



NuFact 2019

The 21st International Workshop on Neutrinos from Accelerators

Daegu, Republic of Korea
August 25 - 31, 2019

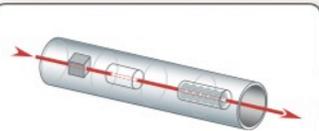
Neutrino CP Violation with the European Spallation Source neutrino Super Beam

Marcos Dracos
IPHC-Strasbourg

European Spallation Source

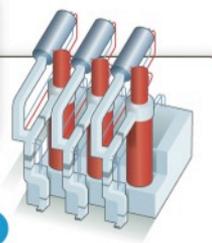


Neutron facility (equivalent to SNS)

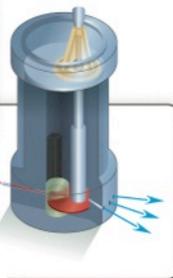


1 Superconducting linear accelerator where protons are accelerated.

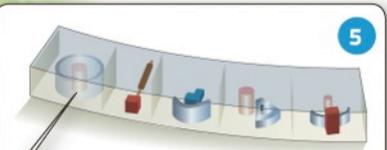
2 Clystrons and modulators provide the power to accelerate the protons.



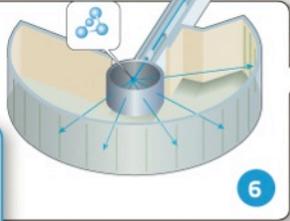
3 Target station where neutrons are emitted and led to neutron beam guides.



4 Laboratory for sample preparation.



5 Instrument hall with instruments for different measurements.

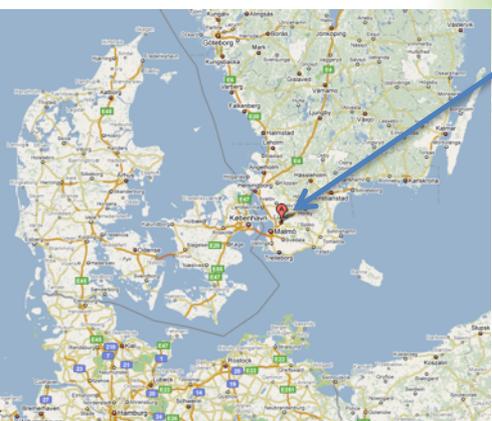


6 Instrument, where the neutrons scatter off the sample, hitting detectors and generating experimental data.



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

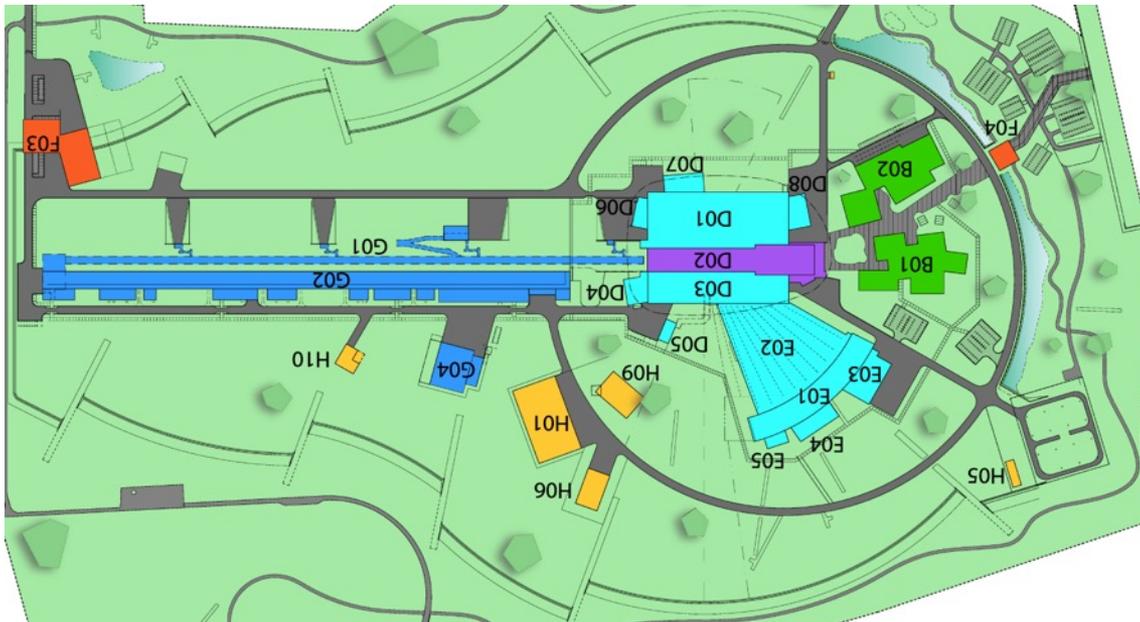
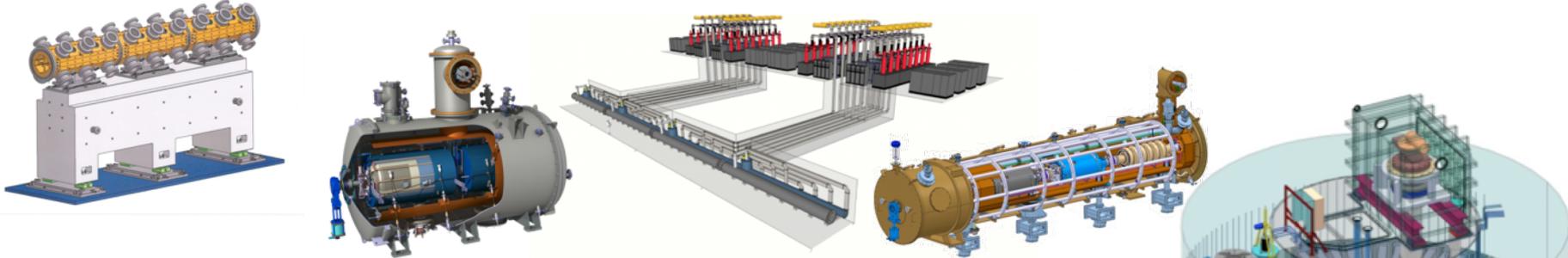
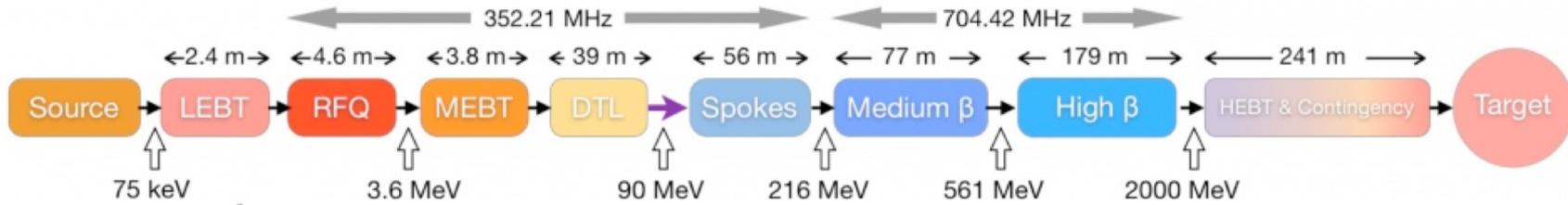
ESS Data Management and Software Centre, Niels Bohr Institute at the University of Copenhagen.



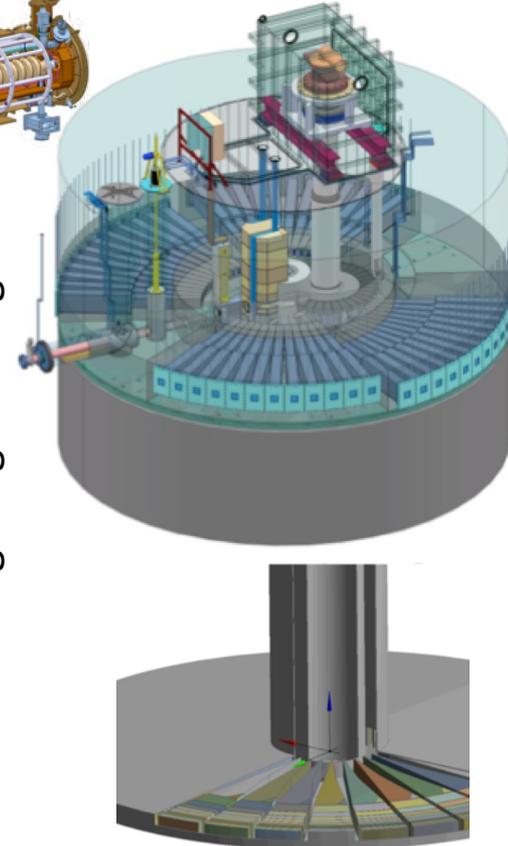
under construction phase (~1.85 B€ facility)

The ESS neutron facility

Optimus+_2013_10_31

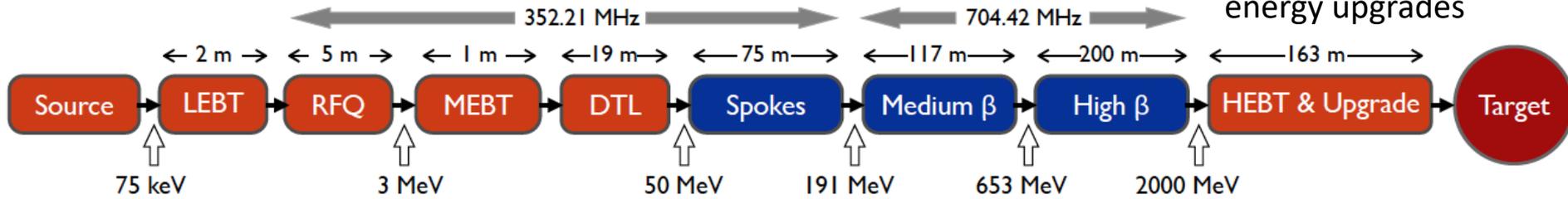


rotating tungsten target

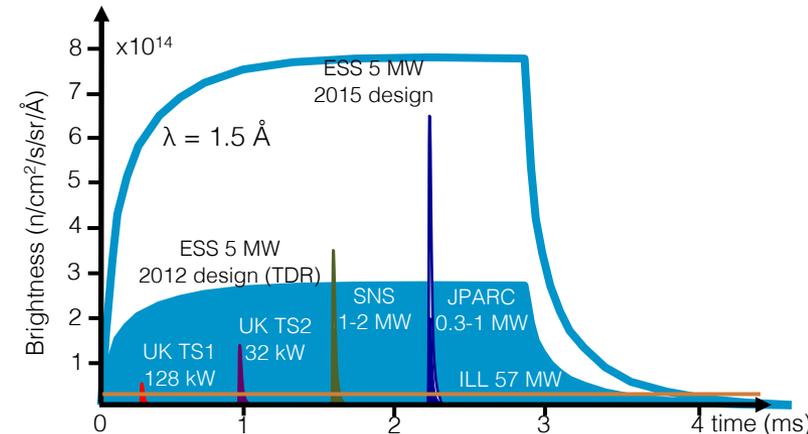
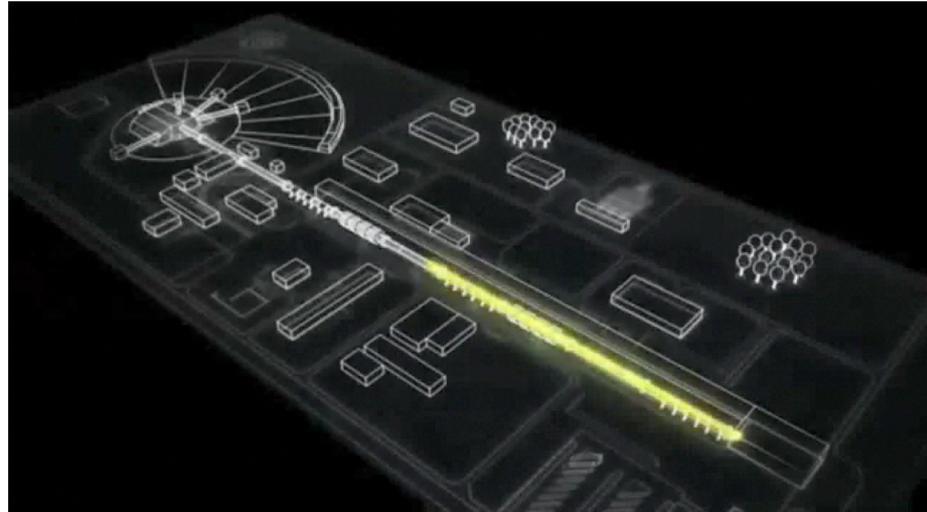


ESS proton linac

empty space for energy upgrades

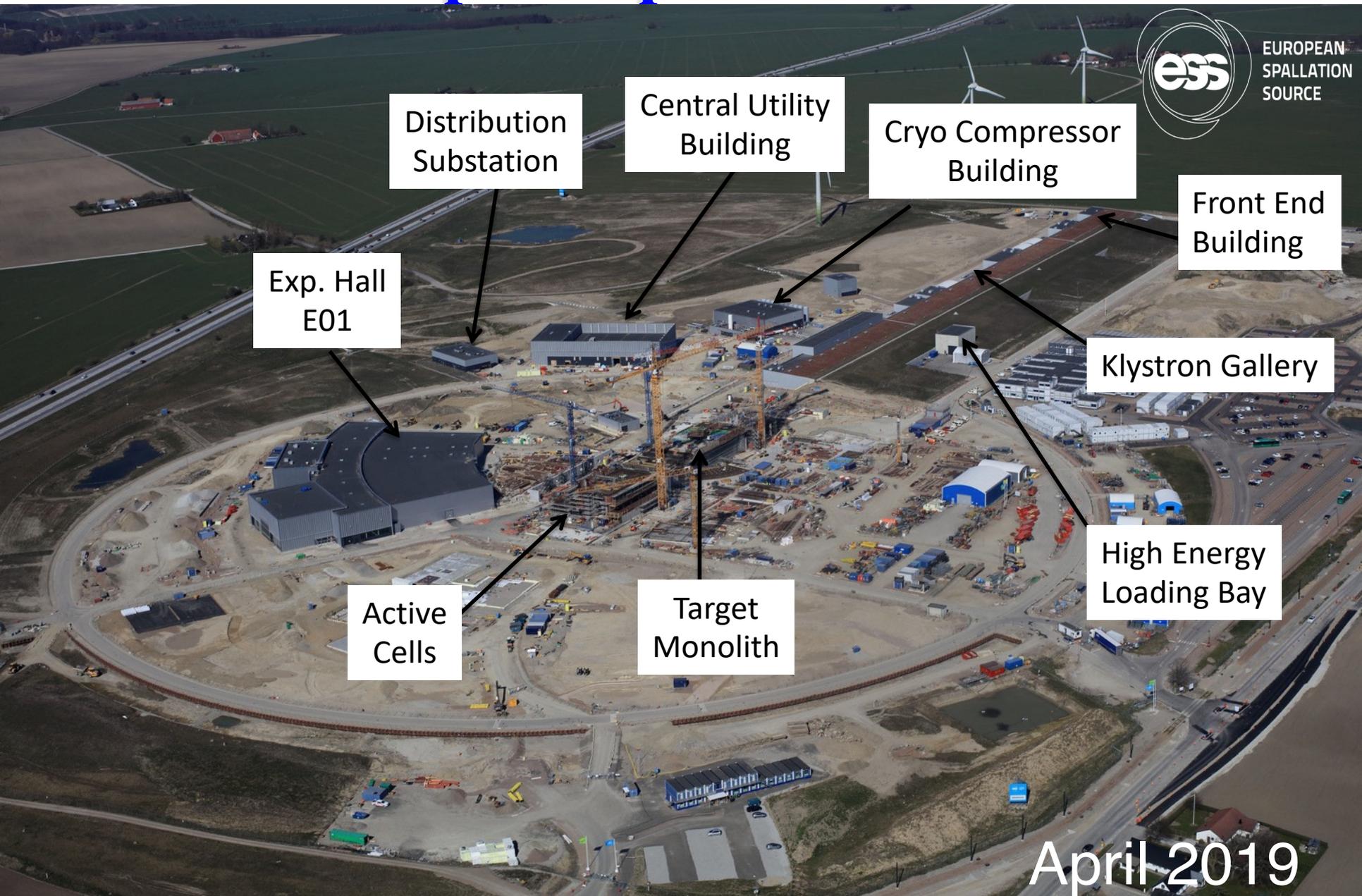


- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
 - up to 3.5 GeV with linac upgrades
- **>2.7x10²³ p.o.t/year.**



Linac ready by 2023 (full power)

European Spallation Source



Distribution Substation

Central Utility Building

Cryo Compressor Building

Front End Building

Exp. Hall E01

Klystron Gallery

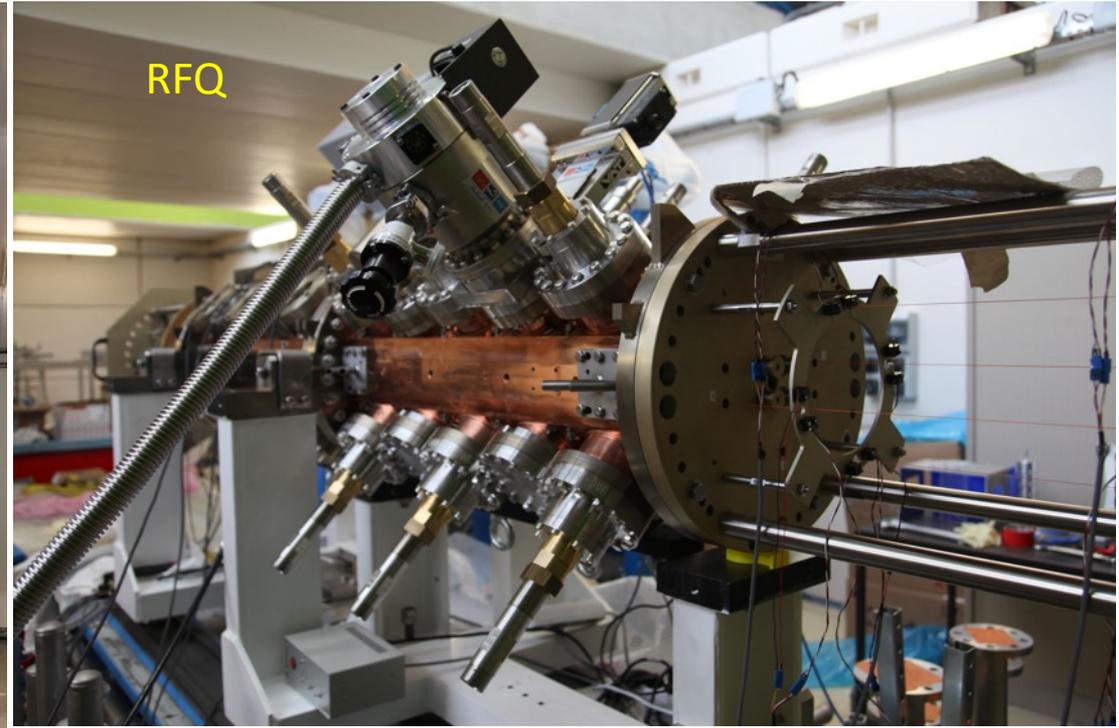
Active Cells

Target Monolith

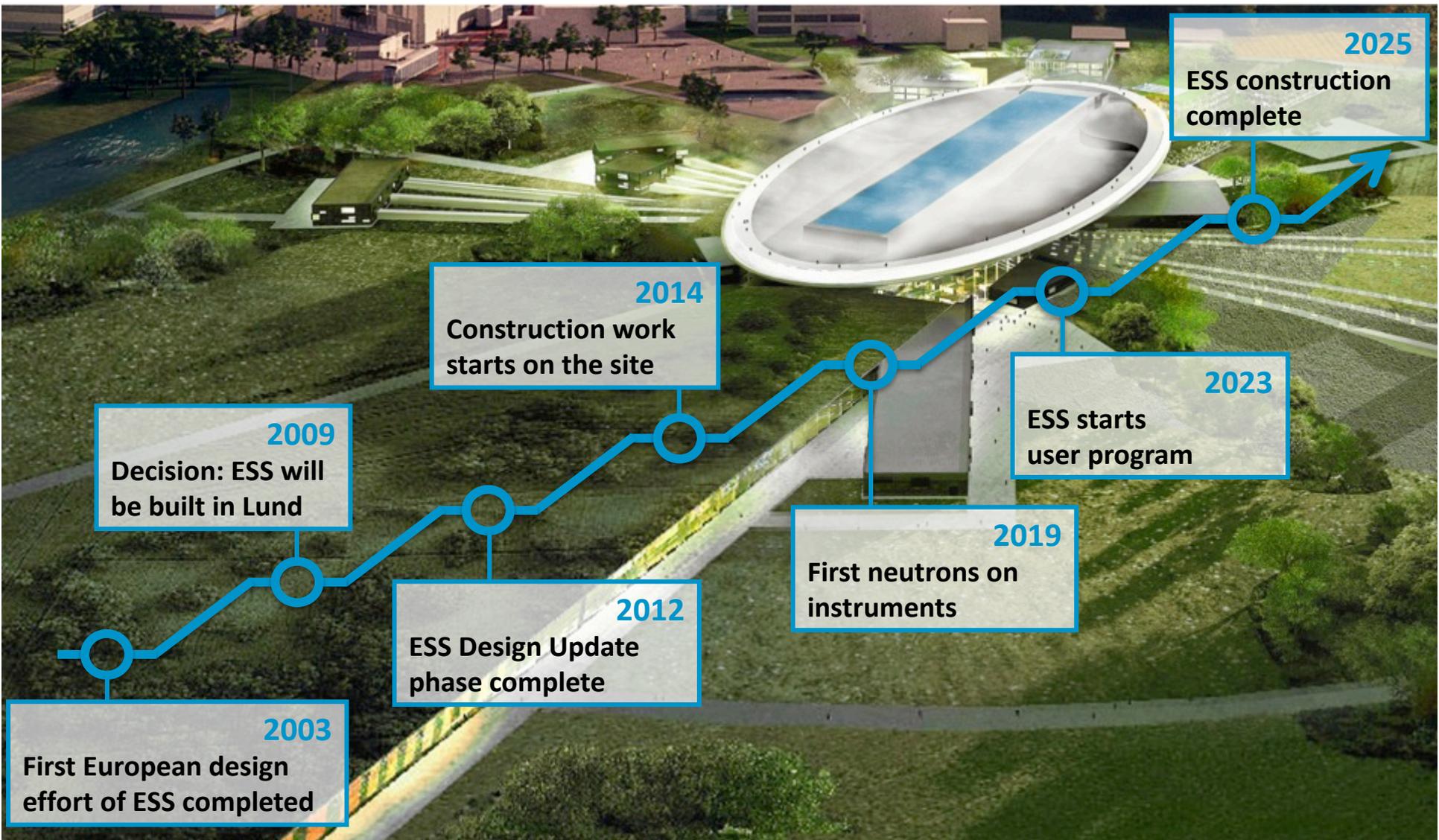
High Energy Loading Bay

April 2019

European Spallation Source



ESS schedule



European Spallation Source as Neutrino Facility for CP violation observation (2nd Oscillation maximum)

v

Oscillation probability (neutrino beams)

$$P_{\nu_\mu \rightarrow \nu_e} \simeq 4s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta L}{2} \quad \text{"atmospheric"}$$

$$+ 8J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta_{CP} - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2} \quad \text{"interference"}$$

$$+ 4c_{23}^2 c_{12}^2 s_{12}^2 \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2} \quad \text{"solar"}$$

$$J_r \equiv c_{12}s_{12}c_{23}s_{23}s_{13}, \Delta \equiv \frac{\Delta m_{31}^2}{2E_\nu}, r_A \equiv \frac{a}{\Delta m_{31}^2}, r_\Delta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, a \equiv 2\sqrt{2}G_F N_e E_\nu \quad \text{matter effect}$$

- for antimatter: $\delta_{CP} \rightarrow -\delta_{CP}$ and $a \rightarrow -a$
- fake matter/antimatter asymmetry due to matter effect

- δ_{CP} dependence,
- sizable matter effect for long baselines

$$\mathcal{A} = \frac{P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}}{P_{\nu_\mu \rightarrow \nu_e} + P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}} \quad \text{Matter-antimatter asymmetry}$$

δ_{CP} and Matter-antimatter asymmetry magnitude

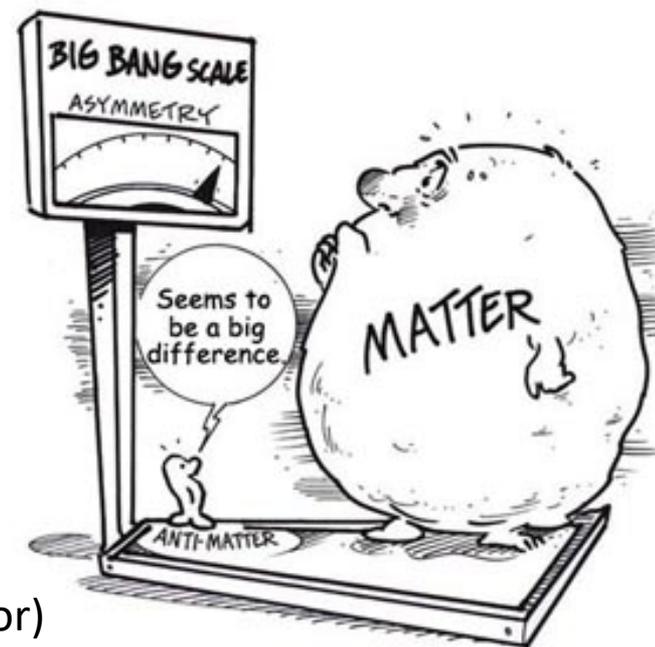
$$A_{\alpha\beta}^{CP} = P(\nu_{\alpha} \rightarrow \nu_{\beta}) - P(\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\beta})$$

$$= J_{CP}^{PMNS} \cdot \sin\delta_{CP}$$

with: $J_{CP}^{PMNS} \sim 3 \times 10^{-3}$ (Jarlskog invariant)

(for hadrons: $J_{CP}^{CKM} \sim 3 \times 10^{-5}$, not enough even if $\delta_{CP} \sim 70^\circ$)

(from the already observed CP violation in the hadronic sector)

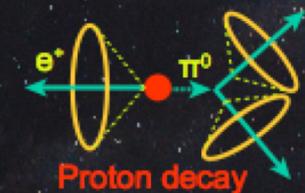


Theoretical models predict that if $|\sin\delta_{CP}| \gtrsim 0.7$ ($45^\circ < \delta_{CP} < 135^\circ$ or $225^\circ < \delta_{CP} < 315^\circ$), this could be enough to explain the observed asymmetry.

(Nucl.Phys.B774:1-52,2007, [arXiv:hep-ph/0611338](https://arxiv.org/abs/hep-ph/0611338))

Use all this ESS linac power to go to the second oscillation maximum

but why?



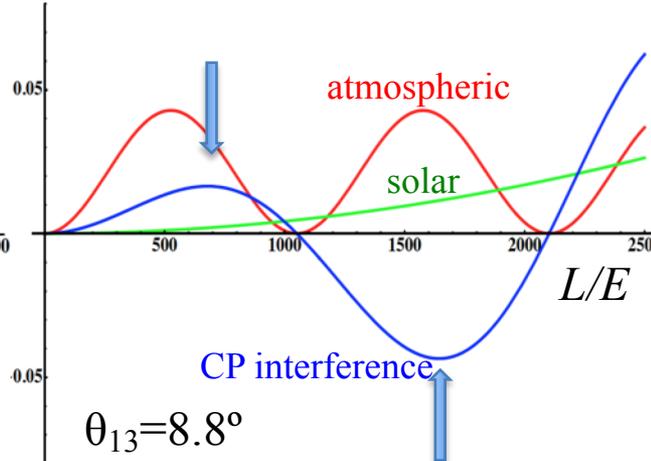
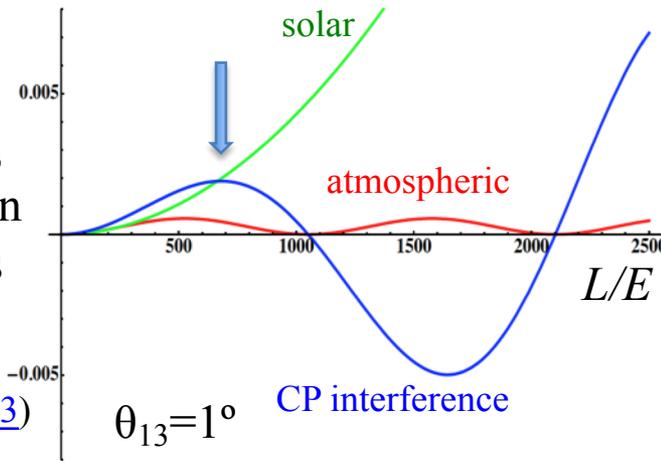
CPV

δ_{CP}

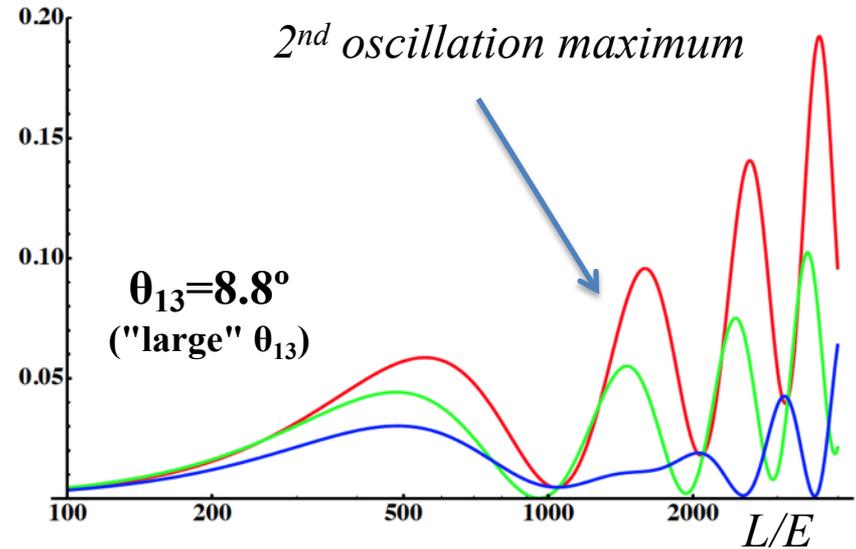
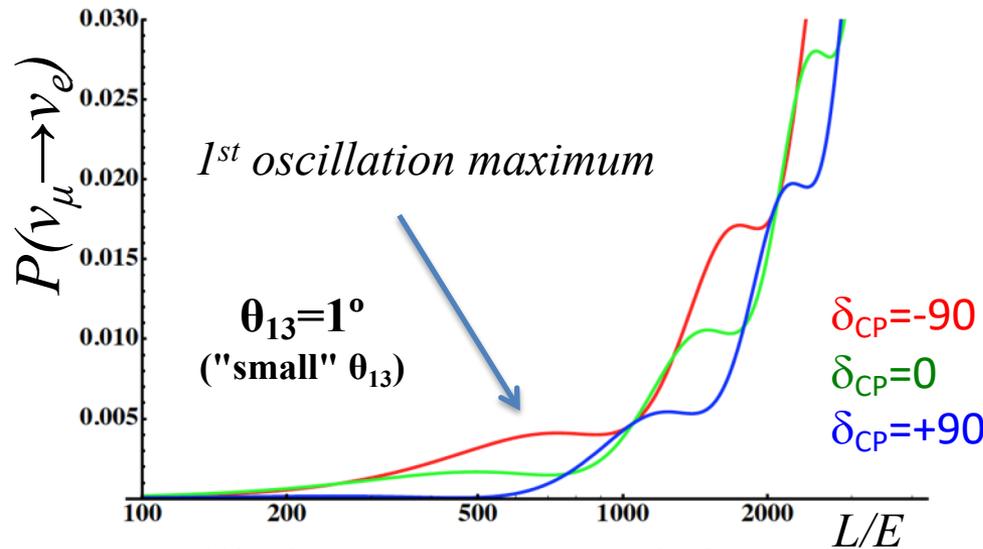
Neutrino Oscillations with "large" θ_{13}

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

([arXiv:1110.4583](https://arxiv.org/abs/1110.4583))



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



- 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

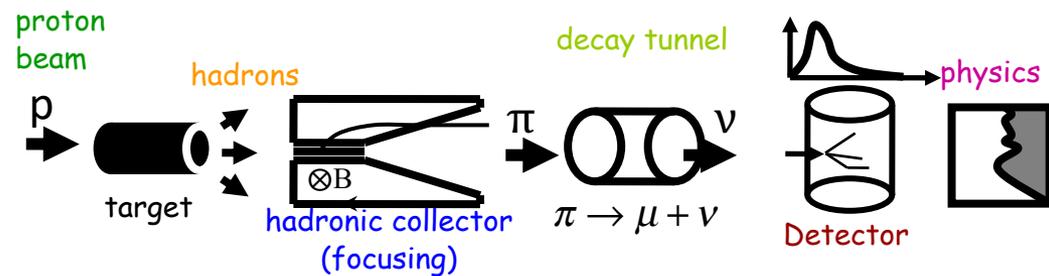


more sensitivity at 2nd oscillation max.
(see [arXiv:1310.5992](https://arxiv.org/abs/1310.5992) and [arXiv:0710.0554](https://arxiv.org/abs/0710.0554))

Having access to a powerful proton beam...

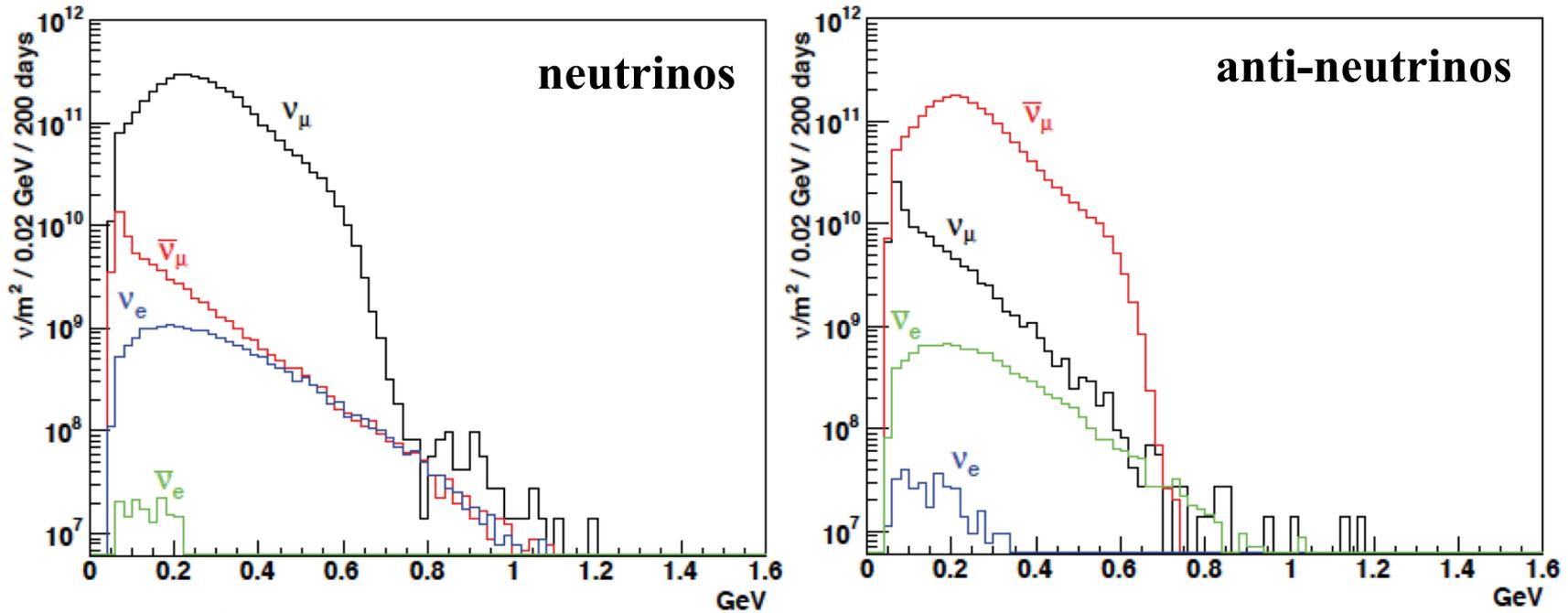
What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7 \times 10^{23}$ protons/year



conventional neutrino (super) beam

ESSvSB ν energy distribution



- 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	
	$N_\nu (\times 10^{10})/\text{m}^2$	%	$N_\nu (\times 10^{10})/\text{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

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

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

Oscillation to be studied

$$\nu_{\mu} \longrightarrow \nu_e$$

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

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

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

(arXiv: hep-ex/0607026)

- **Neutrino Oscillations**

- **Proton decay**

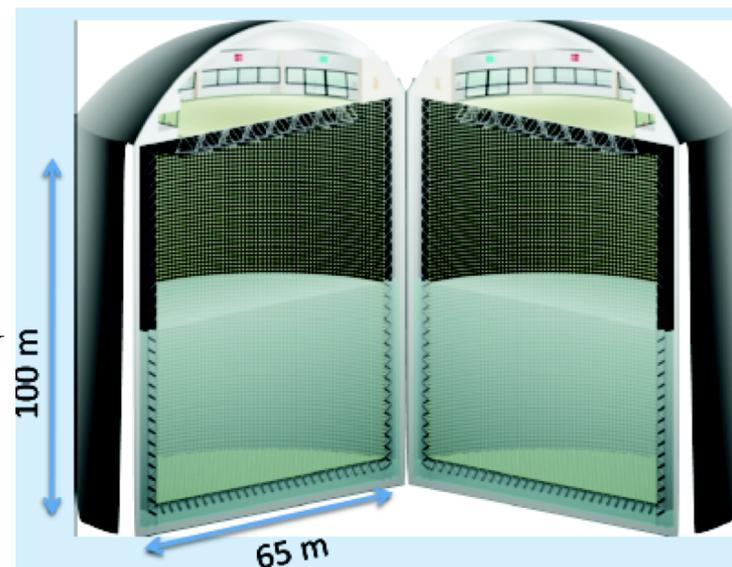
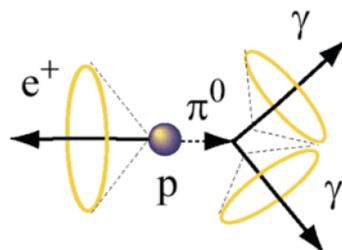
- **Astroparticles**

- Understand the gravitational collapsing: galactic SN

- Supernovae "relics"

- Solar Neutrinos

- Atmospheric Neutrinos



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



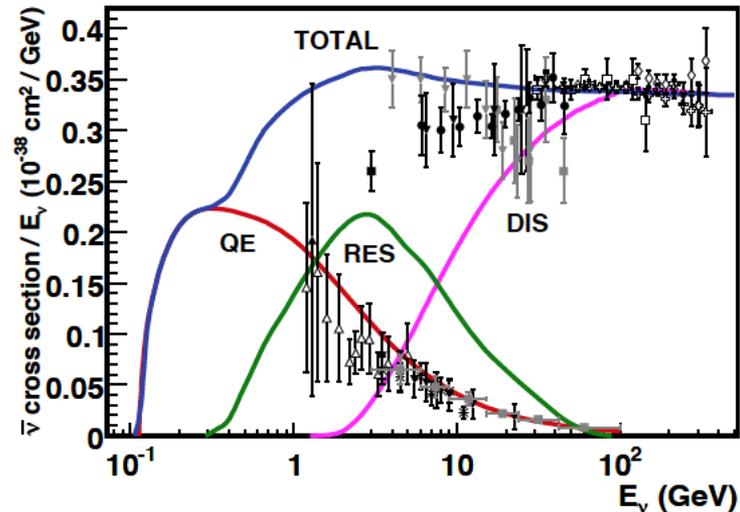
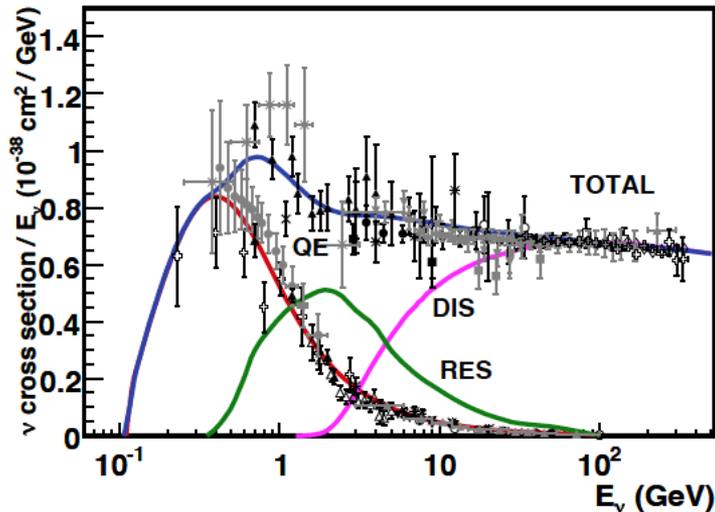
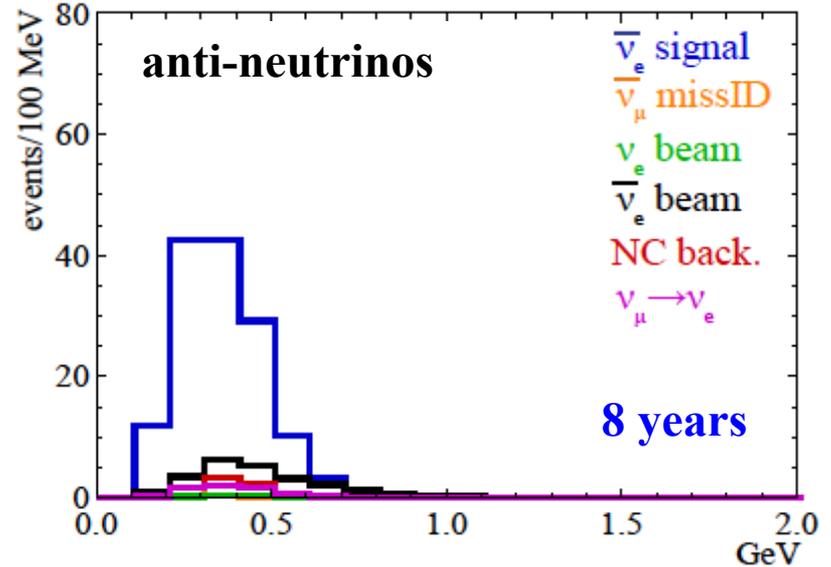
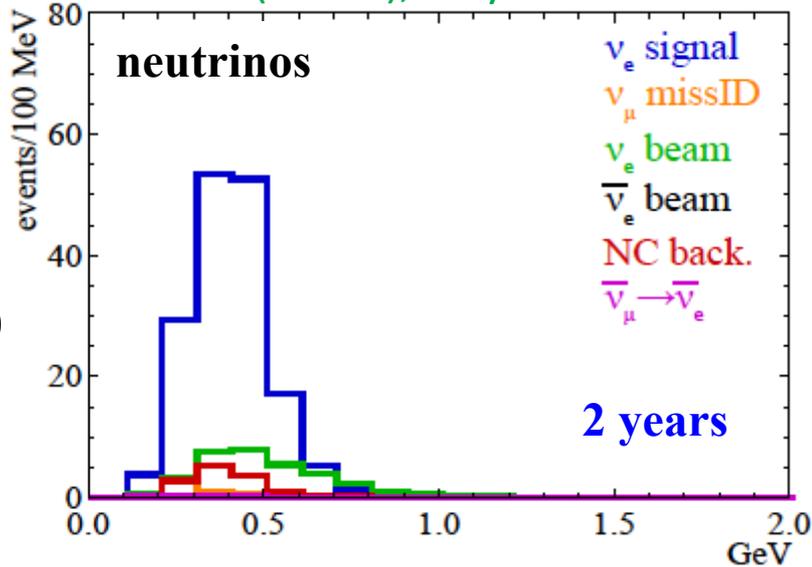
New 20" PMTs with higher QE and cheaper (see JUNO), the detection efficiency will improve the detector performance keeping the price constant, not yet taken into account.

(Joochun Park, WG1, Friday 30/08)

Neutrinos in the far detector

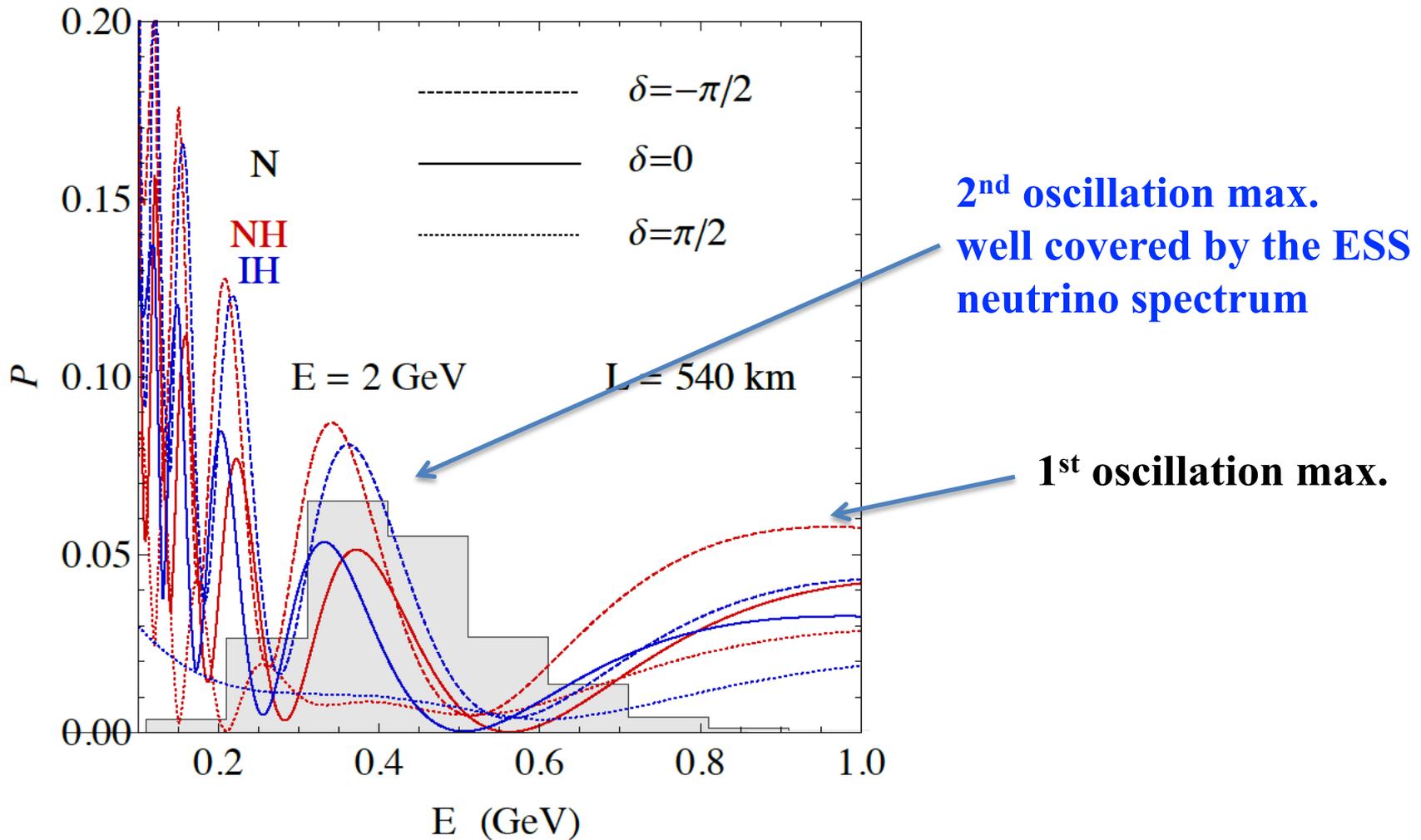
540 km (2 GeV), 10 years

$\delta_{CP}=0$



Below ν_τ production, almost only QE events, not suffering too much by π^0 background.

2nd Oscillation max. coverage



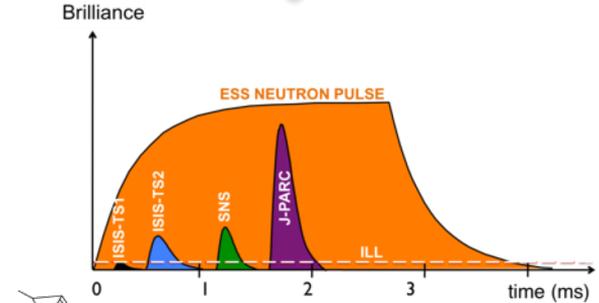
ESS Linac modifications to produce a neutrino Super Beam



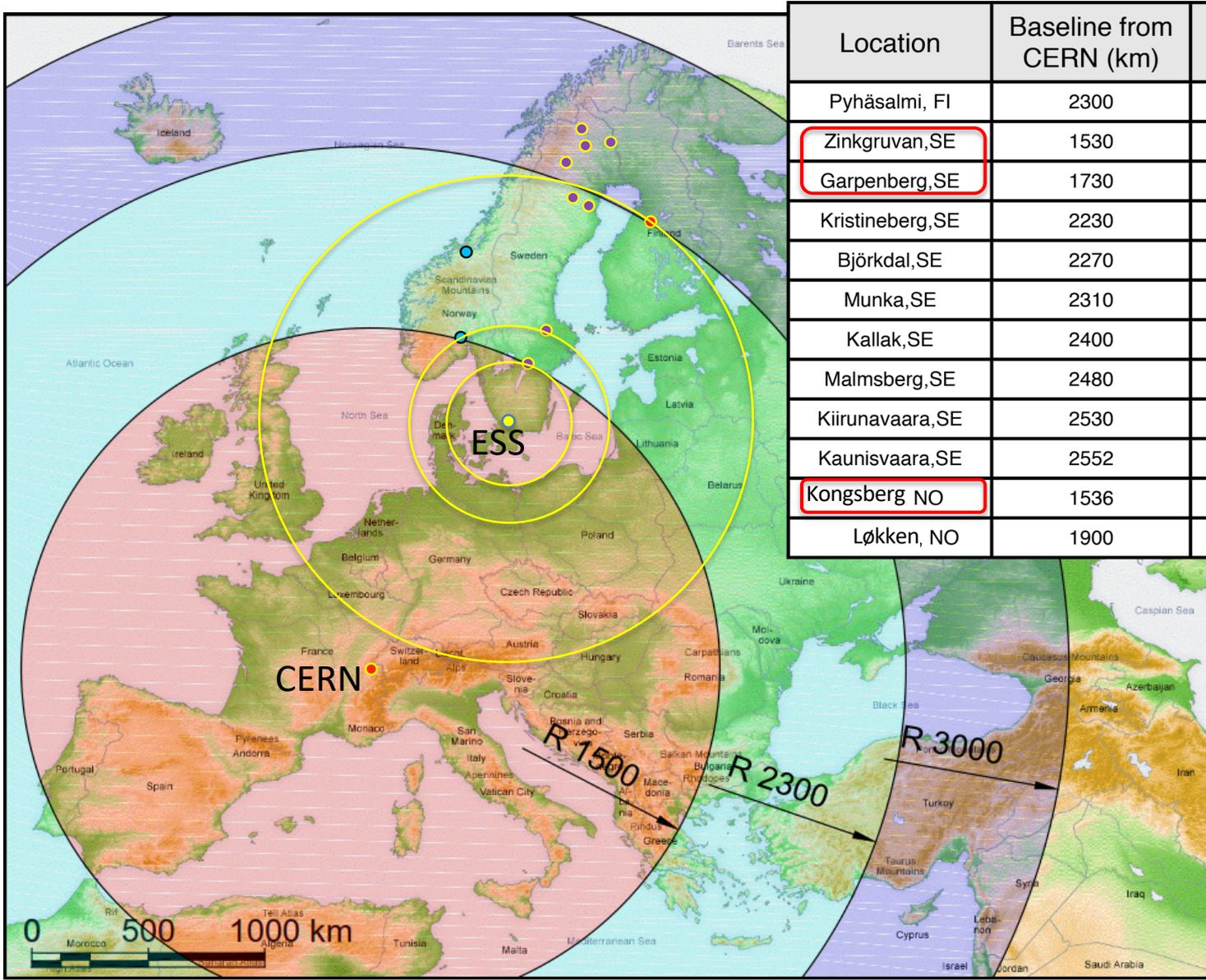
European Spallation Source Linac

How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz \rightarrow 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μ s the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
 - H⁻ source (instead of protons),
 - space charge problems to be solved.
- ~300 MeV neutrinos.
- Target station (studied in EUROv).
- Underground detector (studied in LAGUNA).
- Short pulses ($\sim\mu$ s) will also allow DAR experiments (as those proposed for SNS) using the neutron target.



Possible locations for far detector

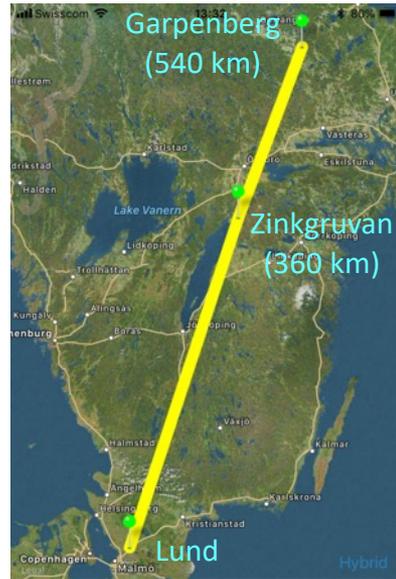


Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan, SE	1530	1420	360
Garpenberg, SE	1730	1300	540
Kristineberg, SE	2230	1530	1080
Björkdal, SE	2270	1450	1100
Munka, SE	2310	1620	1160
Kallak, SE	2400	1700	1260
Malmsberg, SE	2480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

LAGUNA sites

Candidate active mines

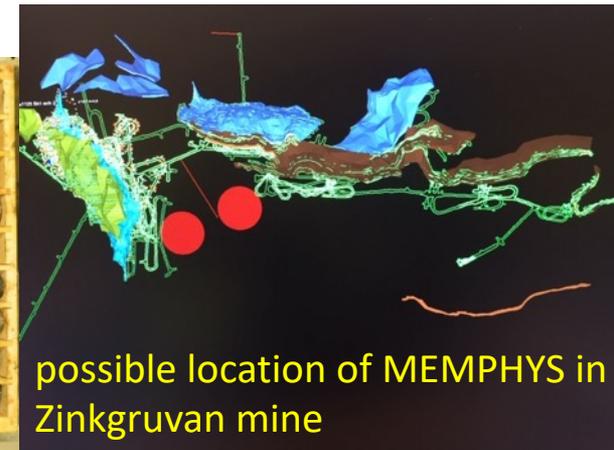
- **Garpenberg mine**
 - Distance from ESS Lund **540 km**
 - Depth **1200 m**
 - Truck access tunnel
- **Zinkgruvan mine**
 - Distance from ESS Lund **360 km**
 - Depth **1500 m**
 - Truck access tunnel



Garpenberg



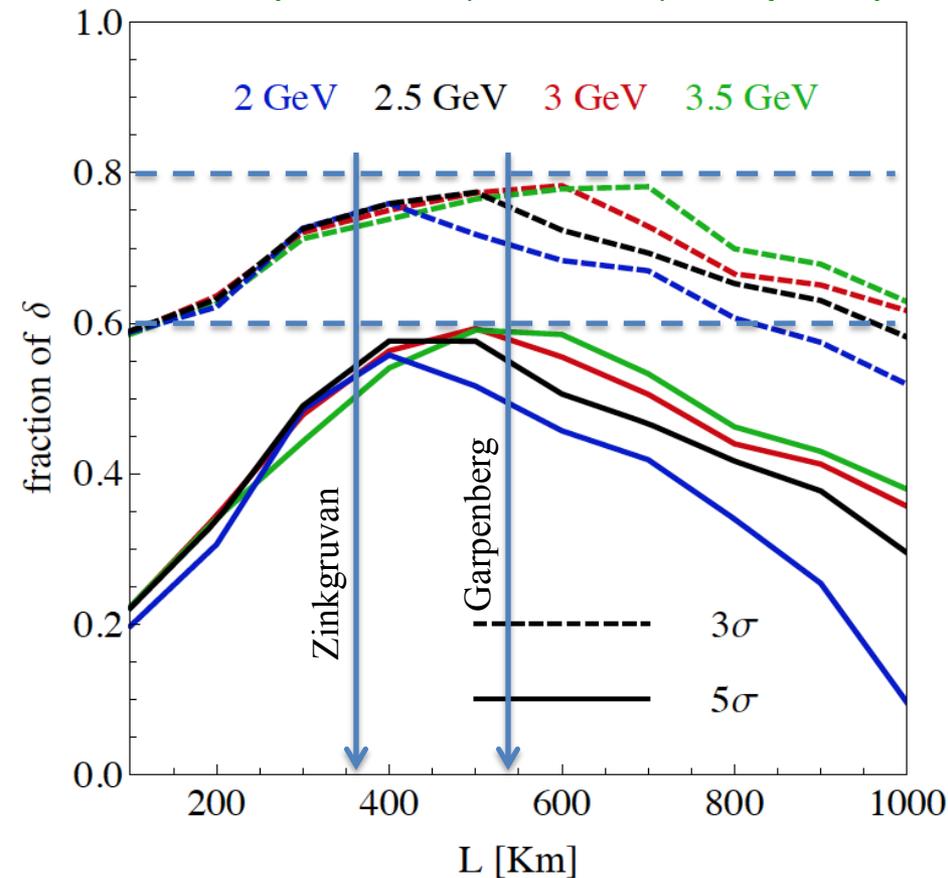
Granite drill cores



possible location of MEMPHYS in Zinkgruvan mine

Which baseline?

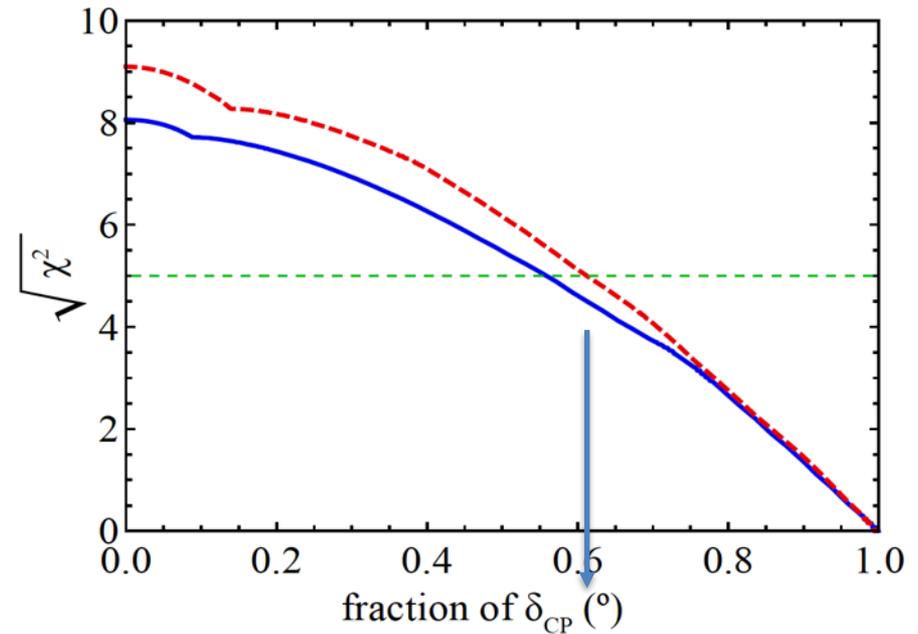
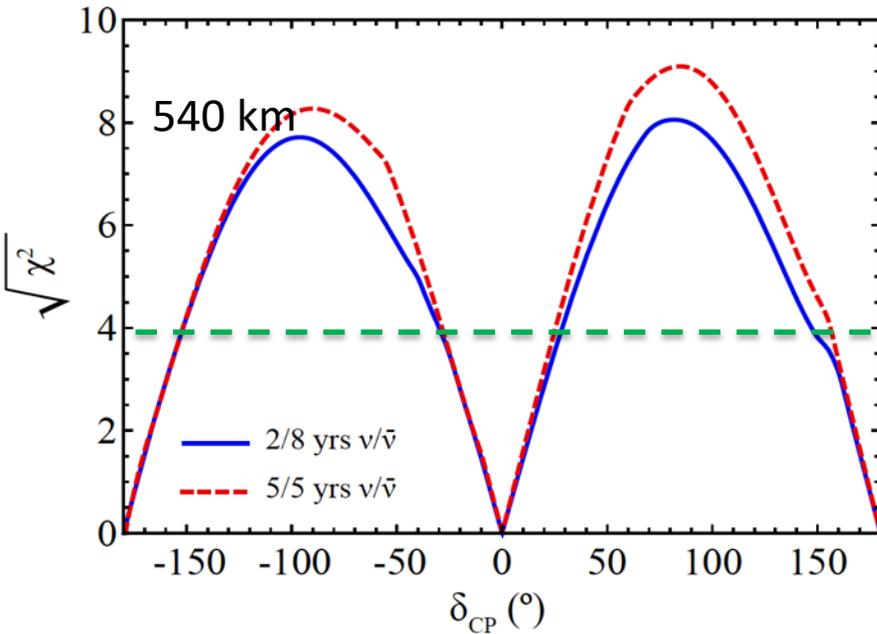
CPV (*Nucl. Phys. B* 885 (2014) 127)



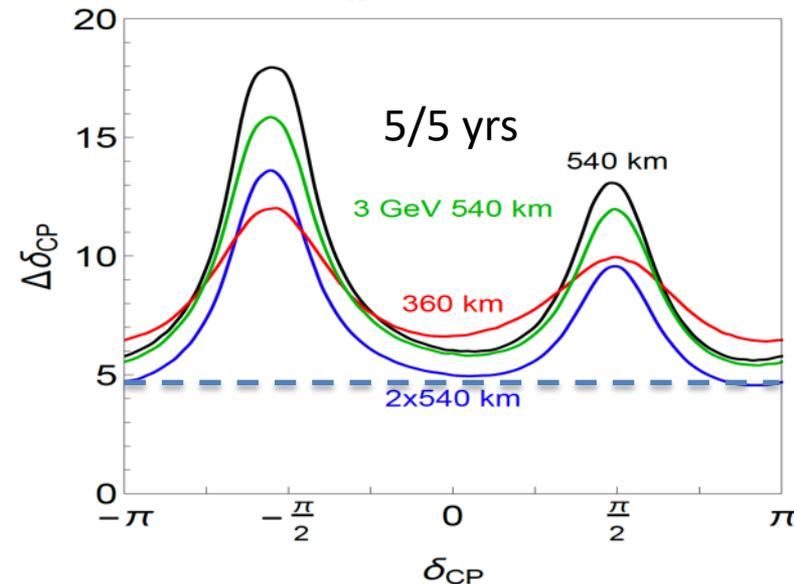
Candidate active mines

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

Physics Performance



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



(Monojit Ghosh, WG1, Thursday 29/08)

Required modifications of the ESS accelerator for ESSvSB

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

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

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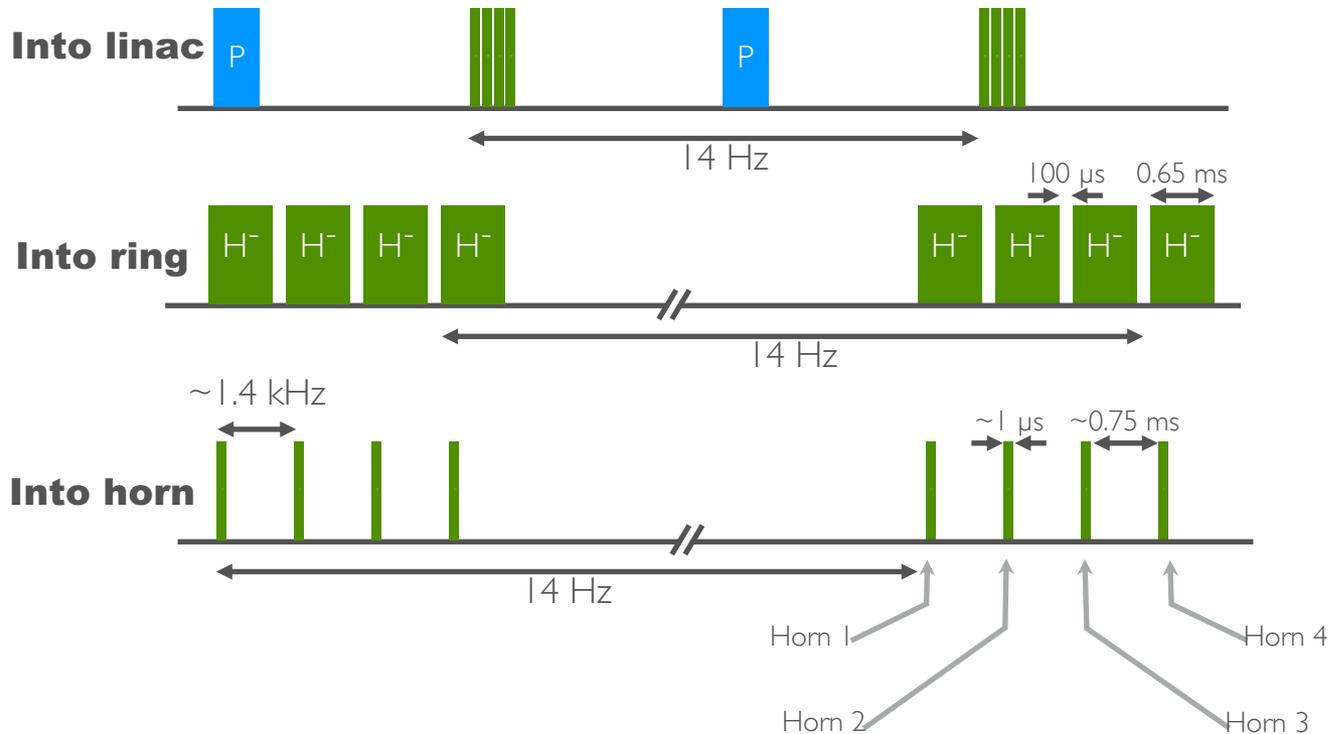
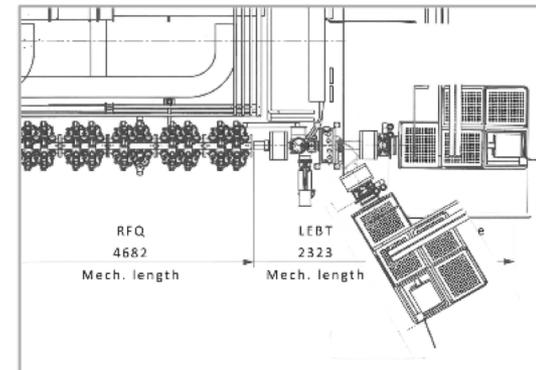
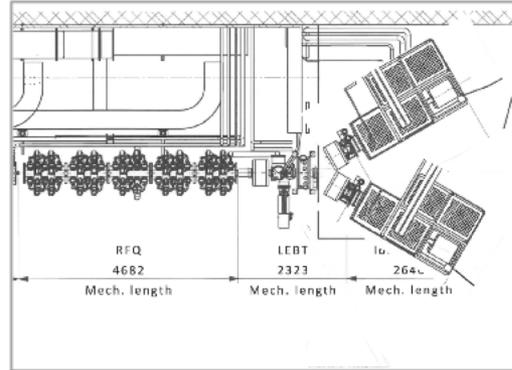
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- [6 Appendix 2: Indicative costing of the upgrade](#)

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.”

Better to go to 2.5 GeV

The Linac modifications and operation

H⁻ source options



(Ben Folsom, WG3, Thursday 29/08)

The Accumulator

lattice development

injection

RF

$$L = 384 \text{ m}$$

$$Q_x = 8.24$$

$$Q_y = 8.38$$

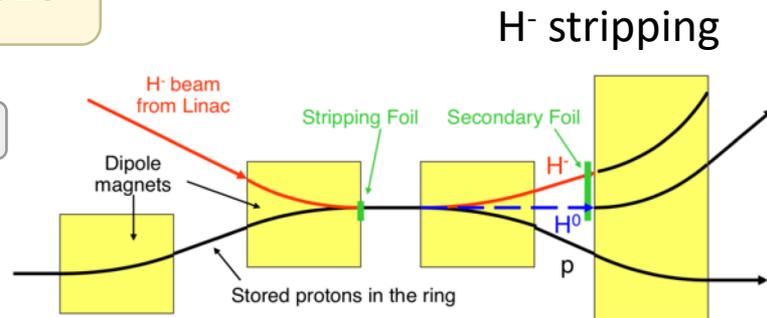
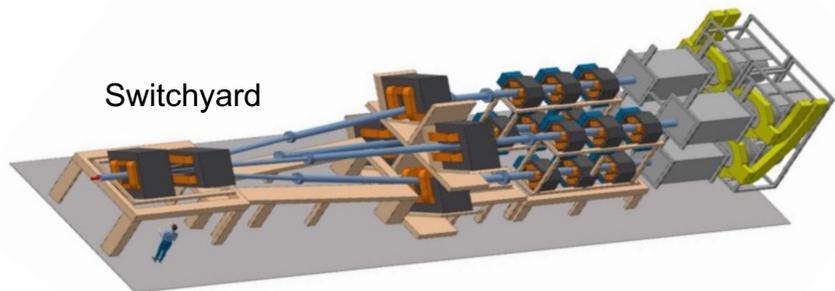
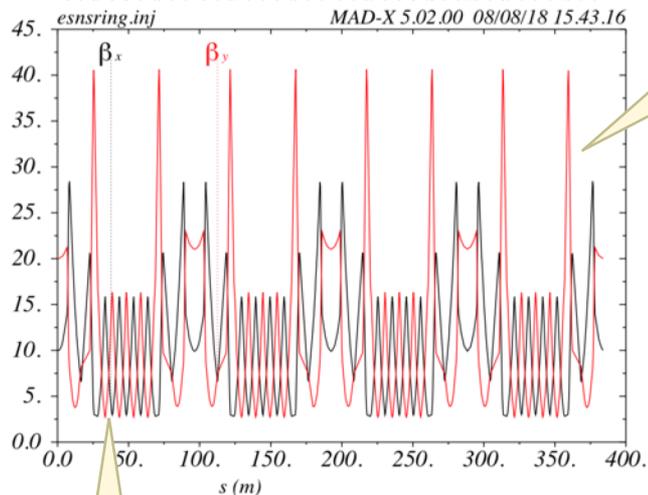
extraction

collimation

Dispersion-free straight sections

FODO cells

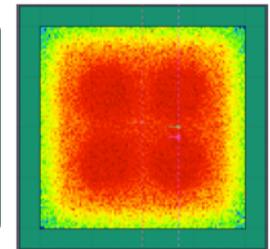
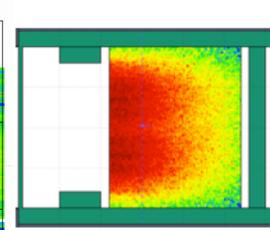
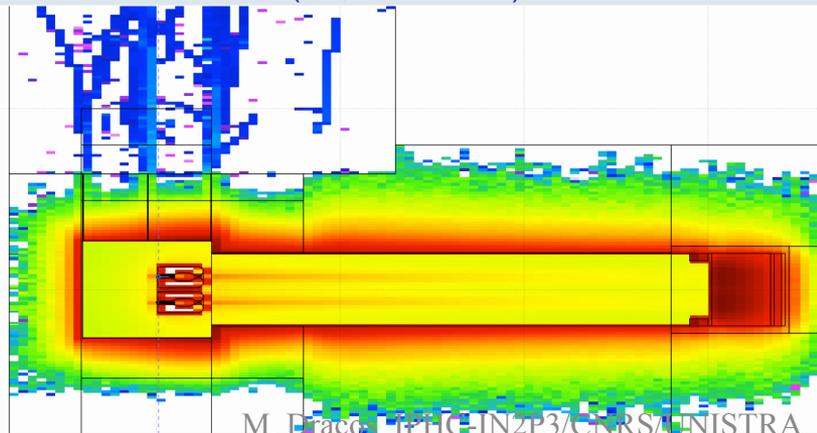
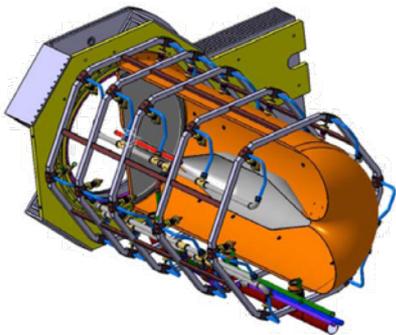
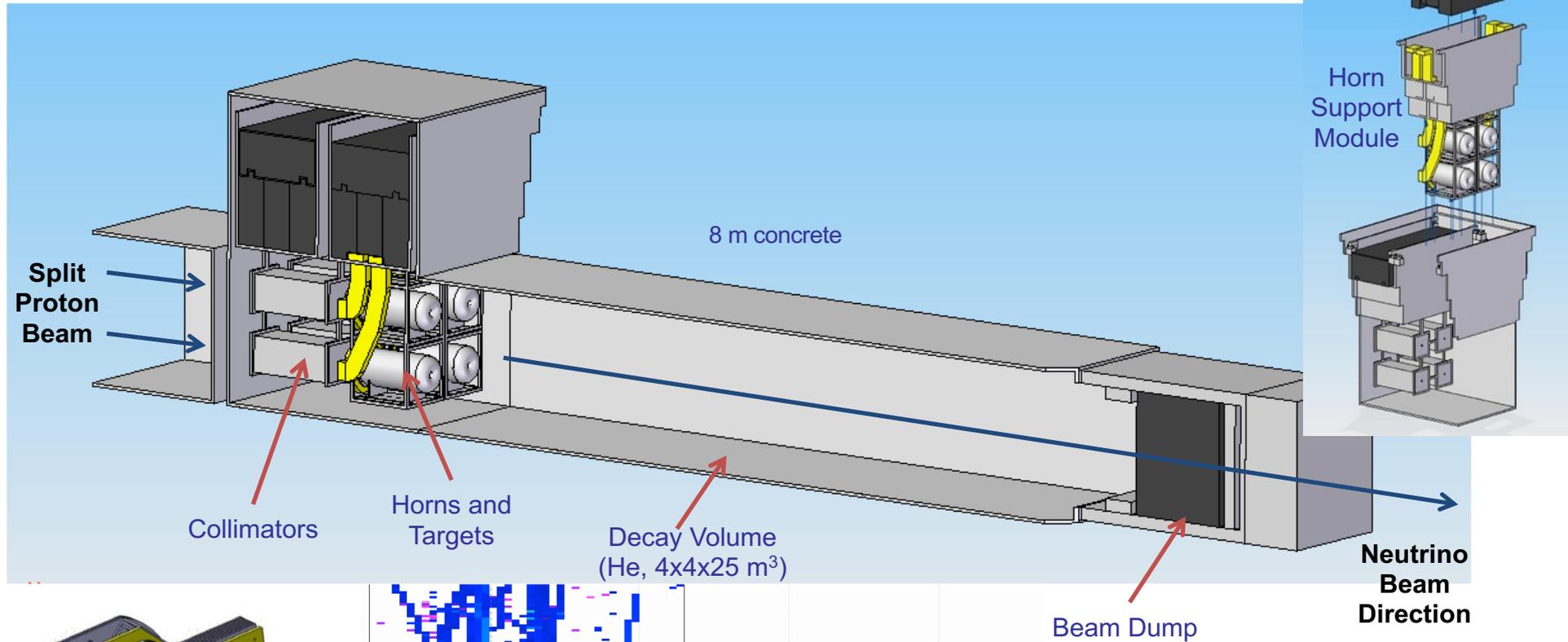
4 superperiods



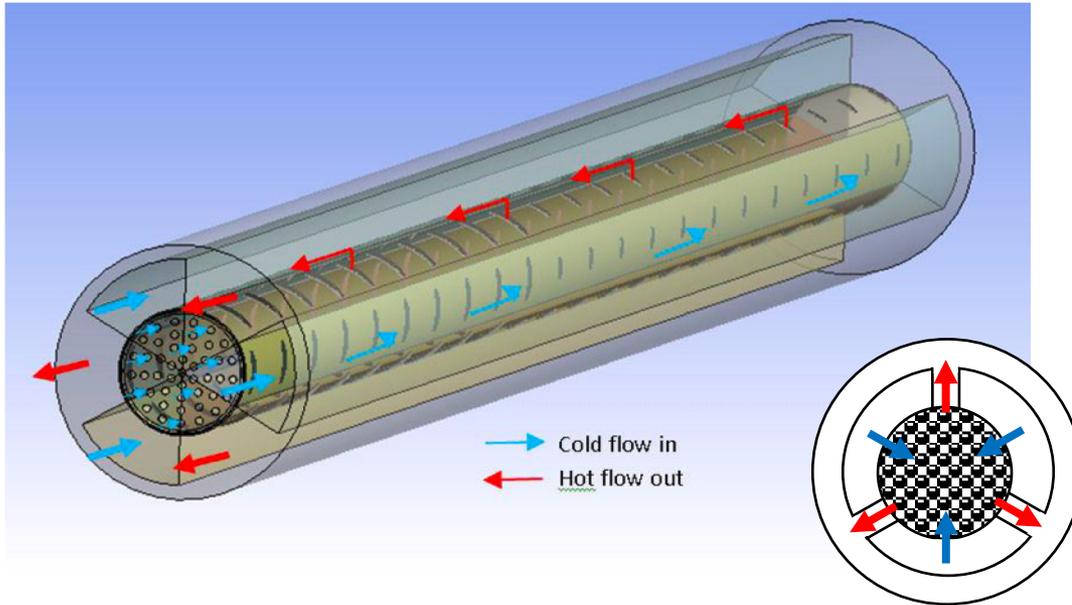
(Ye Zou, WG3, Thursday 29/08)

General Layout of the target station

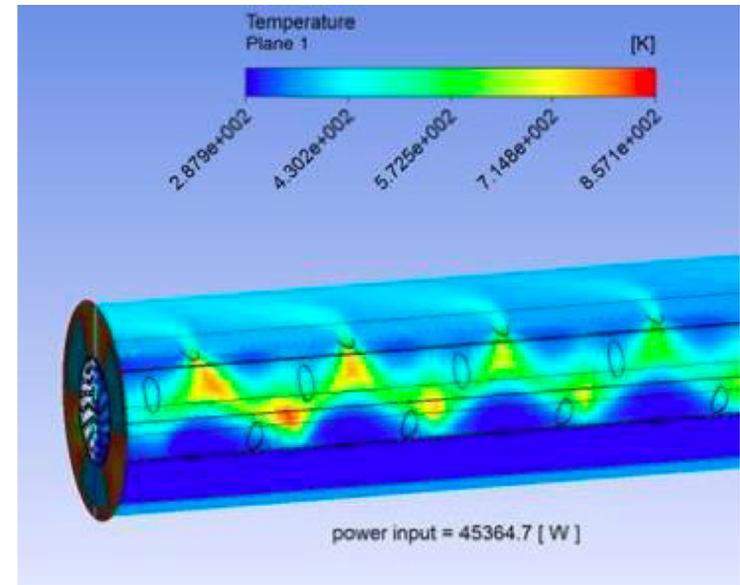
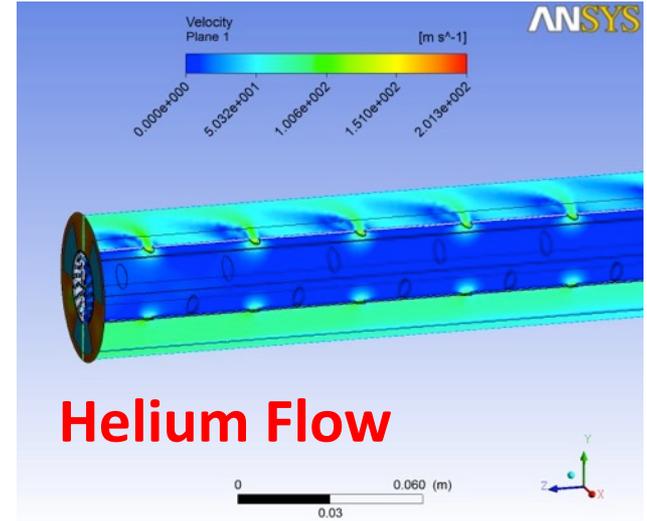
(Loris D'Alessi, WG3, Thursday 29/08)



Target



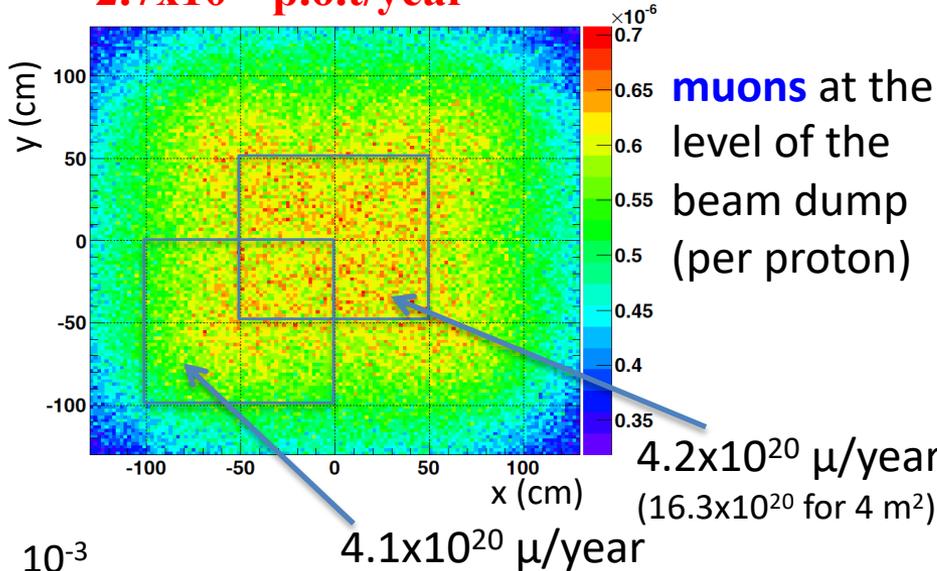
- Packed-bed target studied at RAL within the EuroNu project (arXiv:1212.0732)
- Titanium alloy canister containing packed bed of titanium spheres (Gas Helium as cooling medium)
- Single sphere diameter: 3 mm
- Canister radius/length: 12 mm / 780 mm



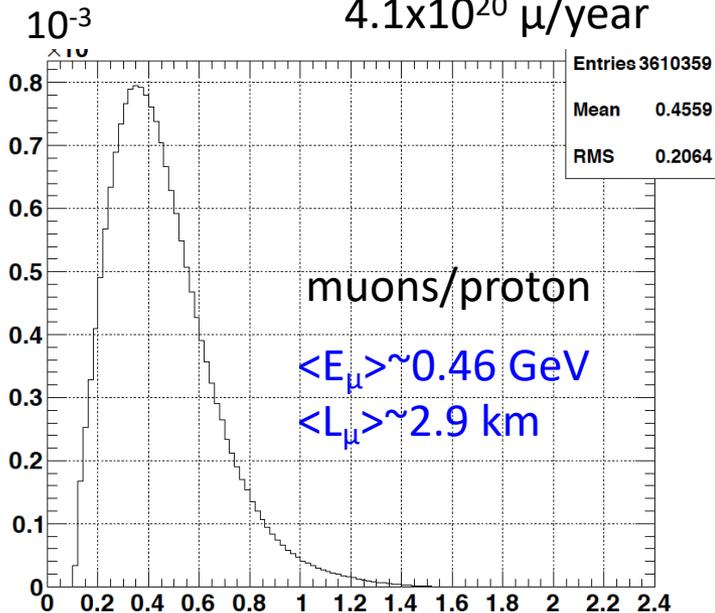
(Loris D'Alessi, WG3, Thursday 29/08)

Muons at the level of the beam dump

2.7×10^{23} p.o.t./year



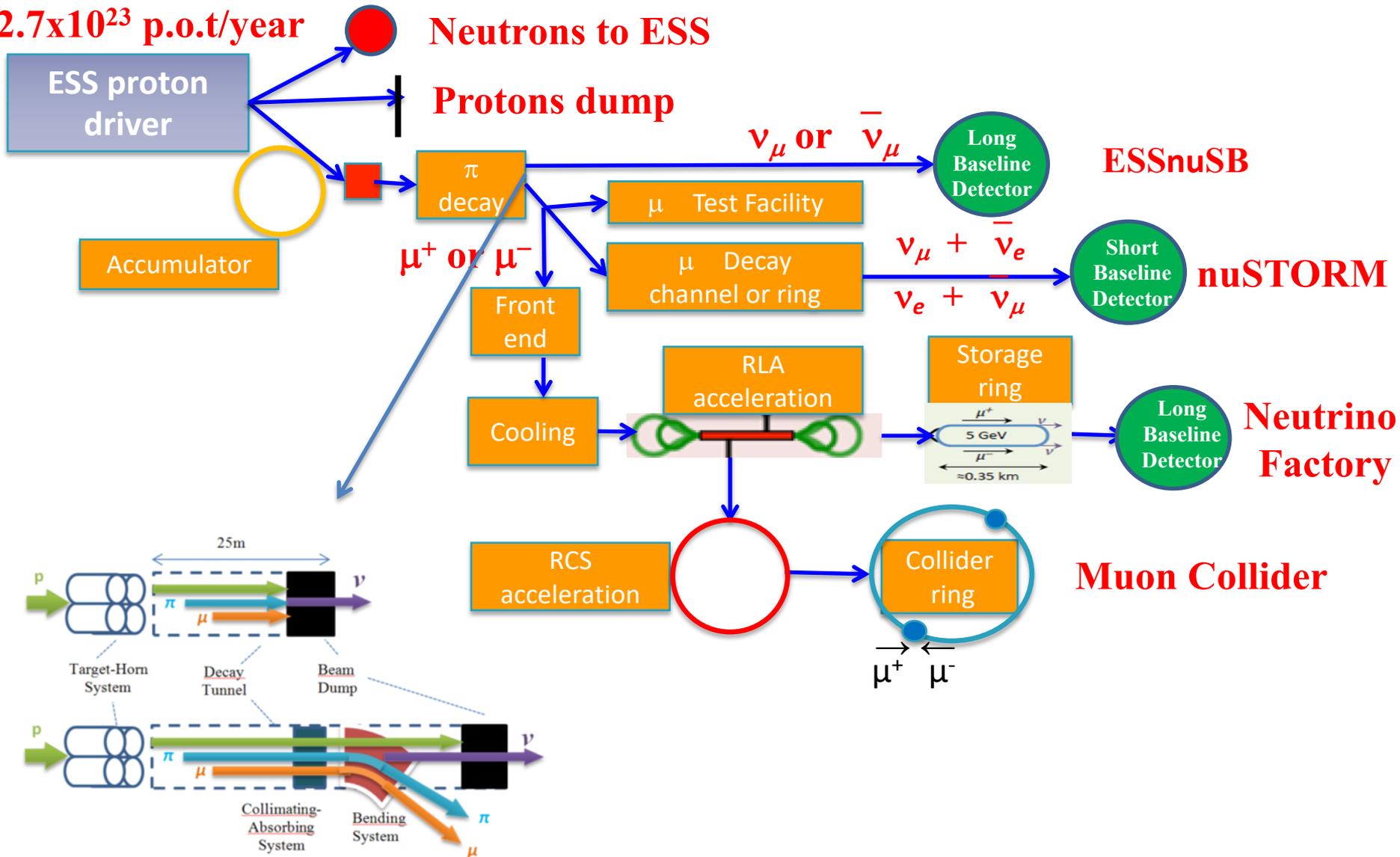
more than $4 \times 10^{20} \mu/\text{year}$ from ESSS compared to $10^{14} \mu$ used by all experiments up to now ($10^{18} \mu$ for COMET in the future).



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

ESS neutrino and muon facility

2.7×10^{23} p.o.t/year



Muons at ESS (ESS μ SB)

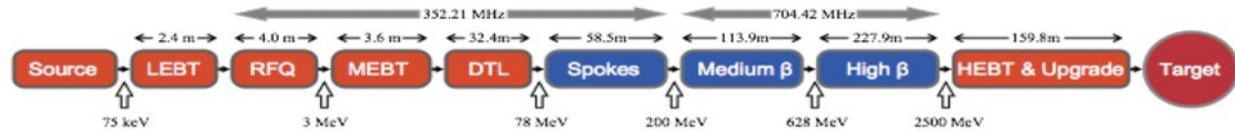
Carlo Rubbia



Venice, March 2019

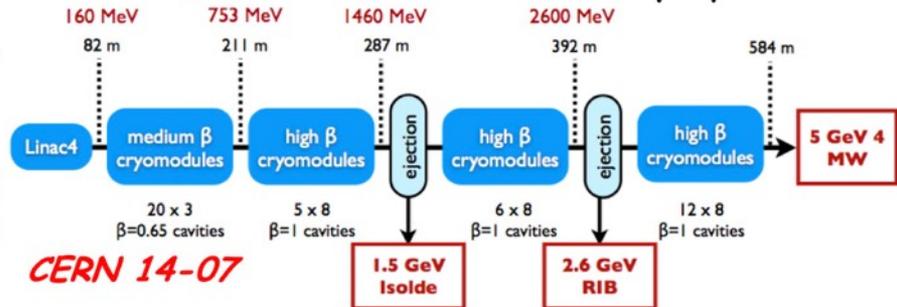
Protons for a muon collider in Europe ?

- The **European Spallation Source**, now in construction in Lund, with 5 MWatt of protons accelerated to a kinetic energy of 2.0 GeV at 14 Hz and 1.1×10^{15} p/p and it may provide adequate intensity and repetition rate for the $O(10^{12} \mu/\text{pulse})$ collider program, FDSL_2012_10_02



- **CERN** had considered the HP-HPL, a proton beam of 5 GeV kinetic energy with 50 Hz, 4 MWatt and 1.0×10^{14} p/ pulse.

- In 2010 HP-HPL project has been cancelled: *Therefore ESS may remain the main option.*



VeniceF, March 2019

Slide# : 15

SM Higgs rate $\approx 10^5$ ev/year (10^7 s) per crossing point

EuroNuNet



- **COST application for networking: CA15139 (2016-2020)**
- **EuroNuNet** : *Combining forces for a novel European facility for neutrino-antineutrino symmetry violation discovery*
(http://www.cost.eu/COST_Actions/ca/CA15139)
- **Major goals of EuroNuNet:**
 - to aggregate the community of neutrino physics in Europe to study a neutrino long baseline 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**

The members are countries which signed the Action MoU



<http://euronunet.in2p3.fr/>

ESSvSB at the European level



- A H2020 EU Design Study (Call INFRADEV-01-2017)

- **Title of Proposal:** Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

- **Duration:** 4 years

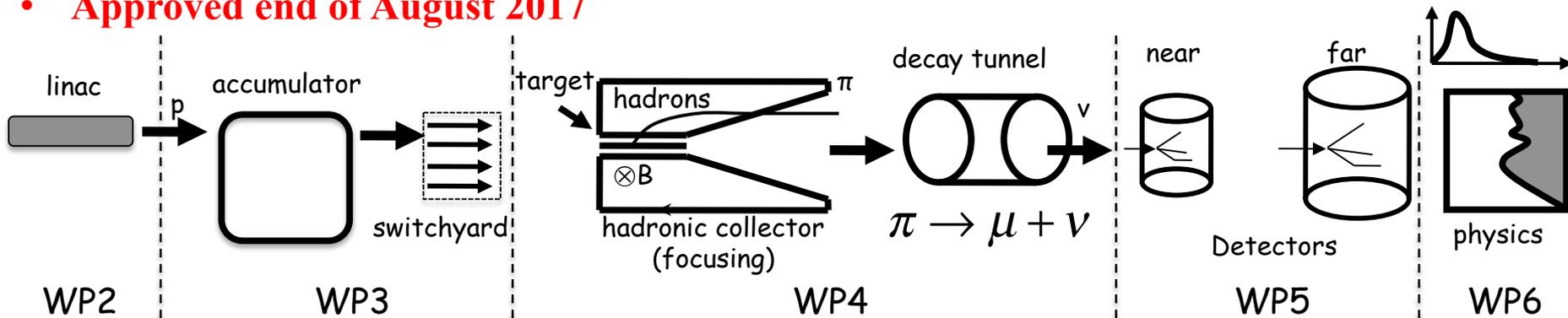
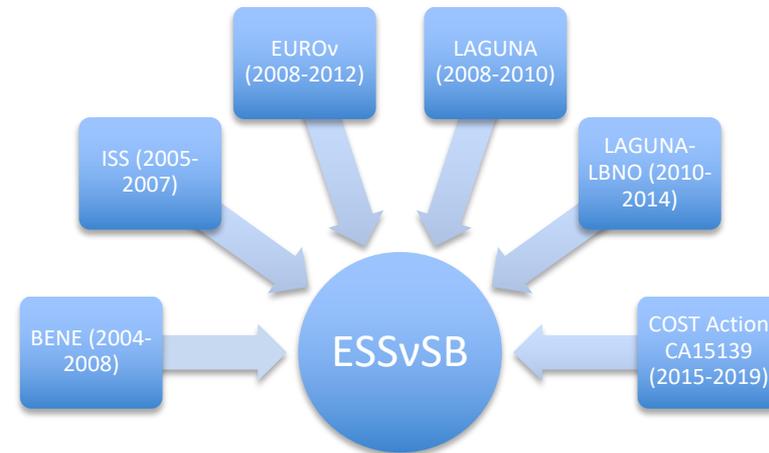
- **Total cost:** 4.7 M€

- **Requested budget:** 3 M€

- **15 participating institutes from 11 European countries including CERN and ESS**

- 6 Work Packages

- **Approved end of August 2017**





Design Study ESSvSB (2018-2021)

Call: H2020-INFRADEV-2017-1
Funding scheme: RIA
Proposal number: 777419 Maximum grant amount (proposed amount, after evaluation): **2,999,018.00 EUR**
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

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:	

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

CDR end of 2021

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

Possible ESSvSB schedule

(2nd generation neutrino Super Beam)



Conclusion

- ESS will be soon the most powerful neutron facility for many applications.
- ESS can also become a neutrino facility with enough protons to go to the 2nd oscillation maximum and increase the CPV sensitivity.
- CPV: 5 σ could be reached over 60% of δ_{CP} range by ESSvSB with large physics potential.
- Large associated detectors have a rich astroparticle physics program.
- The European Spallation Source will be ready by 2025, upgrade decisions by this moment.
- Rich muon program for future ESS upgrades.
- COST network project CA15139 and a EU-H2020 Design Study supports this project.

Backup



How the CPV coverage and resolution curves have been produced

- **T2HK:**

- Same curves that Hyper-K has showed at the Neutrino Town Meeting at CERN and the one that was showed at Neutrino 2018.
- Systematics are said by T2HK to be between 3% to 4%.
- $\sin^2 2\theta_{13} = 0.1$ and $\theta_{23} = \pi / 2$.

- **DUNE:**

- Public globes file released by the DUNE collaboration with the CDR, the only change is to increase the number of years from 7 to 10.
- $\sin^2 2\theta_{13} = 0.1$ and $\theta_{23} = \pi / 2$, to be compatible with the T2HK line.

- **ESSnuSB:**

- Instead of considering as usual "Opt. Snowmass errors" it is only assumed an overall 3% systematic error in the different signal and background channels, more in line with T2HK assumptions.
- $\sin^2 2\theta_{13} = 0.1$ and $\theta_{23} = \pi / 2$, to be compatible with the T2HK line.

Beyond DUNE, JUNO, HyperK: ESSvSB, P2O and Neutrino factory

*European Neutrino "Town" meeting and ESPP 2019
discussion, CERN, 24.10.2018*

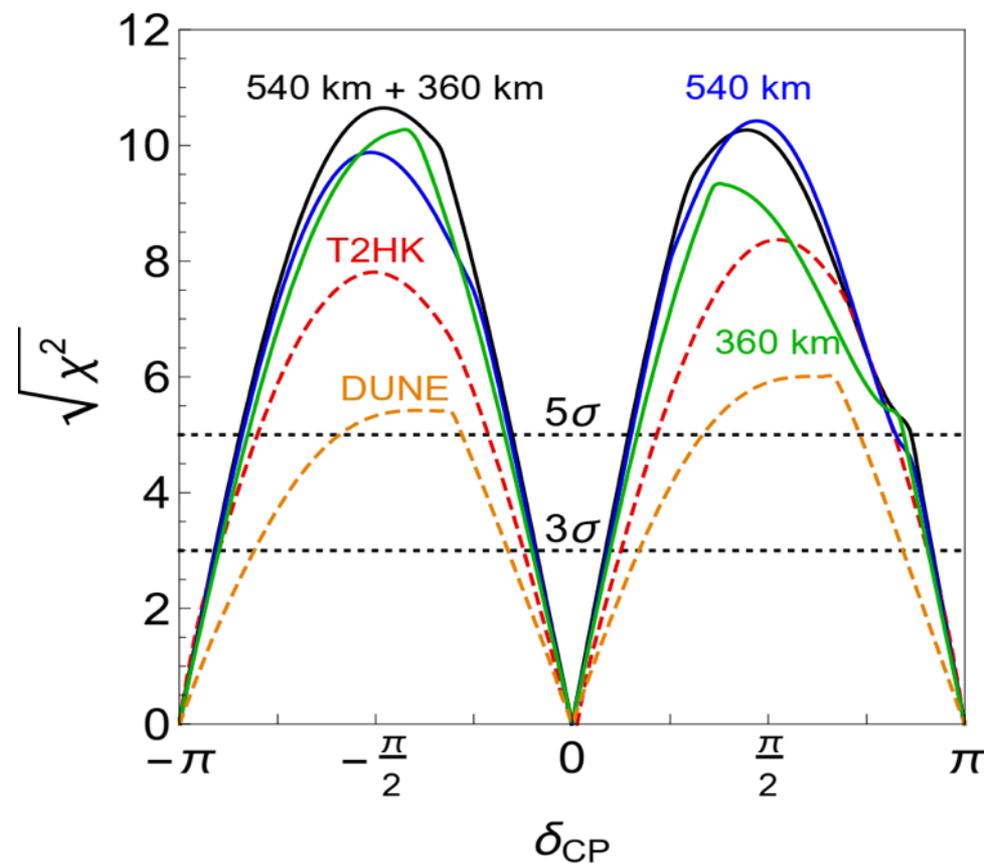
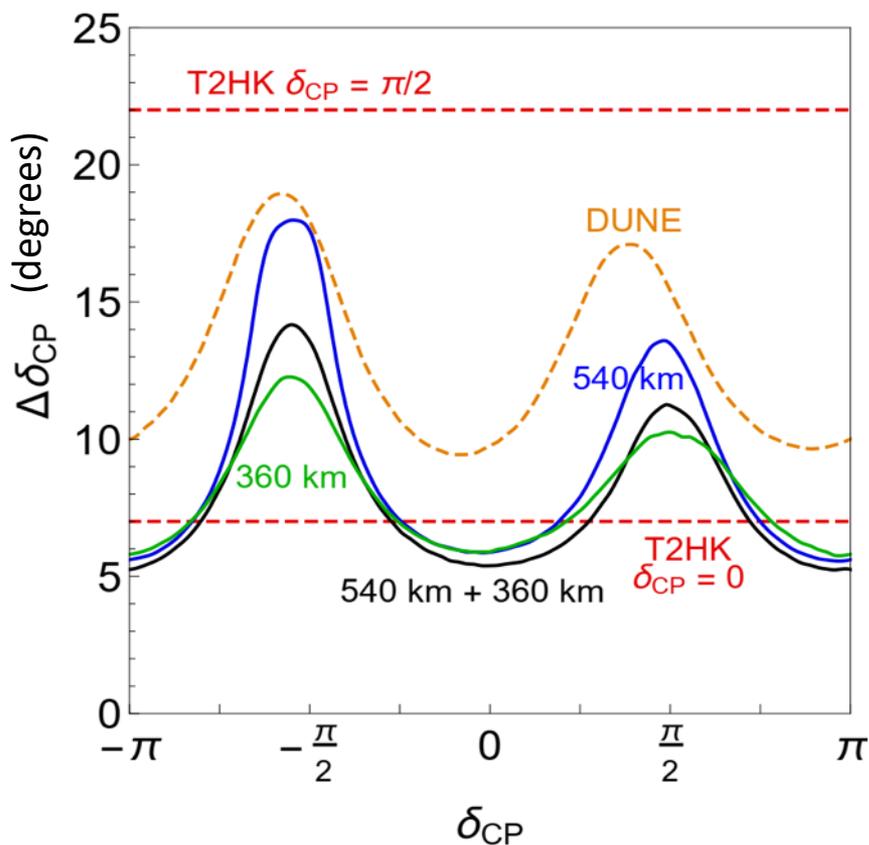


Roumen Tsenov
Department of Atomic Physics,
University of Sofia

CPV performance comparison between ESSnuSB, DUNE and Hyper-K assuming 3% systematic errors for ESSnuSB in line with the other two.

ESSvSB 500 kt tank at 540 km.

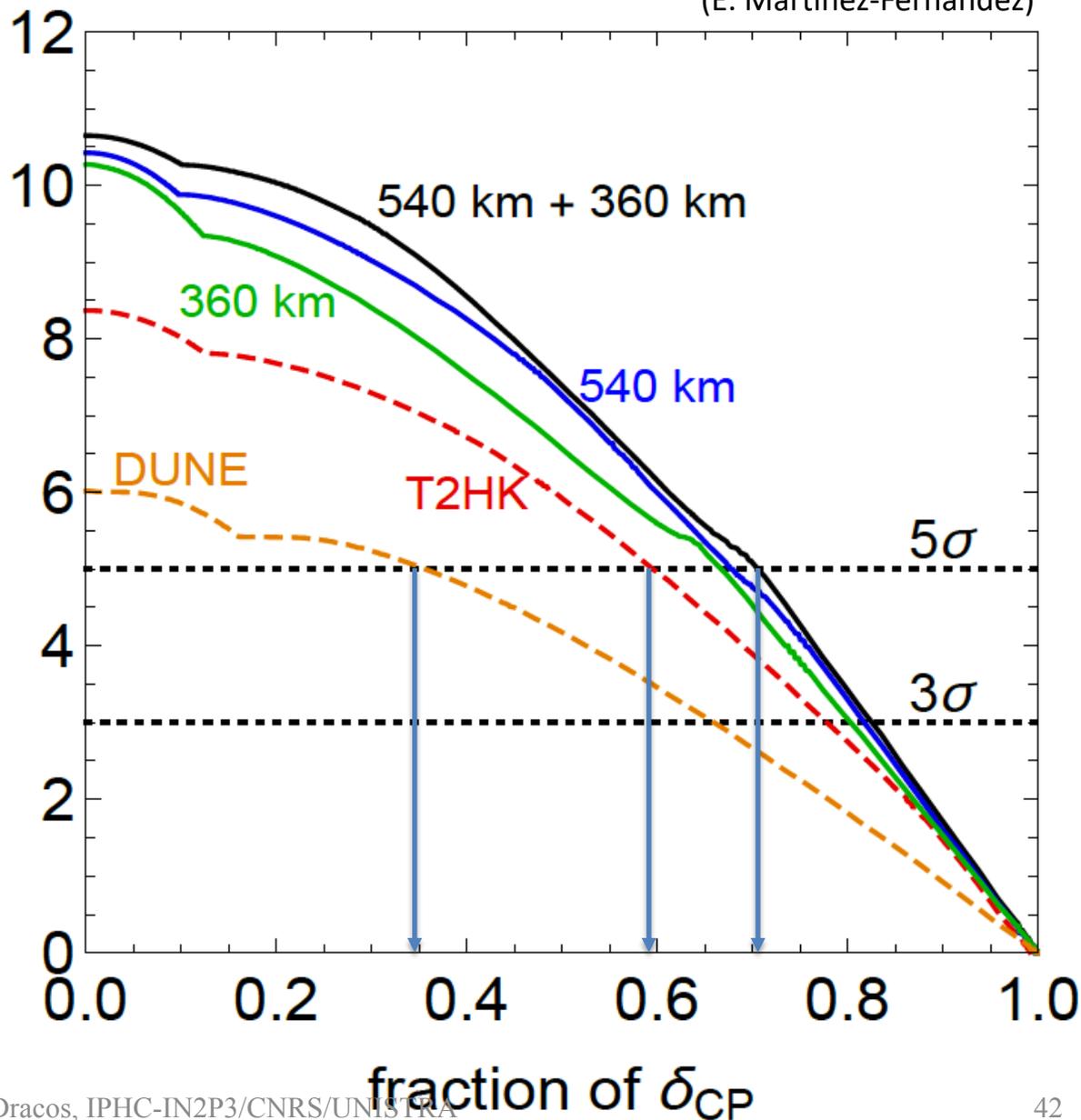
ESSvSB 500 kt tank at 360 km.



ESSvSB 250 kt tank at 540 km and 250 kt tank at 360 km.

Fraction of δ_{CP}

(E. Martinez-Fernandez)



$\sqrt{\chi^2}$

2 active mines aligned...

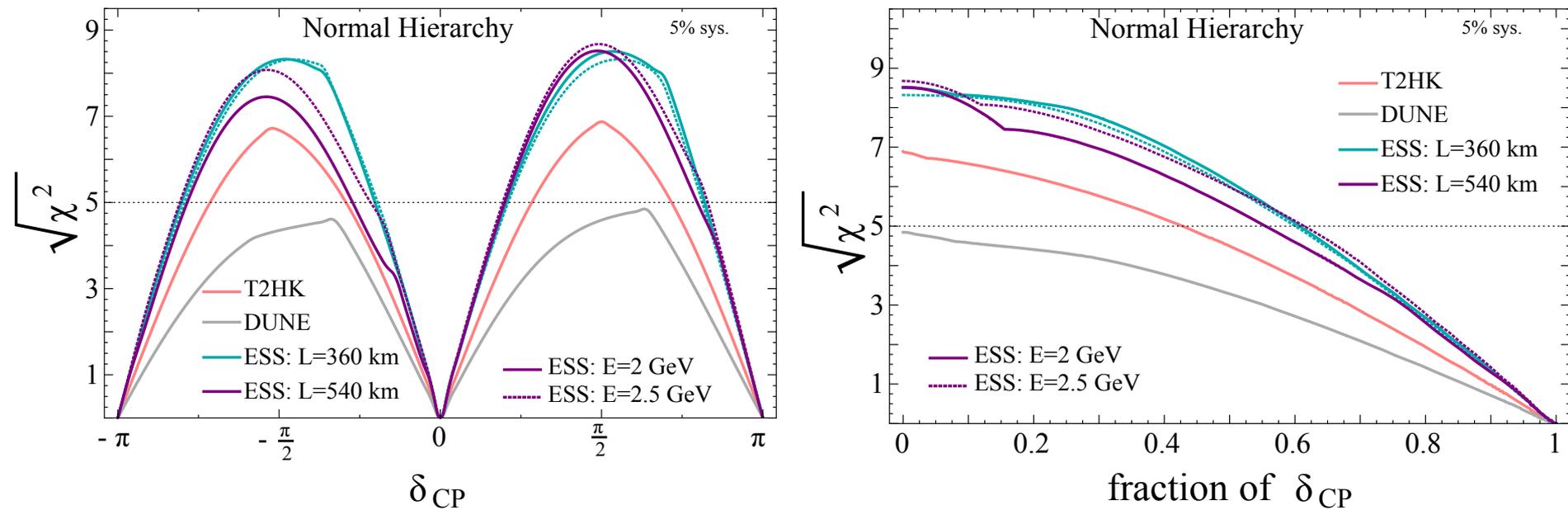
My personal opinion:
these scenarios are too optimistic
for all facilities

Systematic errors

Systematics	SB			BB			NF		
	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 \times eff. QE †	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs \times eff. RES †	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs \times eff. DIS †	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE *	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES *	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS *	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

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

Comparisons



Comparison using the same systematic errors

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