Neutrinos at the forefront of elementary particle physics and astrophysics (LIOneutrino2012)

Future projects for long-baseline experiments

(with accelerator neutrinos)

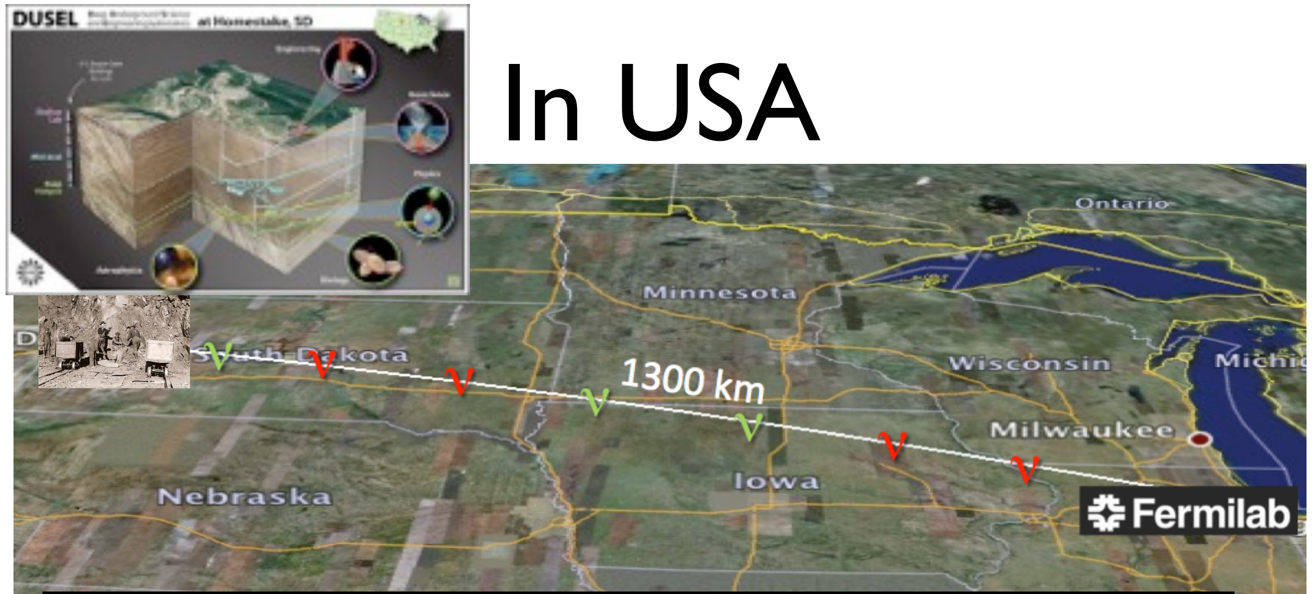
André Rubbia (ETH Zürich)

Lyon (France), 22-24 Oct 2012

v1

Facilities for long baseline accelerator exps.

In USA

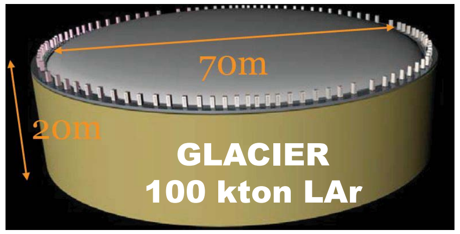


LBNE – a plan to build a new neutrino beam at Fermilab aimed at Homestake, where a 10-kton surface LAr tracking calorimeter would be built

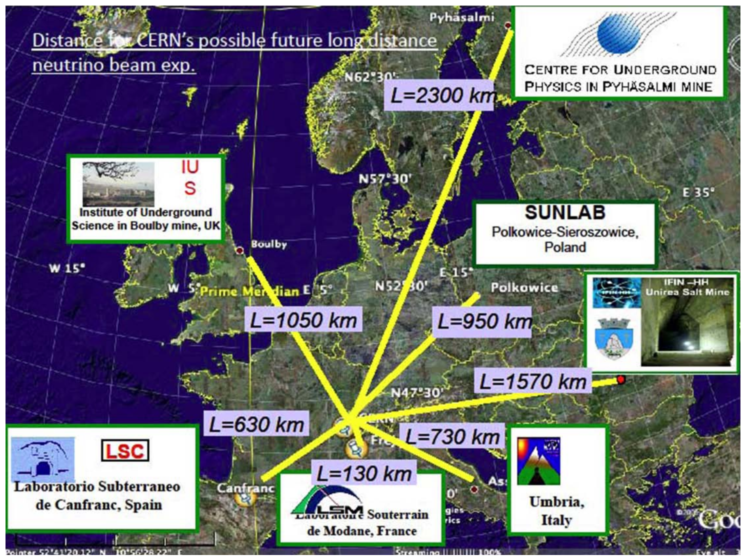
In Europe

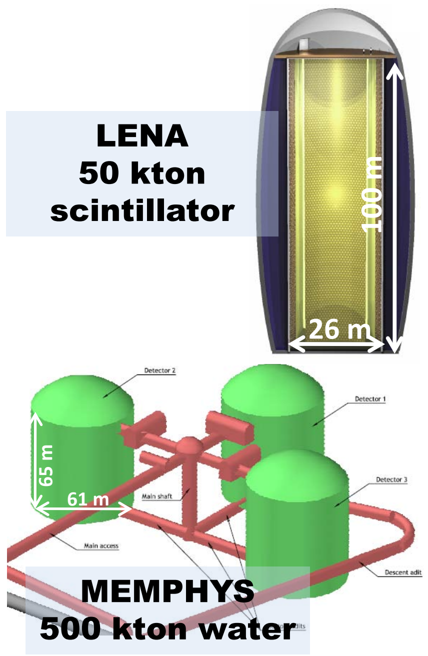
LAGUNA

European design study for Large Apparatus for Grand Unification and Neutrino Astrophysics



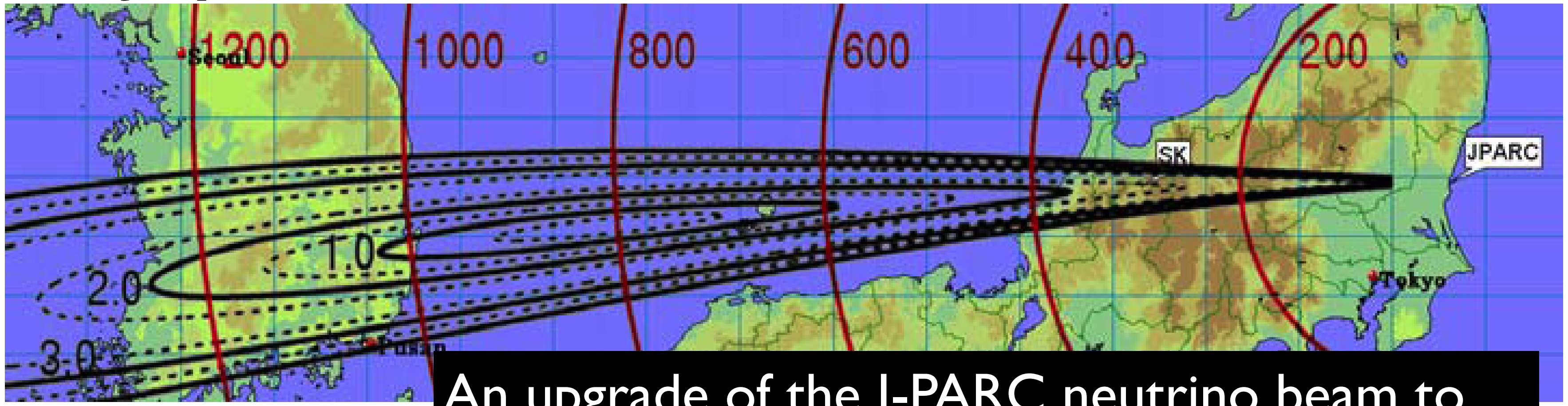
LAGUNA-LBNO





LAGUNA/LAGUNA-LBNO – study considering three detector options for astroparticle physics and new long baseline in Europe

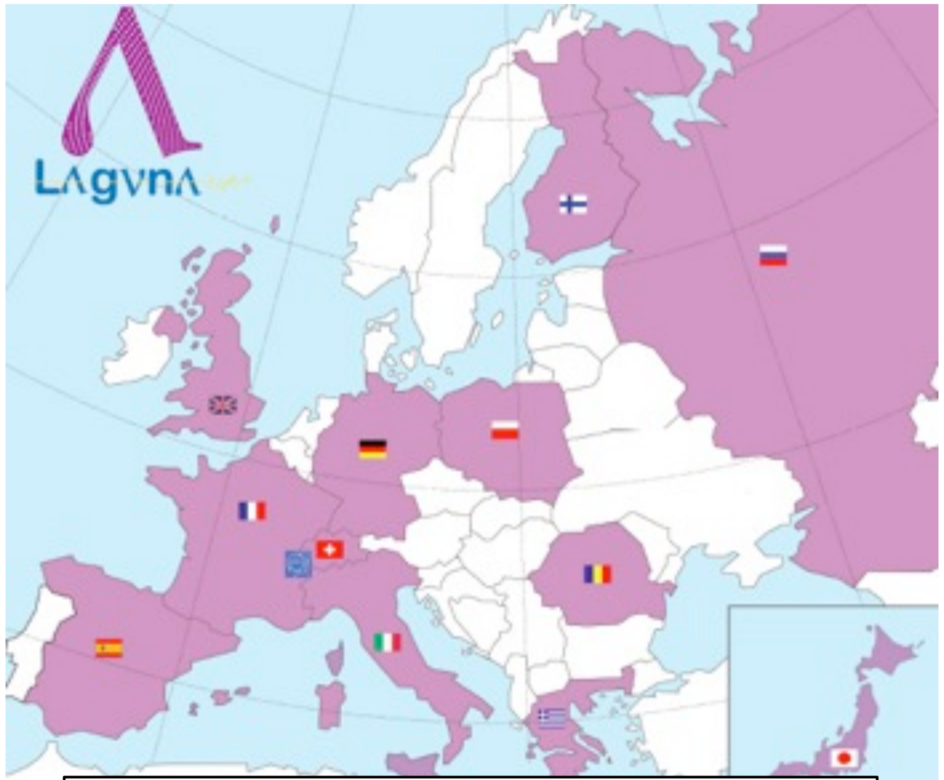
In Japan



An upgrade of the J-PARC neutrino beam to reach 1.6 MW beam power and new far detector(s) at Kamioka, Okinoshima, or Korea

LAGUNA 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** (Long Baseline Neutrino Oscillations)
  – 2011 – 2014
  –~300 members; 14 countries
  – Down selection of sites & detectors

Steering group:

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Ilias Efthymiopoulos (CERN)
Takuya Hasegawa (KEK)
Yuri Kudenko (INR)
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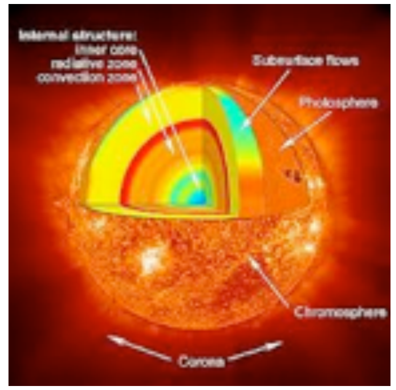
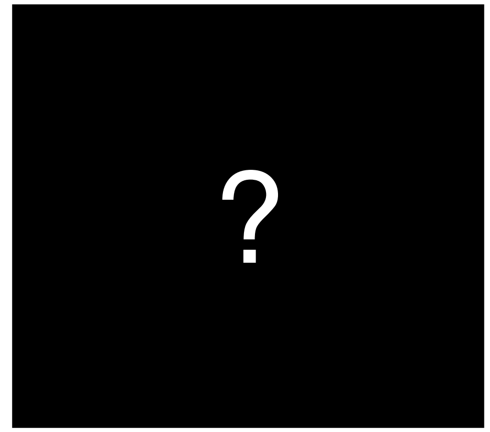
Silvia Pascoli (Durham)
Federico Petrolo (ETH Zürich)
André Rubbia (ETH Zürich)
Chris Thompson (Alan Auld Engineering)
Wladyslaw Trzaska (Jyväskyla)
Alfons Weber (Oxford)
Marco Zito (CEA)

Multipurpose neutrino observatory

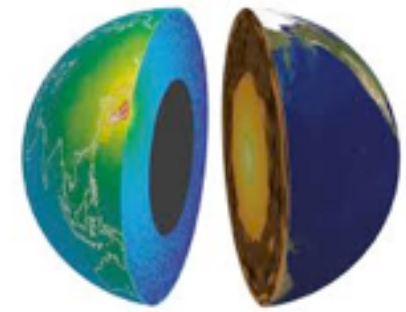
Supernova



Sun

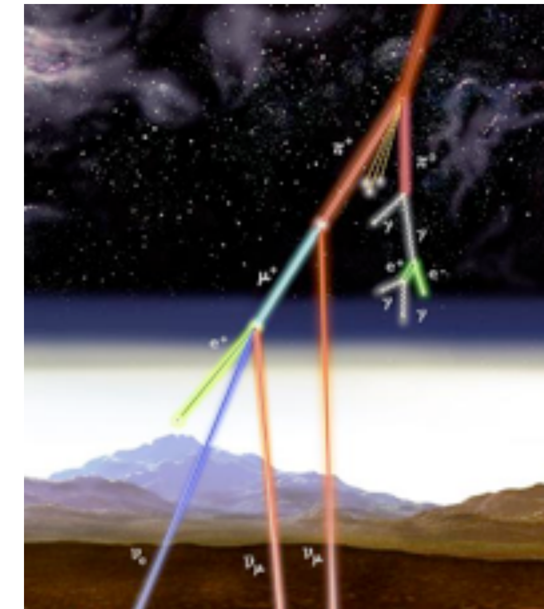


Unknown ?



Earth

Atmosphere



Reactors

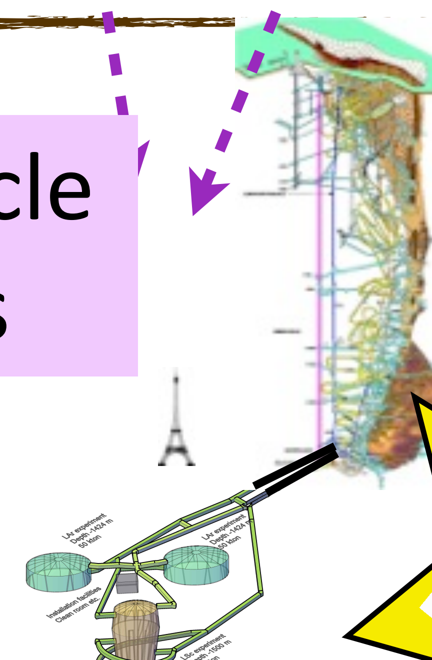
Neutrinos from MeV to 10’s GeV

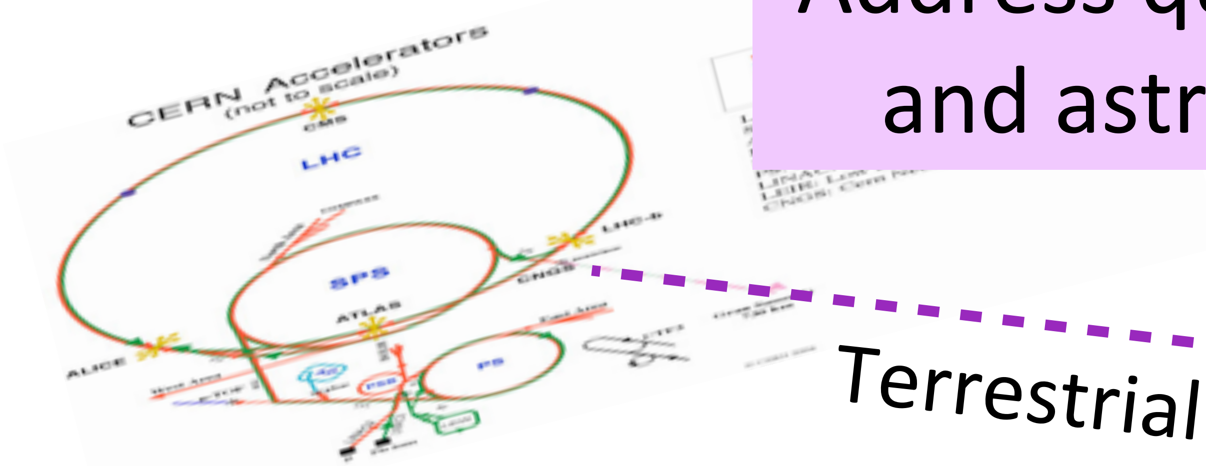
Neutrino oscillations → MH, CPV, precision

Proton lifetime

Address questions of particle and astroparticle physics

Deep underground





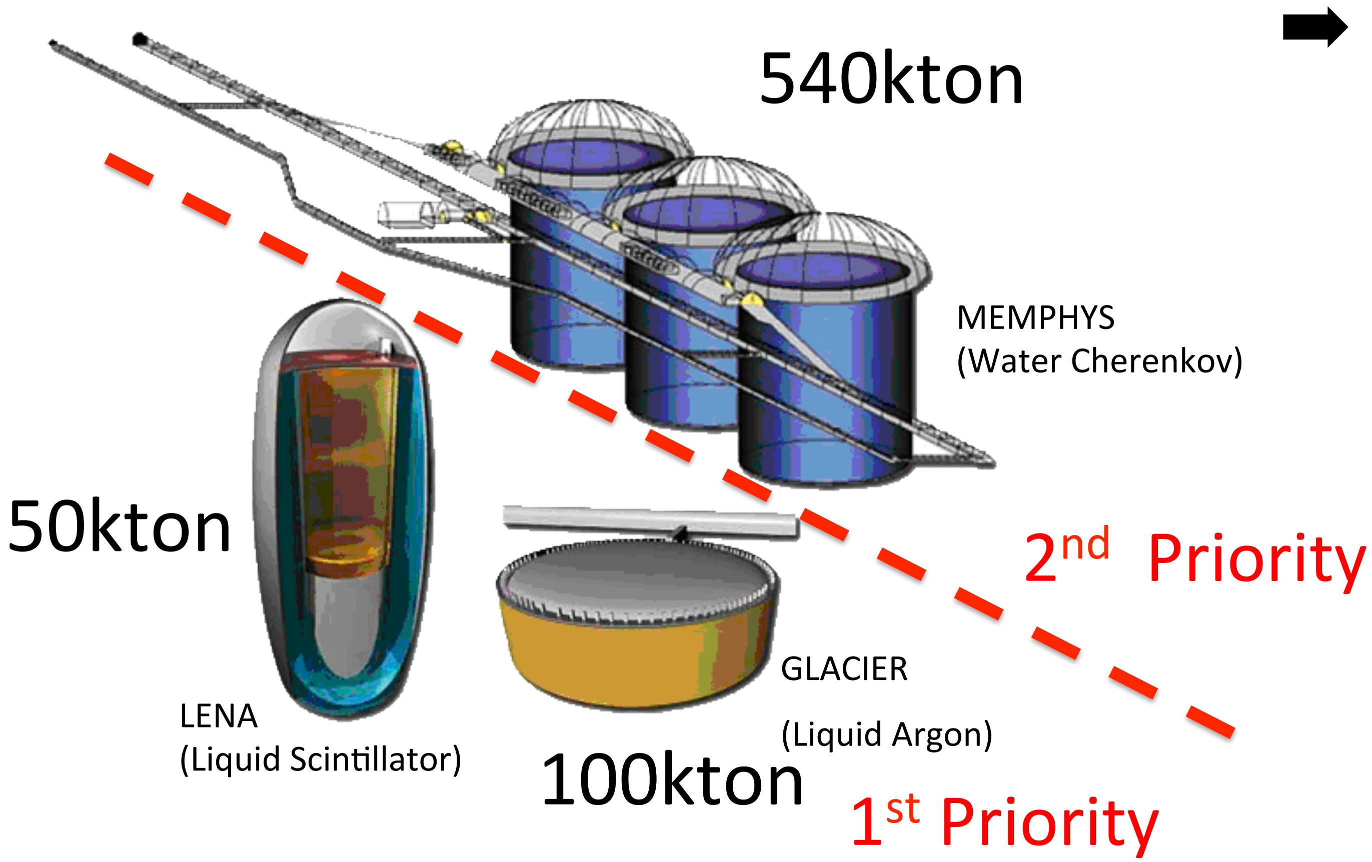
Accelerators

Terrestrial baseline

Proton decays

Which kind of large volume detector?

- In Europe: → LAr (GLACIER, 2004), LSc (LENA, 2005), WCD (MEMPHYS, 2006) efforts fused into an EC FP7-funded consortium for a coherent and synergetic approach to the three liquids (**LAGUNA, 2008-2011**)
- Prioritising the LBL neutrino oscillation (**LAGUNA-LBNO, since 2011**) had an influence on the site down-selection and detector technology prioritisation.



➡ As a consequence for LAGUNA:

- 1st priority: LAr, LSc at the longest baseline (2300km), high energy wide band beam (neutrinos >1 GeV)
- 2nd priority : WCD at the shortest long baseline (130km), low energy beam (neutrinos < 1 GeV)

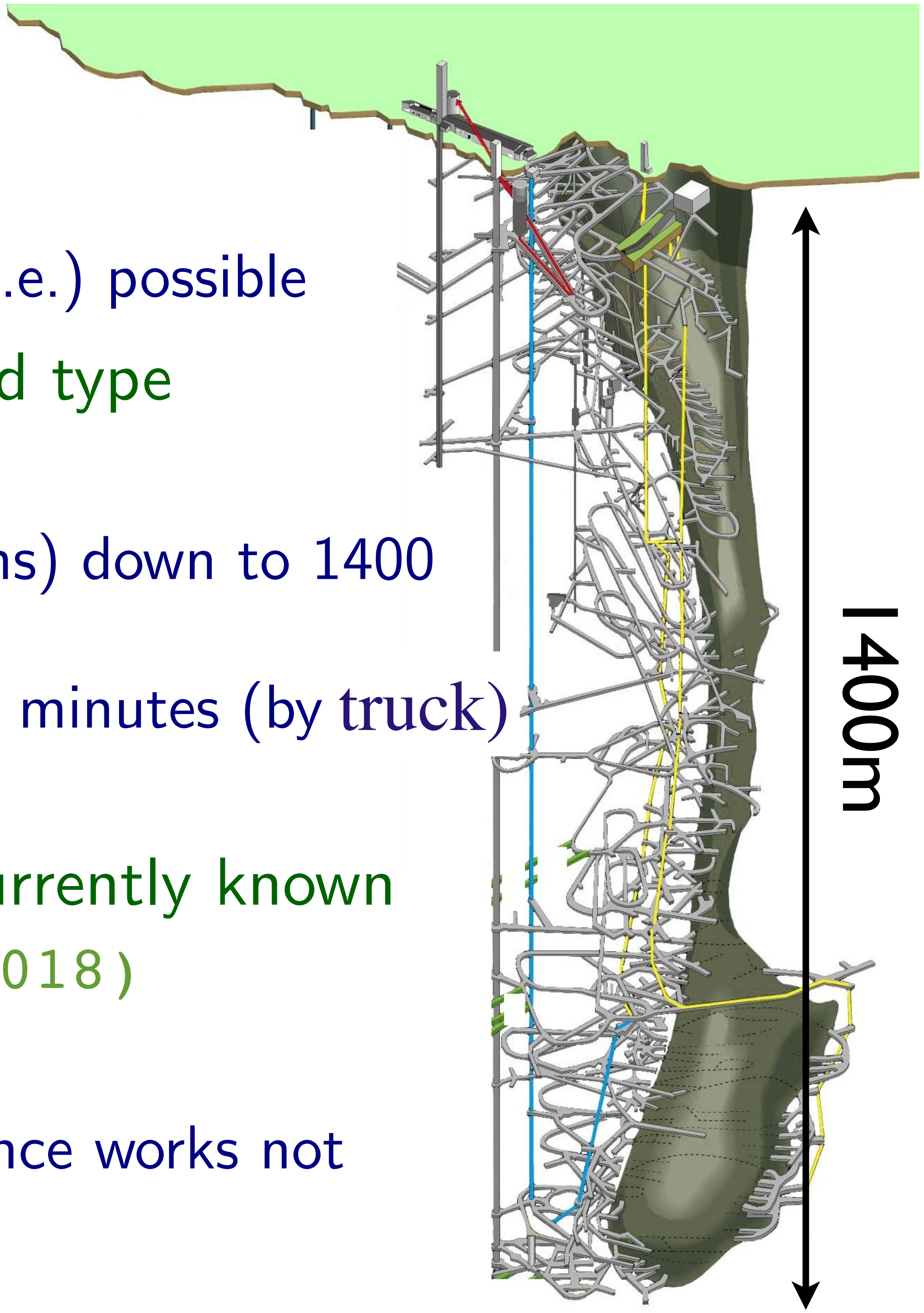
The Pyhäsalmi underground site

- ★ LAGUNA search for the optimal site in Europe for next generation deep underground neutrino detector
  - Very detailed investigations of seven potential sites with three different detector technologies: WCD, LAr and LSc
- ★ Down-selection to top priority site where several optimal conditions satisfied <u>simultaneously</u>: Pyhäsalmi, Finland
  - Infrastructure in perfect state because of current exploitation of the mine
  - Unique assets available (shafts, decline, services, sufficient ventilation, water pumping station, pipes for liquids, underground repair shop...)
  - Very little environmental water
  - Could be dedicated to science activities after the mine exploitation ends (around 2018)
  - One of the deepest location in Europe (4000 m.w.e.)
  - The distance from CERN (2300 km) offers unique long baseline opportunities. It is 1160km from Protvino.
  - The site has the lowest reactor neutrino background in Europe, important for the observation of very low energy MeV neutrinos.
- ★ Second priority: Fréjus, France.
- ★ All other sites are presently considered as backup options for LAGUNA.

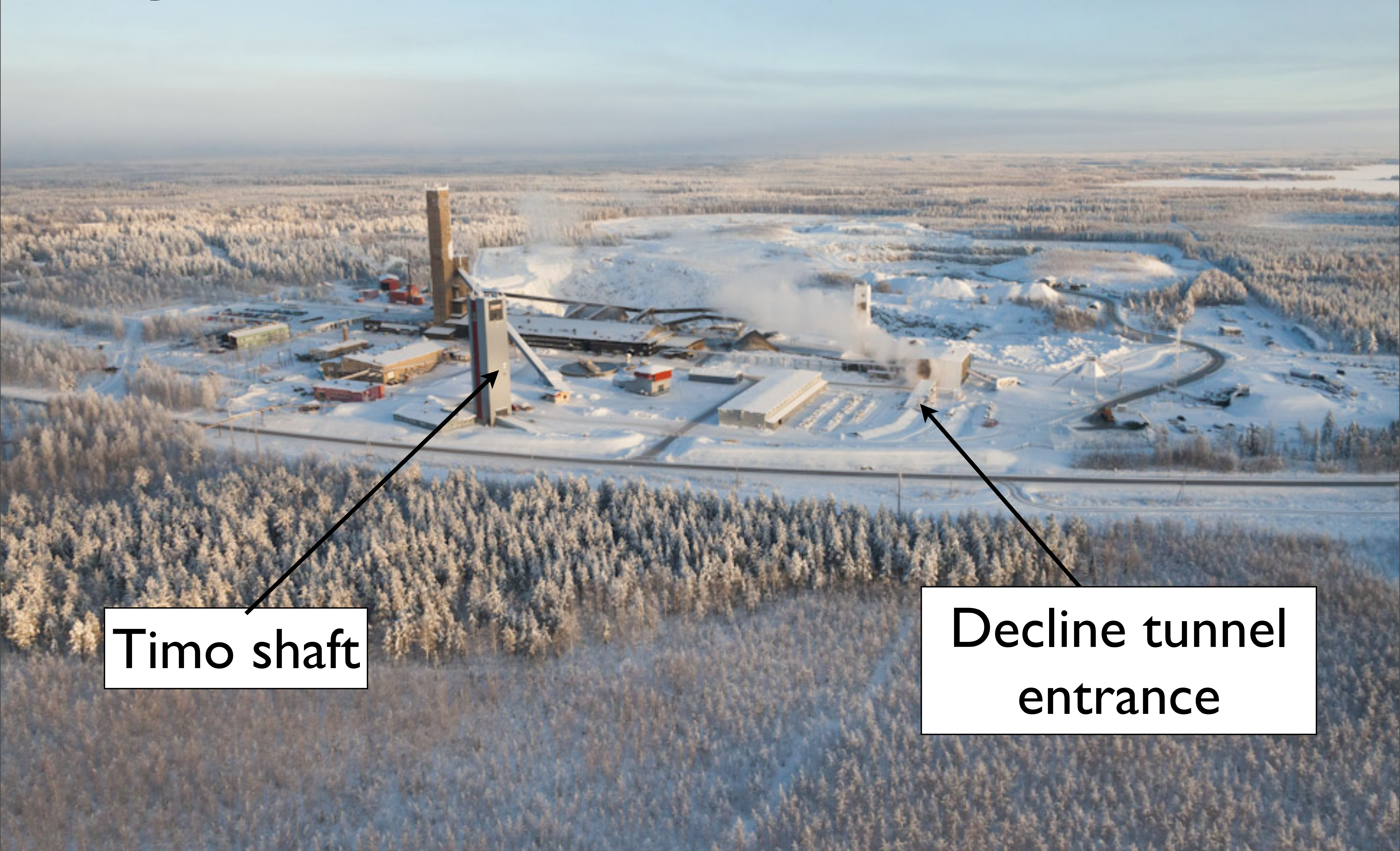
Present state of mine

Present: The Pyhäsalmi mine (Inmet Mining Ltd., Canada)

- Produces Cu, Zn, and FeS_2
- The deepest mine in Europe
  - Depths down to 1400 m (4000 m.w.e.) possible
- The most efficient mine of its size and type
- Very modern infrastructure
  - lift (of 21.5 tons of ore or 20 persons) down to 1400 metres takes ∼3 minutes
  - via 11-km long decline it takes ∼40 minutes (by truck)
  - good communication systems
- Operation time still 7–8 years with currently known ore reserves (presumably until 2018)
- Compact mine, small 'foot print'
  - water pumping and other maintenance works not major issues



Pyhäsalmi mine



This pump alone takes all the water from 645 m to the surface

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

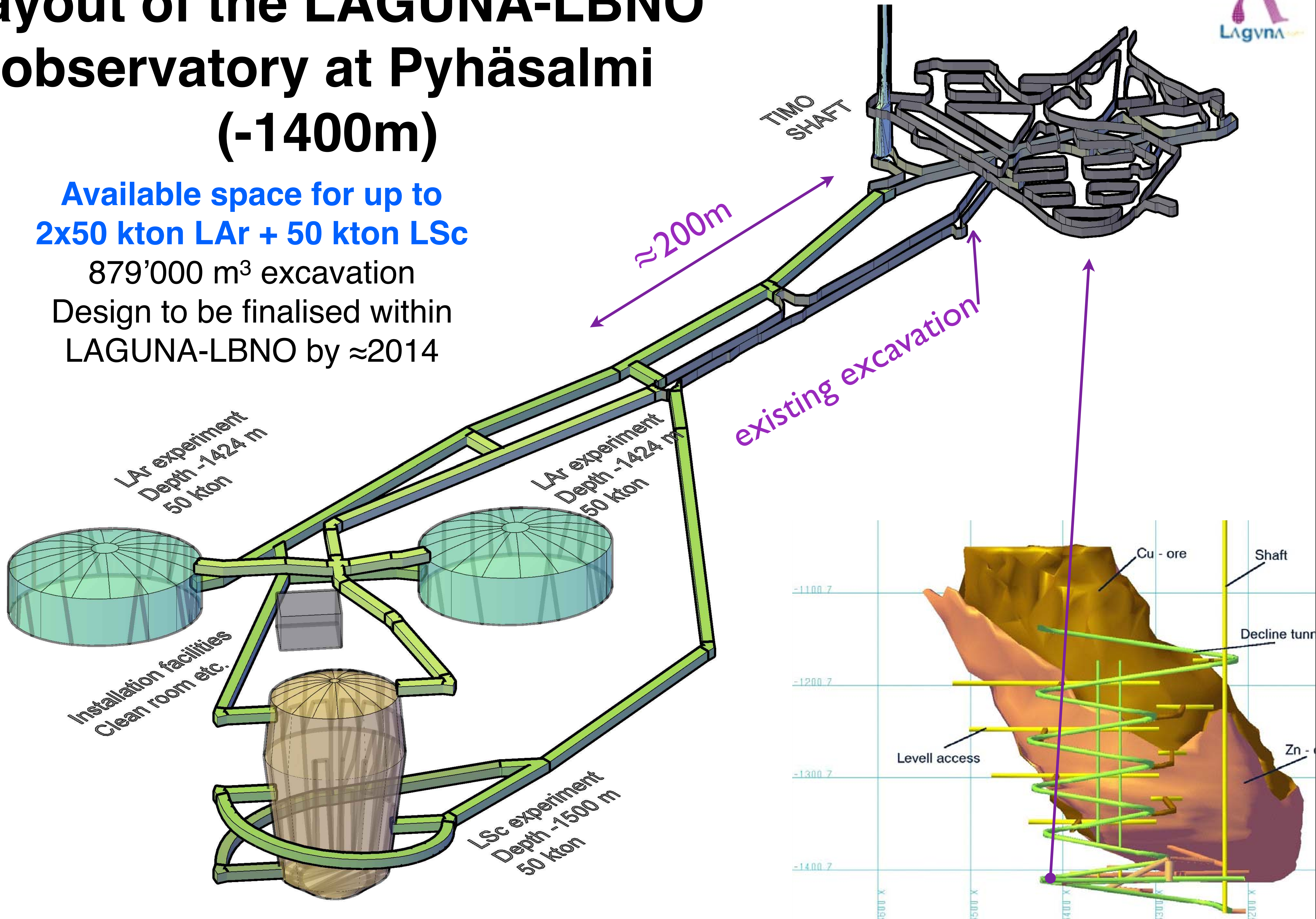
Cafeteria, meeting room and sauna at 1400 m below ground

Mobile phones work and internet available also at 1400 m

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

Available space for up to
2x50 kton LAr + 50 kton LSc

879’000 m^3 excavation
Design to be finalised within LAGUNA-LBNO by ≈2014



LBNO

Expression of Interest for a very long baseline neutrino oscillation experiment

CERN-SPSC-2012-021 ; SPSC-EOI-007

An incremental approach, based on the findings of LAGUNA

Submitted in June 2012

~230 authors, 51 institutions

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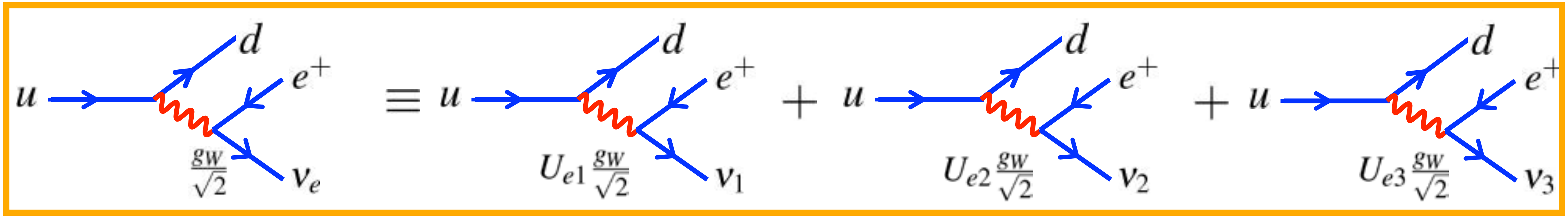
LBNO main physics goals

- **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 observation of the energy dependence of the oscillation probabilities induced by **matter effects** and **CP-phase terms**, independently for ν and anti-ν
  - 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**
  - 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)**
  - (Not surprisingly) optimised distance of 2300km is also optimal for NF and large θ_{13}

Neutrino mixing matrix (PMNS)

- Neutrinos are produced and interact as weak eigenstates.
- The weak eigenstates are coherent superposition of the fundamental mass eigenstates. The mass eigenstates are the solutions of the free Hamiltonian and represent the propagation of the neutrinos in space.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



★ **The 3x3 Unitary matrix U is known as the Pontecorvo-Maki-Nakagawa-Sakata matrix, usually abbreviated PMNS**

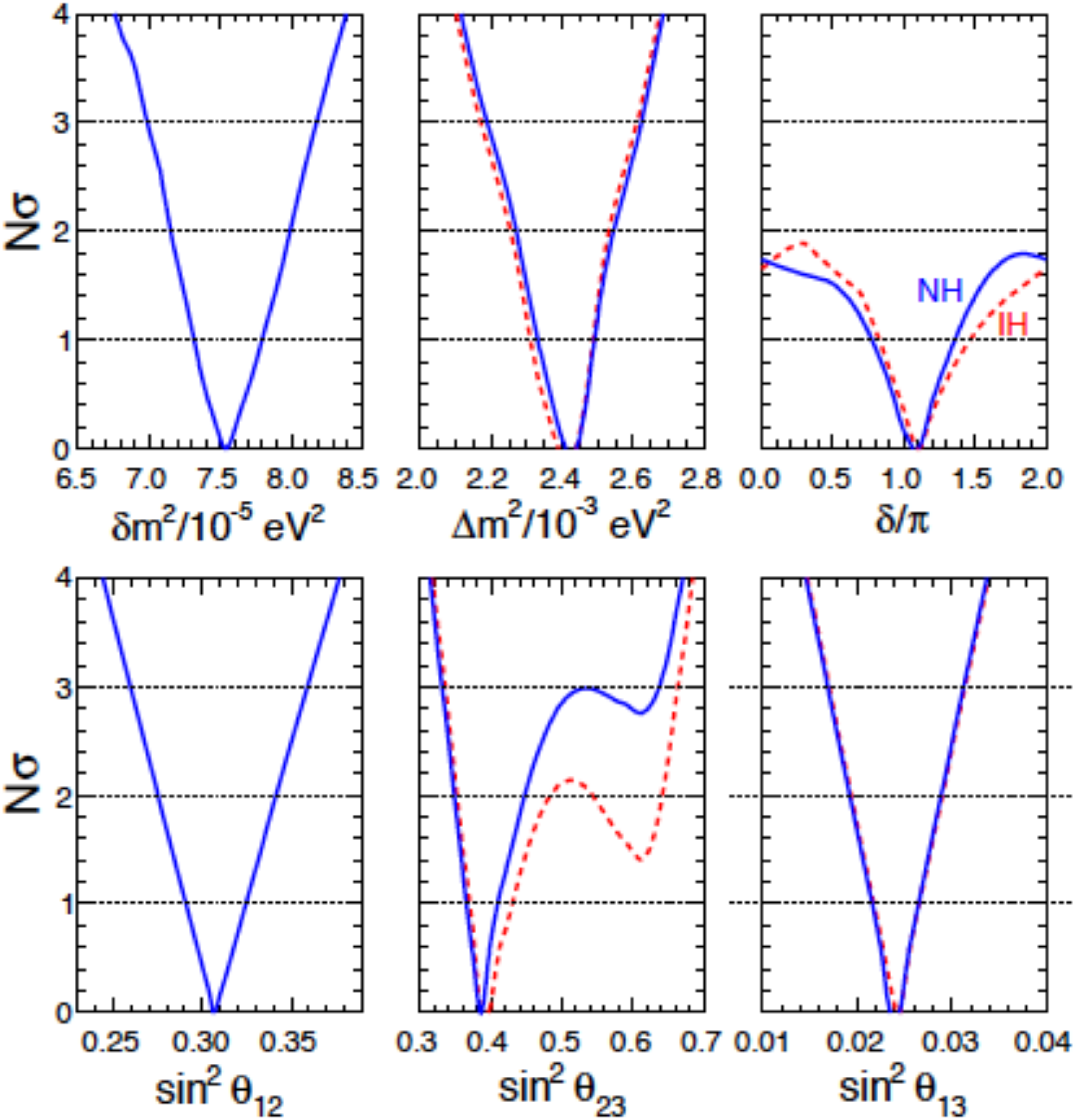
★ **The PMNS matrix is usually expressed in terms of 3 rotation angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a complex phase δ, using the notation $s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$**

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{"Atmospheric"}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{"subleading"}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{"Solar"}}$$

"Atmospheric" "subleading" "Solar"

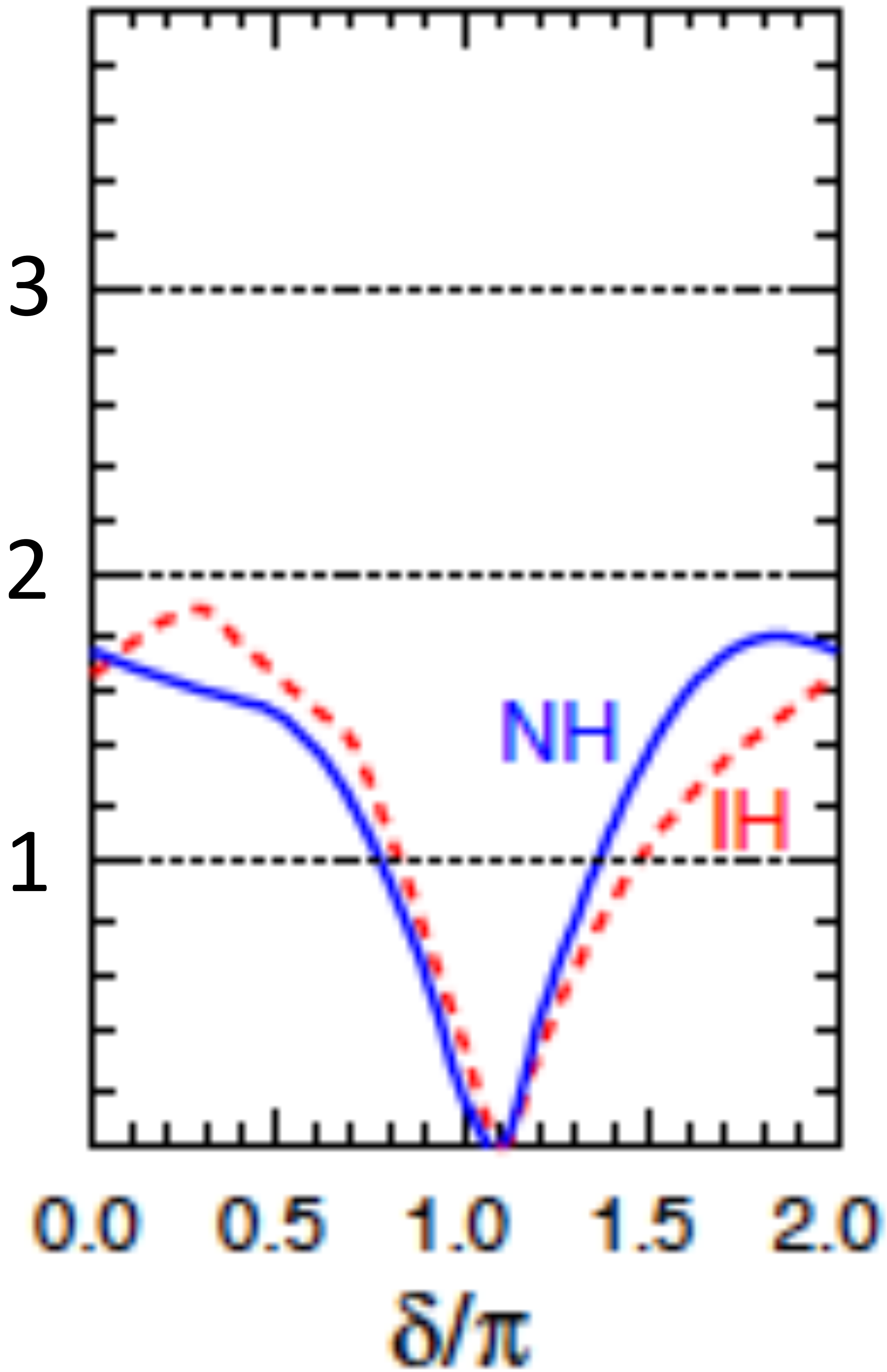
Global fits: e.g. Bari results

G.L. Fogli etal., arXiv: 1205.5254v3

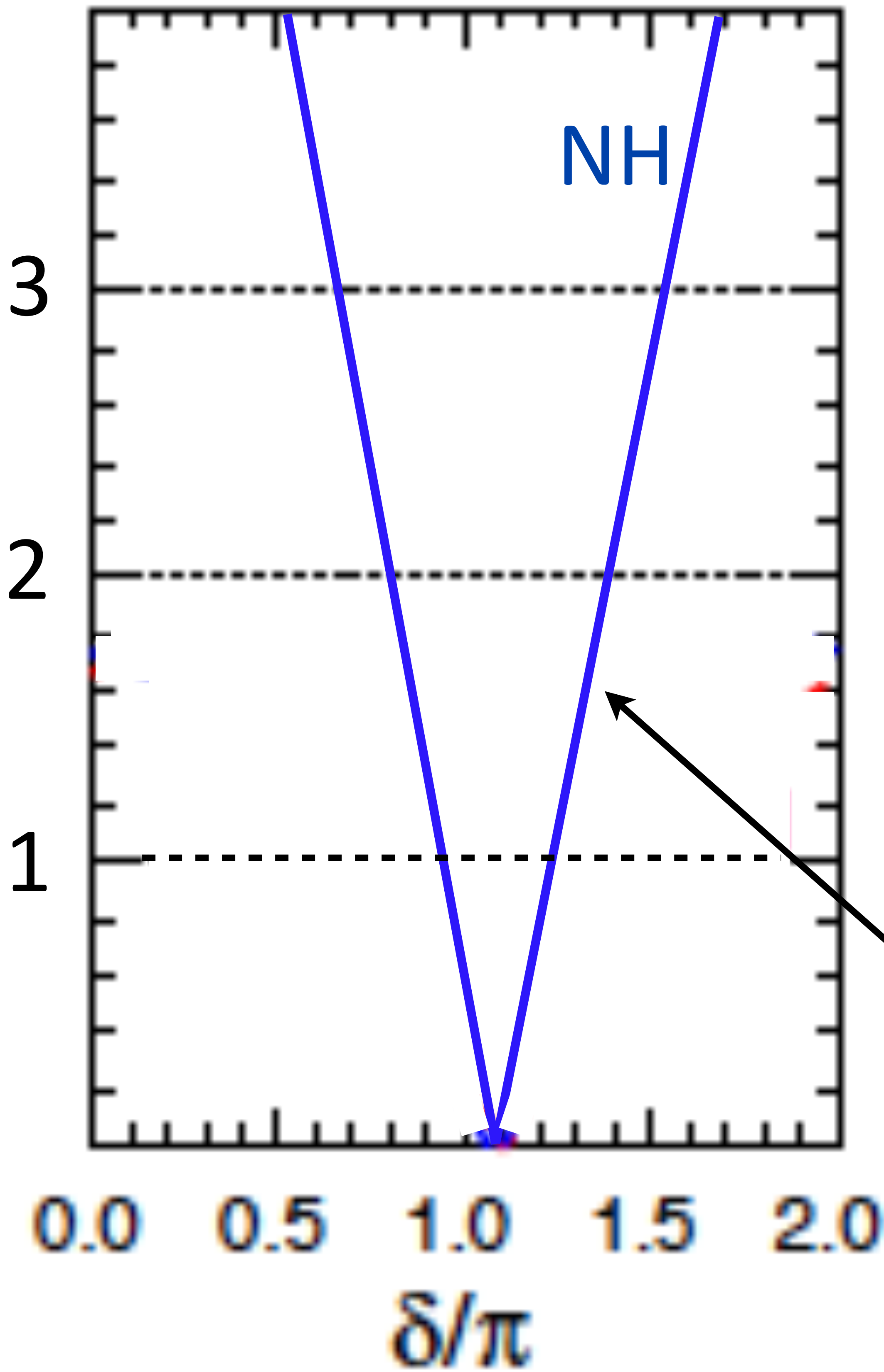


- **No hints for neutrino mass hierarchy (MH)**
- Both NH and IH solutions are allowed
- **All values of δ are allowed at 2σ C.L.**
- δ ≈ π favored (1σ), i.e. CP-conserving ? no PMNS-induced CP ??
- **Is the Bari group right (again) ?**
- Caveat: Global fits cannot replace real data (E.Lisi, NPB2012)

LBNO approach to CP-phase



LBNO approach to CP-phase



- Measure L/E dependence of oscillation probability, independently for neutrinos and antineutrinos
- Resolve MH >5σ C.L. in the first <u>two</u> years of running 50%-50% neutrinos-antineutrinos thanks to the very long baseline (2300km)
- A conclusive knowledge of MH allows to optimise neutrino vs antineutrino running to maximize CP violation sensitivity
- **In <u>ten</u> years reach an error on the CP-phase value of $\Delta\delta \approx \pm 20^{o}$**
- Differentiate the two CP-conserving scenarios ($\delta \approx 0$ and $\delta \approx \pi$) by L/E

Jarlskog invariants: $J(PMNS) \approx 5\times10^{-2}\sin\delta > J(CKM) = 3\times10^{-5}$???

$\nu_\mu \rightarrow \nu_e$ appearance probability

- Rich physics to be explored as a function of L/E

Matter effect

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$ *Leading term*

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$ *CP-terms*

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$ *Solar term*

CPV

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

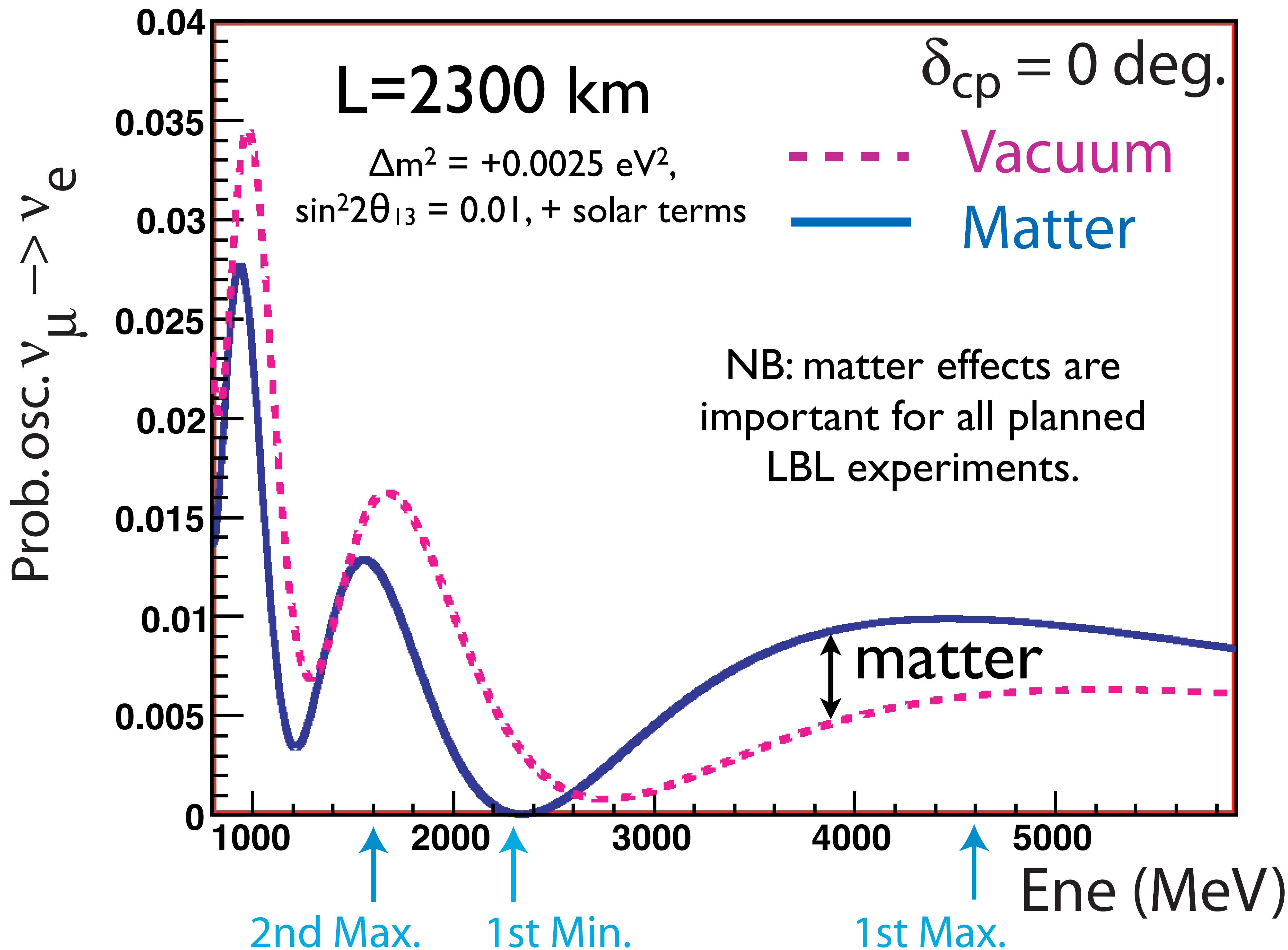
$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$ ***E_ν dependence***

$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

CERN-Pyhäsalmi: matter effect $\nu_\mu \rightarrow \nu_e$

★ Normal mass hierarchy

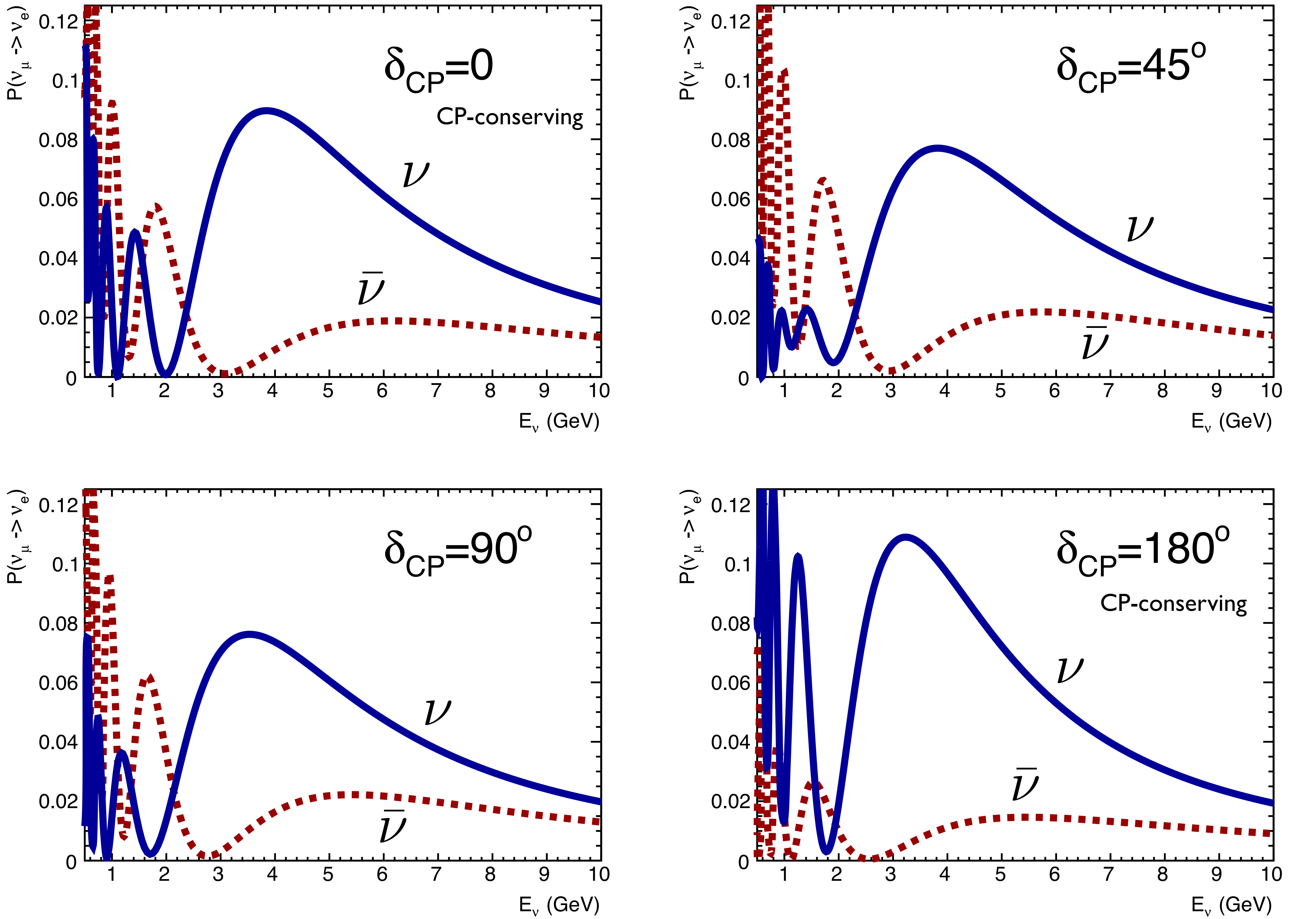


CERN-Pyhäsalmi: CP-effect $\nu_\mu \rightarrow \nu_e$

★Normal mass hierarchy

L=2300 km

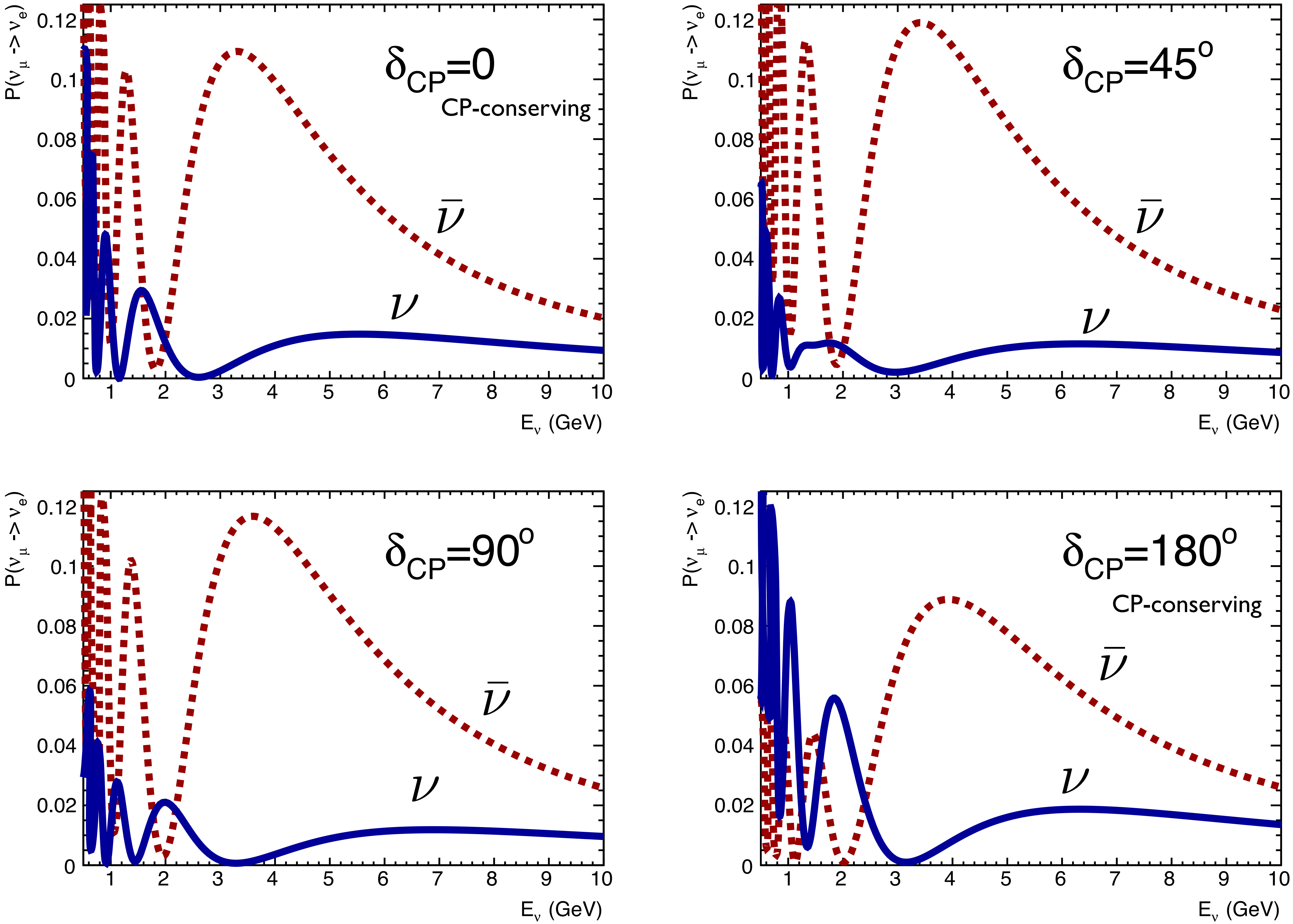
$\sin^2(2\theta_{13}) = 0.09$



CERN-Pyhäsalmi: CP-effect $\nu_\mu \rightarrow \nu_e$

★Inverted mass hierarchy   L=2300 km

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



LBNO experimental requirements

Beam

Fully exploit long baseline neutrino oscillation pattern

⇩

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

⇩

Wide Band Beam (WBB)

$$E_\nu^{2nd\,max} \gtrsim 0.5\,\mathrm{GeV} \Longrightarrow \mathrm{L} \gtrsim 1000\ \mathrm{km}$$

Detector

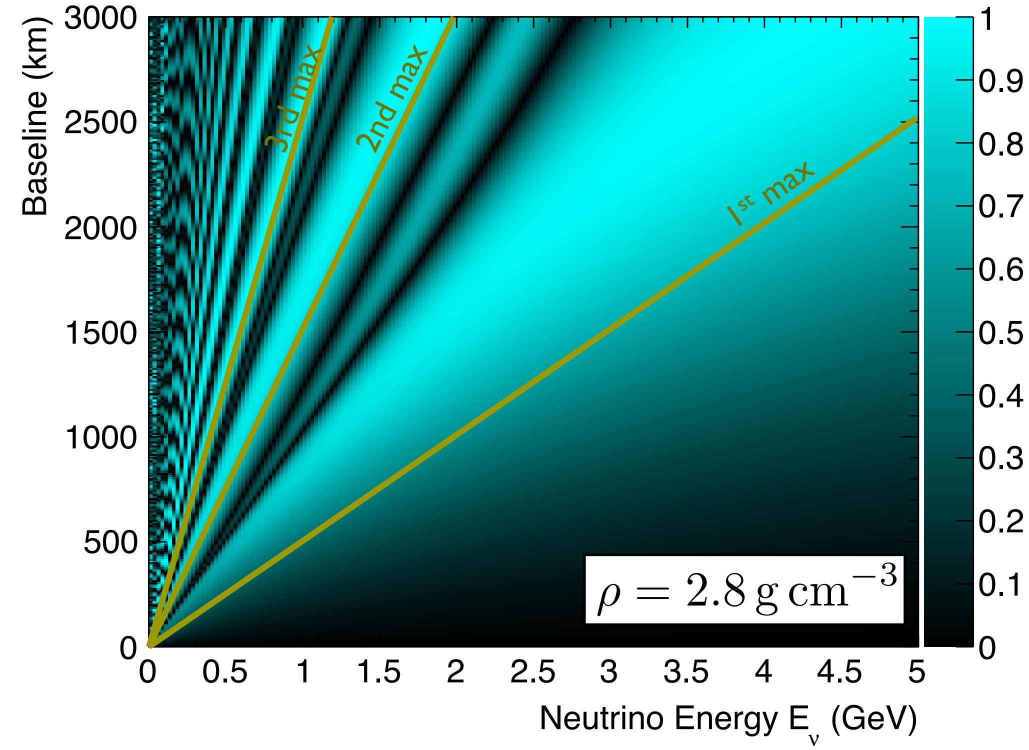
Better signal efficiency and background rejection with a comparable mass

⇩

20 kton fine sampling tracking device

and magnetized muon detector

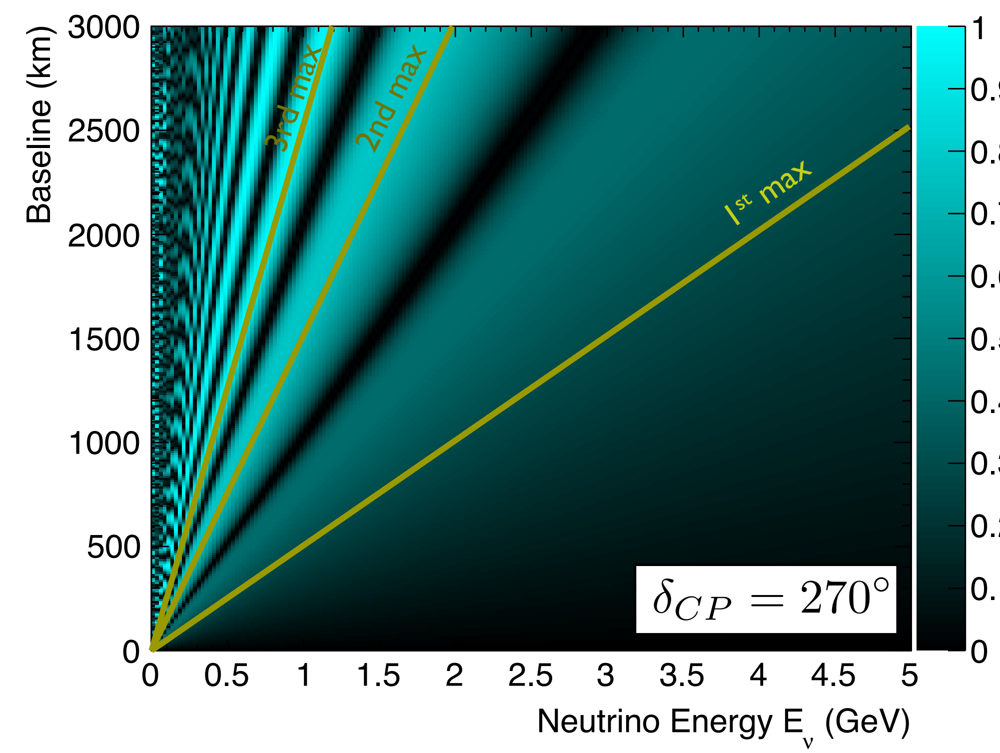
$$\mathcal{A}_{CP}(\rho) \equiv abs\left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$



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

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

Normal mass hierarchy

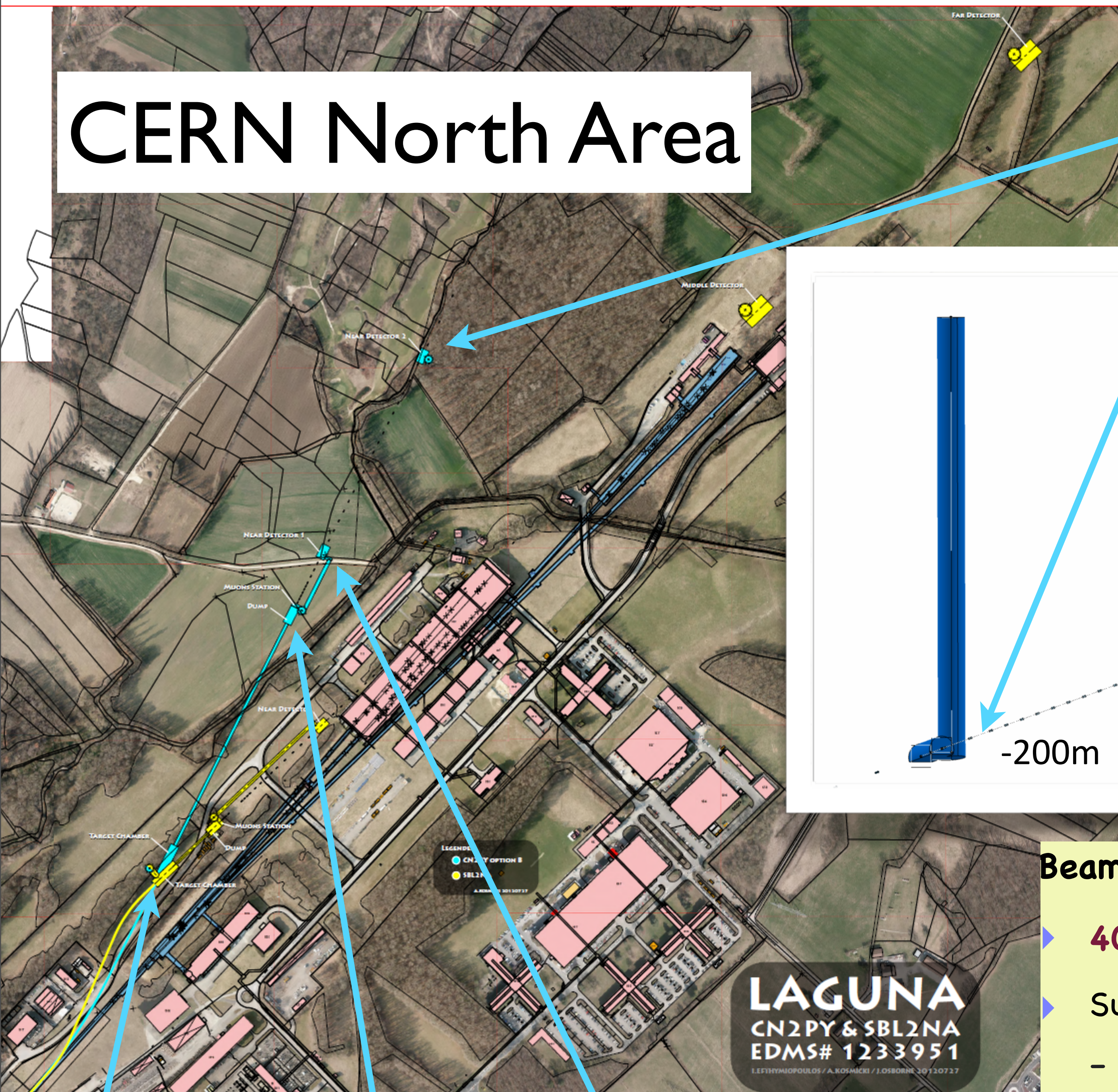


Neutrino beam requirements

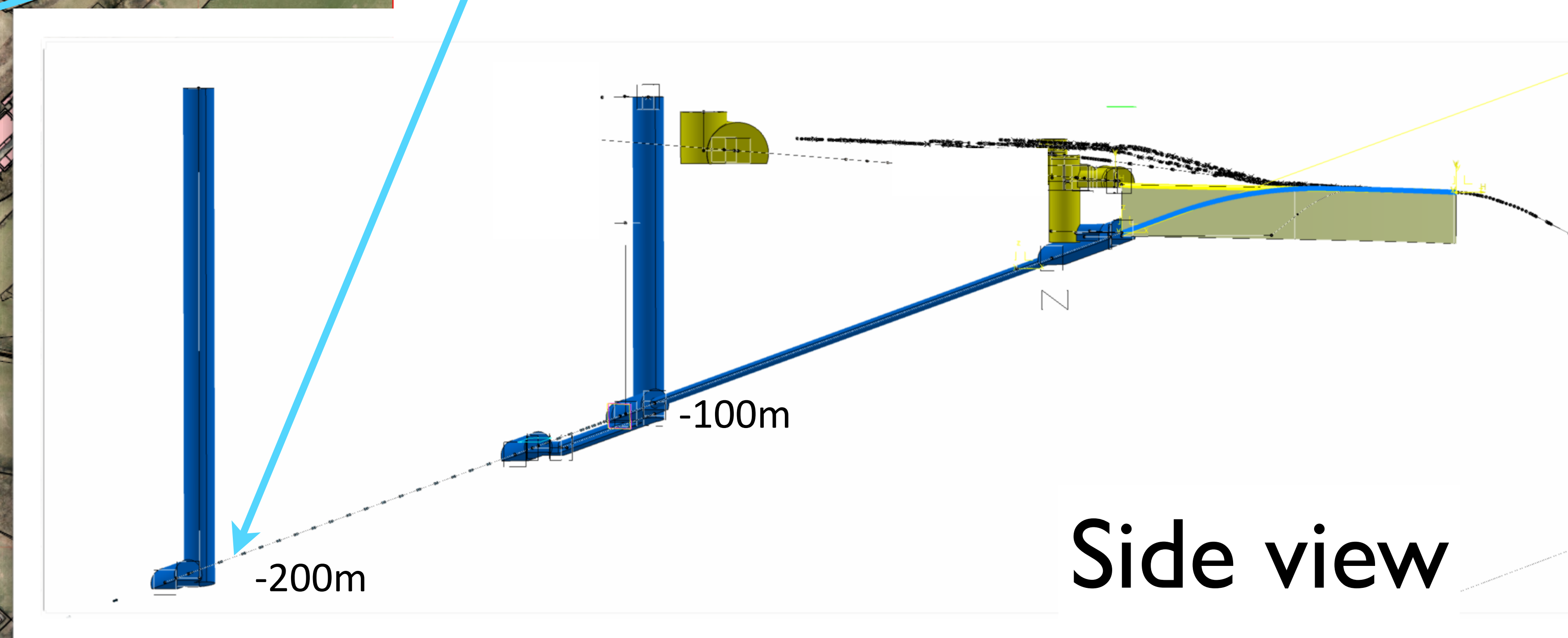
- Medium energy to cover at $E_\nu \approx 4$ GeV (1st maximum)
- Horn focused, wide band to cover 1st and 2nd maximum
- Small tail at high energy
- Positive and negative focus (ν and anti-ν modes)
- High beam power (initially 700 kW)
- Point to Pyhäsalmi (10deg dip angle, distance = 2300km)
- Muon monitors
- Near neutrino detector

❖ Primary protons from SPS (7e13 ppp @ 400 GeV with 6 s cycle)
❖ Yearly integrated pot = (0.8–1.3)x 1e20 pot / yr depending on "sharing" with other fixed target programmes (compared to CNGS 4.5x 1e19 pot / yr)
❖ Secondary horn focusing (horn+reflector)

Neutrino beam layout



LBNO near detector (850m from target)



Beam parameters

- **400 GeV** protons from SPS (initial)
- Survey info:
  - CERN (TCC2 target station -NA) 46°15'26.27"N, 6° 3'8.19"E
  - Inmet Mine (Finland): 63°39'30.92"N, 26° 2'47.65"E
  - distance: **2296 km**
  - dip angle : **10.4 deg, 181 mrad**
- Neutrino beam at Pyhäsalmi ($\theta_{max} \approx 30$ MeV/E_ν) : **14÷34 Km** for $E\nu$ 2÷5 GeV

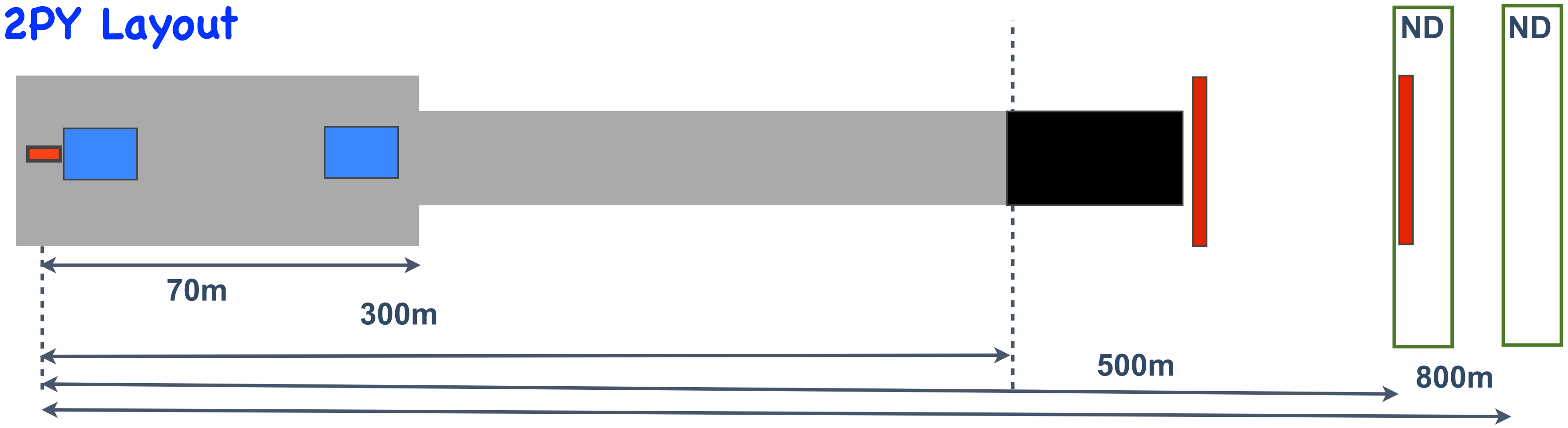
Target station

Beam dump

Muon monitors

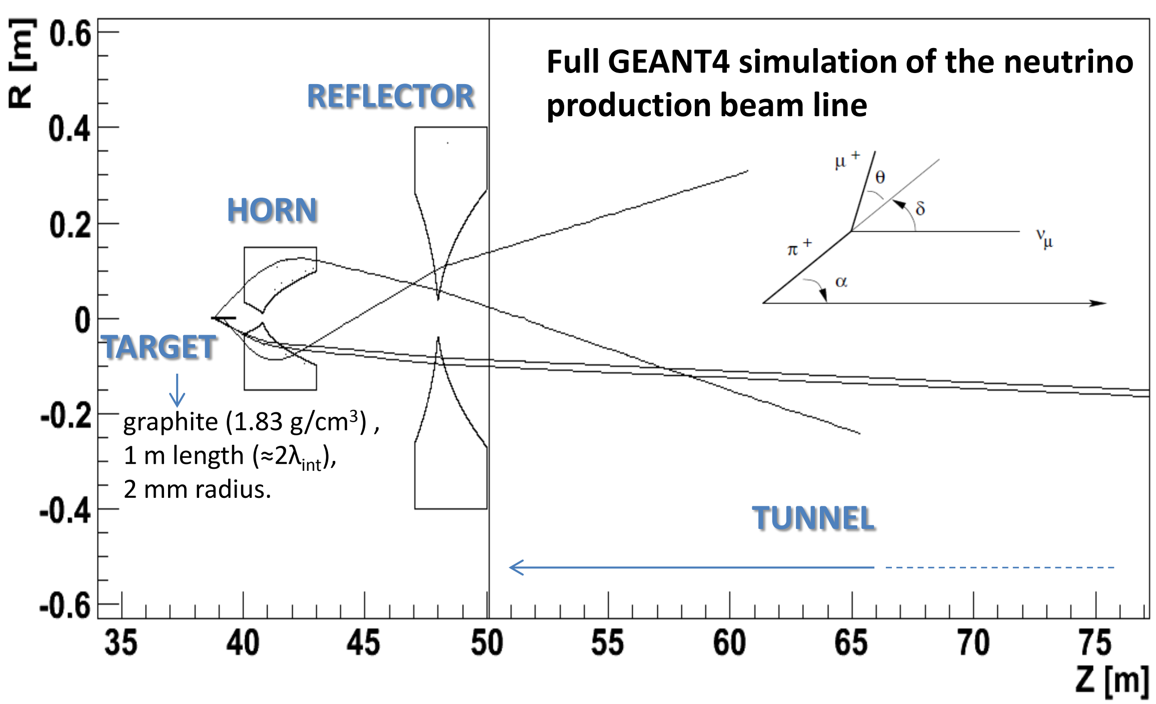
The neutrino focusing

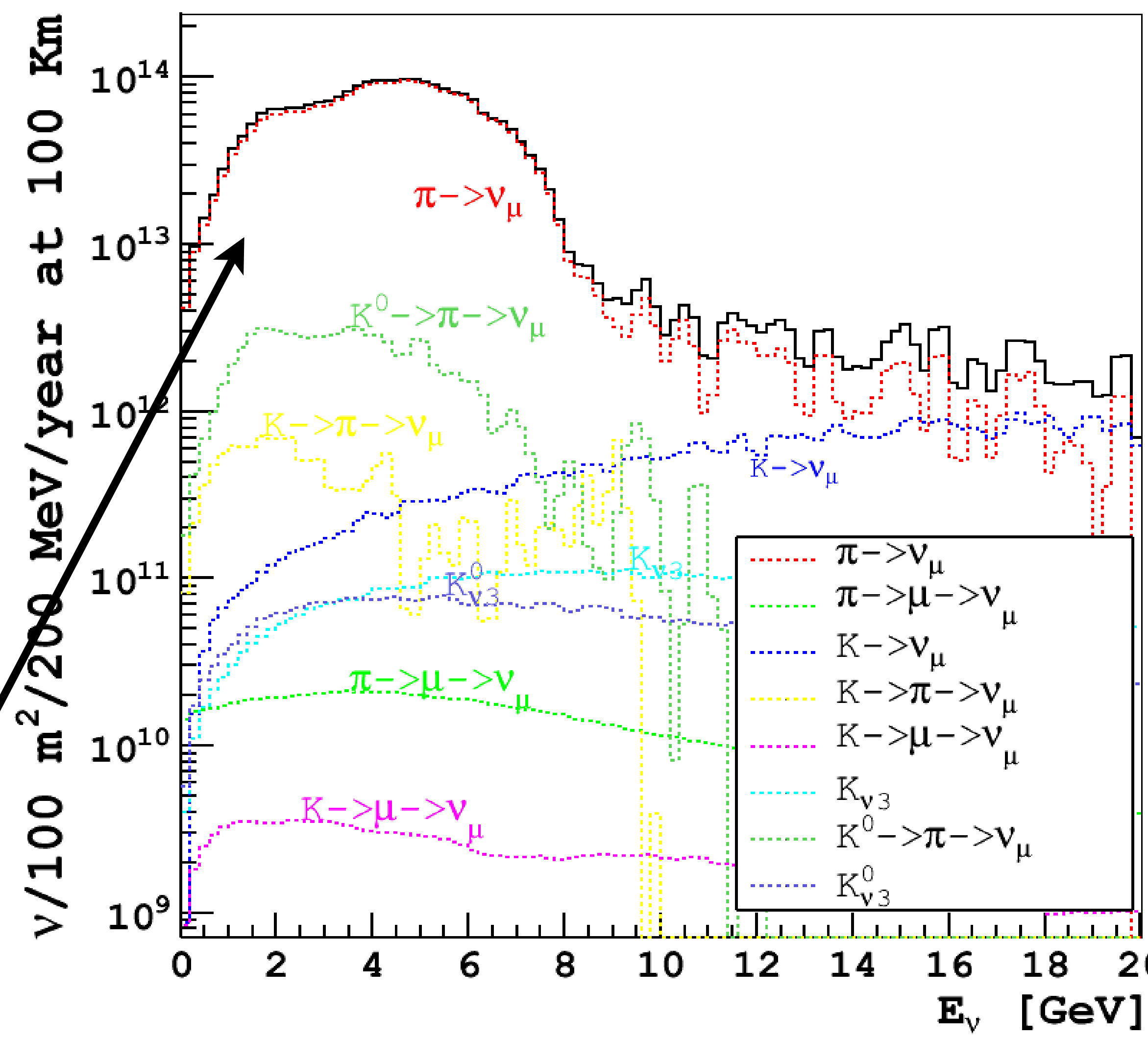
CN2PY Layout



- Design based on CNGS experience
- Parameters still under optimisation

Detailed simulation
Tracking of secondaries

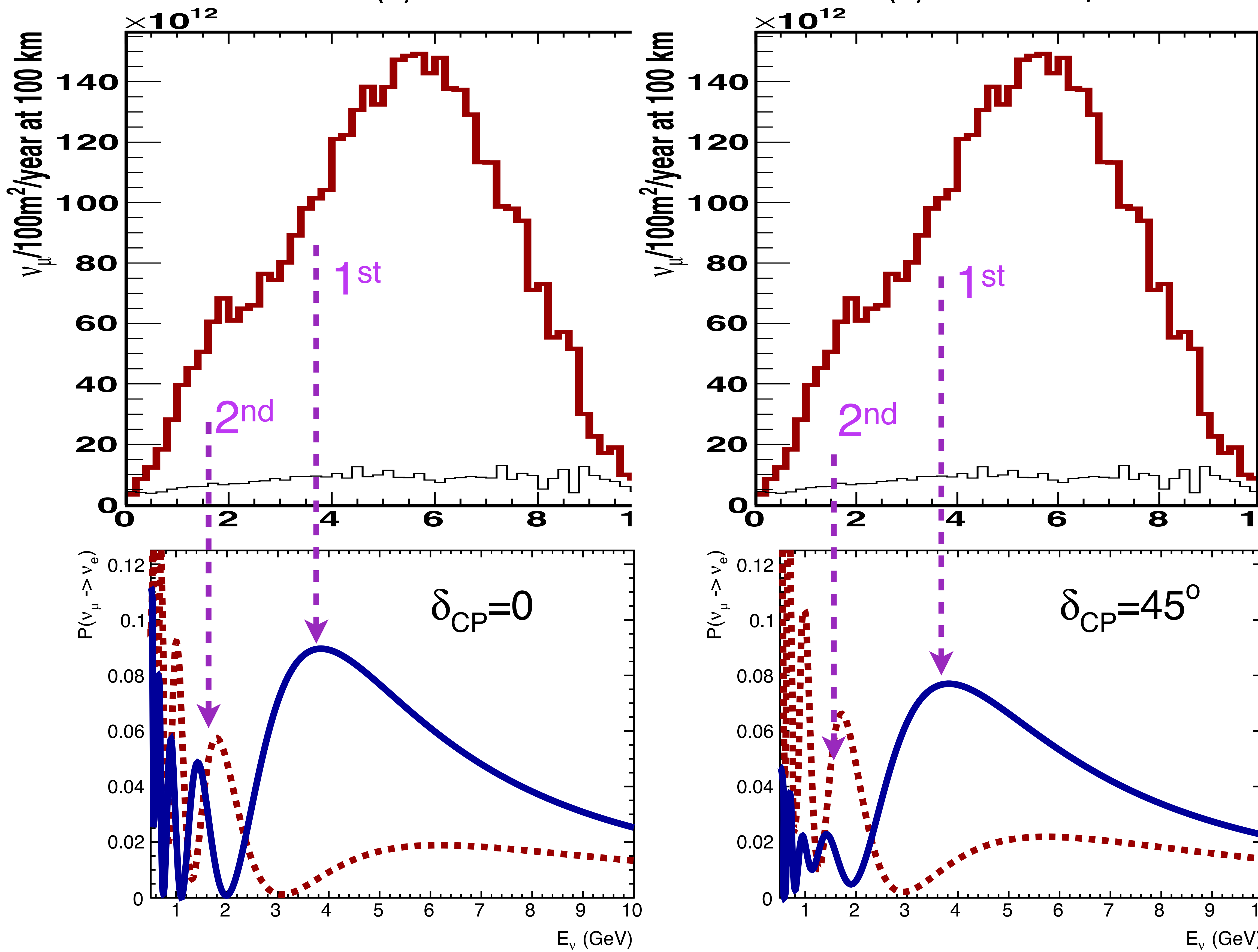




Flux optimised using physics requirements (CPV sensitivity) – effort on going ; improved compared to EoI

Flux optimisation

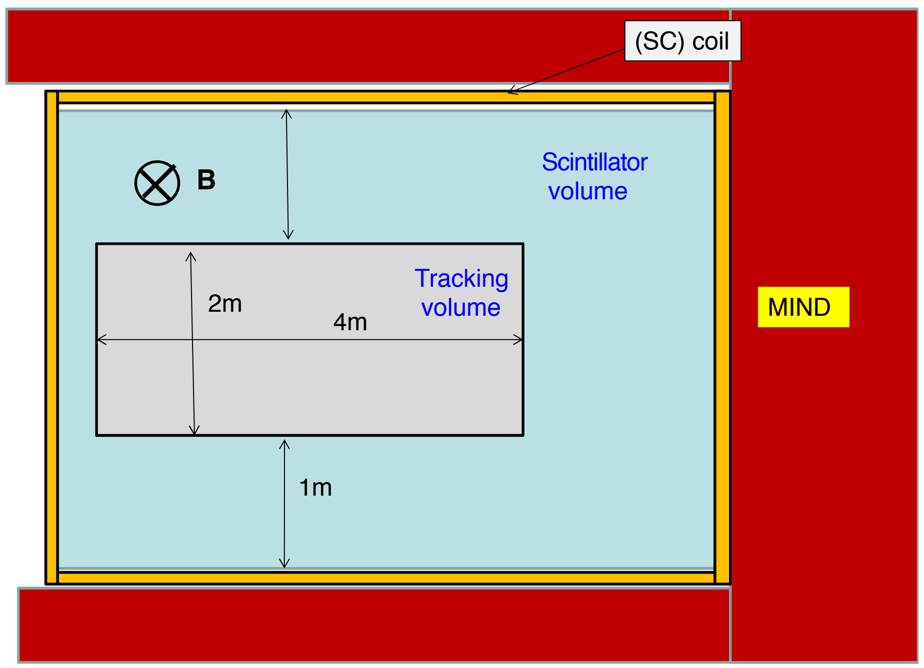
Maximize two conditions: (1) event rate at first maximum and (2) ratio of $2^{nd}/1^{st}$ maximum flux



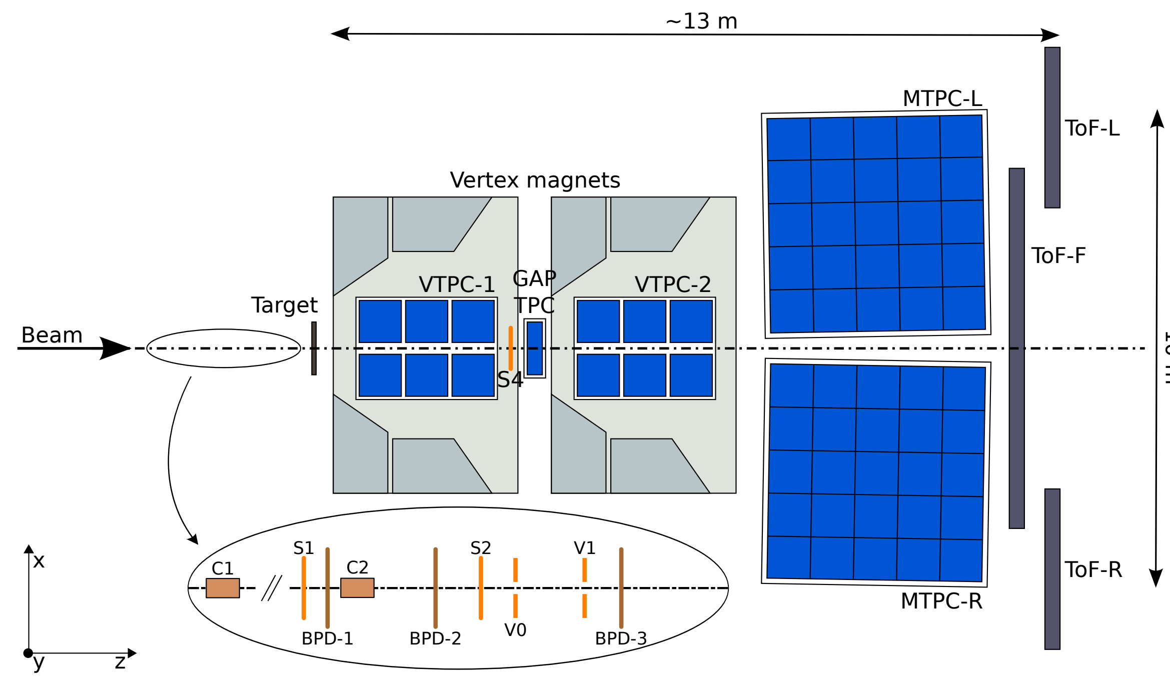
LAGUNA-LBNO, work in progress

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: 10 bar gas argon-mixture TPC surrounded by scintillator bar tracker embedded in an instrumented magnet with field 0.5T
- 270 kg argon mass, of which ≈100 kg fiducial
- 0.2 event/spill @ 700 kW
- 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 acceptance study for 400 GeV incident protons

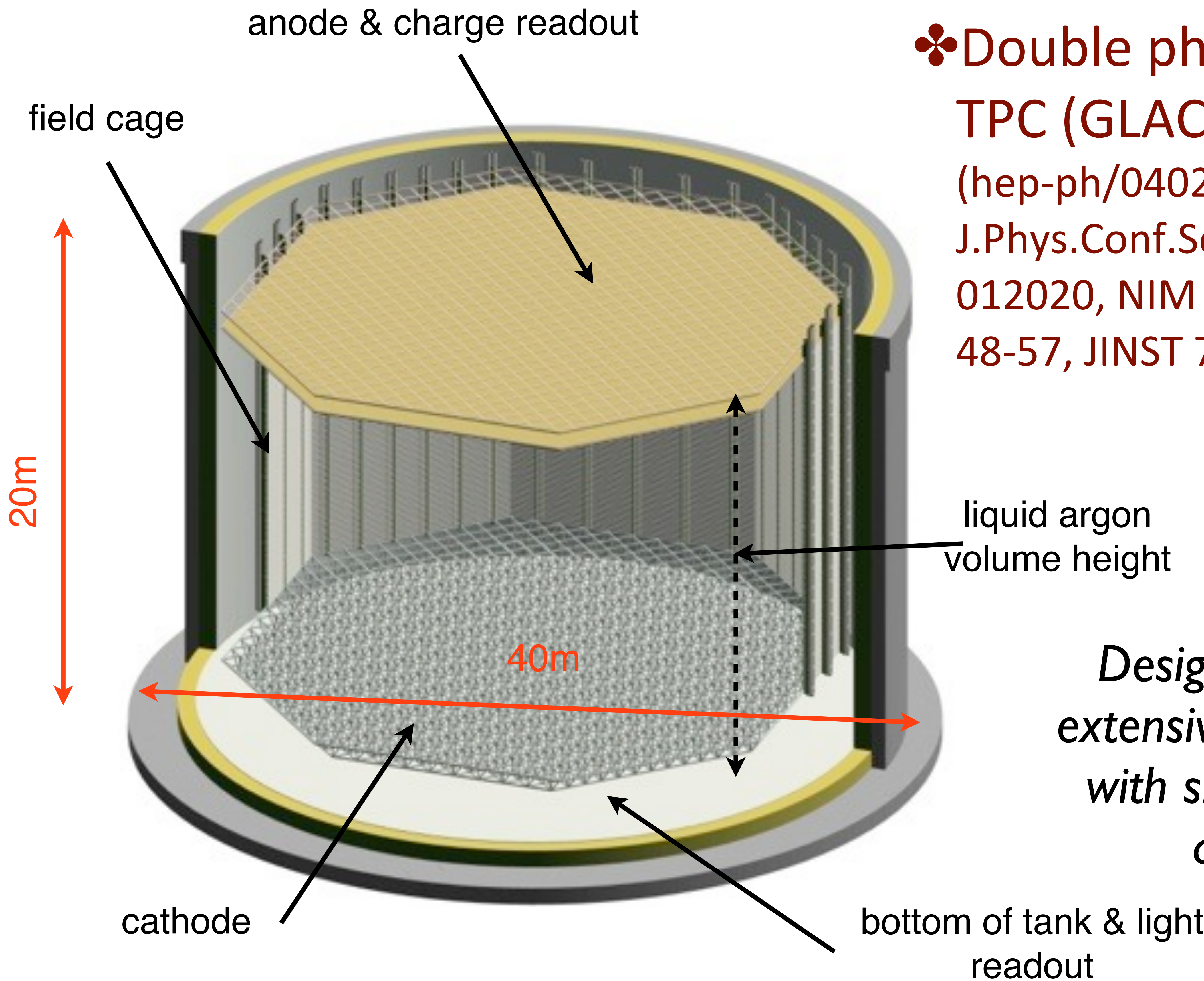
- Precision neutrino cross-section measurements: e.g. MINERVA, T2K-ND280, also nuSTORM (FNAL LoI)

Far detectors requirements

- 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 $\nu_\mu \to \nu_e$ appearance signal
- Neutrino energy resolution $\Delta E_\nu / E_\nu < 10\%$ to observe L/E
- Full kinematical reconstruction, e.g. for $\nu_\mu \to \nu_\tau$
- 4π acceptance for all tracks and neutrals
- Charge and momentum determination for muons, to e.g. study $\bar{\nu}_\mu / \nu_\mu$ in both horn configurations

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

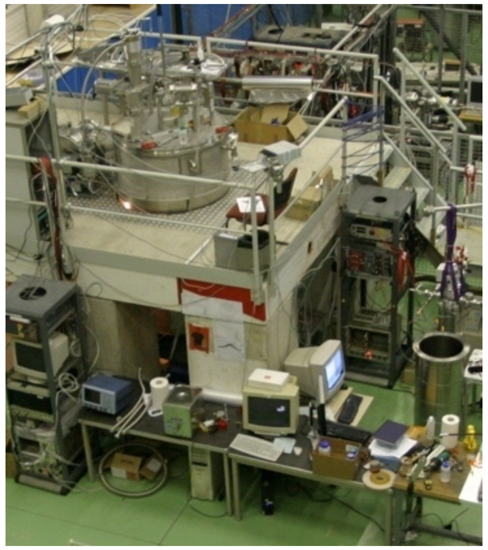
Far liquid Argon detector



✤Double phase LAr LEM TPC (GLACIER,2003) (hep-ph/0402110, J.Phys.Conf.Ser. 171 (2009) 012020, NIM A 641 (2011) 48-57, JINST 7 (2012) P08026)

Design based on extensive experience with smaller scale devices

LAr detector prototyping efforts



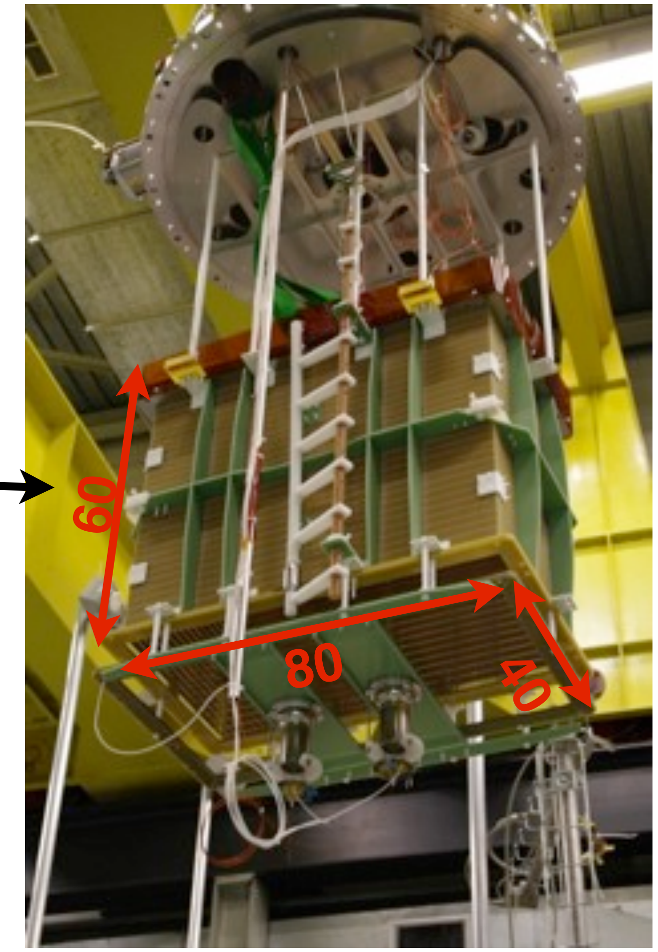
(1) ArDM-1t @ CERN

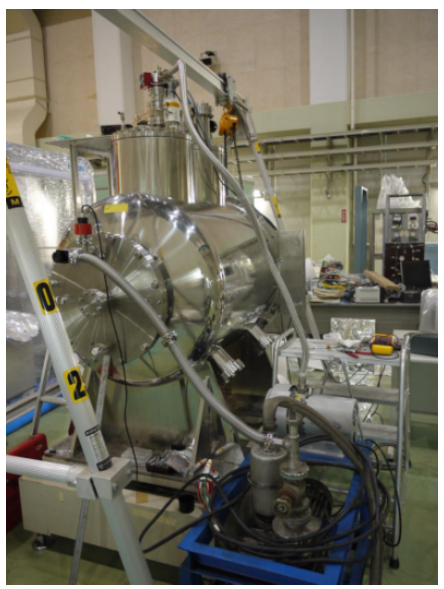
J.Phys.Conf.Ser. 39 (2006) 129-132

World's first double phase liquid argon LEM-TPC successfully operated

40x80cm2

JINST 7 (2012) P08026





(2) J-PARC T32

J.Phys.Conf.Ser. 308 (2011) 012008

0.4 ton LAr TPC

World's largest sample of charged particles events ever collected

(3) ArgonTube @ Bern

Nucl.Phys.Proc.Suppl. 139 (2005) 301-310

Aim to demonstrate world's longest electron drift path

(4) 10T @ CERN

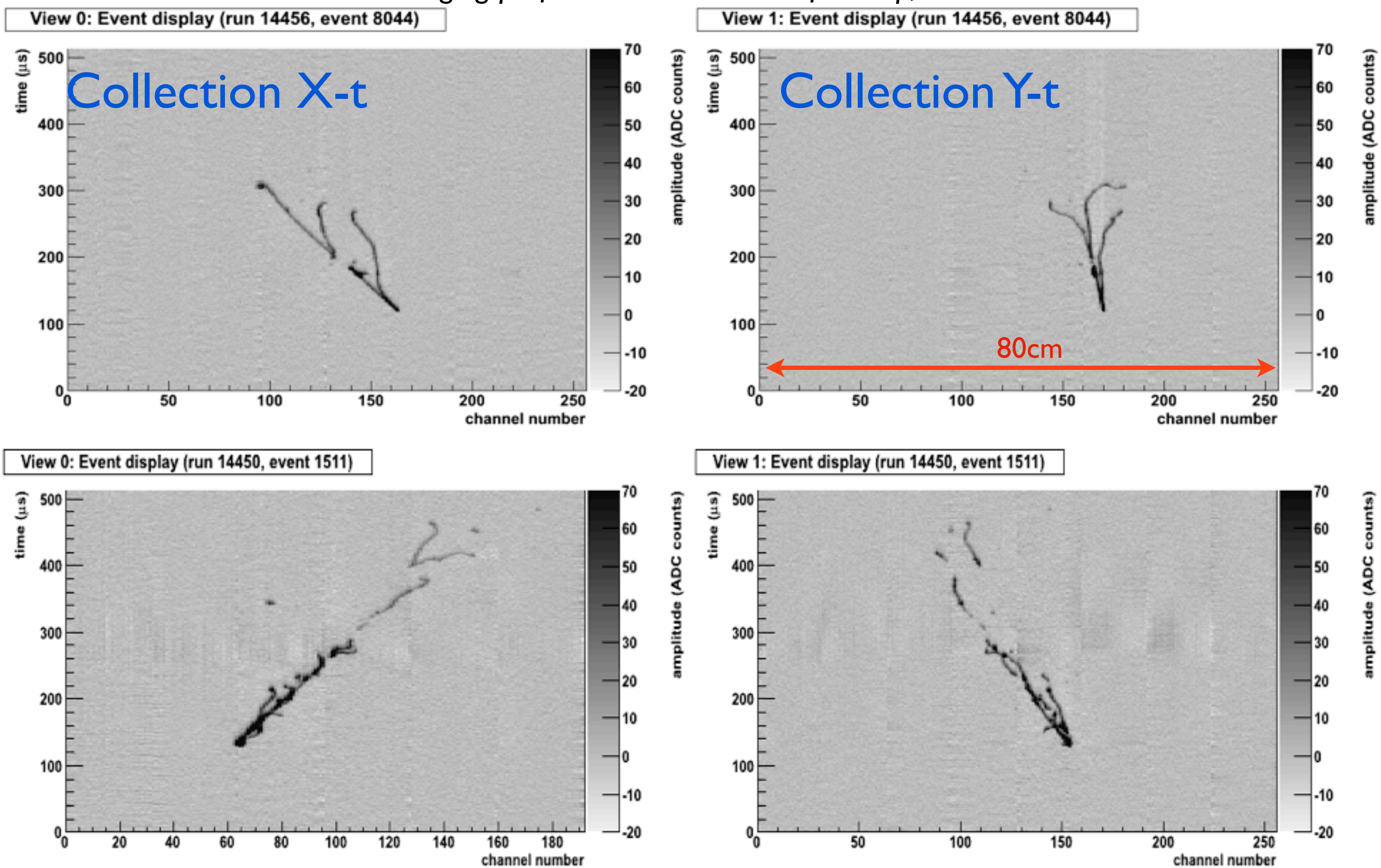
J.Phys.Conf.Ser. 308 (2011) 012024

Purity by flushing w/o evacuation

Real cosmic rays in LAr LEM-TPC

Cosmic track in double phase 80x40cm2 LAr-LEM TPC with adjustable gain

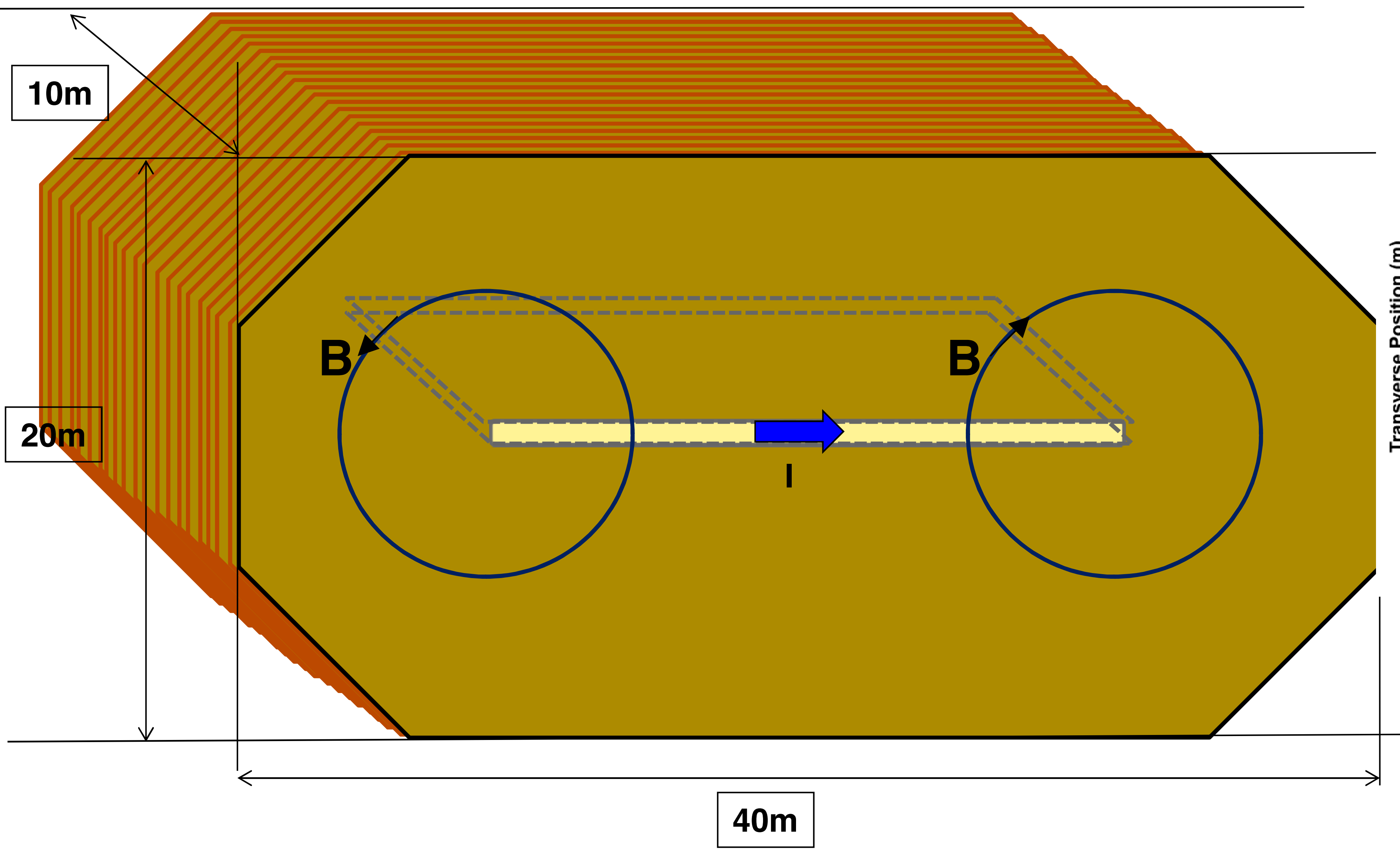
The best imaging performance S/N > 100 for m.i.p, in both views !

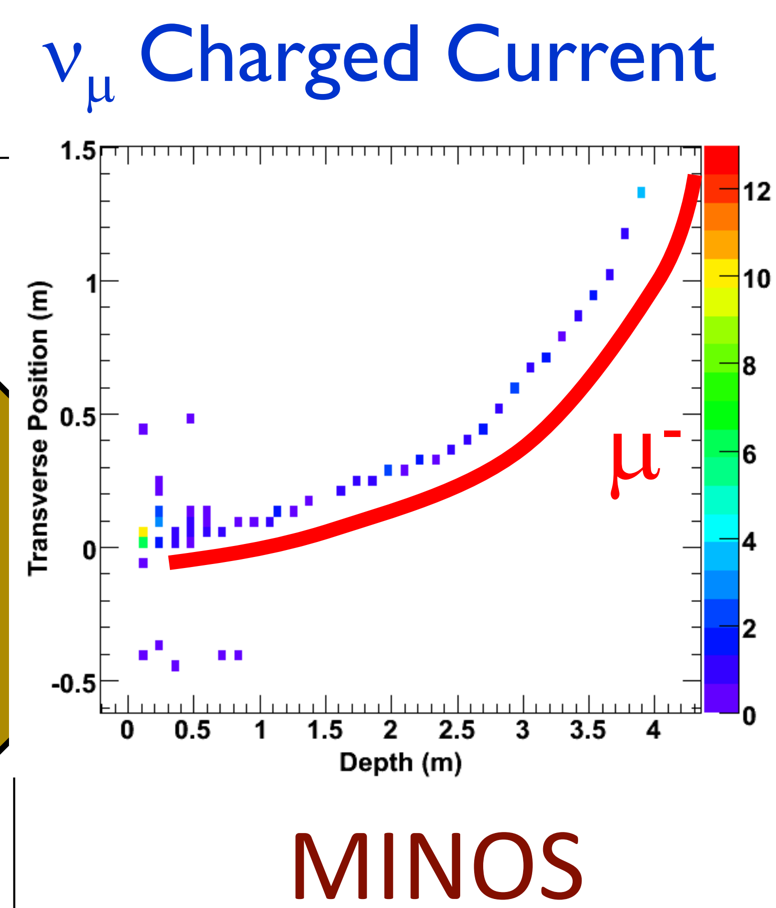


LBNO far muon detector concept

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

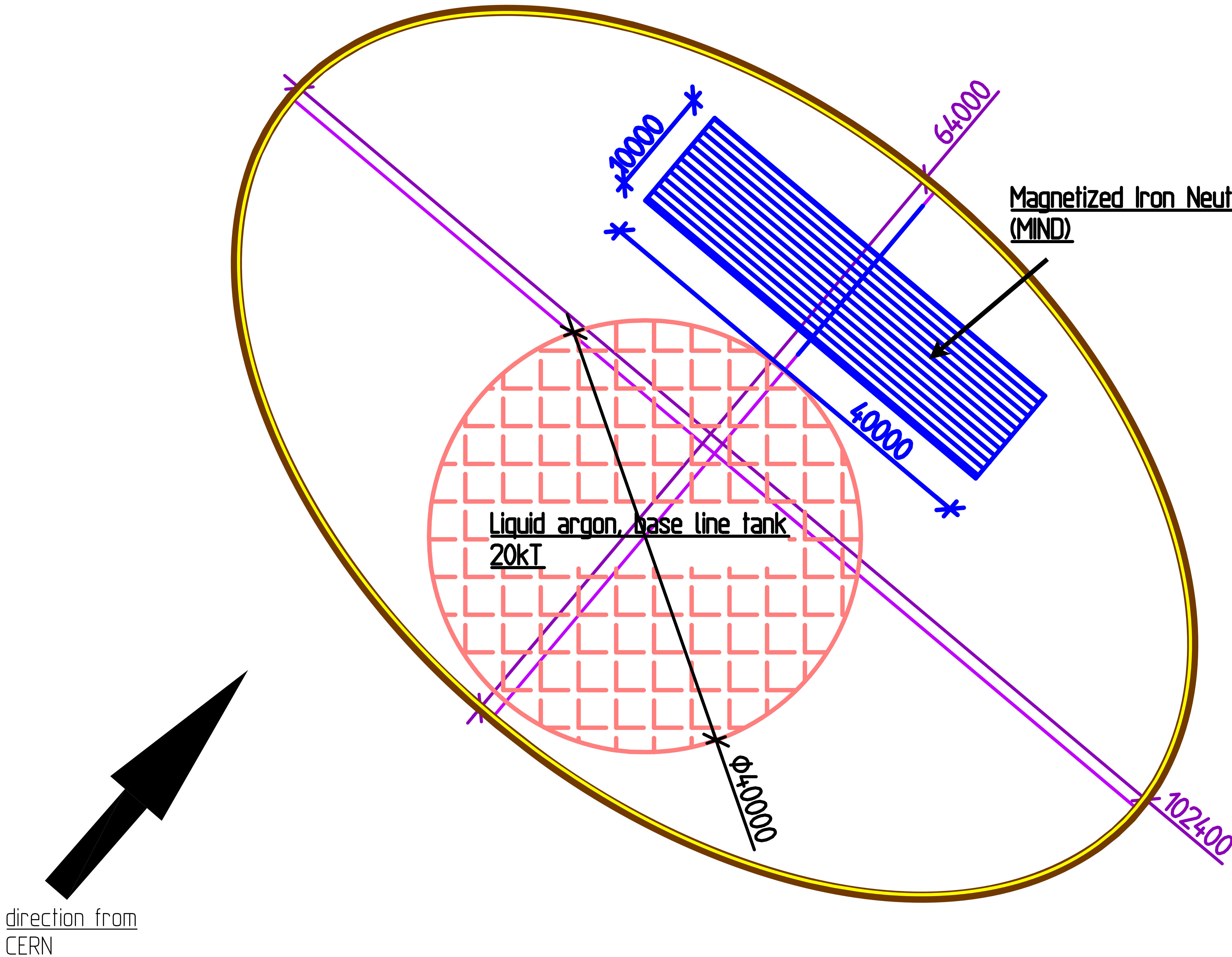
Magnetized Iron Neutrino Detector (MIND)





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

LBNO detectors tentative layout



LBNO sensitivity for MH&CPV

- We estimate the significance C.L. with a chi2sq method, with which we can
  1) exclude the opposite mass hierarchy and
  2) exclude $\delta_{CP} = 0$ or π (CPV)
- Minimize chi2sq w.r.t to the known 3-flavor oscillations and the nuisance parameters using Gaussian constraints

Name	Value	Error (1σ)
L	2300 km	exact
Δm^2_{21}	7.6×10^{-5} eV^2	exact
$\|\Delta m^2_{32}\|$ $\times10^{-3}$ eV^2	2.40	±0.09
$\sin^2\theta_{12}$	0.31	exact
$\sin^2 2\theta_{13}$	0.10	±0.02
$\sin^2\theta_{23}$	0.50	±0.06
Average density of traversed matter (ρ)	3.2 g/cm^3	$\pm4\%$

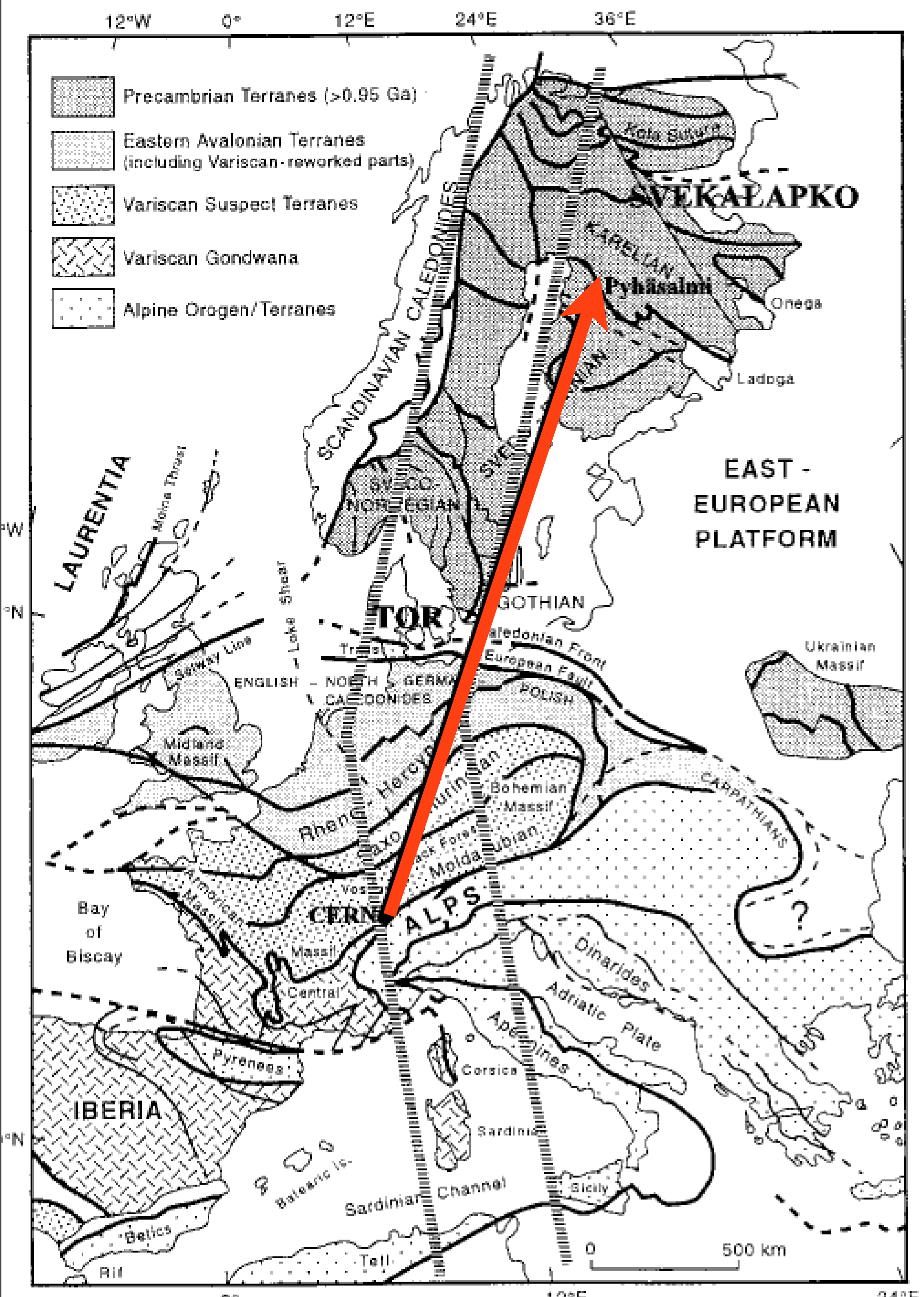
Control of systematic errors will be fundamental

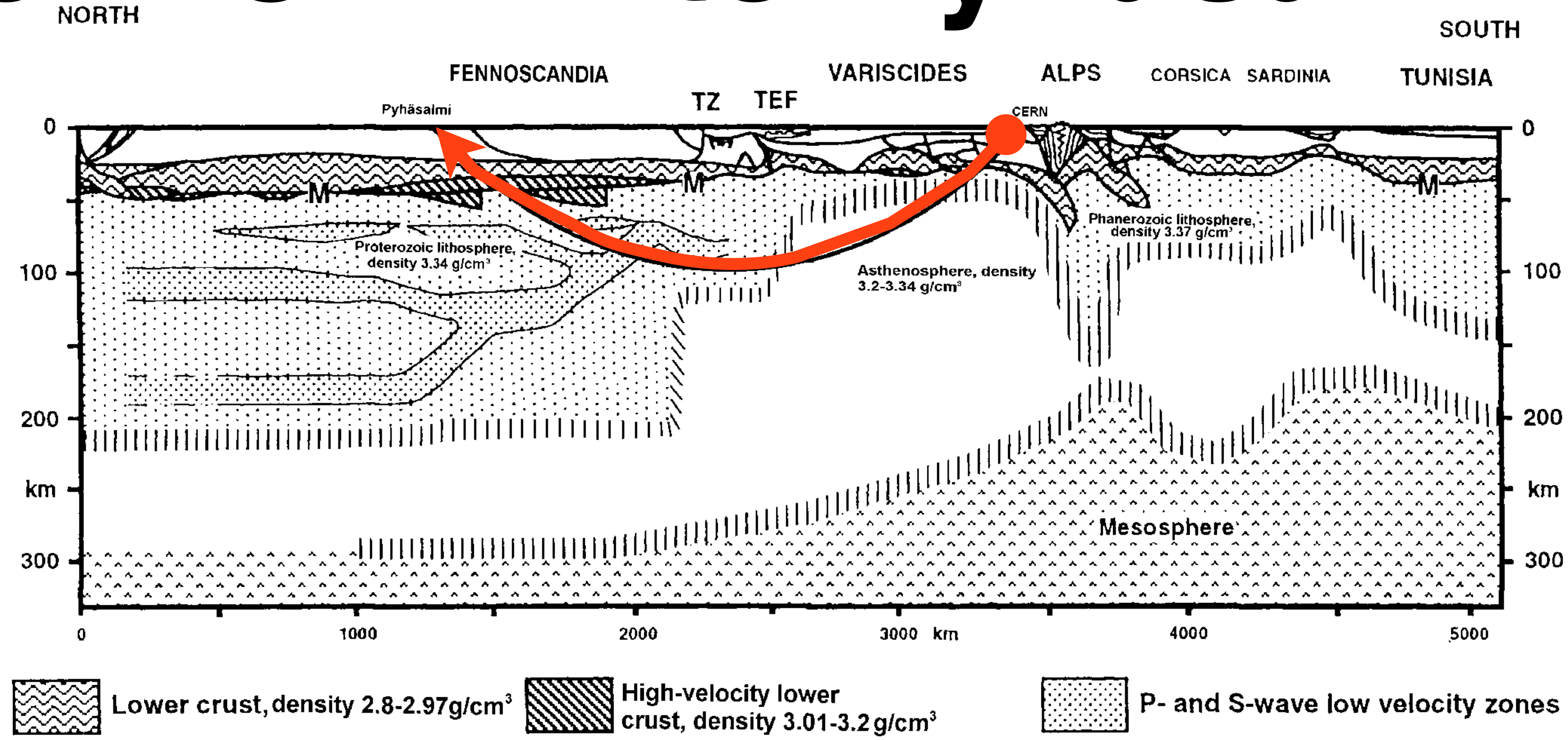
Name	MH determination Error (1σ)	CP determination Error (1σ)
Bin-to-bin correlated:		
Signal normalization (f_{sig})	$\pm5\%$	$\pm5\%$
Beam electron contamination normalization ($f_{\nu_e CC}$)	$\pm5\%$	$\pm5\%$
Tau normalization ($f_{\nu_\tau CC}$)	$\pm50\%$	$\pm20\%$
ν NC and ν_μ CC background ($f_{\nu NC}$)	$\pm10\%$	$\pm10\%$
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	$\pm5\%$	$\pm5\%$
Bin-to-bin uncorrelated	$\pm5\%$	$\pm5\%$

Conservative errors

Neutrinos from CERN to Pyhäsalmi

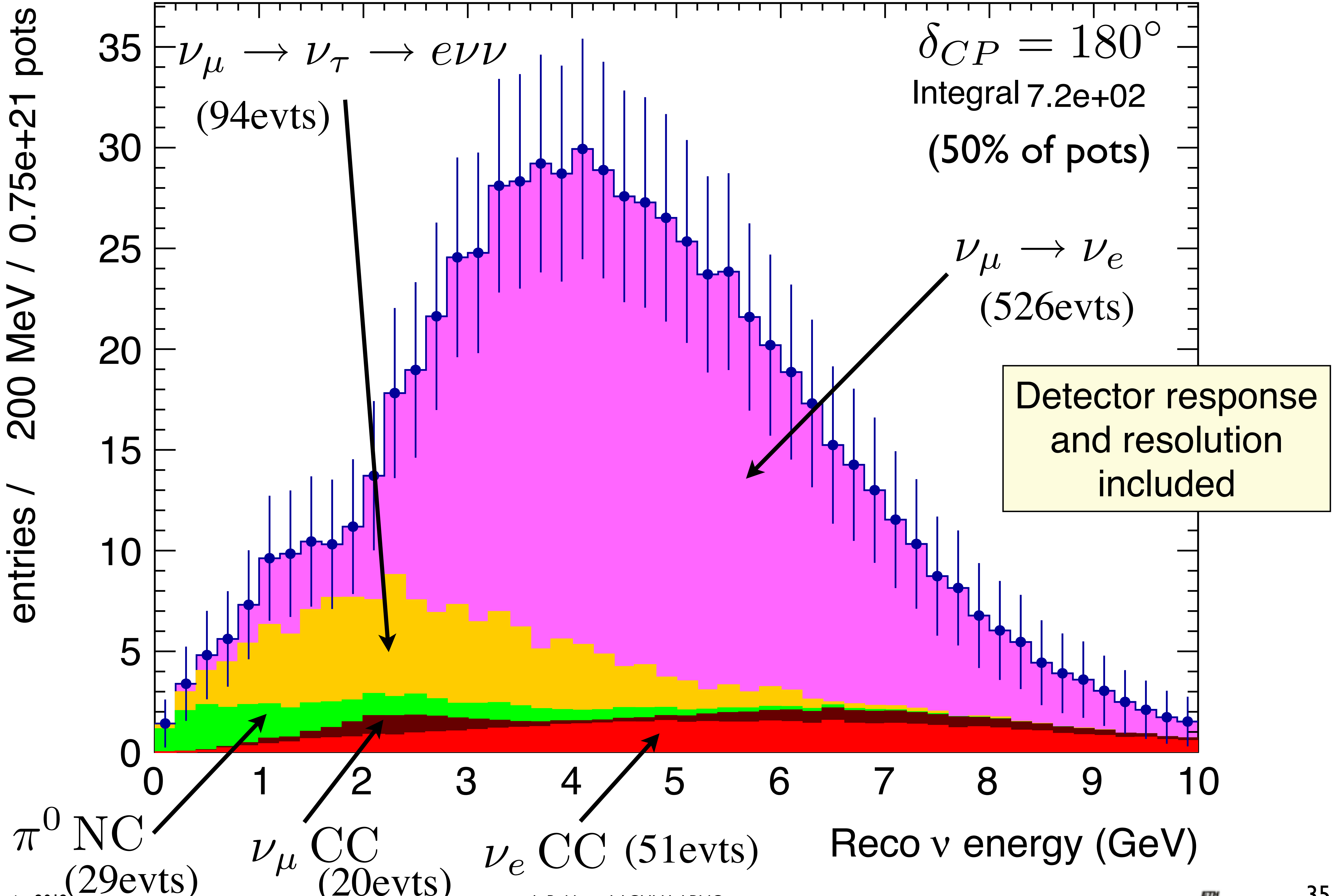
arXiv:hep-ph/0305042v1





- 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)

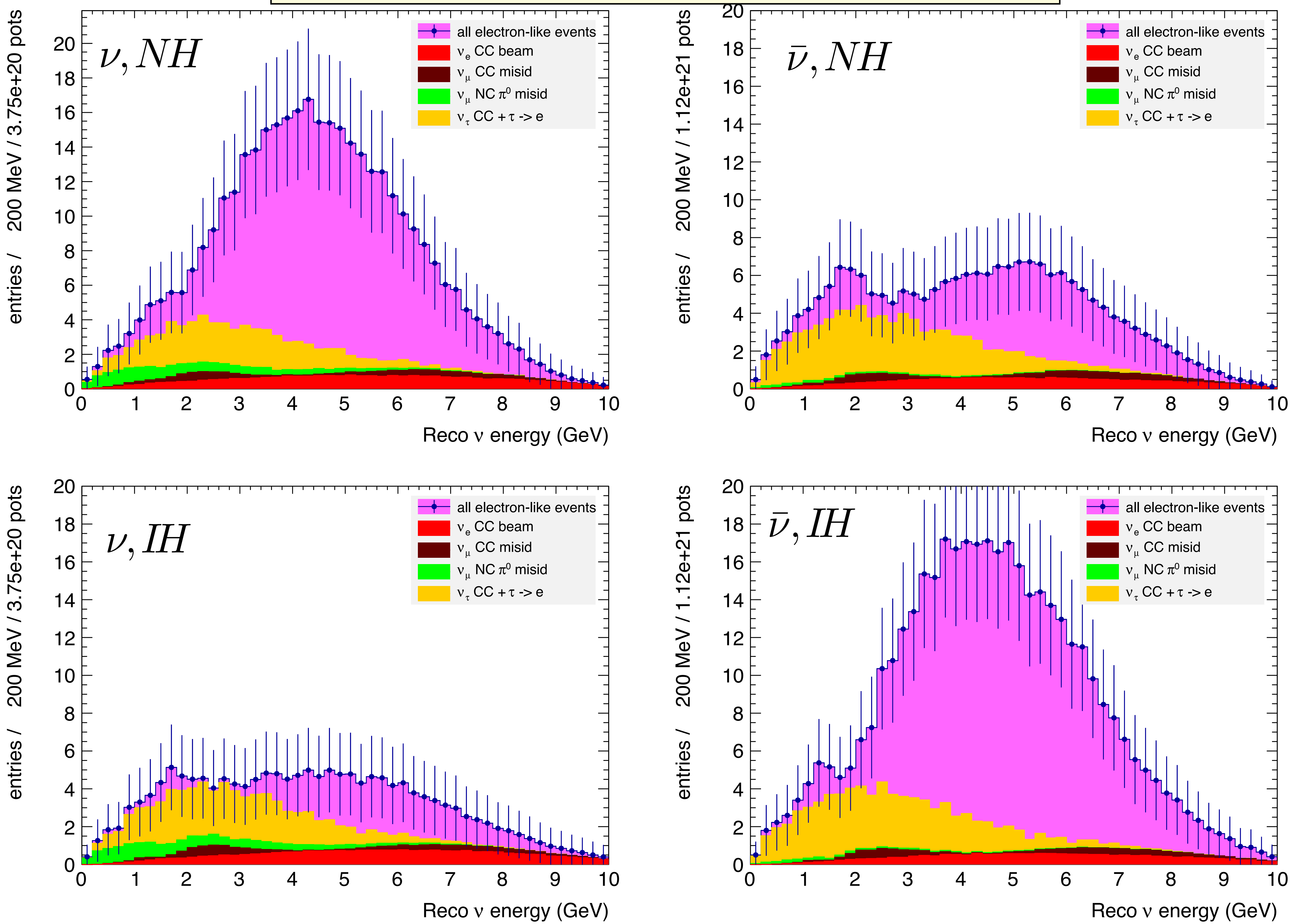
e-like CC sample (+)



Neutrino/antineutrinos and MH

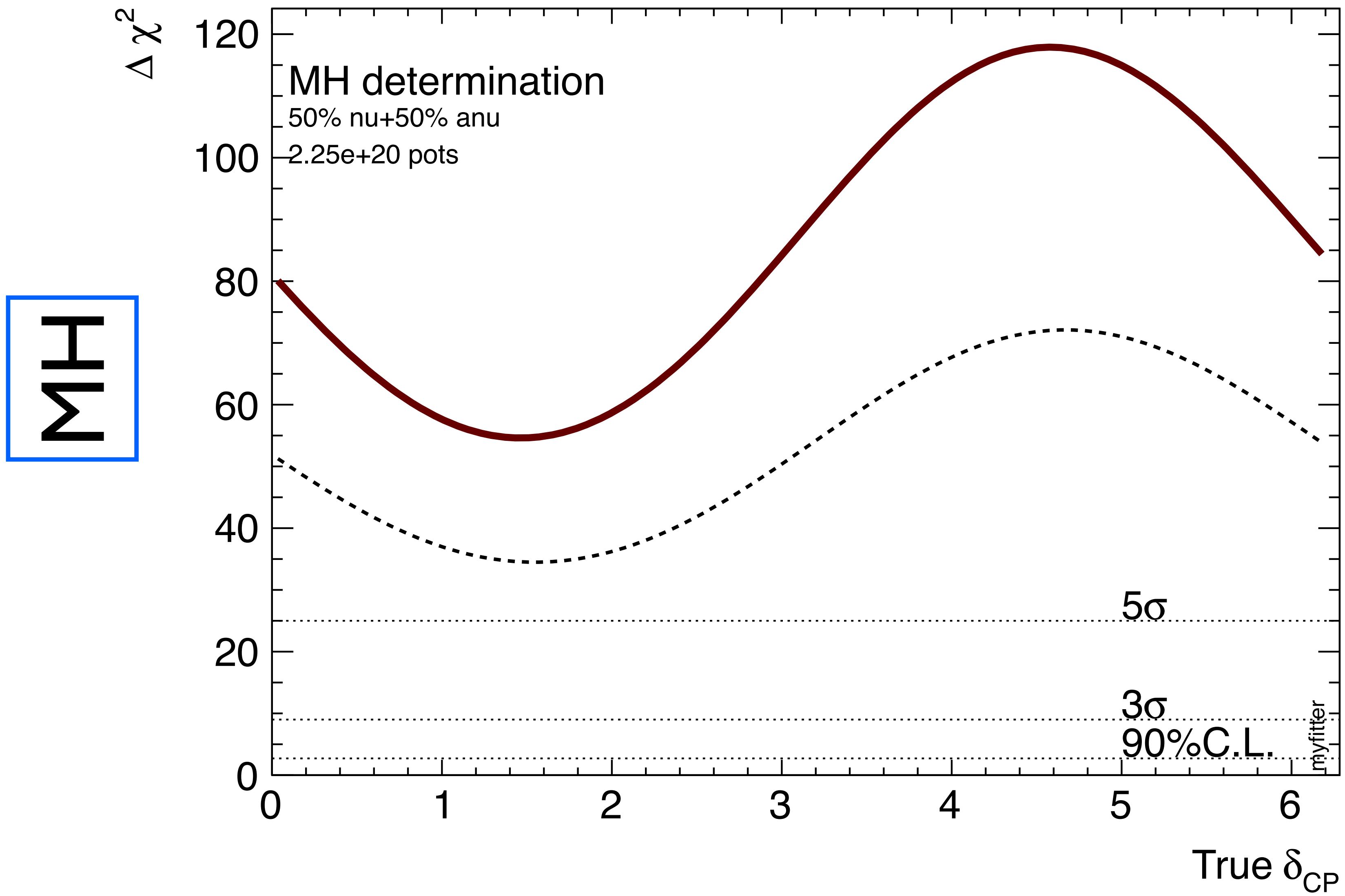
Detector response and resolution included

Running mode:
ν/anti-ν:25%/75%



Sensitivity to matter hierarchy

2.25e20 pot

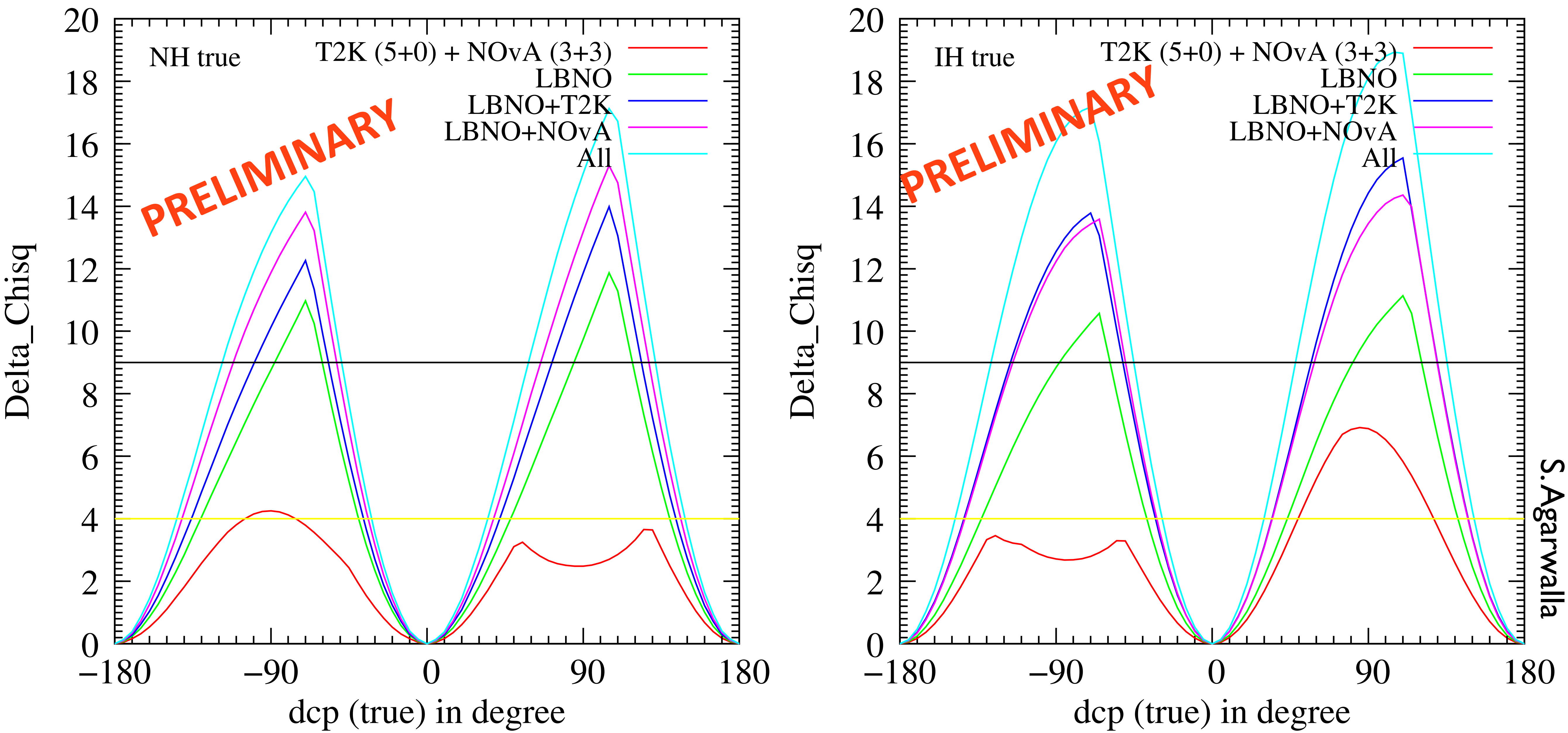


Provide a >5σ direct determination of MH for all values of δ_{CP} within 2.5 years of running

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

Sensitivity combining T2K(295km), NOvA(810km) and LBNO(2300km)



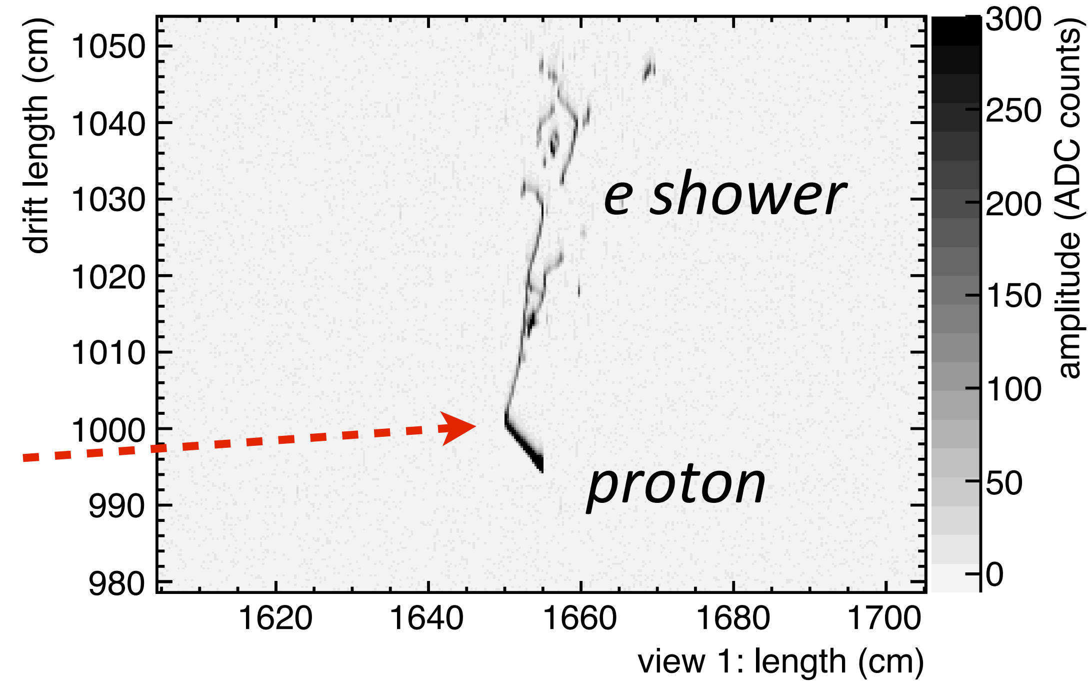
The power of combining several different baselines L:
LBNO 20kton(5+5) + T2K(5+0) + NOvA(3+3) ≈ 40-45% CPV at >3σ C.L.

Atmospheric neutrinos

"Free once you paid for an underground location"

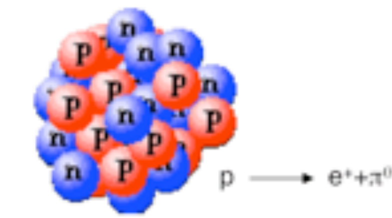
Mode	Events/year
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

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 an 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

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

For a SN explosion at the distance of 5 kpc

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

		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

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** ←
Pyhäsalmi extended site investigation	**2013**
End of LAGUNA-LBNO DS: technical designs, layouts, liquids handling&storage, safety, ...	**2014**
Critical decision	**2015 ?**
Excavation-construction (incremental, pilot?)	**2016-2021 ??**
LBL physics start	**2023 ???**

Conclusions (I)

- **LBNO, proposed to be located underground at Pyhäsalmi 2300km away from CERN, has truly unique scientific opportunities.**
  - ➡ All transitions (e/μ/tau) measurable in neutrino/antineutrino in a single experiment
  - ➡ Test of three neutrino oscillation paradigm, independently for nu's and antinu's
  - ➡ Direct test of matter effects and measurement of CP-phase with ±20^{o} error
  - ➡ A fully conclusive mass hierarchy determination(MH) at >5σ C.L, in a cleaner and more significant way than any other methods/proposals
  - ➡ A very good chance to find CPV with the spectral information providing unambiguous oscillation parameters sensitivity, with 40-45% CPV coverage at >3σ C.L. Increase to 70% CPV coverage with three-fold more exposure or a second beam from another site (at present consider Protvino / OMEGA).
  - ➡ Several background free nucleon decay channels, competitive with HK sensitivity
  - ➡ Detection of several astrophysical sources (SN,...) and fresh new look at atmospheric neutrinos with high granularity and resolution (atm tau app., atm MH, ...).
- **LBNO defines a clear upgrade path** (long term vision / incremental approach) to fully explore CPV, with higher power conventional beam or Neutrino Factory.

Conclusions (II)

- An expression of interest has been submitted to the CERN SPS Committee in June 2012.
- We have called on CERN to engage in a collaborative effort to prepare a full engineering design of the CN2PY beam and to promptly support the necessary detector prototyping and test beams needed to develop a Proposal by the end of 2014.
- The project is OPEN, still being defined and has many opportunities. We welcome all kind of contributions, stressing that the far detectors are already foreseen to be deep underground, with access via the existing and unique infrastructure present at Pyhäsalmi.

Acknowledgements

- FP7 Research Infrastructure "Design Studies" LAGUNA (Grant Agreement No. 212343 FP7-INFRA-2007-1) and LAGUNA-LBNO (Grant Agreement No. 284518 FP7-INFRA-2011-1)
- We are grateful to the CERN Management for supporting the LAGUNA-LBNO design study.
- We thank the CERN staff participating in LAGUNA-LBNO, in particular M.Benedikt, M.Calviani, I.Efthymiopoulos, A.Ferrari, R.Garoby, F.Gerigk, B.Goddard, A.Kosmicki, J.Osborne, Y.Papaphilippou, R.Principe, L.Rossi, E.Shaposhnikova and R.Steerenberg.
- The contributions of Anselmo Cervera are also recognized.

Backup slides

Courtesy PvZ

LAGUNA LAr prototype @ CERN

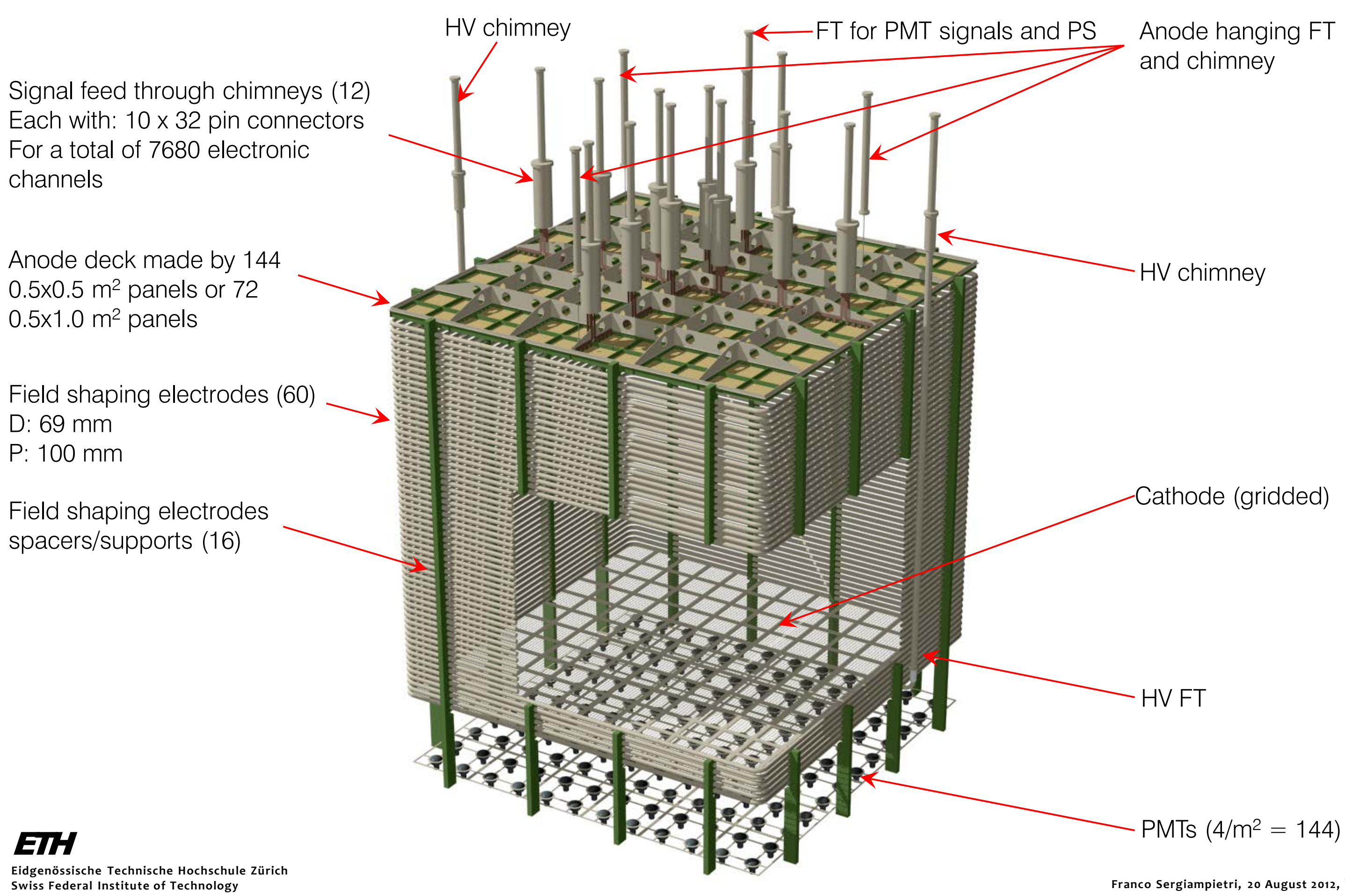
· 6x6x6m^3 prototype to be constructed and operated at CERN, as a prototype of the far detector double-phase TPC

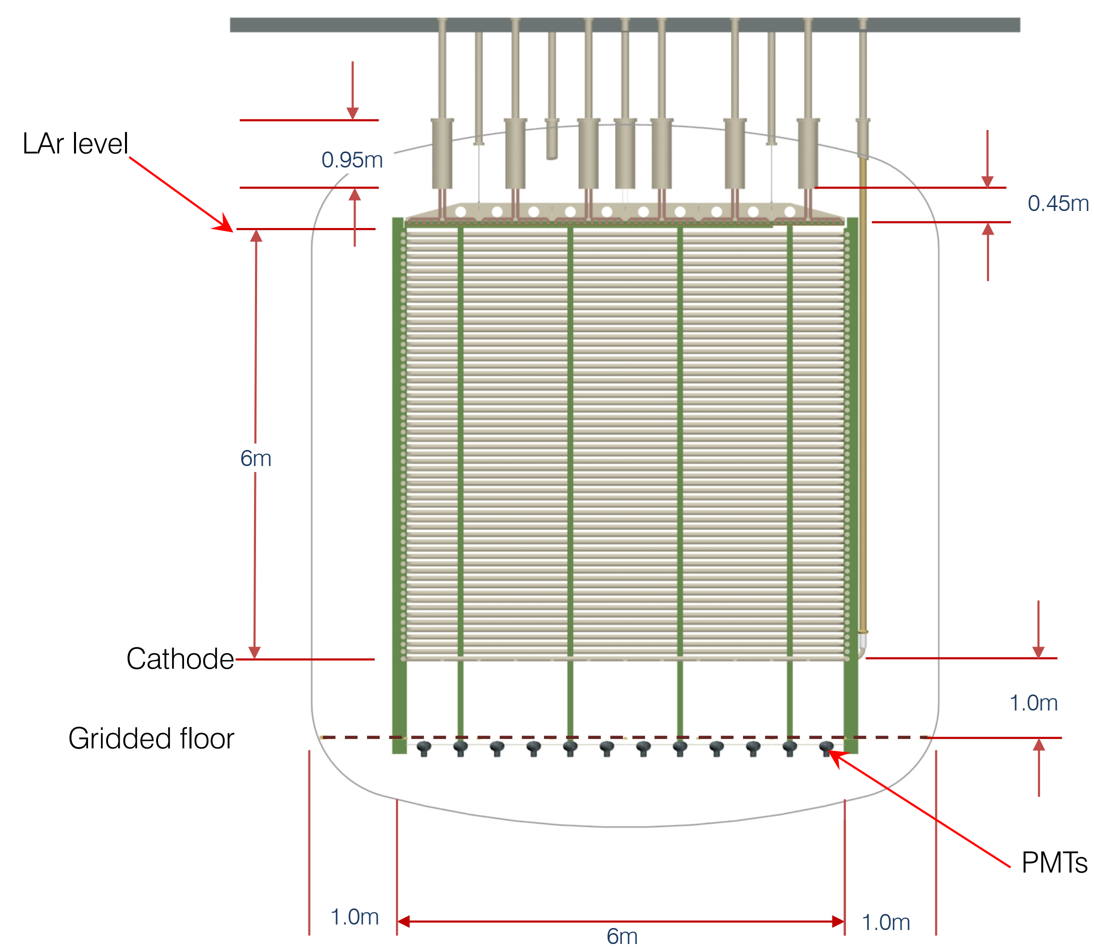
· Charged test beams to collect the large controlled data set allowing electromagnetic and hadronic calorimetry and PID performance to be measured, simulation and reconstruction to be improved and validated

· Detector to be positioned in the North Area in an extension of the EHN1 building

· Timescale: facility for preparation of full LAGUNA-LBNO proposal

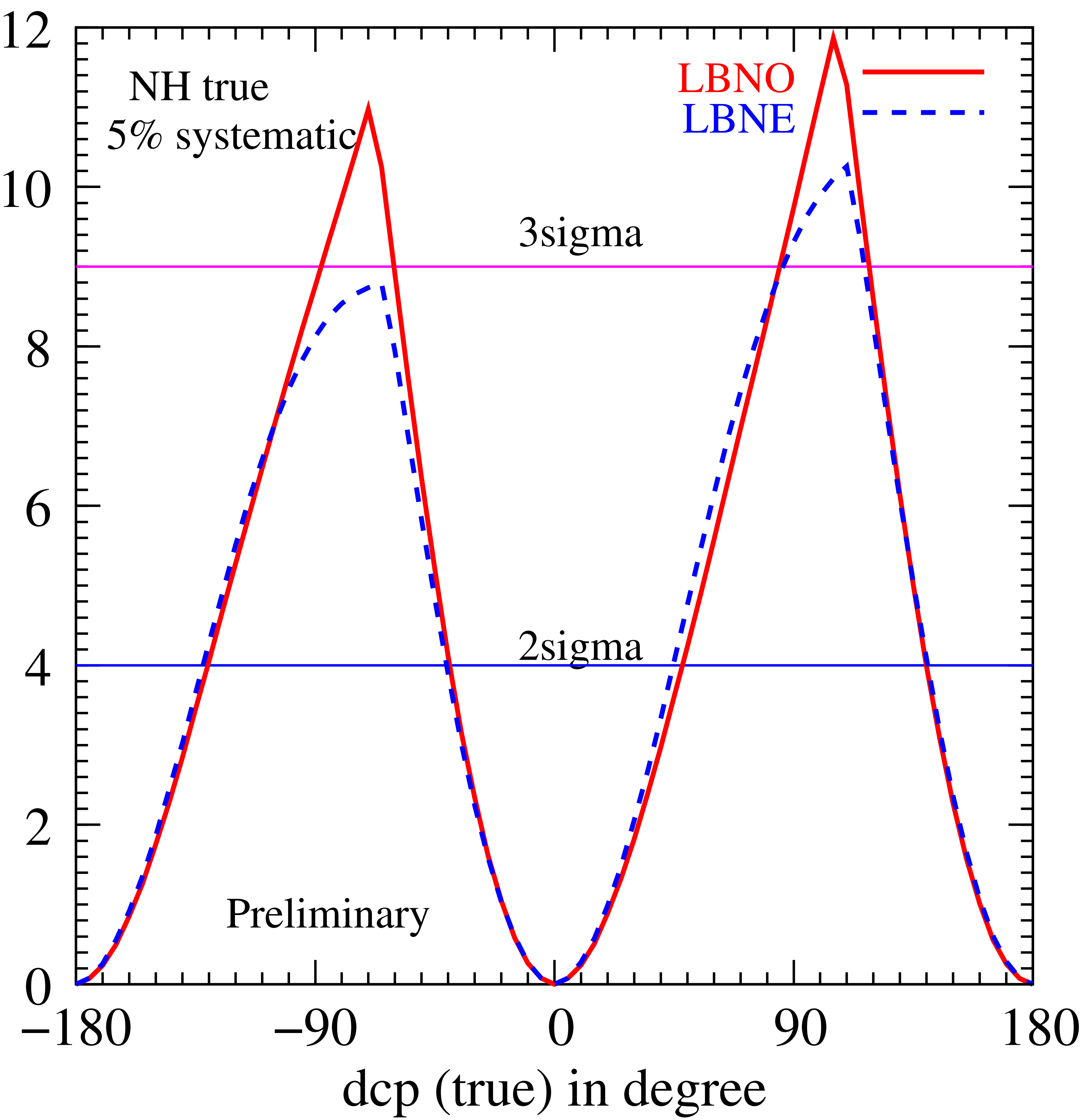
· Also highly relevant to other options wanting to use LAr TPC (LBNE, Okinoshima)





CPV: LBNE vs LBNO

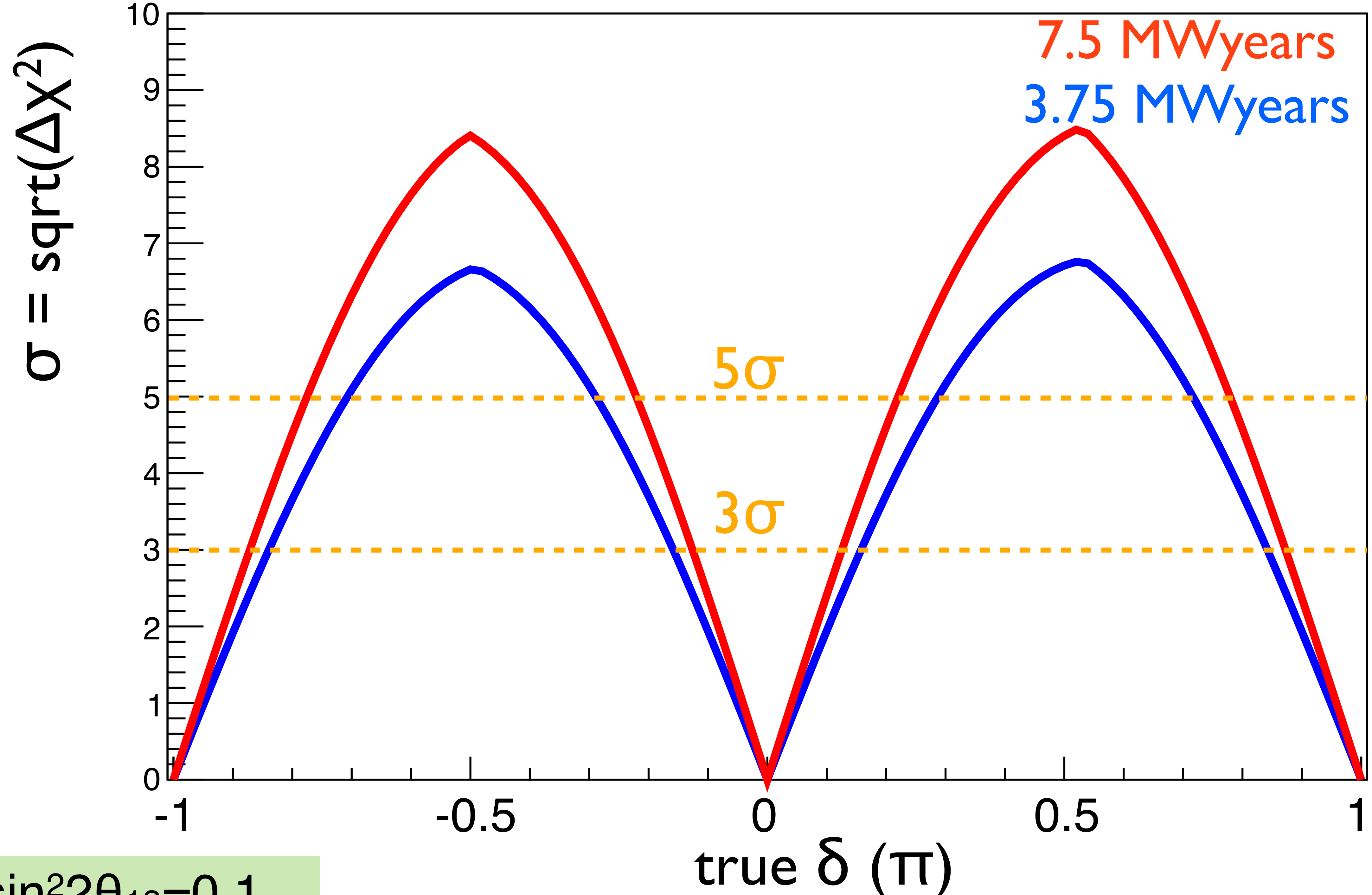
- Assume same systematic errors for both setups
- LBNE 10 kton @ 1300 km
- LBNO 20kton @ 2300 km



Hyper-K CPV sensitivity

(Exclusion of $\delta=0,\pi$)

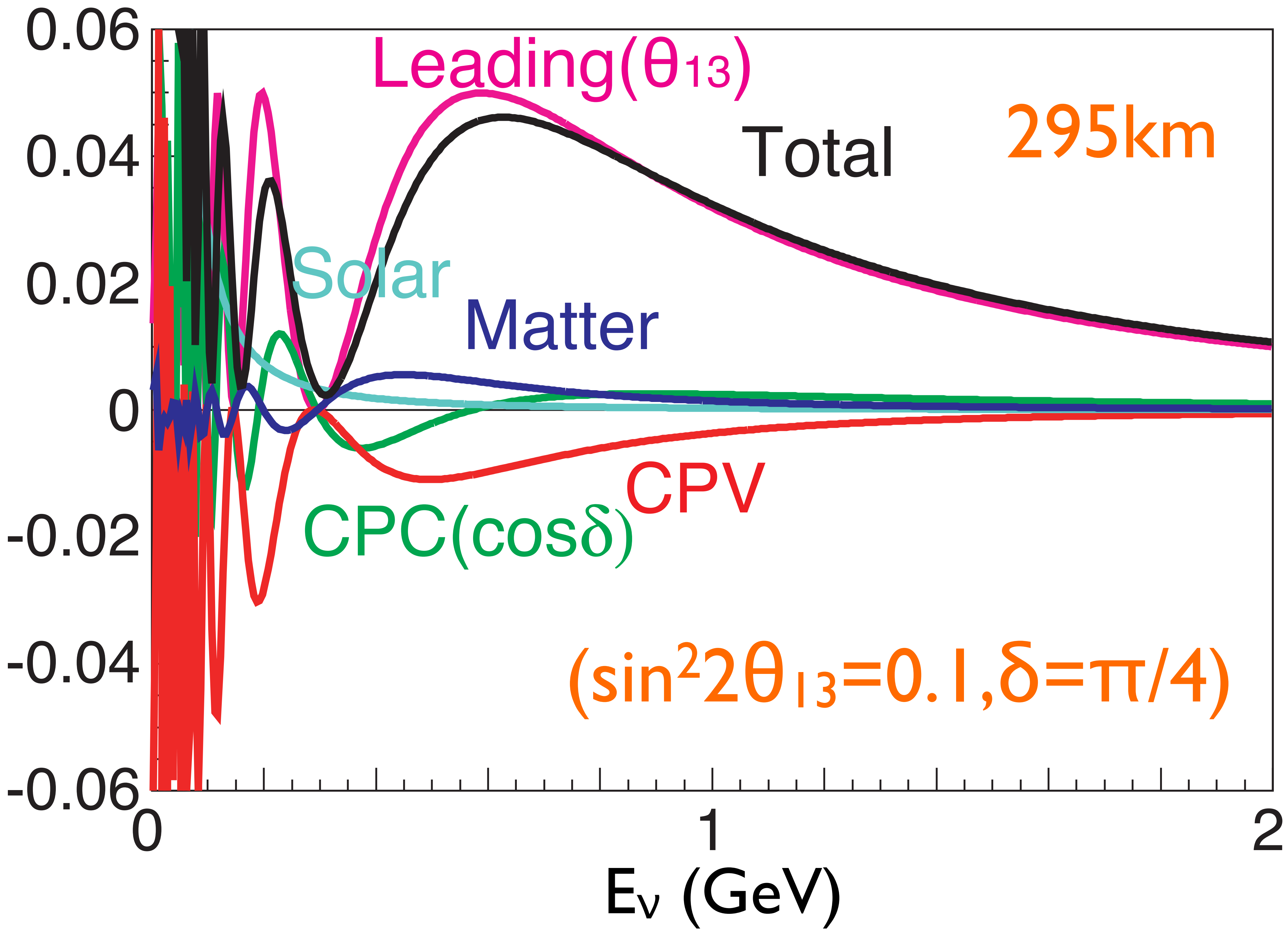
5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



$\sin^2 2\theta_{13}=0.1$
Normal hierarchy

For 74(55)% of δ, >3(5)σ with 7.5MWyrs

CP asymmetry at 295km

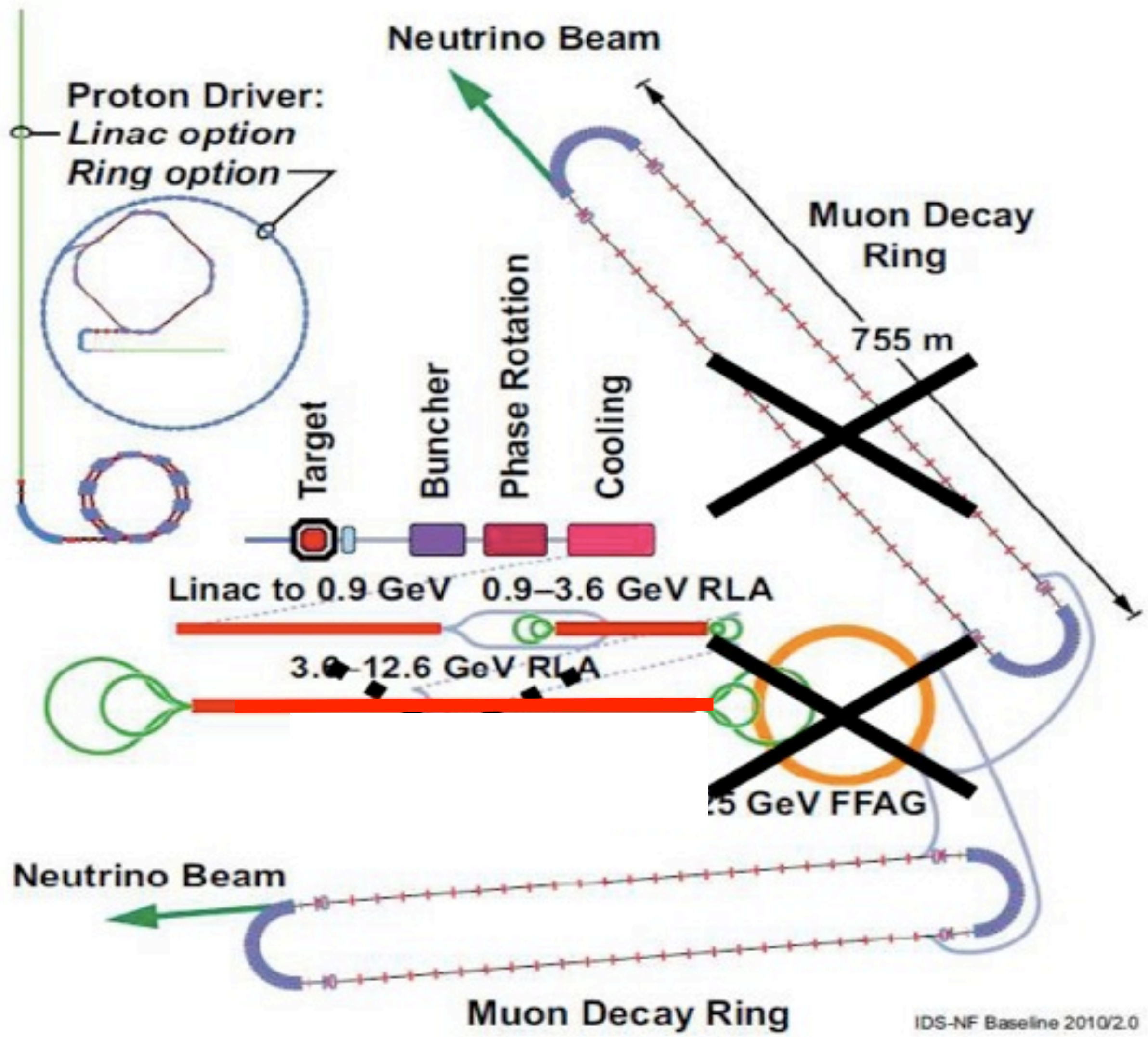


Low Energy Neutrino factory (LENF)

Pure beam and multiple oscillation channels

Requires magnetised far neutrino detector

LENF is the baseline since ϑ_{13} is known to be large



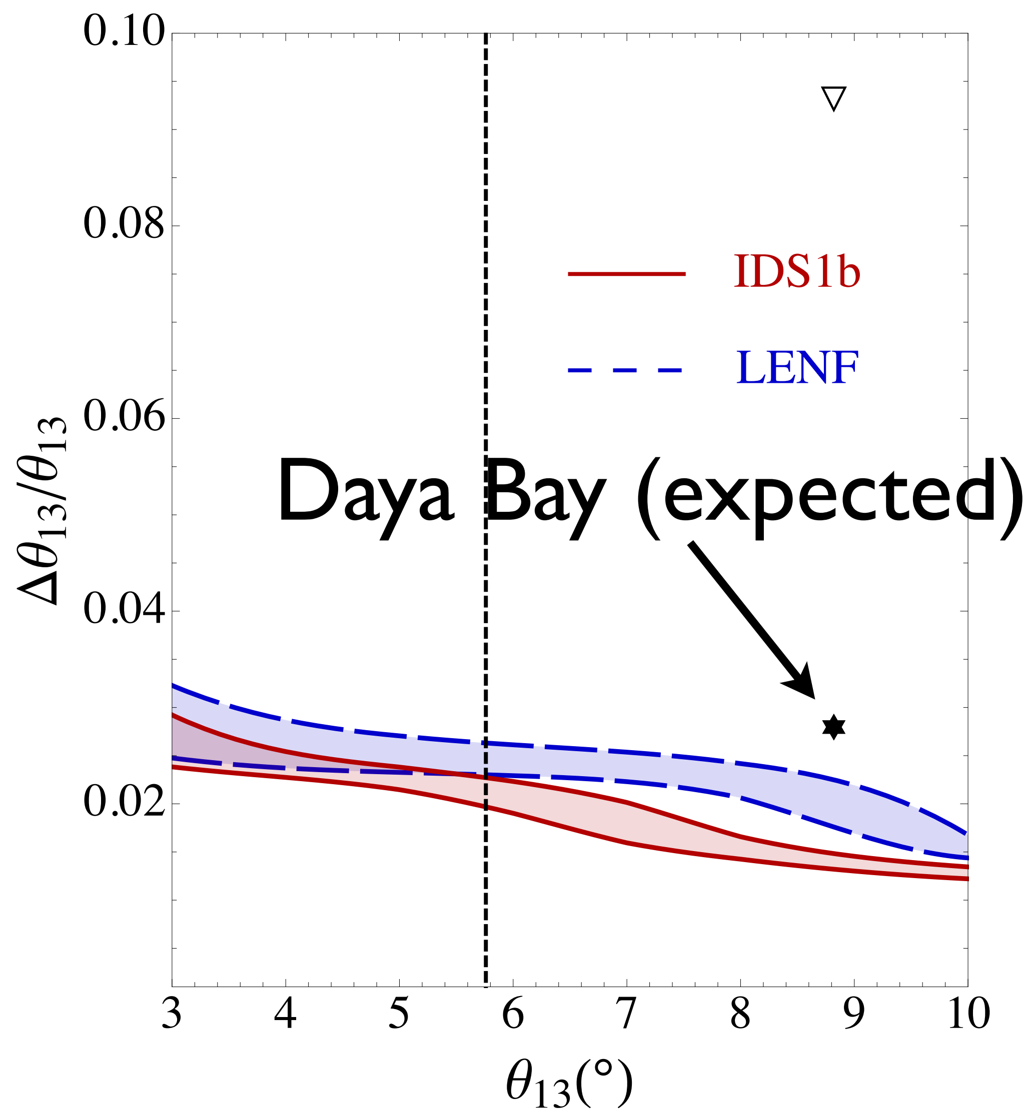
New baseline for IDS-NF (Apr 2012):
LENF:
E=10 GeV and L=2000 km with MIND

The LENF has the power to reach ≈ 80% CPV coverage at >3sigmas

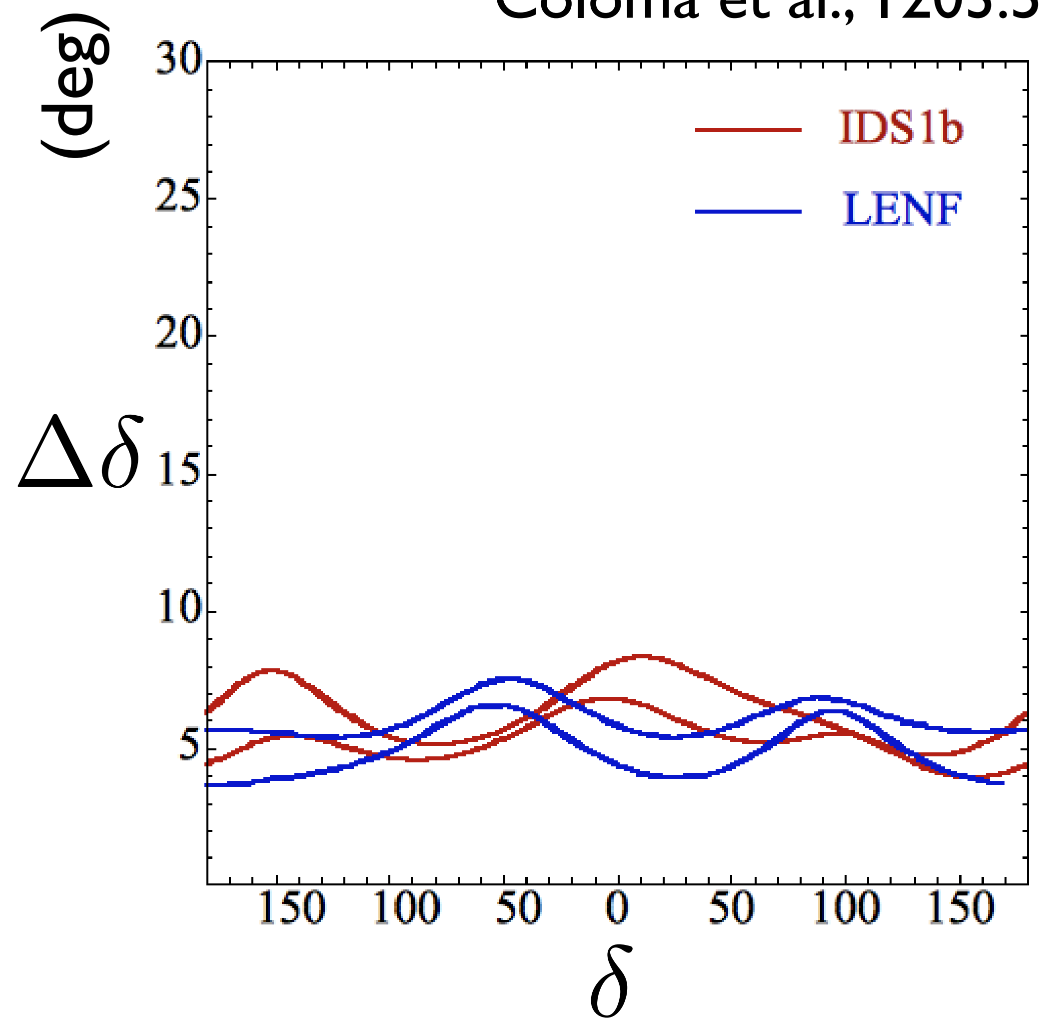
Precision in oscillation parameters

The precision measurement of the oscillation parameters will become very important once the mass hierarchy and CPV are established.

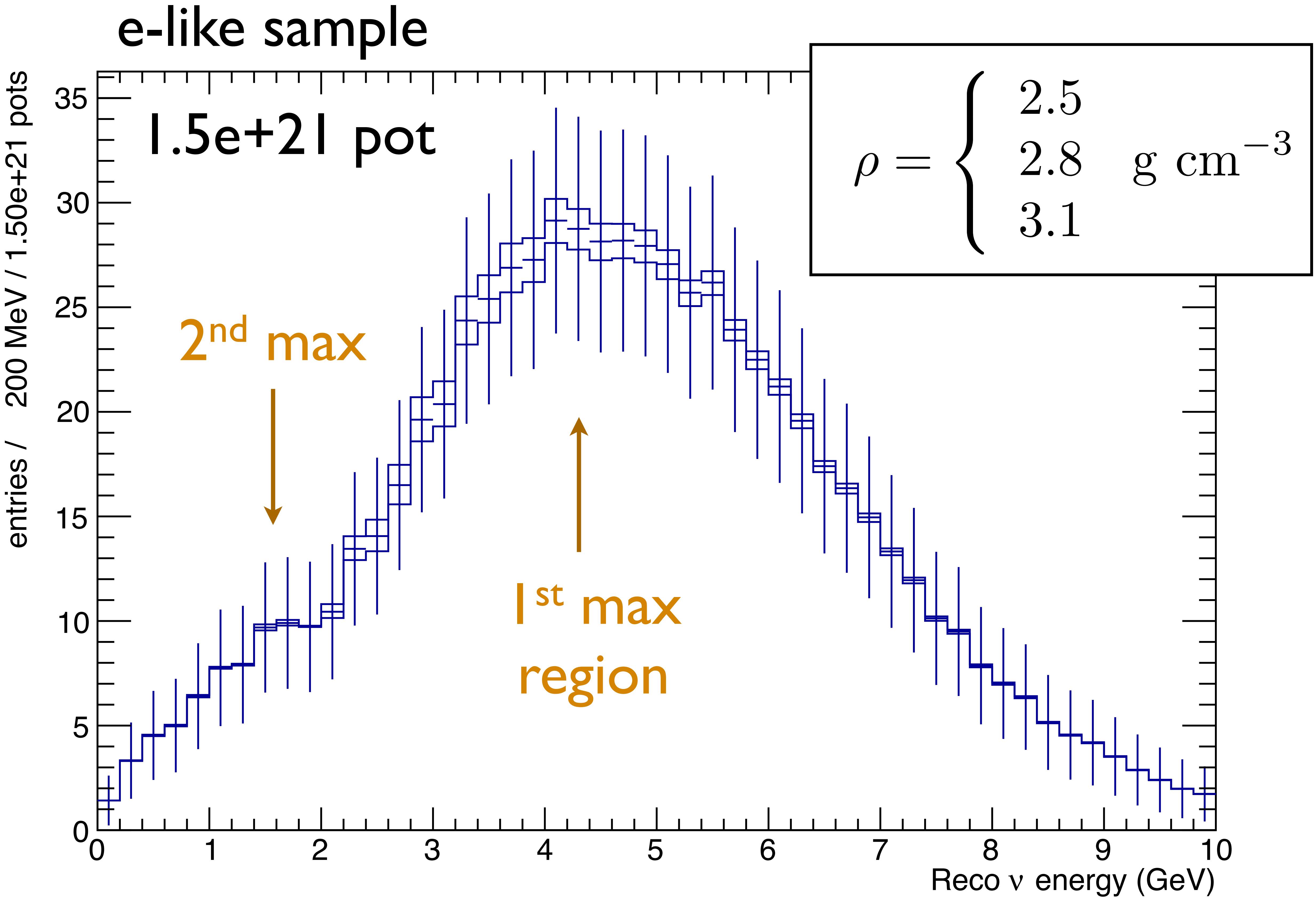
Estimated reachable precision on θ_{13} and δ_{CP}



Coloma et al., 1203.5651



Matter density effects



CP-phase sensitivity

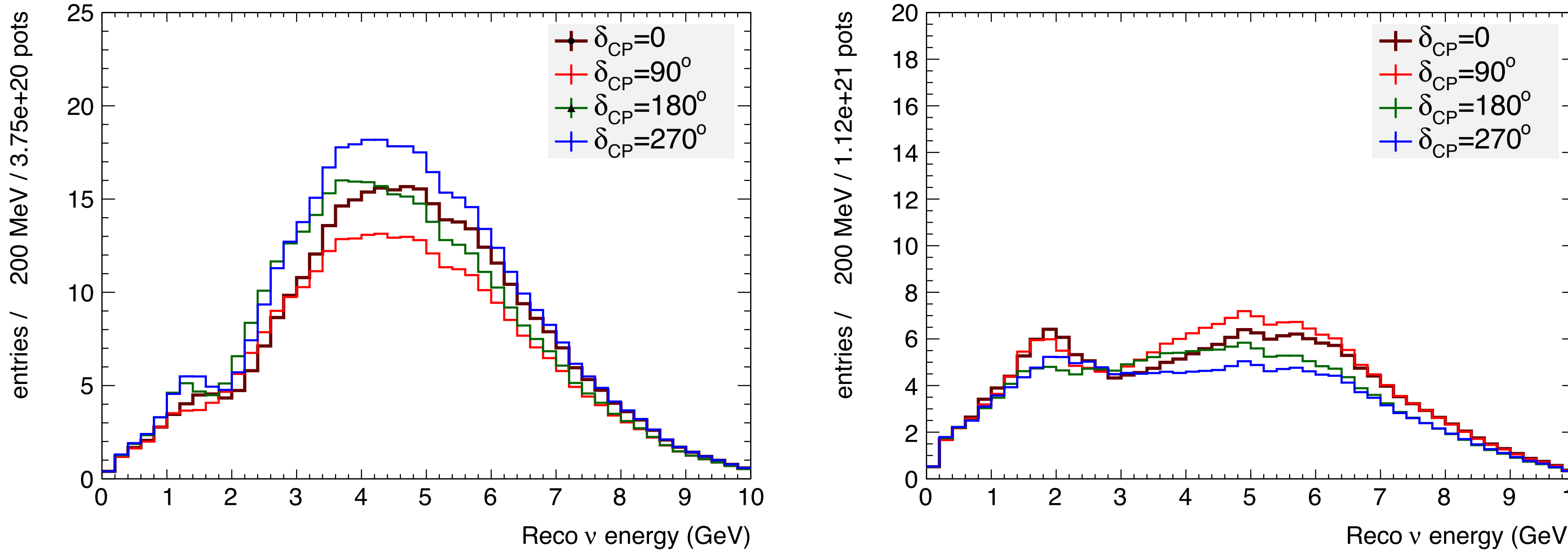


FIG. 73: Reconstructed event energy for (left) neutrino horn polarity running and (right) antineutrino ho polarity running, for different values of true δ_{CP} and for normal mass hierarchy (NH). A 25%-75% shar between neutrino and antineutrino running mode and a total of 1.5×10^{21} pot have been chosen.

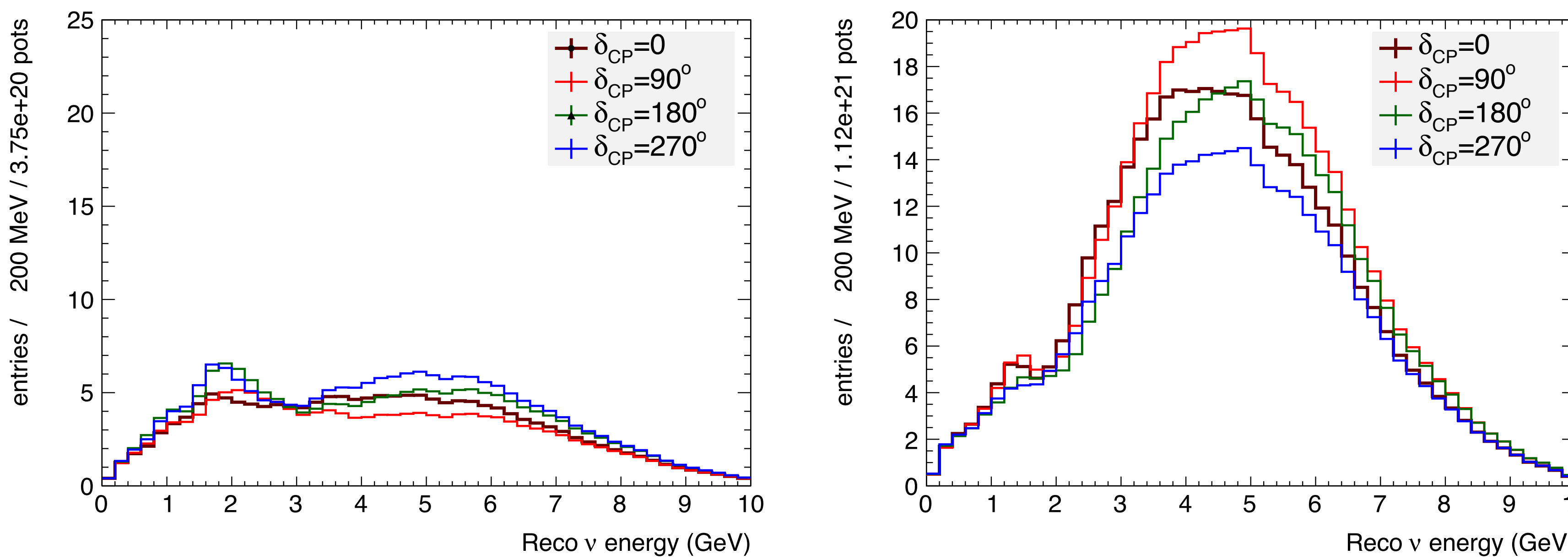


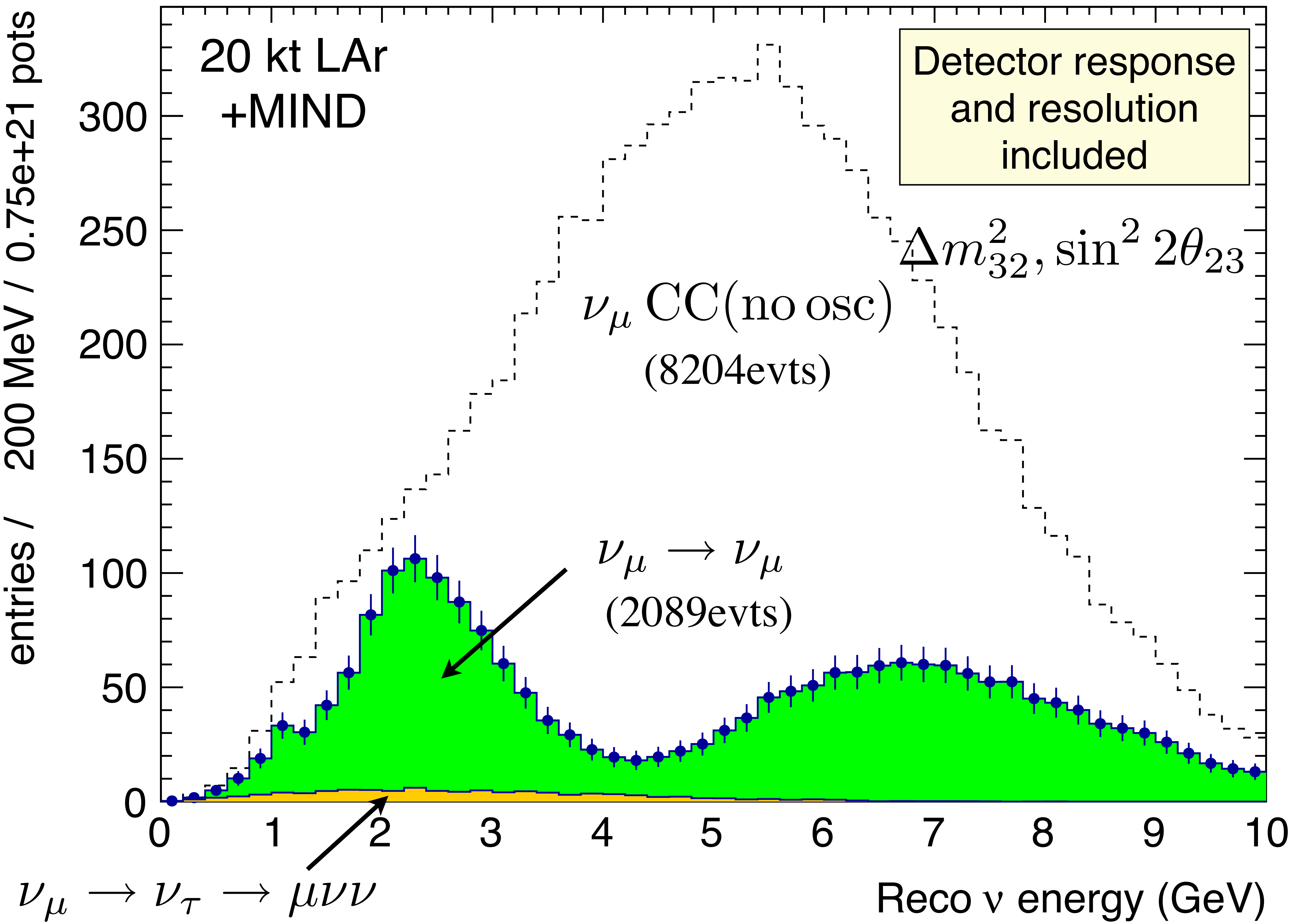
FIG. 74: Same as Figure 73 but for inverted mass hierarchy (IH).

CERN European Strategy for Accelerator-Based Neutrino Physics

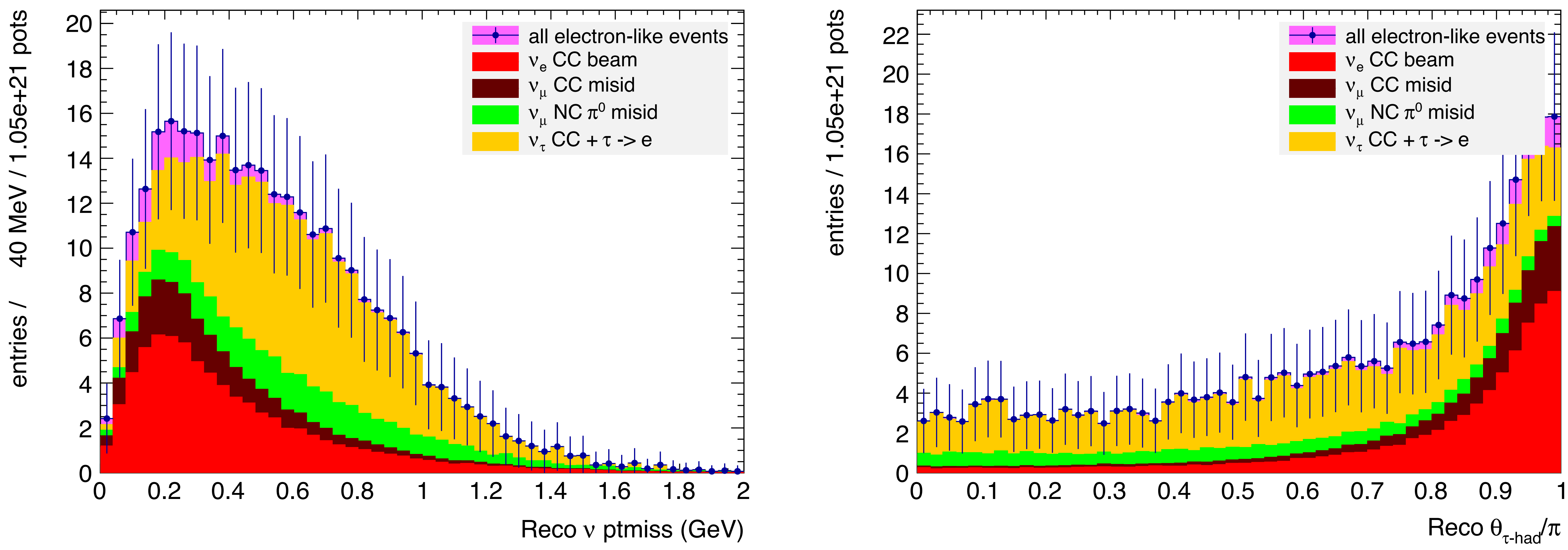
arXiv:1208.0512

1. **Neutrinos must be part of the CERN Roadmap.**
2. **Large discovery potential:** The determination of the neutrino mass hierarchy and the determination of the CP phase are the next steps in long baseline neutrino experiments. These fundamental measurements require and justify dedicated long baseline accelerator-based experiments.
3. **LAGUNA-LBNO and CERN→Pyhäsalmi:** The next step should be an experiment which can start now and be constructed in a reasonable time (less than about 10 years), maintains the community healthy, with a real chance of discovery and long term upgrade possibilities. The existence of a possible long baseline in Europe from CERN to Pyhäsalmi (2300 km) is unique in this regard.
4. **Incremental approach:** The LBNO project, considering an initial 20 kton fine grain LAr tracking-calorimeter (GLACIER) and a magnetized muon detector (MIND) is the first priority of the LAGUNA-LBNO consortium and is endorsed by the Neutrino Factory community. An **Expression of Interest**, signed by enlarged consortium, has been submitted to the CERN SPSC and is presently being reviewed.
5. **Preparing for longer term, precision experiments:** The European Strategy for Particle Physics must provide for European participation in the programme required for a Neutrino Factory proposal (in particular NuSTORM) to be prepared in time for the next update of the European Strategy (2018 ?).

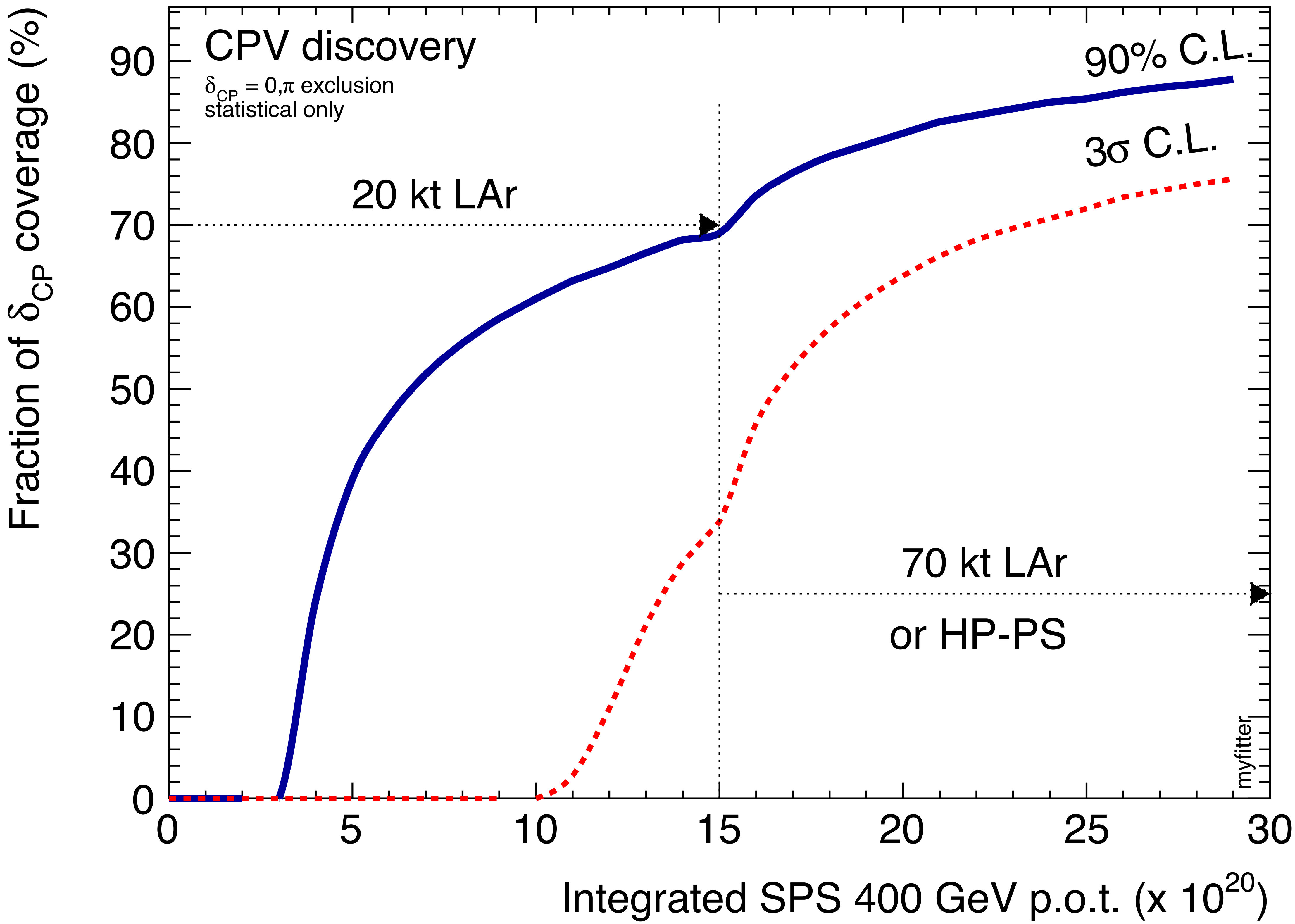
μ-like CC sample (+)



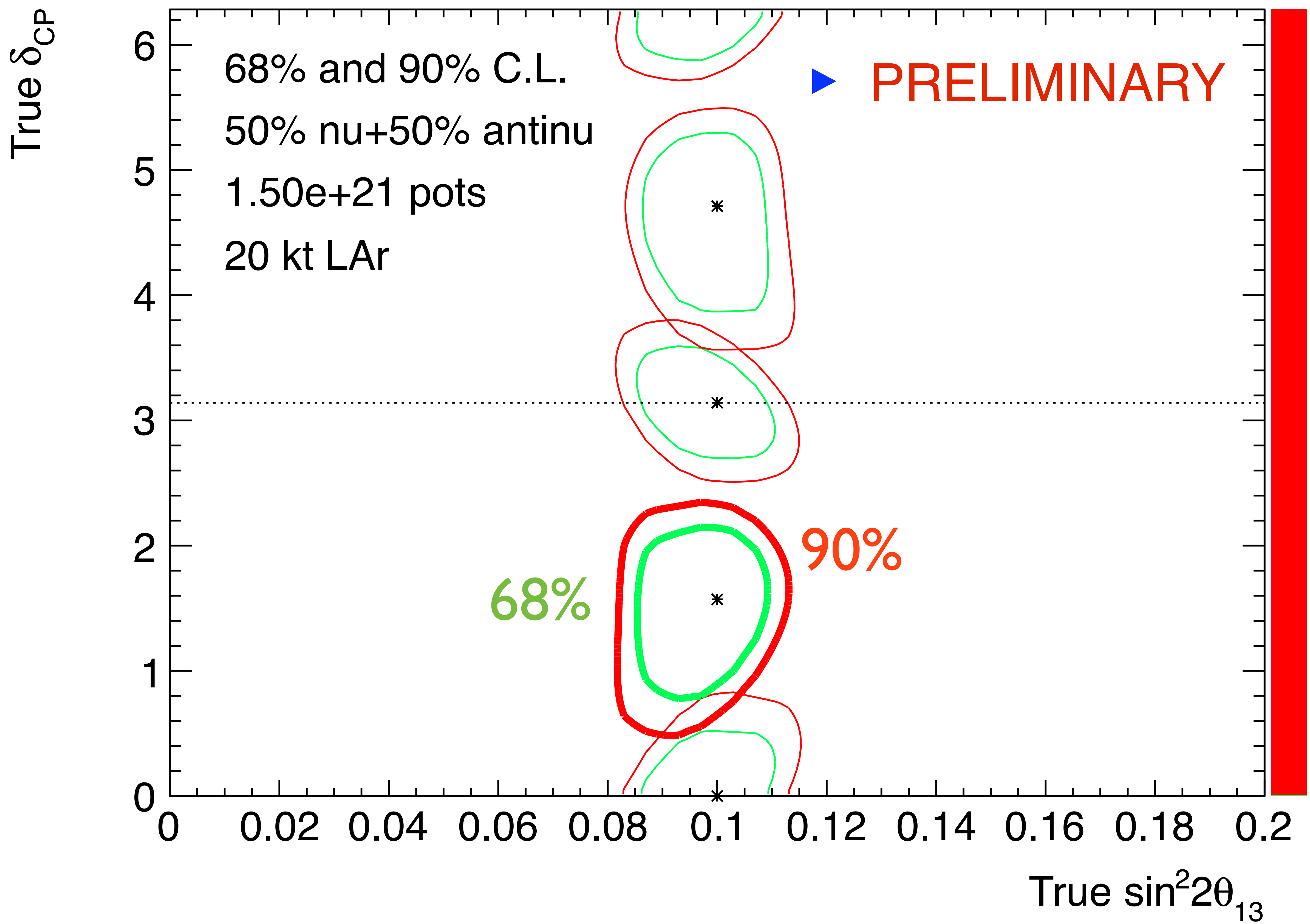
Tau like sample



CPV discovery - statistical only

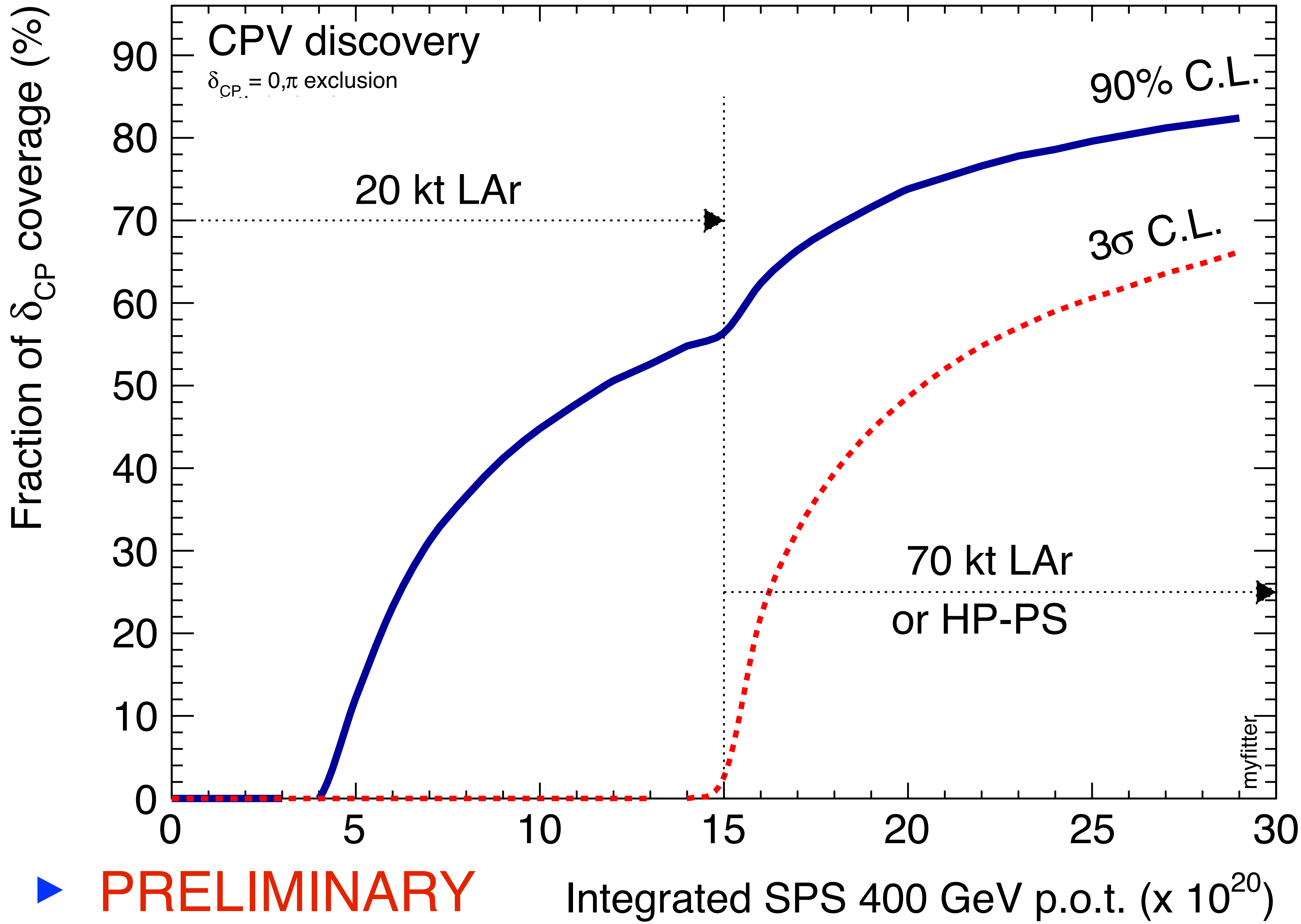


CP-phase determination

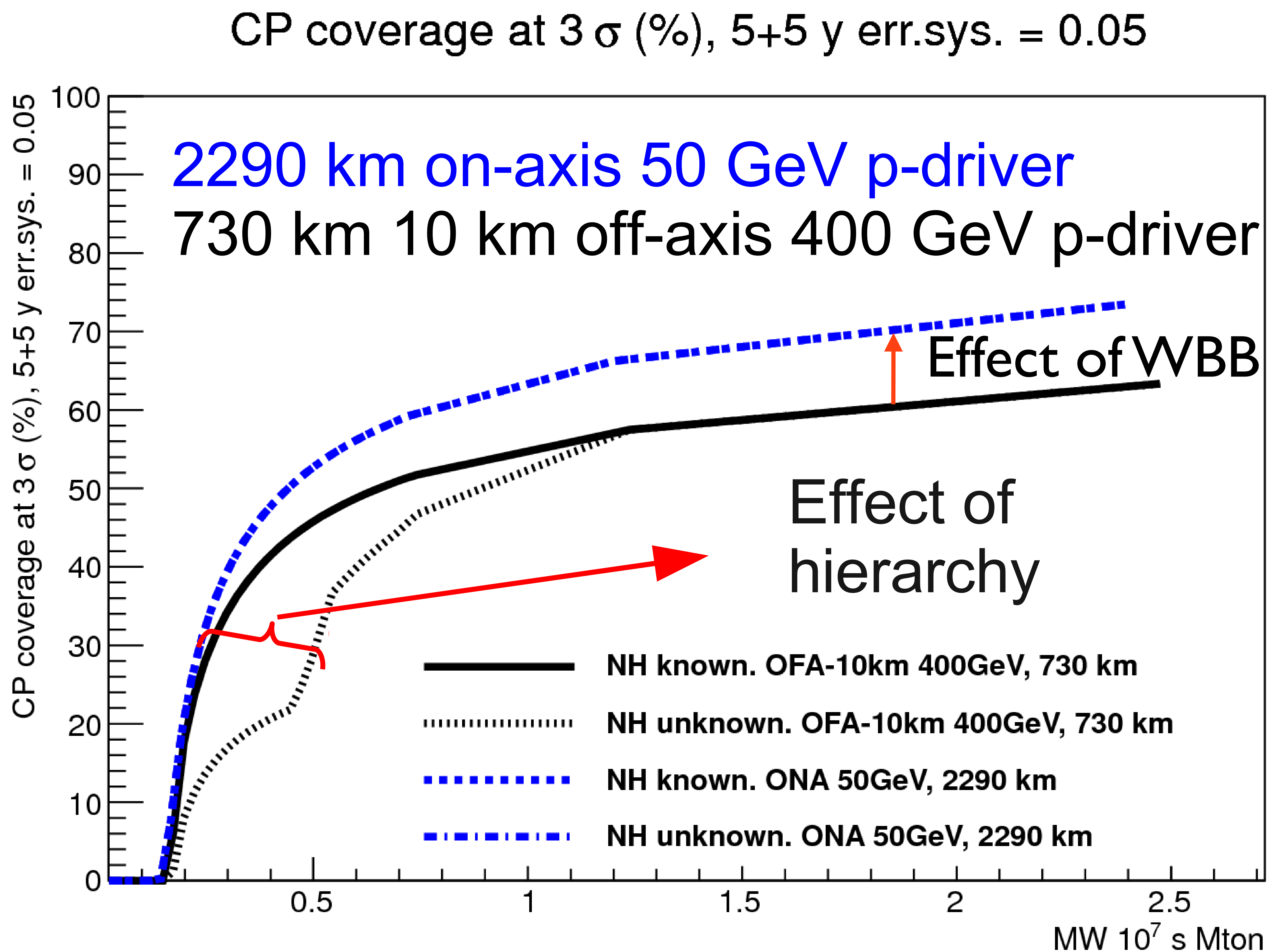


Effect of matter uncertainty

★ INFLATED ERROR ON MATTER DENSITY ±10%



▶ PRELIMINARY

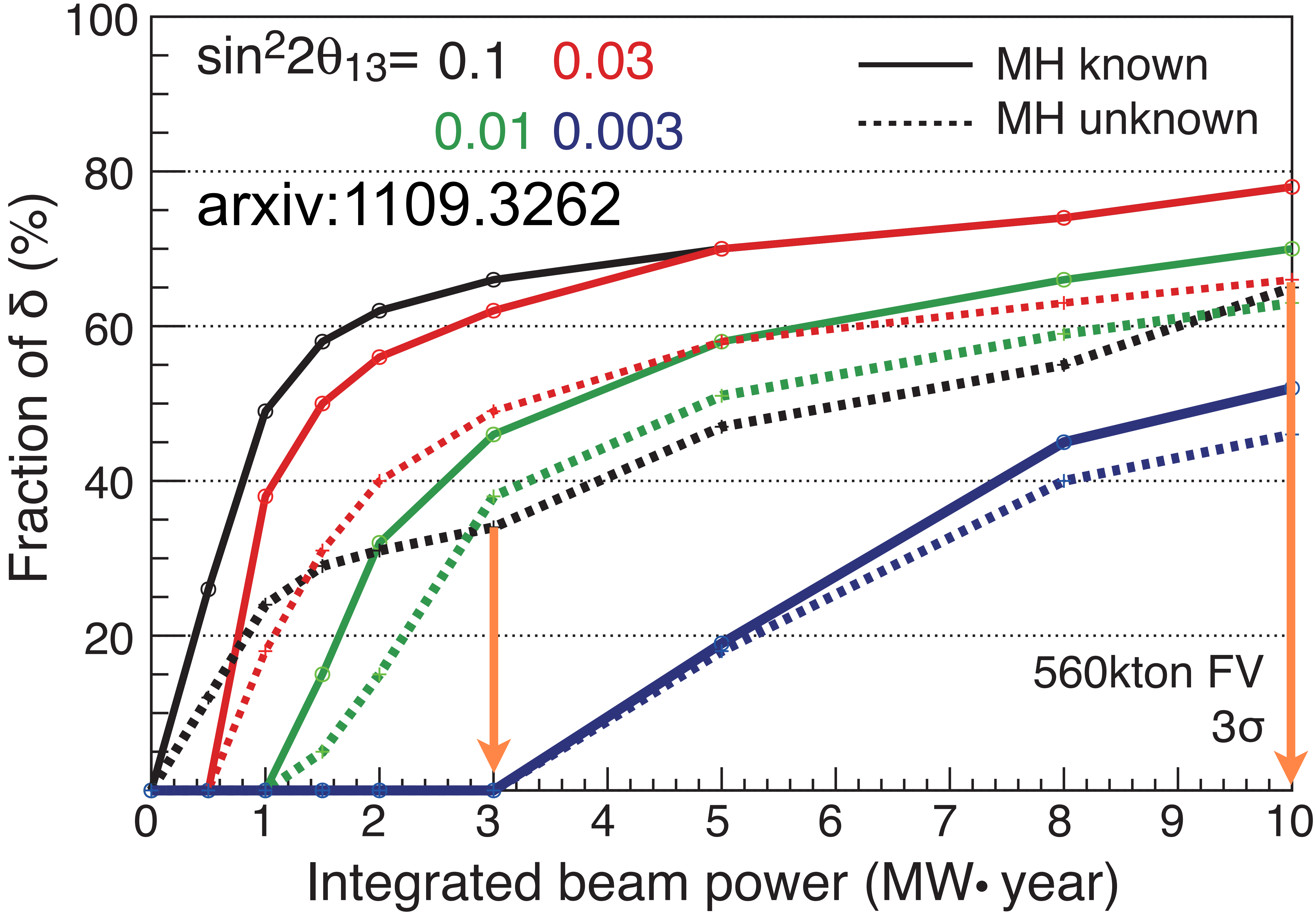


A. Longhin et al., NUTurn12

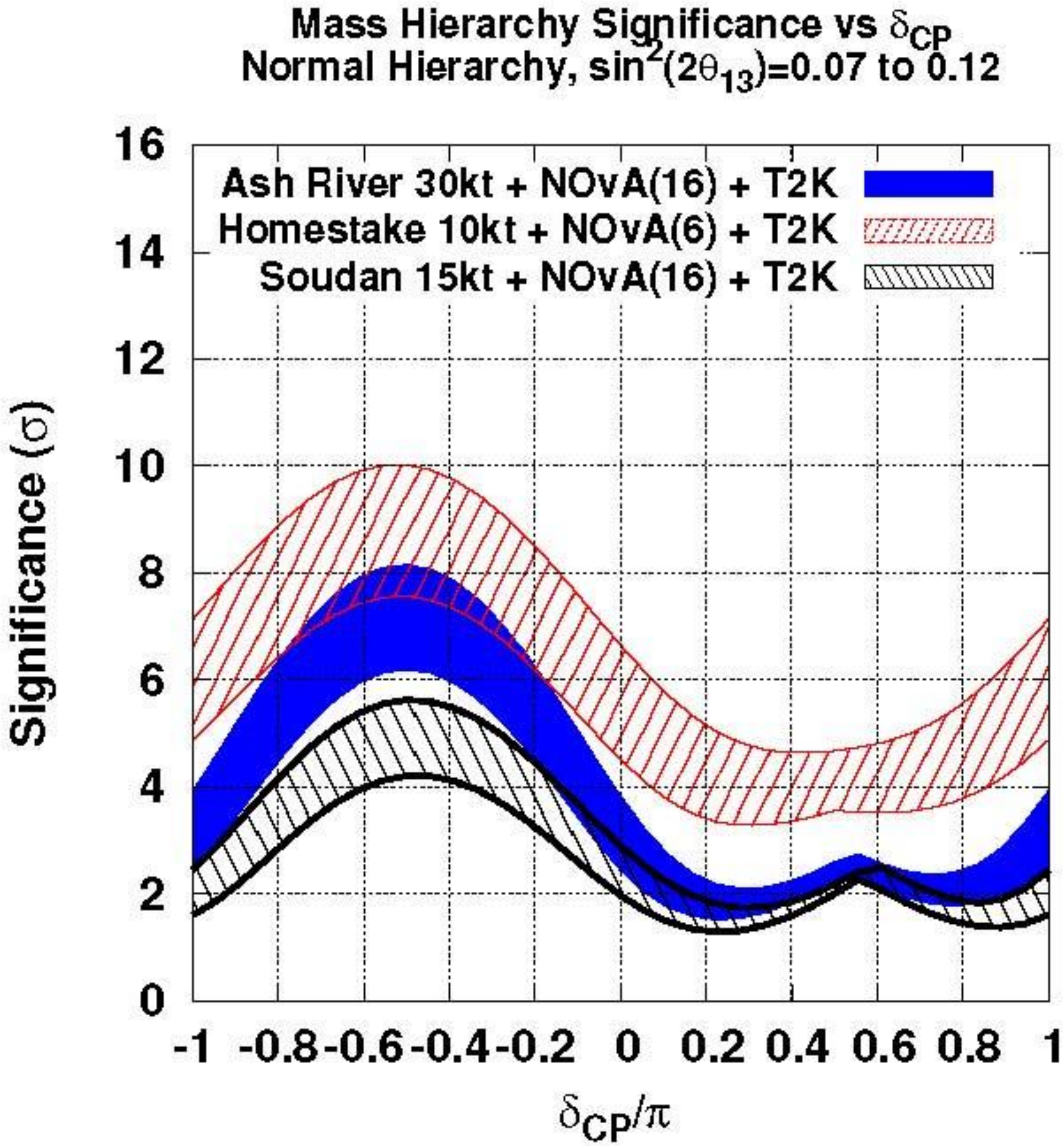
Why the neutrino mass hierarchy ?

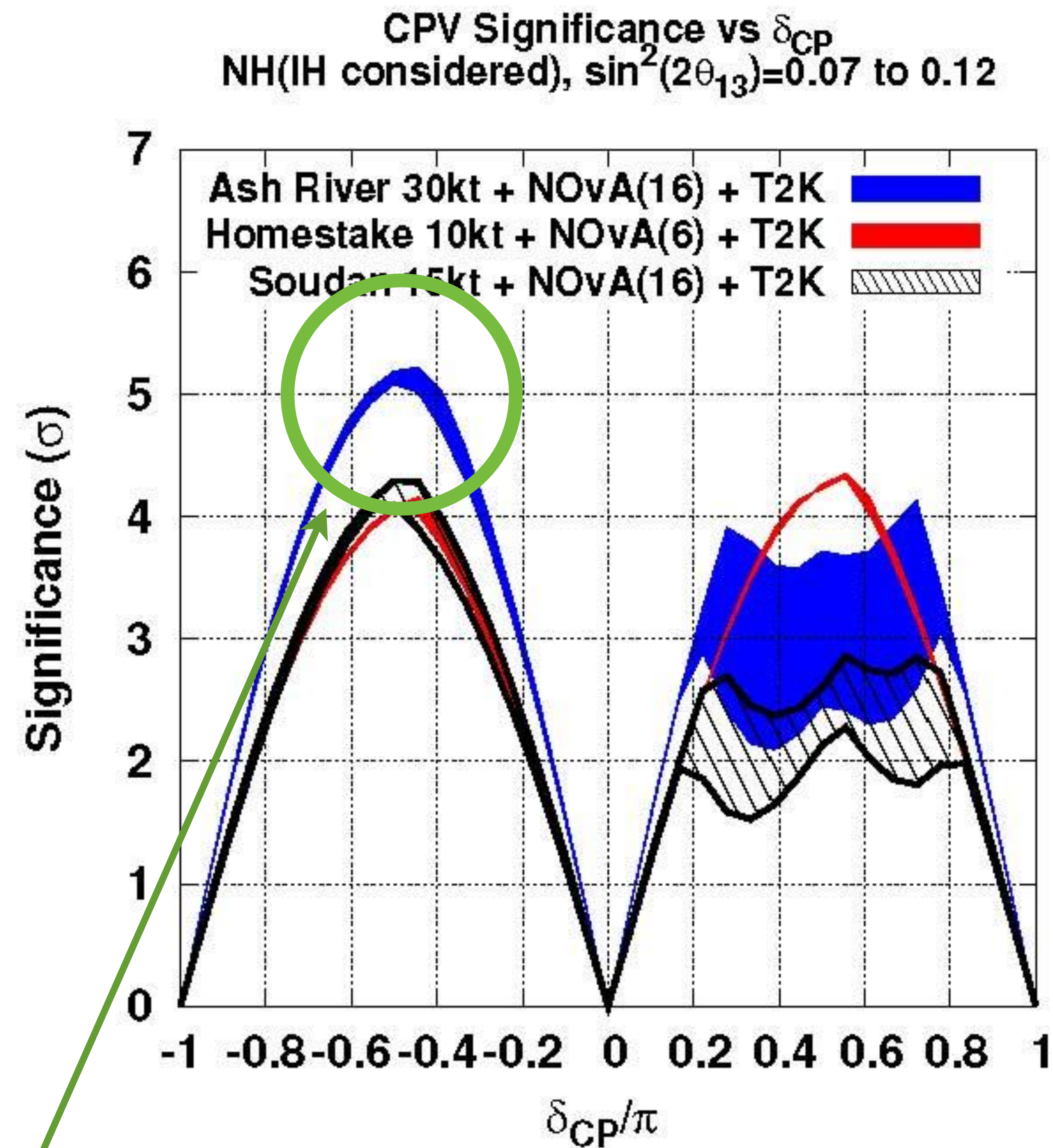
- **CP-violation:** necessary input to solve CPV problem. For example, for the HyperK LOI arxiv:1109.3262 (which considers a 540kton FV and hence has the highest statistical power):
    - ➡ 3 MW×years (note: >10 years at present JPARC MR power) MH known: 65% coverage → MH unknown: 35% coverage
    - ➡ 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 !**

HyperKamiokande CPV



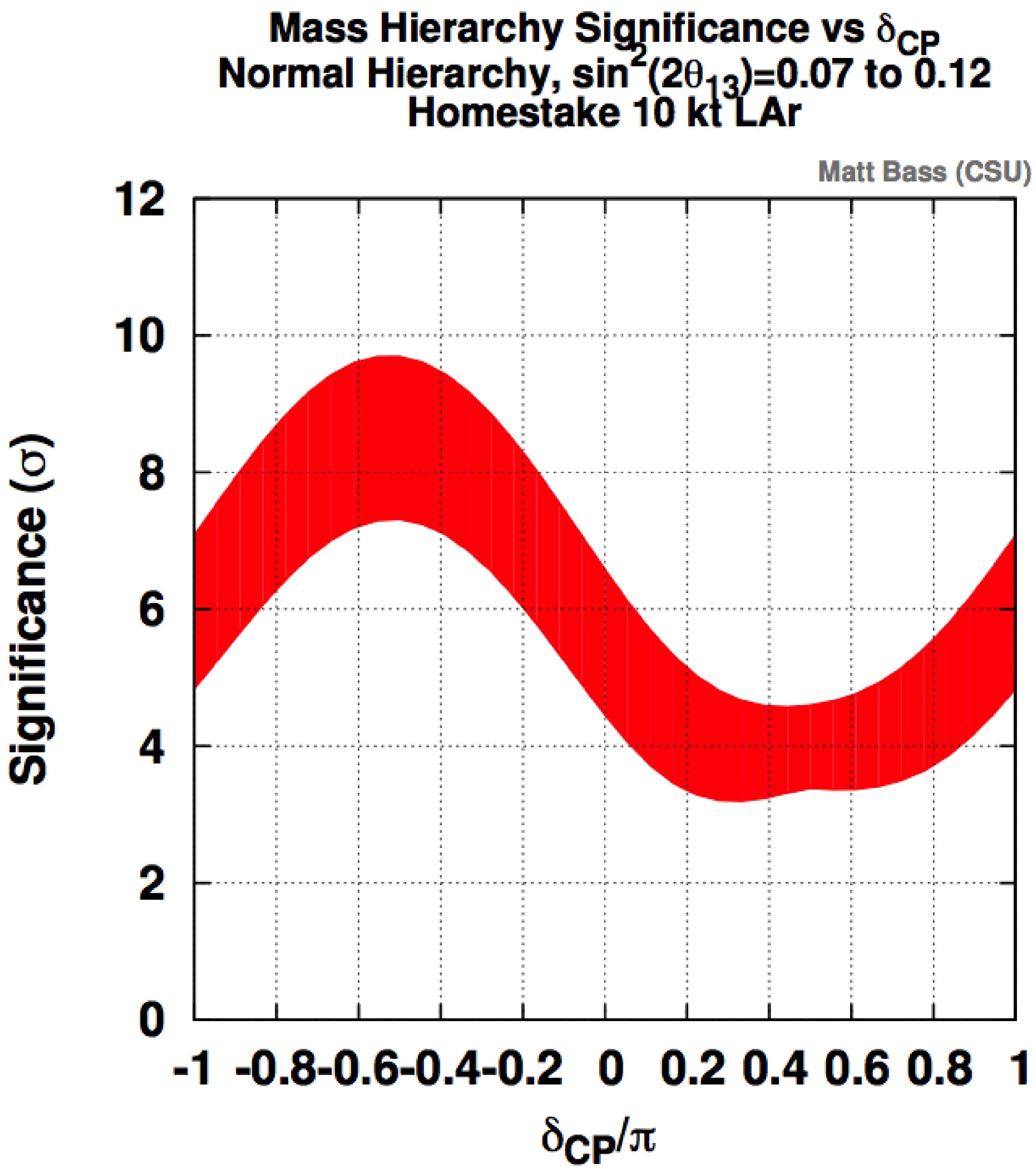
LBNE: 10 years @ 700kW

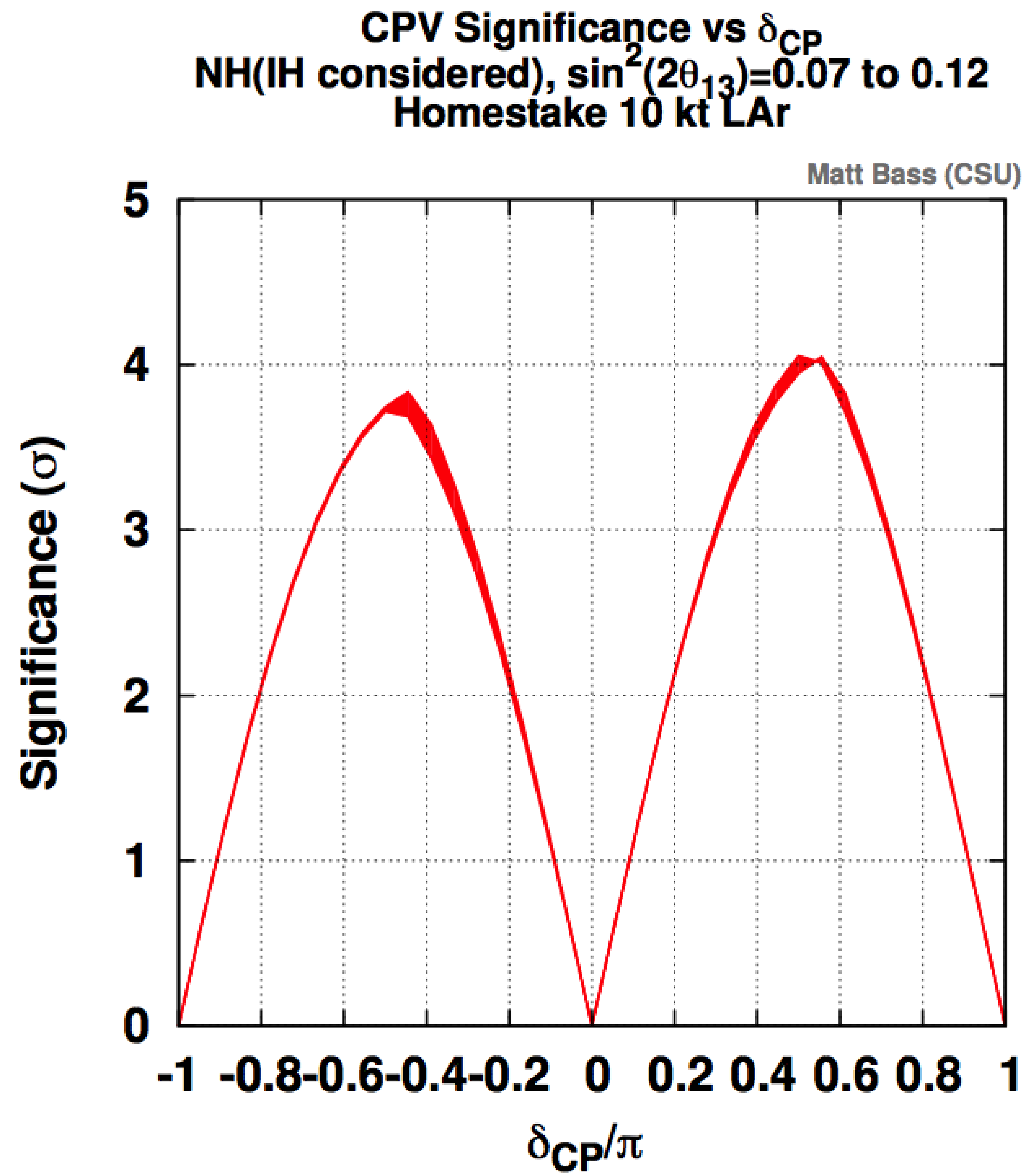




Be aware: Ash River has the best CPV sensitivity when MH is determined ! the displayed sensitivities come mostly from parameter fitting around 1st maximum

LBNE 10-kton (surface?) @ 700 kW

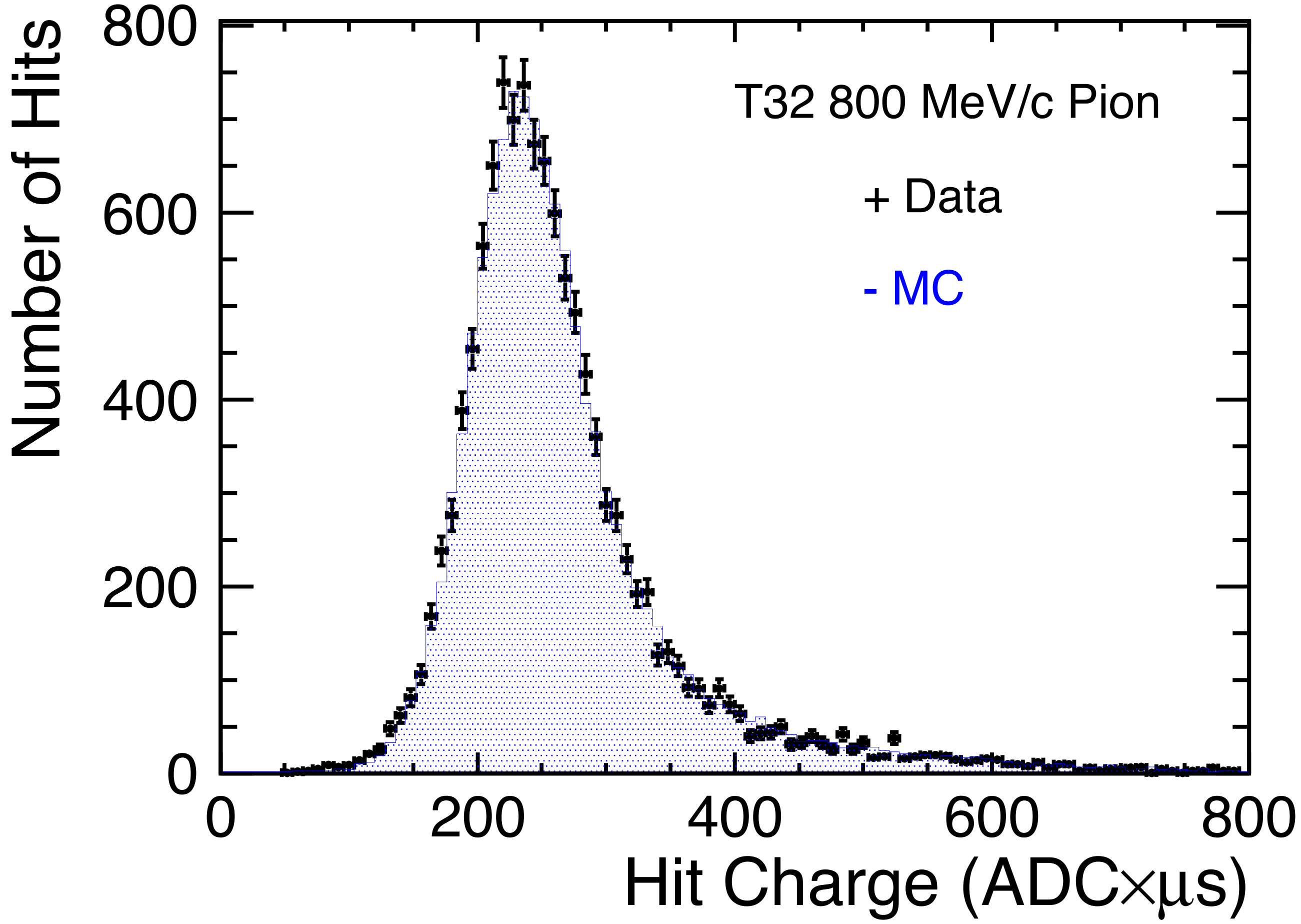




Tracking performance

JPARC T32 exposed to K1.1BR tagged beam

J.Phys.Conf.Ser. 308 (2011) 012008



Data well described by:

Birks Law

$$Q = A \frac{Q_0}{1+(k/\varepsilon)\times(dE/dx)\times(1/\rho)}$$

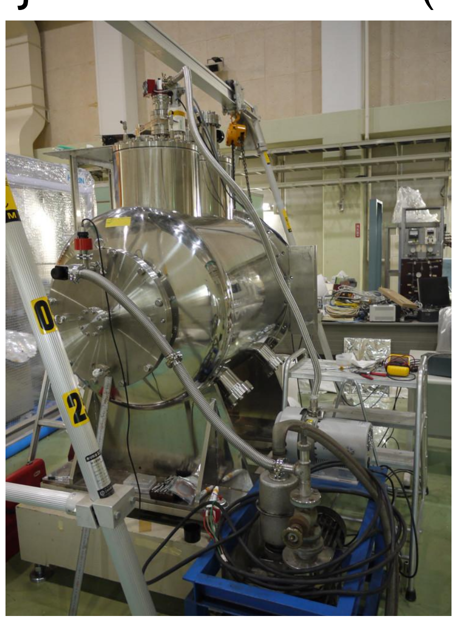
Observable charge (Q), Raw charge (Q_0)

$$A = 0.8$$

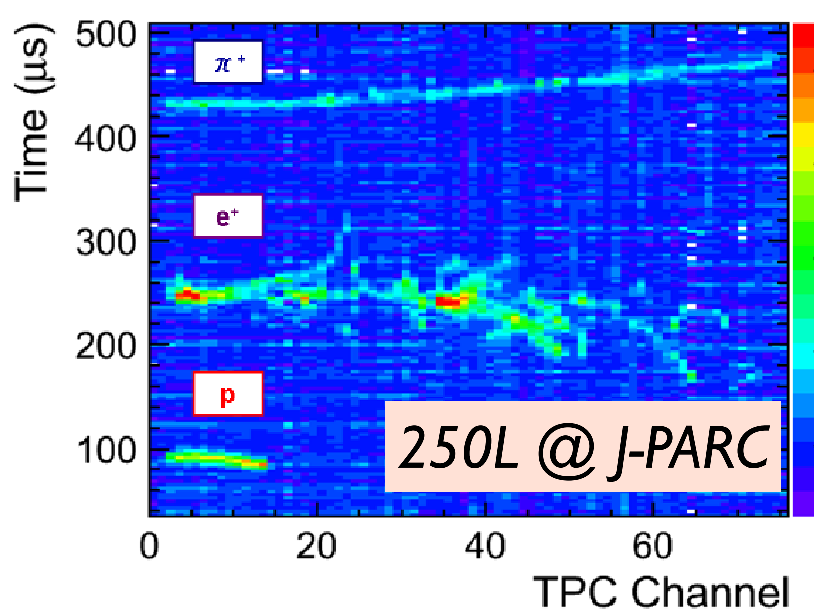
$$k = 0.0486\ \mathrm{kV/cm}\frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

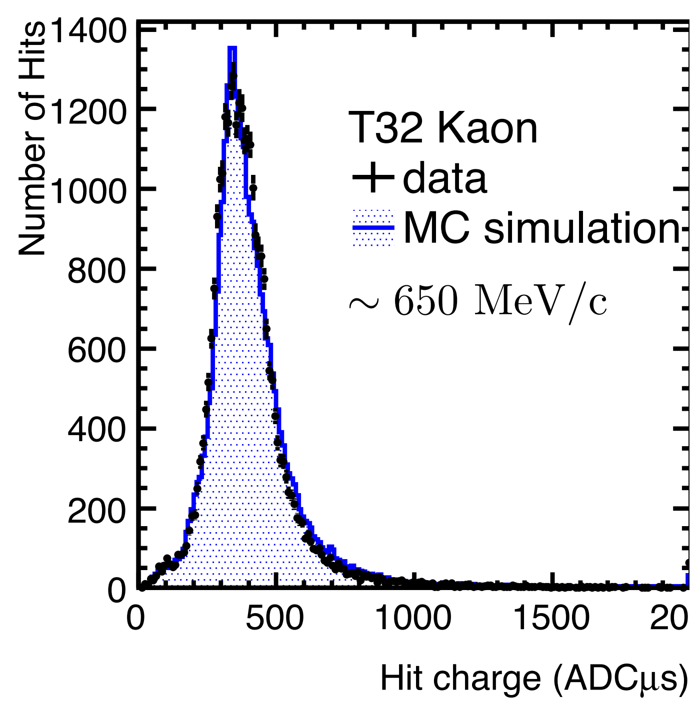
NIM A 523, 275 (2004)

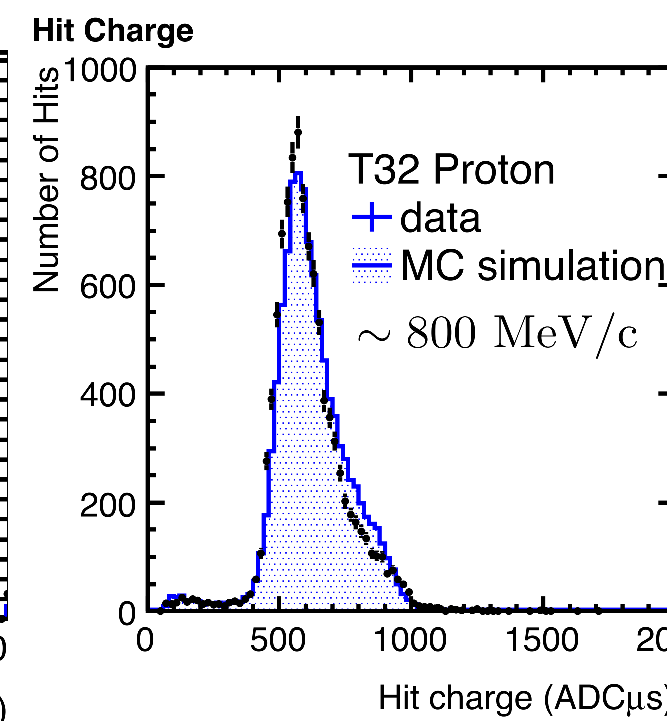
J-PARC T32 chamber (ETHZ-KEK-Iwate-Waseda)



Courtesy T. Maruyama





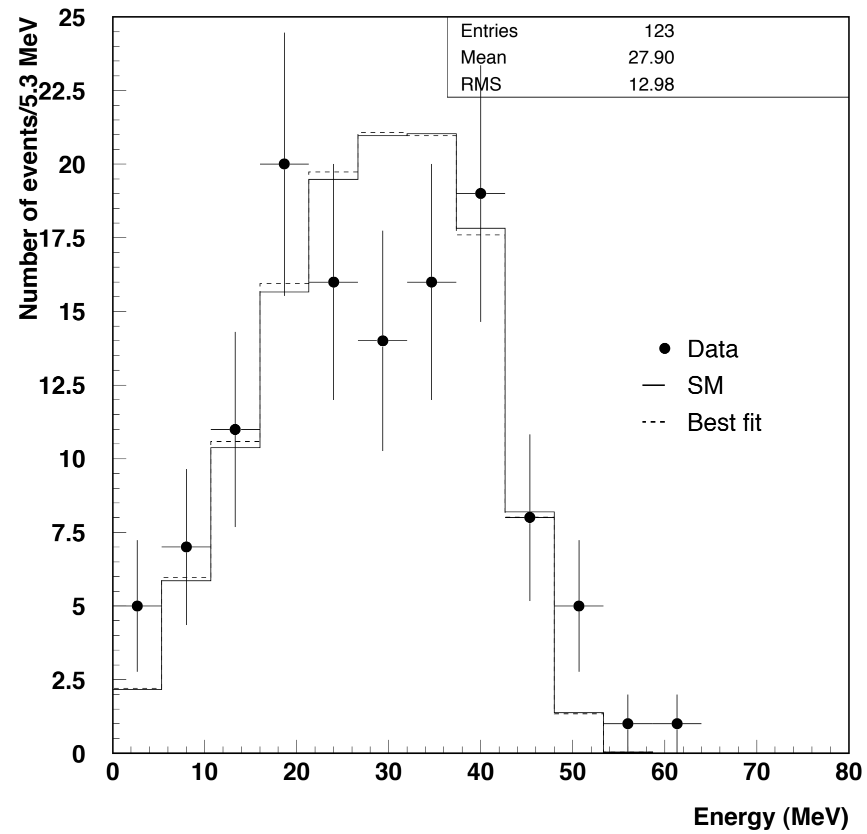


Good understand of tracking

Calorimetric performance

Michel electrons form stopping muon decay sample

$$\frac{\sigma_e}{E} \simeq \frac{11\%}{\sqrt{E(\mathrm{MeV})}} \oplus 4\%$$



Eur. Phys. J. C33, 233 (2004)

MC simulations at higher energies:

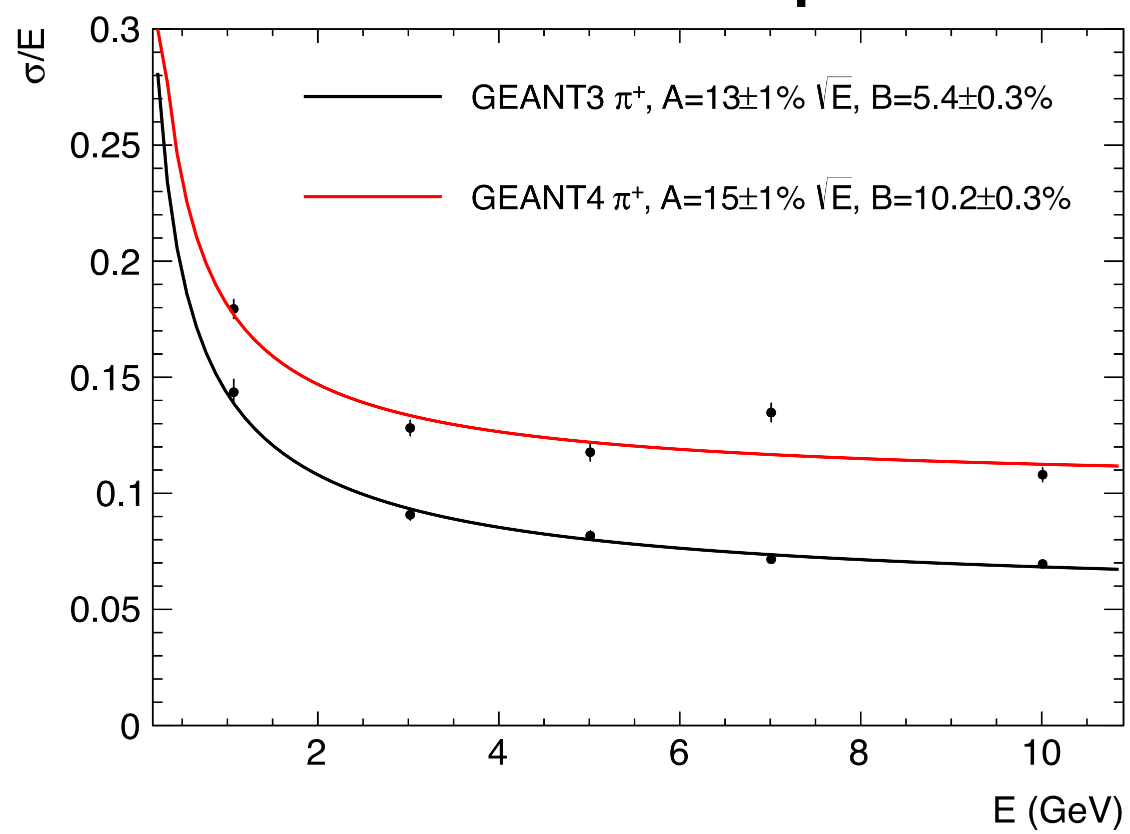
$$\frac{\sigma^{MC}_{em}}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus 1\%$$

$$\frac{\sigma^{MC}_{had}}{E} \simeq \frac{15\%}{\sqrt{E}} \oplus 10\%$$

↑

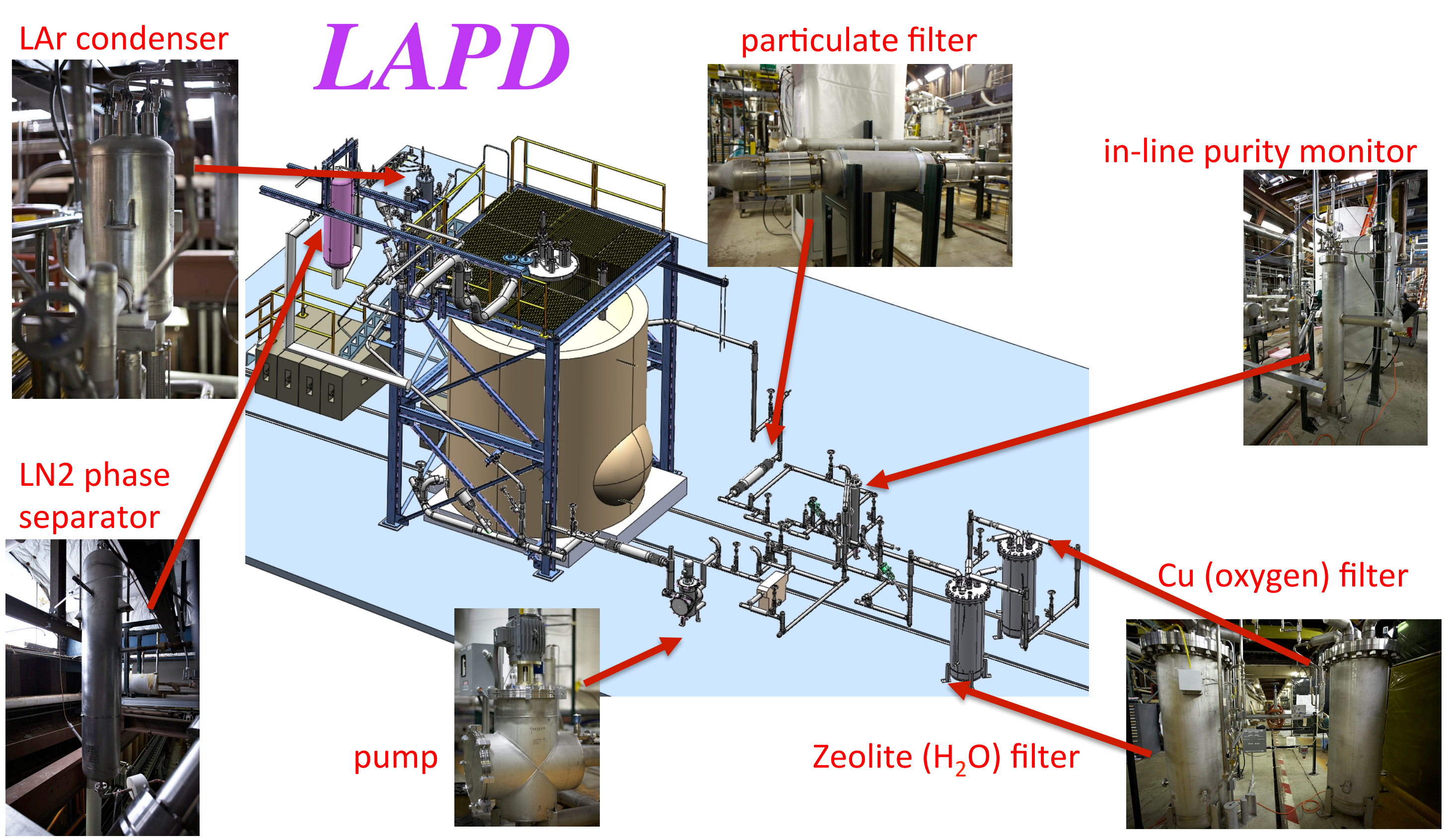
needs to be confirmed by experimental data

G3 and G4 comparison

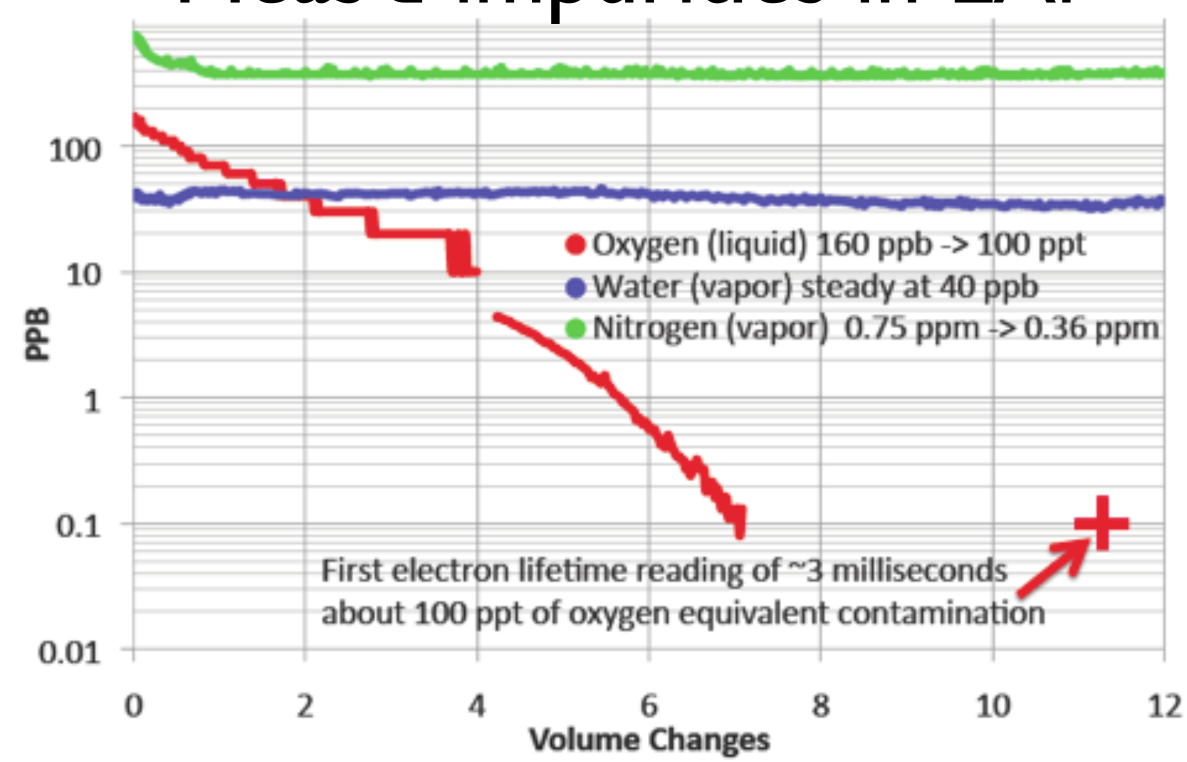


Purity and vessel evacuation

- ★ Several independent groups performed numerical simulations and concluded that the vacuum evacuation phase could be avoided for larger detectors:
  - more favorable surface / volume ratio for large volume (also larger volumes are less sensitive to micro leaks !!)
  - initial purity of argon when delivered is typ. O(1) ppmv O_2 → purification from ppm to << 1 ppb anyhow needed
  - outgassing of material from hot components, impurities “frozen” at low temperature
- ★ GAr flushing and purging are effective ways to remove air and impurities.
- ★ Purging on 6m3 volume (ETHZ-KEK-Liverpool @ CERN)
  - Piston effect seen in gas and reached 3ppm O_2 after several volumes exchange (J.Phys.Conf.Ser. 308 (2011) 012024)
- ★ LAPD @ FNAL – Liquid Argon Purity Demonstrator – First test in Liquid Phase !
  - Tank size: 30 ton LAr (25,000 liters)
  - Milestone successfully reached!! it is possible to obtain a **better than 3 ms electron lifetime** in a large non-evacuated vessel !



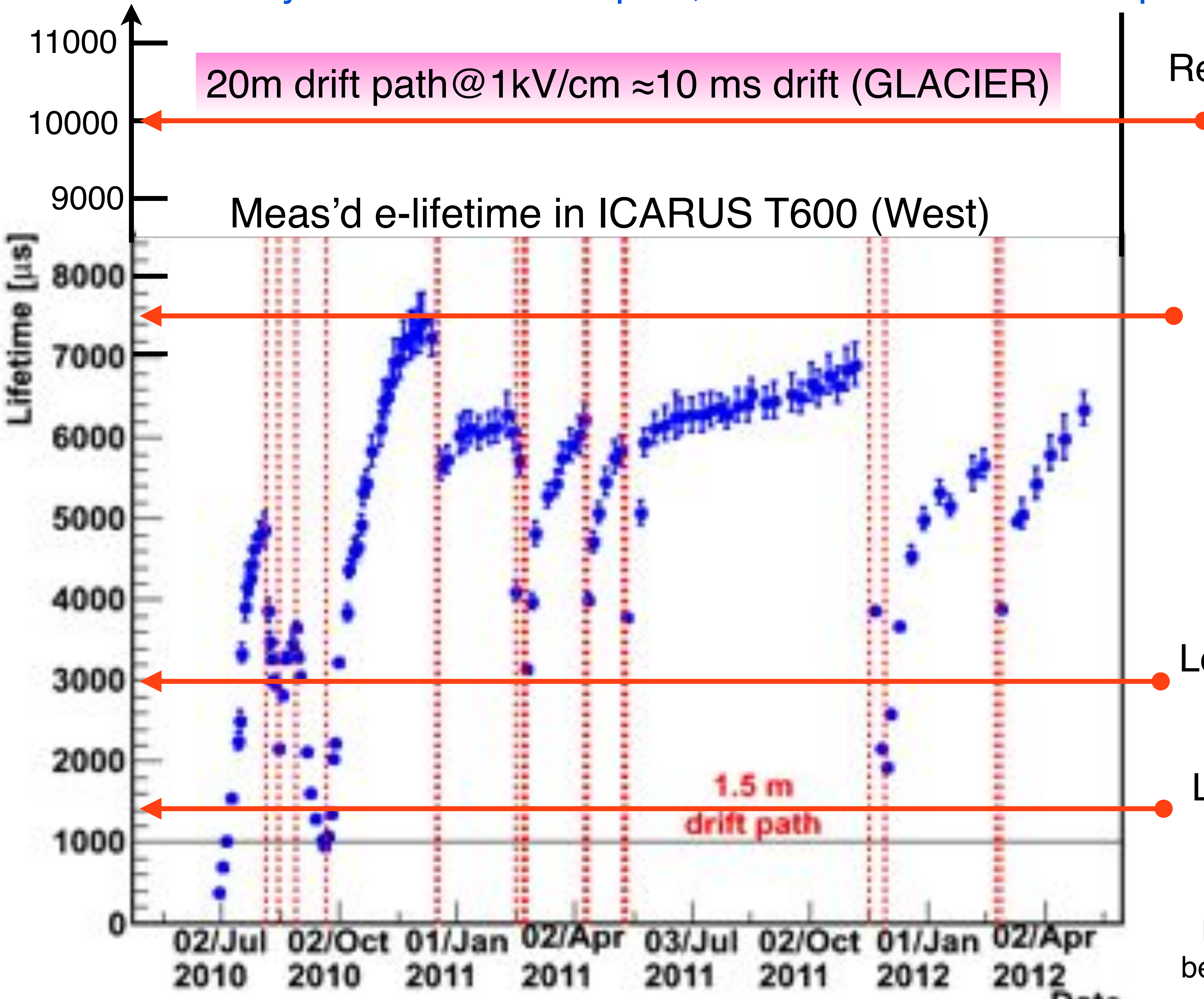
Meas’d impurities in LAr



Courtesy B. Baller & B. Rebel

Purity and evacuation

- ★ Excellent purity has been reproducibly achieved in various setups always relying on commercially available techniques, of various sizes and capacities.



Courtesy F. Pietropaolo

Record purity in ICARUS 50L @ CERN >10 ms (volume evacuated)

Phys.Rev. D74 (2006) 112001

Record purity in ICARUS T600 ≈7.5 ms (volume evacuated)

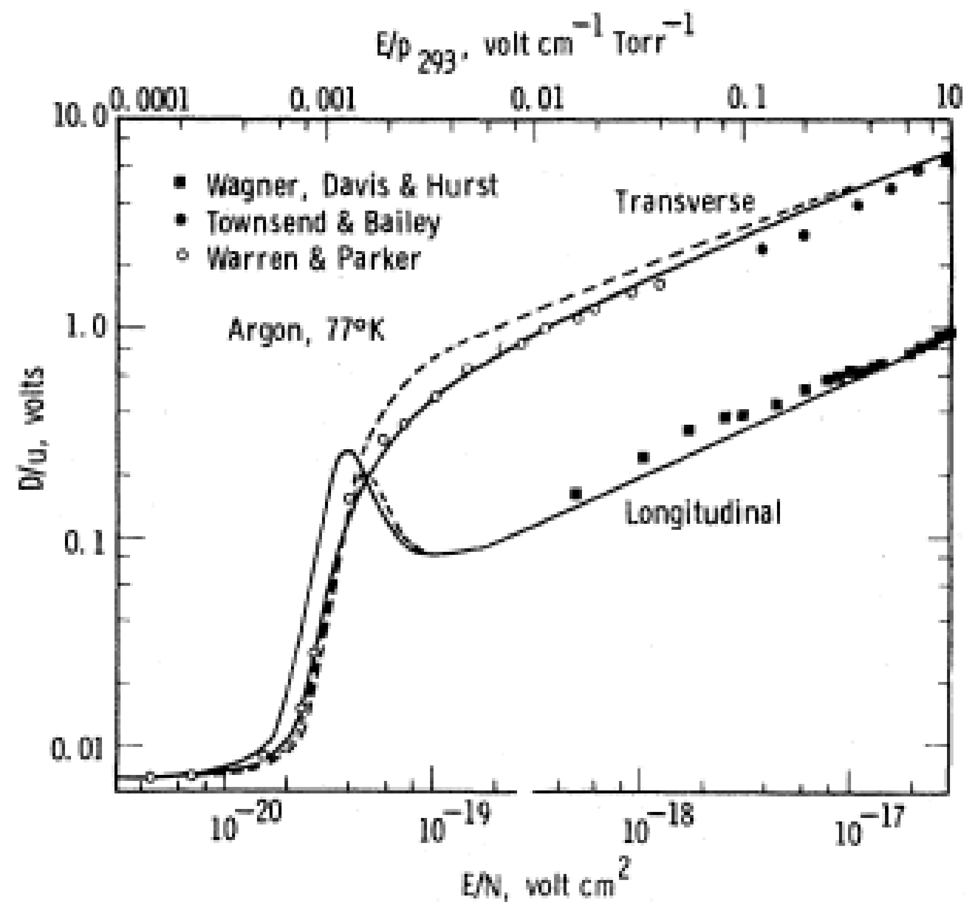
Lower bound in LAPD ≈3 ms (volume non-evacuated !)

LBNE requirement ≈1.4 ms for $S/N_{mip} > 9$

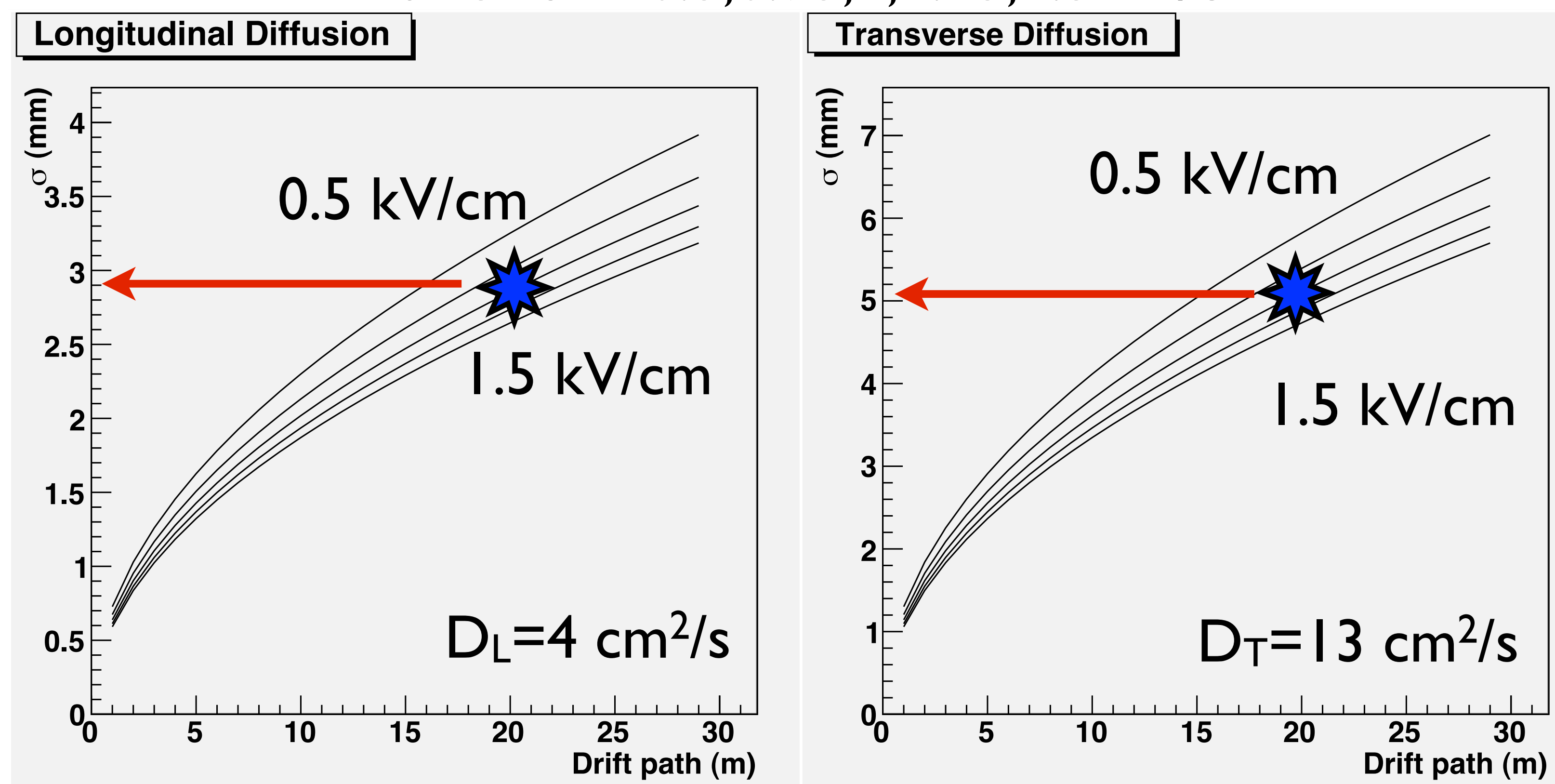
NB: "Outgassing" sources should become negligible after long periods of purification (e.g. 1 year)

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

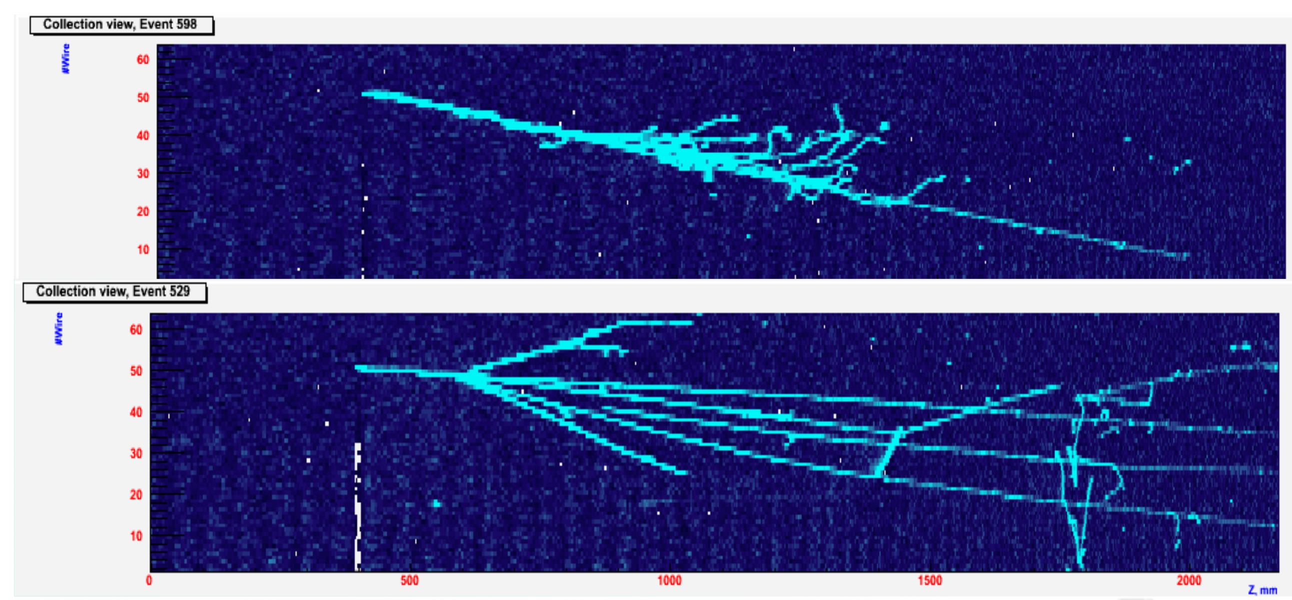


★ Diffusion coefficients not well known (in particular for transverse diff.):

- after 20 m drift: transverse diffusion ≈ **5mm**, longitudinal diffusion ≈ **3mm**

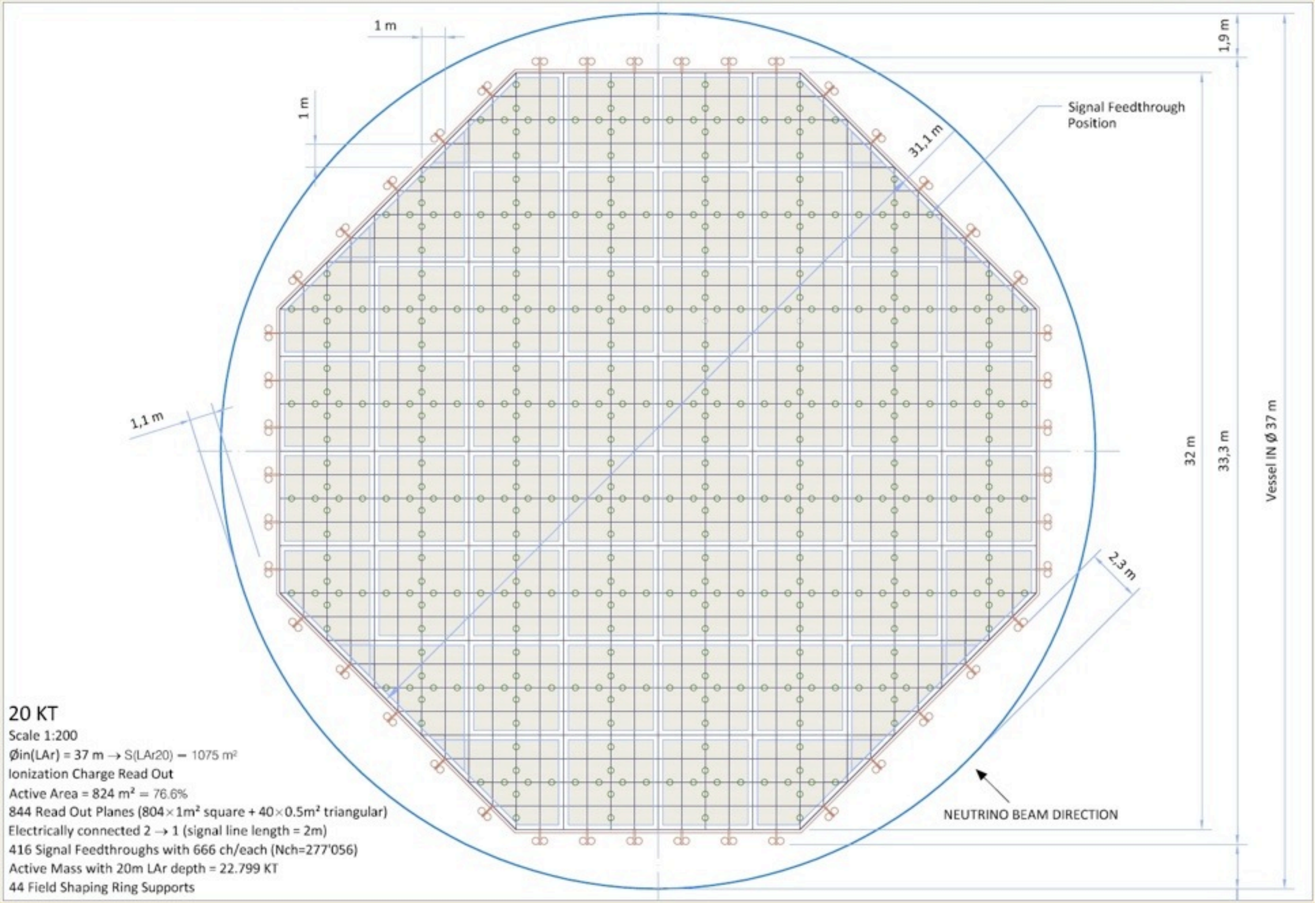
★ New measurements:

- ArgonTube (Bern University)
  - tracks >4 m length observed !
  - lifetime ≈ 2ms after 24hrs
- 5m drift (UCLA)



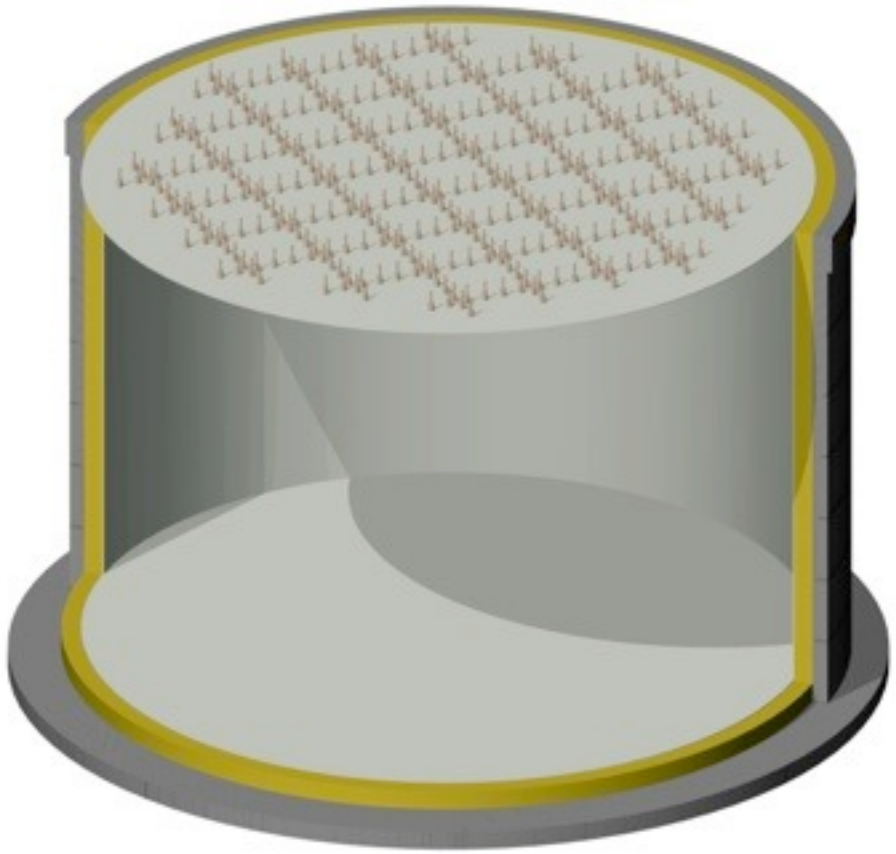
Courtesy I. Kreslo

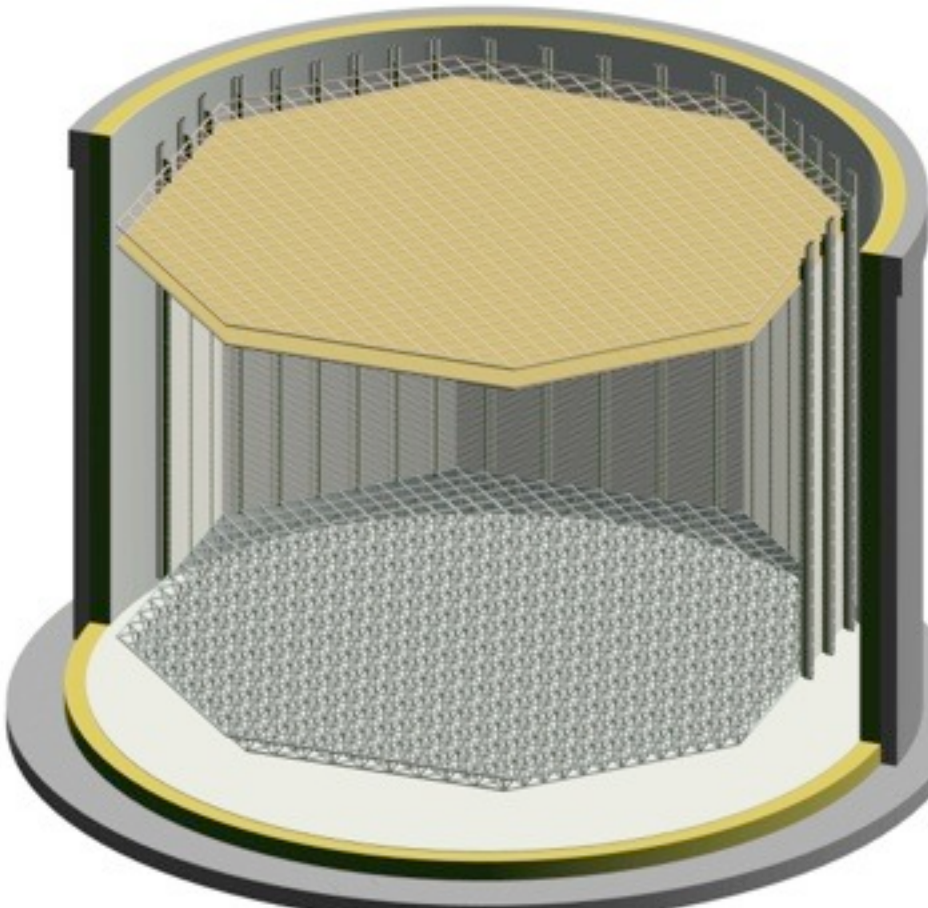
GLACIER charge readout layout



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





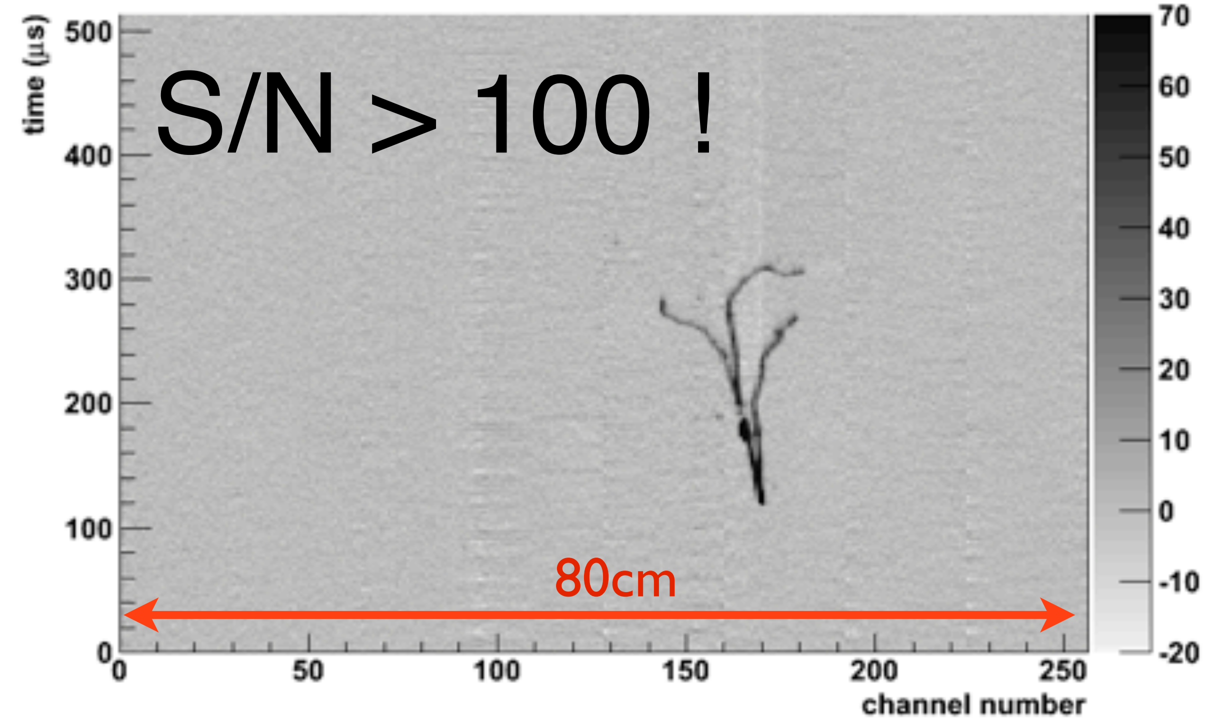
GLACIER charge readout

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

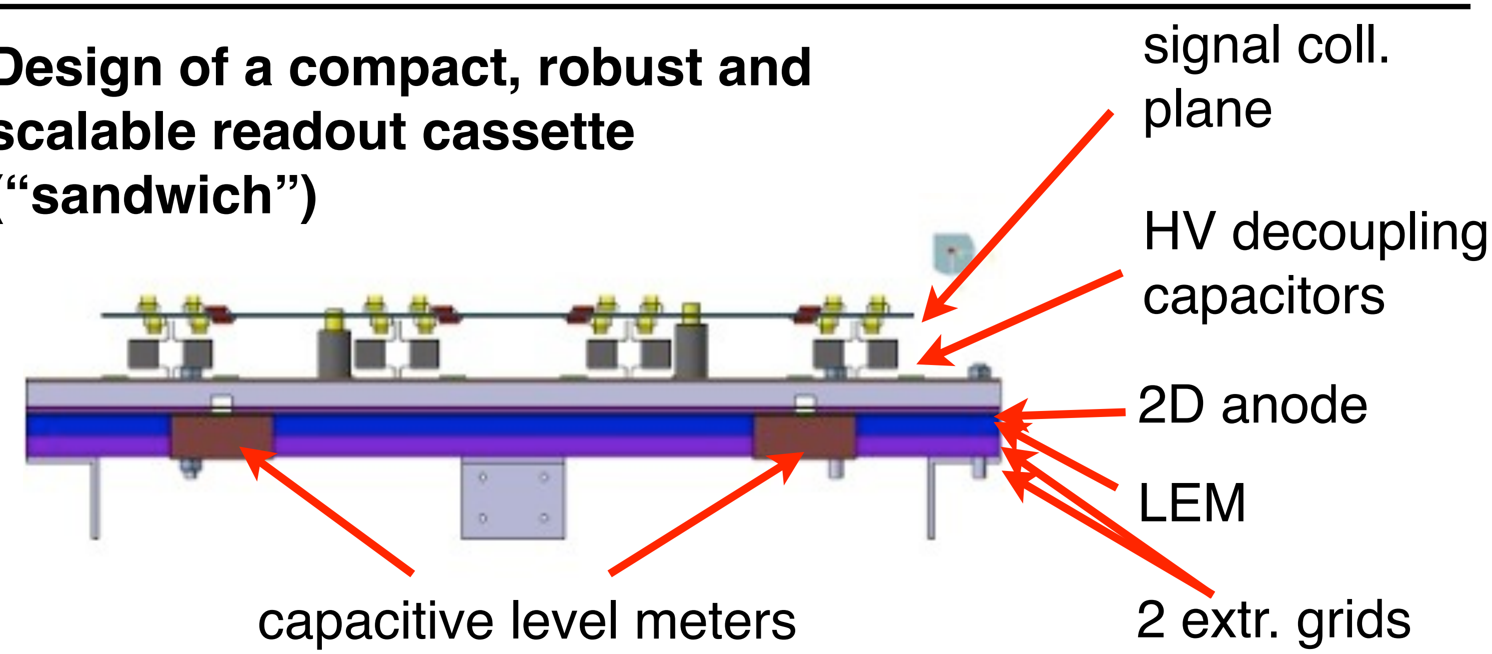
★ Novel double phase LAr LEM-TPC readout:

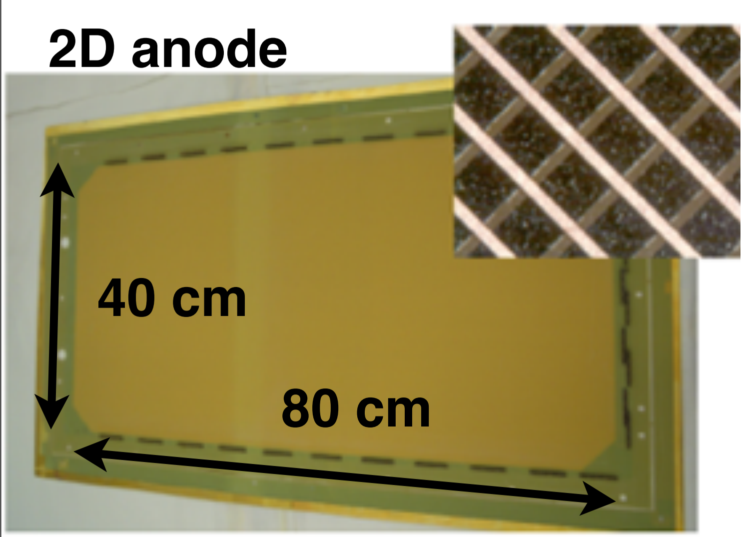
- ionization electrons are drifted to the liquid-gas interface
- if the E-field is high enough (≈ 3 kV/cm) they can efficiently be extracted to the gas phase
- in the holes of the LEM the E-field is high enough to trigger an electron avalanche
- the multiplied charge is collected on a 2D readout
- gain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

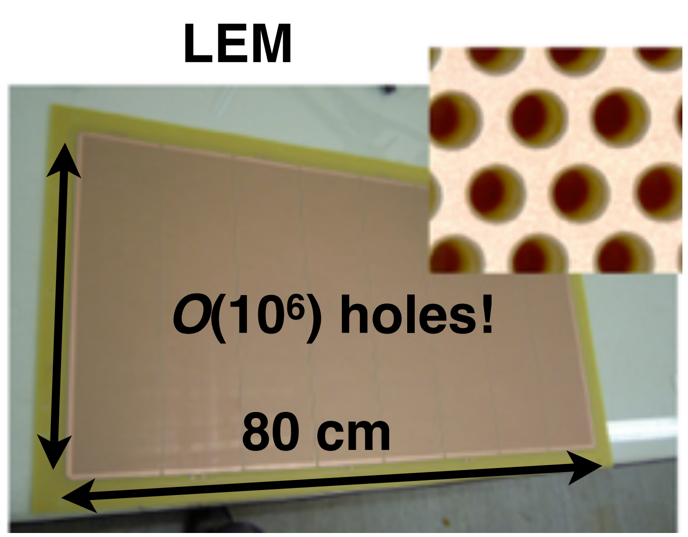
Cosmic Data from 40x80cm^2 LAr LEM TPC@CERN-ETHZ



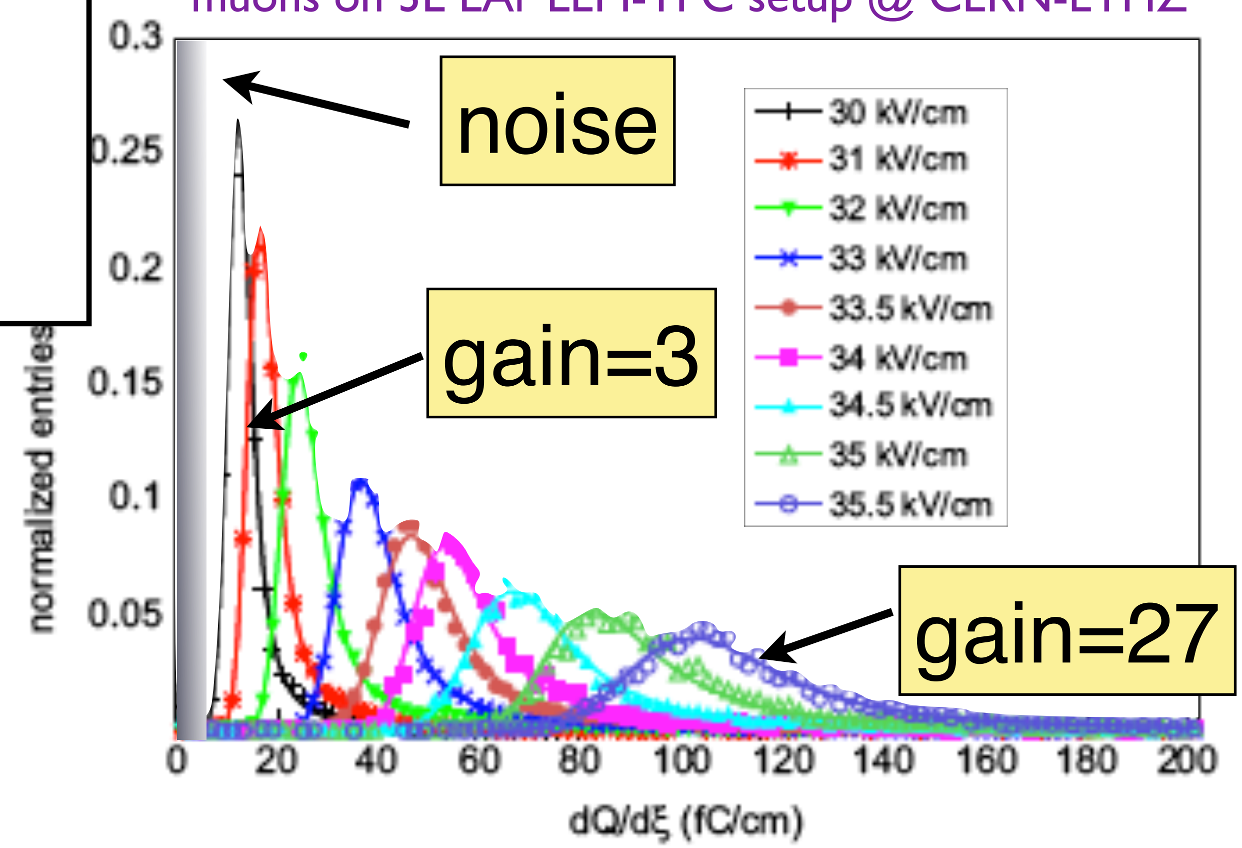
Design of a compact, robust and scalable readout cassette ("sandwich")



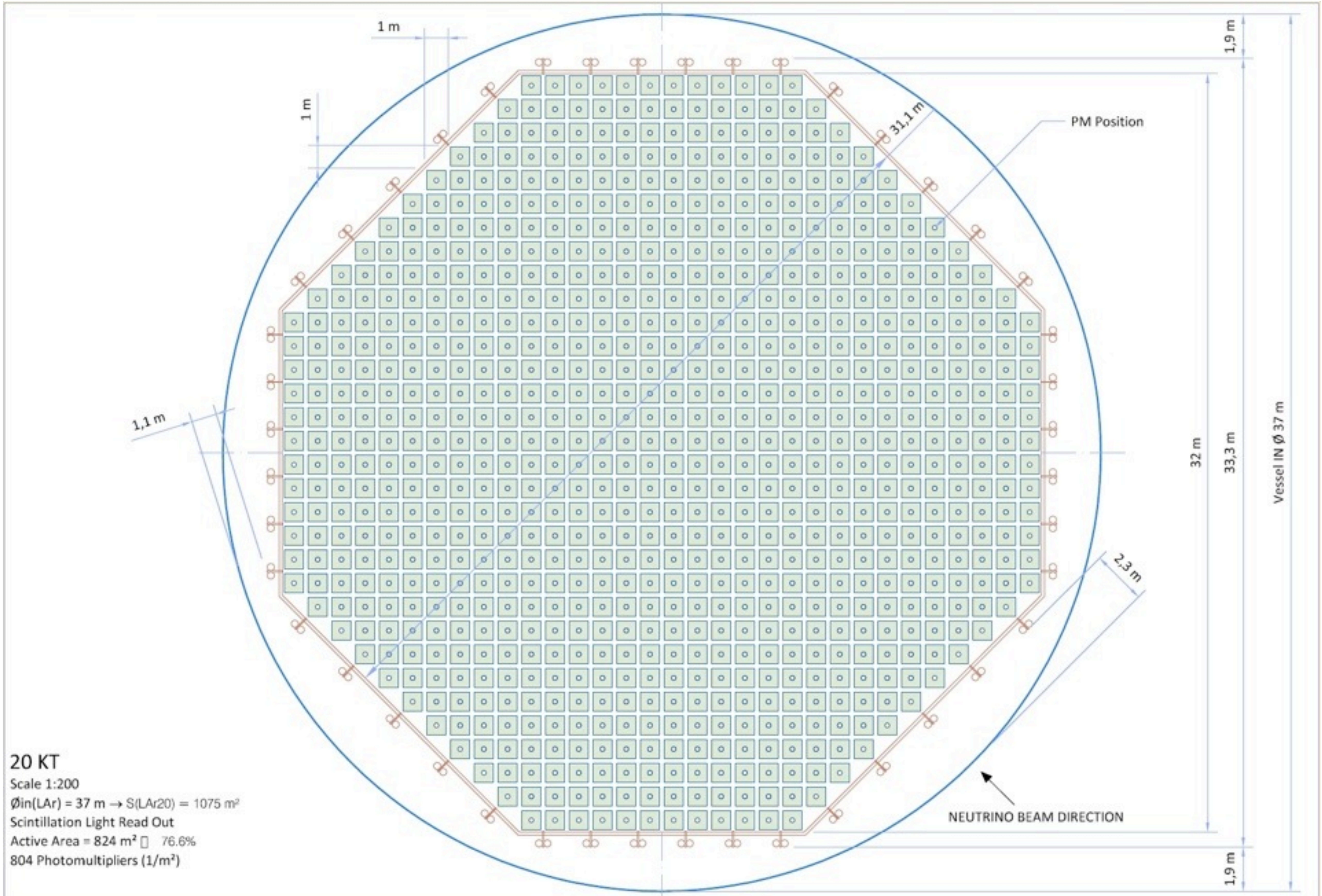




Landau distribution fitted to dE/dx distributions of muons on 3L LAr LEM-TPC setup @ CERN-ETHZ

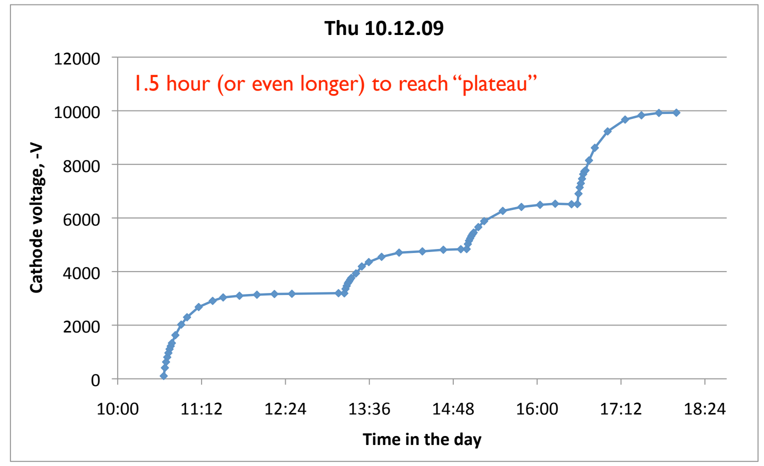


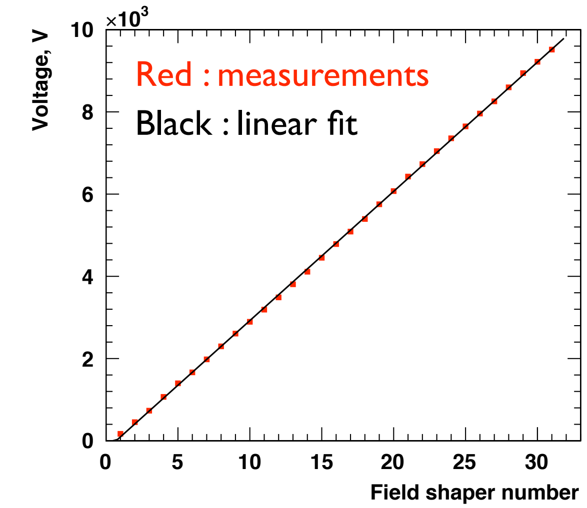
GLACIER light readout layout



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.

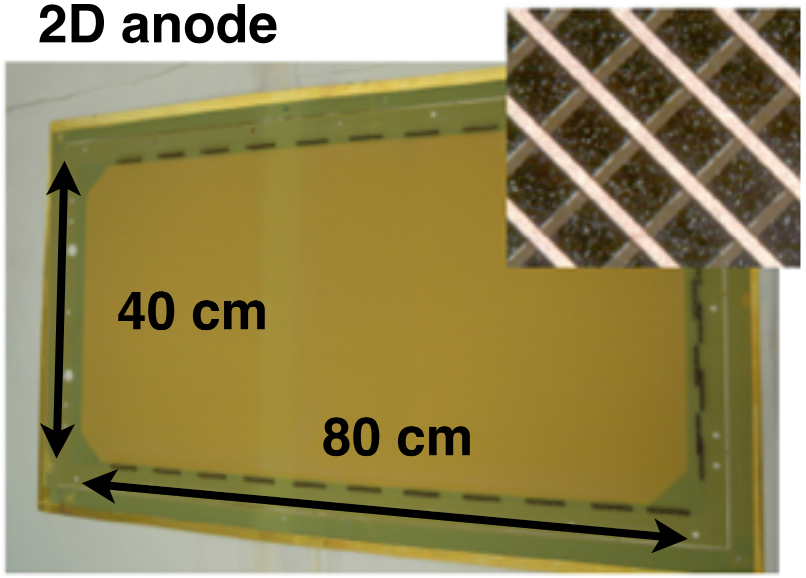
LAr vaporization heat 160 kJ/kg

$$V_{\max} = \frac{E}{\gamma}, \ \gamma \approx \sqrt{\frac{C_p}{C_s}}$$

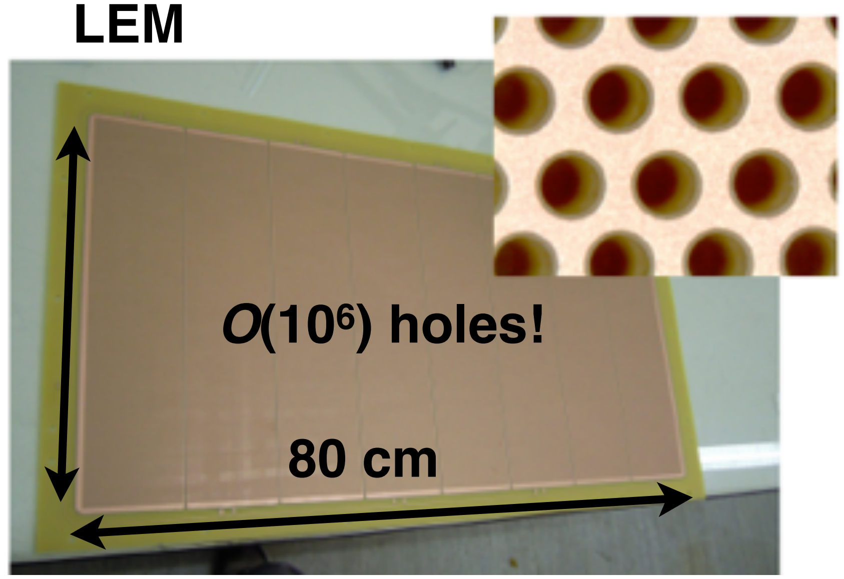
LAr-LEM TPC@CERN: Production of a $40x80\ cm^2$ charge readout sandwich

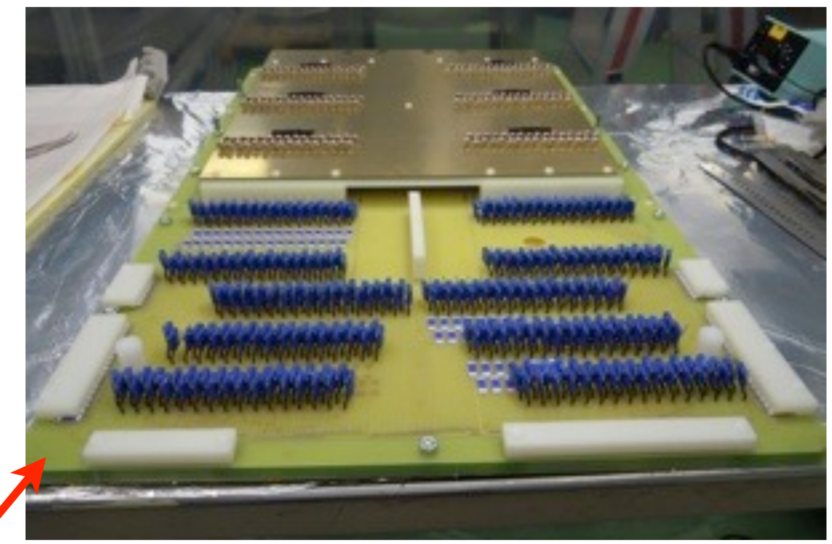
- After successful test of LEM and 2D anode in the 3L setup we designed and produced a $40x80\ cm^2$ charge readout for a new 250L LAr LEM-TPC (production and assembling finished by summer 2011)
- The ArDM cryostat @CERN was used for a first test of the new charge readout system

2D anode



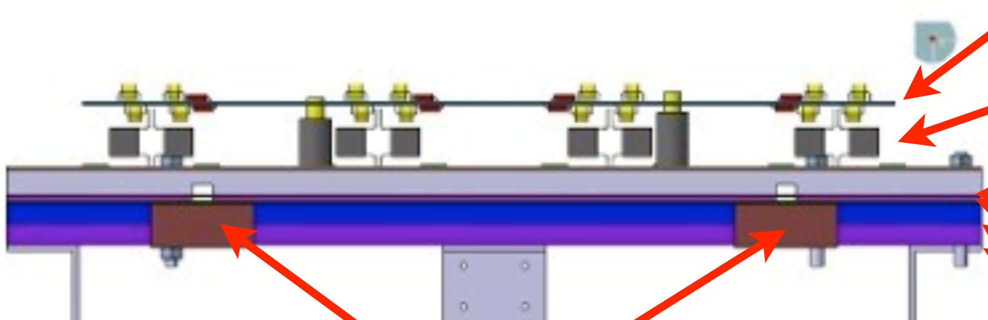
LEM

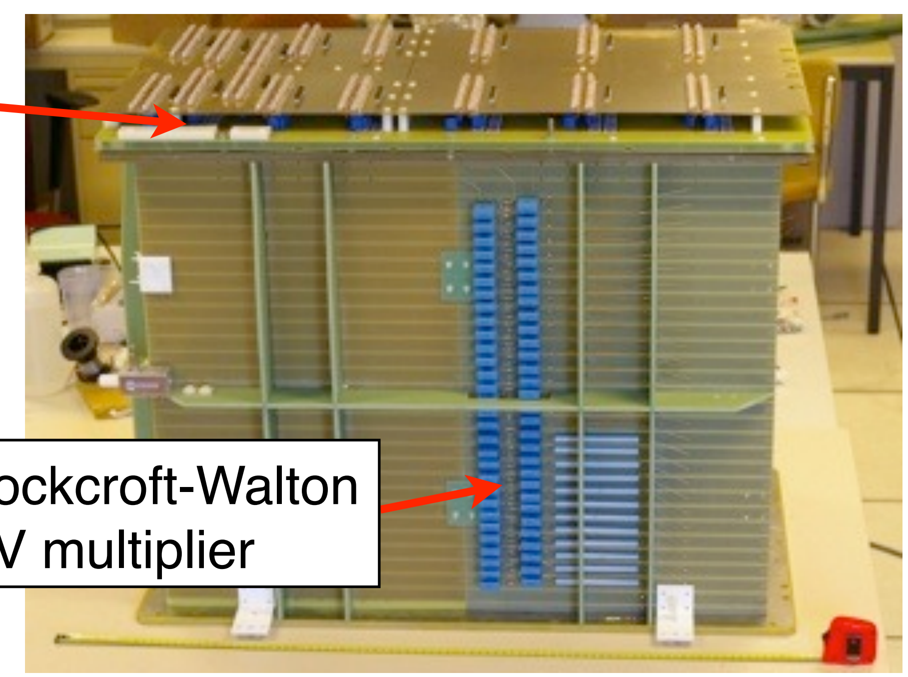




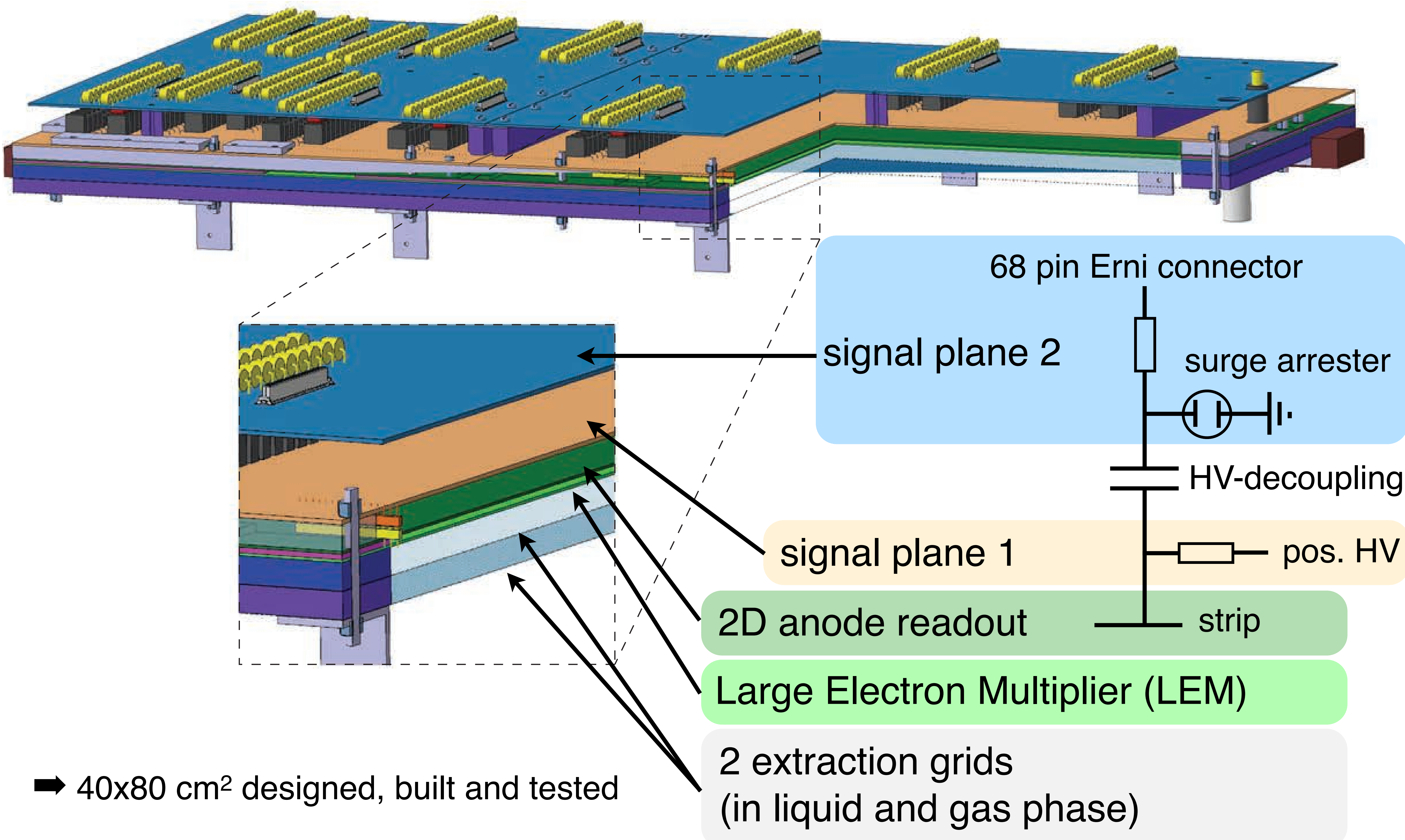
- Manufacturer: CERN TS/DEM group and ELTOS company (Italy)
- Largest LEM/THGEM and 2D readout ever produced!!!

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





Charge readout sandwich

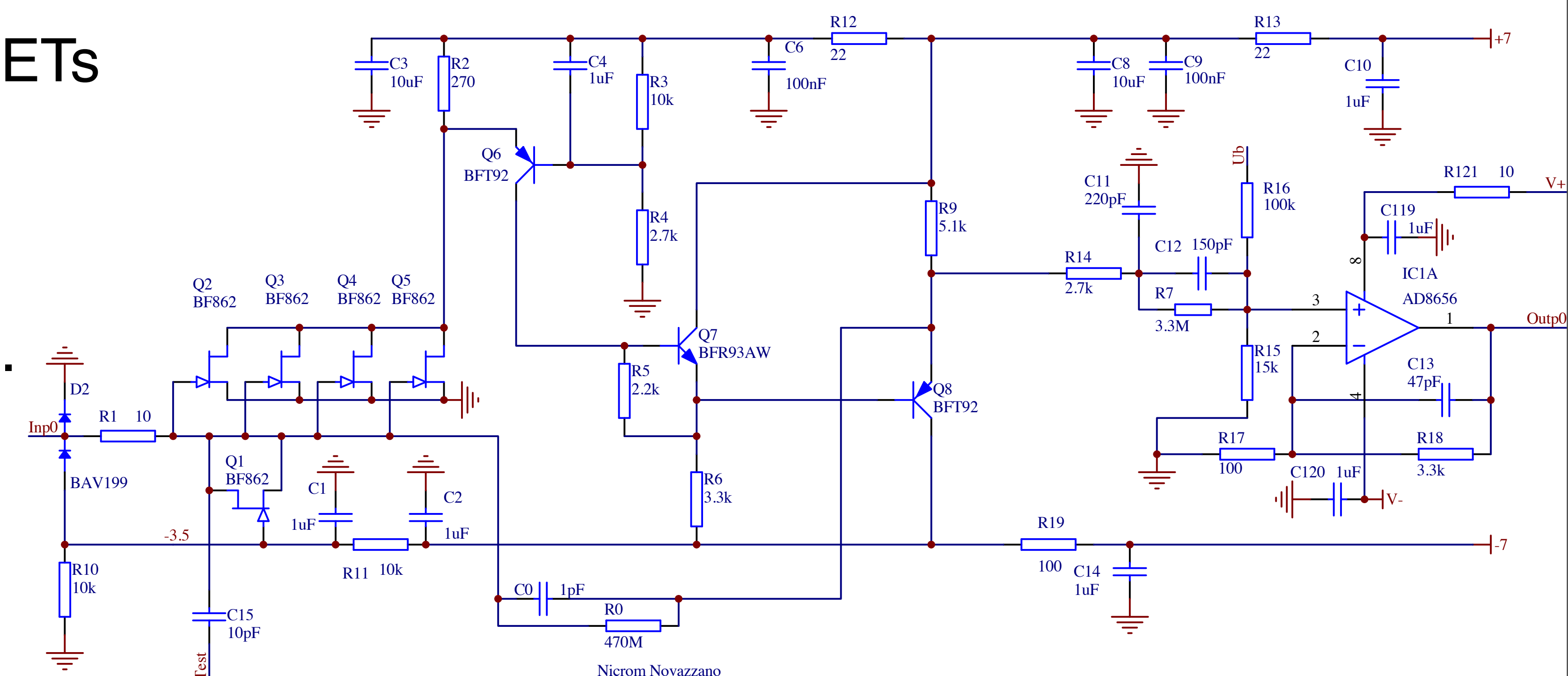


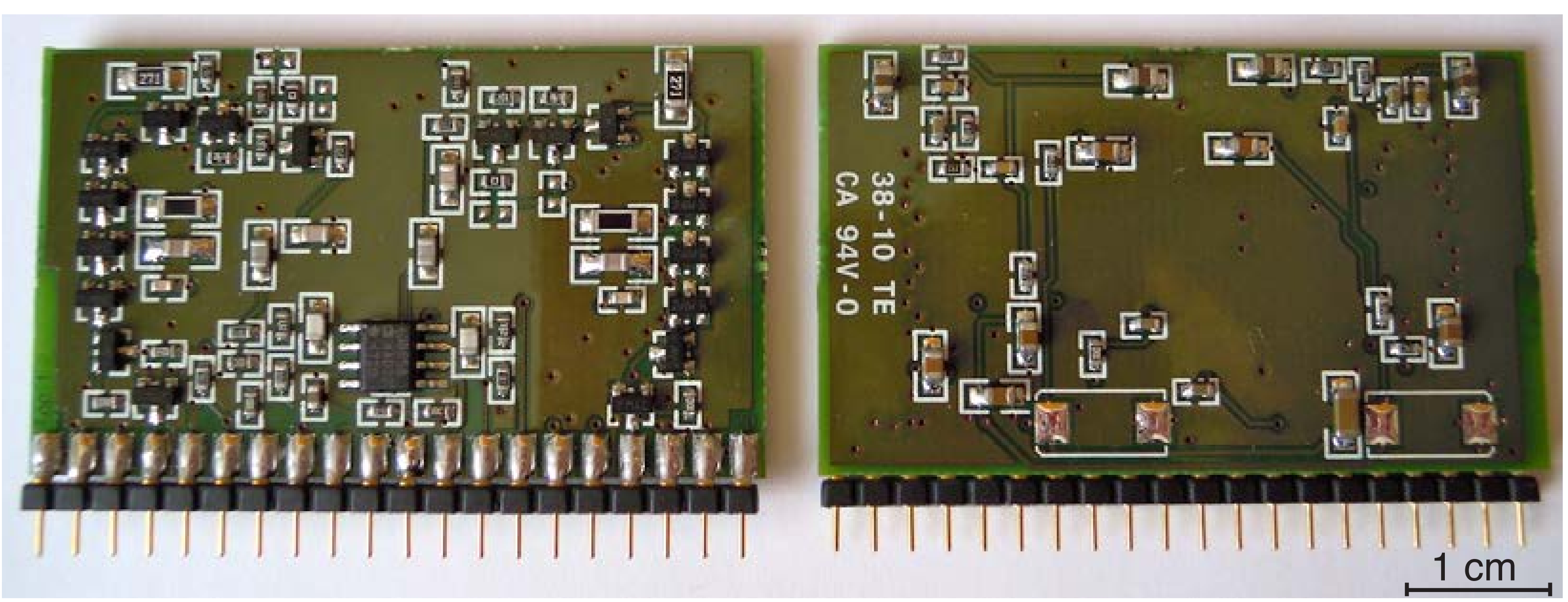
➡ 40x80 cm² designed, built and tested

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



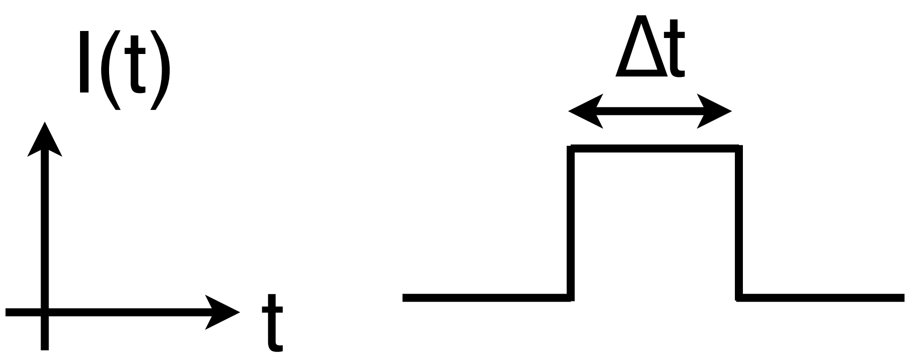


realization

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

Performance of the ETHZ preamplifier

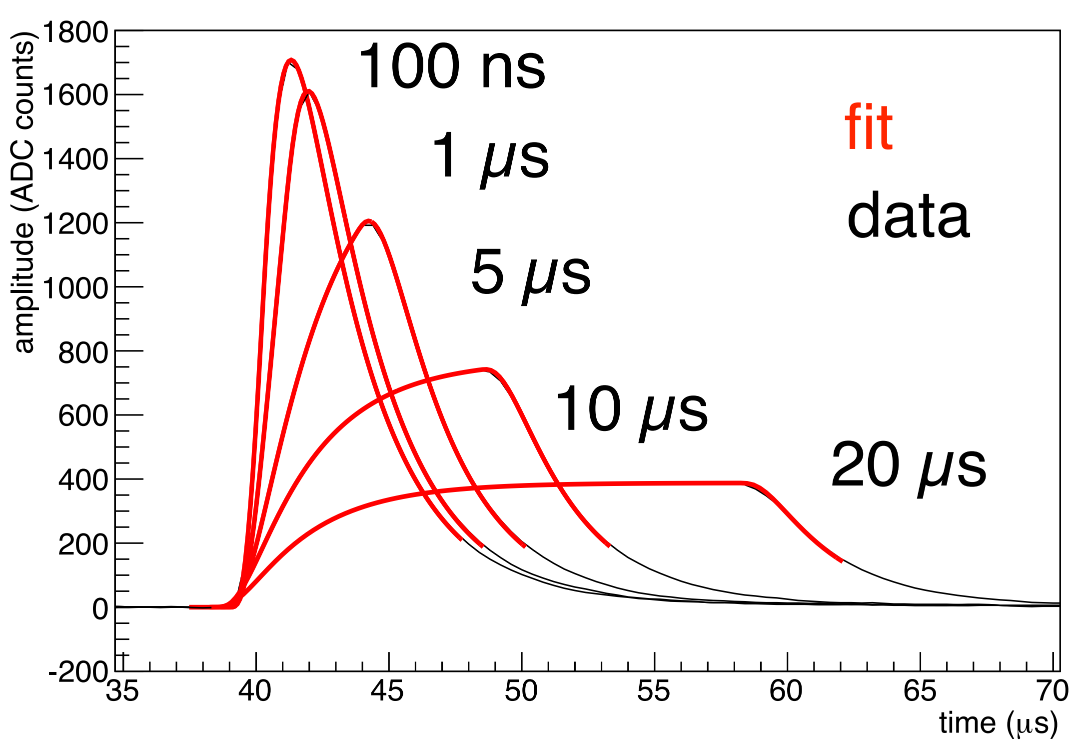
32 preamplifiers have been characterized with a well defined charge input:



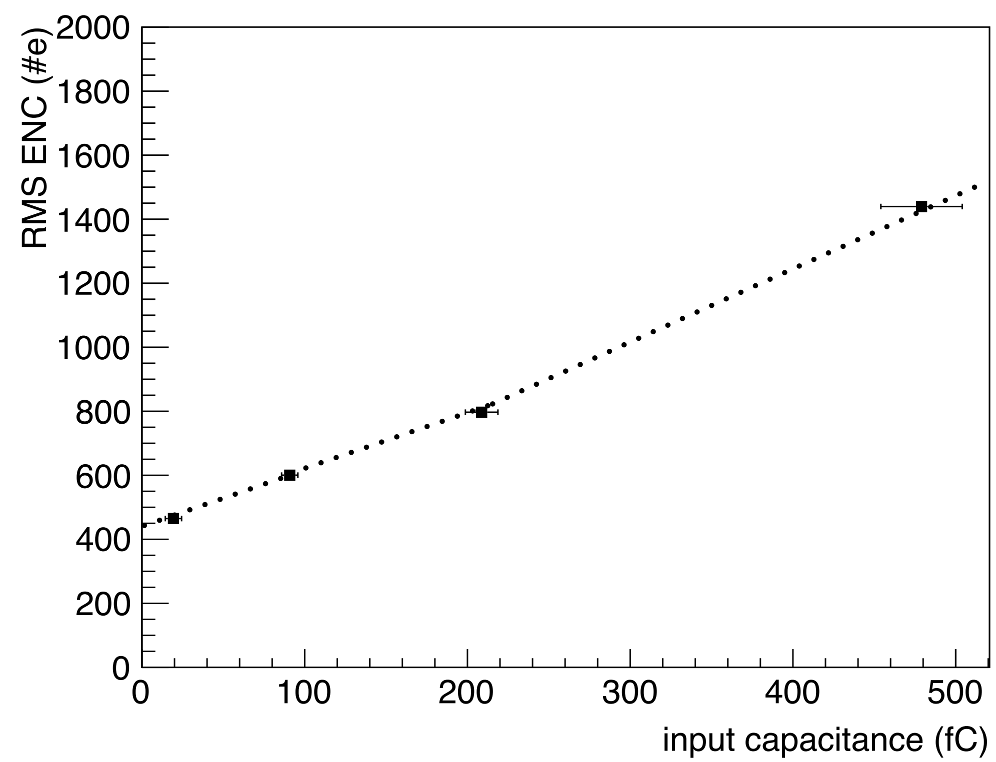
Summary

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

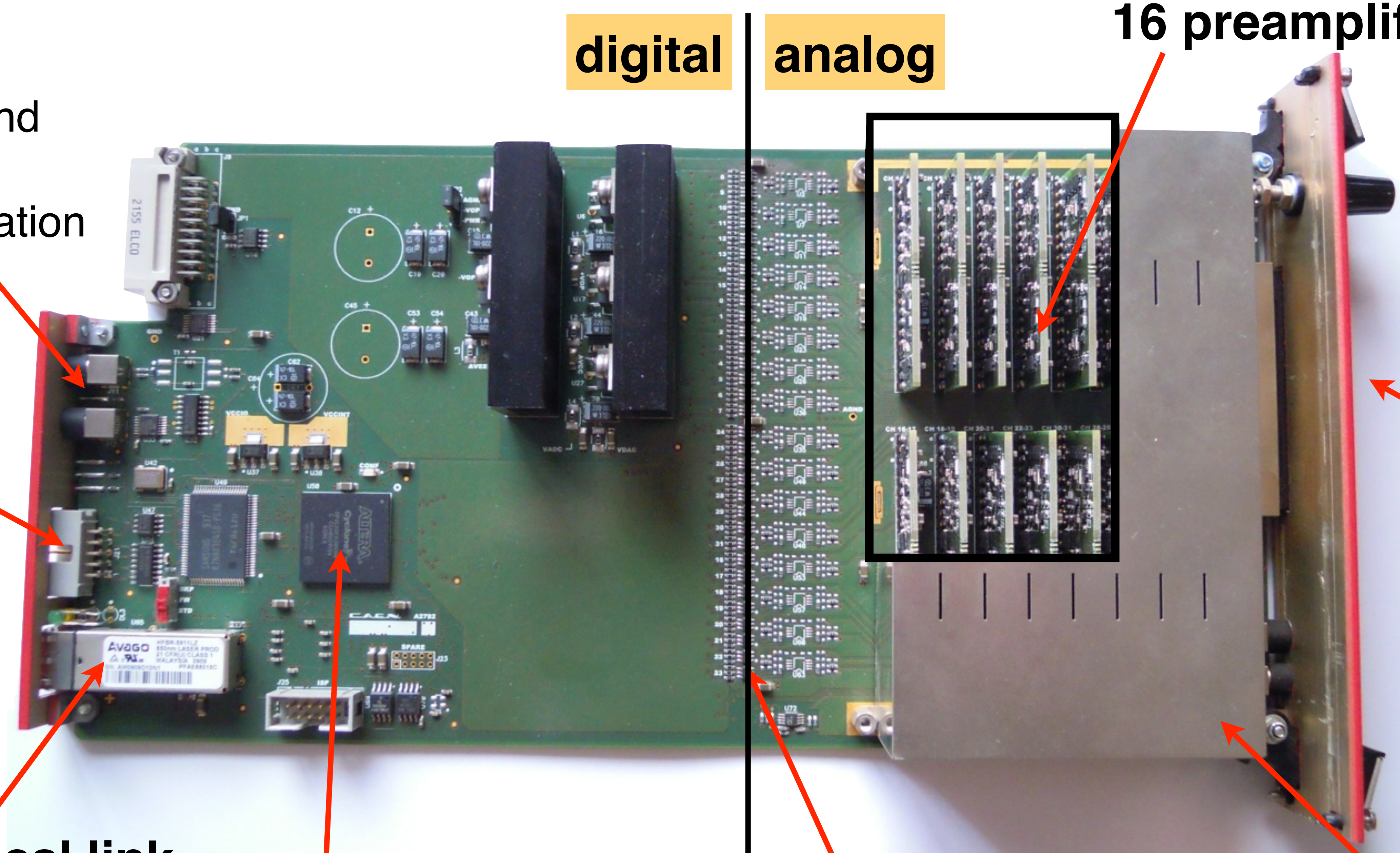
pulse shaping (varying Δt)



RMS ENC vs. input capacitance

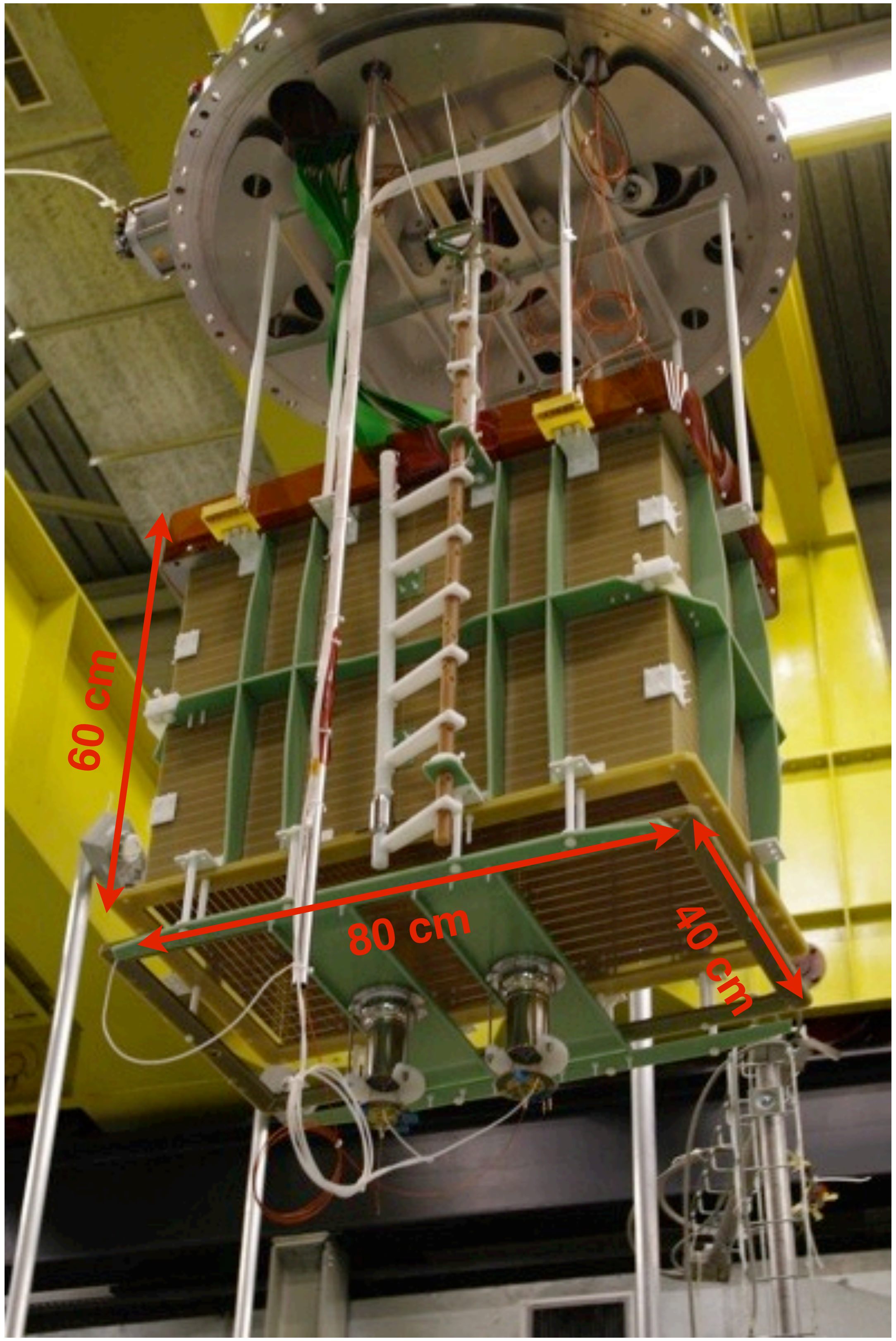


The CAEN A2792 acquisition board

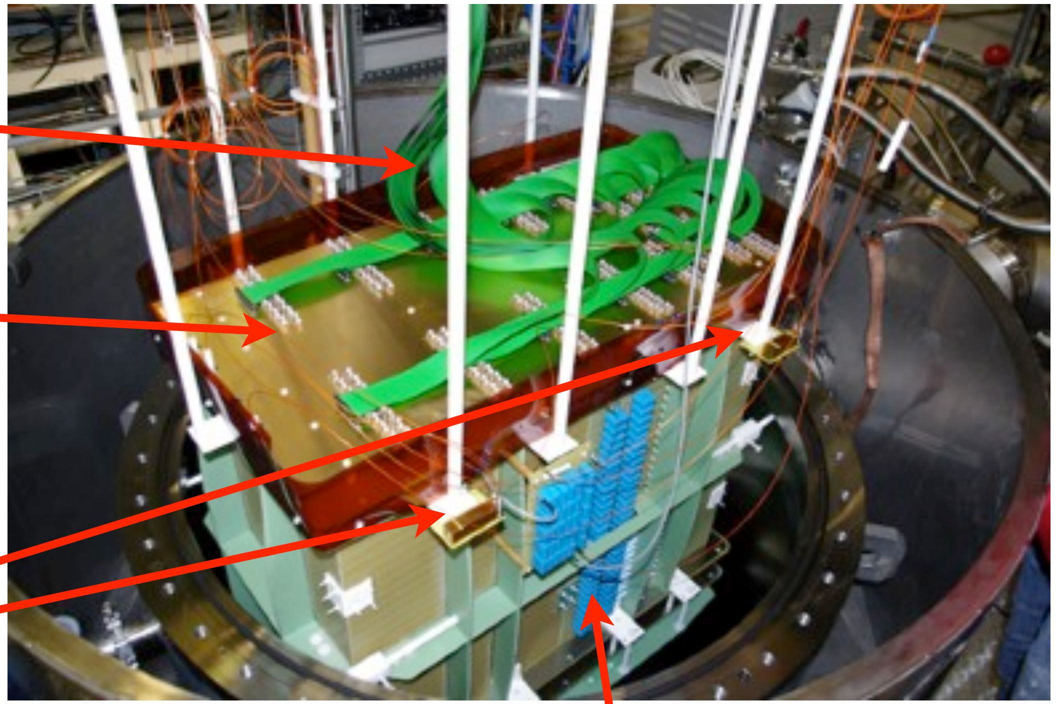


LAr-LEM TPC@CERN:The largest LEM-TPC ever

Detector fully assembled



Chamber going into the ArDM cryostat



Final connection to the DAQ system