ICHEP2016CHICAGO

38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

AUGUST 3 - 10, 2016

CHICAGO

The European Spallation Source Neutrino Super Beam for CP Violation discovery

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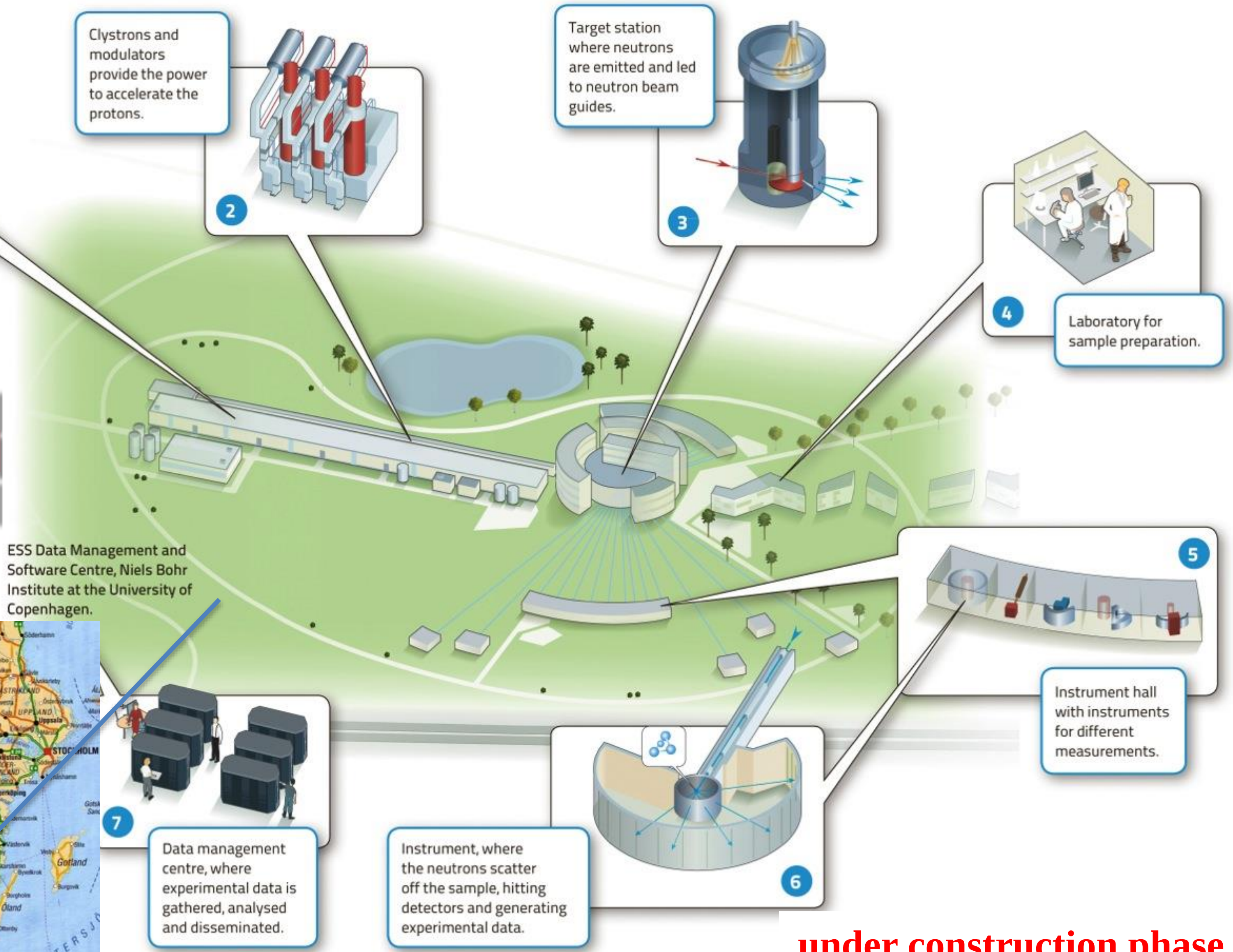
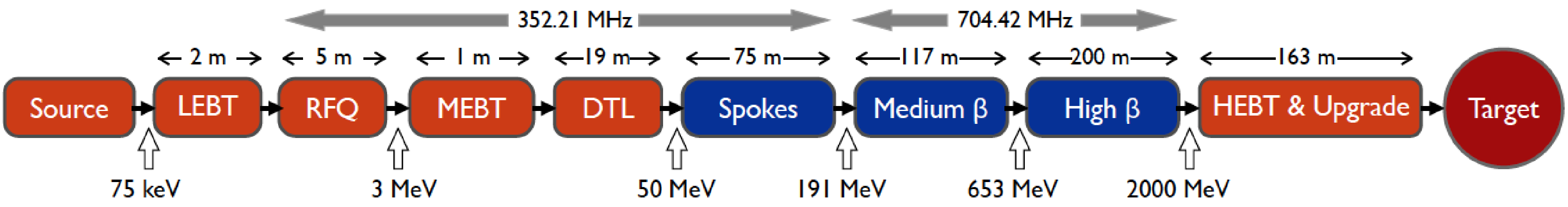
European Spallation Source

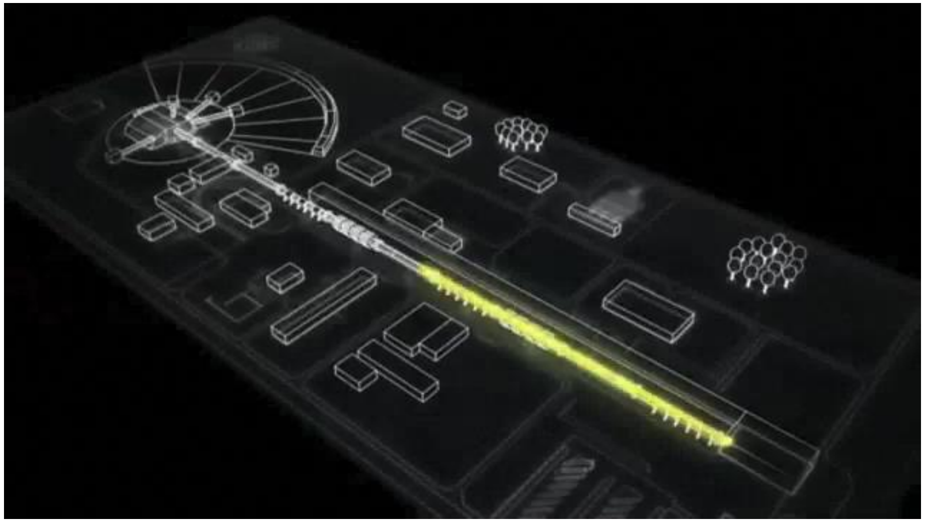


under construction phase (~1.85 B€ facility)

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).
- **>2.7x10^{23} p.o.t/year.**

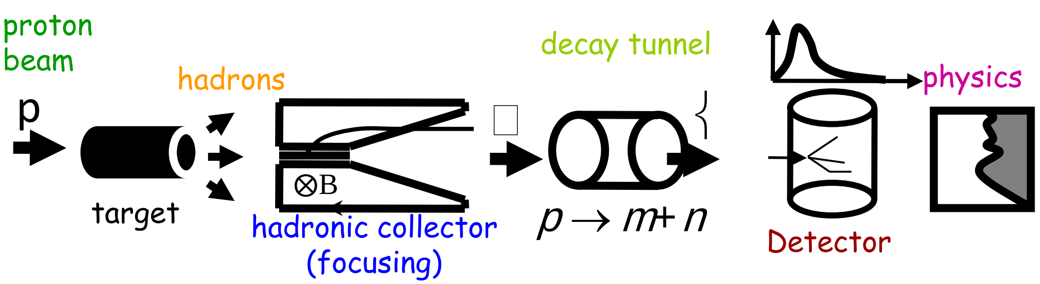


Linac ready by 2023 (full power and energy)

Having access to a powerful proton beam…

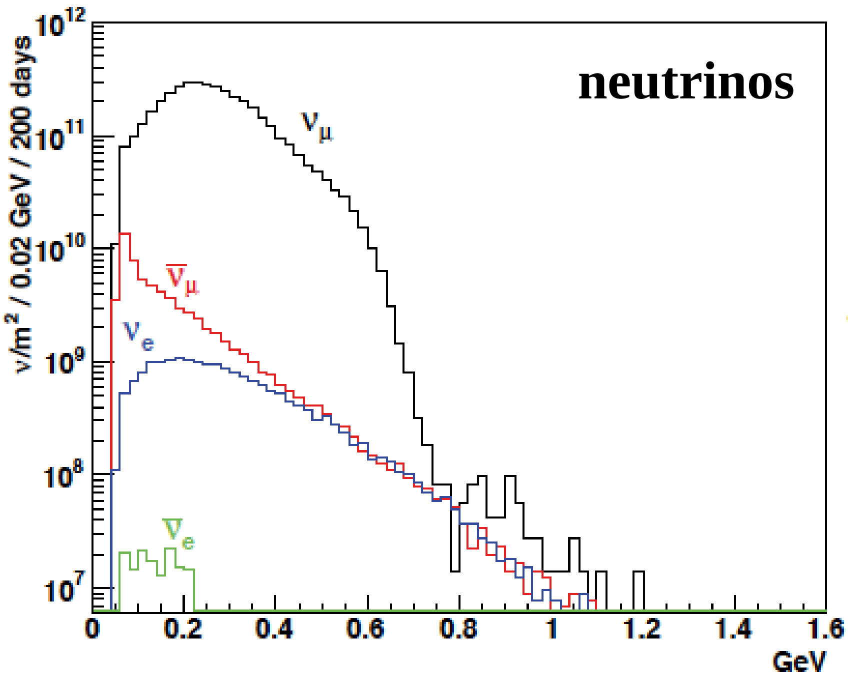
What can we do with:

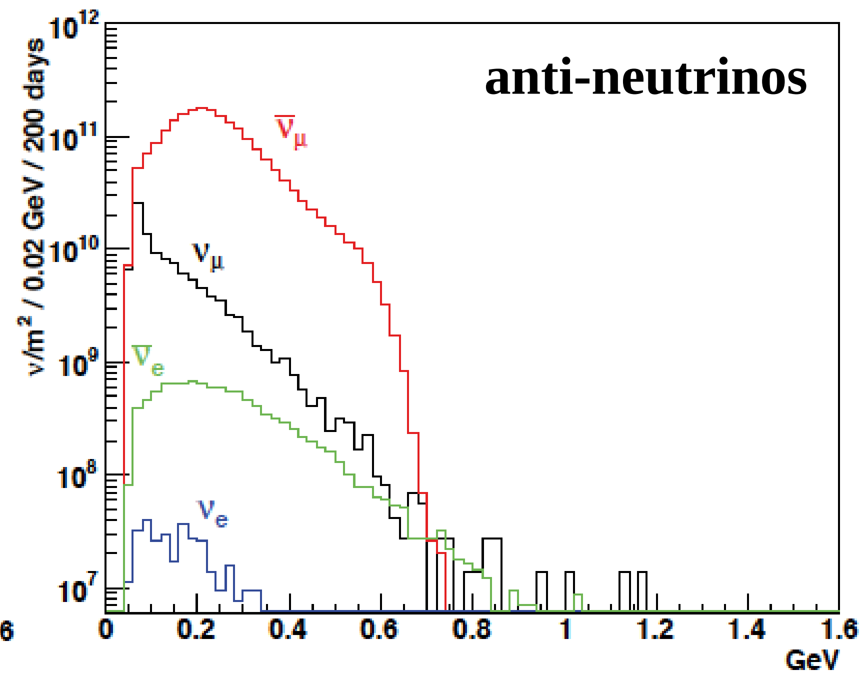
- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7\text{x}10^{23}$ protons/year



conventional neutrino (super) beam

ESSνSB ν energy distribution



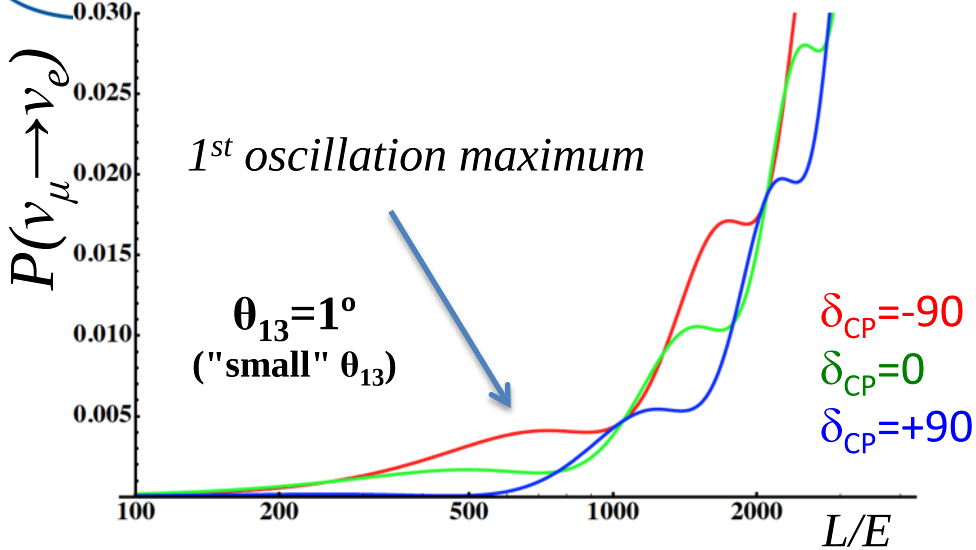


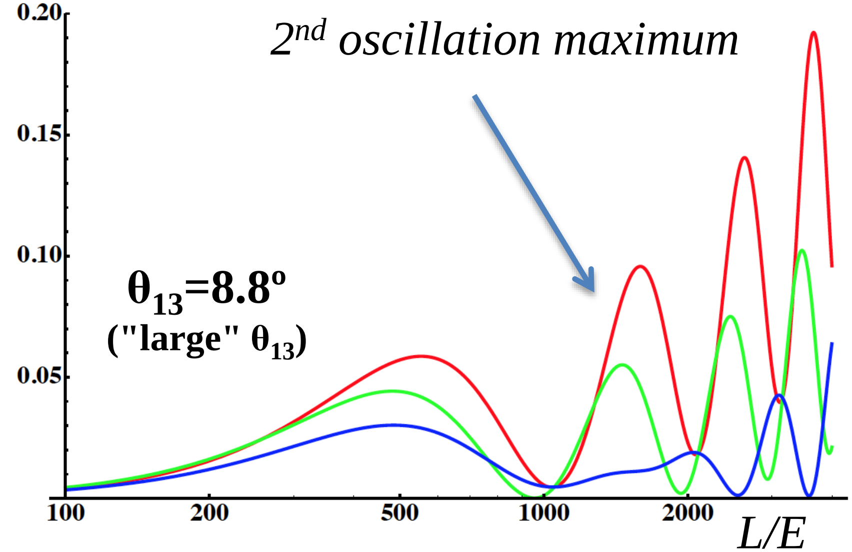
- almost pure ν_μ beam
- small ν_e contamination

	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 and per year (in absence of oscillations)

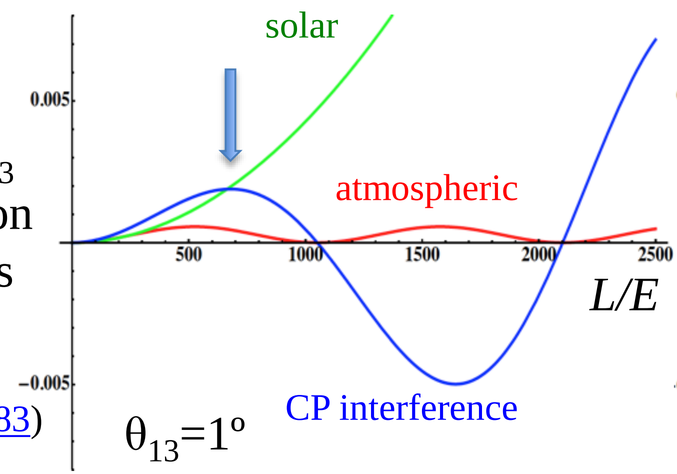
Neutrino Oscillations with "large" θ_{13}

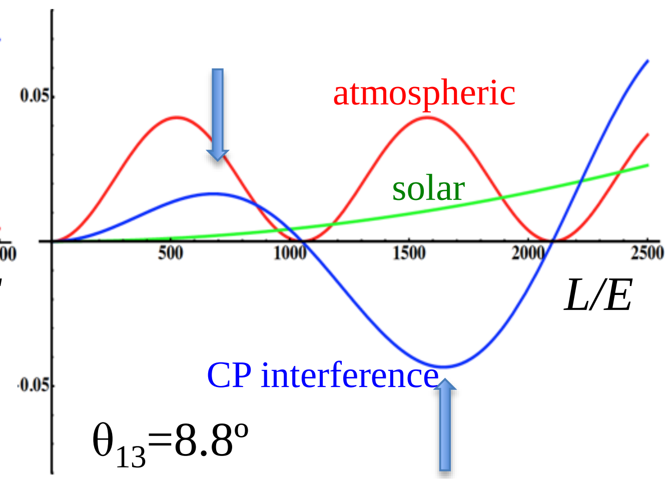




for small θ_{13} 1st oscillation maximum is better

(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.

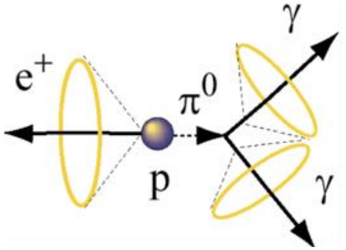
(see arXiv:1310.5992 and arXiv:0710.0554)

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

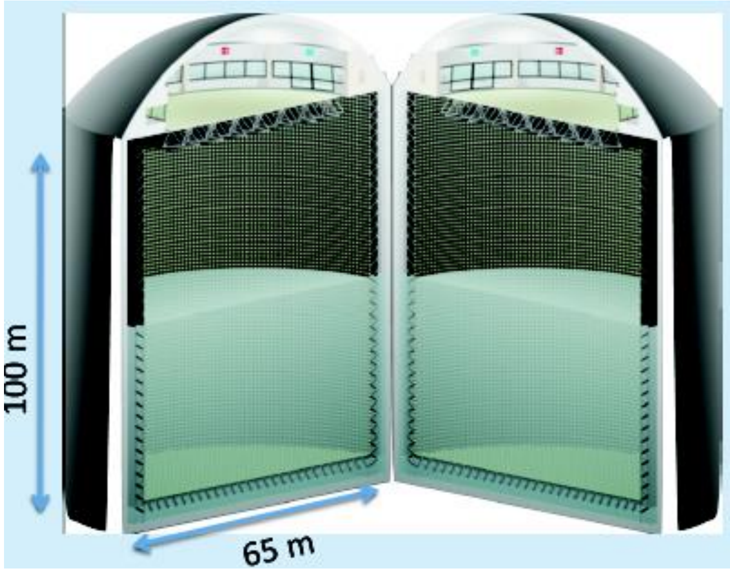
Yes, if we place our far detector at around 500 km from the neutrino source.

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

(arXiv: hep-ex/0607026)



- **Neutrino Oscillations (Super Beam, Beta Beam)**
- **Proton decay**
- **Astroparticles**
- Understand the gravitational collapsing: galactic SN
- Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos



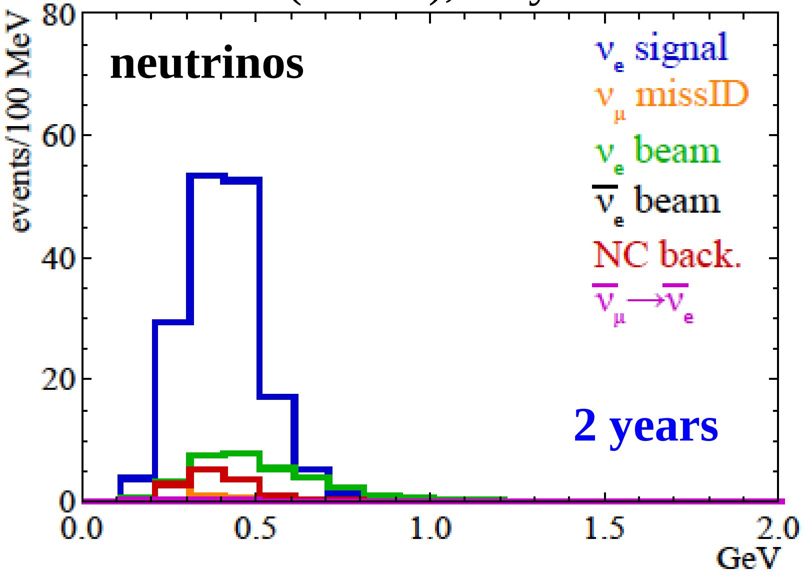
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8" PMTs
- 30% optical coverage

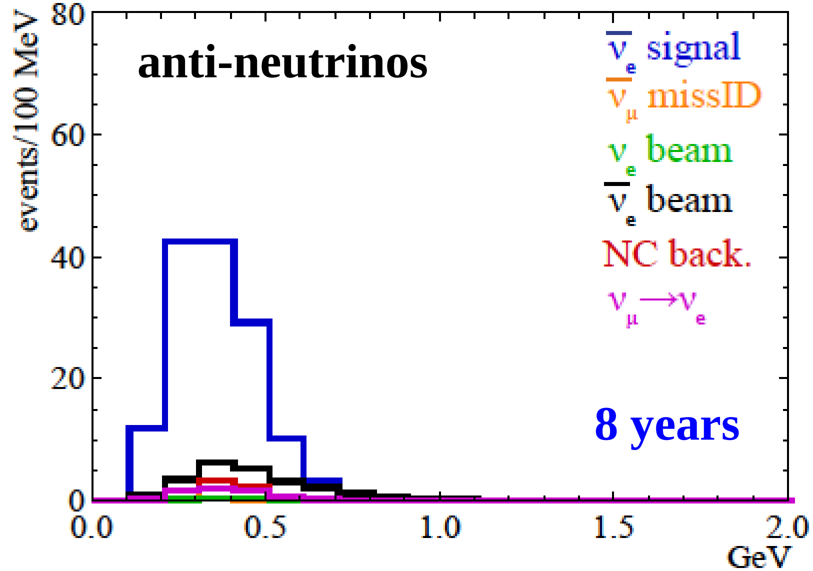
Neutrino spectra

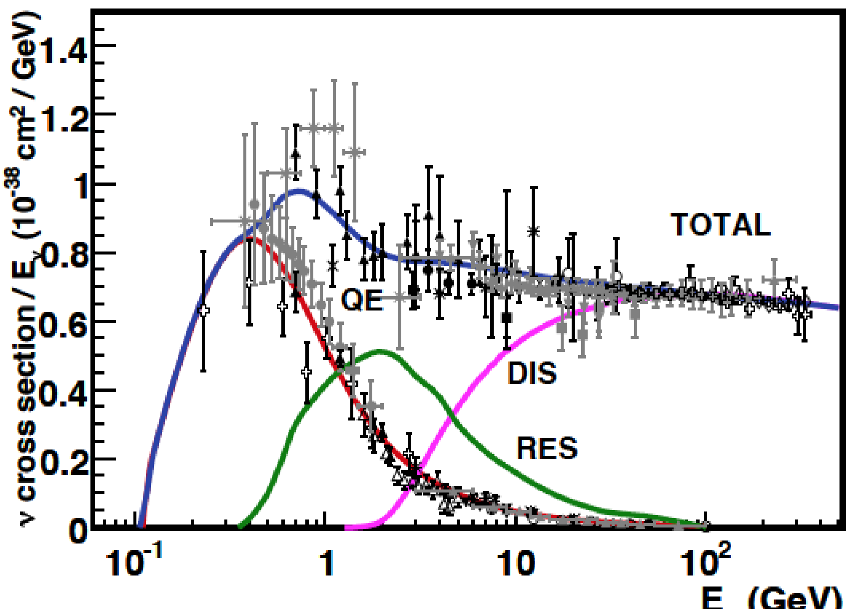
540 km (2 GeV), 10 years

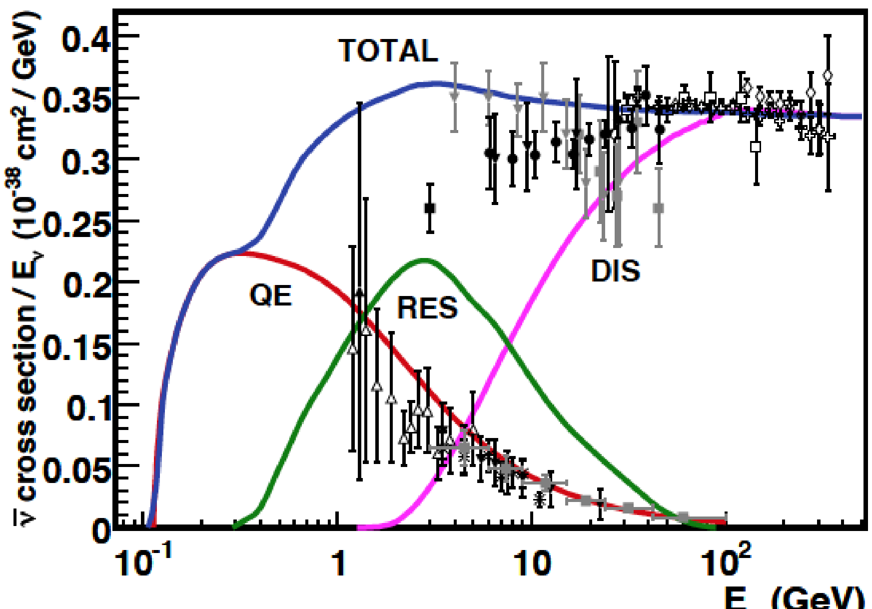
below ν_τ production, almost only QE events

$\delta_{CP}=0$

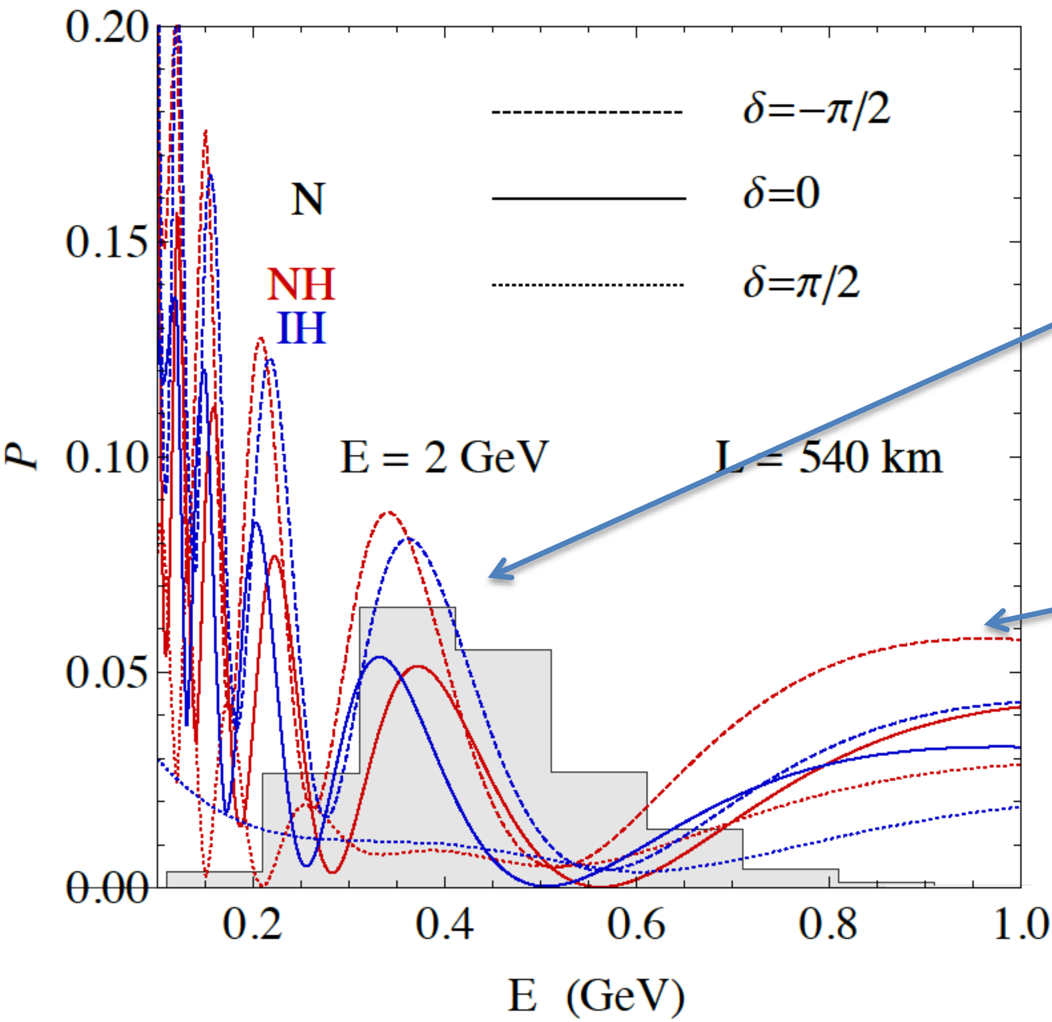








2nd Oscillation max. coverage



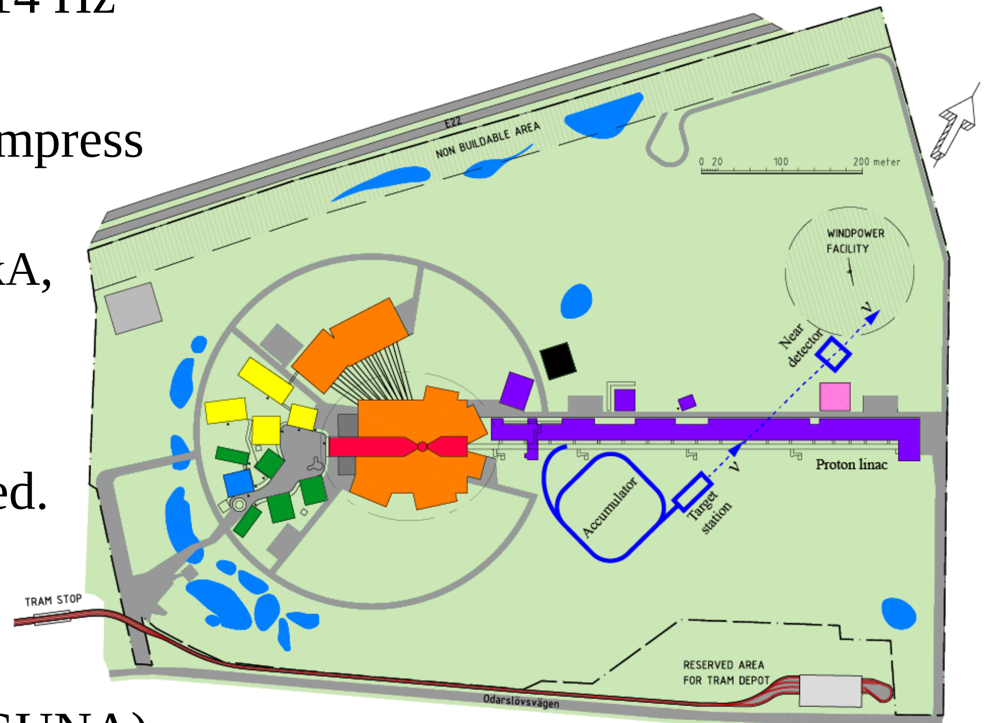
2nd oscillation max. well covered by the ESS neutrino spectrum

1st oscillation max.

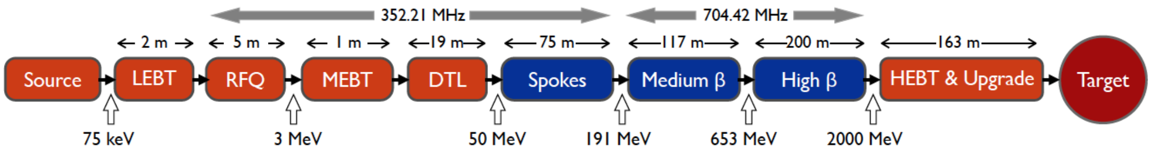
ESS Linac modifications to produce a neutrino Super Beam

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 EUROν).
- Underground detector (studied in LAGUNA).
- Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.



Preparing the ESS linac for operation at 10 MW with a 8% duty cycle and 28 Hz pulsing



For the medium-beta elliptical-cavity part ESS is planning to use tetrodes. Thales has developed a new screen grid with graded wire thickness making operation at **10 % duty cycle** possible.

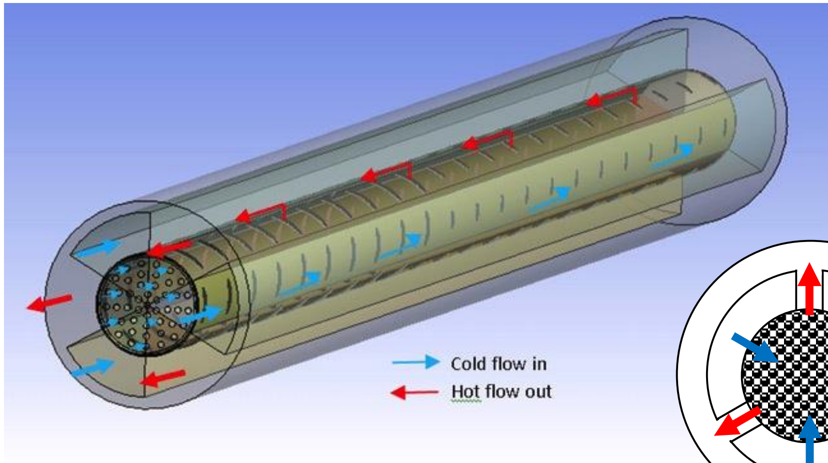
For the warm low-energy part of the ESS linac and the medium energy Elliptical-cavities part, ESS is planning to use modulators of the *modular klystron modulator type* which can be run at 28 Hz at double power by adding a capacitor charger-unit at the input.

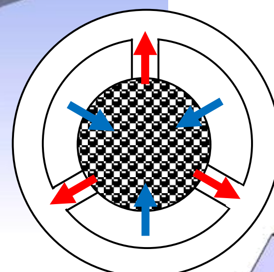
The picture shows the cryostat and test bunker at the FREIA Lab in Uppsala where a first prototype of the ESS 352 MHz spoke accelerating cavity is currently under test at 14 Hz and later on will be tested at 28 Hz.

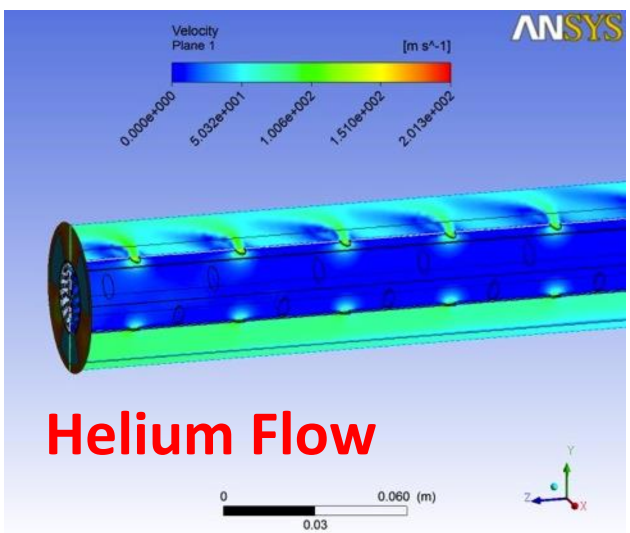
Mitigation of high power effects

(4-Target/Horn system for EUROnu Super Beam)

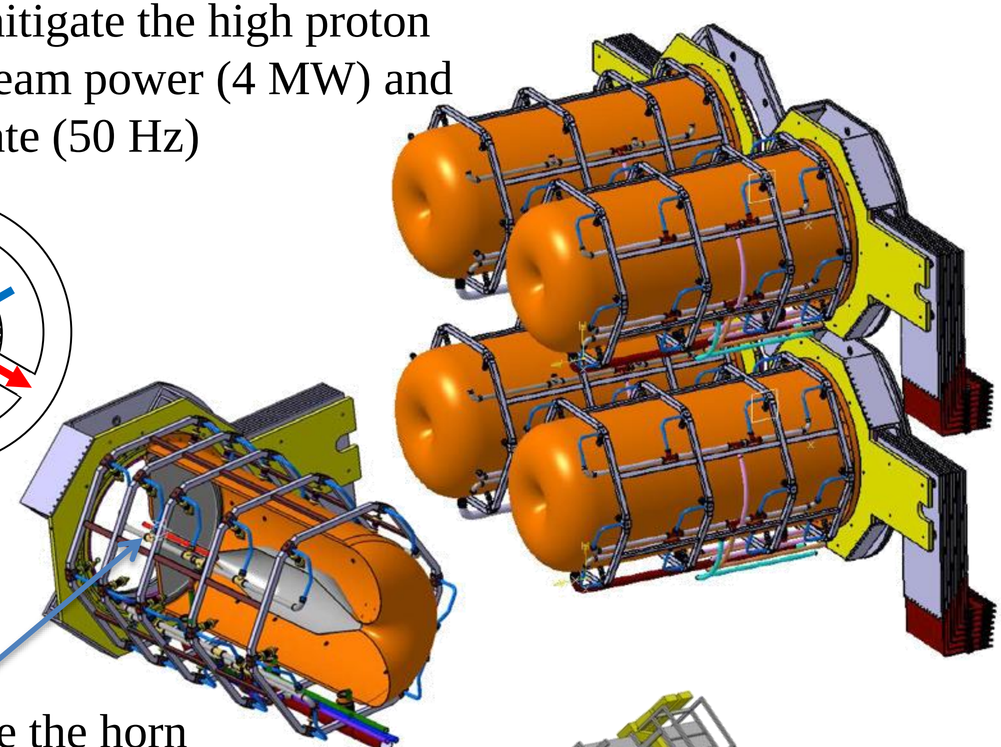
Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)



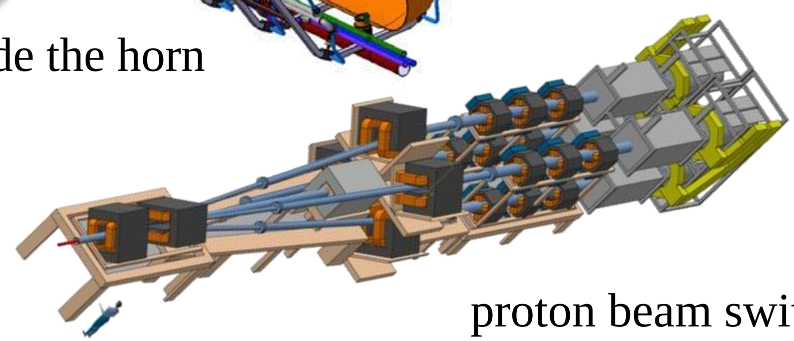




4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)



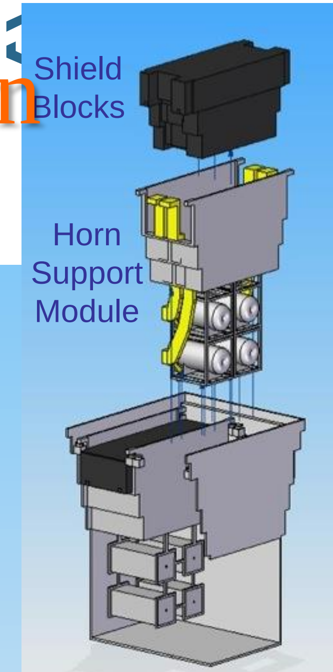
target inside the horn

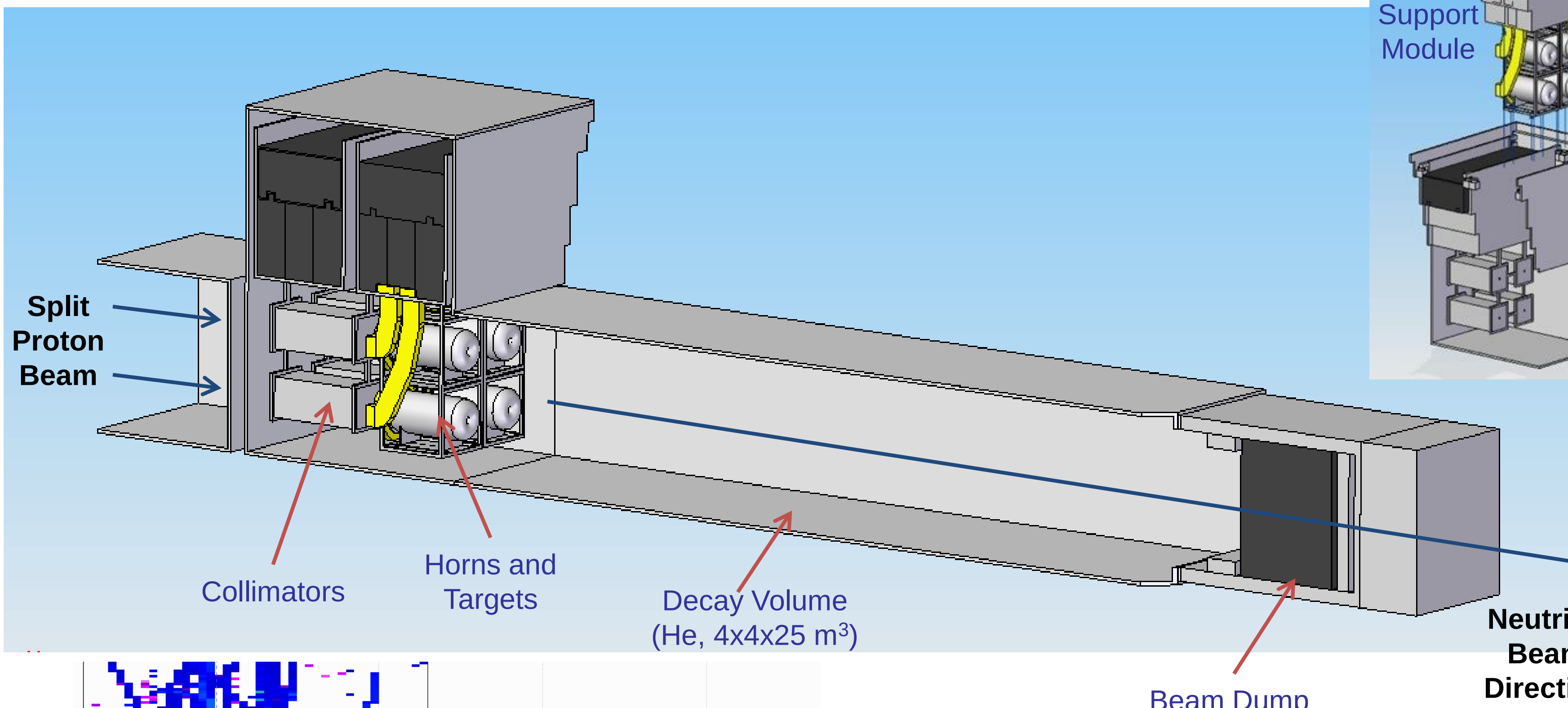


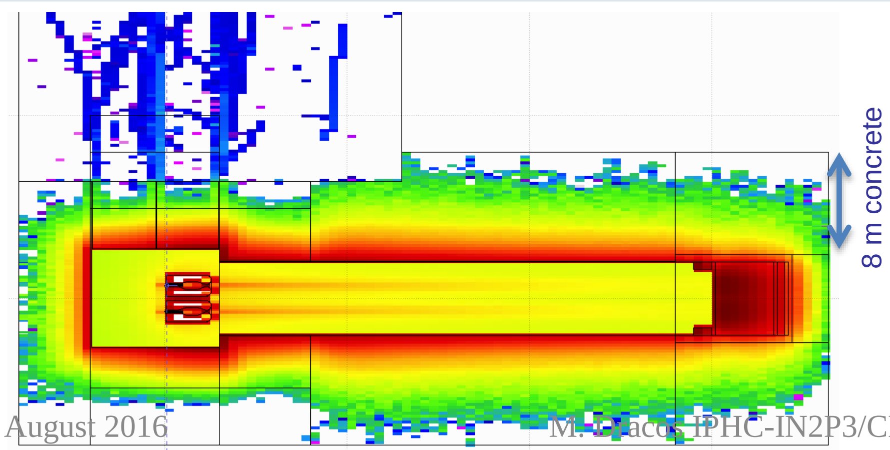
proton beam switchyard

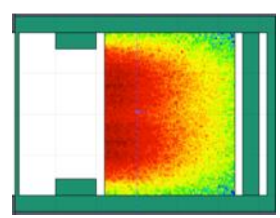
General Layout of the target station

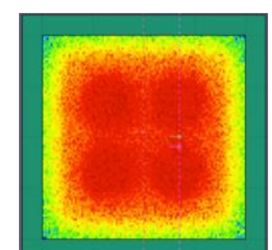
(copied from EUROnu DS)





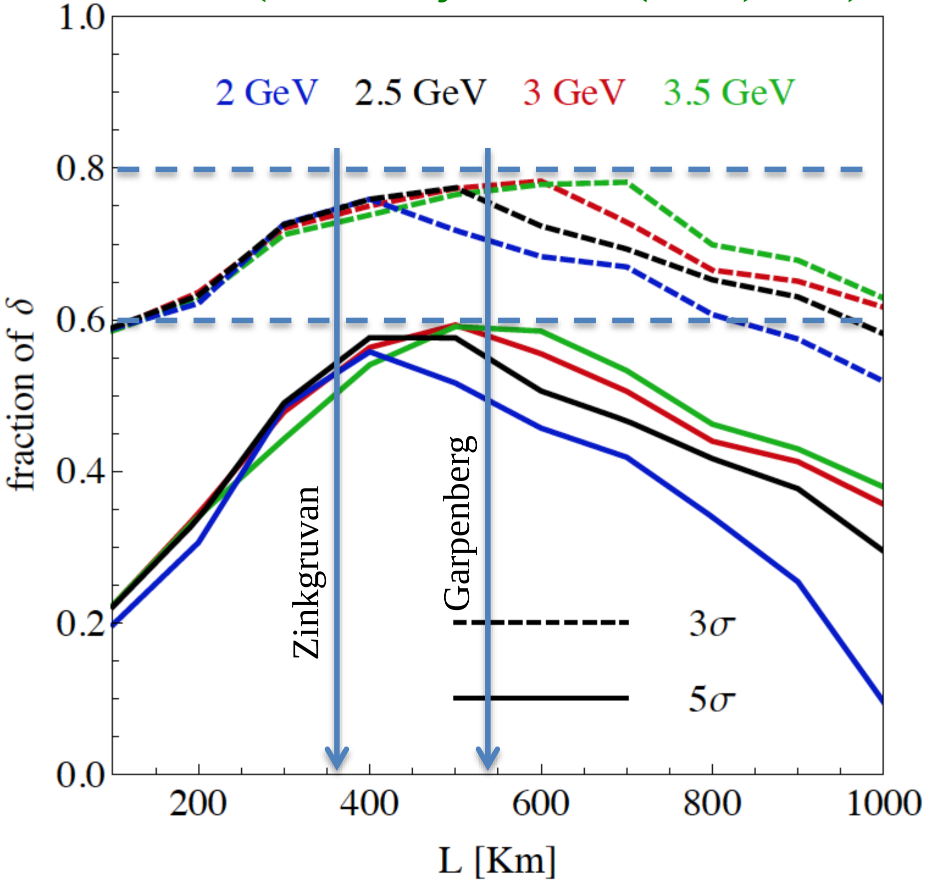






Which baseline?

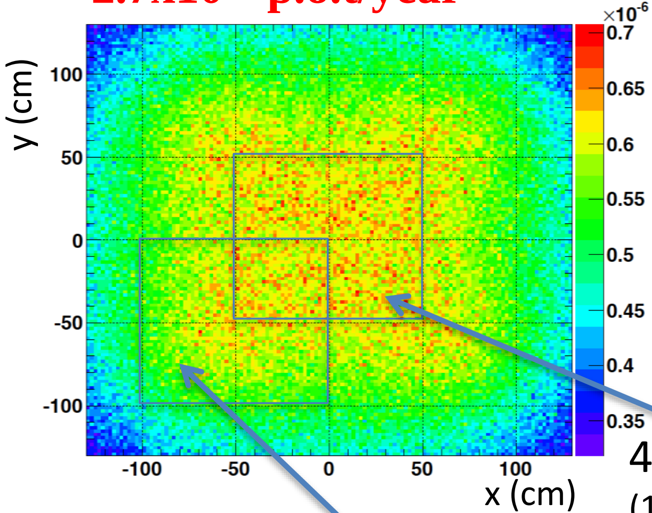
CPV (*Nucl. Phys. B 885 (2014) 127*)



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

Muons at the level of the beam dump

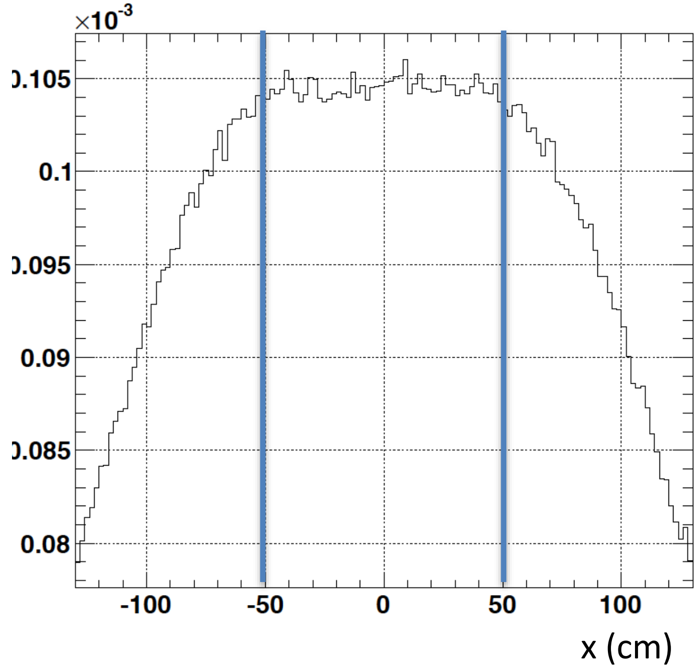
2.7x10^{23} p.o.t/year

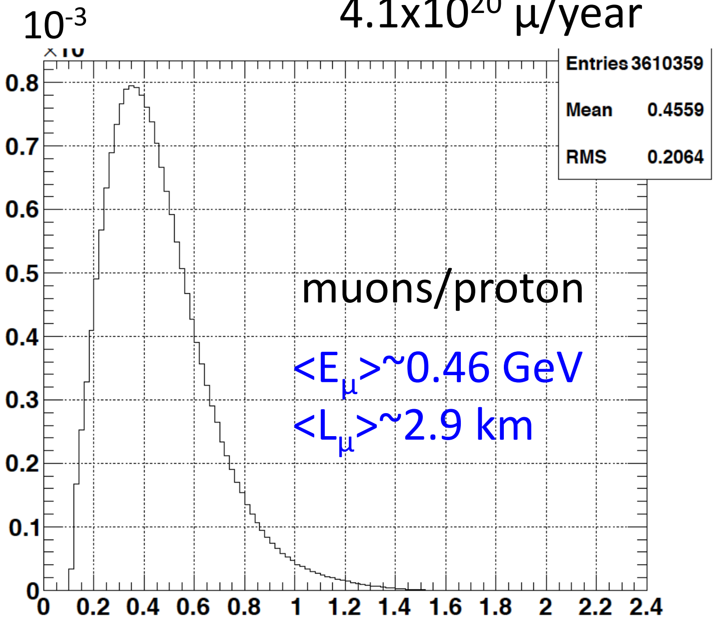


muons at the level of the beam dump (per proton)

4.2x10^{20} μ/year
(16.3x10^{20} for 4 m^2)

4.1x10^{20} μ/year





- input beam for future 6D μ cooling experiments (for muon collider),
- good to measure neutrino x-sections (ν_μ, ν_e) around 200-300 MeV using a near detector,
- low energy nuSTORM,
- Neutrino Factory,
- **Muon Collider**.

Higgs luminosity at ESS

- From 3.3×10^{14} p/pulse 3.5×10^{13} μ+ and 2.4×10^{13} μ- are generated. The cooling process efficiency is 0.4 and the acceleration efficiency to $\sqrt{s}$ = 125 GeV is 0.6.
- The luminosity is given by a formula where: $$L = f\frac{N^+N^-}{4\pi\varepsilon_{rms}\beta}$$
  - $N^+ = N^- = 7 \times 10^{12}$ μ/pulse
  - f is the number of effective luminosity crossings: 43 x 555 =23'865/s
  - $\varepsilon_{rms} = \varepsilon_N/589.5 = 0.36 \times 10^{-4}$ rad cm, with H_2 *but no PIC cooling.*
  - B* = 5 cm is beta at crossing in both dimensions
- Luminosity is $L = 5 \times 10^{32}$ cm^{-2} s^{-1} for one collision crossing
- The cross section at the maximum averaged with ΔE = 3.4 MeV is 1.0×10^{-35} cm^2. Hence the Ho event rate is 18 ev/h or 5×10^4 ev for 10^7 s/y . In 10 y and 2 crossings one million Ho events
- If PIC is successful ε_{rms}/ 10 and 0.5×10^6 events/year/i.p.

(PIC: Parametric Resonance Cooling of muons)

ESSνSB at the European level

- A **H2020** Design Study has been submitted in 2014:
  - Decision:
    - Overall score 13.5/15 (5/5 for Excellence): not enough to be funded (only 15 MEUR for this call)
    - nevertheless, the evaluators recognised that **ESSνSB answers one of the priorities defined in the European Strategy for Particle Physics**.
- New application will be prepared for an ongoing EU H2020 call (deadline beginning 2017)
- **COST application for networking has been succeeded: CA15139**
  - **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 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.
  - 11 participating countries (network still growing).

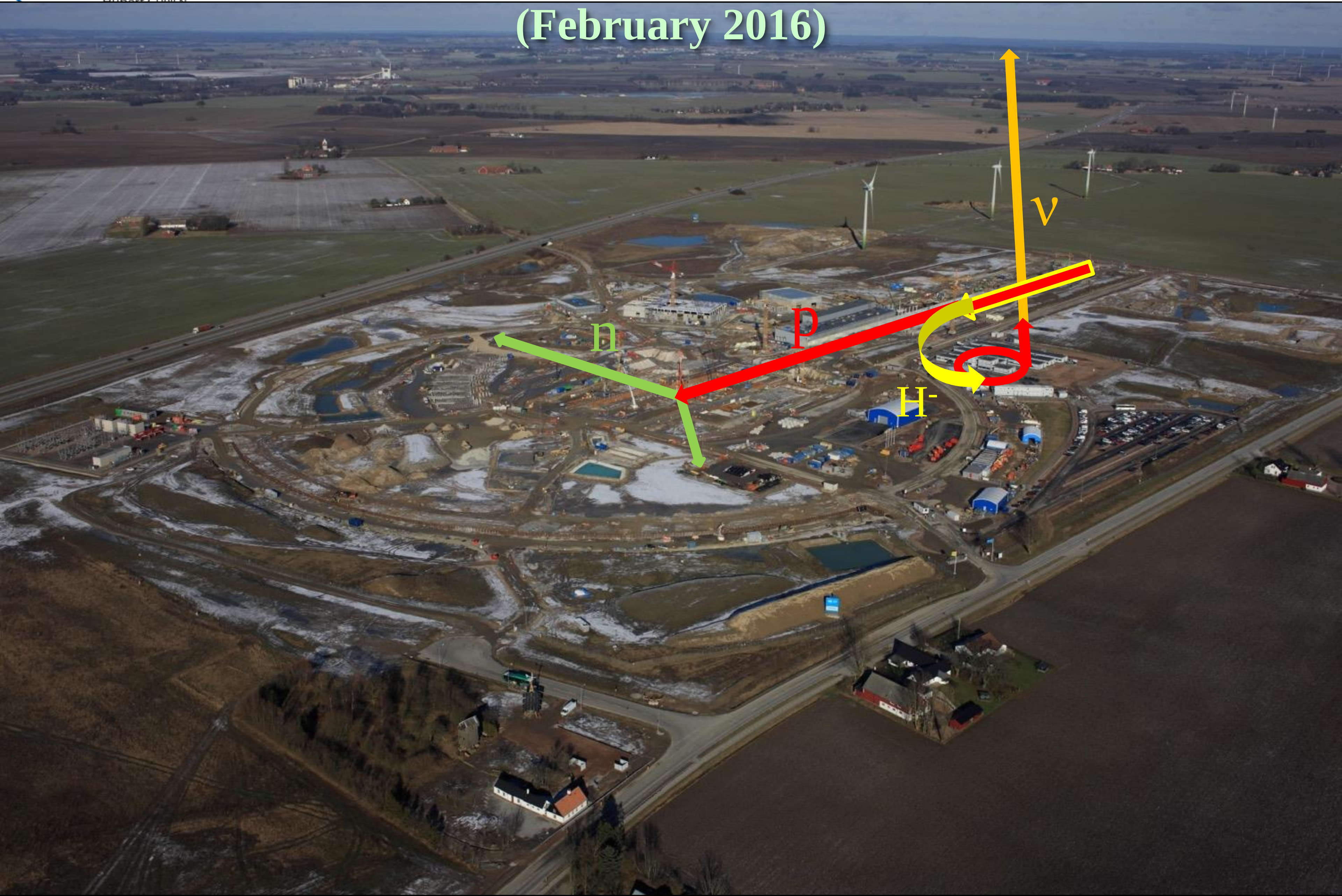
ESS under construction

September 2014


Linac tunnel completed

ESS Construction site

(February 2016)



Possible Schedule for ESSνSB

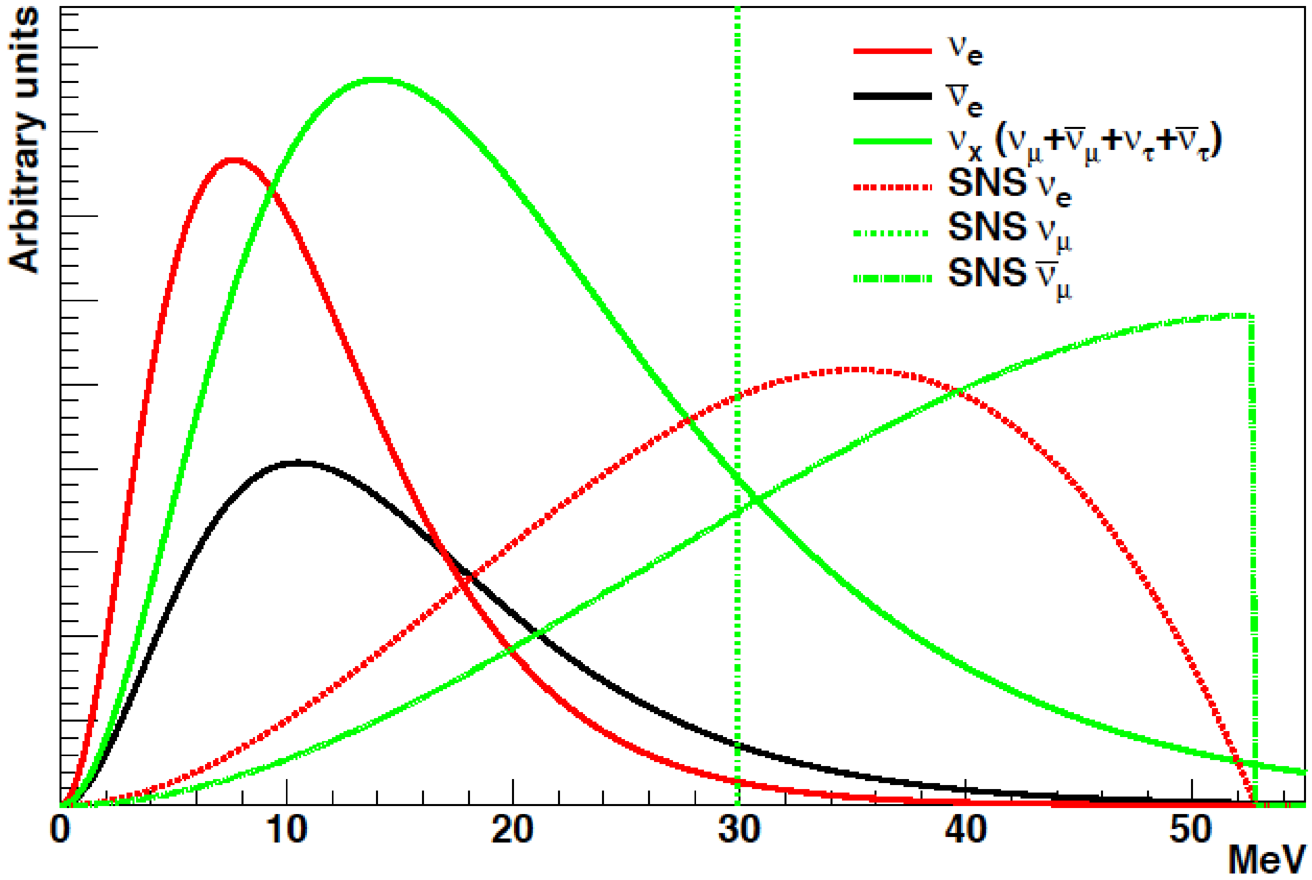
- COST CA15139: 2016-2019 (just networking)
- EU H2020 Design Study: 2018-2021
- Decision for ESSνSB: 2022
- End of Linac construction: 2023
- Construction of ESSνSB: 2023-2030
- Data taking: 2030-2040.
- Rich muon program.
- A Design Study is needed.

Conclusion

- Significantly better CPV sensitivity at the 2nd oscillation maximum.
- The European Spallation Source Linac will be ready in less than 10 years (5 MW, 2 GeV proton beam by 2023).
- Neutrino Super Beam based on ESS linac is very promising.
- 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 (ESSνSB) with large potentiality.
- Large associated detectors have a rich astroparticle physics program.
- Rich muon program.
- A Design Study is needed.
- COST network project CA15139 supports this project.

Backup

DAR experiments (ESS/SNS)



Typical expected supernova neutrino spectrum for different flavours (solid lines) and SNS/ESS neutrino spectrum (dashed and dotted lines)

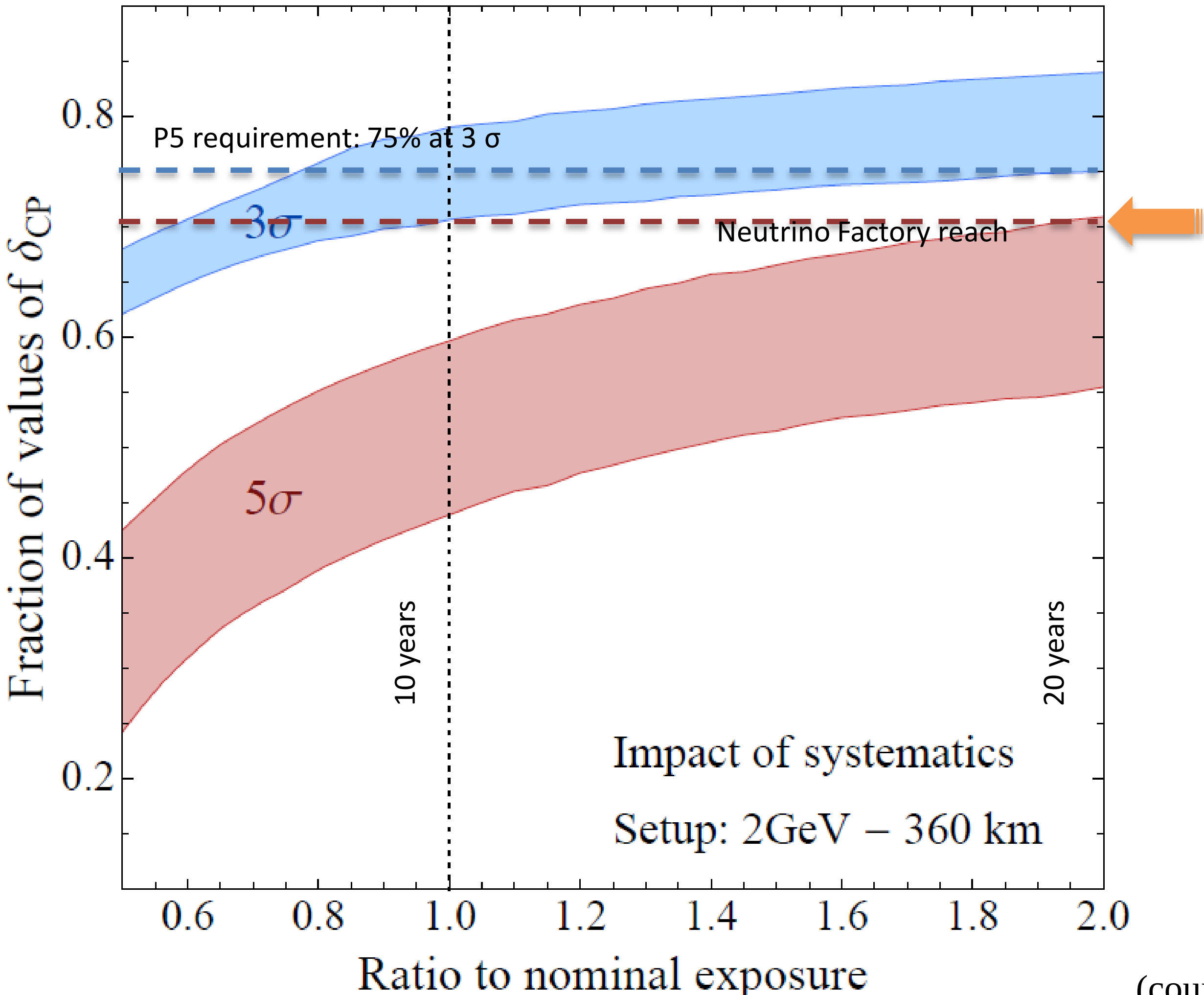
Systematic errors

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

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

Systematic errors and exposure

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



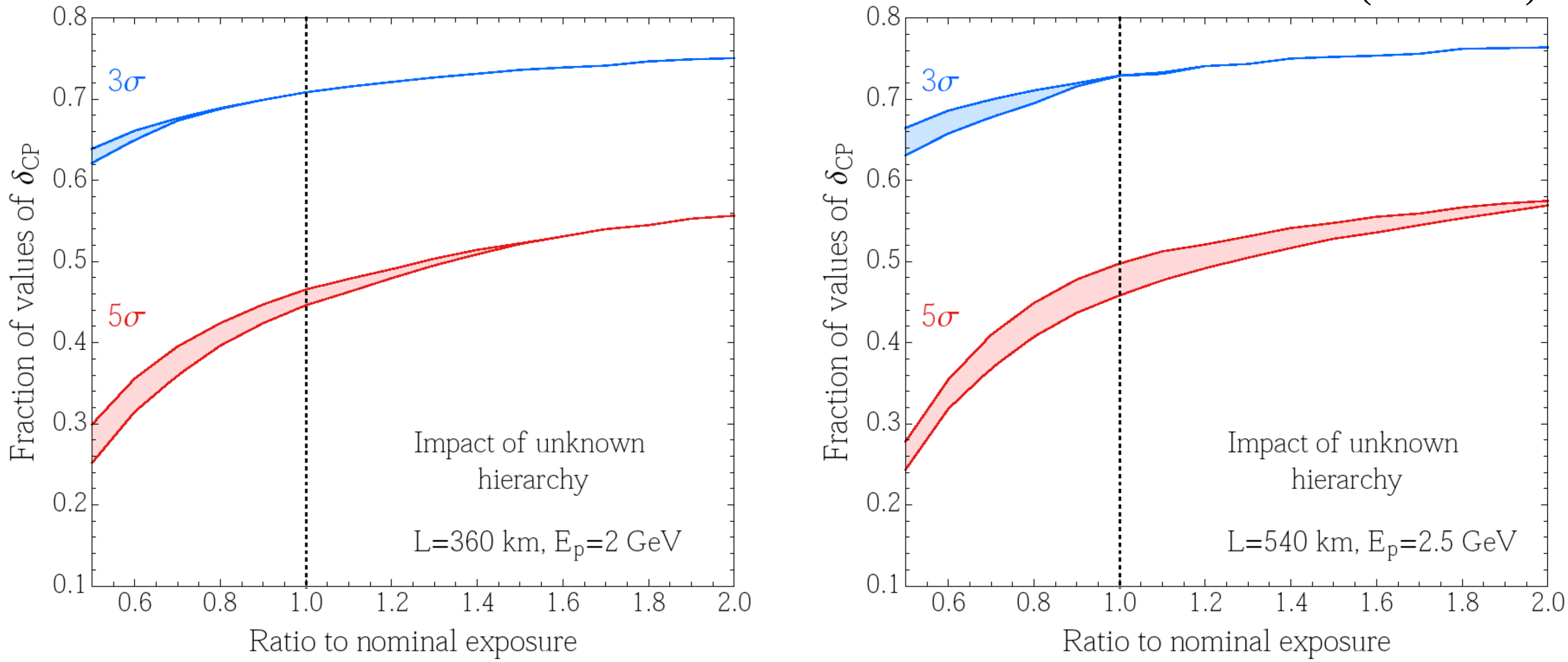
High potentiality

(courtesy P. Coloma)

Effect of the unknown MH on CPV performance

"default" case for systematics

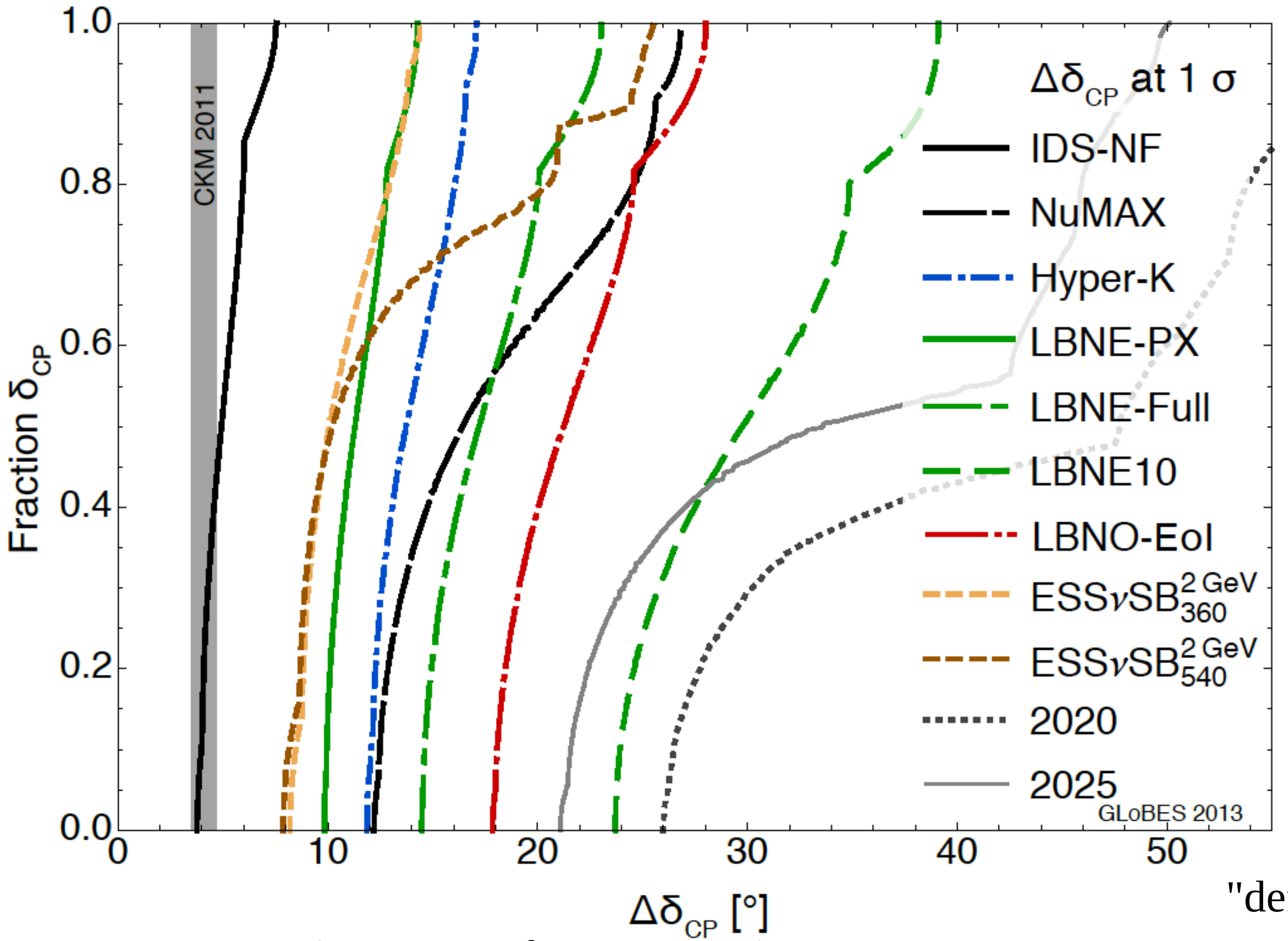
(P. Coloma)



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

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)



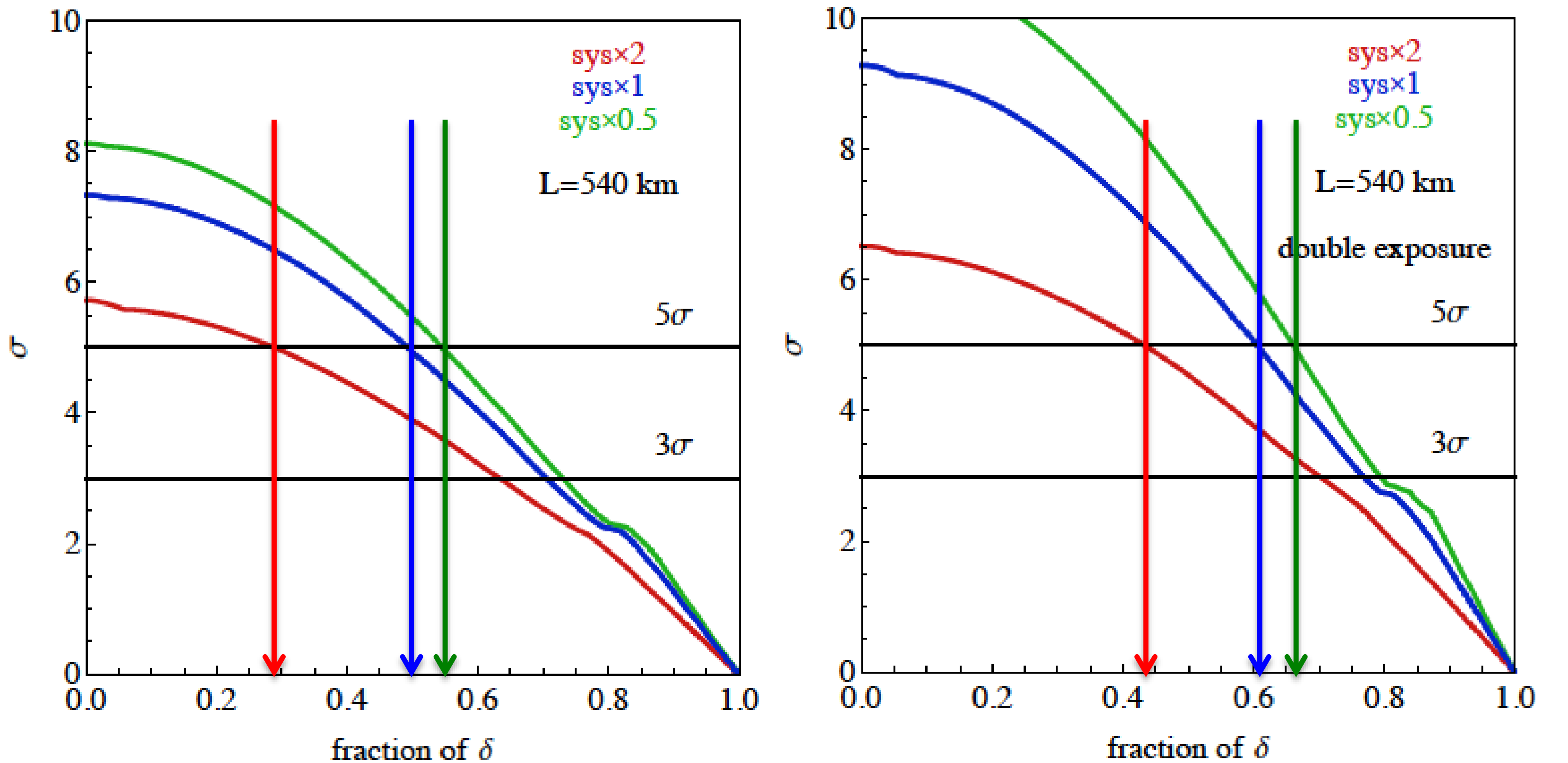
"default" column

for systematic errors see (7.5%/15% for ESSnuSB):

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

δ_{CP} coverage

CPV (2 GeV protons)

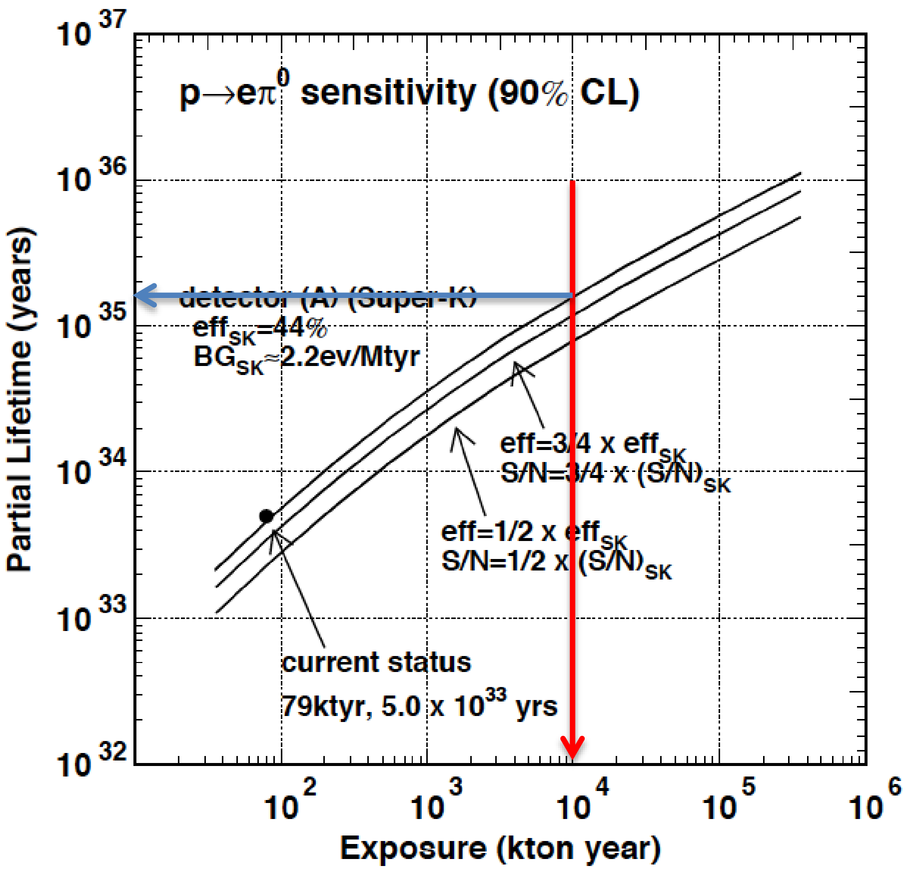


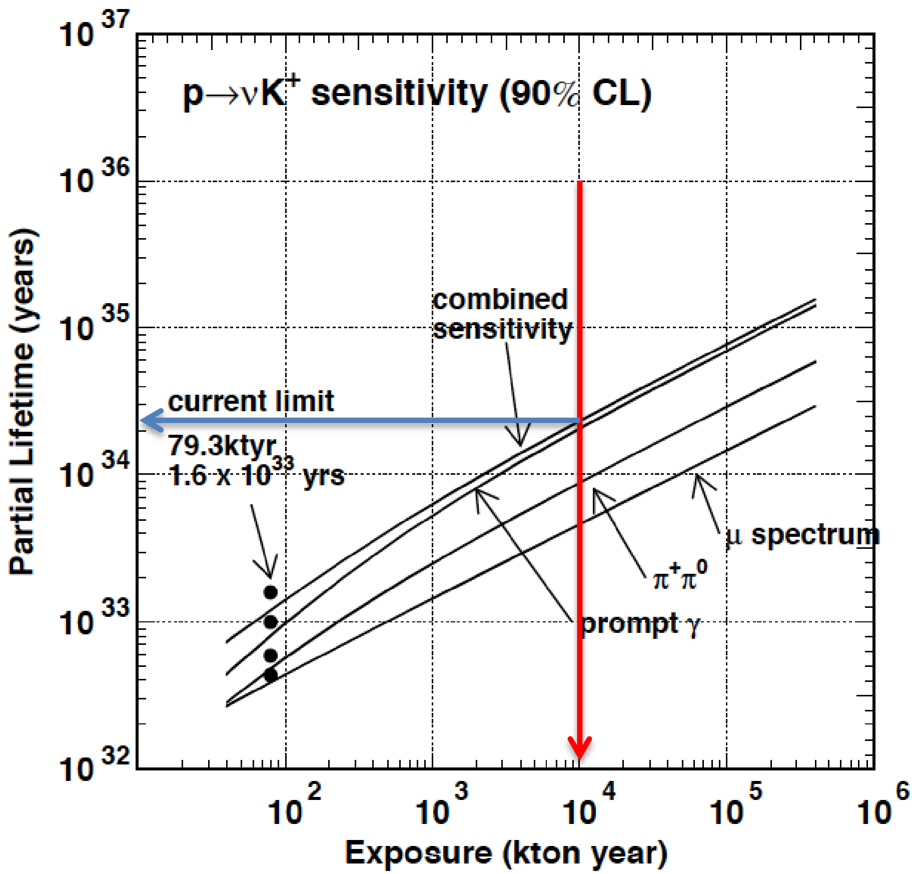
after 10 years — with 2 times more statistics

systematic errors (nominal values): 5%/10% for signal/background

more than 50% δ_{CP} coverage using reasonable assumptions on systematic errors

The MEMPHYS Detector
(Proton decay)

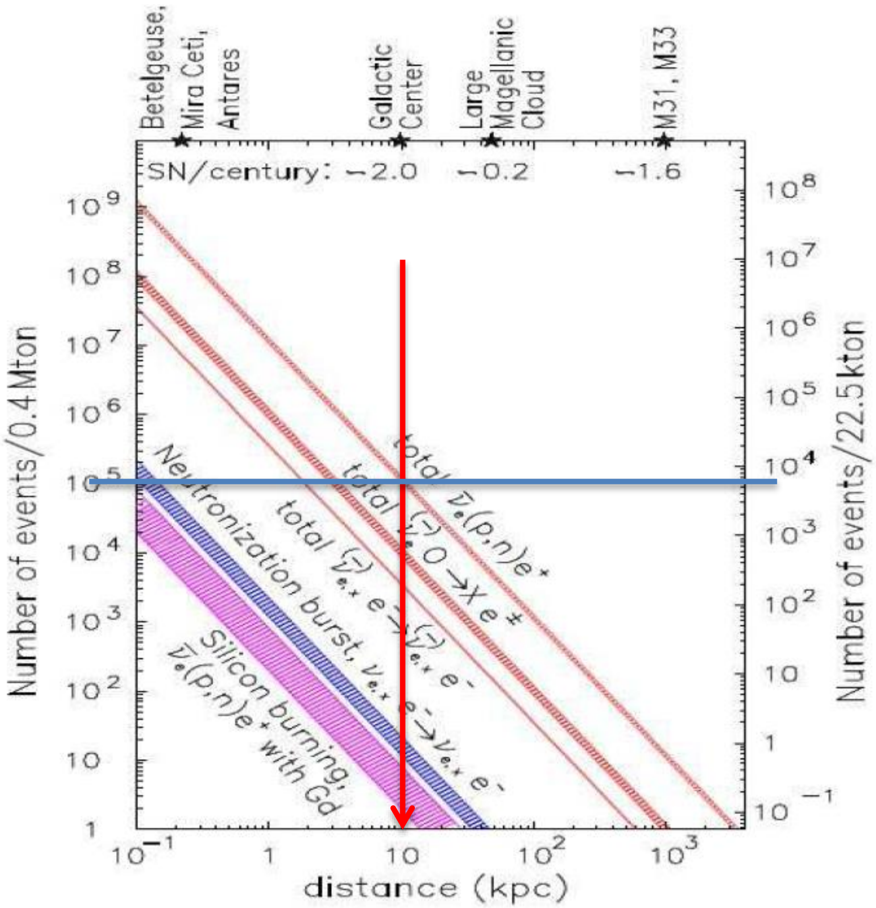




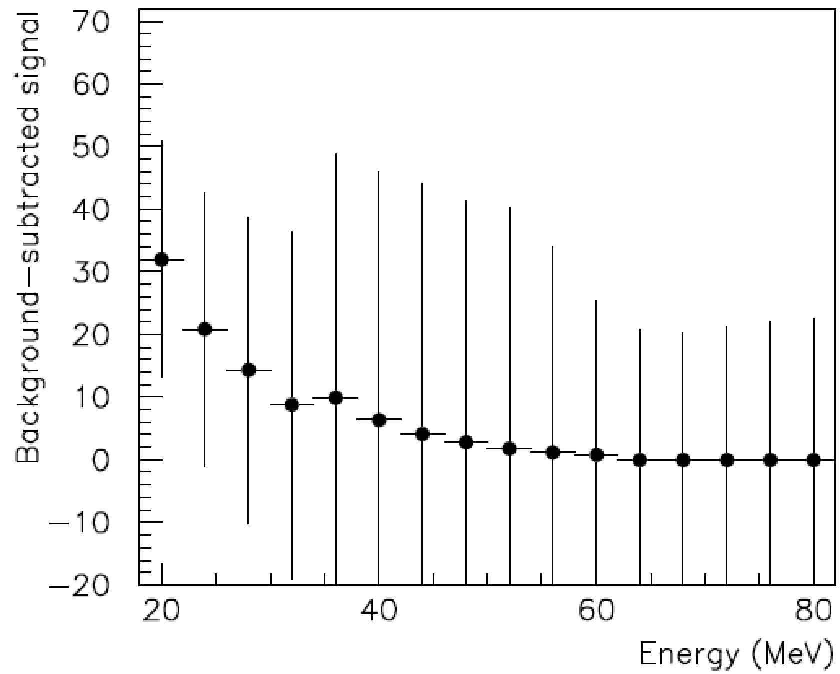
(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Supernova explosion)

MEMPHYS



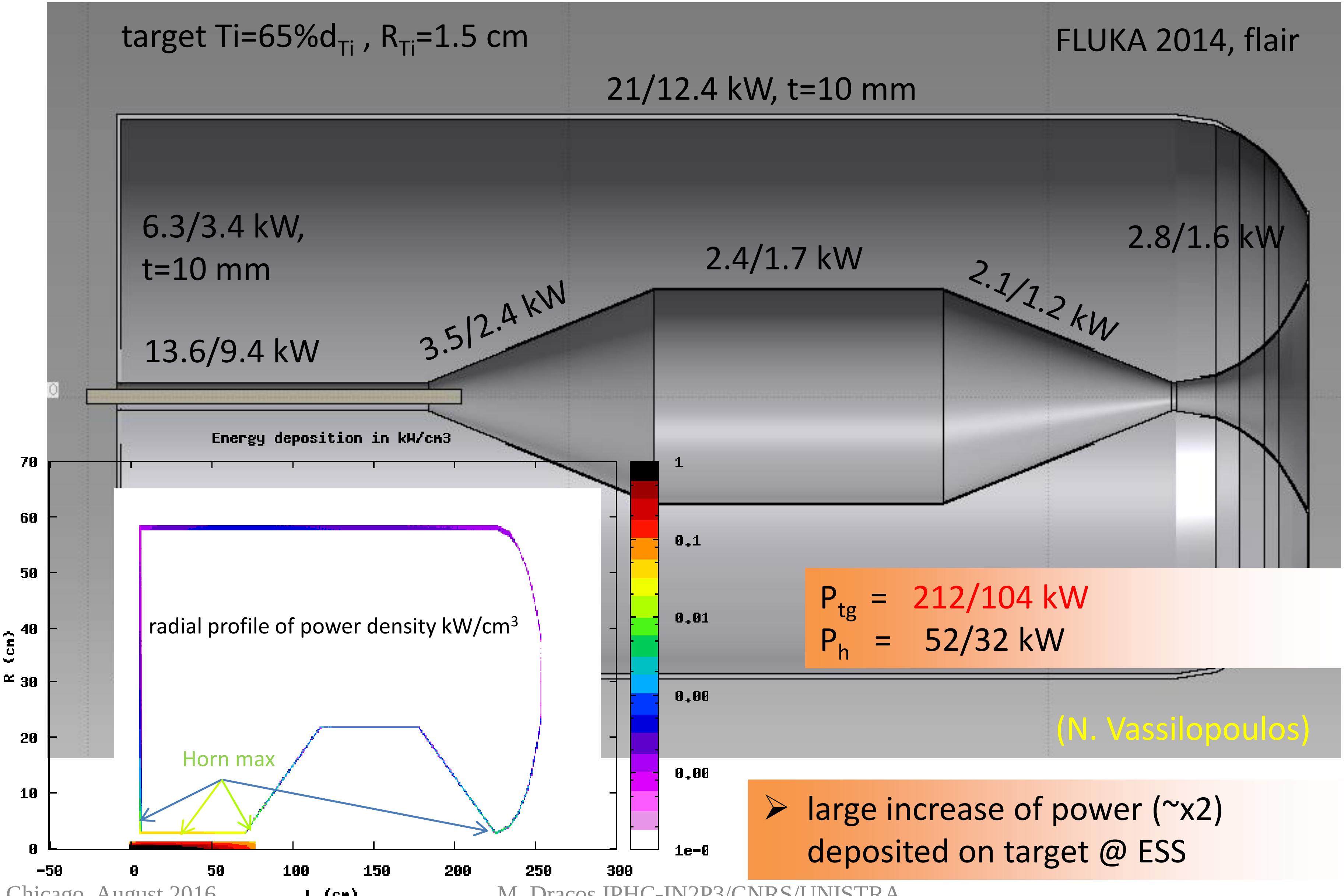
SUPERK



For 10 kpc: ~10^5 events

Diffuse Supernova Neutrinos
(10 years, 440 kt)

Energy Deposition from secondary particles, 3 horns, ESSνSB -1.6 MW/EUROnu -1.3 MW



P_{tg} = 212/104 kW

P_h = 52/32 kW

- large increase of power (~x2) deposited on target @ ESS

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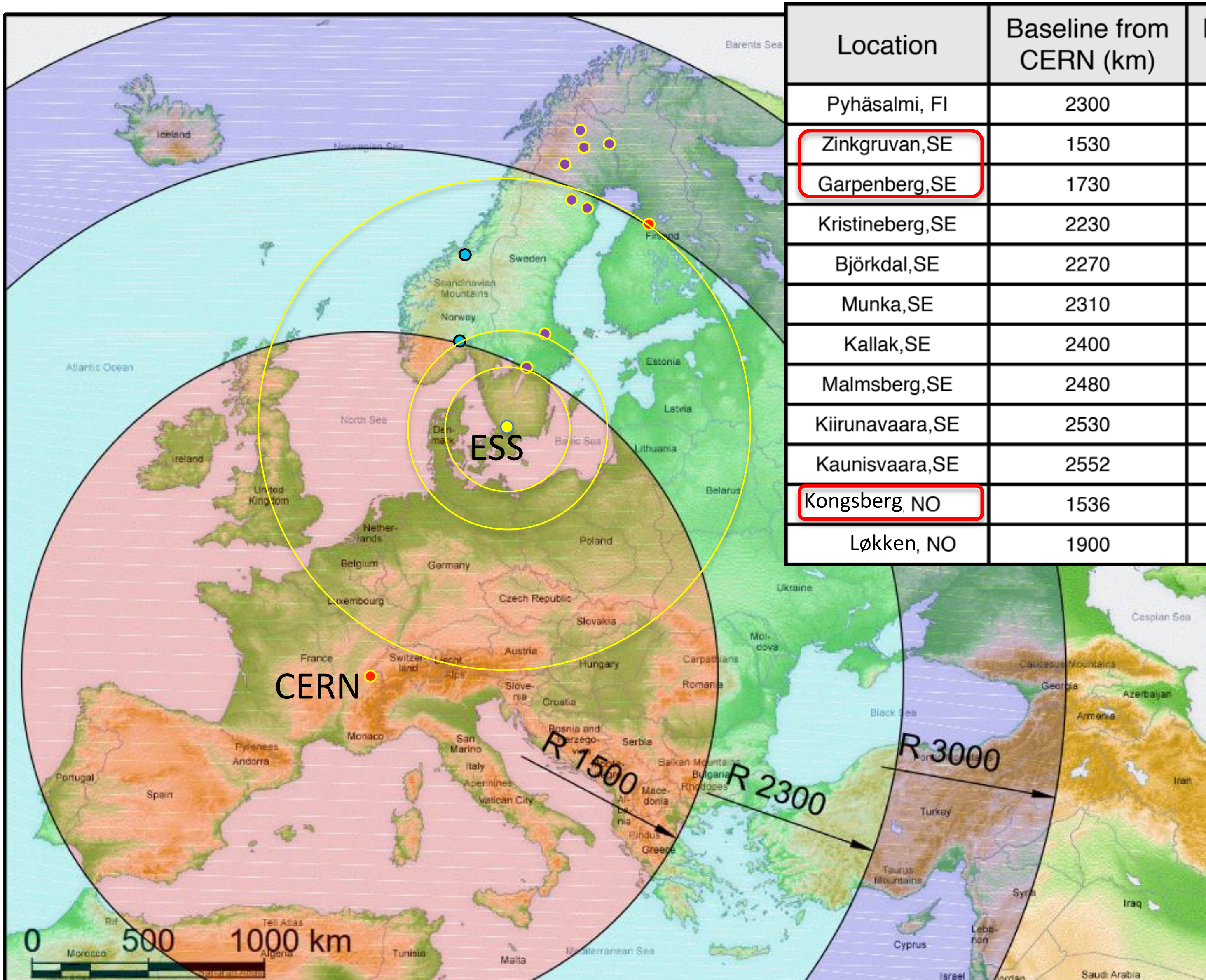
Possible locations for far detector

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