LAGUNA-LBNO: what, where, when ?

André Rubbia (ETH Zurich)

on behalf of the LAGUNA-LBNO consortium

GDR neutrino
28-29 novembre 2011 LAPP, Annecy-le-Vieux

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*" → combined submission to FP7 programme
  - ➡ 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)

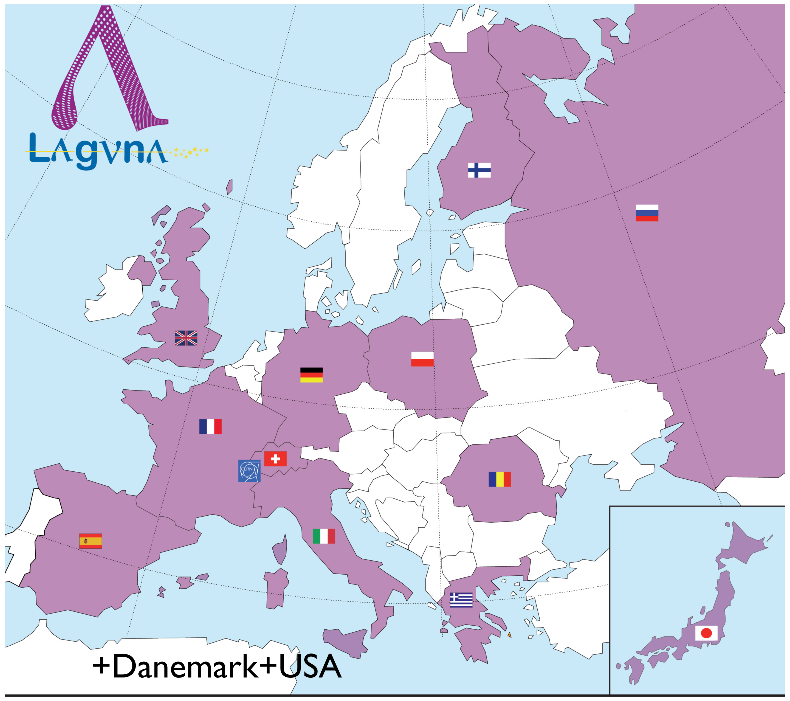
The LAGUNA design study (2011-2014)

- **Large Apparatus for Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations**
  - ➡ FP7 funded LAGUNA-LBNO "Design Study" (2011-2014)
  - ➡ Wider scope (LBNO) & more focus (sites, technologies): continue with the same "successful format" but to address new questions (→detector construction+operation and CERN long baseline beam)
  - ➡ Enlarged, stronger collaboration, and larger budget: includes all LAGUNA beneficiaries and new industrial and academic beneficiaries (in total 39) among them CERN, KEK(Japan) and Russian institutes and additional associated institutes (Denmark, USA)
  - ➡ Investigations must lead to a "preparatory phase"

- **Exploit new opportunities**
  - ➡ T2K, MINOS, Double Chooz point to $\sin^2 2\theta_{13} > 0.01$
  - ➡ CERN European Particle Physics Strategy Review in 2012-2013
  - ➡ Real-time reaction to explore options towards a "realistic plan" for a European LBL programme with great discovery potential

LAGUNA-LBNO consortium

14 countries, 47 institutions, ~300 members (open)



Switzerland
University Bern
University Geneva
ETH Zürich (*coordinator*)
Lombardi Engineering*

Finland
University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

France
CEA
CNRS-IN2P3
Sofregaz*

Germany
TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen
University Tübingen

Poland
IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece
Demokritos

Spain
LSC
UA Madrid
CSIC/IFIC
ACCIONA*

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

Romania
IFIN-HH
University Bucharest

Denmark
Aahrus

Italy
AGT*

Russia
INR
PNPI

Japan
KEK

USA
Virginia Tech

(=industrial partners)*

The EU design study "menu"

LAGUNA

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

LAGUNA-LBNO

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

EuroNu

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

next step(s) ?

The EU design study "menu"

2008

time

LAGUNA

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

EuroNu

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

2011

LAGUNA-LBNO

- -international consortium including EU, Japan and Russia
- -two+one 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 (CERN)

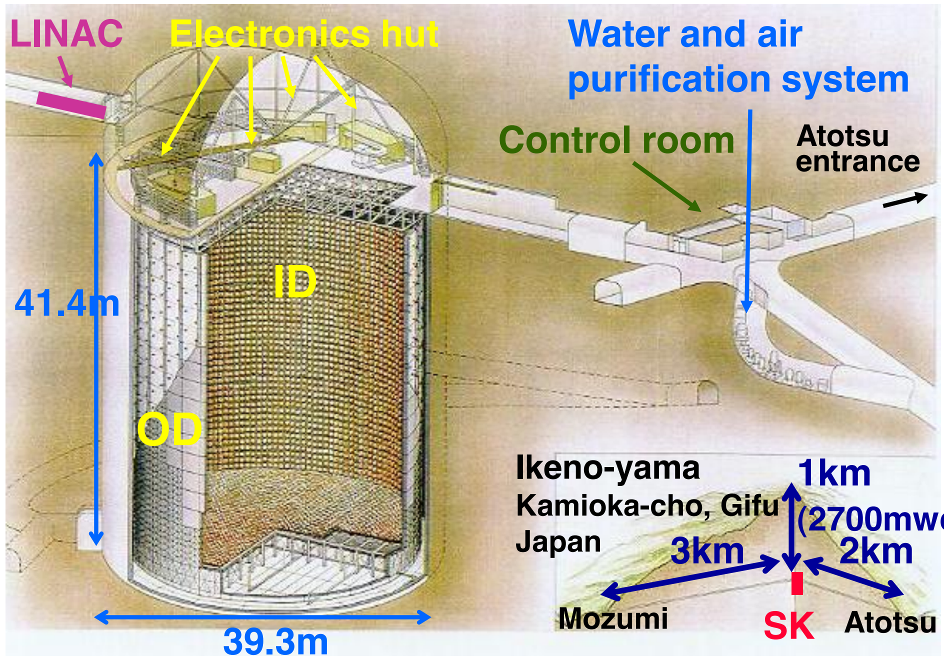
2014

next step(s) ?

Water Cherenkov Detectors (WCD)

Super-Kamiokande

http://www-sk.icrr.u-tokyo.ac.jp/sk/

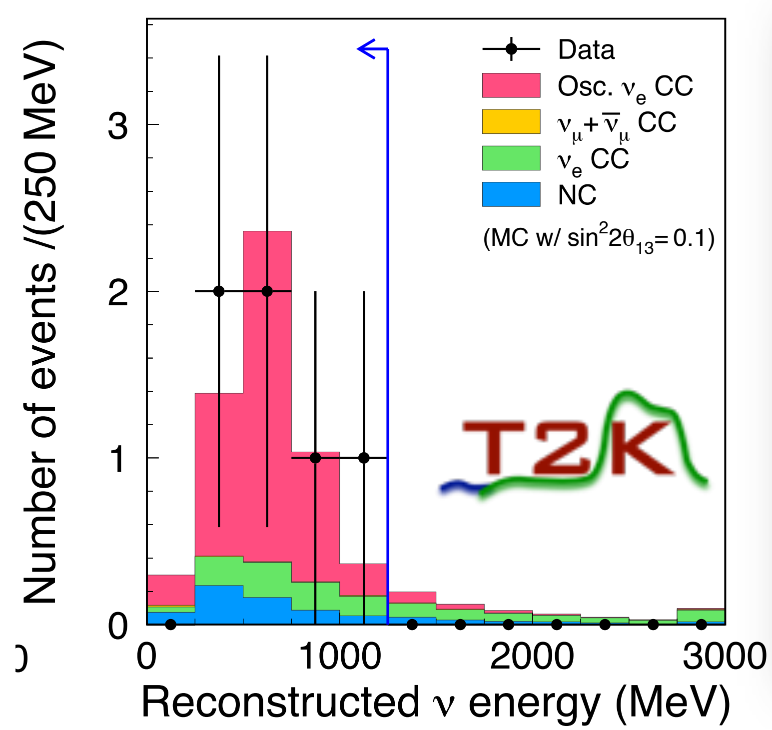


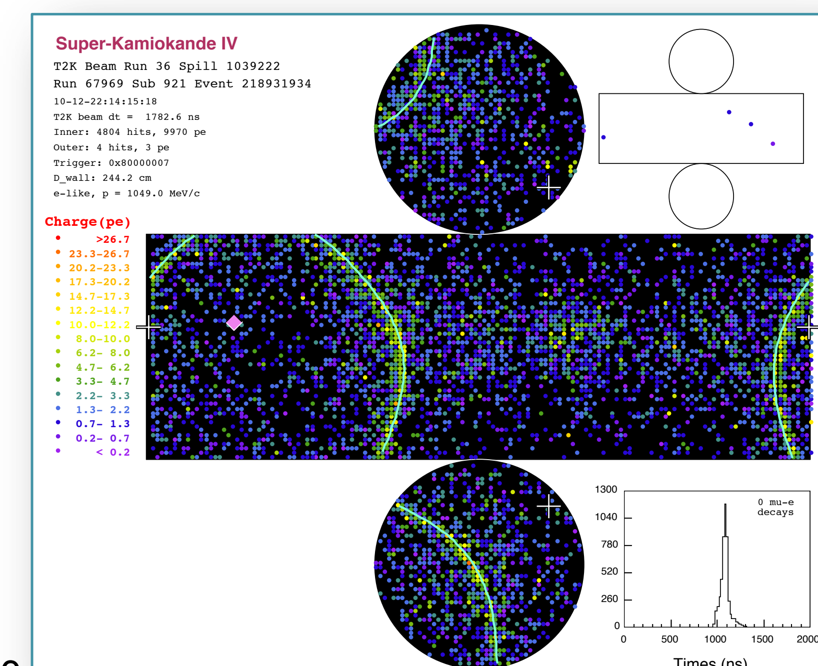
- 50kton water
- 32kt ID viewed by 20-inch PMTs
- ~2m OD viewed by 8-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- E_{total}=~4.5MeV energy threshold
- SK-I: April 1996~
- SK-IV is running

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

Large Size: for rare events, low fluxes
Low Threshold: as low as MeV with high efficiency
Excellent e/μ: >98% from single ring pattern
Low cost/kton: "affordable" way to megaton mass
Free protons
Mature technology: short development time
Safety, Maintenance, Accessibility

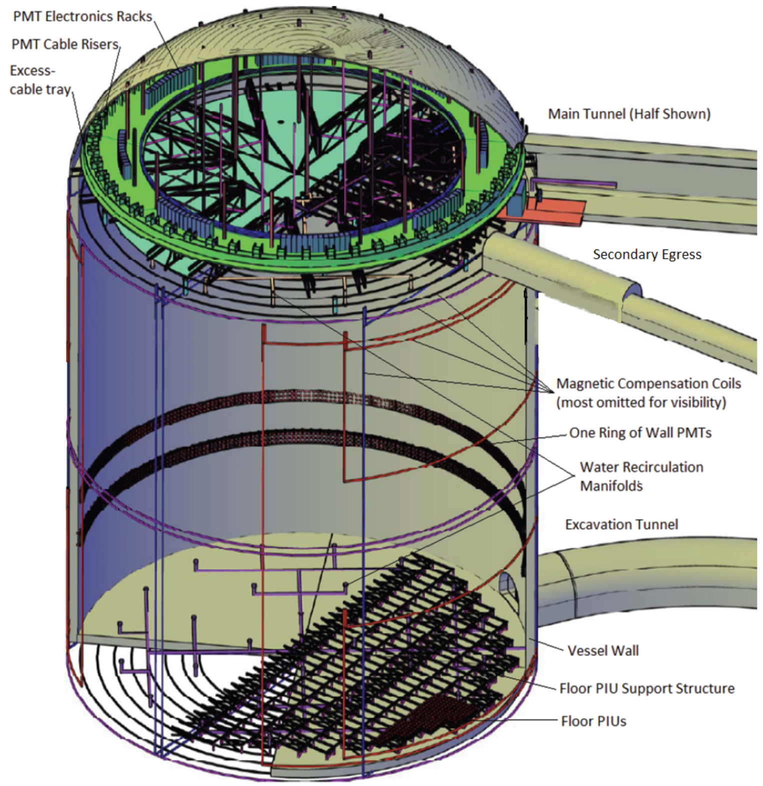
- Excellent performance especially for low energy w/ low multiplicity
- Cherenkov threshold
- Energy reconstruction assuming CCQE
  - Efficient for low energy
- Good PID (μ/e)
- Established analysis
- **Good at low E (<1GeV)**
  - **narrow band beam**
  - Match with low energy off-axis beam





Water Cherenkov Detectors (WCD)

LBNE WCD option

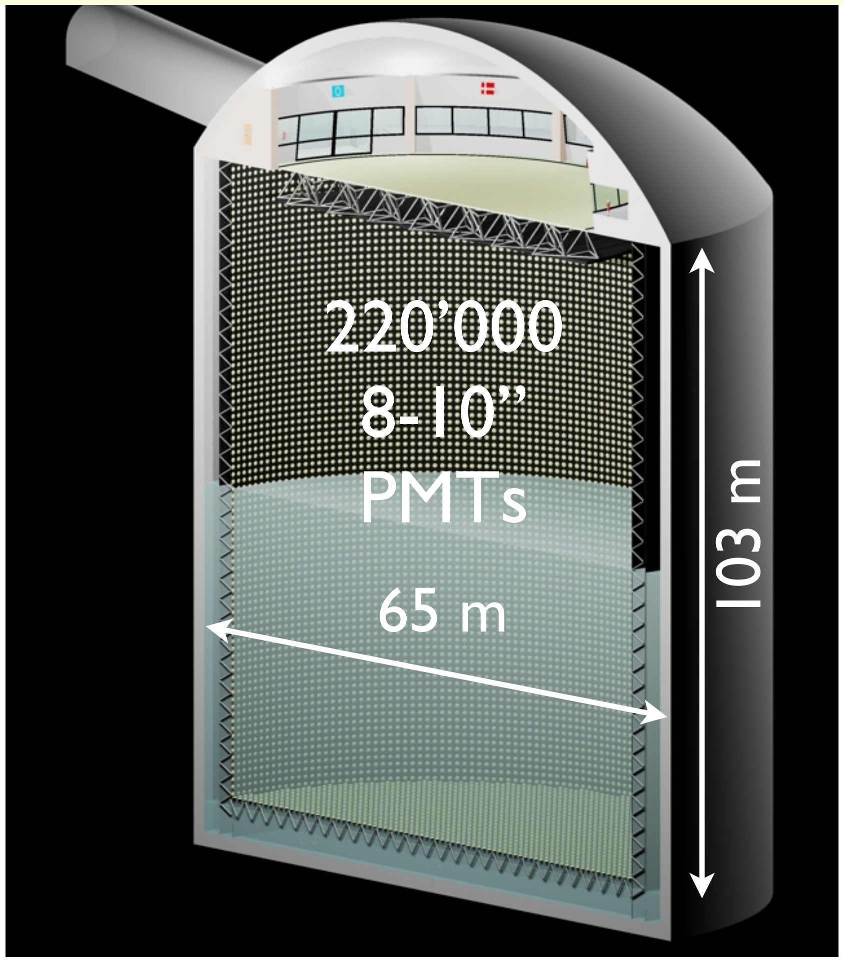


Main Detector Components
- Large Cavern
- Water Vessel
- Ultra-pure water system
- PMTs with Electronics

150-200 kton FD
8-10" PMT to reach
20% photocoverage
4300 mwe depth

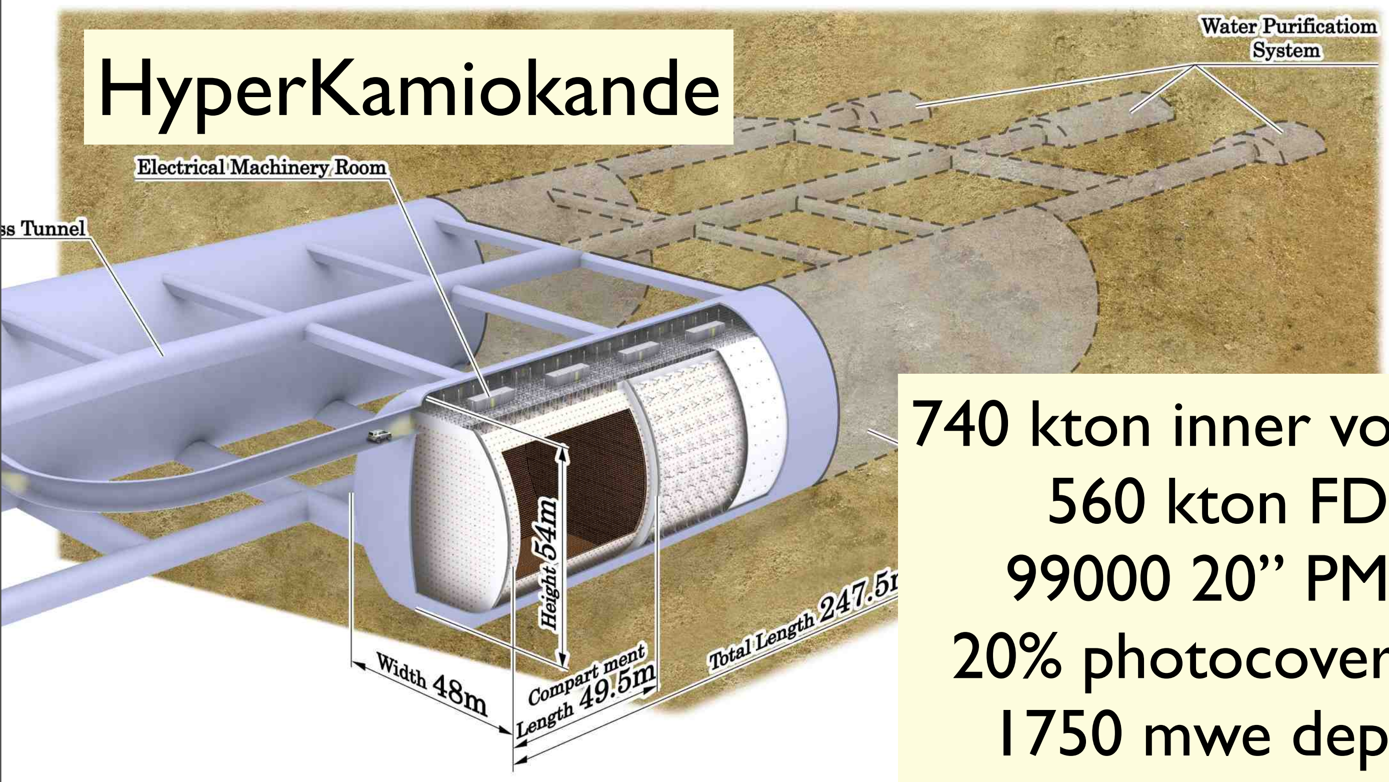
Well-known, "ready to go" technology
Engineering challenges lie in huge excavation and photo-sensors procurement

MEMPHYS (LAGUNA WCD option)



2x330kt total volume
440 kton FD
220'000 8-10" PMT
4800 mwe depth

HyperKamiokande



740 kton inner volume
560 kton FD
99000 20" PMT
20% photocoverage
1750 mwe depth

Liquid Argon Detectors (LArTPC)

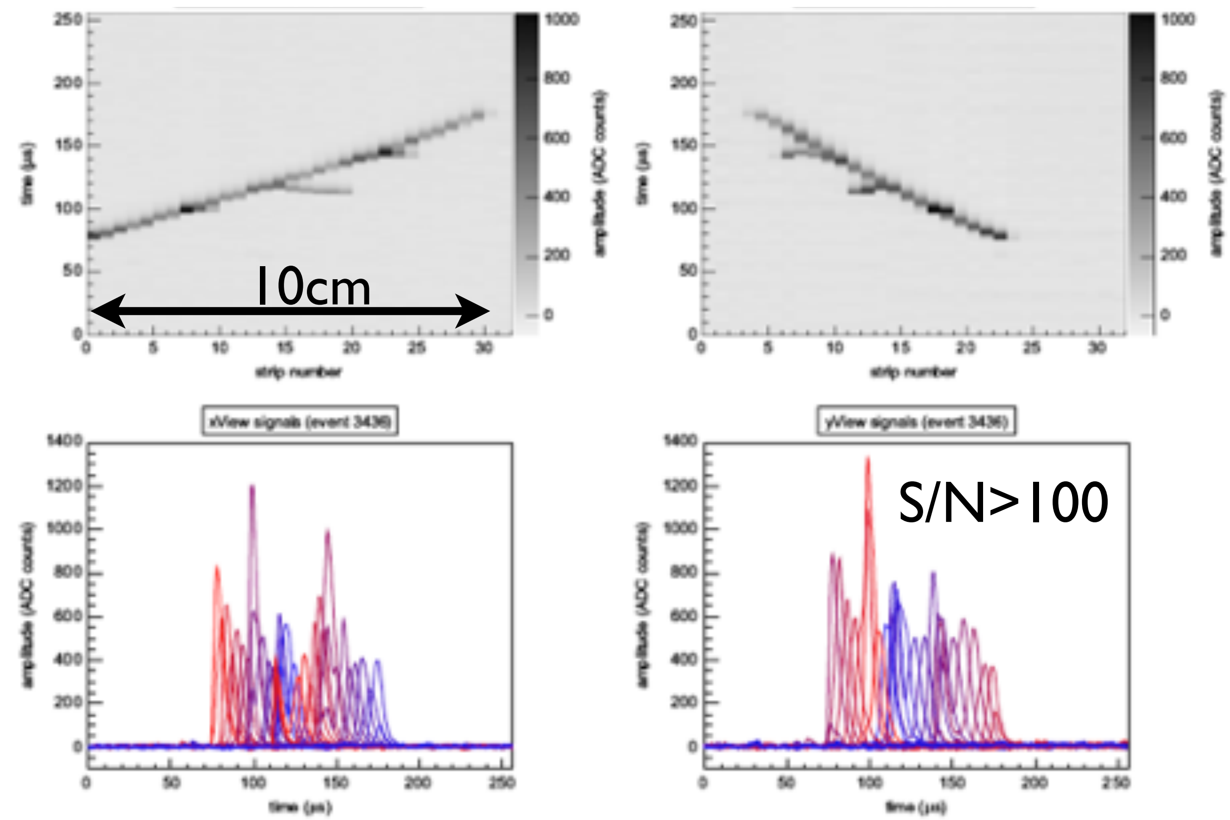
Challenging technology but long term likely to provide best beam physics performance

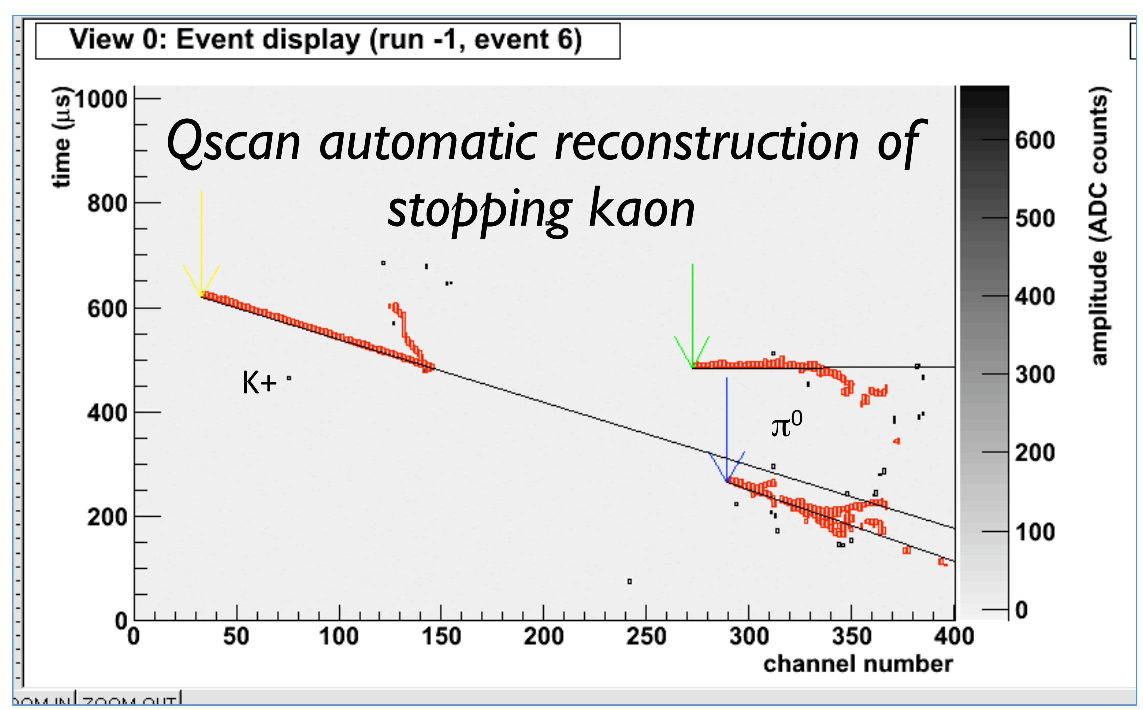
- **Homogeneous 4π full sampling tracking-calorimeter**
  - ➡ 3D tracking of ionizing particles with millimeter space precision
  - ➡ Low detection threshold (<100 keV with charge amplification)
  - ➡ Excellent energy resolution
  - ➡ Measurement of local energy deposition
  - ➡ dE/dx measurement, ≈2% X_0 sampling
  - ➡ Excellent particle identification ($e/\pi 0$, $\mu/\pi/K$, ...)
  - ➡ Exclusive final state event topologies reconstruction
  - ➡ Timing information with light readout
- **Technology applicable to a very wide range of energies**
  - ➡ from 10's keV to 10's GeV
- **Technology scalable to large masses (ICARUS T600)**

Nucl.Instrum.Meth. A527 (2004) 329-410

Cosmic track in double phase LAr-LEM TPC with adjustable gain (e.g. below G≈30) and symmetrical readout views

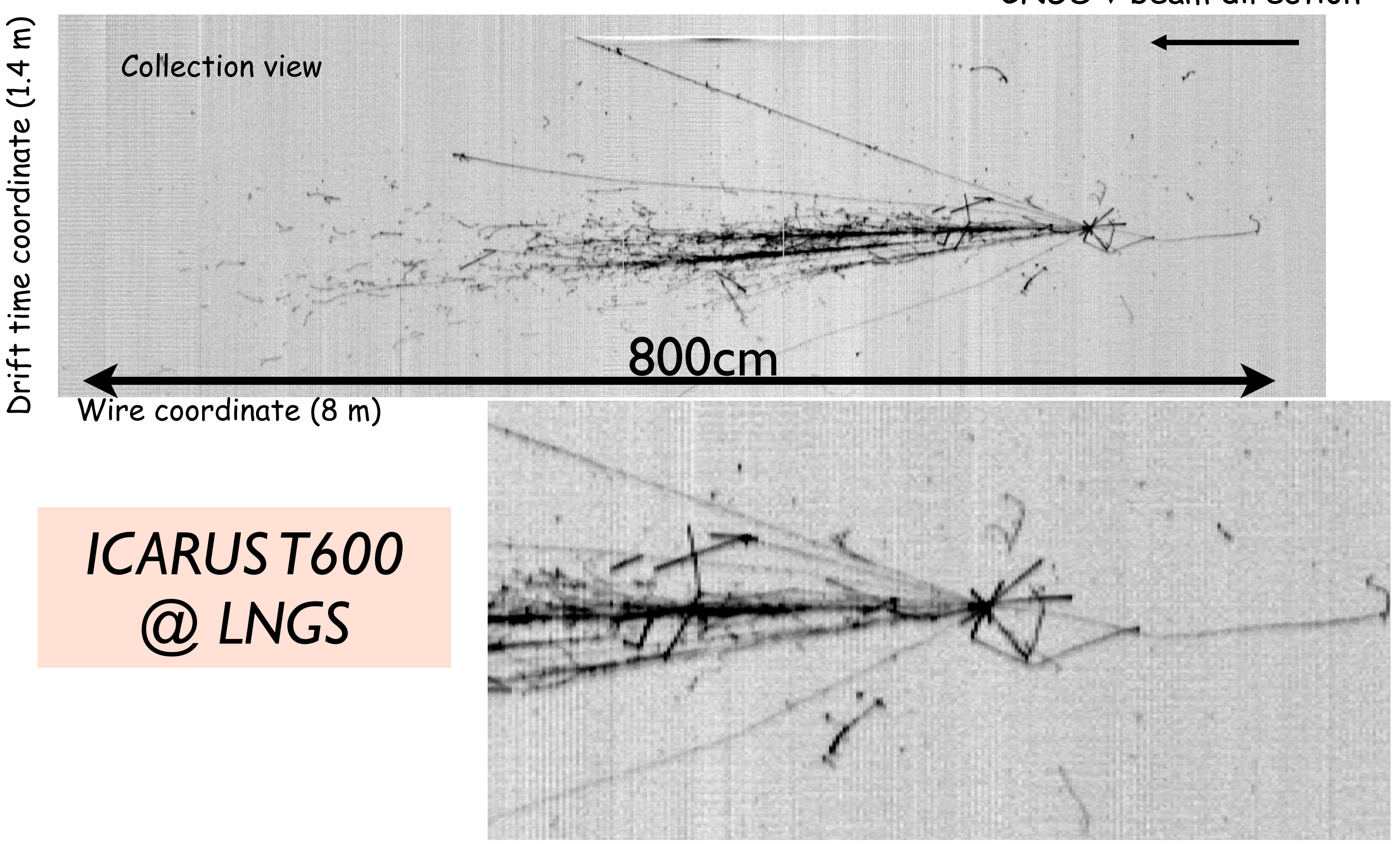
Nucl.Instrum.Meth. A641 (2011) 48-57





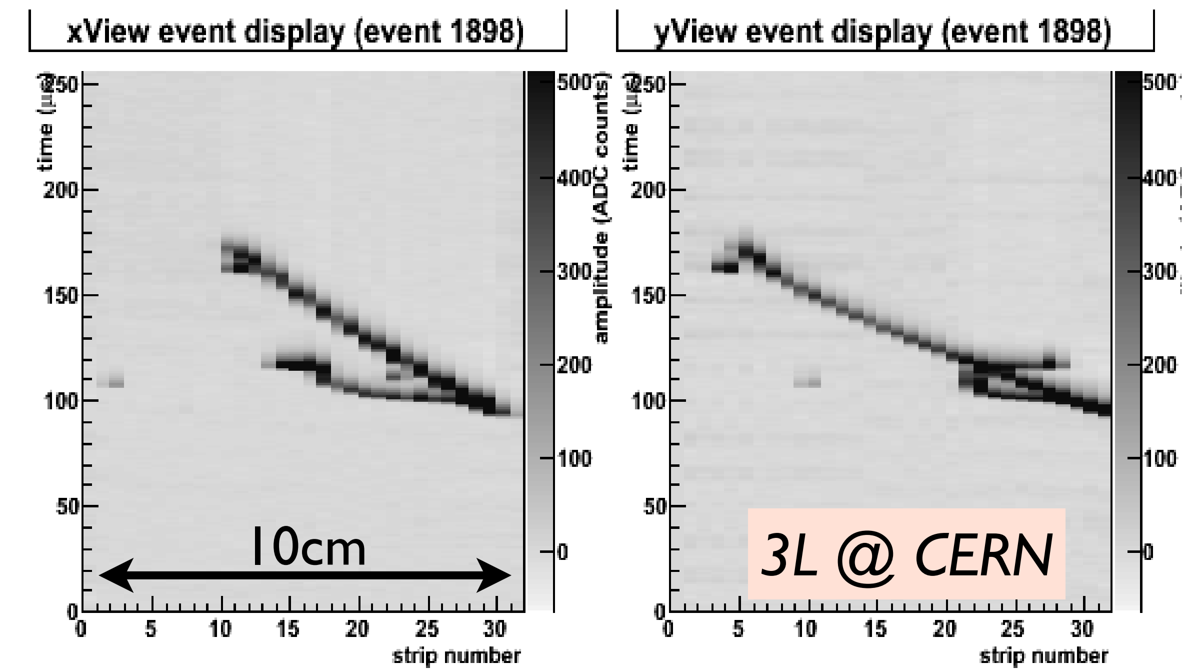
Liquid Argon Detectors (LArTPC)

"electronic bubble chambers"

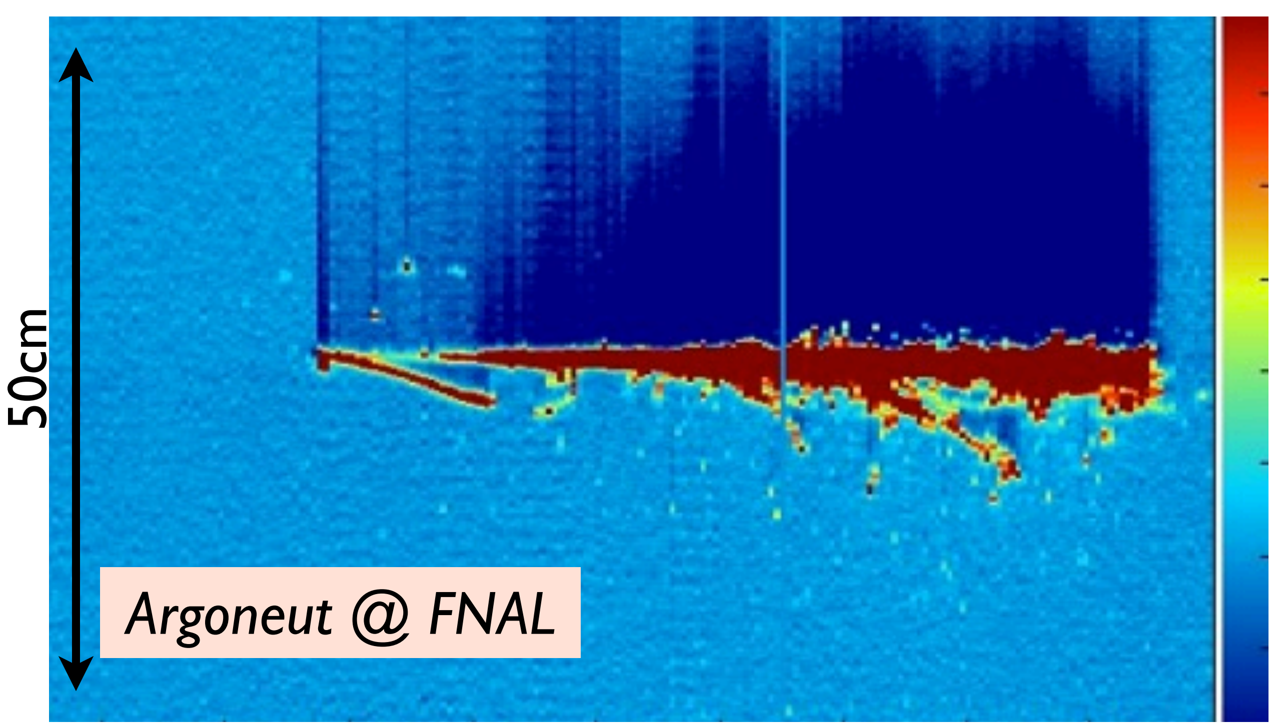


ICARUS T600 @ LNGS

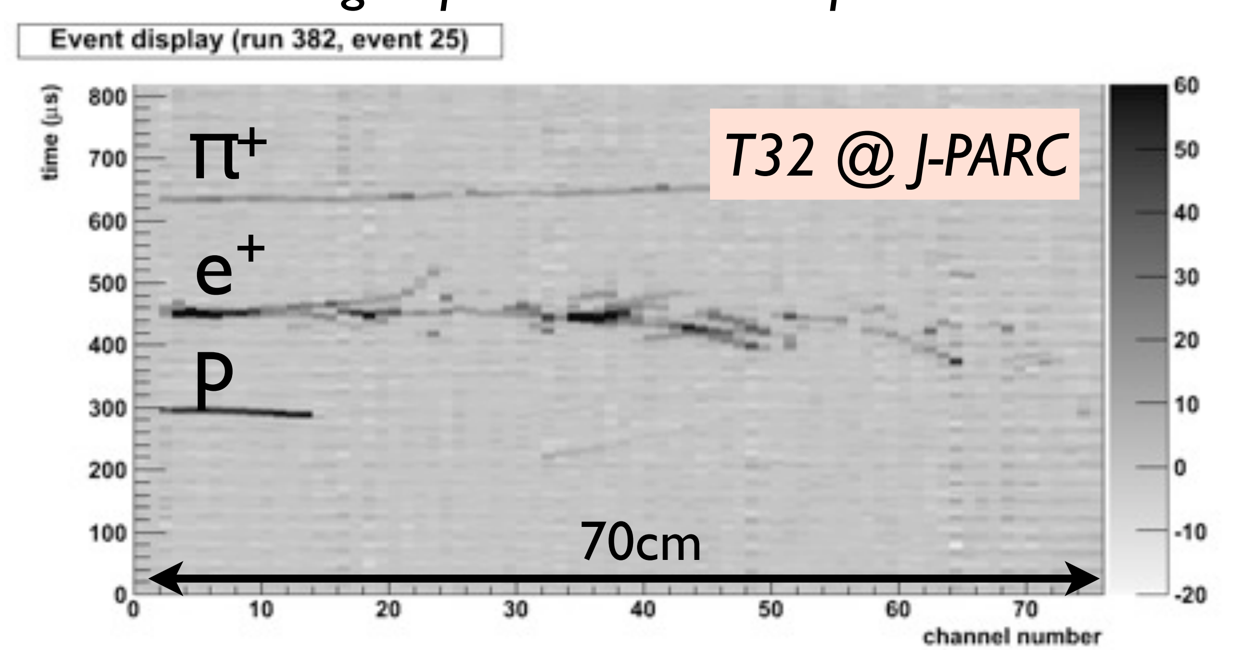
Cosmic track in double phase 3L LAr-LEM TPC with adjustable gain @ CERN



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



Charged particle beam exposure

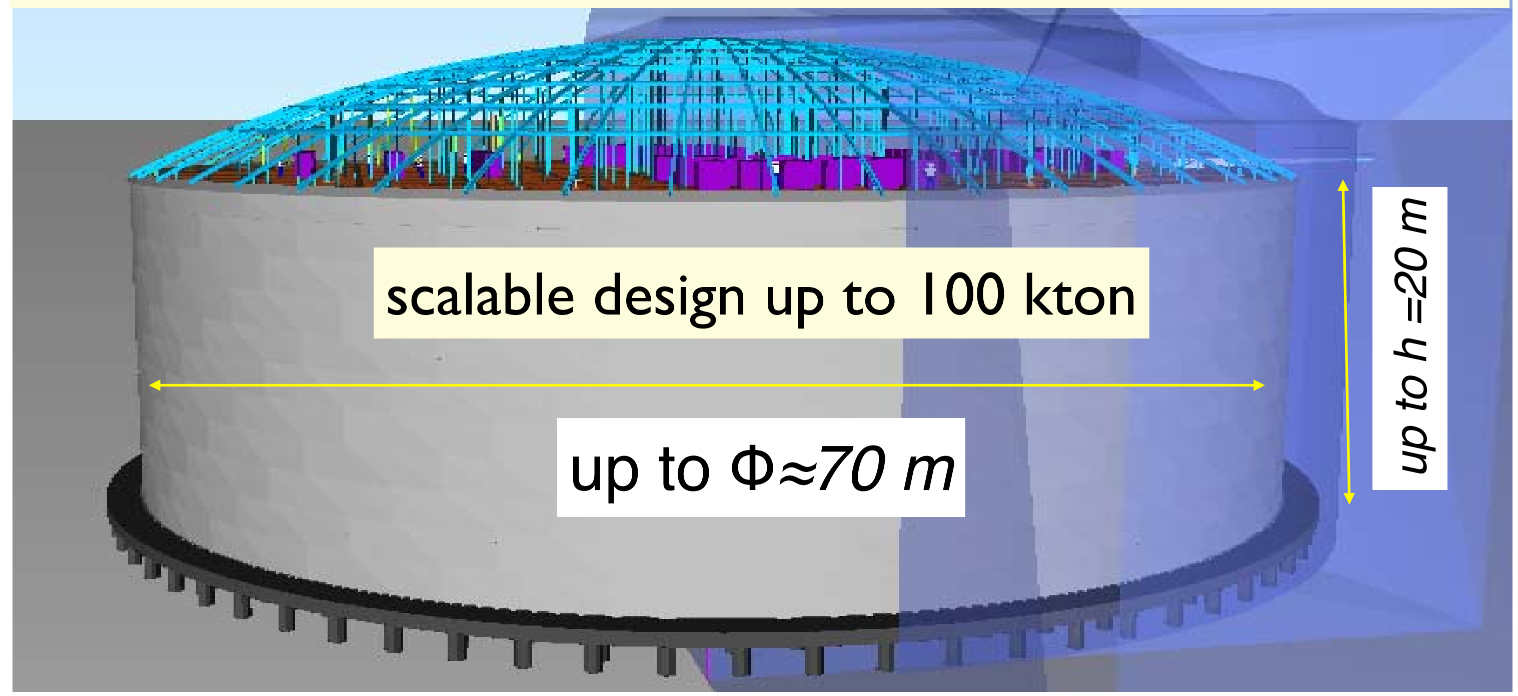


GLACIER detector concept

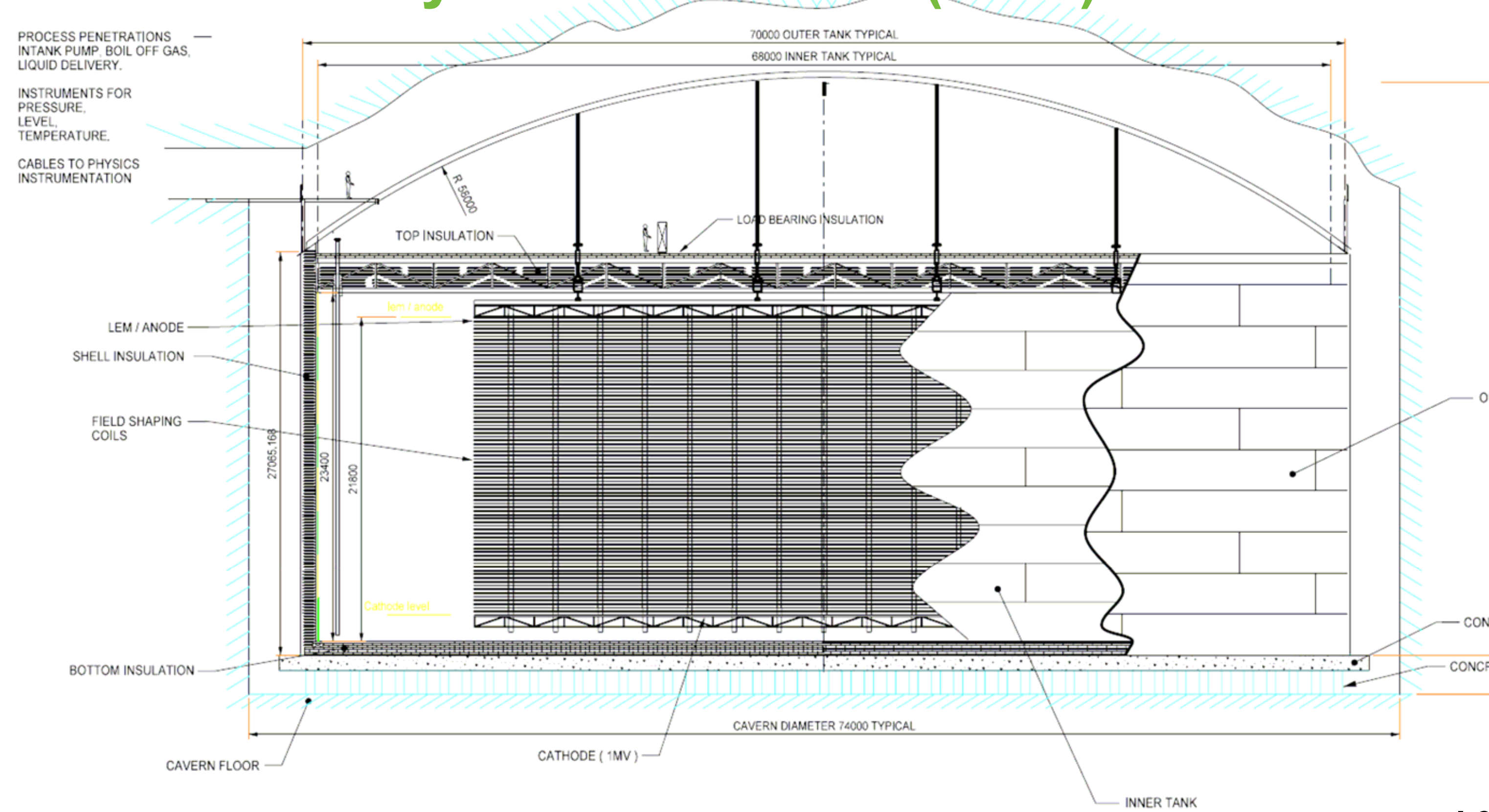
EU+Japan effort

- **Simple, scalable detector design, from one up to 100 kton**
- **Single module non-evacuable cryo-tank based on industrial LNG technology**
- **Cylindrical shape with excellent surface / volume ratio**
- **LAr recirculation (purification) and recondensation of boiloff**
  - ➡ Purity goal <10 ppt O_2 equiv.
- **Engineering study performed in collaboration with Technodyne Ltd**
  - ➡ Cavern and tank decoupled
  - ➡ Tank based on existing design and operating experience
  - ➡ Tank design variations have several known solutions
  - ➡ Excellent safety record (on surface)
  - ➡ Cost for above ground installation, multiplier for below ground (dominant uncertainty → deliverable LAGUNA-LBNO)
- **Reasonable excavation requirements (<250‘000 m3)**

GLACIER (LAGUNA LAr option 2700mwe and Japan 600mwe)

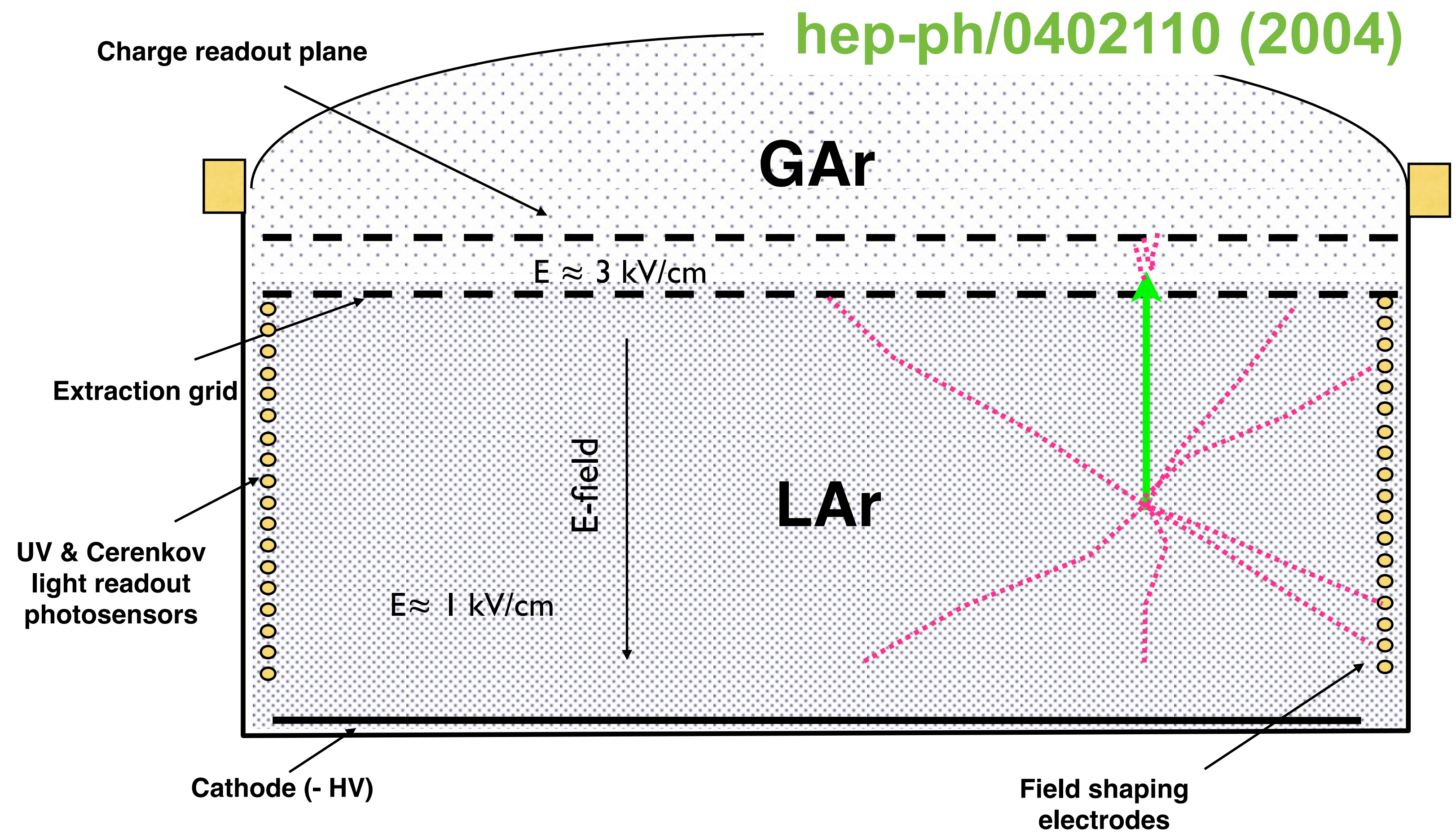


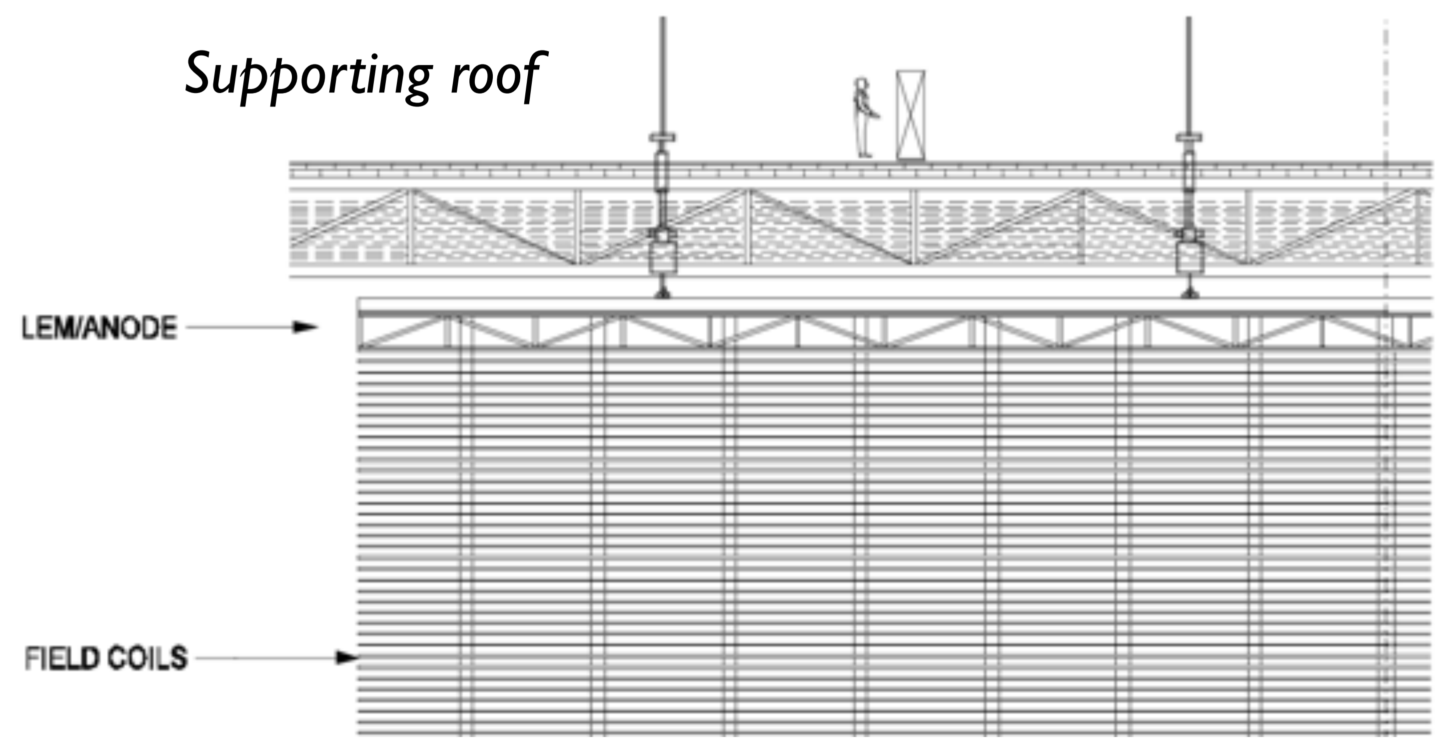
J.Phys.Conf.Ser. 308 (2011) 012030



Detector concept : readout scheme

- **A very large area with single long vertical drift paths with full active mass**
- **Double phase readout with adjustable gain at top**
  - ➡ Full extraction from LAr to GAr with ≈3 kV/cm (local)
  - ➡ MPGD, technologies under test LEM, THGEM, Micromegas
  - ➡ Independent readout units
  - ➡ O(10^6) readout channels
- **Immersed high voltage multiplier for drift field**
  - ➡ 0.5÷1 kV/cm
- **Immersed light readout system**
  - ➡ WLS-coated 1000x 8" PMT and reflectors for DUV light detection
  - ➡ Cerenkov imaging with 27000x 8" uncoated PMT
- **Possibly embedded in magnetic field ?**
  - ➡ 0.1÷1 T depending on goal





Physics performance extensively studied

• Proton decay

JHEP 0704 (2007) 041

- ➡ Many decay modes available, several not easily accessible with WCD
- ➡ E.g. with kaons: ≈10x more sensitive than WCD
- ➡ Lifetime sensitivity 10^{34}-10^{35} years depending on channel for 100 kton*10y

• Astrophysical neutrinos

PRD82, 093012 (2010)
Nucl. Phys. B. Proc. Suppl. 91, 223 (2001)

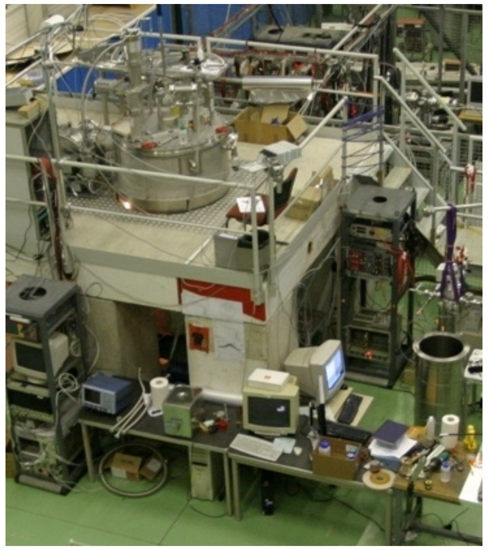
- ➡ Atmospherical neutrinos: e.g. detection of ν_τ
- ➡ Supernova core collapse neutrinos — JCAP 0408 (2004) 001
- ➡ Diffuse supernova neutrino background — JCAP 0412 (2004) 002
- ➡ Indirect DM detection — arXiv:1105.4077 [hep-ph]
- ➡ Solar neutrinos

• Neutrino flavor oscillations and CP violation in leptonic sector

- ➡ Long baseline accelerator neutrinos in wide band beam (1^{st} and 2^{nd} maximum)
- ➡ Experimental proof of 3x3 nature of PMNS matrix, CP-violation discovery and mass hierarchy determination
- ➡ Neutrino factory — Nucl. Phys. B 589 (2000) 577

arXiv:1003.1921 [hep-ph]
arXiv:0804.2111 [hep-ph]
arXiv:0801.4035 [hep-ph]
JHEP 0611 (2006) 032
+ etc...

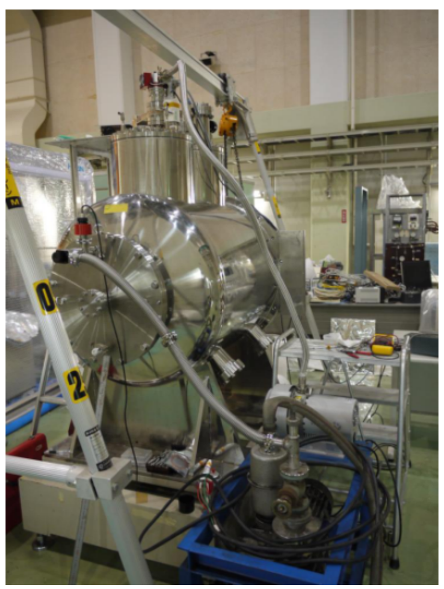
Overview of our LAr activities



(1) ArDM-1t @ CERN

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

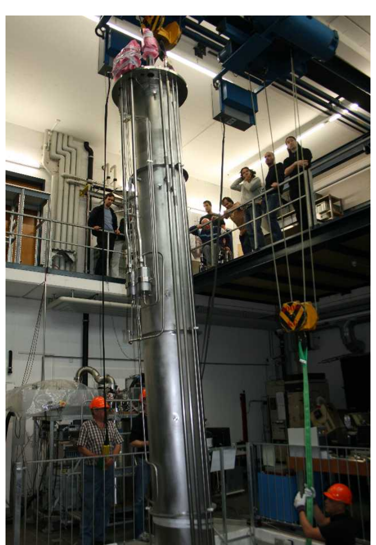
1 ton LAr, large area readout, 1m drift with Cockroft-Walton, LAr recirculation and purification, electronics, safety, optimized for dark matter searches, underground operation



(2) J-PARC P32

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

0.4 ton LAr, vacuum, cryogenic system, gas purging, argon liquefaction, optimized for test beam pion / kaon response, software development



(3) ArgonTube @ Bern

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

R&D towards direct very long drift demonstration, HV, liquid purification

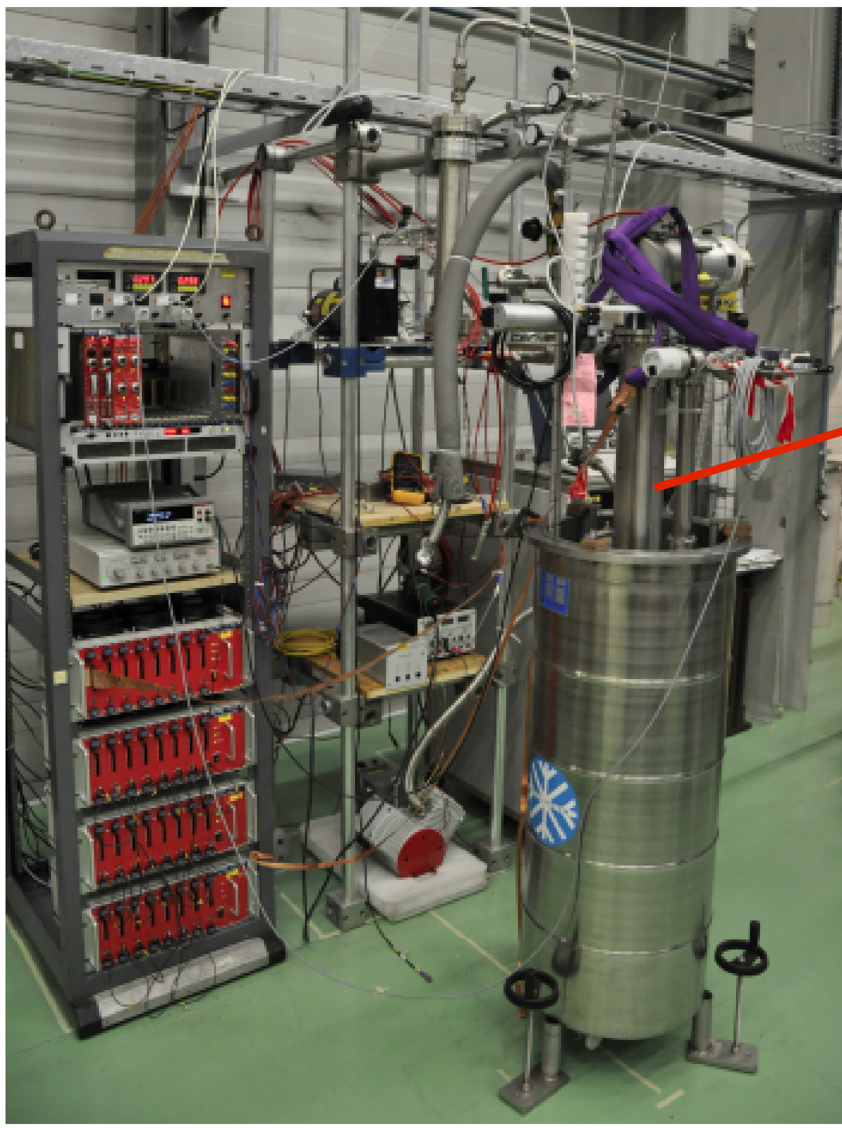
(4) 10T @ CERN

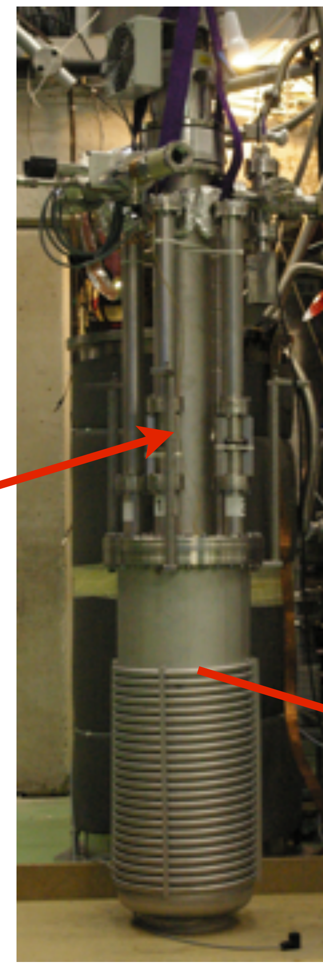
R&D towards non evacuated vessels, warm Ar purging starting from air, high capacity closed gas recirculation

Charge readout R&D: the 3L double phase argon LEM-TPC @CERN

- 3L size LAr-TPC is used to test new readout techniques in order to improve the signal to noise ratio
- Successful tests done with two different gas multipliers: LEM (coupled with 2D anode) and MicroMeGas

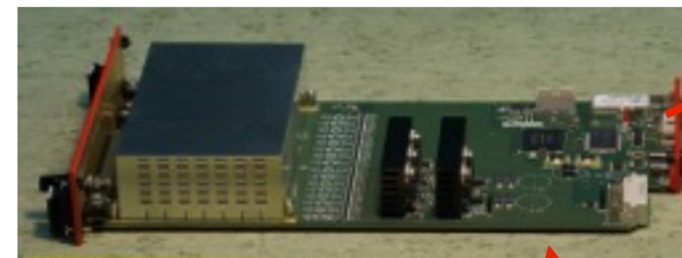
Setup located at CERN

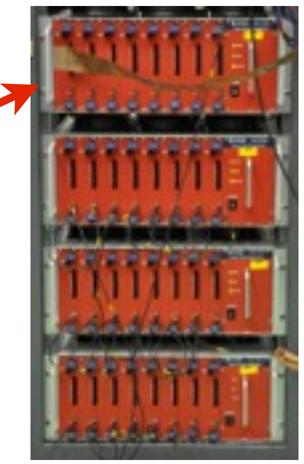




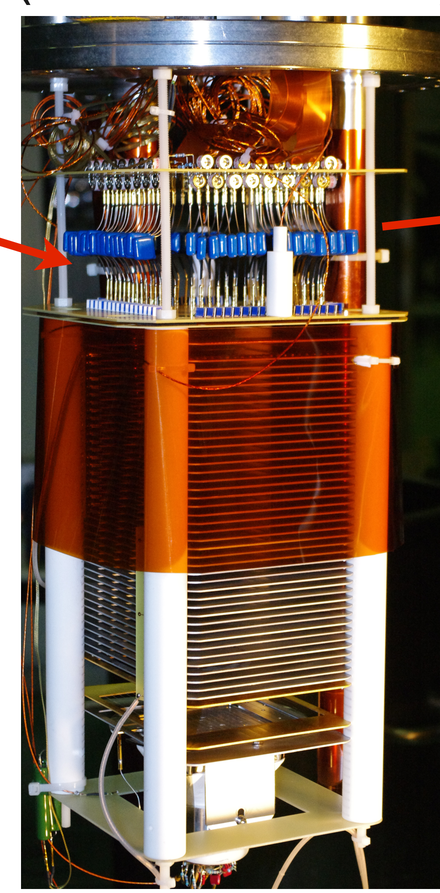
UHV vessel (kept cold with open LAr bath)

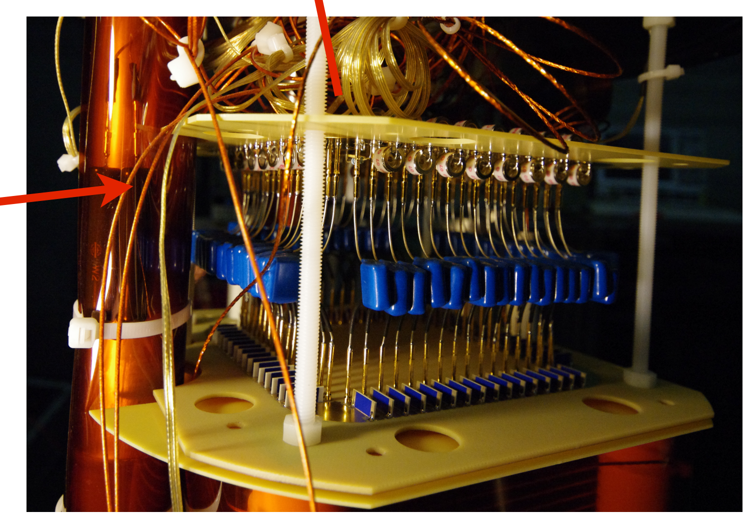
CAEN DAQ system





TPC (10x10x20 cm^3)





Charge Readout system (in gas phase above pure LAr)

In Collaboration with CERN RD51

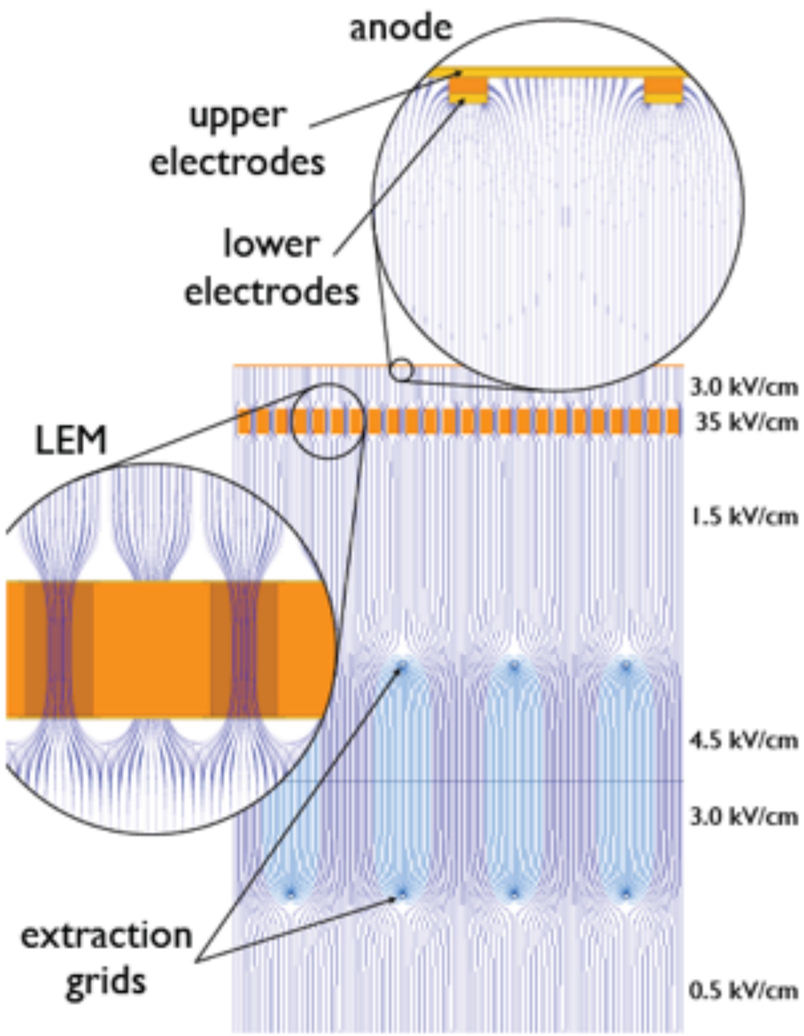
Double phase charge readout principle: LEM and projective 2D anode

A. Badertscher, et al., NIM A 641 (2011) 48-57

Readout principle

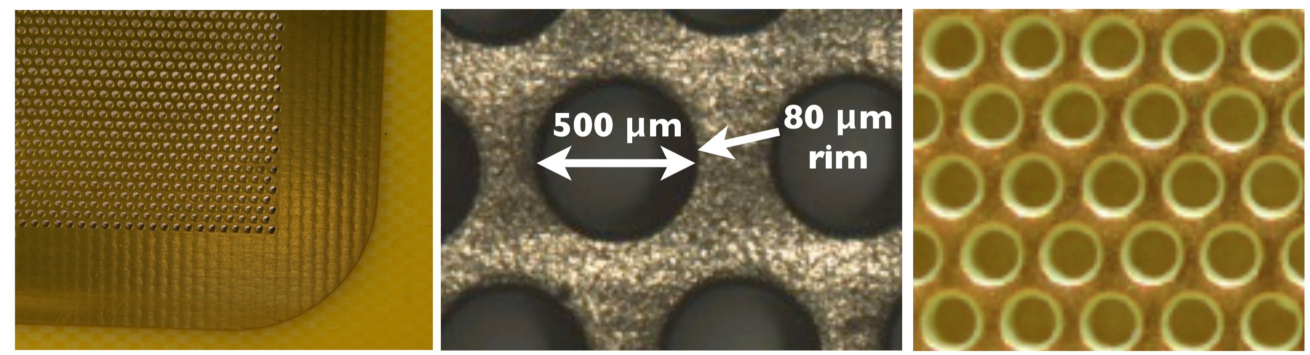
1. ionization electrons are **drifted** to the liquid-gas interphase
2. if the E-field is high enough (≈ 3 kV/cm) they can efficiently be **extracted** to the gas phase
3. in the holes of the LEM the E-field is high enough to trigger an electron avalanche
4. the **multiplied** charge is collected on a 2D readout

Electric fields



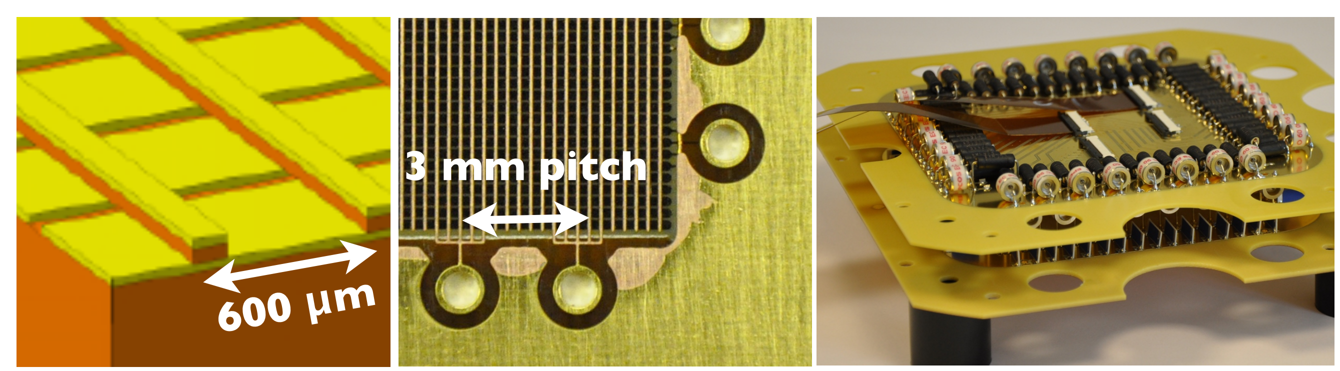
LEM (THGEM): Large electron multiplier

- Macroscopic Gas hole multiplier
- more robust than GEMS (cryogenics, discharges)
- manufactured with std. PCB techniques
- Large area coverable (1 m^2 size modules)



Projective 2D anode readout

- Charge is equally collected on two sets of strips (views)
- induced signals have the same shape for both views
- readout independent of multiplication



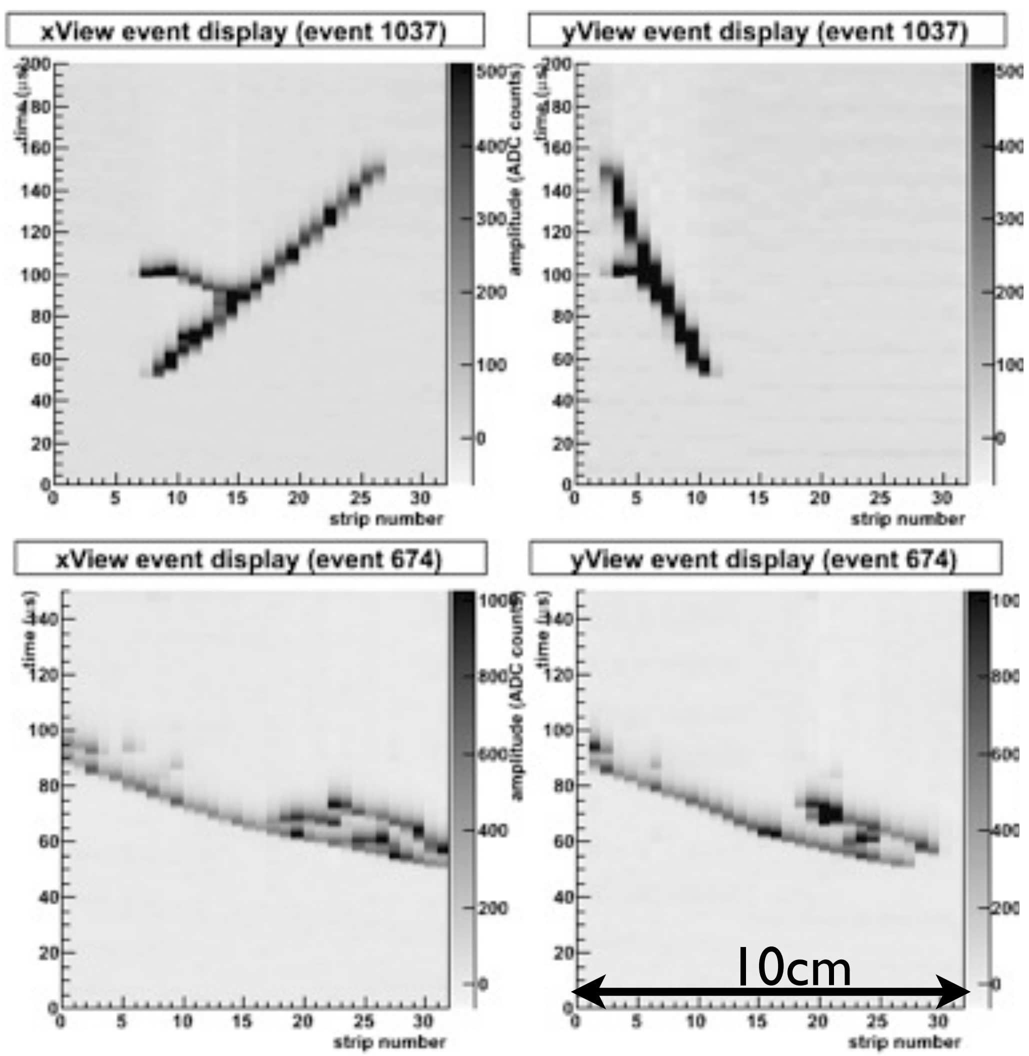
LEM and 2D anode produced by CERN TS/DEM group

Results from the double phase LAr LEM-TPC with projective 2D anode

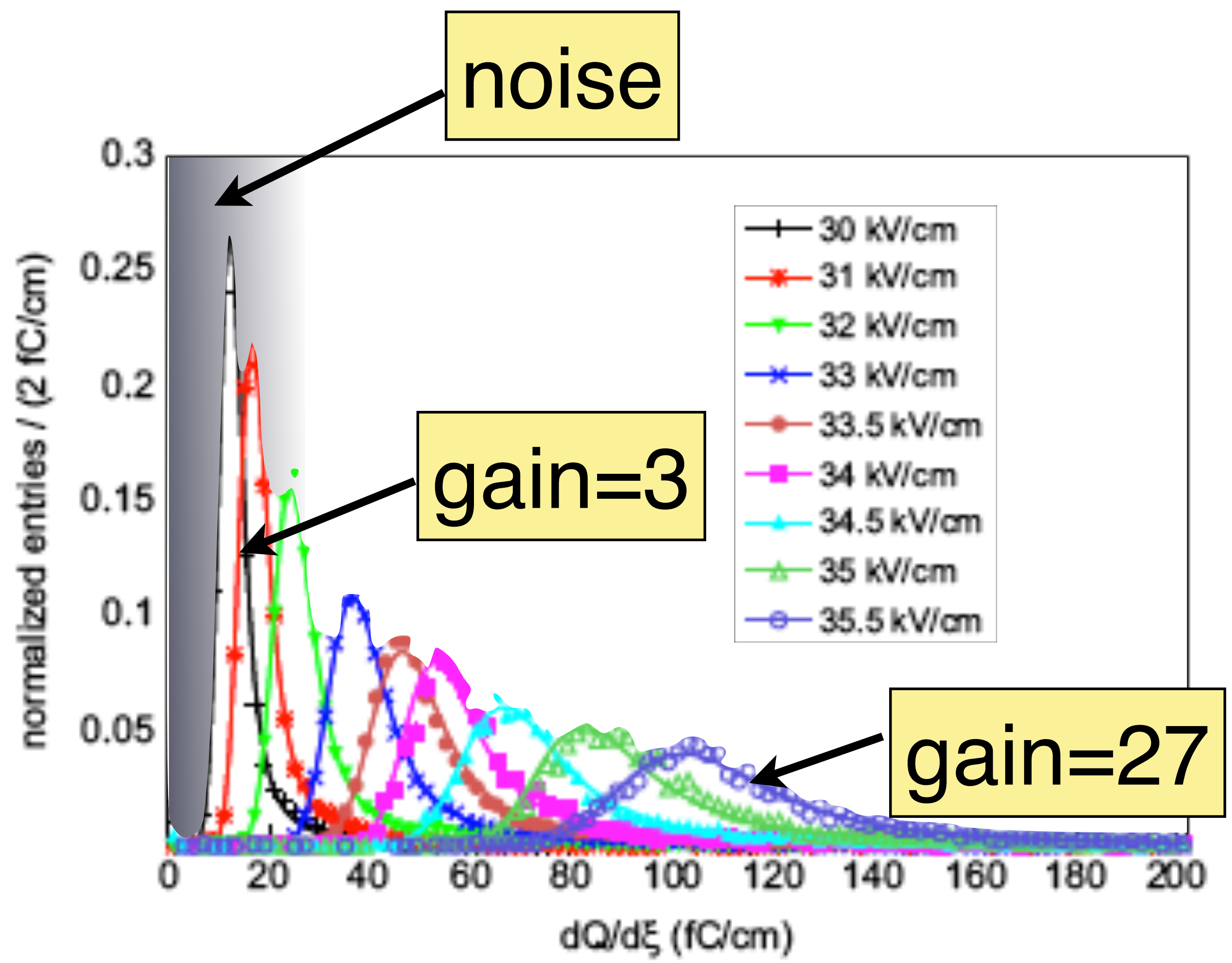
NIM A 641 (2011) 48-57

- Multiplication in gas phase leads to a signal gain of >30 @ 35.5kV/cm (single stage)
- With a projective anode, both views see the same (collection) signal waveform
- System provides excellent S/N ratio >100 allows precise reconstruction of:
  - 3D track topology
  - energy loss (landau fluctuations)

cosmic triggers



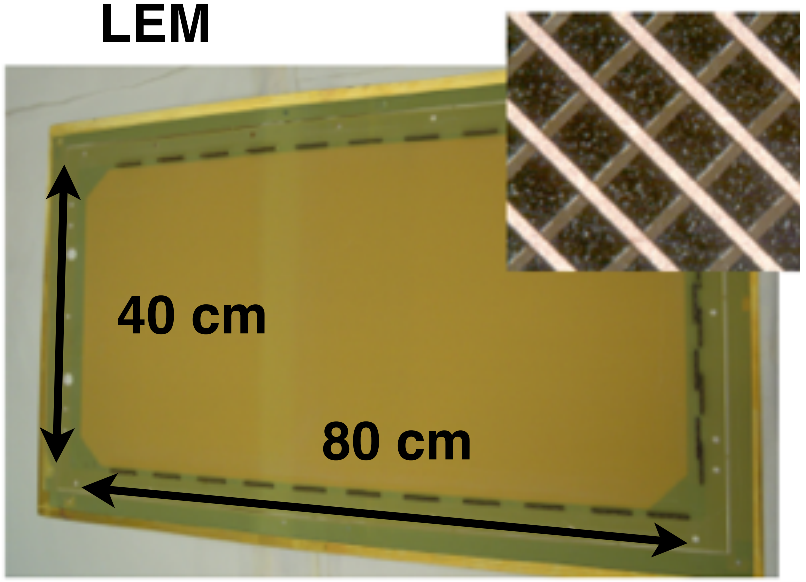
Landau distribution fitted to dE/dx distributions of muons



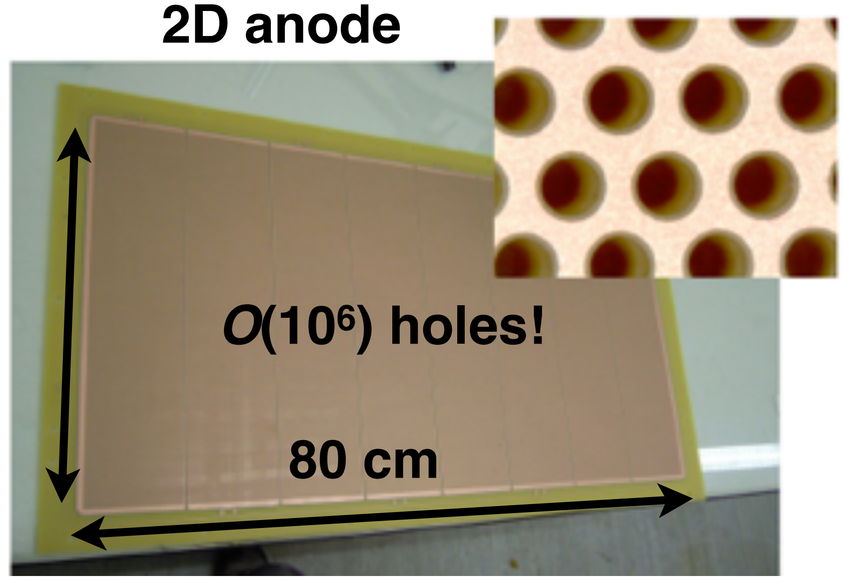
250L LAr-LEM TPC@CERN: Production of a $40x80\ cm^2$ charge readout sandwich

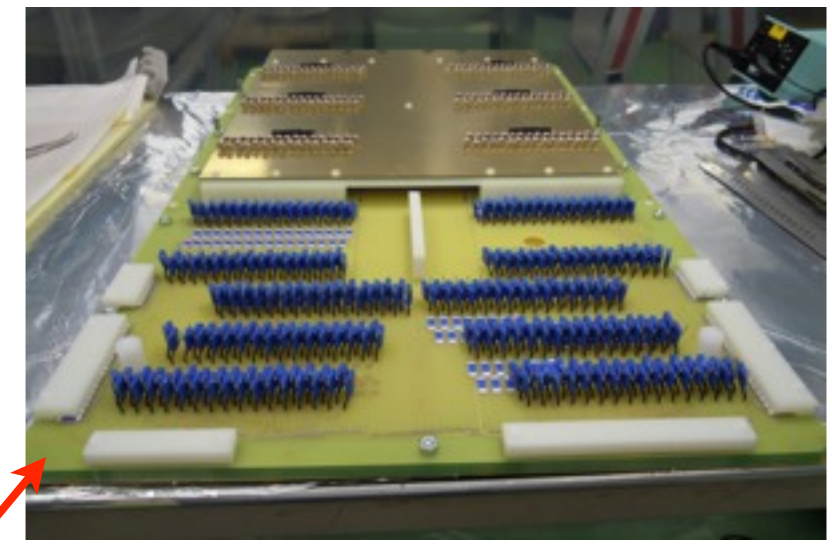
‣After successful test of LEM and 2D anode in the 3L setup we designed and produced a $40x80\ cm^2$ charge readout for a new 250L LAr LEM-TPC (production and assembling finished by summer 2011)
‣The ArDM cryostat @CERN is currently being used for a first test of the new charge readout system

LEM



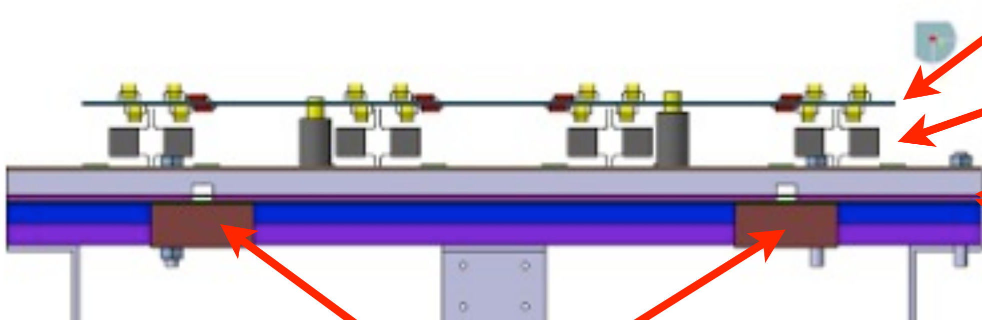
2D anode

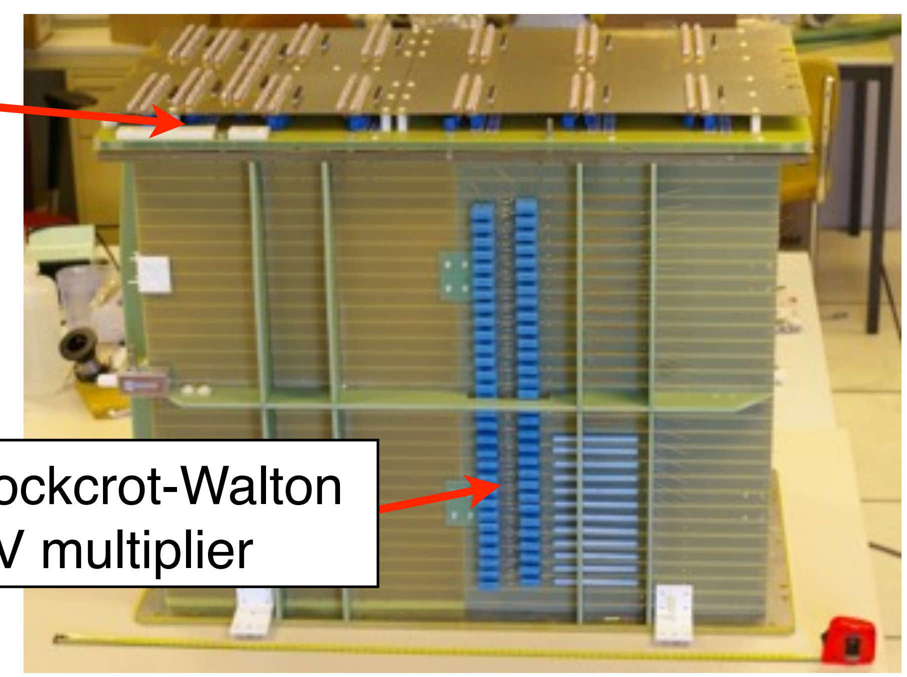




•Manufacturer: CERN TS/DEM group and ELTOS company (Italy)
•Largest LEM/THGEM and 2D readout ever produced!!!

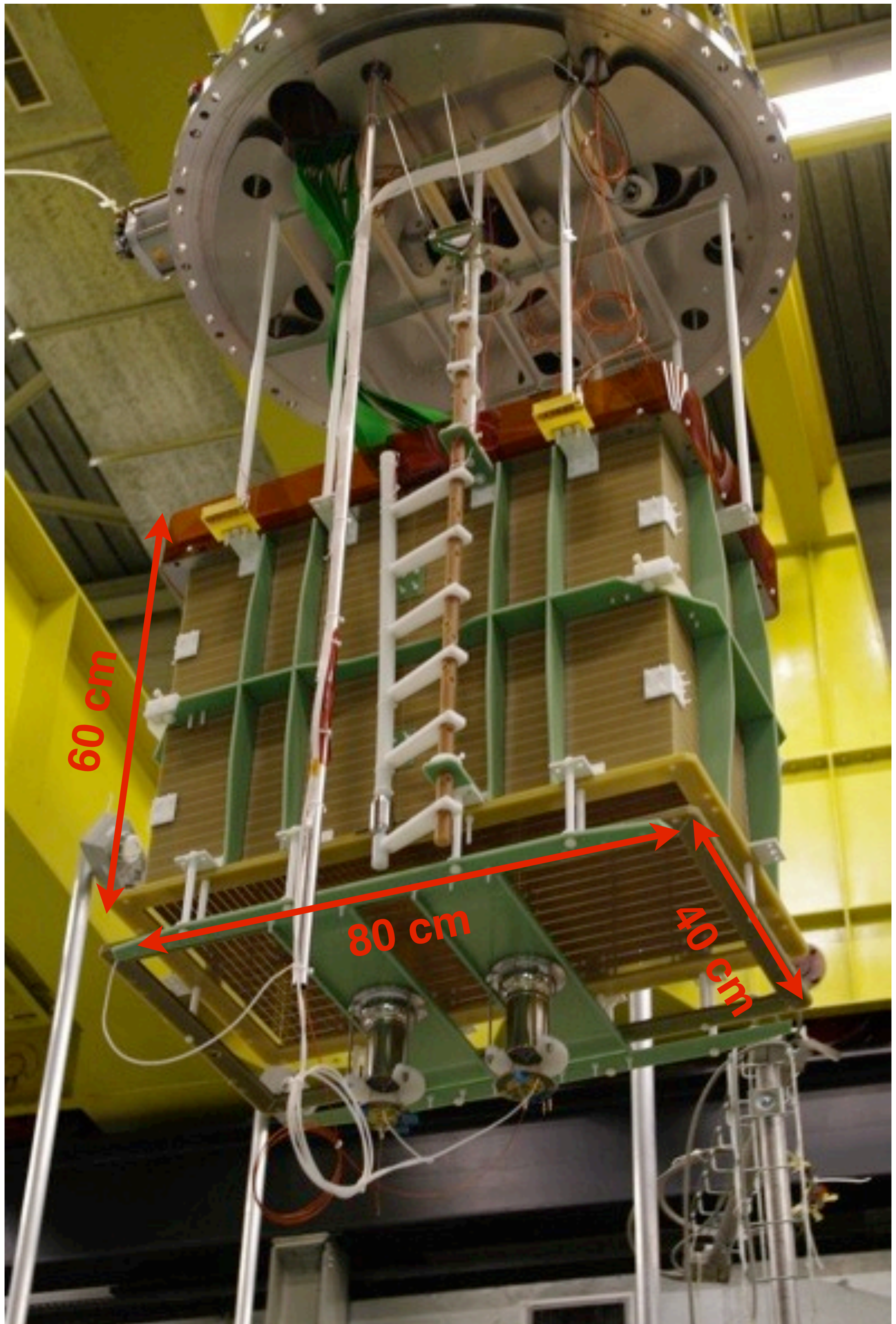
Design of a compact, robust and scalable readout cassette (“sandwich”)



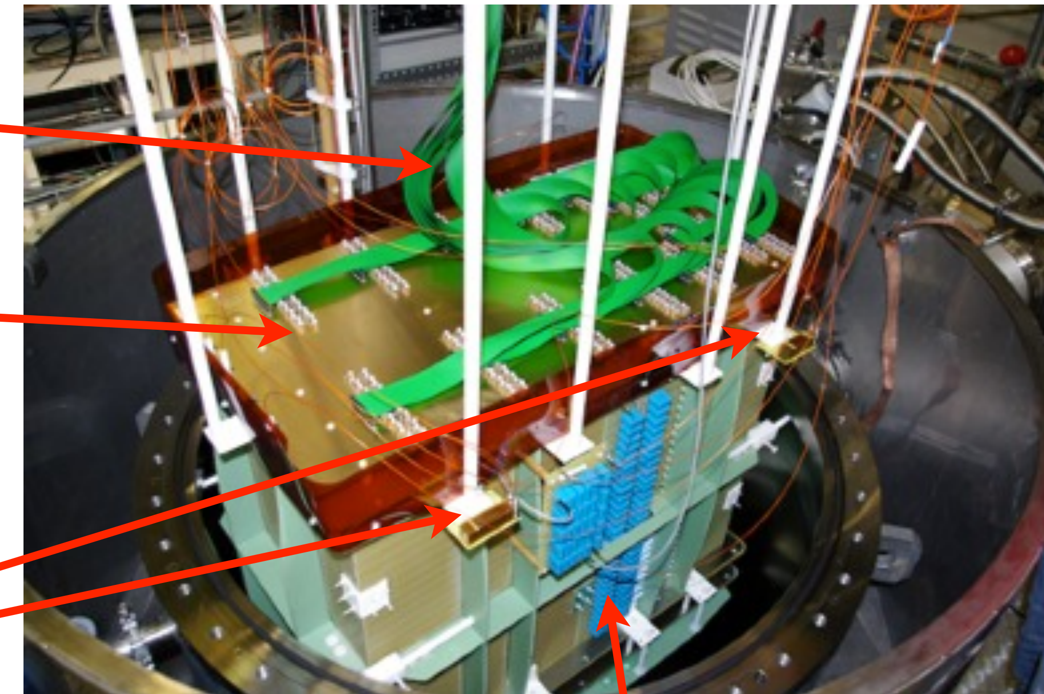


250L LAr-LEM TPC@CERN:The largest LEM-TPC

250L detector fully assembled



250L going into the ArDM cryostat



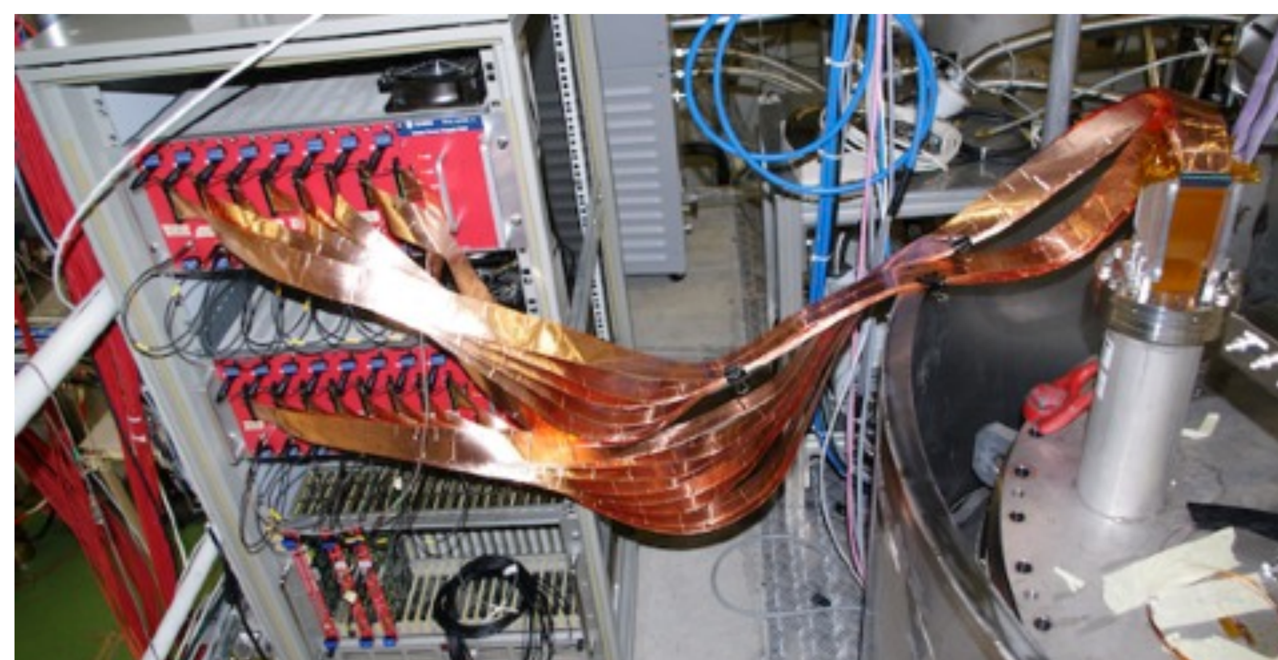
16 signal cables

charge readout sandwich

4 capacitive level meters

Cockcroft-Walton HV system

Final connection to the DAQ system



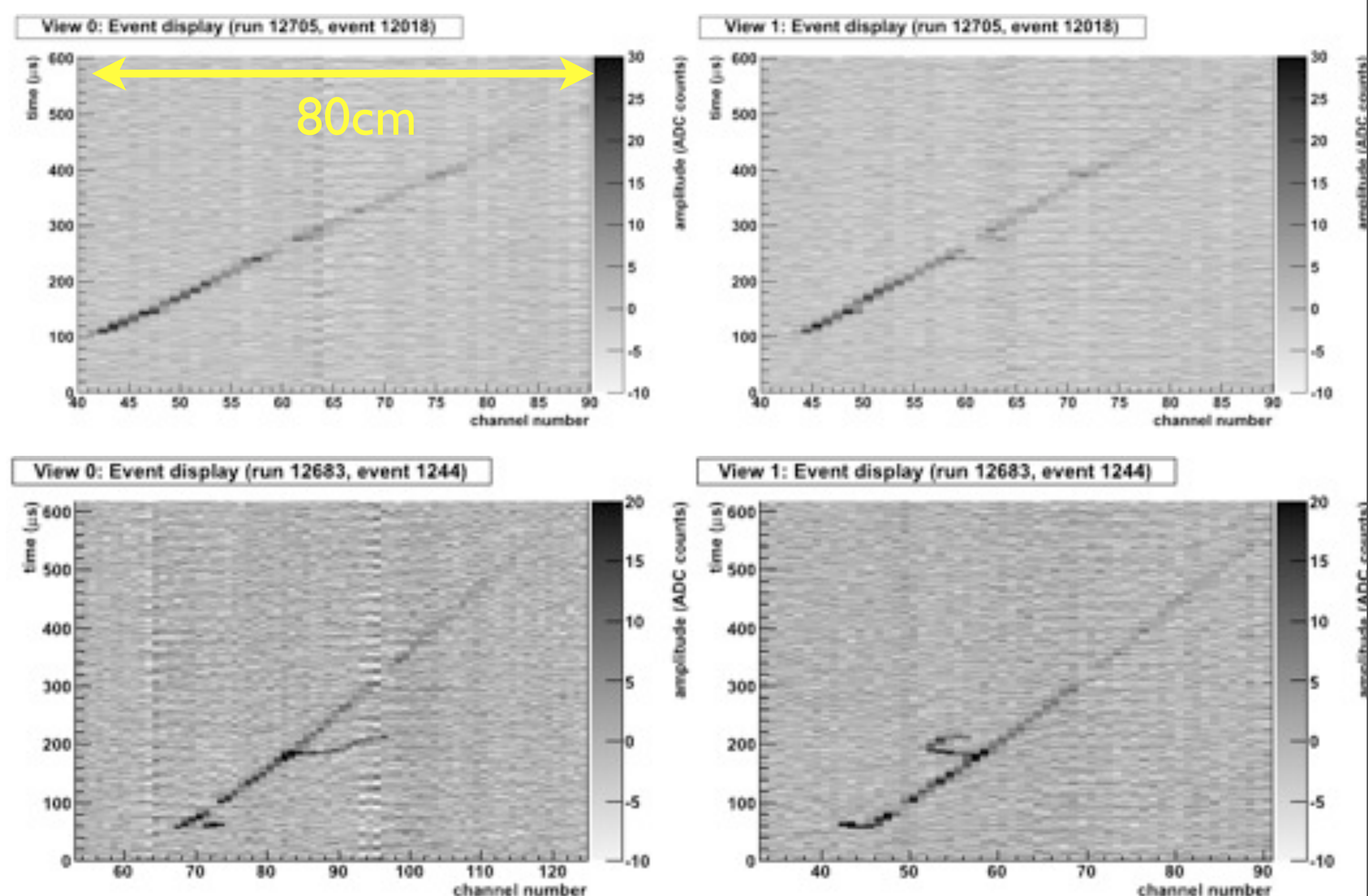
First events from the 250L LAr LEM-TPC! (very preliminary)

Procedure

1. pumping the vacuum down to ≈10^{-6} mbar
2. cool down phase (detector filled with gas being continuously purified)
3. Filling the detector up to the extraction grids

➡After a successful commissioning of the HV system we did a first test of the LEM TPC

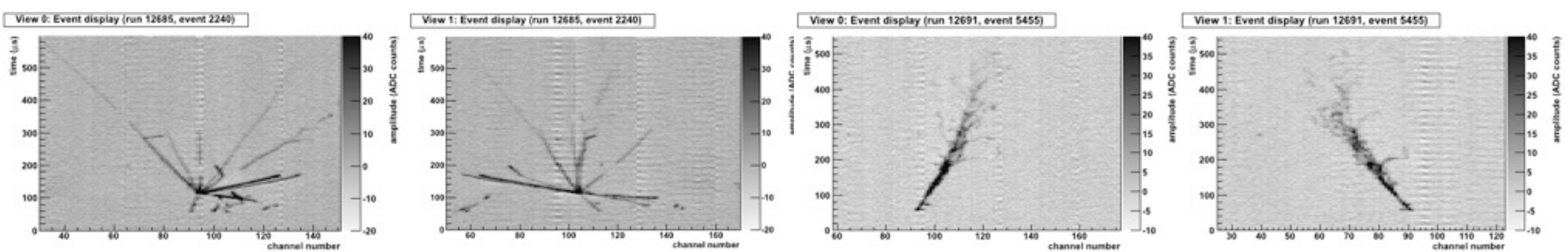
First cosmic ray triggers!



Electric field configuration

LEM-Anode	1800 V/cm
LEM	30.5-31.4 kV/cm
grid-LEM	600 V/cm
extraction	2300 V/cm
drift	200 V/cm

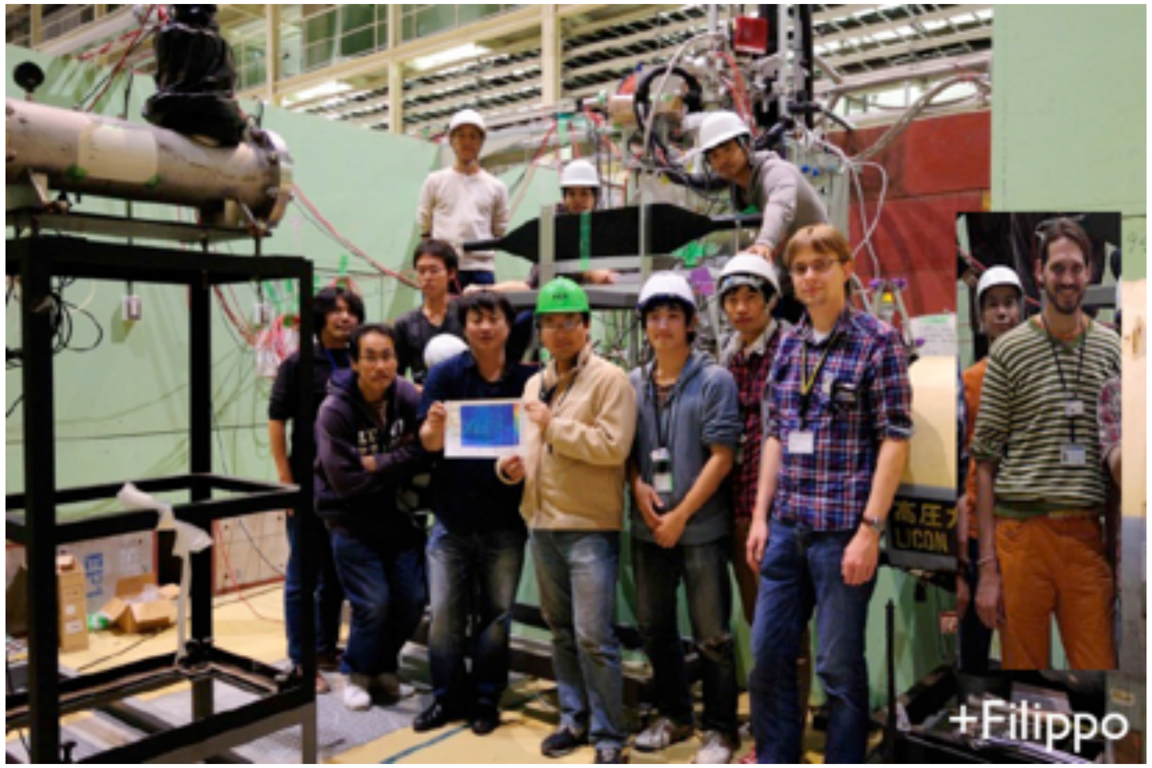
sometimes...

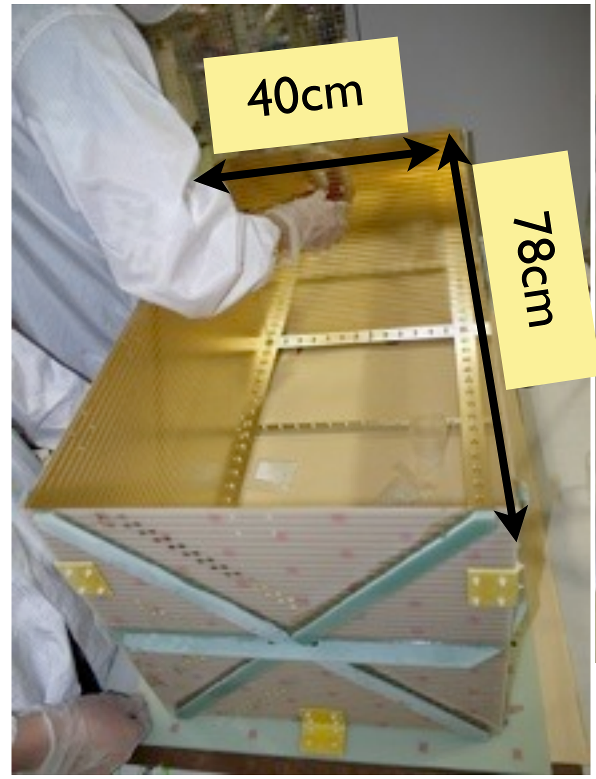


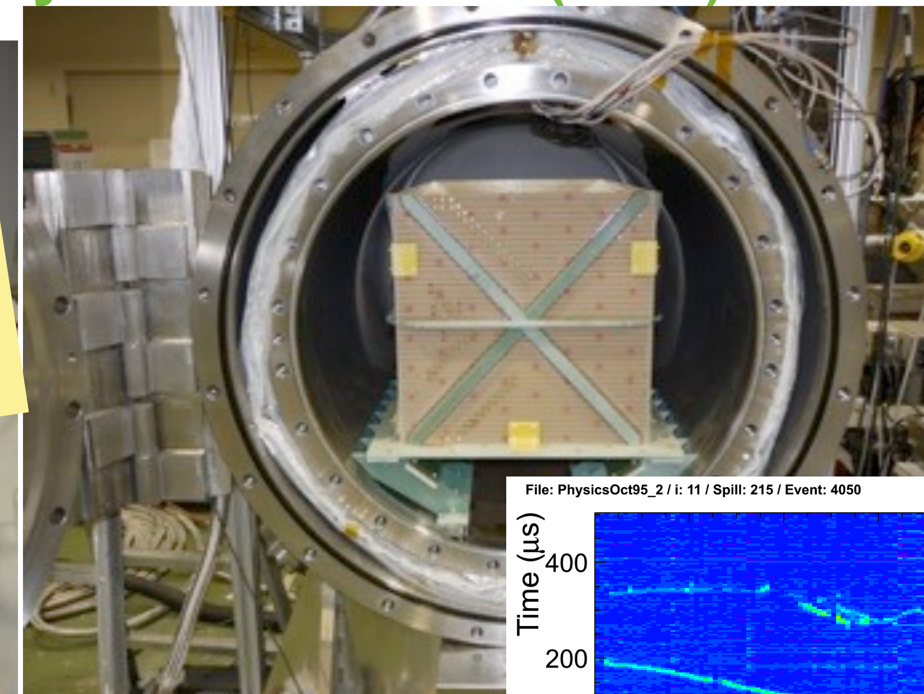
First results from the P32 beam test at JPARC

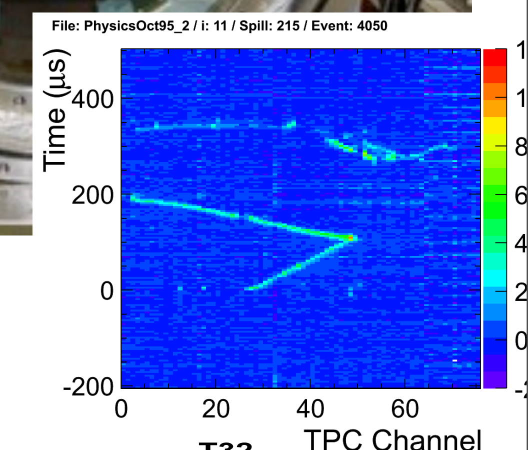
O. Araoka, J.Phys.Conf.Ser. 308 (2011) 012008

First beam event (Oct 2010)



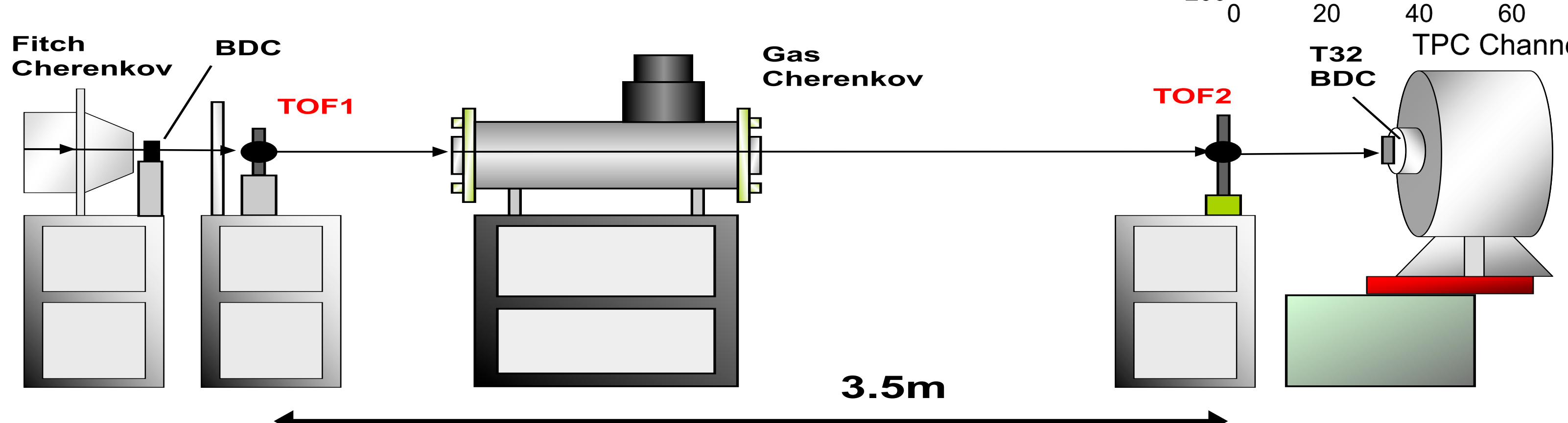




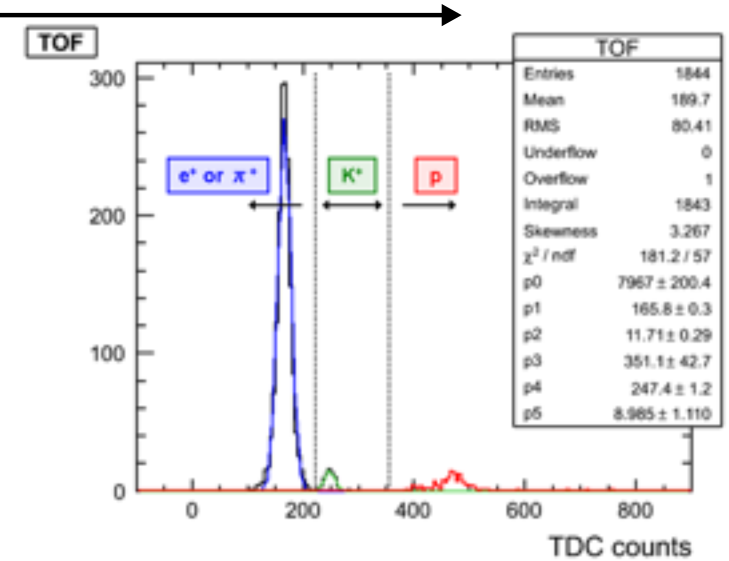


- for the first time ever a LAr-TPC was operated in a tagged charged particle beam
- momentum scale relevant for proton decay studies
- more than 200’000 K^+,π^+,e^+ and proton events acquired

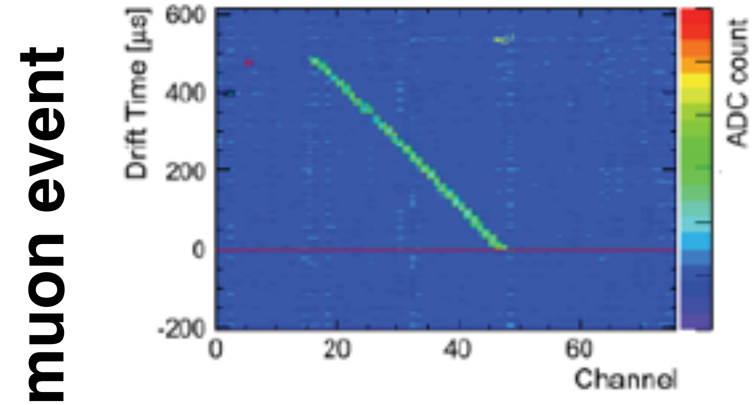
➡ largest amount of K+ events detected with a LAr TPC

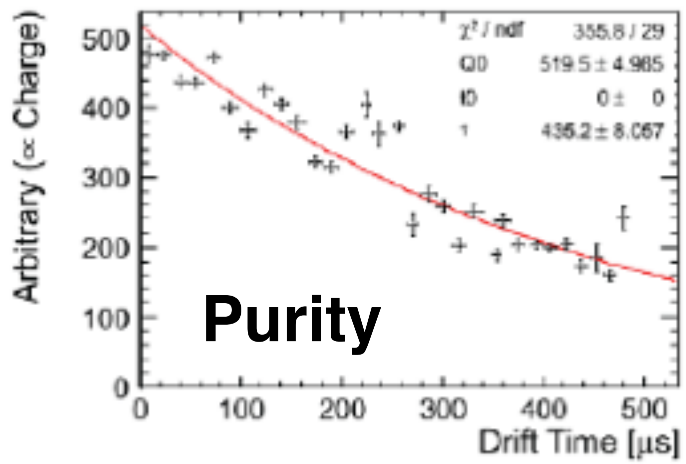


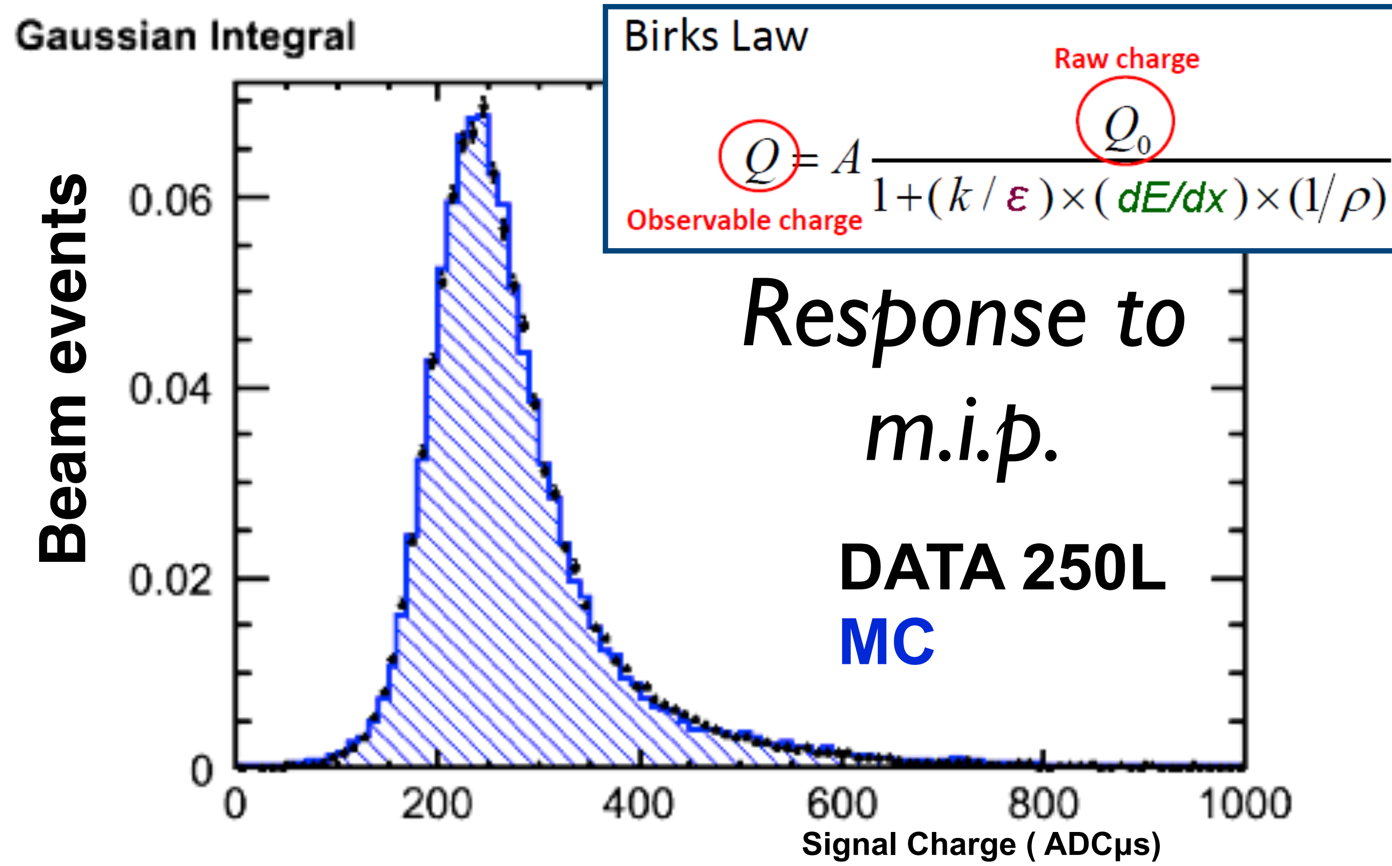
- **External PID power from TOF + Cerenkov equipment is providing ~100% pure K before the degrader(s).**

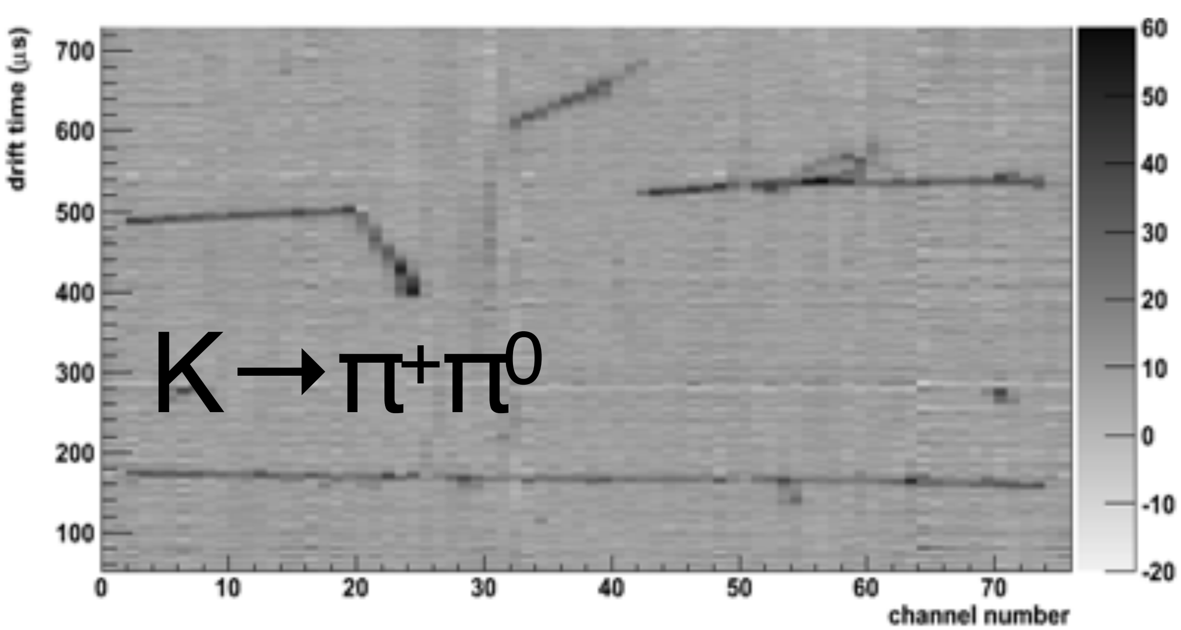


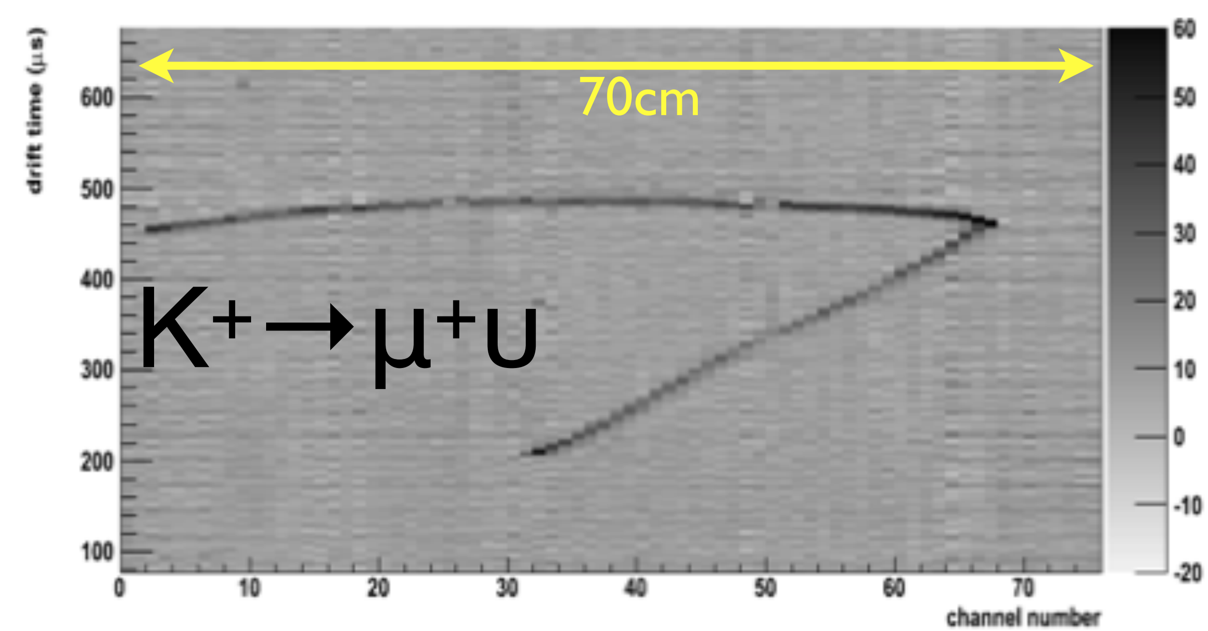
Gallery of events from P32 @ J-PARC







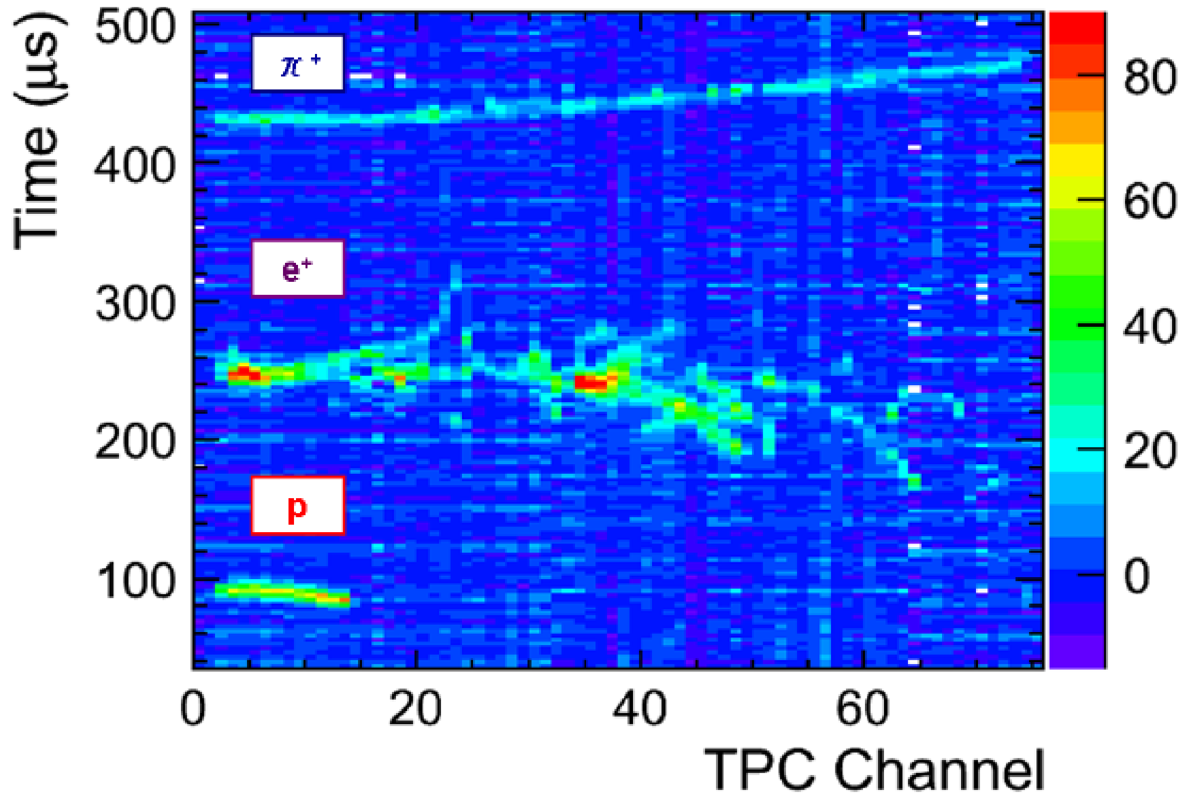




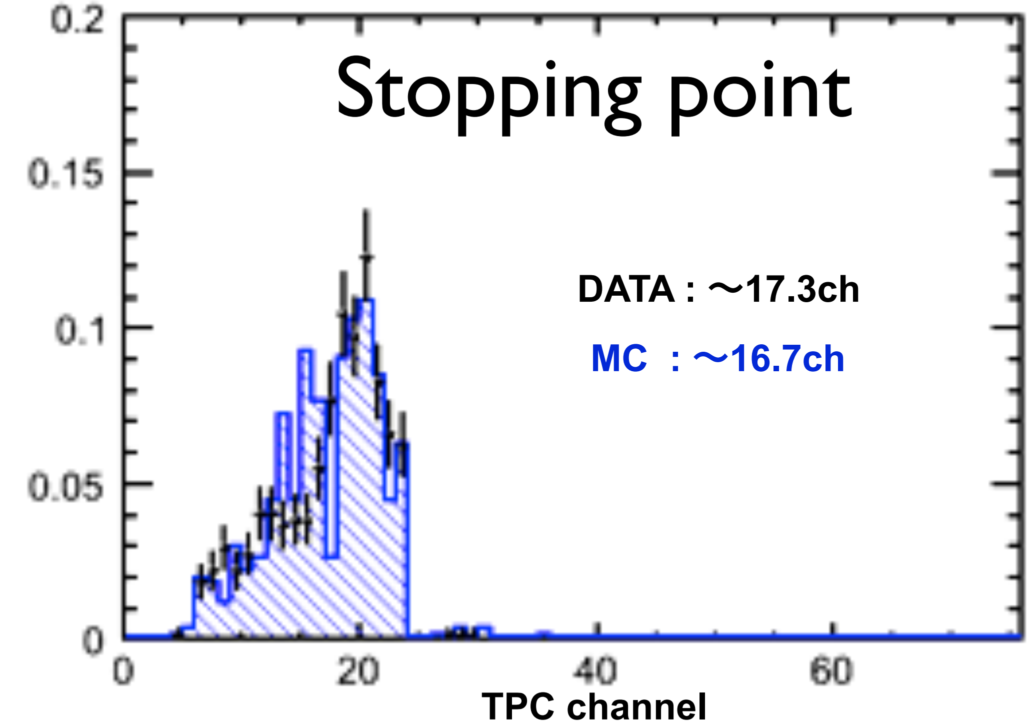
- strength of the LAr-TPC in PID obvious (even with 1D readout, coarse pitch, noise)
- **but:** flawless reconstruction requires excellent signal to noise ratio, as can be obtained with the double phase readout with adjustable gain

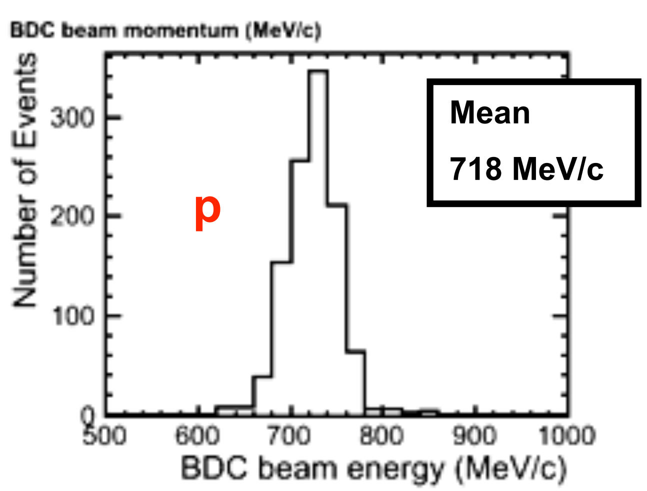
Proton sample reconstruction + analysis

PRELIMINARY



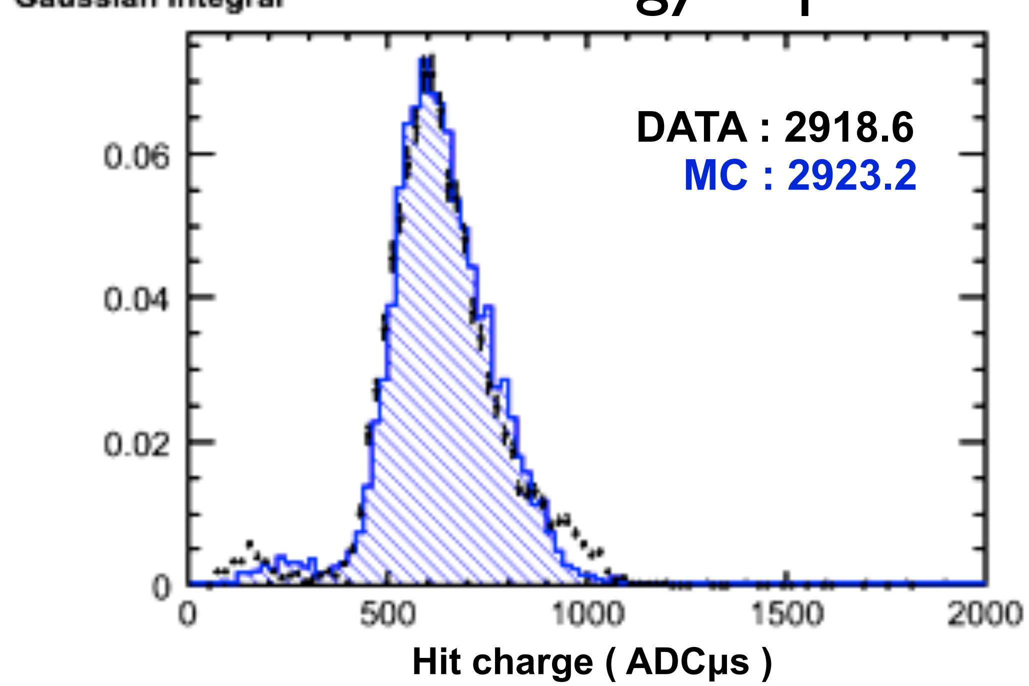
Stopping point



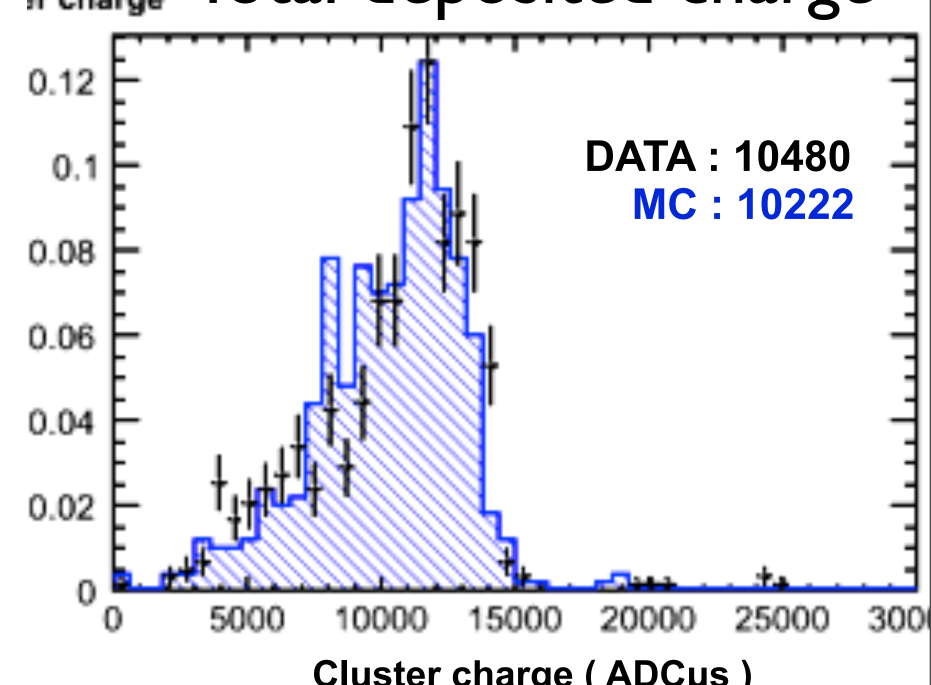


Momentum measured with TOF

Local energy deposit



Total deposited charge



- proton sample shows good agreement between Data and MC – detailed analysis of local energy deposition as a function of stopping point on-going
- **similar results for kaon (analysis still on-going)**

Liquid Scintillator (LScint)

Very high purity liquid scintillator with high light yield, optimized for lowest energy range (large size: KamLAND, Borexino, SNO+, etc.)

ideally matched to study low energy neutrinos (MeV) with high statistics

LENA (LAGUNA LScint option)
4200 mwe

Liquid scintillator
50 kt LAB/PPO+ bisMSB

Inner vessel (nylon)
Radius r = 13m

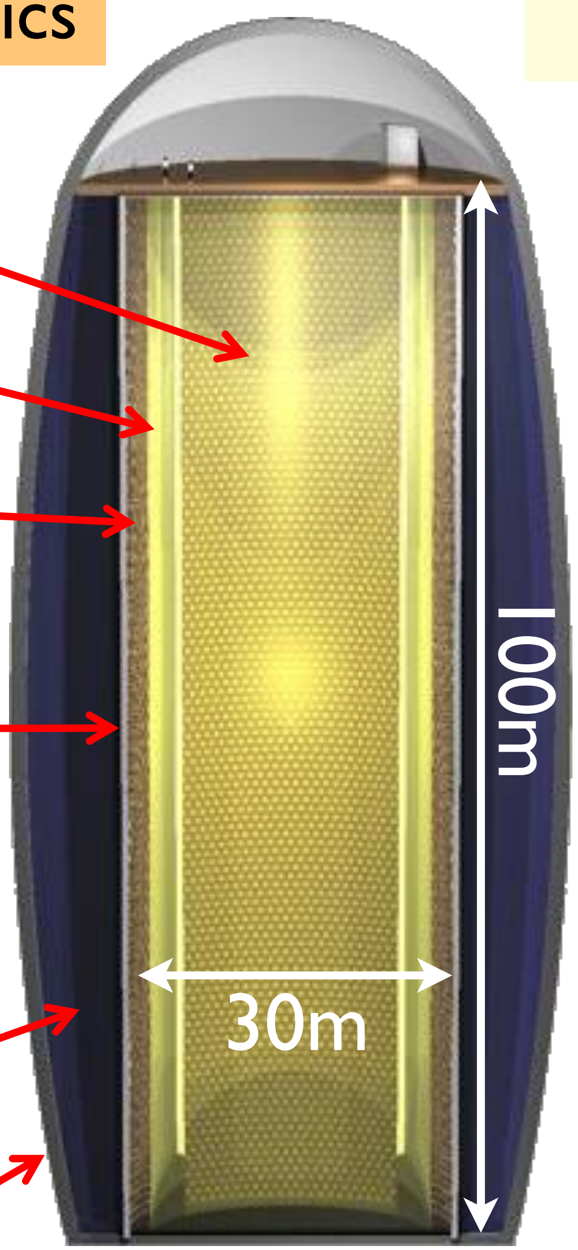
Buffer
15kt LAB, Δr =2m

Cylindrical steel tank, e.g. 55000 PMTs (8") with Winston Cones (2x area)
r = 15m, height = 100m,
optical coverage: 30%

Water cherenkov muon veto
5,000 PMTs, Δr > 2m to shield fast neutrons

Cavern egg-shaped for increased stability

Rock overburden: 4000 mwe



Pyhäsalmi design

Desired **energy resolution**
→ 30% optical coverage
→ 3000m² effective photo-sensitive area

Light yield ≥ 200 pe/MeV

The **tracking option** adds to the requirements of the PMT array and electronics:
→ more, but smaller, faster PMTs
→ full waveform digitizing

response to high energy neutrino beam under study

The standard picture of three neutrino mixing

- flavor oscillation described by PNMS matrix
- parametrized by 3 mixing angles and CP-violating phase δ_{CP}

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

"atmospheric sector"

θ_{23}

$\lvert\Delta m^2_{31}\rvert$	$(2.40^{+0.12}_{-0.11})\ 10^{-3}\ \mathrm{eV}^2$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$

θ_{13}

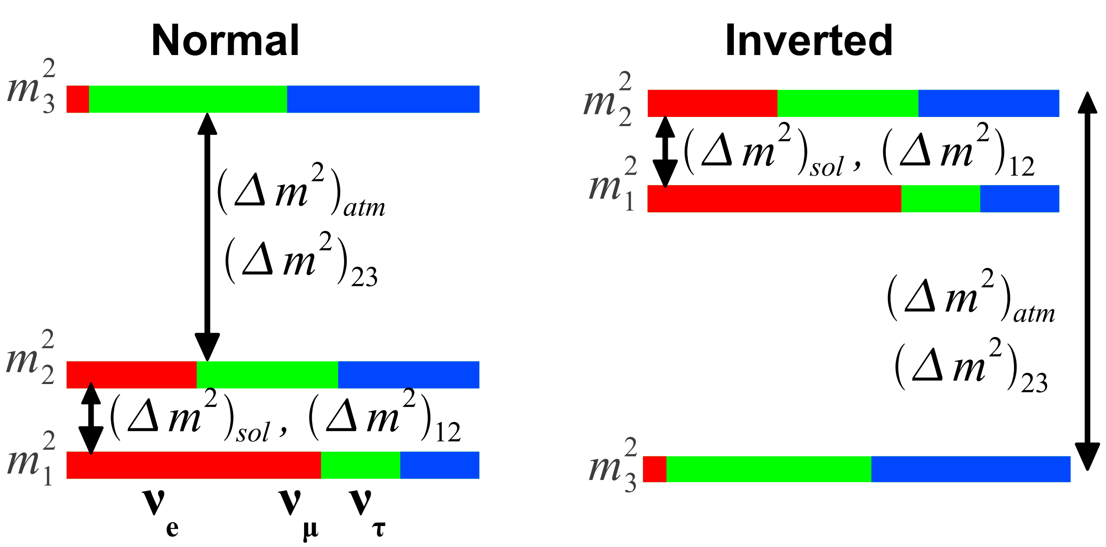
new

$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$

"solar sector"

θ_{12}

Δm^2_{21}	$(7.65^{+0.23}_{-0.20})\ 10^{-5}\ \mathrm{eV}^2$
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$



Most urgent points:

- $\sin^2 2\theta_{13} > 0.01$ at >5σ significance ?
- Mass hierarchy $\Delta m_{31}^2>0$?, $\Delta m_{31}^2<0$?
- CP-phase $\delta \neq 0$, π at >3σ significance, δ true ?
- Unitarity ? tri-bimaximal ? differences between quark and lepton sectors ?

The standard picture of three neutrino mixing

Very impressive progress in the last decade !

- ...scillation described by PNMS matrix
- ...zed by 3 mixing angles and CP-violating phase δ_{CP}

$$\begin{pmatrix} \cdot & 0 \\ \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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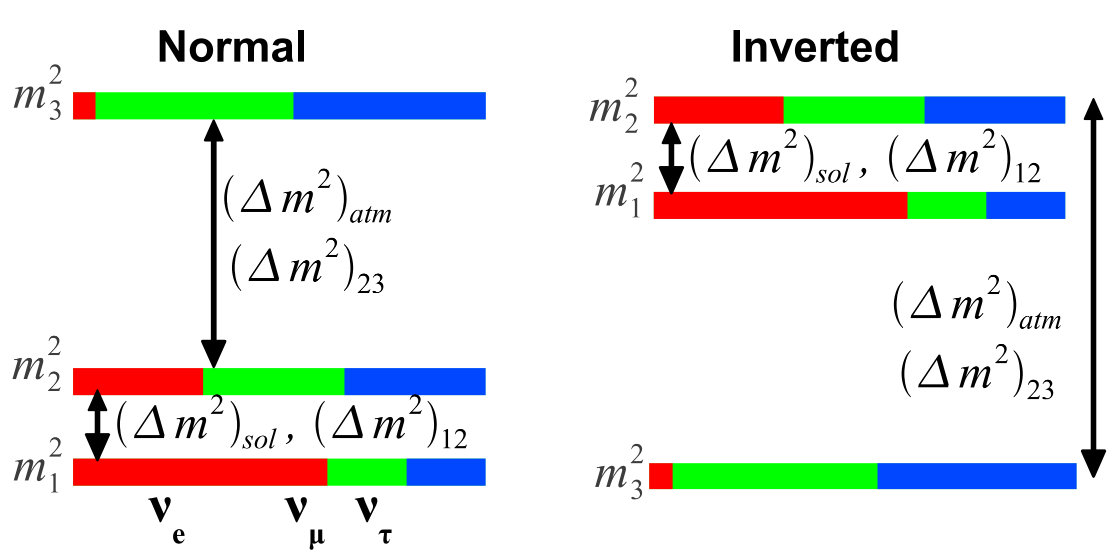

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LAGUNA-LBNO accelerator-driven physics program

- **Standard oscillation phenomenology via precise measurement of muon disappearance, electron appearance and possibly tau appearance**
  - ➡ fix **neutrino mass hierarchy** (>3σ CL for any value of δ_{CP})
    - → input to CP-violation searches and Dirac/Majorana nature with ββ0ν
  - ➡ find **CP-violation in the lepton sector** ($\delta_{CP} \neq 0,\pi$ at >3σ CL) and measure δ_{CP}
  - ➡ determine all PMNS matrix elements w/ errors on θ's < 5%, and mass differences w/ errors on Δm^2 < 1%
  - ➡ **test PMNS picture with neutrinos and antineutrinos** → search for deviations

- **Non-Standard oscillation phenomenology at long baseline**
  - ➡ search for oscillation into **"sterile" states** (e.g. NC/CC)
  - ➡ tests for non standard matter effects or interactions (e.g. NSI)
  - ➡ test of PMNS matrix unitarity

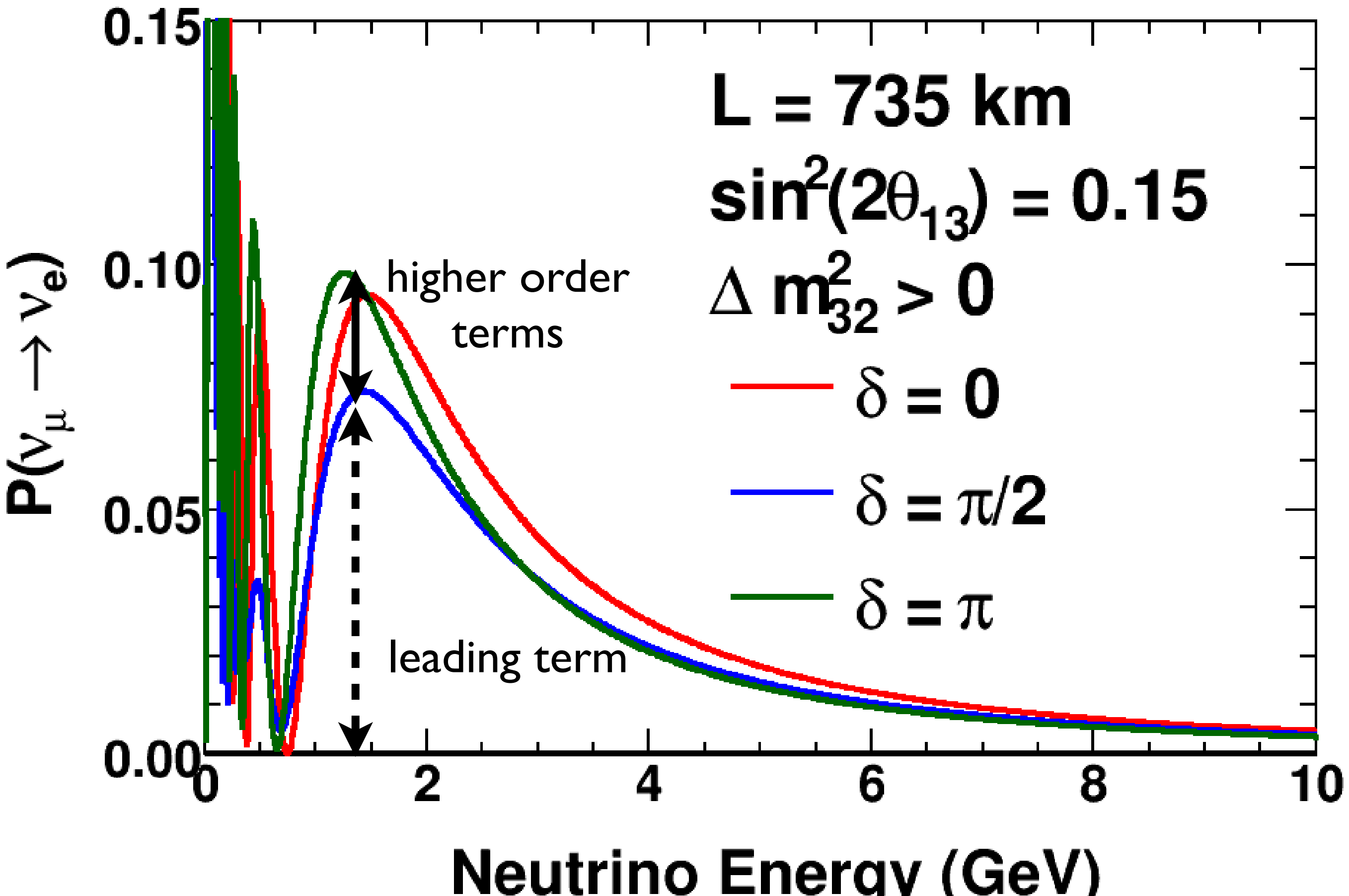
- **Neutrino TOF and velocity measurements at long baseline**

Let's focus on higher order terms in electron appearance

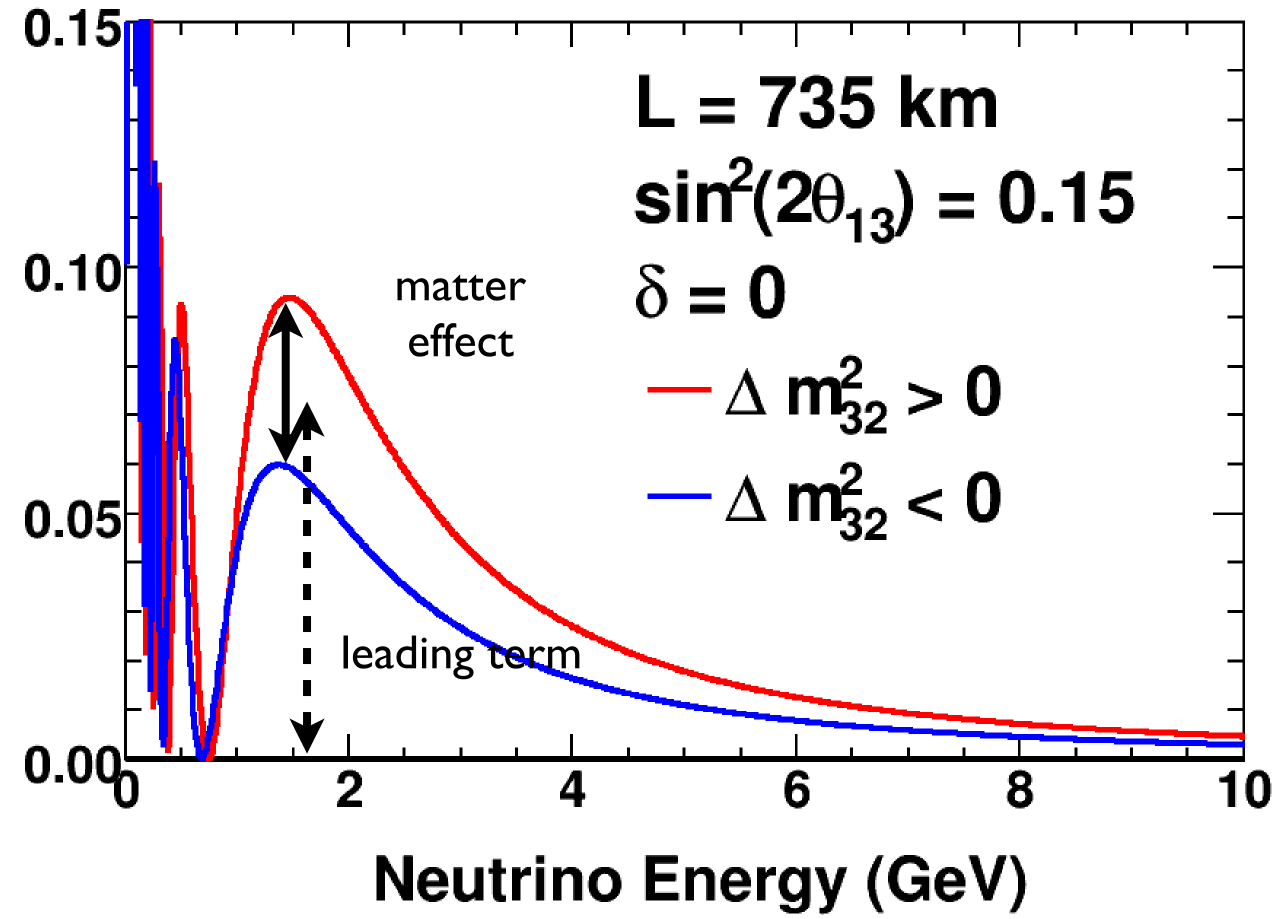
Next step: νe appearance in a νμ beam <u>with high precision</u> to determine the matter effects and to test higher order terms that depend on δ_{CP}

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

δ dependence



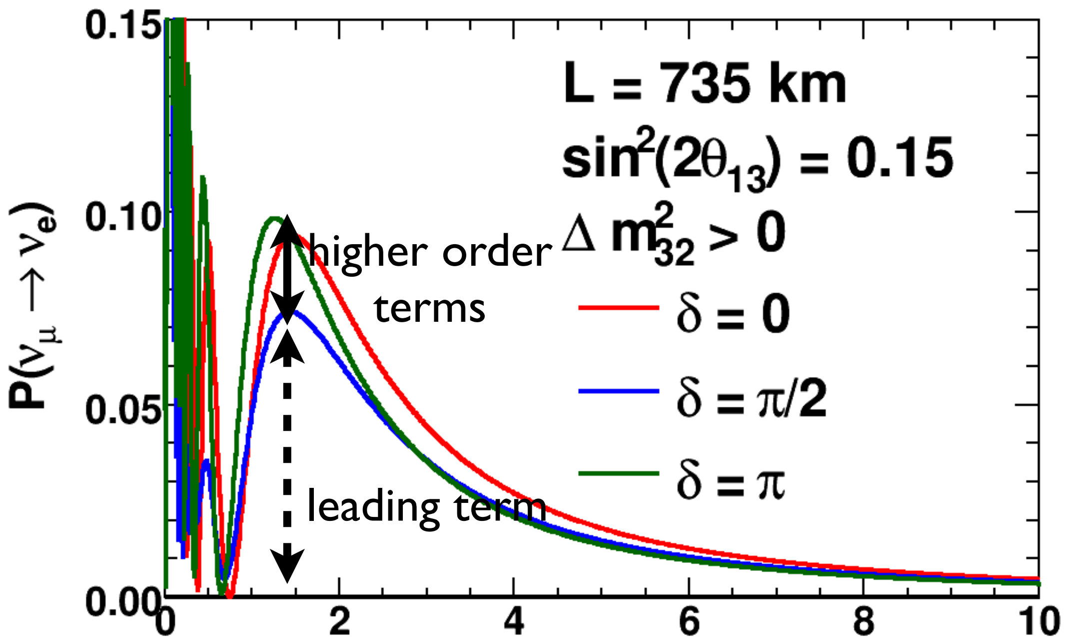
mass hierarchy dependence

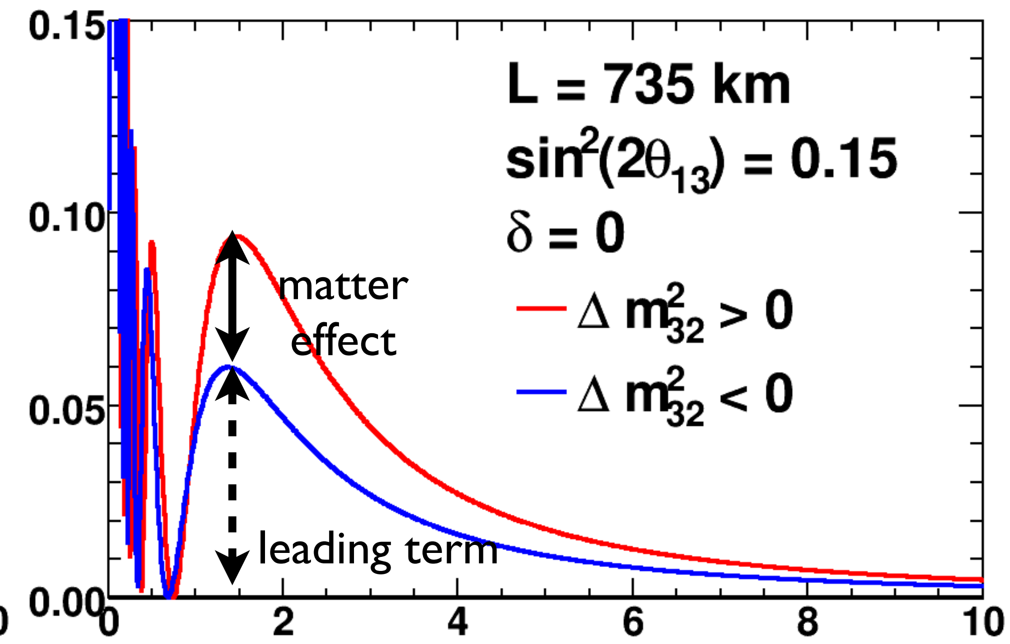


Courtesy: L.Whitehead

Measuring the higher order terms in electron appearance

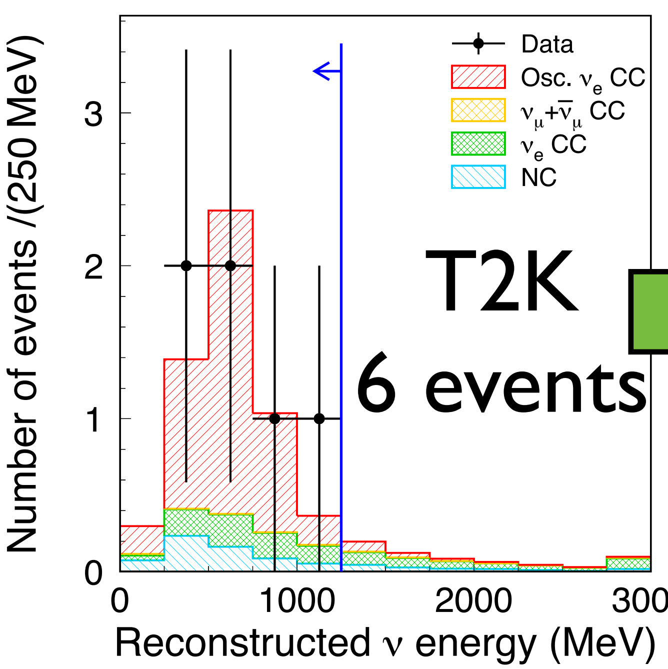
δ_{CP} dependence



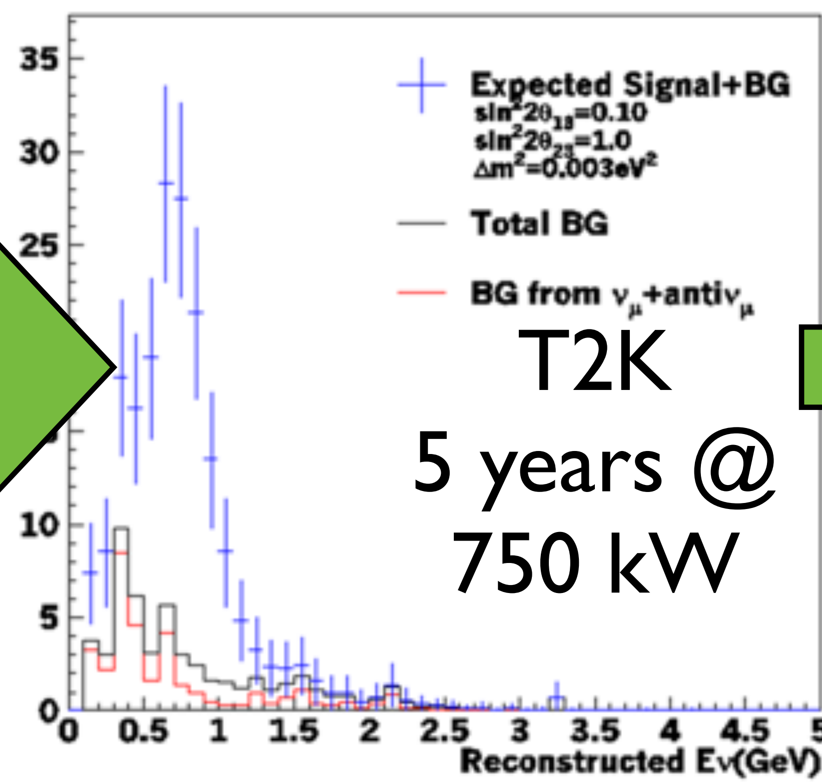


Mass hierarchy dependence

Courtesy: L.Whitehead



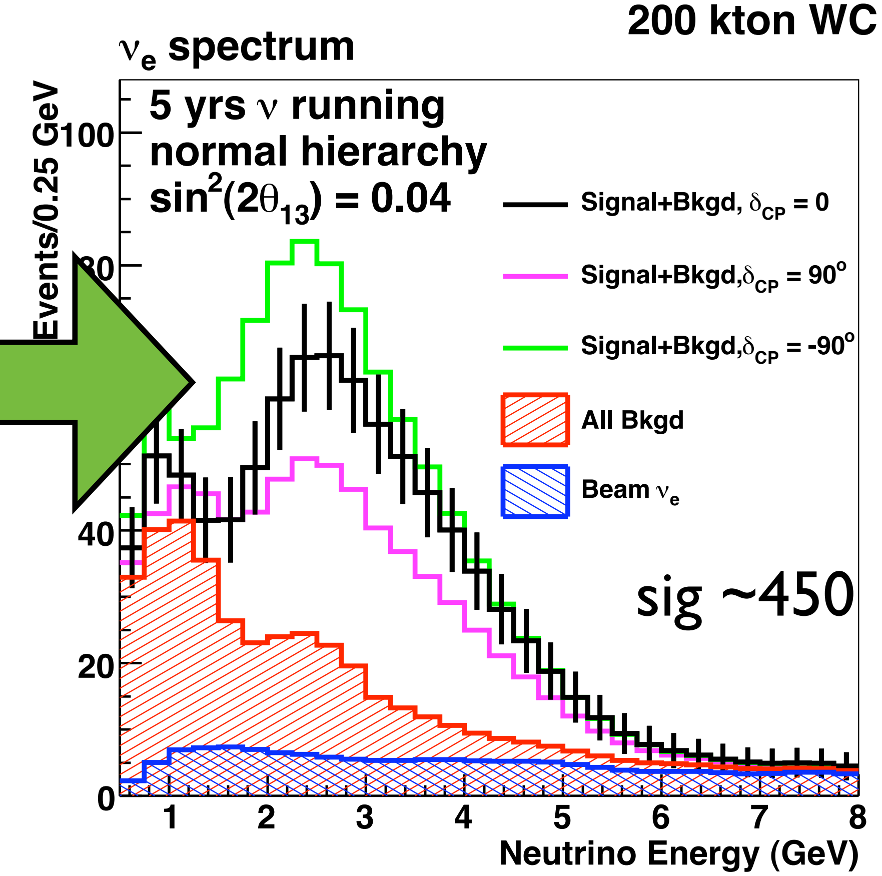
T2K
6 events



T2K
5 years @ 750 kW

+NOvA

200 kton WC



sig ~450

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

Approximate formula (M. Freund)

quadratic dep. on θ_{13}

matter effect ~E

~7500 km magic bln

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

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

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

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

CPV term approximate dependence ~L/E

~2540 km magic bln

solar term

linear dep. on θ_{13}

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

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

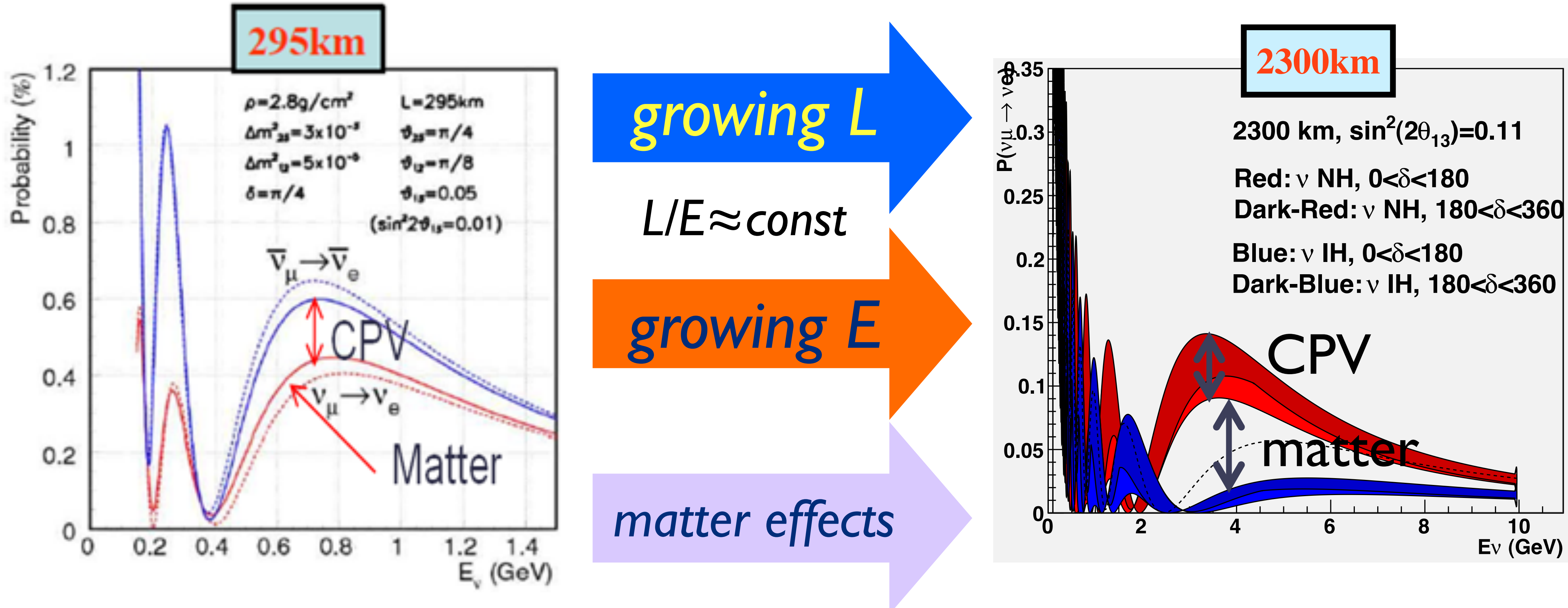
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

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

CP asymmetry grows as θ_{13} becomes smaller !

Correlations !

Different approaches to the problem



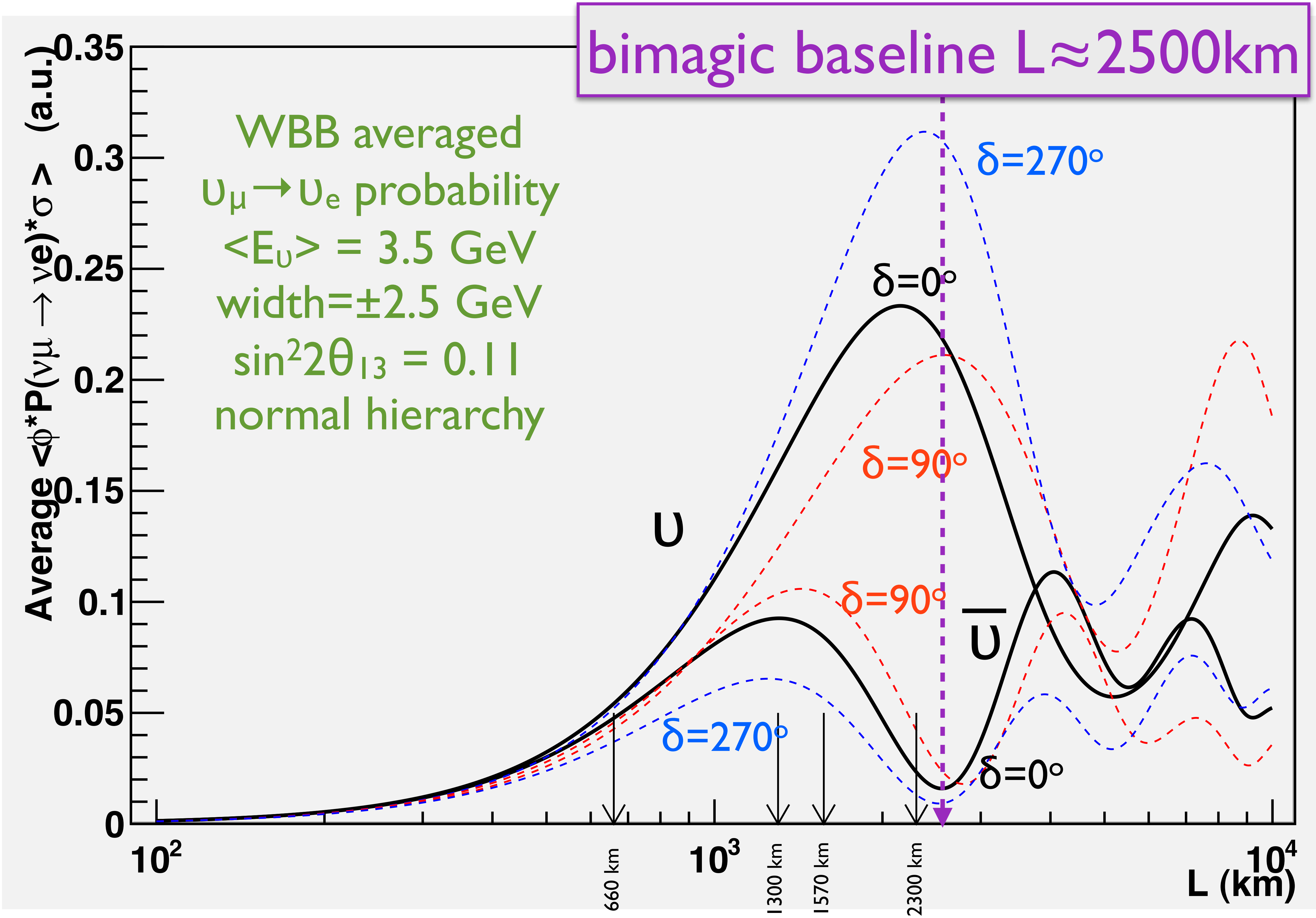
- Two main modes of investigation (or a combination of both)
  - ☑ **ν_e Appearance Energy Spectrum Shape in Wide Band Beam (WBB) at fixed L**
    - Peak position and height for 1st, 2nd maximum and minimum
    - Sensitive to all the non-vanishing δ including 180°
    - Investigate CP phase with ν run 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

Overview of preferred options presently considered worldwide

	Proton driver	Baseline L	Detector / Fiducial mass	Method
LAGUNA Fréjus	CERN SPL 4MW ?	130 km	WC 440kt	$\nu/\bar{\nu}$ asymmetry
J-PARC-Kamioka	J-PARC MR (1.66MW ?)	295 km	WC 540kt (HyperK)	$\nu/\bar{\nu}$ asymmetry
J-PARC-Okinoshima	J-PARC MR (1.66MW ?)	658 km	LAr 100 kt	WBB
LBNE	FNAL MI 750kW (2.3MW ProjectX ?)	1300 km	WC 200kt or LAr 34kt (*)	WBB
LAGUNA Slanic (**)	CERN SPS 750kW (1.6MW HP-PS ?)	1570 km	LAr 100 kt	WBB
LAGUNA Pyhäsalmi	CERN SPS 750kW (1.6MW HP-PS ?)	2300 km	LAr 100 kt and LSc 50 kt	WBB

(*) LBNE plans technology choice by end 2011
(**) Slanic site only allows for shallow depth (300mwe)

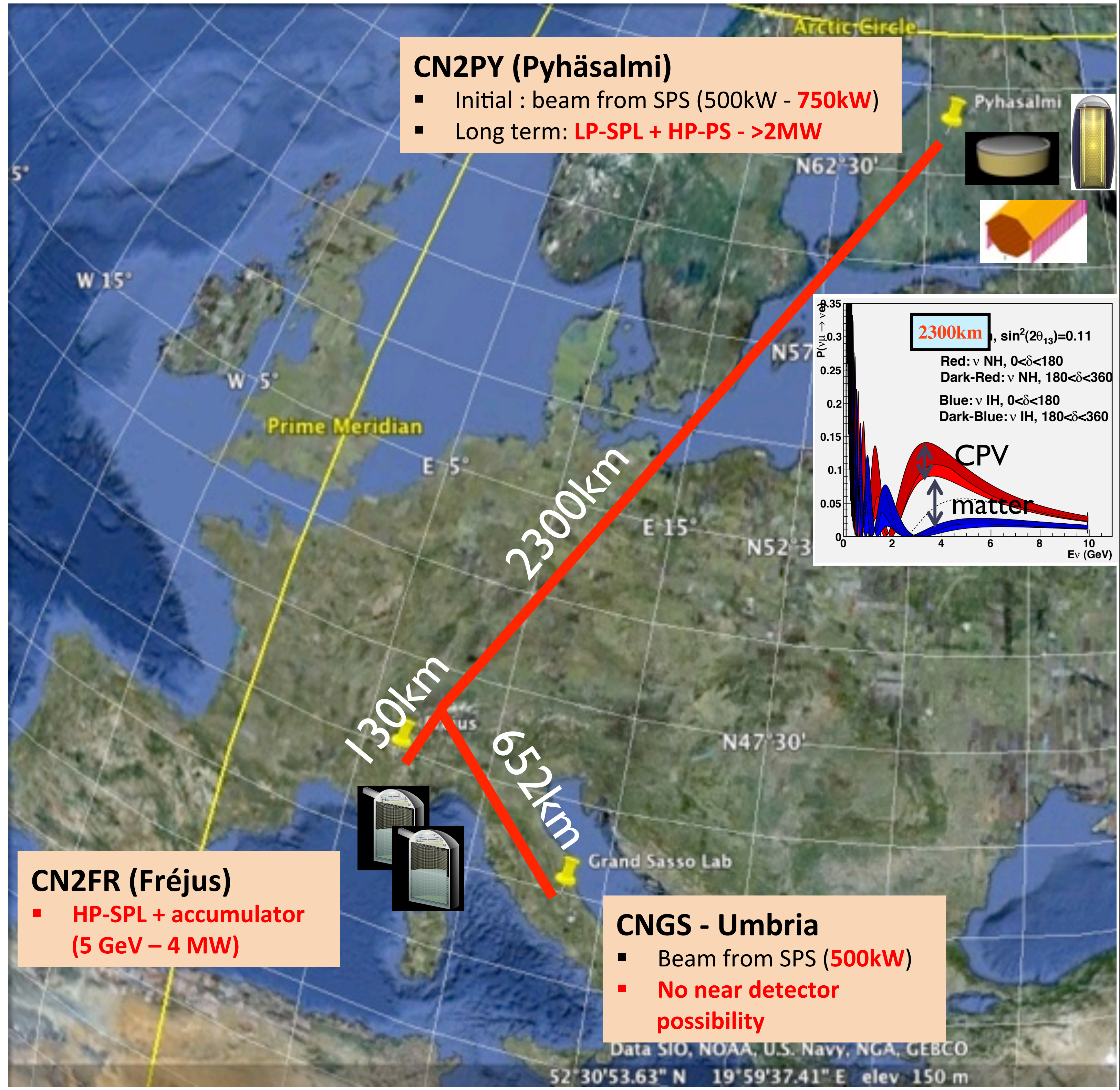
Baseline consideration and mass hierarchy



The optimal baselines are in the range 1300-2500 km

Preparing the LAGUNA-LBNO input to the European Strategy: global view

- Seven different sites were studied in details to assess their ability to host large underground detector (LAGUNA, 2008-2011)
- This design study phase has converged in a prioritization towards **three far sites** which could also be offer very unique opportunities for long baseline physics (LAGUNA-LBNO, 2011-2014)
- **CERN-Fréjus** is a short baseline coupled to the **WCD detector**. It offers good synergy for enhanced physics reach with β-beam at γ=100
- **CERN-Pyhäsalmi** is the longest baseline and is coupled to a **LArTPC, possibly coupled to a magnetized muon ranger**. It offers good synergy for enhanced physics reach with a neutrino factory (NF). In addition, Pyhäsalmi is an adequate site for a large **LSc** with lowest reactor neutrinos background in Europe.
- [**CERN-Umbria** has an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]
- Other LAGUNA sites could serve as alternative options.



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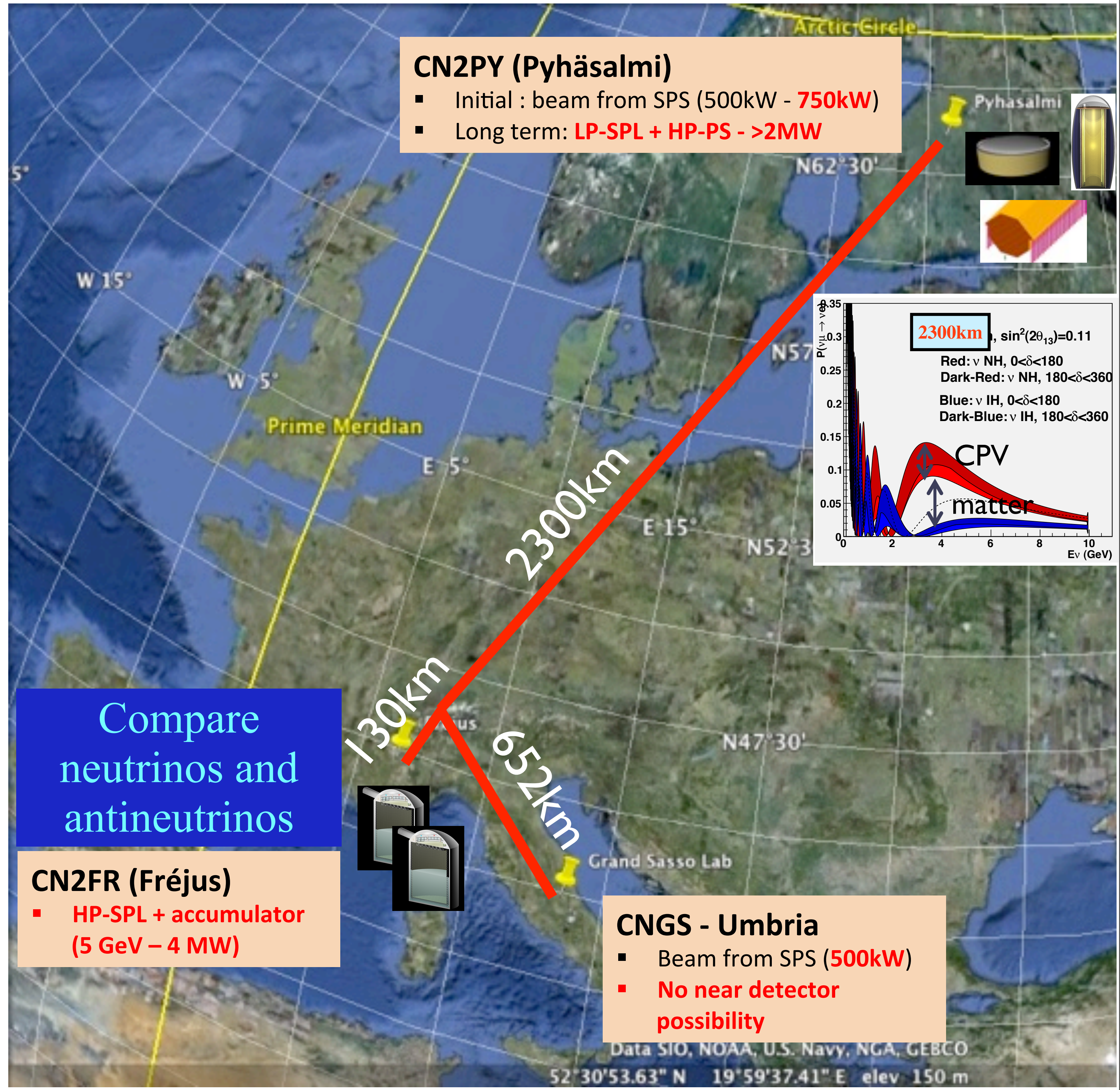

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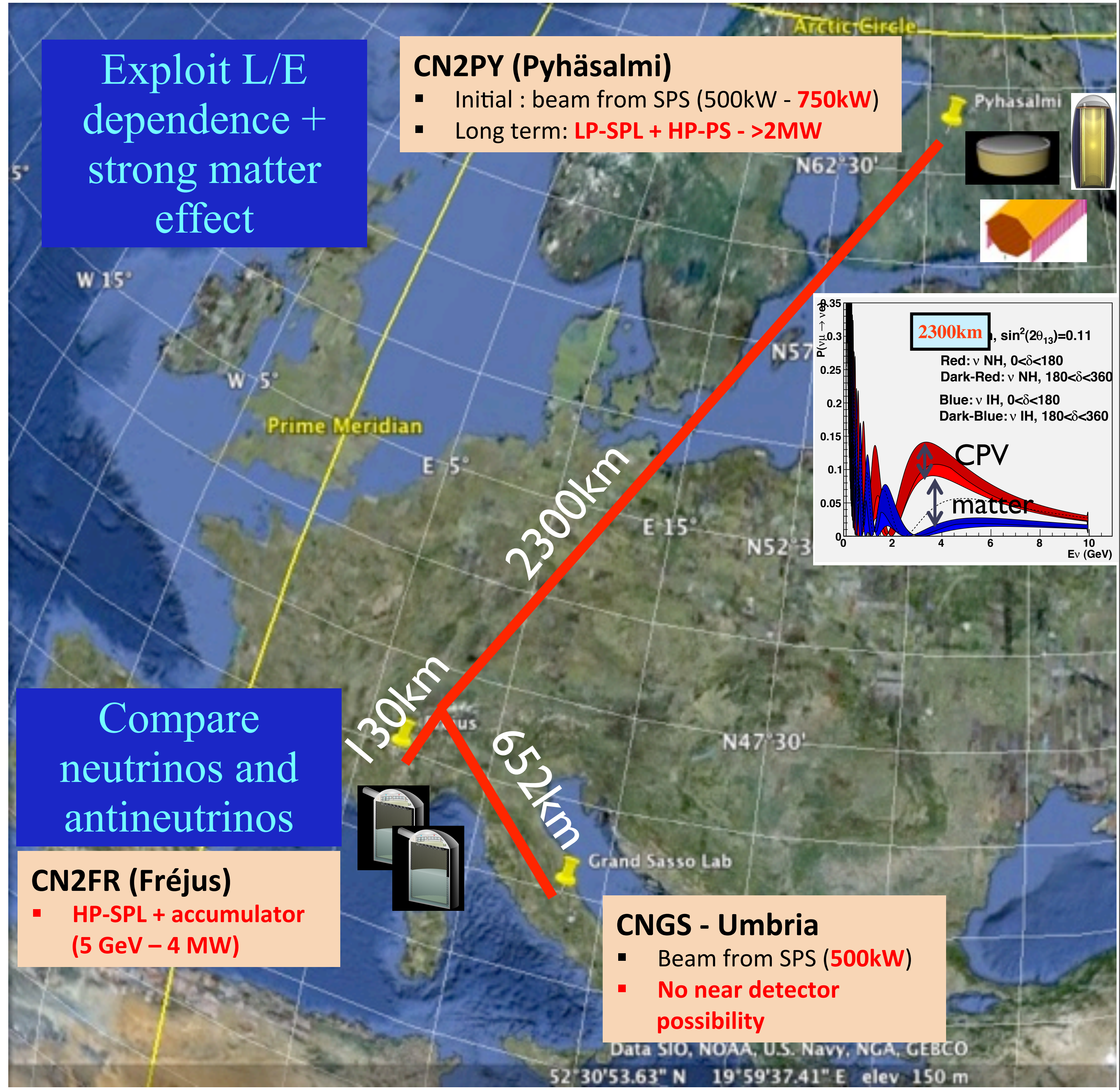

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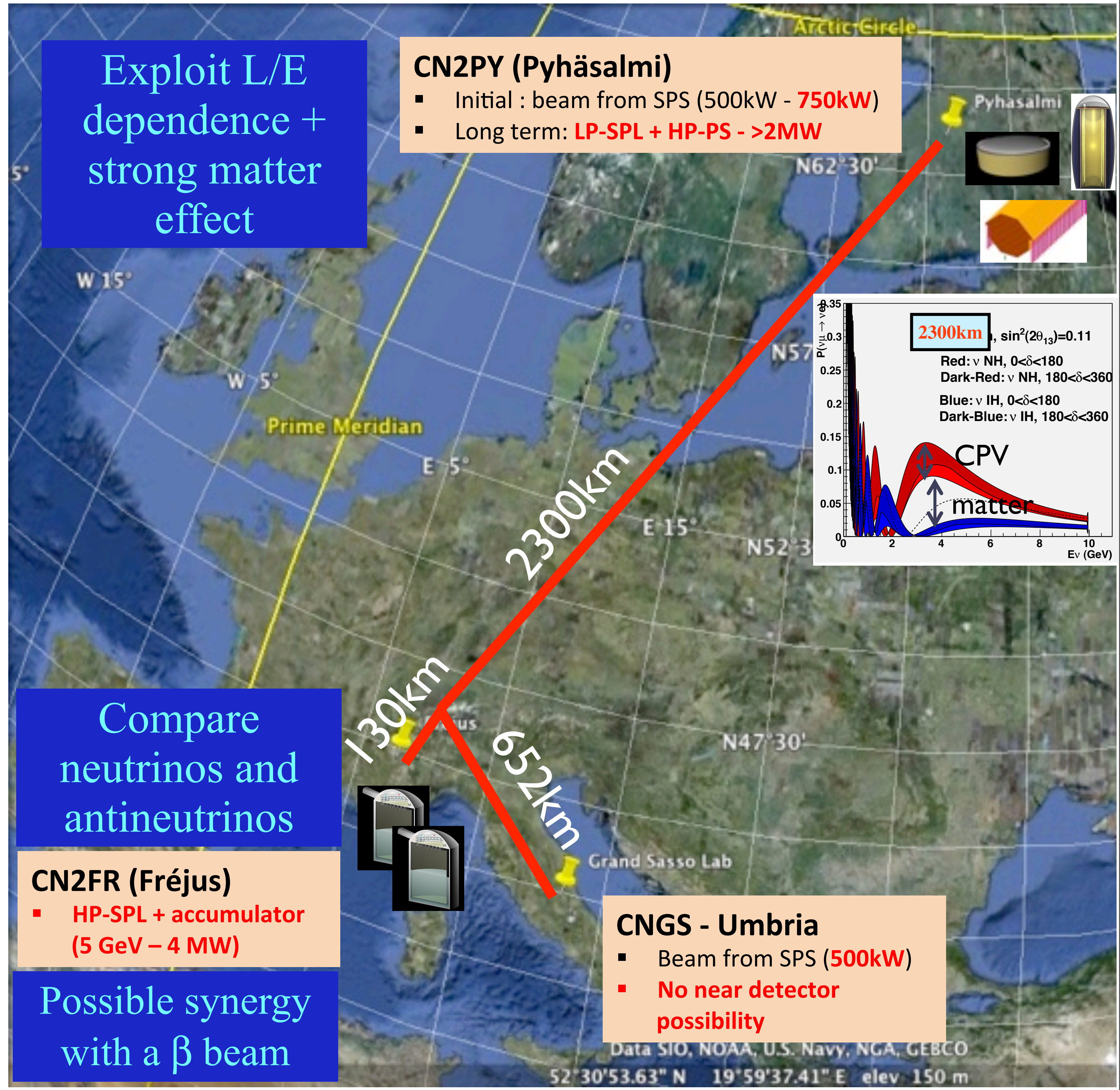

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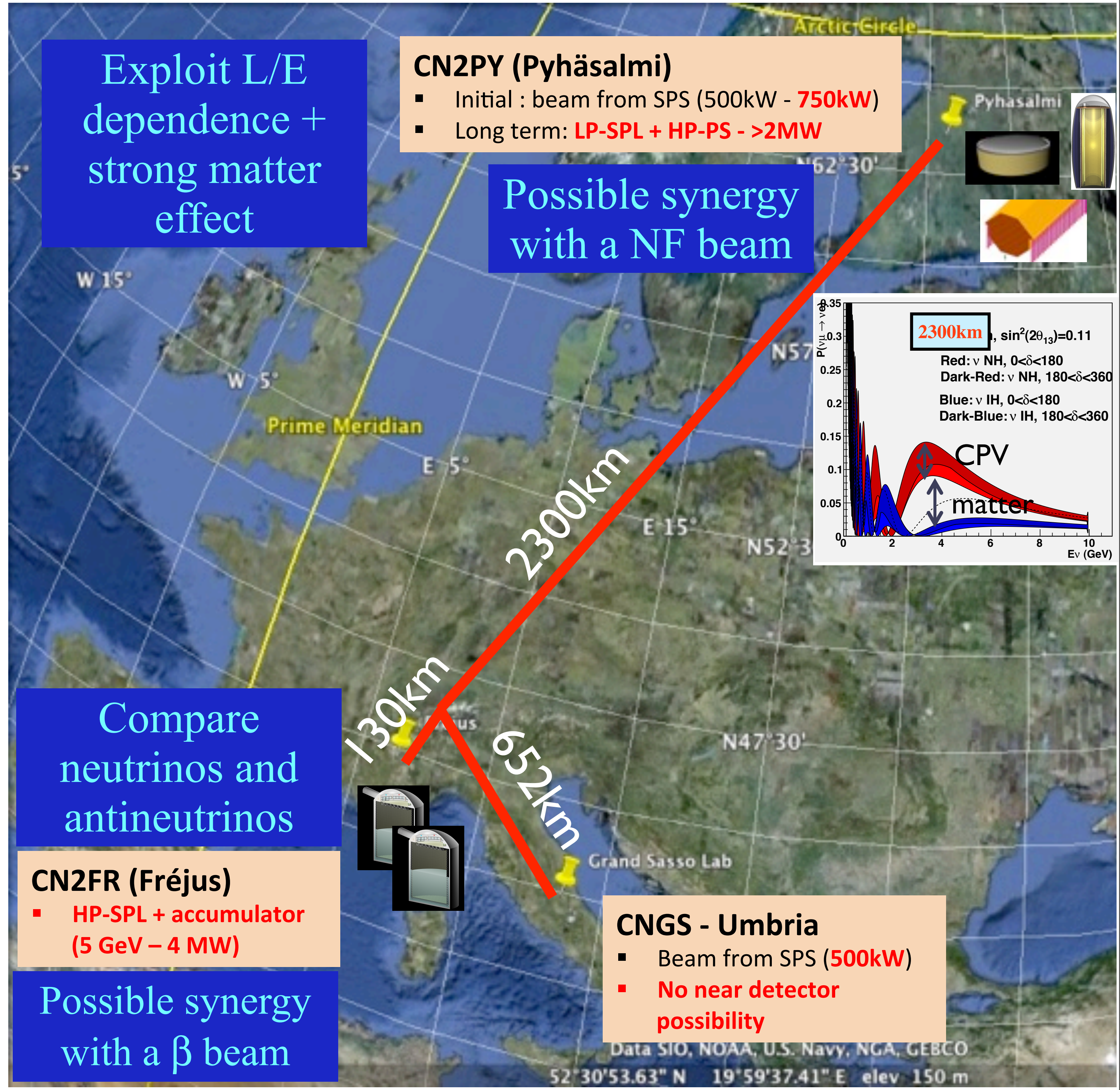
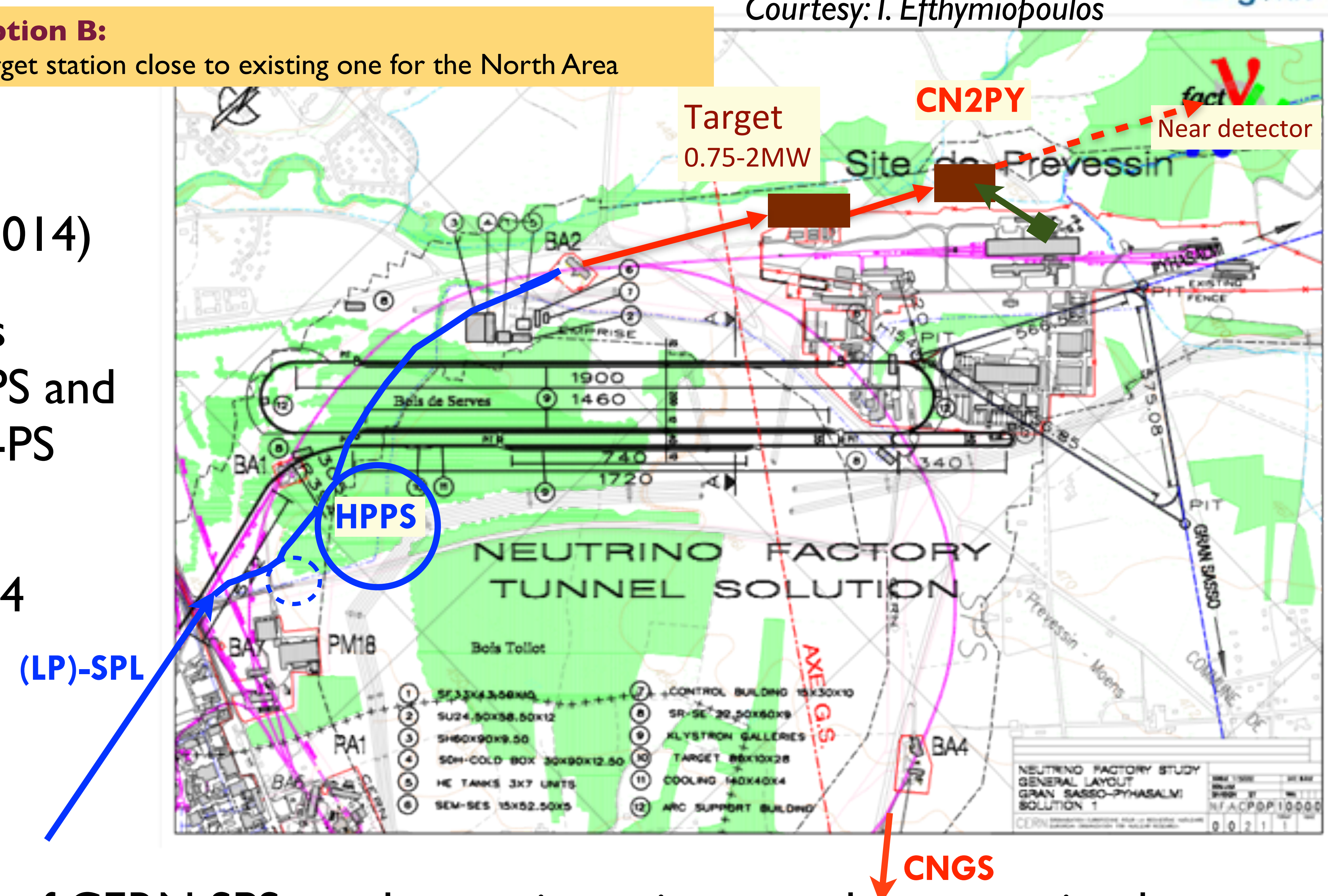
- Seven different sites were studied in details to assess their ability to host large underground detector (LAGUNA, 2008-2011)
- This design study phase has converged in a prioritization towards **three far sites** which could also be offer very unique opportunities for long baseline physics (LAGUNA-LBNO, 2011-2014)
- **CERN-Fréjus** is a short baseline coupled to the **WCD detector**. It offers good synergy for enhanced physics reach with β-beam at γ=100
- **CERN-Pyhäsalmi** is the longest baseline and is coupled to a **LArTPC, possibly coupled to a magnetized muon ranger**. It offers good synergy for enhanced physics reach with a neutrino factory (NF). In addition, Pyhäsalmi is an adequate site for a large **LSc** with lowest reactor neutrinos background in Europe.
- [**CERN-Umbria** has an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]
- Other LAGUNA sites could serve as alternative options.



Study of the CN2PY beam

Courtesy: I. Efthymiopoulos

- Feasibility of new beams approved by CERN study (LAGUNA-LBNO/2011-2014)
- New beam facility accepts protons from 400 GeV SPS and eventual new 50 GeV HP-PS
- Will produce conceptual design reports within 2014

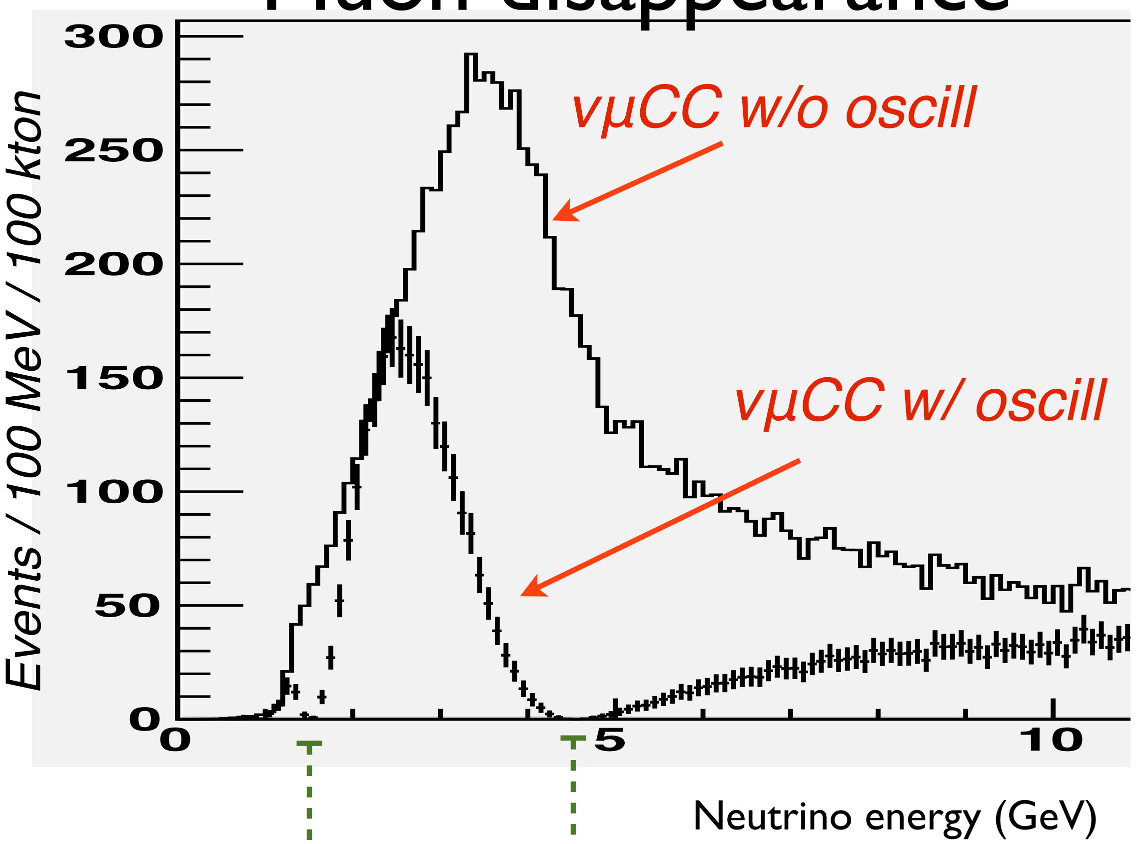


LAGUNA-LBNO:

- **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 initial sensitivity

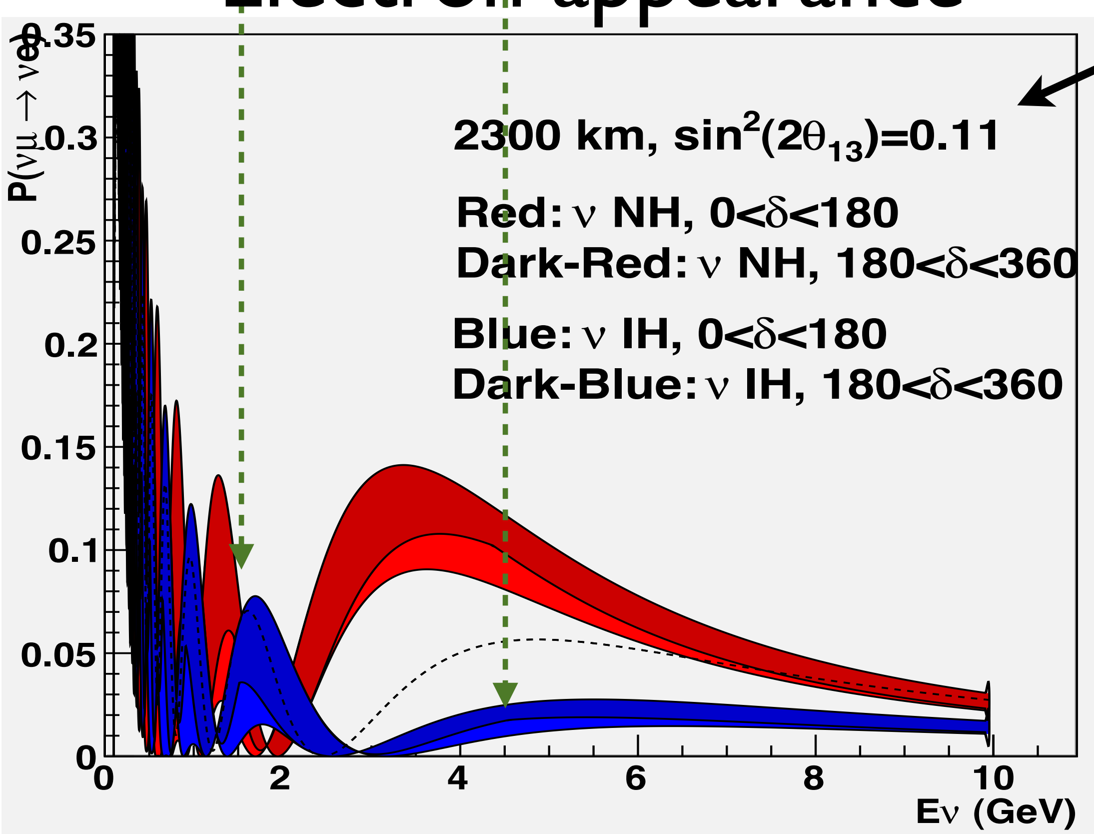
Muon disappearance



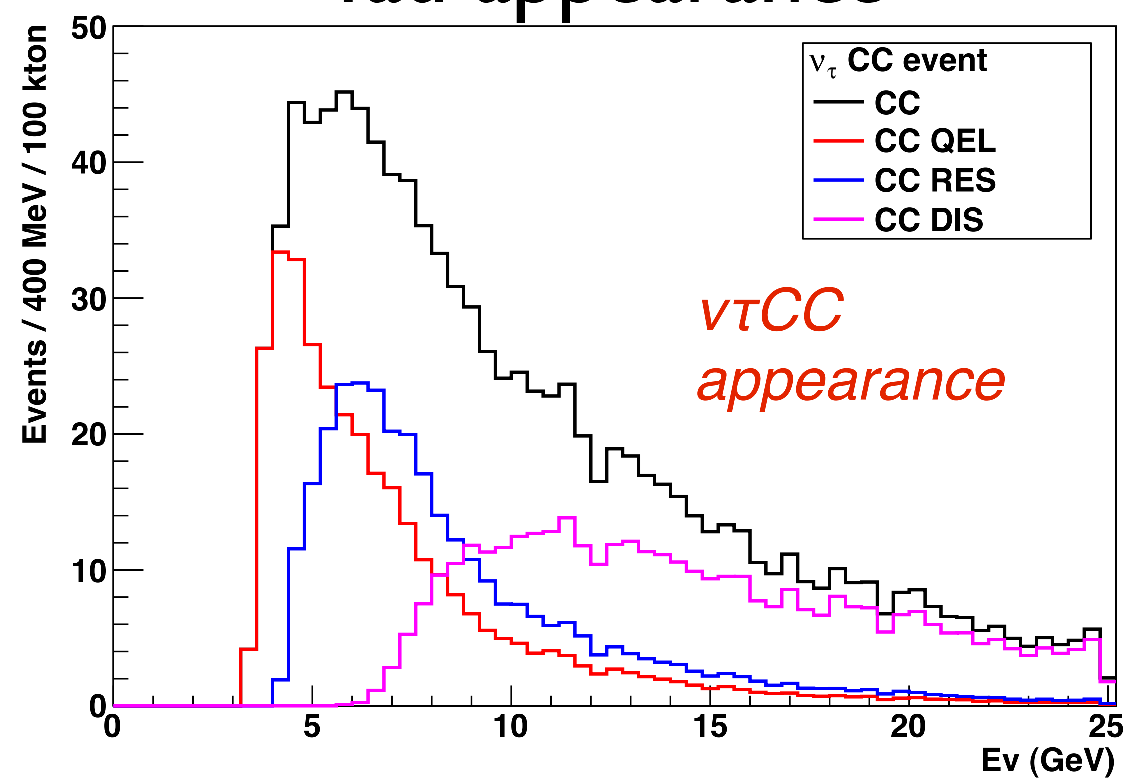
Event rates: CERN SPS 400 GeV
5 years @ 9.4x10[19] pots/year

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

Electron appearance



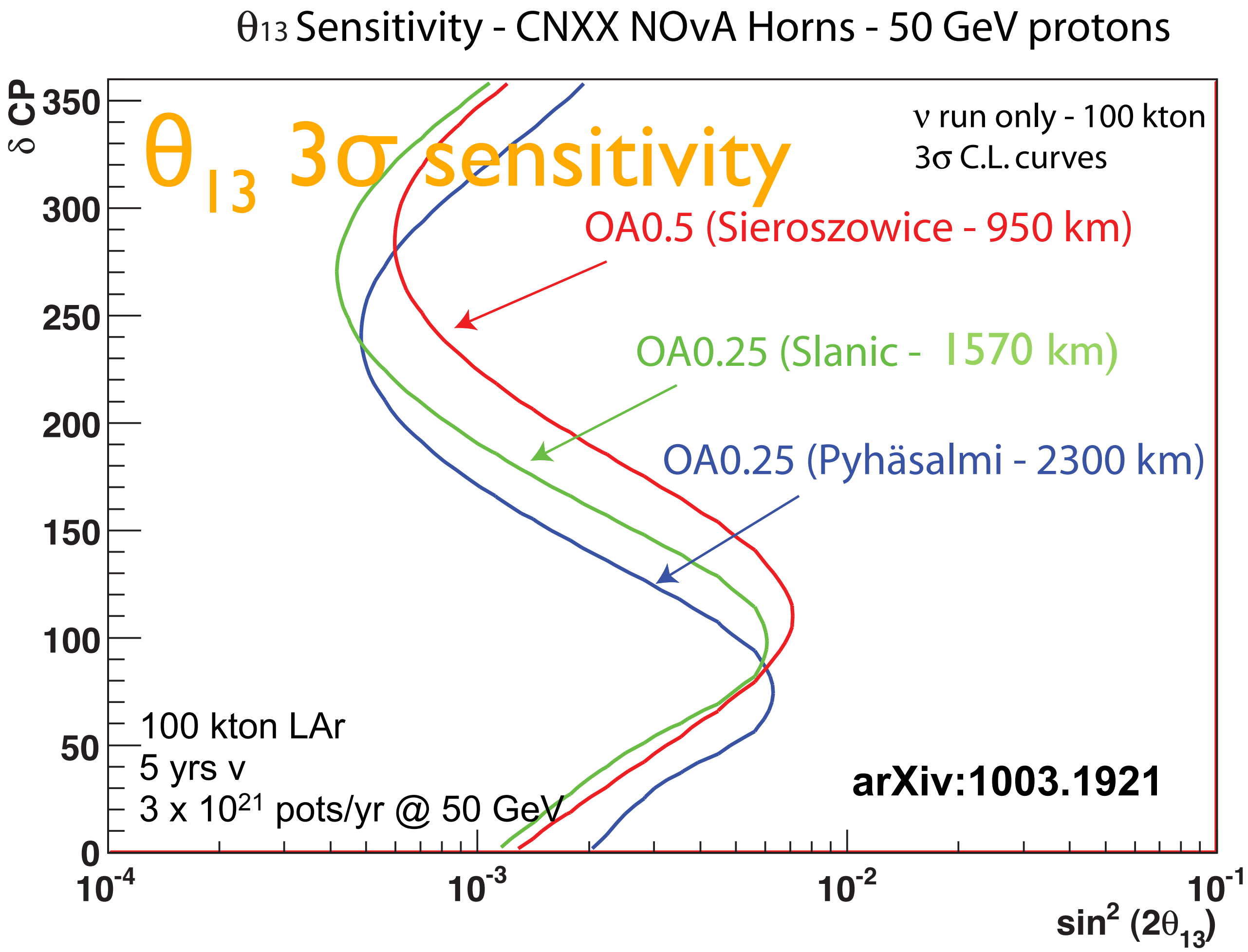
Tau appearance

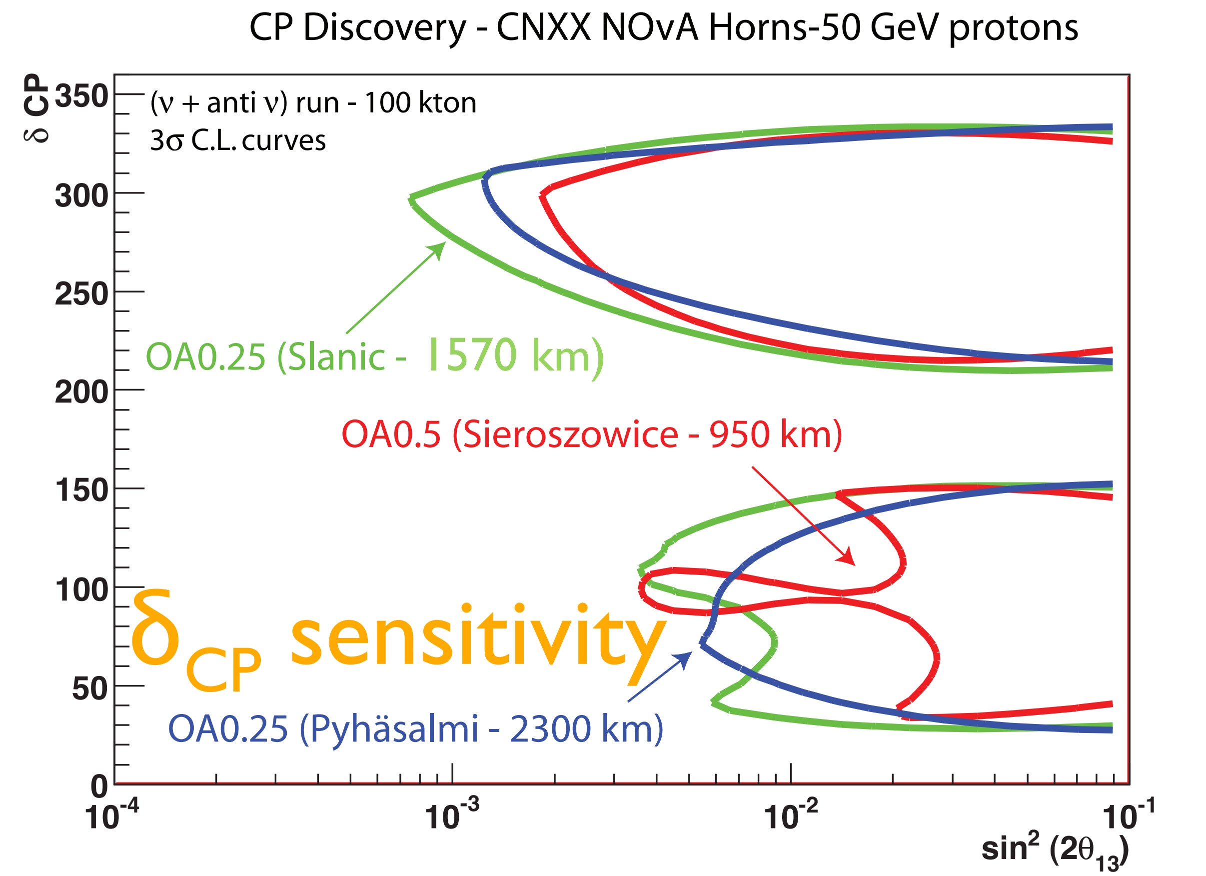


I[st] max above tau threshold

CN2PY ultimate sensitivity

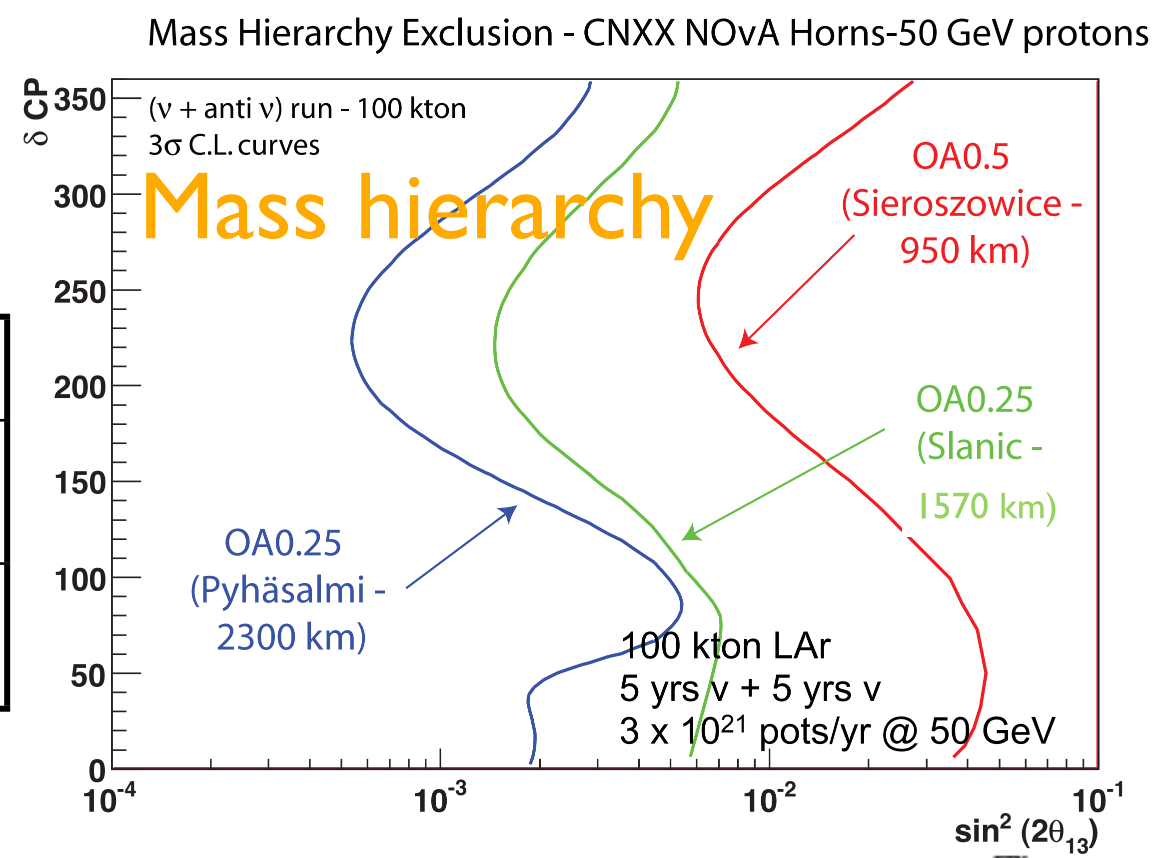
arXiv:1003.1921





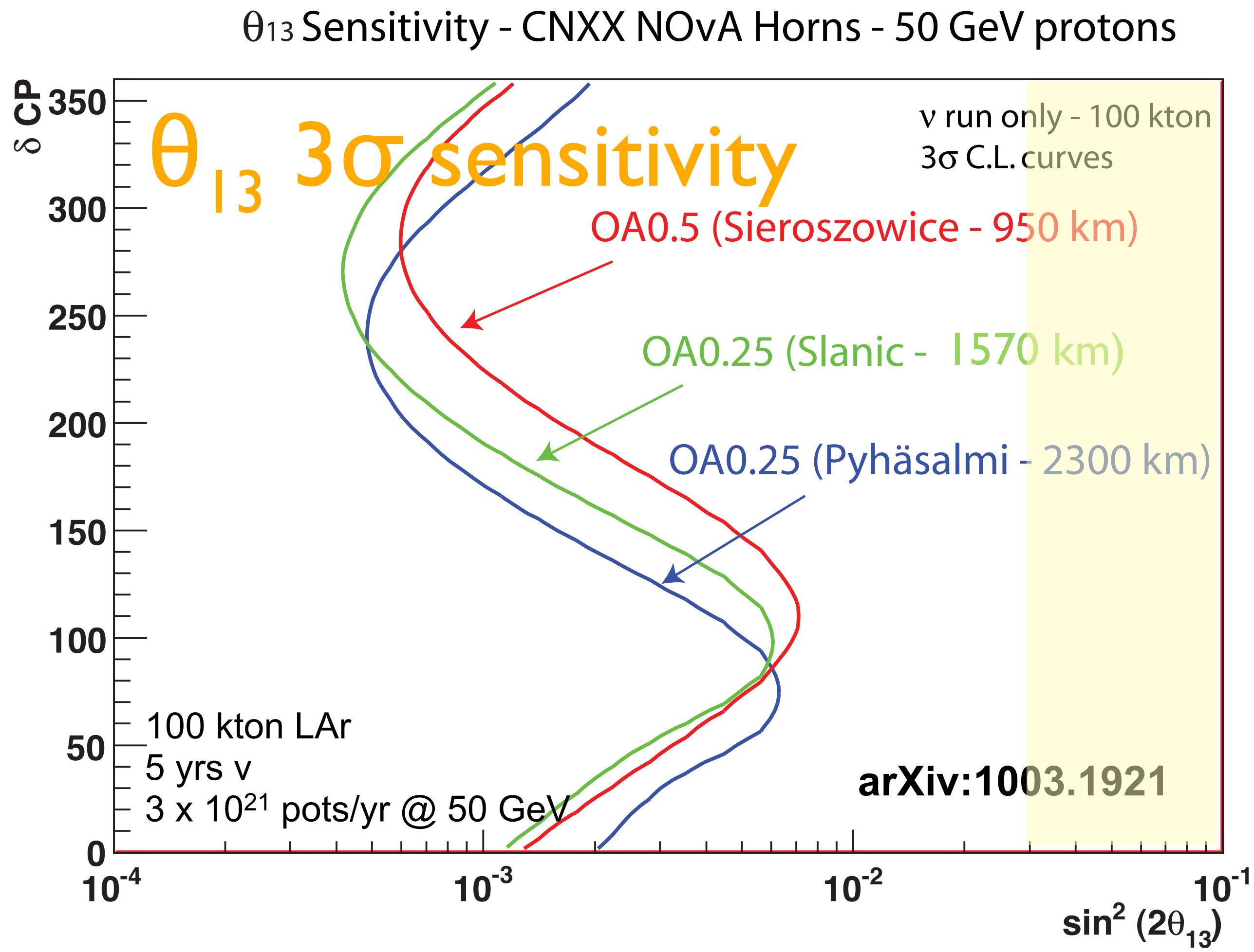
Event rate per year: 50 GeV HP-PS, 3×10^{21} pots/yr, 1.6 MW

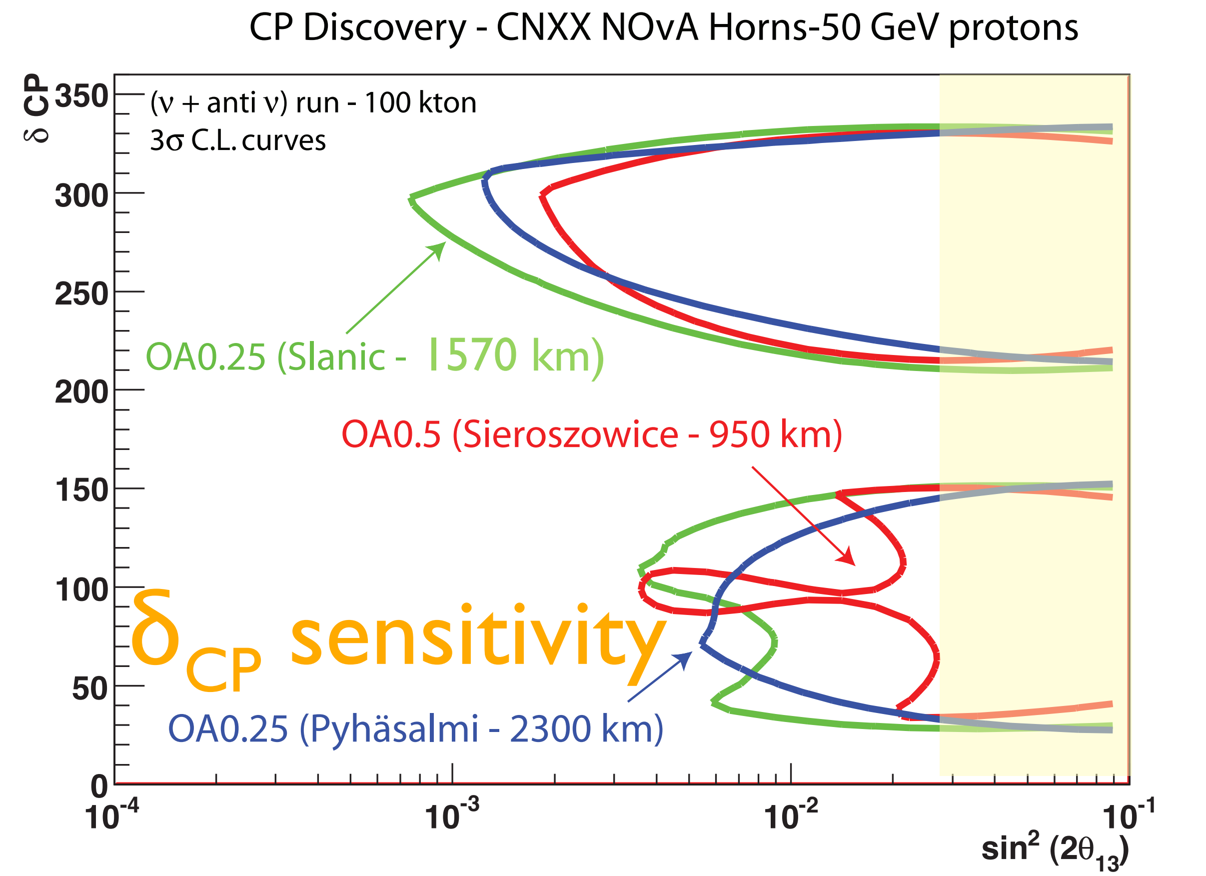
No Osc.	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
positive horn 1 year	17257	110	203	7
negative horn 1 year	471	16	7577	32



CN2PY ultimate sensitivity

arXiv:1003.1921





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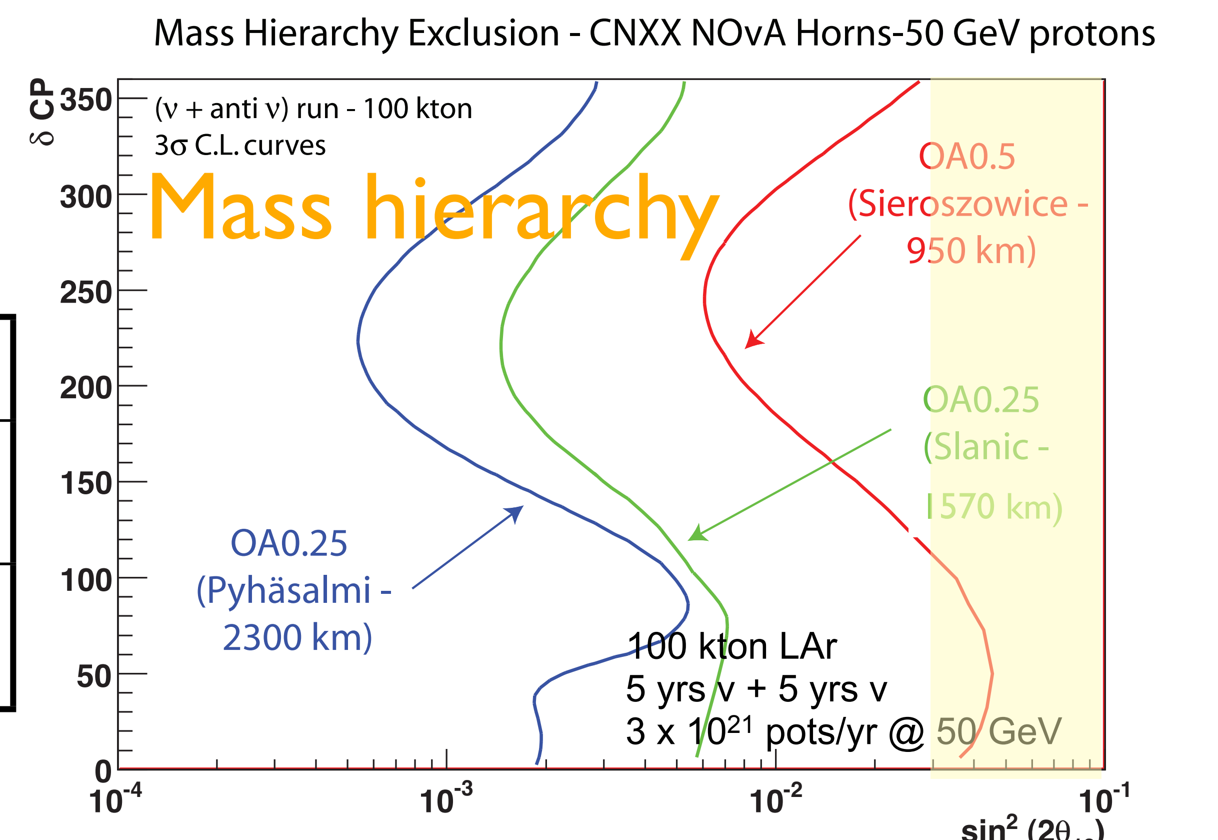
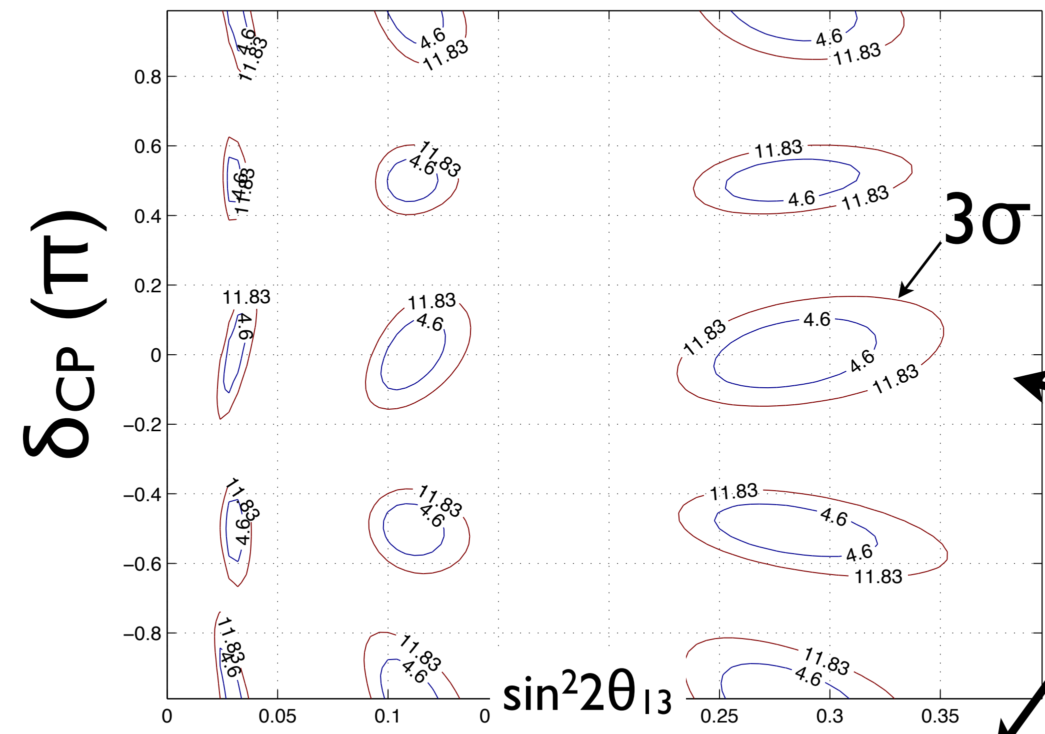


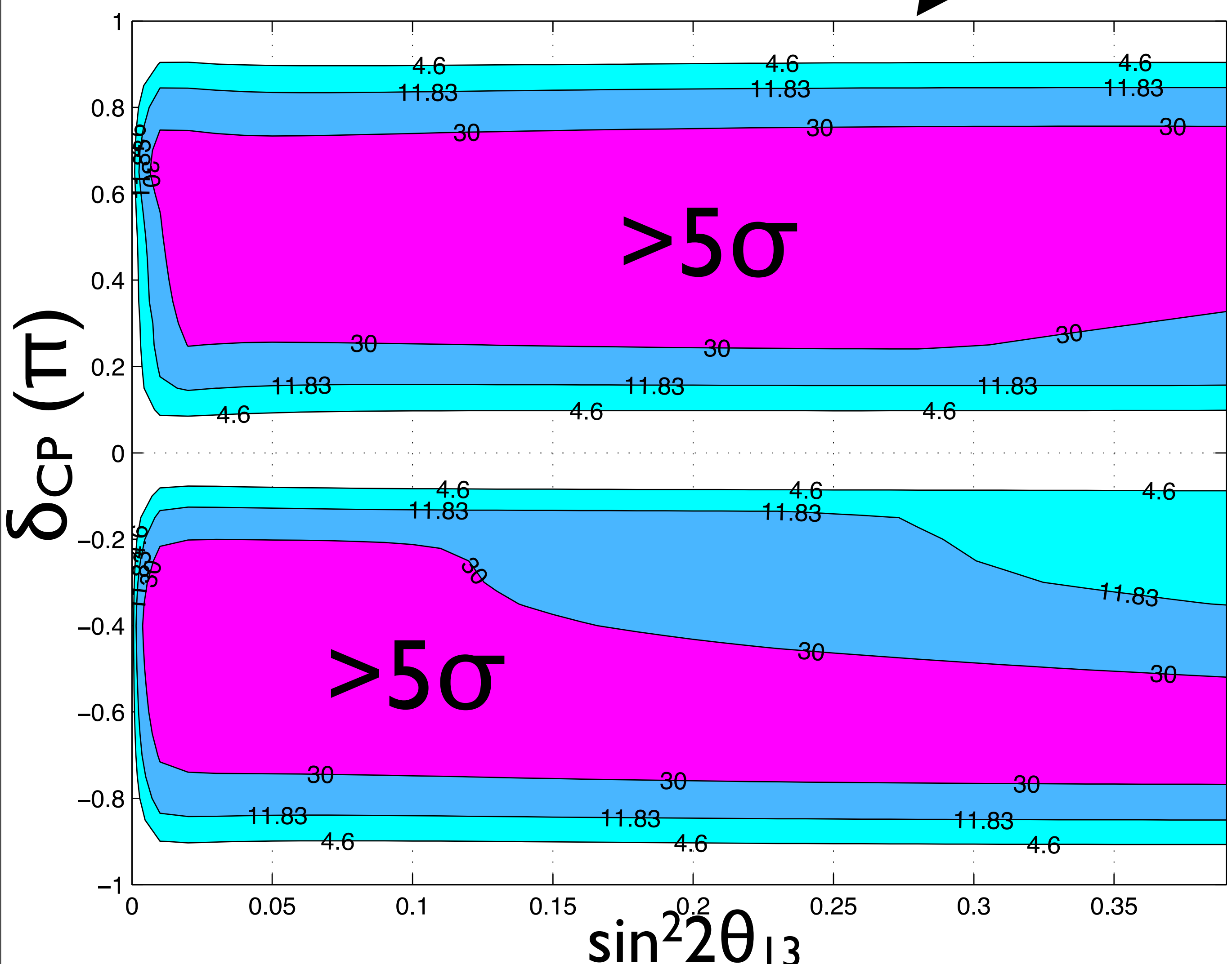
CN2PY ultimate CP sensitivity

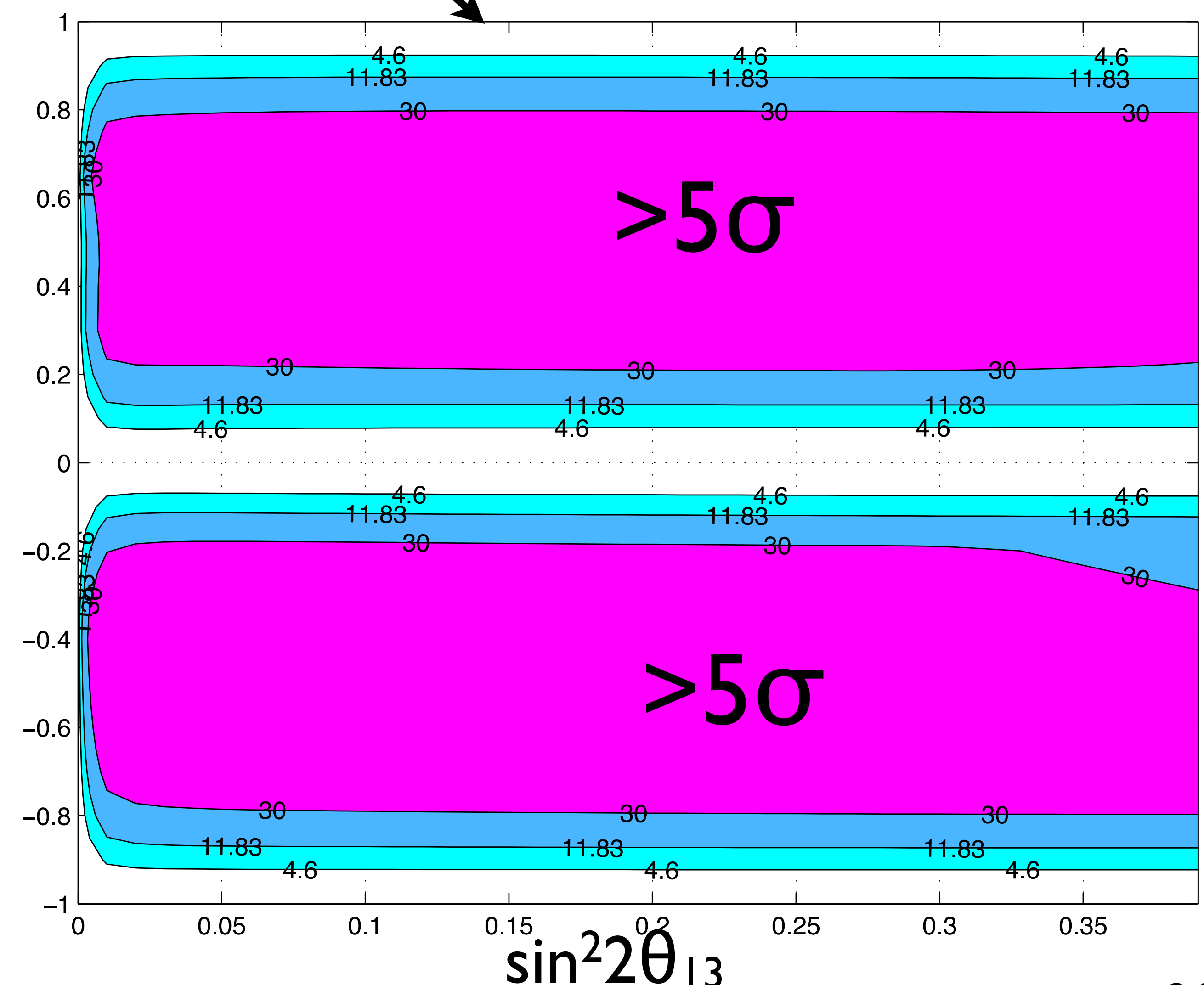
CP-discovery (mass hierarchy **not** known)



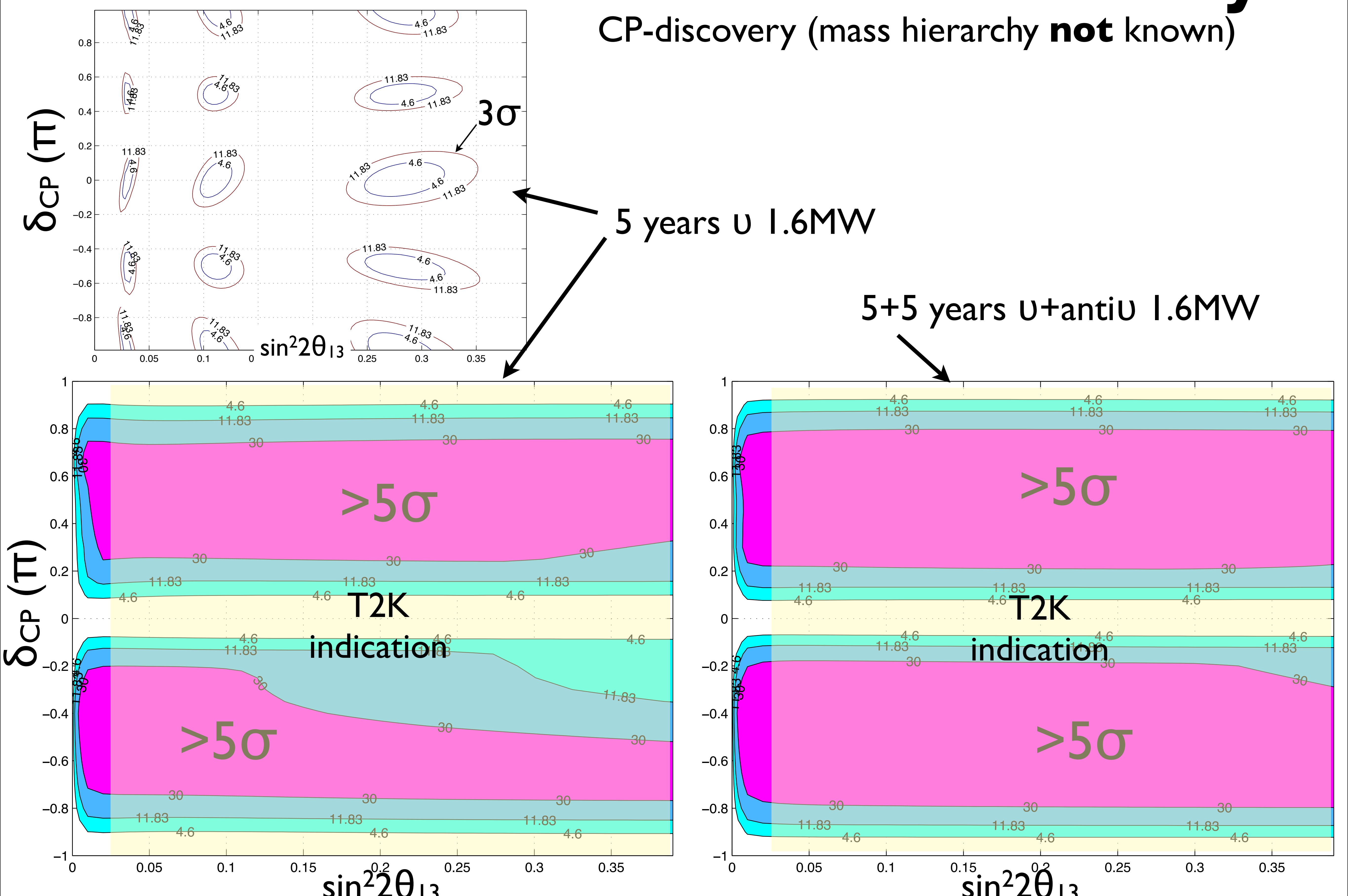
5 years υ 1.6MW

5+5 years υ+antiυ 1.6MW





CN2PY ultimate CP sensitivity

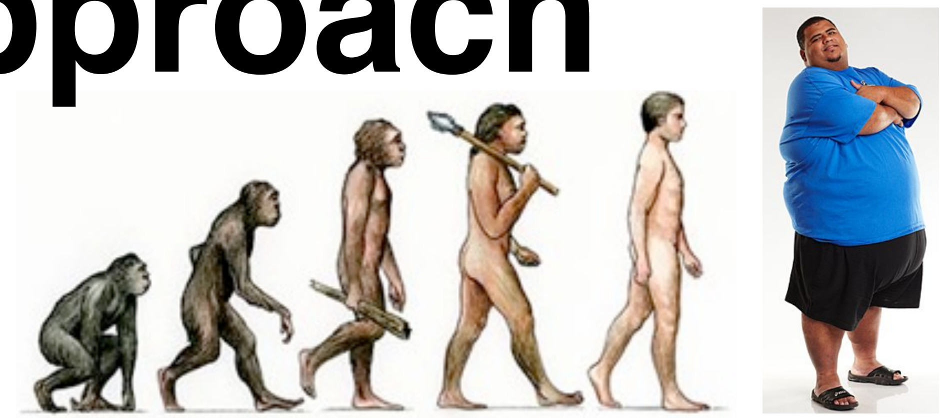


Preparing the LAGUNA-LBNO input to the European Strategy: global view

- **Medium term plan**: Europe is in a unique position to host a facility with a baseline of 2300km, not considered elsewhere in the world. Given the recent experimental results on θ_{13}, a long baseline neutrino programme to provide a guaranteed determination at $\geqq 3\sigma$ of the neutrino mass hierarchy and to address maximal CP-violation, is accessible with a new CNGS-like conventional neutrino beam based on existing CERN accelerators and directed towards the 2300km far site. The far site can be implemented with the creation, likely incremental, of the LAGUNA RI.

- **Long term plan:** A further exploration of the CP-violation parameter phase space can be achieved with increasingly challenging exposures, which could be obtained by a progressive increase of the beam power and/or a progressive increase of the far detector(s) mass(es).
  Alternatively, a new type of neutrino beam facility and/or a second baseline might be envisaged for longer term. If this was the case and depending on the results from the R&D on betabeam and NF, a change of direction and of the far site after the first phase outlined in the medium term plan might be considered.

An incremental approach



- **A possible way to incrementally realize the facility at Pyhäsalmi:**
    - Phase 0 : full excavation (final caverns @900m+1400m) and preparation of underground space
    - Phase 1: LAr 20kt @ 900m + LSc 25kt @ 1400m + Fe detector
    - Phase 2: add LAr 50kt @ 900m + add 2nd LSc 25kt + add Fe
    - Phase 3: replace LAr 20kt by LAr 50kt + add Fe

Produce significant physics results at each phase
Reduce overall risks
Alleviate some funding challenges w/ acceptable total cost
Leave possibility to alter the direction after each phase

Incremental exposure

We define **exposure** ≈ Npot@50GeV * mass(kt)

	SPS now	SPS+LIU	SPS++	LP-SPL+HP-PS
Proton energy (GeV)	400	400	400	50
ppp	4.00E+13	6.00E+13	7.00E+13	2.50E+14
Tc (s)	6	6	6	1.2
Beam power (MW)	0.43	0.64	0.75	1.67
Global eff	0.85	0.85	0.85	0.85
Beam sharing	0.85	0.85	0.85	1
Running (d/year)	200	200	200	200
Npot/year	8.32E+19	1.25E+20	1.46E+20	3.00E+21
Npot equiv at 50 GeV	7.00E+20	1.00E+21	1.20E+21	3.00E+21

}4xPS2

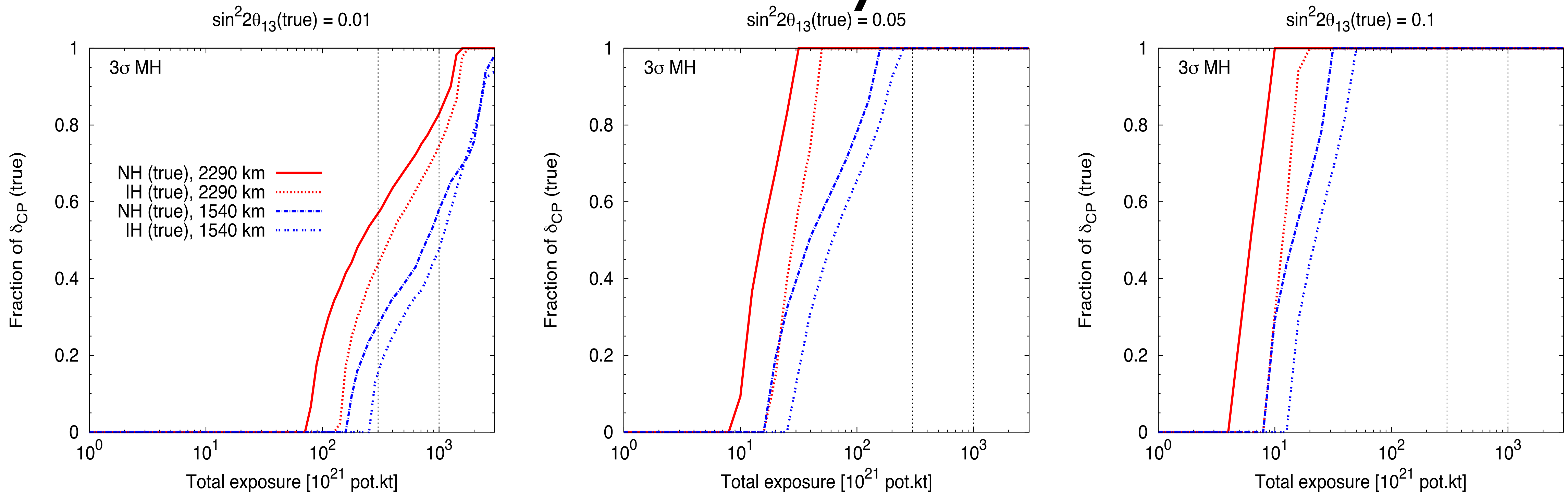
20 kton+SPS+LIU: 5+5 years running : 200e21 pot*kt

70 kton+SPS++: 5+5 years running : 840e21 pot*kt

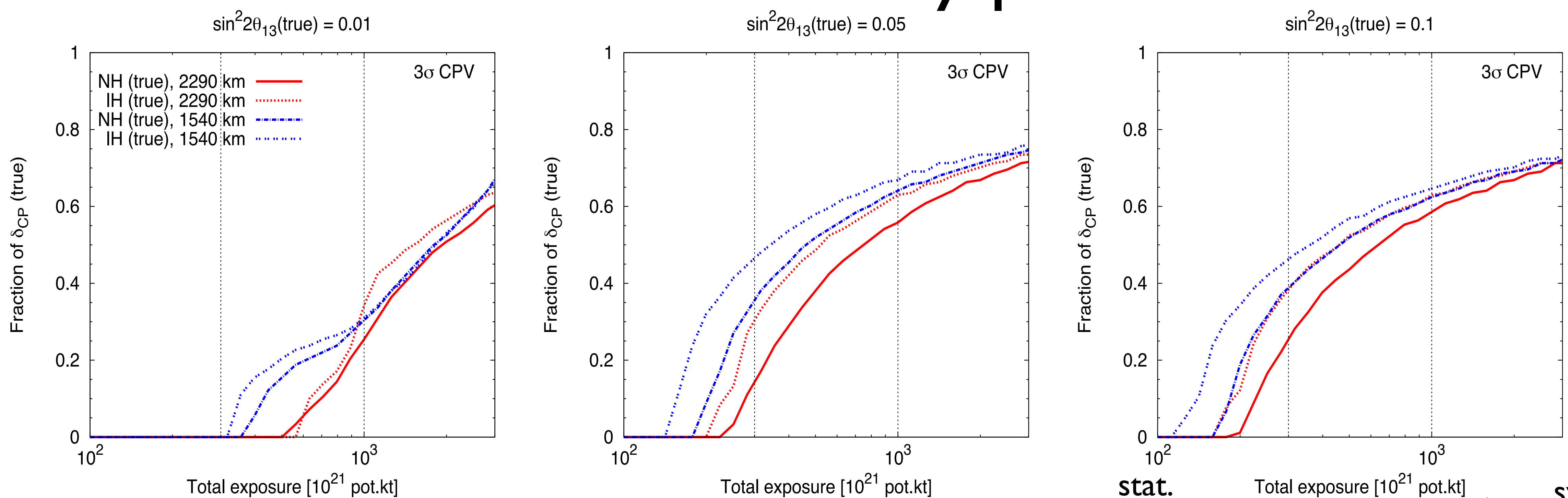
100 kton+HP-PS: 5+5 years running : 3000e21 pot*kt

Incremental discovery reach

3σ mass hierarchy determination



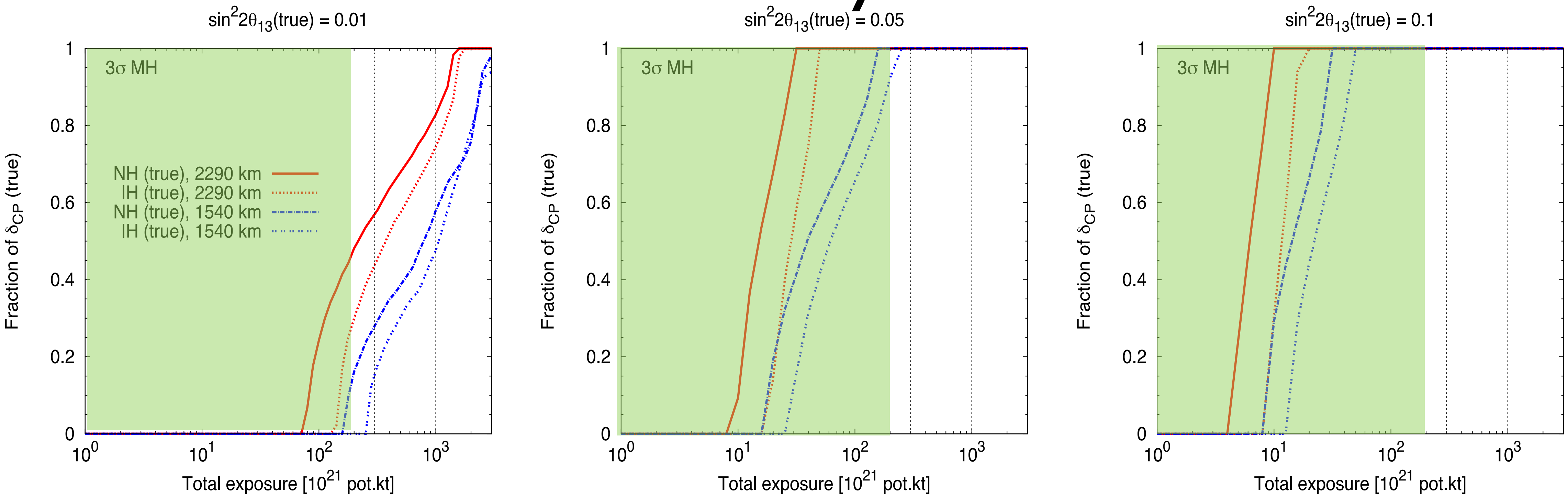
3σ CPV discovery potential



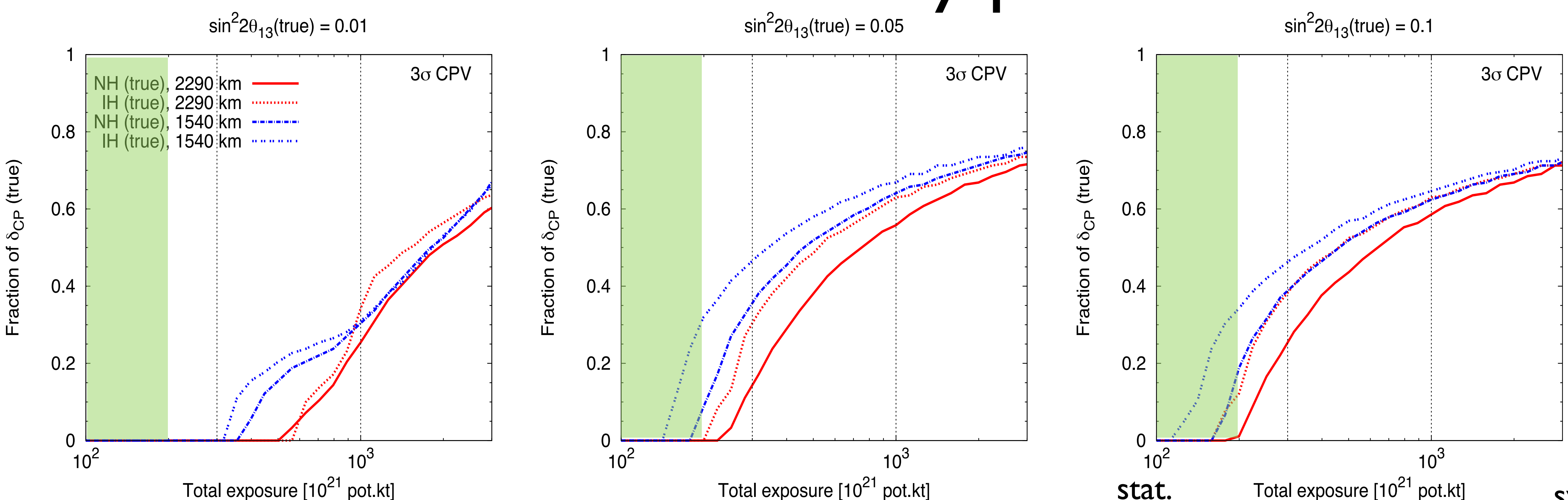
stat. dominated → syst. dominated

Incremental discovery reach

3σ mass hierarchy determination



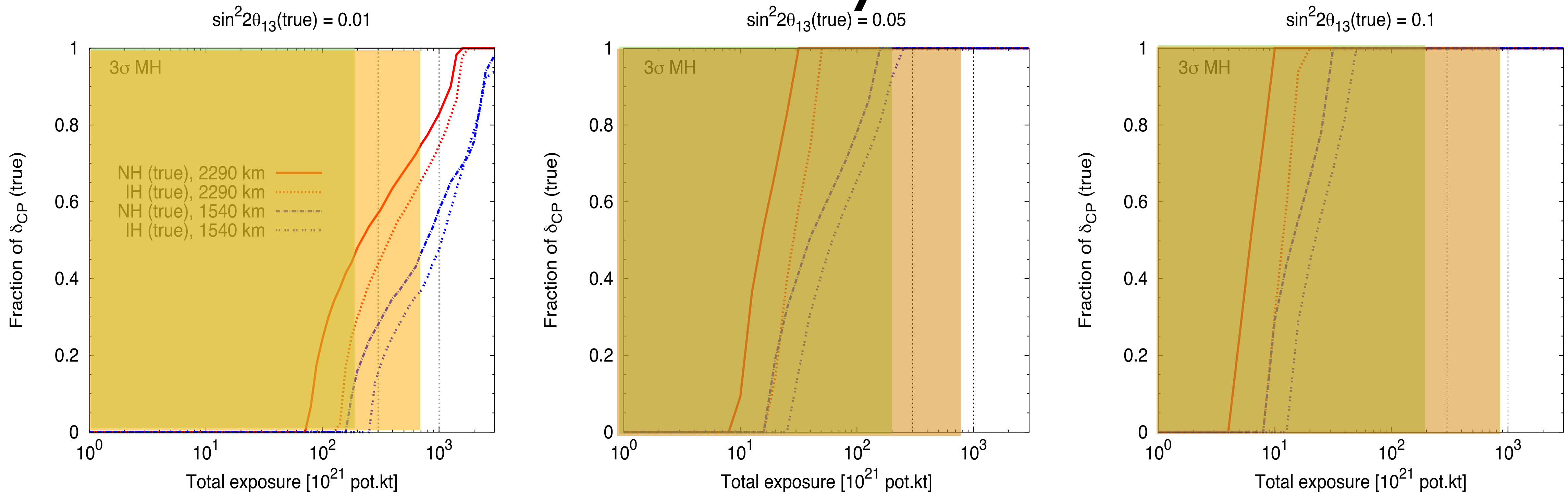
3σ CPV discovery potential



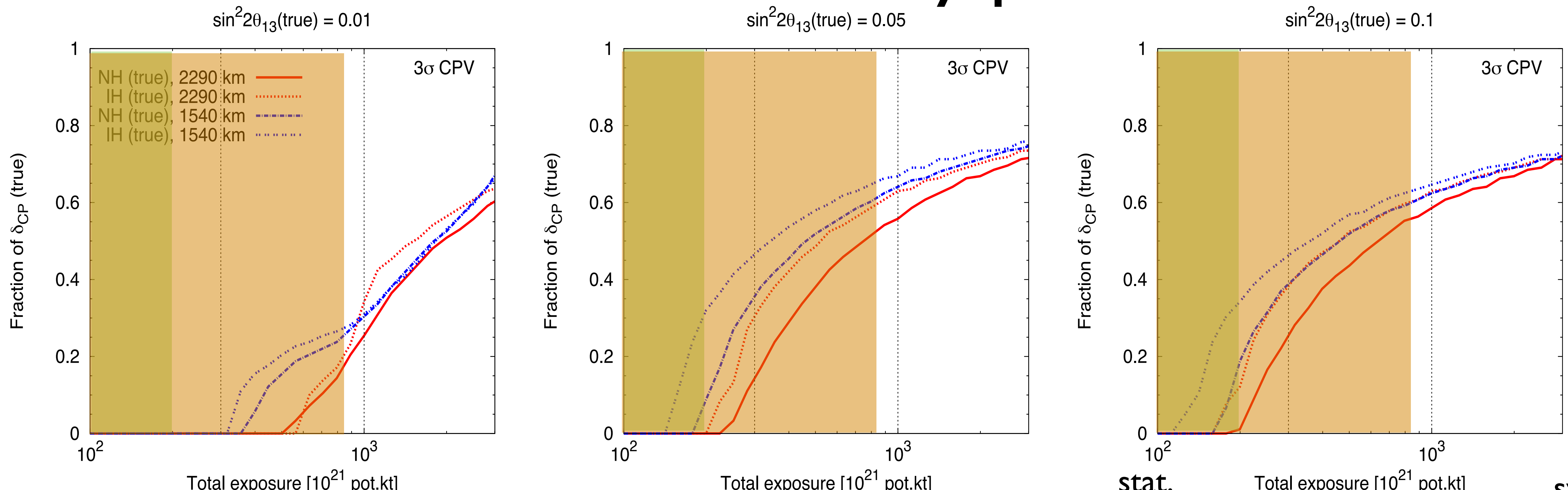
stat. dominated → syst. dominated

Incremental discovery reach

3σ mass hierarchy determination



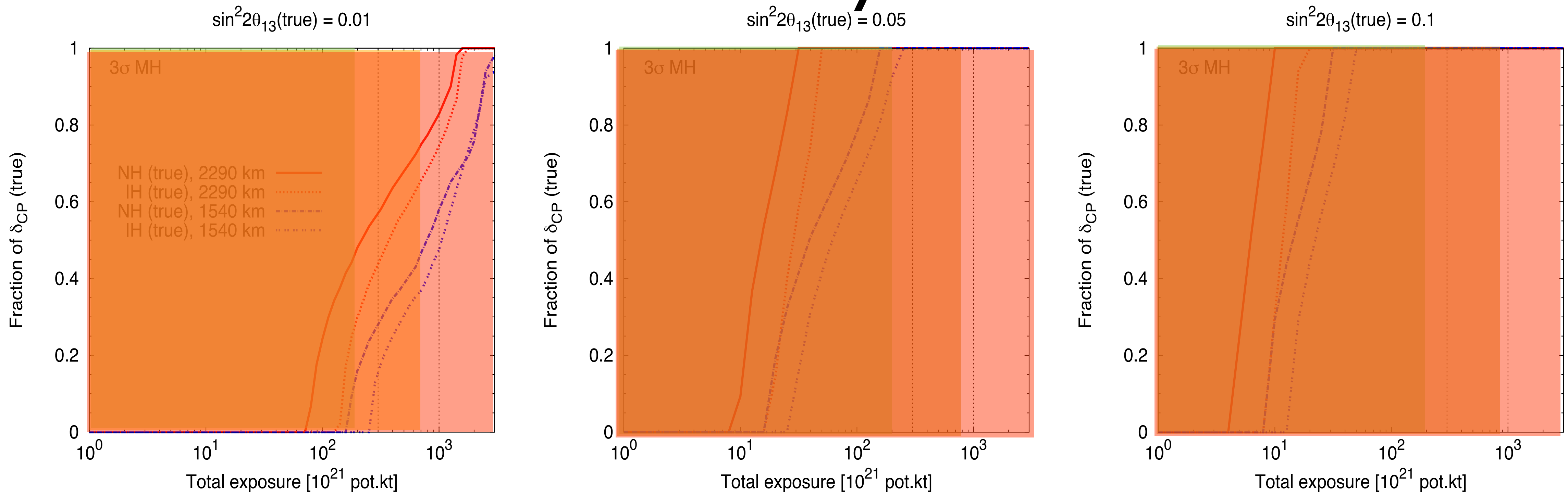
3σ CPV discovery potential



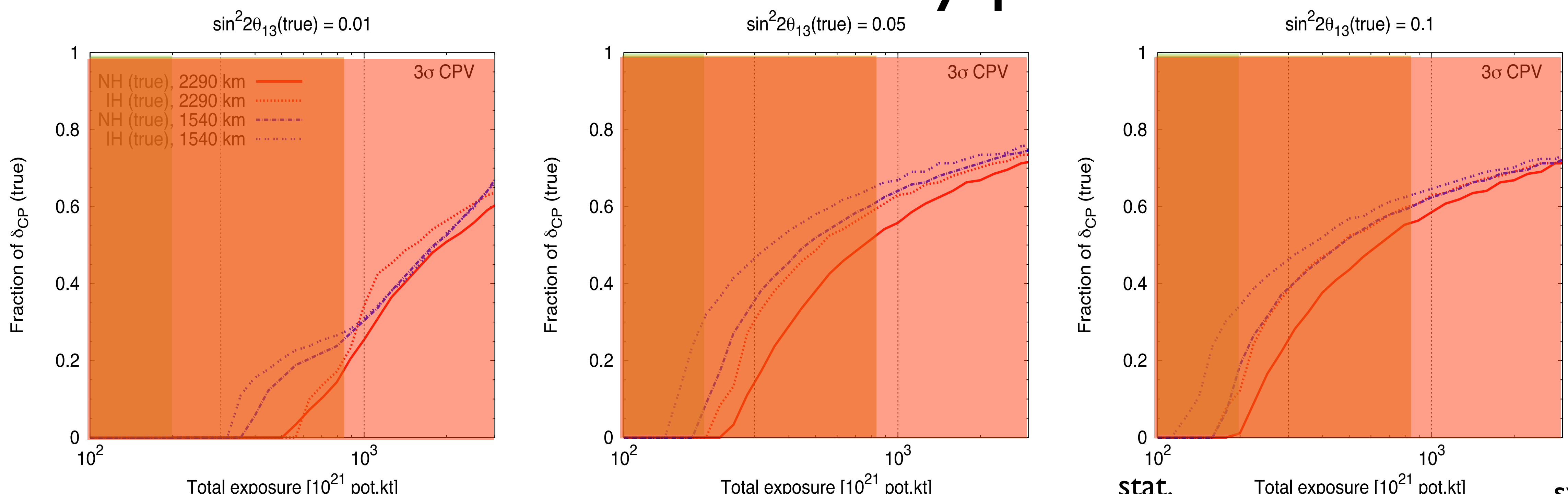
stat. dominated → syst. dominated

Incremental discovery reach

3σ mass hierarchy determination



3σ CPV discovery potential

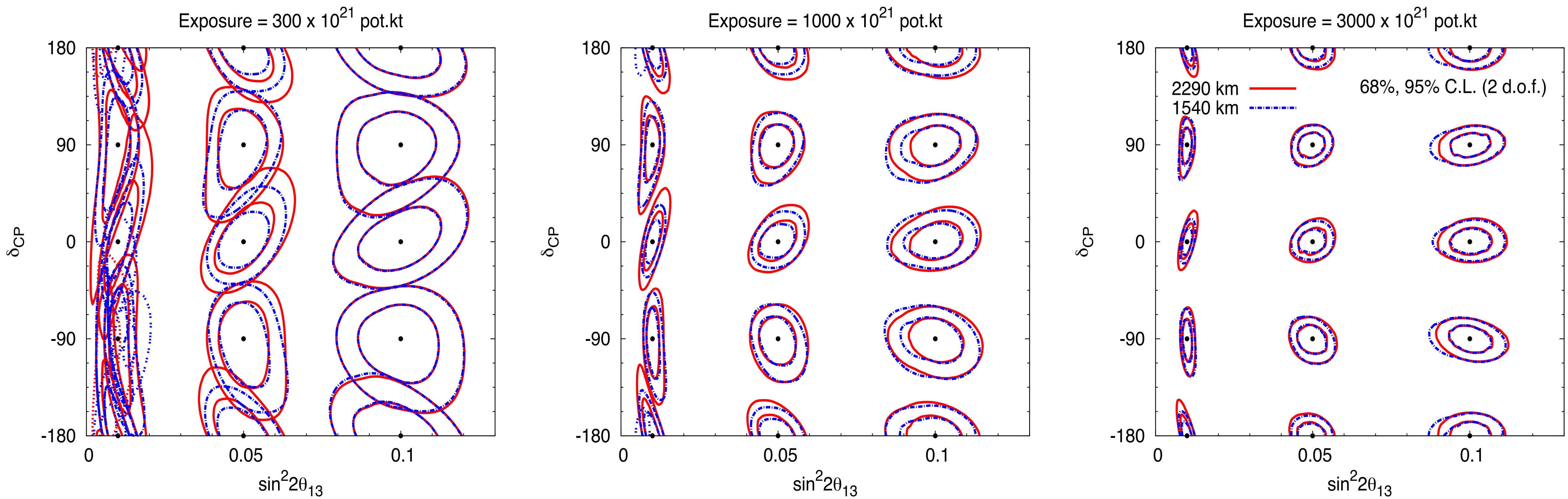


stat. dominated → syst. dominated

Incremental CP-phase measurement

300e21 pot*kt 1000e21 pot*kt 3000e21 pot*kt

stat. dominated → syst. dominated



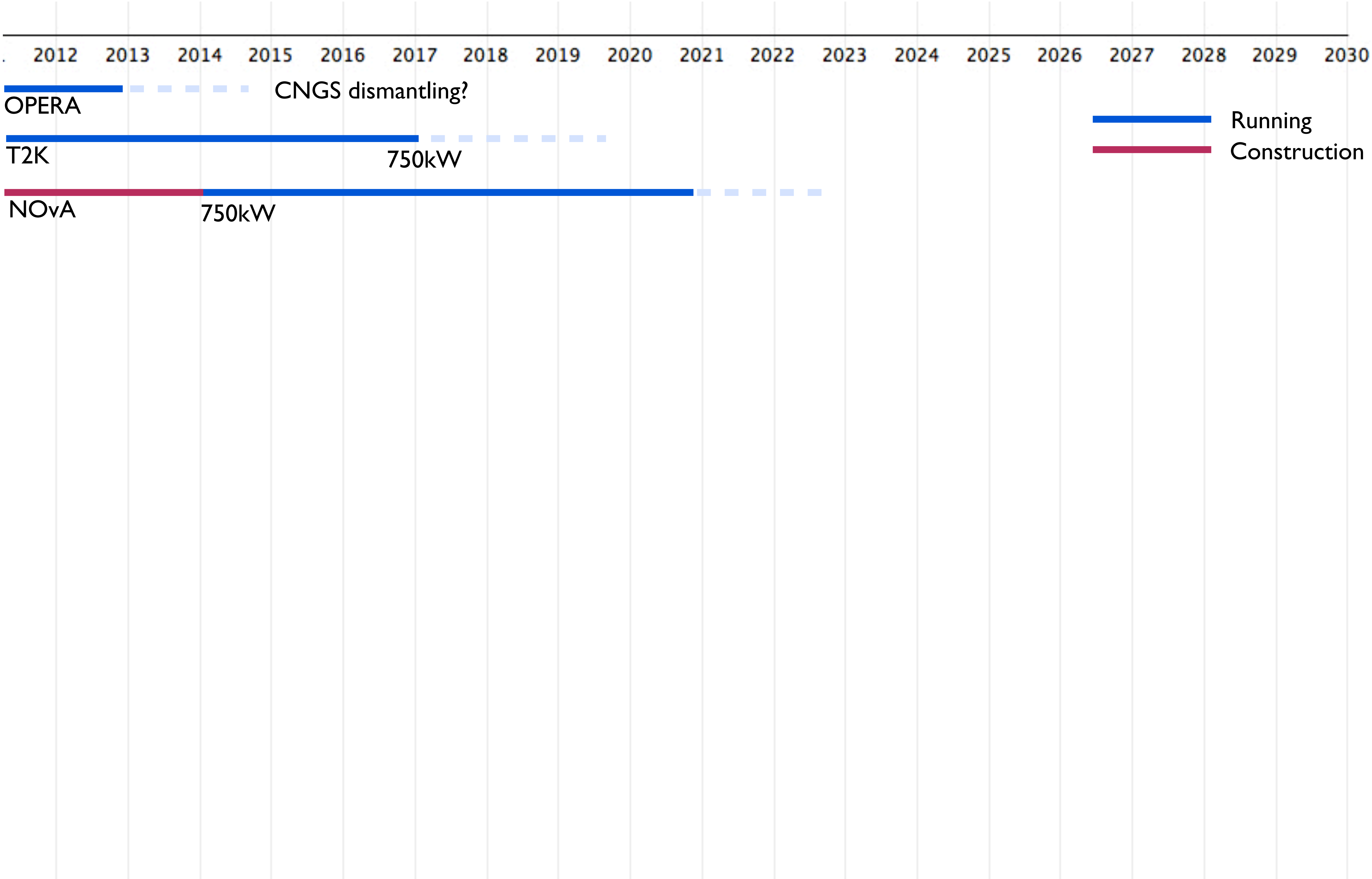
(red) CERN-Pyhäsalmi 2300 km
(blue) CERN-Slanic 1540 km
(similar to FNAL-LBNE)

1540 & 2300 km are both optimal for CP measurement

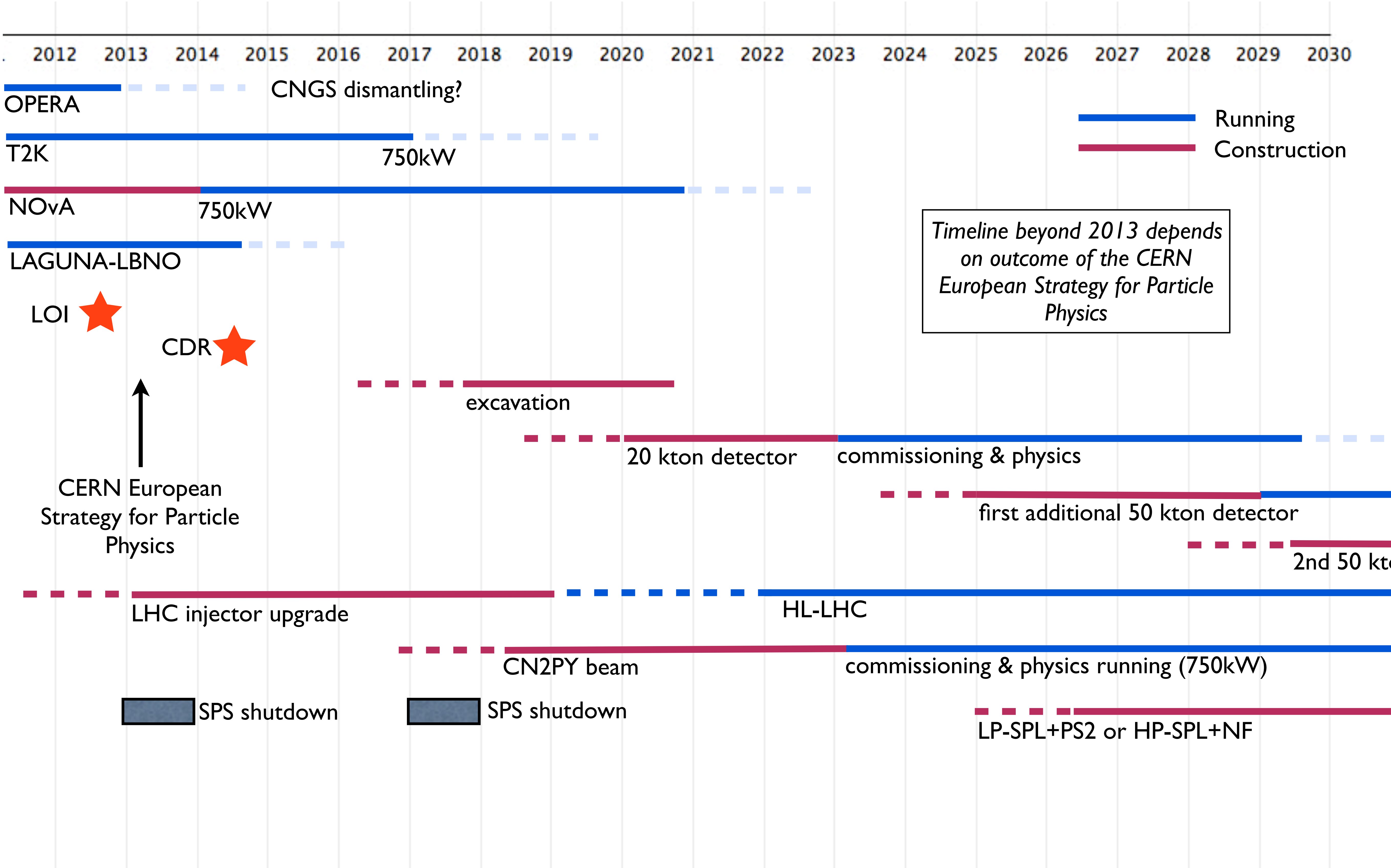
Preparing the LAGUNA-LBNO input to the European Strategy: an action plan

- **To the preparatory group**: submit an expression of interest for a research infrastructure that could host very large mass detectors (LAr, LSc, Fe) with capabilities for particle and astroparticle physics, and in addition probing mass hierarchy and CP-violation in lepton sector with a long baseline beam from CERN
- **To CERN (likely to SPSC)**: submit an expression of interest, highlighting the physics reach of a CERN-Pyhäsalmi long baseline conventional beam coupled to one or more experiment(s) (LAr,Fe, LSc), based on an incremental approach, initially starting from the existing CERN SPS performance (benefitting from the LiU upgrades) and far detector(s) with mass ranges in the 20 kton-scale, and gradually increasing the far detector masses and/or the SPS beam power. Advocate the performance achieved with a CERN SPS reaching 750kW. Describe this phase as a "mandatory" first step in an incremental approach towards discovery of CP-violation. Mention long term options.

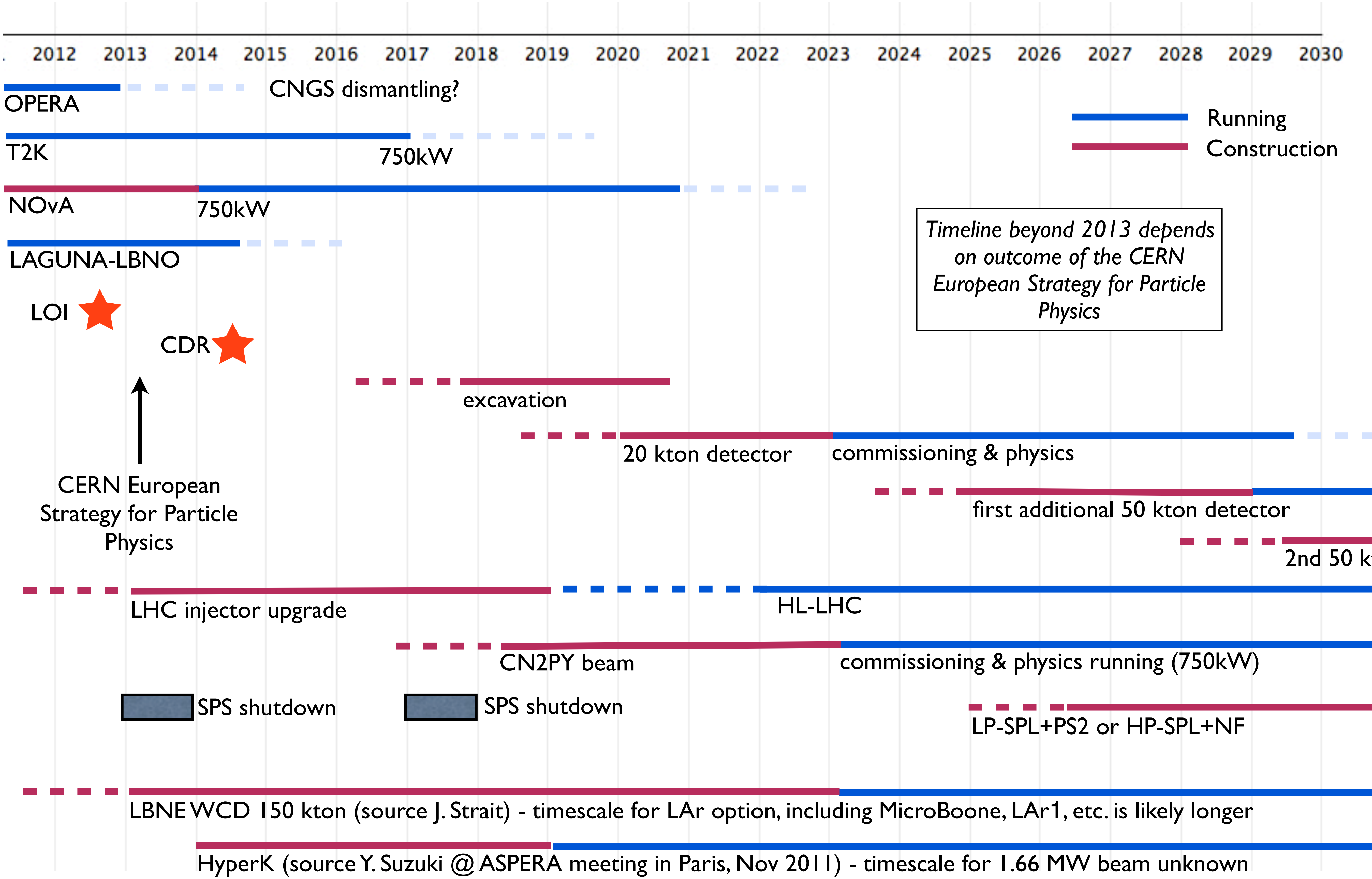
LAGUNA-LBNO Timeline



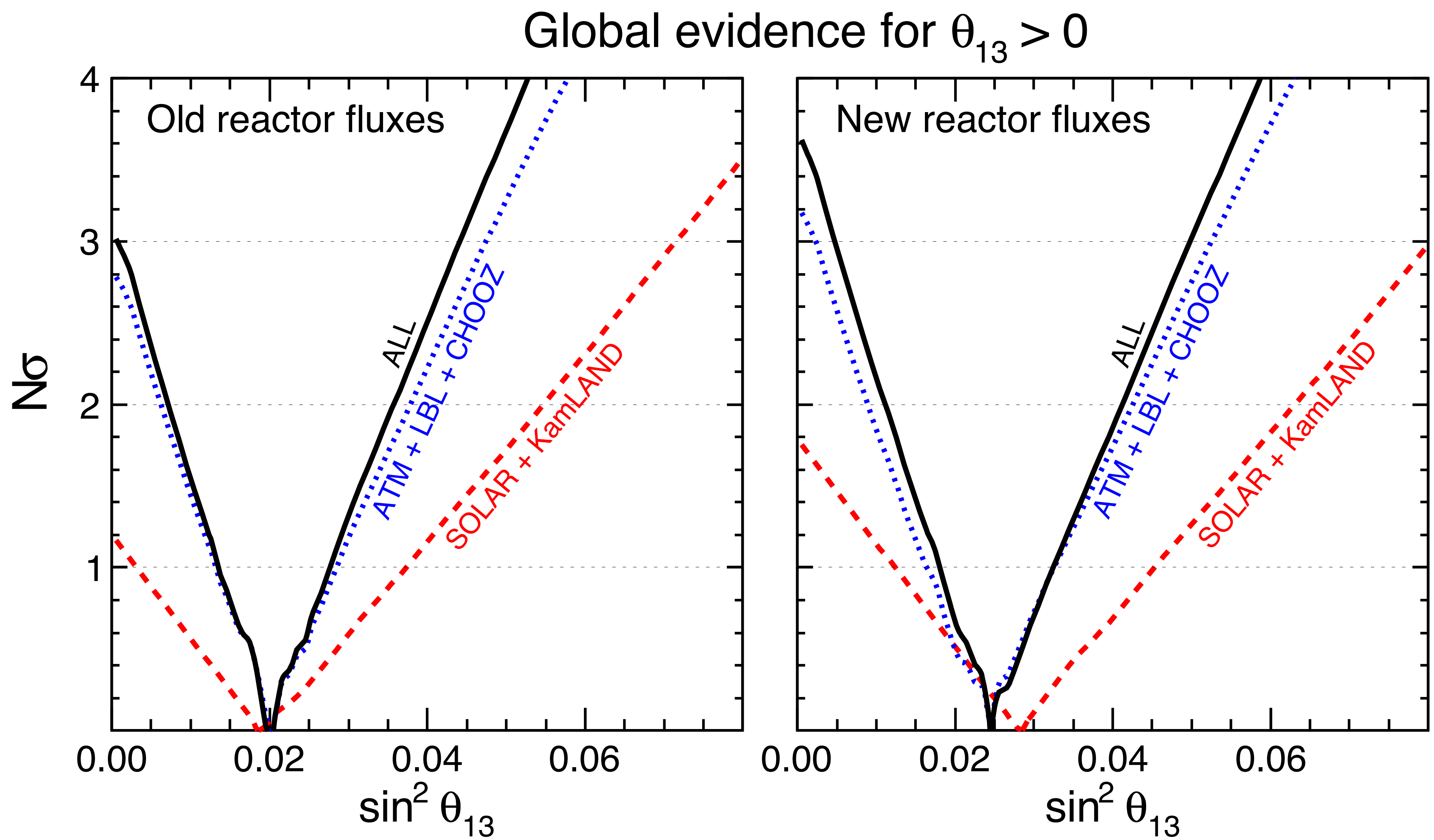
LAGUNA-LBNO Timeline



LAGUNA-LBNO Timeline



Are we there yet ?



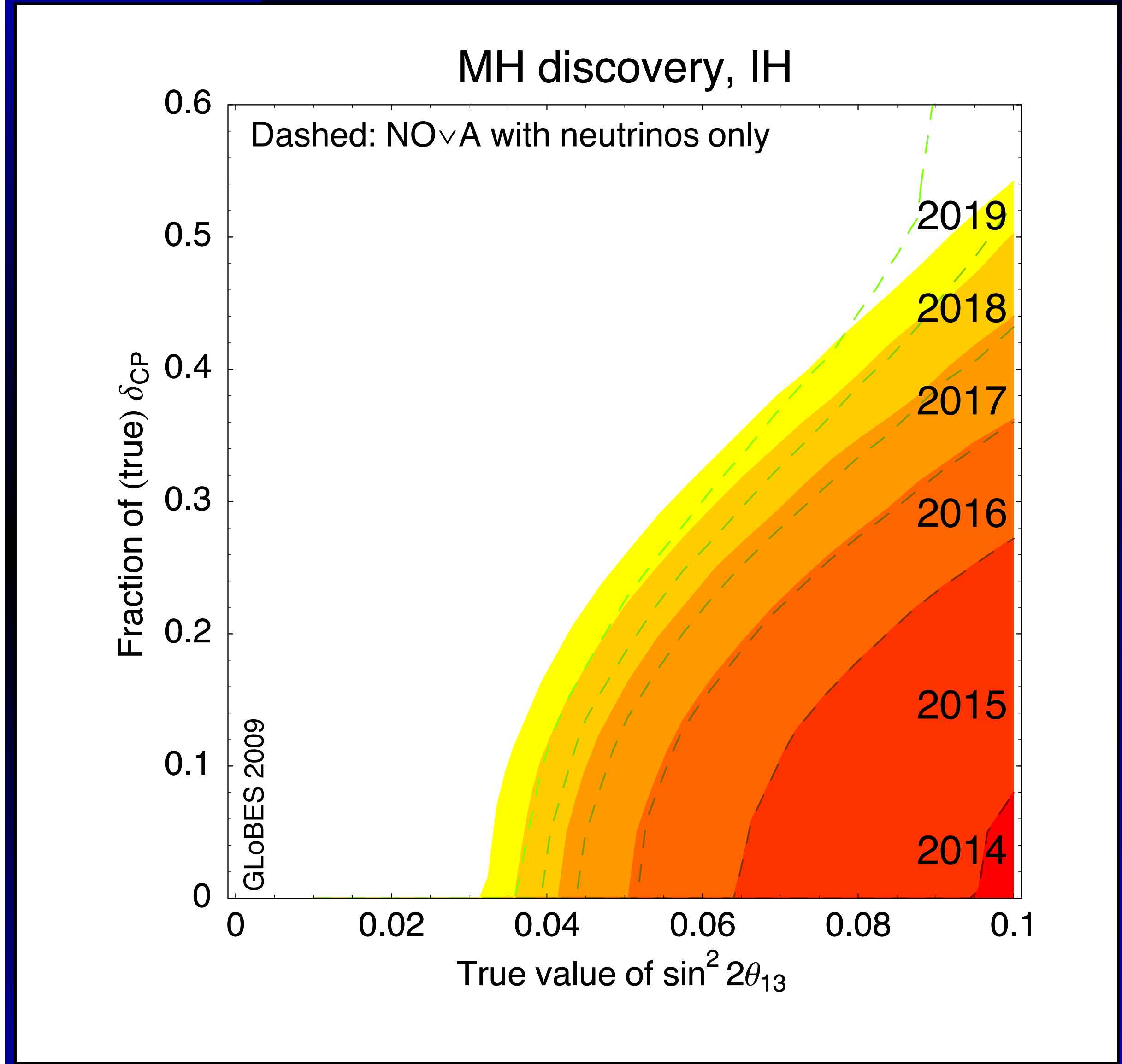
from Fogli, *et al.*, Phys.Rev. **D84** (2011) 053007.

Assuming the new reactor fluxes (and no sterile neutrino), this translates to a 3 σ lower bound of $\sin^2 2\theta_{13} > 0.02$.

P. Huber – VT-CNP – p. 6

Are there other ways ?

Mass hierarchy



90% CL, combines T2K, NOνA, Daya Bay, Double Chooz and RENO At this CL MINOS and T2K have discovered $\theta_{13} \neq 0$!

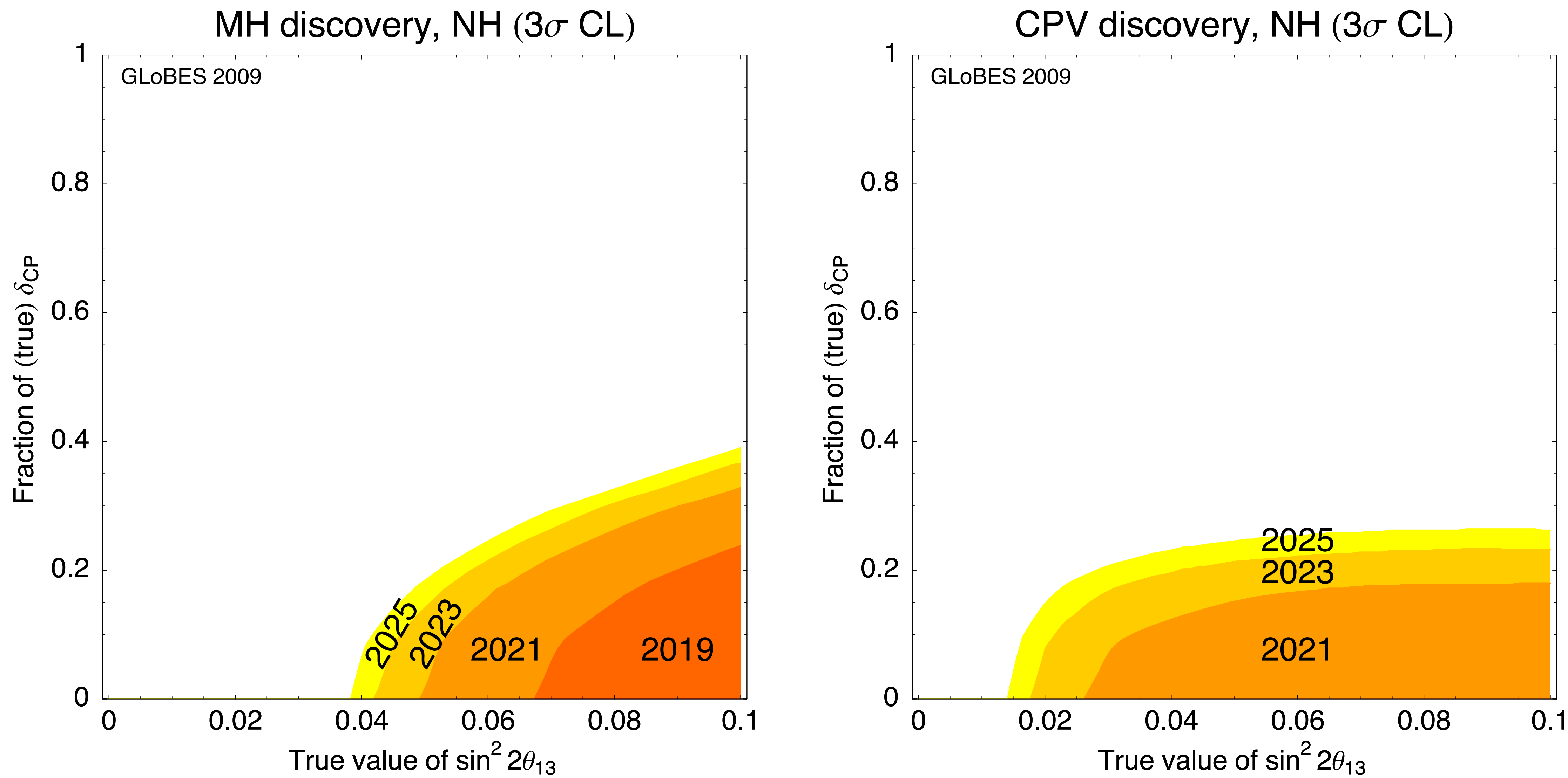
At $3\,\sigma$ this plot would be essentially empty!

PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

P. Huber – VT-CNP – p. 10

Can we avoid very long baselines ?

T2K@1.7MW and NOvA @ Project X



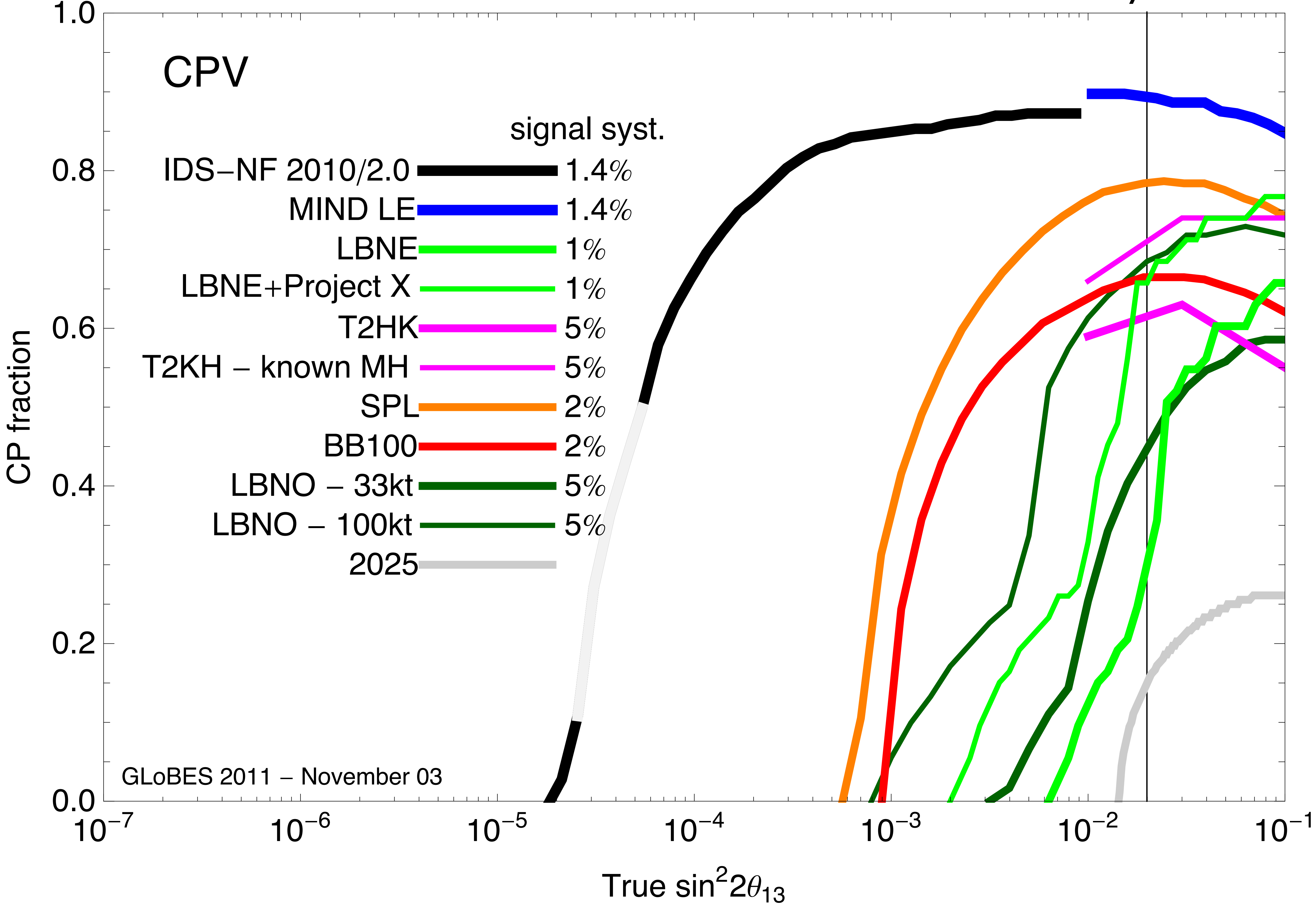
PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

Includes Project X and T2K running at 1.7 MW.

P. Huber – VT-CNP – p. 11

Is a SB enough ?

Courtesy P. Huber



Astroparticle Physics European Strategy

The new 2011 ApP roadmap identifies "four projects to be constructed in the middle of this decade, costing one or more hundreds of Million Euros each"
– Maurice Bourquin, Chairman ApPEC, Paris, November 2011

ASPERA

Large scale projects

1. **Cherenkov Telescope Array (CTA)** is the worldwide priority project, in the domain of TeV gamma-ray astrophysics .
   - Ambitious time schedule for technical design and prototype development , site selection , aiming at a start of construction by the middle of the decade.
2. **High-energy neutrino telescope** in the Mediterranean Sea (**KM3NeT**),
   - Technology definition is in its final stages with prototype deployment within the next 2-3 years, and access to deep-sea research.
3. A global **next-generation ground-based observatory**
   - Need to develop new detection technologies, search for appropriate sites, attract new partners.
4. A megaton-scale detector (**LAGUNA/LAGUNA-LBNO)** for low-energy neutrino astrophysics, proton decay and accelerator driven neutrino physics
   - Global context and interface with CERN European Strategy Update
   - Favourable physics case with recent results by T2K, DCHOOZ, MINOS

European Strategy for Particle Physics

“A range of very important non-accelerator experiments take place at the overlap between particle and astroparticle physics exploring otherwise inaccessible phenomena; Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest.”
– European Strategy for PP, 2006

“Ideal case”: *LAGUNA-LBNO ?*

European “particularity”

CERN Council

Energy frontier — Direct search of new physics at high energy

Flavour physics { quark sector; lepton sector { charged lepton; neutrino

flavour mixing, $\not{C}\not{P}$, rare decays, mass

proton decays, 0ββ decays, etc.

Astroparticle — in/direct search of exotics from the sky

ASPERA Astroparticle Physics European Strategy

T. Nakada (Particle Physics Strategy) European Strategy for Astroparticle Physics, Paris, November 21-22, 2011 7/28

Conclusions

- Next phase of LAGUNA design study successfully started
  - Wider scope (LBNO) & more focus (sites, technologies)
  - Enlarged, stronger collaboration, and larger budget
- We are proposing a "realistic plan" for a European LBL programme with great discovery potentials, starting with mass hierarchy determination and leading to CP-violation.
- In parallel, ultimate search for proton decay and interesting neutrino astrophysics measurements.
- Timely submission (mid-2012 ?) of an expression of interest is the first mandatory step. Positive feedback from the European Strategy Roadmap and support from CERN will be of utmost importance.
- Open to any collaborator – we hope you will too become a "LAGUNA-LBNO associate member" !

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)

Backup slides

CERN SPS/CNGS power limitations

Int. per PS batch	# PS batches	Int. per SPS cycle	200 days, 100% efficiency, no sharing	200 days, 55% efficiency, no sharing	200 days, 55% efficiency, 60% CNGS sharing
		[prot./6s cycle]	[pot/year]	[pot/year]	[pot/year]
2.4×10^{13} - Nominal CNGS	2	4.8×10^{13}	**1.38×10^{20}**	**7.6×10^{19}**	**4.56×10^{19}**
3.5×10^{13} - Ultimate CNGS	2	**7.0×10^{13}**	2.02×10^{20}	1.11×10^{20}	6.65×10^{19}

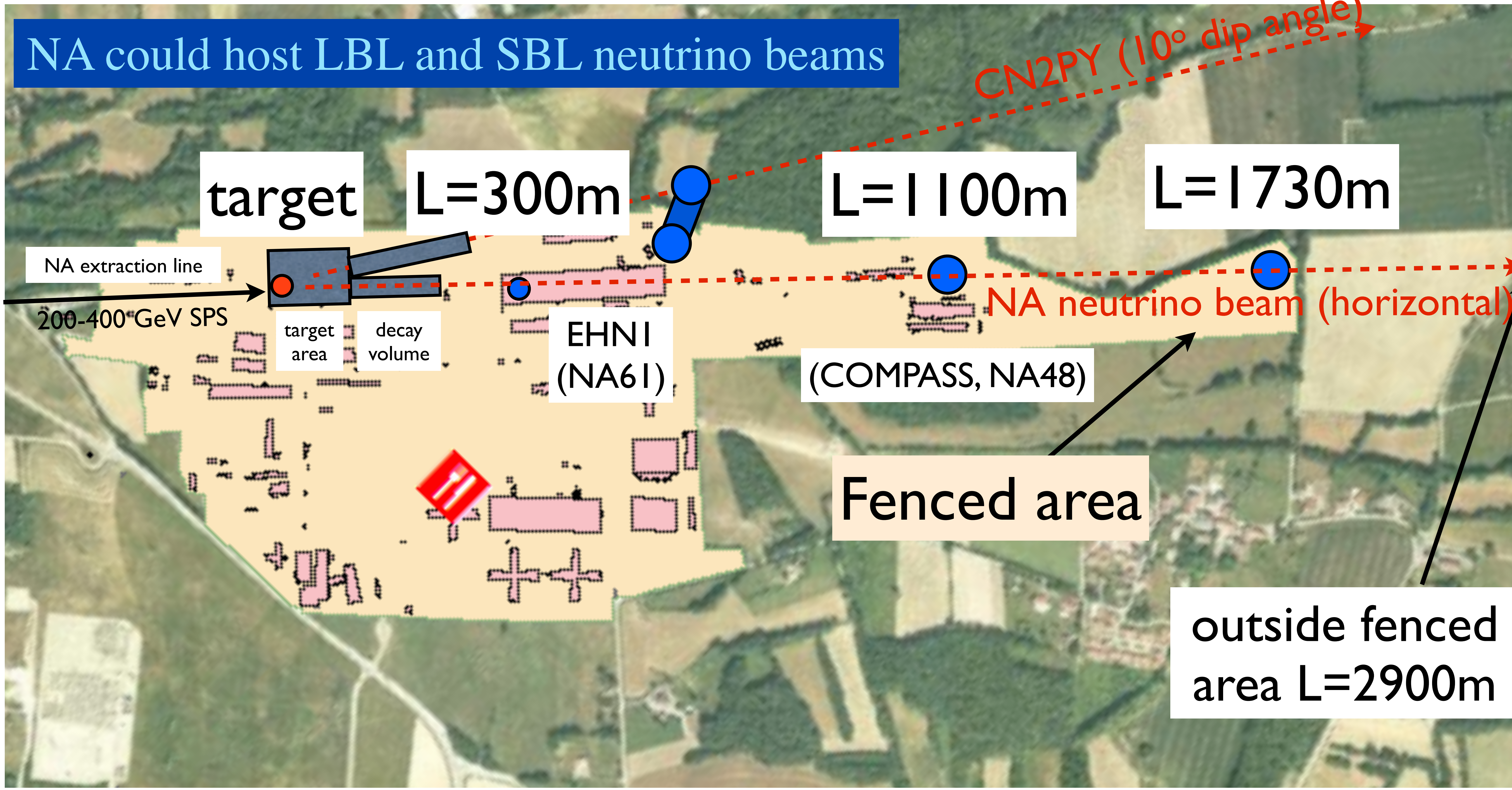
M.Meddahi, E.Schaposnicova - CERN-AB-2007-013 PAF

750kW design limit for the target

working hypothesis for RP calculations

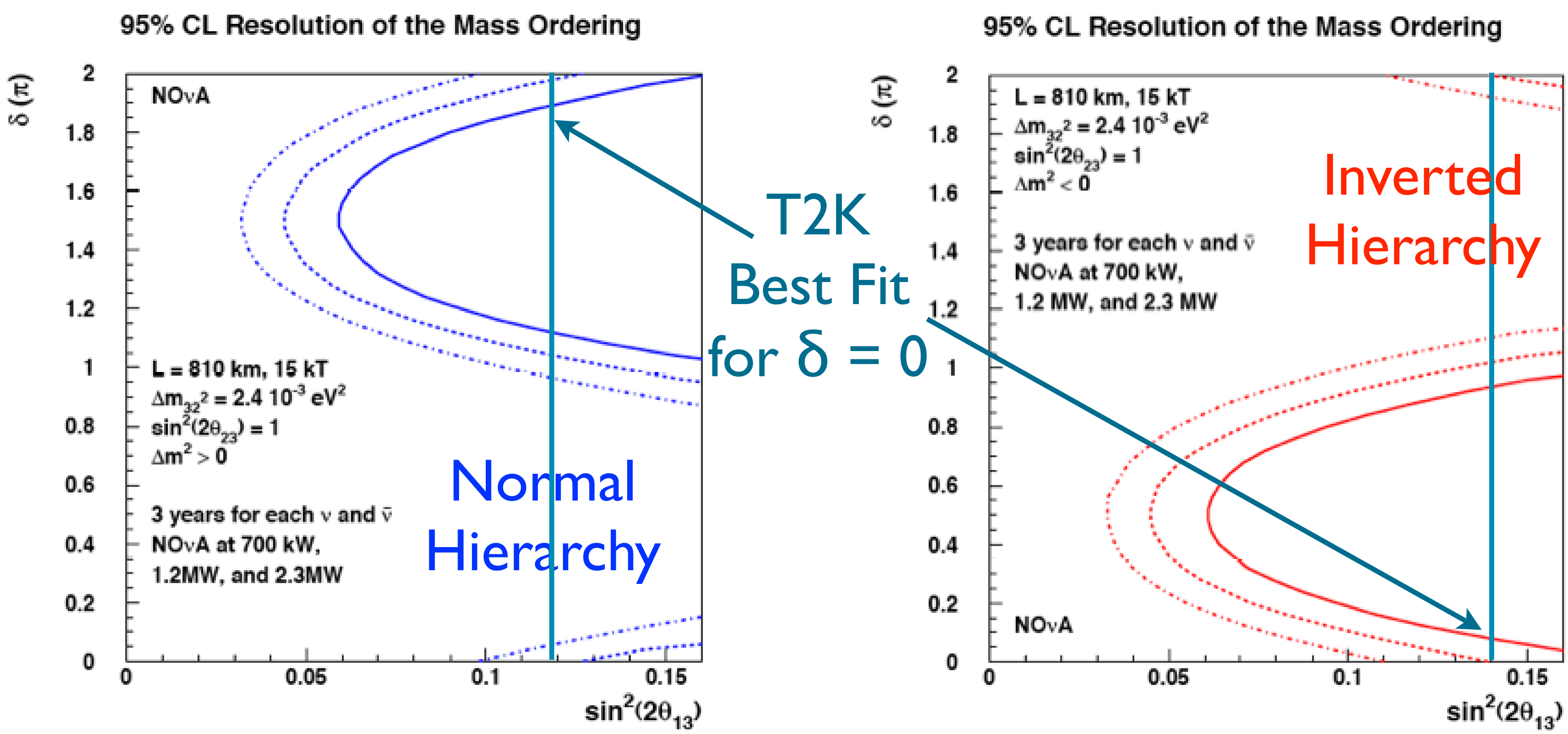
CERN SPS(+LIU) could deliver (1÷2)e20 pot/year in dedicated mode and depending on efficiency (in 2011 was ≈80%)

A low/high-energy neutrino (short baseline) beam in the CERN North Area



High and low energy beam options possible for detector R&D, cross-section measurements, oscillations @ L/E≈1 eV^2, electroweak physics,...

Sensitivity to Mass Ordering



- 95% CL resolution for mass ordering shown for normal and inverted hierarchy, curves represent different beam powers
- Resolve mass ordering for large fraction of possible values of δ if T2K result is correct
- Even better resolution with information from another baseline
- Resolve ambiguity for values of $\sin^2(2\theta_{13})$ to the right of the curves

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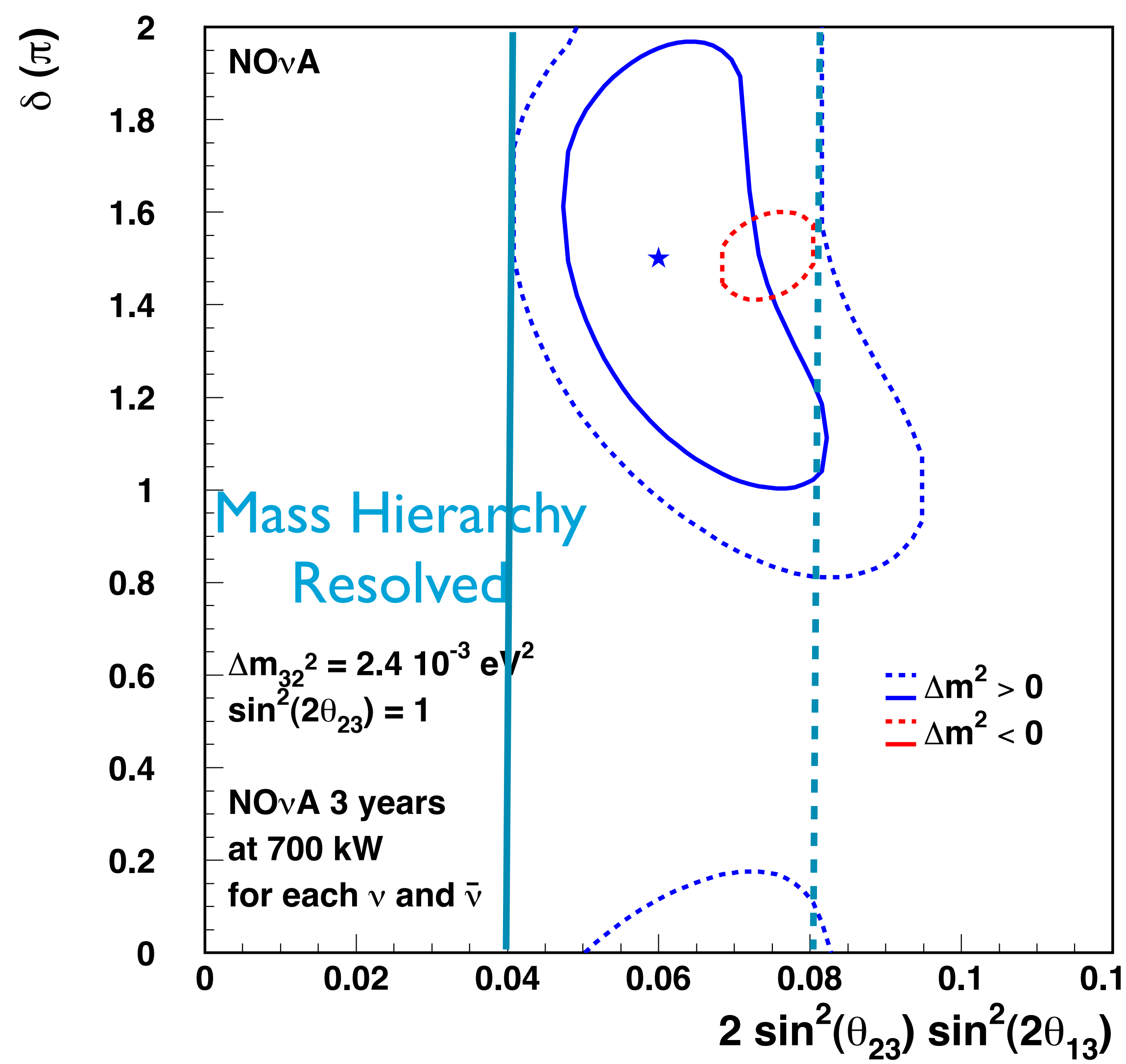
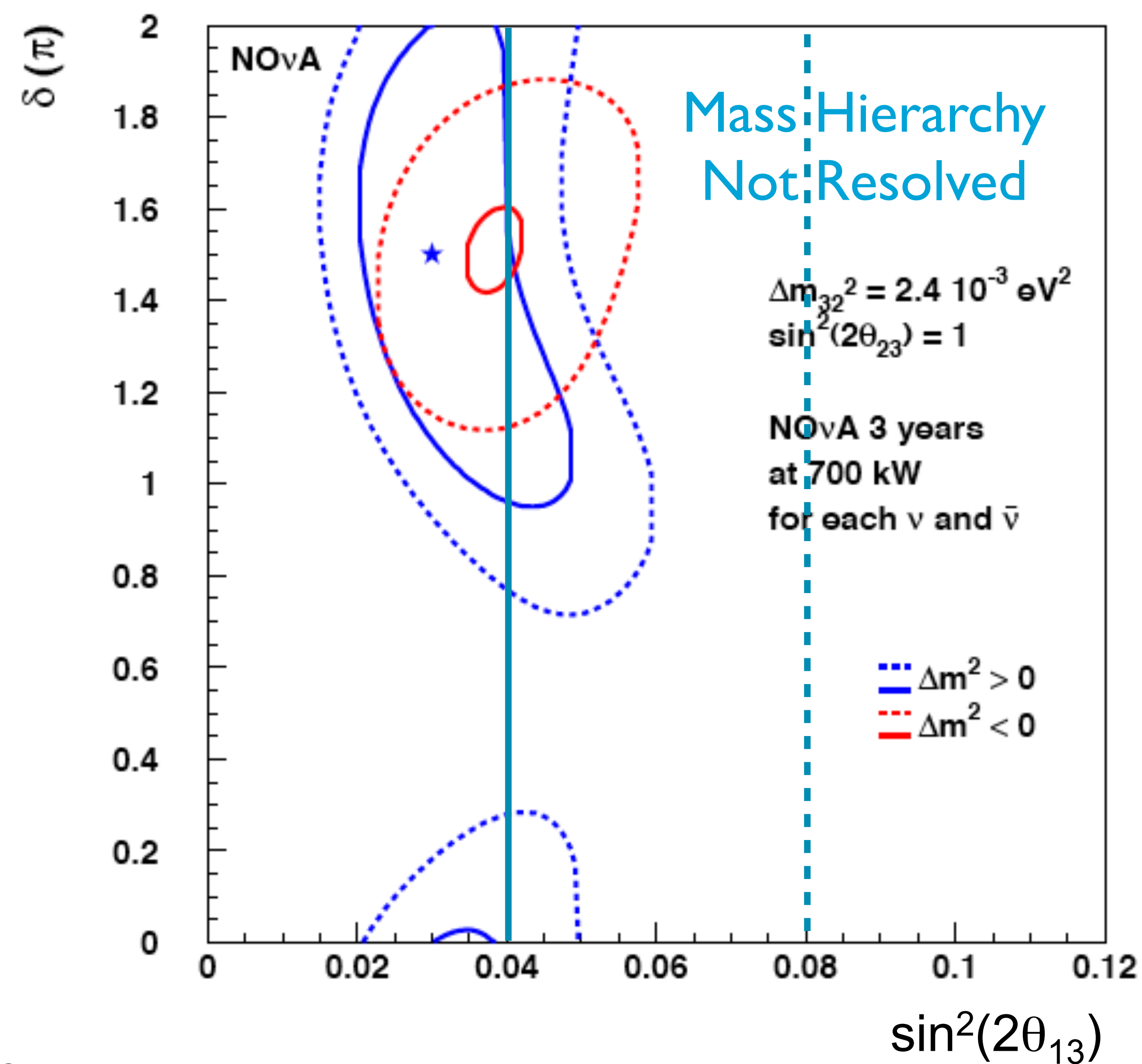
Sensitivity to CP Violating Phase δ

Contours for Starred Point for NOvA



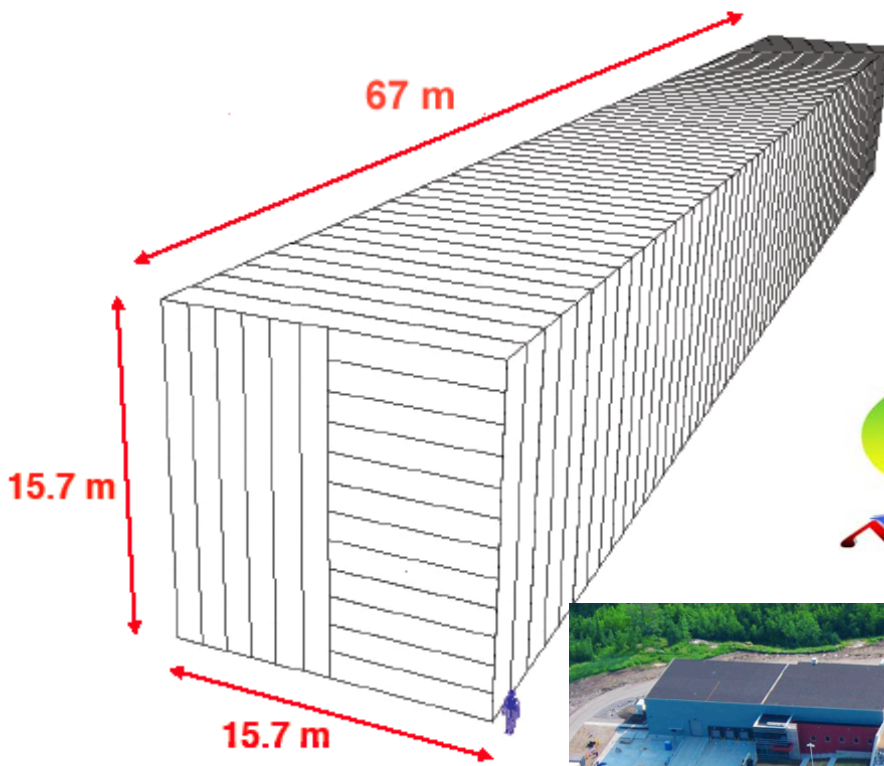
1 and 2 σ Contours for Starred Point for NOvA



- Plots show 1 and 2σ contours for 700 kW beam with chosen point
- Vertical lines show MINOS best fit values for δ = 0, solid is normal hierarchy
- NOνA sensitivity includes δ = 0, π at 2σ
- Can point to which CP phase half plane to target for future measurement

Other (beam only) detectors: TASD and MIND

TASD = NOvA-like

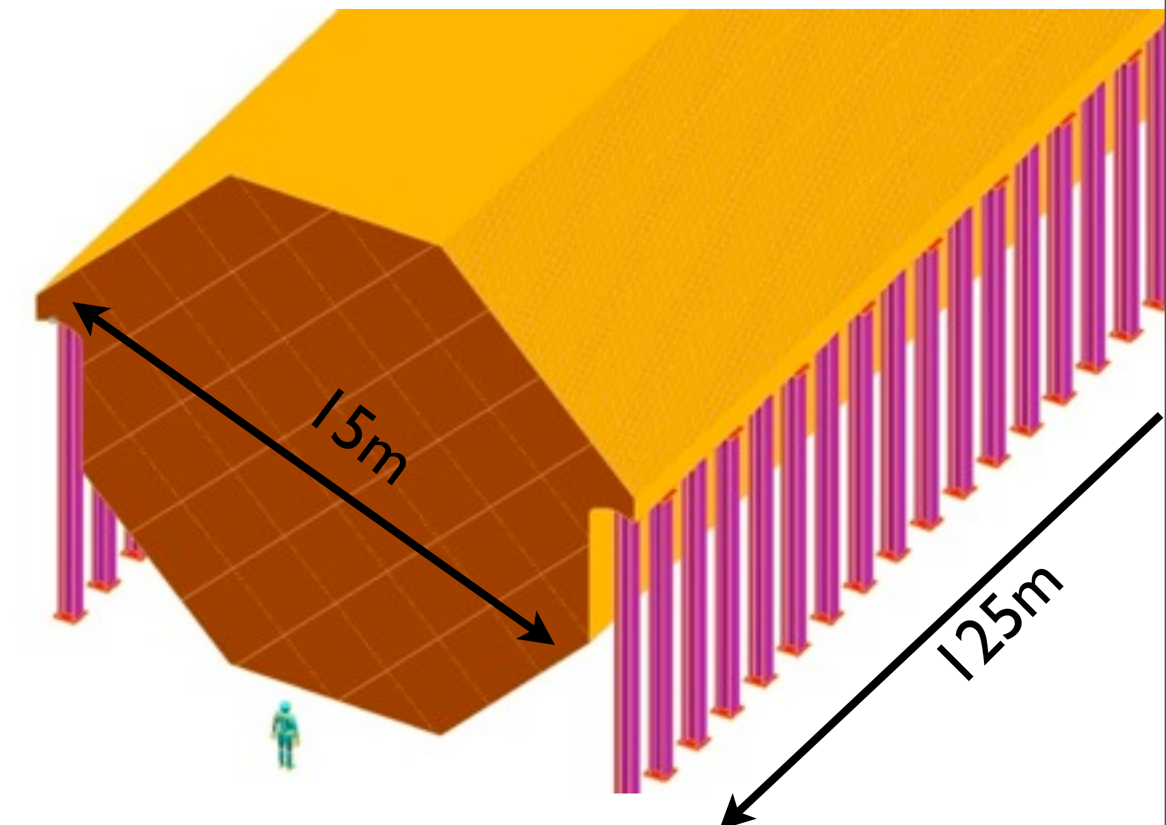


NOVA
3 mwe

- 14 kt total mass, 70% scintillator
- 930 planes
- ~3 m water equivalent earth overburden of barite and concrete

Surface detector (a possible alternative to a deep underground detector if mass scalable up to 100 kton)

MIND = MINOS-like



- 3cm Fe plates, 2cm scintillator bars
- B=1 T
- IDS-NF Magnetised Iron Neutrino Detectors (MIND) with 2500 plates:
  - 100 kton at 2500-5000 km

Can act as a muon spectrometer for a fine-grained target while independently collecting neutrino interactions in Fe