ESS NEUTRINO SUPER BEAM

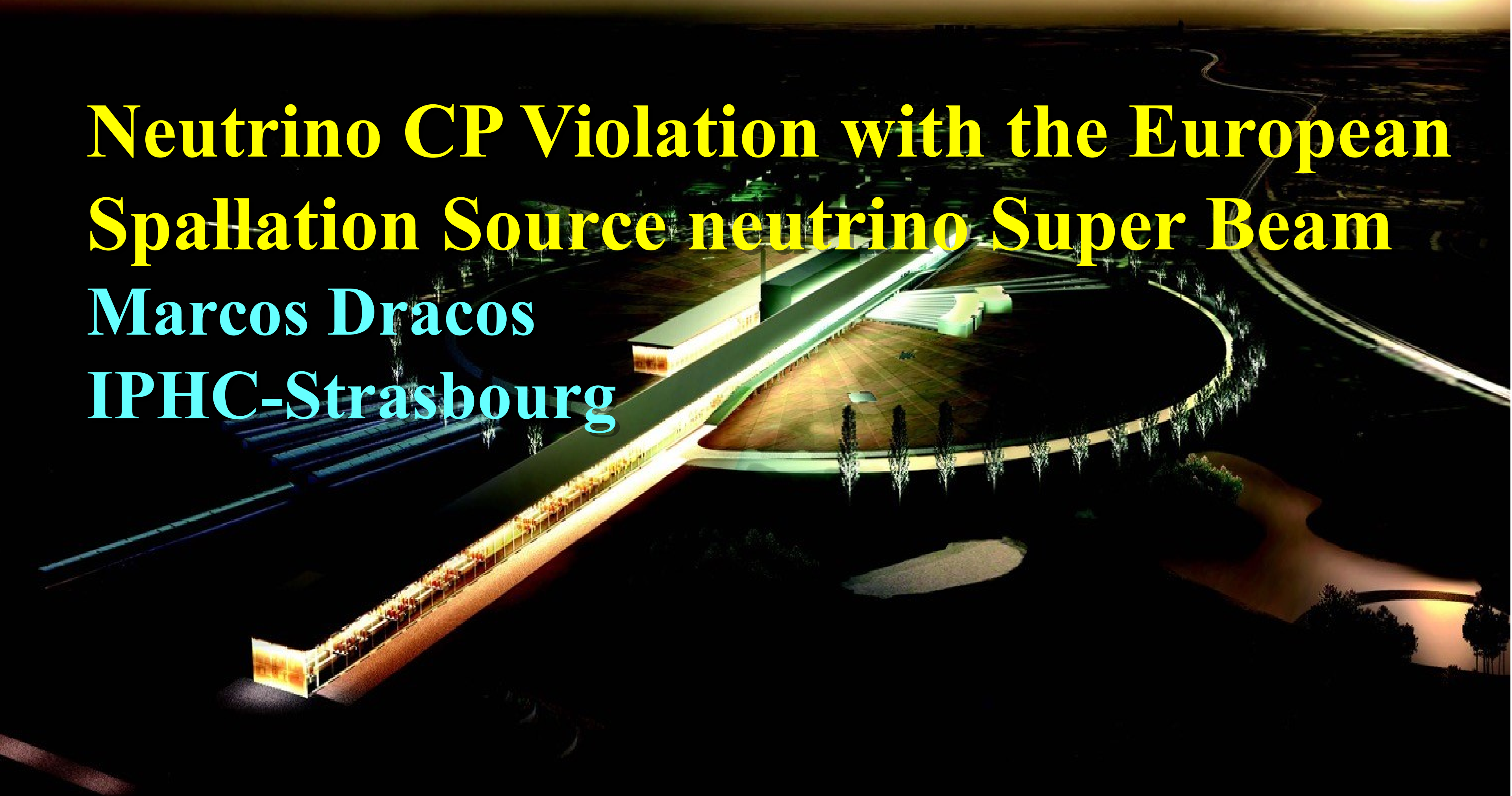
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Workshop on Connecting Insights in Fundamental Physics: Standard Model and Beyond

AUGUST 31 - SEPTEMBER 11, 2019

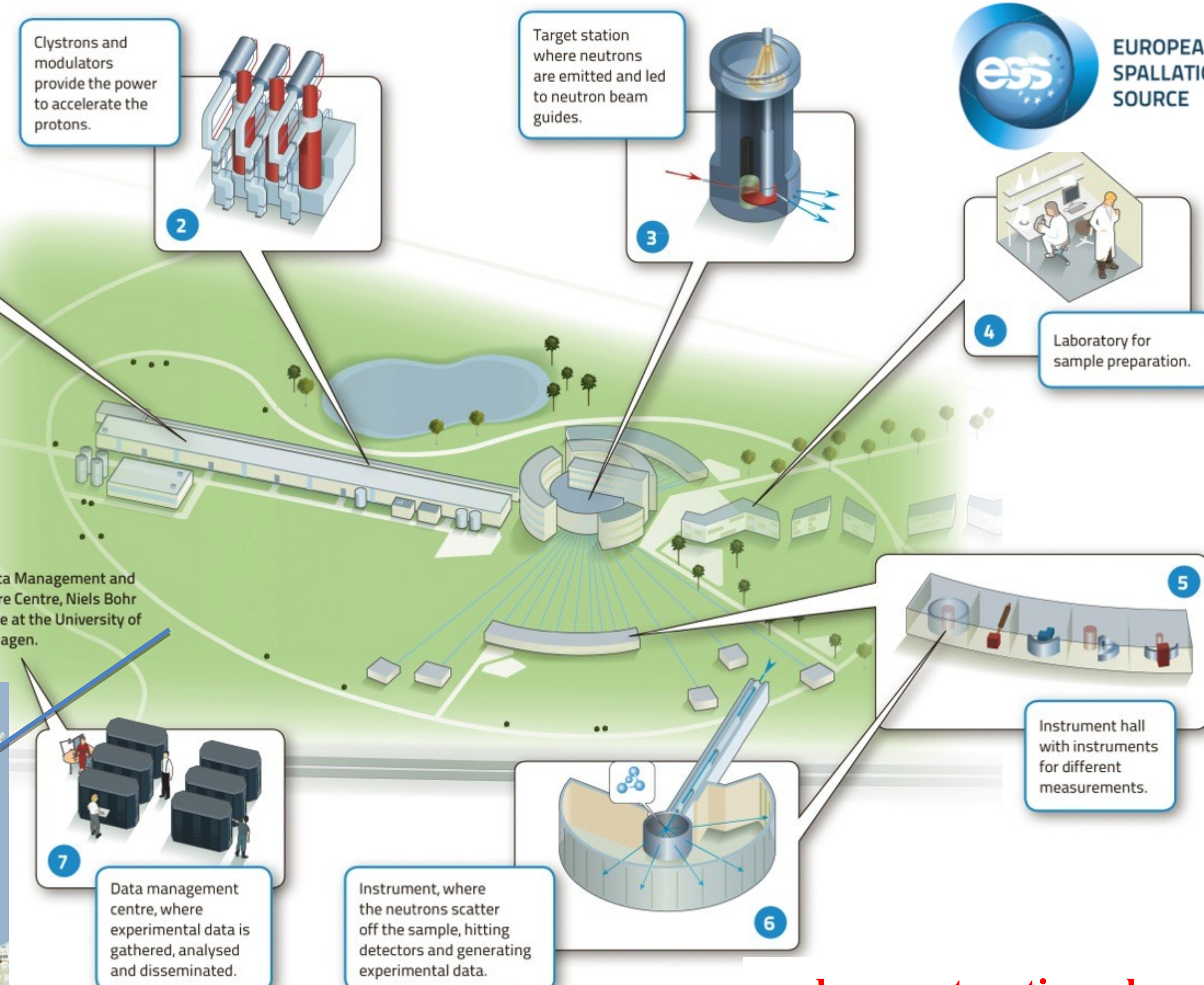
Neutrino CP Violation with the European Spallation Source neutrino Super Beam

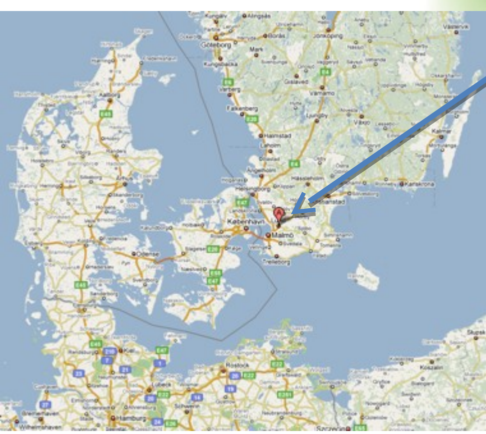
Marcos Dracos
IPHC-Strasbourg



European Spallation Source

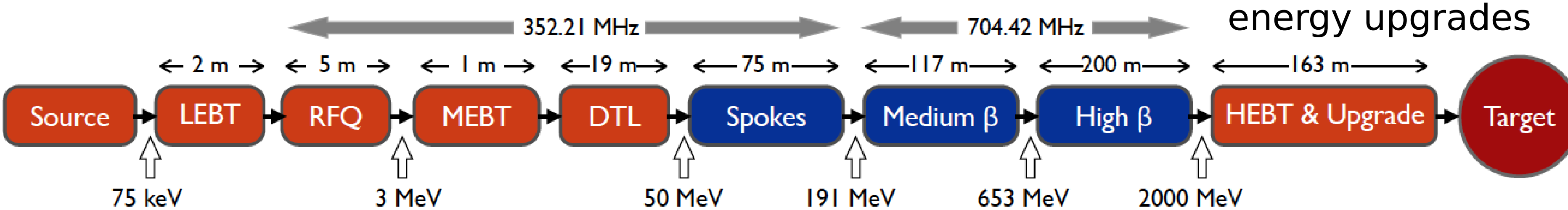
Neutron facility
equivalent to SNS)





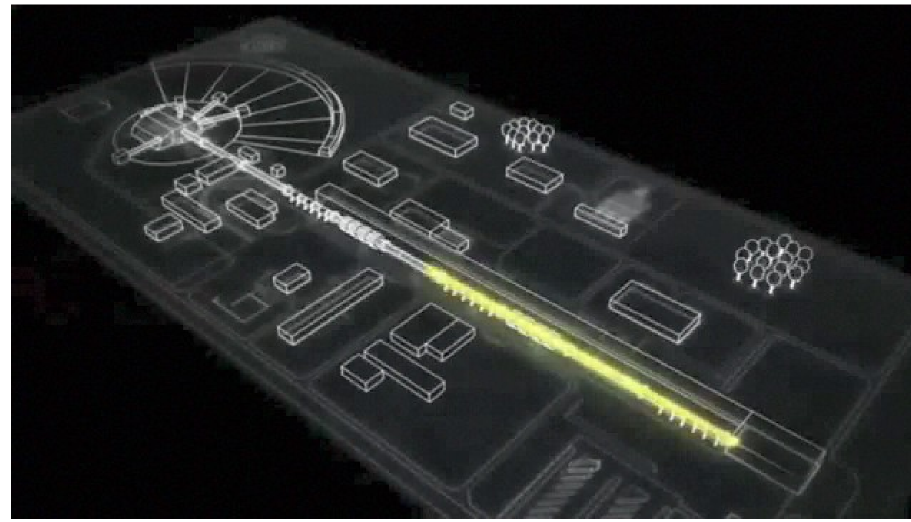
under construction phase
(~1.85 B€ facility)

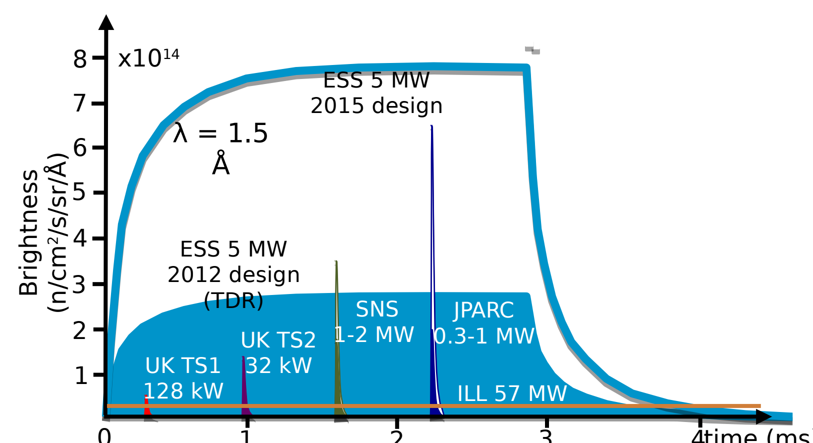
ESS proton linac



- 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)

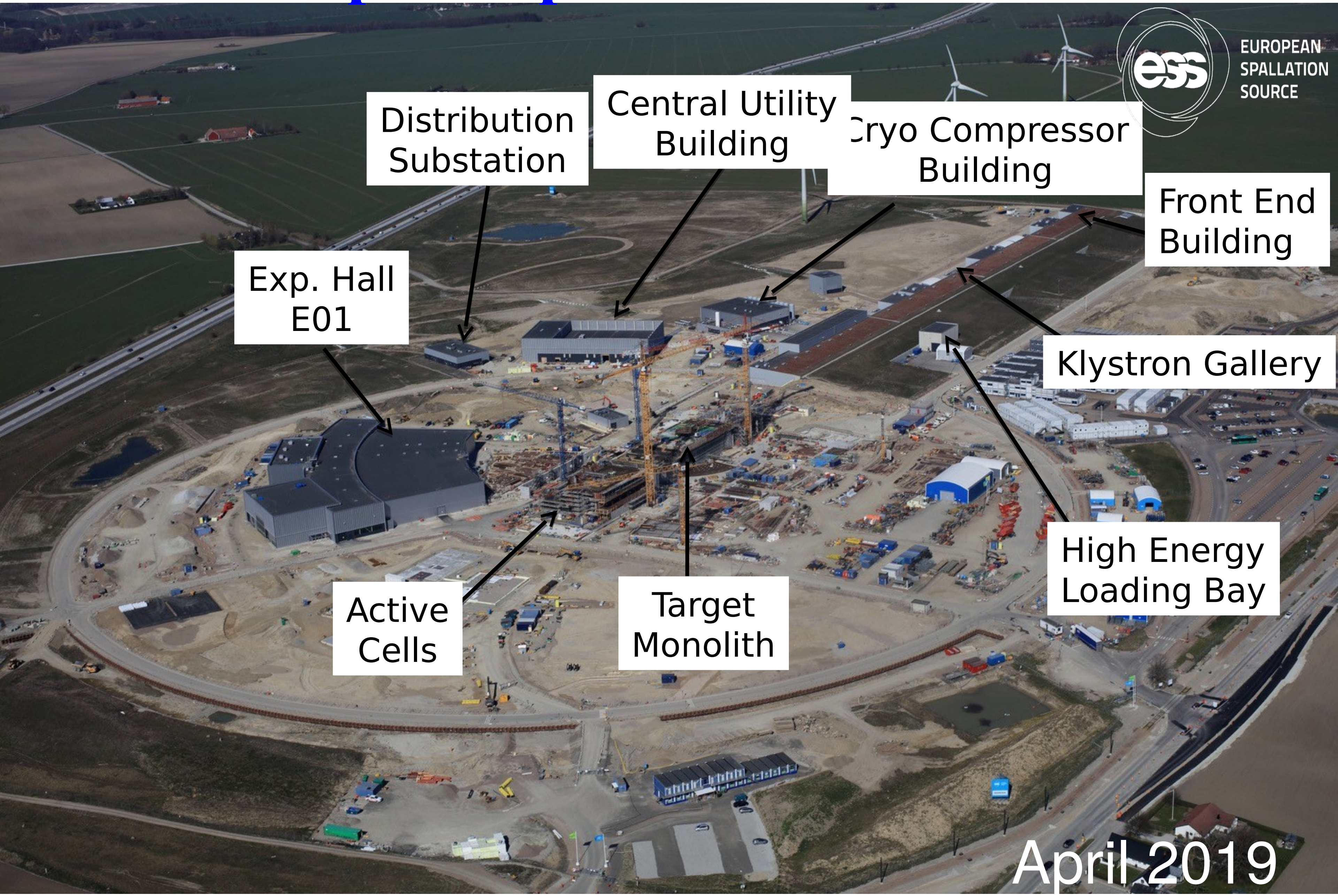




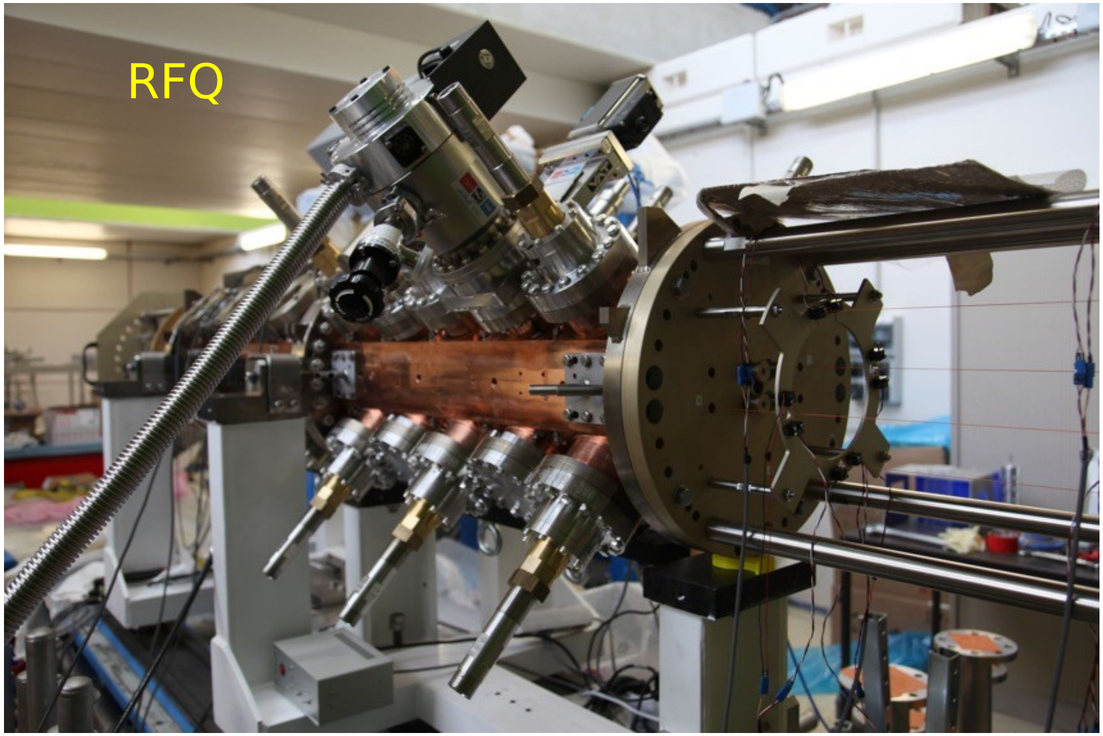
What does it mean 5 MW?

- One beam pulse:
  - has the same energy as a 16 lb (7.2kg) shot traveling at
    - 1100 km/hour
    - Mach 0.93
  - Has the same energy as a 1000 kg car traveling at 96 km/hour
  - You boil 1000 kg of ice in 83 seconds
- And this for 14 pulses/sec…

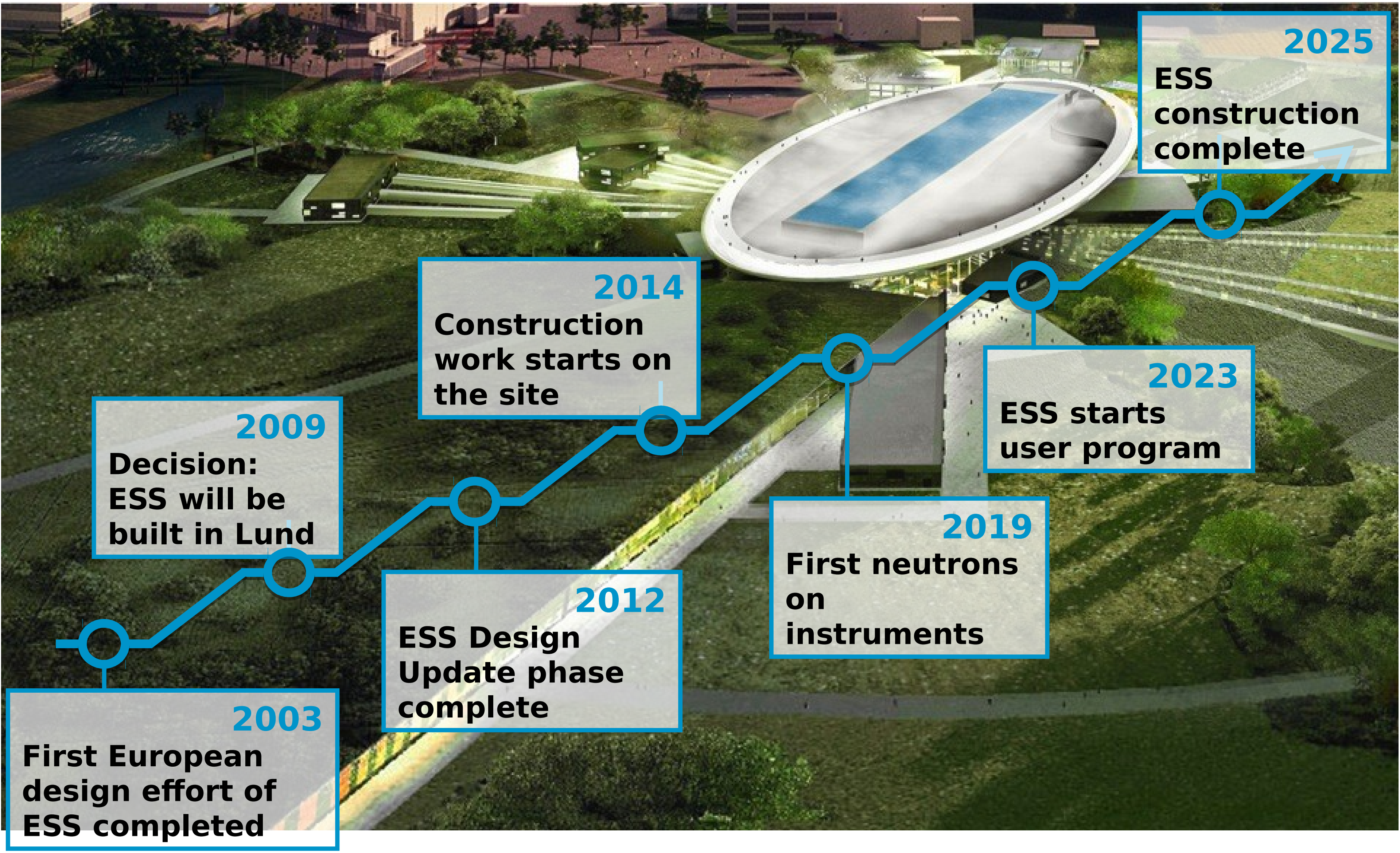
European Spallation Source



European Spallation Source



ESS schedule



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

$$\nu_\mu \longrightarrow \nu_e$$

Oscillation probability
(neutrino beams)

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

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

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

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

matter effect

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

$$\mathcal{A} = \frac{P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e}}$$

Matter-antimatter asymmetry

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

δ_{CP} and matter-antimatter asymmetry magnitude

$$A_{\alpha\beta}^{CP} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$
$$= J_{CP}^{PMNS} \cdot \sin\delta_{CP}$$

with: $J_{CP}^{PMNS} \sim 3\times10^{-3}$ (Jarlskog invariant)

(for hadrons: $J_{CP}^{CKM} \sim 3\times10^{-5}$, not enough even if δ_{CP}~70°)

m the already observed CP violation in the hadronic sector)

Theoretical models predict that if |sinδ_{CP}|≳0.7 (45°<δ_{CP}<135° or 225°<δ_{CP}<315°), this could be enough to explain the observed asymmetry.

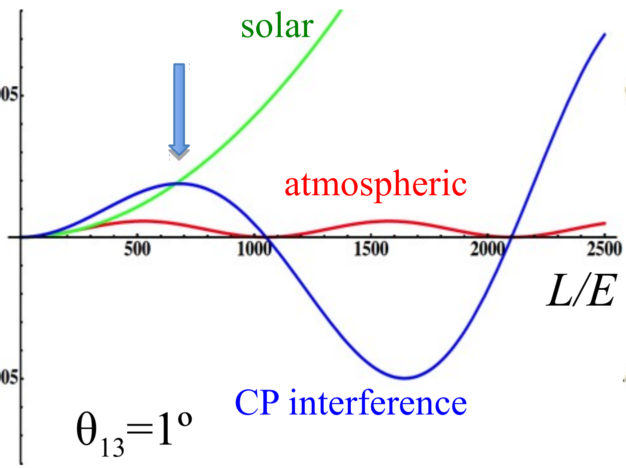
(Nucl.Phys.B774:1-52,2007, arXiv:hep-ph/0611338)

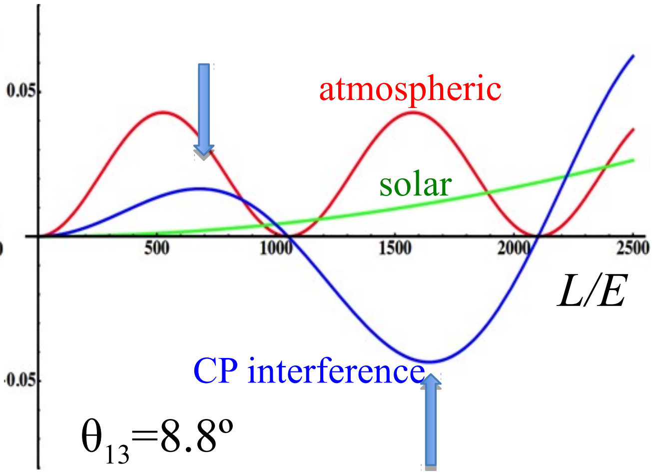
Use all this ESS linac power to go to the second oscillation maximum

Neutrino Oscillations with "large" θ_{13}

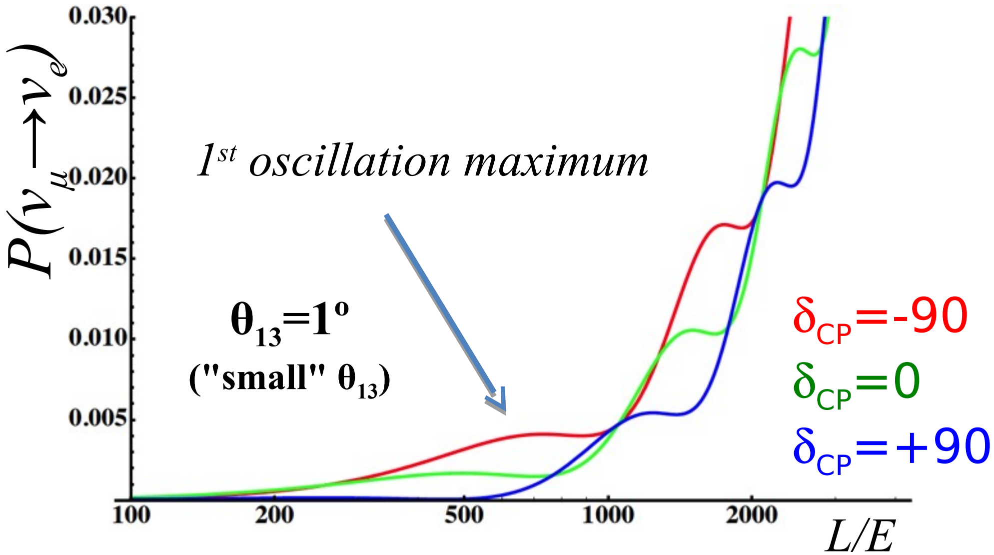
for small θ_{13} 1st oscillation maximum is better

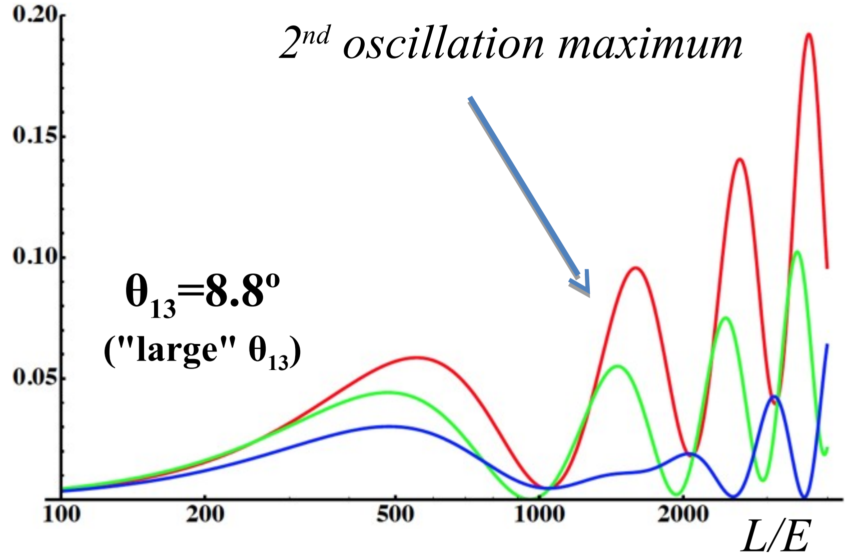
(arXiv:1110.4583)





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





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

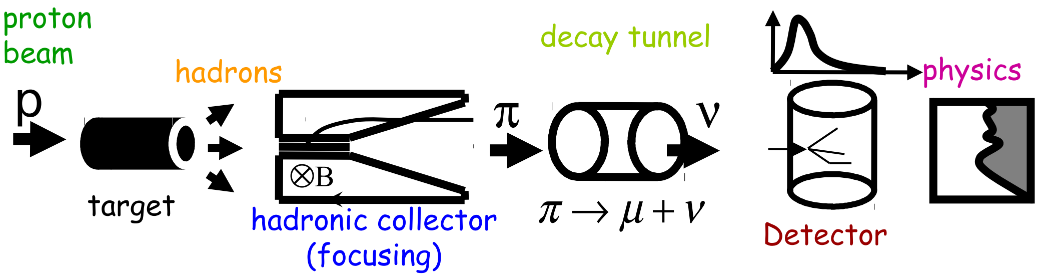
more sensitivity at 2nd oscillation max.

(see arXiv:1310.5992 and arXiv:0710.0554)

Having access to a powerful proton beam…

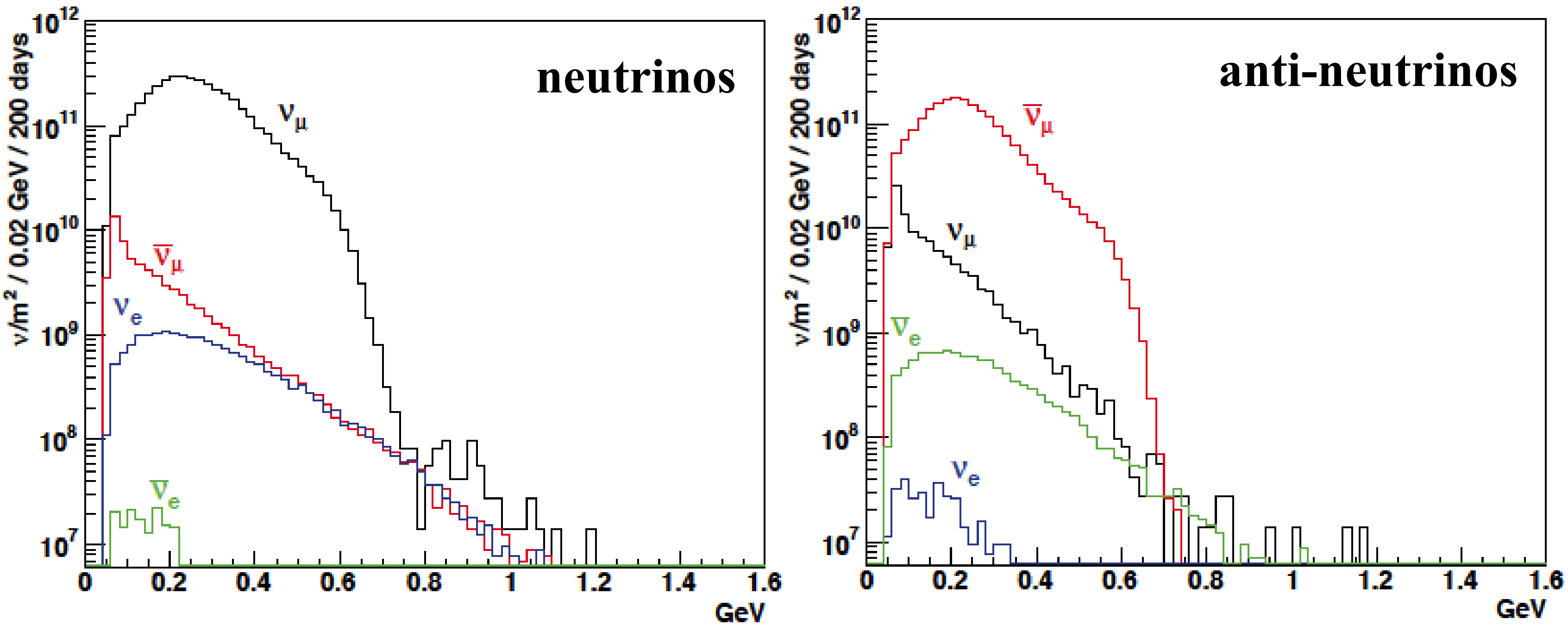
What can we do with:

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



conventional neutrino (super) beam

ESSνSB 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_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

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

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

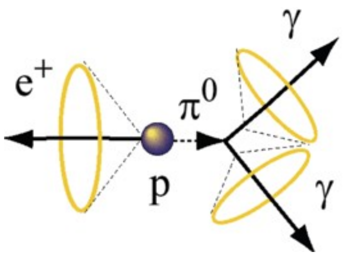
Can we go to the 2nd oscillation maximum using our proton beam?

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

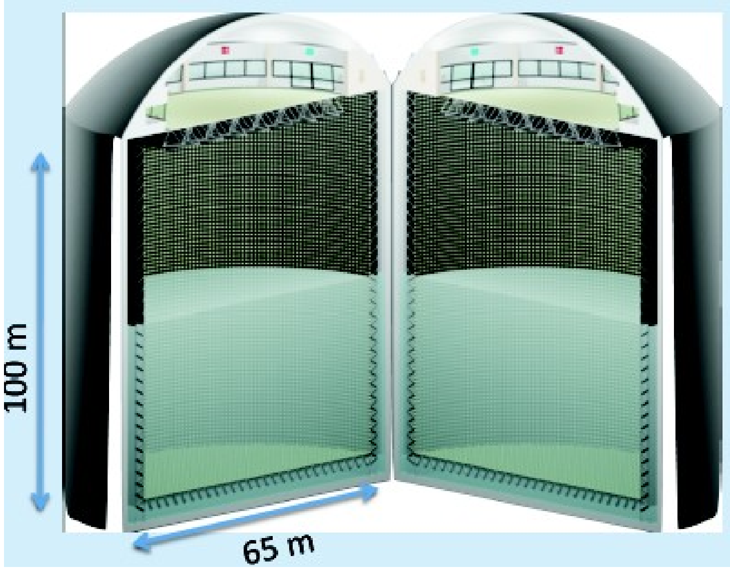
MEMPHYS like Cherenkov detector
(MEgaton Mass PHYSics studied by LAGUNA)

(arXiv: hep-ex/0607026)

- Neutrino Oscillations
- Proton decay
- Astroparticles



- Understand the gravitational collapsing: galactic SN
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos



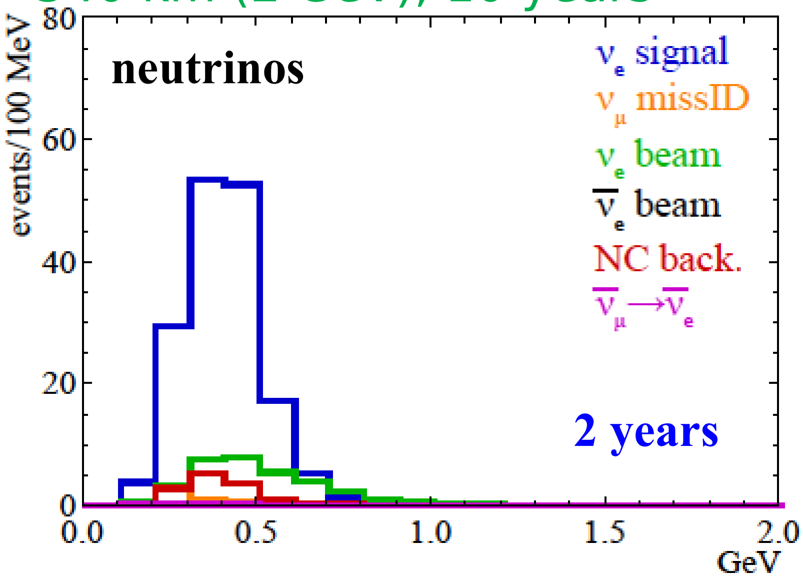
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8" PMTs
- 30% optical coverage

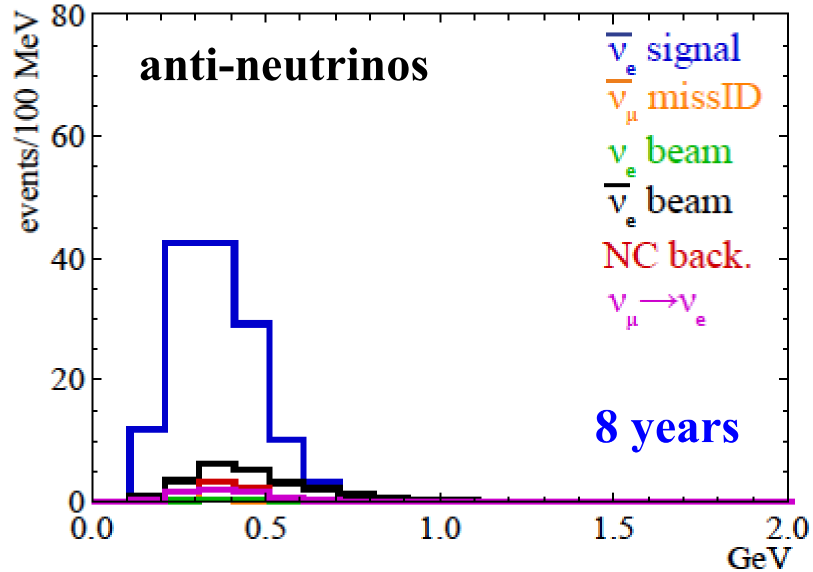
New 20" PMTs with higher QE and cheaper (see JUNO), the detection efficiency will improve the detector performance keeping the price constant, not yet taken into account.

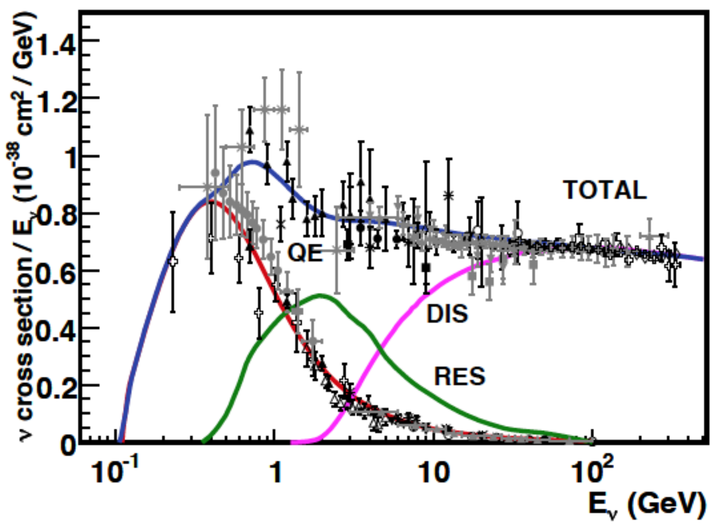
Neutrinos in the far detector

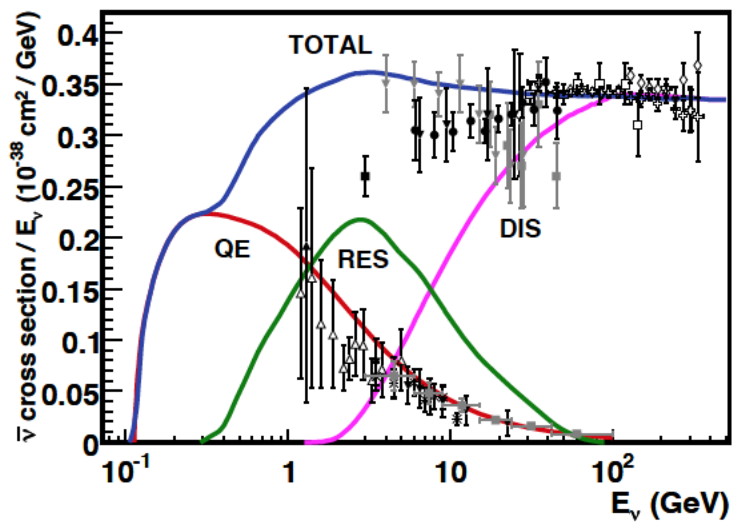
540 km (2 GeV), 10 years

$\delta_{CP}=0$



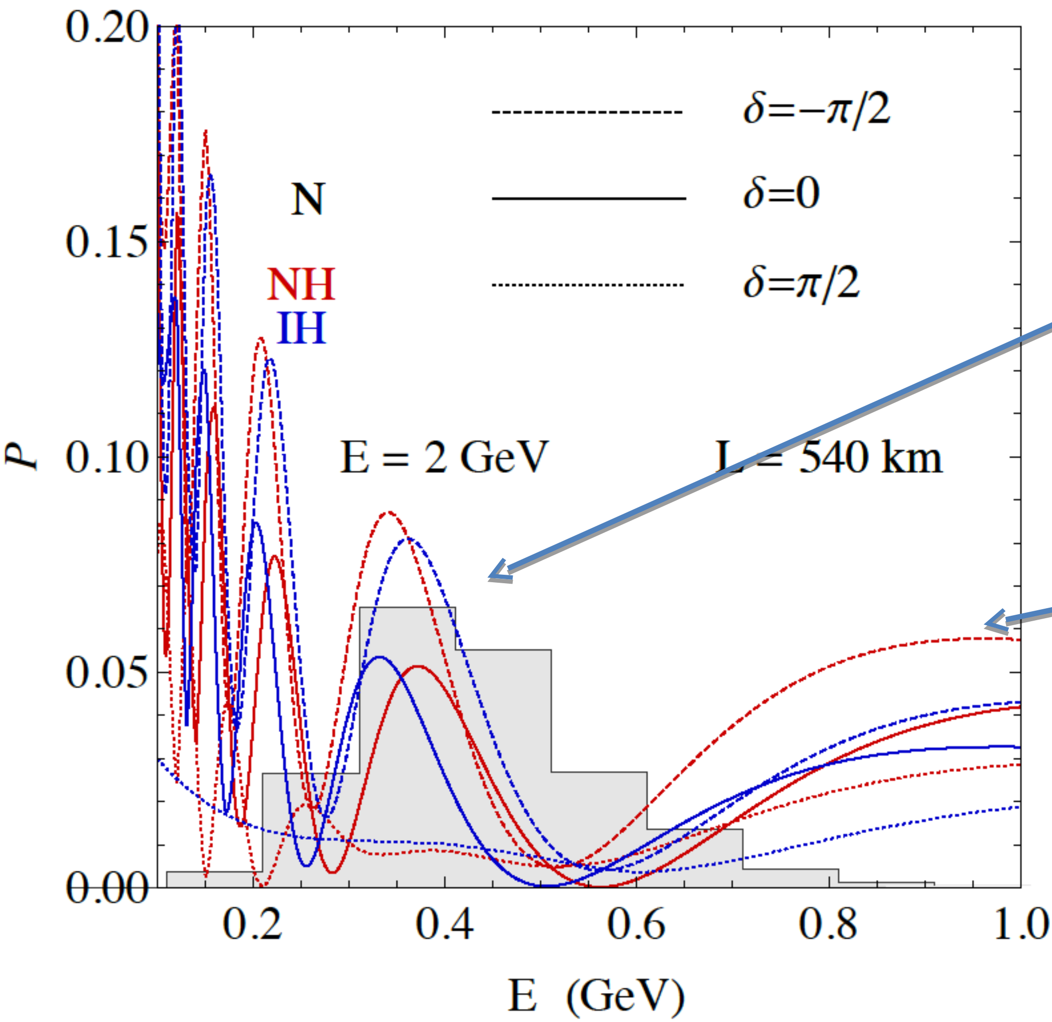






ow ν_τ production, almost only QE events, not suffering too much by π^0 backgrou

2nd Oscillation max. coverage



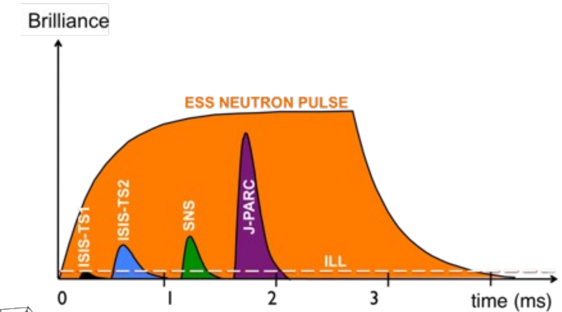
2nd oscillation max. well covered by the ESS neutrino spectrum

1st oscillation max.

full coverage of the 2nd oscillation max.

ESS Linac modifications to produce a neutrino Super Beam

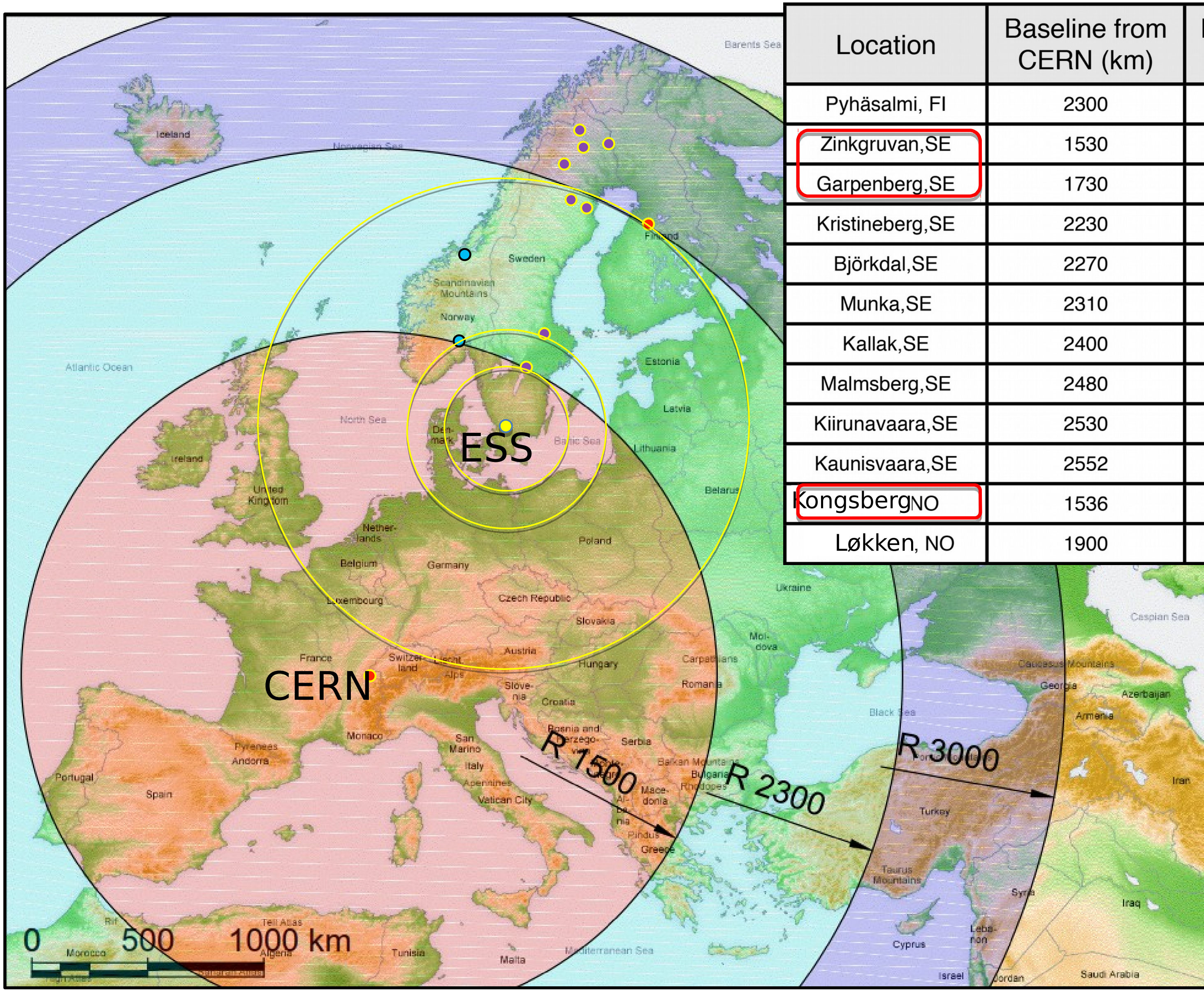
How to add a neutrino facility?



- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs 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 FP7 EUROν).
- Underground detector (studied in FP7 LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.

Possible locations for far detector

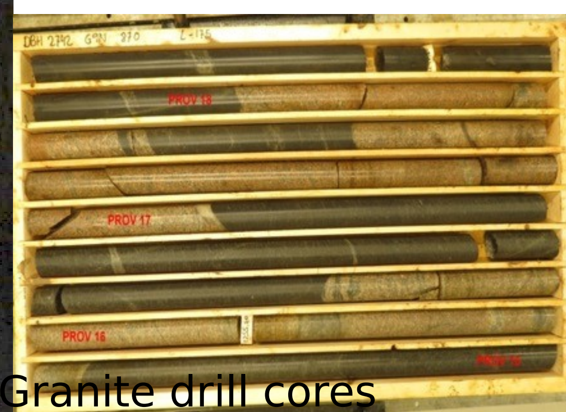
Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320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

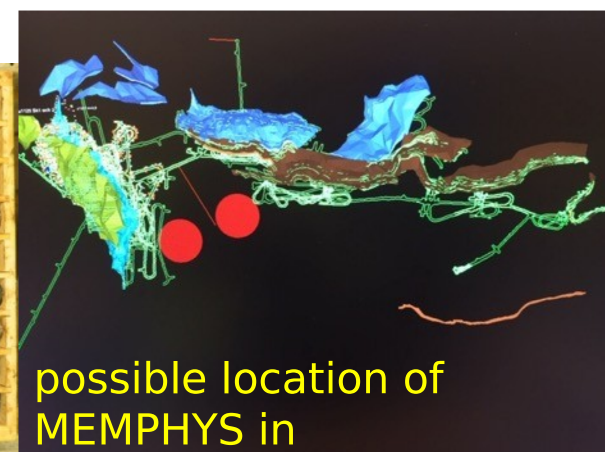


LAGUNA sites

Candidate active mines

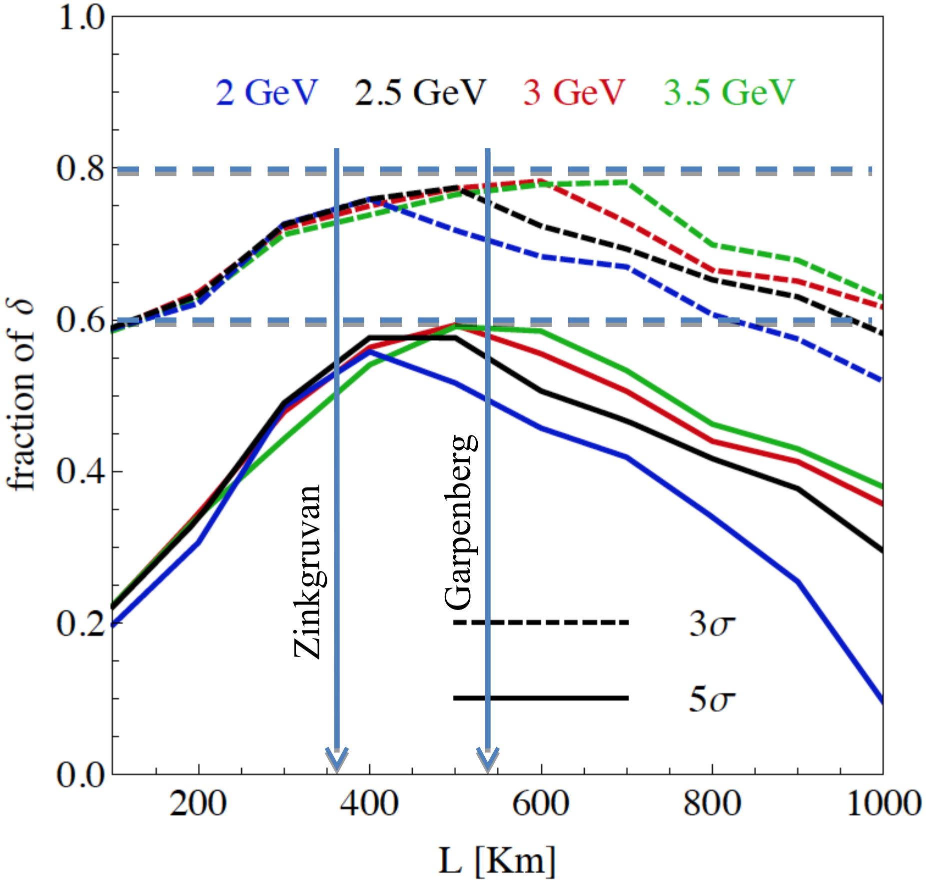
- **Garpenberg mine**
  - –Distance from ESS Lund 5 **km**
  - –Depth **1200 m**
  - –Truck **access tunnel**
- **Zinkgruvan mine**
  - –Distance from ESS Lund 3 **km**
  - –Depth **1500 m**
  - –Truck **access tunnel**





Which baseline?

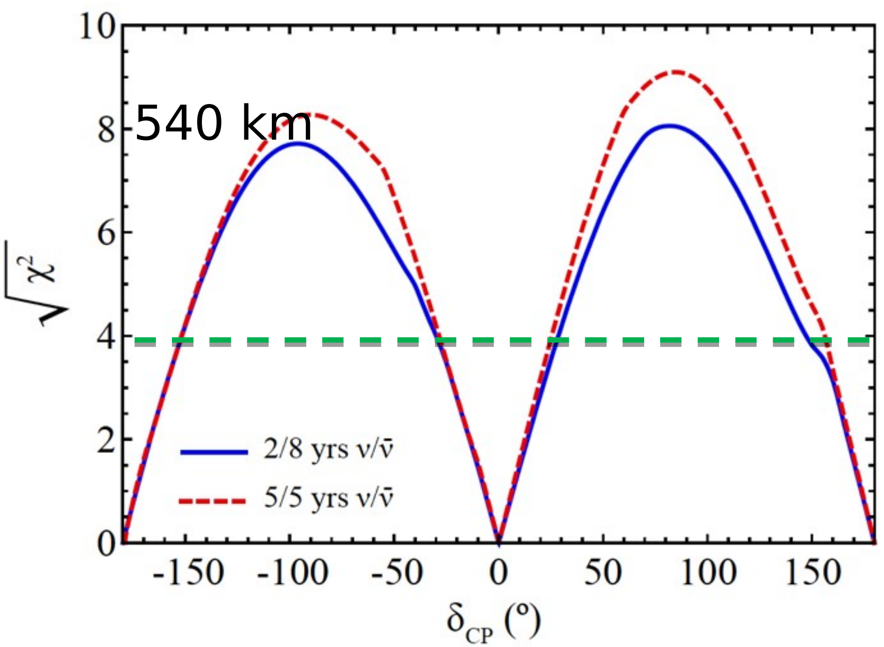
CPV (*Nucl. Phys. B 885 (2014) 127*)

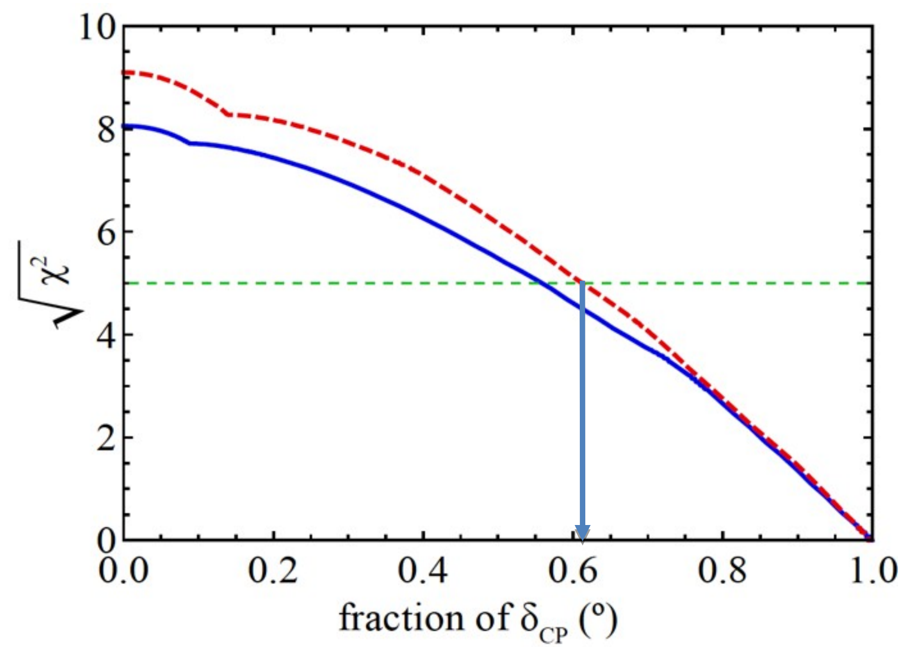


Candidate active mines

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

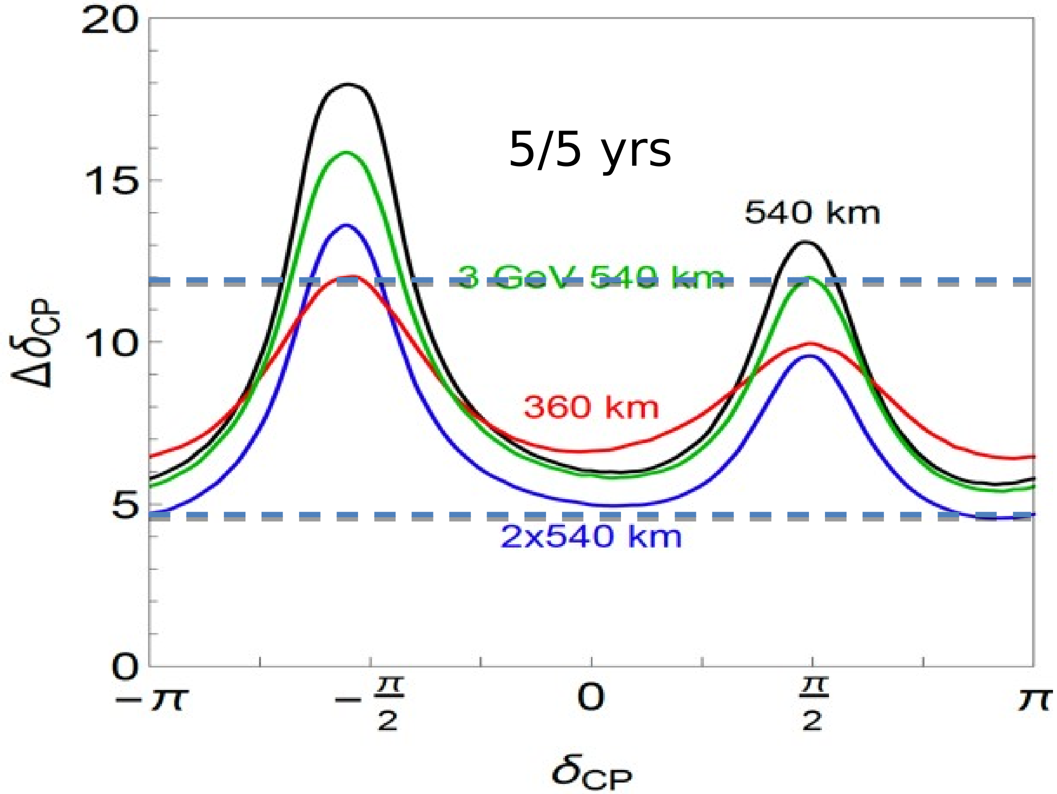
Physics Performance
(CPV discovery)





- 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),
- not yet optimized facility,
- **5/10% systematic errors** on signal/background

Physics Performance (accuracy)



- δ_{CP} accuracy down to **6°** at 0° and 180°
- 12° accuracy at δ_{CP}= -90° and 10° at δ_{CP}= 90°
- **5/10%** systematic errors on

Required modifications of the ESS accelerator for ESSνSB

F. Gerigk and E. Montesinos **CERN-ACC-NOTE-2016-0050 8 July 2016**
CERN, Geneva, Switzerland

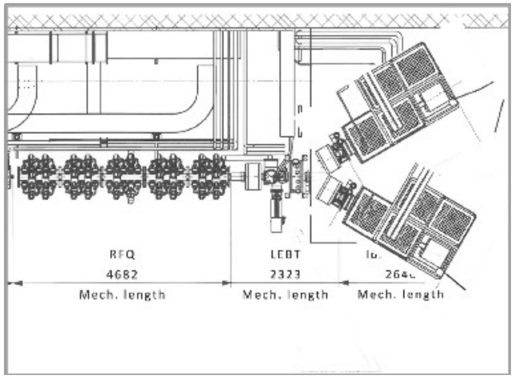
Contents

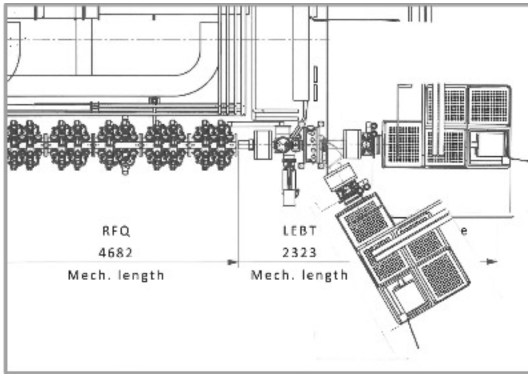
Quotation from "Executive Summary:
"No show stoppers have been identified for a possible future addition of the capability of a 5 MW H- beam to the 5 MW H+ beam of the ESS linac built as presently foreseen. Its additional cost is roughly estimated at 250 MEuros."

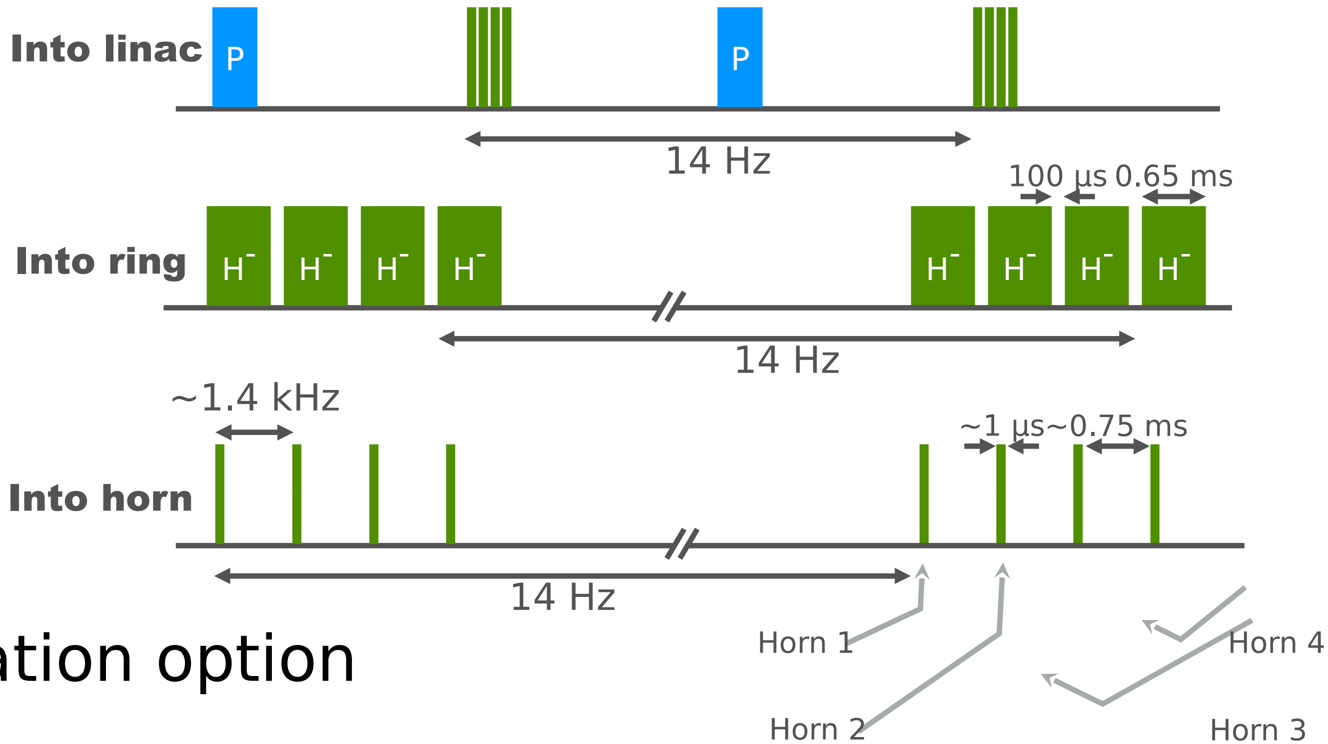
Better to go to 2.5 GeV

The Linac modifications and operation

H^- source options



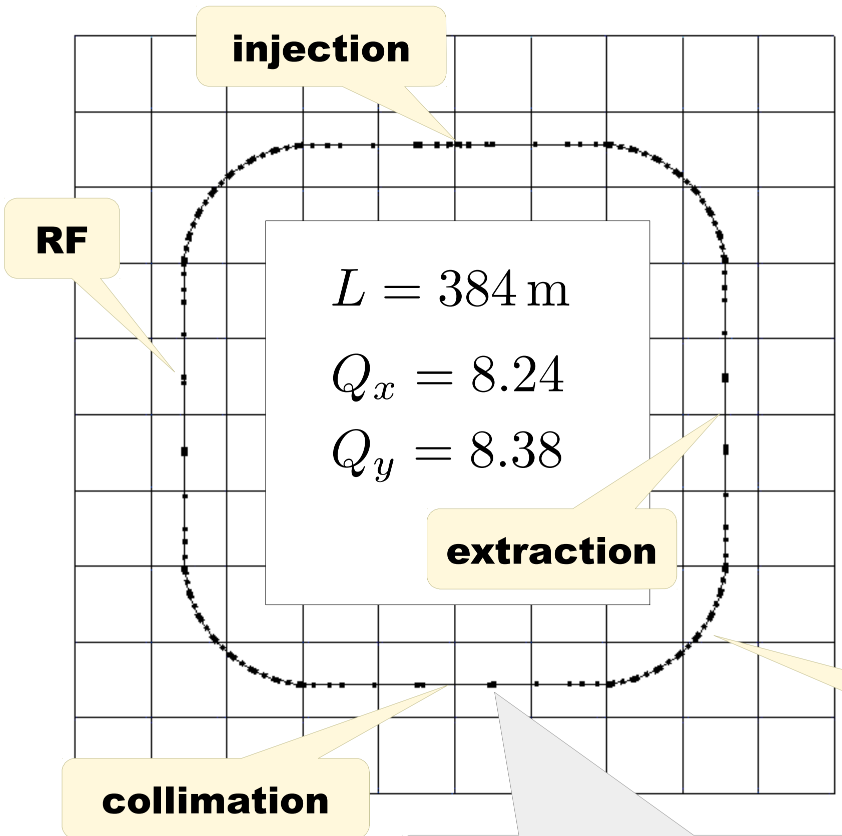




time operation option

The Accumulator

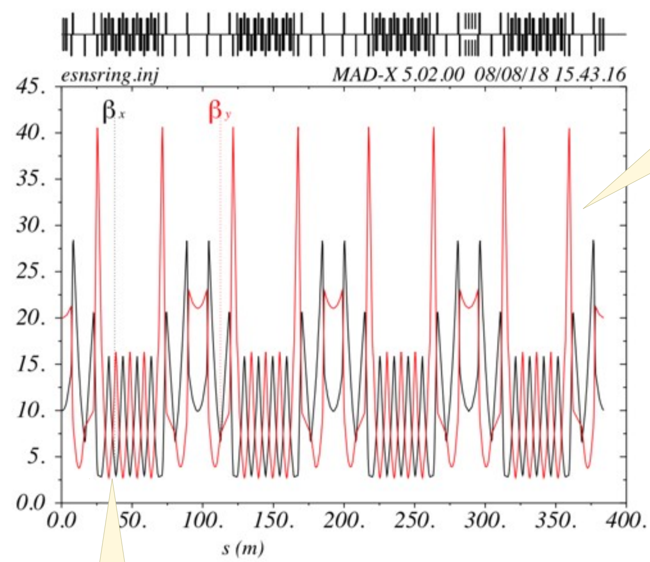
lattice development

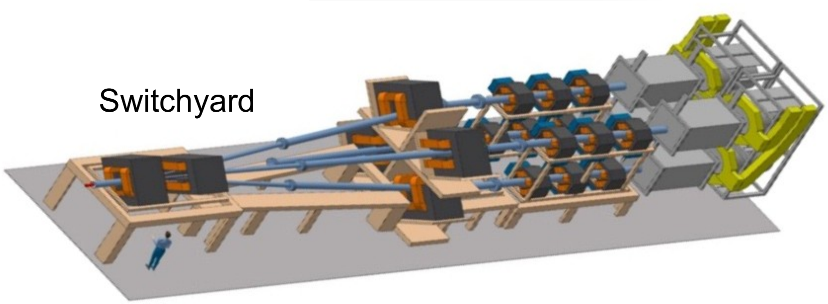


$L = 384\,\mathrm{m}$

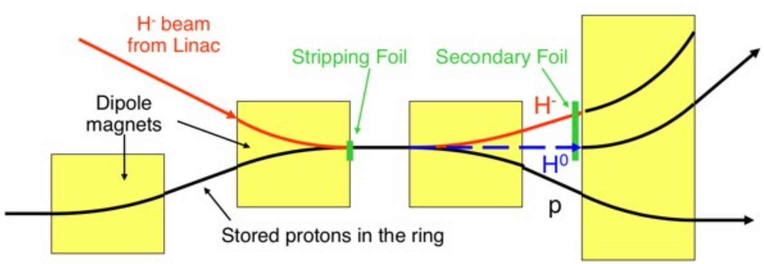
$Q_x = 8.24$

$Q_y = 8.38$

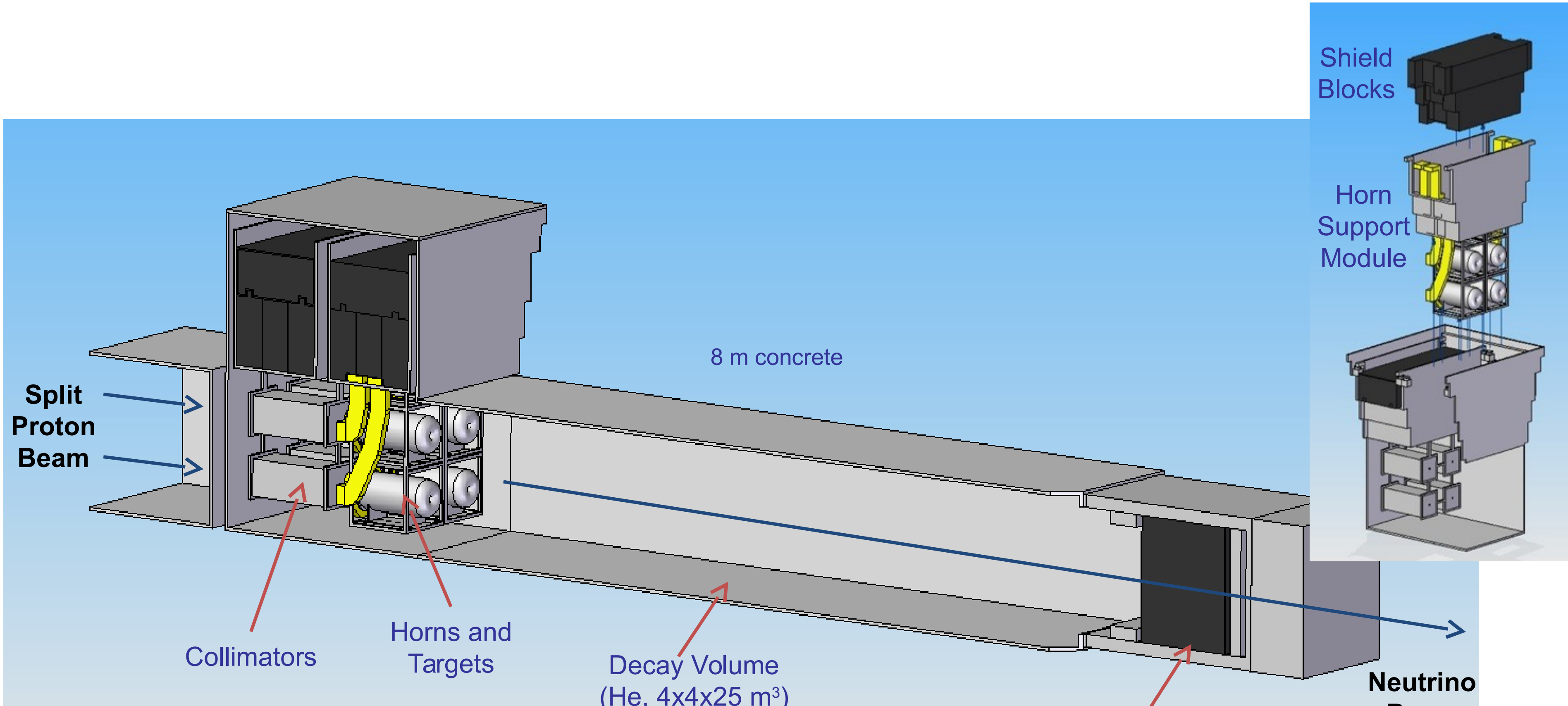


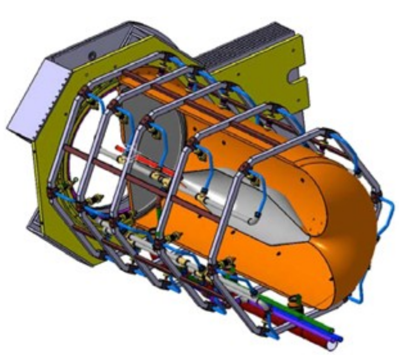


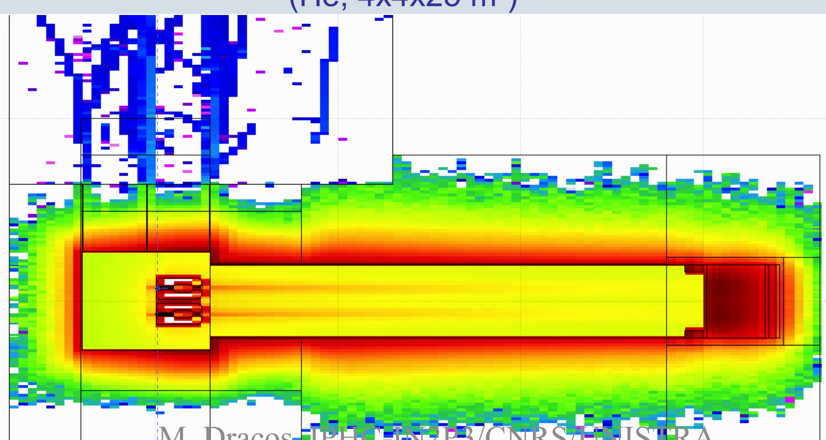
H- stripping

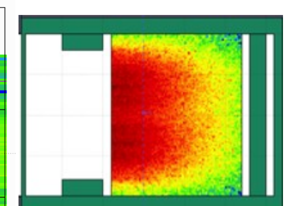


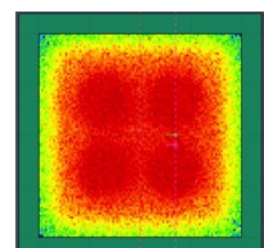
General Layout of the target station



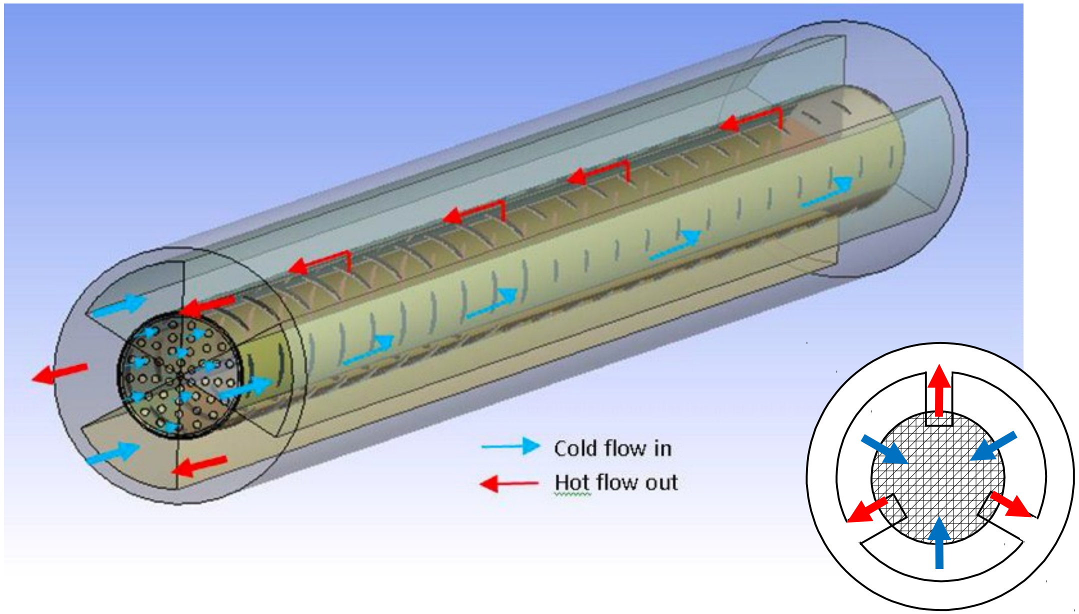


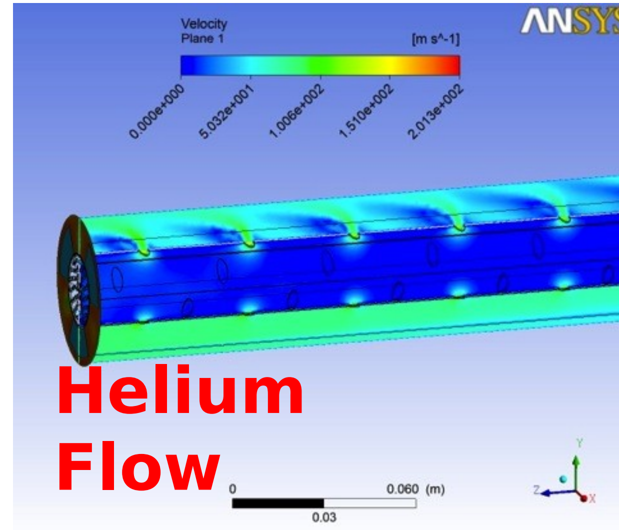




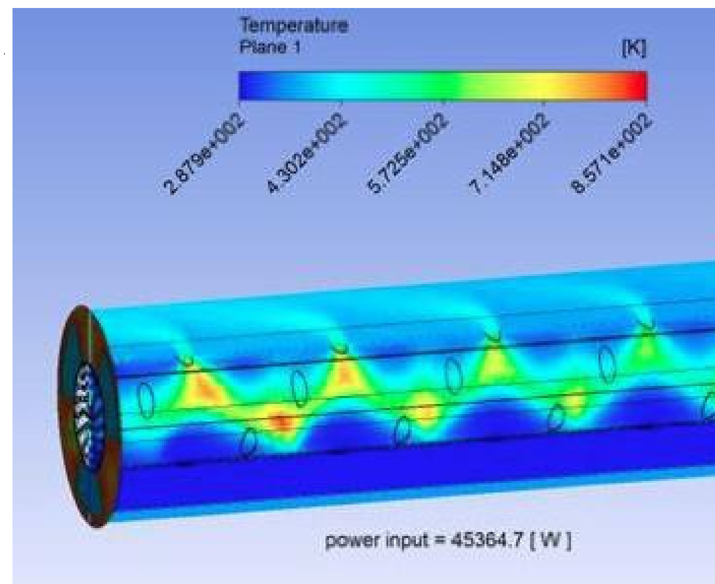


Target



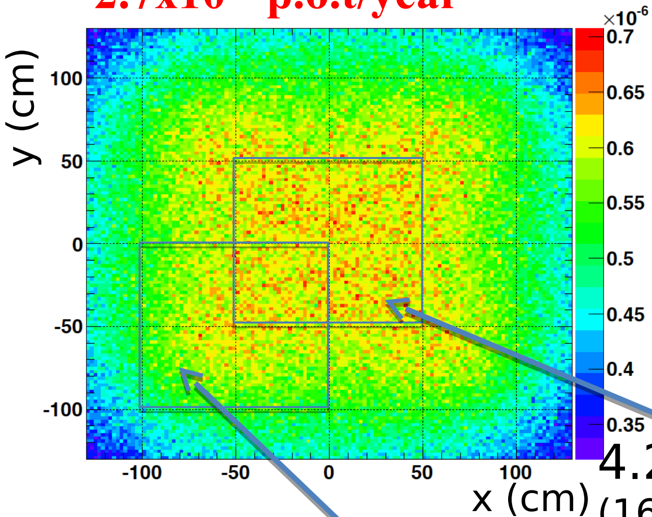


- Packed-bed target studied at RAL within the EuroNu project (arXiv:1212.0732)
- Titanium alloy canister containing packed bed of titanium spheres (Gas Helium as cooling medium)
- Single sphere diameter: 3 mm
- Canister radius/length: 12 mm / 780 mm



Muons at the level of the beam dump

2.7×10^{23} p.o.t/year

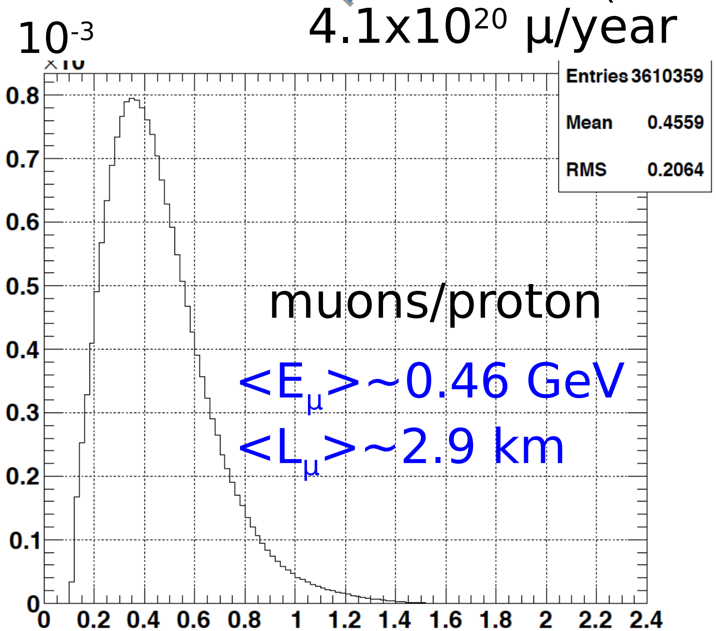


muons at the level of the beam dump (per proton)

4.2×10^{20} μ/year
(16.3×10^{20} for 4 m²)

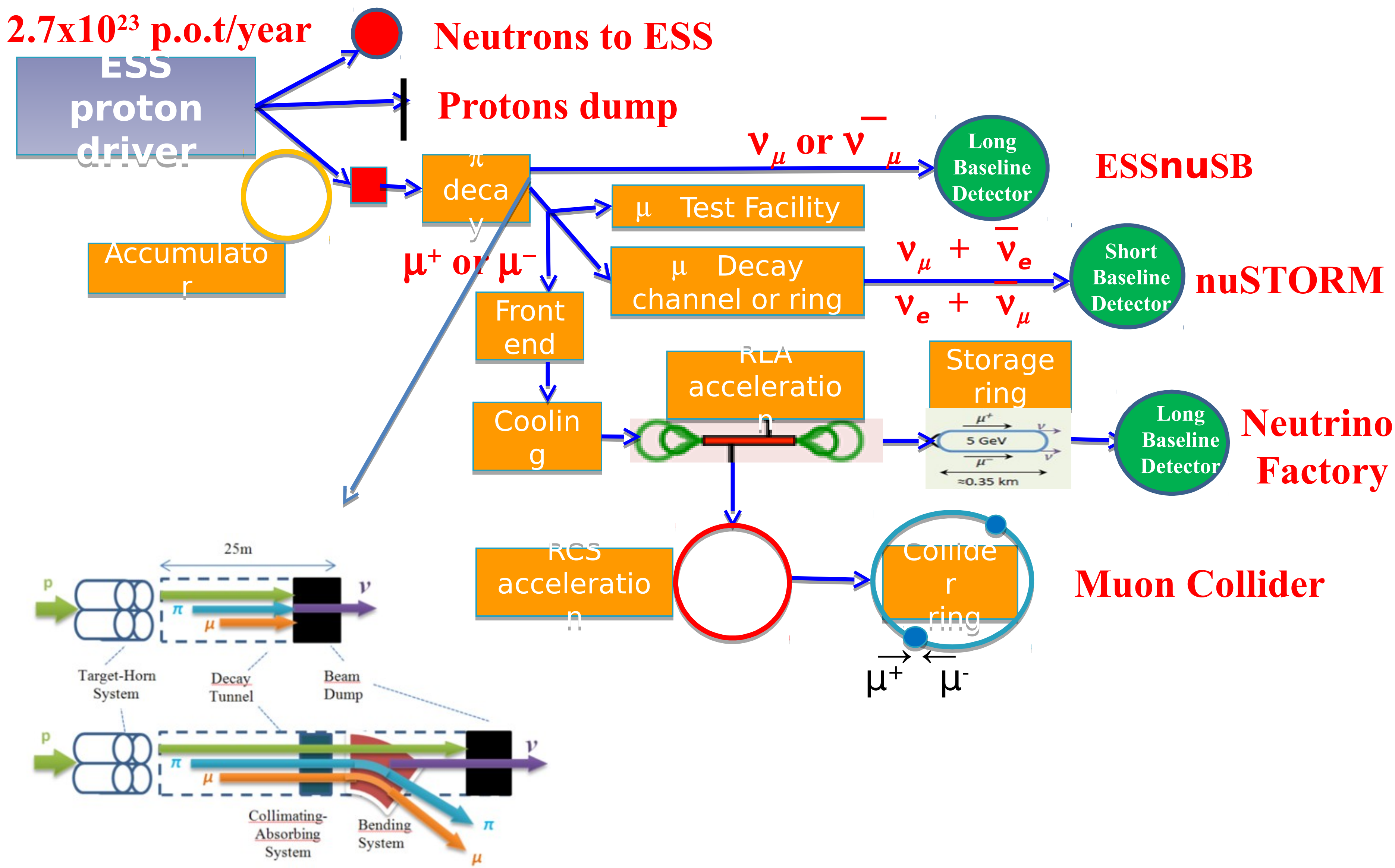
4.1×10^{20} μ/year

more than 4×10^{20} μ/year from ESS compared to 10^{14} μ used by all experiments up to now (10^{18} μ for COMET in the future).

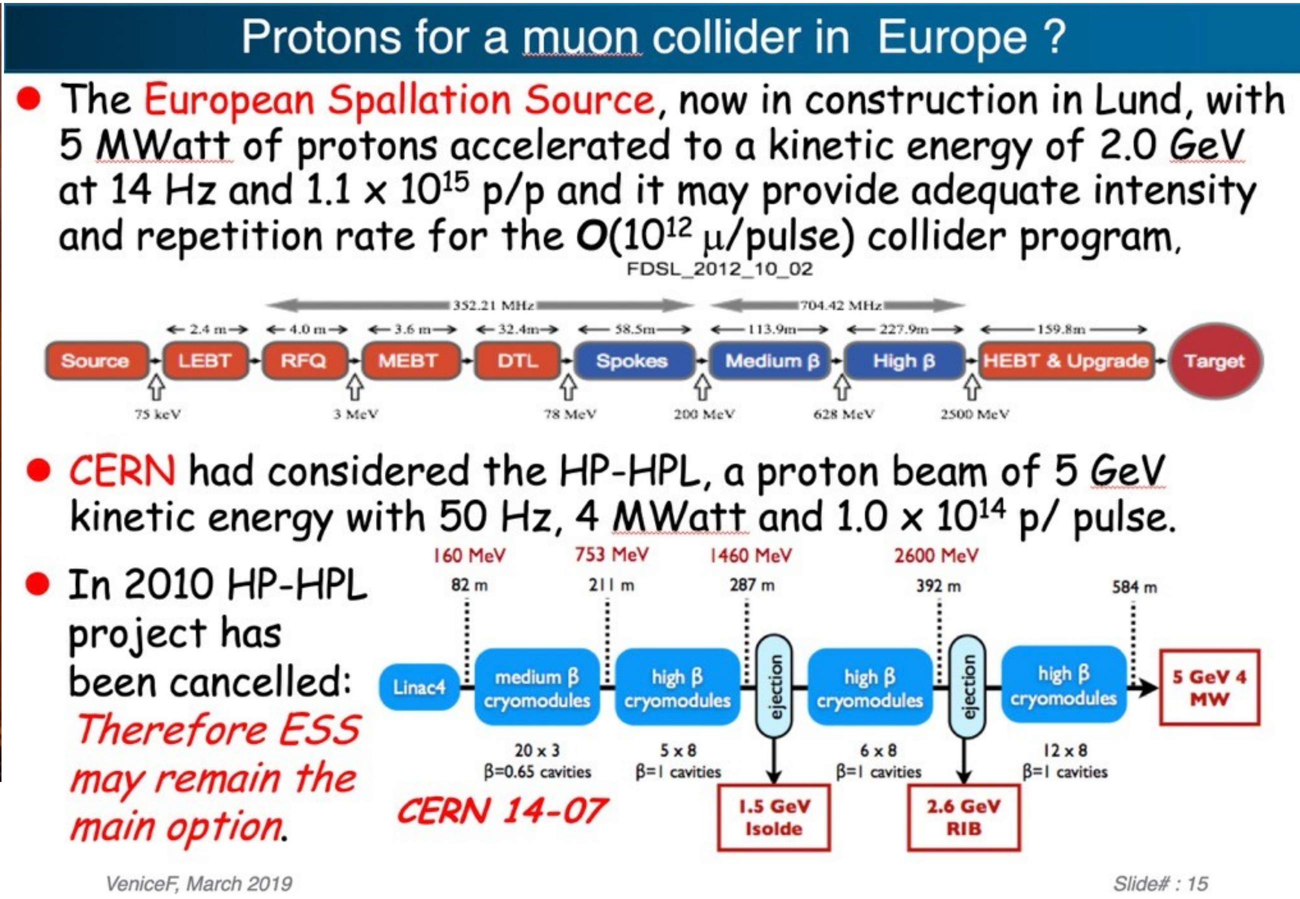


- input beam for future 6D μ cooling experiments (for muon collider),
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

ESS neutrino and muon facility



Muons at ESS (ESSμSB)



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 x 10^{15} p/p and it may provide adequate intensity and repetition rate for the O(10^{12} μ/pulse) collider program,

- CERN had considered the HP-HPL, a proton beam of 5 GeV kinetic energy with 50 Hz, 4 MWatt and 1.0 x 10^{14} p/ pulse.
- In 2010 HP-HPL project has been cancelled: *Therefore ESS may remain the main option.*

VeniceF, March 2019

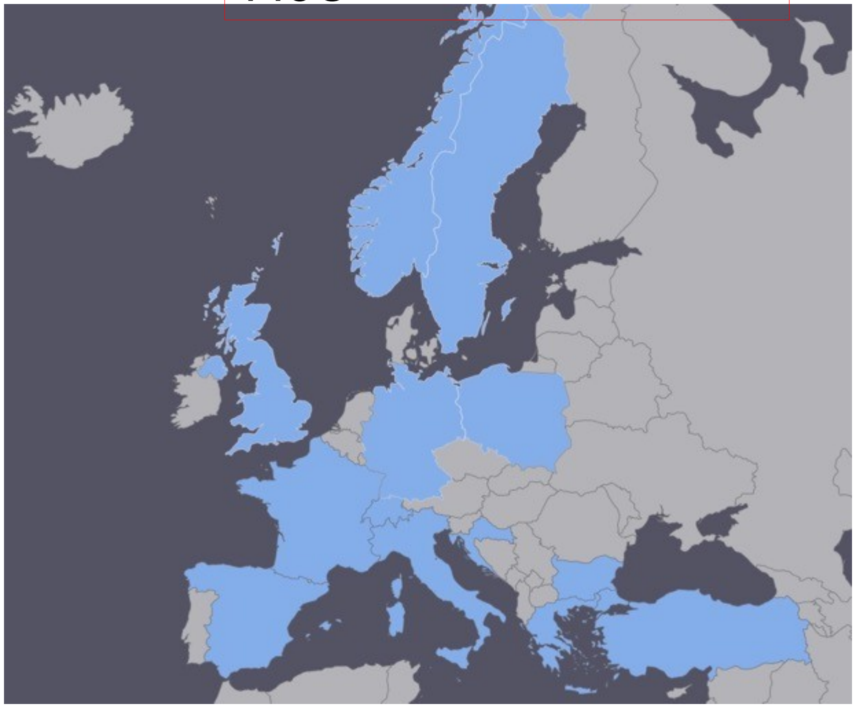
Slide# : 15

SM Higgs rate ≈ 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

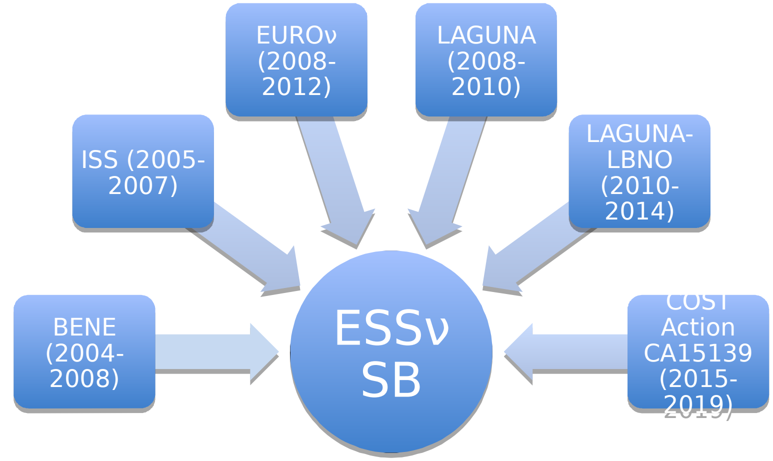
The members are countries which signed the Action MoU

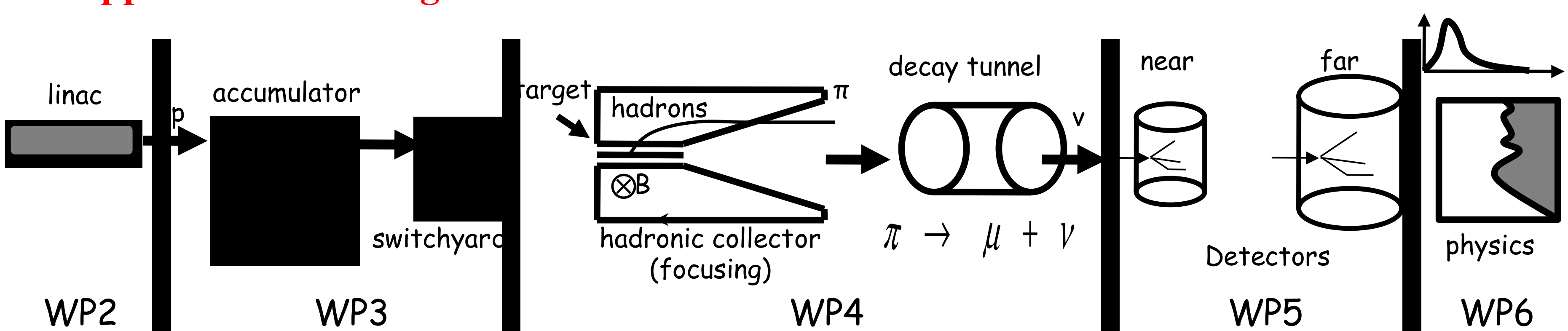


http://euronunet.in2p3.fr/

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**





Design Study ESSνSB (2018-2021)

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

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

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:	

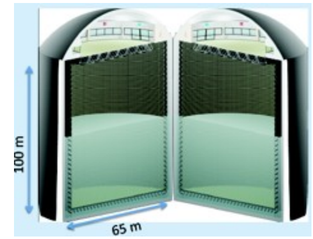
More information on: http://essnusb.eu/

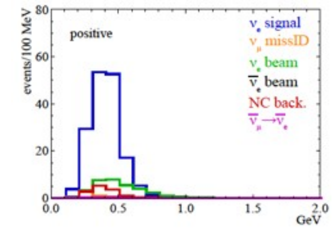
CDR end of 2021

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

Possible ESSνSB schedule

(2nd generation neutrino Super Beam)





2012: inception of the project

Nucl. Phys. B 885 (2014) 127

2016-2019: beginning of COST Action EuroNuNet

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

2021: End of ESSνSB Design Study, CDR and preliminary costing

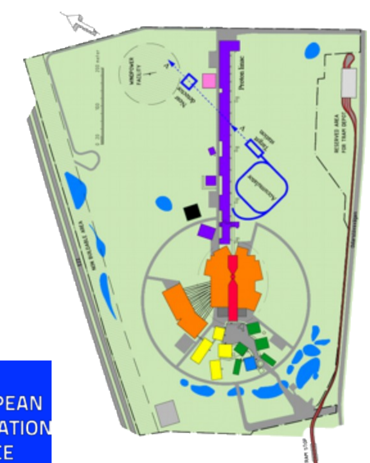
ESFRI

2022-2024: Preparatory Phase, TDR

2025-2026: Preconstruction Phase, International Agreement

2027-2034: Construction of the facility and detectors, including commissioning

2035-: Data taking

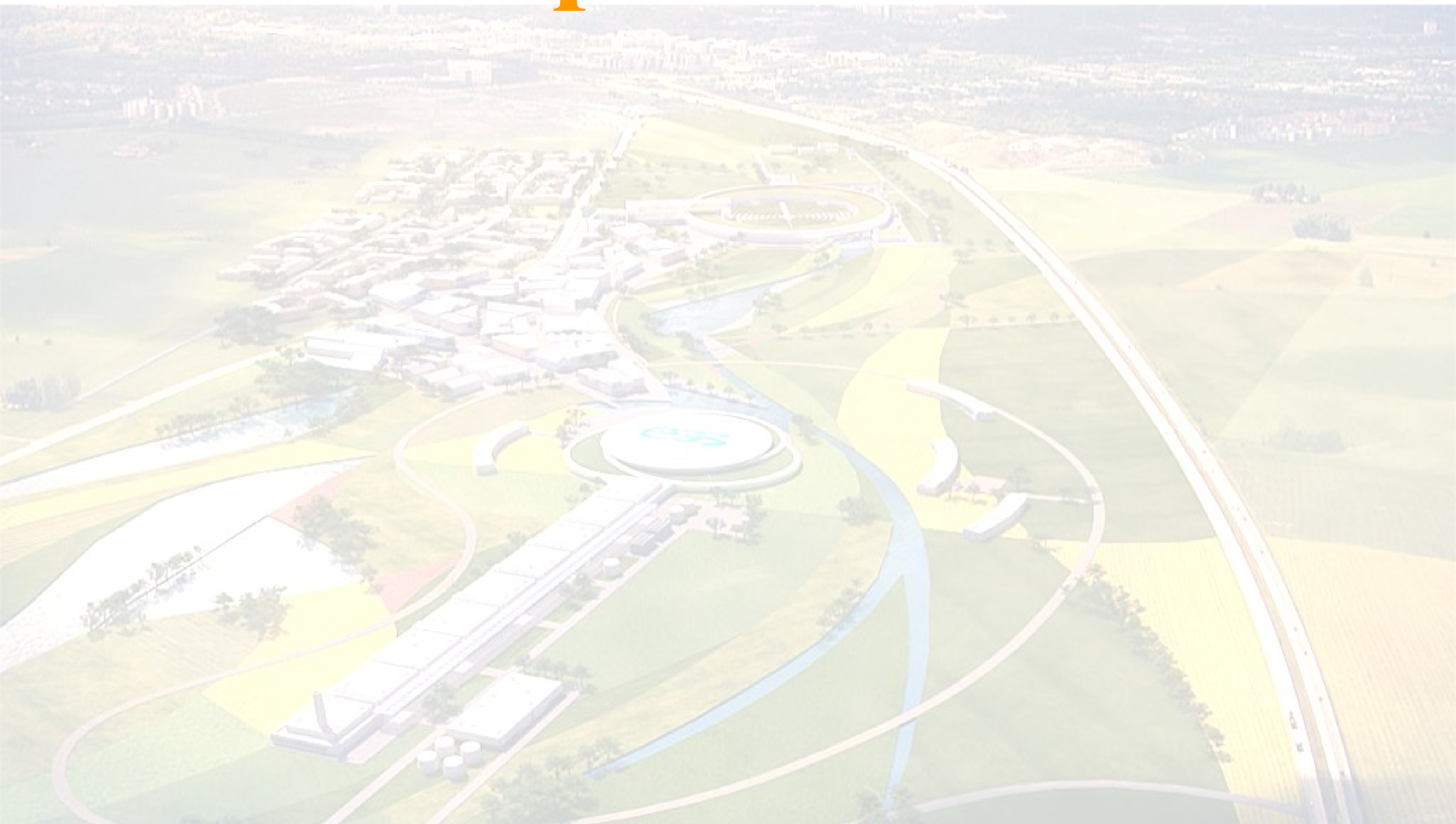


EUROPEAN SPALLATION SOURCE

Conclusion

- The ESS proton linac will be soon the most powerful linac in the world.
- ESS can also become a neutrino facility with enough protons to go to the 2^{nd} oscillation maximum and increase the CPV sensitivity.
- CPV: 5 σ could be reached over 60% of δ_{CP} range by ESSνSB 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 [illegible]% systematic error in the different

ESS NEUTRINO SUPER BEAM

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

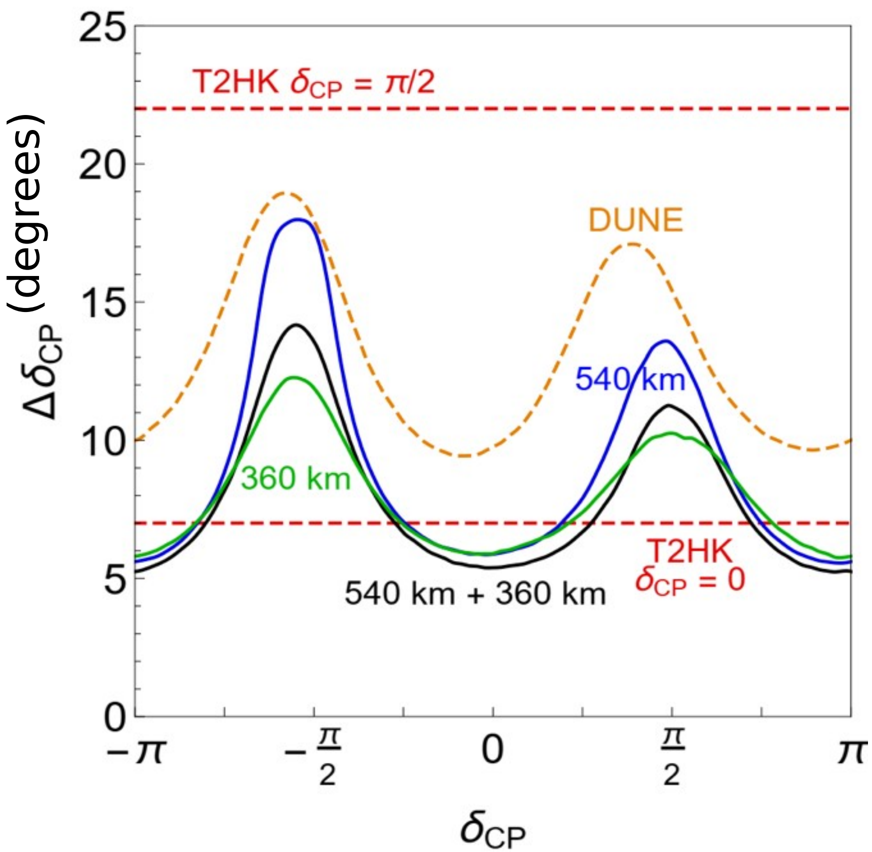
European Neutrino "Town" meeting and ESPP 2019 discussion, CERN, 24.10.2018

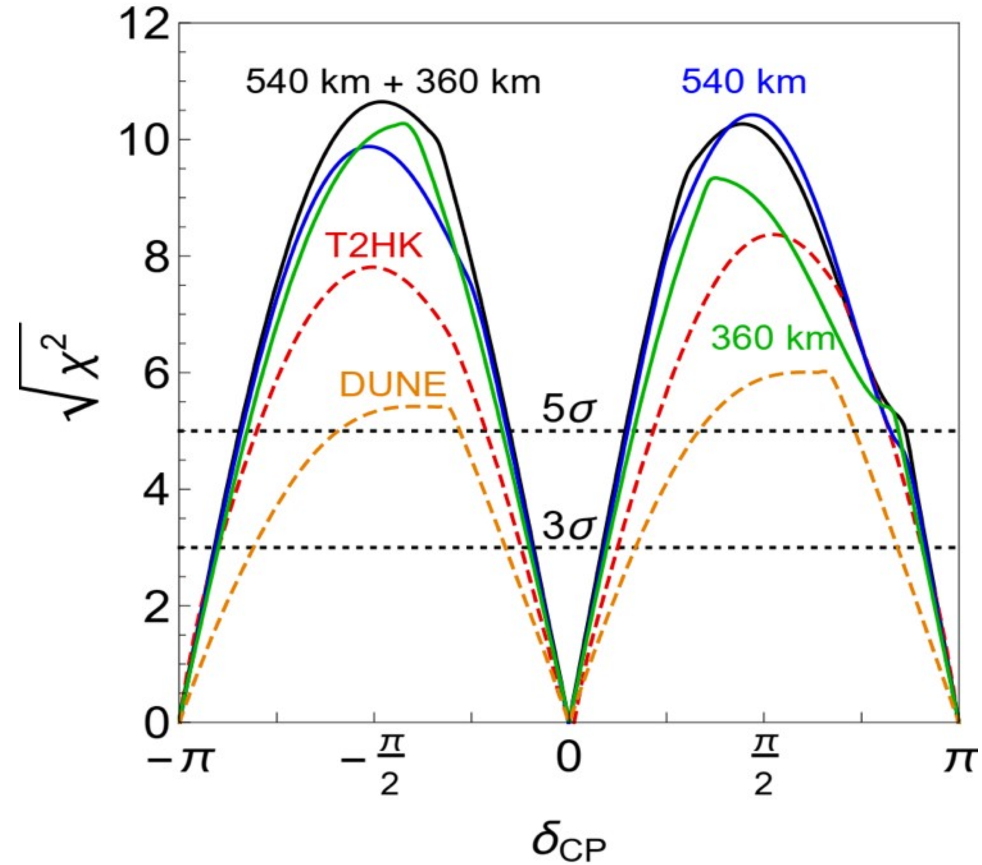
Roumen Tsenov
Department of Atomic Physics, University of Sofia

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

ESSνSB 500 kt tank at 540 km.

ESSνSB 500 kt tank at 360 km.





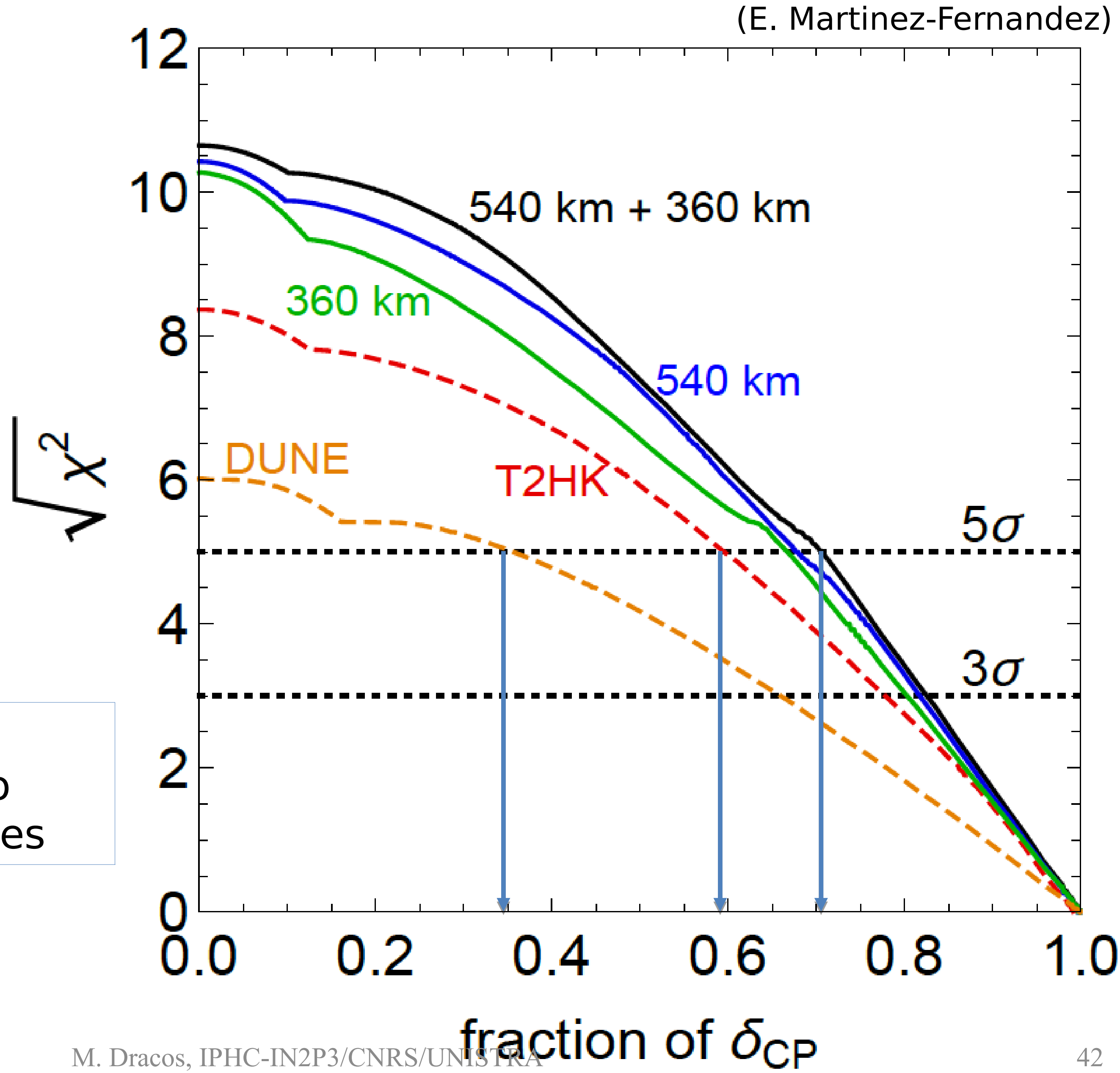
ESSνSB 250 kt tank at 540 km and 250 kt tank at 360 km.

ESS NEUTRINO SUPER BEAM

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Fraction of δ_{CP}

active mines aligned..



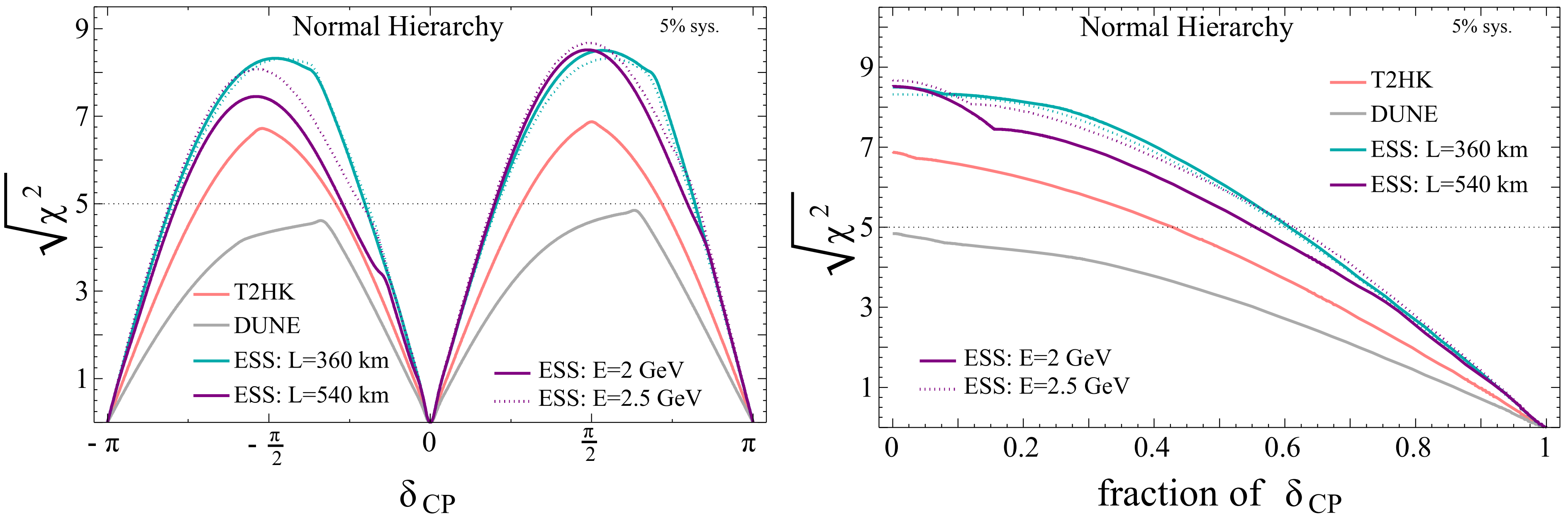
My personal opinion:
these scenarios are too optimistic for all facilities

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 $\times$ 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]]

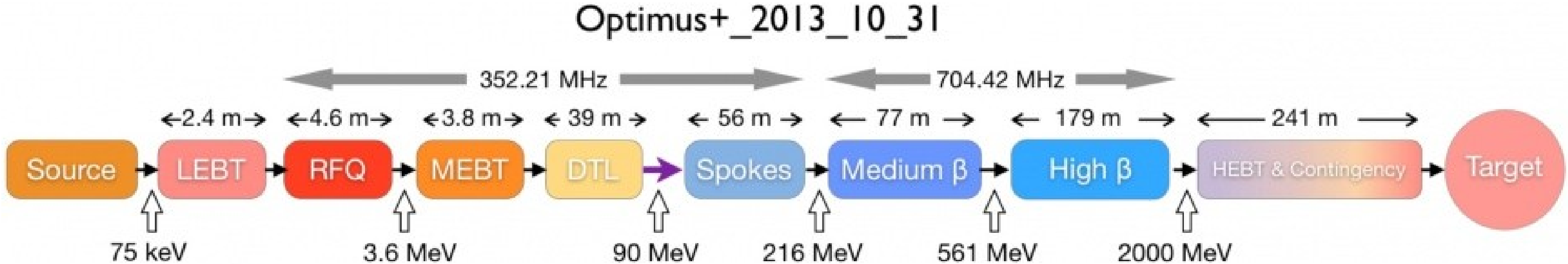
Comparisons

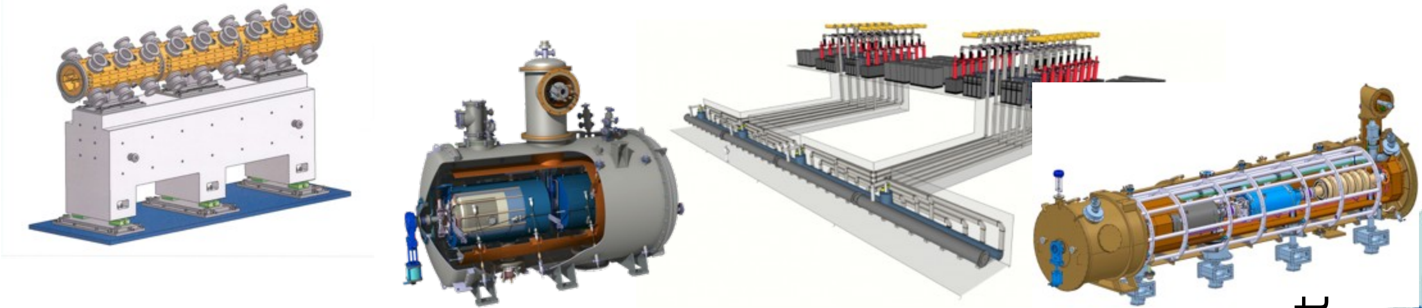


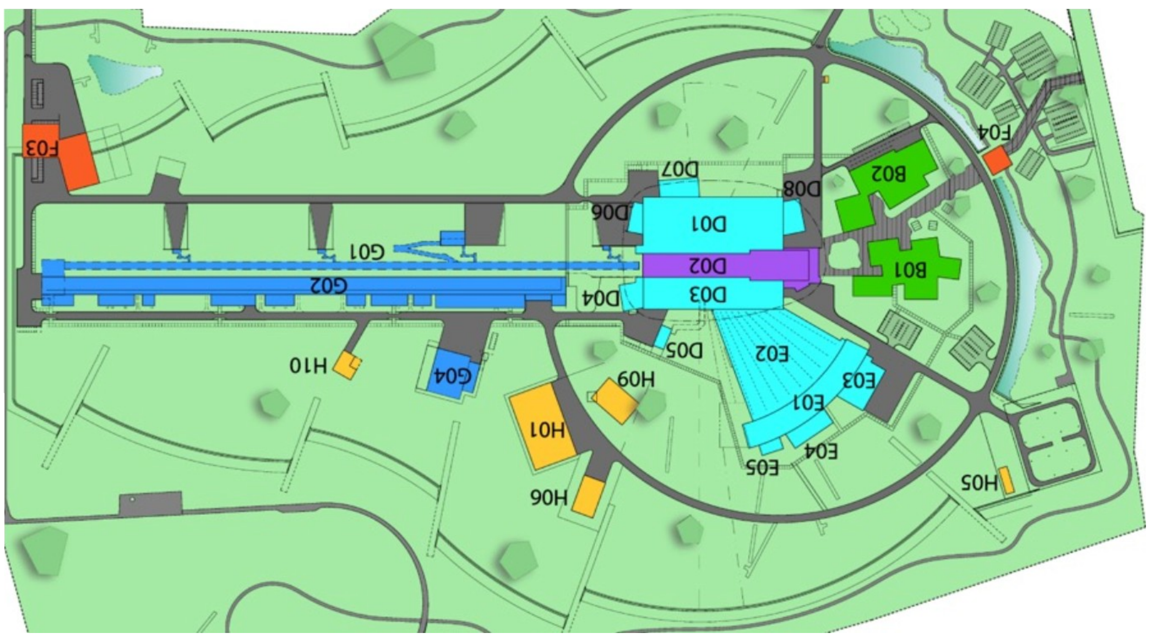
Comparison using the same systematic errors

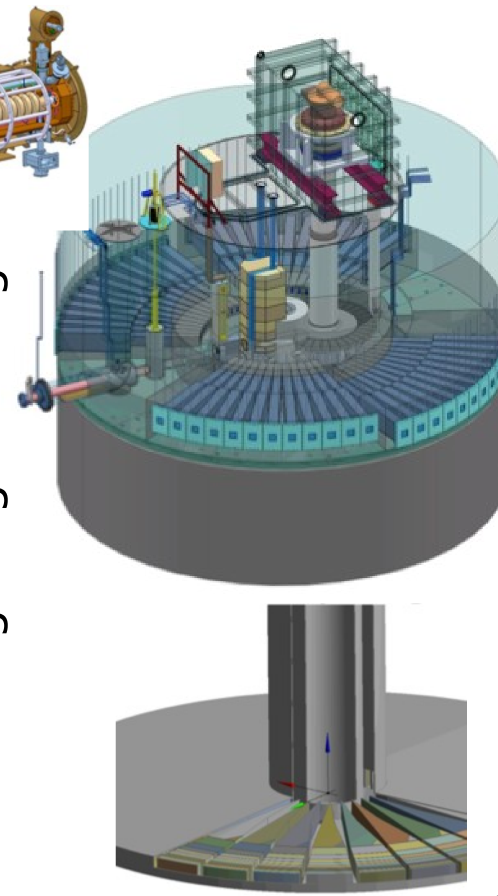
Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]

The ESS neutron facility









rotating tungsten target