The European Spallation Source Neutrino Super Beam for CP Violation discovery

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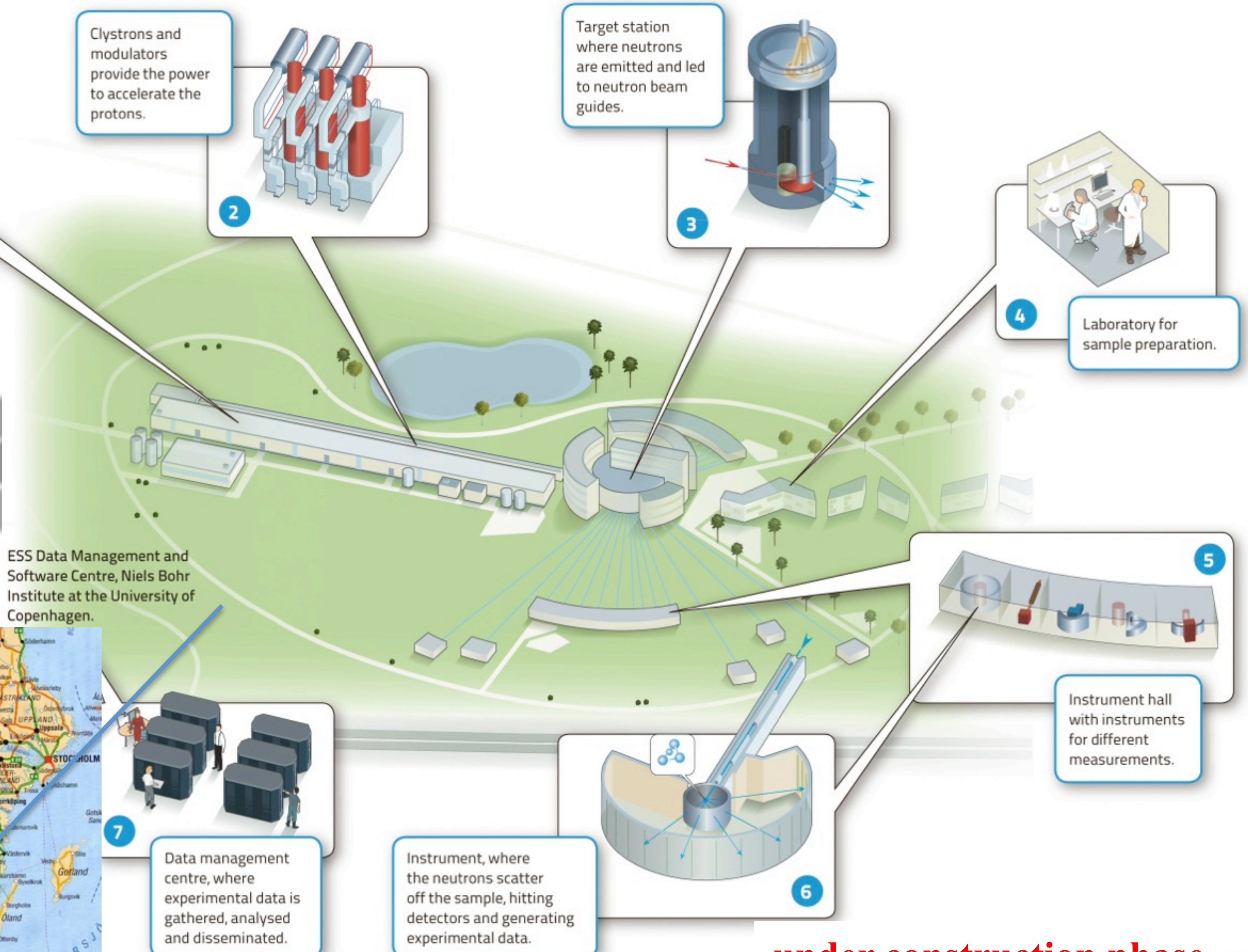
European Spallation Source

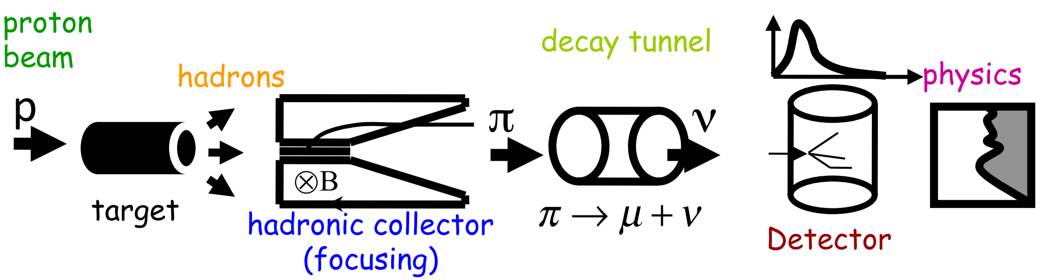


under construction phase
(~1.85 B€ facility)

Having access to a powerful proton beam…

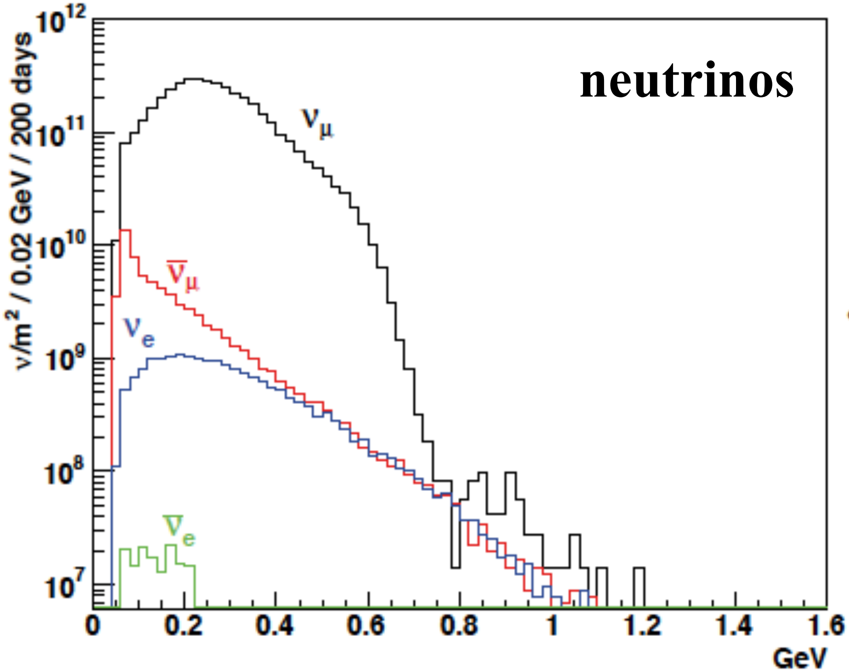
What can we do with:

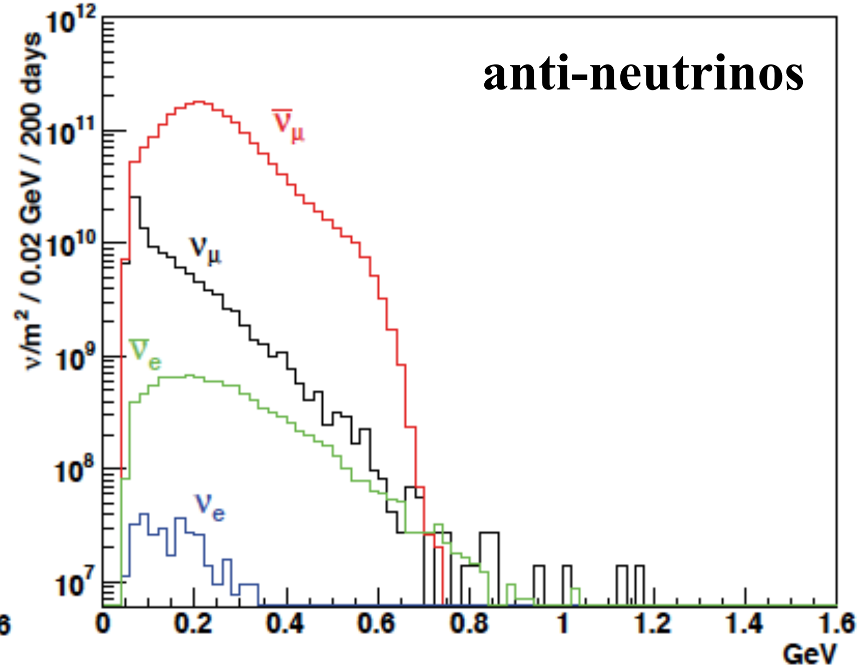
- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- 10^{15} protons/pulse
- $>2.7 \times 10^{23}$ protons/year



conventional neutrino (super) beam

ESSνSB neutrino energy distribution





almost pure ν_μ beam

	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

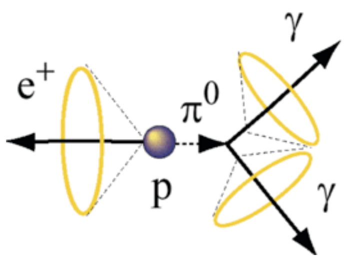
at 100 km from the target and per year (in absence of oscillations)

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

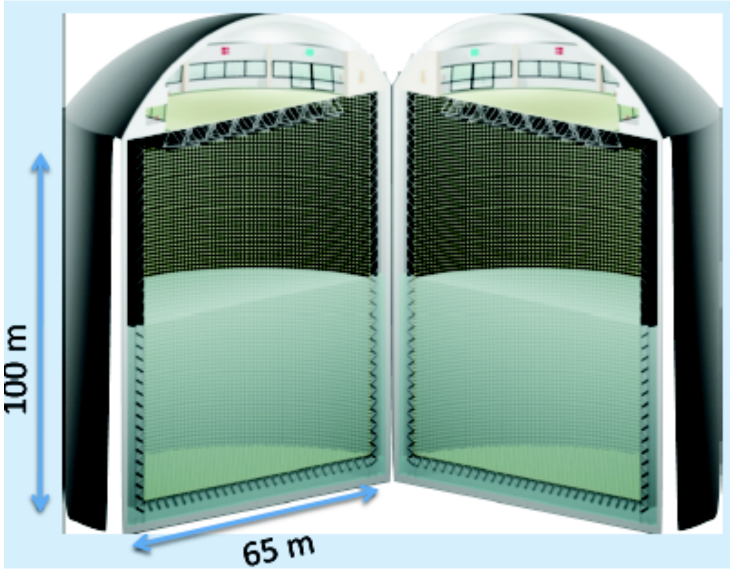
Yes, if we place our far detector at around 500 km from the neutrino source.

MEMPHYS 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



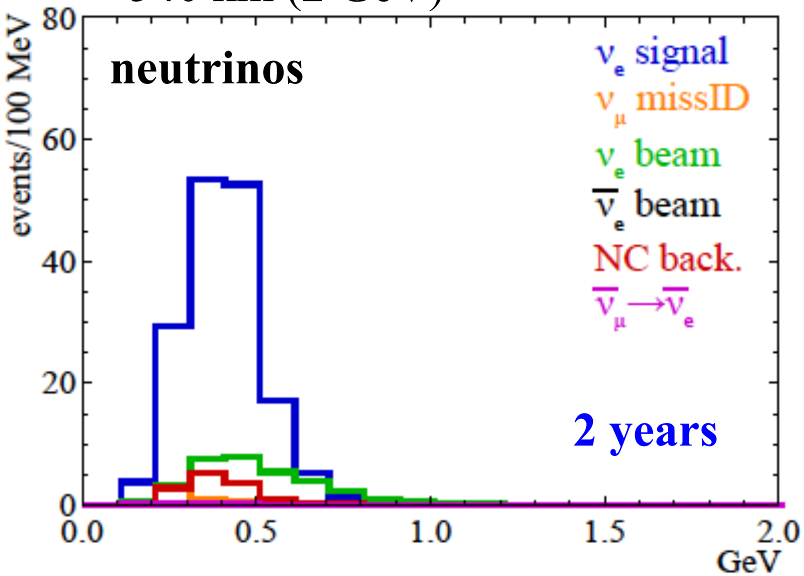
- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage

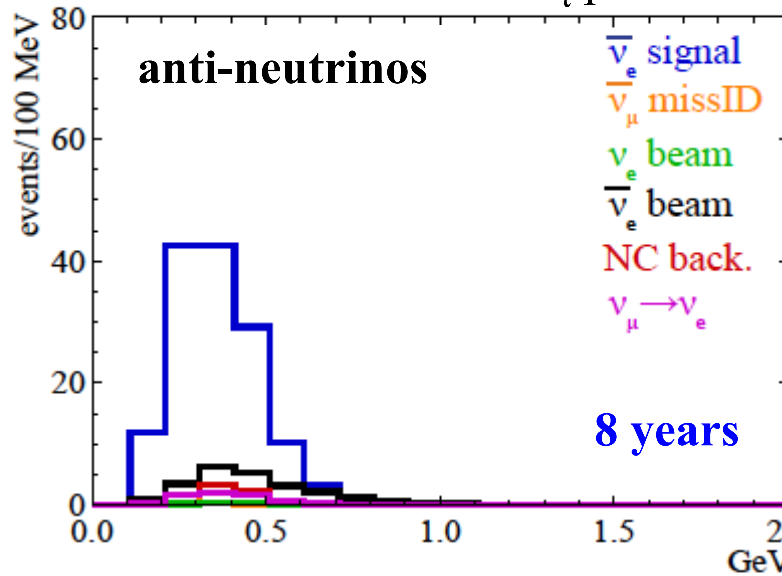
Neutrino spectra

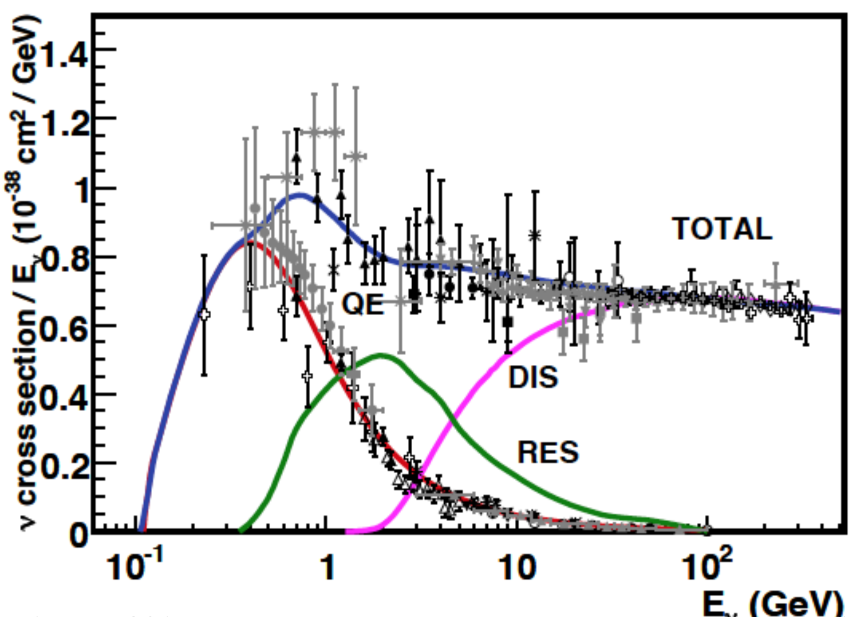
540 km (2 GeV)

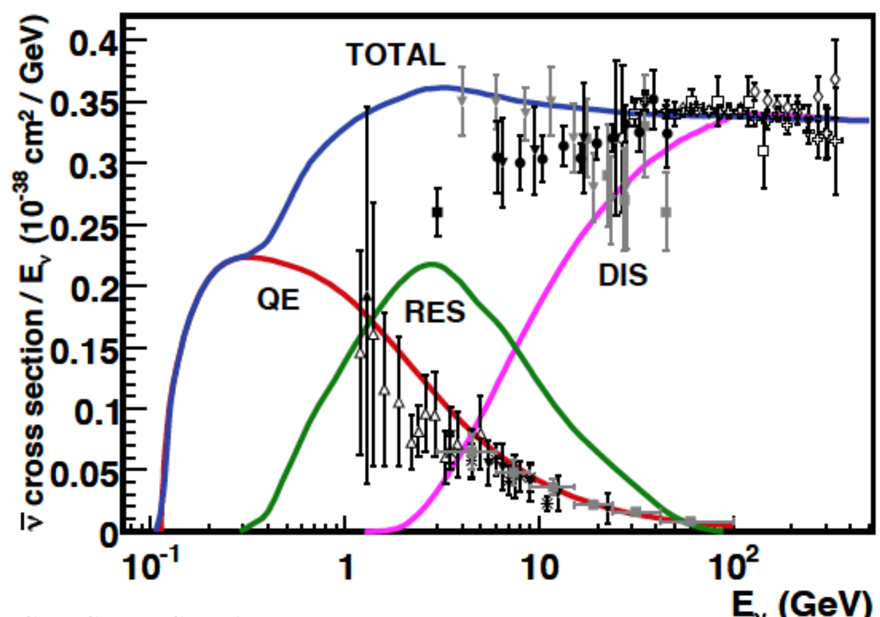
below ν_τ production

$\delta_{CP}=0$

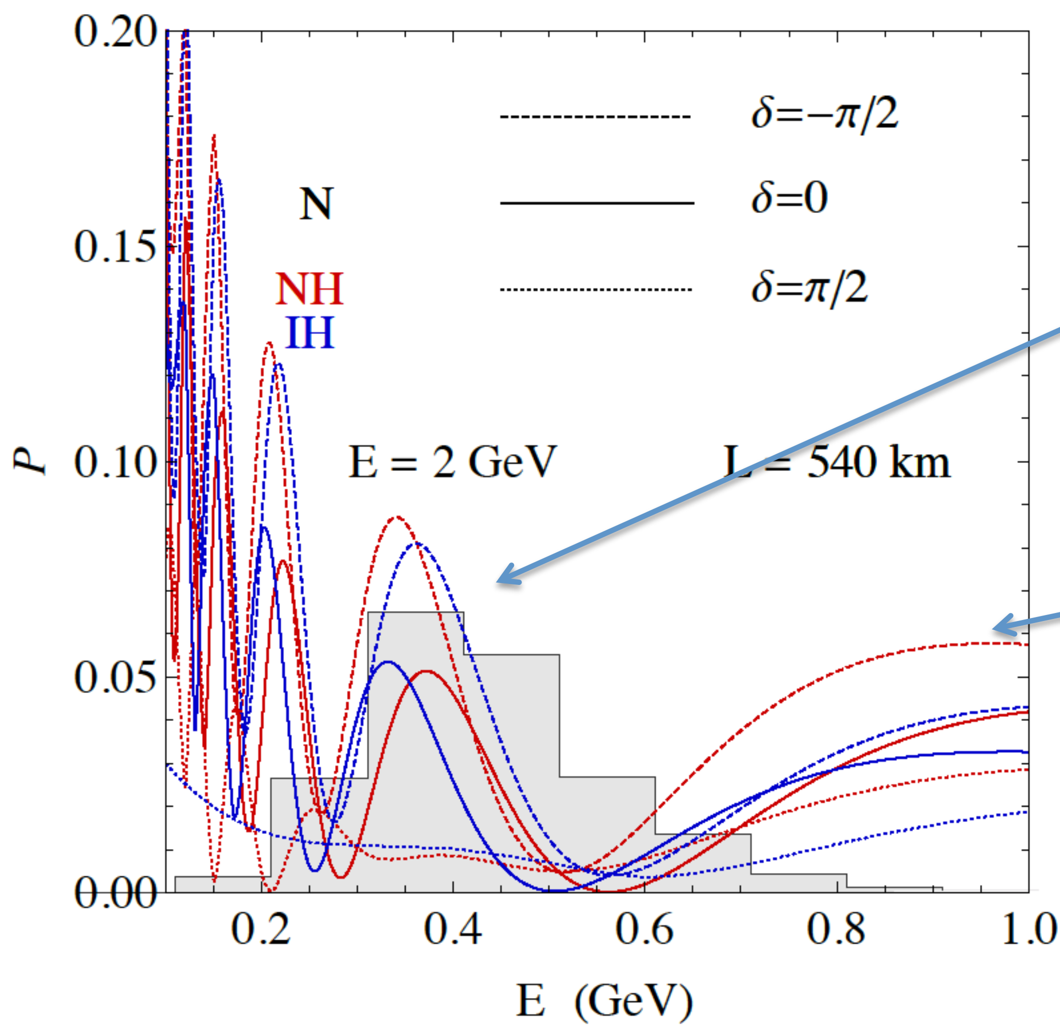








2nd Oscillation max. coverage



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

1st oscillation max.

Where to find all these protons?

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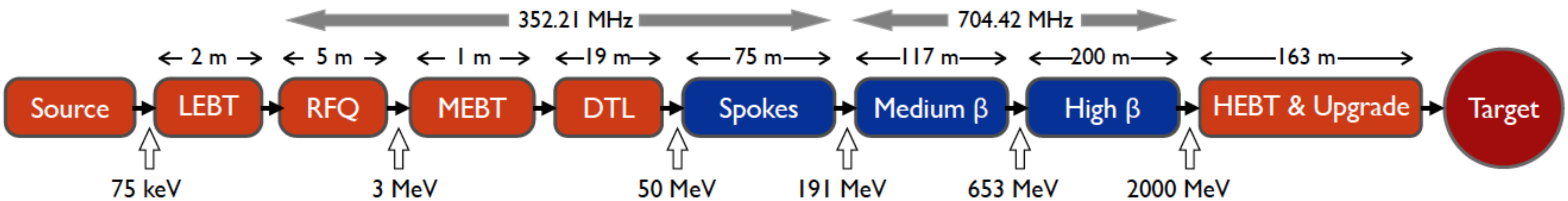
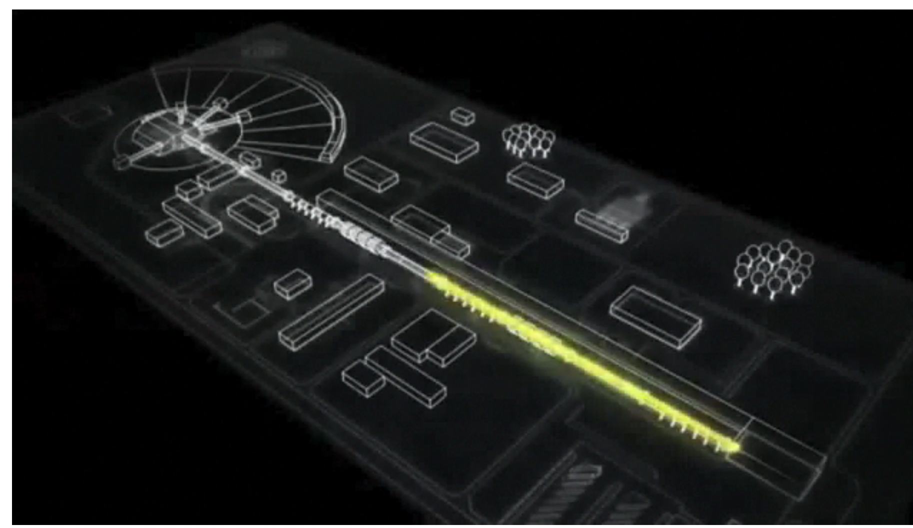
ESS proton linac



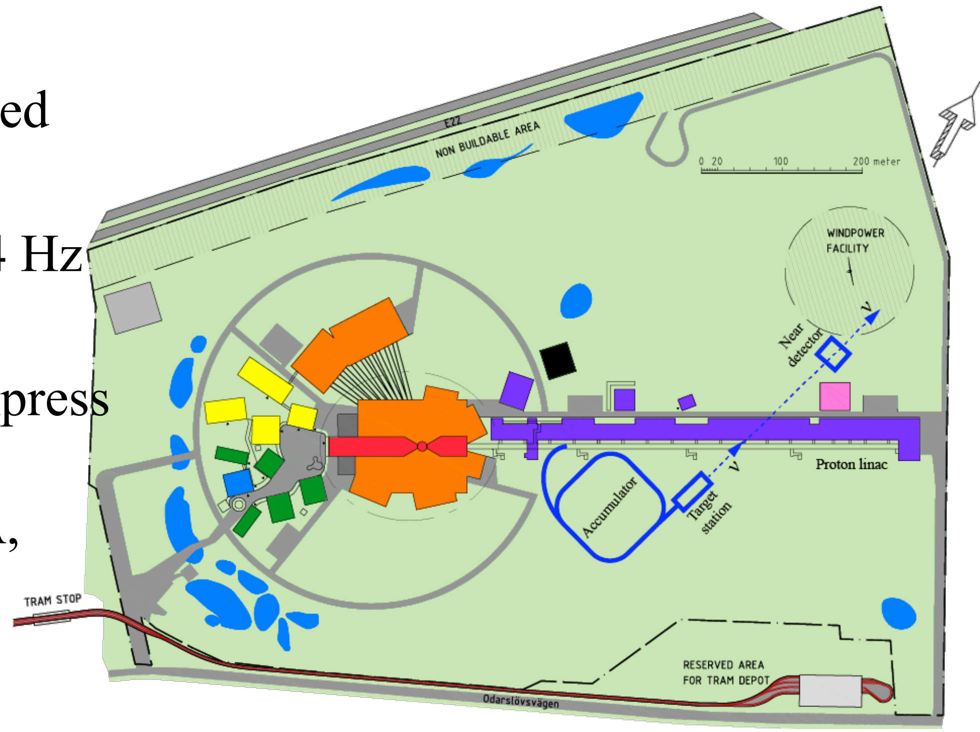
- The ESS will be a copious source of spallation neutrons
- 5 MW average beam power
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
- **>2.7x10^{23} p.o.t/year**

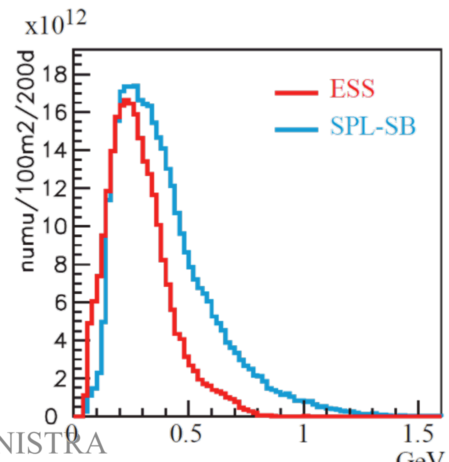


Linac ready by 2023 (full power and energy)

How to add a neutrino facility?

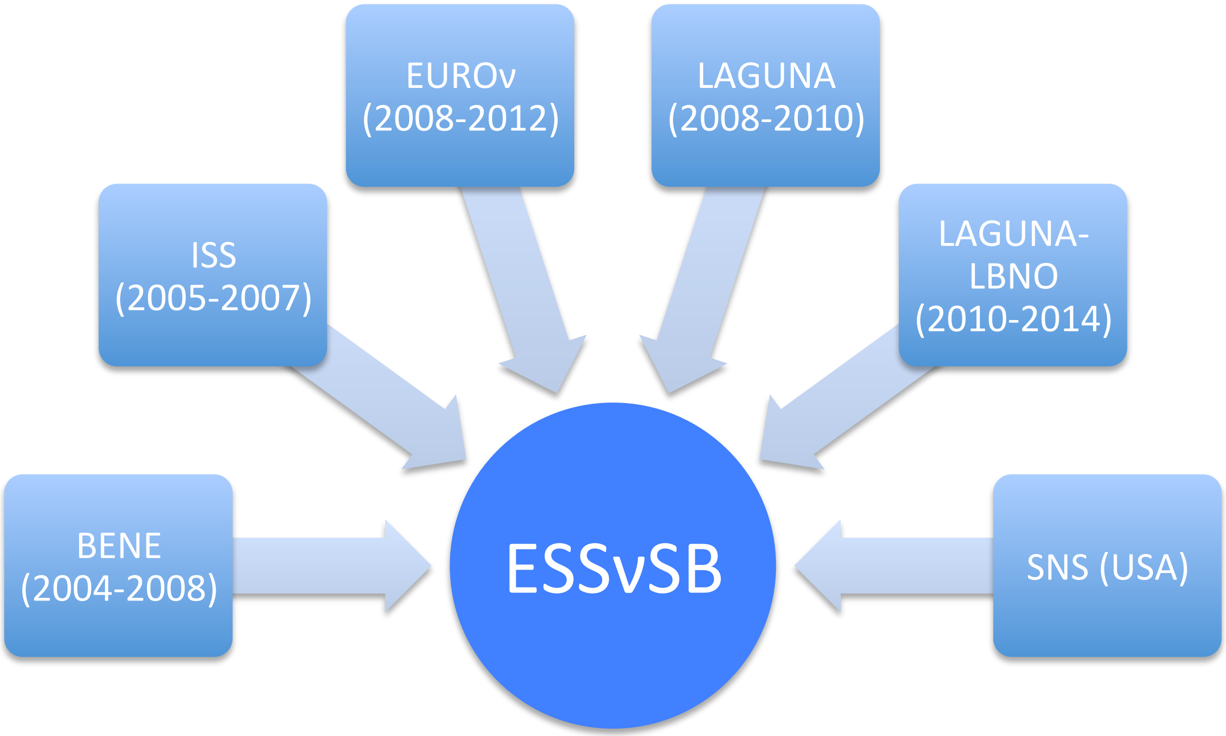
- The neutron program must not be affected and if possible synergetic modifications
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, 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)

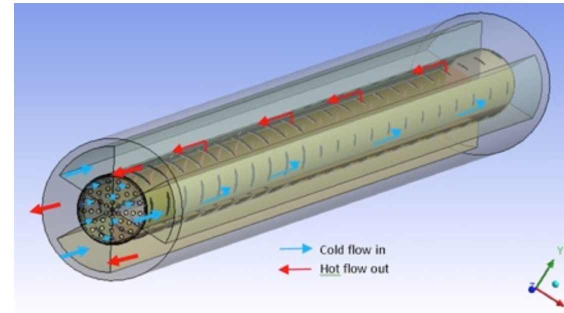


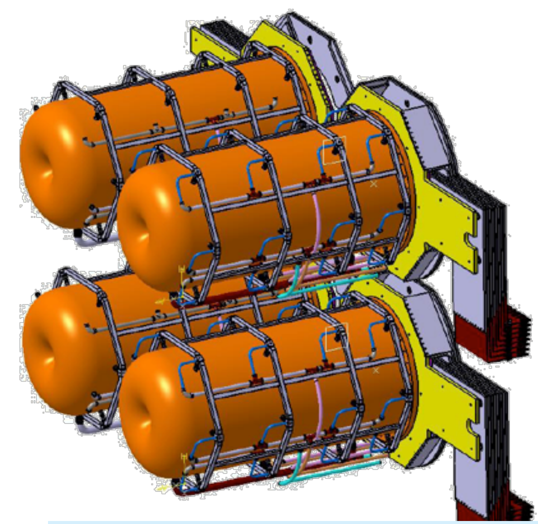


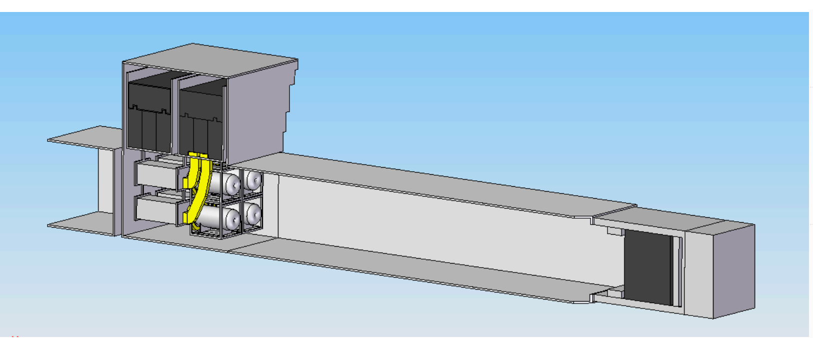
neutrino flux at 100 km (similar spectrum than for EU FP7 EUROν SPL SB)

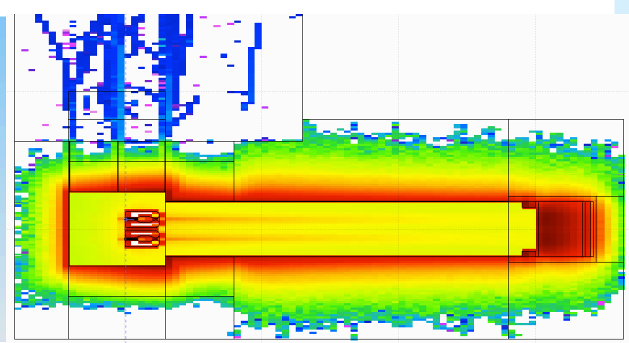
Previous Expertise

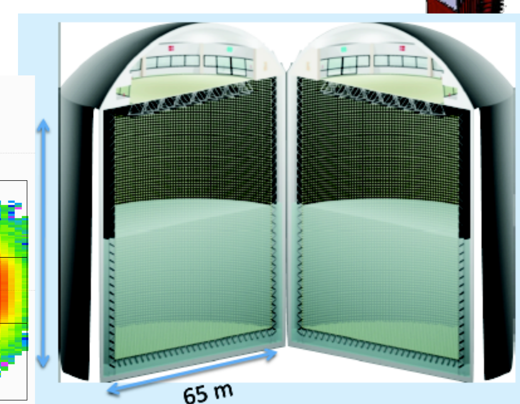








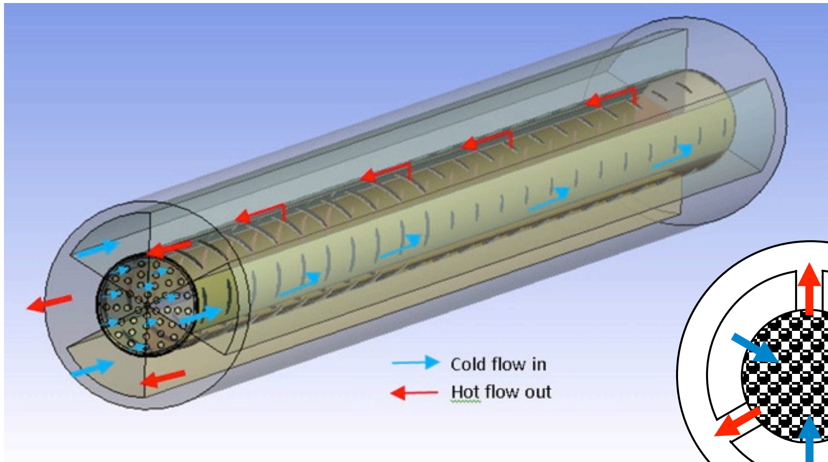


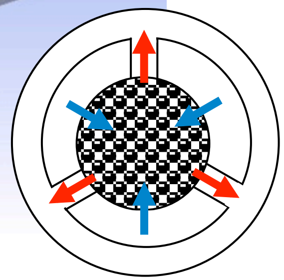


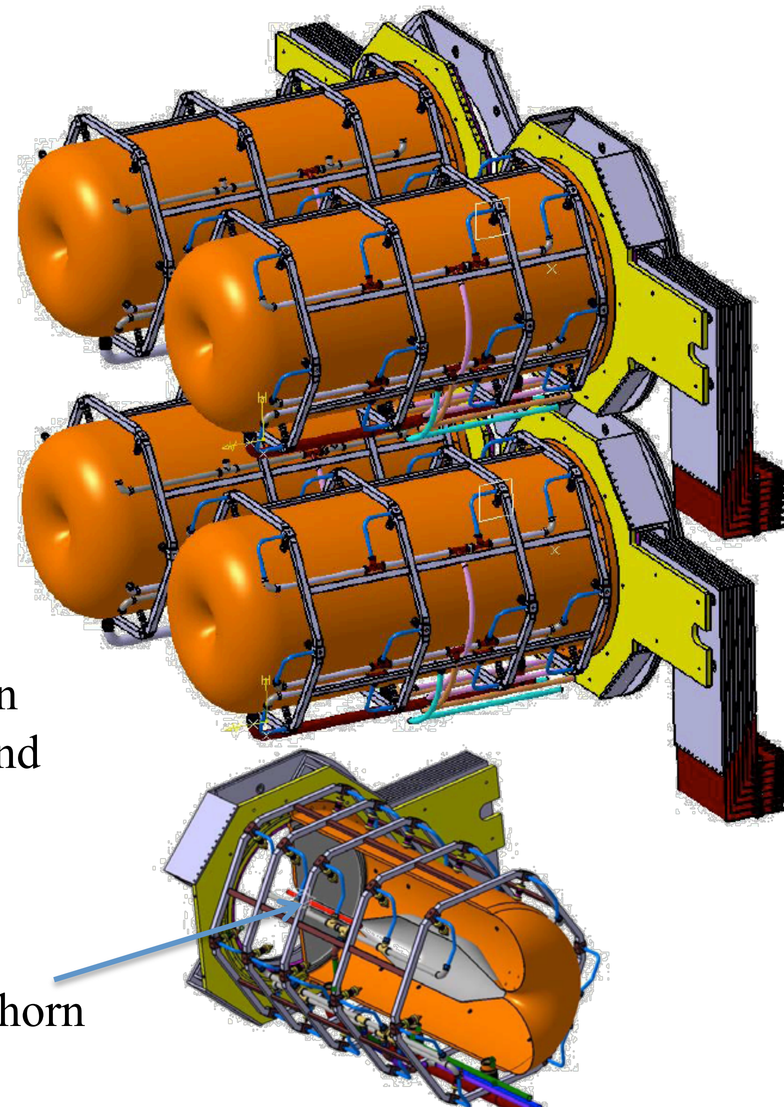
Mitigation of high power effects

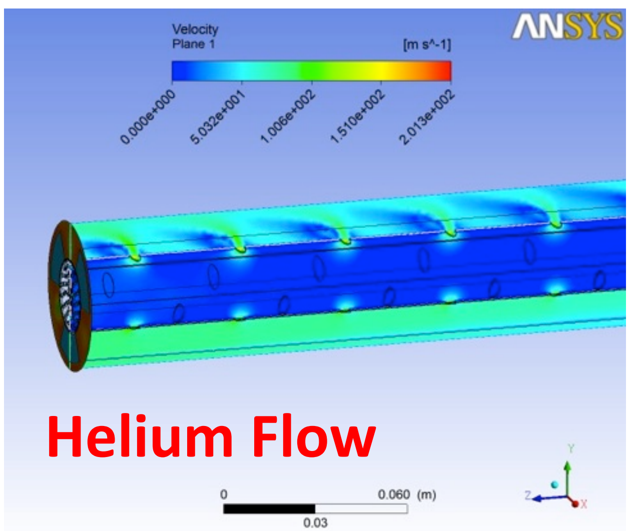
(4-Target/Horn system for EUROnu Super Beam)

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







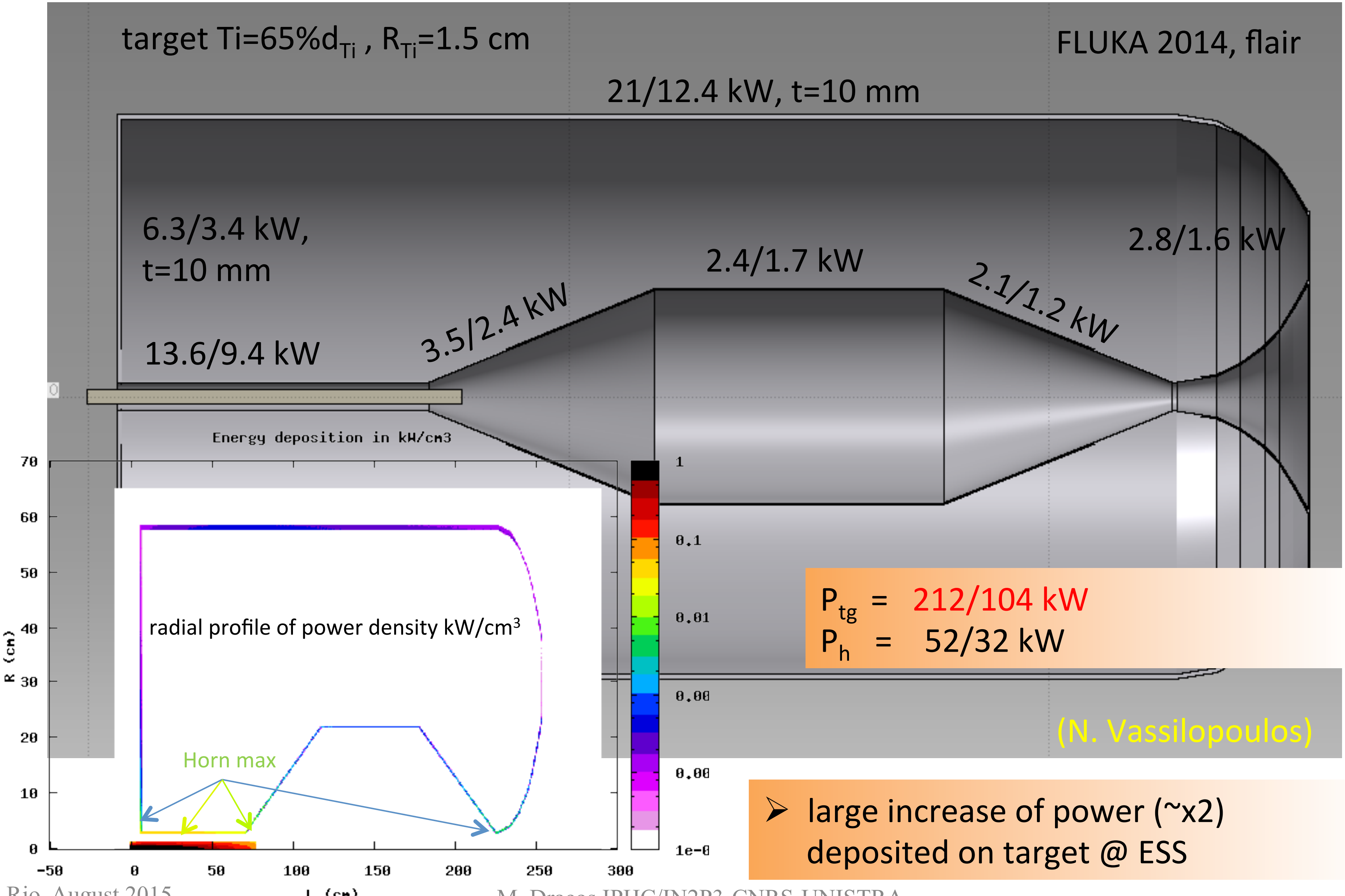


Helium Flow

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

target inside the horn

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

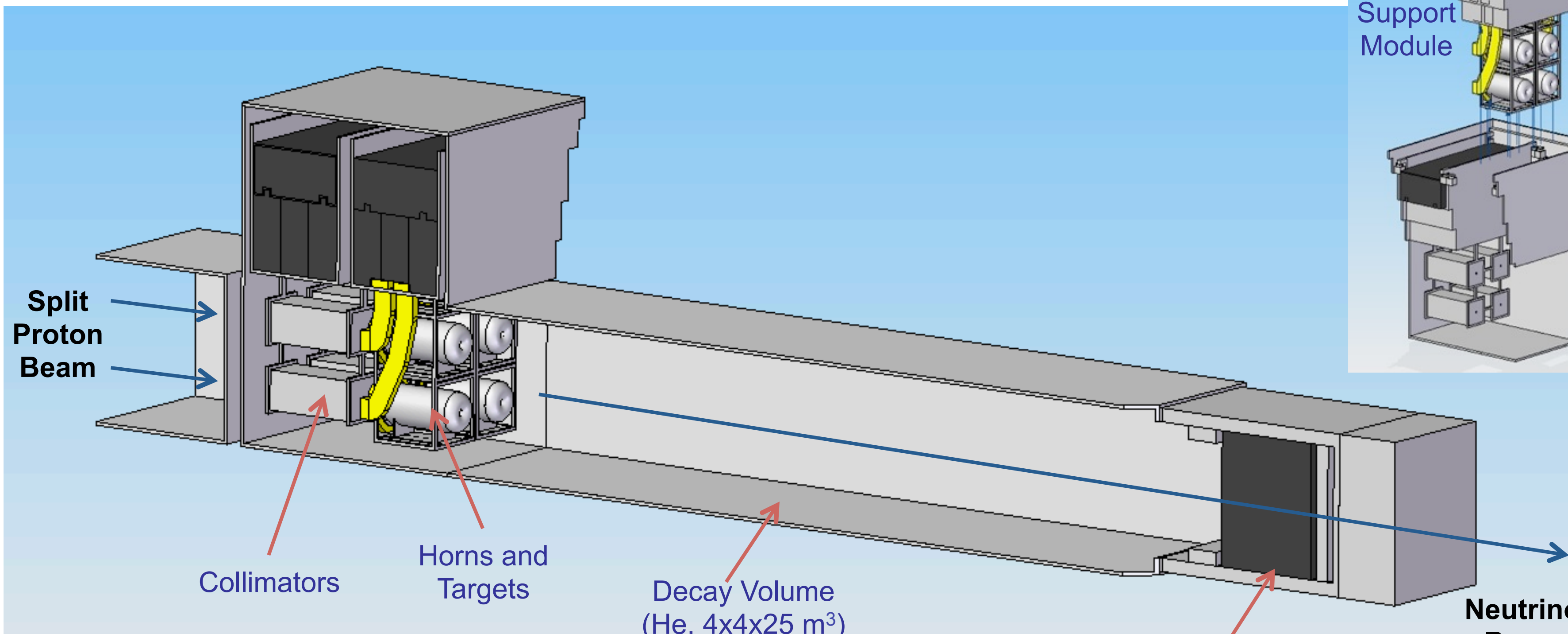


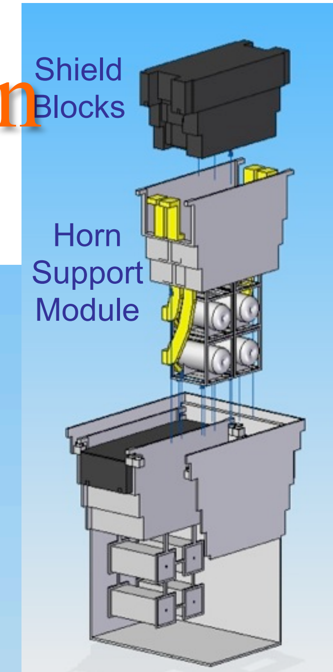
P_{tg} = 212/104 kW
P_h = 52/32 kW

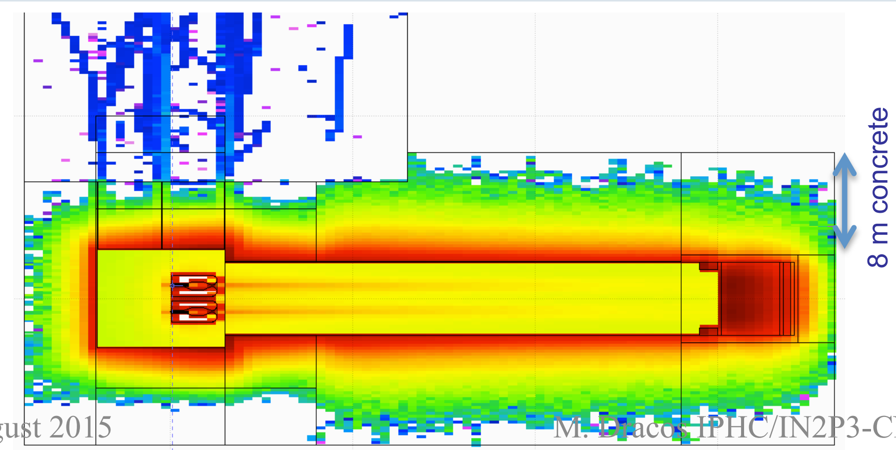
- large increase of power (~x2) deposited on target @ ESS

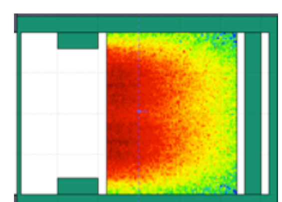
General Layout of the target station

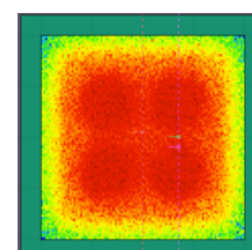
(copied from EUROnu)





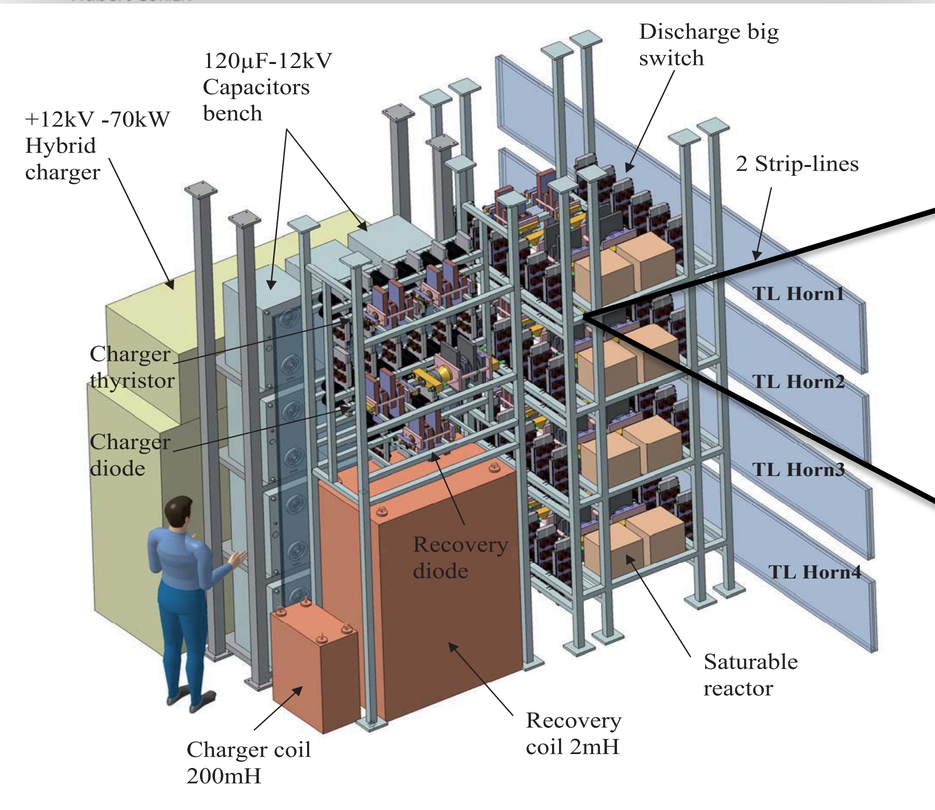




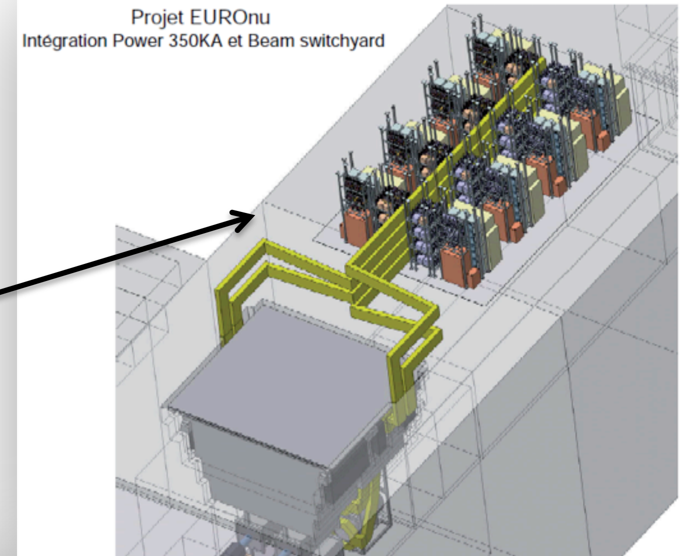


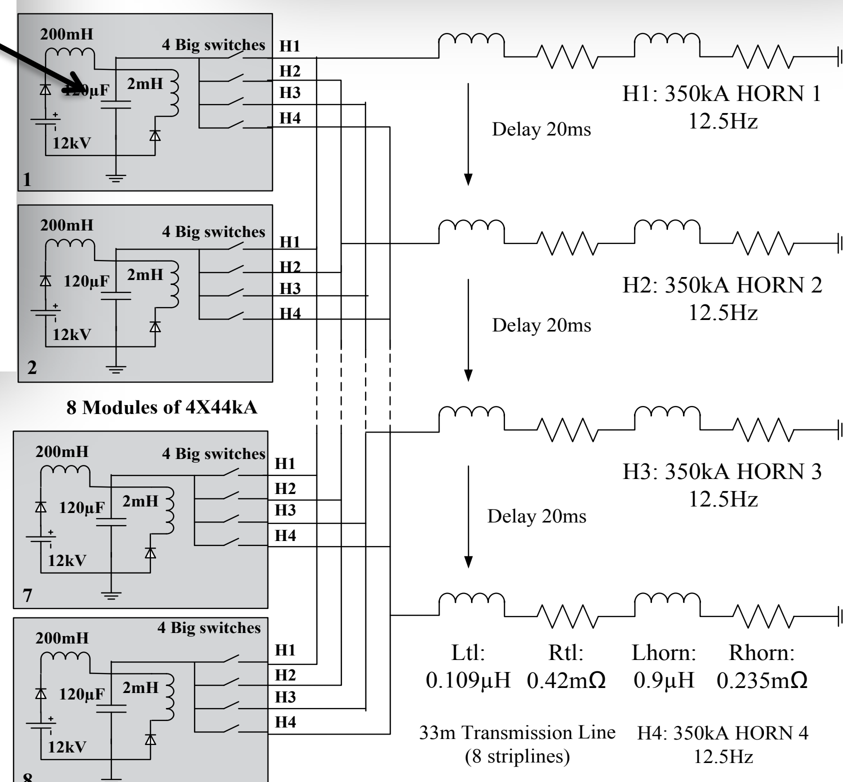
PSU

a 4x44 kA module



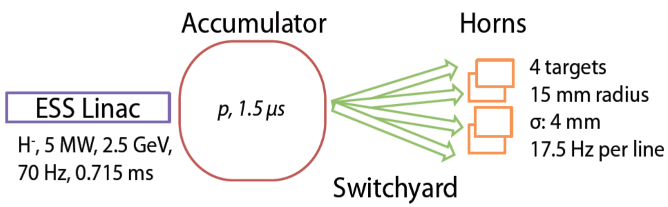
x 8





- PSU: 8 times 4x44 kA modules
- 1-charger/capacitor/coil, 4-switches per 4x44 kA module
- 8 strip lines merged into 4 transmission lines in-out/horn
- Large energy recuperation

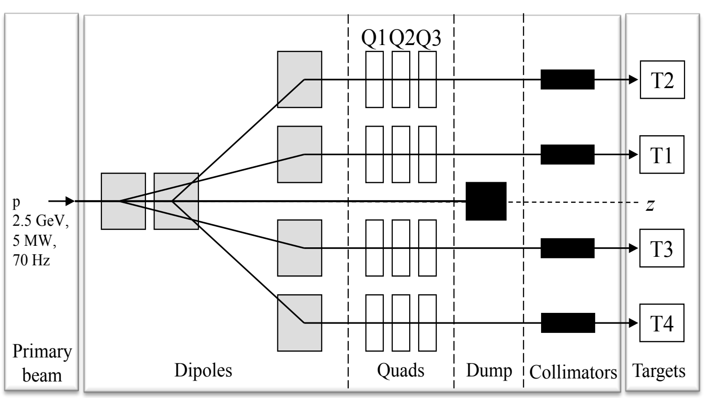
Proton Beam Switchyard



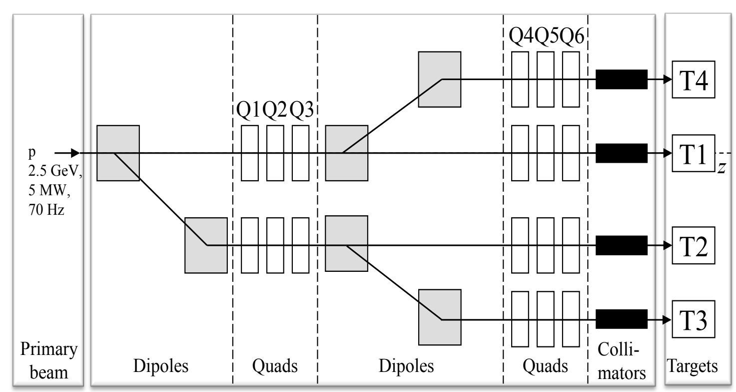
Parameter	EUROν	ESSνSB
Particle	H^-	H^-
Proton kinetic energy (GeV)	4.5	2.5
Pulse intensity (mA)	40	62.5
Avg beam power (MW)	4	5
Beam rigidity (Tm)	17.85	11.02
Macro-pulse length (linac) (ms)	2.86	0.715
Pulse length (accu.) (μs)	1.5	1.5
Pulse repetition rate (Hz)	50	70

- Update of the switchyard preliminarily designed for EUROν with ESS beam parameters (config.1)
- Other possible layouts currently being studied (i.e config.2)
- Selection criteria: number of magnetic elements needed + type of operation (i.e. simple or bi-polar) + prospective of beam dump requirements.

config1.



Total length: **43.4 m**
Max. B-field: 0.65 T (25 kA turns / pole)
Dipole length: 2 m



config2.

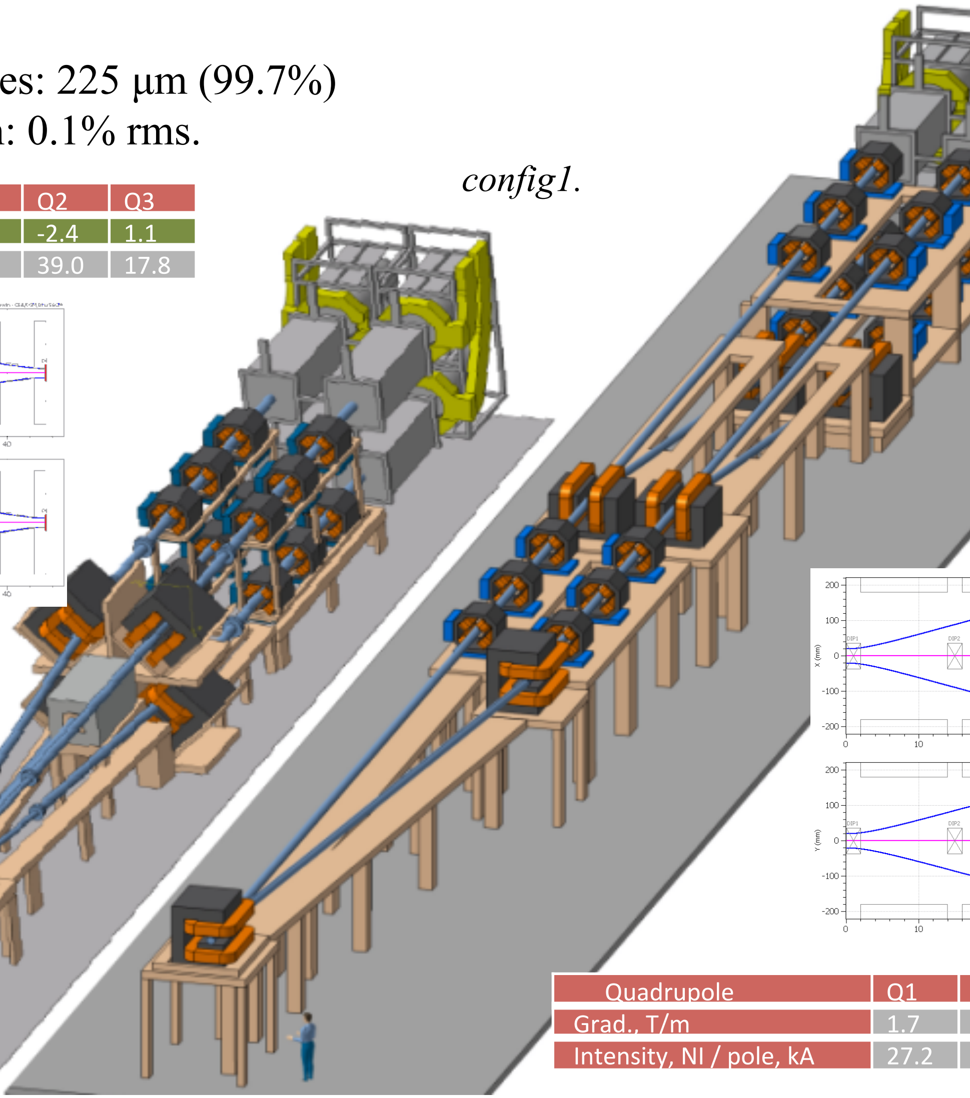
Total length: **72.2 m**
Max. B-field: 0.73 T (29 kA turns / pole)
Dipole length: 2 m

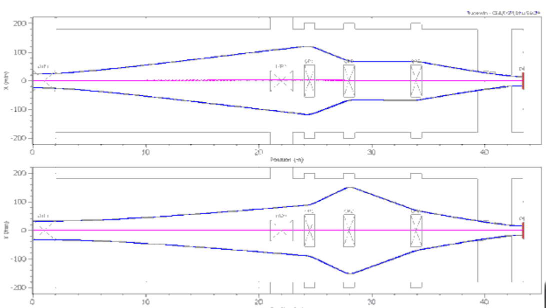
Proton Beam Switchyard

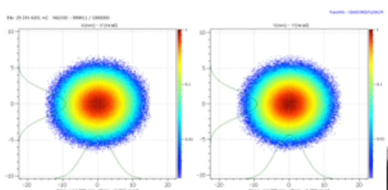
- Assumptions:
  - Norm. trans. Emittances: 225 μm (99.7%)
  - Momentum dispersion: 0.1% rms.

config1.

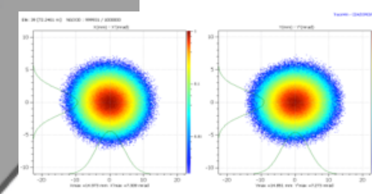
Quadrupole	Q1	Q2	Q3
Field gradient, T/m	1.9	-2.4	1.1
Intensity, NI per pole, kA	30.8	39.0	17.8

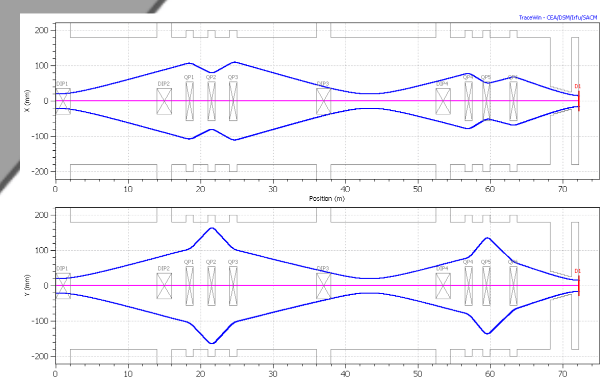






config2.



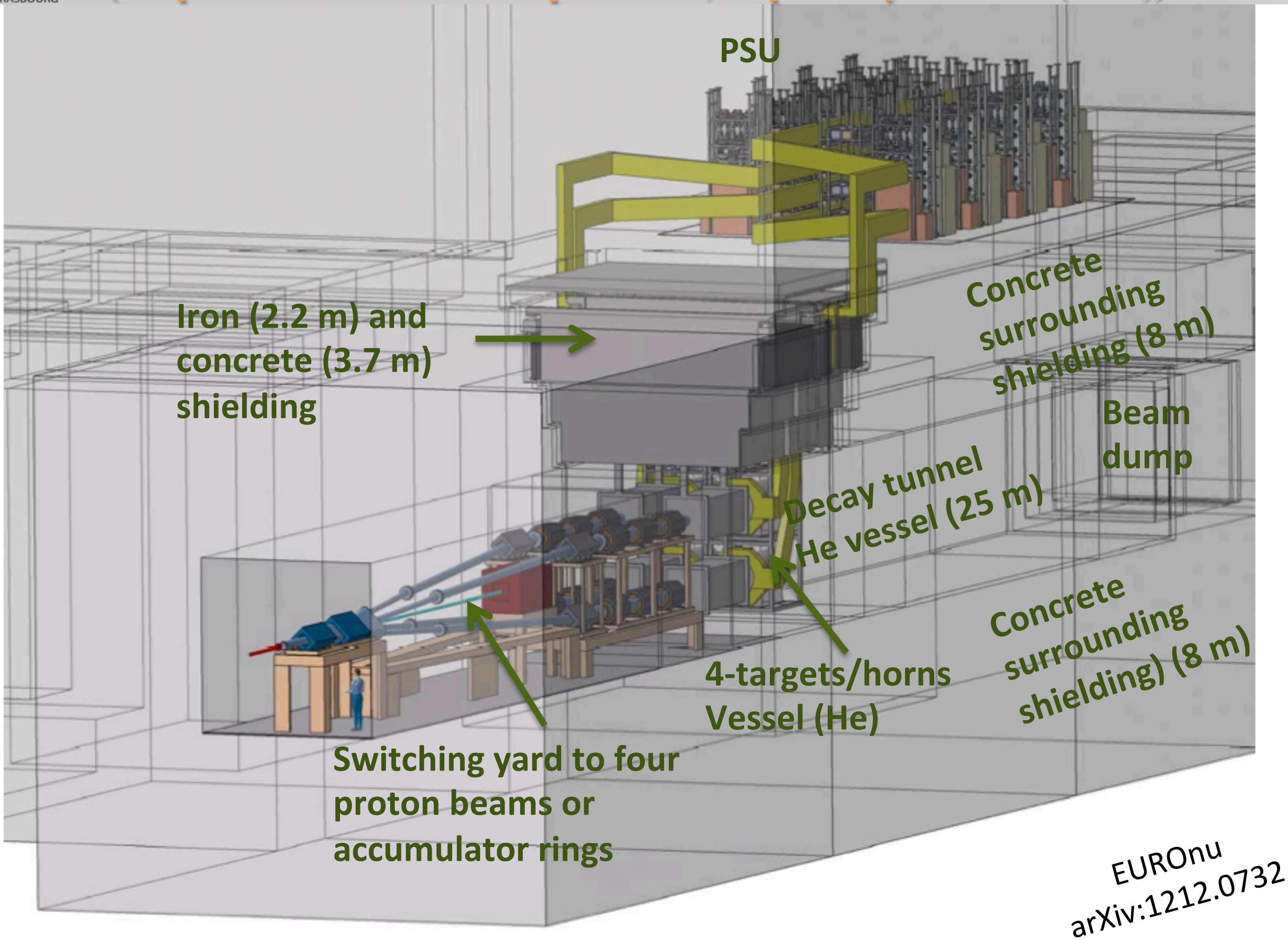


Quadrupole	Q1	Q2	Q3	Q4	Q5	Q6
Grad., T/m	1.7	-3.0	1.7	2.6	-3.6	2.0
Intensity, NI / pole, kA	27.2	48.3	28.5	41.8	59.9	33.7

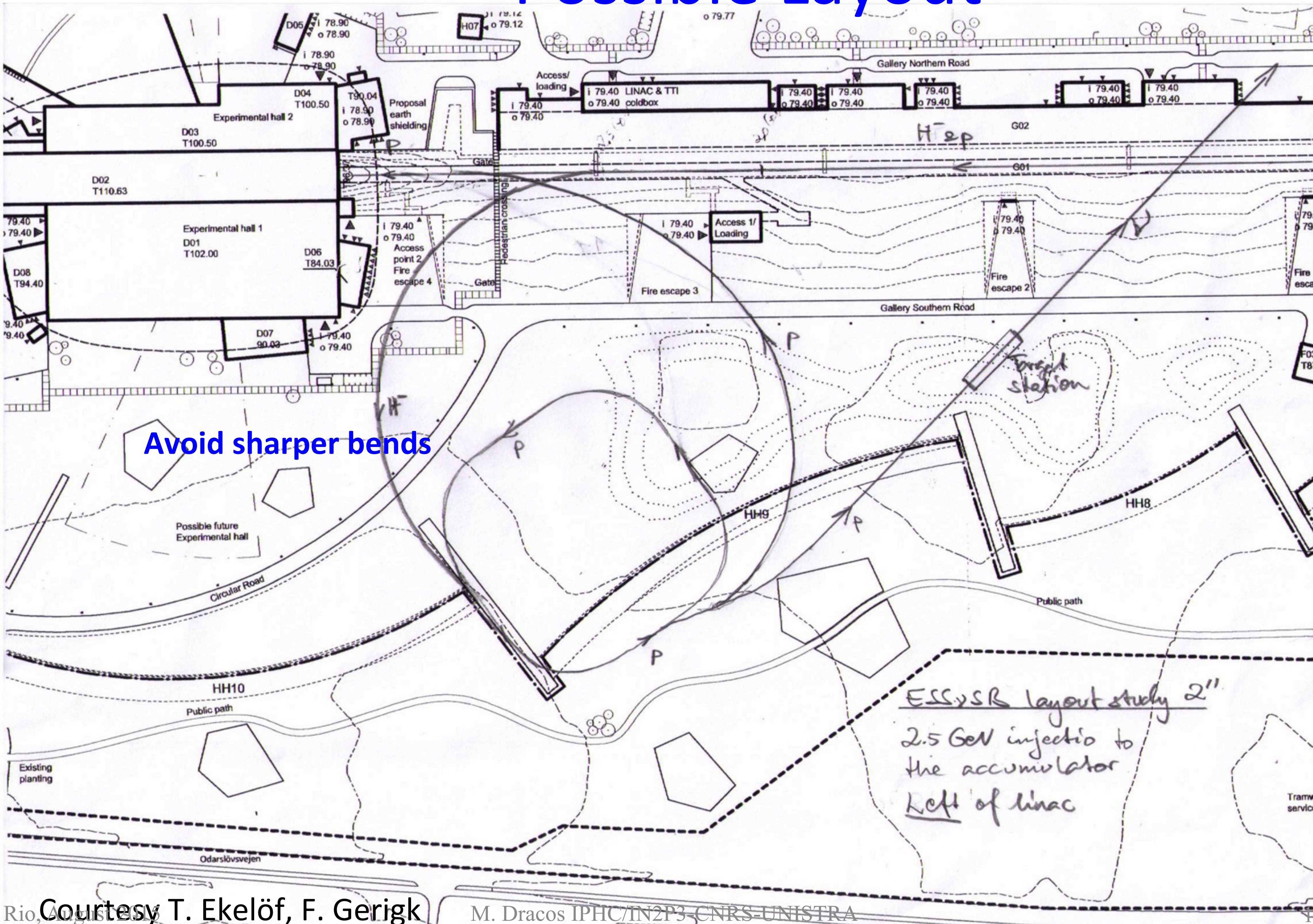
> IPAC'15 Proceedings: E. Bouquerel, "*Design Status of the ESSnuSB Switchyard*", MOPWA017

ESSνSB layout

(adopted from EUROnu Super Beam, inspired by J-PARC (T2K))



Possible Layout



Avoid sharper bends

Courtesy T. Ekelöf, F. Gerigk

Switch from 2.5 GeV linac

Drift-space between quads before dogleg ~ 6.6 m

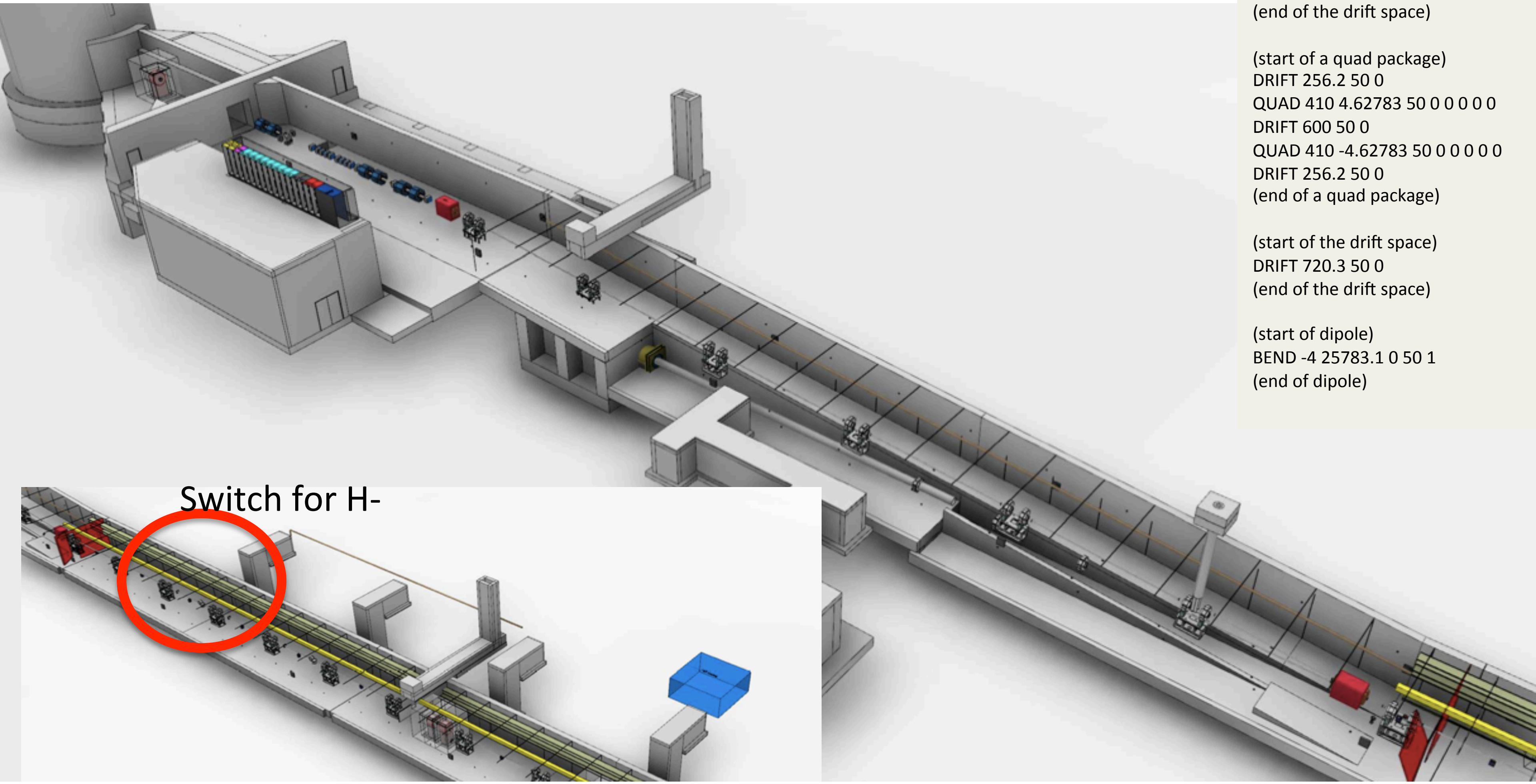
(start of a quad package)
DRIFT 256.2 50 0
QUAD 410 4.61286 50 0 0 0 0 0
DRIFT 600 50 0
QUAD 410 -4.61286 50 0 0 0 0 0
DRIFT 256.2 50 0
(end of a quad package)

(start of the drift space)
DRIFT 1646.9 50 0
DRIFT 1646.9 50 0
DRIFT 1646.9 50 0
DRIFT 1646.9 50 0
(end of the drift space)

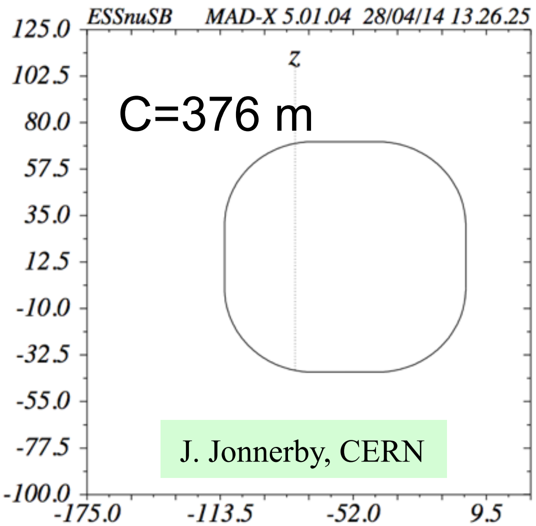
(start of a quad package)
DRIFT 256.2 50 0
QUAD 410 4.62783 50 0 0 0 0 0
DRIFT 600 50 0
QUAD 410 -4.62783 50 0 0 0 0 0
DRIFT 256.2 50 0
(end of a quad package)

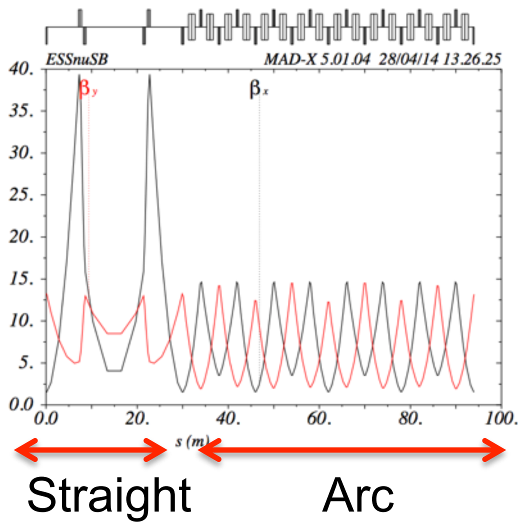
(start of the drift space)
DRIFT 720.3 50 0
(end of the drift space)

(start of dipole)
BEND -4 25783.1 0 50 1
(end of dipole)



The ESSnuSB Accumulator



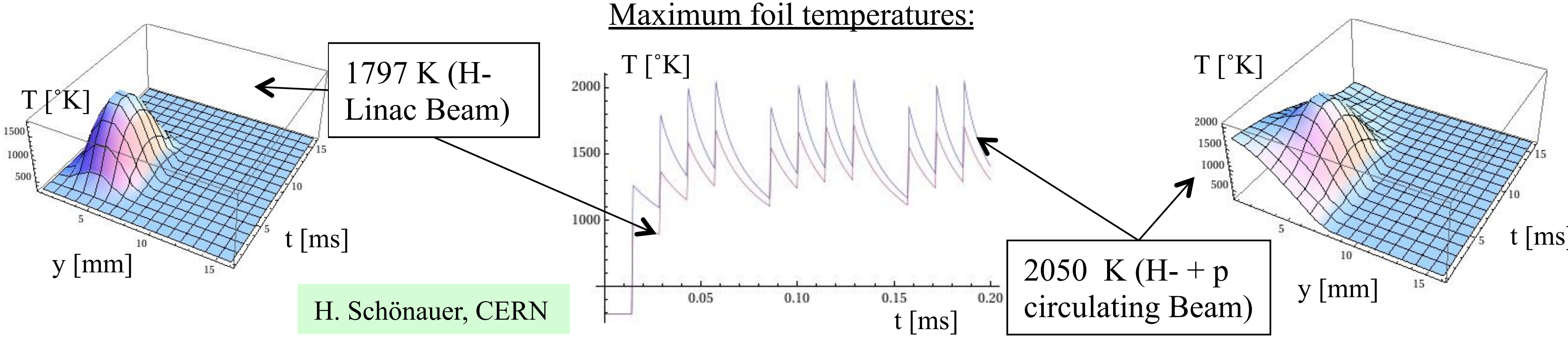


Parameter	Value
Circumference	376 m
Number of dipoles	64
Number of quadrupoles	84
Bending radius	14.6 m
Injection region	12.5 m
Revolution time	1.32 μs

Summary of Lattice Parameters for the Accumulator

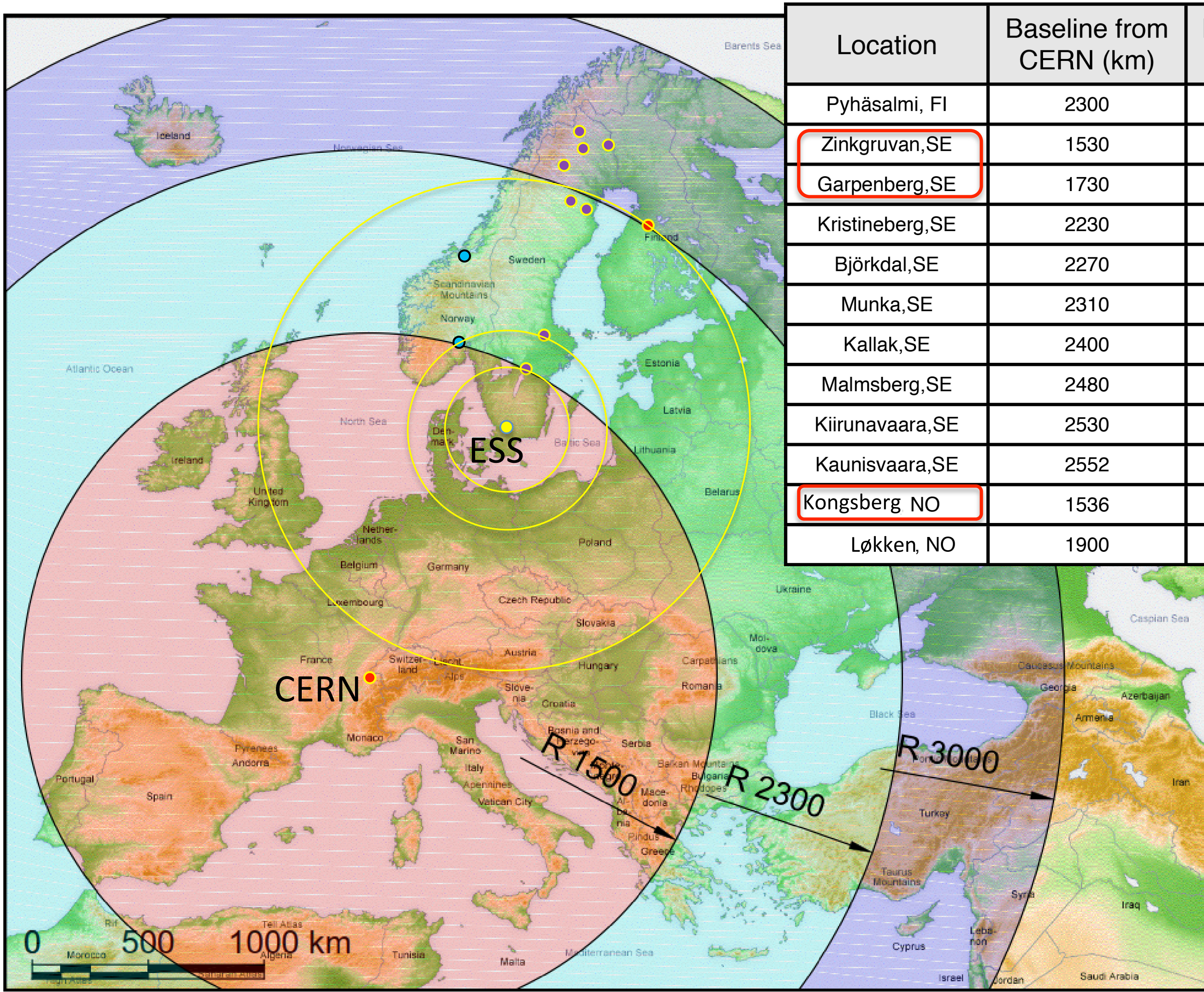
- 376 m long ring as one of the possible layout
- Stripping foil injection: Temperature of the foils currently under studies

Maximum foil temperatures:



> IPAC'15 Proceedings: E. Wildner et al., "*The Accumulator of the ESSnuSB for Neutrino Production*", THPF100

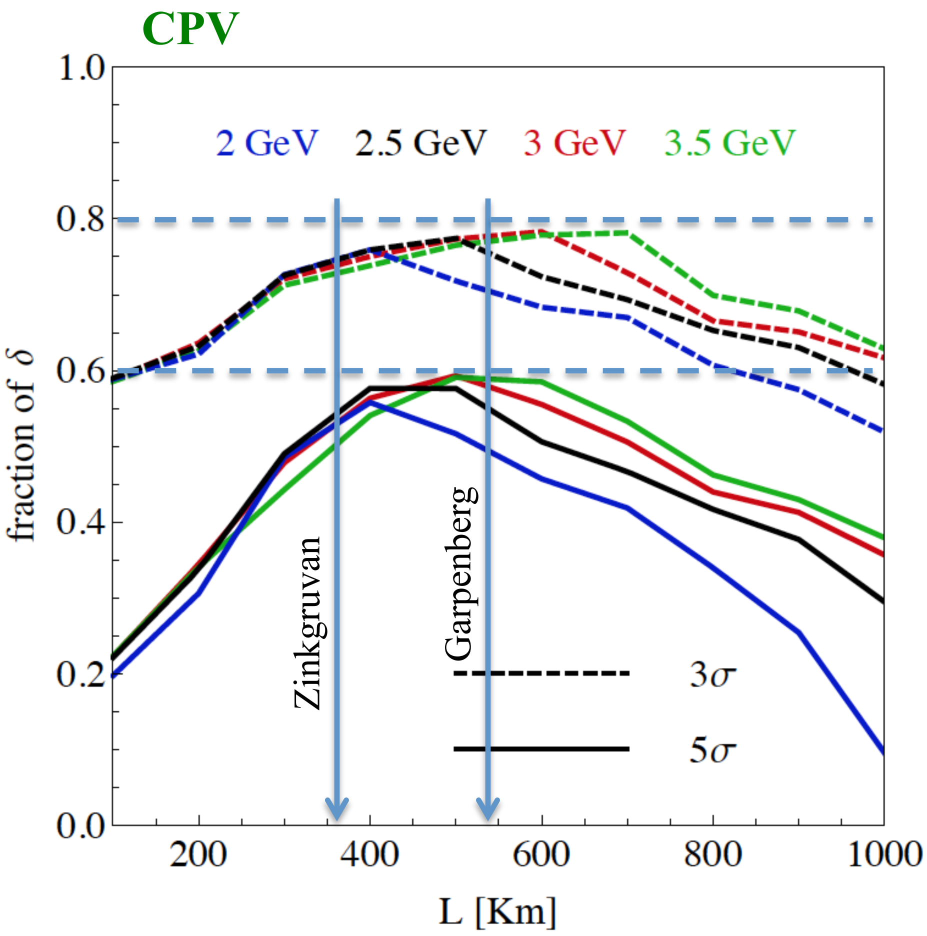
Possible locations for far detector

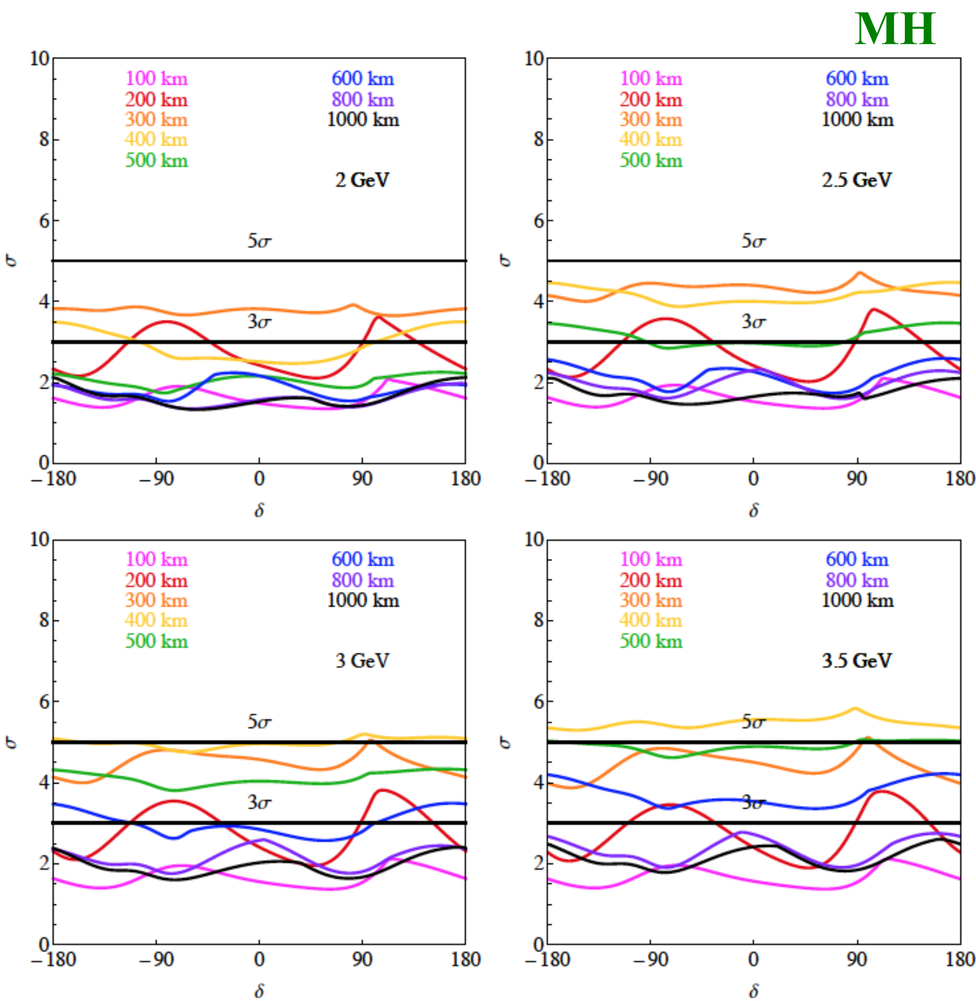


Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320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

LAGUNA sites

Which baseline?





- Zinkgruvan is better for 2 GeV
- Garpenberg is better for > 2.5 GeV
- **systematic errors: 5%/10% (signal/backg.)**

- Zinkgruvan is better
- **atmospheric neutrinos are needed (at least at low energy)**

ESS Neutrino Super Beam DS

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B 885 (2014) 127–149
NUCLEAR PHYSICS B
www.elsevier.com/locate/nuclphysb

arXiv:1212.5048
arXiv:1309.7022

A very intense neutrino super beam experiment for leptonic CP violation discovery based on the European spallation source linac

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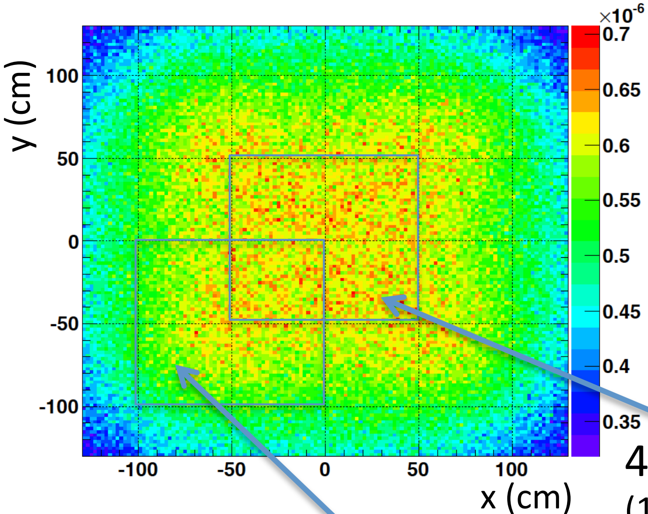
14 participating institutes from 10 different countries, among them ESS and CERN

Muon at the level of the beam dump

2.7×10^{23} p.o.t/year

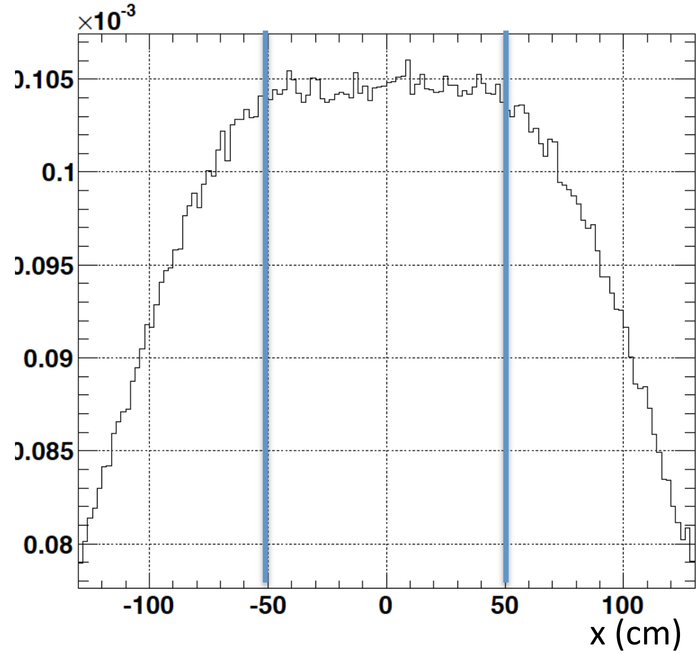


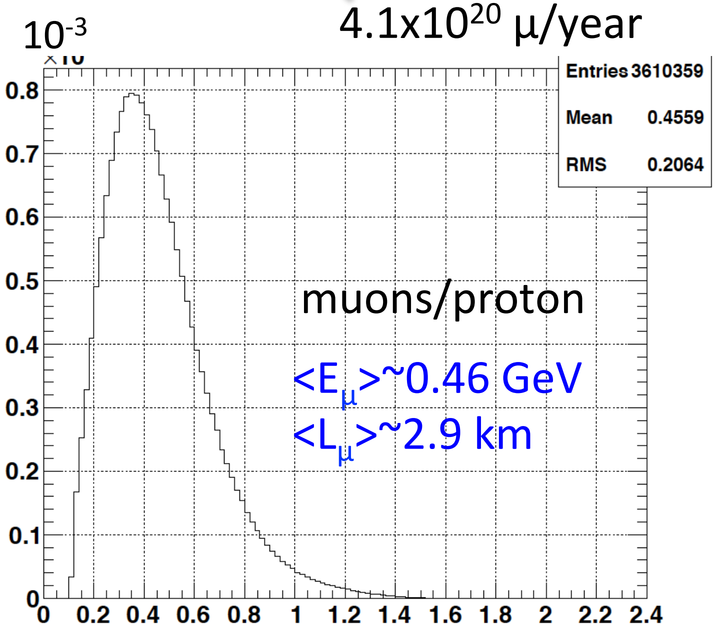
muons at the level of the beam dump (per proton)

4.2×10^{20} μ/year

(16.3×10^{20} for 4 m^2)

4.1×10^{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 (low energy nuSTORM)

ESS Neutrino Super Beam Design Study

- A **H2020** Design Study has been submitted last September
  - 11 institutes (including ESS and CERN) from 8 European countries
  - Decision:
    - Overall score 13.5/15 (5/5 for Excellence)
    - not enough to be funded (only 15 MEUR for this call)
    - nevertheless, the evaluators recognise that **ESSνSB answers one of the priorities defined in the European Strategy for Particle Physics**.
- New funding sources are now investigated in order to continue this design study (probably re-apply to H2020 2016/2017 call).
- Some studies for H^- injection and accumulation ring are included in an approved EU project concerning High Brightness neutron facility.

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

ESS under construction

ESS Construction

- First proton beam by 2019
- Full power/energy by 2023

ESS Construction

ESS Construction

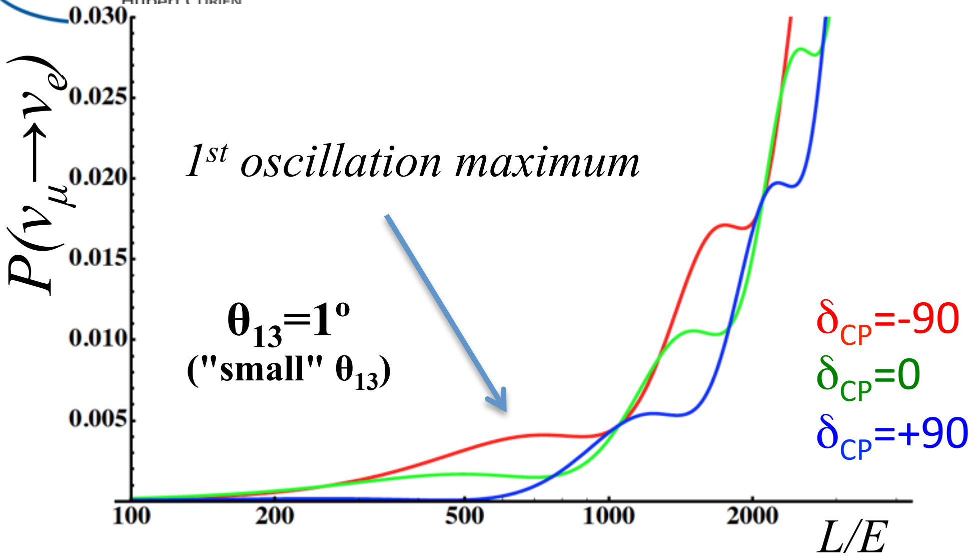
June 2015

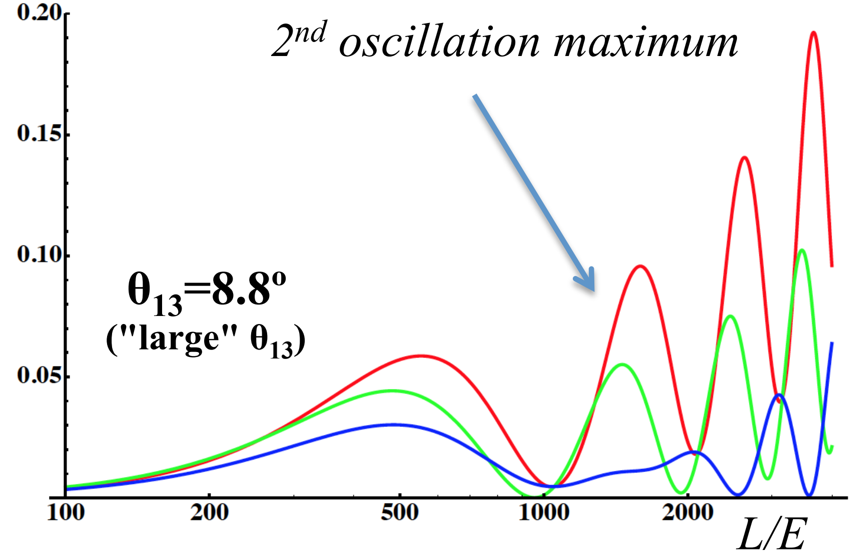
Conclusion

- 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.
- Full complementarity with a long baseline experiment on the 1st oscillation maximum using another detection technique (LAr?).
- A Design Study is urgently needed.

Backup

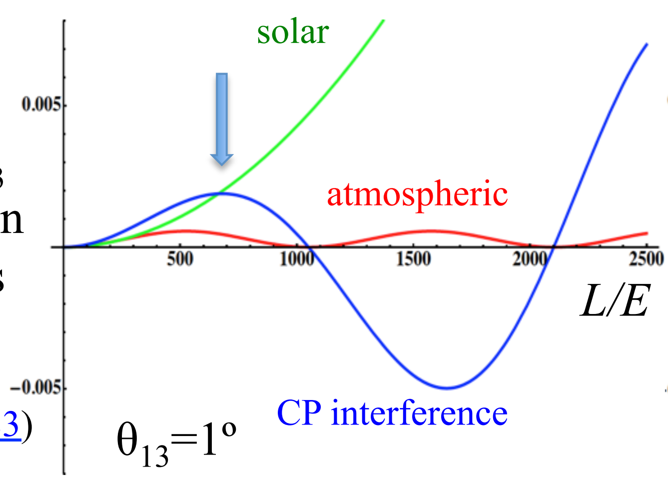
Neutrino Oscillations with "large" θ_{13}

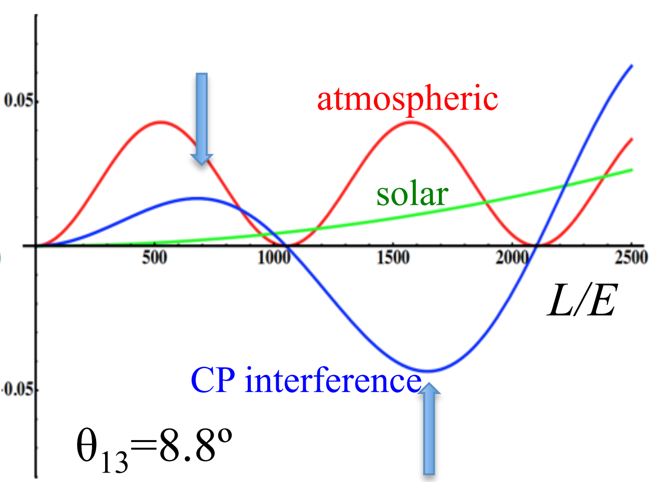




for small θ_{13} 1st oscillation maximum is better

(arXiv:1110.4583)



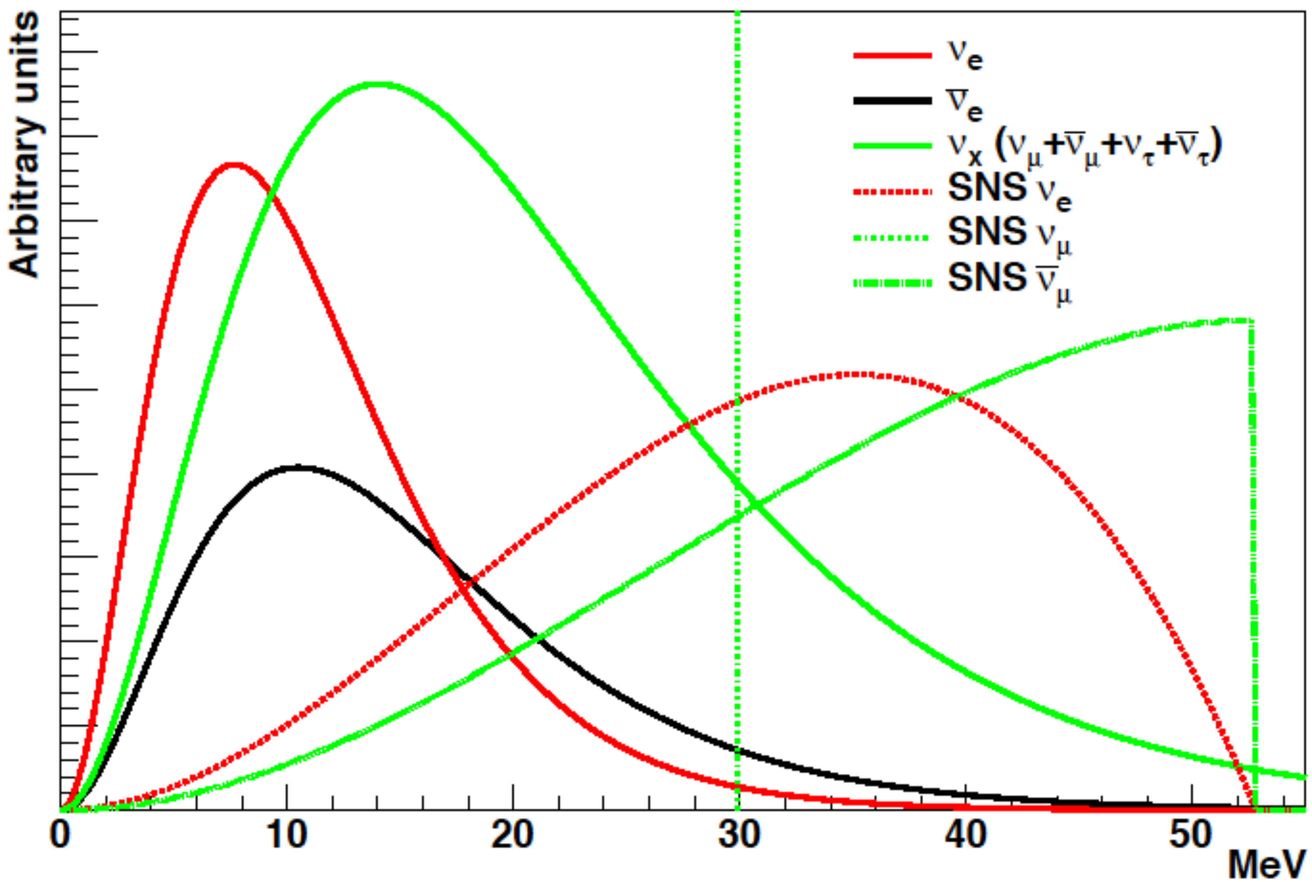


for "large" θ_{13} 1st oscillation maximum is dominated by atmospheric term

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

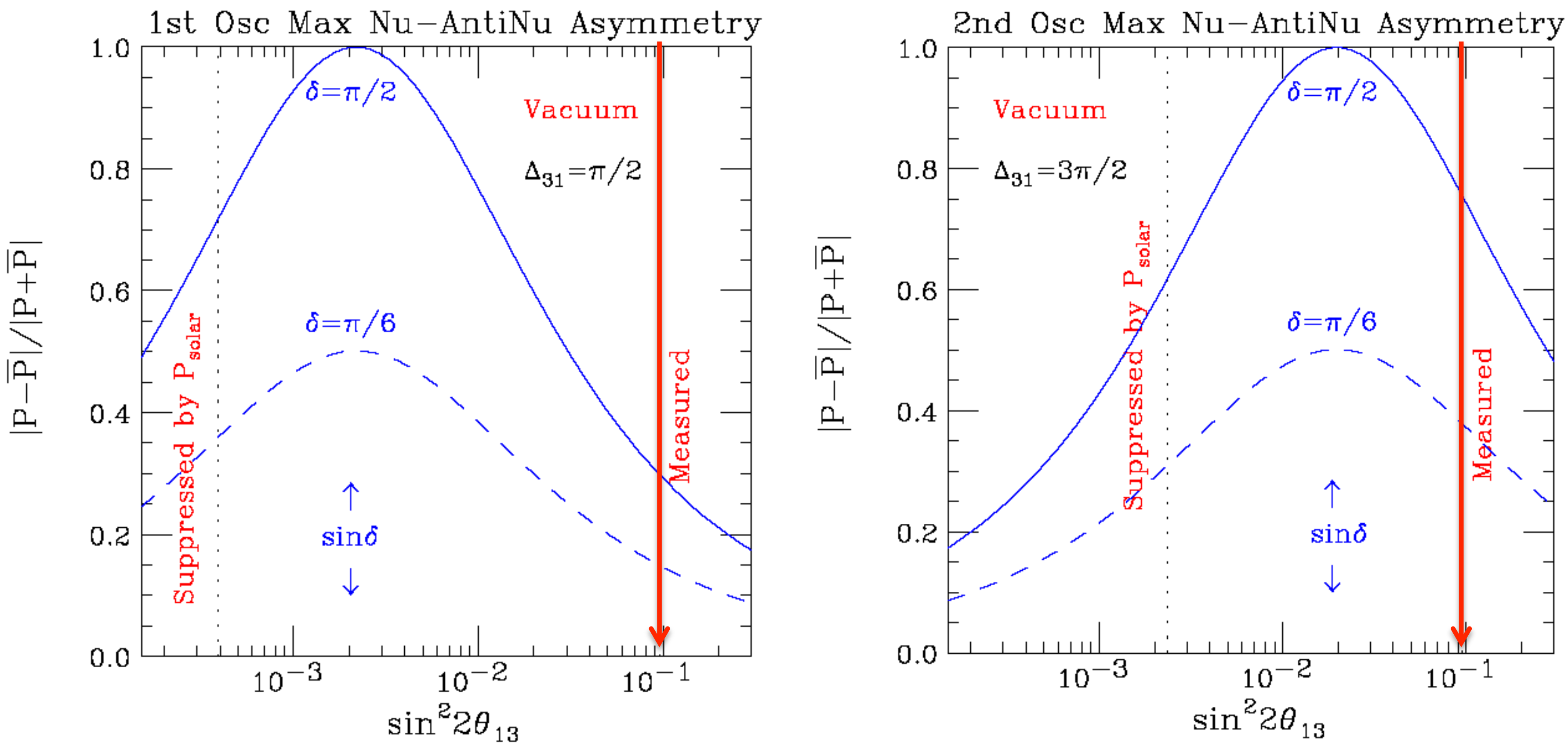
→ more sensitivity at 2nd oscillation max.
(see arXiv:1310.5992 and arXiv:0710.0554)

DAR experiments (ESS/SNS)



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

Neutrino Oscillations with "large" θ_{13}



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

2nd oscillation maximum is better

(see arXiv:1310.5992 and arXiv:0710.0554)

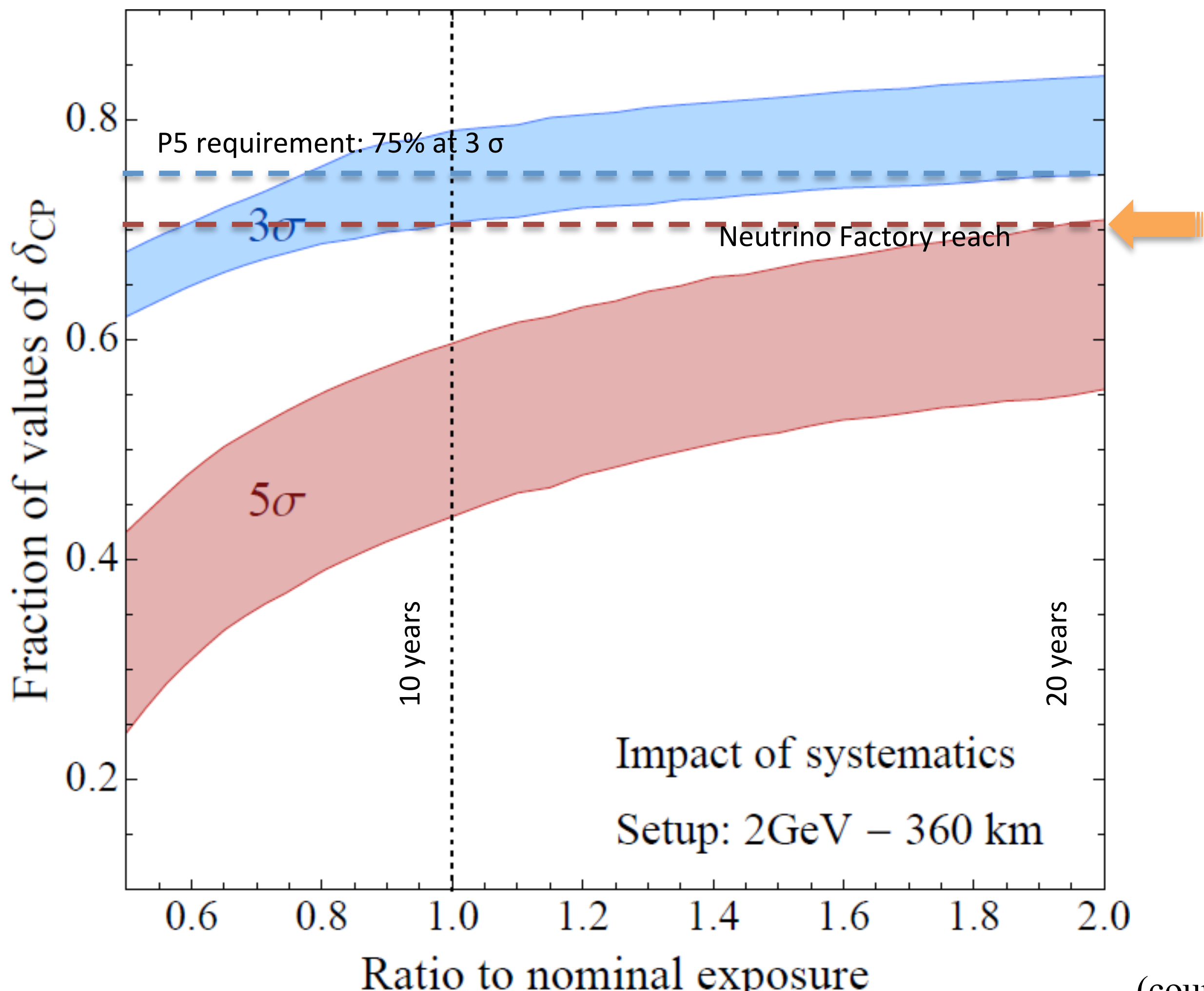
Systematic errors

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 × 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)



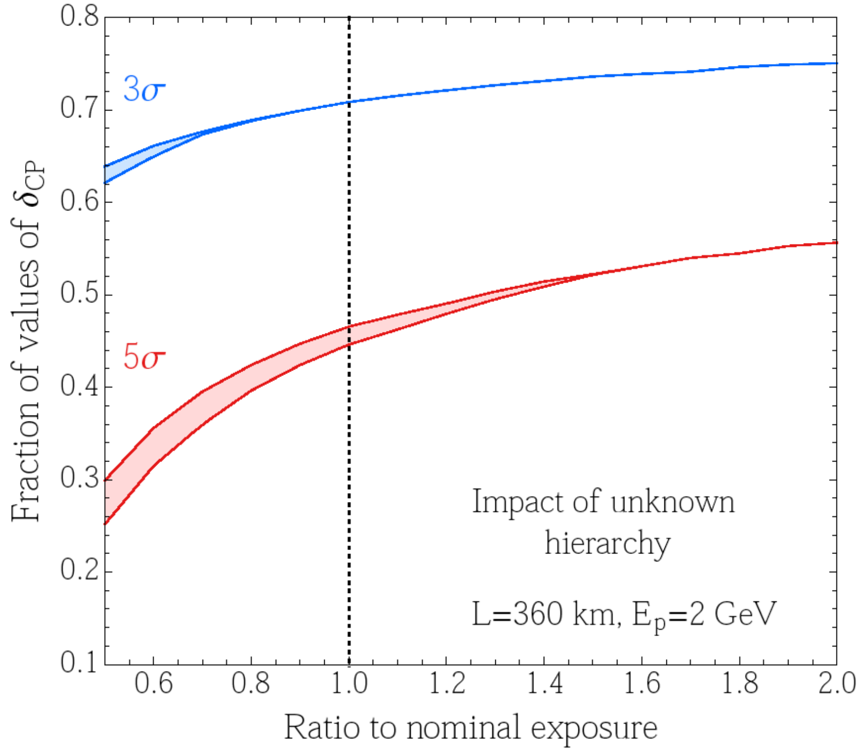
High potentiality

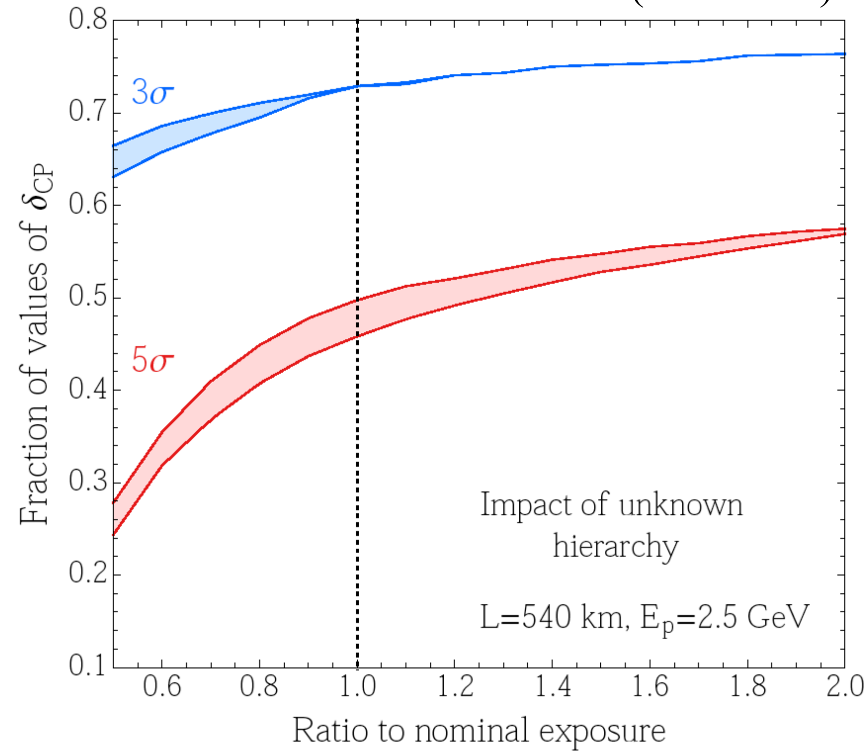
(courtesy P. Coloma)

Effect of the unknown MH on CPV performance

"default" case for systematics

(P. Coloma)

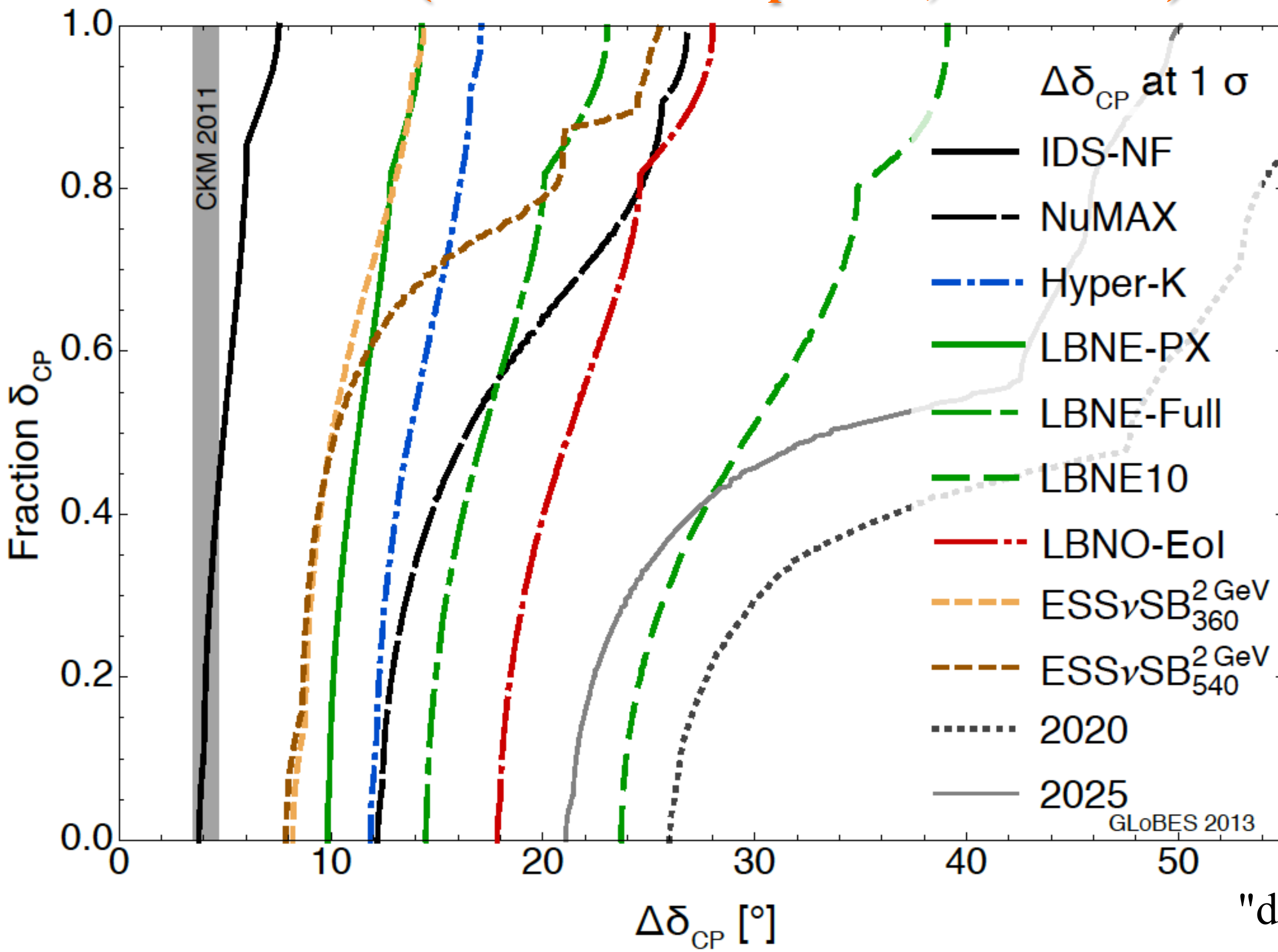




➡ small effect ➡ practically no need to re-optimize when MH will be known

δ_{CP} accuracy performance

(USA snowmass process, P. Coloma)



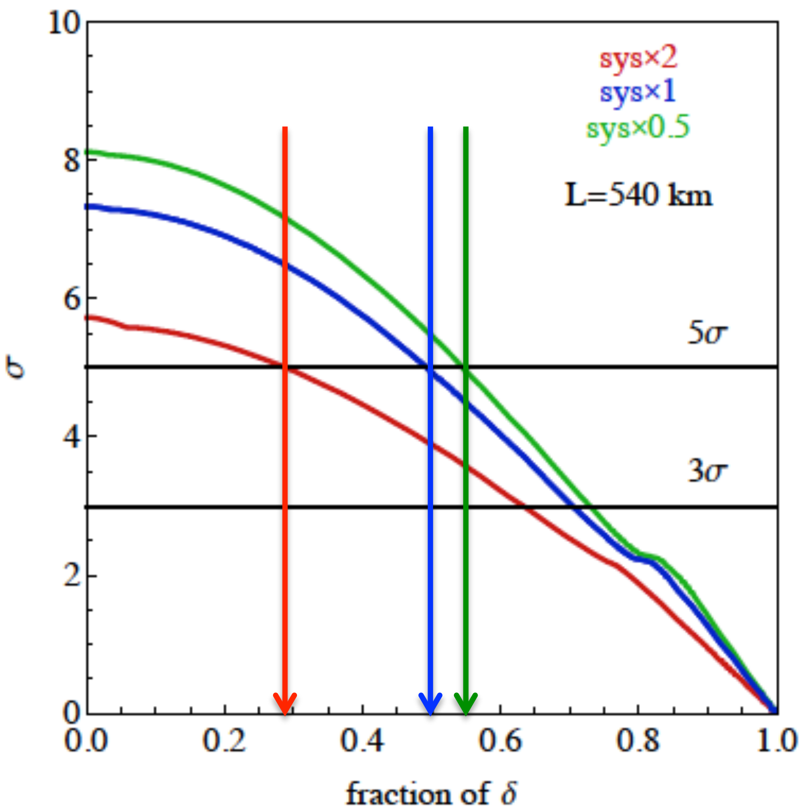
"default" column

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

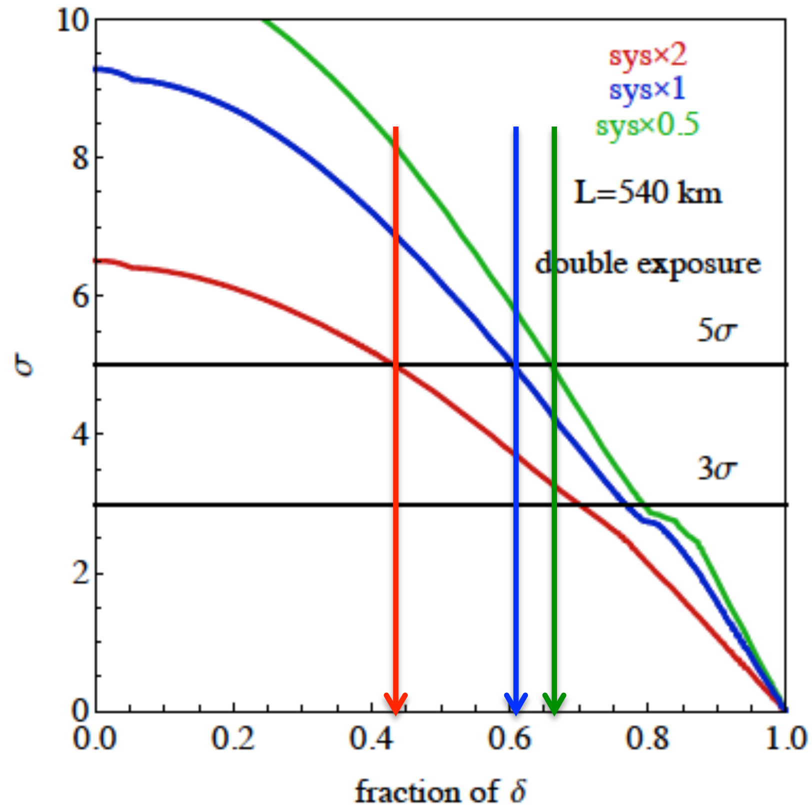
- Phys. Rev. D 87 (2013) 3, 033004 [arXiv:1209.5973 [hep-ph]]
- **arXiv:1310.4340 [hep-ex] Neutrino "snowmass" group conclusions**

δ_{CP} coverage

CPV (2 GeV protons)



after 10 years

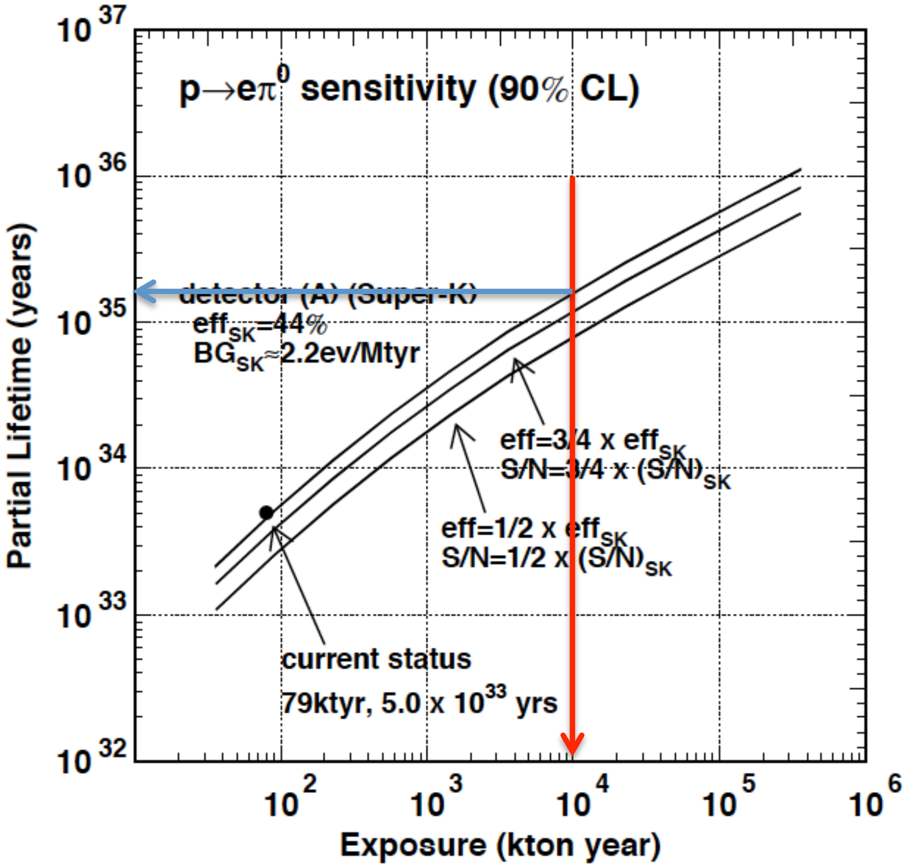


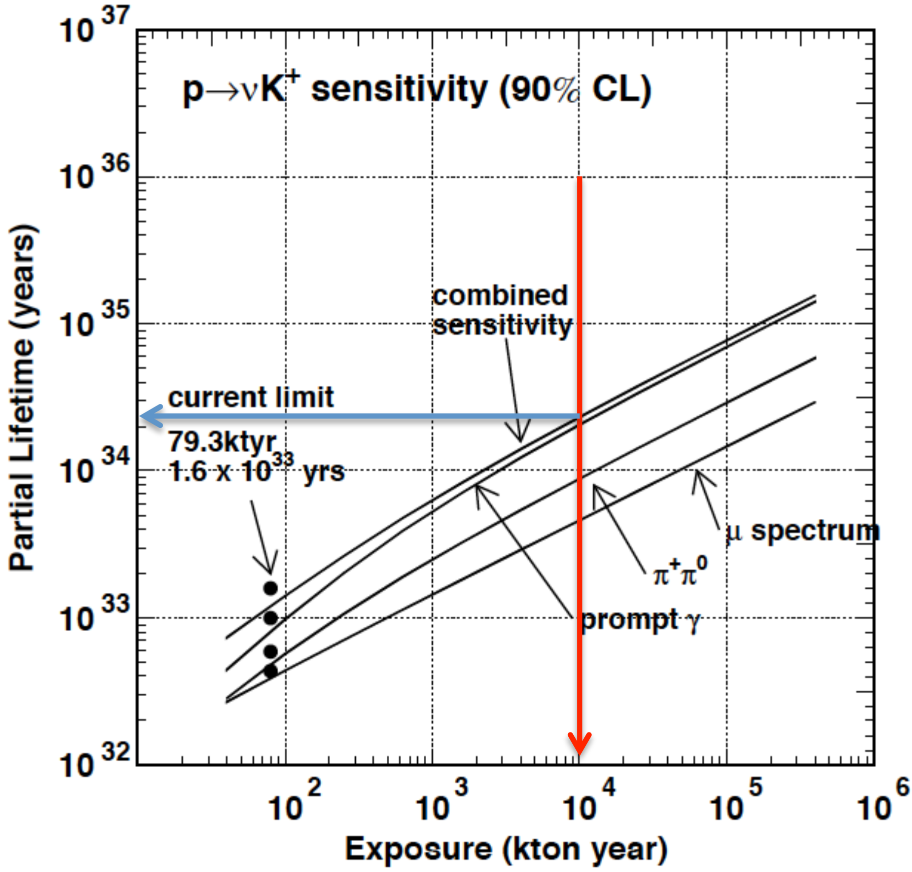
with 2 times more statistics

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

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

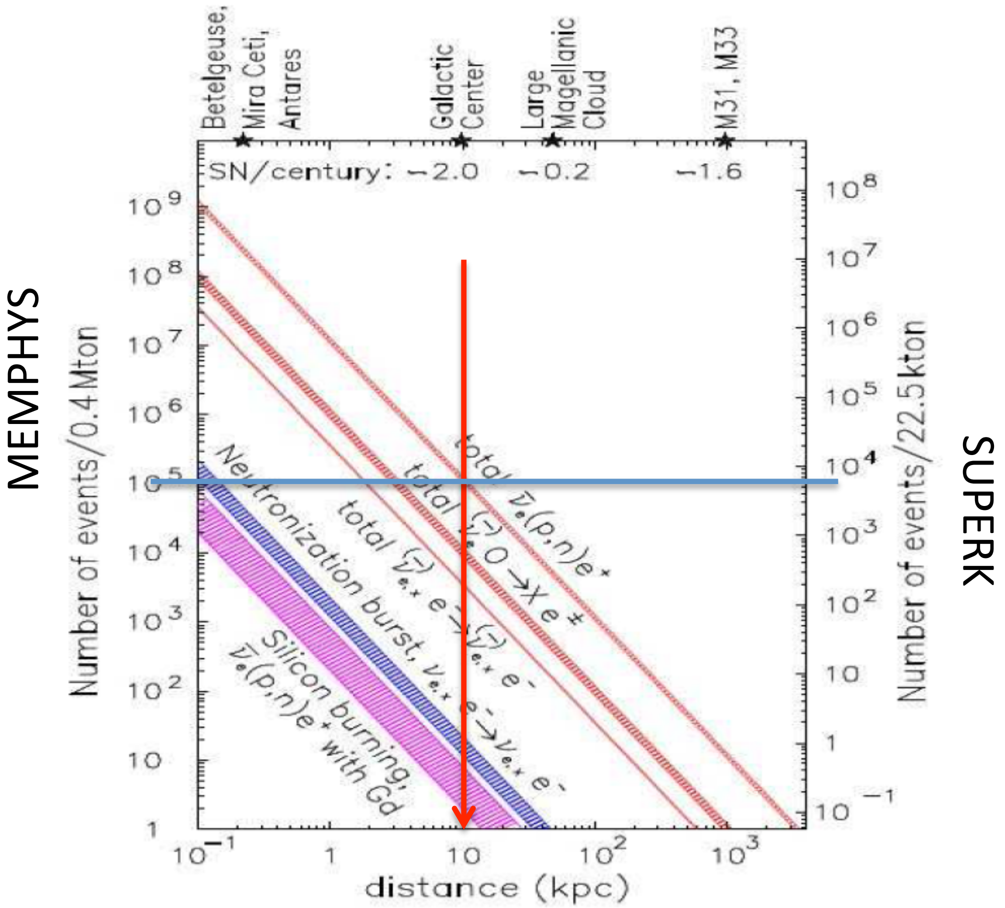
The MEMPHYS Detector (Proton decay)

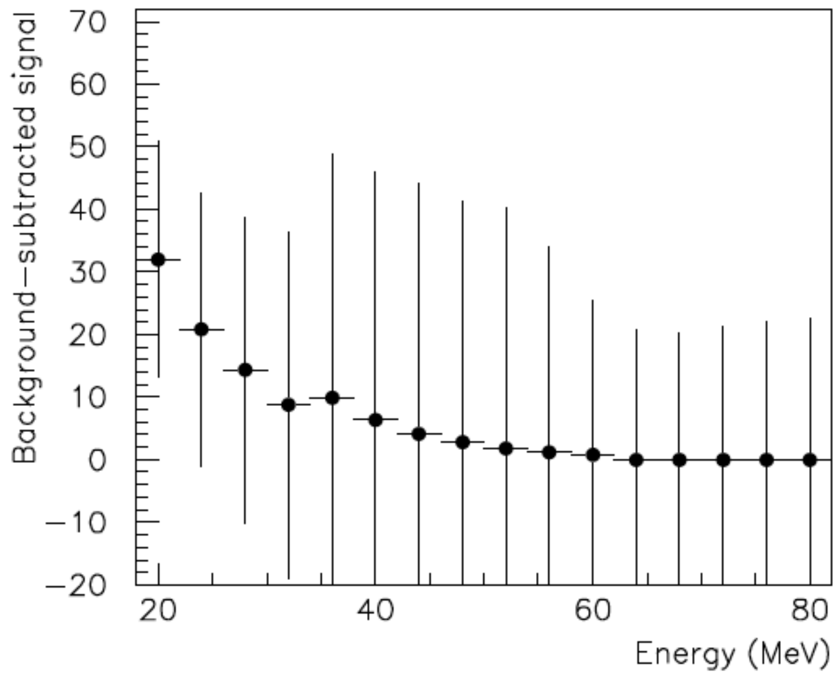




(arXiv: hep-ex/0607026)

The MEMPHYS Detector
(Supernova explosion)





Diffuse Supernova Neutrinos (10 years, 440 kt)

For 10 kpc: ~10^5 events