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Neutrino CP Violation with the ESS neutrino Super Beam (ESSνSB)

Marcos Dracos
on behalf of the ESSνSB/EuroNuNet project

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG
ESS NEUTRINO SUPER BEAM
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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
⇒ very long baseline
(small in our case)

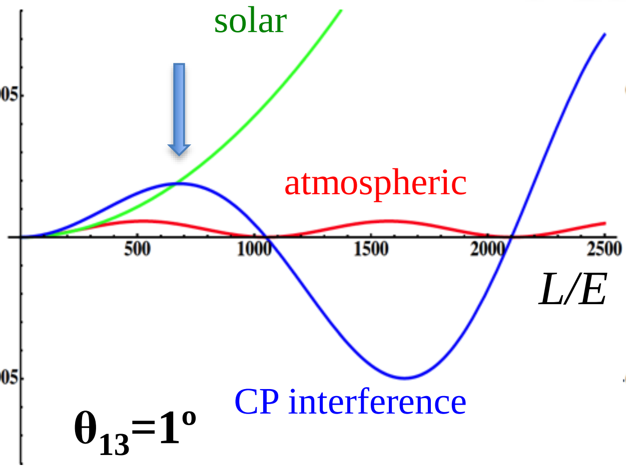
$$\mathcal{A} = \frac{P_{\nu_\mu\rightarrow\nu_e} - P_{\bar{\nu}_\mu\rightarrow\bar{\nu}_e}}{P_{\nu_\mu\rightarrow\nu_e} + P_{\bar{\nu}_\mu\rightarrow\bar{\nu}_e}}$$

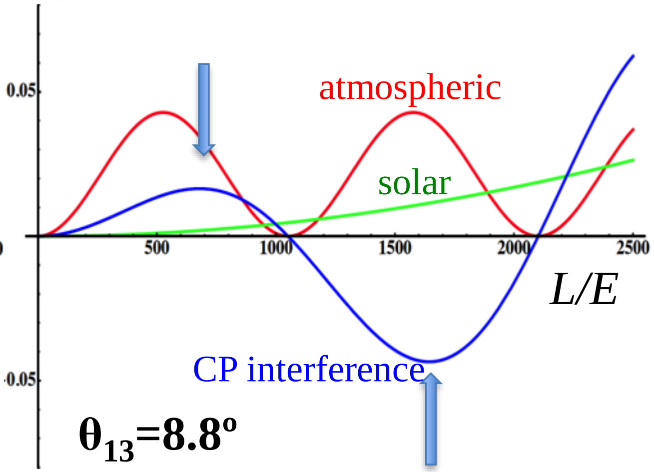
≠0 ⇒ CP Violation
be careful, matter effects also create asymmetry

Why to go to the 2nd Oscillation Max.

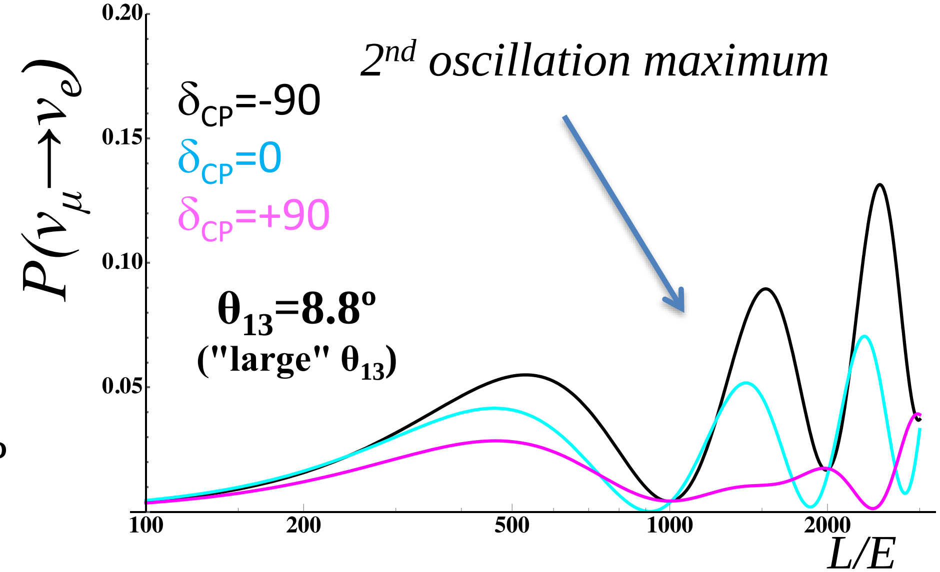
for small θ_{13} 1st oscillation maximum is better

(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.: $A=0.75\sin\delta_{CP}$

(see arXiv:1310.5992 and arXiv:0710.0554)

more sensitivity at 2nd oscillation max.

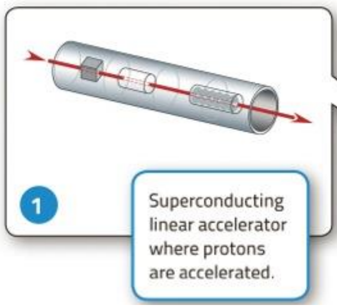
very intense neutrino beam needed

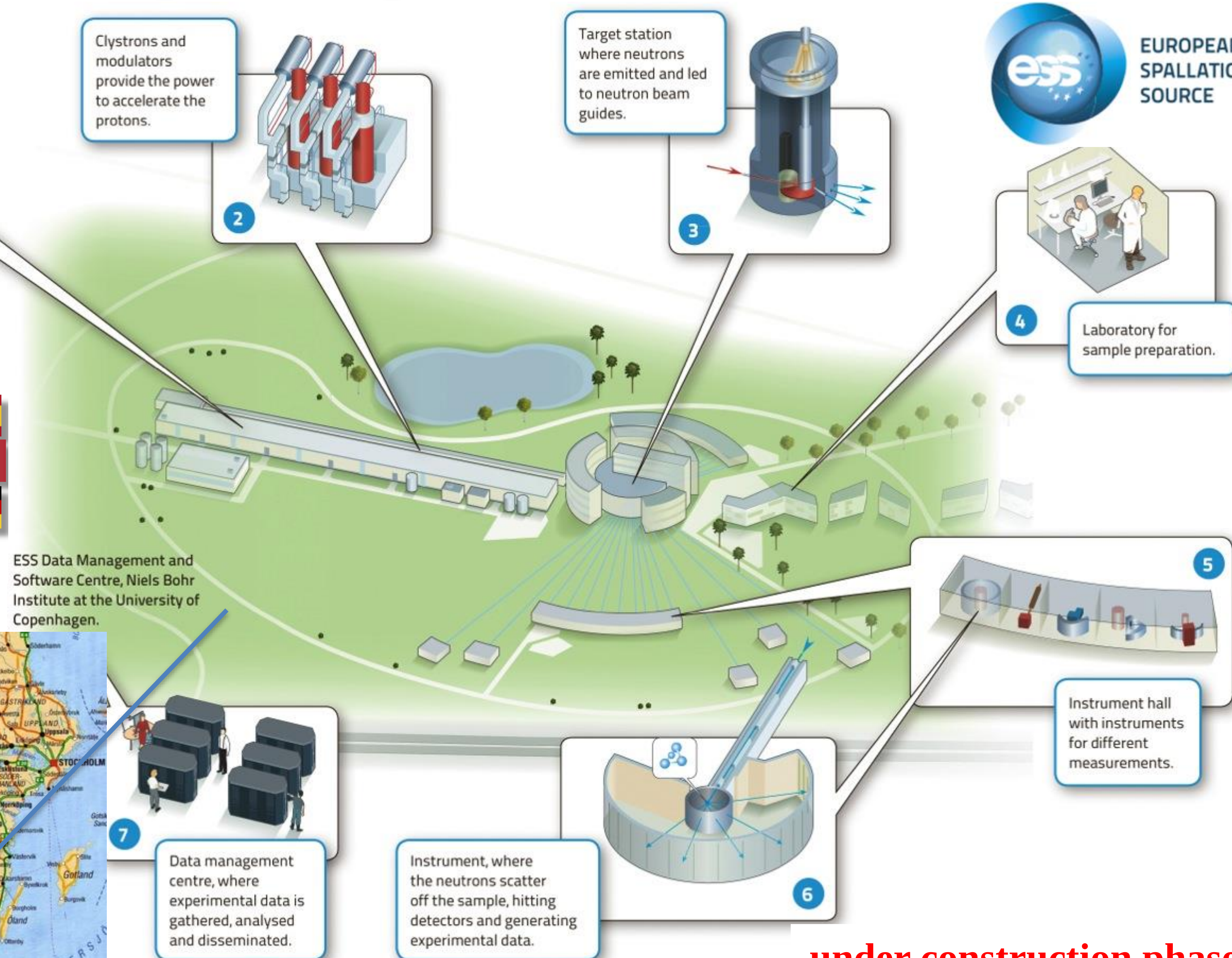
ESS NEUTRINO SUPER BEAM

European Spallation Source

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

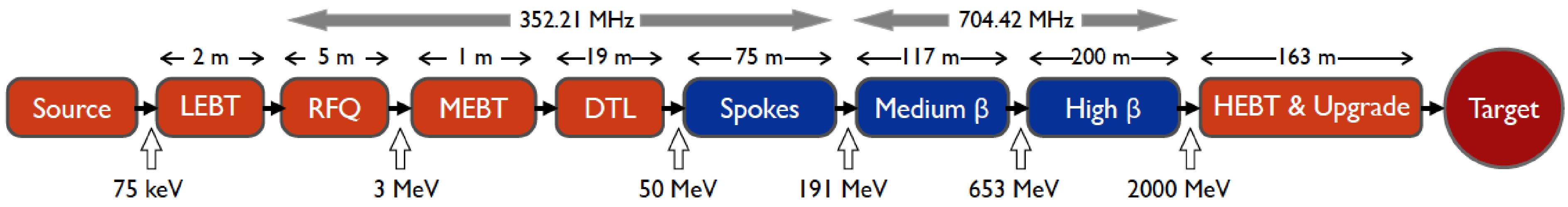
EUROPEAN SPALLATION SOURCE



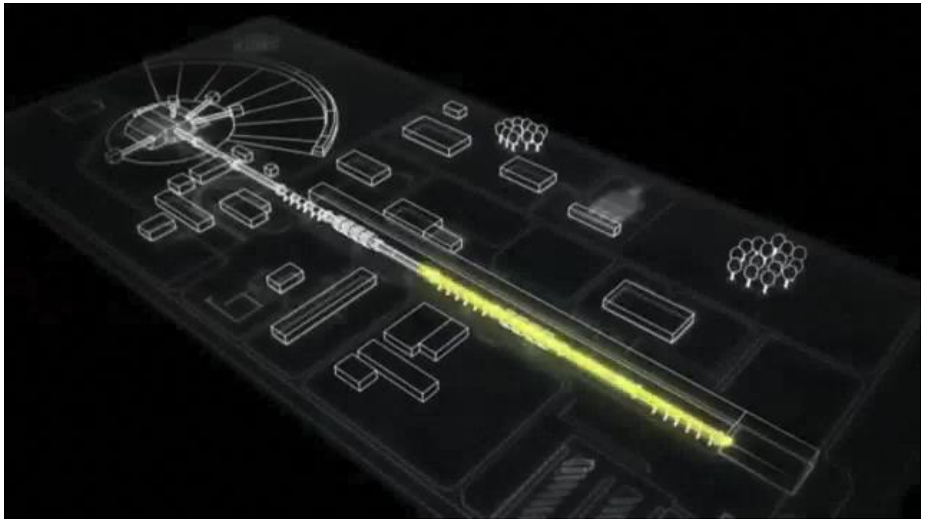


under construction phase (~1.85 B€ facility)

ESS proton linac

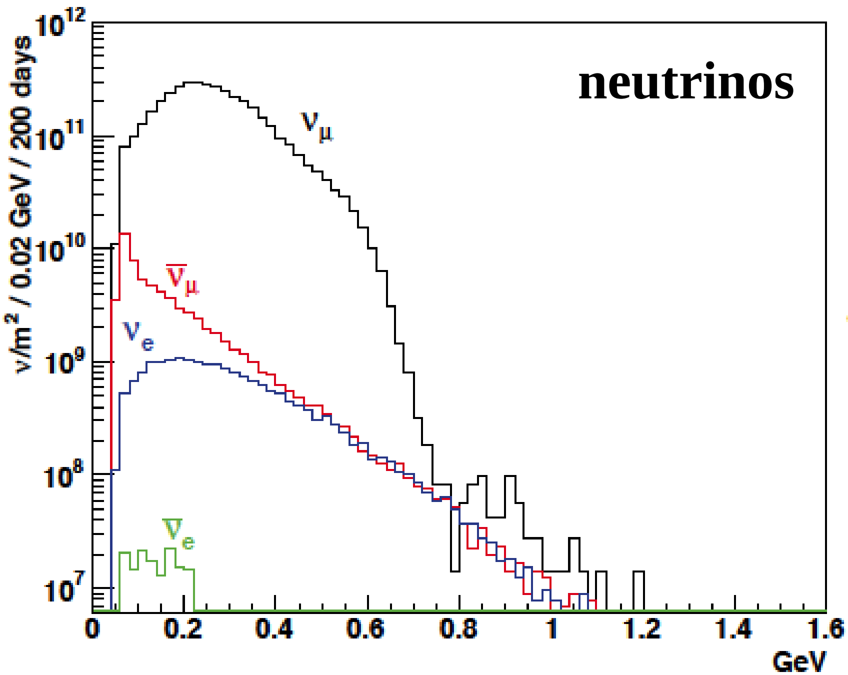


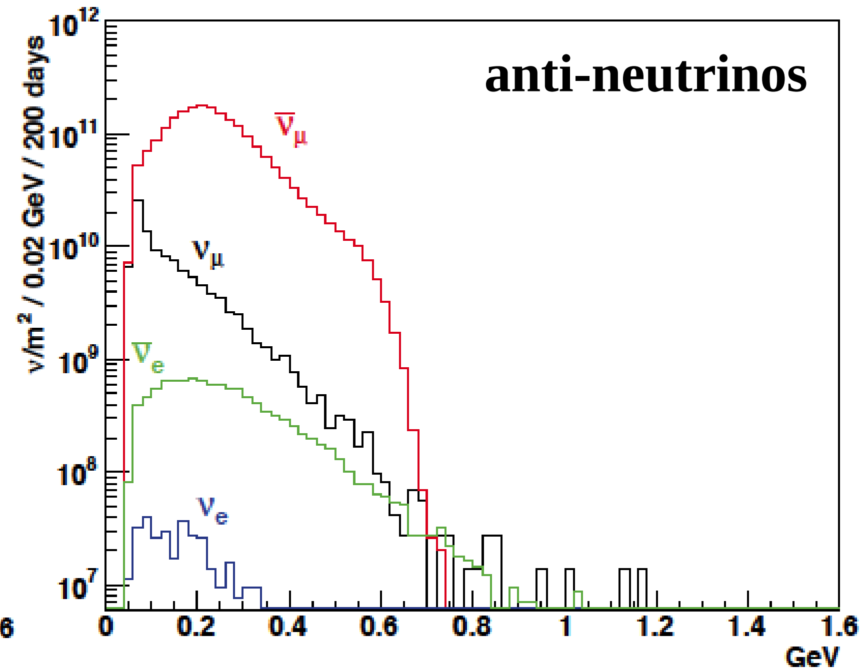
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**



Linac ready by 2023 (full power)

ESSνSB ν energy distribution (without optimisation)





- 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)

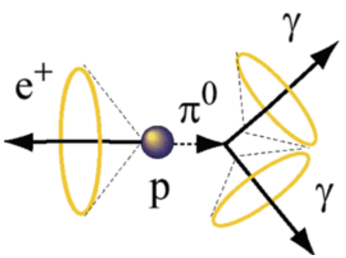
(Nucl. Phys. B 885 (2014) 127)

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

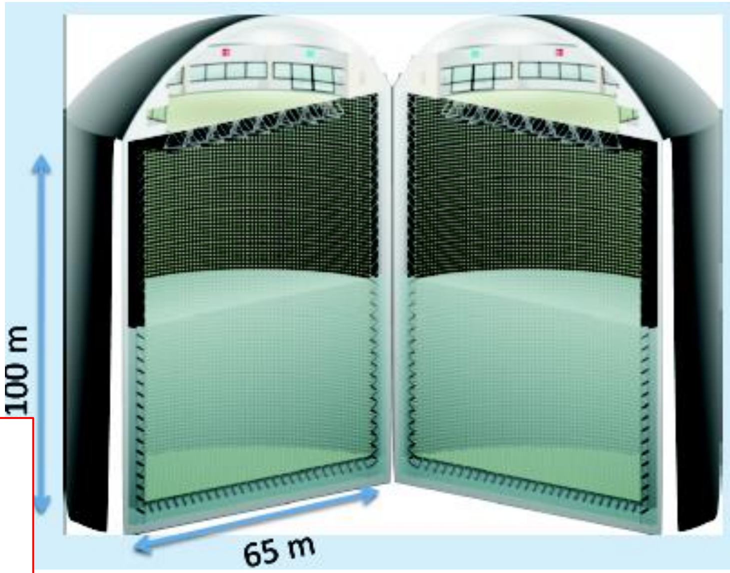
Yes, if we place our far detector at around 500 km from the neutrino source.

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

(arXiv: hep-ex/0607026)



- Neutrino Oscillations
- 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

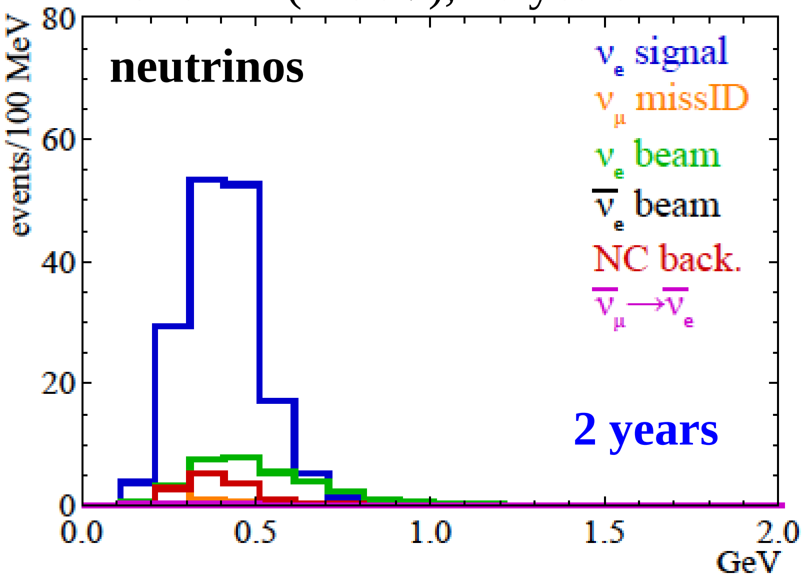
with now improved detection efficiency not yet taken into account

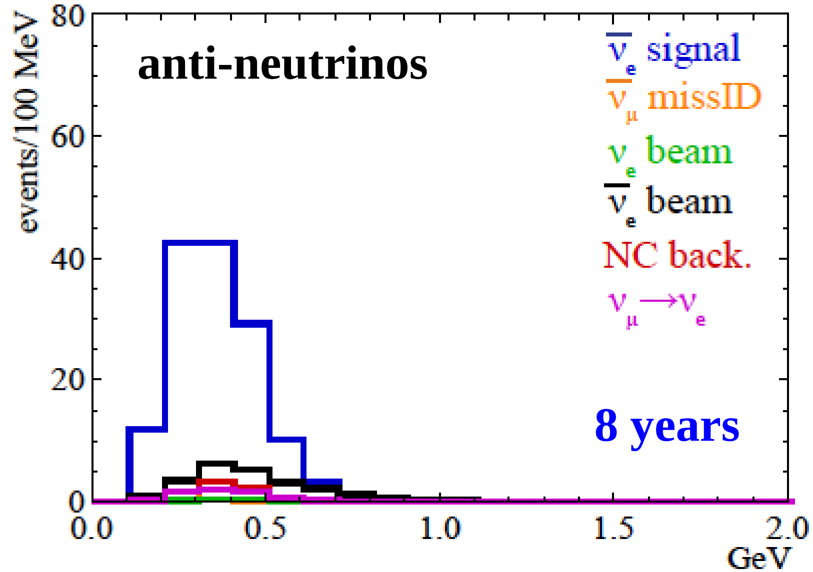
Neutrino spectra

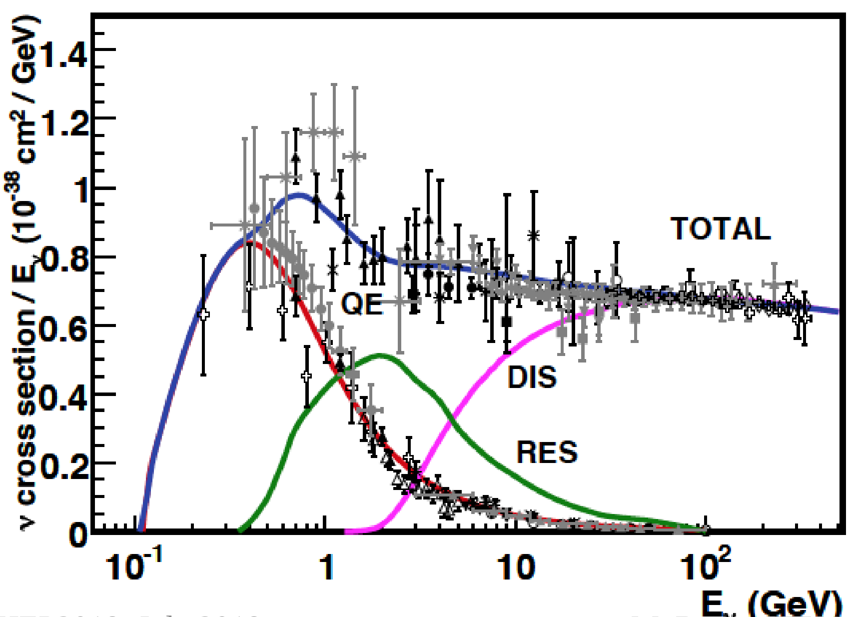
540 km (2 GeV), 10 years

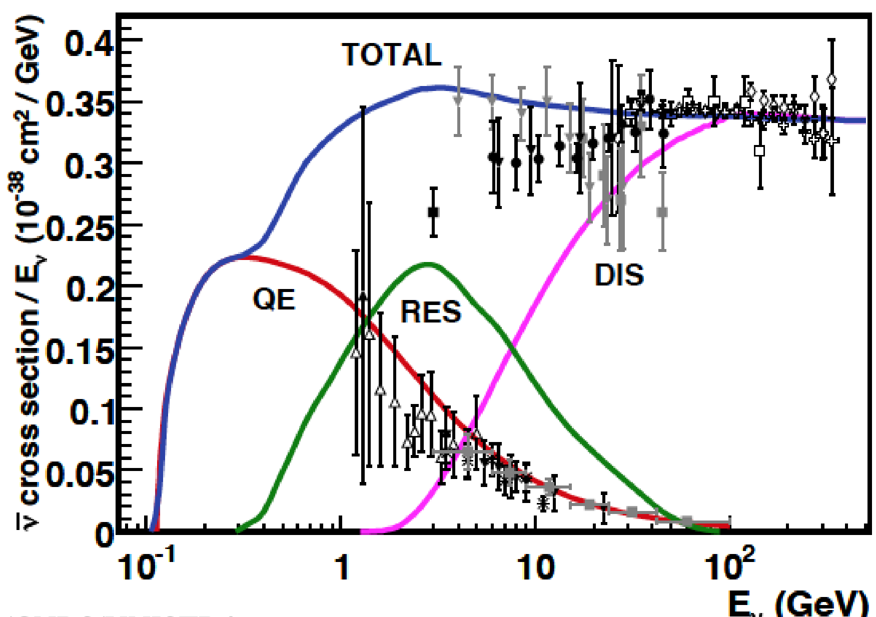
below ν_τ production, almost only QE events

$\delta_{CP}=0$

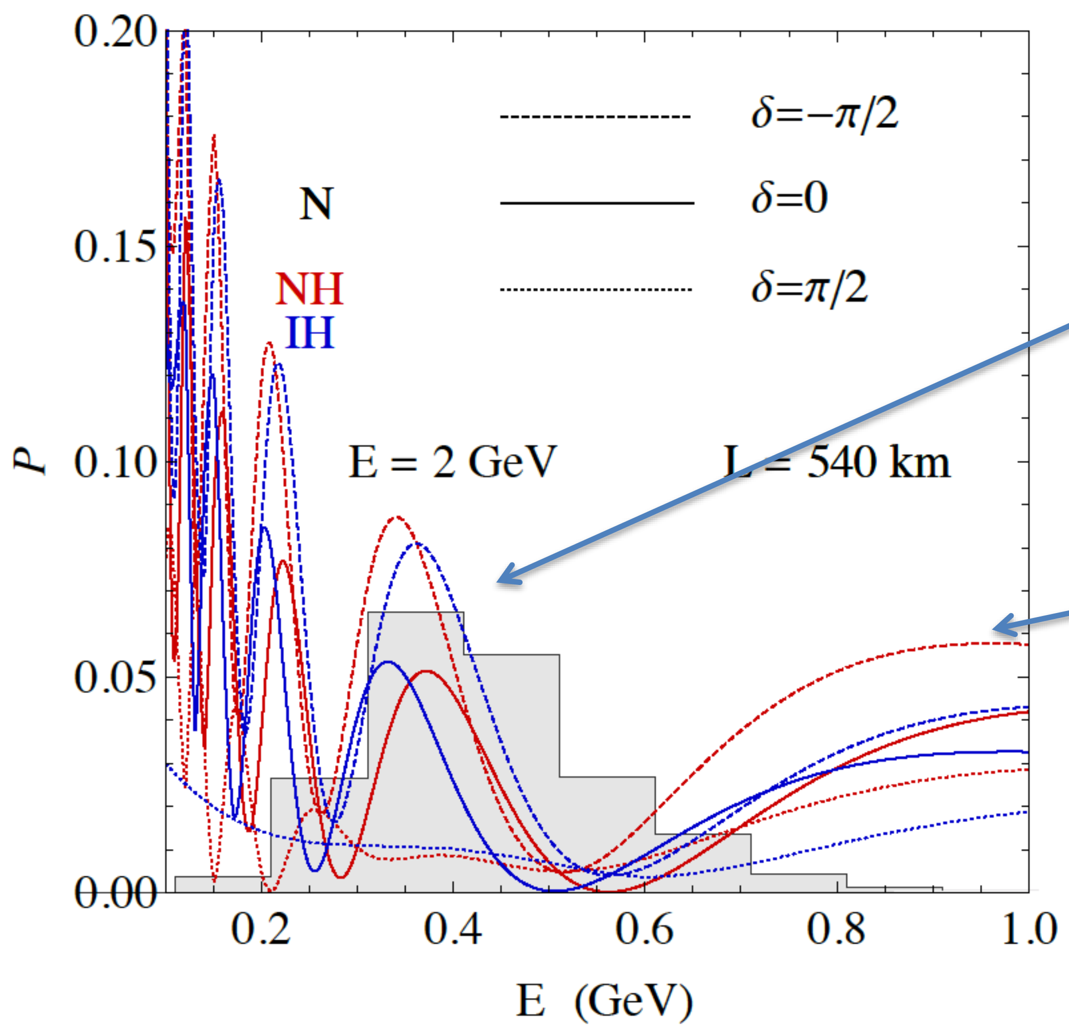








2nd Oscillation max. coverage



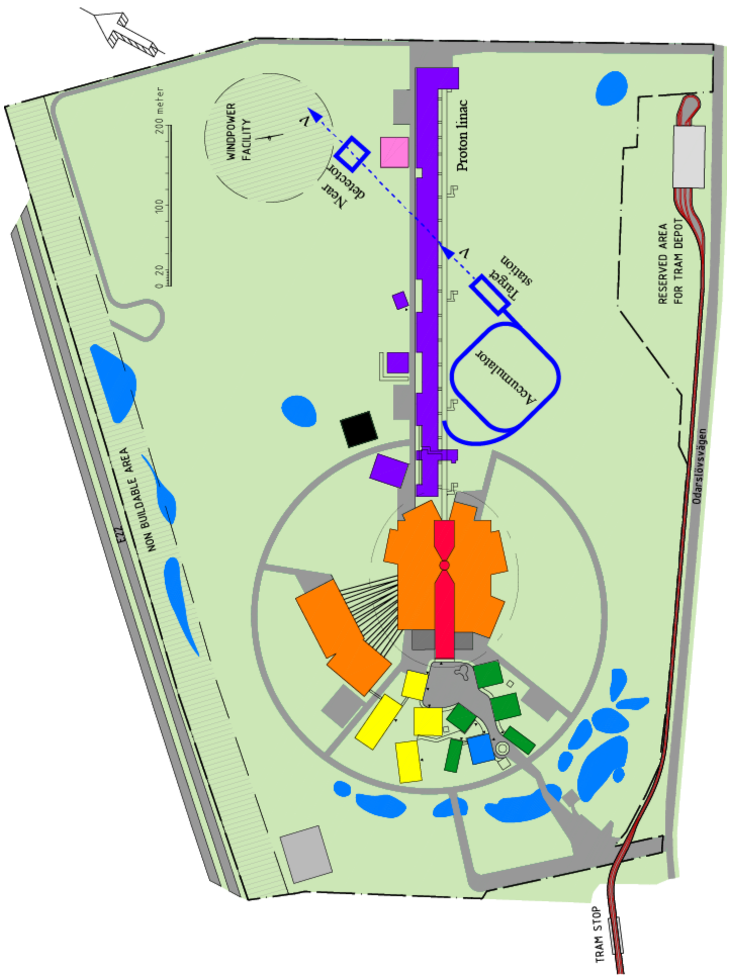
2^{nd} oscillation max. well covered by the ESS neutrino spectrum

1^{st} oscillation max.

ESS Linac modifications to produce a neutrino Super Beam

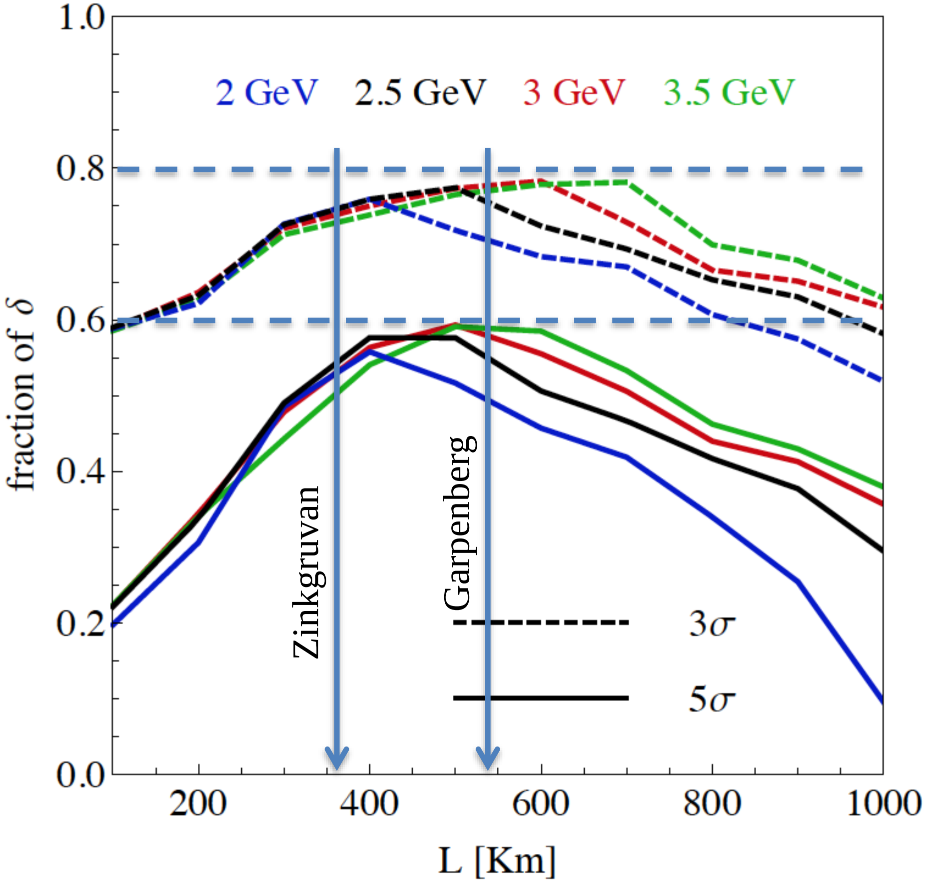
How to add a neutrino facility?

- 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),
  - space charge problems to be solved.
- ~300 MeV neutrinos.
- 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.



Which baseline?

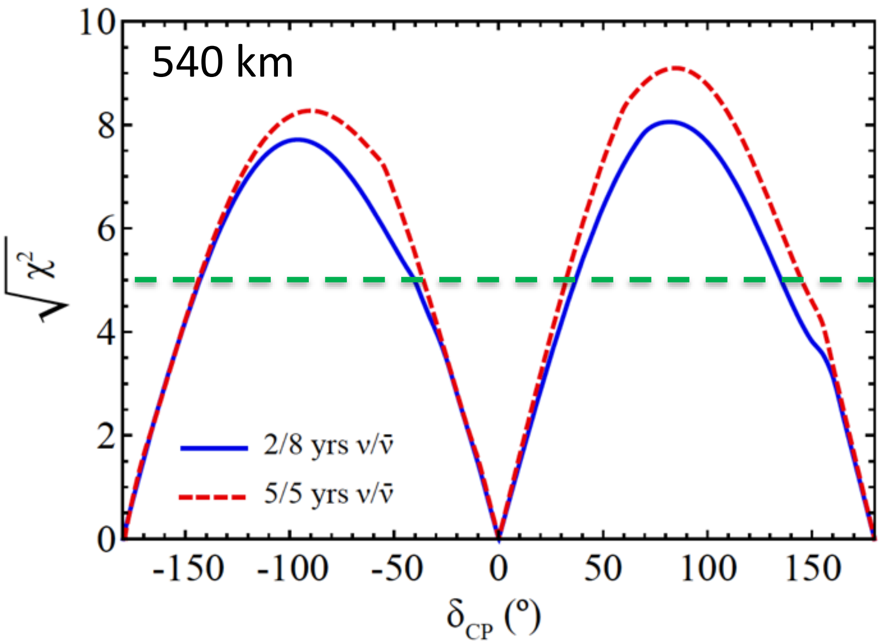
CPV (*Nucl. Phys. B 885 (2014) 127*)

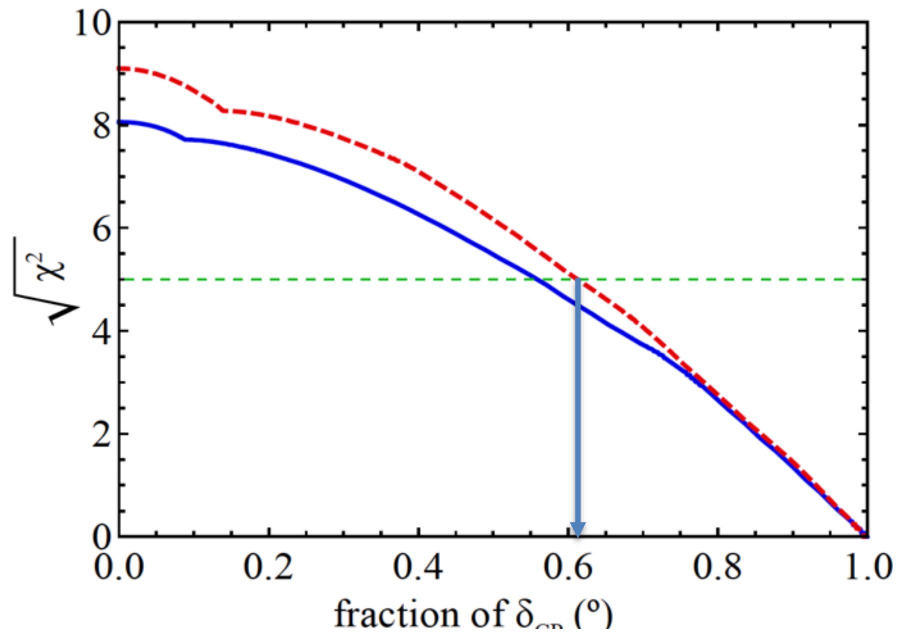


Candidate active mines

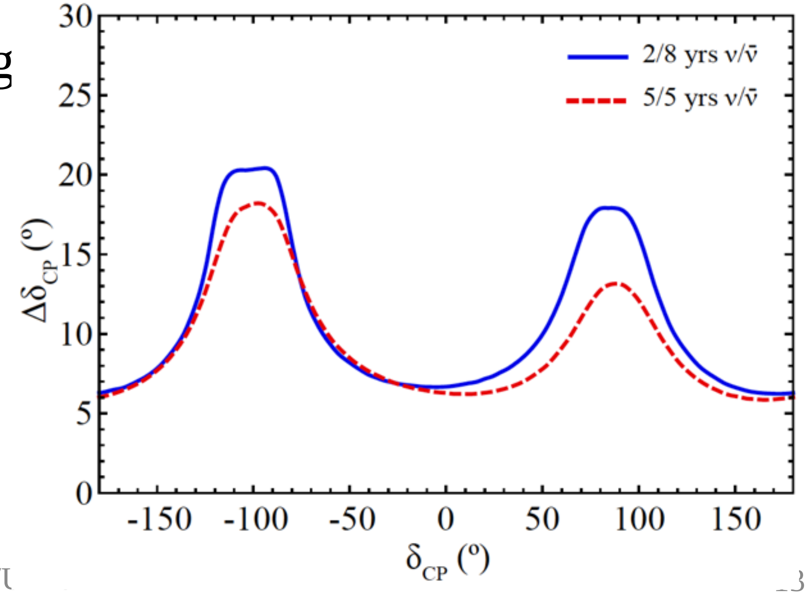
- ~60% δ_{CP} coverage at 5 σ C.L.
- >75% δ_{CP} coverage at 3 σ C.L.
- **systematic errors: 5%/10% (signal/backg.)**

Physics Performance

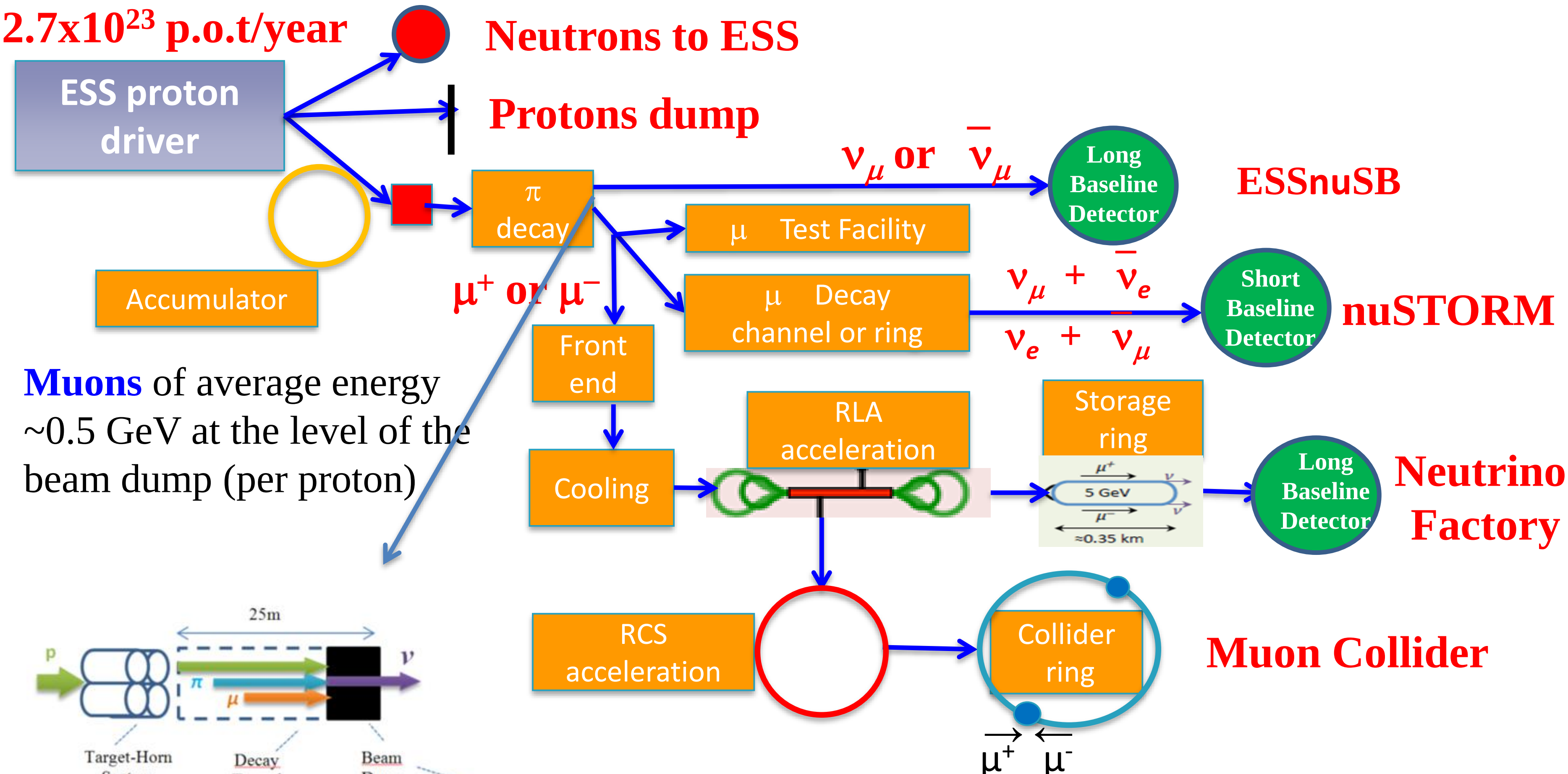




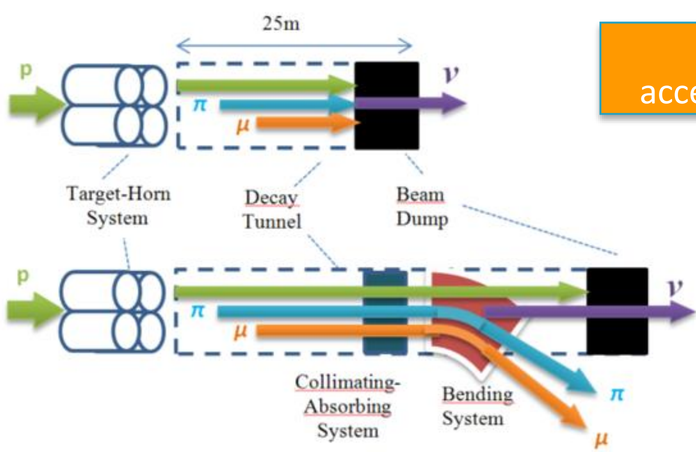
- little dependence on mass hierarchy (not so long baseline),
- δ_{CP} coverage at 5 σ C.L. up to **60%**,
- δ_{CP} accuracy down to **6°** at 0° and 180° (absence of CPV for these two values),
- not yet optimized facility,
- **5/10%** systematic errors on signal/background.



ESS neutrino and muon facility

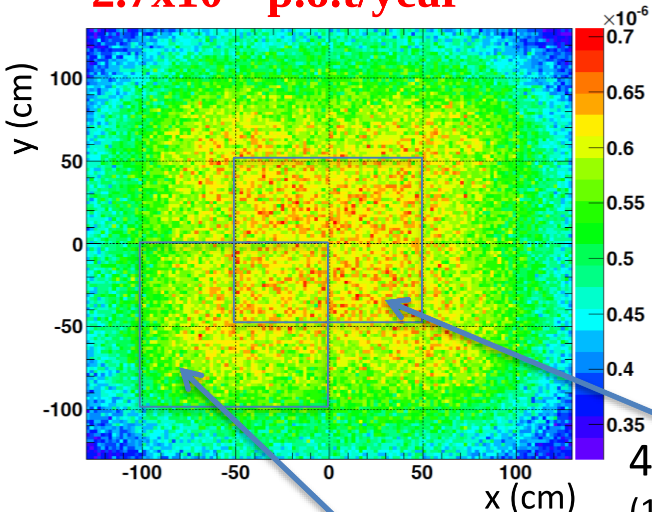


Muons of average energy ~0.5 GeV at the level of the beam dump (per proton)



Muons at the level of the beam dump

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

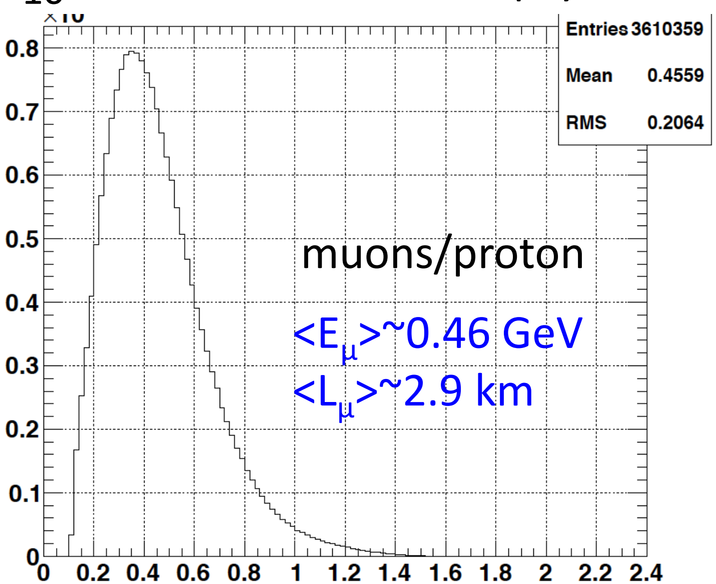


muons at the level of the beam dump (per proton)

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

4.1x10^{20} μ/year

more than 4x10^{20} μ/year from ESSS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).



- input beam for future 6D μ cooling experiments (for muon collider),
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

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European Spallation Source

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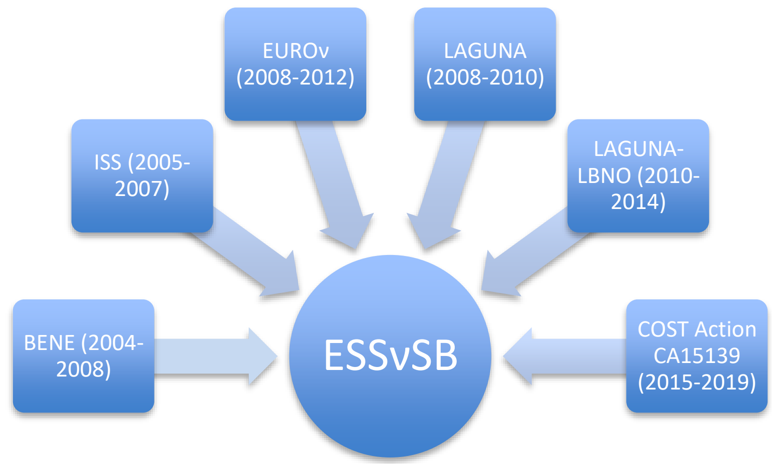
ESSνSB at the European level

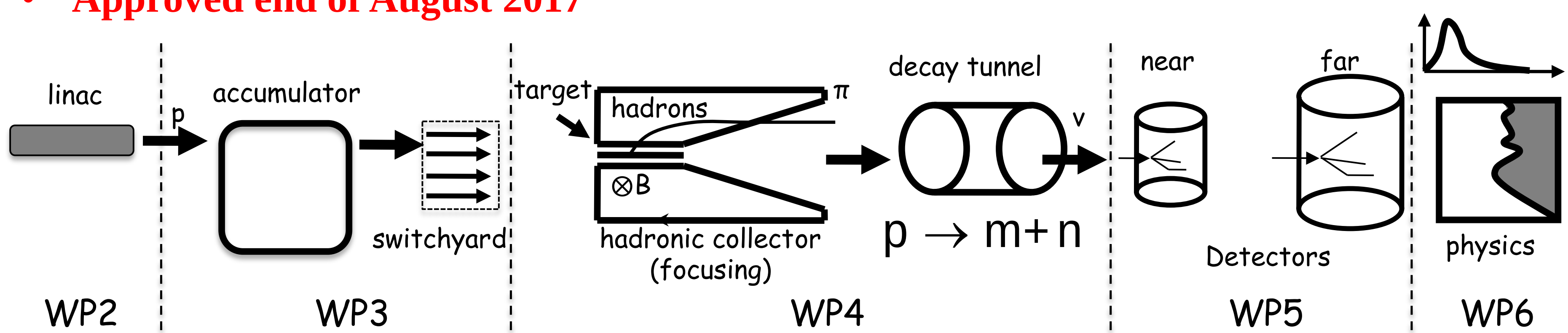
- **COST application for networking: CA15139 (2016-2019)**
  - **EuroNuNet** : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery* (**http://www.cost.eu/COST_Actions/ca/CA15139**)

  - **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).
      http://euronunet.in2p3.fr/

ESSvSB at the European level

- A **H2020** EU **Design Study** (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
  - **Approved end of August 2017**





Design Study ESSνSB (2018-2021)

Call: H2020-INFRADEV-2017-1
Funding scheme: RIA
Proposal number: 777419
Proposal acronym: ESSnuSB
Duration (months): 48
Proposal title: Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
Activity: INFRADEV-01-2017

Maximum grant amount (proposed amount, after evaluation): **2,999,018.00 EUR**

N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
9	RUDER BOSKOVIC INSTITUTE	HR
10	SOFIISKI UNIVERSITET SVETI KLIMENT OHRIDSKI	BG
11	LUNDS UNIVERSITET	SE
12	AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	PL
13	EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH	CH
14	UNIVERSITE DE GENEVE	CH
15	UNIVERSITY OF DURHAM	UK
	Total:	

- Kick-off meeting in January 2018.
- ESSνSB has already started engaging postdocs.

More information on: http://essnusb.eu/

partners: IHEP, BNL, SCK•CEN, SNS, PSI, RAL

ESS NEUTRINO SUPER BEAM

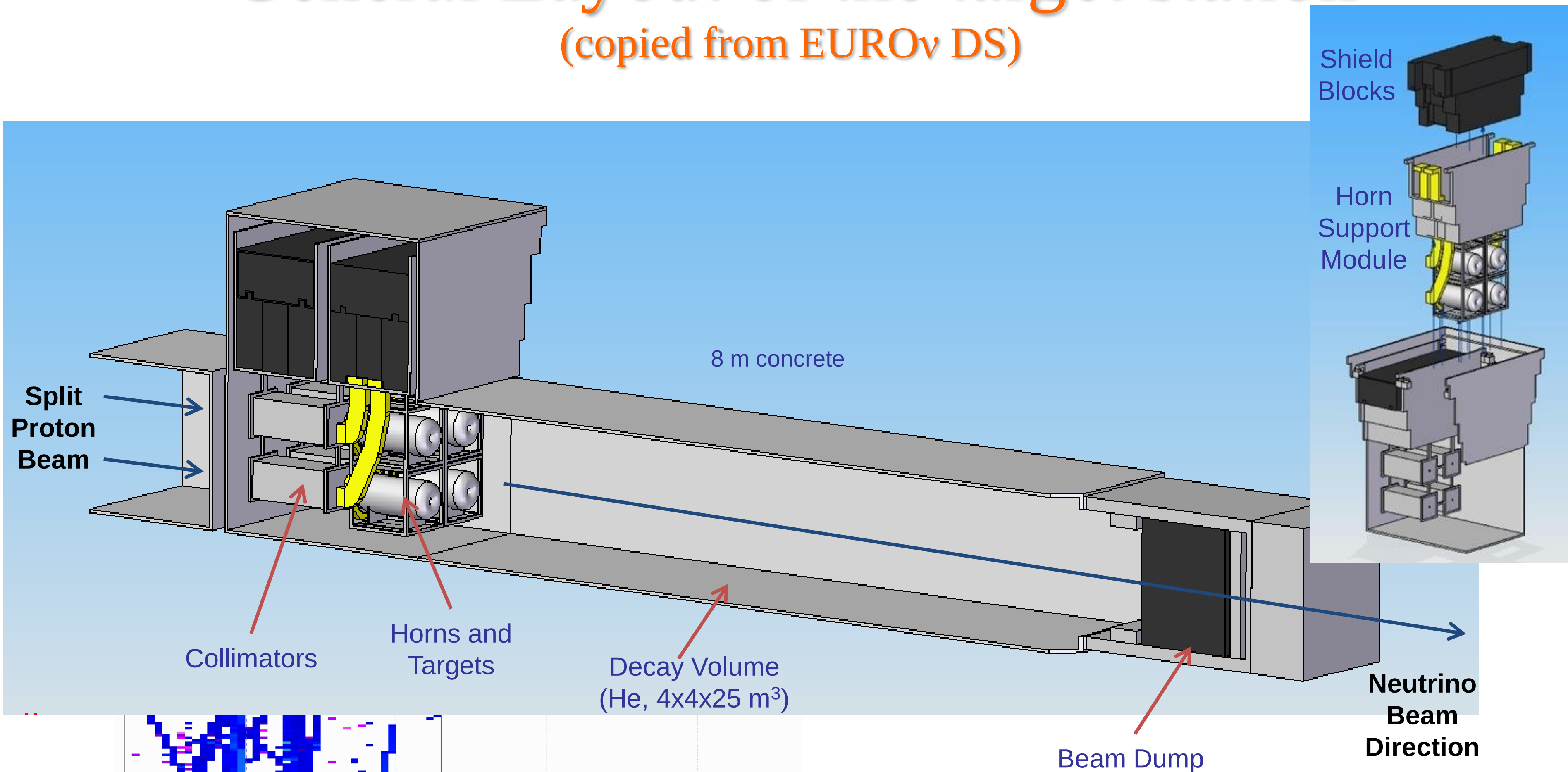
Conclusion

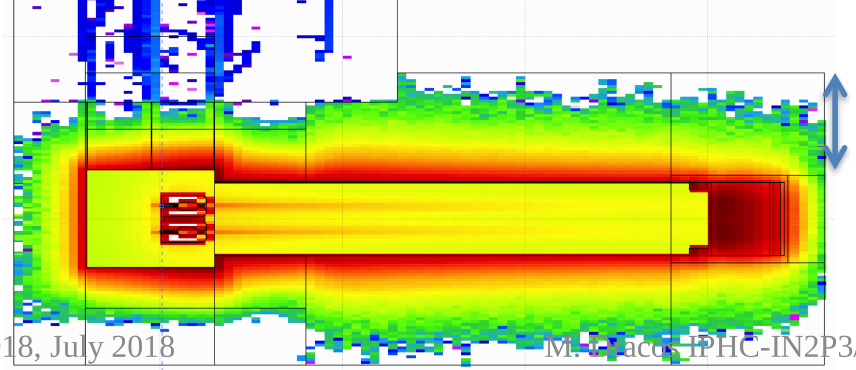
- ESS will have enough protons to go to the 2nd oscillation maximum and increase its CPV sensitivity.
- CPV: 5 σ could be reached over 60% of δ_{CP} range by ESSνSB with large potentiality.
- Large associated detectors have a rich astroparticle physics program.
- The European Spallation Source Linac will be ready by 2023, upgrade decisions by this moment.
- Rich muon program.
- COST network project CA15139 supports this project.
- The EU-H2020 Design Study ESSνSB has just started (2018-2021).

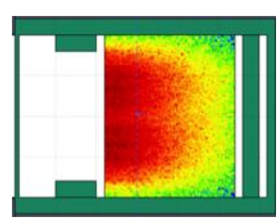
Backup

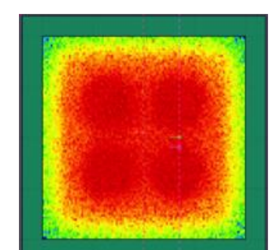
General Layout of the target station

(copied from EUROν DS)









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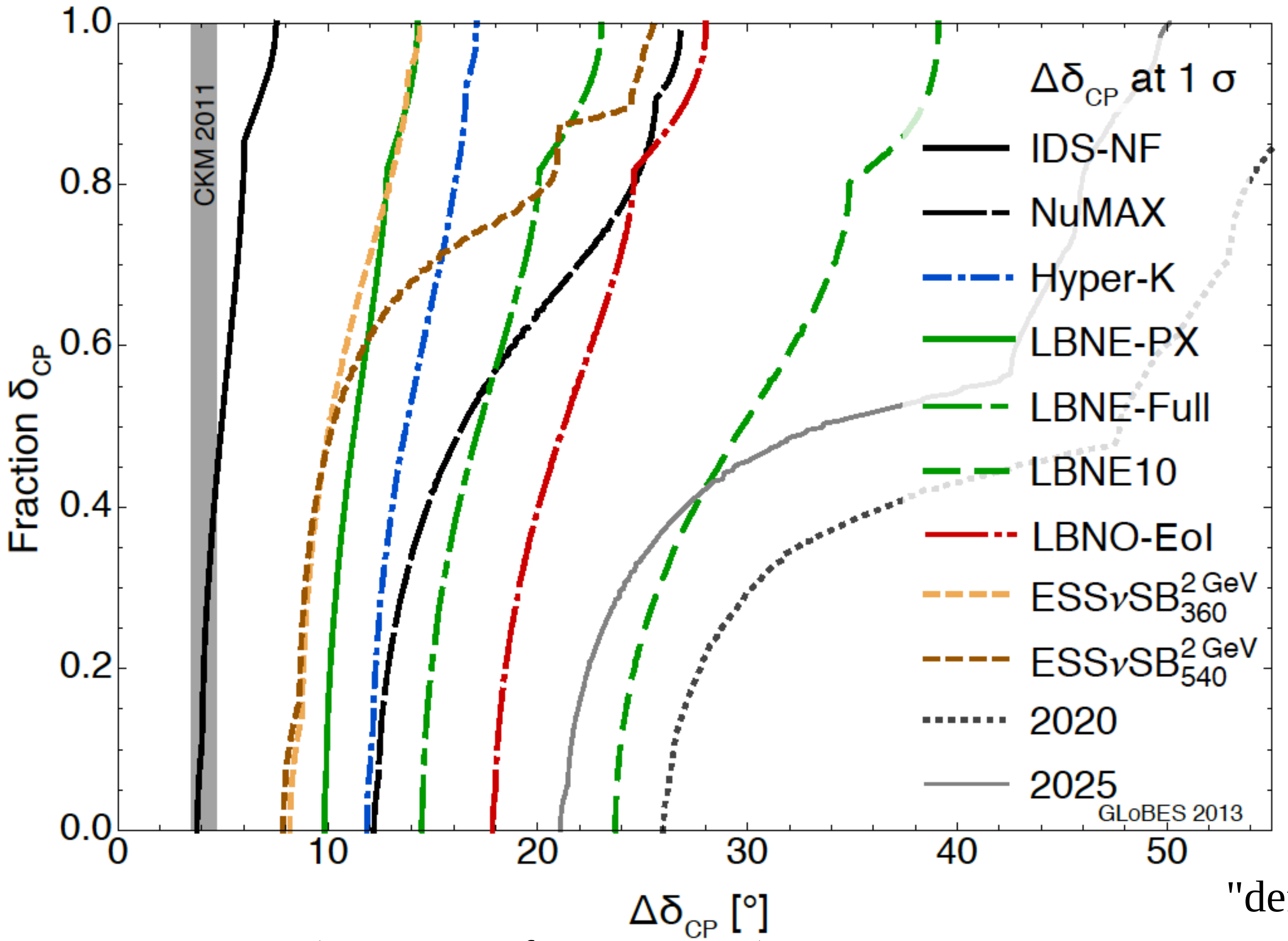
Systematic errors

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 $\times$ eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ 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%

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)

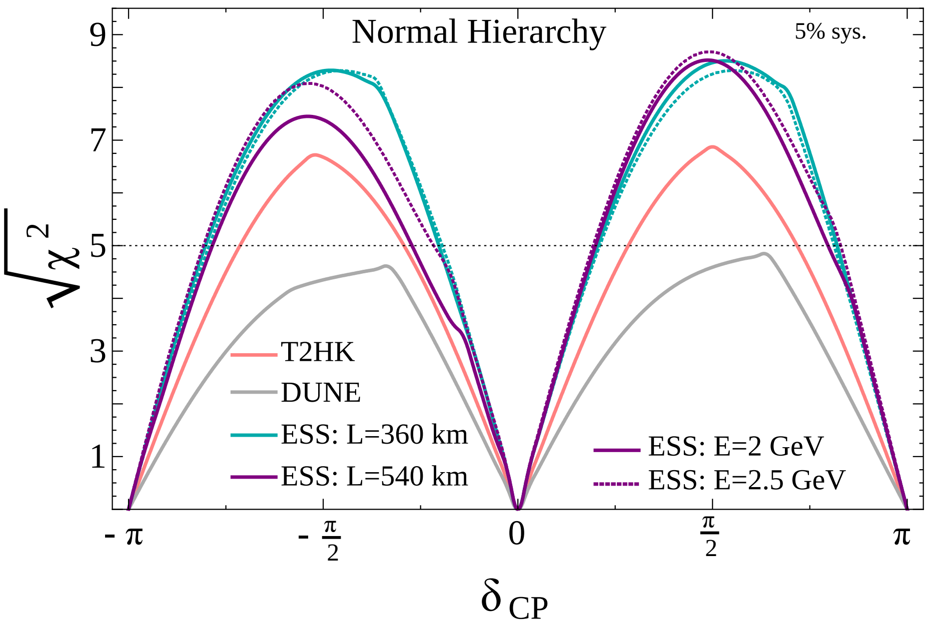


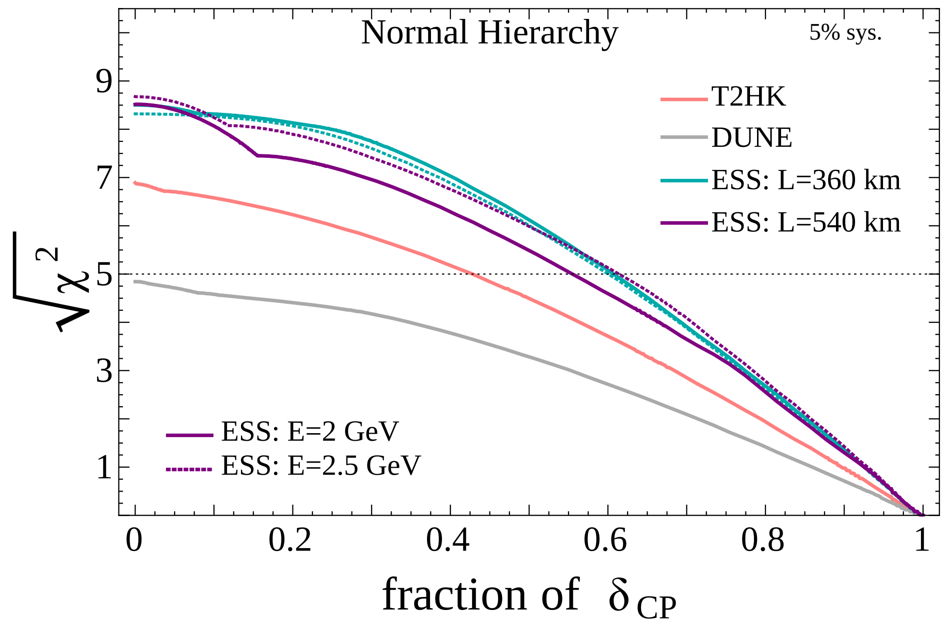
"default" column

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





Comparison using the same systematic errors

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]