Muon Accelerators for the Next Generation of High Energy Physics Experiments

JP.Delahaye/SLAC on behalf of

M. Palmer, Director, U.S. Muon Accelerator Program

and the MAP collaboration effort:

Labs: ANL, BNL, FNAL, JLAB, LBNL, ORNL, SLAC

Universities: Chicago, Cornell, IIT, Princeton, UC-Berkeley, UCLA, UC-Riverside, UMiss

Companies: Muons, Inc; Particle Beam Lasers

The Aims of the Muon Accelerator Program

Muon accelerator R&D is focused on developing a facility that can address critical questions spanning two frontiers…

The Intensity Frontier:

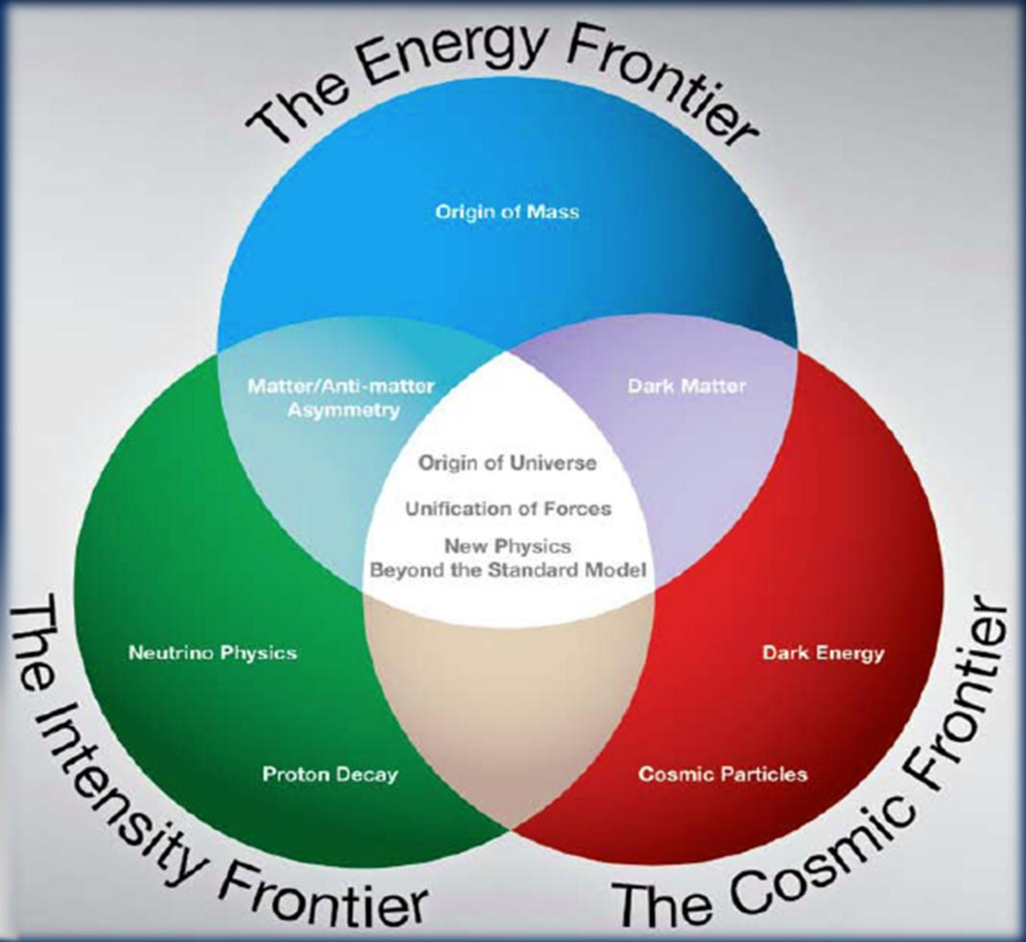
with a ***Neutrino Factory*** producing well-characterized ν beams for precise, high sensitivity studies

The Energy Frontier:

with a ***Muon Collider*** capable of reaching multi-TeV CoM energies

and

*a **Higgs Factory** on the border between these Frontiers*



The unique potential of a facility based on muon accelerators is physics reach that SPANS 2 FRONTIERS

The Physics Motivations

- μ – an elementary charged lepton:
  - 200 times heavier than the electron
  - 2.2 μs lifetime at rest

- Physics potential for the HEP community using muon beams
  - Provides equal fractions of electron and muon neutrinos at high intensity

    ideal for neutrino oscillations studies

    (the Neutrino Factory concept)

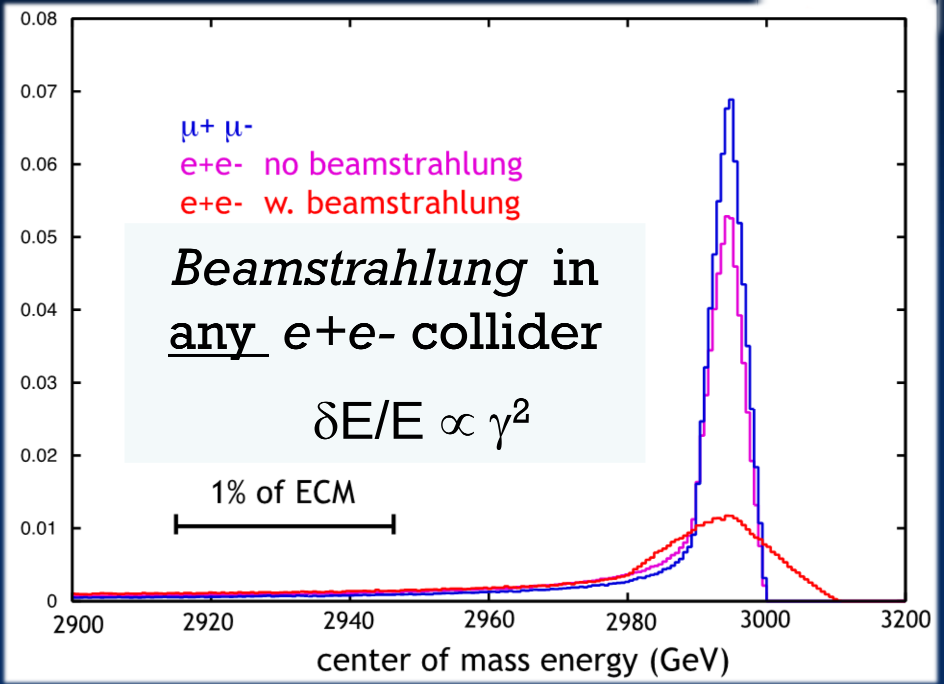
$$m^{+} \to e^{+} n_e \bar{n}_m$$

$$m^{-} \to e^{-} \bar{n}_e n_m$$

  - As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions
  - Large coupling to the "Higgs mechanism" $\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$
    - Precision Higgs width determination by g-2 precision beam energy measurement

Muon Accelerator Physics

- Large muon mass strongly suppresses synchrotron radiation
  - ⇨ Muons can be accelerated & stored using rings at much higher energy than electrons
  - ⇨ Colliding beams of higher quality due to reduced beamstrahlung

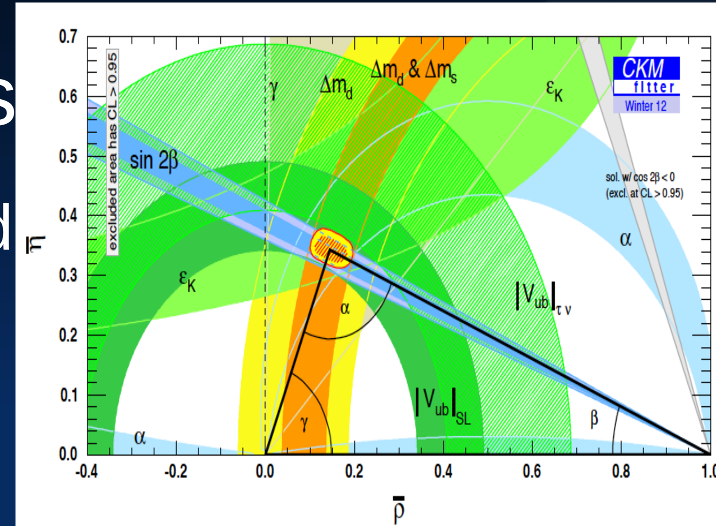


- Novel technology with major technical challenges
  - – Muon beams produced as tertiary beams $p \rightarrow \pi \rightarrow \mu$
  - – Large transveres and longidunial emittances: 6D cooling!
  - – Short muon lifetime
    - Fast acceleration and limited storage time of a muon beam
    - Collider ⇨ a new class of decay backgrounds must be dealt with

Neutrinos: outstanding Physics

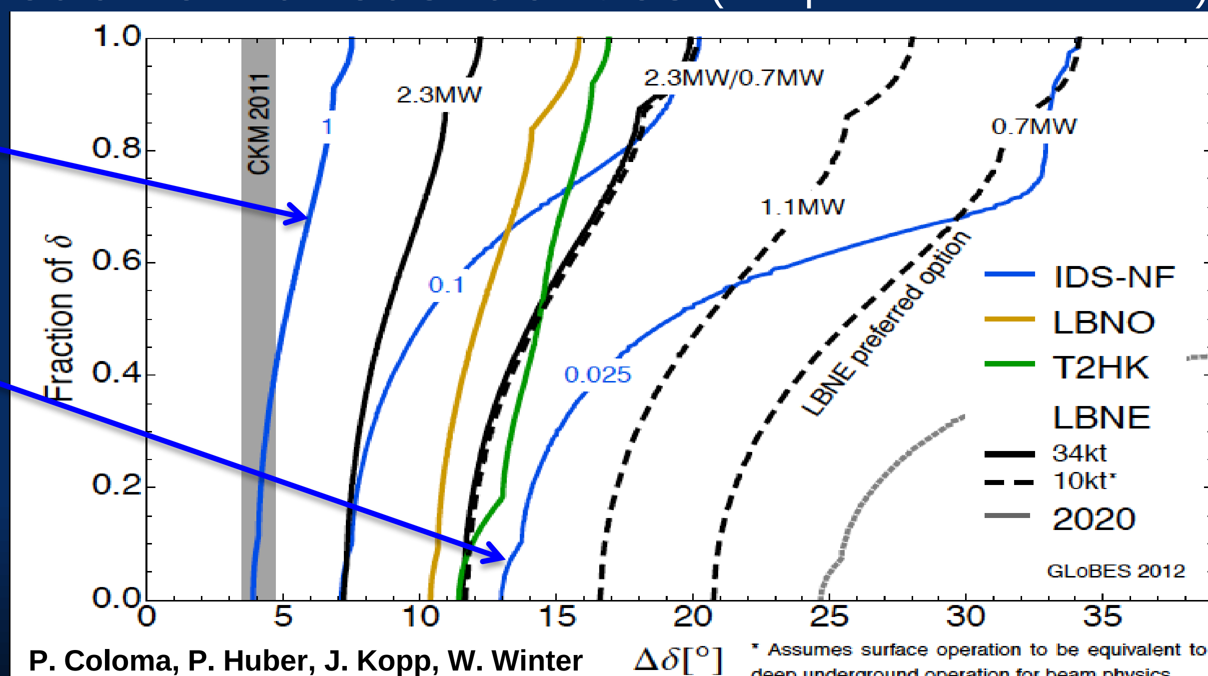
- In neutrino sector critical to understand
  - δ_{CP}
  - The mass hierarchy
  - $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$
  - Resolve LSND and short baseline experimental anomalies
  - And continue to probe for signs new physics
- CP violation physics reach of various facilities (compared to CKM matrix)

P. Huber



IDS-Neutrino Factory

0.025 IDS-NF:
700kW target,
no cooling,
2×10^{8} s running time
10-15 kTon detector

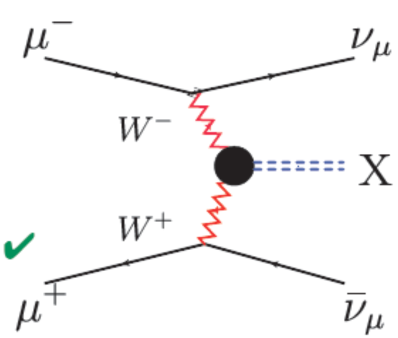


E. Eichten

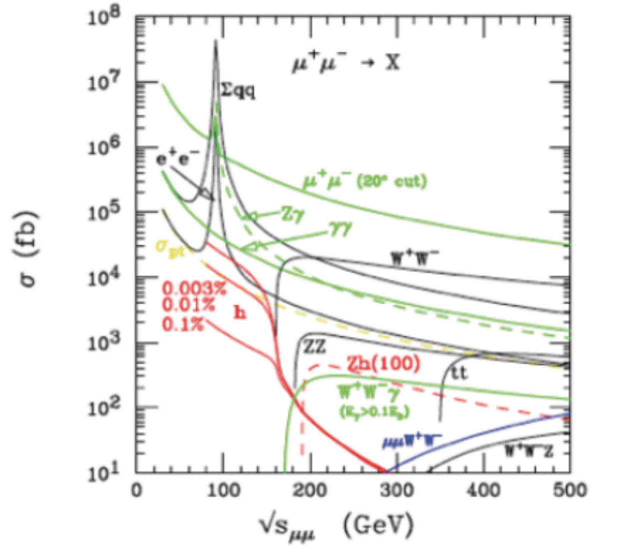
Muon Collider Reach

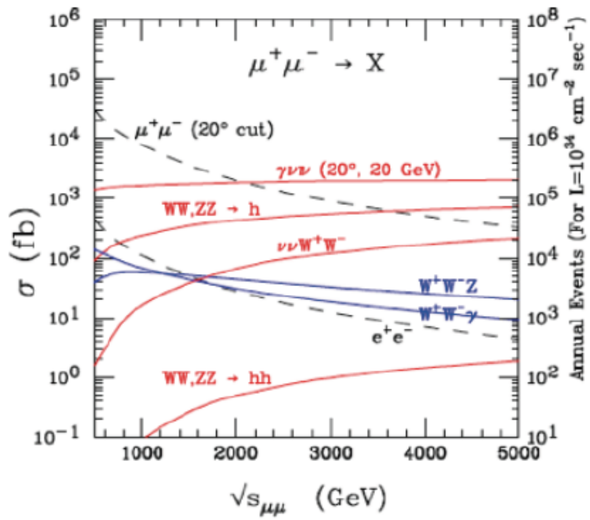
- For √s < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory (√s≈ 126 GeV) ✔
- For √s > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central (| θ | > 10°) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
    - At √s = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)
- For √s > 1 TeV
  - Fusion processes important at multi-TeV MC

$$\sigma(s) = C\ln(\frac{s}{M_X^2}) + \ldots$$



  - An Electroweak Boson Collider ✔





Muon Accelerators

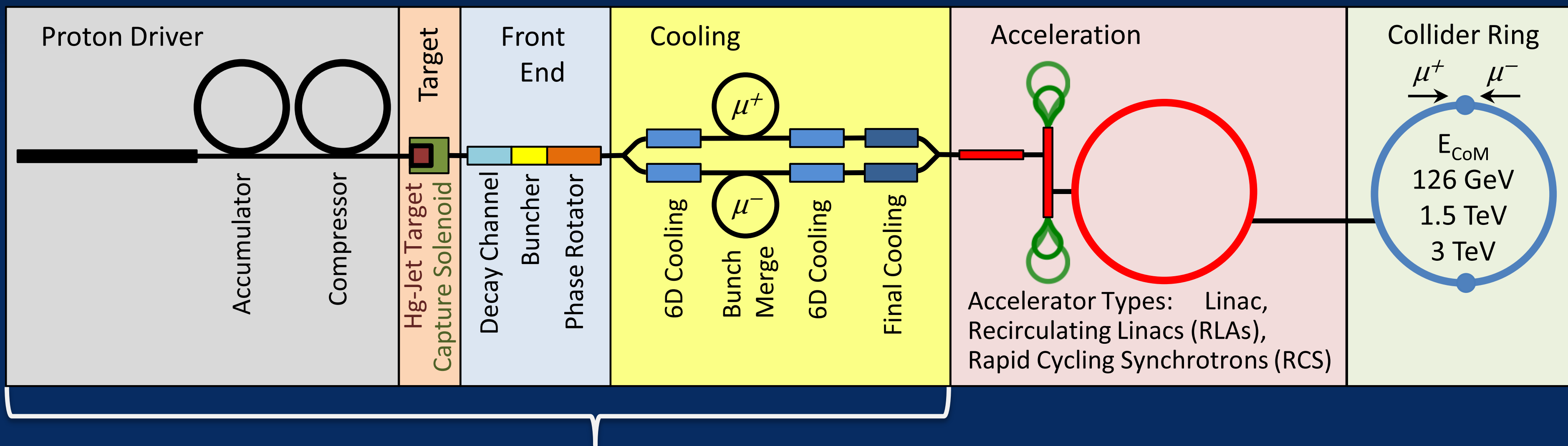
Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*10%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
FNAL NF Phase I (PX Ph 2)	*4-6 GeV*	*$8x10^{19}$*
FNAL NF Phase II (PX Ph 2)	*4-6 GeV*	*$5x10^{20}$*
IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/yr**
s-Channel μ Collider	~126 GeV CoM	5,000-40,000
Energy Frontier μ Collider	**> 1 TeV CoM**	**Avg. Luminosity**
Opt. 1	*1.5 TeV CoM*	*$1.2x10^{34} cm^{-2} s^{-1}$*
Opt. 2	*3 TeV CoM*	*$4.4x10^{34} cm^{-2} s^{-1}$*
Opt. 3	*6 TeV CoM*	*$12x10^{34} cm^{-2} s^{-1}$*

* Decays of an individual species (ie, μ^+ or μ^-)

Program Baselines
And Potential Staging Steps

Muon Collider Concept

Muon Collider Block Diagram



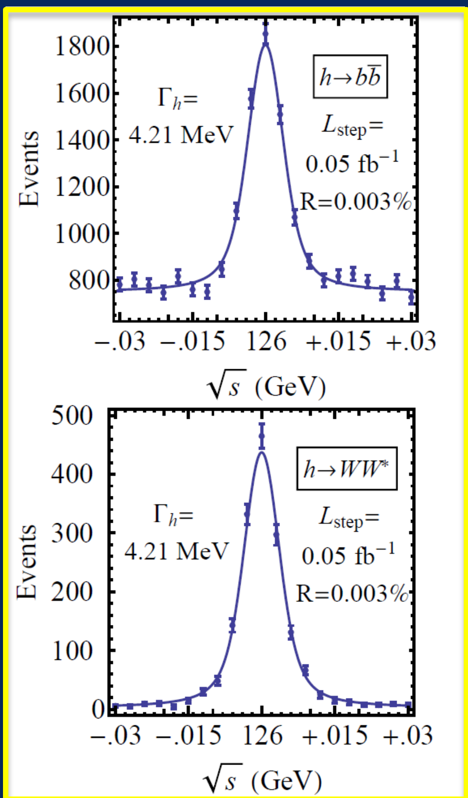
Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

Goal:
Produce a high intensity μ beam whose 6D phase space is reduced by a factor of ~10^6-10^7 from its value at the production target

Collider: $\sqrt{s}$ = 3 TeV
Circumference 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = 2×10^{12}
$\sigma(p)/p$ = 0.1%
$\varepsilon_{\perp N}$ = 25 μm, $\varepsilon_{//N}$=72 mm
β^* = 5mm
Rep. Rate = 12 Hz

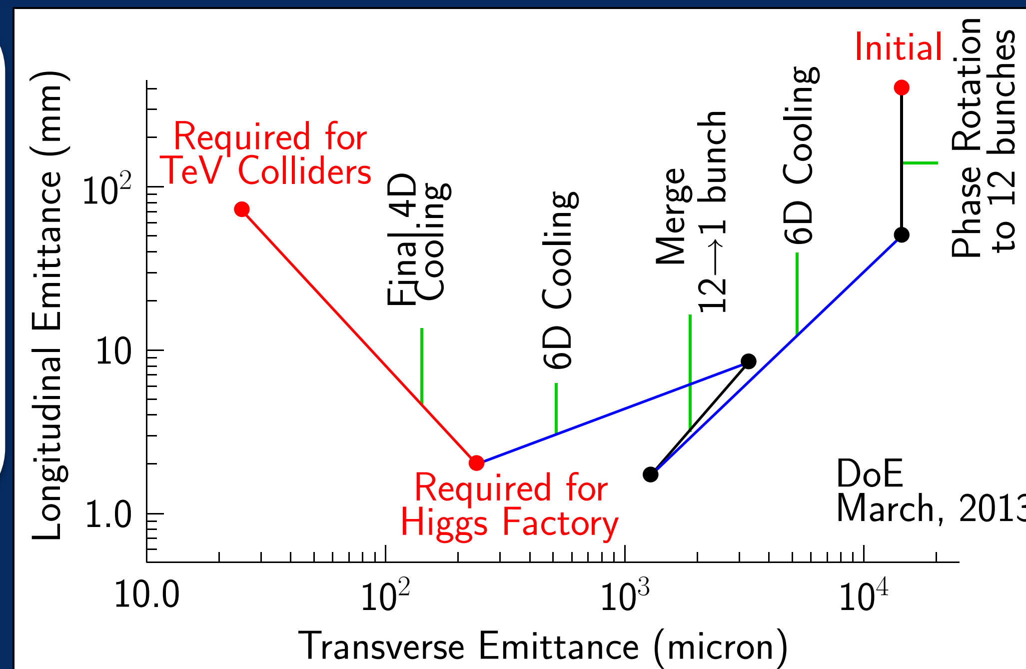
126 GeV Higgs Factory

s-channel coupling of Muons to HIGGS with high cross sections:
Muon Collider of with L = 10^{32} cm^{-2}s^{-1} @ 63 GeV/beam (50000 Higgs/year)
Competitive with e+/e- Linear Collider with L = 2. 10^{34} cm^{-2}s^{-1} @ 126 GeV/beam
Sharp resonance: momentum spread of a few × 10^{-5}



Precision energy measurement provided by g-2 effect and residual polarization in muon beams

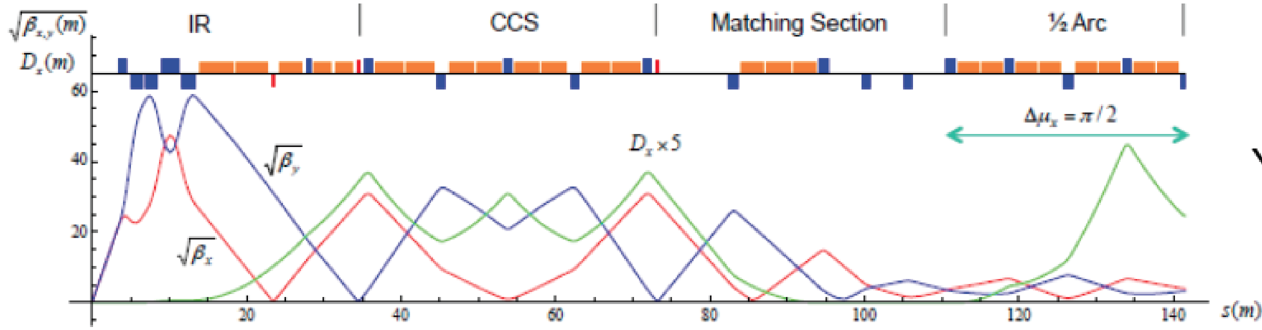
Han and Liu
hep-ph 1210.7803



Reduced cooling:
$\varepsilon_{\perp N}$ =0.3π·mm·rad,
$\varepsilon_{\| N}$ =1π·mm·rad

Major advantage for Physics of a $\mu^+\mu^-$ Higgs Factory: possibility of direct measurement of the Higgs boson width (Γ~4MeV FWHM expected)

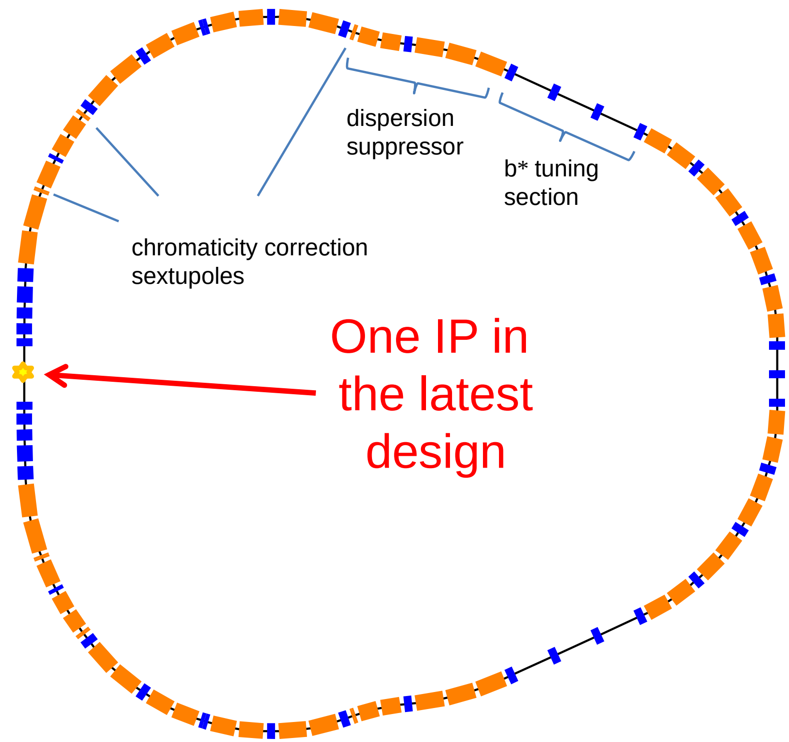
Updated 63 x 63 GeV Lattice



Y. Alexahin

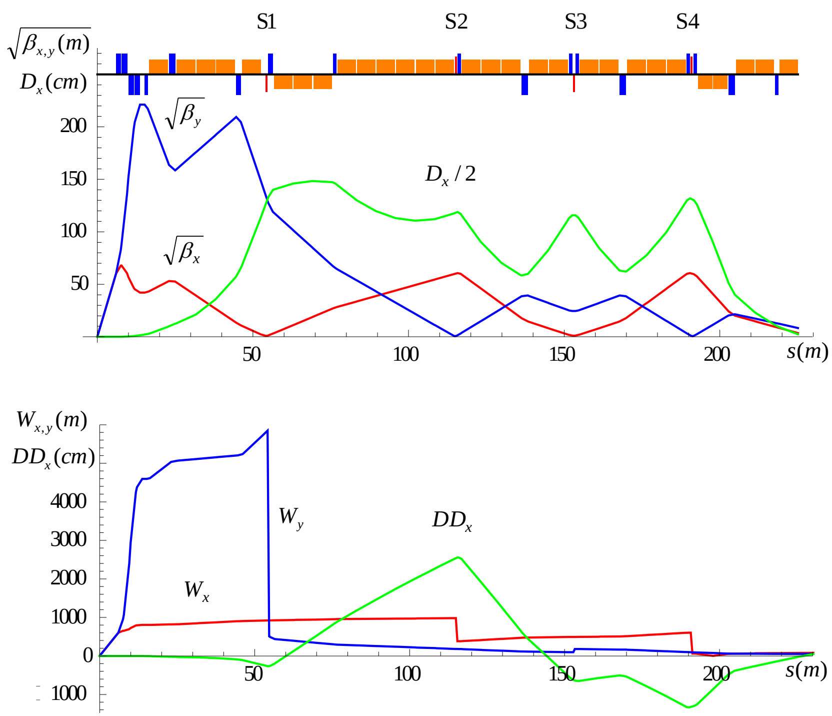
Optics functions in half ring for β*=2.5cm

Parameter			
Beam energy	GeV	63	63
Average luminosity	10^{31}/cm²/s	1.7	8.0
Collision energy spread	MeV	3	4
Circumference, C	m	300	300
Number of IPs	-	1	1
β*	cm	3.3	1.7
Number of muons / bunch	10^{12}	2	4
Number of bunches / beam	-	1	1
Beam energy spread	%	0.003	0.004
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.4	0.2
Longitudinal emittance, $\varepsilon_{\parallel N}$	π·mm	1.0	1.5
Bunch length, σ_s	cm	5.6	6.3
Beam size at IP, r.m.s.	mm	0.15	0.075
Beam size in IR quads, r.m.s.	cm	4	4
Beam-beam parameter	-	0.005	0.02
Repetition rate	Hz	30	15
Proton driver power	MW	4	4



Multi-TeV Collider – 1.5 TeV Baseline

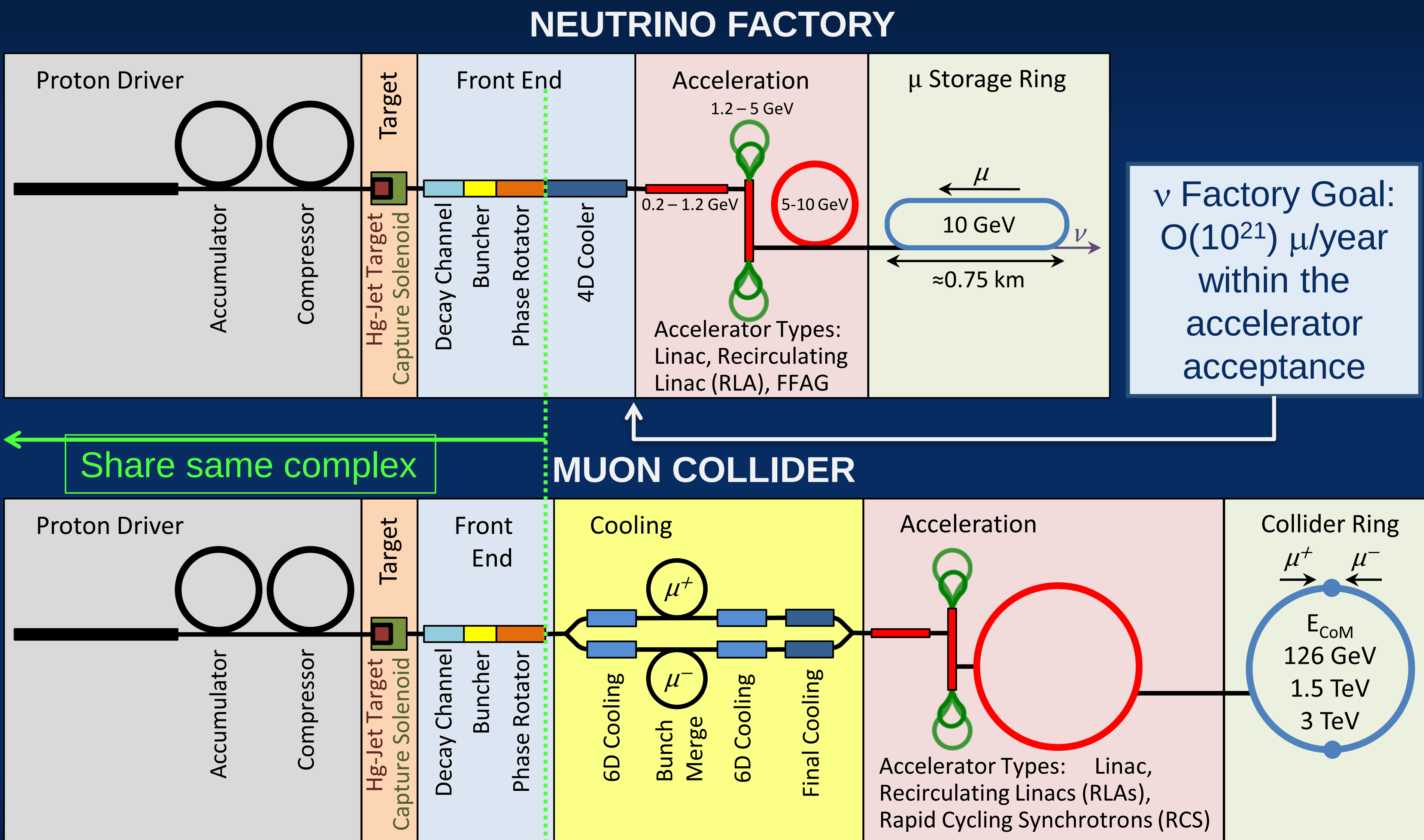
Y. Alexahin



Larger chromatic function (Wy) is corrected first with a single sextupole S1, Wx is corrected with two sextupoles S2, S4 separated by 180° phase advance.

Parameter	Unit	Value
Beam energy	TeV	0.75
Repetition rate	Hz	15
Average luminosity / IP	$10^{34}/cm^2/s$	1.1
Number of IPs, N_{IP}	-	2
Circumference, C	km	2.73
β^*	cm	1 (0.5-2)
Momentum compaction, α_p	10^{-5}	-1.3
Normalized r.m.s. emittance, $\varepsilon_{\perp N}$	π·mm·mrad	25
Momentum spread, σ_p/p	%	0.1
Bunch length, σ_s	cm	1
Number of muons / bunch	10^{12}	2
Number of bunches / beam	-	1
Beam-beam parameter / IP, ξ	-	0.09
RF voltage at 800 MHz	MV	16

Muon Collider - Neutrino Factory Synergies

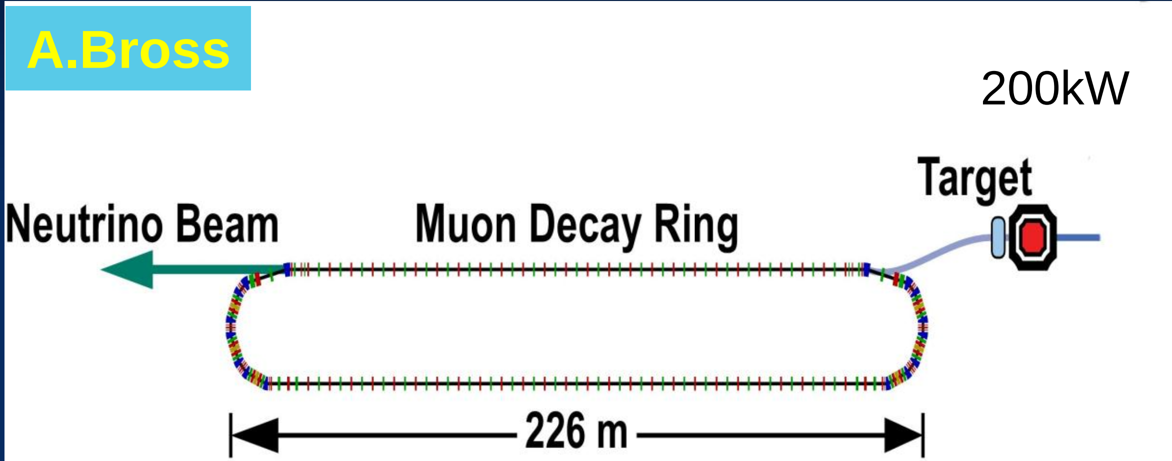


A Staged Muon-Based Neutrino and Collider Physics Program

The plan is conceived in four stages.

- The "entry point" for the plan is the nuSTORM Facility proposed at Fermilab, which can advance SBL oscillation physics by making the definitive measurements regarding the existence of light sterile neutrinos. Secondly, it can provide an unprecedented program of ν interaction physics important in itself and to the long-baseline oscillation program. Finally, it can serve as an R&D platform for demonstration of accelerator capabilities pre-requisite to the later stages.
- A stored-muon-beam Neutrino Factory can take advantange of the large value of θ_{13} to make definitive measurements of neutrino oscillations and their possible violation of CP symmetry.
- Thanks to suppression of radiative effects by the muon mass adnn the m^2_{lepton} proportionality of the *s*-channel Higgs couling, a "Higgs Factory Muon Collider can make uniquely precise measurements of the 126 GeV boson recently discovered at the LHC.
- An energy-frontier Muon Collider can perform unique measurements of Terascale physics, offering both precision and discovery reach.

NuSTORM: Neutrinos from Stored Muons
Fermilab P-1028



An entry-level NF?

DOES NOT
Require the
Development of
ANY
New Technology

Stage I approval requested at last weeks Fermilab PAC meeting

NuSTORM Workshop held Sept 21-22 @ FNAL:

(https://indico.fnal.gov/conferenceDisplay.py?confId=5710)

νSTORM

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

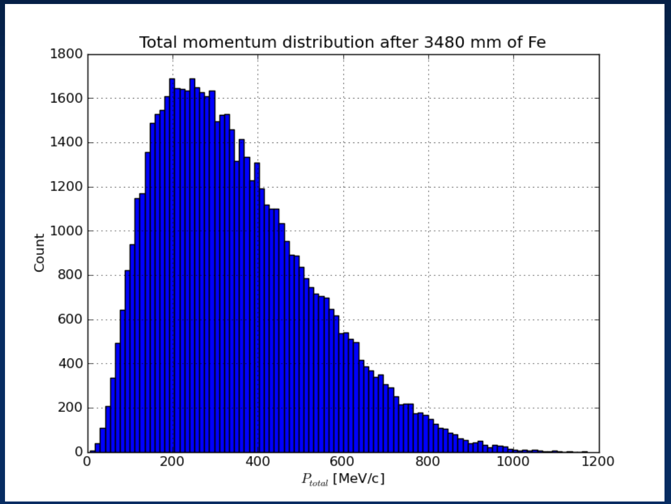
$\nu_e \to \nu_\mu$ CC	330
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47000
$\nu_e \to \nu_e$ NC	74000
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122000
$\nu_e \to \nu_e$ CC	217000

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

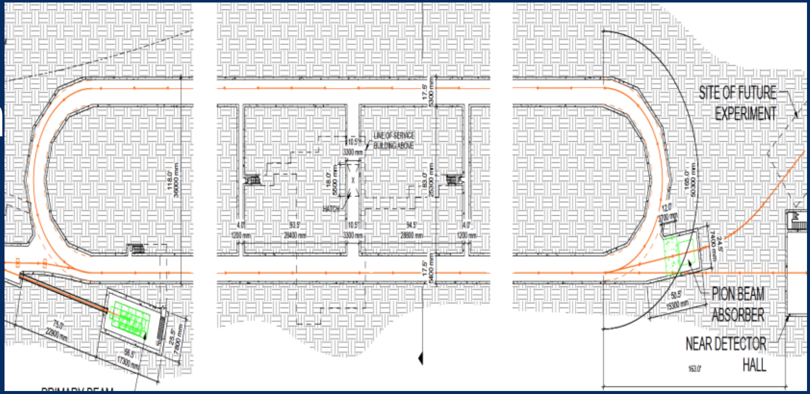
With more than 200 000 ν_e CC events a %-level ν_e cross section measurement should be possible

nuSTORM as an R&D platform

- A high-intensity pulsed muon source
  100<p_μ<300 MeV/c muons
  - Using extracted beam from ring
  - 10^{10} muons per 1 μsec pulse

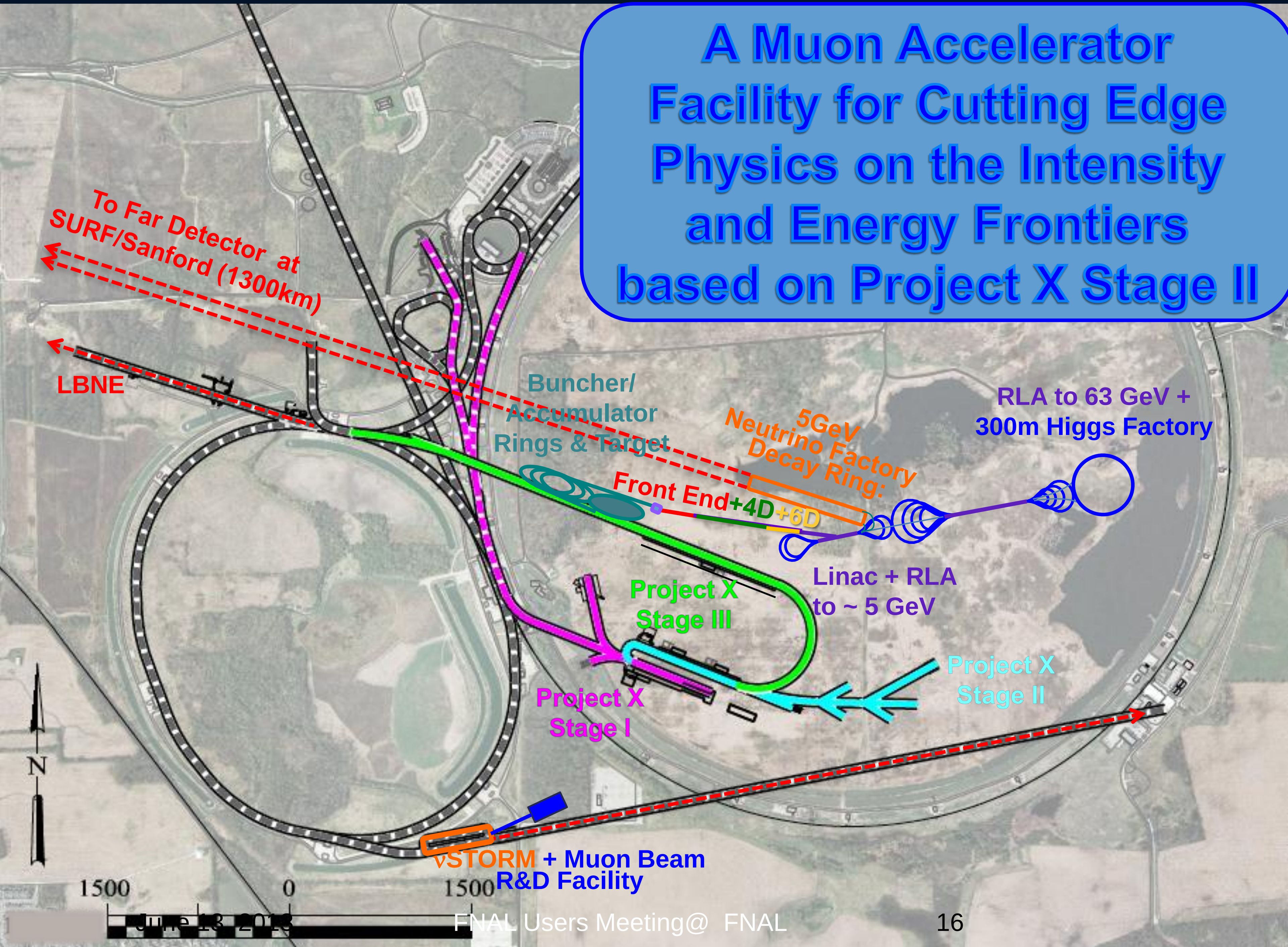


- Beam available simultaneously with physics operation
  - Sterile ν search
  - ν cross interaction physics program



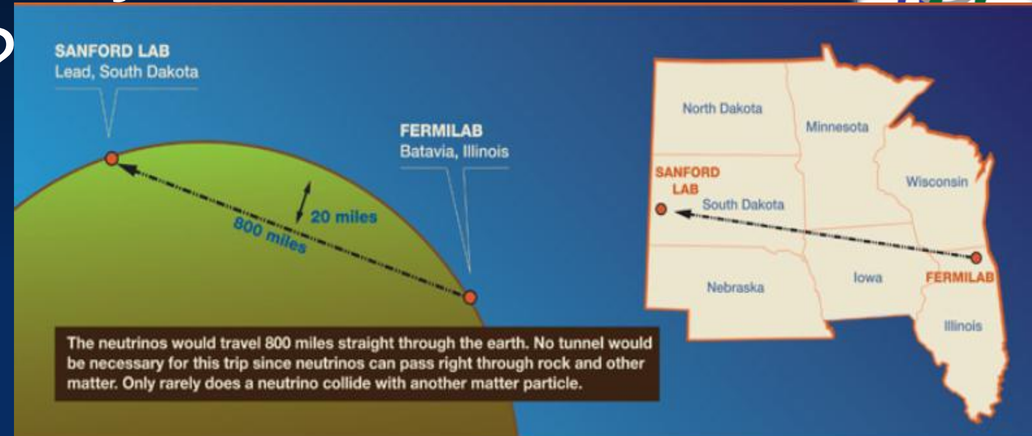
- nuSTORM also provides the opportunity to design,build&test:
  - decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure & characterize the circulating muon flux
  - 6D cooling of high intensity muon beam

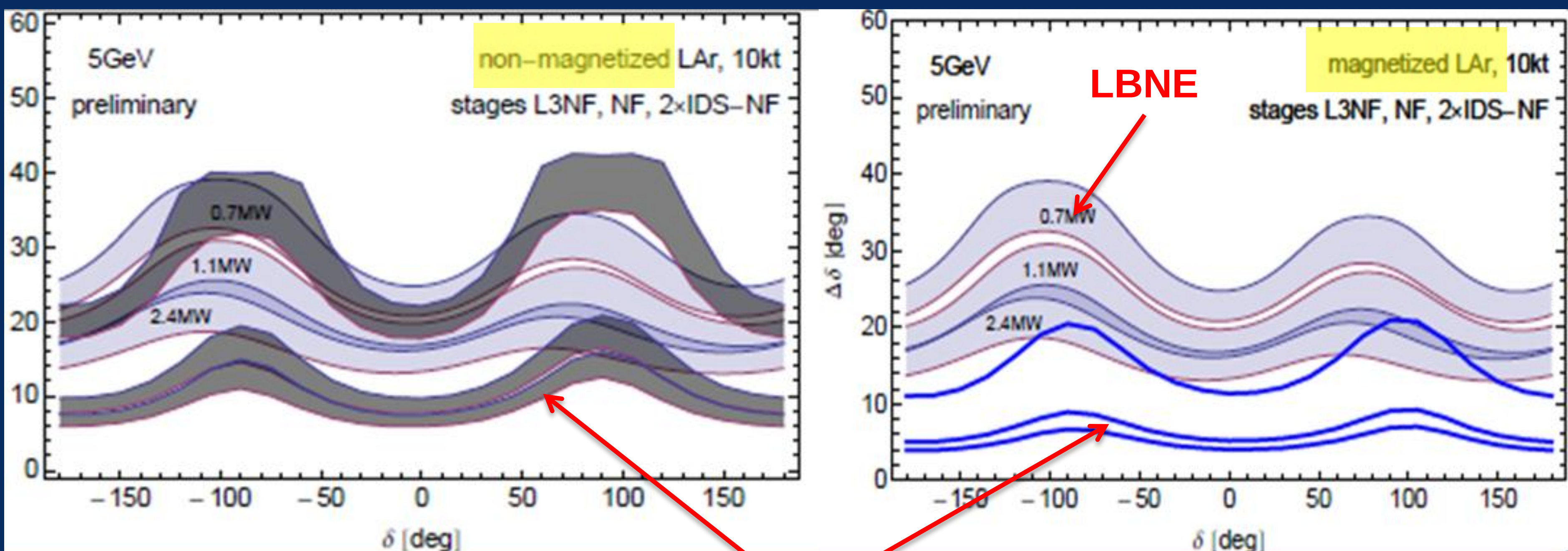
A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers based on Project X Stage II



A Staged Neutrino Factory with far detector at SANFORD (LBNE)?

- ⇨ 1 MW, no muon cooling
- ⇨ 3 MW, with cooling
- ⇨ 4 MW, with cooling





Neutrino Factory

Gray bands represent range of possible detector performance per arXiv:0805.2019

Plots assume 100 kt-years

Plots courtesy of P. Huber

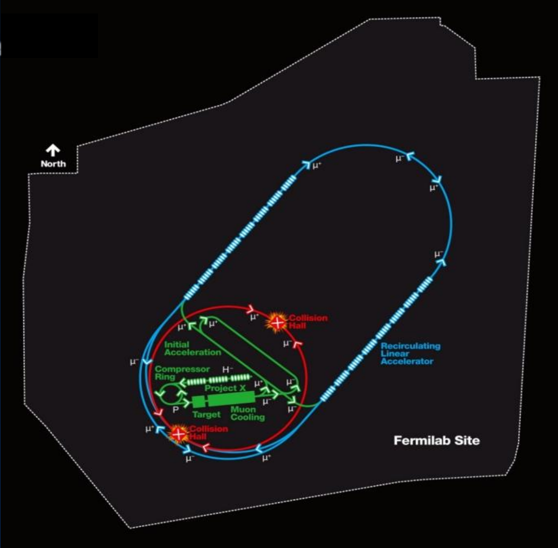
Neutrino Factory Staging (MASS)

Preliminary Staging Plan Based on **Project X Phase 2**

System	Parameters	Unit	NuSTORM	L3NF	NF	IDS-NF
Performance	stored μ+ or μ-/year		8×10^{17}	2×10^{20}	1.2×10^{21}	1×10^{21}
	ν_e or ν_μ^* to detectors/yr		3×10^{17}	8×10^{19}	5×10^{20}	5×10^{20}
Detector	Far Detector	Type	Super-Bind*	Mag LAr	Mag LAr	Super-Bind
	Distance from ring	km	1.5	1300	1300	2000
	Mass	kT	1.3	10	30?	100
	magnetic field	T	2	0.5	0.5	1-->2 ?
	Near Detector	Type	Liquid Ar	Liquid Ar	Liquid Ar	Liquid Ar
	Distance from ring	m	50	100	100	100
	Mass	kT	0.1	1	2.7	2.7
	magnetic field	T	No	No	No	No
Neutrino Ring	Ring Momentum P_μ	GeV/c	3.8	5	5	10
	Circumference C	m	350	600	600	1190
	Straight section Length	m	150	235	235	470
	Arc Length	m	25	65	65	125
Acceleration	Initial Momentum	GeV/c	3.8	0.22	0.22	0.22
	single pass Linac	GeV	None	0.9?	0.9?	0.9
	4.5-pass RLA	GeV	None	0.92?	0.92?	4
	NS-FFAG Ring	GeV	None	None	None	10
	SRF frequency linac/RLA	MHz	None	325/650	325/650	201
	Number of cavities		None	50 + 26?	50 + 26?	50 + 26 + 25
	Total Arc Length	m	50	550?	550?	550 +200
Cooling			No	No	4D	4D
Proton Source	Proton Beam Power	MW	0.2	1	3	4
	Proton Beam Energy	GeV	60	3	3	10
	protons/year	1×10^{21}	0.2	41	125	25
	Repetition Frequency	Hz	1.25	70	70	50

* supports multiple detector technologies

MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Collider



Muon Collider Baseline Parameters

		Higgs Factory		Multi-TeV Baselines	
Parameter	***Units***	Initial Cooling	Upgraded Cooling / Combiner		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
b*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1	1.5	70	70
Bunch Length, s_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	mm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4#	4	4	4

Could begin operation with Project X Phase 2 beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

The MAP Feasibility Assessment

Feasibility Assessment: Phase I

FY13 − FY15:
- Identify ***baseline*** design concepts
- Identify high leverage ***alternative*** concepts
- Identify key engineering paths to pursue:
  - RF
  - High Field Magnets
- Develop critical engineering concepts (eg, 6D Cooling Cell)
- Support major systems tests
  - MICE Step IV
  - MICE RFCC construction & testing

Feasibility Assessment: Phase II

FY16 − FY18:
- Technical demonstration of critical ***baseline*** concepts
  - eg, 6D Cooling cell
- Pursue high leverage ***alternative*** concepts
- Assess technical and cost feasibility of ***baseline*** concepts
- Support major systems tests
  - MICE Step V/VI
  - 6DICE planning

Beyond the Feasibility Assessment

FY19 →
- Plan contingent on the feasibility assessment!
- Can we launch the design effort towards a staged implementation of a NF & MC?
- Advanced systems tests
  - 6DICE?
  - Support Physics?

Recent Progress: MAP Design & Simulation

MAP Design Efforts

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*10%*
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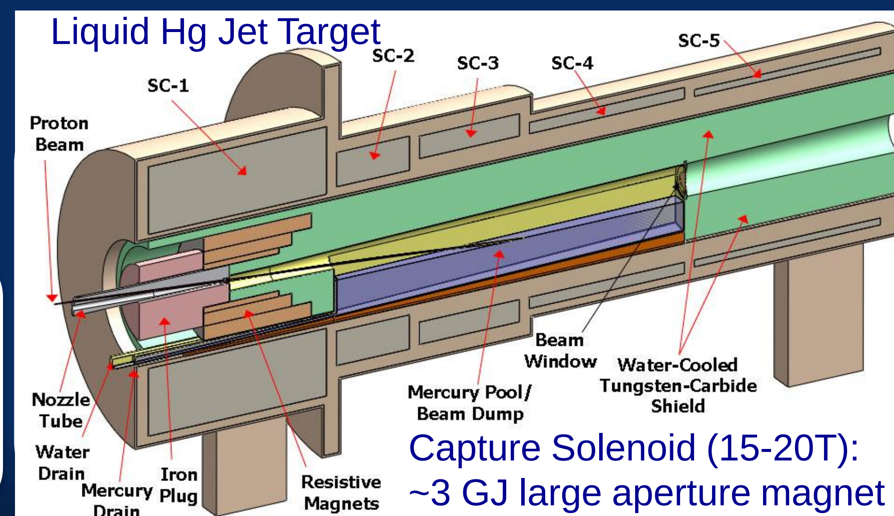
Opt. 3	*6 TeV CoM*	*$12\times10^{34}cm^{-2}s^{-1}$*

* Decays of an individual species (ie, or)

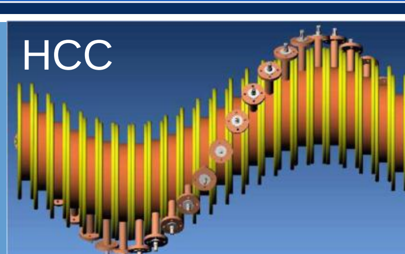
- Program Baselines
- Staging Study (MASS) Contributions

High Performance Computing

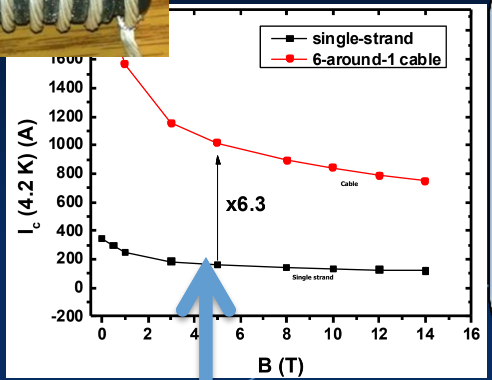
- Code Parallelization (G4Beamline, ICOOL)
  - Performance improvements > 10^4
- Enables Multi-Objective Parallel Optimization of Accelerator Designs



Cooling Channel Concepts

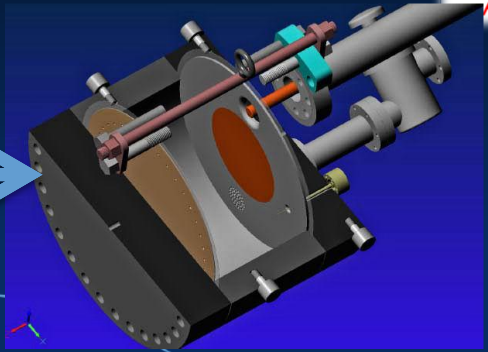


MAP: Recent Technology Highlights



Successful Operation of 805 MHz "All Seasons" Cavity in 3T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc



Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

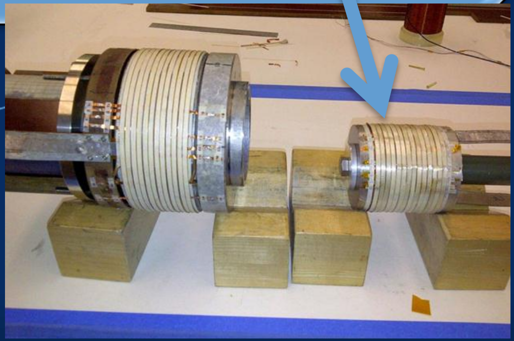
FNAL-Tech Div
T. Shen-Early Career Award

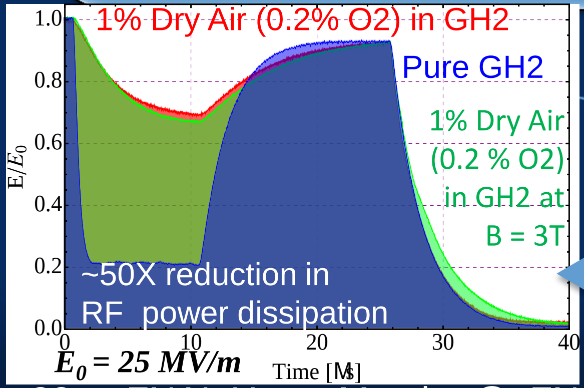
The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

PBL/BNL



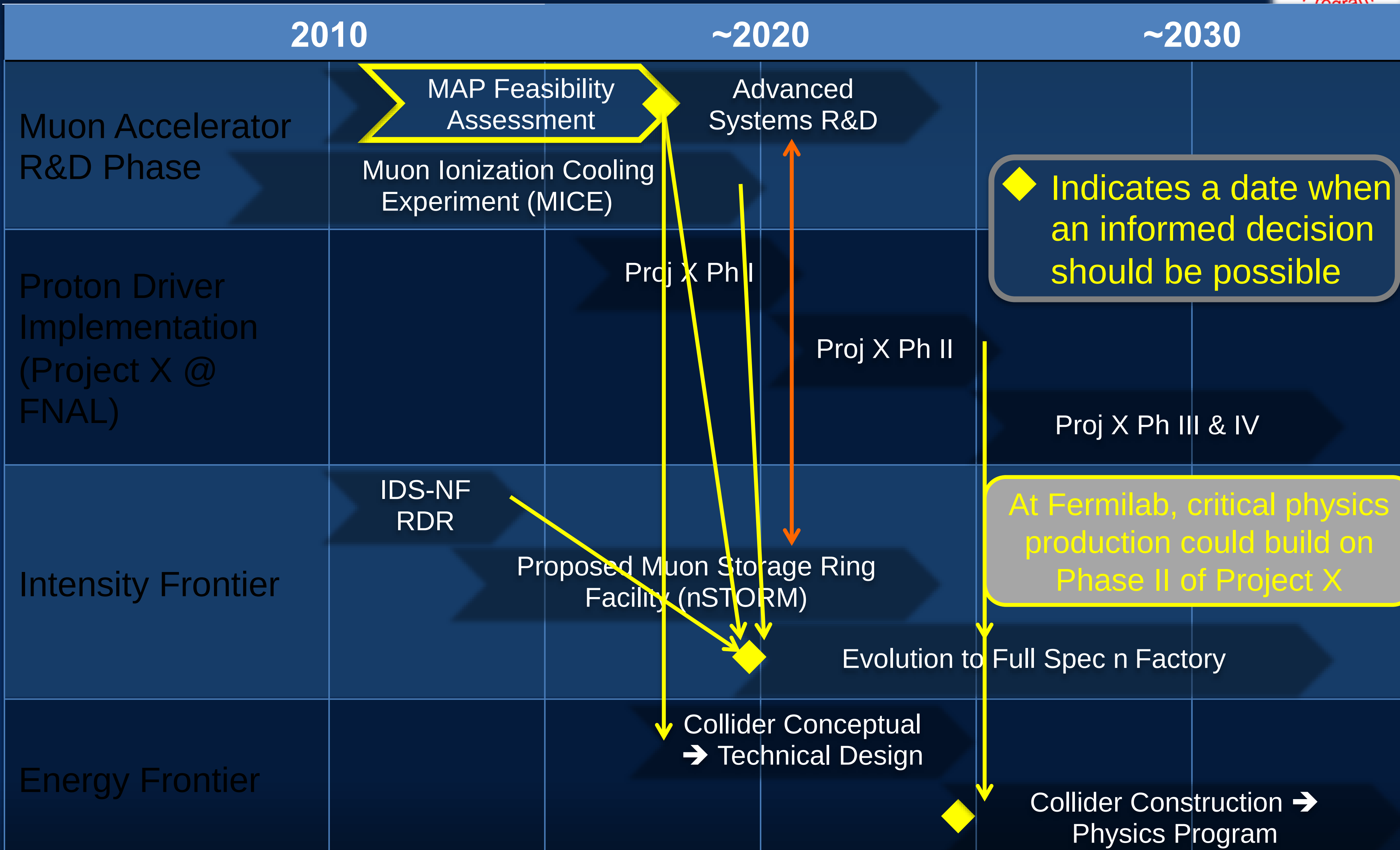


Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to μ-Collider Parameters

MuCool Test Area

The Muon Accelerator Program Timeline



Some Thoughts…

- The unique feature of muon accelerators is the ability to provide cutting edge performance on both the Intensity and Energy Frontiers
  - This is well-matched to the direction specified by the P5 panel for Fermilab
  - The possibilities for a staged approach make this particularly appealing in a time of constrained budgets
  - νSTORM would represent a critical first step in providing a muon-based accelerator complex

- World leading Intensity Frontier performance could be provided with a Neutrino Factory based on Project X Phase II
  - This would also provide the necessary foundation for a return to the Energy Frontier with a muon collider on U.S. soil

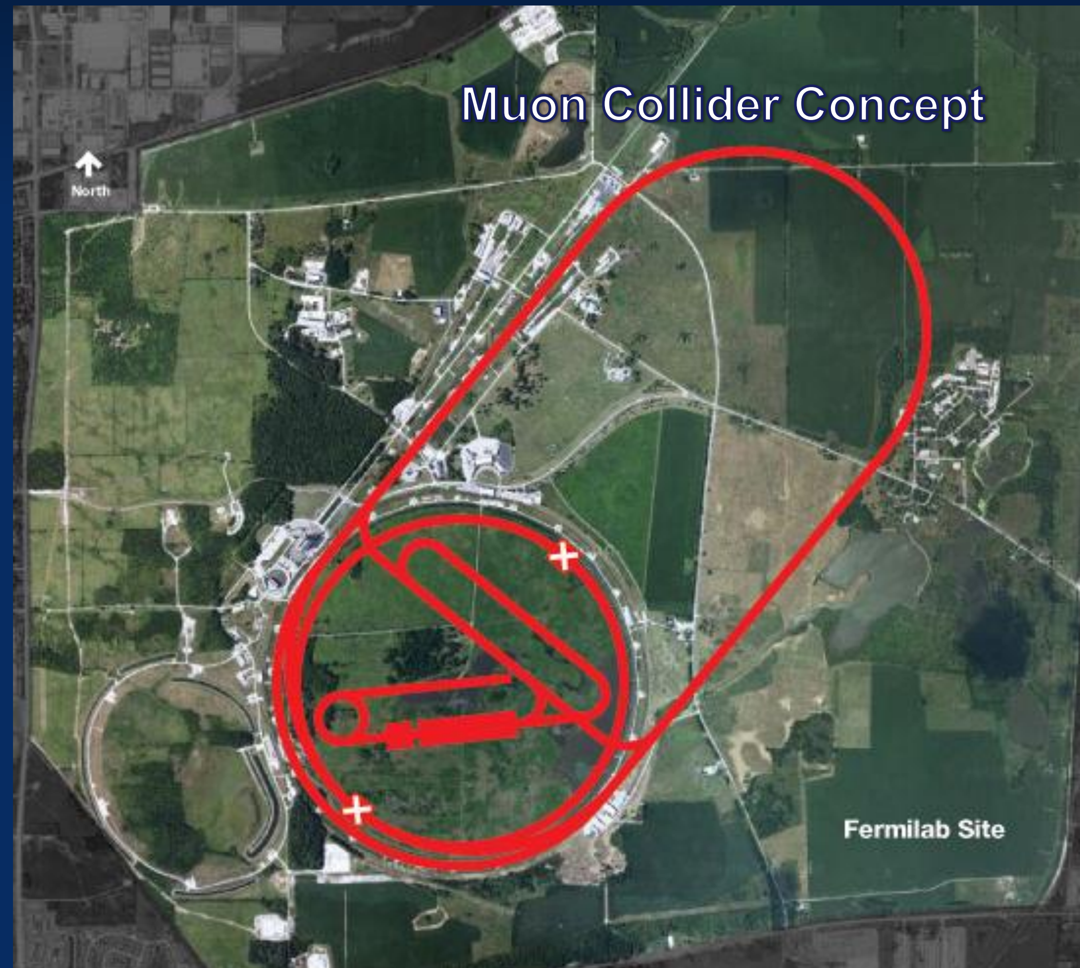
- A Muon Collider Higgs Factory
  - Would provide exquisite energy resolution to directly measure the width of the Higgs. This capability would be of crucial importance in the MSSM doublet scenario.

The first collider on the path to a multi-TeV Energy Frontier machine?

Conclusion

- Through the end of this decade, the primary goal of MAP is demonstrating the feasibility of key concepts needed for a neutrino factory and muon collider

⇨ Thus enabling an informed decision on the path forward for the HEP community



A challenging, but promising, R&D program!