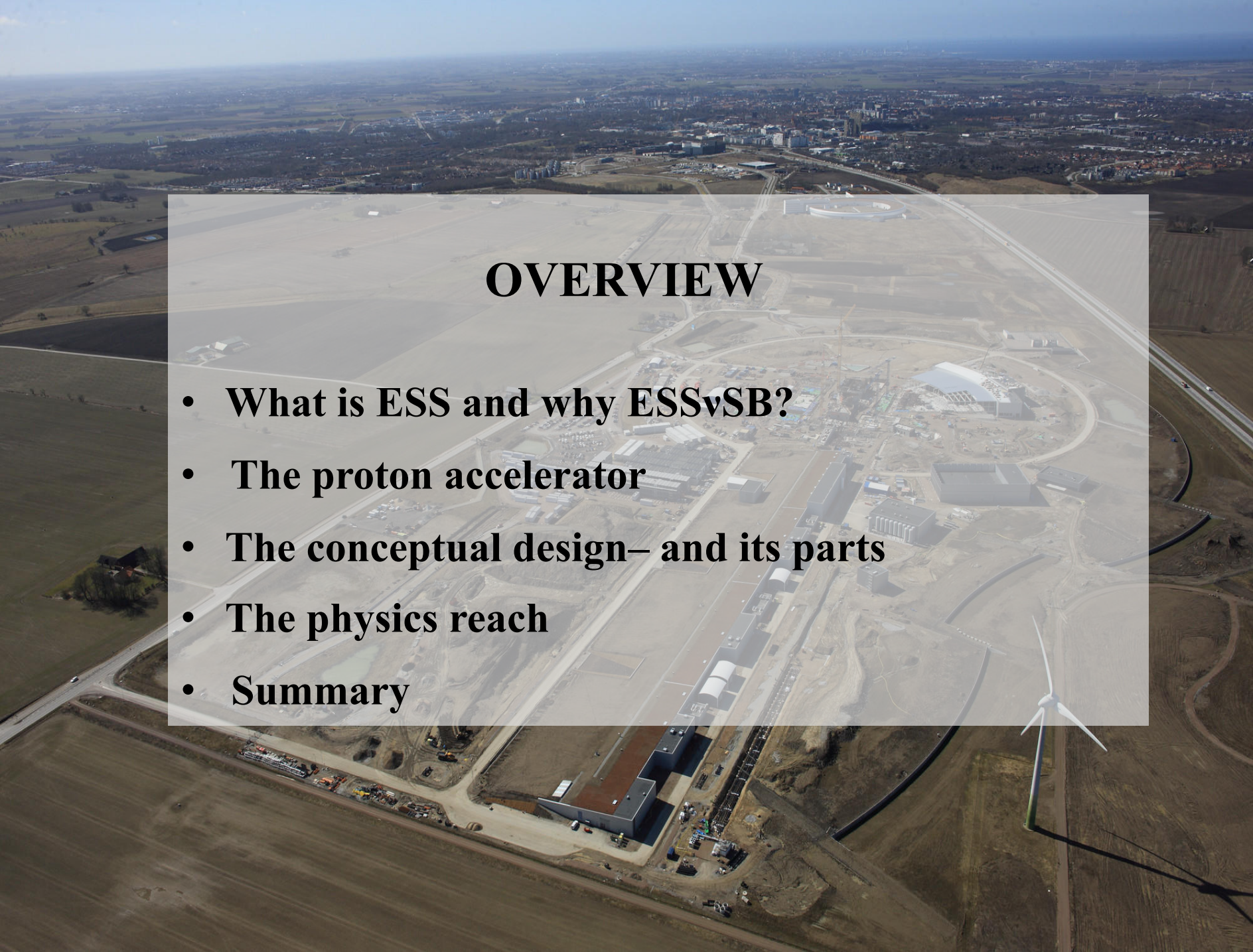
ESSνSB – and δ_{cp}

J. Cederkall with the ESSνSB collaboration

Special credit to: Marcos Dracos, IPHC, Tord Ekelöf, Uppsala university and many colleagues in ESSνSB.

Funded by the Horizon 2020 Framework Programme of the European Union

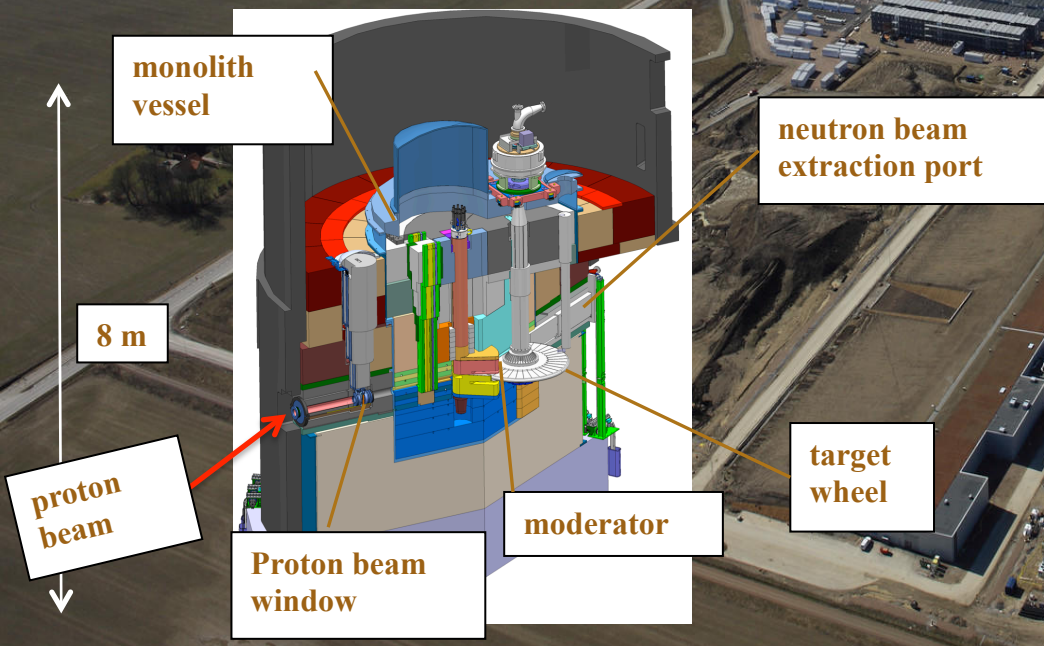


OVERVIEW

- What is ESS and why ESSνSB?
- The proton accelerator
- The conceptual design– and its parts
- The physics reach
- Summary

ESS basic facts:

- Proton accelerator with superconducting cavities
- 2 GeV energy and 5 MW on target
- 4000 kg, ~2.5 m diameter, tungsten target wheel
- 6,000 000 kg steel shielding



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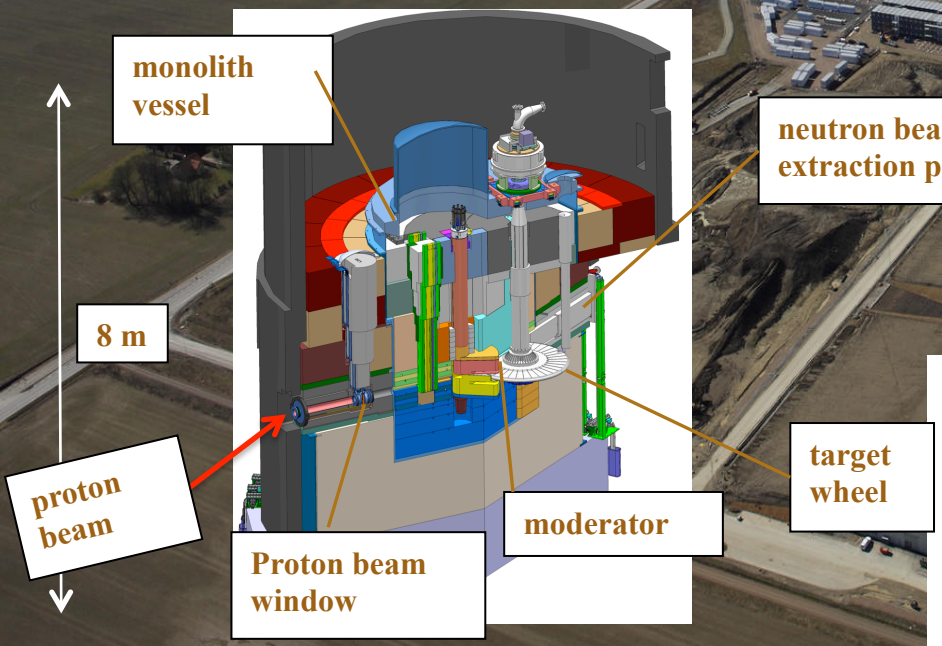

Plan and use:

Main use is for applied physics,
but fundamental physics can be done.

Linac completion by ~2023

ESS basic facts:

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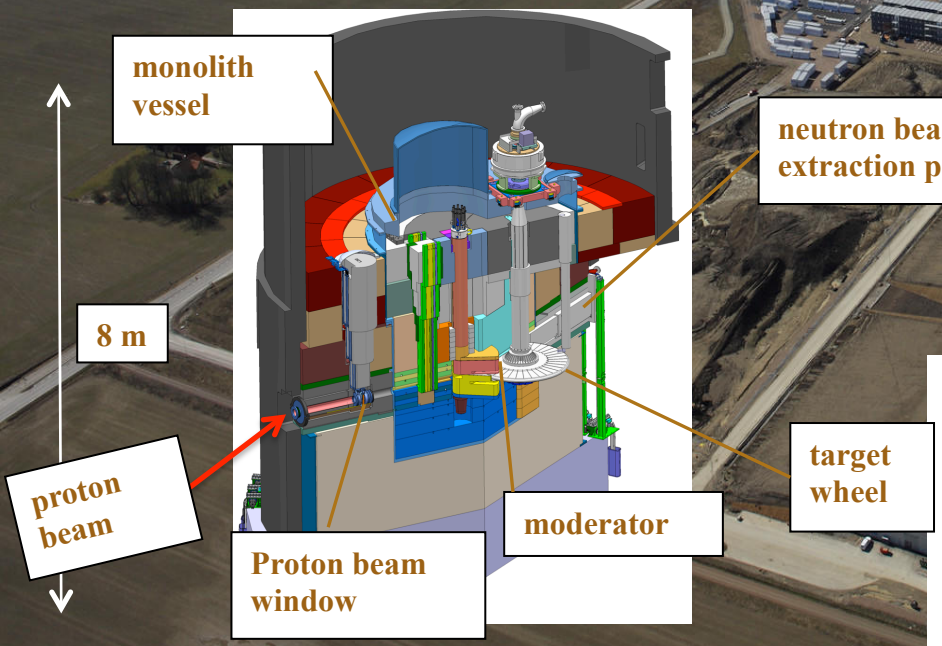

Plan and use:

Main use is for applied physics
(but fundamental physics can be done)

Linac completion by ~2023

Why and how to make it?

Why?

- Physics reach

Practicalities:

- LINAC upgrade
- Accumulator
- Target station
- Near detector
- Far detector

Matter – antimatter asymmetry

- **The Sakharov conditions: needs to be fulfilled to explain the baryon asymmetry in the universe,**

  - At least one B-number violating process
  - C and CP violation
  - Interactions outside thermal equilibrium

- **Currently the observed baryon to photon ratio is much too large (factor ~10^9) to be explained by CP violation of the quarks (the CKM matrix).**

- **Lepton sector CP-violation an option to create asymmetry via leptogenesis scenarios with sphalerons**

- **Otherwise, new physics…?**

Oscillation Probabilities – time evolution

$$
\begin{aligned}
P^{\pm}(\nu_\mu \to \nu_e) &= s_{23}^2 \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) && \text{(atmospheric)} \\
&+ c_{23}^2 \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) && \text{(solar)} \\
&+ J' \cos(\mp\delta_{CP} - \Delta_{31}) && \text{(CP interference)}
\end{aligned}
$$

Where

$$
\begin{aligned}
J' &= c_{13} \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \\
&\times \sin(\Delta_{31}) \sin(\Delta_{21}) \\
\Delta_{ij} &\equiv \frac{\Delta m_{ij}^2 L}{4E} \qquad s_{ij} = \sin\theta_{ij} \\
\Delta m_{ij}^2 &= m_i^2 - m_j^2 \qquad c_{ij} = \cos\theta_{ij}
\end{aligned}
$$

$$
\begin{aligned}
A_{CP} &\equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \\
&\simeq \frac{\cos\theta_{23} \sin(2\theta_{12}) \sin\delta}{\sin\theta_{23} \sin\theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects}
\end{aligned}
$$

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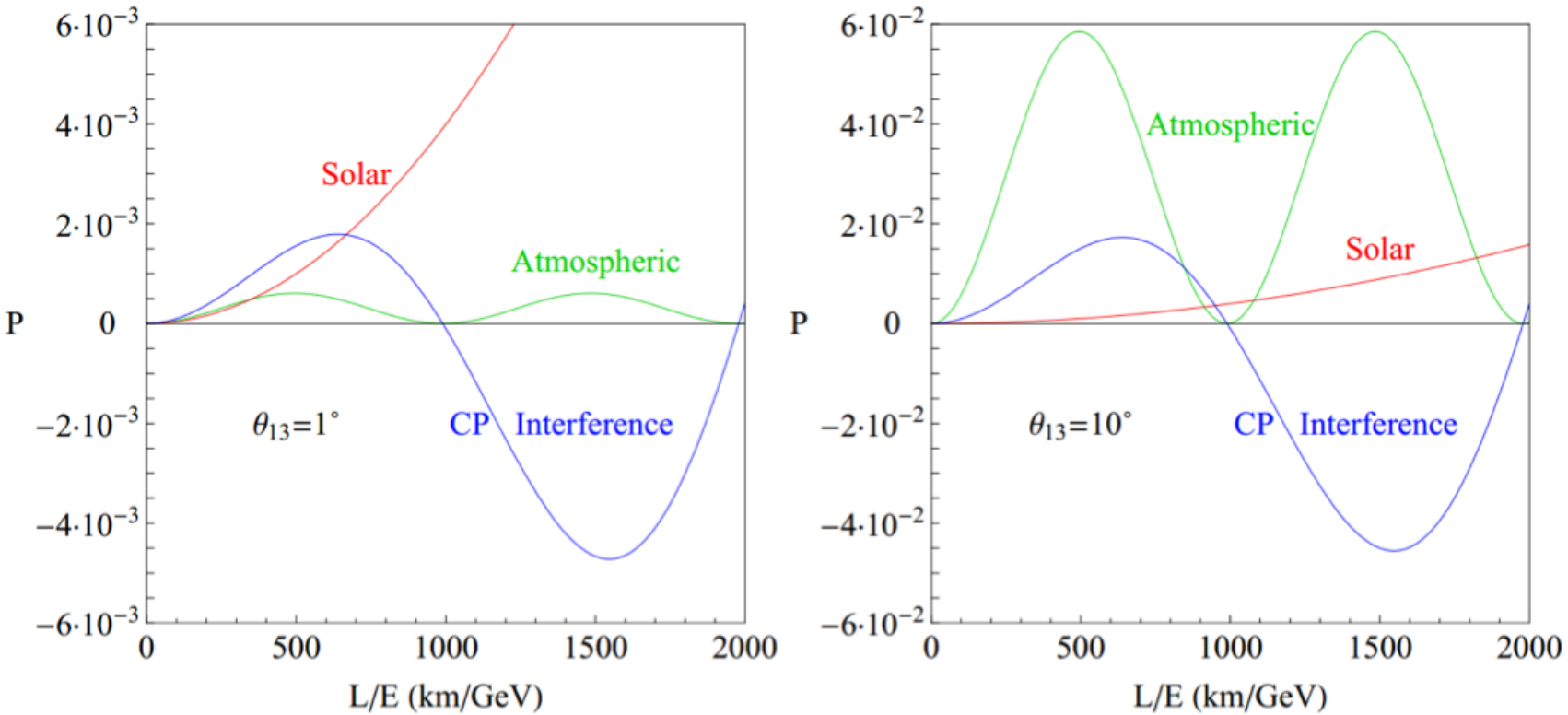
P – separated in its terms



$$\theta_{13} = (8.9 \pm 0.4)^\circ$$

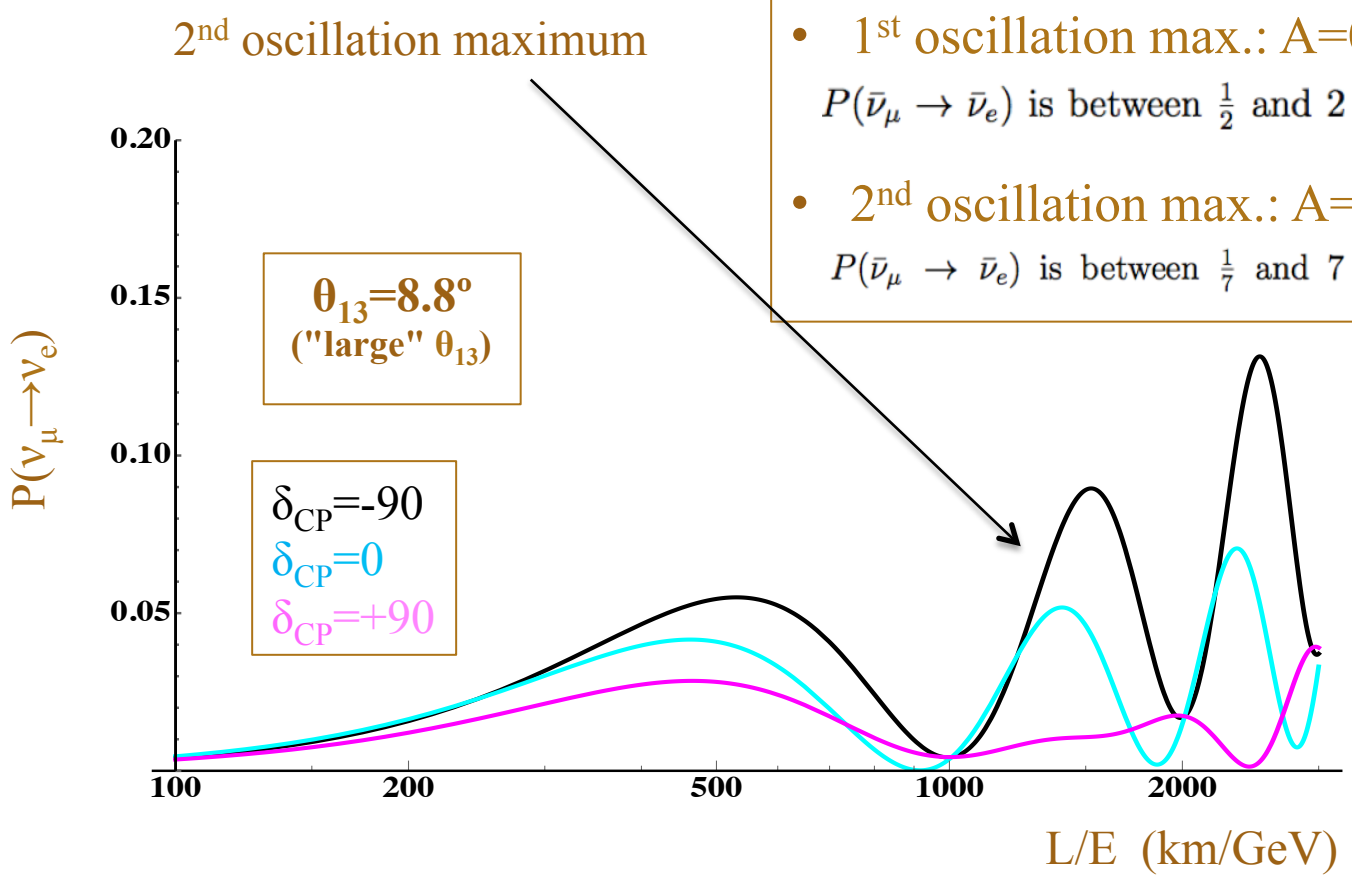
Why second ν oscillation maximum?

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

  $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is between $\frac{1}{2}$ and 2 times $P(\nu_\mu \to \nu_e)$.

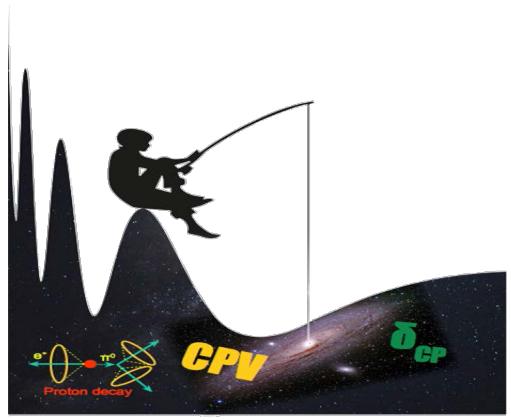
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

  $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is between $\frac{1}{7}$ and 7 times $P(\nu_\mu \to \nu_e)$



(see arXiv:1310.5992 and arXiv:0710.0554)

Why second ν oscillation maximum?



1. The ultimate precision in the determination of the leptonic CP violating angle δ_{CP} from neutrino oscillation measurements will be set by systematic errors.

2. The motivation for the effort to generate a world-uniquely intense neutrino beam using the ESS 5 MW linac is to have enough statistics to reach the second maximum where the CP signal is 3 times higher than at the first maximum, thus reducing the uncertainty in δ_{CP} due to systematic errors by a factor 3.

Measure δ_{CP} precisely, why?

See e.g Silva Pascoli (Durham) contribution to Neutrino Telescopes 2019…

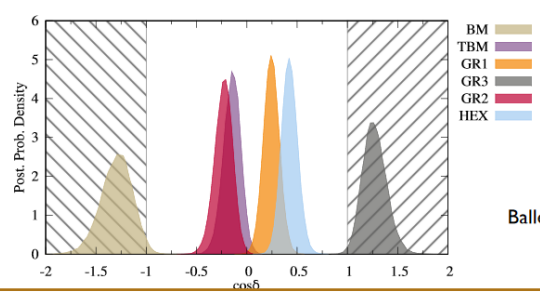
Tests of flavour models

Typically, the models considered have a reduced number of parameters, leading to relations between the masses and/or mixing angles.

Examples are the so-called sumrules, e.g.:

$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = \sin\theta_{13}\cos\delta$$

$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\prime 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$



Ballet at al., 1410.7573

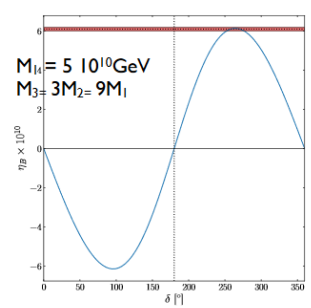
@Silvia Pascoli

Does observing low energy CPV imply baryon asymmetry?

In see-saw type I, let's consider the case of low energy CPV, for instance delta (R real). An approximate formula:

$$|Y_B| \cong 2.4 \times 10^{-11} |\sin\delta| \left(\frac{s_{13}}{0.15}\right)\left(\frac{M_1}{10^{11}\,\mathrm{GeV}}\right)$$

SP, Petcov, Riotto, PRD and NPB 2007; SP 2014



Intermediate flavour regime: 10^9GeV < M_1 < 10^{12}GeV

$$\epsilon_{\tau\tau}^{(1)} = (0.515 - 3.94 c_{13})\, s_{13} \times 10^{-8} \sin\delta$$

$$\epsilon_{\tau\tau}^{(1)} = 3.14 \times 10^{-7} \cos\frac{\alpha_{21}}{2}$$

Moffat, SP, Petcov, Turner, 1804. 05066, 1809.08251

A full study shows that delta can give an important (even dominant) contribution to the baryon asymmetry. For Majorana CPV, effects enhanced by a factor of ~10.

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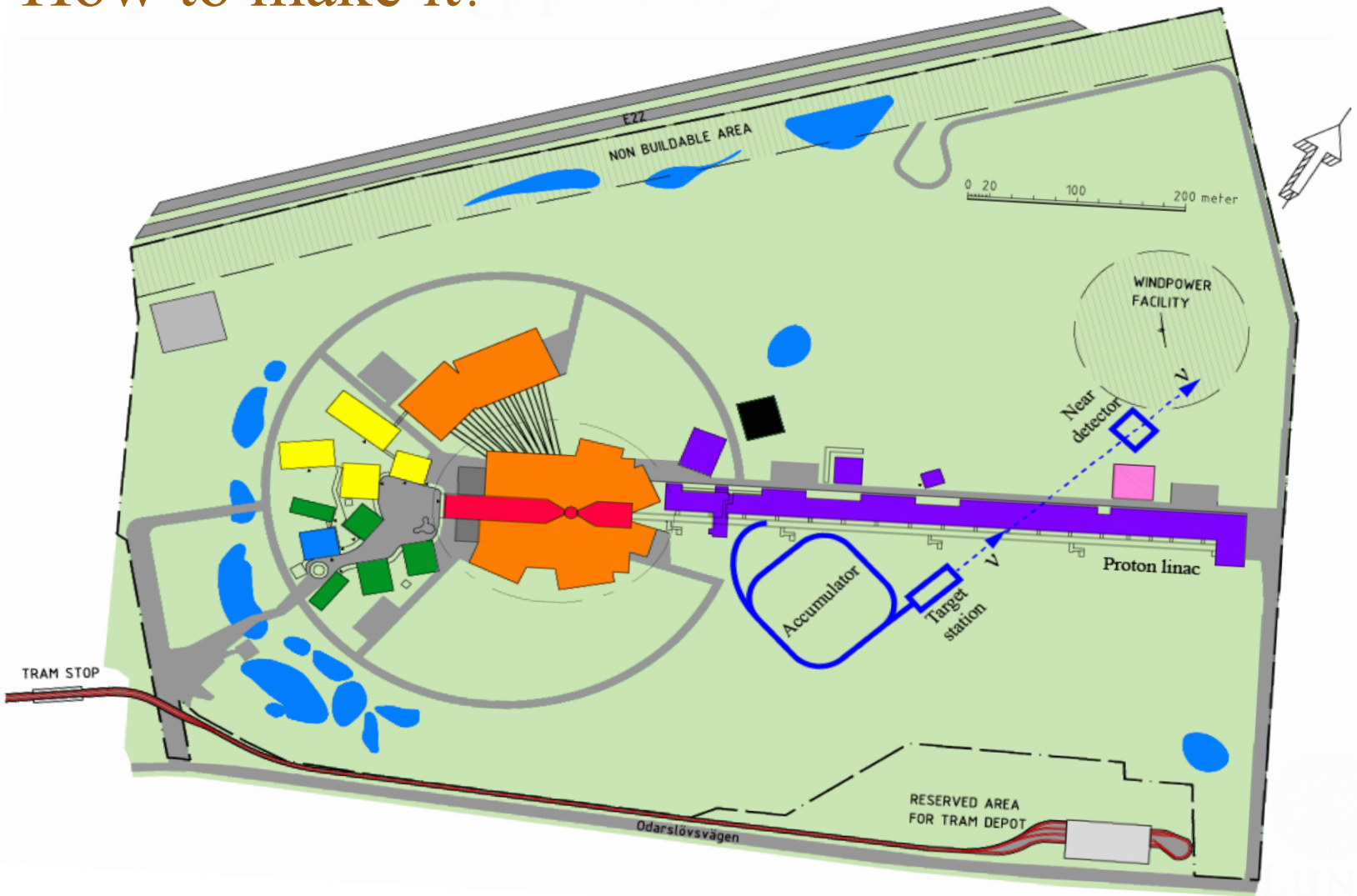
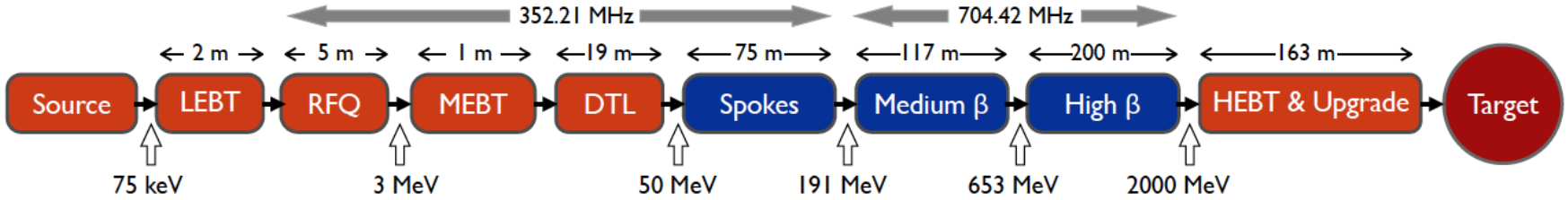
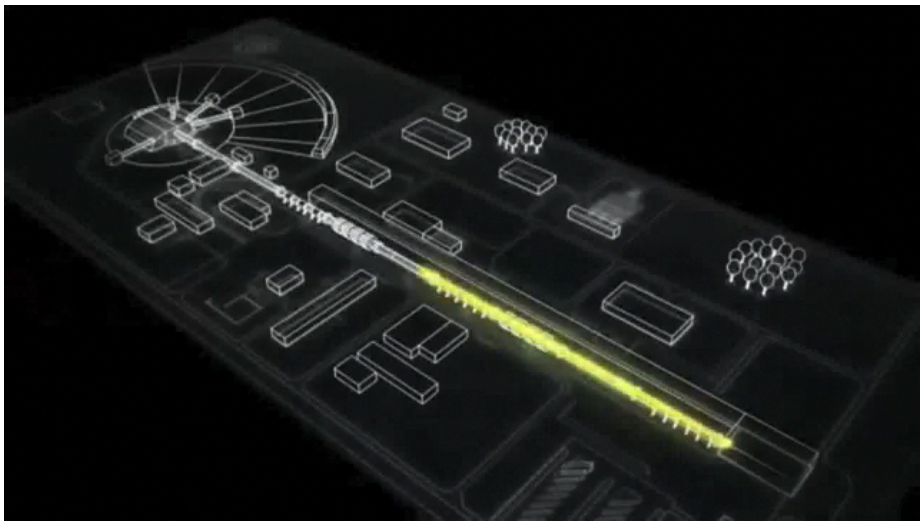
How to make it?



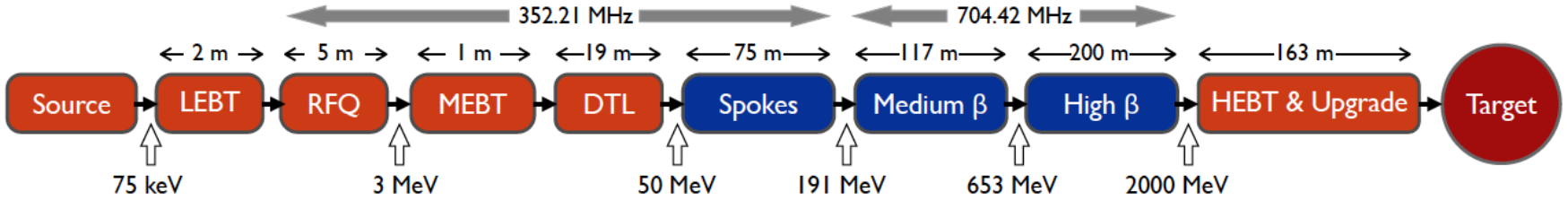
ESS LINAC

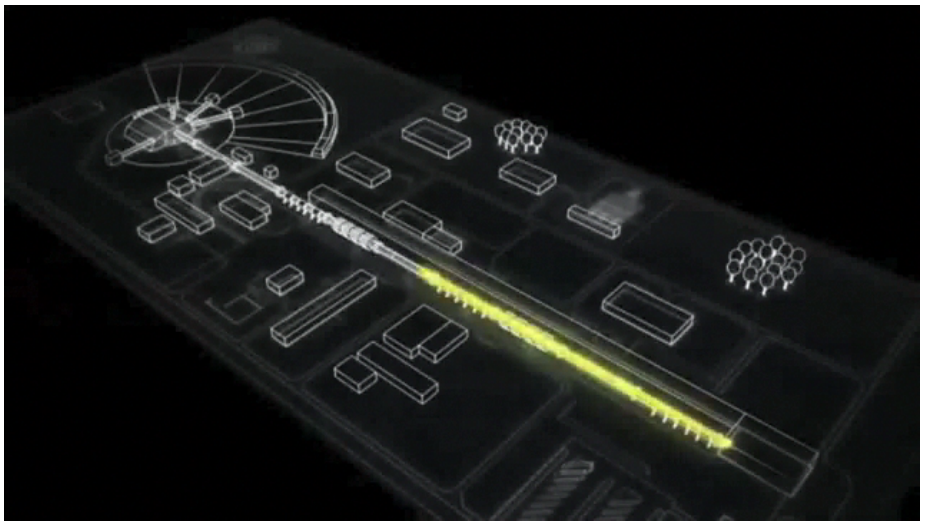




- **5 MW average beam power.**
- **125 MW peak power.**
- **14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).**
- **Duty cycle 4%.**
- **2.0 GeV protons**
  - **up to 3.5 GeV with LINAC upgrades**

ESS LINAC - upgrade





- **Min. effect on neutron program**
- **Double pulse rate 14 Hz -> 28 Hz**
- **Accumulator to compress the 2.86 ms pulse to a few µs.**
- **Use H^- instead of protons**

How?

- **Installation of 8 new cryo modules with RF stations** **to accelerate to 2.5 GeV**
- **Installation of H^- source, RFQ and MEBT**
- **Change/upgrade of klystrons**
- **New electrical station, substations and cabling**
- **~ €250 million construction cost to be compared to the ~€1.8 billion (2013) construction costs for ESS itself**

F. Gerigk and E. Montesinos
CERN, Geneva, Switzerland

CERN-ACC-NOTE-2016-0050 8 July 2016

Contents

Quotation from "Executive Summary: "No show stoppers have been identified for a possible future addition of the capability of a 5 MW H- beam to the 5 MW H+ beam of the ESS linac built as presently foreseen. Its additional cost is roughly estimated at 250 MEuros."

No showstoppers identified

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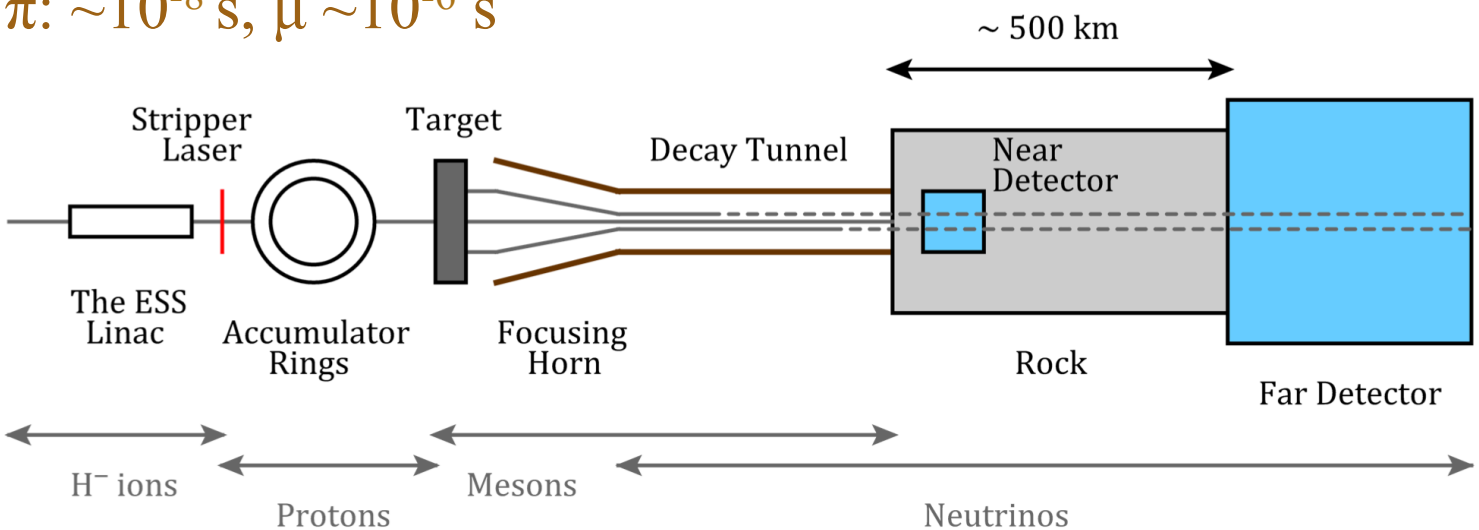
ESSνSB – Principal Layout

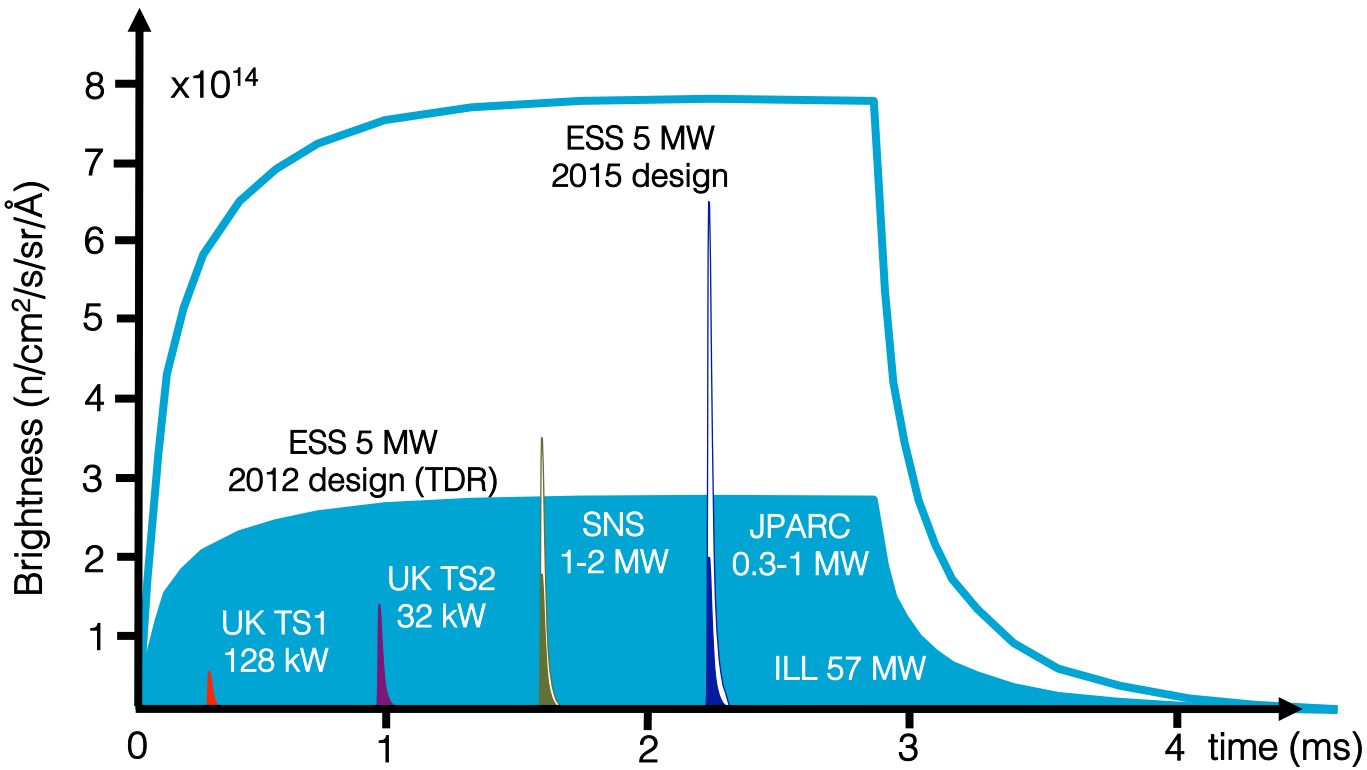
$$pp/pn > \pi^+ \rightarrow \boxed{\mu^+} + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^- > \ldots + \nu_\mu \ldots$$

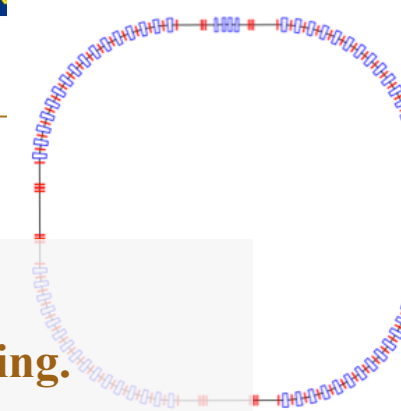
π: ~10^{-8} s, μ ~10^{-6} s



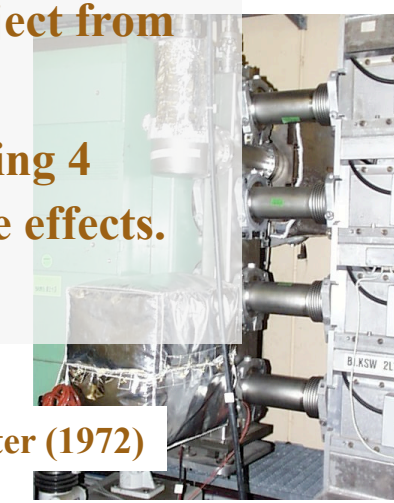
The ESS pulse



ESSνSB – accumulator

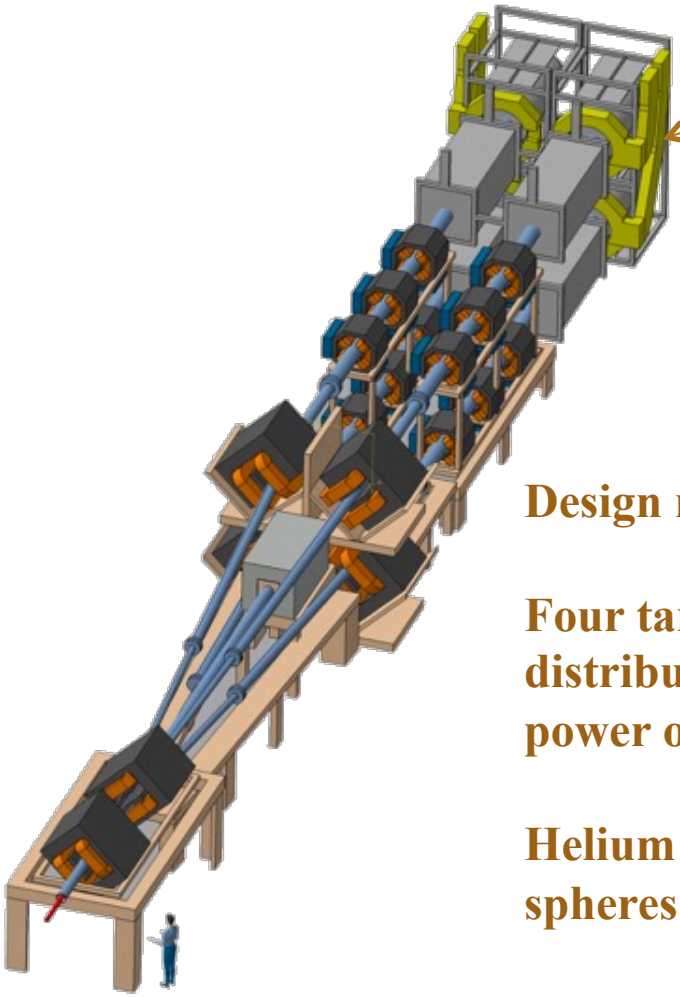


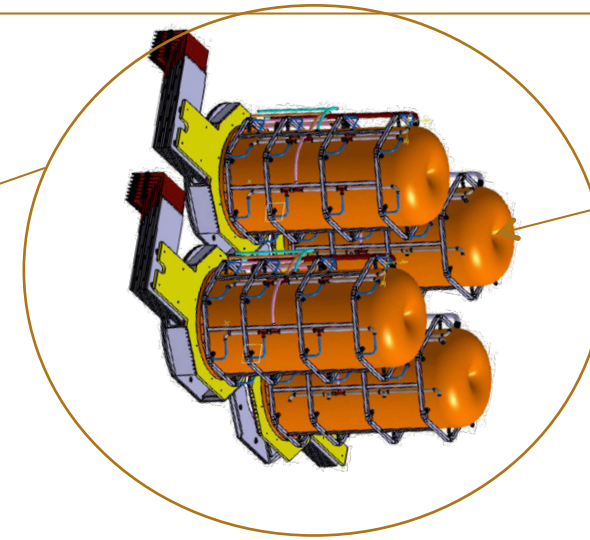
- **Baseline: single-ring accumulator**
  - **Current studies give a 376 m circumference accumulator ring.**
  - **Space charge issues**
- **Option: 4 superposed rings located in the same tunnel,**
  - **Each ring receives 1/4 of the bunches during the multi–turn injection,**
  - **There has to be enough space between the bunches in the bunch train from the linac to permit the beam distribution system to inject from one ring to the next one,**
  - **Experience already exists from the CERN PS Booster of using 4 superimposed rings with the aim to avoid high space charge effects.**
  - **Estimated cost ~€200 million**

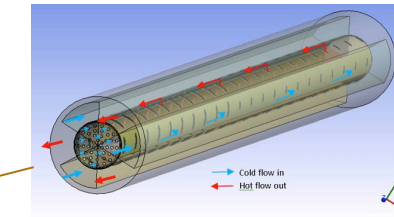


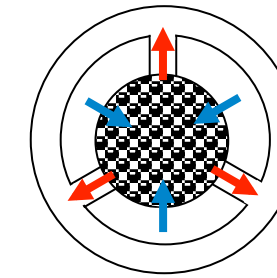
Example: CERN PS Booster (1972)

ESSνSB – production









Design made in the EUROν SB project.

Four targets and horns for focusing to distribute current to run the horns and the power on the targets on several units.

Helium cooled targets with titanium alloy spheres situated inside the horns.

Estimated cost ~€200 million.

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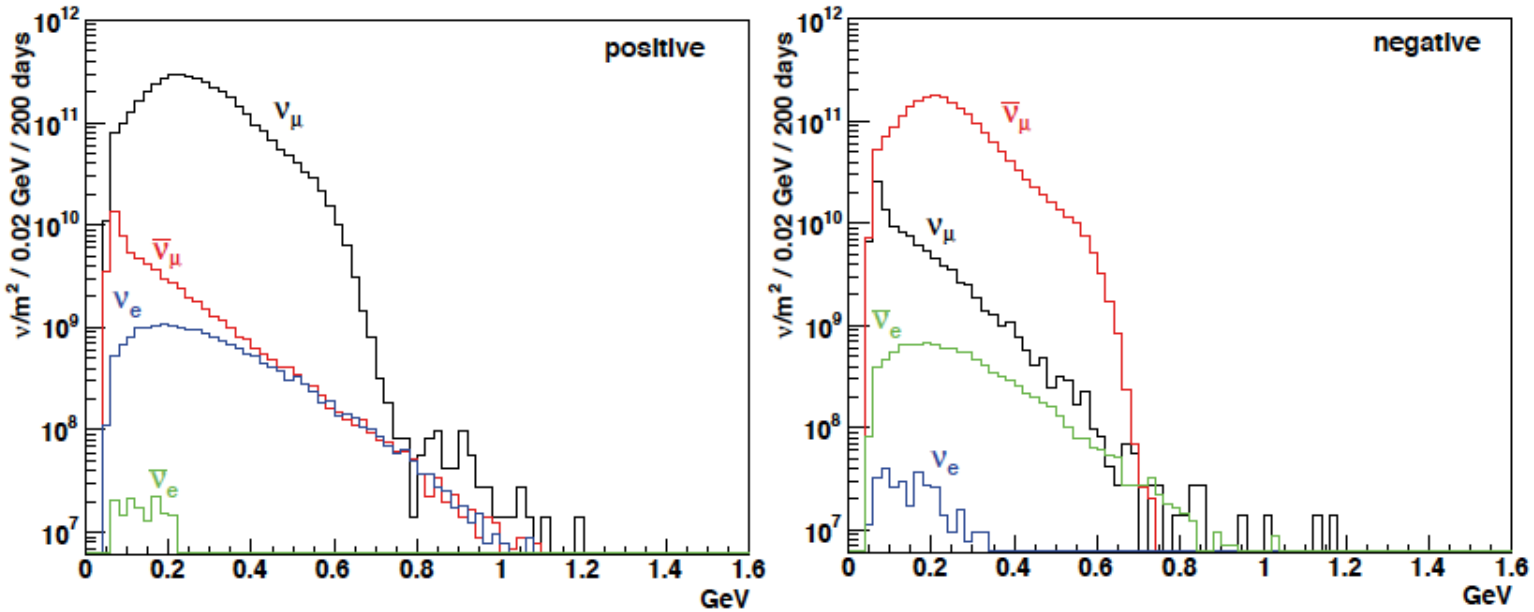
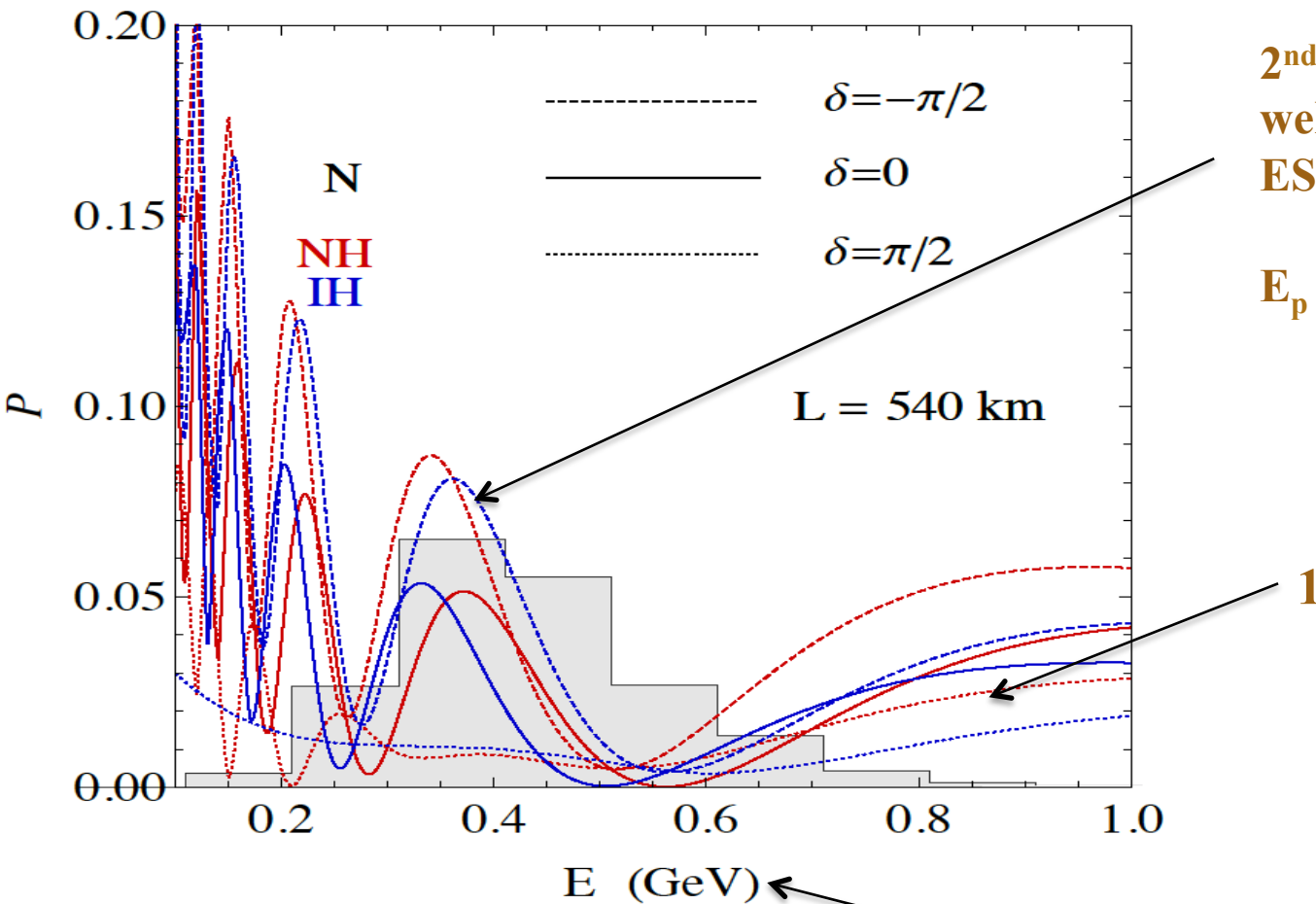
ν_μ and $\bar{\nu}_\mu$ beam production



	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

ESSνSB spectrum and oscillation probability – fixed L and E_{beam}



2nd oscillation max. well covered by the ESSνSB spectrum

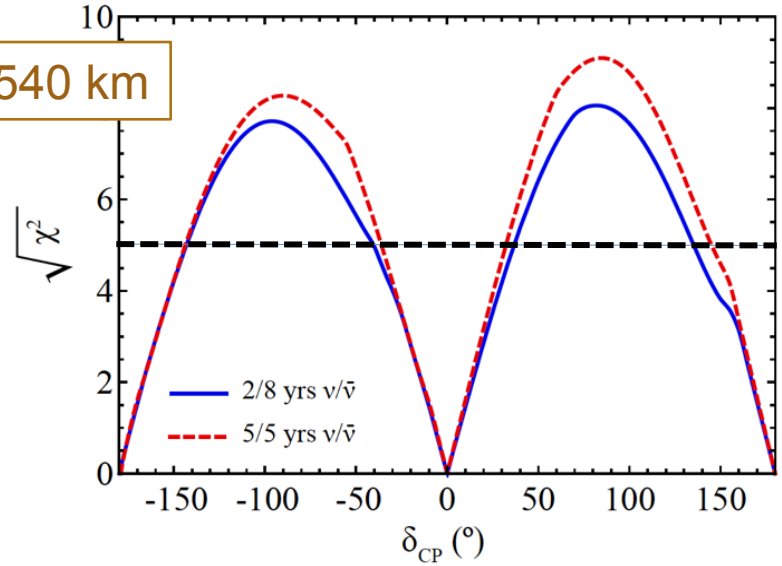
E_p = 2 GeV

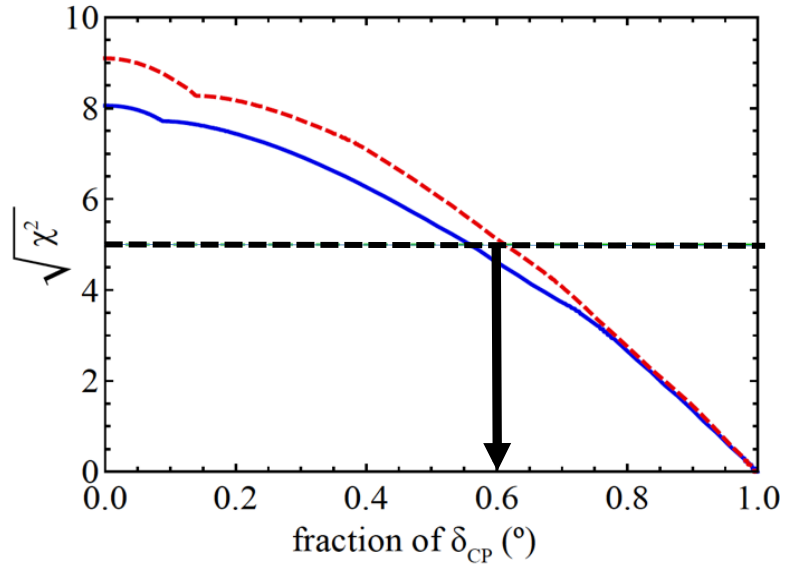
1st oscillation max.

Neutrino energy

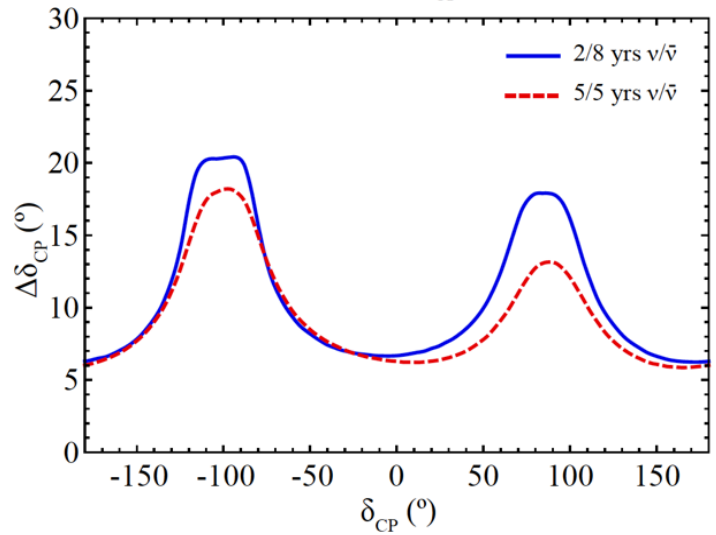
The physics reach

L=540 km

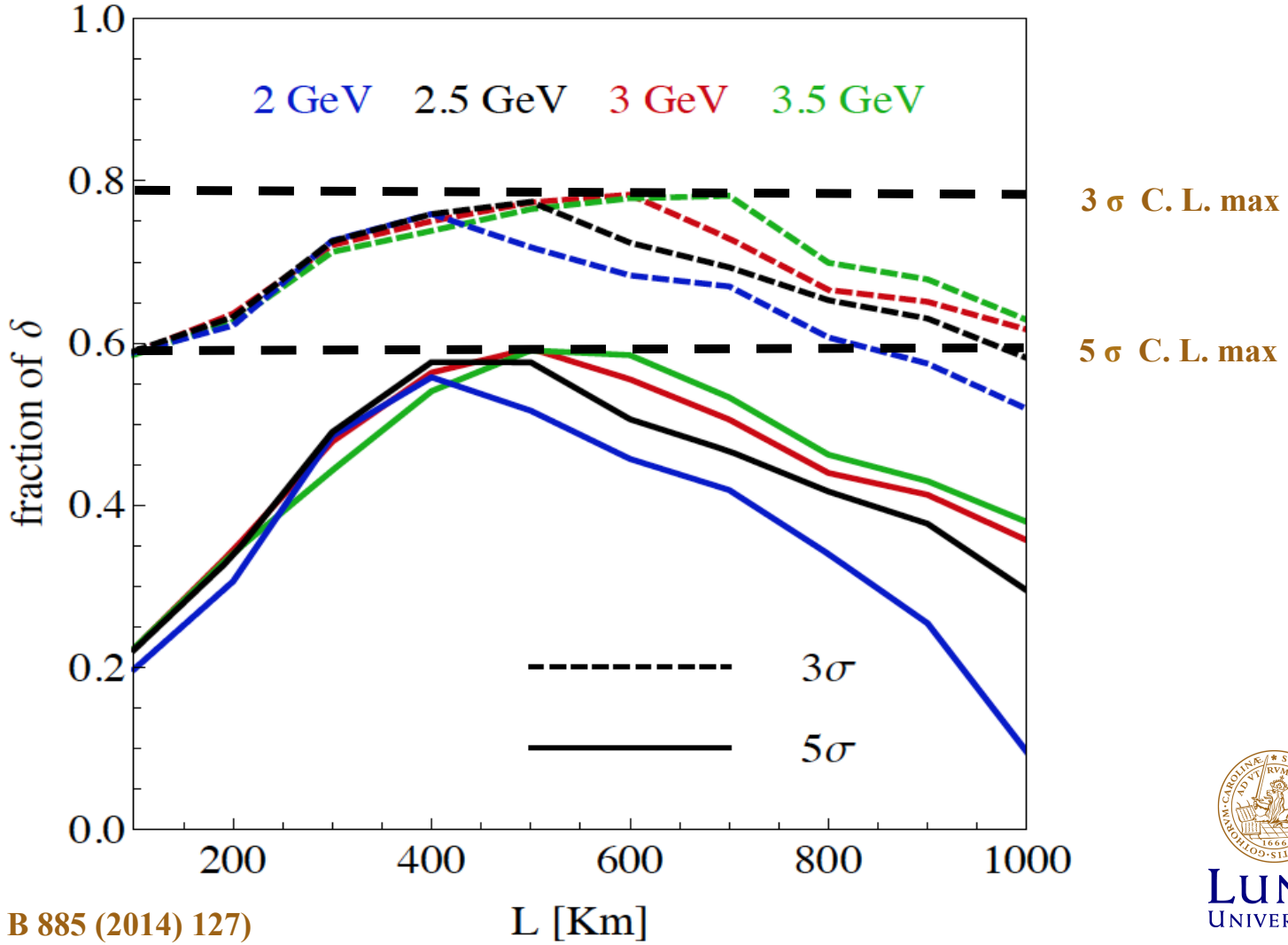




- Little dependence on mass hierarchy,
- δ_{CP} coverage at 5 σ C.L. up to 60%,
- δ_{CP} accuracy down to 6° at 0° and 180° (absence of CPV for these two values),
- 5/10% systematic errors on signal/ background,
- Not yet optimized facility

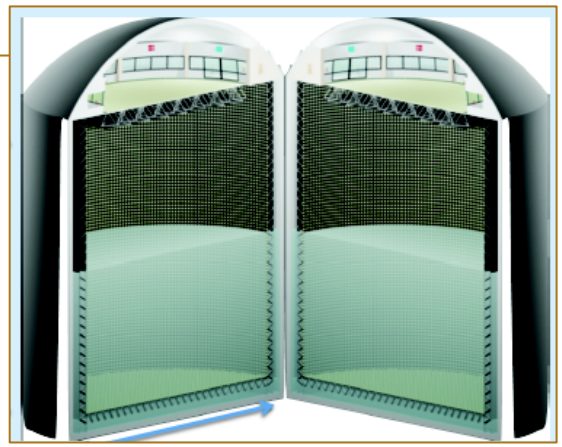


Which baseline?



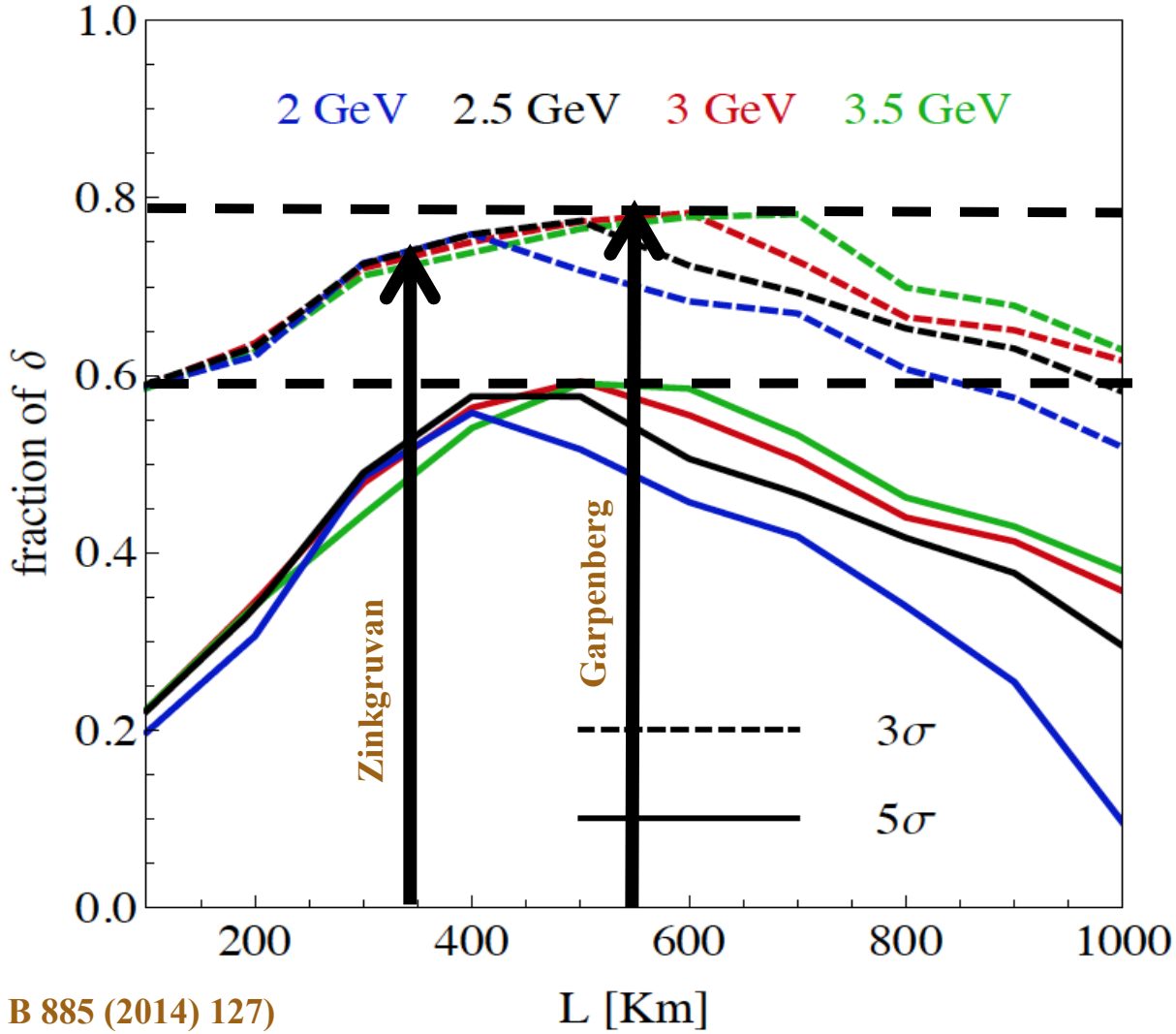
(Nucl. Phys. B 885 (2014) 127)

Baseline: active mine candidates



Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320
Kiirunavaara,SE	2530	1700	1380
Kaunisvaara,SE	2552	1580	1390
Løkken, NO	1536	1740	500
Kongsberg, NO	1900	1800	840

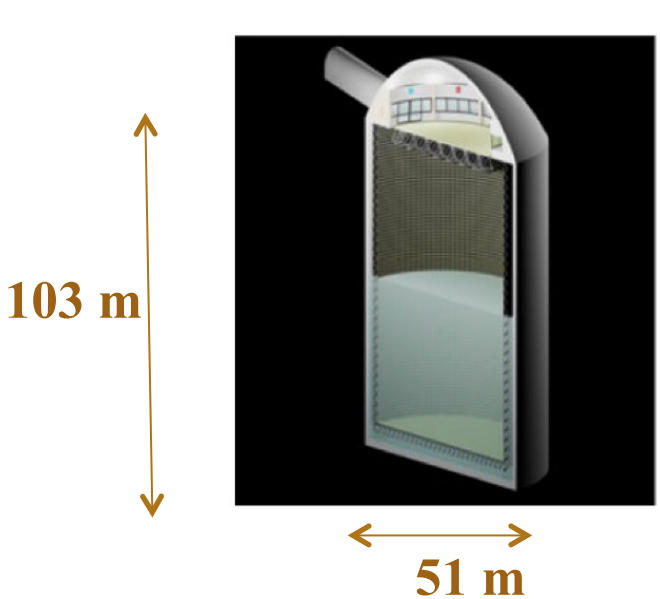
Which baseline?



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

Far Detector – Conceptual Design

MEMPHYS like Cherenkov detector (studied by LAGUNA)



- Neutrino Oscillations
- Proton decay
- Astroparticles
- SN-ν
- Solar Neutrinos
- Atmospheric Neutrinos

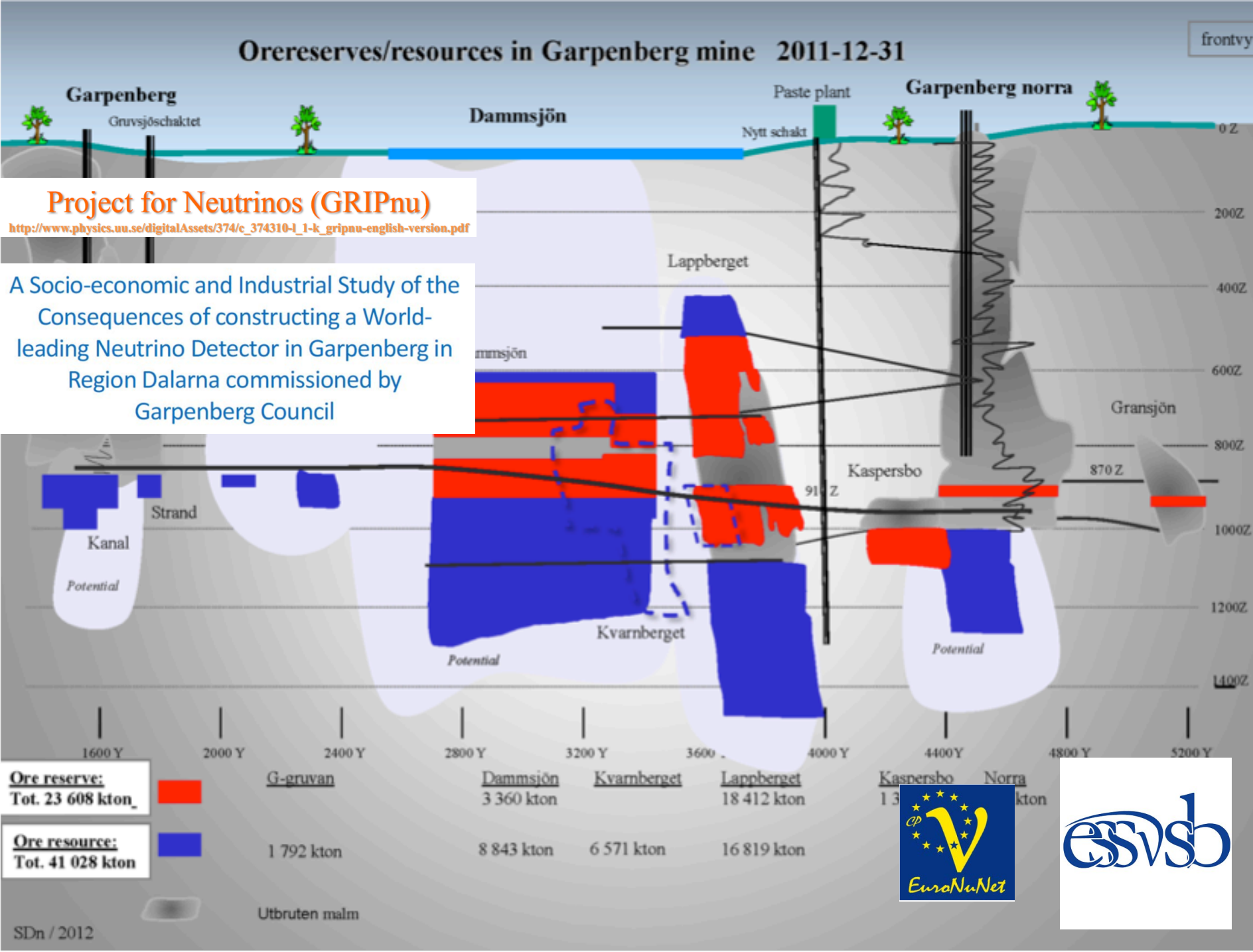
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage
- Estimated cost ~€700 million

Phys. Rev. ST Accel. Beams 16, 061001 (2013)

Project for Neutrinos (GRIPnu)

http://www.physics.uu.se/digitalAssets/374/c_374310-l_1-k_gripnu-english-version.pdf

A Socio-economic and Industrial Study of the Consequences of constructing a World-leading Neutrino Detector in Garpenberg in Region Dalarna commissioned by Garpenberg Council



Funded by the Horizon 2020 Framework Programme of the European Union

Design Study ESSνSB 2018 - 2021

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:	

Search:

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

- **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**

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

Funded by the Horizon 2020 Framework Programme of the European Union

essvsb

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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:	

ESSnuSB - ESS neutrino Super Beams

ESSnuSB is a project introduced by the IPHC (M. Dracos) and the University of Uppsala (T. Ekelöf). It follows the EURONu Design Study FP7 (2008-2012). The aim is to produce very intense neutrino beams using the protons from the [illegible] MW, 2 GeV) [illegible] horn system. In the ESSnuSB proposed facility a copious number of muons will also be produced. These muons could be used by a future Neutrino Factory to study CP violation in the leptonic sector but also to study neutrino cross-sections. They could also be used to feed a future muon collider.

ESSnuSB is supported by the COST Action CA15139 "Combining forces for a novel European facility for neutrino-antineutrino symmetry-violation discovery" (EuroNuNet). 13 countries already joined the project. It has been recently granted from the [illegible] 4-years Design Study. A kick-off meeting is foreseen in January 2018.

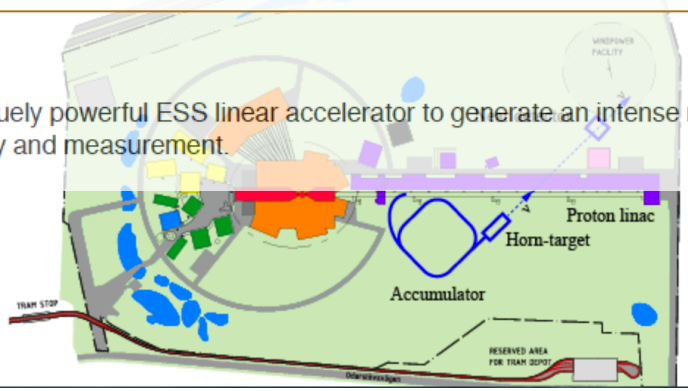
The ESSνSB [illegible] Source Neutrino Super Beam) project proposes to study a Super Beam which uses the high power linac of the ESS facility [1] based at Lund in Sweden as a proton driver and a MEMPHYS type detector [2, 3] located in a deep mine at a distance of about 50[illegible] km, near the second neutrino oscillation maximum (Fi[illegible]

Work packages:

- Management
- Linac Upgrade
- Accumulator
- Target station – alt. to horns?
- Detector performance (ND – FD)
- Physics reach

Search:

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



EuroNuNet

Search this website ...

Funding – EuroNuNet Cost Action

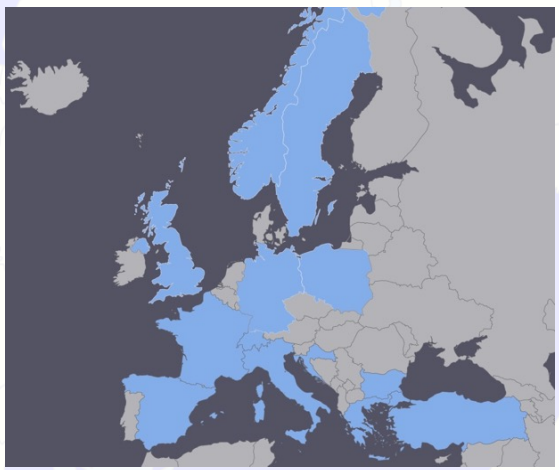
NEWS

- **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).**

- WG meeting, February 25th, 2017, Geneva (CERN)
- "Upgrading Existing High Power Proton Linacs Workshop", November 8-9th, 2016, Lund (ESS)

EuroNuNet

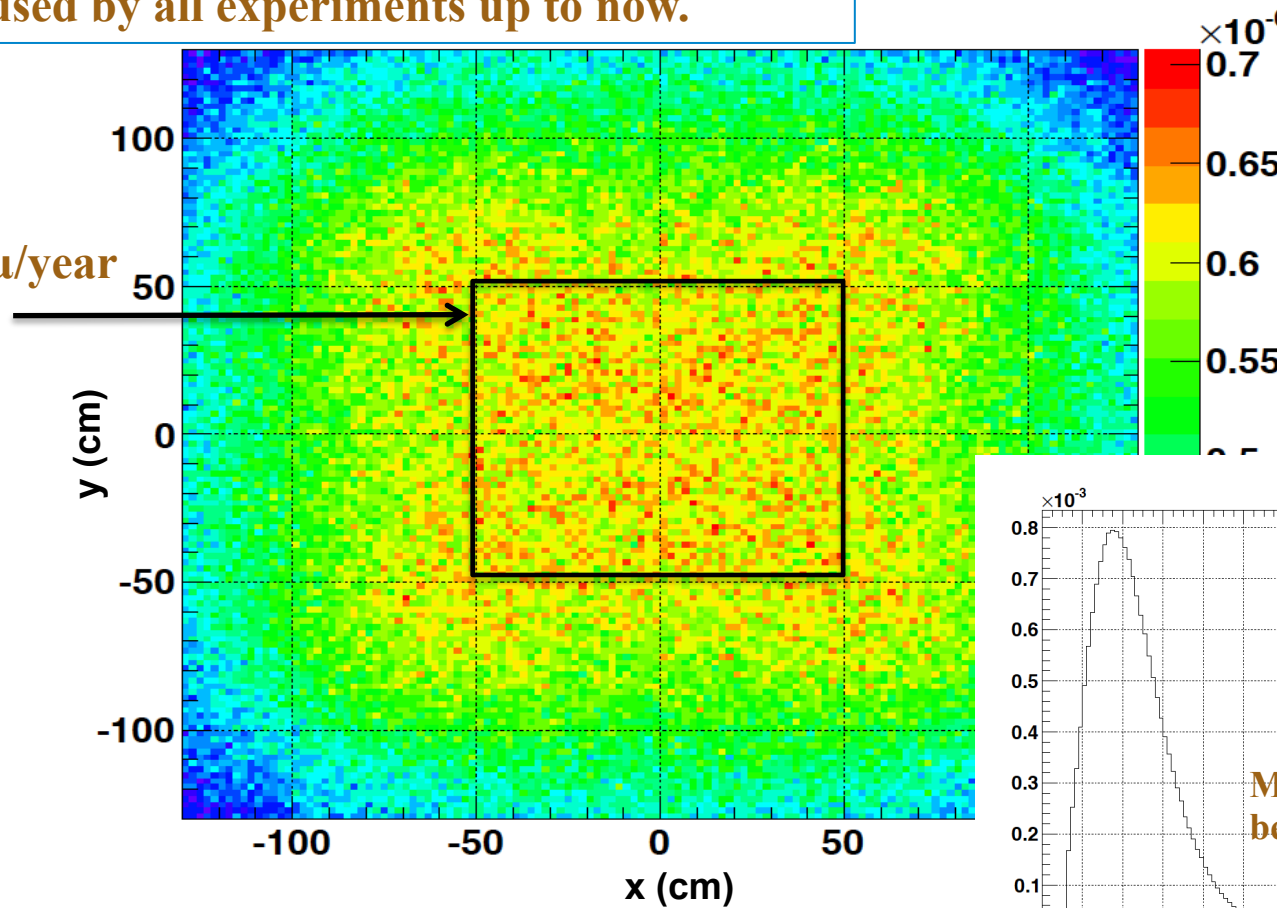
cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

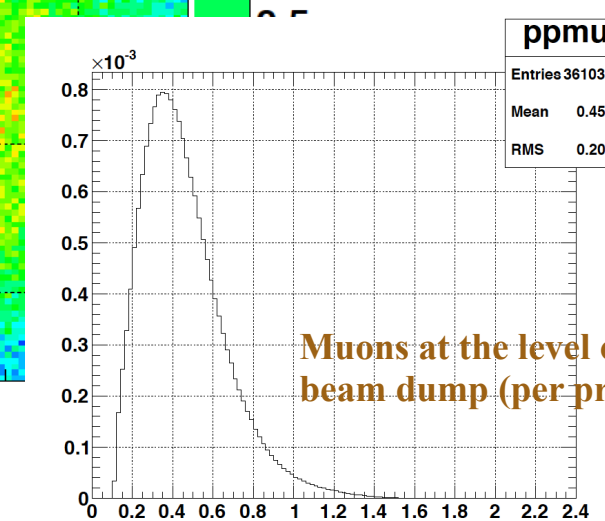


ESSνSB – production

More than 4×10^{20} μ/year from ESS compared to 10^{14} μ used by all experiments up to now.

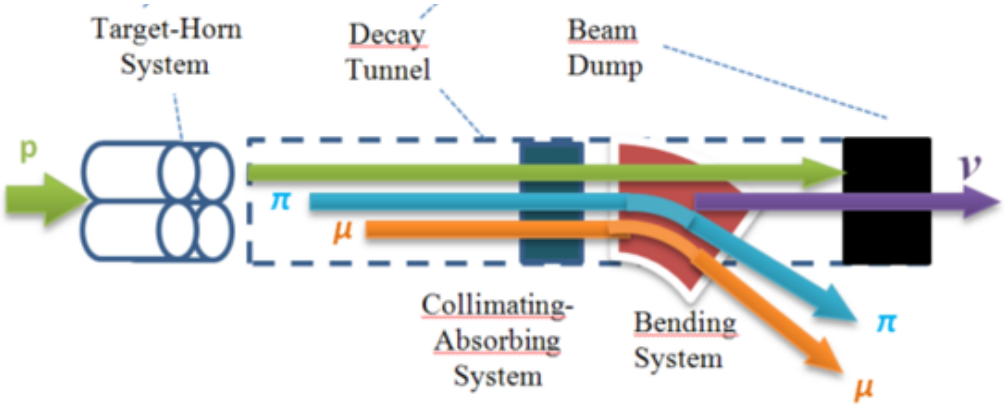
4.2×10^{20} μ/year





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

ESS neutrino and muon facility



Developments for μ physics

μ test facility	μ decay channel or ring	μ storage ring	μ collider
	Short Baseline Detector **nuSTORM**	Long Baseline Detector **Neutrino Factory**	**Next generation collider physics**

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Timeline

2012 → 2021

2012:
Inception of the project

2016-2019:
Beginning of COST Action EuroNuNet

COST
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

2018:
Beginning of ESSνSB Design Study (EU-H2020)

ESS NEUTRINO SUPER BEAM

2021:
ESSνSB design study finished. CDR and preliminary costing

2022 → 2036

2022-2024:
Preparatory Phase, TDR

2025-2026:
Preconstruction Phase, International Agreement

2027-2035:
Construction of the facility and detectors, with commissioning

2036-:
Data taking

ESFRI

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Summary

Infrastructure

- **The European Spallation Source Linac should be ready (5 MW, 2 GeV proton beam) by ~2023.**

ESSνSB science reach

- **Significantly better CPV sensitivity at the 2nd oscillation maximum.**
- **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 at ESSνSB).**
  - **Large associated detectors can be used for astroparticle physics program.**
  - **Potential future muon program.**

Existing funding/collaboration

- **COST network project CA15139 supports the project.**
- **The EU-H2020 Design Study ESSνSB is approved and running**

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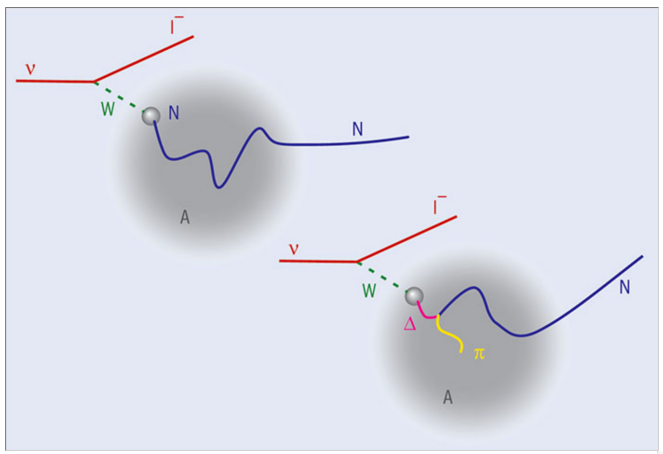
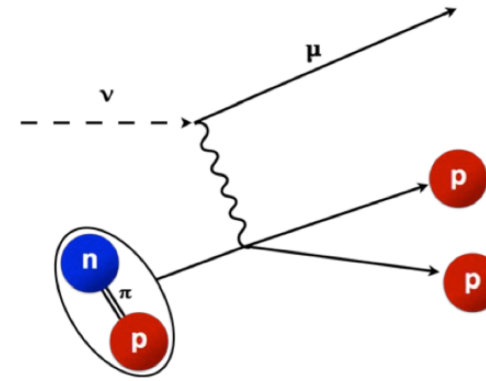
Systematic errors

- ν_e contamination from μ, K
- π^0 going into two γ
- ν_μ misidentified as ν_e
- ν-nucleus cross section (QE, RES, DIS)
- Energy reconstruction error due to multi-nucleon effects





Errors summary

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%

Pilar Coloma et al. Phys. Rev. D, 03304 (2013)

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