

High Intensity Frontier Initiative (HIFI) ν STORM and Neutrino Factory based on the ESS ν SB facility

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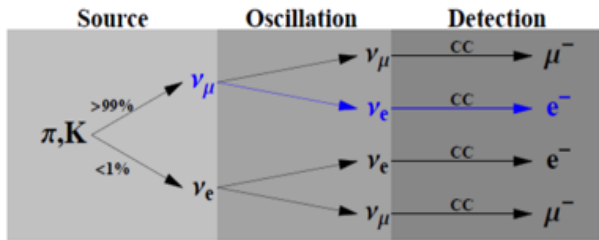
for the ESS ν SB/HIFI collaboration

<https://essnusb.eu/>



Funded by the Horizon 2020
Framework Programme of the
European Union

- Pions decay: The Long Base Line or ESSνSB approach**

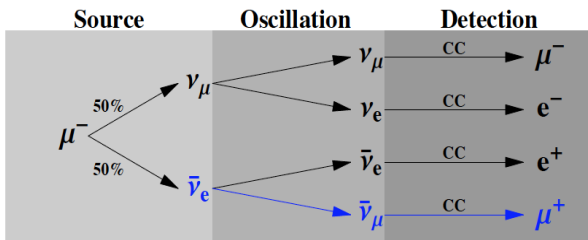
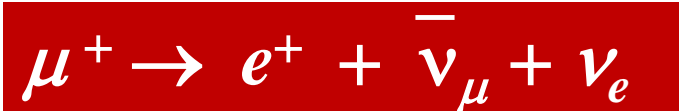


Neutrinos as secondary particles

Mainly: ν_μ and $\bar{\nu}_\mu$

Superbeams
 The only method in existing accelerator based facilities
 Contamination: $< 1\%$ of ν_e & $\bar{\nu}_e$

- Muons decay: Attractive ESSνSB evolution**



Neutrinos as tertiary particles
 Equal quantities of:
 $\nu_\mu, \nu_e, \bar{\nu}_\mu$ and $\bar{\nu}_e$

Multitude channels available
 Neutrino beam known $< \%$ level
 Clean muon detection
 More challenging (expensive)

Beauty of muon beams



Neutrinos as tertiary particles

Equal quantities of:

$\nu_\mu, \nu_e, \bar{\nu}_\mu$ and $\bar{\nu}_e$

Enable facilities at both:

- **High precision frontier (Neutrinos from muons decay)**
 - ✓ **Short Base Line (without acceleration and no cooling)**
 - In a channel (Moment approach)
 - In a storage ring (nuSTORM approach)
 - ✓ **Long Base Line (after acceleration and cooling)**
 - Neutrino Factory (decay in storage ring)
- **High energy frontier (Muon collisions before muon decay)**
 - ✓ **TeV class Lepton Collider**
 - in muon collider ring after acceleration & cooling

European Strategy for Particle Physics Update

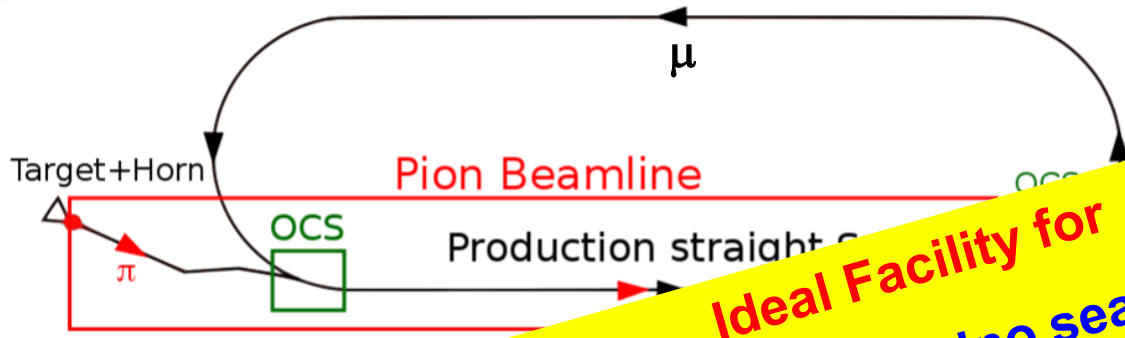
High-priority future initiatives

Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.

Major developments from the 2013 strategy

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

The design studies for next-generation long-baseline neutrino facilities should continue



Ideal Facility for Sterile Neutrino search
Neutrino cross sections measurements with unprecedented precision
LBL performance improvement by systematic error mitigation
 (Luis Alvarez, next presentation)



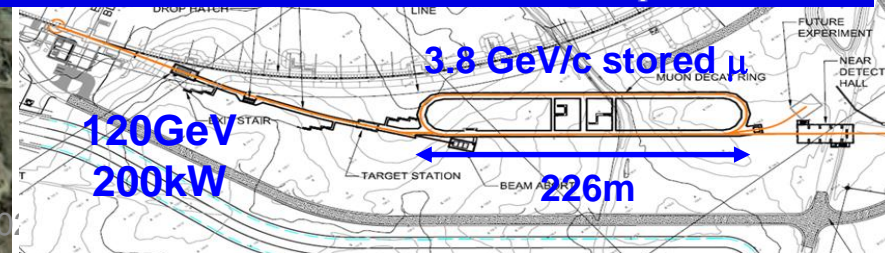
P.Huber
Virginia Tech

new luminosity muon storage ring. With $1.7 \times 10^{18} \mu^+$ stored, the following oscillated event numbers

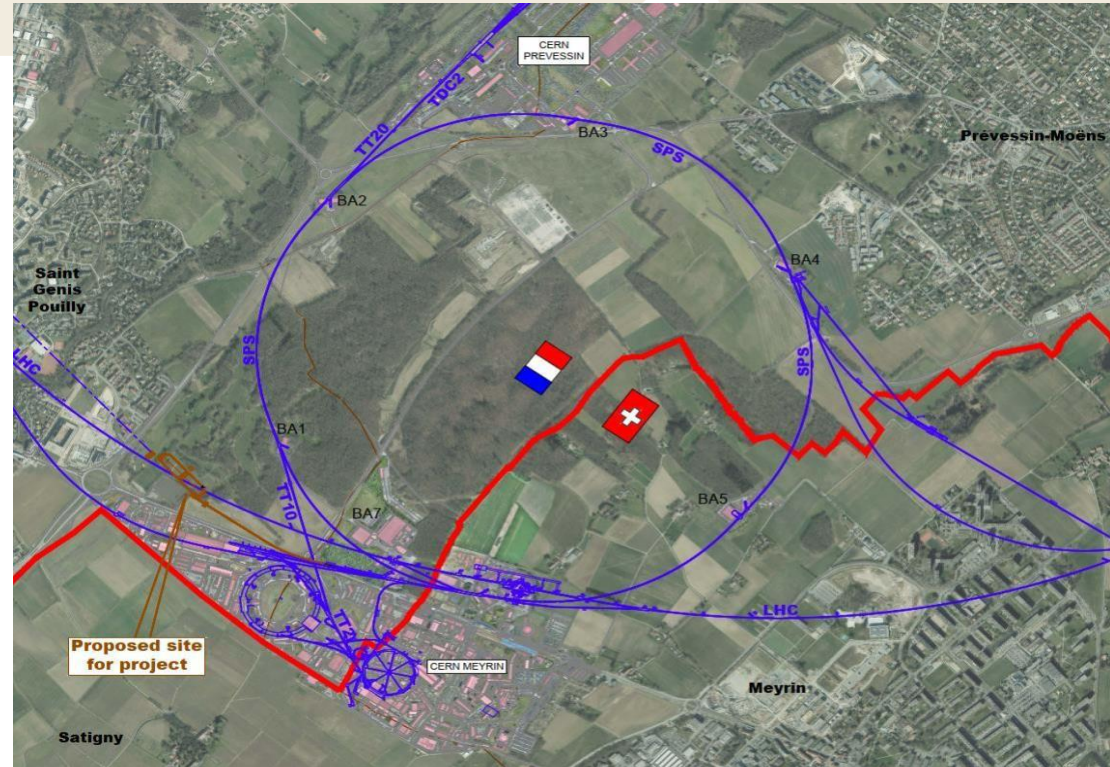
$\nu_e \rightarrow \nu_\mu$ CC	330
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ NC	47000
$\nu_e \rightarrow \nu_e$ NC	74000
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ CC	122000
$\nu_e \rightarrow \nu_e$ CC	217000

and each of these channels has a more than 10σ difference from no oscillations

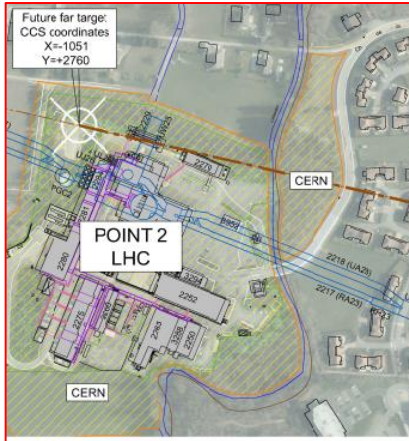
With more than 200 000 ν_e CC events a %-level ν_e cross section measurement should be possible



- Investigated as part of Physics Beyond Colliders
- 100 GeV/250kW H⁺ from SPS
- Muons up to 6.5 GeV/c
- Far detector at LHC point 2 (1.75 km) + near detector
- Feasibility studies done for integration, civil engineering and radiation protection

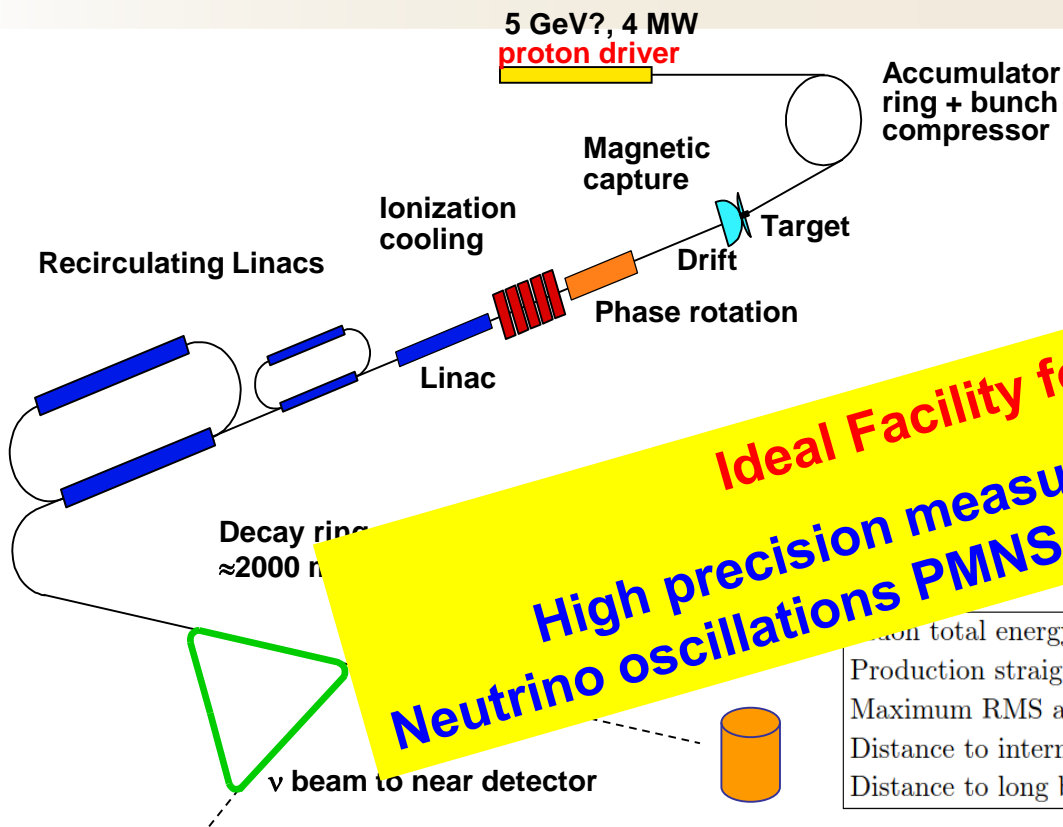


Channel	Oscillation	$N_{osc.}$	N_{null}	$\sigma_{osc.}$
ν_μ Appearance	$\nu_e \rightarrow \nu_\mu$ CC	332	0	18.2
$\bar{\nu}_\mu$ Disappearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ CC	122322	128433	-12.2
ν_e Disappearance	$\nu_e \rightarrow \nu_e$ CC	216657	230766	-21.1
NC Disappearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ NC	47679	50073	-7.7
NC Disappearance	$\nu_e \rightarrow \nu_e$ NC	73941	78805	-12.4



Long Base Line Neutrinos from Stored Muons decay

The Neutrino Factory approach



Muons decay in high energy neutrinos after μ acceleration and circulation in rings

Requires bunching and (some) ionization cooling to match the resonances to the resonances
 (some) by linacs
 (some) and/or recirculating)

Ideal Facility for High precision measurements of Neutrino oscillations PMNS matrix parameters

	Value
muon total energy	25 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to intermediate baseline detector	2 500–5 000 km
Distance to long baseline detector	7 000–8 000 km

magnetized detector needed

$10^{21} \nu_e$ or ν_μ to detectors per year

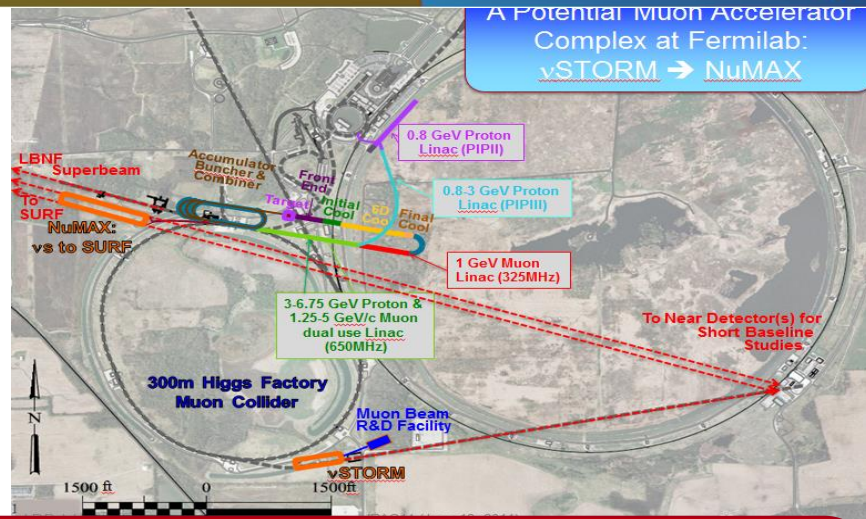
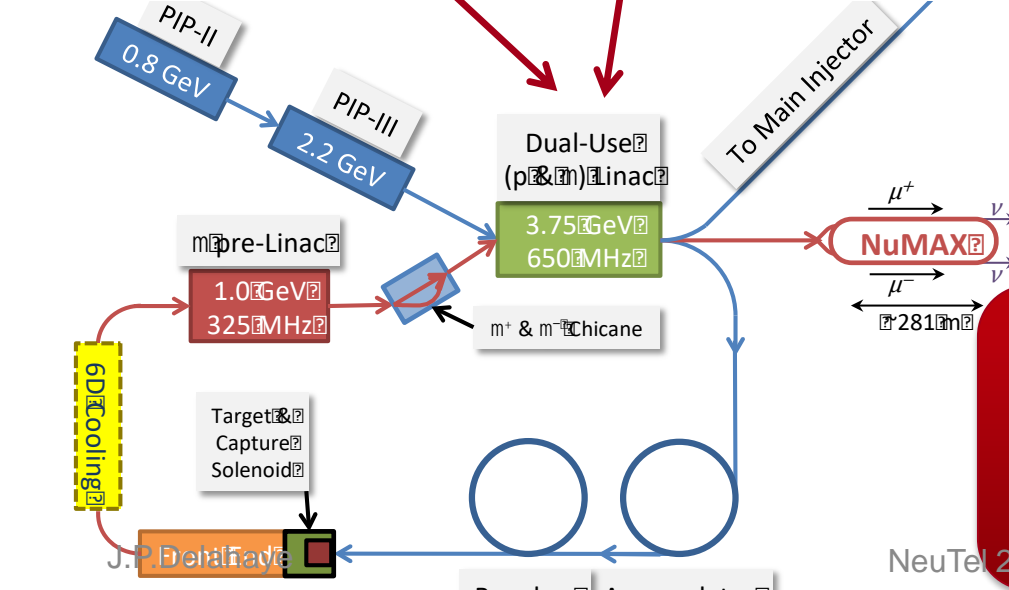
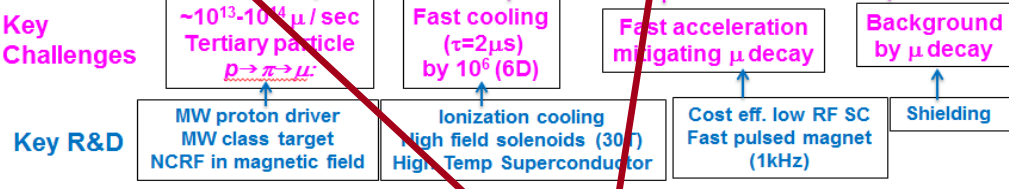
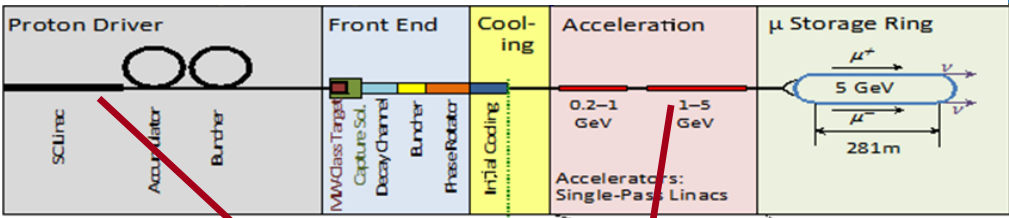
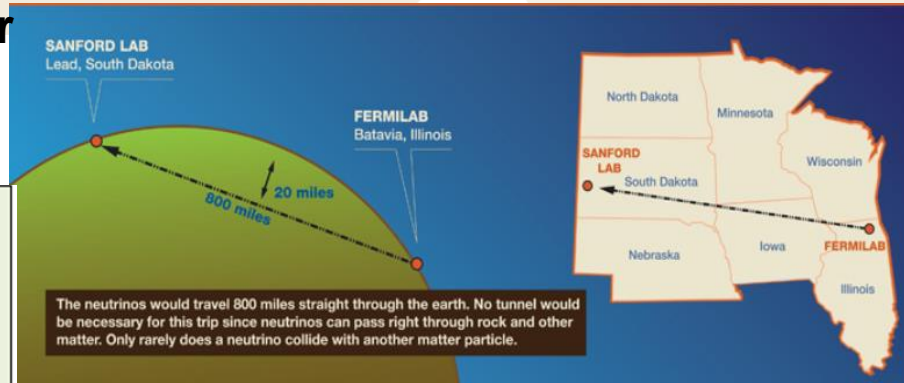
International Design Study (IDS-NF): “Generic” design (not site-specific)
 10 GeV muon storage ring optimized for 1500-2500km baselines

<https://www.ids-nf.org/wiki/FrontPage>



A site specific study: FNAL to SURF NuMAX (Neutrinos from Muon Accelerator Complex)

5GeV staged Neutrino Factory optimized for a far detector at SURF 1300kms from FNAL (arXiv:1803.07431)



NuMAX Staging:

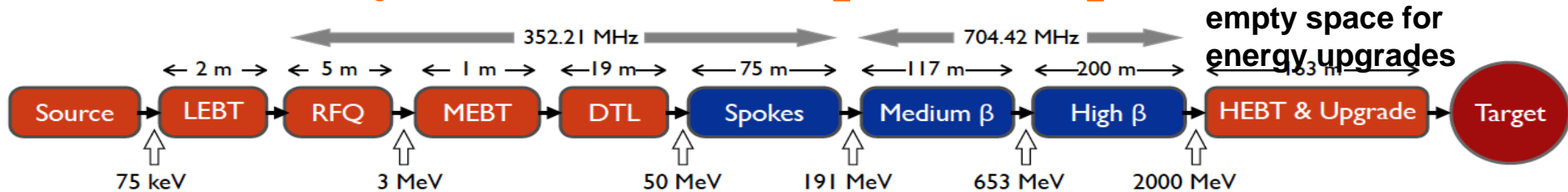
- **Commissioning**
- **NuMAX+**
- 1MW Target
- No Cooling
- 10kT Detector
- 2.75 MW Target
- 6D Cooling
- 34kT Detector



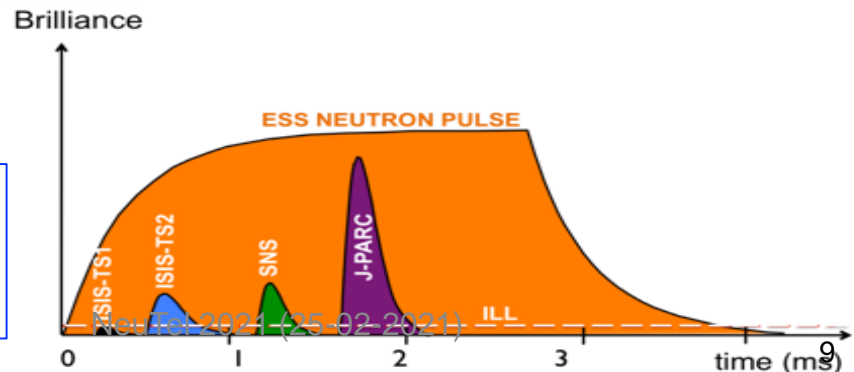
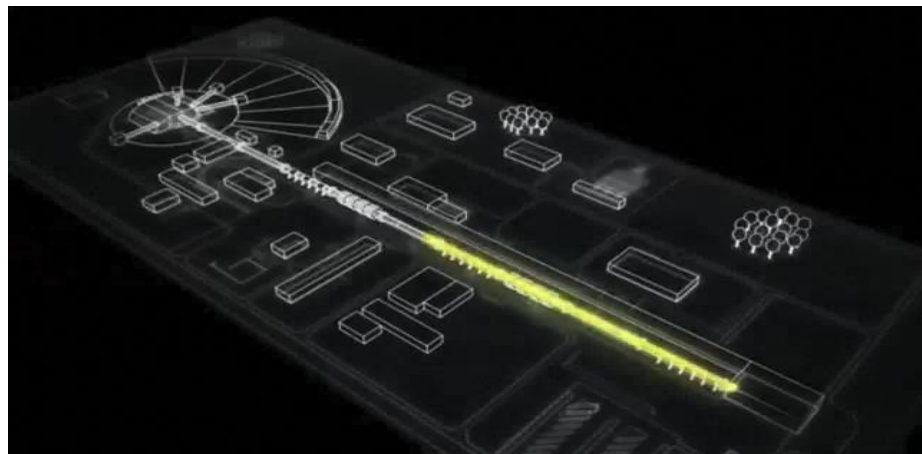
European Spallation Source under construction in Sweden



Driven by the world most powerful 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 (upgradable to 3.5 GeV)
- $>2.7 \times 10^{23}$ p.o.t/year.



**Linac ready by 2023
providing attractive opportunities**

Extending ESS to a neutrino facility

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: **5MW → 10 MW**
(14→28 Hz rep rate, 4→8% duty cycle)
- Accumulator (C~400 m) to compress to few μ s the 2.86 ms proton pulses
H⁻ source (instead of protons)
- Short pulses (~ μ s) will also allow experiments (as those proposed for SNS) using the neutron beam
- **~400 MeV neutrinos.**
- Target station (studied in EUROv).
- Underground detector (studied in LAGUNA).

Great synergies providing considerable cost savings



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

<http://essnusb.eu/>

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

Design of a second generation long base line neutrino for CP violation observation with high sensitivity at 2nd oscillation maximum

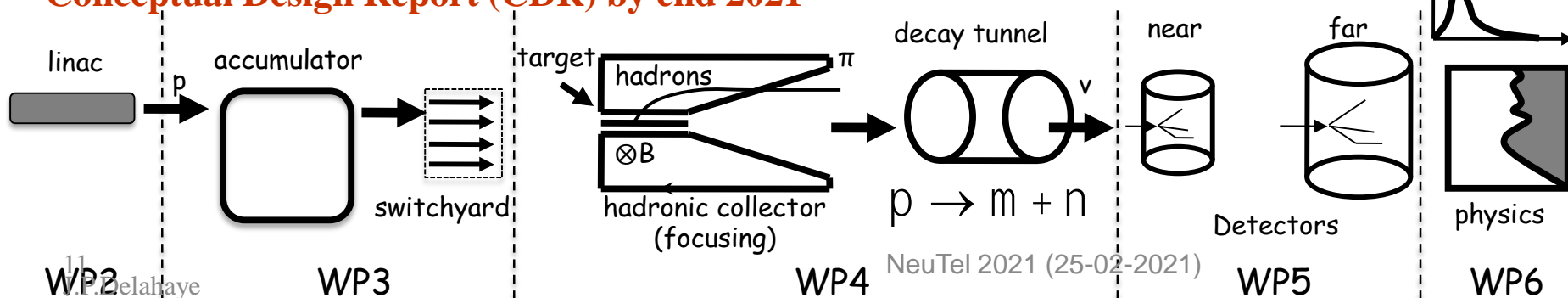
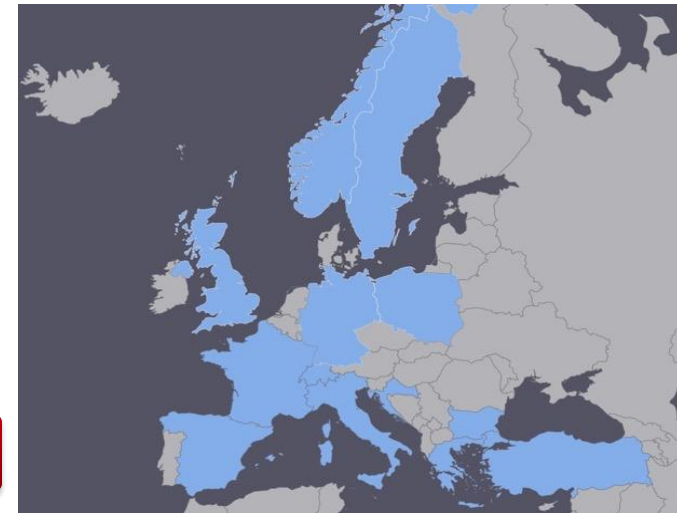
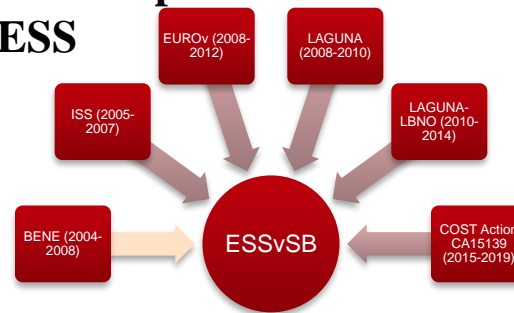
- Total cost: 4.7 M€, EU budget: 3 M€, over 4 years**

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

- 6 Work Packages

- Approved end of August 2017**

- Conceptual Design Report (CDR) by end 2021**





ESSνSB future upgrade

High Intensity Frontier Initiative (HIFI @ ESS)

HIFI @ ESS design study of the possible future implementation in a staged approach of ESSνSB, nuSTORM and Neutrino Factory on the ESS campus

- Taking advantage of the, thus existing, ESS 2 GeV/5 MW world most powerful linac
- Including parameters, performances, R&D to address major feasibility and cost issues
- Building up on the excellent work and progress already achieved in the frame of the IDS-NF, Muon Accelerator Program (MAP) and CERN Beyond Collider Physics.

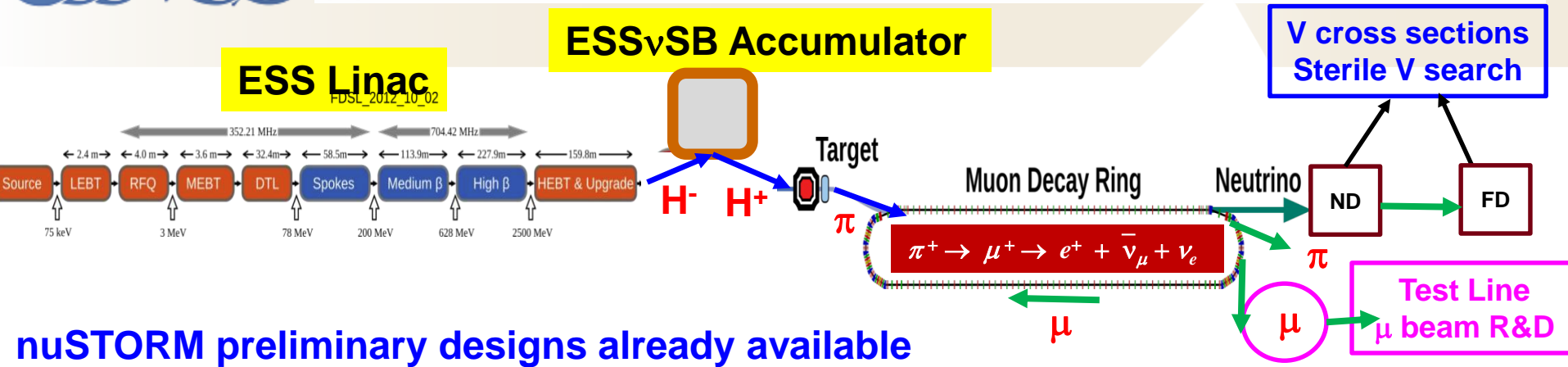
Applying for EU support as Research Infrastructure Concept Development

- 3M€ over 4 years (2022-2025)

Launch of an ESSνSB-HIFI collaboration (presently participating 70 physicists from 24 institutes) extended from existing ESSnuSB collaboration aiming by 2025 at:

- ESSνSB Technical Design Report (TDR)
- ESS-NuSTORM and ESS-Neutrino Factory Preliminary Conceptual Designs

A unique opportunity not to be missed



nuSTORM preliminary designs already available

Driven by FNAL-MI at 120GeV/0.2MW or CERN-SPS at 100GeV/0.25MW

Adaptation to the ESS 2 GeV / 5 MW proton beam

Inspired from IDS & MAP Neutrino Factory driven by 8GeV/4 MW proton beam

Adaptation of the pions production target

Optimisation and characteristics of the muon and neutrino beams

With shorter μ lifetime and lower ν energy (300 MeV)

Lower energy & smaller size (and cost) of the Accumulator & Muon Decay Ring

Physics and Detector optimisation

for precise ν cross section measurements and Sterile ν search

No critical feasibility issues but large acceptances

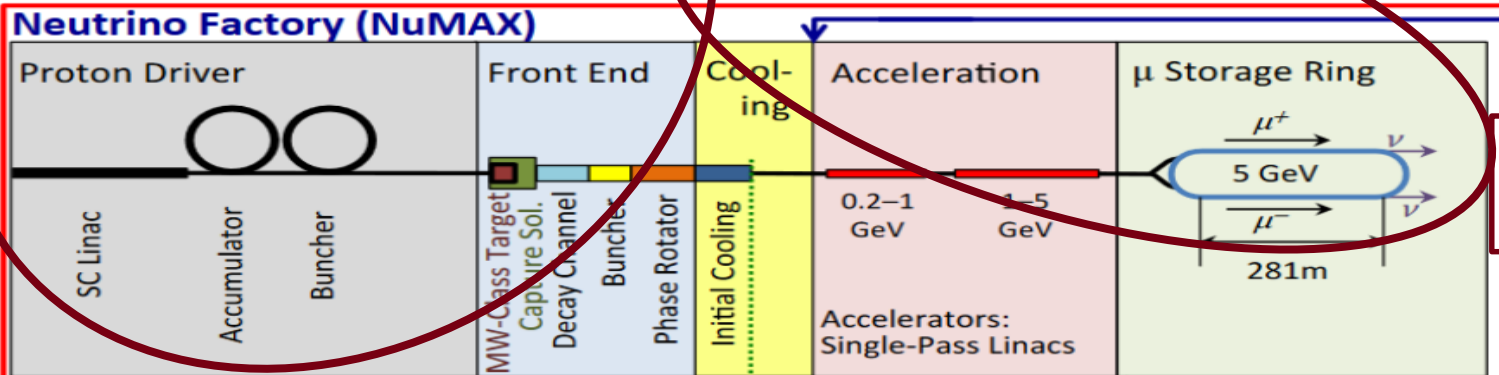
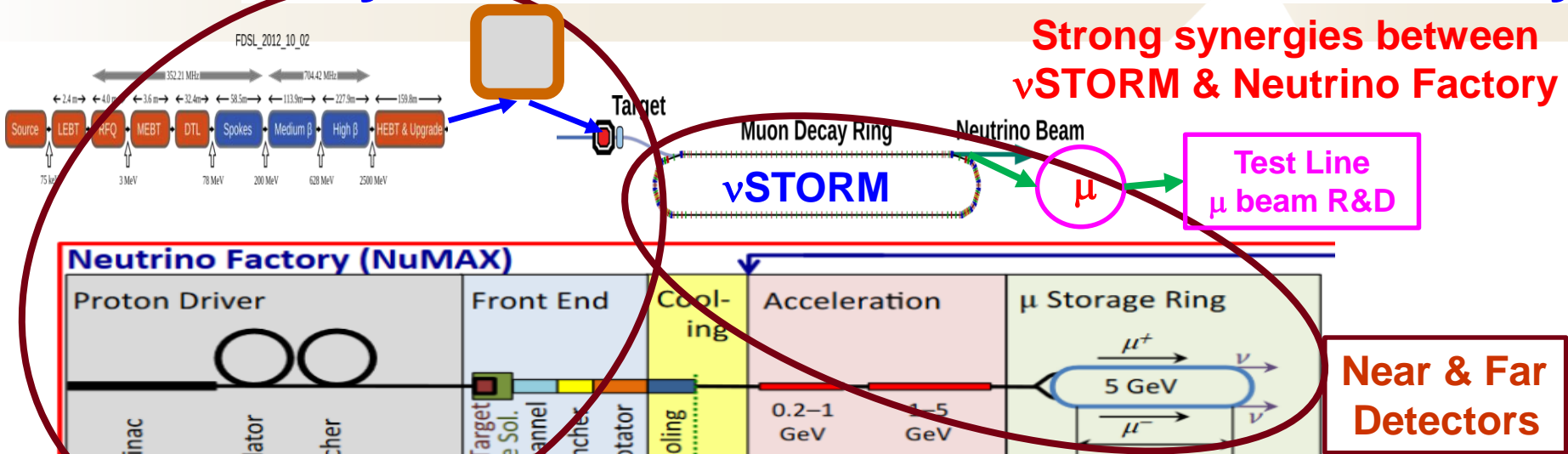
Performance optimisation & cost mitigation R&D

Ideal Test Bed for Muon Science Development, Test & Demonstration

Neutrino Factory @ ESS

Key issues and R&D to address feasibility

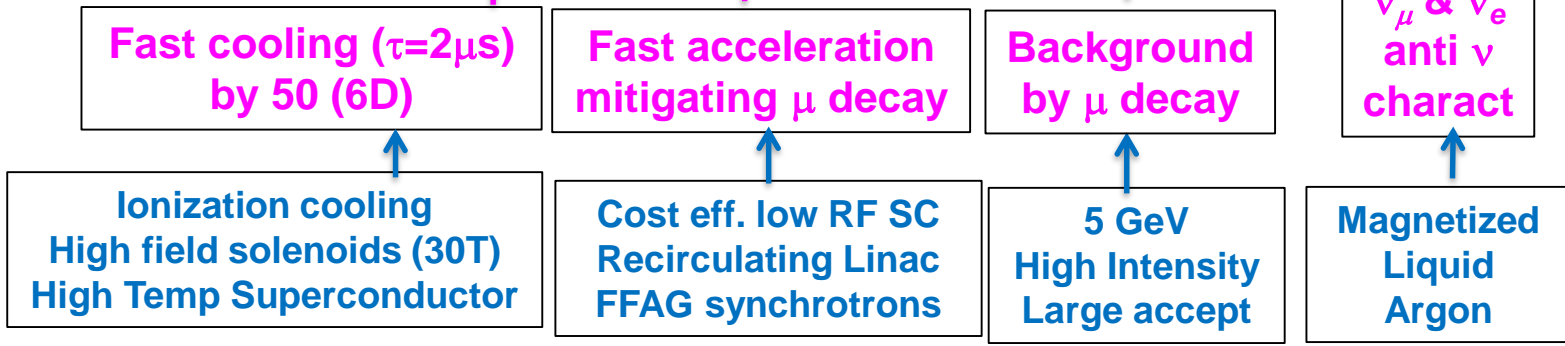
Strong synergies between ν STORM & Neutrino Factory



Near & Far Detectors

Key Additional Challenges

Key R&D



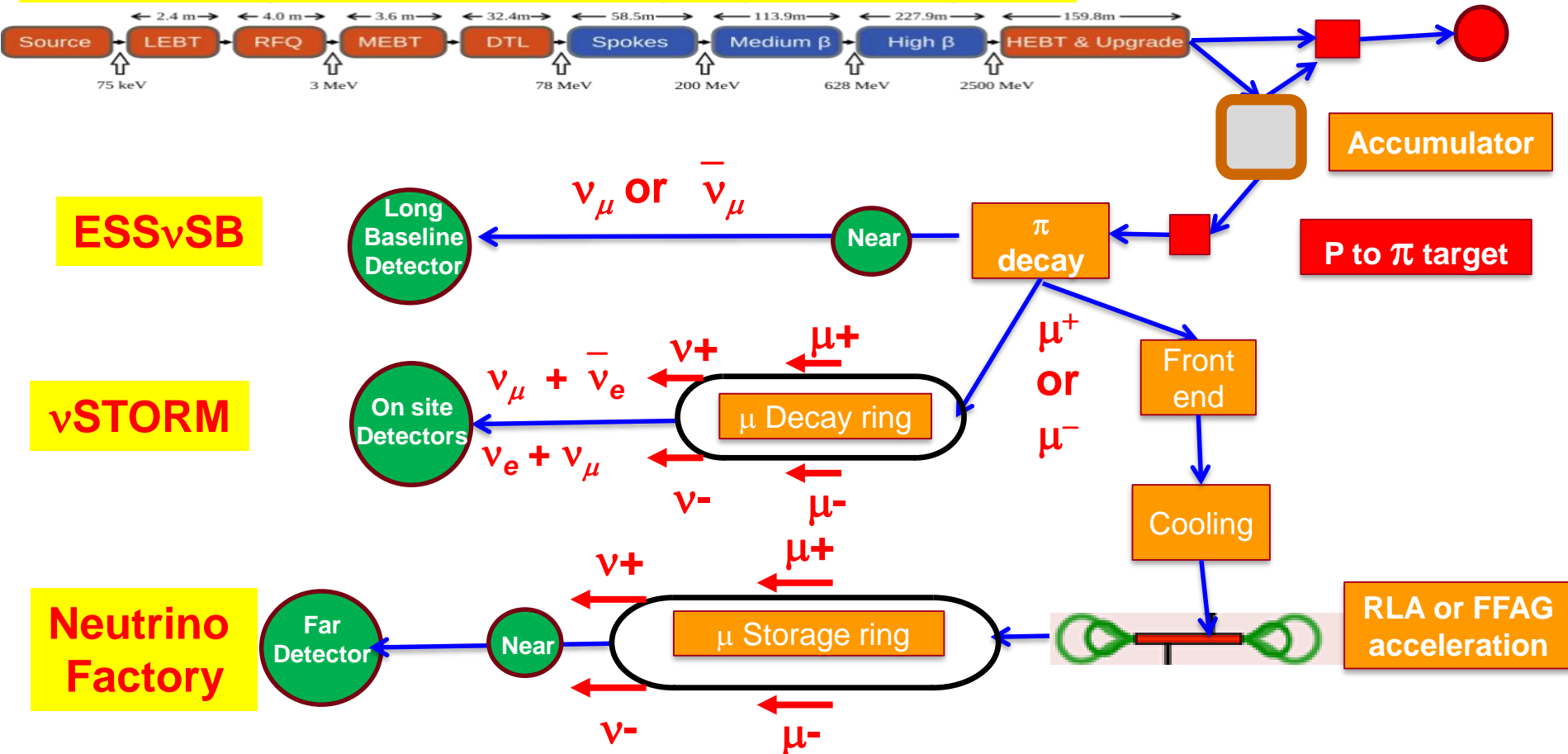
Taking advantage of the excellent work & progress in the frame of IDS-NF & MAP

vSTORM ideal for R&D & test of muon beam science & technology

HIFI @ ESS, Staged Approach

ESS → ESS_{vSB} → ν STORM → Neutrino Fact

ESS upgraded Linac 2GeV / (5MW H⁺ & 5MW H⁻)

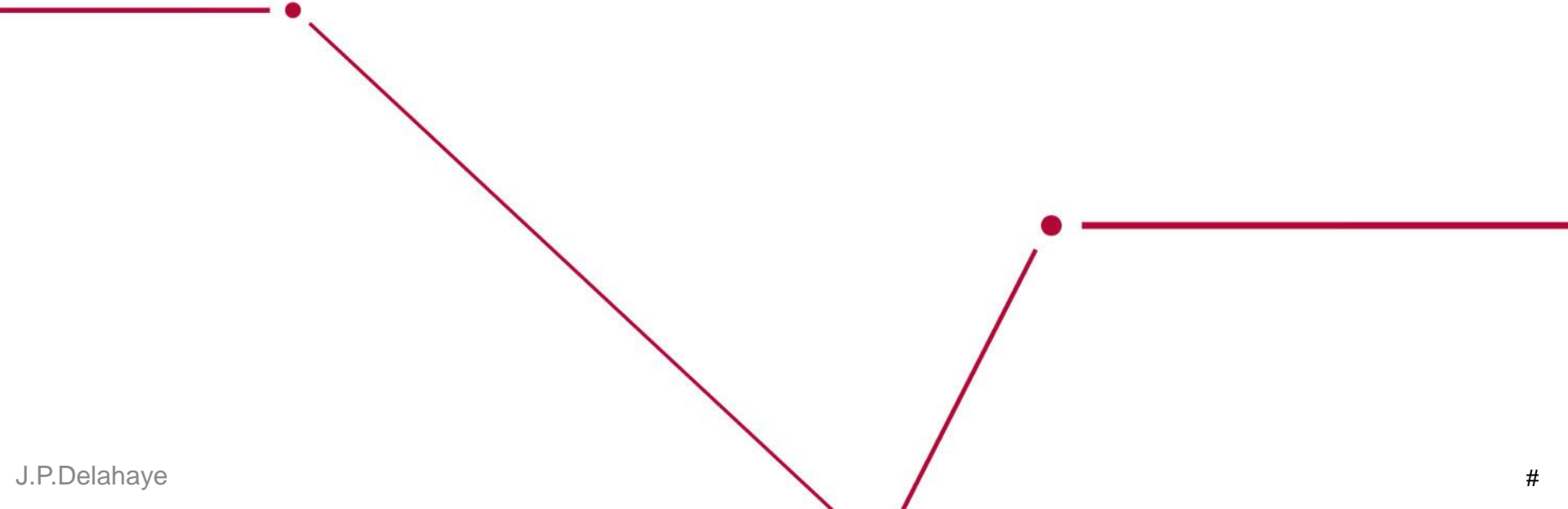


Conclusion

- The ESS facility provides a unique opportunity (not to be missed) for a range (or a selection) of top level muon-based facilities with great synergies, to be considered in a staged approach on the ESS site, complementing the Neutron Source presently being built.
- A novel ESSvSB / HIFI collaboration is being launched, hopefully with EU support aiming, by 2025, at:
 - Technical Design of the world most intense, second generation long base line neutrino facility, ESSvSB, for CP violation observation with high sensitivity at 2nd oscillation maximum.
 - Preliminary Conceptual designs of a short baseline facility for neutrino cross section measurements with unprecedented precision and of a NEUTRINO FACTORY for measurement of NS matrix parameters
- These facilities will be able to take advantage of the, then existing, ESS world most powerful proton driver thus providing substantial cost savings. Their designs would benefit from the excellent work and progress already made during many years in the frame of IDS-NF, MAP and PBC
- Performing μ beams would be available to test beds of Muon Beam Science & Technology for even more ambitious μ -based facilities in the future.

All Interested Welcome

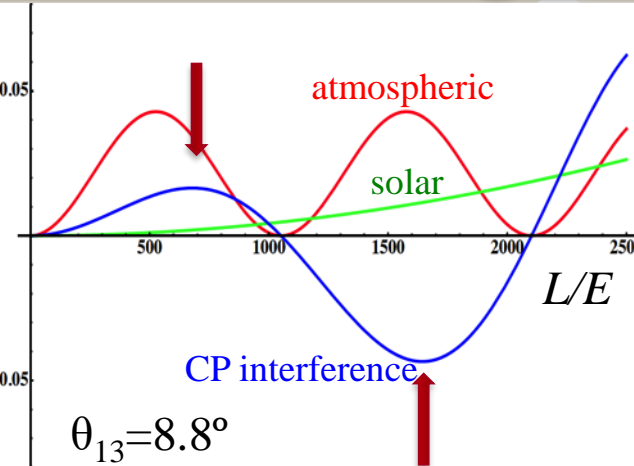
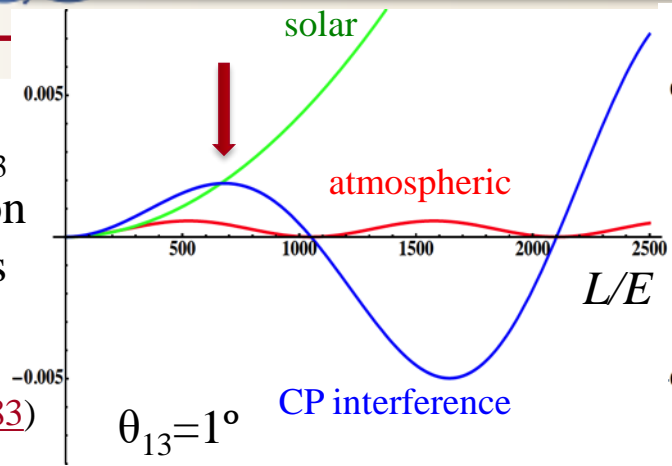
Back-up slides



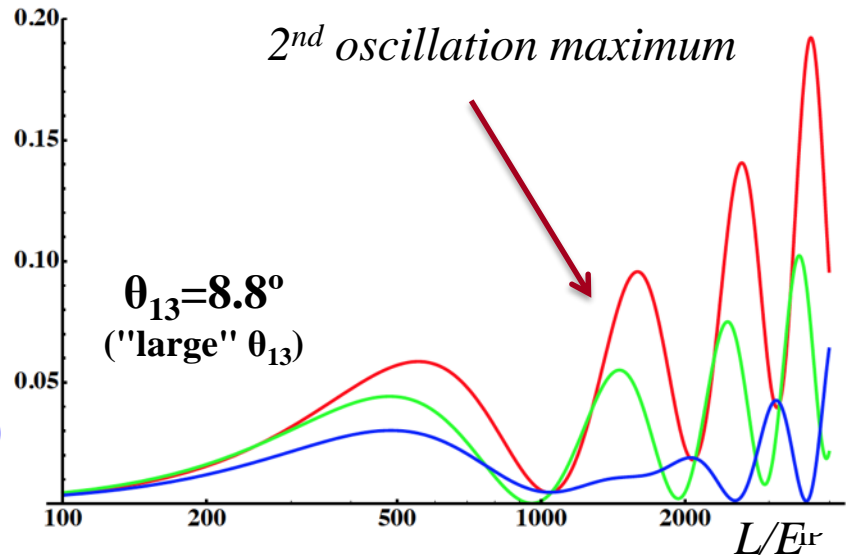
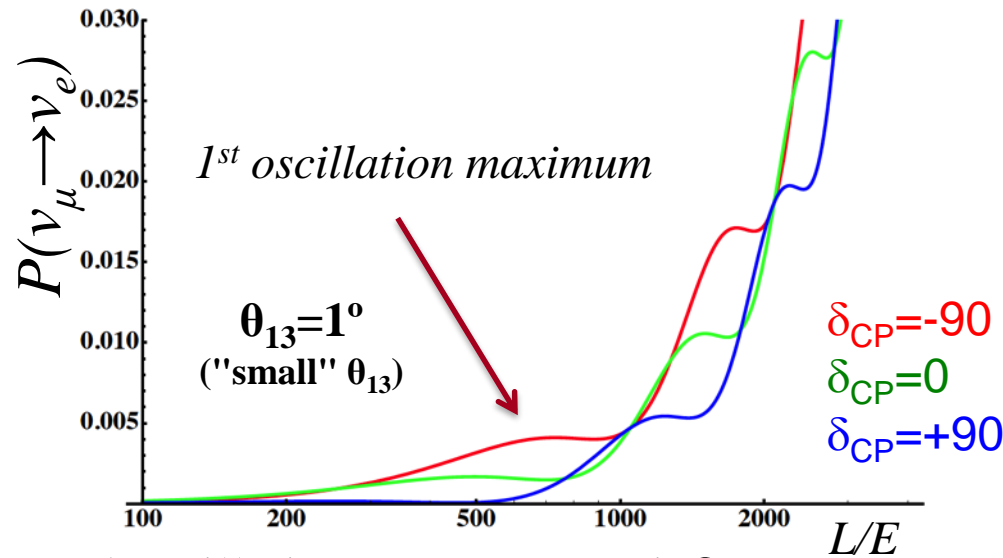
Neutrino Oscillations with "large" θ_{13}

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

(arXiv:1110.4583)



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

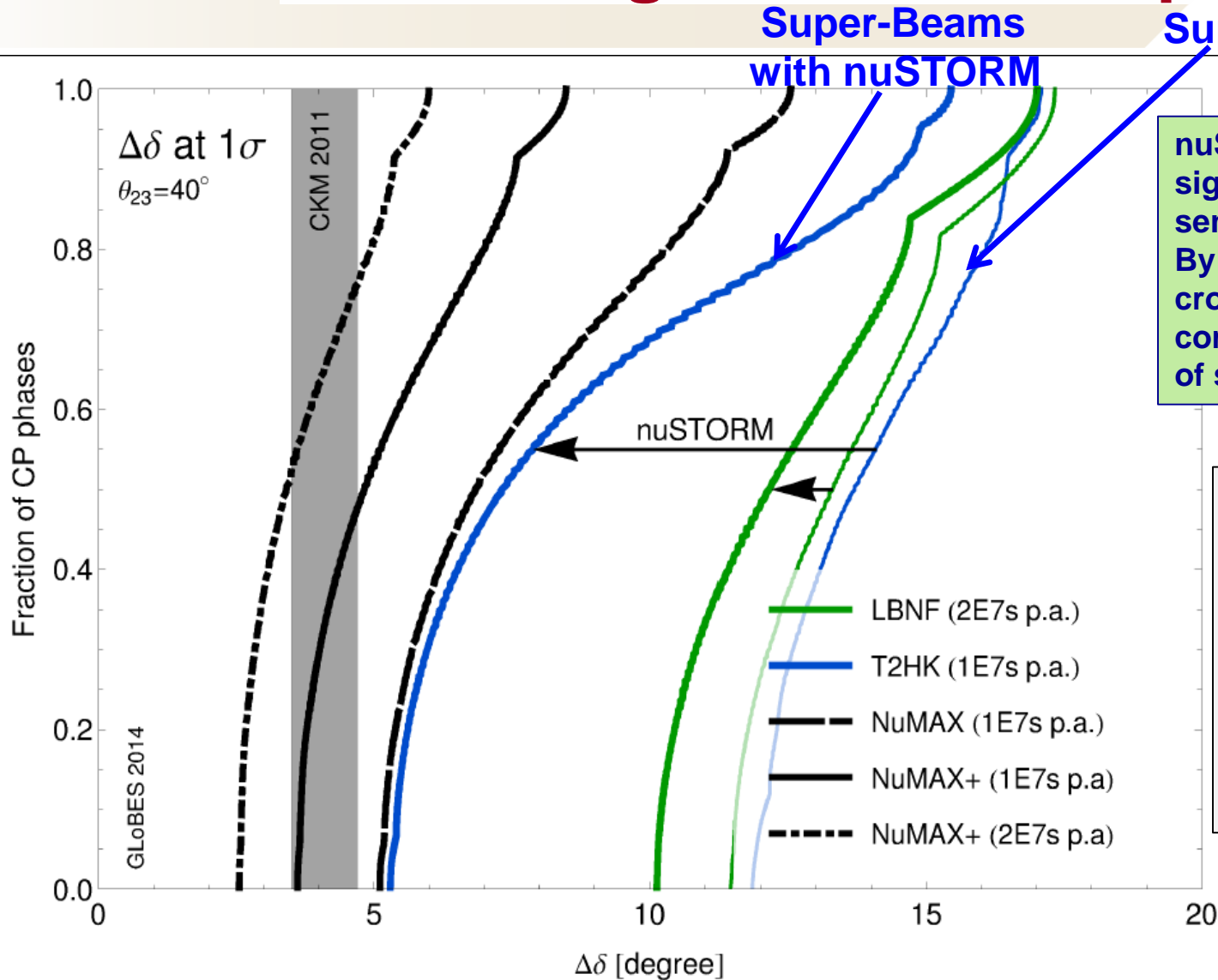


- 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$



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

Leverage potential by nuSTORM for Long Baseline ν Experiments



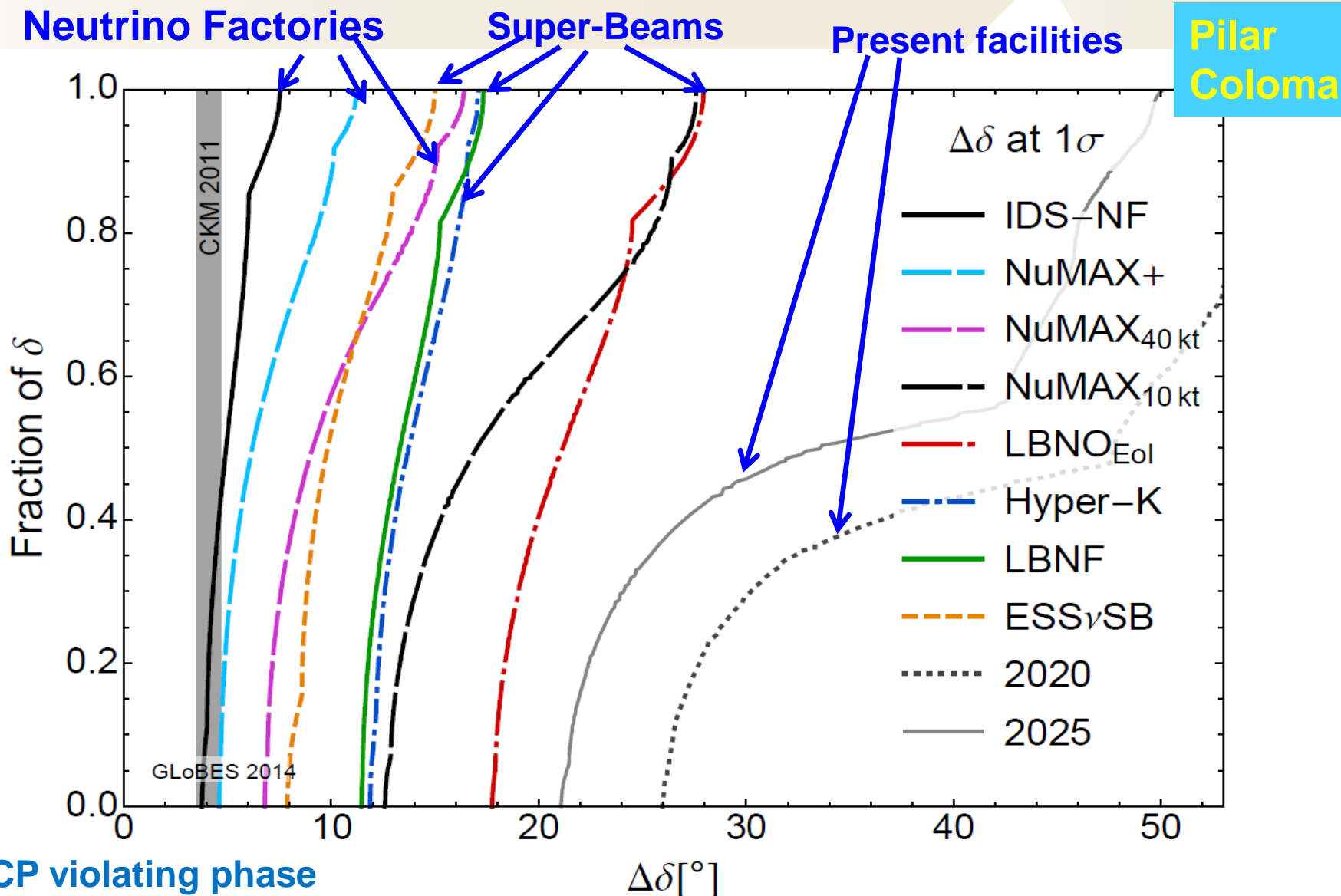
nuSTORM + LBL offers significantly improved sensitivity vs LBL alone. By higher precision of ν cross sections and corresponding reduction of systematic errors.

GLoBES comparison of potential performance of the various Advanced Concepts

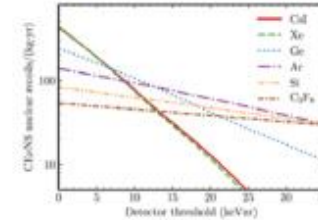
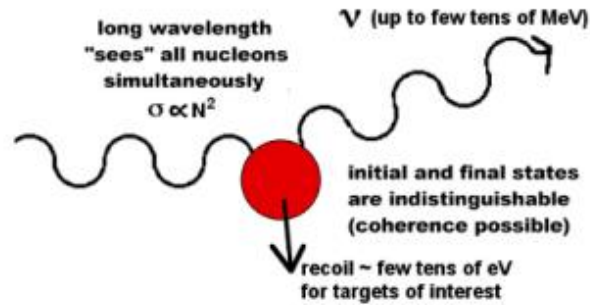
P. Coloma
P. Huber

Physics reach of various technologies

A large improvement potential



Coherent ν -N scattering



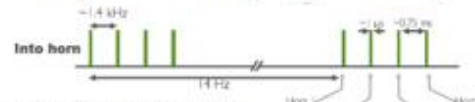
0-20 kg

~10 keV detector threshold

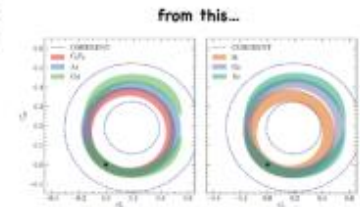
Taking it to the next level: ESSvSB

ESSvSB pulse compression brings:

- background drops with duty factor by x70
- timing information (prompt vs. delayed ν 's)



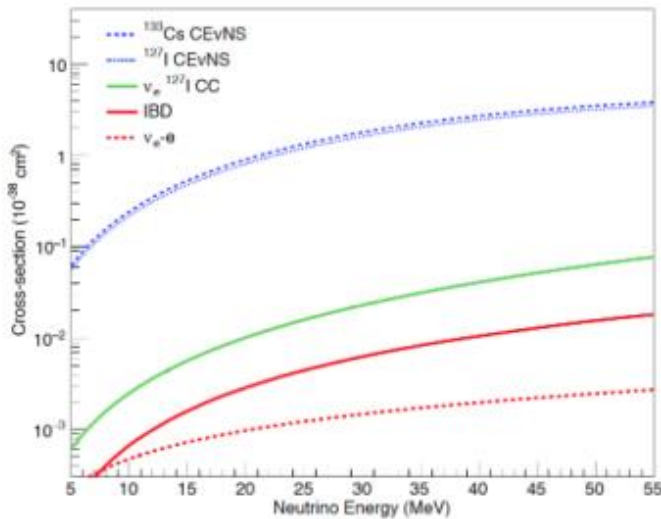
Talks by Dracos & Gáinader @ <https://indico.cern.ch/event/849674>



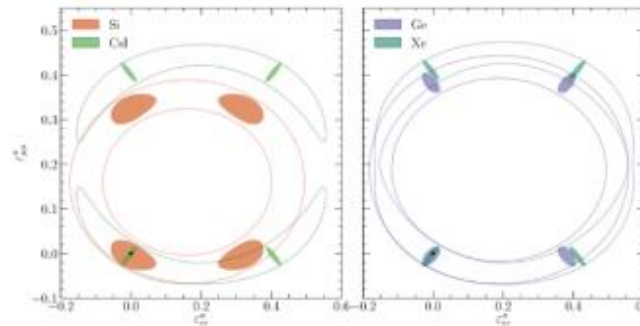
to this...

(improvement not limited to NSI, timing opens up other physics possibilities)

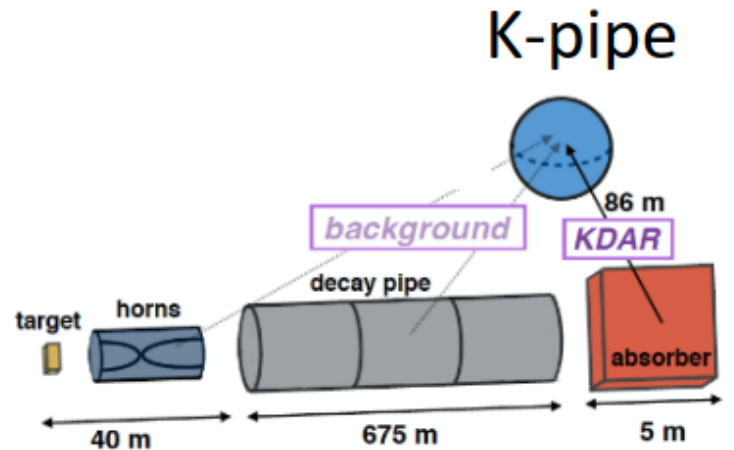
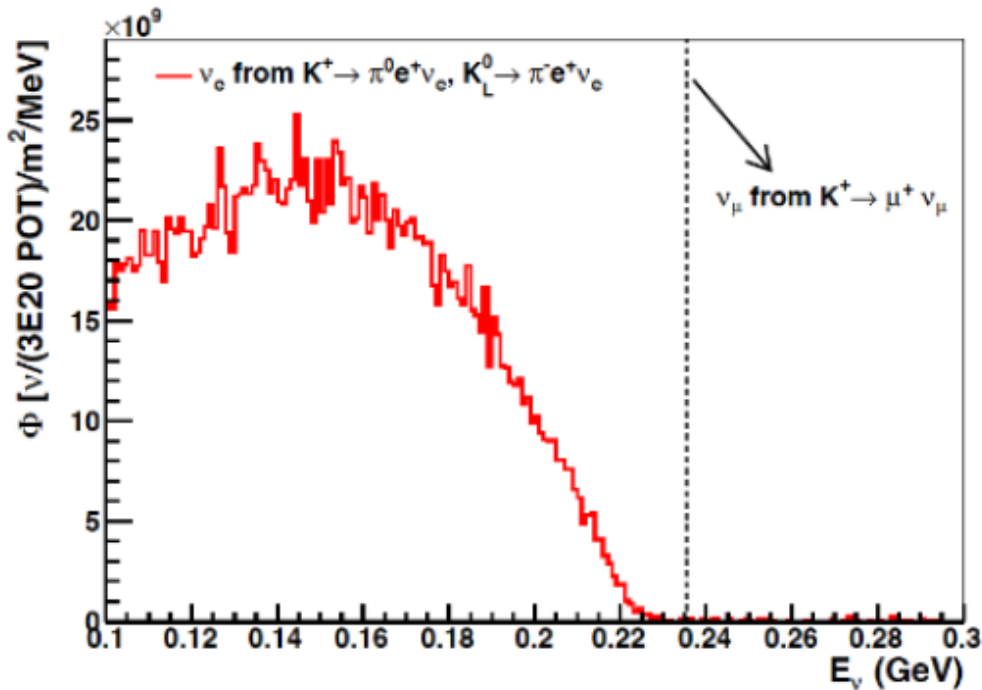
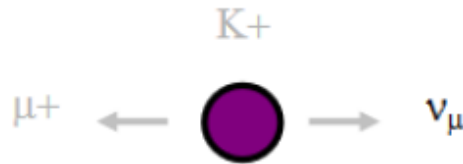
Preliminary study from I. Esteban, C. Gonzalez-Garcia, P. Coloma



Huge cross-sections

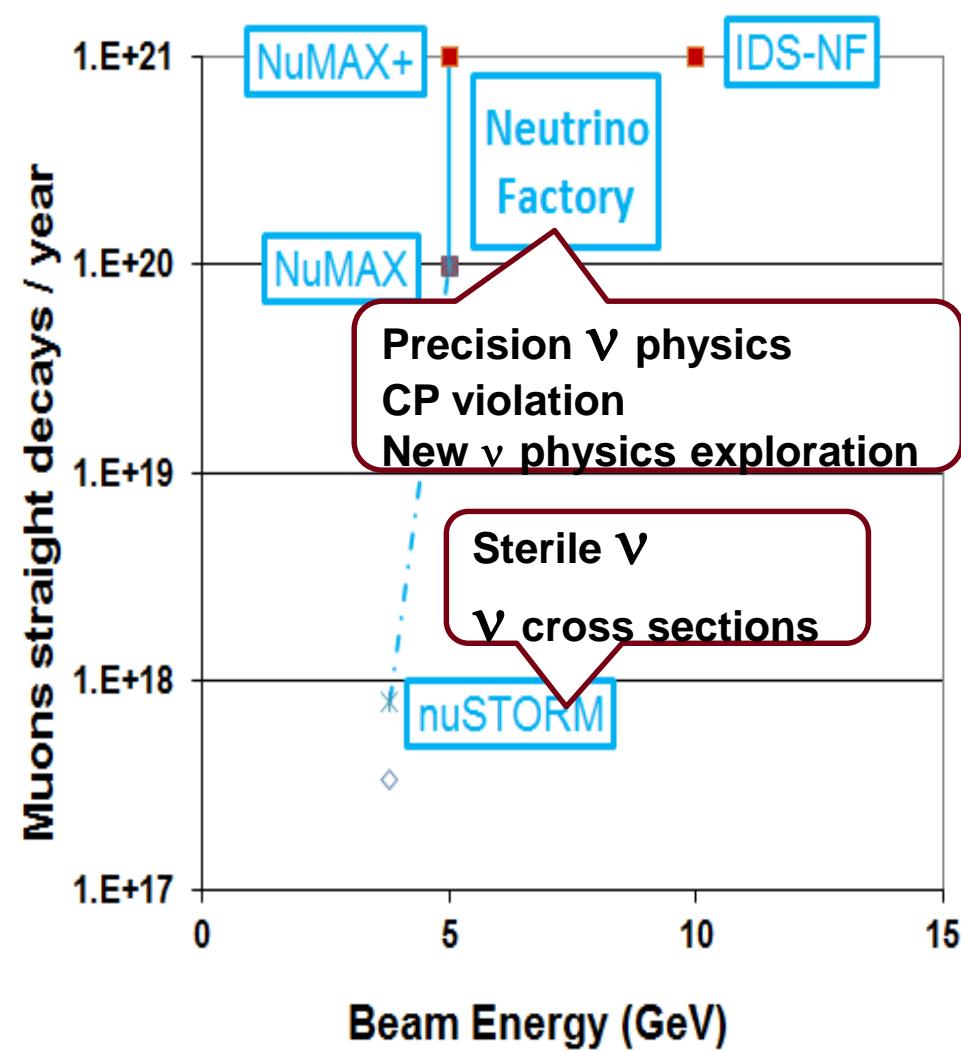


Kaon- decay-at-rest KDAR

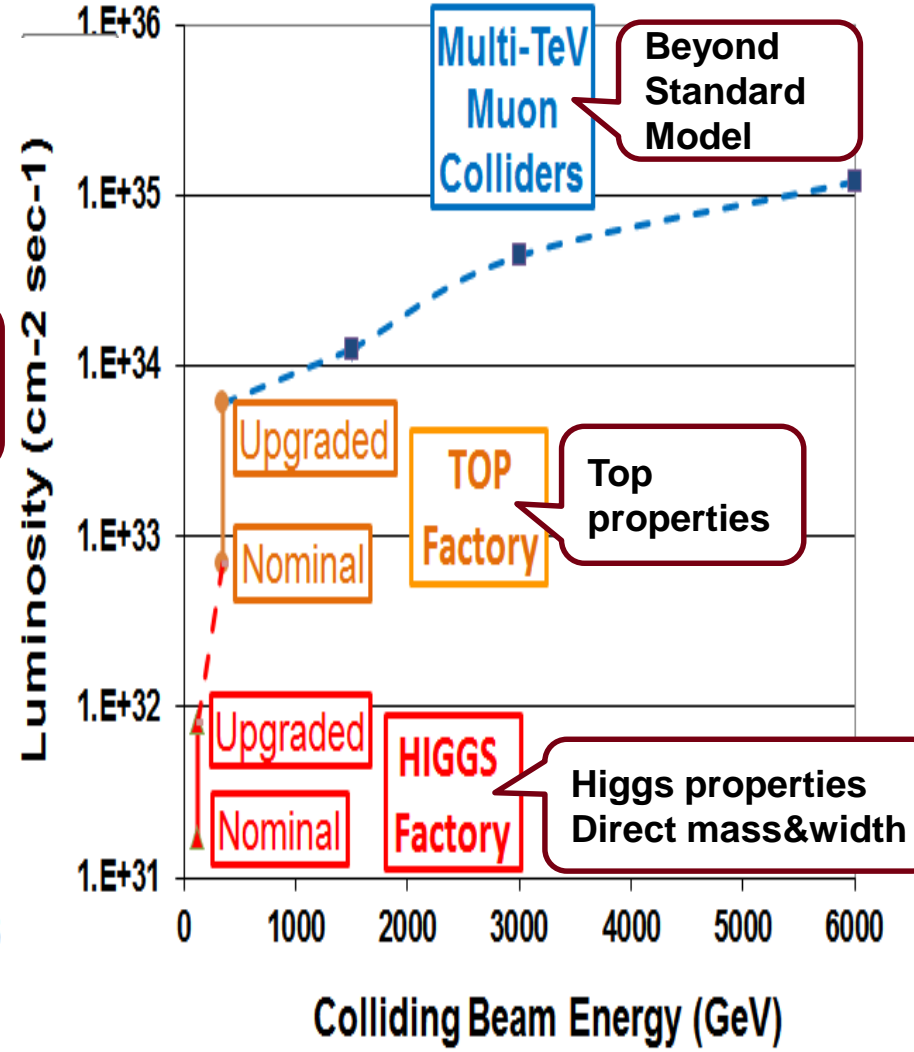


236 ke ν_μ monoenergetic beam from the ESSnuSB beam dump that can be used to search for ν_μ oscillations to sterile ν

Intensity Frontier



Energy Frontier





Staged Neutrino Factory main parameters Increasing complexity and challenges

M.Palmer

Muon Accelerator Program (MAP)

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ^+ or μ^- /year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	Far Detector:	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-	-	60	60	60
	Charge per bunch	1×10^9	-	6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15