LAGUNA-LBNO: a very long baseline neutrino oscillation experiment

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On behalf of the LAGUNA-LBNO collaboration
Swiss Federal Institute of Technology, ETH, Zürich, Switzerland

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ETH
Eidgenössische Technische Hochschule Zürich
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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Expression of Interest

for a very long baseline neutrino oscillation experiment

(LBNO)

- ✓Expression of Interest (EoI) submitted to CERN-SPSC on June 26th 2012
  - CERN-SPSC-2012-021; SPSC-EOI-007
    - Physics Case
    - Experimental Setup
    - Physics potential

~230 authors, 51 institutions

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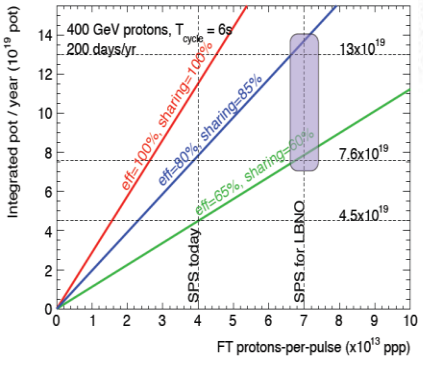
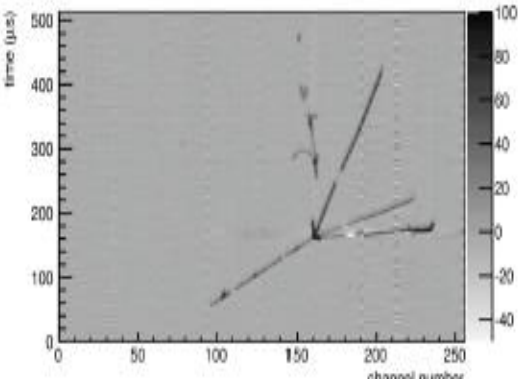
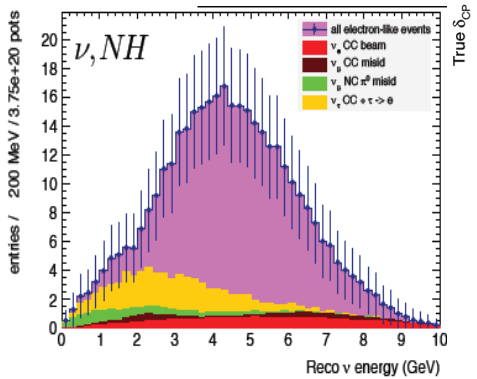
LAGUNA-LBNO: goals

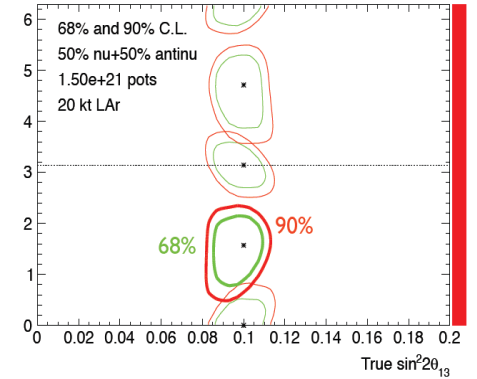
- next generation long baseline experiment → better sensitivity w.r.t. T2K and NOνA
- observe Mass Hierarchy, through matter effect, and CP-Violation
- sign of Δm^2 and δ_{CP} to be measured directly from the oscillation analysis
  - large detectors + intense ν beam → high statistics
  - very long baseline → break Mass Hierarchy-δ_{CP} degeneracy, measure 1st and 2nd oscill. maxima
- extended nucleon decay search: probe BSM physics up to GUT scale
- sound atmospheric and astrophysical neutrino program

A new massive deep underground neutrino observatory
for long baseline neutrino studies,
capable of proton decay searches,
atmospheric and astrophysical neutrino detection









LBNO goals

Better sensitivity w.r.t. T2K+NOνA:

Beam

Fully exploit long baseline neutrino oscillation pattern

⇩

perform L/E analysis over large energy range
(1st and 2nd maxima)

⇩

Wide Band Beam (WBB)

E_ν 2nd max >500 MeV → L > 1000 km

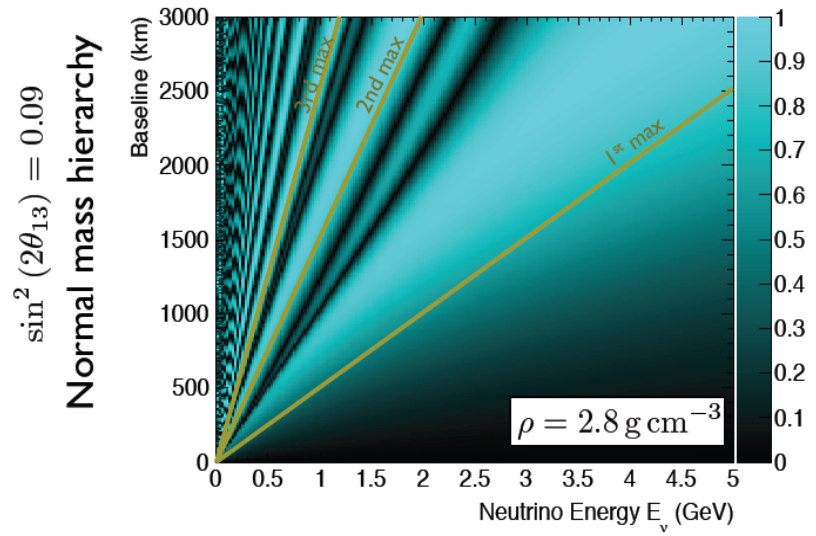
Detector

Better signal efficiency and background rejection
with a comparable mass

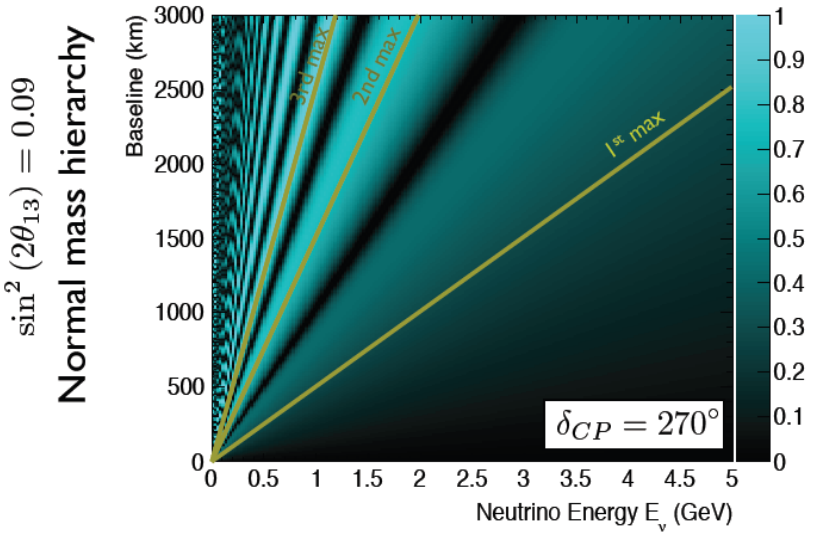
⇩

20 kton fine sampling tracking device

$$\mathcal{A}_{CP}(\rho) \equiv abs\left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$



$$\mathcal{A}^{vac}_{CP}(\delta_{CP}) \equiv abs\left(\frac{P^{vac}(\nu) - P^{vac}(\bar{\nu})}{P^{vac}(\nu) + P^{vac}(\bar{\nu})}\right)$$



The LAGUNA consortium

Large Apparatus studying Grand Unification and Neutrino Astrophysics

✓ 2008-2011: Design Study
- EU funding FP7
- 100 members, 10 countries

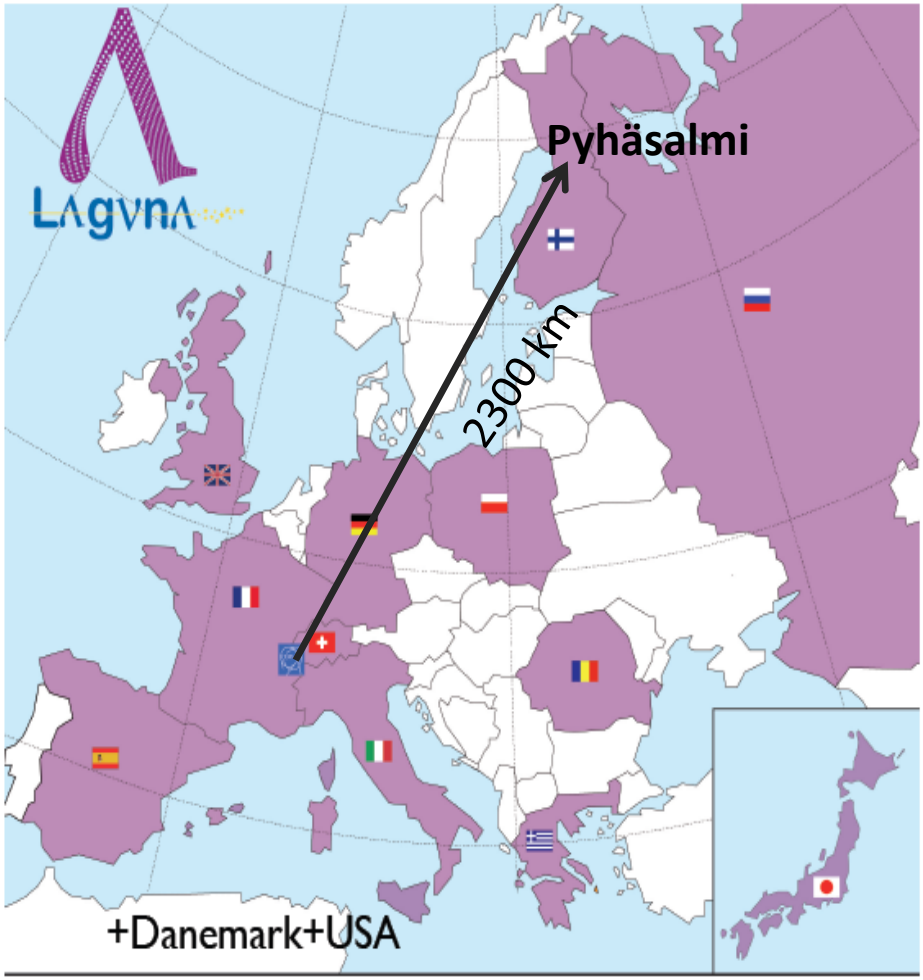
➢ search for optimal site in Europe

detailed investigation of 7 candidate sites

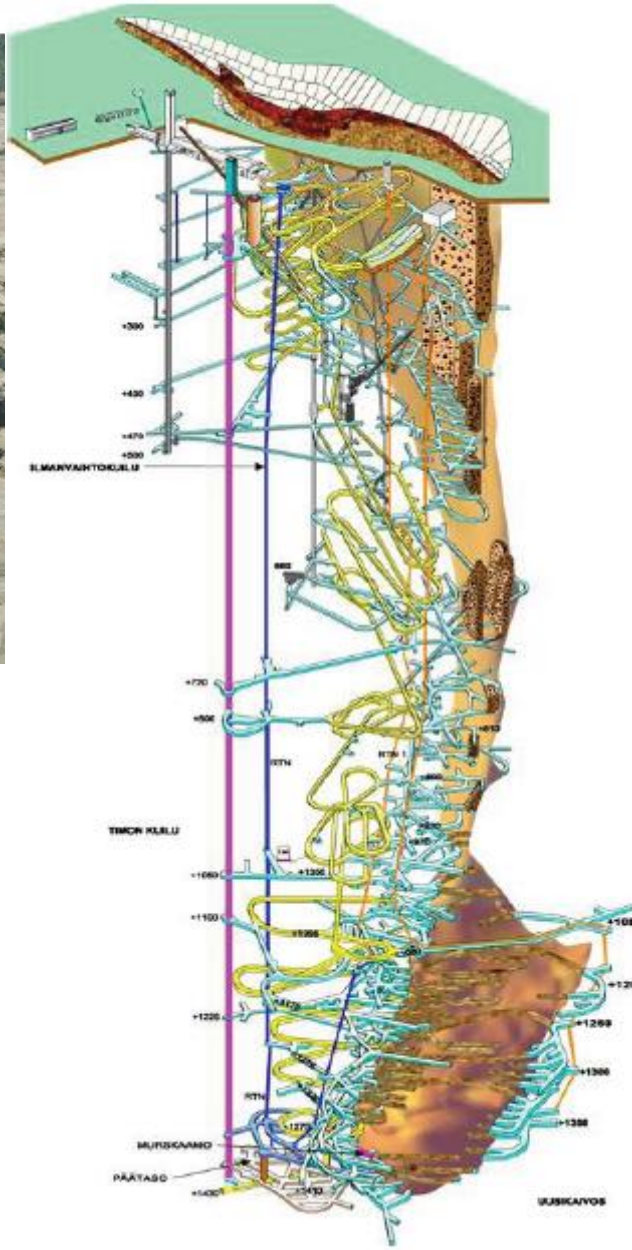
→ **Pyhäsalmi mine, Finland**

✓ 2011-2014: LBNO
- EU funding FP7
- 300 members, 14 countries

➢ extended site investigation

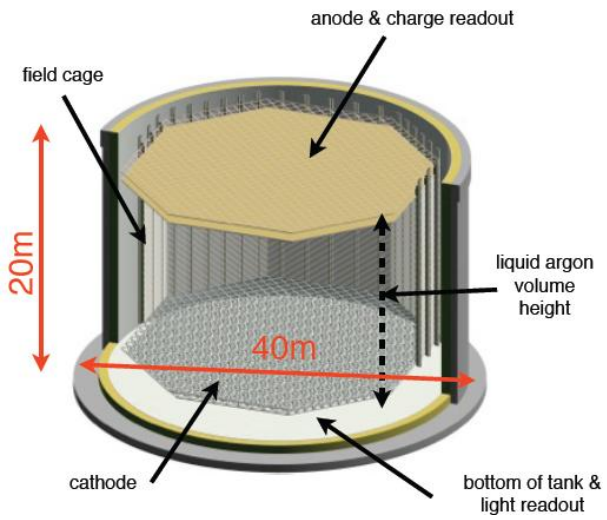


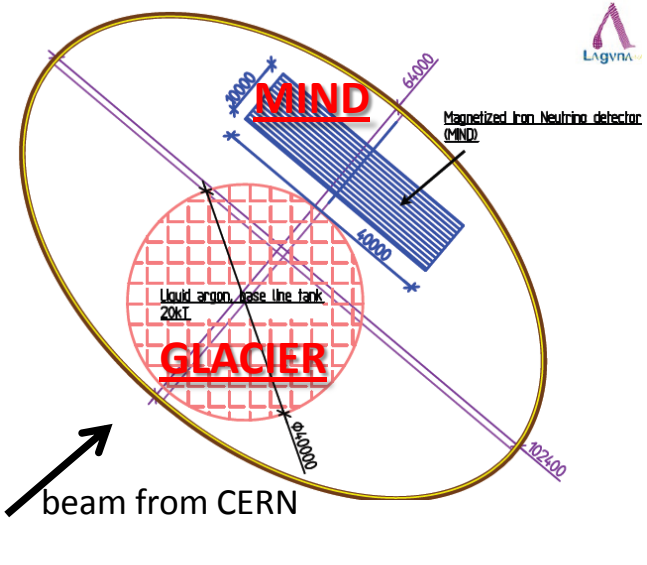
The Pyhäsalmi mine

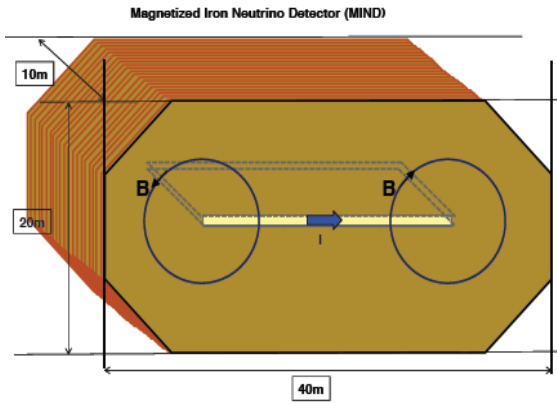


- Available for since from 2016
- Efficient infrastructures already present
- Little environmental water
- Deepest mine in Europe: ~1400m, 4000 m.w.e.
- Rock quality suitable for excavation of large volumes
- Lowest reactor neutrino background in Europe
- Distance from CERN (2288km)
- Interesting distance from other potential neutrino sources
  - DESY(1500km), Protvino(1160km), RAL(2300km)
- Distance compatible with NF setups

The Far underground detectors







GLACIER

20 kt Double Phase LAr LEM TPC

- ✓Low energy threshold: exclusive final states
- ✓Low systematic error
- ✓Excellent energy resolution on a wide energy range
- ✓Excellent π^0/e separation: necessary to suppress NC background, higher for on-axis beam

➢ Electron appearance measurements

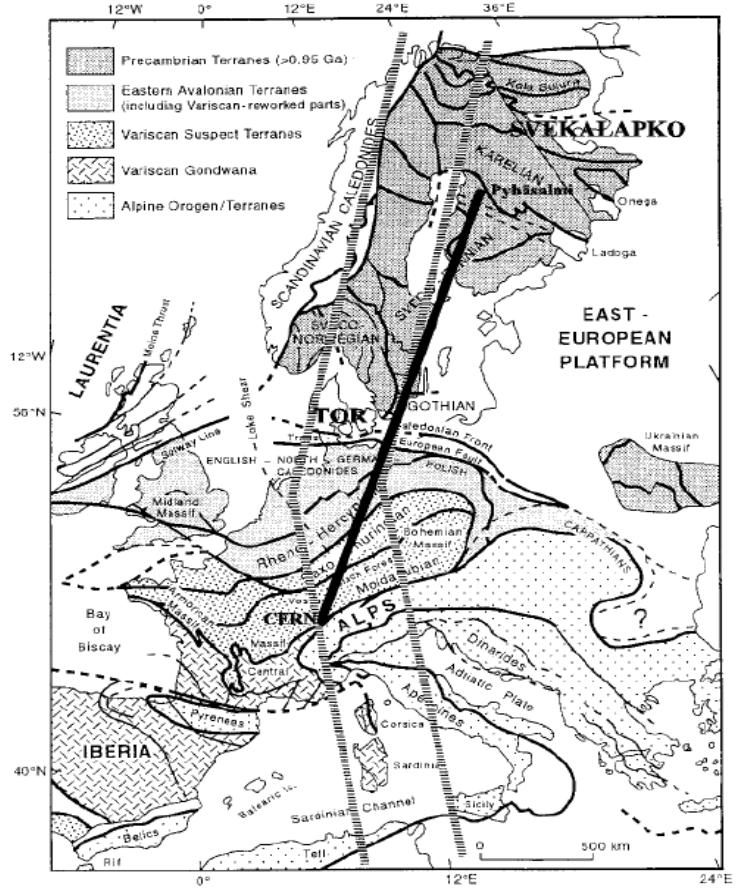
MIND

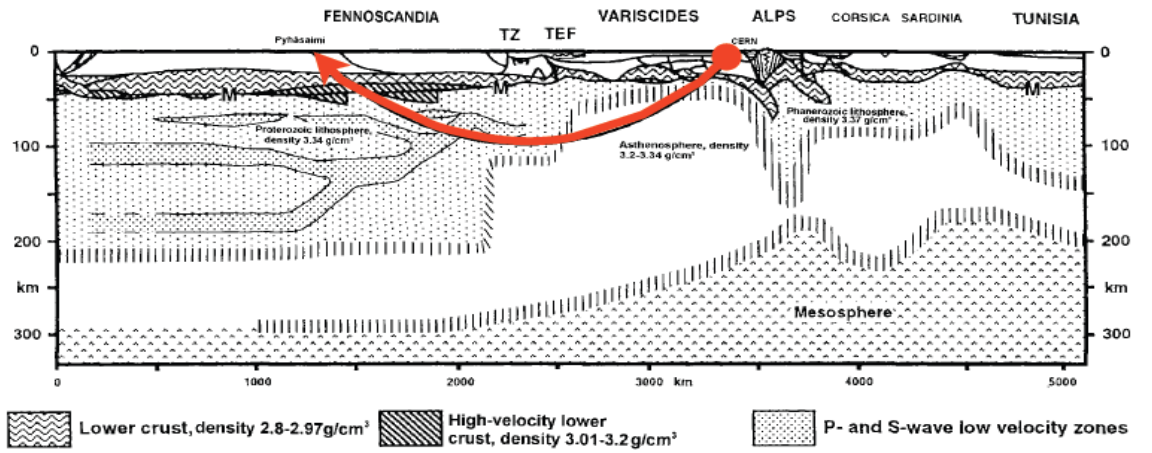
35 kt Magnetized Muon Derector
(3 cm Fe, 1 cm scint. bars, 1.5-2.5 T)

- ✓Muon momentum and charge
- ✓Inclusive neutrino energy rec.

➢ Muon CC, NC measurements

Matter density along the baseline

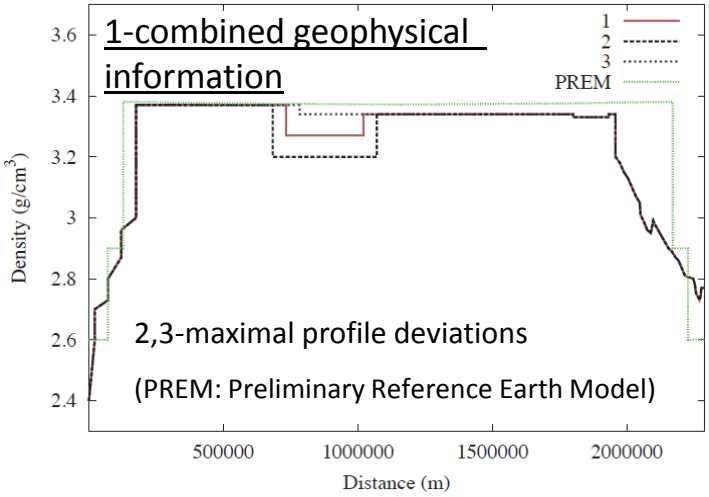




Earth Density Profile

Measured by several Geophysical projects

$2.4<\rho<3.4$ g/cm^3

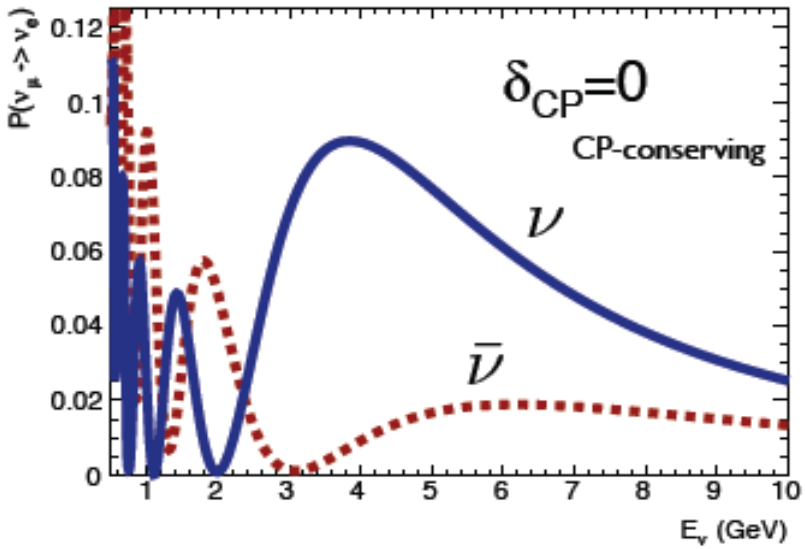


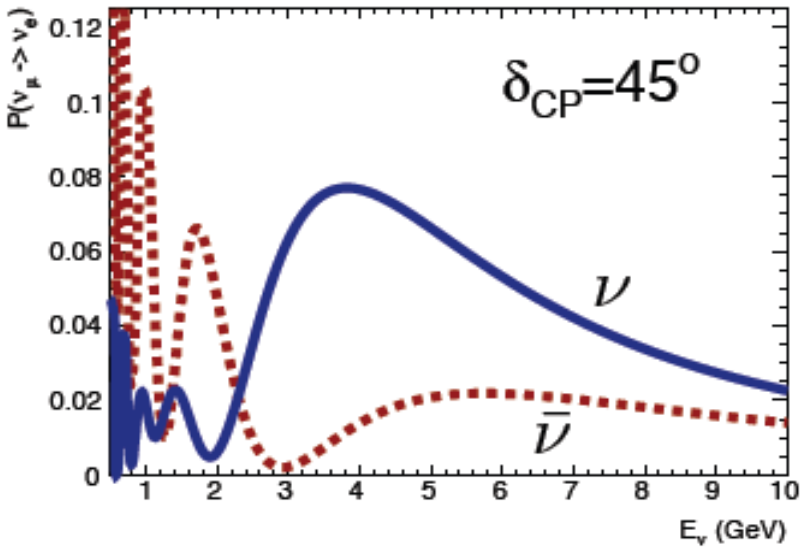
- The ν line of flight is comprised in a geological section extensively studied in the past
  - mean density variations known with high accuracy
- Local density variations are estimated to be of about 5%
  - total effect on oscillation probability averages out
  - conservative approach is to assume $\pm$4% syst. error (global mean shift)

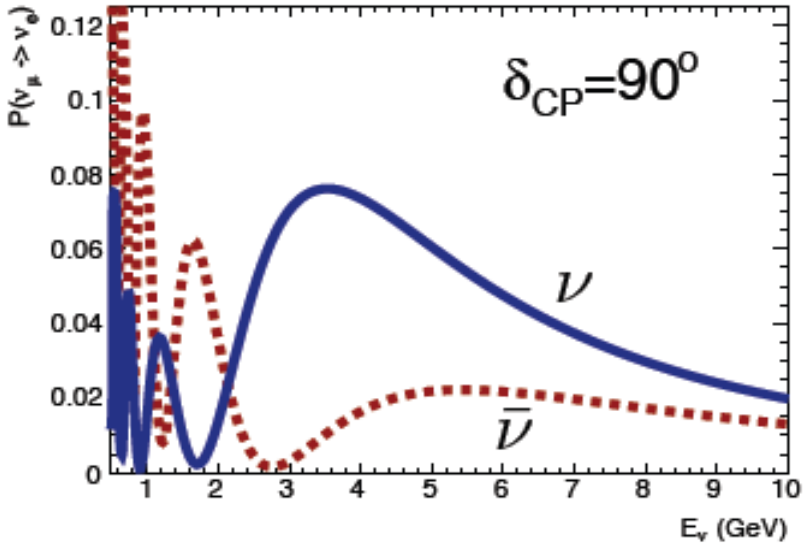
CERN→Pyhäsalmi: $\nu_\mu \rightarrow \nu_e$ Oscillation Probability

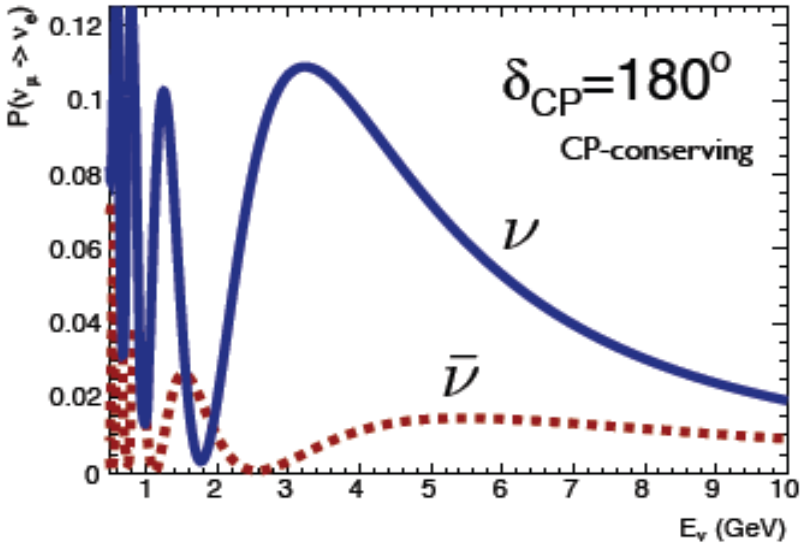
Normal Mass Hierarchy *(L=2300 km)*

$\sin^2(2\theta_{13}) = 0.09$





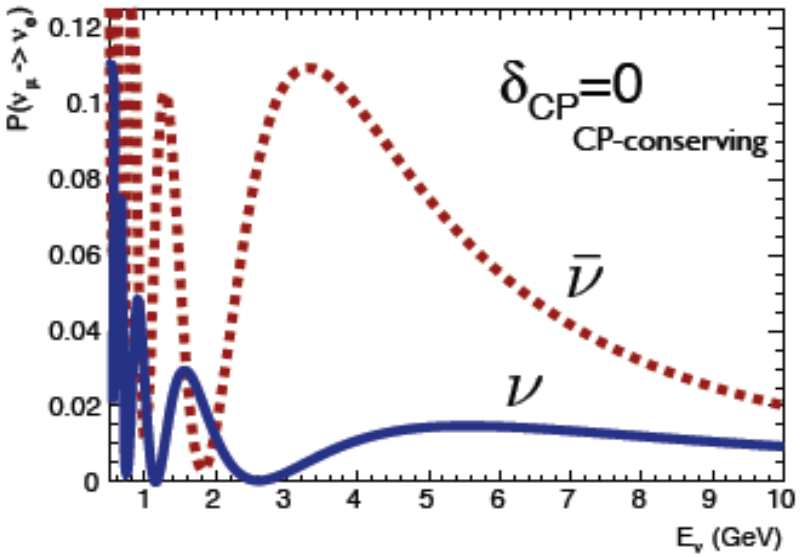


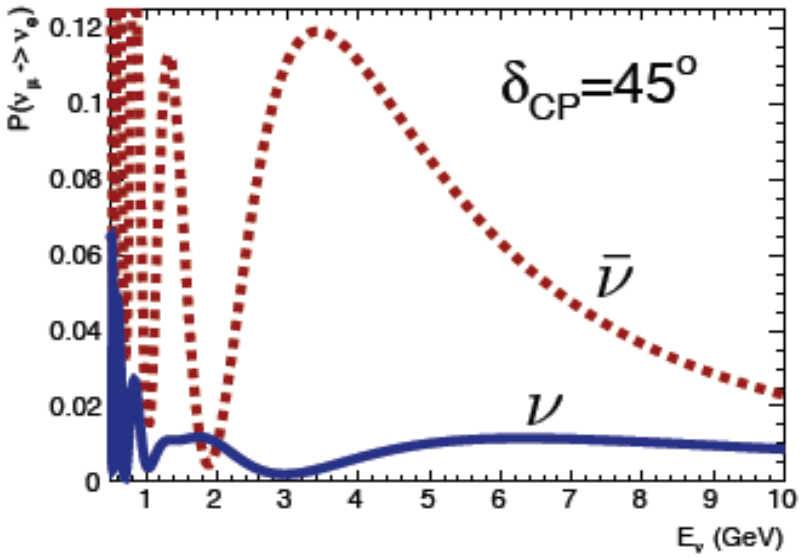


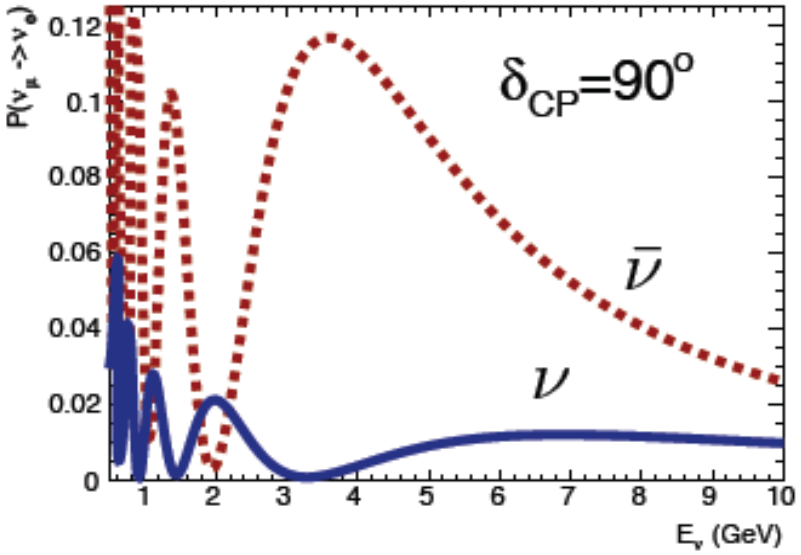
CERN→Pyhäsalmi: $\nu_\mu \rightarrow \nu_e$ Oscillation Probability

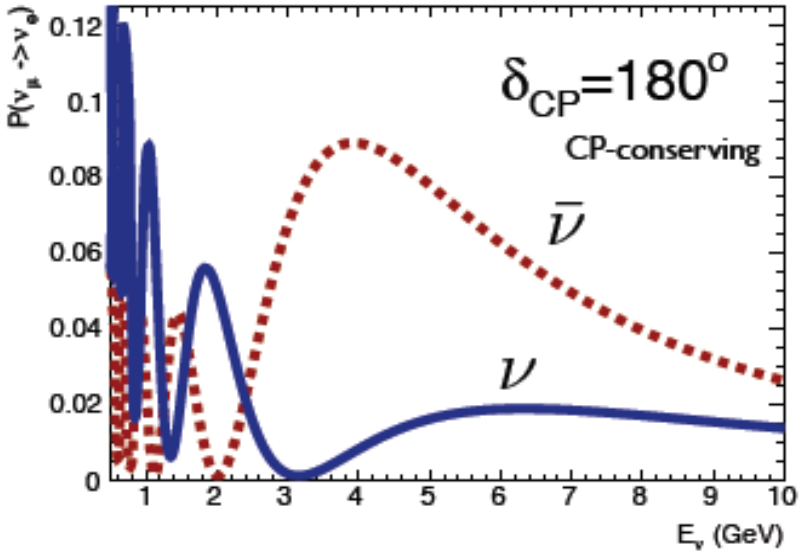
Inverted Mass Hierarchy *(L=2300 km)*

$\sin^2(2\theta_{13}) = 0.09$









LAGUNA-LBNO new neutrino beam line

✓ ***CERN-to-Pyhäsalmi (CN2PY) neutrino beam***

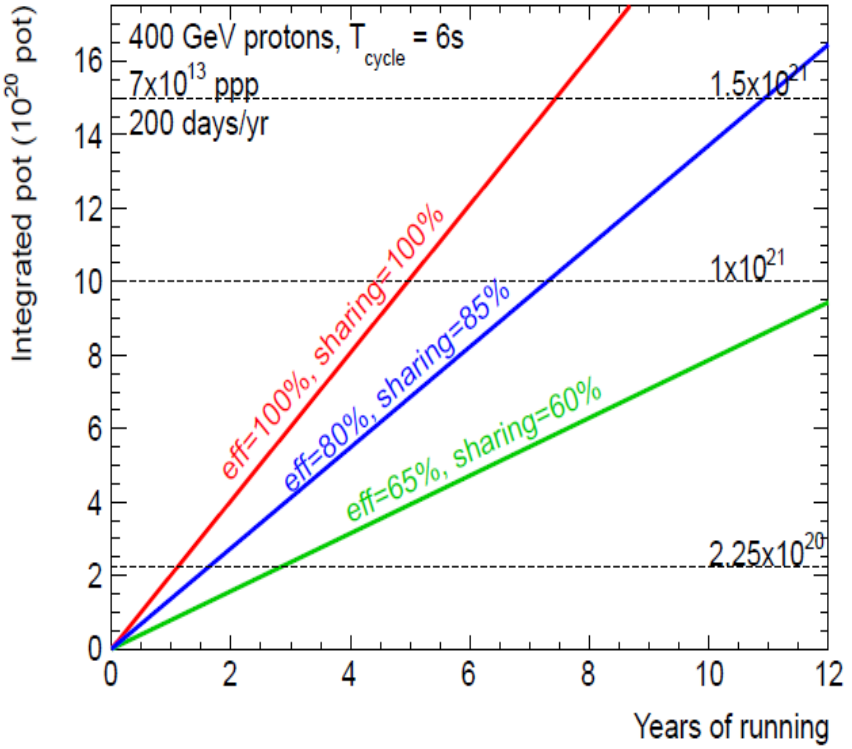
- Design optimized target and focusing systems
- Near detector needed to achieve required systematic
- Consider dedicated set of hadro-production experiment

✓ ***Benefit from improved SPS+Injectors***

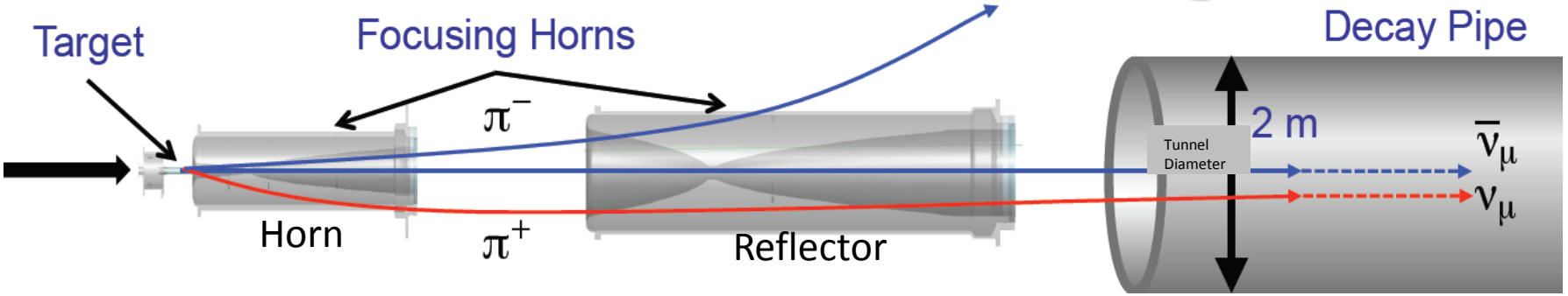
- SPS intensity is upgraded to $7x10^{13}$ p.p.p. @ 400 GeV (6 s cycle)
- 1 year integrated p.o.t.: 0.8-1.3 $1x10^{20}$
- 12 year integrated p.o.t.: 1-1.5$x10^{21}$
- Corresponding sharing: 60-85%
- Studies ongoing with CERN acc. team

✓ ***Upgraded path. Options***

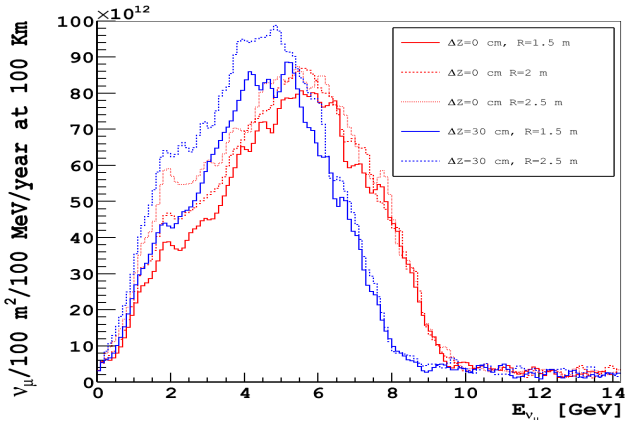
- SPS Upgrade (800 GeV) → 2MW
- New HP-PS accelerator (50 GeV) → 2MW
- NeutrinoFactory storage ring

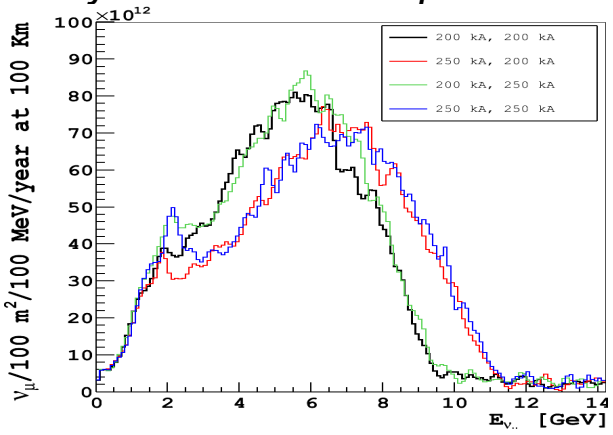


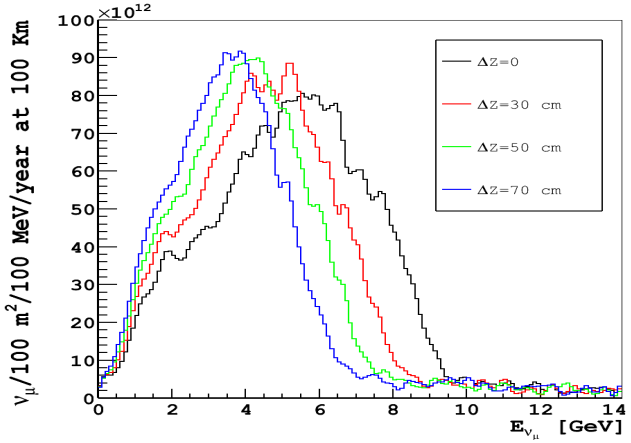
Neutrino beam tuning

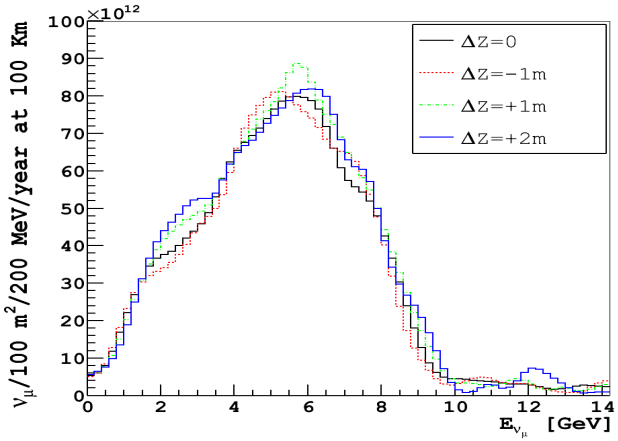


Beam line parameter varied in order to find the configuration which maximize the information extracted from the analysis of the oscillation spectra









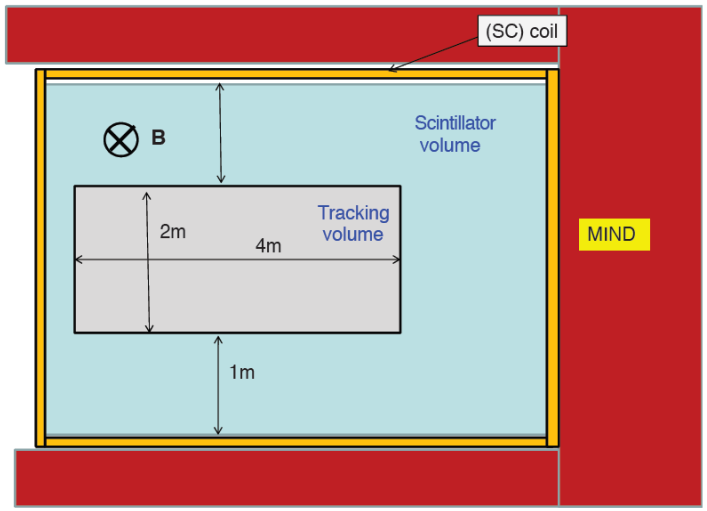
Decay Tunnel dimensions
Target-Horn position
Horn-Reflector Position
Horn(Reflector) shape
Horn(Reflector) current
.....

Near detector & hadro-production experiment

Systematic error on the signal and background in the Far detector ~ 2%

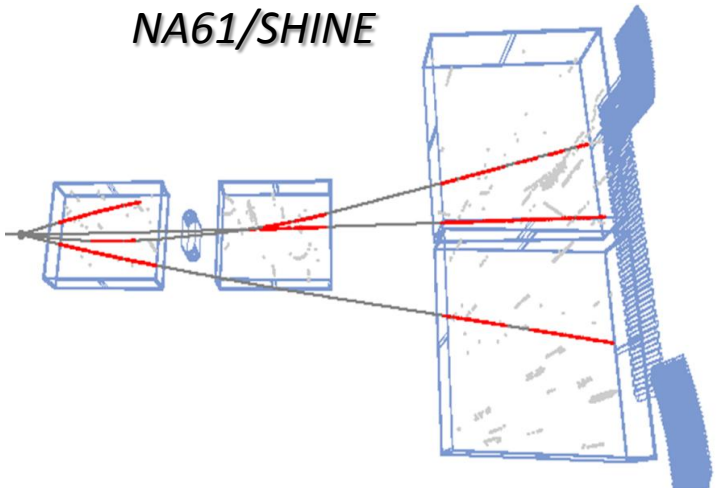
Precise knowledge of fluxes, cross sections...

Near Detector



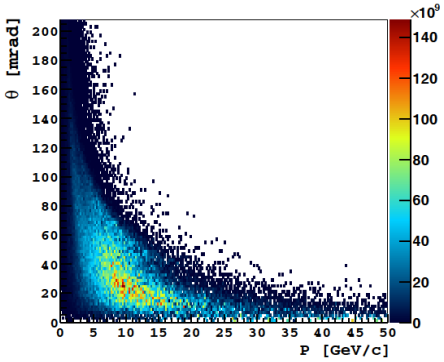
✓Argon TPC (10 bar)
✓Scintillator bar tracker
✓Magnetic Field: 0.5 T
✓0.2 event/spill @ 700 kW

NA61/SHINE



✓Input from hadro-production experiment crucial for precise neutrino experiment (K2K,T2K, MINOS)

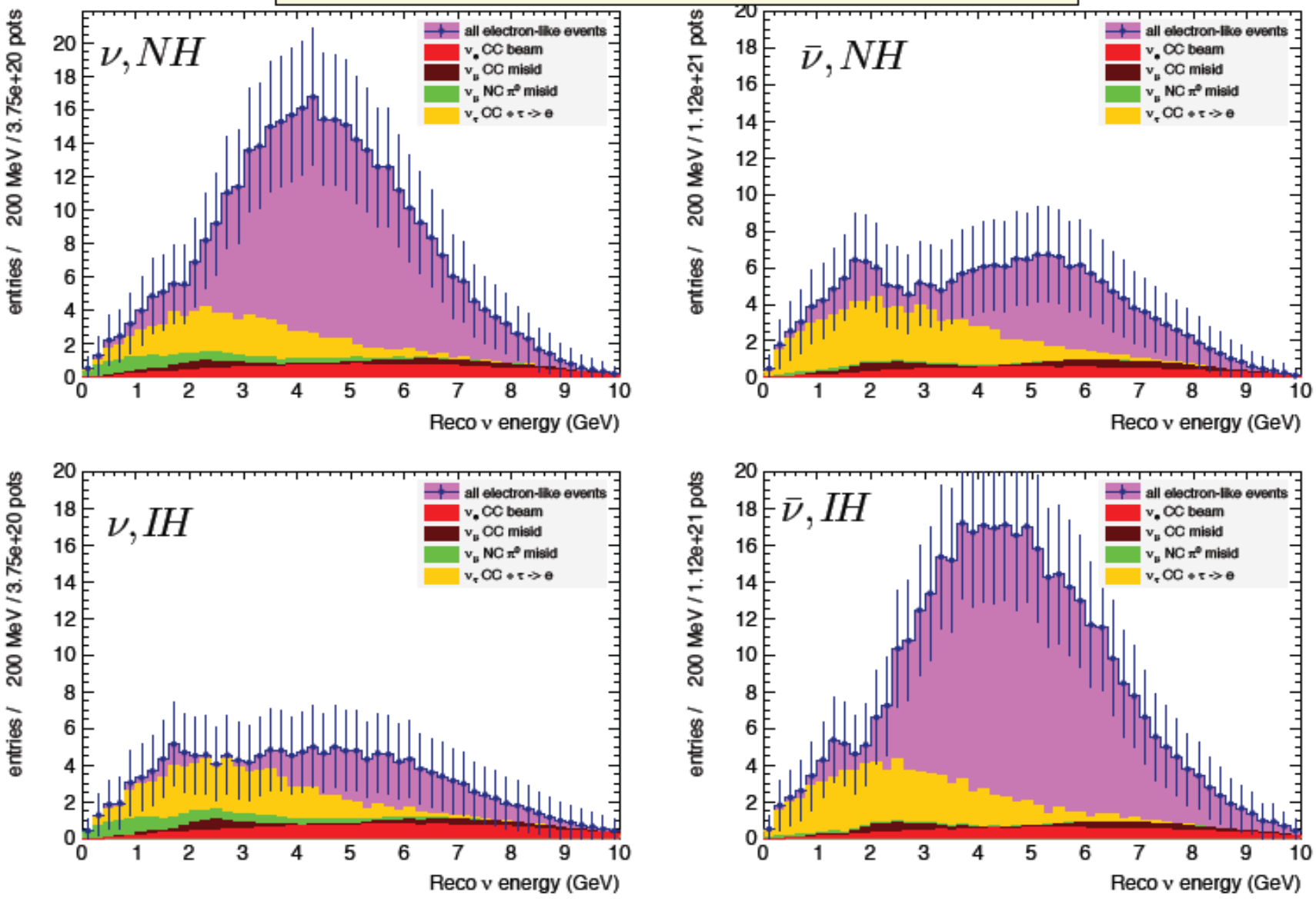
➢CERN NA61 acceptance study



Mass Hierarchy with neutrino/anti-neutrino

Running mode
$\nu/\bar{\nu}$:25%/75%

Detector response and resolution included



Sensitivity to Mass Hierarchy & CP-Violation

Neutrino energy reconstructed from final state events.

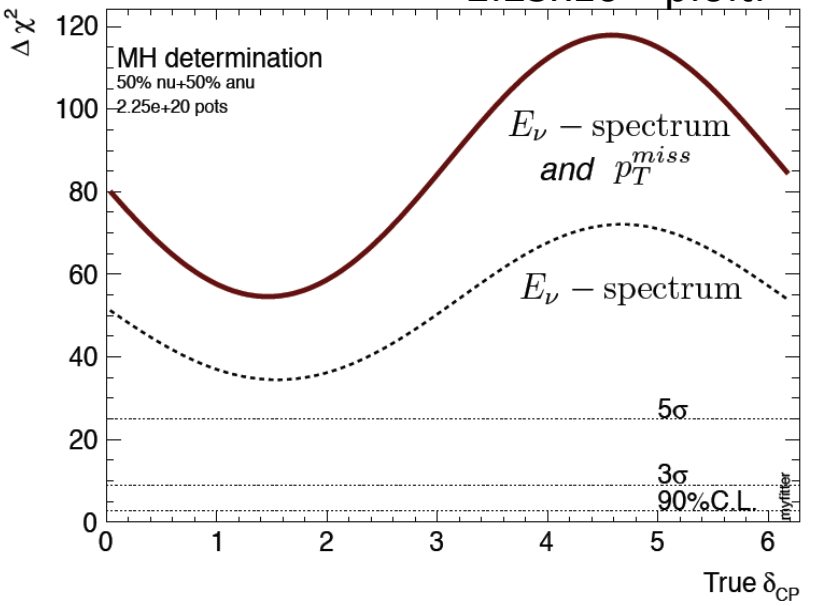
ν_τ background treated with kinematical analysis.

Integrated p.o.t.: 1.5×10^{21}
Target Mass: 20 kton

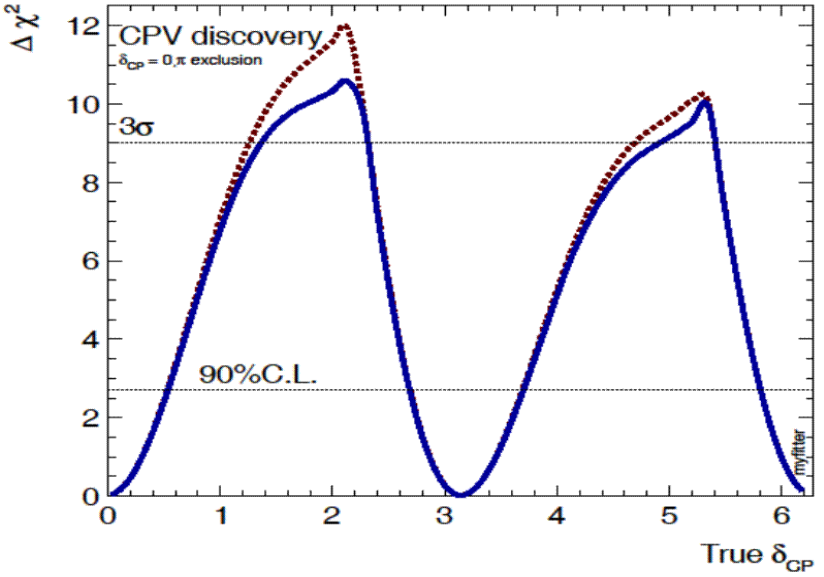
Running mode: 25%:75% sharing neutrino:anti-neutrino

Systematic errors
- signal normalizations: 5% (ν_τ:50%)
- horn polarity: 5%
- NC, CC background: 5%
- matter density: 4%

2.25x10^{20} p.o.t.



1.5x10^{21} p.o.t.



- Mass Hierarchy determination at 5σ in few years

- CPV ~60% coverage 90% C.L. end evidence for maximal δ_{CP} ($\pi/2$, $3/2\pi$) in 10 years

➢ CPV sensitive to systematic effects

➢ In case of negative result
With a factor of 3 higher exposure (beam power × far detector mass) CPV evidence achievable for 75% of the δ_{CP} parameter space.

Conclusions

- Long Baseline Neutrino Oscillation experiment between Pyhäsalmi and CERN (2300 km):
  - all transitions (e,μ, τ) measurable in neutrino/antineutrino in the same experiment
  - conclusive Mass Hierarchy determination
  - Very good chance to find CPV from spectral information.
    With 10 years at 700kW SPS and 20kton LAr: 60% coverage 90% CL
    Three-fold exposure lead to 75% coverage at 3σ
  - > 10 times better sensitivity on several nucleon decay channel
  - detection capability of several astrophysical sources

- EoI submitted to CERN-SPSC in June 2012

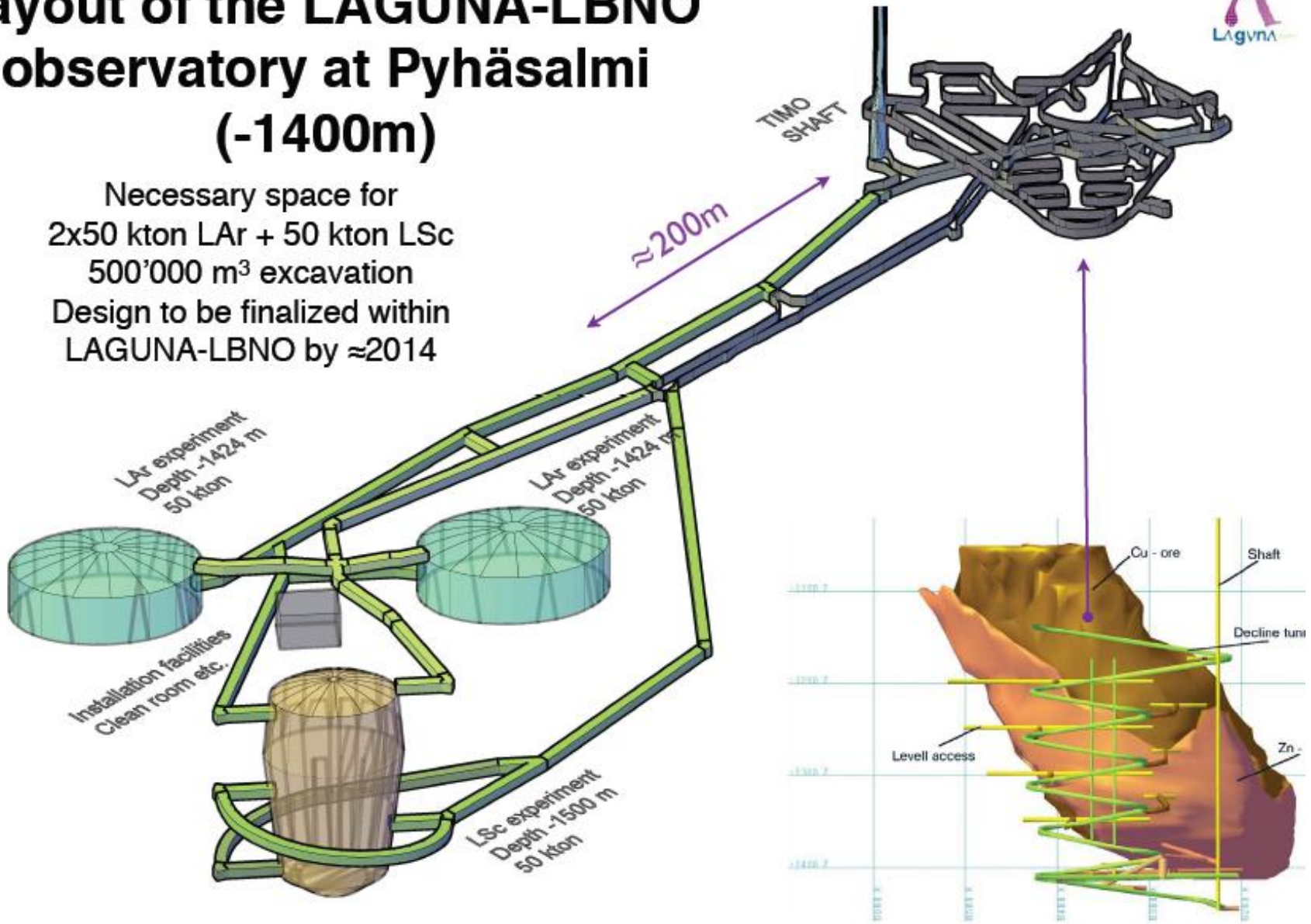
backup

Milestones - Timescale

LAGUNA Design Study funded for site studies:	**2008-2011**
Categorize the sites and down-select:	**Sept. 2010**
Start of LAGUNA-LBNO	**2011**
Submission of LBNO EoI to CERN	**2012**
End of LAGUNA-LBNO DS: technical designs, layouts, liquids handling&storage, safety, ...	**2014**
Critical decision	**2015 ?**
Excavation-construction (incremental):	**2016-2021 ?**
Phase 1 LBL physics start:	**2023 ?**
Phase 2 incremental step implementation:	**>2025 ?**

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

Necessary space for
2x50 kton LAr + 50 kton LSc
500'000 m^3 excavation
Design to be finalized within
LAGUNA-LBNO by ≈2014

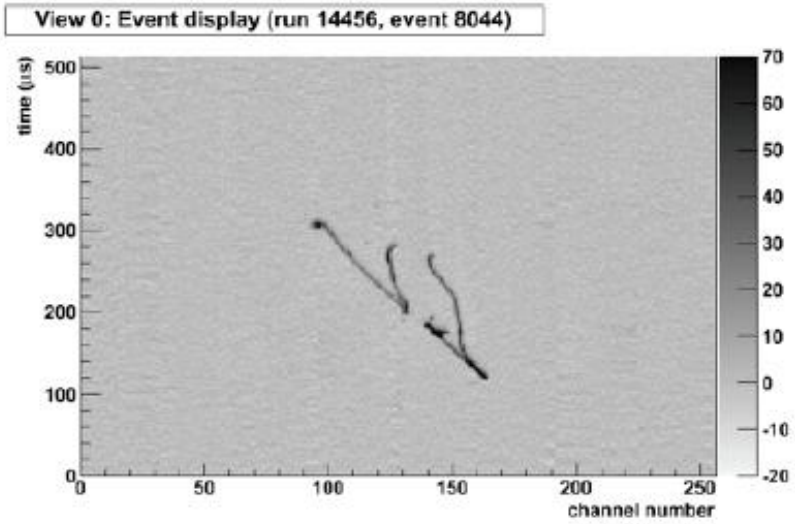


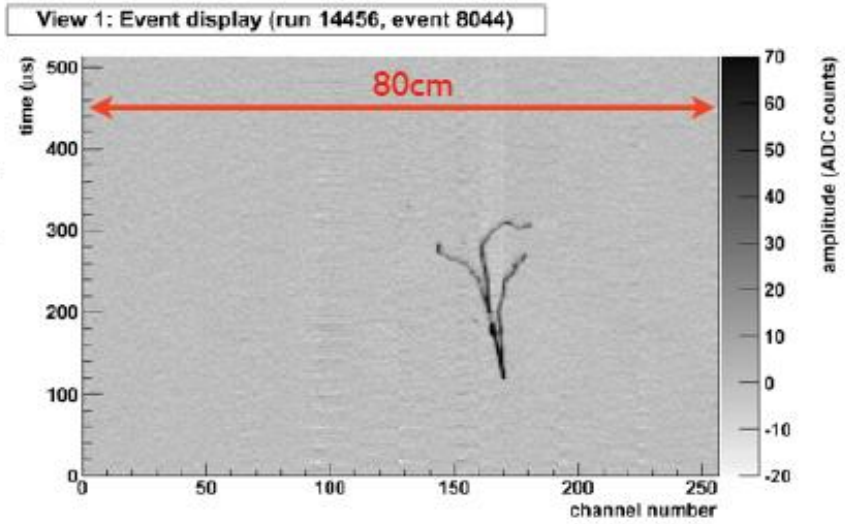
Why the neutrino mass hierarchy ?

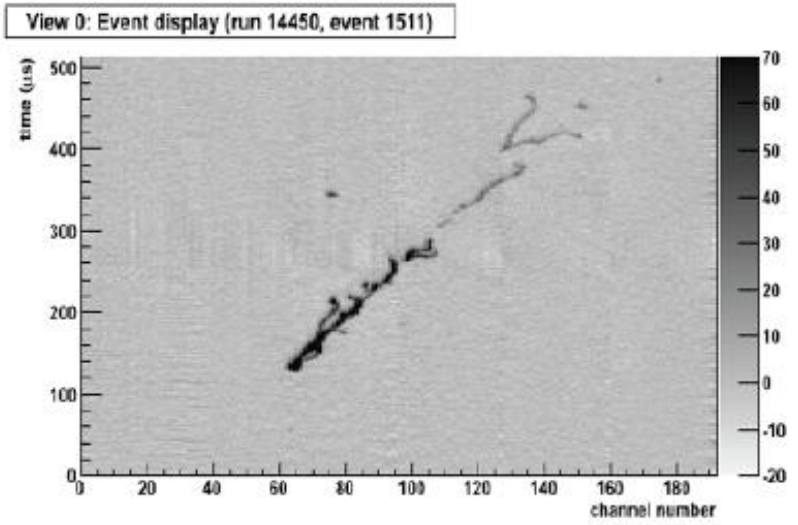
- **CP-violation:** necessary input to solve CPV problem. For example, for the HyperK LOI arxiv:1109.3262 (which considers a 540kton FV and hence has the highest statistical power):
    - 3 MW×years (note: >10 years at present JPARC MR power) MH known: 65% coverage → MH unknown: 35% coverage
    - 10 MW×years needed to reach 65% coverage if MH unknown! rather unlikely within present JPARC projections.
- **0νββ searches:** necessary input to interpret both negative and positive isotope lifetime results, in terms of neutrinos (as opposed to some other source of lepton number violation).
- **BSM/GUT theories:** important ingredient for model building. An inverted hierarchy would have interesting implications.
- **We need a definitive & conclusive determination of the MH !**

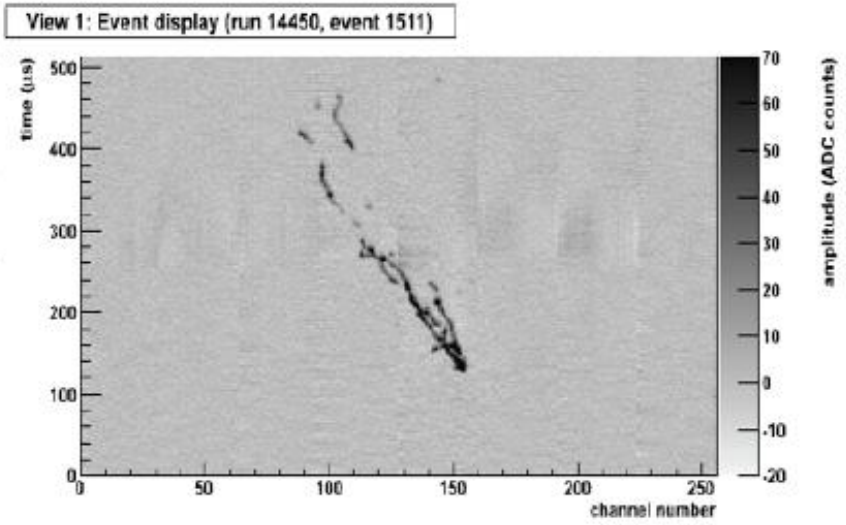
Real cosmic rays in LAr LEM-TPC

Cosmic track in double phase 80x40cm2 LAr-LEM TPC with adjustable gain : S/N > 100 for m.i.p !!



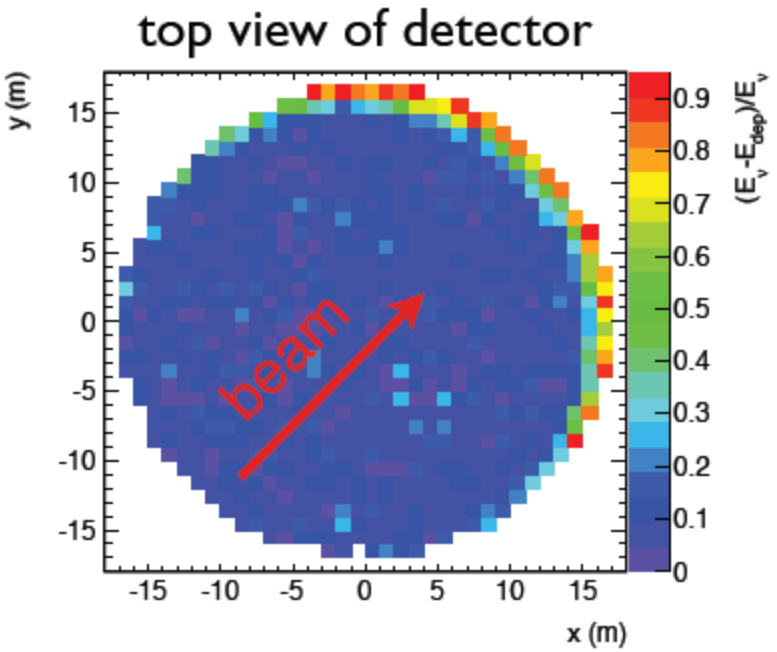


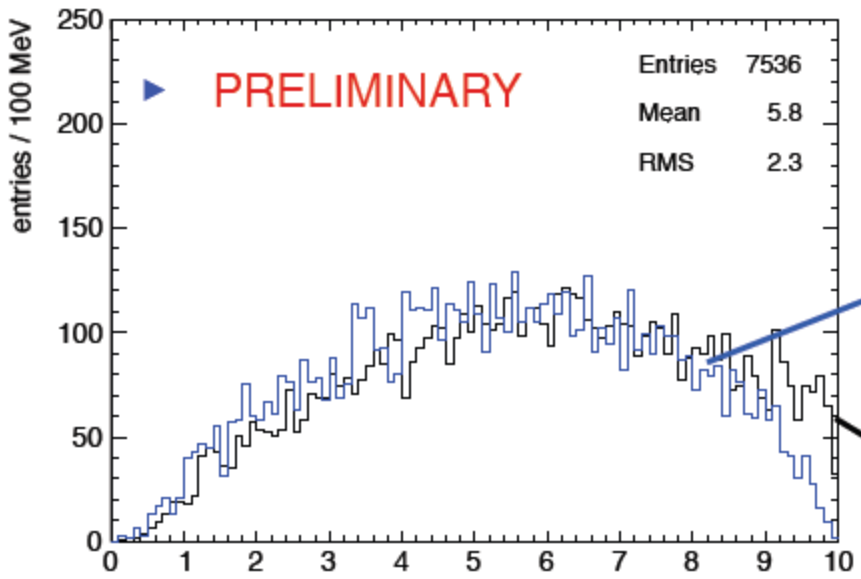




Neutrino energy reconstruction

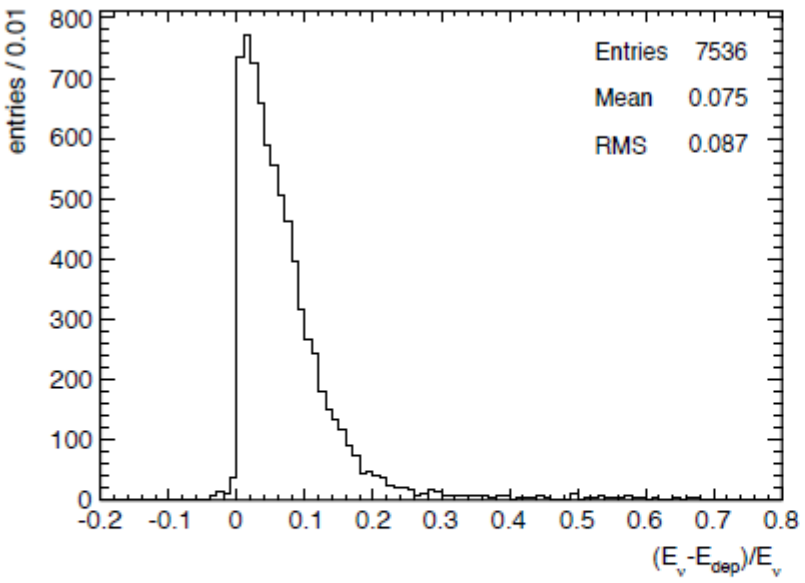
- nue CC events generated with GENIE and CN2PY fluxes
- GEANT4
- CCNuE resolution: **8.7% RMS** for vertex in center of detector
- Preliminary result: **(Edep-Ereco)/Edep ≈ 0.7% RMS**

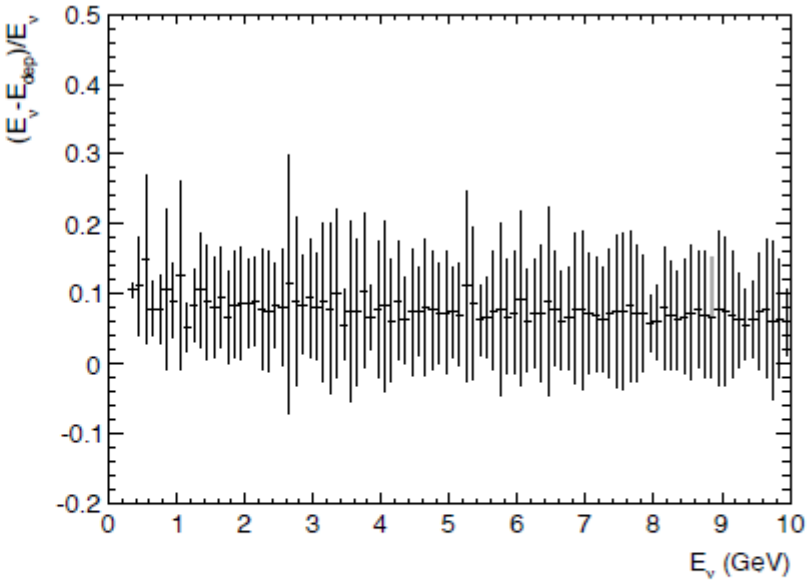




deposited energy in fiducial volume

neutrino energy

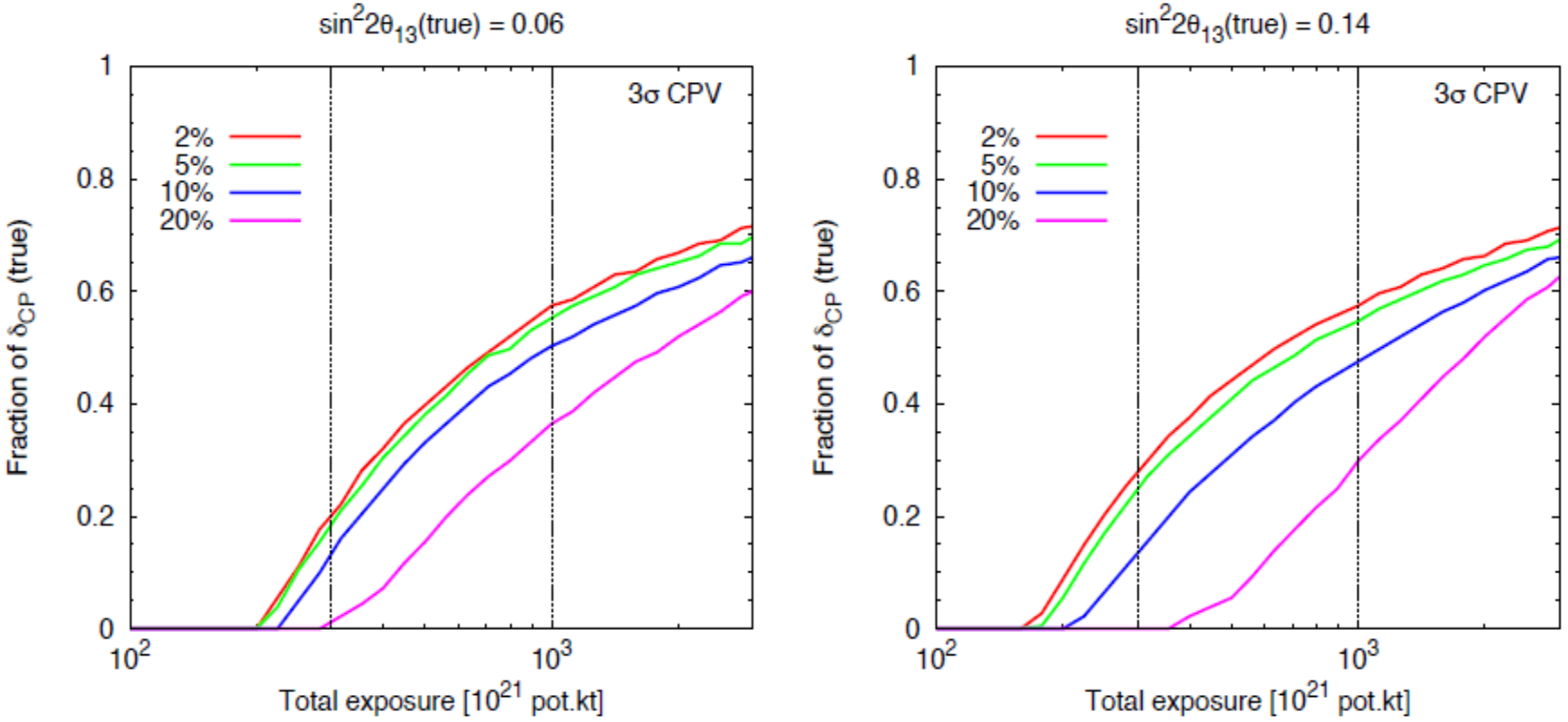




CCNuE resolution
(vertex in center of detector): 8.7% RMS

Matter uncertainty and CPV discovery

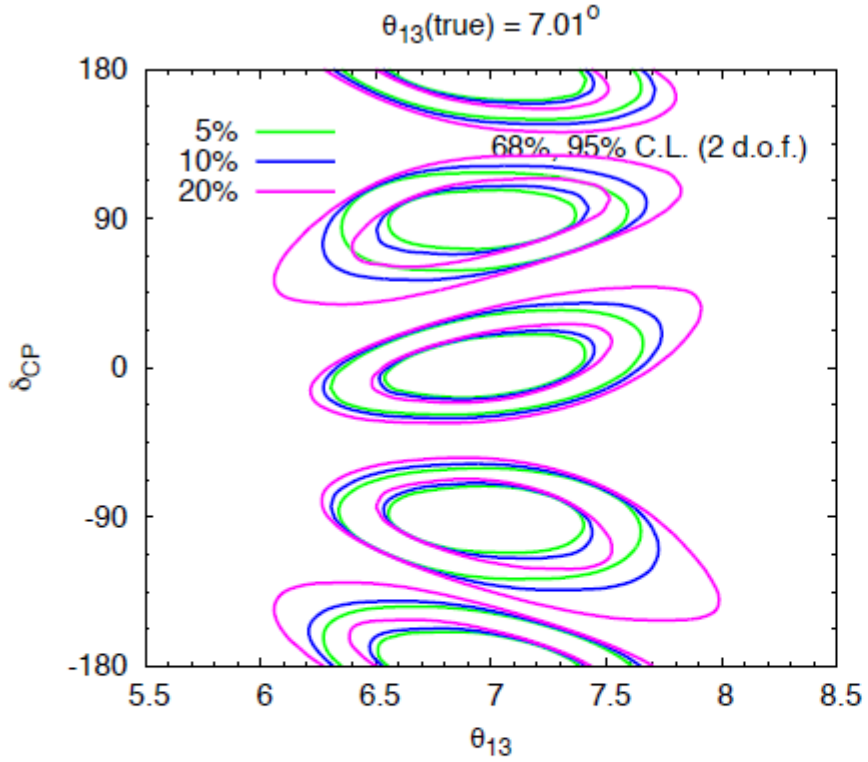
Assuming 5% systematic errors on signal and background:

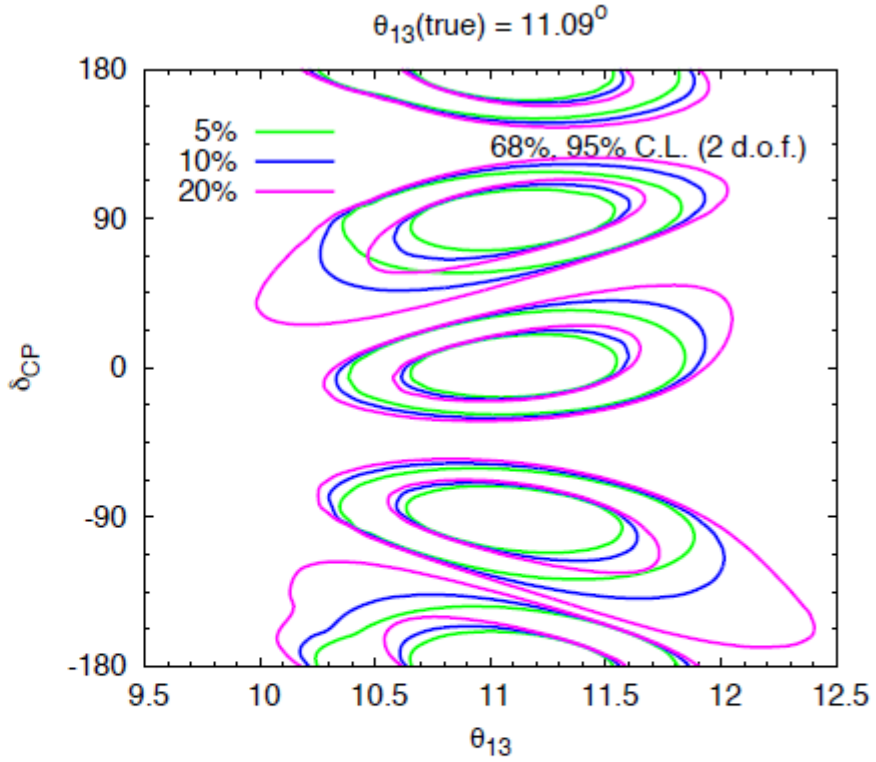


If we start from 2% systematic error on matter density:

- Going to 5% we lose ~ 2% CPV coverage, for all exposures.
- Going to 10% we lose ~ 5% CPV coverage.
- Going to 20% (unrealistic) we lose ~ 20% CPV coverage.

Matter uncertainty and CPV precision





- 2% and 5% similar.
- Lose a little going to 10%.
- Large difference for 20% (unrealistic).

LBNO Expression of Interest

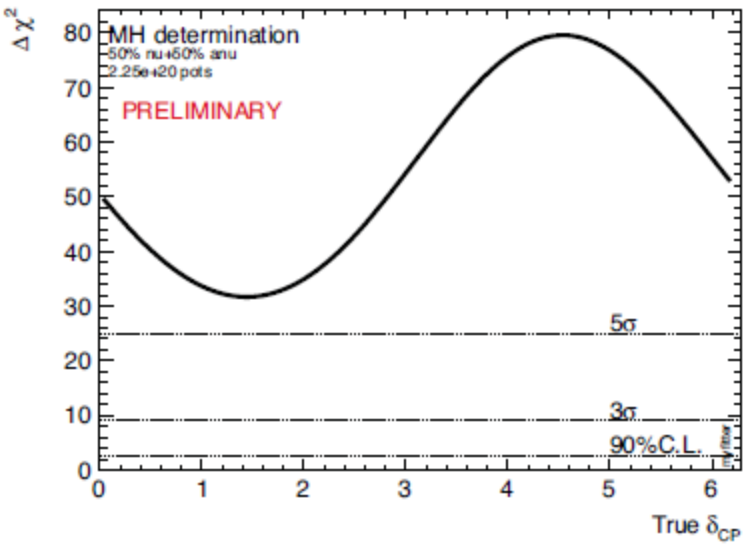
- ★ 20 kton double phase LAr LEM TPC (GLACIER) and magnetized muon detector (MIND design)
- ★ Conventional neutrino beam line with a baseline of 2300 km towards Pyhäsalmi, Finland (CN2PY) with protons from CERN SPS 700kW upgrade
- ★ Initial (Phase 1) physics goals:
  - Measure all transitions (e/μ/tau) and determine precisely oscillation parameters
  - Achieve a >5σ C.L. determination of the neutrino mass hierarchy in a few years
  - Explores a significant part of the CPV parameter space, namely 60% CPV coverage at 90%C.L. in about 10 years running
  - Proton decay, atmospheric and astrophysics neutrinos:

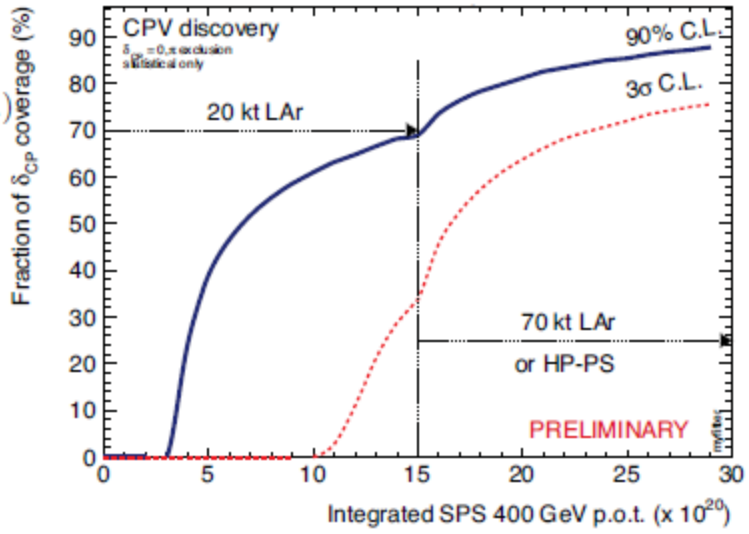
5'600 atm events/yr $Br(p \to \bar{\nu}K) > 2 \times 10^{34} y(90\%C.L.)$

relic SN, WIMP flux, ... $Br(n \to e^- K^+) > 2 \times 10^{34} y(90\%C.L.)$

>10'000's nu-int. @ SN explosion@10kpc

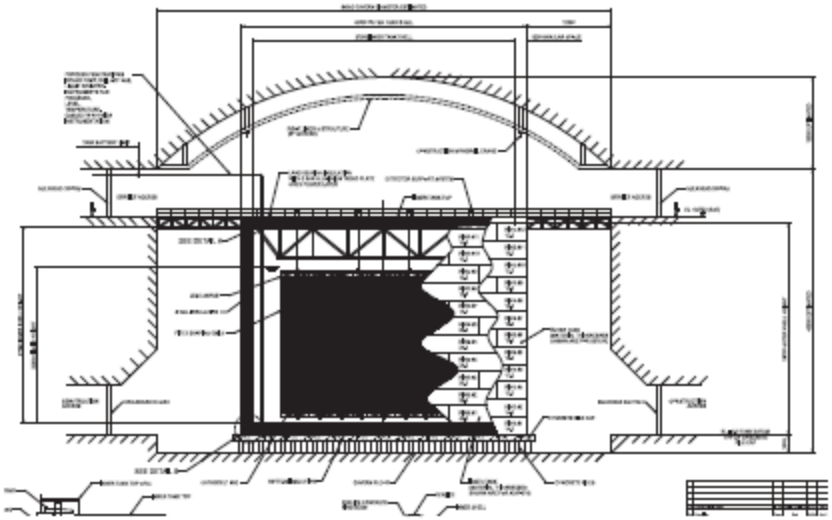
- ★ Phase 2 (>2025): Pyhäsalmi situation and distance allow upgrade into larger detector(s) and a more powerful beams (e.g HP-PS 2MW or NF) and thus, offers a long term vision.
  - For example, with a three-fold increase in exposure, it reaches 75% CPV coverage at 3σ C.L.
- ★ Expression of Interest for CERN scientific committee in preparation (submission 20/6/2012)



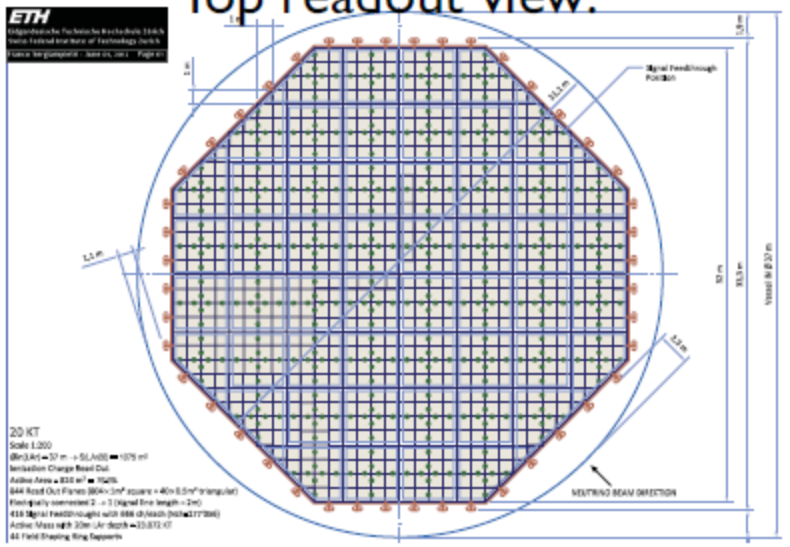


GLACIER detector design

- Concept unchanged since 2003: Simple, scalable detector design, from one up to 100 kton (hep-ph/0402110)
- Single module non-evacuable cryo-tank based on industrial LNG technology
  - industrial conceptual design (Technodyne, AAE, Ryhal engineering, TGE, GTT)
  - two tank options: 9% Ni-steel or membrane (detailed comparison up to costing of assembly in underground cavern)
  - three volumes: 20, 50 and 100 kton
- Liquid filling, purification, and boiloff recondensation
  - industrial conceptual design for liquid argon process (Sofregaz), 70kW total cooling power @ 87 K
  - purity < 10 ppt O_2 equivalent
- Charge readout (e.g. 20 kton fid.)
  - 23'072 kton active, 824 m² active area
  - 844 readout planes, 277'056 channels total
  - 20 m drift
- Light readout (trigger)
  - 804 8" PMT (e.g. Hamamatsu R5912-02MOD) WLS coated placed below cathode
- The concept and the designs are reaching the required level of maturity for submission to SPSC.



Top readout view:



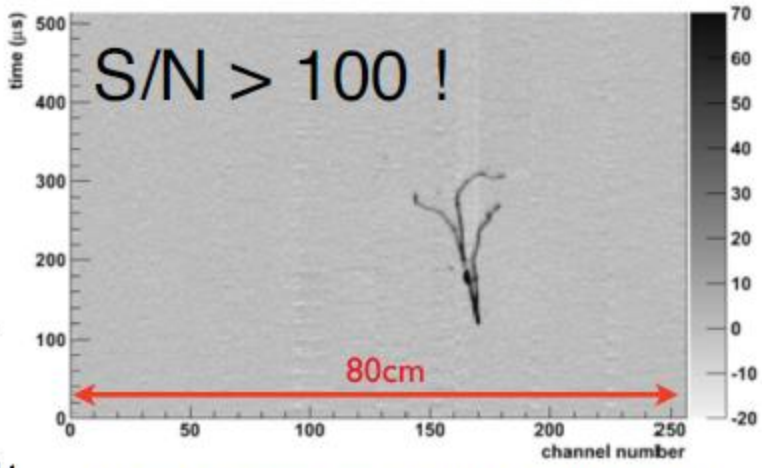
GLACIER charge readout

- A. Badertscher, et al., NIM A 641 (2011) 48-57
- See also arXiv:1204.3530 [physics.ins-det]

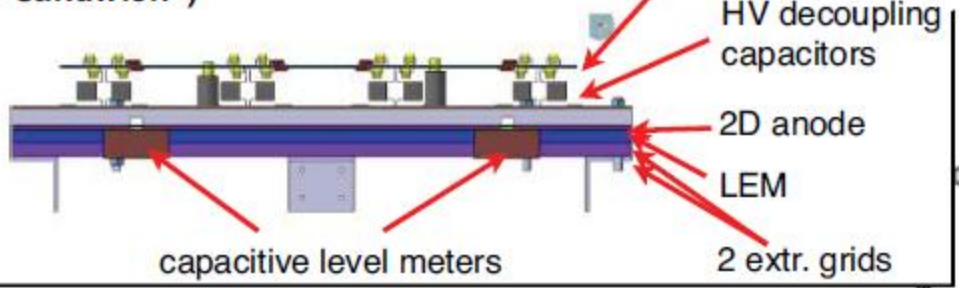
★ Novel double phase LAr LEM-TPC readout:

- ionization electrons are drifted to the liquid-gas interface
- if the E-field is high enough (≈ 3 kV/cm) they can efficiently be extracted to the gas phase
- in the holes of the LEM the E-field is high enough to trigger an electron avalanche
- the multiplied charge is collected on a 2D readout
- gain allows **sharing charge in collection mode for both views!!**

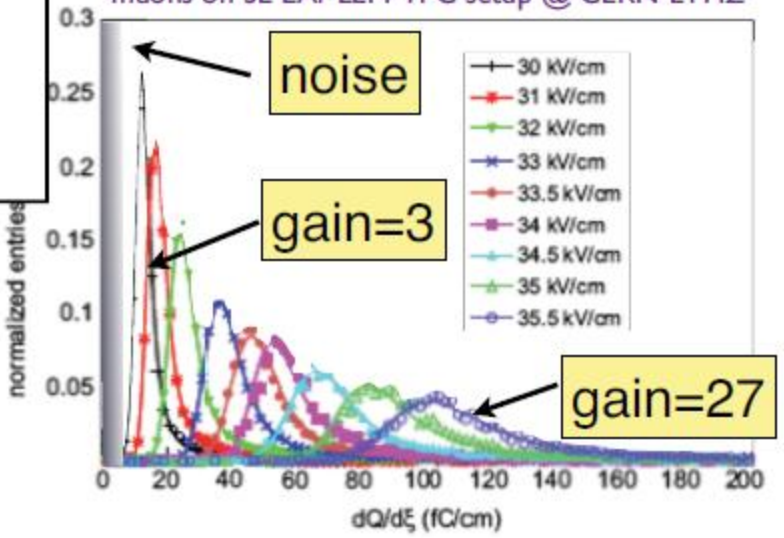
Cosmic Data from 40x80cm² LAr LEM TPC@CERN-ETHZ



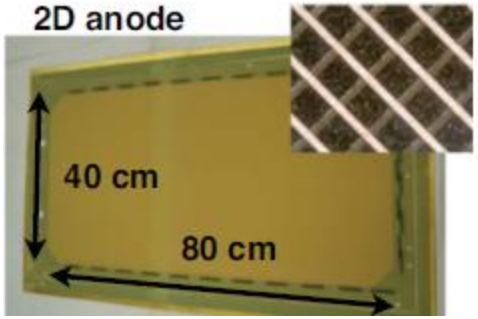
Design of a compact, robust and scalable readout cassette ("sandwich")



Landau distribution fitted to dE/dx distributions of muons on 3L LAr LEM-TPC setup @ CERN-ETHZ



2D anode



LEM