1477

ESS

The European Spallation Source

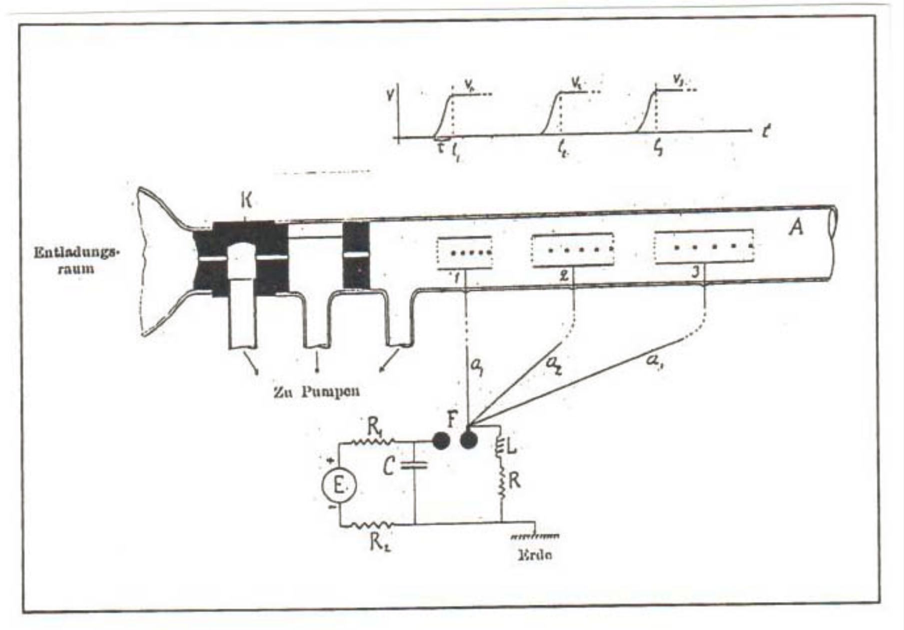
comprising a 5 MW, 2 GeV proton linac for Neutron Spallation Physics with a high potential also for Particle Physics

Tord Ekelof, Uppsala University

90 year anniversary

Gustav Ising
Fil. Kand. Uppsala 1903
Fil. Dr. Stockholm 1919
published in 1924 an accelerator concept with voltage waves propagating from a spark discharge to an array of drift tubes.

Voltage pulses arriving sequentially at the drift tubes produce accelerating fields in the sequence of gaps.

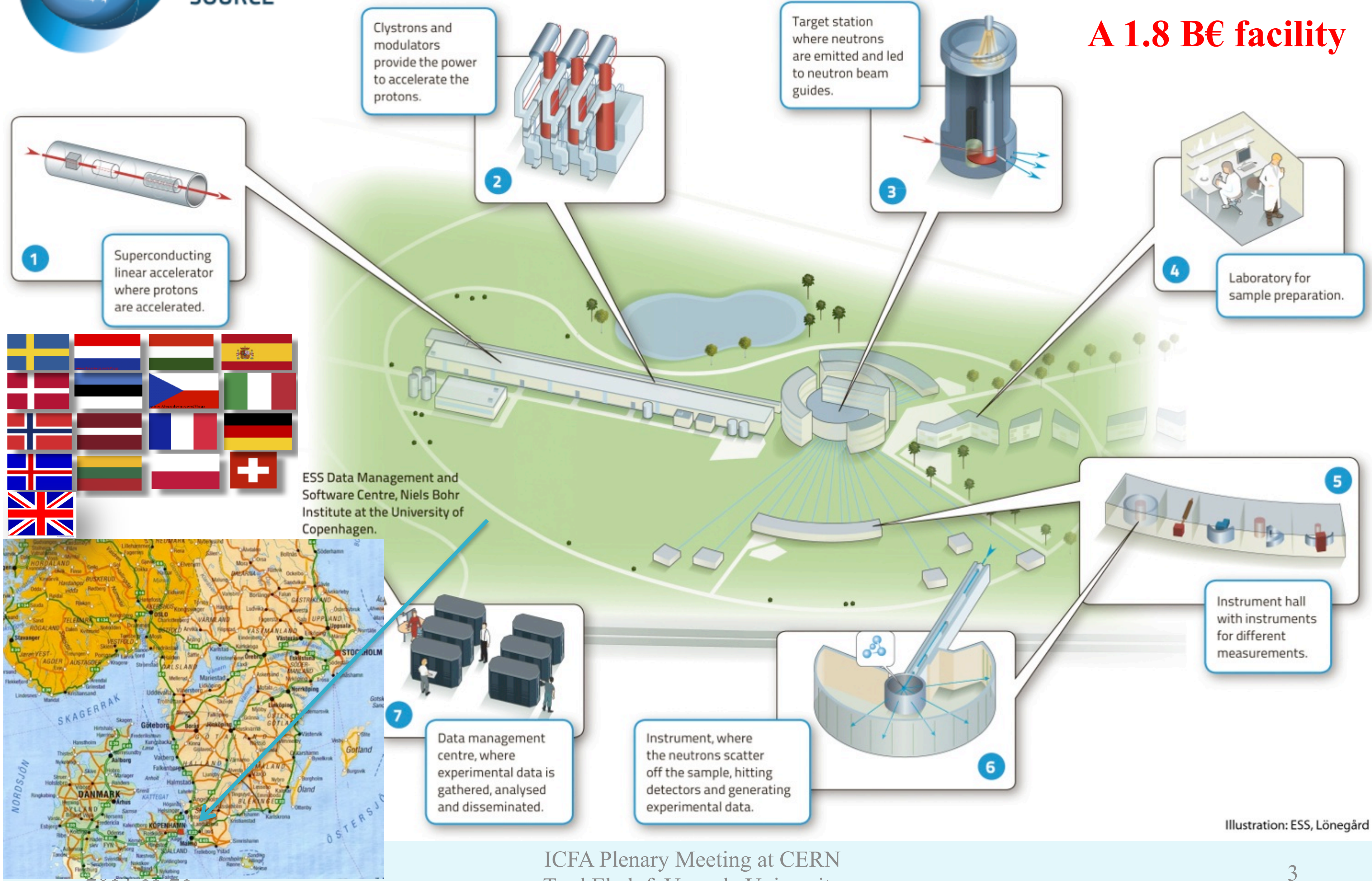


The 5 MW ESS linac is the hitherto most powerful realization of this visionary proposal made 90 years ago!

EUROPEAN SPALLATION SOURCE

European Spallation Source

A 1.8 B€ facility



Superconducting linear accelerator where protons are accelerated.

Clystrons and modulators provide the power to accelerate the protons.

Target station where neutrons are emitted and led to neutron beam guides.

Laboratory for sample preparation.

Instrument hall with instruments for different measurements.

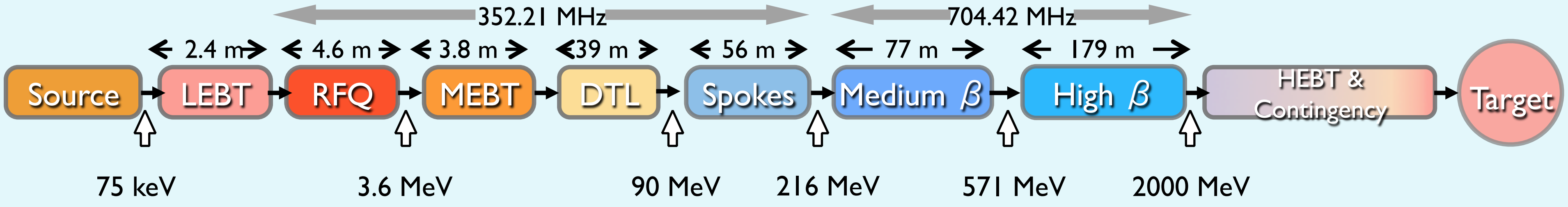
Instrument, where the neutrons scatter off the sample, hitting detectors and generating experimental data.

Data management centre, where experimental data is gathered, analysed and disseminated.

ESS Data Management and Software Centre, Niels Bohr Institute at the University of Copenhagen.

Illustration: ESS, Lönegård

ESS proton linac



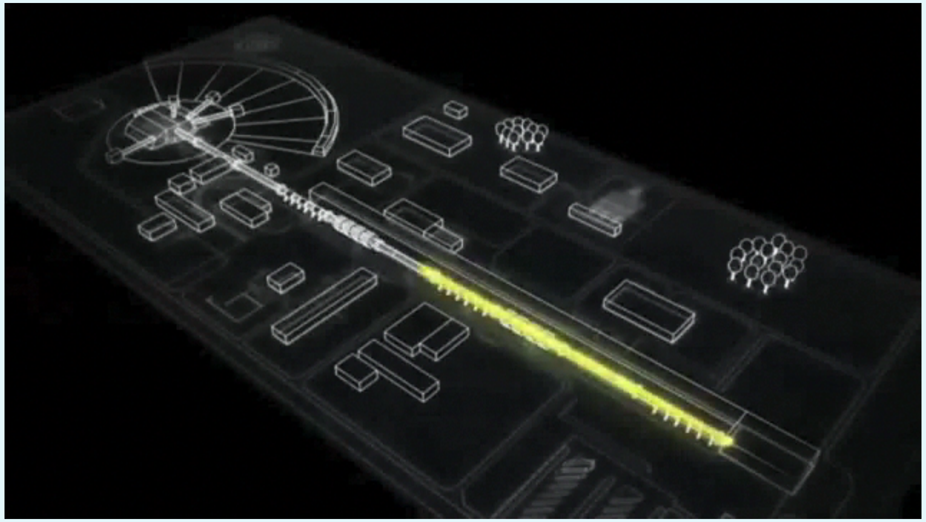
352.21 MHz
704.42 MHz

2.4 m
4.6 m
3.8 m
39 m
56 m
77 m
179 m

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

75 keV
3.6 MeV
90 MeV
216 MeV
571 MeV
2000 MeV

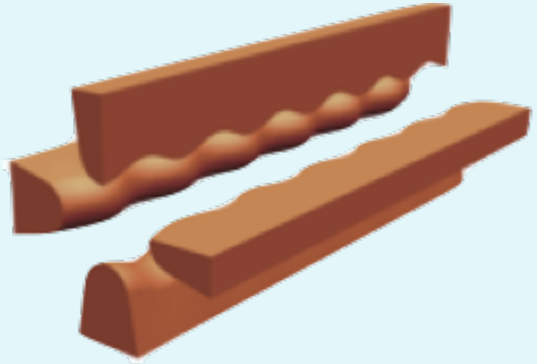
- The ESS linac will be a copious source of protons
- 5 MW average beam power
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
- **>2.7x10^{23} p.o.t/year**



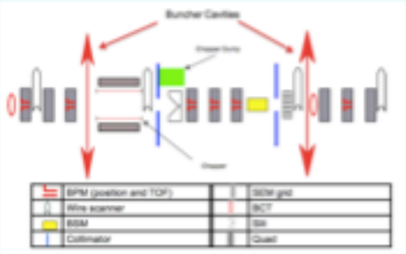
Linac ready by 2023 (full power and energy)

ION SOURCE & NC LINAC

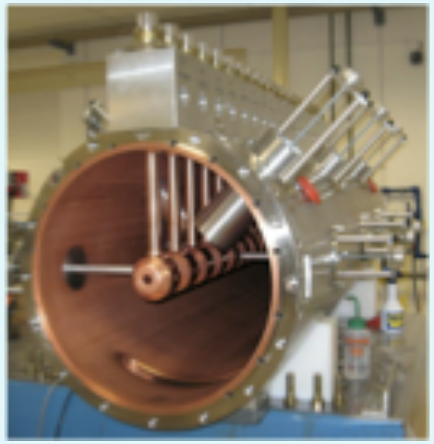
Prototype proton source operational, and under further development, in **Catania**. Output energy 75 keV.



Design exists for ESS RFQ similar to 5 m long IPHI RFQ at **Saclay**.
Energy: 75 keV to 3.6 MeV.



Design work at ESS **Bilbao** for MEBT with instrumentation, chopping and collimation.



DTL design work at ESS and in INFN **Legnaro**.
Energy: 3.6 to 90 MeV.

Picture from **CERN** Linac4 DTL.

THE FIRST ESS SPOKE CAVITY

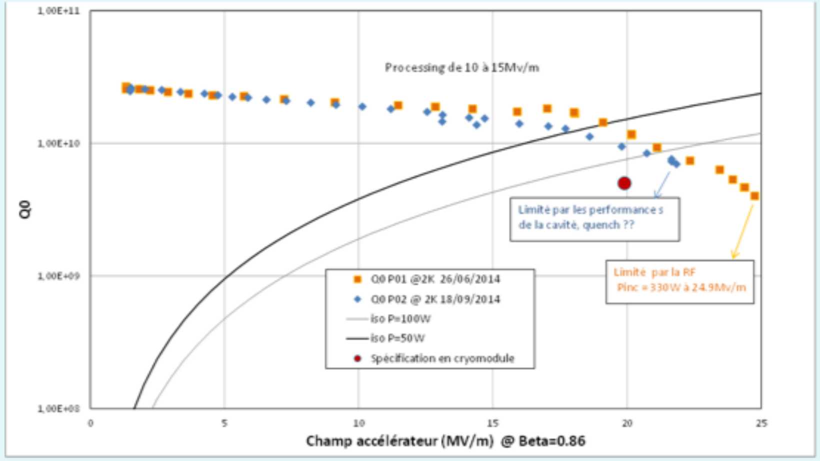
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY SDMS la chaudronnerie blanche August 2014

Designed and produced through **IPN Orsay**, to be tested in 2015 at full power (400 kW) in the FREIA Lab at **Uppsala** University

Personnel of FREIA, IPN Orsay and ESS in the FREIA Lab in Uppsala in the high power test bunker standing in front of the test cryostat in which the first spoke cavity will be tested at full power 400 kW

FIRST COLD TEST RESULT OF FIRST ESS HIGH BETA PROTOTYPE CAVITIES

- Measurements done the 22th of May 2014 in vertical cryostat at **CEA Saclay**
- Testing conditions: CW mode
- Operating temperature: 2 K
- Resonant frequency of π mode (measured): 704.292788 MHz



EUROPEAN
SPALLATION
SOURCE

ESS project approval 4 July 2014

ESS Gets the Green Light

JUL 4, 2014 SCIENCE AND INSTRUMENTS, TARGET, ACCELERATOR, BUILDING ESS, NEWS & PRESS, THE EUROPEAN SPALLATION SOURCE

The European Spallation Source has received approval to start construction. The project will break ground in Lund in the early autumn. Experts all over Europe are prepared to build one of the world's...

Read more

http://europeanspallationsource.se/ess-gets-green-light

Contributions by Member Country

Facility ready by 2023 (full energy and full power)

Sweden	35%	Switzerland	3.5%
Denmark	12.5%	Norway	2.5%
Germany	11%	Poland	2%
U.K.	10%	Hungary	1.5%
France	8%	Czech	0.3%
Italy	6%	Estonia	0.25%
Spain	5%	TBD	2.5%

Groundbreaking

Lund 2 September
2014

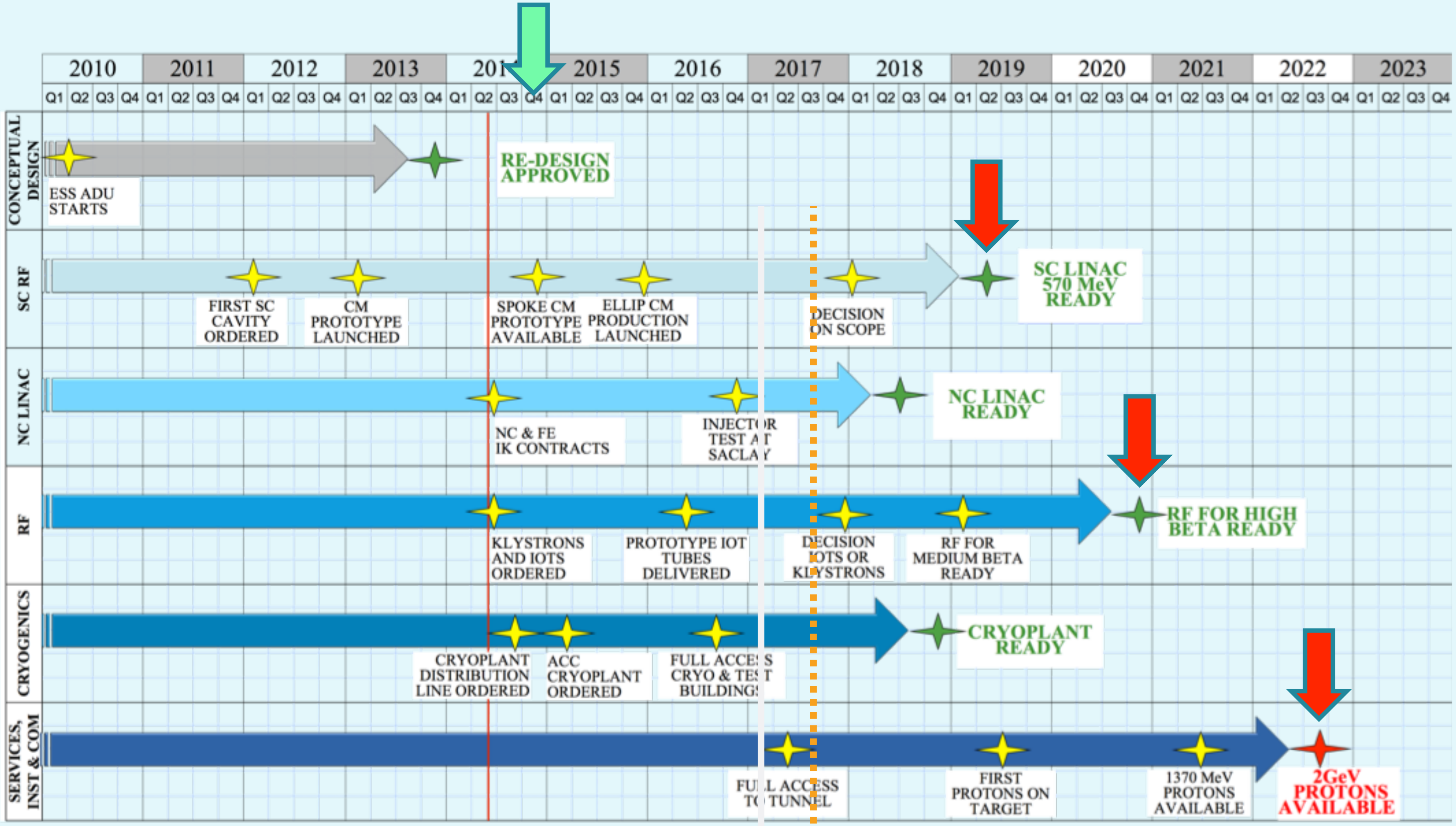
.

Construction work ongoing at the ESS site

Drawings

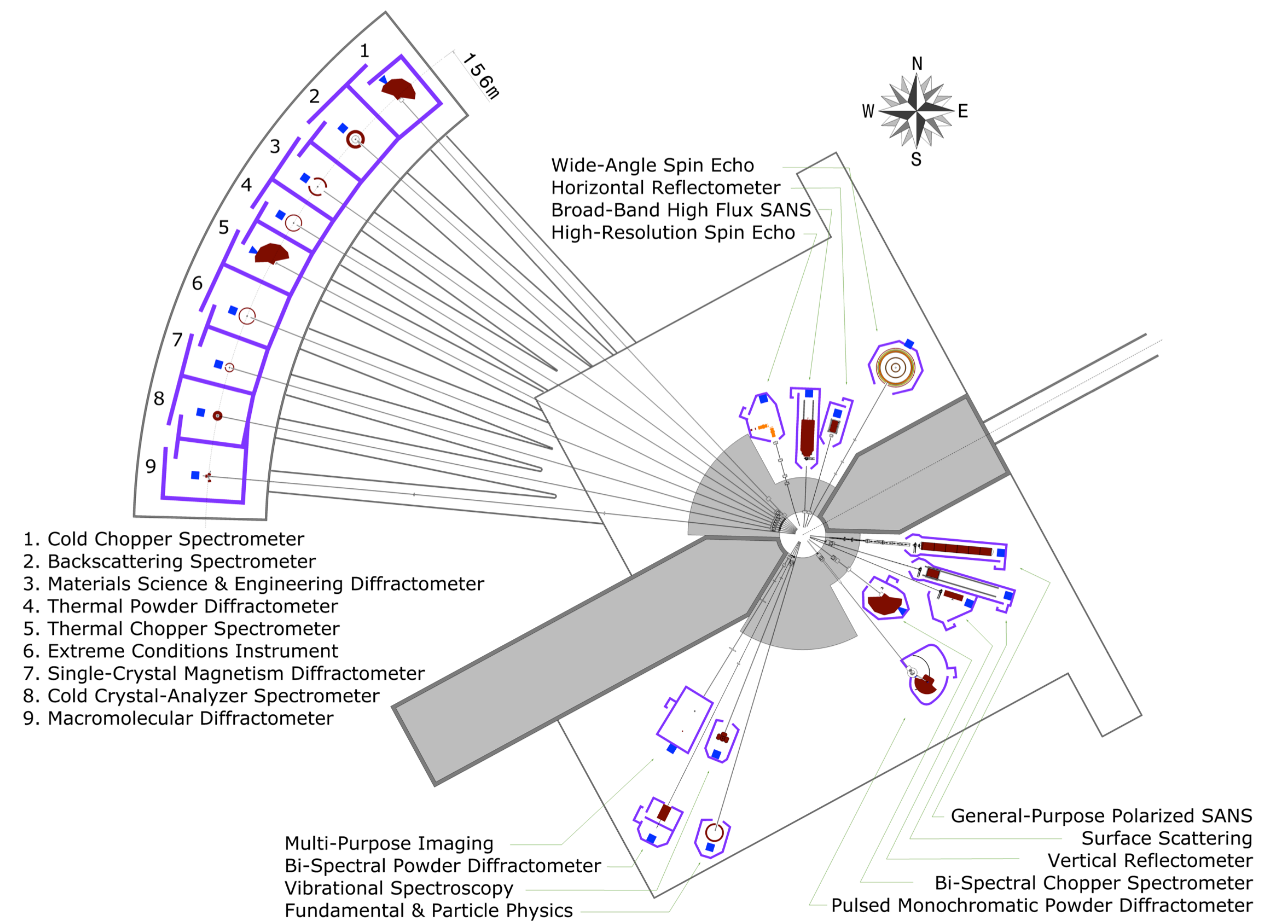
Photos November 2014

ESS LINAC PROJECT SCHEDULE



Spallation Neutron Research

Many different instruments planned



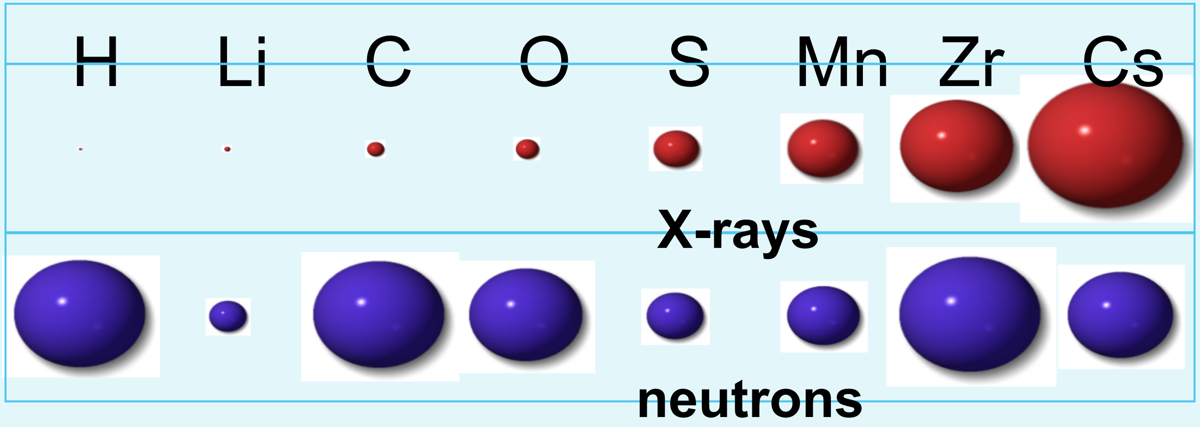
Wide-Angle Spin Echo
Horizontal Reflectometer
Broad-Band High Flux SANS
High-Resolution Spin Echo

1. Cold Chopper Spectrometer
2. Backscattering Spectrometer
3. Materials Science & Engineering Diffractometer
4. Thermal Powder Diffractometer
5. Thermal Chopper Spectrometer
6. Extreme Conditions Instrument
7. Single-Crystal Magnetism Diffractometer
8. Cold Crystal-Analyzer Spectrometer
9. Macromolecular Diffractometer

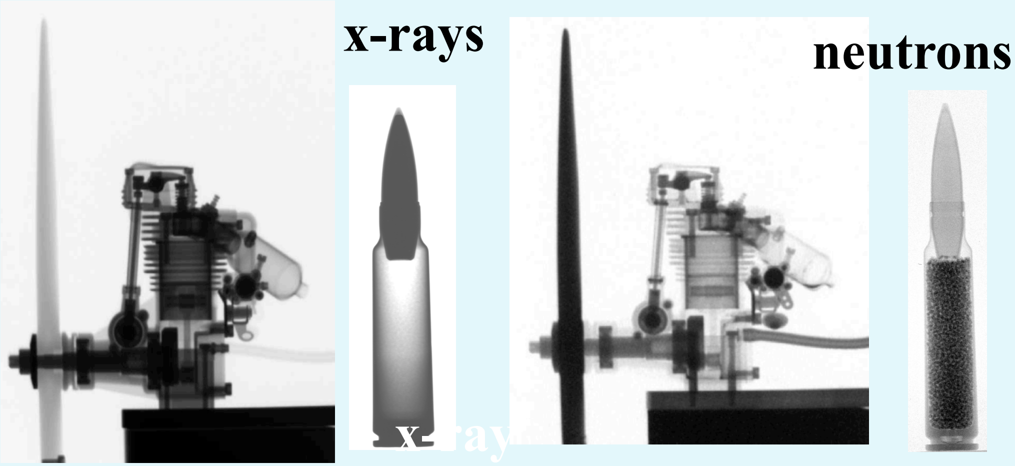
Multi-Purpose Imaging
Bi-Spectral Powder Diffractometer
Vibrational Spectroscopy
Fundamental & Particle Physics

General-Purpose Polarized SANS
Surface Scattering
Vertical Reflectometer
Bi-Spectral Chopper Spectrometer
Pulsed Monochromatic Powder Diffractometer

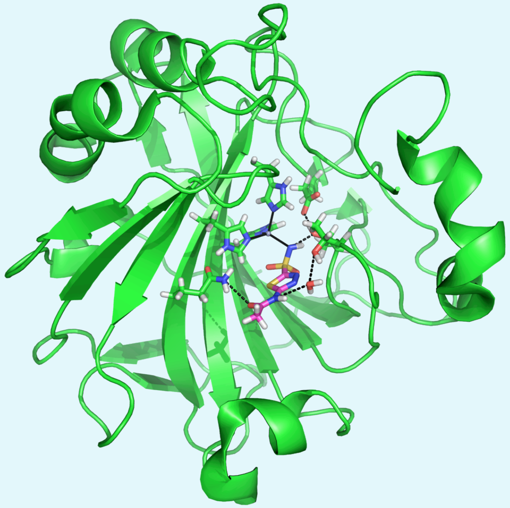
Spallation neutrons an important complement to X rays for material science



Imaging with



Neutron molecular crystallography
Sensitive also to hydrogen



The very high power of the ESS linac provides opportunities also to do **Beyond the Standard Model Particle Physics** at the intensity frontier, complementary to that at the high energy frontier at LHC.

At ESS such physics can be made essentially along two different and still related avenues: measurement of **neutron fundamental properties** and of **neutrino oscillations**.

.

1. Fundamental properties of the neutron

The detection of **neutron-antineutron oscillation** would prove violation of B-L conservation by two units like required by the seesaw mechanism for neutrino masses and could therefore be used to study **the nature and scale of the seesaw mechanism**.

The detection of a non-zero **neutron electric dipole moment** bigger than 10^{-32} excm would signal a source of CP violation stronger than that detected in the K and B decay and could, like leptonic CP violation in the neutrino sector, contribute to the understanding of **the matter-antimatter asymmetry of the Universe**.

Neutron - antiNeutron oscillations

Neutron-Anti-Neutron Oscillations at ESS

12-13 June 2014, CERN, Geneva, Switzerland

Neutral particle oscillations have proven to be extremely valuable probes of fundamental physics. Kaon oscillations provided us with our first insight into CP-violation, fast Bs oscillations provided the first indication that the top quark is extremely heavy, B oscillations form the most fertile ground for the continued study of CP-violation, and neutrino oscillations suggest the existence of a new, important energy scale well below the GUT scale. Neutrons oscillating into antineutrons could offer a unique probe of baryon number violation.

The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers an opportunity to conduct an experiment with at least three orders of magnitude improvement in sensitivity to the neutron oscillation probability.

At this workshop the physics case for such an experiment will be discussed, together with the main experimental challenges and possible solutions. We hope the workshop will conclude with the first steps towards the formation of a collaboration to build and perform the experiment.

Organising committee:

G. Brooijmans (Columbia University)
S. Chattopadhyay (Cockroft Institute)
R. Hall-Wilton (European Spallation Source)
Y. Kamyshkov (University of Tennessee)
E. Klinkby (Technical University of Denmark and European Spallation Source)
M. Lindroos (European Spallation Source and Lund University)
L. Mapelli (CERN)
M. Mezzetto (INFN Padova)
H. M. Shimizu (Nagoya University)
W. M. Snow (Indiana University)
T. Soldner (Institut Laue Langevin)
C. Theroine (European Spallation Source)

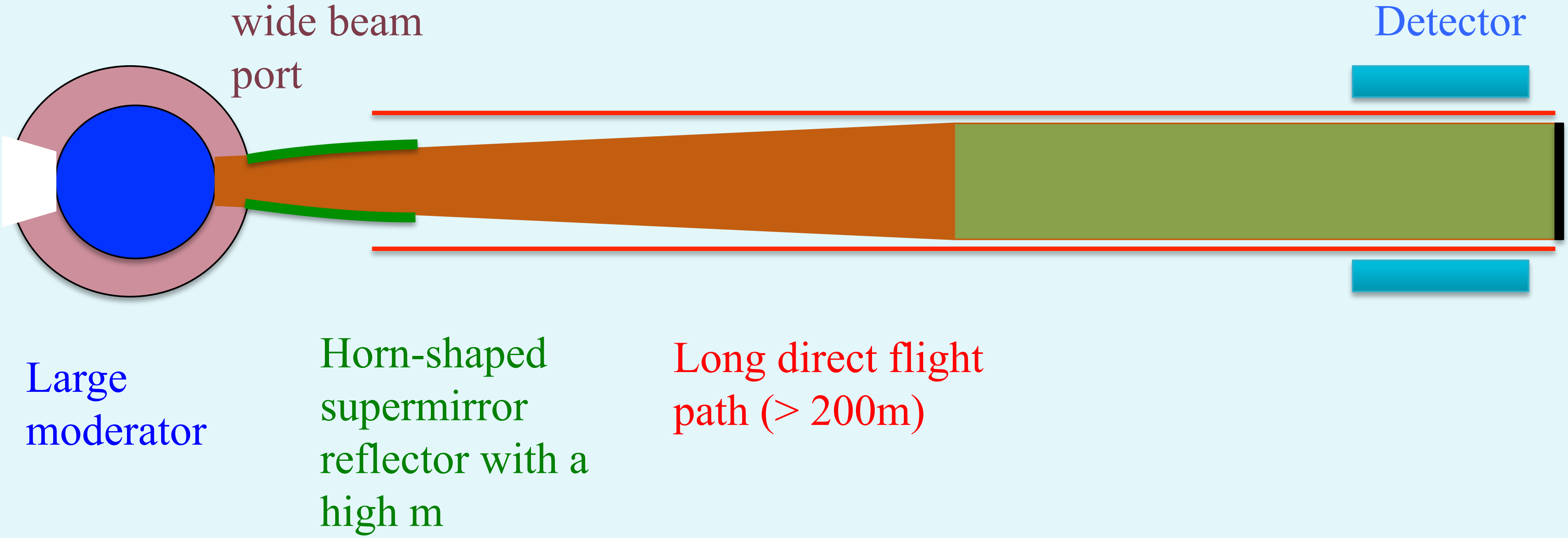
Register before
19 May on
www.nnbar-at-ess.org

EUROPEAN SPALLATION SOURCE

- The experimental search for neutron-antineutron oscillations was done at the ILL high flux reactor at Grenoble (1994). No antineutron was detected in $2.4.10^7$ s running time.

nnbar experiment @ ESS

Observe neutrons propagating in free space for a maximum of time without wall collisions



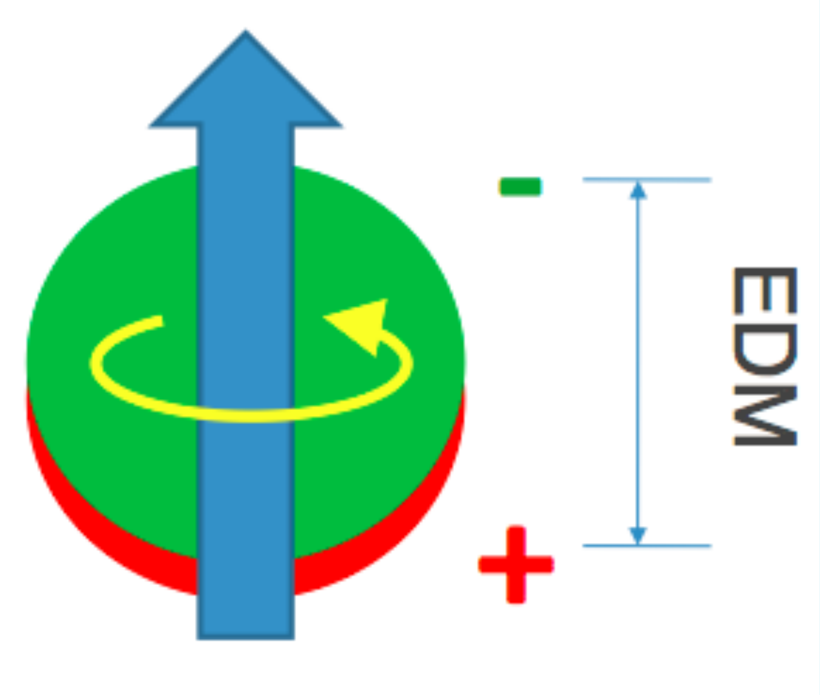
The high intensity of ESS could make possible an improvement of current limits by a factor ~300

The Neutron Electric Dipole Moment

The current upper experimental limit for the neutron electric dipole moment is 1.6×10^{-26} excm.

Current theories of the baryon asymmetry of the Universe predict a level of 10^{-28} excm.

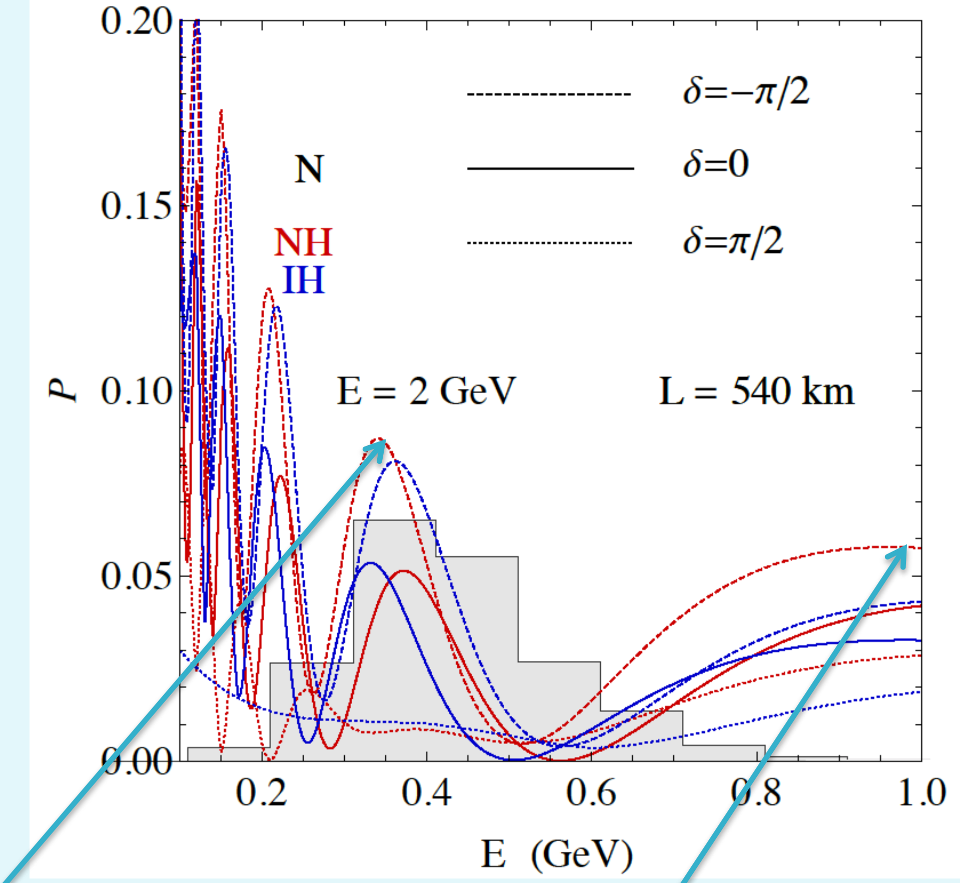
With the use of the intense flow of ultra-cold neutrons that will be possible to provide at ESS, this level could be reached.



2. Neutrino oscillation physics

The high intensity and comparatively low energy of a neutrino beam generated with the ESS 2 GeV linac will allow the effects of leptonic CP violation to be observed at the **second ν_μ-ν_e oscillation maximum,** where the effects are larger, and therefore less sensitive to systematic errors, than those at the first minimum.

A discovery and measurement of leptonic CP violation will indicate if leptogenesis can be the explanation for the matter-antimatter asymmetry of the Universe



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

1st oscillation max.

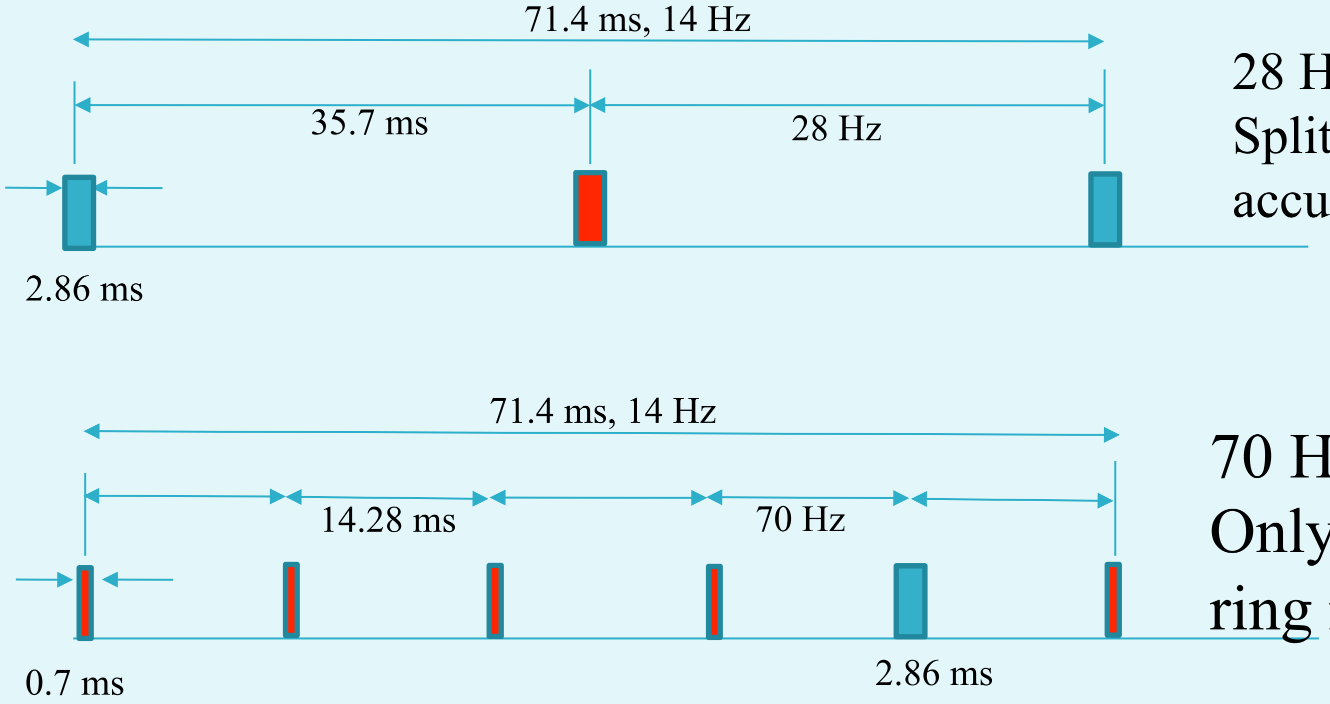
How to use the ESS linac to produce a uniquely intense neutrino beam?

- Increase the linac average power from 5 MW to 10 MW by increasing the linac pulse rate from 14 Hz to 70 Hz, implying that the linac duty cycle increases from 4% to 8%.
- Inject into an accumulator ring (ø 143 m) to compress the 3 ms proton pulse length to 1.5 μs, which is required by the operation of the neutrino horn (fed with 350 kA current pulses). The injection in the ring requires H^- pulses to be accelerated in the linac.
- Add a neutrino target station (studied in EURO ν)
- Build near and far neutrino detectors (studied in LAGUNA)
- Boundary condition: the neutron program must not be affected

Increasing the linac average power from 5 MW to 10 MW by increasing the rate of proton pulses

🟥 neutrino

🟦 neutron

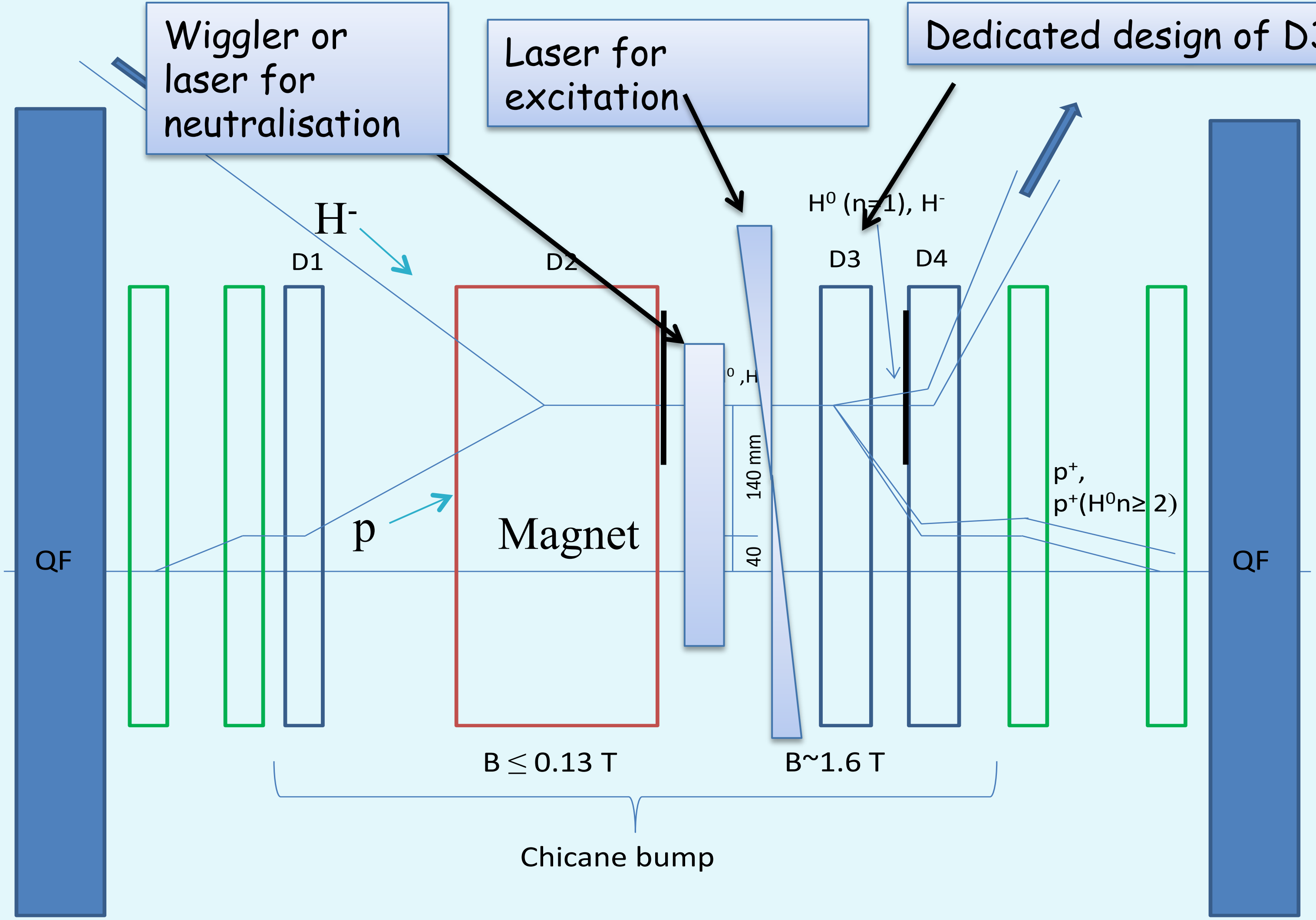


28 Hz pulsing
Split pulse on four accumulators rings

70 Hz pulsing
Only one accumulator ring needed (baseline)

The linac instantaneous power 125 MW remains unchanged

Accumulation of several units of 10^{14} protons in the accumulator ring requires acceleration of a H^- beam in the linac which may entail more beam losses. The H- ion will be stripped of its two electrons at the injection into the ring using either foil or laser stripping

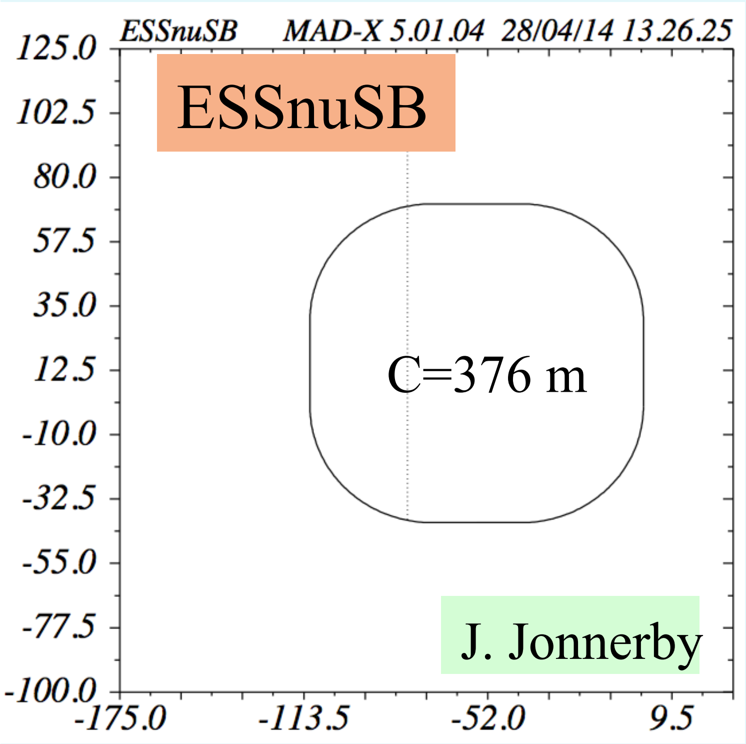


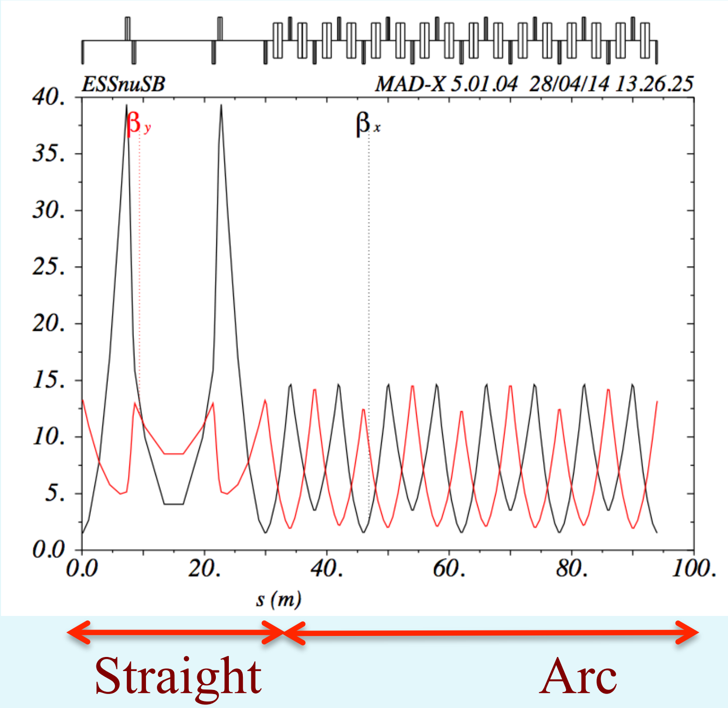
Wiggler or laser for neutralisation

Laser for excitation

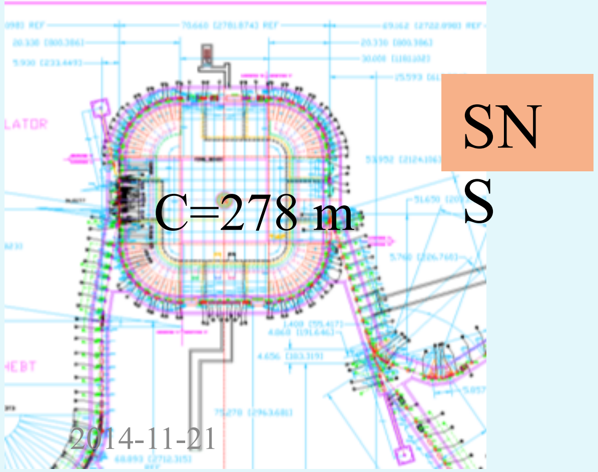
Dedicated design of D3

ESSnuSB Accumulator Ring Lattice





Circumference	376 m
Dipole field	0.635 T
# Dipoles	64
# Quads	84
Bending radius	14.6 m
Injection region	12.5 m
Revolution time	1.32 μs

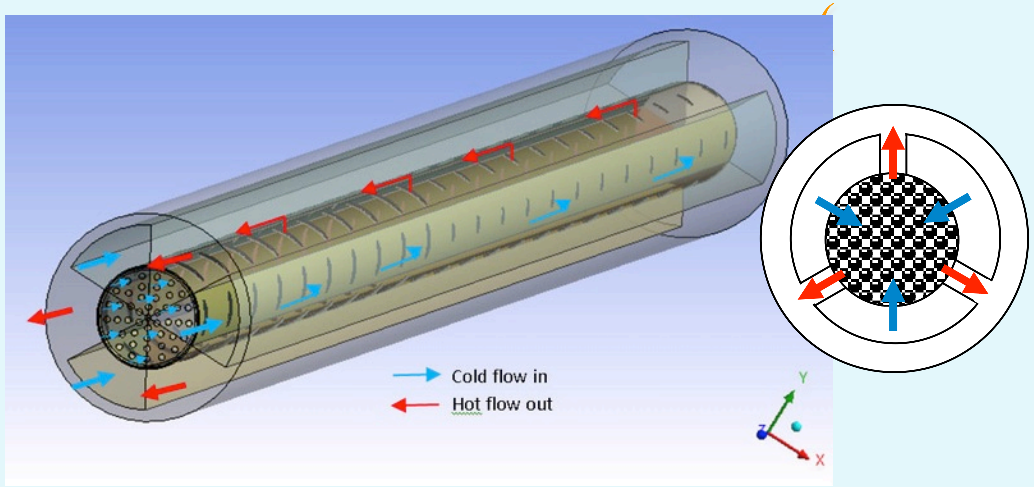


SNS straight section for injection used "as is" for simulations of foil stripping

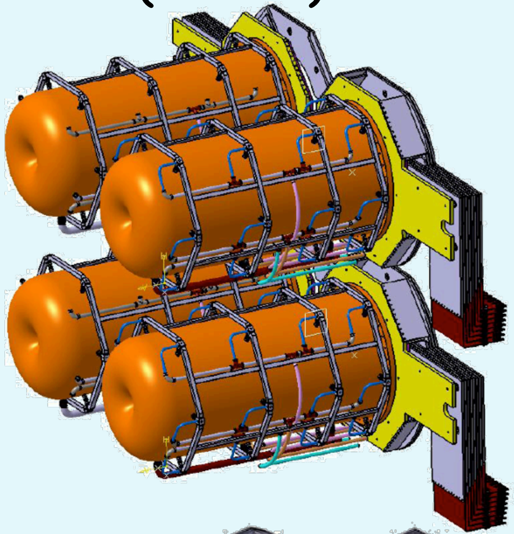
Neutrino production target and horn

Mitigation of high power effects required

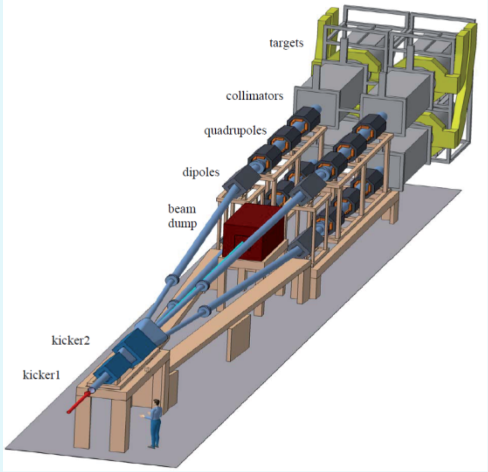
4X



Four-target/horn system to mitigate the high proton beam power (5 MW) and rate (70 Hz)

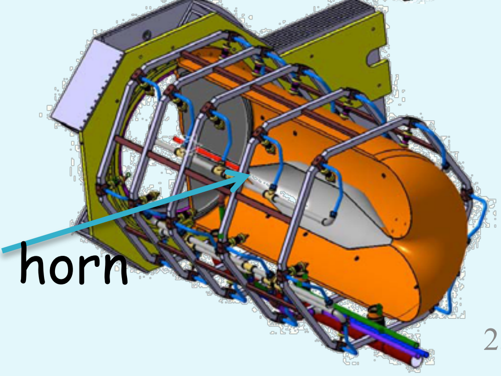


Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)



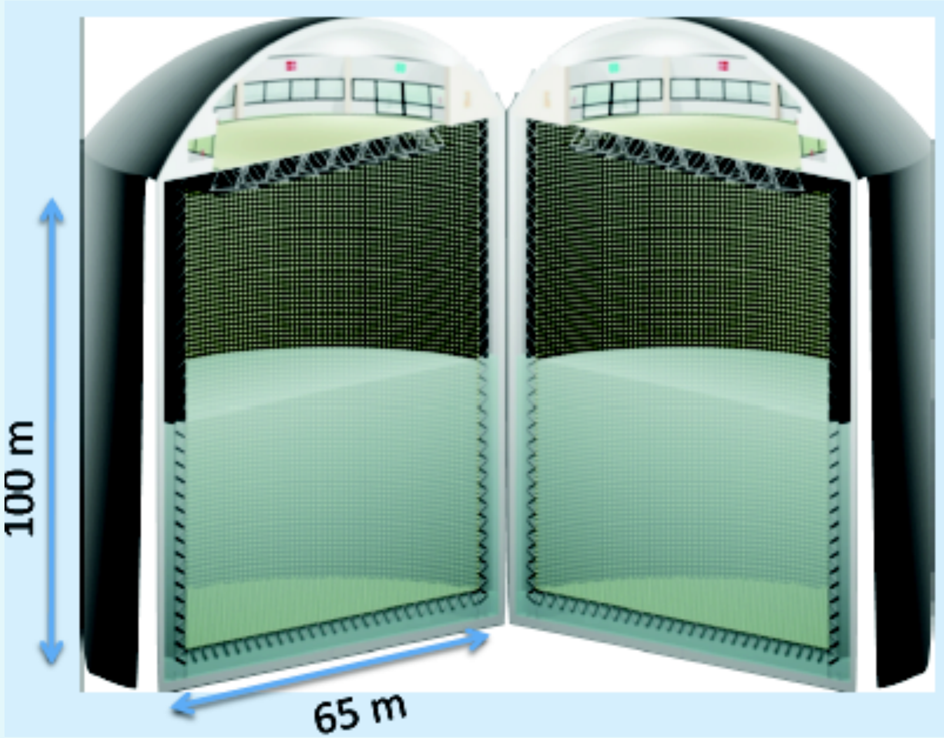
Downstream of the accumulator ring the beam pulses are distributed in sequence on the four targets

Target inside the horn



Neutrino detector: a Megaton Water Cherenkov detector

- Neutrino Oscillations
- Proton decay
- Astroparticles
- Atmospheric Neutrinos
- Solar Neutrinos
- Galactic SuperNova ν
- Supernovae "relics"



MEMPHIS

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

For the large value of Θ_{13} measured in 2012 the sensitivity to leptonic CP violation is significantly higher at the 2nd oscillation maximum as compared to at the 1st maximum, ***both* in the oscillation amplitude as already saw, *and* in the neutrino-antineutrino asymmetry**:

From Stephen Parke/ FNAL; “Neutrinos: Theory and Phenomenology” arXiv:1310.5992v1 [hep-ph] 22 Oct2013, page 12;

“At the **first oscillation maximum** (OM), as is in the running experiments, T2K and NOνA and possible future experiments HyperK and LBNE experiments, the vacuum asymmetry is given by

$A \sim 0.30 * \sin\delta$ at $\Delta_{31}=\pi/2$

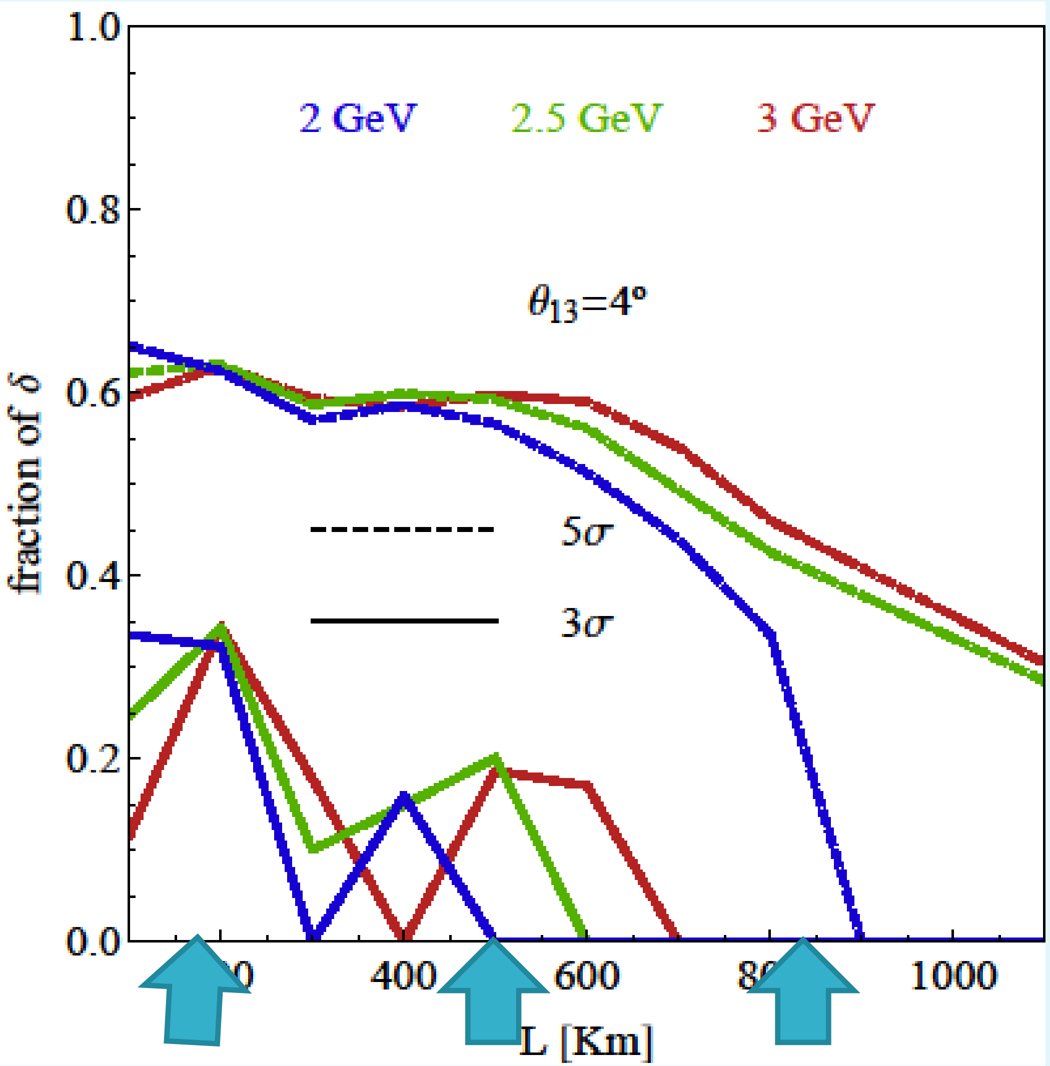
which implies that $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ is between **1/2 and 2** times $P(\nu_\mu \rightarrow \nu_e)$. Whereas at the **second oscillation maximum,** the vacuum asymmetry is

$A \sim 0.75 * \sin\delta$ at $\Delta_{31}=3\pi/2$

which implies that $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ is between **1/7 and 7** times $P(\nu_\mu \rightarrow \nu_e)$. ***So that experiments at the second oscillation maximum, like ESSnuSB [15], have a significantly larger divergence between the neutrino and anti-neutrino channels.”***

Reminder of the situation before 2012 at which time LBNE, Hyper-K and LBNO were designed – the optimum for CP violation discovery was clearly at the first maximum

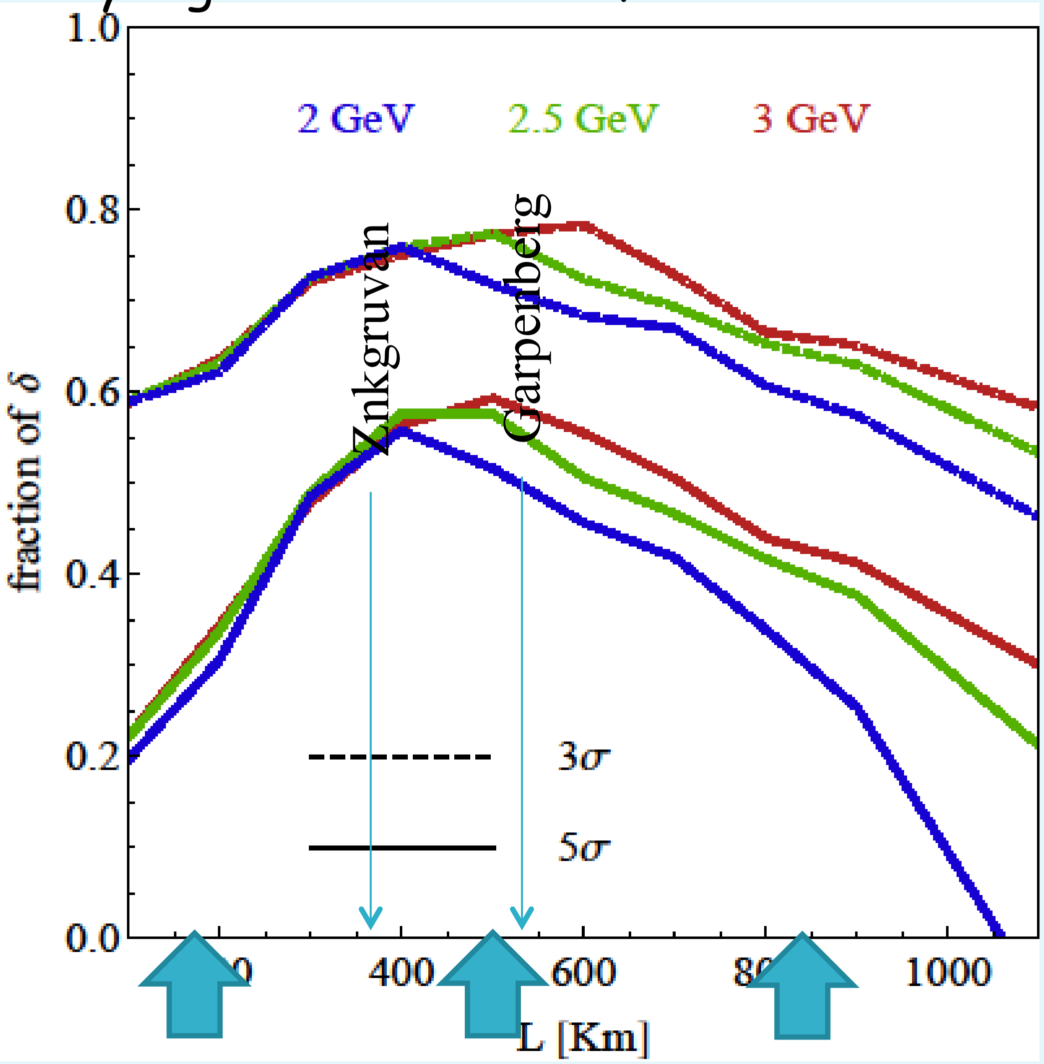
Θ_{13}=4°



1st osc. max 2nd osc. max 3rd osc. max

After the spring 2012, when Θ_{13} had been measured and ESSnuSB was designed, CP violation discovery probability did not increased at the first maximum – at the second maximum it however increased drastically and became significantly higher than at the first

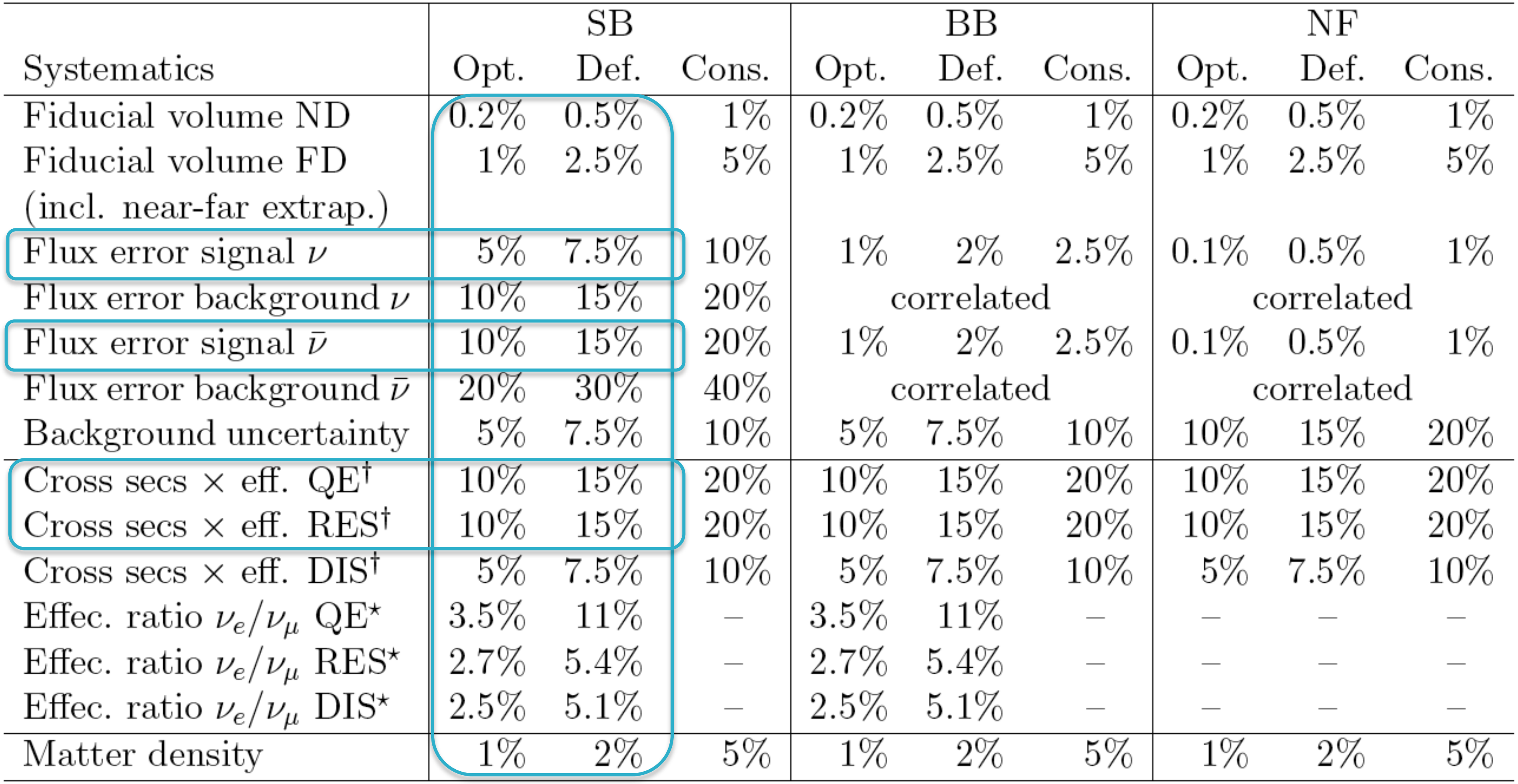
$\Theta_{13}=8.73^{o}$



1st osc. max 2nd osc. max 3rd osc. max

The depth and distance from ESS/ Lund of different mines in Scandinavia

Systematic errors

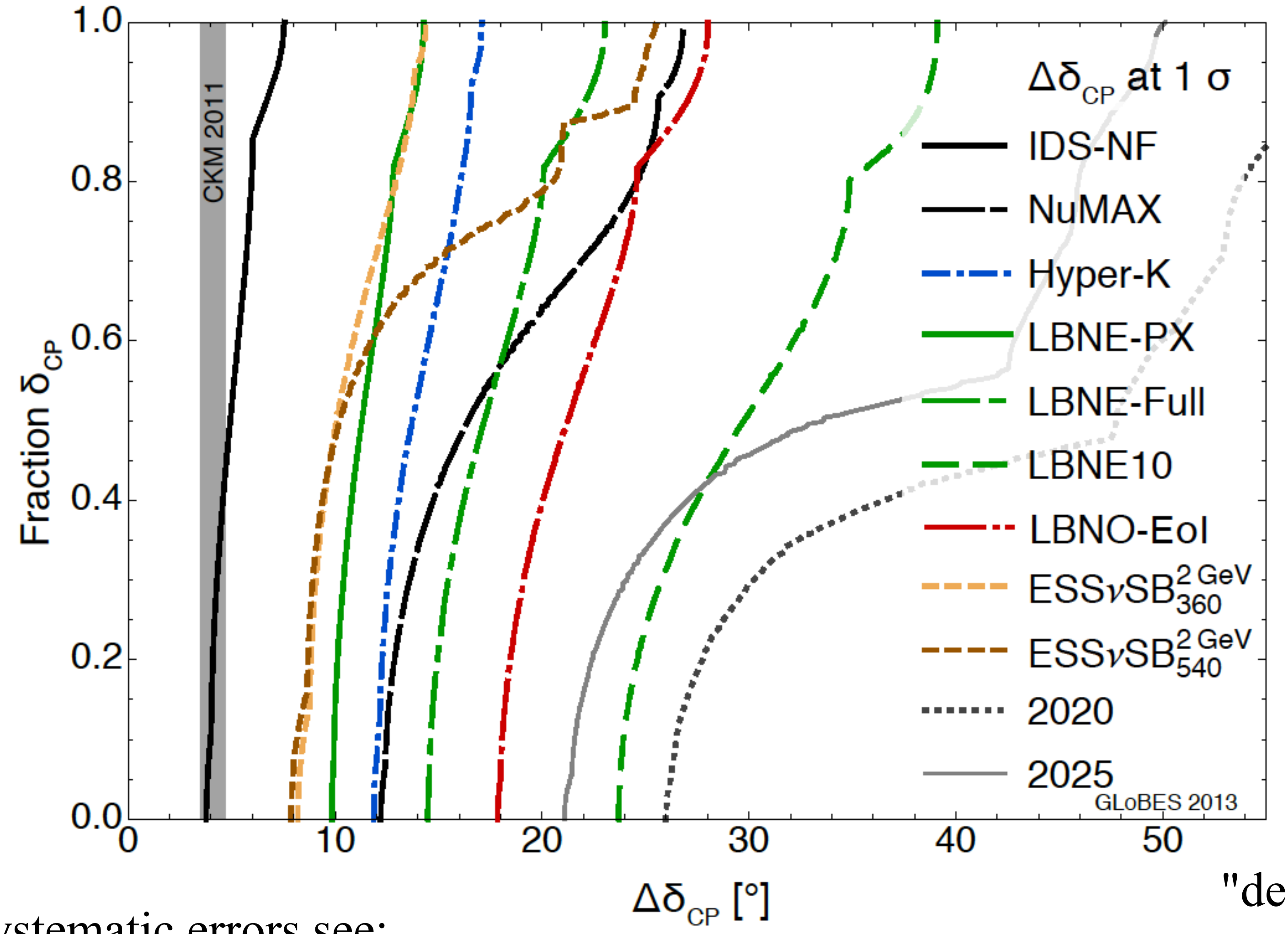


	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%		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%

Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]] published by the Snowmass Neutrino Study Group

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)



"default" colum

for systematic errors see:

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

Research and Innovation actions
Innovation actions

Design Study

H2020-INFRADEV-1-2014-1

Title of Proposal:

Study of the requirements for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.

Acronym of Proposal: ESSνSB

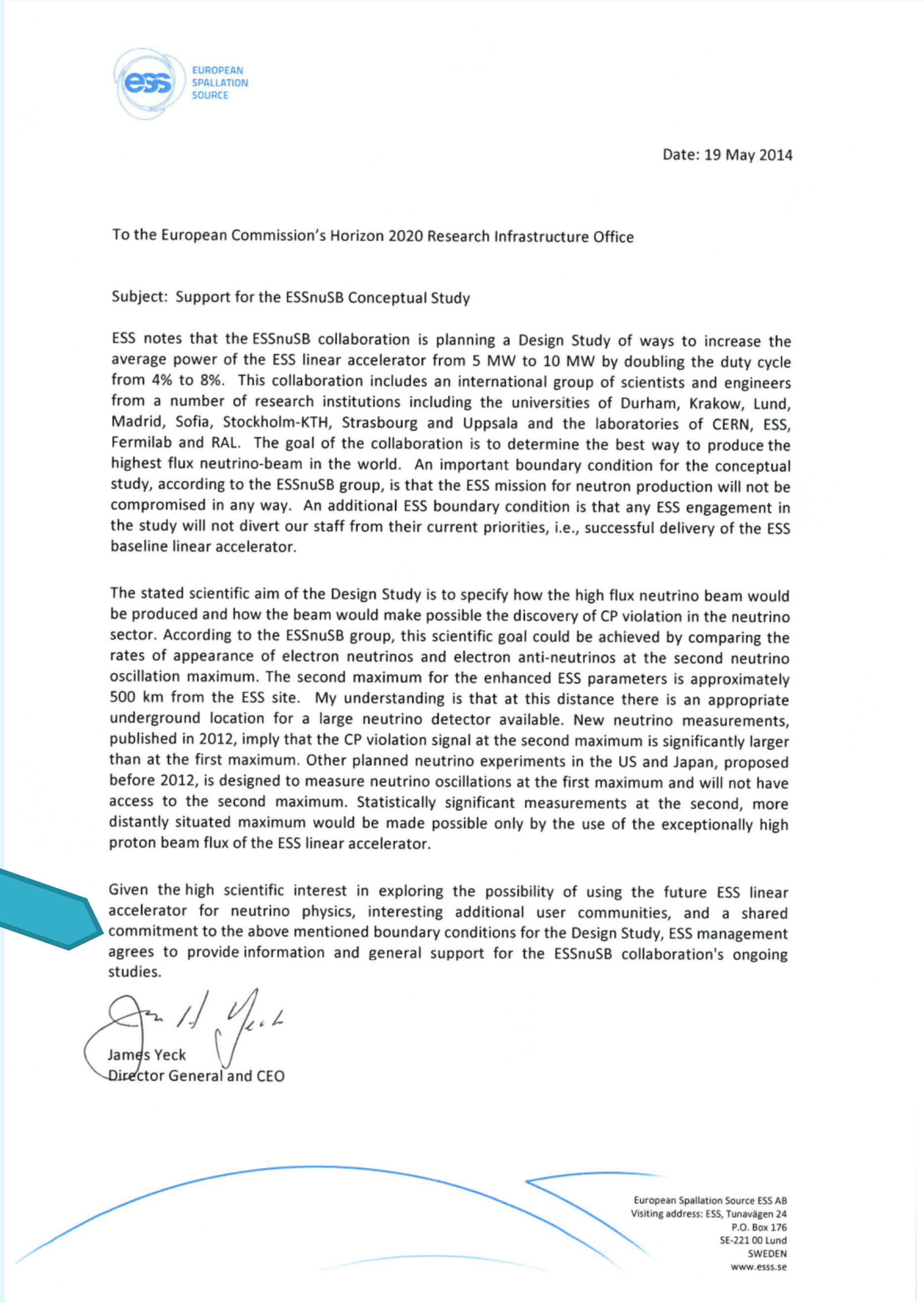
Submitted to European Commission on 2 September 2014
Requested EU funding 1.83 MEUR

List of participants

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Centre National de la Recherche Scientifique	CNRS	France
2	Uppsala University	UU	Sweden
3	European Spallation Source AB	ESS	Sweden
4	European Organisation for Nuclear Research	CERN	IEIO
5	KTH Royal Institute of Technology	KTH	Sweden
6	Universidad Autonoma de Madrid	UAM	Spain
7	AGH University of Science and Technology	AGH	Poland
8	Sofia University St. Kliment Ohridski	UniSofia	Bulgaria
9	Lund University	LU	Sweden
10	University of Durham	UDUR	UK

Letter of support to ESSnuSB by the ESS Management

"Given the high scientific interest in exploring the possibility of using the future ESS linear accelerator for neutrino physics, interesting additional user communities, and a shared commitment to the above mentioned conditions for the Design Study, ESS management agrees to provide information and general support for the ESSnuSB collaboration's ongoing studies."



EUROPEAN
SPALLATION
SOURCE

Date: 19 May 2014

To the European Commission's Horizon 2020 Research Infrastructure Office

Subject: Support for the ESSnuSB Conceptual Study

ESS notes that the ESSnuSB collaboration is planning a Design Study of ways to increase the average power of the ESS linear accelerator from 5 MW to 10 MW by doubling the duty cycle from 4% to 8%. This collaboration includes an international group of scientists and engineers from a number of research institutions including the universities of Durham, Krakow, Lund, Madrid, Sofia, Stockholm-KTH, Strasbourg and Uppsala and the laboratories of CERN, ESS, Fermilab and RAL. The goal of the collaboration is to determine the best way to produce the highest flux neutrino-beam in the world. An important boundary condition for the conceptual study, according to the ESSnuSB group, is that the ESS mission for neutron production will not be compromised in any way. An additional ESS boundary condition is that any ESS engagement in the study will not divert our staff from their current priorities, i.e., successful delivery of the ESS baseline linear accelerator.

The stated scientific aim of the Design Study is to specify how the high flux neutrino beam would be produced and how the beam would make possible the discovery of CP violation in the neutrino sector. According to the ESSnuSB group, this scientific goal could be achieved by comparing the rates of appearance of electron neutrinos and electron anti-neutrinos at the second neutrino oscillation maximum. The second maximum for the enhanced ESS parameters is approximately 500 km from the ESS site. My understanding is that at this distance there is an appropriate underground location for a large neutrino detector available. New neutrino measurements, published in 2012, imply that the CP violation signal at the second maximum is significantly larger than at the first maximum. Other planned neutrino experiments in the US and Japan, proposed before 2012, is designed to measure neutrino oscillations at the first maximum and will not have access to the second maximum. Statistically significant measurements at the second, more distantly situated maximum would be made possible only by the use of the exceptionally high proton beam flux of the ESS linear accelerator.

Given the high scientific interest in exploring the possibility of using the future ESS linear accelerator for neutrino physics, interesting additional user communities, and a shared commitment to the above mentioned boundary conditions for the Design Study, ESS management agrees to provide information and general support for the ESSnuSB collaboration's ongoing studies.

James Yeck
Director General and CEO

European Spallation Source ESS AB
Visiting address: ESS, Tunavägen 24
P.O. Box 176
SE-221 00 Lund
SWEDEN
www.esss.se

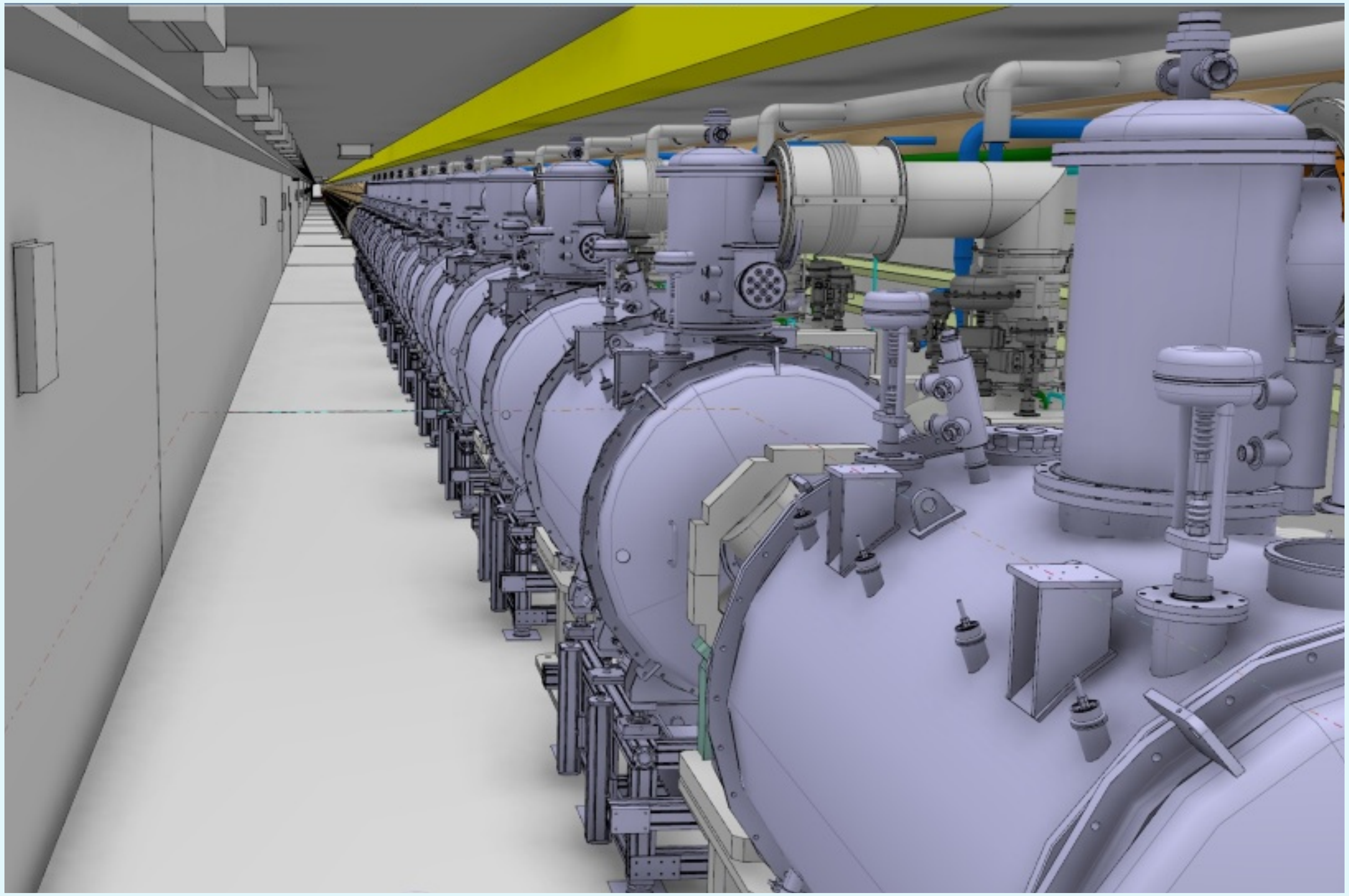
Conclusions

1. The 5 MW ESS linac has started construction this autumn and will be delivering the highest flux of high energy protons in the world, 1.4×10^{16} protons per second, by 2023.

2. By 2025 a number of spallation neutron experiments will be in full operation, taking advantage of the exceptionally high flux of pulsed neutrons.

3. **In addition to spallation neutron experiments, ESS will offer world-unique opportunities to perform Beyond the Standard Model Particle Physics experiments based on high intensity neutron and neutrino beams.**

Thank you



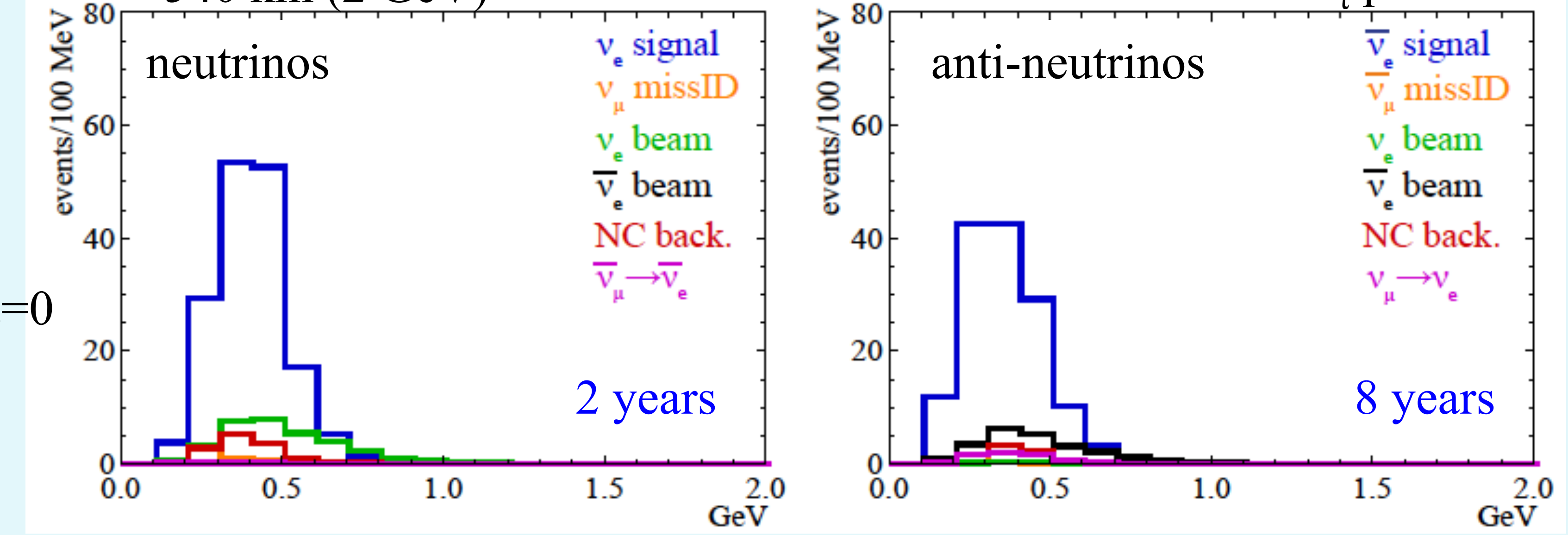
Back-up slides

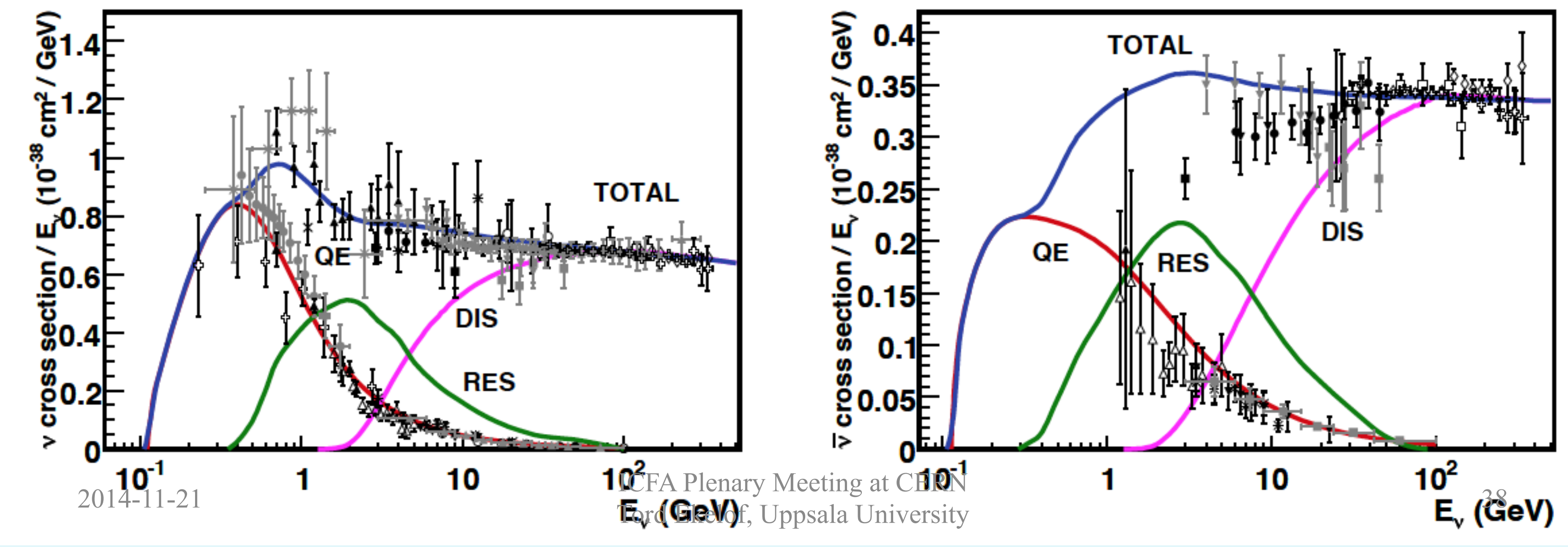
Resulting neutrino energy spectra

540 km (2 GeV)

below ν_τ production

$\delta_{CP}=0$





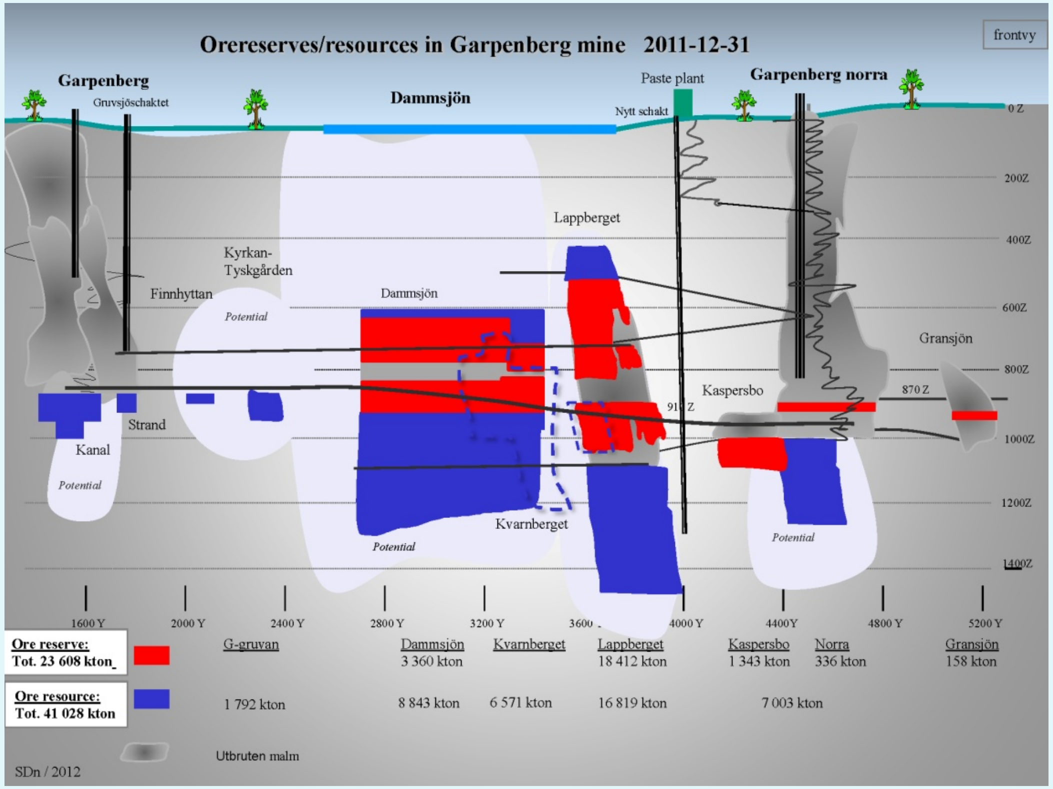
Garpenberg Mine

Distance from ESS Lund **540 km**

Depth 1232 m

Truck access tunnels

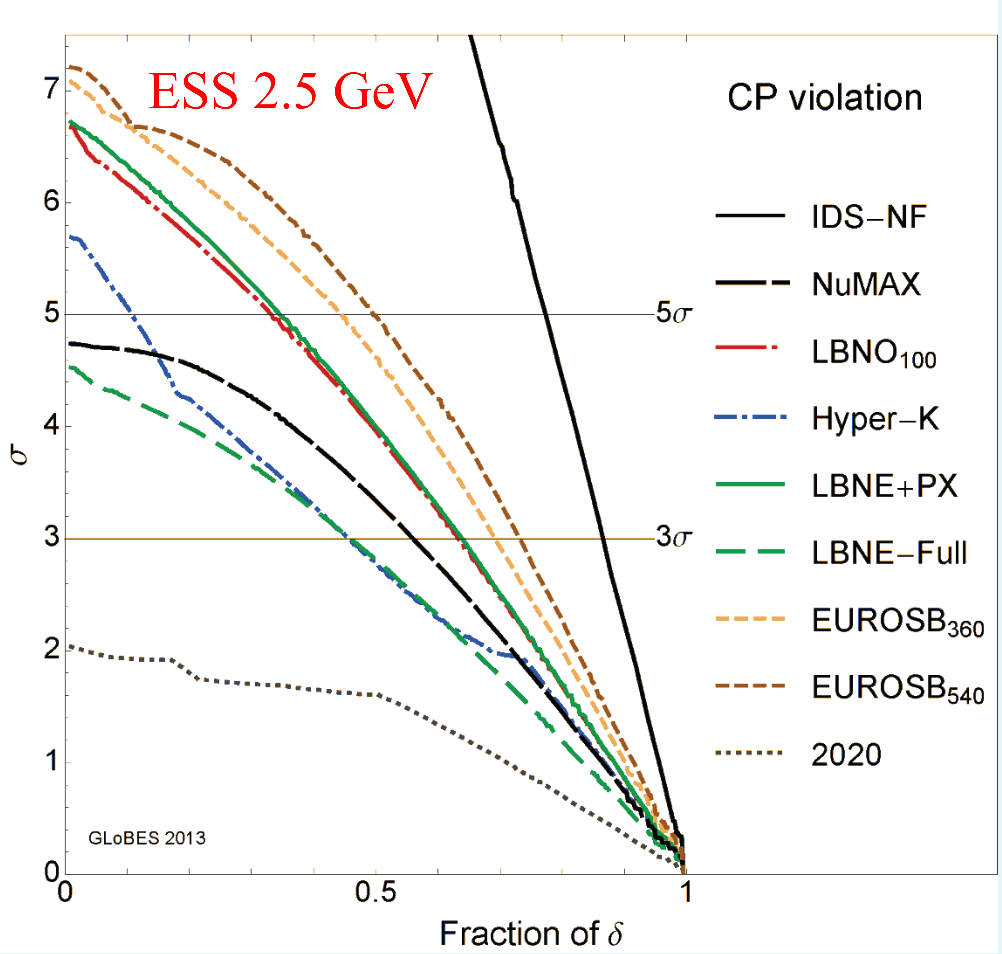
Two ore hoist shafts



A new ore hoist schaft is planned to be ready i 1 year, **leaving the two existing shafts free for other uses**

Granite drill cores

CPV Discovery Performance for Future SB projects, MH unknown, Snowmass comparison

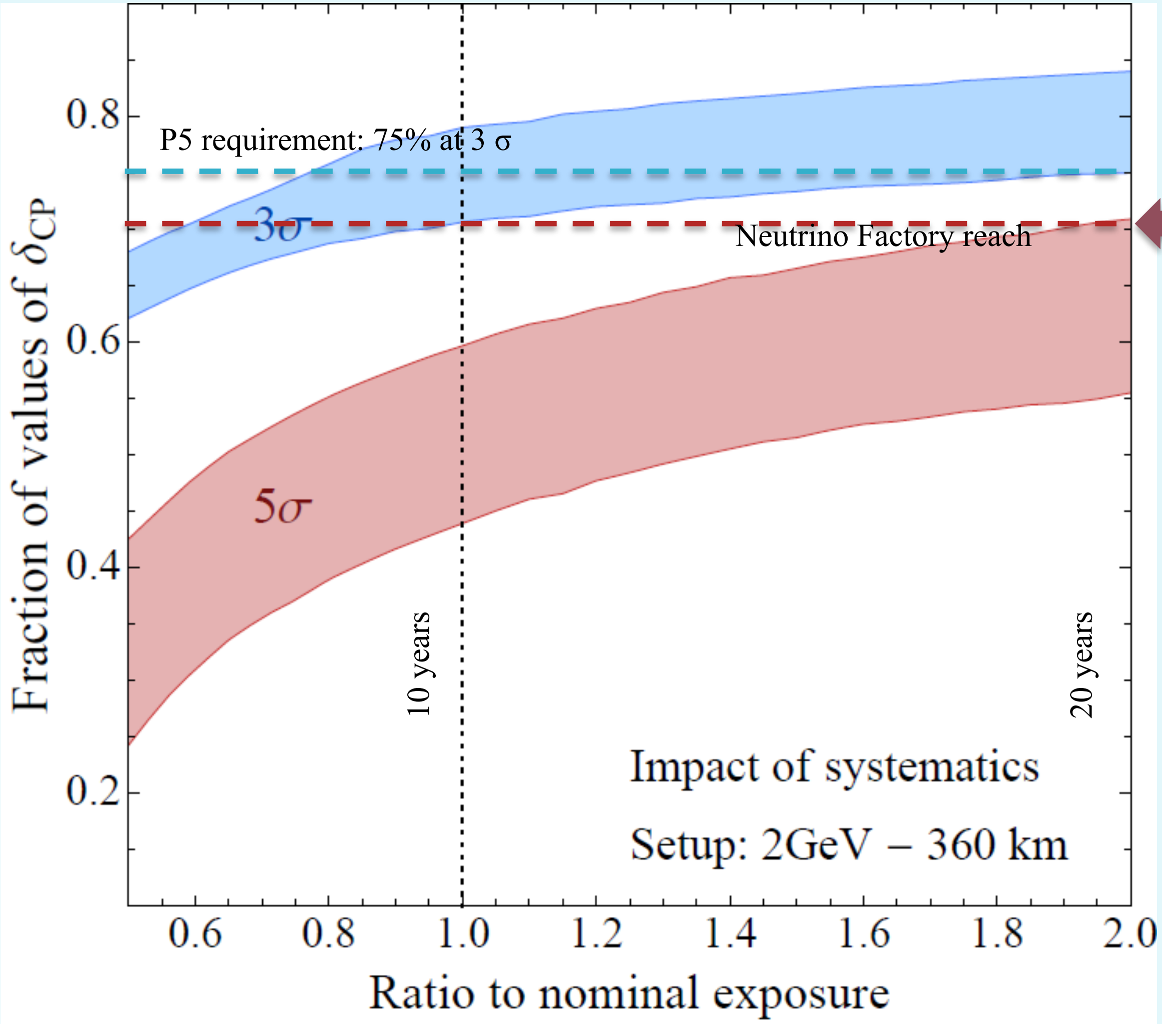


- IDS-NF Neutrino Factory
- NuMAX are: 10 kton magnetized LAr detector, Baseline is 1300 km, and the parent muon energy is 5 GeV
- LBNO100: 100 kt LAr, 0.8 MW, 2300 km
- Hyper-K: 3+7 years, 0.75 MW, 500 kt WC
- LBNE-Full 34 kt, 0.72 MW, 5/5 years ~ 250 MW*kt*yrs.
- LBNE-PX 34 kt, 2.2 MW, 5/5 years ~750 MW*kt*yrs.
- **ESSnuSB, in the figure called EUROSB: 2+8 years, 5 MW, 500 kt WC (2.5 GeV, 360 (upper)/540 km (lower))**
- 2020 currently running experiments by 2020

Pilar Coloma

Systematic errors and exposure

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

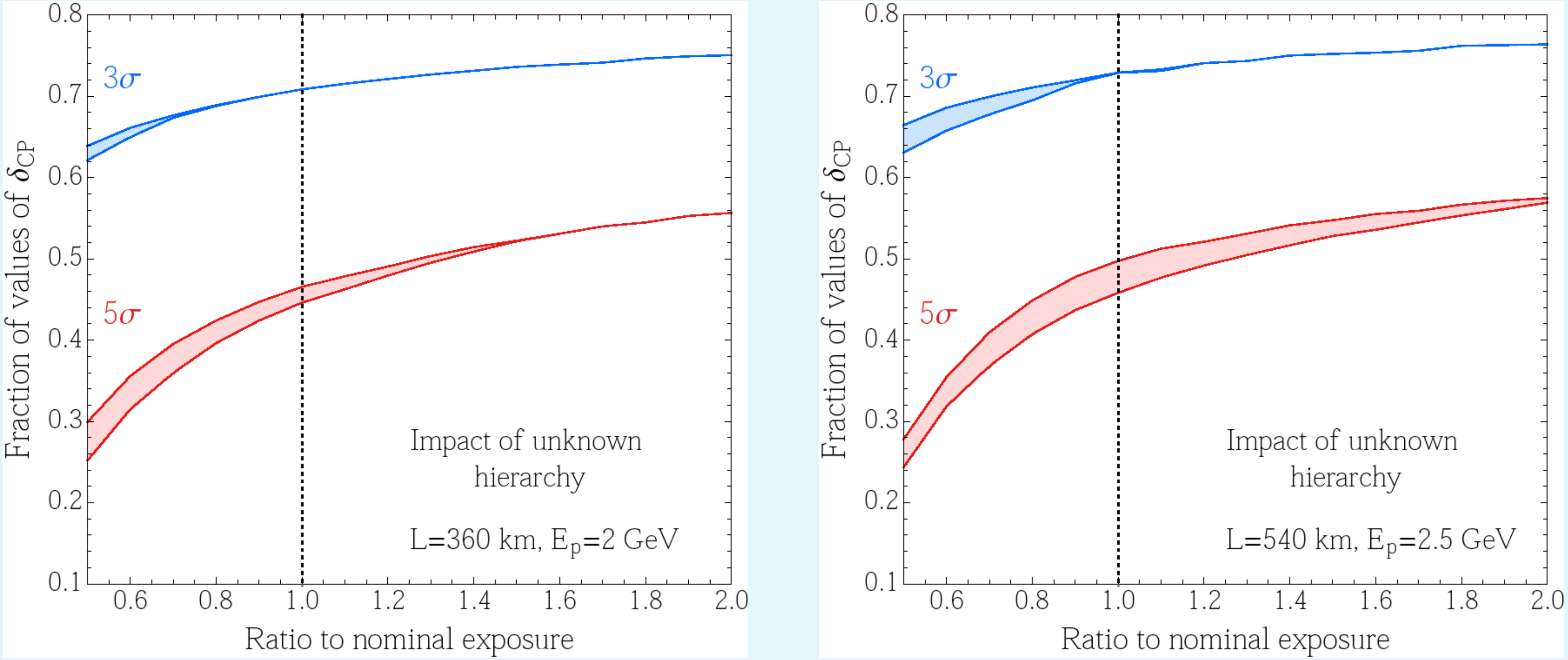


High potentiality

(courtesy P. Coloma)

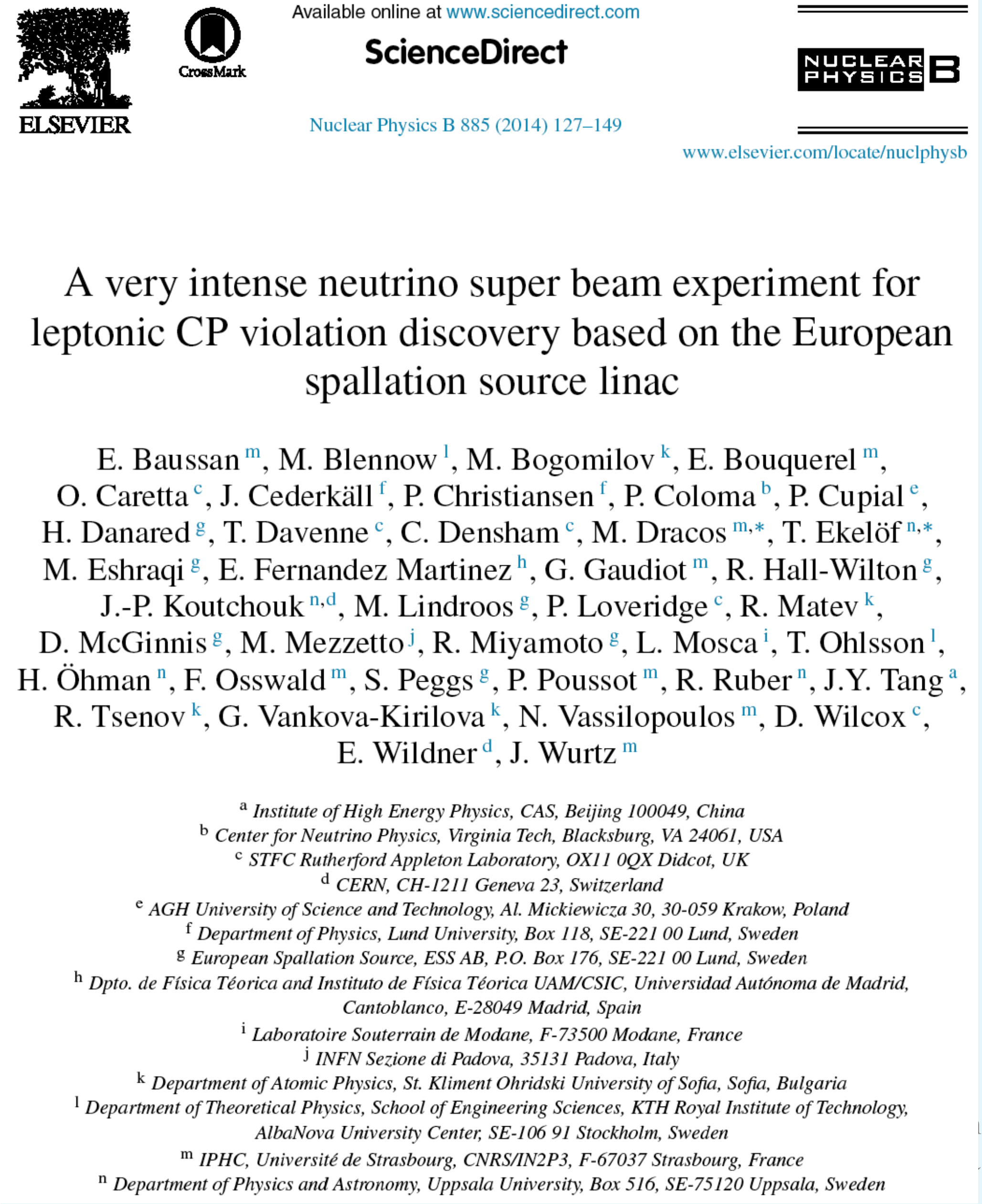
Effect of the unknown MH on CPV performance

"default" case for systematics



➡ small effect ➡ practically no need to re-optimize when MH will be known

ESS Neutrino Super Beam



Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 885 (2014) 127–149

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

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]

[a] *Institute of High Energy Physics, CAS, Beijing 100049, China*
[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*

arXiv:
1212.5048
arXiv:
1309.7022

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

EU H2020 Design Study application to be submitted next week

Distribution of manpower over the six ESSnuSB Design Study Work Packages

Participant no./ short name	WP1 Management	WP2 Linac	WP3 Accumulator	WP4 Target	WP5 Detectors	WP6 Physics	Total Person/ Months per Participant
1/ CNRS FR	**35**	3	30	27	0	0	95
2/ UU SE	3	11	**45**	5	3	0	66
3/ ESS	0	**38**	0	0	0	0	38
4/ CERN	0	2	31	0	2	0	35
5/ KTH SE	0	0	0	0	0	11	11
6/ UAM ES	0	0	0	0	0	**14**	14
7/ AGH PL	0	0	0	**34**	0	0	34
8/ UniSofia BU	0	0	0	0	36	0	36
9/ LU SE	0	0	0	0	**34**	0	34
Total Person/ Months	38	54	106	66	74	27	364

Bold figure for Work Package Lead Institute

Conclusions and summary

We conclude that the ESSnuSB project:

has the best physics potential for CP violation studies, compared to the other Super Beam projects in the world,

has a cost smaller than any of the other proposed projects,

is synergetic with the major new European infrastructure ESS,

is sufficiently advanced in its concept, benefitting from the European EUROnu and Laguna-LBNO design studies and from the ESS studies,

has the support of the ICFA Neutrino Panel Paris meeting for a EU Design Study

has a strong group of 11 institutes that plan to undertake specific, well planned and prepared tasks to bring the project up to a Design Report for which an EU Design Study grant will be a crucial and decisive source of funding,

<u>is</u> coherent with the following conclusion of the 'Expert Group on assessment of the ESFRI Roadmap projects' stated in its report published in December 2013: "ESS indicates that the spallation source will offer opportunities for new science for new user communities. It is advisable to start attracting such communities well before the Operational Stage, inter alia in order to strengthen the case for support by funders",

<u>will</u> create cooperation and synergies between ESFRI projects, i.e. between ESS as an accelerator laboratory and CERN as HEP EU center, and, in future, a possible underground detector project for astroparticle physics as detector site, and can profit from the available experience in major accelerator developments labs in Europe like CERN, CEA & CRNS, DESY, RAL and INFN

<u>has</u>, through its unique feature of providing enough beam power to focus all its statistics at the second maximum and thereby its clear lead for CP violation discovery, the potential to attract collaborators also from the other continents of the world

ESSnSB welcomes new collaborators to join the project.

Answers to the questions asked to ESSnuSB by an international neutrino expert committee

Q1. (Theoretical relevance) What is according to you the theoretical relative urgency of the determination of the

- *neutrino mass hierarchy,*
- *PMNS CP violating phase δ,*
- *θ_{23} octant*
- *existence of sterile neutrinos*
- *Dirac vs Majorana nature of the neutrino*

From a theoretical point of view we se the fundamental questions to be those of the existence of leptonic CP violation, and, if so, the value of the PMNS CP violating phase δ, and the establishment of whether the neutrino is Dirac or Majorana particle.

The establishment of which is the octant of θ_{23} and of the neutrino mass hierarchy can in part be seen as important steps on the way, to which ESSnuSB can contribute, but which are not crucial to ESSnuSB for the CP violation discovery. These measurements will be, if not yet done, a byproduct of the next generation leptonic CP Violation projects.

The existence of sterile neutrinos would, on the one hand, open completely new perspectives but is, on the other hand, a more speculative possibility.

Q1''. Compare, if relevant, to other attempts of measurement direct or indirect (e.g. in cosmology). Describe also synergies with other topics of science e.g. proton decay or neutrino astrophysics (supernova burst and relic, solar neutrinos,…).

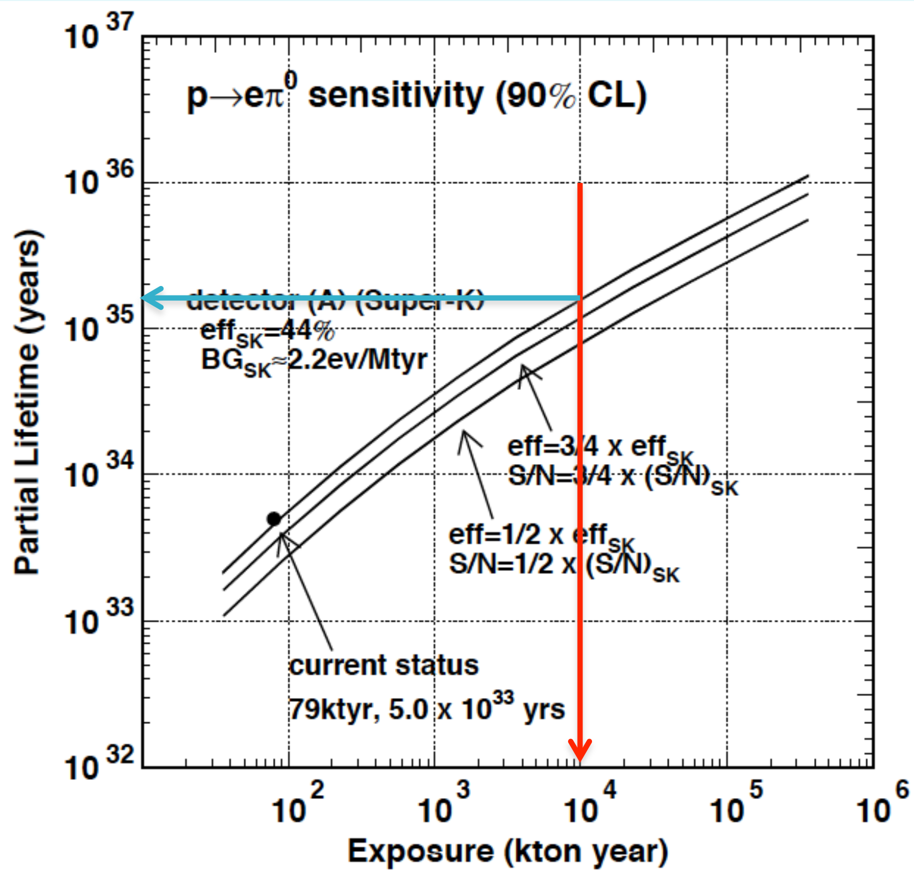
The discovery and measurement of leptonic CP violation can only be made with a neutrino Super Beam experiment.

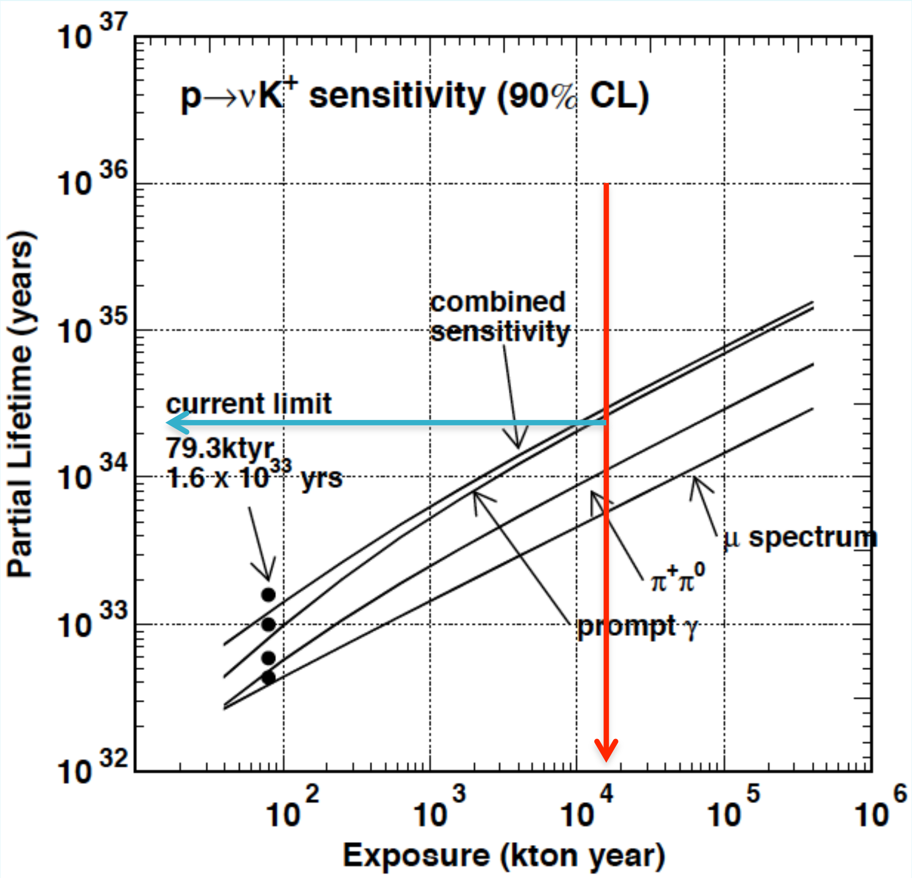
As the ESSnuSB far detector is a Megaton water Cherenkov detector it will, with its huge mass and relatively low energy threshold, have substantial reach for proton life time measurements (10^{35} years) and neutrino astrophysics (10^5 Supernova explosion neutrinos detected, can attempt detection of relic neutrinos, high statistics solar neutrino measurements).

We are currently in contact with APPEC for the planning of the latter measurements.

The MEMPHYS Detector

proton decay

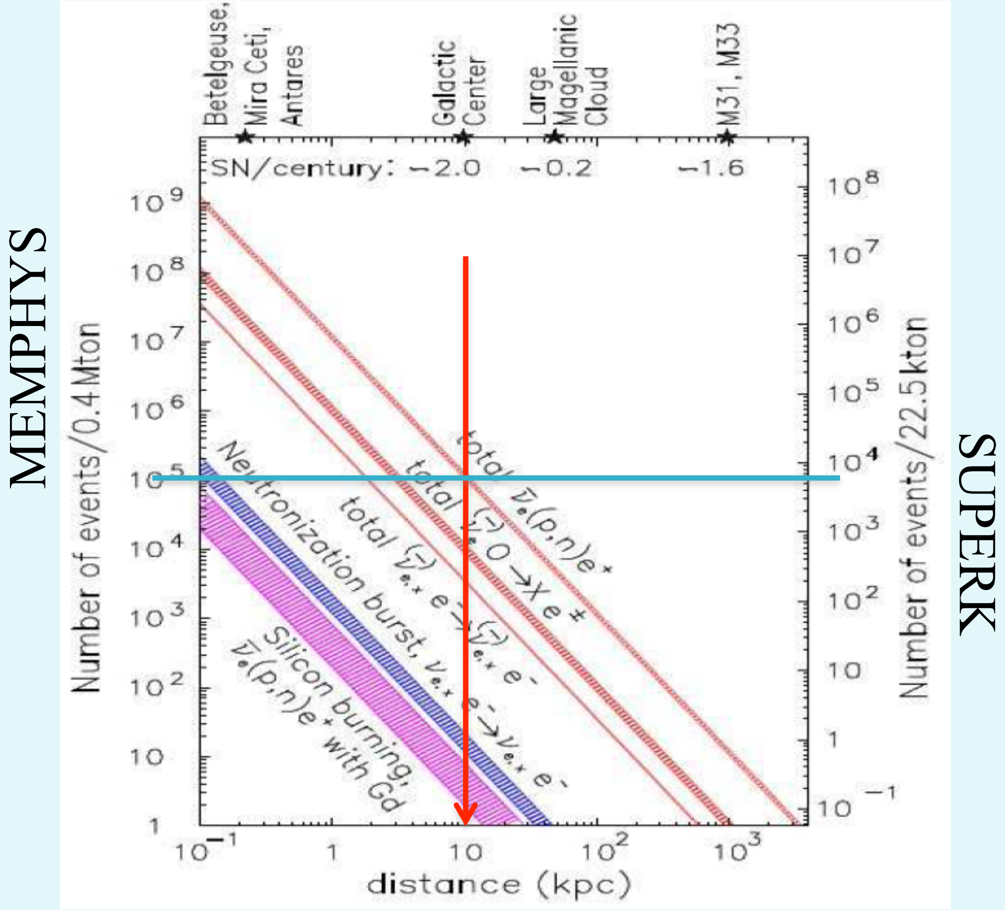


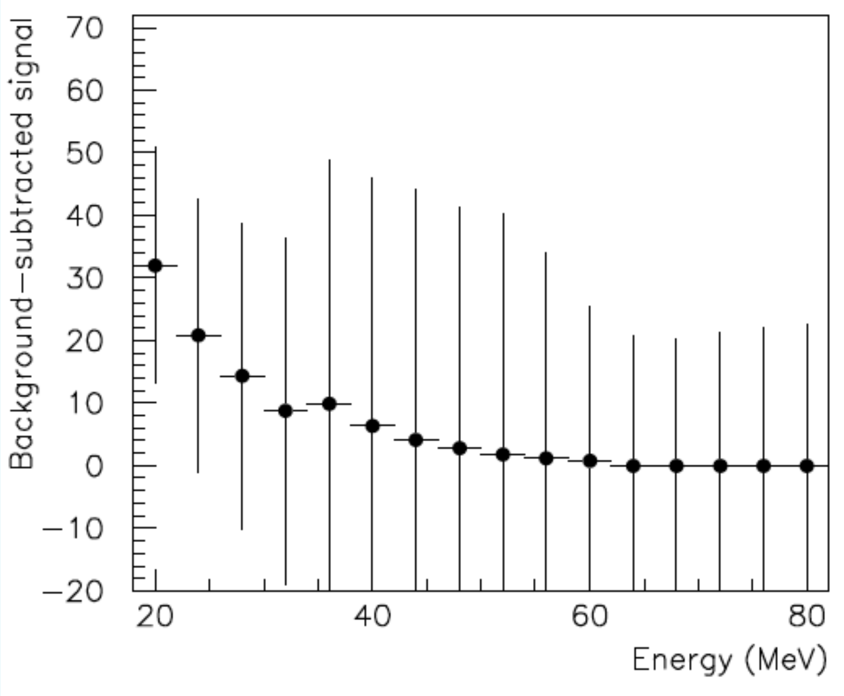


(arXiv: hep-ex/0607026)

The MEMPHYS Detector

Supernova explosion and relics





Diffuse Supernova Neutrinos
(10 years, 440 kt)

For 10 kpc: ~10^5 events

Q2.' (Experimental Strategy) What is according to you the experimental strategy that needs to be deployed worldwide in order to answer the above questions?

There are several non-super-beam experiments that aim at determining the θ_{23} octant and the mass hierarchy and which will probably manage to do so before any of the currently planned super-beam experiments will have collected enough data for such determination.

The fundamental question of leptonic CP violation, on the other hand, can only be answered by a super-beam experiment.

Since it is also, in our view, one of the two most fundamental questions in neutrino physics it should, in our view, be the first priority of a super-beam experiment.

As to the second fundamental question, i.e. the Dirac/Majorana question, only a double-beta-decay experiments can provide the answer.

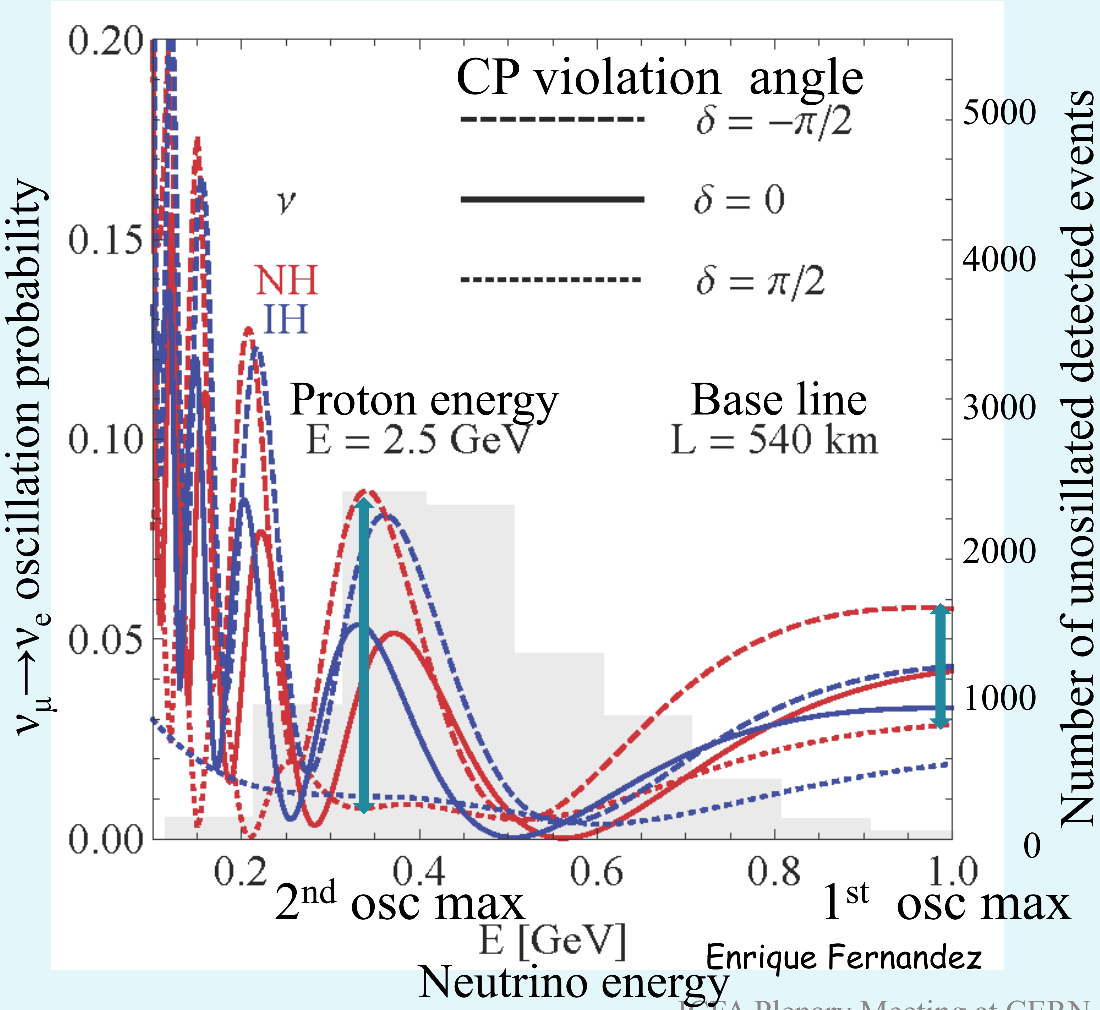
Q2". And in particular, how many experiments should there be worldwide, what complementarities or double check features should they exhibit?

One of the basic requirements for certifying an important discovery is to have confirmation from several experiments, motivating thus at least two neutrino Super Beam experiments.

Another basic requirement when planning experiments for an important discovery is to apply complementarity measurement strategies in order to be sure to attain the goal. LBNE and LBNO propose to use liquid Argon detectors and high energy beams, ESSnuSB and Hyper-K water Cherenkov detectors and low energy beams.

LBNE, LBNO and Hyper-K will all three collect the major part of their statistics at the first oscillation maximum whereas ESSnuSB is the only to collect almost all its statistics at the second maximum, where the CP violating signal is at least 3 times larger that at the first. This is the important complementarity feature of ESSnuSB.

Maximum CP violation sensitivity at the 2nd oscillation maximum



Enrique Fernandez

With the newly measured high value of ca 0.1 for $\sin^2 2\theta_{13}$ the CP angle sensitivity is significantly higher at the second $\nu_\mu \to \nu_e$ oscillation maximum than at the first. **With low energy neutrinos the neutrino detector can be placed at the second oscillation maximum.** *All* other earlier planned experiments have higher neutrino energy and their detector at the first oscillations maximum

Q2'''. In this world-wide context describe the phases of your project, its timeline and the expected statistical significance per phase.

ESSnuSB is currently in its Design Study phase. (It could hardly be in a more advanced phase as its design is based on the discovery of the large value for θ_{13}, published only in spring 2012). The aim is to achieve a Design Report by 2018. This will be possible because of the already extensive experience existing from the operation of the US spallation source SNS (which uses H^- acceleration) and from the water Cherenkov detector designs made for Super-K (in operation), Hyper–K, MEMPHYS and LBNE.

Certain limited modifications need to be made to the ESS linac during its build-up phase which will start in 2018 (first industrial series orders will be placed already in 2017) with a first low power beam by end 2019 and the final full power beam in 2023. The design and construction of the accumulator (to shorten the linac pulses), the target station (divided up on four target/horn assemblies) and the detector cavern, to be followed by the photodetector installation, can start when the Design Report will be ready in 2018.

The construction phase will take about 8 years implying start of data taking in 2026. About the statistics see answer to Q2'''' here below.

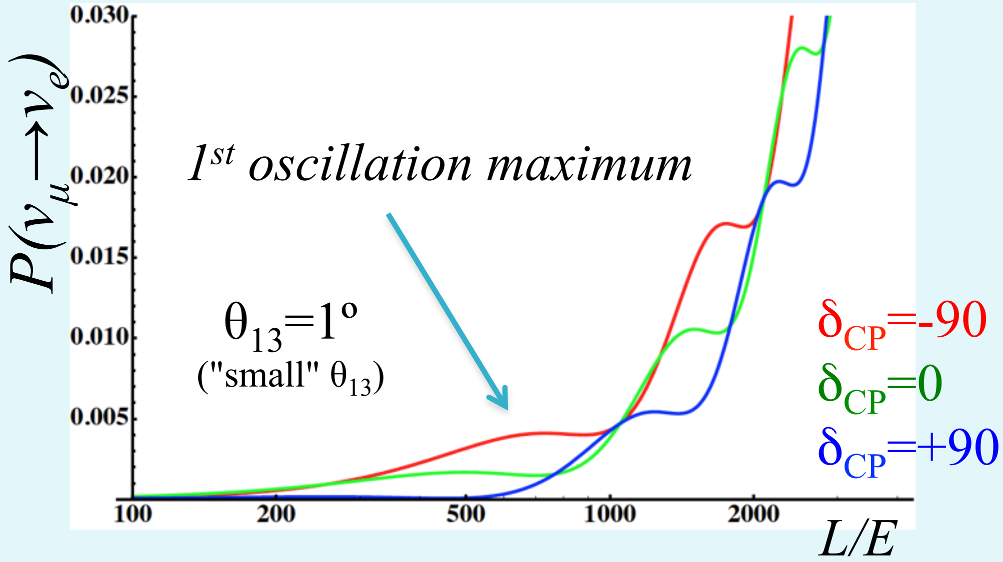
Q2""Discuss the relevant systematics, how well you know them and in particular do you need any supporting measurements to further determine them?

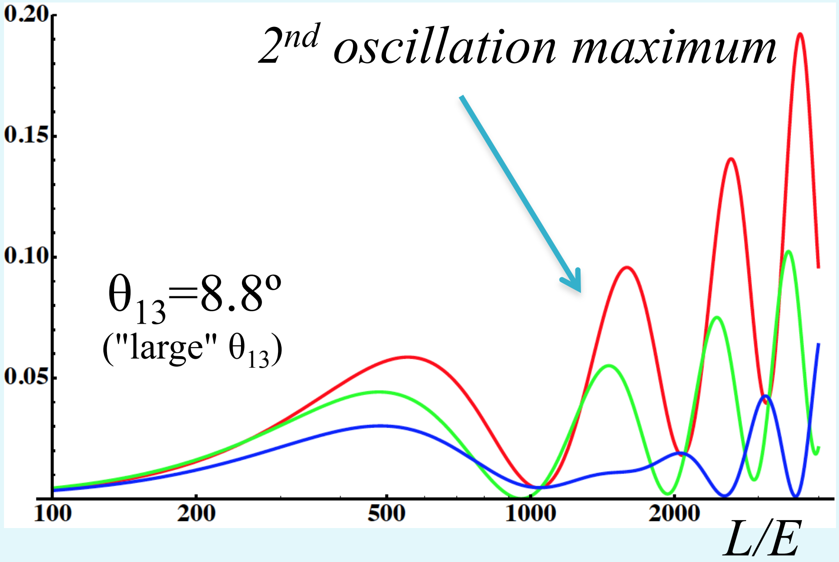
The fundamental distinction of ESSnuSB, when comparing to other proposed super-beam experiments, is that it will collect nearly all its statistics at the second oscillation maximum, where the CP violating signal is at least 3 times larger than at the first. This has radical consequences for its reach for CP discovery.

As the signal is more than 3 times larger than at the first maximum, the requirements on both the systematic and the statistical errors are correspondingly relaxed.

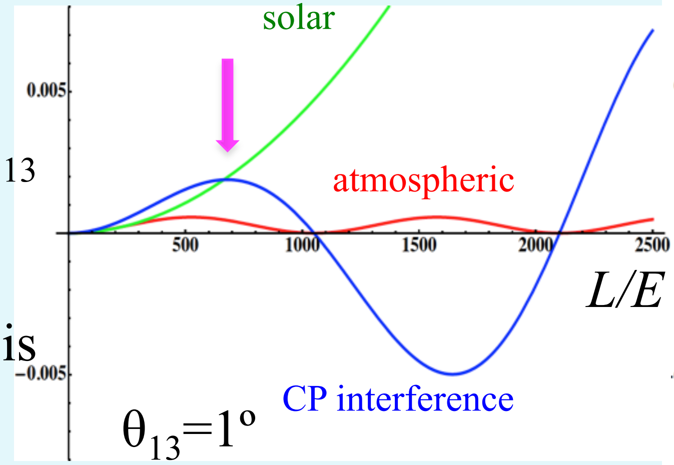
Based on the experience of previous and current neutrino beams and on the feasibility of measuring the electron-neutrino cross-section using the ESSnuSB near detector, we can plan to obtain 5% signal systematic error and 10% background systematic error.

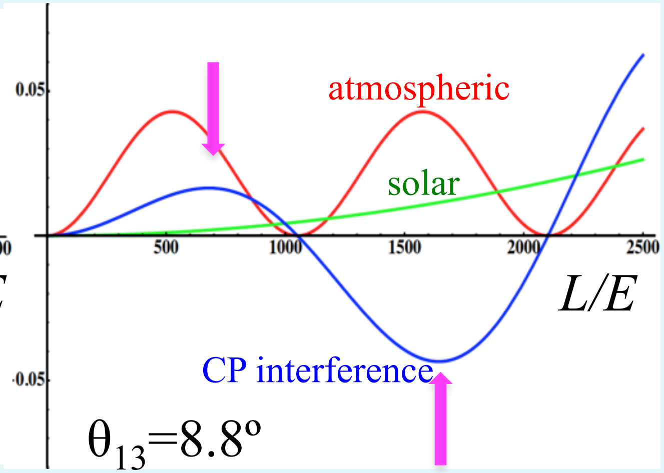
Neutrino Oscillations with "large" θ_{13}





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





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

(arXiv:1110.4583)

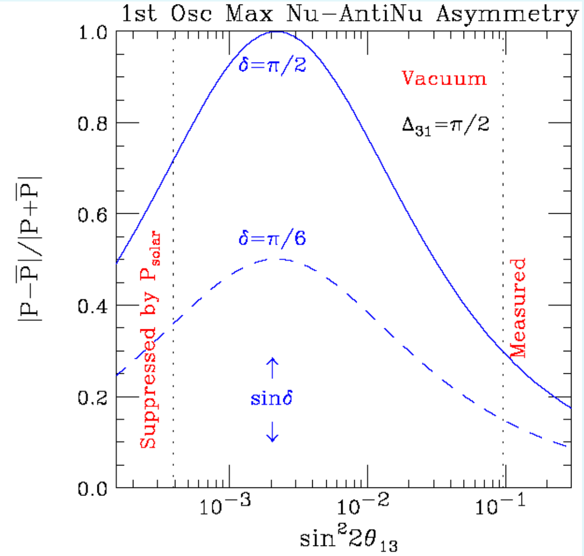
2^{nd} oscillation maximum is better (less affected by systematic errors)

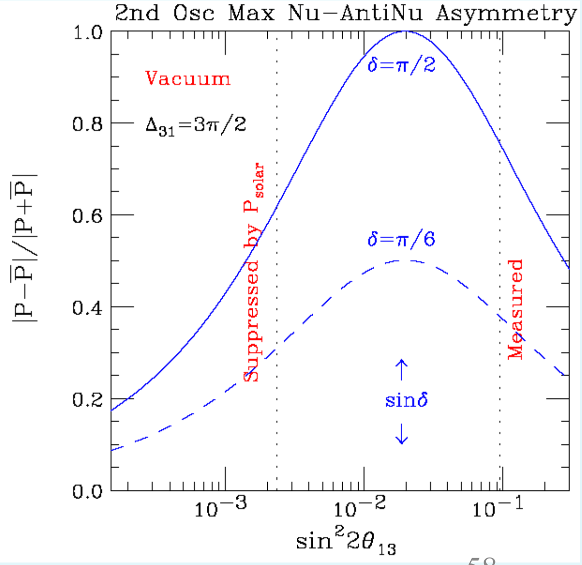
From Stephen Parke/ FNAL; “Neutrinos: Theory and Phenomenology”; arXiv:1310.5992v1 [hep-ph] 22 Oct2013, page 12;

“At the **first oscillation maximum** (OM), as is in the running experiments, T2K and NOνA and possible future experiments HyperK and LBNE experiments, the vacuum asymmetry is given by
$A \sim 0.30 * \sin\delta$ at $\Delta_{31}=\pi/2$
which implies that **$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is between 1/2 and 2 times $P(\nu_\mu \to \nu_e)$.**

Whereas at the **second oscillation maximum**, the vacuum asymmetry is
$A \sim 0.75 * \sin\delta$ at $\Delta_{31}=3\pi/2$
which implies **that $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is between 1/7 and 7 times $P(\nu_\mu \to \nu_e)$.**

So that experiments at the second oscillation maximum, like ESSnuSB [15], have a significantly larger divergence between the neutrino and anti-neutrino channels.”



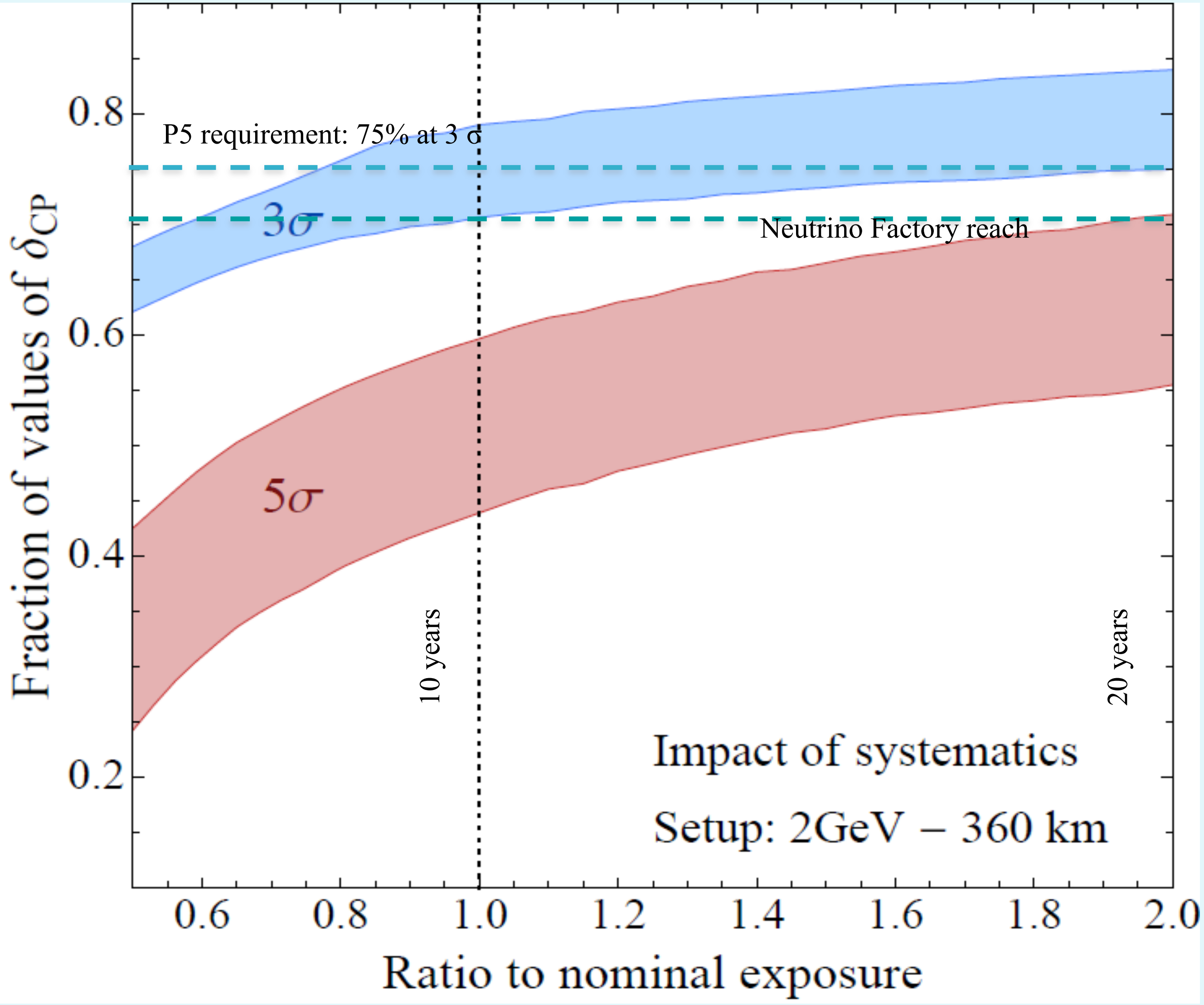


To balance the statistic error with the systematic we only need of order 400 events. At the second maximum, three times more distant than the first maximum, such event statistics can only be obtained using an exceptionally powerful proton driver.

The next slide shows the interplay between statistics (“exposure”) and the coverage of the CP-phase-angular range for 5 sigma discovery (upper bound curves), implying 60% coverage after 10 years and 72% coverage after 20 years.

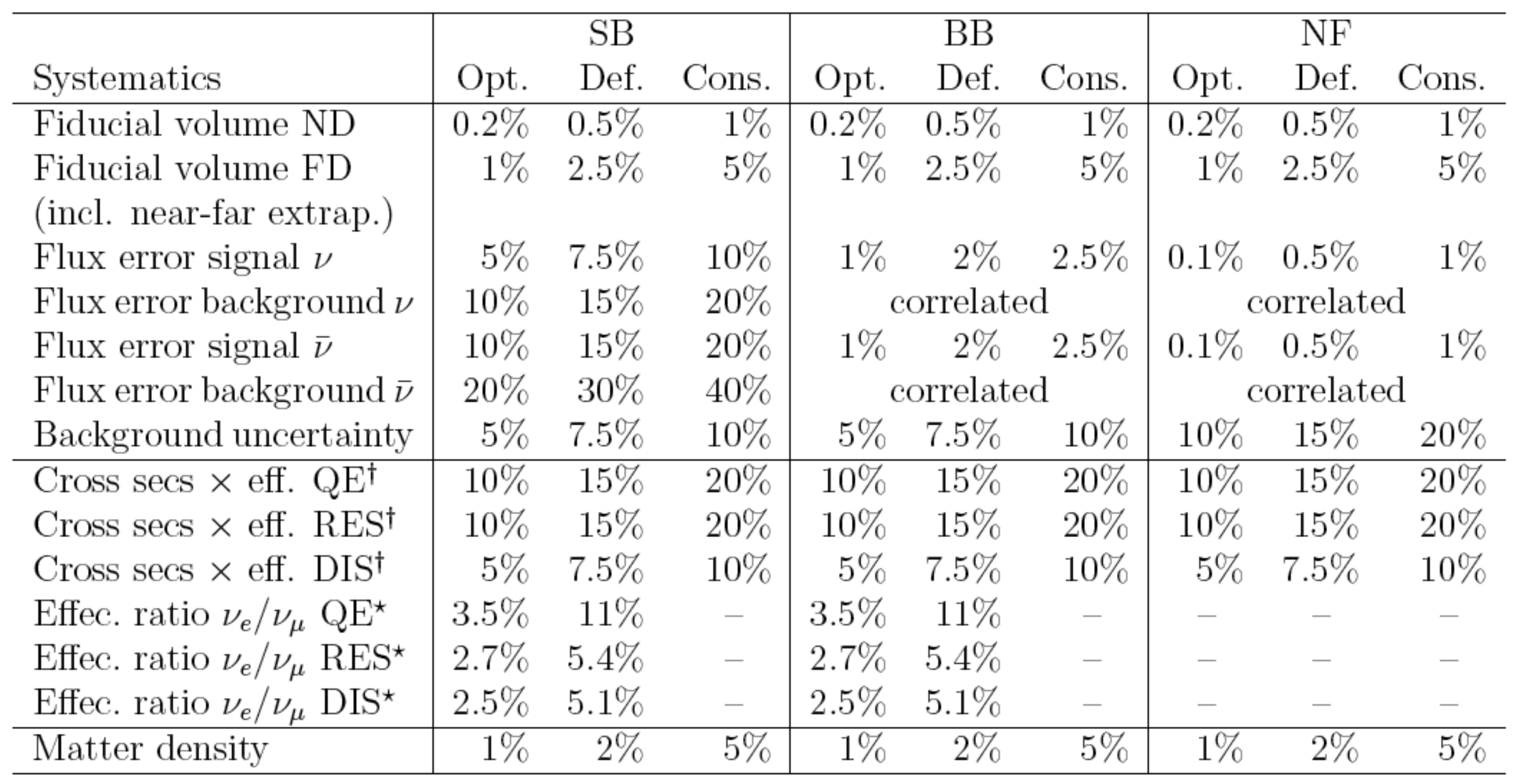
The robustness of the CP violation discovery potential is demonstrated by the fact that even under the assumption of as large systematic errors as 10% on the signal and 15% on the background (the lower bound curves), a 25%/ 42%/ 55% coverage with five sigma discovery potential will be attained after 5 years/ 10 years/ 20 years.

This also indicates that after the first few years, before that all systematic uncertainties have been reliably determined, there is a non-negligibel discovery potential for CP violation. One may also conclude that running ESSnuSB for 20 year, we will reach the same performance for CP violation discovery as the Neutrino Factory.


P5 requirement: 75% at 3 σ
Neutrino Factory reach
3σ
5σ
10 years
20 years
Impact of systematics
Setup: 2GeV – 360 km
Fraction of values of δ_{CP}
Ratio to nominal exposure
0.2
0.4
0.6
0.8
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Systematic errors

Pilar Coloma et al arXiv:1209.5973



	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	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%

Q3'. (Experimental readiness) Evaluate the readiness of the technology you are planning to use. Describe the phases (or R&D) towards its final validation.

The readiness of ESSnuSB is foremost determined by the design and construction of the neutrino beam.

The neutrino detector technology, even for the near detector, is sufficiently mature to start build-up of the far and near detectors by the time the far-detector cavern has been constructed.

There have also been studies for several different underground sites (Kamioka, Pyhäsalmi, Frejus) made for how to excavate and secure a Megata-ton detector cavern.

Investigation of the specific geological properties at the planned location in Garpenberg, Sweden has already started with promising results.As the rock foreseen for the cavern is stable and strong granite, much of earlier cavern design studies are of use in the design of the cavern.

The readiness of ESSnuSB is thus determined by the requirements for the design and construction of the neutrino ESS beam.

We are currently preparing a fund request to EU for a ESSnuSB Design Study. This Study will focus on the required upgrade of the linac power from 5 to 10 MW, on the design of the combiner ring needed to shorten the 3 ms long ESS linac pulses and on the target station – we plan to use four target/horn assemblies in parallel so each will receive a 1.25 MW beam .

We already have support from ESS and CERN accelerator division staff to study these challenging tasks. Tomorrow and the day after (24-25 June) a team of two CERN accelerator specialists will visit ESS in Lund to work out, in collaboration with ESS accelerator staff, the required modifications to the current base-line ESS linac design to enable 10 MW operation for concurrent neutron and neutrino production.

Program for the visit 24-25 June 2014 of Eric Montesinos and Frank Gerigk of CERN to ESS in Lund

Tuesday June 24
0900-1000: Overview - D. McGinnis, S. Molloy
1000-1100: Beam Physics M. Eshraqi, R. Miyamoto
1100-1200: Front-End - E. Sargsyan, A. Ponton,
1300-1400: Modulators - C Martins
1530-1630: Civil Construction - G. Lanfranco, K. Svendin
1830-2359: Dinner - Pizza, Wine, Beer - Everybody

Wednesday June 25
0900-1000: Power Distribution - F. Jensen
1000-1100: Water Systems - J. Jurns
1100-1200: Cryogenics - X. Wang, P. Arnold
1300-1400: Cryomodules - C. Darve
1400-1500: RF - A. Sunesson, M. Jensen, R Yogi
1500-1600: Wrapup - D. McGinnis, S. Mollo

Q3"What are the risks associated.

There are some design risks associated with the high power of the neutrino beam required to reach the second oscillation maximum.

The power upgrade of the linac using a H^- beam (needed for injection in the accumulator ring) should not entail more than 1 W/m beam loss in the linac (to limit activation by irradiation). The beam loss for the current 5 MW proton linac design is for 0.1 W/m and experience from SNS shows that with H^- there may be an increase by a factor up to 10, which is thus still tolerable.

For the accumulator ring the stripping of the 5 MW H^- beam using foils or a laser techniques need detailed studies – our current Monte Carlo investigation of foil stripping indicates that we can stay below 1200 K temperature with "painting" of the beam on the foil.

Q3'''. Is there place for global sharing and coordination of the R&D or validation effort?

There is ample, not only place but also need, for global sharing and coordination of the R&D and validation effort.

We already have the collaboration of ESS, CERN and 9 European Universities. As to validation of our project the European Steering Group for Accelerator R&D ESGARD and the ICFA Neutrino Panel are playing an important role.

We welcome new collaborators, in particular also from outside Europe, to share the R&D effort and new external bodies for the validation effort.

Q3''''Are there industrial issues e.g. in procurement?

For the accelerator upgrade the additional devices required should not have neither technical, nor procurement capacity problems. The supply of photo-detectors could have some procurement capacity problems if both Hyper-K and ESSnuSB would order at about the same point in time.

Q4. (Site issues) What are the optimisation criteria for the site you propose? What is the regional support for the site you propose? Is your proposal site specific? Could the same or better performances be obtained in another site in the same continent or some other region?

The optimisation criterion for the accelerator site is that it should house the most intense proton driver in the world in order to make measurements at the second oscillation maximum feasible, thereby significantly decreasing the uncertainty in the prediction of systematic measurement errors. The linear accelerator of ESS with 10 MW, of which 5 MW for neutrinos, will be the worlds most intense pulsed proton source for neutrinos.

To attain a 5 MW proton beam for neutrino production with the Fermilab or Tokai accelerators will most probably not be possible, because these accelerator are circular and therefore substantially more subjected to space charge limitations than a linear accelerator.

As the ESS linac cannot reasonably be moved the ESSnuSB proposal is accelerator site specific.

We have received a letter of support from the ESS AB CEO Jim Yeck.

The optimisation criterion for the far detector site is that that it should be located at the second oscillation maximum (around 400-500 km base line for the ESS 350 MeV neutrino beam) and that there should be a ~1 km deep mine there.

There are several different candidate sites for the far ESSnuSB detector possible, among those the Garpenberg (540 km from ESS) and the Zinkgruvan (370 km) mines in Sweden and the Kongsberg (480 km) mine in Norway.

It has so far not been possible to show that mines at approximately the right distance in Poland and Germany fulfil the geological requirements for excavation and detector operation (rock strength, ambient temperature…).

Currently the Garpenberg mine is being investigated in detail as it presents the advantage of having a shaft and rock hoist that will become free for crushing and transportation to the ground level of the ESSnuSB excavation rock debris.

There are Swedish groups at the universities in Lund, Stockholm, KTH and Uppsala forming part of the ESSnuSB Collaboration.

We have had several contacts with the Garpenberg mine management who support our investigation of Garpenberg as detector site

Q5'. (Financial and internationalisation issues) What is the cost of the experimental configuration (beam where relevant and detector)?

As the Design Report will be finished only in 2018 it is difficult to make a precise cost estimate now.

An estimate of 700 MEUR has been made for the detector and its cavern, compatible with the Hyper-K detector and MEMPHIS cost estimates. Our first cost estimate for the accelerator upgrade, the accumulator and the target area is 100 MEUR, 200 MEUR and 200 MEUR, respectively, summing up to a total construction cost of 1200 MEUR. In view of the interest among the ESS neutron users to have also short neutron pulses, there is the prospect of sharing the cost for the accumulator with the neutron community.

Q5". What is your financial plan? What is the current level of international participation and what level of participation would be necessary to move to a construction decision? What models would you propose for international participation and at which parts of the beam or detectors? What would be the parts of the configuration whose leadership you would be willing to negotiate in exchange of international participation ?

We currently have about 30 collaborators from 11 different institutions in Europe. We have been designing ESSnuSB during the 2 years since 2012, when the high value of θ_{13} was discovered, and are currently continuously welcoming new members. We obviously need to welcome many more collaborators, in particular also from outside Europe.

We are continuously informing the ICFA Neutrino Panel, the European Steering Group for Accelerator R&D (ESGARD), the Swedish government, the ESS and CERN Managements, the Garpenberg Mine management, APPEC and the EU Research Directorate about the evolution of our project plans. By 2018, when first funding acquisitions need to start on the basis of the Design Report, we need to be of the order of 200 collaborators from 30-40 institutions in several continents. Collaboration will be both on the accelerator and on the detector side.

ESSnuSB is driven primarily by scientific (not regional) interest and we are therefore ready to negotiate leadership of any part of the project in exchange of international participation.