Fermilab Neutrino Beam Upgrade Plans and Possibilities

Matt Toups, Fermilab

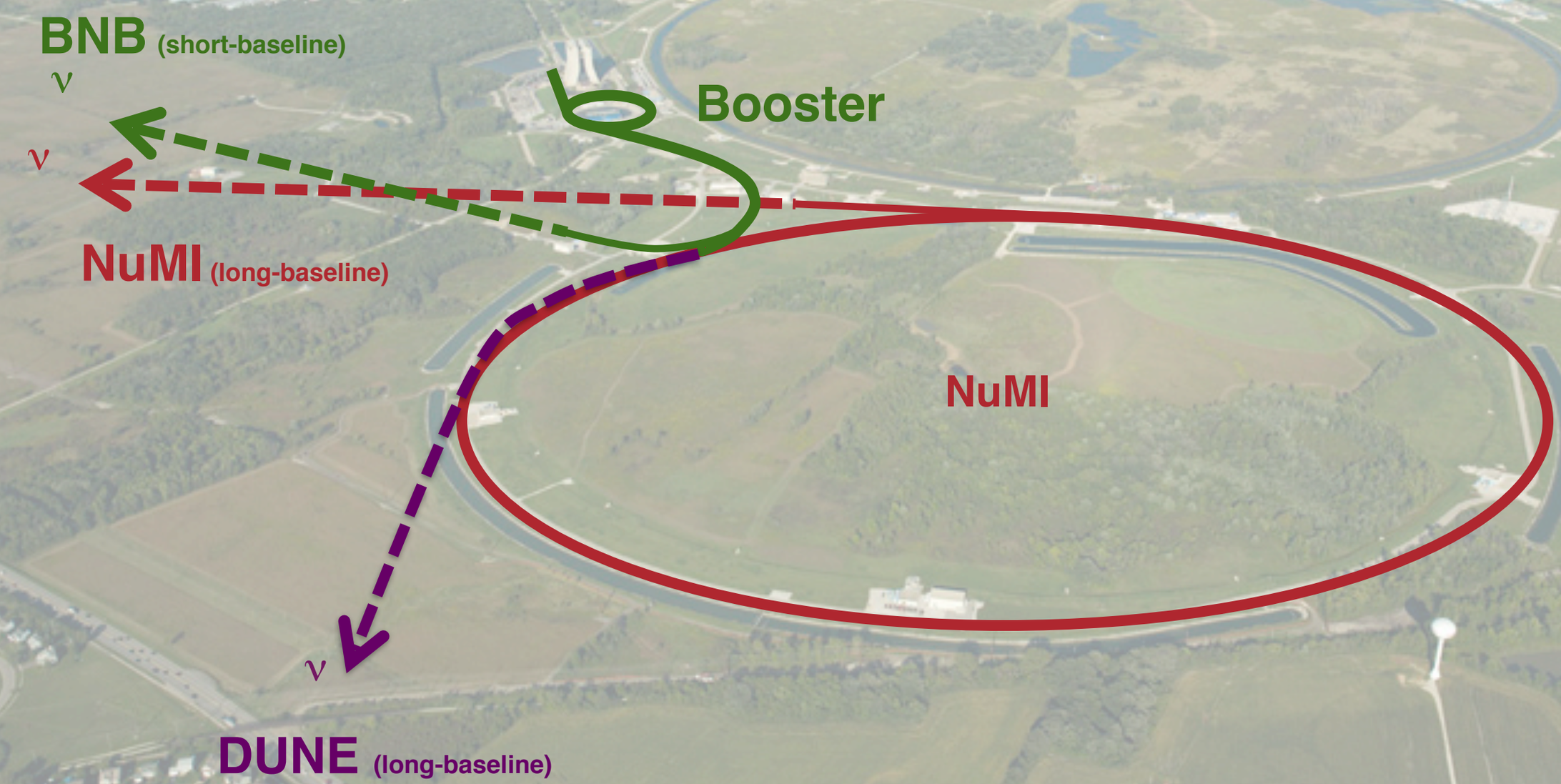
2 Dec 2020

Fermilab operates the nation's largest particle accelerator complex

Produces the world's most powerful low & high energy ν beams

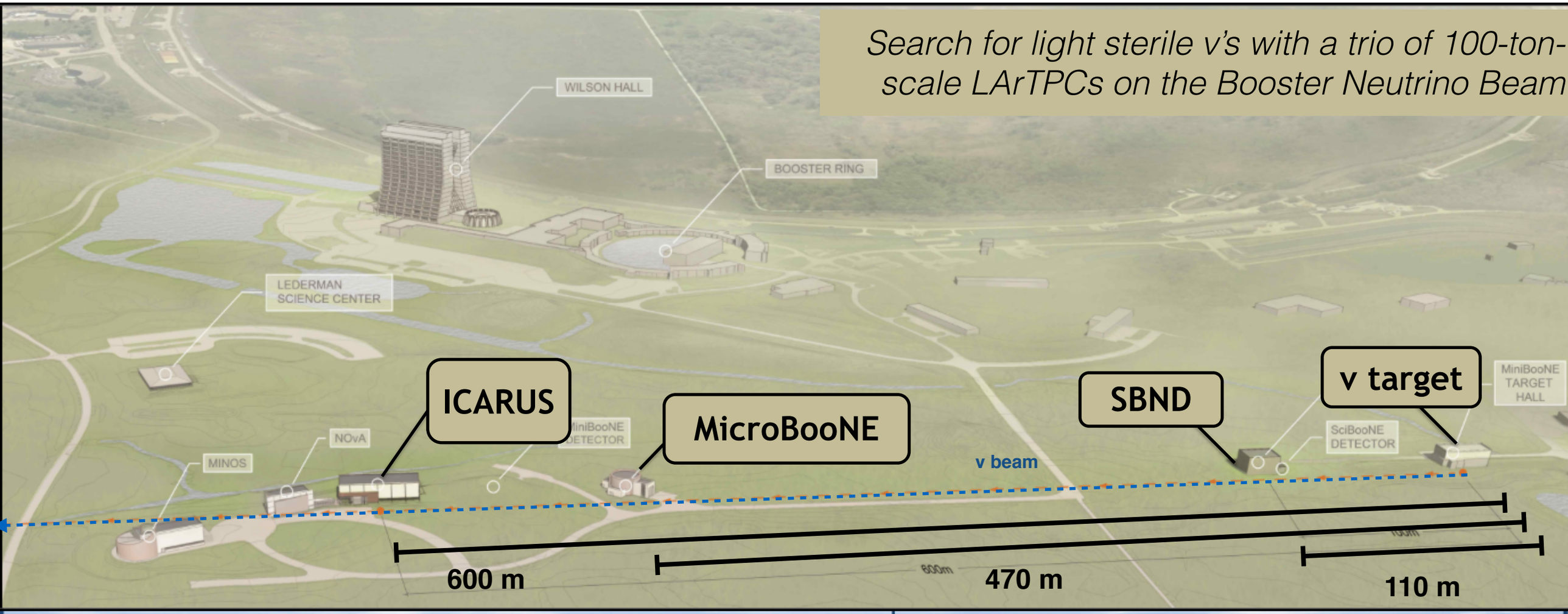
LBNF extends complex to include multi-megawatt ν beam to DUNE

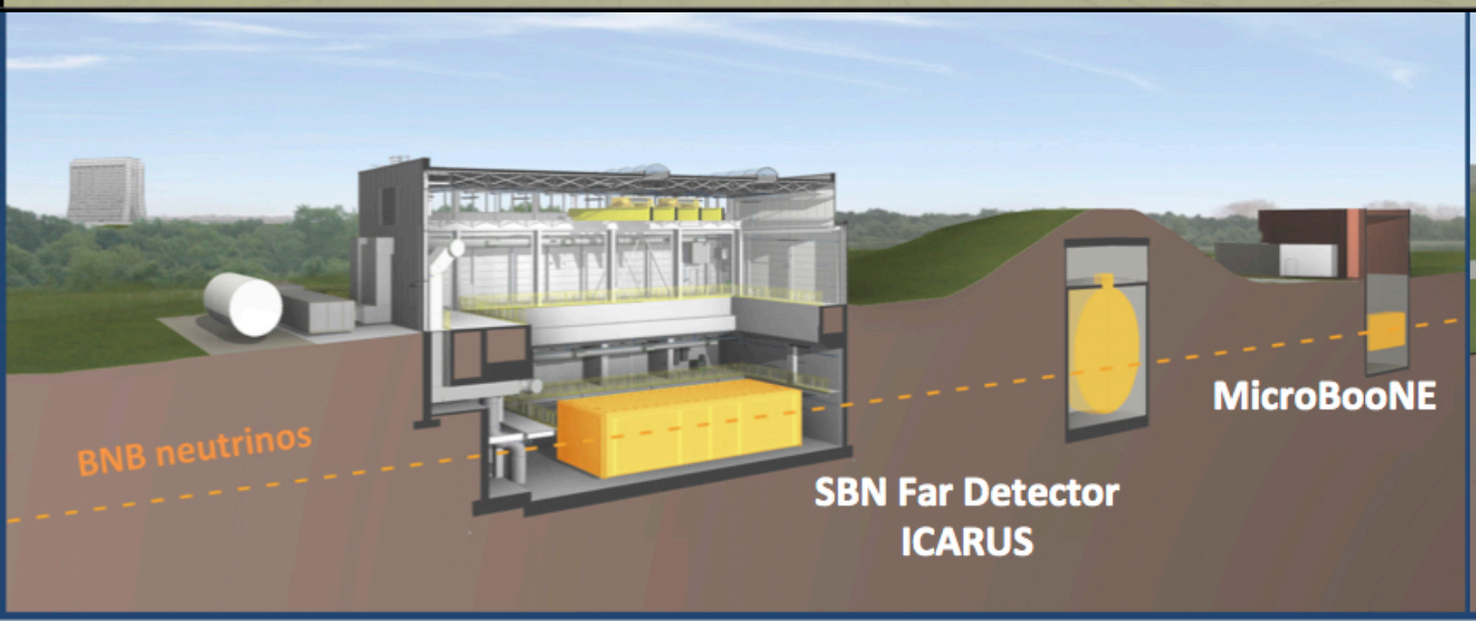
Will cover these along with other neutrino beam upgrade possibilities

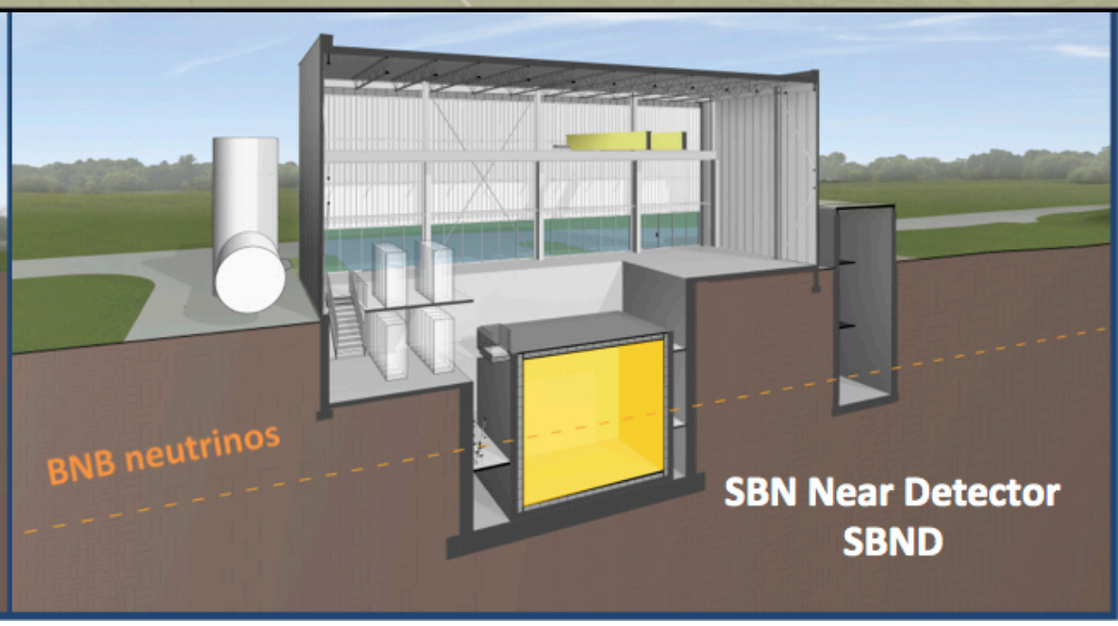


Short Baseline Neutrino (SBN) Program at Fermilab

Search for light sterile ν's with a trio of 100-ton-scale LArTPCs on the Booster Neutrino Beam







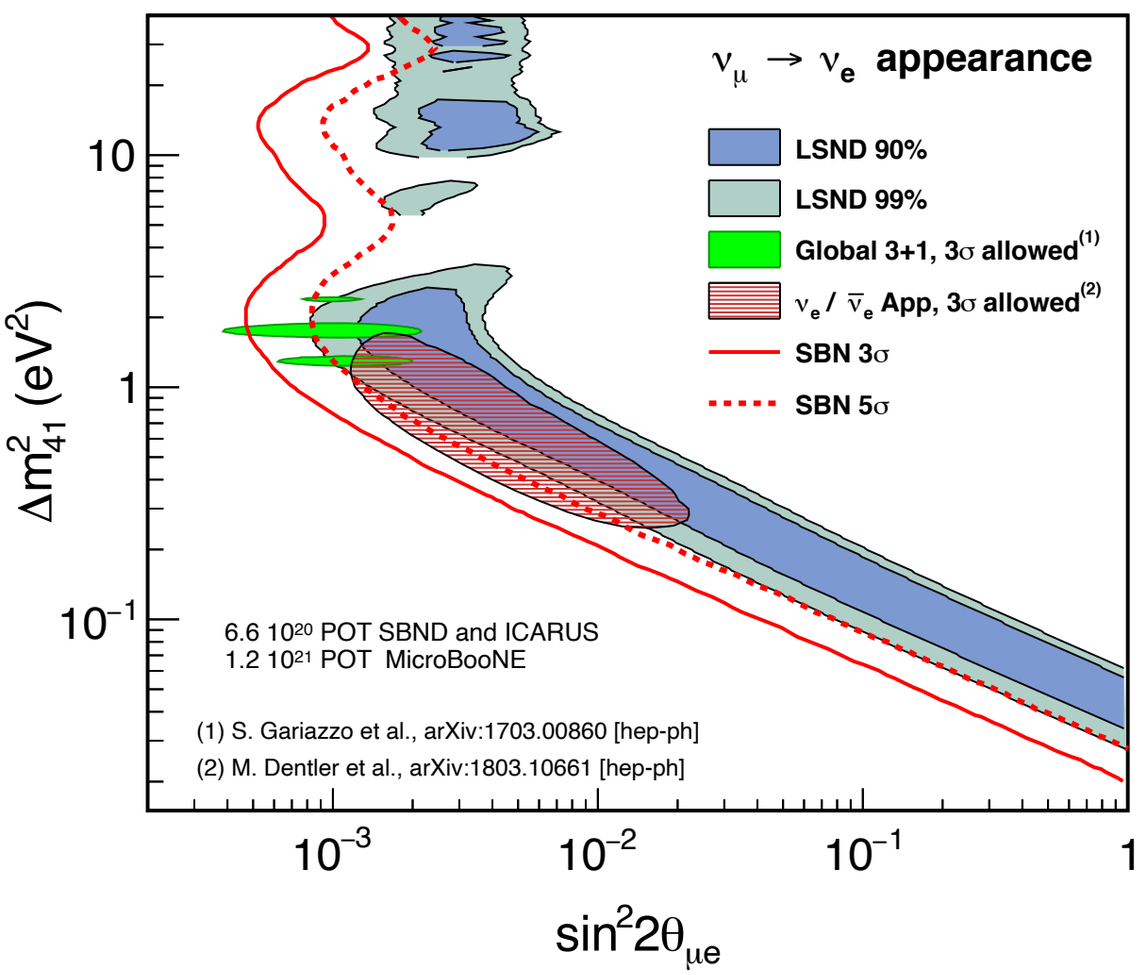
SBN Primary Science Goals

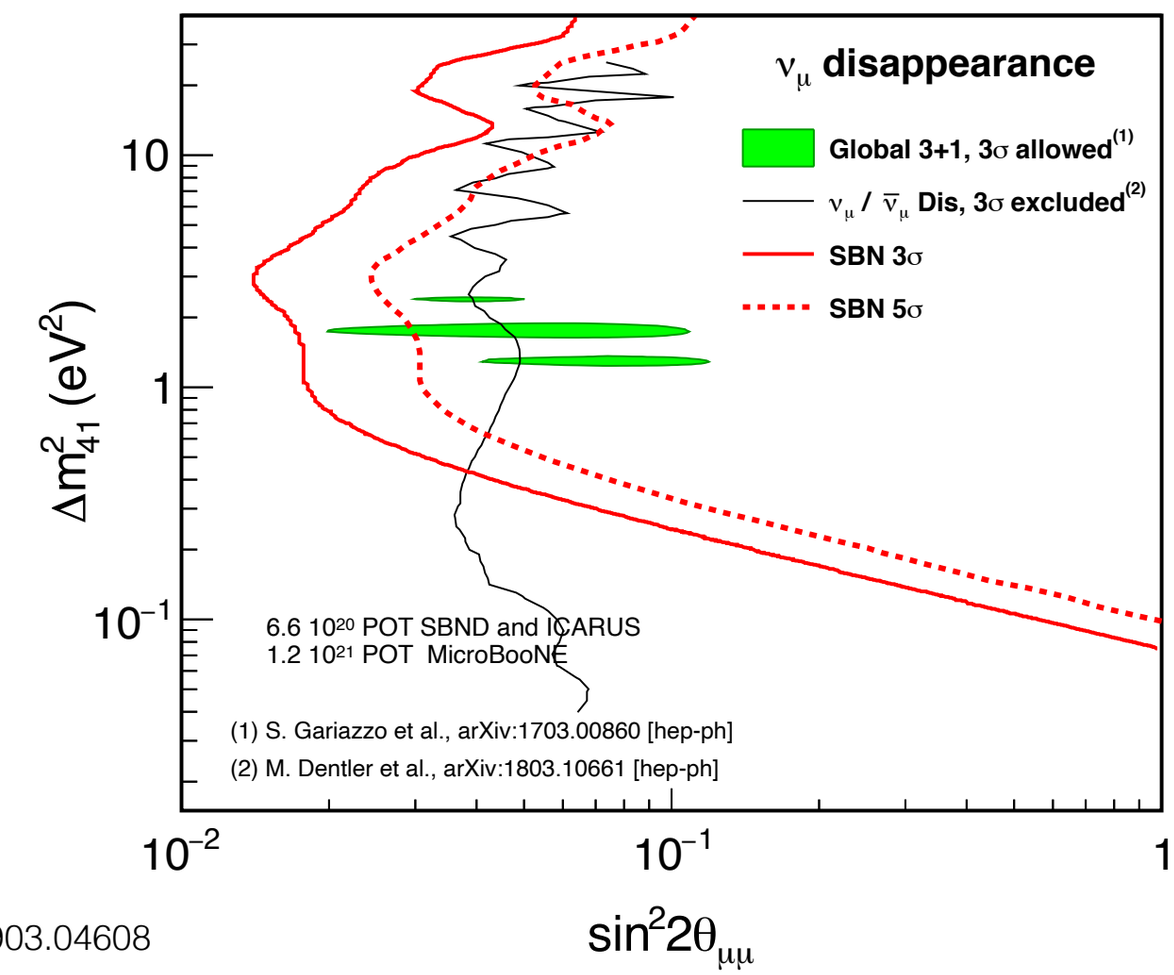
Definitive search for ν_e appearance

- Covers allowed ν_e appearance region for benchmark 3+1 sterile neutrino model at 5σ

Setup simultaneously provides sensitivity to ν_μ disappearance

- Essential to combine with any ν_e appearance to constrain models of new physics

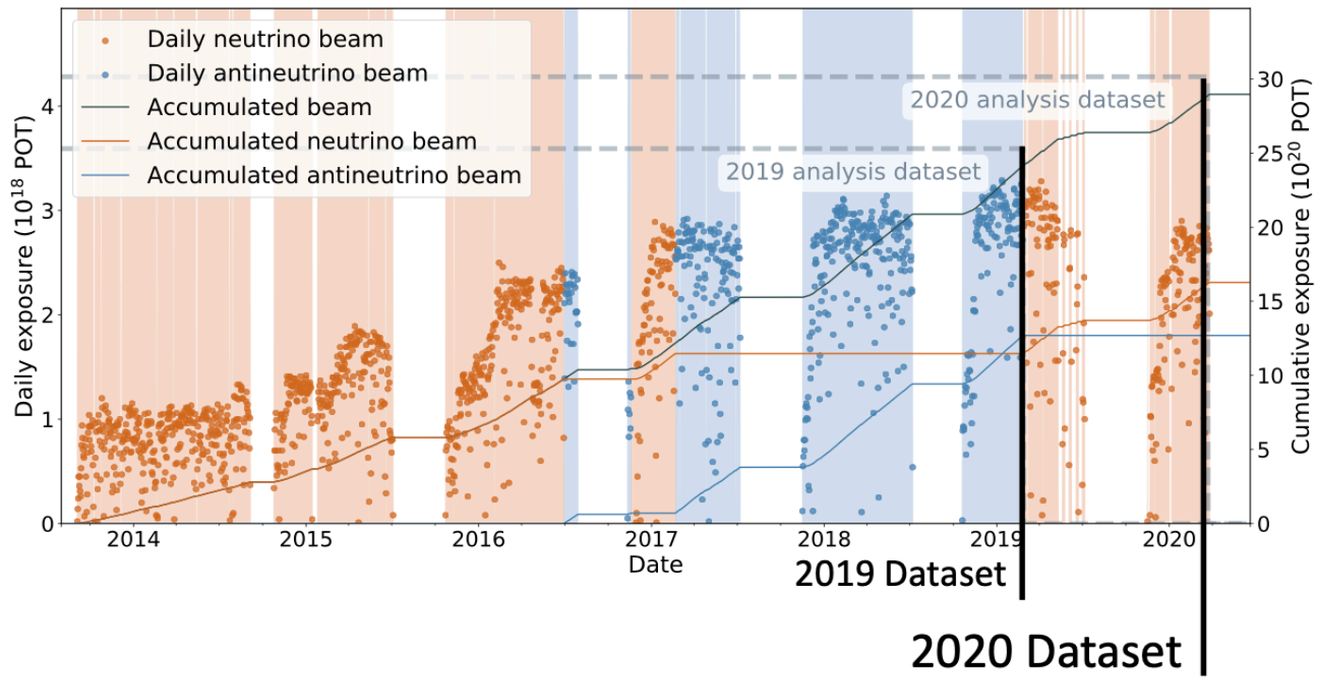




arXiv:1903.04608

NuMI Beam Drives NOvA Long-baseline Neutrino Experiment

The NuMI Beam



- Typically ~670 kW
- Peaks >750 kW
- 50% more neutrino beam data in this analysis

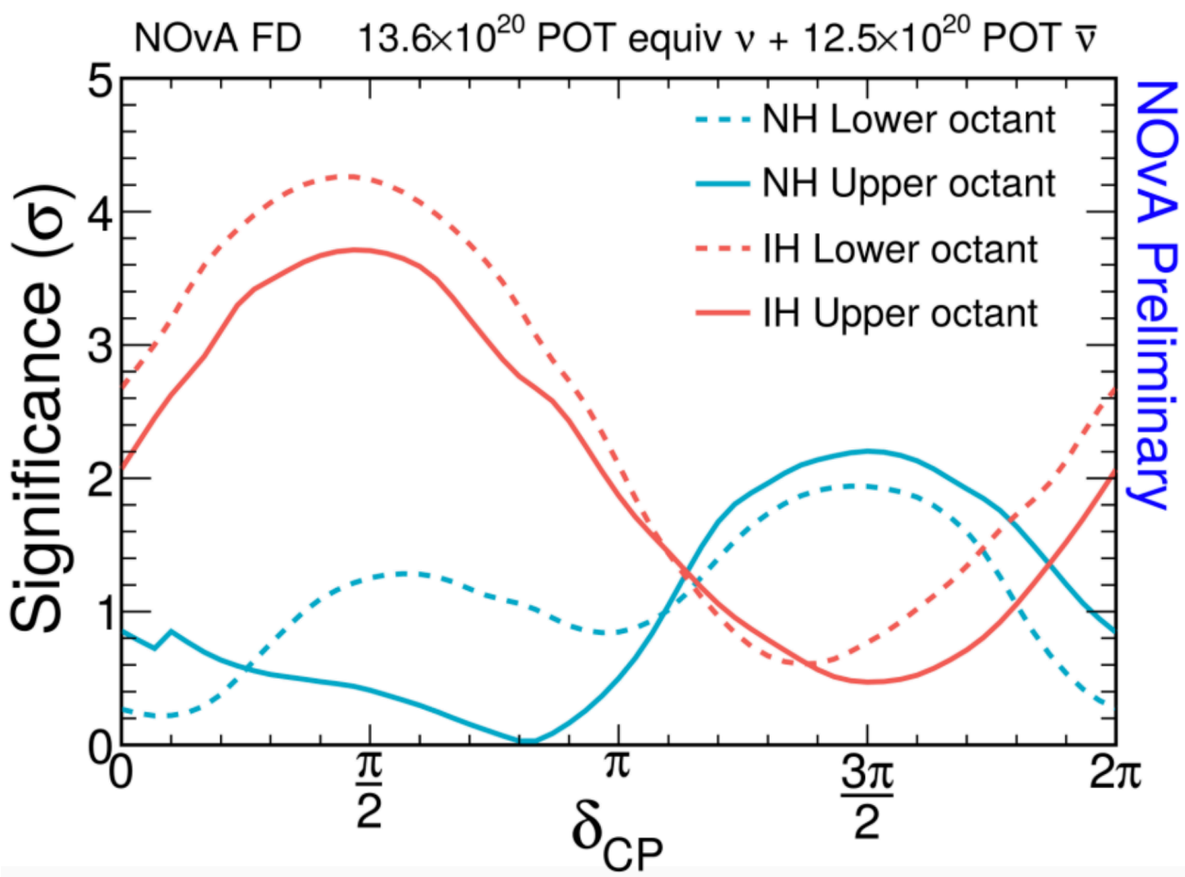
MW-capable target

MW-capable horn

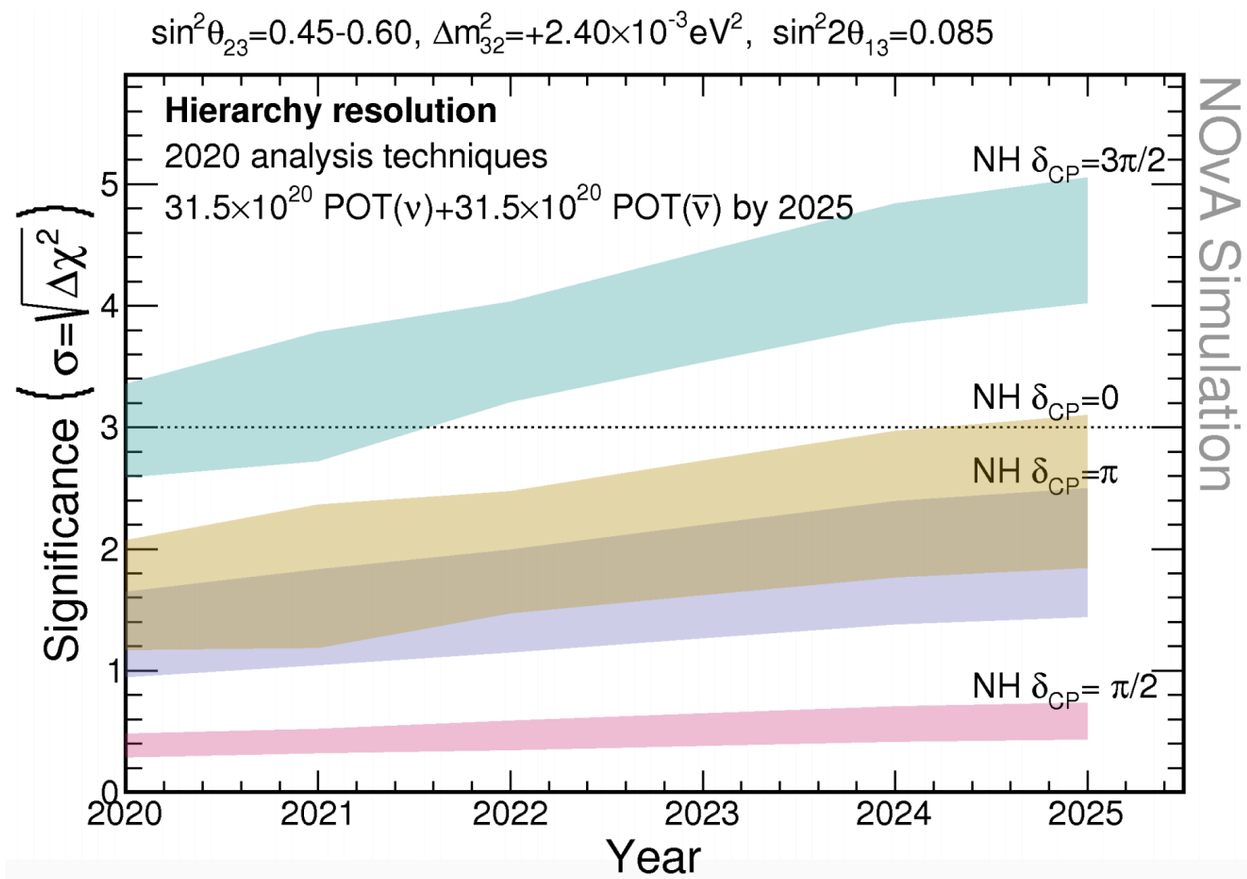
- Working towards 900+ kW
  - Upgrading the NuMI beamline components
  - Allows gradual increase in power up to 850 kW with faster cycle times
  - Early PIP-II upgrades allow 900+ KW

Alex Himmel, Neutrino 2020

NOvA Summer 2020 Results and Projections



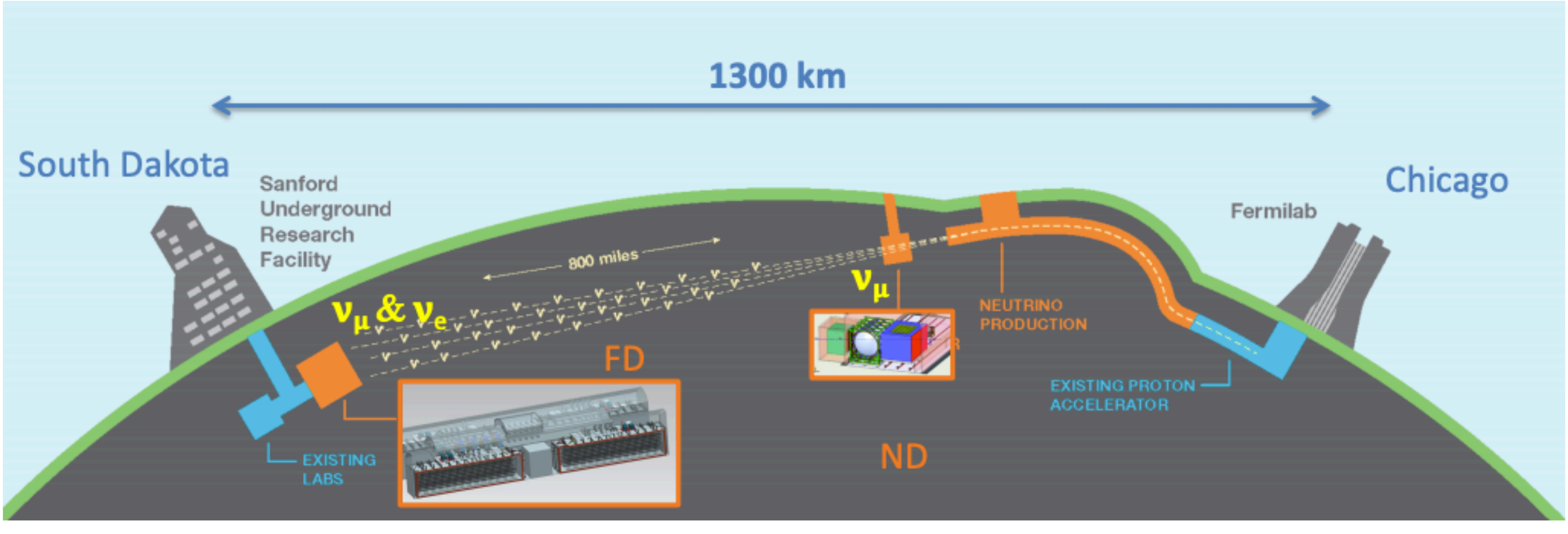
Combined neutrino and antineutrino oscillation fit



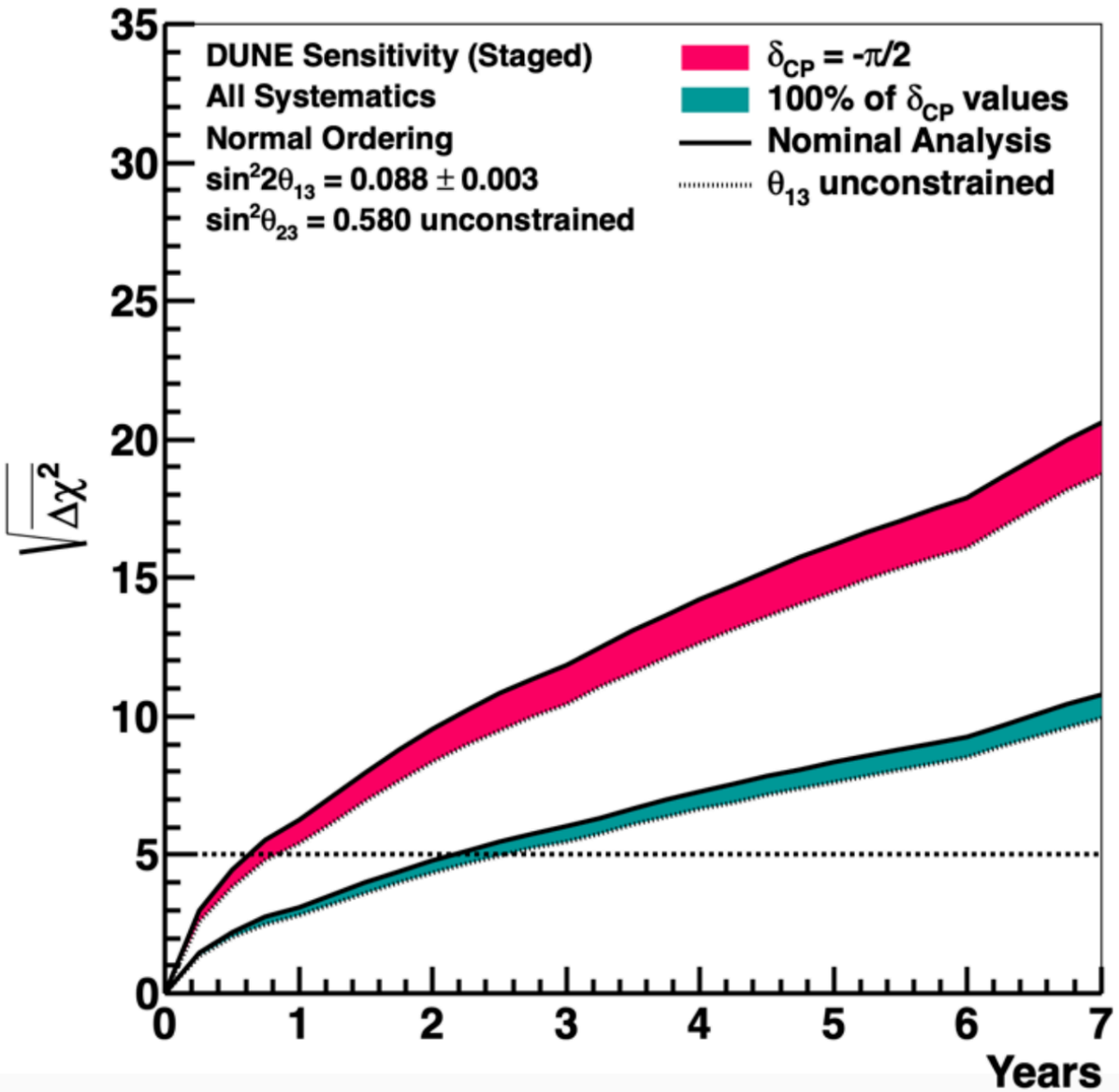
With accelerator upgrades and increased data statistics up until 2025 when NuMI beam is turned off

LBNF/DUNE Drives Fermilab's Accelerator Upgrades

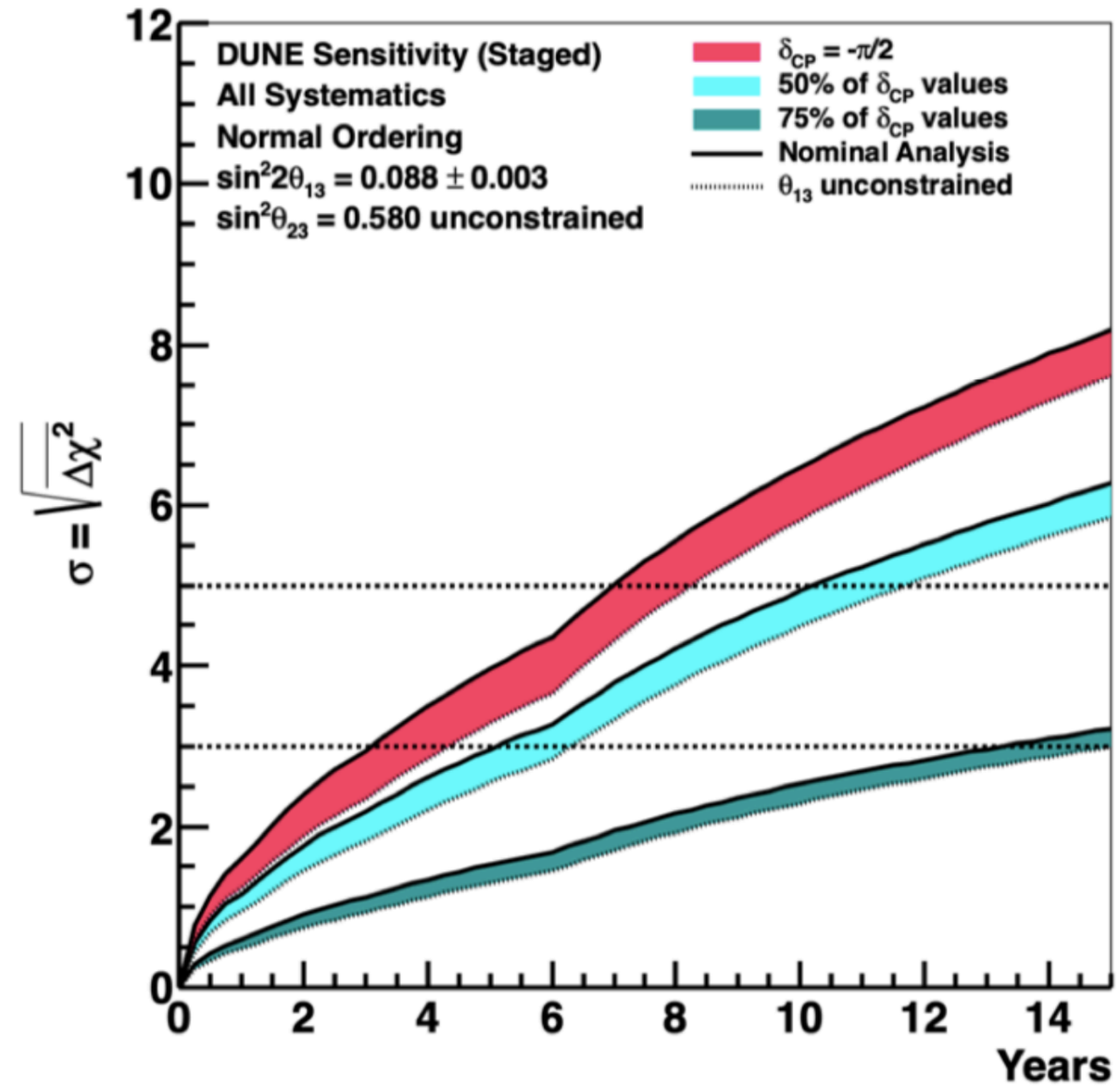
- Massive underground Liquid Argon Time Projection Chambers
  - Fiducial mass > 40 kton
- Near detector to characterize the beam
- Neutrinos & antineutrinos provided by high-power, wide band proton beam
  - **1.2 MW from day one; upgradeable to 2.4 MW (related to P5 recommendations)**



DUNE Physics Reach

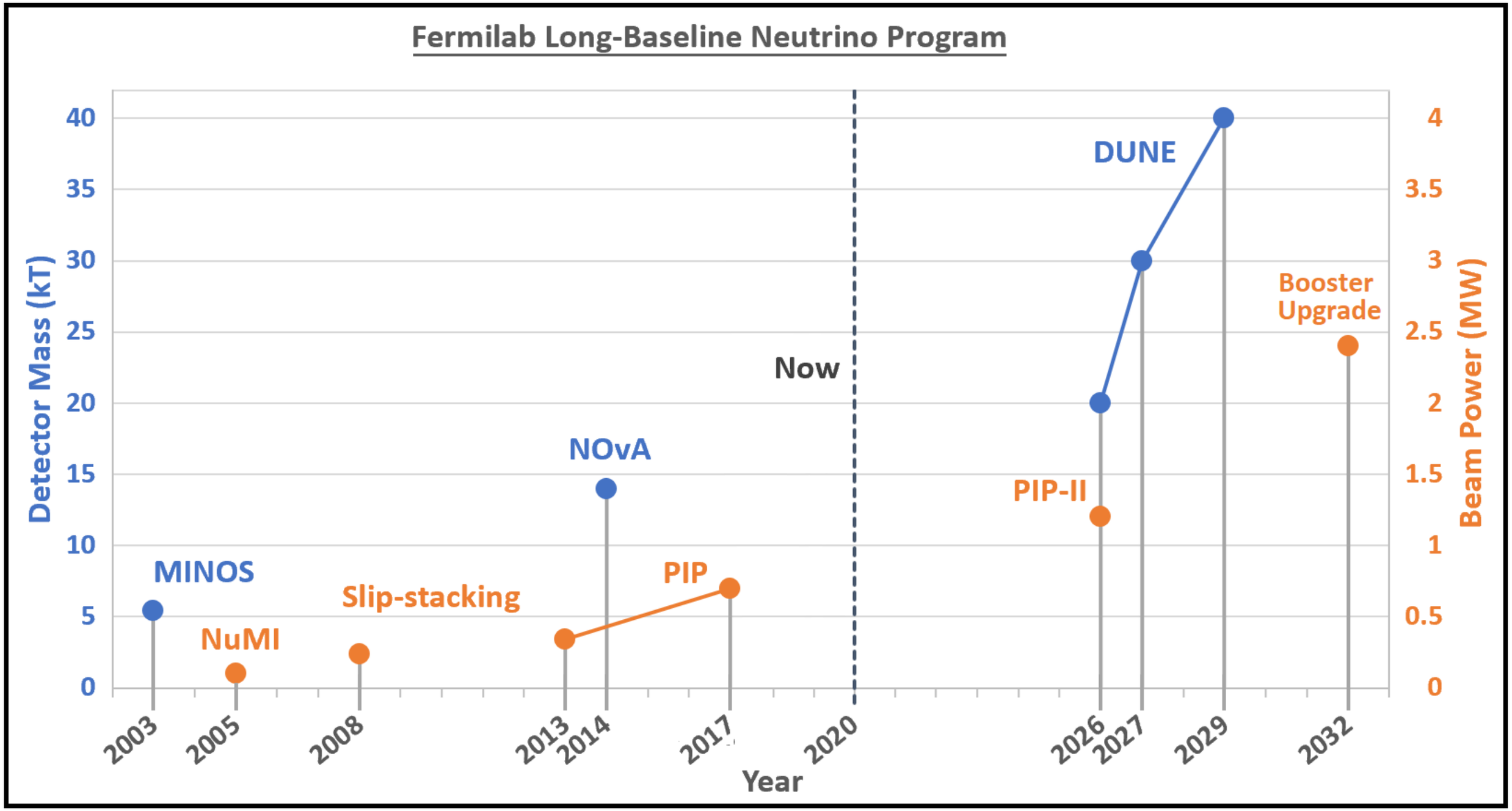


Mass ordering sensitivity



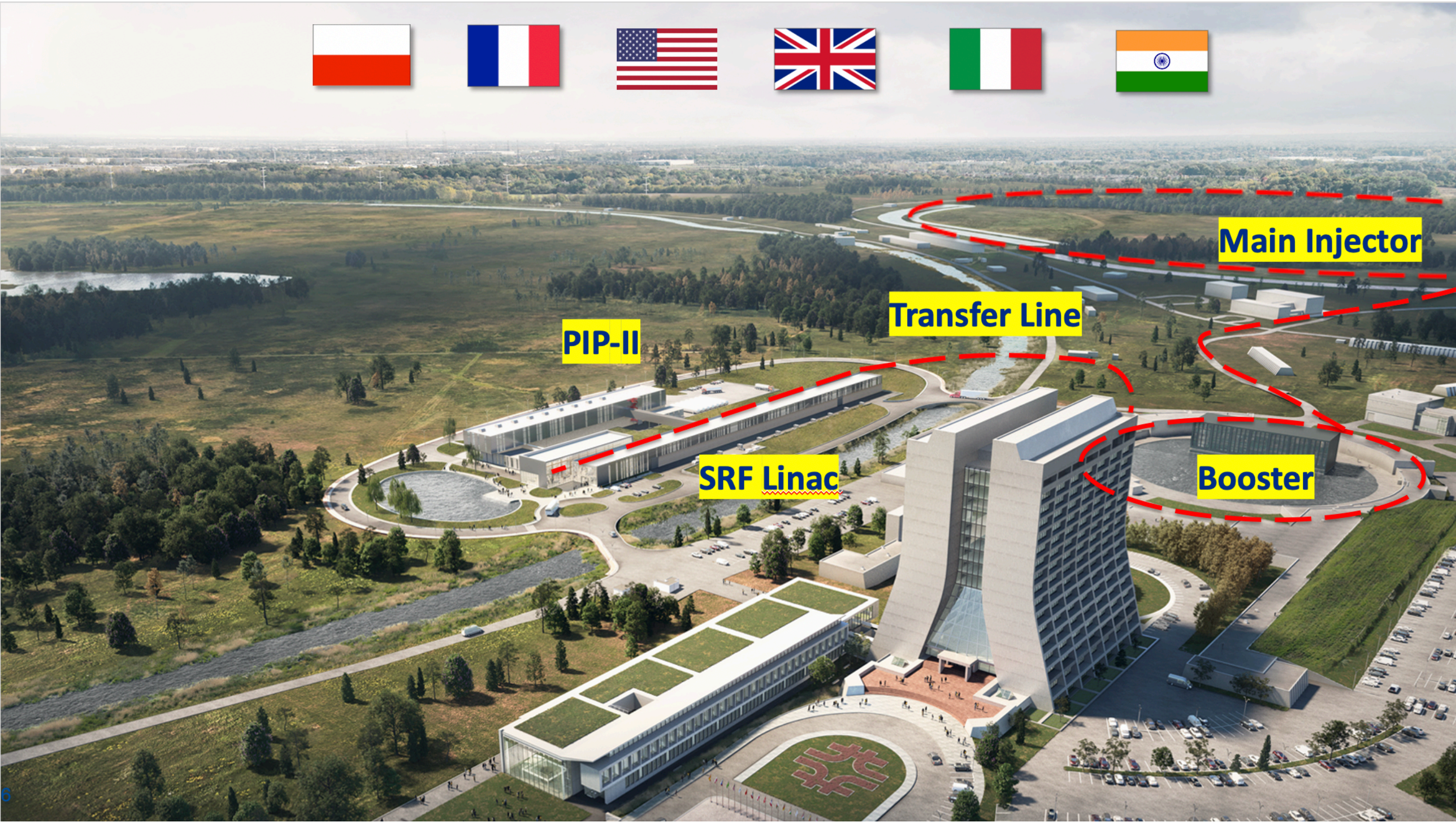
CP violation sensitivity

DUNE Sensitivity Staging Assumptions



Evolution of Fermilab Accelerator Complex with PIP-II

Evolution of Fermilab Accelerator Complex with PIP-II



PIP-II Key Metrics

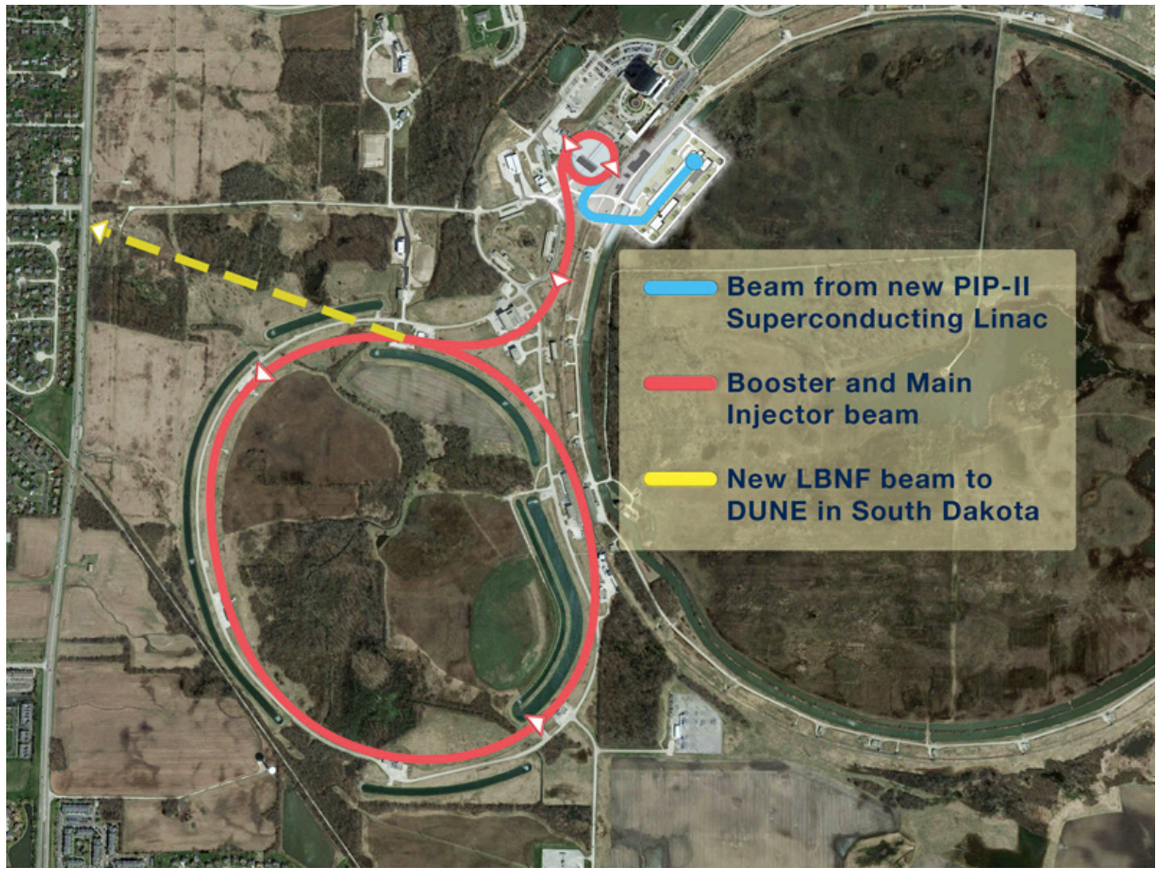
Linac Injection into Booster	PIP-II	Current Performance
Delivered H- Beam Energy	800 MeV	400 MeV
Particles per Linac Pulse	6.7×10^{12}	4.7×10^{12}
Average Beam Current in Pulse	2 mA	25 mA
Pulse Length	550 μs	30 μs
Pulse Repetition Rate	20 Hz	15 Hz

Main Injector	PIP-II	Current Performance
Beam Energy	60-120 GeV	120 GeV
Cycle time	1.2 sec	1.33 sec
Beam Power (60 - 120 GeV)	1.1 - 1.2 MW	0.75 MW (@120 GeV)

Potential Upgrades		
Upgrade potential	2.4 MW	

PIP-II will support a world-leading neutrino program @ FNAL

- Expected LINAC commissioning in FY27
  - Ready for baselining this year
- Will be among the highest-power ~GeV proton beams in the world
- Key high-level metrics for SC LINAC:
  - Capable of 2 mA @ 800 MeV (1.6 MW)
  - **DUNE only uses 1.1% of this beam to achieve its physics goals**
  - See Eduard Pozdeyev's talk at the RF townhall
- How can we best leverage this advanced beam facility to search for new physics?



Fixed-Target Searches for New Physics with O(10 GeV) Proton Beams at Fermi National Accelerator Laboratory

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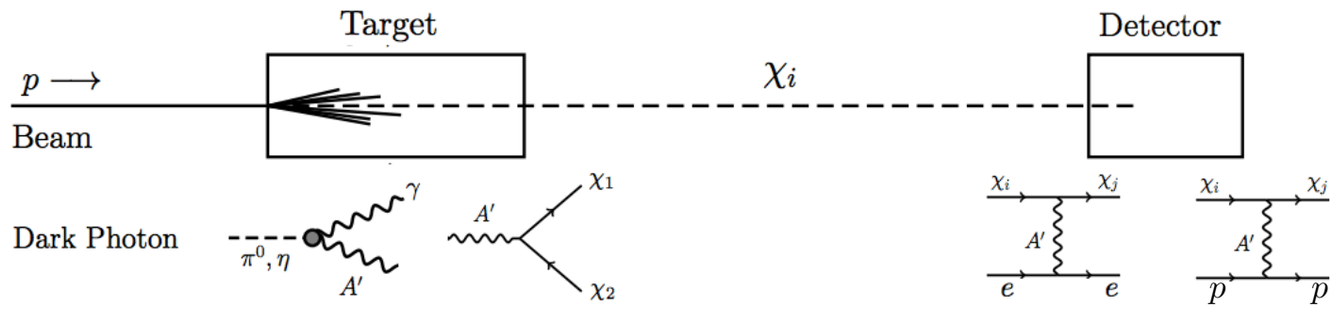
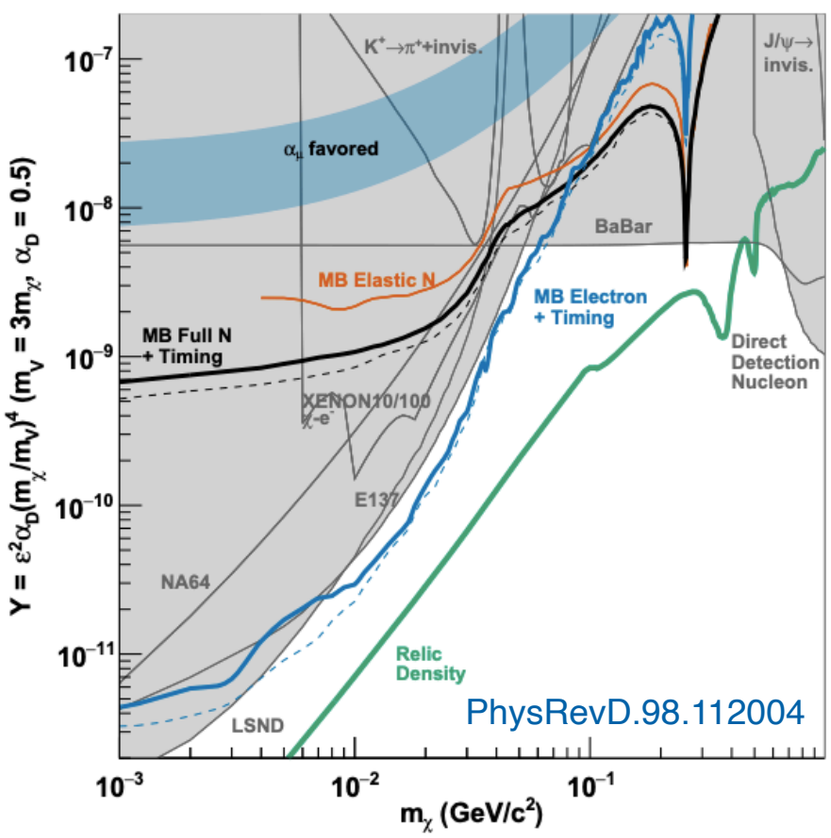
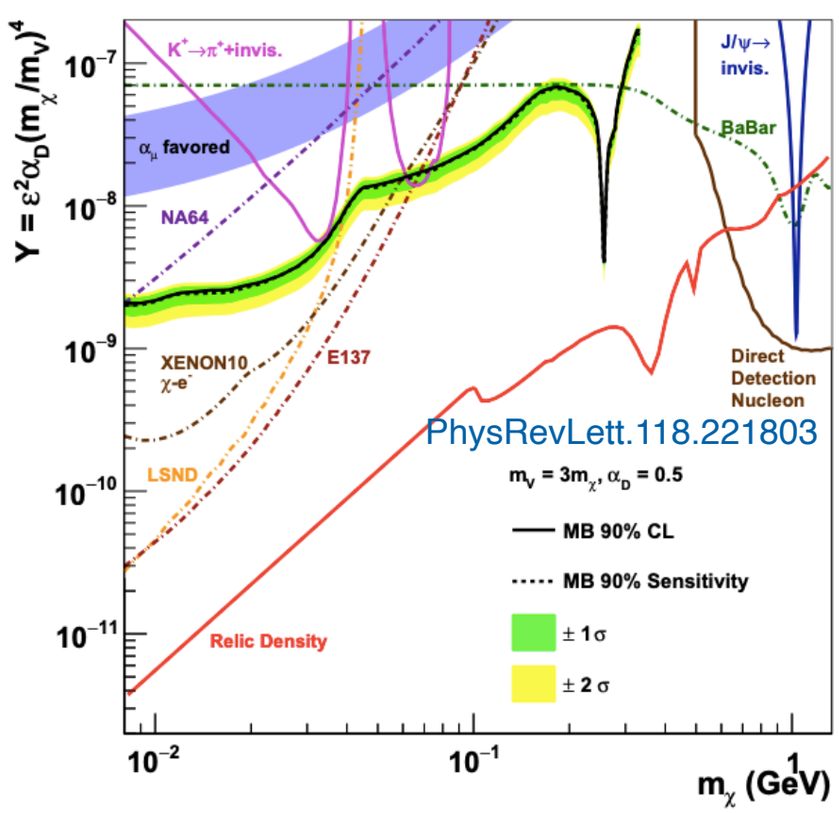
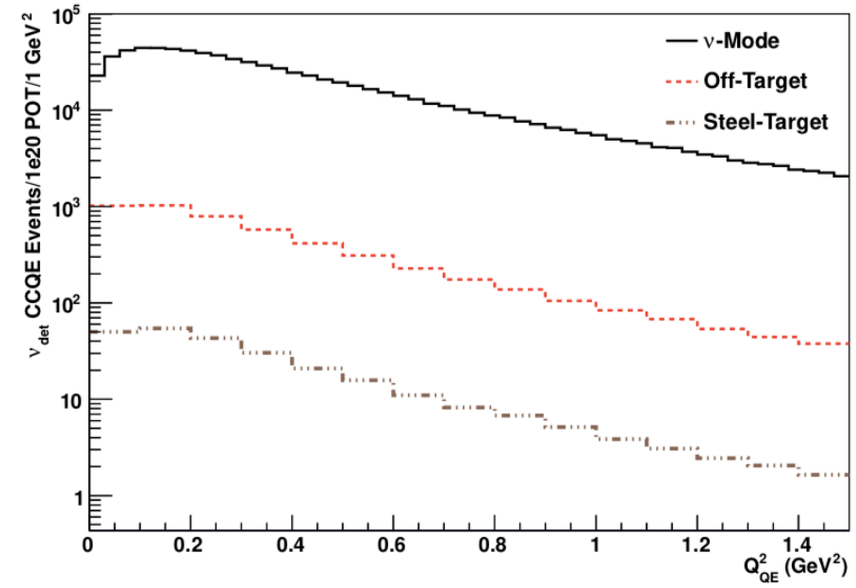
Dark Sector (DS) Searches on the Booster Neutrino Beamline (BNB)

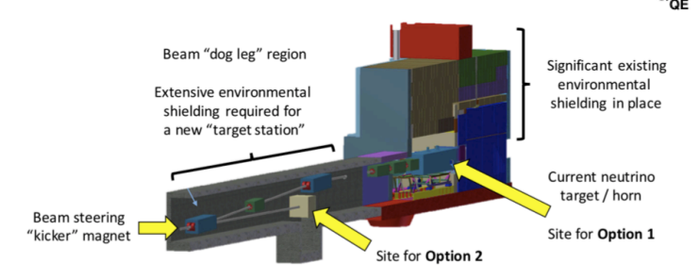
MiniBooNE-DM pioneered accelerator-based searches for benchmark models such as vector portal dark matter (DM) with a light U(1) gauge boson that kinetically mixes with the photon by running off target in beam dump mode





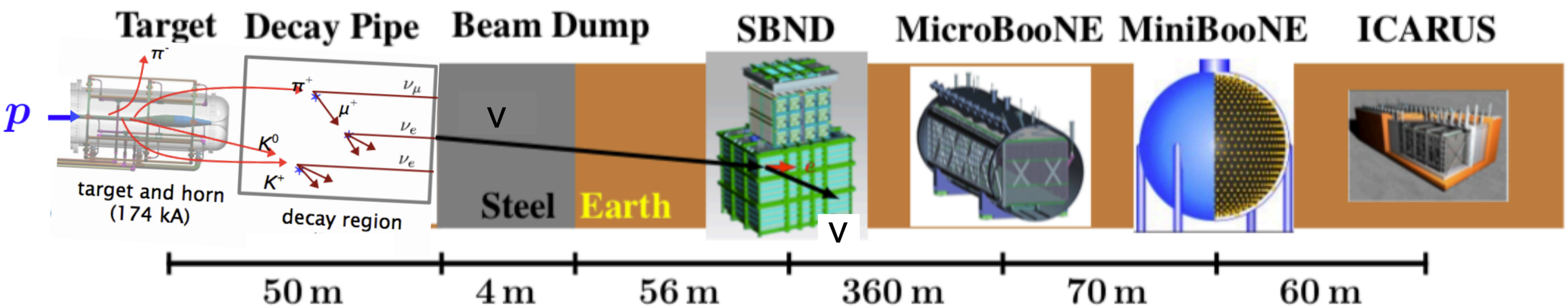






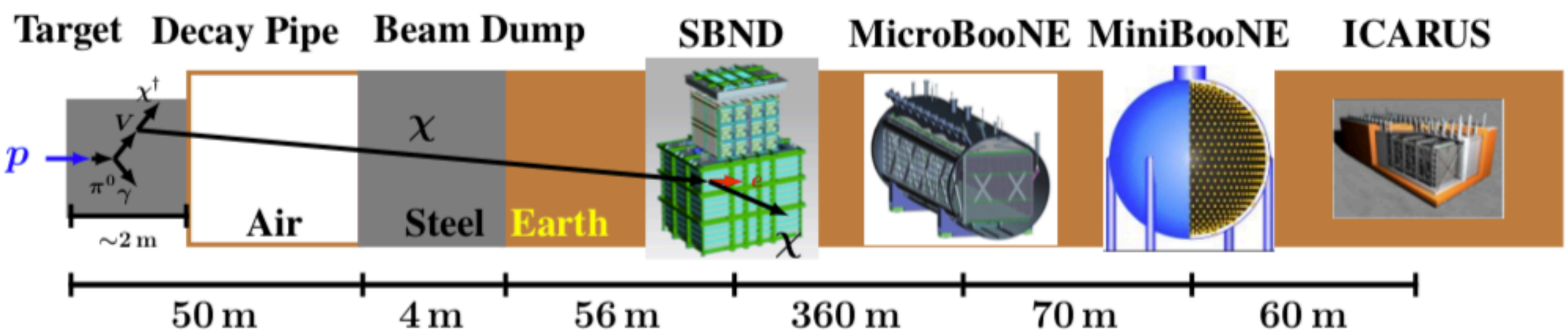
Short Baseline Neutrino program integration

Current short-baseline neutrino program uses horn-focused, decay-in-flight neutrino beam:



→ Currently at 35 kW, but we can imagine a similar setup with much higher intensities

Impinging proton beam on absorber enables DS search program:



→ With kicker magnets and second target station, can run concurrently with the above

Booster Beam Line in the PIP-II Era

- PIP-II enables higher power to be delivered to the BNB concurrent with LBNF
- The BNB neutrino target and horn have a power limit of 35 kW, but a new dedicated beam dump could be designed to handle increased power
- We consider a light dark matter search in SBND 100 m downstream of a dedicated beam dump receiving 80 kW of beam power
- In a five year run this would result in 6×10^{21} Proton on Target (POT) and achieve an order of magnitude better sensitivity to a benchmark vector portal scalar dark matter model than the current MiniBooNE dark matter sensitivity due to the reduced neutrino background from the dedicated beam dump, the detector's close proximity to the beam dump, and higher protons on target.

DM Event Sensitivities

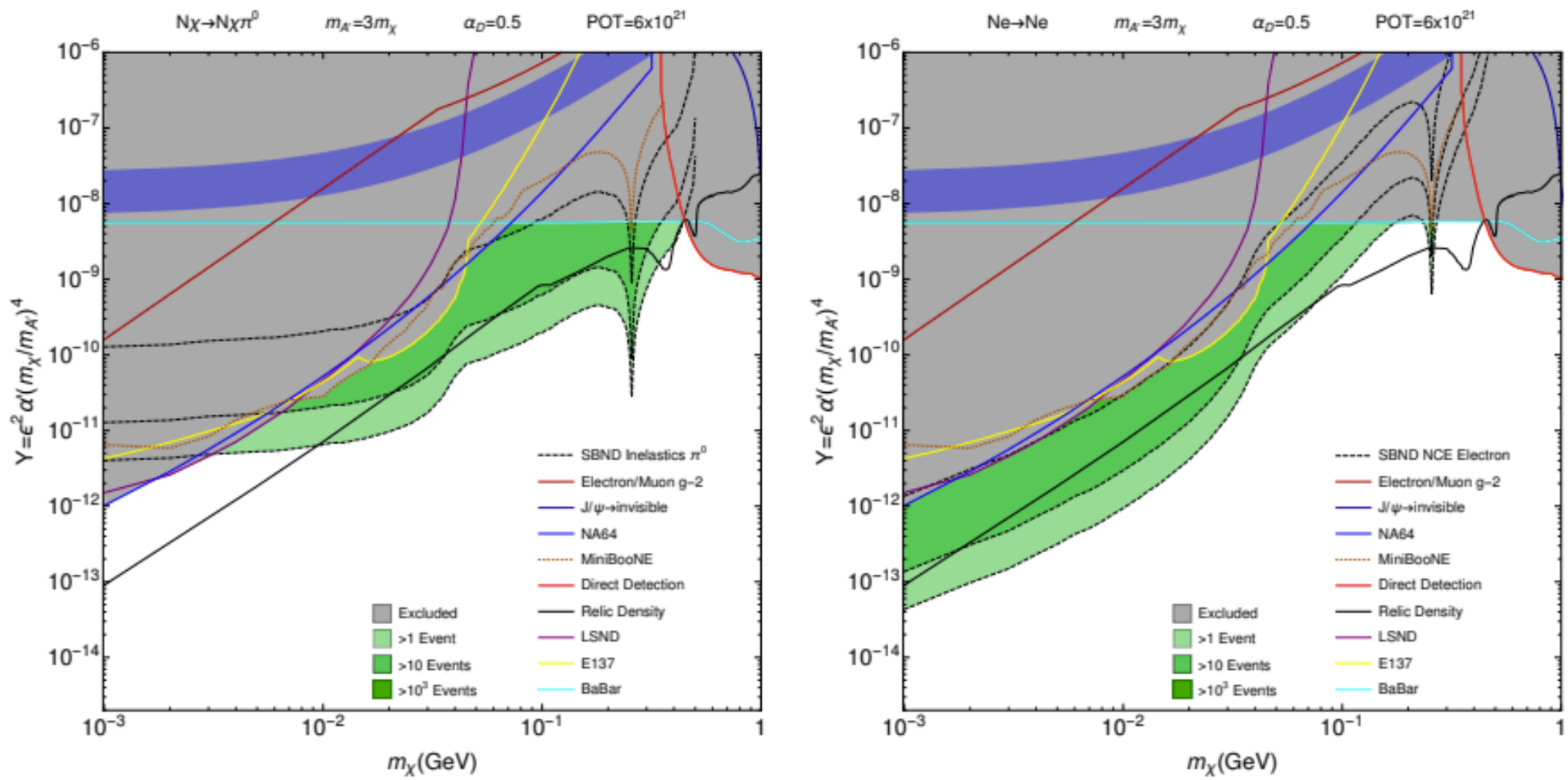


Figure 1: Regions of relic abundance parameter (mixing strength) Y vs. dark matter mass m_χ for 6×10^{21} POT that could be achieved in a five year run with dedicated proton beam dump medium energy running in the PIP-II era. Left is the signal sensitivity for NCπ^0 and right for NC-electron scattering with the SBND detector at 100 m from the dedicated beam dump. Both panels show regions where we expect 1–10 (light green), 10–1000 (green), and more than 1000 (dark green) scattering events. The solid black line is the scalar relic density line that can be probed.

- Although DM search highlighted here, can also imagine how to use additional beam power on a second or upgraded target station for neutrino physics

Fixed-Target Searches for New Physics with O(1 GeV) Proton Beams at Fermi National Accelerator Laboratory

M. Toups,[1,*] R.G. Van de Water,[2,*] Brian Batell,[3] S.J. Brice,[1] Patrick deNiverville,[2] Jeff Eldred,[1] Roni Harnik,[1] Kevin J. Kelly,[1] Tom Kobilarcik,[1] Gordan Krnjaic,[1] B. R. Littlejohn,[4] Bill Louis,[2] Pedro A. N. Machado,[1] Z. Pavlovic,[1] Bill Pellico,[1] Michael Shaevitz,[5] P. Snopok,[4] Rex Tayloe,[6] R. T. Thornton,[2] Jacob Zettlemoyer,[1] and Bob Zwaska[1]

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PIP-II is simultaneously capable of driving a MW-class GeV-scale proton fixed target program and a 2.4 MW beam line for DUNE

- Physics Opportunities At Such a Facility

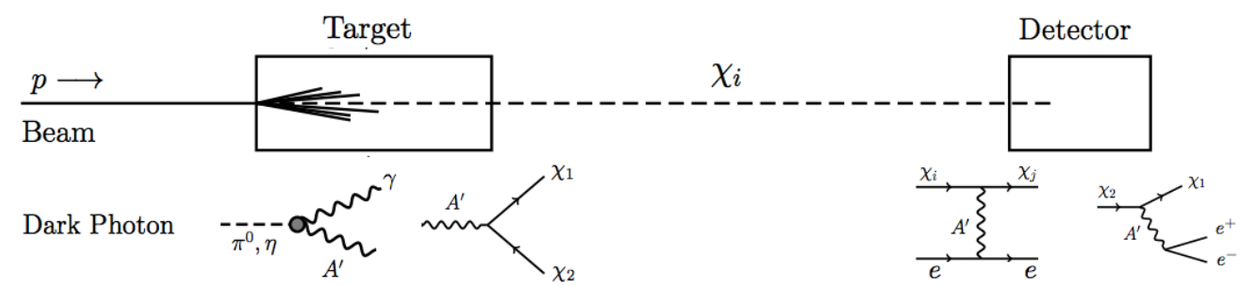
  - Light DM / DS Searches
    - Decay and/or scattering signatures

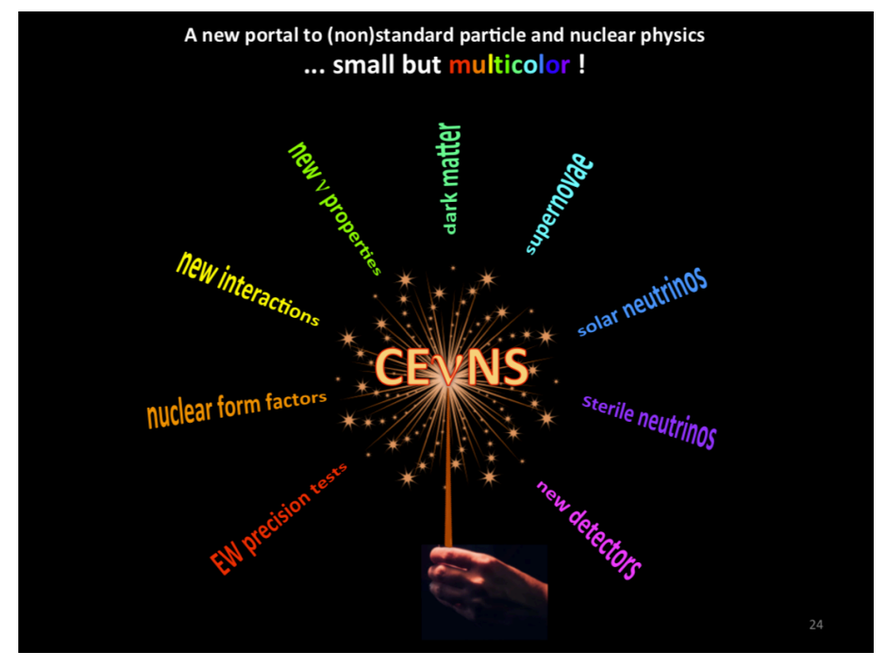
  - Light Sterile Neutrino Searches
    - Both appearance and disappearance possible

  - Coherent elastic neutrino-nucleus scattering (CEvNS)
    - Provides new way to search for LDM and sterile neutrinos

  - Searches for Non-standard interactions (NSIs), tests of the Standard Model

  - Neutrino Cross Section Measurements and more

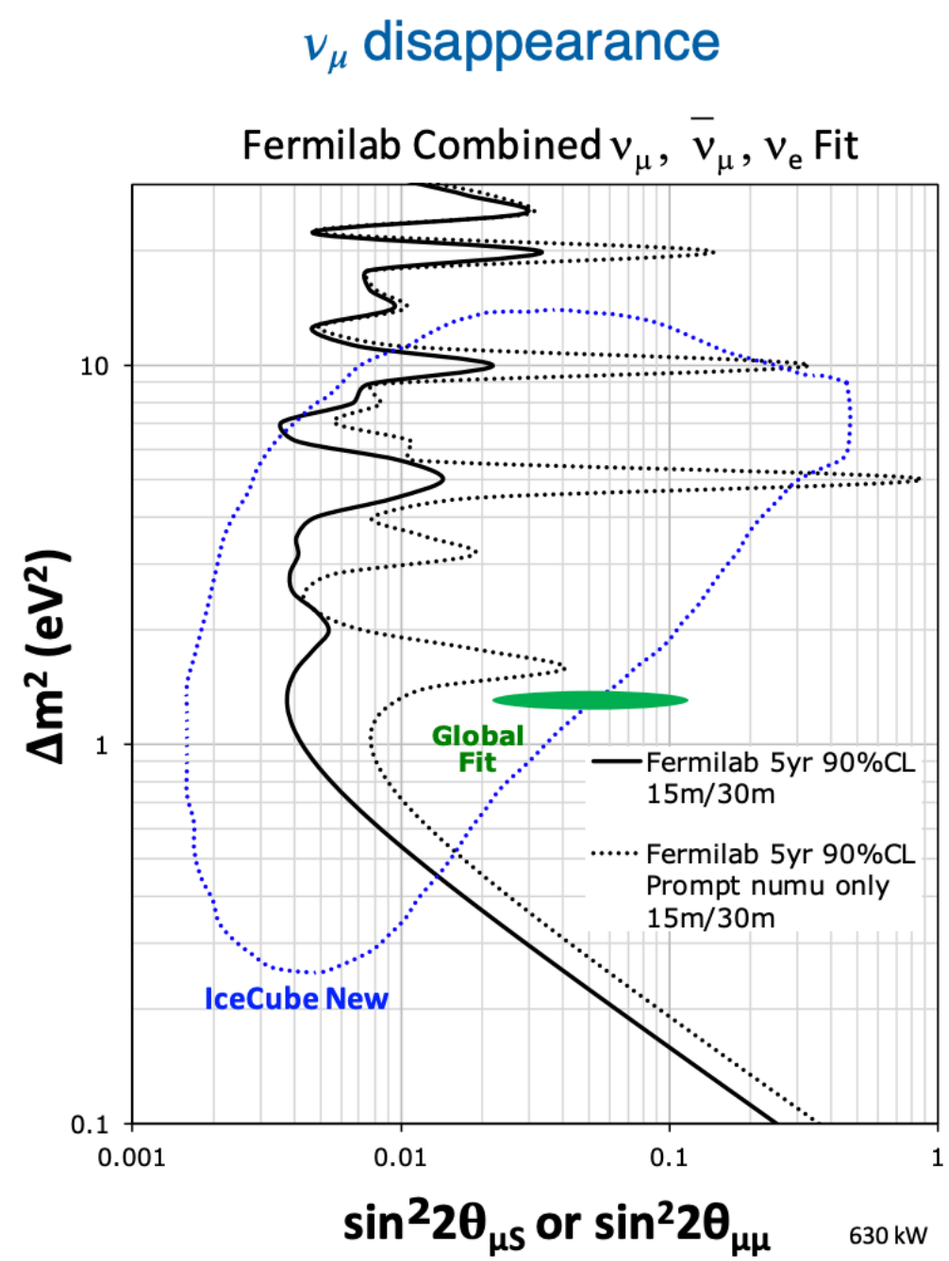




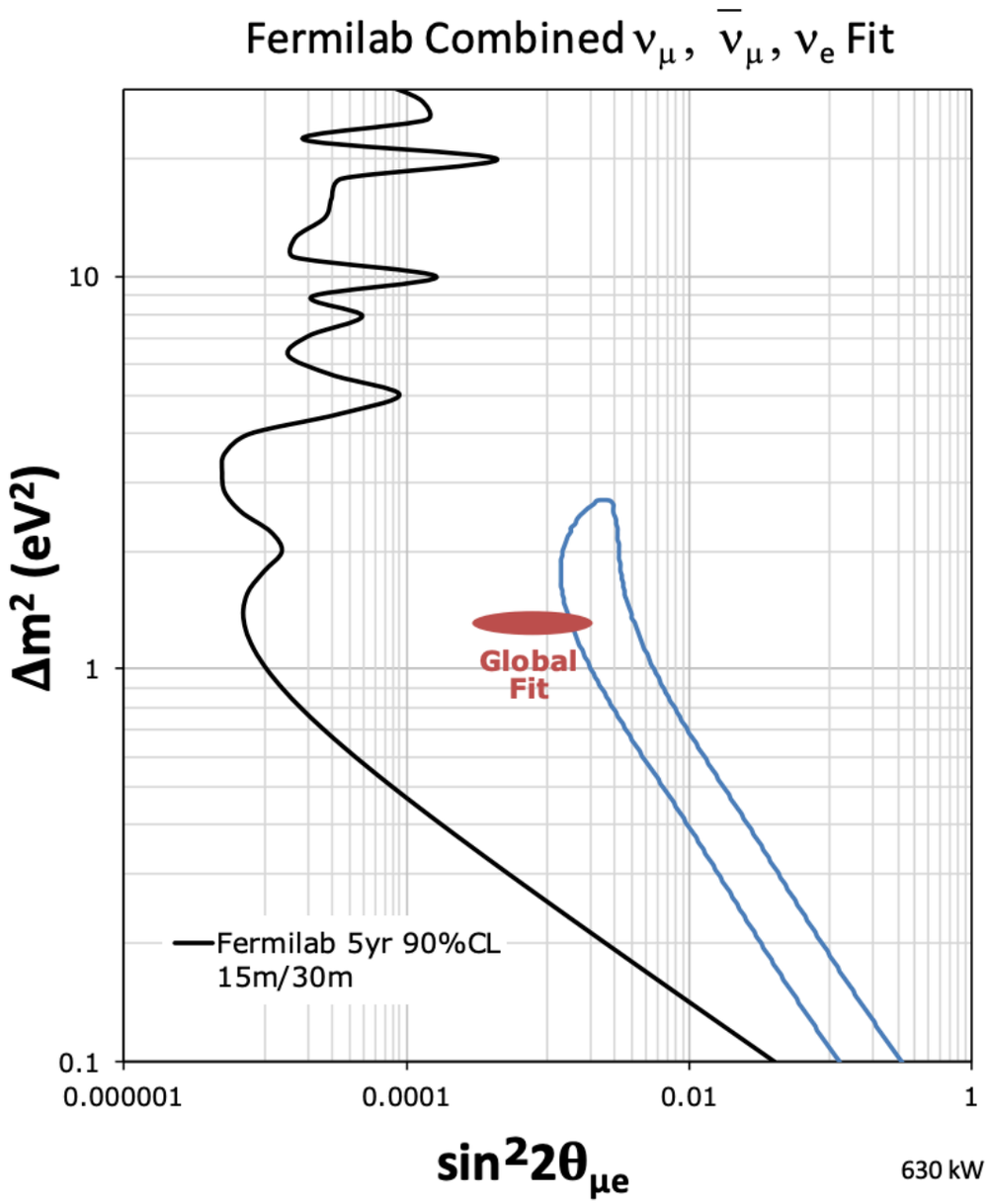
- Need pulsed beam to fully probe these opportunities

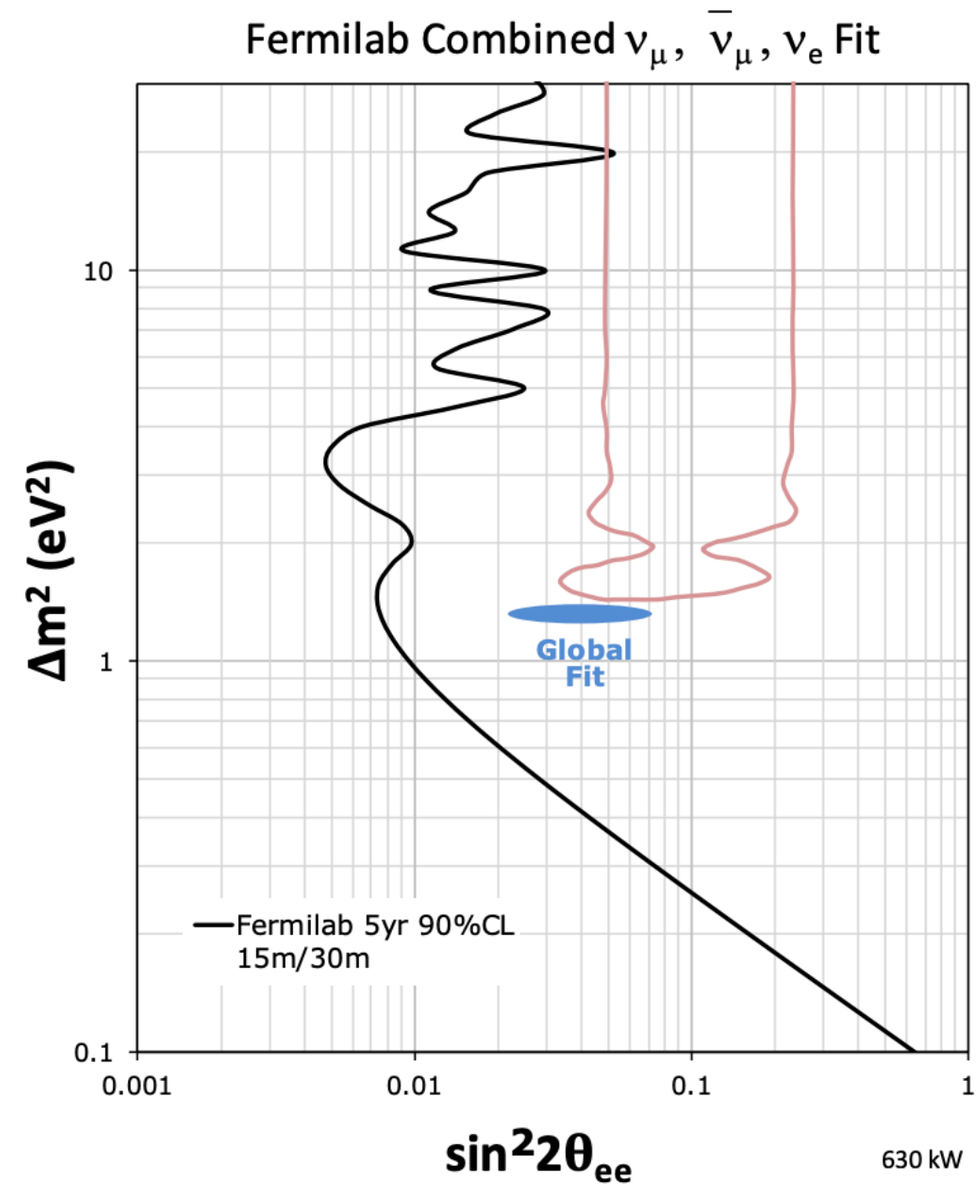
CEvNS-based Sterile Neutrino Search (I)

- Based on 630 kW beam power at 800 MeV with 75% uptime and identical O(100 ton) LAr detectors off axis, 15 m and 30 m from target
  - Assume 70% efficiency above 20 keVnr threshold and 9% correlated normalization uncertainty between the two detectors
- Beam dump facility can be optimized and designed from the ground-up for HEP (neutron suppression, large detectors, flexible locations)
  - Assume beam-correlated backgrounds reduced to negligible levels and 1:1 signal-to-background for remaining backgrounds



CEvNS-based Sterile Neutrino Search (II)





Assumes one can separate prompt and delayed neutrinos from pion decay-at-rest

FNAL Booster Accumulator Ring

William Pellico, Jeff Eldred, Kiyomi Seiya, CY Tan, C. M. Bhat, Matthew Toups[1], Takahiro Watanabe [2], Richard Van De Water [3], and Chamseddine Benabderrahmane[4]

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Booster Accumulator Ring (BAR) Concept

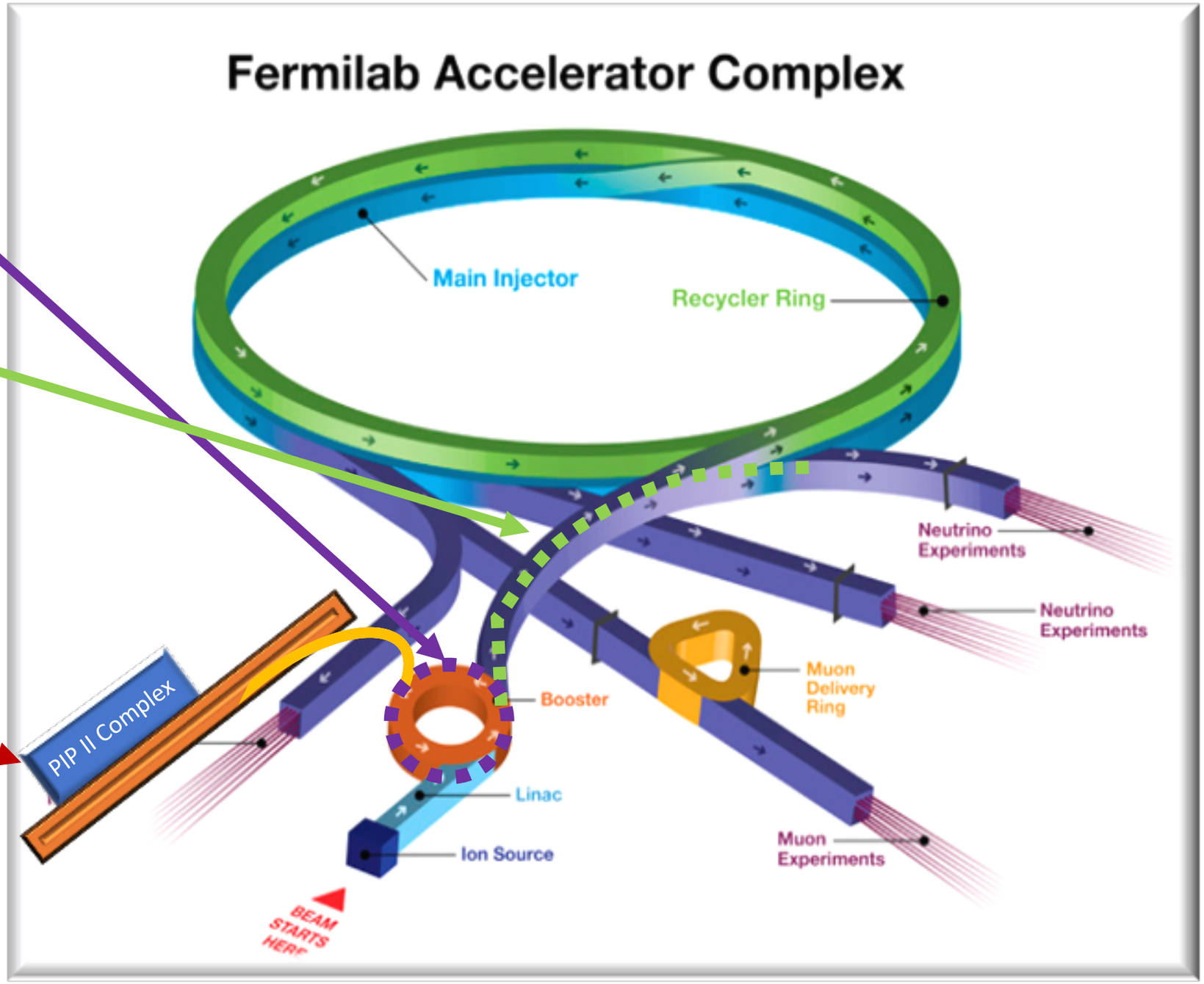
Overview

- A permanent magnet accumulator ring could be built in the Booster enclosure that could greatly benefit PIP II/DUNE program and set FNAL on the path to a large DS program.
- The existing Booster to BNB enclosure will be contain the new 1 GeV line.

Cost and time for this approach is greatly reduced due to synergy to PIP II and present BNB complex.

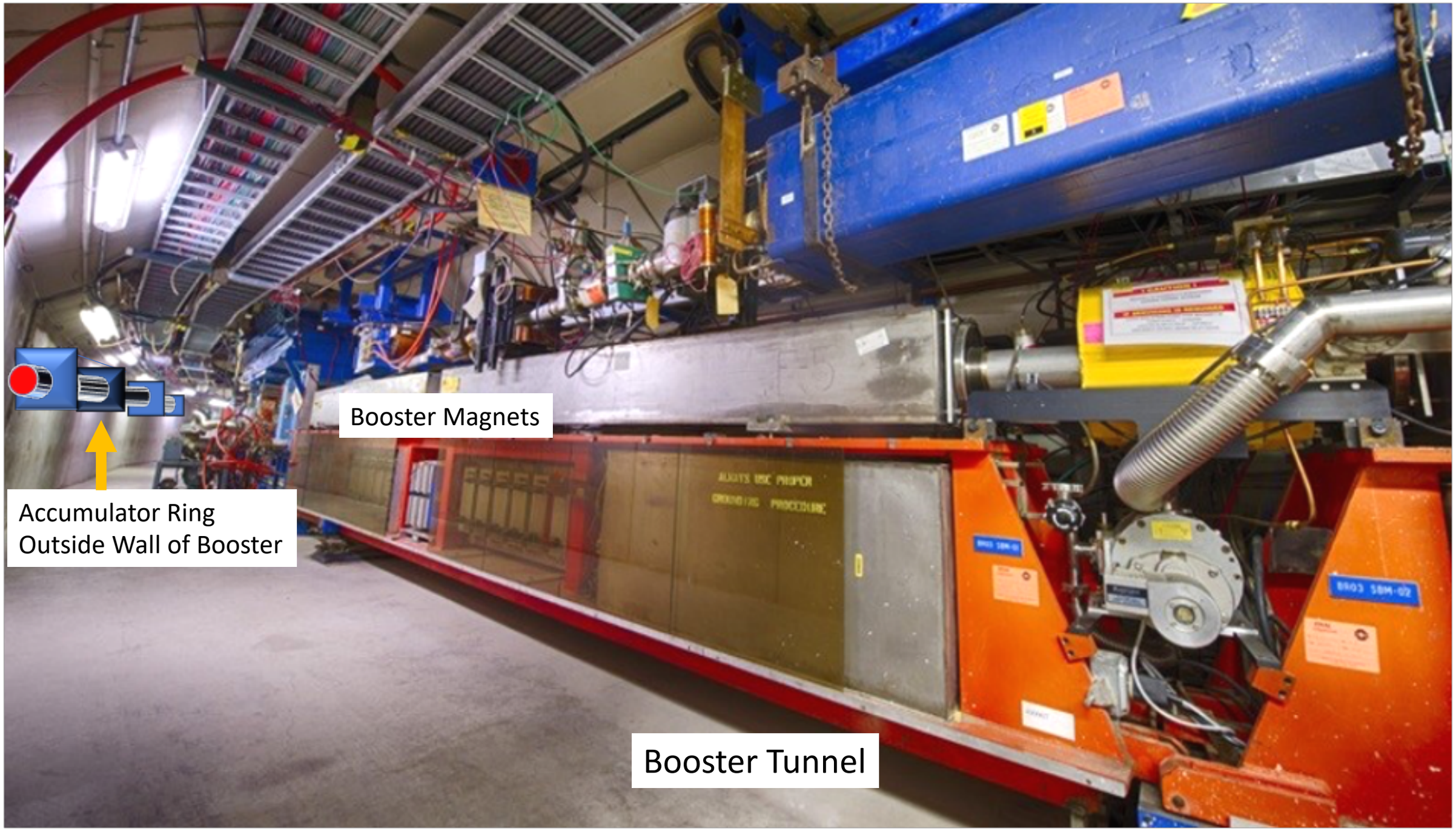
A new 800 MeV line is being designed for the PIP II to Booster Injection. A new accumulator would instead receive the PIP-II linac beam and transfer it to the Booster for DUNE operations.

With the rest of the Linac pulses being used for delivery to the BAR for DS operations.



BAR workshop on Dec. 15: https://indico.fnal.gov/event/46607/

Location Inside Booster Enclosure



BAR Parameters

Hardware

- Aperture: ~3”
- Cycle rate (being explored)
  - Hardware limitations
    - At least 100 Hz
  - Radiation limitations
    - Shielding assessment
- RF Structure(s)
  - System for Booster/DUNE
    - Pulsed
    - 44 MHz
  - System for Dark Sector RF (CW)
    - Bucket loading
    - Barrier bucket
    - Harmonic flattening
    - Compression

Beam

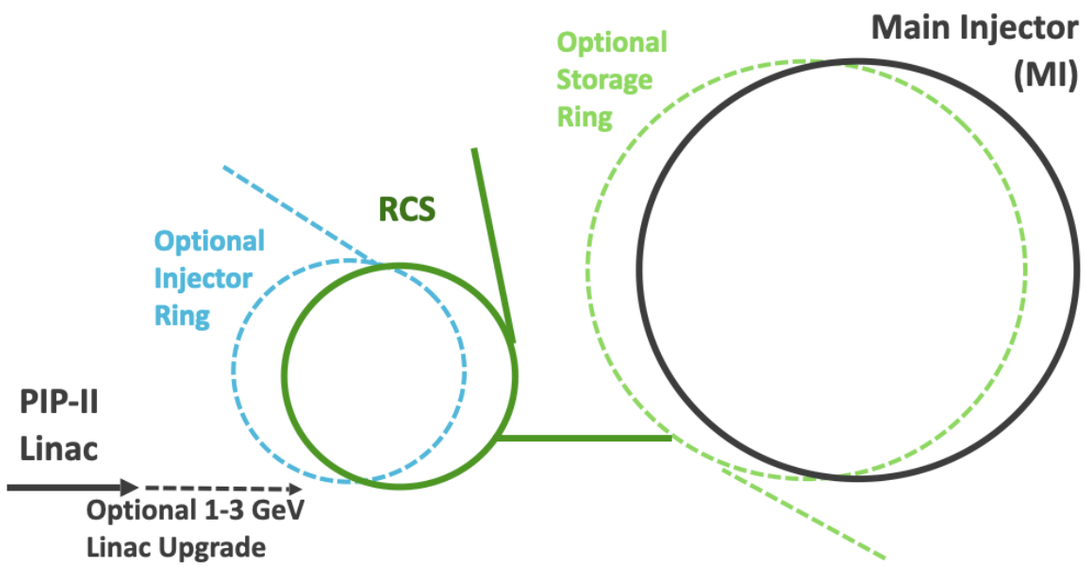
- Base Power: 130 kW
  - 1.0×10^{13} / batch
    - Space charge limitations
    - Painting
    - RF power
  - 100 Hz
- Goal Power: 200 kW
  - 1.5×10^{13} / batch
    - Upper limit TBD
- Pulses
  - Load time: ~1.5 ms
  - Pulse width TBD
    - Goal of 300-400 ns

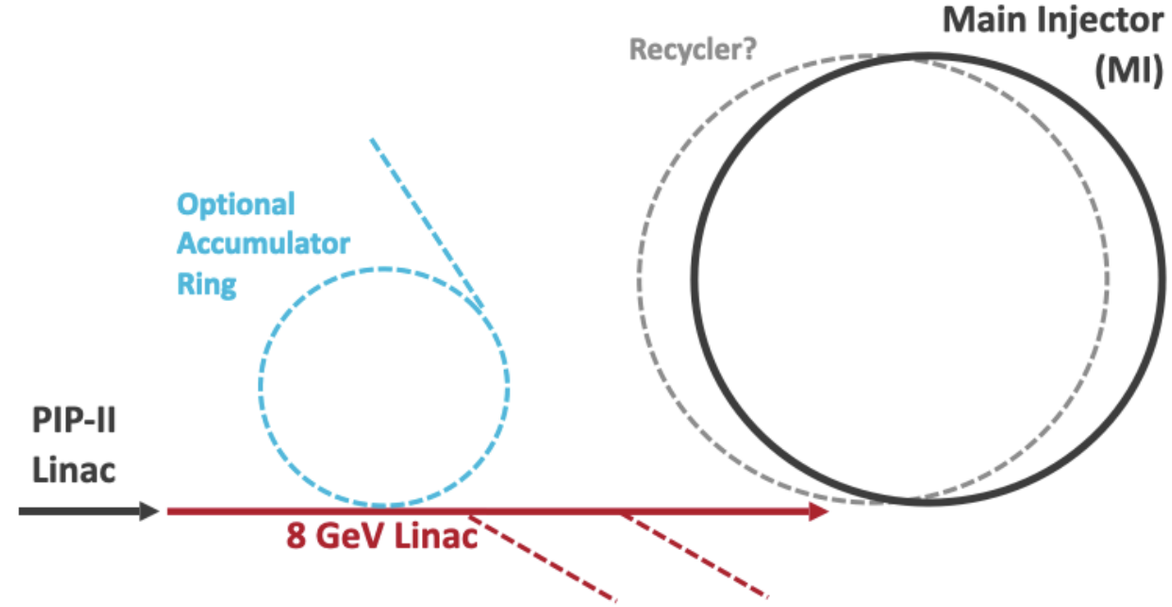
BAR/PIP-II Upgrade

- 1 GeV Injection
  - Design to be upgraded
- Power upgraded
  - Base: 160 kW
  - Goal: 240 kW

Booster Replacement

- Extending beyond PIP-II
  - P5 recommendation is for 2.4MW to DUNE
  - 2.4 MW requires 1.5×10^{14} particles from the Main Injector (MI) @ 120 GeV
  - Booster is not capable of accelerating 2.5×10^{13} no matter what the injection energy, or how it is upgraded
  - Achieving 2+ MW will require replacement of the Booster and possible upgrades of the MI
    - E.g. construct rapid cycling synchrotron (RCS) with optional injector or extend the LINAC





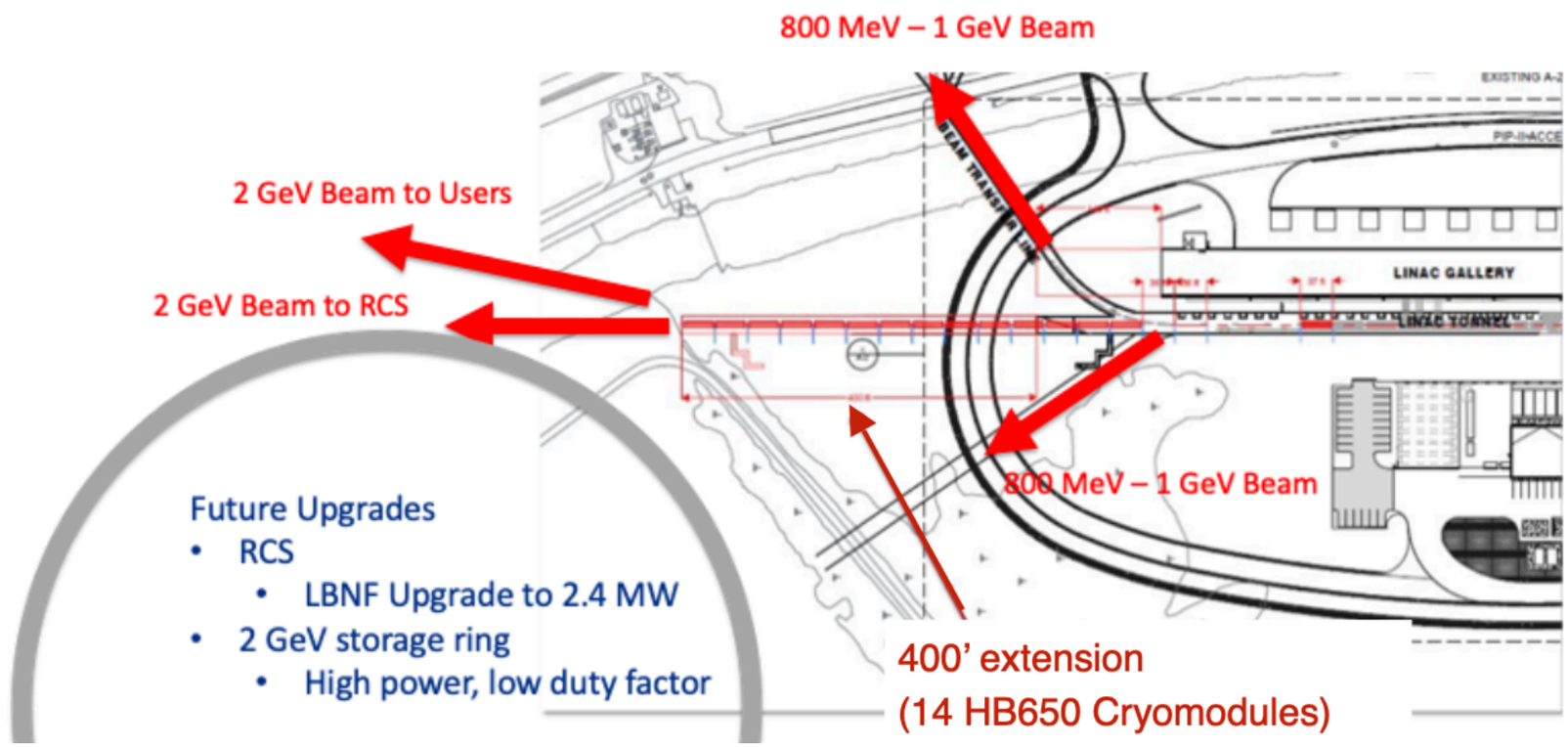
- Engaging with the community on science opportunities for the different options
  - Workshop held in May; working on write-up —> white paper input to Snowmass process

PIP-II Linac – Flexible, Extendable Proton Driver Compatible with Science Driven Upgrades

Linac Parameters	*PIP-II Multi-users*	*with 2 GeV Upgrade*	
Beam Energy	*0.8*	*2.0*	*GeV*
Ave. Beam Current	*2*	*2**	*mA*
Bunch Length	*4*	*4*	*ps*
Min. Bunch Spacing	*6.2*	*6.2*	*ns*
Max. H- per bunch	*4*	*4*	*10^8*
Beam Power	*1.6*	*4**	*MW*

- 2 GeV Energy Upgrade – 400' linac extension and an additional 14 HB650 Cryomodules
- Multi-user capability provided by RF separators and fast switching magnets
- PIP-II will deliver customized beam patterns and intensities to users concurrently
- Can deliver H- and proton beams simultaneously

* - Average beam intensity can be increased if more powerful RF amplifiers are installed



Facility Capabilities (2mA CW + 2 GeV accumulator ring scenario)

2 GeV CW-capable beam, 2mA
- upgradeable to 4 MW shared with any pulsed 2 GeV program

2 GeV pulsed beam from accumulator ring, MW-scale
- requires laser stripping and 2 GeV accumulator Ring.
- 36-54 e12 at 60-120 Hz.
- investigating ~400ns pulse compression.

8 GeV RCS program, ~1 MW
- 1 MW concurrent with 120 GeV program.
- upgradeable to ~2 MW with RCS ramp-rate and optics improvement.

120 GeV DUNE/LBNF program, 2.4 MW
- upgradeable to ~4 MW with MI ramp-rate.

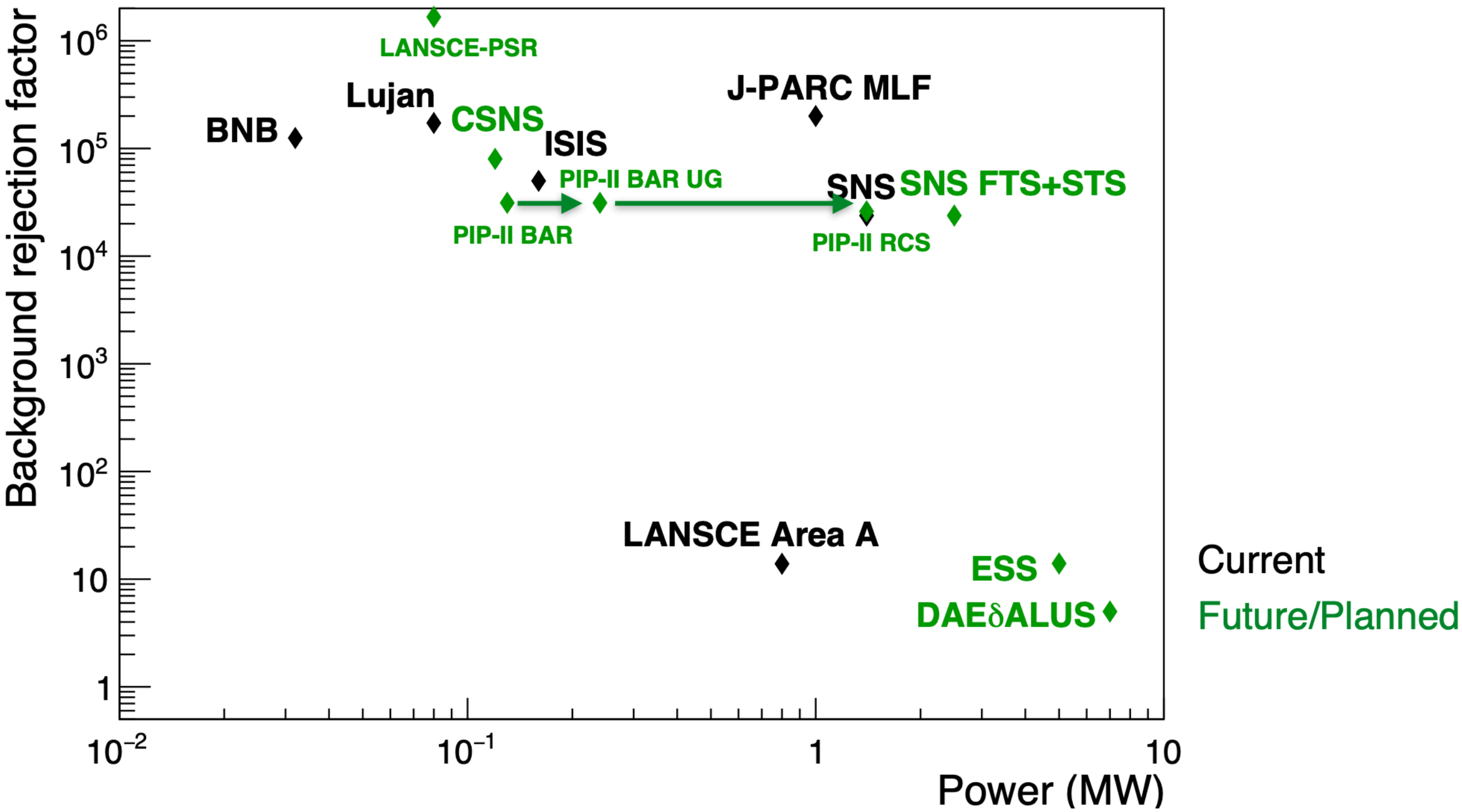
120 GeV Slow-Extraction program, 8e12 over six second, once per min
- loss-limited, may be highly upgradeable.

Accumulator Ring Option Example

- Modest upgrades to PIP-II and the BAR would allow for 1 GeV proton energy and increases the available beam power to 240 kW while increasing the power to LBNF
- Ultimately, if an accumulator ring is constructed as part of the Booster replacement (e.g. as an injector to an RCS), >2.4 MW could be delivered to LBNF and the available beam power for an O(1 GeV) fixed target program could be increased to the MW scale

Technology	BAR	BAR Upgrade	RCS Accumulator Ring
Intensity	1e13 protons/spill	1.5e13 protons/spill	3.6e13 protons/spill
Repetition Rate	100 Hz	100 Hz	120 Hz
Proton Energy	0.8 GeV	1 GeV	2 GeV
Beam Power	130 kW	240 kW	1.4 MW
Pulse Width	300-400 ns	300-400 ns	300-400 ns
Timescale	2027	Late 2020's-early 2030's	in the 2030s

Evolution of Fermilab 1 GeV Proton Beam Dump Facility



Plot via K. Scholberg

Summary

- Fermilab accelerator complex provides the world's most powerful low & high energy ν beams

- PIP-II will deliver high power beams (1.2 MW, upgradeable to multi-MW) to LBNF to enable DUNE's long-baseline physics program
  - Only 1.1% of PIP-II's full beam capability is required for DUNE long-baseline ν beam

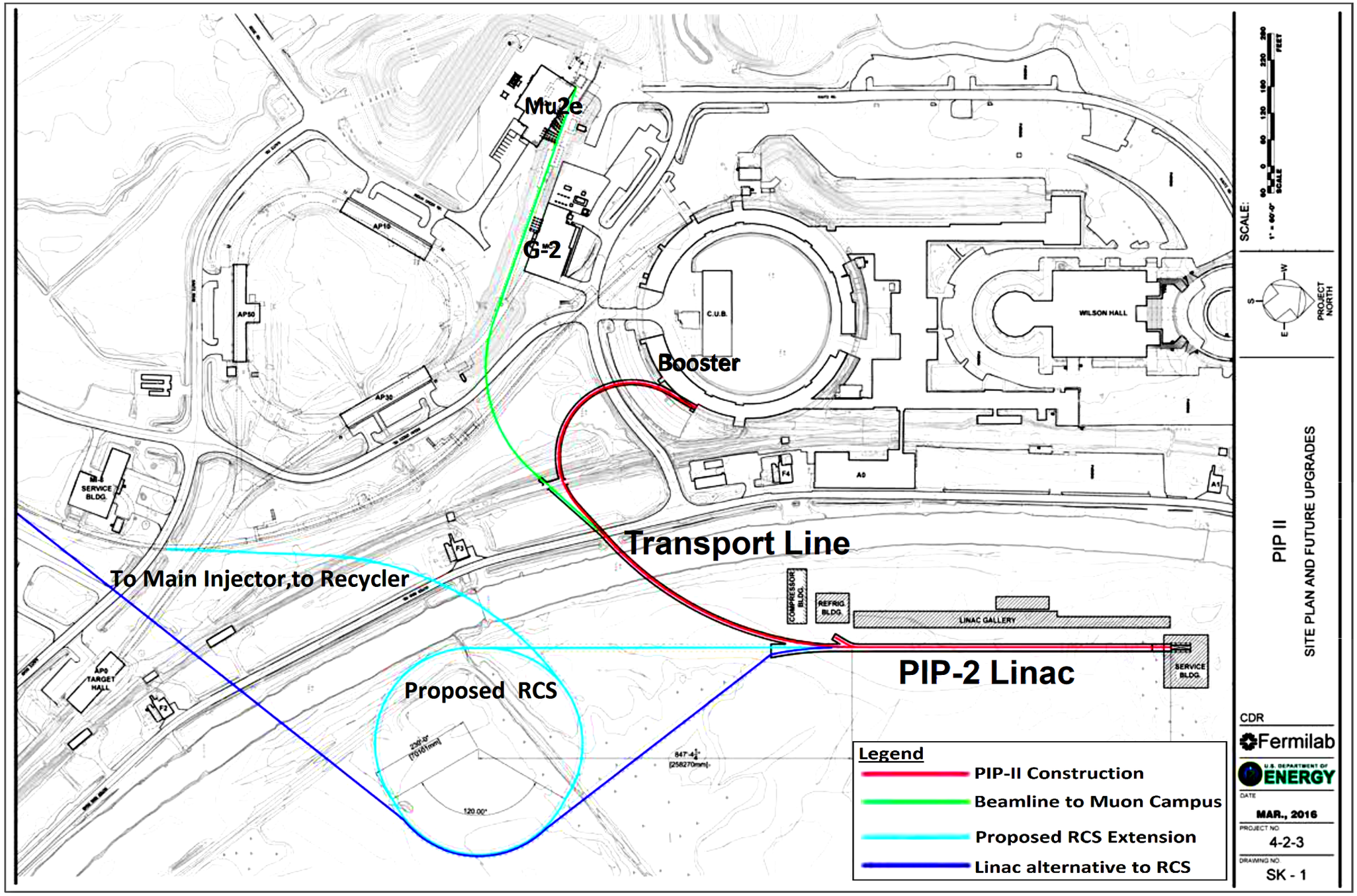
- PIP-II also provides an extendable platform that brings broad physics opportunities for multiple users at Fermilab and enables a path forward for future upgrades of the accelerator complex

- Booster replacement studies are underway to design upgrade paths for the accelerator complex that will deliver 2.4 MW @ 60-120 GeV from the Main Injector to LBNF in support of DUNE as well as identify additional science opportunities using high power low (~1 GeV) and intermediate (~10 GeV) energy proton beams

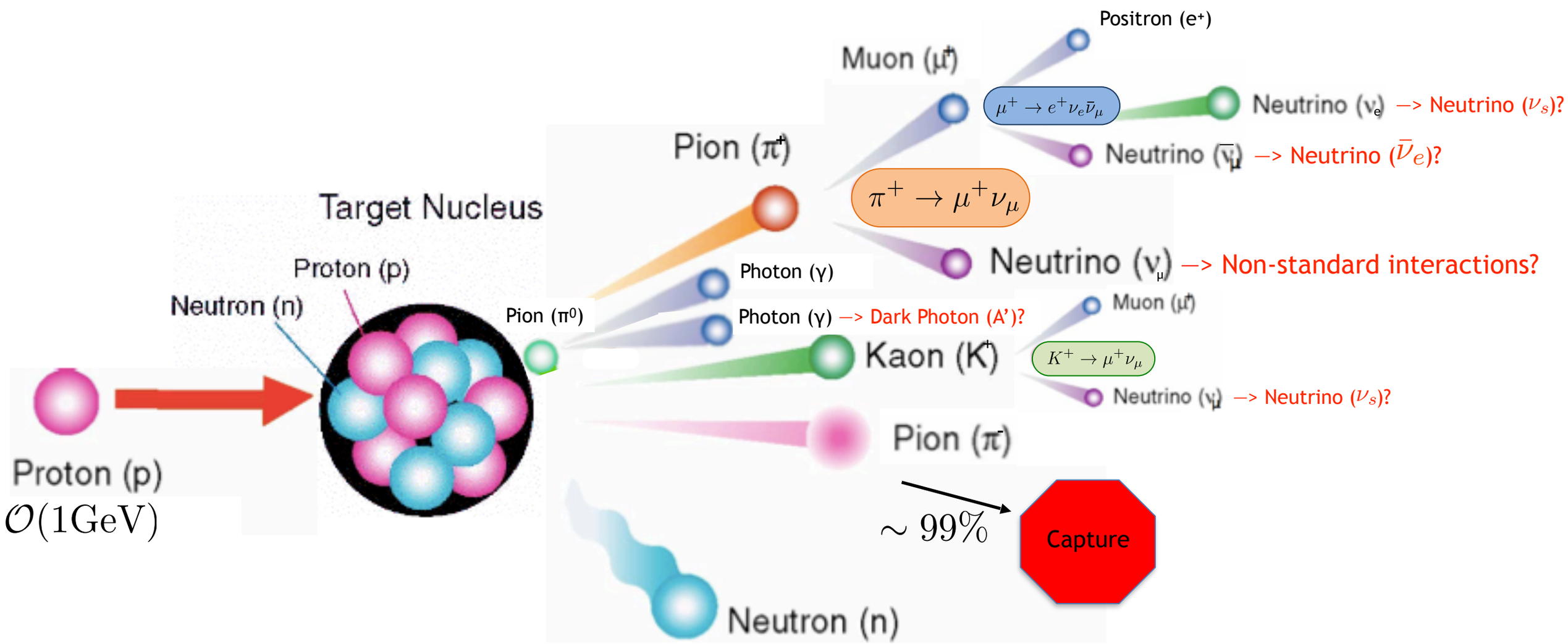
- Excellent opportunity for a proton beam dump based dark sector and neutrino physics program at Fermilab that more fully utilizes PIP-II infrastructure as well as the existing BNB complex

Thank you

Replace Booster with RCS and/or Linac



(Linac and RCS not to scale)

S. Dixon

PIP-II is simultaneously capable of driving a MW-class GeV-scale proton fixed target program and a 2.4 MW beam line for DUNE