Fermilab Program and Plans

Dmitri Denisov, Fermilab

RDMS CMS Collaboration Meeting, September 14 2018

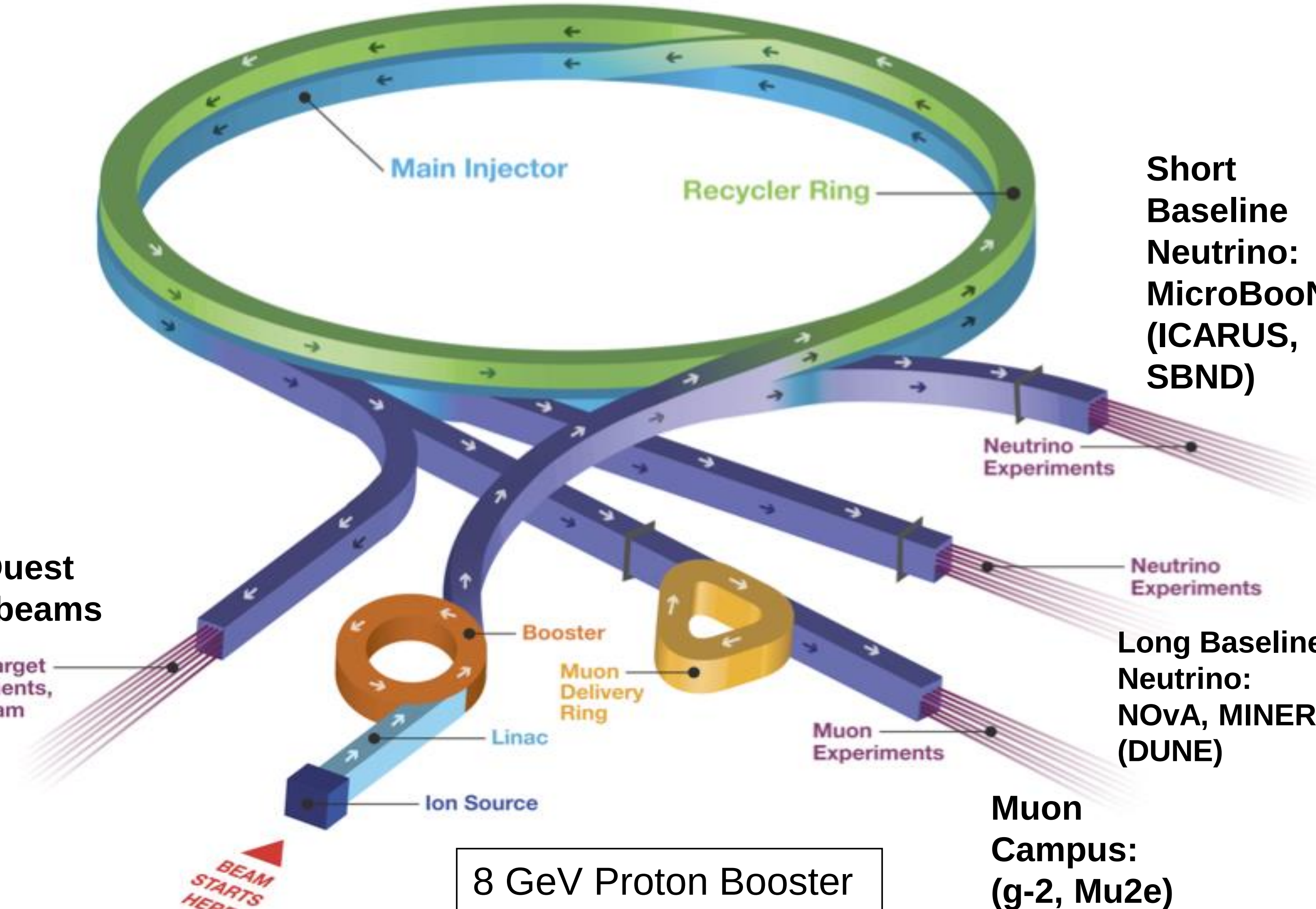
U.S. Particle Physics Strategy

- In 2014 U.S. strategic planning panel provided recommendations covering main topics of the U.S. particle physics

- They are grouped around "science drivers"
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles

- Fermilab is leading and actively involved in the experiments devoted to all "science drivers"

Fermilab Accelerator Complex



Short Baseline Neutrino: MicroBooNE (ICARUS, SBND)

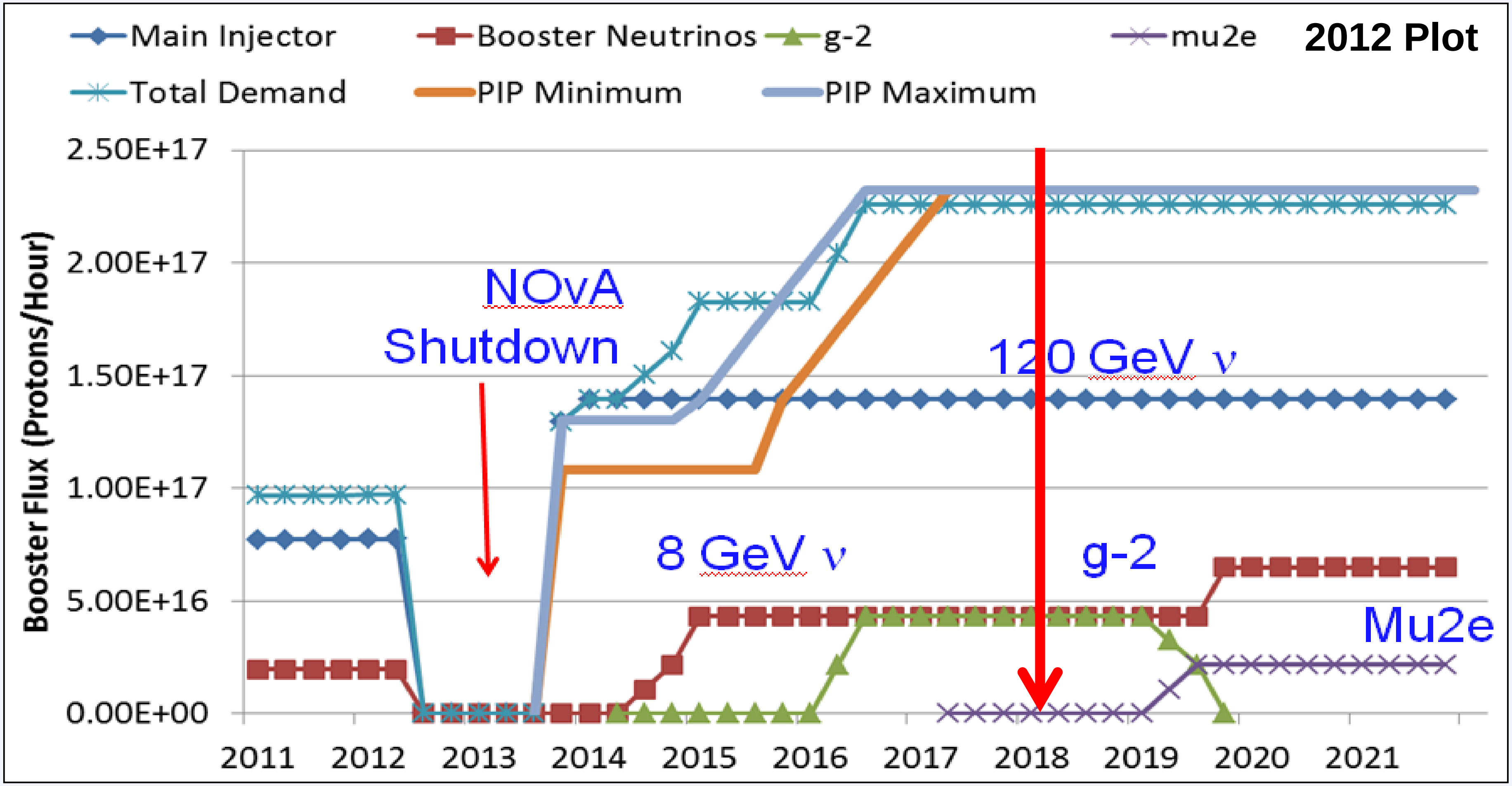
SeaQuest Test beams

Long Baseline Neutrino: NOvA, MINERvA (DUNE)

Muon Campus: (g-2, Mu2e)

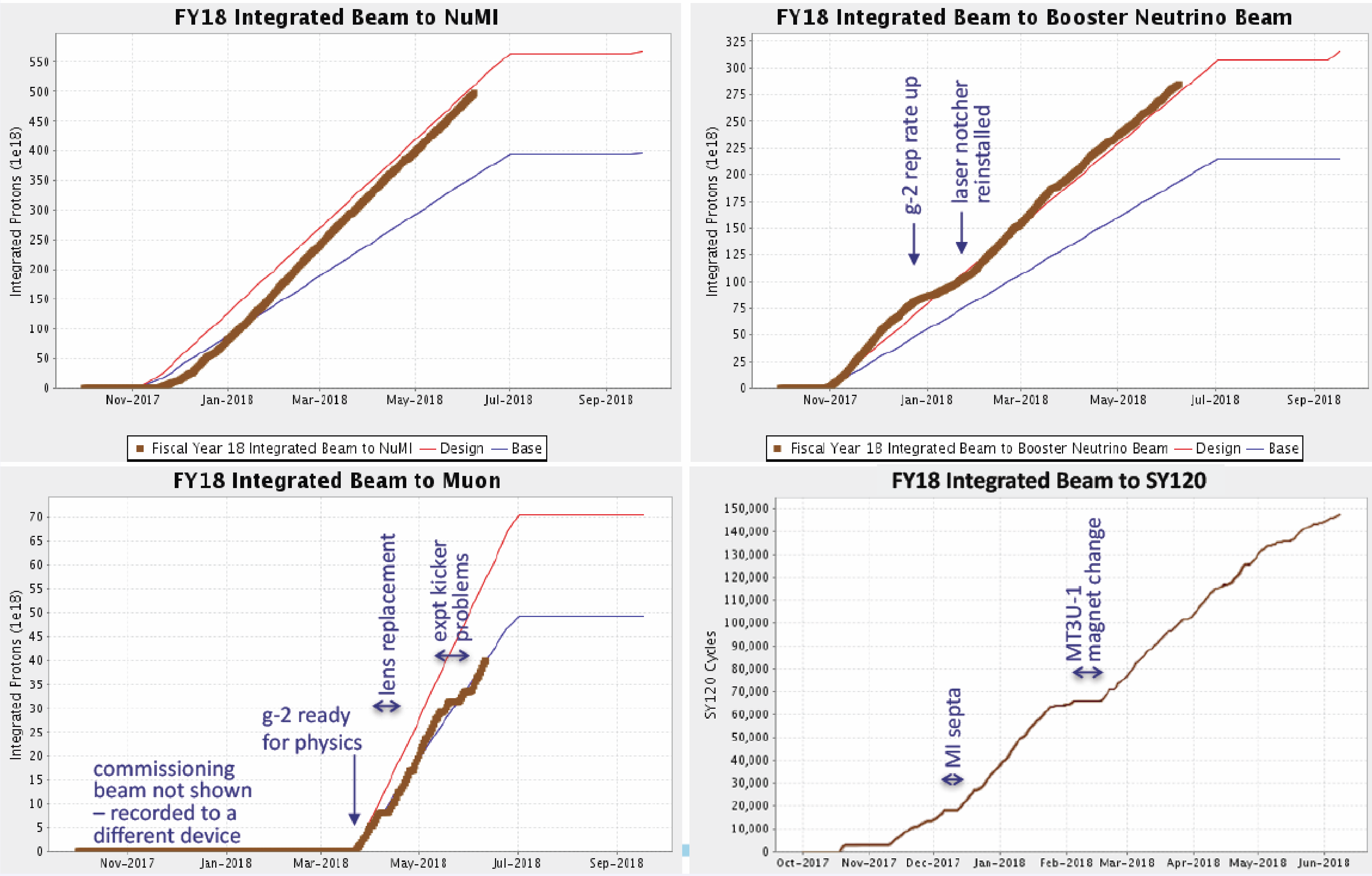
8 GeV Proton Booster
120 GeV Main Injector

Long Term Beam Delivery Plans



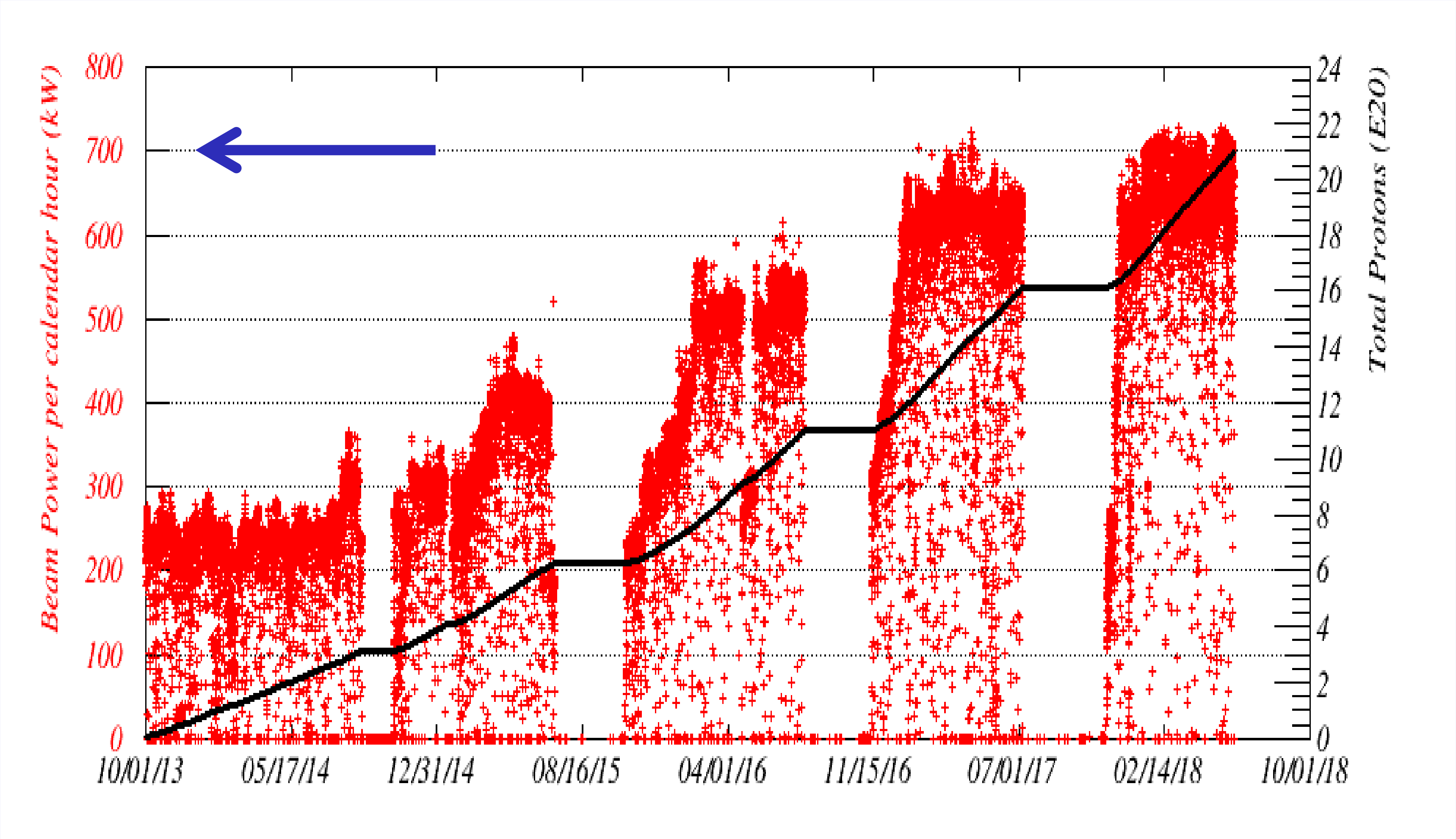
- The accelerator complex is focusing on delivering beams to
  - Neutrino, fixed target, high intensity muon beams and test beam experiments
  - Increased beam power from ~ 350 kW to ~700 kW

Fermilab's Beams Delivery



Providing ~$5 \cdot 10^{20}$ protons at 120 GeV to the neutrino program per year

Beam Power to Main Injector Neutrino Program

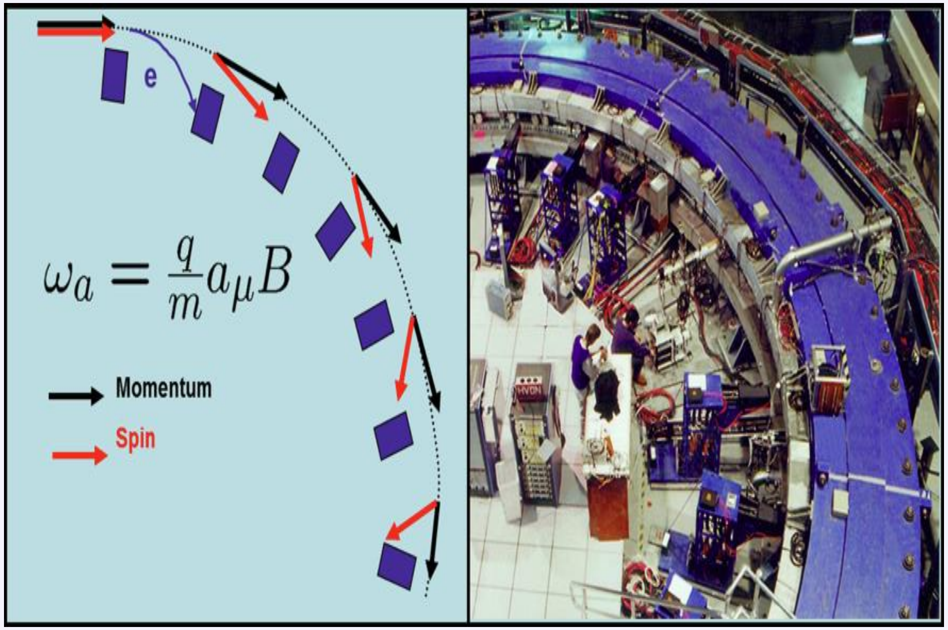


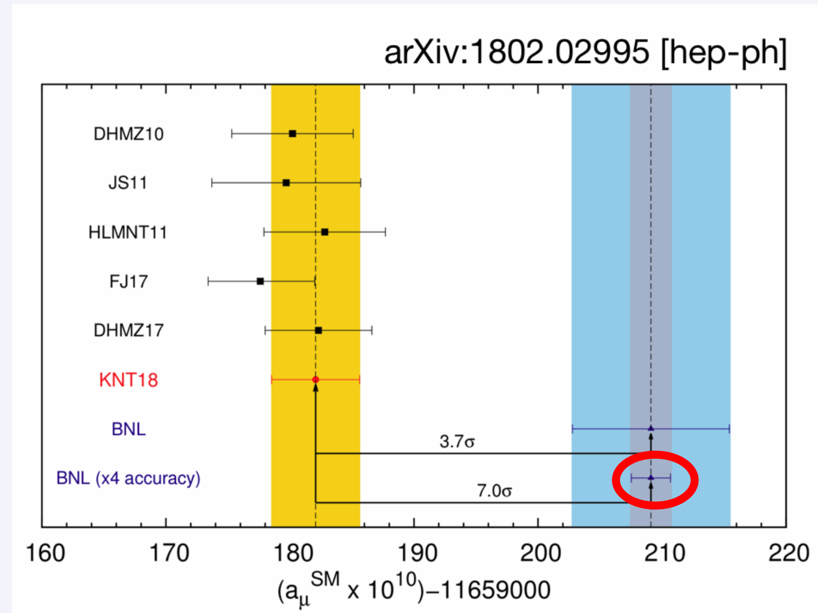
- Upgraded booster and main injector over last three years
- Doubled beam power to ~700 kW
- Delivered 21E20 protons to NoVA experiment since 2013

Fermilab Muon Campus

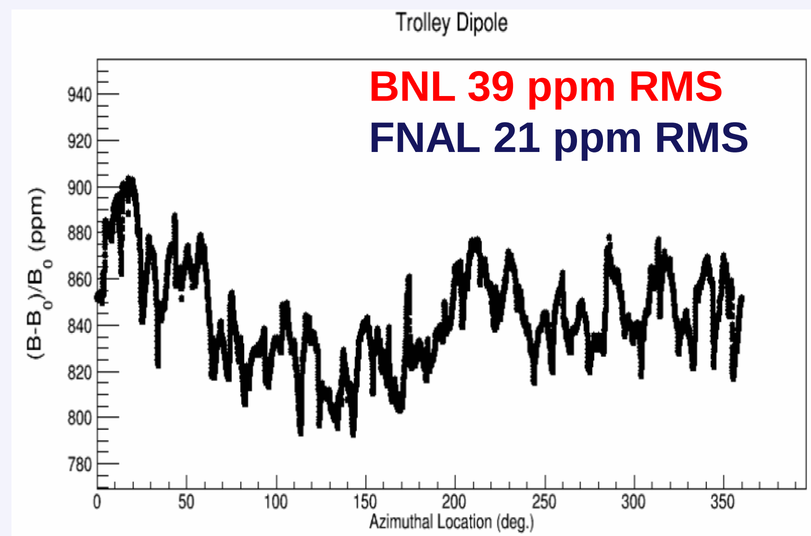
- **Re-use of the antiproton production tunnels for muon production/cooling**
- **First muon beam to g-2 experiment last year, to mu2e experiment in 2020**

Muon Magnetic Moment g-2 experiment



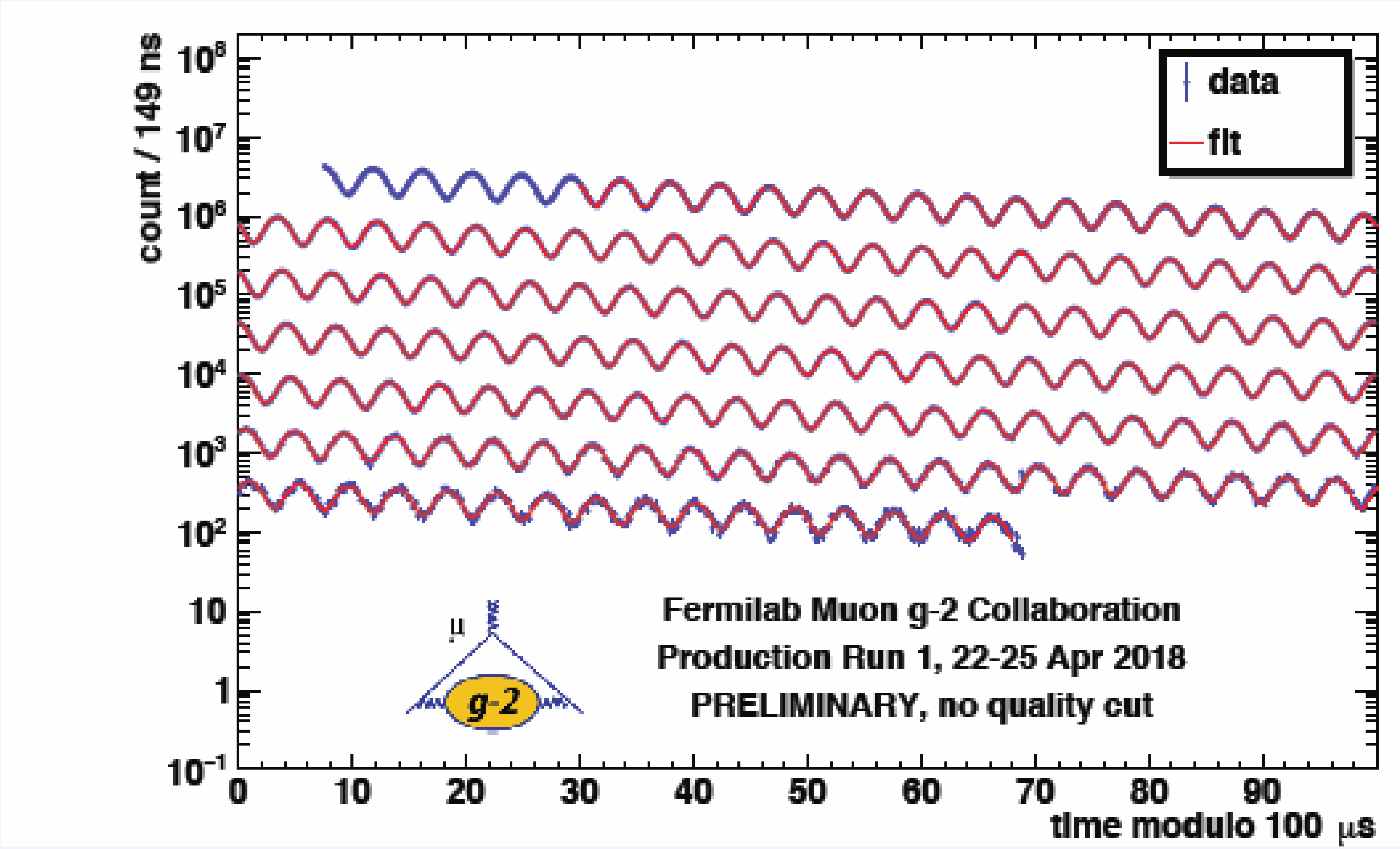


- Puzzle of ~3σ from BNL 2004 result
  - New physics?
  - Experimental effect?
- Coil moved to Fermilab from BNL
  - Higher intensity beam
  - Better systematics
- ~4 times better accuracy, x20 data by 2019
- Start data collection in early 2018



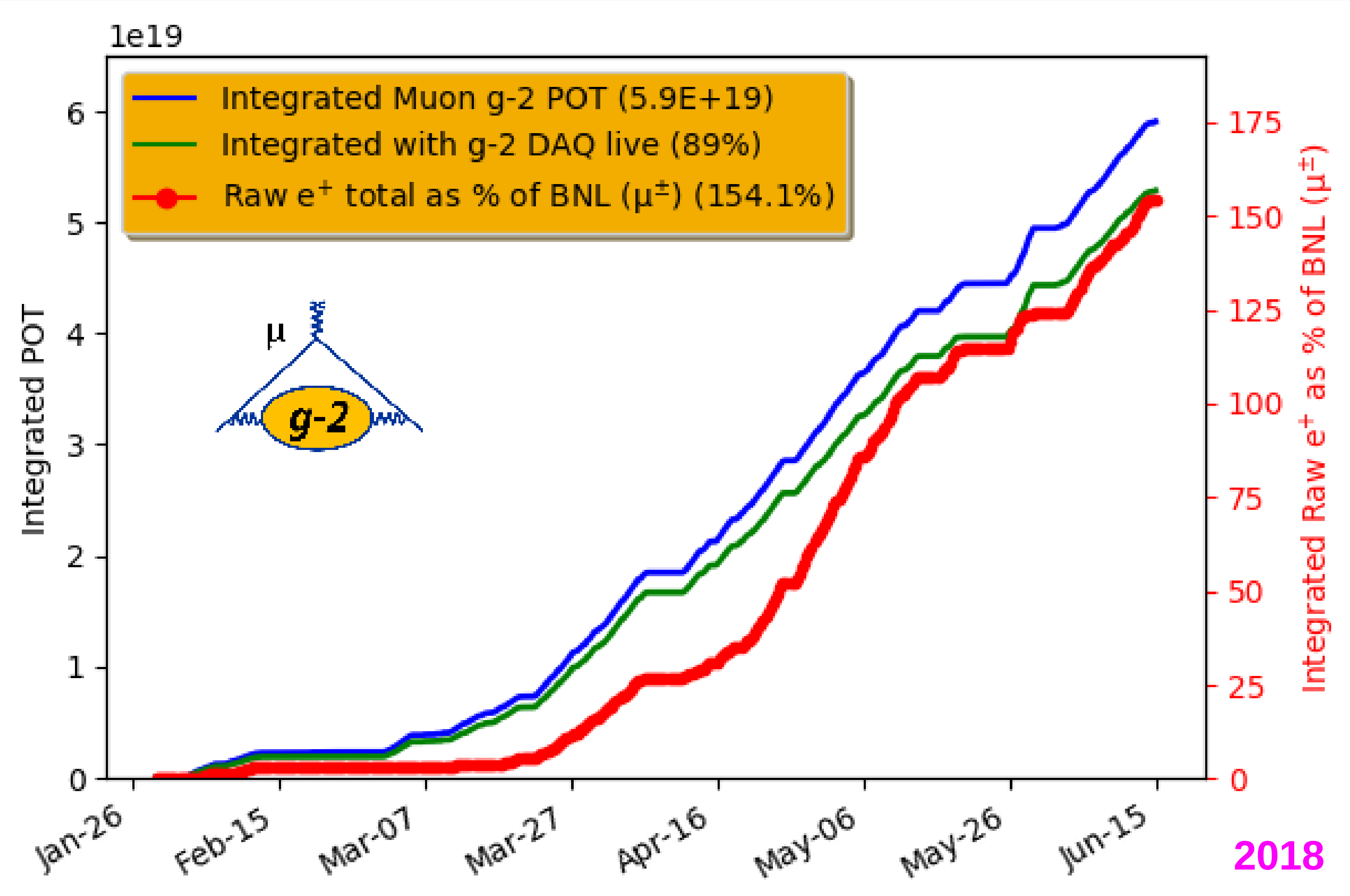
Magnetic field uniformity

g-2 Oscillations at Fermilab



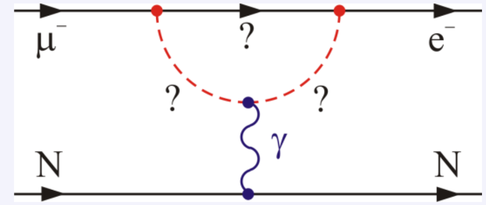
- First g-2 oscillation plot from Fermilab's g-2 analysis
- Expect g-2 value update in 2019

Muons to g-2 Ring

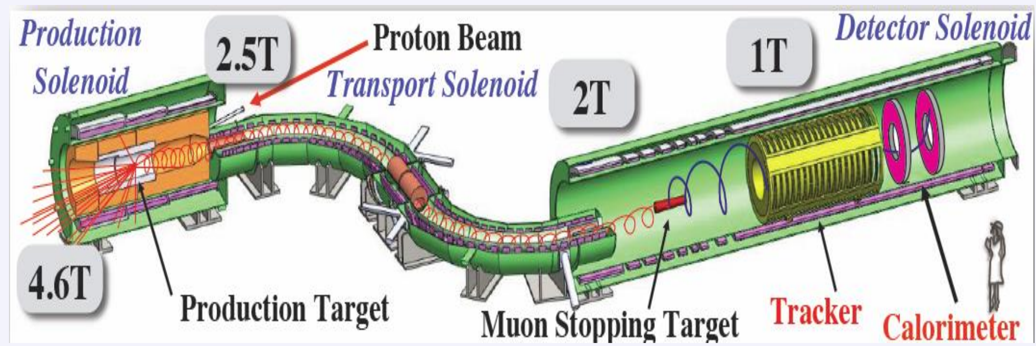


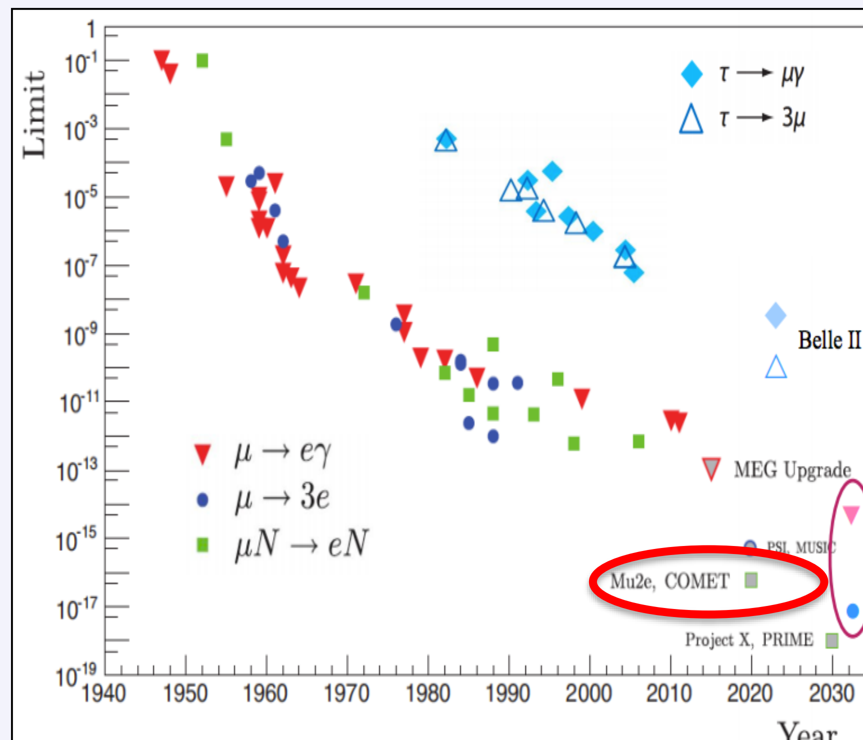
By early July 2018 Fermilab g-2 experiment got two times the number of muons delivered to g-2 experiment at BNL

Lepton Flavor Violation: Mu2e



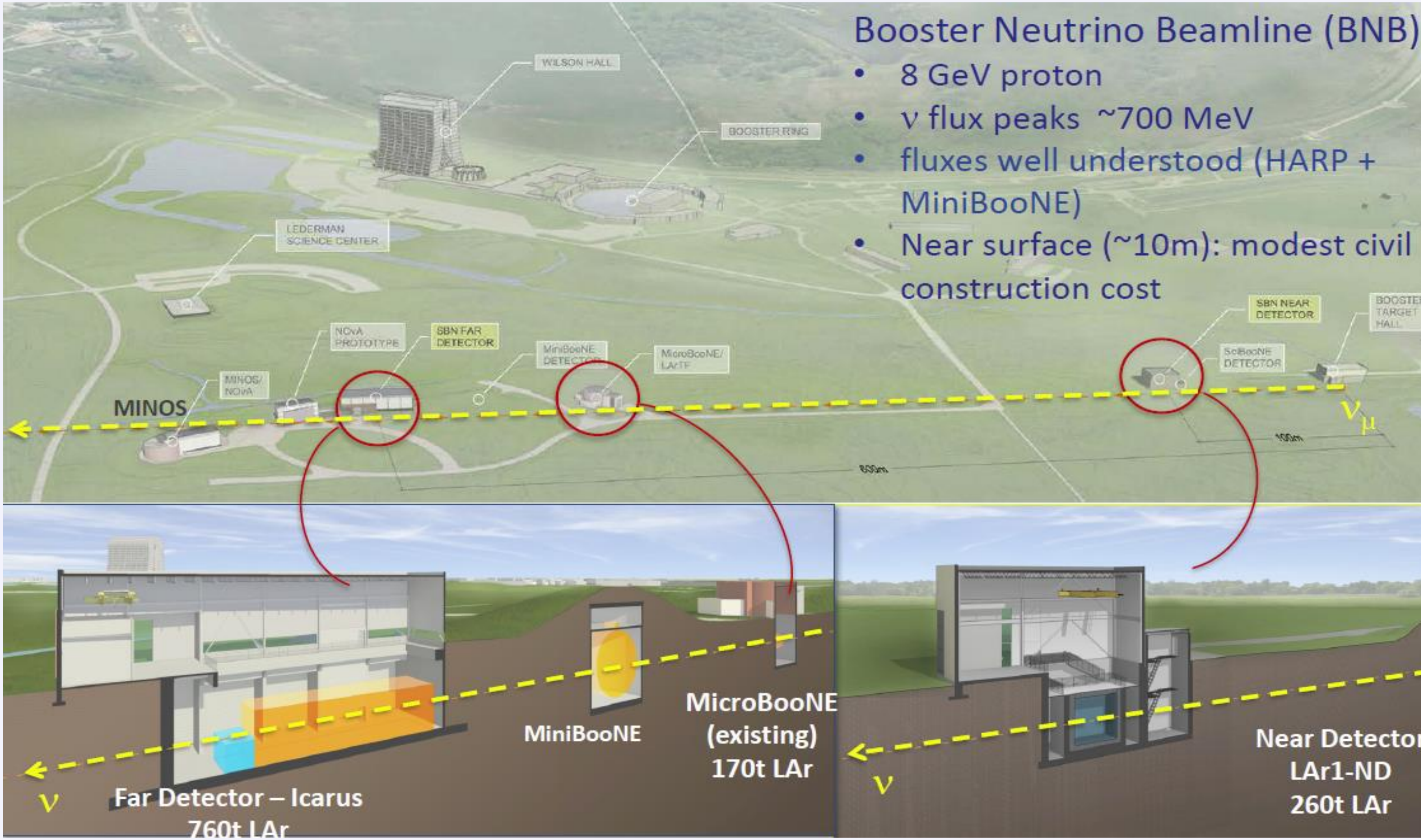
- **Constructing experiment mu2e**
  - **High intensity muon flux stopped on a nuclear target**
- **Monochromatic electron emission from μ to e conversion**
  - **~4 orders of magnitude improvement vs today's limits down to ~10^{-17} branching fraction**



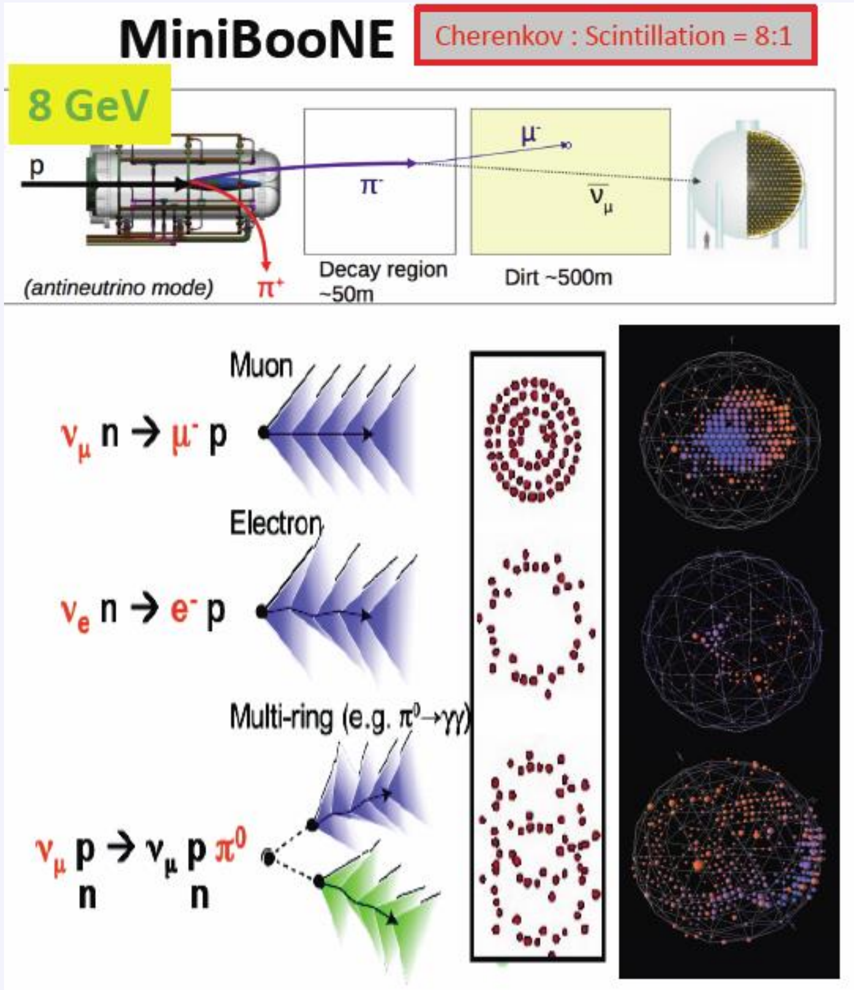


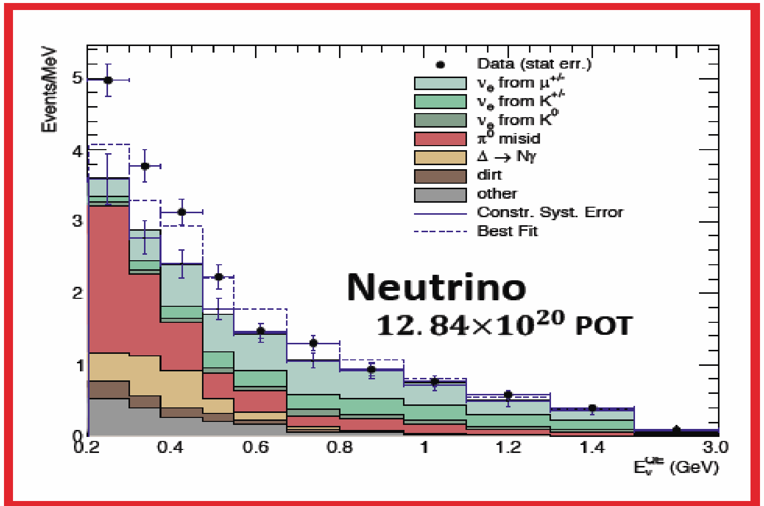
Short Baseline Neutrino (SBN) Program

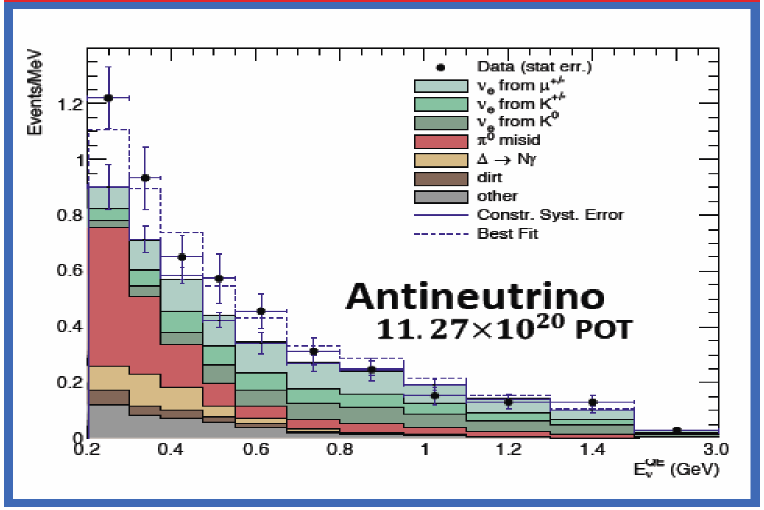
The three detectors SBN program can make a definitive statement on the LSND/miniBooNE anomaly with the potential for discoveries in neutrino physics and developments in LAr technology for DUNE



Summer 2018 miniBooNE New Result

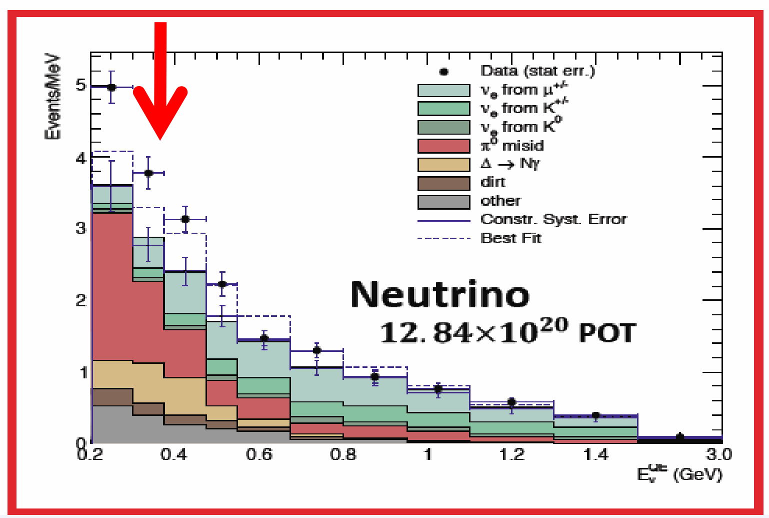


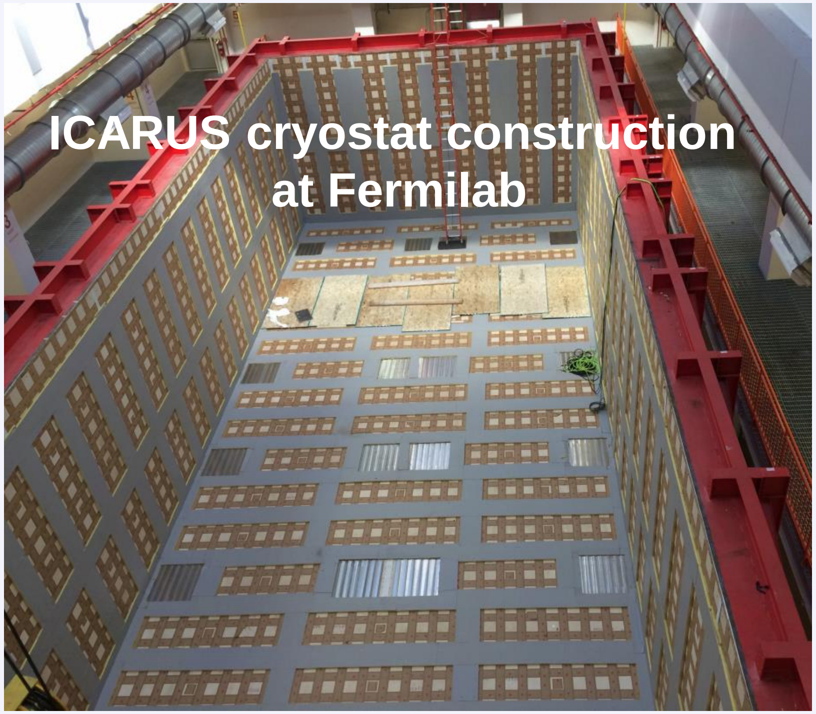




- **Excess of events is confirmed in both neutrino and anti-neutrino beams**
  - **New Physics? Sterile neutrinos?**
- **Tension with other experiments, such as at reactors**
  - **More data, experiments with different systematics**

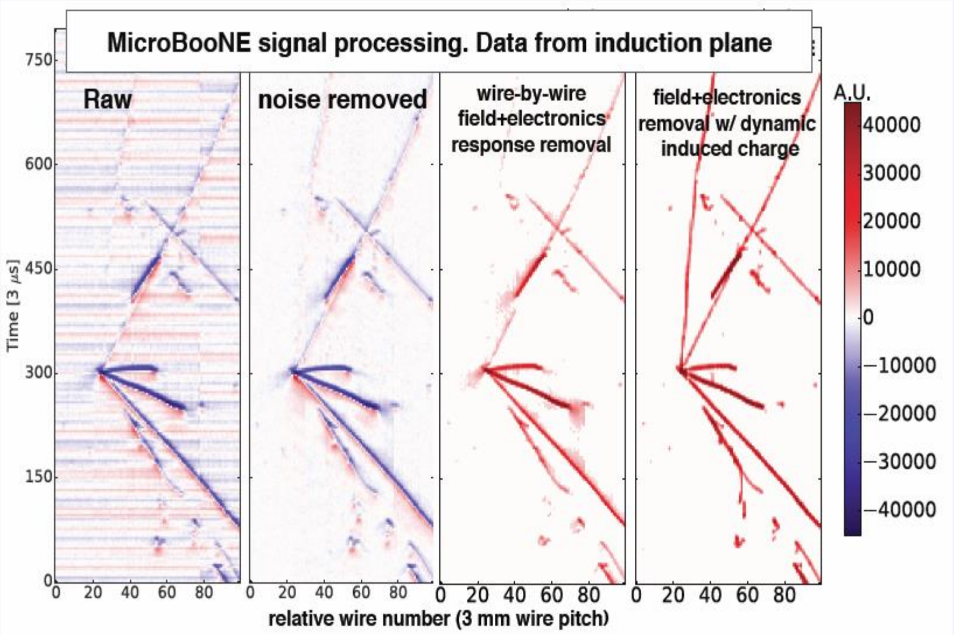
MiniBooNE Excess and ICARUS



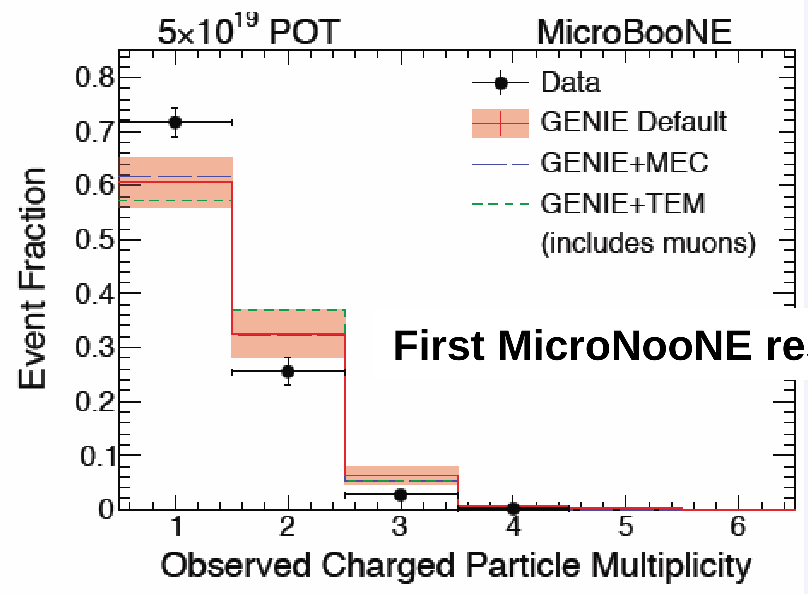


- Excess of low energy neutrino events might be an indication of new physics
- ICARUS detector is now installed in the cryostat and expected to start data collection next year
  - Largest LAr TPC detector

MicroBooNE Experiment



- **MicroBooNE is the first LAr TPC detector designed and built at Fermilab**
- **170 tons of ultra-pure argon**
- **Collecting data since 2015**
- **First physics results this year**
  - **Expect to address miniBooNE anomaly next year**



First MicroNooNE result

Long Baseline Neutrino Program

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}] \sin^2\left[\frac{\Delta m^2_{ij}}{4E}L\right] + 2\sum_{i<j} \mathrm{Im}[U_{\alpha i}U^*_{\alpha j}U_{\beta i}U^*_{\beta j}] \sin\left[\frac{\Delta m^2_{ij}}{2E}L\right].$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha/2} & 0\\ 0 & 0 & e^{i\alpha/2+i\beta}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\Delta m_{21}^2 = 7.54\ ^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m_{32}^2| = 2.42\ ^{+0.07}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$

$m(\nu_e) < 2.3$ eV (95% CL)

$\theta_{12} = 33.6\ ^{+1.1}_{-1.0}$ deg

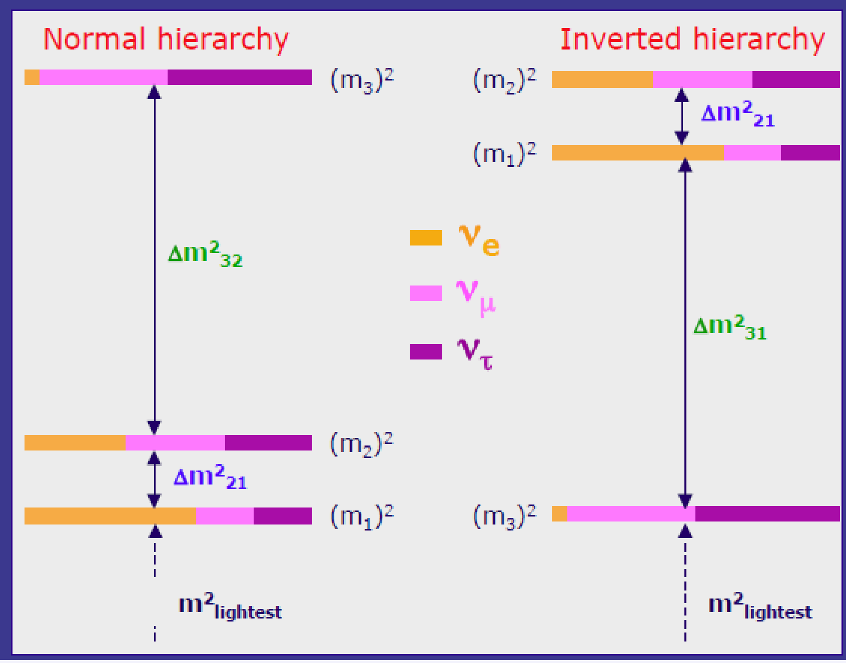
$\theta_{23} = 38.6\ ^{+2.4}_{-1.4}$ deg

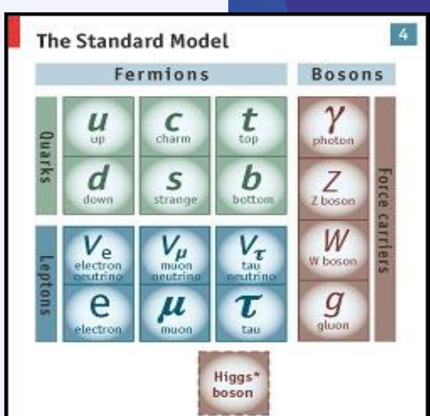
$\theta_{13} = 9.0\ ^{+0.4}_{-0.5}$ deg

$m_{lightest} = ?$

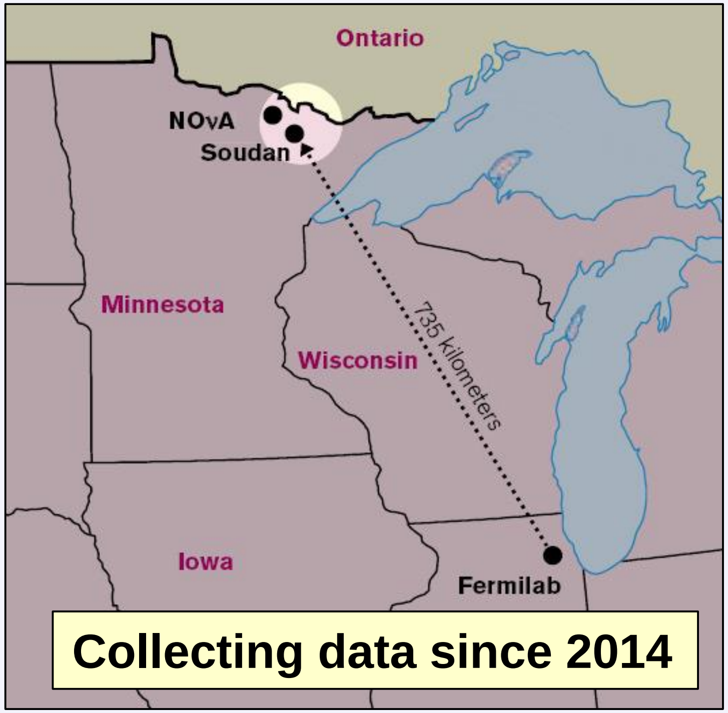
sign $\Delta m_{32}^2 = ?$

$\delta = ?$

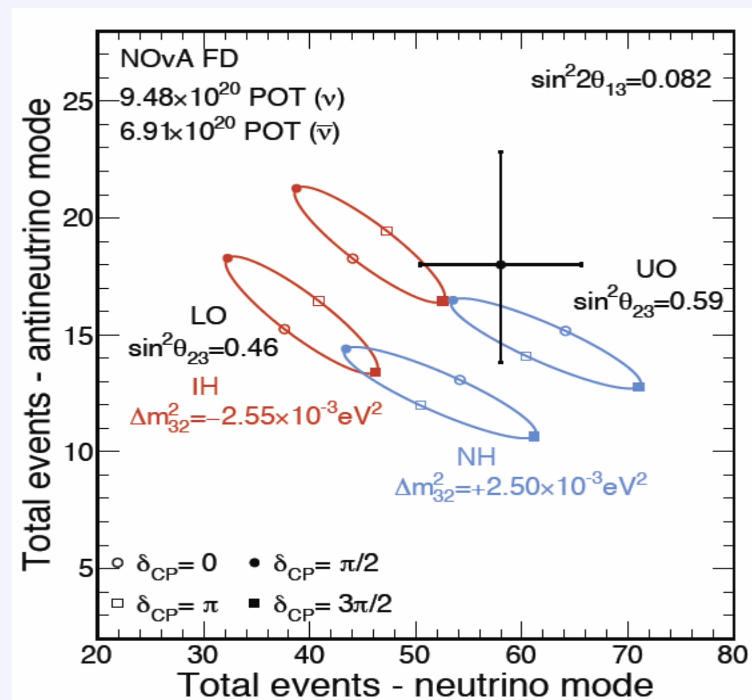




NOvA Experiment at Fermilab

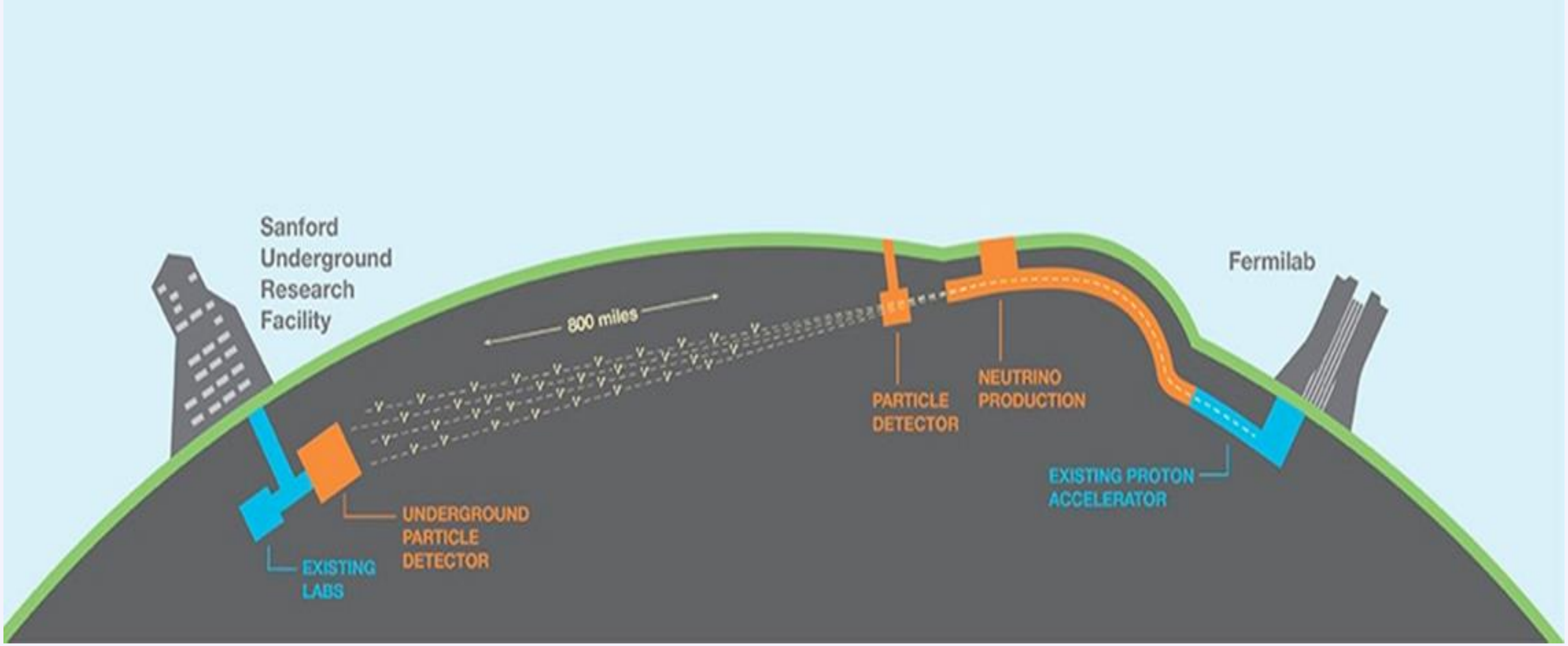


- "Off axis" neutrino experiment with 14 kton far detector and 300 ton near detector
  - 3σ mass hierarchy sensitivity
- Summer 2018 results
  - Observed 18 events in anti-neutrino beam
    - 4σ evidence of electron anti-neutrino appearance in long-baseline beam
  - Favor normal mass hierarchy at 2σ



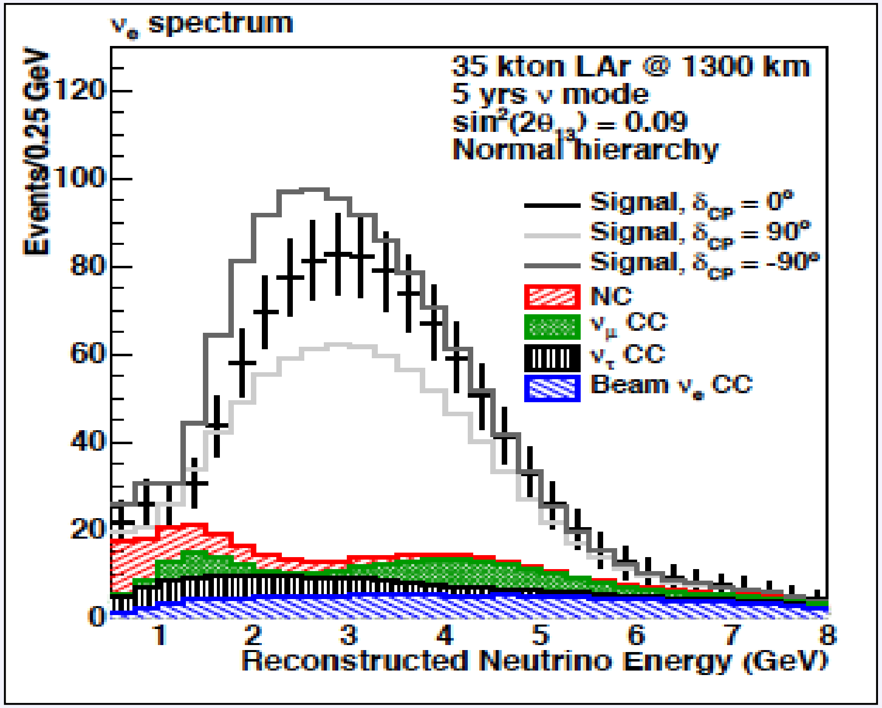
Projects Overview: LBNF and DUNE

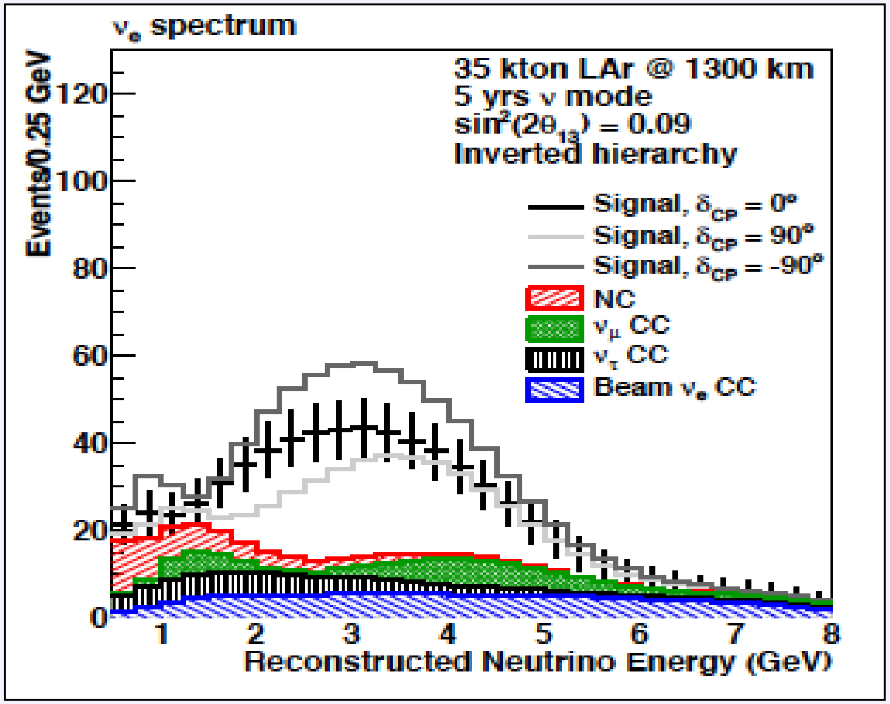
- **LBNF**: DOE project with support from non-DOE partners. Provides facility infrastructure at two locations to support the experiment
  - **Near site**: Fermilab – facilities to **create neutrino beam**
  - **Far site**: Sanford Underground Research Facility, South Dakota
- **DUNE**: Deep Underground Neutrino Experiment – 40 kt of LAr at Stanford
  - **Near and far site detectors**: U.S. as **partner** in international project



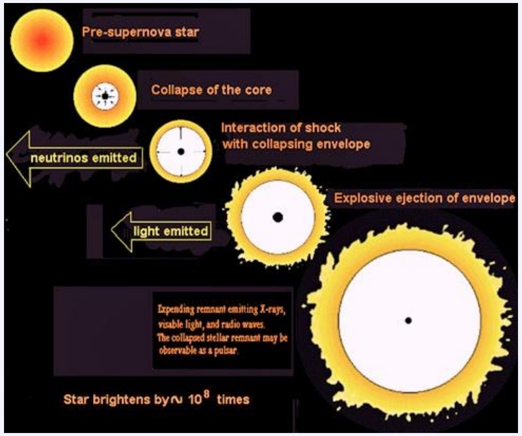
DUNE Experiment Physics Program

Normal hierarchy | **Inverted hierarchy**

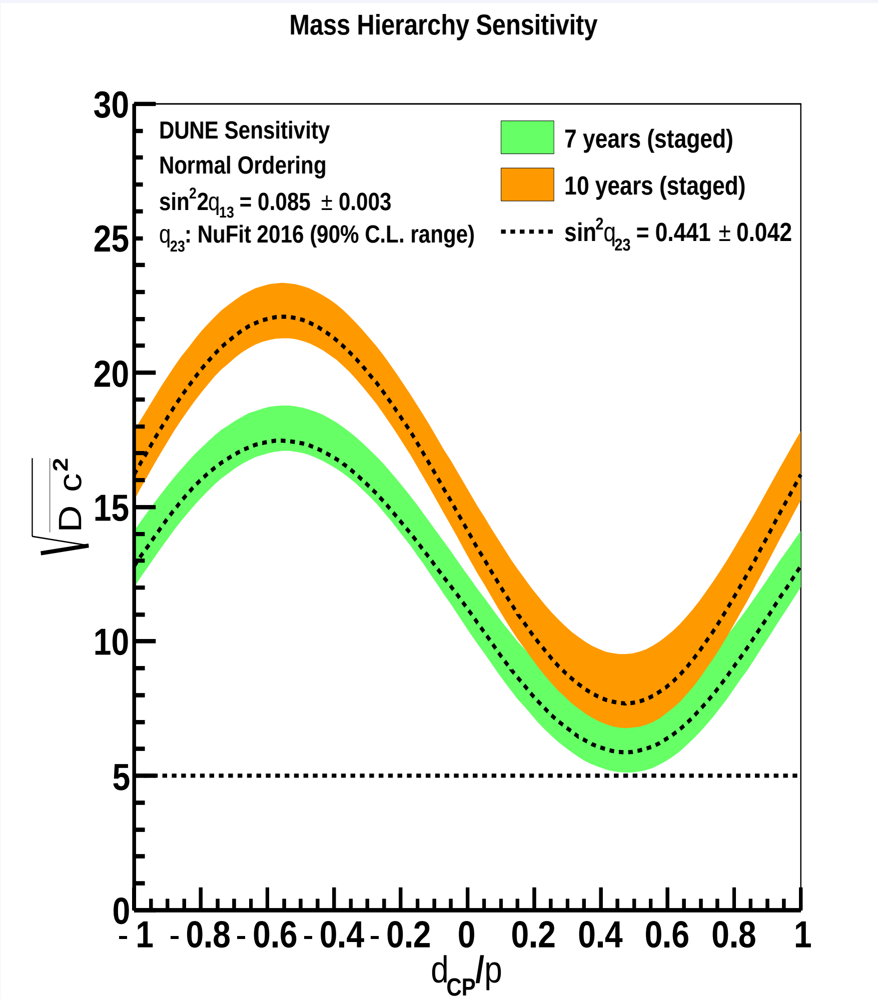


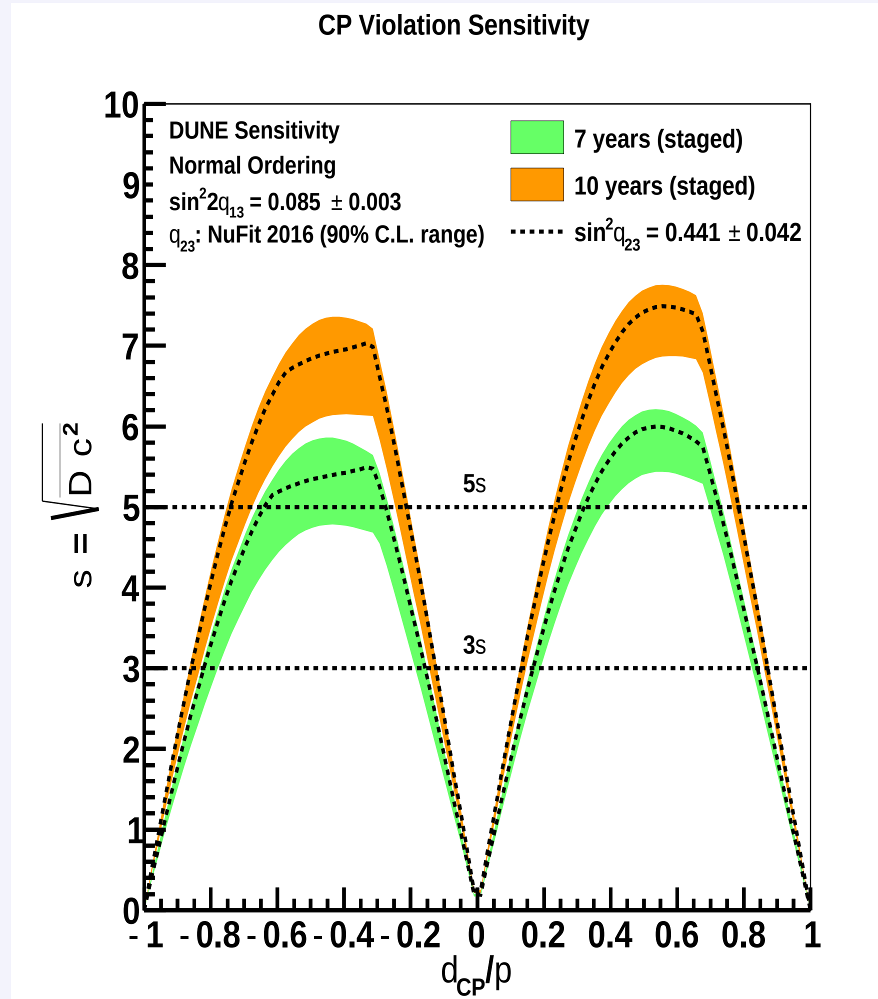


- **Neutrino oscillation physics**
  - **CP Violation in the leptonic sector**
  - **Mass Hierarchy**
- **Nucleon decay**
- **Supernova burst physics and astrophysics**



Mass Ordering and CP Violation Reach





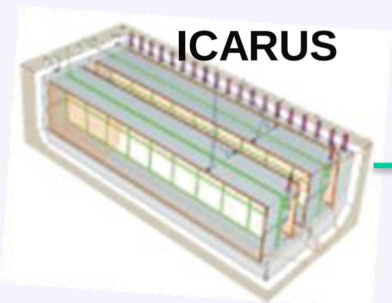
Excellent prospects in wide range of parameters space

LAr-TPC Development Path

Fermilab and CERN neutrino platform provide a strong LArTPC development and prototyping program

Single-Phase

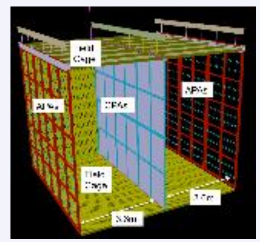
ICARUS



2015

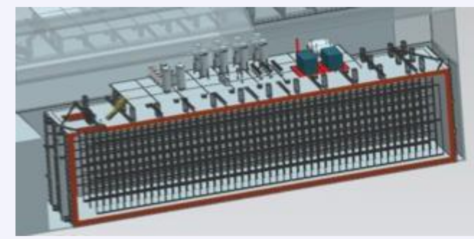
MicroBooNE

2018



ProtoDUNE at CERN

DUNE Reference Design



Dual-Phase

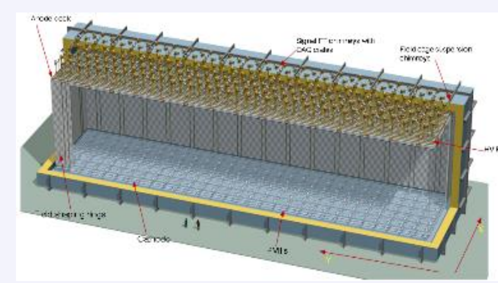
2016

WA 105

2018

WA 105

DUNE Alternative Design



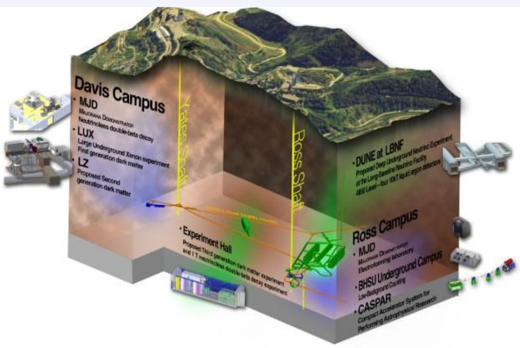
DUNE Collaboration

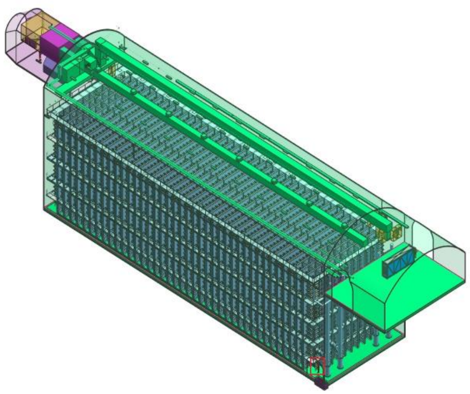
- 1132 collaborators from 179 institutions in 32 countries
- 624 faculty/scientists, 188 postdocs, 106 engineers, 214 PhD students
- Growing at a rate of about 100 collaborators/year

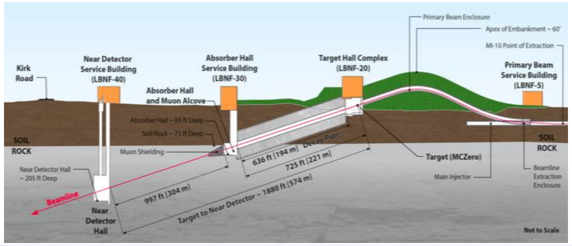
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

Recently joined: Portugal

LBNF/DUNE Timeline







2017: Far Site Construction Begins

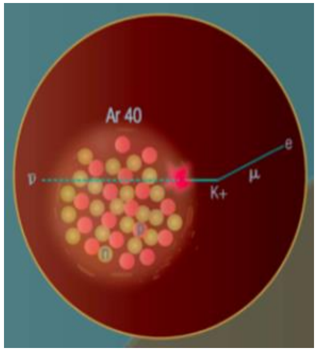
2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

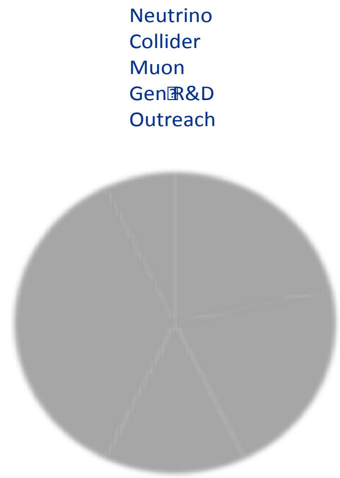
2026: Neutrino Beam Available

The CERN Neutrino Platform



Fermilab Test Beam Facility - FTBF

The Fermilab Test Beam Facility



- Since 2005, FTBF has hosted more than 1000 users from 177 institutions and 30 countries
  - Broad range of research topics, not just HEP
- Two beamlines
  - MTest: 120 GeV protons, 2-80 GeV mix
  - MCenter: 200 MeV to 80 GeV mix

Test beams operate ~10 months per year, except July-August shutdown

Test beam experiments from a few hours to a few months are welcome!

Fermilab Accelerators Long Range Plan

Fermilab Program Planning 5-April-18

LONG-RANGE PLAN

		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF / PIP II	SANFORD				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	
	FNAL					LBNF	LBNF	LBNF	LBNF	LBN F	LBNF	LBNF	LBNF	LBNF	
NuMI	MI	MINERv	MINERv	OPEN	OPEN	OPEN	OPEN	OPEN							ν
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA							
BNB	B	μBooNE	μBooNE	μBooNE	OPEN	OPEN	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	OPEN			OPEN	OPEN	OPEN	OPEN	
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN			OPEN	OPEN	OPEN	OPEN	
Muon Complex		g-2	g-2	g-2					LONG SHUTDOWN					OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	Mu2e	OPEN	
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	p
	NM4	OPEN	E1039	E1039	E1039	E1039	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	

Construction / commissioning · Run · Subject to PAC review · Shutdown

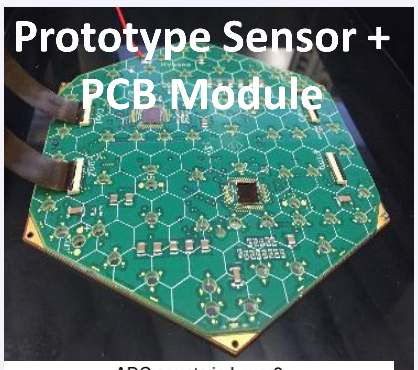
Capability ended · Capability unavailable

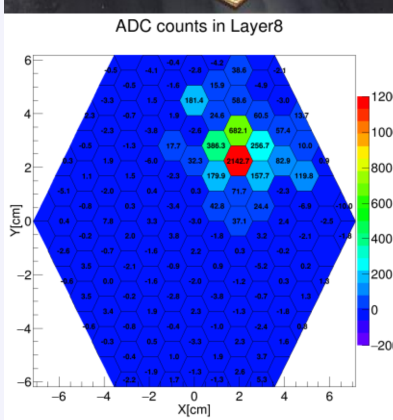
NOTES:
1. Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning. Assume, with contingency, 5.5 years data taking.
2. DUNE: 1st 10kT detector module commissioned in FY24. Runs without beam FY25 to mid-FY26.
3. NOvA runs as long as possible [in the spirit of PAC Nov 2017].
4. Assume NuMI in nubar mode through FY19 - facilitates 12E20 POT for MINERvA [PAC Nov 2017]. Assumption may need revision.
5. Assume g-2 completed before Mu2e commissioning start mid-FY20. Very tight. Needs scrutiny.
6. Assume E1039 fully approved & commissioned by mid-FY19.
   Experiment estimates 2 yrs run. Add 1 yr contingency. [Stage 1 approval PAC June 2013, update July 2017]
7. FY19 and FY20 MicroBooNE running subject to future PAC review [PAC July 2017].

Fermilab Coordinates US-CMS Program

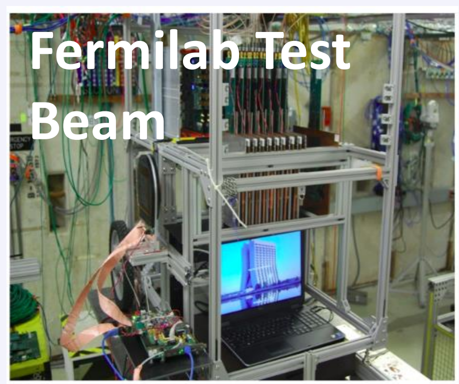
- CMS is steady progressing with FNAL making critical contributions
  - ~50 Fermilab's scientists involved
- Phase 1 upgrades are on track
- HL-LHC upgrades are under development
  - Major project with over $200 million U.S. contribution
- LHC Accelerator Research Program (LARP) is developing interaction region quadroupoles for the high luminosity LHC

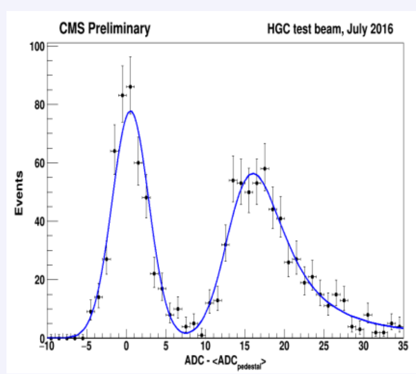
Prototype Sensor + PCB Module





Fermilab Test Beam

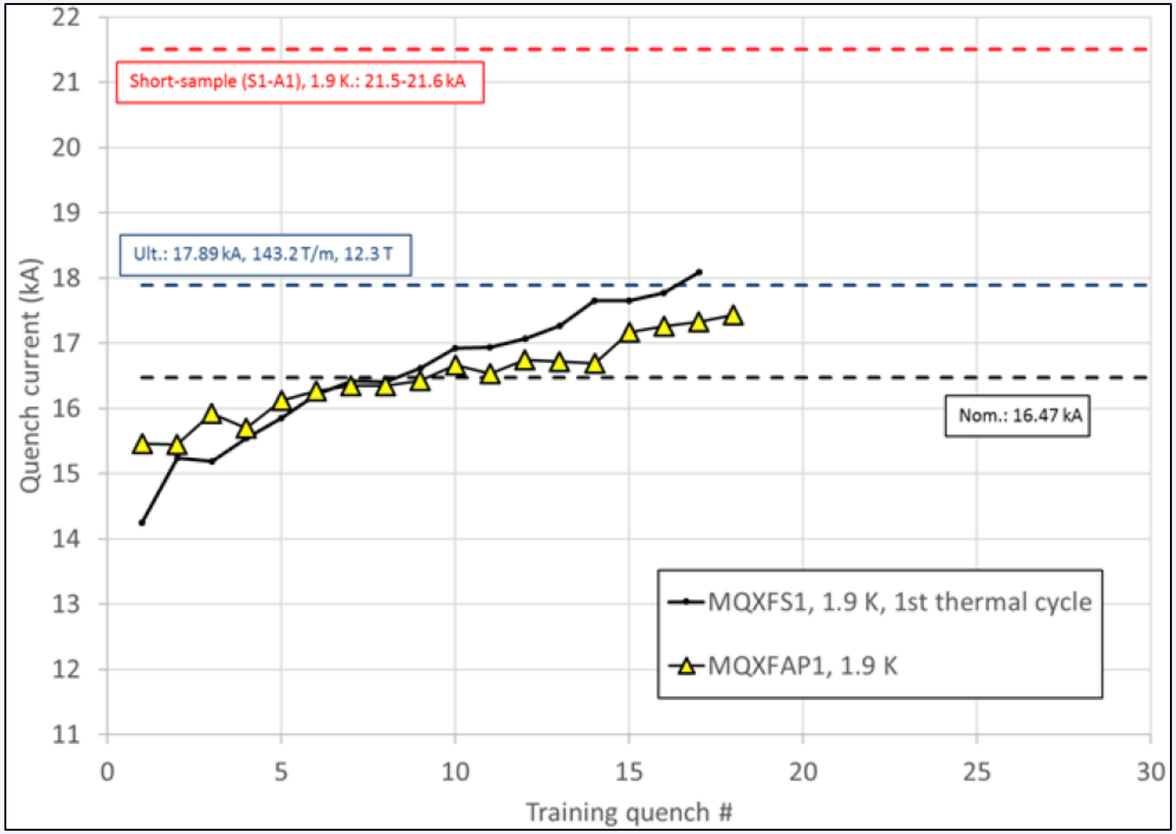




Pixel Detector Reintegration at CERN

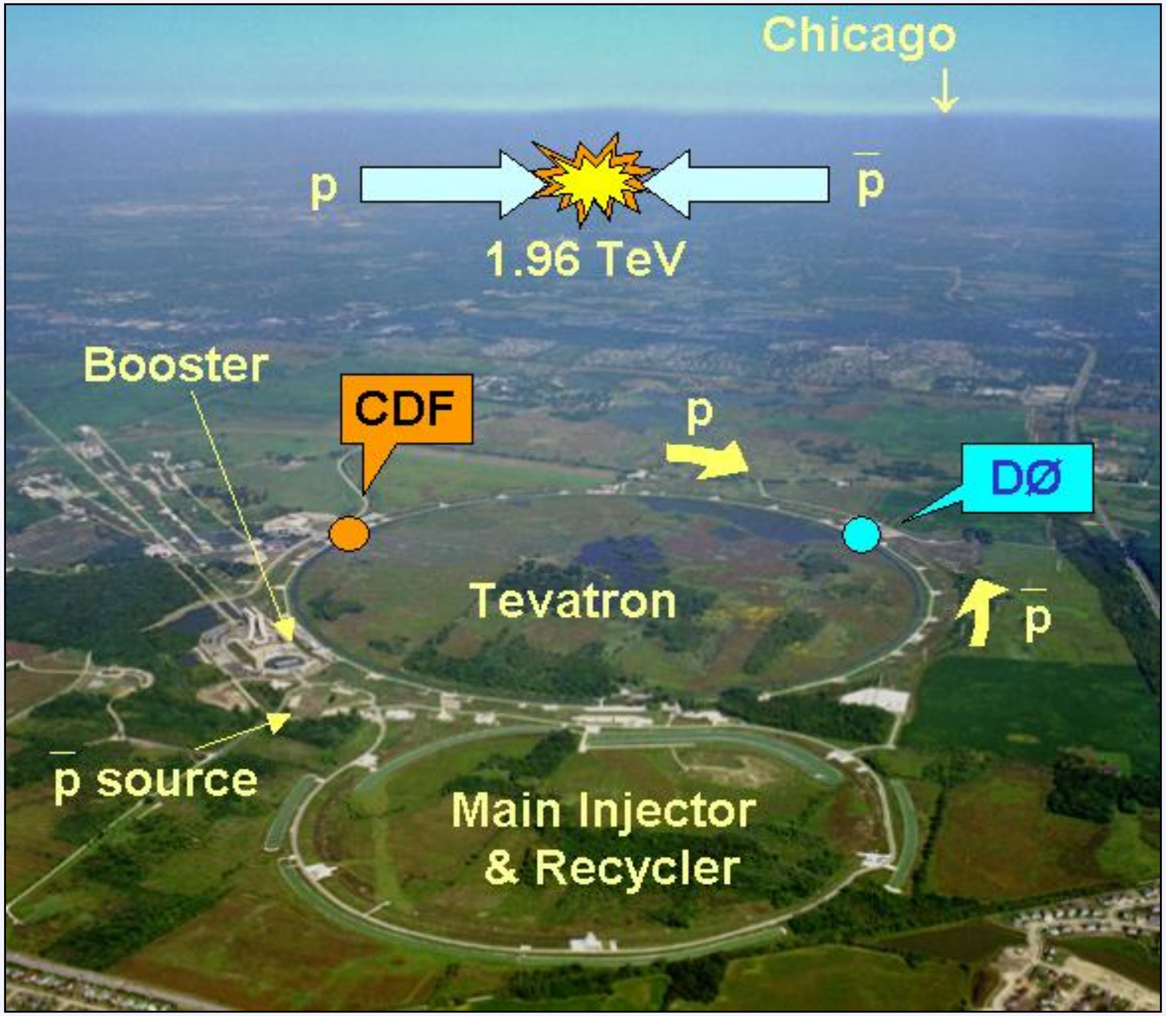
U.S. HL-LHC Accelerator Upgrade Project

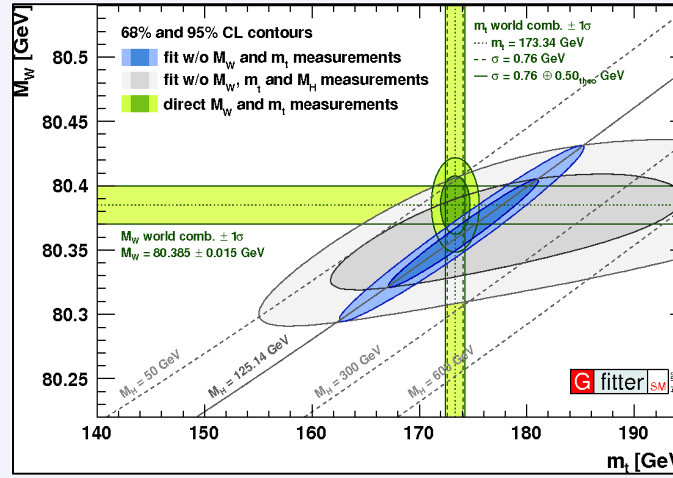
- Niobium-Tin superconducting magnets
- Designed/built/tested in the U.S., shipped to CERN



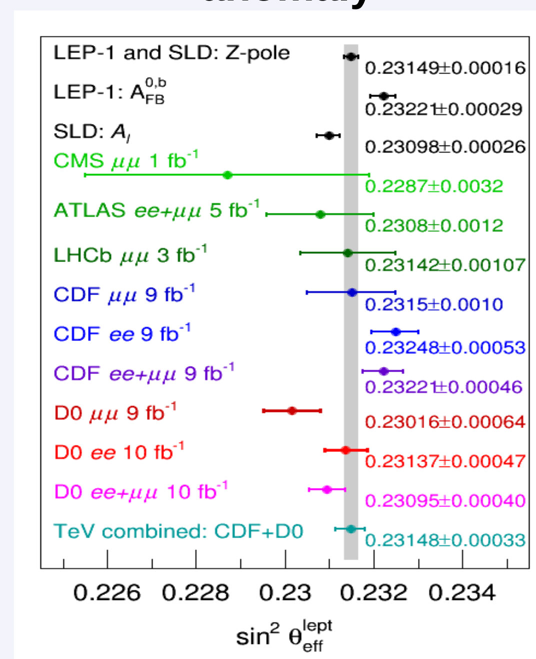
Training of first long prototype magnet reached 97.4% of critical current goal

Tevatron Program



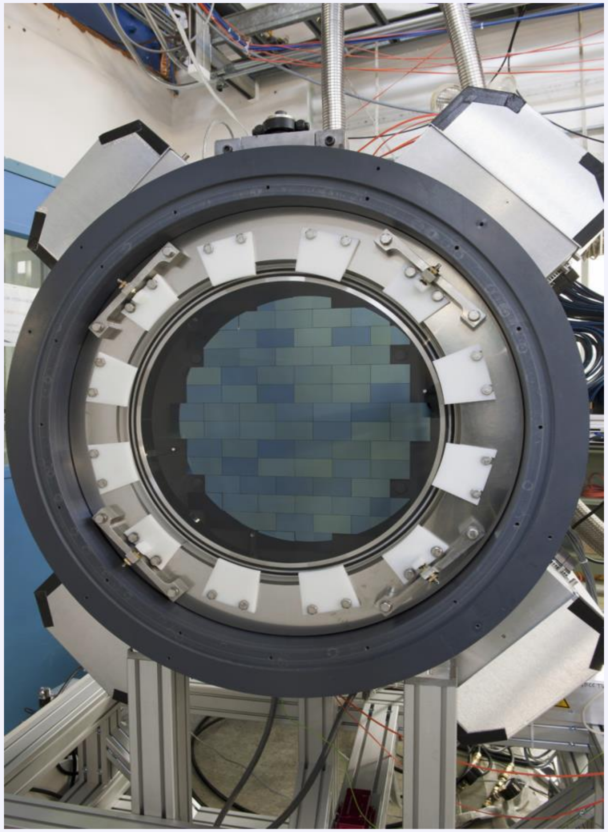


2018 – Tevatron resolves $\sin^2\theta$ anomaly

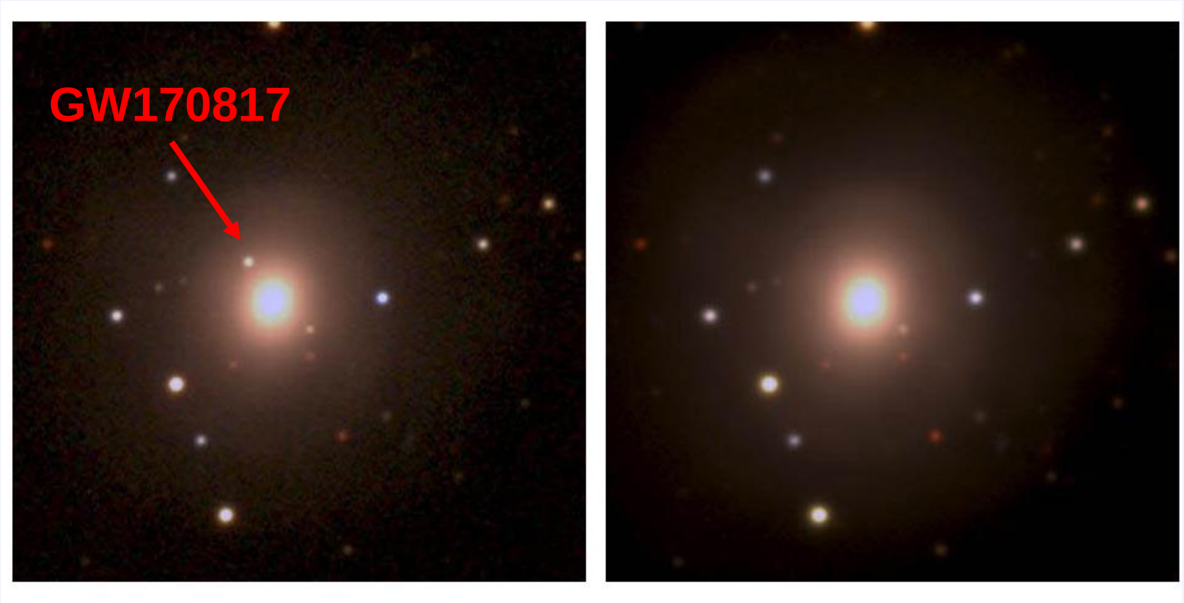


- **From the top quark discovery to the Higgs boson evidence – 25 years program**
- **Over 1200 papers cementing the Standard Model**

Dark Energy Survey - DES

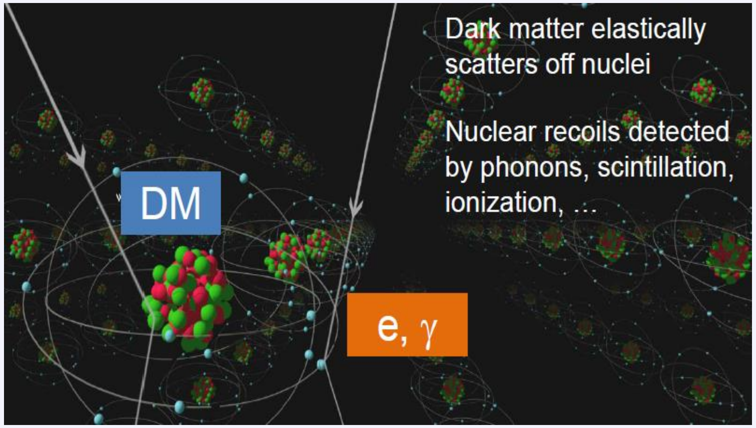


Independent discovery of a binary neutron star a gravitational wave source with electromagnetic counterpart.

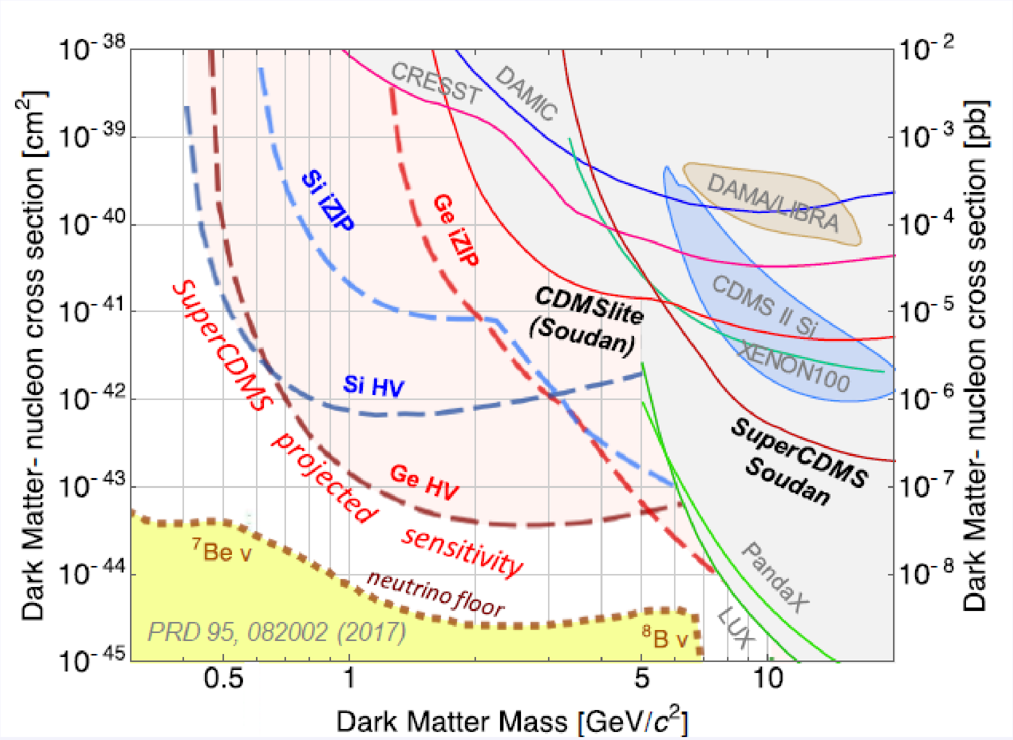


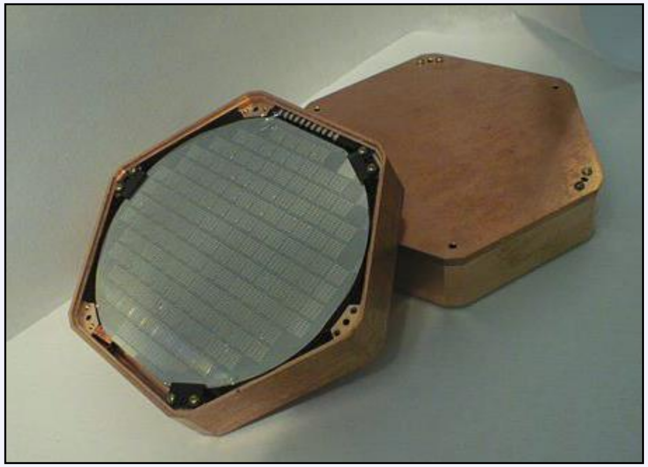
- **DES is creating scans of night sky using 4 meters telescope and 570 megapixels camera (camera built at Fermilab) located in Chile**
  - **Started data collection in September of 2013**
  - **10’s of papers already published or in review**
- **Major scientific areas: studies of dark matter, dark energy, supernova, solar system survey, spectroscopically-confirmed quasars and many other topics**

Dark Matter Direct Detection



- Many models expect dark matter to consist of heavy WIMP particles
- Multiple methods used to detect elastic scattering of WIMPs
  - Ionization, scintillation, phonons
- Fermilab is actively involved in CDMS experiment in Soudan mine (and others)

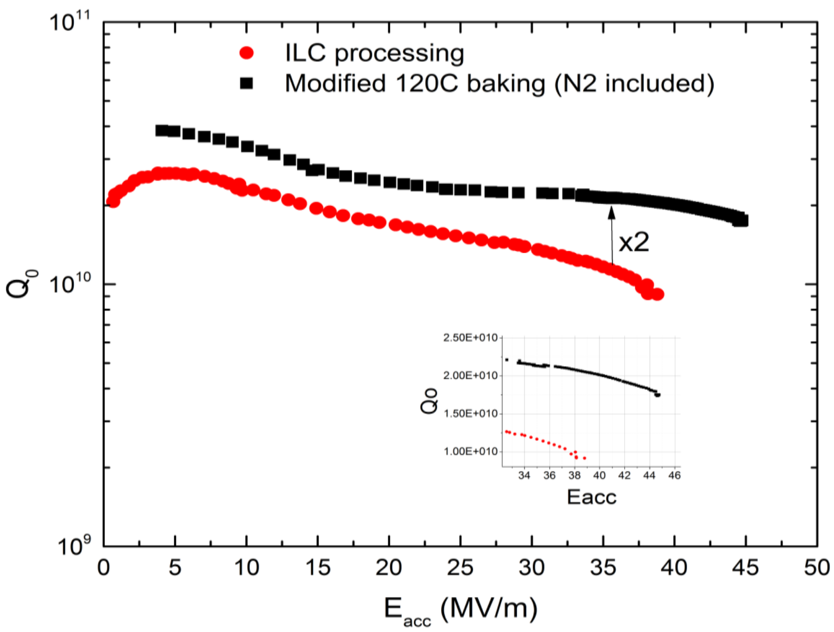




- 9kg SuperCDMS is currently operating at Sudan
- Observed best low mass WIMP limit

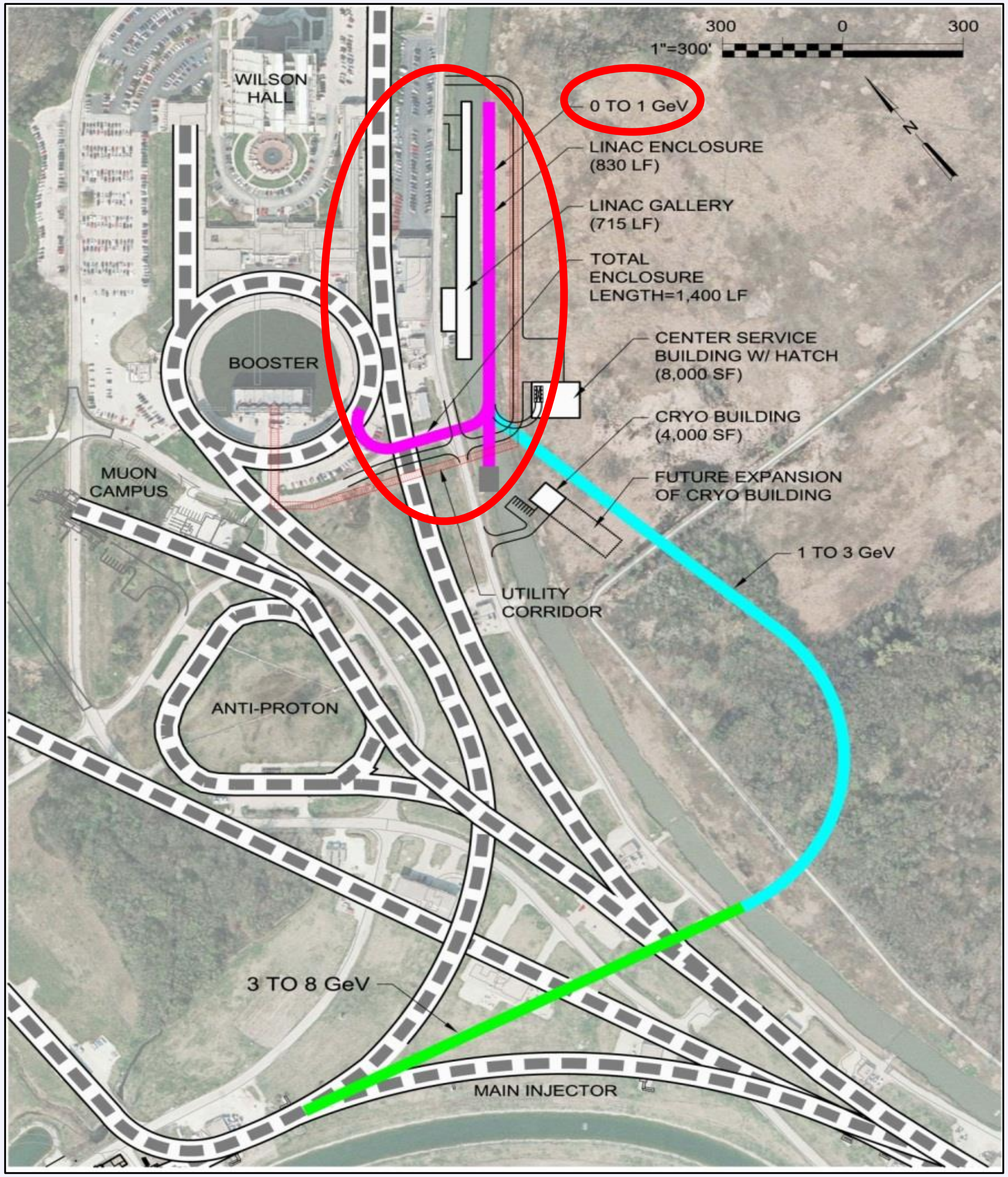
SCRF Developments at Fermilab

Successful nitrogen doping technology transfer to industry for LCLS-II production

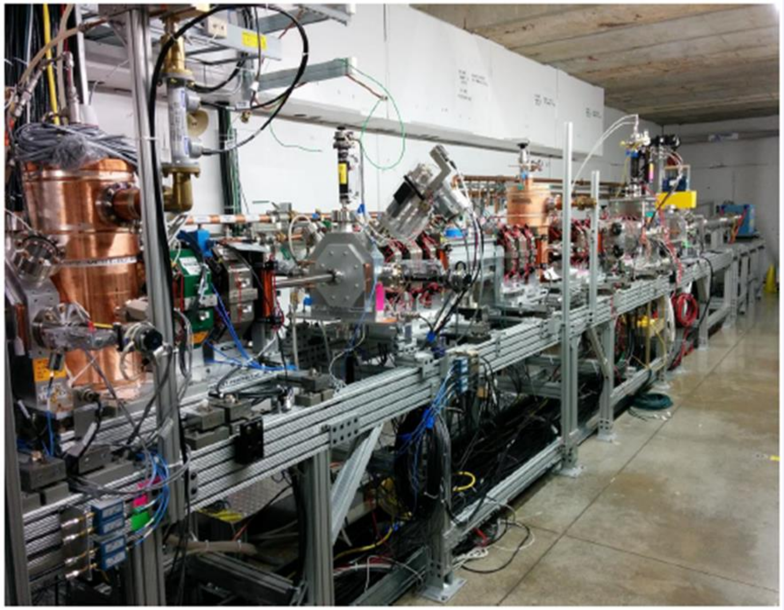


- Superconducting RF is the key technology for the ILC where U.S. is interested to contribute
- Coherence with production of cryo-modules by Fermilab for LCLS-II light source at SLAC and PIP-II upgrade at Fermilab

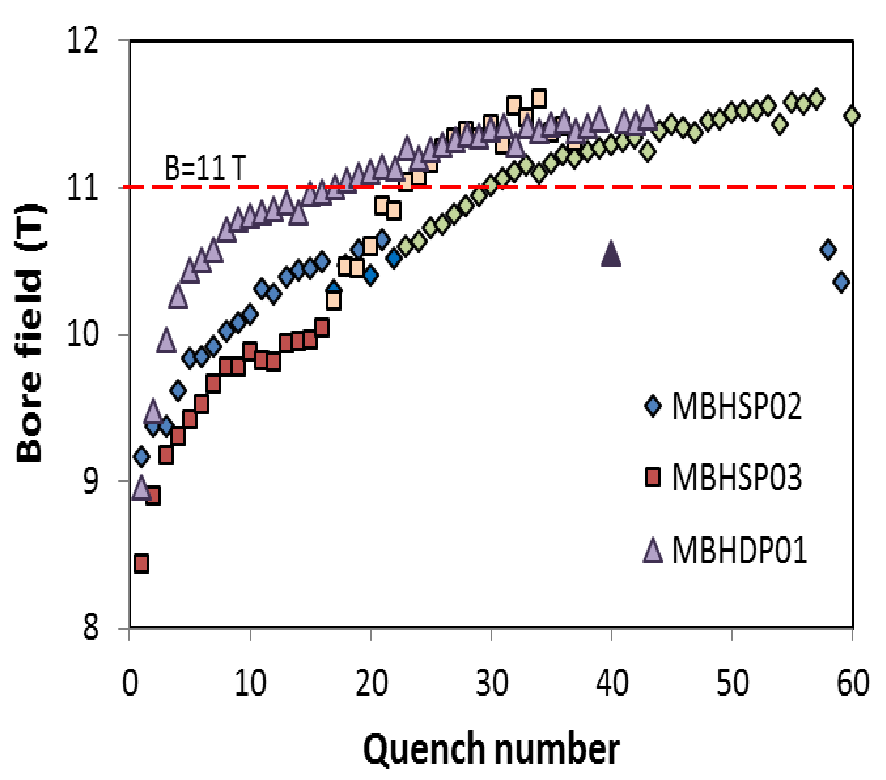
Planned Accelerator Upgrade – PIP II



- Proton linear accelerator with flexible beam structure based on SCRF technology
  - Increase of beam power to ~1 MW
  - Large scale partnership with India
- Platform for future neutrino and muon facilities



High Field Magnets Developments

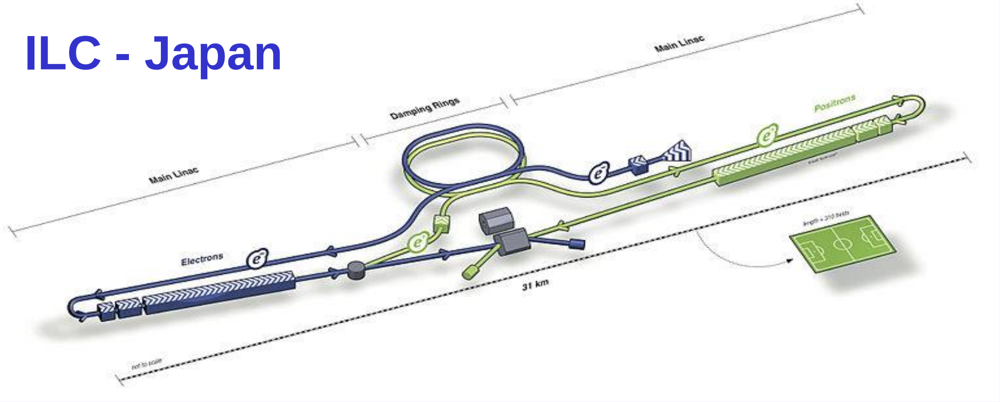


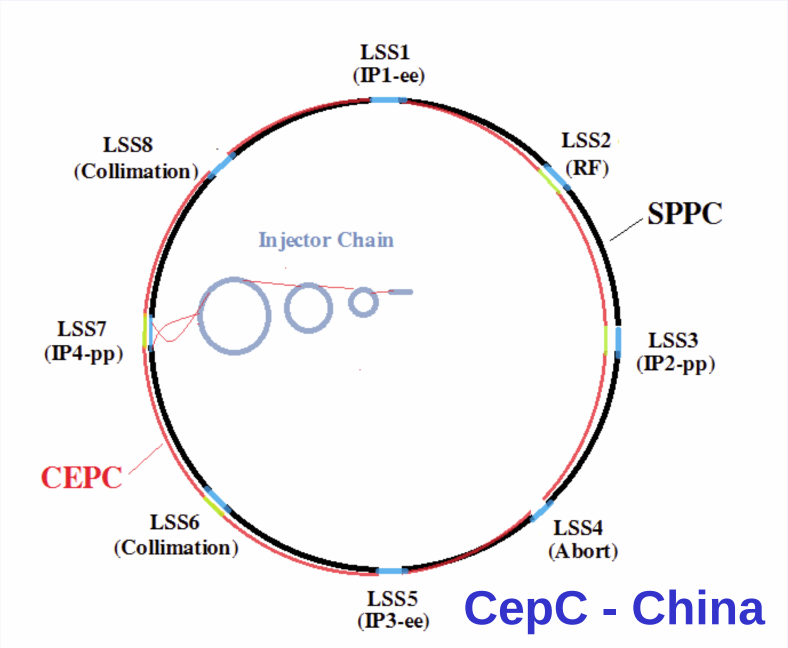
1 meter long Nb_3Sn magnet successfully tested at Fermilab to 11.6T

- Area of Fermilab's experitse since design and construction of the first superconducting accelerator – the Tevatron
- Breakthroughs in materials, systems, engineering are needed for higher fields
- Fermilab focuses on Nb_3Sn (conductor and magnet engineering)
  - Short term goal is to build 15-16 T magnet suitable for FCC at CERN

Future Energy Frontier Colliders

ILC - Japan





CepC - China

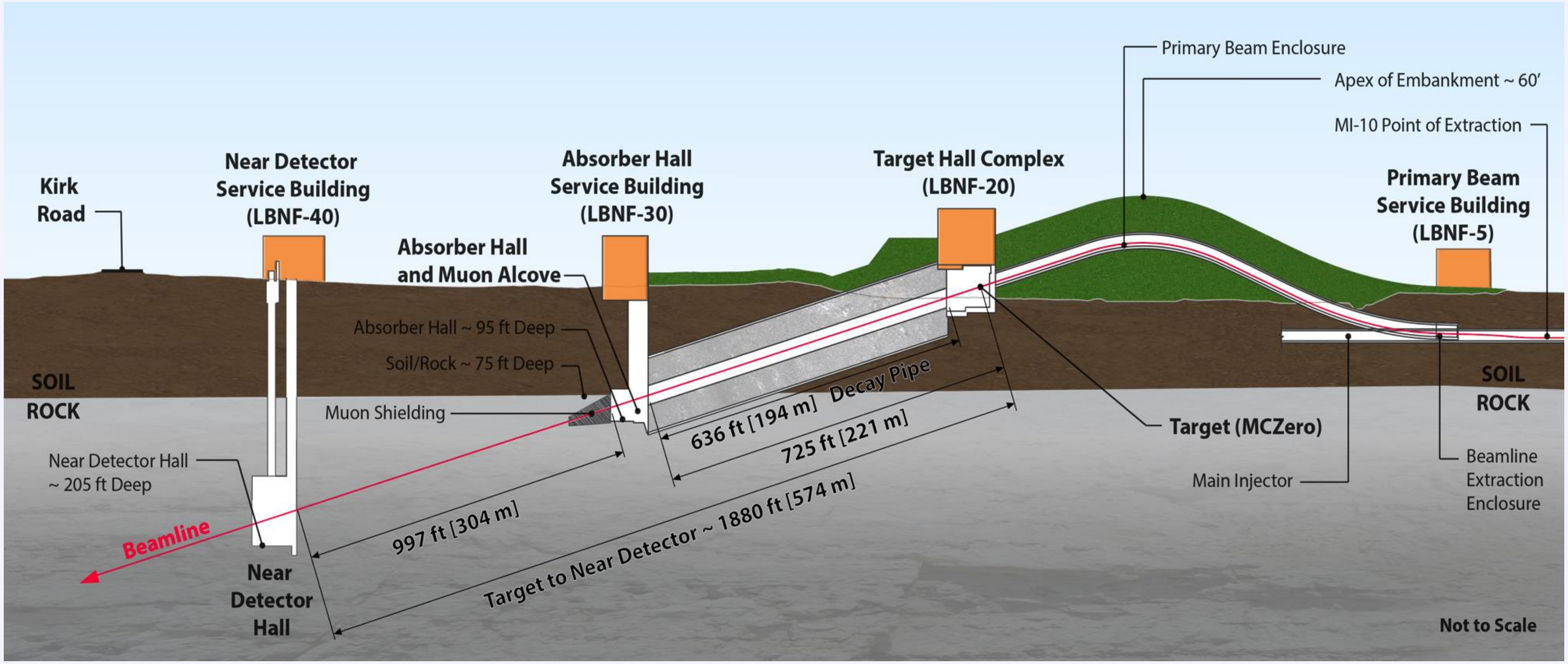
- **Fermilab is participating in future colliders developments, including ILC and FCC**
  - **Based on Fermilab's experience in accelerator and detector technologies**

Fermilab Program Overview

- Accelerator complex is running providing powerful beams
- LHC Run 2 is progressing, CMS detector is running well
- LBNF/DUNE program is actively progressing
- NOvA and MicroBooNE neutrino experiments all running well
- g-2 experiment collecting data
- Mu2e experiment construction actively progressing
- Experiments on direct dark matter search progressing
- The Dark Energy Survey produces excellent results
- Developing future accelerator/detector technologies
- Theory group supporting LHC, neutrinos, lattice
- Several Tevatron analyses are concluding
- Involvement in future colliders activities, including ILC

Backup Slides

Overview - Near Site – LBNF/DUNE at Fermilab



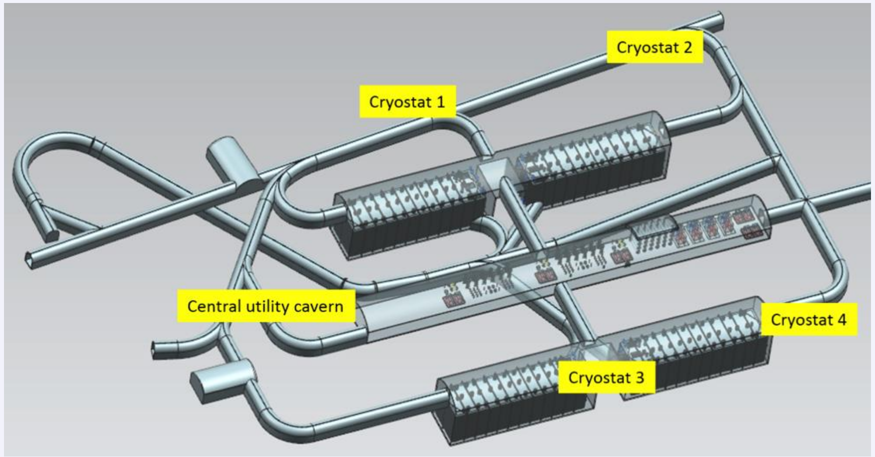
- Primary proton beam at 60-120 GeV extracted from the Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankment allows target complex to be at grade and neutrino beam to be aimed to South Dakota mine
- Decay region followed by the absorber
- Four surface support buildings
- DUNE Near Detector

Beamline design based on Fermilab's NOvA beam, currently the most powerful neutrino beam in the world

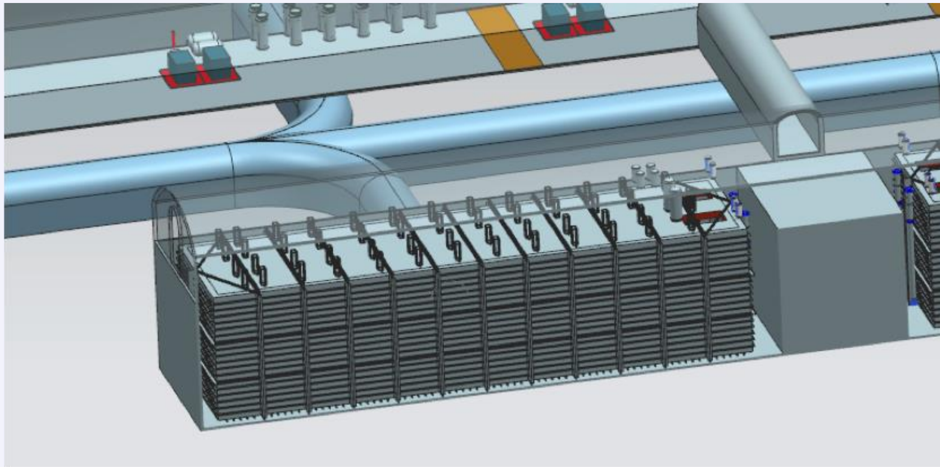
Overview – Far Site – LBNF/DUNE at South Dakota

- **Conventional Facilities**:
  - Two **caverns** for detectors and connection tunnels
  - **Central utility cavern** for conventional and cryogenic equipment
  - **Surface** and **shaft** Infrastructure including utilities
- **Cryostats**:
  - Four **membrane** cryostats supported by external steel frames
- **Cryogenic Systems**:
  - **LN_2 refrigeration system** for cooling and re-condensing gaseous Argon
  - Systems for **purification** and **recirculation** of LAr
- **Argon**: **70kt LAr** (~40kt fiducial mass)
- **DUNE LAr-TPC Detectors**

Extensive prototyping program in progress to scale LAr TPC detector technology to 10kt fiducial volume

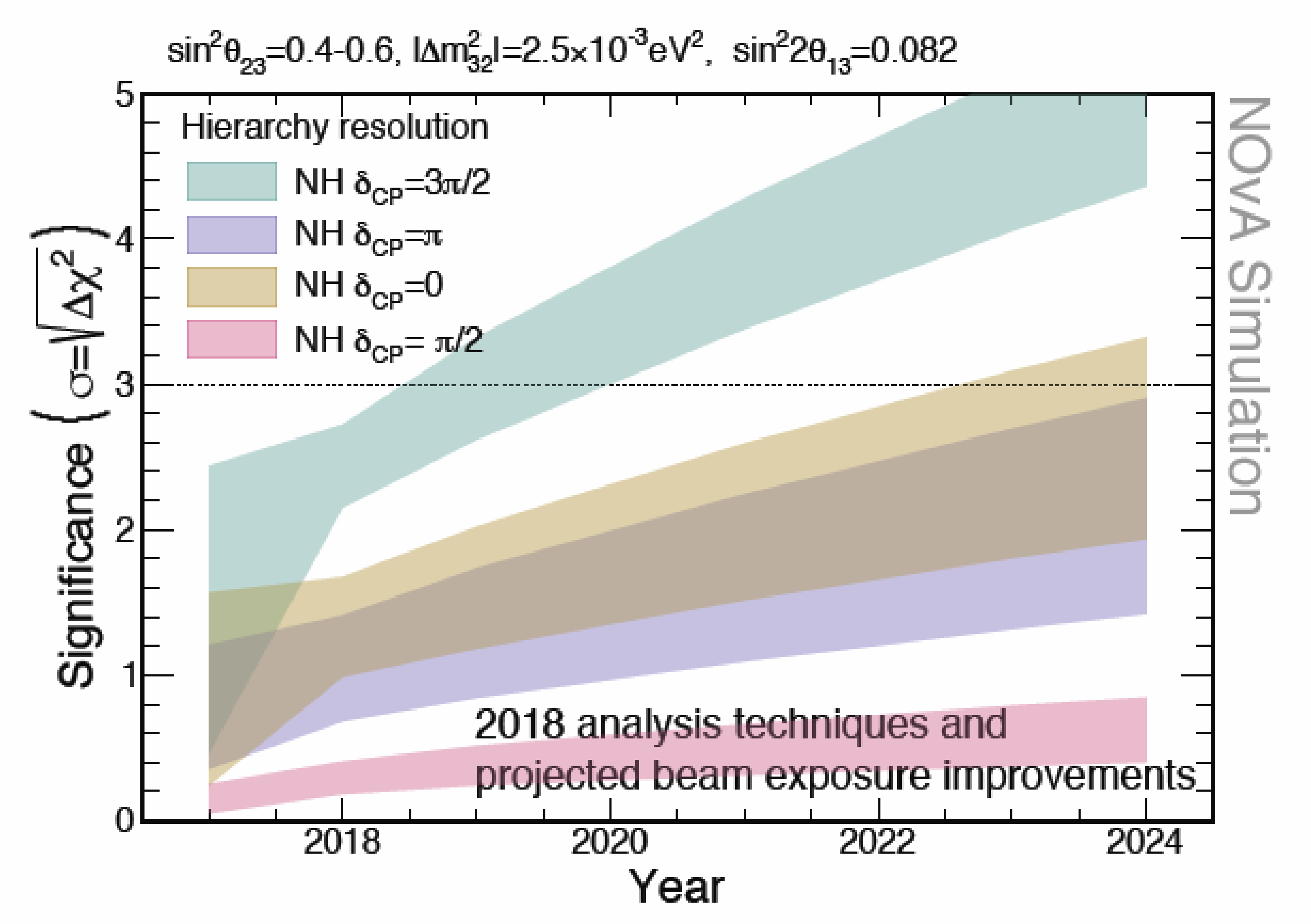


DUNE caverns and tunnels layout



Single cryostat

NoVA Projections



- **Will resolve mass hierarchy at 3σ by 2020**
- **Have a good chance for 3σ measurement of δ_{CP} by 2024**

LBNF / DUNE

2017 - 50 years of Fermilab

LBNF / DUNE