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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Neutrino Program at Fermilab - Enhancing proton beam power and accelerator infrastructure

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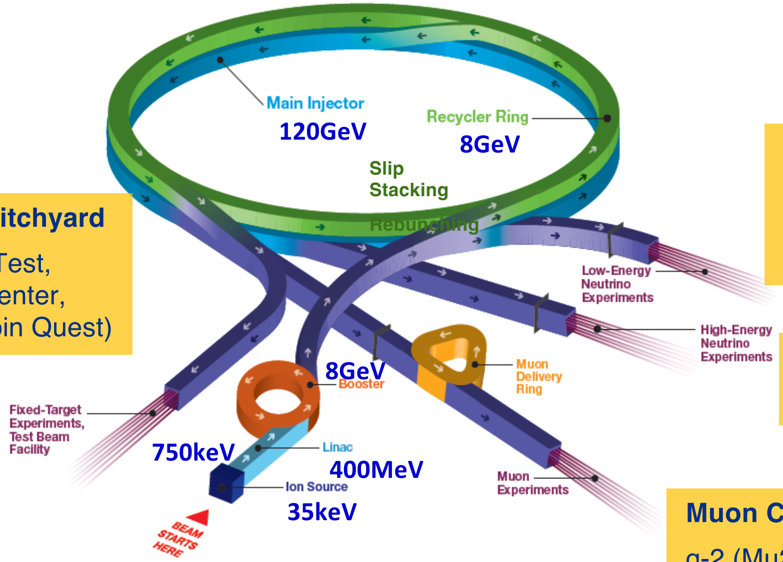
Current Accelerator Complex at Fermilab



Switchyard

MTest,
Mcenter,
(Spin Quest)

Short Baseline Neutrino

ICARUS, SBND, ANNIE

Long Baseline Neutrino

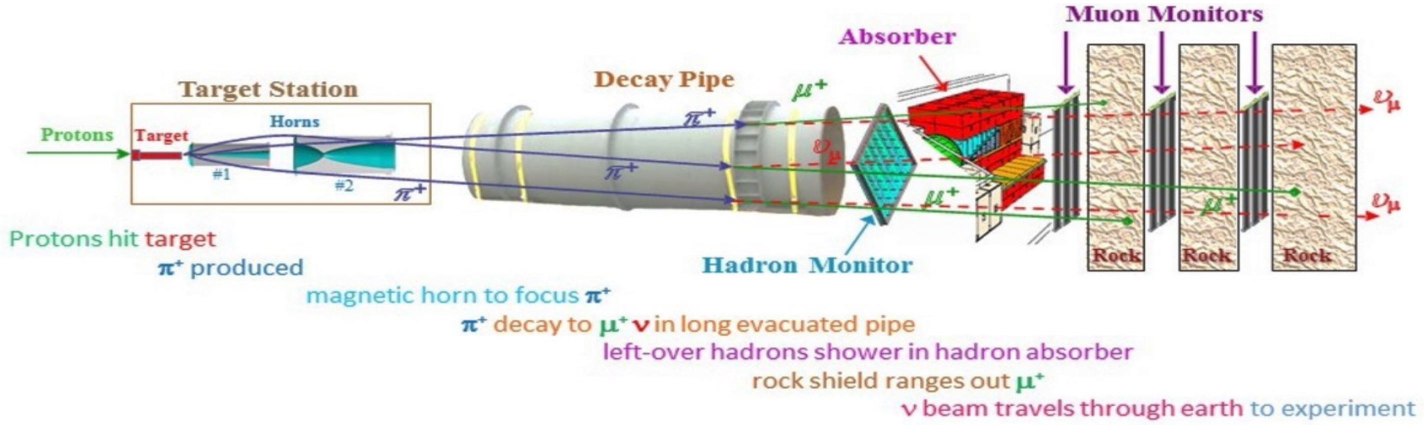
NOvA, (LBNF/DUNE)

Muon Campus

g-2,(Mu2e)

- **Fermilab operates largest particle accelerator complex in USA, 6,800 acres of federal land**
- **~1,900 staff with a yearly budget of ~ $600M**
- **Hosts facilities utilized by over 4,000 scientists from 50+ countries**
- **Continues its mission to unravel mysteries of matter, energy, space, and time for global benefit**

NuMI Beamline



- Intense beam of muon-neutrinos aimed towards Minnesota
- Main Injector provides 50–70 trillion 120GeV protons every 1.2 seconds
  - Originally designed for 400 kW
- Each pulse generates ~ 2x10^{14} ν_μ

  ~20 million pulses annually
- Commissioned in 2005, run until ~2027

NuMI Megawatt Upgrade

	NuMI Design	NOvA	1 MW upgrade
Proton beam energy	120 GeV		
Beam power (kW)	400	700	1 MW
Energy Spectrum	Low Energy	Medium Energy	
Cycle time (s)	1.87	1.33	1.2
Protons per spill	4.0×10^{13}	4.9×10^{13}	6.5×10^{13}
Spot Size (mm)	1.0	1.3	1.5
Beam pulse width	10 microsec		

R. Zwaska I Next-Gen Accelerators at Fermilab I NAPAC 2022

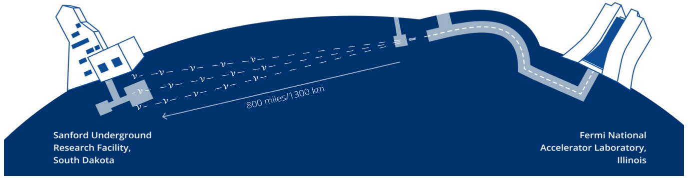
- **Enhanced Beam Power:**
  - Upgraded from 400 kW to 700 kW with NOvA /Accelerator & NuMI Upgrades (ANU)
  - NuMI Megawatt Accelerator Improvement Project (AIP): 2018-2021
- **Extended Capacity:** Modified to accept up to 1 MW beam power
  - Upgrade of target, horns, and supporting systems to be capable of accepting 1 MW beam power through 2025
- **Completion in 2021:** Finished upgrades after three annual shutdowns for component replacement
  - Various upgrade done, beam σ on target $= 1 - 1.5$ mm
- **Power Milestone:**
  - Set a record of nearly 959 kW in May 2023
  - Demonstrated capability with 1.133s MI cycle run

LBNF/DUNE

LBNF/DUNE-US Project provides

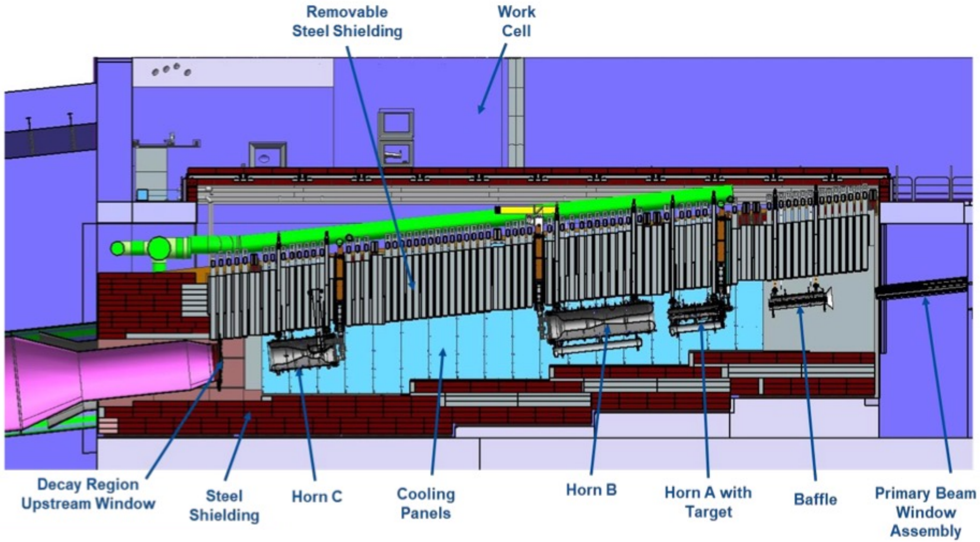
- Up to 2.4 MW proton beamline
- 1.2 MW target systems
- Up to 2.4 MW of shielding and absorber

DUNE: World's most powerful neutrino experiment, powered by PIP-II & LBNF



Capability Description	Phase I (LBNF/DUNE-US Project + DUNE Int'l Project)	Phase II
Beamline		
1.2MW (includes 2.4MW infrastructure)	X	
2.4MW		X[1]
Far Detectors		
FD1 – 17 kton	X	
FD2 – 17 kton	X	
FD3		X
FD4		X
Near Detectors[2]		
ND Lar	X	
TMS	X	
SAND	X	
MCND (ND GAr)		X

Note 1: requires upgrades to LBNF neutrino target and upgrades to Fermilab accelerator complex. The LBNF facility is built to support 2.4MW in Phase I.
Note 2: Near Detector Subproject threshold scope provides "day 1" requirements to start the DUNE experiment



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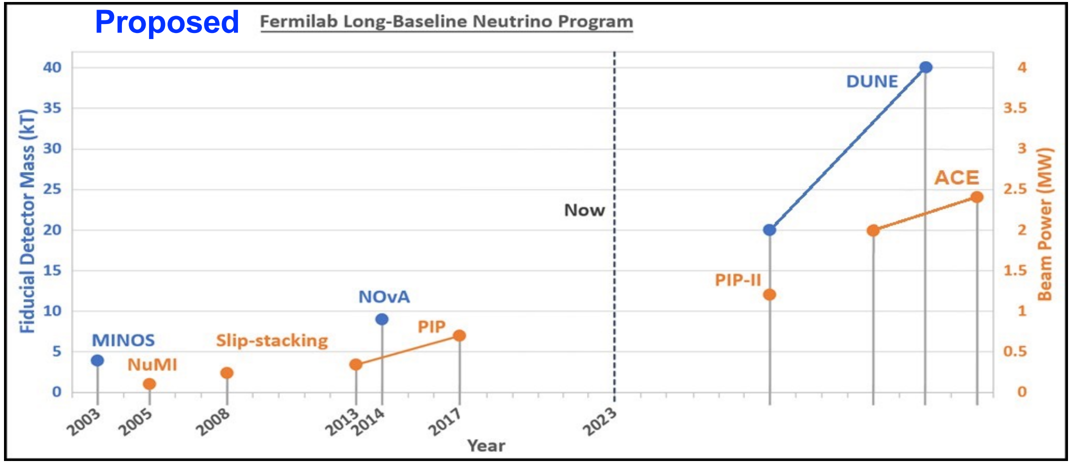
Accelerator Capabilities Enhancement (ACE) overview and opportunities



From J. Eldred, JINST 2019

- ACE upgrade: accelerate beam delivery to LBNF/DUNE via MI cycle time reduction – faster way to 2+ MW
- ACE-MIRT upgrade: Main Injector Ramp & Targetry: MI cycle time + improvements of Target Systems capabilities

PIP-II upgrades will provide proton power of 1.2 MW (at max 1.35 MW)

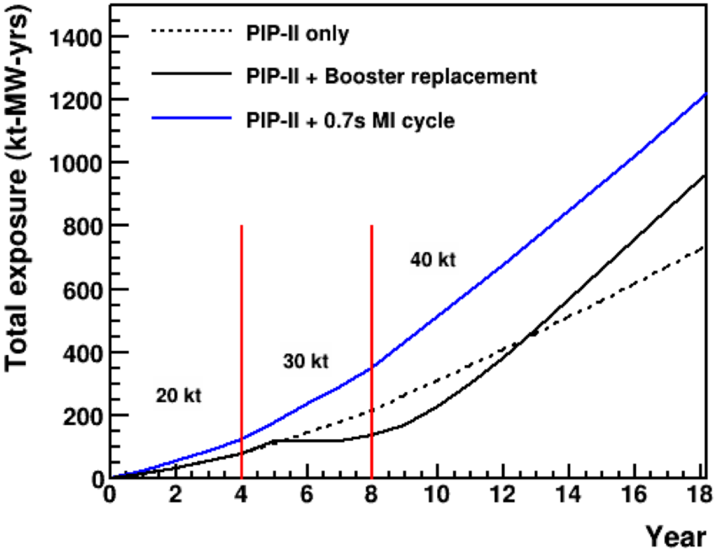
Set maximum energy (E) to 120 GeV; one option is to boost beam pulse intensity (N), requiring additional 8 GeV upgrades to beam intensity

Other option is to decrease MI ramp time

$$P = \frac{eNE}{T}$$

Accelerator Capabilities Enhancement (ACE) overview and opportunities

- DUNE sensitivities depend on exposure (kt*MW*yrs)
- Oscillation sensitivities depend on total Far Detector exposure
- ACE upgrade to 2+ MW optimizes 40 kT DUNE detector



From C. Marshall, ACE Workshop, 2023

Assume an initial capacity of 20 kt (Phase I; 2 FD modules), with an additional 10 kt module added in year 4 and another 10 kt module in year 8

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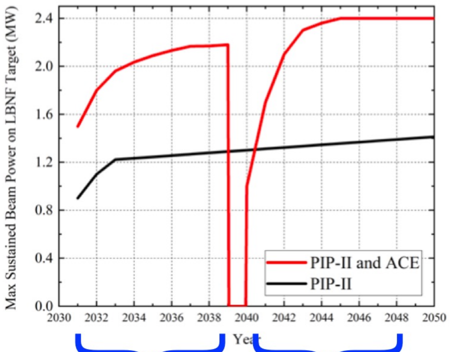
Accelerator Capabilities Enhancement (ACE) overview and opportunities

ACE-MIRT proposed to reduce Main Injector cycler to ~0.65s to increase beam power

In ACE-MIRT period:

- Significant beams at 0.8 GeV
- Less at 8 GeV (because of MI cycle time, absolute minimum slip stacking time is 0.65s)
- More beam power with 120 GeV slow extraction



From N. Tran, ACE Science Workshop, Fermilab Users Meeting 2023

ACE-MIRT
Reduce Main Injector Ramp time
+ Target R&D to get to > 2 MW

ACE-BR
(Booster replacement)

		PIP-II Booster			
Operation scenario	**Nominal**	**PIP-II**	**A**	**B**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	s
Booster intensity	**4.5**			**6.5**	10^{12} p
Booster ramp rate	15			**20**	Hz
Number of batches	12		12		
MI power	0.75	**1.2**	1.7	**2.14**	MW
cycles for 8 GeV	6	12	6	2	
Available 8 GeV power	29	**83**	56	**24**	kW

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Neutrino Beam Challenges

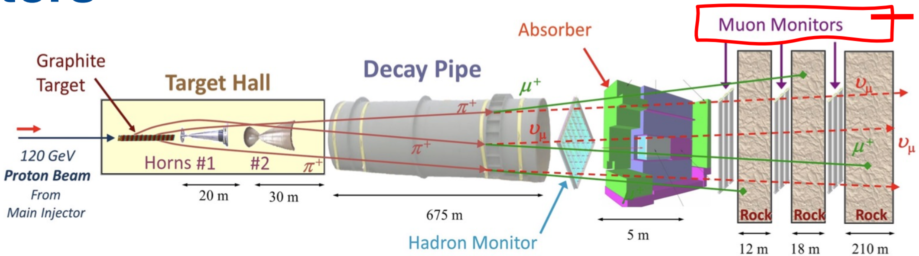
Beam Instrumentation

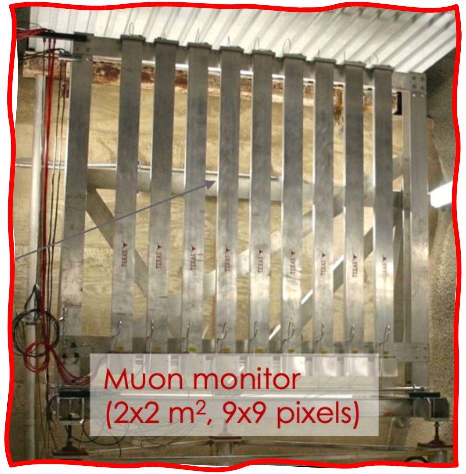
- Essential for smooth operation of accelerator complexes
- Impacted by immediate/cumulative radiation exposure, ambient temperature, humidity etc.
  e.g. NuMI Muon monitor1 damaged by radiation
- Affects range of operational beam parameters, e.g. highest possible beam power
- Essential for reliable and efficient operations at higher beam power for future multi-MW facilities
- Fermilab, KEK/J-PARC collaborating on a global R&D efforts to enhance beam instrumentation

Ideas for radiation hardened beam instrumentations

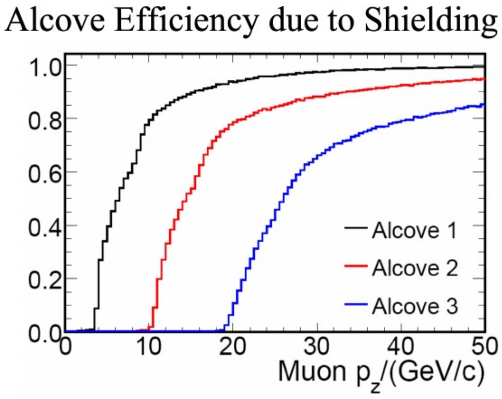
Facility	Beam Energy	Beam Power	Instruments
LBNF	60 - 120 GeV	1.2 MW - 2.4 MW (50-70e12 protons per spill, 0.6-1.2 sec repetition time)	1. Target Health Monitor. (non-contact sensor) 2. More radiation hardened Beam Loss Monitors (BLMs). 3. More radiation hardened Hadron Monitor. 4. Pico-second muon monitor. 5. Primary Proton Beam monitor.
Mu2e	8 GeV	8 kW (slow extraction beam, 1e9 protons per spill)	1. Target health monitor. (non-contact sensor) 2. Use same radiation hardened hadron monitor technology as production target monitor. 3. Primary Proton Beam Monitor.
Mu2e-II	0.8 GeV	100 kW	1. Target health monitor. 2. Primary Proton Beam Monitor.

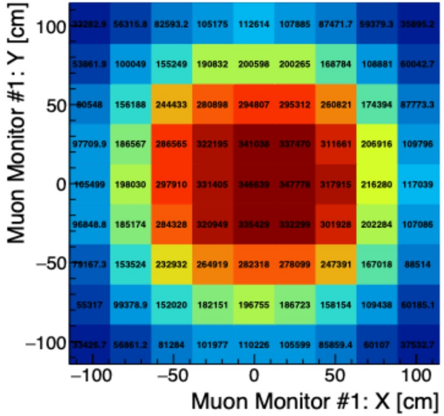
Muon Monitors





Three monitor receive different energy muons





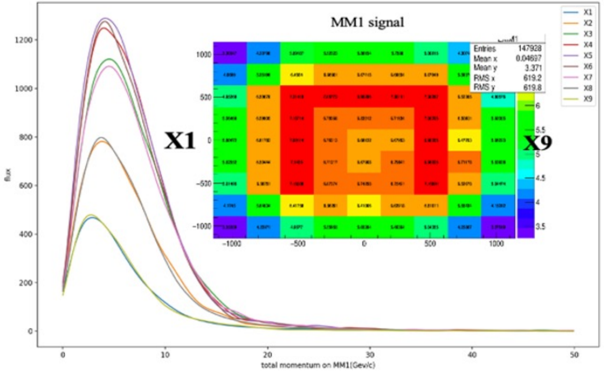
Muon Monitor 1 signal

https://arxiv.org/pdf/2309.08029.pdf

New Instrumentation Ideas

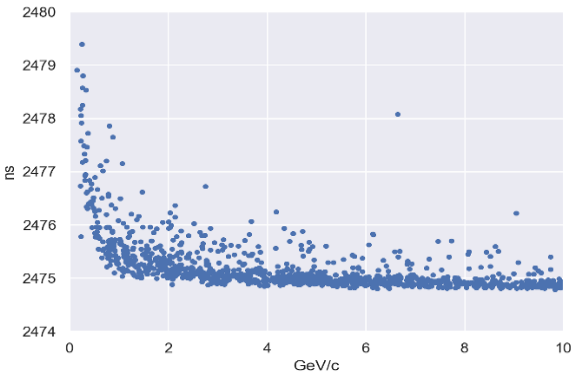
- Large Area Picosecond Photodetector (LAPPD)
  - Use LAPPD as muon monitors, provides muon TOF measurement in alcoves across transverse plane
  - Allows application of precision timing in neutrino experiments
- LAPPDs already offer a space resolution of 1x1 mm and a time resolution of ~55 ps or better

Simulated momentum spectra on central row of MM1



- Individual pixel sees different muon spectrum
- X1 & X9, X2 & X8, X3 & X7, X4 & X6 shows similar shape

Simulated time-of-flight vs muon momentum at MM1



- Observed time distribution will be different at different pixel position

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New Instrumentation Ideas

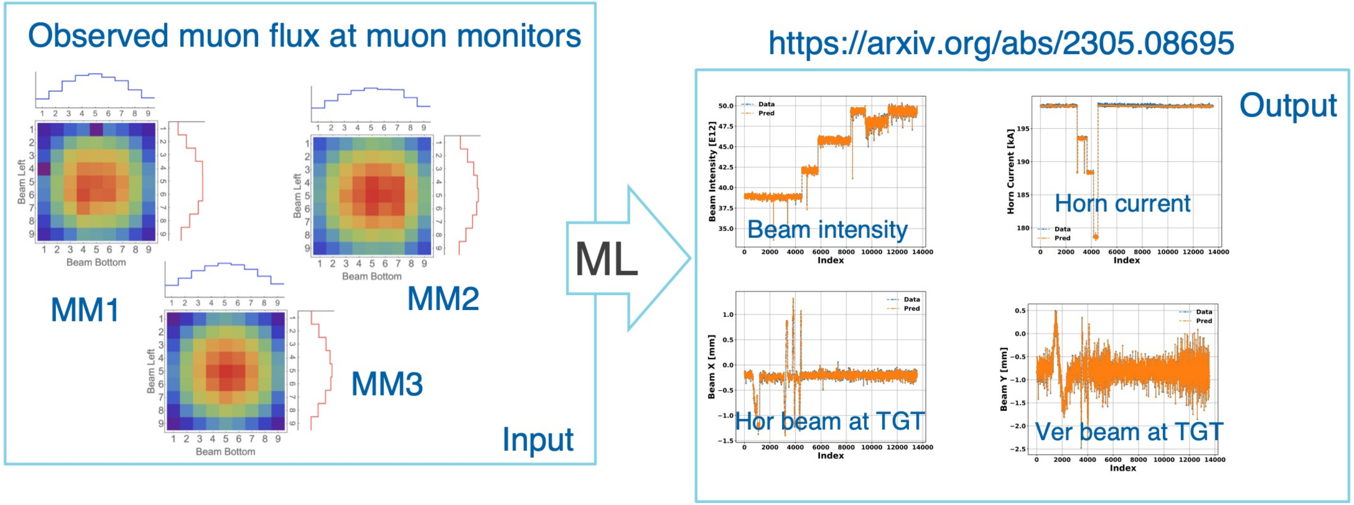
Machine Learning for Beam Quality Assessment in NuMI:

•NuMI horn's linear beam optics implies linear response to beam changes.

•ML algorithm with ANN predicts target beam positions.

•Based on 241 observed values, accuracy: ±0.018 mm horizontally, ±0.013 mm vertically observed

•ML matches traditional instrumentation accuracy



> 1,000 flux images are required for training ML

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Summary

- ACE-MIRT plans to upgrade Main Injector to reduce ramp time and deliver more beam power to DUNE (max ~ 2.1 MW) as soon as possible
- Requires target R&D to ensure that DUNE can handle up to 2.4 MW of beam power
- Need significant R&D efforts focused on radiation-hard beam instrumentation
- Fermilab and KEK/J-PARC accelerator and beamline groups have joined forces – plan to expand

Backup

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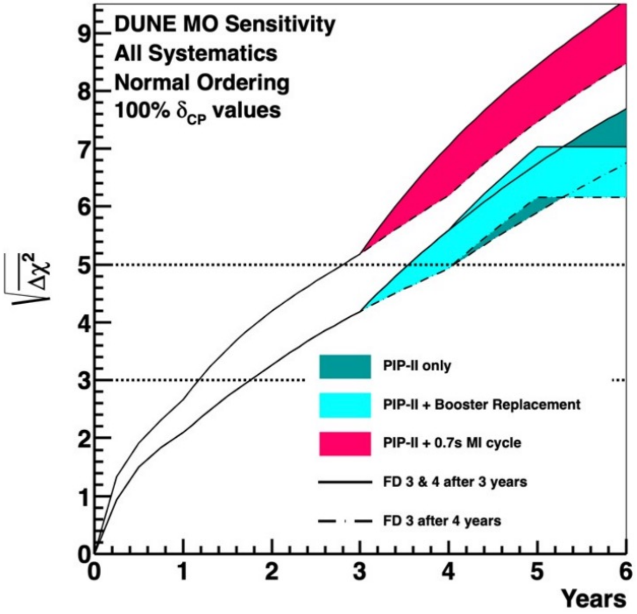
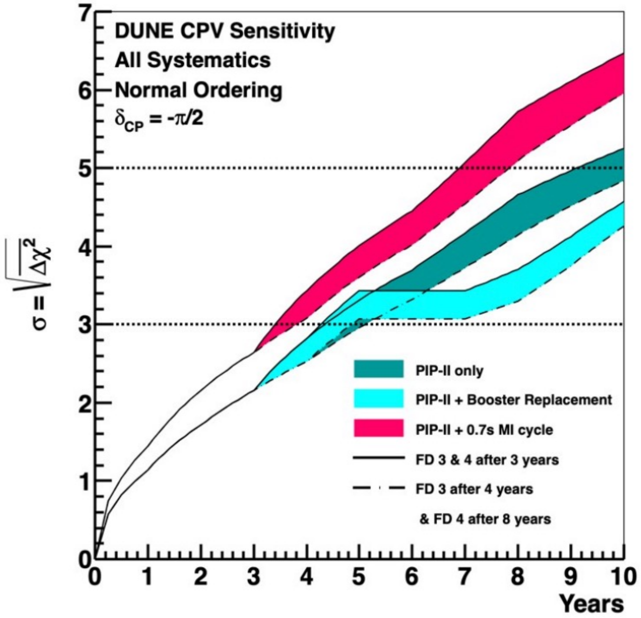
Mass ordering sensitivity with updated beamline scenarios



- Band corresponds to different FD staging scenarios
- This is shown for the **worst case** scenario in other oscillation parameters
- **DUNE determines the mass ordering at >5σ in Phase I no matter what**
- Option 0 pushes milestones earlier by ~1 year

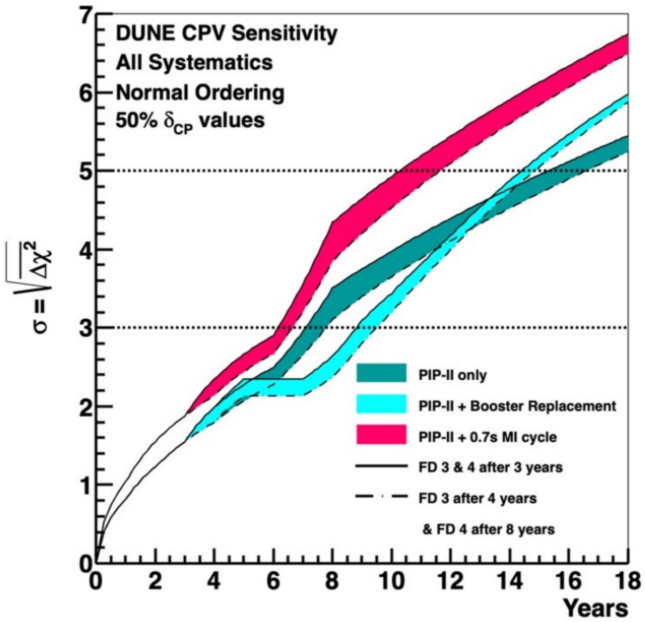
ACE - DUNE Physics

CP violation sensitivity for maximal CPV (easiest case)



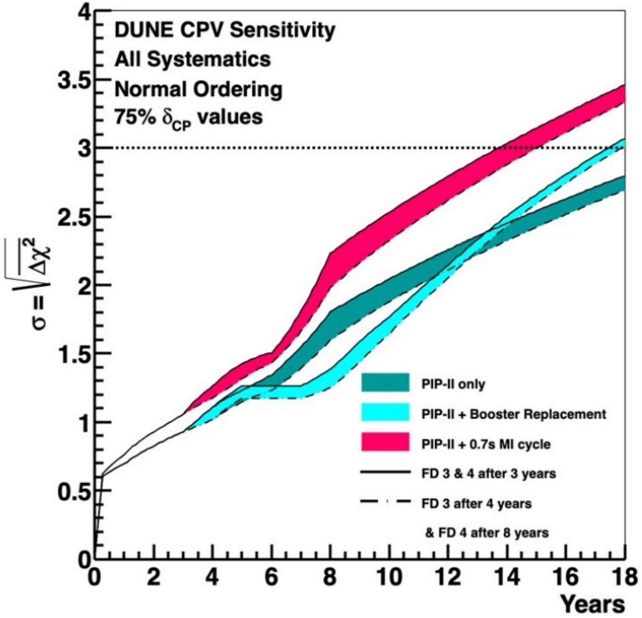
- Scenario where $\delta_{CP} = -\pi/2$, the easiest possible scenario for establishing CPV
- **3σ milestone is achieved DUNE Phase I**
- Option 0 pushes milestone forward by ~1 year

CP violation sensitivity in more challenging case: 50% δ values



- CP violation significance over 50% of possible δ_{CP} values, essentially the median significance if you have a flat prior on true δ_{CP}
- DUNE could be competitive with Hyper-K if 5σ can be achieved in 10 years
- Kinks at 6-8 years are due to incorporation of constraint from upgraded Near Detector installed by year 6
- **Option 0 significantly increases DUNE's competitiveness**

Even more challenging scenario: 75% δ values



- CP violation significance over 75% of possible δ_{CP} values
- This is the primary physics goal established in the 2014 P5 recommendations
- It is extremely challenging to establish CPV at 3σ in this scenario
- **DUNE and Hyper-K are competitive in this scenario, and Option 0 significantly increases DUNE's competitiveness**