ESS NEUTRINO SUPER BEAM

Funded by the Horizon 2020 Framework Programme of the European Union

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Status of ESSnuSB and summary of workshop

Budimir Kliček
Ruđer Bošković Institute, Zagreb
on behalf of the ESSnuSB project

NuFact 20|21

The 22nd International Workshop on neutrinos from accelerators

7 Sep 2021

ESSnuSB

A design study for an experiment to measure CP violation at 2nd neutrino oscillation maximum.

CP violation in neutrino oscillations

Oscillation probability for neutrinos is different than oscillation probability for anti-neutrinos in vaccum.

probability of oscillation

$$P_{\alpha \to \beta} \neq P_{\overline{\alpha} \to \overline{\beta}}$$

neutrino flavour at production

neutrino flavour at detection

CP violation in ESSnuSB

$$P_{\mu\to e} \neq P_{\overline{\mu}\to\overline{e}}$$

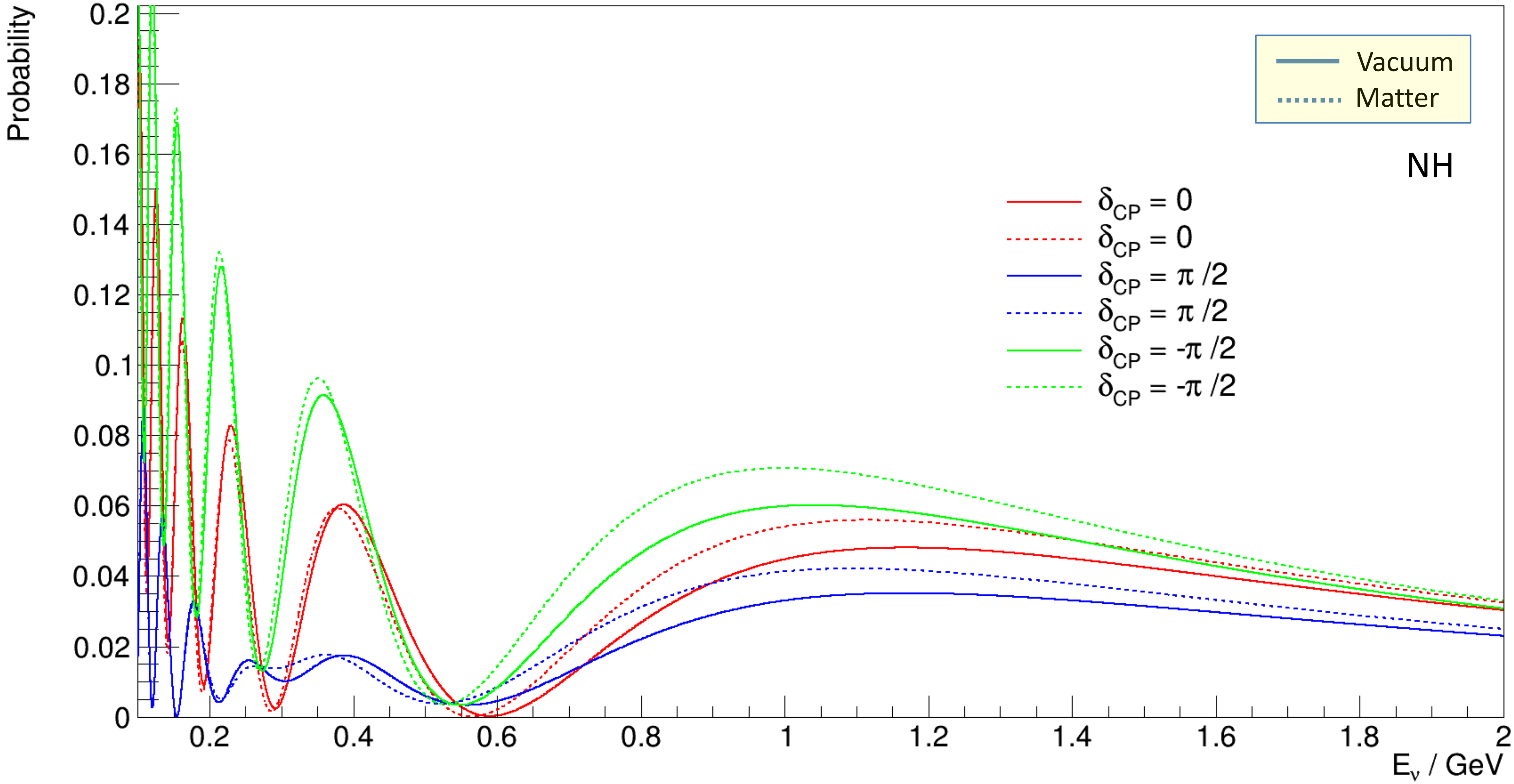
We will study ν_e and $\overline{\nu}_e$ appearance in ν_μ and $\overline{\nu}_\mu$ beam, respectively

The plan:

1. Run with ν_μ and look at ν_e appearance, then
2. Run with $\overline{\nu}_\mu$ and look at $\overline{\nu}_e$ appearance

Why 2nd maximum?

$$P_{\nu_\mu \to \nu_e} (E_\nu; L = 540 \text{ km})$$



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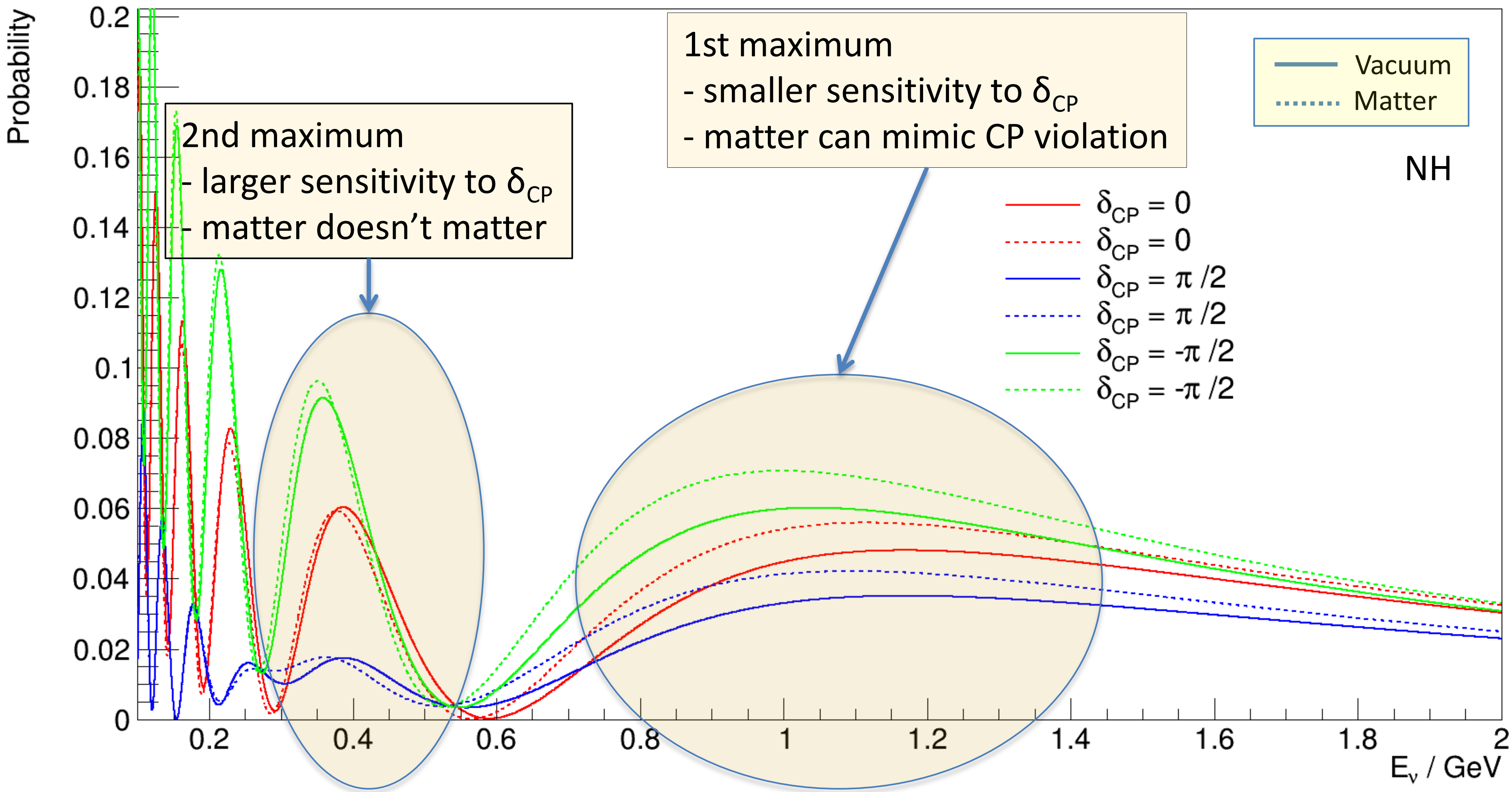

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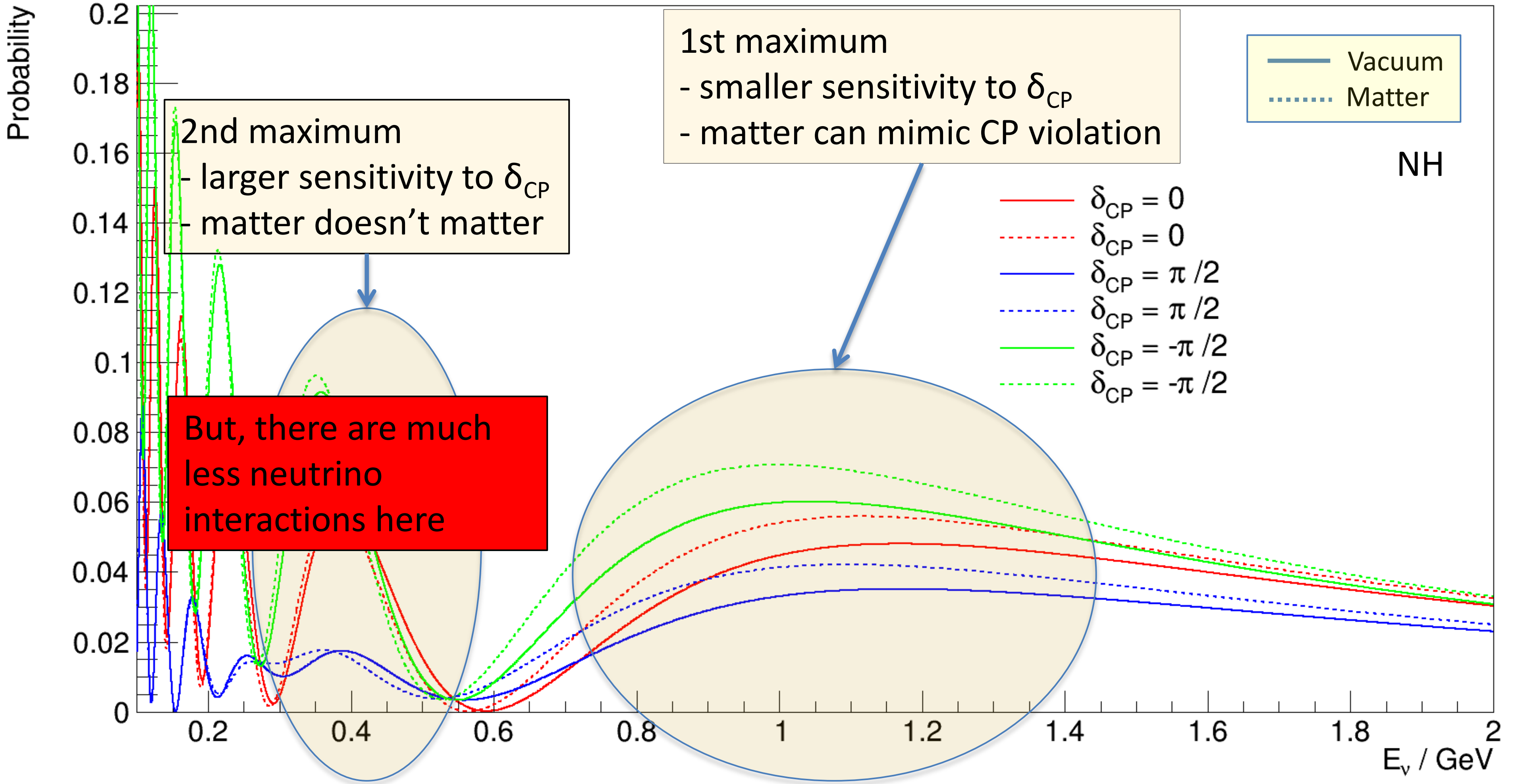


Why 2nd maximum? (summary)

The good

$$\frac{\left(P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e}\right) \text{@ 2 osc. max.}}{\left(P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e}\right) \text{@ 1 osc. max.}} \sim 2.7$$

In vaccum, this ratio depends only on neutrino mass square differences

The bad

You get less statistics because you have to either:

- Move 3x further than 1st maximum - flux 9x smaller
- Reduce energy 3x – cross-section at least 3x smaller

The optimal

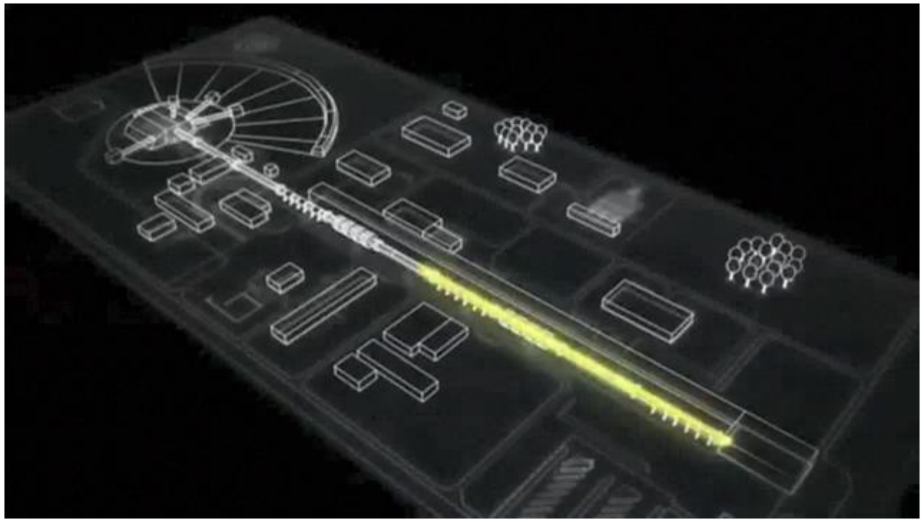
- **Depends on the systematic error and beam intensity**

- 3x signal at 2nd osc. maximum is less obscured by systematics, but we have less statistics (measured appearance events).
  - If the signal at 2nd maximum is not obscured by larger statistical error, then 2nd maximum is better.
  - Intense beam helps here, as does having larger θ_{13} because $P_{\mu\to e}$ and $P_{\overline{\mu}\to\overline{e}}$ are larger and we get more events.
- With no systematic error, first maximum is better
  - more statistics, even though the effect is smaller.

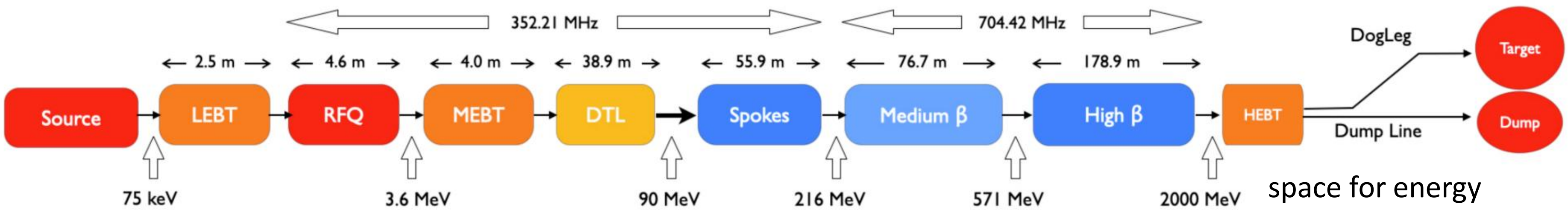
Can we afford 2nd maximum?

As it happens, a very intense proton linac is in construction near Lund, Sweden.

And θ_{13} is large enough.



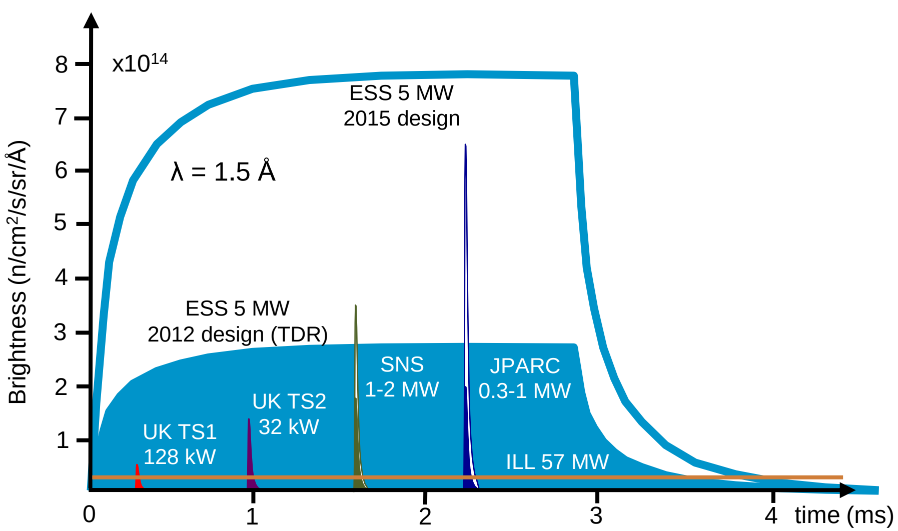
ESS proton linac



space for energy upgrades

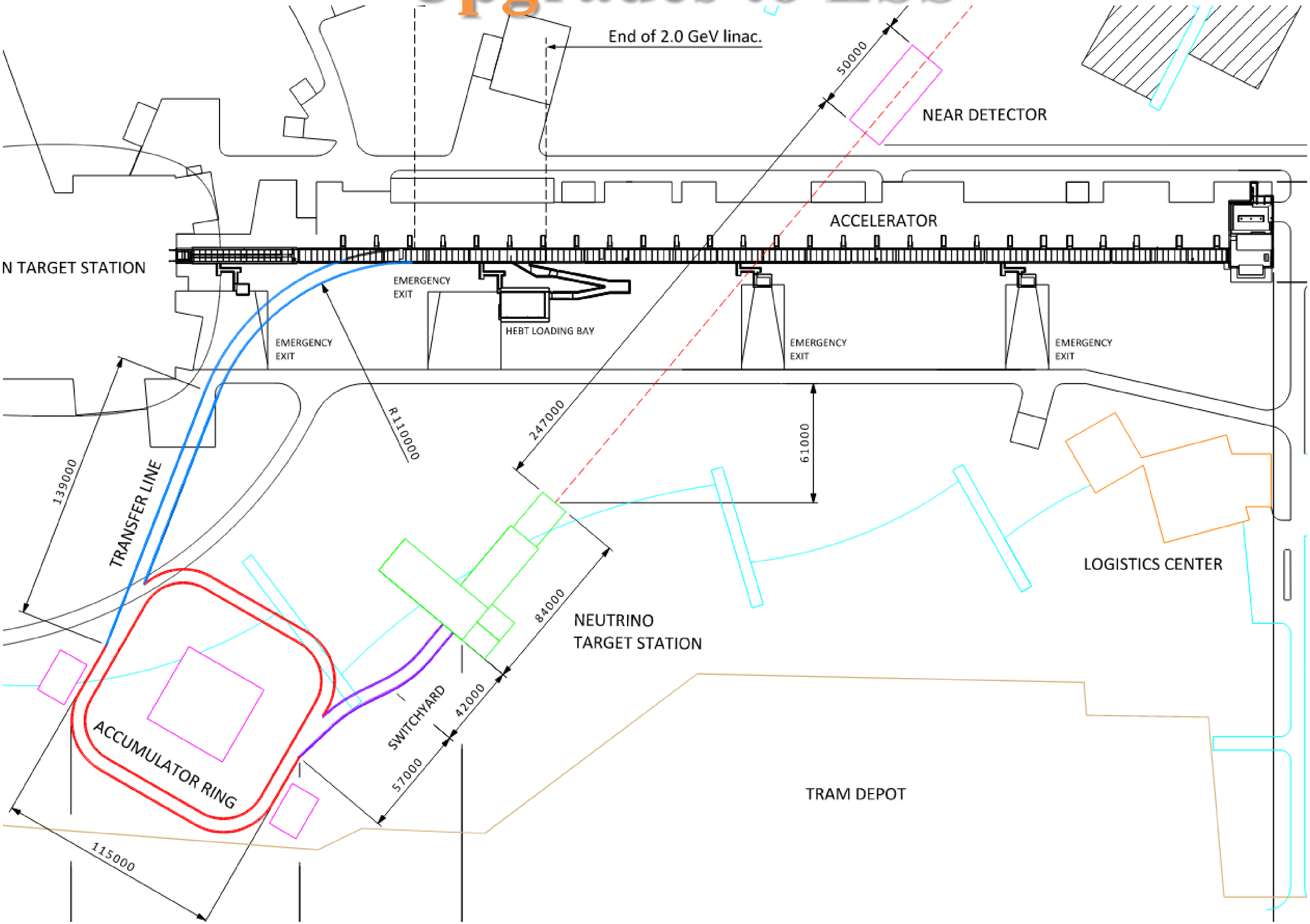
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons
    - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**

450 mg of protons/year at 95% speed of light!



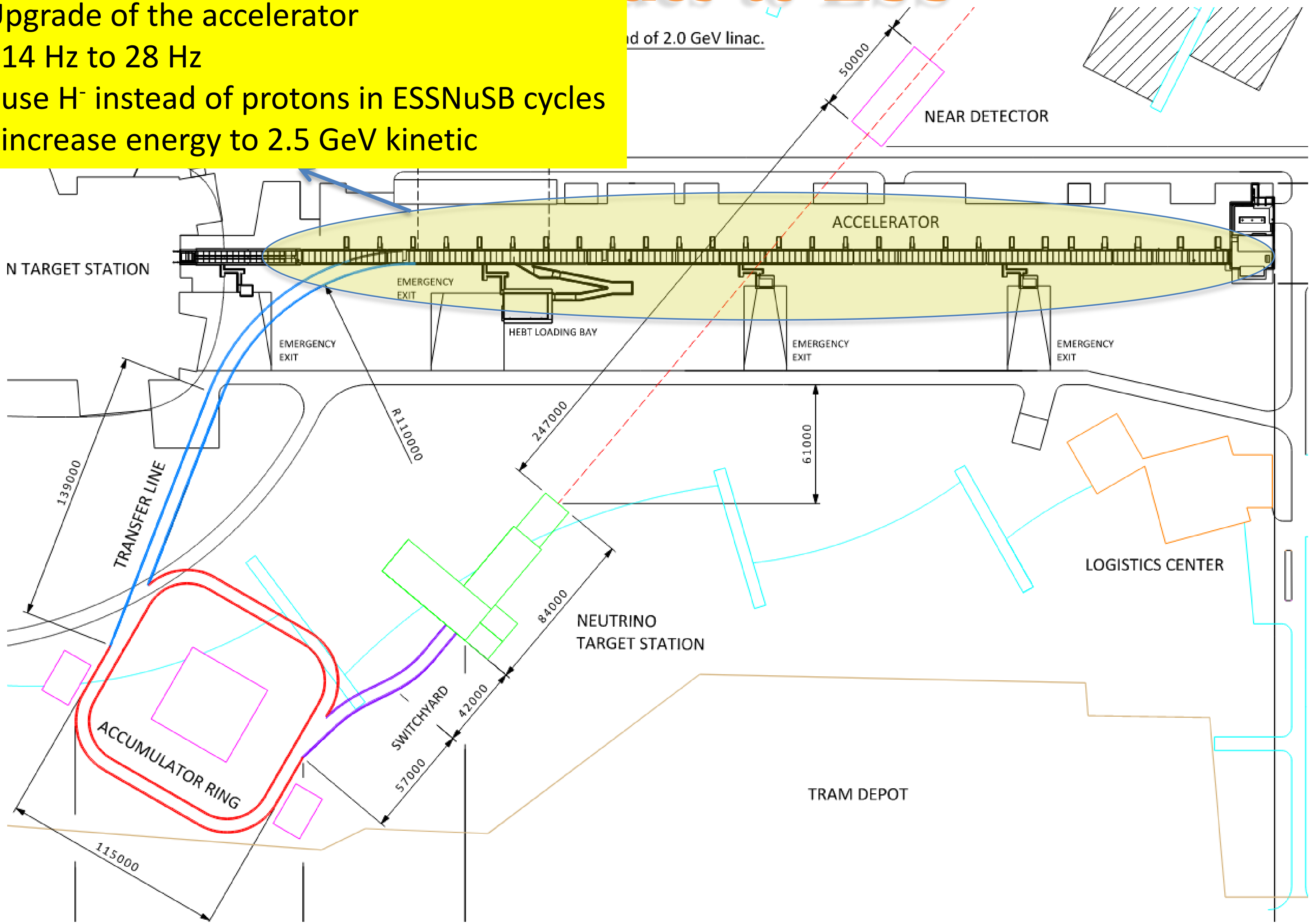
First operation of the linac in 2023.

Upgrades to ESS



Upgrades to ESS

Upgrade of the accelerator
- 14 Hz to 28 Hz
- use H^- instead of protons in ESSNuSB cycles
- increase energy to 2.5 GeV kinetic



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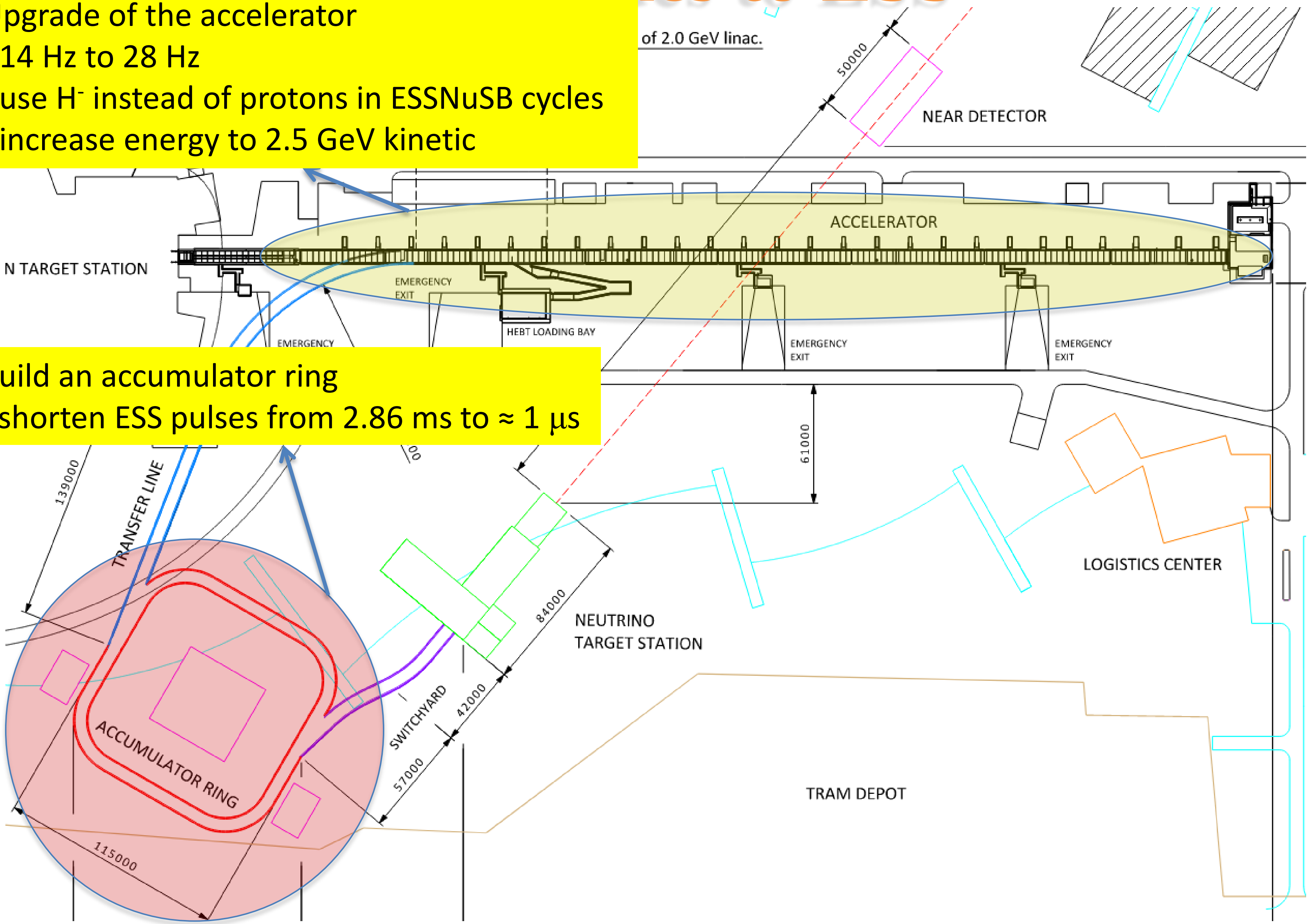
Build an accumulator ring
- shorten ESS pulses from 2.86 ms to ≈ 1 μs



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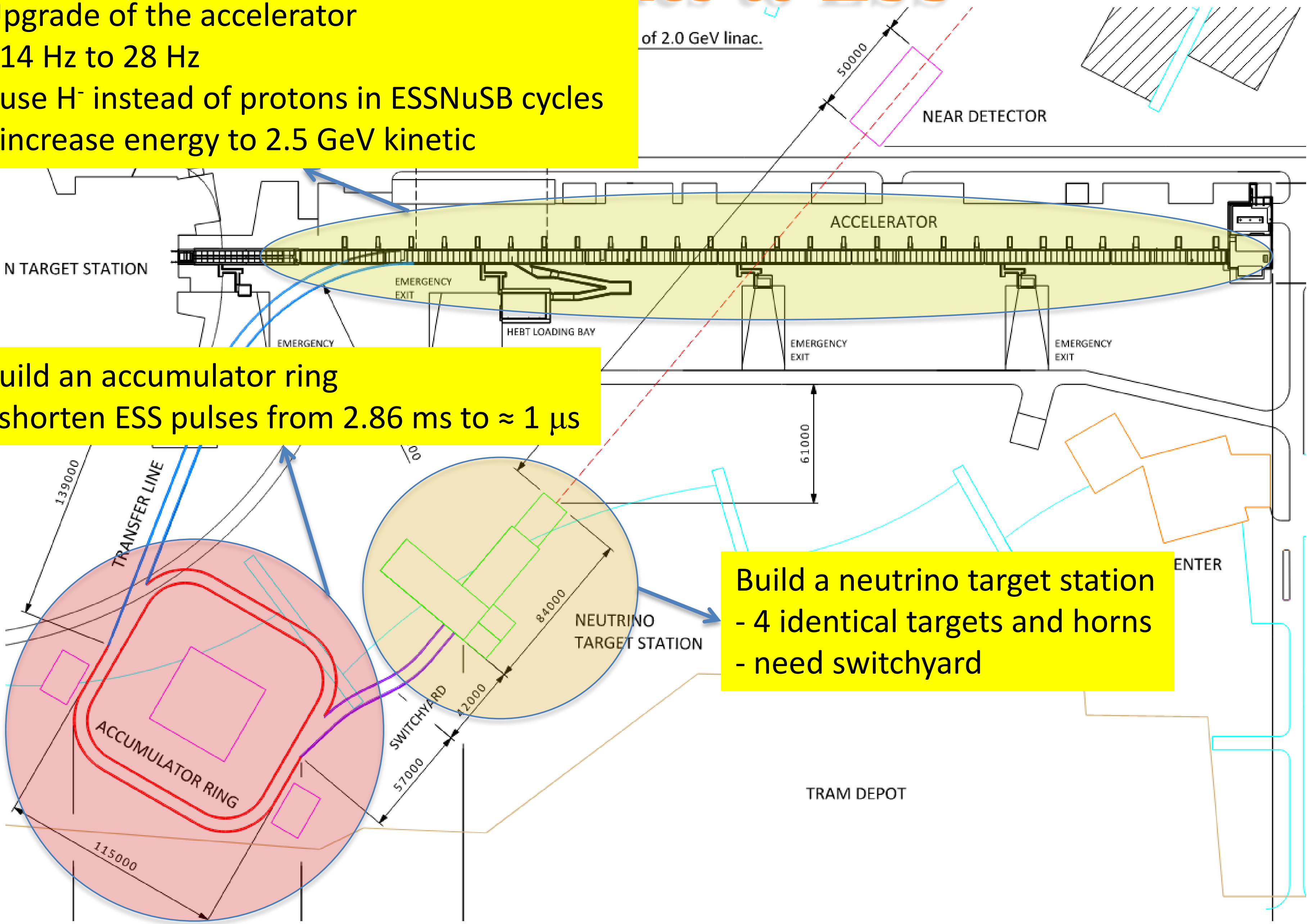
Build a neutrino target station
- 4 identical targets and horns
- need switchyard



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- water Cherenkov detector
- fine grained scintillator
- emulsion detector

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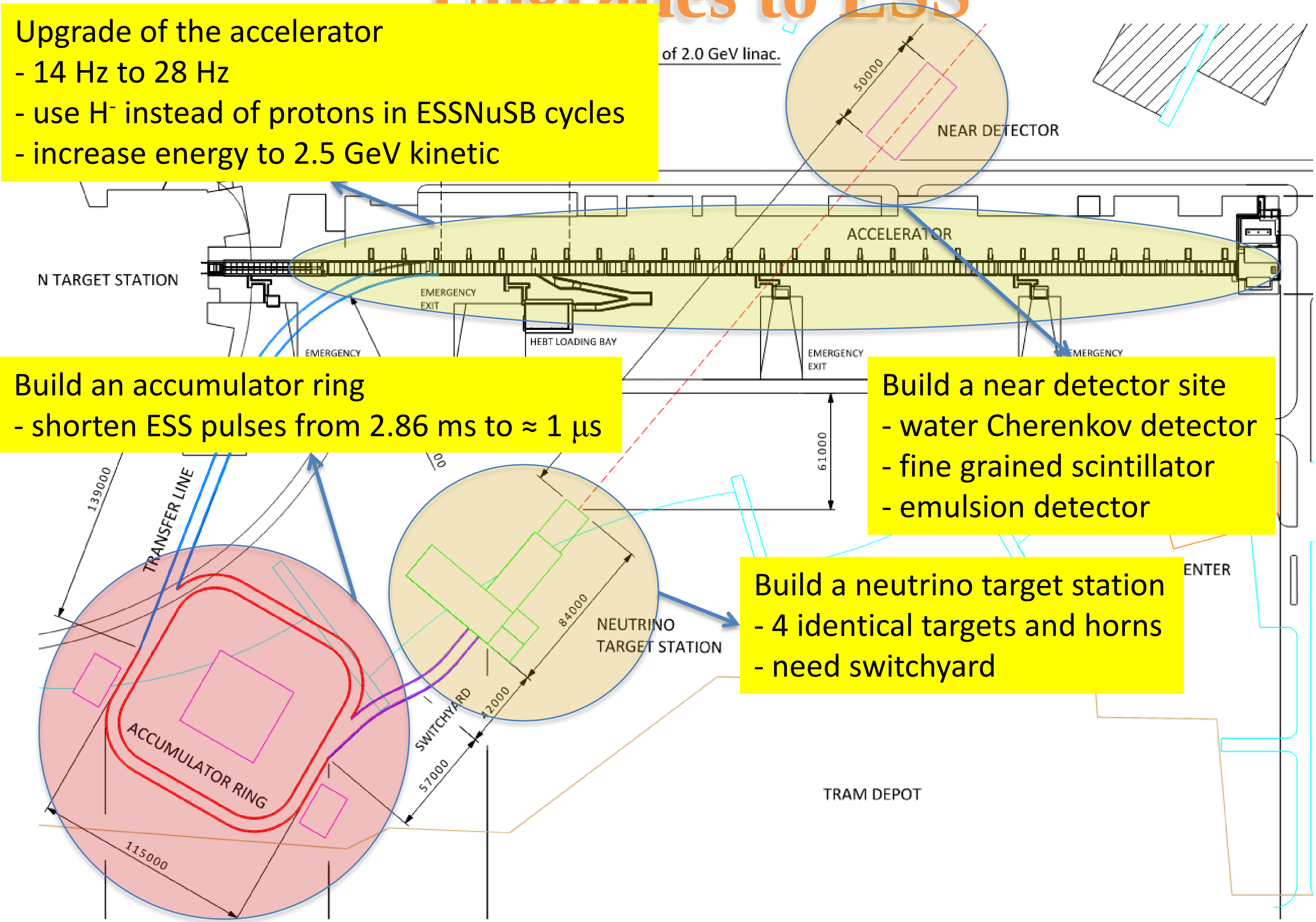

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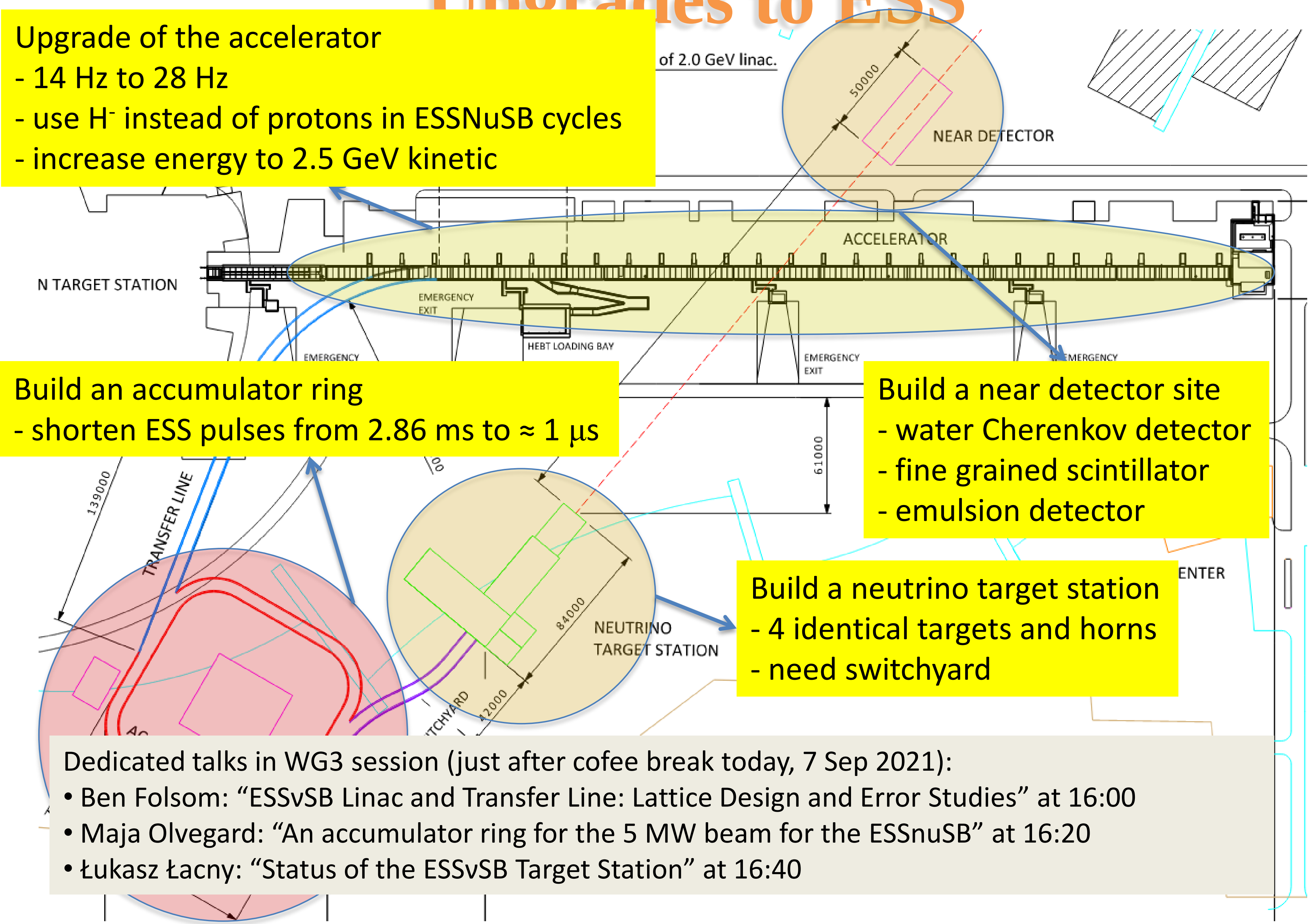

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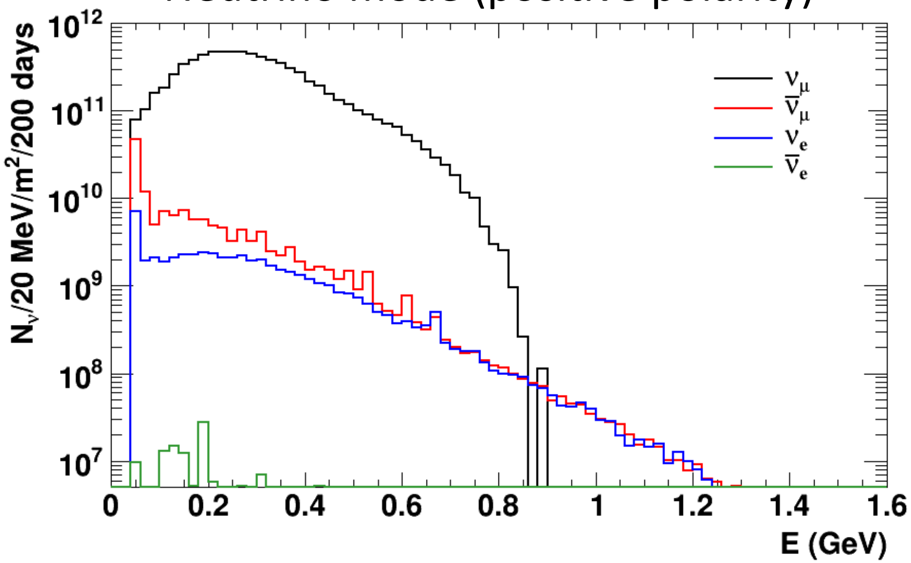
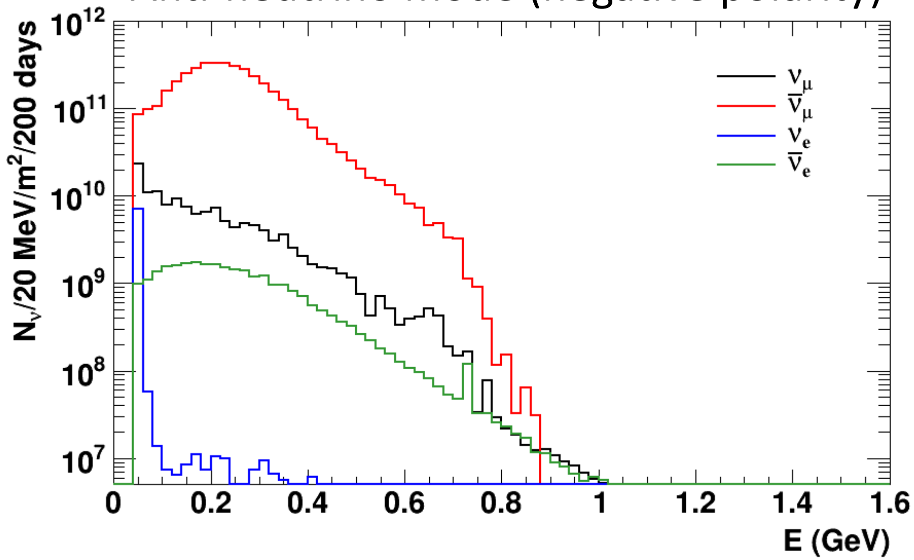
Dedicated talks in WG3 session (just after cofee break today, 7 Sep 2021):
- Ben Folsom: “ESSvSB Linac and Transfer Line: Lattice Design and Error Studies” at 16:00
- Maja Olvegard: “An accumulator ring for the 5 MW beam for the ESSnuSB” at 16:20
- Łukasz Łacny: “Status of the ESSvSB Target Station” at 16:40

ESSνSB ν energy distribution (after optimisation)

Neutrino mode (positive polarity)



Anti-neutrino mode (negative polarity)

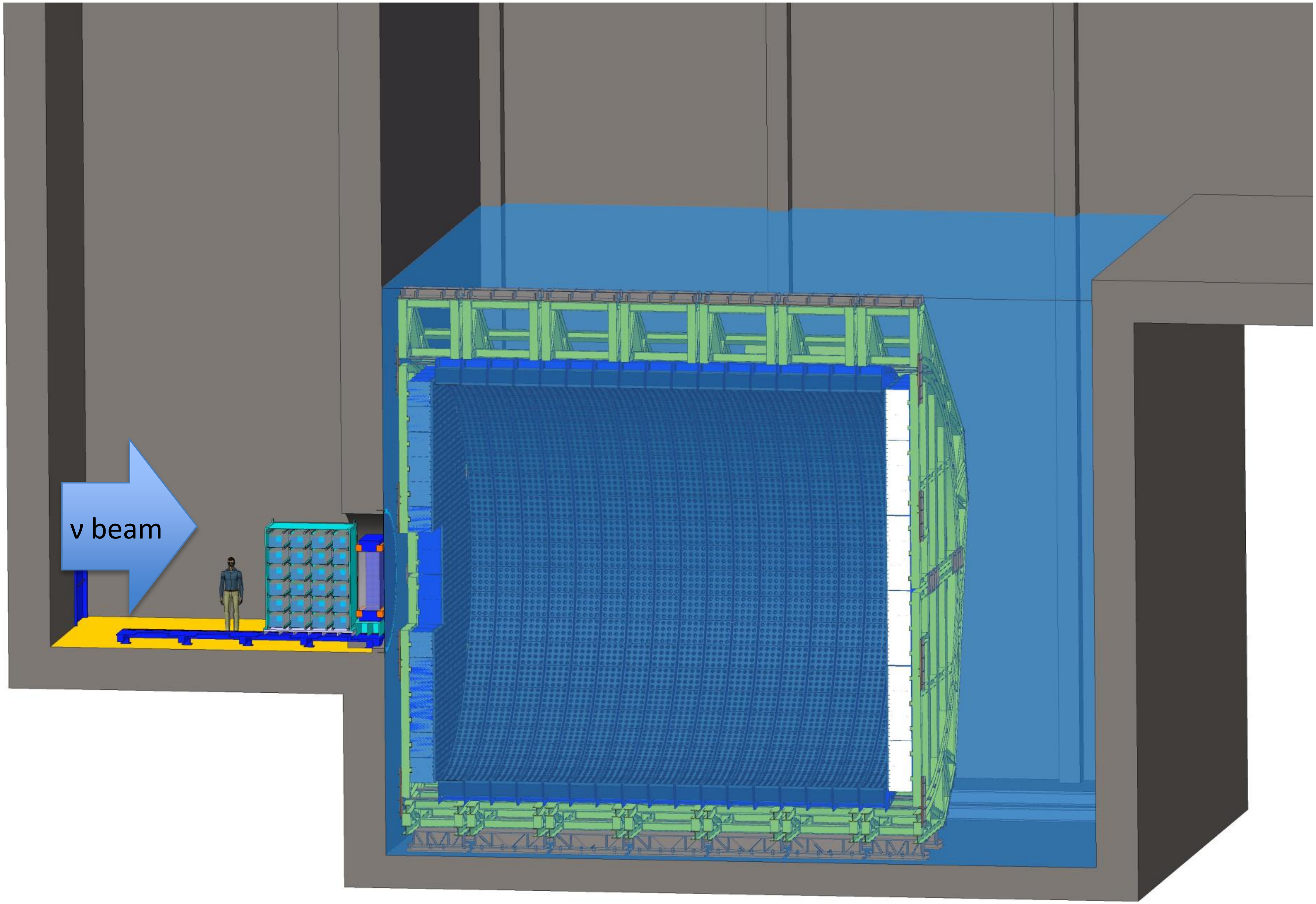


- almost pure ν_μ beam
- small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

	Positive		Negative	
	$N_\nu\,(10^{10}/m^2)$	%	$N_\nu\,(10^{10}/m^2)$	%
ν_μ	743	97.4	13.7	3.3
$\bar{\nu}_\mu$	14.5	1.9	397	95.9
ν_e	5.2	0.7	0.7	0.02
$\bar{\nu}_e$	0.01	0.002	2.7	0.7

at 100 km from the target and per year (in absence of oscillations)

Near detectors



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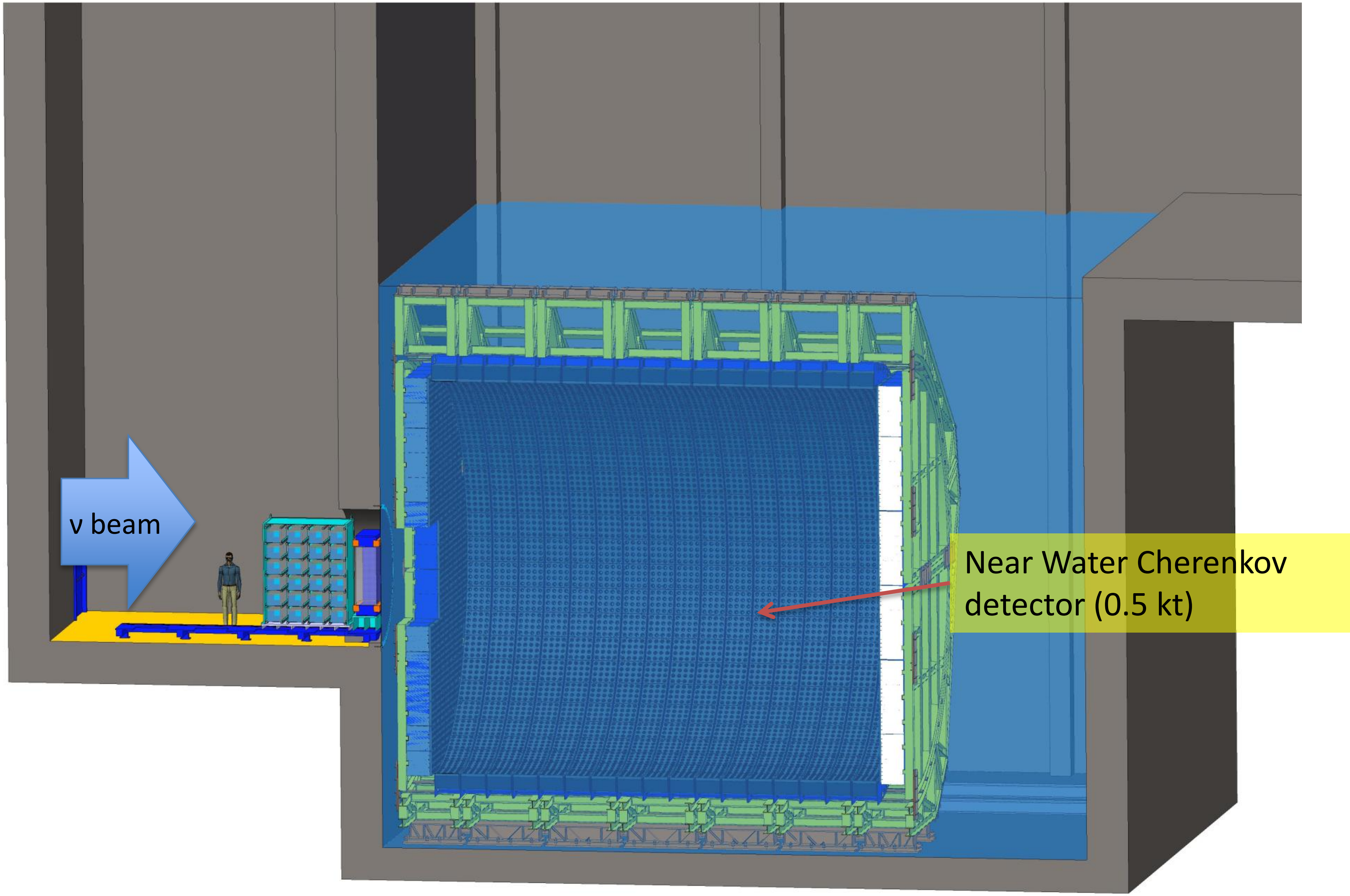

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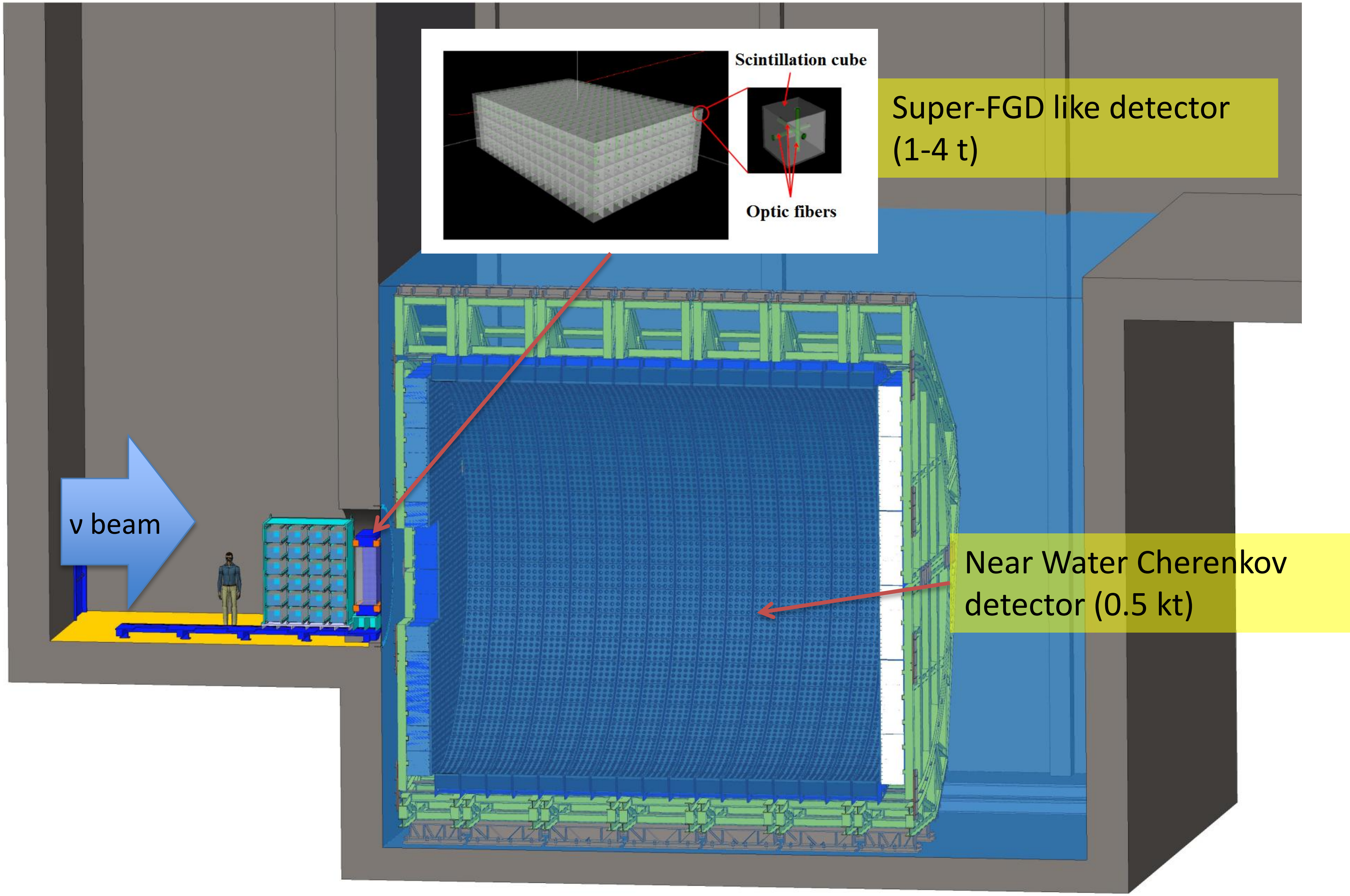
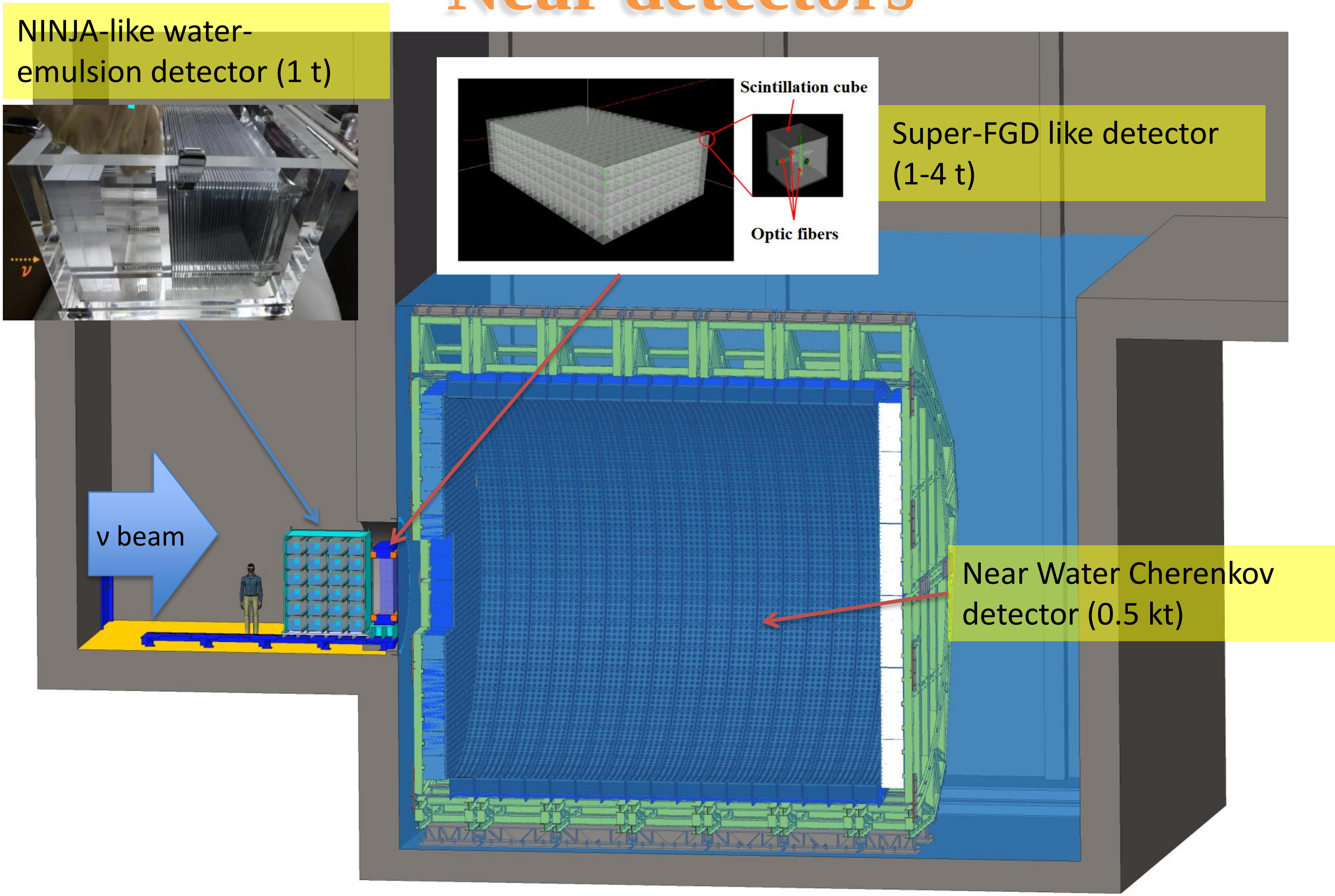
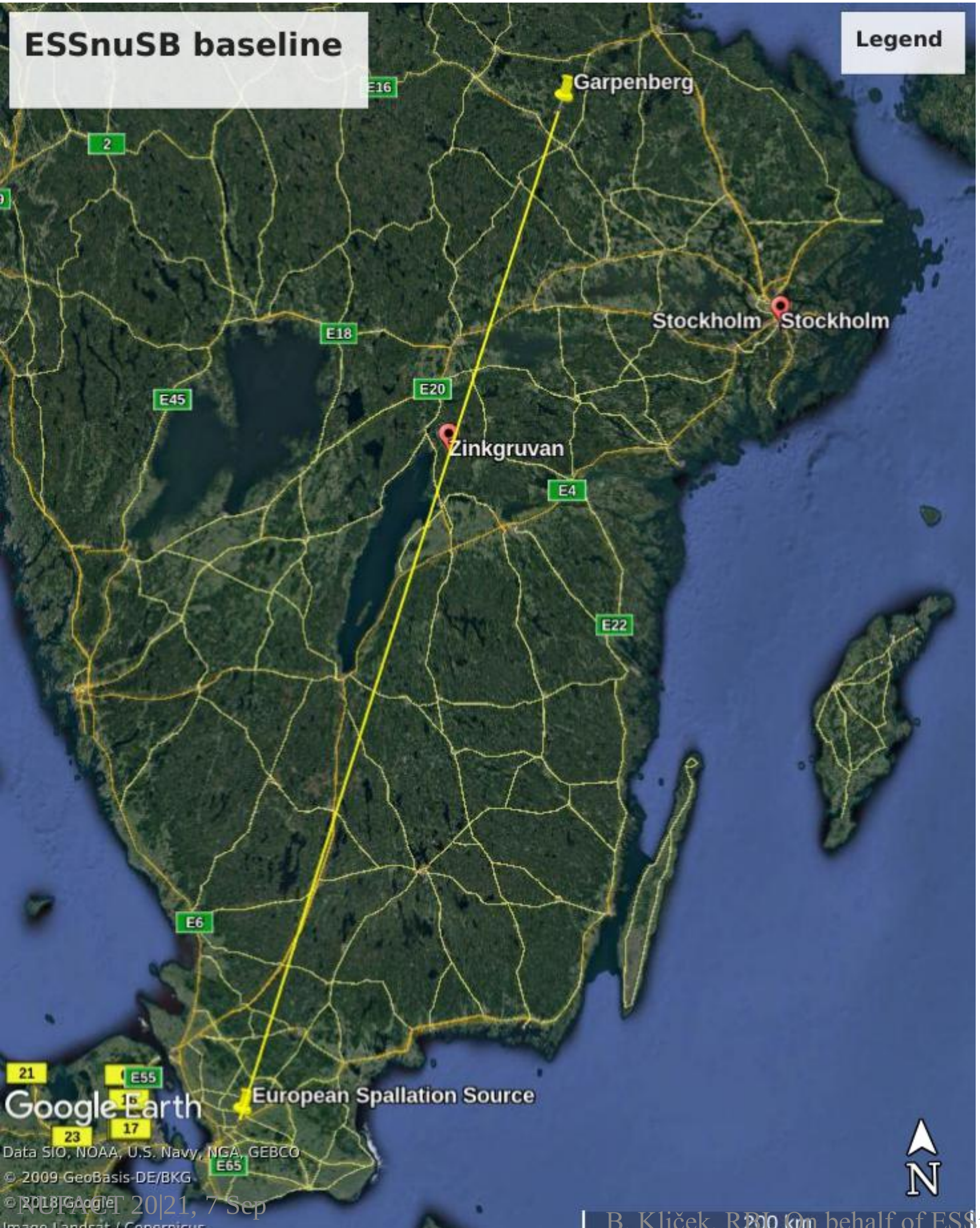


Near detectors



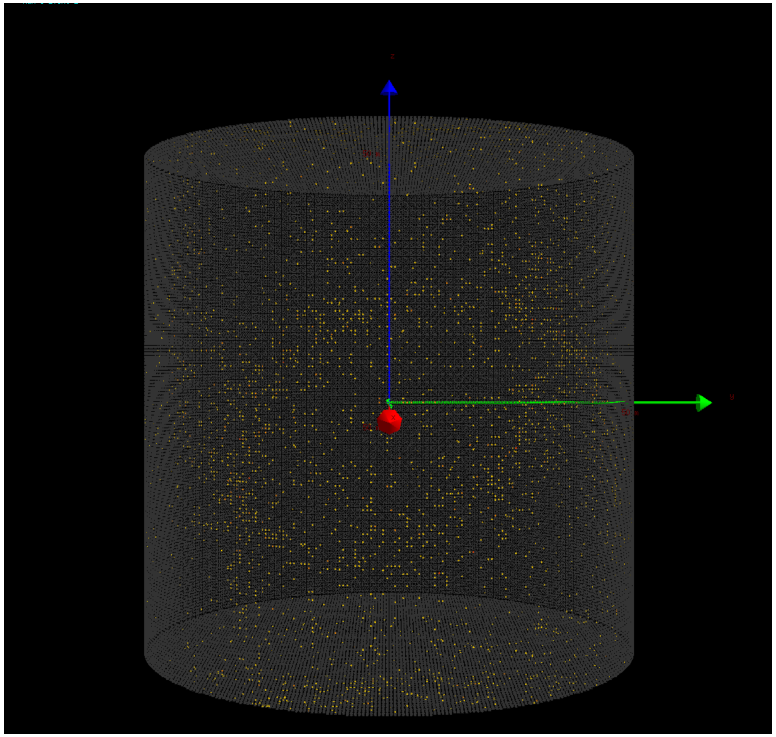


Far detector position

Baselines:

- Garpenberg mine, 540 km from the neutrino source, corresponding to 2nd oscillation maximum.
- Zinkgruvan mine, 340 km from source, partly covernig 1st and 2nd maximum

Far detectors

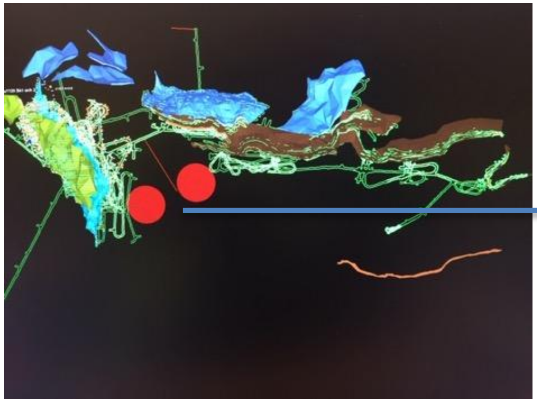


Baseline

- 2 x 270 kt fiducial volume (~20xSuperK)
- Readout: 2 x 38k 20” PMTs
- 30% optical coverage
    - currently using 40% for analysis

Can also be used for other purposes:

- Proton decay
- Astroparticles
- Galactic SN ν
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

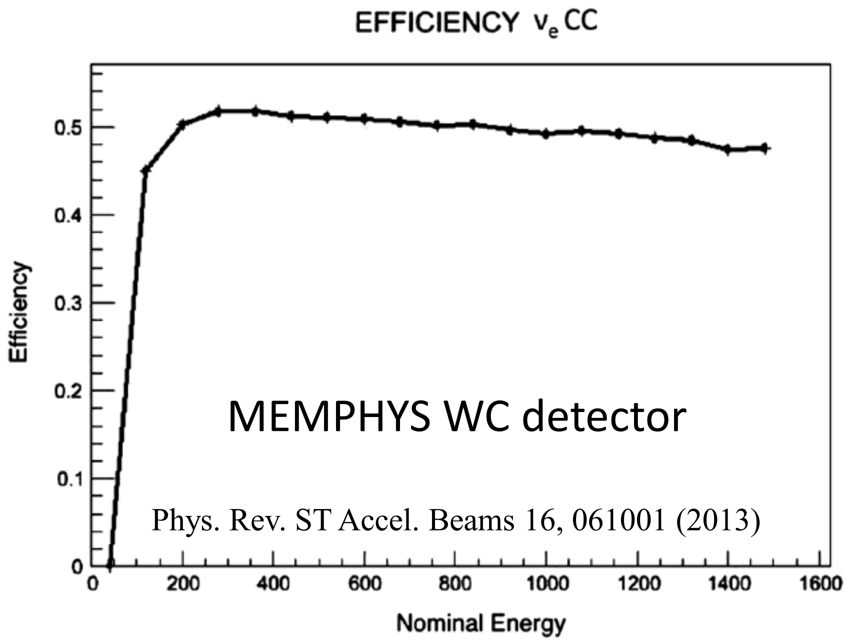


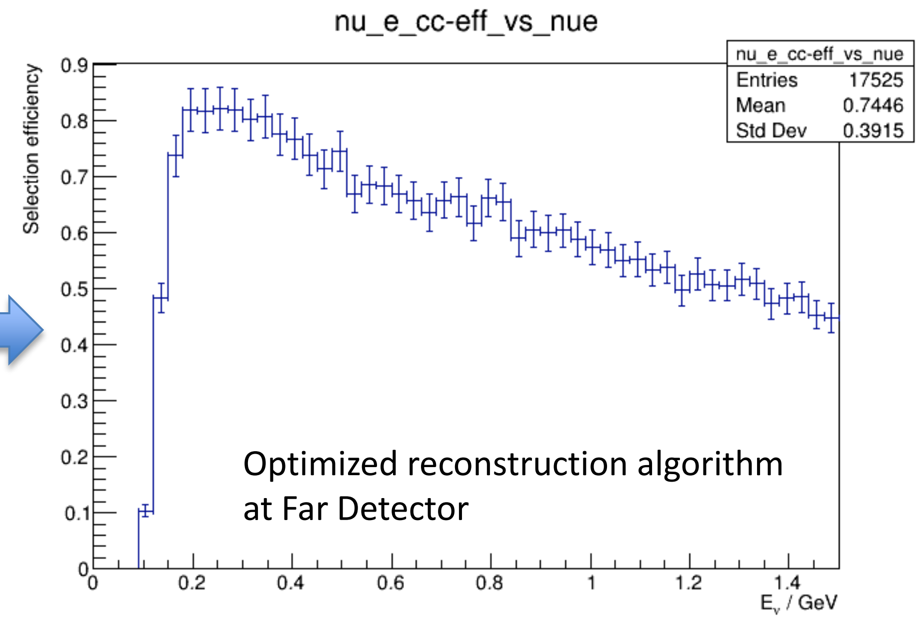
Possible positions at Zinkgruvan mine

See poster by Olga Zormpa: “ESSnuSB detector performance” for much more details on migration matrices, efficiencies, ..

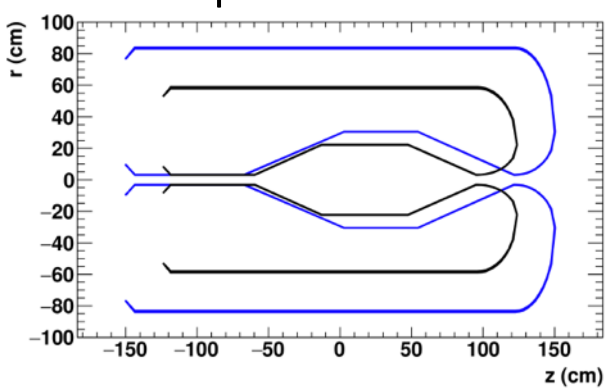
Improvements on sensitivity

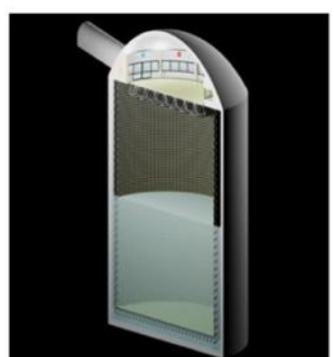
- New Migration Matrices for the far detector compared to those of MEMPHYS
- Genetic Algorithm for Target Station optimisation

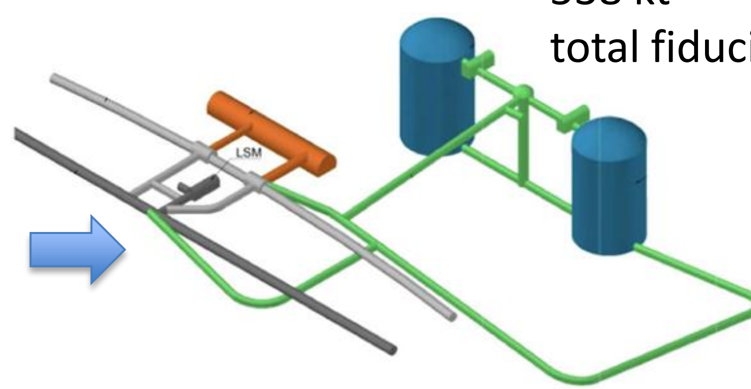




horn optimisation







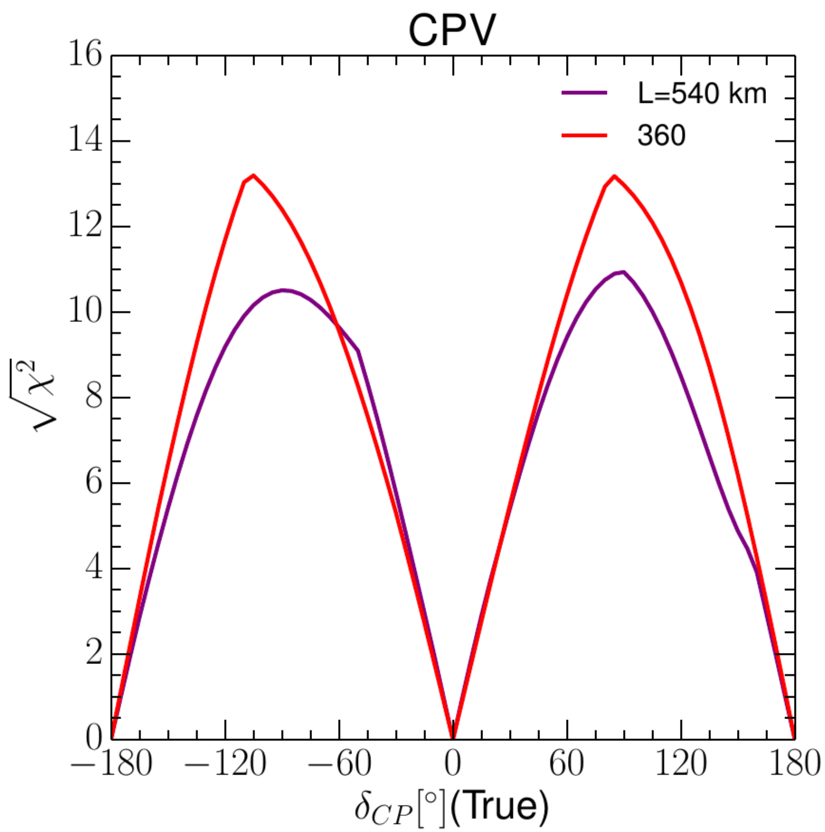
538 kt
total fiducial

Updated physics performance (assumptions)

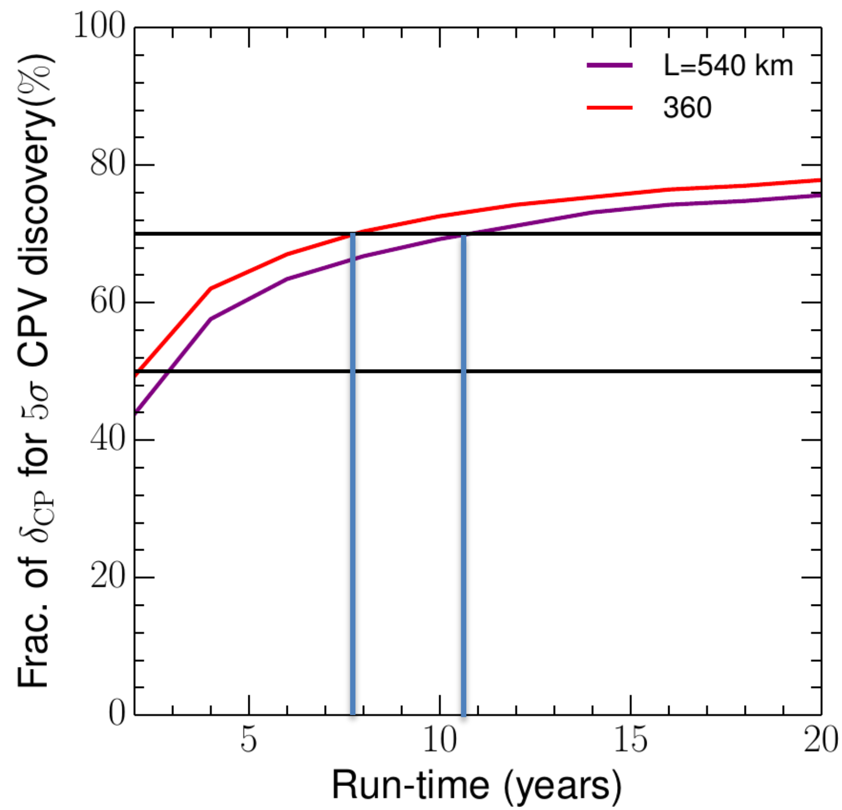
- **Distance from neutrino source (baseline)**
  - 540 km (Garpenberg)
  - 360 km (Zinkgruvan)
- **Experiment run time**
  - 5 years neutrino mode, 5 years anti-neutrino mode
- **Assumed systematic error**
  - 5 % on signal normalization
  - 10 % on background normalization
- **For more information see:** arXiv:2107.07585

- **Dedicated talk:** Salvador Rosauro @ WG1: "Physics potential of ESSnuSB", 9 Sep 2021 at 13:30-13:50.
  - also including preliminary shape uncertainty, inclusion of atmospheric neutrinos...

Updated physics performance (sensitivity)



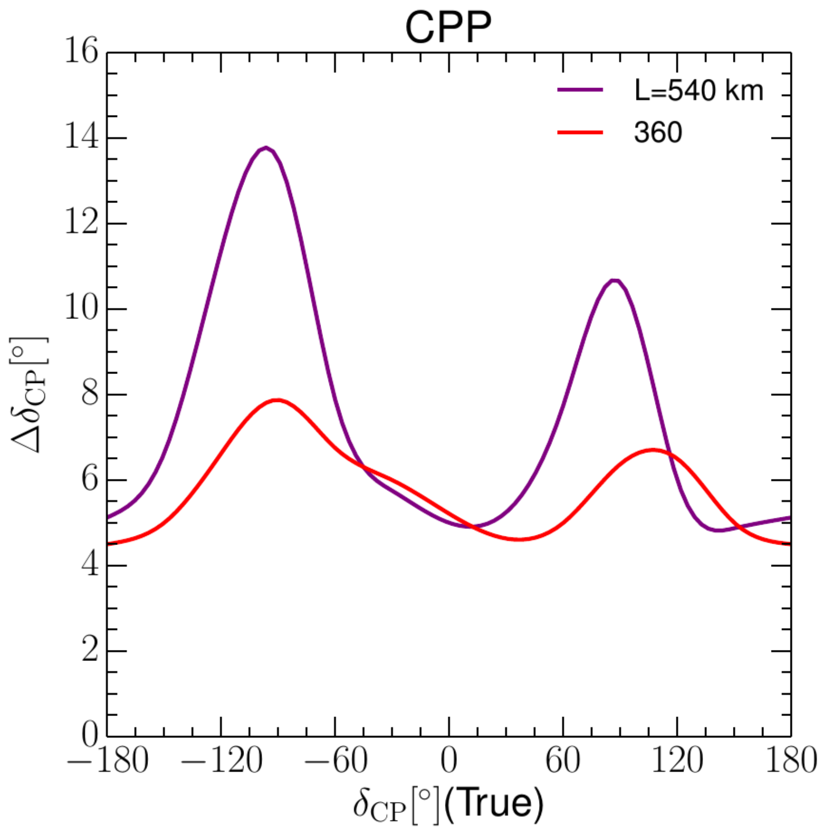
Sensitivity for $\delta_{CP} = \pm \pi/2$:
11 σ (540 km)
13 σ (360 km)

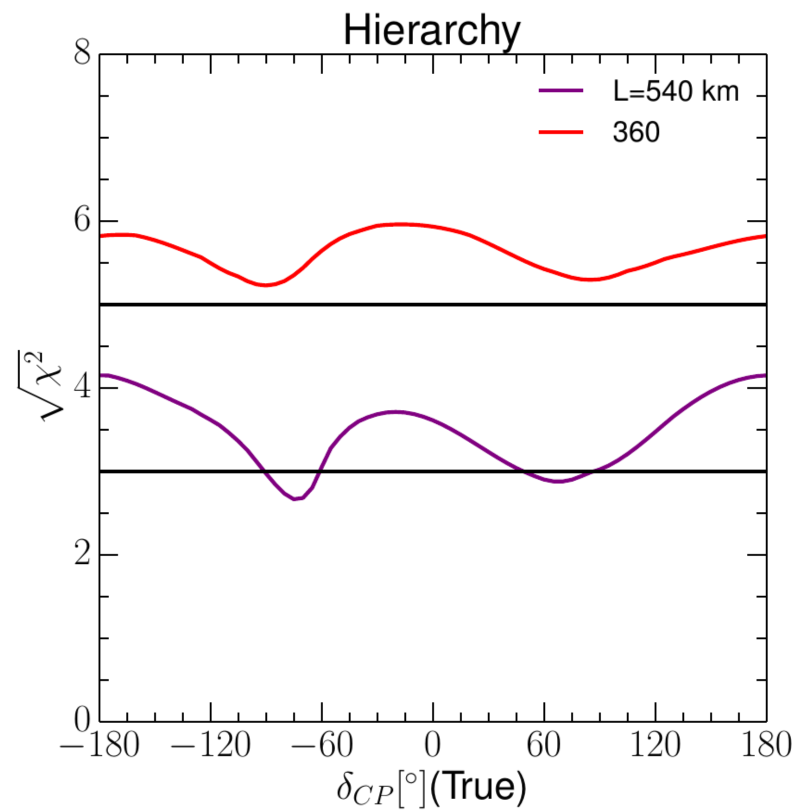


75% δ_{CP} coverage @ 5 σ:
11 years (540 km)
6 years (360 km)

From: arXiv:2107.07585

Updated physics performance (resolution and hierarchy)





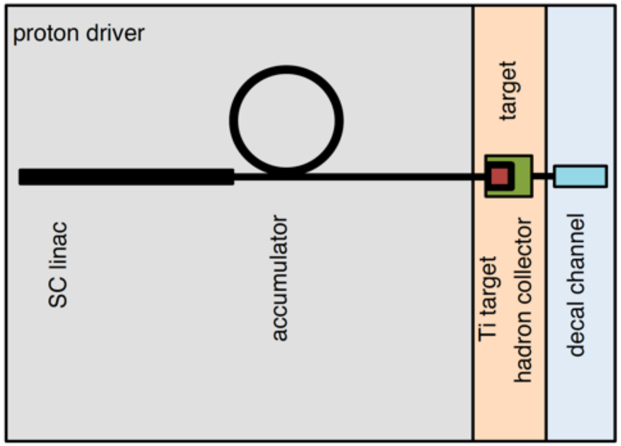
High precision of δ_{CP} measurement

At 360 km mass hierarchy determined at 5 σ

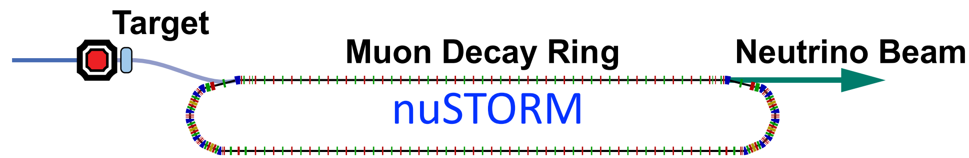
From: arXiv:2107.07585

ESSνSB and (R&D) synergies

Super Beam



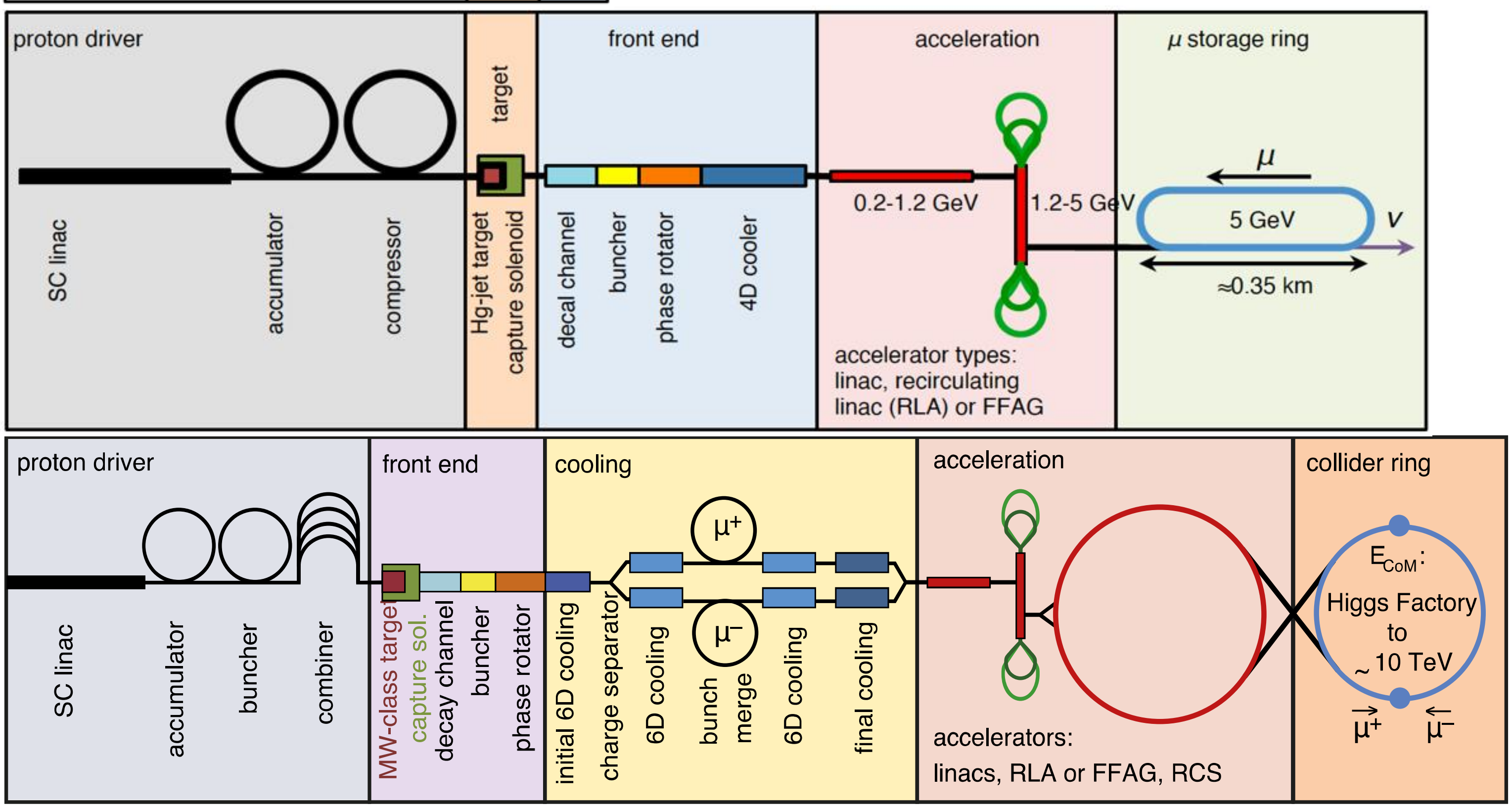
Dedicated series of workshops is organized
https://indico.cern.ch/event/849674/



+Decay At Rest and Coherent scat.
(with short pulses)

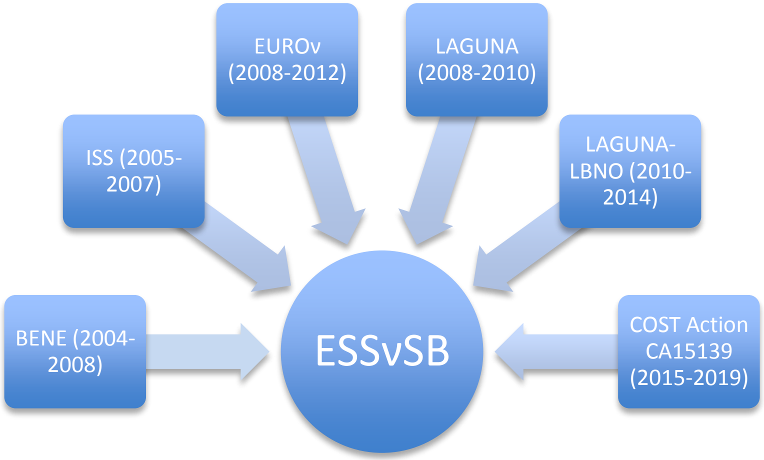
Neutrino Factory

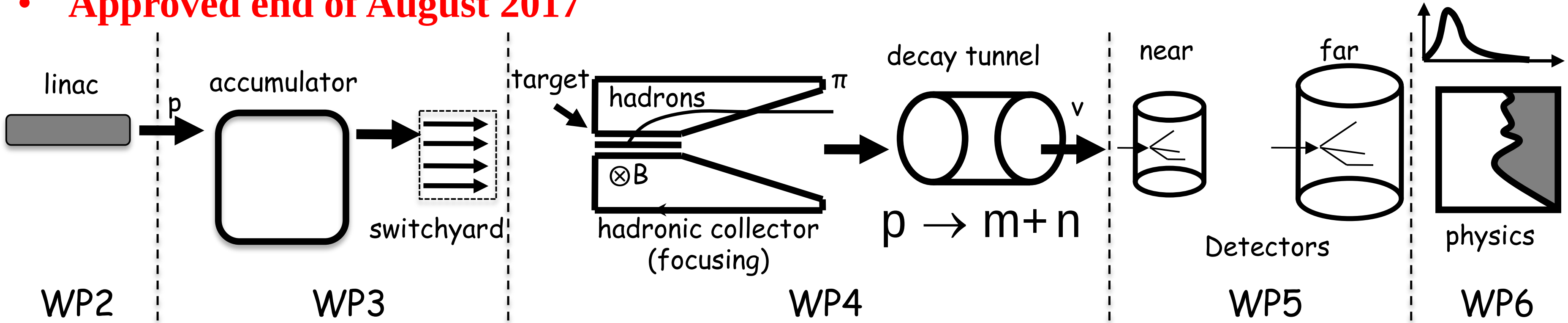
Muon Collider



ESSνSB at the European level

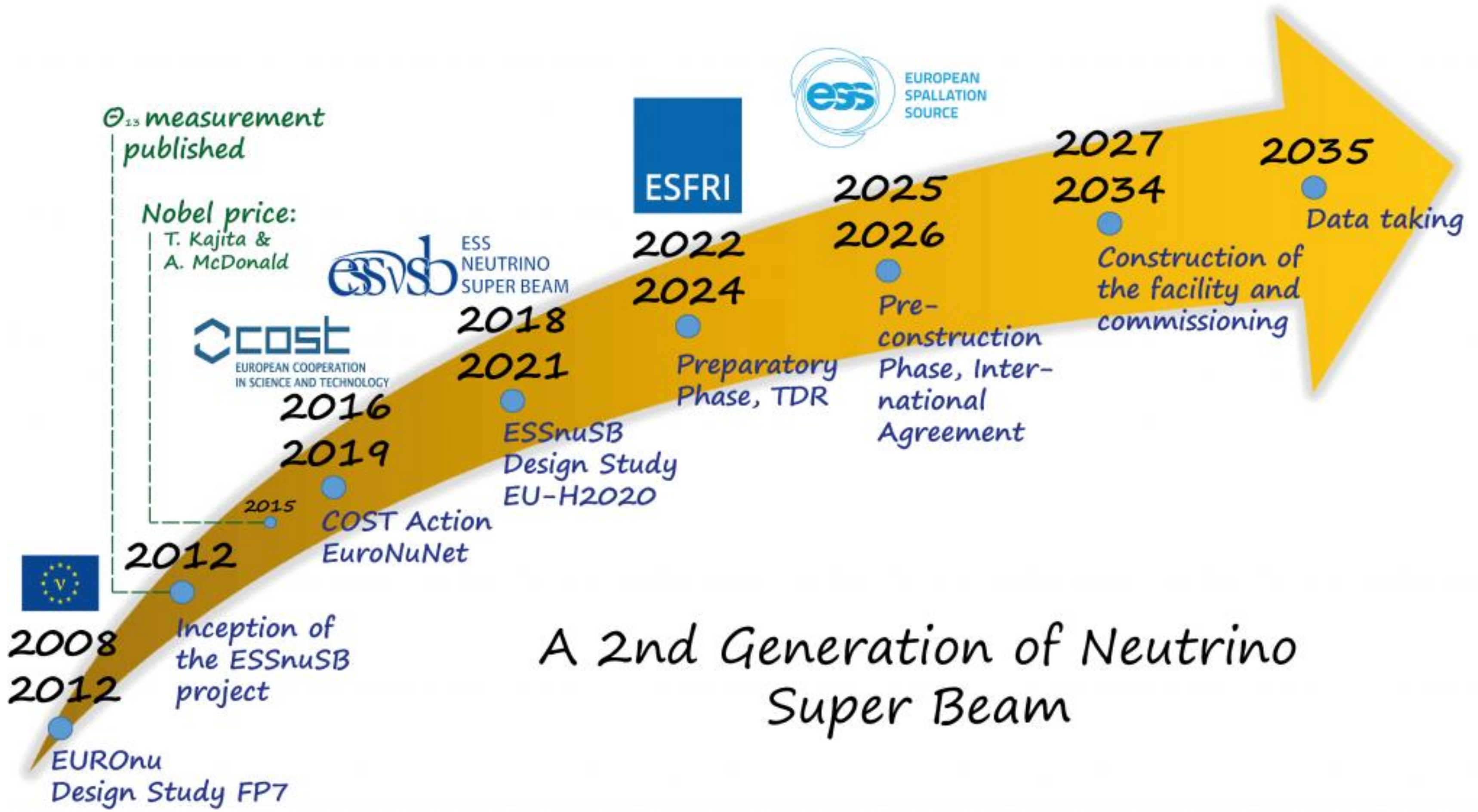
- A **H2020** EU **Design Study** (Call INFRADEV-01-2017)
  - **Title of Proposal**: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
  - **Duration: 4 years**
  - **Total cost: 4.7 M€**
  - **Requested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





Possible ESSνSB schedule

(2nd generation neutrino Super Beam)



Summary of ESSnuSB workshop

Introduction of the ESSnuSB/HIFI Design Study program 2022-2025	*THotel*	*Marcos Dracos* 09:00 - 09:20
Civil engineering and safety requirements for ESSnuSB at the ESS site	*THotel*	*Boris Kildetoft* 09:20 - 09:40
Civil engineering and safety requirements for ESSnuSB at the Far Detector site	*THotel*	*David Saiang* 09:40 - 10:00
Environment preservation and societal commitment	*THotel*	*Colin Carlile* 10:00 - 10:20
Prospects for decay-at-rest and coherent neutrino scattering at ESS	*THotel*	*janet conrad* 10:20 - 10:40
Design of a Low Energy (0.4 GeV) nuSTORM race-track ring	*THotel*	*Maja Olvegard* 10:40 - 11:00
Upgrades of the ESSnuSB design required to enable tests of the Muon Collider Proton Complex	*THotel*	*Tord Johan Carl Ekelof* 11:00 - 11:20
A possible ultimate goal: A Muon Collider Higgs Factor based at ESS	*THotel*	*Carlo Rubbia* 11:20 - 11:45

Summary of ESSnuSB workshop

HIFI - High Intensity Frontier Initiative

Introduction of the ESSnuSB/HIFI Design Study program 2022-2025 *Marcos Dracos*

THotel

Civil engineering

THotel

Civil engineering

THotel

Environment pres

THotel

Prospects for dec

THotel

Design of a Low E

THotel

Upgrades of the E

THotel

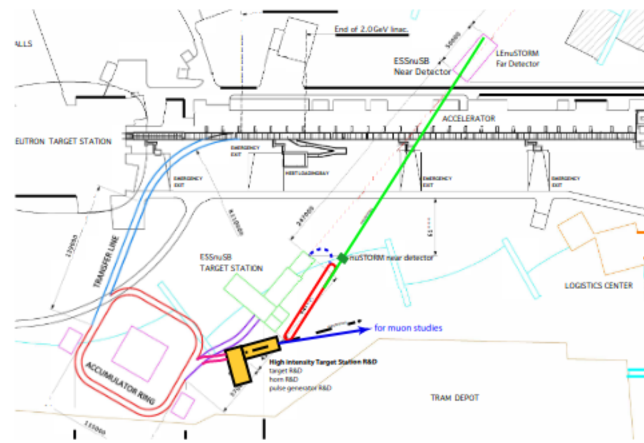
A possible ultima

THotel

Proposed scenario for the period 2022-25

Possible WPs:

1. Civil engineering (ESS and mine site), safety and environment preservation.
2. Linac, accumulator/compressor and LEnuSTORM race-track.
3. ¼ Target Station, hadron/muon production and muon extraction for Low Energy nuSTORM.
4. Detectors and physics performance (synergy between ESSnuSB and LEnuSTORM).
5. Partial design studies of initial steps towards a Muon Collider, of the compression of 1.3 μs bunches of 10^{14} protons to order 1 ns and a target that can withstand such short bunches.



The asset: in ~2025 (or so…) ESS will have the LINAC in operation with a MMW proton beams the high scientific potential of which **cannot be ignored or disregarded.**

preparation of the R&D phase

M. DRACOS NuFact2021, 07/09/2021 17

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COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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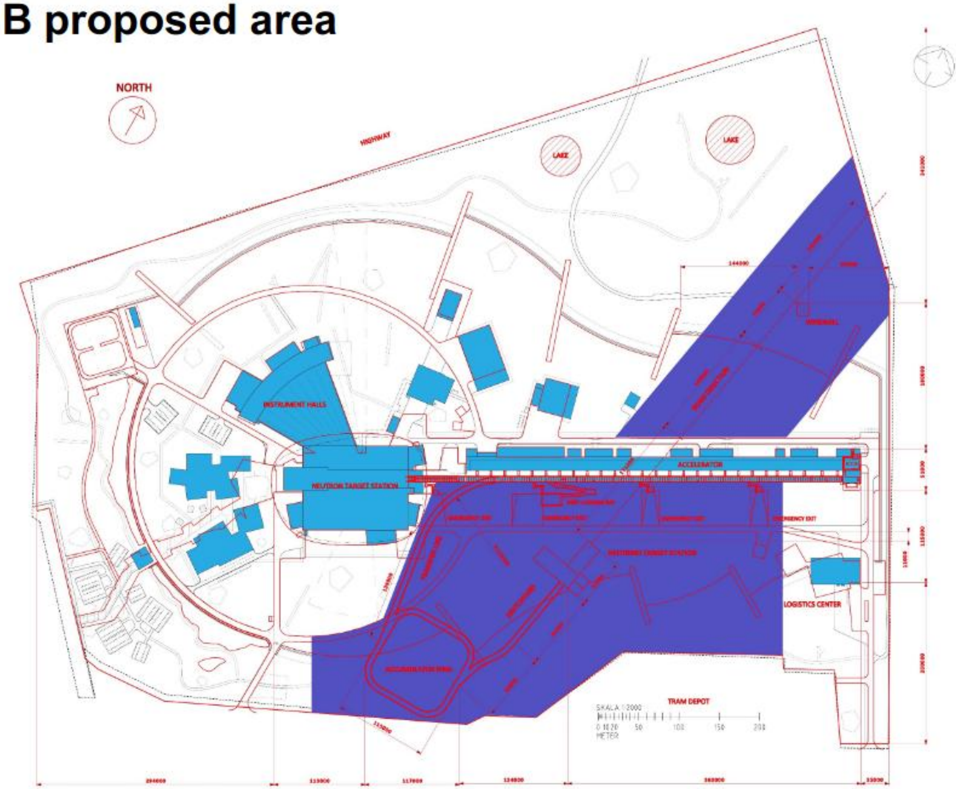
ESSnuSB proposed area



EUROPEAN SPALLATION SOURCE

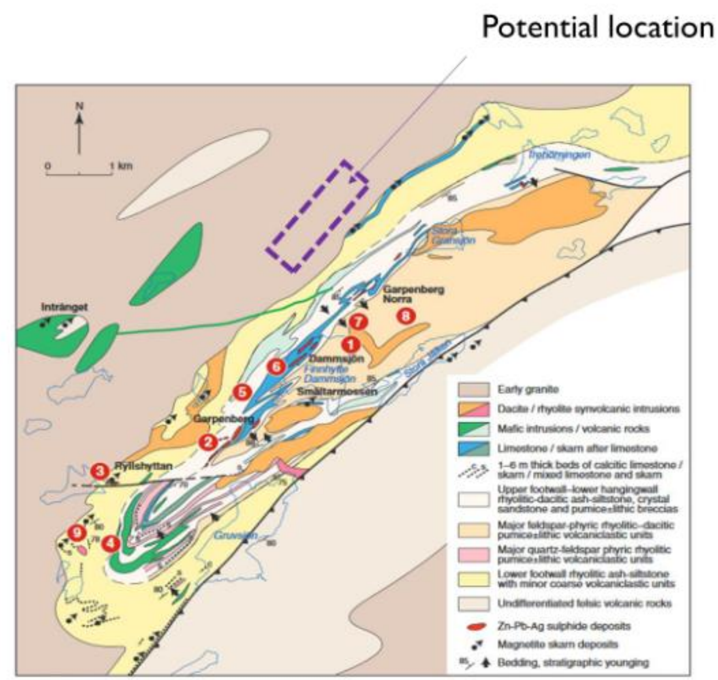
THotel 09:00 - 09:20

Summary of ESSnuSB workshop

Civil engineering and safety requirements for ESSnuSB at the Far Detector site	*David Saiang*
THotel	09:40 - 10:00
Environment preservation and societal commitment	*Colin Carlile*
THotel	10:00 - 10:20

Site of interest – Garpenberg mine

ESS NEUTRINO SUPER BEAM



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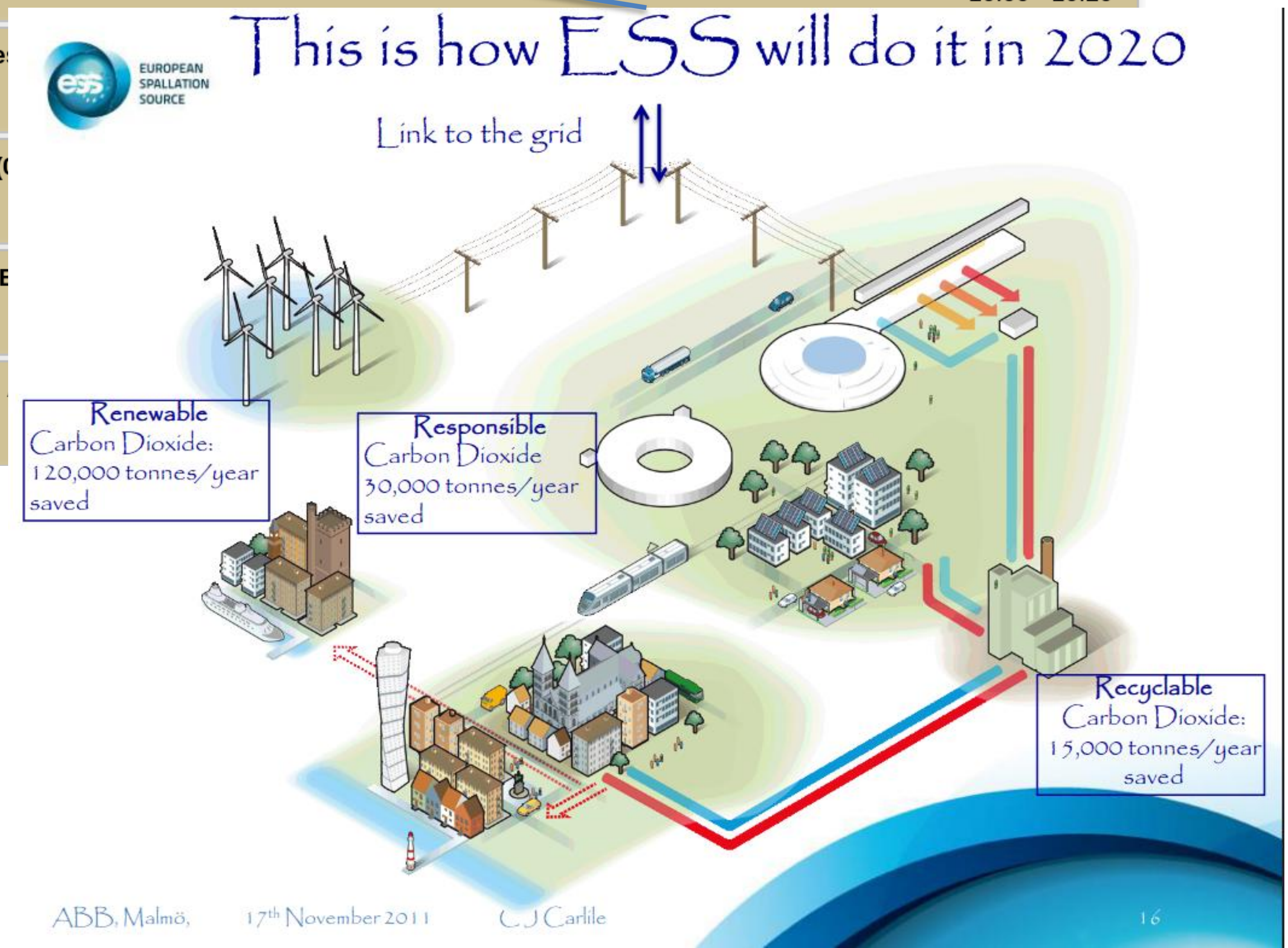
A possible ultimate goal:	
THotel	



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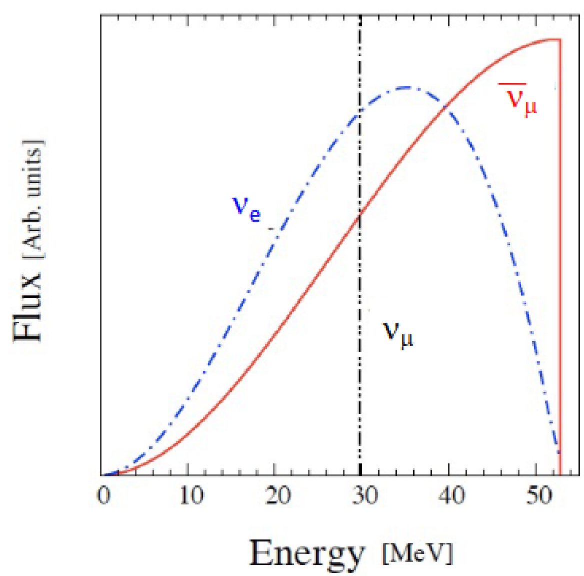
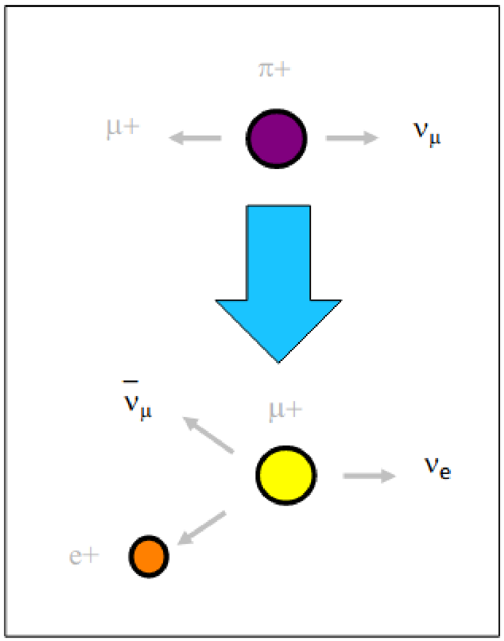
THotel	
A possible ultimate goal: A Muo	
THotel	

Most of the running and proposed experiments use Pion/muon decay-at-rest fluxes





π- chain absorbed, so negligible $\bar{\nu}_e$

Summary of ESSnuSB workshop

ESS based nuSTORM

Introduction
THotel

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- Pions from separate target or muons from ESSnuSB decay tunnel?
  - Capturing of muons directly, with kicker magnets
  - Less efficient?
  - No need to transport two species simultaneously.
- Low energy muons
  - Can or should have a smaller ring and/or shorter arcs
  - Wide angle neutrino source
- Fewer turns?
  - Less losses
  - Lower flux control?

Design of a Low Energy (0.4 GeV) nuSTORM race-track ring — *Maja Olvegard*
THotel — 10:40 - 11:00

Upgrades of the ESSnuSB design required to enable tests of the Muon Collider Proton Complex — *Tord Johan Carl Ekelof*
THotel — 11:00 - 11:20

A possible ultimate goal: A Muon Collider Higgs Factor based at ESS — *Carlo Rubbia*
THotel — 11:20 - 11:45

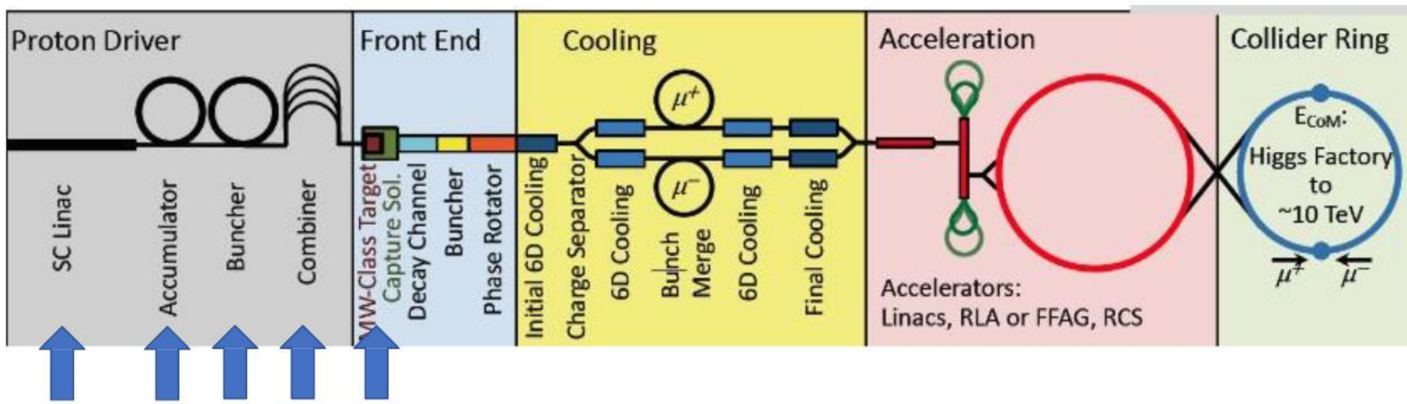
ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Summary of ESSnuSB workshop

The Muon Collider Proton Complex

The Muon Collider proton complex and the target with pion collector is one of the critical parts of the Muon Collider project because of the combination of very high power, order 2 MW, to be delivered in 5 pulses per second, each pulse being of about 2 ns length and each containing 5×10^{14} protons of 5 GeV.



Given the ESS proton linac under construction and the ESSnuSB design already made of the linac upgrade and of an accumulator ring, it is proposed to enlarge the scope of the current design study of the linac and the accumulator and fading adding a design study of a compressor/buncher ring generating 2 ns bunches of order 10^{14}-10^{15} protons and of a target and capturing system (horn or solenoid) that can stand such bunches.

2021-07-12 NUFACT2021 in Cagliari Tord Ekelof Uppsala University 22

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Design of a Low Ene
THotel 10:40 - 11:00

Upgrades of the ESSnuSB design required to enable tests of the Muon Collider Proton Complex *Tord Johan Carl Ekelof*
THotel 11:00 - 11:20

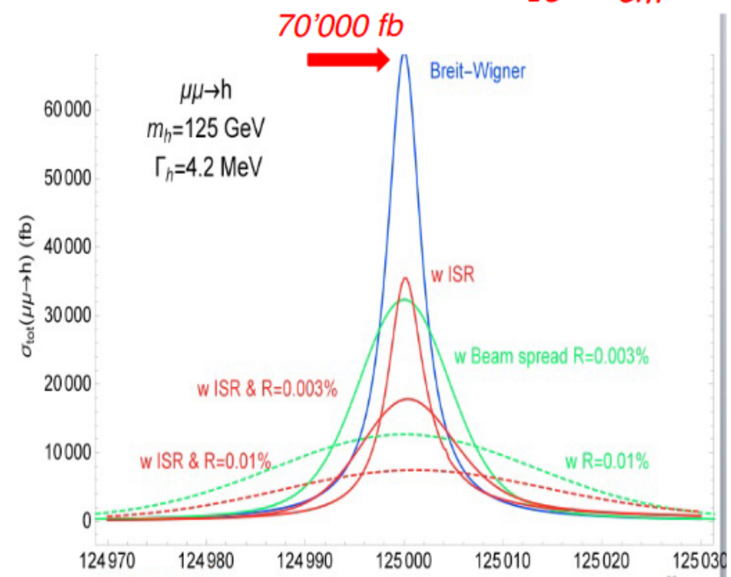
A possible ultimate goal: A Muon Collider Higgs Factor based at ESS *Carlo Rubbia*
THotel 11:20 - 11:45

Summary of ESSnuSB workshop

Comparing $\mu+\mu-$ and e+e- at the Ho resonance peak

- The narrow Ho width may be quantified convoluting the Breit-Wigner resonance with a gaussian Beam Energy Spread (BES) and the Initial State Radiation (ISR) QED effects.
- The $\mu+\mu-$ cross sections are 71 pb for resonance profile alone and of 10 pb and 22 pb with both BES and ISR and energy resolution R = 0.01 % and R = 0.003 %. (1 pb = 10^{-36} cm^2)
- The e+e– cross sections are 0.15 fb for both the BES and ISR effects and R = 0.01 %.
- *In these conditions, the $\mu+\mu-$ is ≈ 100'000 times the e+e– cross section.*

1 femtobarn (fb) = 10^{-39} cm^2



Huge BES an ISR correctins

NuFact -Sept 7th 2021

Slide# : 4

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THotel		11:00 - 11:20
A possible ultimate goal: A Muon Collider Higgs Factor based at ESS		*Carlo Rubbia*
THotel		11:20 - 11:45

Conclusions

- **ESSnuSB** aims to observe CP violation in neutrino oscillations at the 2nd oscillation maximum using 538 kt WC detector
  - **Recent optimizations** predict that in 10 years of data taking ESSnuSB will be able to
    - reach 5 σ over 75% of δ_{CP} range
    - reach δ_{CP} resolution of less than 8
    - determine neutrino mass hierarchy
- **ESS linac** will be most powerful proton accelerator in the world
  - can be used to generate intense neutrino beam to go to 2nd maximum
  - will start operation by 2023, decision on neutrino programme pending
  - proposed modifications would allow a **rich additional physics** programme at ESS
    - muon physics, DAR experiments, short neutron pulses, ...
- **Large far detectors** can also be used for rich astroparticle physics programme
- **ESSnuSB EU-H2020** Design Study support this project

The end

ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Expected appearance events at FD

	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	292.77 (70.04)	557.52 (118.80)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	20.41 (4.41)	68.12 (13.81)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	133.06 (25.13)	298.28 (57.13)
	$\bar{\nu}_e \to \bar{\nu}_e$ ($\nu_e \to \nu_e$)	0.08 (0.92)	0.20 (2.10)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	14.14 (2.27)	31.82 (5.11)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	2.31 (5.63)	3.99 (11.69)
	$\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$)	0.04 (-)	0.08 (-)
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ ($\nu_\mu \to \nu_\mu$)	0.14 (0.49)	0.45 (1.26)
	$\bar{\nu}_\mu$ NC (ν_μ NC)	0.24 (0.43)	0.54 (0.96)
	ν_e NC ($\bar{\nu}_e$ NC)	0.57 (-)	1.27 (-)

Table 2: Signal and background events for the appearance channel corresponding to positive (negative) polarity per year.

From: arXiv:2107.07585

Expected disappearance events at FD

	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	3077.56 (603.68)	7118.58 (1481.54)
Background	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	13.42 (0.07)	29.45 (0.16)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	38.41 (5.92)	86.43 (13.32)
	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	11.67 (0.031)	35.71 (0.07)
	$\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$)	2.86 (0.63)	7.47 (1.17)
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ ($\nu_\mu \to \nu_\mu$)	25.44 (67.83)	52.22 (131.05)
	ν_e NC ($\bar{\nu}_e$ NC)	0.57 (0.10)	1.27 (0.23)
	$\bar{\nu}_\mu$ NC (ν_μ NC)	0.50 (1.06)	1.12 (2.37)
	$\bar{\nu}_\mu \to \bar{\nu}_e$ ($\nu_\mu \to \nu_e$)	- (0.30)	- (1.07)
	$\bar{\nu}_e \to \bar{\nu}_e$ ($\nu_e \to \nu_e$)	- (0.12)	- (0.28)

From: arXiv:2107.07585

Appearance event spectra at FD

From: [arXiv:2107.07585](https://arxiv.org/abs/2107.07585)

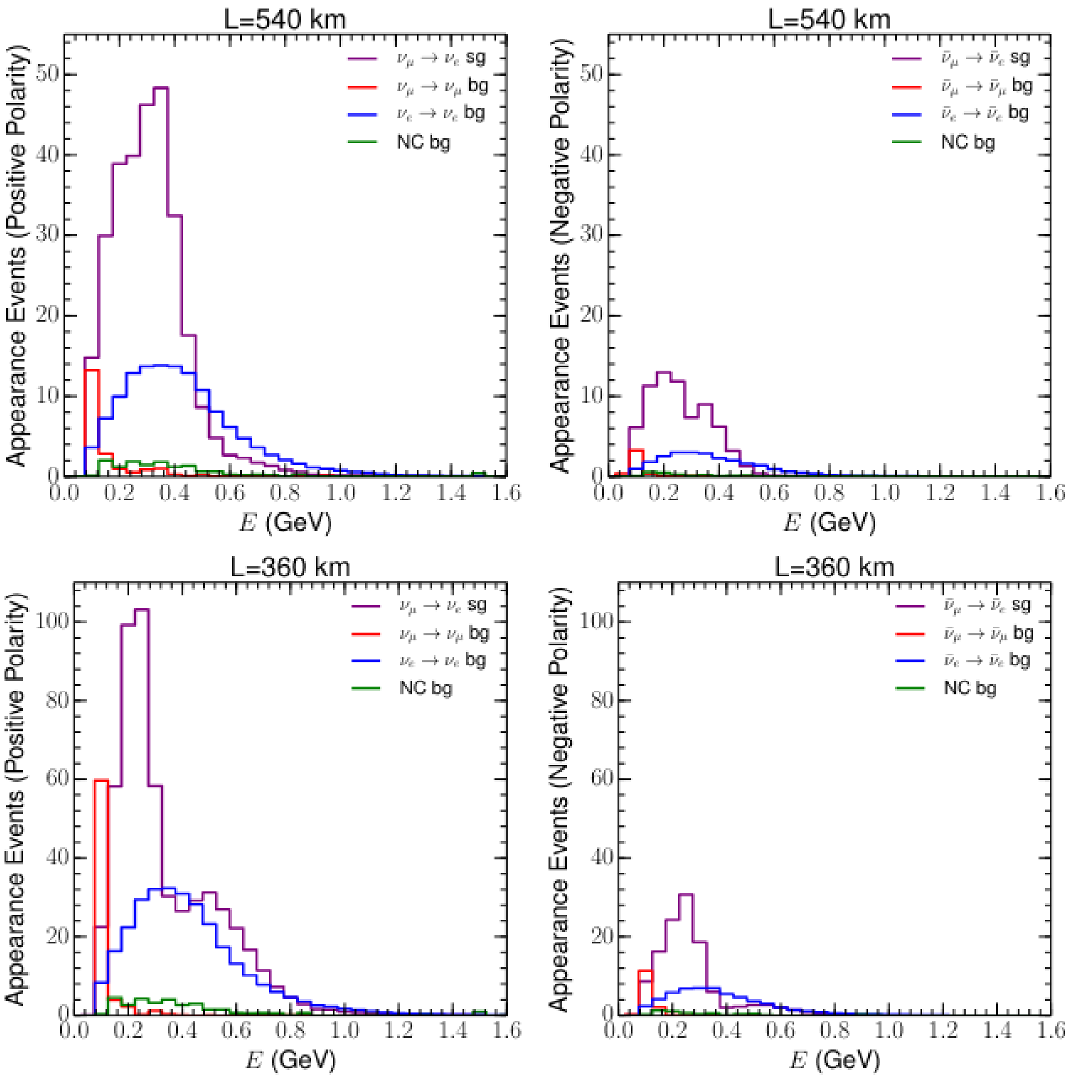


Figure 3: Appearance channel event spectrum vs reconstructed energy. The upper panels are for the baseline option of 540 km and the lower panels are for the baseline option of 360 km. Note the difference in scales between upper and lower panels.

Disappearance event spectra at FD

From: [arXiv:2107.07585](https://arxiv.org/abs/2107.07585)

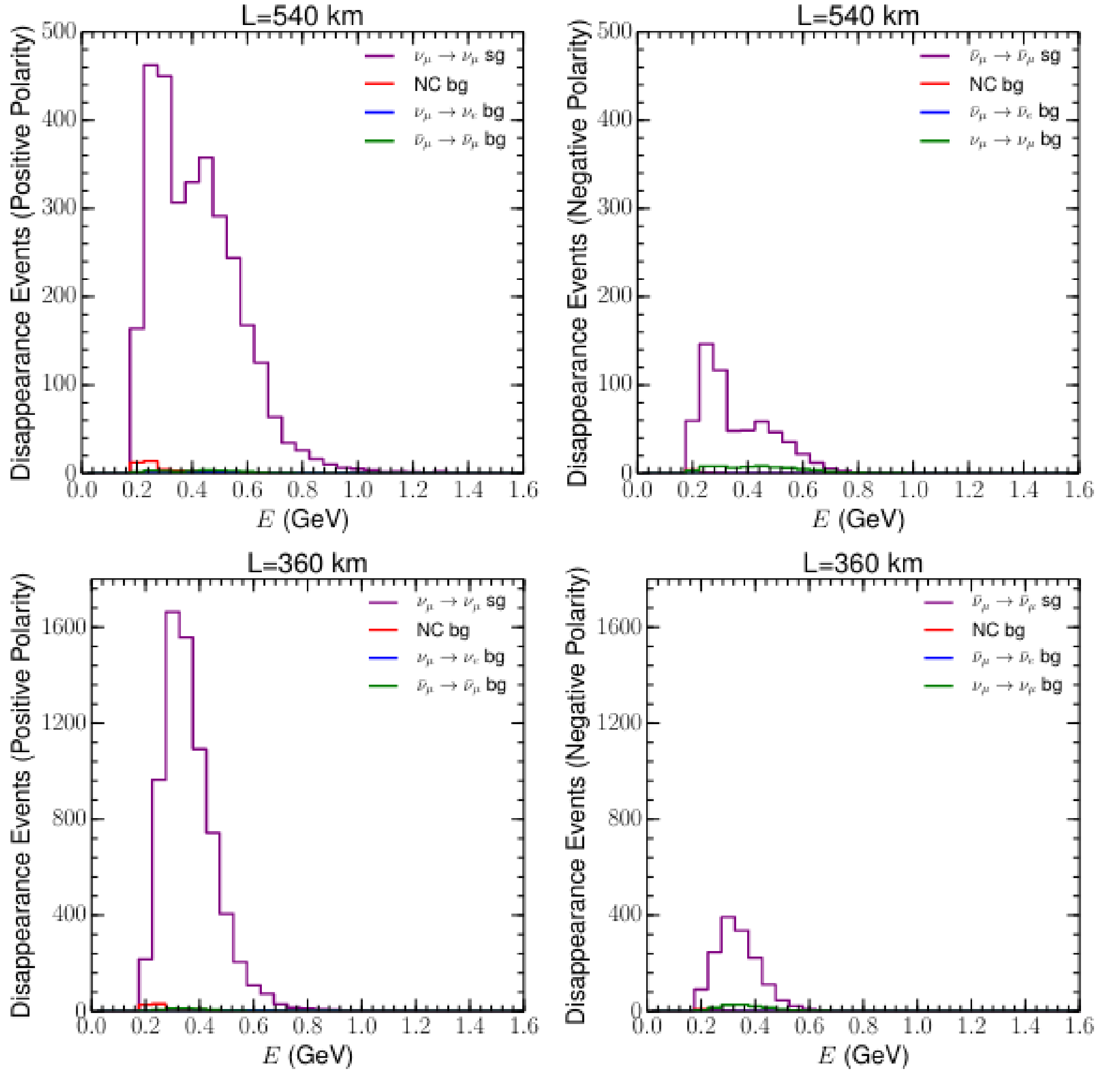
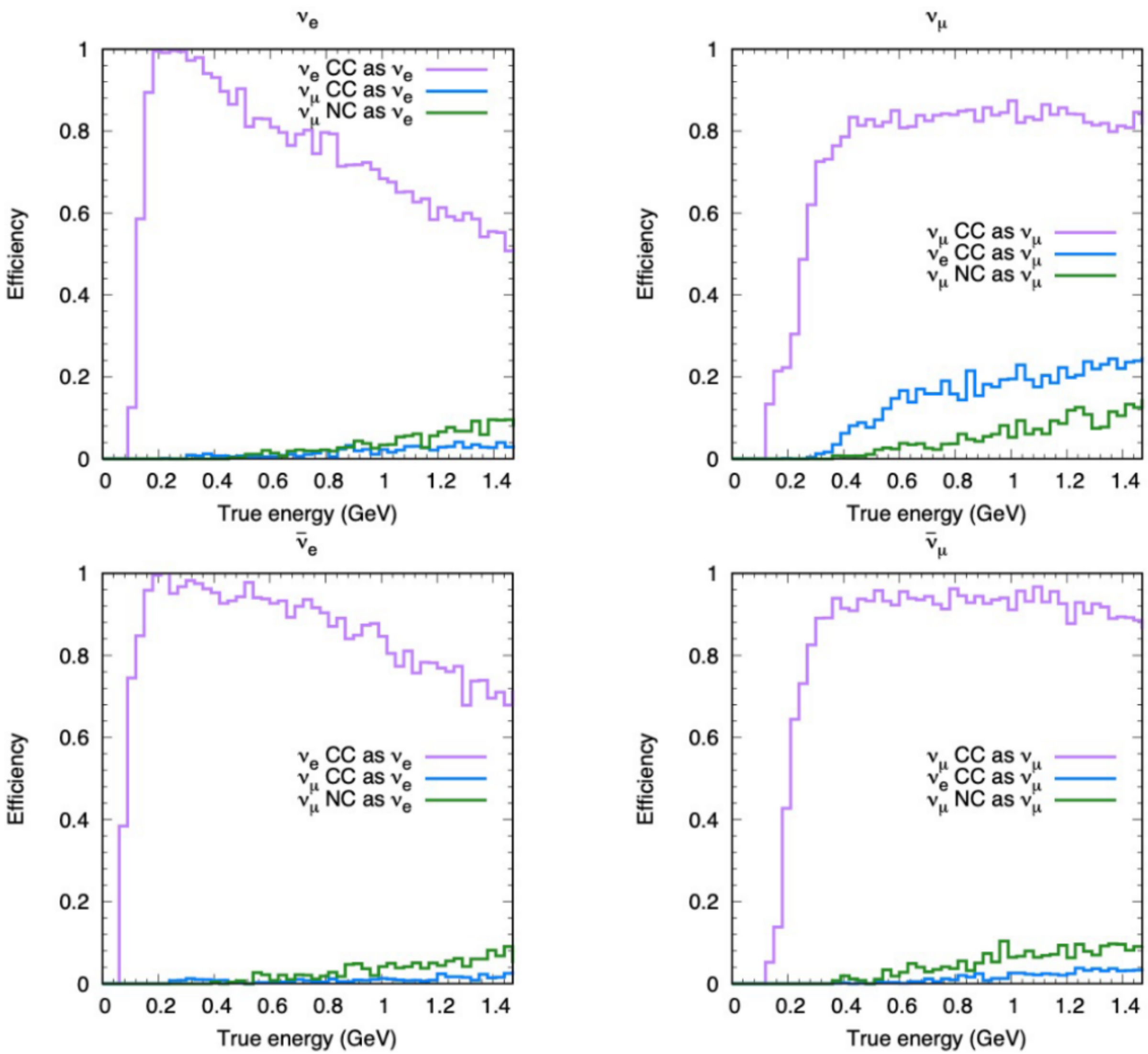


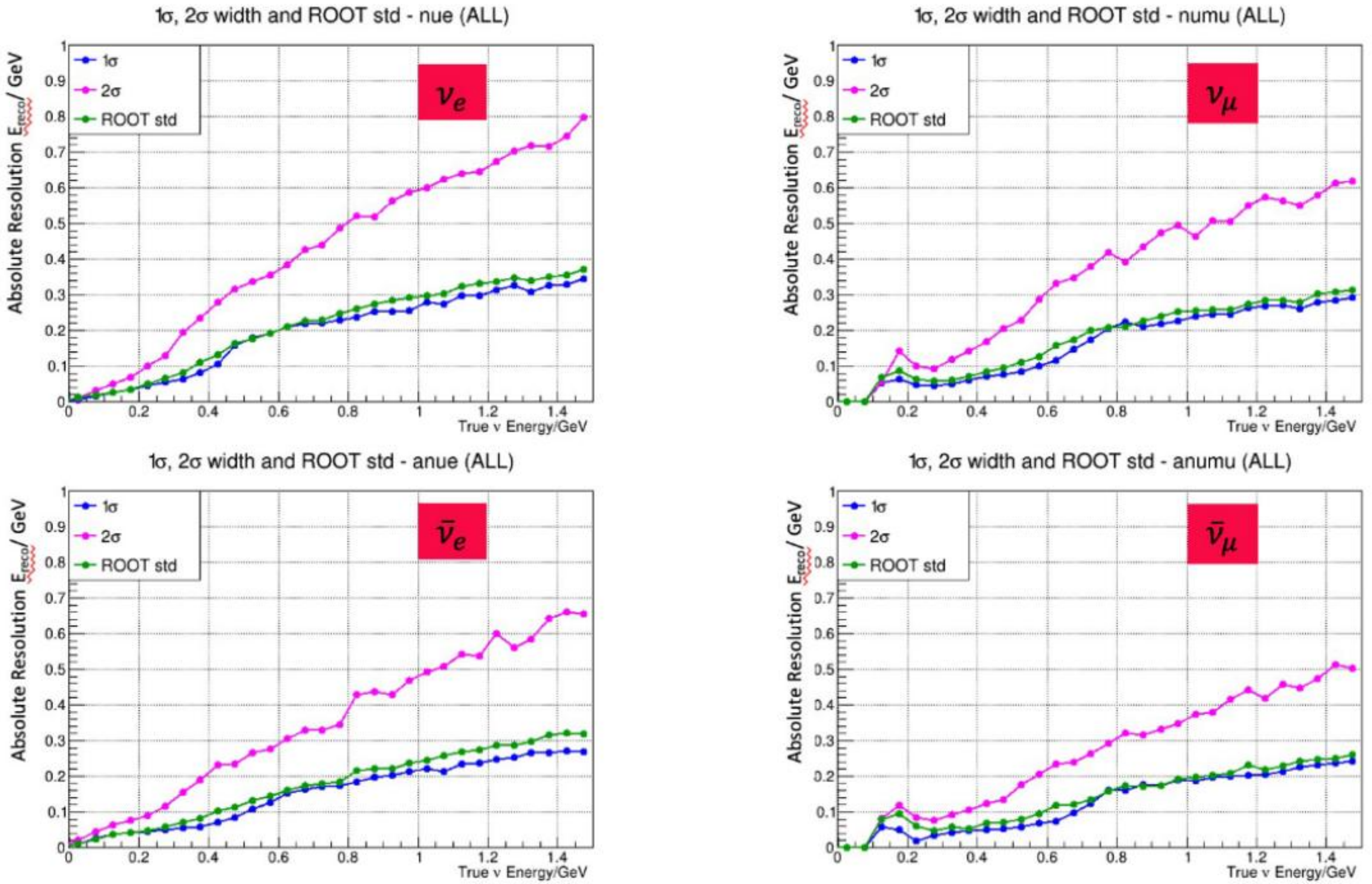
Figure 4: Disappearance channel event spectrum vs reconstructed energy. The upper panels are for the baseline option of 540 km and the lower panels are for the baseline option of 360 km. Note the difference in scales between upper and lower panels.

Efficiencies at FD



From the poster by Olga Zormpa

Absolute FD resolutions



From the poster by Olga Zormpa

Migration matrices at FD

From the poster by Olga Zormpa