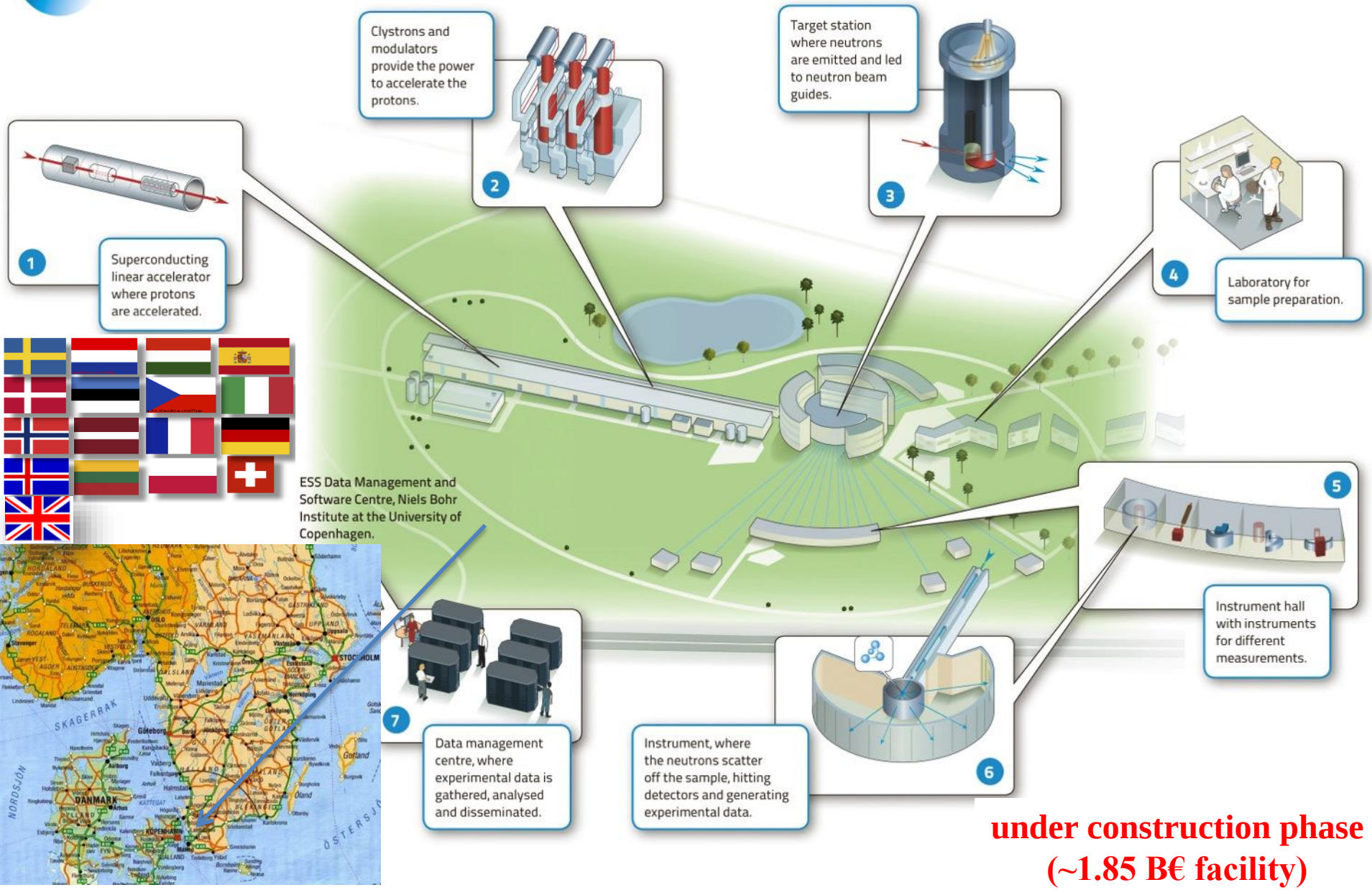
EPS Conference on High Energy Physics Venice, Italy 5-12 July 2017

Neutrino CP Violation with the ESSνSB project

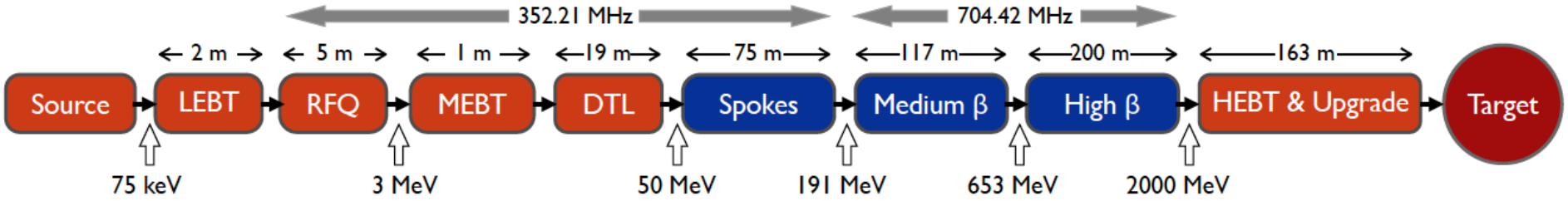
Marcos Dracos
on behalf of the ESSνSB group

European Spallation Source

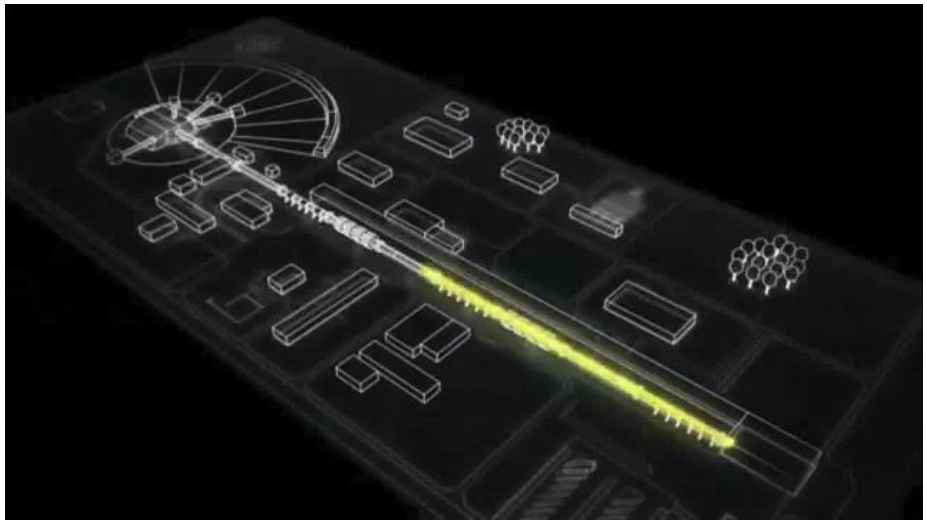


under construction phase (~1.85 B€ facility)

ESS proton linac

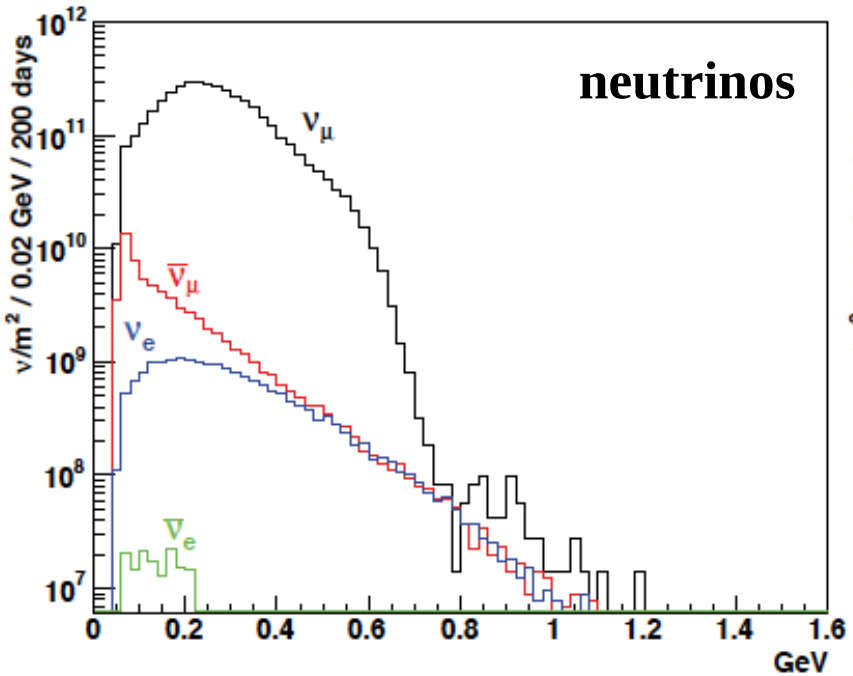


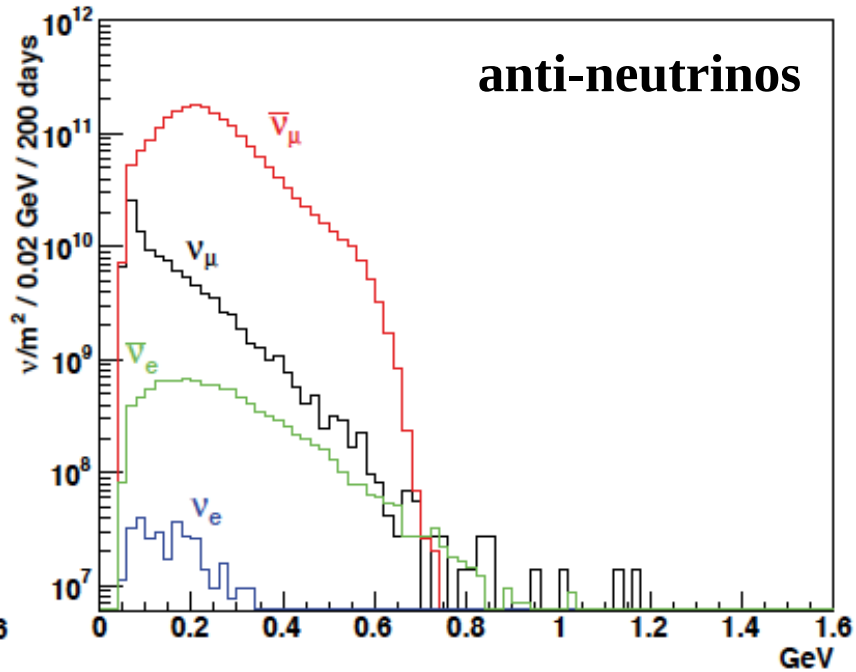
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades).
- **>2.7x10^{23} p.o.t/year.**



Linac ready by 2023 (full power and energy)

ESSνSB ν energy distribution





- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

	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 (in absence of oscillations)

CP Violating Observables ($\nu_\mu \rightarrow \nu_e$)

$$P_{\nu_\mu \rightarrow \nu_e (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp} \right)^2 \sin^2 \left(\frac{\tilde{B}_\mp L}{2} \right)$$ 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-CP 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
⇒ accessibility to mass hierarchy
⇒ long baseline

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

≠0 ⇒ CP Violation
be careful, matter effects also create asymmetry

δ_{CP} and matter-antimatter asymmetry magnitude

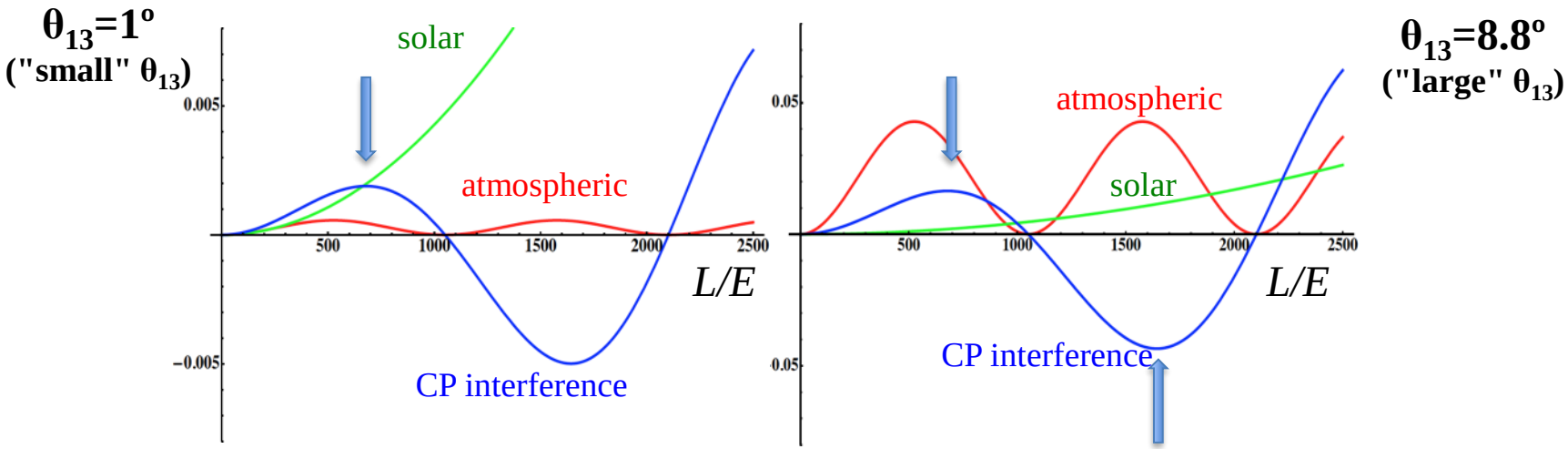
$$A_{\alpha\beta}^{CP} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$
$$= J_{CP}^{PMNS} \cdot \sin\delta_{CP}$$

with: $J_{CP}^{PMNS} \sim 3\times 10^{-3}$ (Jarlskog invariant)

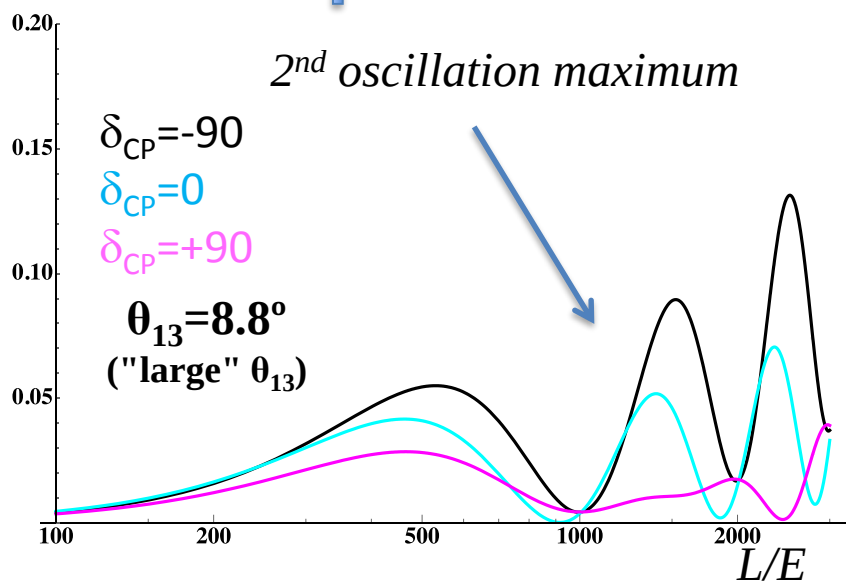
(for hadrons: $J_{CP}^{CKM} \sim 3\times 10^{-5}$, not enough to explain the matter-antimatter asymmetry in the Universe even if $\delta_{CP} \sim 70°$)

Theoretical models predict that if $|\sin\delta_{CP}| \gtrsim 0.7$ ($45° < \delta_{CP} < 135°$ or $225° < \delta_{CP} < 315°$), it could be enough to explain the observed asymmetry.

Neutrino Oscillations with "large" θ_{13}



- for small θ_{13} 1st oscillation maximum is better (arXiv:1110.4583)
- for "large" θ_{13} 1st oscillation maximum is dominated by atmospheric term



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

→ more sensitivity at 2nd oscillation max.

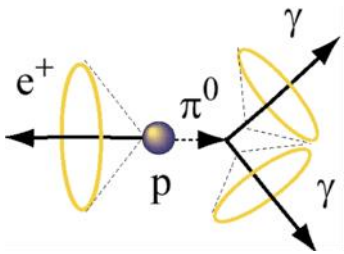
(see arXiv:1310.5992 and arXiv:0710.0554)

Can we go to the 2nd oscillation maximum using our proton beam?

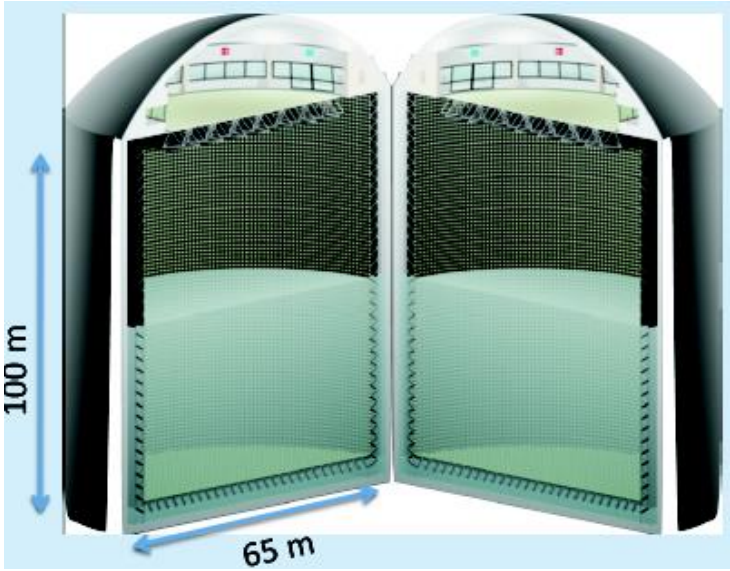
Yes, if we place our far detector at around 500 km from the neutrino source.

MEMPHYS like Cherenkov detector
(MEgaton Mass PHYSics studied by LAGUNA)

(arXiv: hep-ex/0607026)

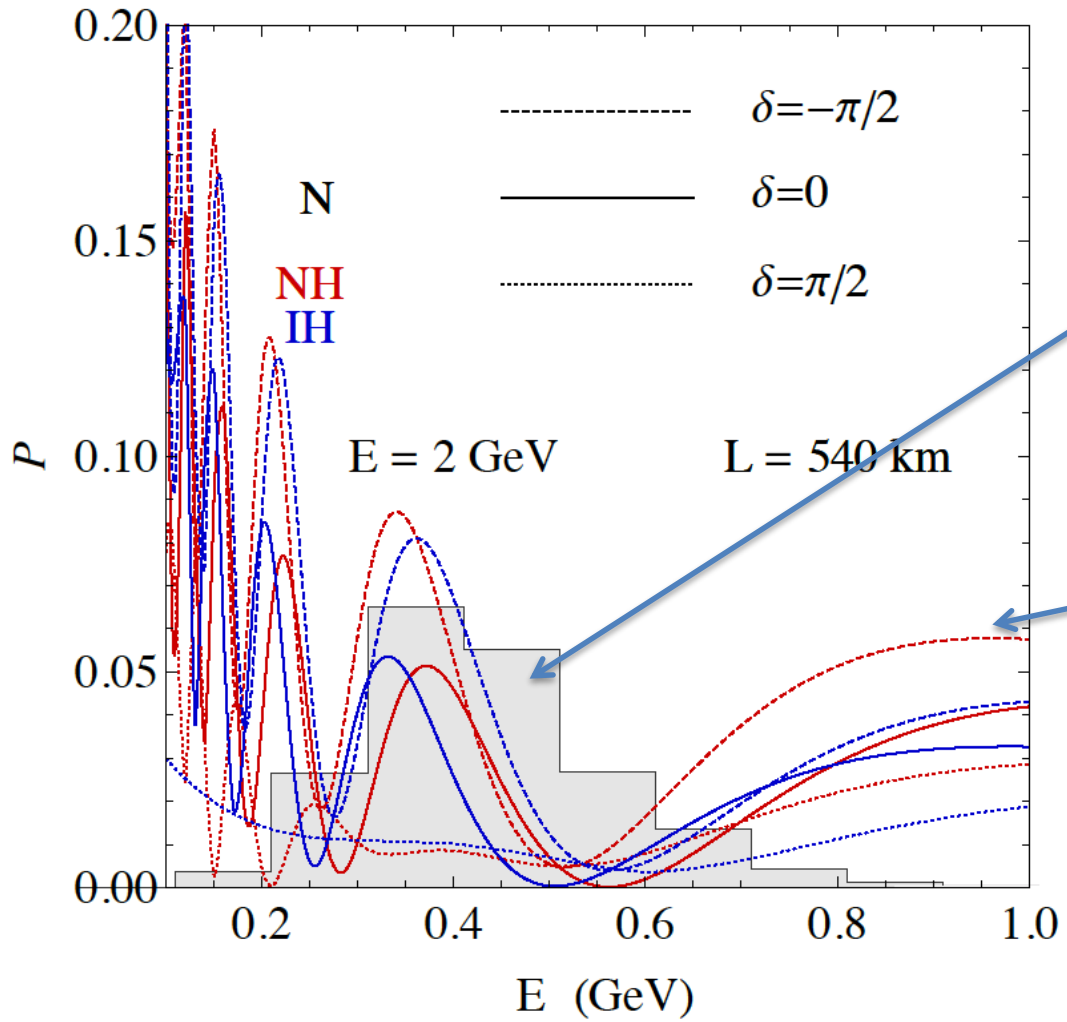


- **Neutrino Oscillations (Super Beam, Beta Beam)**
- **Proton decay**
- **Astroparticles**
- Understand the gravitational collapsing: galactic SN
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos



- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage

2nd Oscillation max. coverage



detected (electron) neutrinos by MEMPHYS detector

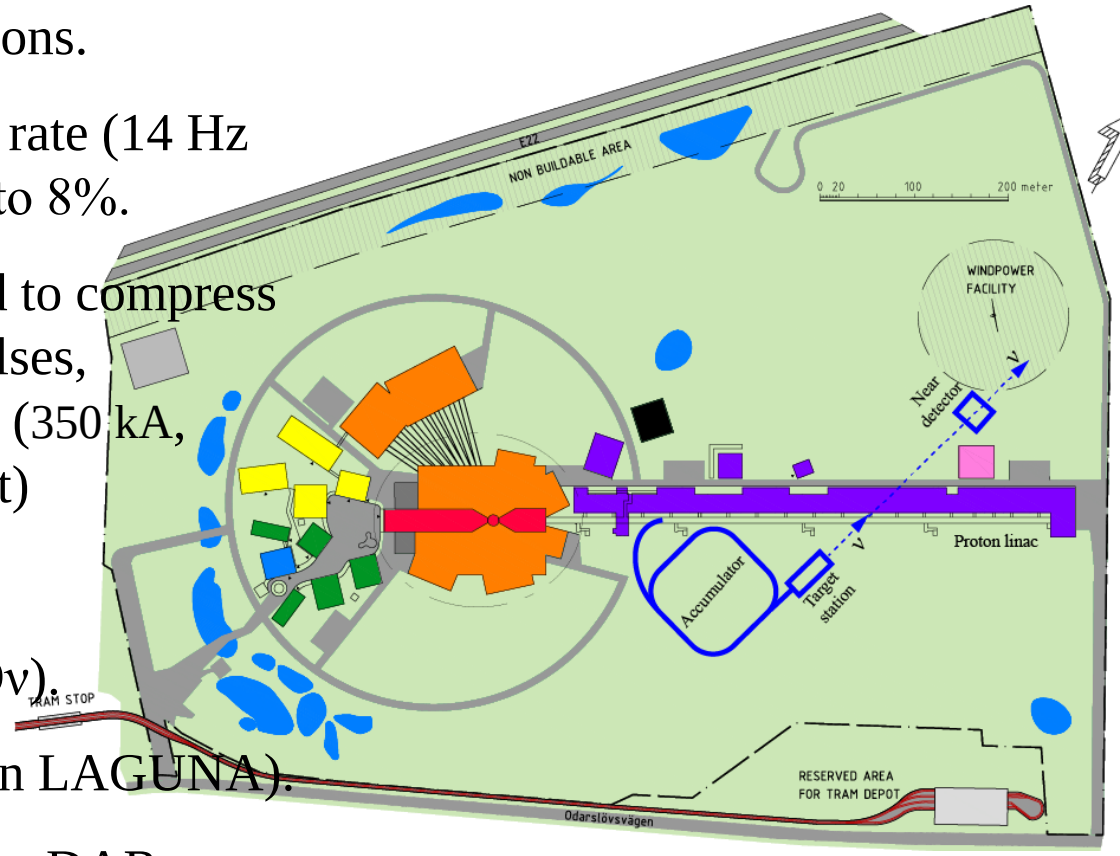
1st oscillation max.

2nd oscillation max. well covered by the ESS neutrino spectrum

ESS Linac modifications to produce a neutrino Super Beam

How to add a neutrino facility?

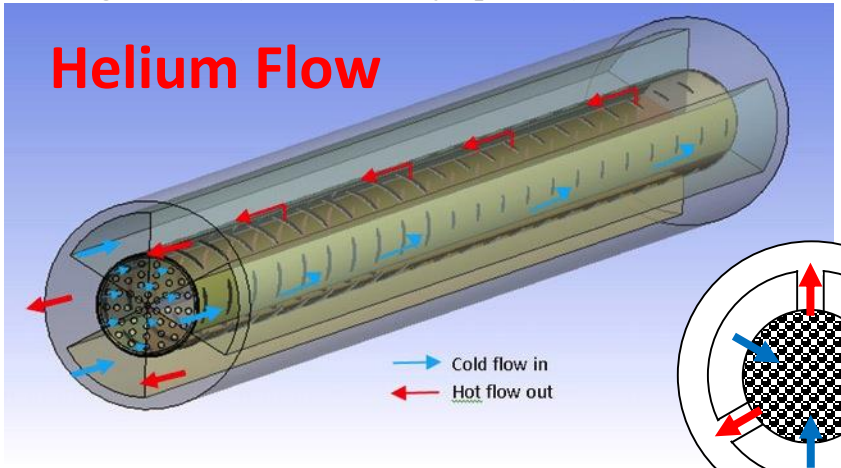
- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
- H^- source (instead of protons),
- Target station (studied in EUROν).
- Underground detector (studied in LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.



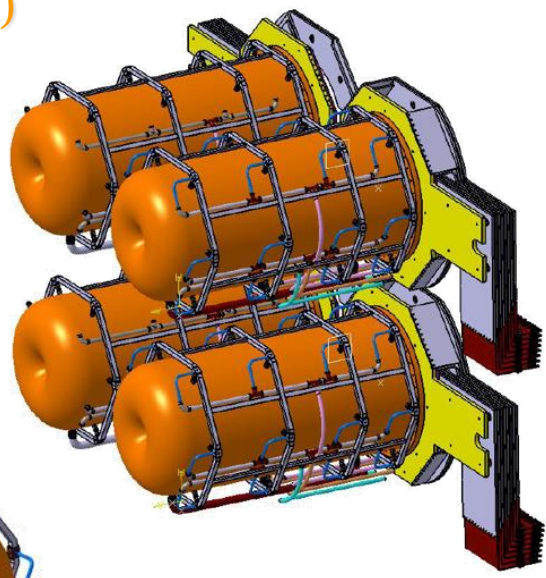
Mitigation of high power effects

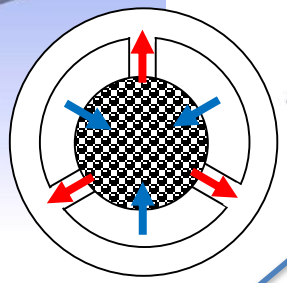
(4-Target/Horn system for EUROnu Super Beam)

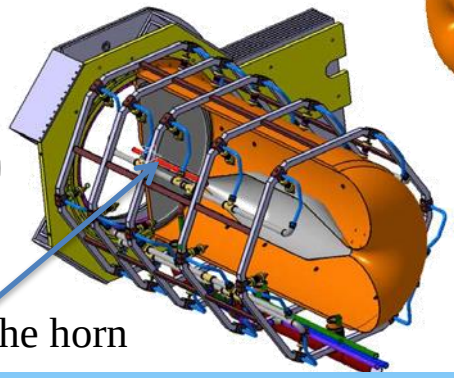
Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)



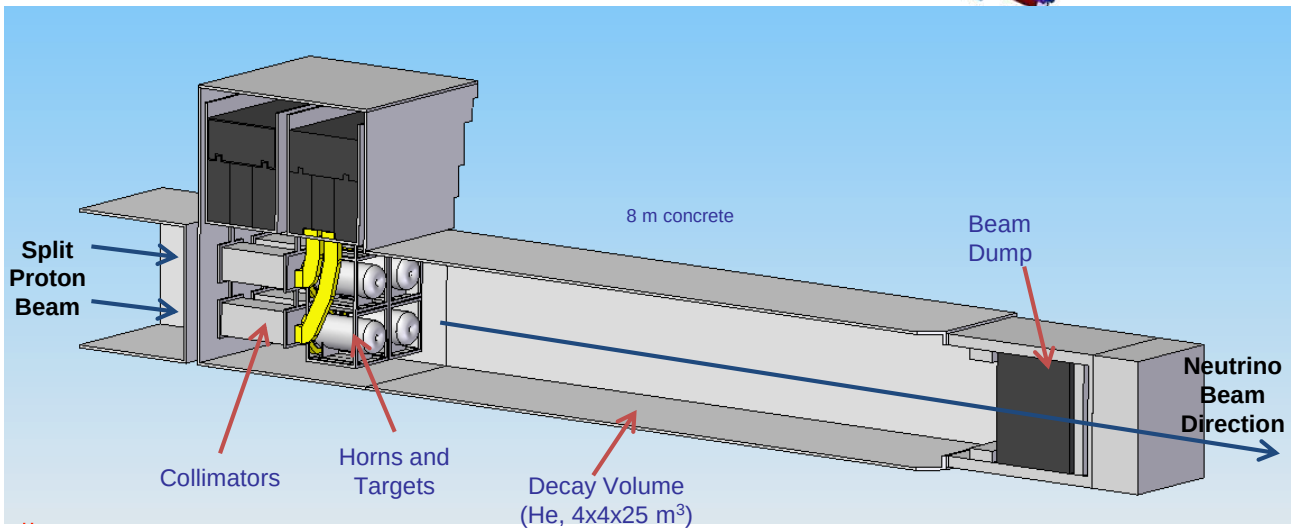
4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)



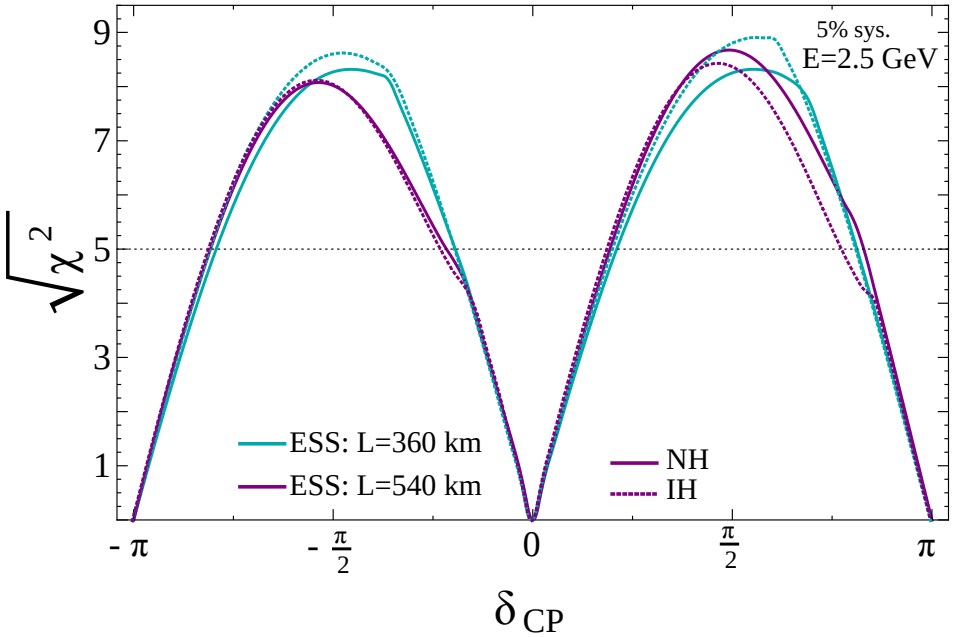


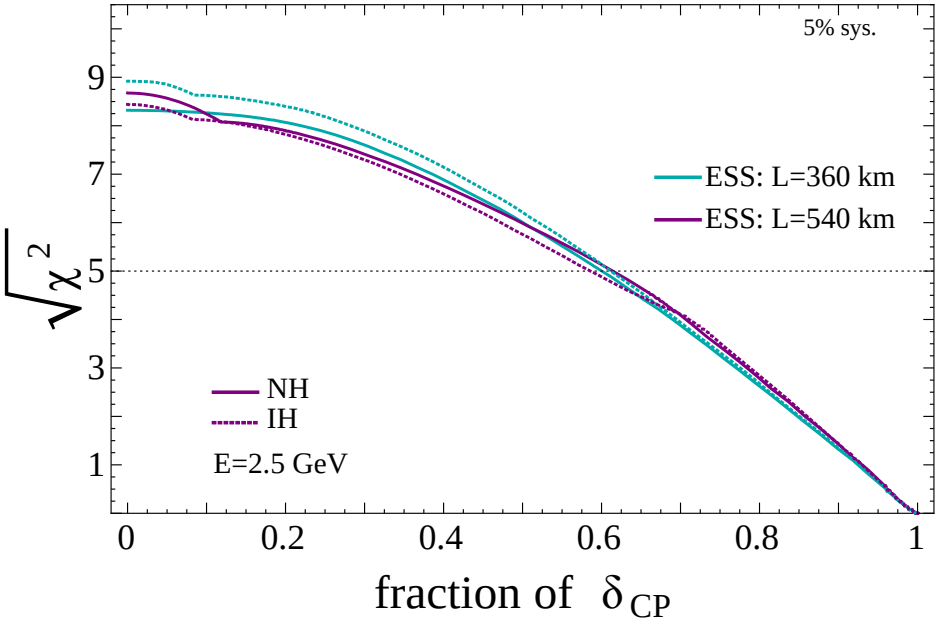


target inside the horn

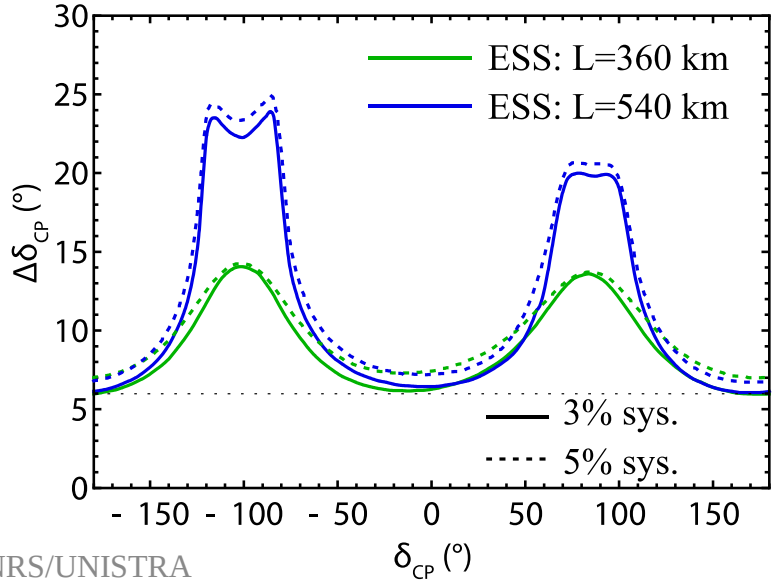


Physics Performance



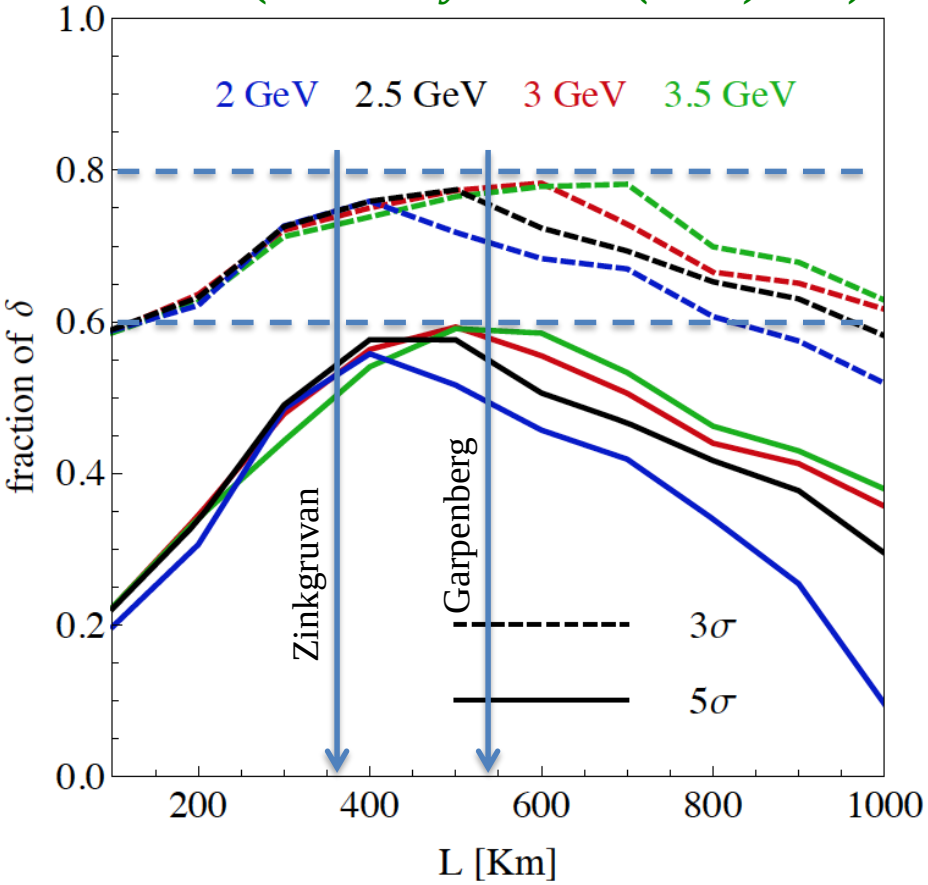


- little dependence on mass hierarchy (not so long baseline),
- δ_{CP} coverage at 5 σ C.L. up to 60%,
- δ_{CP} accuracy down to 6° at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility.



Which baseline?

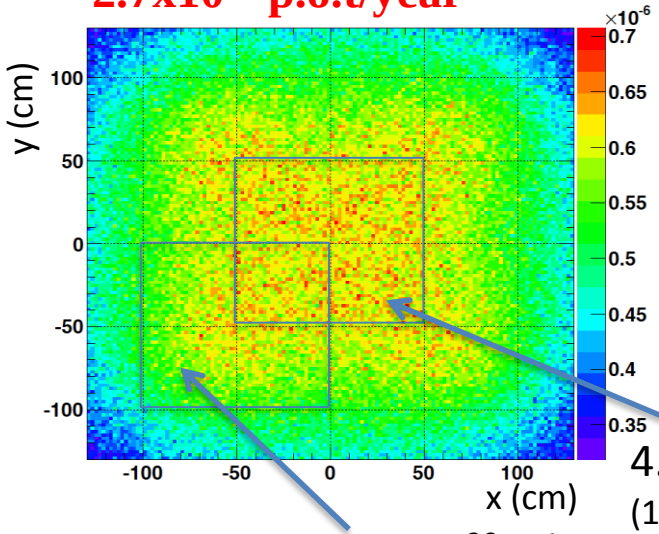
CPV (*Nucl. Phys. B 885 (2014) 127*)



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

Muons at the level of the beam dump

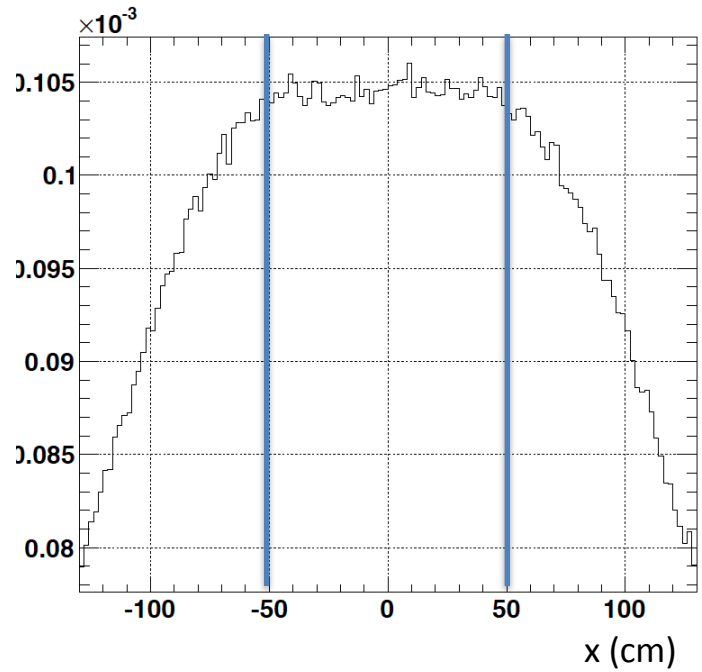
2.7x10^{23} p.o.t/year

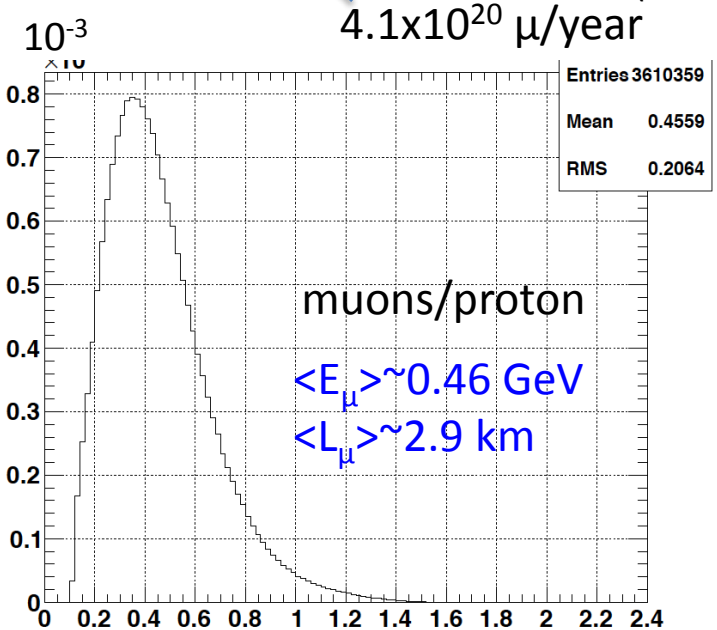


muons at the level of the beam dump (per proton)

4.2x10^{20} μ/year
(16.3x10^{20} for 4 m^2)

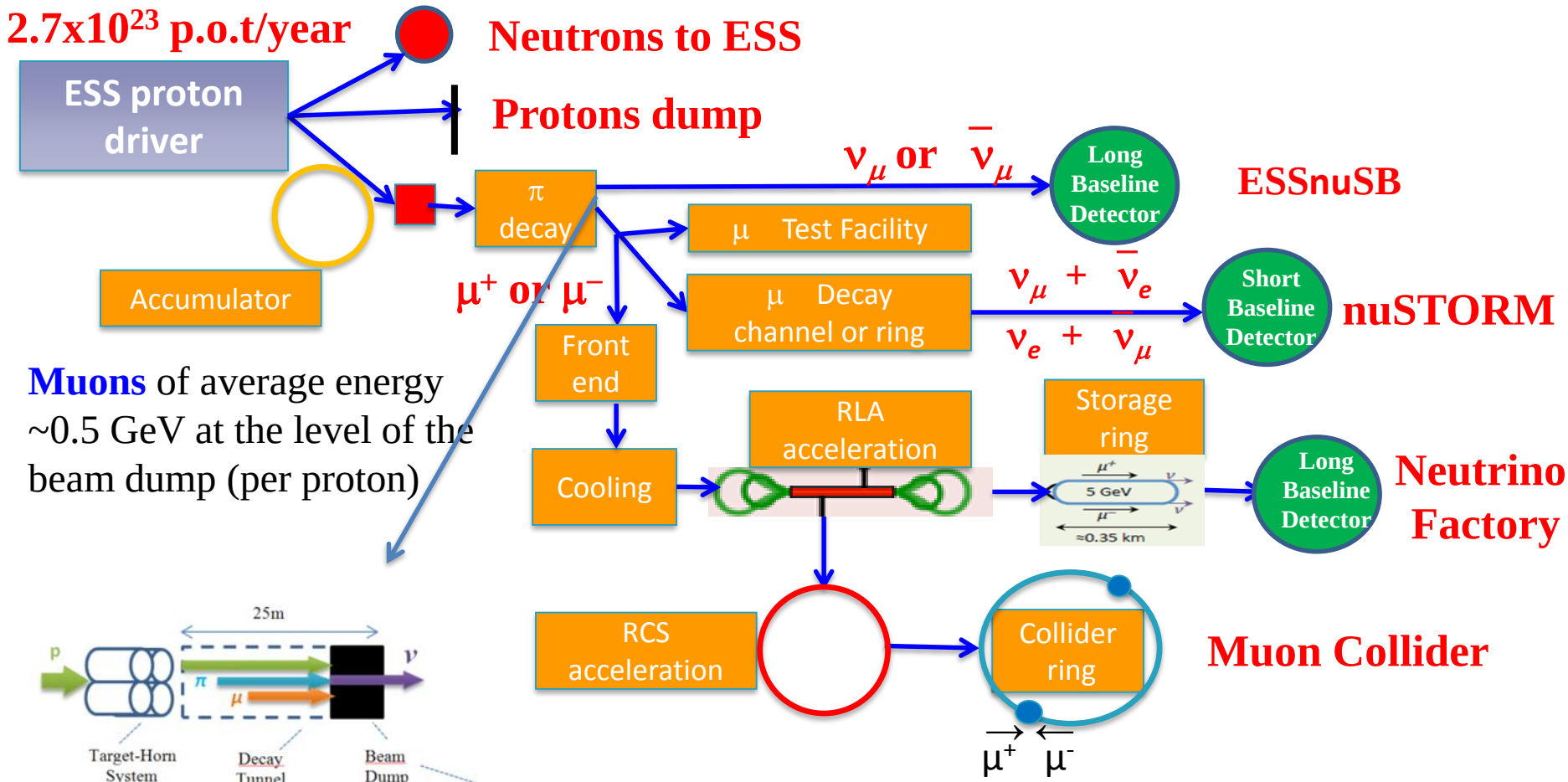
4.1x10^{20} μ/year



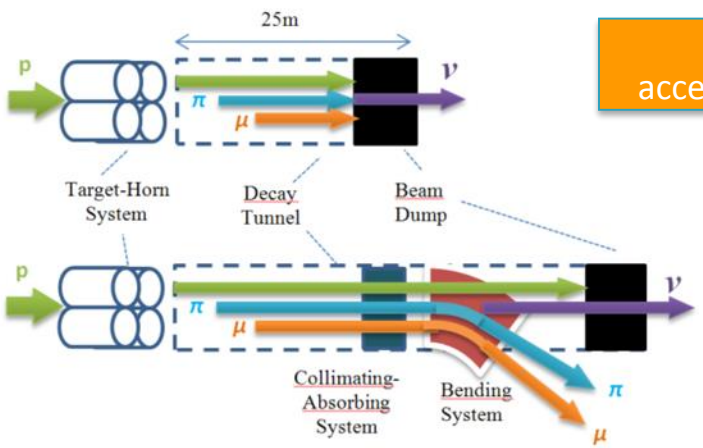


- input beam for future 6D μ cooling experiments (for muon collider),
- good to measure neutrino x-sections (ν_μ, ν_e) around 200-300 MeV using a near detector,
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

ESS neutrino and muon facility



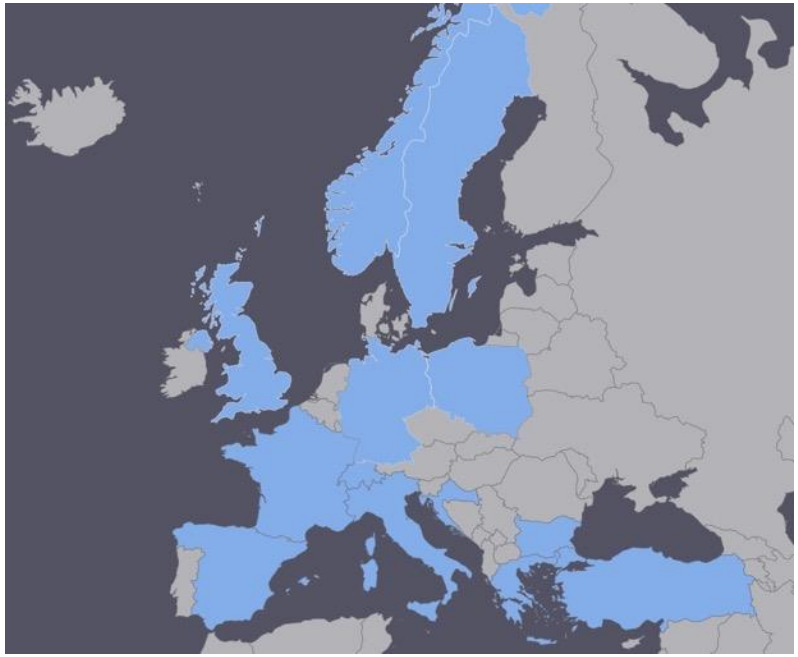
Muons of average energy ~0.5 GeV at the level of the beam dump (per proton)



more than 4×10^{20} μ/year from ESS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).

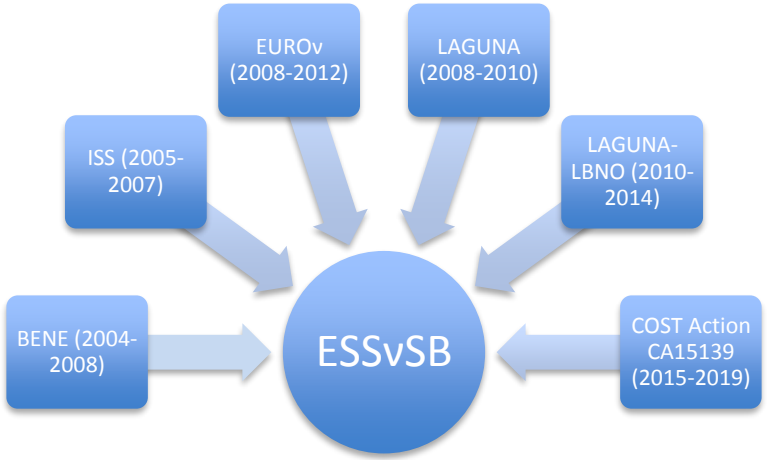
ESSνSB at the European level

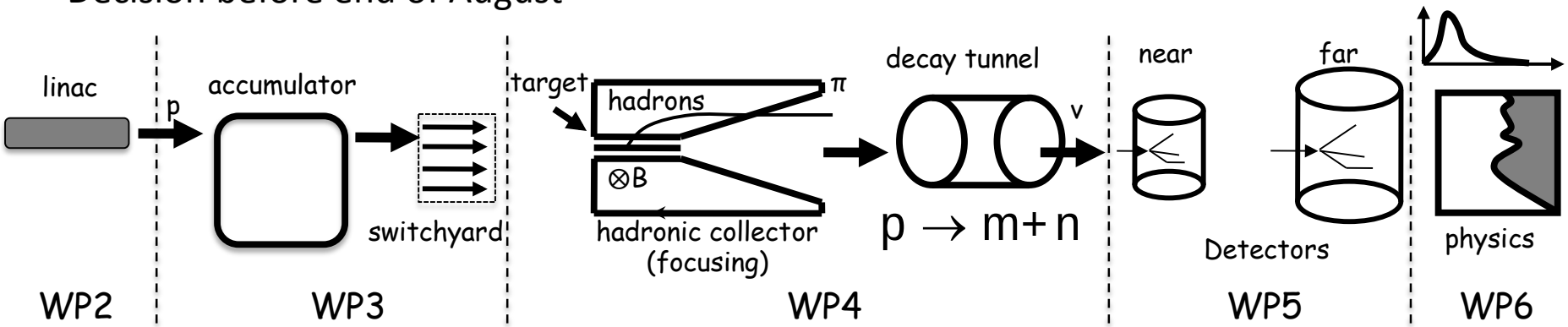
- **COST application for networking has been succeeded: CA15139 (2016-2019)**
  - **EuroNuNet** : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* (**http://www.cost.eu/COST_Actions/ca/CA15139**)
  - **Major goals of EuroNuNet**:
    - to aggregate the community of neutrino physics in Europe to study the ESSνSB concept in a spirit of inclusiveness,
    - to impact the priority list of High Energy Physics policy makers and of funding agencies to this new approach to the experimental discovery of leptonic CP violation.
    - 13 participating countries (network still growing).



ESSνSB at the European level

- A **H2020** EU **Design Study** has been submitted end of March (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested budget: 3 M€**
  - 15 participating institutes from 11 European countries including CERN and ESS
  - 6 Work Packages
  - Decision before end of August



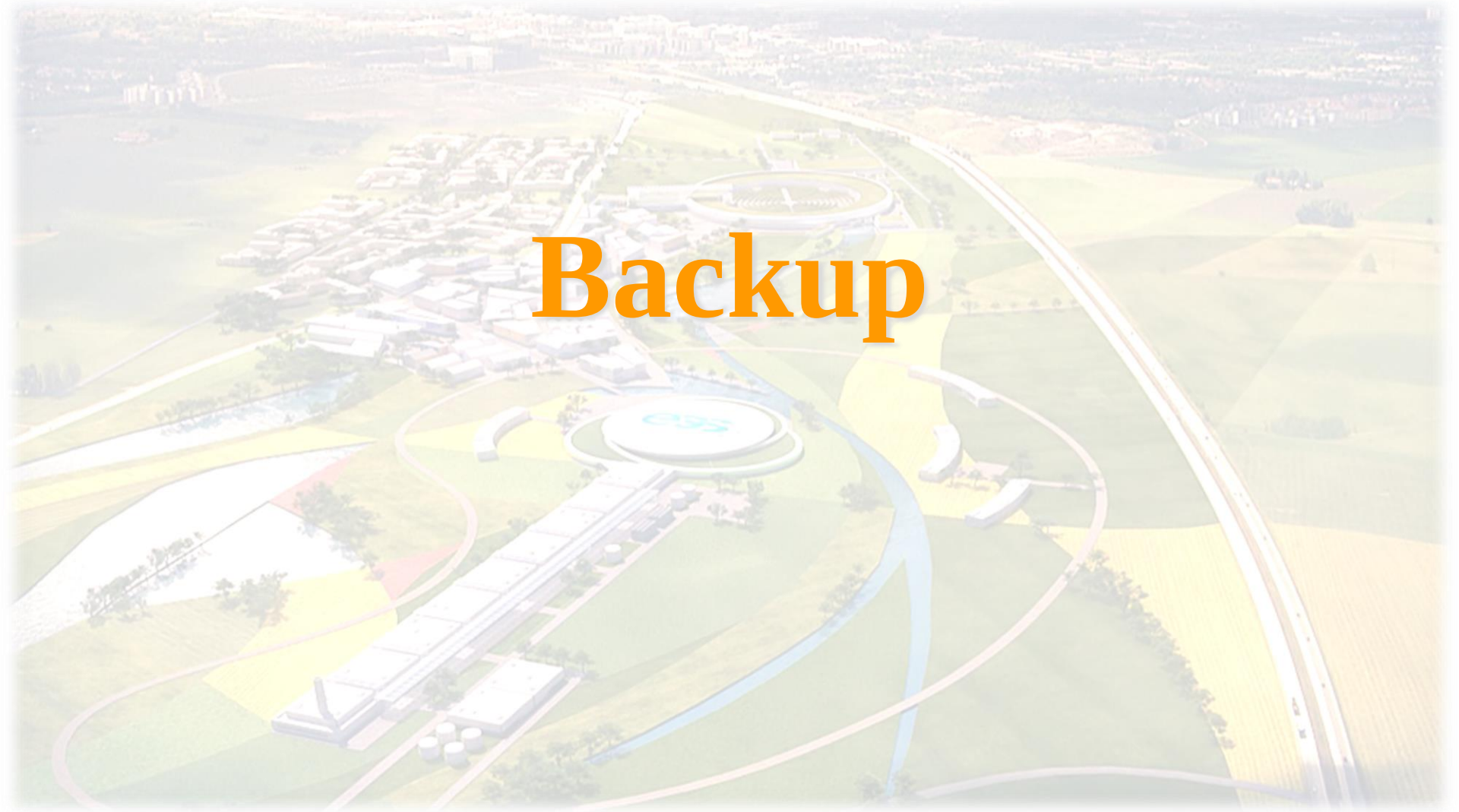


Possible Schedule for ESSνSB

- COST CA15139: 2016-2019
- EU H2020 Design Study: 2018-2021
- Decision for ESSνSB: 2022
- End of Linac construction: 2023
- Construction of ESSνSB: 2023-2030
- Data taking: 2030-2040 (for CPV).
- Rich muon program after.

Conclusion

- Significantly better CPV sensitivity at the 2nd oscillation maximum.
- The European Spallation Source Linac will be ready in less than 10 years (5 MW, 2 GeV proton beam by 2023).
- ESS will have enough protons to go to the 2nd oscillation maximum and increase its CPV sensitivity.
- CPV: 5 σ could be reached over 60% of δ_{CP} range (ESSνSB) with large potentiality.
- Large associated detectors have a rich astroparticle physics program.
- Rich muon program.
- A Design Study is needed.
- COST network project CA15139 already supports this project.



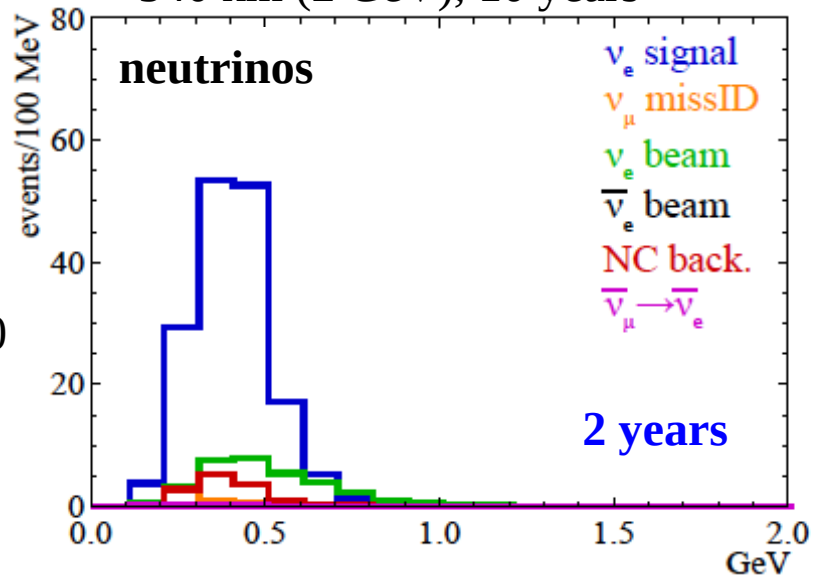
Backup

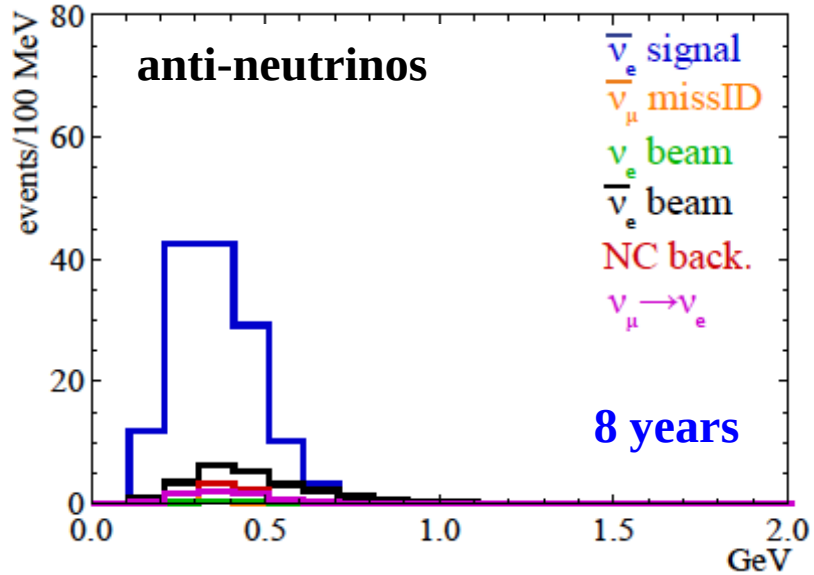
Neutrino spectra

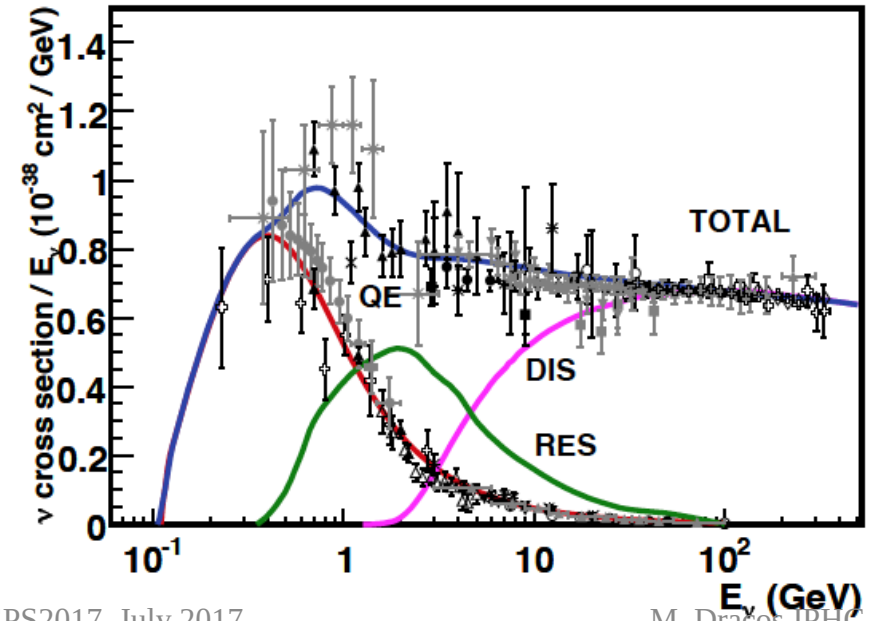
540 km (2 GeV), 10 years

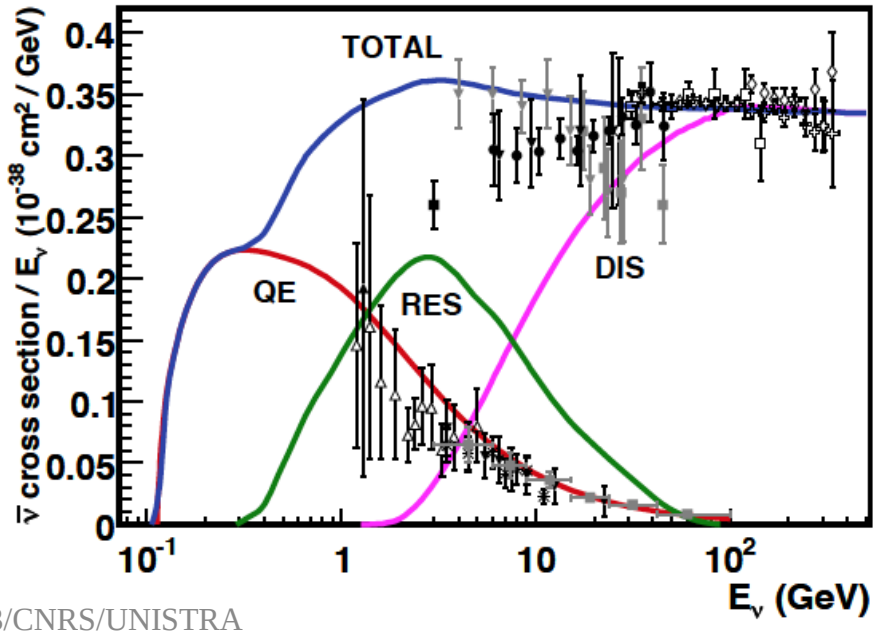
below ν_τ production, almost only QE events

$\delta_{CP}=0$

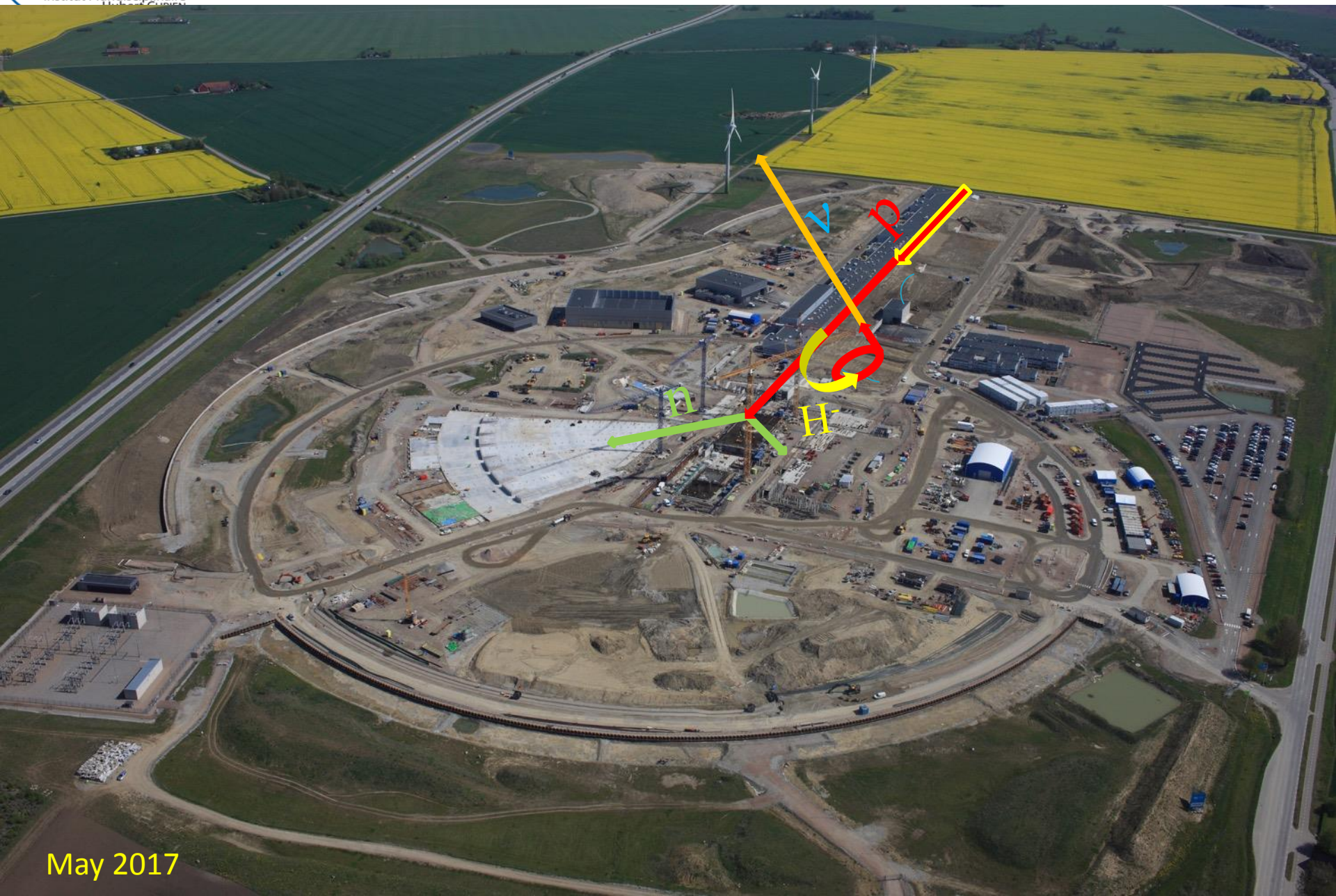








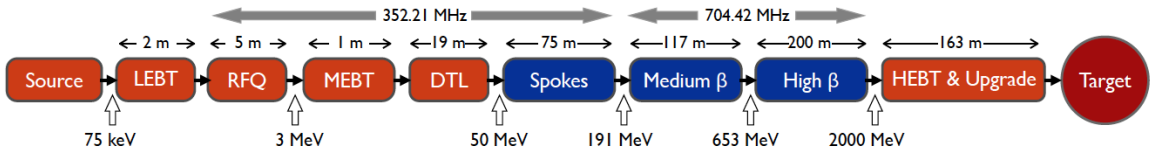
ESS under construction



May 2017

ESS under construction

Preparing the ESS linac for operation at 10 MW with a 8% duty cycle and 28 Hz pulsing

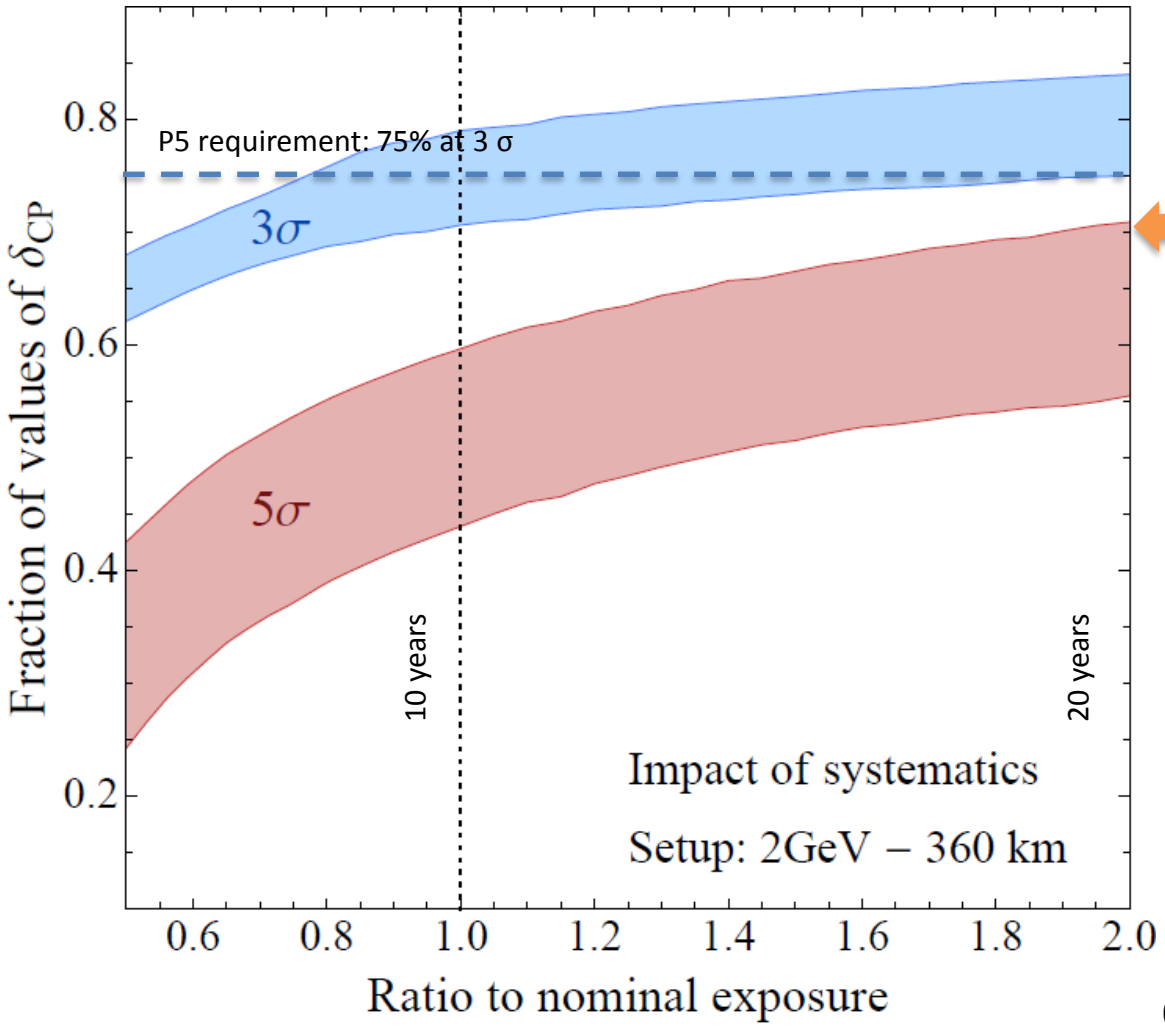


For the medium-beta elliptical-cavity part ESS is planning to use tetrodes. Thales has developed a new screen grid with graded wire thickness making operation at **10 % duty cycle** possible.

The picture shows the cryostat and test bunker at the FREIA Lab in Uppsala where a first prototype of the ESS 352 MHz spoke accelerating cavity is currently under test at 14 Hz and later on will be tested at 28 Hz.

Systematic errors and exposure

for ESSnuSB systematic errors see 1209.5973 [hep-ph] (lower limit "default" case, upper limit "optimistic" case)

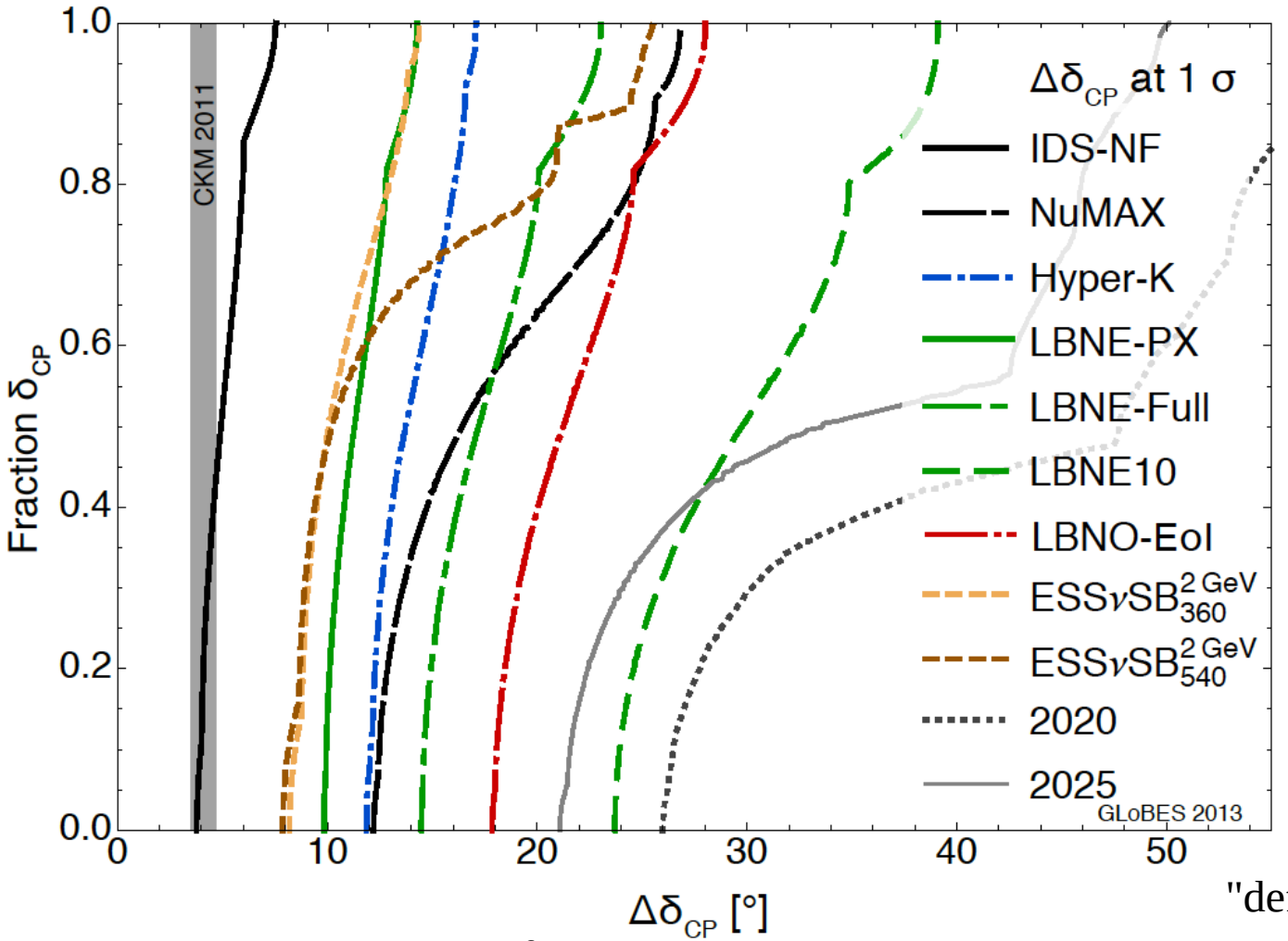


High potentiality

(courtesy P. Coloma)

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)

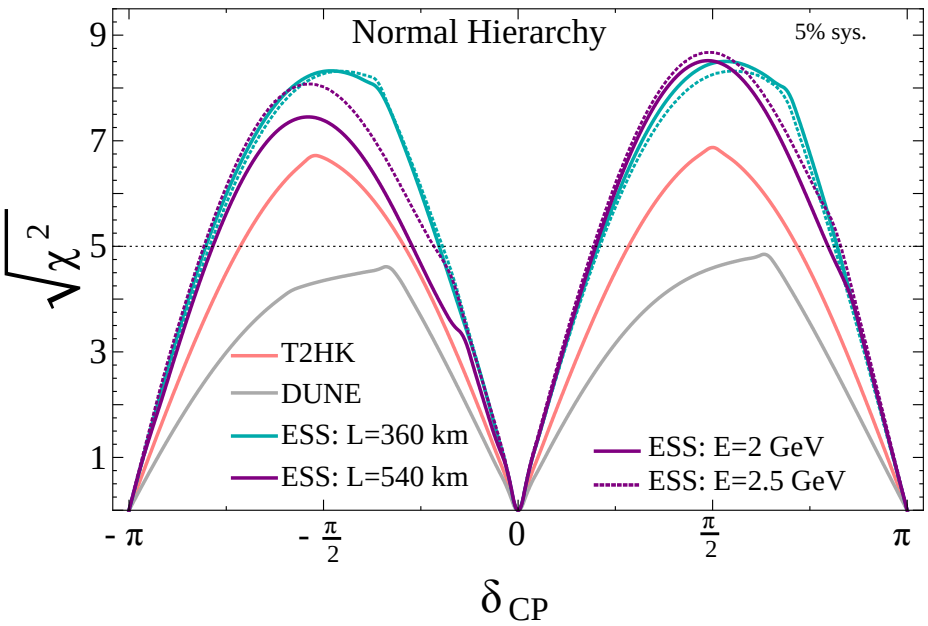


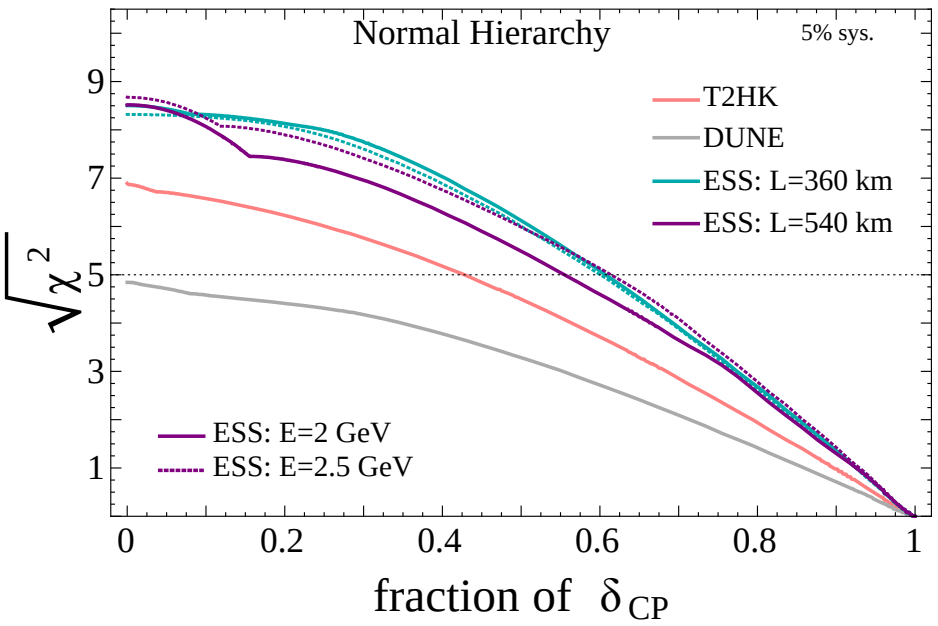
"default" column

for systematic errors see (7.5%/15% for ESSnuSB):

- Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]
- **arXiv:1310.4340 [hep-ex] Neutrino "snowmass" group conclusions**

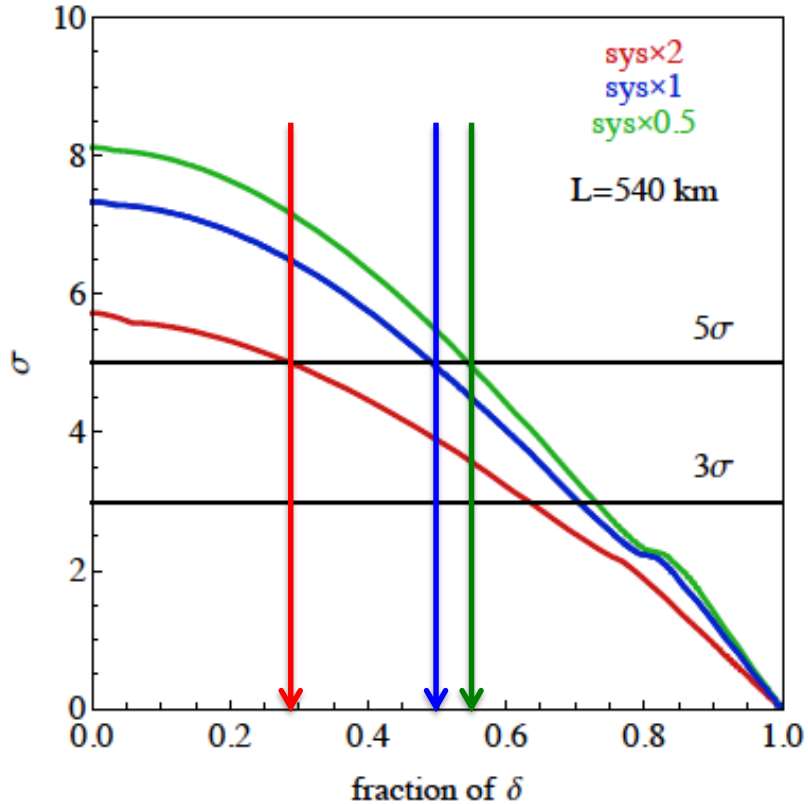
Comparisons



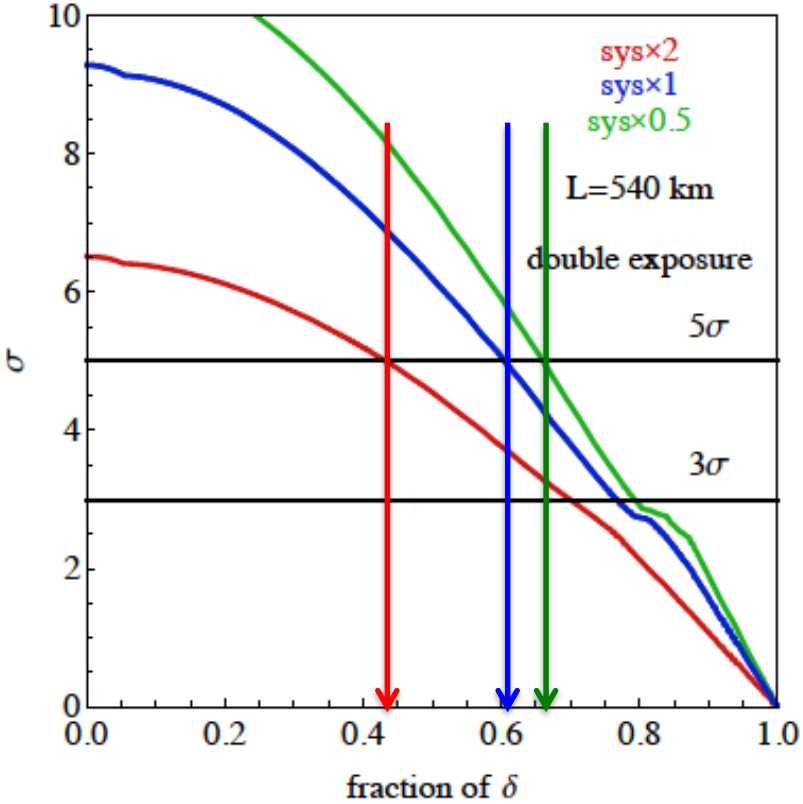


δ_{CP} coverage

CPV (2 GeV protons)



after 10 years

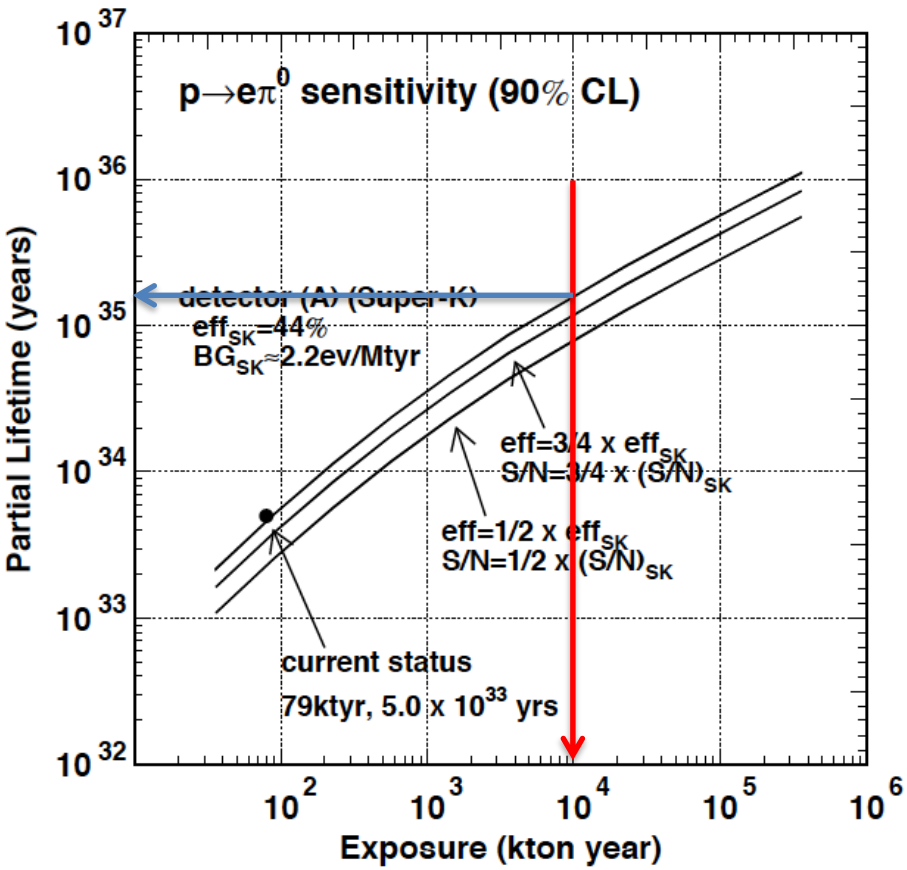


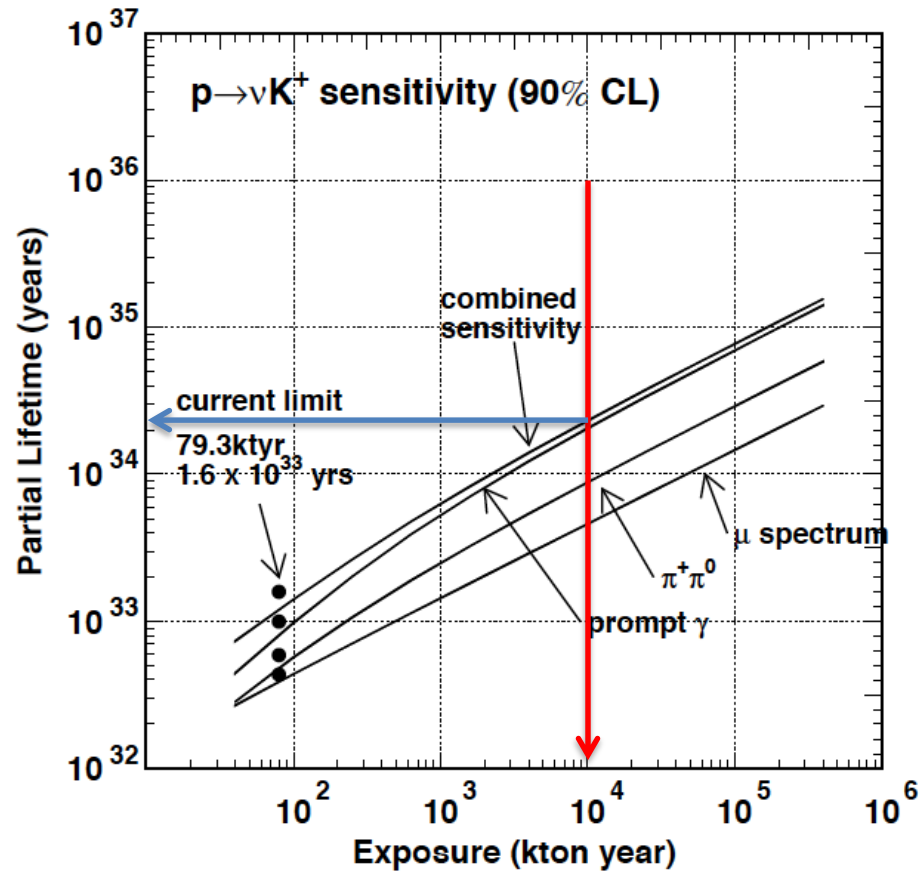
with 2 times more statistics

systematic errors (nominal values): 5%/10% for signal/background

more than 50% δ_{CP} coverage using reasonable assumptions on systematic errors

The MEMPHYS Detector (Proton decay)

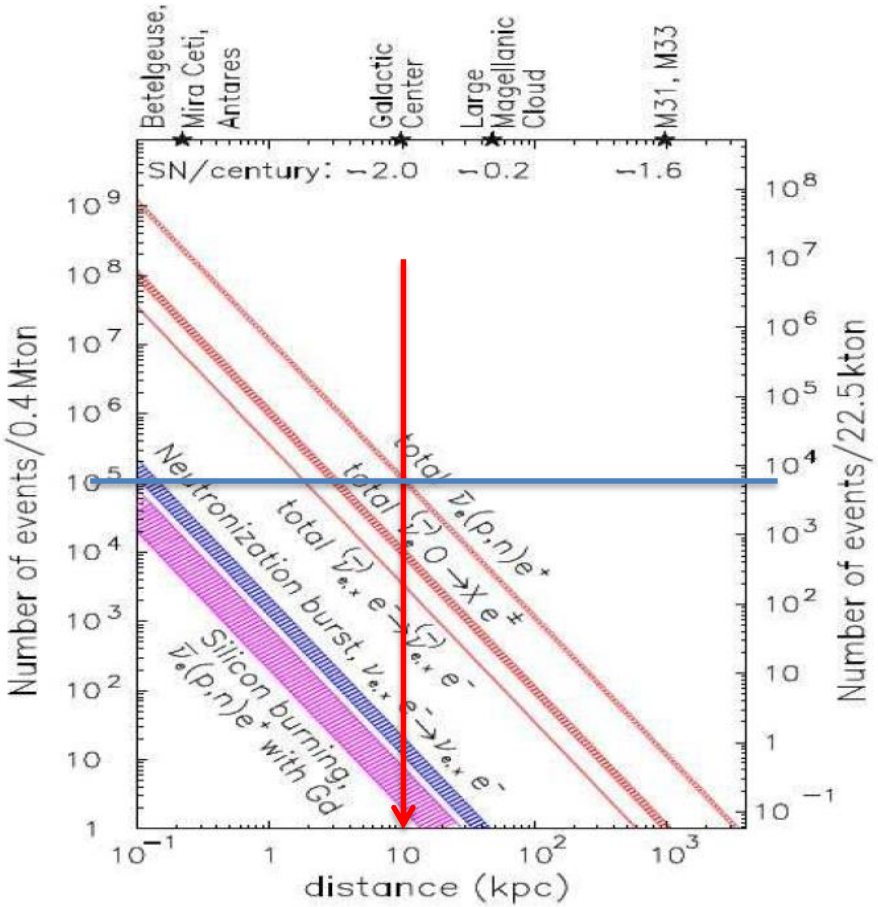




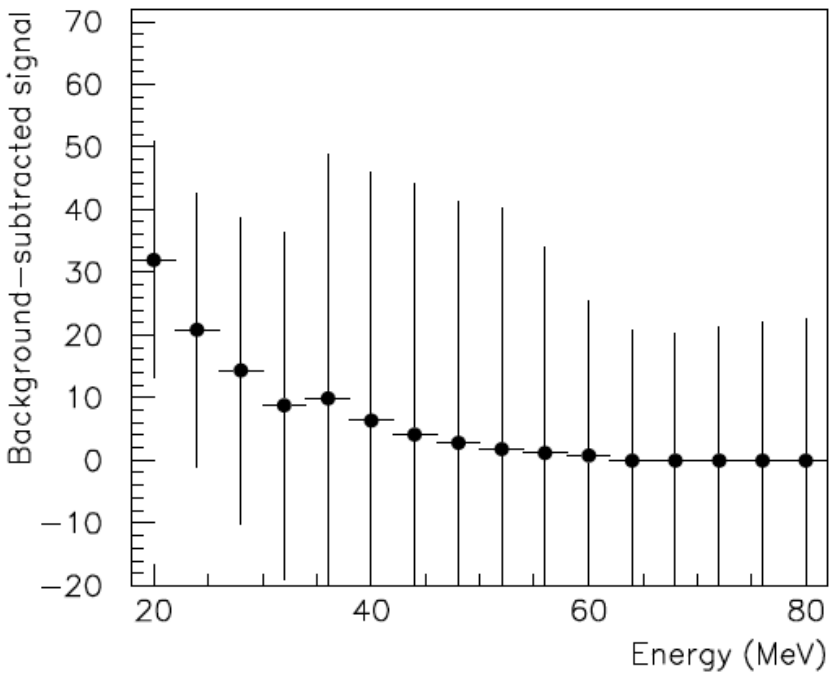
(arXiv: hep-ex/0607026)

The MEMPHYS Detector (Supernova explosion)

MEMPHYS



SUPERK



Diffuse Supernova Neutrinos (10 years, 440 kt)

For 10 kpc: ~10^5 events