The Muon Accelerator Program Research Effort

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LINAC14

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Fermilab

Muon Accelerators for HEP

- 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
  - Tests of Lepton Flavor Violation
  - Anomalous magnetic moment ⇨ 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

$$\boxed{\begin{array}{l} \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \\ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \end{array}}$$

  - Offers a large coupling to the "Higgs mechanism" $\sim \left(\frac{m_\mu^2}{m_e^2} \right) \cong 4 \times 10^4$
  - As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision leptonic probe of fundamental interactions

Outline

- Why Neutrino Factories?

- Neutrino Factory Concepts
  - Short baseline ⇨ νSTORM
  - 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

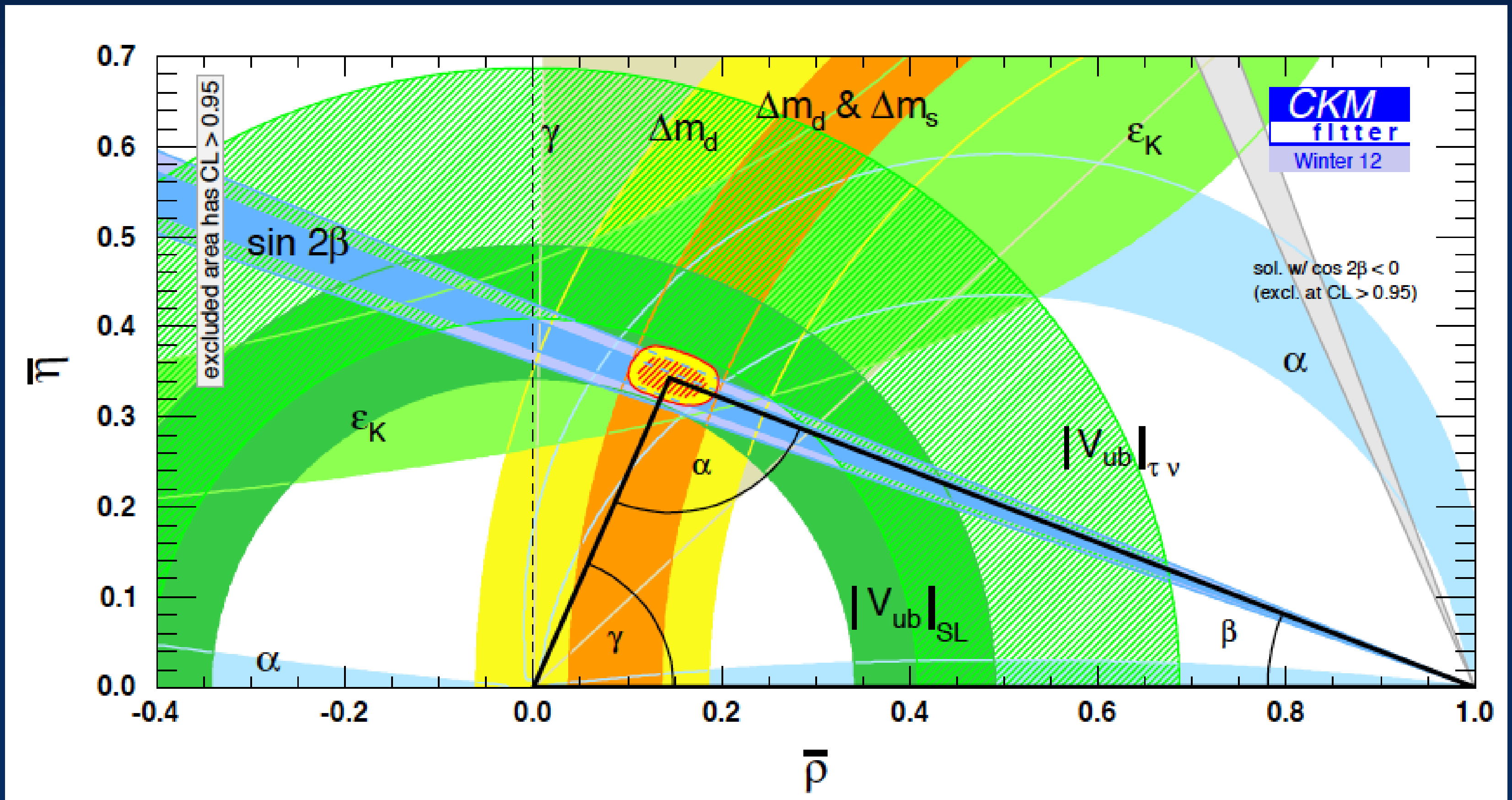
- Going Beyond a Neutrino Factory Facility
  - Possibilities for a future Muon Collider Capability

- Conclusion

WHY NEUTRINO FACTORIES?

The Key Issues

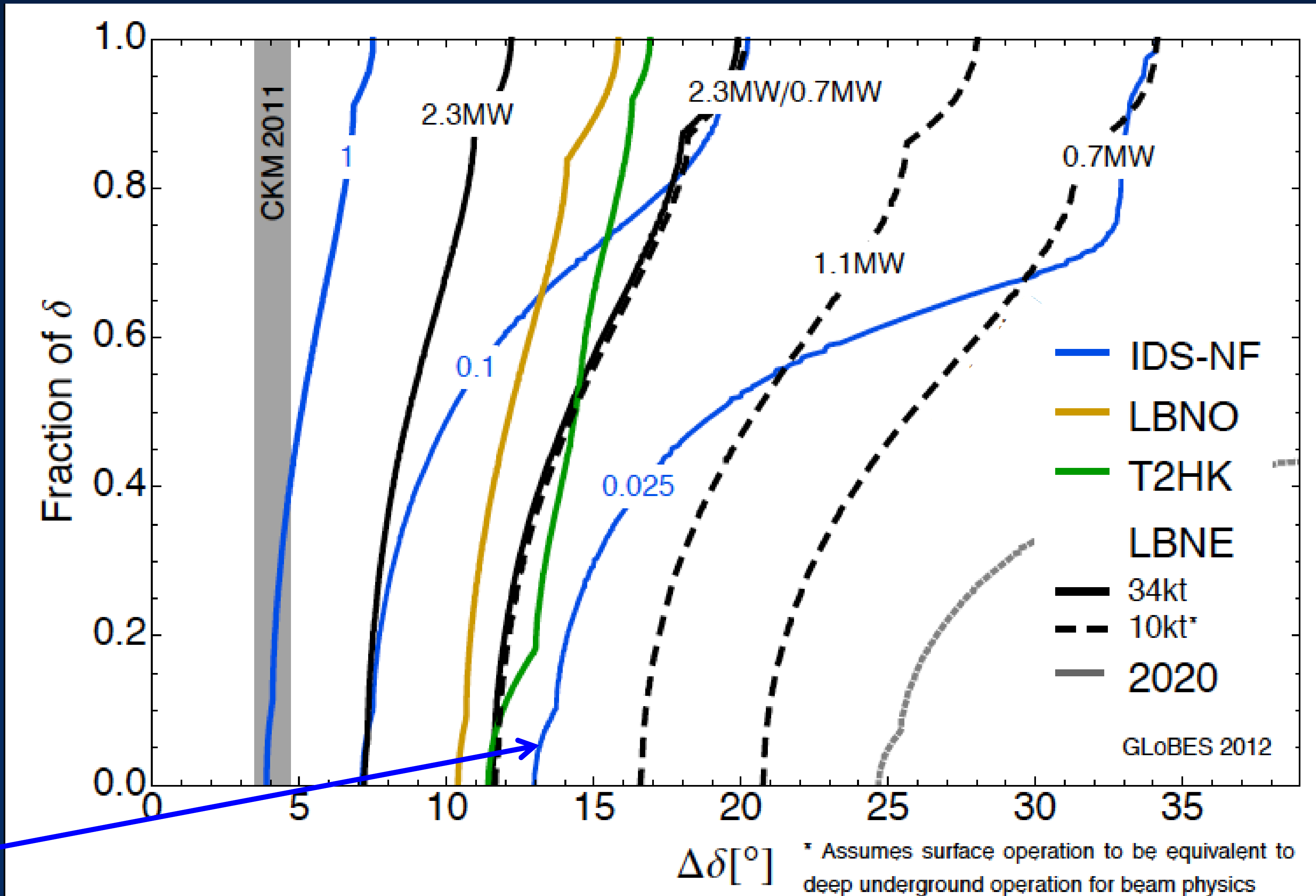
- What things must we understand in the neutrino sector?
  - δ_{CP}
  - The mass hierarchy
  - The value of $\theta_{23}-\pi/4$: +, - or zero?
  - Resolve the LSND and other short baseline experimental anomalies
  - And enable the search for new physics



Neutrino Factory ⇨ 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

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*

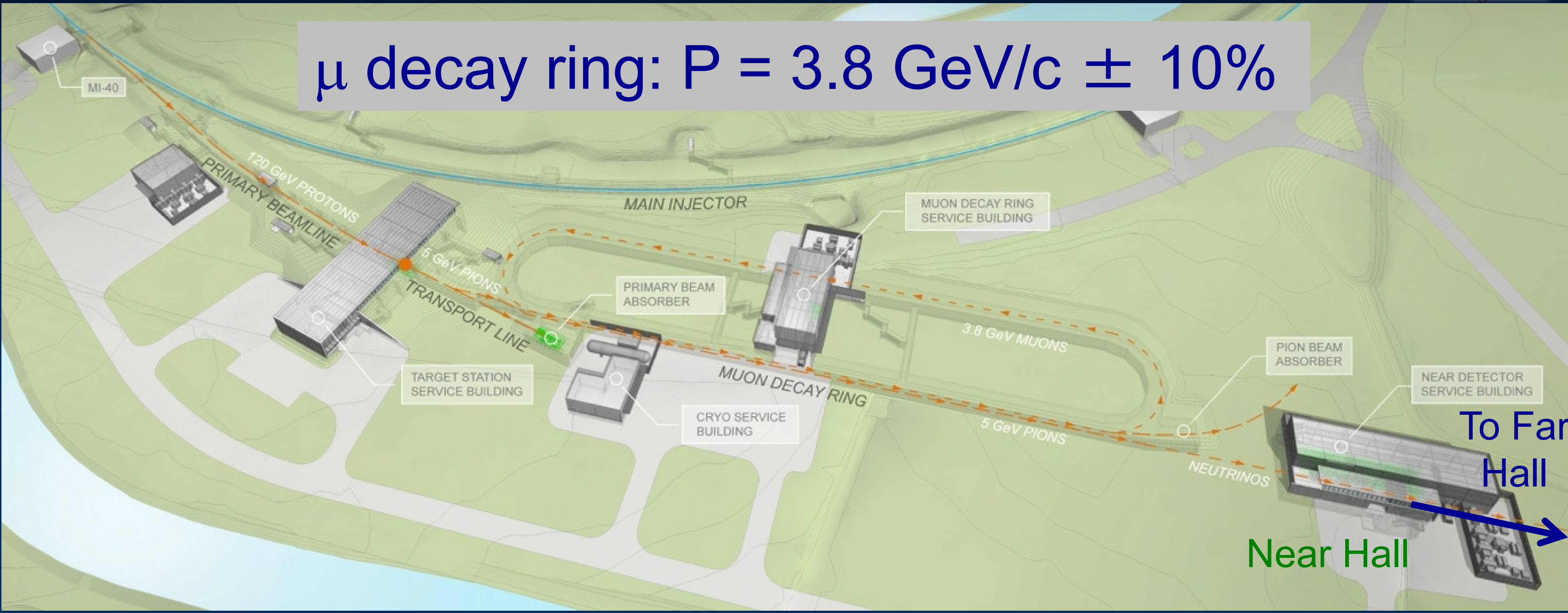
NEUTRINO FACTORY CONCEPTS

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 ⇨ 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

νSTORM



μ decay ring: P = 3.8 GeV/c ± 10%
MI-40
120 GeV PROTONS
PRIMARY BEAMLINE
MAIN INJECTOR
MUON DECAY RING SERVICE BUILDING
5 GeV PIONS
TRANSPORT LINE
PRIMARY BEAM ABSORBER
3.8 GeV MUONS
TARGET STATION SERVICE BUILDING
MUON DECAY RING
CRYO SERVICE BUILDING
PION BEAM ABSORBER
NEAR DETECTOR SERVICE BUILDING
5 GeV PIONS
NEUTRINOS
To Far Hall
Near Hall

νSTORM

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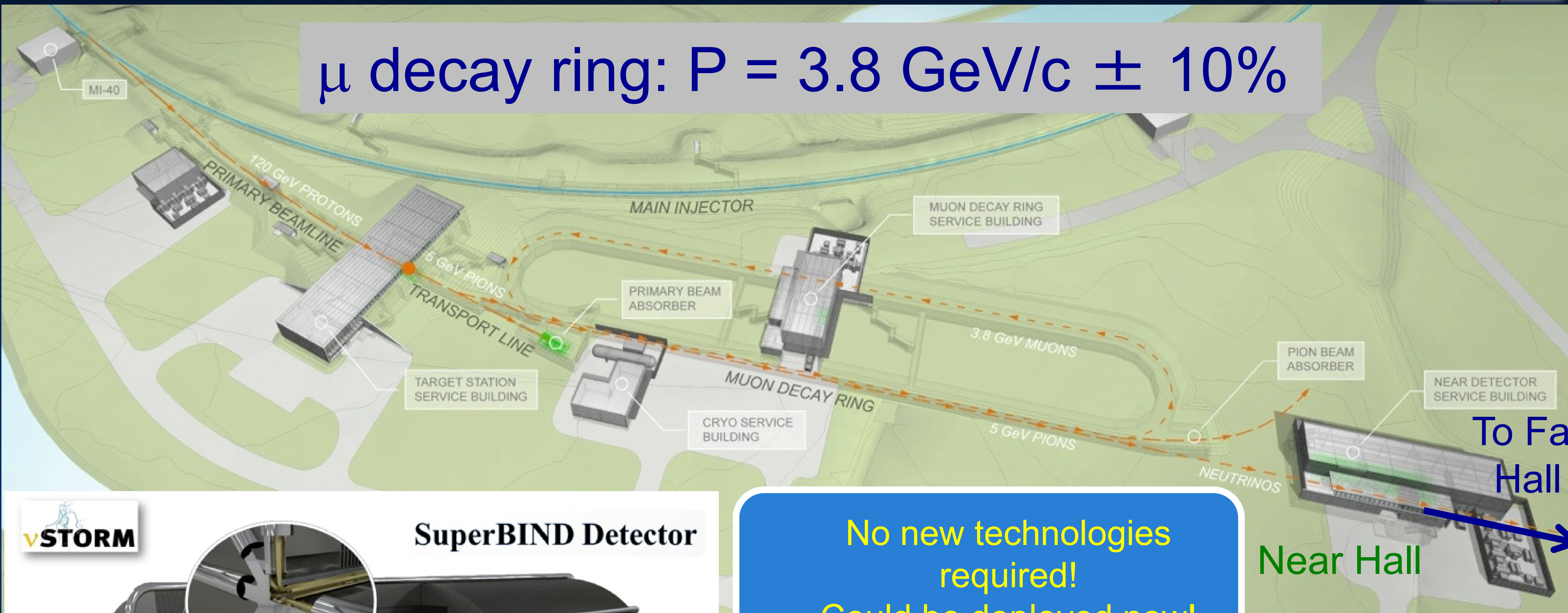
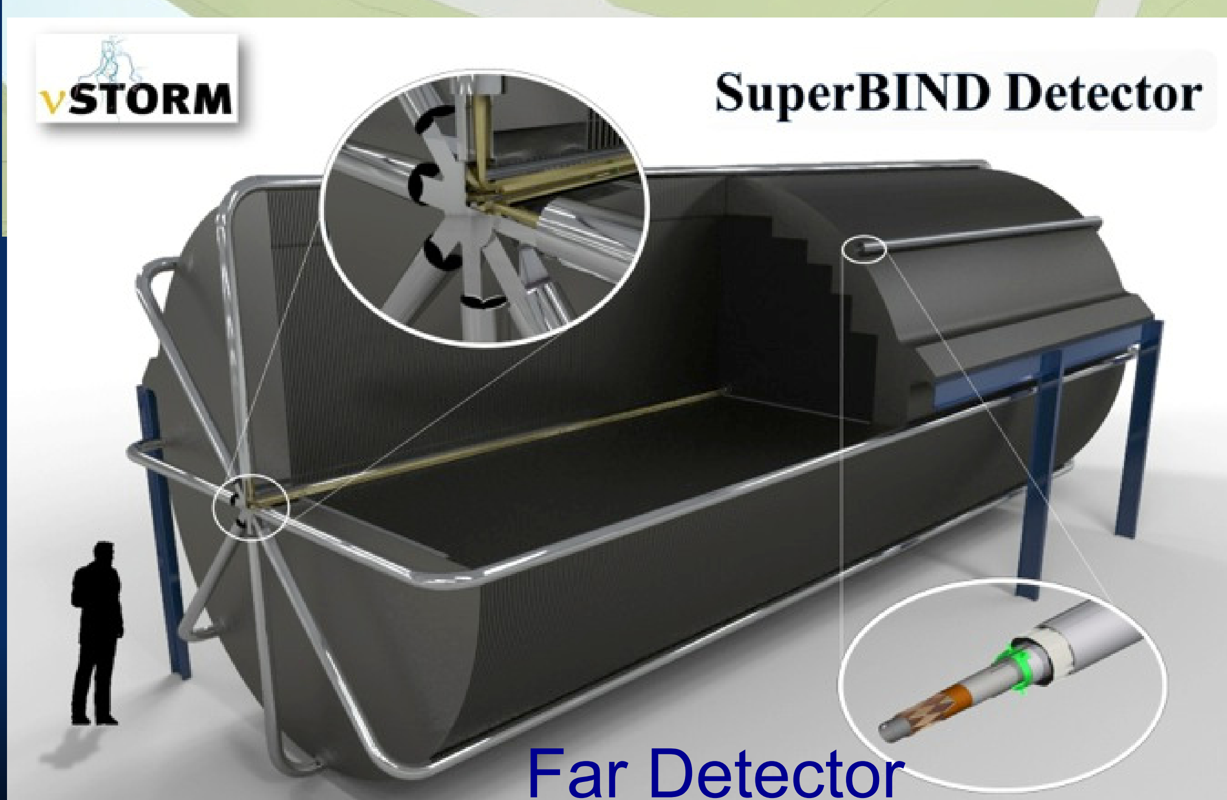
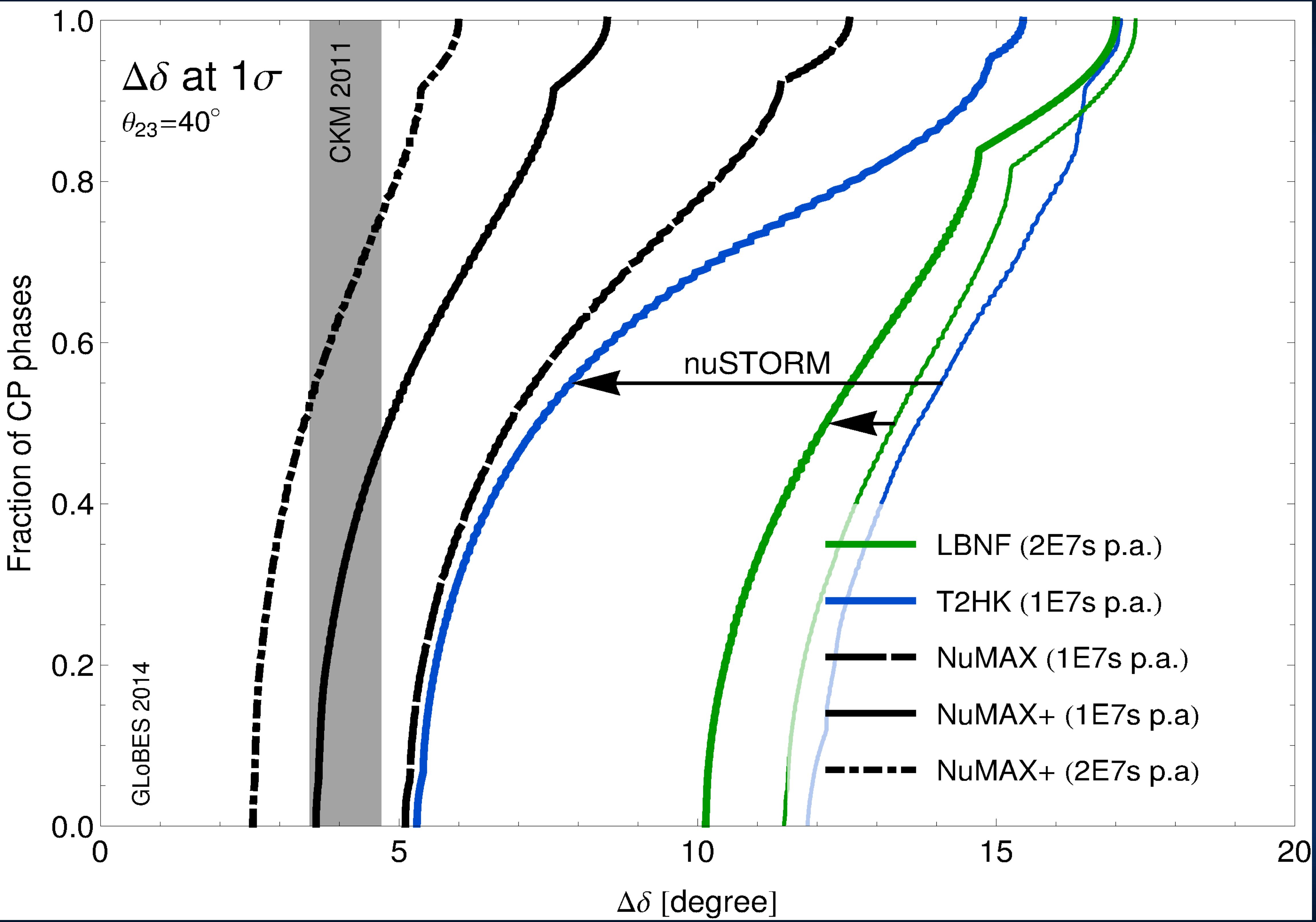




No new technologies required!
Could be deployed now!

Performance Benefits from Precision ν Sources



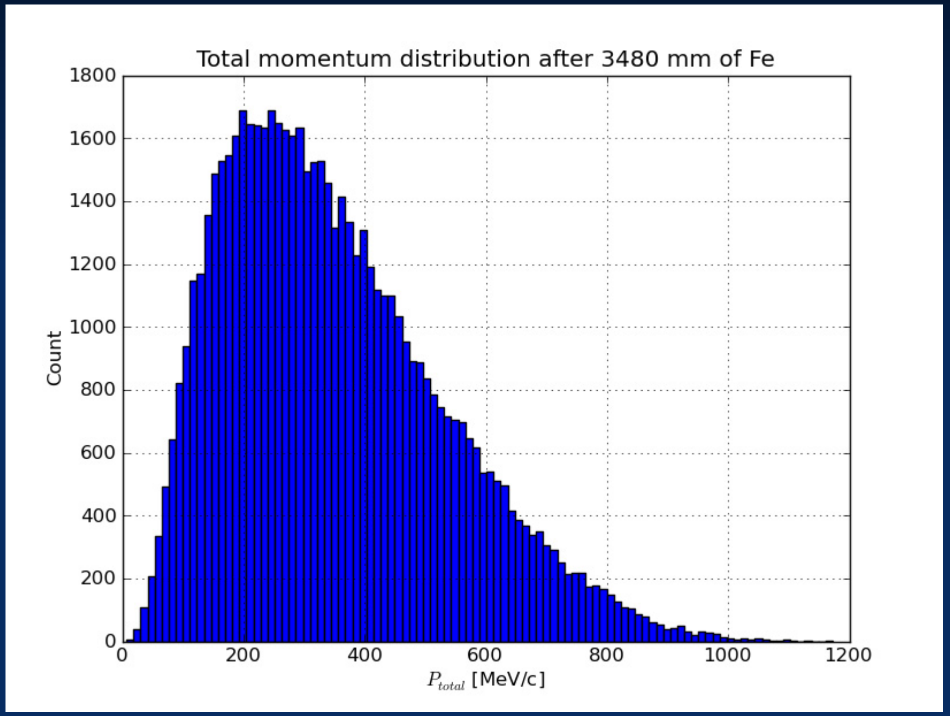
GLoBES Comparison of Potential Performance of the Various Advanced Concepts *(courtesy P. Huber)*

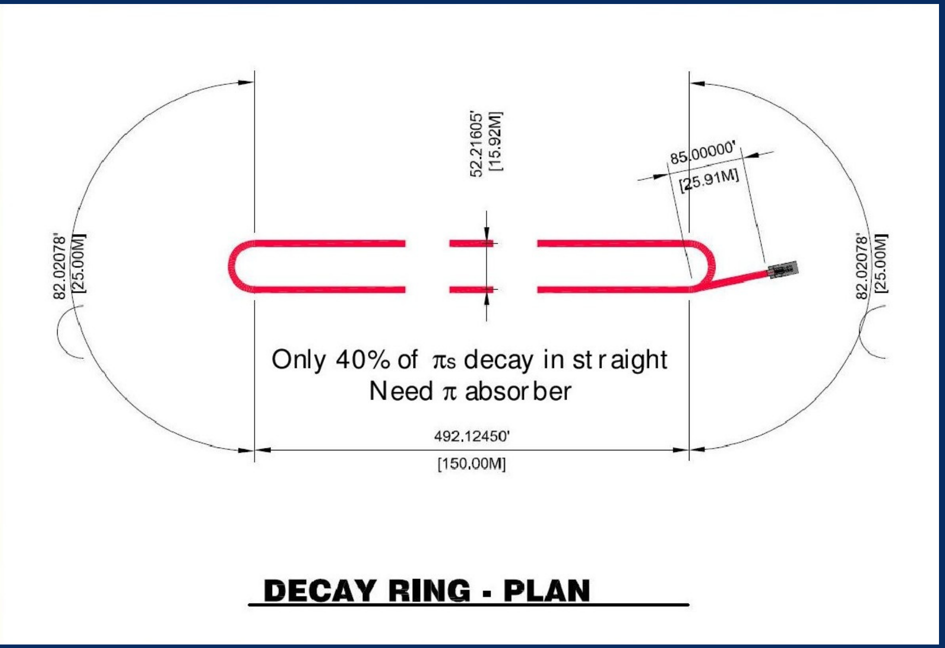
νStorm as an R&D platform

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

- Beam available simultaneously with physics operation

- νSTORM also provides the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon beam



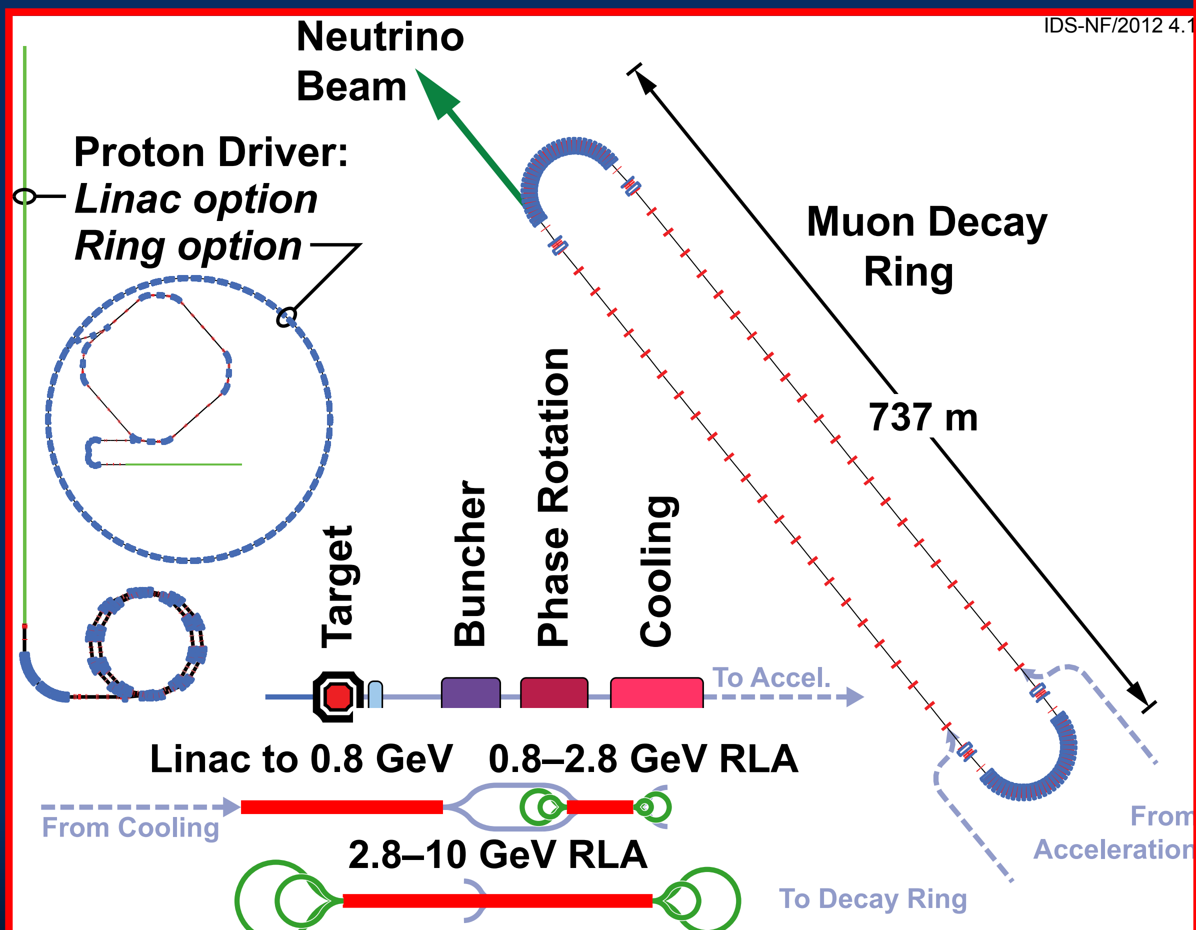


The Long Baseline Neutrino Factory

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

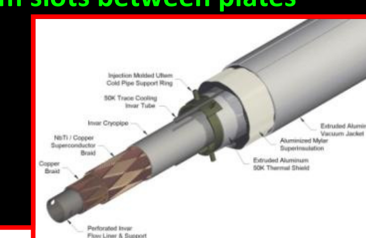
NuMAX@5 GeV ⇨SURF

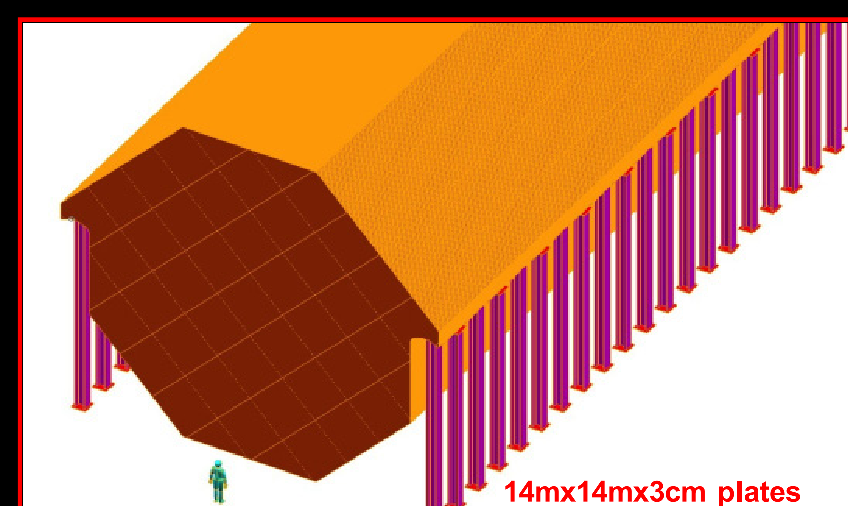
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

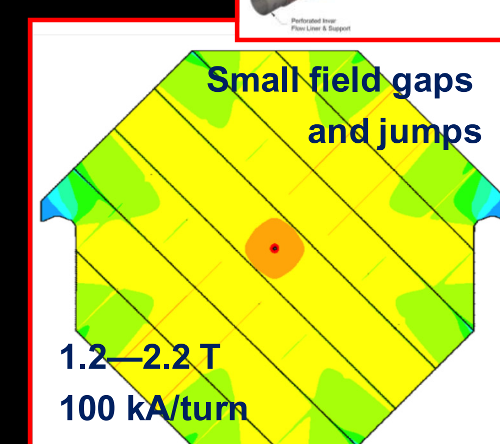


MagneHzed'Iron'Neutrino'Detector'(MIND):'

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

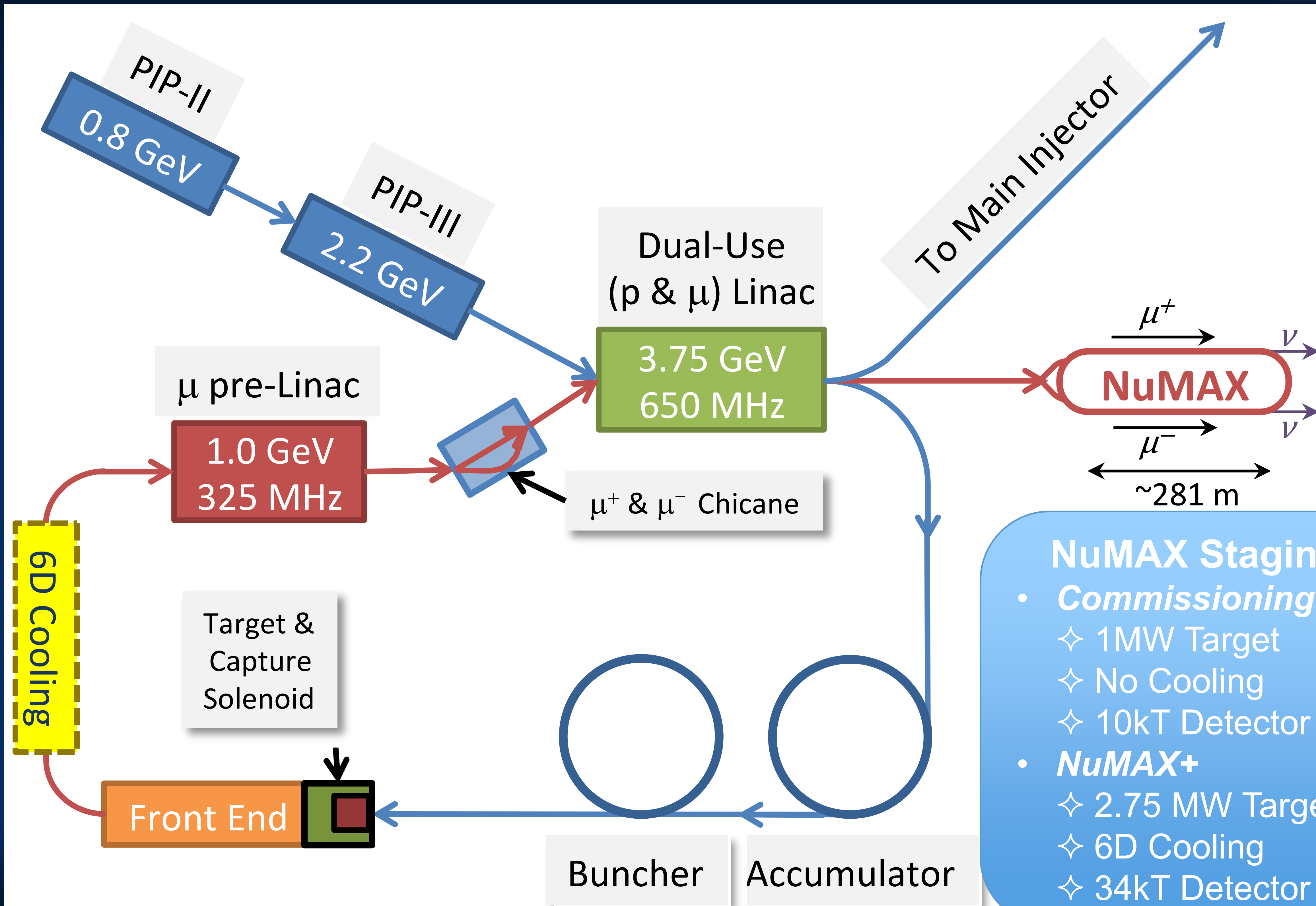






Bross,'Soler'

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	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 (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			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	15	15

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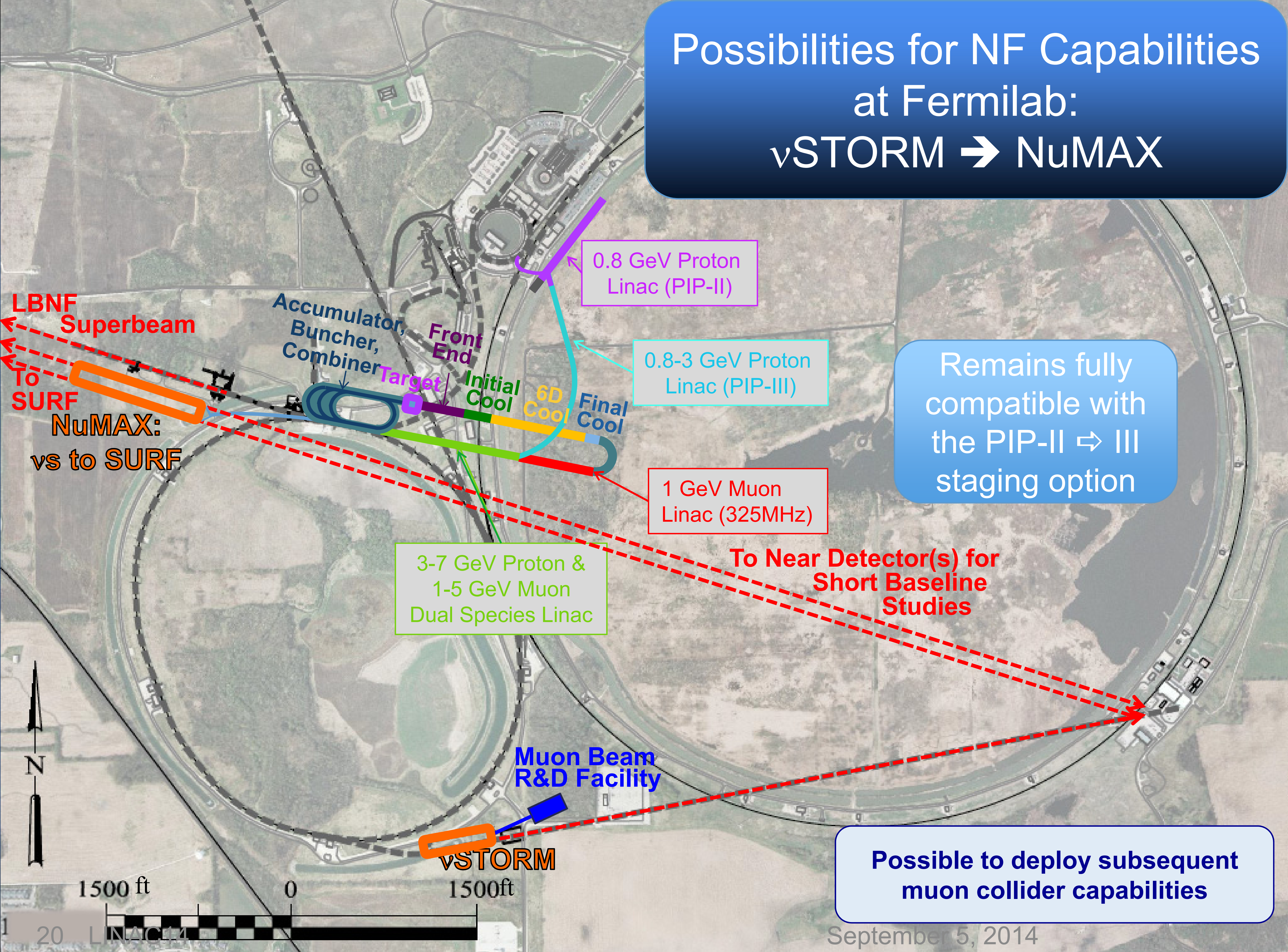
Possibilities for NF Capabilities at Fermilab: νSTORM ➔ NuMAX



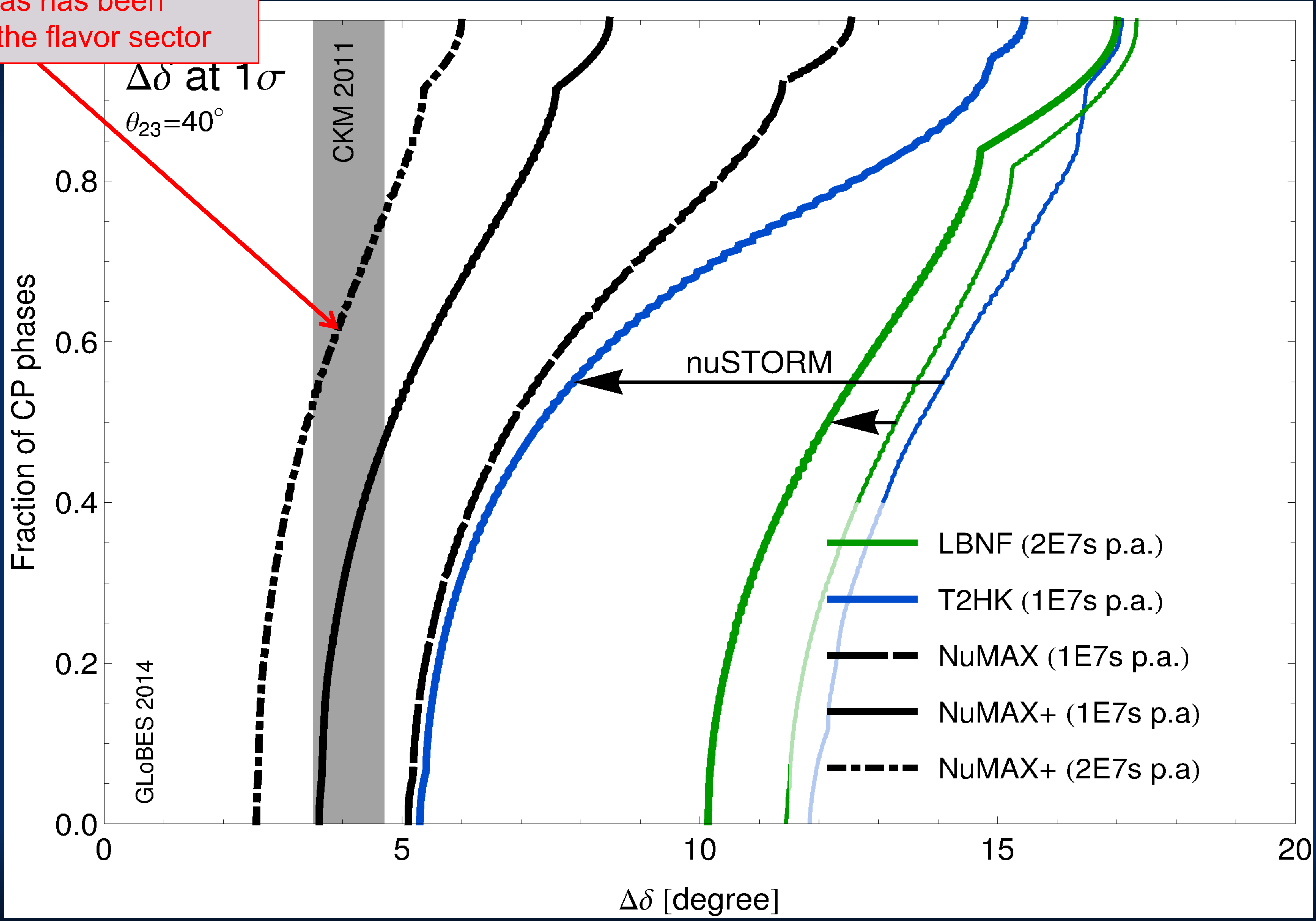
Remains fully compatible with the PIP-II ⇨ III staging option

Possible to deploy subsequent muon collider capabilities

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)*



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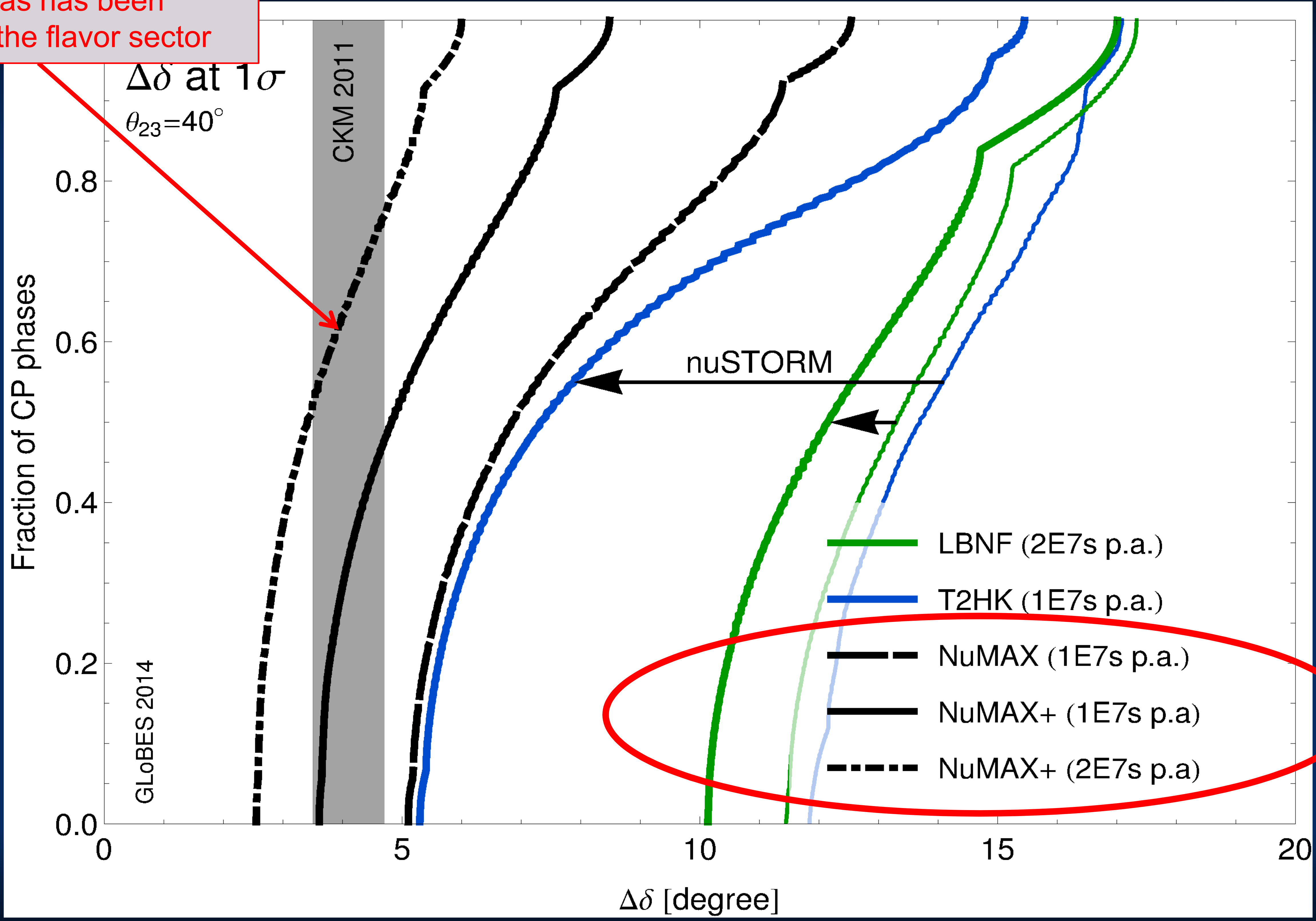

Accelerator R&D Effort (U.S. MAP)

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Design Studies

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

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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)

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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

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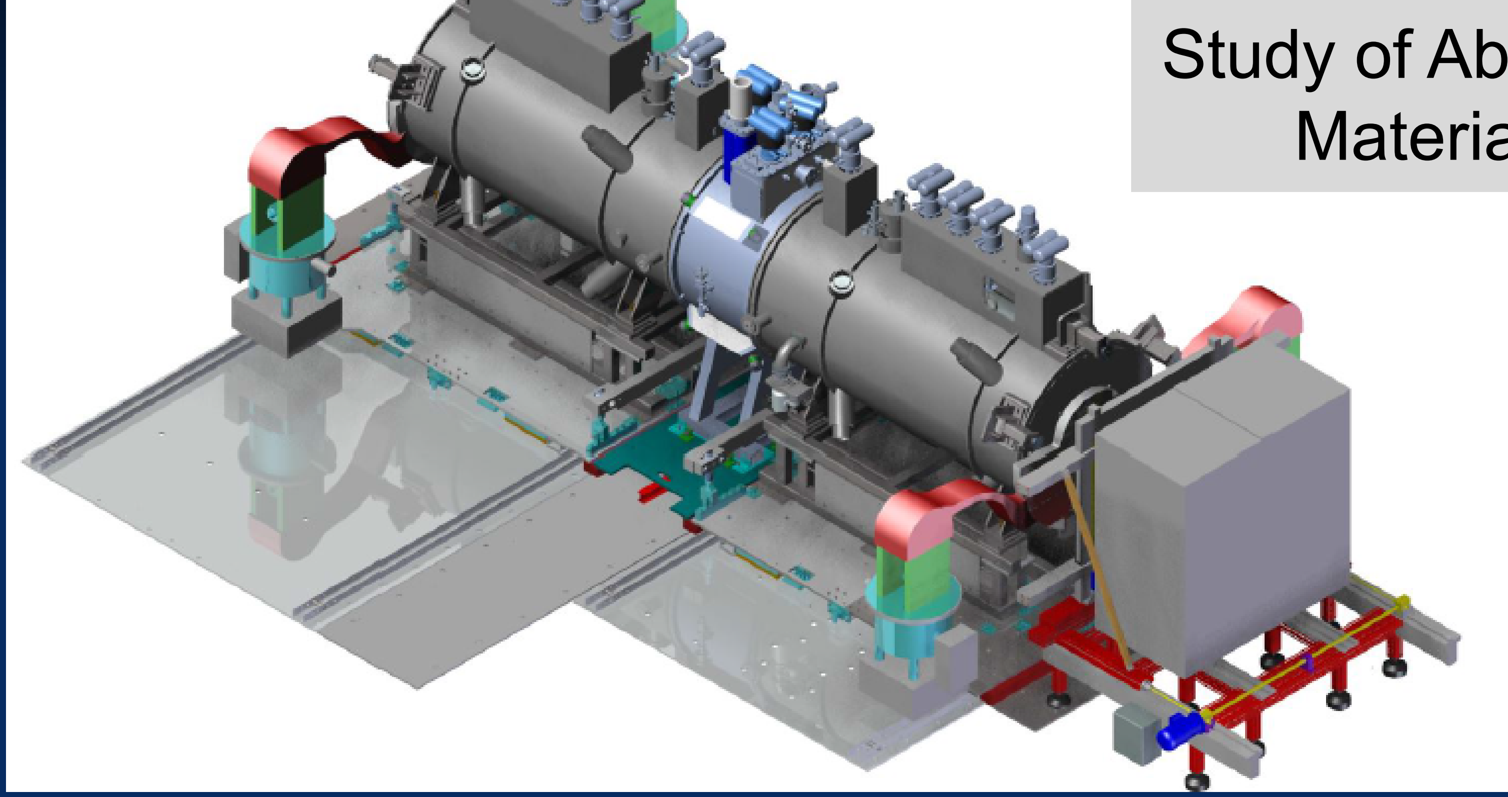
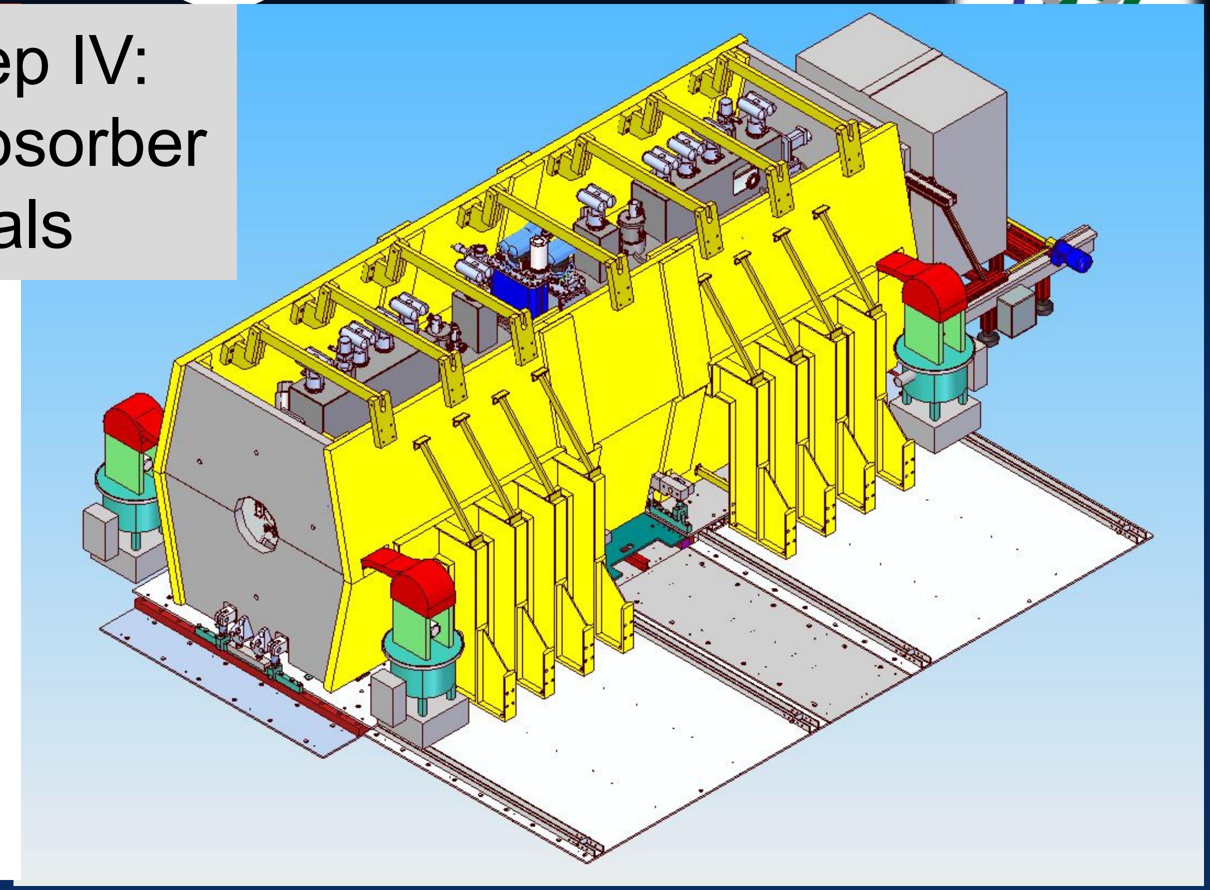
2015 Data



MICE Step IV:
Study of Absorber Materials



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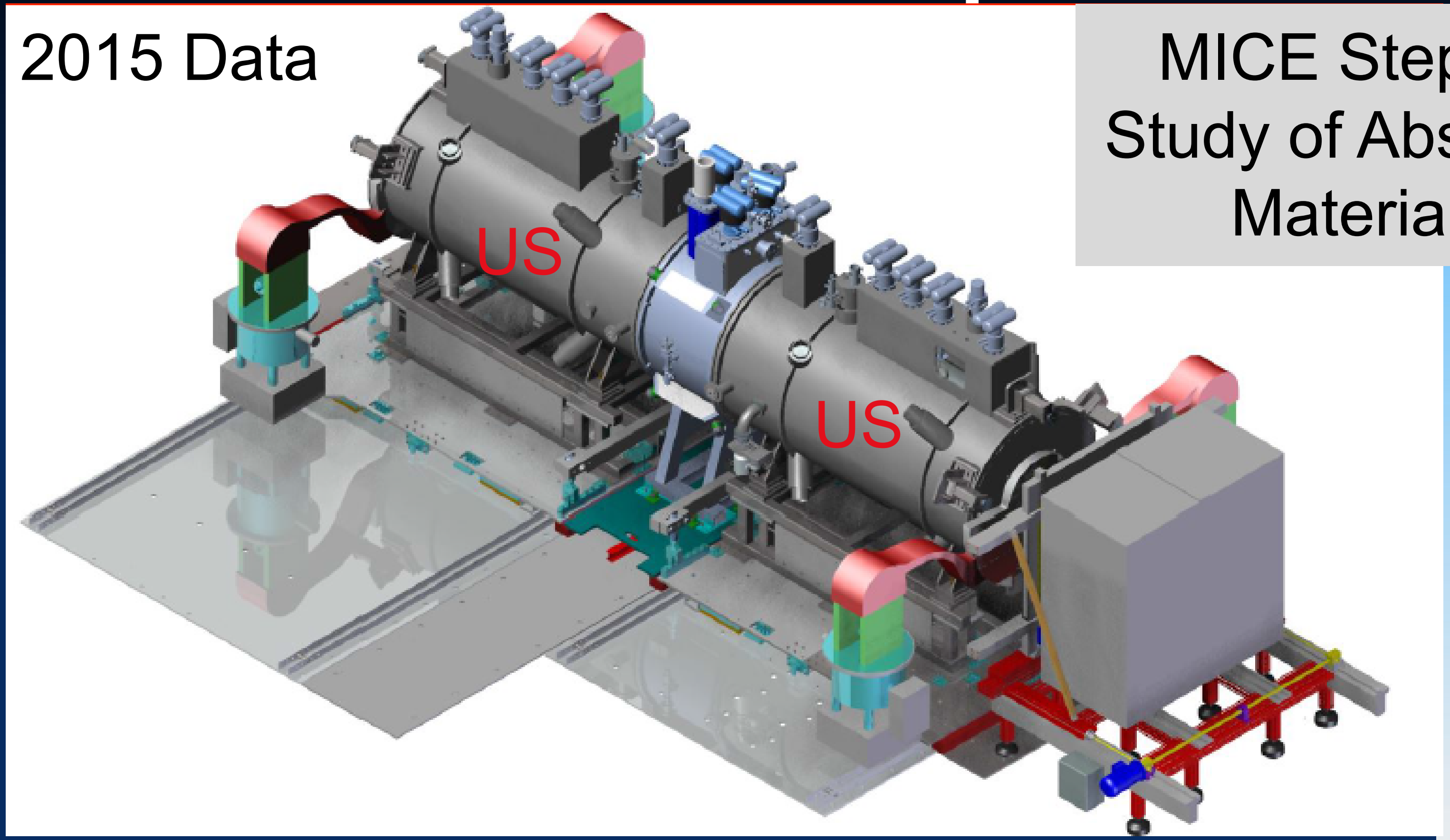

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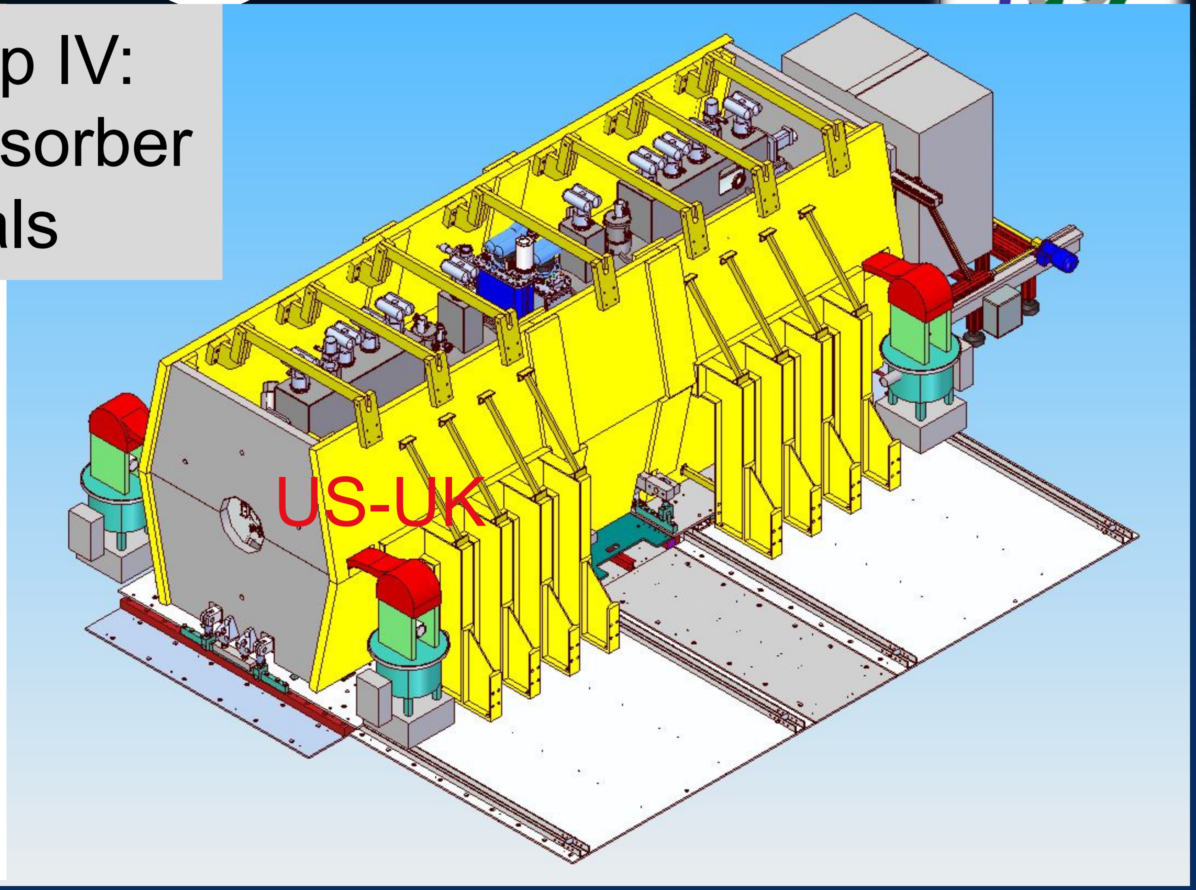

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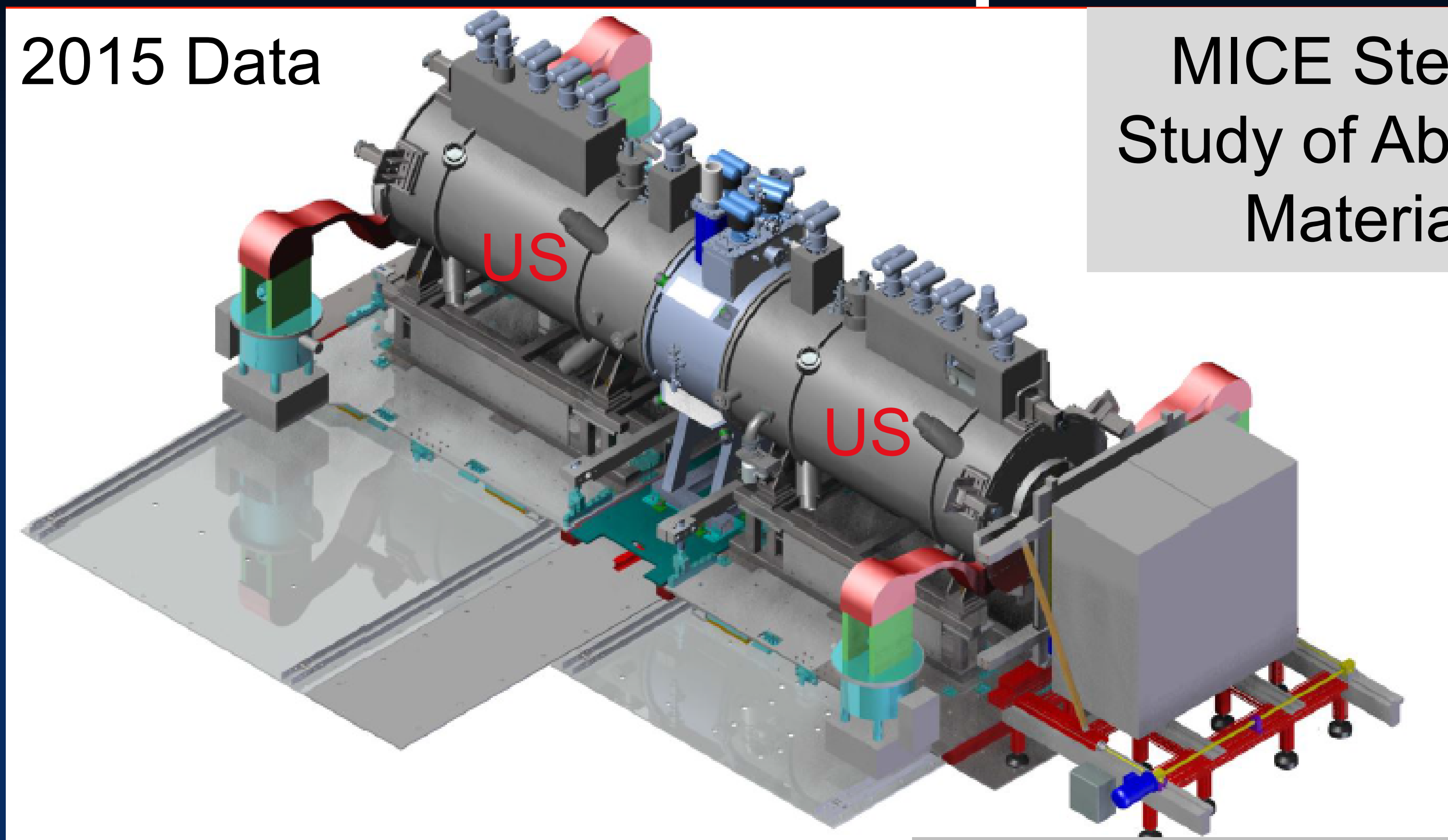

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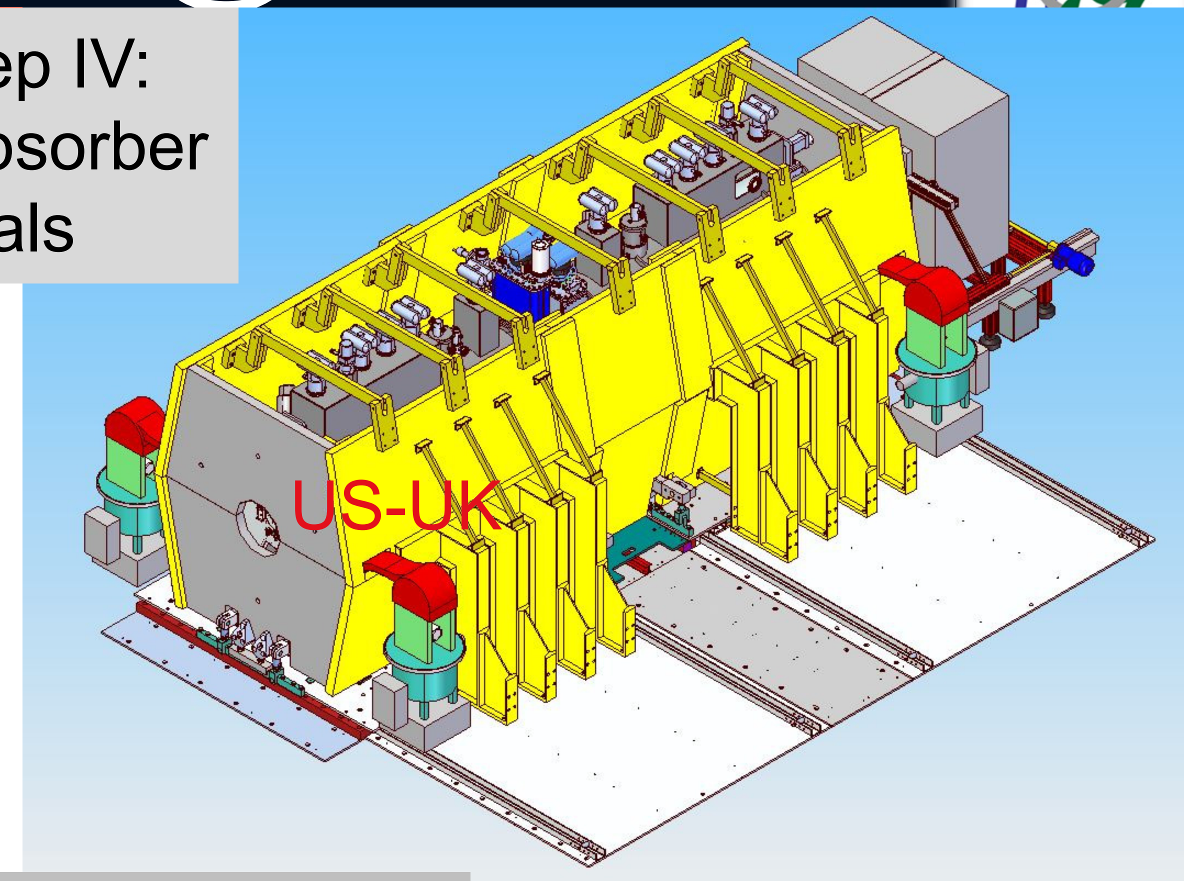
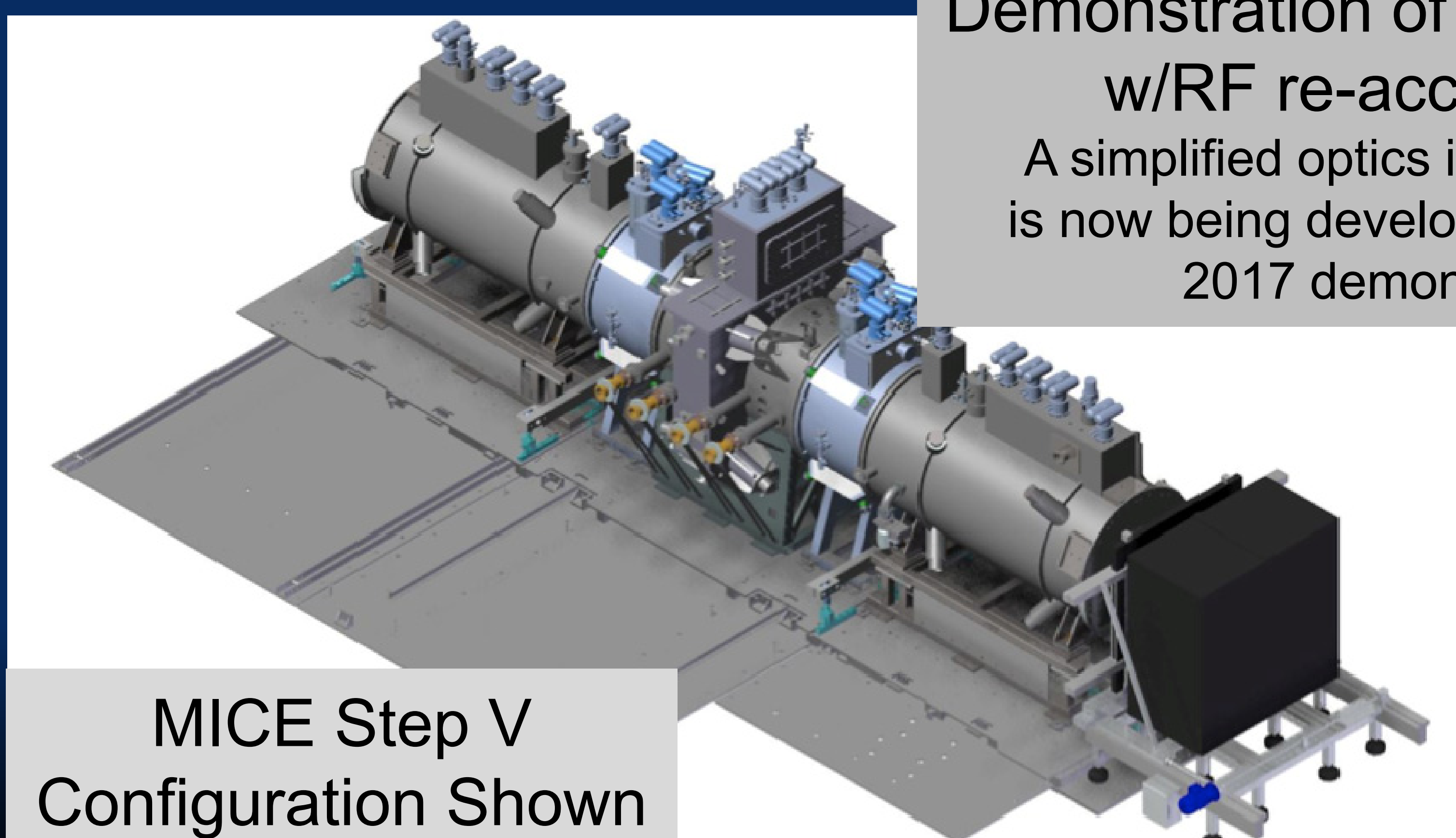
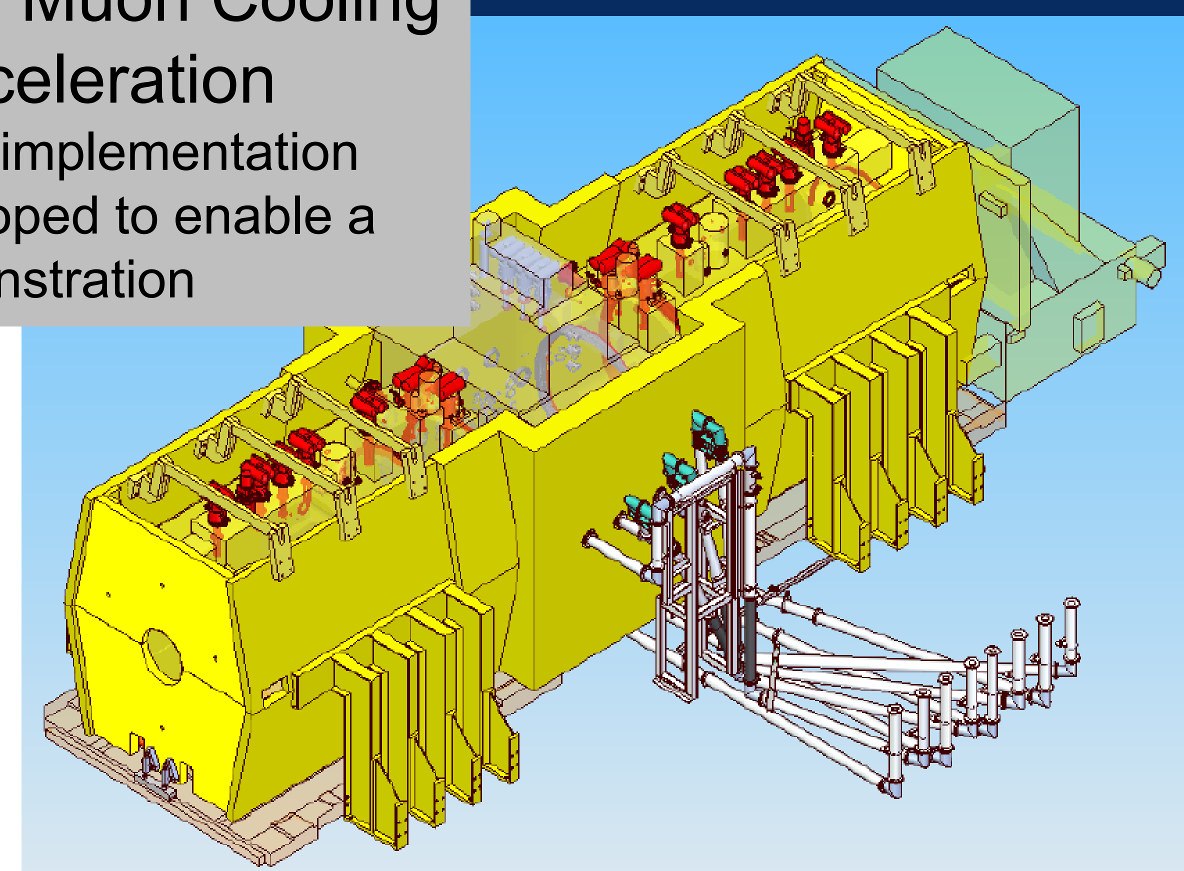


Demonstration of Muon Cooling w/RF re-acceleration

A simplified optics implementation is now being developed to enable a 2017 demonstration





MICE Step V Configuration Shown

MICE Experiment @RAL

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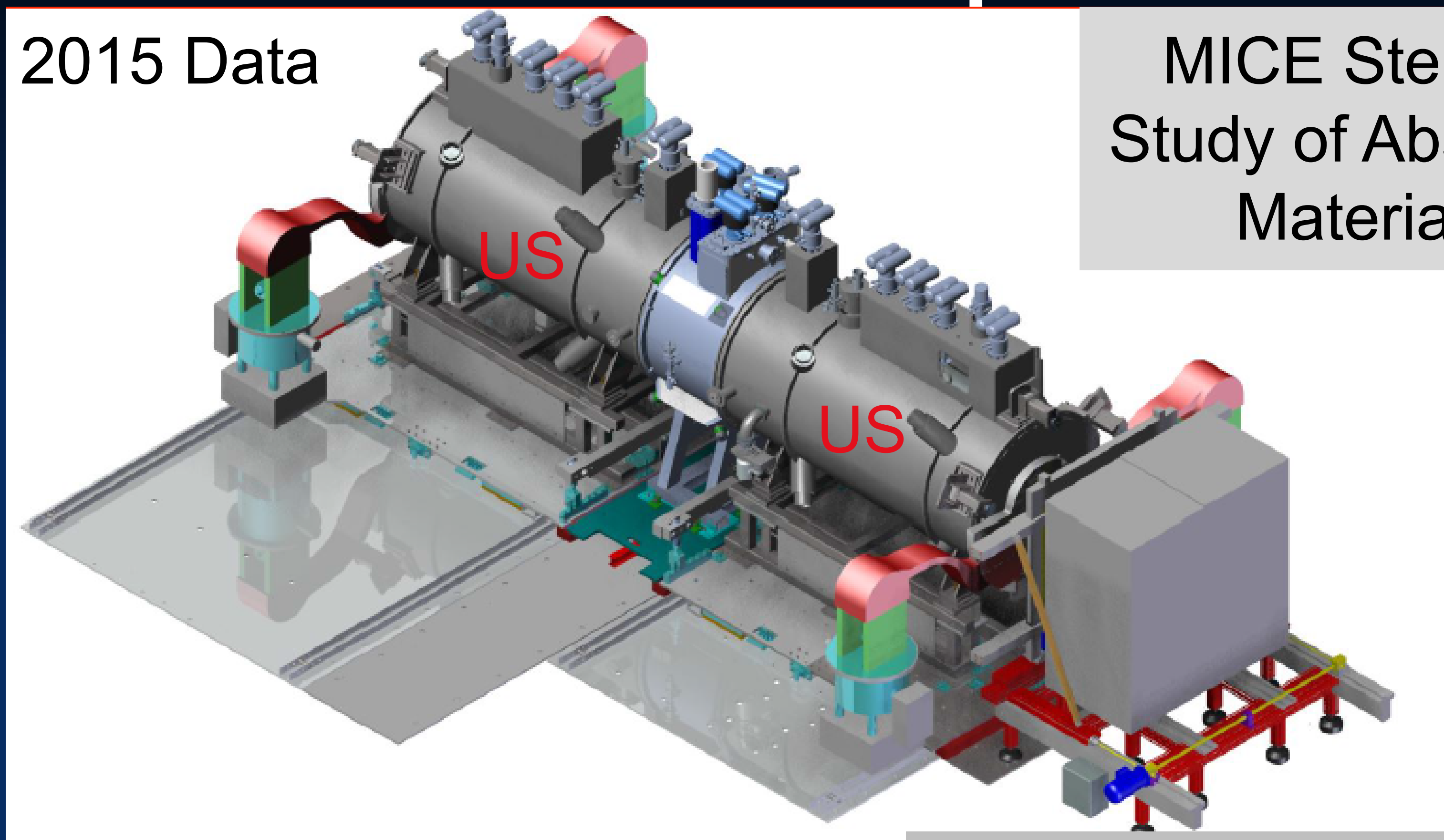

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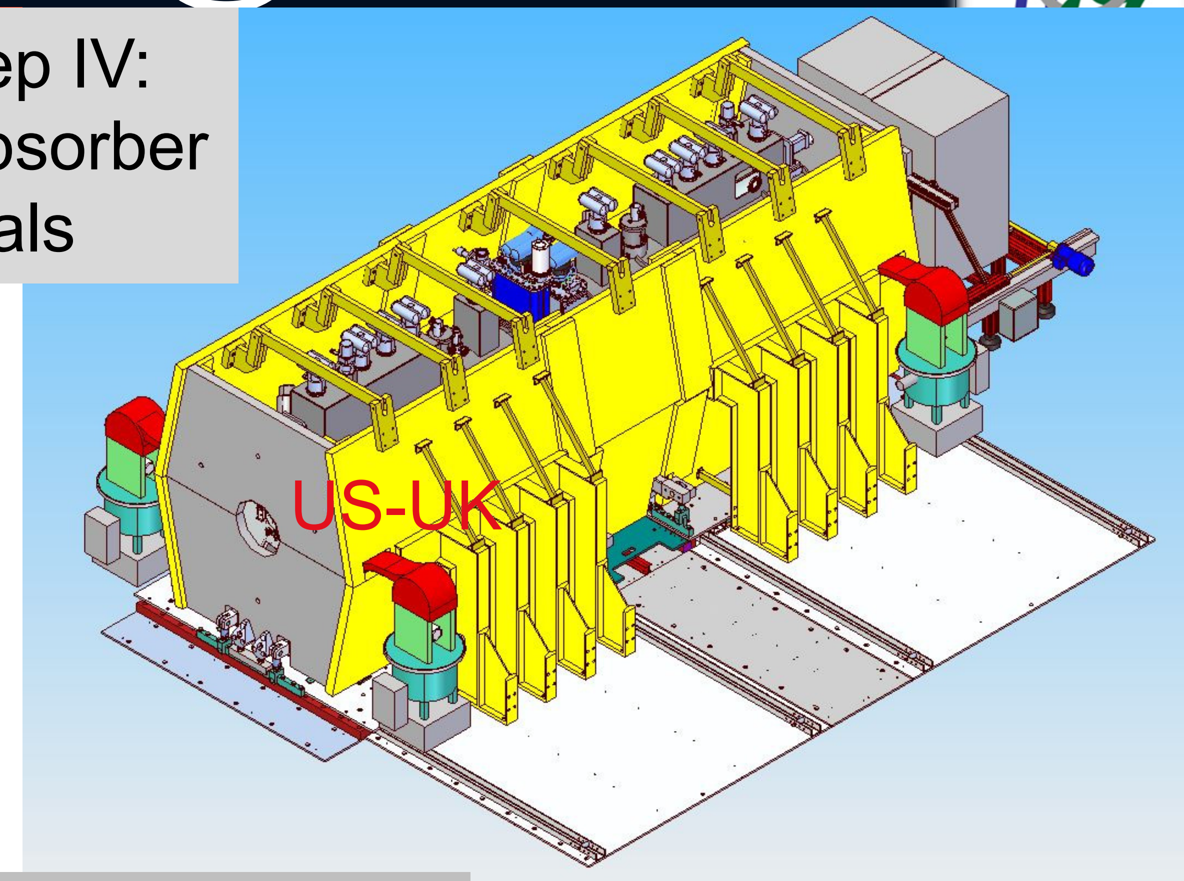

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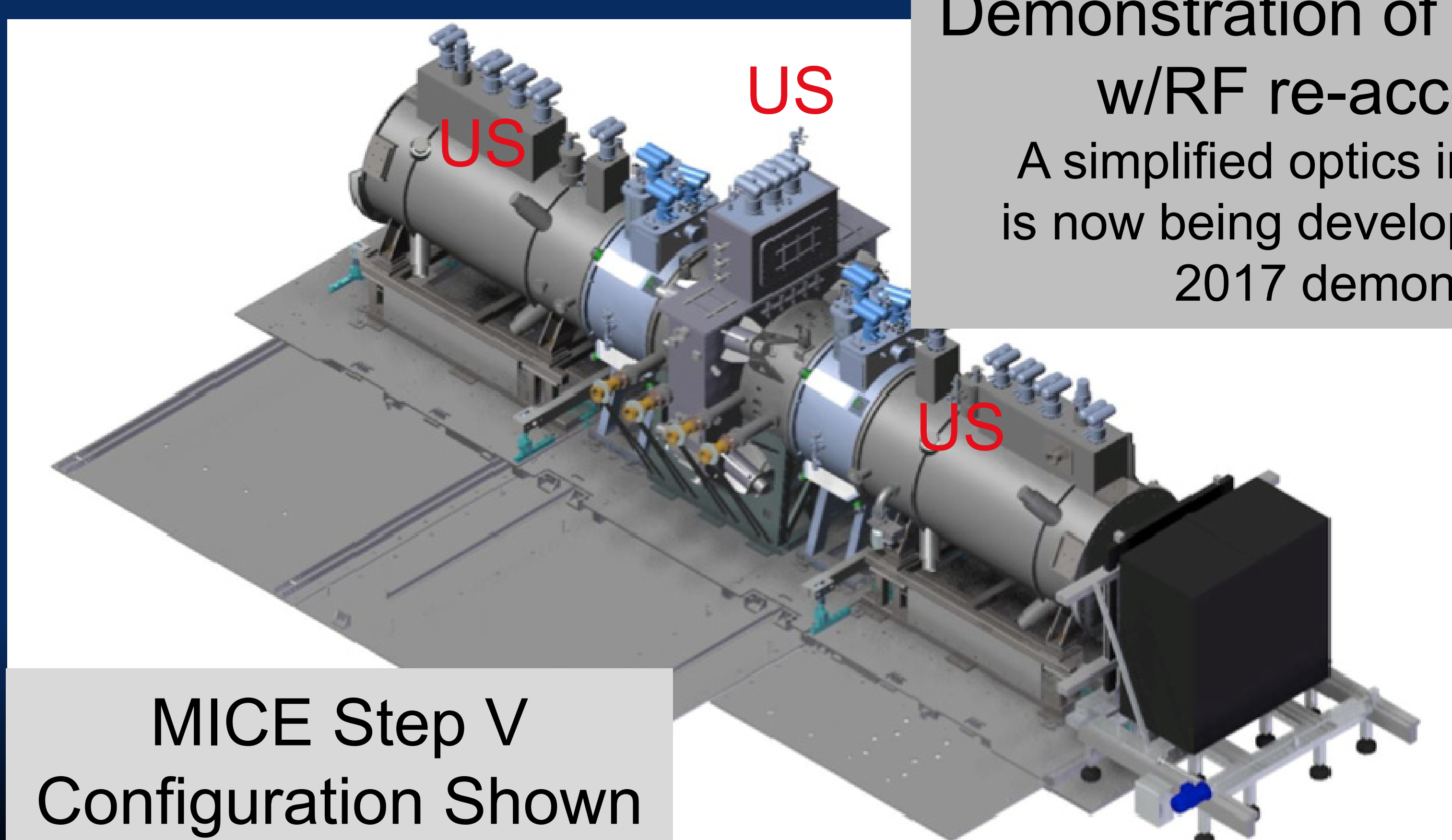
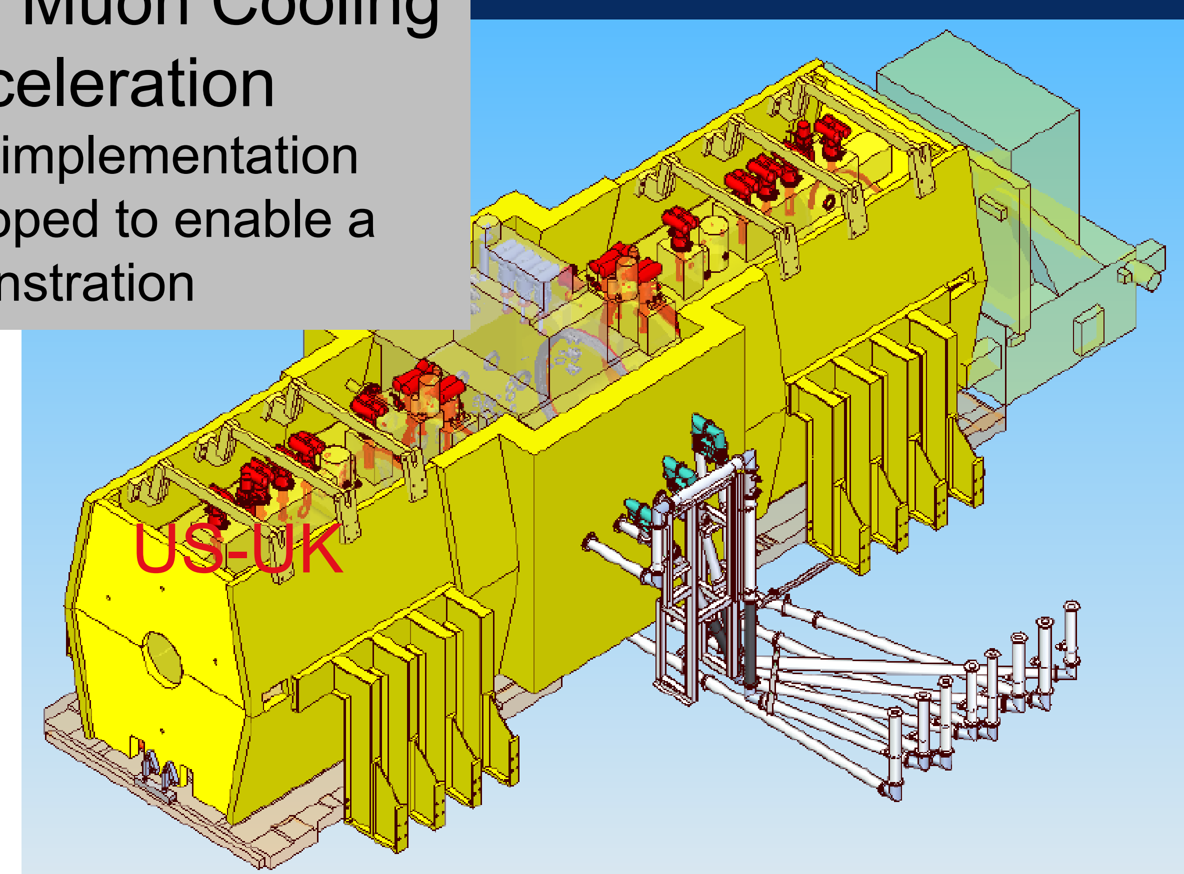


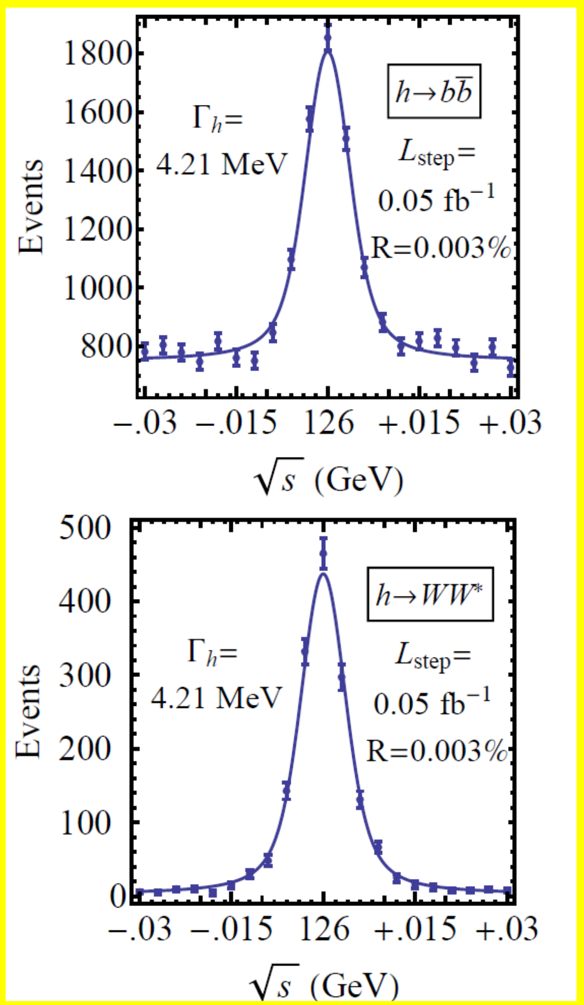


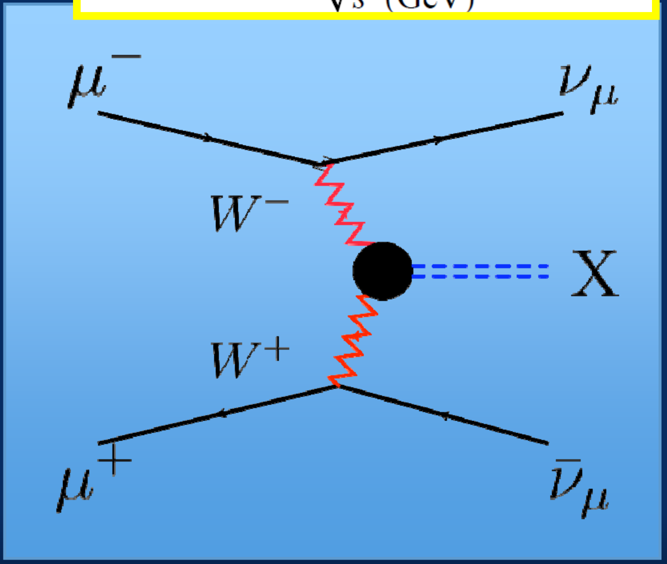
MICE Step V Configuration Shown

GOING BEYOND NEUTRINO FACTORY CAPABILITIES

Features of the Muon Collider

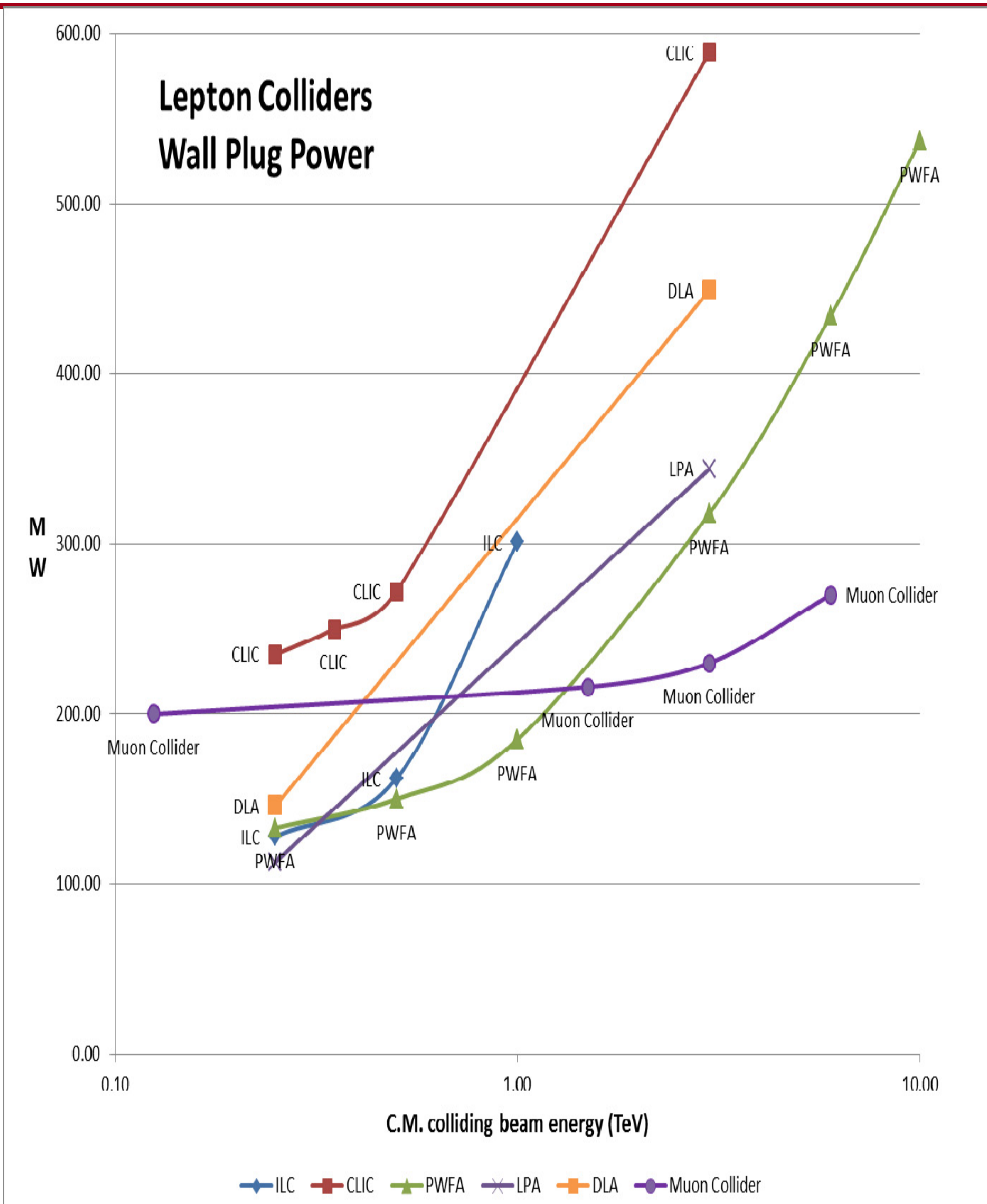
- Superb Energy Resolution
  - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability (≤ 10TeV):
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for 2 detectors in the ring
  - For $\sqrt{s}$ > 1 TeV: Fusion processes dominate
    - ⇨ an Electroweak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

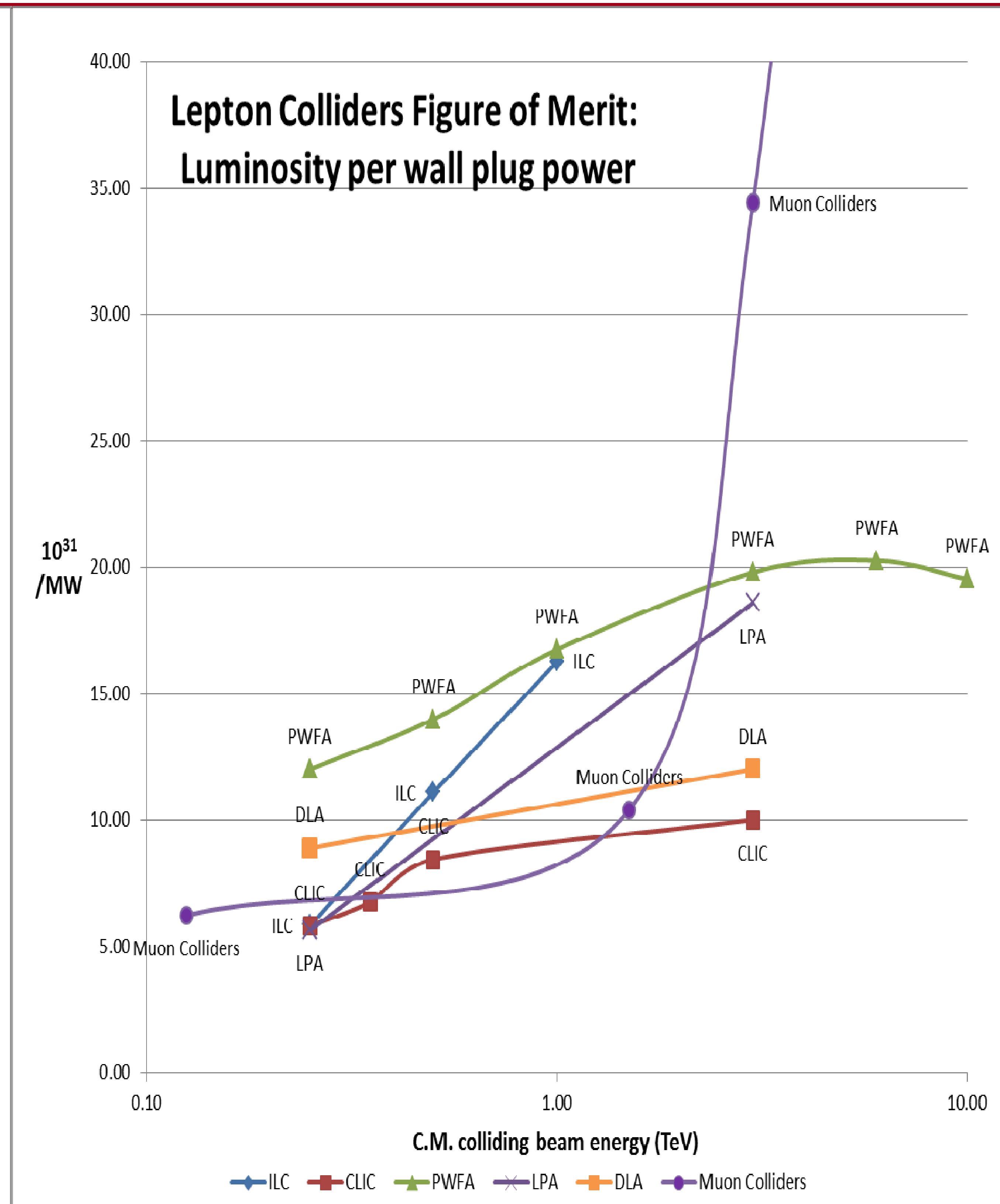




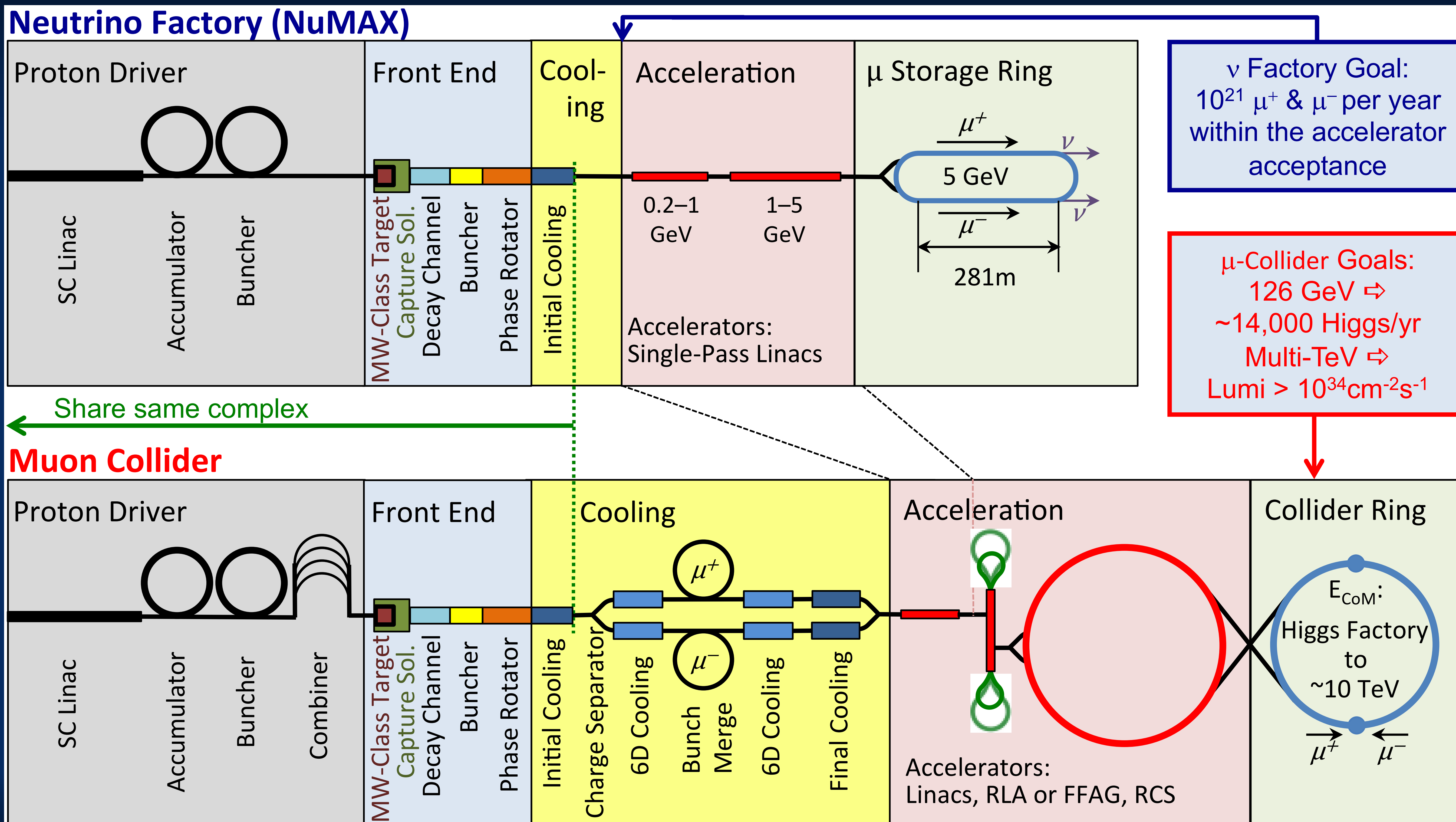
What are our accelerator options if new LHC data shows evidence for a multi-TeV particle spectrum?

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





NF/MC Synergies



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, optimized for a detector at SURF, affording a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeam technology.
- NuMAX+: a full-intensity Neutrino Factory, upgraded from 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 13,500 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.

The Staging Study (MASS)

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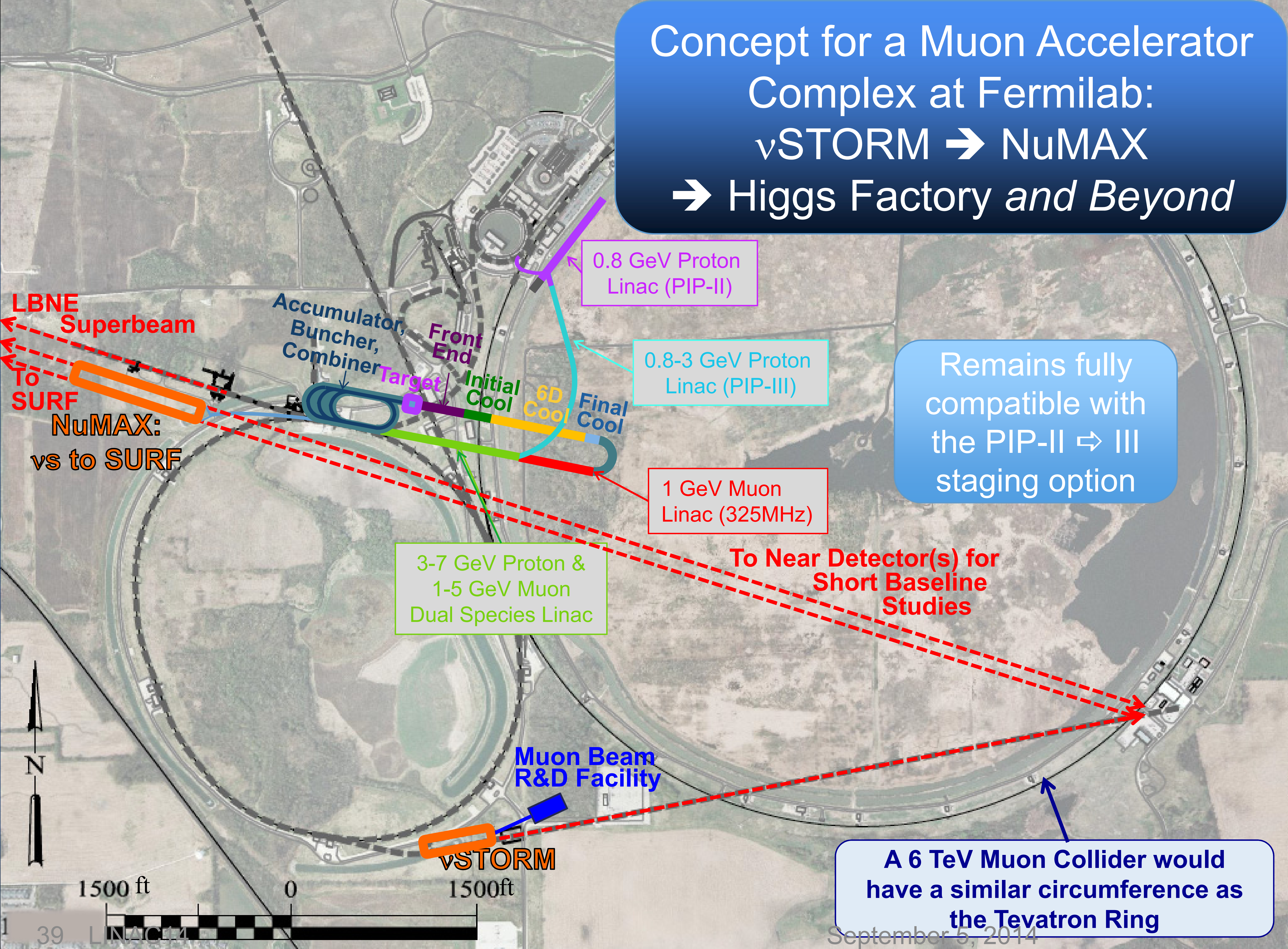
Ability to utilize some or all stages

Concept for a Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory *and Beyond*



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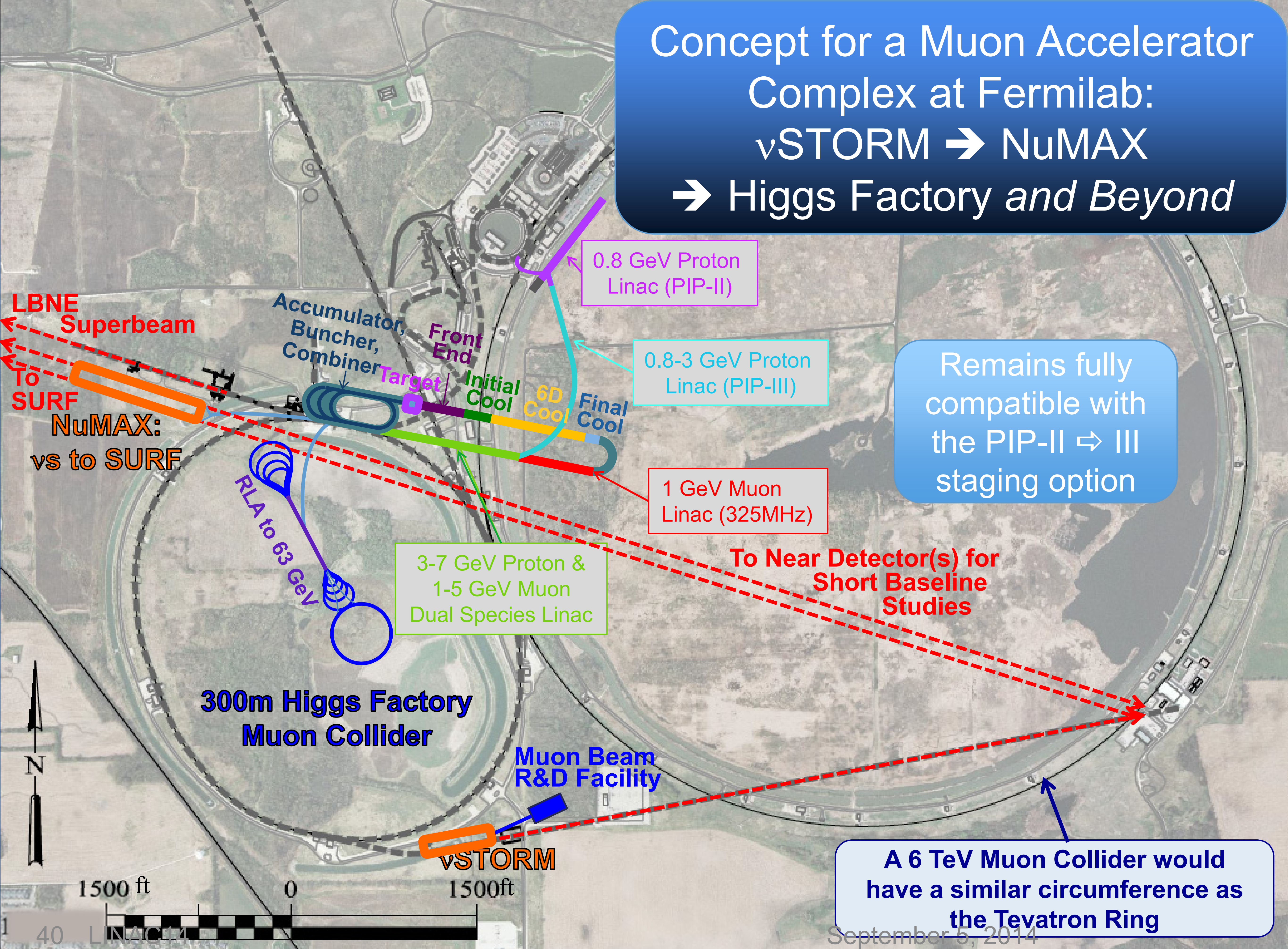
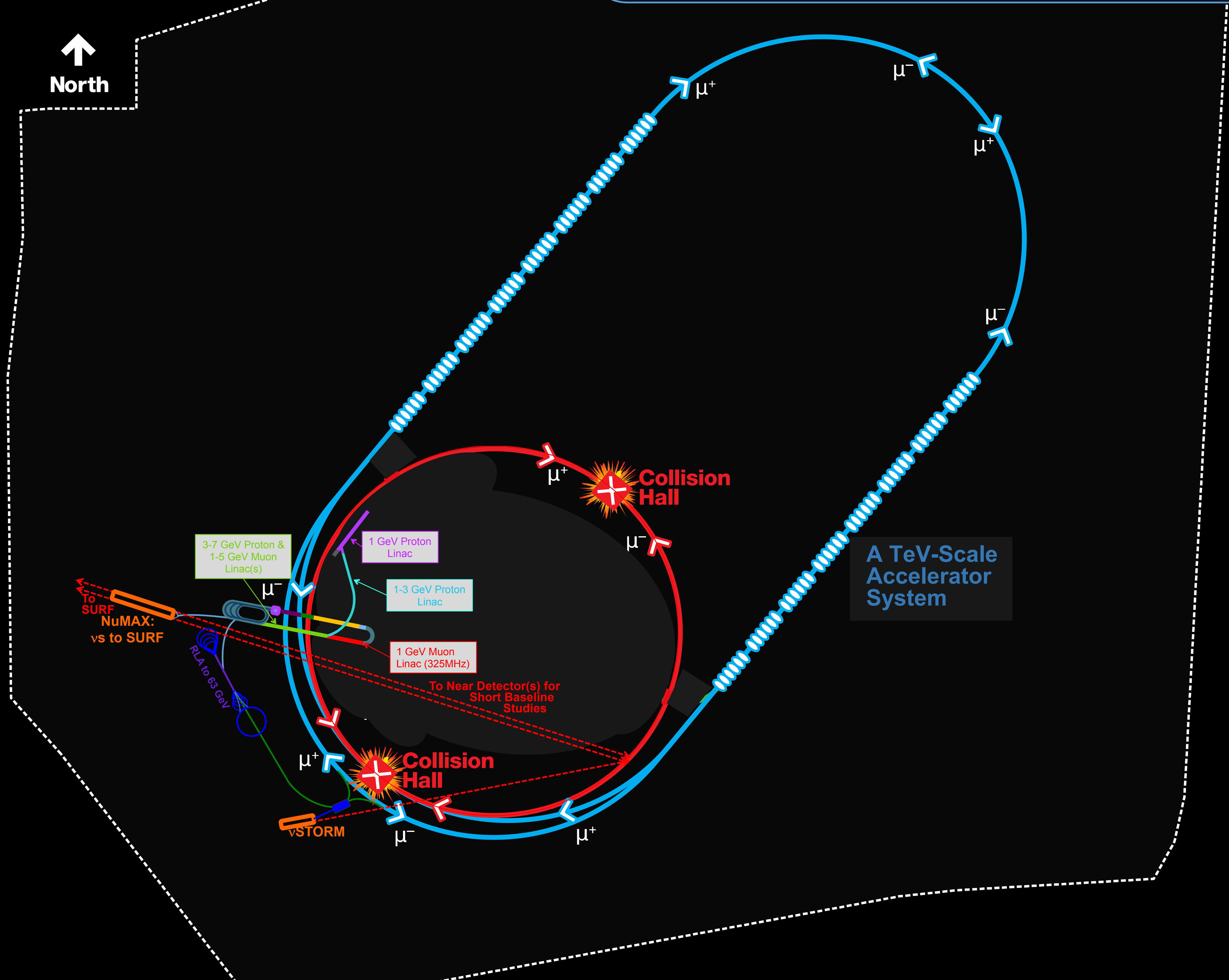
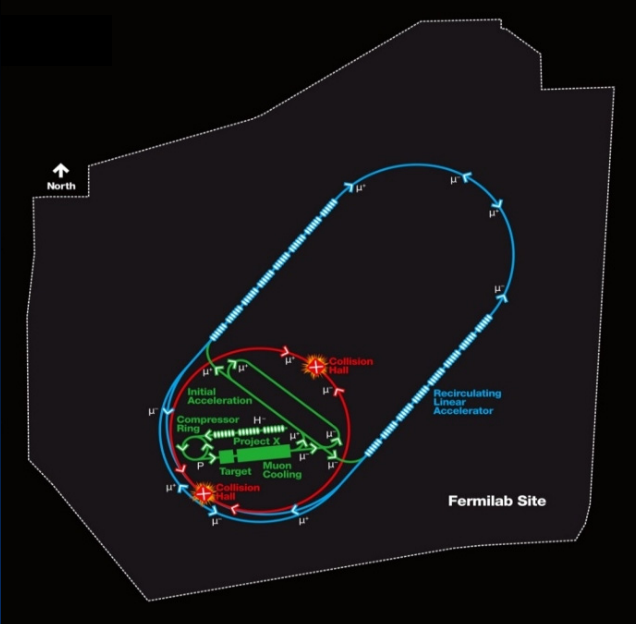


Concept for a Muon Accelerator Complex at Fermilab:

→ Multi-TeV Lepton Collider



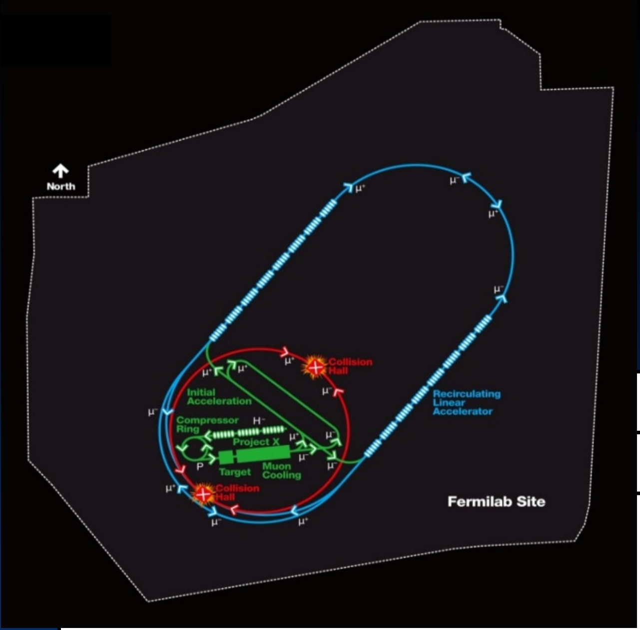


Muon Collider Parameters

Muon Collider Parameters								
		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

Could begin operation with Project X Stage II beam

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



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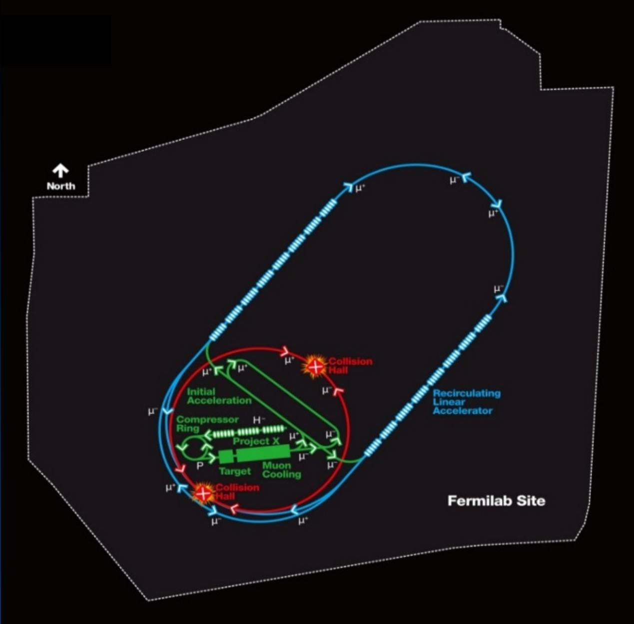
Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width



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Success of advanced cooling concepts ⇨ several × 10^{32}

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 (νSTORM)
  - 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