Long baseline neutrino beam options at CERN

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NuFact'11 XIIIth Workshop on Neutrino Factories, Superbeams and Beta-beams

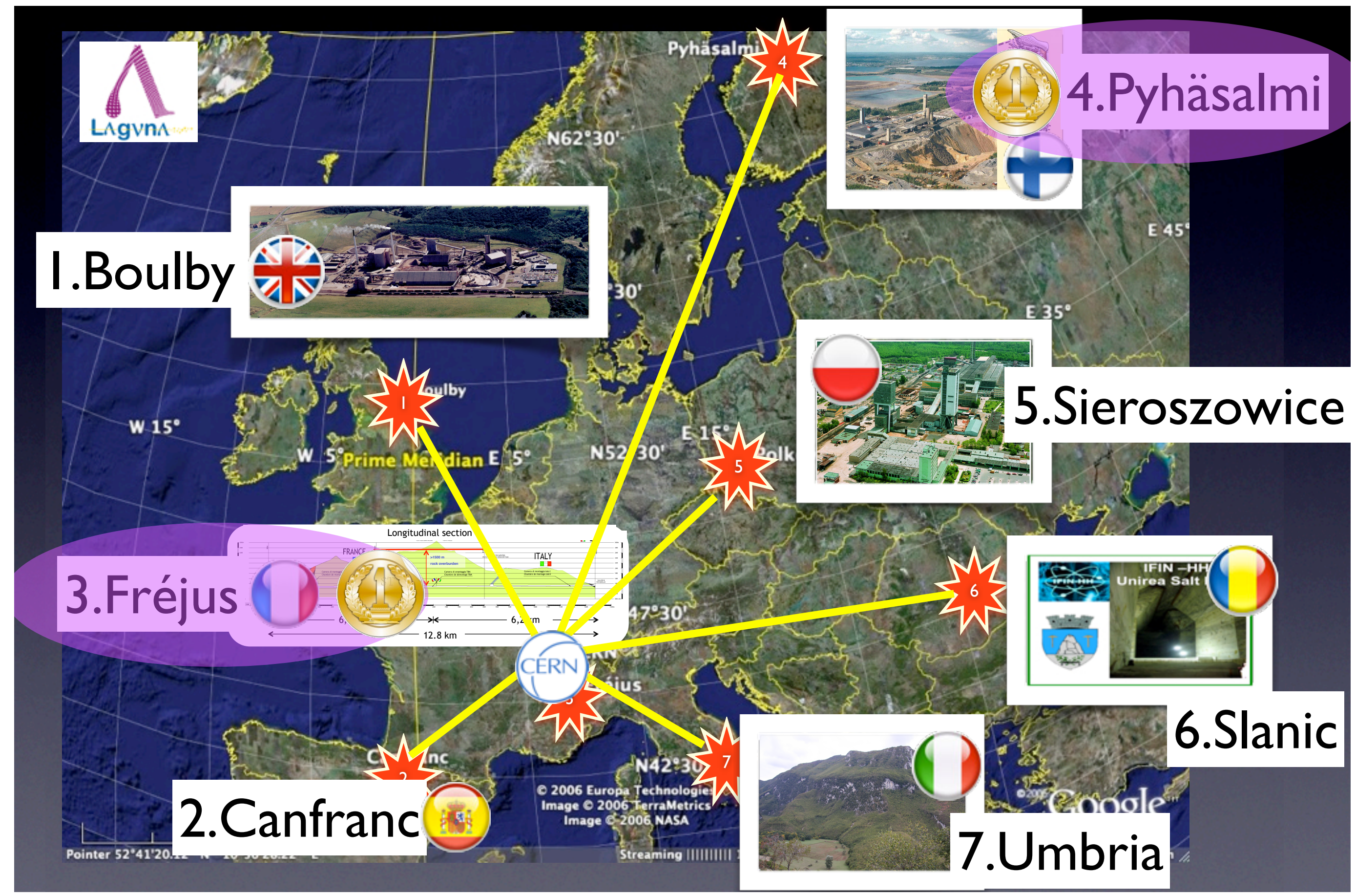
Three “conventional beam” proposals

We are not alone !

In USA

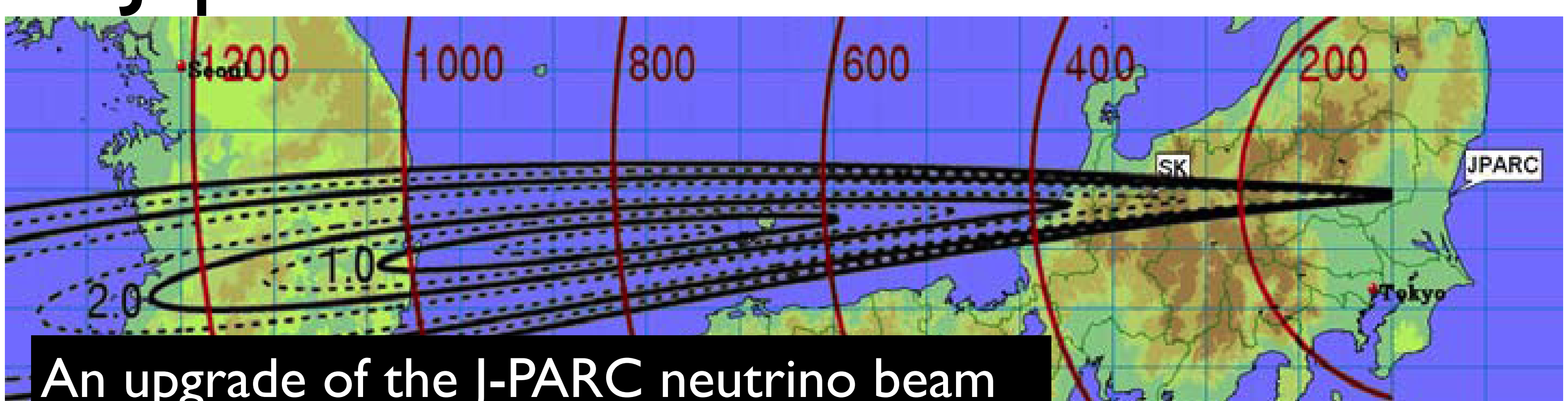
LBNE – a plan to build a new neutrino beam at Fermilab aimed at Homestake, where either a large water Cerenkov detector or a LAr tracking calorimeter would be built

In Europe



LAGUNA/LAGUNA-LBNO – three different 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 a new far detector

Recent results from T2K/MINOS further boosted the interest in these “incremental” options.

Comments about scenarios in Europe

- **The chicken and egg problem**
  - ➡ Does the baseline define the far site or does the far site define the baseline ?
  - ➡ Do(es) the far detector(s) decide upon the kind of baseline / beam ? or do the baseline / beam decide upon the far detector(s) ?
  - ➡ Does the non-accelerator based physics programme define the underground location or does an underground location enable the non-accelerator physics programme ?

- **The European /CERN Context**
  - ➡ The (current) priority is the high energy frontier
  - ➡ The long baseline neutrino programme is presently CERN-LNGS (CNGS), and will likely end towards 2013-2014. Many EU neutrino physicists are "abroad".
  - ➡ No approved neutrino programme exists beyond CNGS
  - ➡ Several FP7-Research Infrastructures "design studies" funded (LAGUNA, EuroNU, LAGUNA-LBNO) ➠ we like to interpret these as "CD-0-equivalent"
  - ➡ LAGUNA has a very high priority in the ASPERA European Astroparticle Physics Roadmap ("magnificent seven")
  - ➡ Look for an endorsement from the Updated European Strategy for Particle Physics ? What kind of endorsement ? "Global" input expected at the next ICFA meeting at CERN in October 2011.

A new EU “Research Infrastructure”

- **New “megaton-scale” detectors pose us scientific, technical and financial challenges.**

- **In addition, establishing the infrastructure and the legal status of the far detector(s) is an additional challenge that we are starting to address in LAGUNA**
  - ➡ In Europe, there is at present no existing infrastructure that can host the far detector(s) for the next generations of long baseline experiments
  - ➡ In the EC language, we need to establish a new **RI = Research Infrastructure**. This involves at least (a) a legal status (b) construction funds and (c) operational funds (for several decades)
  - ➡ In contrast, given funds / time / priority, CERN has the proper framework and technical expertise to consider and likely build any kind of neutrino beam.

- **What should / will be the role of CERN ?**
  - ➡ The far detector RI is unlikely to be a “100%-CERN project”
  - ➡ It will probably be managed by an international consortium involving several national funding agencies, with the support from the CERN Council and with participation from CERN.

The LAGUNA design study (2008-2011)

- **Large Apparatus for Grand Unification and Neutrino Astrophysics**
  - ➡ Proposal discussed for the first time at ASPERA "Town meeting" in 2005 to "combine efforts" and "regroup all European physicists interested in this kind of physics"
  - ➡ FP7 funded LAGUNA "Design Study" (2008-2011)
  - ➡ Detailed investigation of the feasibility of a deep underground "megaton-scale" detector, considering three detector technologies (WC, LAr, LS) and seven potential European sites
  - ➡ Focused on European options, but following closely developments of other options worldwide (Americas, Asia)
  - ➡ Outcome of studies summarized in 16 deliverables: fundamental material for site prioritization

- **Recommendation to consider potential beam options**
  - ➡ In 2008, LAGUNA evaluation expert panel (ESR) strongly suggested to take into account potential neutrino beams (from CERN)

The EU design study "menu"

LAGUNA

- far detector "RI" for astroparticle and beam physics
- three detector options
- seven potential sites
- excavation costs
- industrial links

2008

time

2011

EuroNu

- international consortium
- low energy MW-superbeam (HP-SPL)
- beta beam
- neutrino factory
- costs
- comparison of facilities

LAGUNA-LBNO

- international consortium including EU, Japan and Russia
- two main far sites
- new conventional beam from SPS
- high energy MW-superbeam (HP-PS)
- near detector infrastructure
- detector magnetization
- detector construction and costs

- Update European Strategy for Particle Physics

2013

next step(s) ?

LAGUNA at work (2008-2011)

Typical questions addressed

- assessment of strengths and weaknesses
- rock mechanics of caverns
- design of tanks in relation to sites
- overburden vs. detector options
- transport, access, delivery of liquids
- safety e.g. tunnel vs. mine
- environment e.g. rock removal
- relative costs

Site visits and meeting

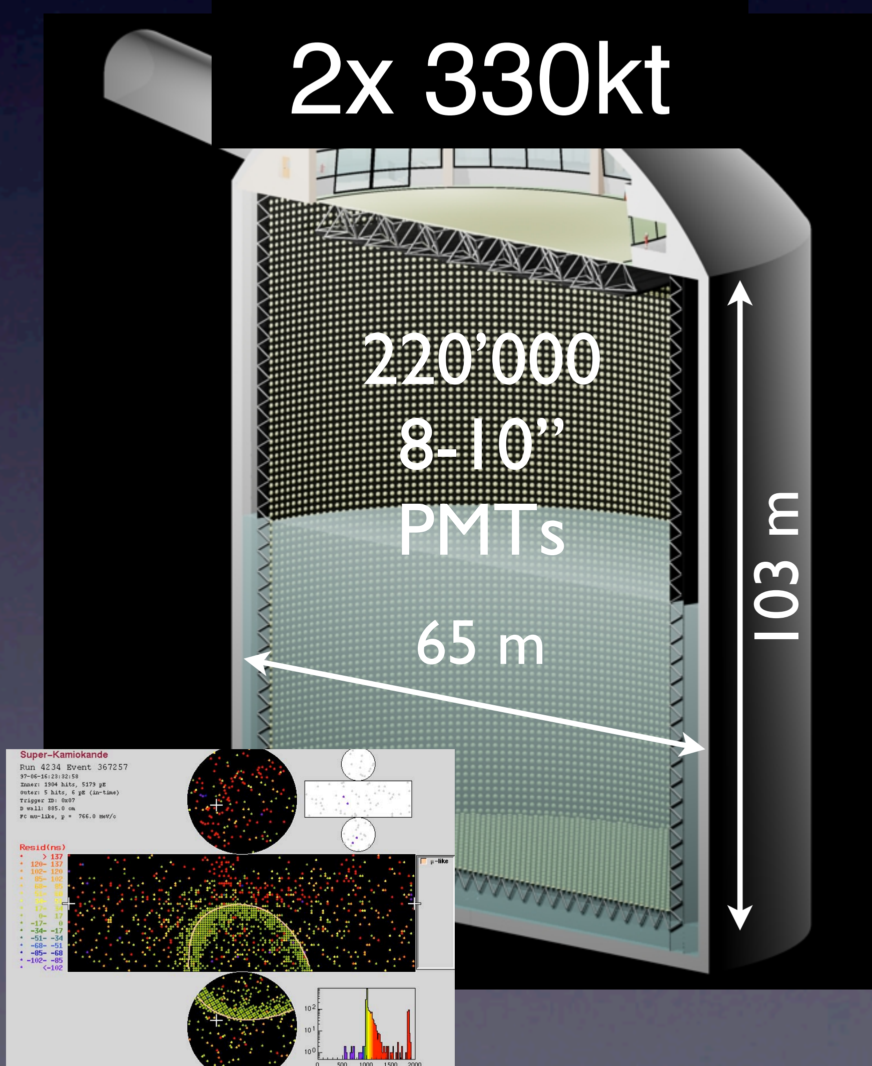
- sites work together on common areas

LAGUNA detector options

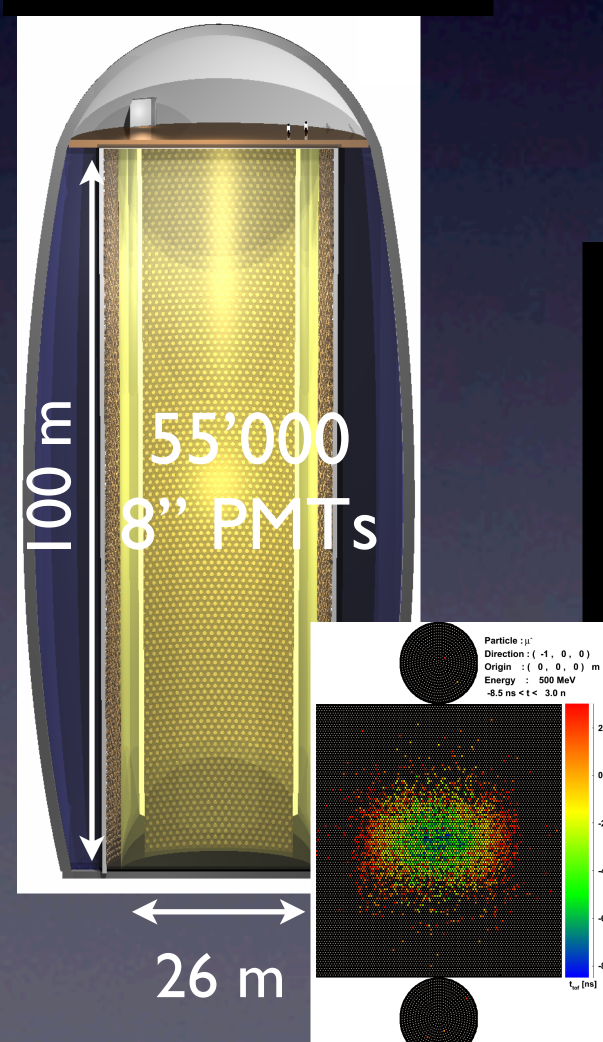
The rationale: *Large liquid volumes observed by photodetectors and/or charge electrodes on the surfaces of the tanks*
(a) Target mass M scales like volume excavated
(b) Amount of instrumentation scales roughly like sqrt(M)
(c) the amount of material to bring underground (e.g. tank material) is <<< target mass M
(d) Liquids are sent underground via pipes into the tanks

This is one reason why we focus on liquid detectors

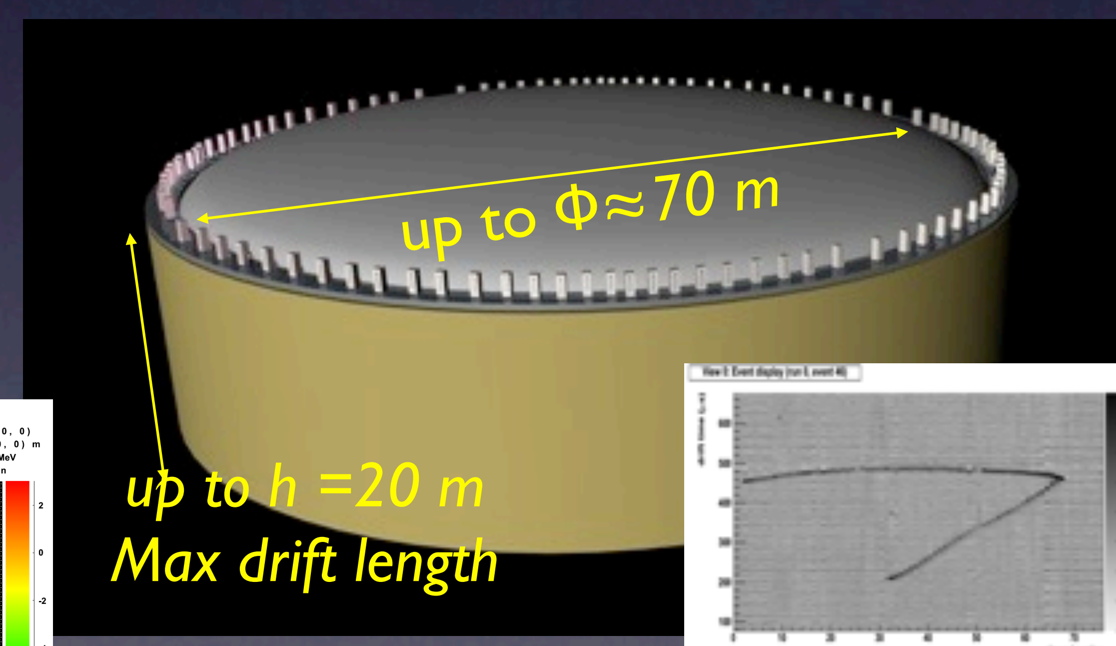
MEMPHYS
2x 330kt



LENA 50kt



GLACIER 100kt

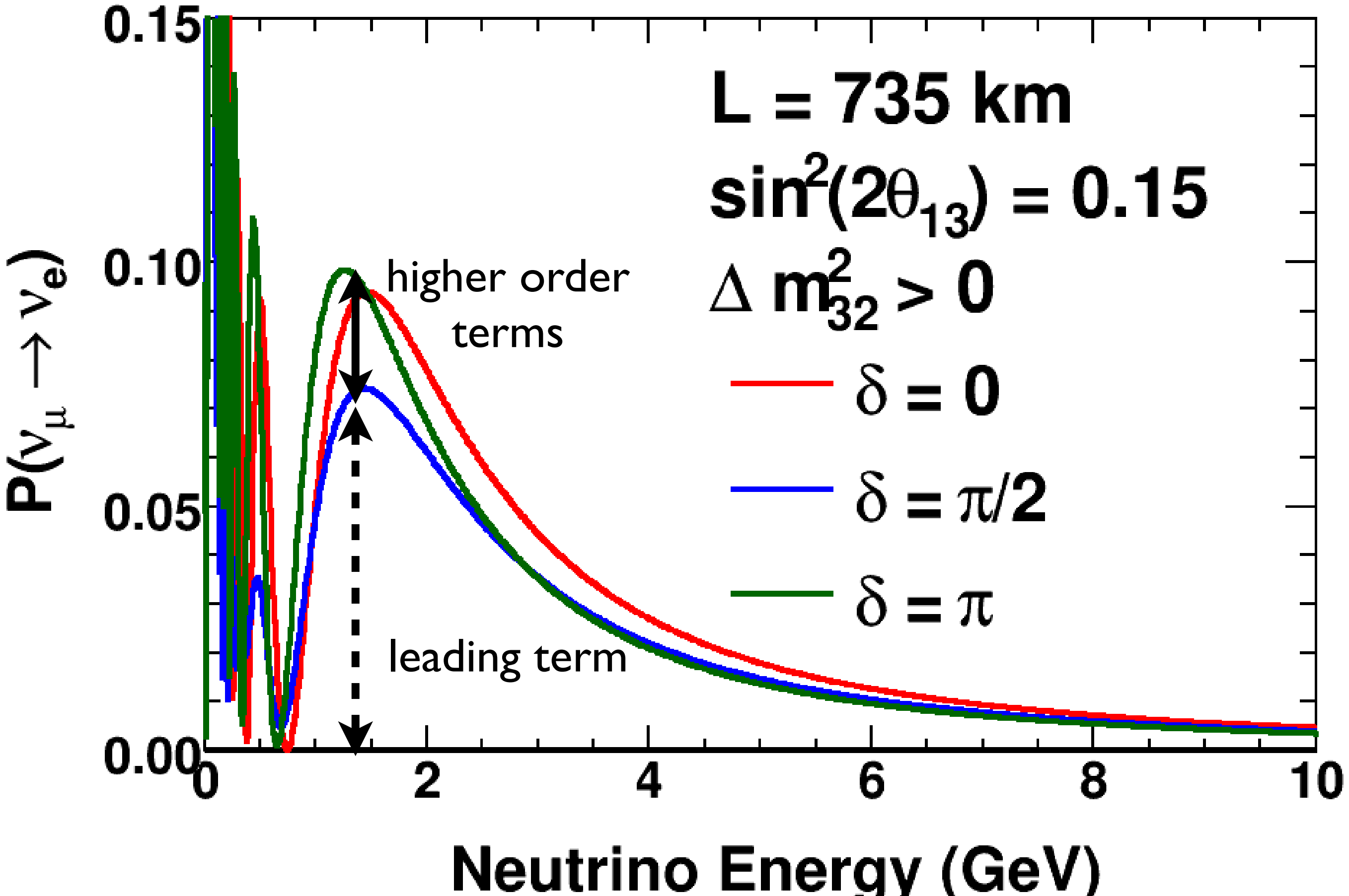


Main LBL physics programme

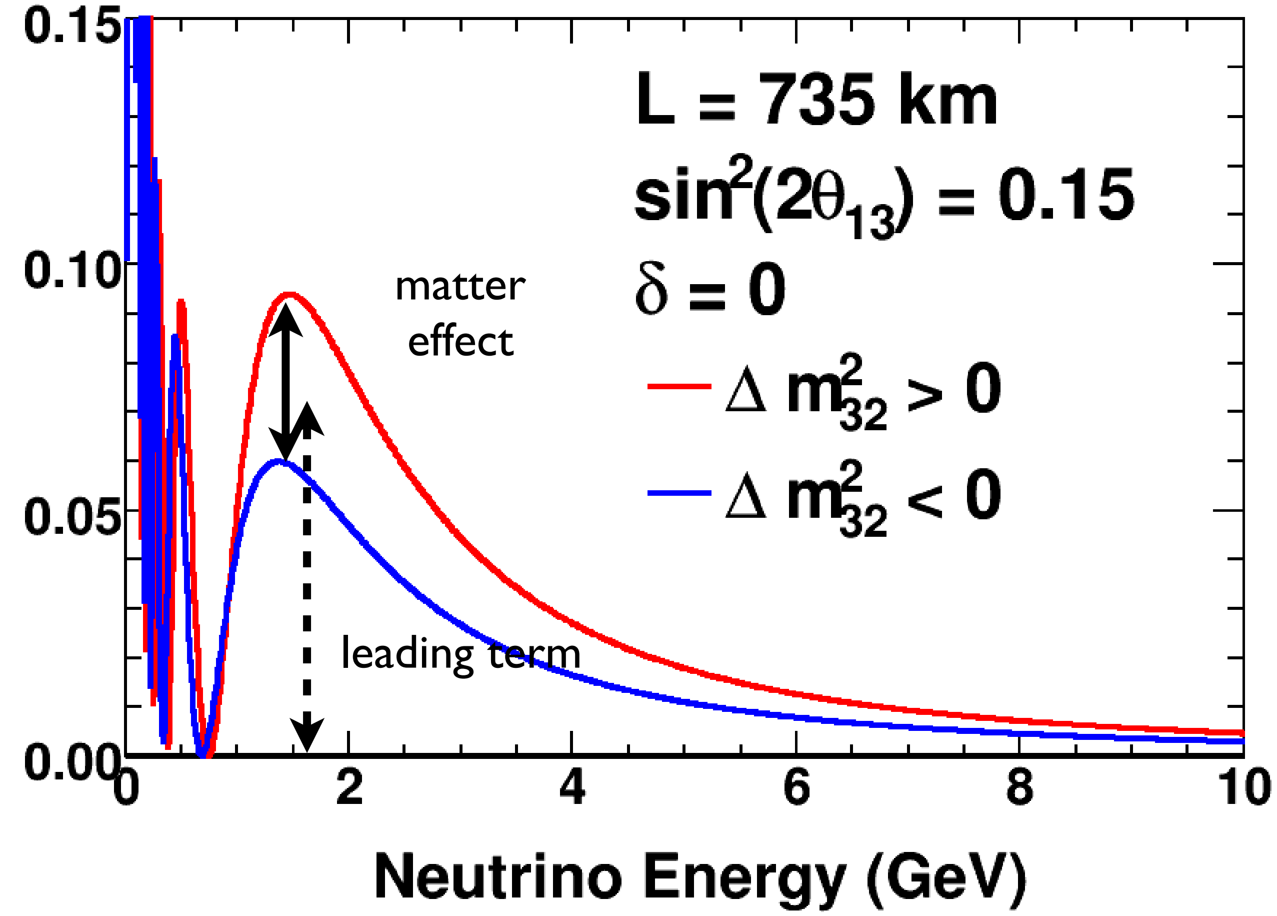
νe appearance in a νμ beam <u>with high precision</u> to test higher order terms that depend on δ_{CP} and determine the matter effects

➠ Measure energy-binned probability with rel. error < O(5%)

δ dependence



mass hierarchy dependence



Courtesy: L. Whitehead

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

quadratic dep. on θ_{13}

matter effect ~E

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

~7500 km magic bln

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

CPV term approximate dependence ~L/E

~2540 km magic bln

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

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

solar term

linear dep. on θ_{13}

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

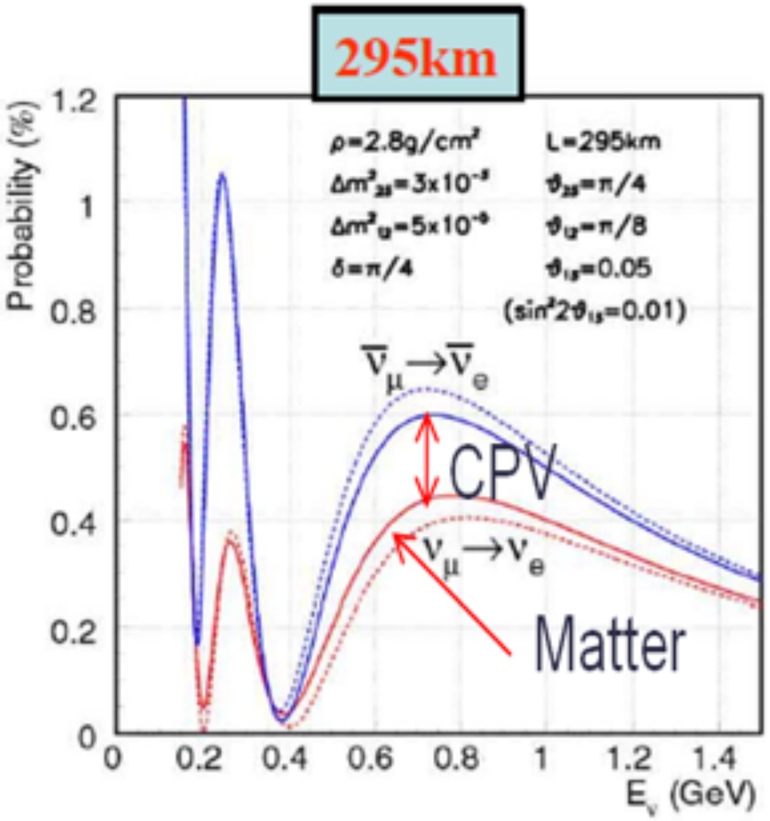
$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

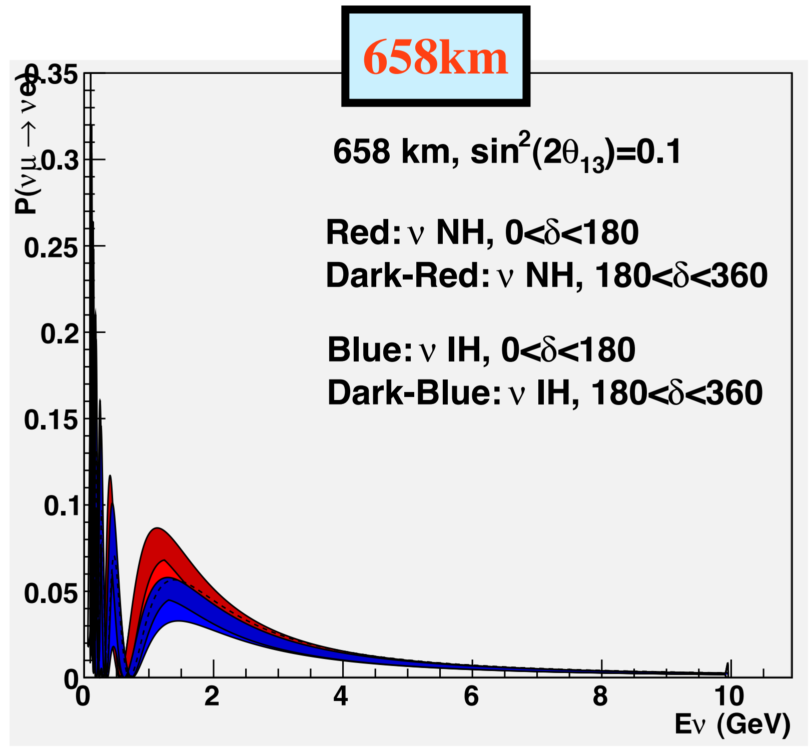
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

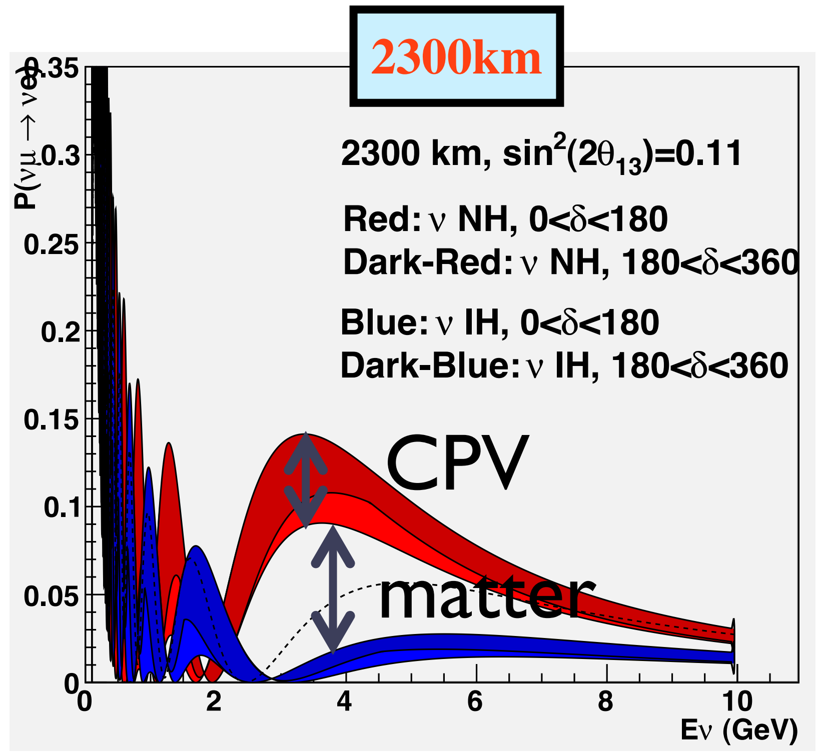
$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.

CP asymmetry grows as θ_{13} becomes smaller !

Different approaches to the problem

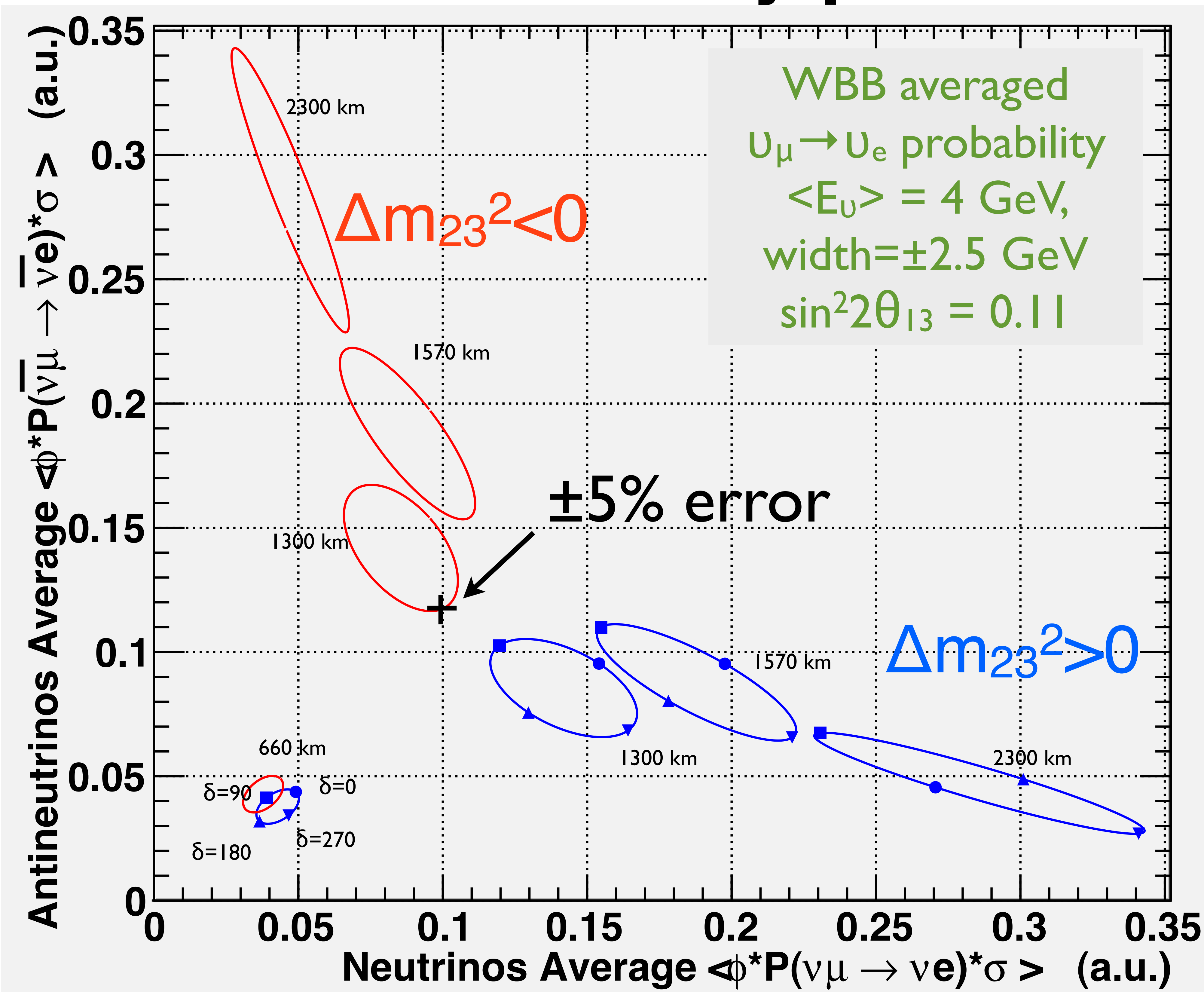






- Two main modes of investigation (or a combination of both)
  - ☆ ν_e Appearance Energy Spectrum Shape in Wide Band Beam (WBB) at fixed L
    - Peak position and height for 1st, 2nd maximum and minimum
    - Sensitive to all the non-vanishing δ including 180°
    - Investigate CP phase with ν run only, but need WBB
    - Need very good energy resolution and low background systematics
  - ☆ Difference between ν_e and $\bar{\nu}_e$ Appearance Behaviors (CP asymmetry)
    - Also in Narrow Band Beam (off-axis)
    - Need both beam polarities with similar statistics to study effect
    - Need good control of systematic errors between neutrino & antineutrino run

Simultaneous solution to CP and mass hierarchy problems



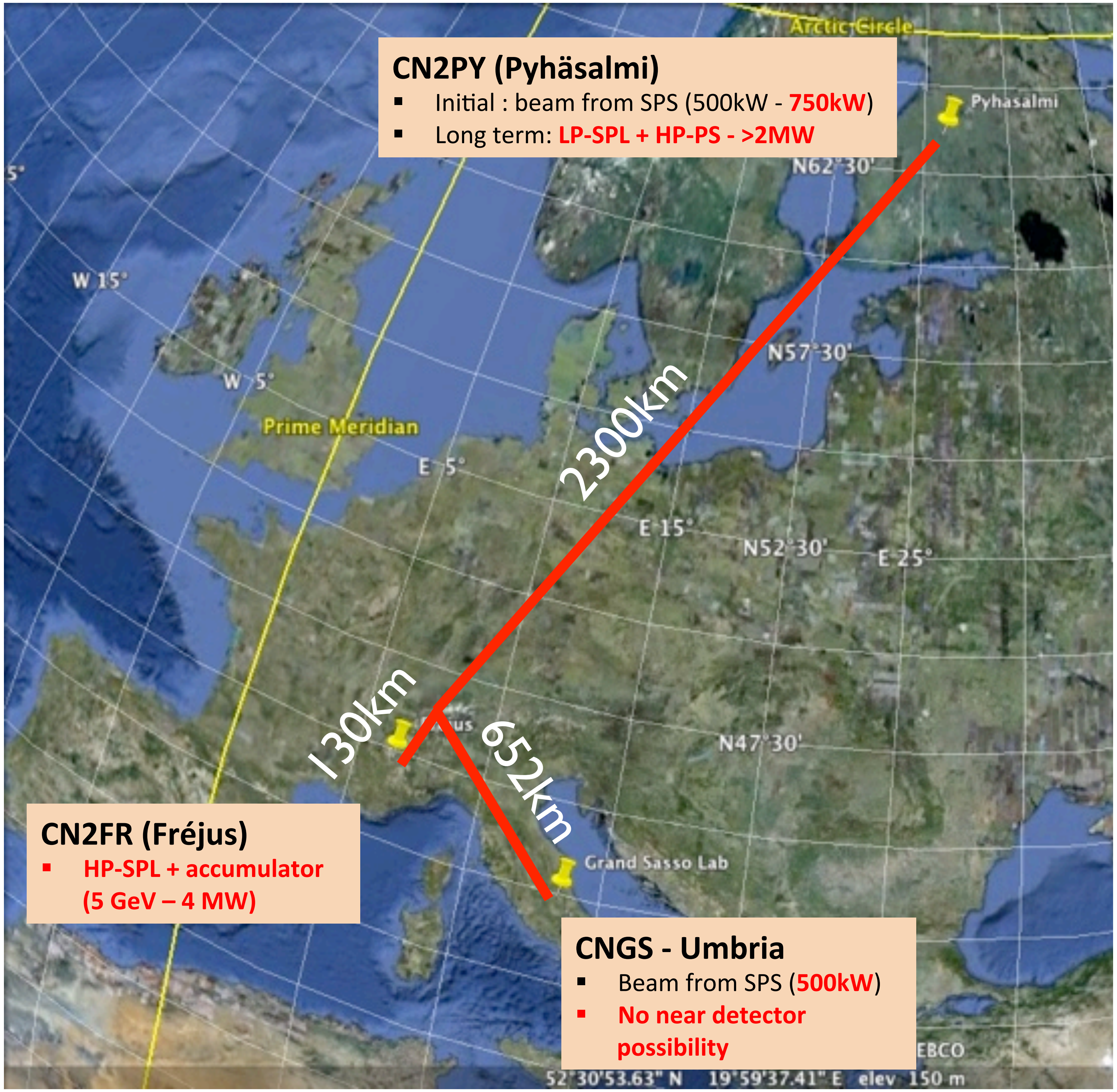
Longer baselines are better to determine mass hierarchy.

And the two ellipses are better separated, which provides an unambiguous δ_{CP} determination

LAGUNA-LBNO sites

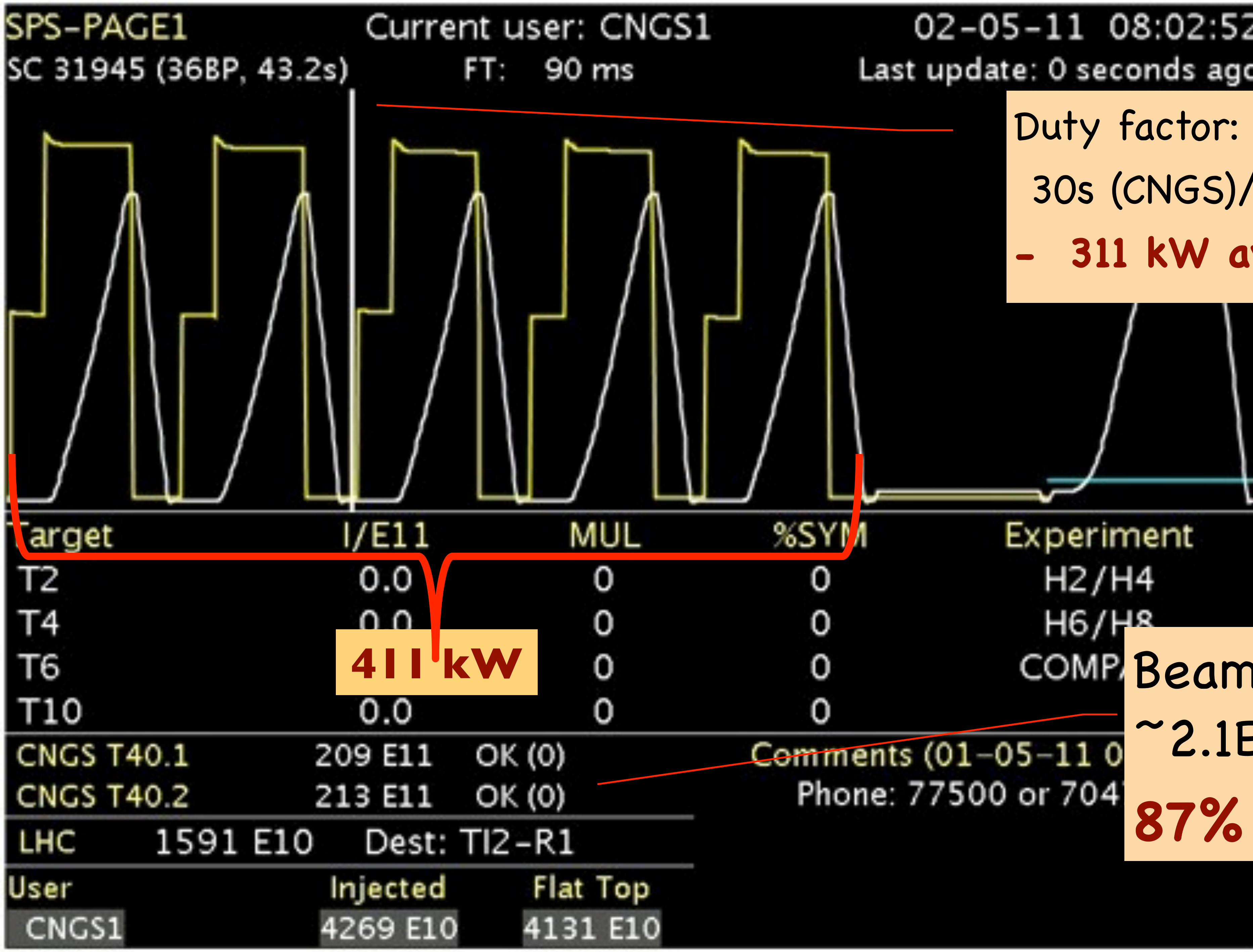
New conventional beams to be considered based on CNGS experience

- CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100
- CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with a NF
- [CERN-Umbria has an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]



CNGS/SPS present performance

Courtesy: I. Efthymiopoulos



Duty factor:
30s (CNGS)/43.2s (total) = **69%**
- **311 kW average power**

Beam Intensity:
~2.1E19 pot/extr
87% nominal

- **311 kW average beam power**
- **1.5×10^{20} p.o.t** @ 400 GeV accumulated so far
- Integrated intensity limited by shared mode of operation

CERN new conventional beams study

- **The feasibility study of new conventional beams has been approved by the CERN Management (LAGUNA-LBNO GPF signed by DG). It includes the following tasks**
    - The new beam facility for high energy towards Pyhäsalmi initally accepts protons from the 400 GeV SPS after the intensity upgrade for HL-LHC, and eventually from a new potential accelerator involving LP-SPL + 50 GeV HP-PS.
    - Starting from the EuroNU studies, a layout of the HP-SPL+accumulator+target station for the low energy superbeam to Fréjus will be developed.
- Conceptual design reports will be delivered within 2014

Workpackage:

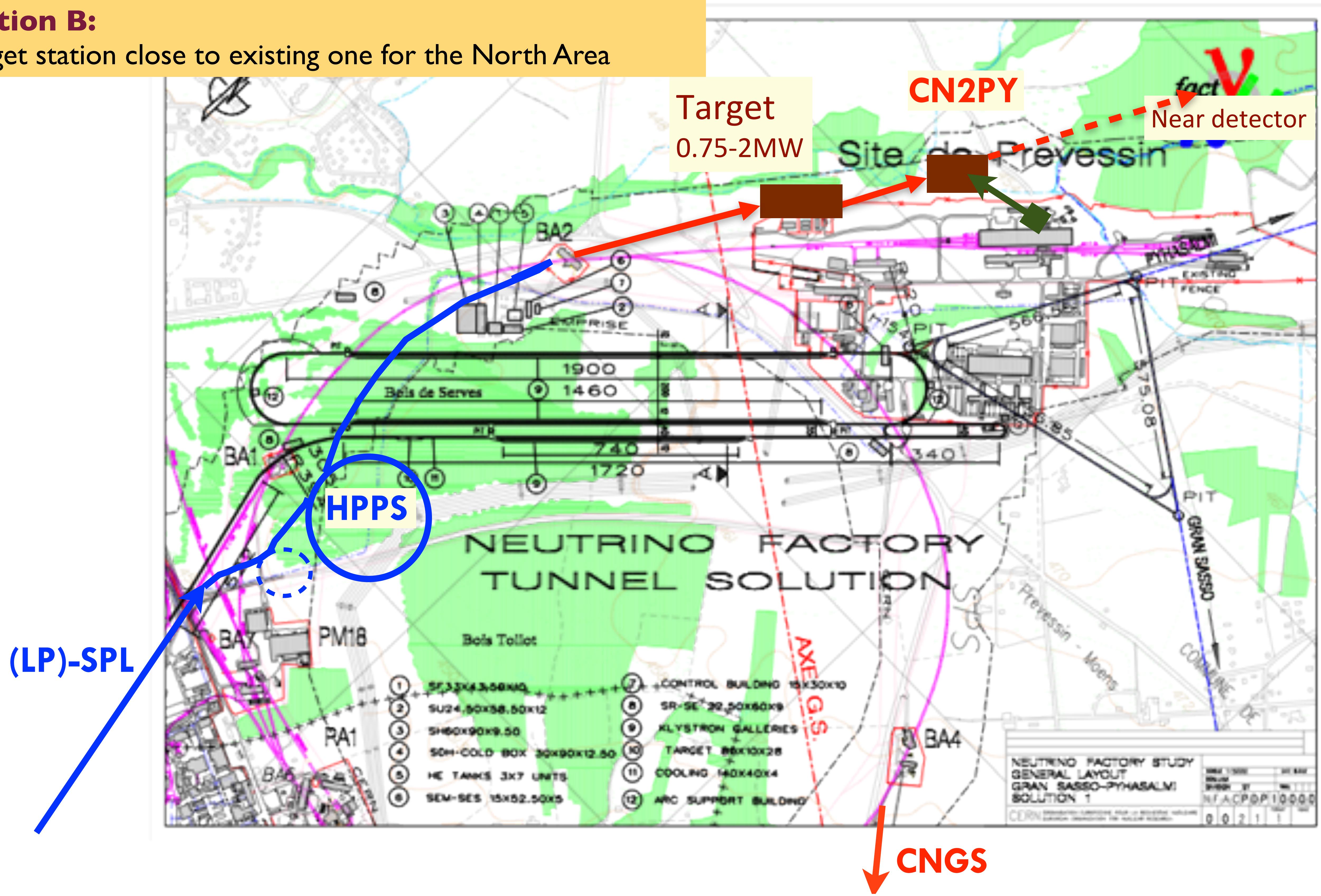
- **Task 4.1** Study of impact of CERN SPS accelerator intensity upgrade to neutrino beams
- **Task 4.2** Feasibility of intensity upgrade of CNGS facility
- **Task 4.3** Conceptual design of the CN2PY neutrino beam
- **Task 4.4** Feasibility study of a 30-50 GeV high power PS
- **Task 4.5** Definition of the accelerators and beamlines layout at CERN
- **Task 4.6** Study of the Magnetic Configuration for the LAGUNA detector
- **Task 4.7** Definition of near detector requirements and development of conceptual design

CN2PY beam concept

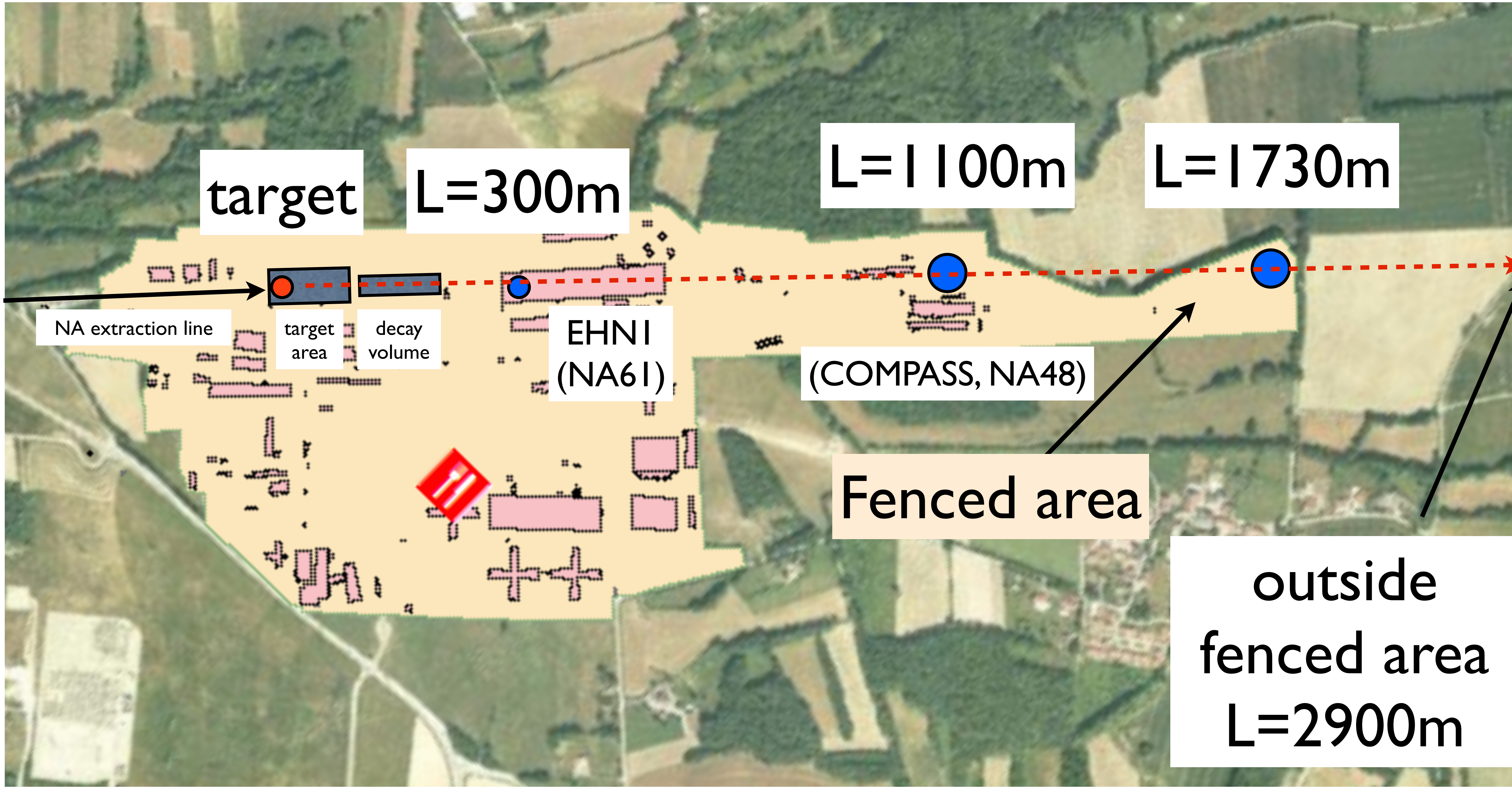
- **Re-use existing CNGS equipment for the proton beam line and as much as possible from the secondary beam**
  - CNGS anyhow must be dismantled (cost saving, avoiding permanent disposal of active materials)
- **Target station design for 2 MW facility**
  - Upgraded engineering for the CNGS target station, follow R&D for LBNE, T2K beams
  - Beam flux optimization for the high energy superbeam to LAGUNA sites demonstrates that target and first horn can be separated, simplifying the design and operation
    - key advantage of the high beam energy
    - $1/L^2$ flux decrease is compensated by the higher E (cross-section) and by the higher focusing efficiency for higher energy pions compared to low energy horn focused options.
- **The decay tunnel will be shorter (~200-300m) but steeper (~10 degrees) than CNGS**
- **The near detector can be located in the CERN Prevessin area**
  - design issues for such a detector to be considered
    - detector technology ?
    - magnetized ?
    - size of near detector cavern ?
  - possibility of synergy with short baseline programme

CN2PY tentative layout

Option B:
Target station close to existing one for the North Area



Short baseline synergy in North Area ?



<u>Area presently in operation</u>: 400 GeV protons, slow extraction, 3e13 / extraction, 3 targets (T2/T4/T6)

CN2PY HP-PS upgrade option

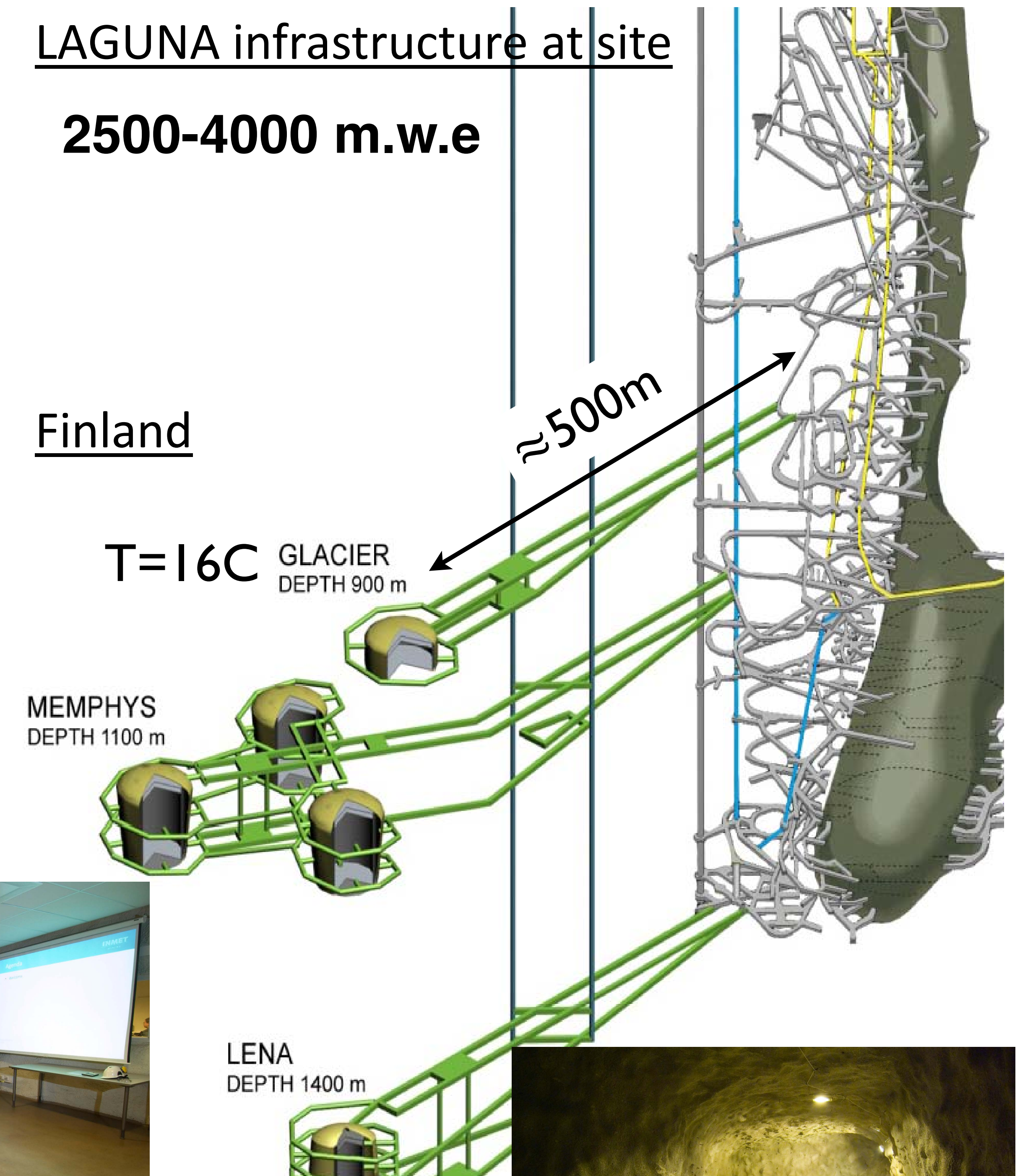
- **Aim for 2 MW at 50 GeV proton beam**
  - For example: 1.4E14 ppp, 1.2s cycle, 3e21 pot per year
  - Table of parameters to be defined / finalized
  - Lattice
- **A LP-SPL could be the injector (but other options exist)**
  - Power at injection (3 GeV) : 120 kW
- **J-PARC MR is a prototype of such a configuration**
  - Consider common R&D
- **Design to consider synergies with other ν-beam options and possible needs for other CERN programs**
- **Layout (3-D) of possible implementation of such facilities at CERN to be performed**
  - consider safety arguments (feedback from EUROnu studies)

LAGUNA @ Pyhäsalmi

LAGUNA infrastructure at site

2500-4000 m.w.e

Finland



Main aspects of the infrastructure

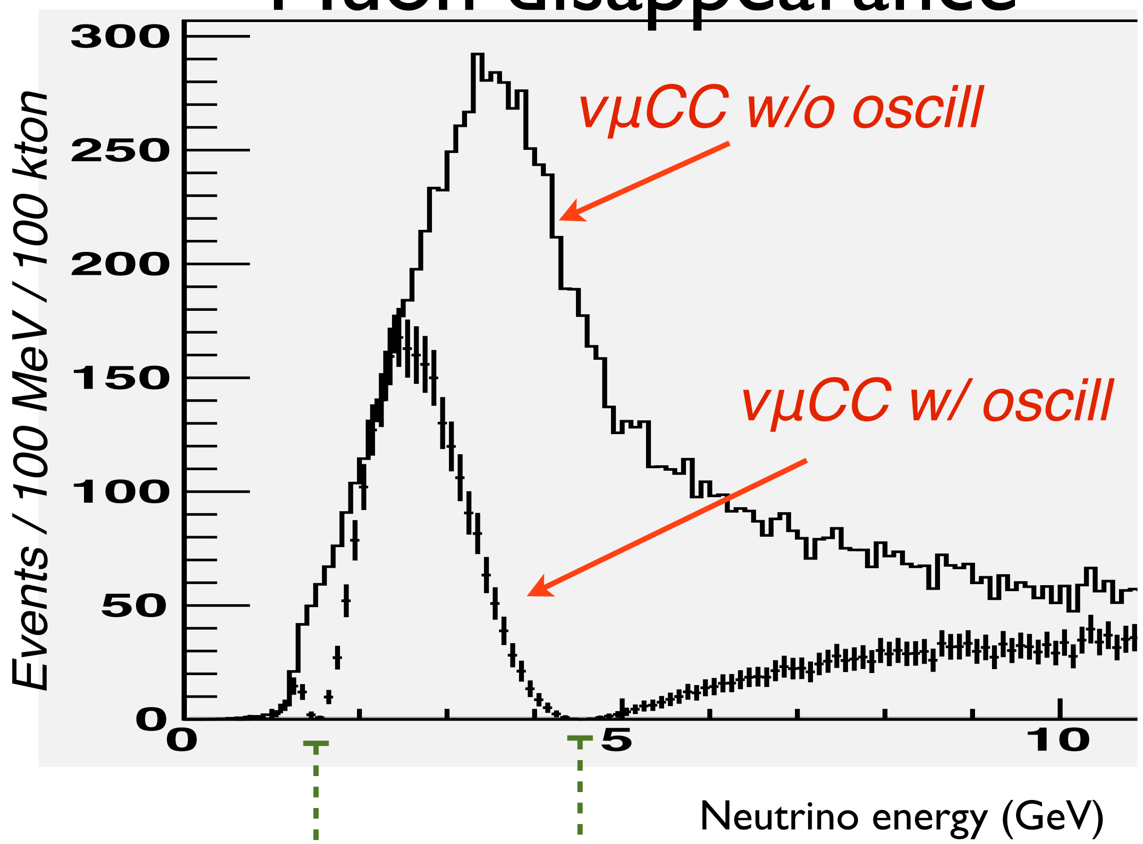
- *existing working mine with very high standards*
- *existing decline tunnel access to deepest level*
- *excellent excavation strategy*
- *efficient rock disposal*
- *no disturbance with hosting site*
- *sufficient fresh air inlet*
- *effective outlet of return air*
- *safety*
- *supply routes for construction*
- *storage of material*
- *quality control of material at the vicinity*
- *supply route (pipe lines) for liquids*


Cafeteria, meeting room and sauna at 1400 m below ground


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

LAGUNA-LBNO Pyhäsalmi physics prospects

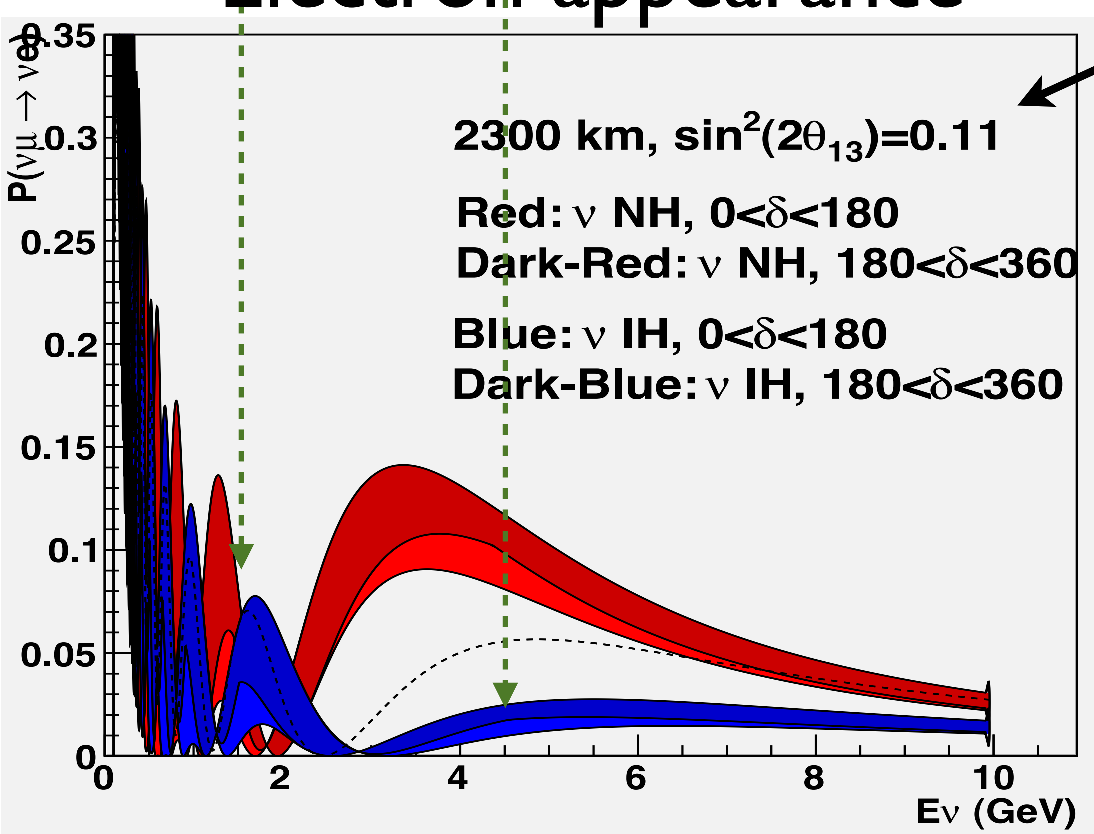
Muon disappearance



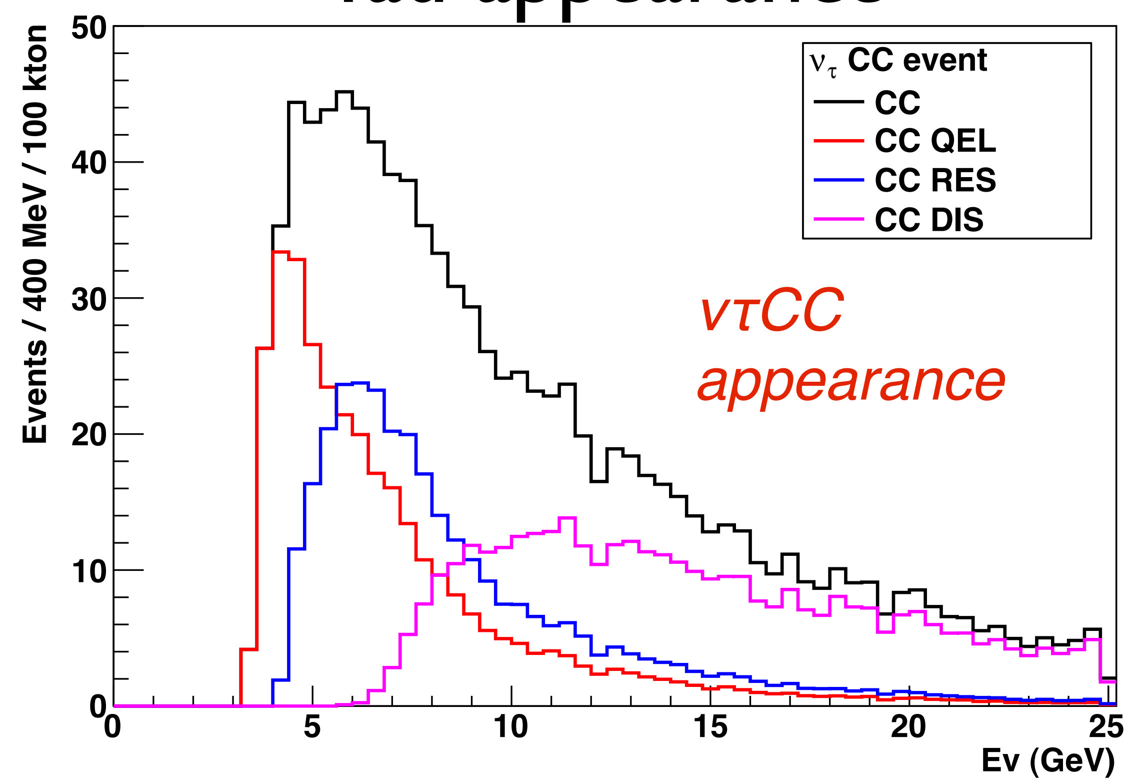
Event rates: CERN SPS 400 GeV
5 years @ 9.4x10¹⁹ pots/year

	Neutrino horn polarity $sin^2 2\theta_{23}$=1.0, $sin^2 2\theta_{13}$=0.1			
Distance/OA	ν_μCC	ν_eCC	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Pyhäsalmi 2300 km 0.25 deg	17152	250	880	1018

Electron appearance

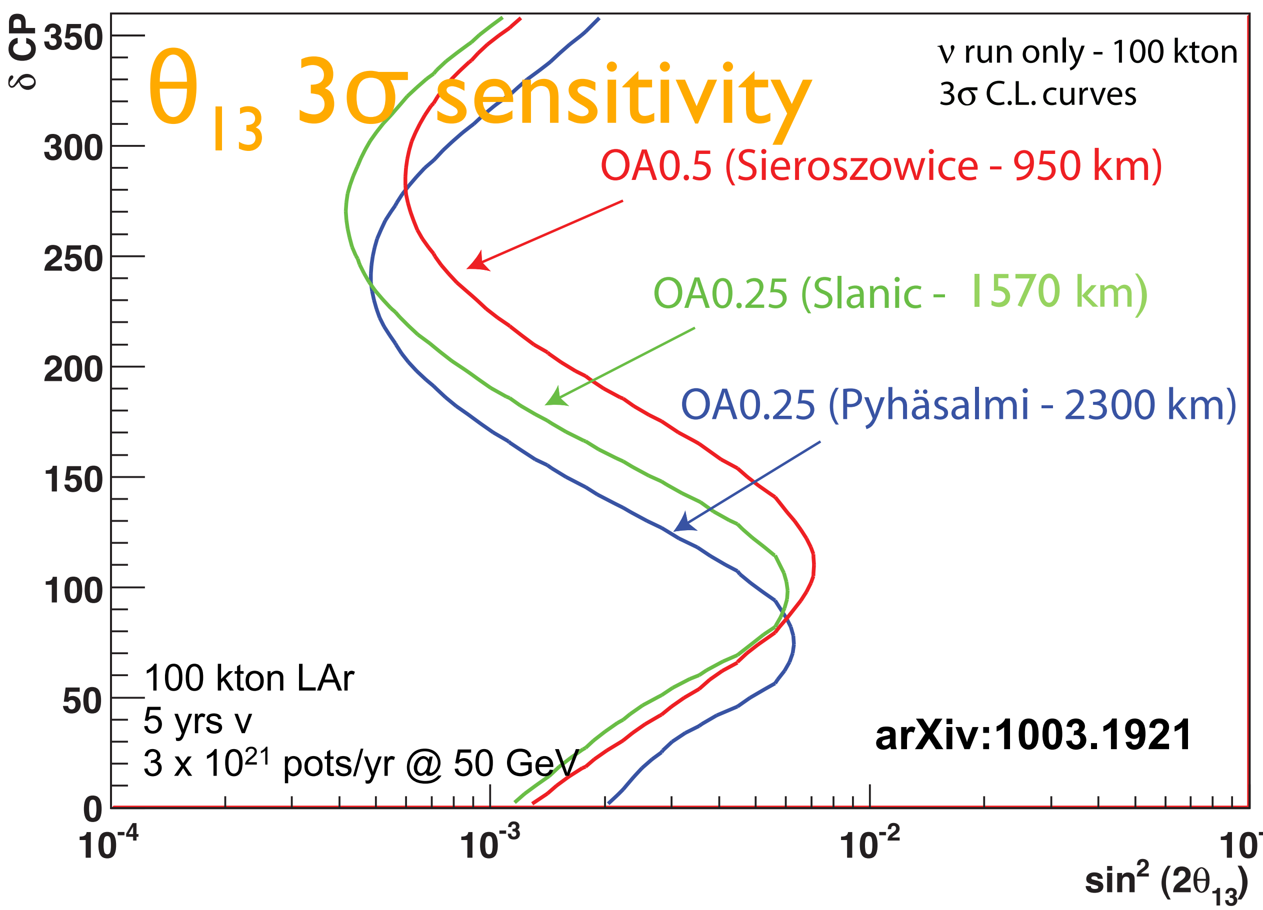


Tau appearance

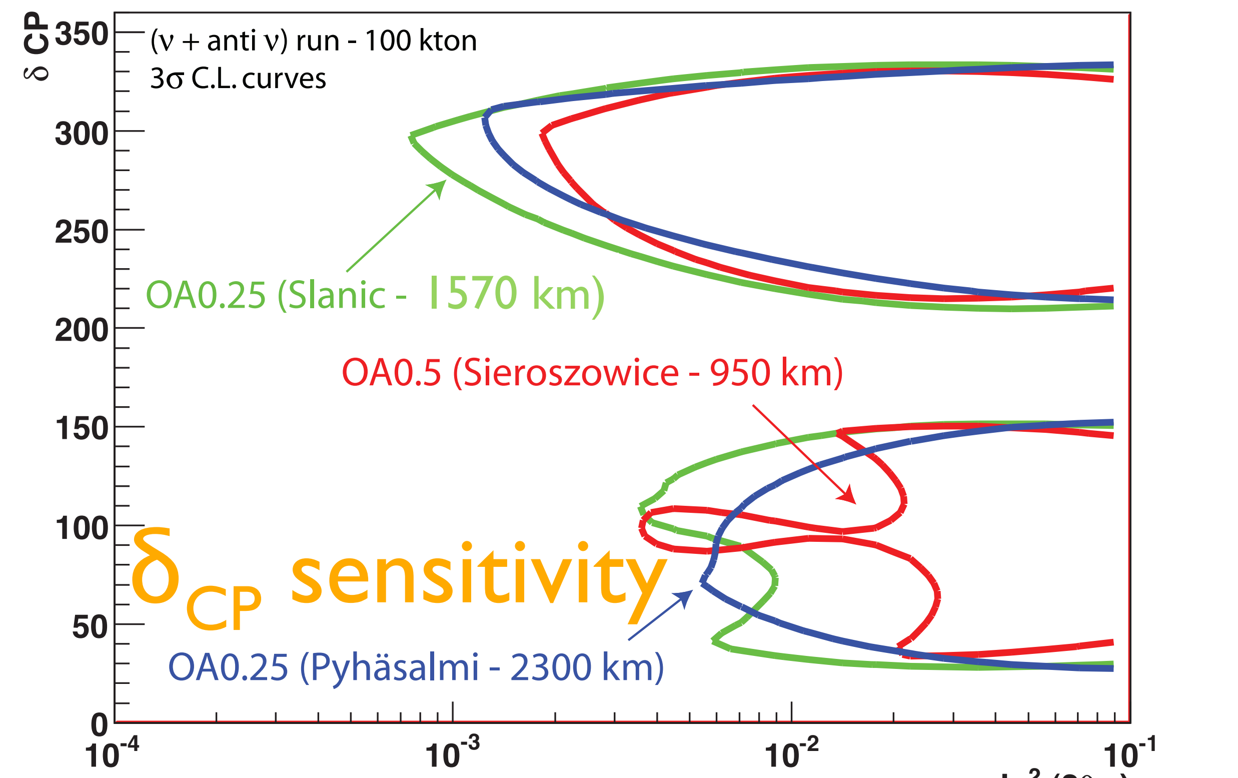


LAGUNA-LBNO Pyhäsalmi physics prospects

θ_{13} Sensitivity - CNXX NOvA Horns - 50 GeV protons

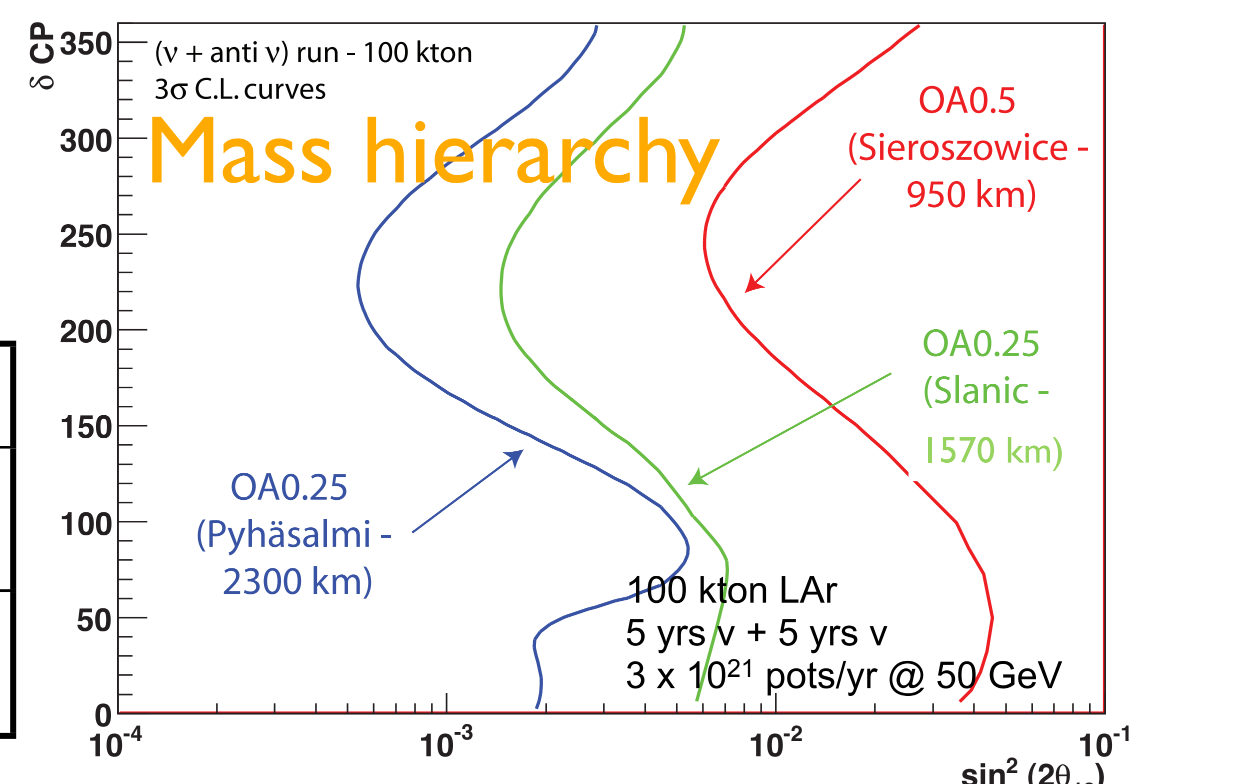


CP Discovery - CNXX NOvA Horns-50 GeV protons



arXiv:1003.1921

Mass Hierarchy Exclusion - CNXX NOvA Horns-50 GeV protons

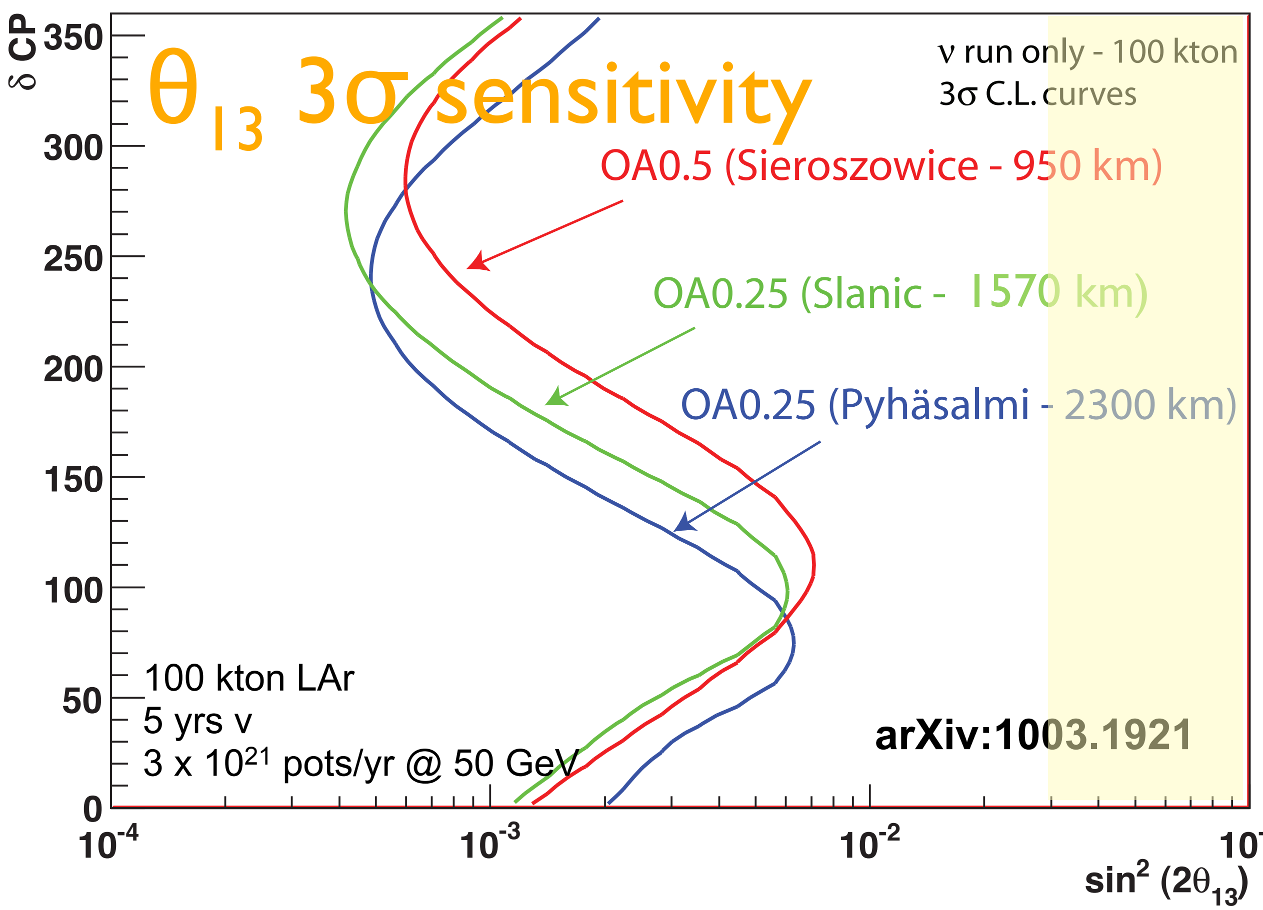


Event rate per year: 50 GeV HP-PS,
3 x 10^{21} pots/yr, 1.6 MW
100 kton liquid Argon (GLACIER option)

No Osc.	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
positive horn 1 year	17257	110	203	7
negative horn 1 year	471	16	7577	32

LAGUNA-LBNO Pyhäsalmi physics prospects

θ_{13} Sensitivity - CNXX NOvA Horns - 50 GeV protons



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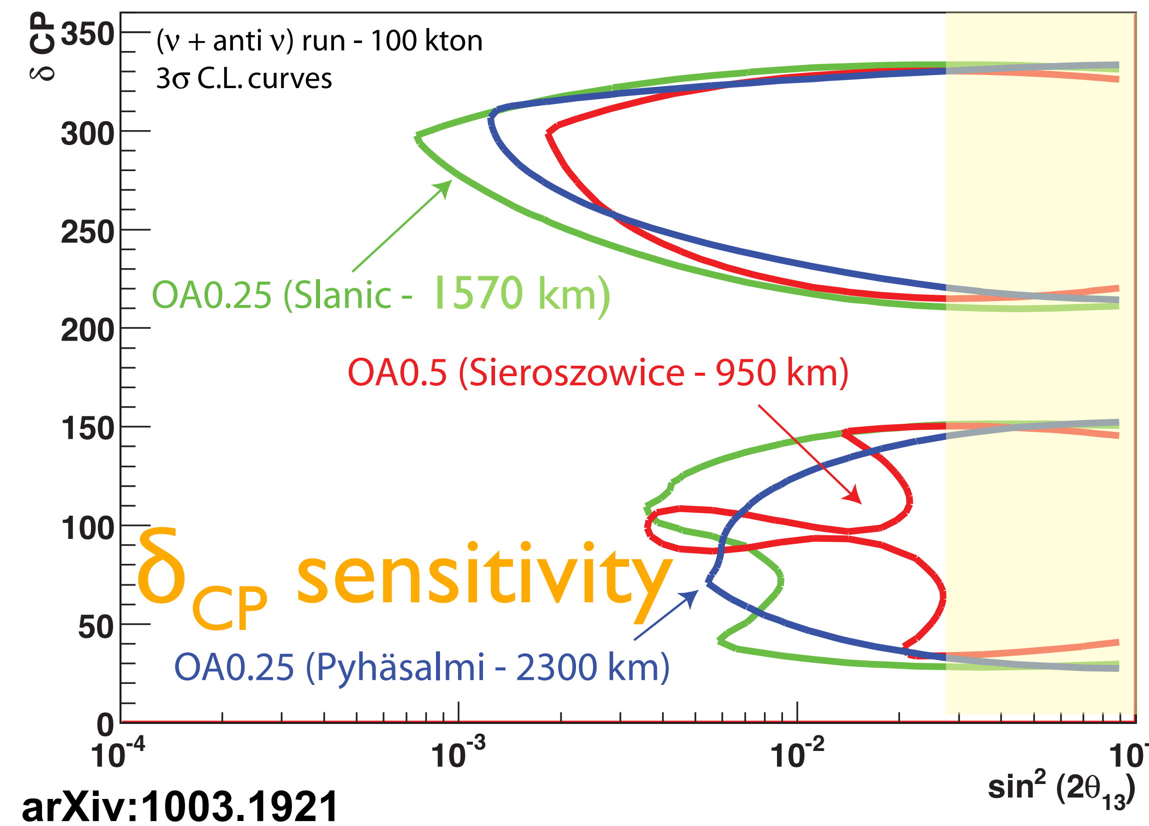

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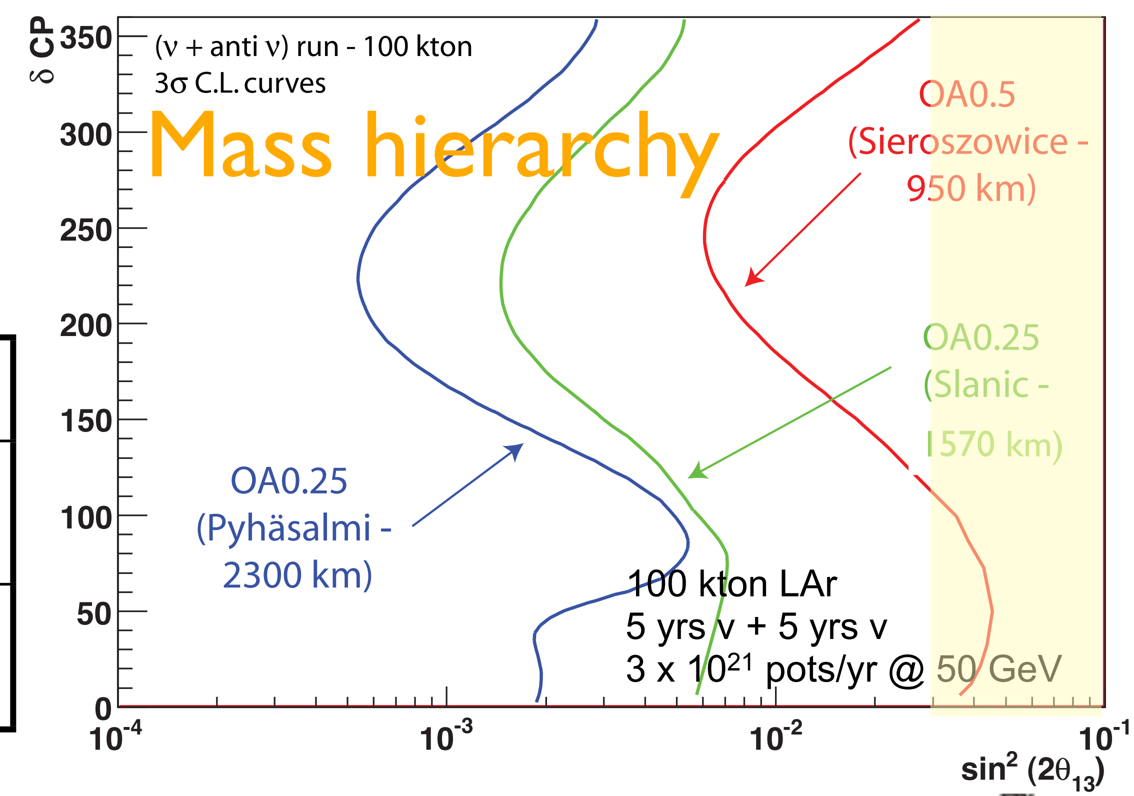

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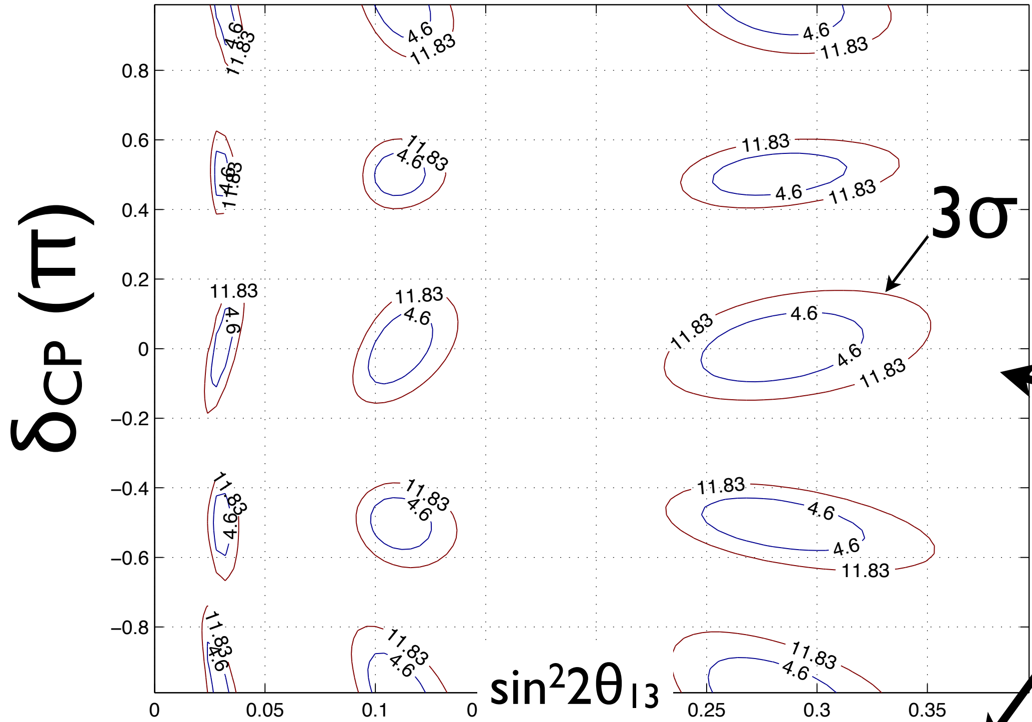
LAGUNA-LBNO Pyhäsalmi physics prospects

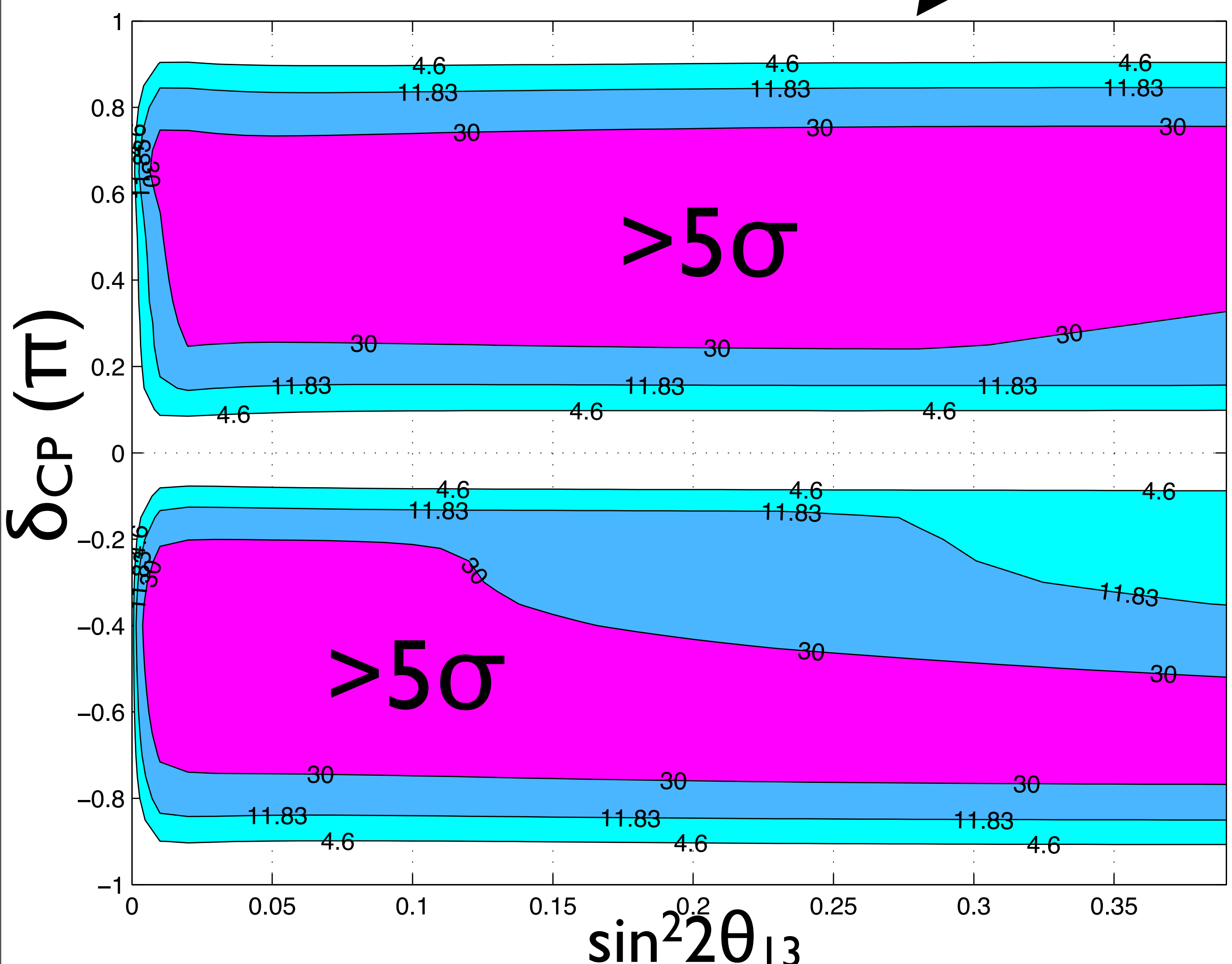
CP-discovery (mass hierarchy **not** known)

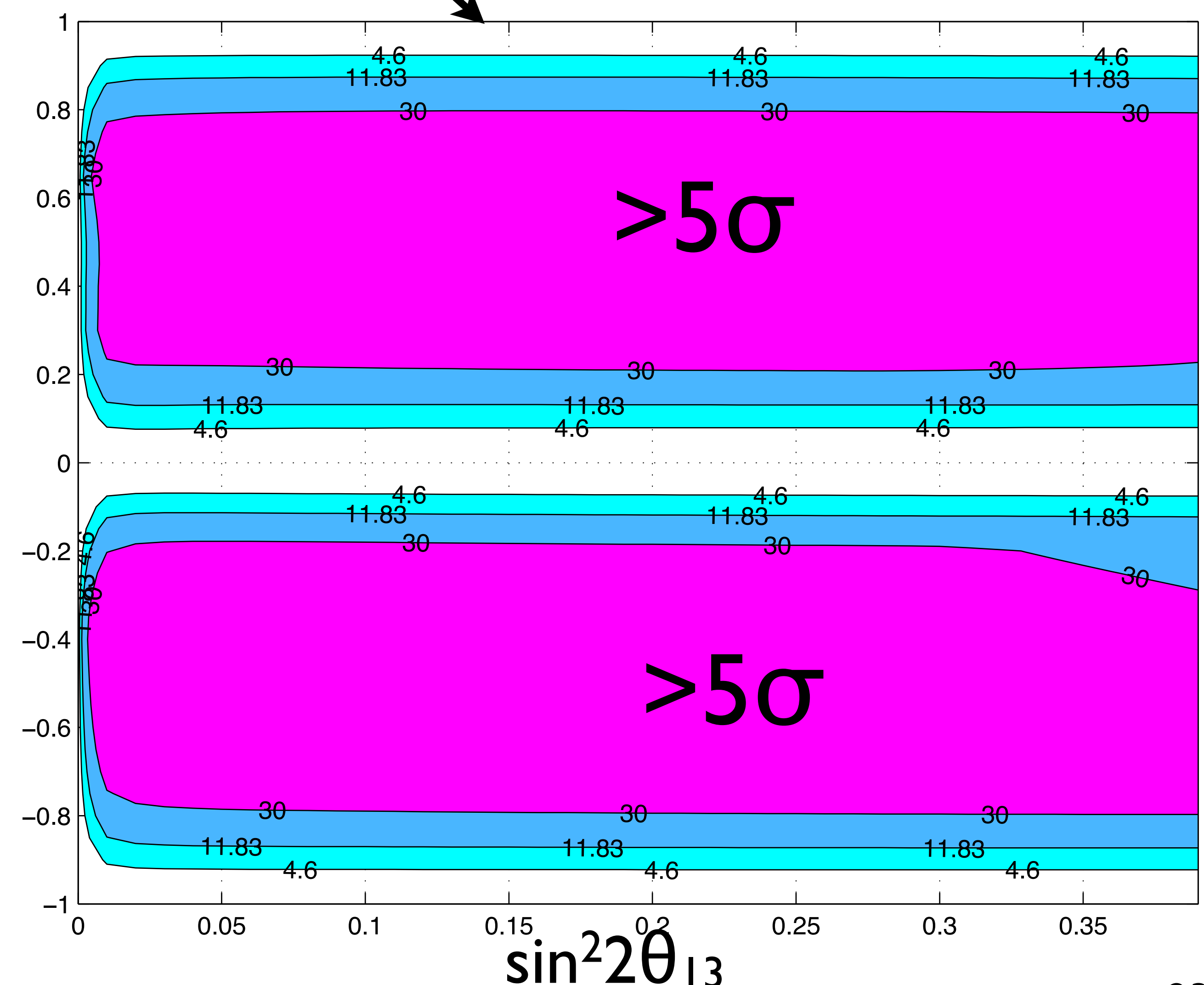
100 kton liquid Argon TPC (GLACIER option)



5 years υ 1.6MW

5+5 years υ+antiυ 1.6MW

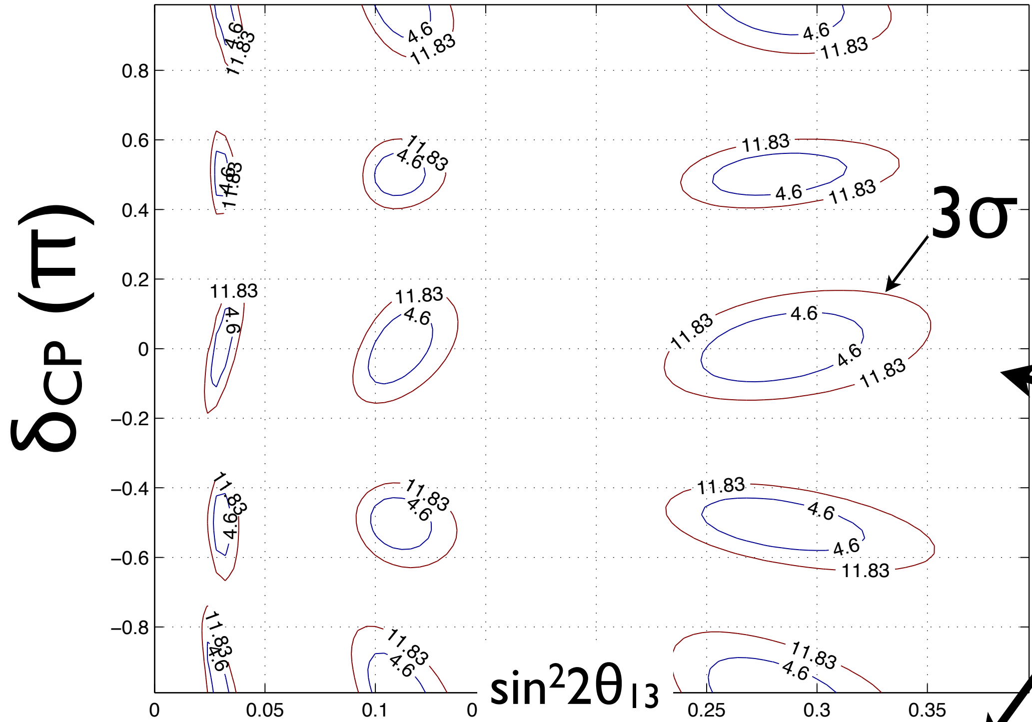




LAGUNA-LBNO Pyhäsalmi physics prospects

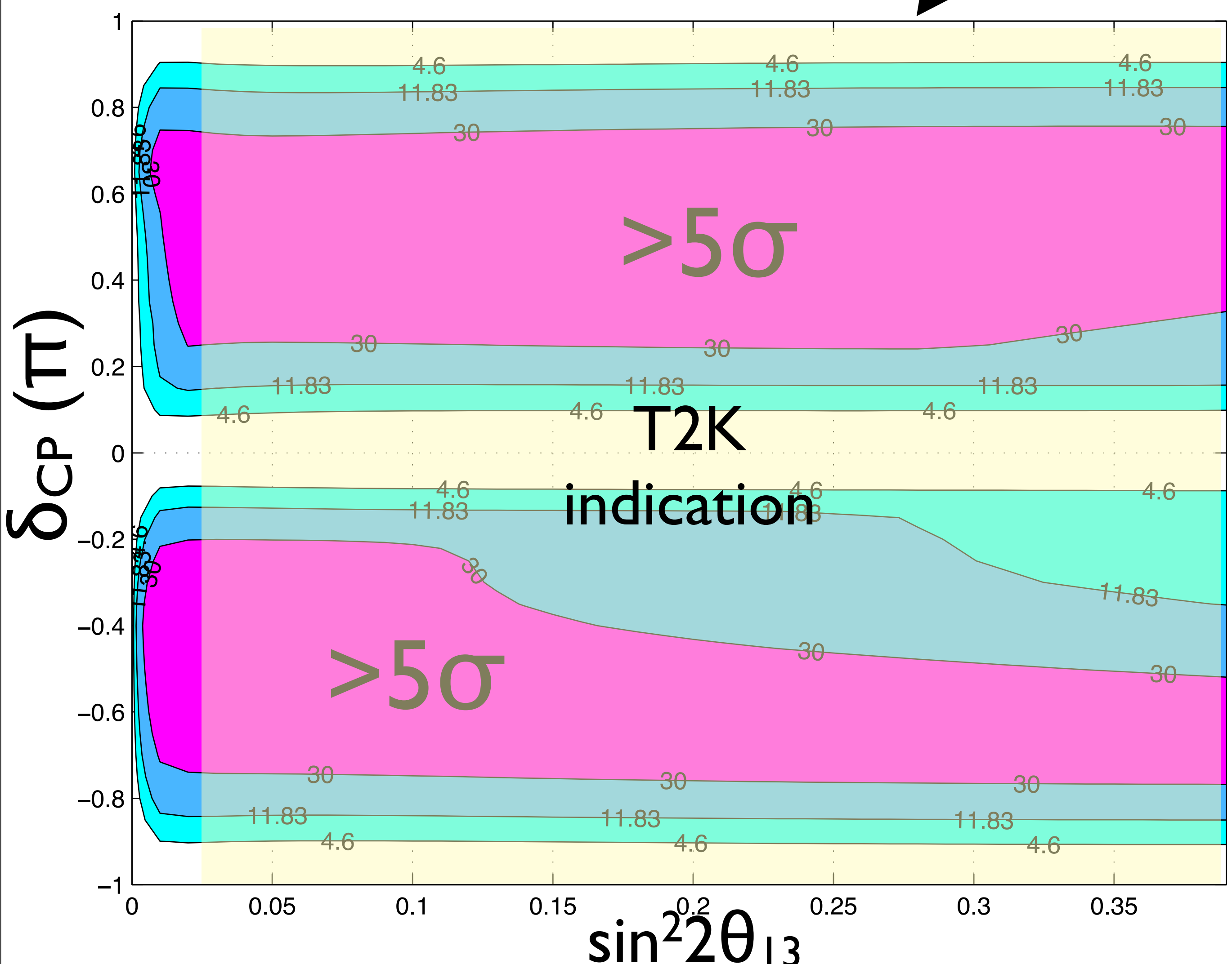
CP-discovery (mass hierarchy **not** known)

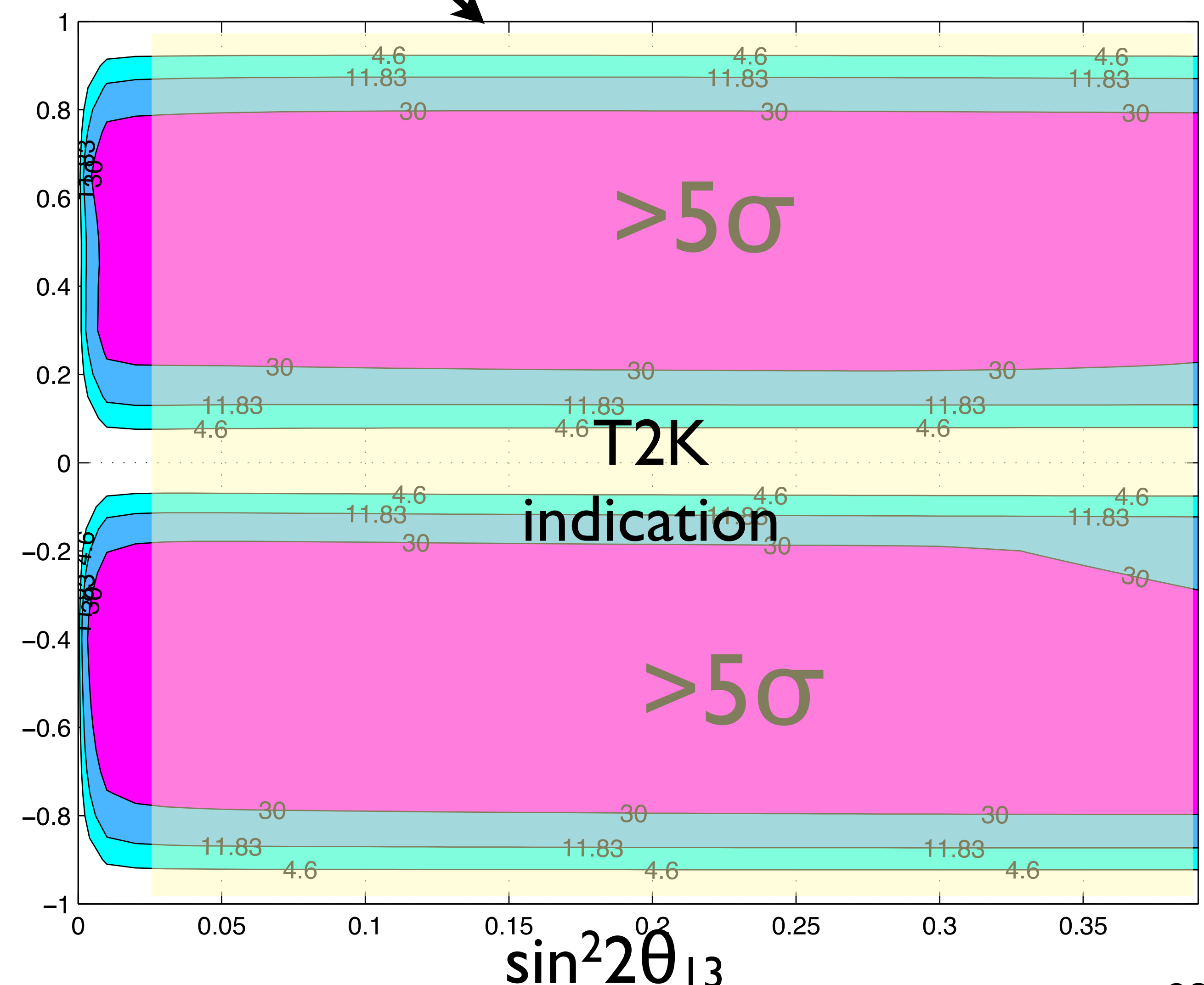
100 kton liquid Argon TPC (GLACIER option)



5 years ν 1.6MW

5+5 years ν+antiν 1.6MW

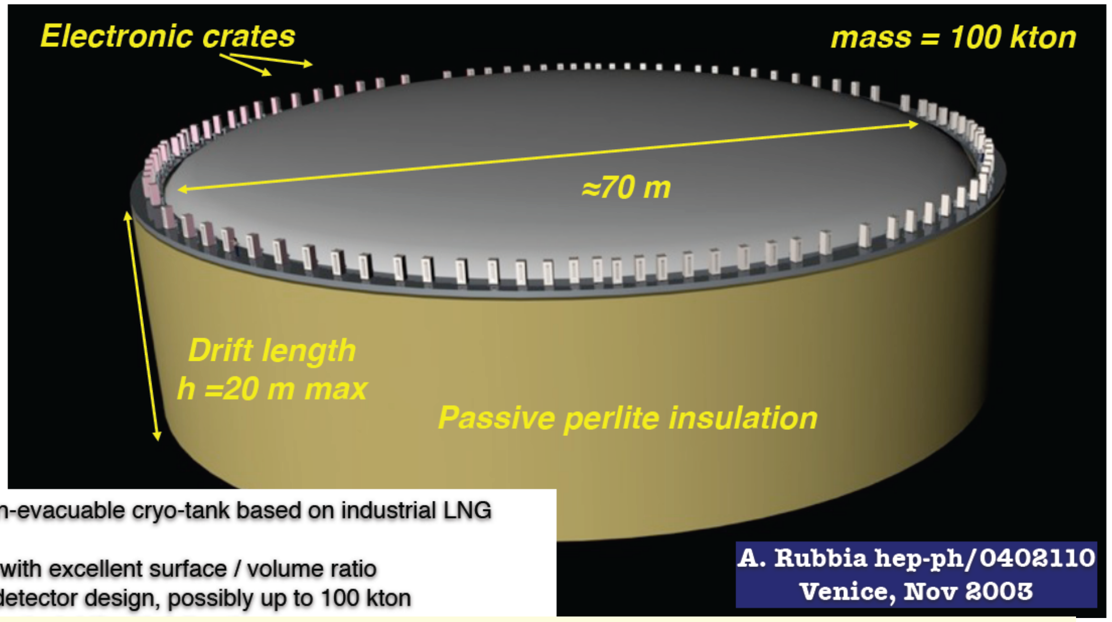




Giant Liquid Argon Detector R&D (KEK-ETHZ)

Giant Liquid Argon Charge Imaging ExpeRiment

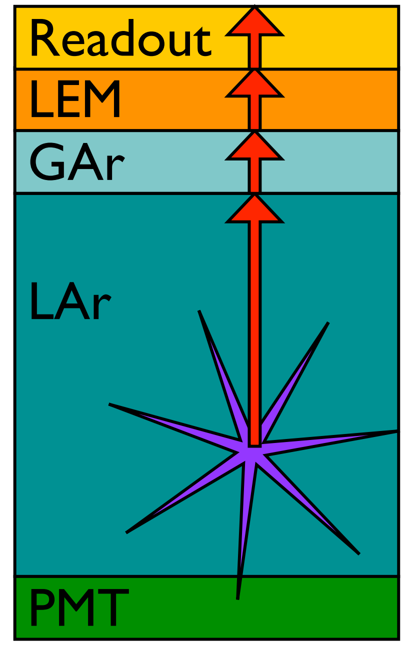
A scalable detector with a non-evacuable dewar and ionization charge detection with amplification

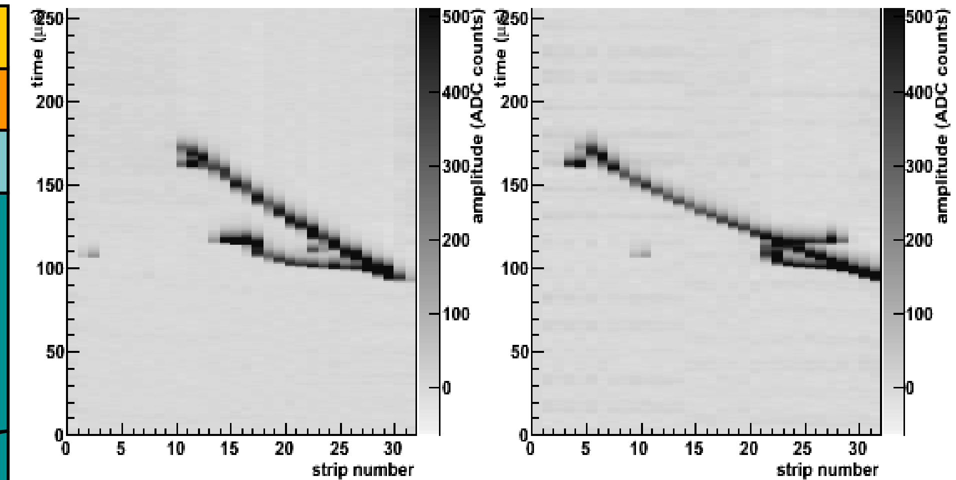


Single module non-evacuable cryo-tank based on industrial LNG technology
Cylindrical shape with excellent surface / volume ratio
Simple, scalable detector design, possibly up to 100 kton

- Extremely high performance
- "Electronic Bubble Chamber"
- 3D tracking of all charged particle from very low energy threshold
- Precise resolution of ~mm
- Fully active homogeneous 4π detector (as WC)
- Good PID w/ dE/dx, π0 rejection
- Double phase w/ Gas amplification
- <10ppt purity needed
- LEM readout (~10^6ch)
- 600ton detector realized and working

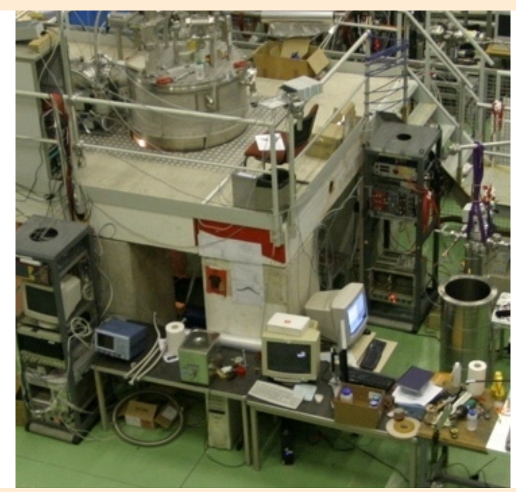
Double phase charge readout w/ adjustable gain



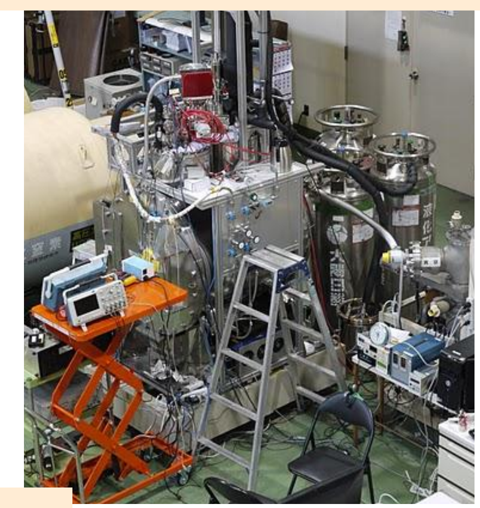


Much improved S/N (>100) compared to single-phase LAr operation (≈15)

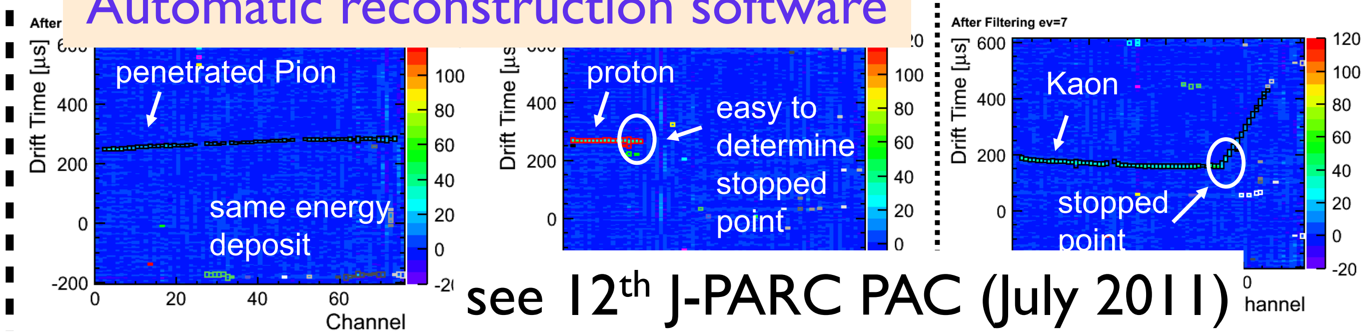
ArDM-1ton (CERN RE18 Collab)



Test beam at J-PARC (T32 Collaboration)



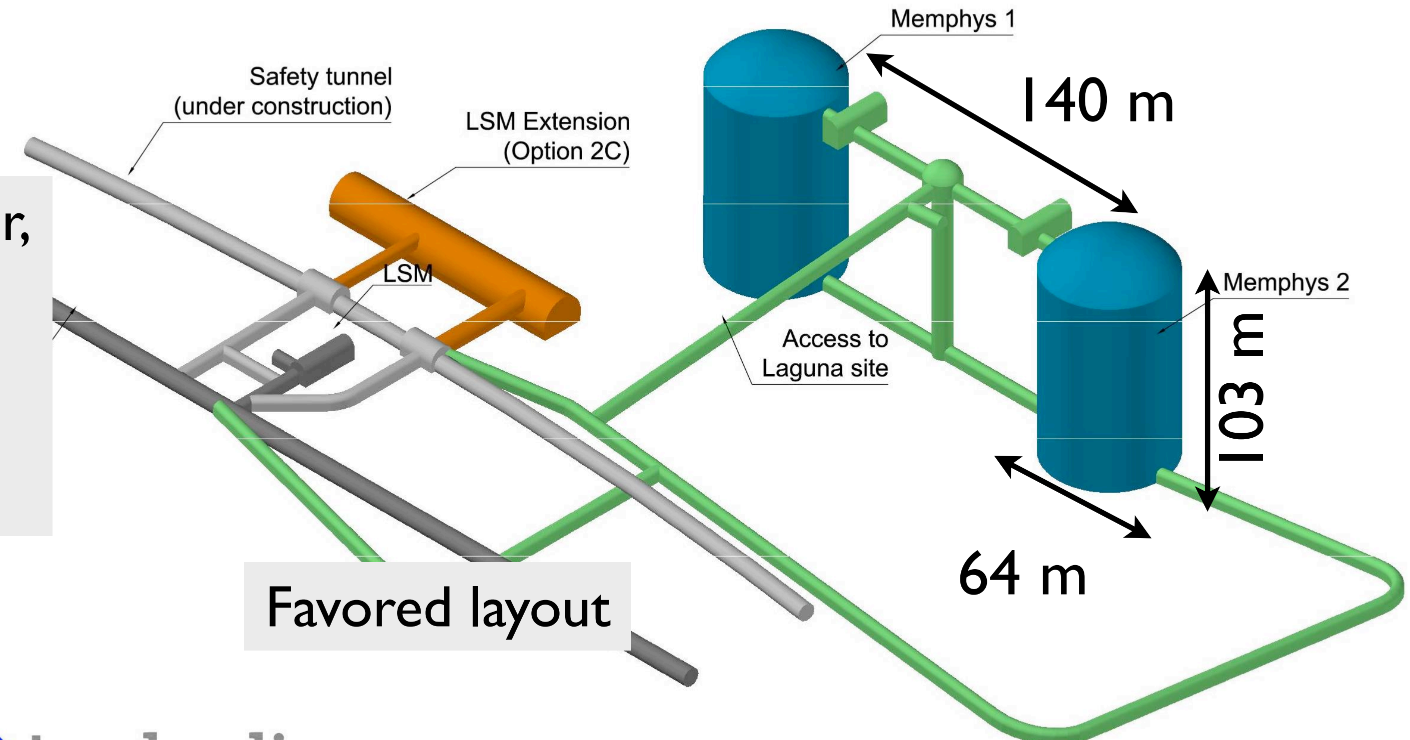
Automatic reconstruction software



see 12th J-PARC PAC (July 2011)

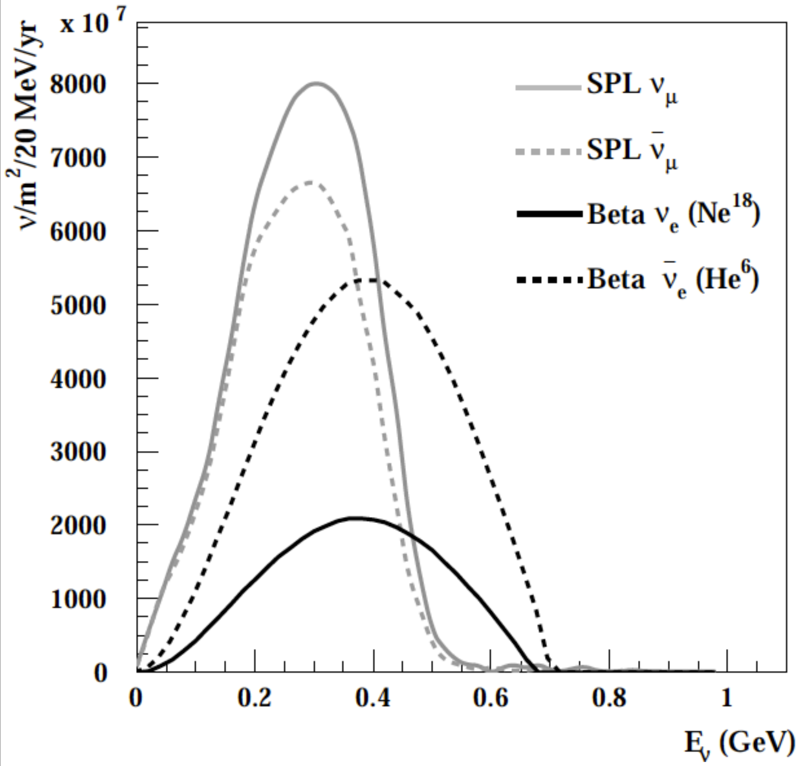
LAGUNA Fréjus w/ MEMPHYS

Water Cerenkov detector,
2 independent modules,
330’000 m^3 each
220’000 8-10” PMTs
≈500 kton fiducial mass



Favored layout

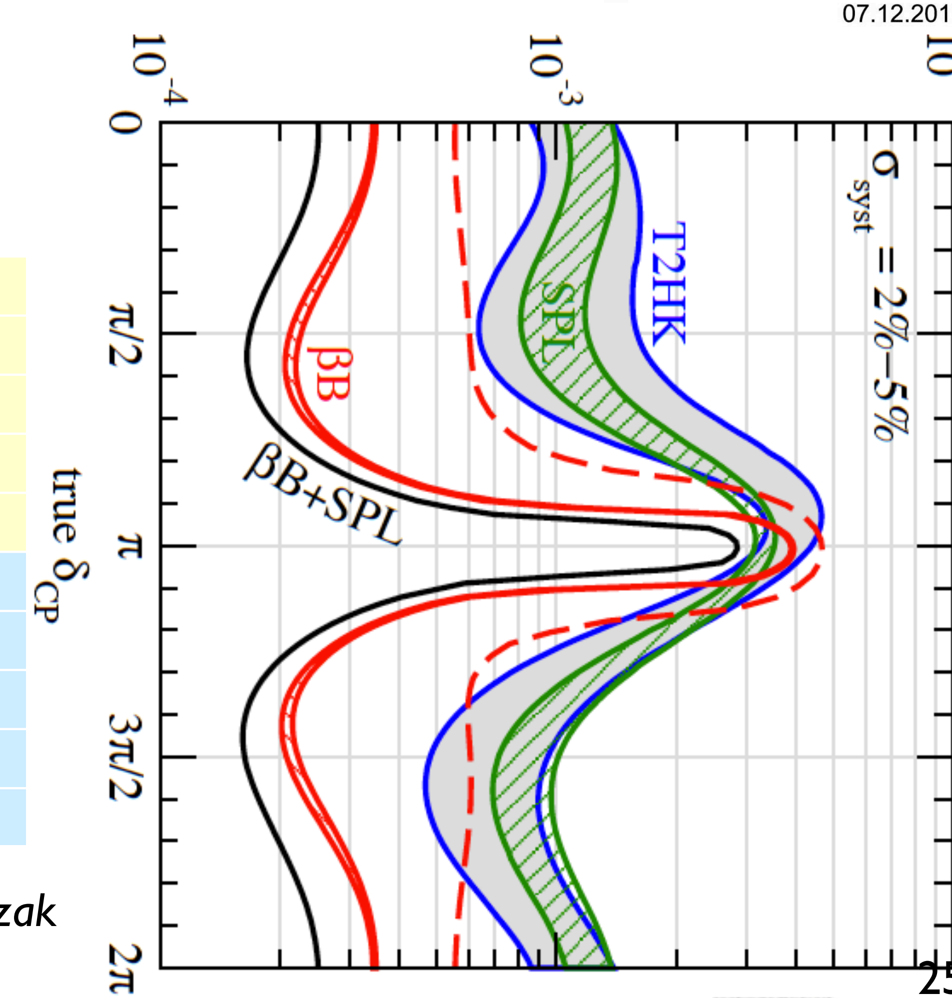
CERN SPL 5 GeV 4MW



2 yr ν + 8yrs $\bar{\nu}$ @ 4 MW

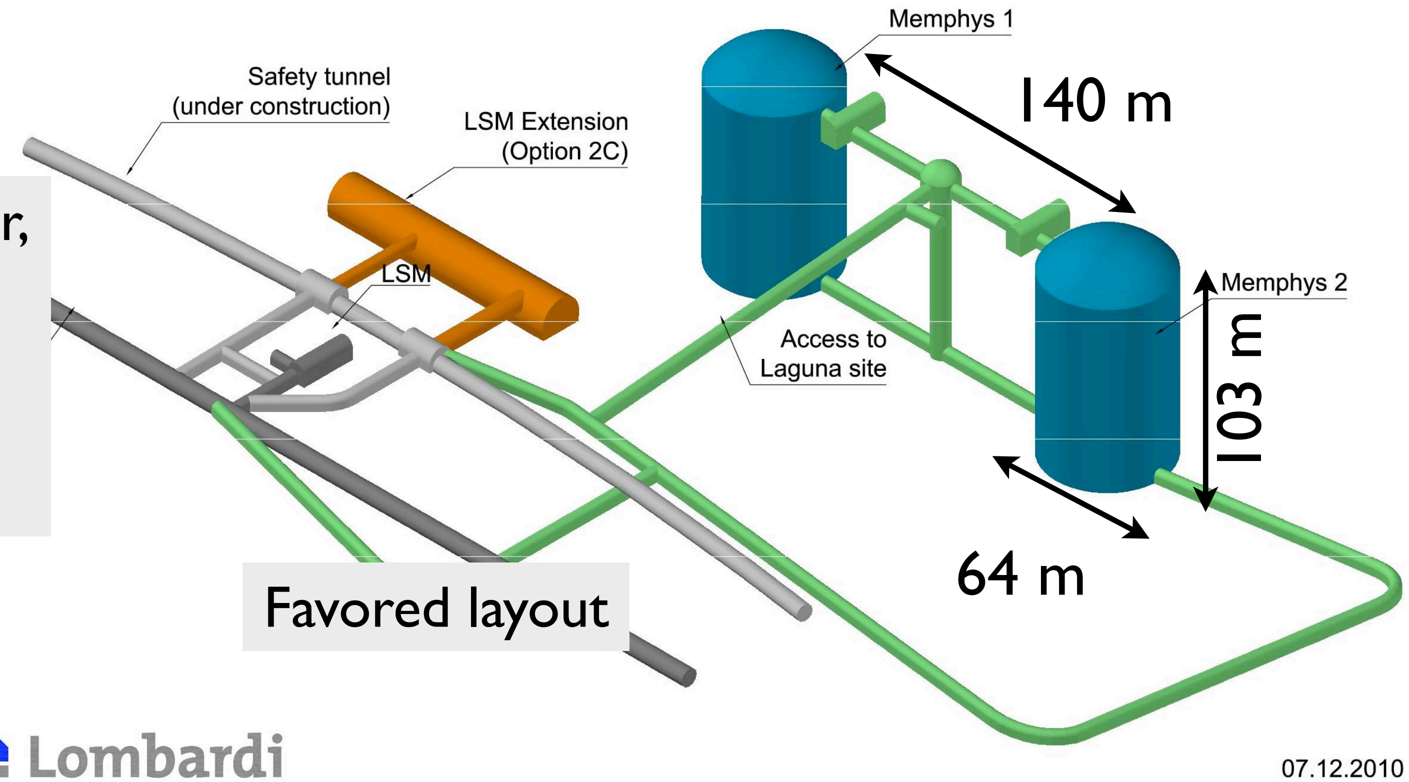
	βB		SB	
	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$
Appearance ν				
Bkgd	143		622	
$\sin^2 2\theta_{13} = 0$	28		51	
10^{-3}	76	88	105	14
10^{-2}	326	365	423	137
Appearance $\bar{\nu}$				
Bkgd	157		640	
$\sin^2 2\theta_{13} = 0$	31		57	
10^{-3}	83	12	102	146
10^{-2}	351	126	376	516

Courtesy: T. Patzak

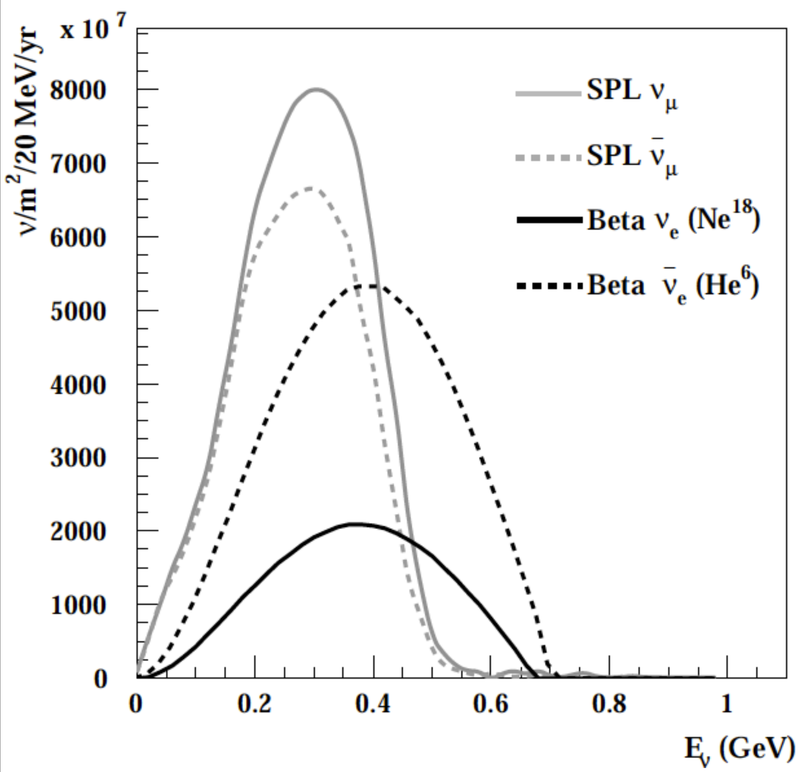


LAGUNA Fréjus w/ MEMPHYS

Water Cerenkov detector,
2 independent modules,
330'000 m^3 each
220'000 8-10" PMTs
≈500 kton fiducial mass



CERN SPL 5 GeV 4MW



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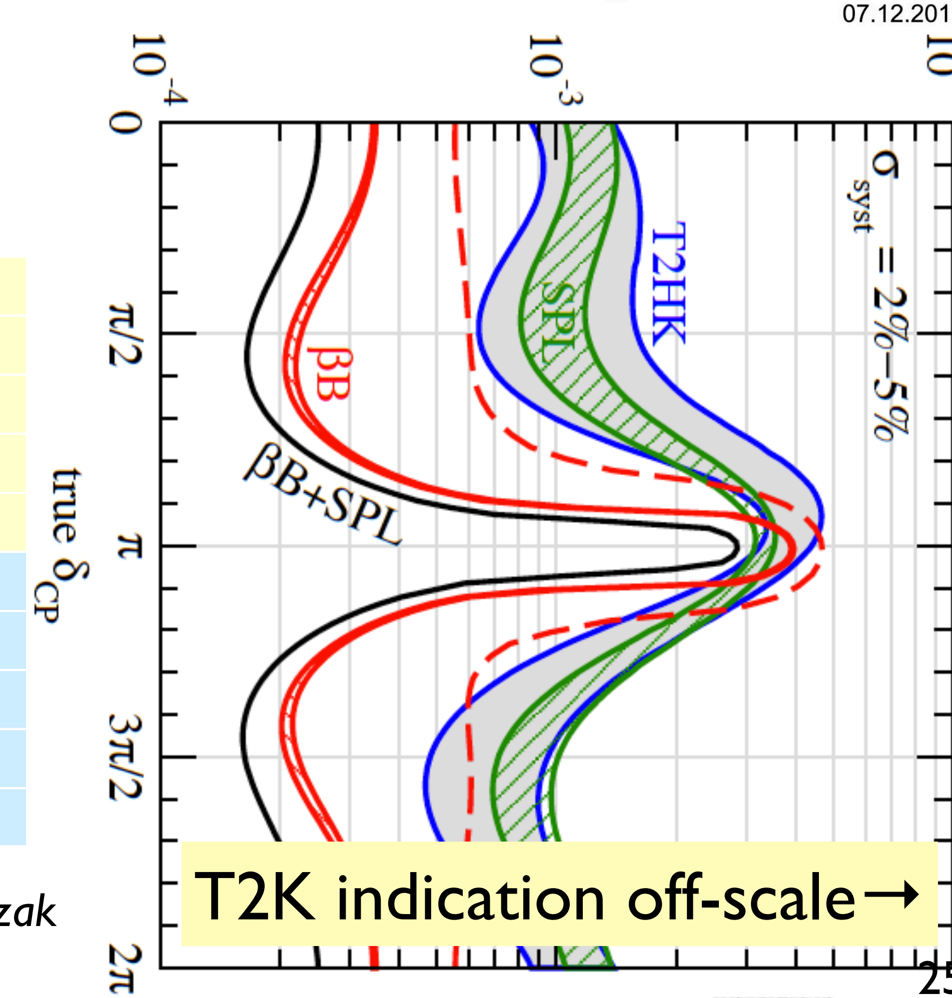
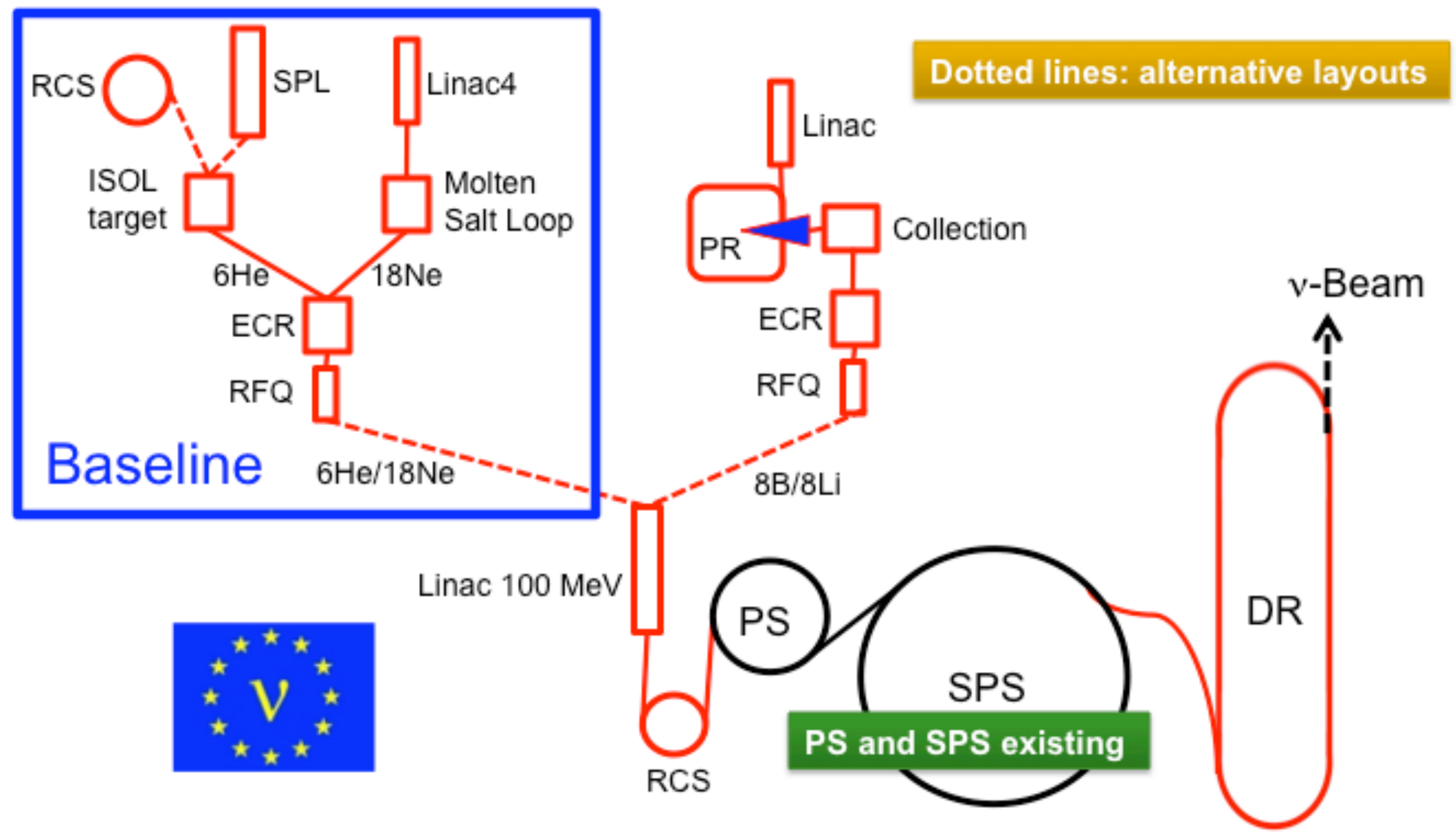


Prospects for long term upgrades with enhanced neutrino beams

Beta Beam :

Ion production ? Ion collection and bunching ? Ion acceleration ?

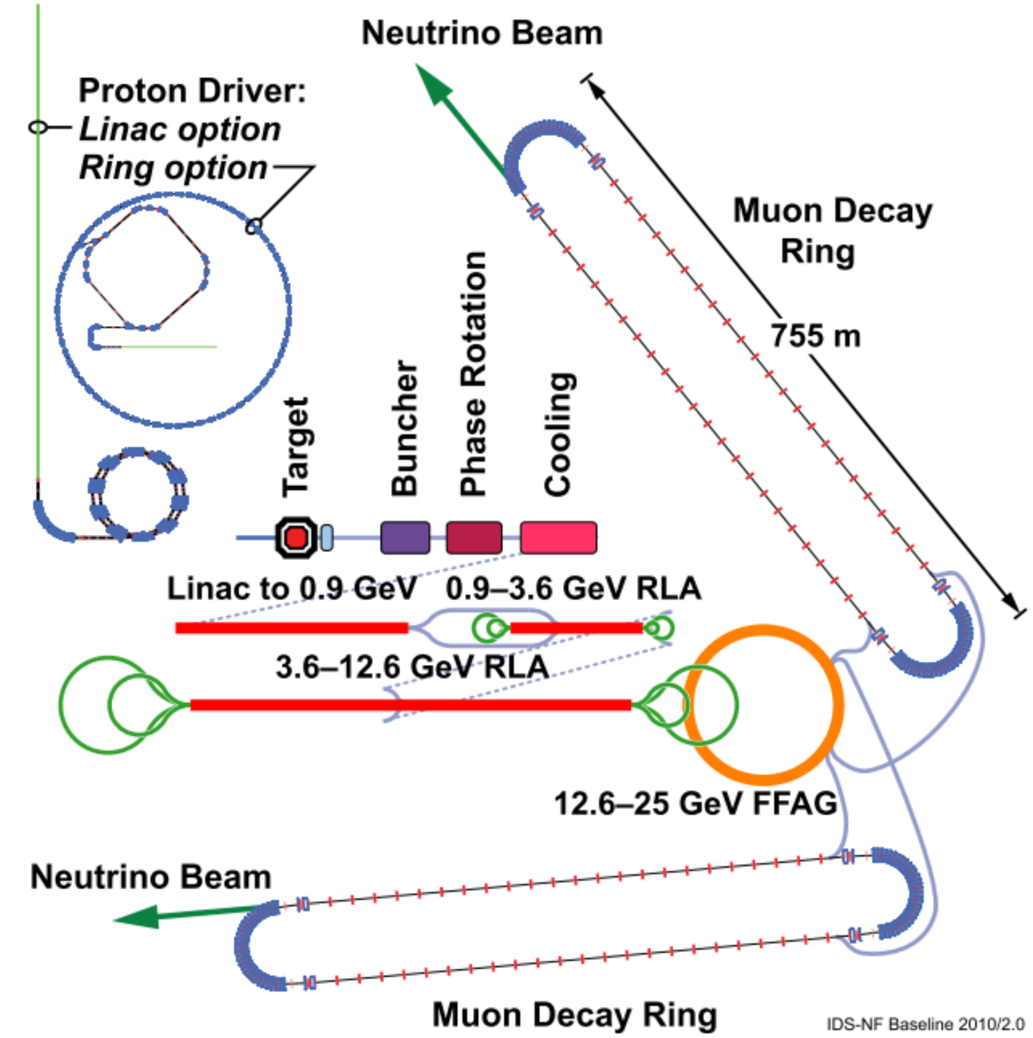


$B\rho$ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

The considered LAGUNA-Fréjus with MEMPHYS is already an adequate far detector

Neutrino Factory:

High power target? Muon cooling ? Muon acceleration ?



The magnetization of the LAGUNA-Pyhäsalmi detector(s) will be considered. Alternatively, "hybrid" options are possible.

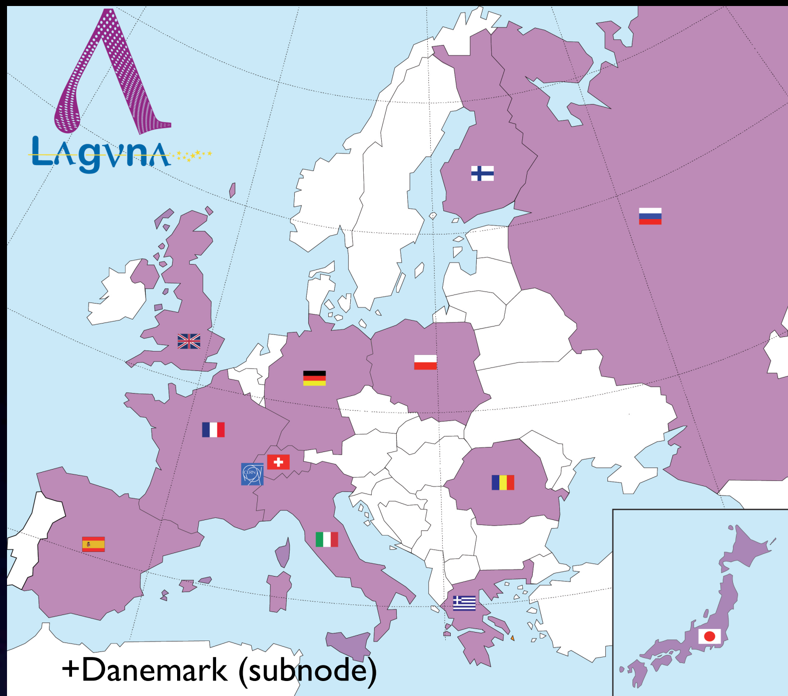
Conclusions

- World-wide interest for next generation long-baseline based on the conventional neutrino beam technology, with longer baselines to address CP-violation and mass hierarchy, as the next step beyond T2K/NOvA.
- Physics case is strongly reinforced by recent evidence for $\sin^2 2\theta_{13} > 0.01$ in T2K (and MINOS). Situation will clarify further in the coming year.
- As a community, we should aim at realizing two complementary projects (but many challenges ahead, including world peace and politics). Worldwide global coordination is surely necessary, but a bottom-up approach is even more necessary.
- In Europe, based on the success of LAGUNA, the LAGUNA-LBNO consortium, now including EU, Russian and KEK colleagues, is getting ready to define further the project, in synergy with the J-PARC options.
- A LAGUNA-LBNO staged approach ("pilot project") will likely be proposed. Open to all interested !
- For the longer term: the LAGUNA Fréjus option would be readily available for a beta-beam. Magnetization or a hybrid solution should be considered for the LAGUNA Pyhäsalmi in case of a neutrino factory.

Acknowledgements

- FP7 Research Infrastructure “Design Studies” LAGUNA (Grant Agreement No. 212343 FP7-INFRA-2007-1)

LAGUNA-LBNO consortium



13 countries, 45 institutions, ~300 members

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen(**)
University Tübingen(**)

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

Romania
IFIN-HH
University Bucharest

Denmark
Aahrus(**)

Switzerland
University Bern
University Geneva
ETH Zürich
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

United Kingdom
Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Italy
AGT*

Russia
INR
PNPI

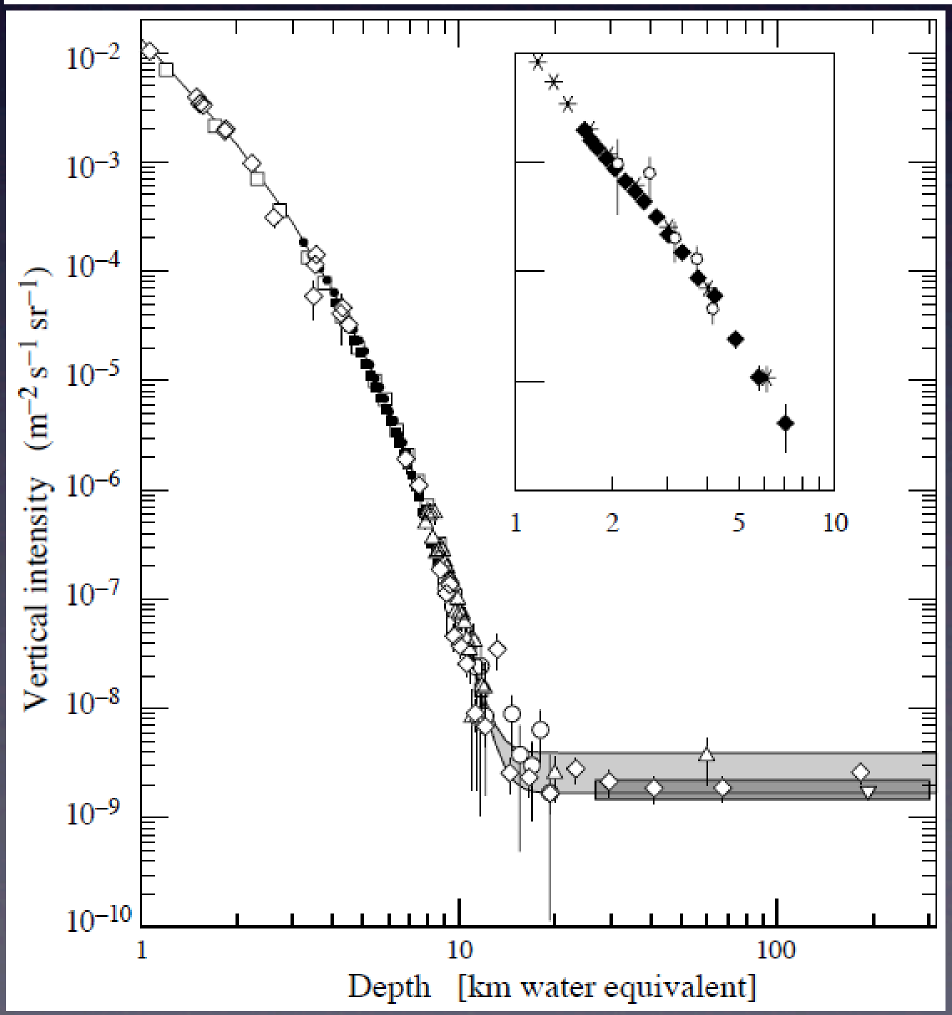
Japan
KEK

(=industrial partners*
***=associated)*

LAGUNA Underground Labs

Basic characteristics of the studied underground sites:

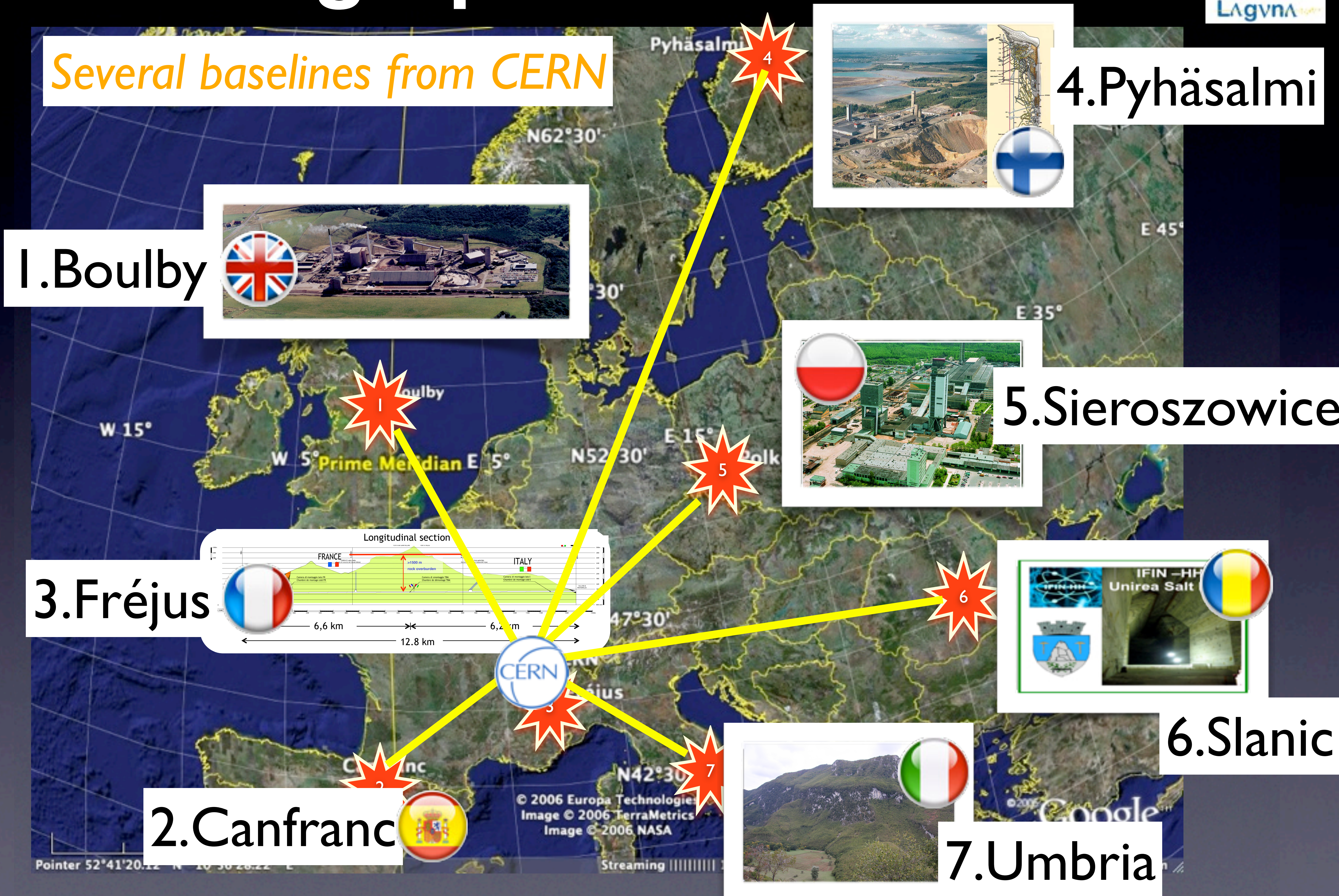
From existing road tunnels:	Canfranc (1500-2700mwe), Fréjus (4800mwe)
From existing deep mines:	Boulby (3400-4000mwe), Pyhäsalmi (2500-4000mwe), Sieroszowice (1400mwe)
Existing large salt-mine:	Slanic (840mwe)
Greenfield site(off-axis CNGS):	Umbria (1500-2300mwe)



Guidelines for detector overburden:

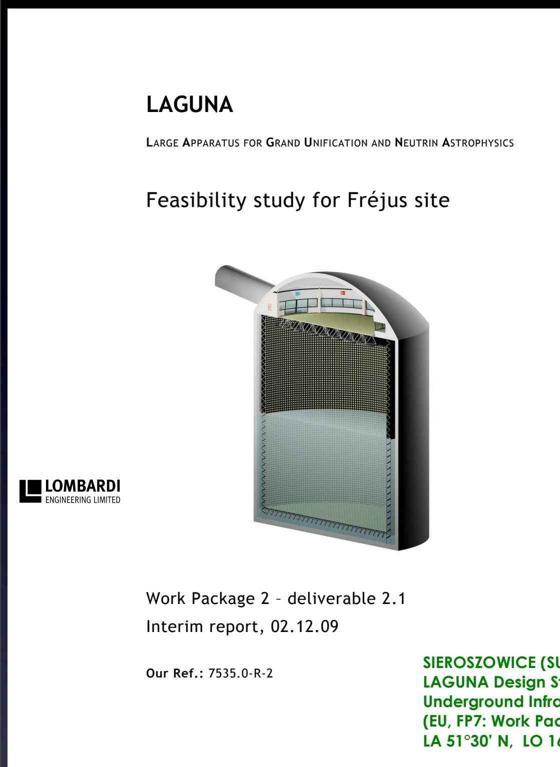
GLACIER ≥ 2500 m.w.e (900 m of rock)
LENA ≥ 4000 m.w.e (1400 m of rock)
MEMPHYS ≥ 3000 m.w.e (1100 m of rock)

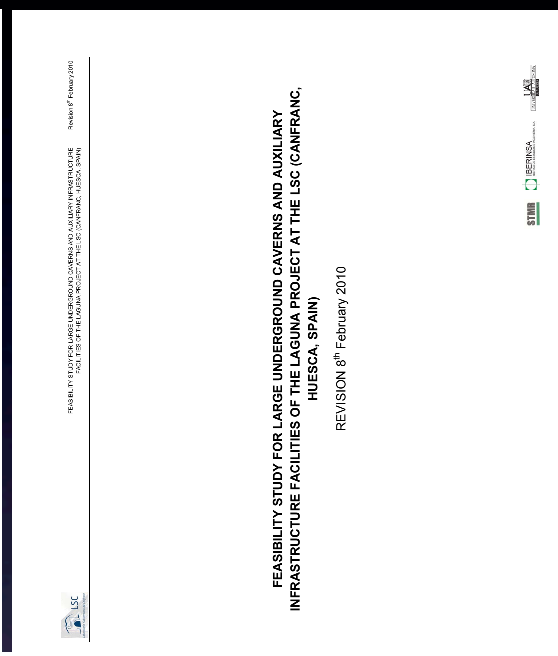
Geographic locations

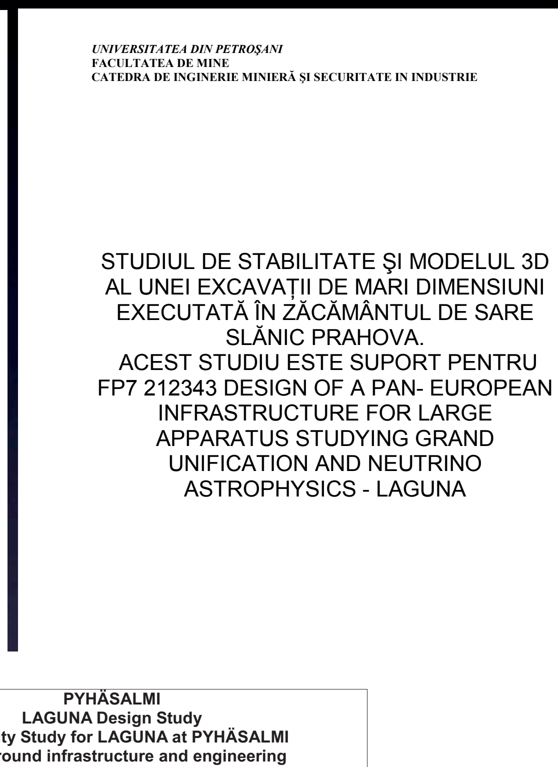


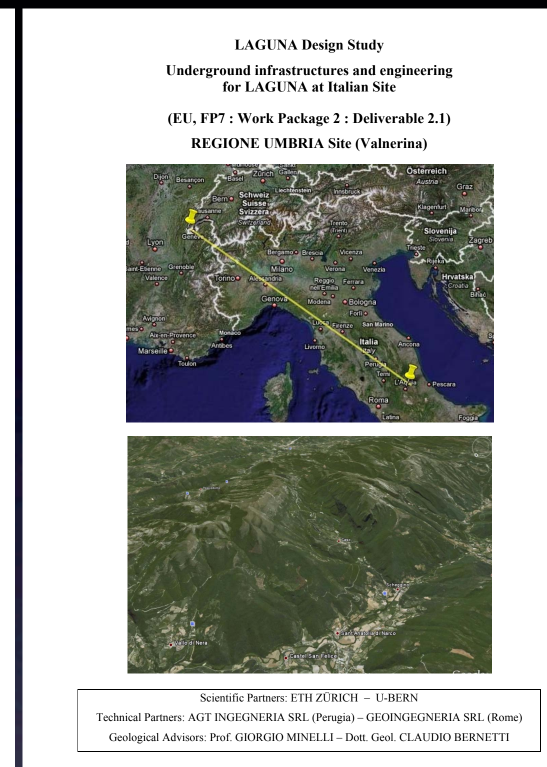
Seven technical reports

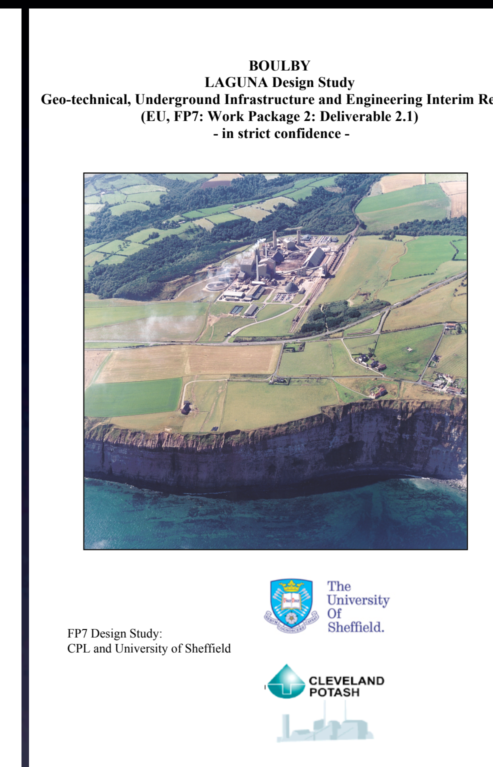
Interim site-dependent geotechnical reports: published
Final joint report on potential European sites: finalized

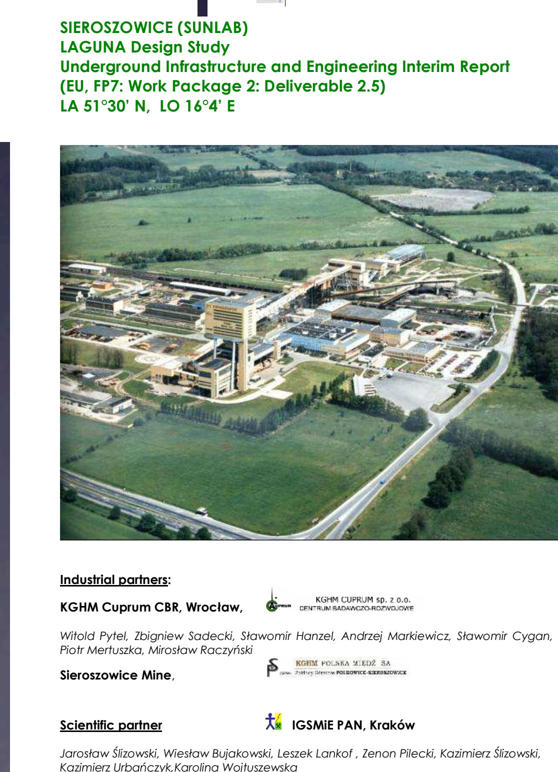


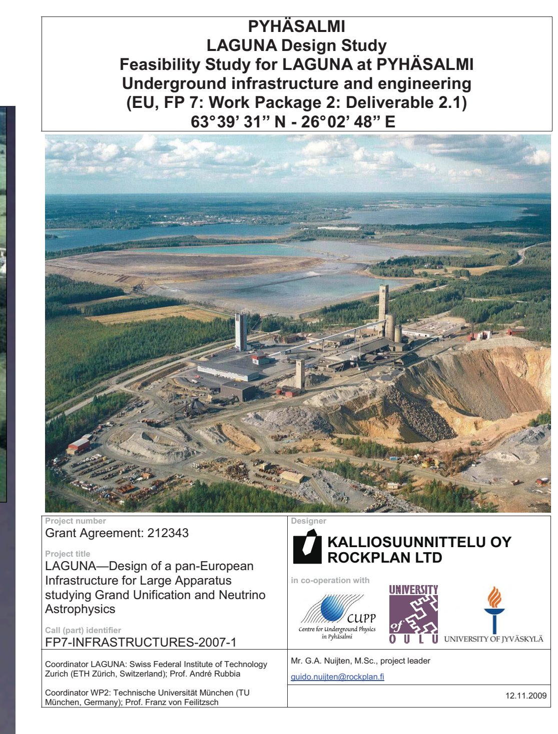












- more than 1200 pages
- large amount of information and details
- healthy competition among sites
- technical basis for site selection

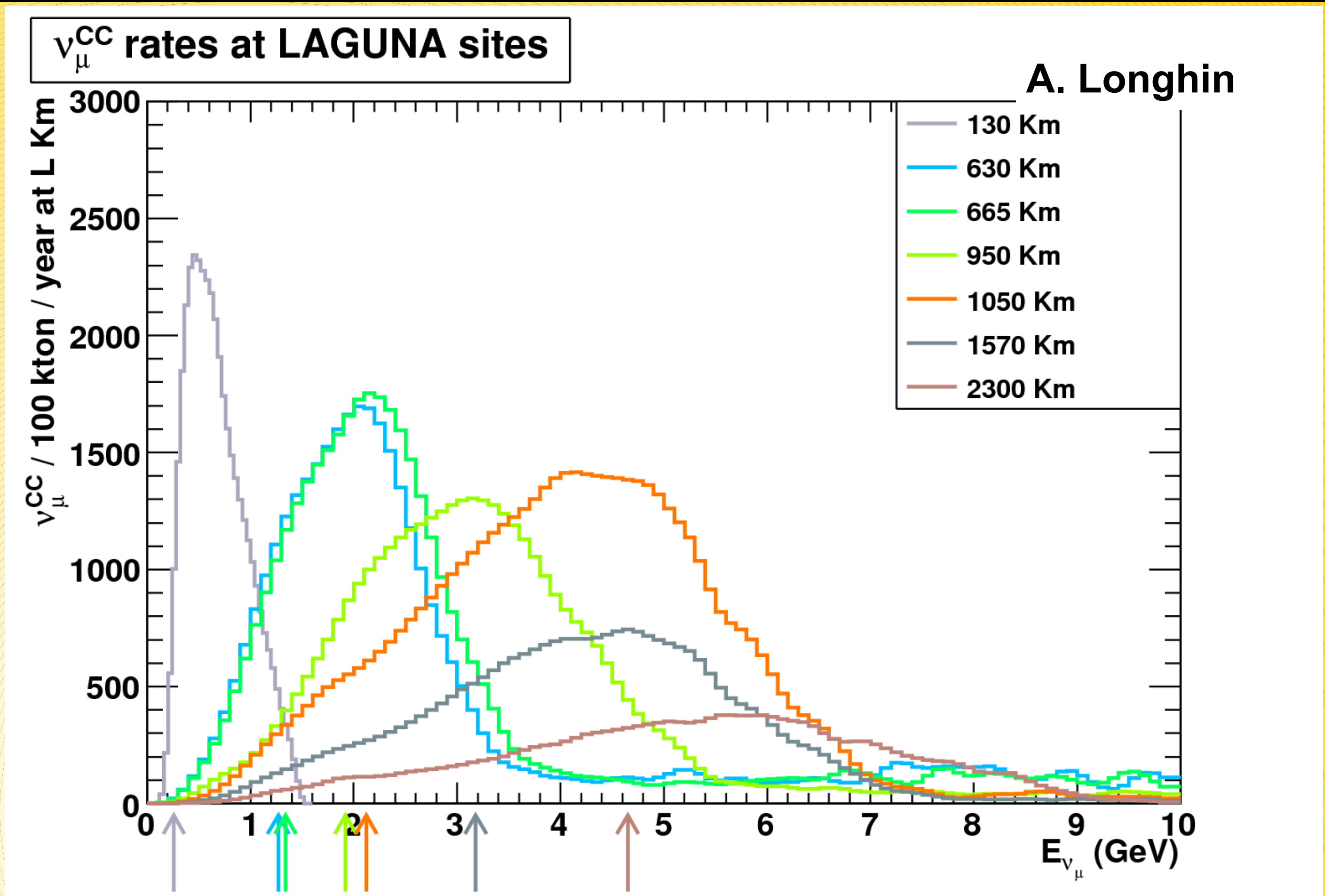
Fluxes full optimization vs baseline

ν_μ^{CC} rates

at "L" Km
for 1 year running
on a 100 kton mass

Two effects:

- N ~ σ(E) ~ E
- N ~ 1/L²



	ν run			$\bar{\nu}$ run		
L (km)	$\nu_\mu^{CC}(\bar{\nu}_\mu^{CC})$	$\nu_e^{CC}(\bar{\nu}_e^{CC})$	$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$ (%)	$\nu_\mu^{CC}(\bar{\nu}_\mu^{CC})$	$\nu_e^{CC}(\bar{\nu}_e^{CC})$	$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu}$ (%)
130	41316 (94)	174 (2)	0.42	527 (5915)	12 (15)	0.42
630	36844 (2903)	486 (95)	1.5	7930 (13652)	270 (157)	2.0
665	38815 (2967)	516 (96)	1.5	7516 (14287)	280 (158)	2.0
950	37844 (1363)	349 (48)	1.0	3504 (14700)	110 (107)	1.3
1050	51787 (761)	314 (23)	0.64	1964 (21728)	54 (88)	0.60
1570	26785 (385)	174 (10)	0.67	945 (11184)	22 (47)	0.57
2300	17257 (203)	110 (7)	0.67	471 (7577)	16 (32)	0.60

A. Longhin LAGUNA meeting Modane 6-9 Sept 2010