Proposal for extension of the ESSνSB design study to include a long term staged muon complex (ESSμ)

J.P Delahaye / CERN

strongly inspired by the

Muon Accelerator Staging Scenario (MASS)

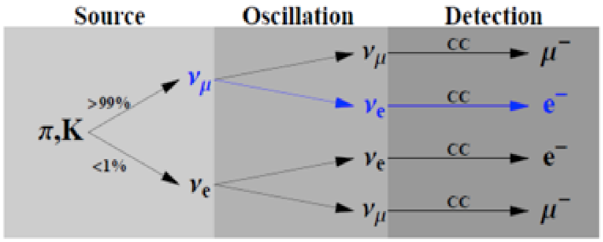
in the frame of the Muon Accelerator Program (MAP)

Accelerator based neutrino production

(Euronu comparison as a service to the community: http://euronu.org)

- **Pions decay: The ESSnuSB approach**

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



Neutrinos as secondary particles

Mainly: ν_μ and $\bar{\nu}_\mu$

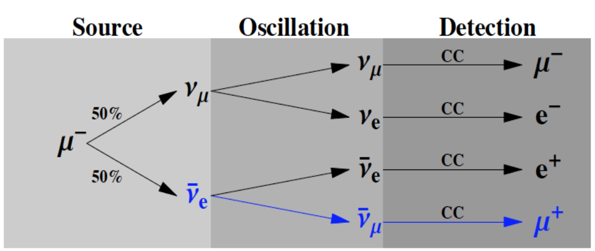
Superbeams

The only method in existing accelerator based facilities

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

- **Muons decay: Attractive ESSnuSB 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 to% level

Clean muon detection

More challenging (expensive)

Beauty of muon beams

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

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

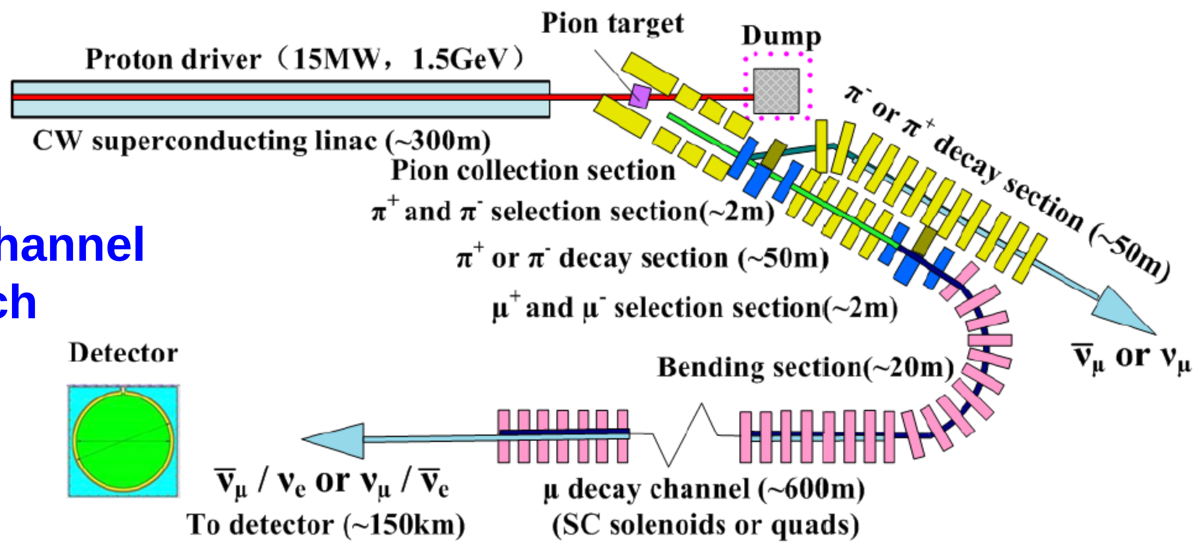
Neutrinos as tertiary particles
Equal quantities of:
ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$

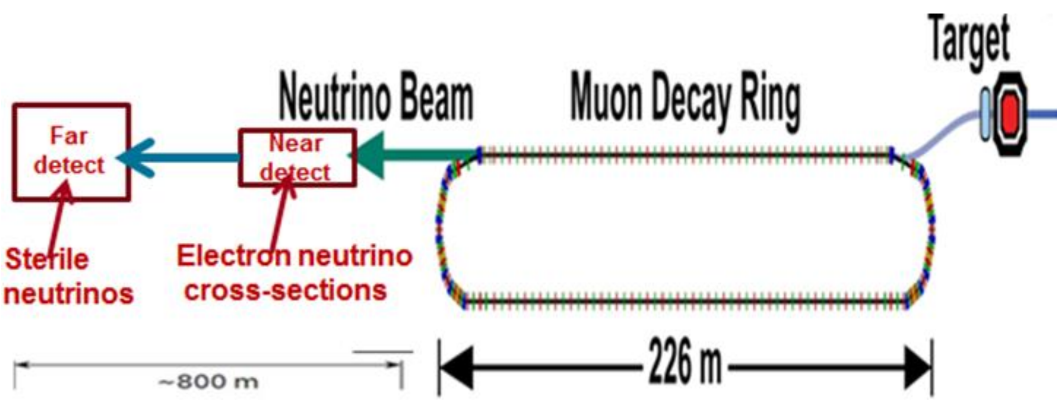
Enable facilities at both:

- **High precision frontier (Neutrinos from muons decay)**
  - ✓ **Short Base Line (without acceleration)**
    - **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**

Neutrinos from Muons decay: Short Base Line

Muon decay in a straight channel
The MOMENT approach
(J.Tang / NuFACT13)





Proton driver: 120GeV/0.2MW

Muon decay in a storage ring
The NuSTORM approach
(A.Bross / FNAL)

nuSTORM

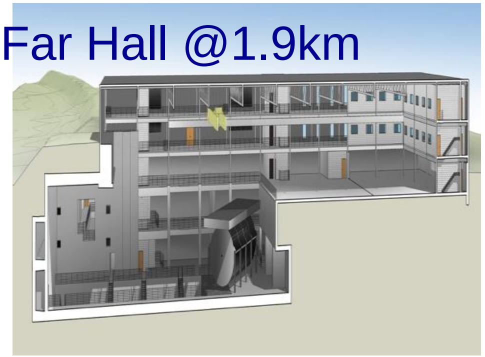
neutrinos from STORed Muons

(A.Bross / FNAL)

μ decay ring:
P = 3.8 GeV/c ± 10%

200 kW / 120GeV proton beam from MI on target

No new technologies required!
Could be deployed now!



νSTORM

Low energy, low luminosity muon storage ring.
Provides with 1.7×10^{18} μ^+ stored, the following oscillated event numbers

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

and each of these channels has a more than $10\,\sigma$ difference from no oscillations

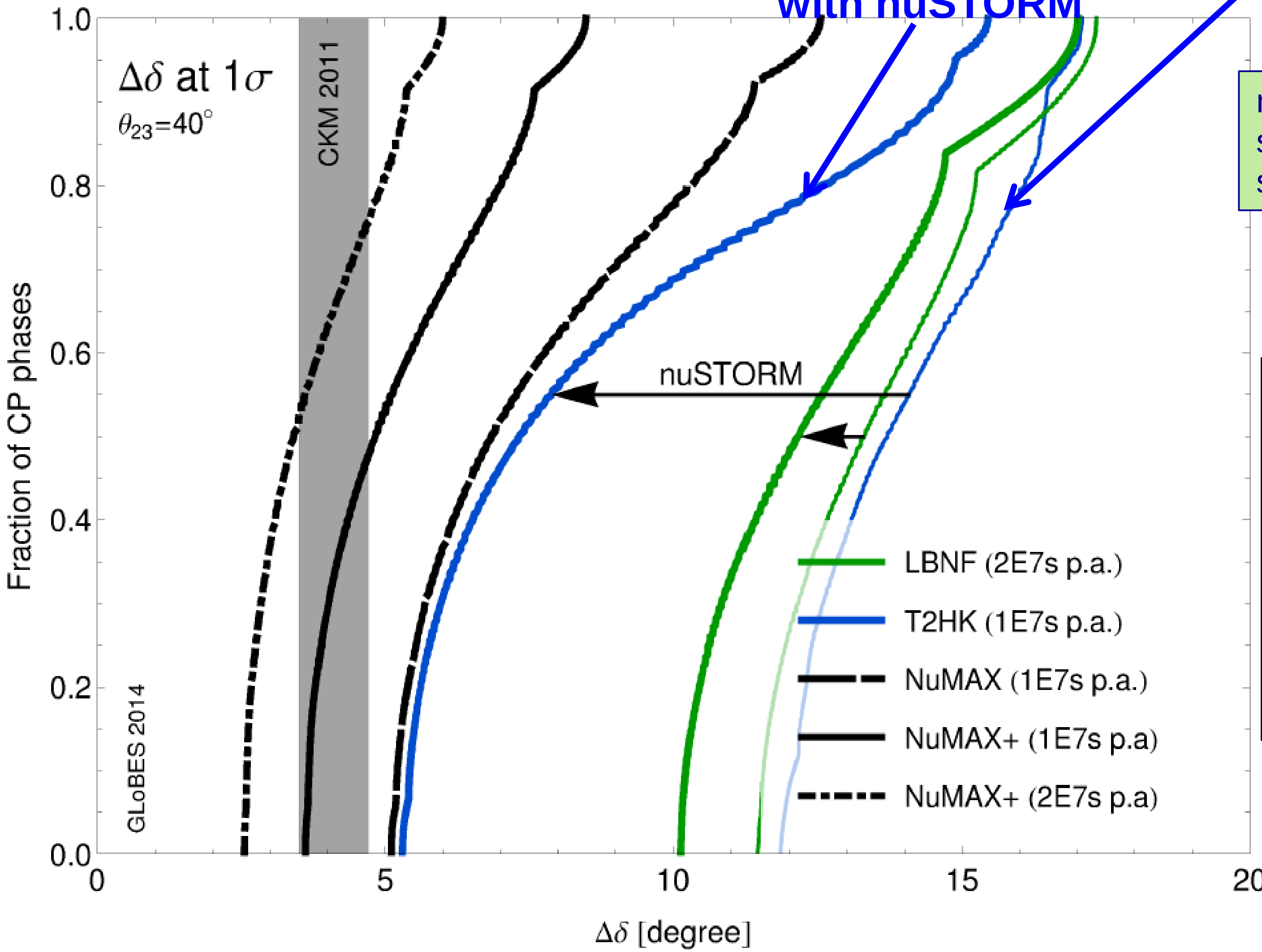
With more than 200 000 ν_e CC events a %-level ν_e cross section measurement should be possible

Example of leverage potential by nuSTORM for Long Baseline Experiments

P. Coloma
P.Huber

Super-Beams with nuSTORM

Super-Beams alone



nuSTORM + T2HK offers significantly improved sensitivity vs T2HK alone

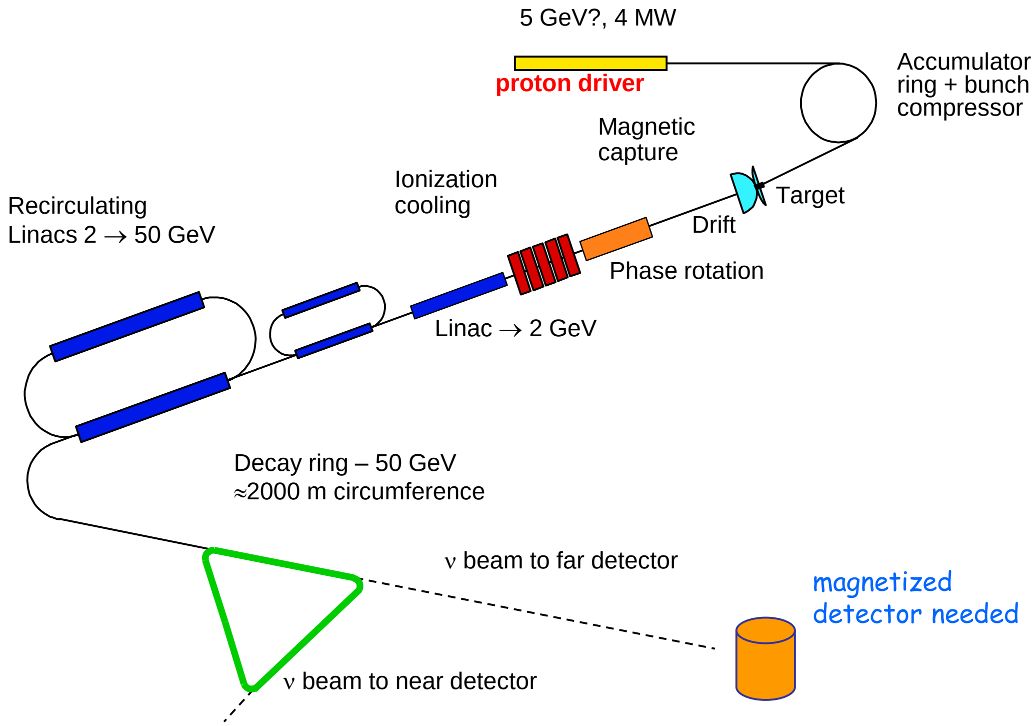
GLoBES comparison of potential performance of the various Advanced Concepts

Long Base Line Neutrinos from Stored Muons decay
The Neutrino Factory approach

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

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

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

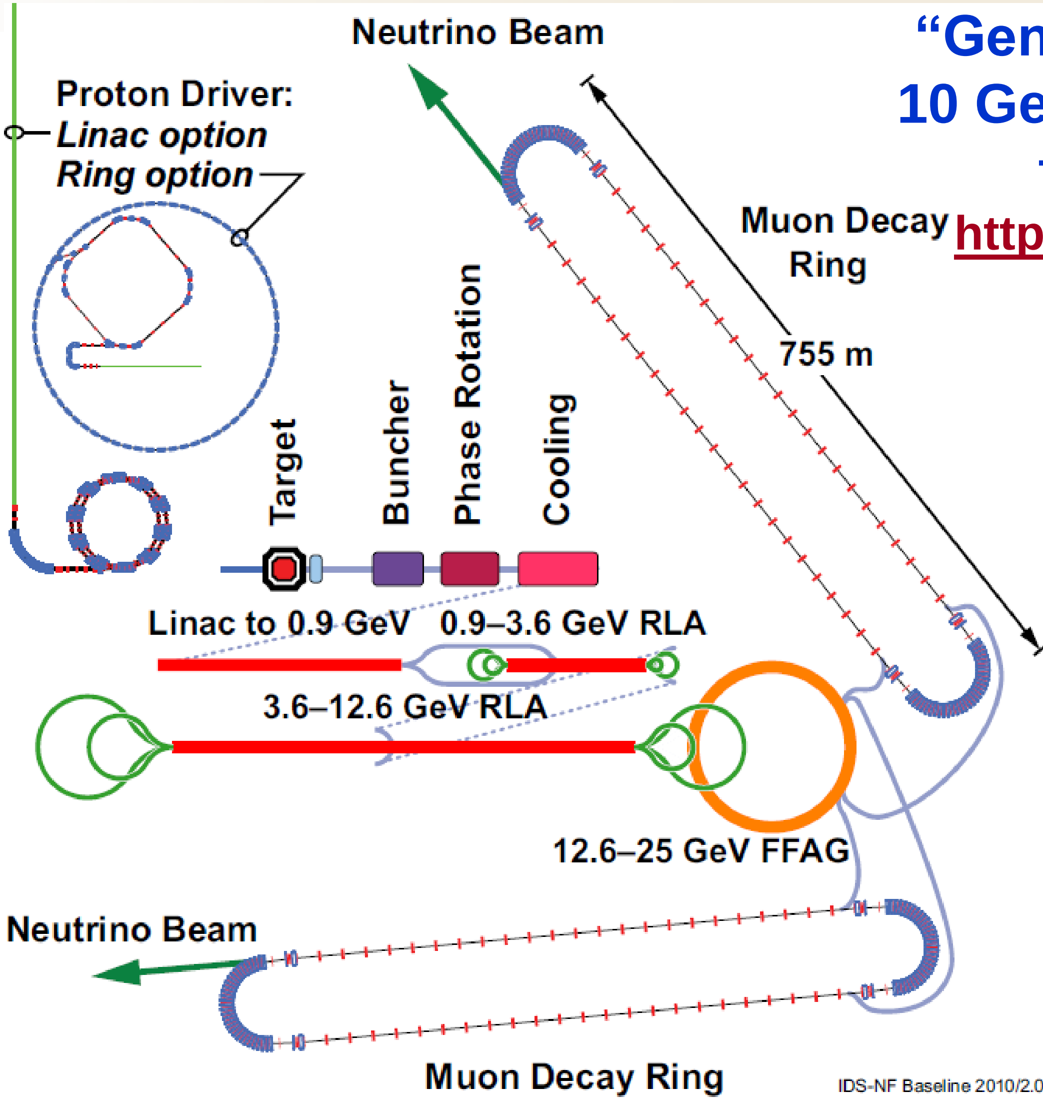


Muons decay in high energy neutrinos after acceleration and circulation in rings

Requires bunching and ionization cooling to match the muon beam emittances to the accelerator acceptances

Fast acceleration by linacs (straight and/or recirculating)

International design Study Neutrino Factory (IDS-NF)



"Generic" design (not site-specific)
10 GeV muon storage ring optimized for 1500-2500km baselines

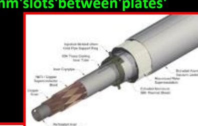
https://www.ids-nf.org/wiki/FrontPage

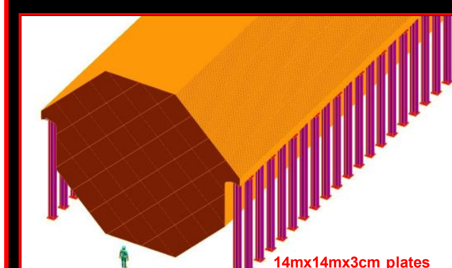
Interim design report:

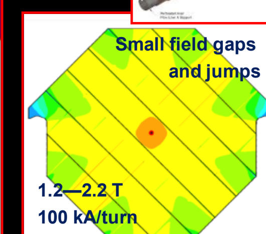
http://arxiv.org/abs/1112.2853

MagneHzed'Iron'Neutrino'Detector'(MIND):'

- IDS$NF'baseline:'
  - Intermediate'baseline'detector:'
    - 100'kton'at'2500—5000'km'
  - Magic'baseline'detector:''
    - 50'kton'at'7000—8000'km'
  - Appearance'of'"wrong$sign"'muons'
  - Toroidal'magneHc'field'>'1'T'
    - Excited'with'"superconducHng' transmission'line"'
  - SegmentaHon:'3'cm'Fe'+'2'cm' scinHllator'
  - 50$100'm'long'
  - Octagonal'shape'
  - Welded'double$sheet'
    - Width'2m;'3mm'slots'between'plates'







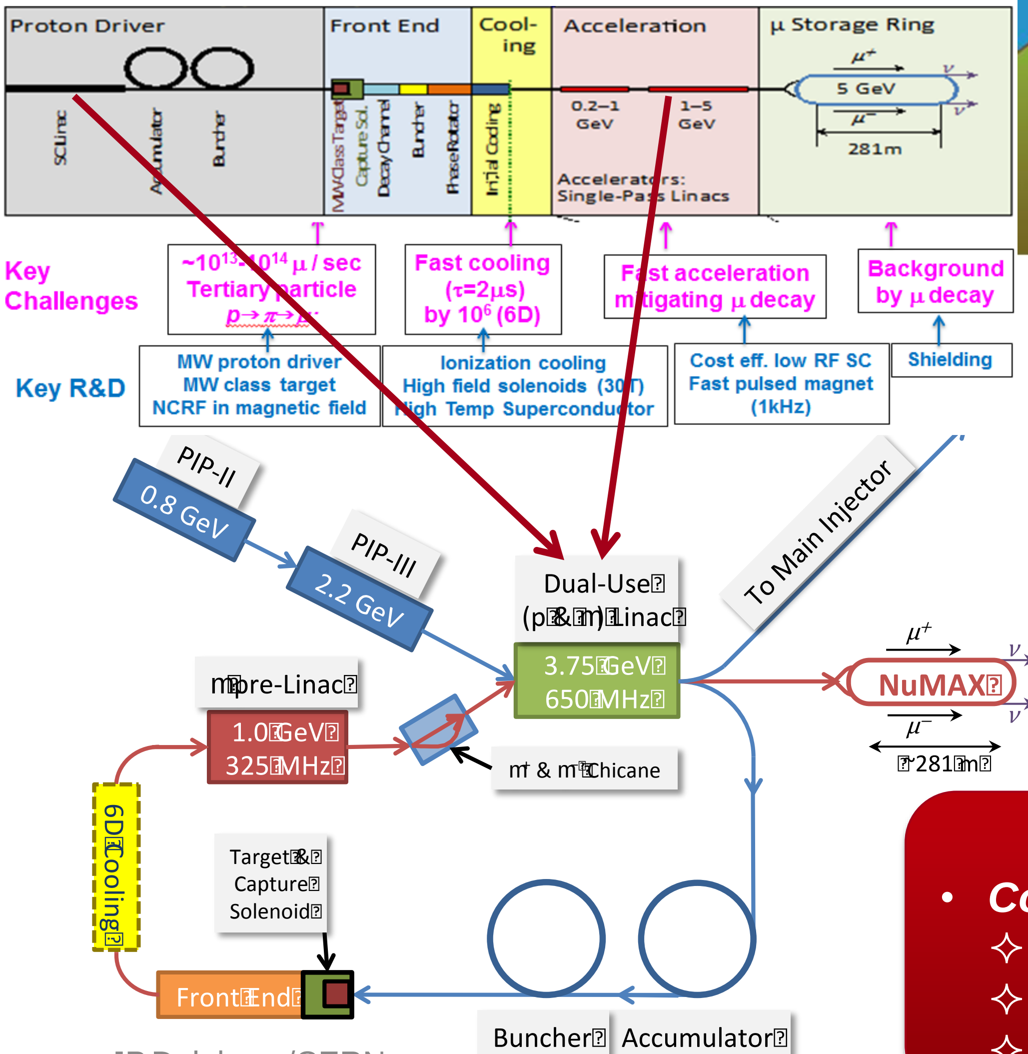
Bross,'Soler'

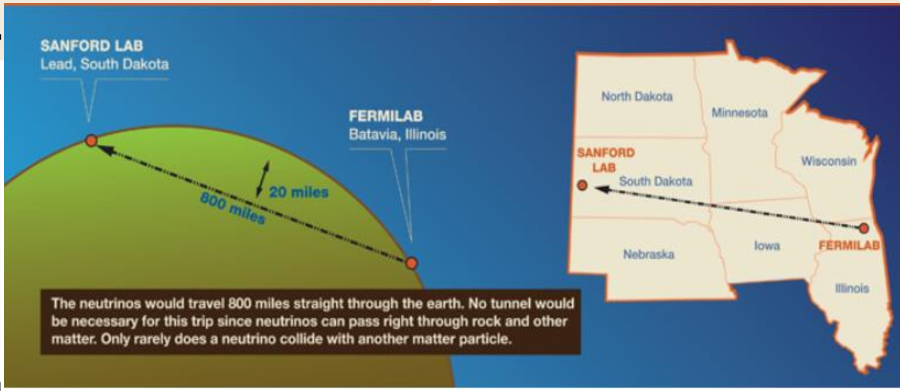
A site specific study: FNAL to SURF

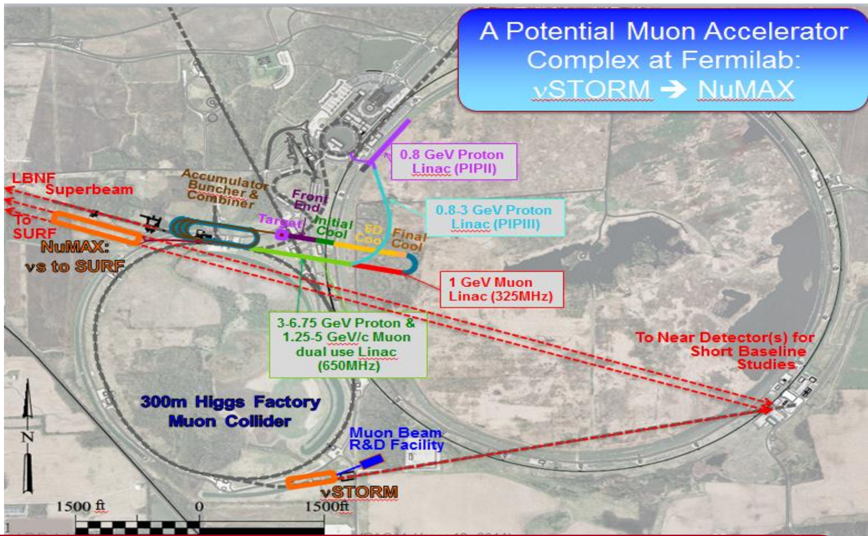
Muon Accel. Prog. (MAP)

NuMAX (Neutrinos from Muon Accelerator CompleX)

5GeV staged Neutrino Factory optimized for a far detector at SURF 1300kms from FNAL





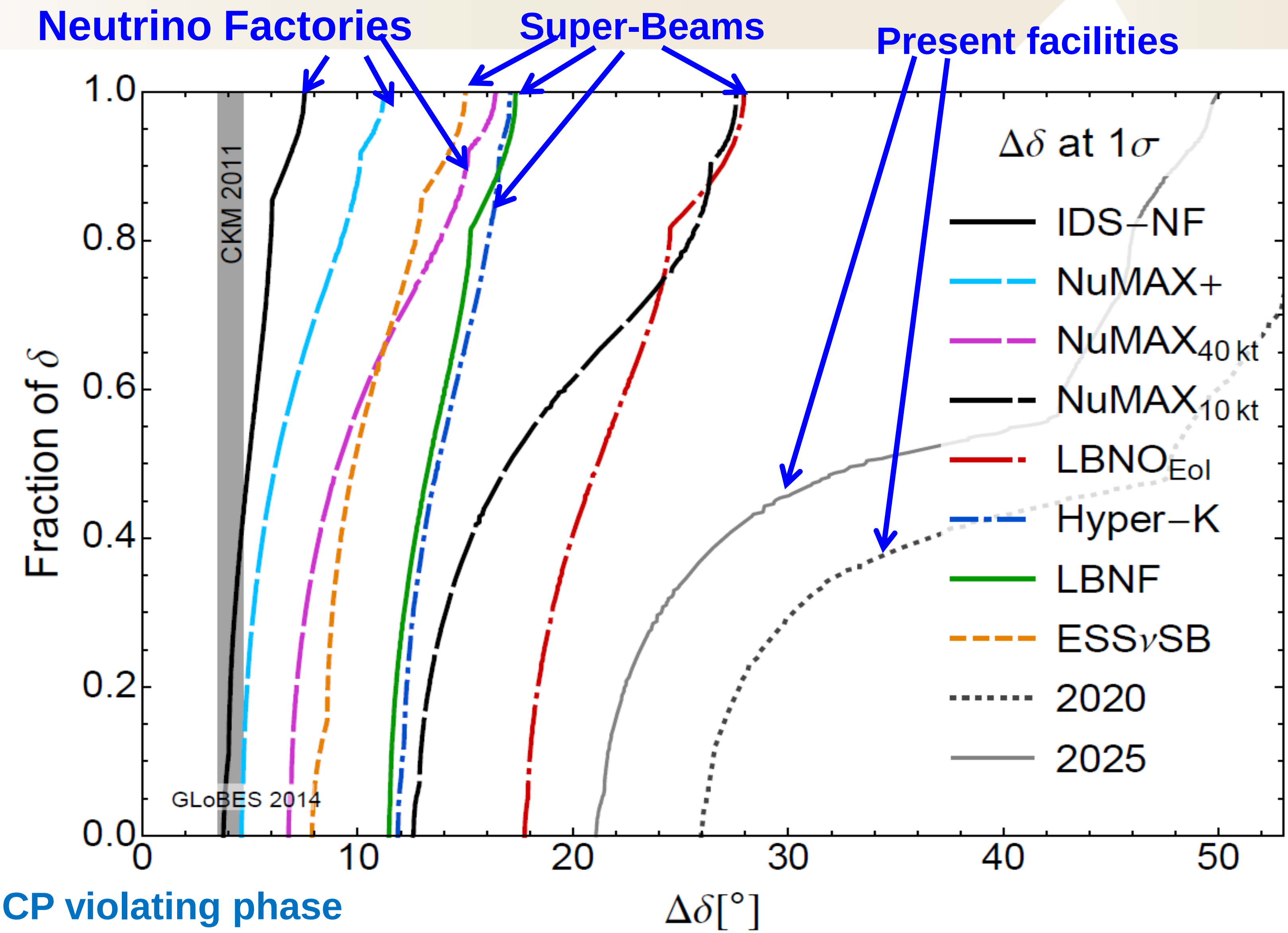


NuMAX Staging:

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

Physics reach of various technologies
A large improvement potential

Pilar Coloma

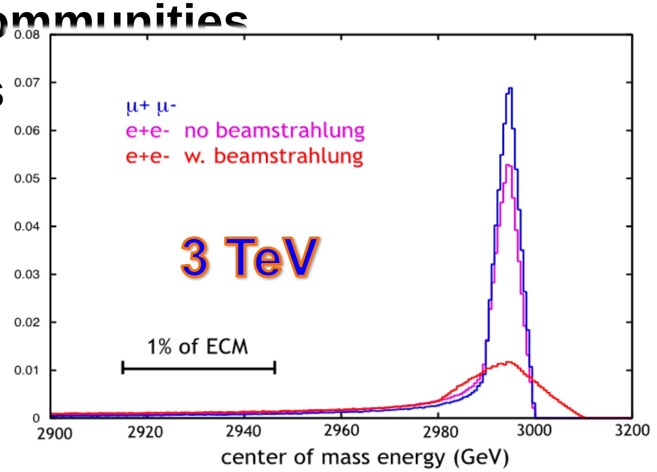


δ = CP violating phase

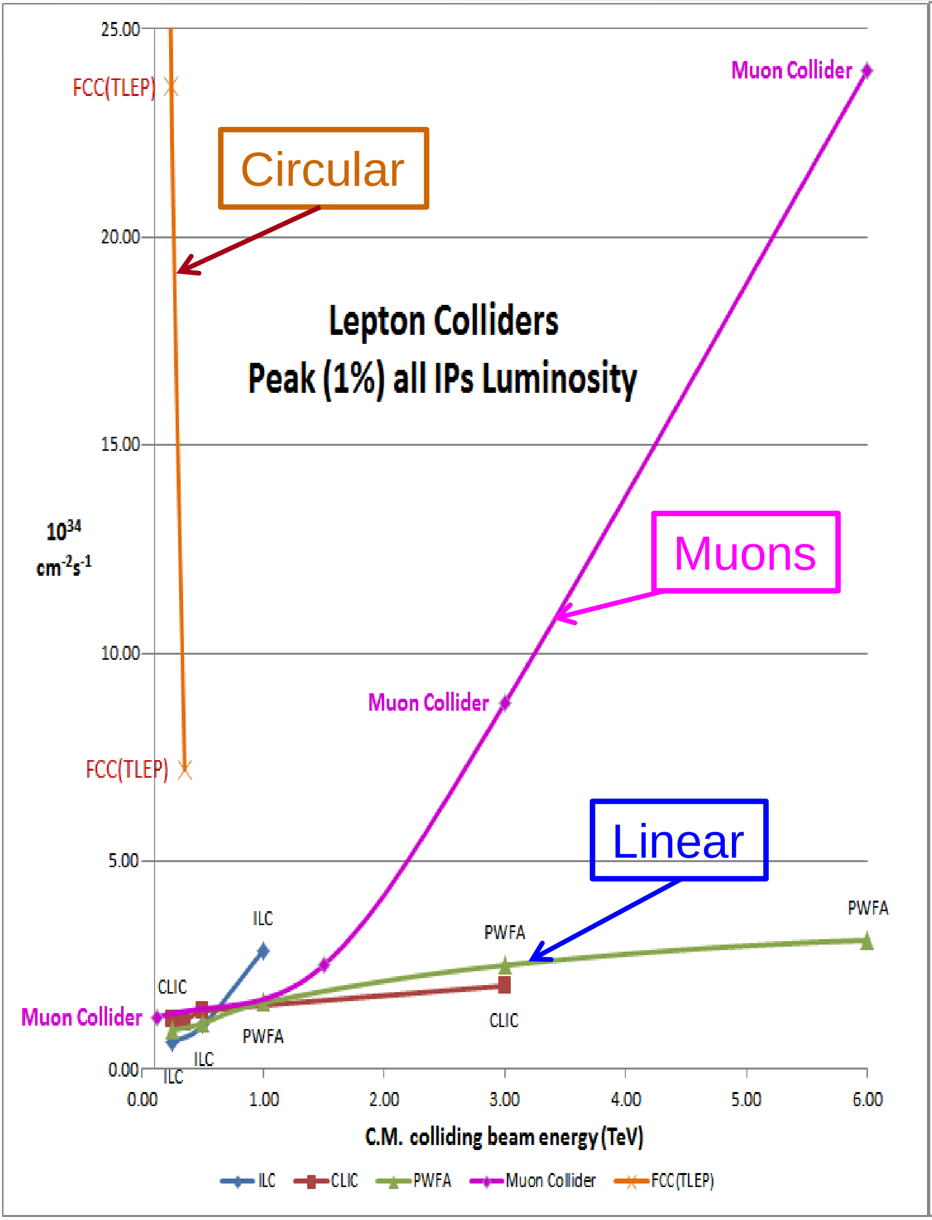
Muons based facilities: a novel and attractive technology for lepton colliders at high energy frontier

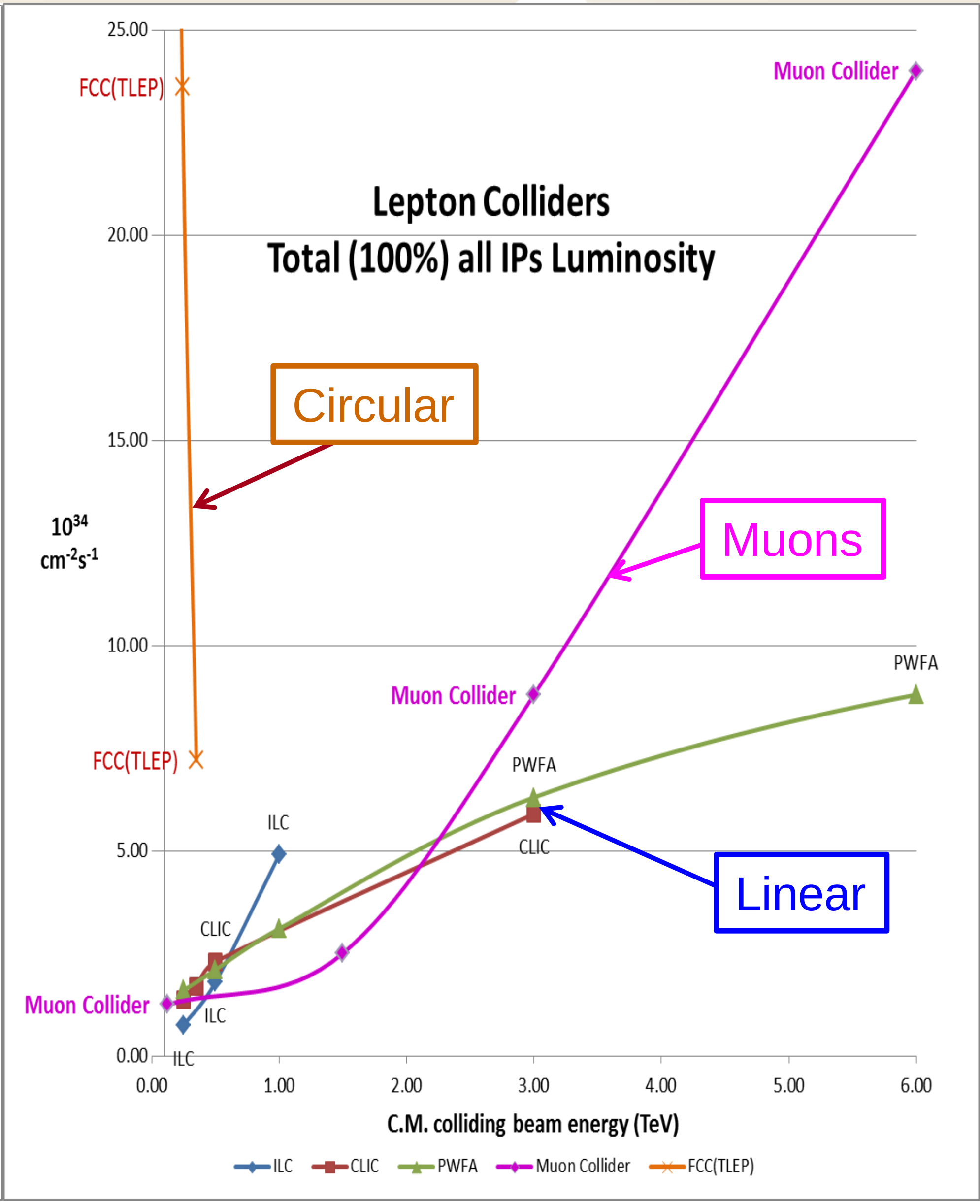
Muons are leptons like electrons & positrons but with a mass 207 times larger

- Negligible synchrotron radiation emission ($\alpha\ m^{-2}$)
  - Multi-pass collisions (1000 turns) in ring
    - High luminosity with reasonable beam power and power consumption
      - relaxed beam emittances & sizes, alignment & stability
    - Multi-detectors supporting broad physics communities
    - Large time (15 μs) between bunch crossings
  - No beam-strahlung at collision:
    - narrow luminosity spectrum
  - Multi-pass acceleration:
    - Cost effective construction & operation
    - Compact acceleration system and collider
  - No cooling by synchrotron radiation in standard damping rings
    - Requires development of novel cooling method

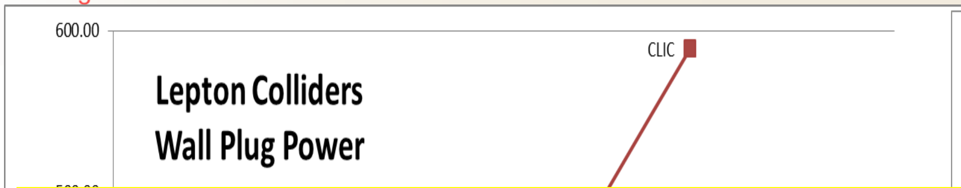


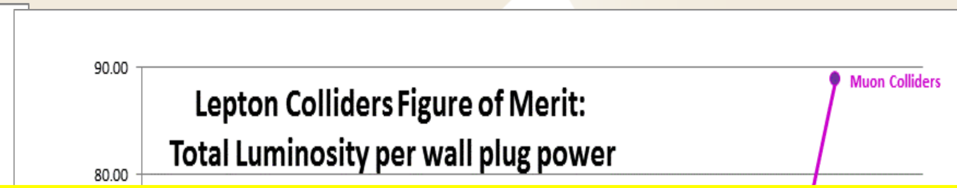
Muon Colliders extending high energy frontier with improved performances





Muon Colliders extending high energy frontier with potential of considerable power savings



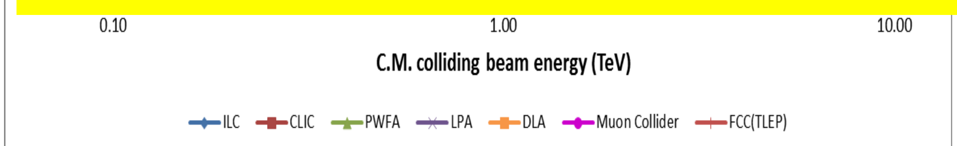


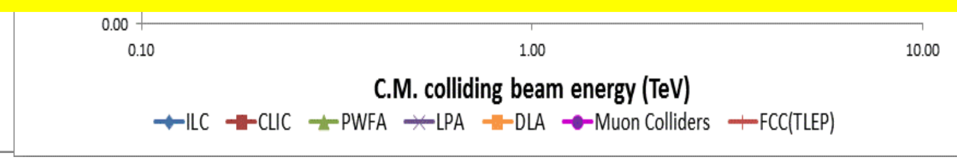
As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions without energy limitations

- **By synchrotron radiation as e^+e^- circular colliders**
- **By beams-trahlung as e^+e^- linear colliders**

Muon Collider the ideal technology to extend high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

If feasibility demonstrated





Muons: Issues & Challenges

- Limited lifetime: 2.2 μs at rest
  - ☹ Race against death: generation, acceleration & collision before decay
  - Muons decay in accelerator and detector
    - Shielding of detector and facility irradiation
    - Physics feasibility with large background?
  - Decays in neutrinos:
    - ☺ Ideal source of well defined electron and muon neutrinos in equal quantities :

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

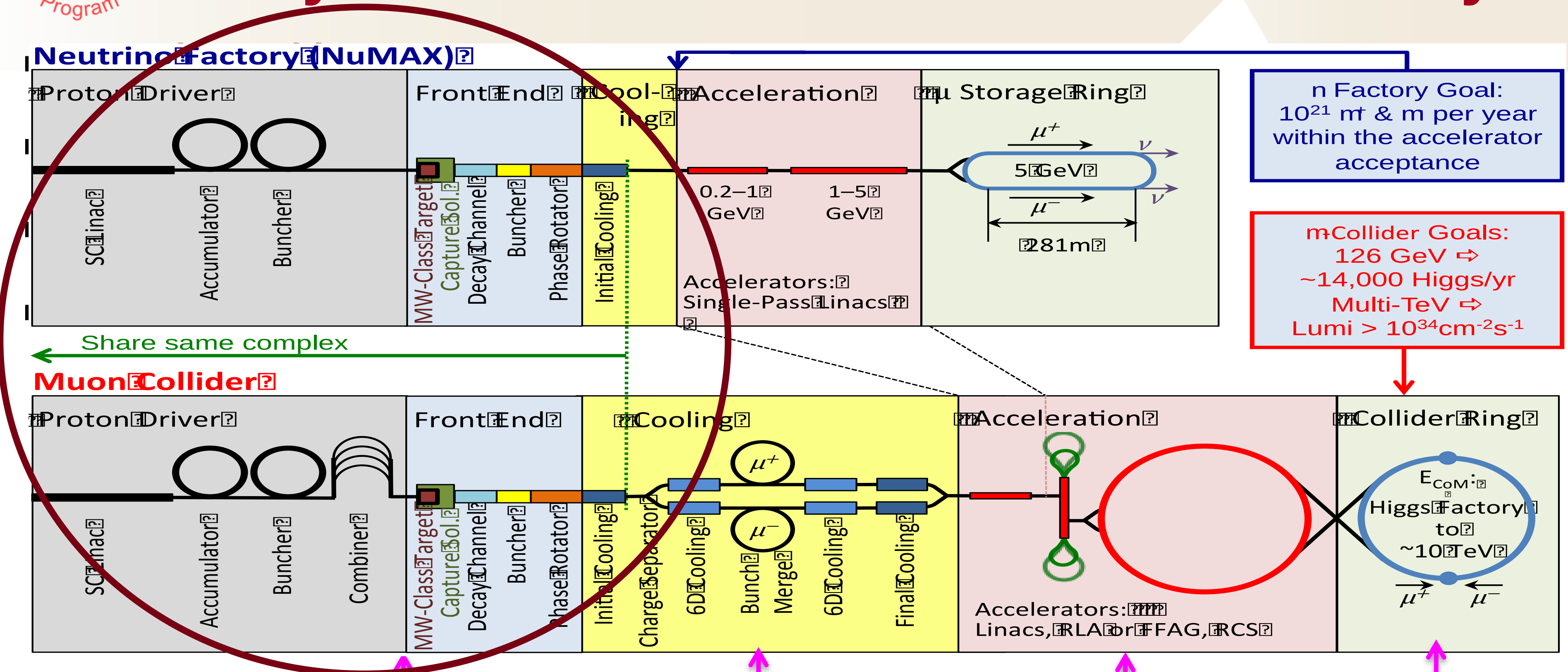
The neutrino factory concept

- Generated as tertiary particles in large emittances
  - ☹ powerful MW(s) driver: provided "for free" by ESSnuSB ☺
  - novel (fast) cooling method

Development of novel technologies

with key accelerator and detector challenges

Muon Accelerator Concepts
Key issues and R&D to address feasibility



Key Challenges

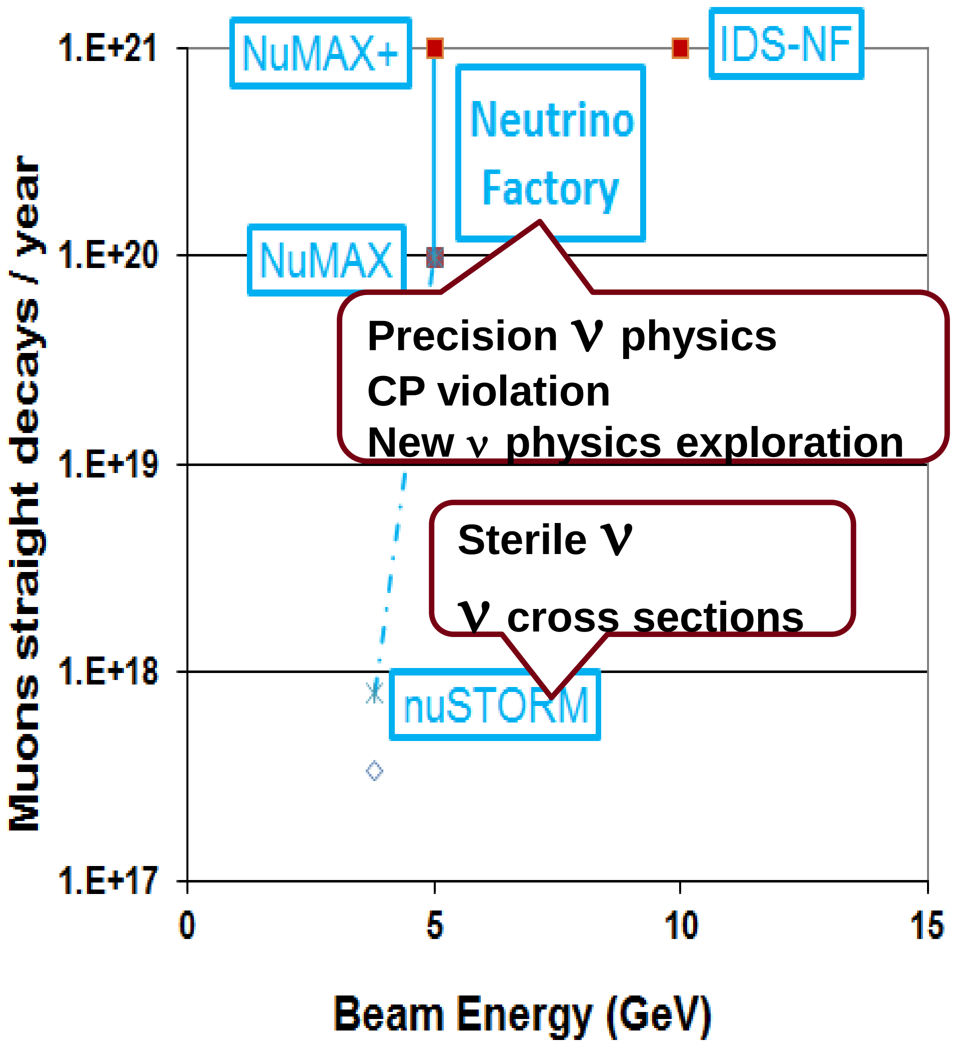
- ~10^{13}-10^{14} μ / sec
  Tertiary particle
  $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling
  (τ=2μs)
  by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D addressed by MAP

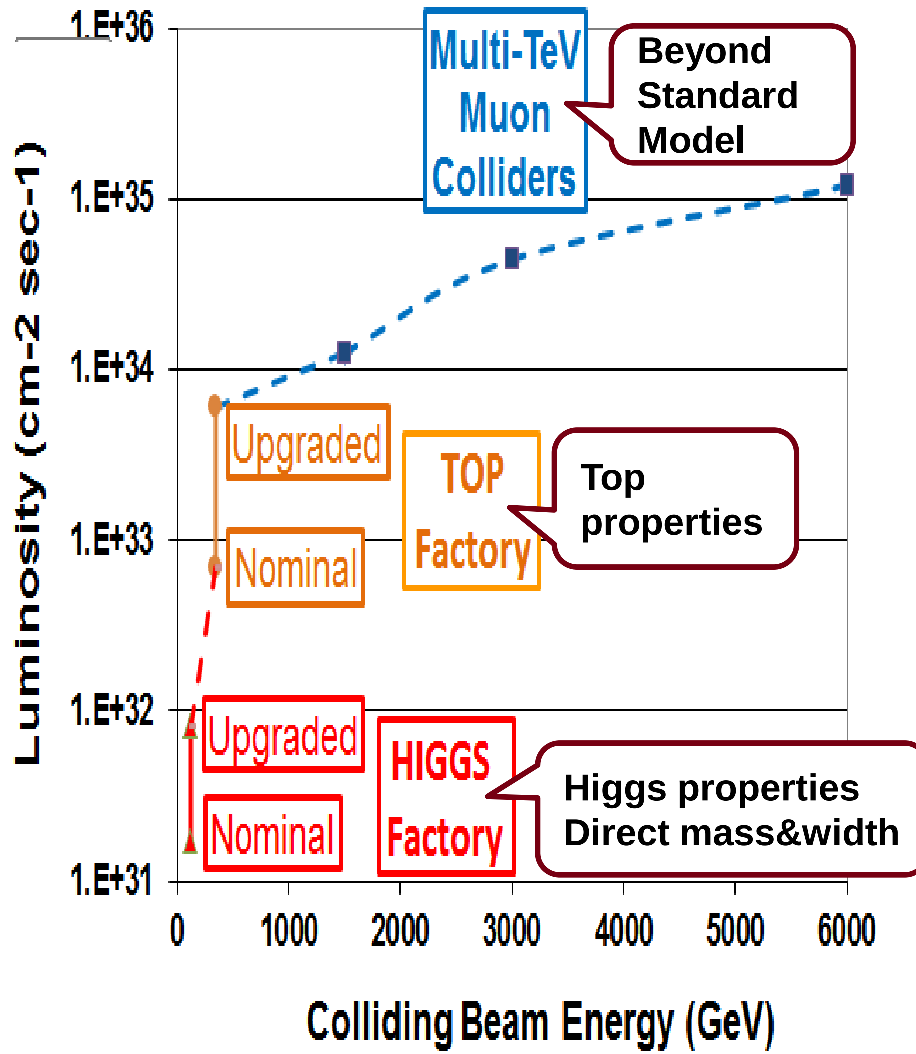
- MW proton driver
  MW class target
  NCRF in magnetic field
- Ionization cooling
  High field solenoids (30T)
  High Temp Superconductor
- Cost eff. low RF SC
  Fast pulsed magnet
  (1kHz)
- Detector/ machine interface

An attractive staging scenario of facilities with physics interest at each stage

Intensity Frontier



Energy Frontier



Staged Neutrino Factory and Muon Colliders
Increasing complexity and challenges
main parameters

Neutrino Factory at intensity frontier

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

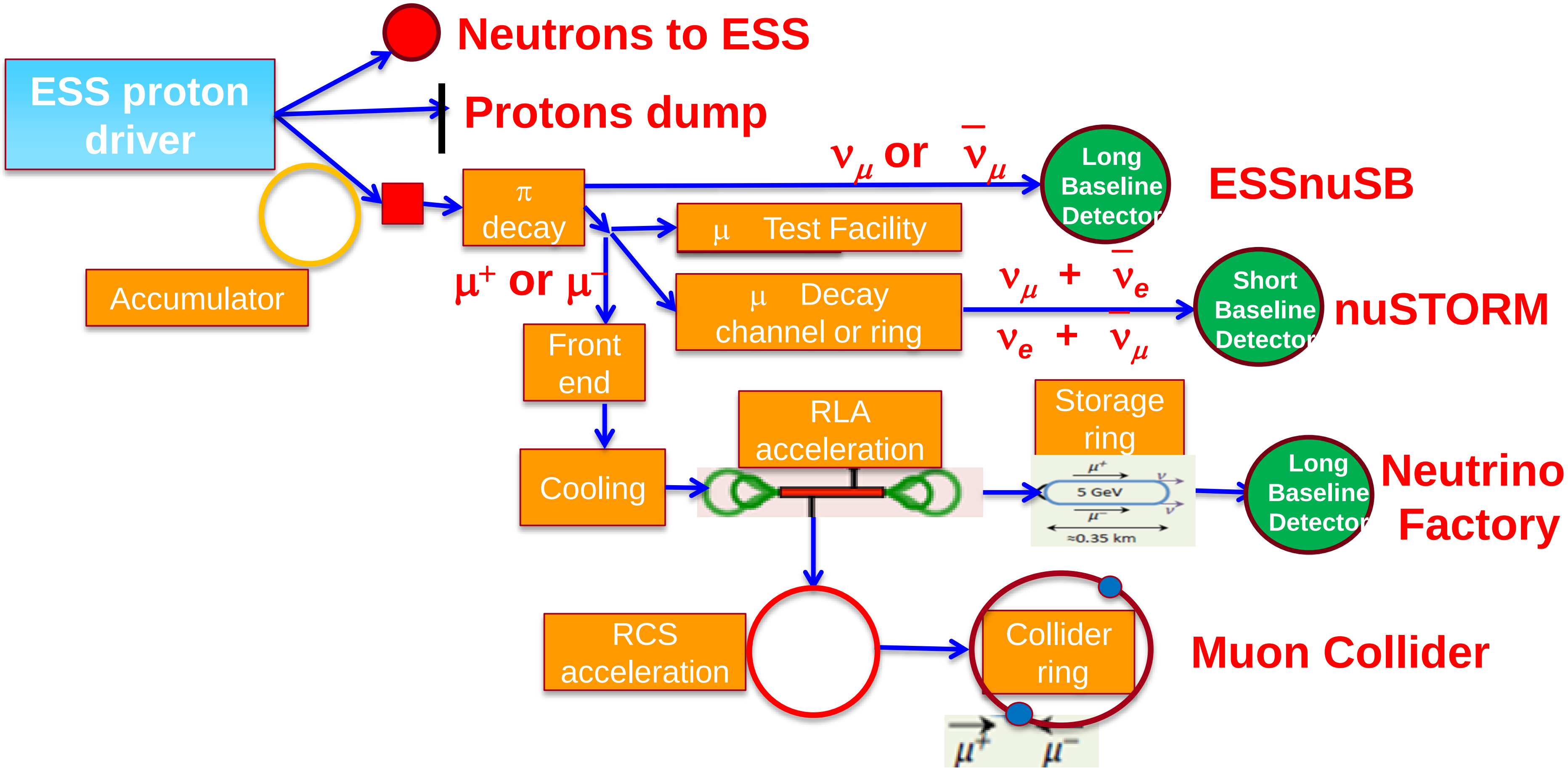
Muon Collider at the energy frontier

		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top$^+$ Production/10^7sec		3,500*	13,500*	7,000$^+$	60,000$^+$	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^{\#}$	4	4	4	4	4	1.6

Cooling — 6D no final (Higgs Factory) — Full 6D (Top Threshold Options, Multi-TeV Baselines)

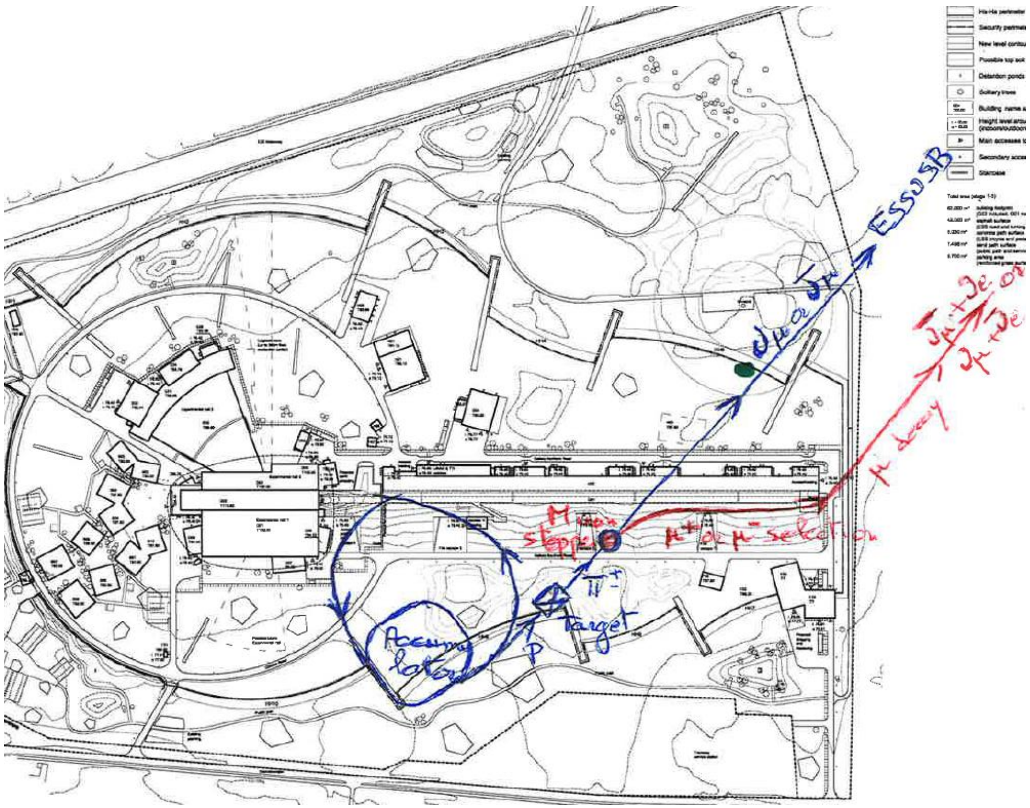
ESS linac with 5 MW beam power an appropriate proton driver

ESS neutrino and muons facility Built in stages (or some of them) with increasing complexity

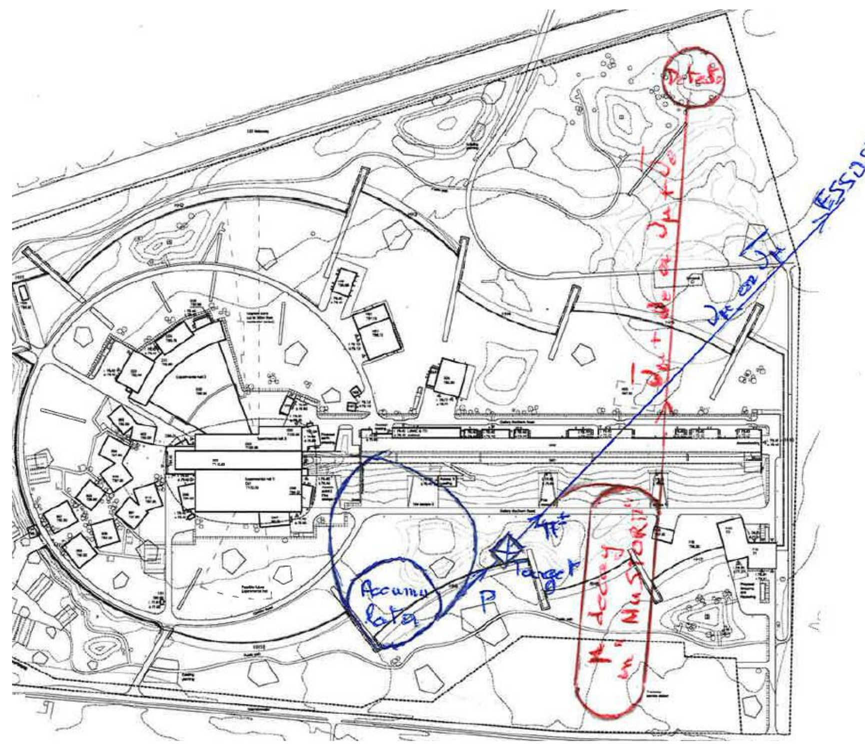


ESS-short-base-line-Neutrinos
Tentative layout on ESS site

ESS-MOMENT



ESS-nuSTORM



R&D to be included in design study

- ESS-muon facilities conceptual design study would strongly benefit and take advantage from the excellent work performed in the frame of the Muon Accelerator Program (MAP) especially:
  - the design, parameters and performance of the various options
- Nevertheless, the HB-2020 proposal should include ESS specificity issues:
  - Review and optimisation of design, parameters and performance of the various staged options based on ESS linac upgrade as foreseen for ESSnuSB, in particular:
    - Muon production with a 2.5GeV/5MW linac (MAP based on 8GeV/4MW)
    - Adaptation of the pions production target
  - Identification of further ESSnuSB upgrade of particular interest or necessary modifications for muon based facilities
  - Selection of the most attractive options in the ESS context and schedule
  - Their Implementation on ESS site and identification of possible conflicts
  - Identification of:
    - the major technical issues
    - the necessary R&D to demonstrate their feasibility
    - the corresponding cost drivers.

Conclusion

- **The ESS facility provides a unique opportunity for a range of top level muon-based facilities in parallel and complementary to the proposed superbeam neutrino long baseline facility, ESSnuSB.**
- **A cost efficient series of facilities, ranging from short baseline neutrino facility to neutrino factory and muon collider (or a selection of them depending on physics requirements), could be realistically considered in a staged approach.**
- **It would make the best use of the muons generated in parallel with neutrinos at the exit of the ESSnuSB pions decay channel instead of dumping them.**
- **It would leverage and take advantage of the, then existing, ESS world most powerful proton driver and of the ESSnuSB target & pions decay.**
- **Plea to include in the ESSnuSB conceptual study a possible extension in the future towards a staged series of (a selection of) muon based facilities including:**
  - ✓ **an estimation of their performance,**
  - ✓ **the required R&D to address their feasibility,**
  - ✓ **their adaptation and implementation on the ESS site in parallel with ESS as a neutron facility and ESSnuSB as a first stage neutrino facility.**