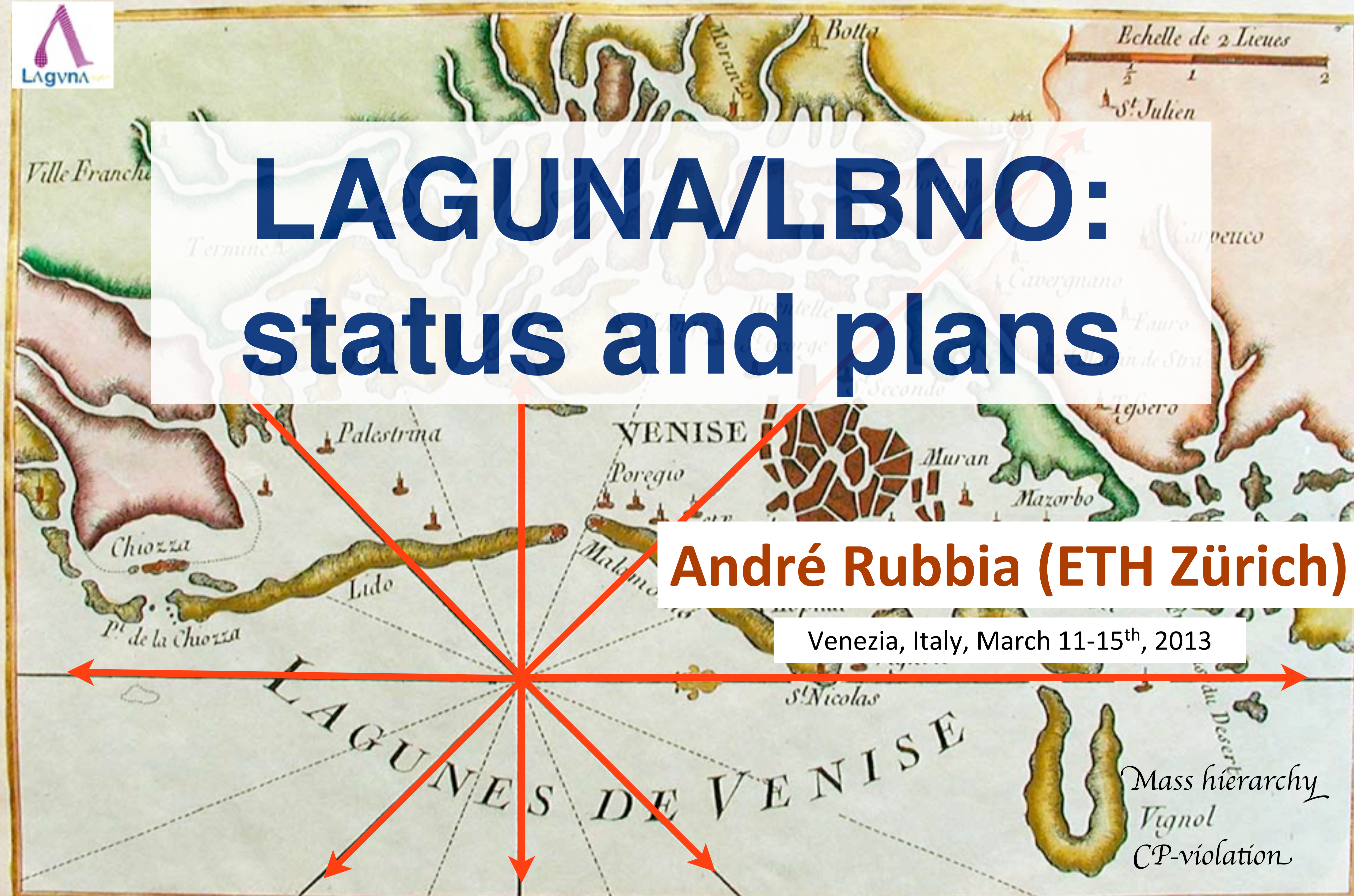
LAGUNA/LBNO: status and plans

André Rubbia (ETH Zürich)

Venezia, Italy, March 11-15th, 2013



Mappa della Laguna di Venezia
Incisore Joseph Roux, 1764

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

v3

Thursday, March 14, 13

LAGUNA/LBNO consortium

Large Apparatus for Grand Unification and Neutrino Astrophysics - Long Baseline Neutrino Oscillations

- **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
  - Down selection of sites & detectors
- **LBNO** (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, June 2012)
  - An incremental approach, based on the findings of LAGUNA
  - ~230 authors; 51 institutions
  - CERN-SPSC-2012-021 ; SPSC-EOI-007, under review

Steering group:

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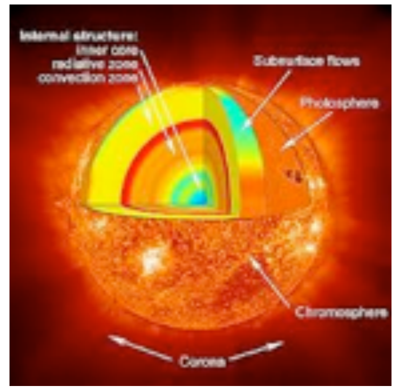
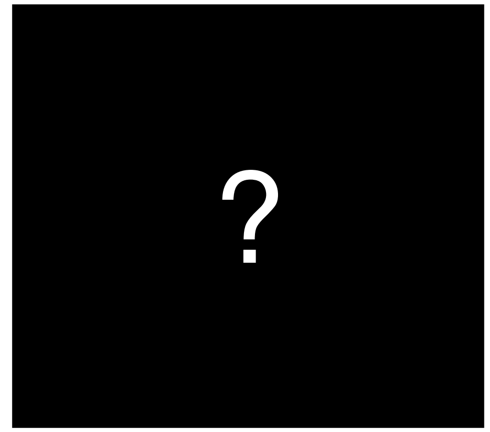
LAGUNA neutrino observatory

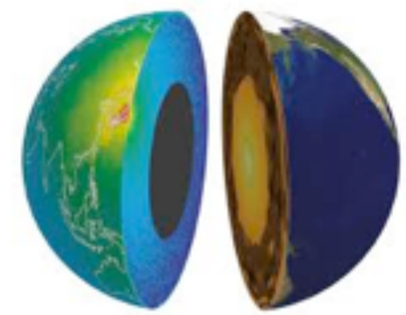
Supernova



Sun

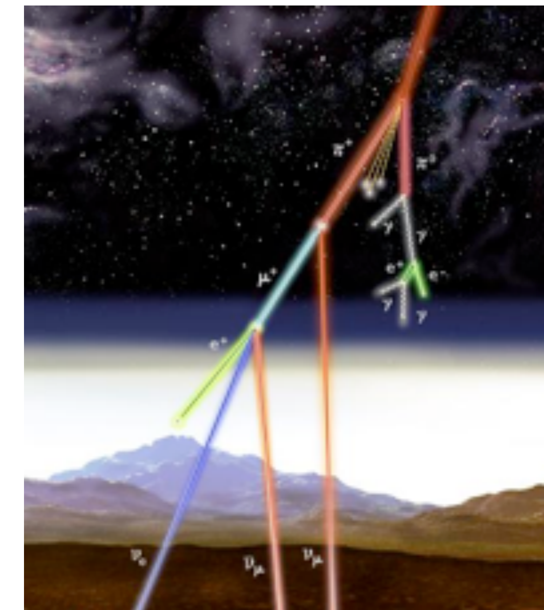


Unknown ?



Earth

Atmosphere



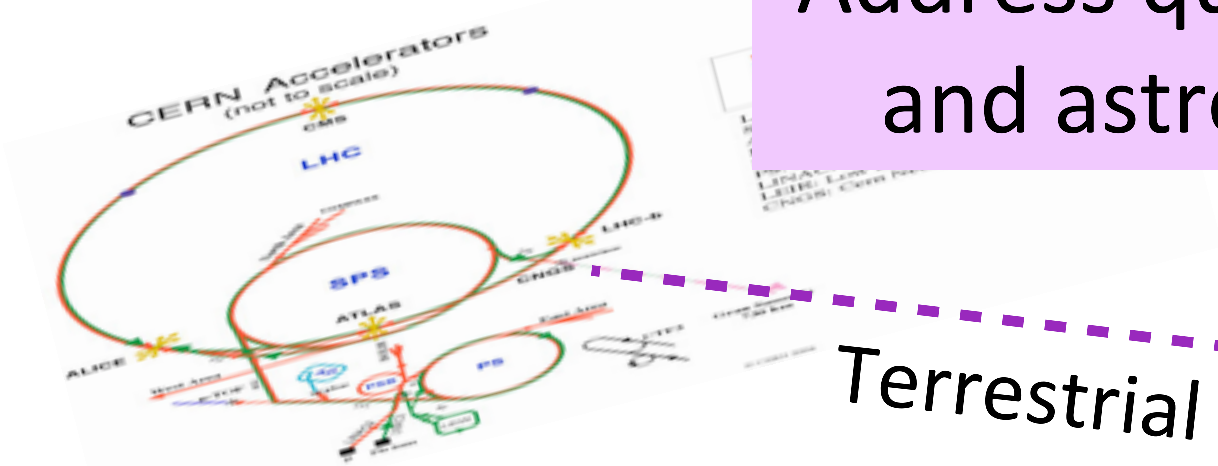
Neutrinos from MeV to 10’s GeV

Neutrino oscillations → MH, CPV, precision

Proton lifetime

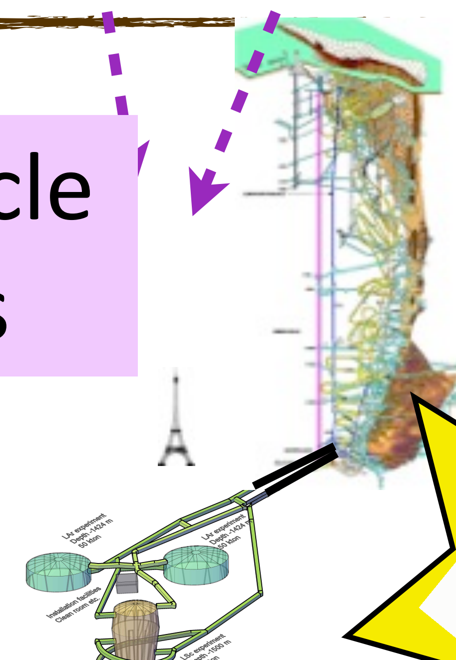
Reactors

Address questions of particle and astroparticle physics



Terrestrial baseline

Accelerators



Deep underground

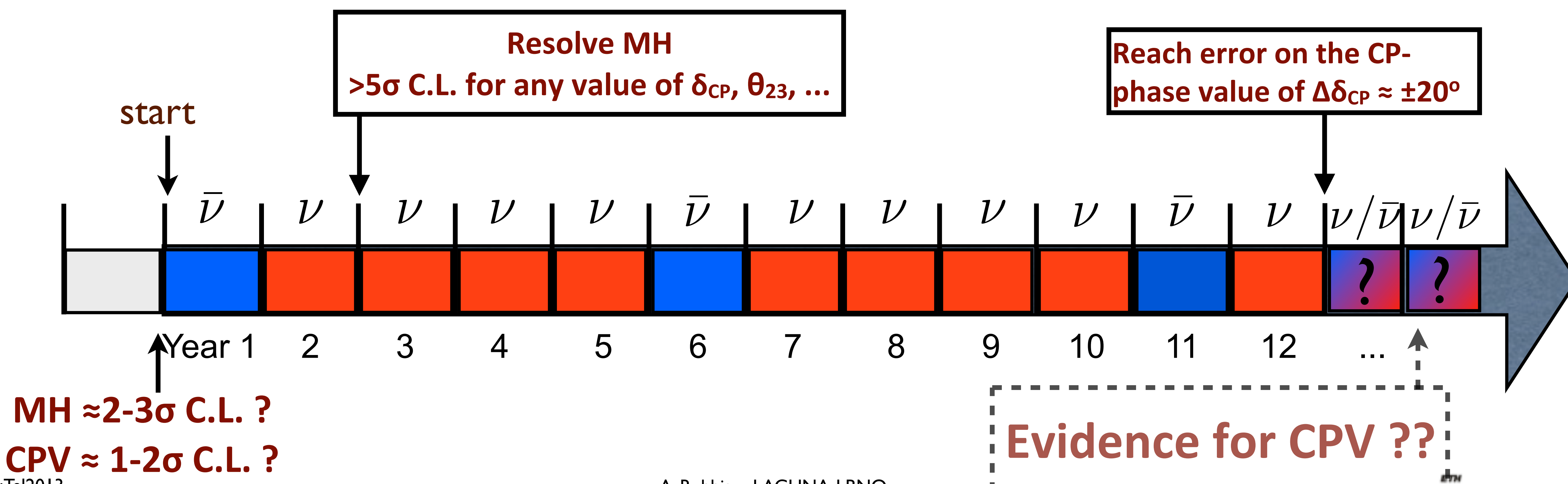
Proton decays

LBNO approach to CPV and MH

- We recall the historical **discovery of atmospheric neutrino oscillations**. **The most credible proof was given in 1998 by Superkamiokande with its striking zenith angle distribution, compatible with the predicted L/E behaviour induced by flavour oscillations.**
- Other attempts based on **μ/e ratios** or **up-down asymmetries**, *although statistically significant*, were less able to ascertaining the origin of the effect, as other interpretations of the data could not be fully excluded.
- Following the same spirit, **LBNO aims at exploring and resolve the mass hierarchy and the CP-phase problem by observing clear signatures and ascertaining their L/E dependence.**
- **This approach is different from extracting MH or CPV from multidimensional fits combining several experimental measurements. Global fits cannot replace direct evidence and we are seeking direct signal patterns.**
- **Efforts at combining data from existing facilities, just as was the case before the determination of the θ_{13} angle, will guide the searches but will not replace an ultimate direct demonstration of CP from new dedicated experiments, even if these latter will come online in a decade.**

Matter effects and MH

- A fully conclusive knowledge of matter effects and of the neutrino MH is a **mandatory prerequisite to any CP violation search.**
- In LBNO, **one single year of running followed by another year with horn polarity reversed**, can determine MH regardless of the prior knowledge on the value of the other oscillation parameters.
- The method to switch polarity of the horn is robust to most systematic errors and will provide a direct proof of the effects of propagation of neutrino and antineutrinos through the Earth crust.

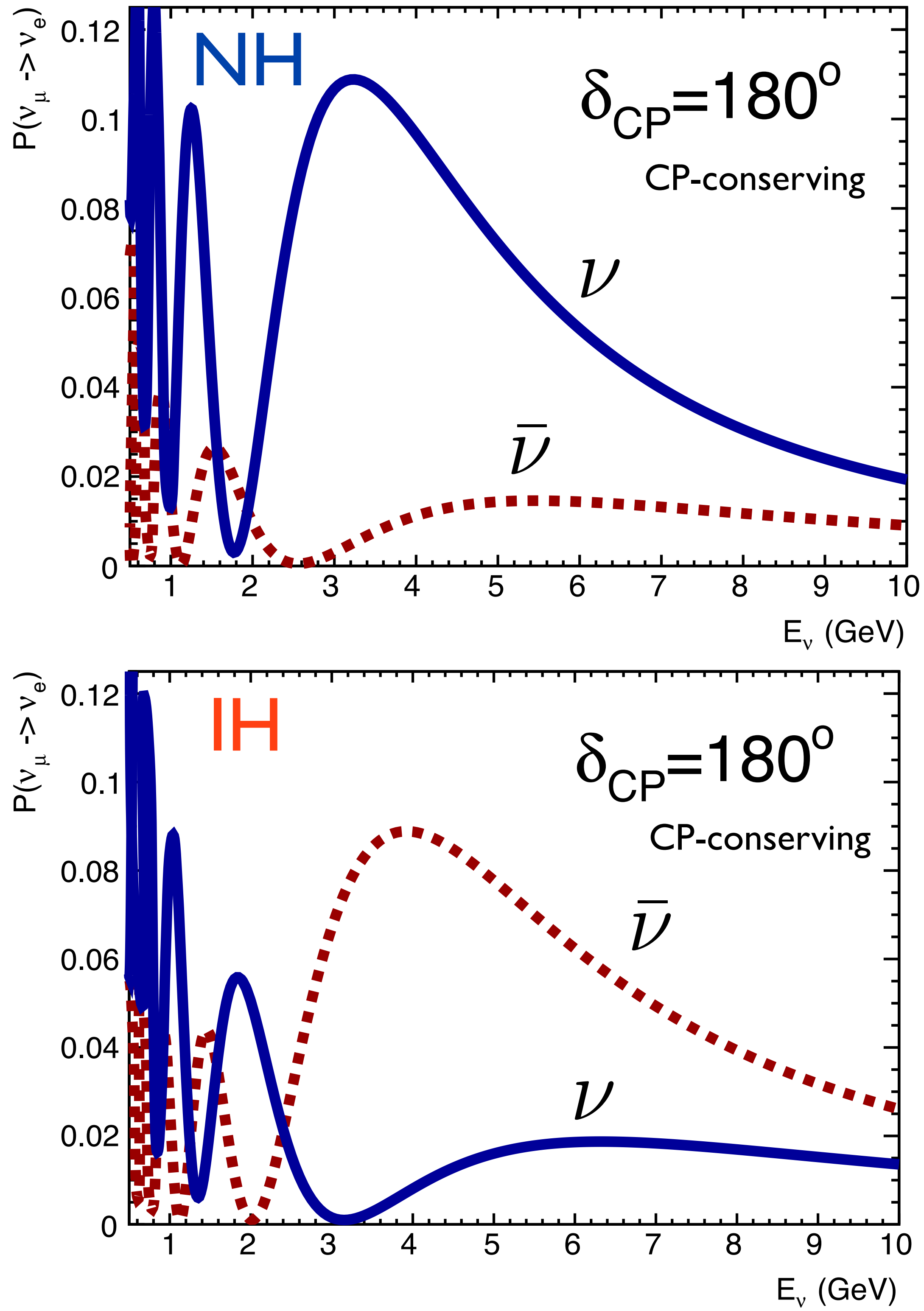


Reaching very long baselines

- ★ **"Zoom effect"**: The L/E dependence can be observed in an "expanded" scale at large L
  ➠ Measure the full spectral information for unambiguous sensitivity and a direct proof of the observed phenomenon.
- ★ **Decoupling of MH and CPV:** at medium and short baselines, the absence of knowledge of MH can completely compromise the efforts to discover CPV. A guaranteed & conclusive sensitivity to MH with existing beam power and initial mass requires a very long baseline.
  ➠ Opt for a guaranteed MH measurement in two years of running, not relying on the success of other experiments to give necessary inputs. After MH fixed, optimise the running for CP (this depends on NH/IH)!
- ★ **Ultimate upgrade possibilities:** make a step towards the NF

→ now is the time to move to very long baselines !!

L=2300 km



→ very clear signature !

An incremental approach

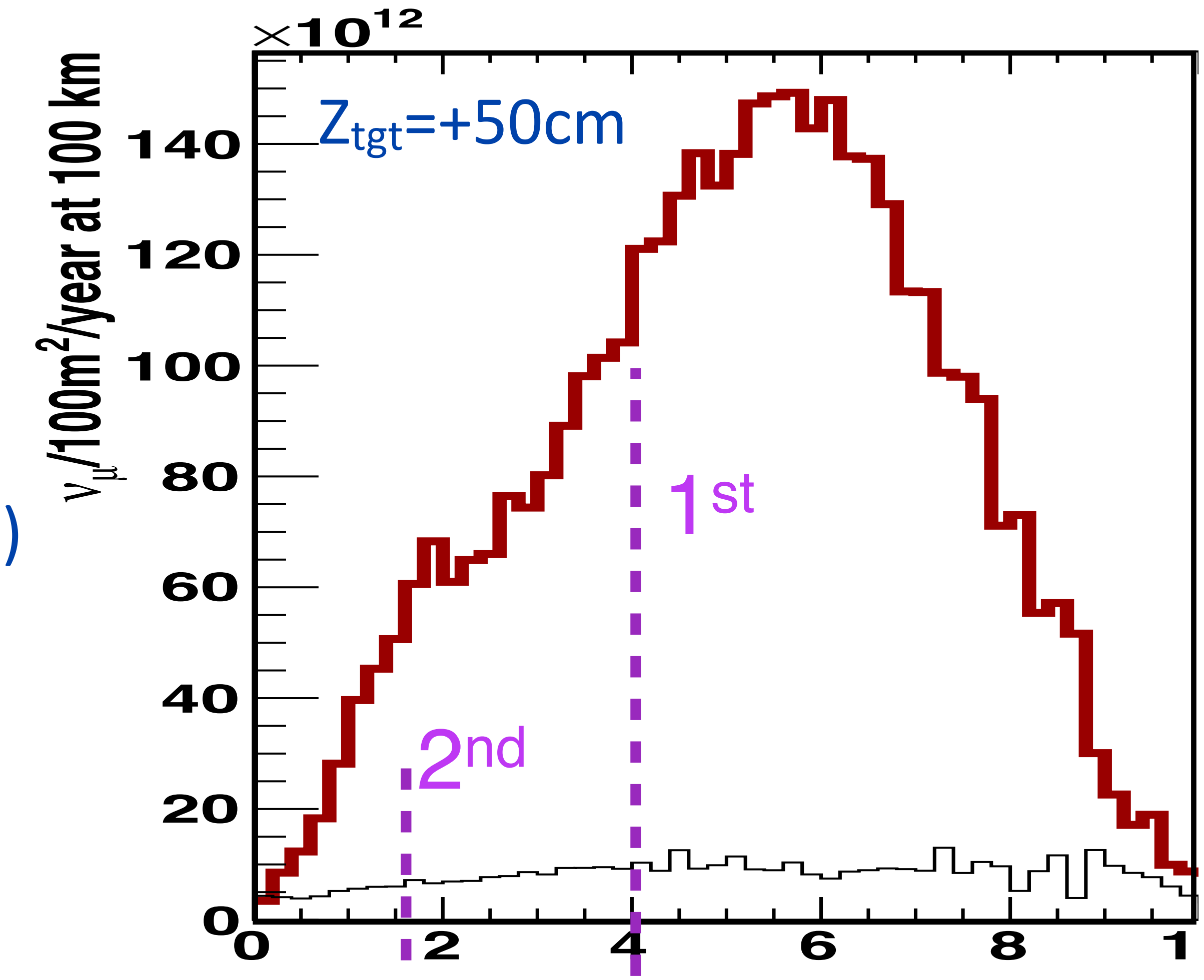
- **Subleading effects:** The CP-violation measurement requires the measurement of the oscillation probabilities with high precision.
- **Exposure**: Compared to present generation "discovery" experiment, the next generation will require precision, hence more than ten-fold increase in statistics and an improved knowledge of systematics. This will require very large **exposures** (where exposure = mass x beam integrated intensity expressed e.g. in kton * GeV * pots) and improved far detector technologies.
- **What is the right far detector mass?** 10 kton seems definitely too small (half SuperK!). 20 kton might be better, but maybe not even enough. Since 2003, we have been considering the GLACIER concept "up to 100 kton".
- **What is the "right" exposure ?** **We do not know.** The larger exposure, the better the coverage in CP. On the other hand, Nature might be kind to us (just as she was for the other oscillation parameters!!) and CPV of neutrinos might be a large effect !
- **An incremental approach:** We advocate an initial LAr mass of 20kton to be complemented by a 50 kton in a second phase, each with significant physics reach and chances to find CPV. Before considering this approach, we have successfully addressed the critical issues of the **the scalability of the detector design and its cost-effectiveness**.

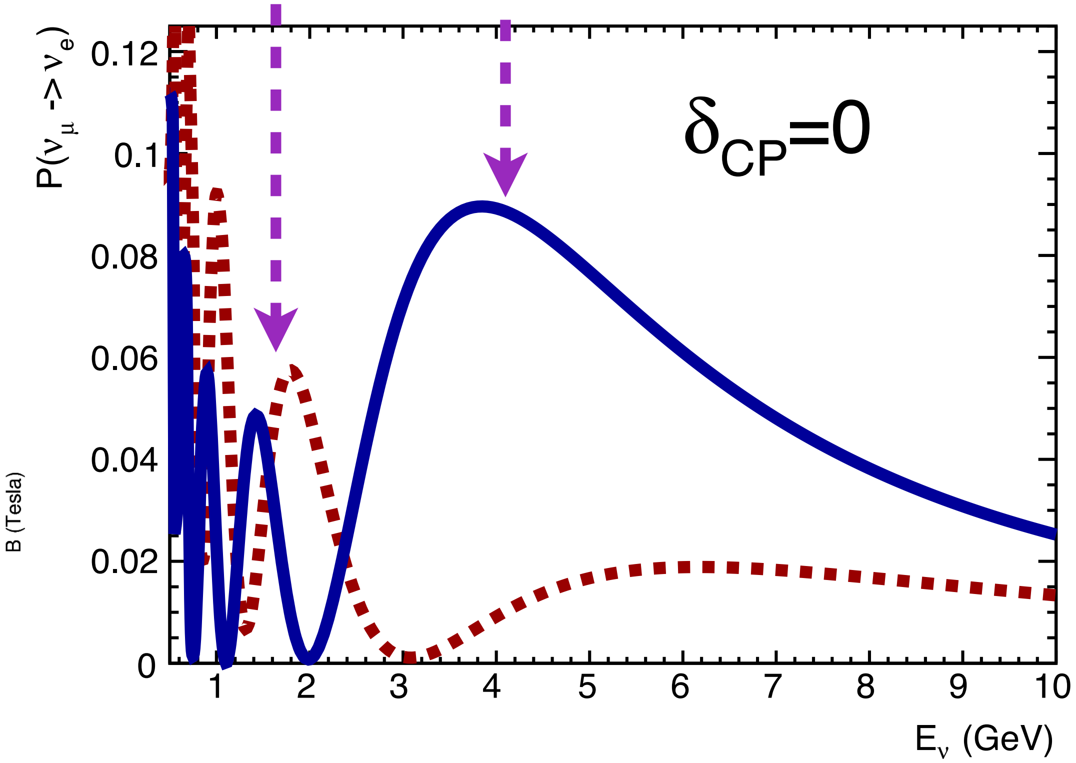
LBNO main physics goals

- **Long baseline neutrino oscillations**
  - Appearance: $\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_\tau$ and Disappearance: $\nu_\mu \rightarrow \nu_\mu$ & neutral currents
  - Separately for ν and anti-ν
  - Test of **three generation mixing paradigm** by direct measurement of the oscillation probabilities as a function of energy (L/E behaviour) – in particular covering 1st and 2nd oscillation maxima
  - Direct measurement of the energy dependence of the oscillation probabilities induced by **matter effects** and **CP-phase terms**, independently for ν and anti-ν
  - Jarlskog invariants: **$J(PMNS) \approx 5\times10^{-2}\sin\delta_{CP} > J(CKM) = 3\times10^{-5}$???**
  - Break parameter degeneracy between MH and CP phase (E_ν coverage and large L)
  - Direct determination of **neutrino mass hierarchy** (MH) and test of **CPV in lepton sector** (CPV), which is different from extracting this information from global fits
- **Nucleon decays (direct GUT evidence)**
- **Atmospheric neutrino detection**
  - Complementary oscillation measurements and Earth spectroscopy
- **Astrophysical neutrino detection**
  - Galactic supernova burst
- **Search for unknown sources of neutrinos (e.g. DM annihilation)**
- **First very long baseline experiment, towards the Neutrino Factory (NF)**
  - Distance of 2300km is also optimal for NF and large θ_{13} (Not surprisingly?)

LBNO baseline beam design

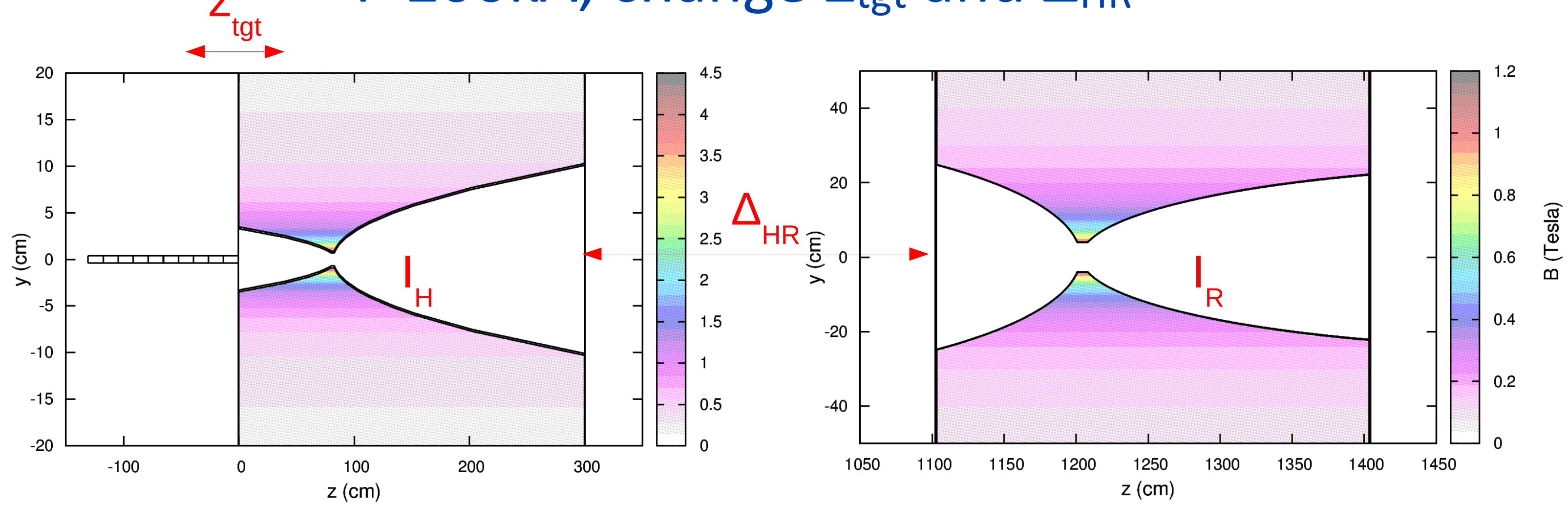
- Conventional beam, horn focused
- Medium energy to cover at $E_\nu \approx 4$ GeV (1st max) and $E_\nu \approx 1.5$ GeV (2nd max)
- Wide band covering 1st and 2nd maximum
- Small tail at high energy
- Positive and negative focus (ν and anti-ν modes)
- High beam power (initially 700 kW then 2MW)
- Angle 10deg dip angle (distance = 2300km)
- Muon monitors
- Magnetised near neutrino detector





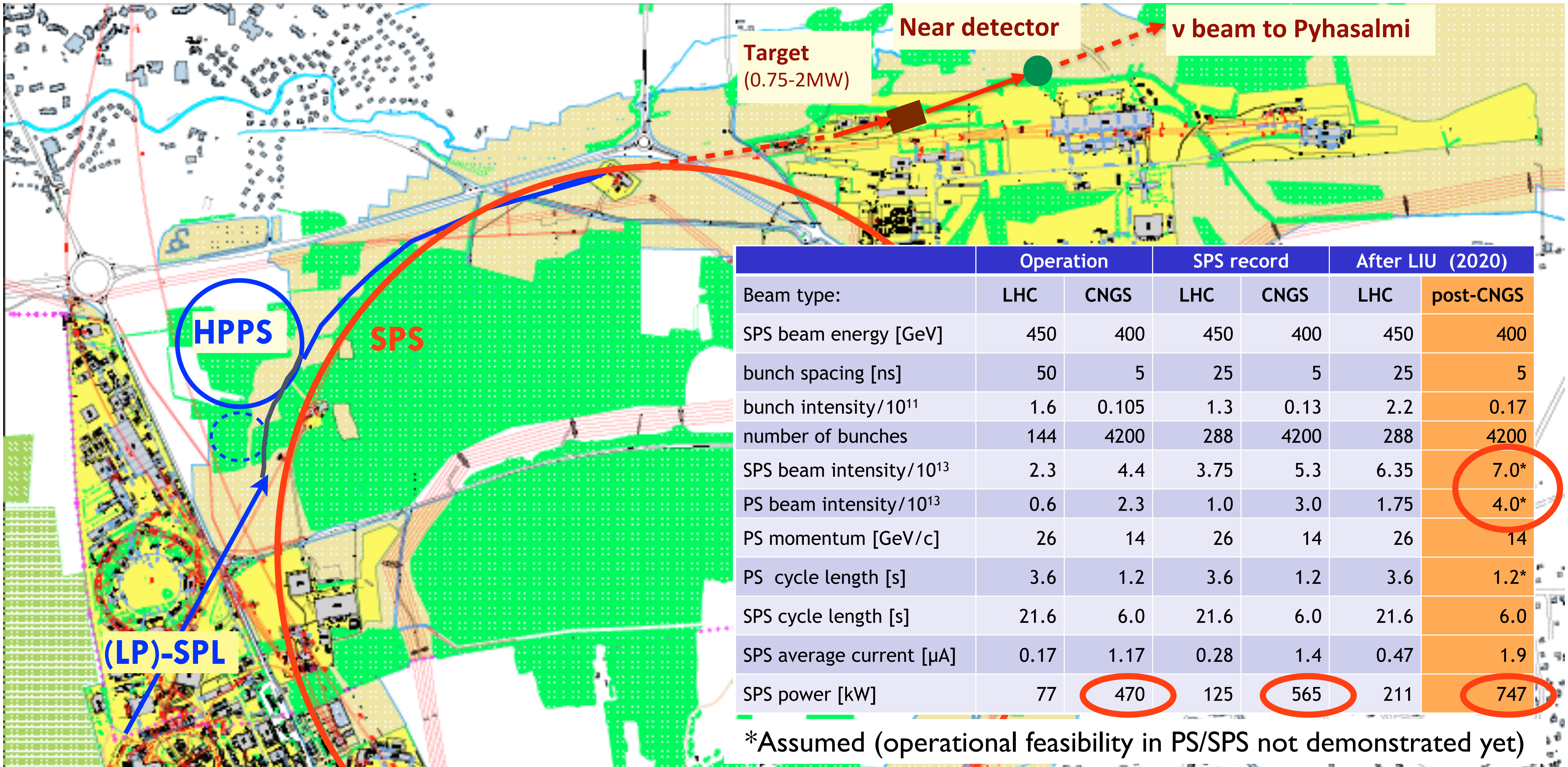
Focusing optimisation (preliminary)

Graphite target (r=4mm), Horn shapes fixed, I≈200kA, change Z_{tgt} and Δ_{HR}



The CN2PY beam

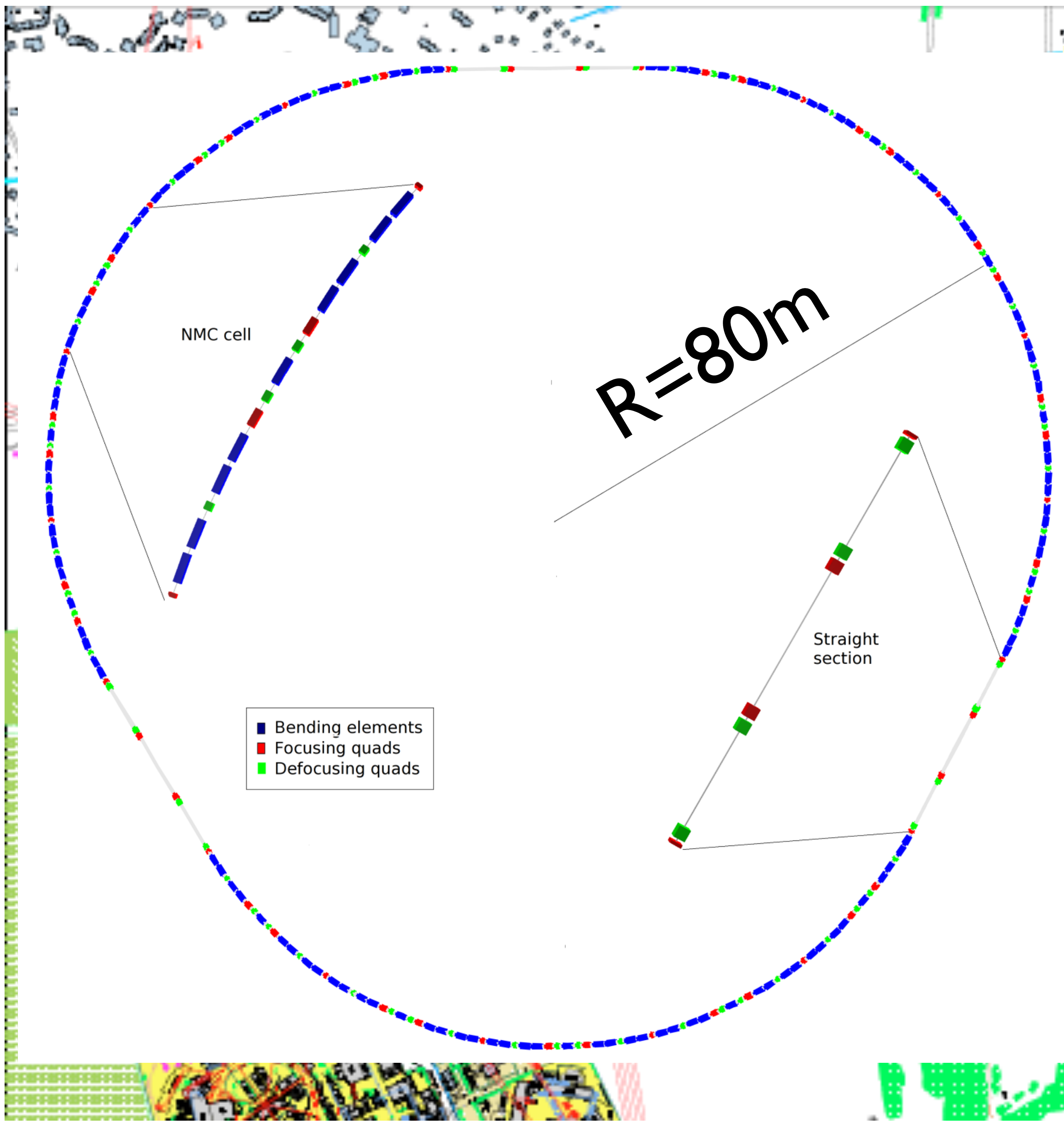
- **Phase 1** : use the proton beam extracted beam from SPS
  - **400 GeV**, max 7.0 10^{13} protons every 6 sec, **750 kW** nominal beam power, 10 μs pulse
  - Yearly integrated pot = (8-13)x 1e19 pot / yr depending on "sharing" with other fixed target programmes (compared to CNGS 4.5x 1e19 pot / yr)
- **Phase 2** : use the proton beam from the new HP-PS
  - **50**(70) GeV, 1 Hz, 2.5 10^{14} ppp, **2 MW** nominal beam power, 4 μs pulse

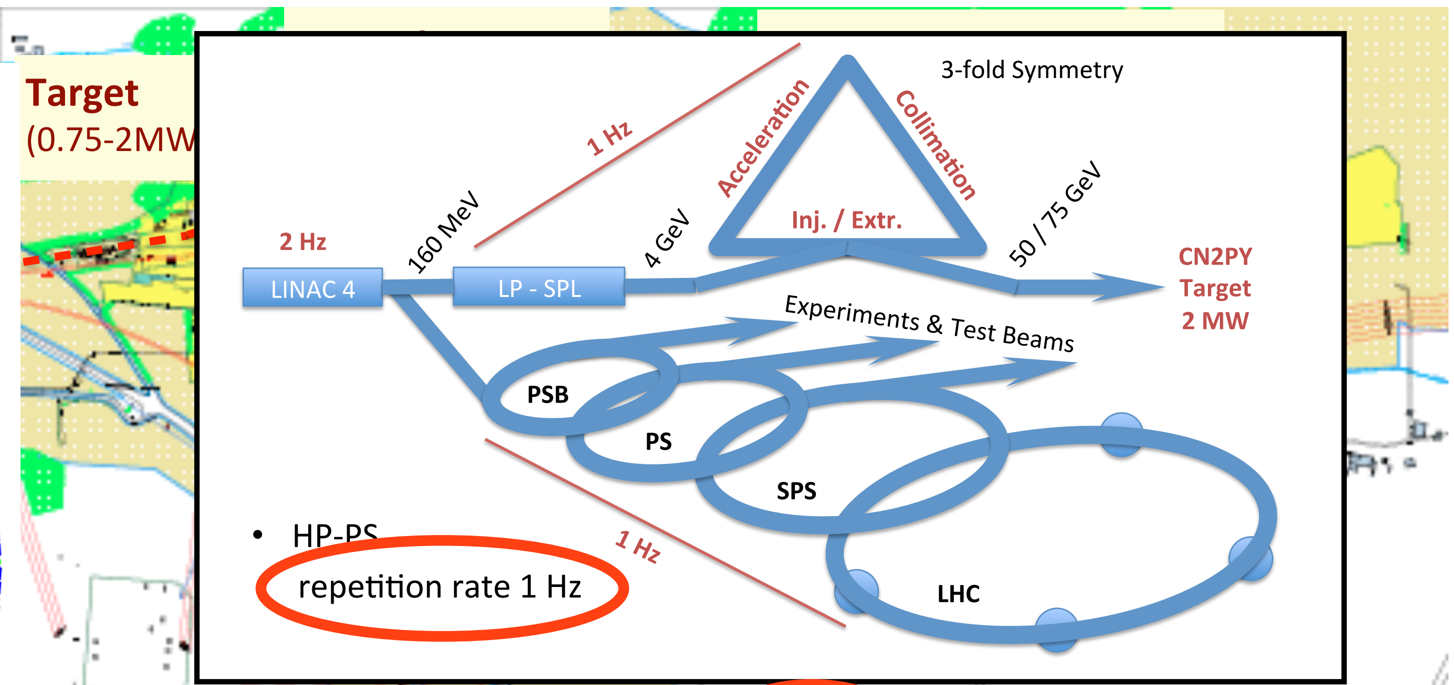


	Operation		SPS record		After LIU (2020)	
Beam type:	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity/10^{11}	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS beam intensity/10^{13}	2.3	4.4	3.75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

High power HP-PS study

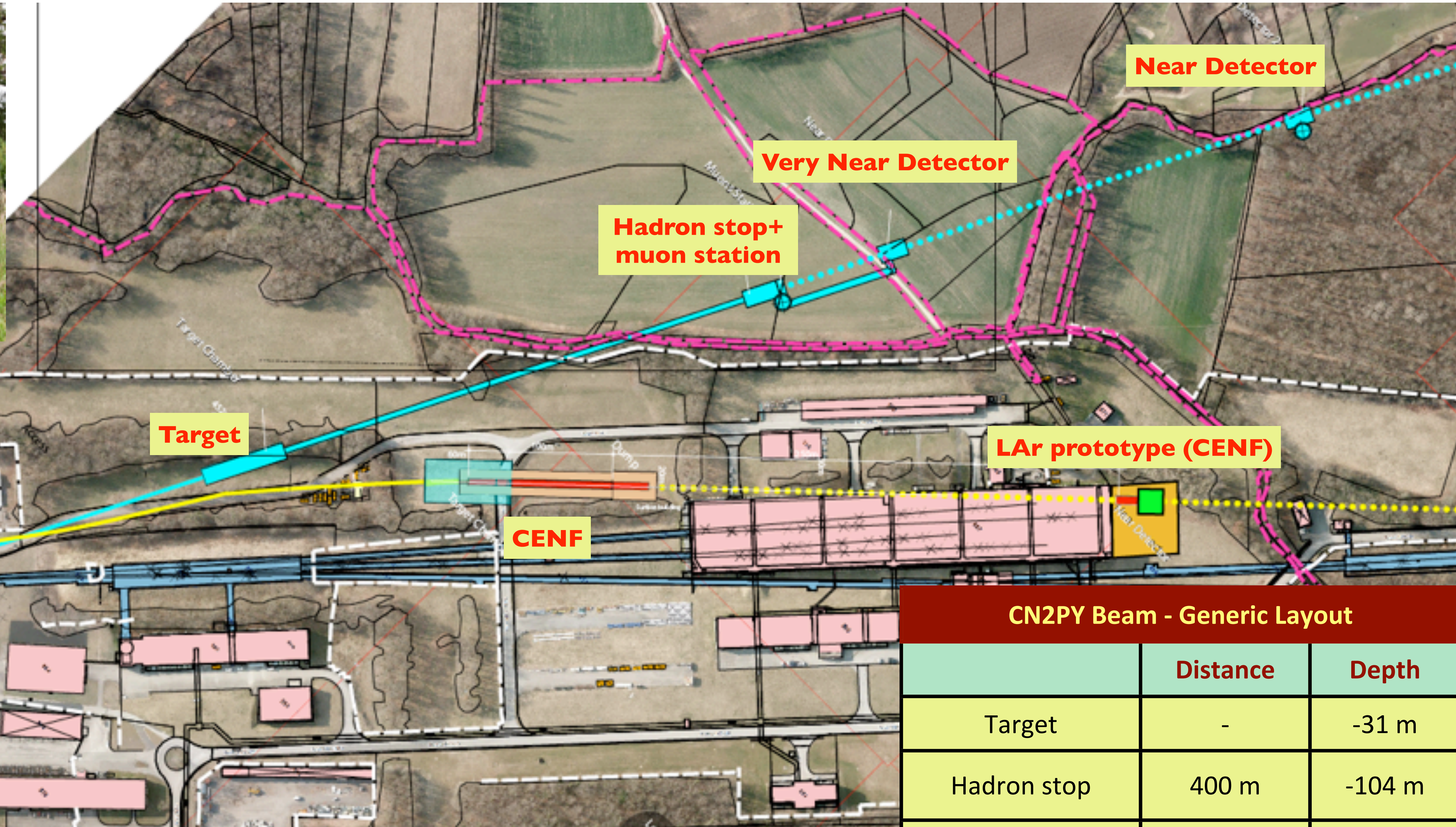




Parameter	50 GeV	75 GeV	Units
Inj. / Extr. Kinetic Energy	4 / 50	4 / 75	[GeV]
Beam power	2		[MW]
Repetition rate	1		[Hz]
f_{rev} / f_{RF} @ inj.	0.248 / 38.97		[MHz]
RF harmonic	157		-
f_{rev} / f_{RF} @ extr.	0.255 / 40.08	0.255 / 40.09	[MHz]
Bunch spacing @ extr.	25		[ns]
Total beam intensity	2.5×10^{14}	1.7×10^{14}	-
Number of bunches	147		-
Intensity per bunch	1.7×10^{12}	1.25×10^{12}	-
Main dipole field inj. / extr.	0.17 / 2.1	0.17 / 3.13	[T]
Ramp time	500	500	[ms]
Dipole field rate dB/dt (acc. ramp)	3.9	5.9	[T/s]

- Basic design well underway and main parameters available
- Optics design well advanced
- Injection and extraction concepts are available
- Basic ideas about accelerating RF system
- Basic ideas about collimation
- Consolidate optics and establish set of requirements for different magnet families.
- Make preliminary magnet designs.

CN2PY beam layout



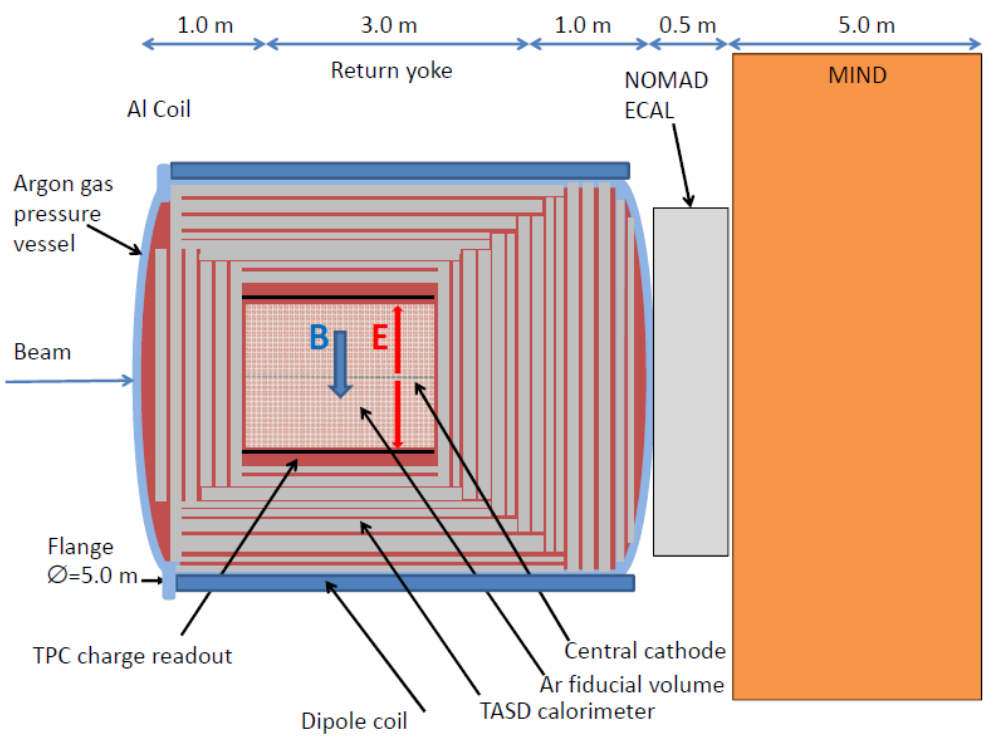
CN2PY Beam - Generic Layout

	Distance	Depth
Target	-	-31 m
Hadron stop	400 m	-104 m
Muon station	450 m	-113 m
Very Near detector	500 m	-122 m
Near detector	830 m	-176 m

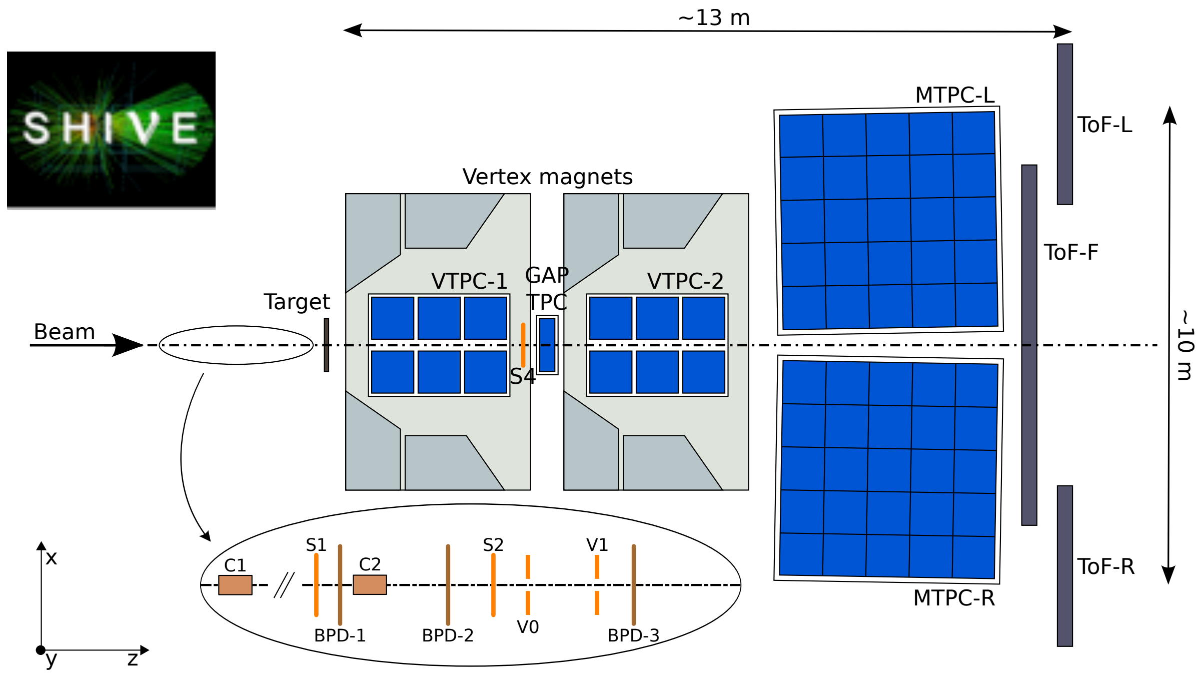
- Target location inside the CERN area
- Hadron stop inside the reserved area
- ND just outside - no problem, use an access shaft!

Near detector and hadro-production

- **Aim**: systematic errors for signal and backgrounds in the far detectors below ±5%, possibly at the level of ±2% ⇒ control of fluxes, cross-sections, efficiencies,...



- Concept: 20 bar gas argon-mixture TPC (2.4 m × 2.4 m × 3 m) surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 600 kg argon mass in TPC
- 0.2 event/spill @ 7e13 ppp 400 GeV
- O(100’000) events/year



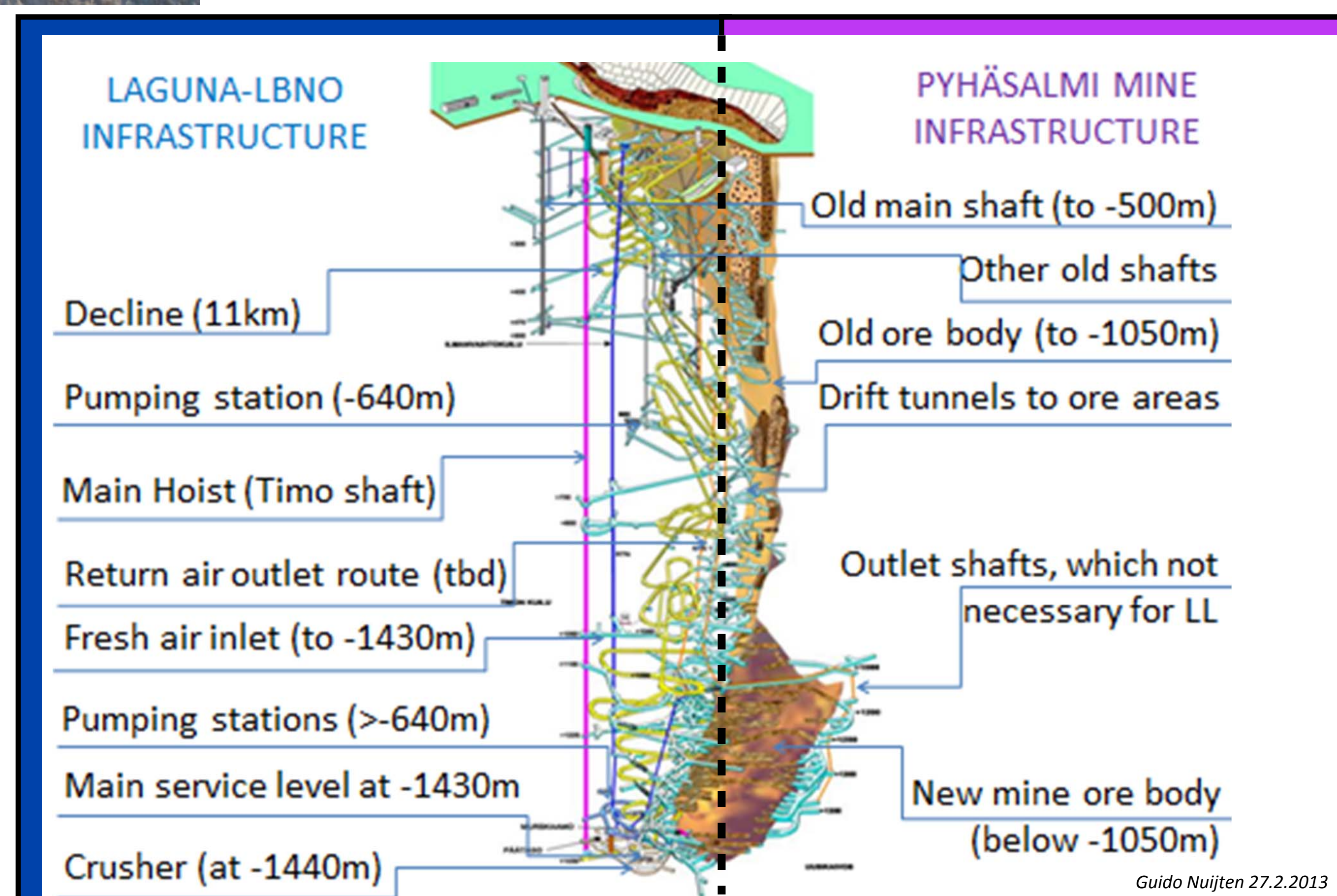
- It is widely recognized that hadro-production measurements with thin or replica target are really crucial for precision neutrino experiments (eg. K2K, T2K, MINOS).
- CERN NA61 upgrade needed for 400 GeV incident protons

- Precision neutrino cross-section measurements: e.g. MINERVA, T2K-ND280, also nuSTORM

Pyhäsalmi mine (Inmet/PM Oy)

- ★ Underground mining activities foreseen to stop in 2018. On-surface activities will continue afterwards.
- ★ The mining company has never expressed an intention to benefit from LAGUNA, so some of the mine-related cost concerns that have been uttered are unfounded.
- ★ An **extended site investigation** is in progress in the location where LAGUNA caverns would be excavated (funded by Finland+mine). So far 750m of rock have been drilled. Results expected in 2014.

- ★ Only those parts that are necessary for LAGUNA/LBNO during construction and operation would be transferred to the new 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.

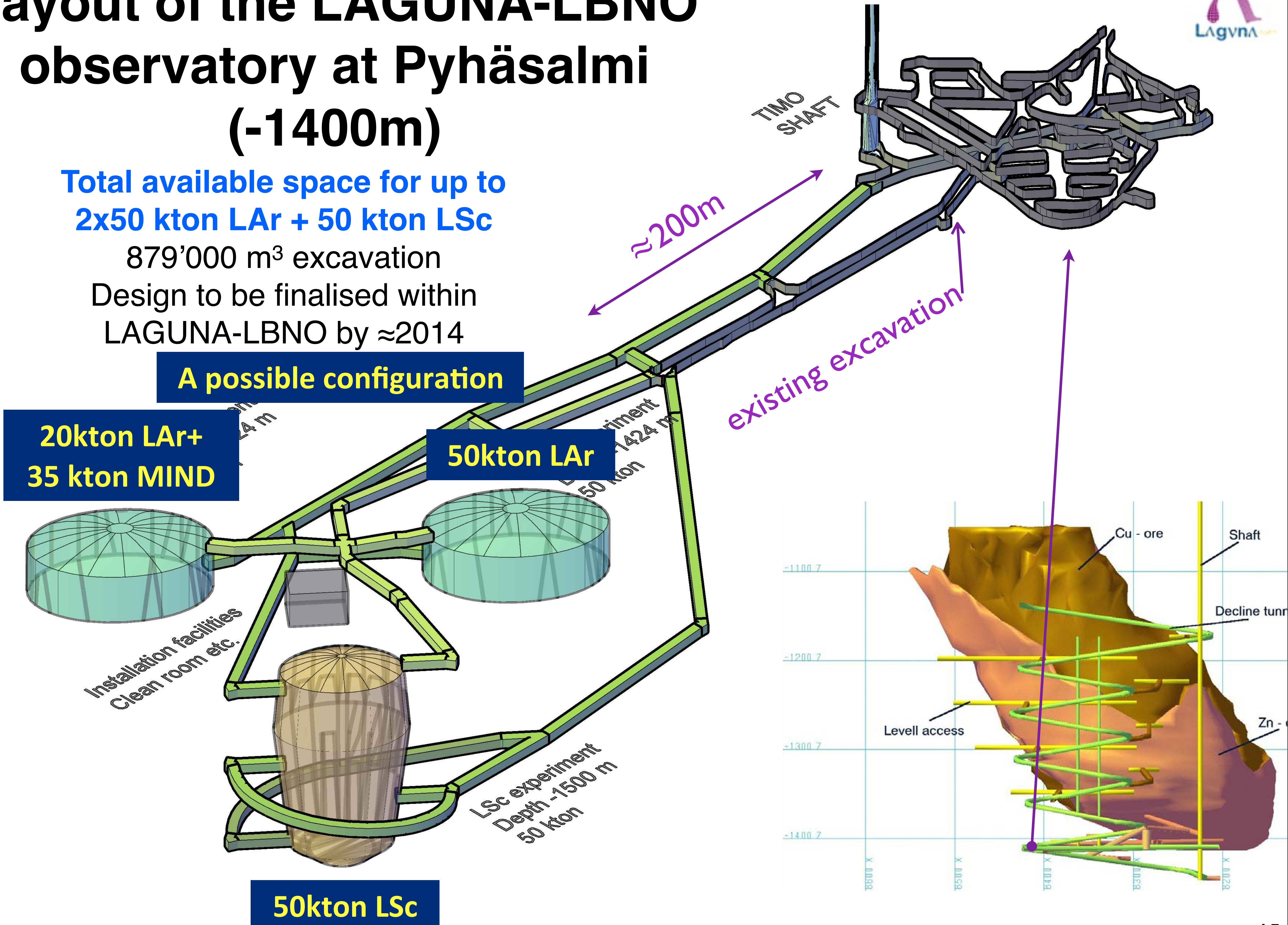


Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)

Total available space for up to 2x50 kton LAr + 50 kton LSc

879’000 m³ excavation

Design to be finalised within LAGUNA-LBNO by ≈2014

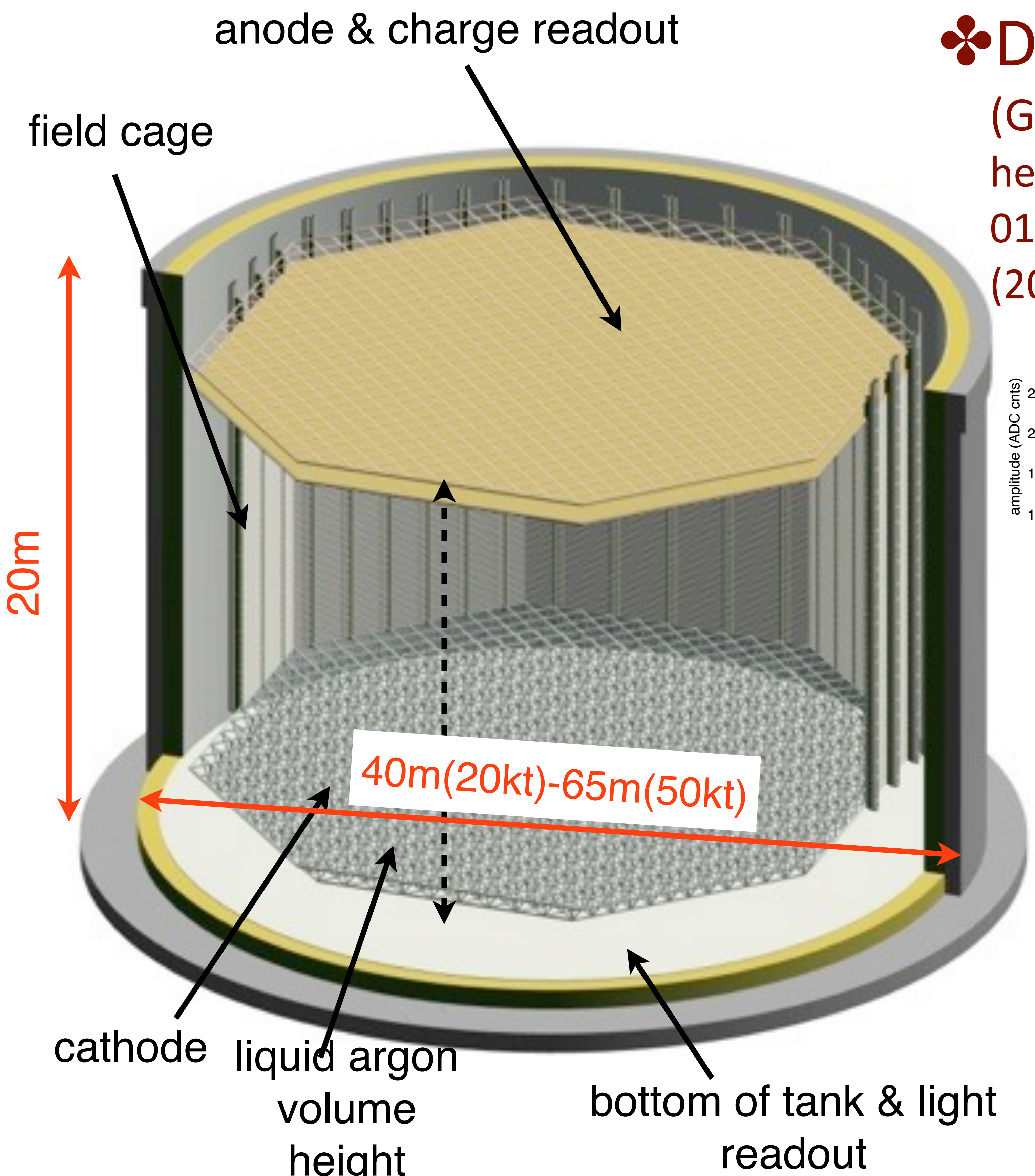


Far detectors requirements

- **Detect electron&tau appearance and muon disappearance + NC**
- Fiducial mass at least equal to that of SuperK (>20kton)
- Clean neutrino detection in the energy range $0.5<E_\nu<10$ GeV (→ multi-prong events, not only QE)
- Fine granularity for clean $\nu_\mu \rightarrow \nu_e$ appearance signal
- Neutrino energy resolution $\Delta E_\nu/E_\nu < 10\%$ to observe L/E
- Full kinematical reconstruction, e.g. for $\nu_\mu \rightarrow \nu_\tau$
- 4π acceptance for all tracks and neutrals
- Charge and momentum determination for muons, to e.g. study $\nu_\mu/\overline{\nu_\mu}$ in both horn configurations

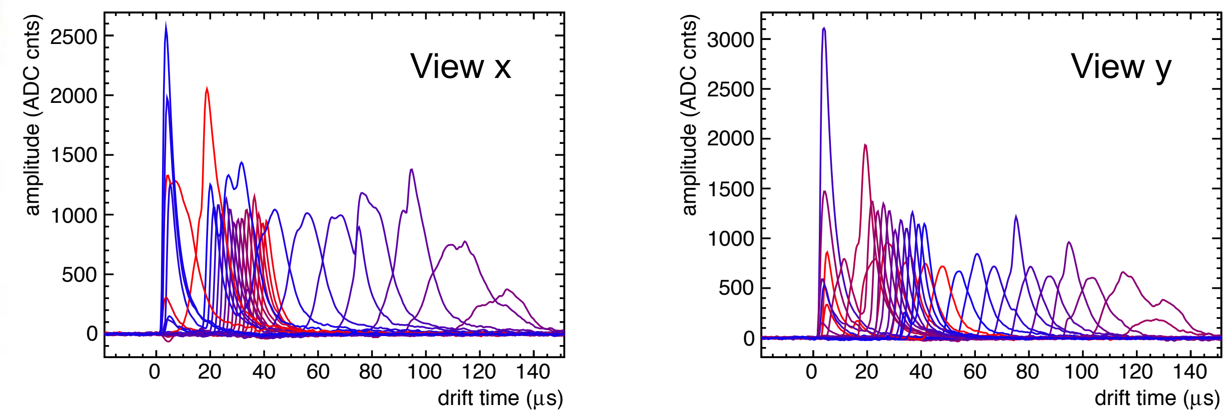
→ ❖**Liquid argon TPC complemented by magnetized iron detector (MIND)**

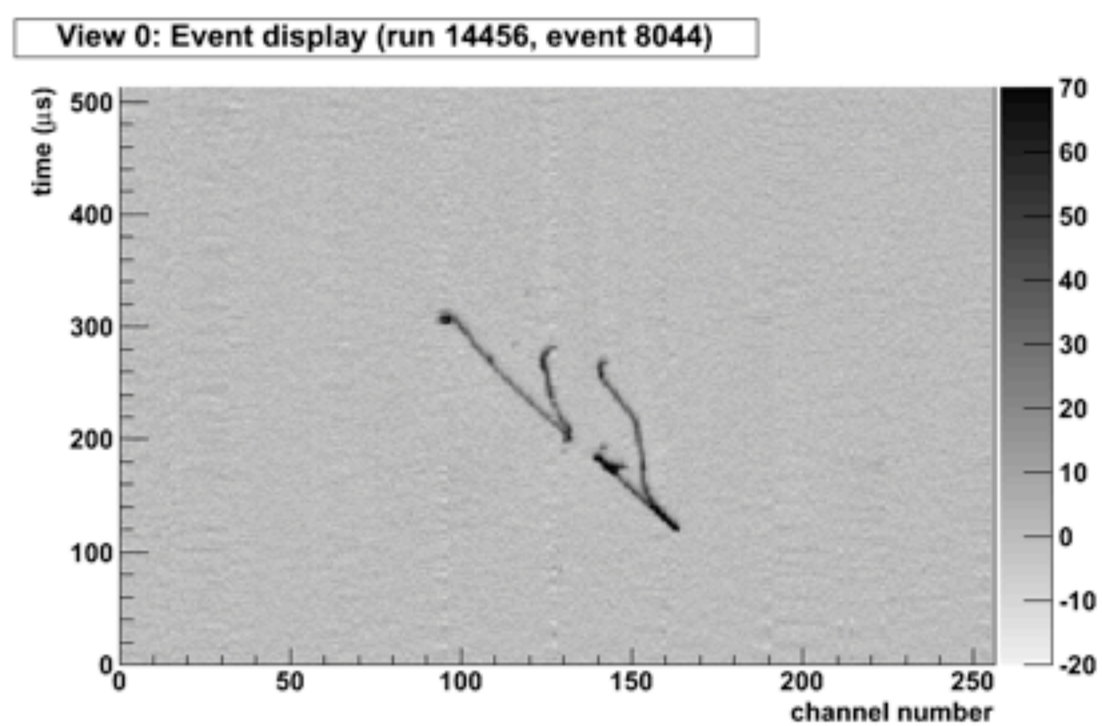
LBNO far liquid Argon detector



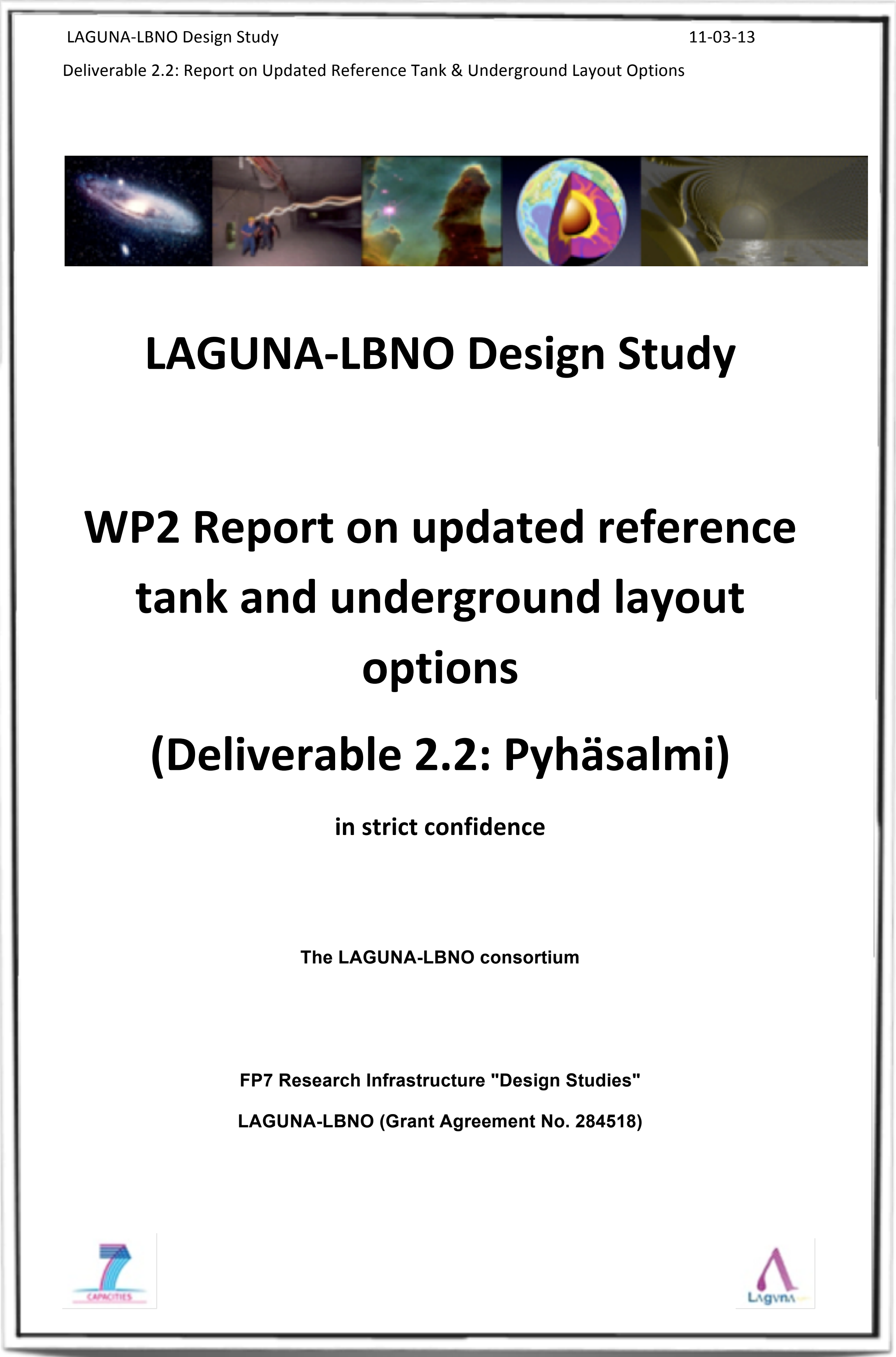
✤Double phase LAr LEM TPC

(GLACIER "up to 100 kton", Venice 2003 !) hep-ph/0402110; J.Phys.Conf.Ser. 171 (2009) 012020; NIM A 641 (2011) 48-57; JINST 7 (2012) P08026; arXiv:1301.4817





LBNO far liquid Argon detector


LAGUNA-LBNO Design Study 11-03-13

Deliverable 2.2: Report on Updated Reference Tank & Underground Layout Options

LAGUNA-LBNO Design Study

WP2 Report on updated reference tank and underground layout options

(Deliverable 2.2: Pyhäsalmi)

in strict confidence

The LAGUNA-LBNO consortium

FP7 Research Infrastructure "Design Studies"

LAGUNA-LBNO (Grant Agreement No. 284518)

- **475 pages report**
- **20, 50 and 100 kton baseline engineering designs**
- **Scalability study**
- **SS 9% Ni steel tank and "membrane" versions and comparison of the two**

DELIVERABLE 2.2 - CHAPTER 3 CONTENTS LIST

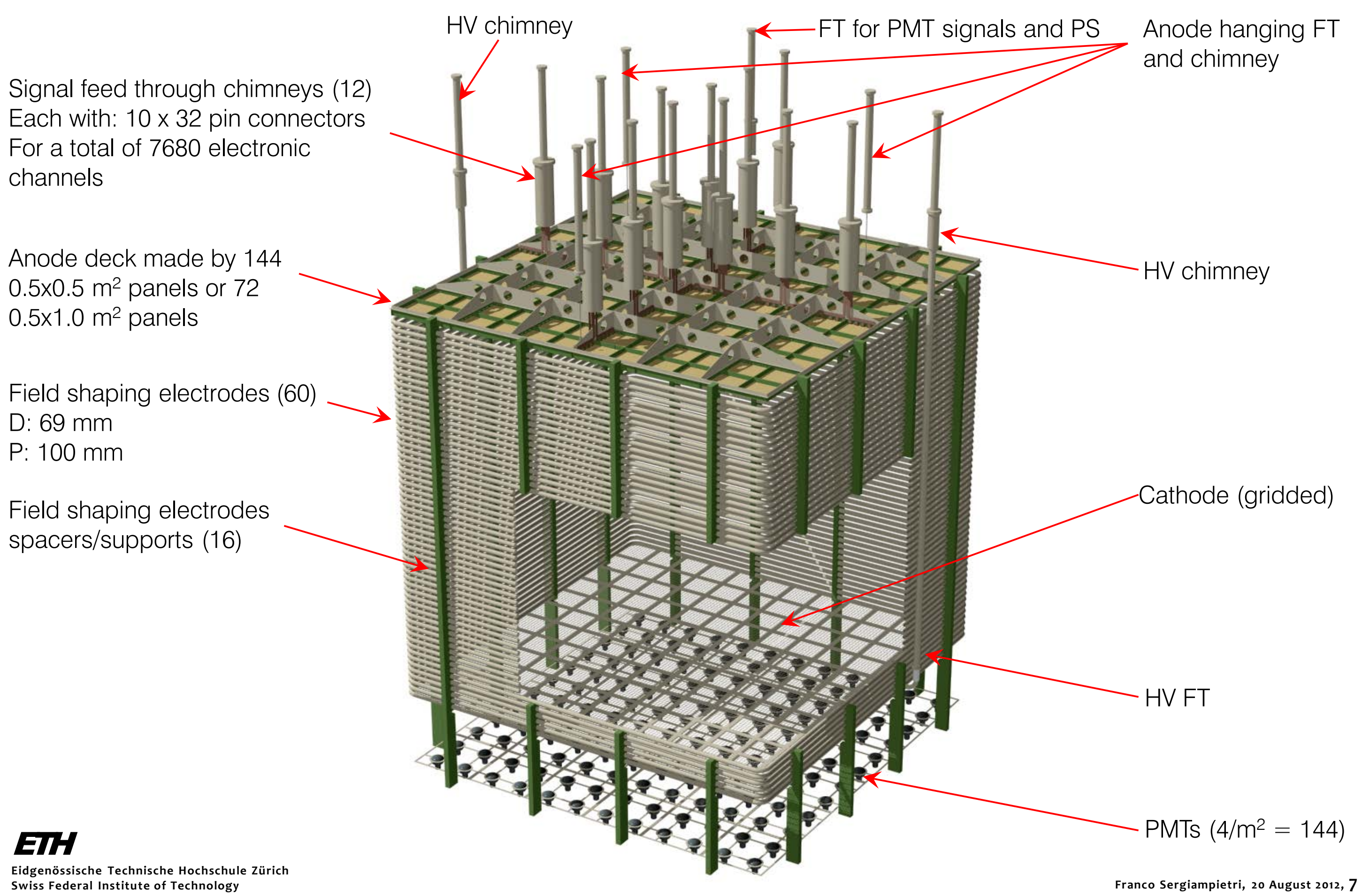
- **More reports in preparation (detector design, costs, ...)**

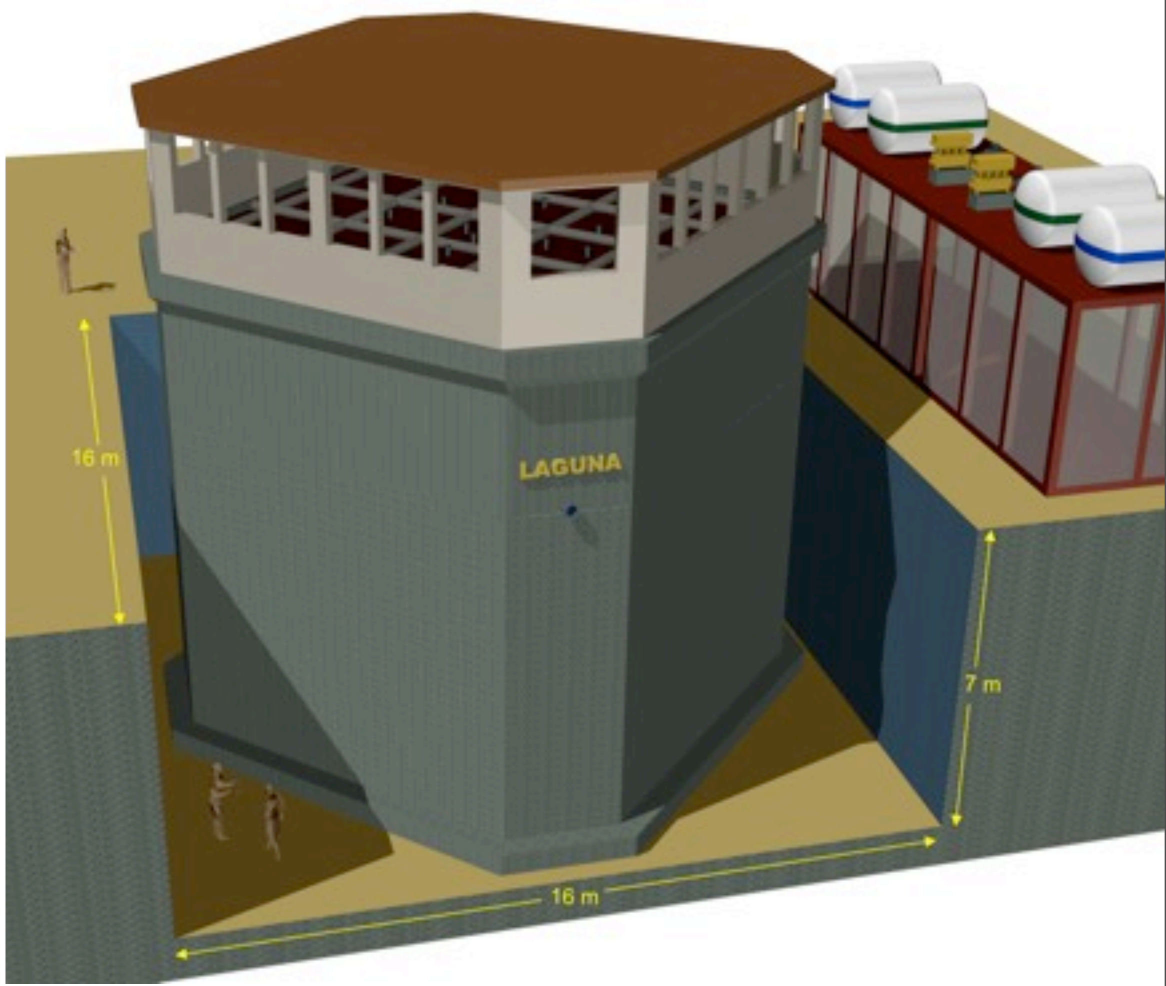
LBNO LAr design parameters

		20 KT	50 KT	100 KT
Liquid argon density at 1.2 bar	[T/m³]	1.38346		
Liquid argon volume height	[m]	22		
Active liquid argon height	[m]	20		
Pressure on the bottom due to LAr	[T/m²]	30.4 (≡ 0.3 MPa ≡ 3 bar)		
Inner vessel diameter	[m]	37	55	76
Inner vessel base surface	[m²]	1075.2	2375.8	4536.5
Liquid argon volume	[m³]	23654.6	52268.2	99802.1
Total liquid argon mass	[T]	32525.6	71869.8	137229.9
Active LAr area (percentage)	[m²]	824 (76.6%)	1854 (78%)	3634 (80.1%)
Active (instrumented) mass	[KT]	22.799	51.299	100.550
Charge readout square panels (1m×1m)		804	1824	3596
Charge readout triangular panels (1m×1m)		40	60	72
Number of signal feedthroughs (666 channels/FT)		416	1028	1872
Number of readout channels		277056	660672	1246752
Number of PMT (area for 1 PMT)		804 (1m×1m)	1288 (1.2m×1.2m)	909 (2m×2m)
Number of field shaping electrode supports (with suspension SS ropes linked to the outer deck)		44	64	92

A large scale demonstrator ?

- Consider a **6x6x6 = 216 m³ active volume detector** to be constructed and operated as a prototype of the far detector double-phase TPC
- Charged test beams to collect the large controlled data set allowing **electromagnetic** and **hadronic calorimetry** and general **detector performance** (PID, ...) to be measured, **simulation and reconstruction** to be improved and validated
- Considering detector to be positioned in the CERN North Area (EHN1 building ?)
- Opportunities offered by the CENF neutrino beam under study
- **Technical proposal to CERN SPSC in preparation**

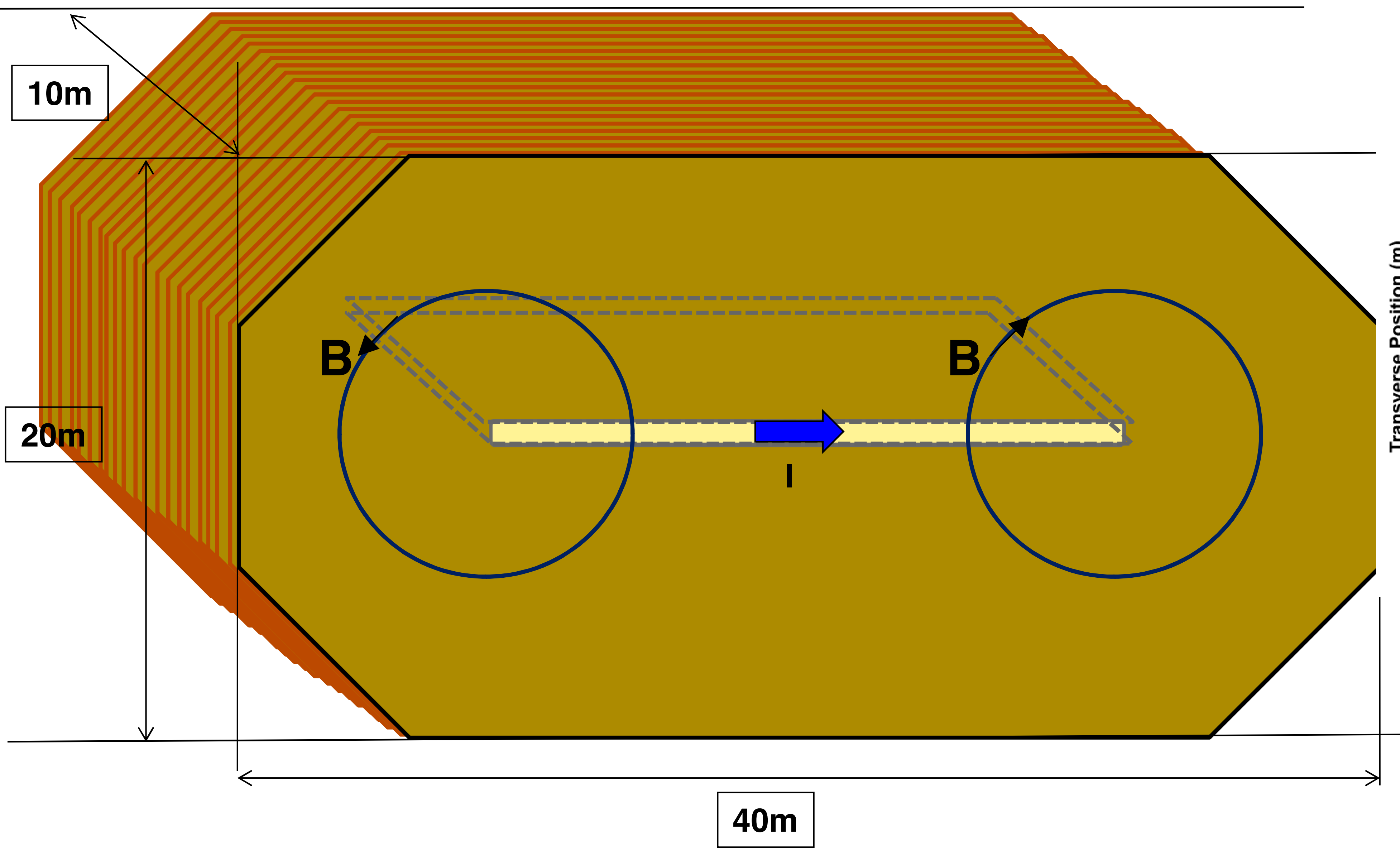




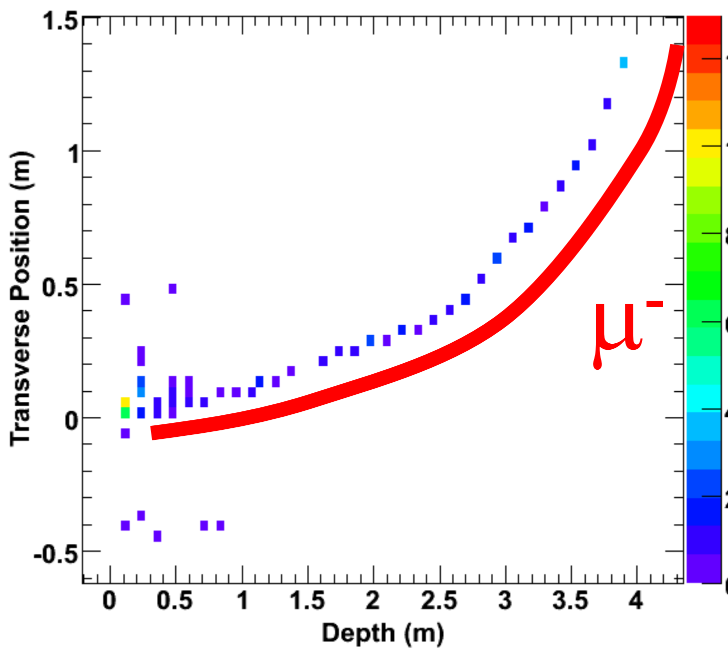
LBNO far muon detector concept

35kton MIND magnetised iron with scintillator slabs (MINOS-like, reference IDS-NF)

Magnetized Iron Neutrino Detector (MIND)



ν_μ Charged Current

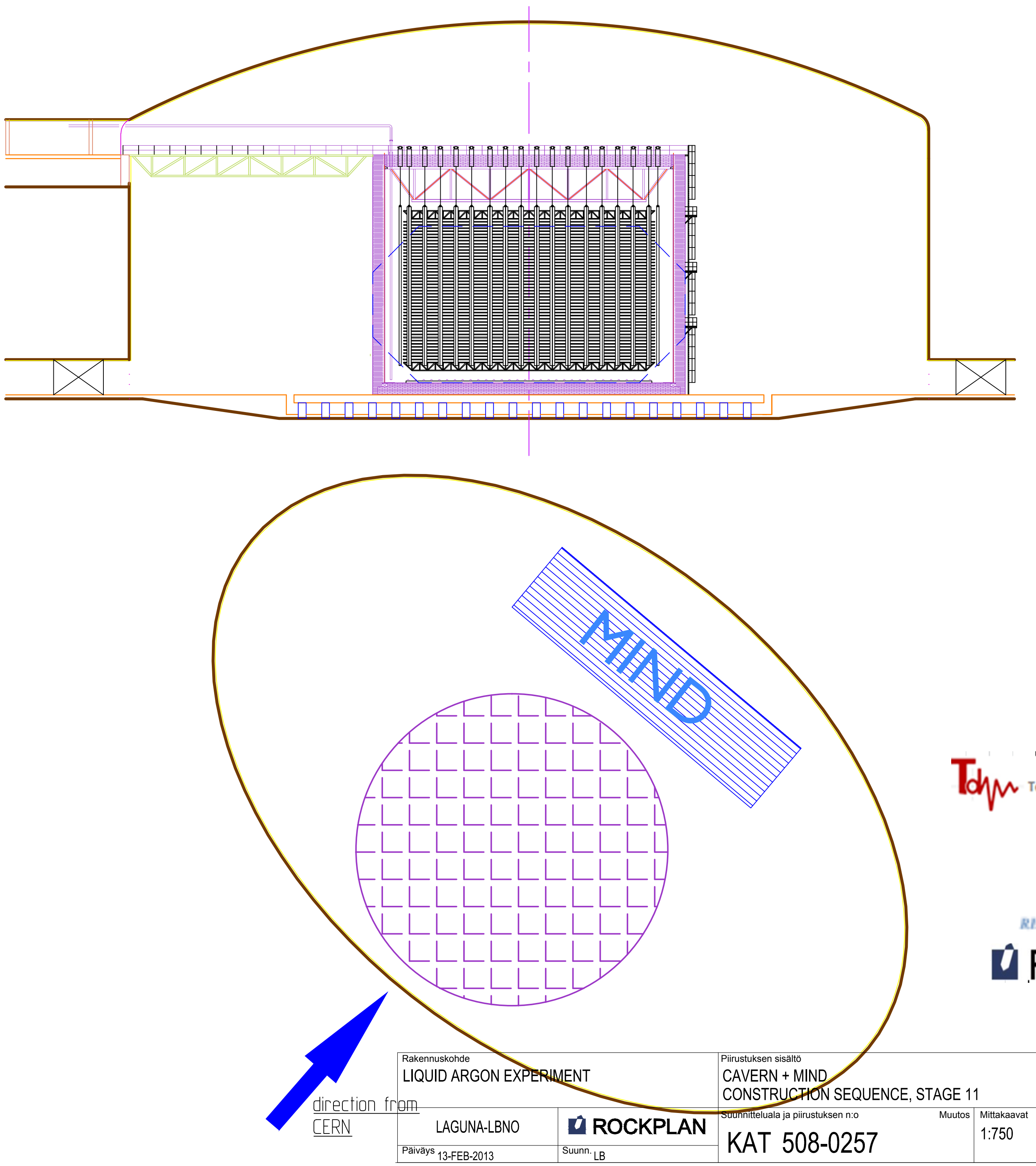


MINOS

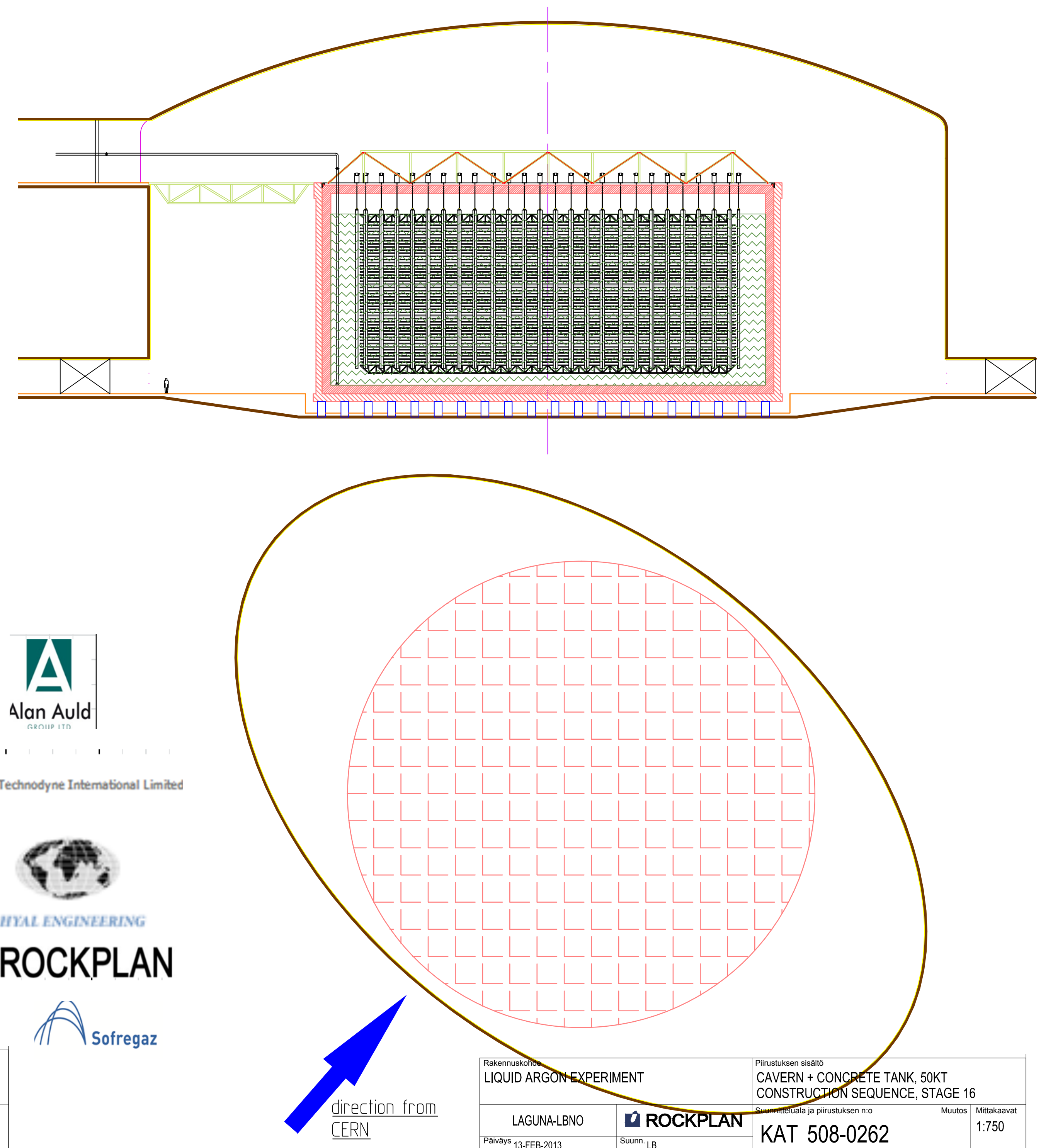
- 3cm Fe plates, 1cm scintillator bars, B=1.5-2.5 T

LBNO caverns layout

20kton LAr + 35 kton MIND

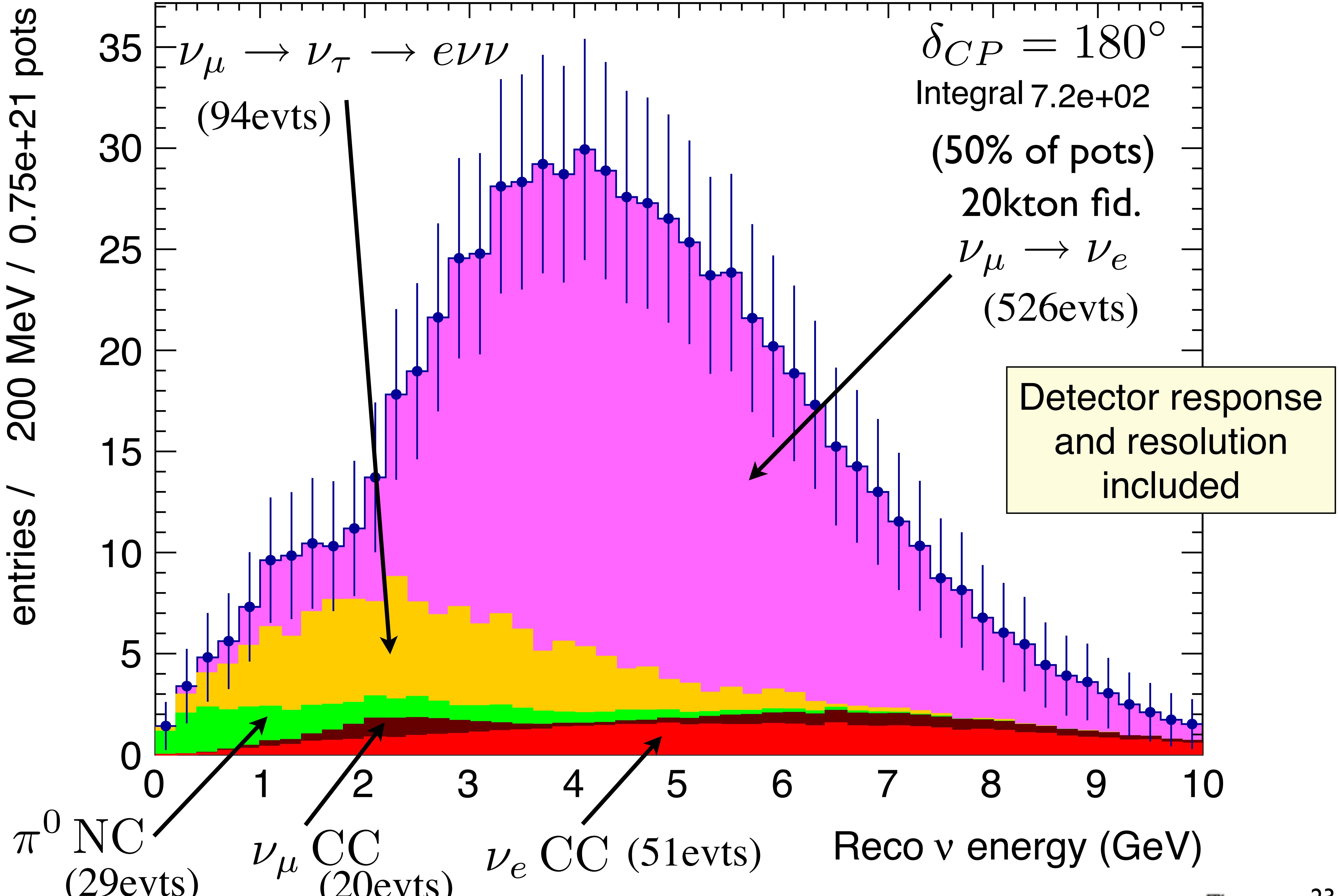


50kton LAr



Alan Auld GROUP LTD
Technodyne International Limited
RHYAL ENGINEERING
ROCKPLAN
Sofregaz

LBNO 20kton LAr: e-like CC sample



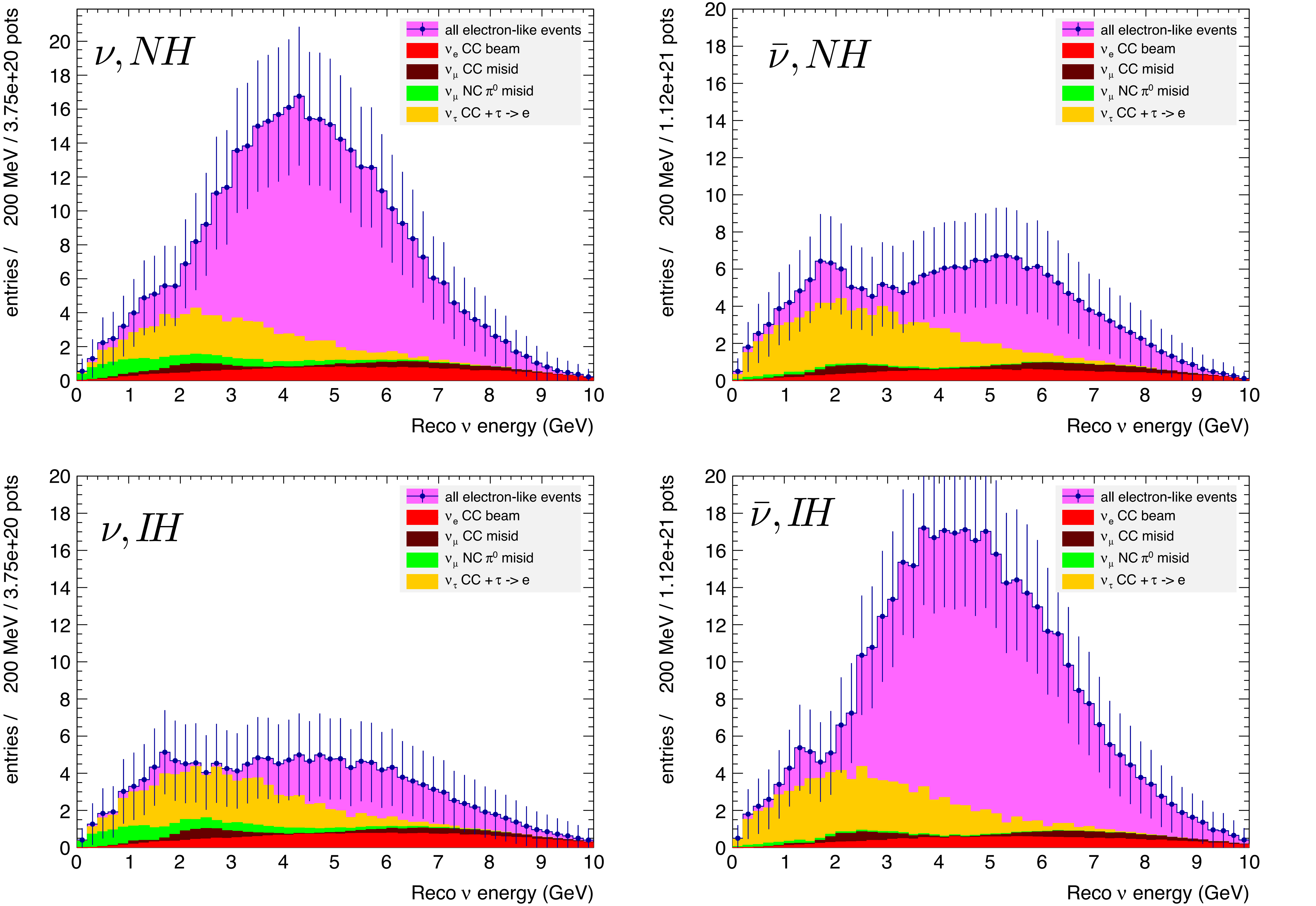
Thursday, March 14, 13

Neutrino/antineutrinos and MH

Detector response and resolution included

20kton fid.

Running mode:
ν/anti-ν:25%/75%



LBNO sensitivity for MH&CPV

- Include impact of systematic uncertainties in sensitivity computations

Oscillation parameters:

Name	Value	Error (1σ)
L (km)	2300	exact
Δm^2_{21} eV^2	7.60E-05	exact
$\lvert \Delta m^2_{32} \rvert$ eV^2	2.40E-03	±4%
$\sin^2\theta_{12}$	0.30	exact
$\sin^2 2\theta_{13}$	0.09	±10%
$\sin^2\theta_{23}$	0.50	±10%
<ρ>	3.2 g/cm3	±4%

Oscillation values & errors from http://www.nu-fit.org

$$\chi^2 = \sum_i (N_i - n_i)^2 / \mathrm{N_i} + \sum_j f_j^2 / \sigma^2_{\_f\,j}$$

True rate (all sys parameter fixed to default values)

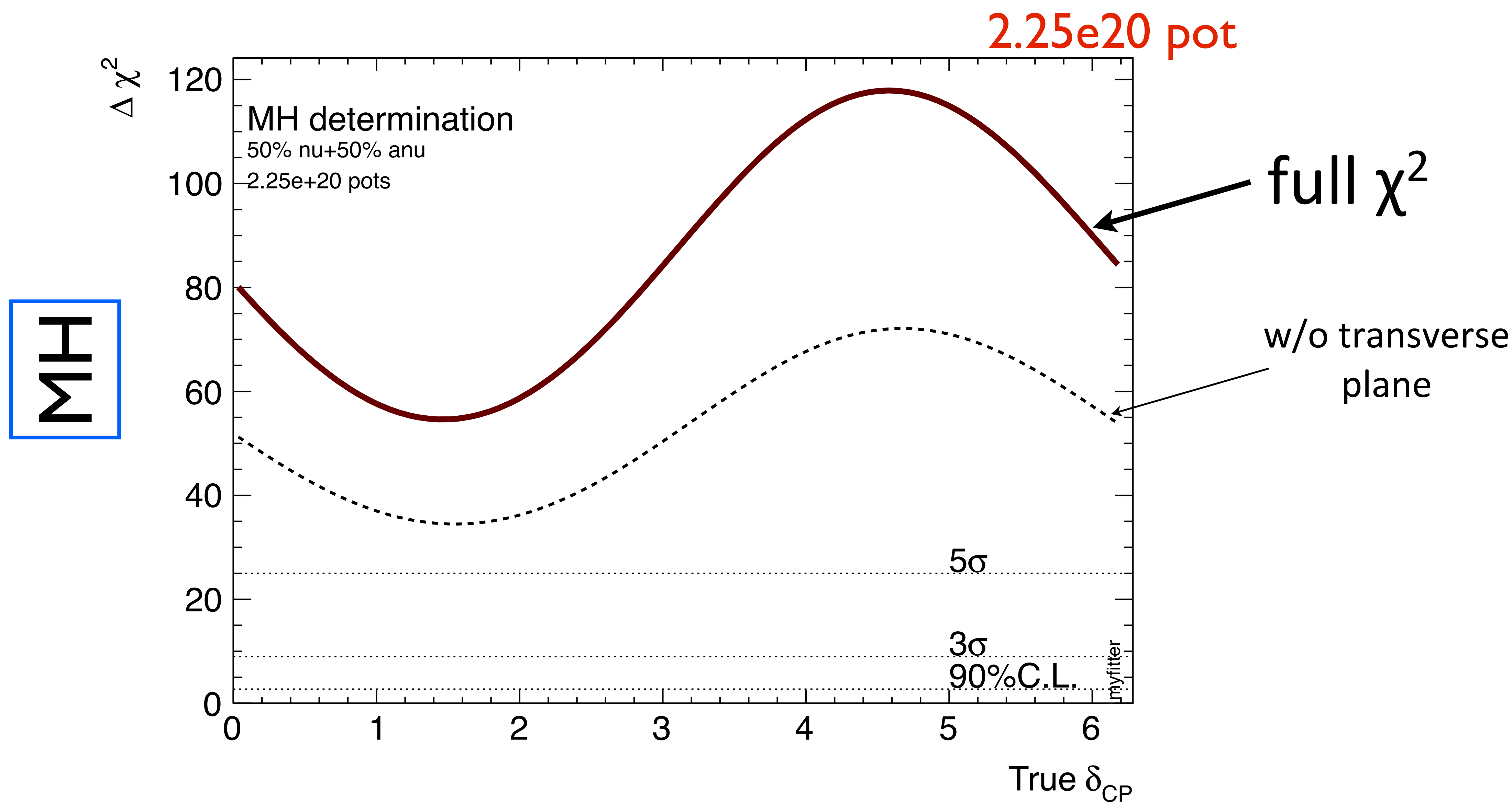
Systematic terms and their priors

$$\mathrm{n} = \left(1 \pm \frac{\mathrm{f}_\pm}{2}\right)\left((1+\mathrm{f_{sig}})\mathrm{n_{sig}} + (1+\mathrm{f_{NC}})\mathrm{n_{NC}} + (1+\mathrm{f}_{\nu_e})\mathrm{n}_{\nu_e} + (1+\mathrm{f}_{\nu_\tau})\mathrm{n}_{\nu_\tau}\right)$$

Syst. error on rates in bins of energy

Name	MH determination Error (1σ)	CP determination Error (1σ)
Bin-to-bin correlated:		
Signal normalization (f_{sig})	±5%	±5%
Beam electron contamination normalization ($f_{\nu_e CC}$)	±5%	±5%
Tau normalization ($f_{\nu_\tau CC}$)	±50%	±20%
ν NC and ν_μ CC background ($f_{\nu NC}$)	±10%	±10%
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	±5%	±5%
Bin-to-bin uncorrelated	±5%	±5%

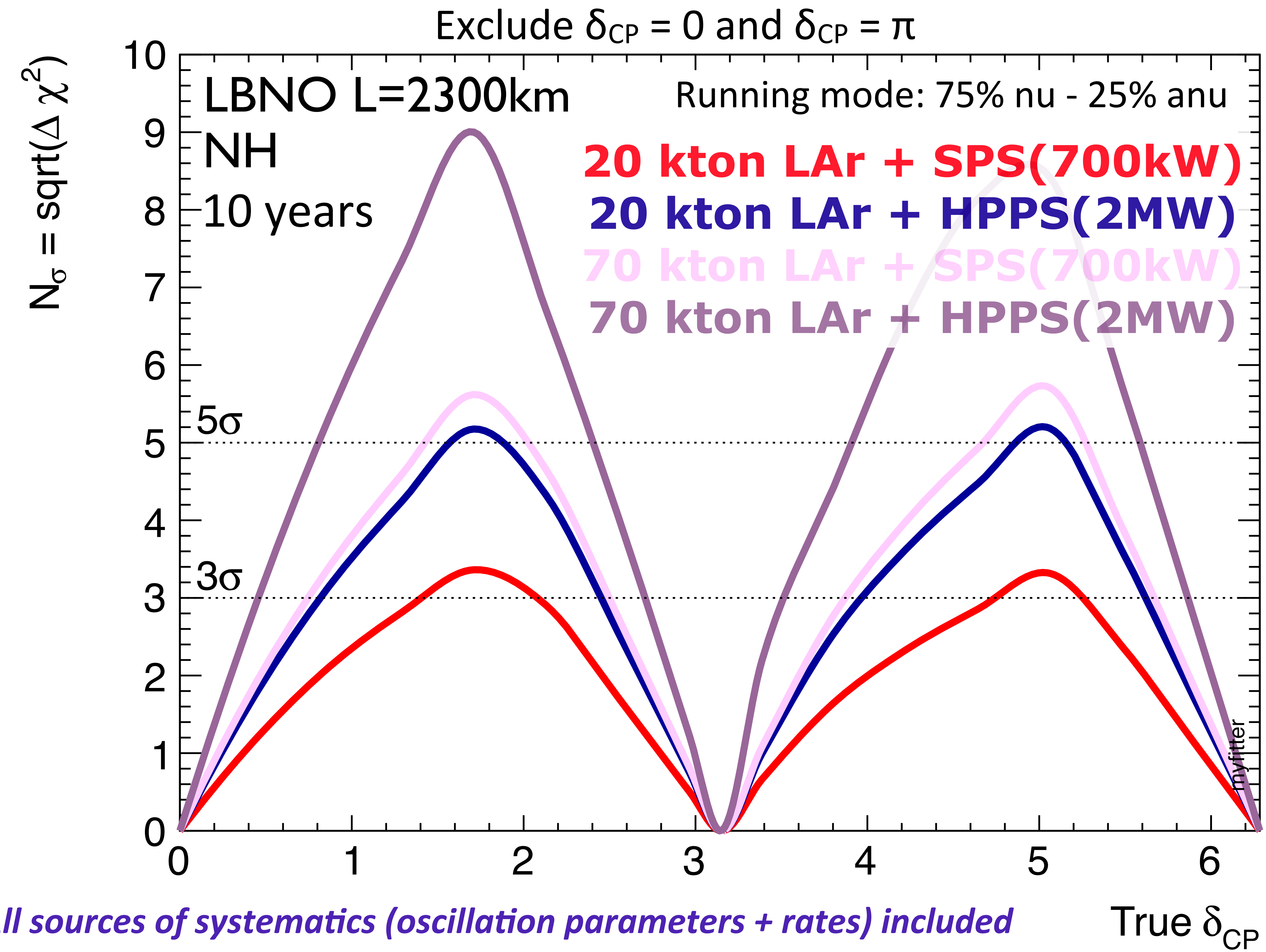
Sensitivity to mass hierarchy



Provide a >5σ direct determination of MH independent of the values of θ_{23} & δ_{CP} in ≈2 years of running

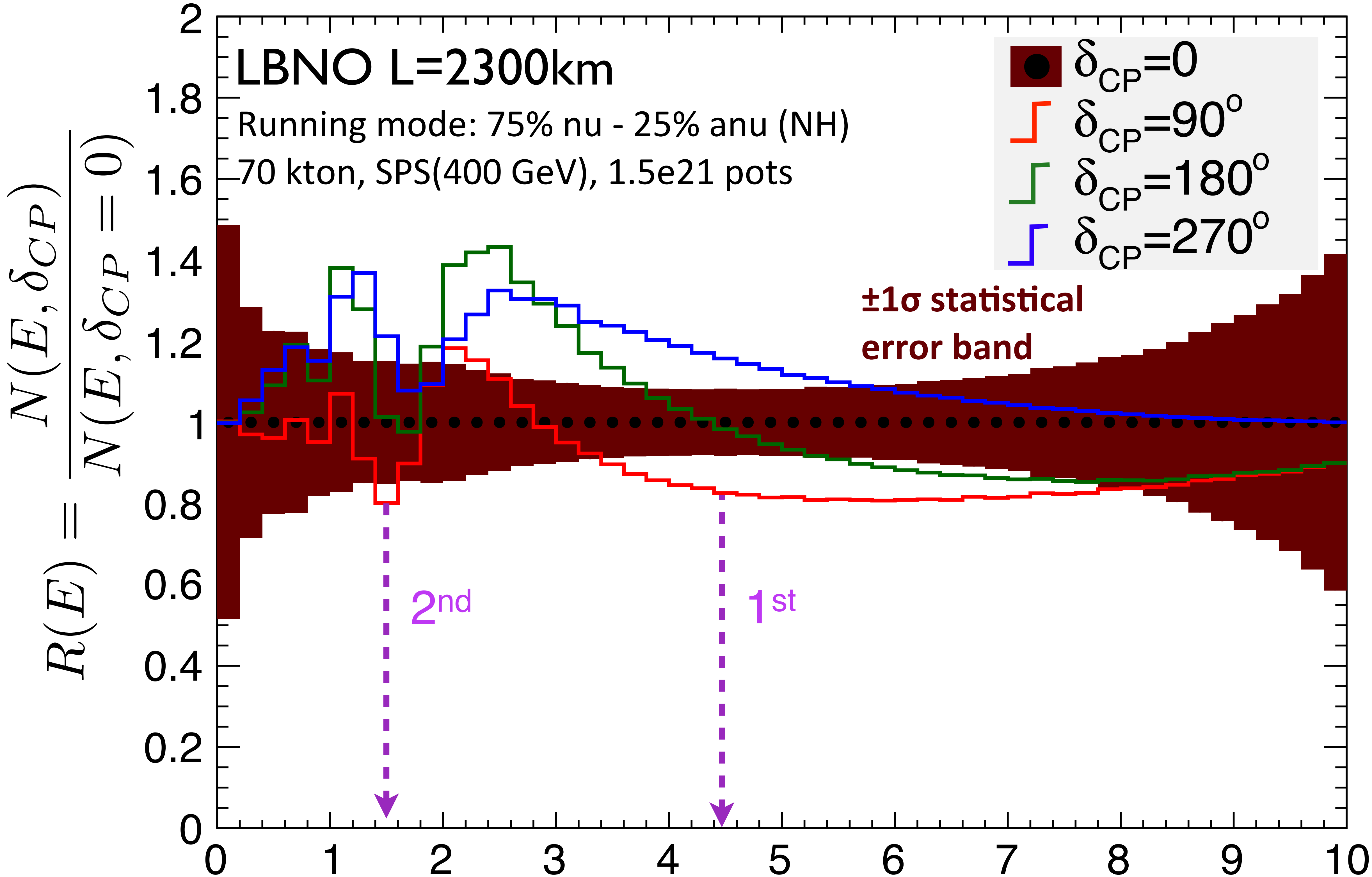
Other methods proposed (atmospheric neutrinos, reactors) do not provide such a level of sensitivity and could be prone to irreducible systematic errors

Sensitivity to CP violation



All sources of systematics (oscillation parameters + rates) included

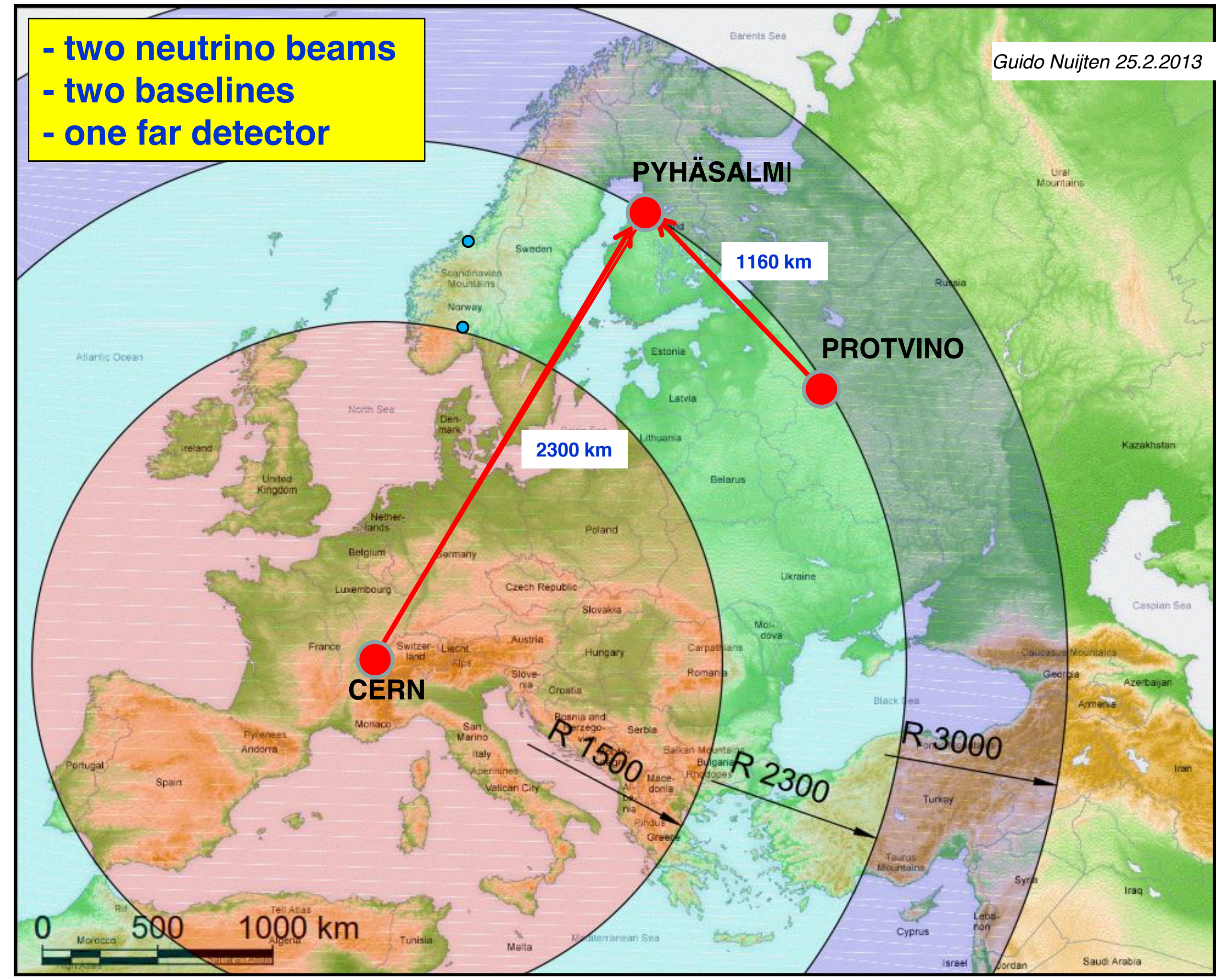
Sensitivity to CP violation: importance of low E region



The 1st maximum, although statistically significant, is rather featureless !

Possibility of neutrinos from Protvino

PRELIMINARY

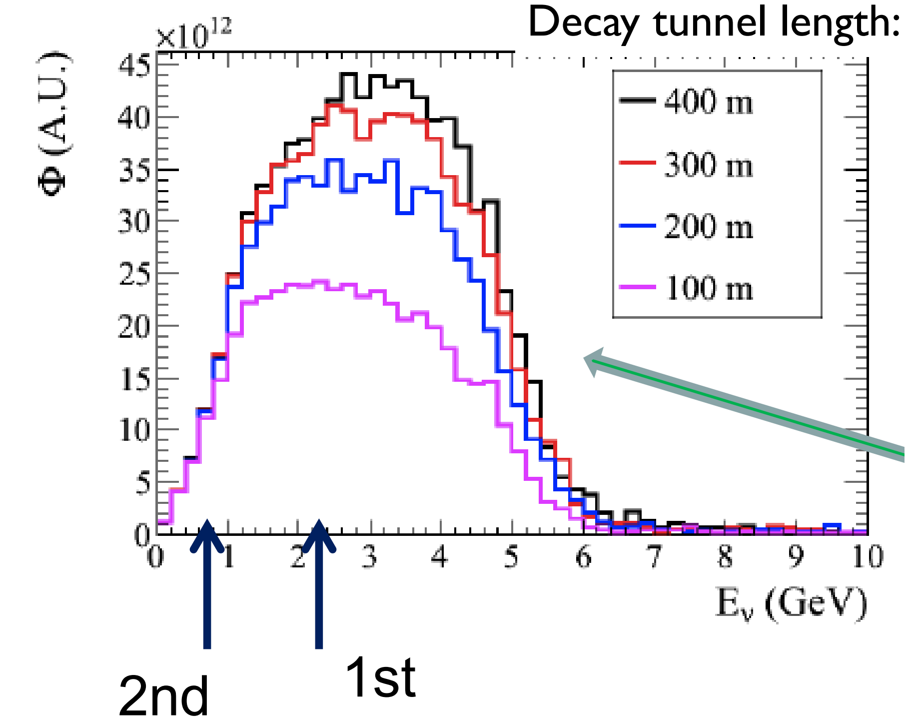


Desired parameters for neutrino beam:

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



Summary

- LAGUNA/LBNO is a project with a very rich and interesting physics program with fundamental discovery potential.
- Much progress has already been achieved in defining a very long baseline experiment in Europe. Although challenging, initial studies show that it offers unique and attractive possibilities.
- R&D efforts show promising prospects, with a focus now shifting to larger scale demonstrators (as suggested by CERN SPSC). Far and near detectors engineering has started. Detailed technical investigations are being pursued at the Pyhäsalmi mine. Detailed cost estimates for construction are being developed.
- Need more collaborators, more support from the community, local governments, funding agencies and CERN. The project is OPEN and is still being defined. In particular, we are open to interested groups wanting to join the 6x6x6m3 prototype effort.

LBNO Expression of Interest

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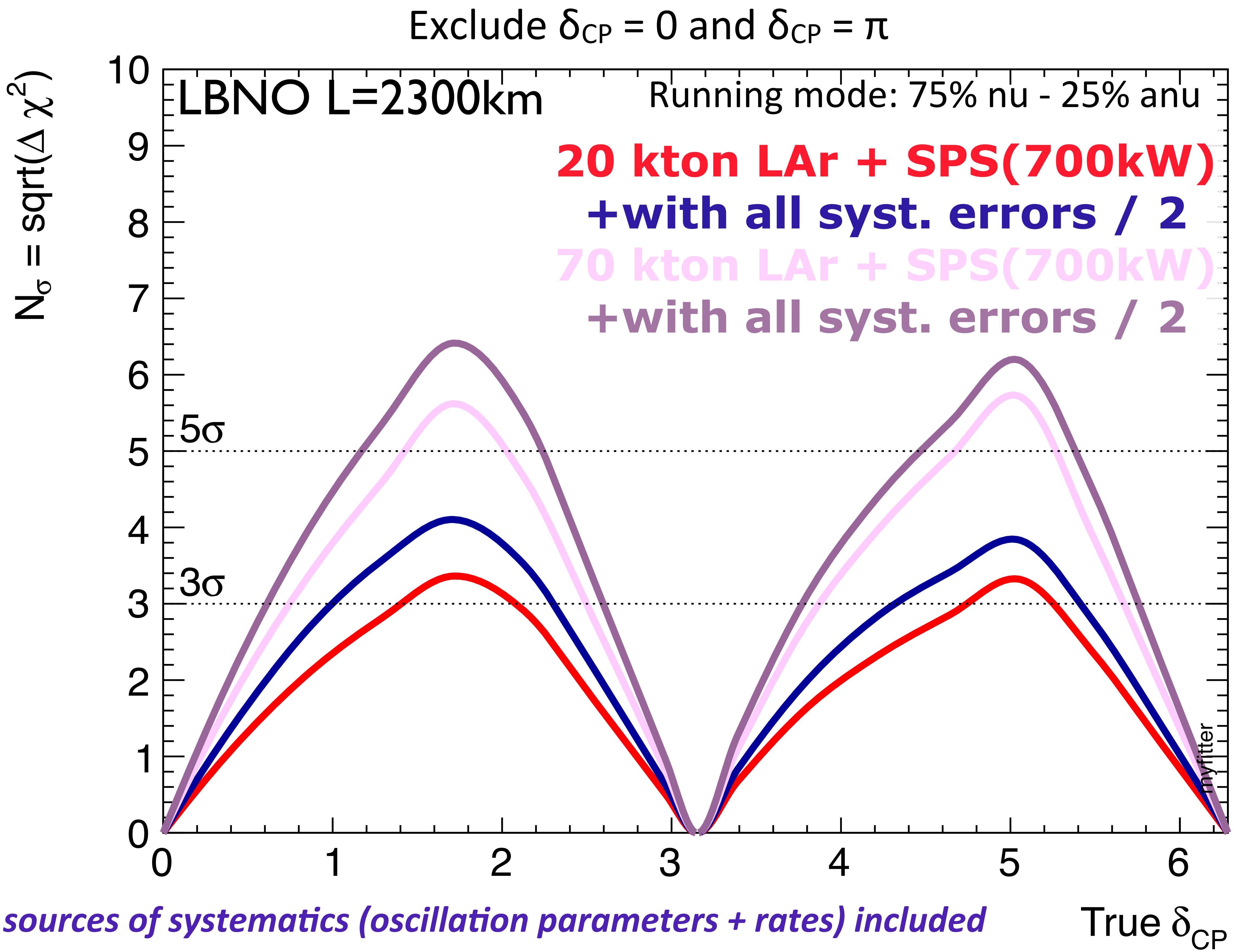
- The contributions of Anselmo Cervera are also recognized.

Backup slides

Courtesy PvZ

Sensitivity to CP violation: systematic errors



All sources of systematics (oscillation parameters + rates) included

LBNO cost estimate

Preparation underground + surface and excavation two full size LAr caverns + shaft and auxiliary infrastructure	**67 M€**

1st 20kT LAr tank + detector Cryogenic handling facility (full capacity) 2nd 50kT LAr tank + detector Total LAr procurement (quantity = 106kton)	**400 M€**

MIND 35kton magnetised detector: (based on EuroNU)	**230 M€**

Full LBNO far 70kton LAr + MIND 35kton: ~700 M€*

Cost of beam facility + Near Detector to be added

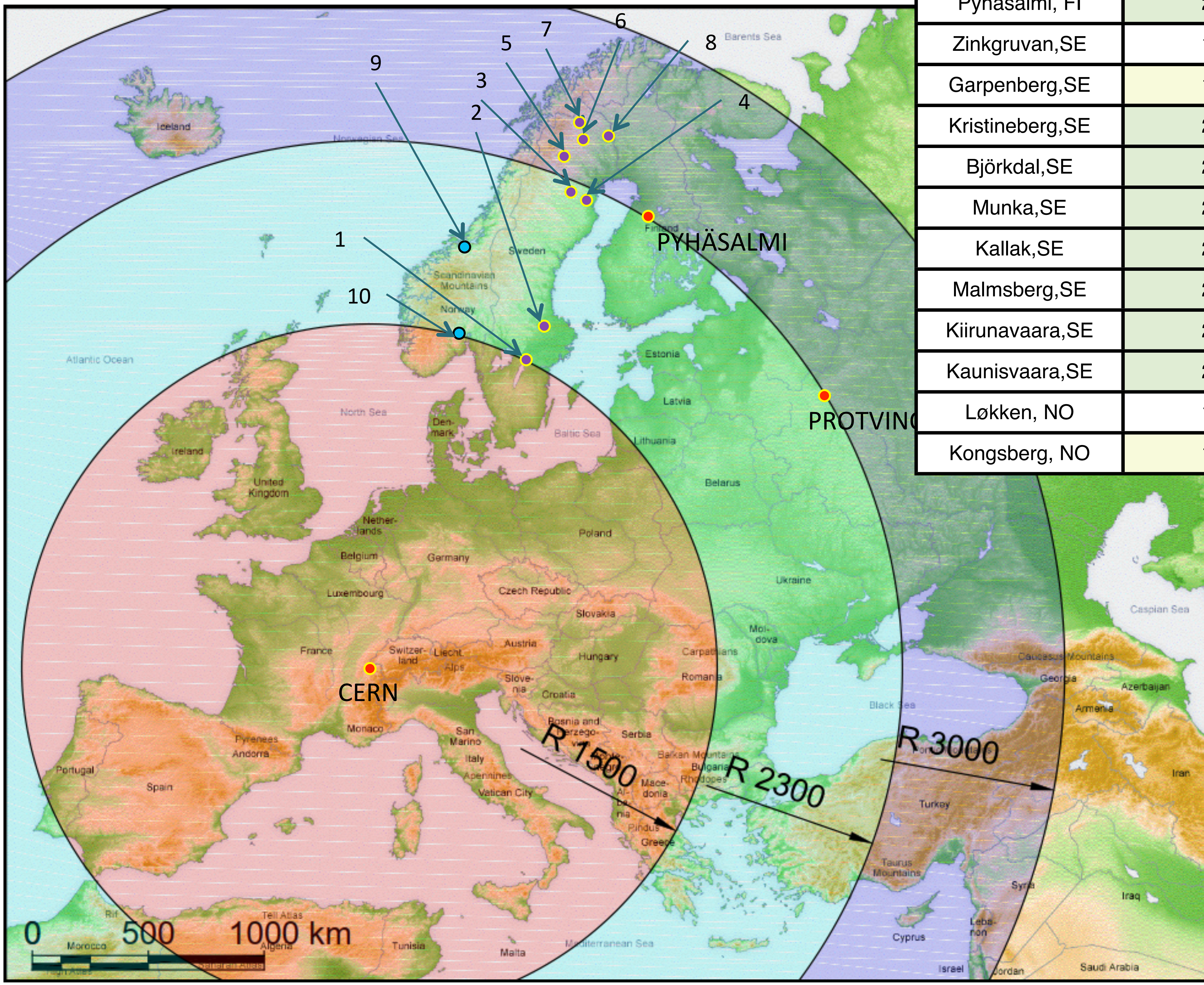
(*No contingency, no escalation)

Political situation in Finland

- When approached (by LAGUNA-LBNO) for a statement of support, the Finnish government stated that it could not commit to host the LAGUNA-LBNO project, partly because of the **high costs** and **limited predicted impact on economy and employment in Finland**.
- Some assumptions on which this was based were: The construction cost for the LAGUNA project is, according to the **initial estimates, 900-1600 million Euro**. The host country is expected to contribute a larger fraction of the costs than other countries. **It was assumed to be 20-50%**.
- The sharing expected from Finland seems to have been misinterpret and does not conform to the usual CERN model for funding experiments. **The cost does not correspond to the LBNO project submitted to CERN and is significantly overestimated.**
- The Finnish Government has previously indicated support for LAGUNA (regional government funded the site exploration, and a recent governmental committee of Finland put LAGUNA as one of the top projects to promote the development of the region). The Finnish education minister has stated in an newspaper interview that **the government could reconsider if it turned out that the situation was different than they had assumed**.
- The concerns that the Finnish government expressed are obviously serious, however a decision towards LAGUNA/LBNO will have to involve CERN actively and we believe that progress can still be made, so the LAGUNA collaboration has by no means given up on Pyhäsalmi.
- The collaboration has already explored other possible backup sites. **The Finnish statement has reignited the interest of several other nations to host LAGUNA.**

A first look at nearby mines...

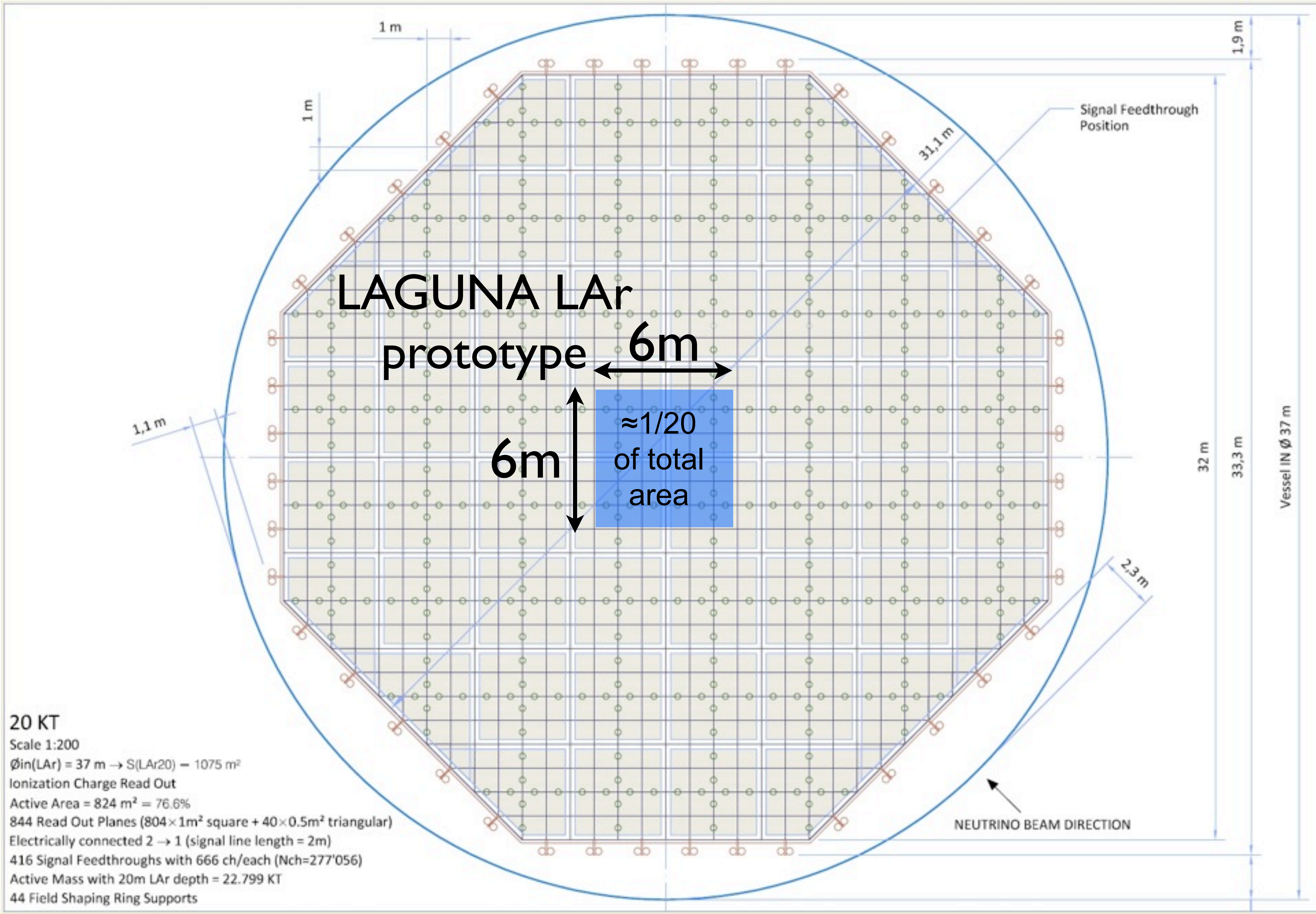
- LAGUNA/LBNO retains Pyhäsalmi as its **first choice** for far site



Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320
Kiirunavaara,SE	2530	1700	1380
Kaunisvaara,SE	2552	1580	1390
Løkken, NO	1536	1740	500
Kongsberg, NO	1900	1800	840

- The concerns that the Finnish government expressed are obviously serious, one cannot exclude that other sites with similar advantages need to be found.
- There are several mines nearby.
- See also talk by Tord Ekelof (next talk)

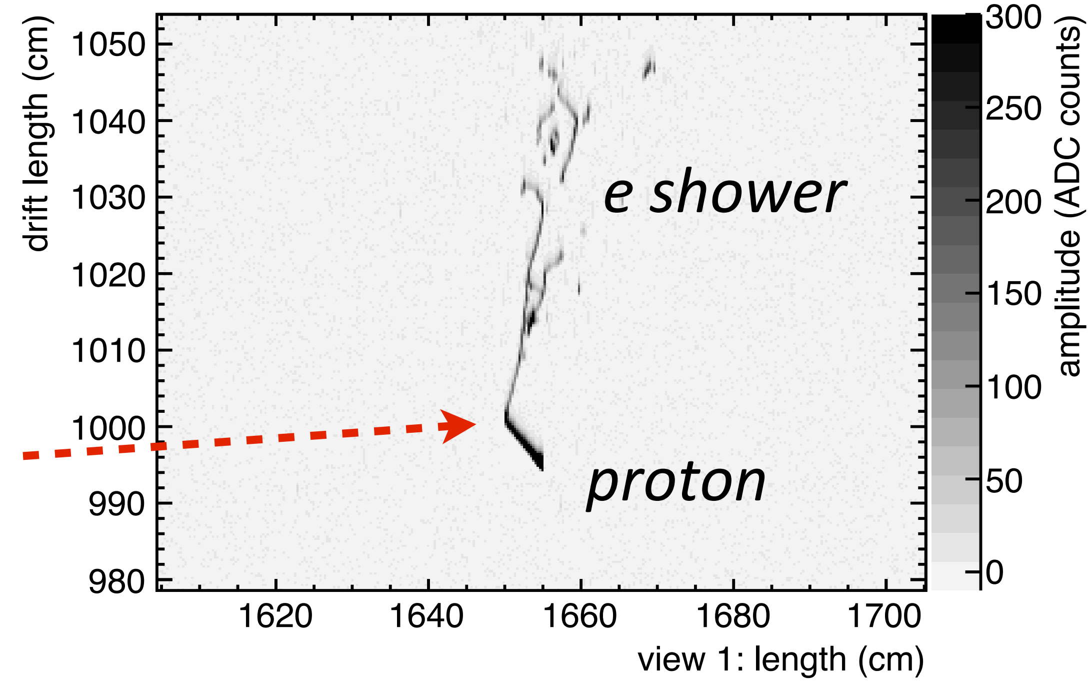
LAGUNA 6x6x6 m³ prototype compared to 20kton



Atmospheric neutrinos

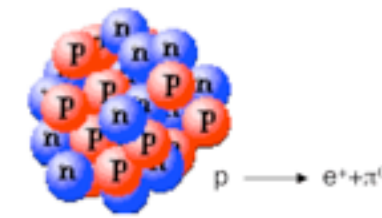
Mode	Events/20kt/yr
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

MC: ν_eCC



- **Neutrino oscillation physics complementary to long baseline beam**
- Clean ν_e & ν_μ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 ν_τ CC / year)

Proton decay sensitivity



For a 20kton exposure of 10 years (200 kton×year)

JHEP 0704 (2007) 041

Mode	Lifetime (90%C.L.)
$p \rightarrow \nu K^+$	**$>3\times10^{34}$ yrs**
$p \rightarrow e^+\gamma$, $p \rightarrow \mu^+\gamma$	**$>3\times10^{34}$ yrs**
$p \rightarrow \mu^-\pi^+K^+$	**$>3\times10^{34}$ yrs**
$n \rightarrow e^-K^+$	**$>3\times10^{34}$ yrs**
$p \rightarrow \mu^+K^0$, $p \rightarrow e^+K^0$	$>1\times10^{34}$ yrs
$p \rightarrow e^+\pi^0$	$>1\times10^{34}$ yrs
$p \rightarrow \mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n \rightarrow e^+\pi^-$	$>0.8\times10^{34}$ yrs

Expect ≈linear sensitivity improvement with exposure until 1000 kton×year

Supernova detection channels

For 20 kton and a SN explosion at the distance of 5 kpc:

JCAP 0310 (2003) 009
JCAP 0408 (2004) 001

$$\langle E_{\nu_e}\rangle = 11MeV, \langle E_{\bar{\nu}_e}\rangle = 16MeV, \langle E_{\nu_x}\rangle = \langle E_{\bar{\nu}_x}\rangle = 25MeV$$

		Events:
$\nu_e \; {}^{40}Ar \rightarrow e^- \; {}^{40}K^*$	(E_ν > 1.5 MeV)	≈23820
$\bar{\nu}_e \; {}^{40}Ar \rightarrow e^+ \; {}^{40}Cl^*$	(E_ν > 7.48 MeV)	≈2420
$\nu_x \; {}^{40}Ar \rightarrow \nu_x + \; {}^{40}Ar^*$		≈30440
$\nu_x \; e^- \rightarrow \nu_x \; e^-$		≈1330

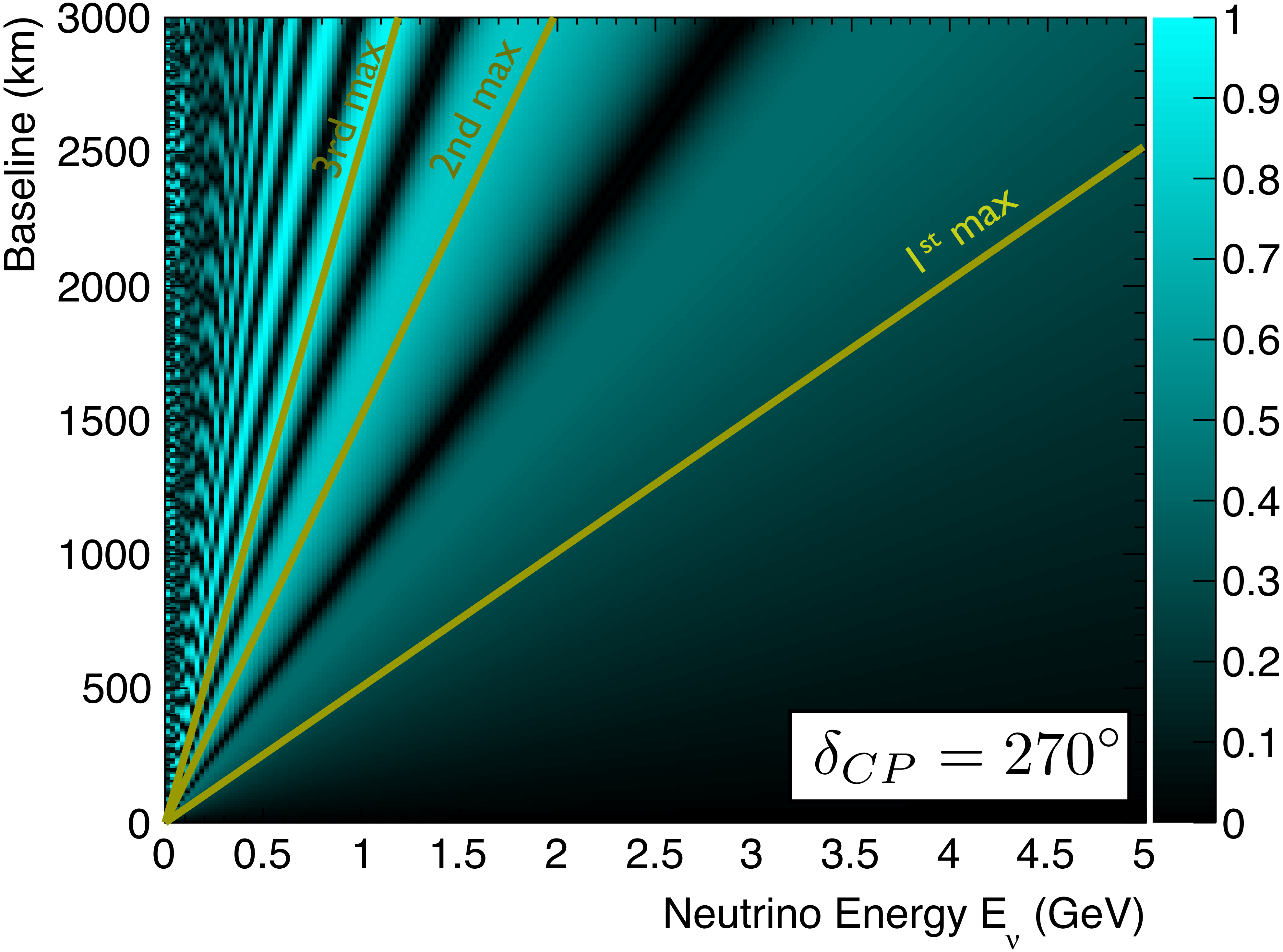
- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Combined analysis of all reaction modes
- Neutrino mass via TOF

CP-violation determination (CPV)

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

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

Normal mass hierarchy

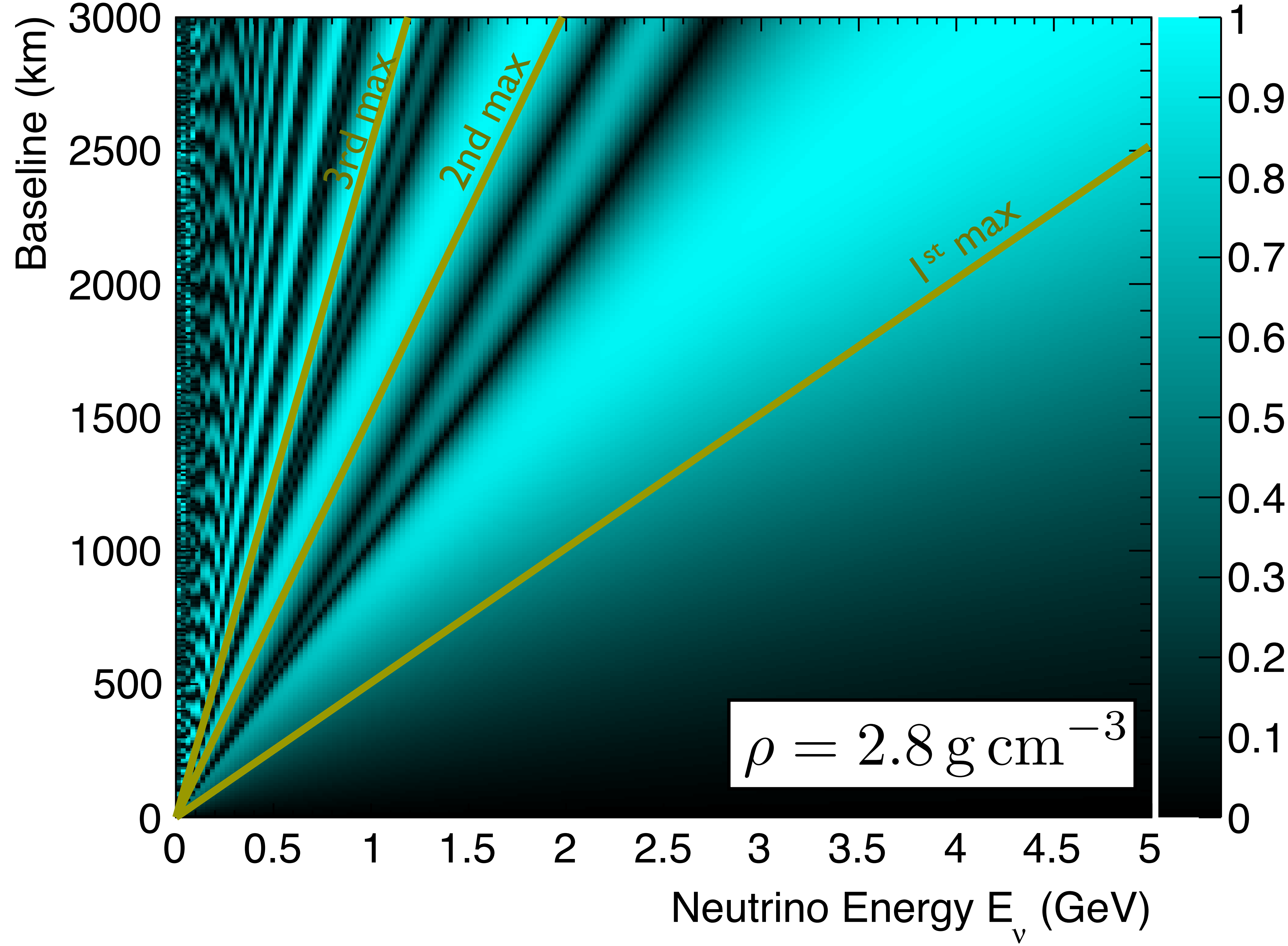


Mass hierarchy determination (MH)

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

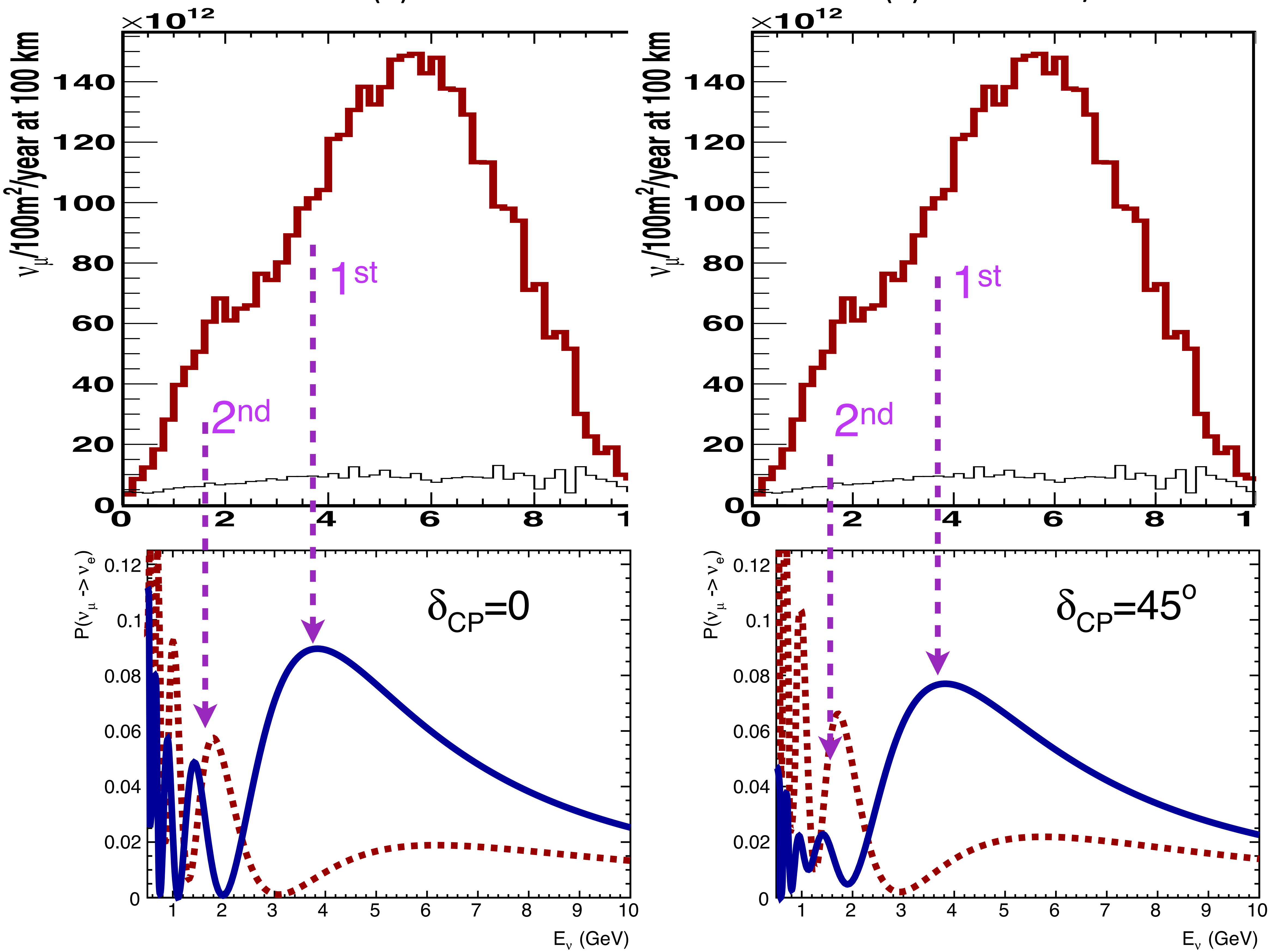
$\sin^2(2\theta_{13}) = 0.09$

Normal mass hierarchy



Flux optimisation

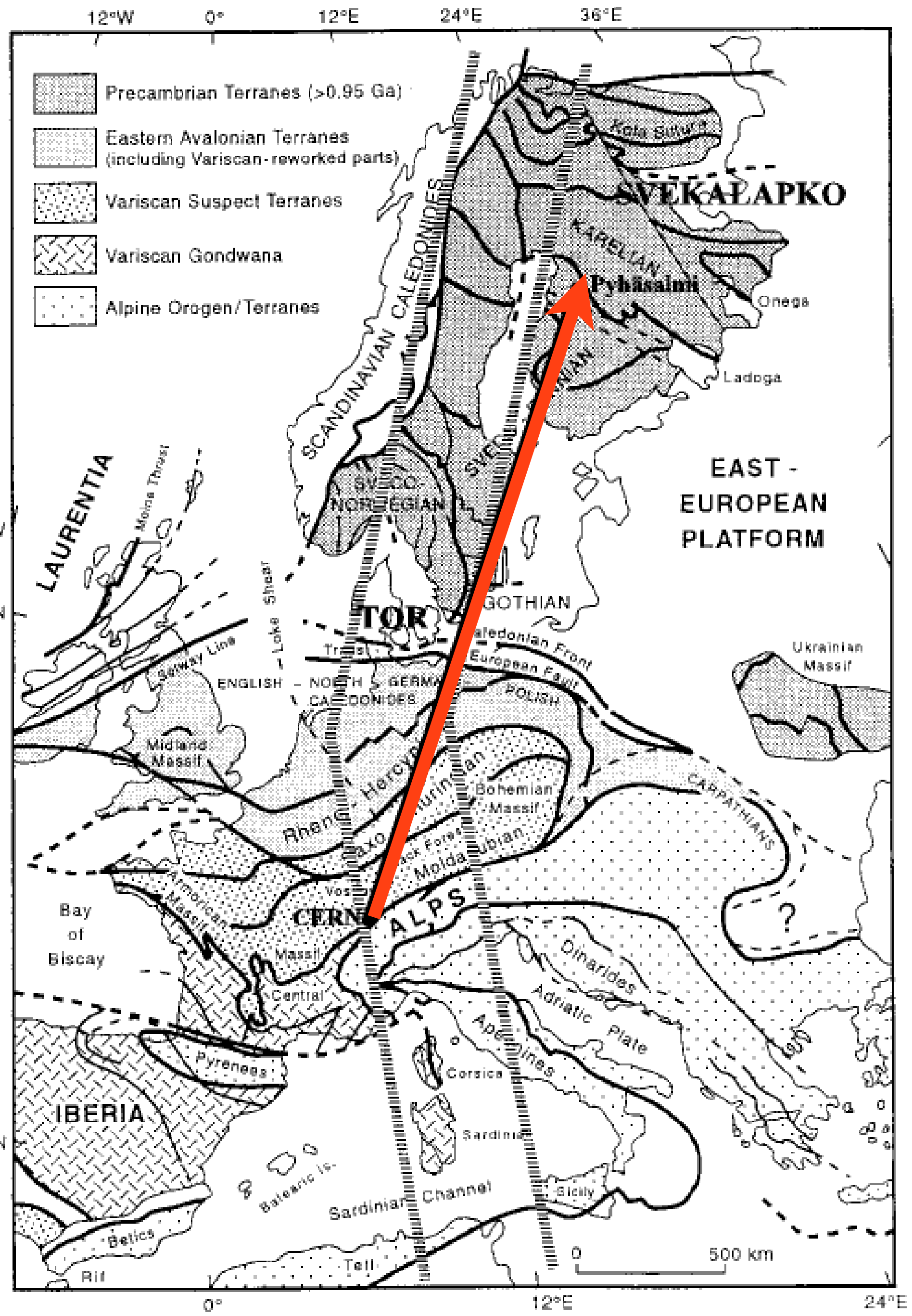
Maximize two conditions: (1) event rate at first maximum and (2) ratio of 2nd/1st maximum flux

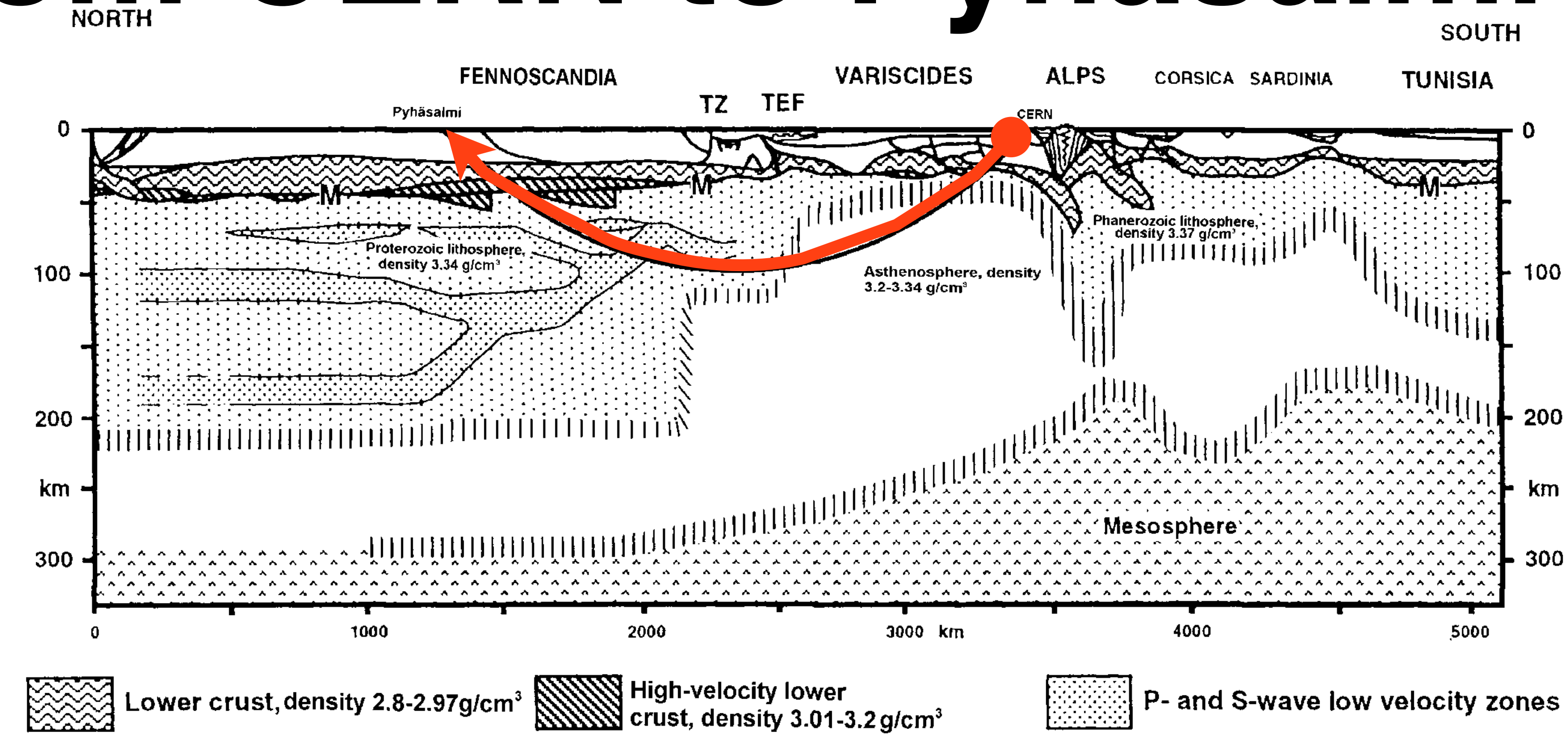


LAGUNA-LBNO, work in progress

Neutrinos from CERN to Pyhäsalmi

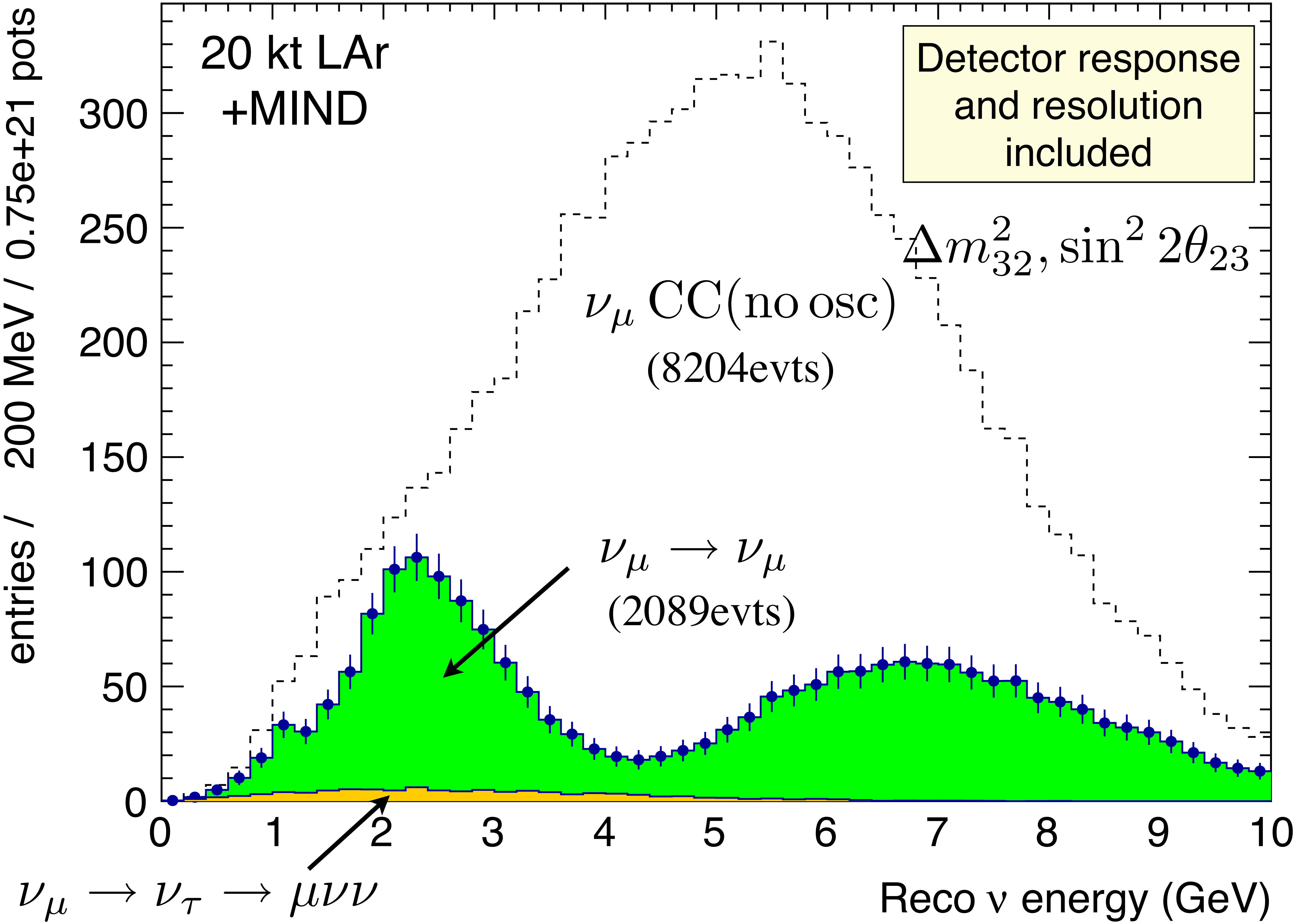
arXiv:hep-ph/0305042v1





- Distance CERN-Pyhäsalmi = 2288 km
- Deepest point = 103.8 km
- **Abundant geophysical data about crust and upper mantle available: largest part of the baseline is located within the study area of the European Geotraverse project (EGT), seismological EUROPROBE/TOR & SVEKALAPKO)**
- Densities = 2.4÷3.4 g/cm^3
- Remaining uncertainty has small effect on neutrino oscillations (equivalent to less than ±4% global change in matter density)

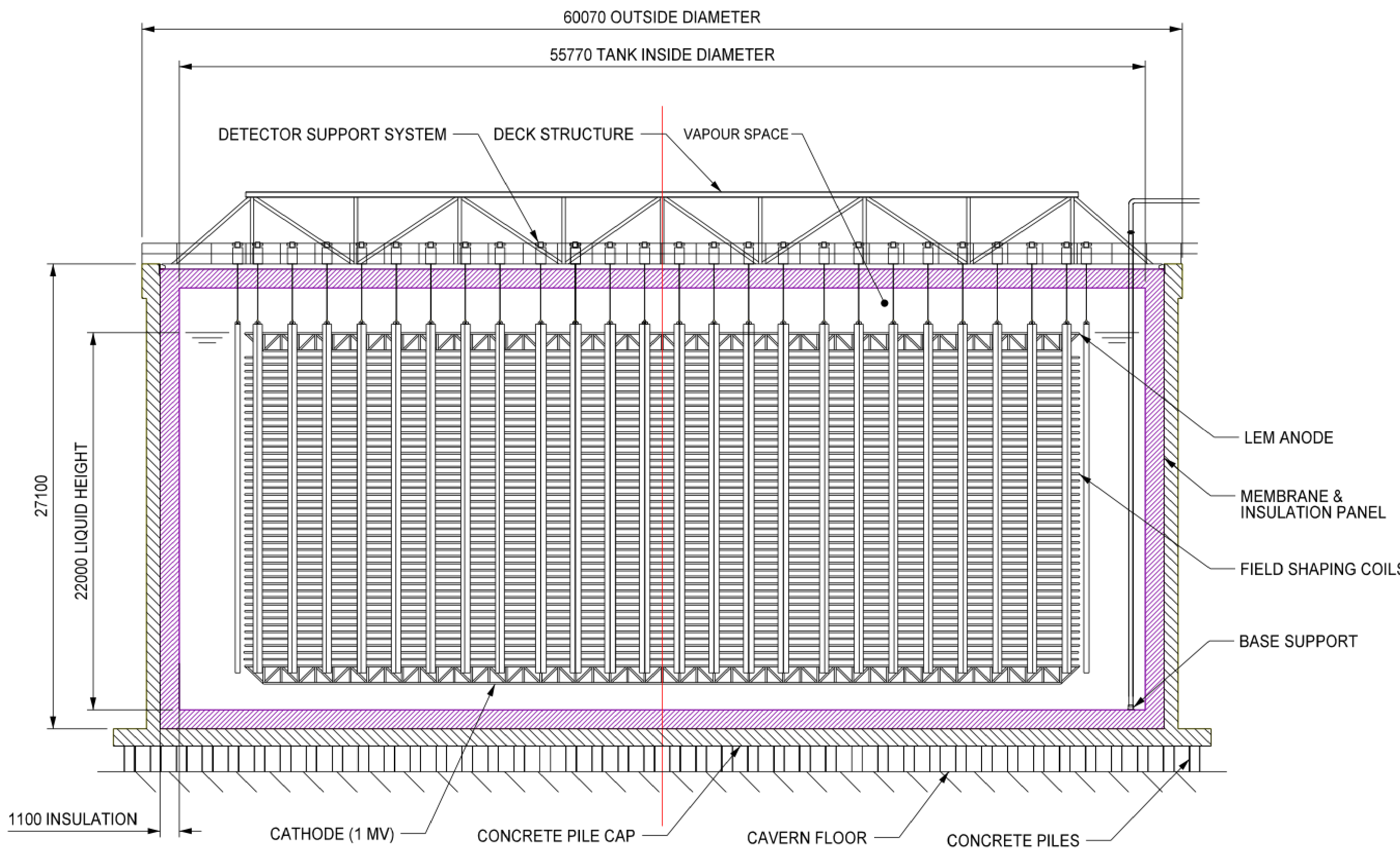
μ-like CC sample (+)



Membrane Tank (50 kton)

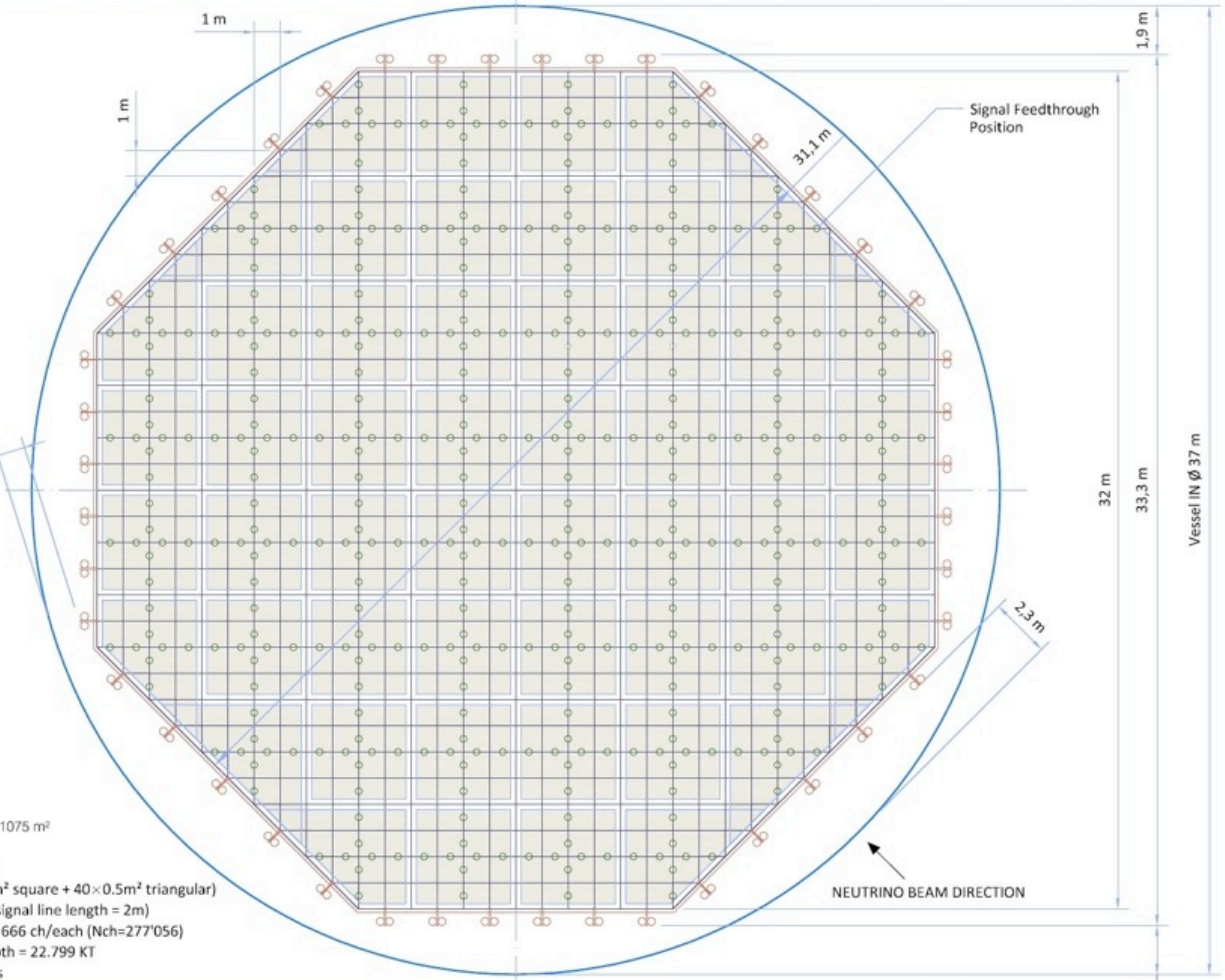
3.3.1 50 ktonne Membrane Tank

3.3.1.3 Tank Concept Design (Combined GST/Mk III LNGC Technologies



Combined GST/Mk III Concept Design for GLACIER LAr Membrane Tank

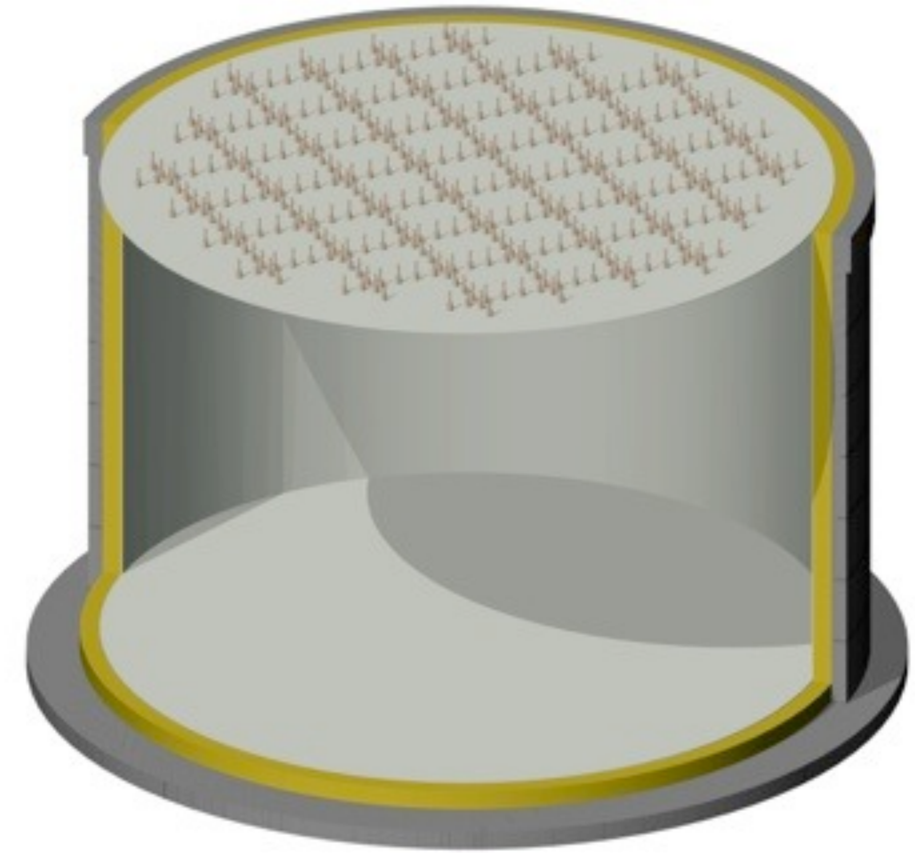
GLACIER charge readout layout

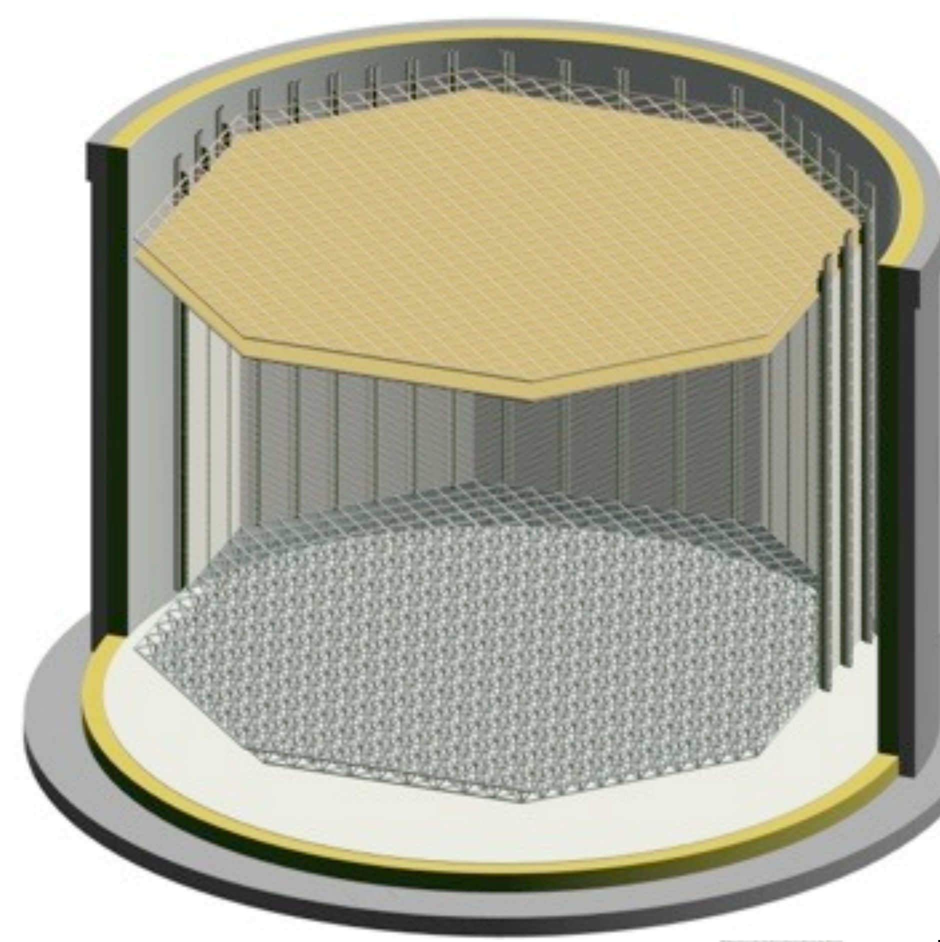


20 KT
Scale 1:200
Øin(LAr) = 37 m → S(LAr20) = 1075 m²
Ionization Charge Read Out
Active Area = 824 m² = 76.6%
844 Read Out Planes (804×1m² square + 40×0.5m² triangular)
Electrically connected 2 → 1 (signal line length = 2m)
416 Signal Feedthroughs with 666 ch/each (Nch=277'056)
Active Mass with 20m LAr depth = 22.799 KT
44 Field Shaping Ring Supports

Scaling detector parameters

	20 KT	50 KT	100 KT
Liquid argon density at 1.2 bar [T/m^3]	1.38346		
Liquid argon volume height [m]	22		
Active liquid argon height [m]	20		
Pressure on the bottom due to LAr [T/m^2]	30.4 (≡ 0.3 MPa ≡ 3 bar)		
Inner vessel diameter [m]	37	55	76
Inner vessel base surface [m^2]	1075.2	2375.8	4536.5
Liquid argon volume [m^3]	23654.6	52268.2	99802.1
Total liquid argon mass [T]	32525.6	71869.8	137229.9
Active LAr area (percentage) [m^2]	824 (76.6%)	1854 (78%)	3634 (80.1%)
Active (instrumented) mass [KT]	22.799	51.299	100.550
Charge readout square panels (1m×1m)	804	1824	3596
Charge readout triangular panels (1m×1m)	40	60	72
Number of signal feedthroughs (666 channels/FT)	416	1028	1872
Number of readout channels	277056	660672	1246752
Number of PMT (area for 1 PMT)	804 (1m×1m)	1288 (1.2m×1.2m)	909 (2m×2m)
Number of field shaping electrode supports (with suspension SS ropes linked to the outer deck)	44	64	92





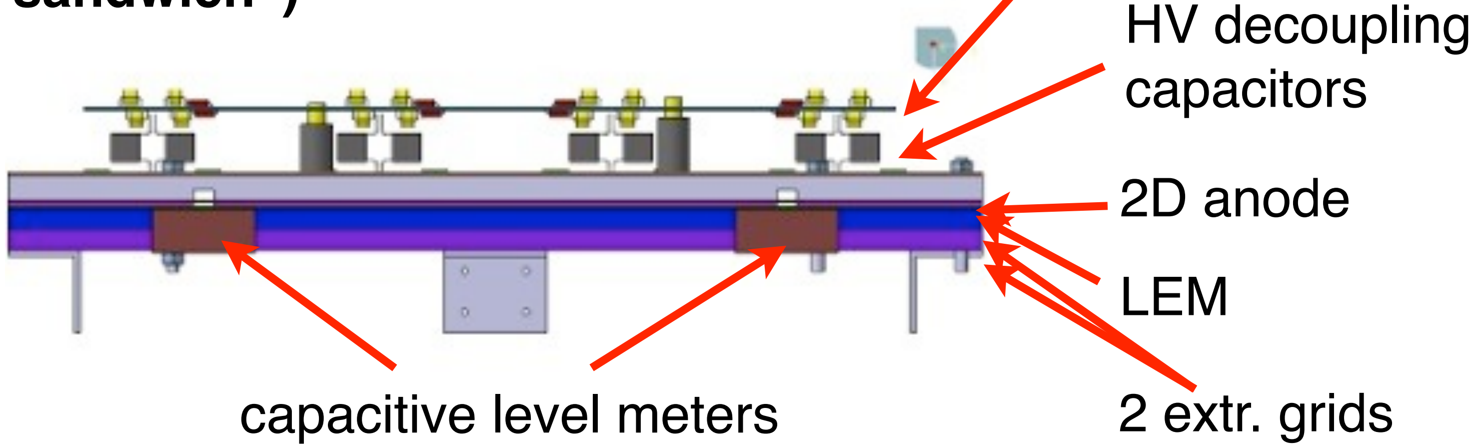
GLACIER charge readout

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

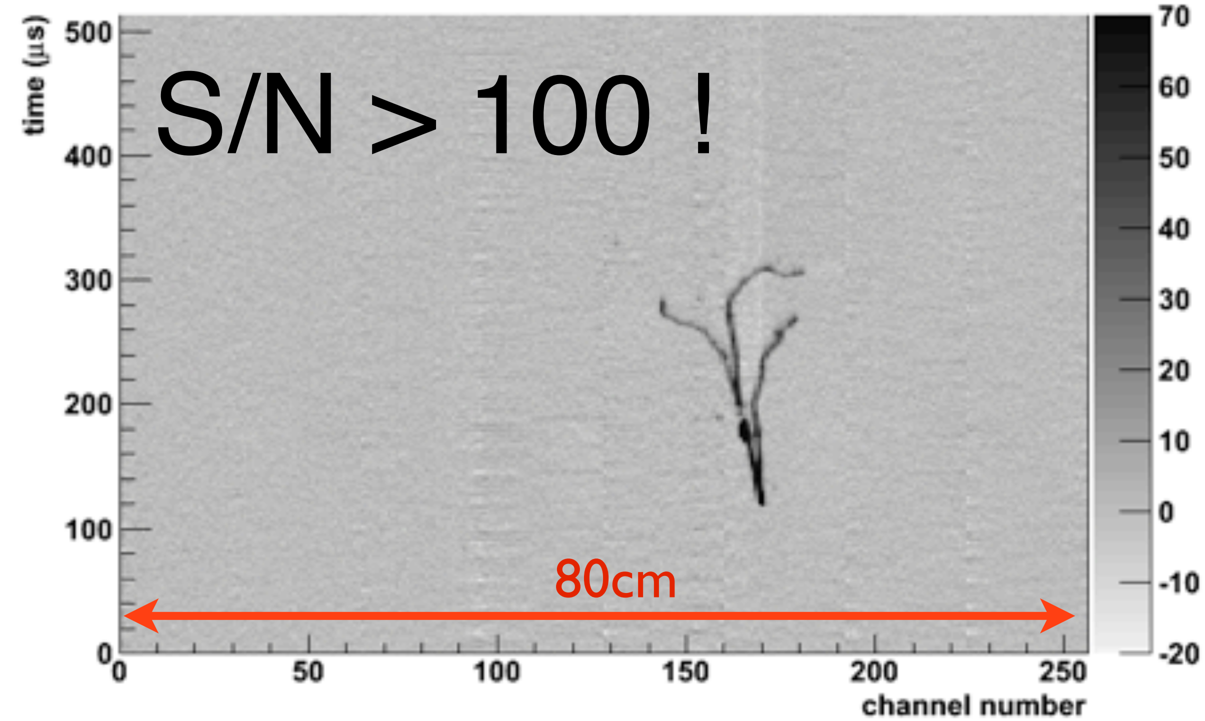
★ Novel double phase LAr LEM-TPC readout:

- 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!!**

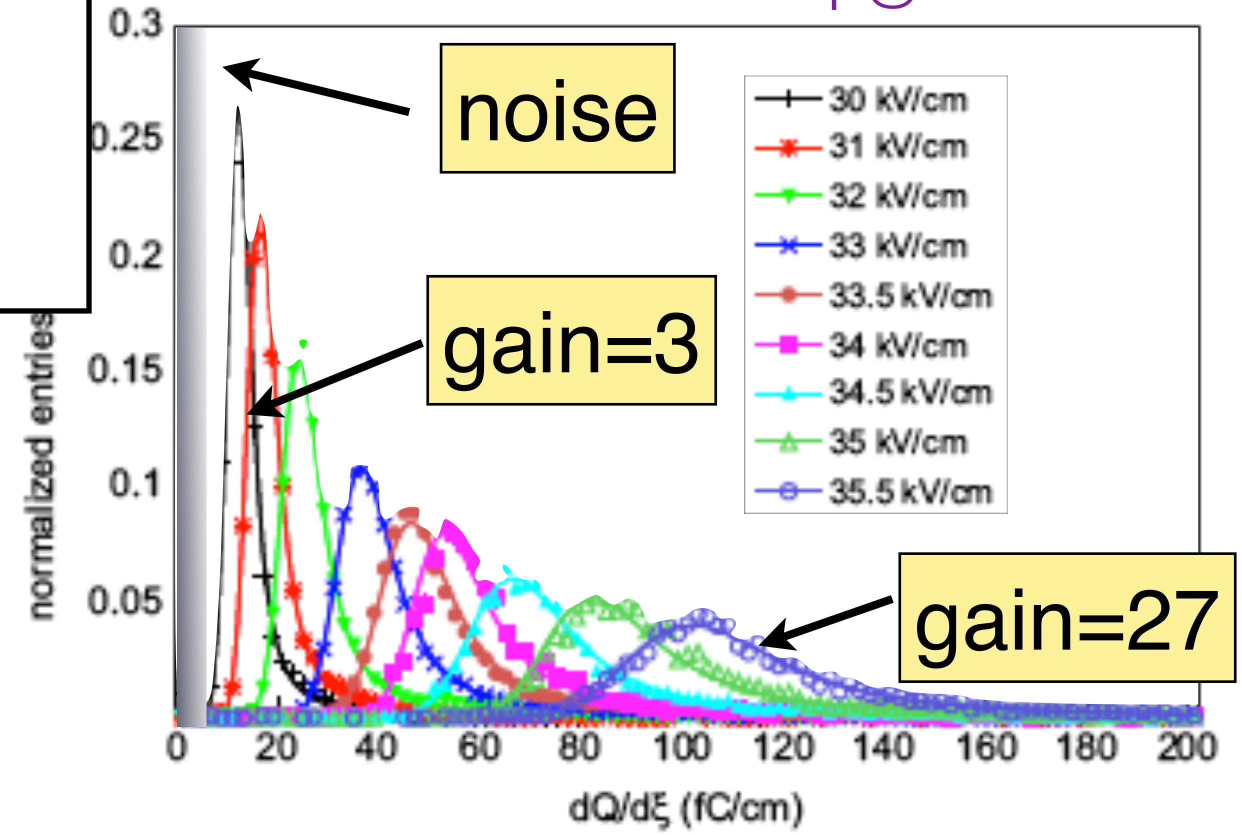
Design of a compact, robust and scalable readout cassette ("sandwich")



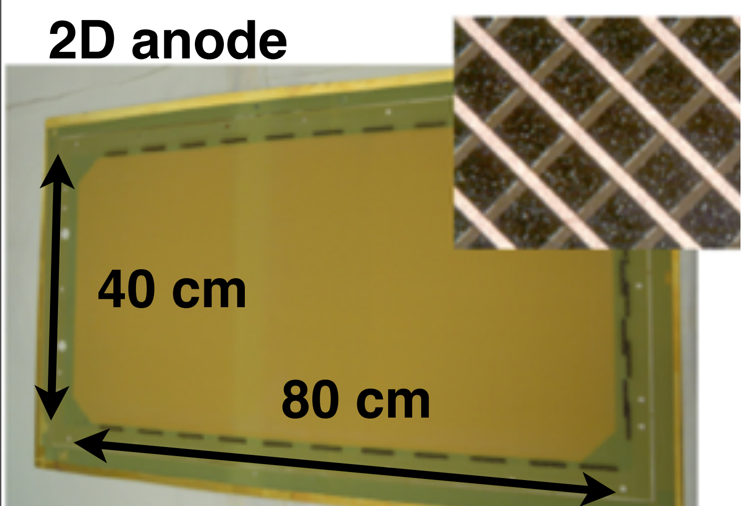
Cosmic Data from 40x80cm^2 LAr LEM TPC@CERN-ETHZ



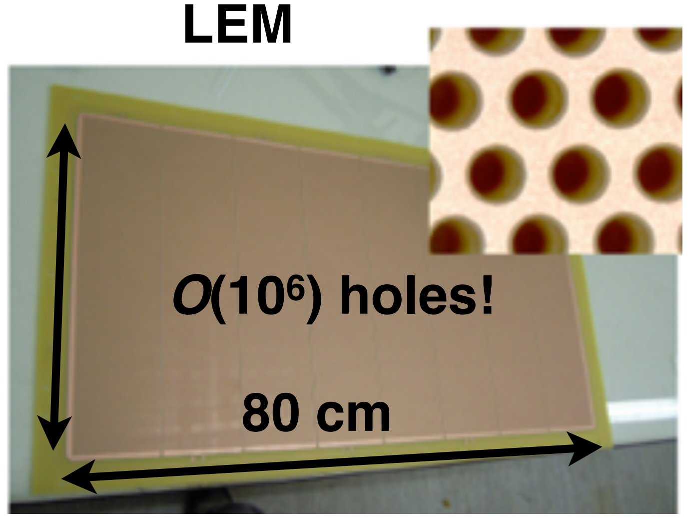
Landau distribution fitted to dE/dx distributions of muons on 3L LAr LEM-TPC setup @ CERN-ETHZ



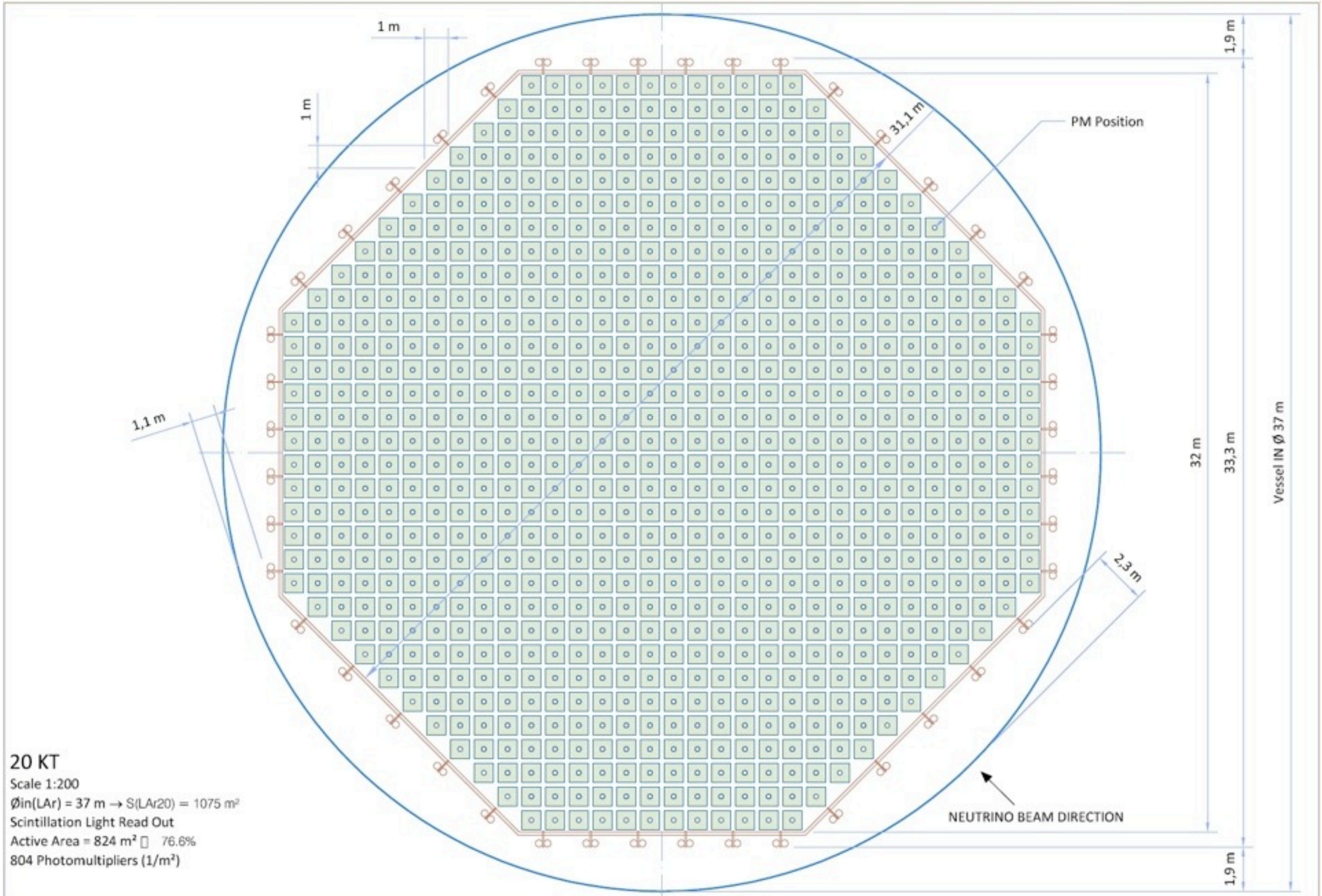
2D anode



LEM

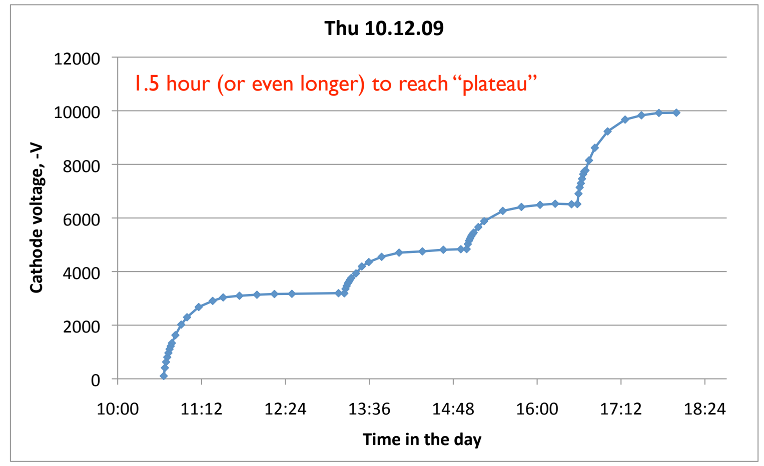


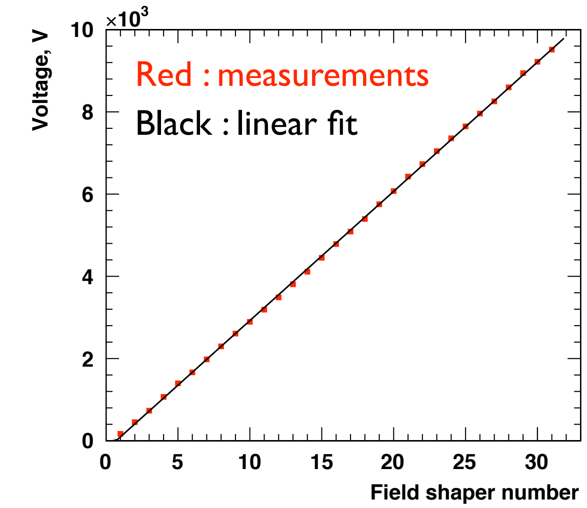
GLACIER light readout layout



Drift high voltage multiplier

J.Phys.Conf.Ser. 308 (2011) 012027
arXiv:1204.3530 [physics.ins-det]





Extrapolation to long drift

Extrapolation of the ArDM design

Changing Cs for fixed Cp = 2.35 pF and Vpp-in = 2E = 2.5 kV

		ArDM				
Drift length	m	1.24	5	10		20
Total output voltage for 1 kV/cm	V	124k	500k	1M		2M
Input voltage Vpp-in = 2E	V	820	2.5k	2.5k	$\times\sqrt{2}$	3.5k
Shunt capacitance, Cp	F	2.35p	2.35p	2.35p	$\times 1/2$	1.18p
Capacitor	F	328/164n	475n	1.90μ		1.90μ
Number of stages, N	–	210	319	638		903
N per 10 cm	–	16.9	6.38	6.38		4.51
Total capacitance	F	125μ	303μ	2.43m		3.43m
Capacitance per 10 cm	F	10.4μ	5.99μ	24.3μ		17.2μ
Total stored energy	J	21.7	948	7.58k		21.5k

Actual ArDM parameters are given just for comparison.

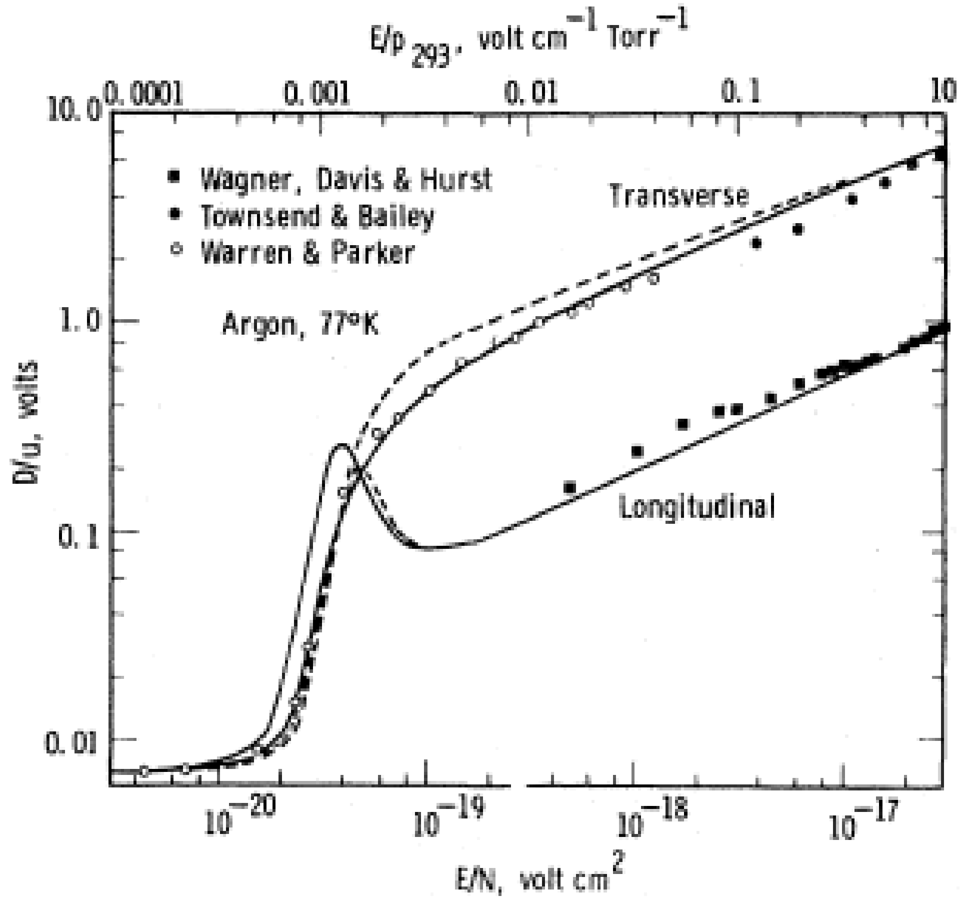
For extrapolation, 2γN = 1.42 is always assumed.

LAr vaporization heat 160 kJ/kg

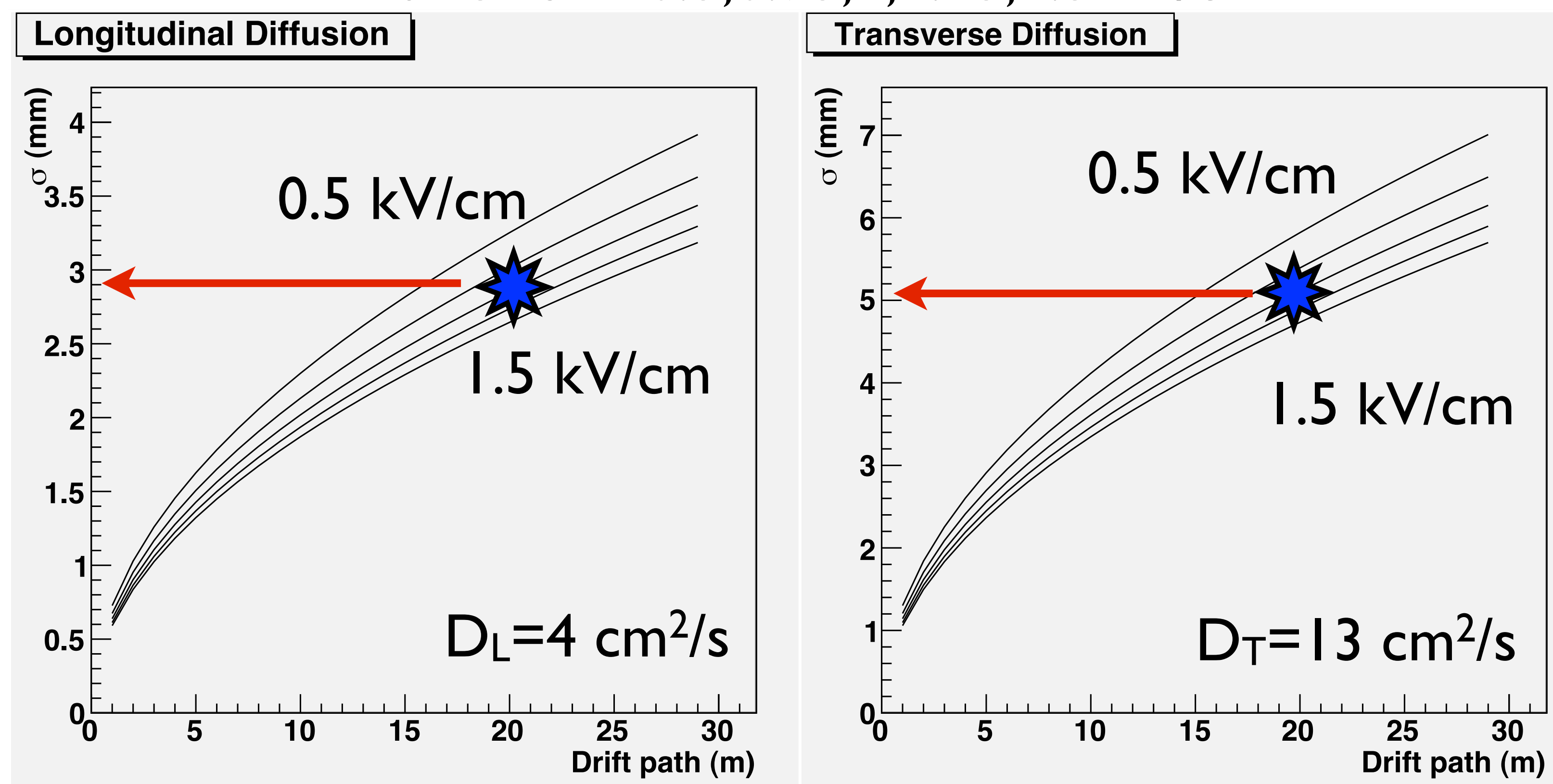
$$V_{\mathrm{max}} = \frac{E}{\gamma}, \quad \gamma \approx \sqrt{\frac{C_{\mathrm{p}}}{C_{\mathrm{s}}}}$$

Electron cloud diffusion

- ★ The physical limit to long drifts is determined by diffusion ➠ likely 20m !



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



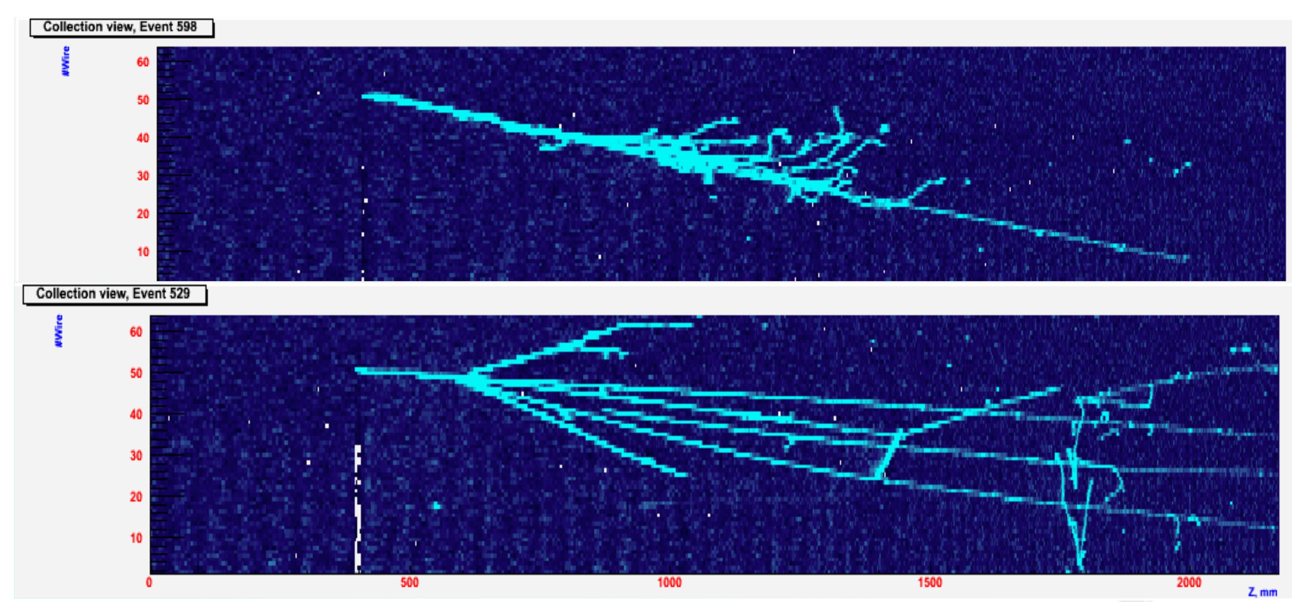
- ★ Diffusion coefficients not well known (in particular for transverse diff.):
  - after 20 m drift: transverse diffusion ≈ **5mm**, longitudinal diffusion ≈ **3mm**
- ★ New measurements:

•ArgonTube (Bern University)

-tracks >4 m length observed !

-lifetime ≈ 2ms after 24hrs

•5m drift (UCLA)

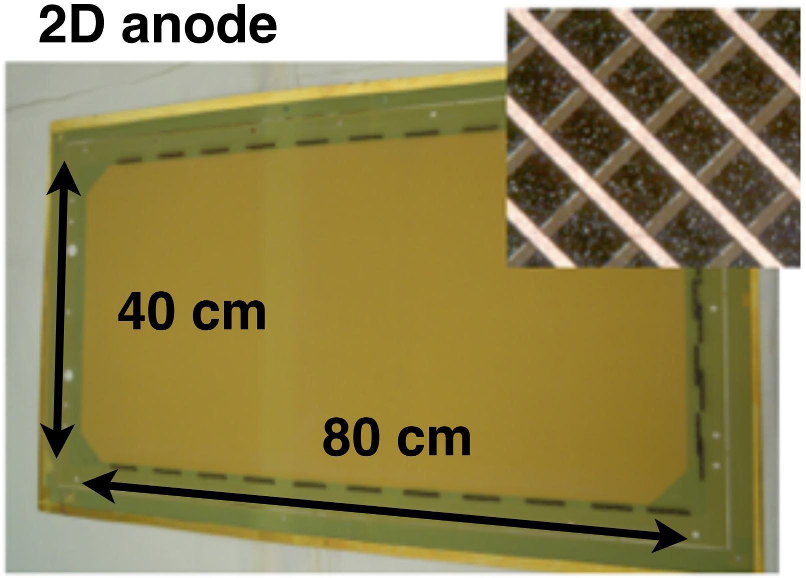


Courtesy I. Kreslo

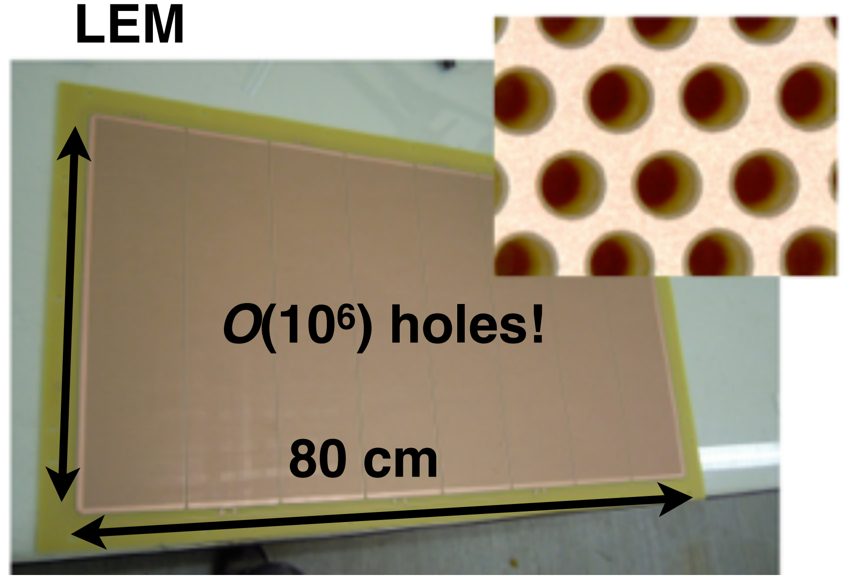
LAr-LEM TPC@CERN: Production of a 40x80 cm^2 charge readout sandwich

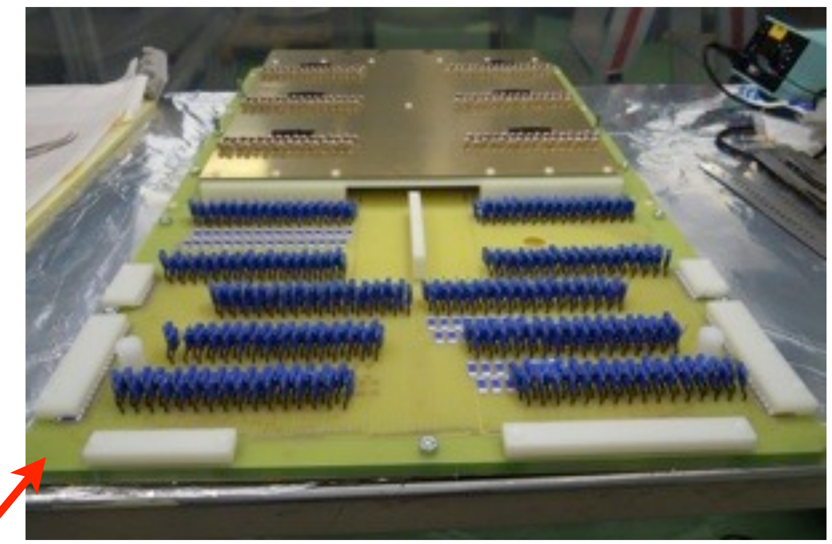
- After successful test of LEM and 2D anode in the 3L setup we designed and produced a 40x80 cm^2 charge readout for a new 250L LAr LEM-TPC (production and assembling finished by summer 2011)
- The ArDM cryostat @CERN was used for a first test of the new charge readout system

2D anode



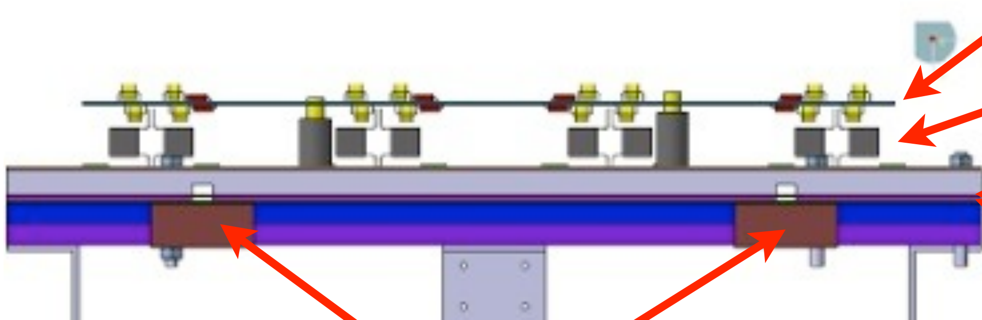
LEM





- Manufacturer: CERN TS/DEM group and ELTOS company (Italy)
- Largest LEM/THGEM and 2D readout ever produced!!!

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



signal coll. plane

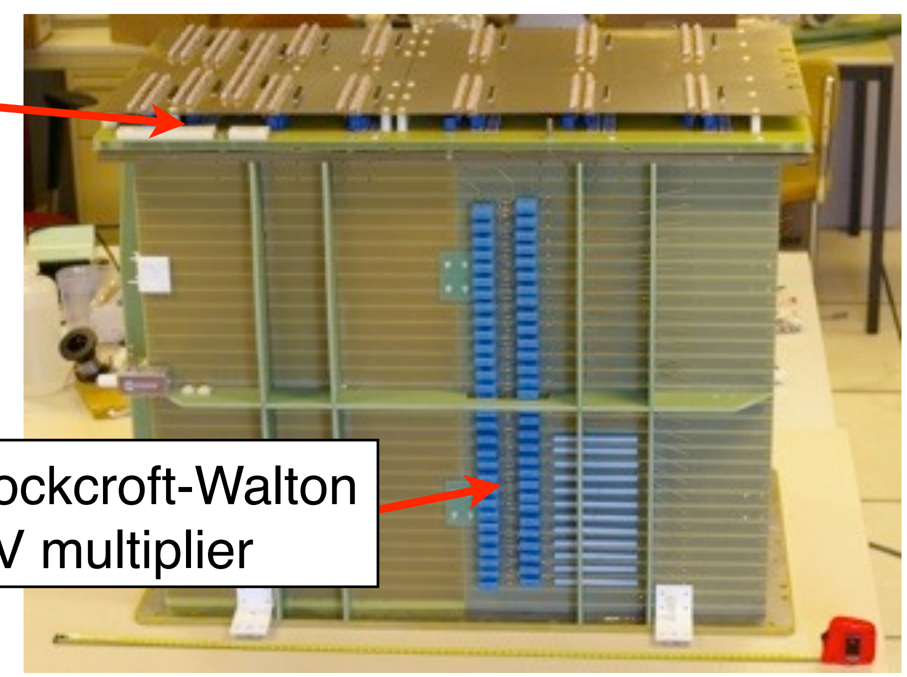
HV decoupling capacitors

2D anode

LEM

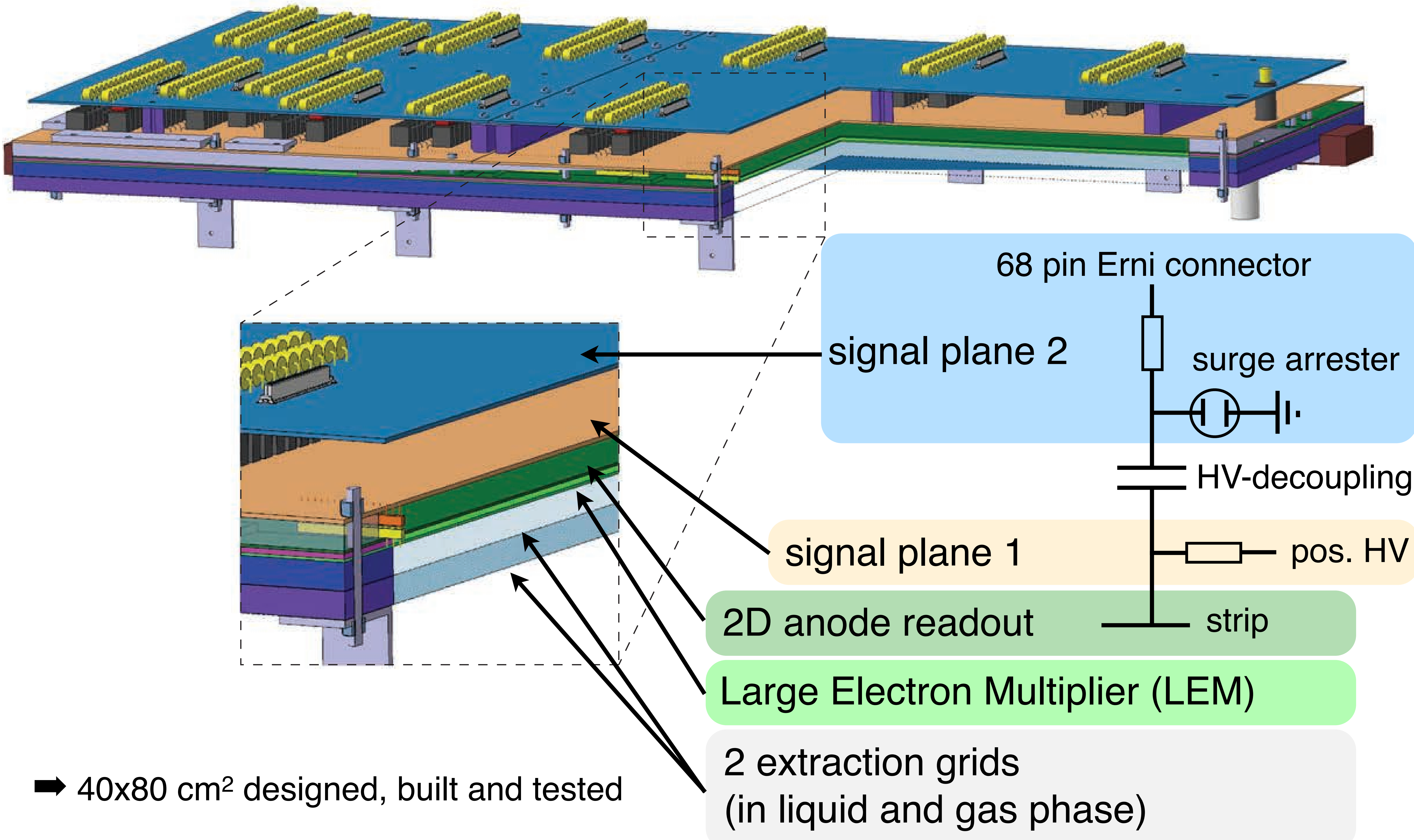
2 extr. grids

capacitive level meters



Cockcroft-Walton HV multiplier

Charge readout sandwich

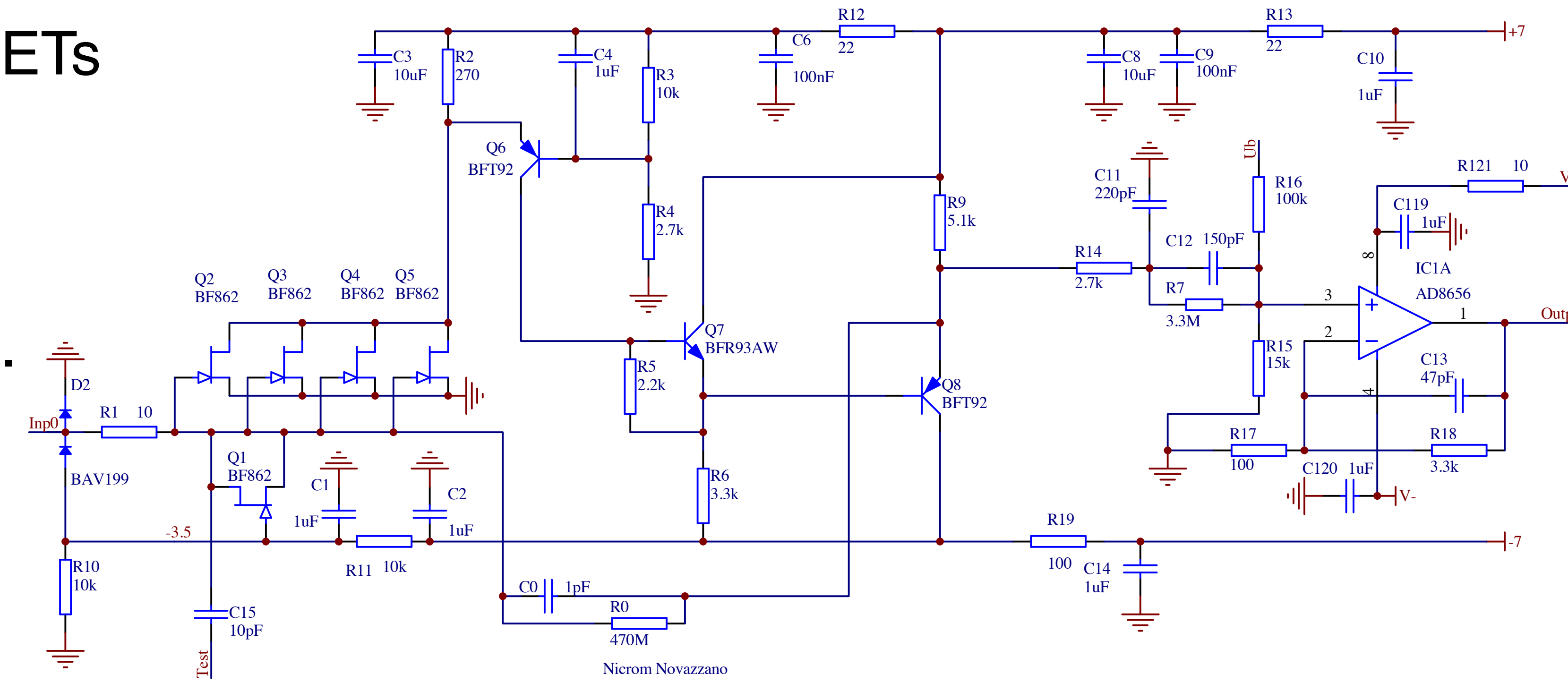


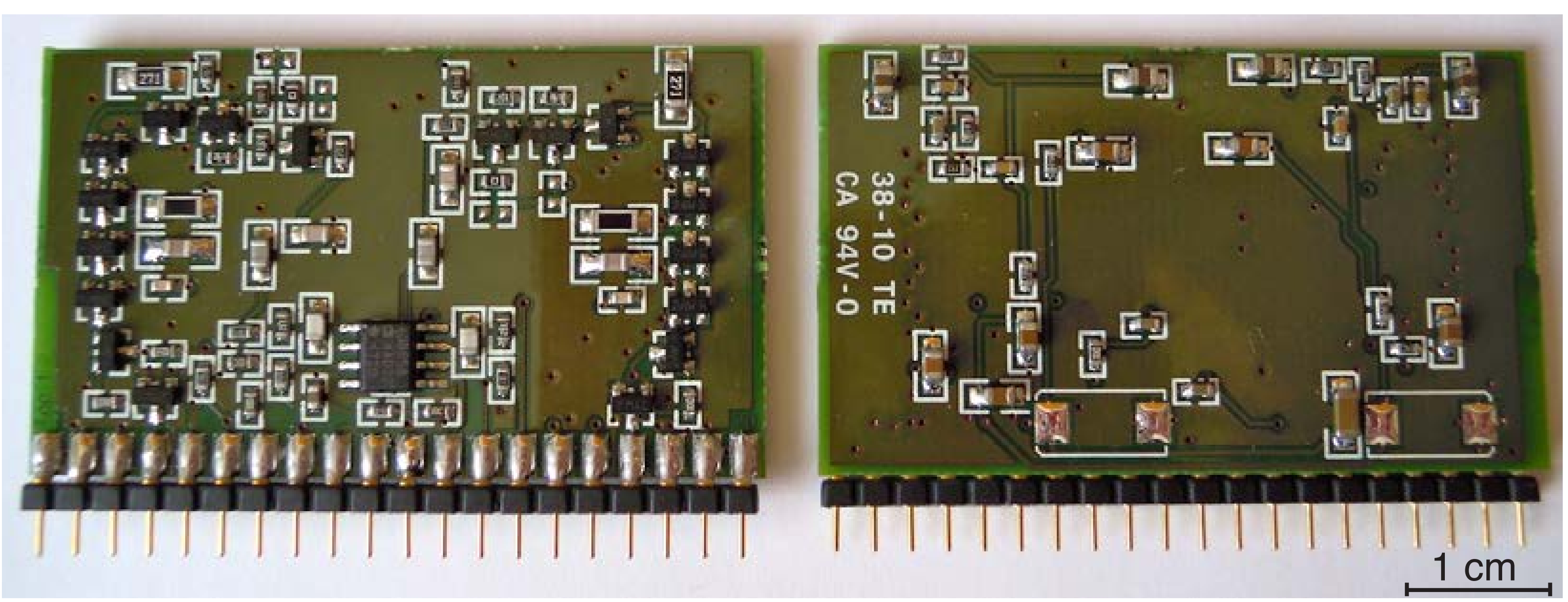
➡ 40x80 cm² designed, built and tested

The ETHZ preamplifier

electric layout

- Cascode design with 4 parallel JFETs at the input (C. Boiano et al. IEEE Trans. Nucl. Sci. 52 (2004) 1931)
- RC=470 μs feedback (C=1pF)
- RC-CR shaper with zero-pole sub. mechanism (no undershoot)
- over-voltage protection at input



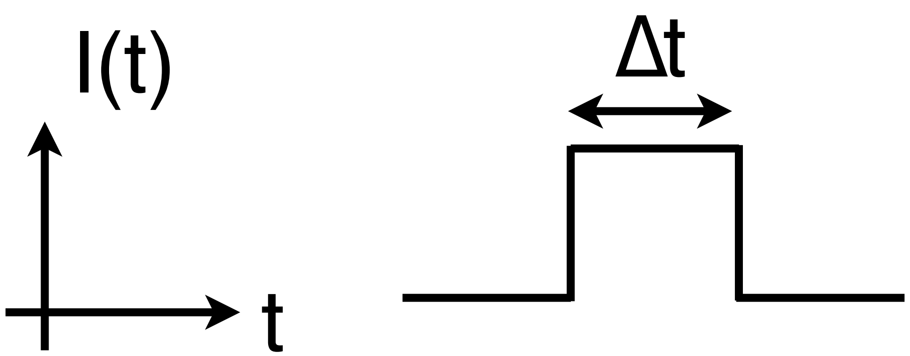


realization

- preamplifier is realized with discrete components
- two preamplifier circuits are implemented on a single 4-layer PCB

Performance of the ETHZ preamplifier

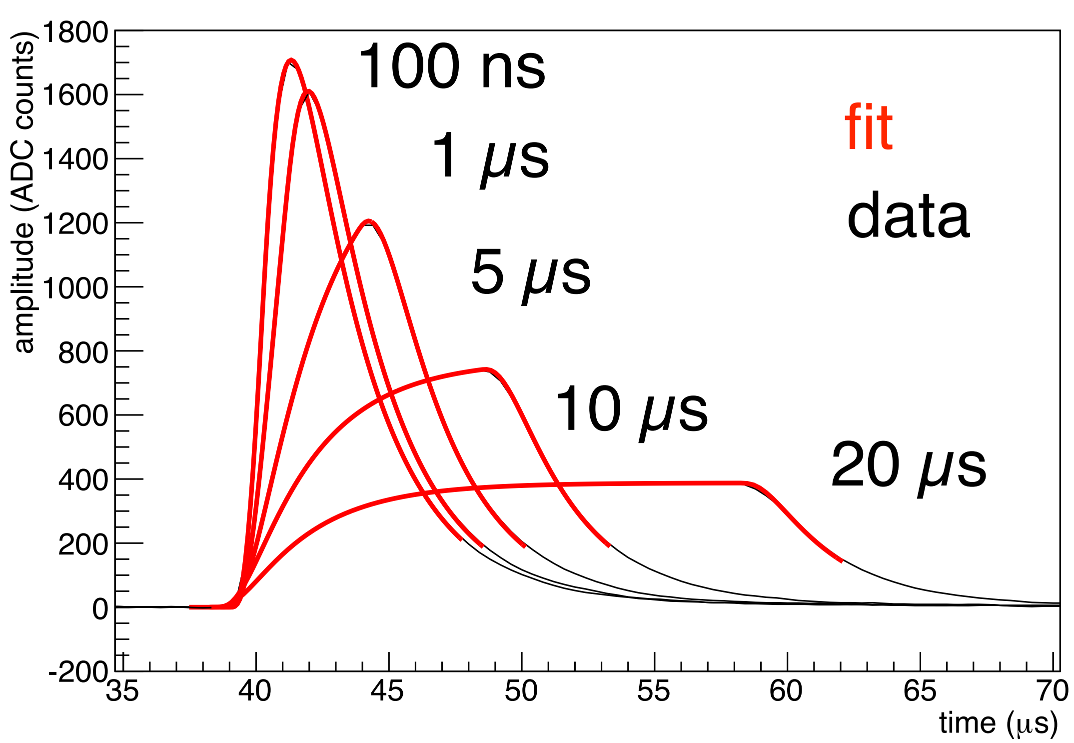
32 preamplifiers have been characterized with a well defined charge input:



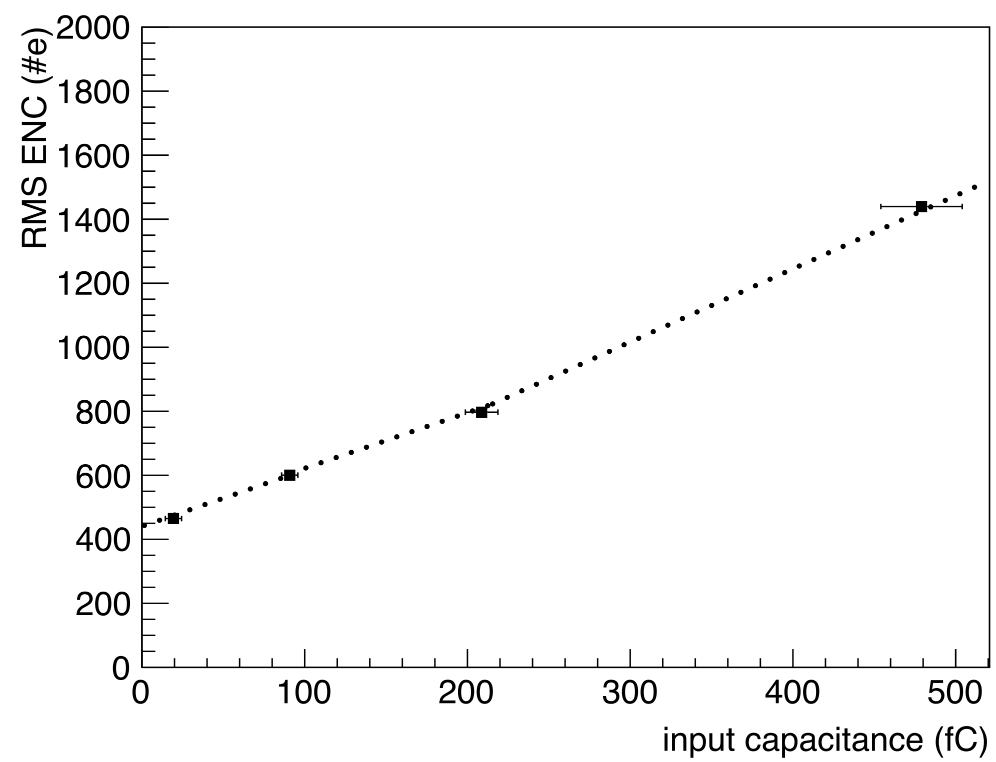
Summary

shaping time τ_D	$2.8 \pm 0.1\ \mu s$
shaping time τ_I	$0.45 \pm 0.02\ \mu s$
sensitivity	13.8 ± 0.4 mV/fC
open loop gain	$\approx 10^4$
linearity (0-180 fC)	$\pm 1\%$
ENC (RMS, $C \approx 200$ pF)	770 ± 30 electrons
S/N (1 fC, $C \approx 200$ pF)	8.1 ± 0.3

pulse shaping (varying Δt)

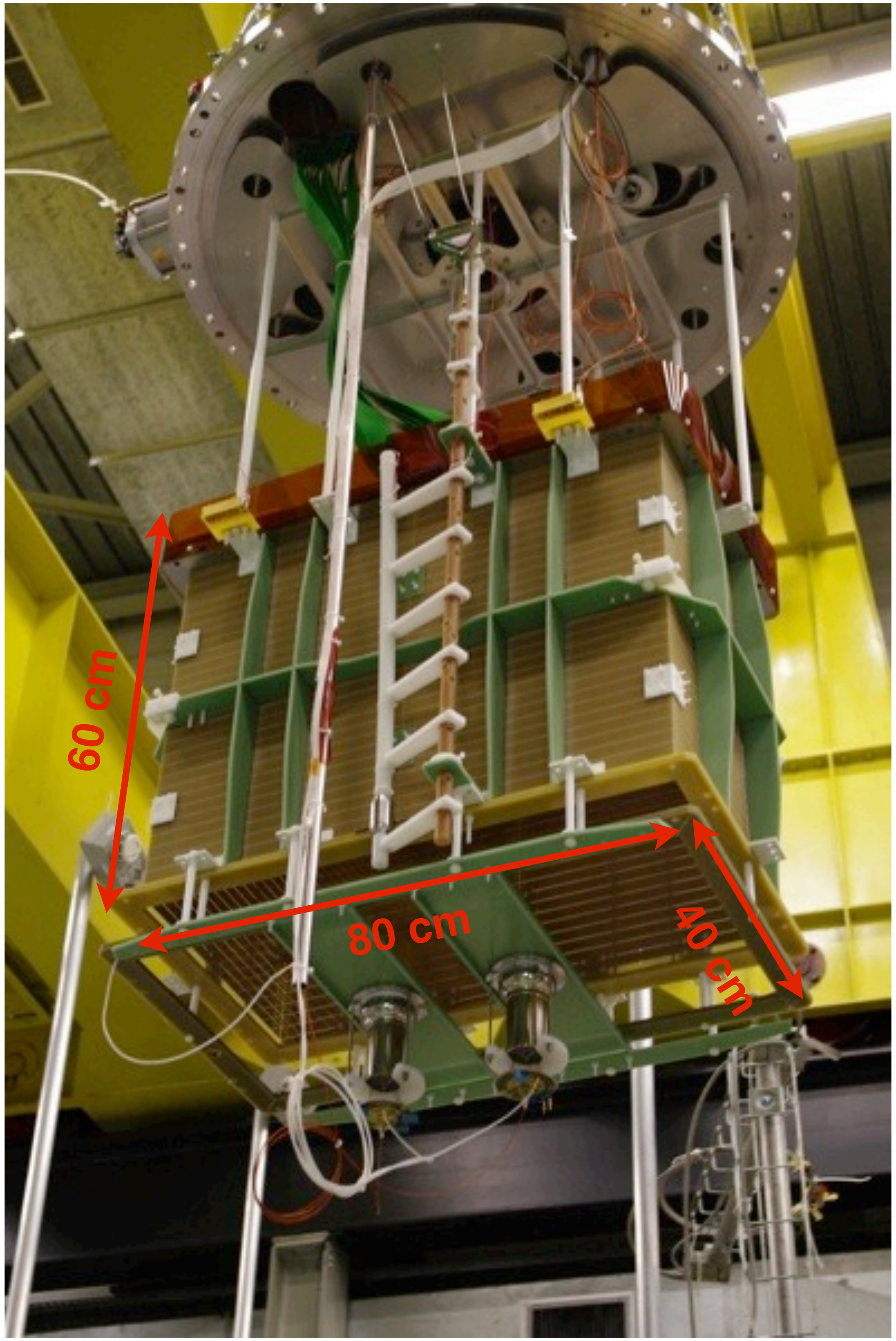


RMS ENC vs. input capacitance



LAr-LEM TPC@CERN:The largest LEM-TPC ever

Detector fully assembled

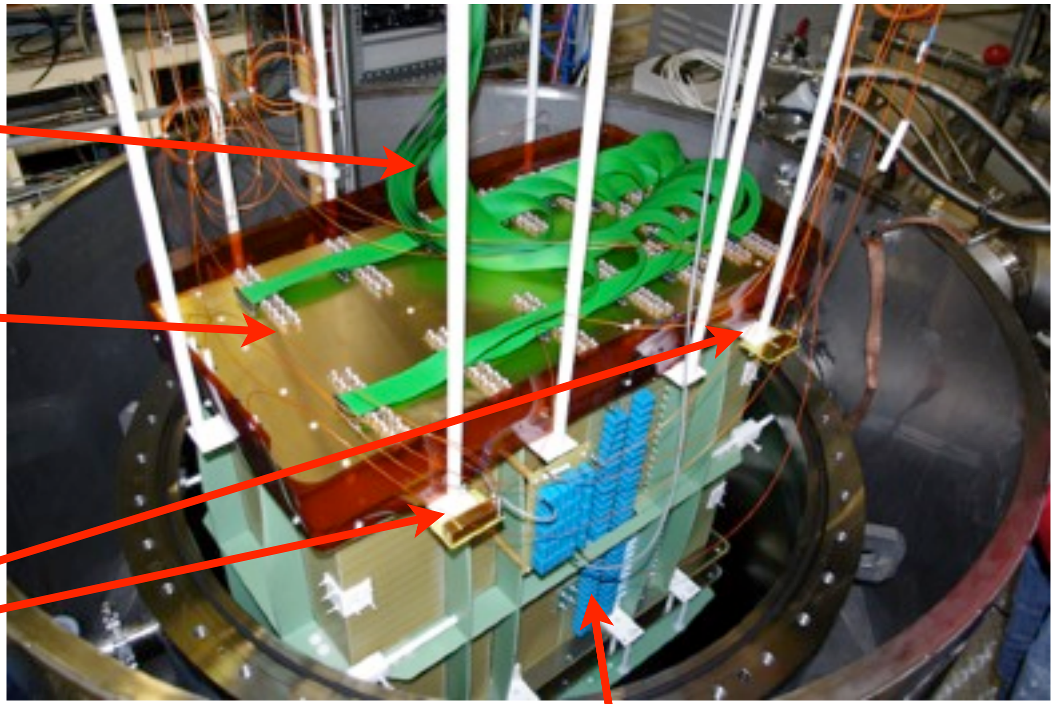


Chamber going into the ArDM cryostat

16 signal cables

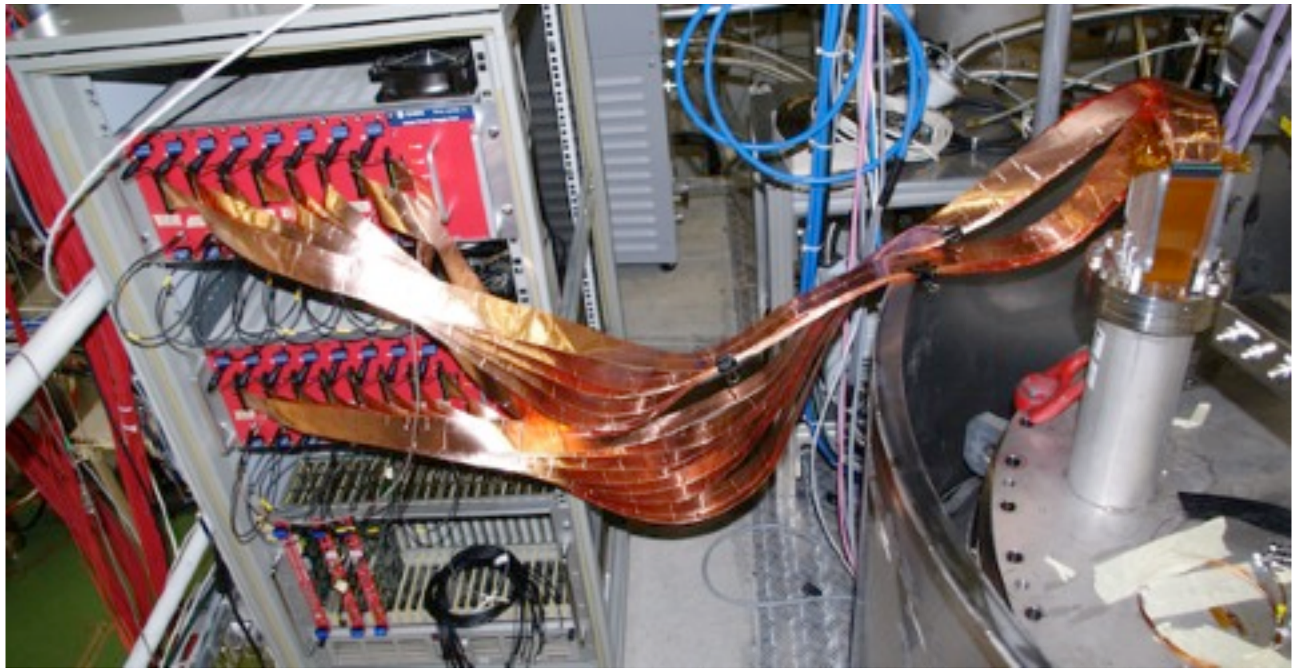
charge readout sandwich

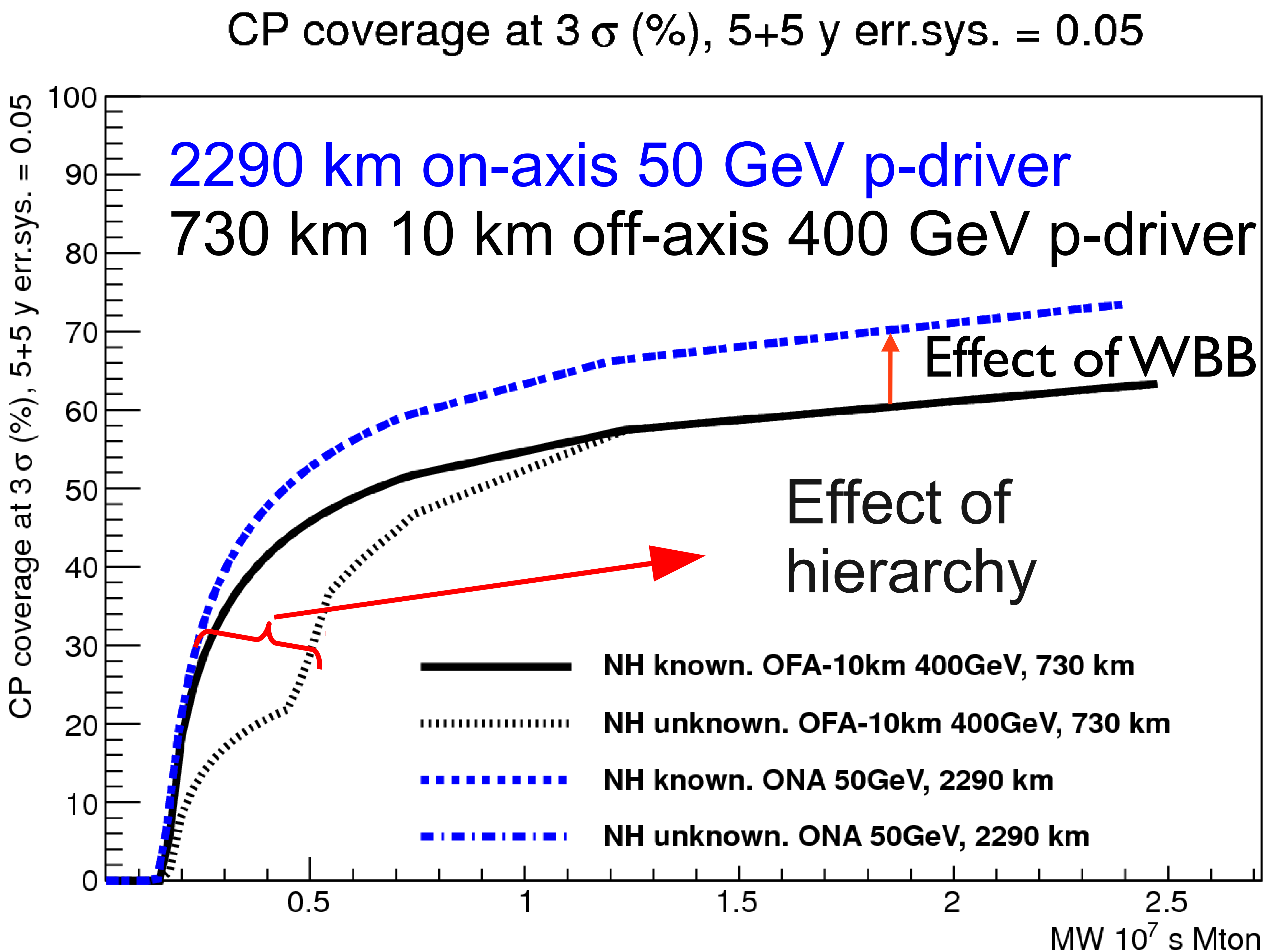
4 capacitive level meters



Cockcroft-Walton HV system

Final connection to the DAQ system





A. Longhin et al., NUTurn12