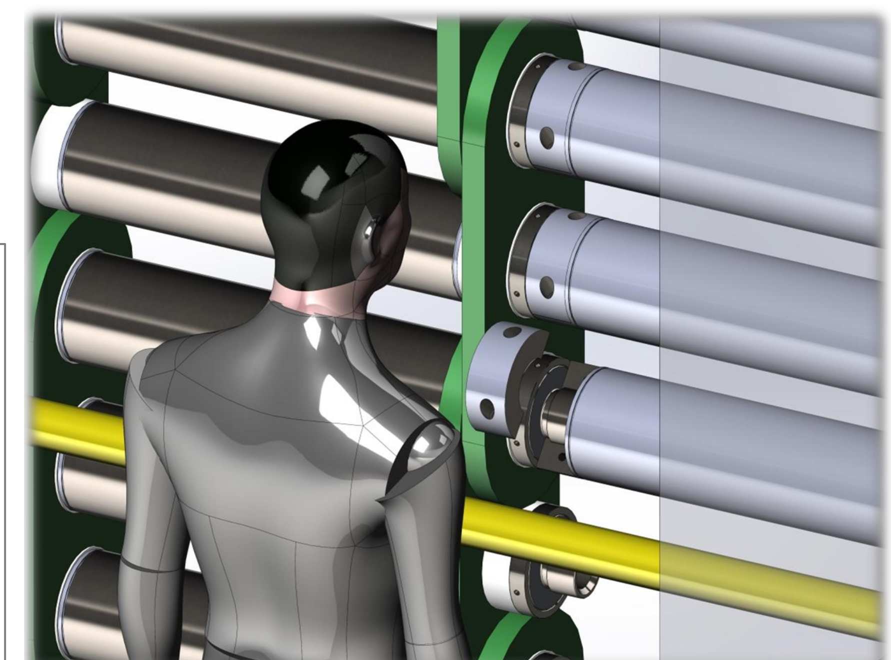
- ❑ Grid



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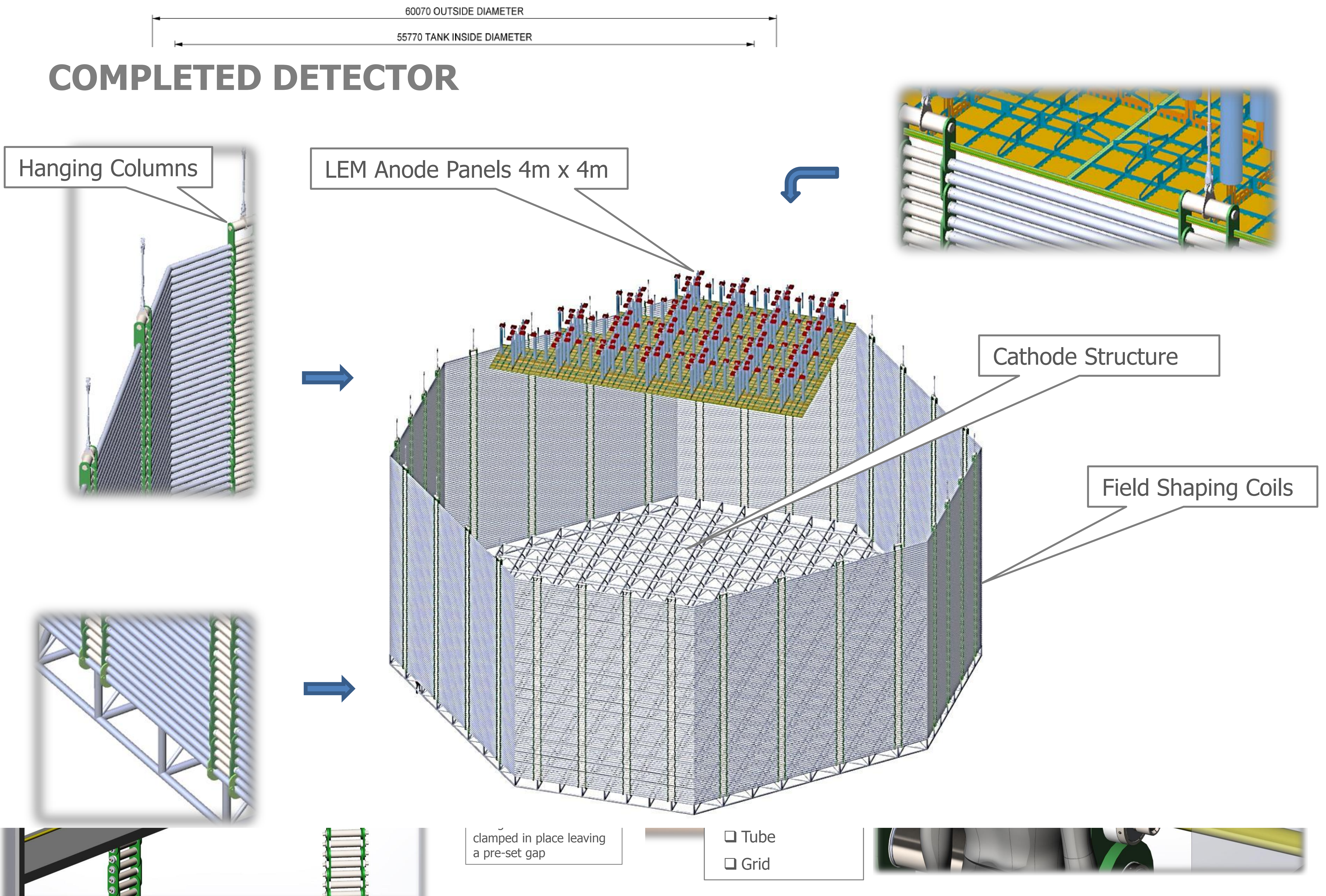

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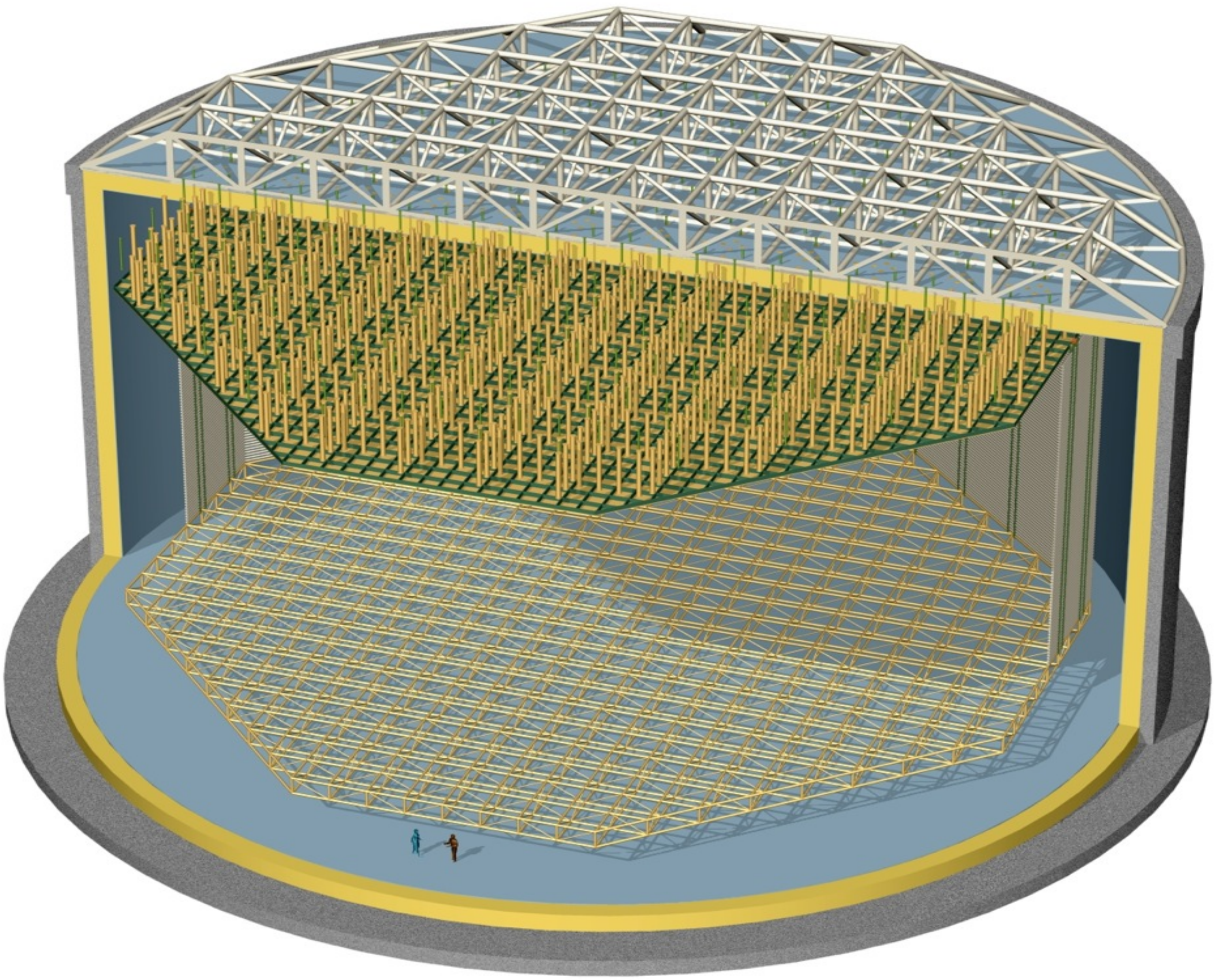


Poster S. Murphy (ID 26)

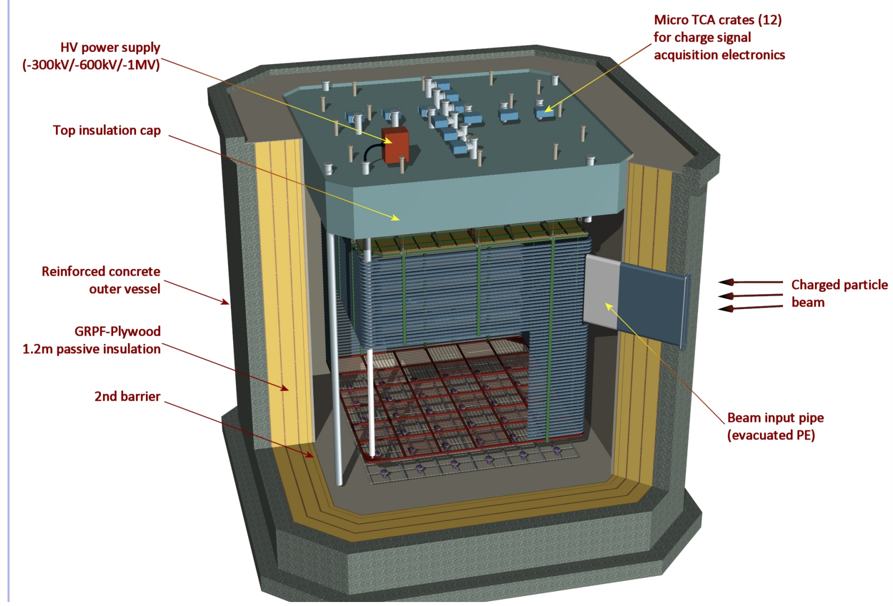
LAGUNA-LBNO and CERN

- In June 2012, we had put forward an "Expression of Interest" to CERN
- Positive feedback from CERN SPSC in January 2013
- 108th SPSC recommendations on new neutrino projects at CERN :
  - *The SPSC* ***supports*** *the physics cases of both projects and* ***recognizes*** *their timely relevance in the rapidly evolving neutrino physics landscape.*
  - The SPSC **supports** the focus of the European neutrino community on the LAr TPC technology, for which it has a unique expertise worldwide from the operation of the largest underground LAr detector
  - Concerning LAGUNA-LBNO, the SPSC **supports** the double-phase LAr TPC option as a promising technique to instrument with the very large LAr neutrino detectors in the future. The SPSC therefore **encourages** the LBNO consortium to proceed R&D necessary to validate the technology on a large scale.
- Activity embedded in CERN Neutrino R&D platform
- TDR for the 6x6x6 m^3 Demonstrator for DLAr in the North Area recommended

↳ **LBNO-DEMO (WA 105)**

LBNO-DEMO:Technical demonstrator: Active vol.: 6 x 6 x 6 m^3 (0.3 kt)

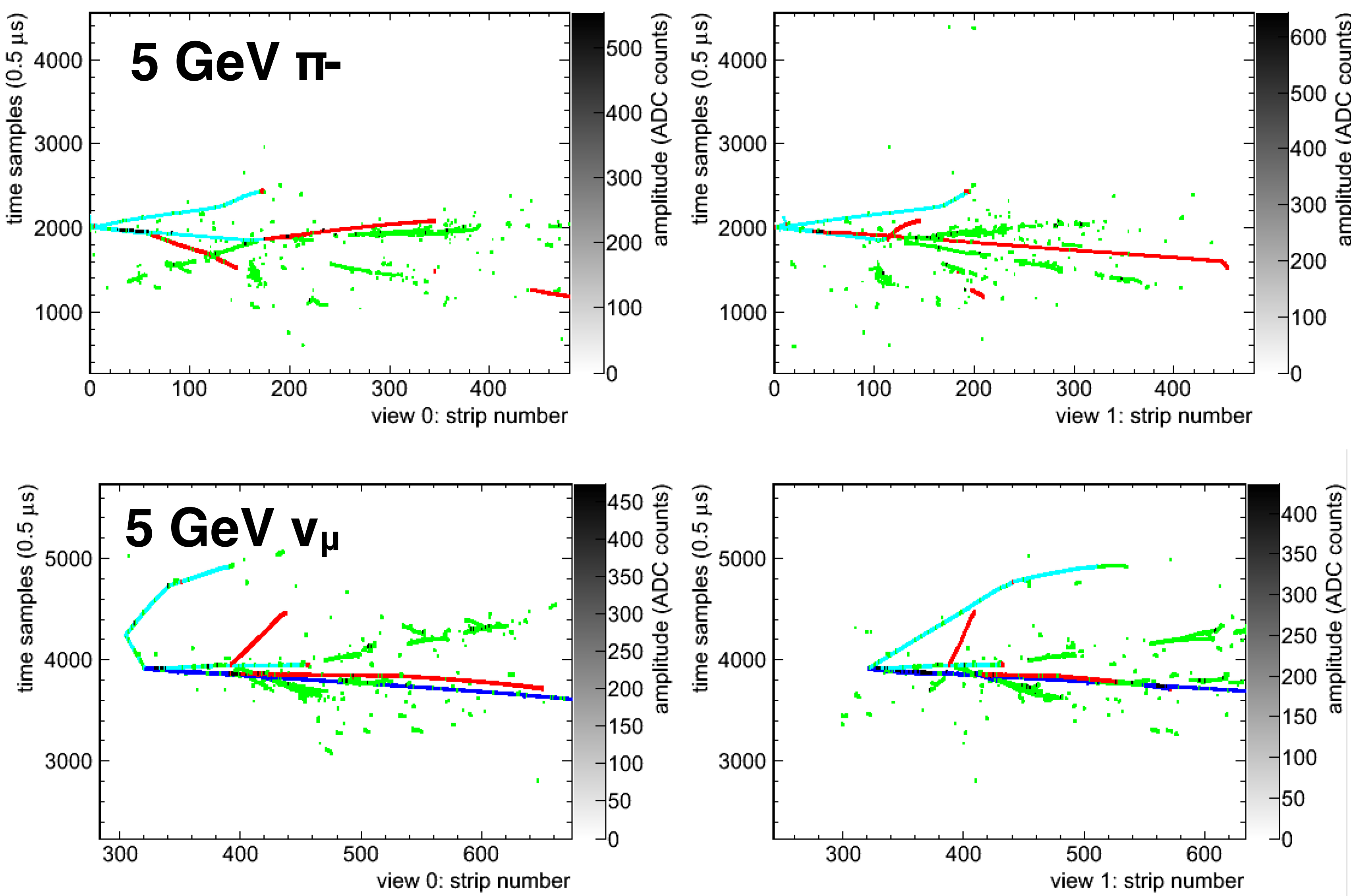
CERN WA105 R&D programme (SPSC-TDR-004-2014).



Some goals

- ✳ Development of automatic event **reconstruction**
- ✳ **test NC background rejection** algorithms on “ν_e free” events
- ✳ Charged **pions** and proton **cross-section** on Argon nuclei. Rate of pion production is important!
- ✳ What is the achievable **energy resolution?**
- ✳ **Development** and proof-check of industrial solutions

pions, electrons/positrons, protons, muons



Conclusions

- After 2 consecutive DS the LBNO collaboration has a clear end-to-end path to propose an experiment capable to
  - Determine unambiguously (>5 σ) MH (no need for external input) and
  - Cover 80% of the CPV phase space at 3σ and 65 % at 5σ with realistic systematic error assumptions -> P5 requirement satisfied
  - Deep underground location:
    - Astrophysics program
    - p-decay

    } Complementary to WCD
- Full conceptual design available, developed in collaboration with industrial partners leading to: Underground facility, construction sequence, well defined costs,…
- LAGUNA-LBNO DS final report August 2014, stay tuned!
- Planned next step: construction and operation of LBNO-DEMO (WA 105)

LAGUNA-LBNO DS	WA 105	LBNO – PILOT (2.5 – 5 kt)	LBNO Phase I (LBNO20)	LBNO Phase II (LBNO70)
Site selection Full assessment of physics Full engineering costing	DLAr demonstrator Calibration Software development	Underground installation Astro particle physics	MH CPV 3 σ: 46% Proton decay Astrophysics	CPV 3 σ: 80 % Proton decay Astrophysics
2014	2018	202X	202X	203X

Concluding LAGUNA-LBNO DS Meeting

LAGUNA 2014

Open Meeting Marking Completion of the Design Studies and Transition to the Realisation Phase

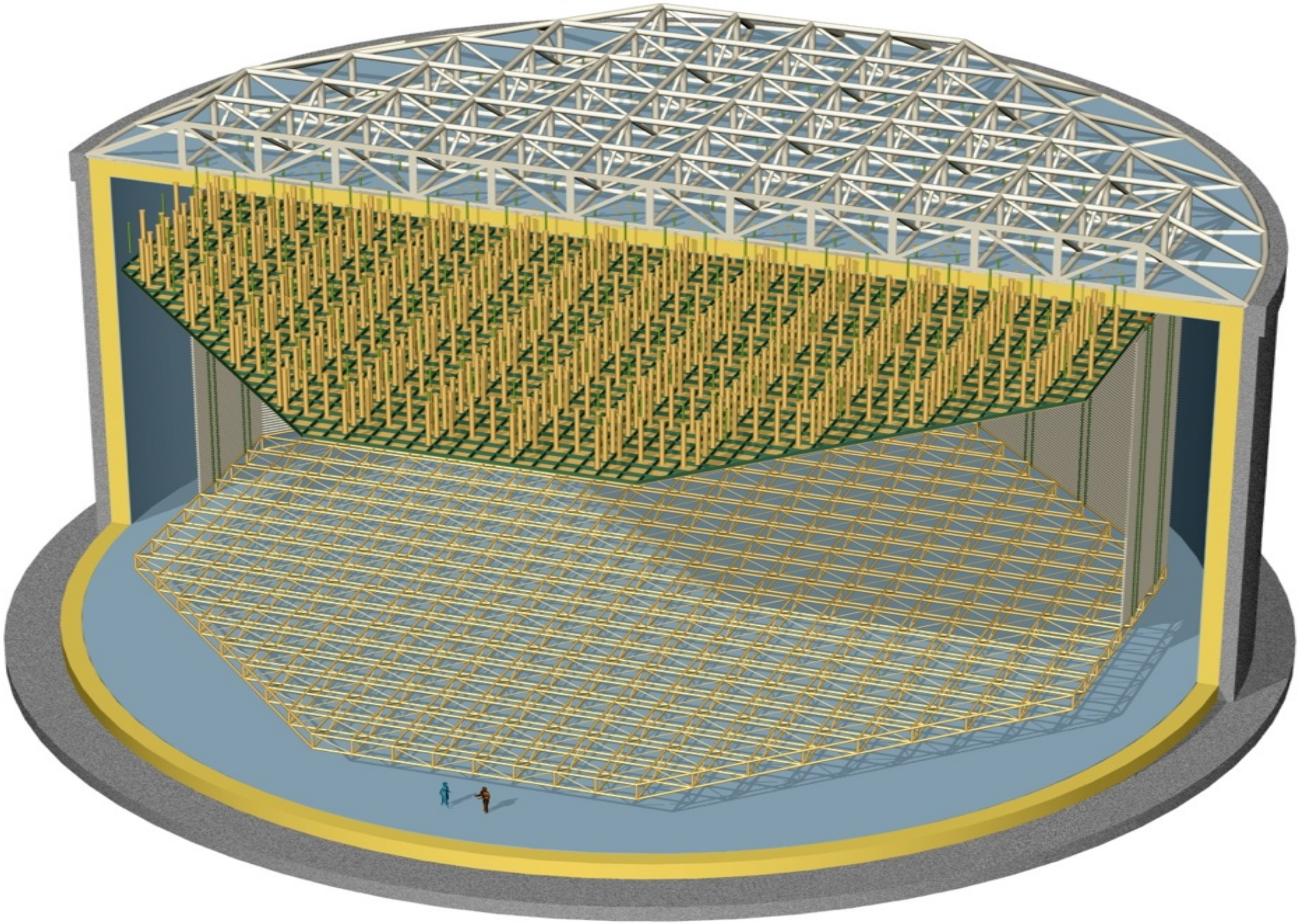
25 – 27 August 2014, Hanasaari, Finland

Hiukkasen parempi Pyhäjärvi

Pyhäsalmi Mine

https://www.jyu.fi/fysiikka/en/laguna2014

Thank you for your attention.



Backup

Summary

- Next generation Neutrino Physics will come from new, large scale underground detectors
- Europe has substantially invested in design studies since 2008
- We are ready to go for the experiment!
- The LAGUNA-LBNO collaboration decided to propose stage I with a 24 kt DLAr + 750 kW SPS
- LAGUNA/LBNO is a project with a very rich and interesting physics program with fundamental discovery potential:
  - Guaranteed determination of MH at > 5 σ within 4 y with statistical power ≈ 1
  - Early determination of MH is crucial to:
    - Tune the beam for the CPV measurement and
    - Provide the long awaited input to the community
  - Measurement of CPV with SPS 750 kW, 400 GeV protons: 24 kt -> 3 sigma 46 % of the phase space
70 kt -> 3 sigma ~64 % , 5 sigma 36 %
  - Full exploration of the 1st and 2nd maximum and the L/E behavior
  - MSNP precision measurement
  - Proton decay search: significantly extended sensitivity in many channels
  - Supernova neutrinos > 10,000 events for SN explosion @ 10 kpc
  - Diffuse SN Neutrinos
  - Neutrinos from DM annihilation
  - Atmospheric Neutrinos (5600 events/year)

- 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.

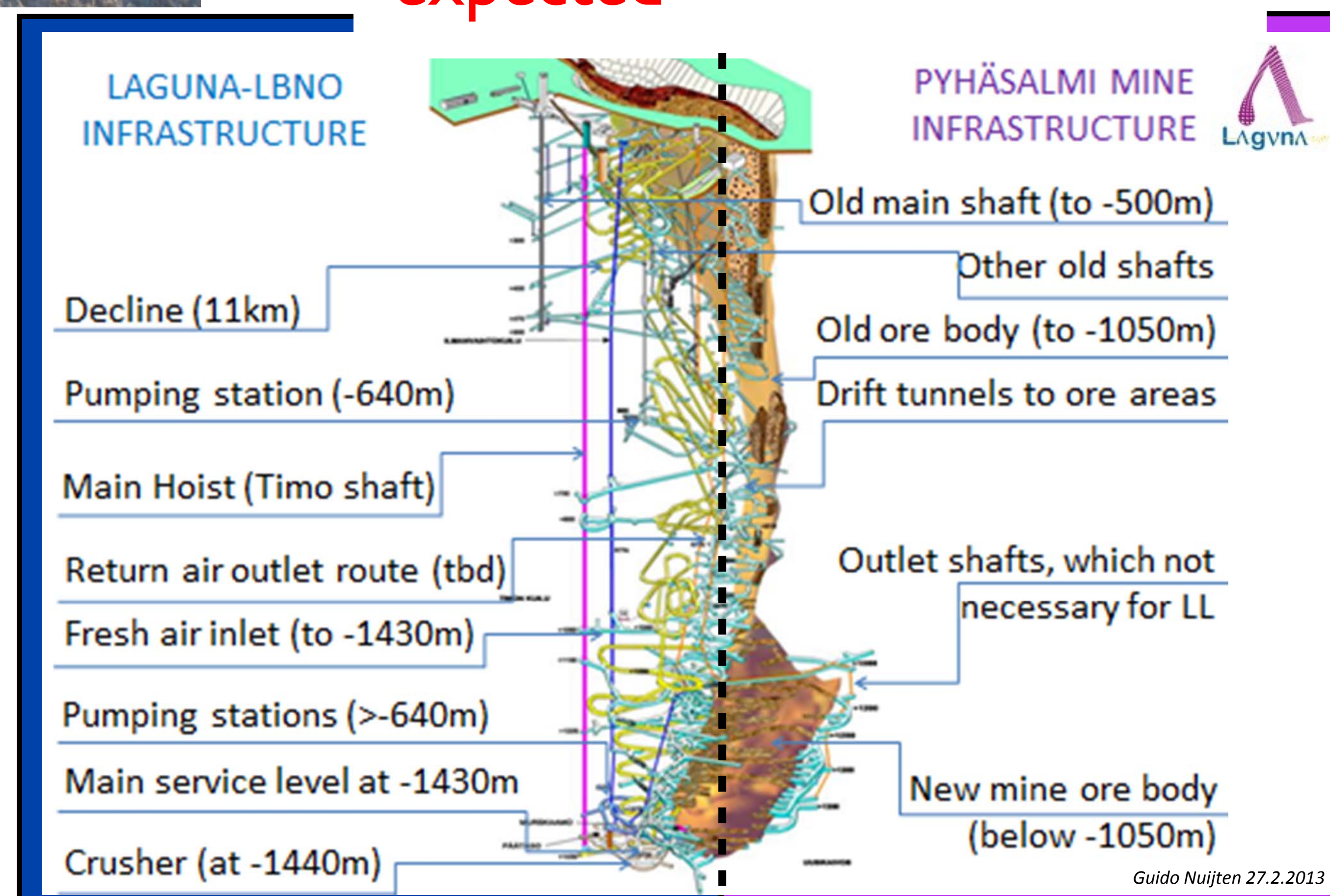
- The 2300 km baseline of LBNO is perfect for the ultimate neutrino factory.

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
  - 6.8 km drilled, rock quality as expected

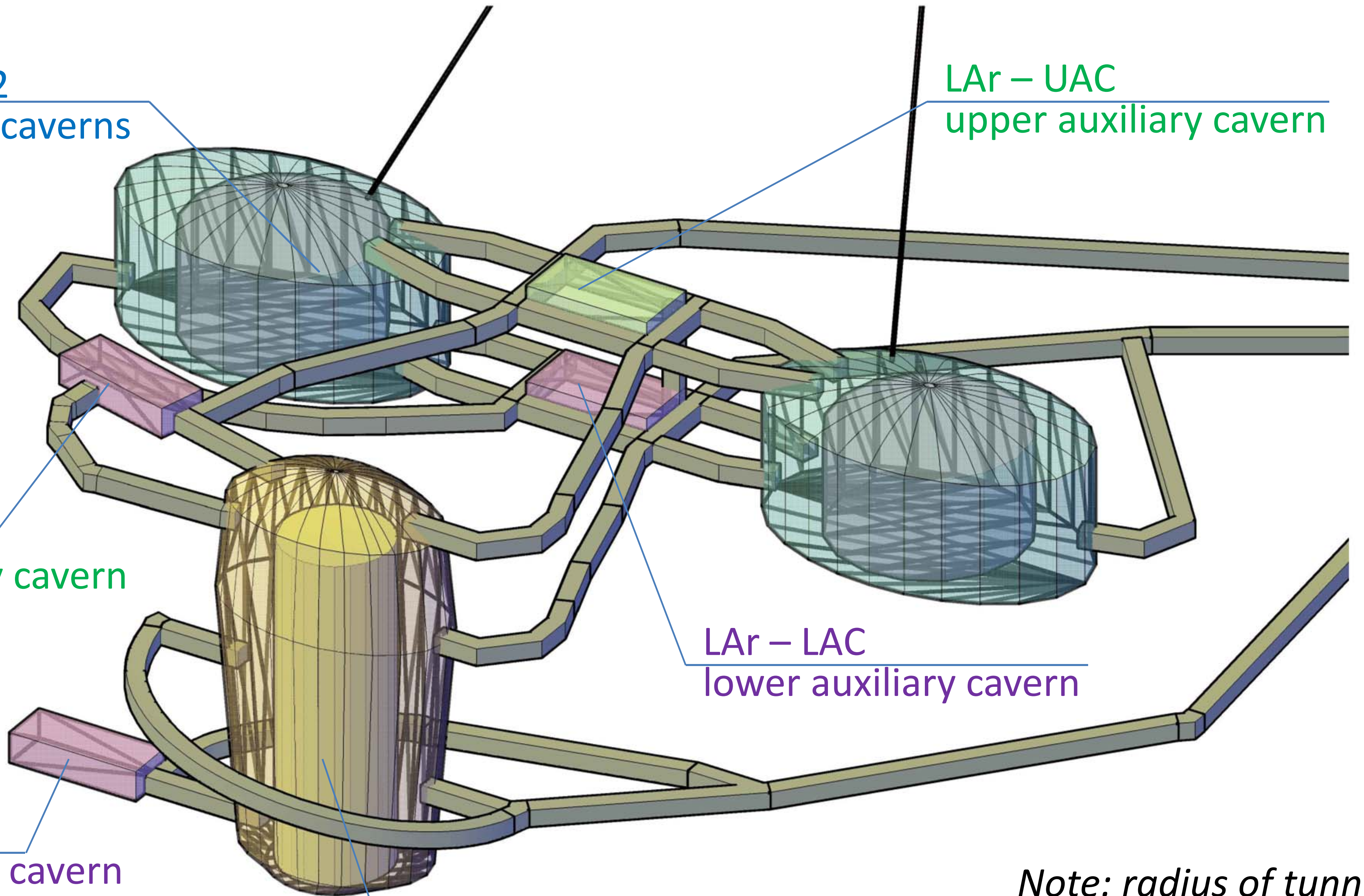
- Only those parts that are necessary for LAGUNA/LBNO during construction and operation would be transferred to the LAGUNA lab's entity.
  - The decline (length about 11km)
  - The main hoist (Timo shaft, from surface to -1440m)
  - The fresh air inlet shaft (from surface to -1440m)
  - An return air 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.



Main detectors facility

LAGUNA-LBNO: **LAr** + **LSc** LAYOUT @ PYHÄSALMI

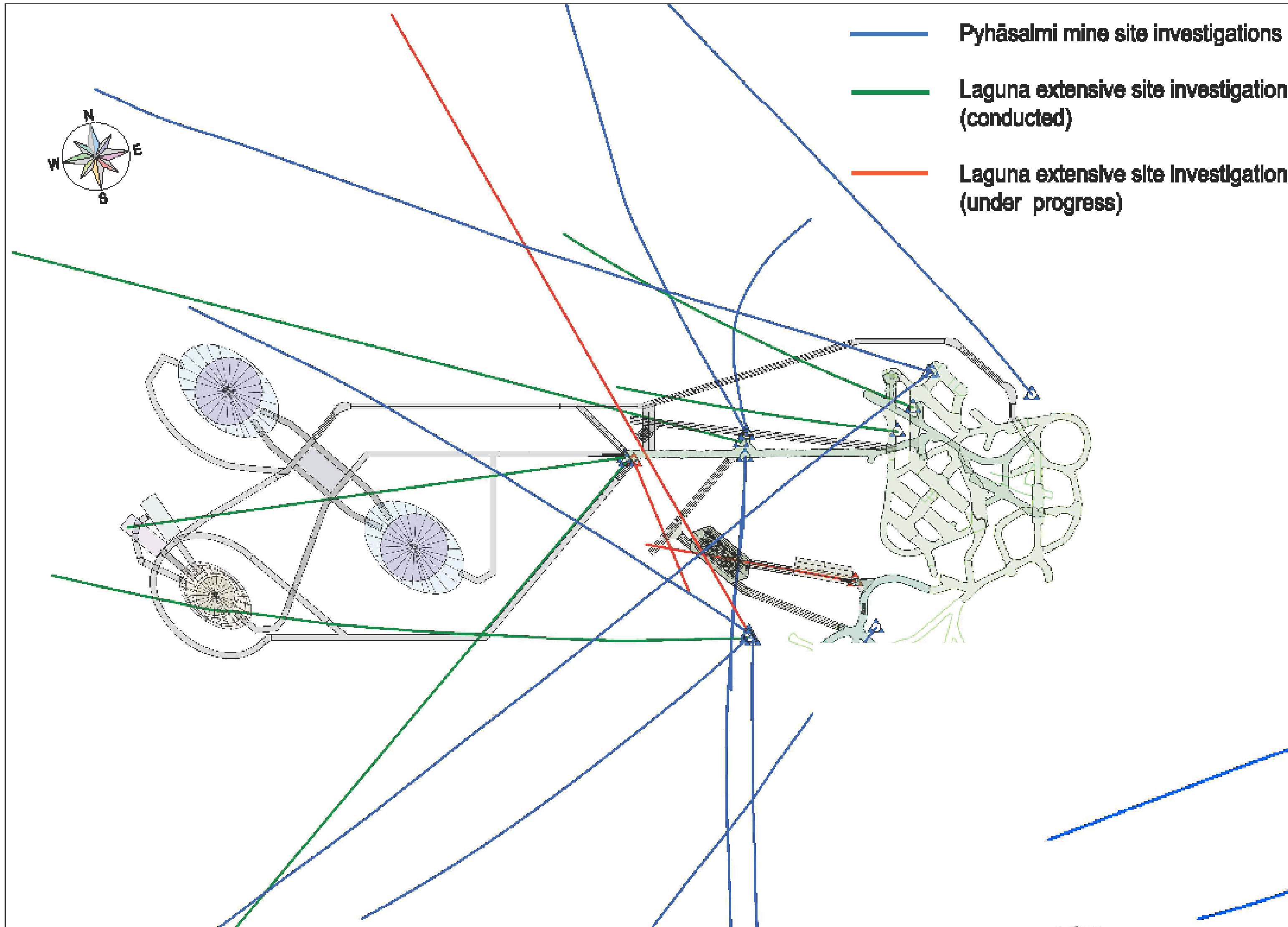


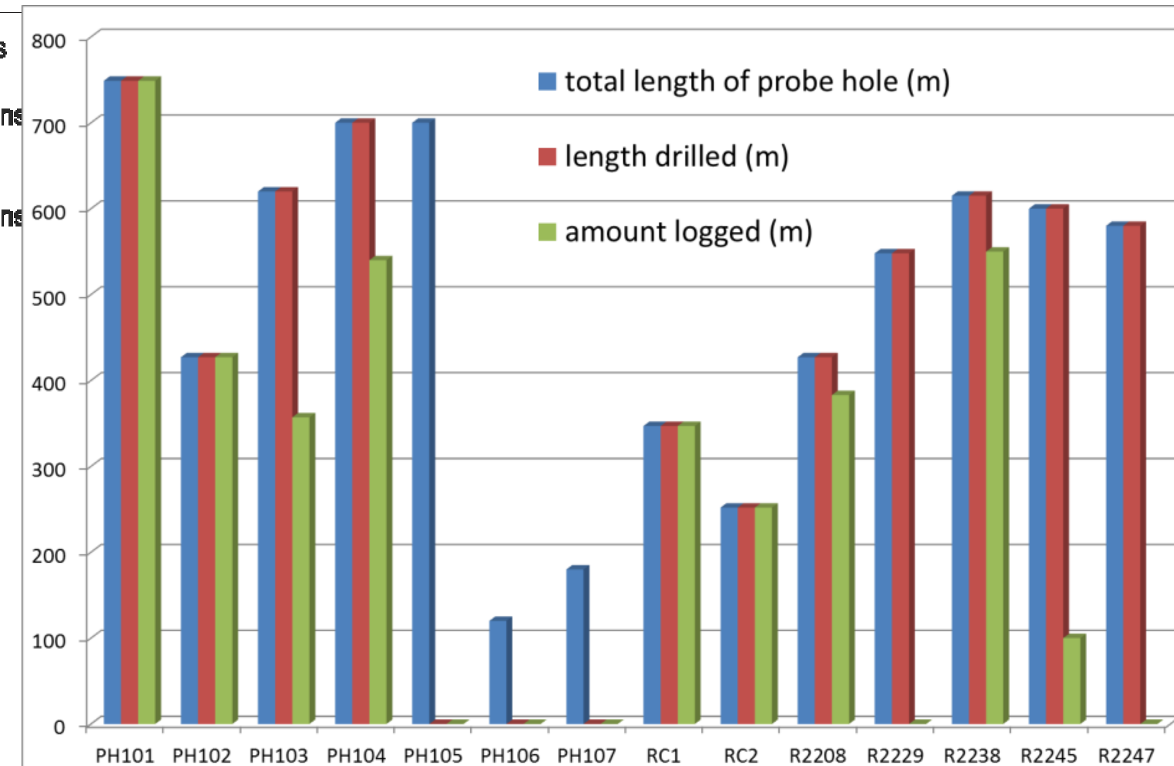
Note: radius of tunnels still to be fine tuned.

ROCKPLAN

Lagvna

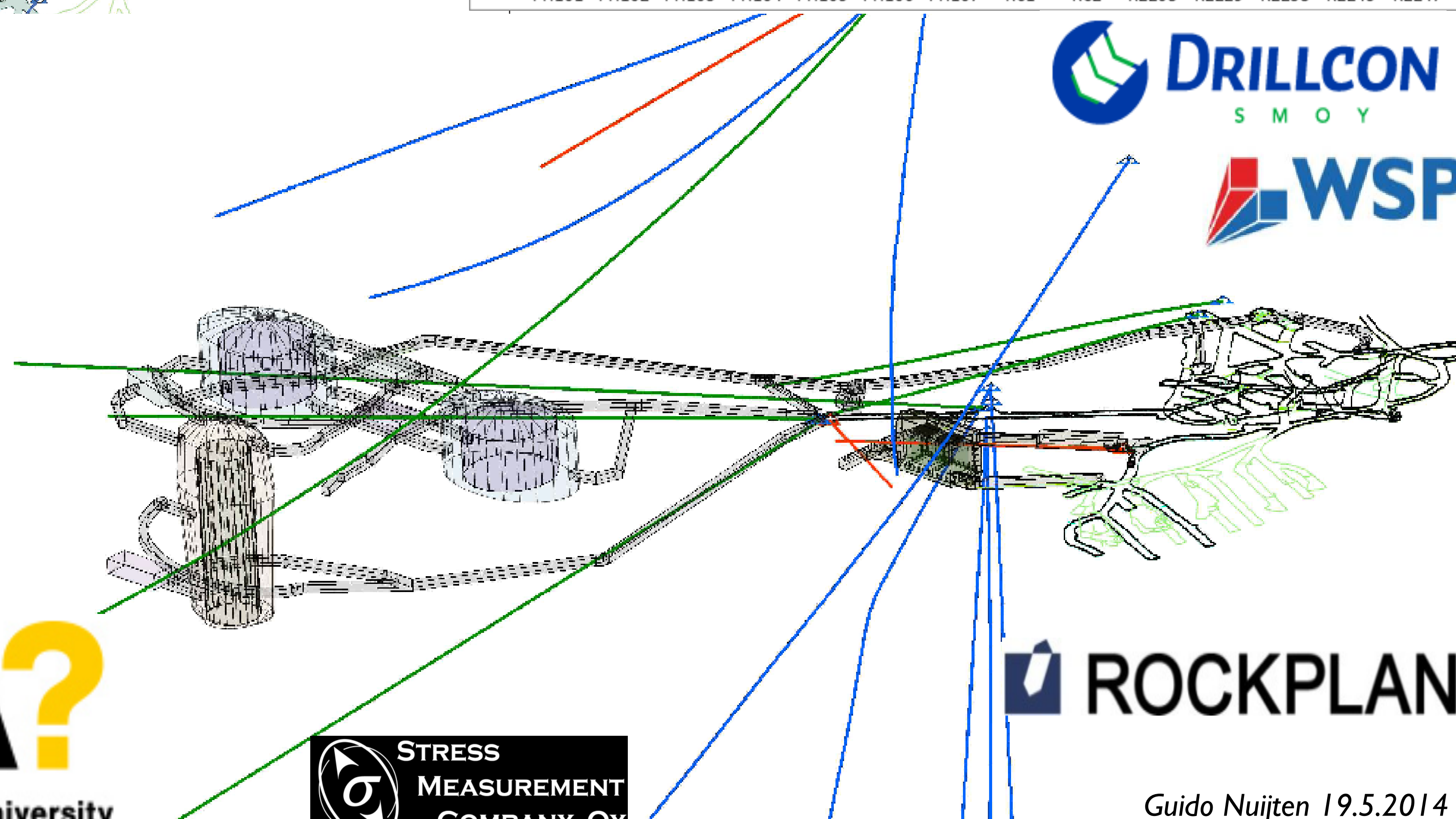
LAGUNA-LBNO SITE INVESTIGATION





DRILLCON SMOY

WSP



TOTAL AMOUNT OF CORE DRILLING: 6.8 KM / 14 HOLES

100% DRILLED BY 23ND MAY 2014

RESULTS SO FAR CONFIRM ESTIMATED ROCK CONDITIC

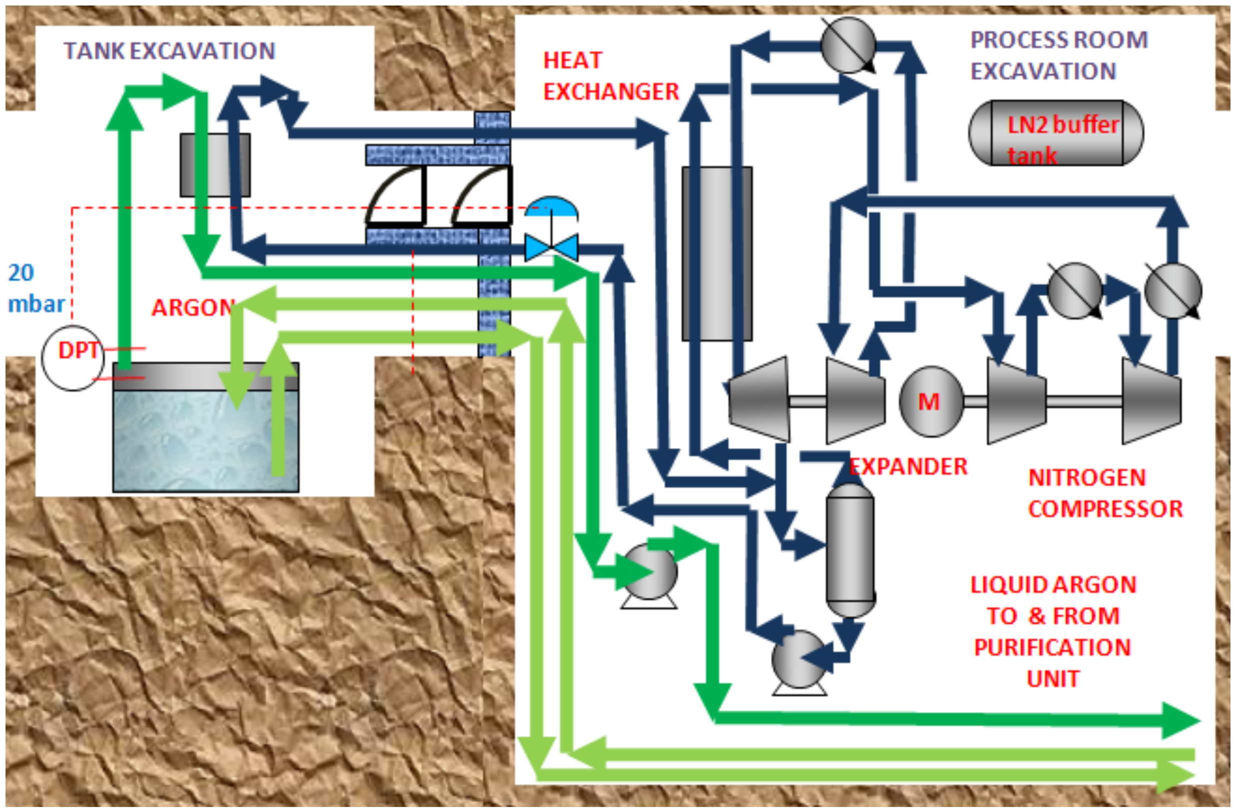
Aalto University

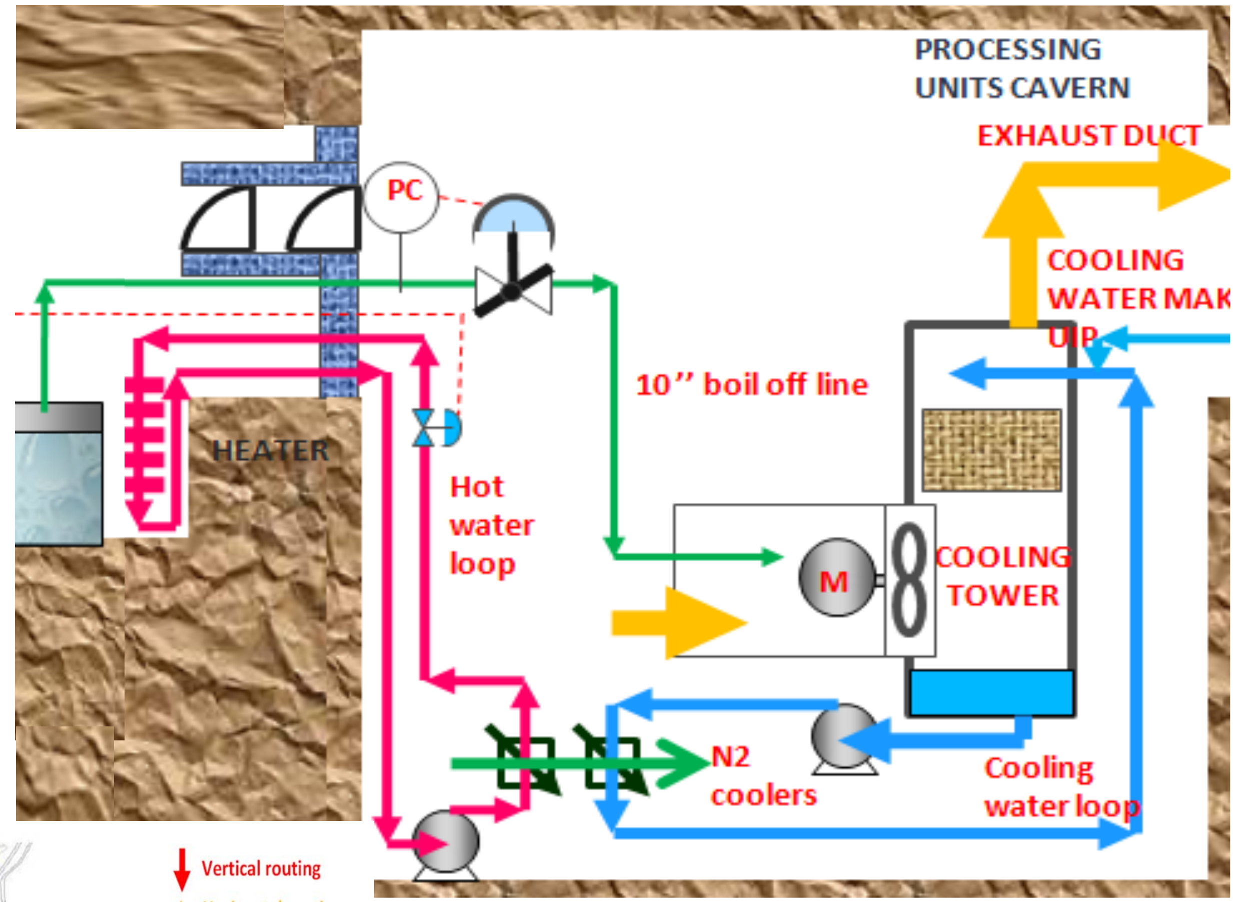
STRESS MEASUREMENT COMPANY OY

ROCKPLAN

Guido Nuijten 19.5.2014

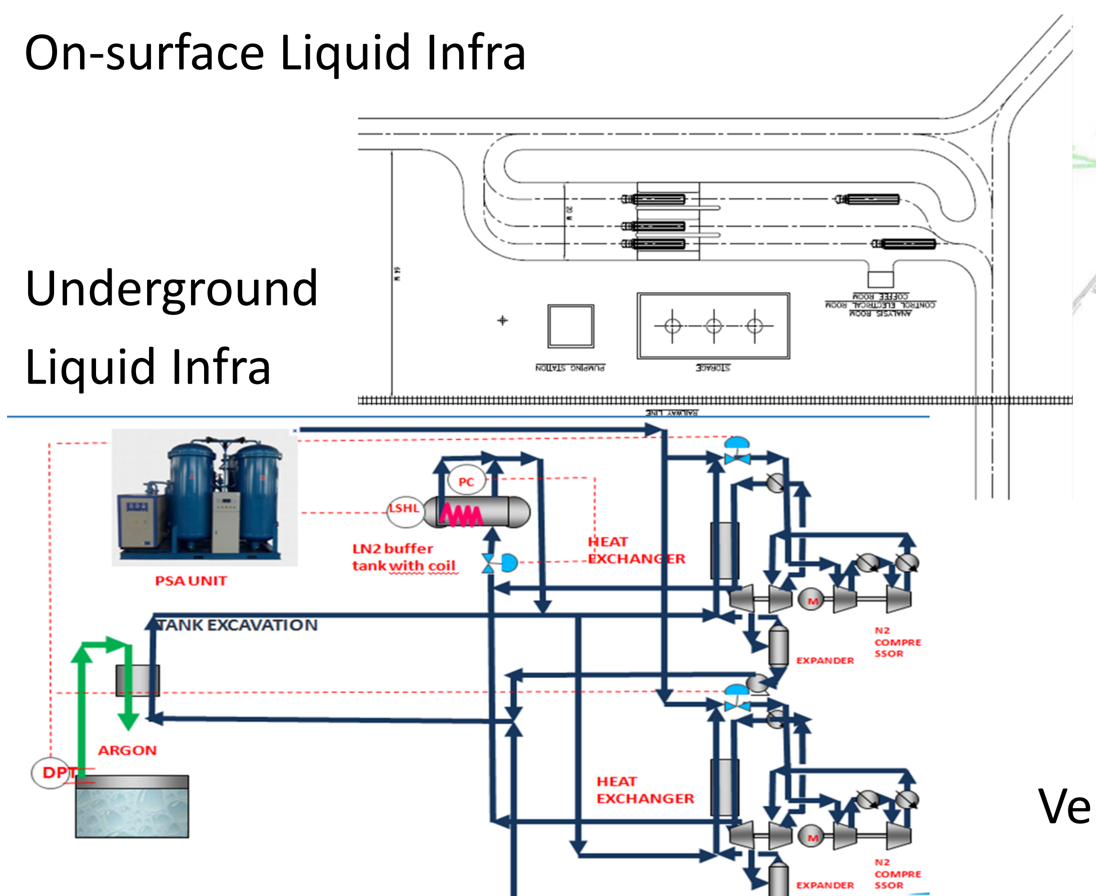
Fully engineered process designs

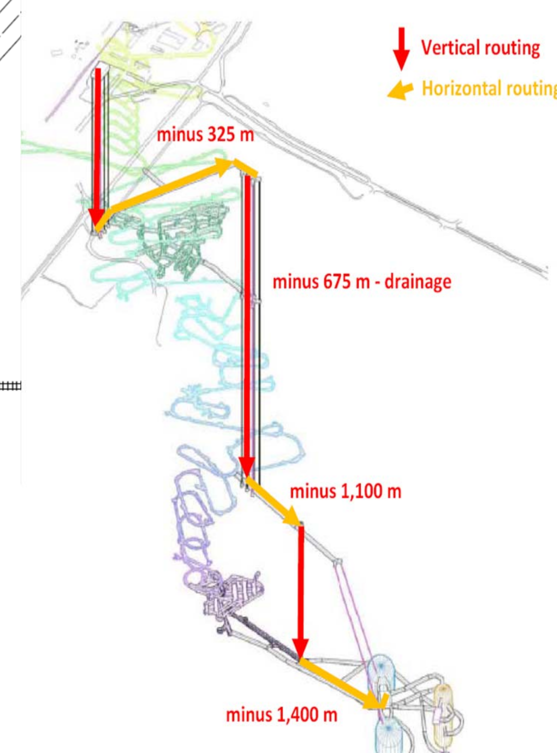




On-surface Liquid Infra

Underground Liquid Infra





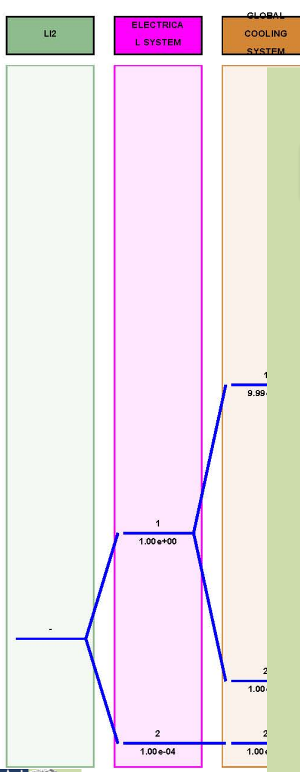
Vertical Infra (LAr pipeline)

Sofregaz

Guido Nuijten 11.2.2014

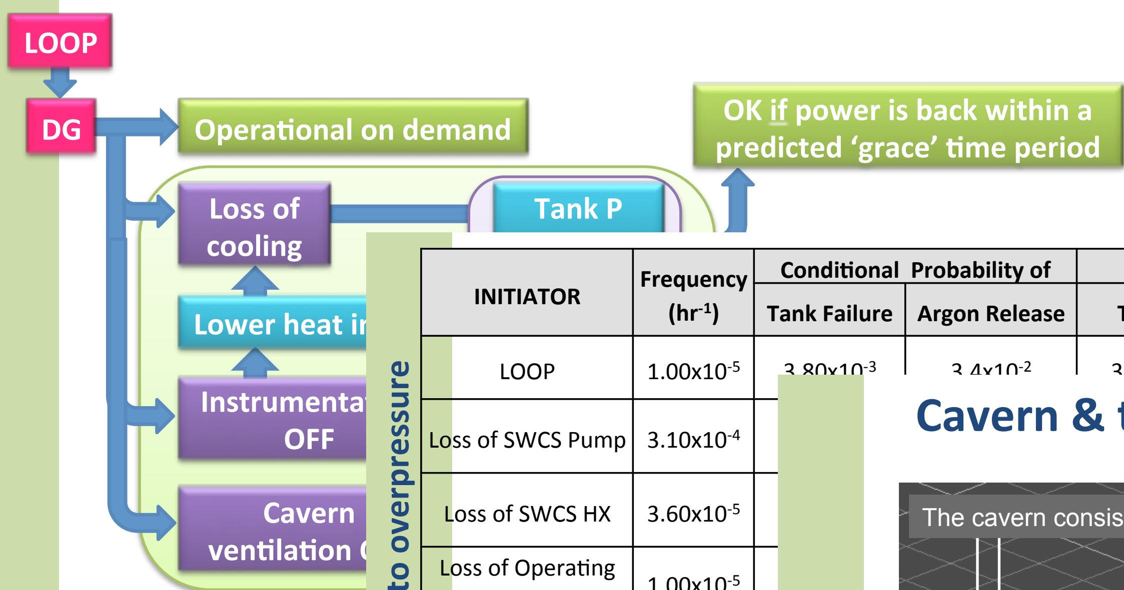
Detailed risk analyses

Reduced Event Tree for Loss of Insulation



O1 = ok
O2 = tank break
O3 = release

Ex1: Loss of: Offsite Power + Diesel Generator



Loss of offsite Power (LOO
Mission Duration (grace p
Failure to recover Offsite P
Emergency Diesel Generat
Emergency Diesel Generat
Given that Emergency DG s

Frequencies for LOC owning to overpressure

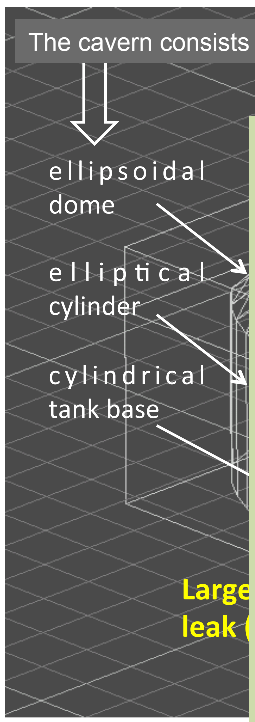
INITIATOR	Frequency (hr^{-1})	Conditional Probability of Tank Failure	Conditional Probability of Argon Release	Frequency of TF (hr^{-1})	Frequency of ArR (hr^{-1})	Contribution of each initiator	
LOOP	$1.00x10^{-5}$	$3.80x10^{-3}$	$3.4x10^{-2}$	$3.80x10^{-8}$	$3.4x10^{-7}$	0.013%	0.524%
Loss of SWCS Pump	$3.10x10^{-4}$						
Loss of SWCS HX	$3.60x10^{-5}$						
Loss of Operating Pressurizer Train	$1.00x10^{-5}$						
Loss of Cavern Heating System	$3.10x10^{-4}$						
Loss of Ar Pump	$3.10x10^{-4}$						
Loss of Operating N_2 train	$5.00x10^{-5}$						
Loss of Insulation type LI1	$9.12x10^{-7}$						
Loss of Insulation type LI2	$1.14x10^{-7}$						
Loss of Insulation type LI3	$7.98x10^{-8}$						
Loss of Insulation type LI4	$3.42x10^{-8}$						
TOTAL							

NCSR DEMOKRITOS –

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
nstitute of Nuclear & Radiological Sciences & Technology, Energy & Safety
'or Scientific Research DEMOKRITOS
Greece

Cavern & tank geometry used in CFD simulations



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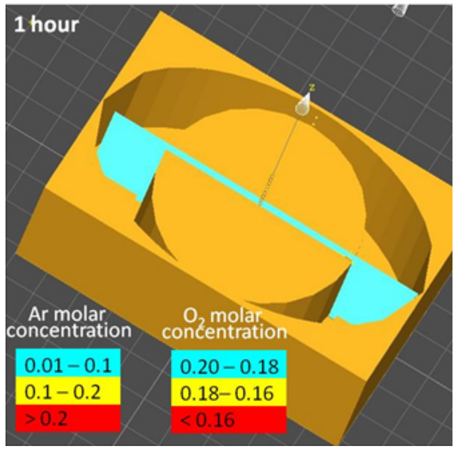
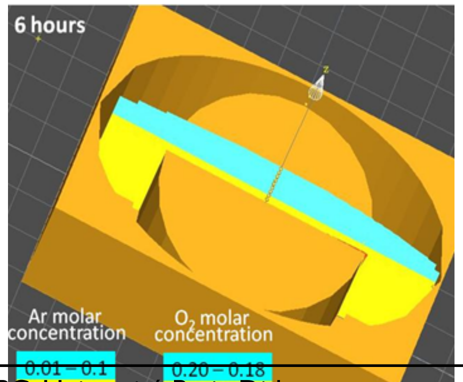
NCSR DEMOKRIT

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	

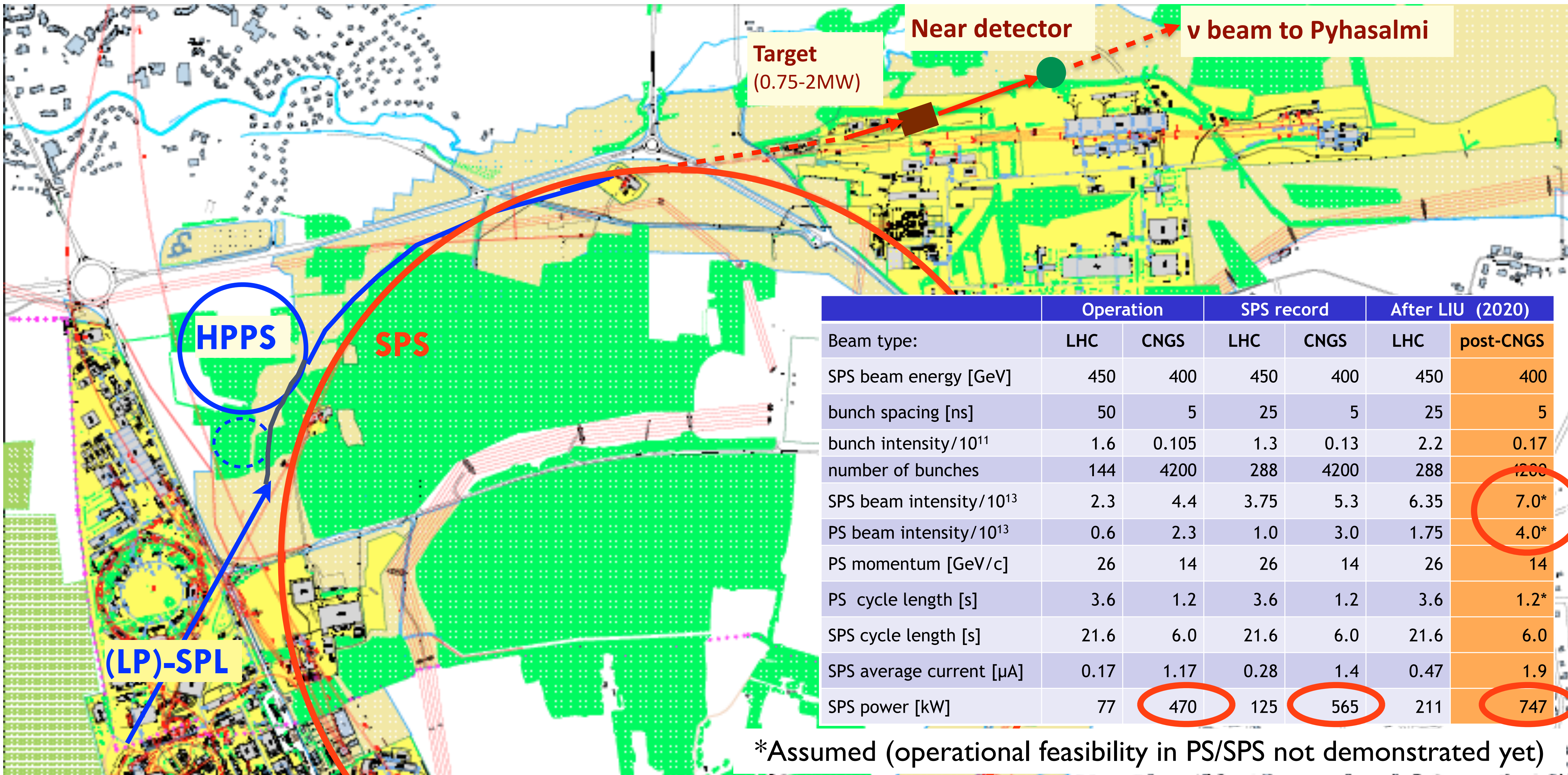
- In the centre of the cavern above the tank the Ar concentrations remain below 10% during the first 24 hours, and take two days to go over 20%.
- Near the cavern walls around the tank the concentrations are significantly higher and reach 10% Ar within 5 hours, and 20% within 8 to 10 hours.
- **The CFD predicts O2 concentrations to remain over 18% for a day above the tank and for 5 hours at lower heights.**





CERN effort in LAGUNA-LBNO

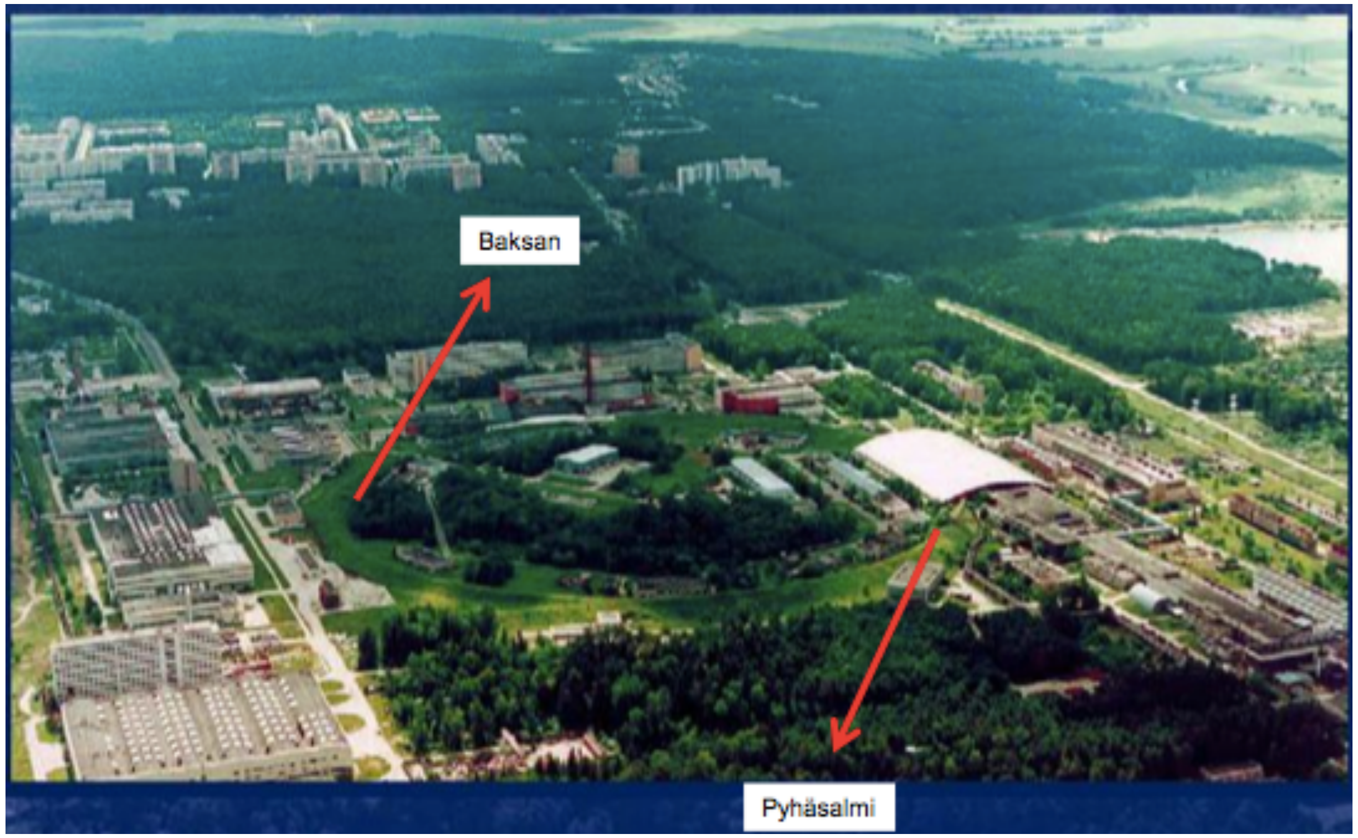
- **Phase 1** : use the proton beam extracted beam from SPS
  - **400 GeV**, max 7.0 10^{13} protons every 6 sec, **750 kW** nominal beam power, 10 μs pulse
  - Yearly integrated pot = (8–13)e19 pot / yr depending on "sharing" with other fixed target programmes.
- **Phase 2** : use the proton beam from the new HP-PS
  - **50**(70) GeV, 1 Hz, 2.5e14 ppp, **2 MW** nominal beam power, 4 μs pulse

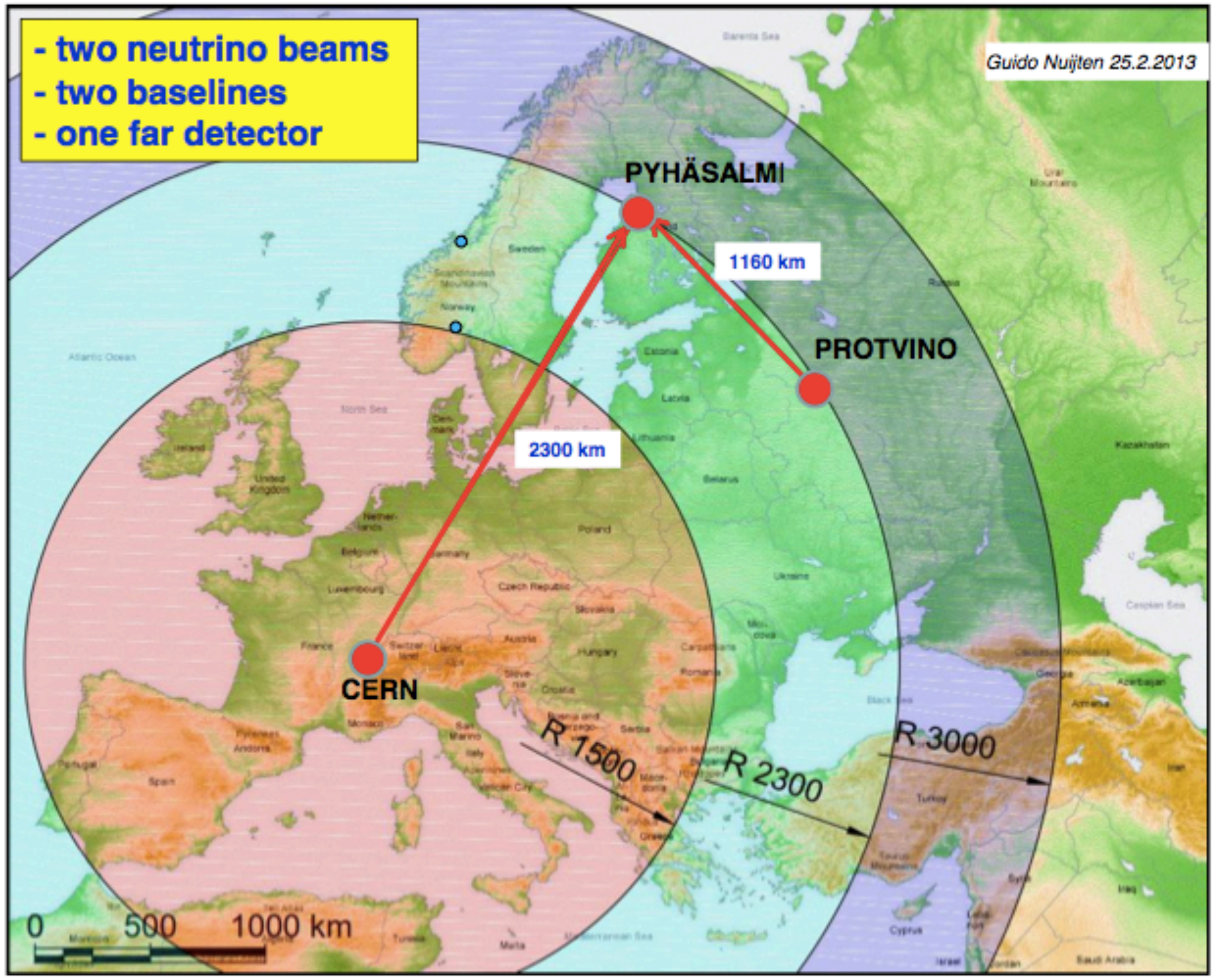


	Operation		SPS record		After LIU (2020)	
Beam type:	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity/10^{11}	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS beam intensity/10^{13}	2.3	4.4	3.75	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)

Possibility of neutrinos from Protvino



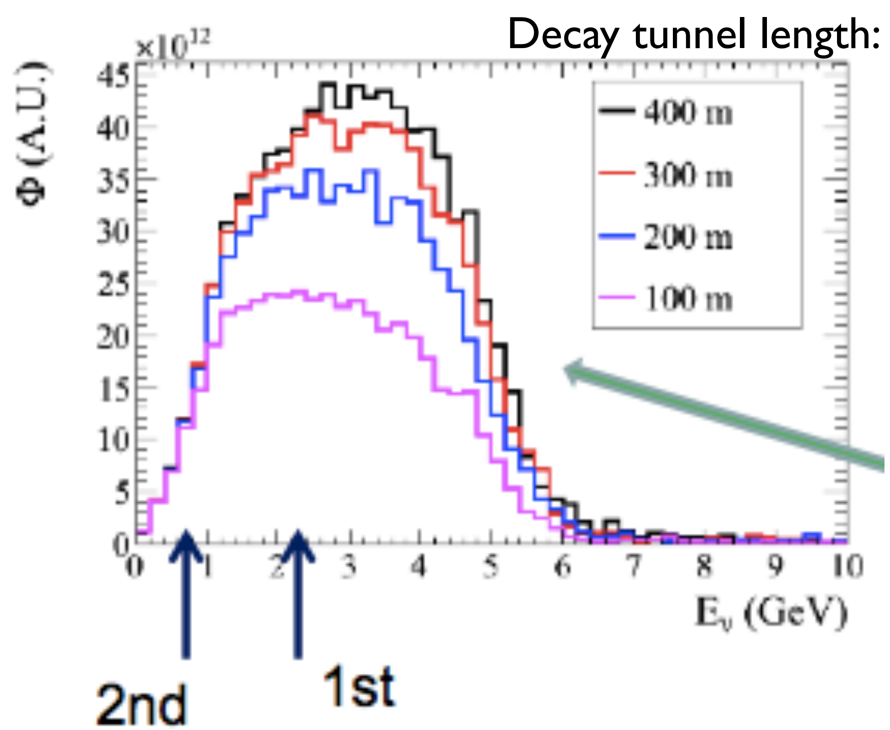


Desired parameters for neutrino beam:

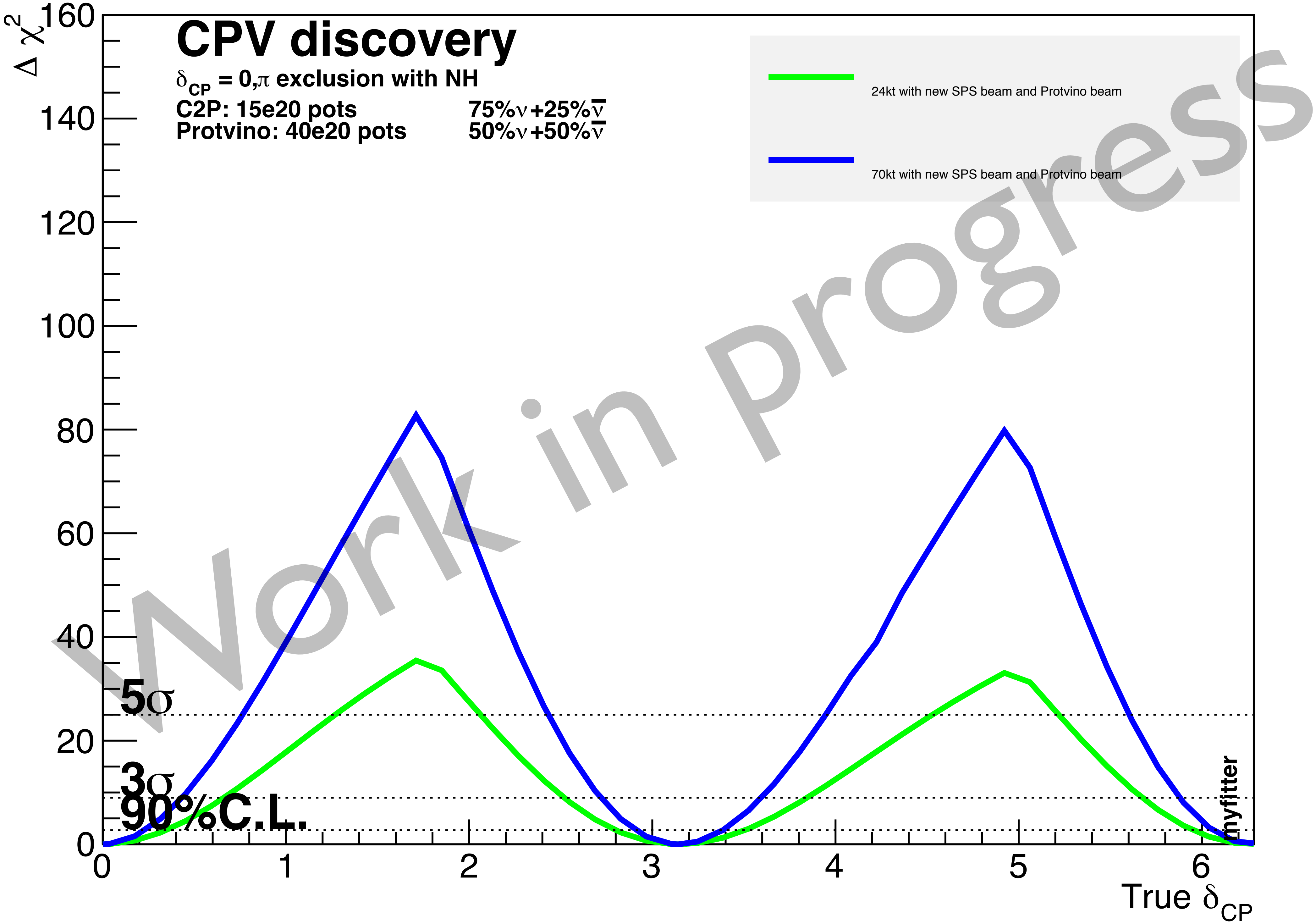
Proton energy	70 GeV
Repetition rate	0.2 Hz
Intensity	2.2×10^{14} ppp
Power	450 kW
Neutrino channel	200-300 m
Angle to Pyhäsalmi	5.2 deg
Distance to ND	500 - 750 m
ND depth (at 500m)	46 m

≈2000 ν_μ CC / 20 kton / year (no osc.)

C2P+P2P sensitivity under study



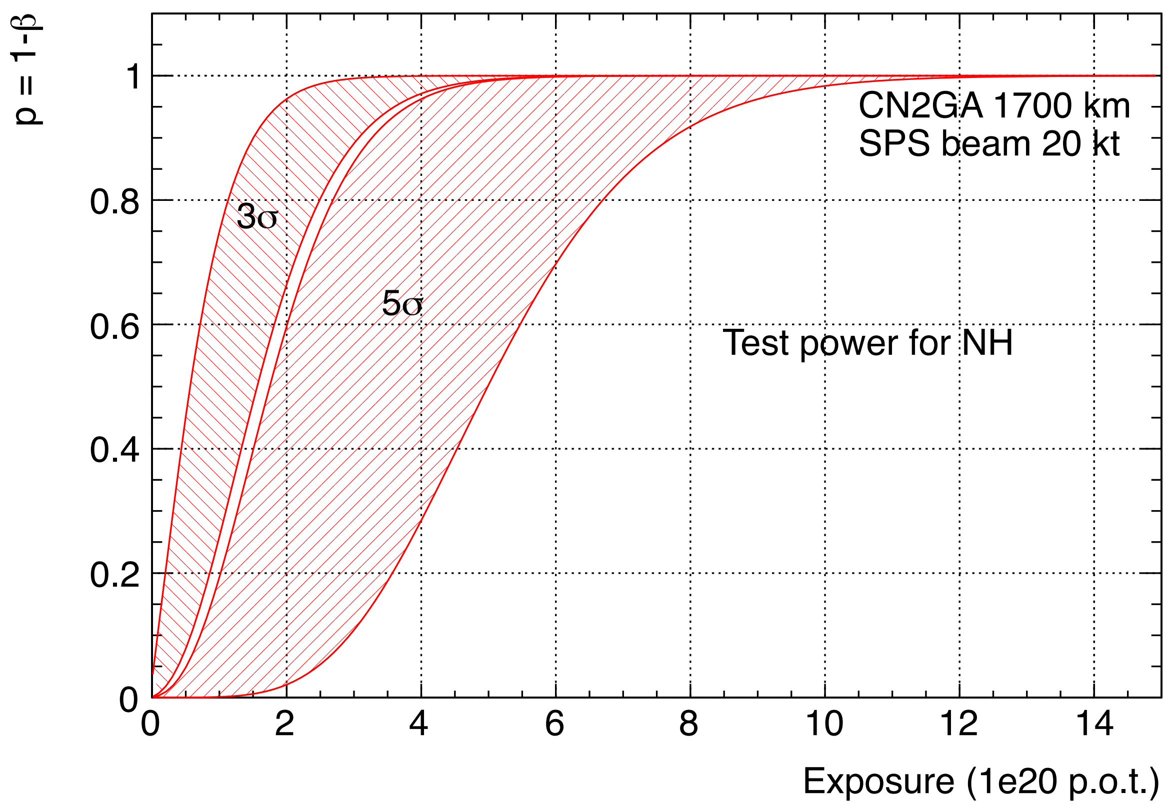
LBNO with 2nd beam from Protvino

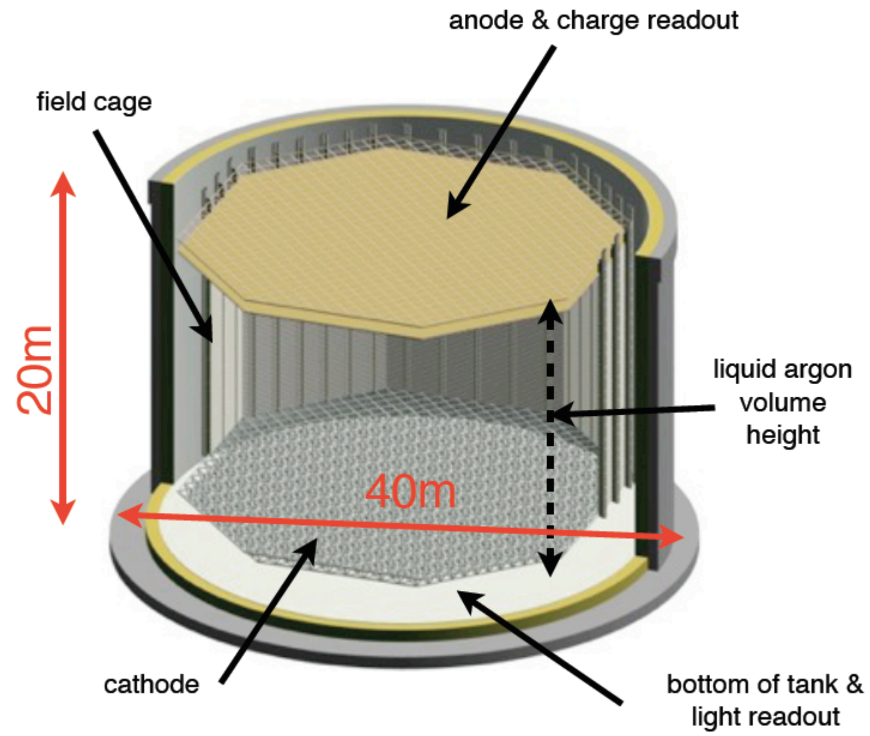


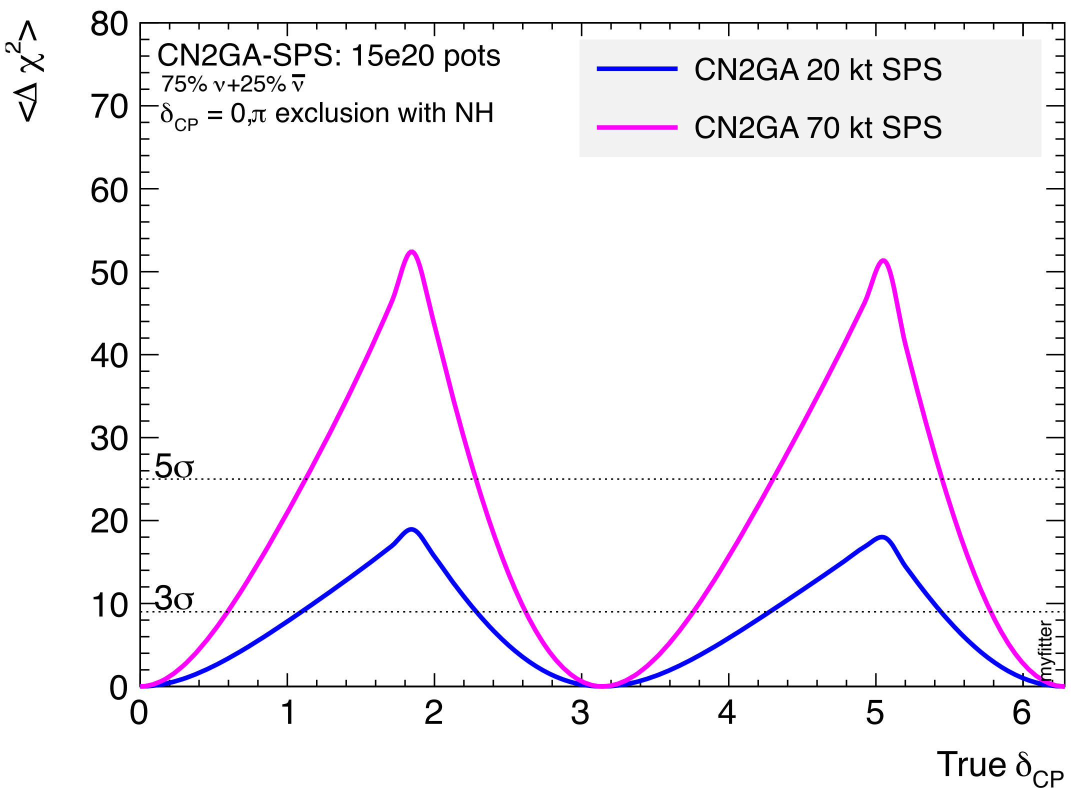
LBNO20 (24kt): 57.3% @ 3 σ & 23.7% @ 5 σ

LBNO70 (70k): 73% @ 3 σ & 53% @ 5 σ

THE GARPENBERG HYPOTESIS **CN2GR**







CP Violation with LBNO

Updated values and errors for oscillation parameters and systematics

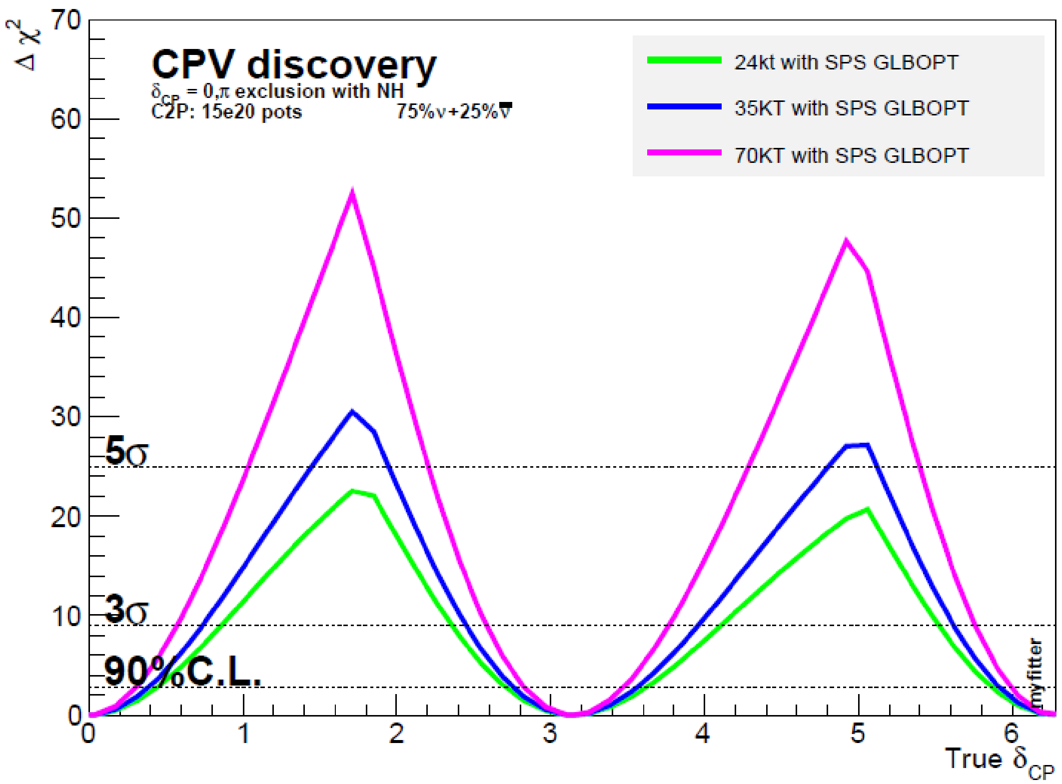
www.nu-fit.org

After TAUP 2013

Parameter	Value	Error
L	2300 km	exact
Δm^2_{21}	7.45×10^{-5} eV^2	fixed
Δm^2_{31}	2.42×10^{-3} eV^2	2 %
$\sin^2\theta_{12}$	0.306	fixed
$\sin^2\theta_{23}$	0.446	5 %
$\sin^2 2\theta_{13}$	0.09	3 %
ρ	3.20 g/cm^3	4 %

Parameter	Value	Error
Signal normalization (f_{sig})	1	3 %
Beam electron contamination normalization ($f_{\nu e}$)	1	5 %
Tau normalization ($f_{\nu\tau}$)	1	20 %
ν NC and ν_μ CC background (f_{NC})	1	10 %

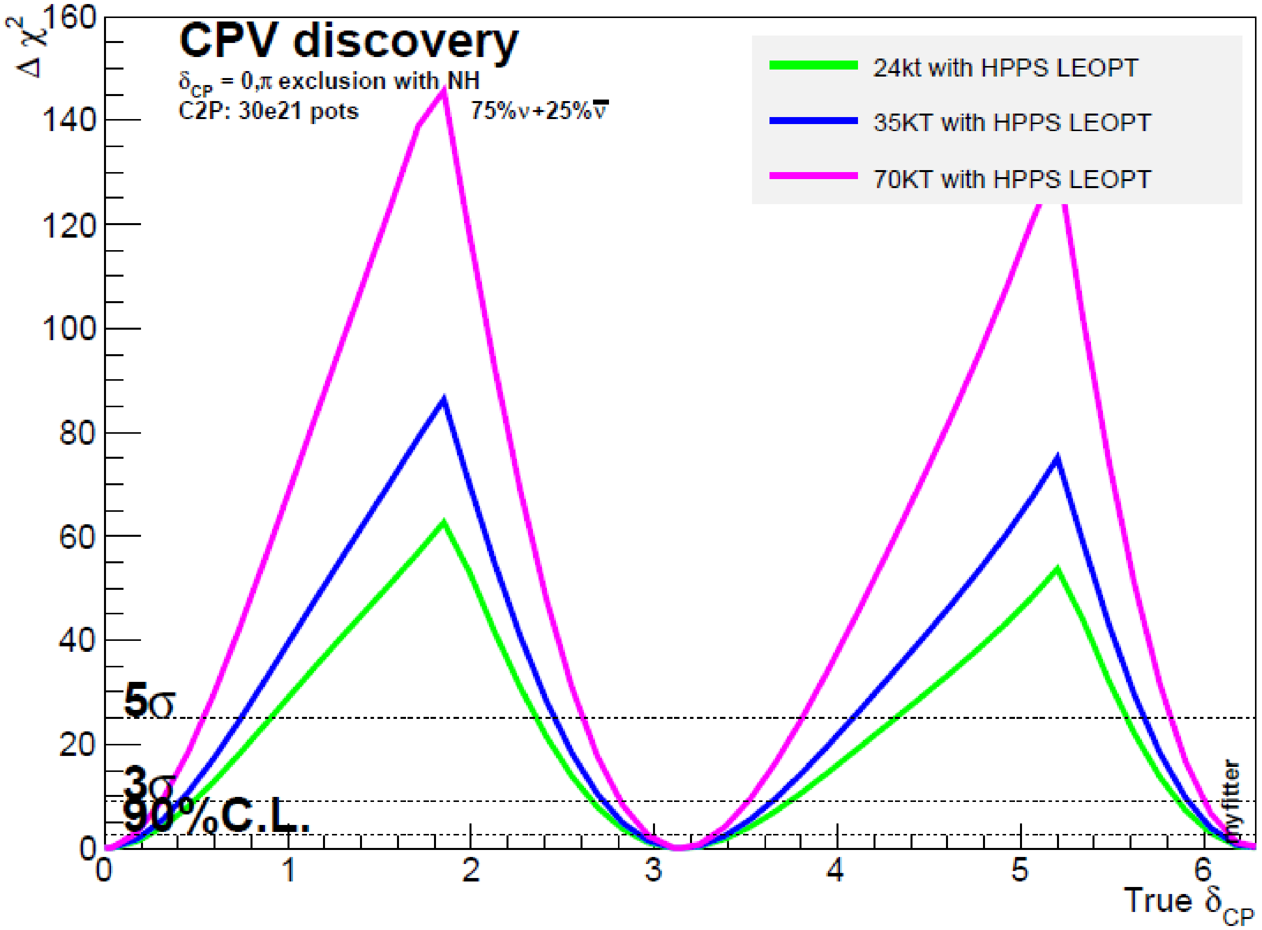
Optimized SPS beam:



Detector		Normal Hierarchy		Inverted Hierarchy	
		3 σ	5 σ	3 σ	5 σ
LBNO Phase I "20 kt"	24 kt	46.5 %	0 %	44.2 %	0 %
	35 kt	53.7 %	13.0 %	54.3 %	0%
LBNO Phase II "70 kt"	70 kt	63.8 %	36.4 %	66.4 %	37.9 %

CP Violation with LBNO

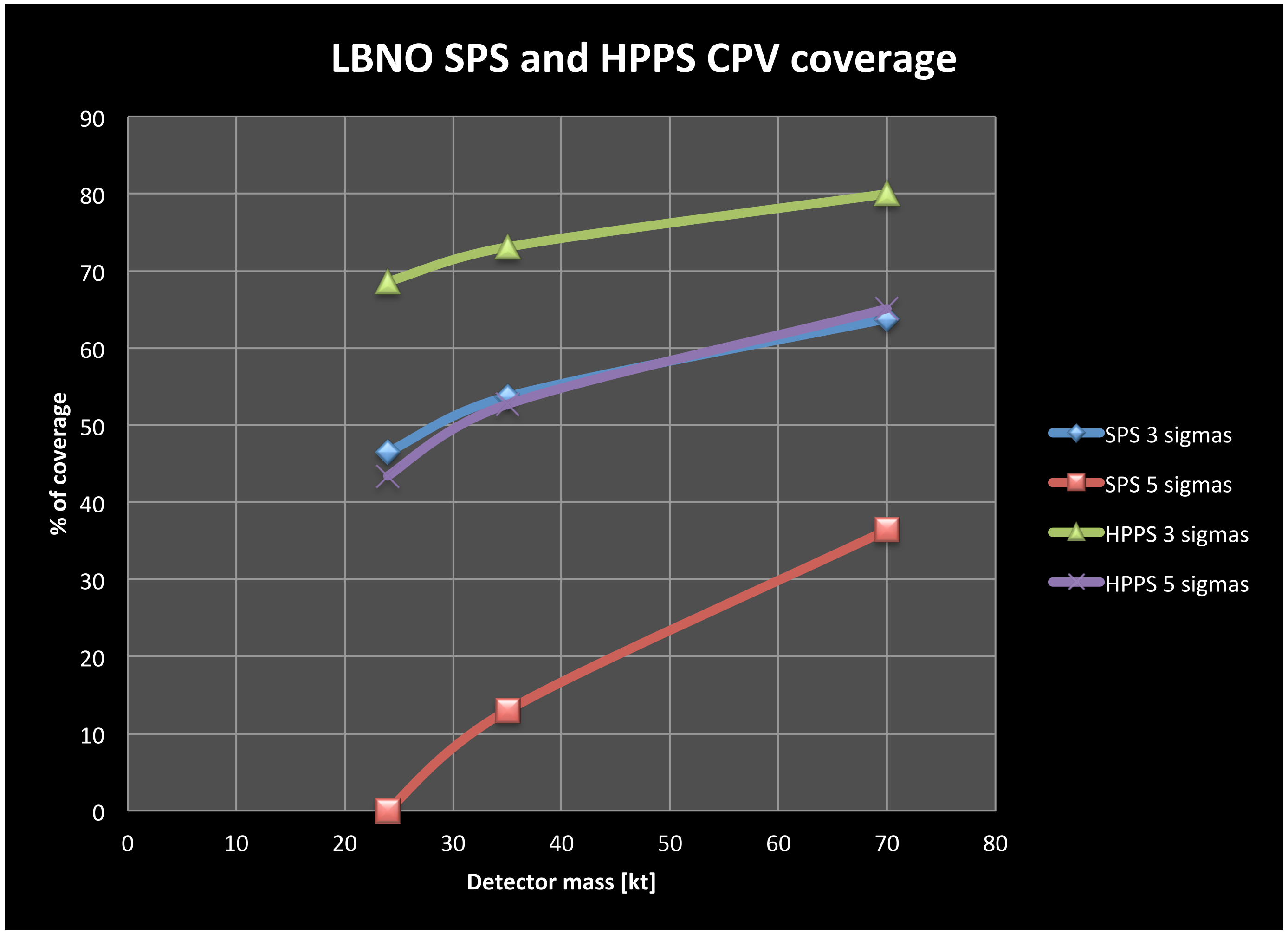
Optimized HPPS:



Detector		Normal Hierarchy		Inverted Hierarchy	
		3 σ	5 σ	3 σ	5 σ
LBNO Phase I "20 kt"	24 kt	68.6%	43.4%	67.9%	38.6 %
	35 kt	73.1%	52.7%	73.1%	50.8 %
LBNO Phase II "70 kt"	70 kt	79.7%	65.1%	80 %	65.4%

CP Violation with LBNO

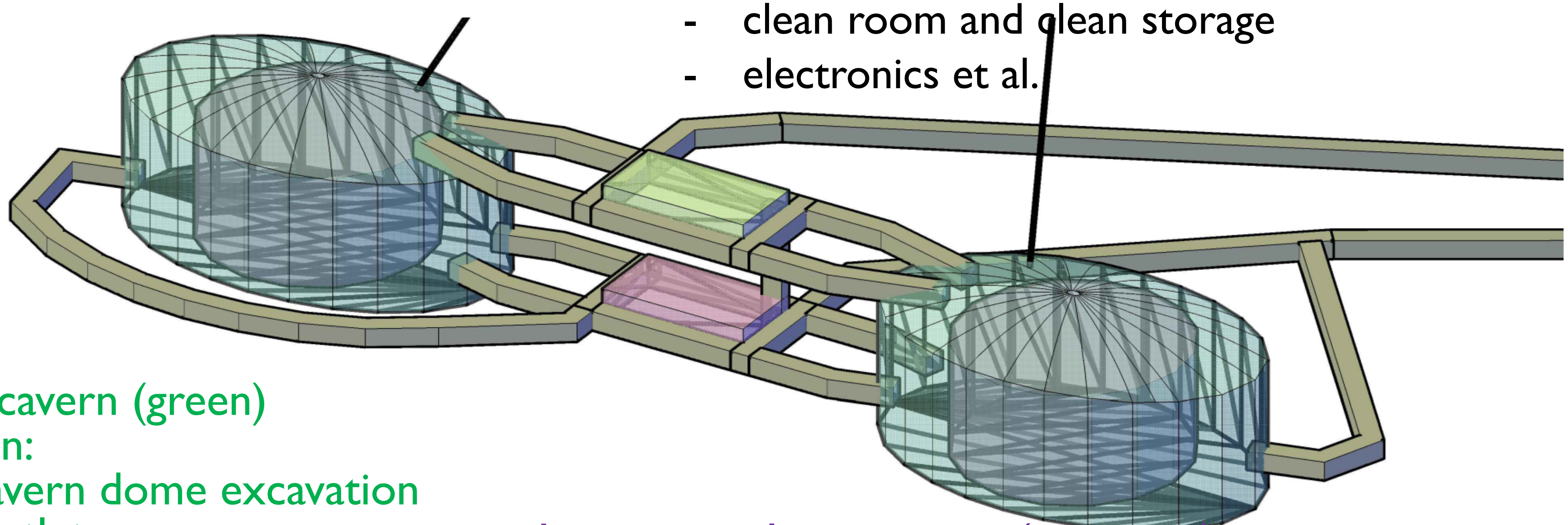
- With the optimized HPPS LBNO can cover **73 %** of the CPV phase space with a **35 kt DLAR**
- **LBNO meets the P5 requirement with 3% syst. error on the signal normalization**
- LBNO fully exploits the L/E behavior and is therefore highly complementary to HK
- From the LAGUNA-LBNO Design Study we have for the 20 kt and 70 kt DLAr and both beams:
  - A fully engineered cavern design + excavation sequence and costing
  - A fully engineered detector design + construction sequence and costing
  - A fully engineered detector instrumentation and costing
  - A complete risk register
  - Estimated running costs
- **LBNO is ready for deployment.**



LAGUNA-LBNO 20+50KT DESIGN SUMMARY

LAYOUT + SAFETY

Main Detector Cavern MDC (in operation):
- equipment space/room
- liquid & gas handling
- clean room and clean storage
- electronics et al.



Upper auxiliary cavern (green)
during excavation:
- access for cavern dome excavation
- ventilation outlet

during construction:
- supply for roof construction

during operation:
- processing, electrical and control room
- power transformation
- ventilation power room

Lower auxiliary cavern (magenta)
during excavation:
- access to cavern invert
- ventilation inlet to caverns
- equipment storage

during construction:
- supply for tank construction

during operation:
- pump installation
- safety and emergency rooms

Guido Nuijten 19.3.2014

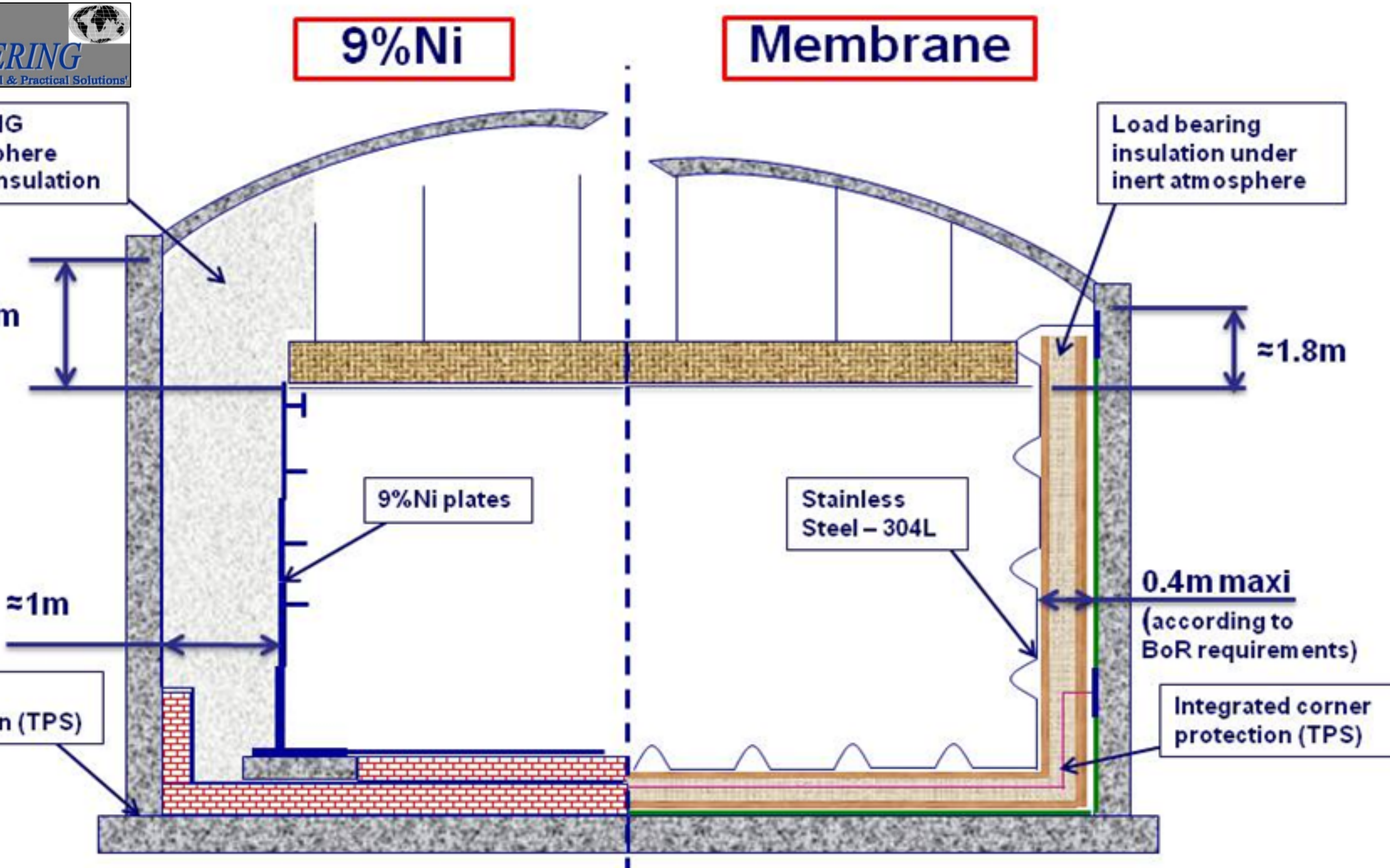
ROCKPLAN

LAGUNA-LBNO 20+50KT DESIGN SUMMARY

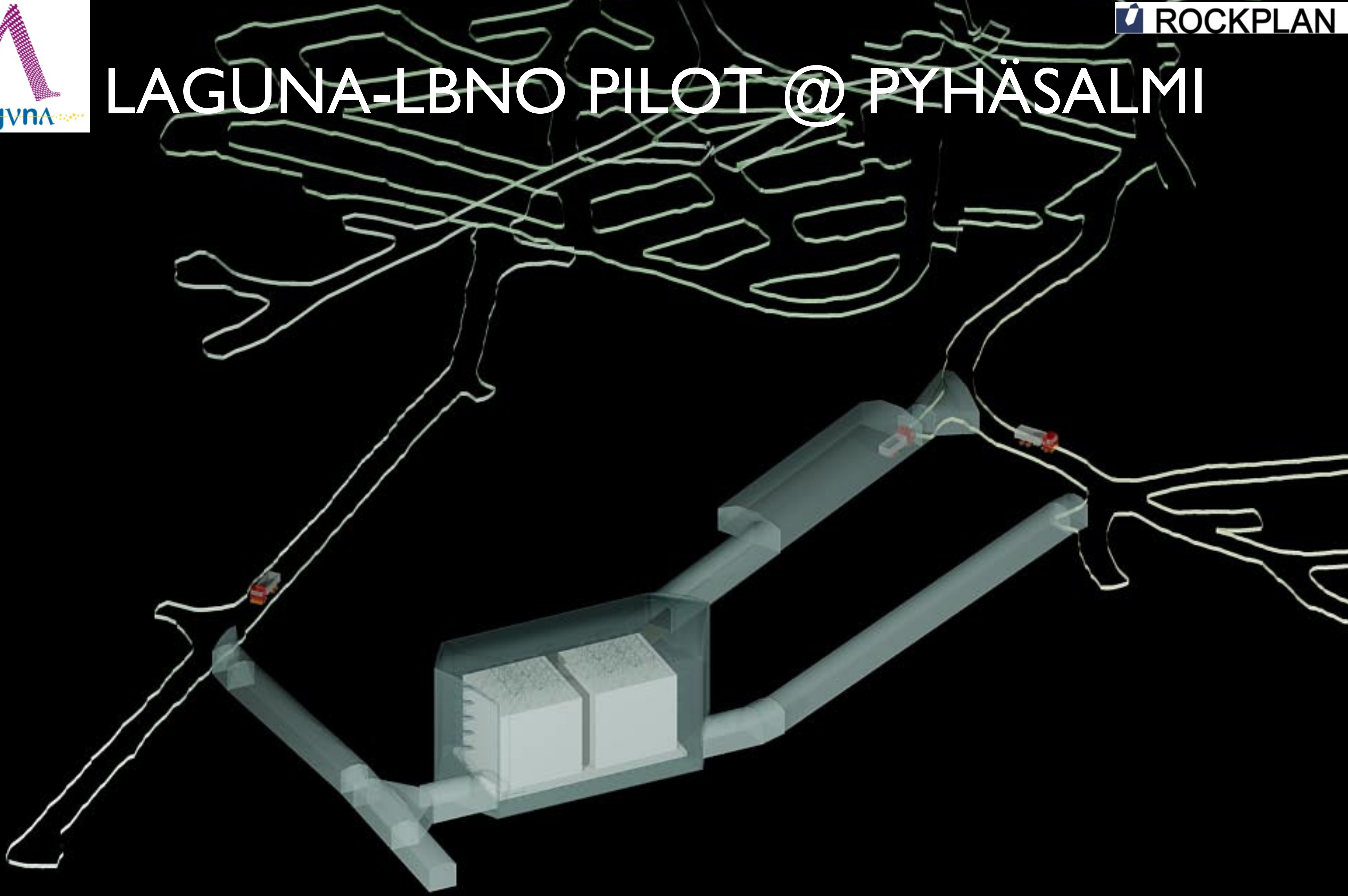
TANK DESIGN (STEEL BASE + MEMBRANE)

Technodyne International Limited

RHYAL ENGINEERING
'Technical, Professional & Practical Solutions'

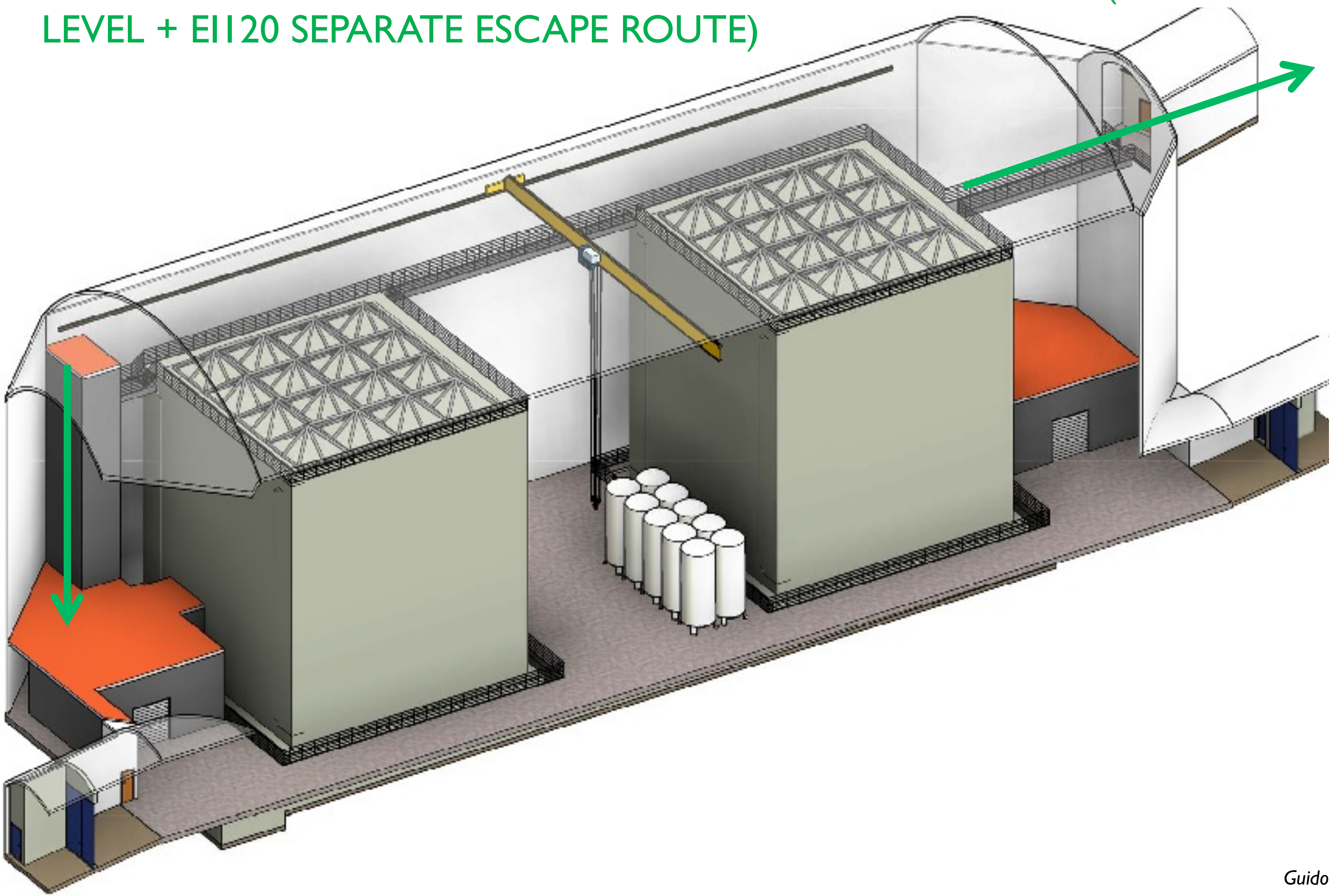


LAGUNA-LBNO PILOT @ PYHÄSALMI



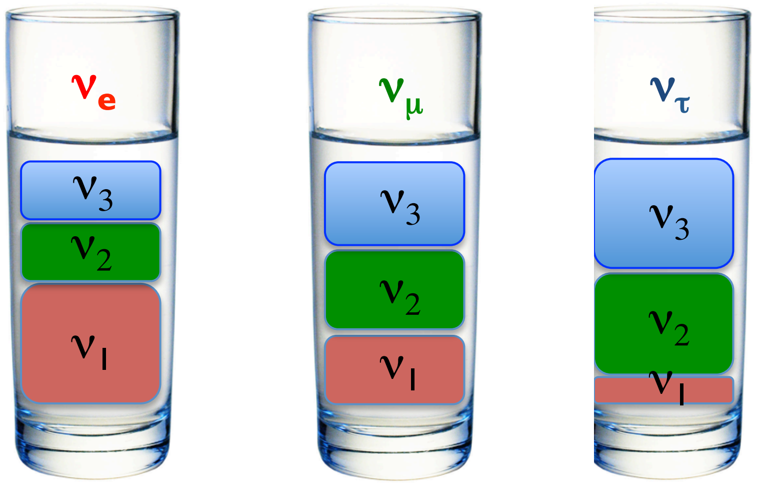
LAGUNA PILOT DESIGN

- COVERING A SAFETY STRATEGY IN CASE OF LAR LEAKAGE (ESCAPE ON TOP LEVEL + EI120 SEPARATE ESCAPE ROUTE)



Guido Nuijten 27.5.2014

Oscillation basics - the flavor cocktail…



(Pontecorvo–Maki–Nakagawa–Sakata)

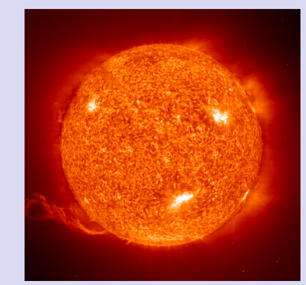
Atmospheric neutrinos	Reactor Neutrinos	Solar neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\sin^2 2\theta_{23} \geq 0.92$

$\Delta m^2_{23} = (2.35 \pm 0.13) \times 10^{-3} eV^2$

$\sin^2 2\theta_{13} = 0.092 \pm 0.017$



$\sin^2 2\theta_{12} = 0.87 \pm 0.03$

$\Delta m^2_{12} = (7.59 \pm 0.20) \times 10^{-5} eV^2$

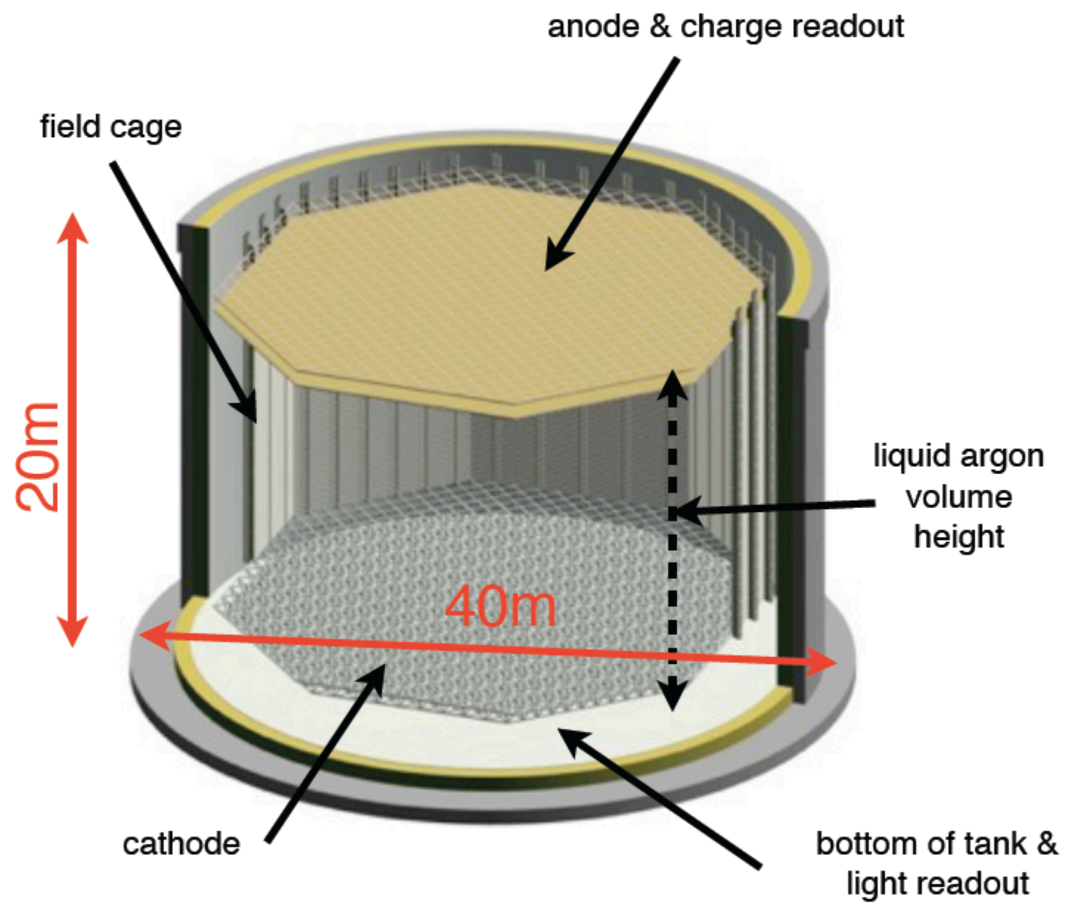
$$\begin{aligned} P(\nu_\mu \to \nu_e) \approx\ & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\hat{\Delta}_{31}) \\ & - \alpha\frac{J_{CP}\sin\delta_{CP}}{\hat{A}(1-\hat{A})}\sin(\hat{\Delta}_{31})\sin(\hat{A}\hat{\Delta}_{31})\sin((1-\hat{A})\hat{\Delta}_{31}) \\ & + \alpha\frac{J_{CP}\cos\delta_{CP}}{\hat{A}(1-\hat{A})}\cos(\hat{\Delta}_{31})\sin(\hat{A}\hat{\Delta}_{31})\sin((1-\hat{A})\hat{\Delta}_{31}) \\ & + \alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\hat{\Delta}_{31}) \end{aligned}$$

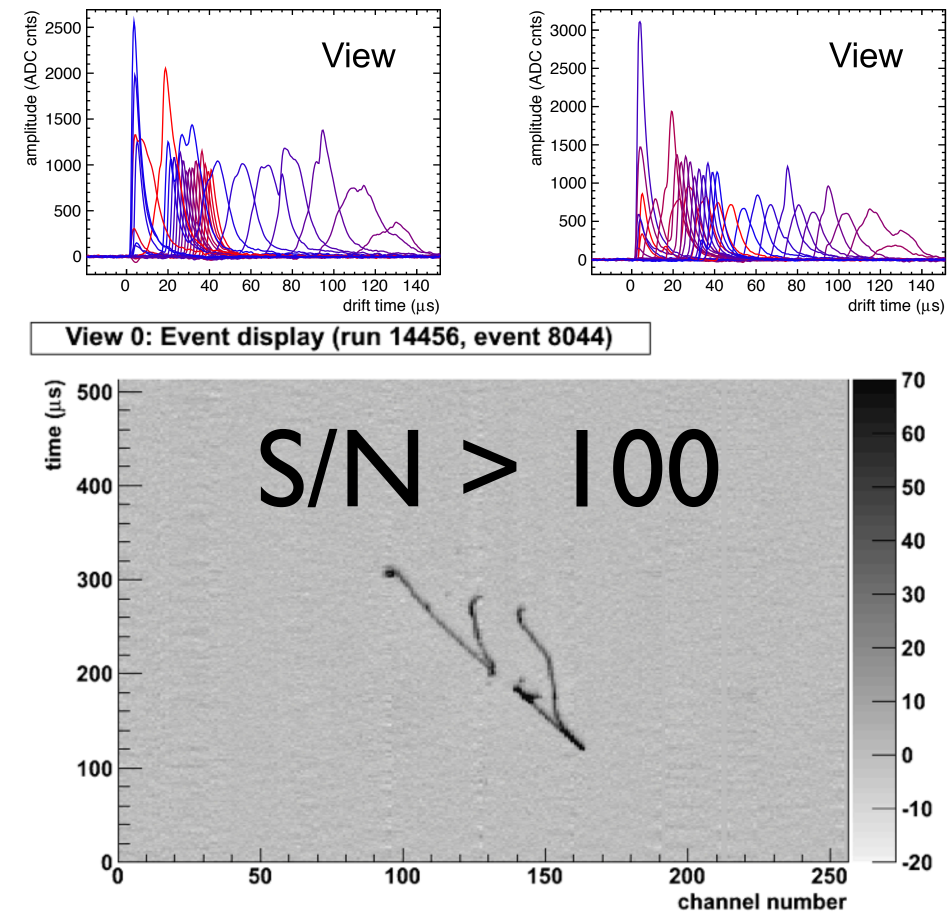
CP odd term: flips sign between nu and anti-nu and therefore introduces the CP asymmetry.

$\Delta m^2_{21} = \alpha\Delta m^2_{31}$ and $\hat{A} = A/\Delta m^2_{31} = 2VE_\nu/\Delta m^2_{31} \approx E_\nu(\mathrm{GeV})/11$ for the Earth's crust.

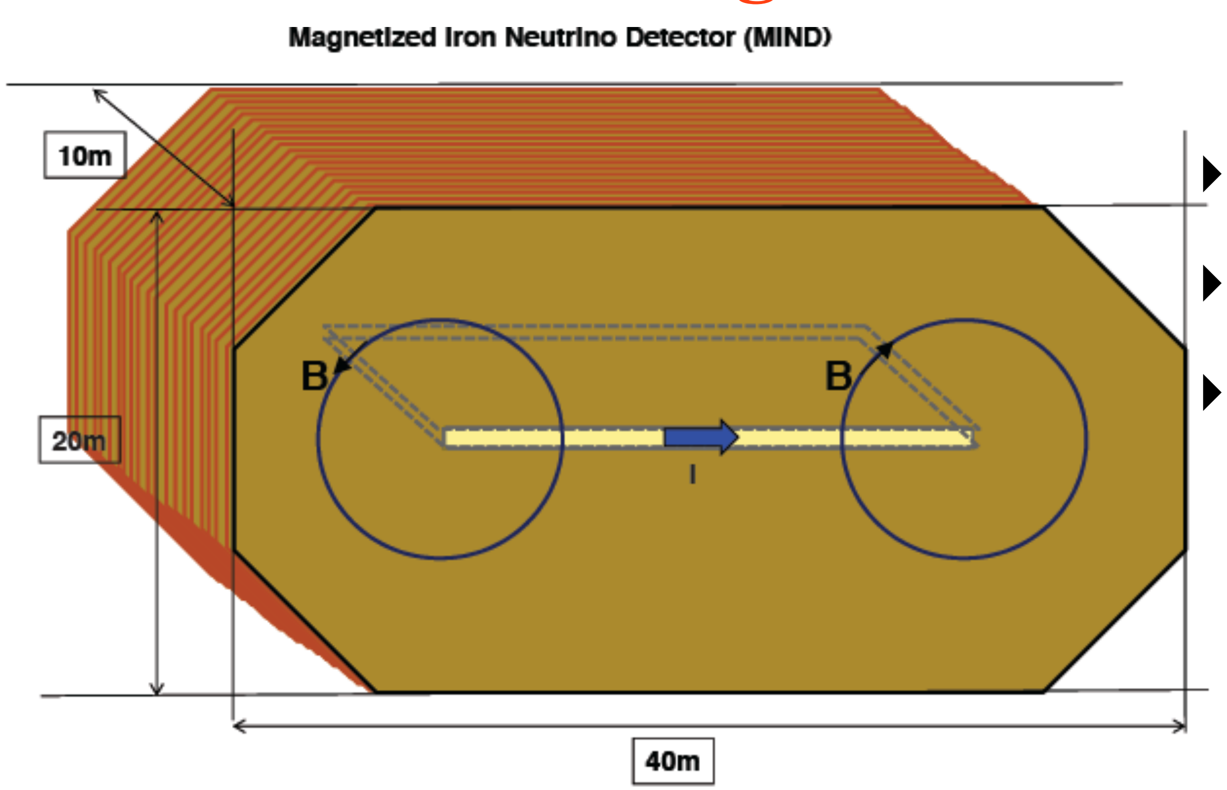
probability for $\bar{\nu}_\mu \to \bar{\nu}_e$ transition is obtained by replacing $\delta_{CP} \to -\delta_{CP}$ and $A \to -A$.

Stage I: 20 kt LAr with 700 kW SPS



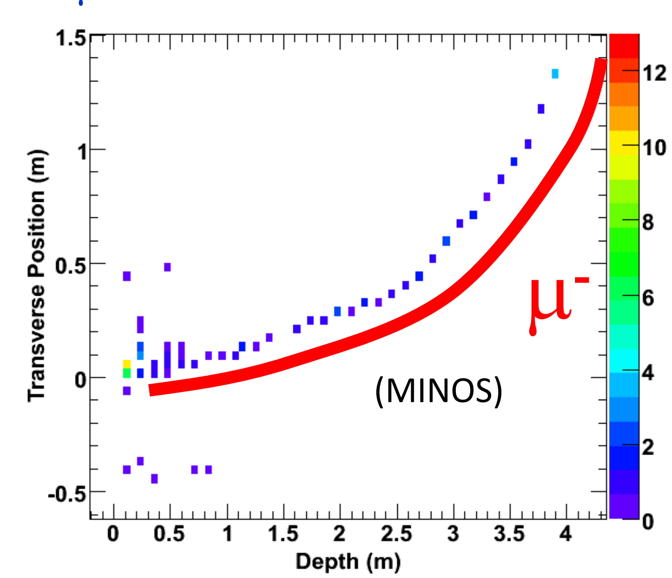


35kton MIND magnetised iron with scintillator slabs (MINOS-like)



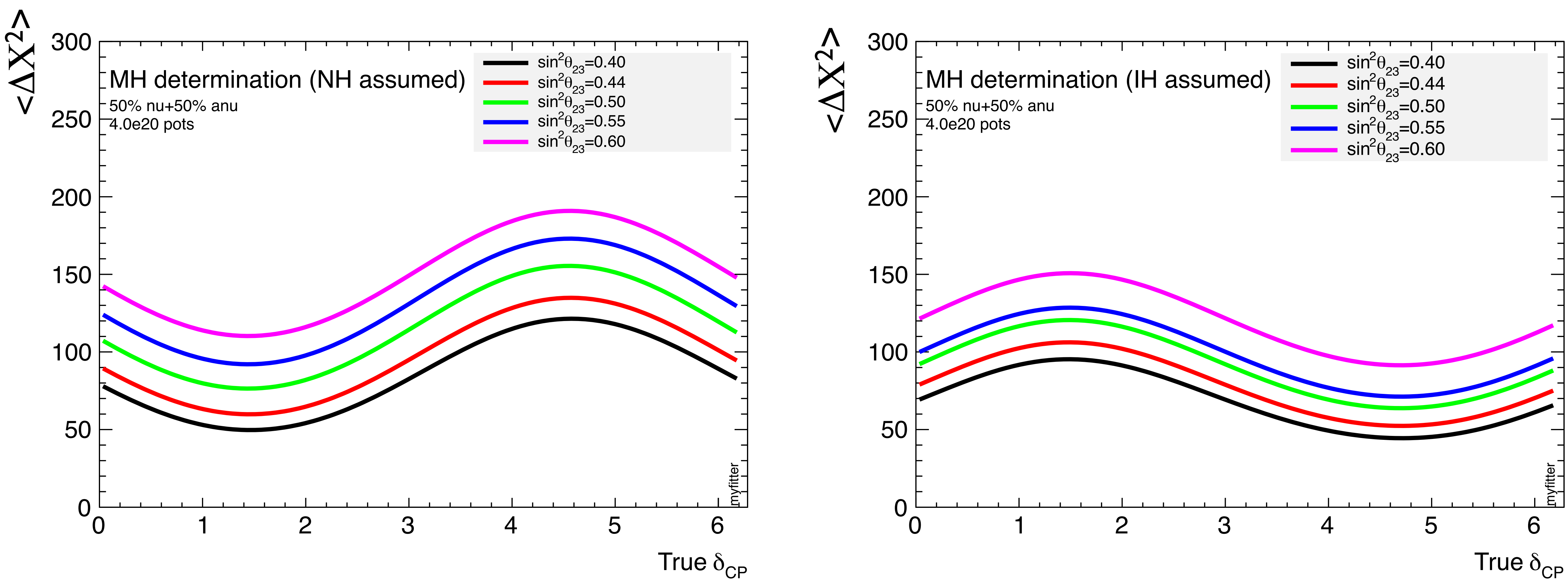
- 3cm Fe plates,
- 1cm scintillator bars,
- B=1.5-2.5 T

ν_μ Charged Current



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.



5 σ MH measurement can be guaranteed by LBNO independent of the octant of θ_{23}

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

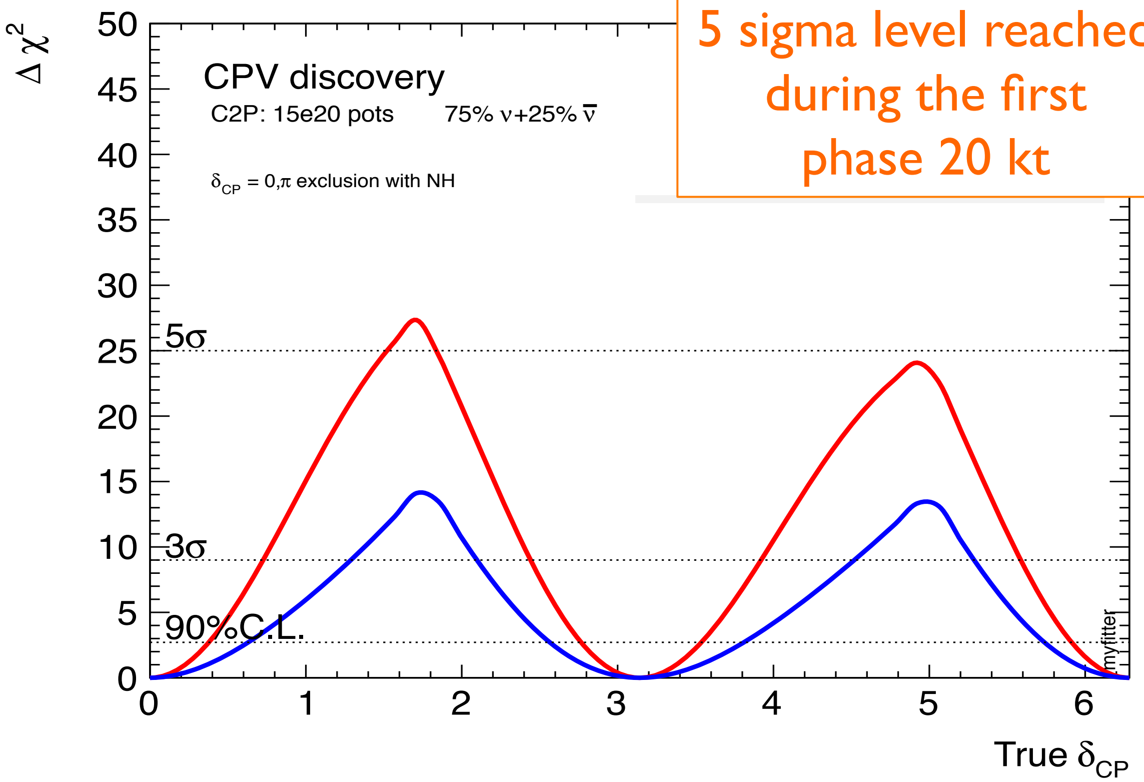
Curves are simulated for 20 kt and 1.5e21 POT at 2300 km

-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	±10% 3%
$sin^2\theta_{23}$	0.44 0.38	±0.04	±9%
Average density of traversed matter (ρ)	$3.20\ g/cm^3$ $2.8\ g/cm^3$	±0.[illegible]	[illegible]4%

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

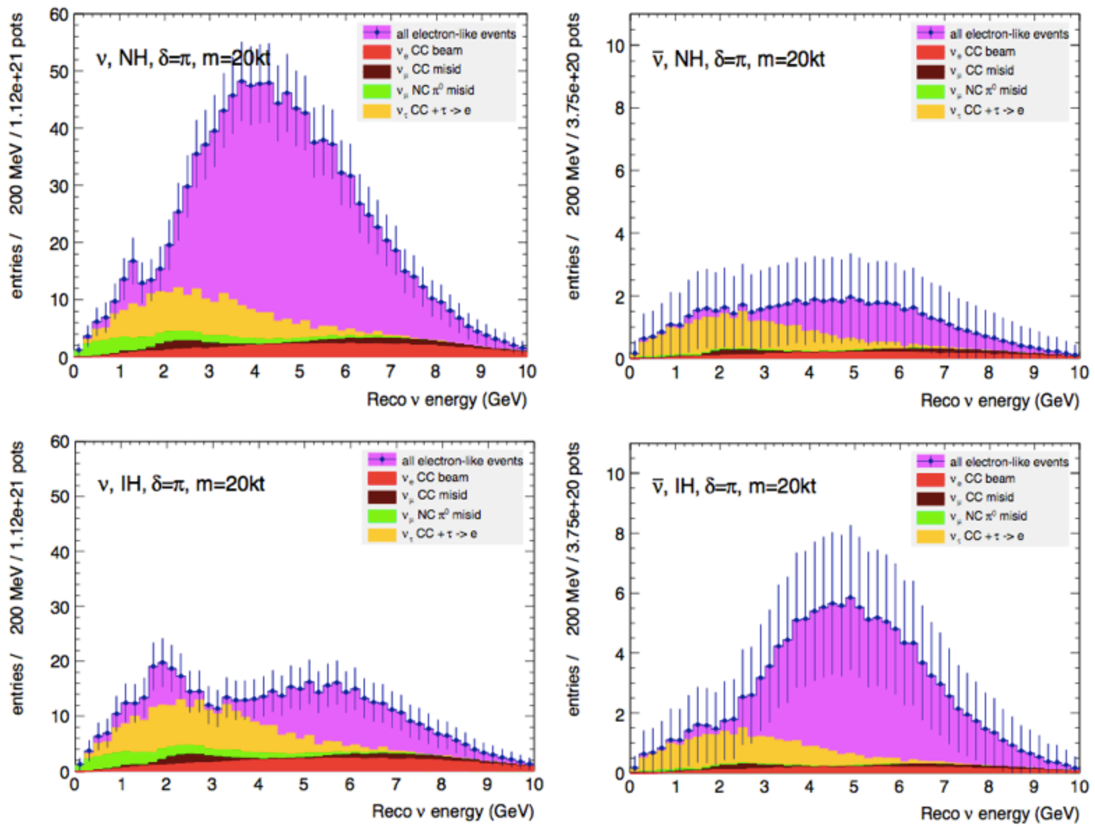
-The value of θ_{23} Fogli et al. arXiv:1205.5254v3 (ours: Gonzales et al. arXiv:1209.3023)

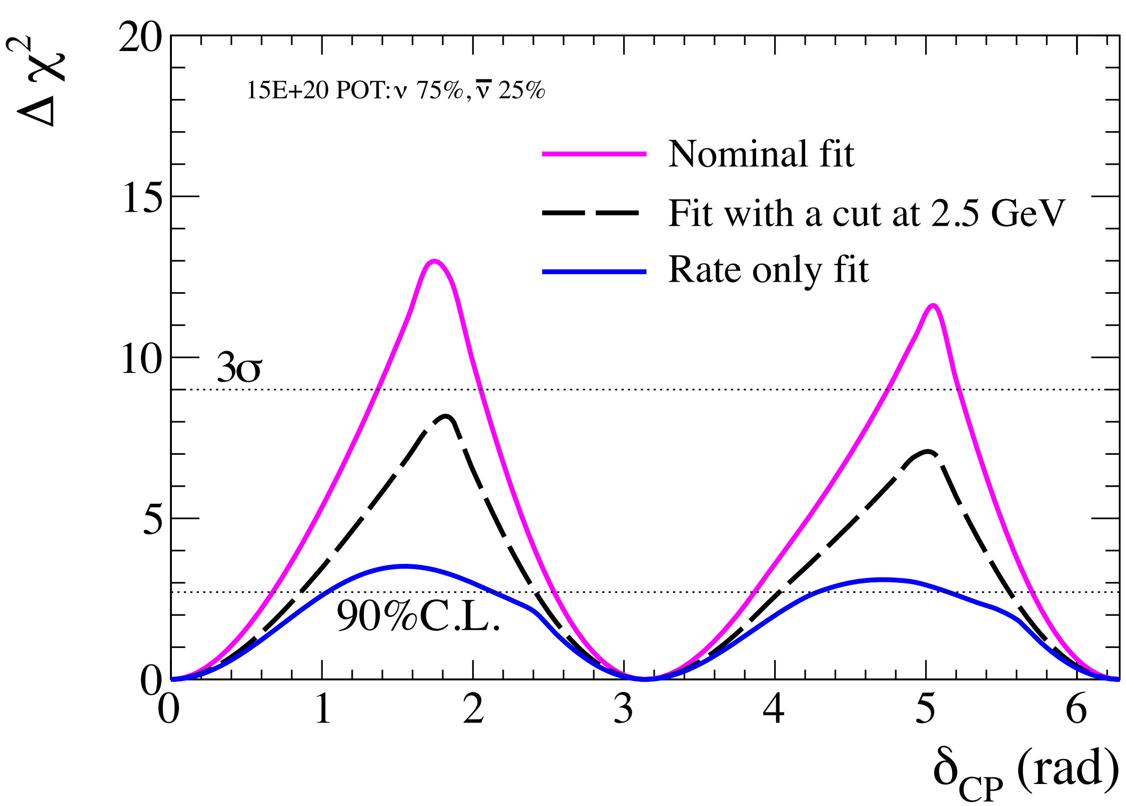
-Error on sin^22 θ_{13}

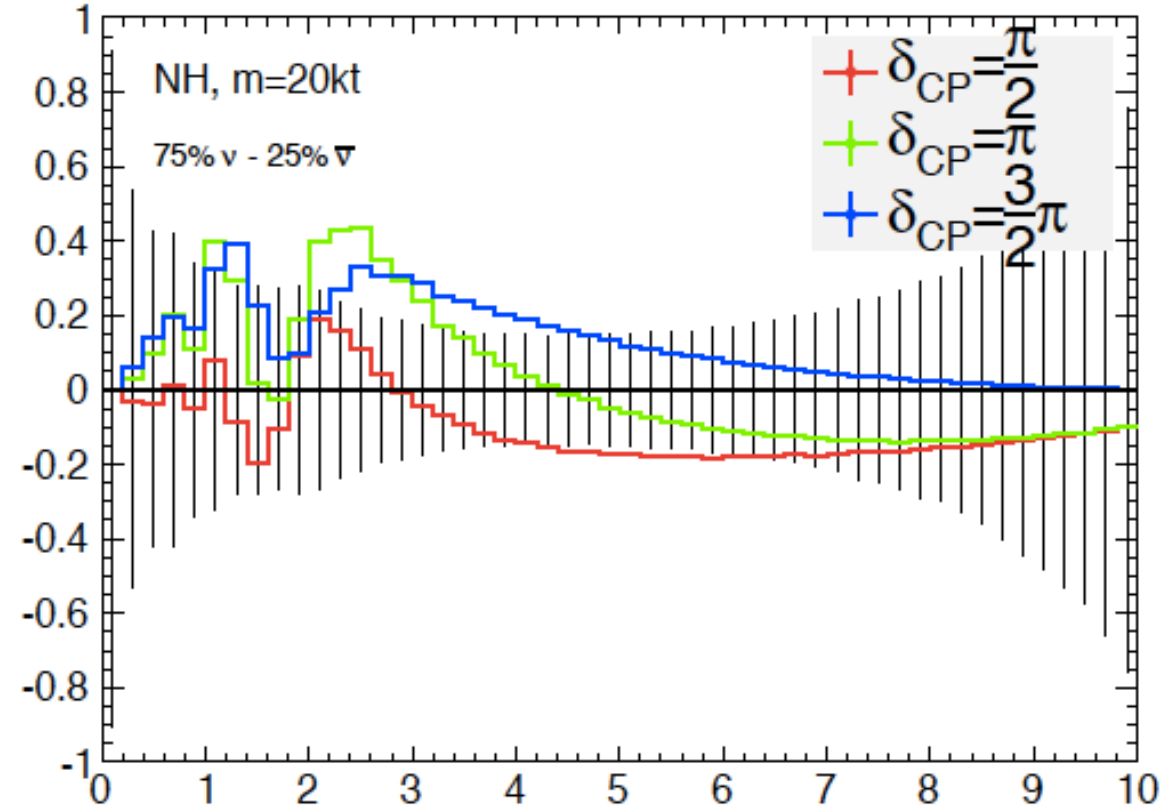
-Systematics on signal and background

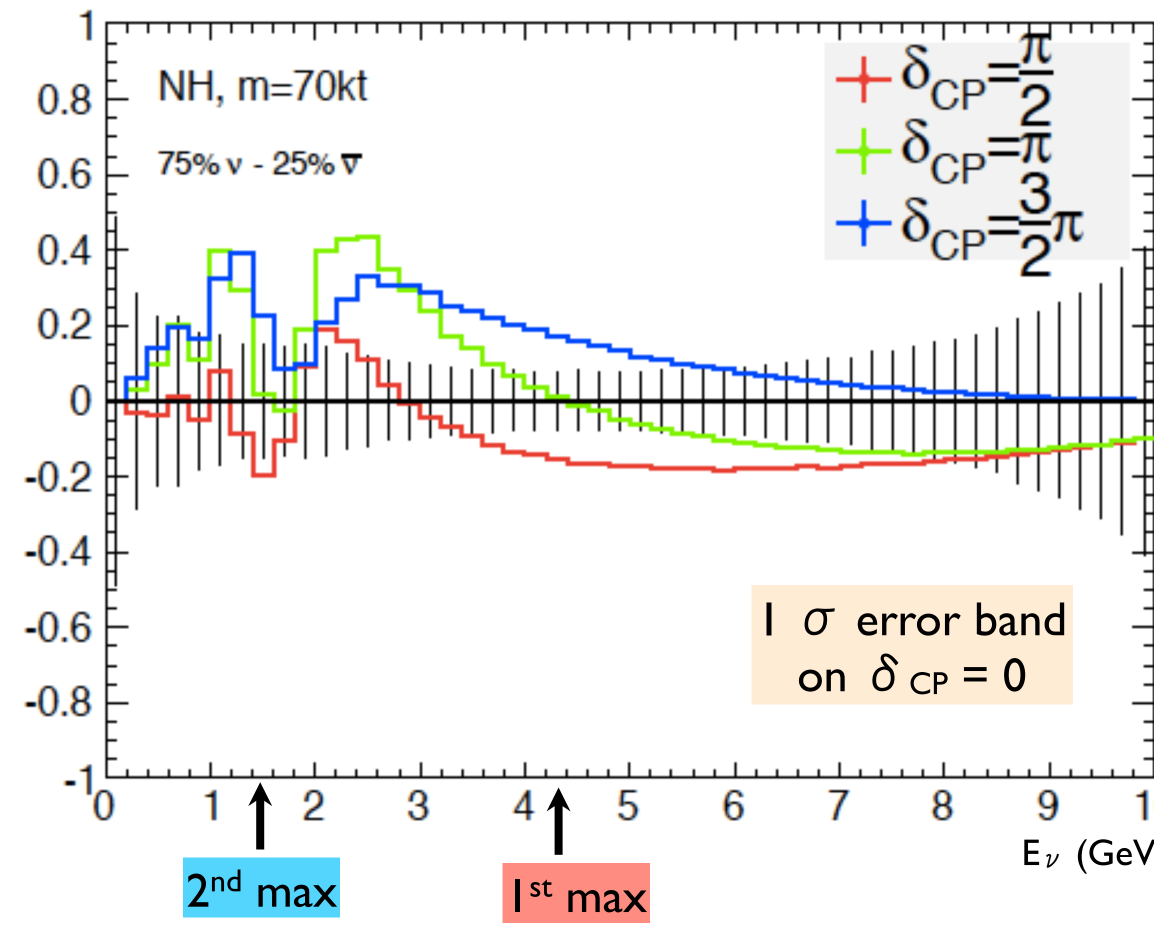
LBNO Strategy on δ_{CP}

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



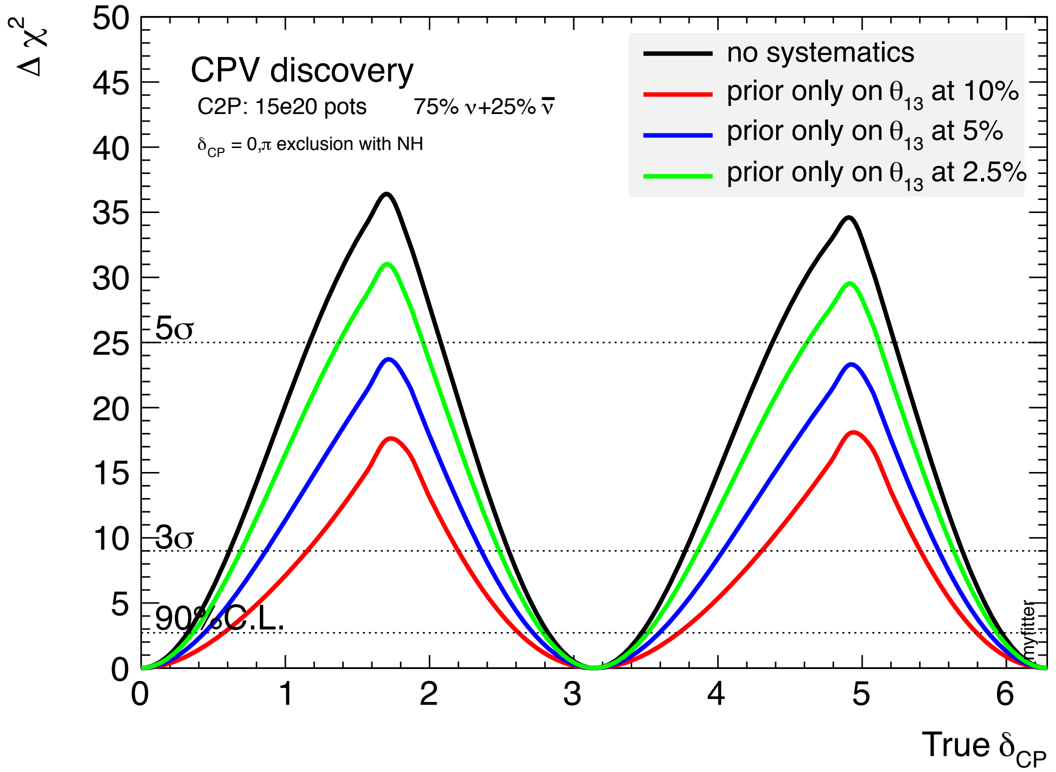


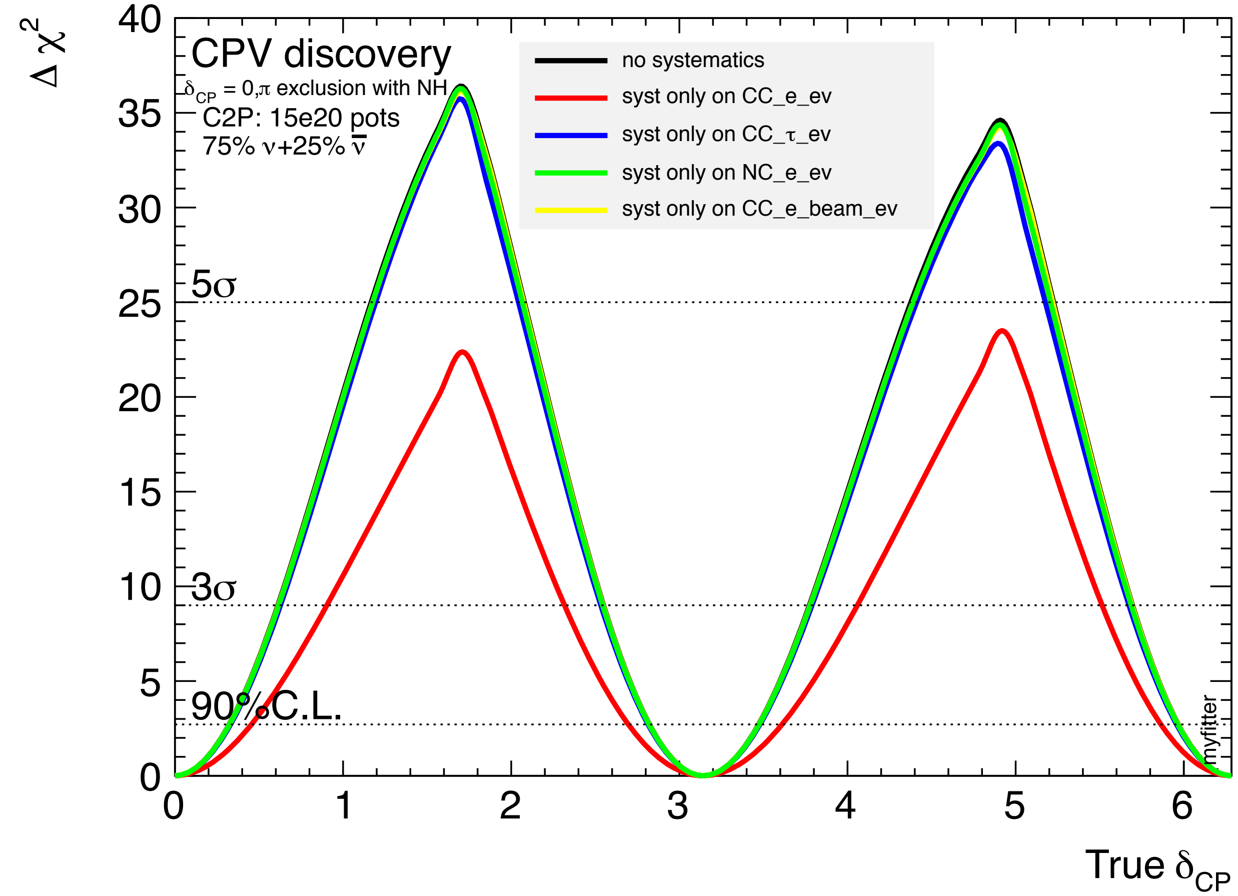


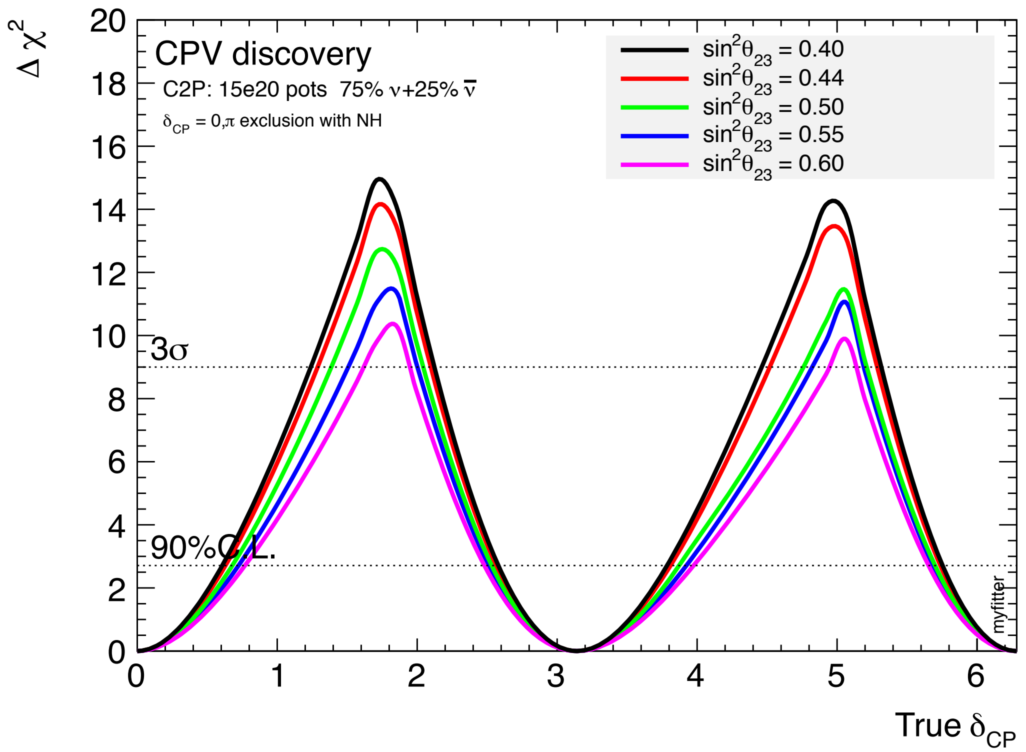


LBNO Strategy on δ_{CP}

Use best knowledge and realistic assumptions on systematics and oscillation parameters

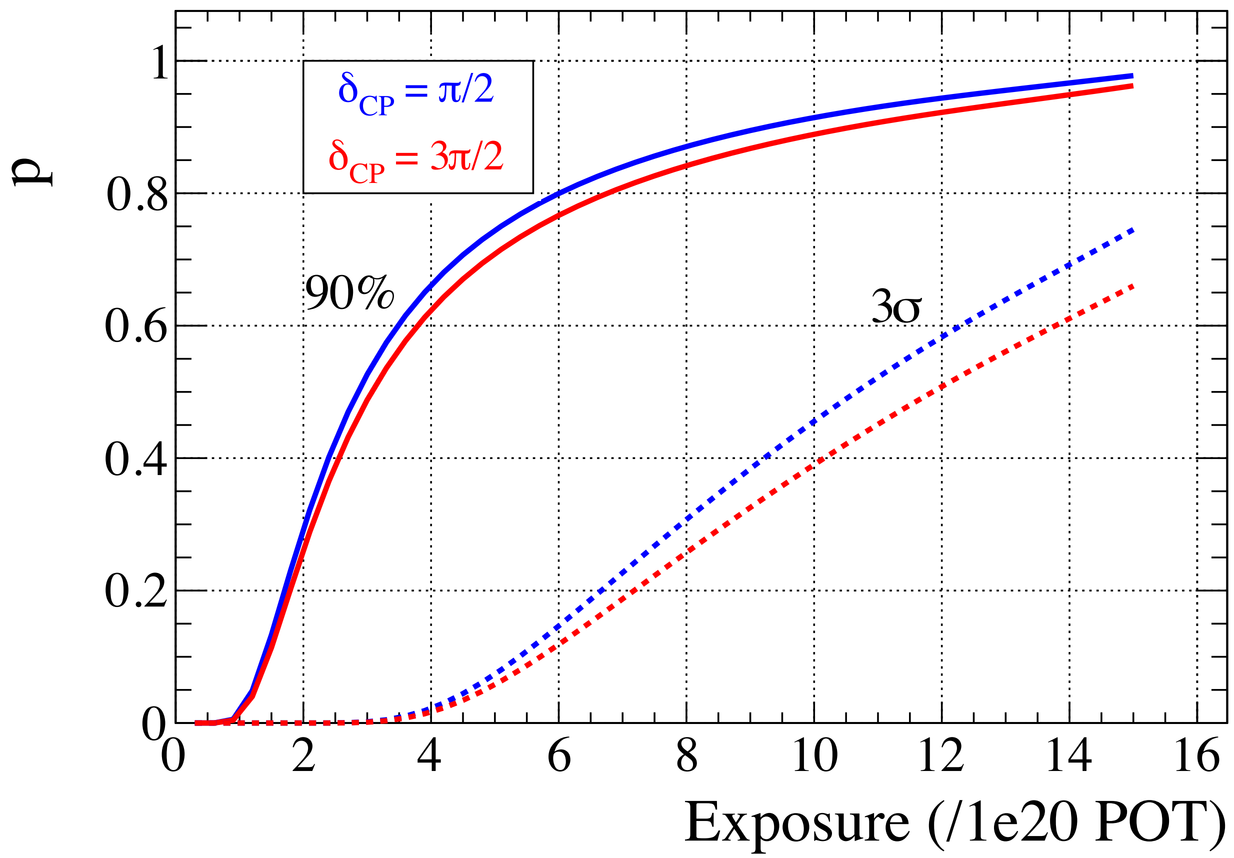






The most important oscillation parameters are θ_{23} and θ_{13} and the most important systematics is the knowledge of the absolute rate of ν_e CC events.

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



Name	Value	error (1σ)	error (%)
L	2300 km	exact	exact
Δm^2_{21}	$7.6 \times 10^{-5}\ eV^2$	exact	exact
$\|\Delta m^2_{31}\| \times 10^{-3}\ eV^2$	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	$\pm 10\%$
verage density of traversed matter (ρ)	3.20 g/cm^3	± 0.13	$\pm 4\%$

e 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	$\pm 10\%$

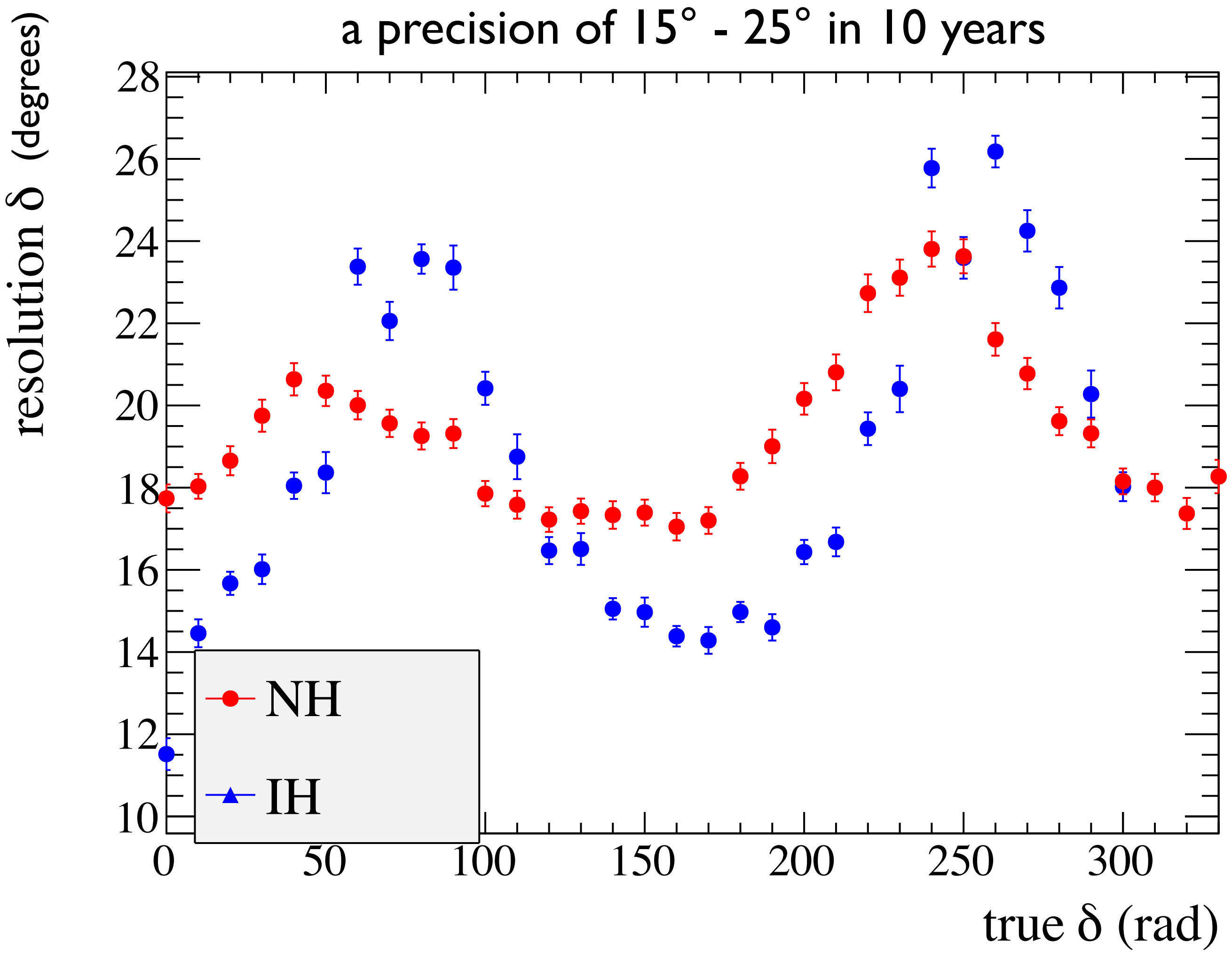
e 6: Assumptions on event normalization uncertainties (bin-to-bin correlated errors).

- 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.

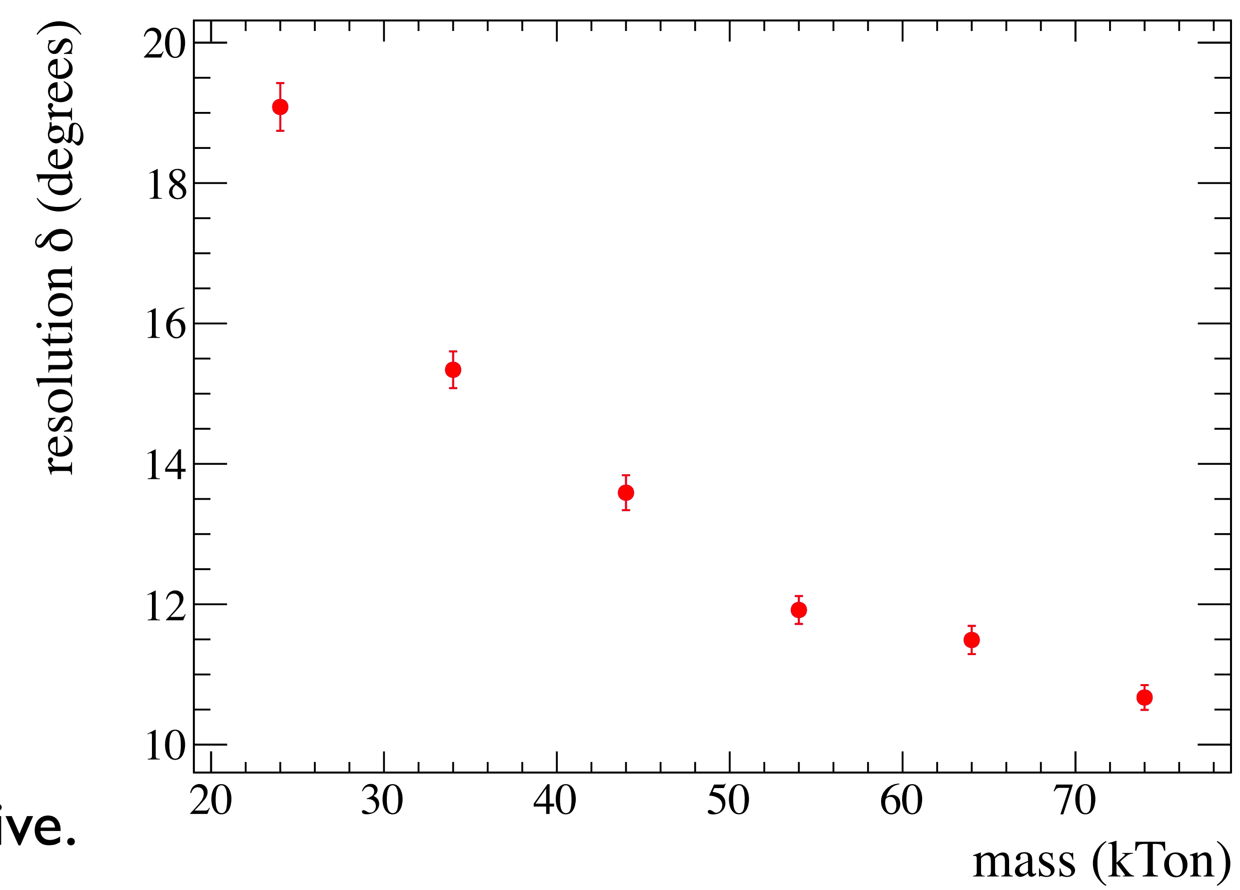
For all details see our paper: arXiv:1312.6520

Measuring the δ_{CP} with LBNO:

LBNO phase 1 can measure the dCP phase with a precision of 15° - 25° in 10 years



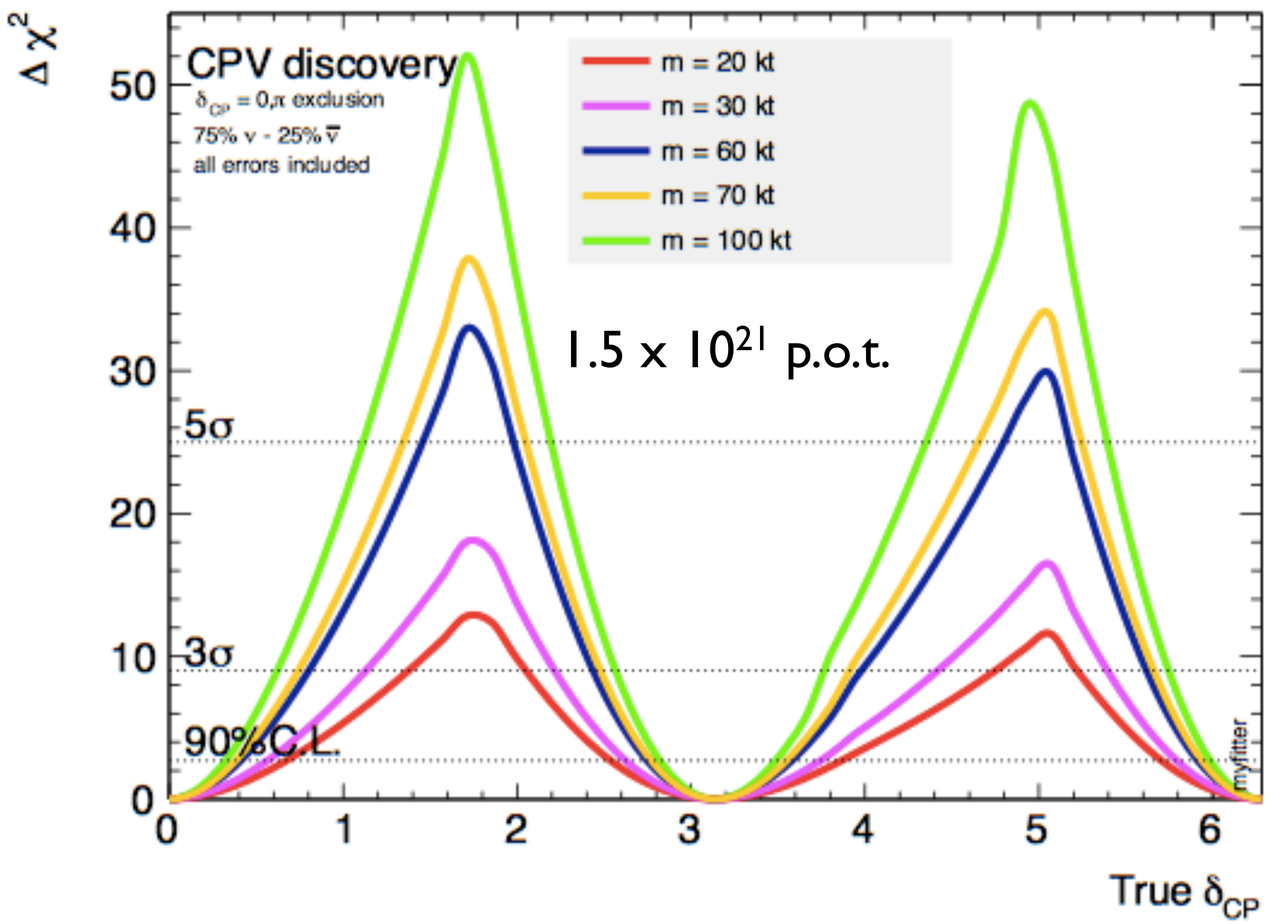
LBNO 70 kt can measure the δ_{CP} phase with a precision of 10° in 10 years



LBNO physics potential even phase 1 is competitive.

LBNO Strategy on δ$_{CP}$

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



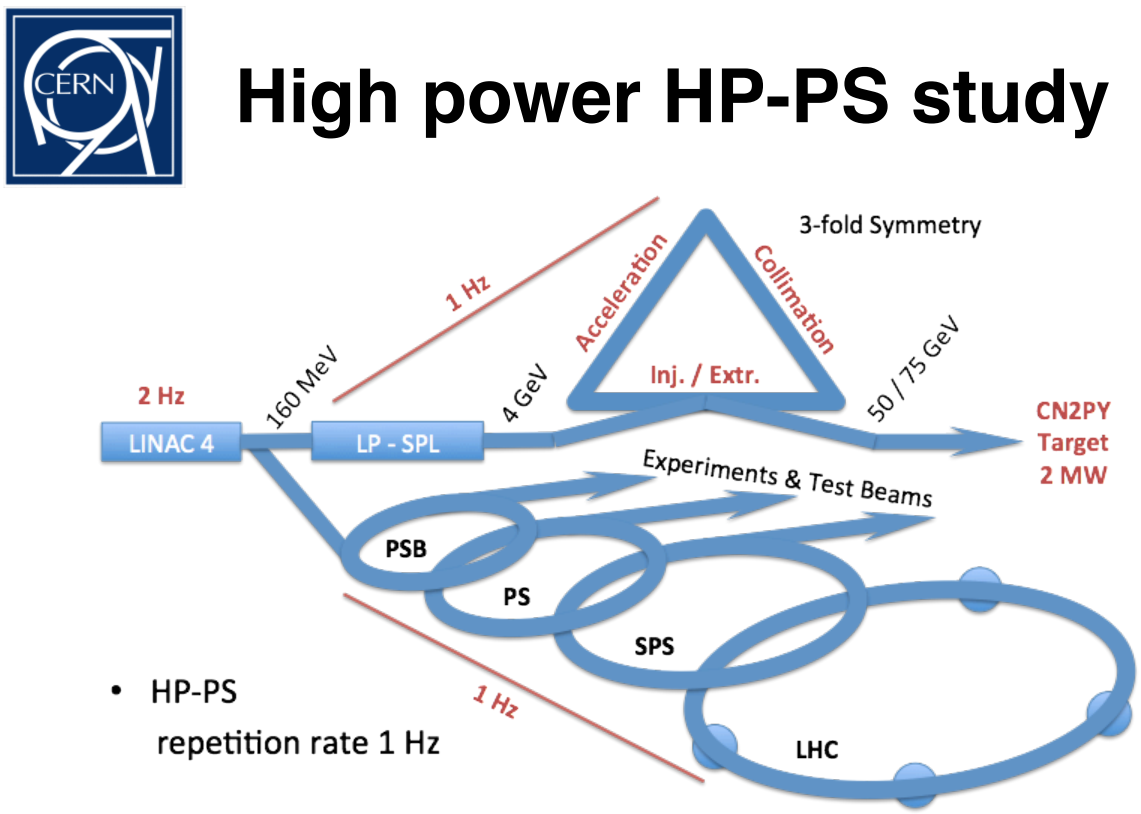
Name	Value	error (1σ)	error (%)
L	2300 km	exact	exact
Δm^2_{21}	$7.6 \times 10^{-5}\ eV^2$	exact	exact
$\lvert\Delta m^2_{31}\rvert \times 10^{-3}\ eV^2$	2.420	±0.091	±3.75 %
$\sin^2\theta_{12}$	0.31	exact	exact
$\sin^2 2\theta_{13}$	0.10	±0.01	±10%
$\sin^2\theta_{23}$	0.440	±0.044	±10%
Average density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

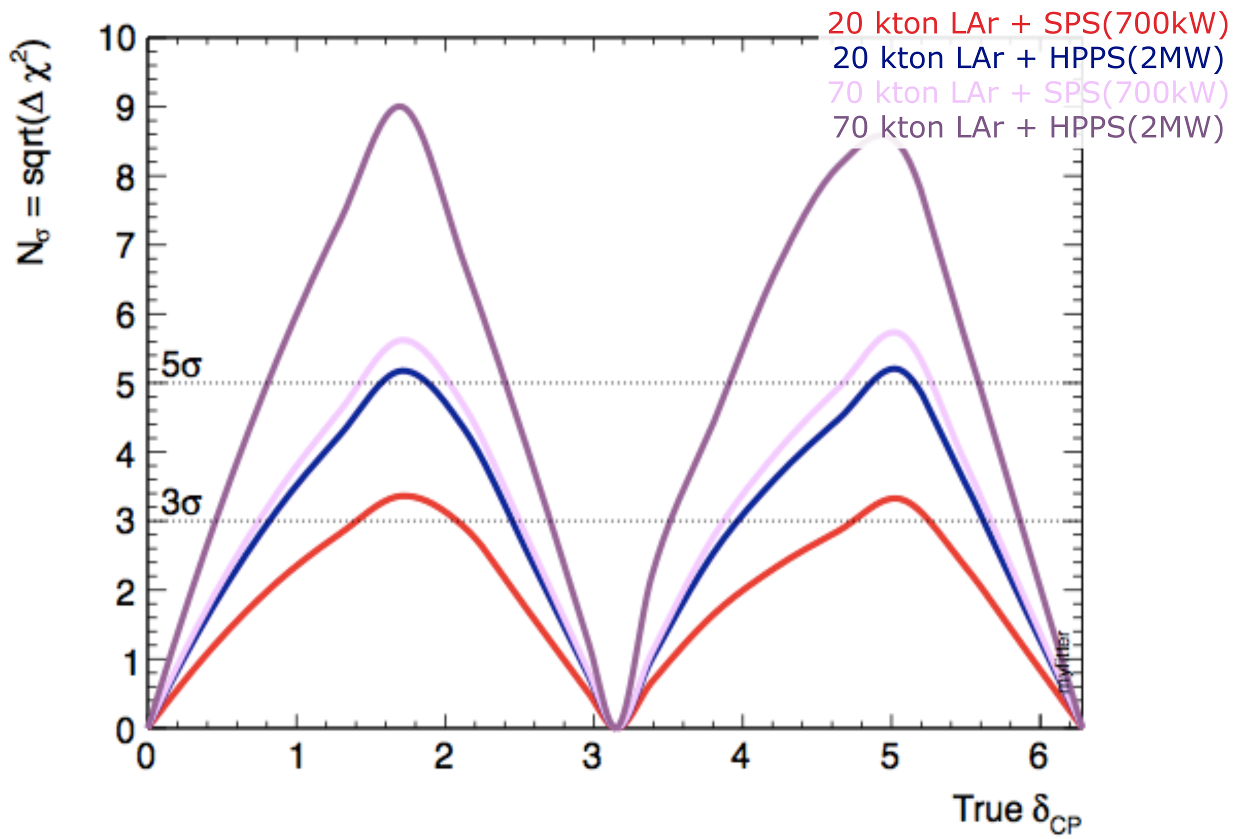
Name	Value	error (1σ)
Signal normalization (f_{sig})	1	±5%
Beam electron contamination normalization (f_{ν_e})	1	±5%
Tau normalization (f_{ν_τ})	1	±20% – ±50%
ν NC and ν_μ CC background (f_{NC})	1	±10%

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

High power HP-PS study

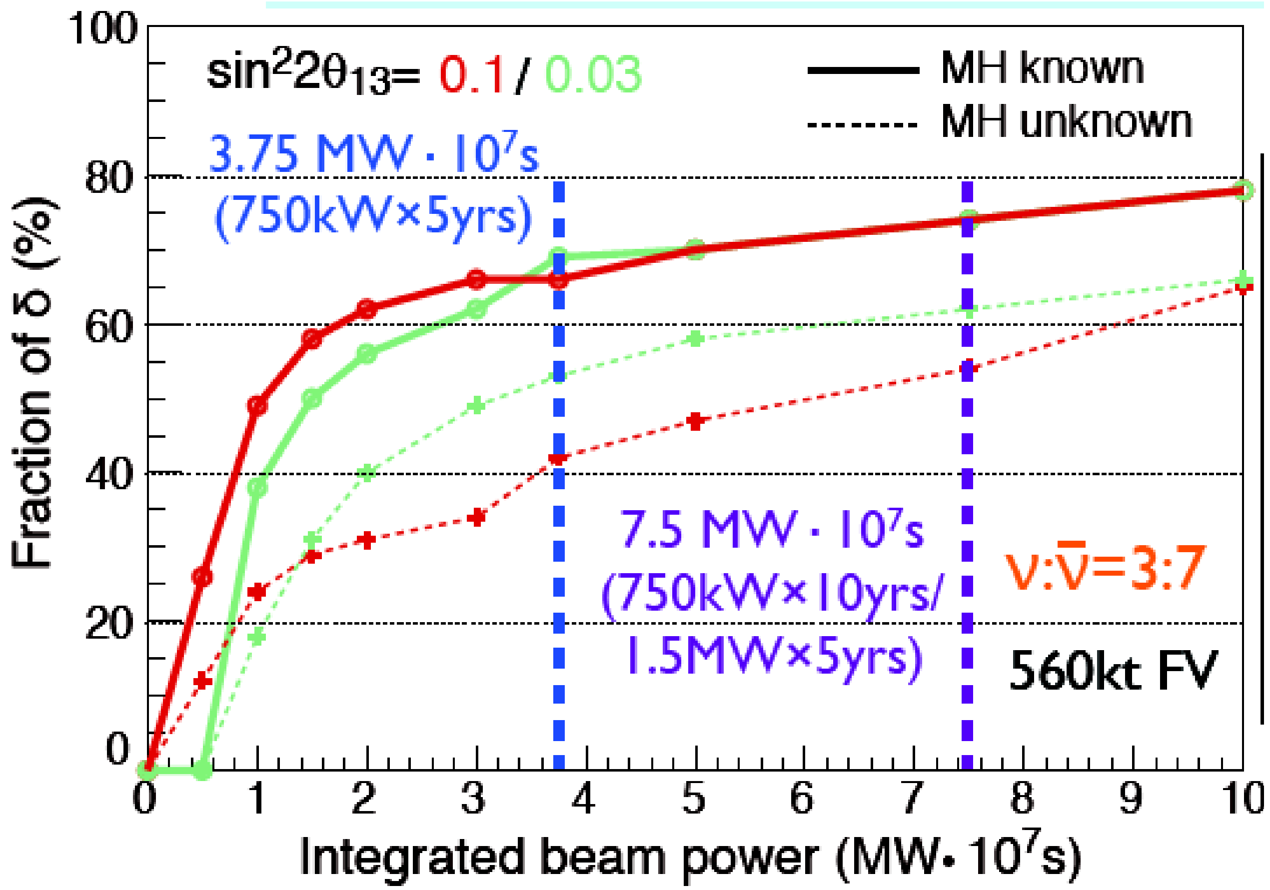


- HP-PS
  repetition rate 1 Hz



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.