Muon Accelerators: An Integrated Path to Intensity and Energy Frontier Physics Capabilities

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Introduction and Context (I)

The US Muon Accelerator Program (MAP) is one of two Facilities R&D efforts presently supported by OHEP

- The other is LARP
- Both are *directed* accelerator R&D efforts ⇨ next generation capabilities for deployment at existing HEP facilities

MAP's focus is on the R&D required to demonstrate feasibility of the HEP applications for muon accelerators

- The Neutrino Factory (NF) on the Intensity Frontier
- The Muon Collider (MC) on the Energy Frontier

The two Muon Accelerator capabilities are strongly linked

- With key synergies that can be exploited to control technical risk and cost
- A unique breadth of physics that can be supported

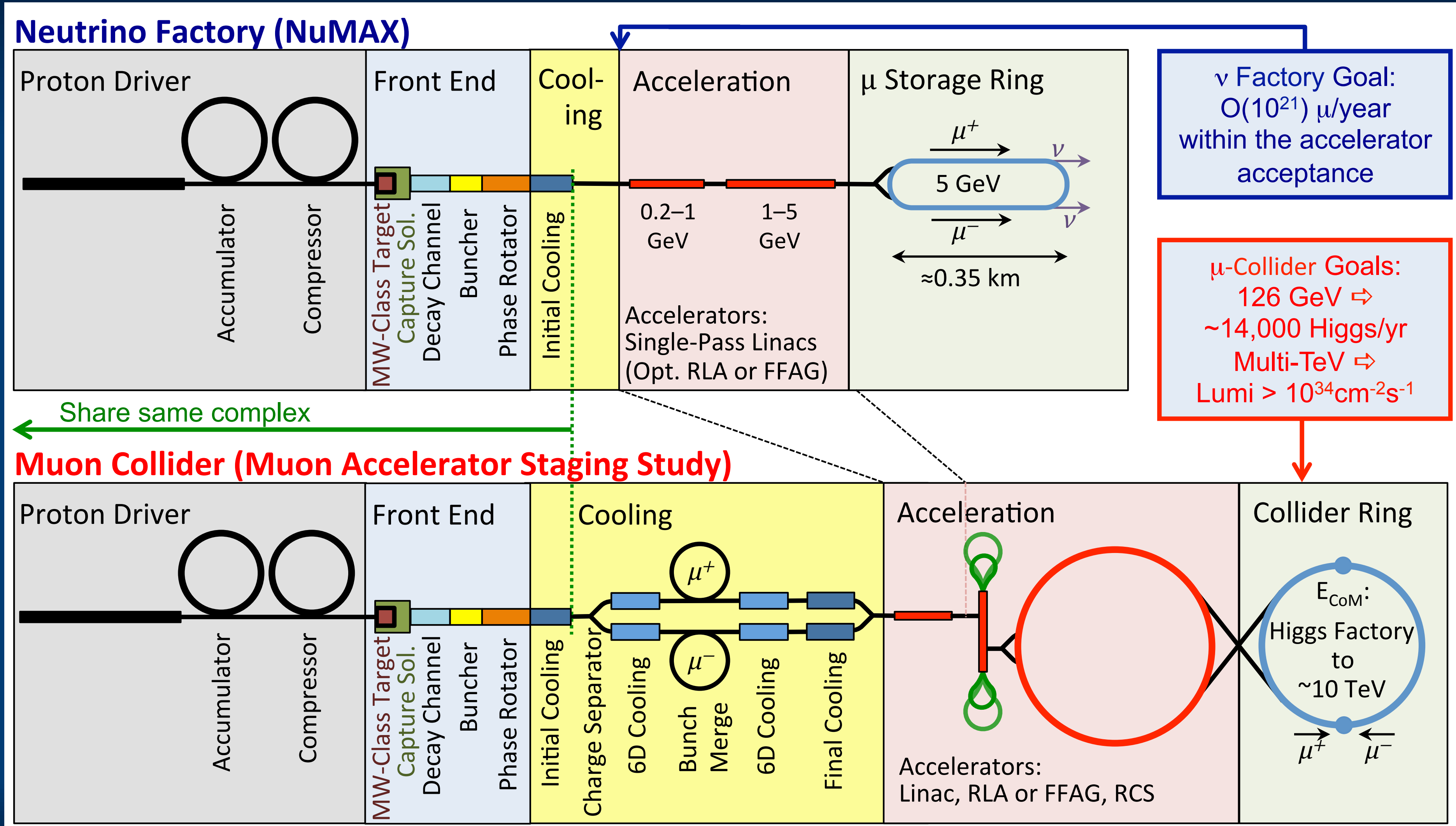
Introduction and Context (II)

- The synergies and potential physics reach have been explored by the Muon Accelerator Staging Study (MASS) and documented in the Snowmass whitepaper:

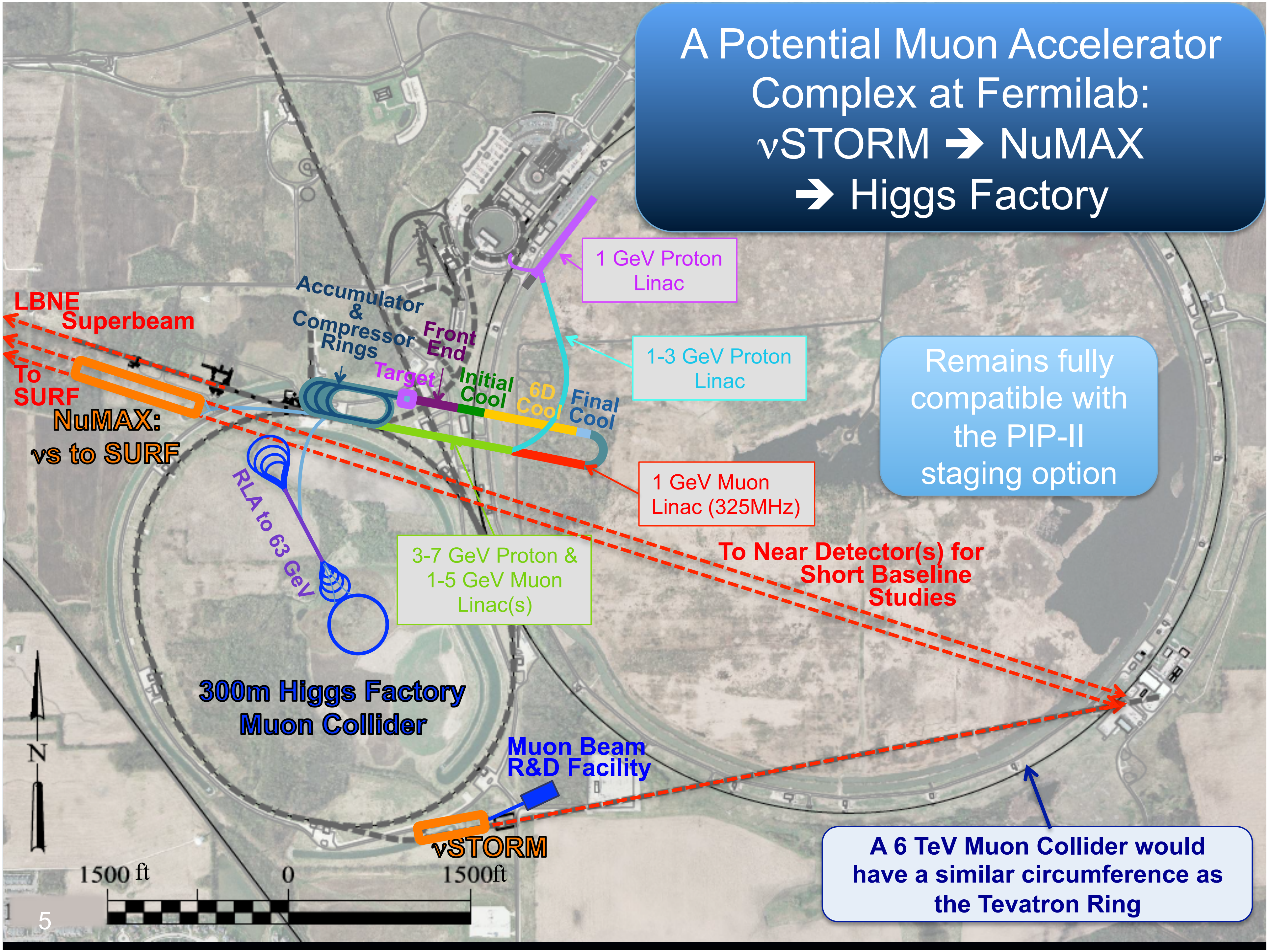
  Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US - http://arxiv.org/pdf/1308.0494

- Thus the committee has requested a joint presentation of the NF and MC concepts and capabilities

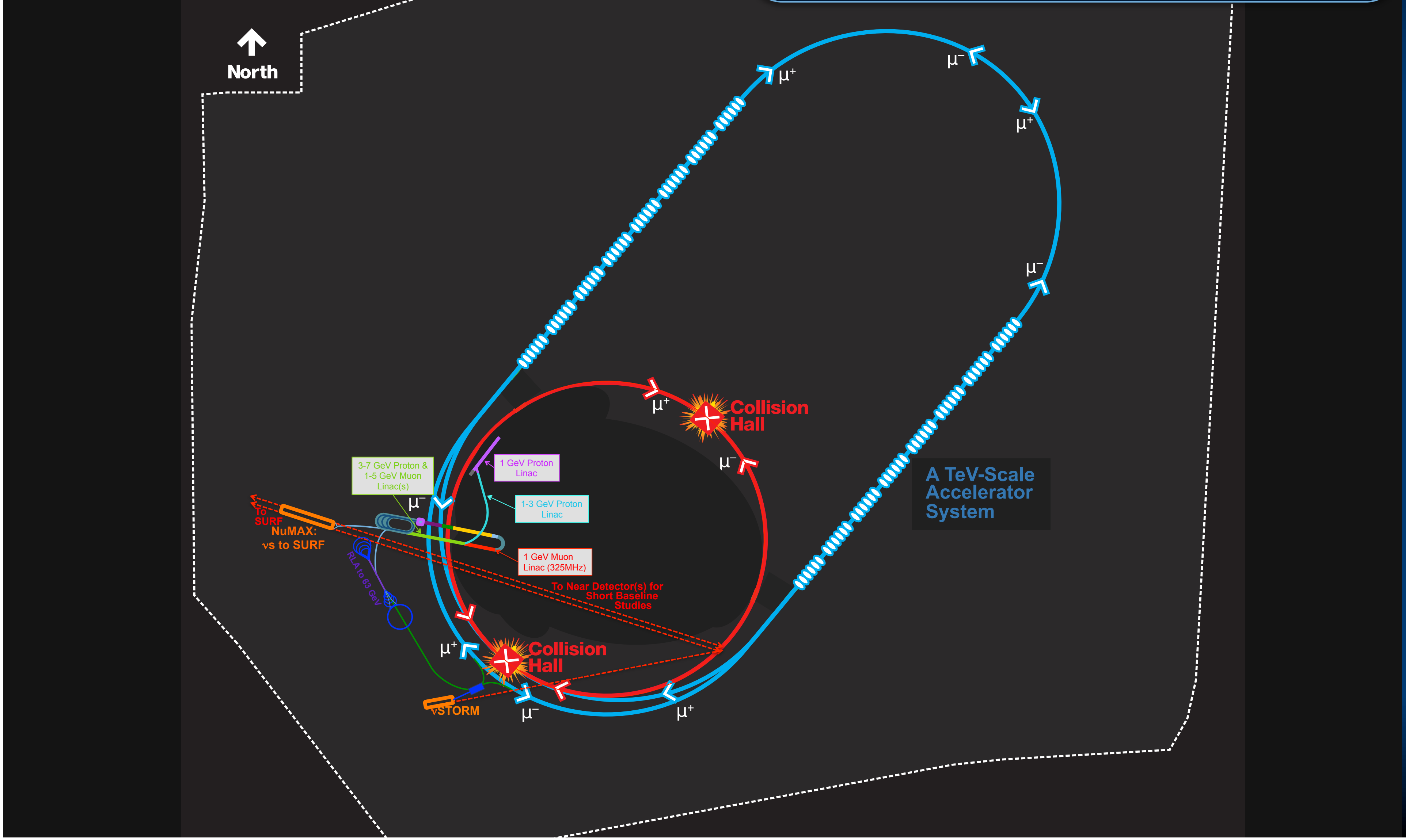
MC/NF Synergies



A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory



A Potential Muon Accelerator Complex at Fermilab:
➔ Multi-TeV Collider



Brief summary of the physics cases coupled with the explicit scope of the experiments

- Notional Timeline (construction start, data taking, specific anticipated results)
- Unique features and fit to overall picture

ITEM 1 FROM P5

Physics Case for the Neutrino Factory

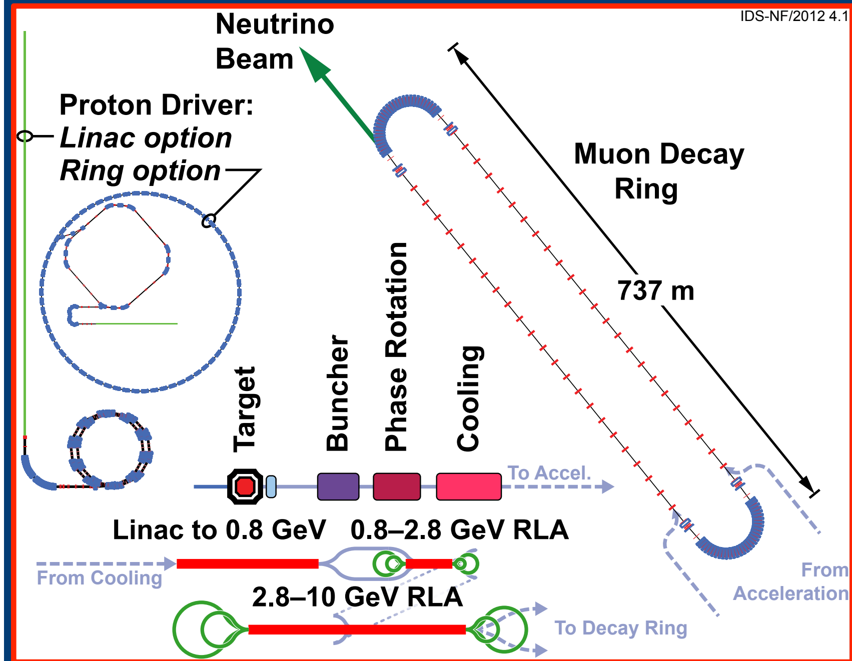
- Short Baseline Neutrino Factory
  - nuSTORM
    - Definitive measurement of sterile neutrinos
    - Precision ν_e cross-section measurements (systematics issue for long baseline SuperBeam experiments)
    - Could serve as a muon accelerator proving ground…

- Long Baseline Neutrino Factory 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
    - 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
  - Both options provide a route to high precision measurements in the ν sector with very well understood systematics

    ⇨ The advantage of high intensity "precision beams"

The Neutrino Factory

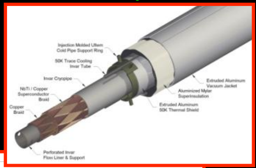
- IDS-NF

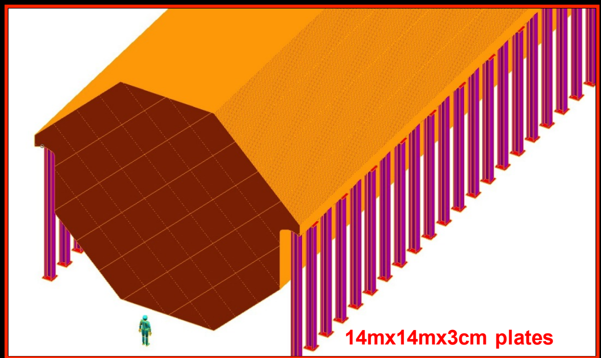


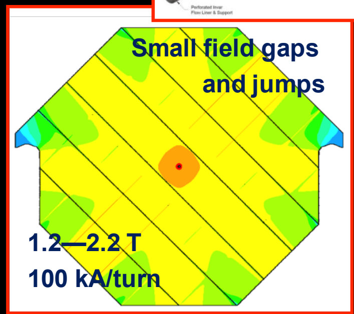
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

Magnetized 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 magnetic field > 1 T
    - Excited with "superconducting transmission line"
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates





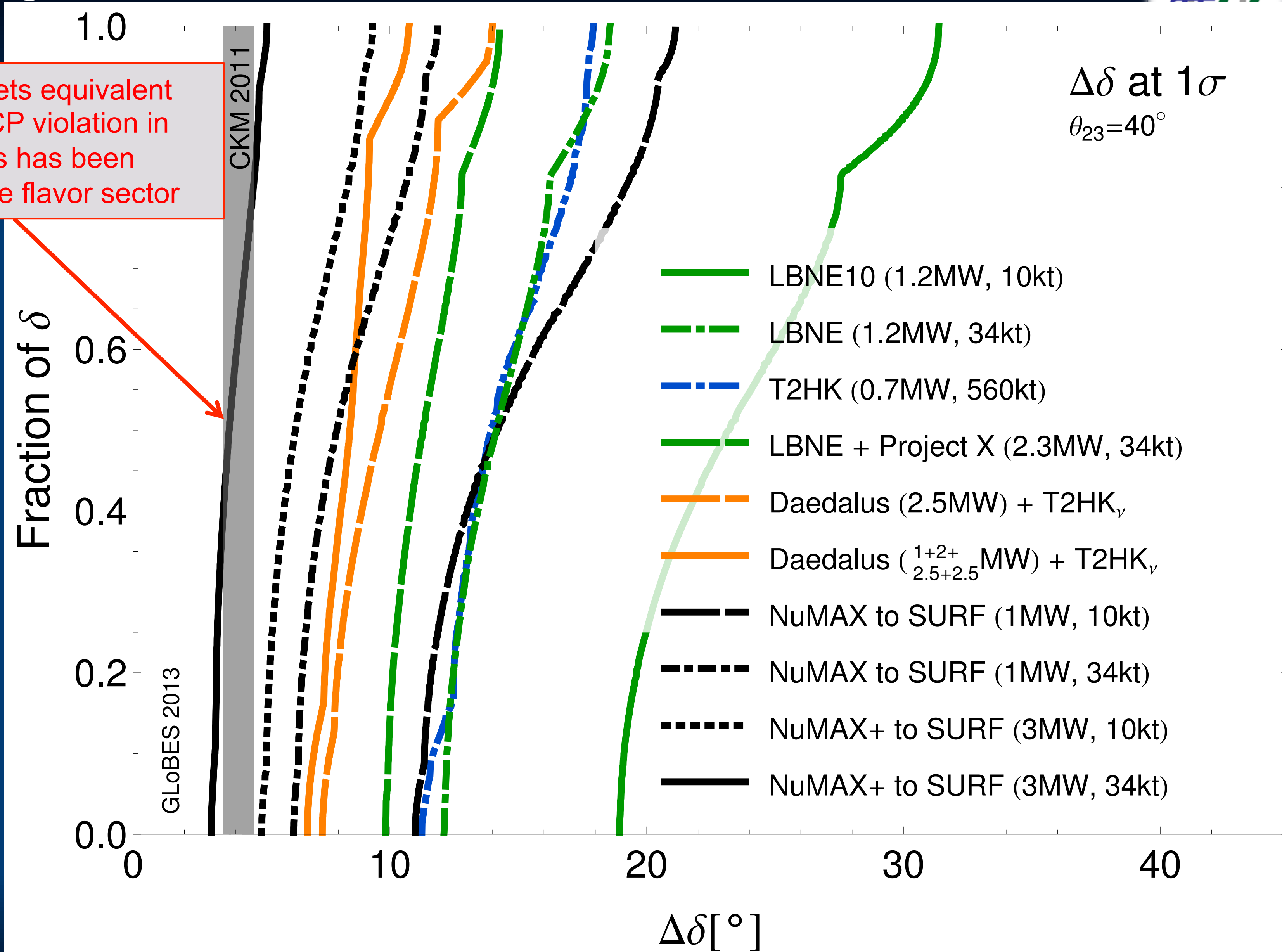


Bross, Soler

A Staged Plan with NuMAX at Fermilab

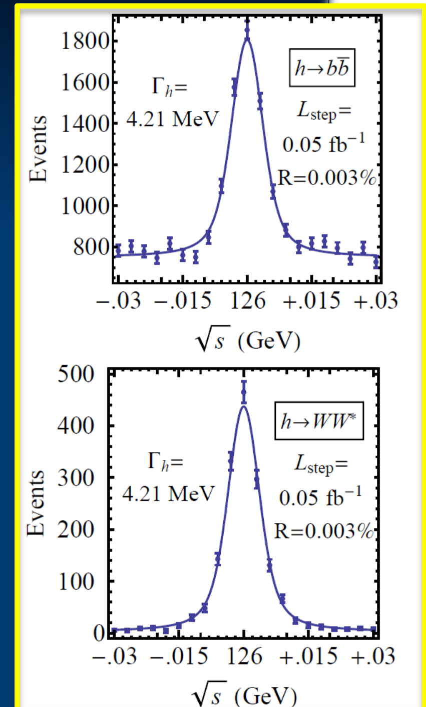
NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector

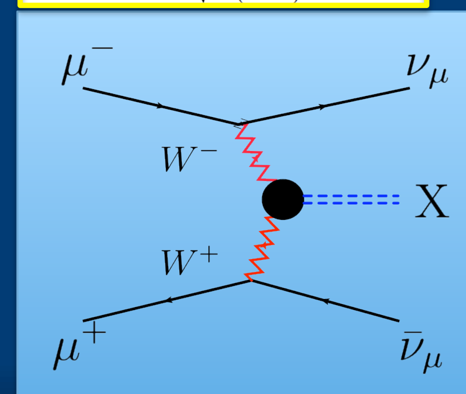
GLoBES Comparison of Potential Performance of the Various Advanced Concepts *(courtesy P. Huber)*



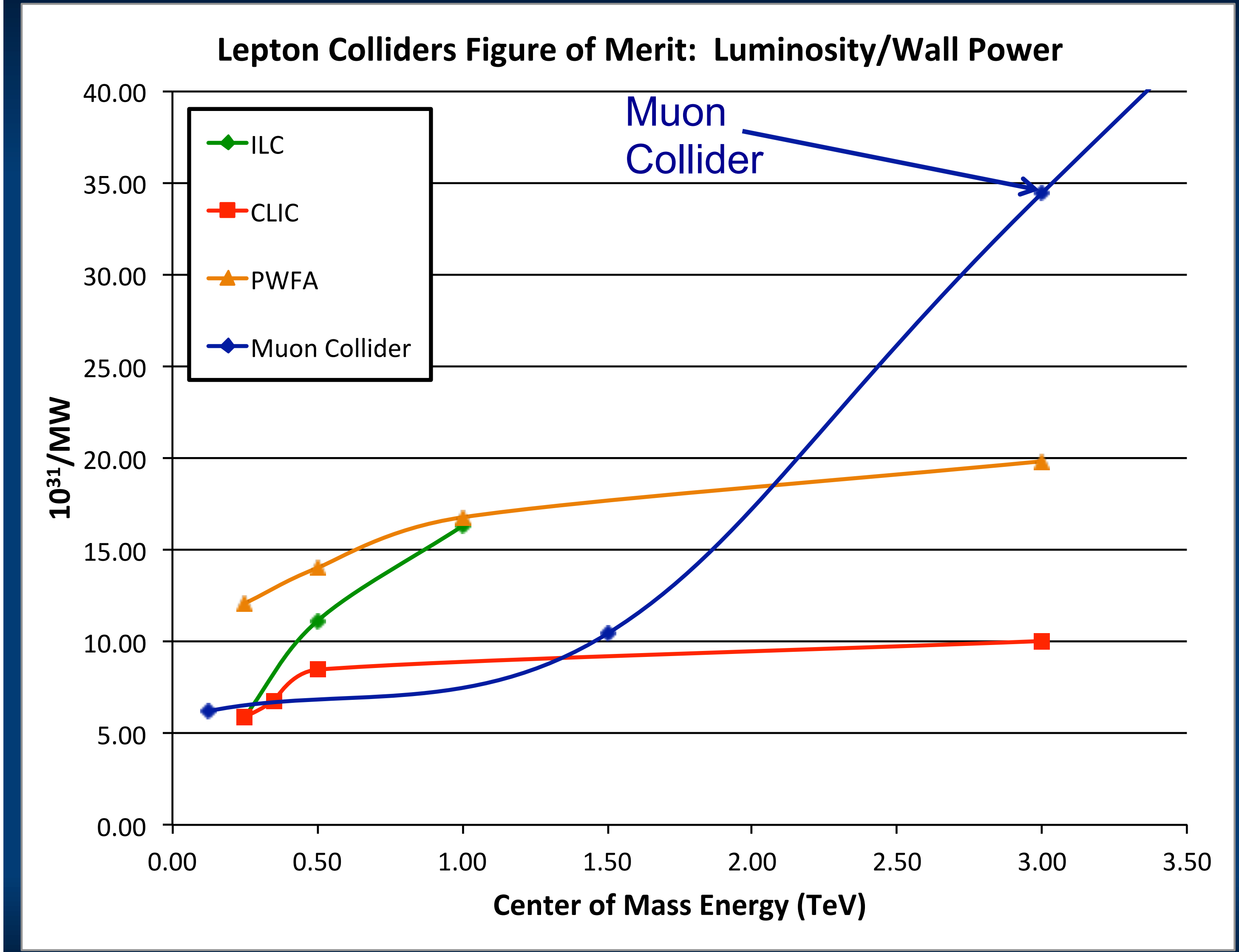
Physics Case for a Muon Collider

- Superb Energy Resolution
  - SM Thresholds and Higgs Factory operation
- At multi-TeV
  - Compact 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 pp collider with $E_{pp} \approx 7E_{MC}$
- At >5TeV CoM, could provide Higgs self-coupling resolutions of <10%
- What if upcoming runs with the LHC shows evidence for a multi-TeV particle spectrum?





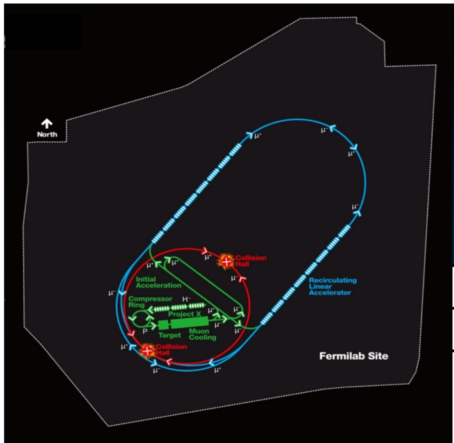
Luminosity Production Metric



Luminosity Metric:

$N_{det} \times L_{avg} / P_{tot}$

Muon Collider Parameters



Muon Collider Parameters

Parameter	*Units*	Higgs Factory: *Startup Operation*	Higgs Factory: *Production Operation*	Top Threshold Options: *High Resolution*	Top Threshold Options: *High Luminosity*	Multi-TeV Baselines	Multi-TeV Baselines	*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^{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. 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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

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

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

A Muon Accelerator Capabilities Technical Decision Tree

| Thru ~2020 | ~2020 | ~2025 | Late 2020s |

MAP Feasibility Study

- Success with NF cooling demo (MICE)
  ⇨ Begin full technical design for a NF-based upgrade to LBNE
  - If decide to pursue precision ν sector capabilities
    ⇨ **Begin the NF upgrade path**
- Failure ⇨ No path to NF and/or MC capabilities
  ⇨ **STOP NF/MC R&D Effort**
- Success with MC Concepts
  ⇨ Begin the MC CDR and Advanced Systems Tests
  - CDR Completion and success Advanced Systems Tests
    ⇨ Begin full MC Engineering Design
  - Failure of Advanced Systems Tests
    ⇨ **Terminate MC development**

If LHC finds evidence for Supersymmetry AND when MC Engineering Design ready
⇨ **Decision point on a return to the EF with a Muon Collider** (which would build on the infrastructure deployed for a NF)

The Notional Timeline

- The preceding slide focuses on key decision points
  - Construction

    ~2025: NF decision possible

    Late 2020s: MC decision possible late in the next decade

    - Both decision points assume a successful MAP Feasibility Assessment
      - This requires a suitable funding profile
    - Assume a decade for construction approval and execution for each
      - Availability of various staging scenarios provides flexibility
    - Exact deployment schedule determined by budget profile
      And would be part of a global planning process…
  - Physics
    - Together these capabilities would provide a multi-decade set of capabilities (hence extending beyond the middle of the century)

The Key Choices

- The breadth of science that can be supported by a muon accelerator capability argues for continued support of the directed national accelerator R&D program (integrated with a global R&D effort) which is now in its 3rd year
  - Feasibility Assessment available by the end of the decade – in time for the next P5 round
- NF:
  The R&D would support future high precision capabilities with well-understood systematics
- MC:
  The R&D would prepare for the possibility that LHC running reveals the lowest states of a new particle spectrum

  Note that the MC may be the only viable route to a several TeV lepton collider capability in the next 20 years

Scope of international participation required:

- For machine and detectors
- Status of the arrangements
- How are the arrangements anticipated to develop over time?

ITEM 2 FROM P5

Scope of International Participation Required

- Staging scenarios assume
  - The US would host the machine effort
    - With strong international participation
  - Detector efforts (NF & MC) are assumed to be global

- The R&D effort already involves significant international connections and more are being pursued

- It is premature to speculate on the balance of involvement during a project until the feasibility assessment is complete

Current estimate of US contributions and why they are necessary?

How would the effort benefit US facilities and development of key US capabilities

What R&D is still required?

- Detailed scope
- Required resources
- Projected timeline

How are the MC and NF connected (both necessarily and optionally)?

If this is a multi-agency project, what are the envisioned roles and division of scope?

ITEM 3 FROM P5

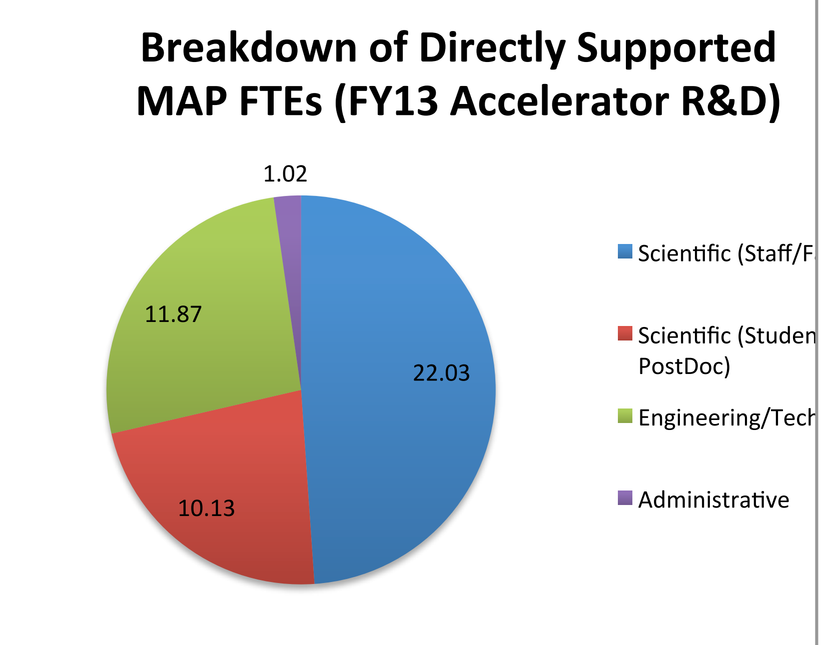
R&D Effort

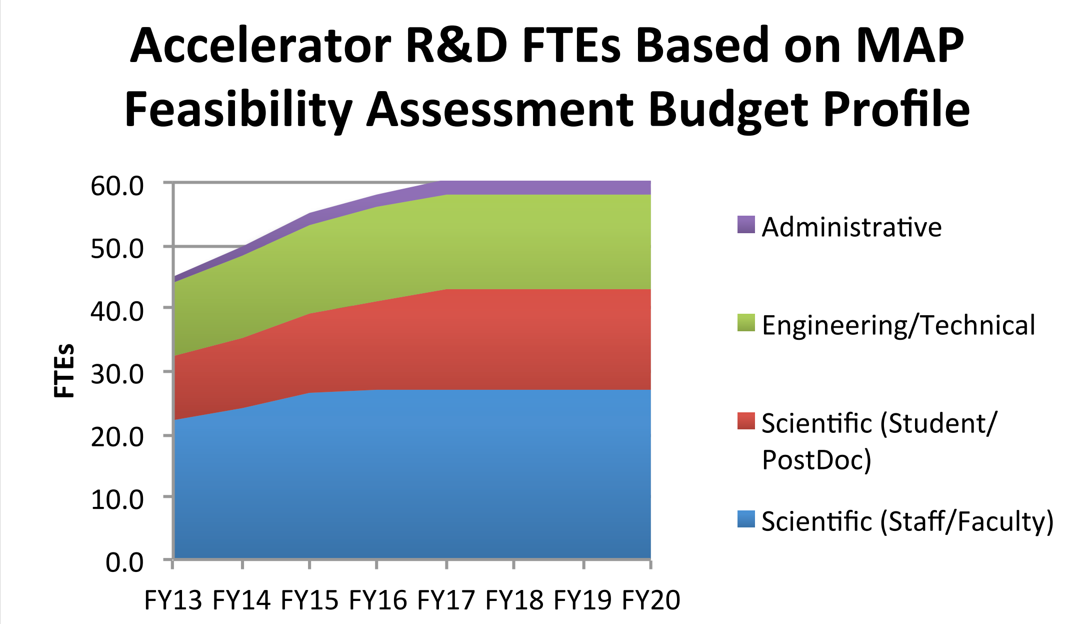
- Scope
  - Provide:
    - Specifications for all required technologies
    - Baseline design concepts for each accelerator system (see block diagram to follow)
  - For novel technologies:
    - Carry out the necessary design effort and R&D to assess feasibility
    - Note: a program of advanced systems R&D is anticipated ***after*** completion of the feasibility assessment
  - Ongoing Technology R&D and feasibility demonstrations include:
    - MuCool Test Area experimental program (FNAL): RF in high magnetic fields
    - The Muon Ionization Cooling Experiment (MICE@RAL):
      - Demonstration of emmittance reduction
      - Validation of cooling channel codes
    - Advanced magnet R&D
      - Very high field magnets (cooling channel and storage rings)
      - Rapid cycling magnets for acceleration of short-lived beams

R&D Effort (cont'd)

Projected Resources – US Accelerator R&D from DOE HEP

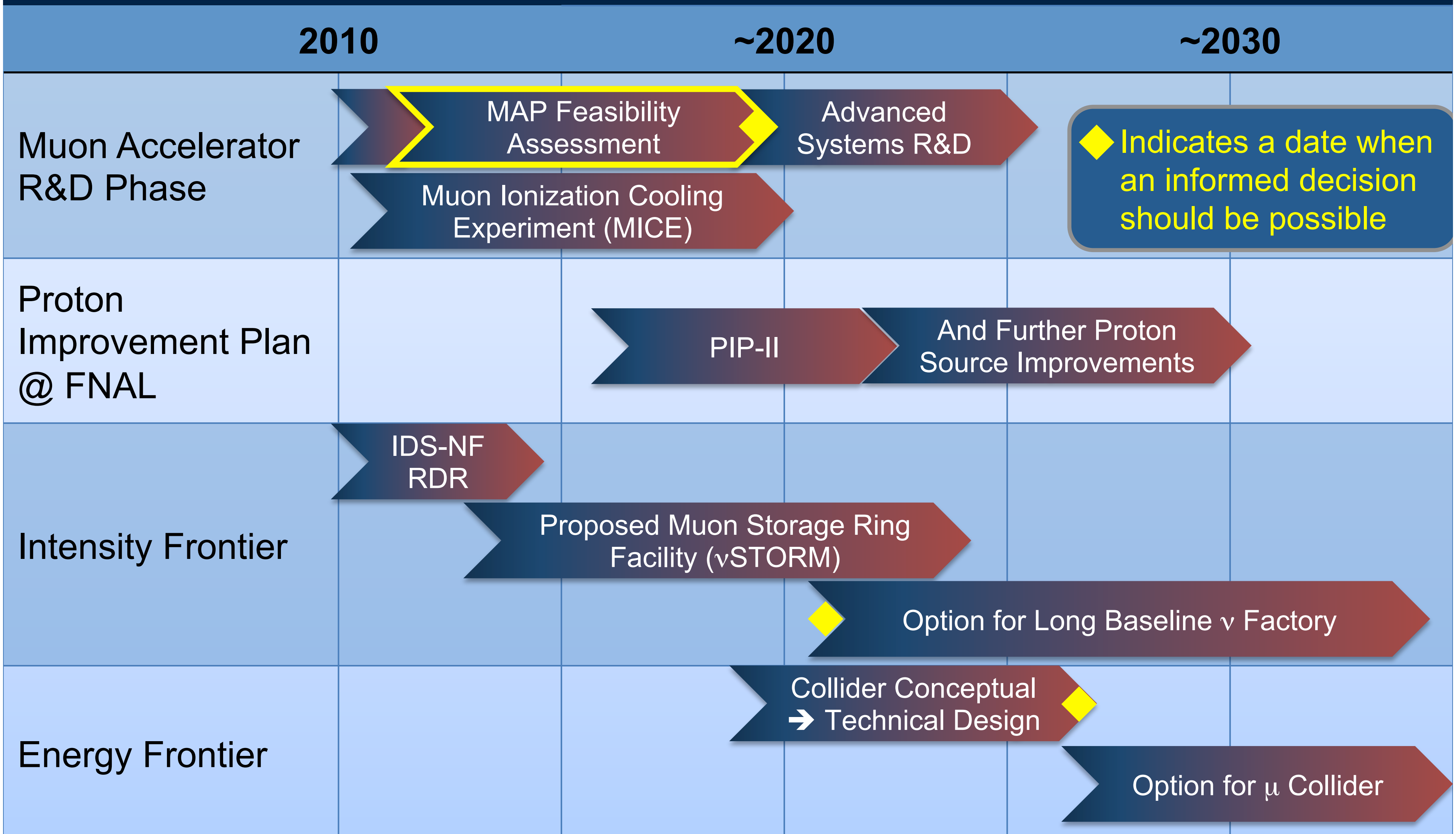
- Feasibility Phase ONLY
- A subsequent technical design phase would likely require at least a doubling of resources for a 3-5 year period.





- NF Detector/Physics – supported globally by IDS-NF (48 institutions, 136 authors)
- MC Detector/Physics – not formally supported (MAP funding ⇨ Accel R&D).
  - In FY13, ≤2 FTEs from Fermilab along with some community involvement.
  - Need ~10-20% (ie, 5-10 FTEs) of the accelerator effort required to validate detector capabilities.

MAP Timeline ⇨ Provide Informed Decision Points



NF & MC Connections

- Key connections were shown in the block diagrams in slide 4
- Conclusions:
  - Development of the foundation for either capability (ie, proton driver, target system, front end) supports the other, thus offering significant advantages
  - In terms of cost effectiveness, staging options, and potential support for two of the major thrusts in HEP, integrating both options for the R&D phase is the most desirable approach

Multi-agency Issues

- MAP R&D Program is supported by DOE HEP
  - NSF has provided some added support for
    - SRF
    - MICE Experiment
- A successful transition to a project would assume a multi-agency model

Estimate the number of physicists needed by project phase, including operations and data analysis

ITEM 4 FROM P5

Physicist Requirements

- Feasibility Phase – see slide 20
- Construction Phase
  - A staged approach would enable much of the effort to be accomplished with existing US accelerator resources
- The NF supports a major detector at SURF
  - To 1st order would appear as an extension of ongoing upgrade and operations needs on the detector side
- A MC option with 2 detectors would be expected to have a collaboration of O(1000) physicists/detector

⇨ Both would require accelerator support at the level of the Fermilab Accelerator Division for operations

Any other information we wish to communicate to P5

ITEM 5 FROM P5

Concluding Remarks

- Our accelerator-based HEP program in the US is reliant on accelerators that were deployed 15-40 years ago. For more than a decade, the focus has been on operations and experiments, as well as the possibility of new green field facilities

- A major question for this P5 is whether there is room to plan for the possibility of significant upgrades to the US HEP accelerator capabilities.

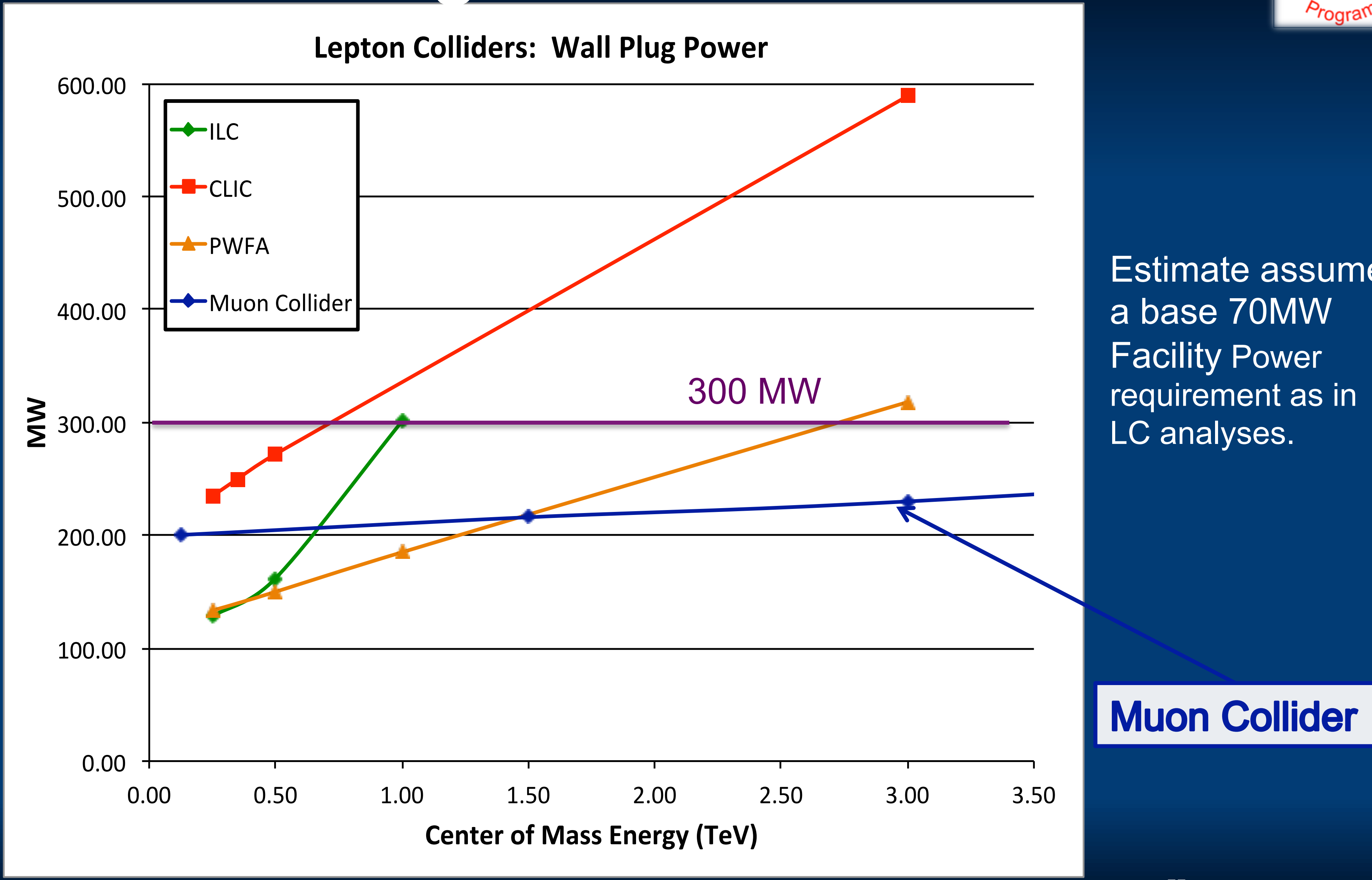
  Muon accelerator capabilities offer tremendous promise for the field and would be well-suited for implementation at our domestic HEP facility

- A recommendation from the Accelerator Capabilities report:

  A vigorous, integrated U.S. research program toward demonstrating feasibility of a muon collider is highly desirable. The current funding level is inadequate to assure timely progress.

BACKUP SLIDES

Wall Plug Power Estimates



Estimate assumes a base 70MW Facility Power requirement as in LC analyses.