High Intensity Frontier Initiative (HIFI) νSTORM and Neutrino Factory based on the ESSνSB facility

J.P Delahaye / CERN

M.Dracos / IN2P3, T.Ekelof / UU

for the ESSνSB/HIFI collaboration

https://essnusb.eu/

ESS NEUTRINO SUPER BEAM

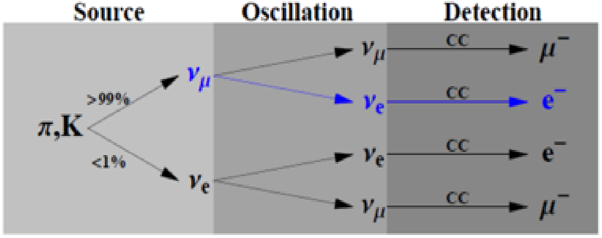
Funded by the Horizon 2020 Framework Programme of the European Union

Accelerator based neutrino production

(http://euronu.org)

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



Neutrinos as secondary particles

Mainly: ν_μ and $\bar{\nu}_\mu$

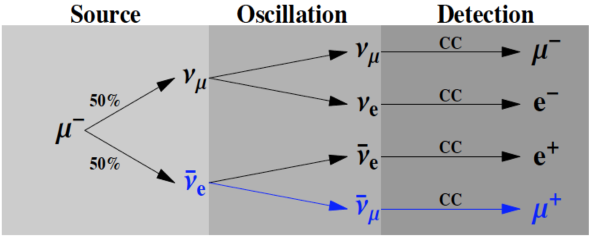
Superbeams

The only method in existing accelerator based facilities

Contamination: < 1% of ν_e & $\bar{\nu}_e$

- **Muons decay: Attractive ESSνSB evolution**

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \qquad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$



Neutrinos as tertiary particles

Equal quantities of: ν_μ, ν_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

$$\pi^+ \rightarrow \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Neutrinos as tertiary particles
Equal quantities of:
ν_μ , ν_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.

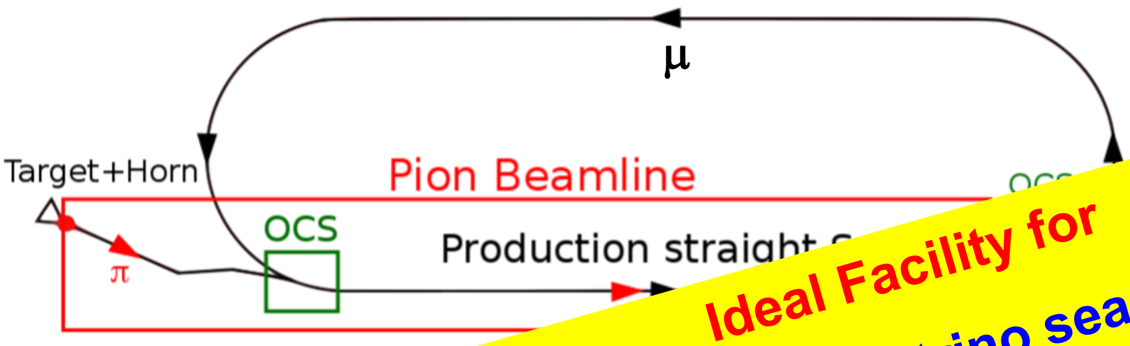
Major developments from the 2013 strategy

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

nuSTORM
neutrinos from STOred Muons

A.Bross/FNAL
C.Rogers/RAL
This workshop



Ideal Facility for

Sterile Neutrino search

Neutrino cross sections measurements with unprecedented precision

LBL performance improvement by systematic error mitigation

(Luis Alvarez, next presentation)

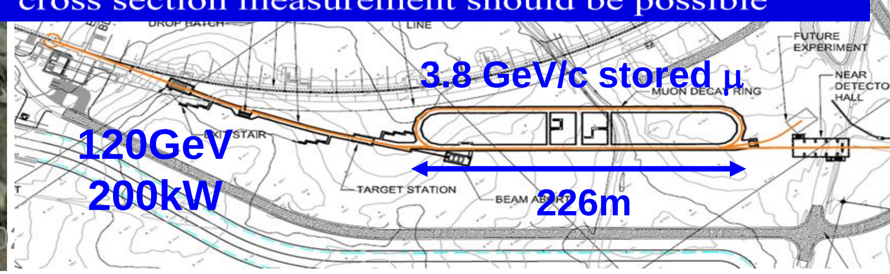
P.Huber
Virginia Tech

...w luminosity muon storage ring.
...s with 1.7×10^{18} μ^+ stored, the following
...scillated 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 10 σ difference from no oscillations

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



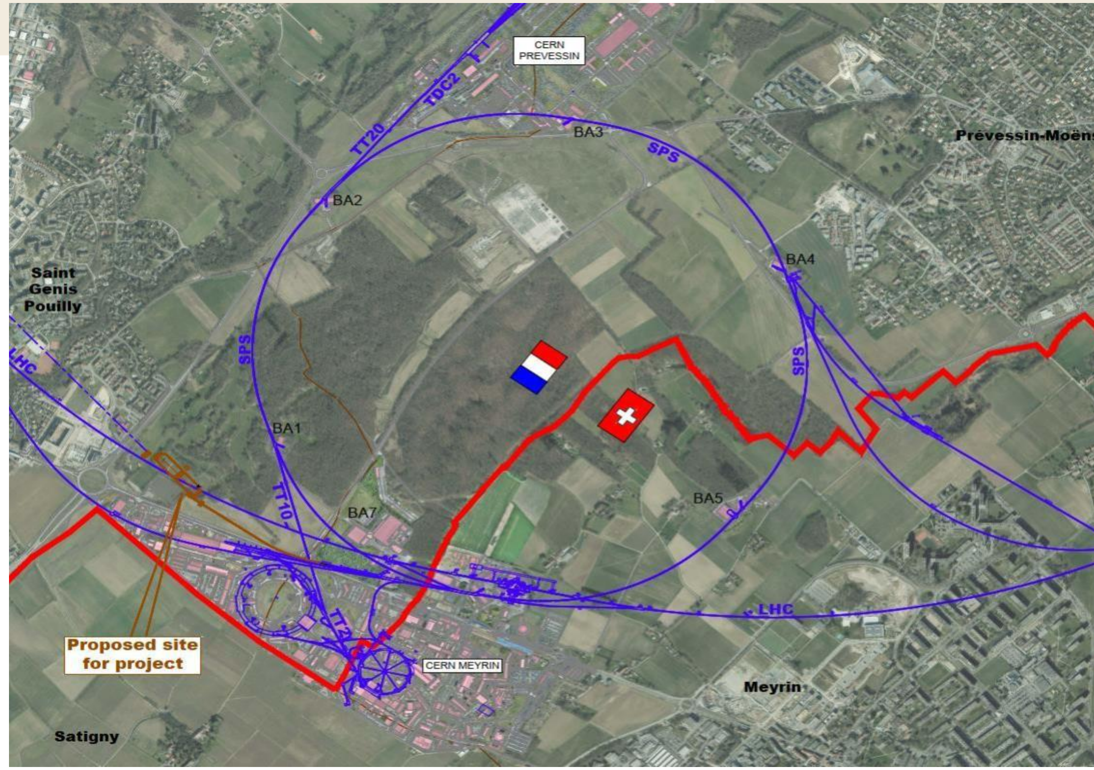
nuSTORM @ CERN

Feasibility study: CERN-PBC-2019-003

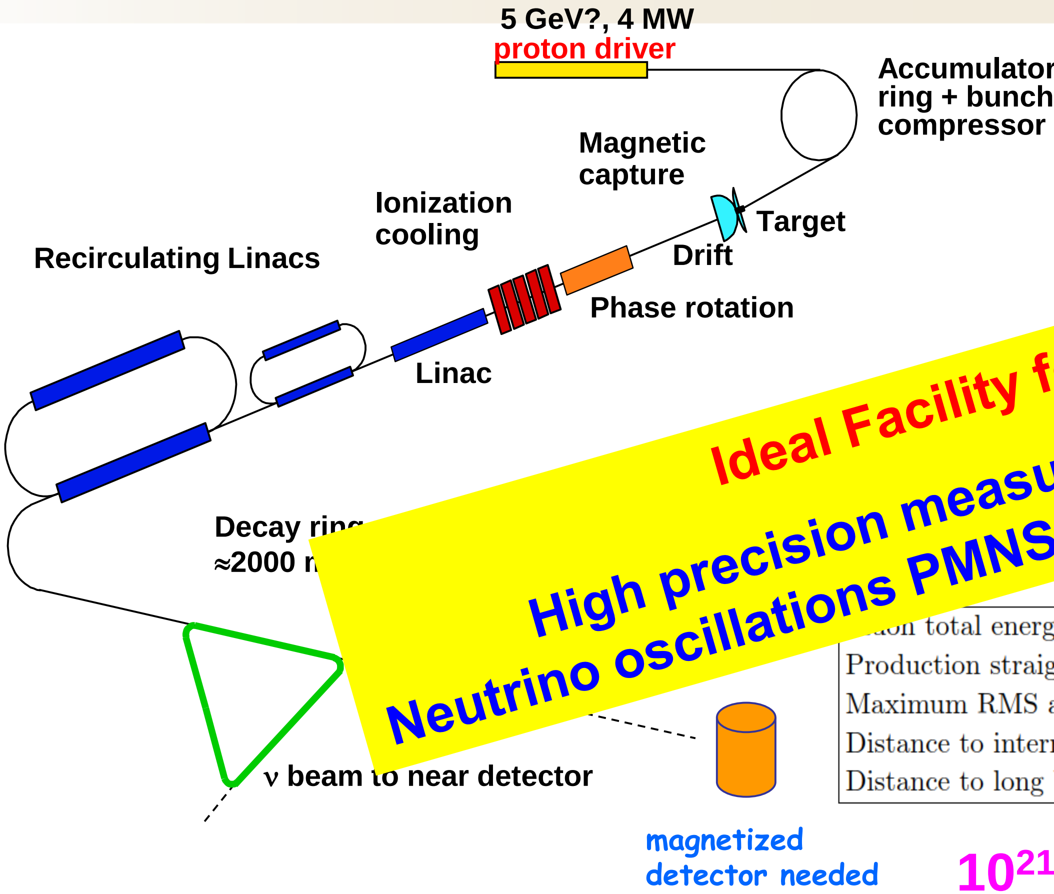
S.Tygier
I.Efthymopioulos

- **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	$\nu_e \to \nu_\mu$ CC	332	0	18.2
$\bar{\nu}_\mu$ Disappearance	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-12.2
ν_e Disappearance	$\nu_e \to \nu_e$ CC	216657	230766	-21.1
NC Disappearance	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-7.7
NC Disappearance	$\nu_e \to \nu_e$ 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) ionizati... to match the ...nces to the ...ances ...on by linacs ...and/or recirculating)

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

	Value
...uon 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

10^{21} ν_e or ν_μ to detectors per year

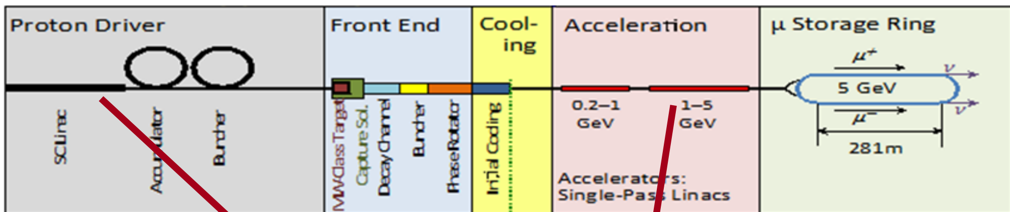
International Design Study (IDS-NF): “Generic” design (not site-specific)
10 GeV muon storage ring optimized for 1500-2500km baselines
https://www.ids-nf.org/wiki/FrontPage

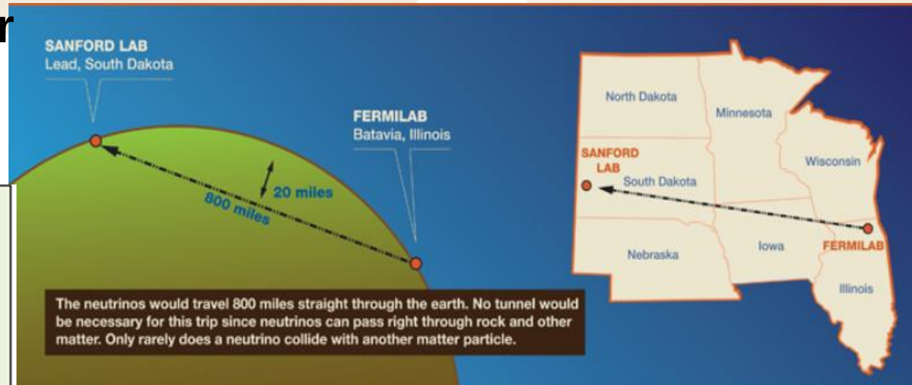
A site specific study: FNAL to SURF

Muon Accel. Prog. (MAP) M.Palmer/BNL

NuMAX (Neutrinos from Muon Accelerator CompleX)

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



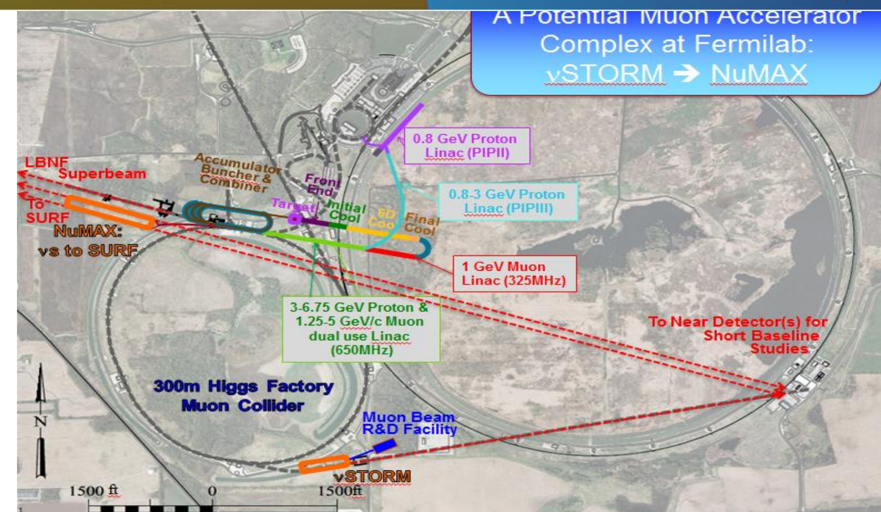


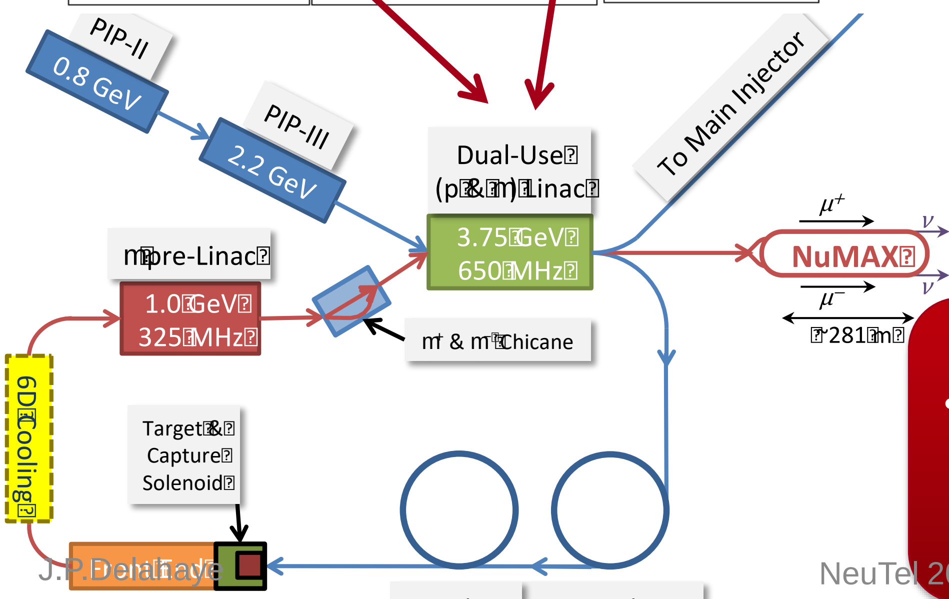
Key Challenges

- ~10^{13}-10^{14} μ / sec Tertiary particle $p \to \pi \to \mu$
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

- MW proton driver, MW class target, NCRF in magnetic field
- Ionization cooling, High field solenoids (30T), High Temp Superconductor
- Cost eff. low RF SC, Fast pulsed magnet (1kHz)
- Shielding



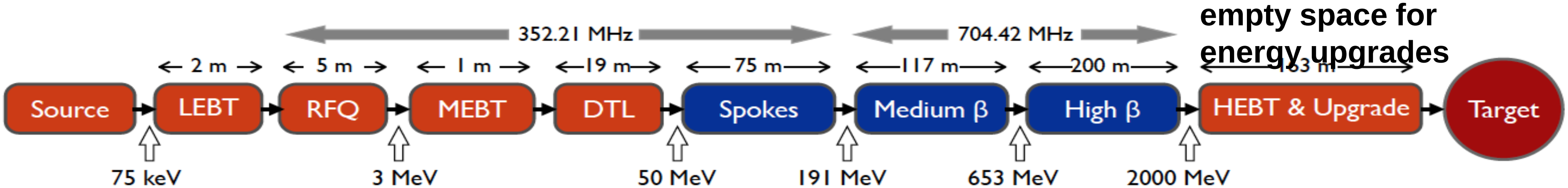


NuMAX Staging:

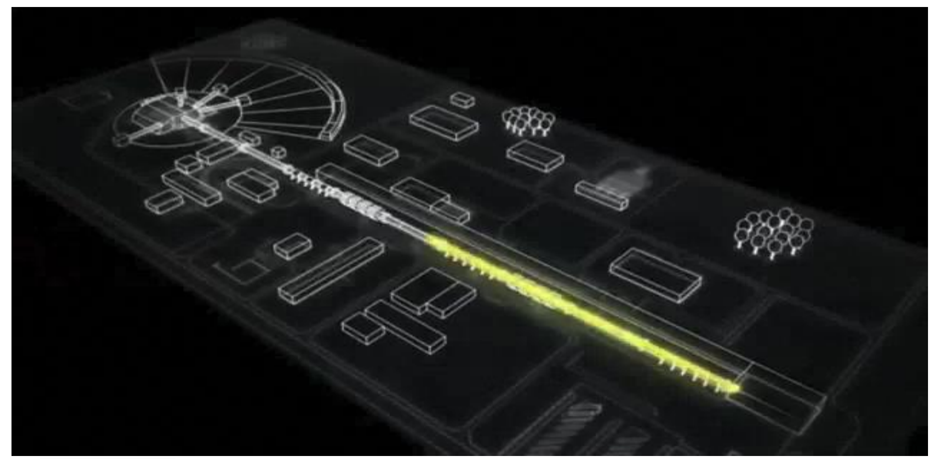
- ***Commissioning***
  - ✧ 1MW Target
  - ✧ No Cooling
  - ✧ 10kT Detector
- ***NuMAX+***
  - ✧ 2.75 MW Target
  - ✧ 6D Cooling
  - ✧ 34kT Detector

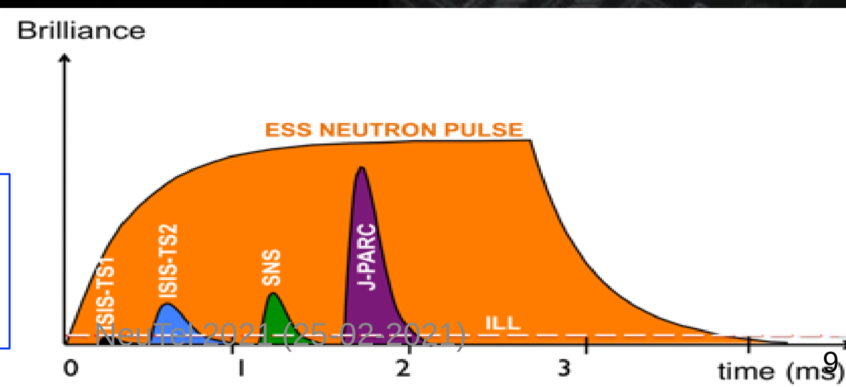
European Spallation Source under construction in Sweden

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





Linac ready by 2023
providing attractive opportunities

Extending ESS to a neutrino facility

M.Dracos
T.Ekelof

- 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 μs the 2.86 ms proton pulses

  H^- source (instead of protons)
- Short pulses (~μs) will also al… experiments (as those pr… SNS) using the neutr…
- ~400 MeV neutrinos…
- Target station (studied … EUROν).
- Underground detector (studied in LAGUNA).

Great synergies providing considerable cost savings

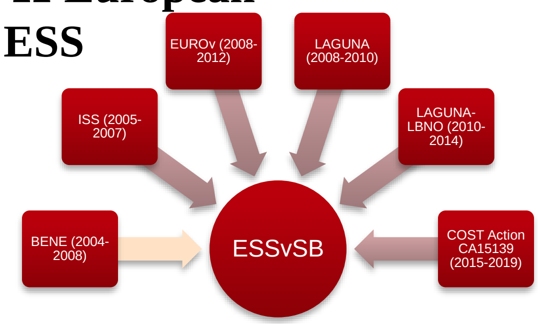
ESSvSB design study (2018-2021)

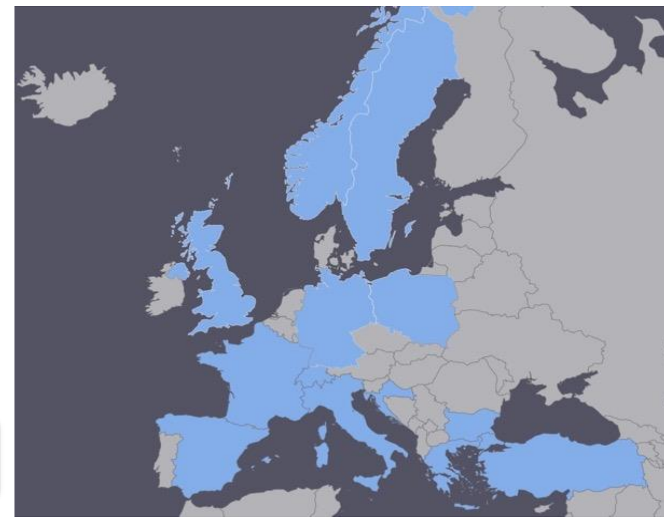
M.Bogomilov
Sofia University
This workshop

- 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

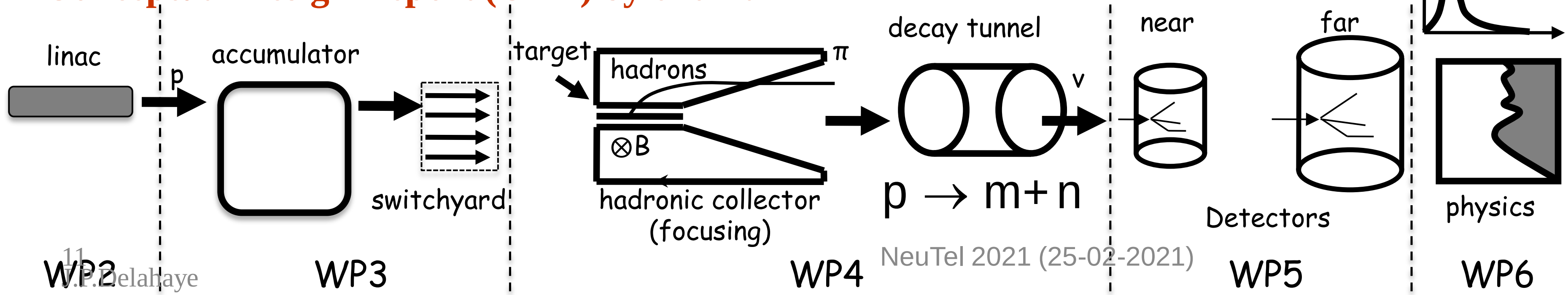
Design of a second generation long base line neutrino for CP violation observation with high sensitivity at 2nd oscillation maximum

- **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

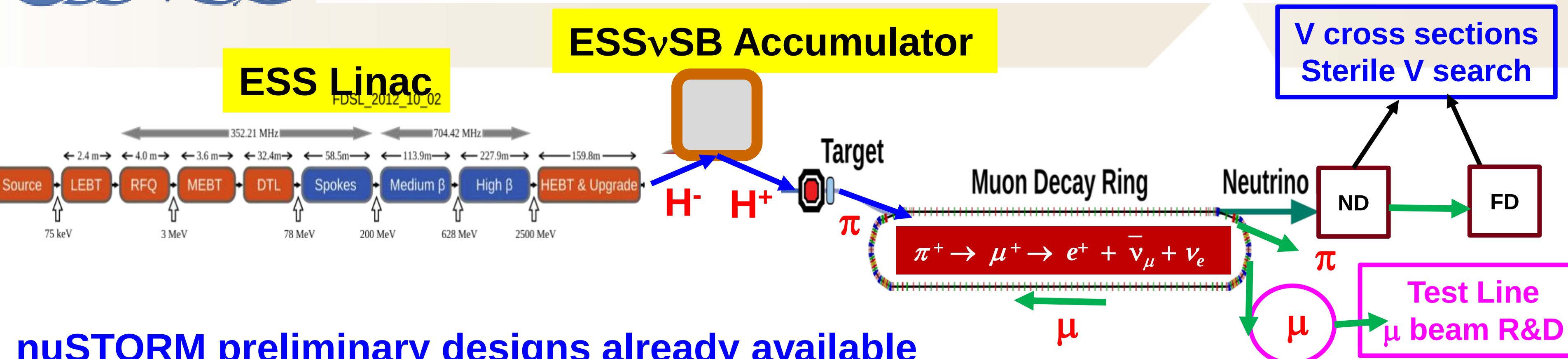
- **3M€ over 4 years (2022-2025)**

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

νSTORM @ ESS



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

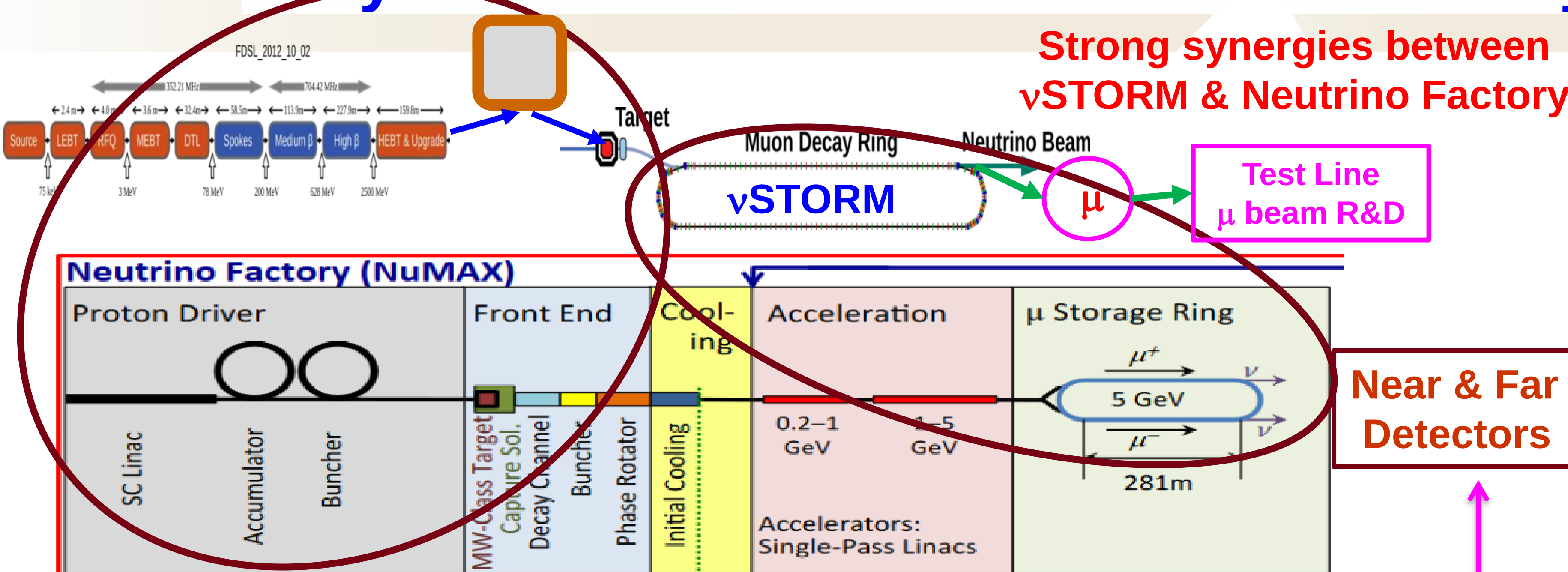
Physics and Detector optimisation

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 νSTORM & Neutrino Factory



Key Additional Challenges

- Fast cooling (τ=2μs) by 50 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay
- ν_μ & ν_e anti ν charact

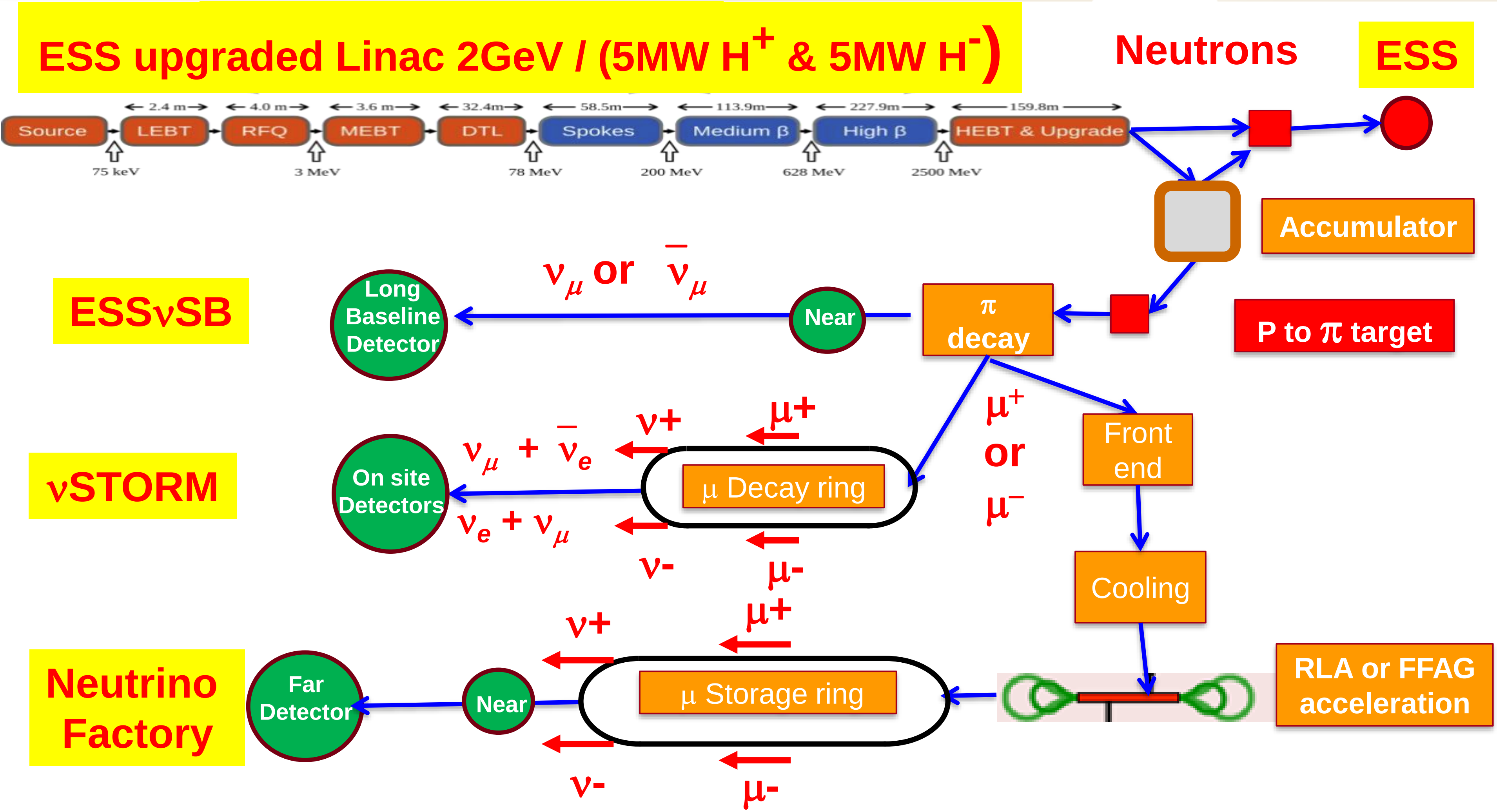
Key R&D

- Ionization cooling; High field solenoids (30T); High Temp Superconductor
- Cost eff. low RF SC; Recirculating Linac; FFAG synchrotrons
- 5 GeV; High Intensity; Large accept
- Magnetized Liquid Argon

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

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

HIFI @ ESS, Staged Approach
ESS → ESSνSB → νSTORM → Neutrino Fact



ESS NEUTRINO SUPER BEAM

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 ESSνSB / HIFI collaboration is being launched, hopefully with EU support aiming, by 2025, at:
  - Technical Design of the world most intense, secon… …tion long base line neutrino facility, ESSνSB, for CP violation ob… …igh sensitivity at 2nd oscillation maximum.
  - Preliminary Conceptual designs … short baseline facility for neutrino cross section measureme… …cedented precision and of a NEUTRINO FACTORY for meas… …NS matrix parameters
- These facilities … …ge and take advantage of the, then existing, ESS world most pow… 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.

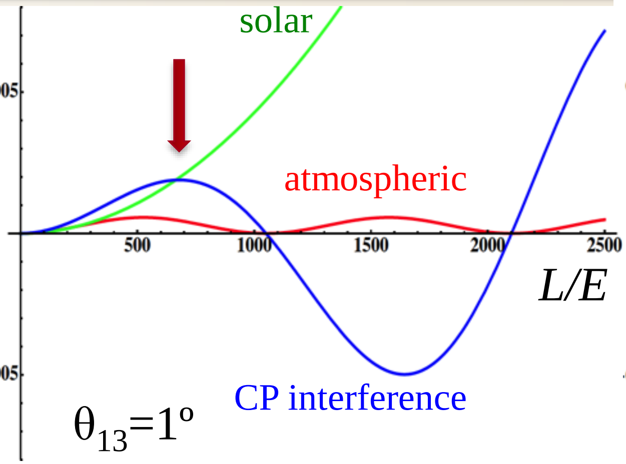
All Interested Welcome

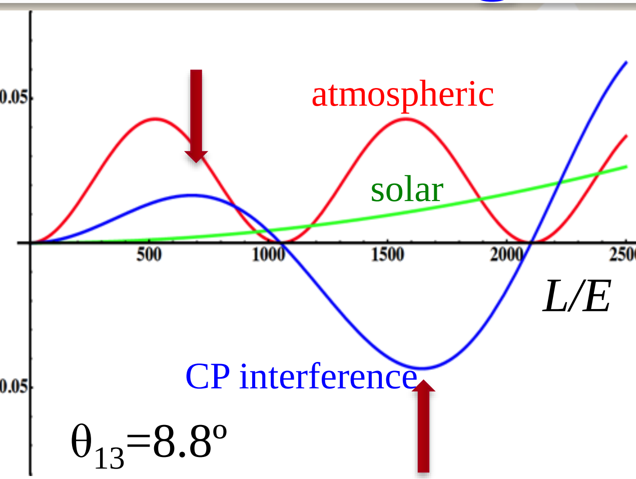
Back-up slides

Neutrino Oscillations with "large" θ_{13}

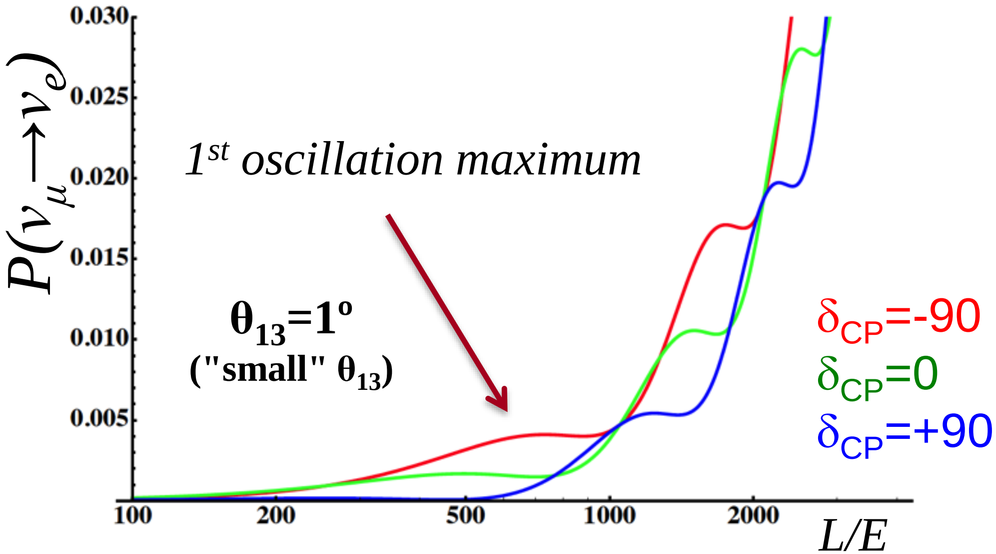
for small θ_{13} 1[st] oscillation maximum is better

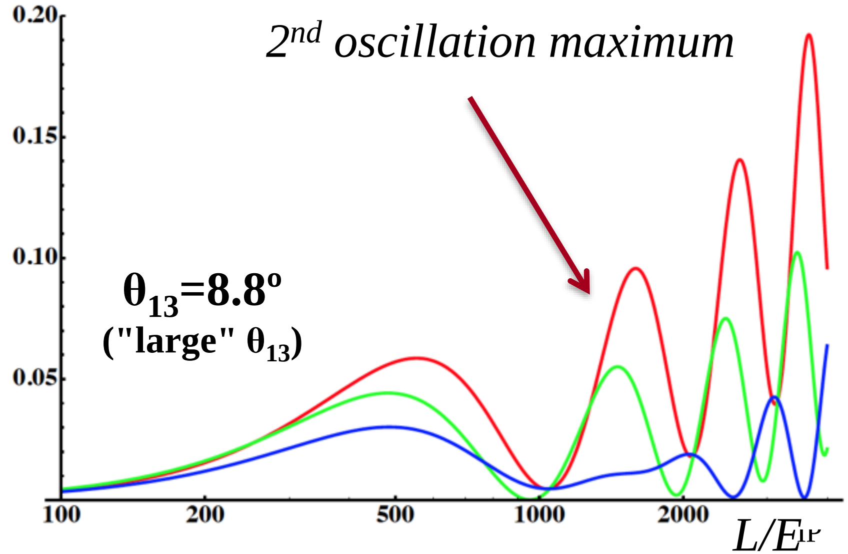
(arXiv:1110.4583)





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





- 1[st] oscillation max.: A=0.3sinδ_{CP}
- 2[nd] oscillation max.: A=0.75sinδ_{CP}

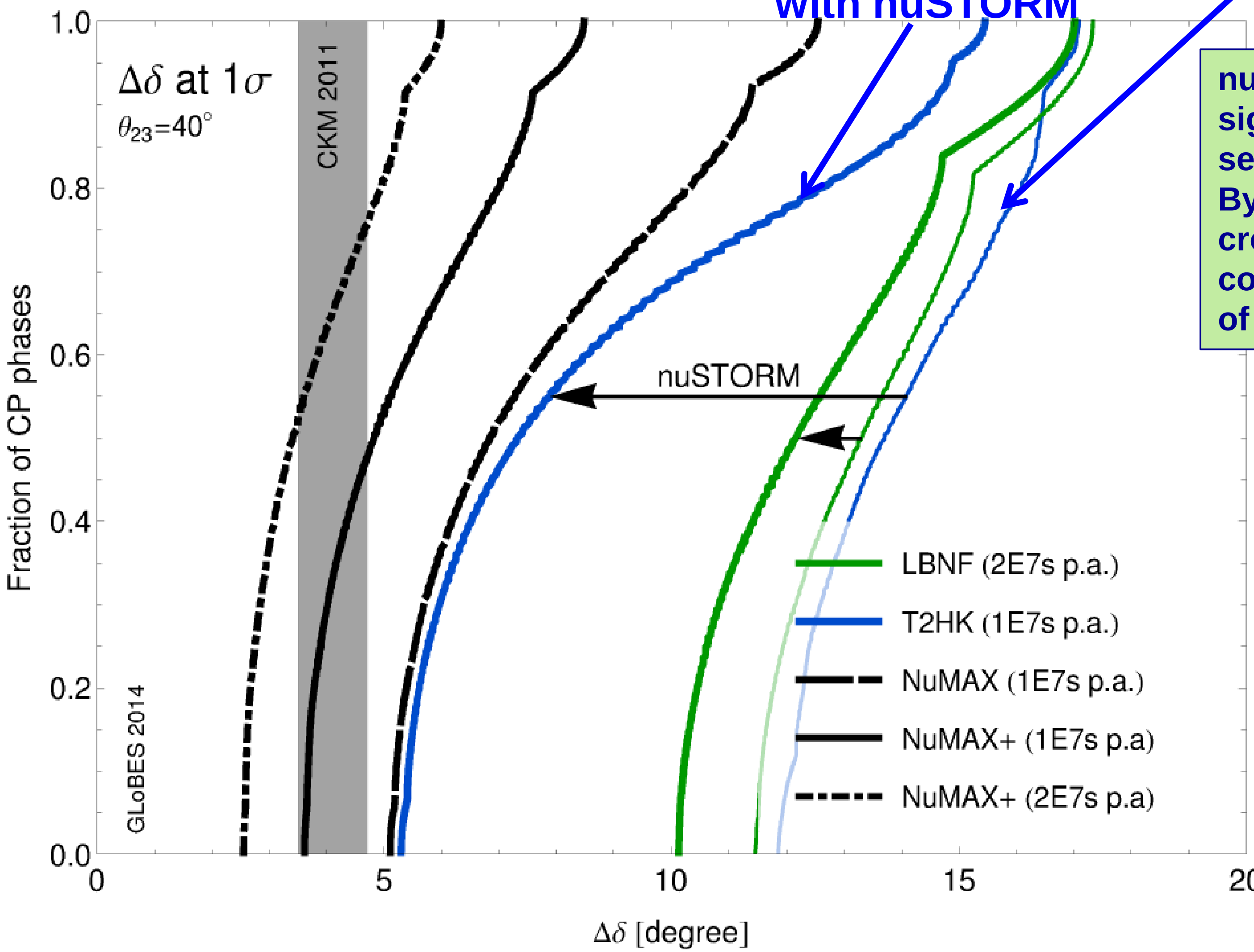
more sensitivity at 2[nd] oscillation max.

(see arXiv:1310.5992 and arXiv:0710.0554)

Leverage potential by nuSTORM for Long Baseline ν Experiments

Super-Beams with nuSTORM

Super-Beams alone



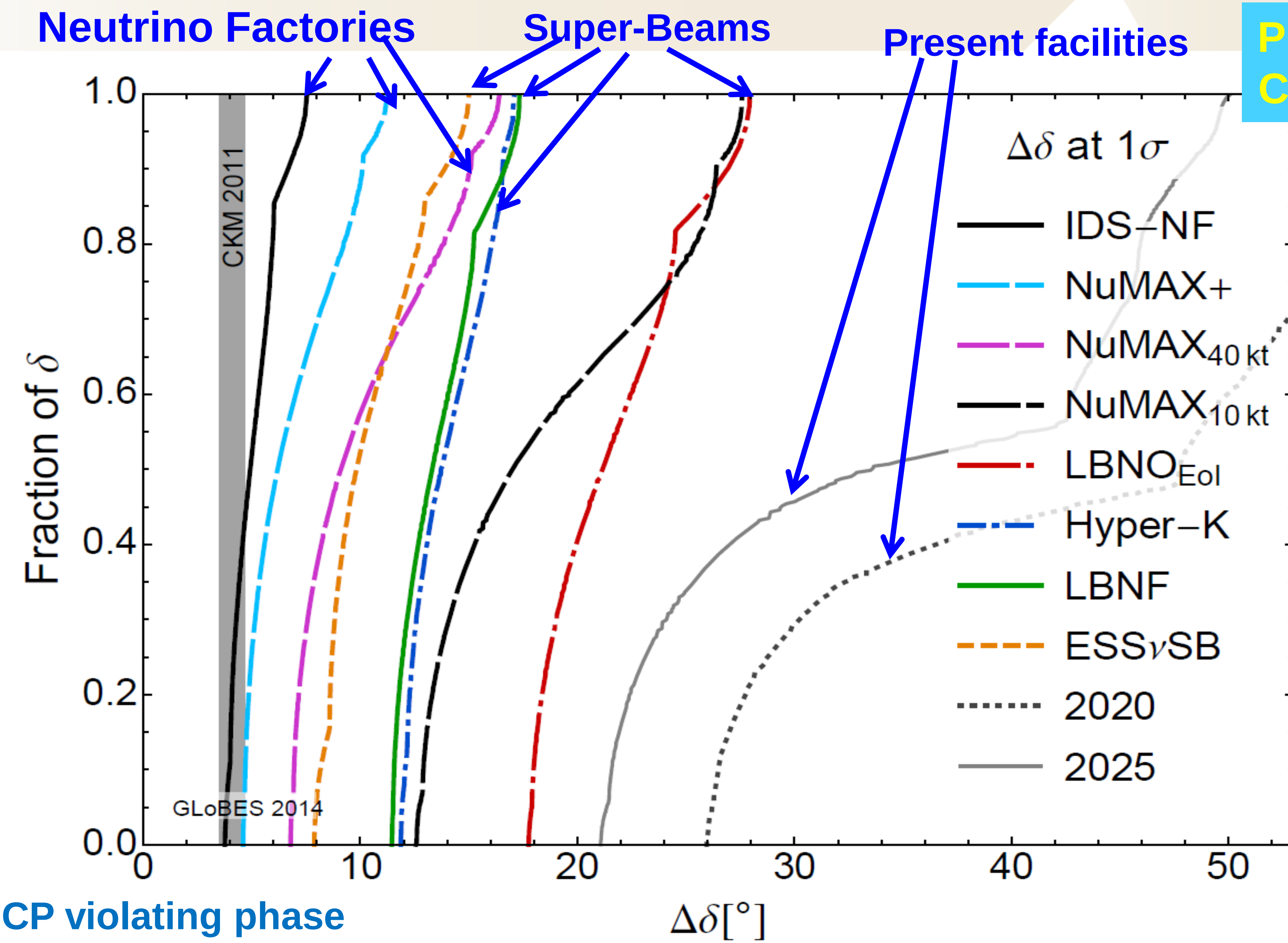
nuSTORM + LBL offers significantly improved sensitivity vs LBL alone By higher precision of ν cross sections and corresponding reduction of systematic errors

GLoBES comparison of potential performance of the various Advanced Concepts

P. Coloma P.Huber

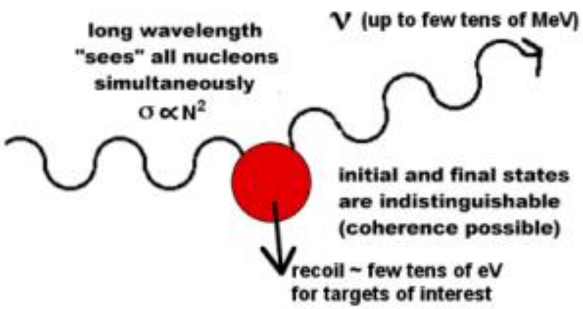
Physics reach of various technologies
A large improvement potential

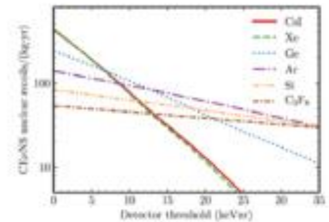
Pilar Coloma



δ = CP violating phase

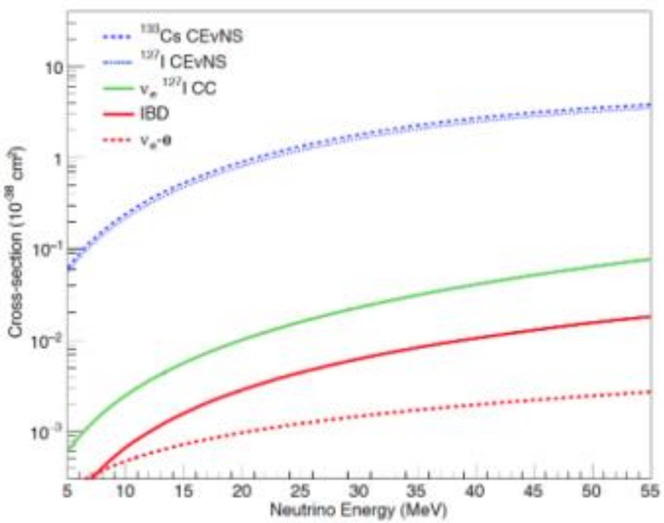
Coherent ν-N scattering





0-20 kg

~10 keV detector threshold

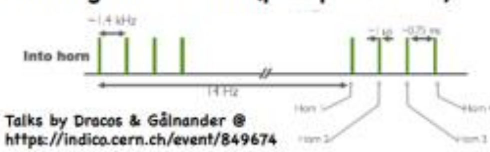


Huge cross-sections

Taking it to the next level: ESSνSB

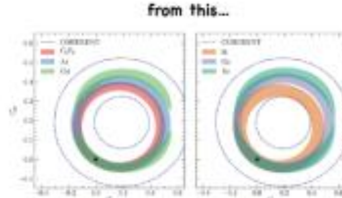
ESSνSB pulse compression brings:

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

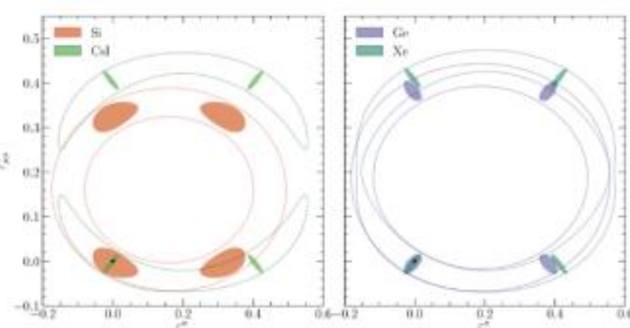


Talks by Dracos & Gålnander @ https://indico.cern.ch/event/849674

from this...



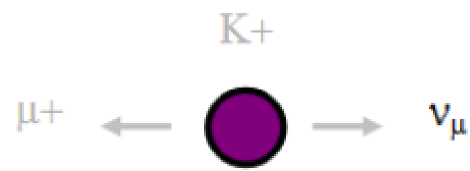
to this...

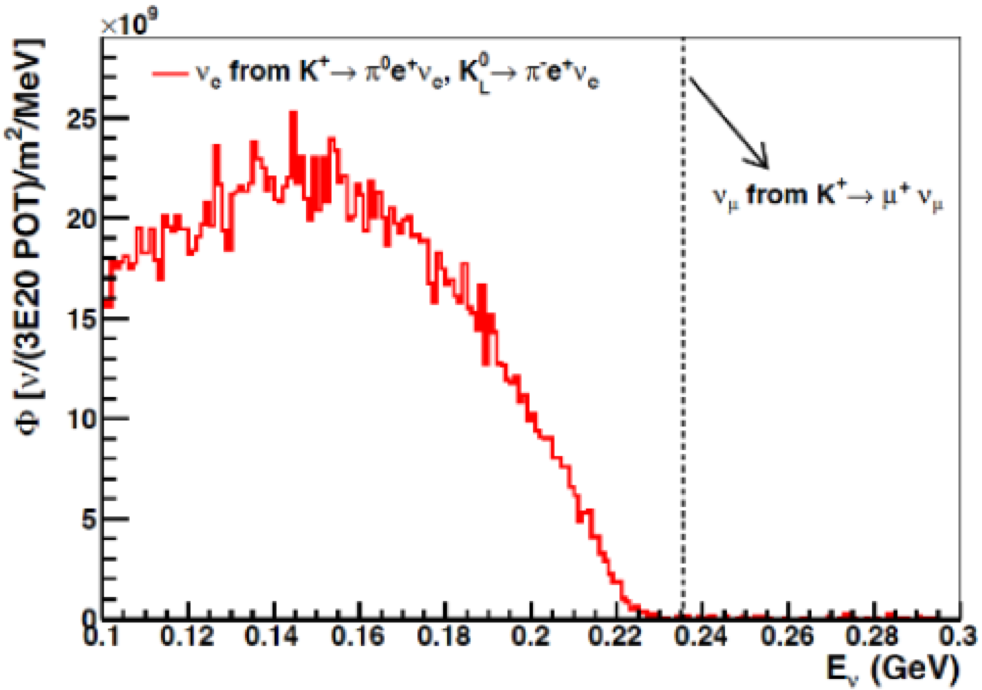


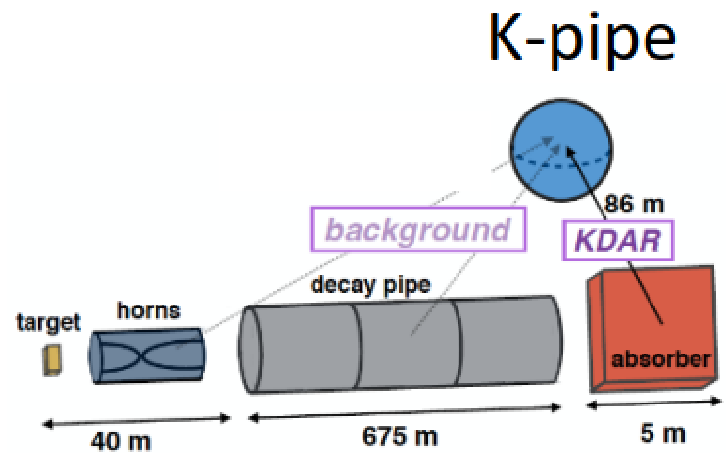
(improvement not limited to NSI, timing opens up other physics possibilities)

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

Kaon- decay-at-rest KDAR



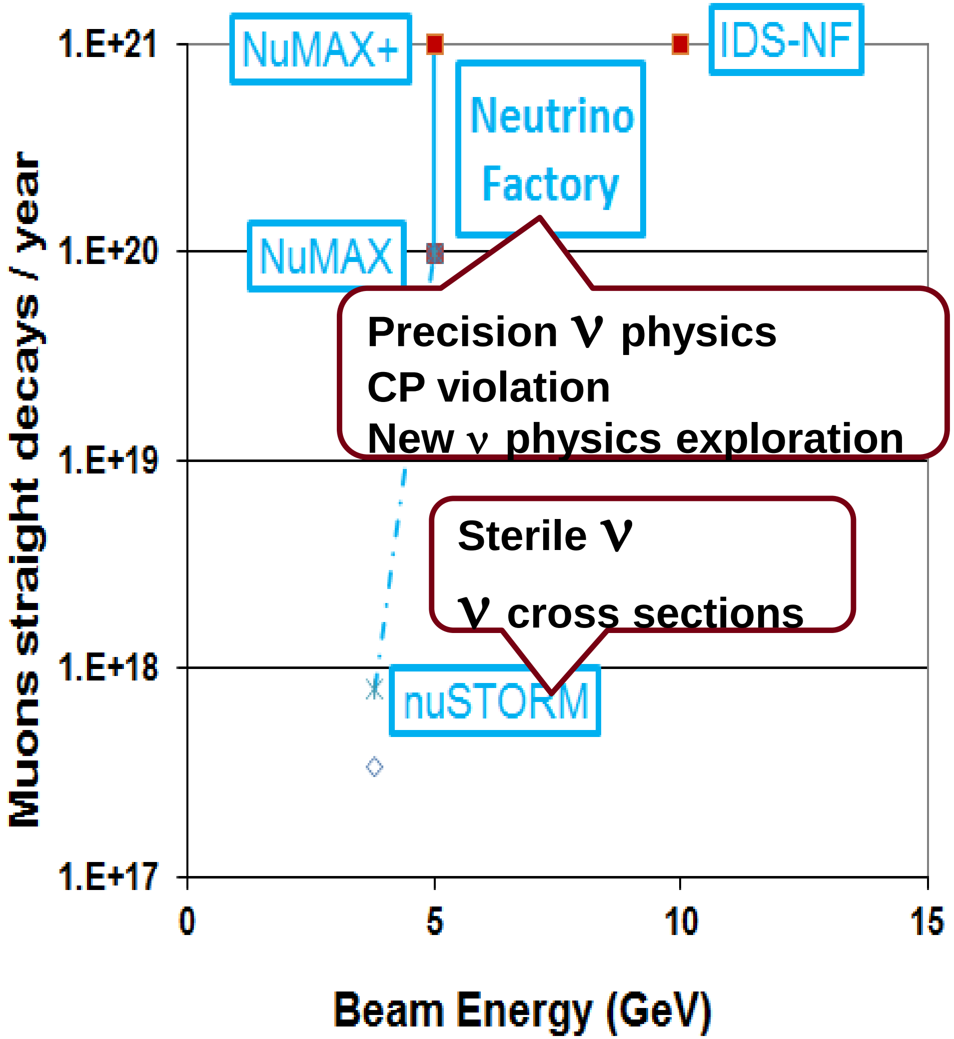




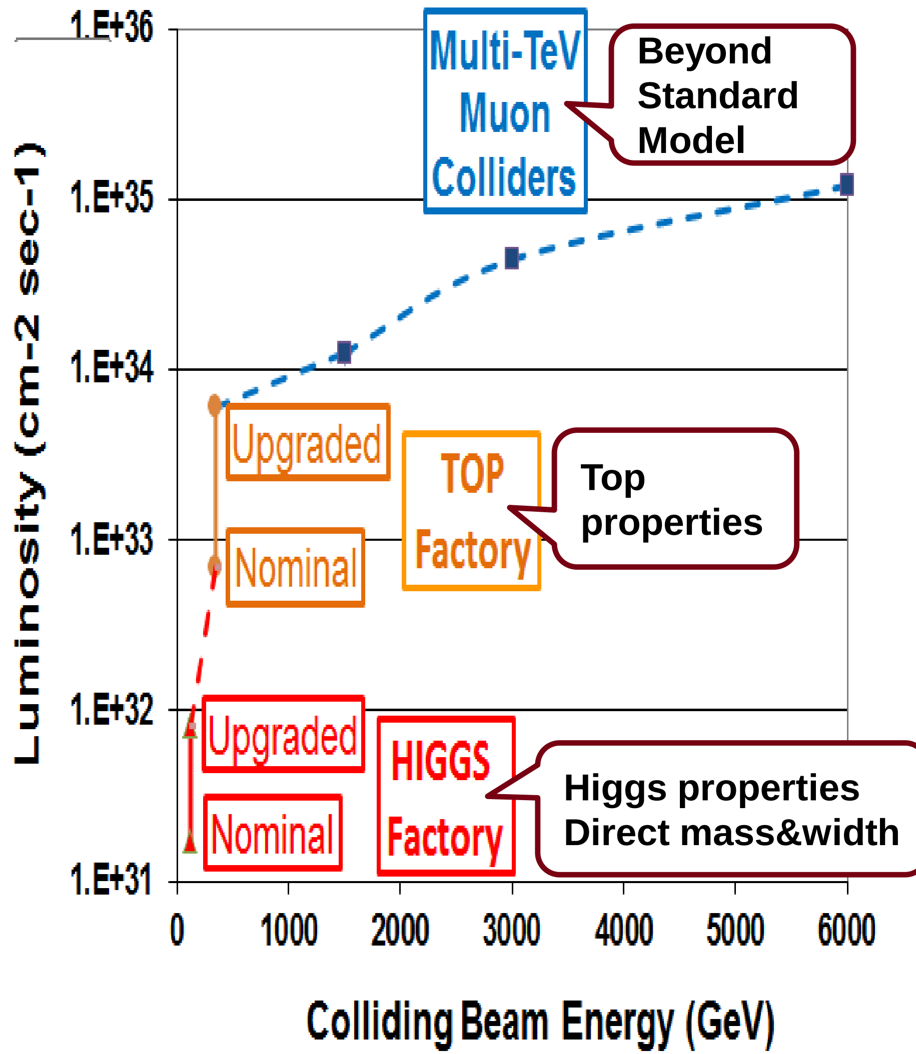
236 kE ν_μ monoenergetic beam from the ESSnuSB beam dump that can be used to search for ν_μ oscillations to sterile ν

facilities
with physics interest at each stage

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