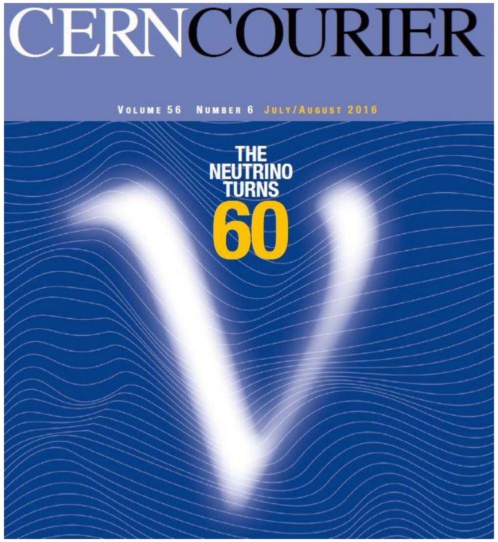
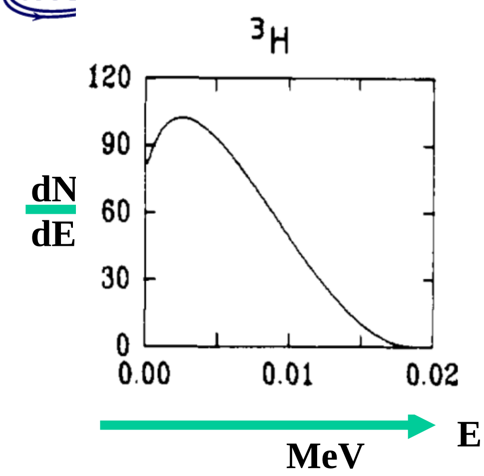
A very intense neutrino super beam experiment for leptonic CP violation discovery based on the European Spallation Source linac

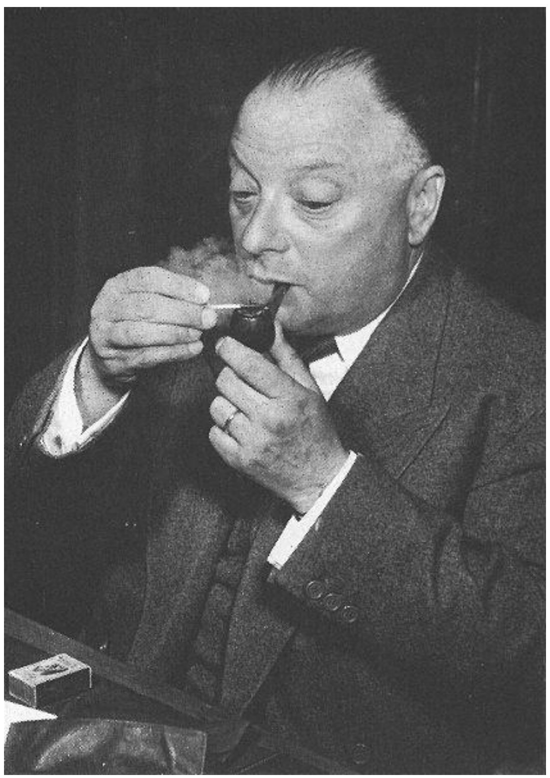


Roumen Tsenov
LHEP-JINR and Department of Atomic Physics, University of Sofia
(on behalf of the ESSνSB Collaboration)

Neutrinos: *the birth of the idea*

e^- spectrum in beta decay





Pauli's letter of the 4th of December 1930

1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

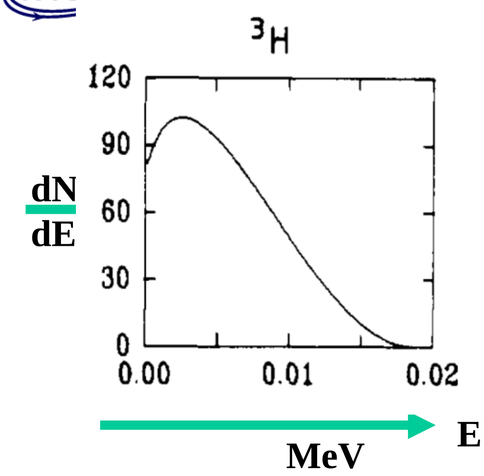
. W. Pauli

translation: L.M. Brown, Phys. Today, Sept.1978, 23

Wolfgang Pauli

Neutrinos: *the birth of the idea*

e⁻ spectrum in beta decay



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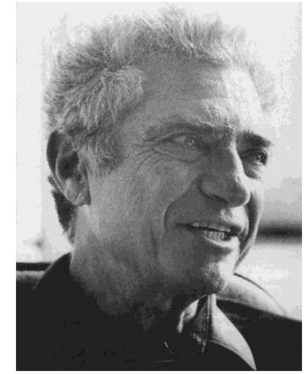
Two Neutrinos

1962

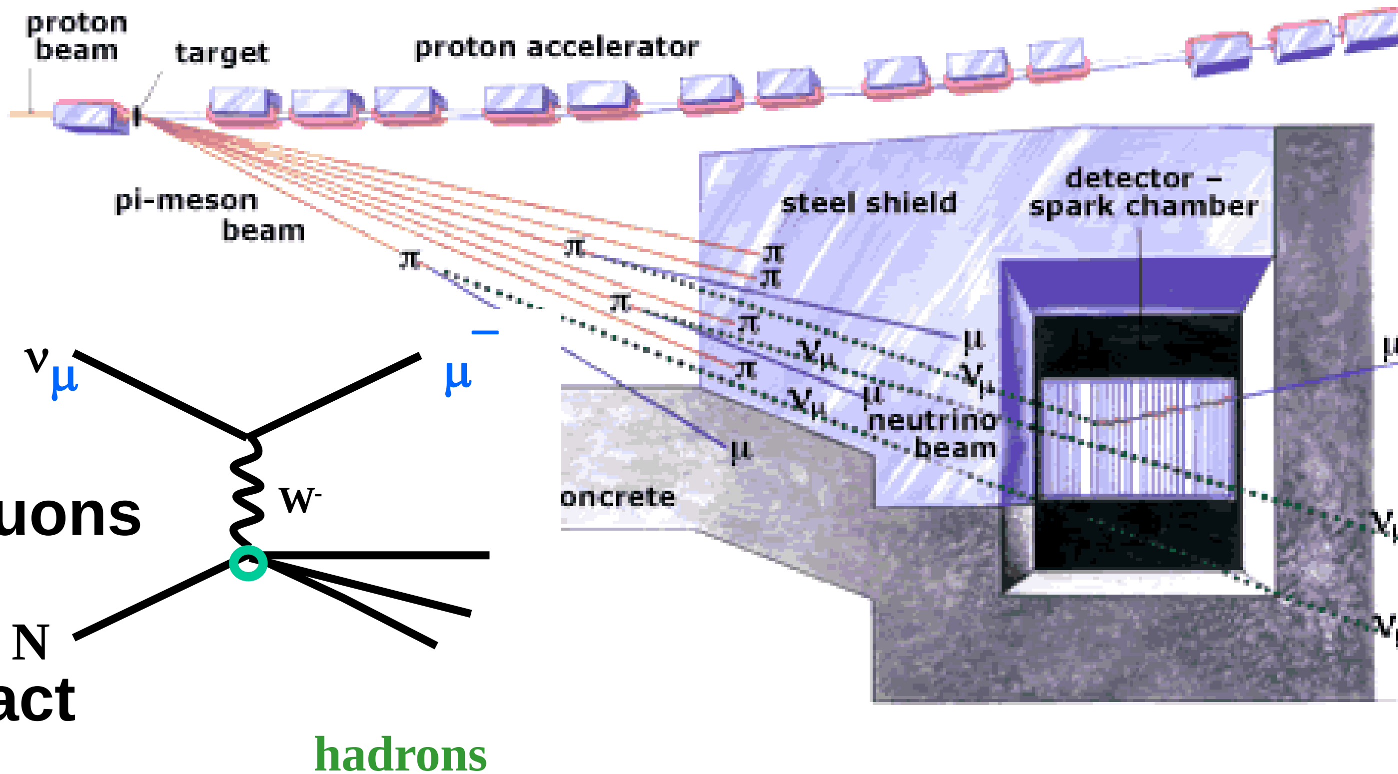




AGS Proton Beam

M.Schwartz L.Lederman J.Steinberger

Neutrinos from π-decay produce only muons (not electrons) when they interact in matter.

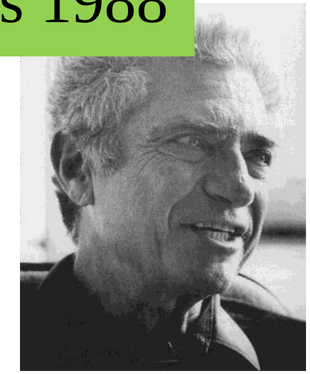


Two Neutrinos

1962

Nobel Prize in Physics 1988





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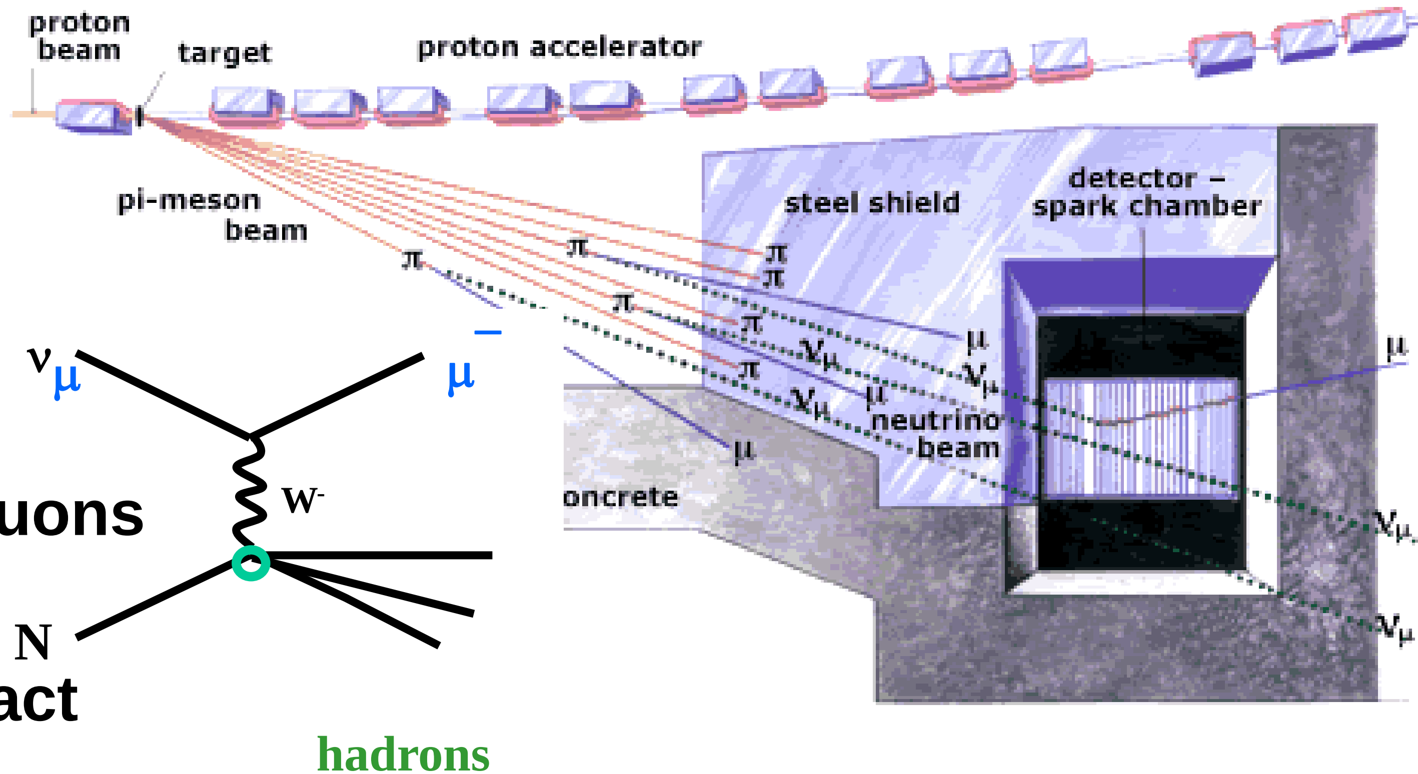
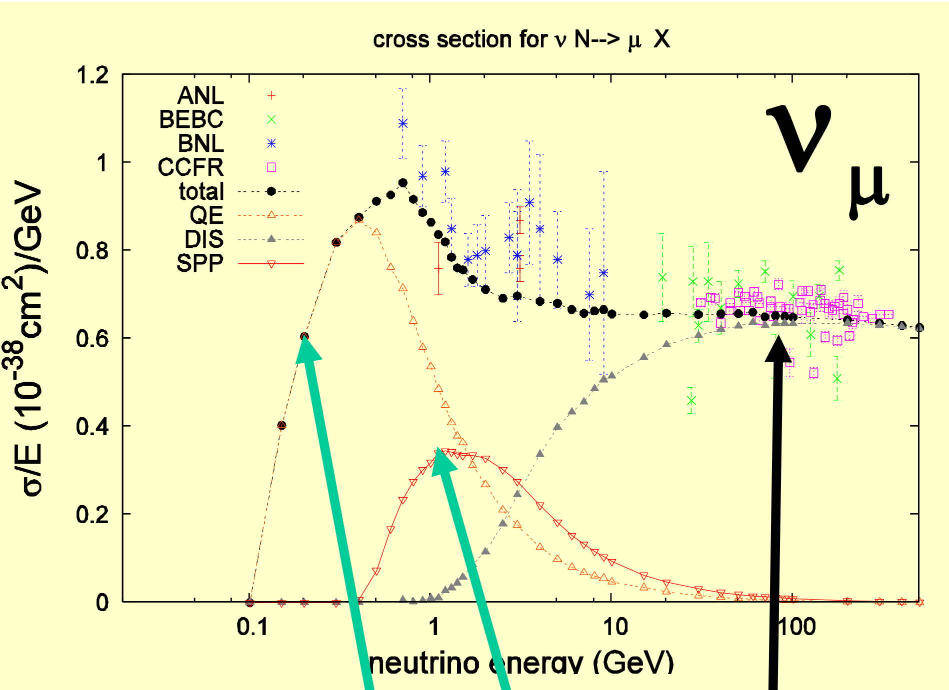
AGS Proton Beam

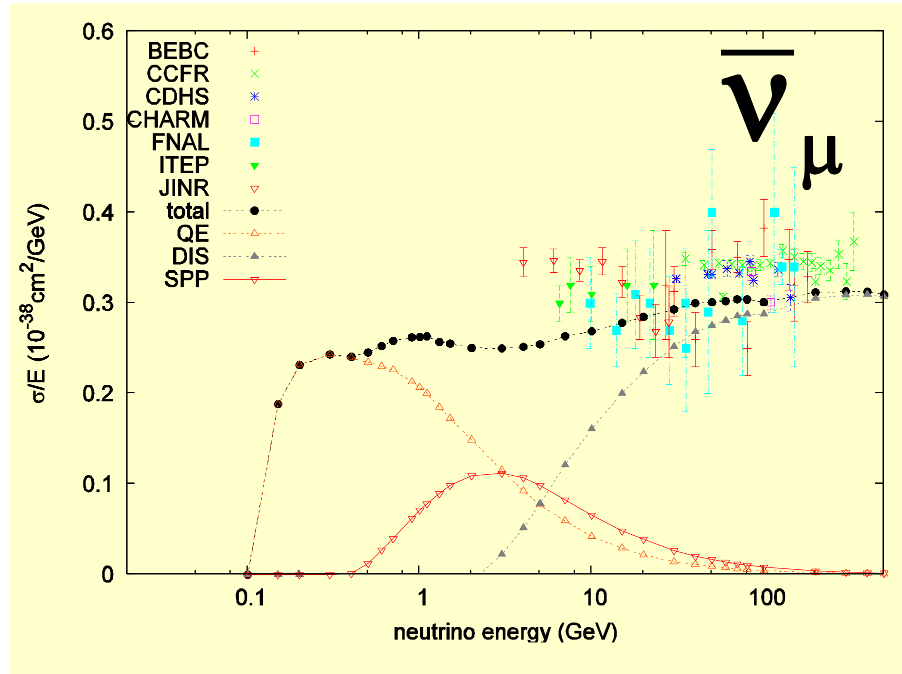


Neutrinos from π-decay produce only muons (not electrons) when they interact in matter.

Total neutrino – nucleon CC cross section



neutrino



anti-neutrino

We distinguish:

- quasi-elastic
- single pion production („RES region", e.g. W<=2 GeV)
- more inelastic („DIS region")

σ_ν is very small: λ_{int} in water for 30 GeV neutrino is 8×10^{10}m (~ 0.55 AU) !

Neutrino Oscillations

source → propagation in vacuum (or matter) → detection

L

weak interaction produces
'flavour' neutrinos
e.g. pion decay $\pi \to \mu\nu$

$$|\nu_\mu\rangle = \alpha\, |\nu_1\rangle + \beta\, |\nu_2\rangle + \gamma\, |\nu_3\rangle$$

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha\, |\nu_1\rangle \exp(i E_1 t) + \beta\, |\nu_2\rangle \exp(i E_2 t) + \gamma\, |\nu_3\rangle \exp(i E_3 t)$$

proper time $\propto$ L/E

weak interaction: (CC)

$$\nu_\mu N \to \mu^- X$$
$$\nu_e N \to e^- X$$
$$\nu_\tau N \to \tau^- X$$

$$P(\mu \to e) = |\langle \nu_e | \nu(t)\rangle|^2$$

First idea by Bruno Pontecorvo, 1957

Oscillation Probability

- The case with two neutrinos:
  - → A mixing angle: θ
  - → A mass difference:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

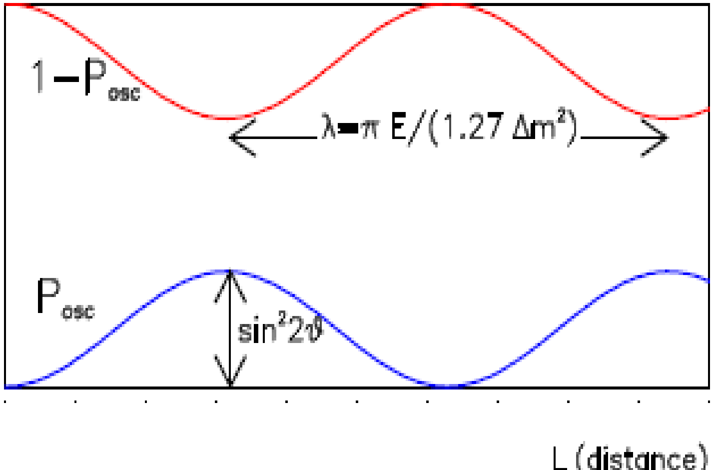
$$\Delta m^2 = m_2^2 - m_1^2$$

- The oscillation probability is:

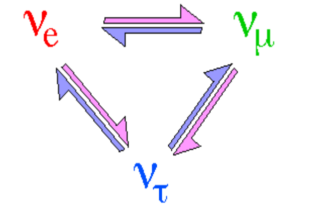
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

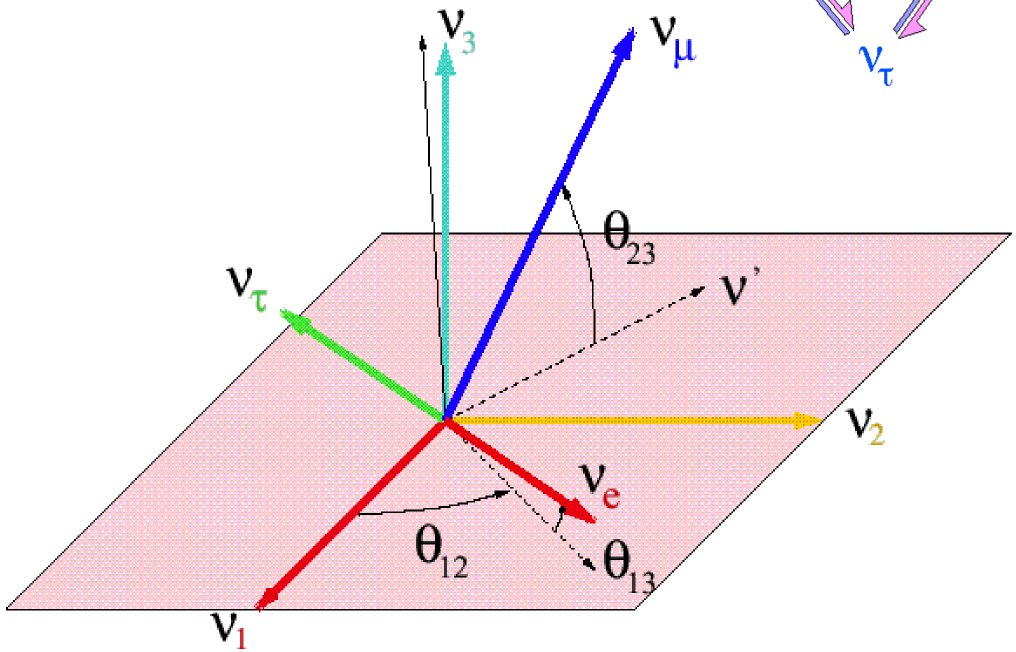
Δm^2 in ev^2
L in km
E in GeV

where L = distance between source and detector
E = neutrino energy



Three neutrino mixing





3 mixing angles, θ_{12}, θ_{23}, θ_{13}, and one phase, δ_{CP}

Usual parameterization

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta ij$$

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

solar, reactors | atmospheric, accelerators | reactors, accelerators, CP violation | Majorana phases

- δ_{CP} for neutrinos
- $-\delta_{CP}$ for anti-neutrinos

LBL experiments at accelerators

K2K (Japan)

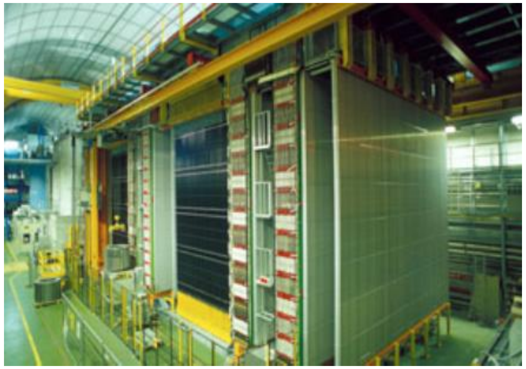
MINOS (USA)

NOνA (USA)

NuMI Off-Axis ν_e Appearance Experiment

T2K (Japan)

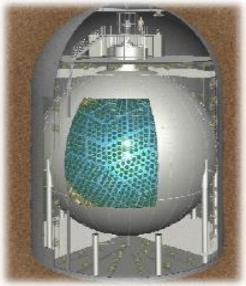
OPERA (Europe)

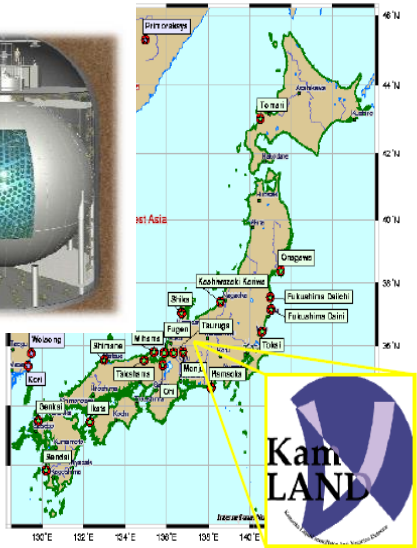


SBL experiments at reactors

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

1 kton scintillator detector



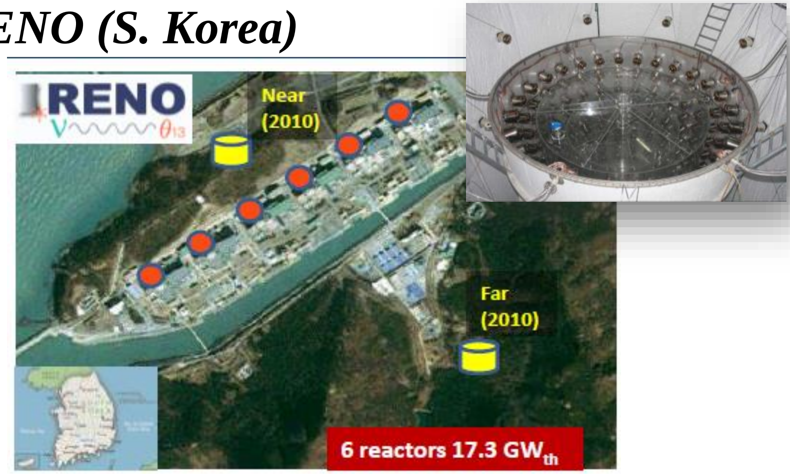


KamLAND (Japan)

Double CHOOZ (France)

Daya Bay (China)

RENO (S. Korea)



What have we measured up to now?

Global fit Aug 2016 (www.nu-fit.org)

NuFIT 2.2 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.56$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.348$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.348$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.440^{+0.023}_{-0.019}$	$0.388 \to 0.630$	$0.584^{+0.018}_{-0.022}$	$0.398 \to 0.634$	$0.388 \to 0.632$
$\theta_{23}/^\circ$	$41.5^{+1.3}_{-1.1}$	$38.6 \to 52.5$	$49.9^{+1.1}_{-1.3}$	$39.1 \to 52.8$	$38.6 \to 52.7$
$\sin^2\theta_{13}$	$0.02163^{+0.00074}_{-0.00074}$	$0.01938 \to 0.02388$	$0.02175^{+0.00075}_{-0.00074}$	$0.01950 \to 0.02403$	$0.01938 \to 0.02396$
$\theta_{13}/^\circ$	$8.46^{+0.14}_{-0.15}$	$8.00 \to 8.89$	$8.48^{+0.15}_{-0.15}$	$8.03 \to 8.92$	$8.00 \to 8.90$
$\delta_{CP}/^\circ$	289^{+38}_{-51}	$0 \to 360$	269^{+39}_{-45}	$146 \to 377$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.526^{+0.039}_{-0.037}$	$+2.413 \to +2.645$	$-2.518^{+0.038}_{-0.037}$	$-2.634 \to -2.406$	$\begin{bmatrix} +2.413 \to +2.645 \\ -2.630 \to -2.409 \end{bmatrix}$

What have we measured up to now?

Global fit Aug 2016 (www.nu-fit.org)

What is not know yet:

- the mass hierarchy: sign Δm_{13}^2
- the CP violating phase δ

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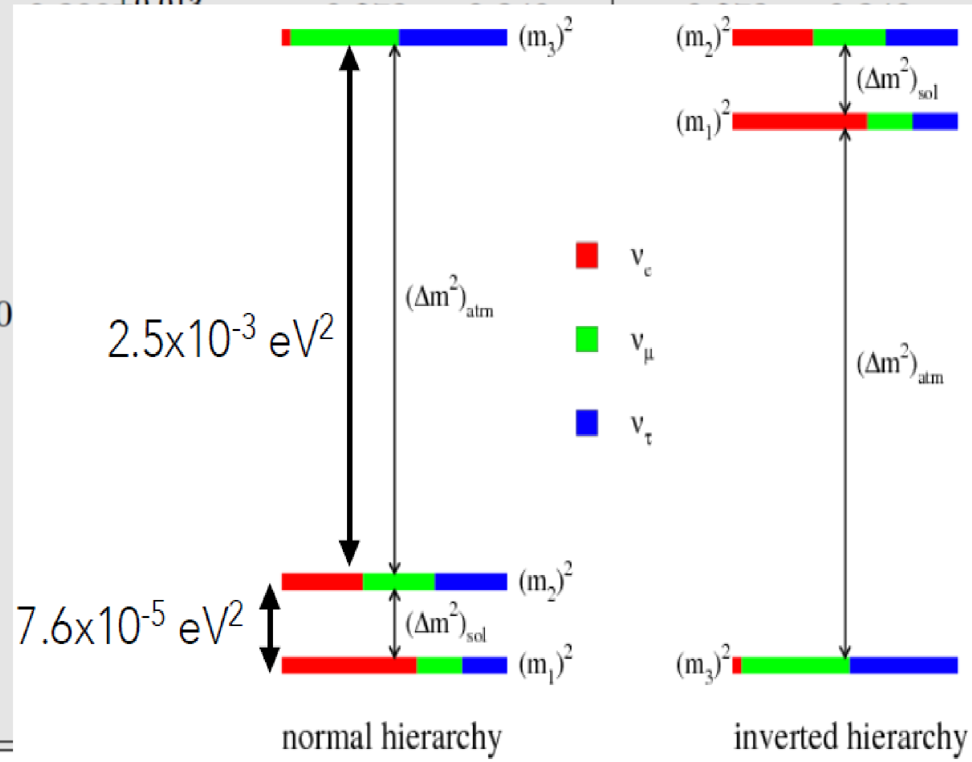


CP Violating observables (and mass hierarchy)

$$P_{\nu_\mu\to\nu_e(\bar{\nu}_\mu\to\bar{\nu}_e)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$ atmospheric

$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ solar

Non-CPV terms

$$+\tilde{J}\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde{B}_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta_{CP} - \frac{\Delta_{13}L}{2}\right)$$ interference

CP violating

$$\tilde{J} \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde{B}_\mp \equiv \left|A \mp \Delta_{13}\right|,\ \ A = \sqrt{2}G_F N_e$$

matter effect

$\Rightarrow$ accessibility to

mass hierarchy

$\Rightarrow$ long baseline

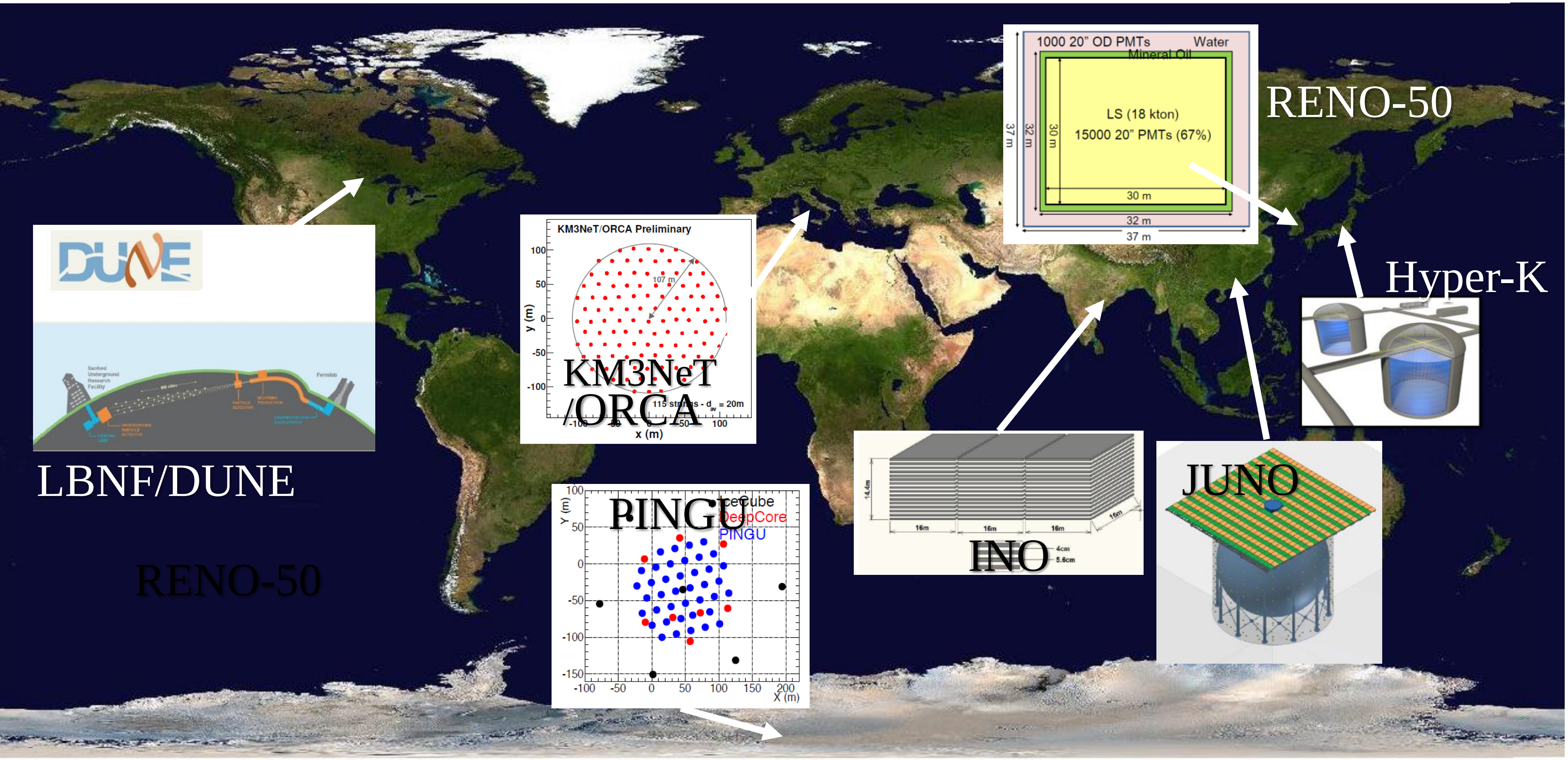
$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar{\nu}_\mu\to\bar{\nu}_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar{\nu}_\mu\to\bar{\nu}_e}}$$

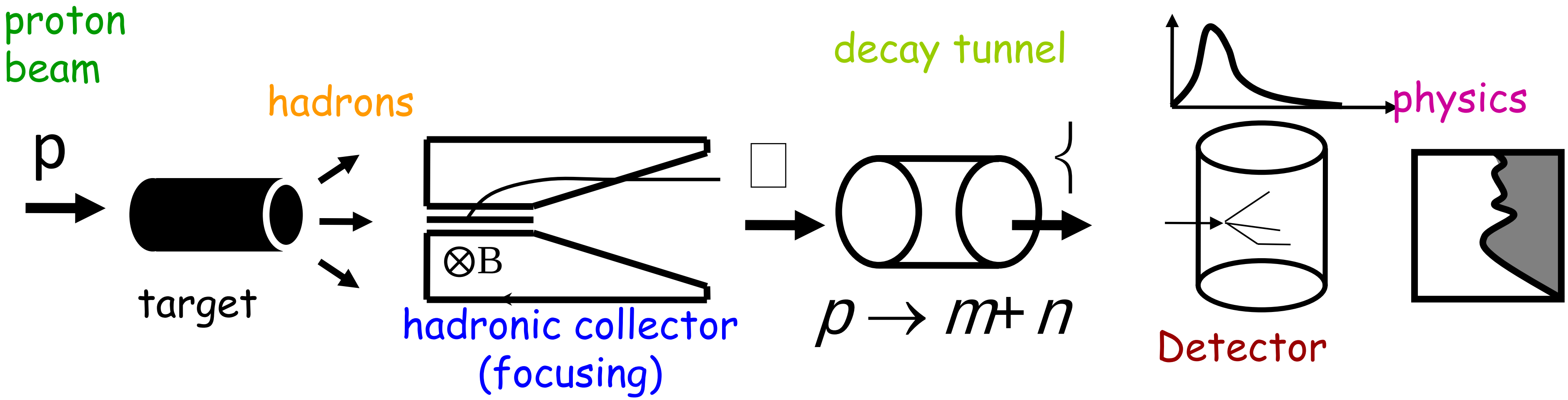
$\neq 0 \Rightarrow$ CP Violation

be careful, matter effects also create asymmetry

Future neutrino experiments

(in construction / approved / in preparation)





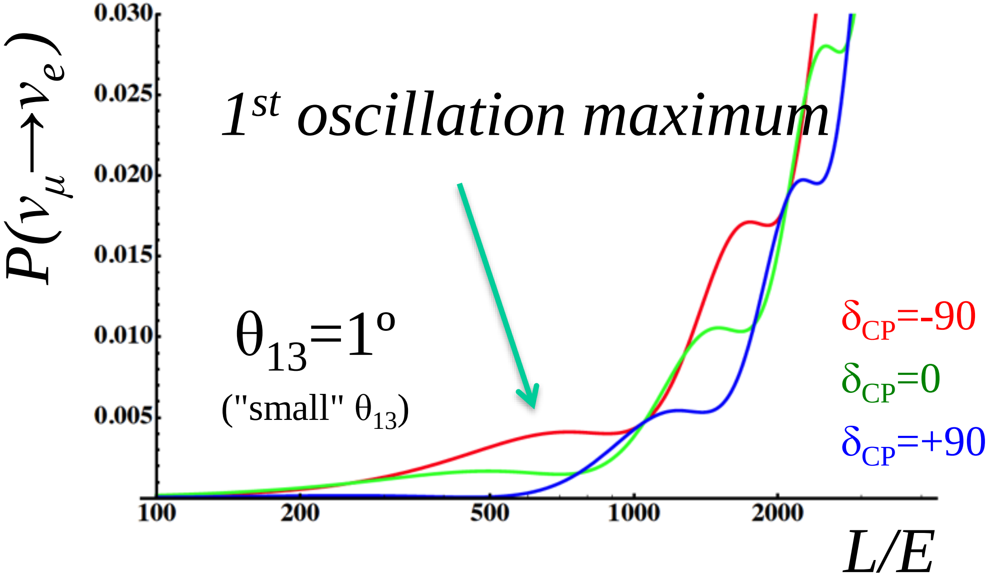
- Maximum proton power up to now: ~700 kW
- For CP violation neutrino experiments power of few MW is needed.

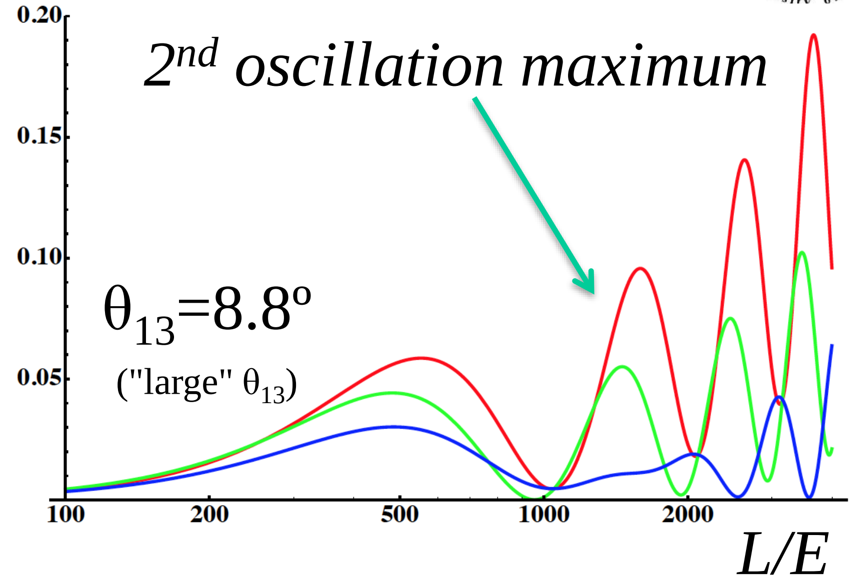
Super Beams

Challenges:

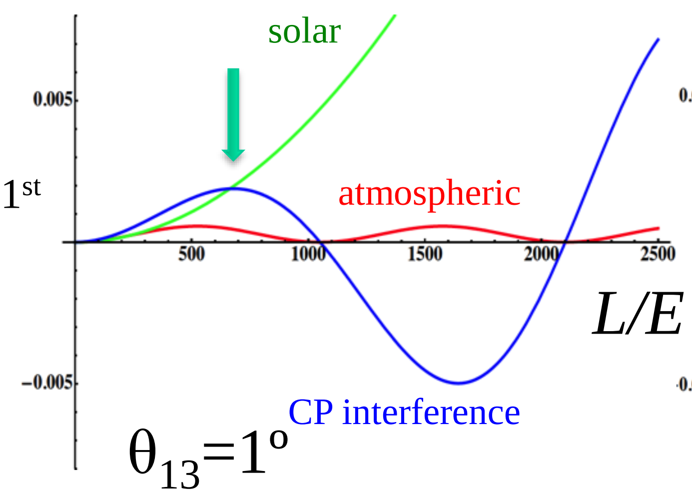
- high repetition rate (pulsing the whole system faster)
- targets able to afford the proton beam intensity
- power dissipation
- radiations
- …

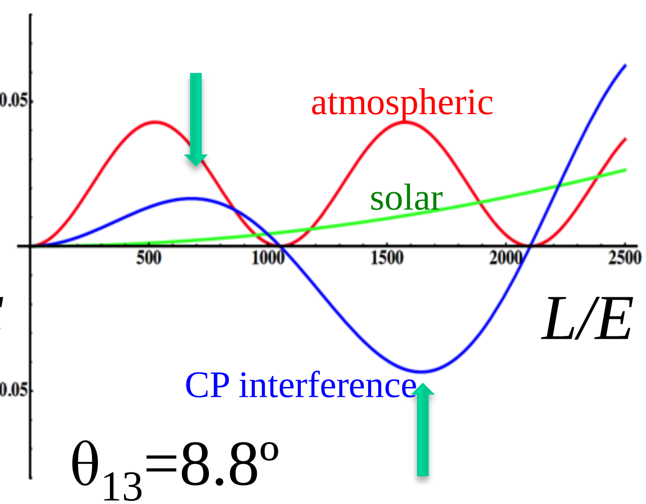
Neutrino Oscillations with "large" θ_{13}





for small θ_{13} 1^{st} oscillation maximum is better

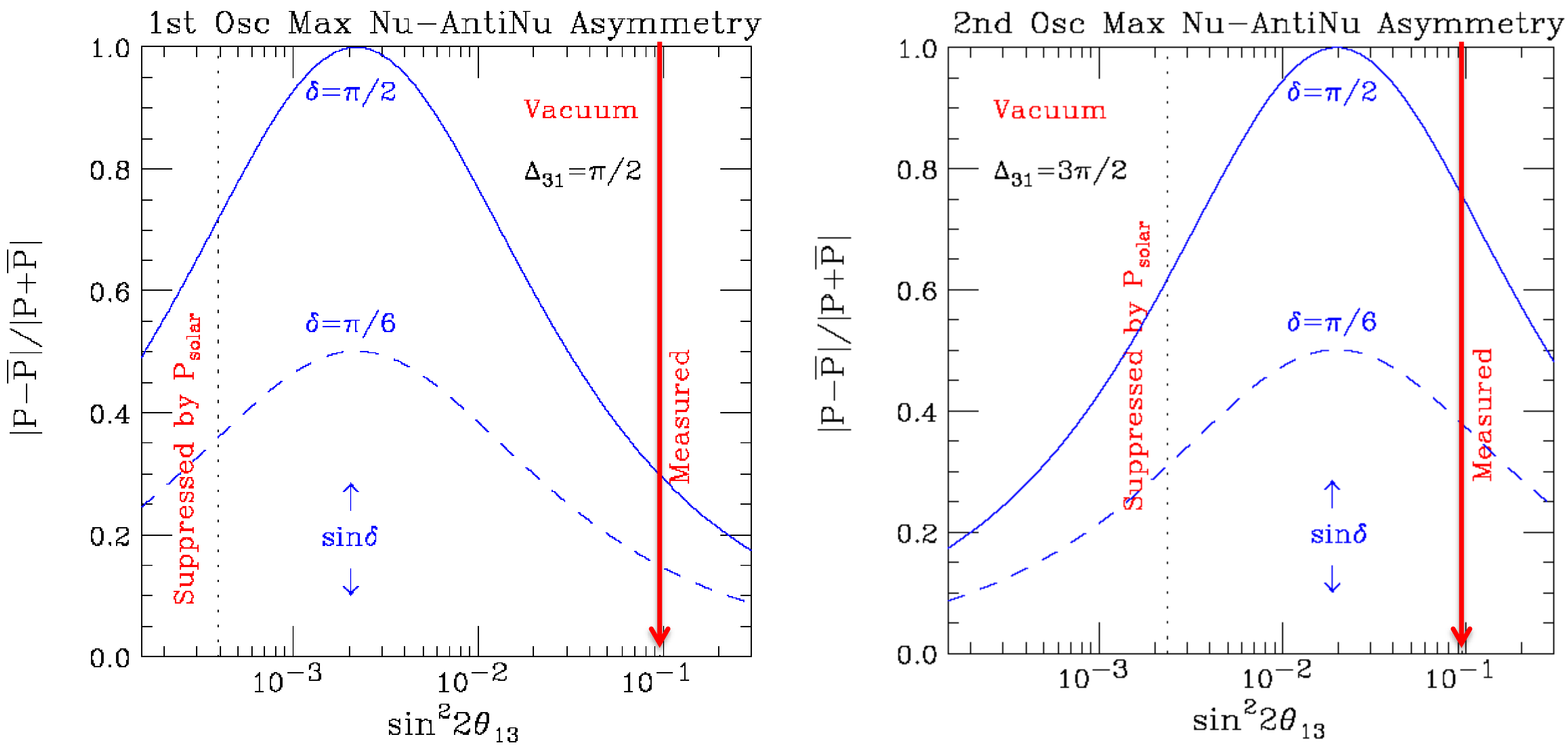




for "large" θ_{13} 1^{st} oscillation maximum is dominated by atmospheric term,

→ 2^{nd} oscillation maximum is better

Neutrino oscillations with "large" θ_{13}



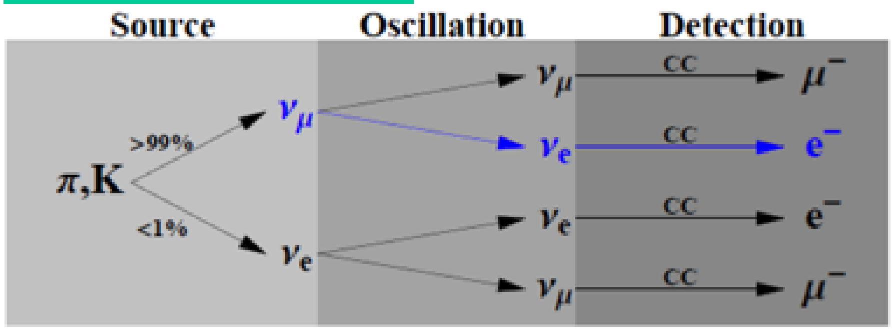
- at the 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- at the 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

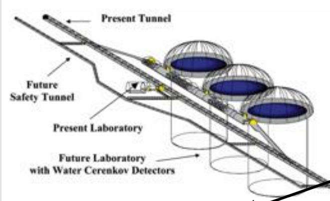
→ 2nd oscillation maximum is better

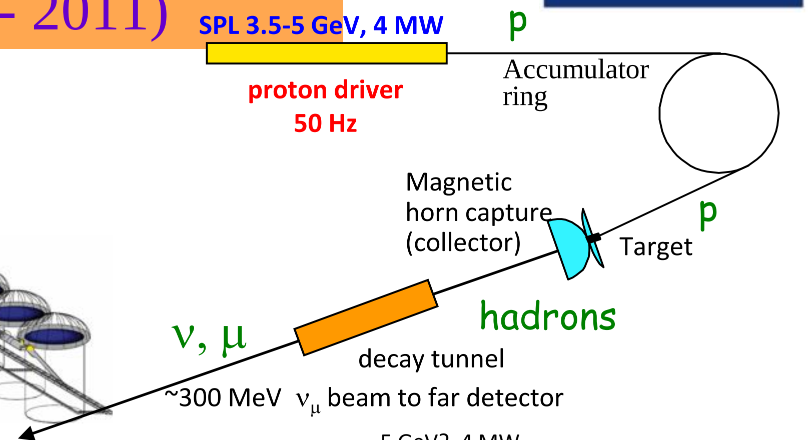
The EUROν project

(FP7 design study, 2008 - 2011)

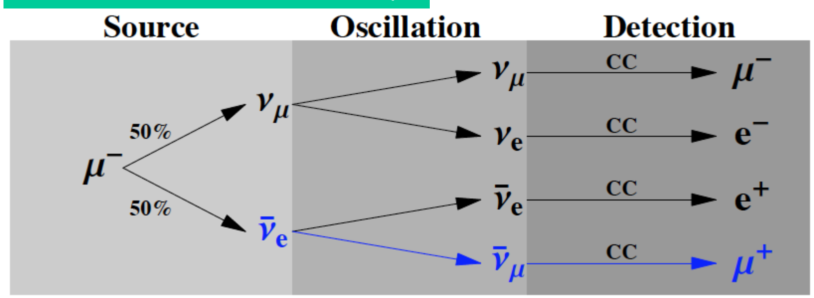
SPL Super-Beam

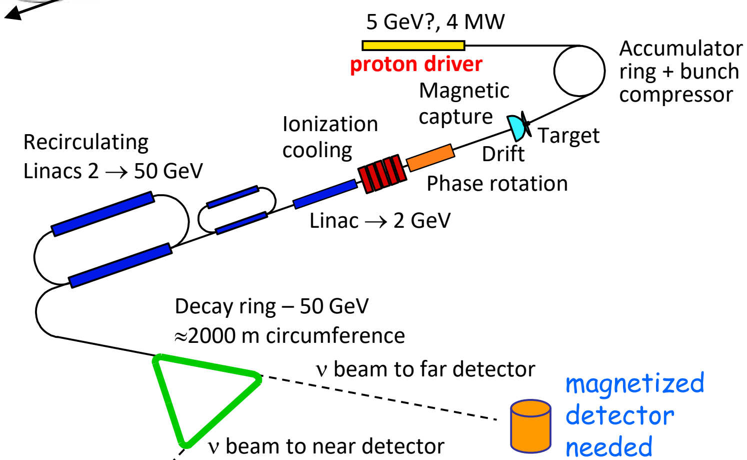




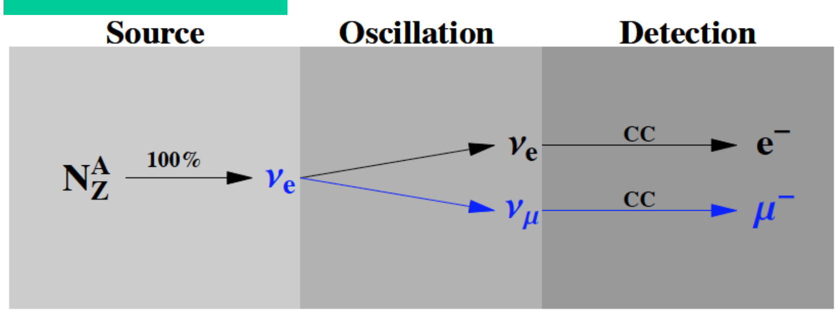


Neutrino Factory

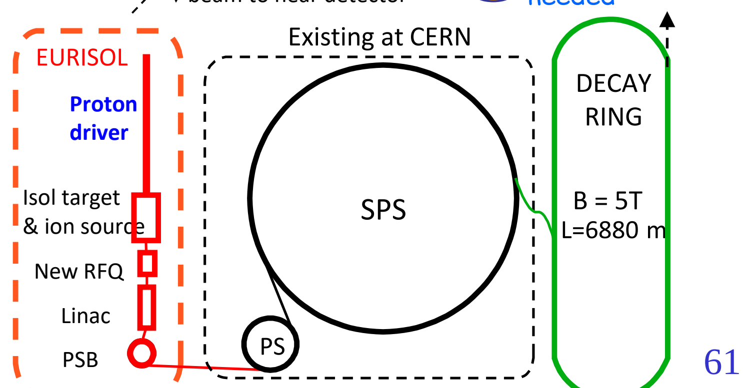




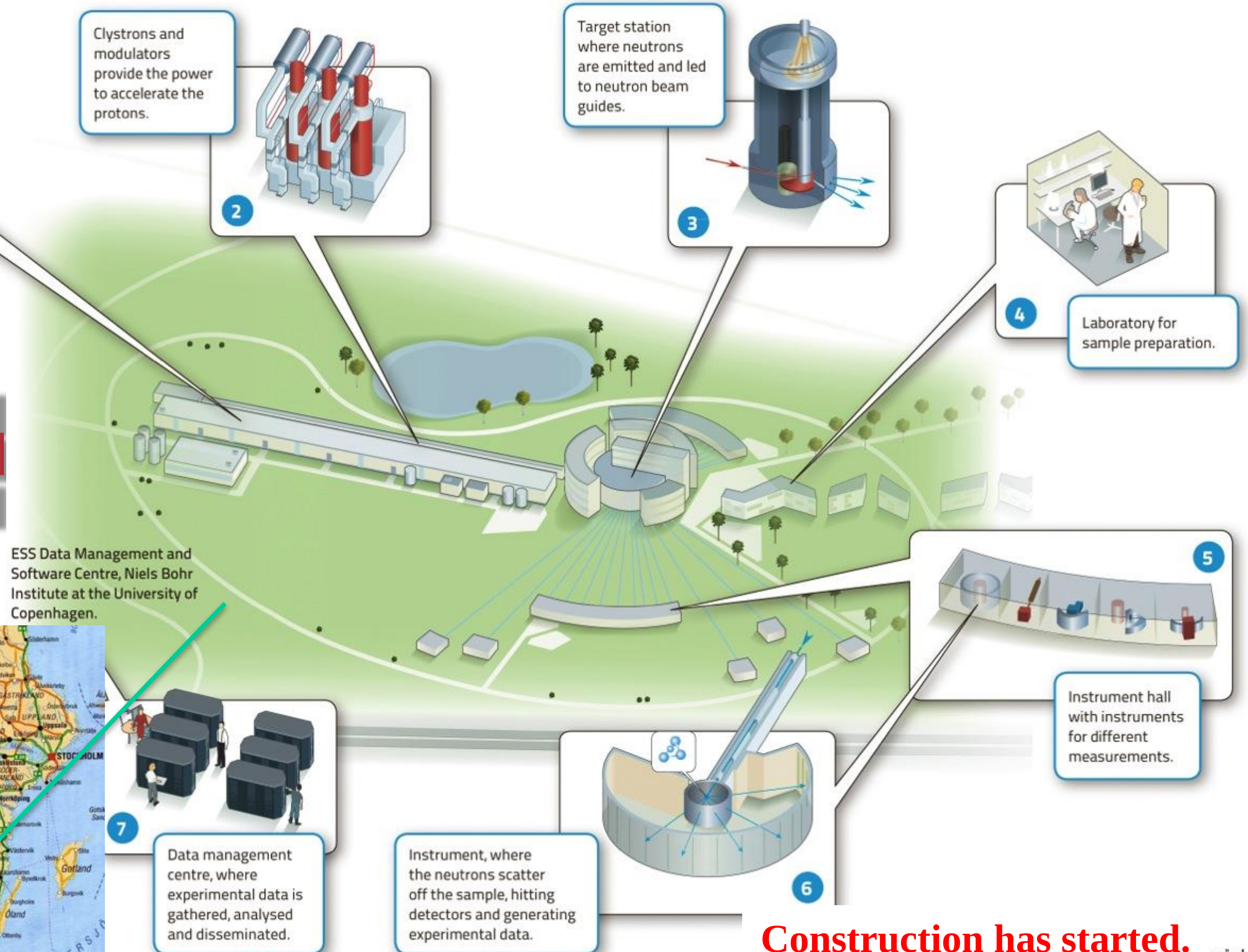
Beta-Beam



^{6}He for ν_e and
^{18}Ne for ν_e
γ~100

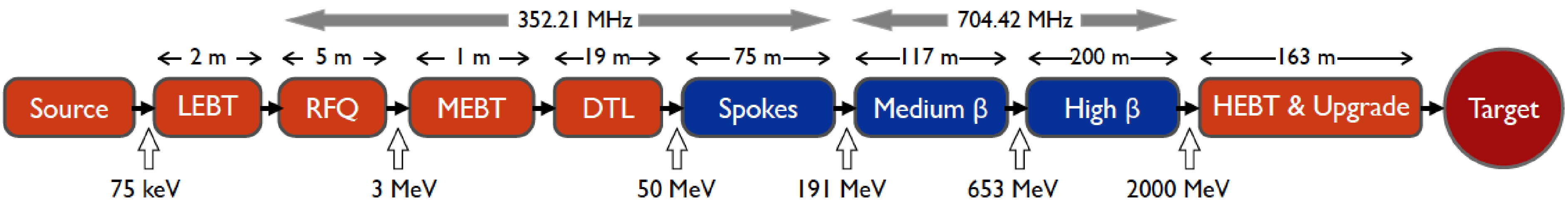


European Spallation Source



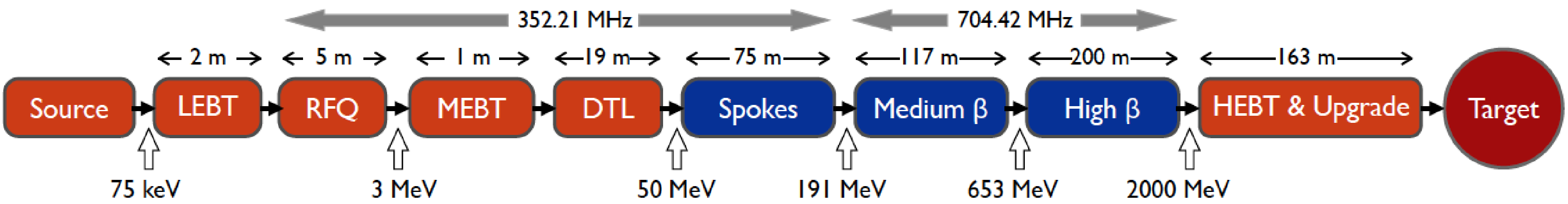
Construction has started.
(~1.8 B€ facility)

ESS proton linac



- The ESS will be a copious source of spallation neutrons
- 5 MW average beam power
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
- **>2.7x10^{23} p.o.t/year**

ESS proton linac



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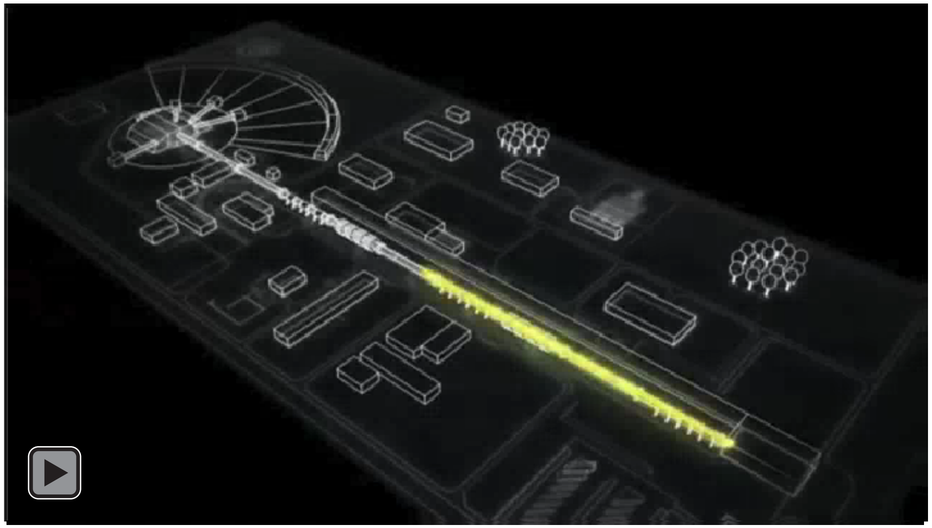


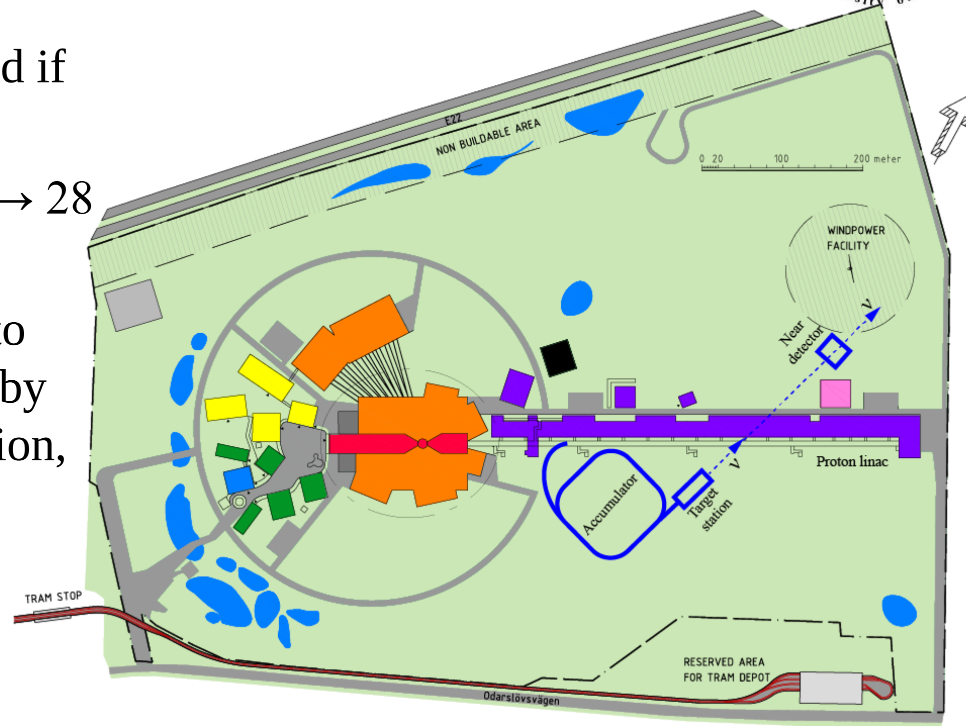
ESS Schedule

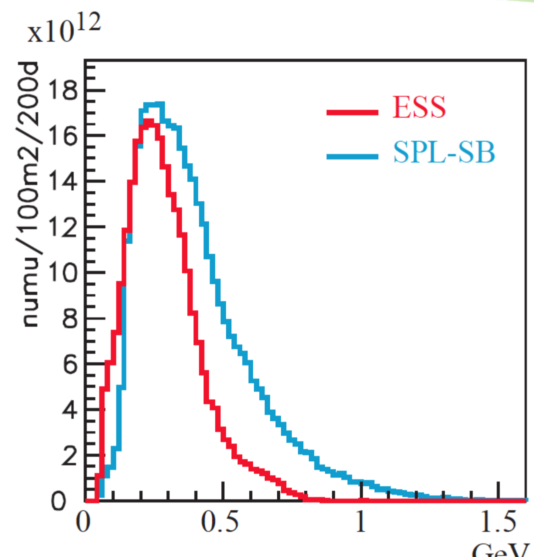
2010 -	**ESS Company set up**
2010 - 2012	**Technical Design Review**
2010 - 2012	**Pre-Construction & Site Planning**
2009 - 2012	**Licensing and Planning**
2010 - 2012	**Finalisation of international negotiations**
2013 - 2019	**Construction Phase - 7 instruments**
2019 - 2025	**Completion Phase - all 22-33 instruments in place**
2026 - 2066	**Operations Phase**
2066 – 2071	**Decommissioning Phase**

- 1st beam before the end of the decade
- 5 MW by 2023

How to add a neutrino facility to ESS?

- The neutron program must not be affected and if possible synergetic modifications
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (ø 143 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H^- source (instead of protons)
  - space charge problems to be solved
- ~300 MeV neutrinos
- Target station (studied in EUROnu)
- Underground detector (studied in LAGUNA)
- Short pulses (~μs) will also allow DAR experiments
- The linac and accumulator could be the first step towards Neutrino Factory, Muon Collider, etc.





neutrino flux at 100 km (similar spectrum than for EUROnu SPL SB)

ESS Neutrino Super Beam Collaboration (ESSνSB)

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B 885 (2014) 127–149
NUCLEAR PHYSICS B
www.elsevier.com/locate/nuclphysb

arXiv:1212.5048
arXiv:1309.7022

A very intense neutrino super beam experiment for leptonic CP violation discovery based on the European spallation source linac

E. Baussan [m], M. Blennow [l], M. Bogomilov [k], E. Bouquerel [m], O. Caretta [c], J. Cederkäll [f], P. Christiansen [f], P. Coloma [b], P. Cupial [e], H. Danared [g], T. Davenne [c], C. Densham [c], M. Dracos [m,*], T. Ekelöf [n,*], M. Eshraqi [g], E. Fernandez Martinez [h], G. Gaudiot [m], R. Hall-Wilton [g], J.-P. Koutchouk [n,d], M. Lindroos [g], P. Loveridge [c], R. Matev [k], D. McGinnis [g], M. Mezzetto [j], R. Miyamoto [g], L. Mosca [i], T. Ohlsson [l], H. Öhman [n], F. Osswald [m], S. Peggs [g], P. Poussot [m], R. Ruber [n], J.Y. Tang [a], R. Tsenov [k], G. Vankova-Kirilova [k], N. Vassilopoulos [m], D. Wilcox [c], E. Wildner [d], J. Wurtz [m]

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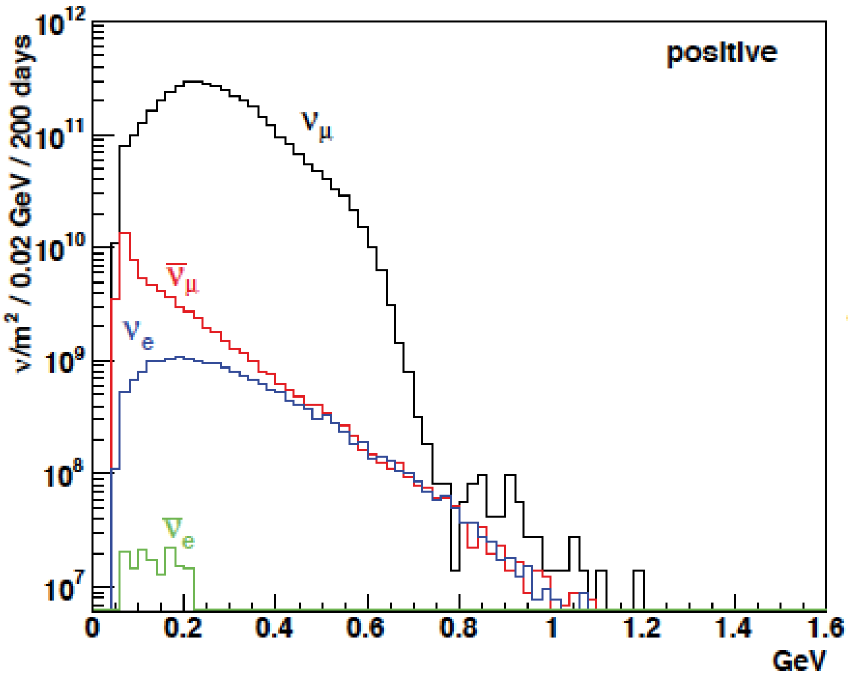
[b] *Center for Neutrino Physics, Virginia Tech, Blacksburg, VA 24061, USA*
[c] *STFC Rutherford Appleton Laboratory, OX11 0QX Didcot, UK*
[d] *CERN, CH-1211 Geneva 23, Switzerland*
[e] *AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow, Poland*
[f] *Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden*
[g] *European Spallation Source, ESS AB, P.O. Box 176, SE-221 00 Lund, Sweden*
[h] *Dpto. de Física Téorica and Instituto de Física Téorica UAM/CSIC, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[i] *Laboratoire Souterrain de Modane, F-73500 Modane, France*
[j] *INFN Sezione di Padova, 35131 Padova, Italy*
[k] *Department of Atomic Physics, St. Kliment Ohridski University of Sofia, Sofia, Bulgaria*
[l] *Department of Theoretical Physics, School of Engineering Sciences, KTH Royal Institute of Technology, AlbaNova University Center, SE-106 91 Stockholm, Sweden*
[m] *IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France*
[n] *Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden*

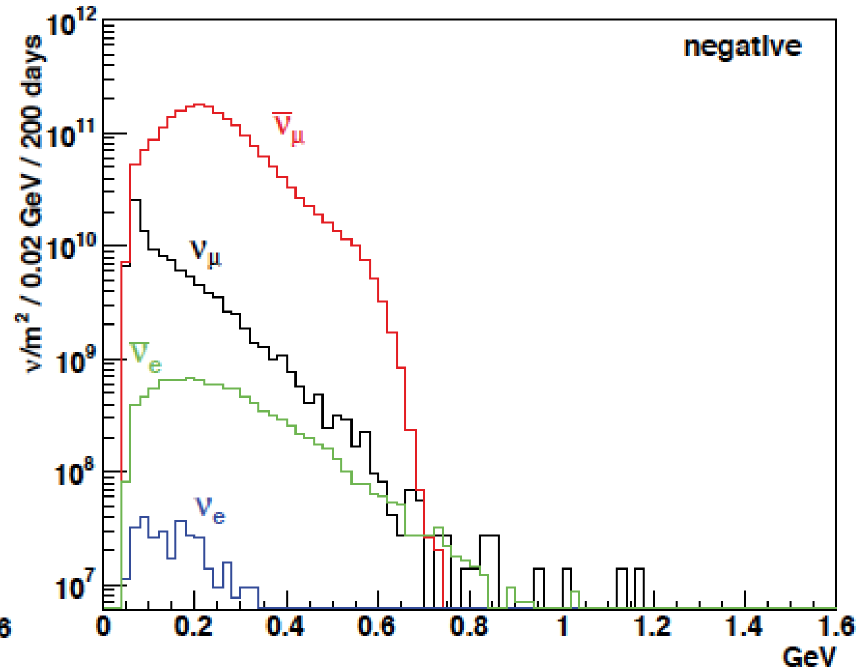
14 participating institutes form 10 different countries, among them ESS and CERN

ESS neutrino energy distribution

	positive		negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

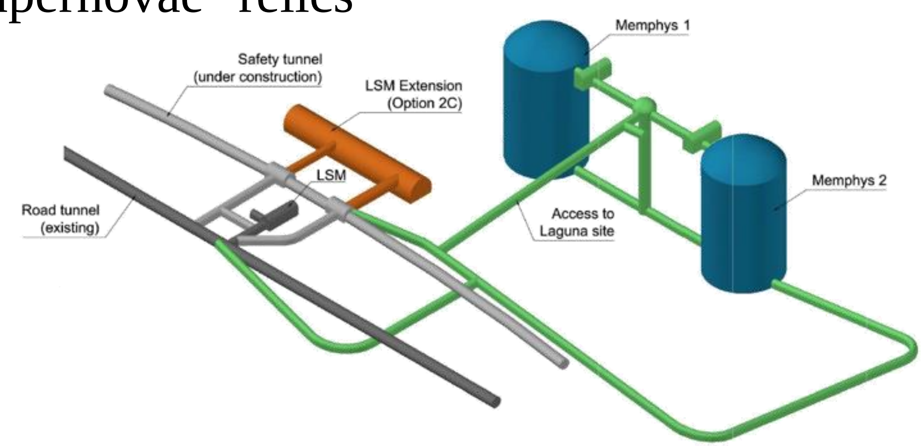
at 100 km from the target and per year

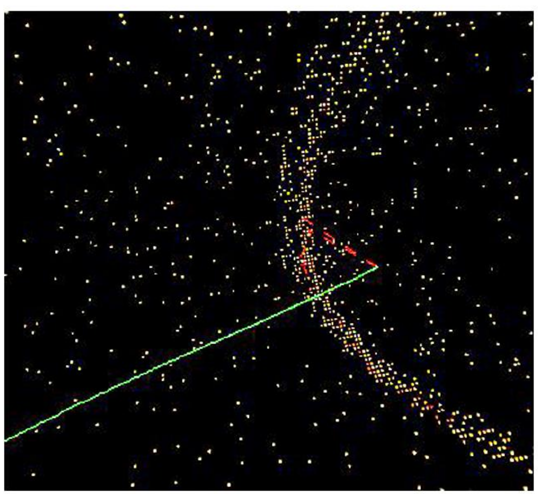




The MEMPHYS (MEgaton Mass PHYSics) Water Cherenkov Detector

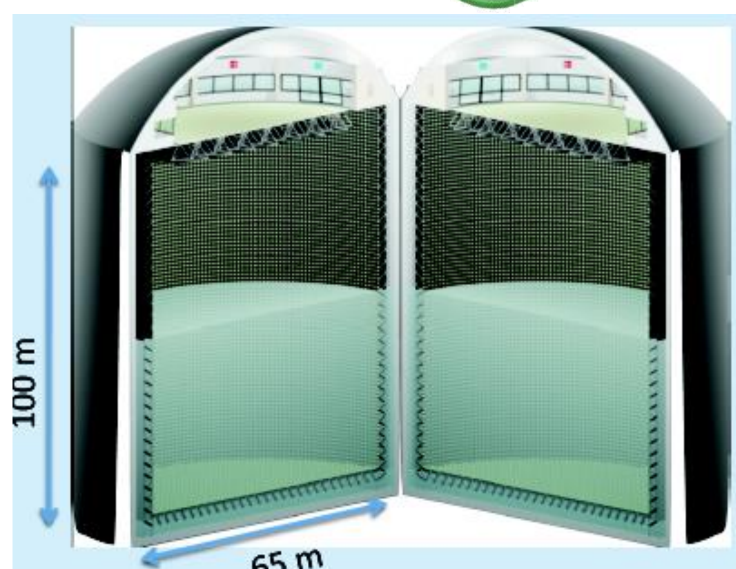
- Proton decay
- Astroparticle physics: galactic SN ν, Supernovae "relics"
- Solar and atmospheric neutrinos
- Neutrino oscillations (Super Beam)
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage





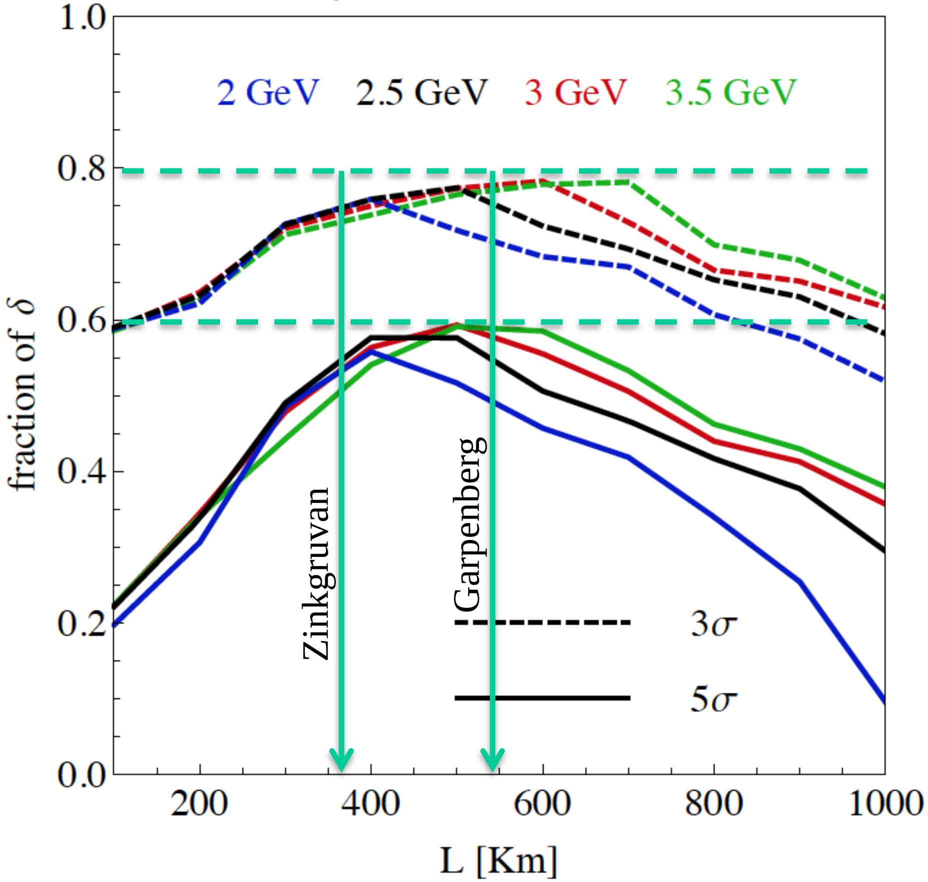
(arXiv: hep-ex/0607026)

FIG. 4. Pattern of hit PMTs after the interaction of a 500 MeV muon with the full MEMPHYS simulation. The green line is the muon track, the red dashed lines are gammas from muon capture, each white dot represents one hit PMT.



WC detector possible locations

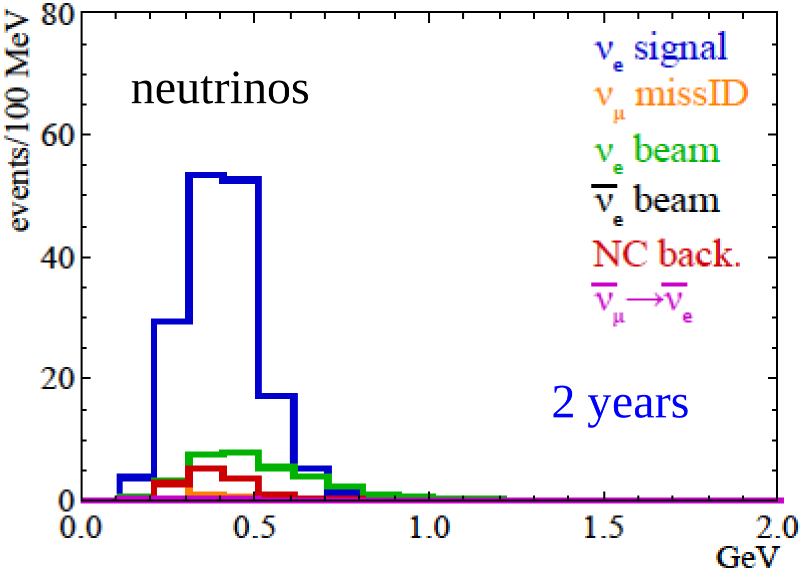
(Nucl. Phys. B 885 (2014) 127)

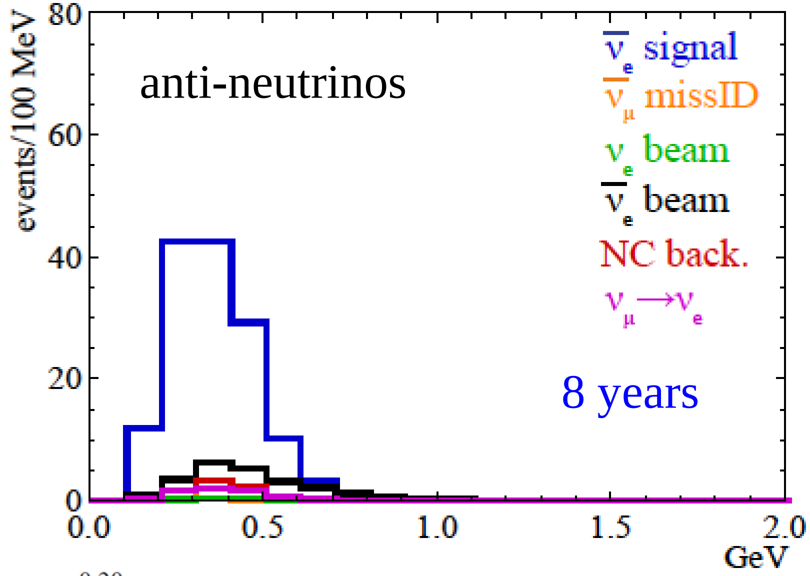


Garpenberg mine (1230 m)

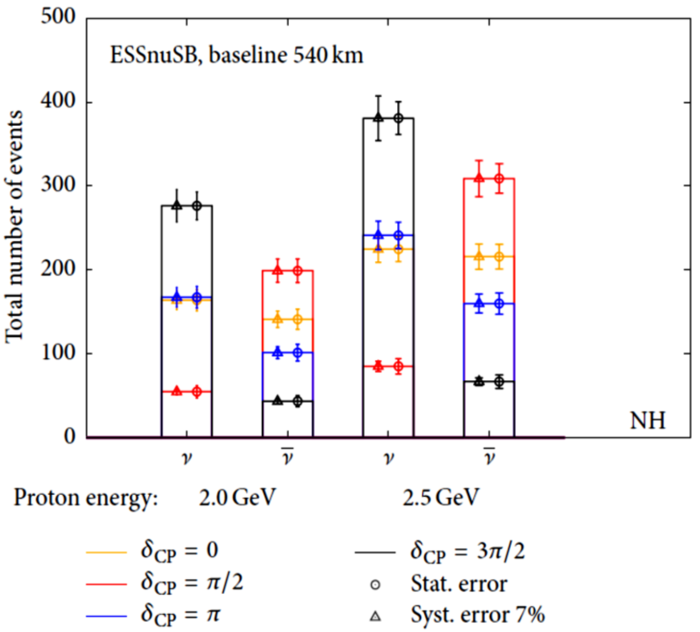
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/background)**

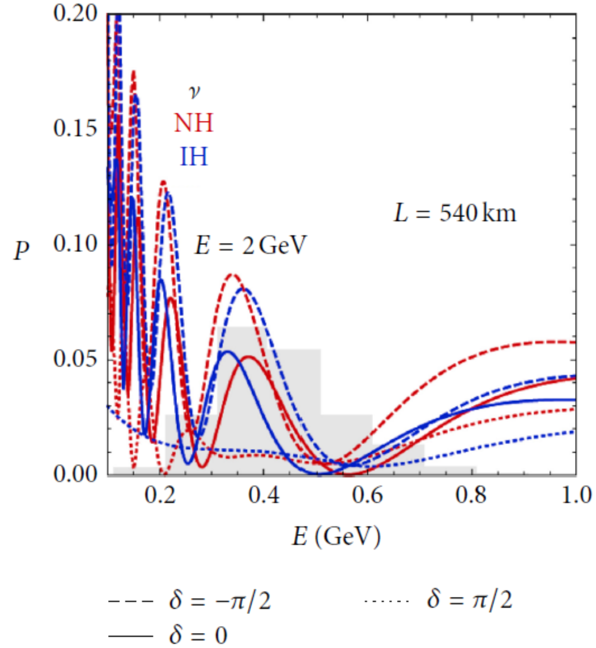
Physics Performance of ESSνSB



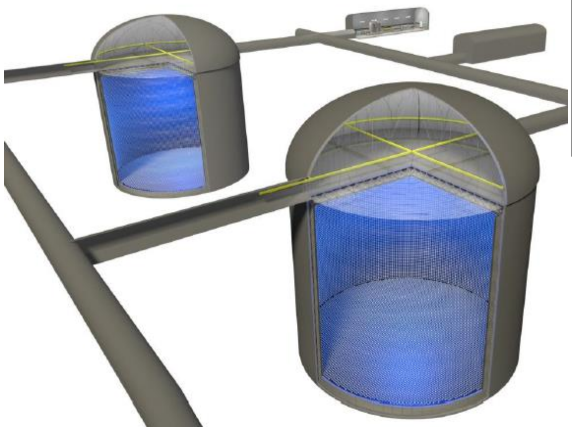


540 km
(2 GeV
protons)





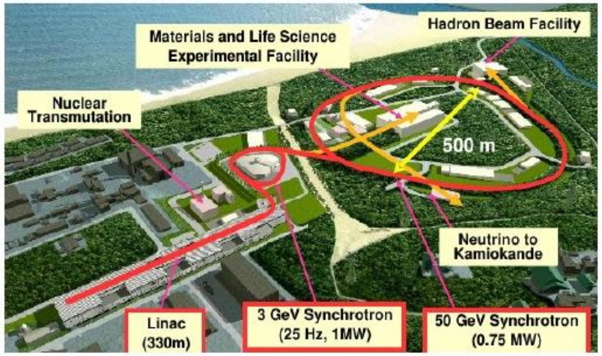
Hyper-Kamiokande



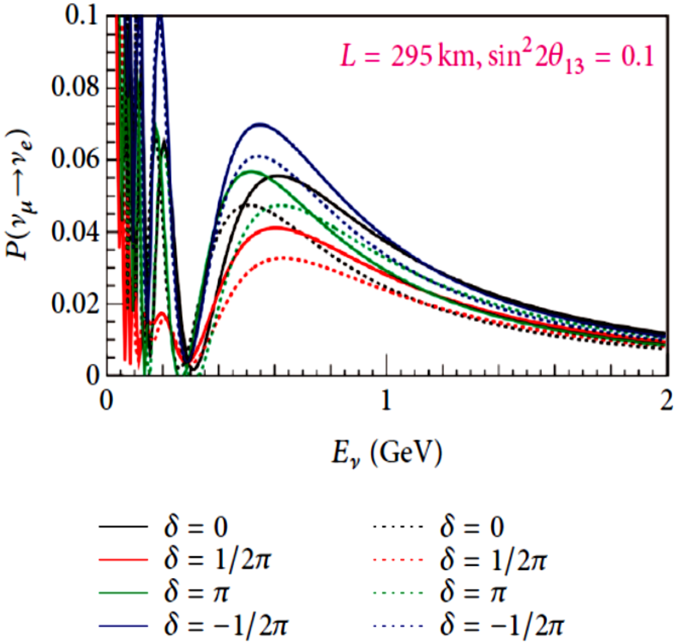
New design,
2/3 of the reference one

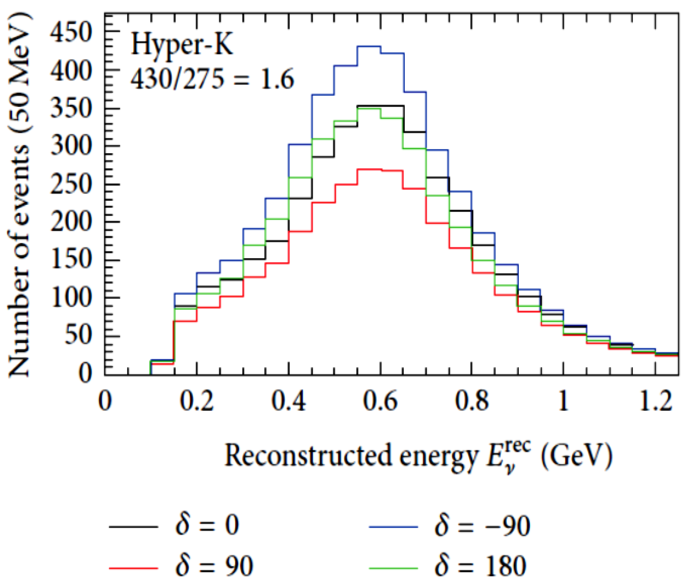
EACH TANK

- 260 Kton total
- 10 x SK fiducial volume
- Very good PMT coverage (40%)
- 60 m height x 74 m diameter



J-PARC 1.3 MW

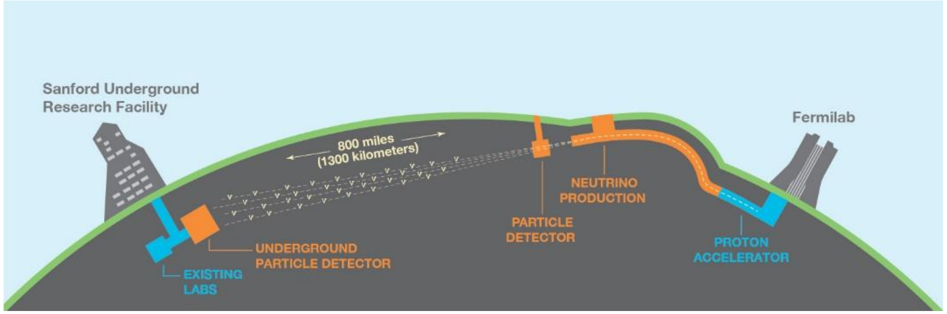


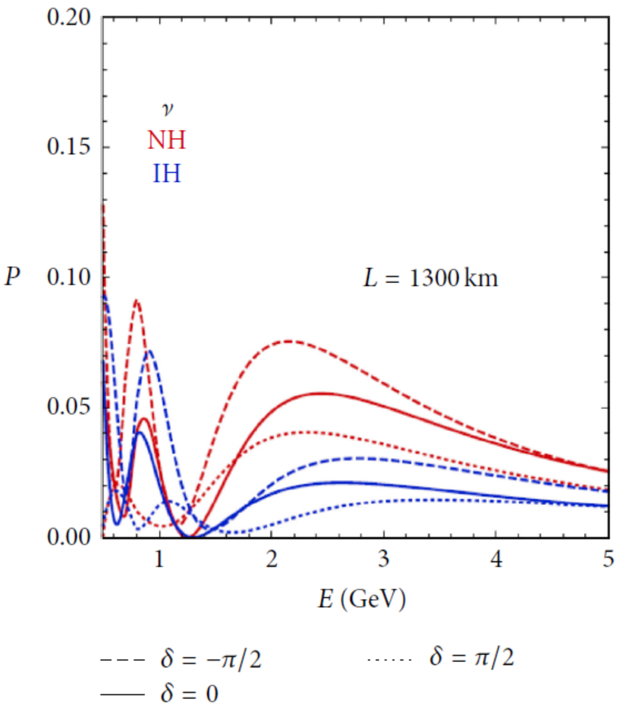


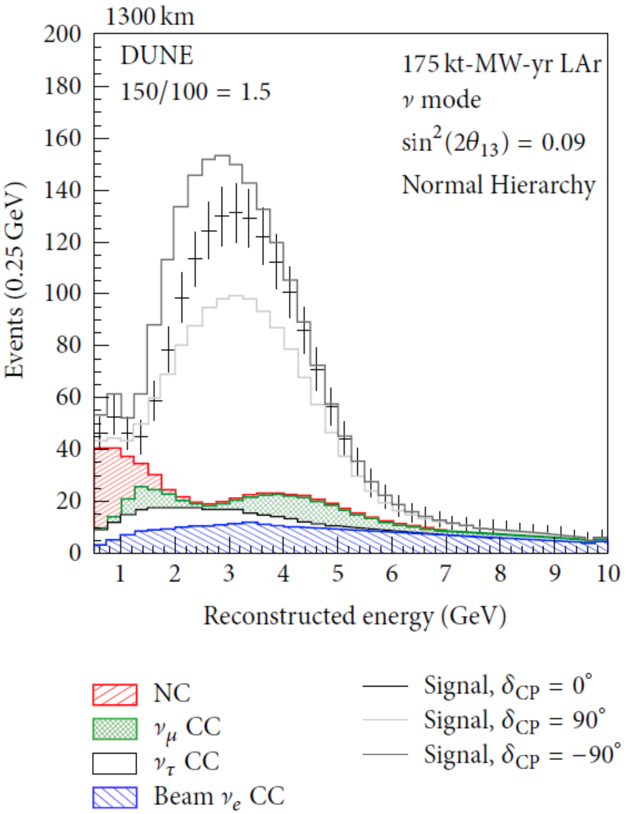
reference design

Initial beam power: 1.07 MW at 80 GeV
Planned upgrade to > 2 MW

See Dr. Zelimir DJURCIC's talk

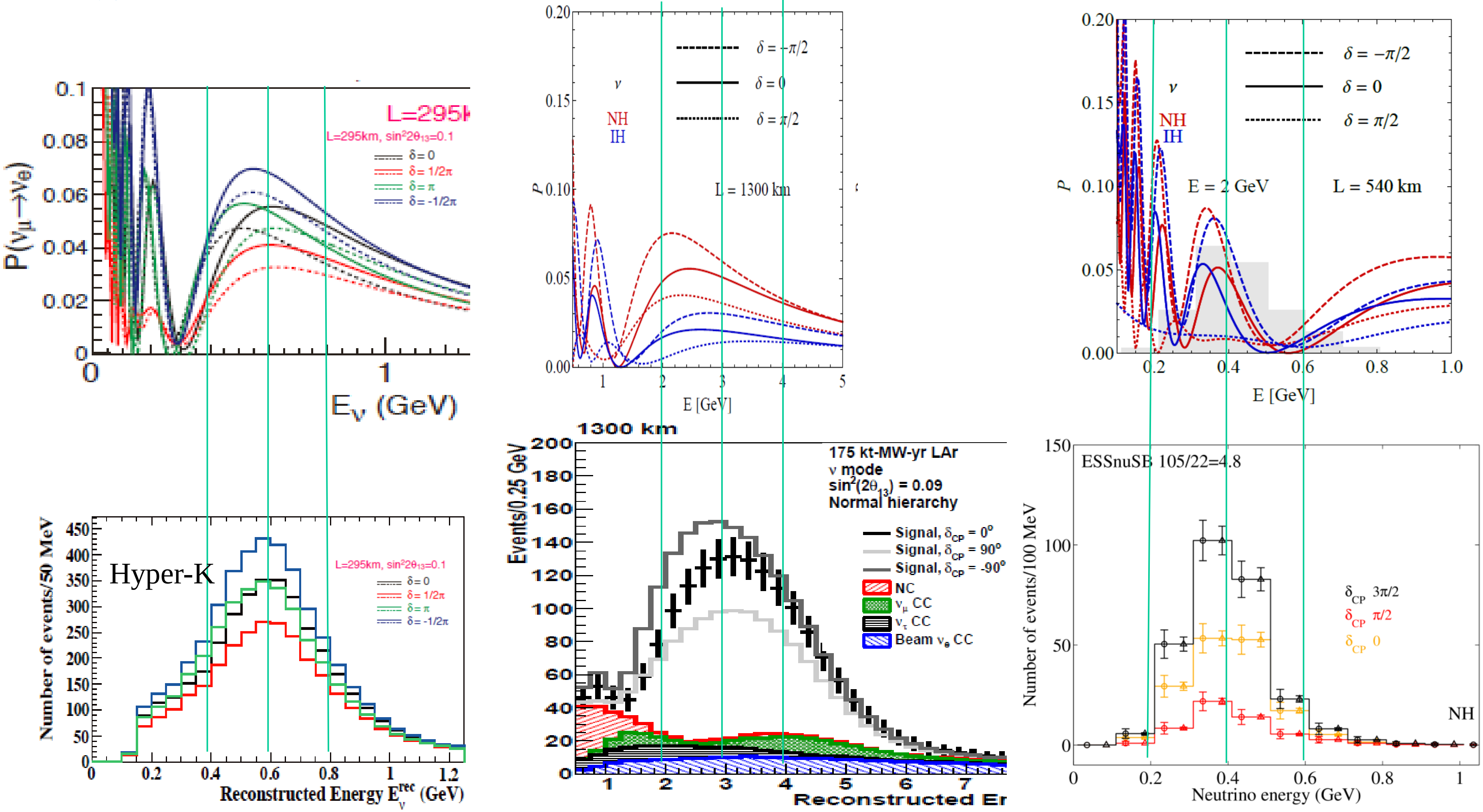






Sensitivity to δ_{CP} - neutrino energy spectra

Hyper-K first maximum | LBNE/DUNE first maximum | ESSnuSB second maximum



Relative difference in counts at maximum between $\delta_{CP} = 3\pi/2$ and $\pi/2$:

430/275 = 1.6 | 150/100 = 1.5 | 105/22 = 4.8

ESSνSB in comparison with others

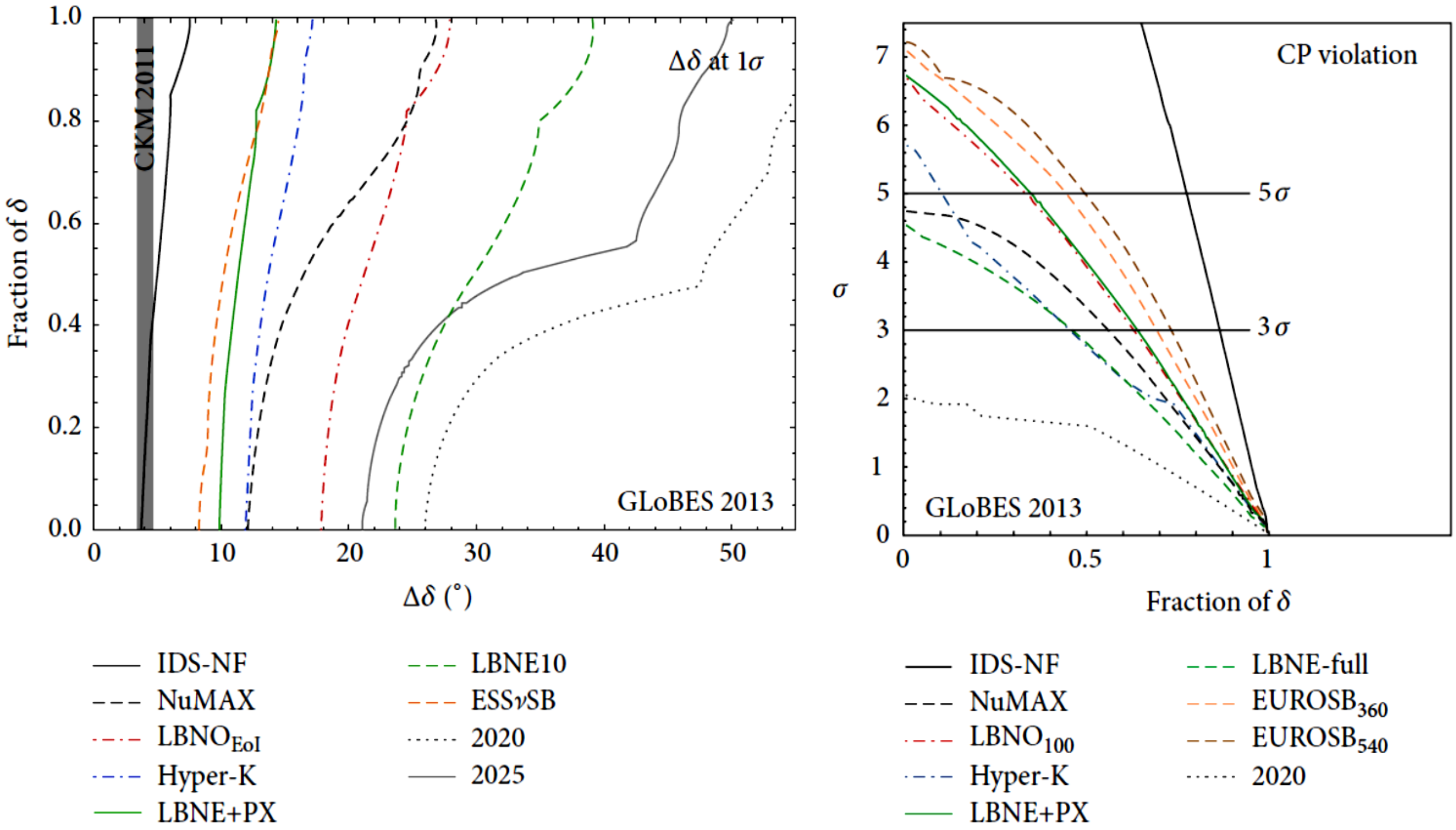


Fig. 11. The significance in terms of number of standard deviations σ with which CP violation can be discovered as function of the fraction of the full δ_{CP} range for different proposed experiments. For ESSνSB the two baselines of 360 km and 540 km and two proton energies (2.0 GeV on left and 3.0 GeV on right) are shown. "2020" considers 3 + 3 years of NOvA, and 5 years only for neutrinos in T2K (at its nominal luminosity, 0.75 MW); "2025" considers 5 + 5 years of NOvA, and 5 + 5 years for T2K. The detector simulation details for T2K follow [41], while for NOvA see

Conclusion

- The European Spallation Source linac will be ready in less than 10 years (5 MW, 2 GeV proton beam by 2023).
- Neutrino Super Beam based on ESS linac is very promising.
- ESS will have enough protons to go to the 2nd oscillation maximum where the sensitivity to CP violation is larger.
- CP violation discovery: 5 σ could be reached over 60% of δ_{CP} range in ESSνSB.
- The megaton far detector has a potential for a rich astroparticle physics programme.
- Rich muon programme.
- A Design Study is needed.
- **EuroNuNet** : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* (**http://www.cost.eu/COST_Actions/ca/CA15139**)

δ_{CP}, not just one more parameter to measure…

- **Why is the Universe as we know it made of matter, with no antimatter present?**
- **What is the origin of this matter-antimatter asymmetry?**
- **Are neutrinos connected to the matter-antimatter asymmetry, and if so, how?**
- **If neutrinos exhibit CP violation, is it related to the CP violation observed in the quark interactions?**
    - **Already observed CP violation in the quark sector is not enough to explain the matter-antimatter asymmetry.**
    - **CP violation in the lepton sector could be enough to explain matter-antimatter asymmetry if $|\sin\theta_{13}\sin\delta_{CP}| \gtrsim 0.11$ (hep-ph/0611338) $\Rightarrow$ $|\sin\delta_{CP}| \gtrsim 0.7$ ($45^o \lesssim \delta_{CP} \lesssim 135^o$ or $225^o \lesssim \delta_{CP} \lesssim 315^o$).**
- **Are neutrinos their own antiparticles (do we need Majorana phases)?**
- **What role did neutrinos play in the evolution of the universe?**

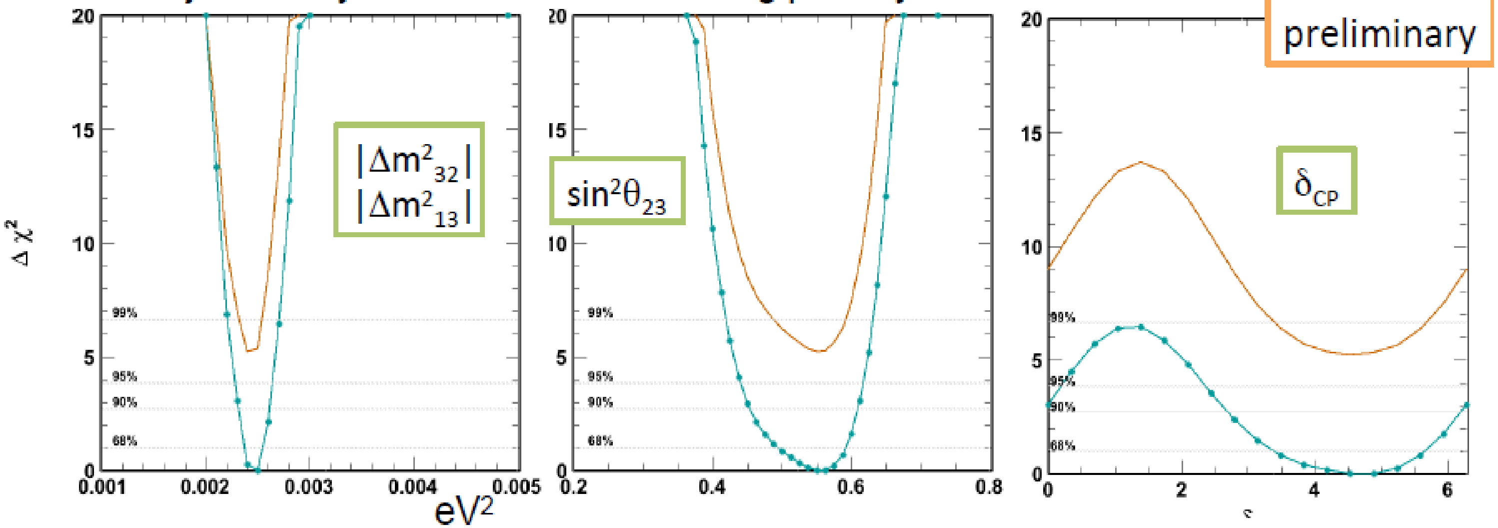
Back-up

NH ↔ IH

Neutrino 2016

SK+T2K ν_μ, ν_e parameter determination

Not a joint analysis, fit external data using publicly available T2K info.



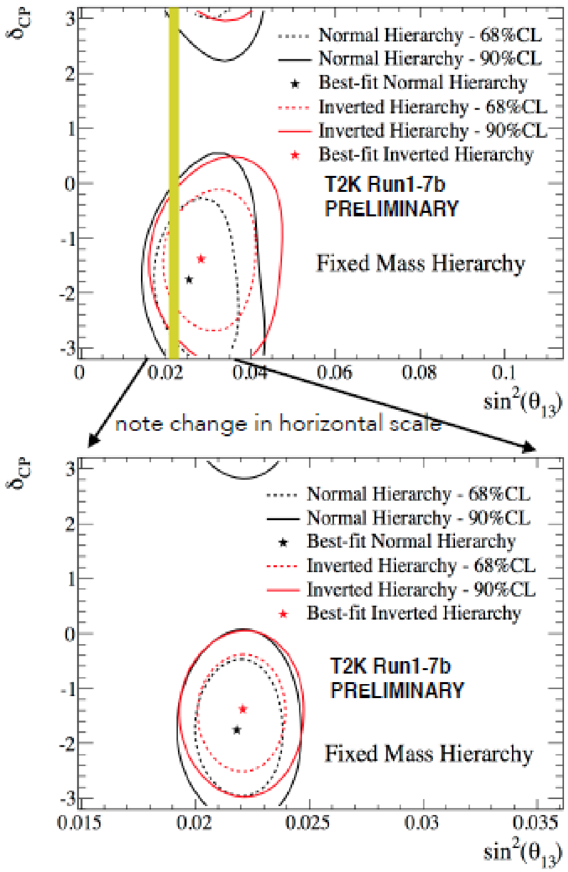
Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$

  (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). NH: 0.43 ($\sin^2\theta_{23}$=0.6)

13

δ_{CP} vs. θ_{13}

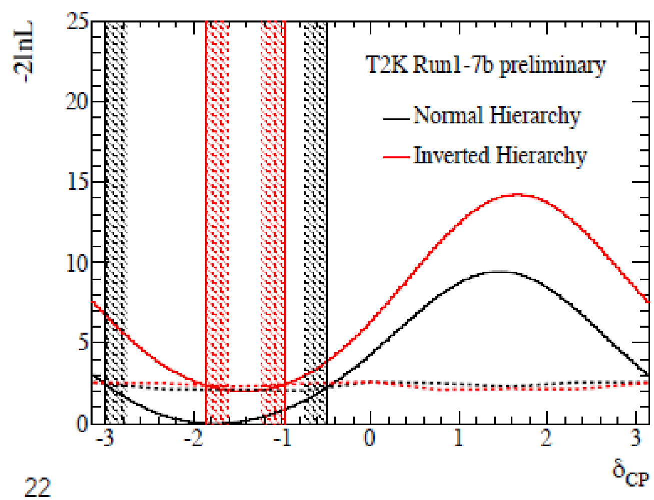


Left: δ_{CP} vs. θ_{13} (fixed $\Delta\chi^2$, fixed hierarchy)

- T2K-only
- T2K with reactor $\sin^2 2\theta_{13}$= 0.085±0.005

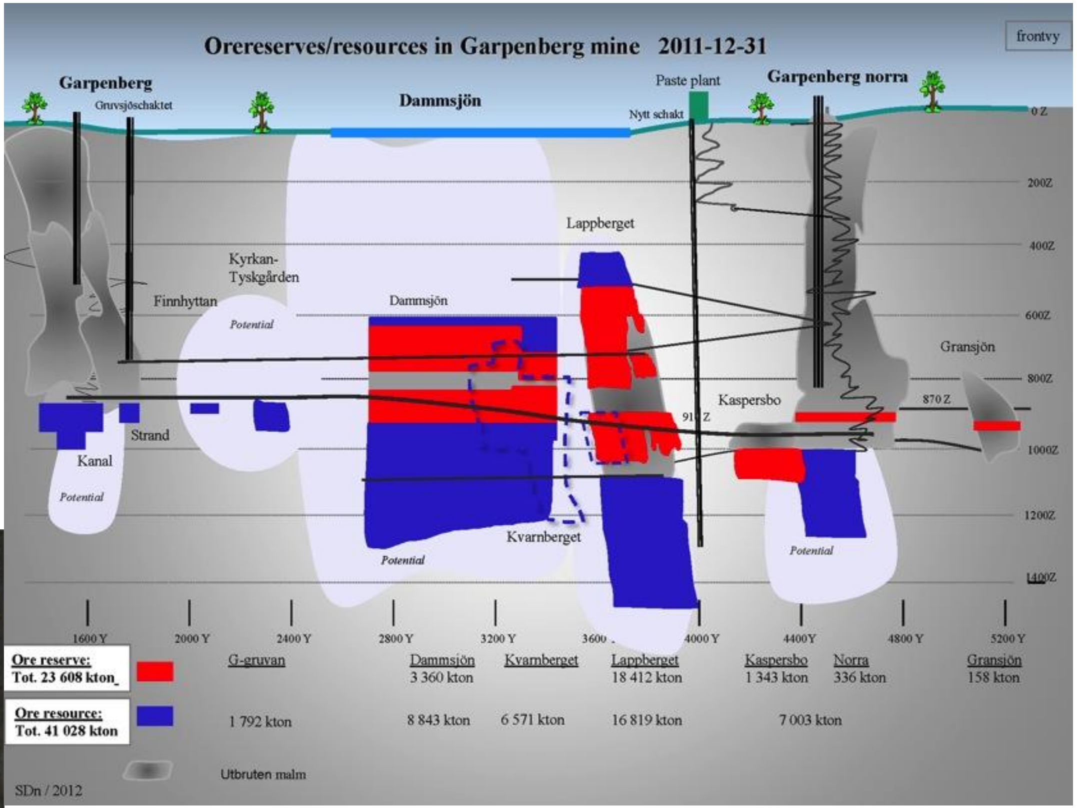
Below: δ_{CP} with Feldman-Cousins critical values and reactor θ_{13}

δ_{CP} = [-3.02, -0.49] (NH), [-1.87, -0.98] (IH) @90% CL



Garpenberg Mine (Boliden)

- Distance from ESS: 540 km
- Depth: 1232 m
- Truck access tunnels
- Two ore hoist shafts
- A new ore hoist shaft is planned to be ready in 3 years, leaving the two existing shafts free for other uses

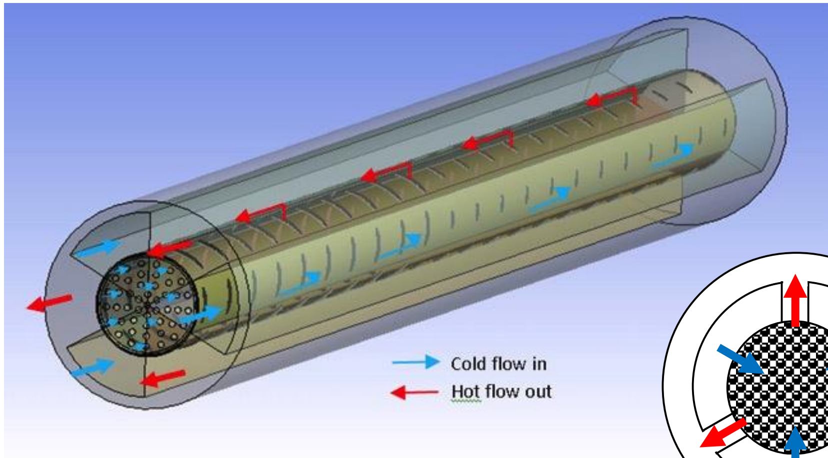


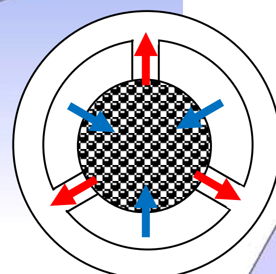
Granite drill cores around a candidate position

Mitigation of high power effects

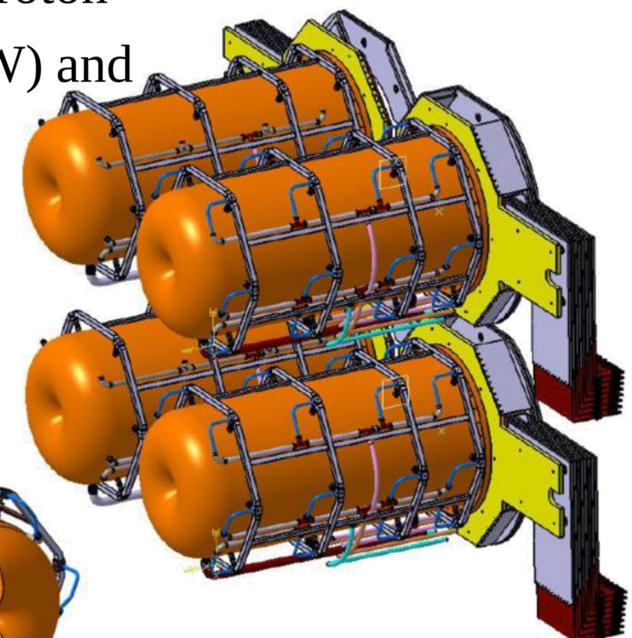
(4-Target/Horn system for EUROnu Super Beam)

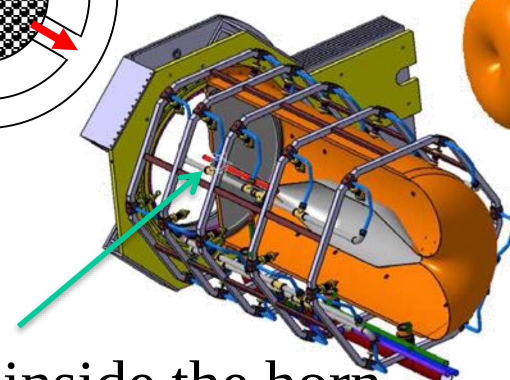
Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)



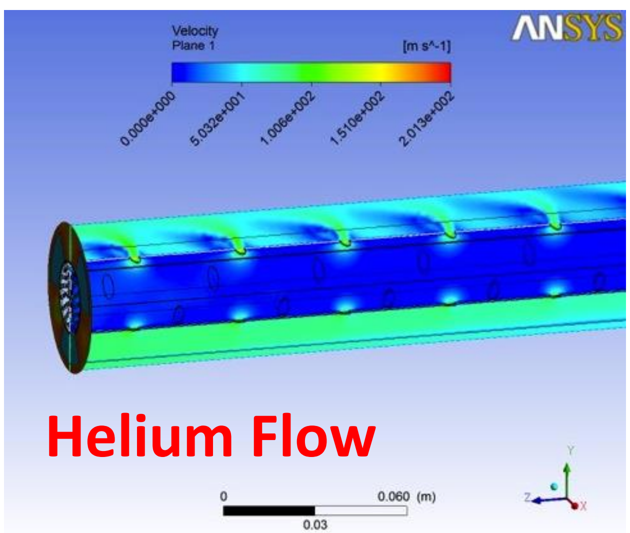


4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)





target inside the horn



proton beam switchyard

Number of events

Table 3
Number of neutrinos for two plus eight years running with neutrinos and anti-neutrinos respectively (Fig. 7).

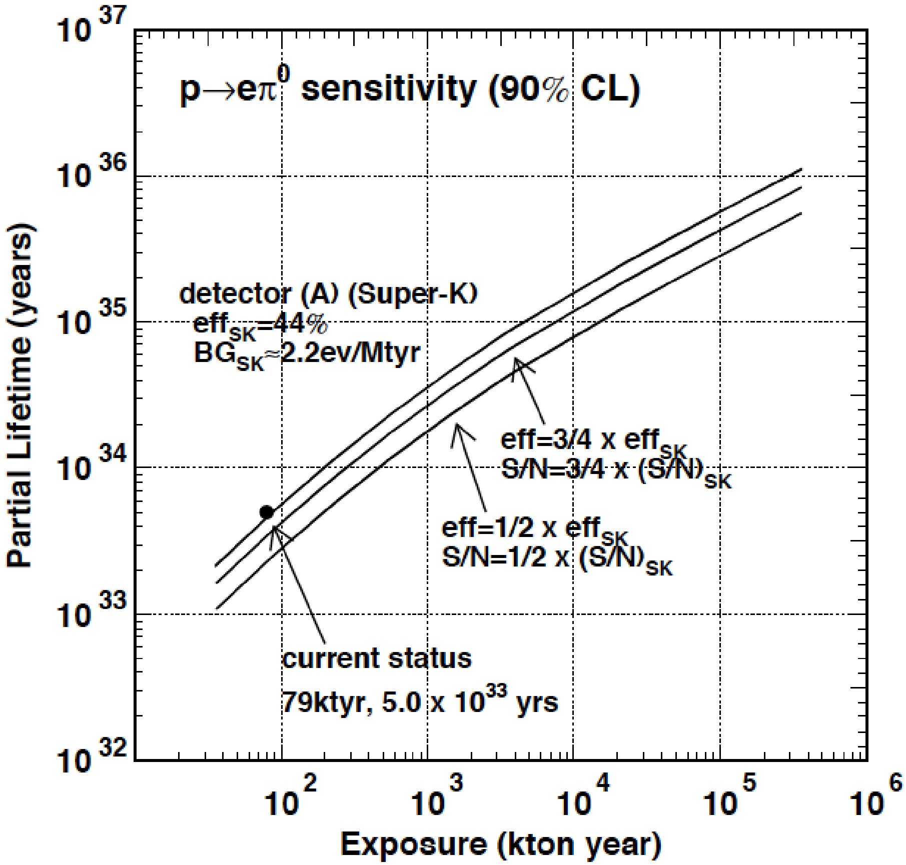
Experiment configuration	ν_e ($\bar{\nu}_e$) signal	ν_μ ($\bar{\nu}_\mu$) miss-ID	ν_e beam	$\bar{\nu}_e$ beam	NC back.	$\bar{\nu}_\mu(\nu_\mu) \to \bar{\nu}_e(\nu_e)$
360 km						
positive	303.3	10.7	70.8	0.08	29.2	1.4
negative	246.1	6.1	2.4	50.6	17.4	13.3
540 km						
positive	196.7	4.6	33.3	0.04	13.7	0.9
negative	162.9	2.8	1.1	23.5	8.2	7.8

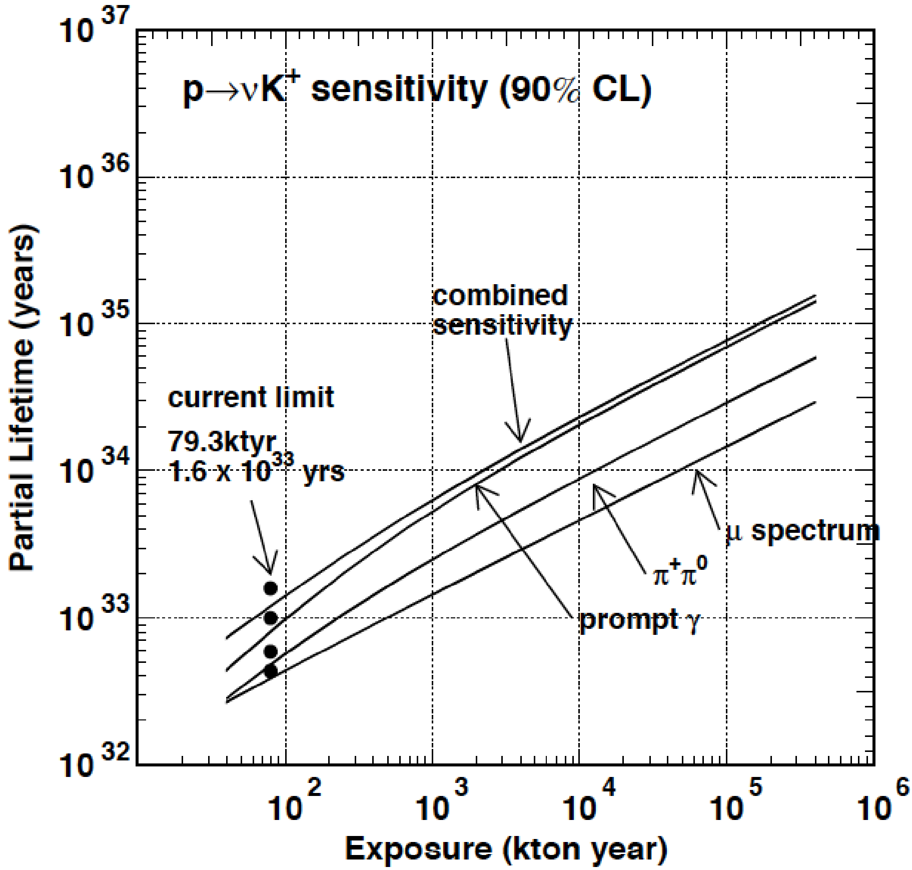
Conditions under which Fig. 11 has been prepared.

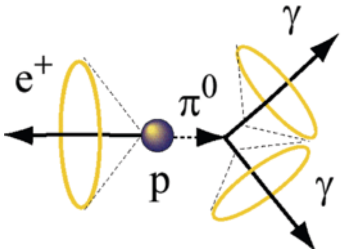
	Detector vol. (kt)/type	Dist. (km)	Power (MW)	Proton driver energy (GeV)	Years $\nu/\bar{\nu}$
ESSνSB-360	500/WC	360	5	2.0/3.0	2/8
ESSνSB-540	500/WC	540	5	2.0/3.0	2/8
Hyper-K [31,44,45]	560/WC	295	0.75	30	3/7
LBNE-10 [46–48]	10/LAr	1290	0.72	120	5/5
LBNE-PX	34/LAr	1290	2.2	120	5/5
LBNO-EoI [49]	20/LAr	2300	0.7	400	5/5
IDS-NF [50,51]	100/MIND	2000	4	10*	10**
NuMAX [52,53]	10/LAr (magnetized)	1300	1	5*	5/5

* Muon beam energy, relevant for IDS-NF (Low Energy Neutrino Factory) and NuMax.
** IDS-NF is supposed to use at the same time muons and anti-muons.

The MEMPHYS Detector
(Proton decay)

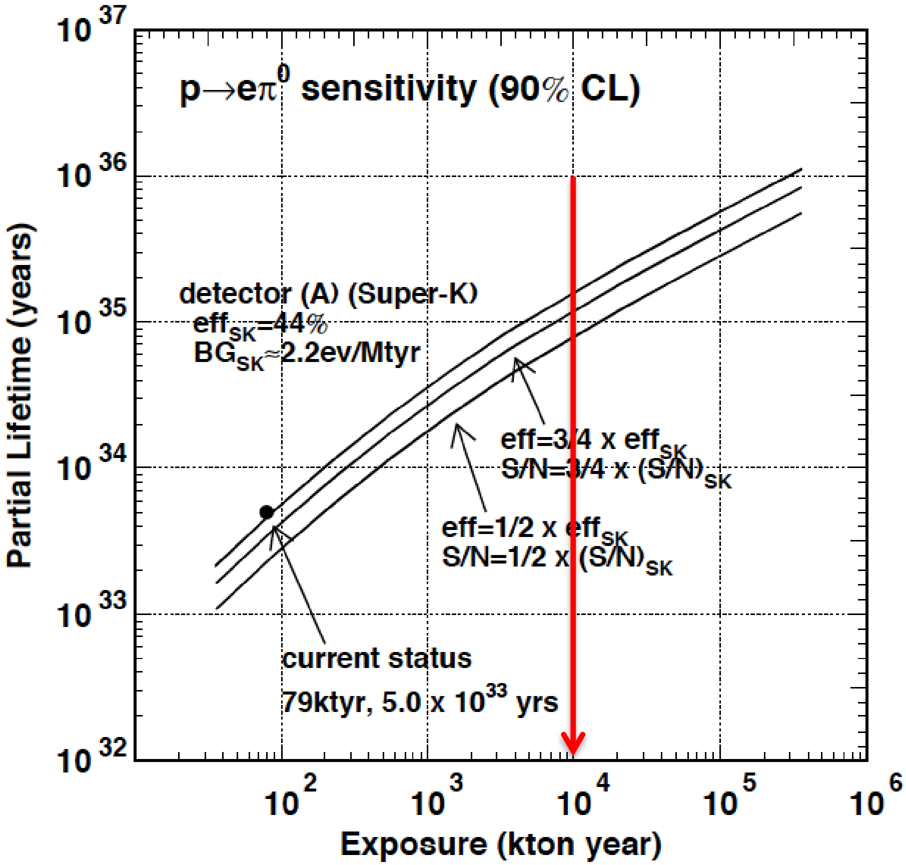


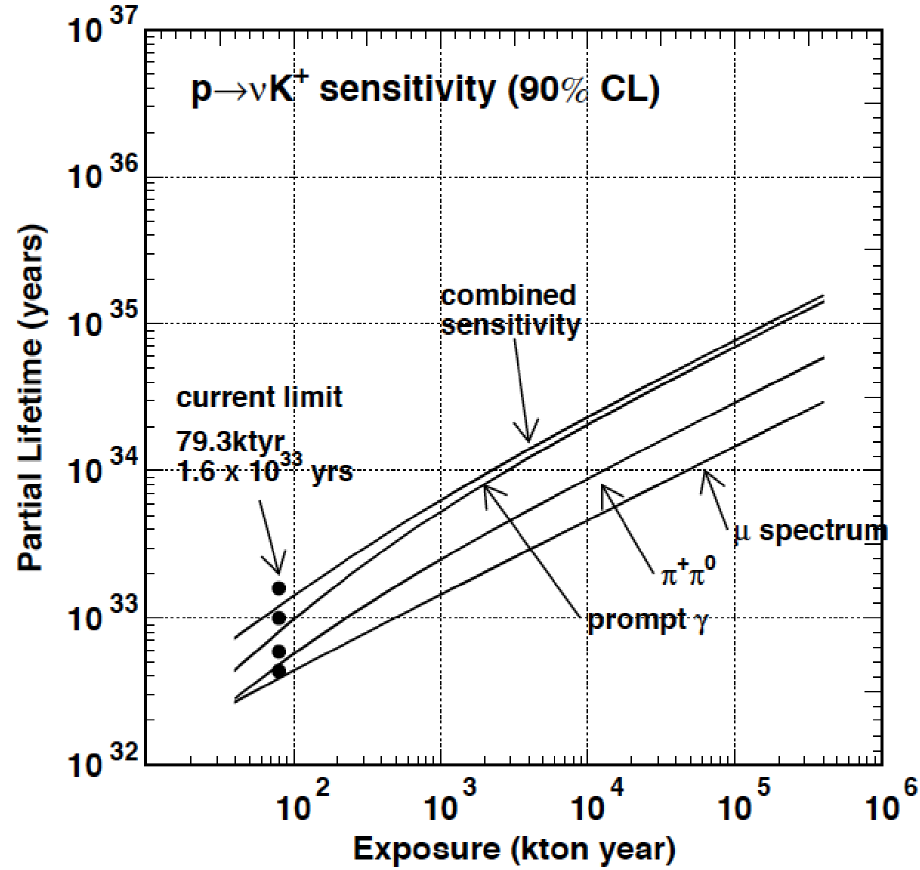


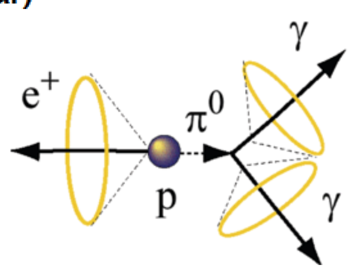


(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Proton decay)

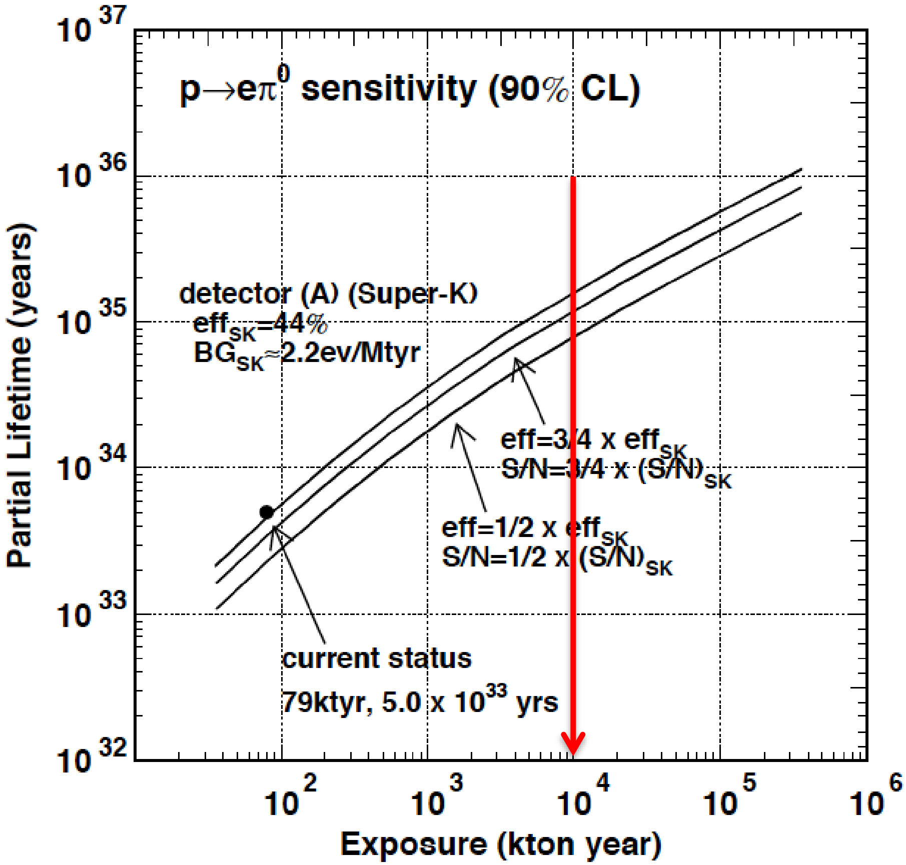


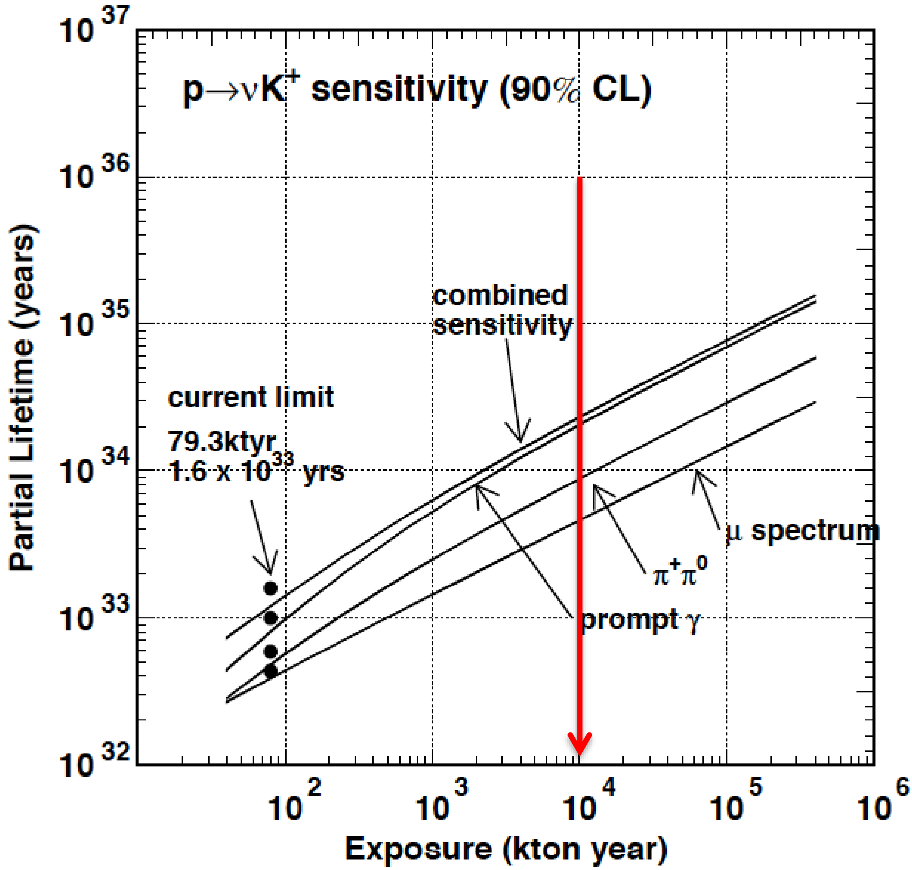


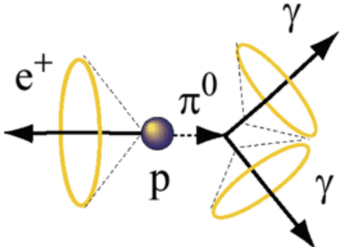


(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Proton decay)







(arXiv: hep-ex/0607026)

The MEMPHYS Detector
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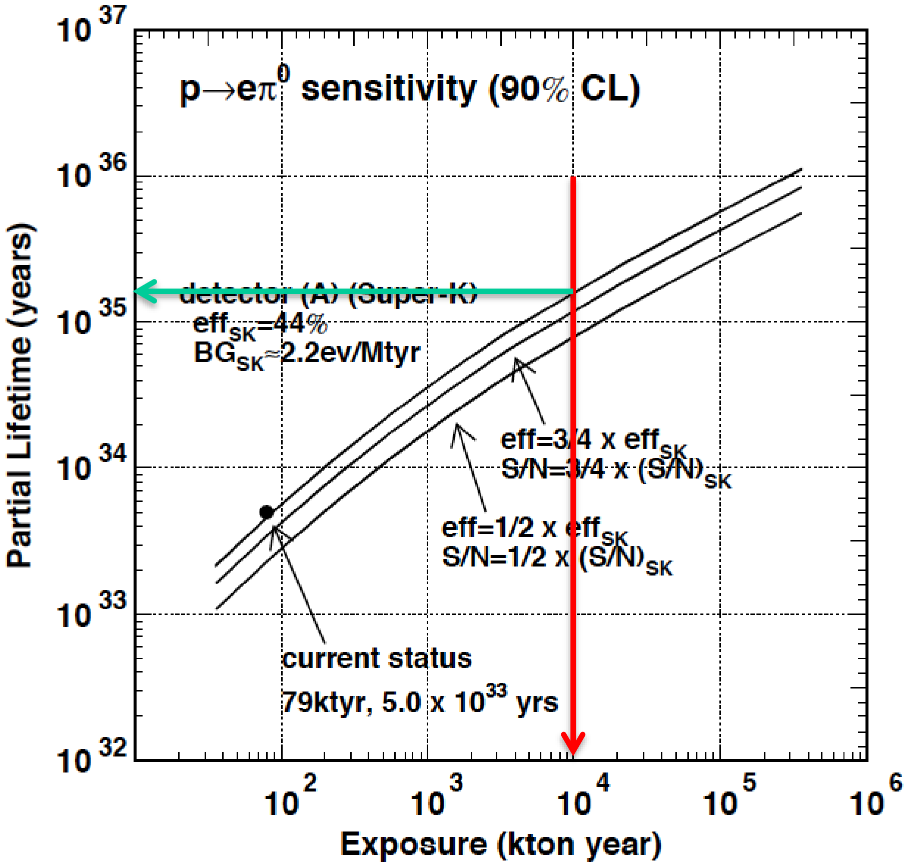
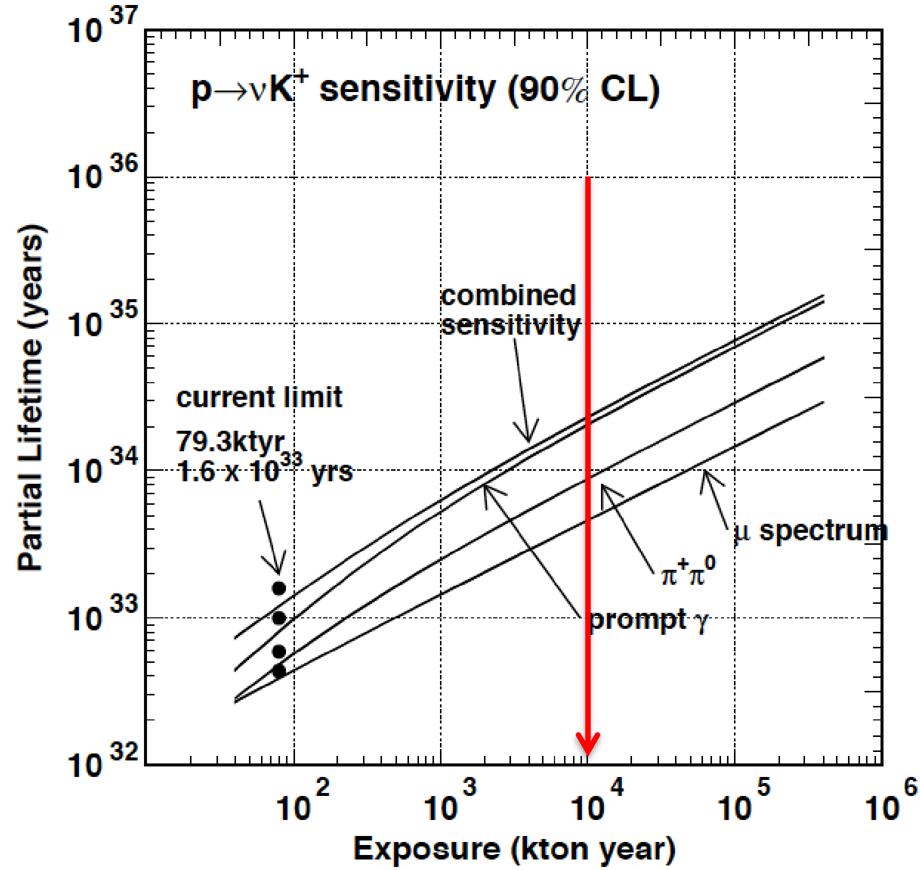
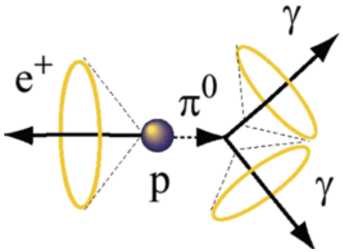
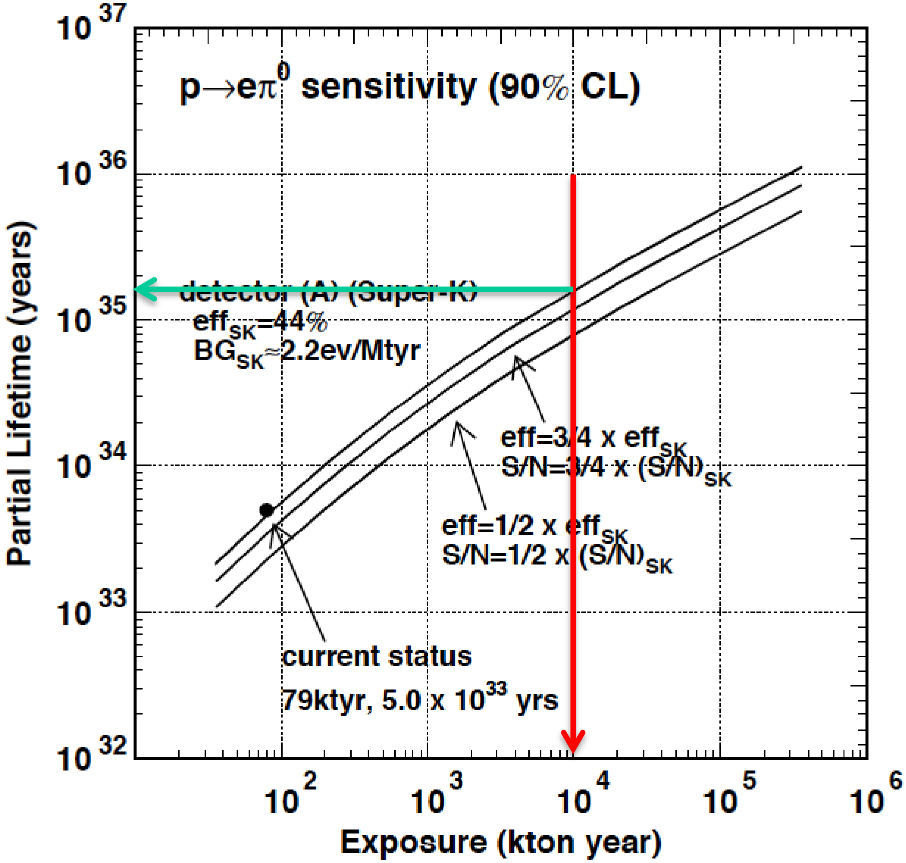


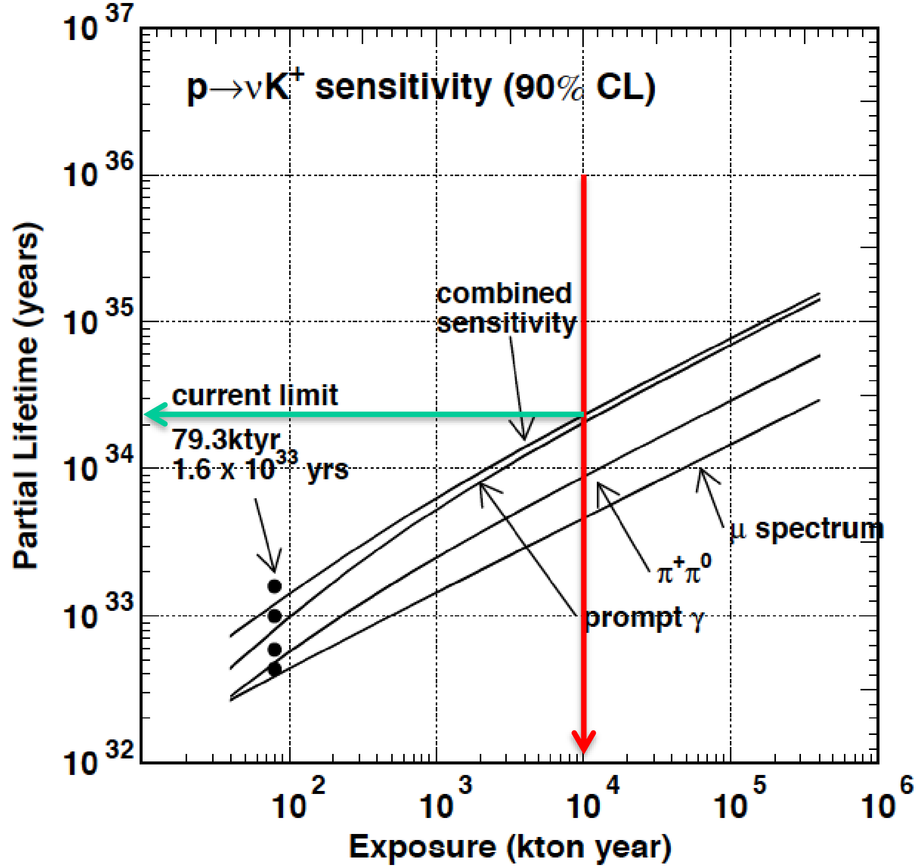


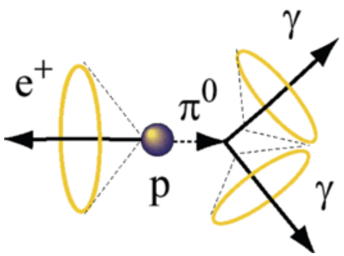


(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Proton decay)



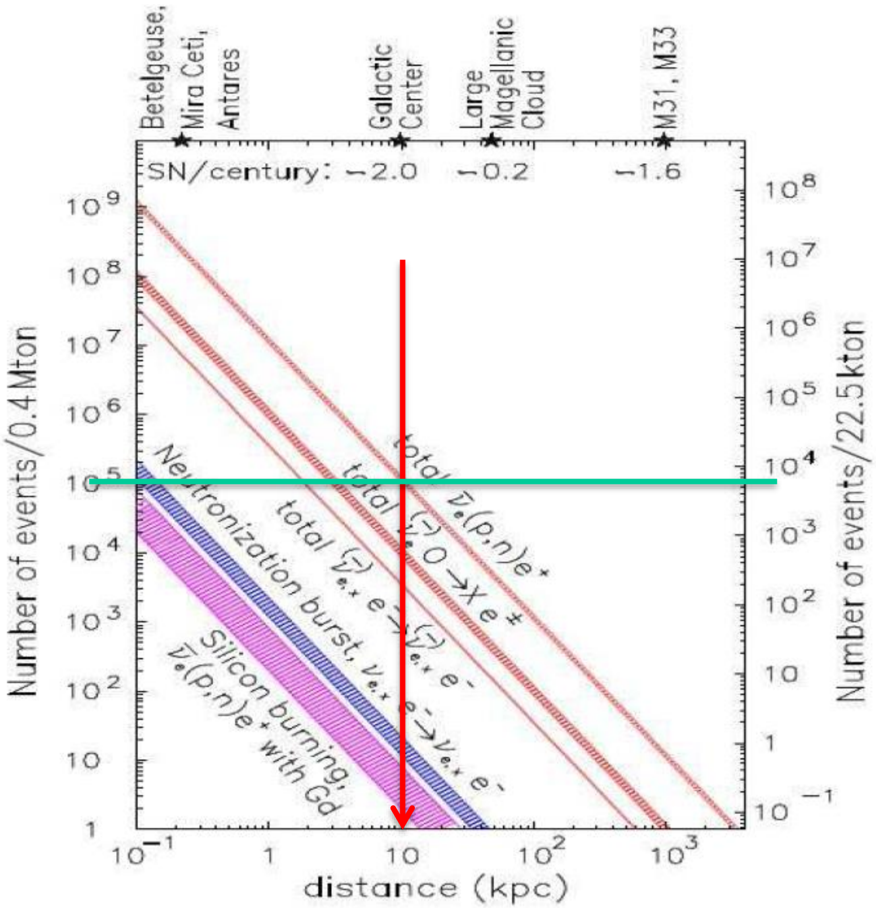




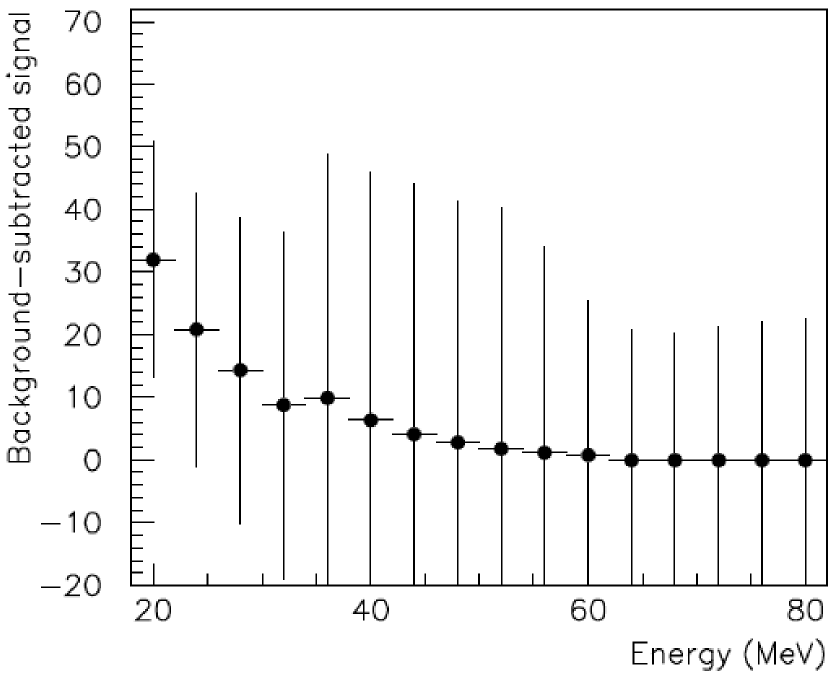
(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Supernova explosion)

MEMPHYS



SUPERK



Diffuse Supernova Neutrinos

(10 years, 440 kt)

For 10 kpc: ~10^5 events

Systematic errors

Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

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