UPPSALA UNIVERSITET

Measuring CP violation with an ESS neutrino beam

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right)$$

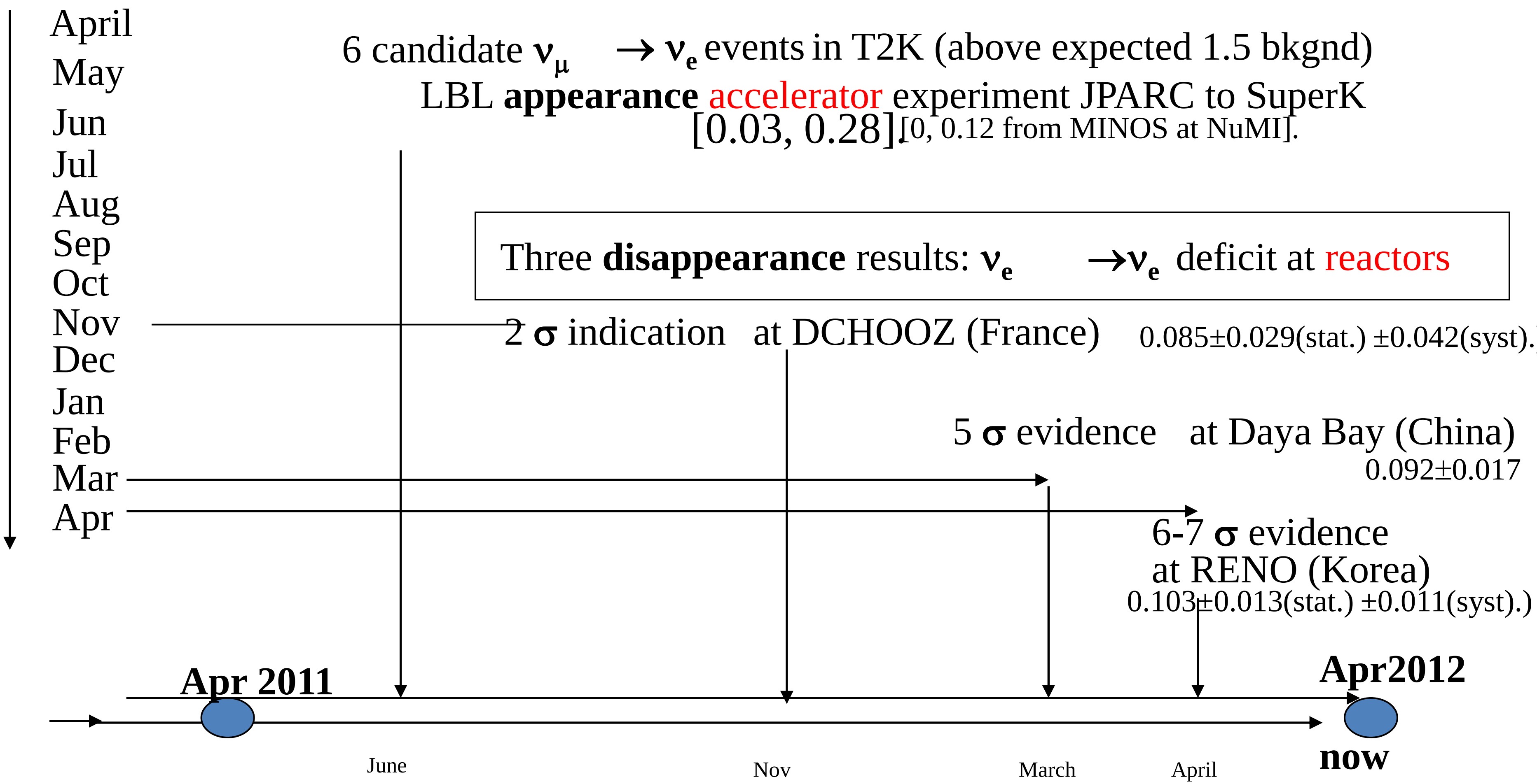
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

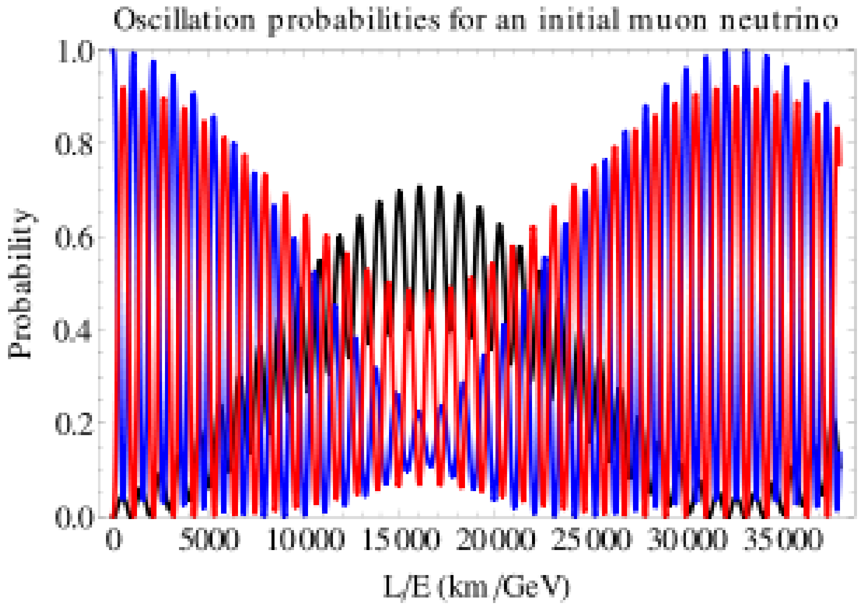
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

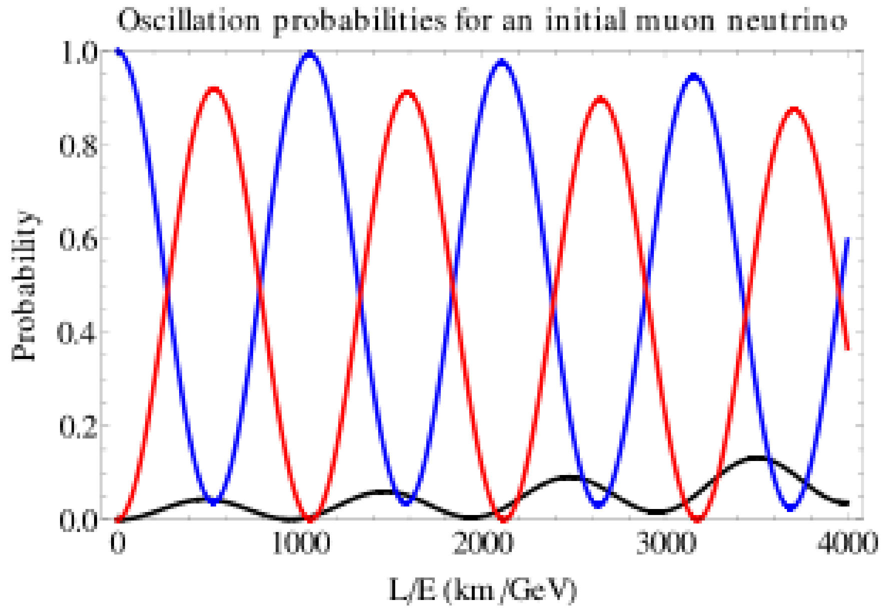
$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E}\ \frac{aL}{4E}\ (1 - 2S_{13}^2)$$

2011-2012 $\sin^2 2\theta_{13} \cong 10\%$







Blue is mu neutrino, red tao neutrino and black electron neutrino

Currently measured values

$\sin^2(2\theta_{13})$ = 0.103±0.013stat±0.011 (Reno)
$\tan^2(\theta_{12})$ = 0.457+0.040−0.029 "the solar angel"
$\sin^2(2\theta_{23})$ > 0.92 at 90% CL "the atmospheric angle"
$\Delta m^2_{21} \equiv \Delta m^2_{sol}$ = 7.59+0.20−0.21×10^{-5} eV^2
$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{atm}$ = 2.43+0.13−0.13×10^{-3} eV^2
δ and the sign of Δm^2_{32} are currently unknown

Values used for the curves

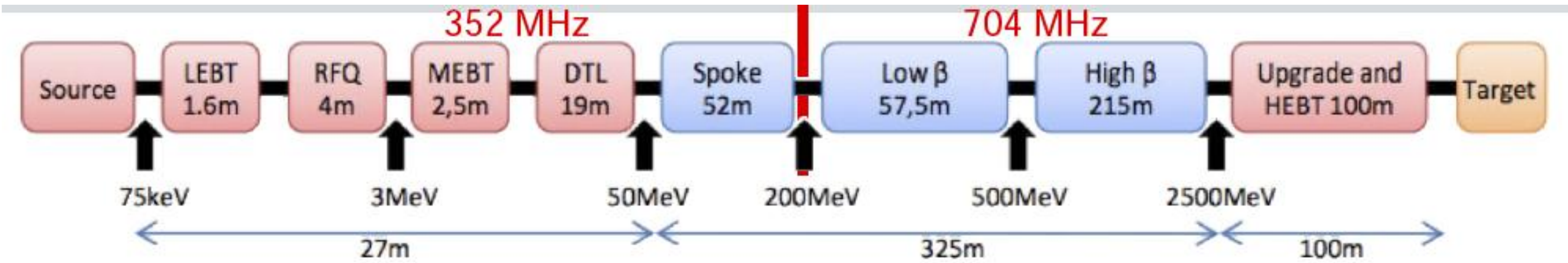
$\sin^2 2\theta_{13} = 0.10$
$\sin^2 2\theta_{12} = 0.861$
$\sin^2 2\theta_{23} = 0.97$
$\Delta m^2_{12} = 7.59\times10^{-5}\ eV^2$.
$\Delta m^2_{32} \approx \Delta m^2_{13} = 2.32\times10^{-3}\ eV^2$
δ = 0; normal mass hierarchy.

If CP is violated, i.e. if δ is not =0 or =π, the absolute level of the oscillation probabilities, as well as the ratio between the neutrino and antineutrino oscillation probabilities (as ratio insensitive to errors in the absolute neutrino flux) will vary with δ.

The ESS proton linac

- European 5 MW Neutron Spallation Source will be built in Lund producing ***10^{23} protons on target/year***
- Finance volume: ~1 600 MEuro
- 3 y design + 4 y construction, First beams ~2019
- Uppsala University has taken responsibility for the development of the 352 MHz radio-frequency distribution system of the ESS – project
- Project cost 178 MSEK financed by KAW 40 MSEK, Swedish Government 50 MSEK, ESS AB 60 MSEK, VR 13 MSEK and UU 15 MSEK
- Contract signed by UU and ESS managements 10 June 2011 and delegated to the Uppsala Dept of Physics and Astronomy (IFA)
- FREIA Sub-Department in IFA created in September 2011, Board Members: T. Ekelöf (föreståndare), R. Ruber (projektledare), A. Rydberg (RF), V. Ziemann (v. projektledare)

Which is the High Energy Physics potential of the ESS project?



Order of magnitude cost 700 MEuro

The ESS will be a copious source of spallation neutrons but also of

neutrinos

Running ESS with a thinner target that lets the charged pions out in the forward direction will produce a collimated neutrino beam of around 400 MeV energy.

Additions to the present ESS proton linac required for the generation of such a beam;

1. A special (thinner) neutrino target with a neutrino horn (studied in detail in EUROν)

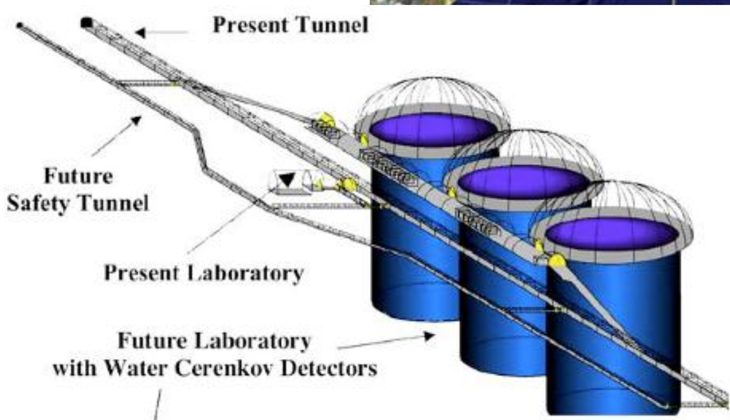
2. A 2.5 GeV accumulator ring to compress the ca 3ms long ESS pulse to a few microseconds pulse (to reduce the cosmic ray background in the underground ν detector)

3. Acceleration of H^- pulses in the ca 70 ms long empty buckets between the ESS proton 3 ms pulses (70 ms spacing is needed for the TOF measurement of the spallation neutrons) requiering a doubling of the rf power generation capacity (either doubling of the number of modulators or doubling of the capacitors and the cooling of the modulators, also more liquid Helium cooling of accelerting cavities needed)

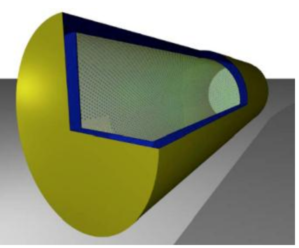
4. A very large, order Megaton, water Cherenkov neutrino detector + a smaller near detector

Sites and detection techniques and possible neutrino beams, all from CERN, that have been under consideration by LAGUNA

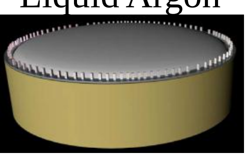
MEMPHYS 450 Ktons
Water Chernkov

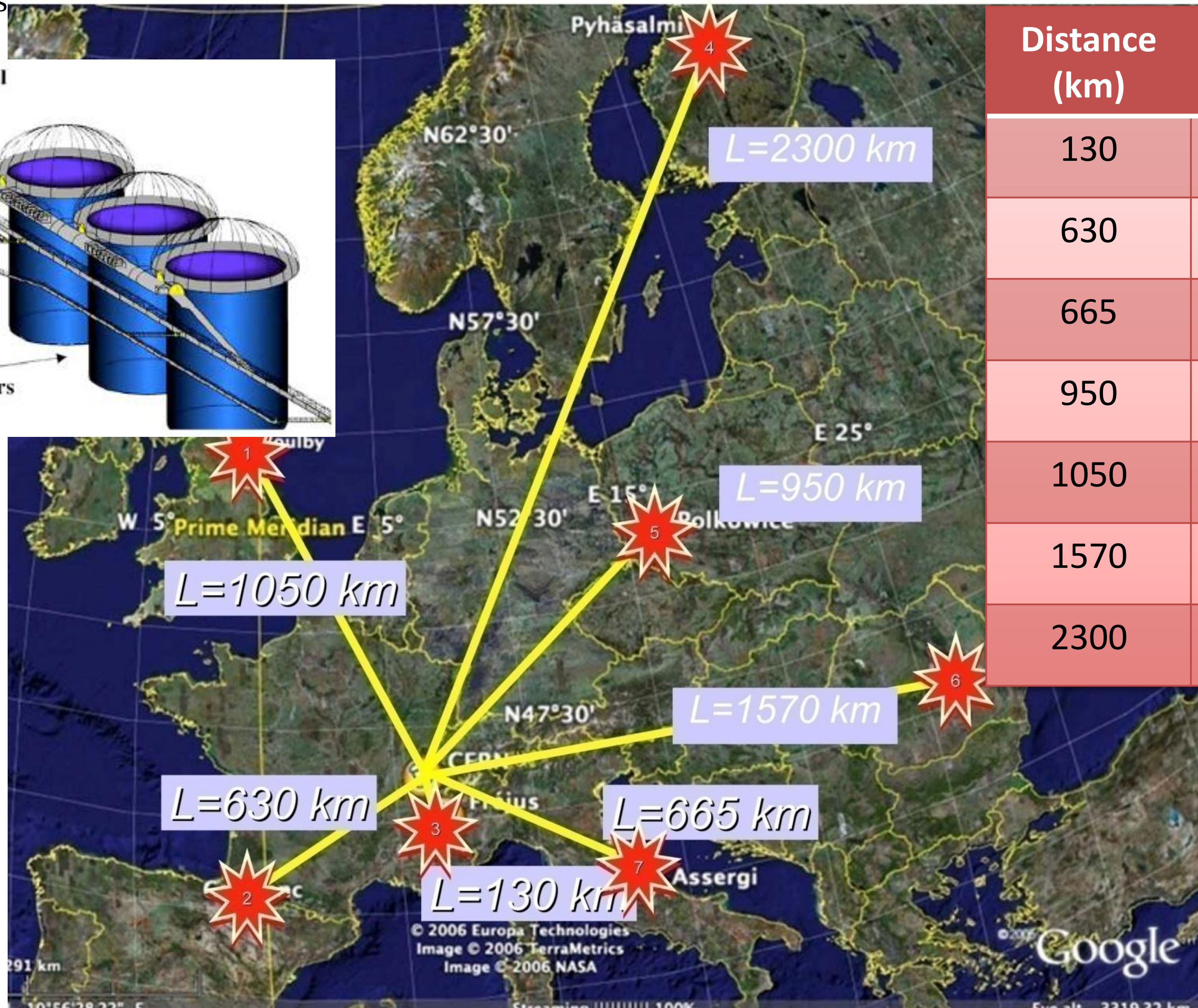


LENA 50 ktons
Scintillator oil



GLACIER 100 ktons
Liquid Argon





Distance (km)	1st osc. max (GeV)
130	0.26
630	1.27
665	1.34
950	1.92
1050	2.12
1570	3.18
2300	4.65

A LENA scintillator υ detector and a GLACIER Liquid Argon υ detector in a long base line neutrino Beam from the CERN SPS

Of all the detector sites previously studied the main option of the LAGUNA Collaboration is currently the Pyhäsalmi mine project using a high energy (4.65 GeV) neutrino beam from the CERN SPS with a scintillator detector and a liquid argon detector at a distance of 2300 km.

This experiment is, due to its long base line and thereby its sensitivity to the matter effect, well suited to attack the next main problem in neutrino physics, after the recent measurement of $\sin^2 2\theta$, which is the determination of the mass hierarchy. It will subsequently be used for the main purpose of searching for CP violation from the rate of appearance of υ_e in the $\upsilon_\mu \rightarrow \upsilon_e$ oscillation.

Study presented in this talk:

A MEMPHYS type water Cherenkov detector in a short base-line υ beam from the ESS in Lund

The 2.5 GeV protons beam from the ESS proton linac can be used to produce both a neutrino and an anti-neutrino beam and detect both ν_e and anti-ν_e using a large water Cherenkov detector of the MEMPHYS type.

• Due to the short base line the matter effect does not alter the ratio between ν_e and anti-ν_e.

• Due to the low beam energy,
-below the K production threshold, the background of ν_e from K decays is suppressed and
- the gamma background from π^0 decays is less serious as background.

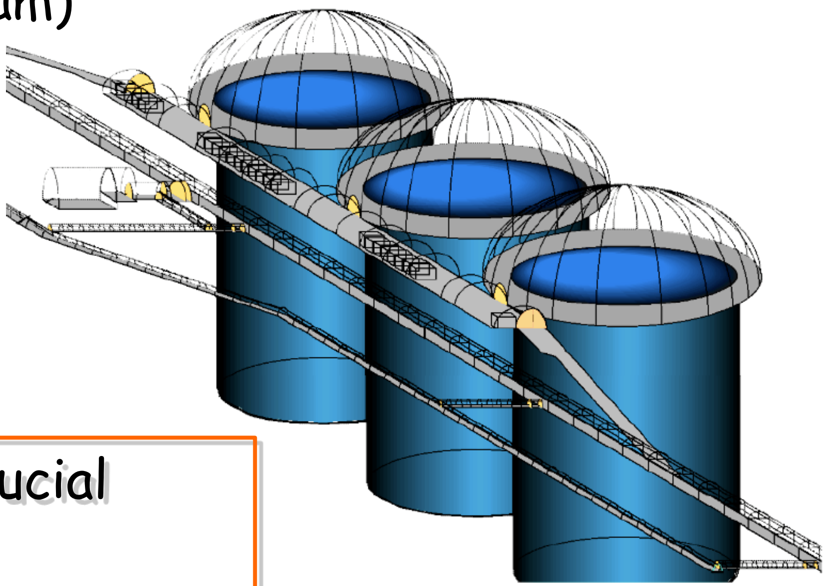
• This enhances the sensitivity of this experiment to CP violation and makes it complementary to the Pyhäsalmi project.

• In addition the MEMPHYS type detector could also, in a second stage, be made to receive a long baseline (1500 km) neutrino beam from the CERN SPS.

The MEMPHYS Project
(within FP7 LAGUNA)

A "Hyperkamiokande" detector to study

- Neutrinos from accelerators (Super Beam)
- Supernovae (burst + "relics")
- Solar neutrinos
- Atmospheric neutrino
- Geoneutrinos
- Proton decay up to ~35 years life time

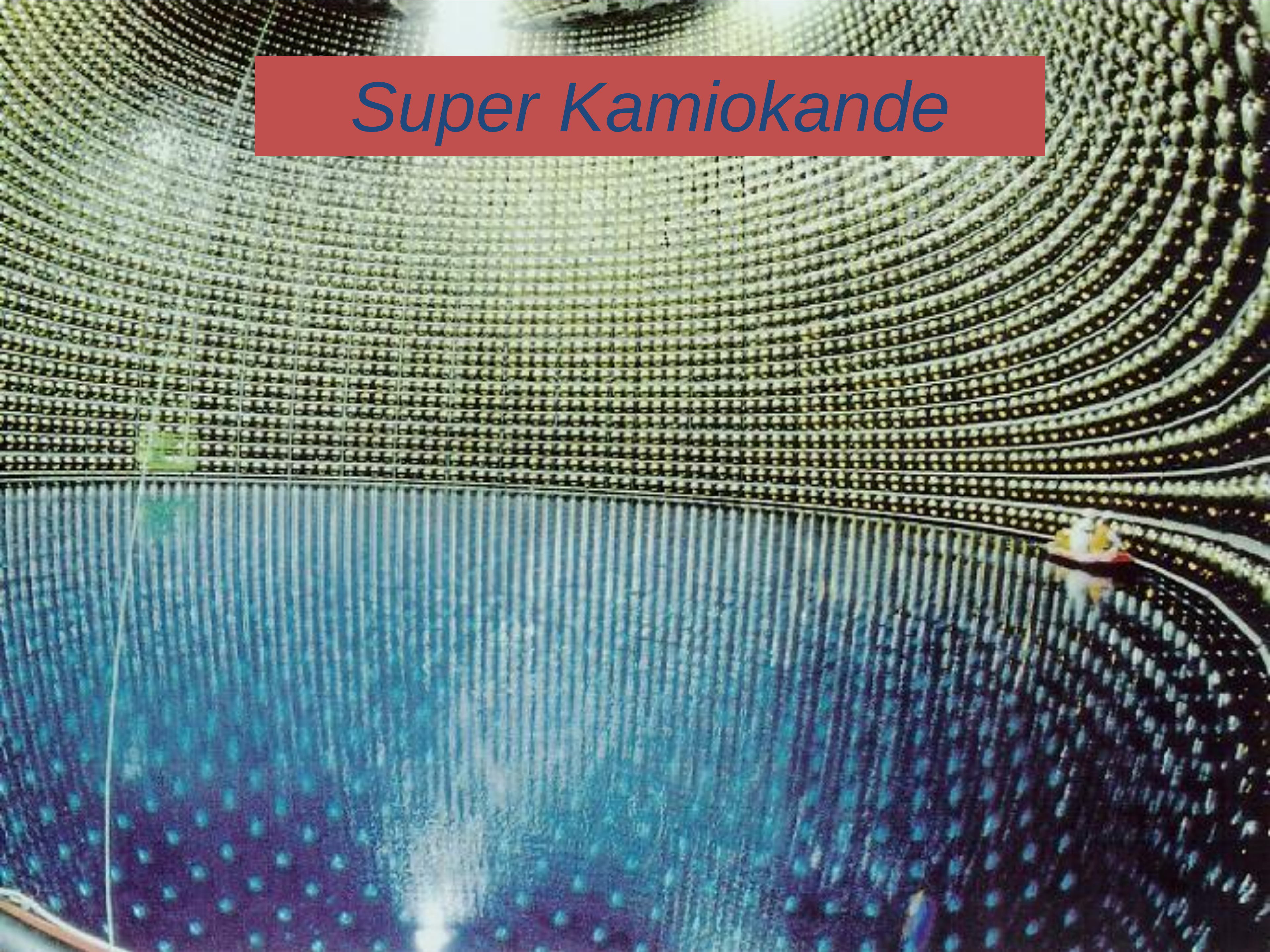


Water Cerenkov Detector with total fiducial mass: 440 kt:
- 3 Cylindrical modules 65x65 m
- Readout: 3x81k 12" PMTs, 30% geom. cover. (#PEs =40% cov. with 20" PMTs).

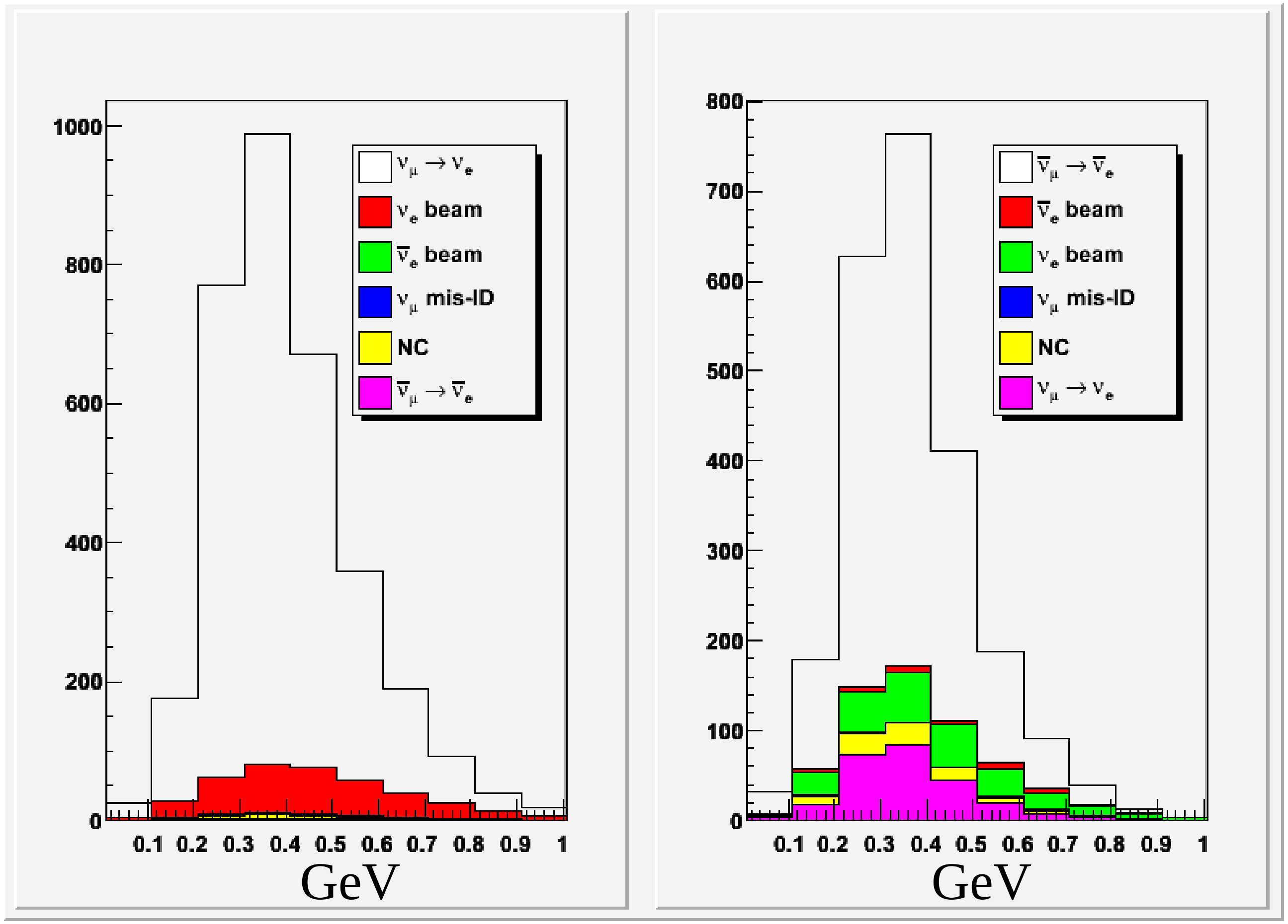
(arXiv: hep-ex/0607026)

Order of magnitude cost : 700 MEuro

Super Kamiokande

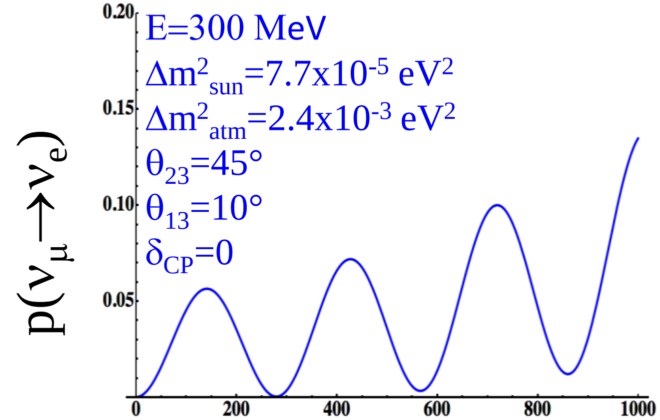


ν_e and anti-ν_e energy spectra at 150 km from Lund around the first oscillation maximum



$\nu_\mu \to \nu_e$ oscillation probability

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
&+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
&- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
&+ 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \\
&- 8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}\left(1 - 2S_{13}^2\right)
\end{aligned}
$$

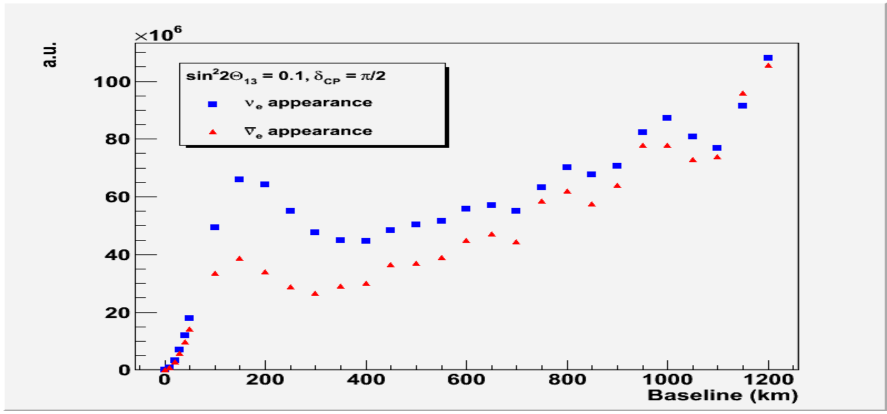


ν_e and anti-ν_e fluxes

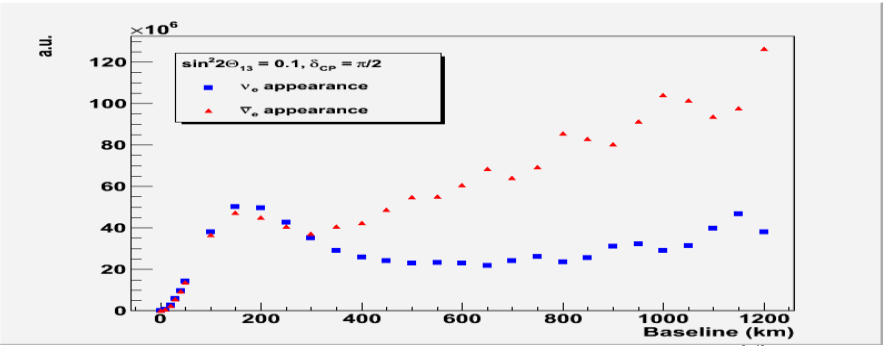
Calculations using GLOBES of ν_e and anti-ν_e fluxes as function of the distance from the ν_μ source produced by a ESS 2.5 GeV proton beam, <u>8 years anti-ν_e + 2 years ν_e running</u>.

Calculations performed by Henrik Öhman/ Uppsala Univ.

δ_{CP}=0



δ_{CP}= π/2



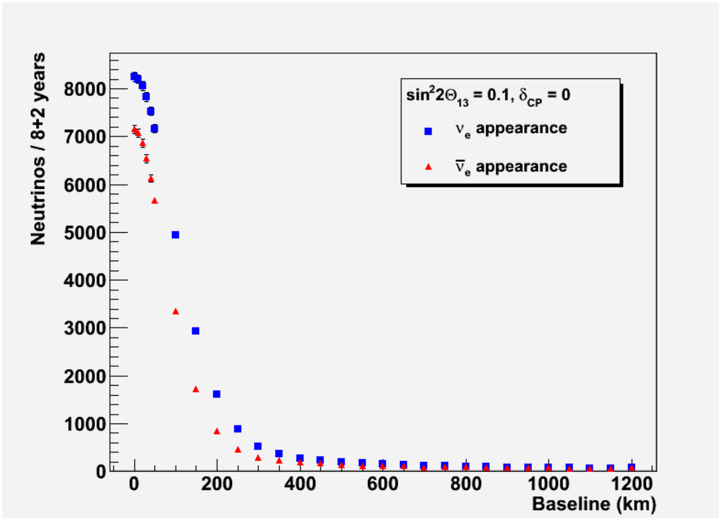
Blue crosses ν_e Red crosses anti- ν_e

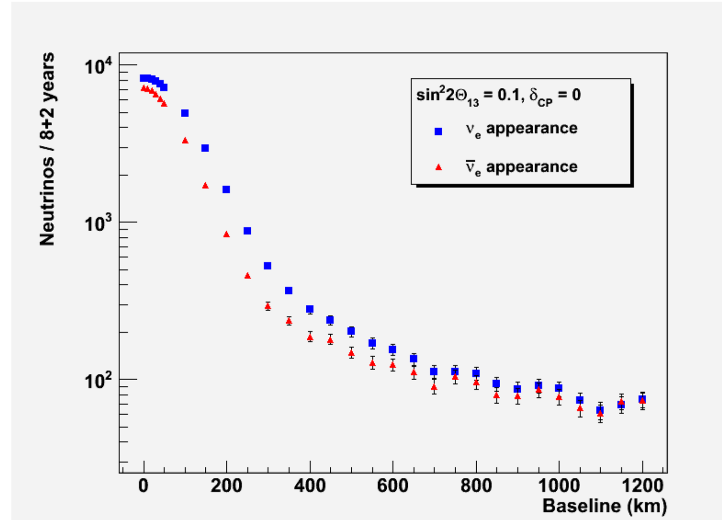
Question

Which is the optimal base-line length for
a neutrino beam generated from 2.5 GeV protons
– i.e. which would be the
optimal distance from Lund at which to place
a neutrino detector?

ν_e and anti-ν_e flux detected in the MEMPHIS detector versus the distances from the neutrino source

δ_{CP}=0

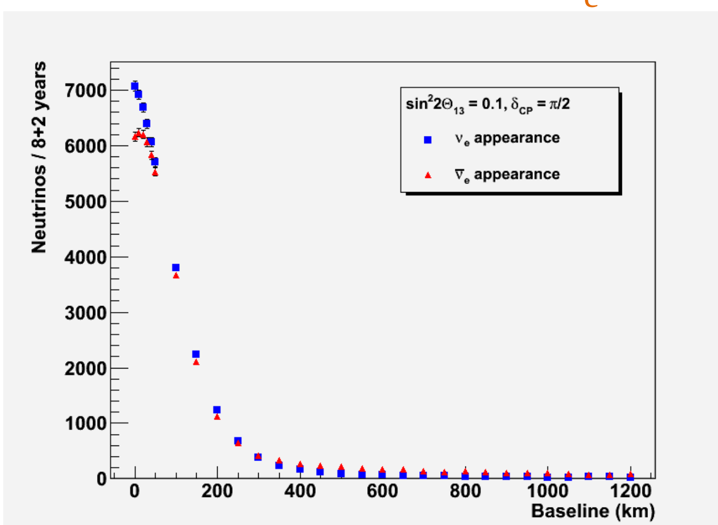


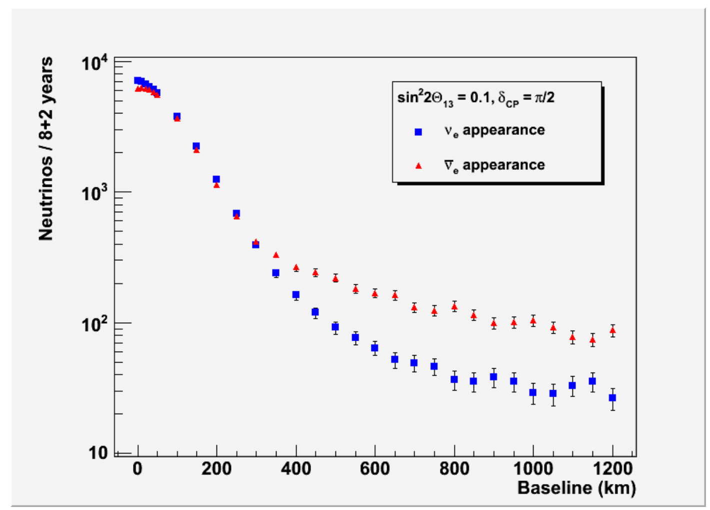


Blue crosses ν_e

Red crosses anti- ν_e

δ_{CP}= $\pi/2$



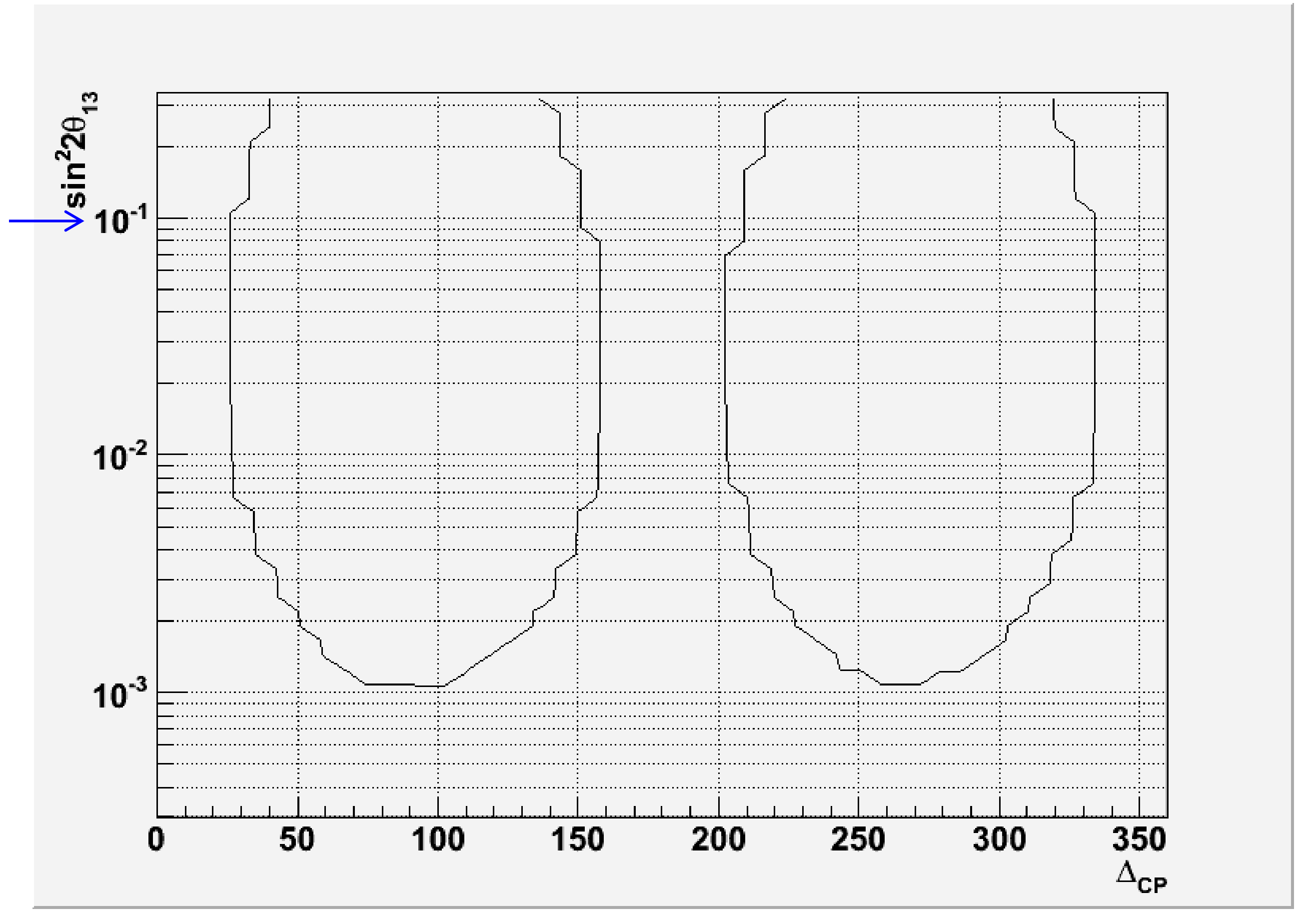


Linear scale

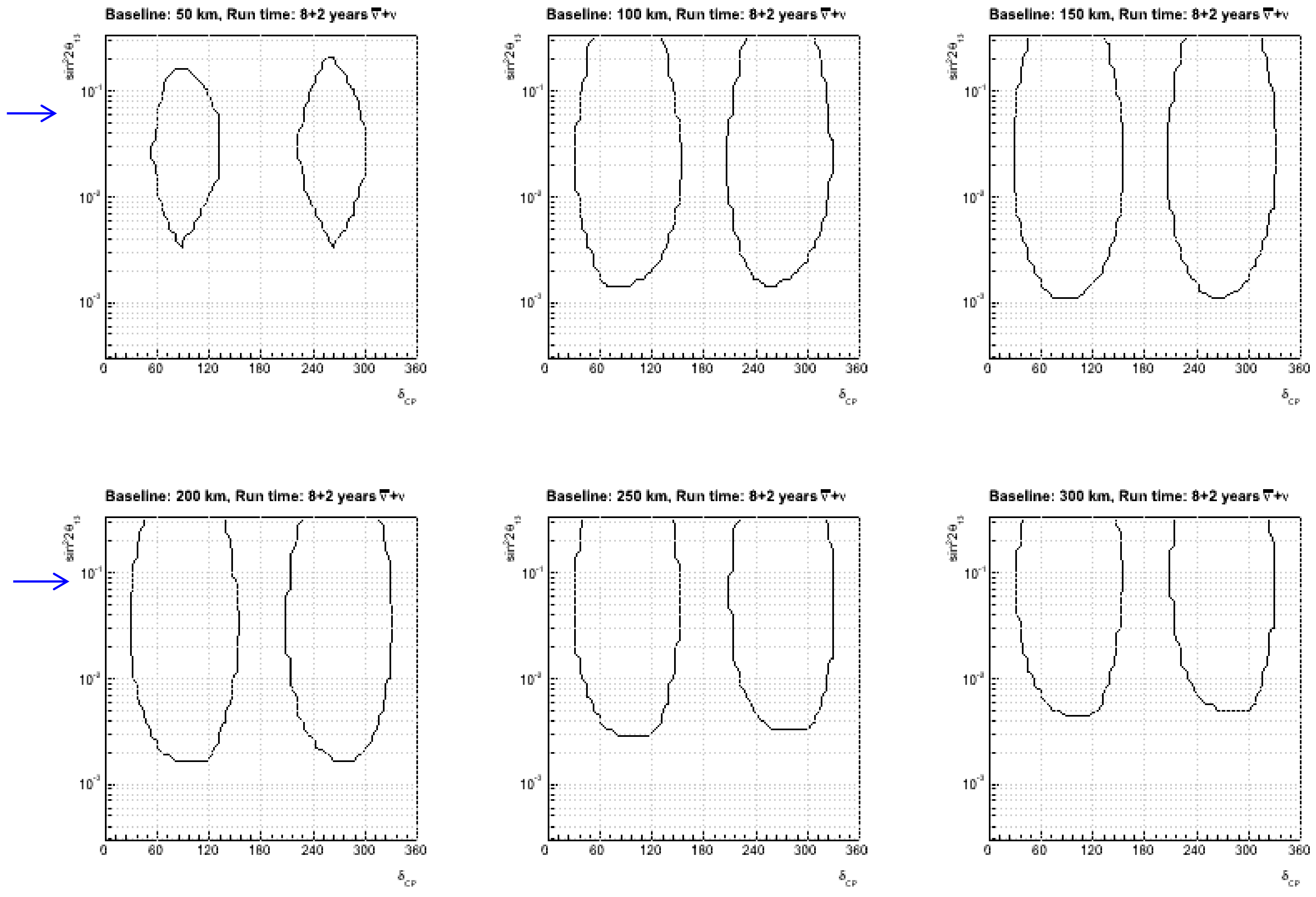
Log scale

Neutrino CP violation discovery potential at 3σ level in the $\sin^2 2\theta_{13}$ vs Δ_{CP} plane.

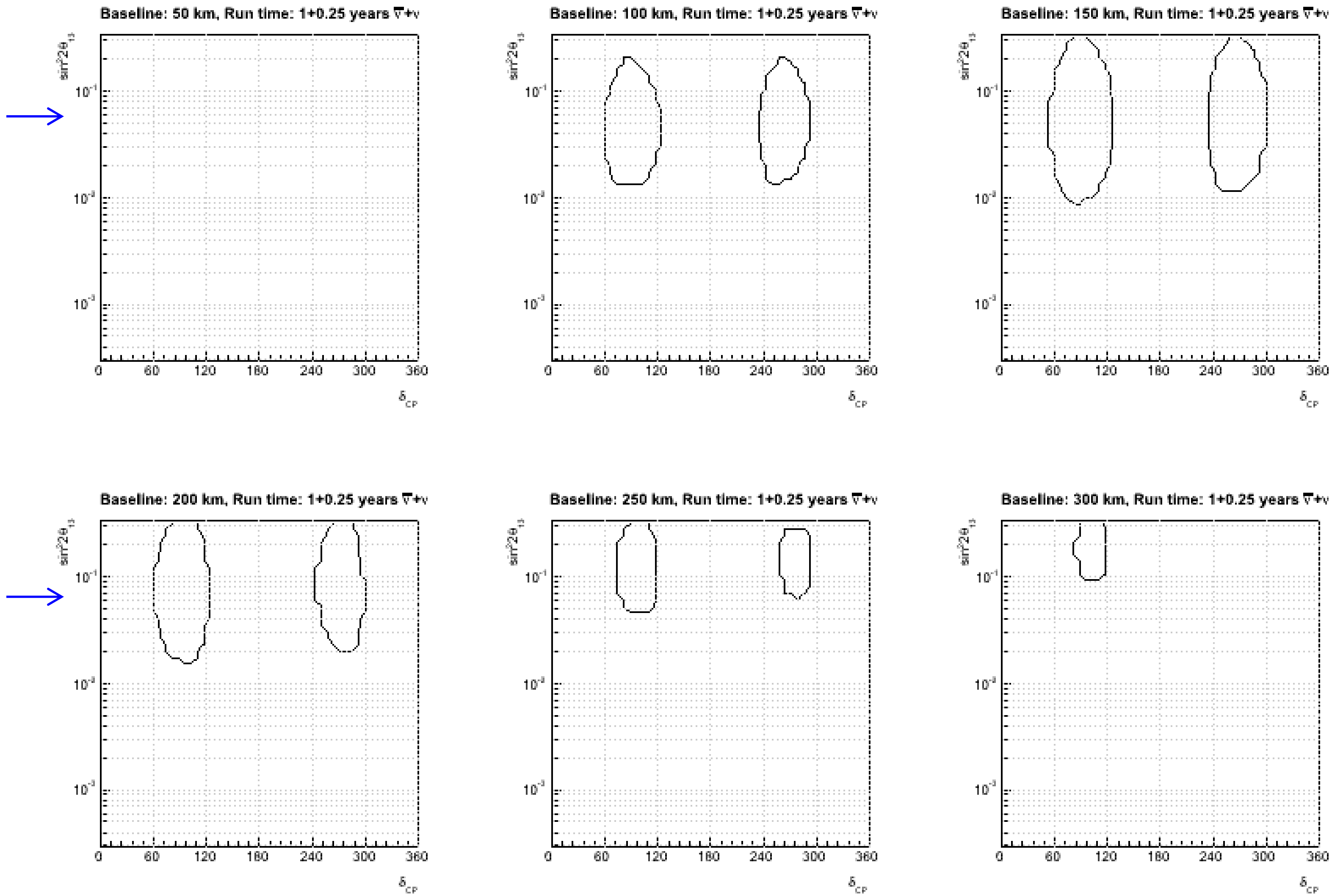
The parameter values used in the GLOBES calculation are;
$\Delta m^2_{12} = 7*10^{-5}$ eV^2,
$\Delta m^2_{31} = +2.43*10^{-3}$ eV^2 (normal hierarchy),
$\theta_{12} = 0.591$ and
$\theta_{23} = \pi/4$.
These parameters are included in the fit assuming a prior knowledge with an accuracy of 10% for θ_{12} , θ_{23} , 5% for Δm^2_{31} and 3% for at Δm^2_{12} at 1σ level.
The running time is (2ν+8anti-ν) years



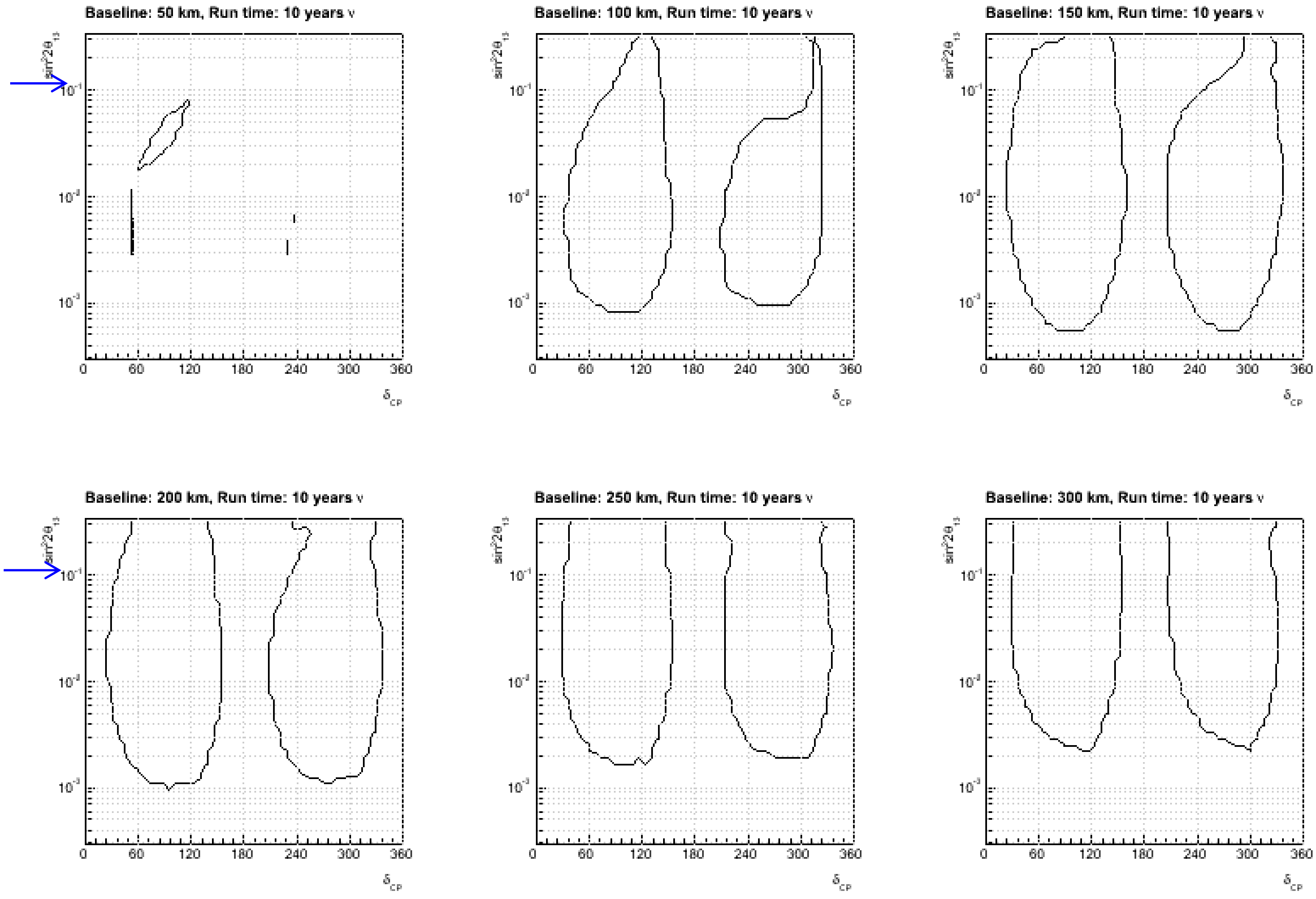
CP violation discovery plots for 8 antineutrino and 2 neutrino years at different base-lines 50, 100, 150, 200, 250 and 300 km



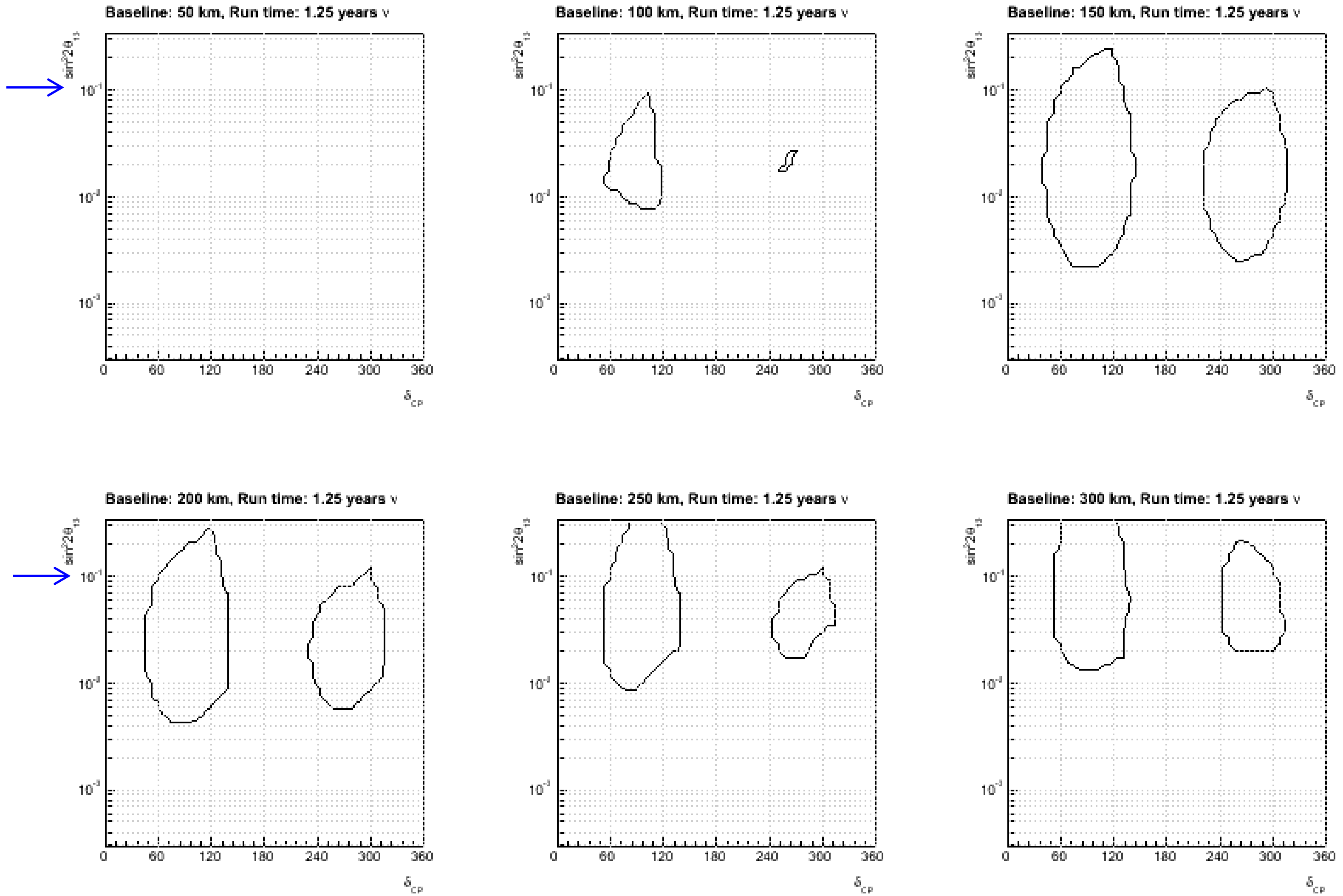
CP violation discovery plots for 1 antineutrion and 0.25 neutrino years with different base-lines 50, 100, 150, 200, 250 and 300 km



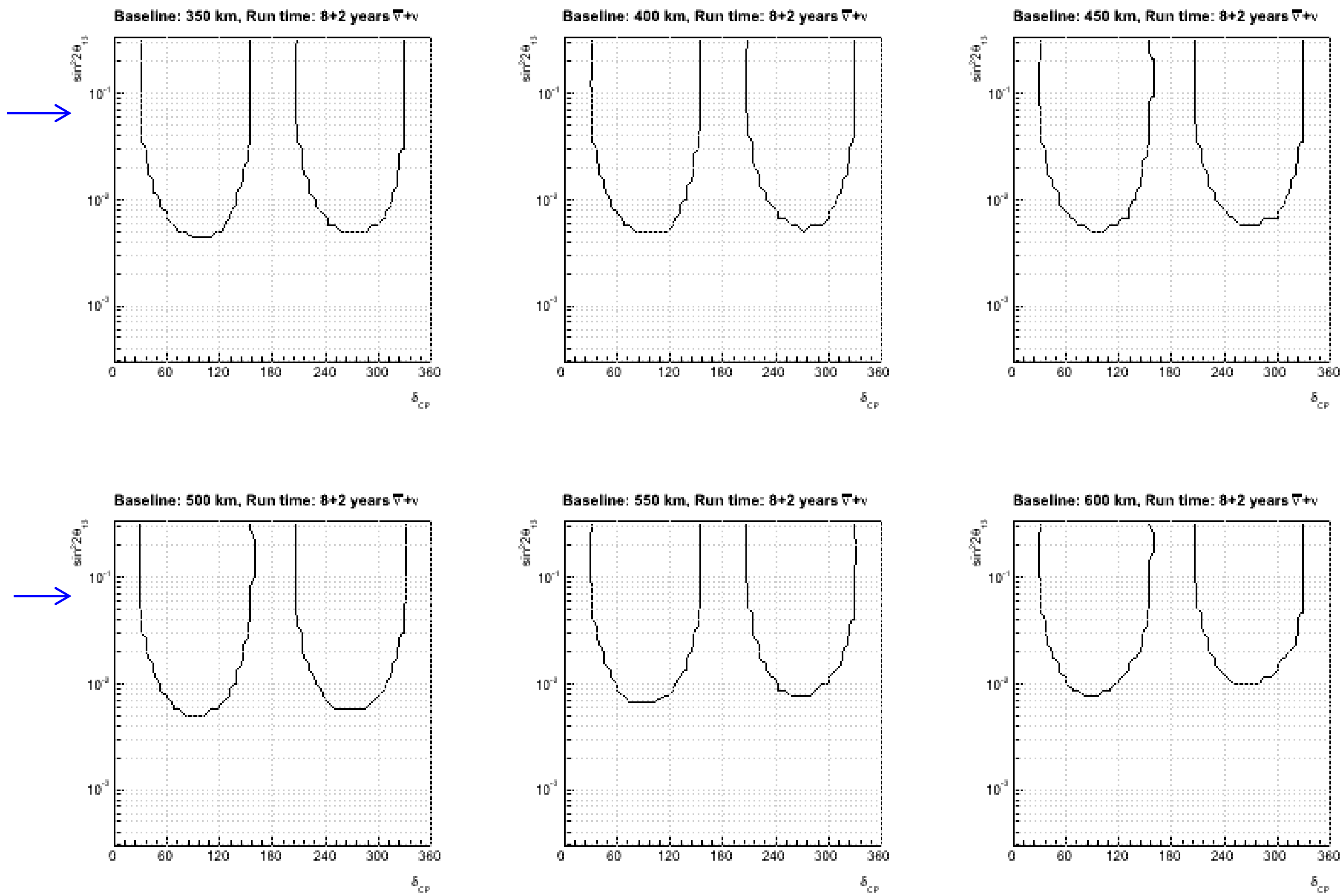
CP violation discovery plots for 10 neutrino (ONLY) years with different base-lines 50, 100, 150, 200, 250 and 300 km



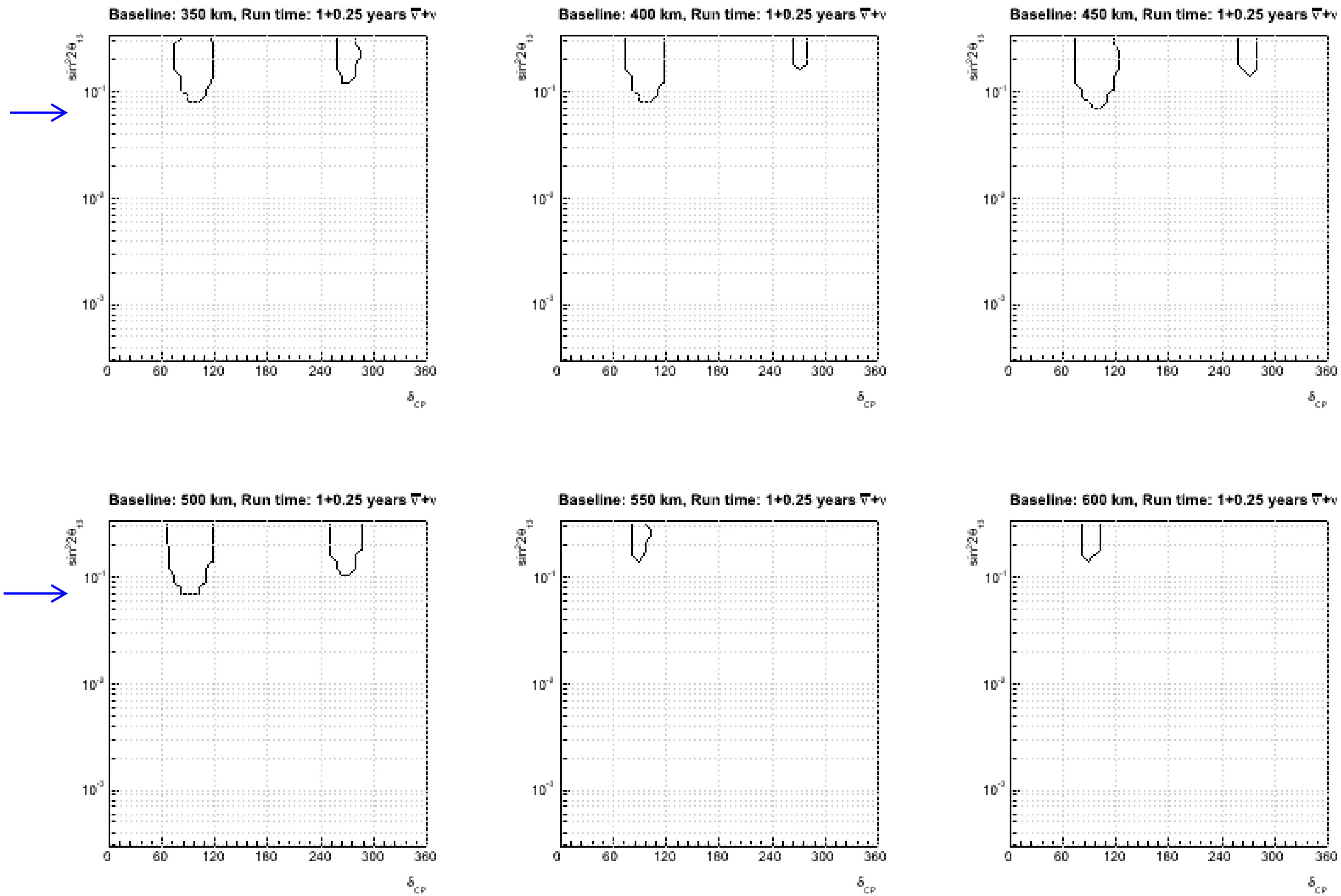
CP violation discovery plots for 1.25 neutrino (ONLY) years with different base-lines 50, 100, 150, 200, 250 and 300 km



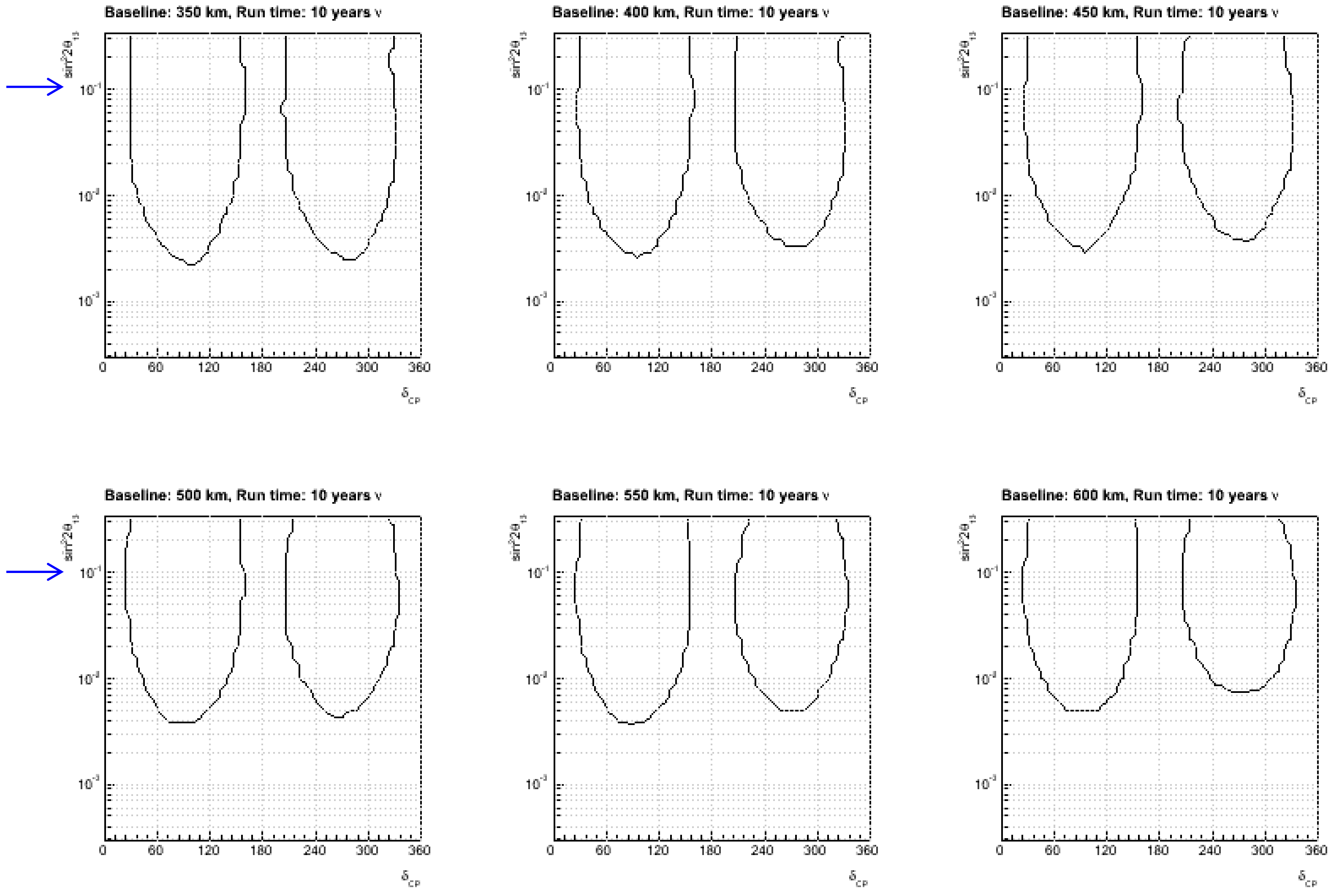
CP violation discovery plots for 8 antineutrion and 2 neutrino years with different base-lines 350, 400, 450, 500, 550 and 600 km



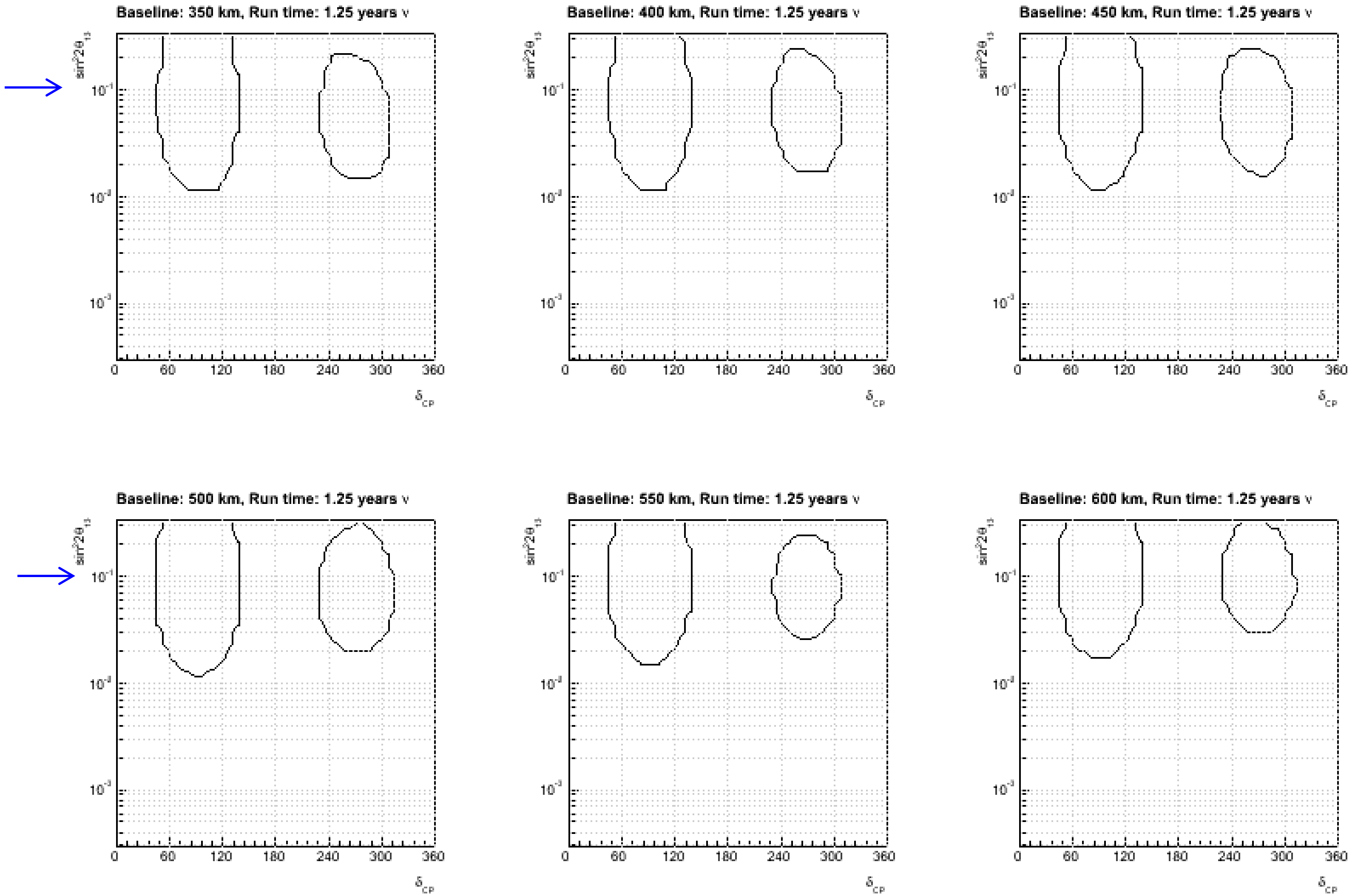
CP violation discovery plots for 1 antineutrino and 0.25 neutrino years with different base-lines 350, 400, 450, 500, 550 and 600 km



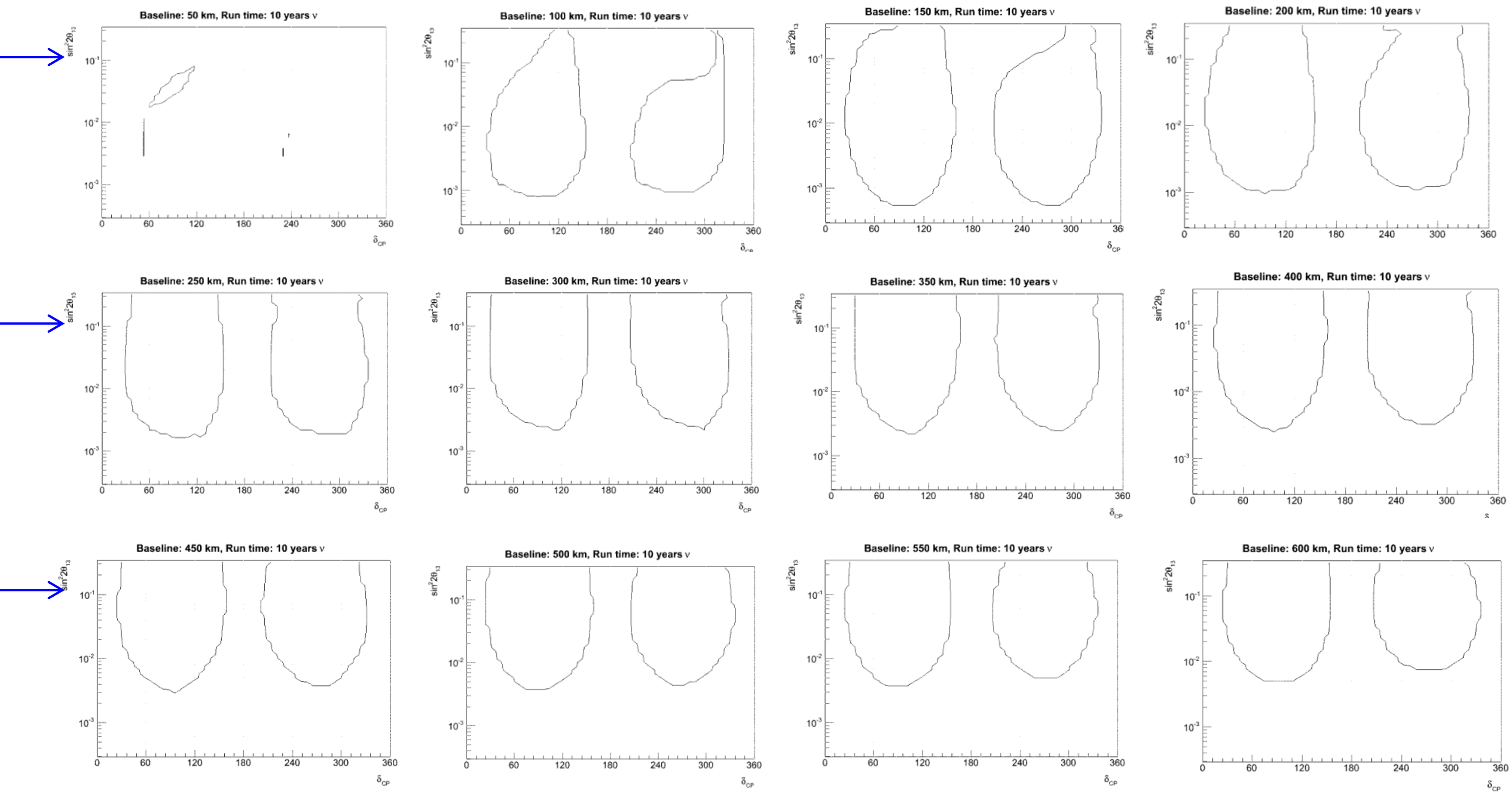
CP violation discovery plots for 10 neutrino (ONLY) years with different base-lines 350, 400, 450, 500, 550 and 600 km



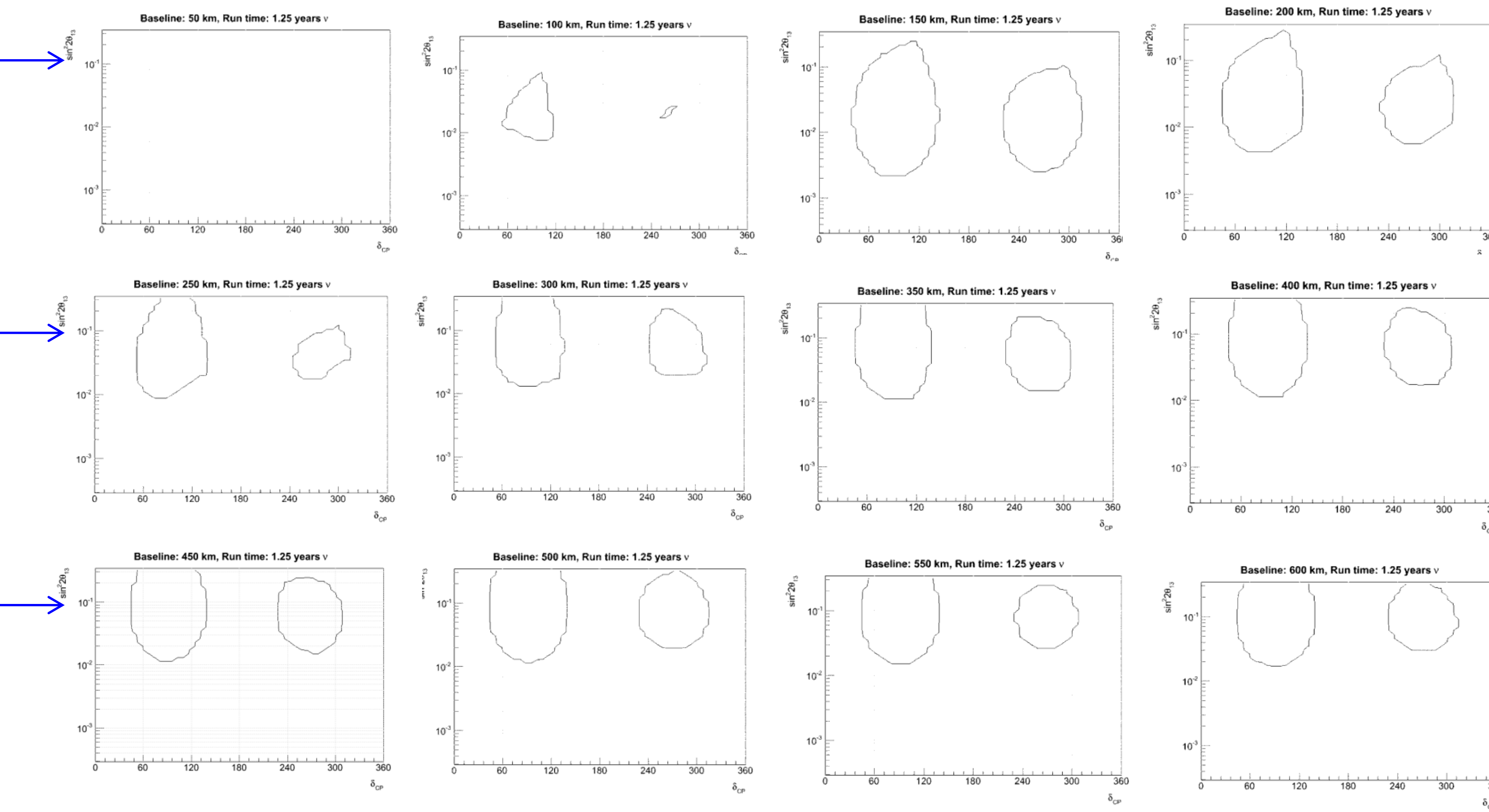
CP violation discovery plots for 1.25 neutrino (ONLY) years with different base-lines 350, 400, 450, 500, 550 and 600 km



CP violation discovery plots for 10 neutrino (ONLY) years with different base-lines from 50 to 600 km



CP violation discovery plots for 1.25 neutrino (ONLY) years with different base-lines from 50 to 600 km



Different base-line lengths from ESS Lund

Zinkgruvan mine 360 km
1200 m deep

Oskarshamn nuclear waste depository 270 km
500 m deep

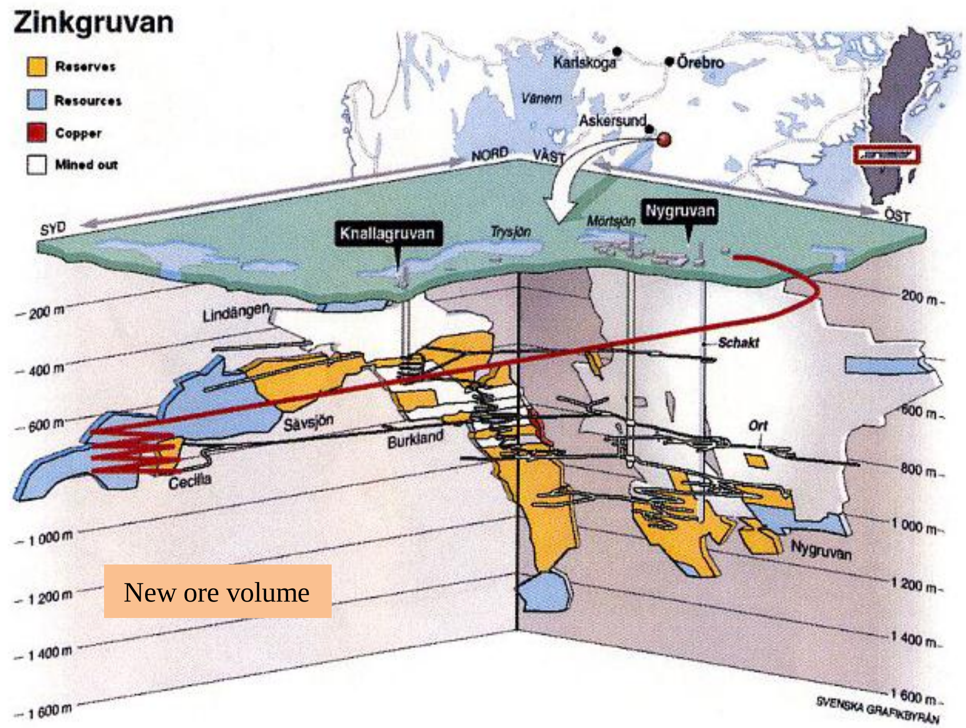
For 300 MeV ν_μ->ν_e
First minimum 140 km
Second maximum 430 km

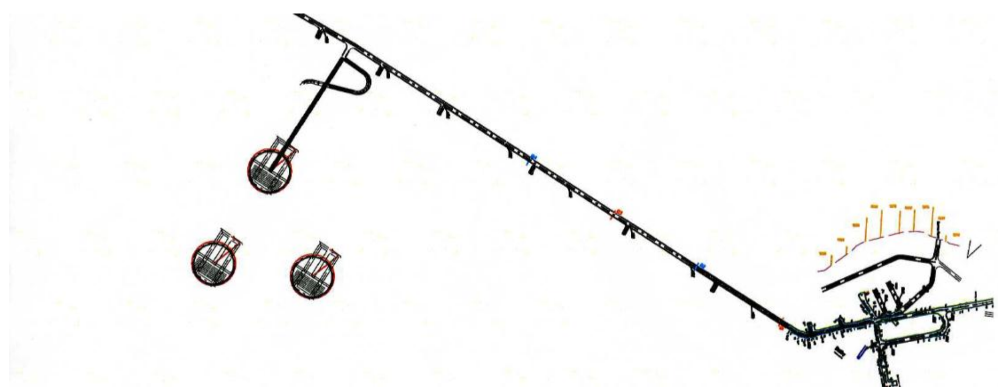
Zinkgruvan mine

Distance from ESS Lund 360 km

Depth 1200 m
Access tunnel 15 km
Ore hoist shaft 7m/s 20 tons
Personnel hoist shaft

2 km long tunnel planned
for new ore volume –
3 Memphys cavities could be
built adjacent to this tunnel
Extension of access tunnel and
second hoist shaft needed4e

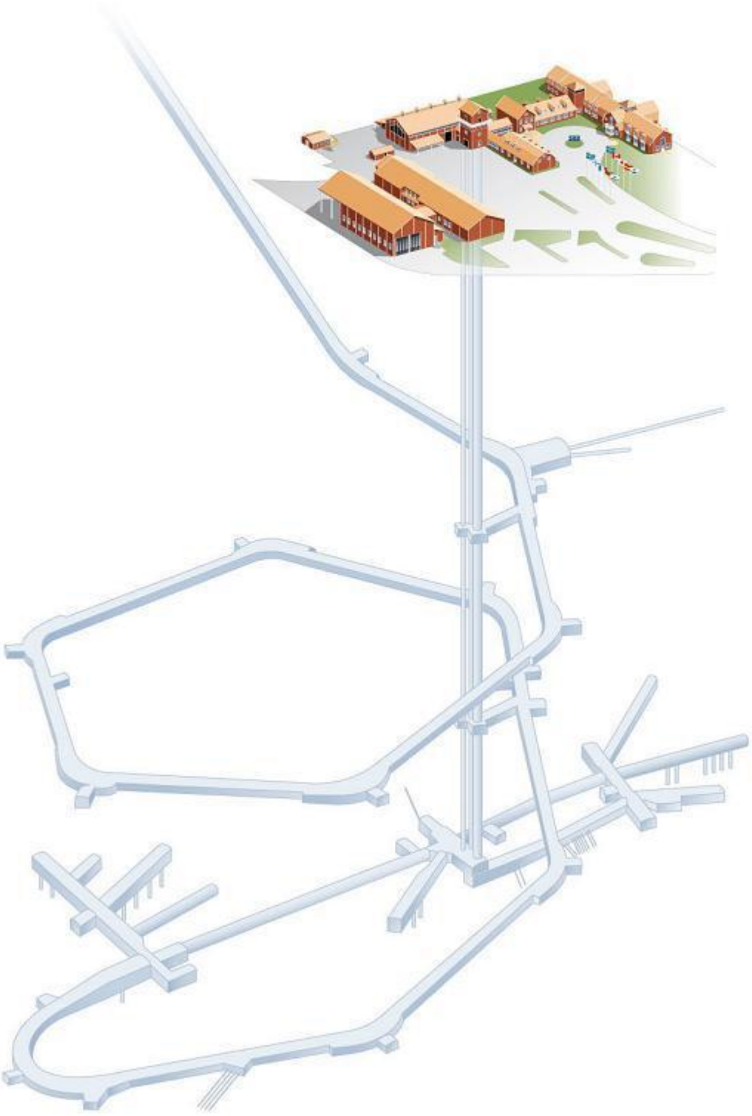




Oskarshamn nuclear waste depository

Distance from ESS Lund 270 km

Depth 460 m
Access tunnel 3.6 km
Personnel hoist shaft diam. 4m
Two ventilation shafts diam. 1.5 m
The rock is investigated down to 1 000 m.



Price list for the new mine-infrastructure needed

<u>Zinkgruvan 360 km from ESS Lund</u>	
Extension of access tunnel ramp	3 MEuro
A new ore transport shaft	100 MEuro
Excavation of 650 000 m^3	37 MEuro
Lining of 40 000 m^2 cave surface	40 MEuro
Sum	**170 MEuro**
<u>Oskarhamn 270 km from ESS Lund</u>	
Extension of access tunnel 4 km and of personnel shaft down to 1000 m	50 MEuro
Excavation of 650 000 m^3	36 MEuro
Lining of 40 000 m^2 cave surface	40 MEuro
Sum	**126 MEuro**
<u>Green field site 150 km from ESS Lund</u>	
Access tunnel ramp and personnel shaft down to 1000 m	100 MEuro
Excavation of 650 000 m^3	36 MEuro
Lining of 40 000 m^2 cave surface	40 MEuro
Ground level buildings/infrastructure	? MEuro
Sum	**176+? MEuro**

Outlook

•The ESS proton linac has great potential as generator of the most intense neutrino beam in the world during the coming decade(s).

•Such a beam, in combination with a large underground water Cherenkov detector, would make possible the discovery and measurement of neutrino CP violation, a parameter which is fundamental for our understanding of the dominance of matter over antimatter in the Universe.

•Our current work aims at determining the optimal parameters of the detector, in particular its size and location.

•This detector would also be used for other high precision measurements of atmospheric, solar and supernovae neutrinos as well as for proton decay.