

# Fermilab Program and Plans

Dmitri Denisov, Fermilab

Instrumentation for Colliding Beam Physics, February 27 2017



# U.S. Particle Physics Strategy



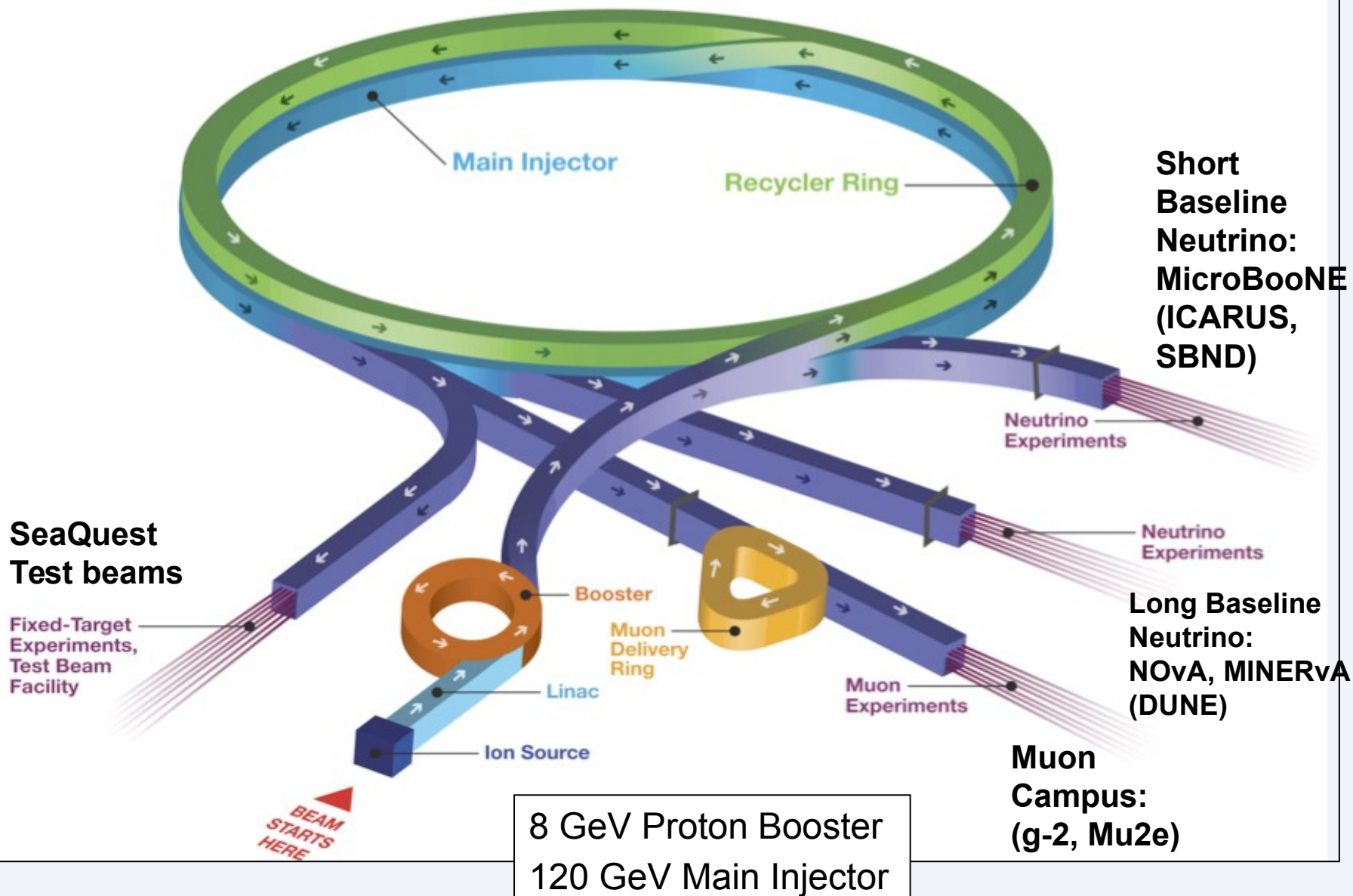
- In 2014 U.S. strategic planning panel provided recommendations covering all main topics of the U.S. particle physics
- They are grouped around “science drivers”
  - Use the **Higgs boson** as a new tool for discovery
  - Pursue the physics associated with **neutrino mass**
  - Identify the new physics 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”



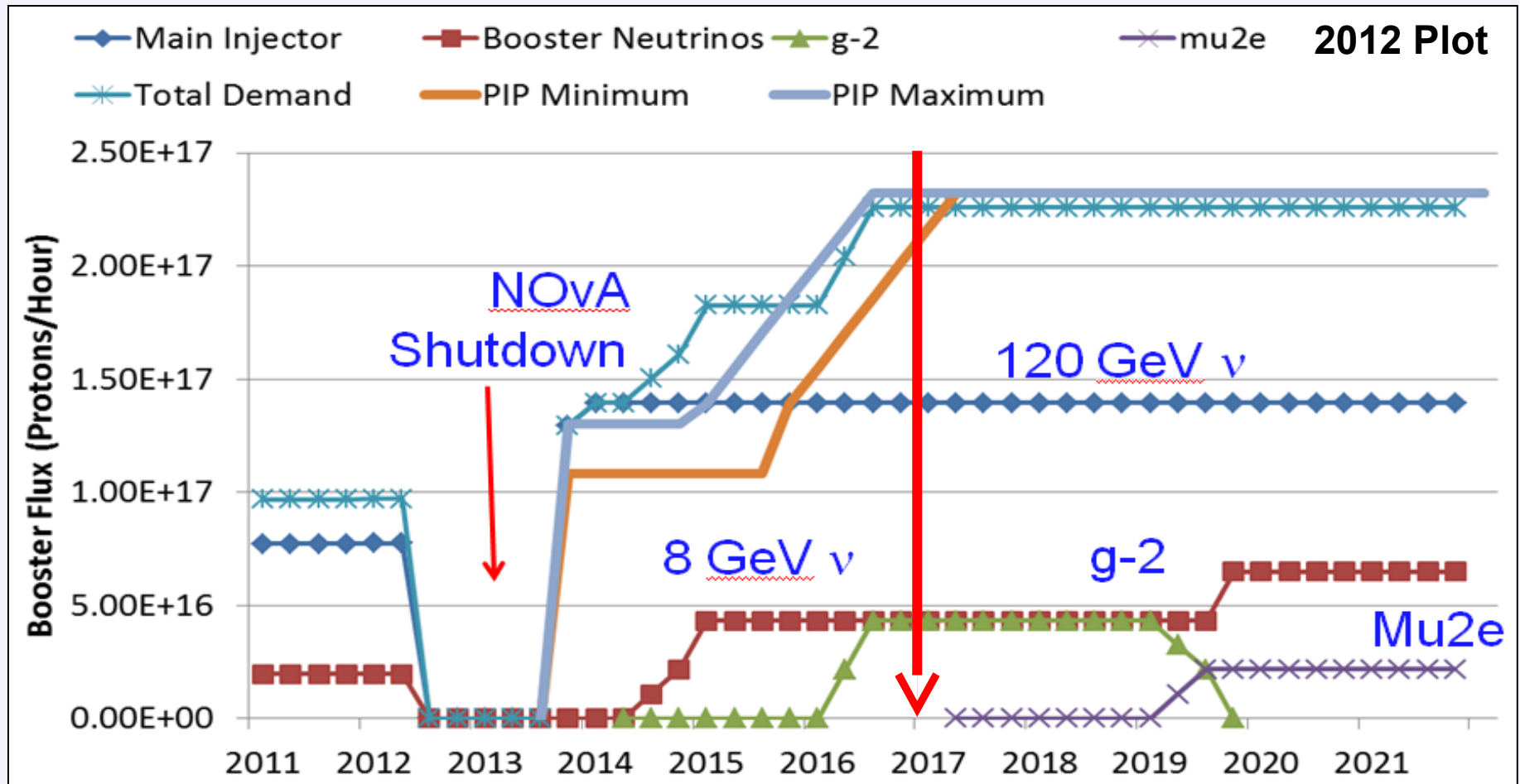




# Fermilab Accelerator Complex



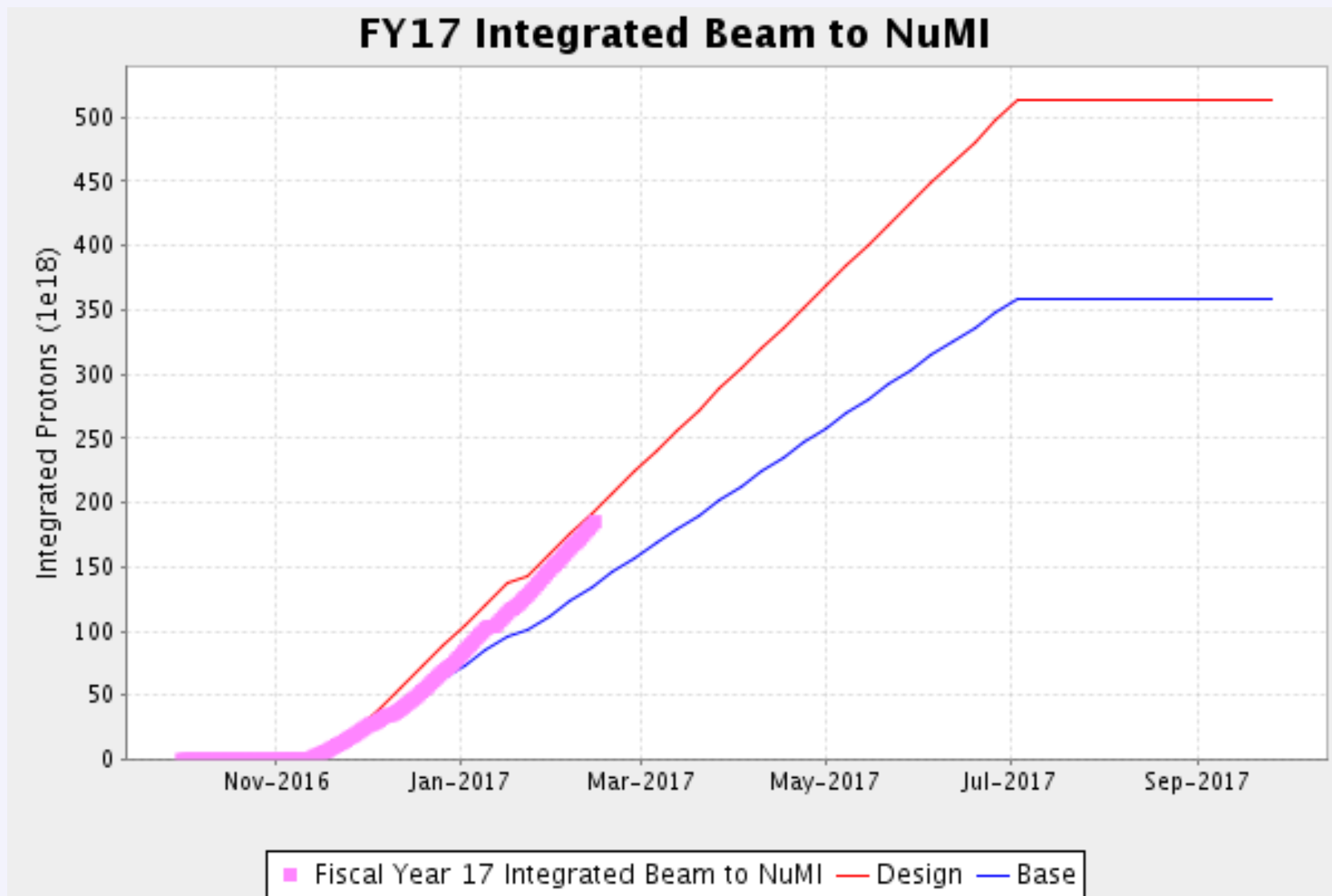
# Long Term Beam Delivery Plans



- 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 (PIP project)

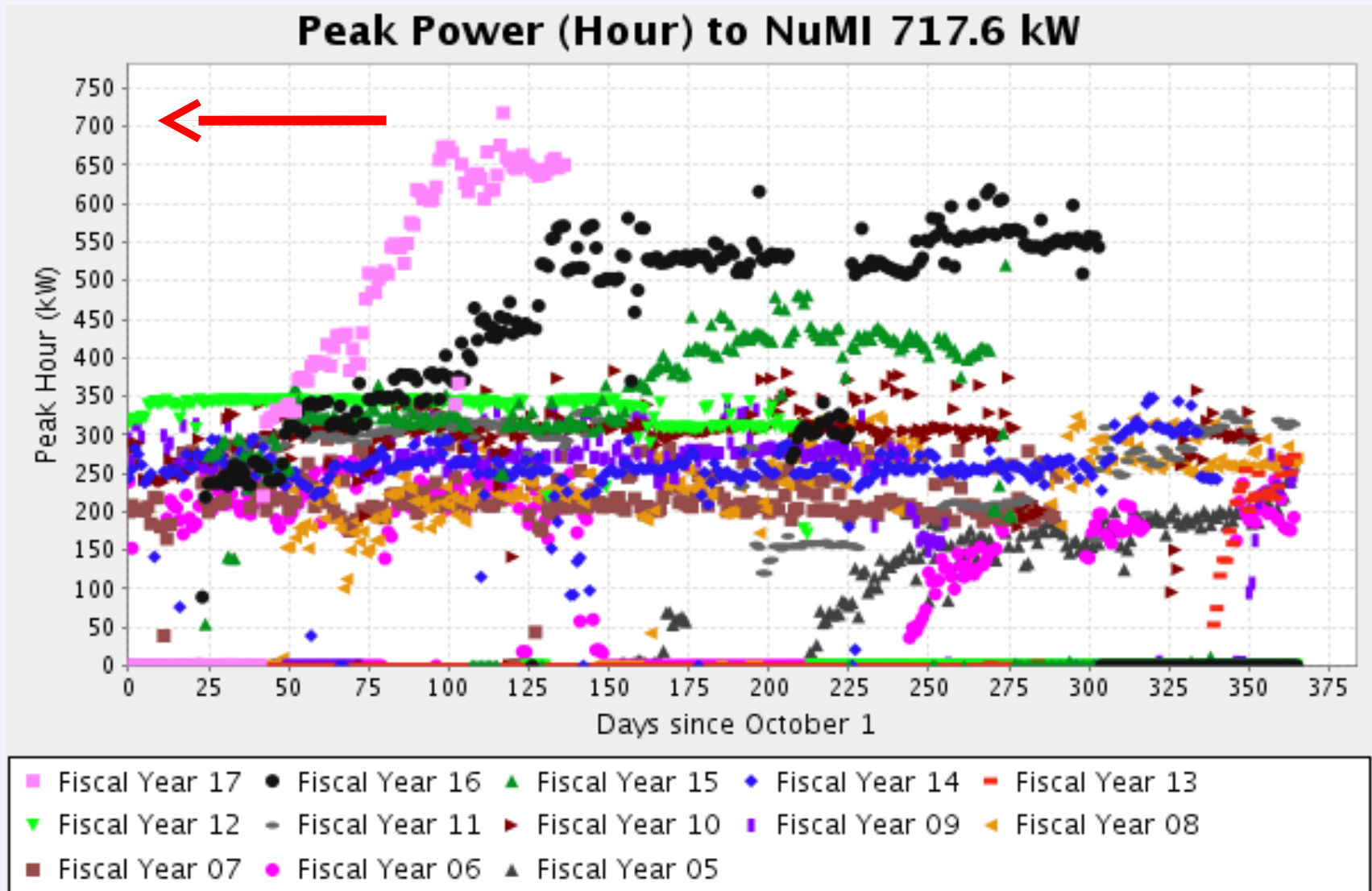


# Main Injector Beam Delivery in FY 2017



**Providing  $\sim 5 \cdot 10^{20}$  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

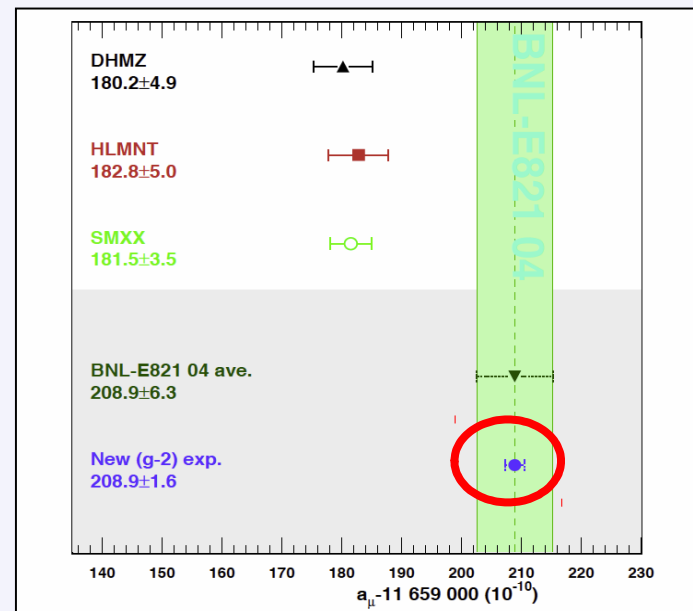
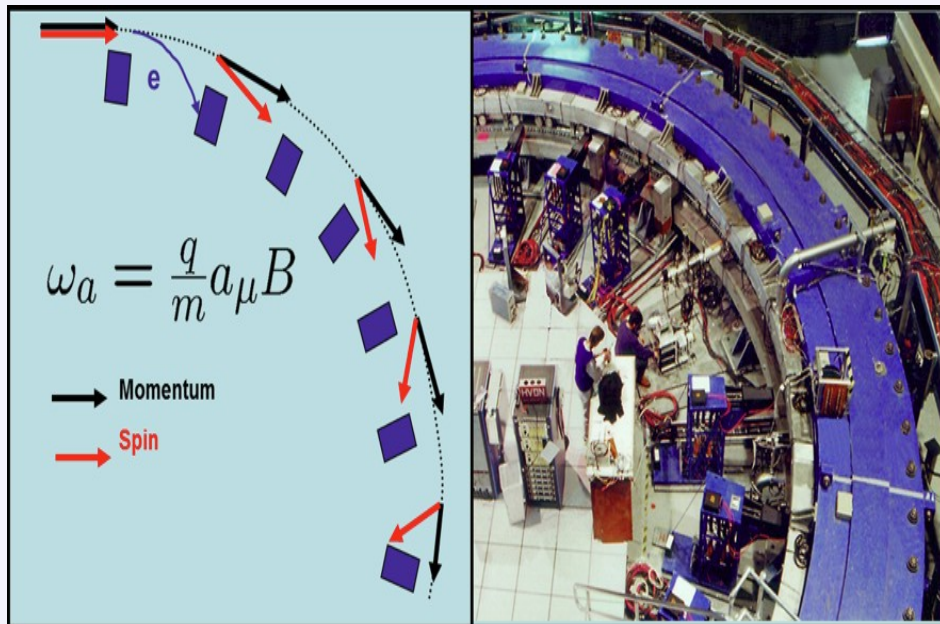
# Fermilab Muon Campus



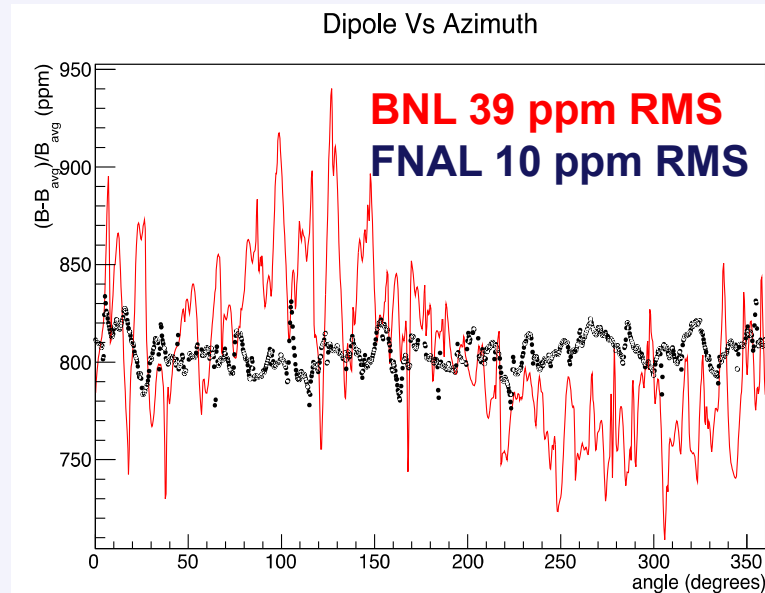
- Re-use of the antiproton production tunnels for muon production/cooling
- First muon beam to g-2 experiment this year, to mu2e experiment in 2020



# Muon Magnetic Moment g-2 experiment



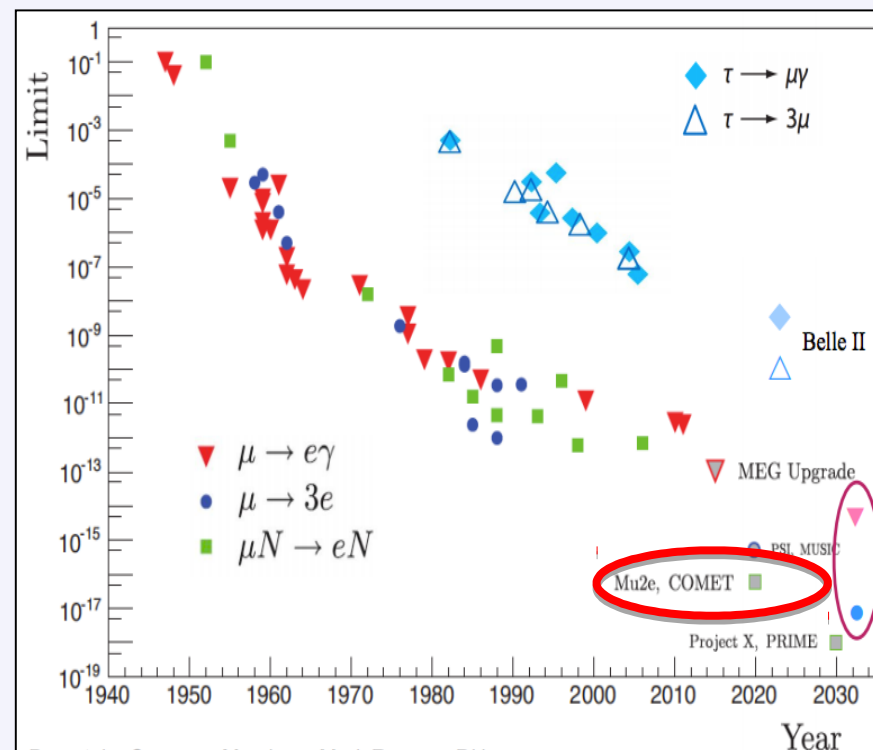
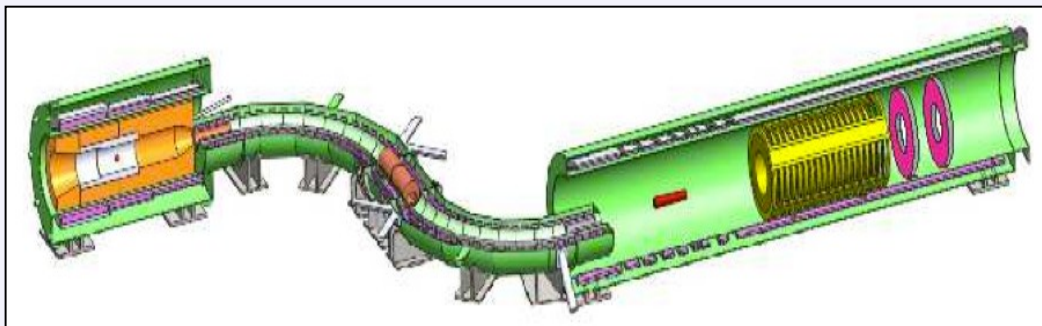
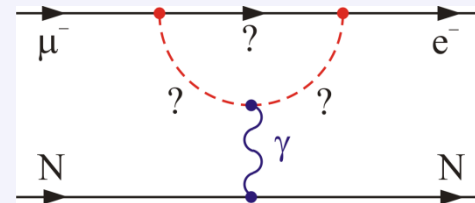
- **Puzzle of ~3σ from BNL 2004 result**
  - New physics?
  - Experimental effect?
- **Coil moved to Fermilab from BNL**
  - Higher intensity beam
  - Better systematics
- ~4 times better accuracy, x20 data by 2019
- Start data collection in 2017



# Lepton Flavor Violation: Mu2e



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

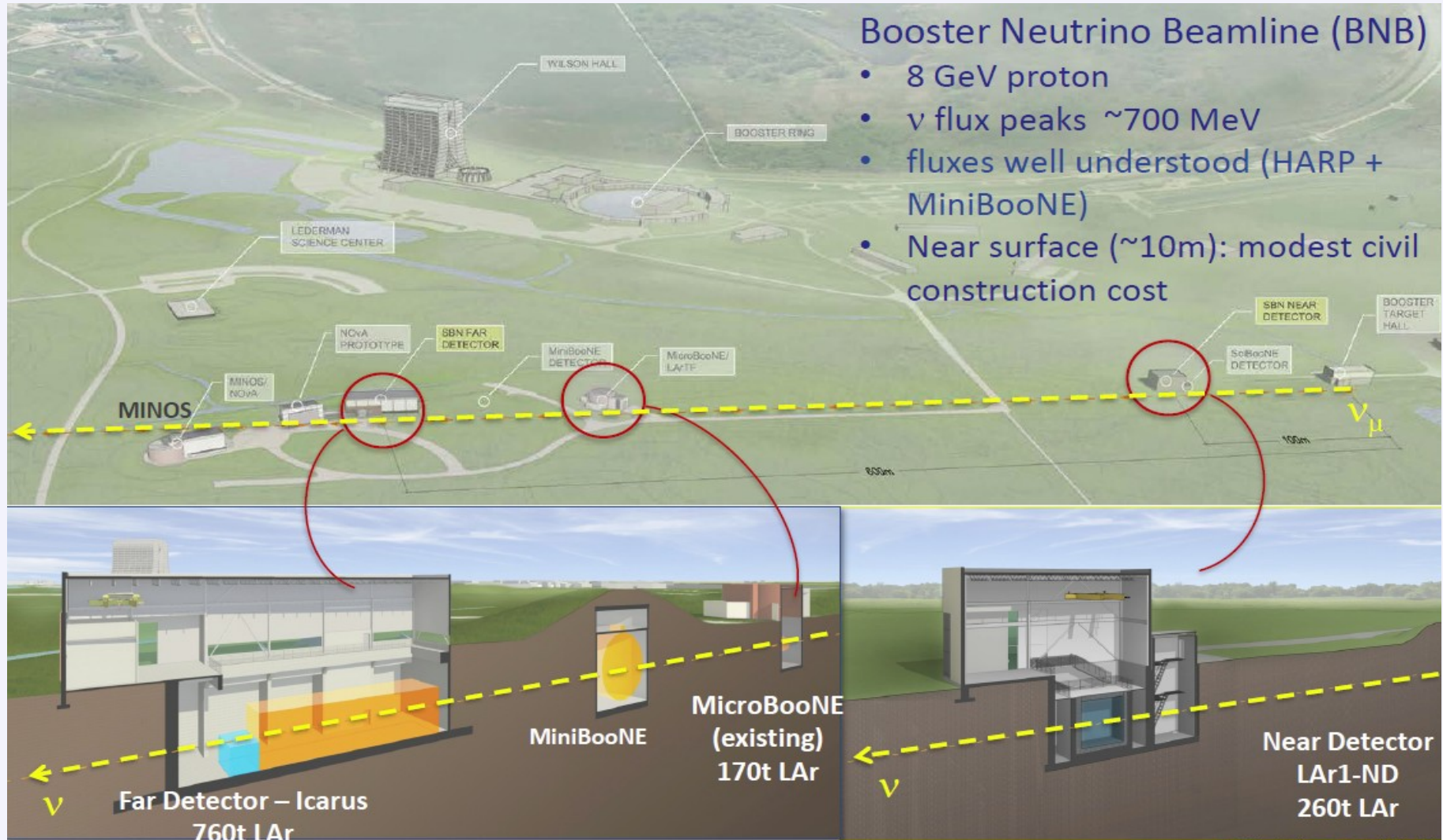




# Short Baseline Neutrino (SBN) Program

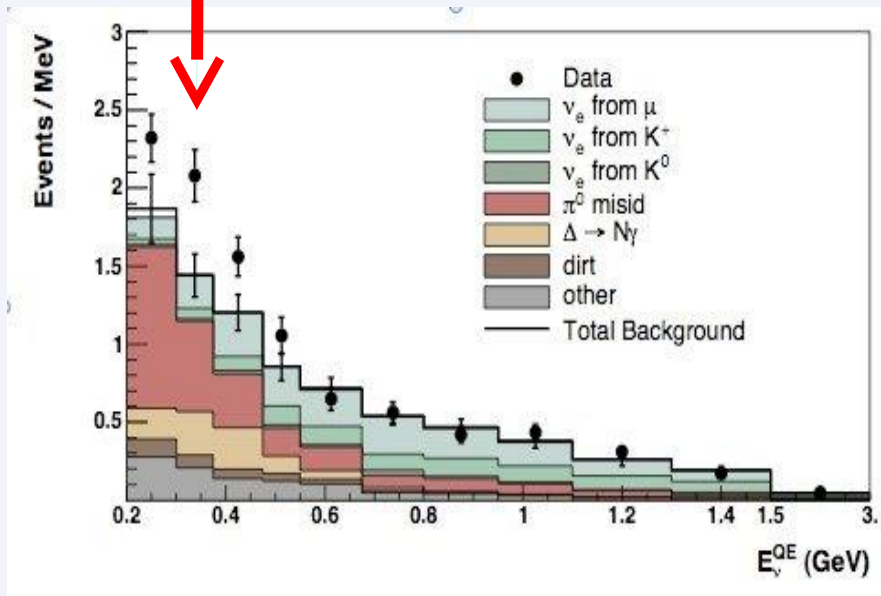


The three detector SBN program can make a definitive statement on the LSND/miniBooNE anomaly with the potential for discoveries in neutrino physics and developments in LAr technology for DUNE





# MiniBooNE Excess and ICARUS



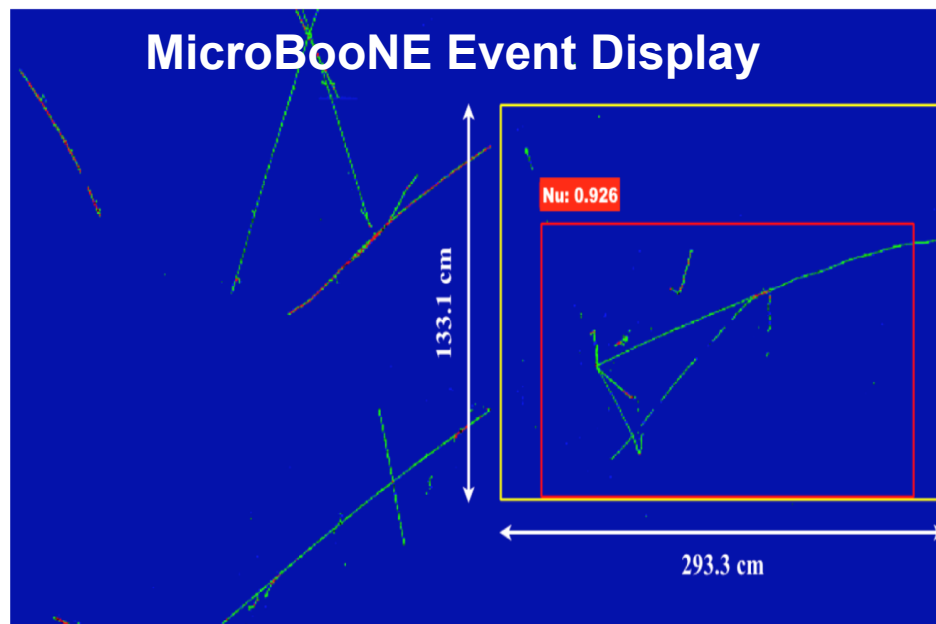
ICARUS refurbishment at CERN

## ICARUS building construction at Fermilab

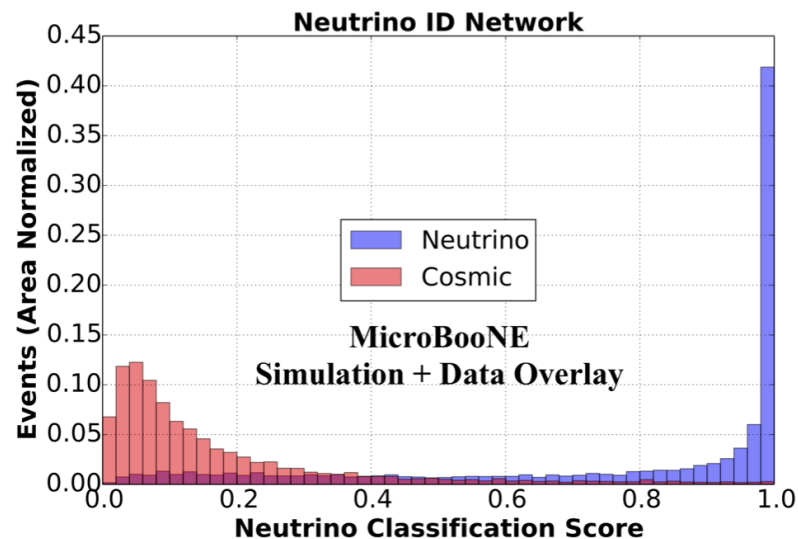


- Excess of low energy neutrino events might be an indication of new physics
- ICARUS detector is under refurbishment at CERN and will arrive at Fermilab this year
  - Largest LAr TPC detector

# MicroBooNE Experiment Operational



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



# Long Baseline Neutrino Program

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta}$$

$$-4 \sum_{i < j} \text{Re}[U_{\alpha i} U_{\alpha j}^* U_{\beta i} U_{\beta j}] \sin^2 \left[ \frac{\Delta m_{ij}^2}{4E} L \right] \\ + 2 \sum_{i < j} \text{Im}[U_{\alpha i} U_{\alpha j}^* U_{\beta i} U_{\beta j}] \sin \left[ \frac{\Delta m_{ij}^2}{2E} L \right].$$

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

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

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

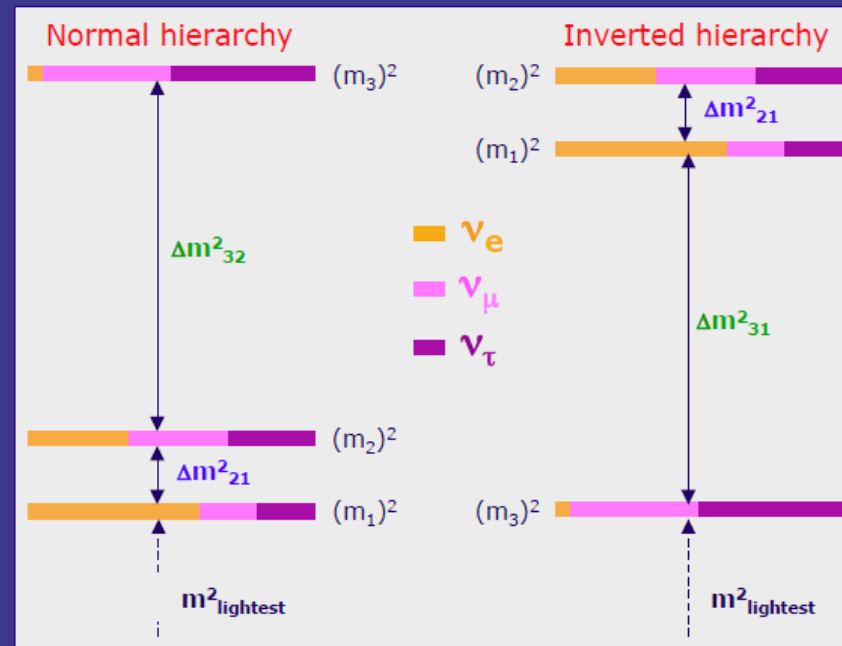
$$m(\nu_e) < 2.3 \text{ eV (95\% CL)}$$

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

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

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

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

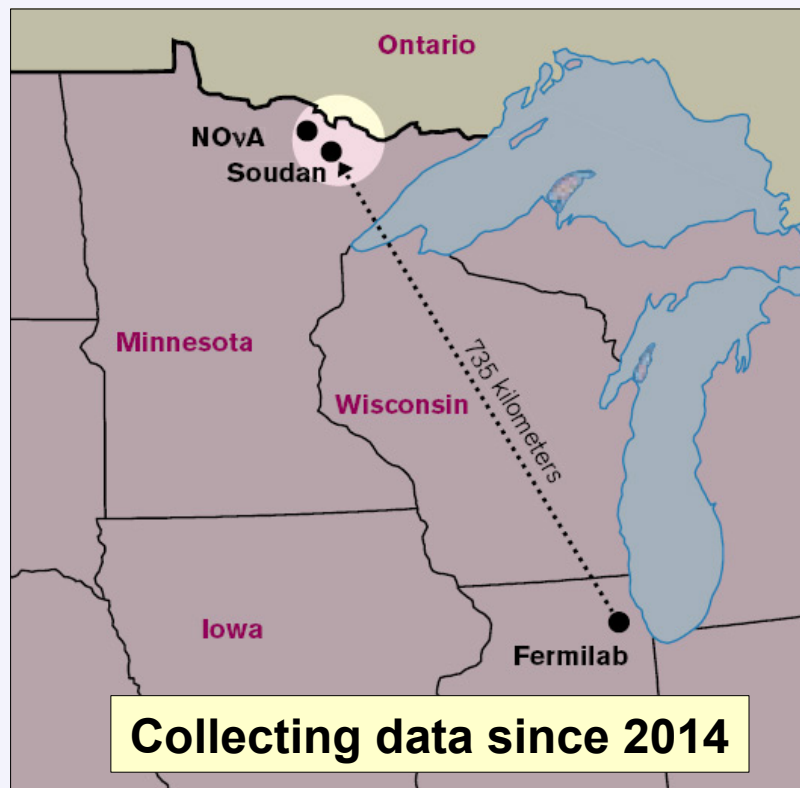


## The Standard Model

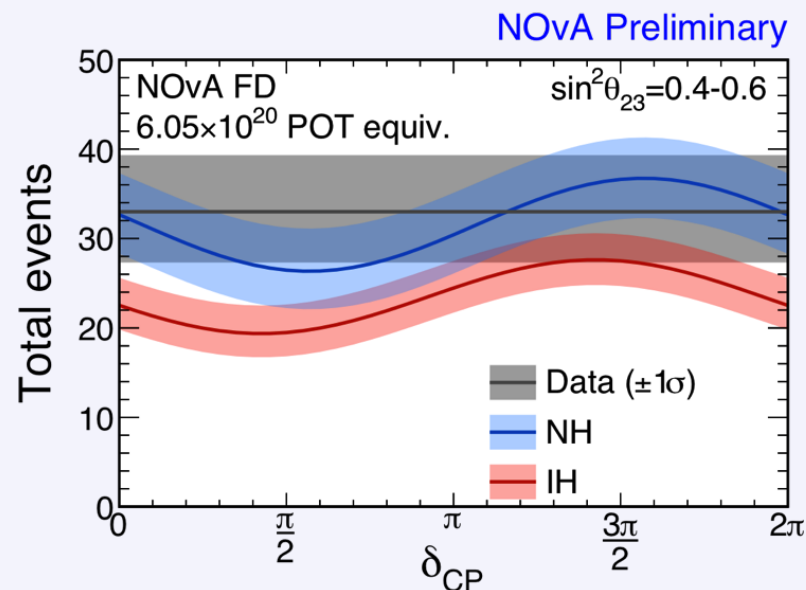
Fermions			Bosons
Quarks	$u$ up	$c$ charm	$t$ top
	$d$ down	$s$ strange	$b$ bottom
Leptons	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino
	$e$ electron	$\mu$ muon	$\tau$ tau
			Higgs* boson



# NOvA Experiment at Fermilab



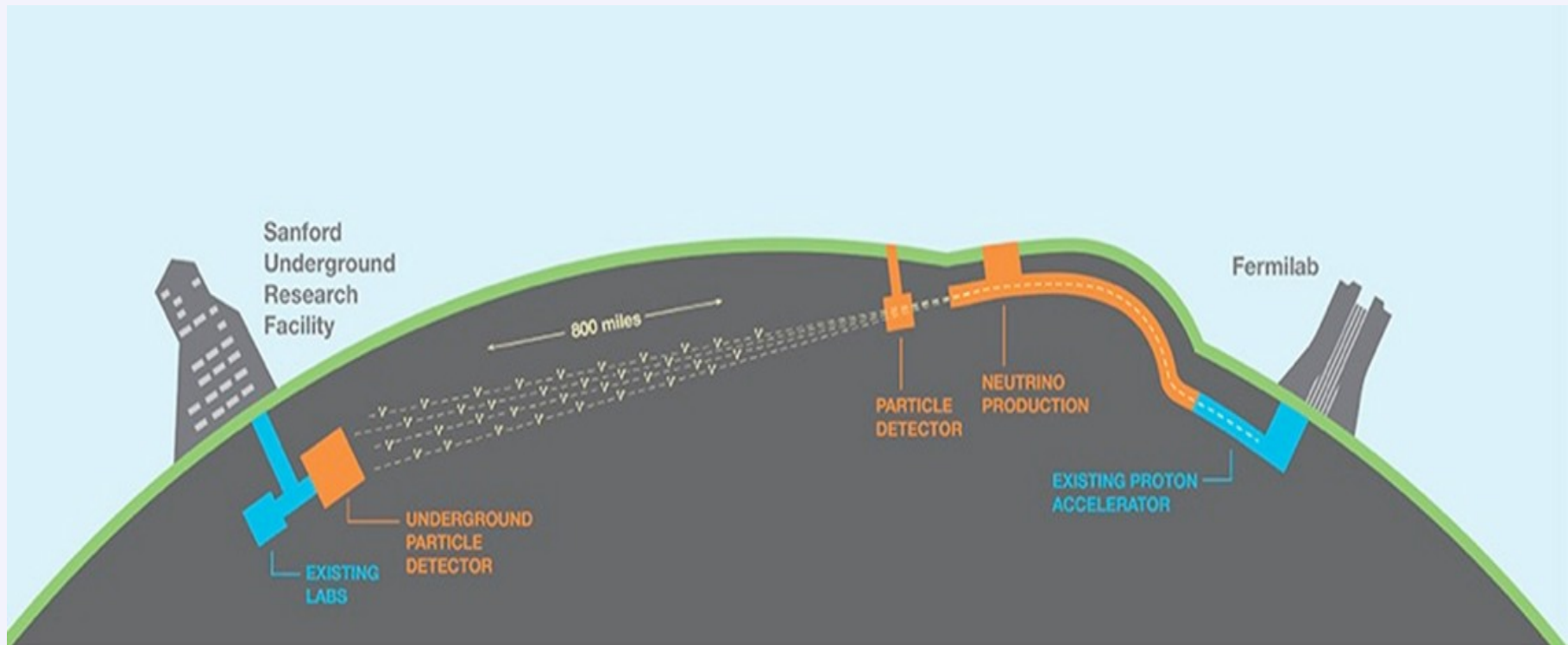
- “Off axis” neutrino experiment with 14 kton far detector and 300 ton near detector
  - Expected  $3\sigma$  mass hierarchy sensitivity
- Summer 2016 result
  - 33 electron neutrino events at far detector tends to favor Normal Mass Hierarchy





# Projects Overview: LBNF and DUNE

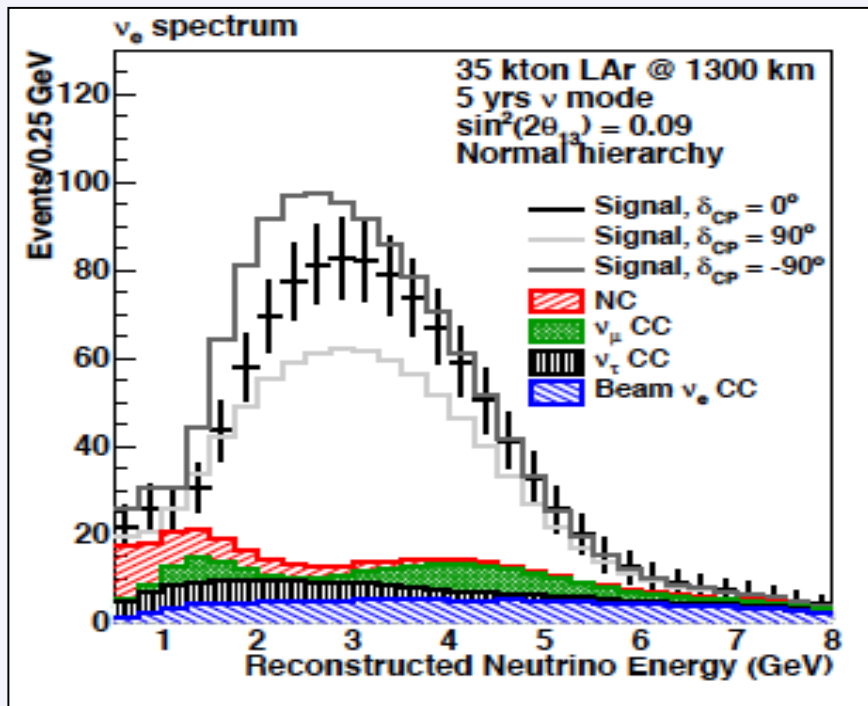
- **LBNF**: DOE project with support from non-DOE partners. Provides facility infrastructure at two locations to support the experiment
  - **Near site**: Fermilab – facilities to **create neutrino beam**
  - **Far site**: Sanford Underground Research Facility, South Dakota
- **DUNE**: Deep Underground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



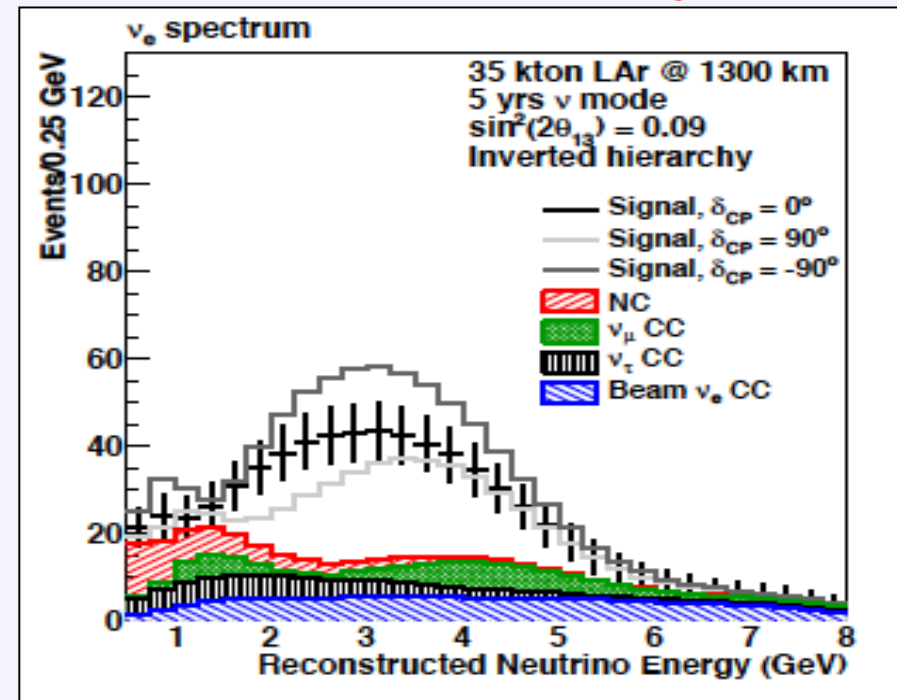
# DUNE Experiment Physics Program



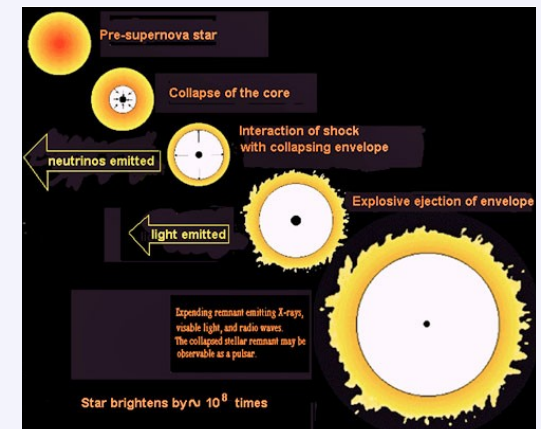
## Normal hierarchy



## Inverted hierarchy



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









# LBNF / DUNE

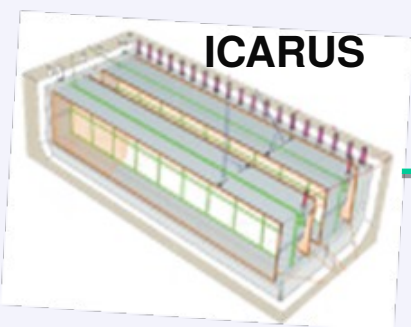


# LAr-TPC Development Path



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

## Single-Phase

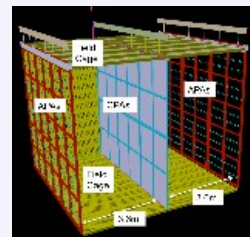


2015



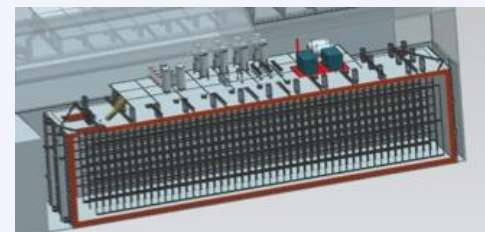
MicroBooNE

2018



ProtoDUNE at CERN

DUNE Reference Design



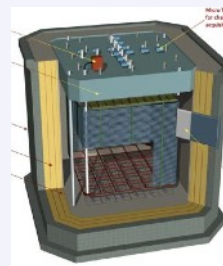
## Dual-Phase

2016



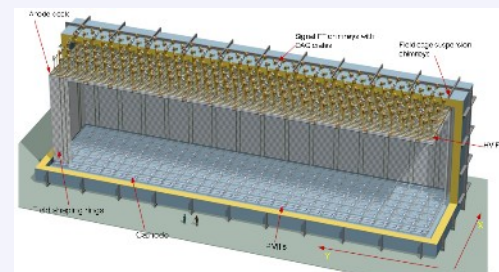
WA 105

2018



WA 105

DUNE Alternative Design







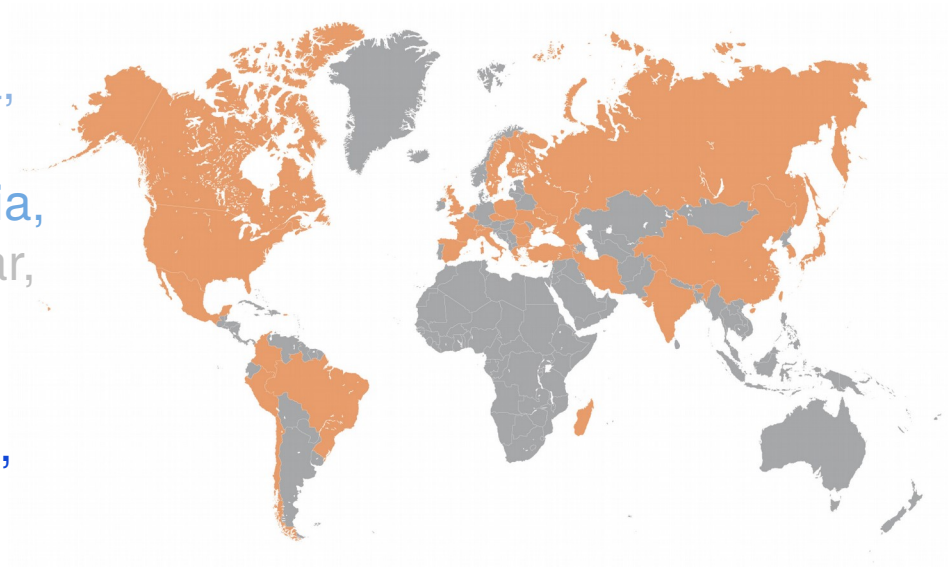
# The DUNE Collaboration

As of today:

60% non-US

965 collaborators from 161 institutions in 30 nations

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

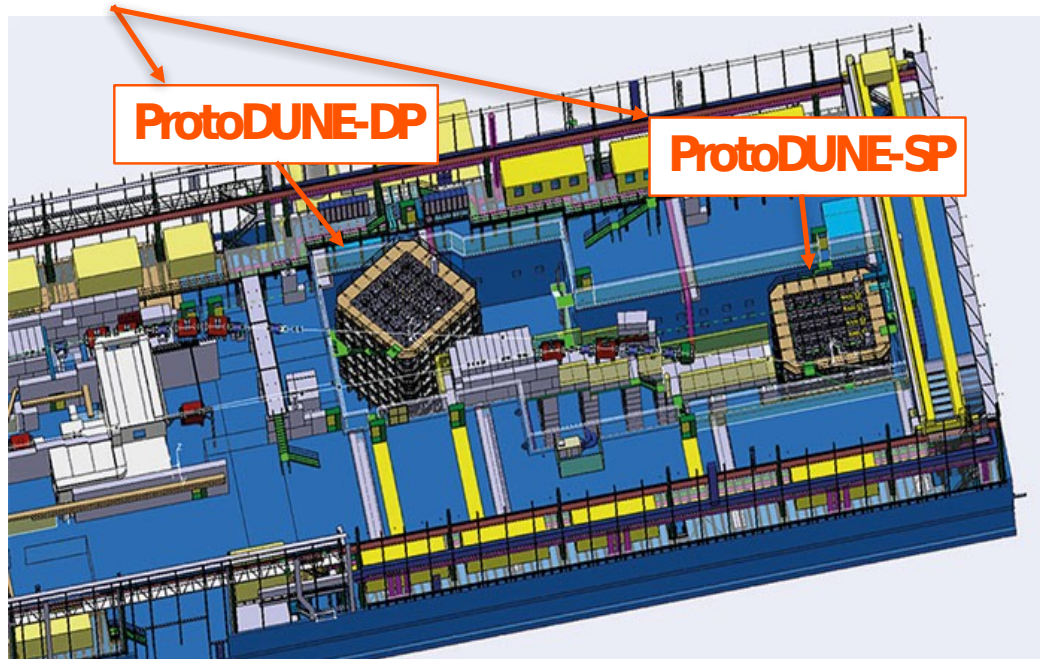


DUNE has broad international support and is growing

# CERN Neutrino Program

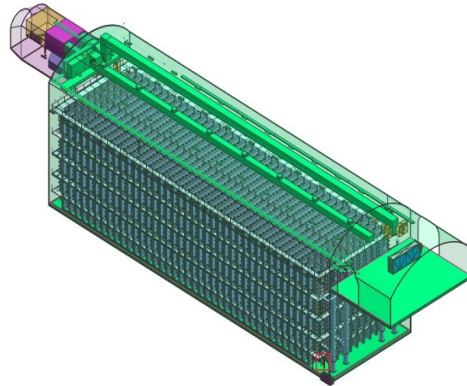
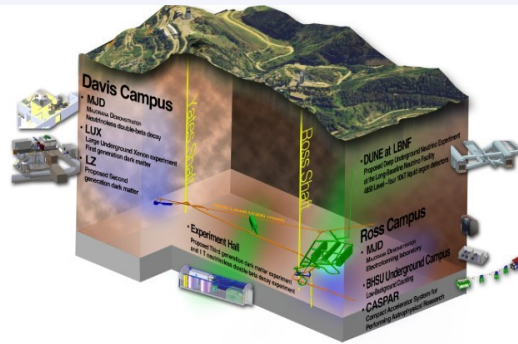


- New building: EHN1 extension in the North area
- Two tertiary charged-particle beam lines
- Two large ( $8 \times 8 \times 8 \text{ m}^3$ ) cryostats & cryogenic systems



- DUNE is the first large scale experiment CERN is participating “outside CERN”
- Major infrastructure developments (protoDUNE) and hardware contributions
- Critical for the success of the LBNF/DUNE participation

# LBNF/DUNE Timeline



2017: Far Site Construction Begins

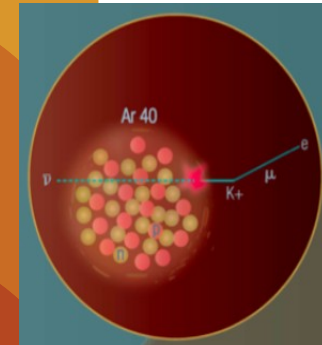
2018: protoDUNE at CERN

The CERN Neutrino Platform

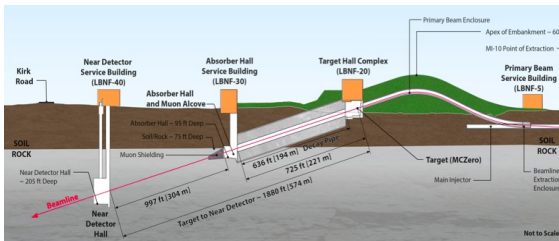


2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)



2026: Neutrino Beam Available







## 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

Neutrino  
Collider  
Muon  
Gen R&D  
Outreach



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  
9-Nov-16

LONG-RANGE PLAN: DRAFT Version 5

		FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	
LBNF/DUNE	PIP II								PIP II	PIP II	PIP II	
	DUNE								DUNE	DUNE	DUNE	
	LBNF								LBNF	LBNF	LBNF	
NuMI		MINOS+	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN				$\nu$
		MINERvA	MINERvA	MINERvA	OPEN	OPEN	OPEN	OPEN				
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	OPEN				
BNB	B	$\mu$ BooNE	$\mu$ BooNE	$\mu$ BooNE	$\mu$ BooNE	$\mu$ BooNE	$\mu$ BooNE	OPEN	OPEN	OPEN	OPEN	$\mu$
			ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	OPEN	OPEN	OPEN	
			SBND	SBND	SBND	SBND	SBND	SBND	OPEN	OPEN	OPEN	
Muon Campus		g-2	g-2	g-2	g-2	OPEN	OPEN	OPEN		OPEN	OPEN	$\mu$
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu 2e		Mu2e	Mu2e	
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	OPEN		OPEN	OPEN	$p$
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	OPEN		OPEN	OPEN	
	NM4	SeaQuest	SeaQuest	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN		OPEN	
		FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	



Summer shutdown



Construction / commissioning



Run

## NOTES:

1. Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning
2. DUNE without beam operates in FY25-FY26
3. Need to update understanding of PIP II schedule
4. Switching off NuMI for the LBNF beamline work could be earlier by 6 months or later by 18 months
5. MI shutdown (optimistically) assumed to be for 1 year, for LBNF work, nominally FY23 but Mu2e run plan may put pressure on MI shutdown to be as late as possible

# Generic Detectors R&D



- We encourage a high degree of collaboration with the university community and other national labs.
- Presence of research facilities such as:
  - Test beam facility
  - Silicon Detector facility
  - Precision Metrology facility
  - Rapid prototyping and Special Materials
  - Scintillator Detector Development
  - Thin-Film Facility
  - Liquid Argon Detector Development
  - ASIC Development Facility
- Experienced, well established engineering groups, such as
  - ASIC development
  - Cryogenics
  - Data Acquisition
  - Mechanical & Electronics Engineering



Scintillator extrusion at Lab 5



Clean rooms and metrology at SiDet



CALICE at the test beam

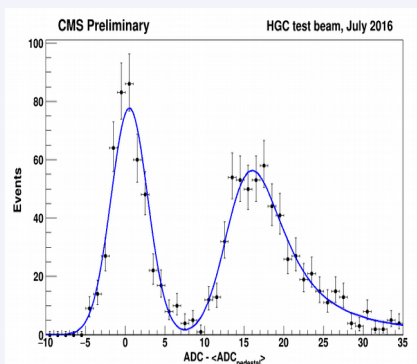
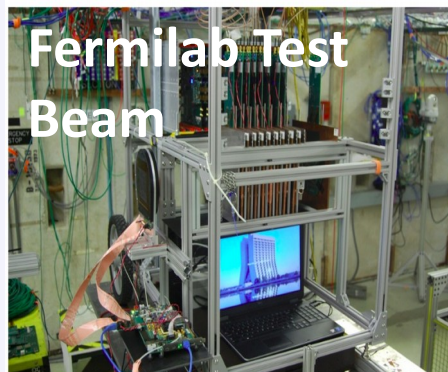
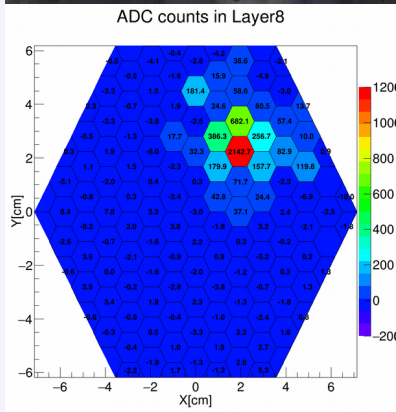
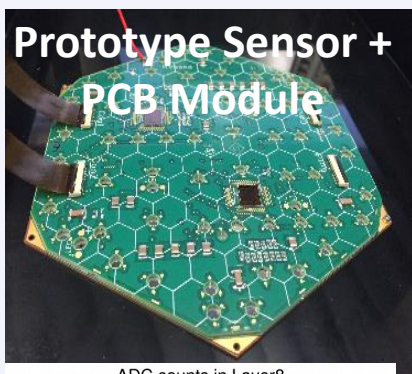
- **Fermilab is actively engaged in generic detectors R&D program**
- **Efforts are concentrated along long term plans of the experiments at Fermilab**



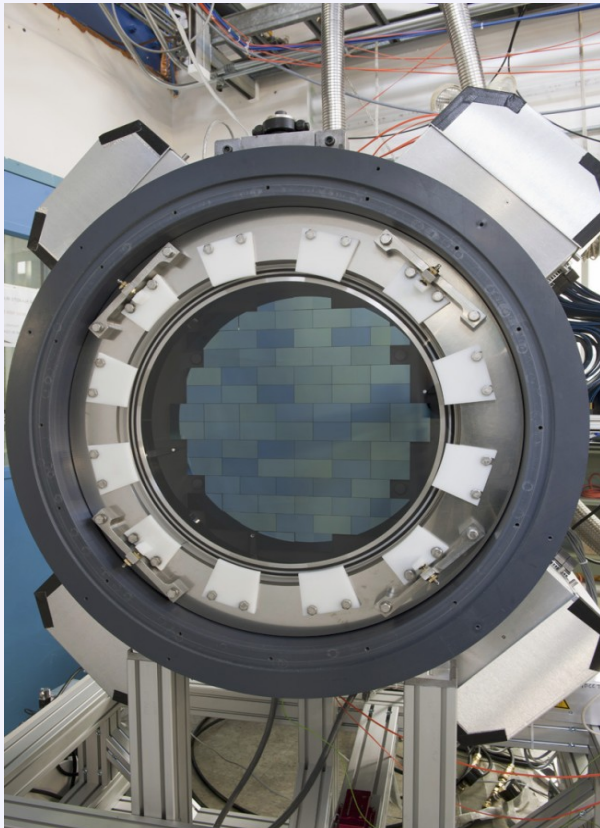
# Fermilab Coordinates US-CMS Program



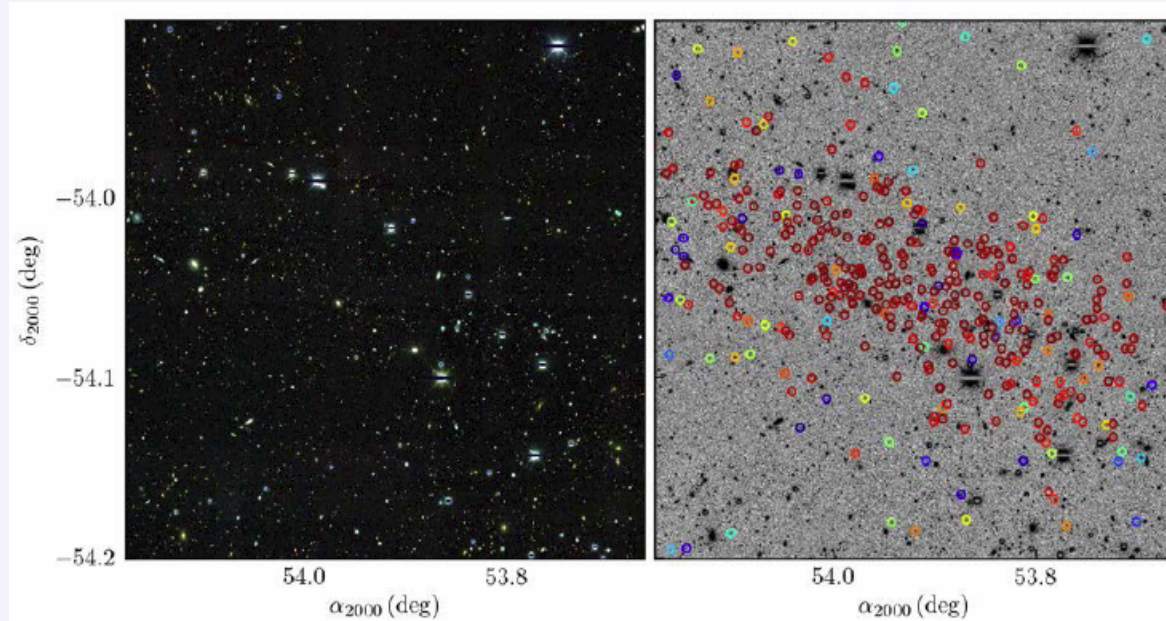
- CMS is steady progressing with FNAL making critical contributions
  - ~50 Fermilab's scientists involved
- Phase 1 upgrades are on track
- HL-LHC upgrades are under development
  - Major project with over \$200 million U.S. contribution
- LHC Accelerator Research Program (LARP) is developing interaction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



# Dark Energy Survey - DES



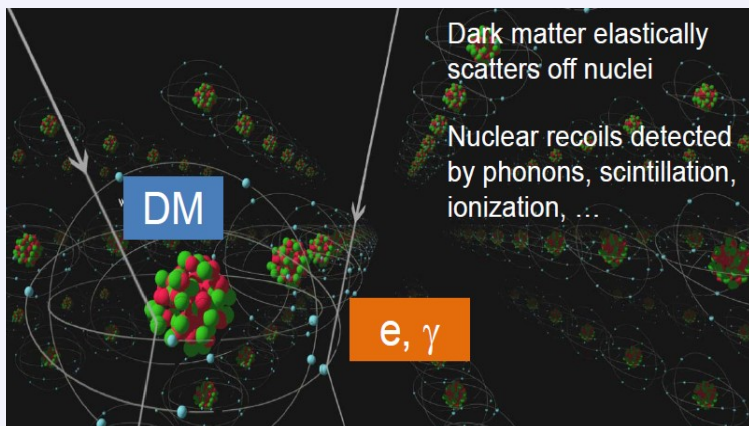
Left: cutout of DES image  
Right: the stars from one of the dwarf galaxies



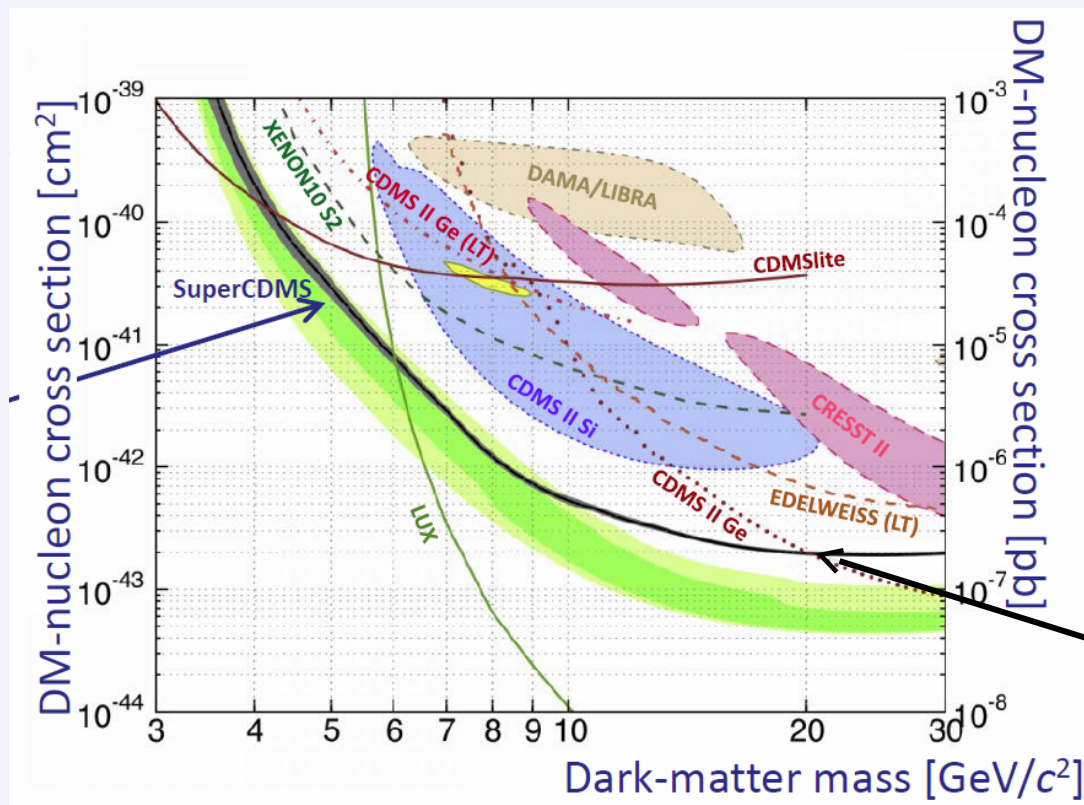
- DES goal is creating scans of night sky using 4 meters telescope and 570 megapixels camera (camera built at Fermilab) located in Chile
  - Started data collection in September of 2013
  - 40+ papers already published or in review
- Major scientific areas: studies of dark matter, dark energy, supernova,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



# Dark Matter Direct Detection



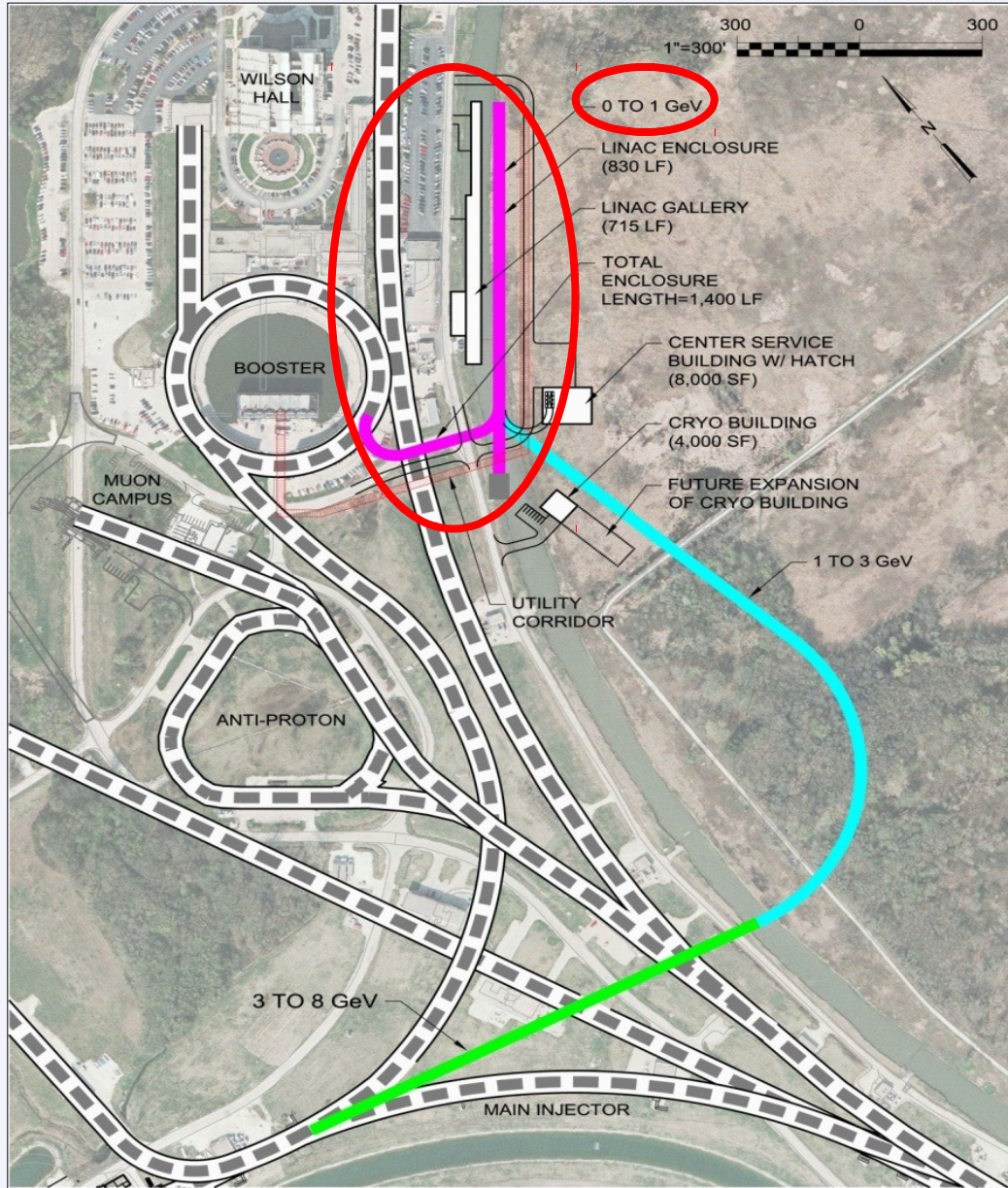
- Many models expect dark matter to consist of heavy WIMP particles
- Multiple methods used to detect elastic scattering of WIMPs
  - Ionization, scintillation, phonons
- Fermilab is actively involved in CDMS experiment in Soudan mine (and others)



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



# Planned Accelerator Upgrade – PIP II



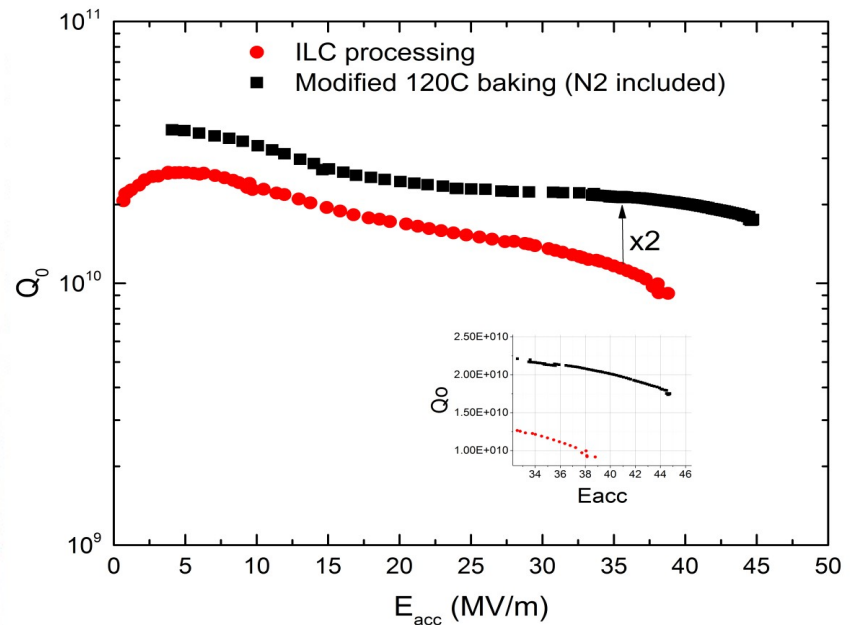
- Proton linear accelerator with flexible beam structure based on SCRF technology
  - Increase of beam power to ~1 MW
  - Large scale partnership with India
- Platform for future neutrino and muon facilities



# SCRF Developments at Fermilab



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

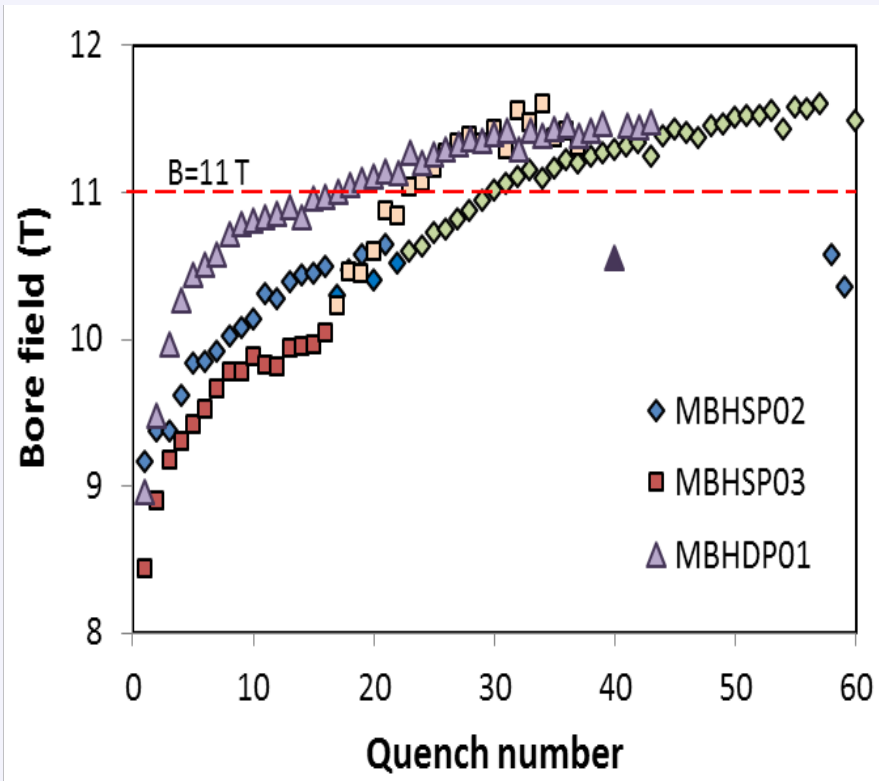


- Superconducting RF is the key technology for the ILC where U.S. is interested to contribute
- Coherence with production of cryo-modules by Fermilab for LCLS-II light source at SLAC and PIP-II upgrade at Fermilab





# High Field Magnets Developments



**1 meter long Nb<sub>3</sub>Sn magnet successfully tested at Fermilab to 11.6T**

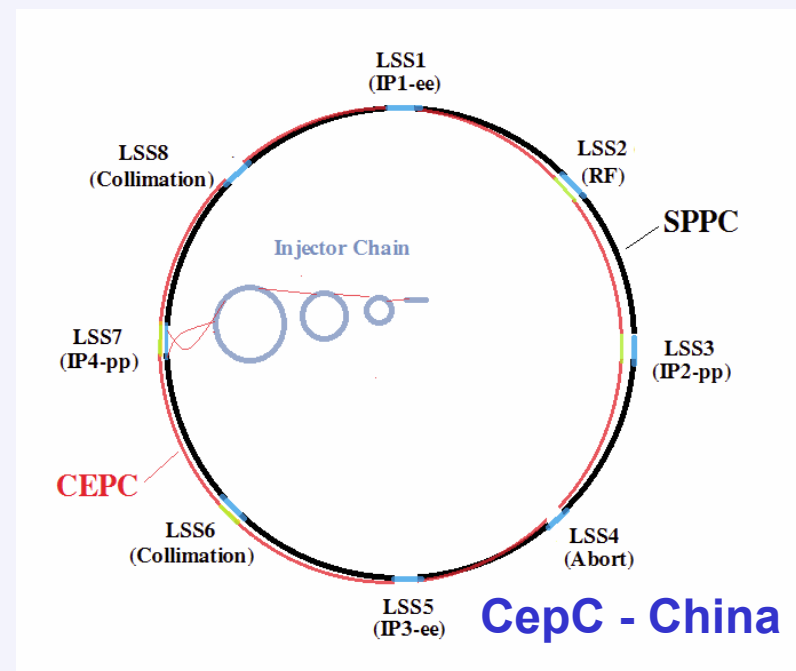
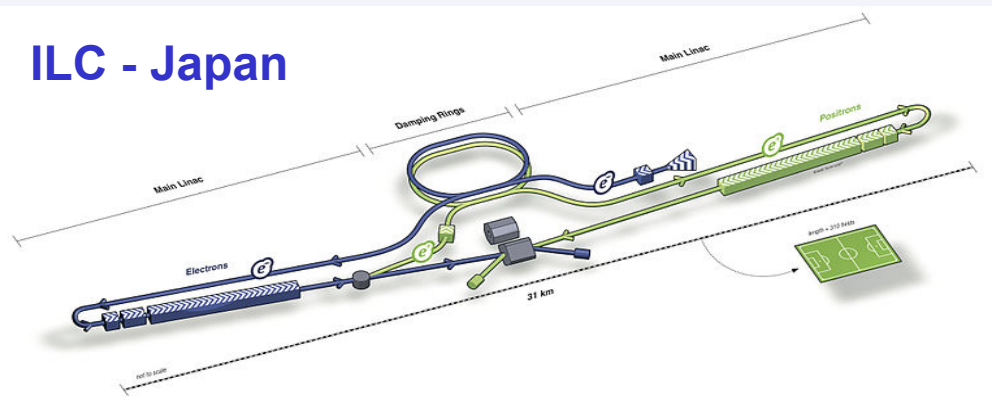
- Area of Fermilab's expertise since design and construction of the first superconducting accelerator – the Tevatron
- Breakthroughs in materials, systems, engineering are needed for higher fields
- Fermilab focuses on Nb<sub>3</sub>Sn (conductor and magnet engineering)
  - **Medium term goal is to build 15-16 T magnet suitable for FCC at CERN**



# Future Energy Frontier Colliders



## ILC - Japan



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

# 2017 - 50 years of Fermilab





# Fermilab Program Overview



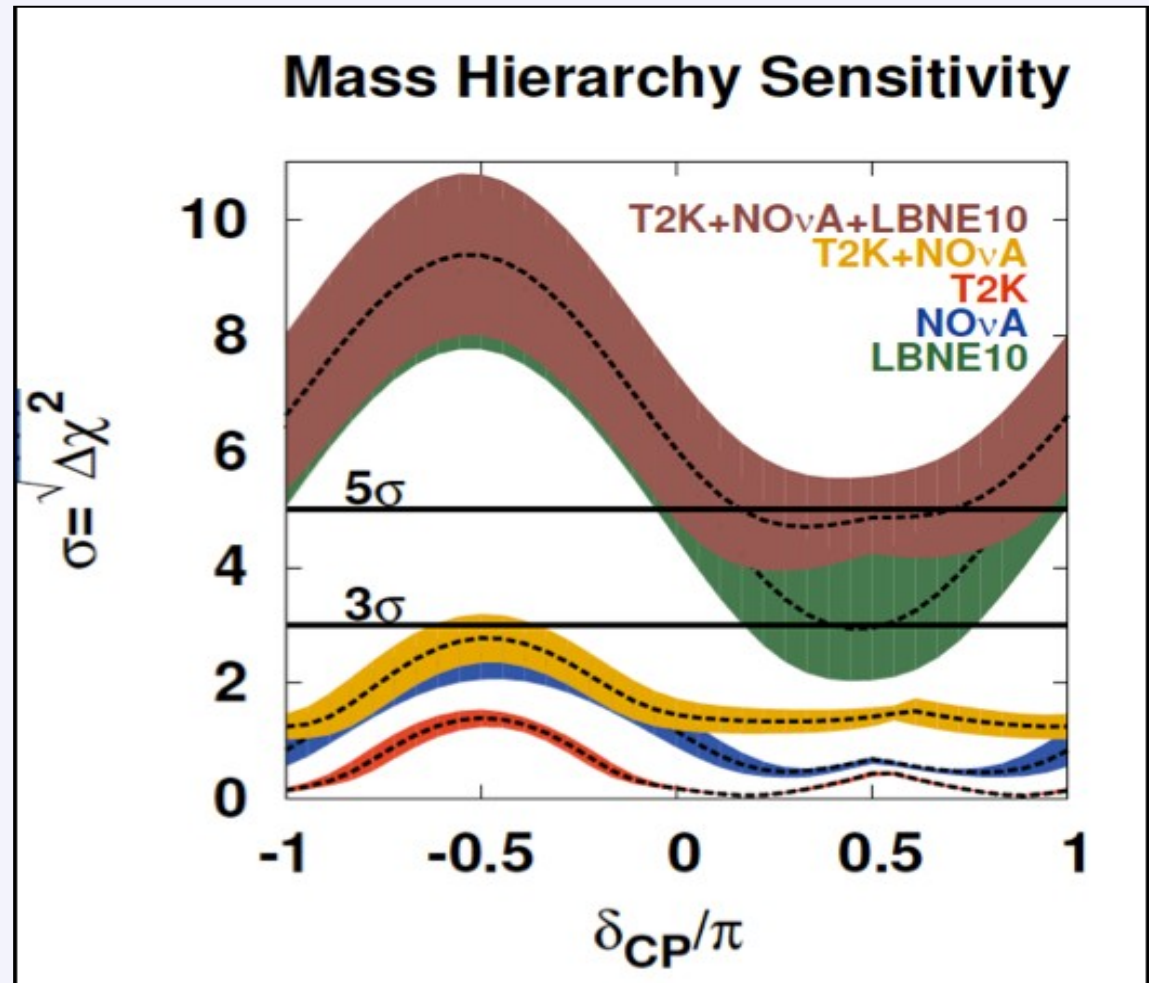
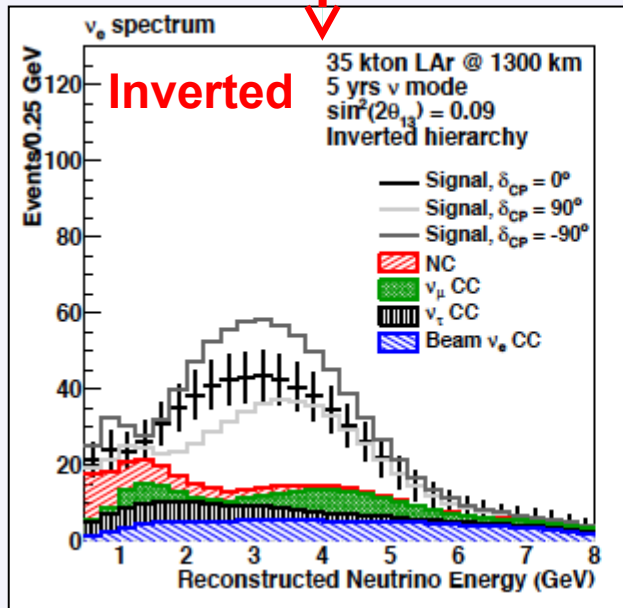
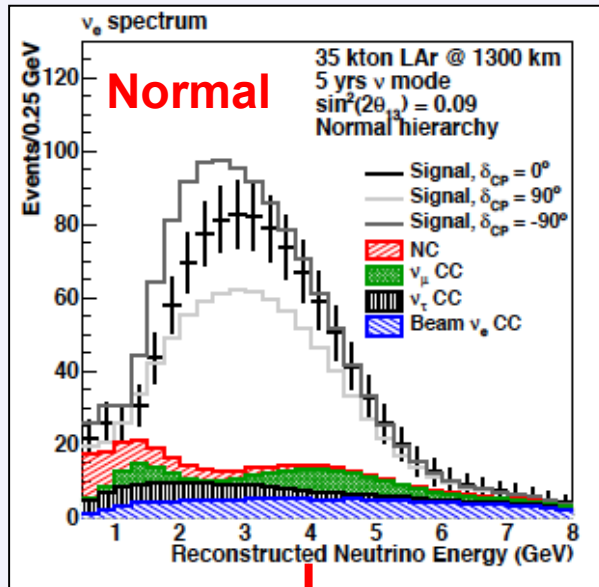
- Accelerator complex is running providing powerful beams
- LHC Run 2 is progressing, CMS detector is running well
- LBNF/DUNE program is actively progressing
- NOvA and MicroBooNE neutrino experiments all running well
- g-2 experiment will be ready for beam this year
- Mu2e experiment construction actively 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
- Modest involvement in future colliders activities, including ILC





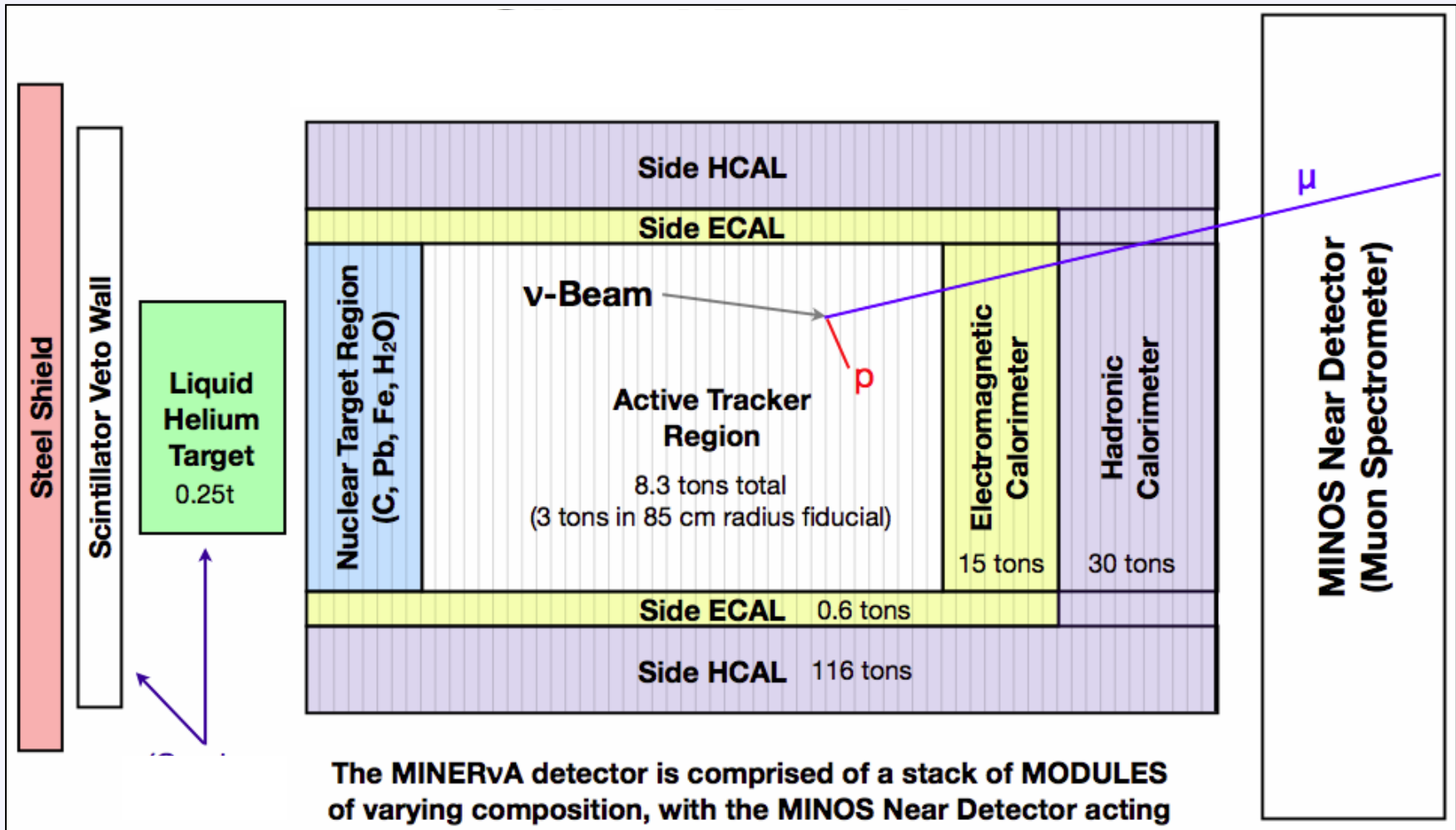
## **Backup Slides**

# Long Baseline Neutrino Experiment



- Superior option to resolve mass hierarchy
- Find proton decay up to lifetime of  $10^{35}$  years
- Detect supernova neutrinos

# MINERvA Experiment

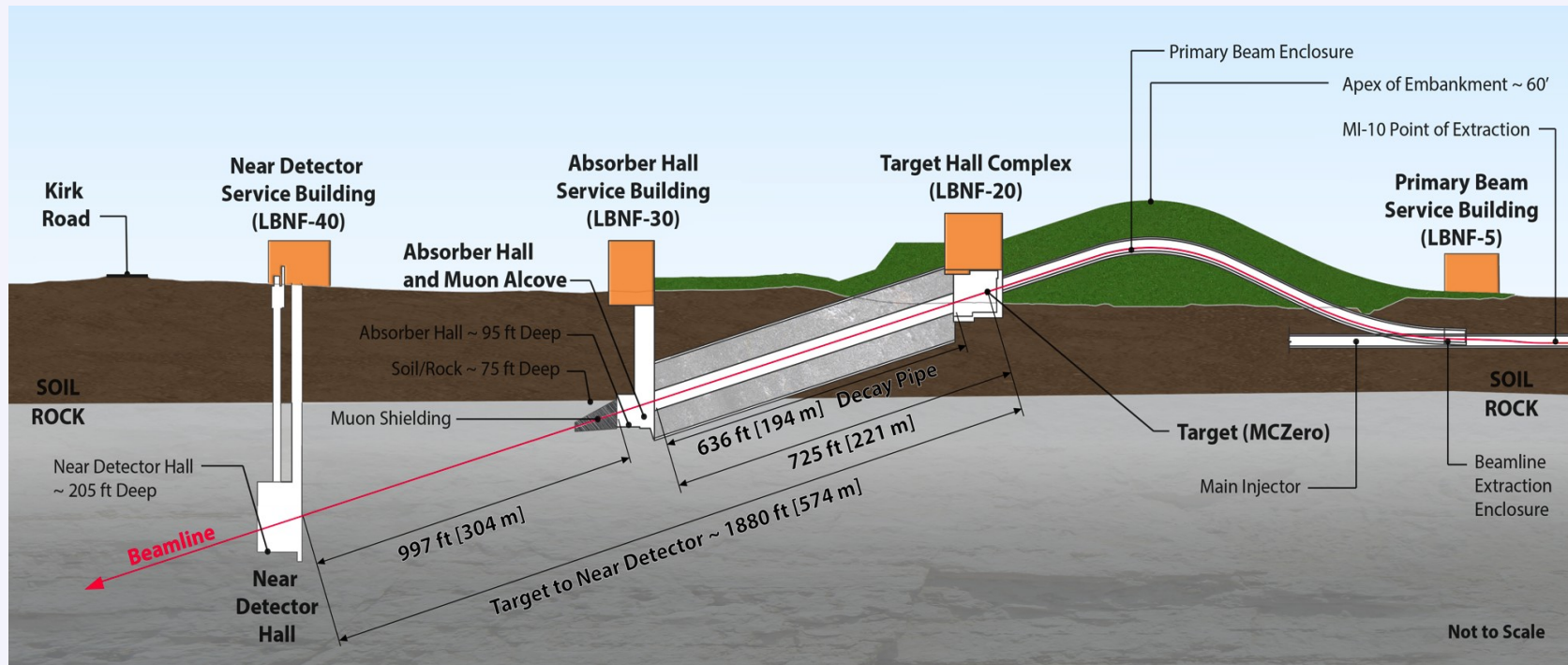


The MINERvA detector is comprised of a stack of **MODULES** of varying composition, with the MINOS Near Detector acting

- MINERvA (just in front of MINOS) is studying neutrino interactions in unprecedented detail on a variety of different nuclei – He, C, CH<sub>2</sub>, H<sub>2</sub>O, Fe, Pb
- Important information for all neutrino based experiments



# Overview - Near Site – LBNF/DUNE at Fermilab



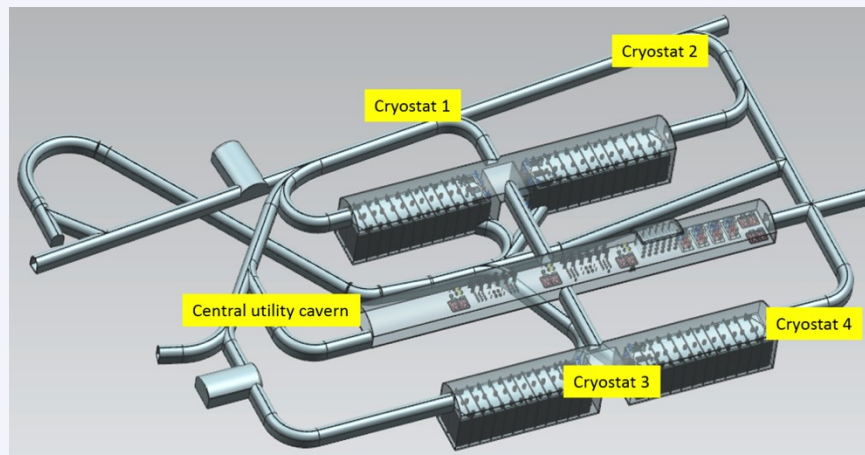
- Primary proton beam at 60-120 GeV extracted from the Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankment allows target complex to be at grade and neutrino beam to be aimed to South Dakota mine
- Decay region followed by the absorber
- Four surface support buildings
- **DUNE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

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

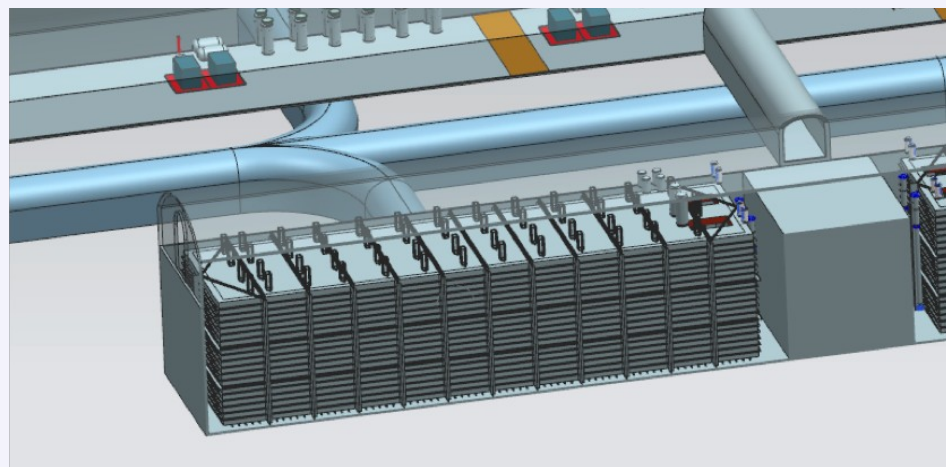


# Overview – Far Site – LBNF/DUNE at South Dakota

- **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<sub>2</sub> 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**



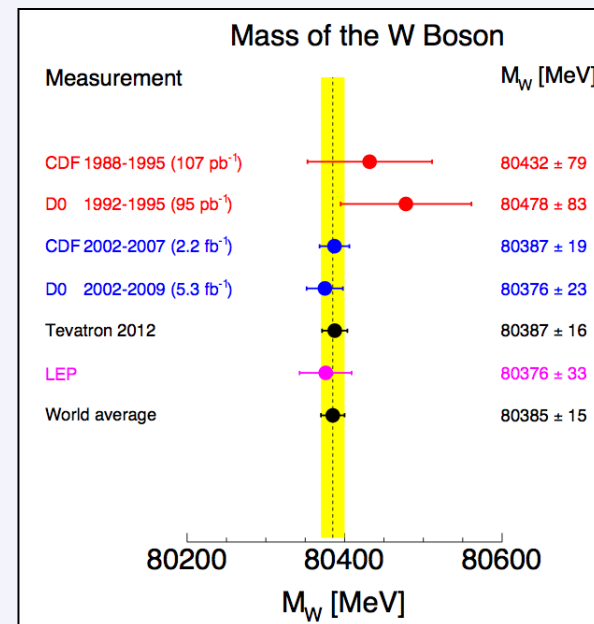
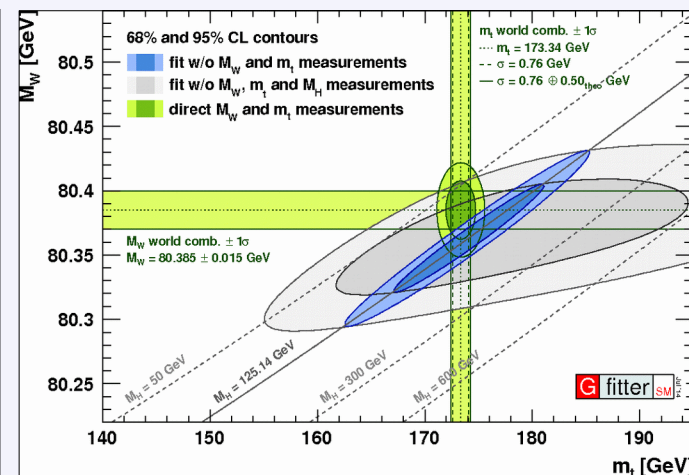
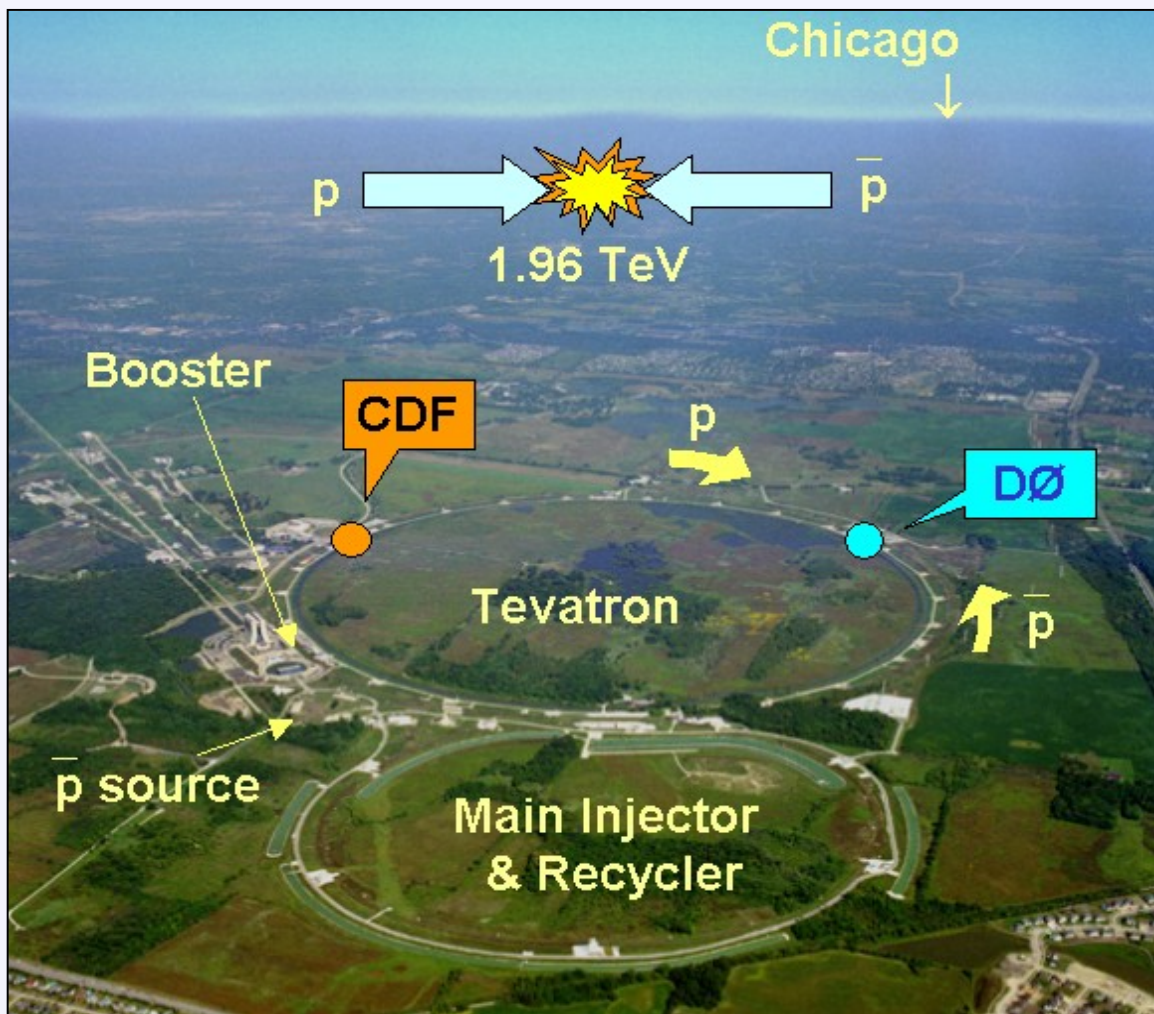
DUNE caverns and tunnels layout



Single cryostat

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

# Tevatron Program Analysis



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

Most accurate measurement of W boson mass