THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

Neutrino Factories

Neutrino 2014
Boston University, Boston

Paul Soler, 4 June 2014

University of Glasgow

Neutrino Factory

- Definition of a Neutrino Factory:
  - Modern definition of a Neutrino Factory is that of an accelerator that produces intense neutrino beams from the decay of muons:

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

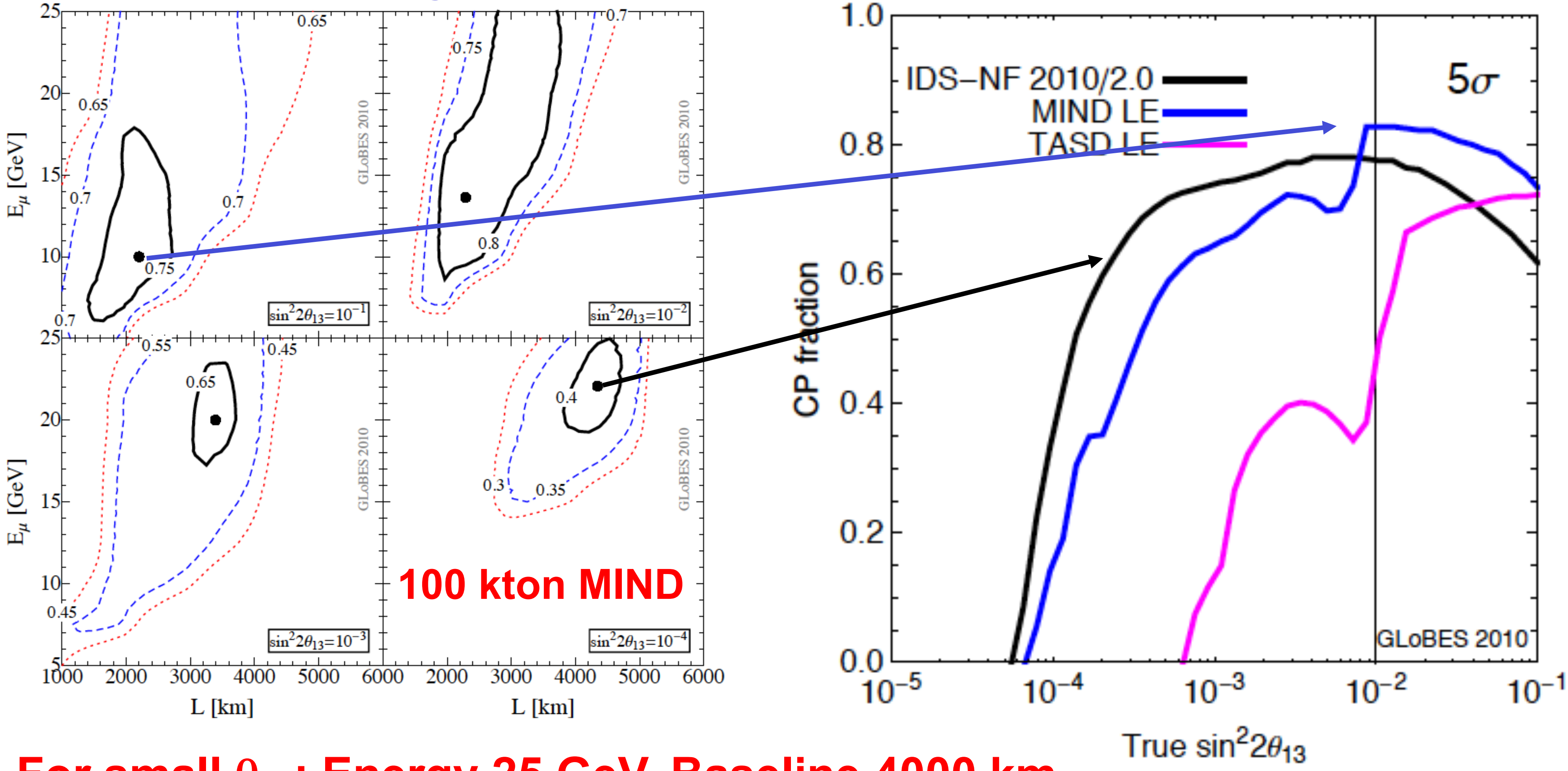
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

  - Birth of modern neutrino factory: S. Geer: Phys Rev D57, 6989 (1998)
  - Then, came **seven** design studies: CERN (Yellow Report 99-02, 1999), Fermilab (Study I) and Brookhaven (Study II, IIa), ECFA/CERN Study (CERN-2004-002), Scoping Study (JINST 4 P07001 & T05001, 2009, Rept. Prog. Phys. 72, 2009, 106201) and …
  - International Design Study (IDS-NF): launched 2008, Reference Design Report in 2014 (Interim Design Report arXiv:1102.2402)
  - Lately: Muon Accelerator Programme in USA to stage Neutrino Factory (arXiv:1308.0494) and nuSTORM proposal (arXiv:1308.6822)

Optimisation of Neutrino Factory

- Optimisation of Neutrino Factory for high θ_{13}

Contours of CP coverage



For small θ_{13}: Energy 25 GeV, Baseline 4000 km

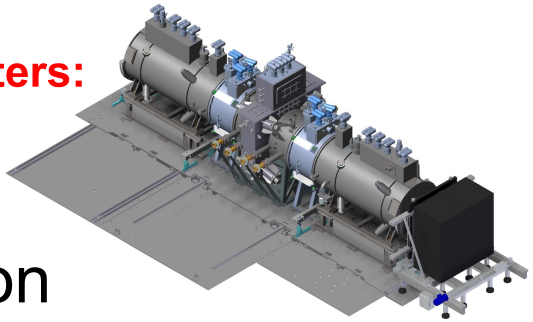
For large θ_{13}: Energy 10 GeV, Baseline 2000 km, L/E ~ 200 km/GeV

International Design Study for a Neutrino Factory

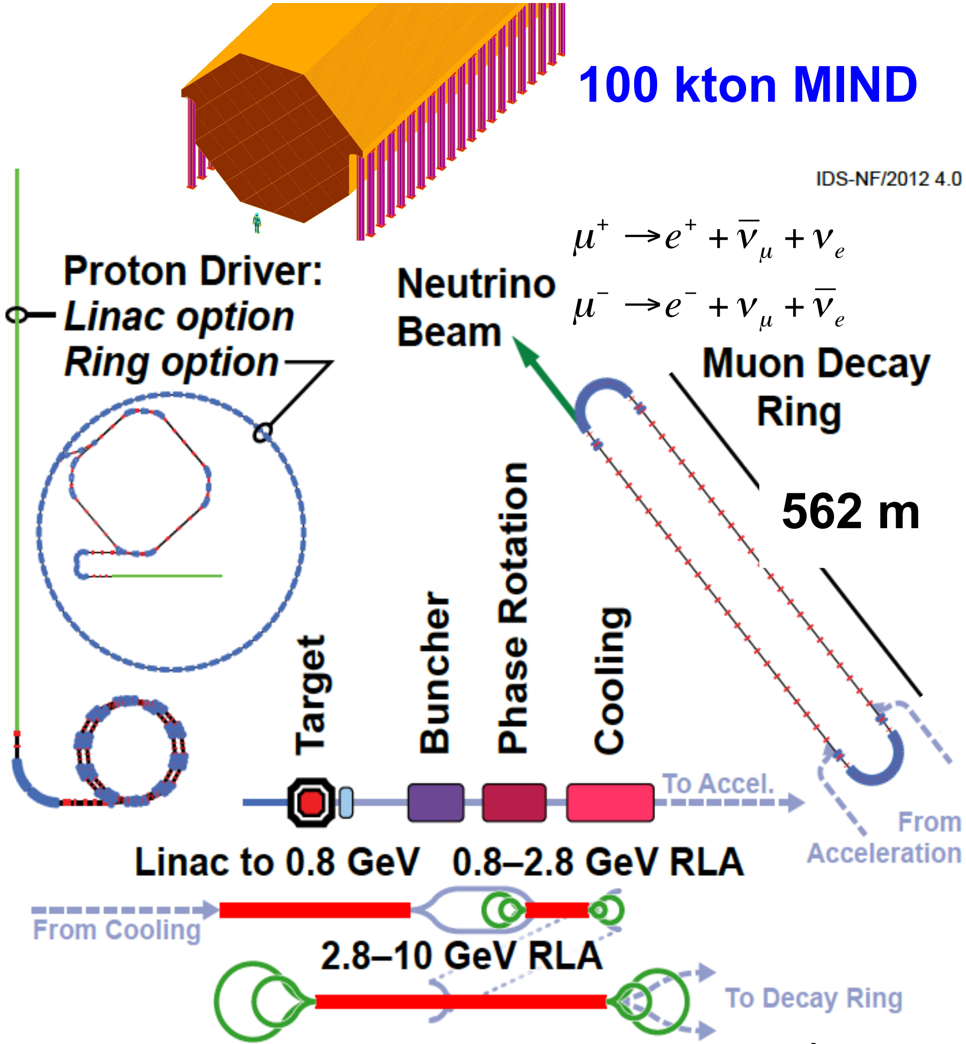
IDS-NF baseline review 2012: from 25 GeV to 10 GeV muons, one storage ring with detector at 2000 km, due to large θ_{13} results

- Proton driver
  - Proton beam ~8 GeV on target
- Target, capture and decay
  - Create π, decay into μ
- Bunching and phase rotation
  - Reduce ΔE of bunch
- Ionization Cooling
  - Reduce transverse emittance

See MICE Posters:
M. Leonova,
D. Rajaram

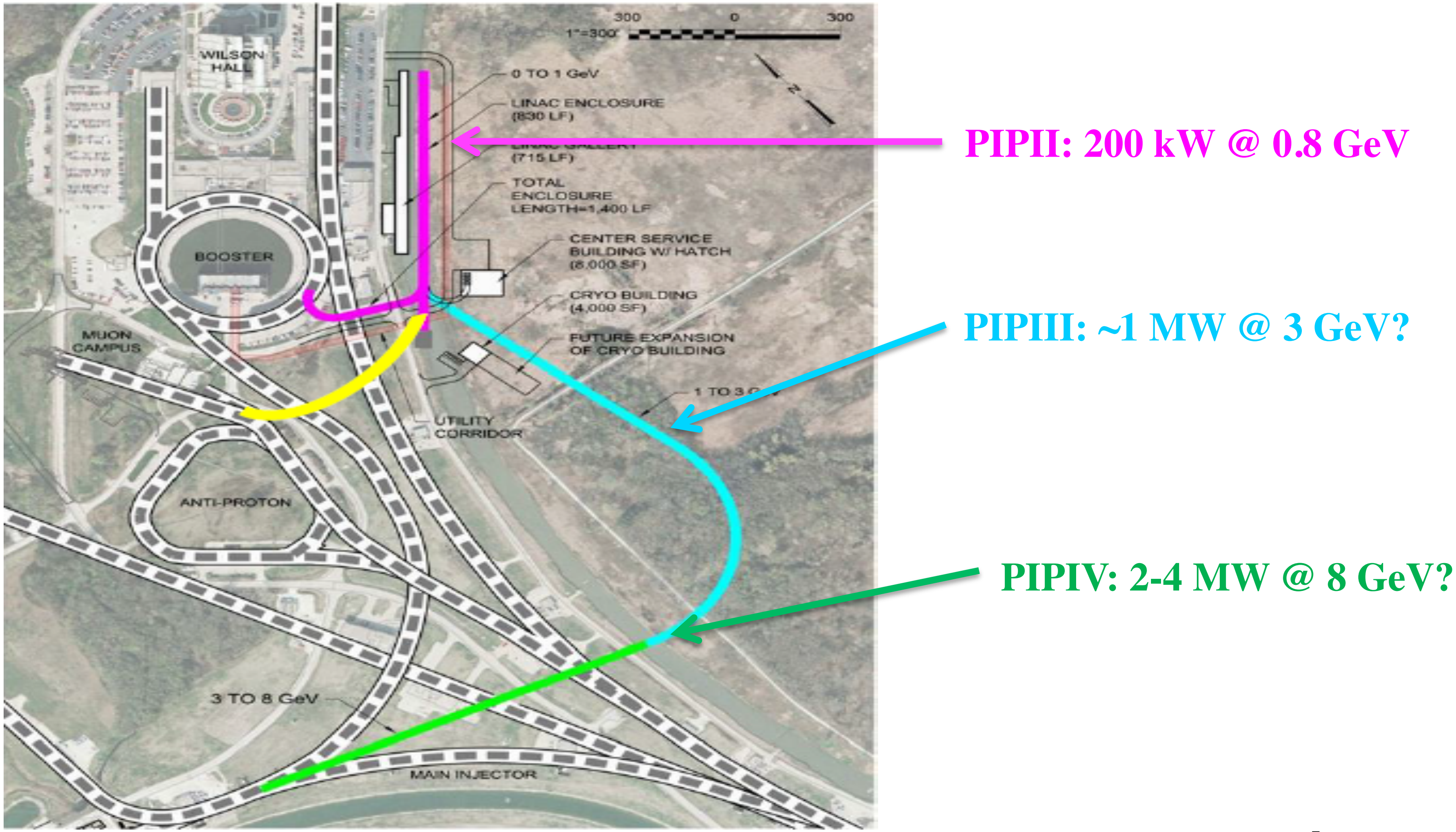


- Acceleration
  - 120 MeV→ 10 GeV with RLAs
- Decay ring: 10^{21} muons/year
  - Store for ~100 turns
  - Long straight sections



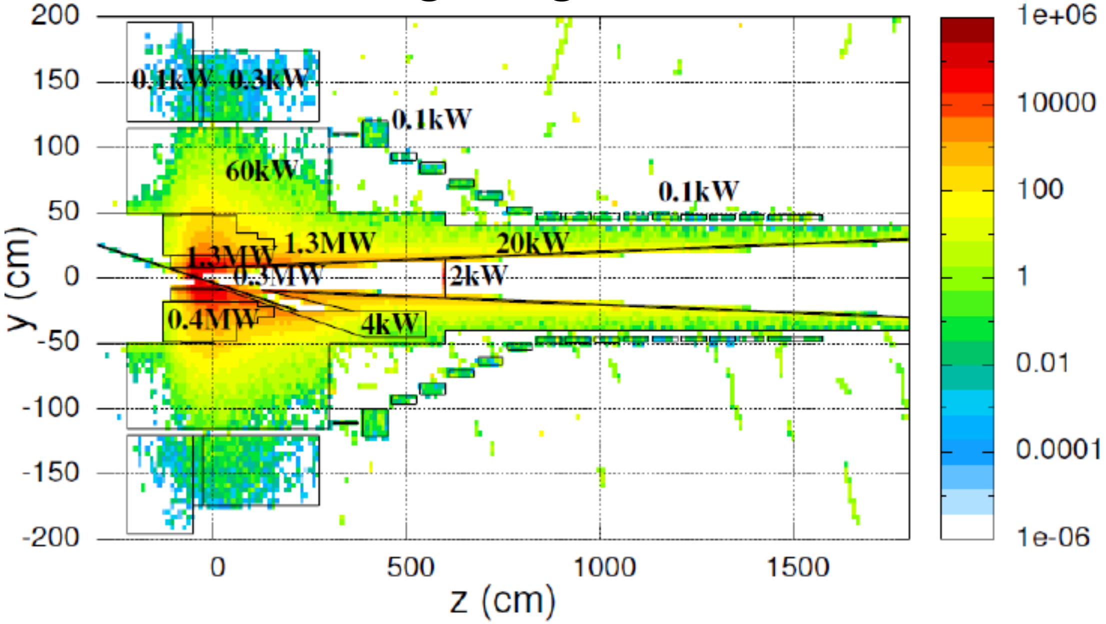
Proton Improvement Plan (PIP)

- Fermilab option: 1-4 MW operation from 3-8 GeV
  - Proton Improvement Plan (PIP): staging Linac facility at Fermilab

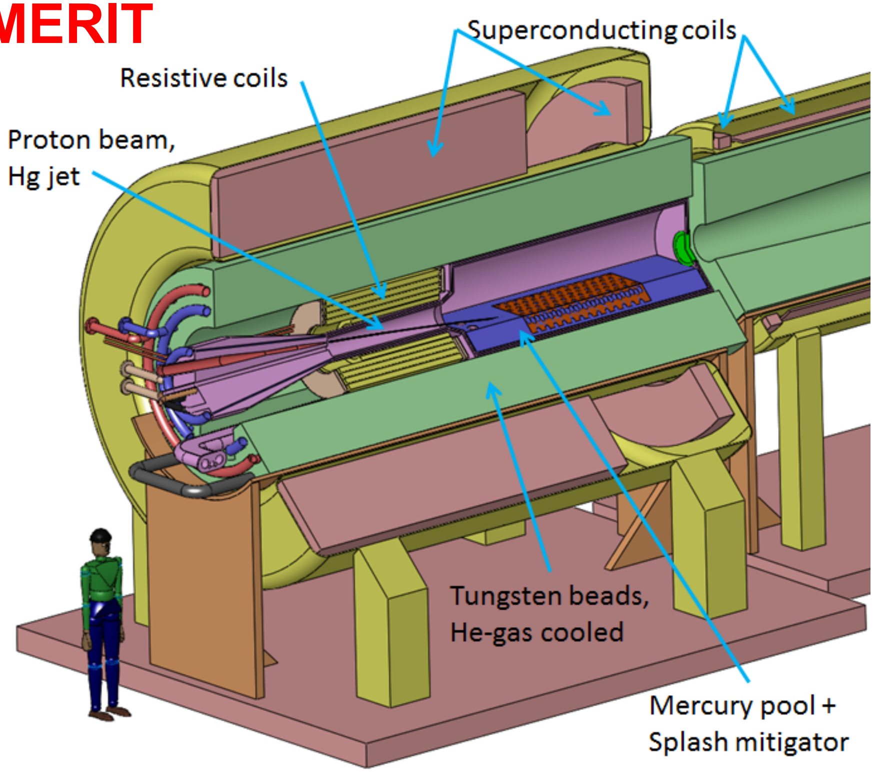


Target

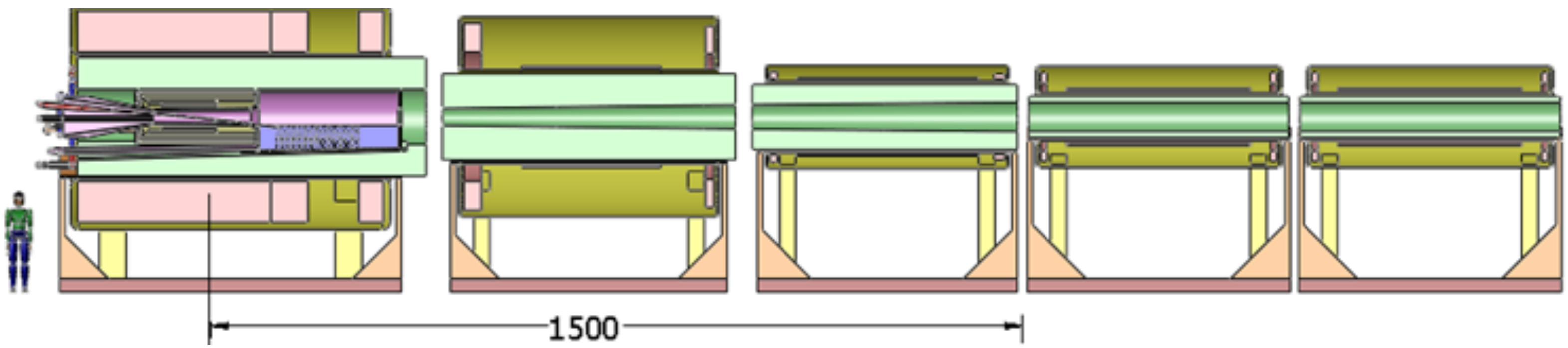
- Liquid Hg target in 20 T solenoid
- Increased radiation shielding in surrounding target solenoid



Proof-of-principle: MERIT

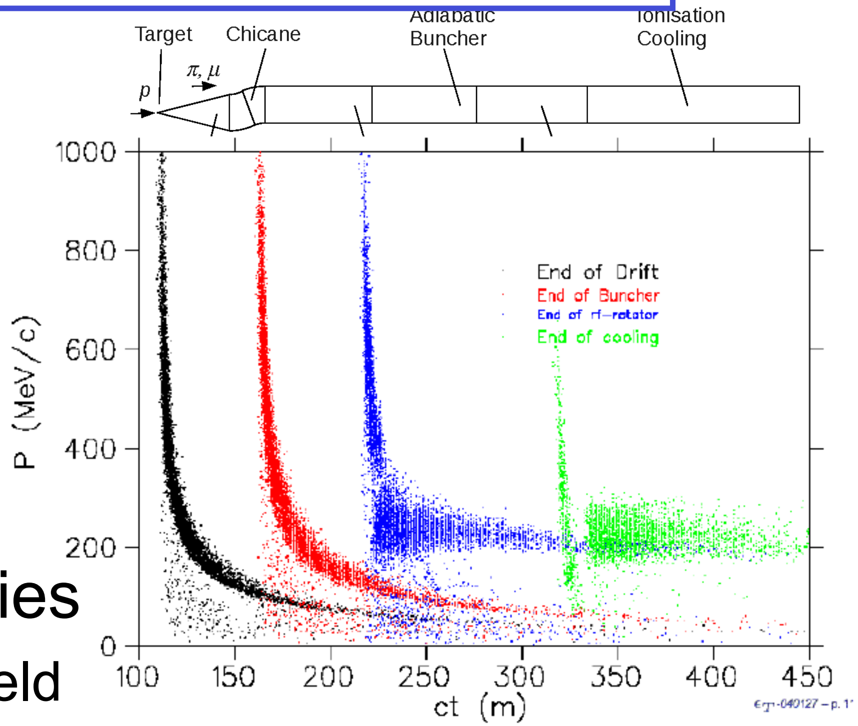


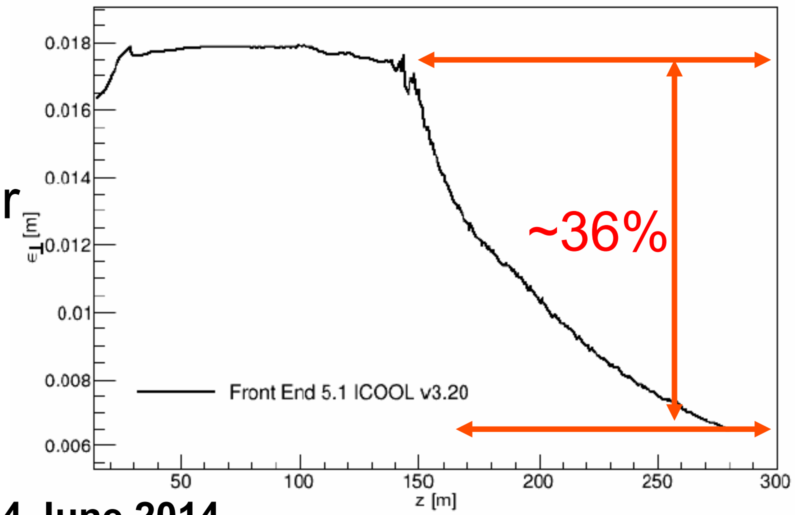
Target station and start of decay channel



Muon Front End

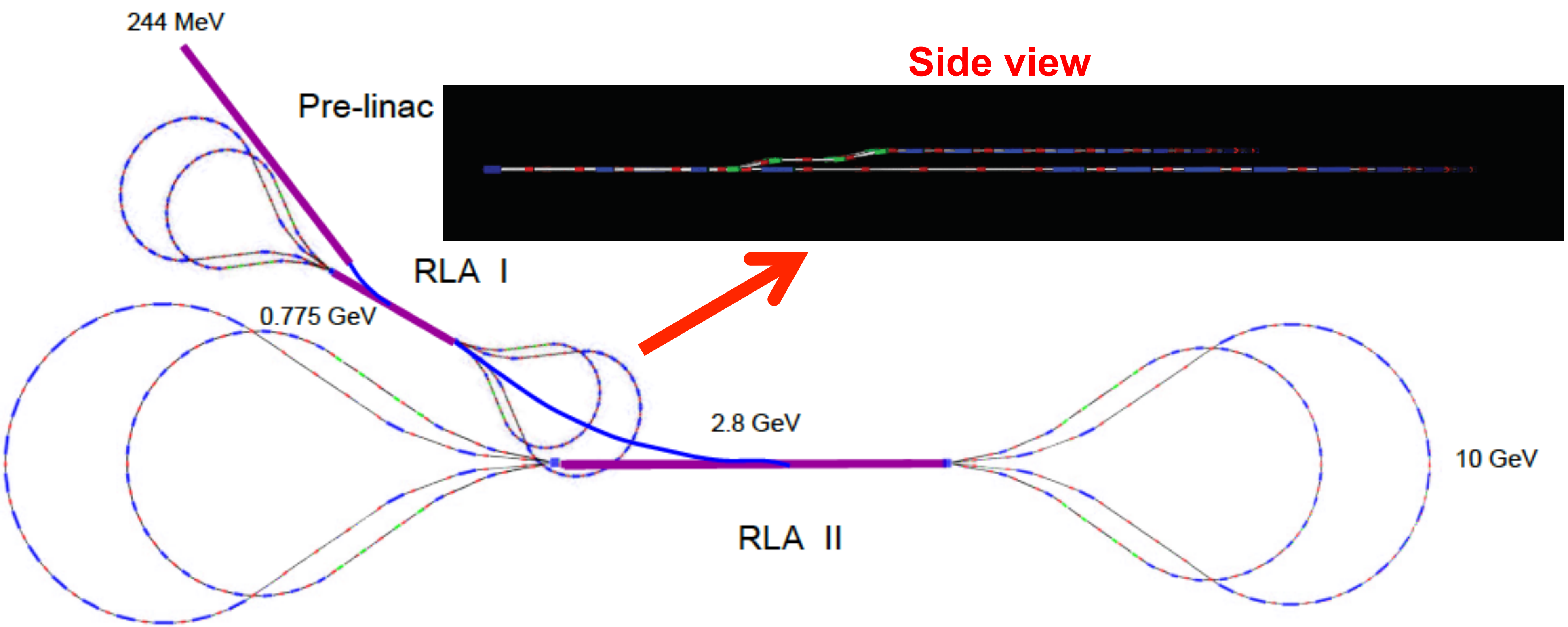
- Adiabatic B-field taper from Hg target to longitudinal drift
- Add chicane to remove protons
- Drift in ~1.5 T, ~60 m solenoid
- Adiabatically bring on RF voltage to bunch beam
- Phase rotation: variable frequencies
  - High energy front sees negative E-field
  - Low energy tail sees positive E-field
  - End up with smaller energy spread
- Ionisation Cooling: MICE demonstrator
  - Transverse emittance reduced to 36%
  - Performance: 0.066 μ/proton
  - Cooling increases muon yield by ~2.2





Acceleration

- Baseline acceleration scheme at 10 GeV
  - Two “dog-bone” Recirculating Linear Accelerators (RLA)
  - First RLA up to 2.8 GeV
  - Second RLA up to 10 GeV

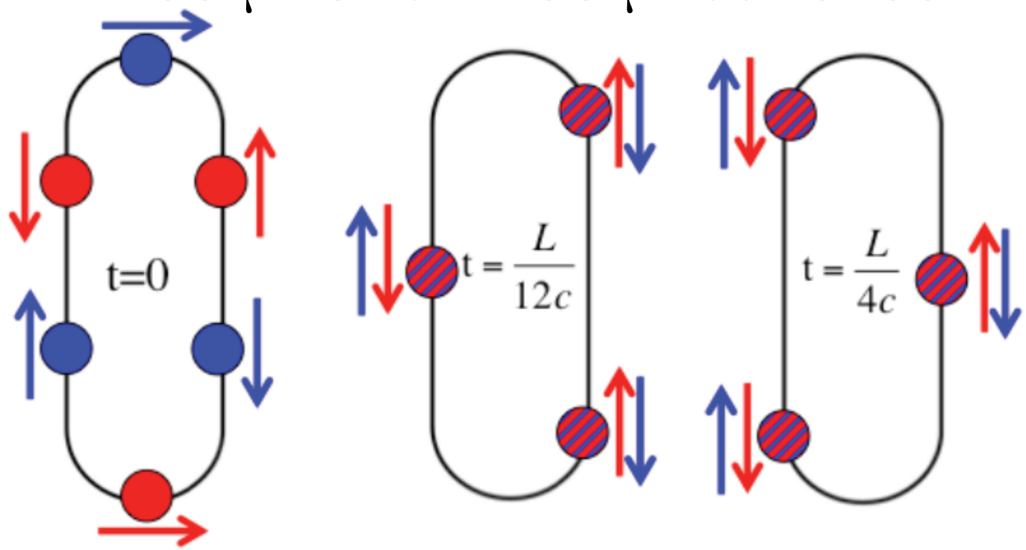


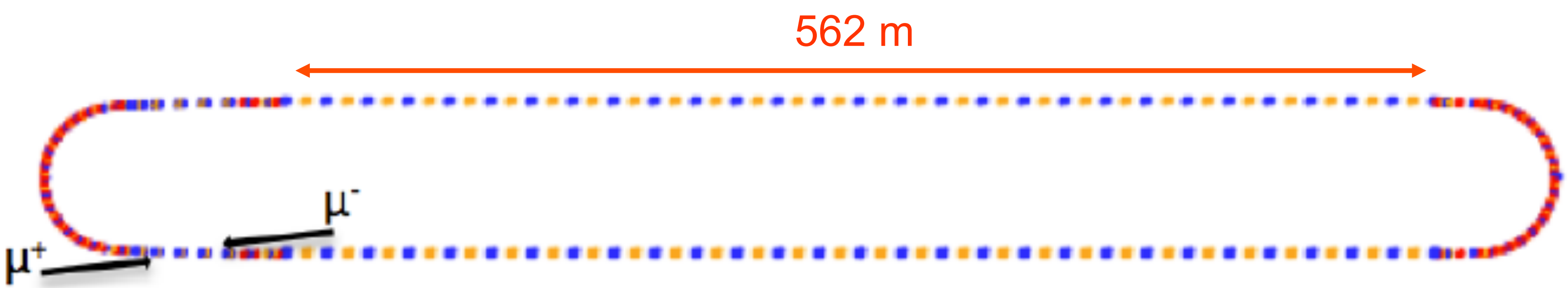
Decay Ring Geometry

- Racetrack geometry for decay ring with insertion
  - Straight: 562 m
  - Upper arc: 121 m
  - Lower arc: 113 m
  - Insertion: 46 m
  - Matching: 105 m (total)

➔ Circumference = 1556 m

Three μ^+ and three μ^- bunches

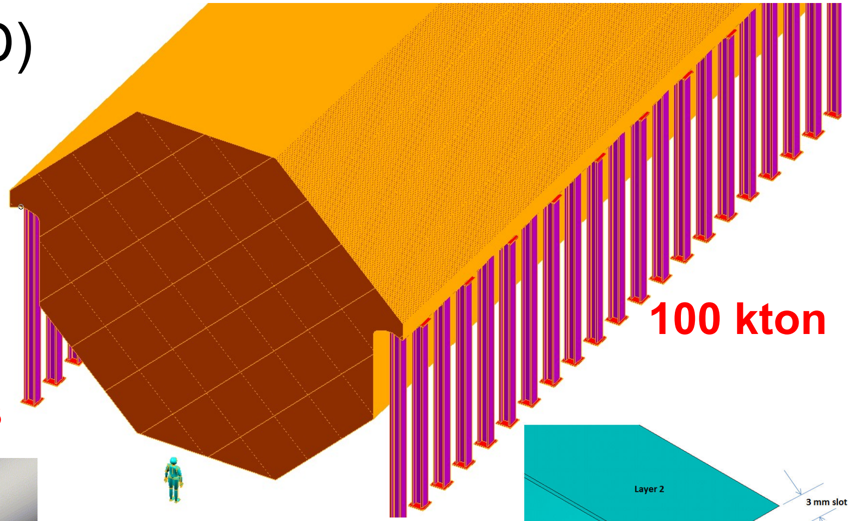




Divergence < $0.1/\gamma$

MIND Far Detector

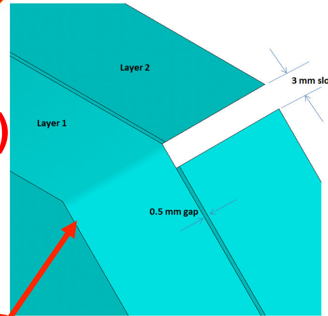
- Magnetised Iron neutrino Detector (MIND)
- Octagonal plates and toroidal field
- Magnetic field 1.2-2.2 T from 8x15 kA current delivered by Superconducting Transmission Line (STL): ~10cm hole

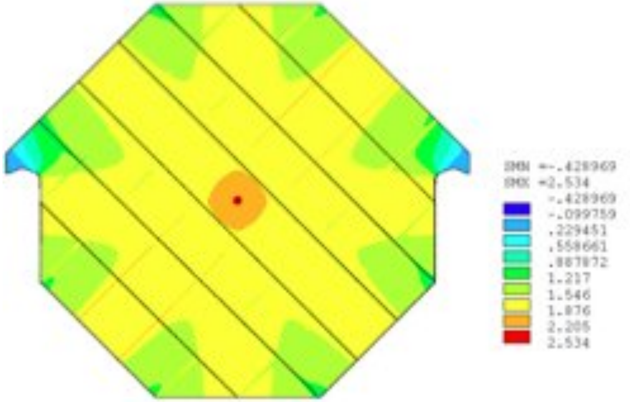


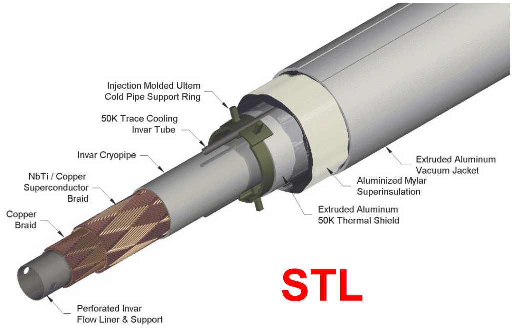
100 kton

14mx14mx3cm plates

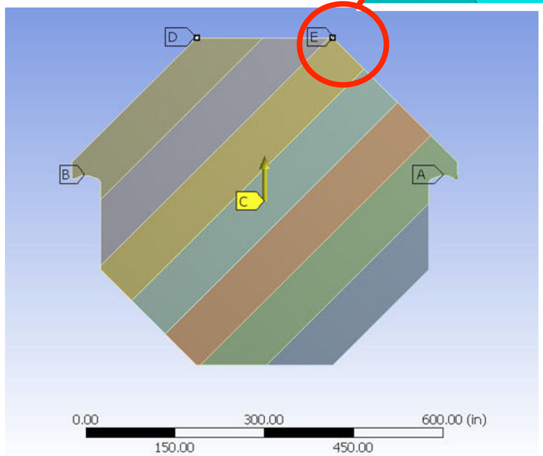
Bross, Wands (FNAL)



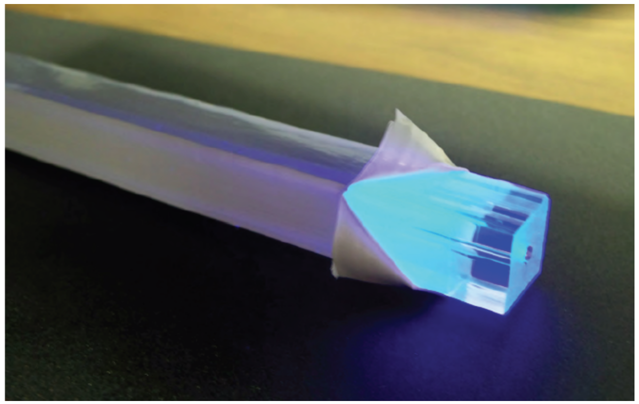


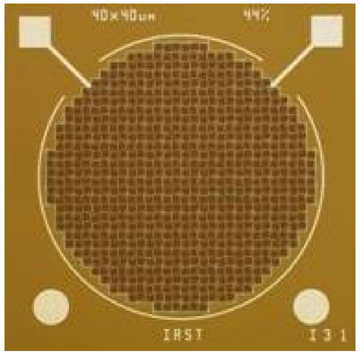


STL



- Extruded scintillator with WLS fibre and SiPMT

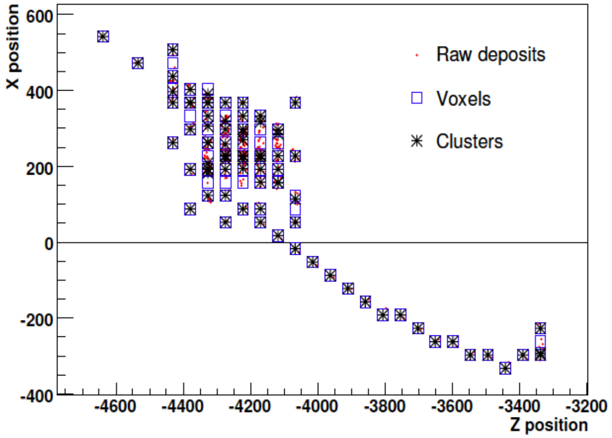


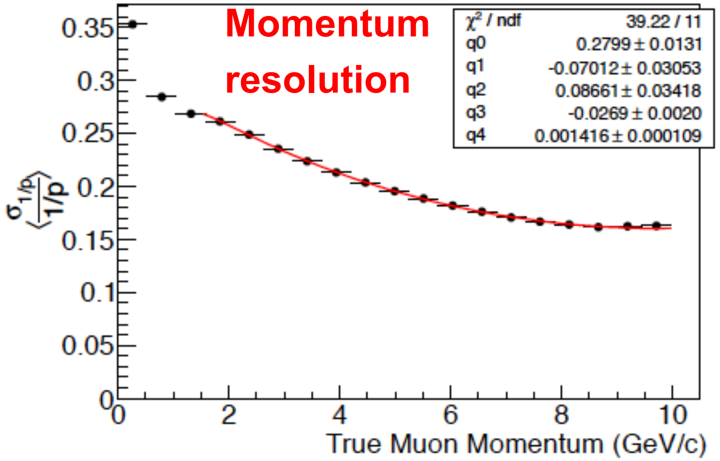


Golden Channel $\nu_e \rightarrow \nu_\mu$ analysis

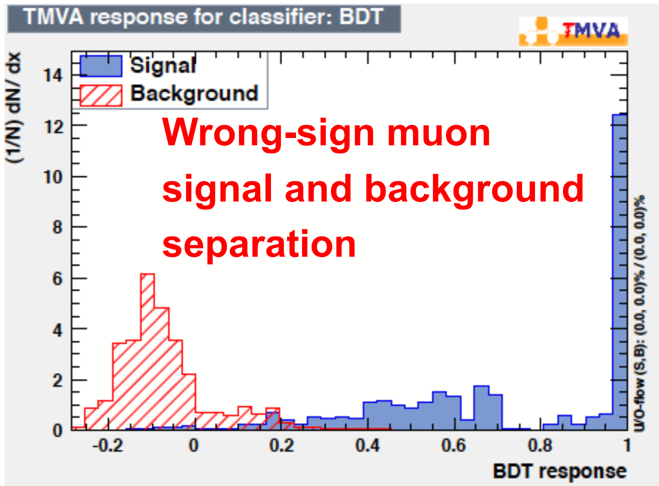
- Full simulation and reconstruction of neutrino interactions

R. Bayes

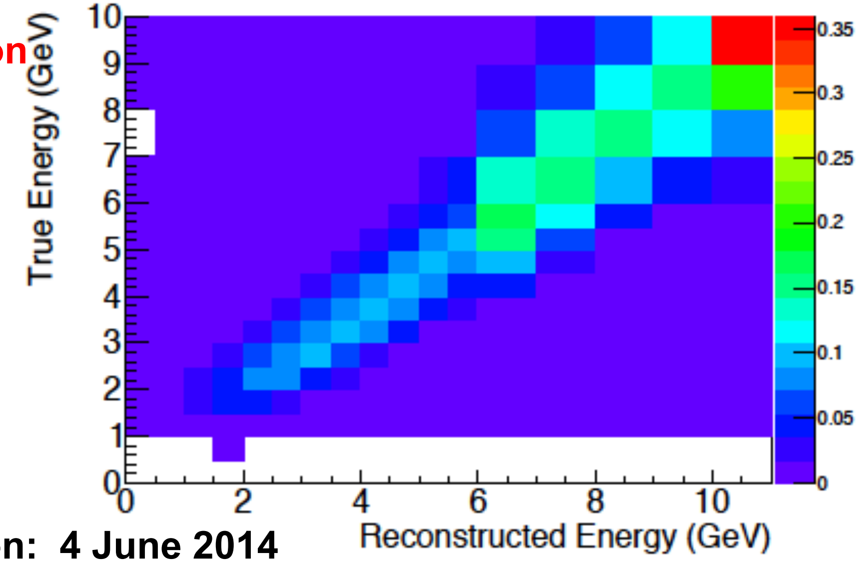




- Multi-variate analysis (MVA) with five variables, tuned for $\sin^2 2\theta_{13}$~0.1: Boosted Decision Tree (BDT) adopted

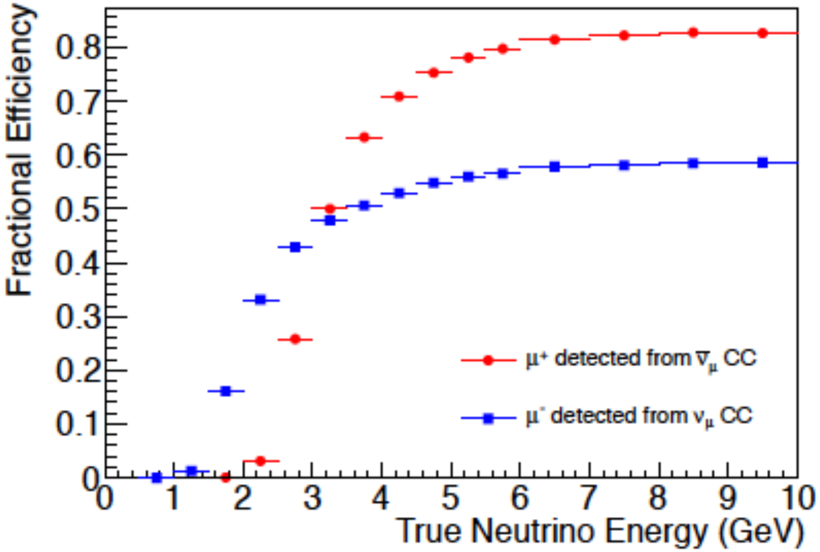


Migration matrix



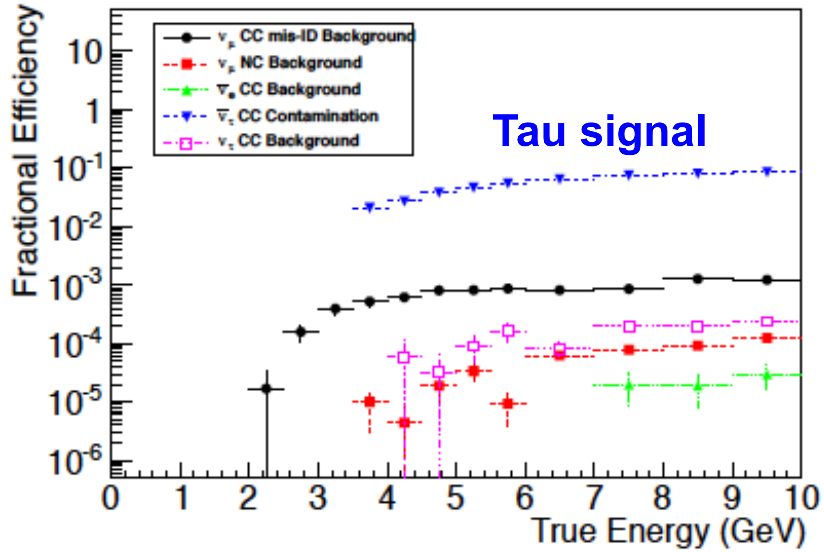
MIND efficiencies and background

BDT efficiency, focussing μ^+

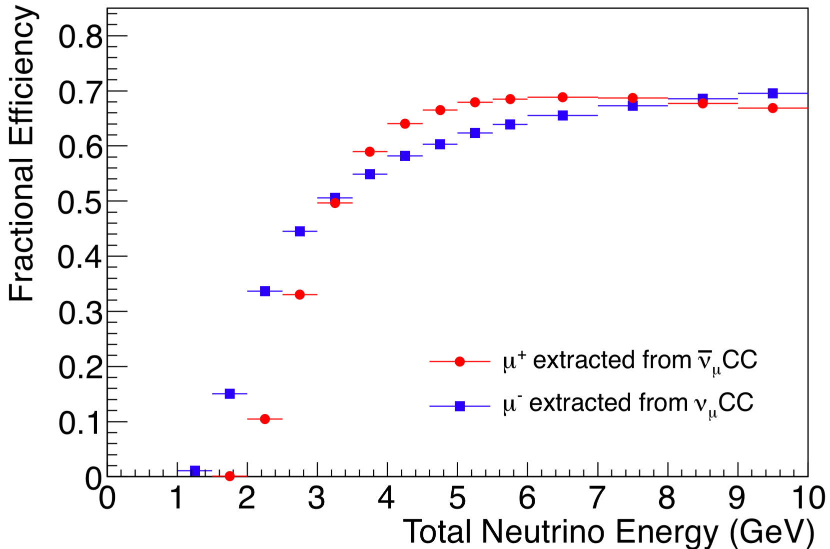


R. Bayes

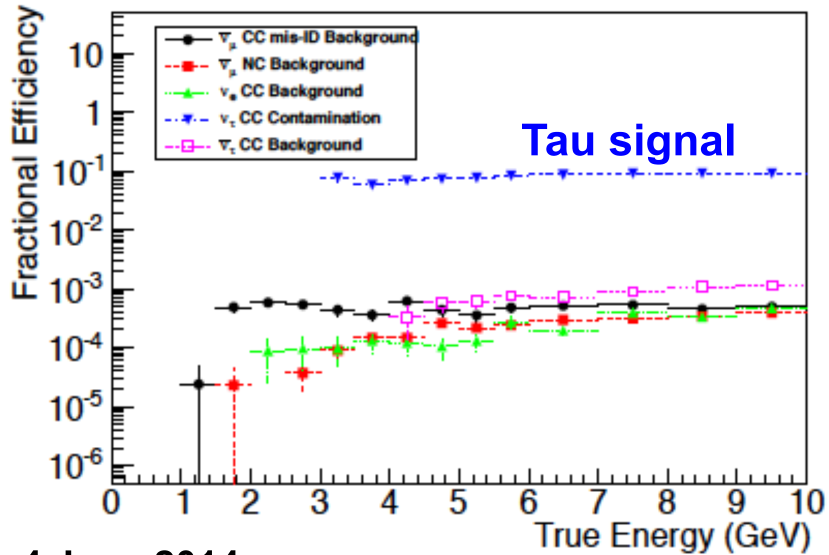
BDT background (stored μ^-, focussing μ^+)



BDT efficiency, focussing μ^-



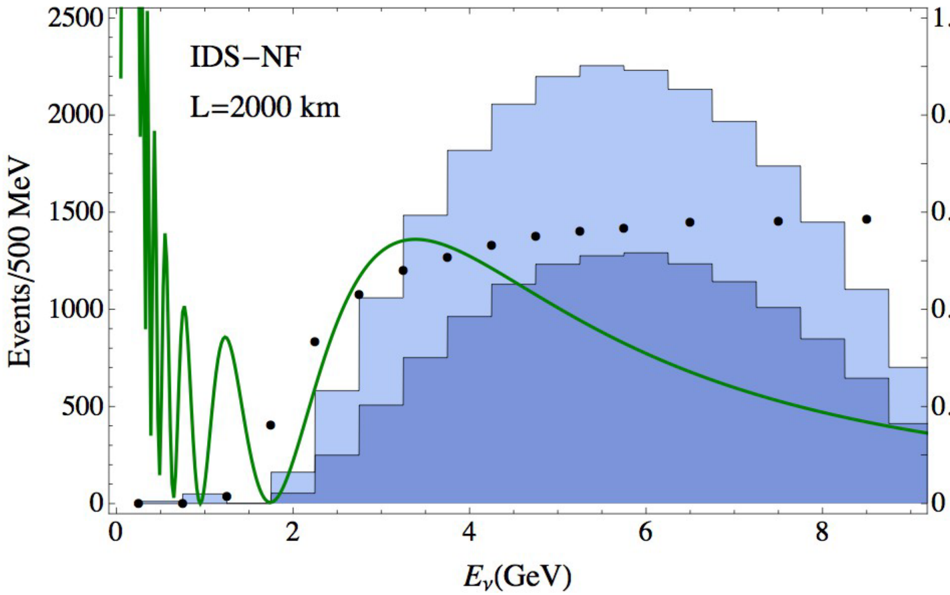
BDT background (stored μ^+, focussing μ^+)

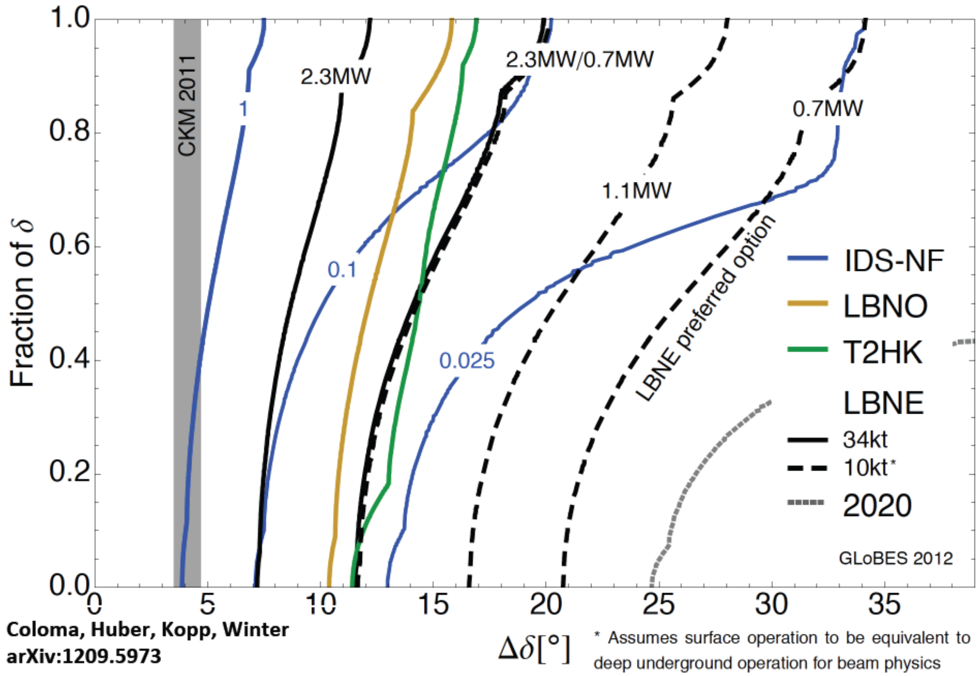


Performance 10 GeV Neutrino Factory

- Systematic errors: 1% signal and 20% background
- Results 10 GeV Neutrino Factory, 10^{21} μ/year for 10 years with 100 kton MIND at 2000 km gives best sensitivity to CP violation
- This is the "best of all possible neutrino factories"

arXiv:1209.5973





CP violation 5σ coverage is 85% (ie. 85% probability of CPV discovery!)

The case for staging

- The IDS-NF Neutrino Factory defines the "best of all possible neutrino factories"
- However, just like in Voltaire's "Candide", reality imposes other worldly contraints
- The Neutrino Factory needs a staged approach, with physics at each stage:
  - First stage: "entry-level" neutrino factory (nuSTORM) for precision cross-sections and sterile neutrinos
  - In a Fermilab setting, the upgradeable proton drivers PIP-2,3,4 are required for LBNE beam from FNAL to Homestake (1300 km)
  - NuMAX (Neutrinos from Muon Accelerator CompleX): 5 GeV neutrino factory with 10^{20} muon decays per year
  - NuMAX+: 5 GeV neutrino factory with 10^{21} muons/year
  - Provides upgrade path towards muon collider

Voltaire

CANDIDE,

OU

L'OPTIMISME,

TRADUIT DE L'ALLEMAND

DE

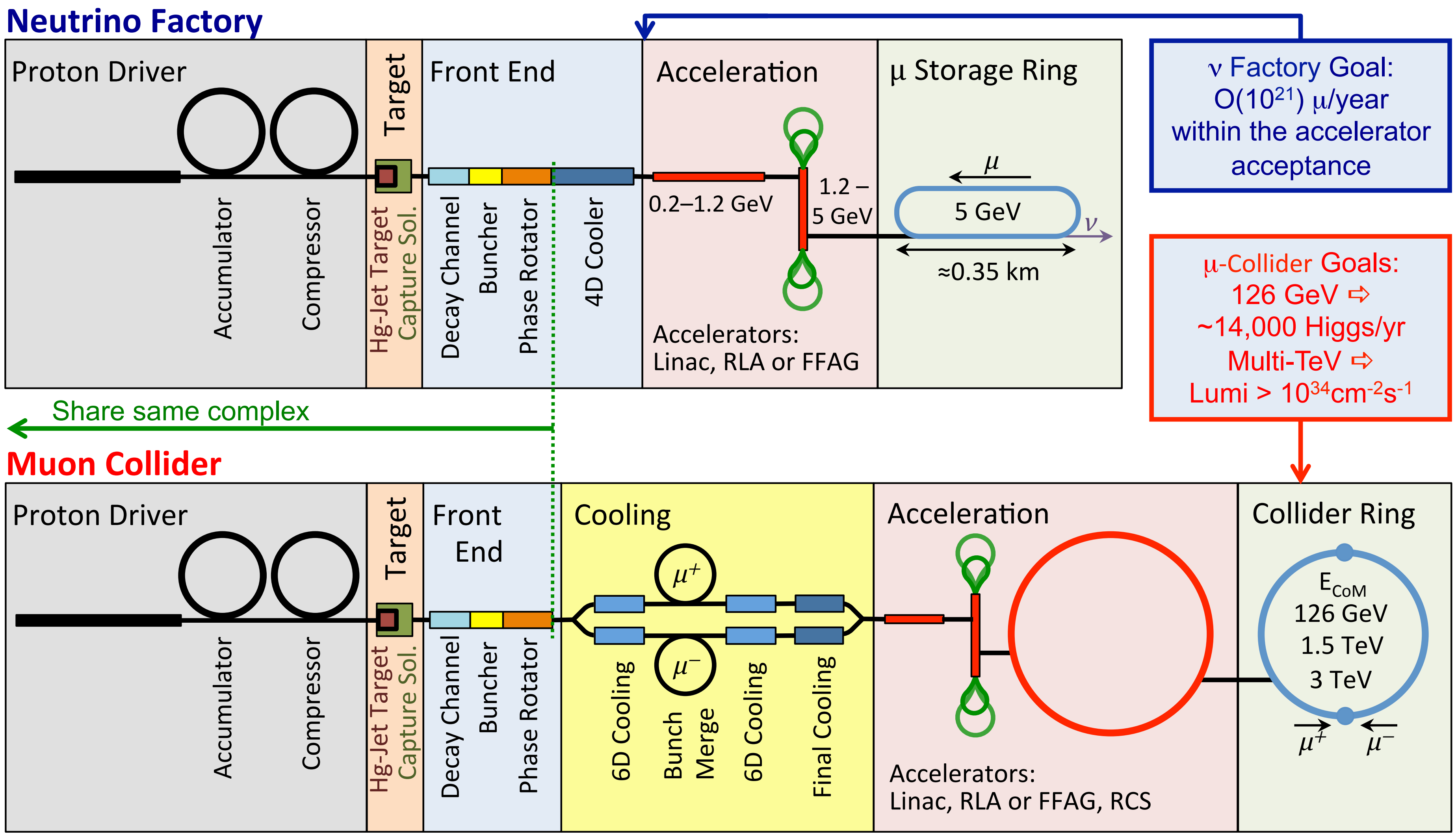
MR. LE DOCTEUR RALPH.

MDCCLIX.

Muon Accelerator Staging Programme

- Synergies between NuMAX and Muon Collider components

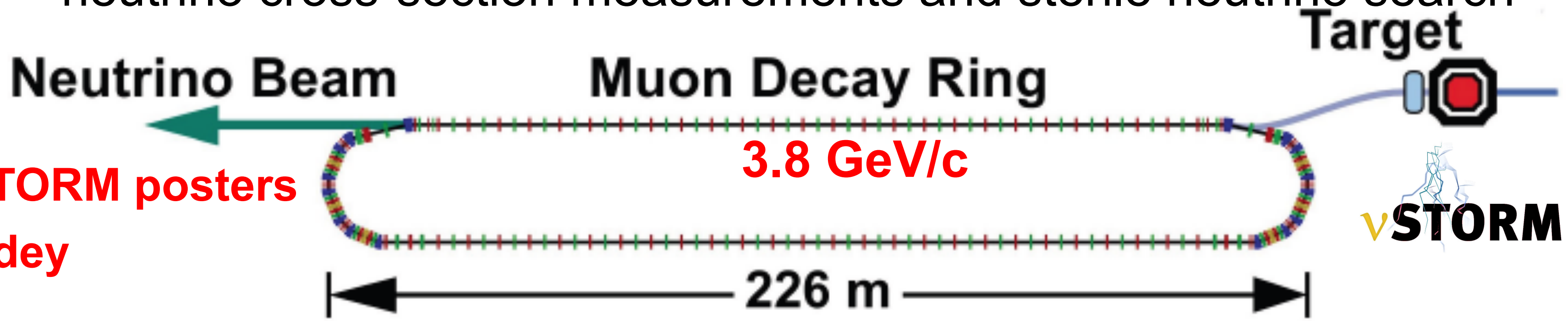
Muon Accelerator Staging Study (MASS)



Stage 1: nuSTORM

- nuSTORM is entry-level neutrino factory from 3.8 GeV/c muons that can be realised now without any new technology
  - Pions captured in horn, transported and stochastically injected into ring
  - 52% of pions decay to muons before first turn: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - For 10^{20} POT, we expect flash of neutrinos from 8.6×10^{18} pion decays
  - Muons within momentum acceptance (3.8 GeV ± 20%) circulate in ring.
  - Muon lifetime is 27 orbits of decay
  - For 10^{20} POT, we expect 2.6×10^{17} μ^+ that decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

    New horn optimisation: $3.2\text{x}10^{17}$ μ^+ decays (poster Ao Liu, A Bross)
  - Hybrid beam from pion and muon decay: rich physics programme of neutrino cross-section measurements and sterile neutrino search

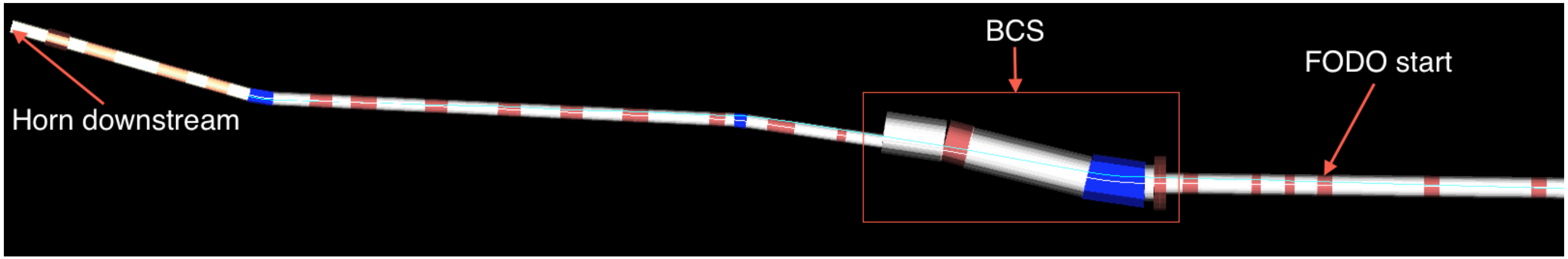


nuSTORM posters
D. Adey

arXiv:1308.6822

Stage 1: nuSTORM

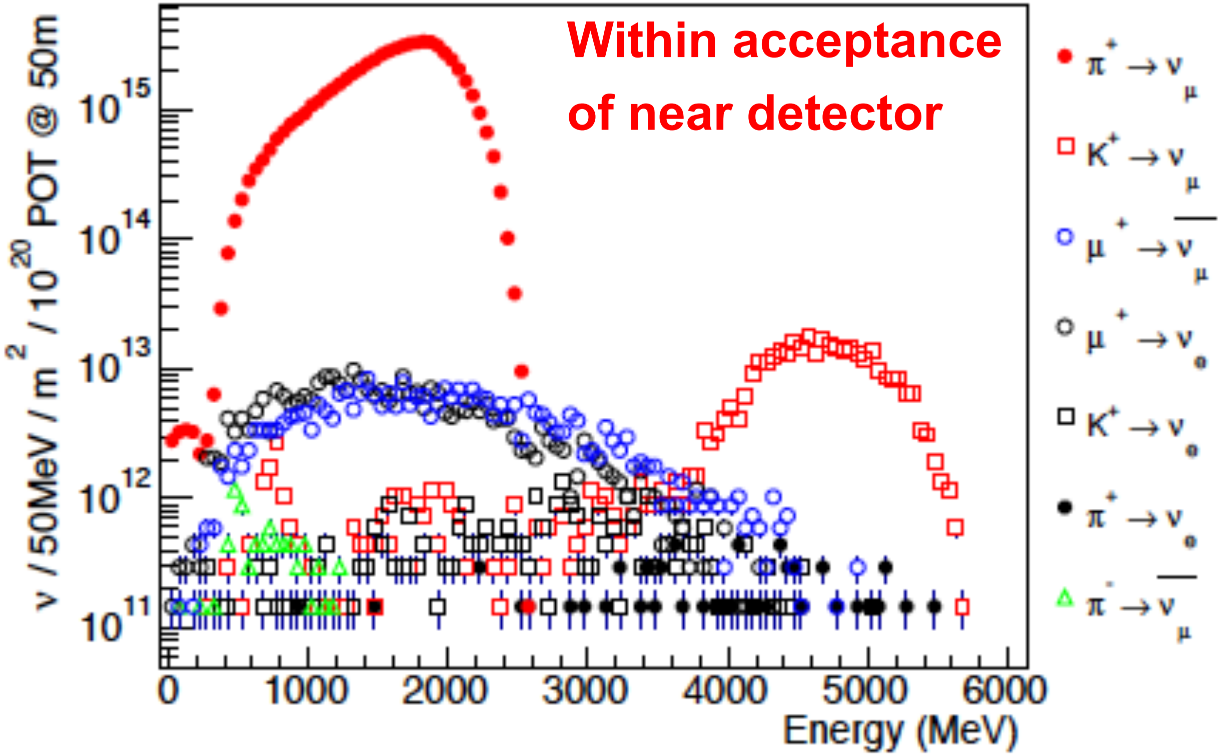
- nuSTORM facility:
  - 120 GeV protons on carbon or inconel target (100 kW)
  - NuMI-style horn for pion collection
  - Stochastic injection pions (5 GeV/c ± 20%) into storage ring: 0.11 π/POT
  - Storage ring: large aperture FODO lattice (3.8 GeV/c ± 10%) muons: 8×10^{-3} μ/POT



Stage 1: nuSTORM

- nuSTORM flux and energy spectrum **D. Adey Posters**

Use muon decay neutrinos to calibrate hadron decay neutrinos



– ν_μ from pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ flux: 6.3×10^{16} ν/m^2 at 50 m
– ν_e from muon decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ flux: 3.0×10^{14} ν/m^2 at 50 m
– ν_μ from kaon decay $K^+ \rightarrow \mu^+ + \nu_\mu$ flux: 3.8×10^{14} ν/m^2 at 50 m
– Used for cross-section measurements and short baseline experiments

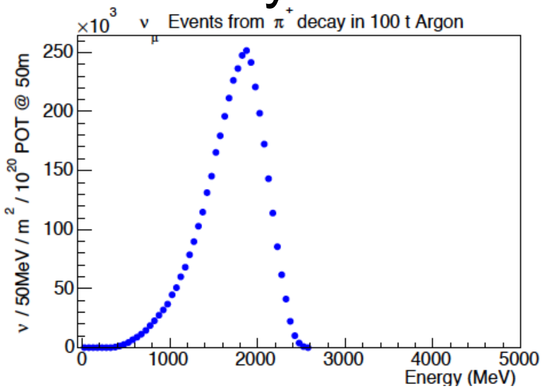
Stage 1: nuSTORM

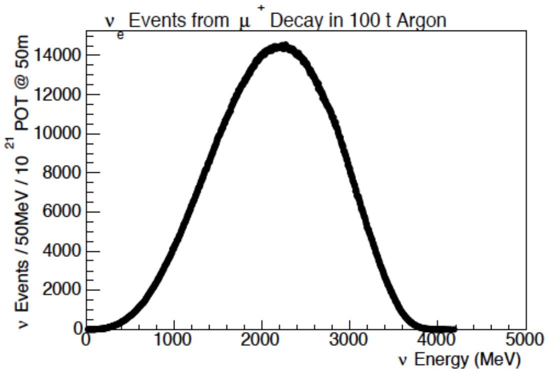
- Flux uncertainties for nuSTORM: < 1% **D. Adey Posters**
- Event rates per 10^{21} POT in 100 tons Liquid Argon at 50 m

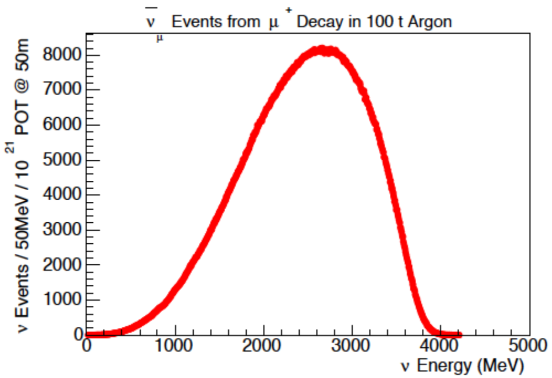
Essential to pin down ν_e cross-sections for long-baseline experiments!

μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

– Limited by detector systematics:







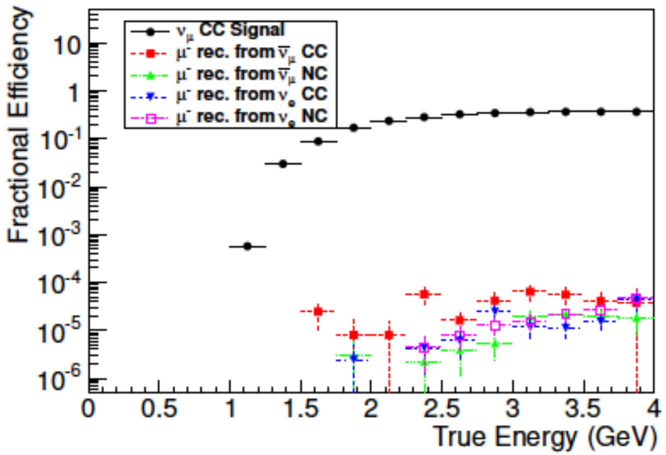
Stage 1: nuSTORM

- Sterile neutrino search in short-baseline experiment
- Far detector: 1.3 kton magnetised iron (Super BIND) at 2 km
- Magnetic field: 1.5-2.6 fed by 240 kA by STL
- Appearance and disappearance searches:

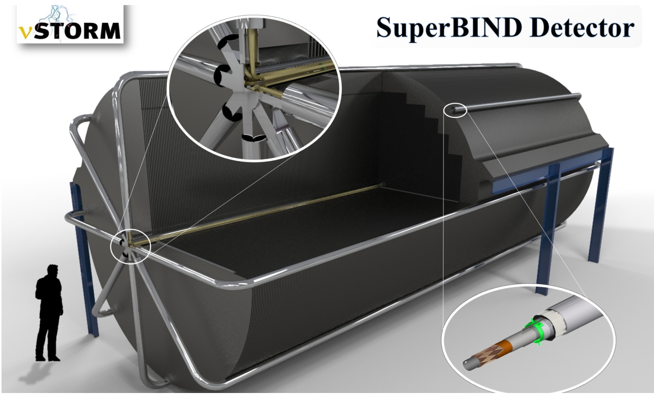
$$P_{e\mu}(x) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{e\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

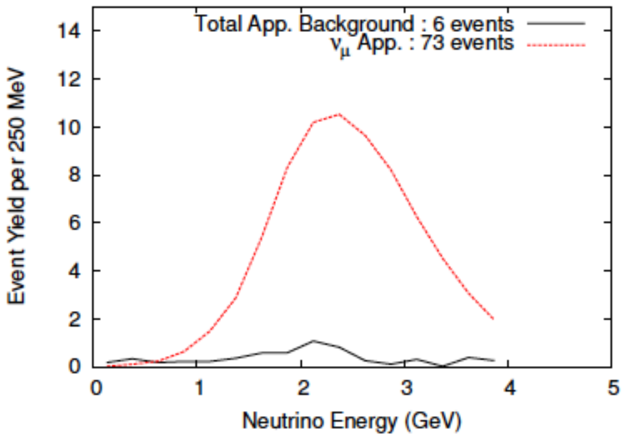
$$P_{\mu\mu}(x) = 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)\sin^2\left(\frac{m_{14}^2 x}{4E}\right) \equiv \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{m_{14}^2 x}{4E}\right)$$

Appearance efficiencies

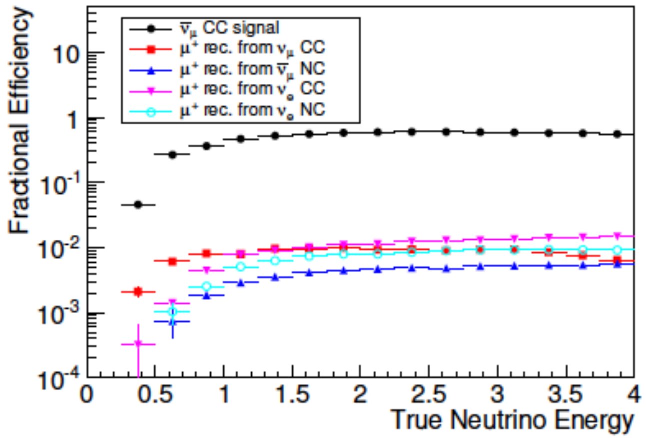


Adey et al., PRD 89 (2014) 071301





Disappearance efficiencies



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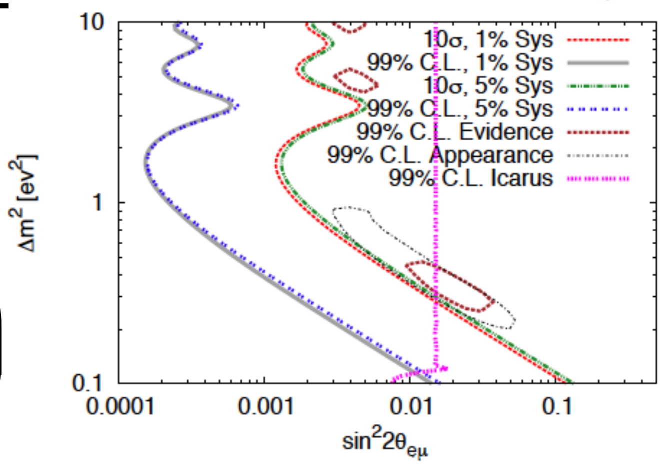
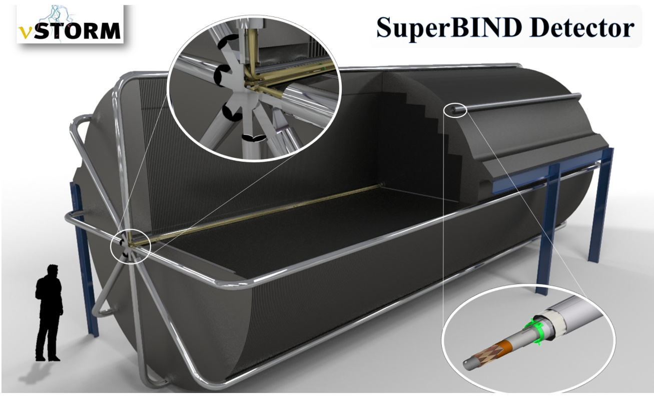
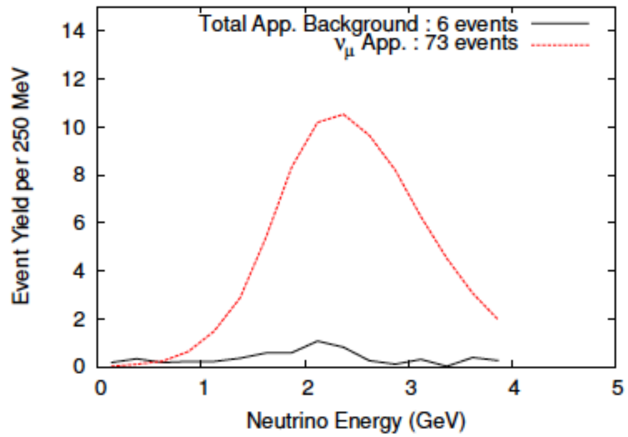
Adey et al., PRD 89 (2014) 071301

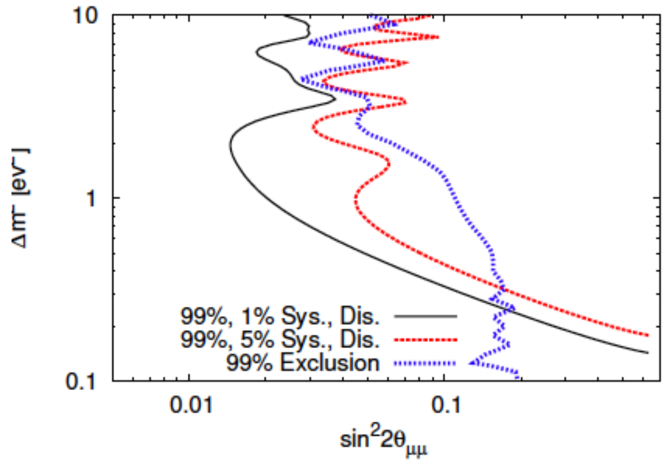
10σ Appearance sensitivity





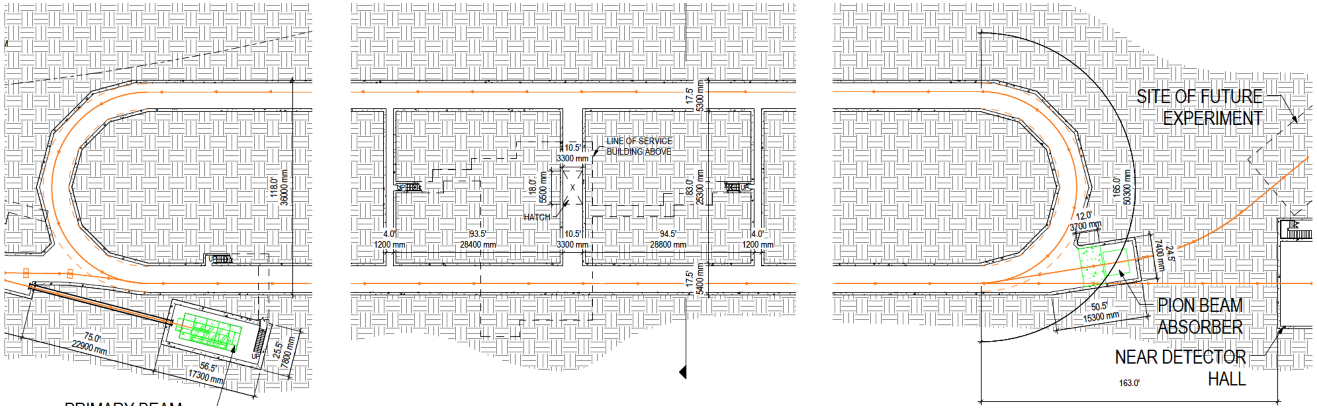


99% CL Disappearance sensitivity

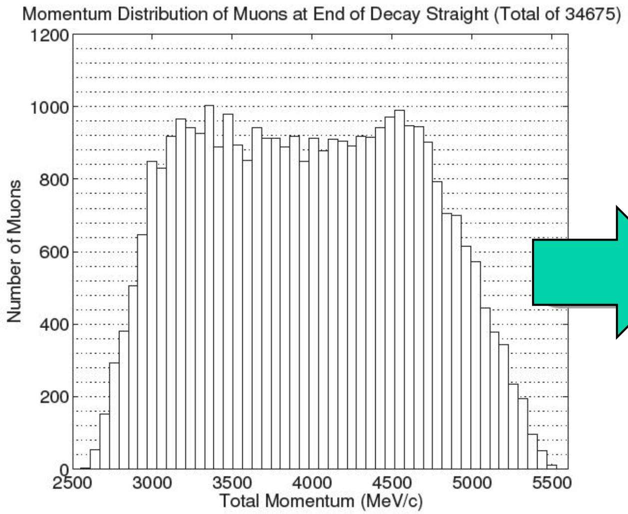


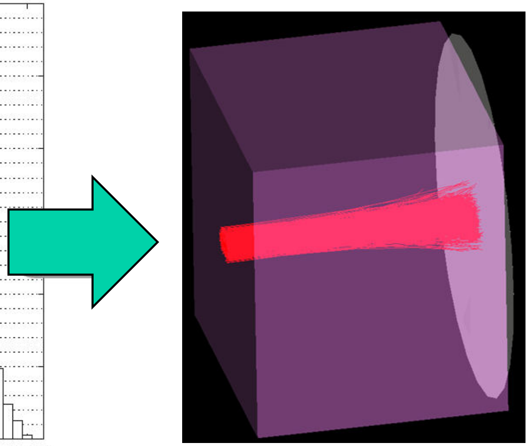
Stage 1: nuSTORM

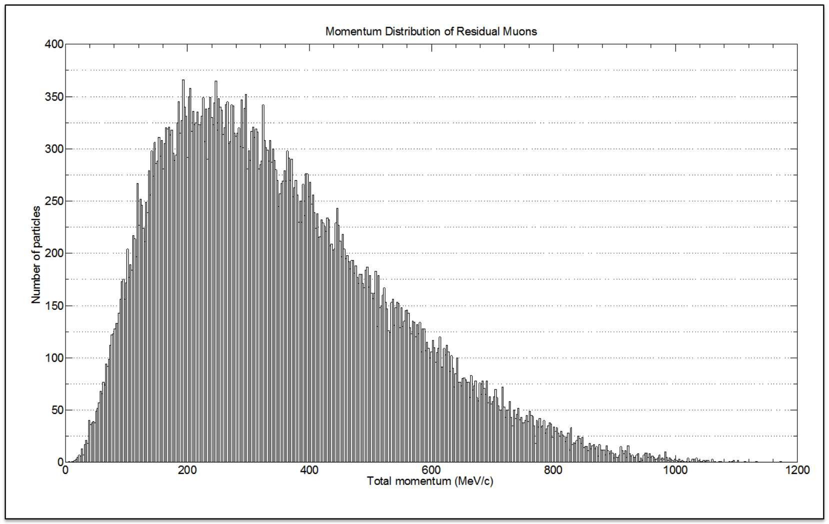
- nuSTORM: testbed for 6D muon cooling experiment
  - At end of straight: 3.5 m iron pion absorber



  - After absorber: 10^{10} μ/pulse between 100-300 MeV/c



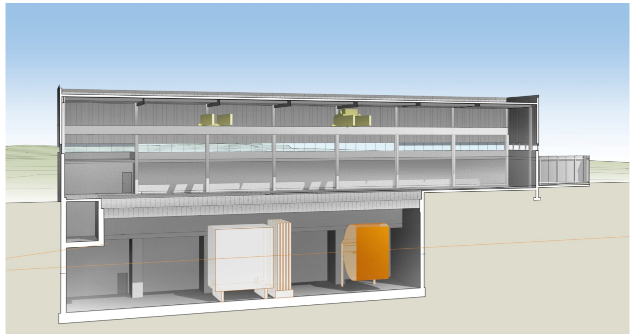


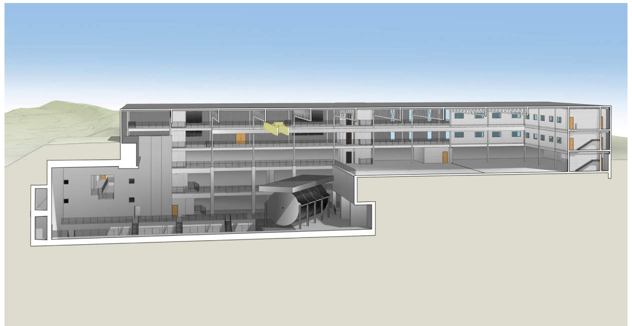


Stage 1: nuSTORM

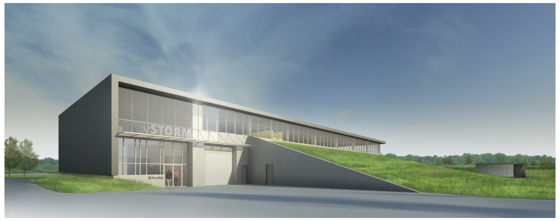
- nuSTORM could be sited at Fermilab (also at CERN)

Near Detector Hall





Far Detector Hall (D0)

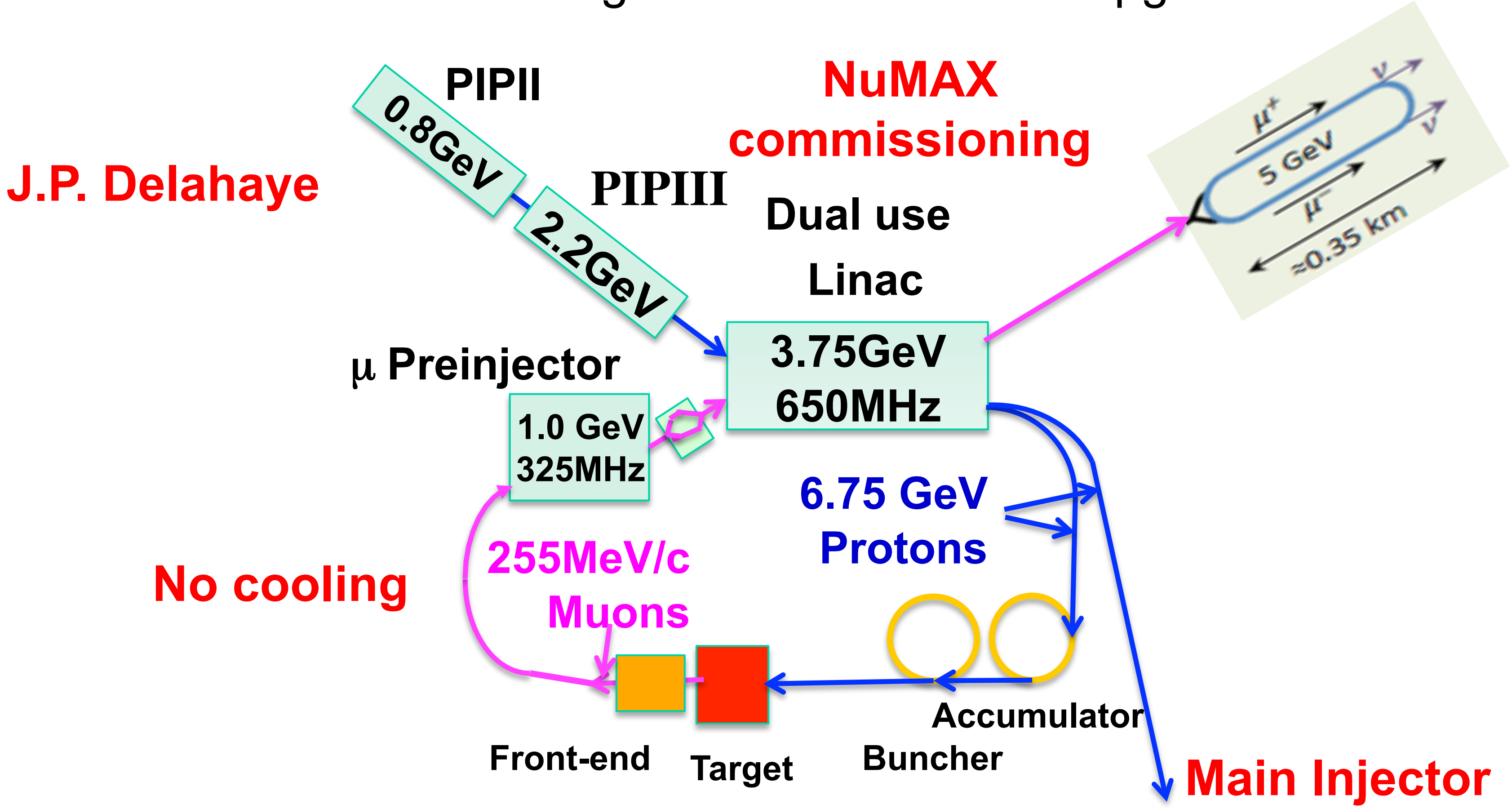


Target building

Decay ring

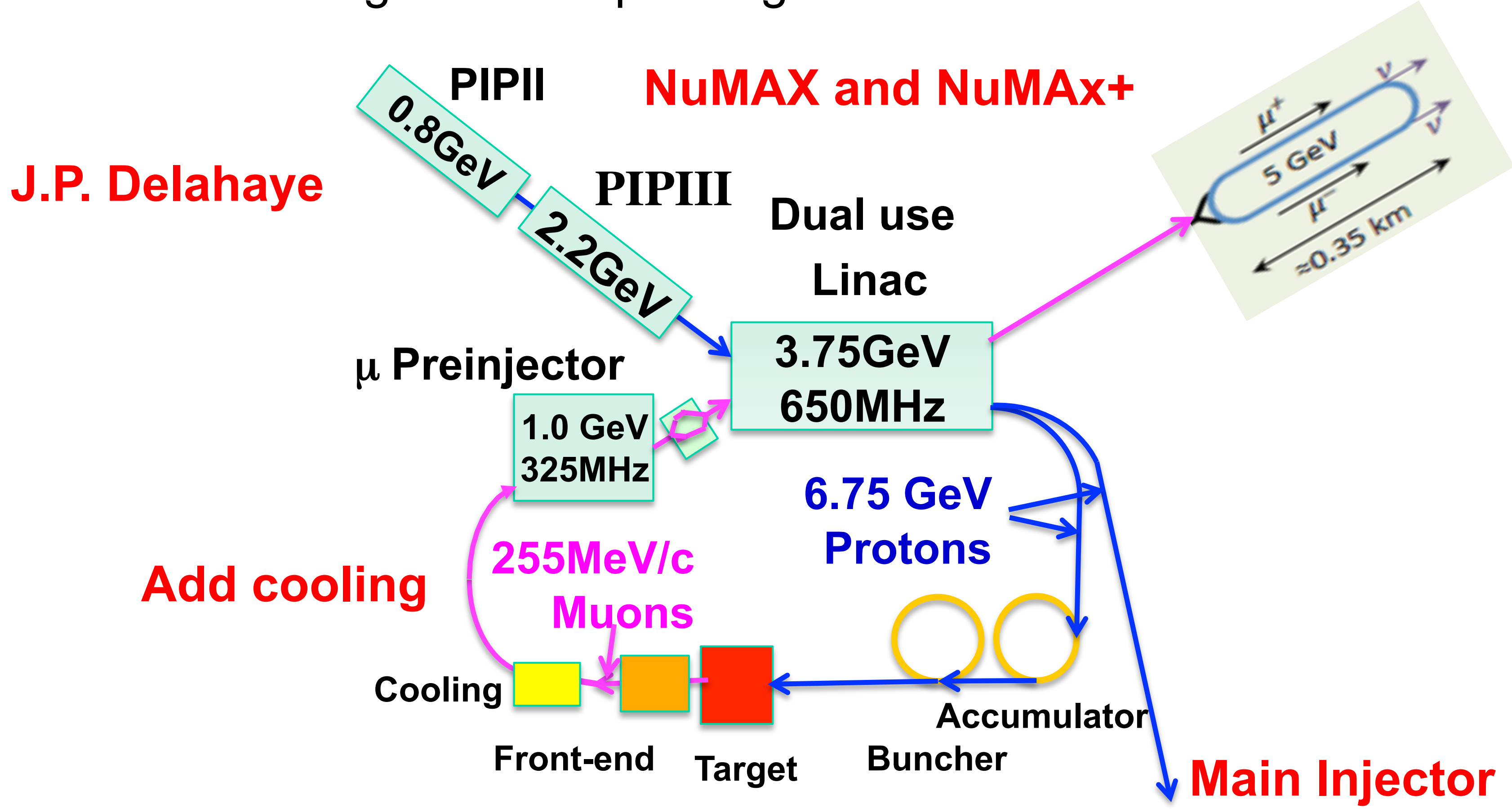
Stage 2: NuMAX commissioning

- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Neutrino Factory with 10^{20} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - A 10kT MIND or magnetized LAr detector upgraded from LBNE



Stage 3: NuMAX

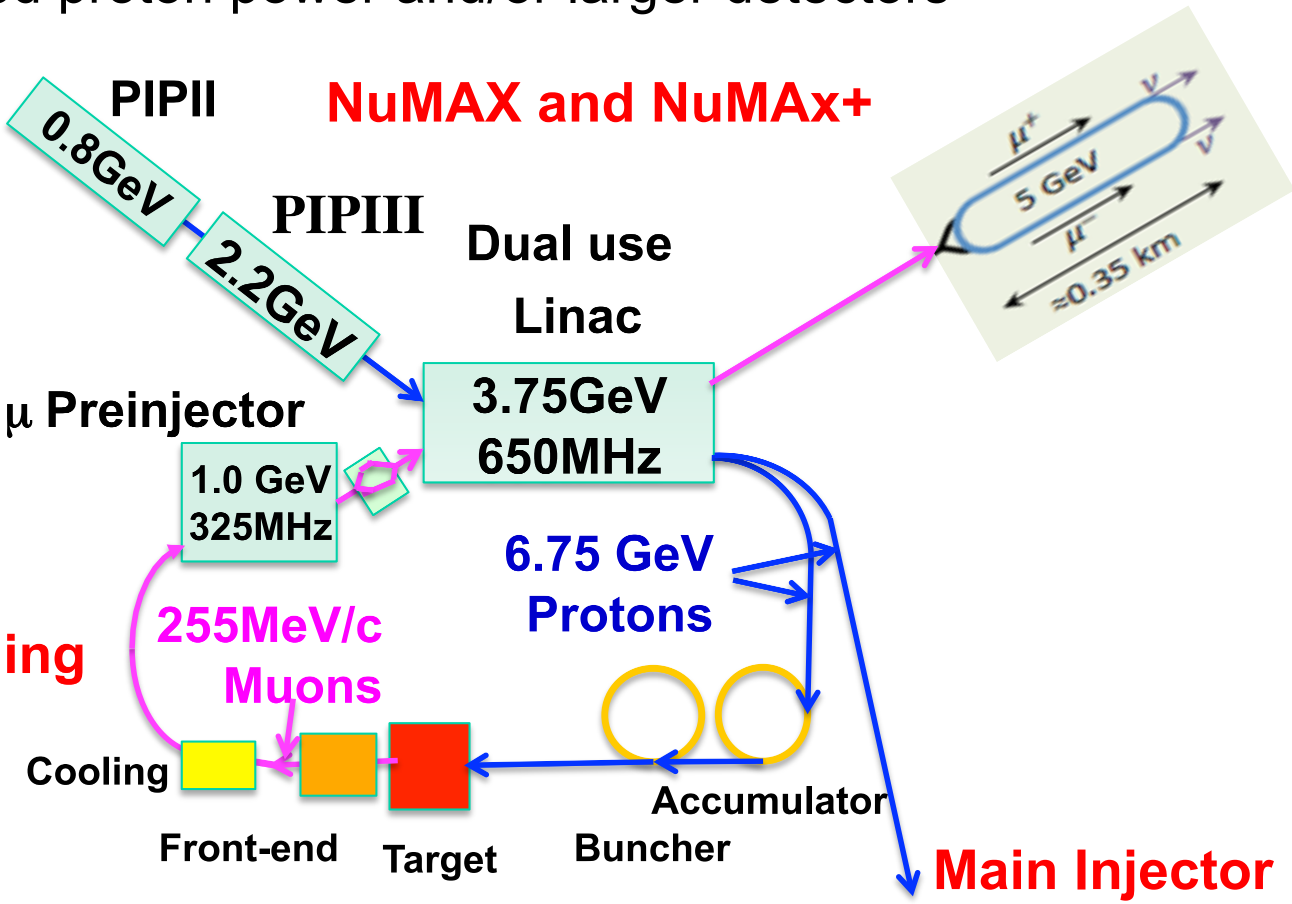
- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Add small amount of 6D cooling
  - Neutrino Factory with 5×10^{20} straight muon decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford



Stage 4: NuMAX+

- Neutrinos from a Muon Accelerator CompleX (NuMAX+)
  - Neutrino Factory with 10^{21} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - Increased proton power and/or larger detectors

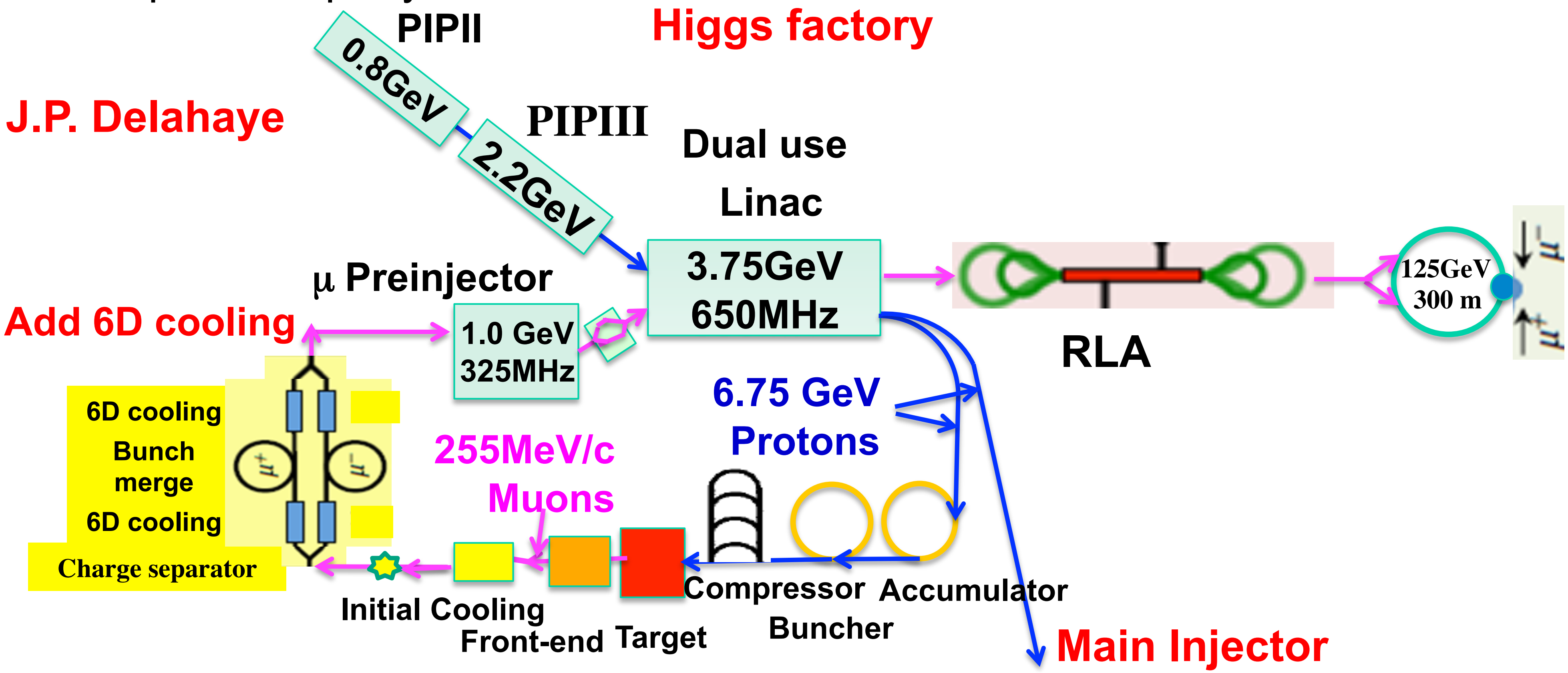
J.P. Delahaye



Add cooling

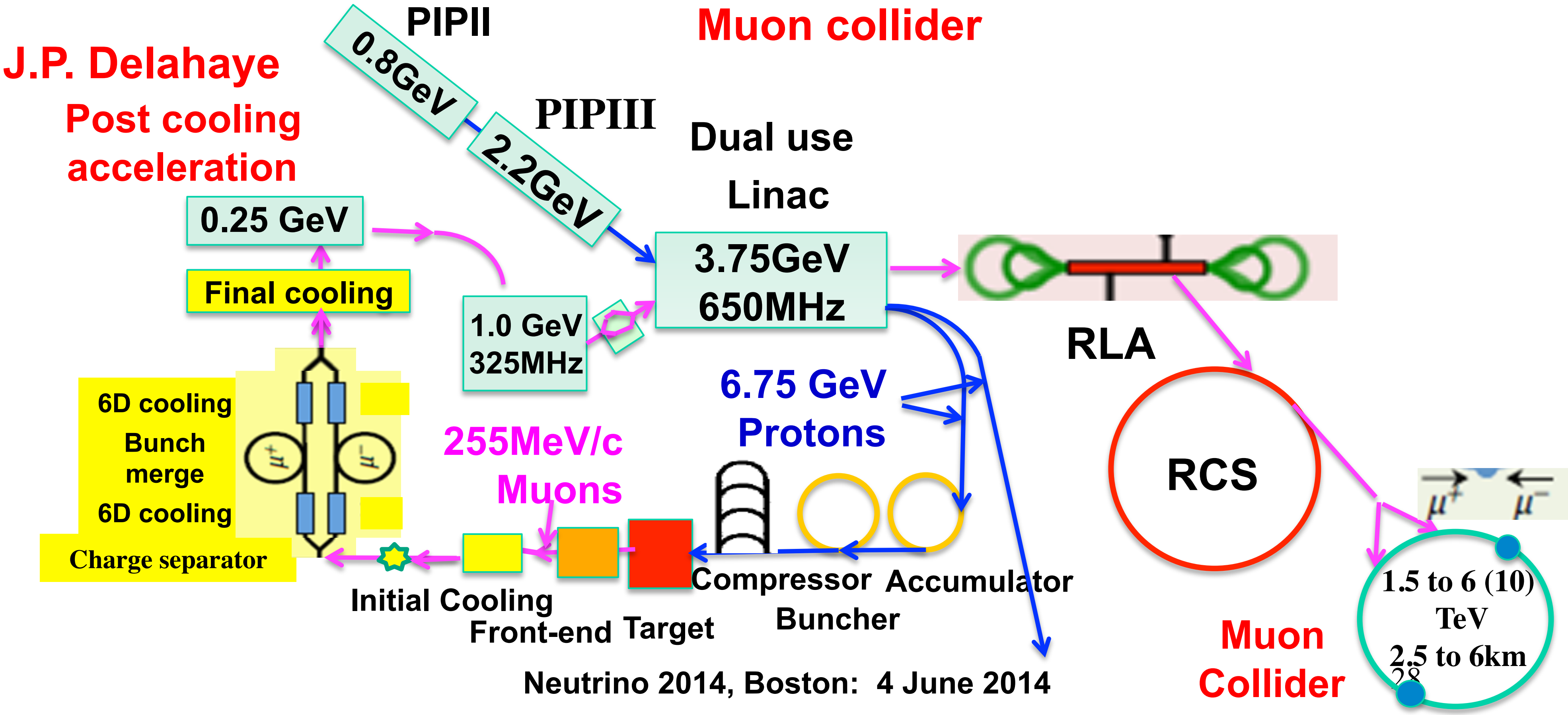
Stage 5: Muon Collider-Higgs Factory Option

- Higgs Factory: production of Higgs at 126 GeV CM
  - Collider capable of providing ~13,500 Higgs events per year with exquisite energy resolution: direct Higgs mass and width
  - Possible upgrade to a Top Factory with production of up to 60,000 top particles per year

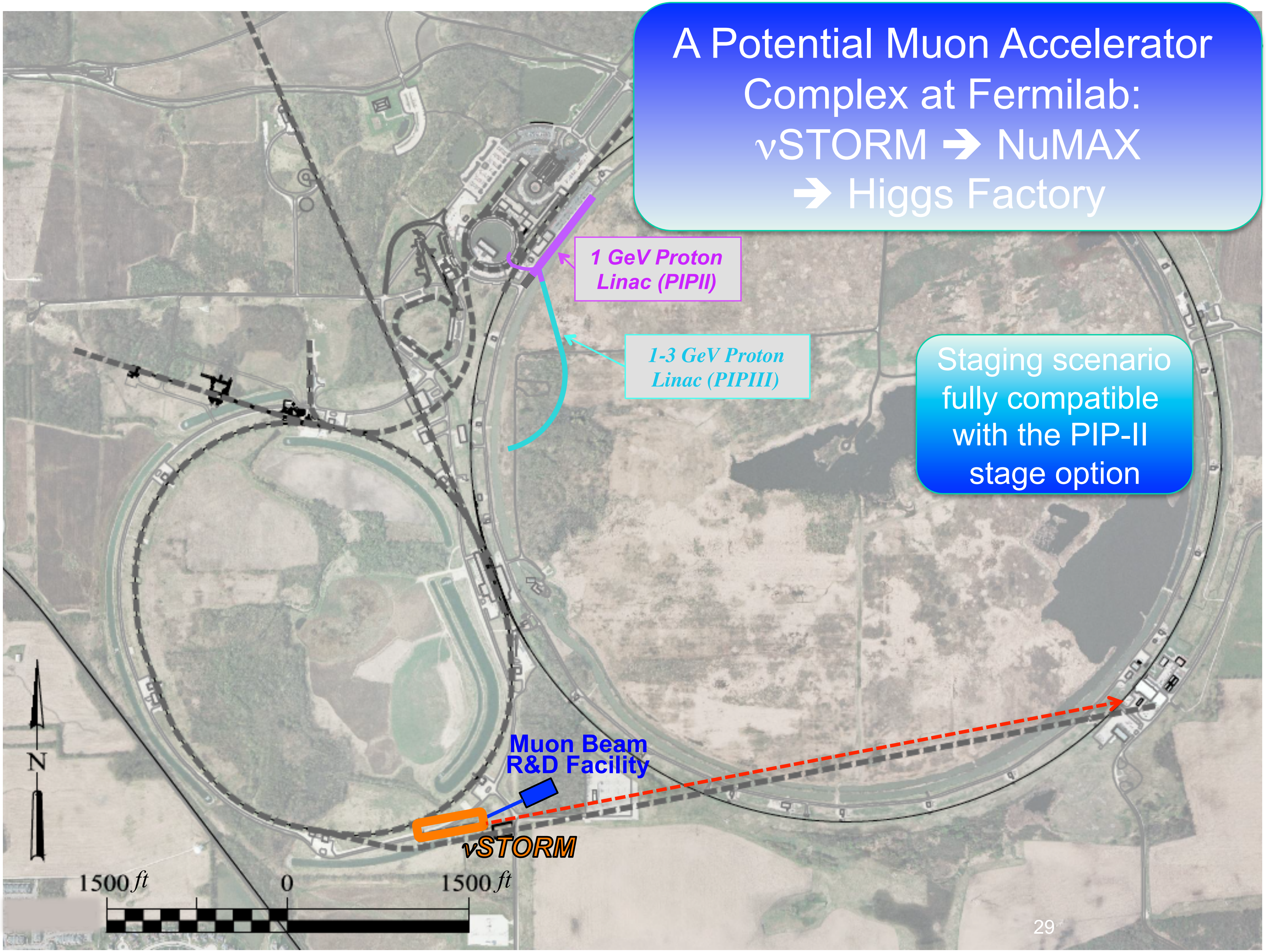


Stage 6: Multi-TeV Muon Collider

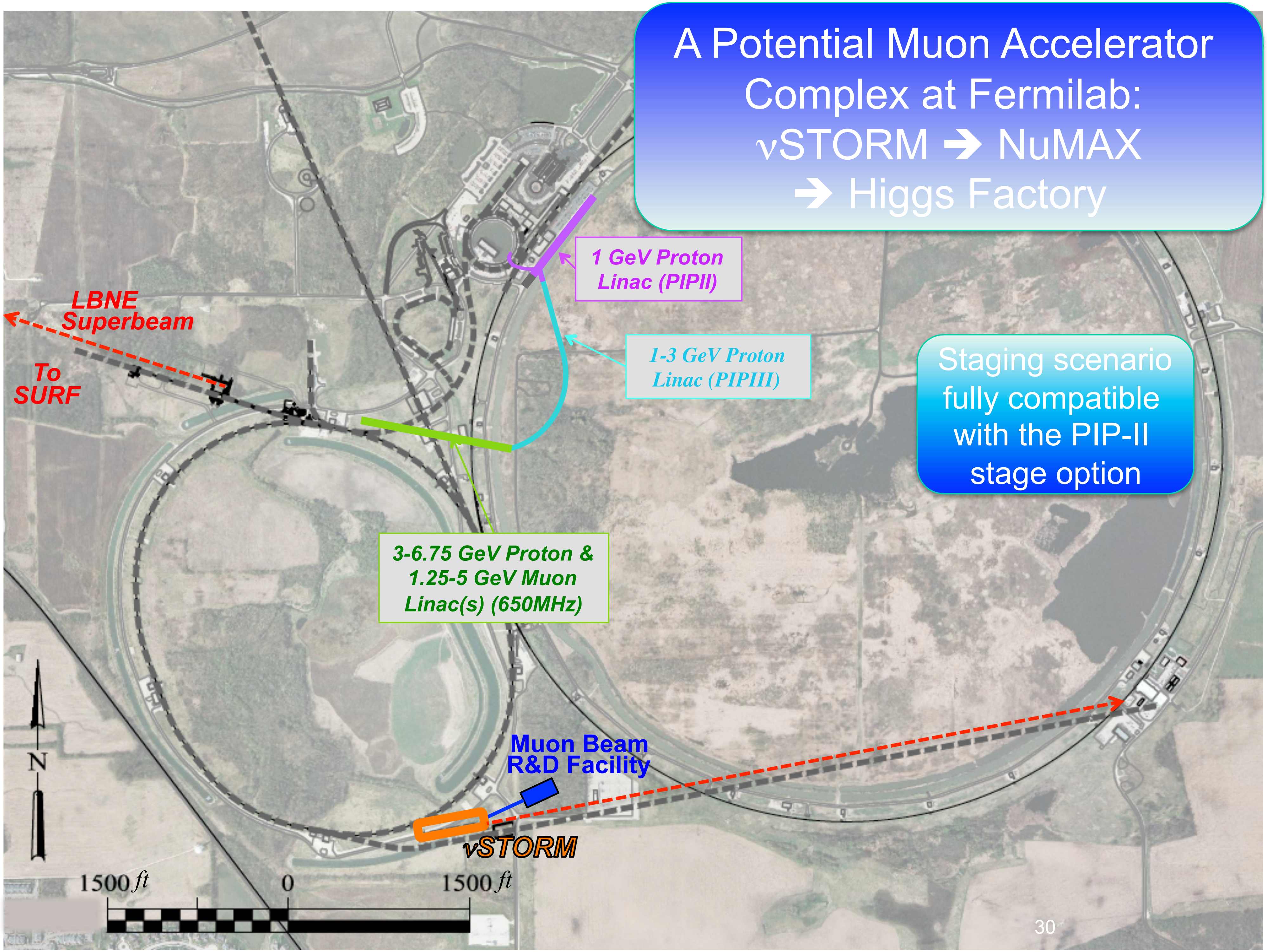
- Multi-TeV muon collider:
  - If warranted by LHC results a muon collider can reach up to 10 TeV
  - Likely offers the best performance, least cost and power consumption of any lepton collider operating in the multi-TeV regime.



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

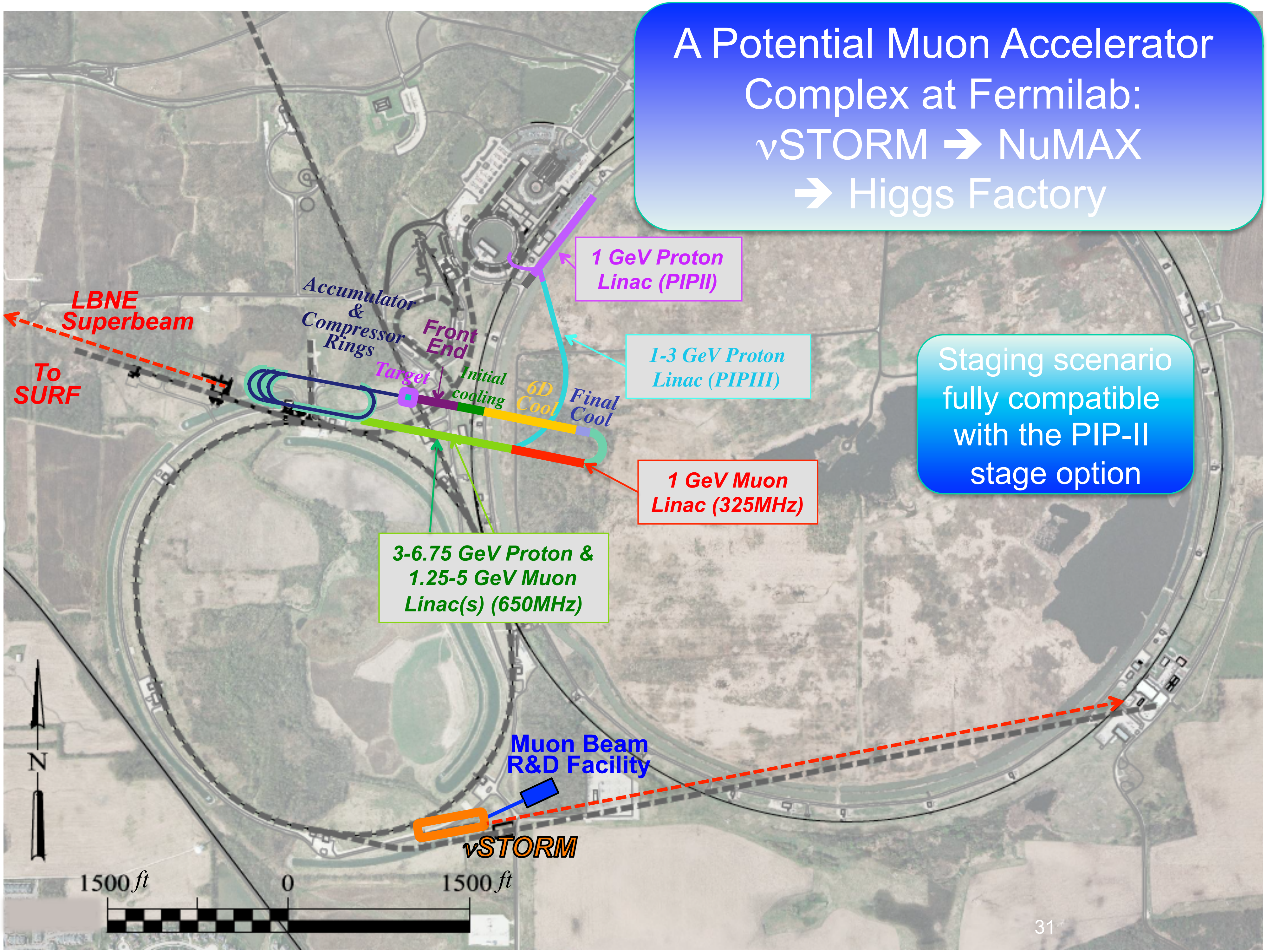


A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory



Staging scenario fully compatible with the PIP-II stage option

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



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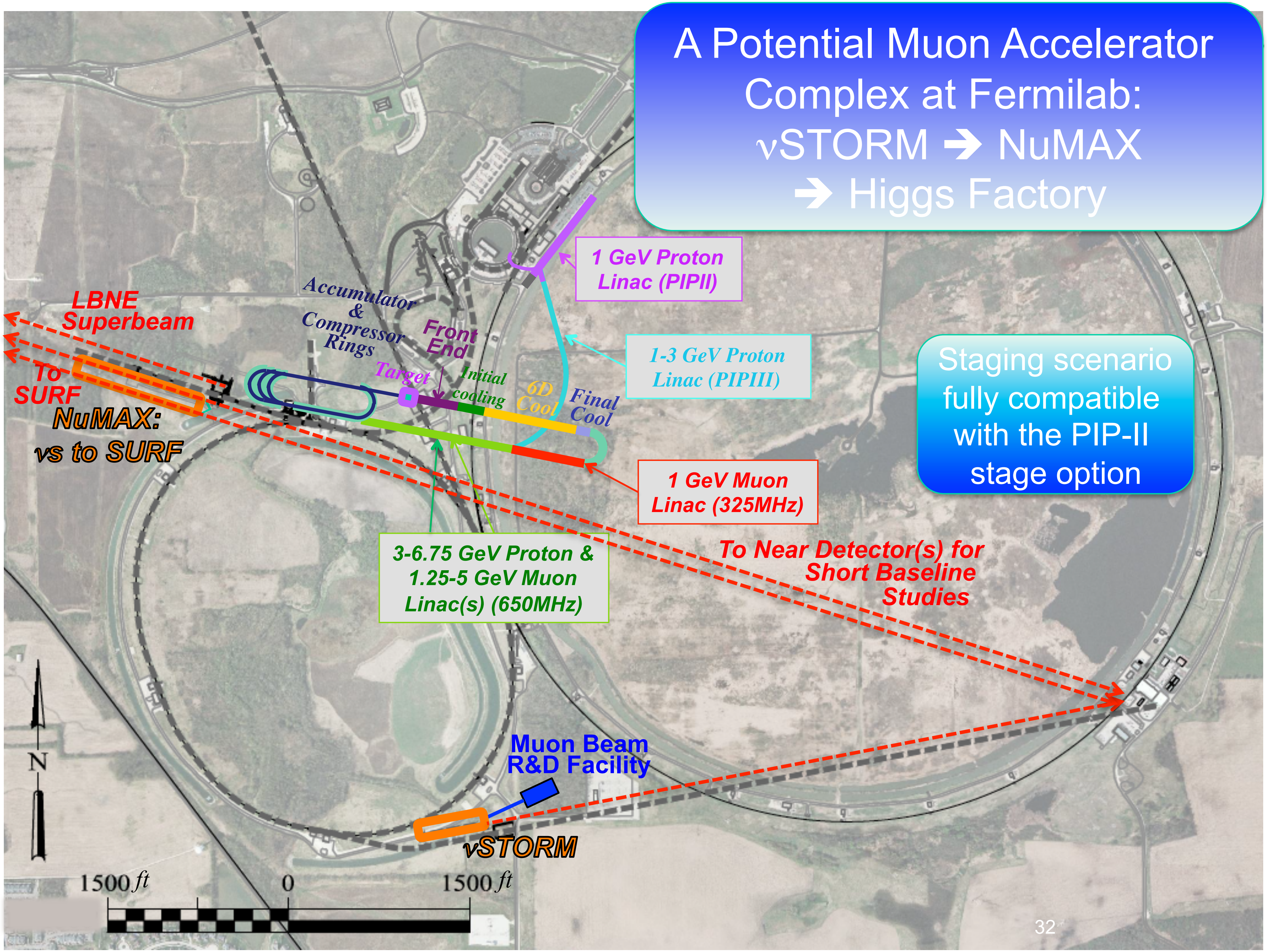

Staging scenario fully compatible with the PIP-II stage option

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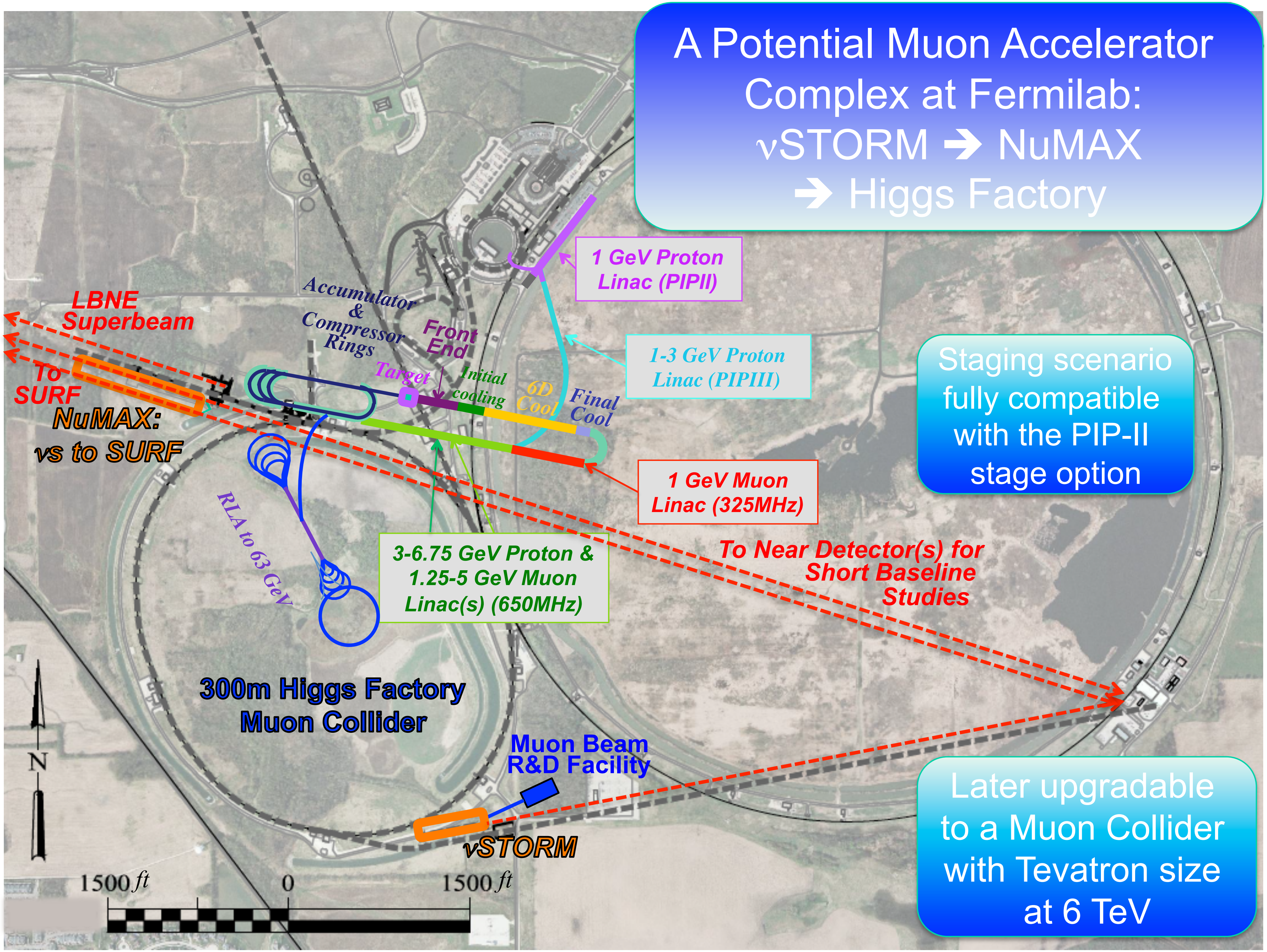
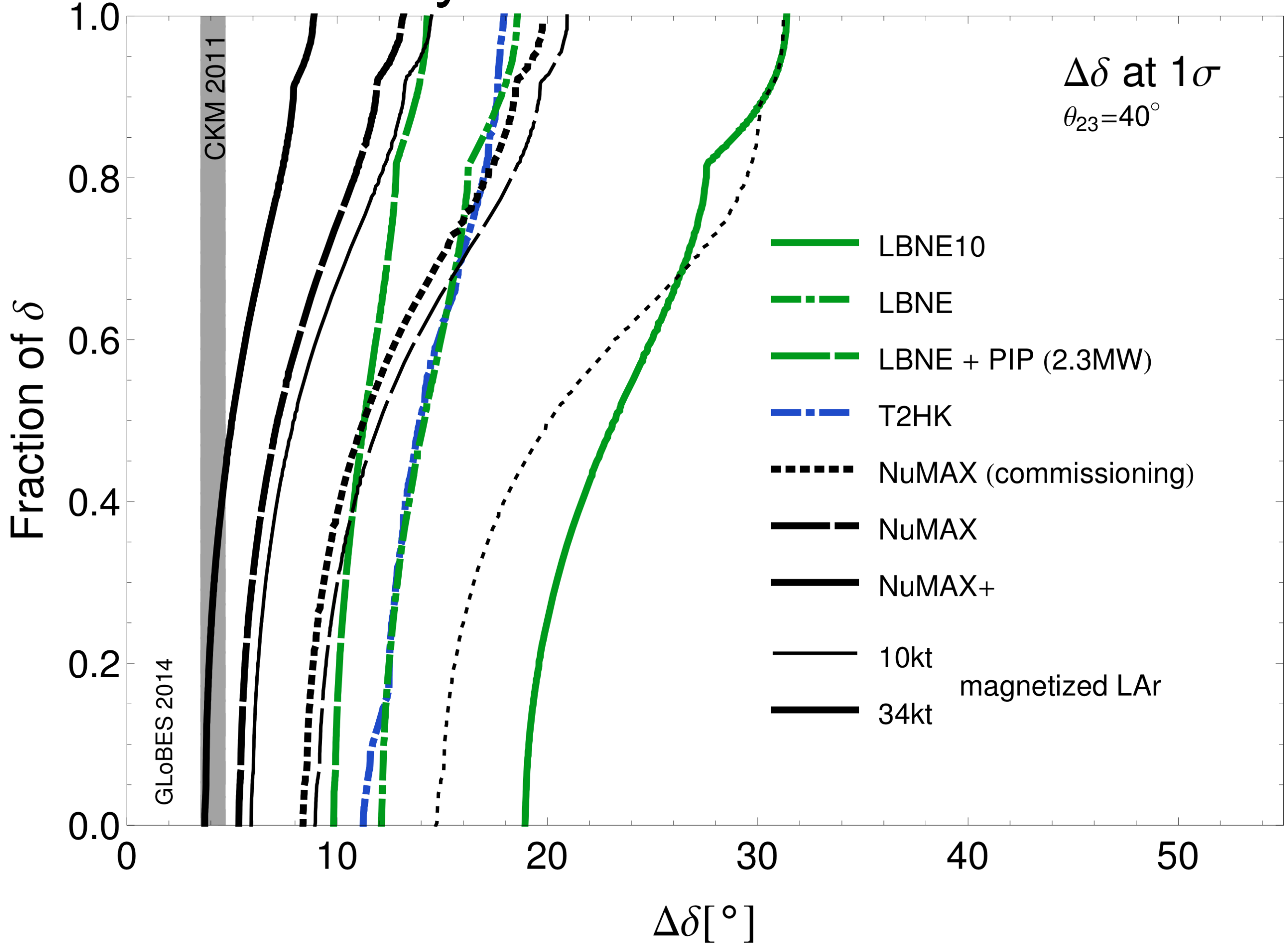


Physics performance of NuMAX

- Physics performance in terms of fraction of CP phase δ with measurement accuracy at or below Δδ

P. Huber



Matches performance IDS-NF Neutrino Factory

Conclusions

- International Design Study for a Neutrino Factory (IDS-NF) has concluded its study
  - Interim Design Report delivered March 2011
  - Reference Design Report should be published by this summer
  - It defines benchmark 10 GeV Neutrino Factory
  - However, expensive and very challenging so needs staging
- Staging scenario assumes:
  - Stage 1: nuSTORM for short-baseline and neutrino scattering physics
  - Stage 2: commissioning of NuMAX to SURF (no cooling)
  - Stage 3: NuMAX includes a 6D cooling stage
  - Stage 4: NUMAX+ includes full power, cooling and detector size
  - Stages 5 & 6: upgradeable to Higgs Factory or TeV-scale Muon Collider
- Neutrino Factories offer best potential for discovery of neutrino CP violation, with upgrade path towards muon colliders

NUFACT 2014

- You are all welcome to attend NUFACT 2014 to be held at University of Glasgow 25-30 August 2014
- Preceded by International Neutrino Summer School (INSS 2014) to be held at St Andrews 10-22 August 2014

http://www.nufact2014.physics.gla.ac.uk/

http://www.inss2014.physics.gla.ac.uk/