



The Muon Accelerator Program Research Effort

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14
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Fermilab

Muon Accelerators for HEP



- μ – an elementary charged lepton:
 - 200 times heavier than the electron
 - $2.2 \mu\text{s}$ lifetime at rest
- Physics potential for the HEP community using muon beams
 - Tests of Lepton Flavor Violation
 - Anomalous magnetic moment \Rightarrow hints of new physics ($g-2$)
 - Can provide equal fractions of electron and muon neutrinos at high intensity for studies of neutrino oscillations – the Neutrino Factory concept
 - Offers a large coupling to the “Higgs mechanism”
 - $m^+ \rightarrow e^+ n_e \bar{n}_m$
 - $m^- \rightarrow e^- \bar{n}_e n_m$
 - As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision leptonic probe of fundamental interactions

$$m^+ \rightarrow e^+ n_e \bar{n}_m$$
$$m^- \rightarrow e^- \bar{n}_e n_m$$

$$\sim \left(\frac{m_\mu^2}{m_e^2} \right) \cong 4 \times 10^4$$

Outline

- Why Neutrino Factories?
- Neutrino Factory Concepts
 - Short baseline \Leftrightarrow vSTORM
 - Long Baseline
 - The IDS-NF Reference Design
 - Options for a staged implementation:
 - The MAP Muon Accelerator Staging Study
 - The staged NuMAX Concept
 - Accelerator R&D Effort
- Going Beyond a Neutrino Factory Facility
 - Possibilities for a future Muon Collider Capability
- Conclusion

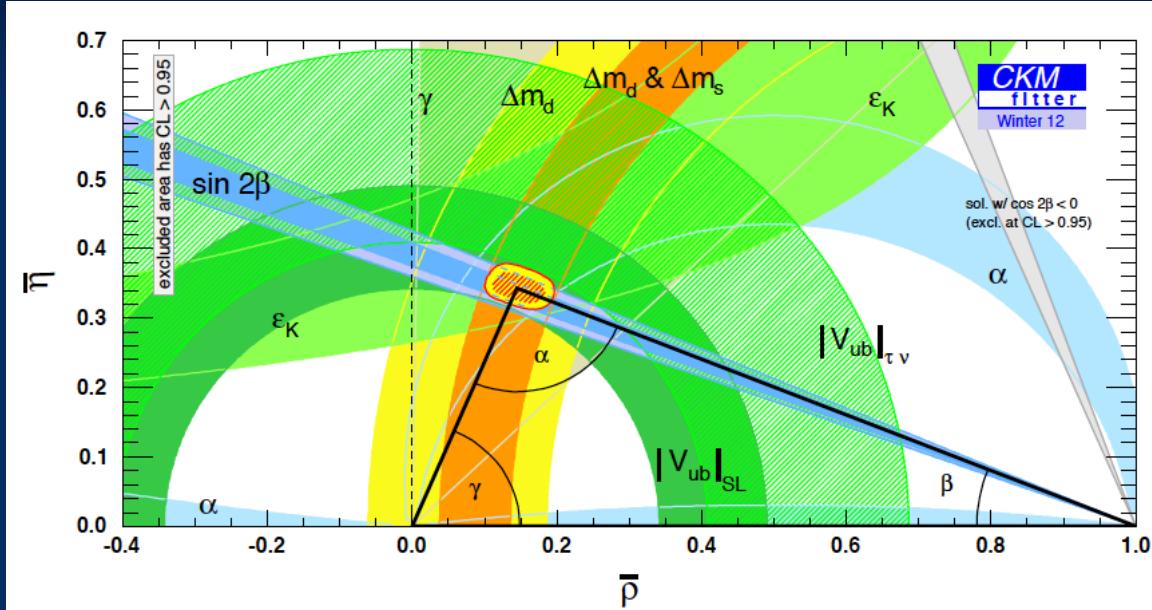


WHY NEUTRINO FACTORIES?

The Key Issues

- What things must we understand in the neutrino sector?

- δ_{CP}
- The mass hierarchy
- The value of $\theta_{23} - \pi/4$:
+, - or zero?



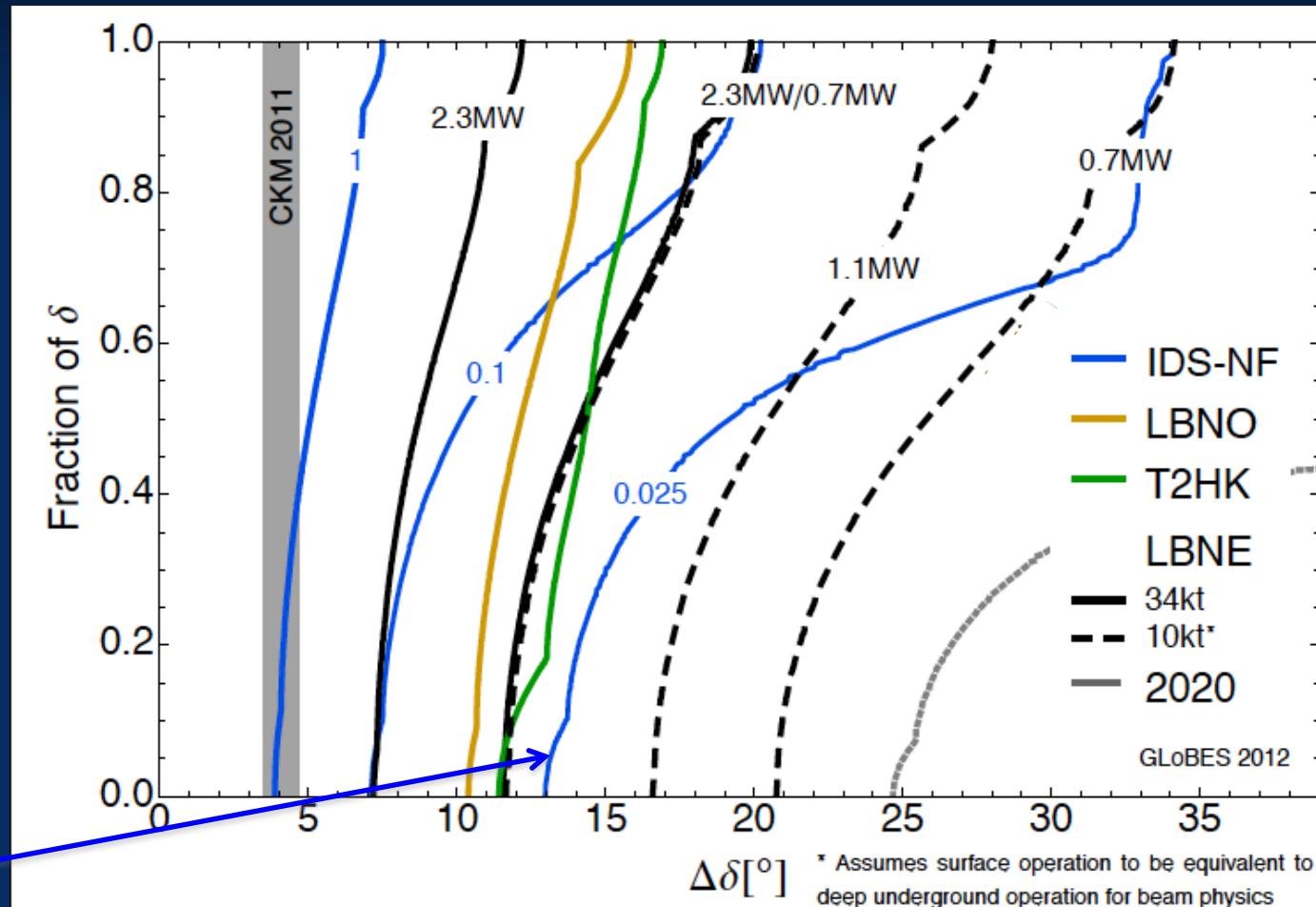
- Resolve the LSND and other short baseline experimental anomalies
- And enable the search for new physics

Neutrino Factory \Rightarrow Precision

- CP violation physics reach of various facilities

Can we probe the CP violation in the neutrino sector at the same level as in the CKM Matrix?

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



P. Coloma, P. Huber, J. Kopp, W. Winter – arxiv:1209.5973



Microscopes for the ν Sector

- Superbeam technology will continue to drive initial observations in the coming years
- However, anomalies and new discoveries will drive our need for precision studies to develop a complete physical understanding
- Neutrino Factory capabilities (both long- and short-baseline) offer a route to *controlled systematics* and *precision measurements* to fully elucidate the relevant physics principles

⇒ *Precision Microscopes for the ν sector*



NEUTRINO FACTORY CONCEPTS

Neutrino Factory Overview

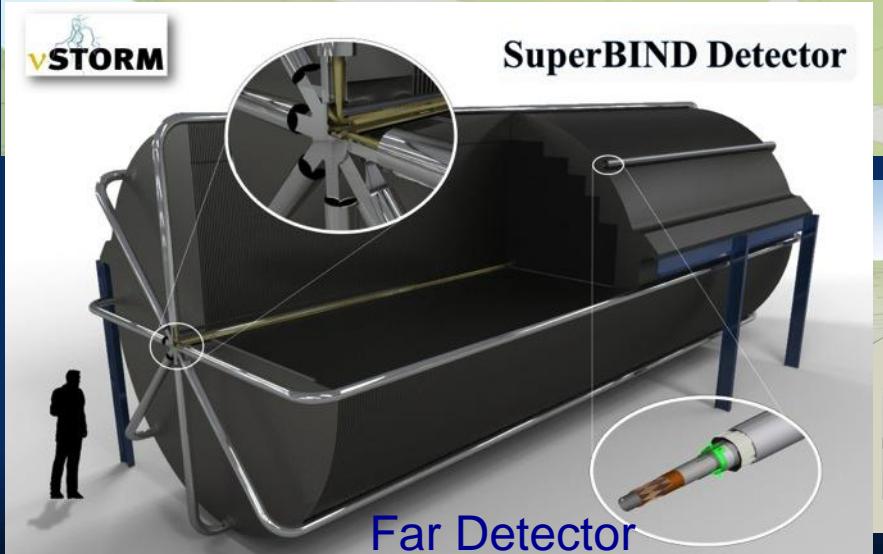
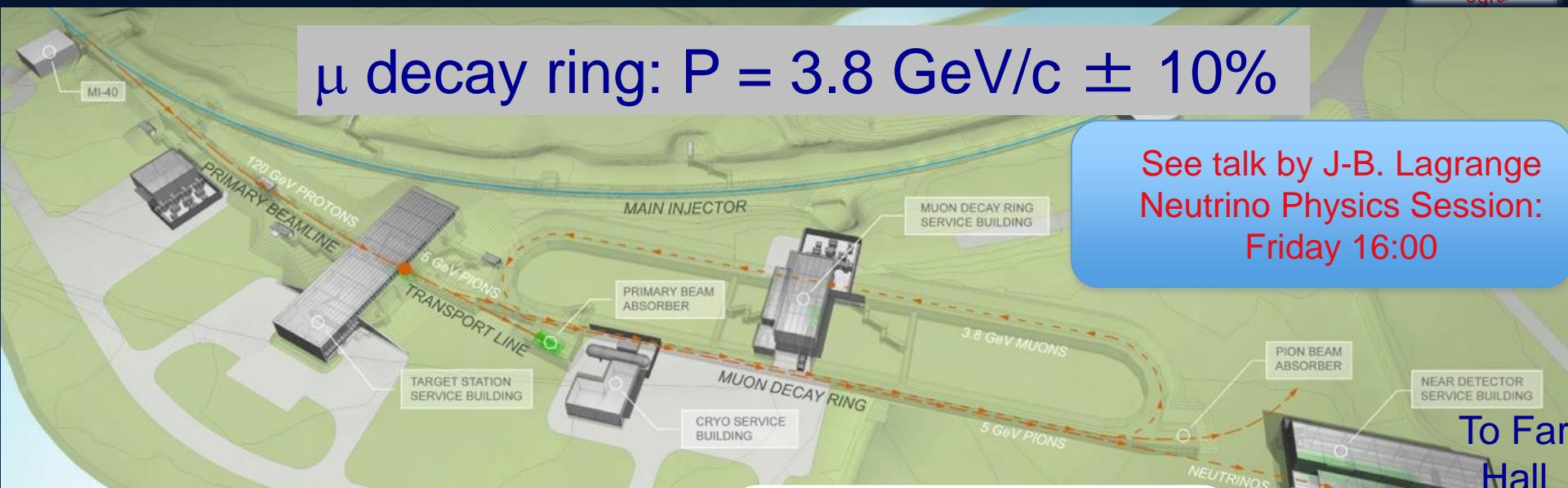
- Short Baseline NF
 - nuSTORM
 - Definitive measurement of sterile neutrinos
 - Precision ν_e cross-section measurements (systematics issue for long baseline SuperBeam experiments)
 - Would serve as an HEP muon accelerator proving ground...
- Long Baseline NF with a Magnetized Detector
 - IDS-NF (International Design Study for a Neutrino Factory)
 - 10 GeV muon storage ring optimized for 1500-2500km baselines
 - “Generic” design (ie, not site-specific)
 - NuMAX (Neutrinos from a Muon Accelerator CompleX)
 - Site-specific: FNAL \Leftrightarrow SURF (1300km baseline)
 - 4-6 GeV beam energy optimized for CP studies
 - Flexibility to allow for other operating energies
 - Can provide an ongoing short baseline measurement option
 - Detector options
 - Magnetized LAr is the goal
 - Magnetized iron provides equivalent CP sensitivities using ~3x the mass

vSTORM



μ decay ring: $P = 3.8 \text{ GeV}/c \pm 10\%$

See talk by J-B. Lagrange
Neutrino Physics Session:
Friday 16:00



SuperBIND Detector

No new technologies
required!
Could be deployed now!

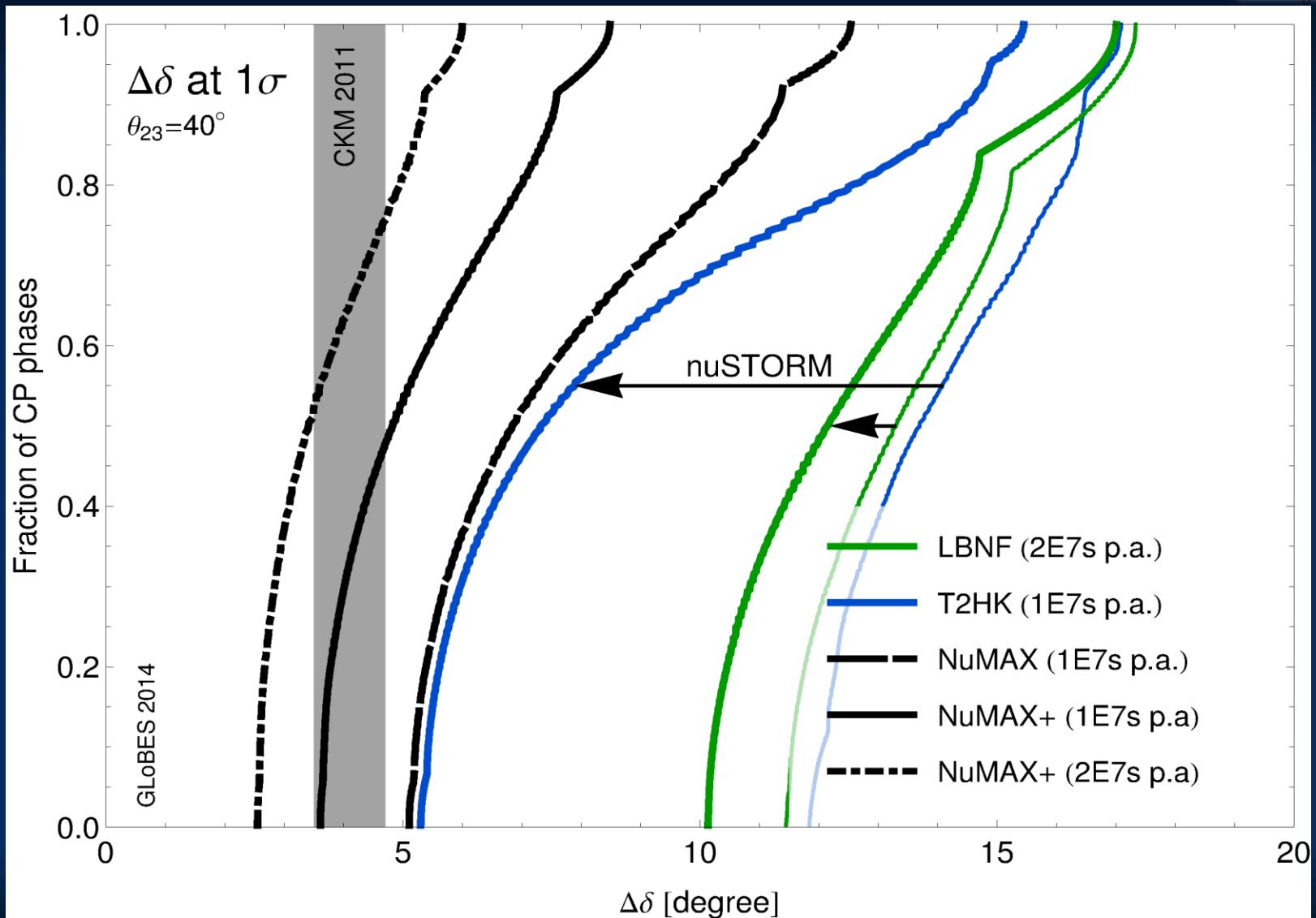


Far Hall @ 1.9km

Performance Benefits from Precision ν Sources

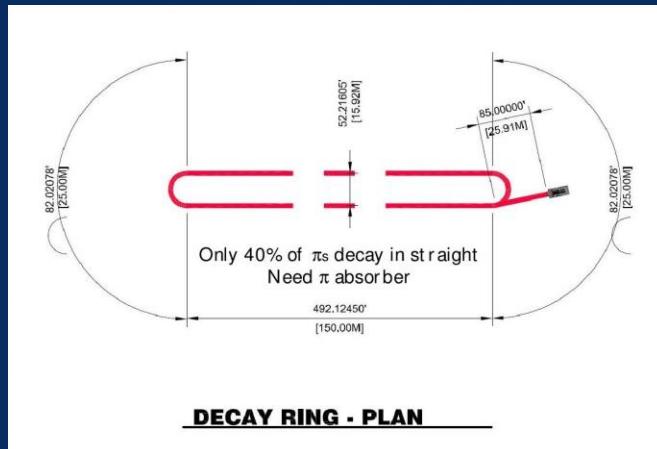
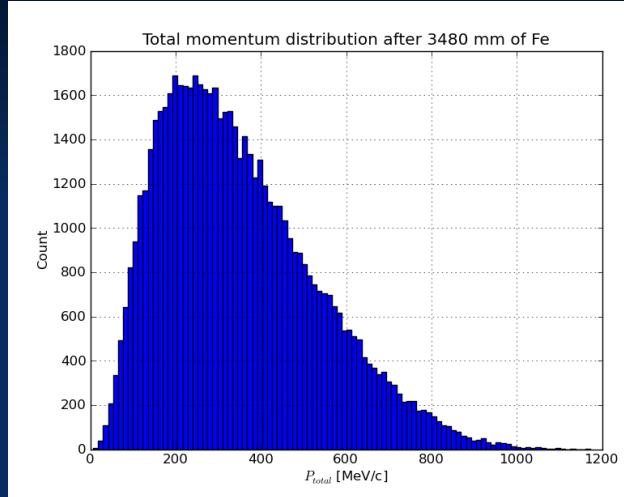


GLoBES Comparison of Potential Performance of the Various Advanced Concepts (courtesy P. Huber)



vStorm as an R&D platform

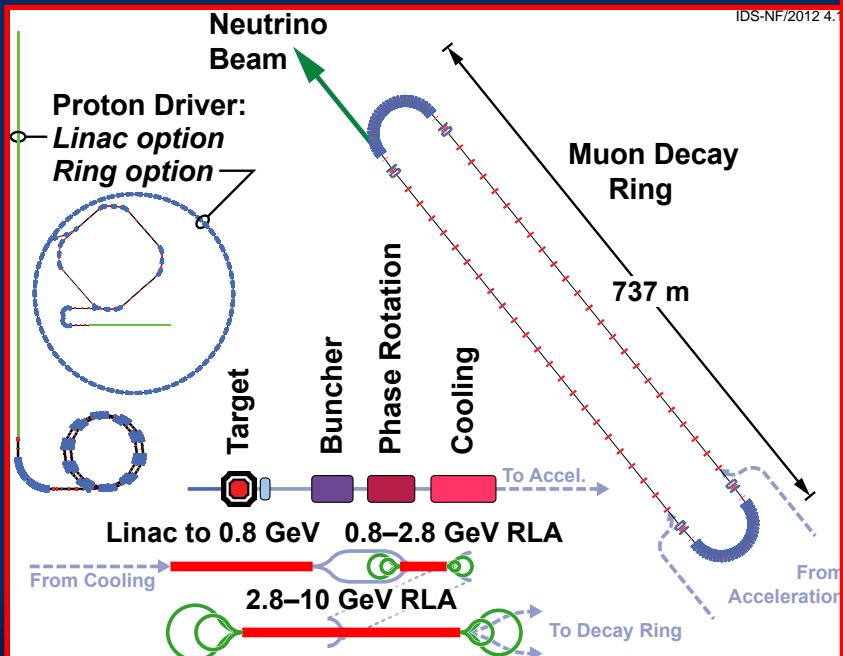
- A high-intensity pulsed muon source
- $100 < p_\mu < 300$ MeV/c muons
 - Using extracted beam from ring
 - 10^{10} muons per 1 μ sec pulse
- Beam available simultaneously with physics operation
- vSTORM also provides the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon beam



The Long Baseline Neutrino Factory

- IDS-NF: the *ideal* NF
 - Supported by MAP
- MASS working group:
A staged approach -

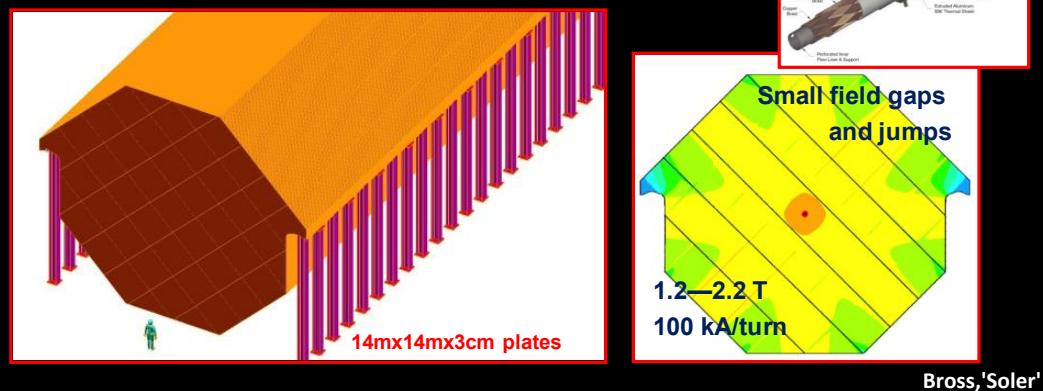
NuMAX@5 GeV ↔ SURF



	Value
Accelerator facility	
Muon total energy	10 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 long-baseline neutrino detector	1 500–2 500 km

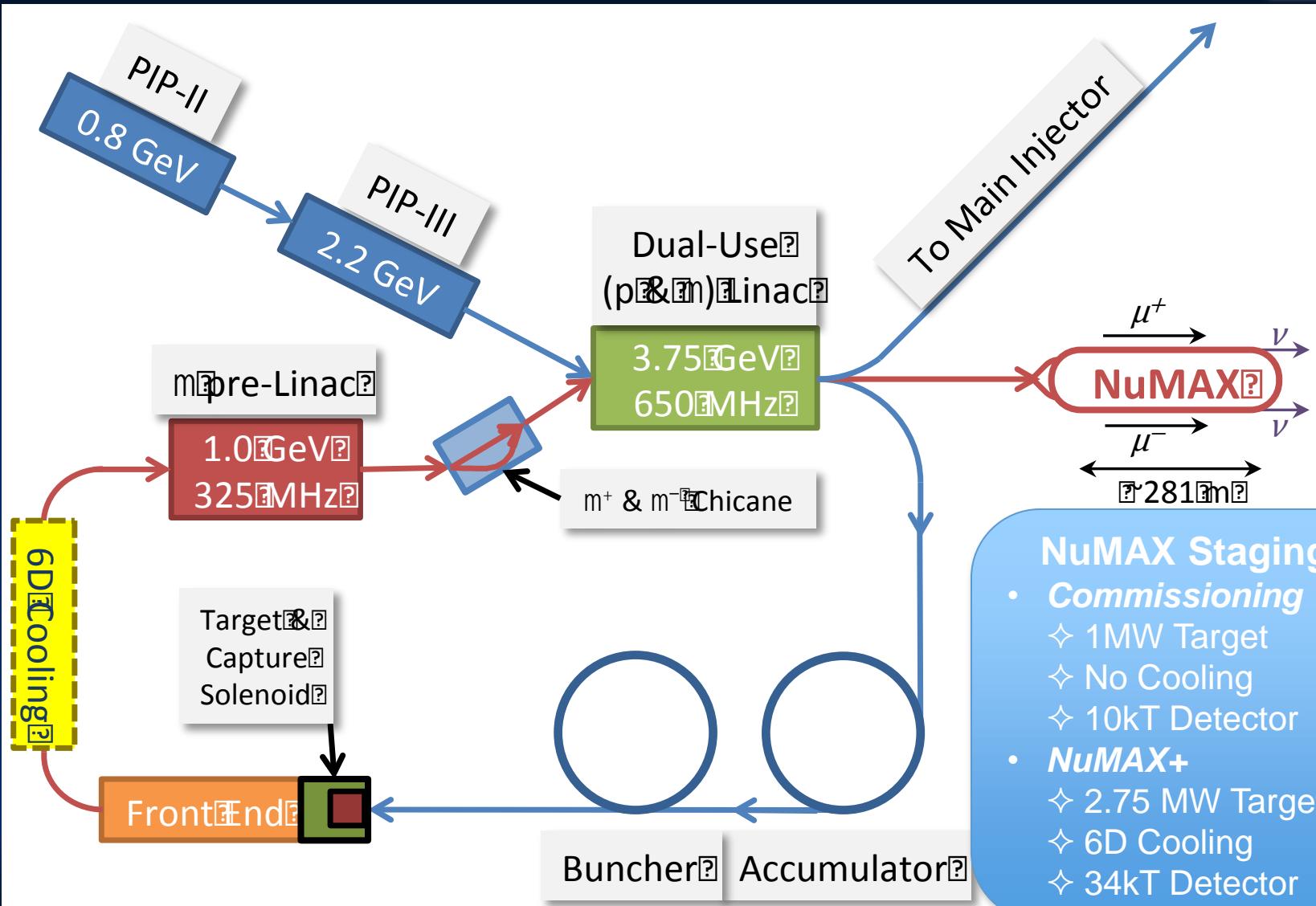
MagneHzed'Iron'Neutrino'Detector'(MIND):

- 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'sciHillator'
- 50\$100'm'long'
- Octagonal'shape'
- Welded'double\$sheet'
 - Width'2m;3mm'slots'between'plates'



The MAP Muon Accelerator Staging Study

⇒ NuMAX



NuMAX Staging:

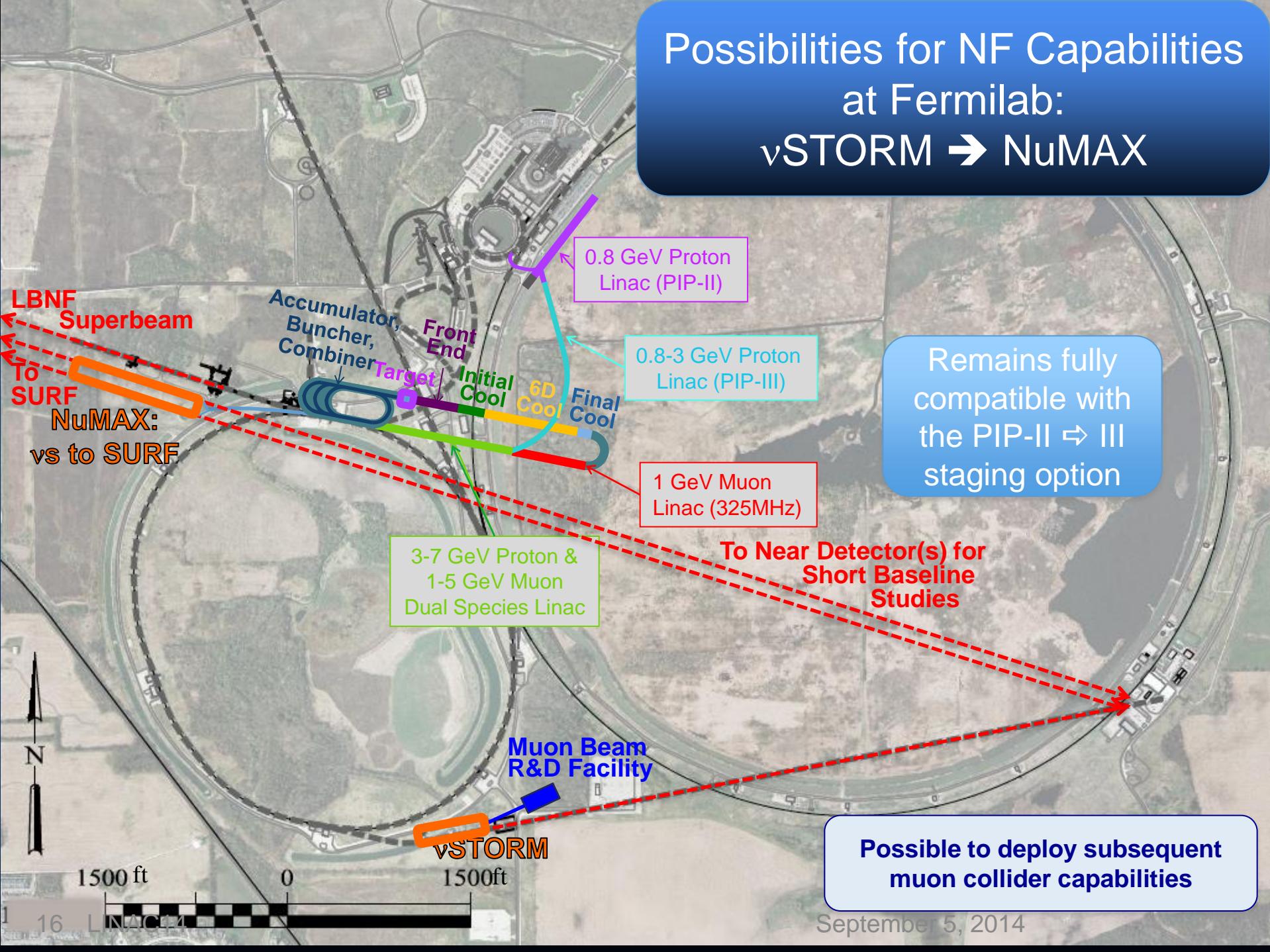
- **Commissioning**
 - ◊ 1MW Target
 - ◊ No Cooling
 - ◊ 10kT Detector
- **NuMAX+**
 - ◊ 2.75 MW Target
 - ◊ 6D Cooling
 - ◊ 34kT Detector

NF Staging (MASS)



System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	V _e or V _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 (P _μ)	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 Frequency	Hz	-	30	30	60
Cooling	6D		No	No →	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam Energy	GeV	120	6.75	6.75	6.75
	Protons/year	1×10 ²¹	0.1	9.2	9.2	25.4
	Repetition Frequency	Hz	0.75	15	September 15, 2014	15

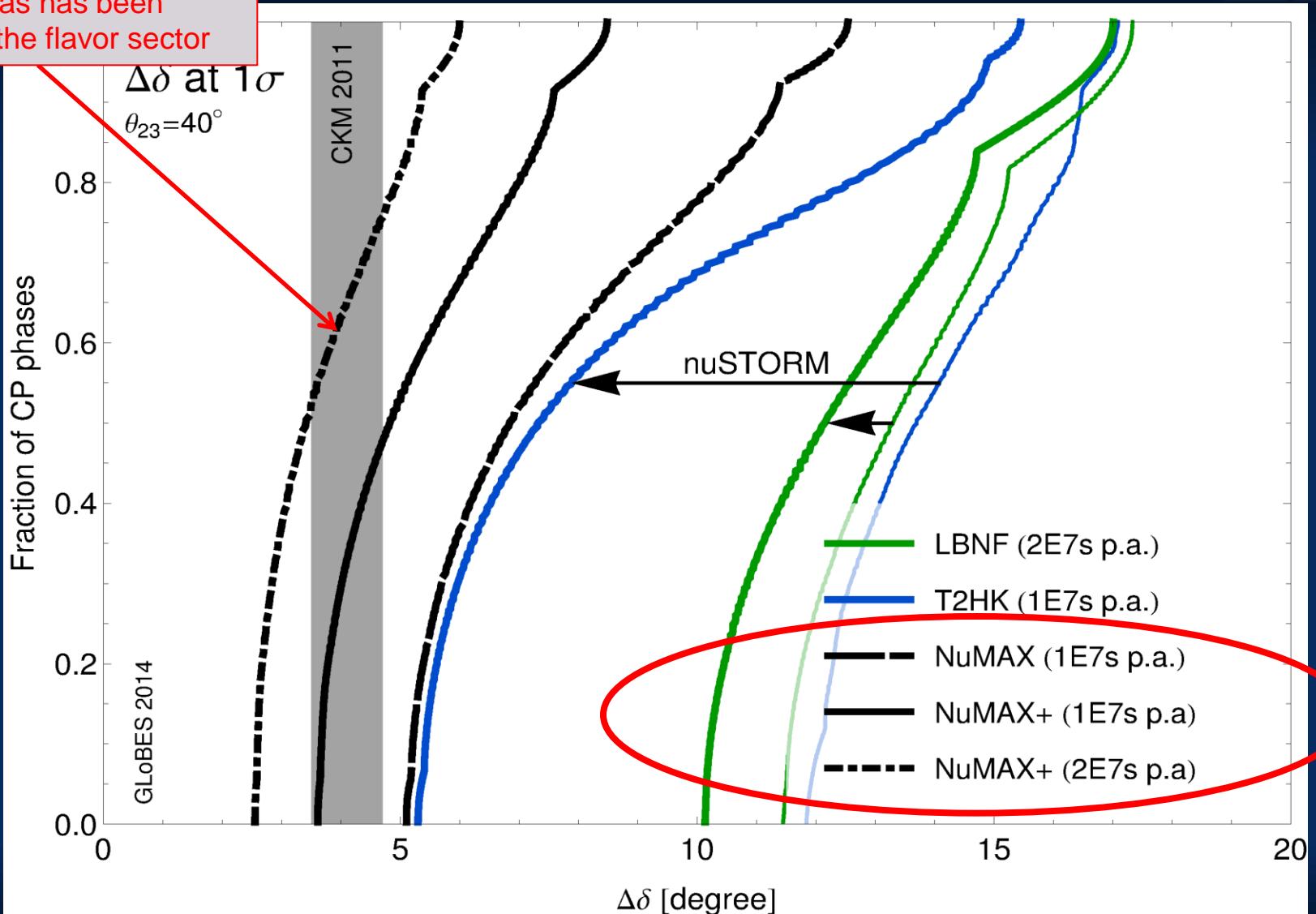
Possibilities for NF Capabilities at Fermilab: vSTORM → NuMAX



Performance Benefits from Precision ν Sources

NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector

GLoBES Comparison of Potential Performance of the Various Advanced Concepts (courtesy P. Huber)



Accelerator R&D Effort (U.S. MAP)



Design Studies

- Proton Driver
- Front End
- Cooling
- Acceleration and Storage
- Collider
- Machine-Detector Interface
- Work closely with physics and detector efforts

Technology R&D

- RF in magnetic fields
- SCRF for acceleration chain (Nb on Cu technology)
- High field magnets
 - Utilizing HTS technologies
- Targets & Absorbers
- MuCool Test Area (MTA)

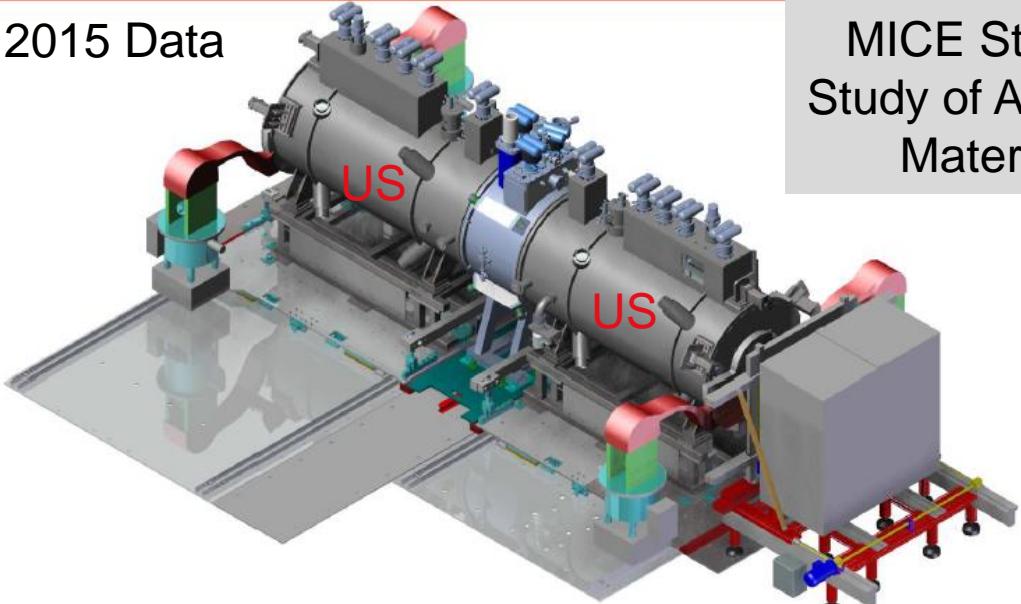
Major System Demonstration

- The Muon Ionization Cooling Experiment – MICE
 - Major U.S. effort to provide key hardware: RF Cavities and couplers, Spectrometer Solenoids, Coupling Coil(s), Partial Return Yoke
 - Experimental and Operations Support

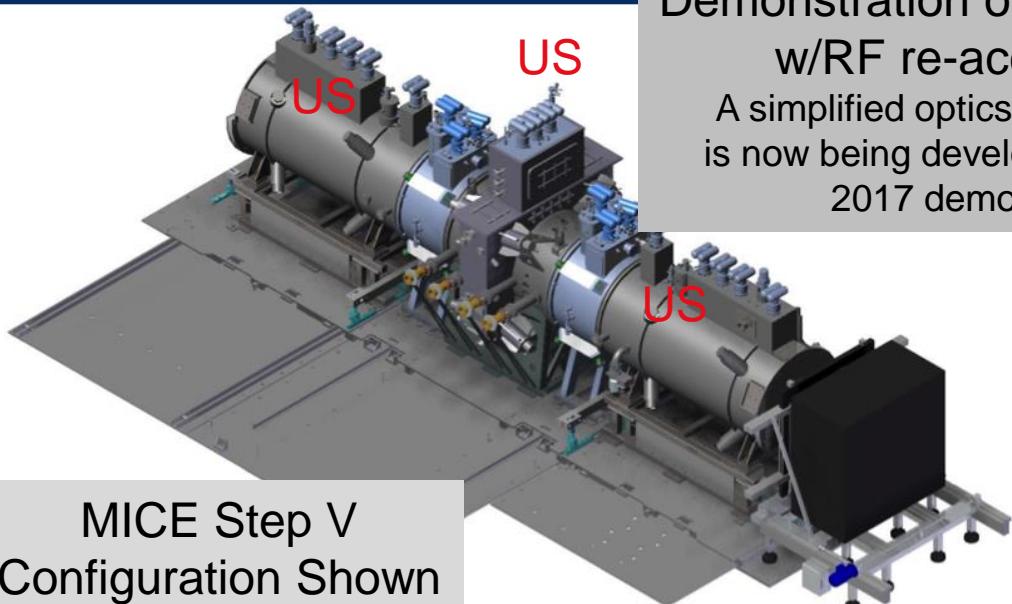
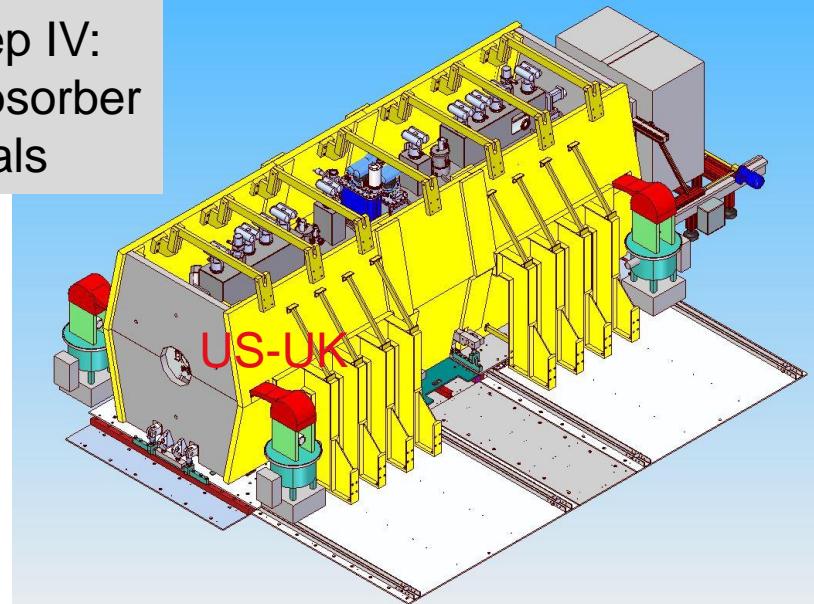
MICE Experiment @ RAL



2015 Data

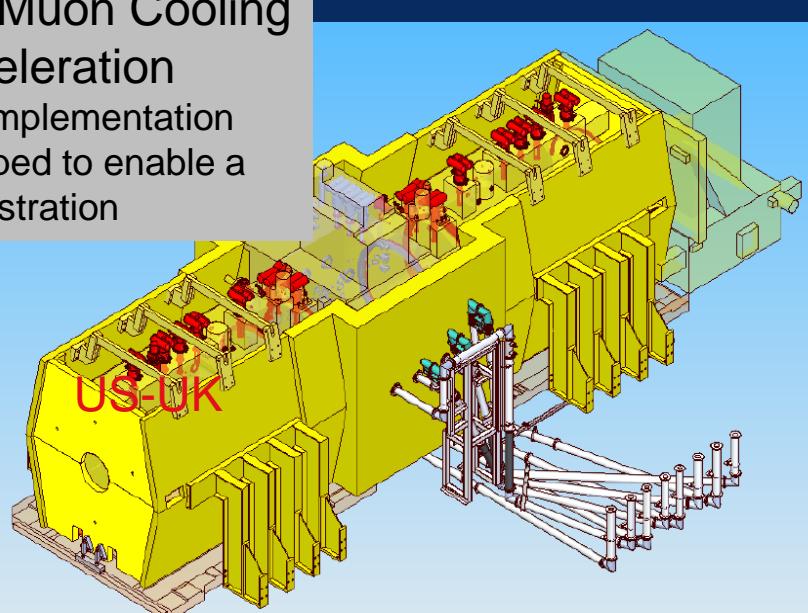


MICE Step IV:
Study of Absorber
Materials



MICE Step V
Configuration Shown

Demonstration of Muon Cooling
w/RF re-acceleration
A simplified optics implementation
is now being developed to enable a
2017 demonstration



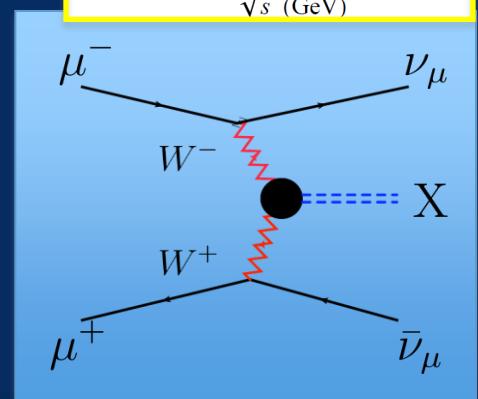
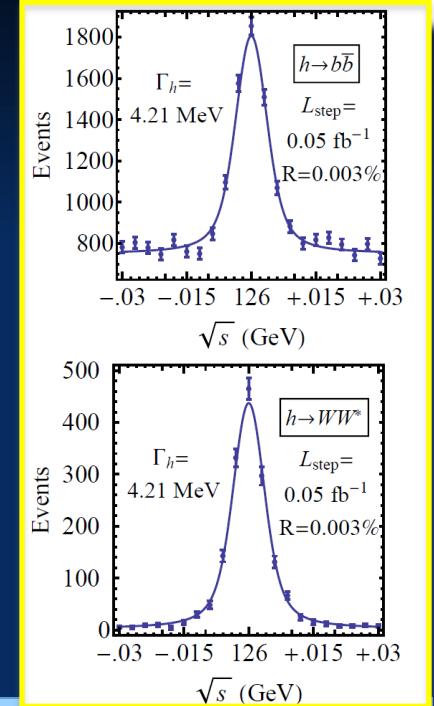


GOING BEYOND NEUTRINO FACTORY CAPABILITIES

Features of the Muon Collider

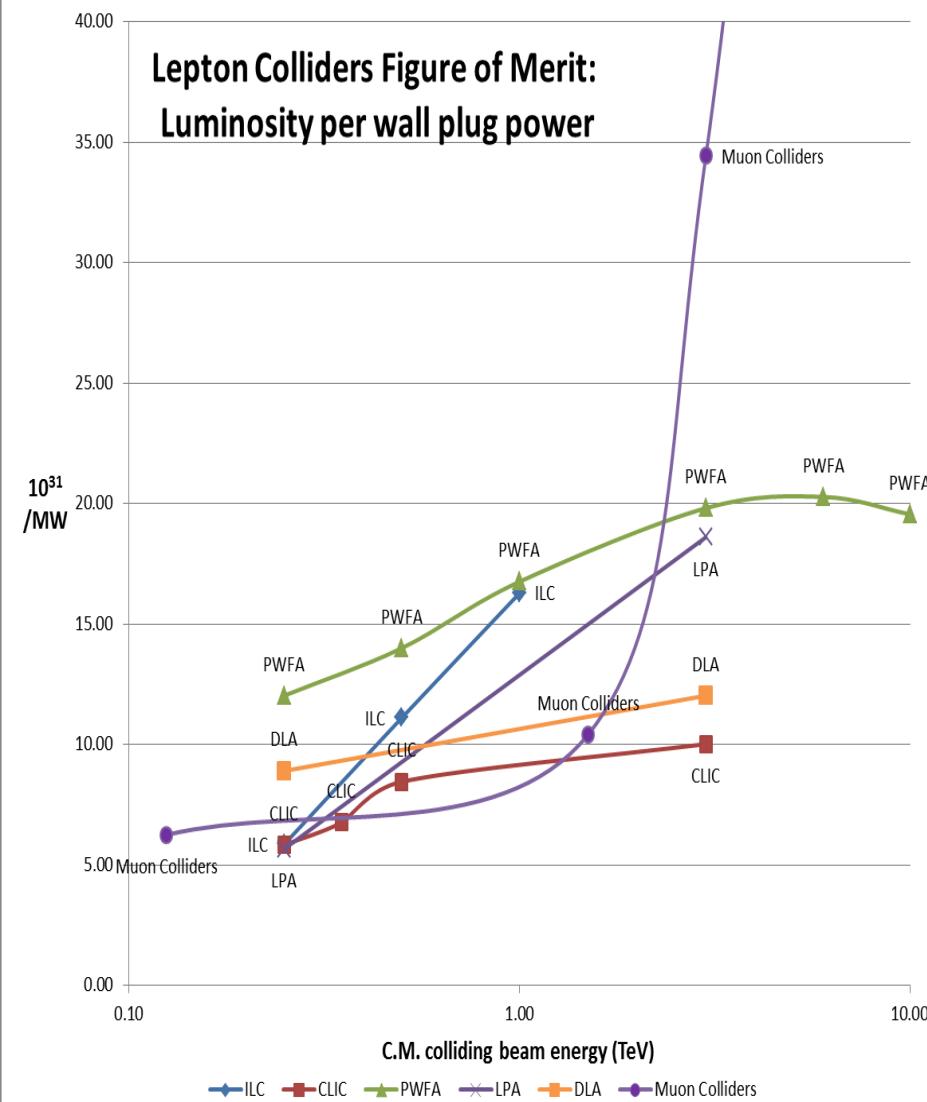
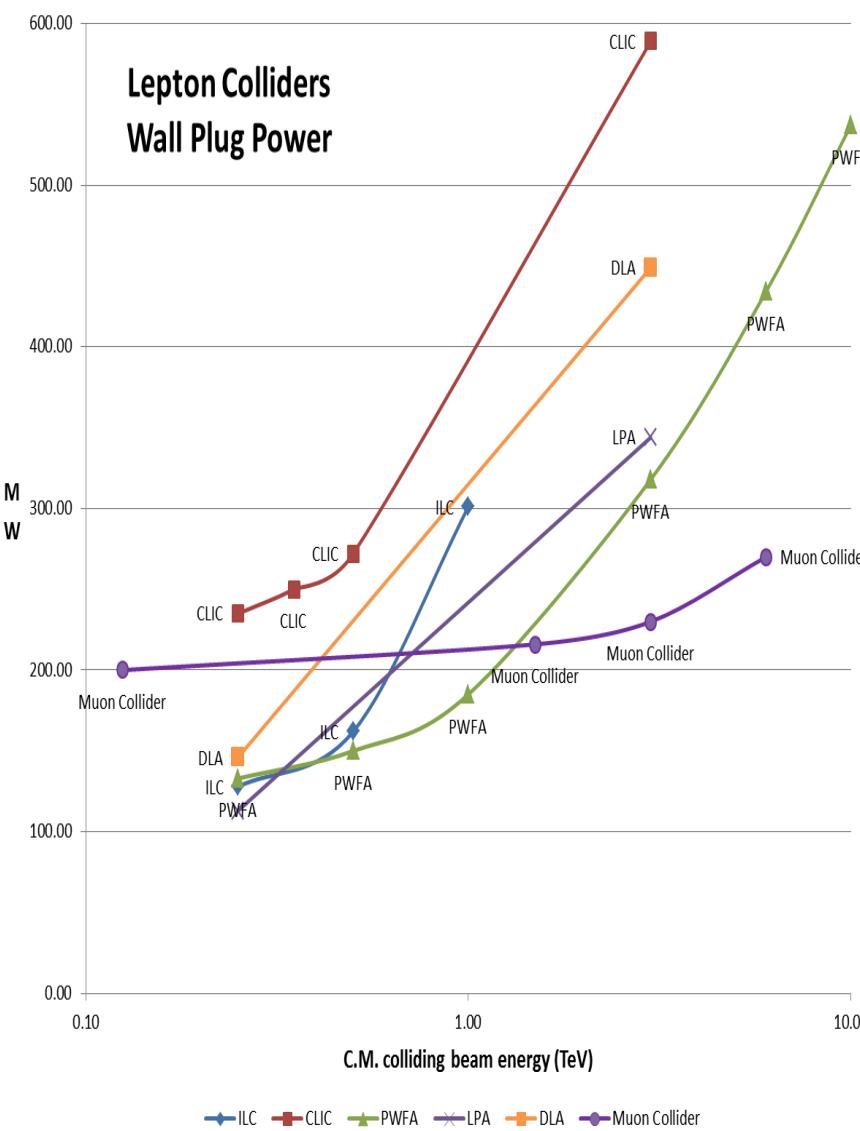


- Superb Energy Resolution
 - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability ($\leq 10\text{TeV}$):
 - Compact & energy efficient machine
 - Luminosity $> 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - Option for 2 detectors in the ring
 - For $\sqrt{s} > 1 \text{ TeV}$: Fusion processes dominate
 - ⇒ an Electroweak Boson Collider
 - ⇒ a discovery machine complementary to a very high energy pp collider
 - At $>5\text{TeV}$: Higgs self-coupling resolutions of $<10\%$



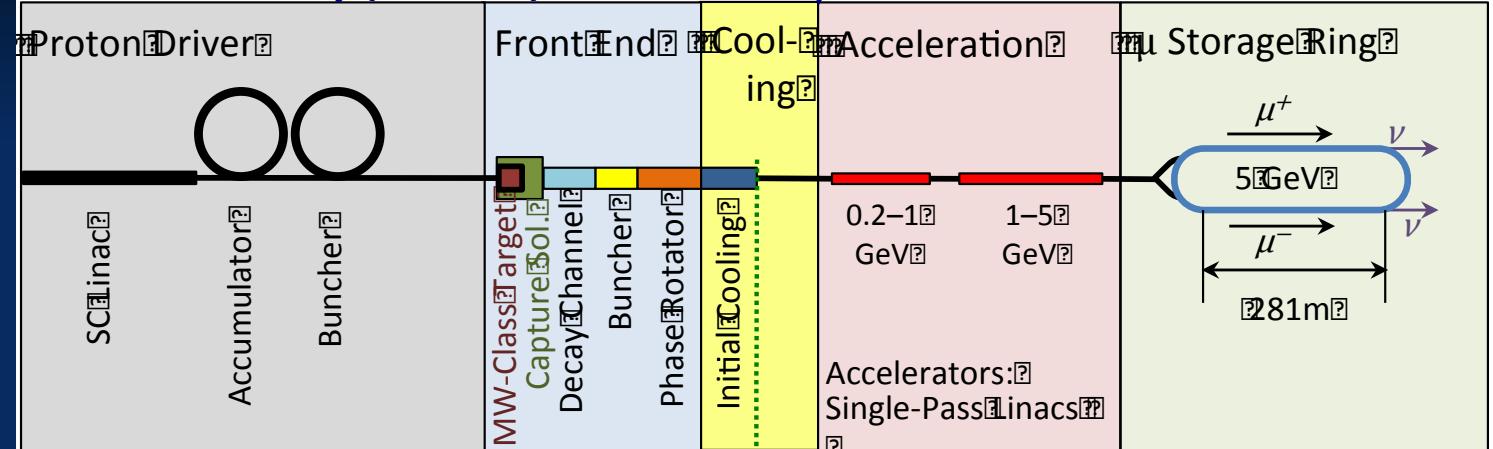
What are our accelerator options if new LHC data shows evidence for a multi-TeV particle spectrum?

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



NF/MC Synergies

Neutrino Factory (NuMAX)

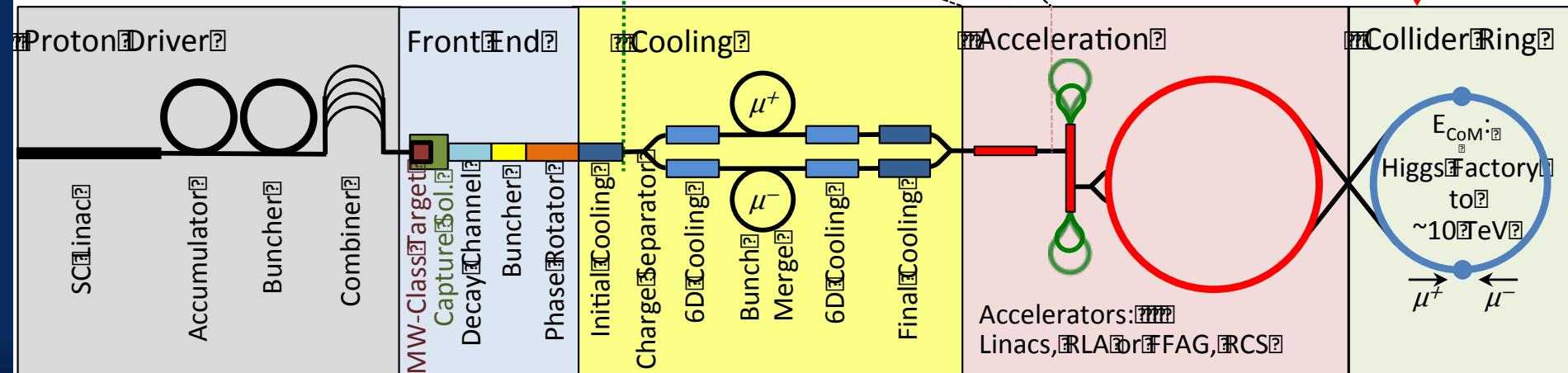


n Factory Goal:
 $10^{21} \text{ m}^+ \& \text{ m}^- \text{ per year}$
 within the accelerator acceptance

m-Collider Goals:
 $126 \text{ GeV} \Rightarrow$
 $\sim 14,000 \text{ Higgs/yr}$
 $126 \text{ GeV} \Rightarrow$
 $\text{Multi-TeV} \Rightarrow$
 $\text{Lumi} > 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

Share same complex

Muon Collider



The Staging Study (MASS)

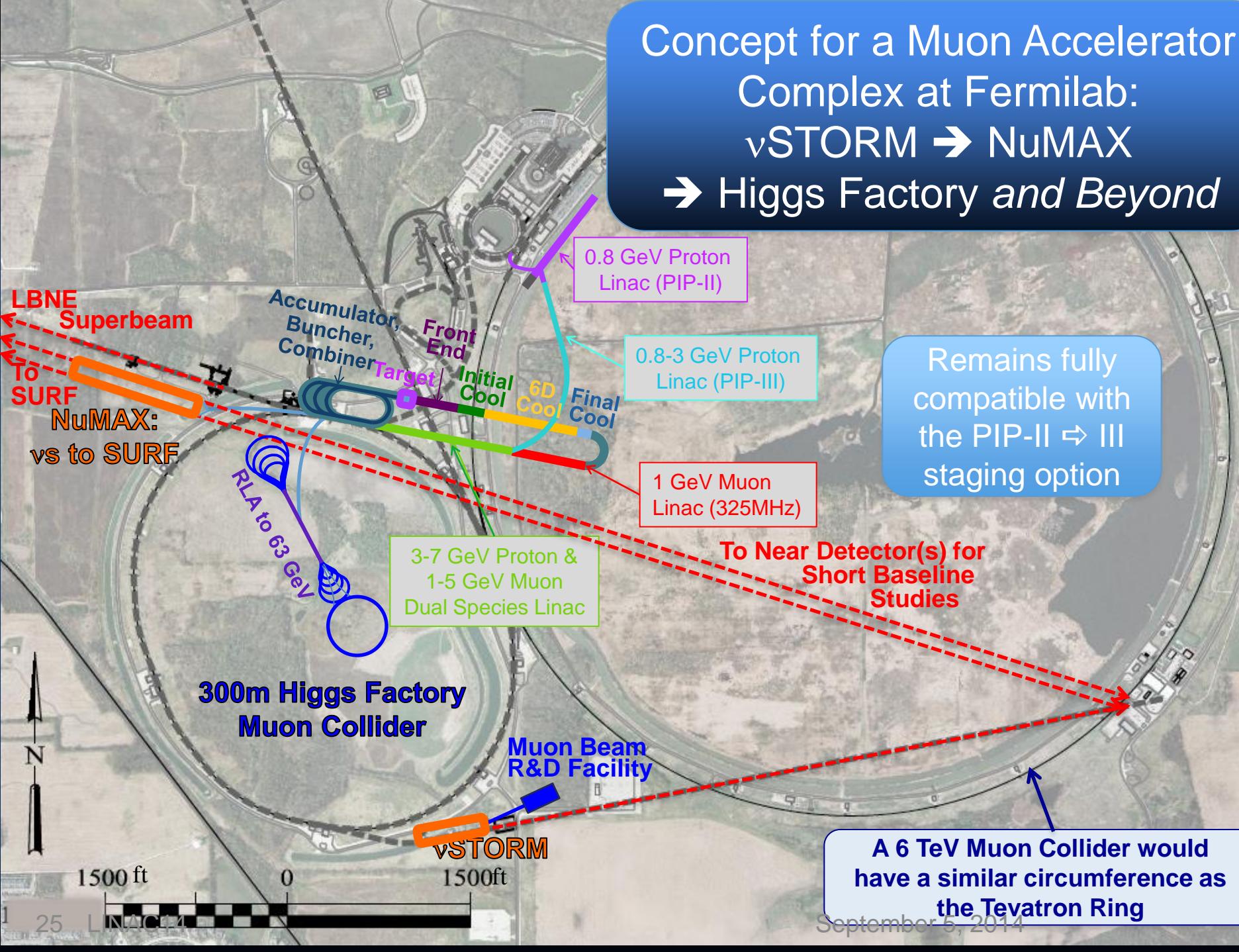
Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US - <http://arxiv.org/pdf/1308.0494>

The plan consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

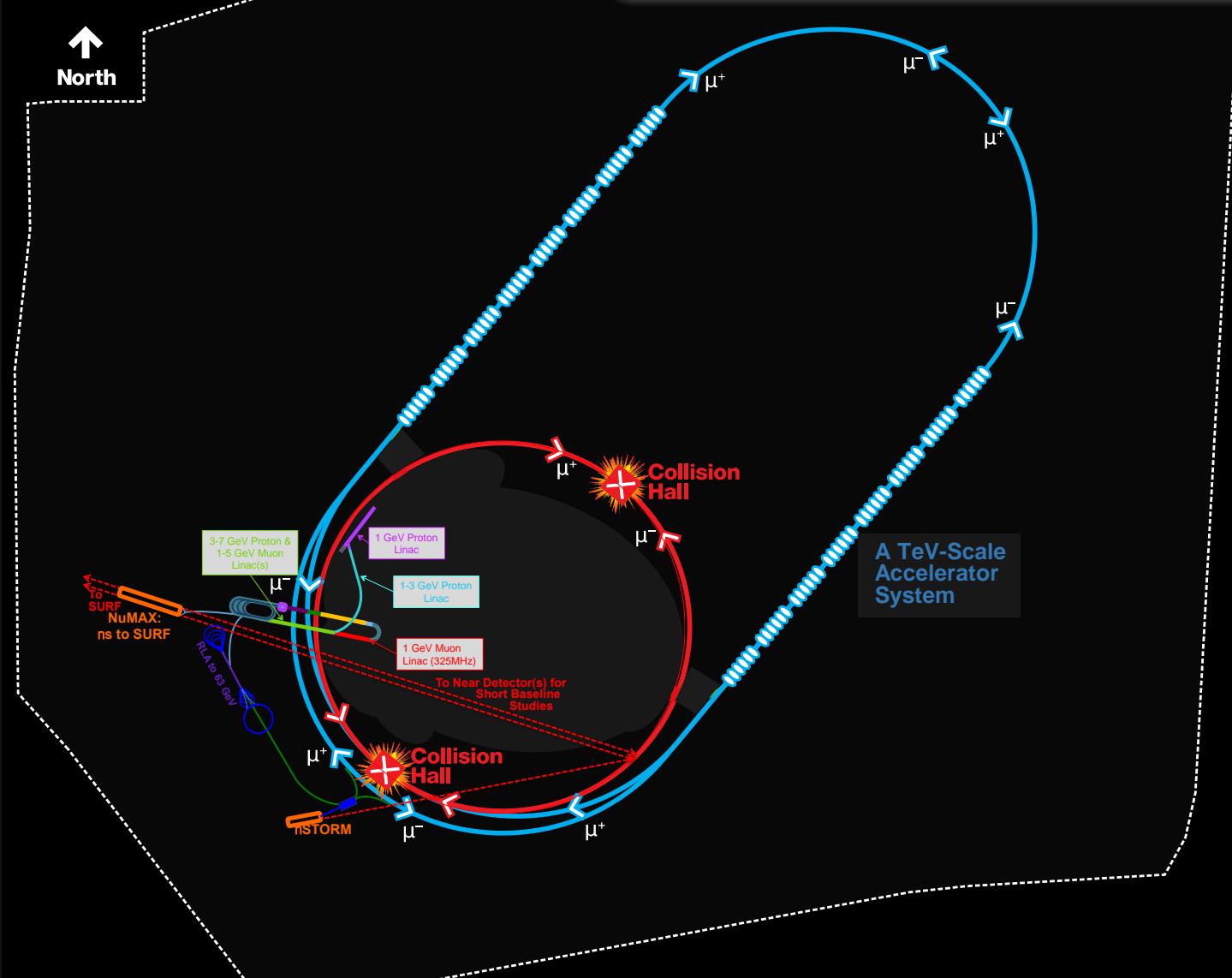
- **nuSTORM:** a short-baseline Neutrino Factory-like ring enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long-baseline experiment.
- **NuMAX:** an initial long-baseline Neutrino Factory, operating at SURF, affording a precise and well-characterized neutrino source to enable precision CP-violation measurements in the neutrino sector.
- **NuMAX+:** a full-intensity Neutrino Factory, extending NuMAX, as the ultimate source to enable precision CP-violation measurements in the neutrino sector.
- **Higgs Factory:** a collider whose baseline configurations are capable of providing between 3500 (during startup operations) and 15,000 Higgs events per year (10^7 sec) with exquisite energy resolution.
- **Multi-TeV Collider:** if warranted by LHC results, a multi-TeV Muon Collider likely offers the best performance and least cost for any lepton collider operating in the multi-TeV regime.

Ability to utilize some
or all stages

Concept for a Muon Accelerator Complex at Fermilab: vSTORM → NuMAX → Higgs Factory and Beyond

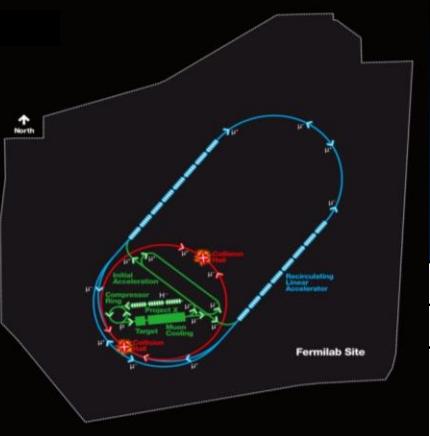


Concept for a Muon Accelerator Complex at Fermilab: → Multi-TeV Lepton Collider





Muon Collider Parameters



Muon Collider Parameters								
Parameter	Units	Higgs Factory		Top Threshold Options		Multi-TeV Baselines		Accounts for Site Radiation Mitigation
		Startup Operation	Production Operation	High Resolution	High Luminosity			
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34} \text{ cm}^{-2} \text{s}^{-1}$	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* Top Production/ 10^7 sec		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. RF IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	15	12
b*	cm	3.3	1.7	1.5	0.5	(0.5-2)	(0.5-3)	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}	p mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ϵ_{LN}	p mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, τ_s	ns	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

[#] Could begin operation with Project X Stage II beam

Exquisite Energy Resolution
Allows Direct Measurement
of Higgs Width

Success of advanced cooling
concepts \Rightarrow several $\times 10^{32}$

Site Radiation
mitigation with
depth and lattice
design: $\leq 10 \text{ TeV}$



CONCLUSION

Concluding Remarks



- Neutrino Factory capabilities offer a precision microscope that will likely be needed to fully probe the physics of the neutrino sector
- A multi-TeV muon collider may be the only cost-effective route to lepton collider capabilities at energies > 5 TeV
- For the last 3 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities
 - Near term (**vSTORM**)
 - Long term (**NuMAX**)
 - A muon collider capability that would build on a NF complex
- In light of the recent P5 recommendations that this directed facility effort no longer fits within the budget-constrained US research portfolio, the US effort is entering a ramp-down phase
- Nevertheless, muon accelerator capabilities offer unique potential for the future of high energy physics research