UiO : Department of Physics
University of Oslo

ESS NEUTRINO SUPER BEAM

Neutrino CP Violation with the European Spallation Source neutrino Super Beam project

Eirik Gramstad
University of Oslo (UiO)
on behalf of the ESSνSB collaboration

ESS NEUTRINO SUPER BEAM

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

The 26th Nordic Particle Physics Meeting (Spaatind 2020)
January 2-7, 2020
Skeikampen, Norway

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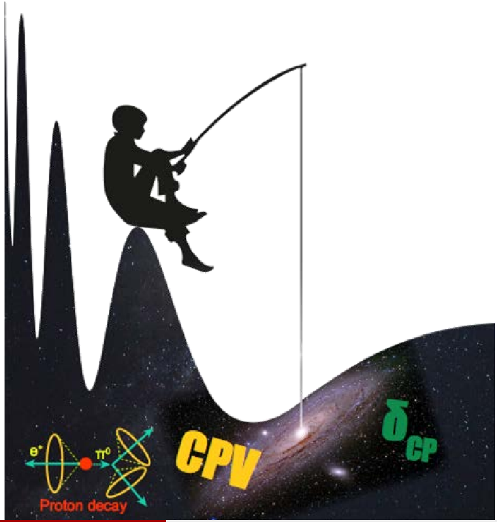
Fishing for CP violation at the 2nd oscillation maximum!



EUROPEAN SPALLATION SOURCE

Neutrino Oscillations

Neutrino Oscillations were discovered $\sim$ 20 years ago, still there are several open questions:

- value of Dirac CP violating phase (δ_{CP})
- the sign of Δm^2_{31} (normal versus inverted neutrino mass ordering)
- octant of θ_{23}
- if neutrinos are Dirac or Majorana particles

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$

[Esteban et al., 2019] and NuFIT 4.1 (2019), www.nu-fit.org

Neutrino Oscillations were discovered $\sim$ 20 years ago, still there are several open questions:

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CP Violation

A measurement of δ_{CP} would imply a completely new source of CP violation

- potentially **four orders** of magnitude larger than in the quark sector
- provide information on the origin of the baryon asymmetry of the Universe

Going to the 2^{nd} oscillation maximum

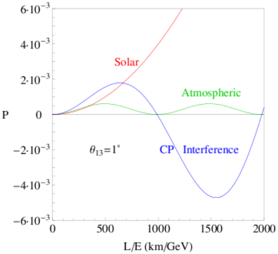
$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{31}L}{2}\right) + \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta_{21}L}{2}\right)$$
$$+ \tilde{J}\cos\left(\delta_{CP} - \frac{\Delta_{31}L}{2}\right)\sin\left(\frac{\Delta_{21}L}{2}\right)\sin\left(\frac{\Delta_{31}L}{2}\right)$$

- the observation of a relatively large θ_{13} implies that the second oscillation maximum is more sensitivity to δ_{CP} than the first oscillation maximum
  1. the interference term is significantly smaller than the dominant atmospheric term at the first maximum whereas it is comparable to the atmospheric term at the second maximum (the solar term is sub-dominant at both maxima)
     - less sensitive to systematic uncertainties
  2. larger matter/antimatter asymmetry:
     - 1st oscillation maximum: $A \sim 0.3\sin\delta_{CP}$
     - 2nd oscillation maximum: $A \sim 0.75\sin\delta_{CP}$

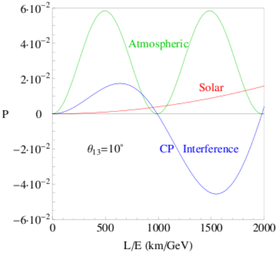
$$A = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

- the source-to-detector baseline needs to be ~ 3 times larger
  - significantly decreased statistics
  - necessitating a multi–MW proton beam

Small θ_{13}



Large θ_{13}



[Coloma and Fernandez-Martinez, 2012]

From ESS to ESSνSB

ESS NEUTRINO SUPER BEAM
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Funded by the Horizon 2020 Framework Programme of the European Union

- The European Spallation Source (ESS) is under construction in Lund
- the most powerful linear proton accelerator ever built
- will become the world's leading neutron source when operational in 2023

	ESS	νSB
duty cycle	4%	8%
beam power	5 MW	10 MW
particles	protons	H^--ions and protons
kinetic energy	2.0 GeV	2.5 GeV
pulse length	2.86 ms	$\sim 1.3\ \mu$s
pulse current	62.5 mA	50 mA

† Possible to upgrade to **3.6** GeV

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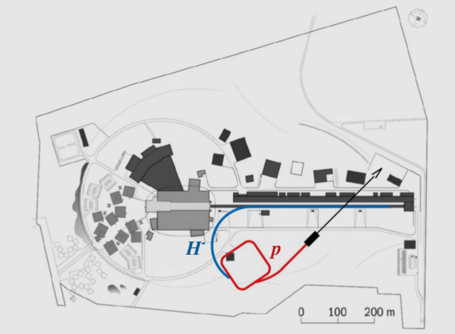
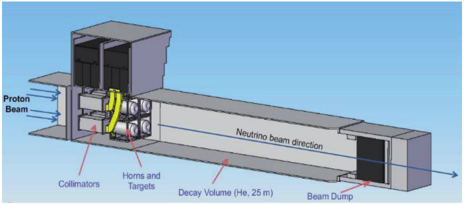
ESSνSB



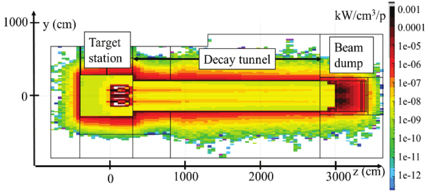
The following needs to be added:

- H^- source at the beginning of the proton linac
- transfer line from linac to accumulator
- 384 m circumference proton accumulator
- stripping of ions at the entrance of the accumulator
- a target switch yard

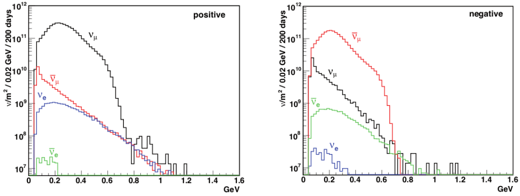
- the target station will be a packed bed of titanium spheres cooled with pressurized helium gas
  - due to the very high power (5 MW) of the proton beam hitting the target a system with four targets and four horns will be used
  - each target taking 1.25 MW
- protons interacting in the target material will lead to the production of short-lived mesons eventually decaying into **neutrinos**
- the magnetic horns will focus the produced mesons towards the decay tunnel
- the decay tunnel (∼ 25 m) will allow the mesons to decay



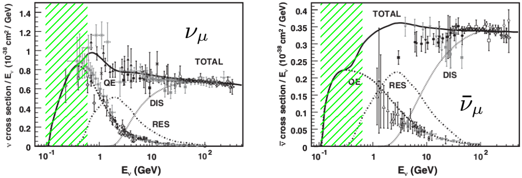
Energy deposition has been simulated in FLUKA



[Bouquerel et al., 2017]



	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



[Formaggio and Zeller, 2012]

- energy spectrum for ν and $\bar{\nu}$ at a distance of 100 km on-axis from the target using 2.0 GeV protons during 200 days
- have to detect neutrino interactions in the energy range 0.1-0.6 GeV
  - lower than any other long baseline neutrino oscillation experiment before
- mainly charge Current (CC) Quasi-Elastic (QE) scattering

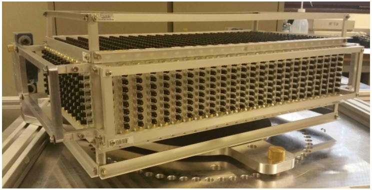
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$
$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- backgrounds from deep inelastic and resonant scattering (with π) are strongly suppressed compared with the situation in Hyper-K and Dune

The baseline design of a near detector in ESSνSB consists of two parts

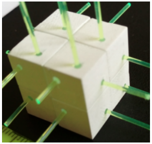
1 a 3D plastic scintillation detector

- needed to measure the topology of the events and properly identify the different neutrino interactions
- active tracking volume consist of several millions of $1 \times 1 \times 1$ cm^3 plastic scintillator cubes
- three orthogonal holes are drilled in the cubes to accommodate wave length shifting fibers for readout
    - provide projections of charged particle trajectories onto three planes without any inactive regions
- **mass**: 5 tons
- **magnetic field**: 0.5 Tesla



prototype detector tested at CERN in 2018

[Abe et al., 2019]



2 a water Cherenkov detector

- needed for flux monitoring and event rate measurements using the same technology as the far detector (water Cherenkov)
- **fiducial mass**: 250 tons
- **size**: radius 5 m, length 10 m

The Far Detector

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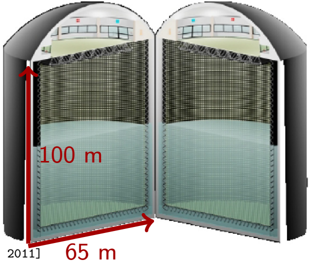
- the design of the far detector in ESSνSB build upon studies of the MEMPHYS Far Detector evaluated by the EUROν project
    - large-scale water Cherenkov detector with a fiducial mass of the order of half a megaton
    - baseline design is two cylindrical detector modules of 65 m in diameter and 100 m height
- Possible locations of the far detector in Garpenberg mine (540 km) or in Zinkgruvan (360 km), both located near the second maximum



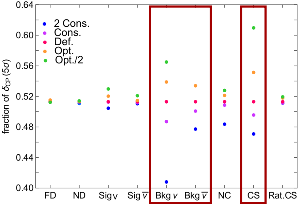
[Borne et al., 2011]

- the baseline requirements of the near detector in ESSνSB are based on recent studies comparing the physics reach of future long baseline neutrino oscillation experiments
- the default (`Def.`) option below is considered in the ESSνSB near detector design

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

[Coloma et al., 2013]

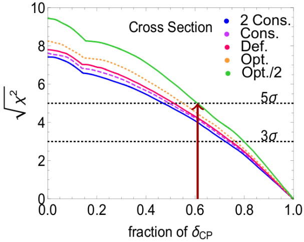
The effect of each systematic uncertainty on the 5σ discovery reach of δ_{CP}:



uncertainty on neutrino cross-sections and $\nu_e/\bar{\nu}_e$ flux dominates

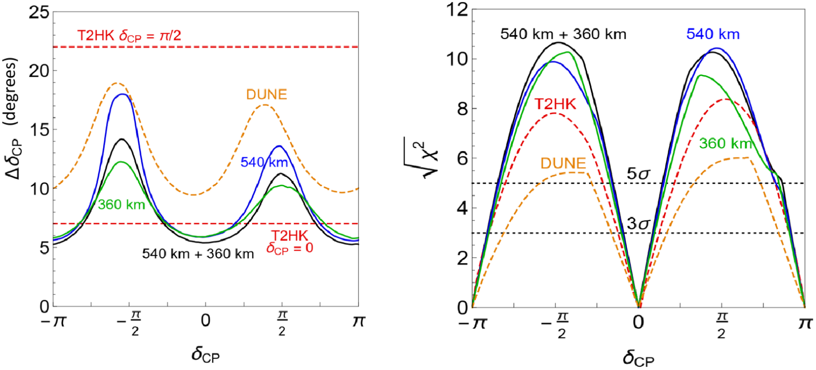
[Alcaraz, 2018]

The effect on the discovery reach for δ_{CP} with different levels of the systematic uncertainties:



62% coverage of the δ_{CP} range can be reached with $\geq 5\sigma$ [Alcaraz, 2018]

Comparison of resolution (left) and sensitivity (right) to δ_{CP} between ESSνSB (with three options for the location of the far detector), DUNE and Hyper-K



- assuming 10 years of data taking
- Hyper-K sensitivity from presentation at the Neutrino 2018 conference [Shiozawa, 2018]
- DUNE curves have been derived using the public GLoBES file released by the DUNE collaboration with its Conceptual Design Report in 2016
- the systematic uncertainties are set to 3% for all experiments

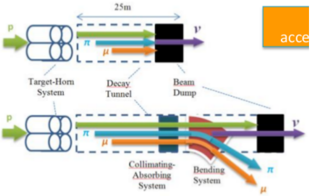
Not just neutrino osciallltions...

The Far Detector

- given the large volume of the far detector in ESSνSB (twice the size of Hyper-Kamiokande) it can be used
  1. precise measurements of the neutrino mixing parameters, testing the unitarity of the PMNS matrix
  2. measurements to determine the mass ordering between the neutrinos
  3. more detailed information about the nuclear processes in the sun (from solar neutrinos)
  4. study proton decays
  5. study neutrinos from supernova explosions

Muon Factory

- several possibilities to use the high intensity and short-pulsed proton beam from the ESSνSB accumulator ring for other activities
  - more than $4 \times 10^{20} \mu$/year with an average energy of 0.5 GeV expected (at the level of the beam dump)
  - muon storage ring to produce high-energy neutrino beam for short- (`nuSTORM`) and long (`Neutrino Factory`) baseline detectors
  - a muon collider



Open Workshop in Uppsala 2-3 March 2020: Prospects for Intensity Frontier Physics with Compressed Pulses from the ESS Linac

Conclusions

the uniquely high beam power of 5 **MW**
of the ESS linear proton accelerator
the relatively large θ_{13}

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Neutrino oscillation measurement at the 2^{nd} maximum
Negligible backgrounds from inelastic and resonant scattering

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COST Action EuroNuNet (CA15139)
EU-H2020 DesignStudy ESSνSB (€3M)

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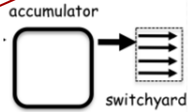
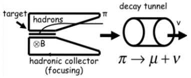
linac

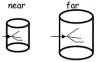
accumulator



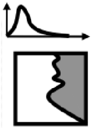
target station



detectors



physics



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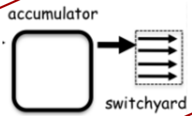
linac

accumulator



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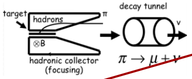

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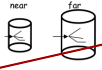
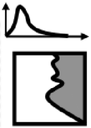
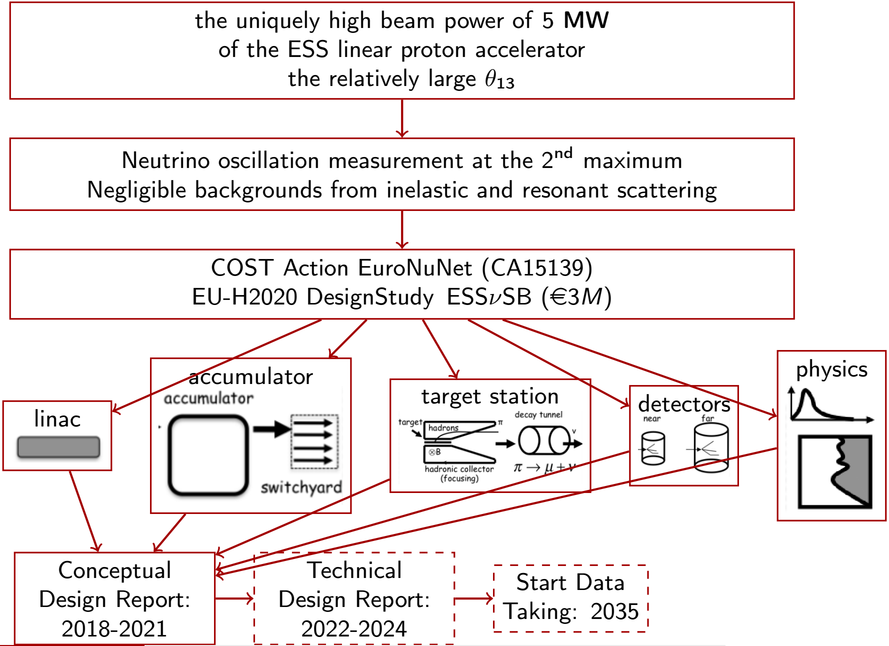


physics



Conceptual
Design Report:
2018-2021


the uniquely high beam power of 5 **MW**
of the ESS linear proton accelerator
the relatively large θ_{13}
Neutrino oscillation measurement at the 2nd maximum
Negligible backgrounds from inelastic and resonant scattering
COST Action EuroNuNet (CA15139)
EU-H2020 DesignStudy ESSνSB (€3M)
linac
accumulator
accumulator
switchyard
target station
target
hadrons
π
decay tunnel
ν
⊗B
hadronic collector
(focusing)
$\pi \rightarrow \mu + \nu$
detectors
near
far
physics
Conceptual Design Report: 2018-2021
Technical Design Report: 2022-2024
Start Data Taking: 2035

BACKUP

Neutrino Parameters

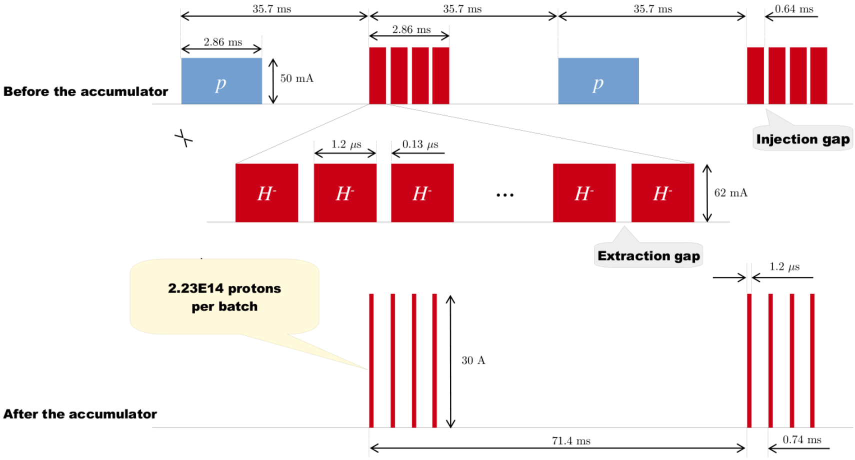
ESS NEUTRINO SUPER BEAM
COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Funded by the Horizon 2020 Framework Programme of the European Union

NuFIT 4.1 (2019)

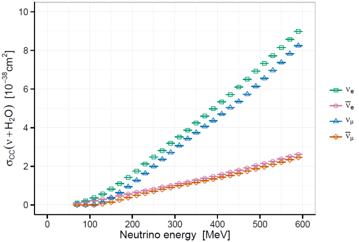
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

[Esteban et al., 2019] and NuFIT 4.1 (2019), www.nu-fit.org

Pulse Structure



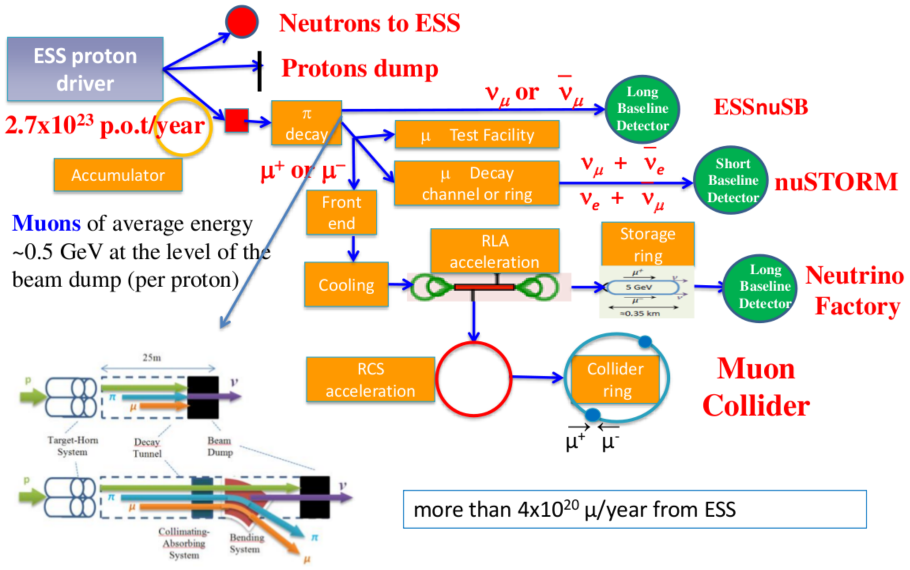
- the cross-sections of electron neutrino/anti neutrinos at the ESSνSB energies are not measured
- rely on theoretical predictions from e.g. the GENIE generator
- to reduce the systematic uncertainties it will be particularly important to measure these cross-sections with a near detector at ESS



Total cross-section for neutrino interactions with water molecules

Requirements for the cross-section measurements by the near detector:

Measurement	Uncertainty
Overall neutrino flux	5%
Overall neutrino flux monitoring	1%
Lepton flavor identification	$<0.05\%$
Lepton charge identification	10%



more than 4×10^{20} μ/year from ESS

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