Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

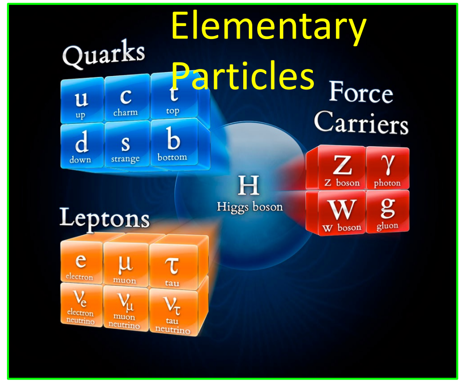
Welcome and Introduction to Fermilab

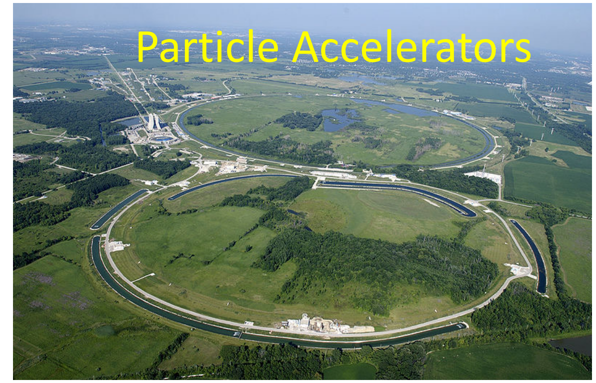
Pushpa Bhat, Fermilab

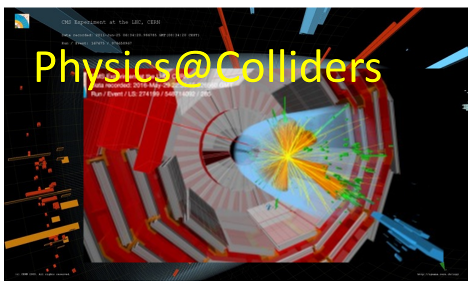
Summer Lecture Series

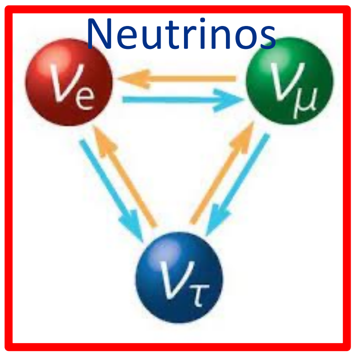
May 25, 2023

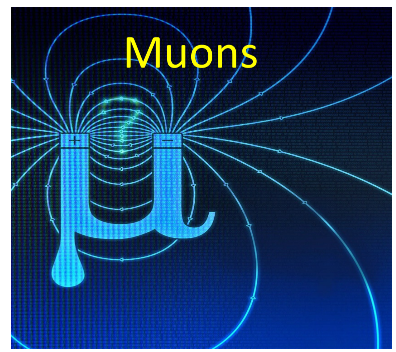
A Brief Overview

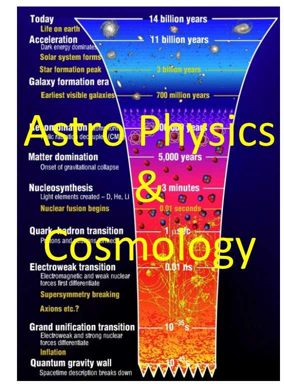


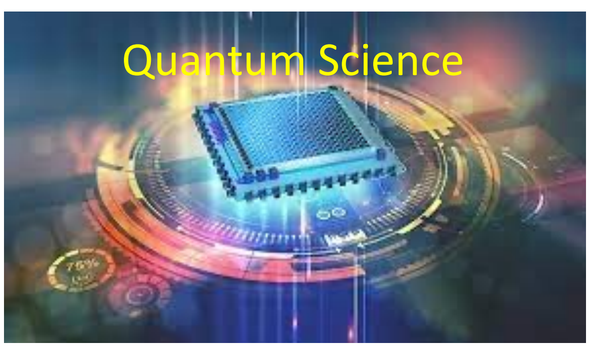


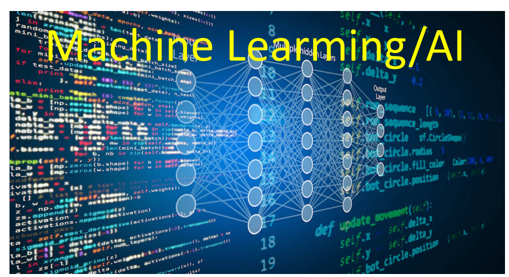






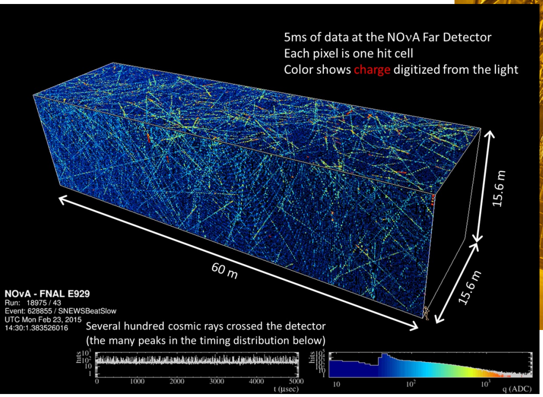


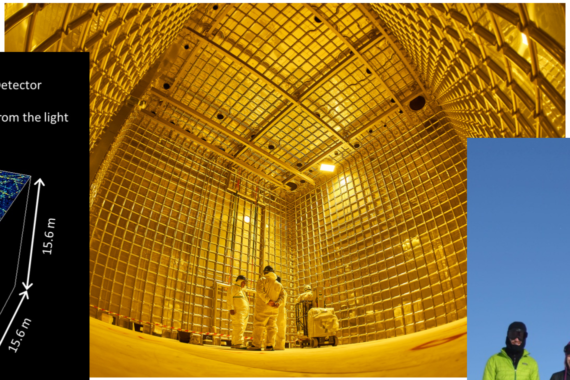


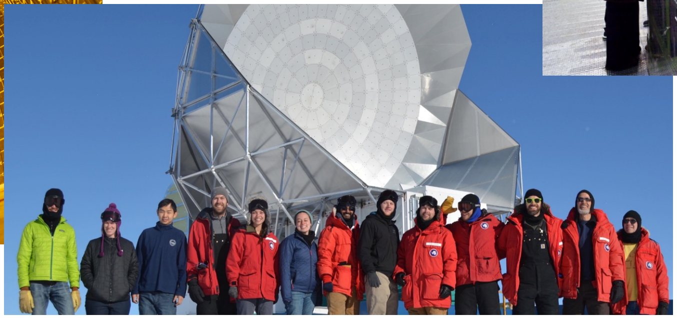


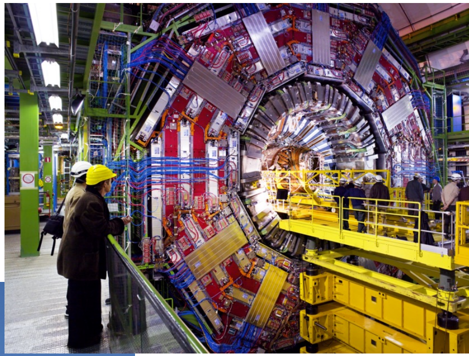
Fermilab at a glance

- The premier DOE national laboratory for **high energy particle physics & particle accelerators**
- Conducting fundamental science research to unlock the mysteries of matter, energy, space and time for the benefit of all.
- 6,800 acres of federal land including restored prairie
- About 1,800 staff, Over 4000 scientists from across the U.S. and over 50 countries across the globe use Fermilab's research facilities
- Hosting large experiments on site, at CERN, Chile, the South Pole, and other locations; hosting large international collaborations









History: Early Milestones

- November 1962: President JFK's science advisory committee and the AEC's advisory committee create the Ramsey panel
- April 1963: Ramsey Panel Report
  - Recommends building a 200 GeV proton accelerator
- June 1963: Leon Lederman's "Truly National Laboratory"
- November 1965: URA organized to manage the lab
- December 7, 1966: Site selection (then Weston, Illinois) by the Atomic Energy Commission (AEC, predecessor to DOE).
- Robert Rathbun Wilson appointed the first director on February 28, 1967
- Official start of the Laboratory: **June 15, 1967**

History: Making of a new National Laboratory

May 11, 1974
Dedicated as
Fermi National Accelerator Laboratory

Fermilab

Director Robert Wilson offers a toast to celebrate the milestone.

< 5 years from start of the new Lab

200 GeV March 1972

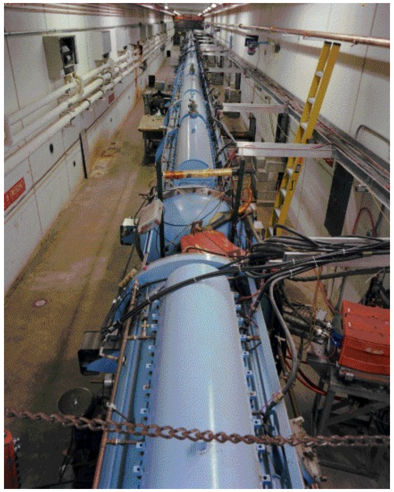
Accelerator Reaches Design Energy

After years of design and construction, the NAL Main Ring achieved its design energy of 200 GeV on March 1, 1972, ahead of schedule and under its authorized $250 million budget. It quickly surpassed that energy goal, reaching 300 GeV on July 16, 1972, and 500 GeV on May 14, 1976.

400 GeV December 1972

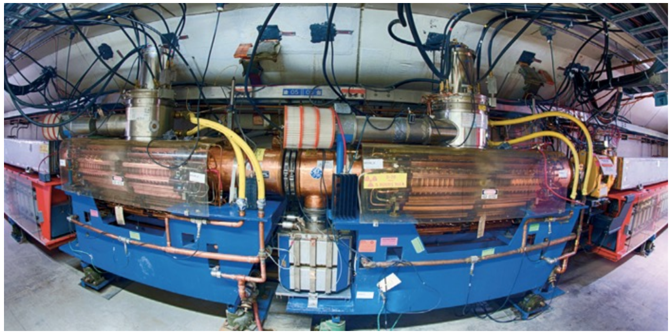
Accelerators built 1968-71

Cockroft-Walton
720 keV



Linac
170 m long
200 MeV

Groundbreaking:
December 1, 1968

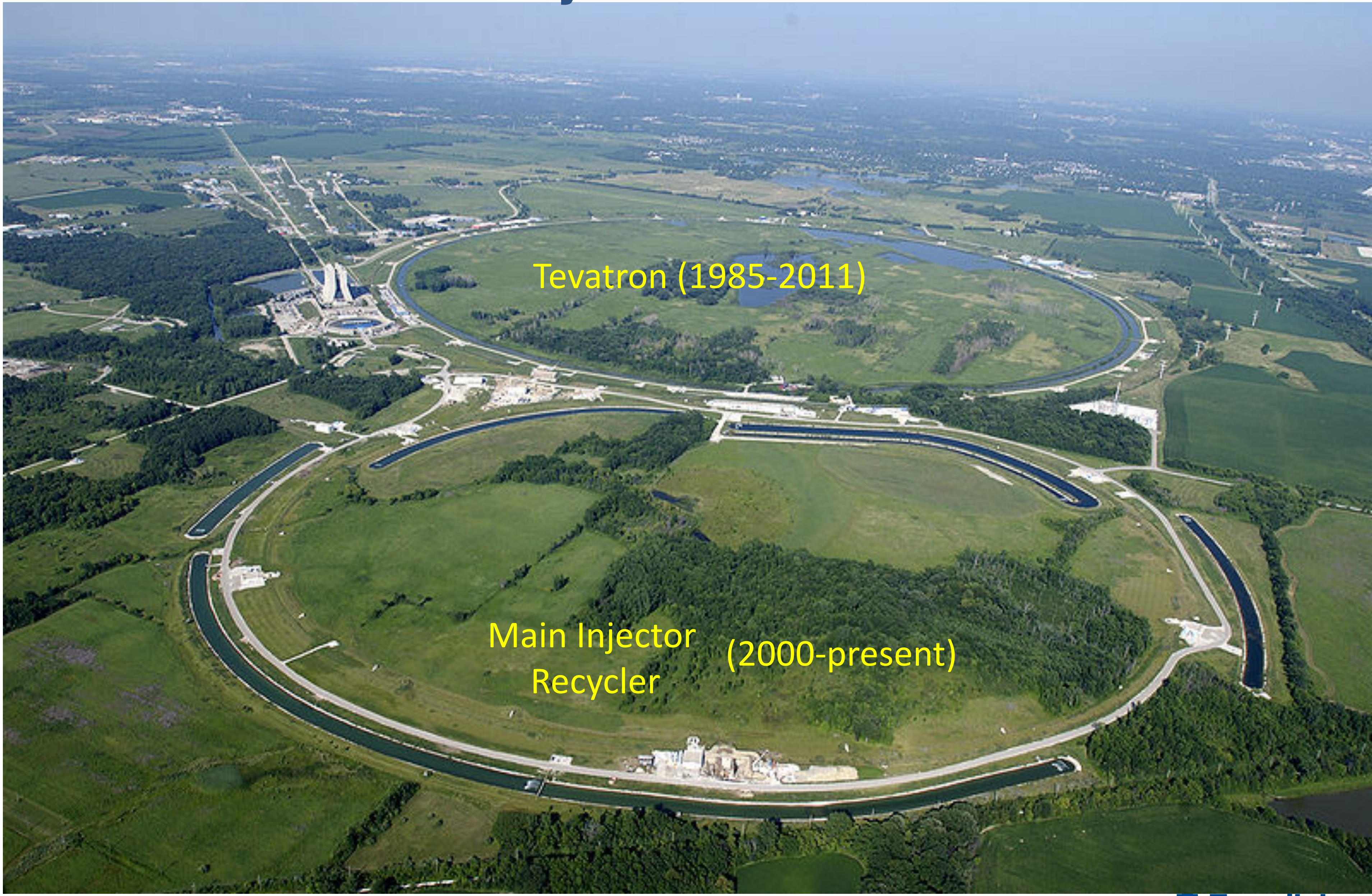


Booster 8 GeV
Rapid-cycling synchrotron
0.5 km circumference

Main Ring Accelerator
6.4 km circumference
200 – 400 GeV

Groundbreaking:
October 3, 1969

A National Laboratory on the Illinois Prairie



Blending Art with Science

Wilson's Legacy **Architectural Grandeur**

Restoring and Preserving Nature

Wilson's Legacy

Environmental Beauty

Flora and Fauna

The Prairie and the Bisons

Wilson’s Legacy

An International Laboratory

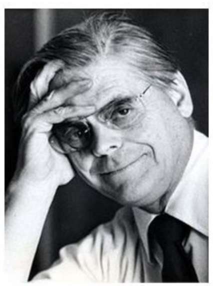
Cultural Splendor

50 Years of Discovery

50th Anniversary
Celebrated in 2017

Fermilab science drives technology innovation

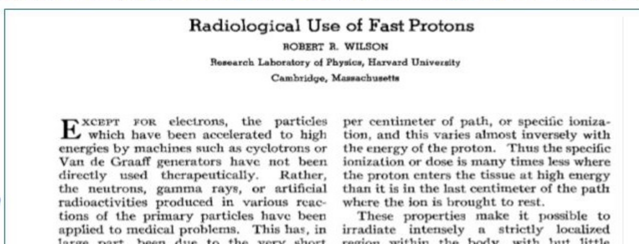
Superconducting magnets for the Tevatron, first industrial scale use of such magnets



Robert Rathbun Wilson

1946: R. Wilson first proposed a possible therapeutic application of proton and ion beams

R. Wilson, Radiologial use of fast protons, Radiology 47, 487-491, 1946



Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University

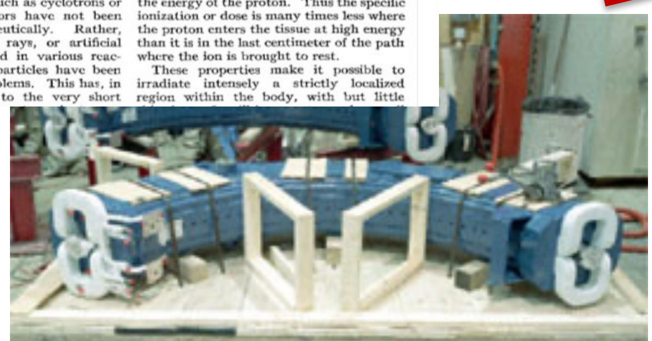
Cambridge, Massachusetts

EXCEPT FOR electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in large part, been due to the very short

per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

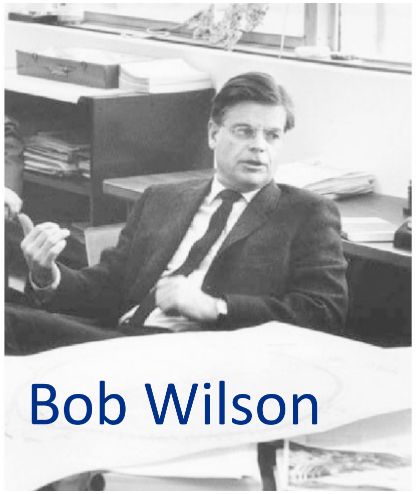
These properties make it possible to irradiate intensely a strictly localized region within the body, with but little

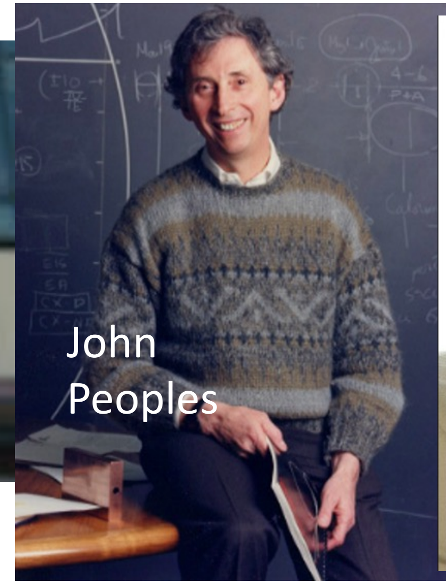
Invented by Fermilab Director, first working system built here



Fermilab had a neutron therapy facility on-site, 1976-2013; treated >3000 patients https://www-bd.fnal.gov/ntf/

Fermilab Directors since inception



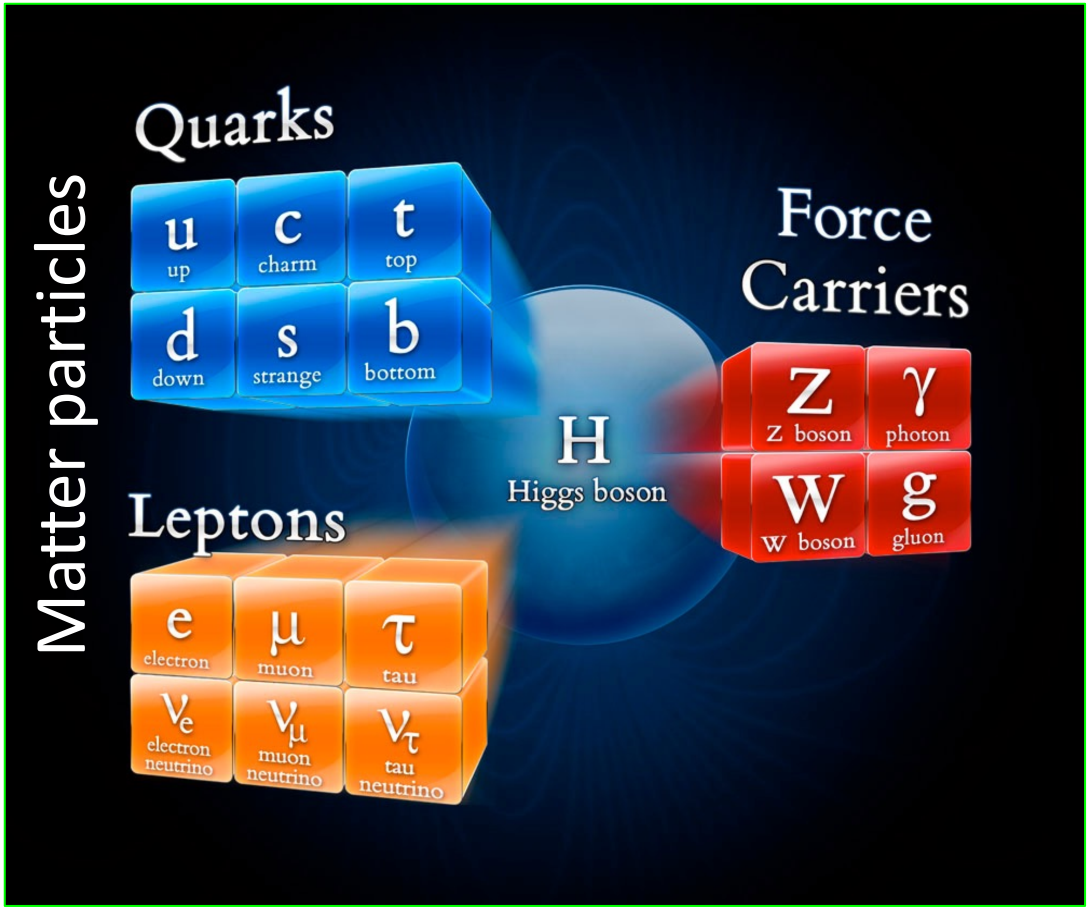


FUNDAMENTAL SCIENCE FROM QUARKS TO THE COSMOS

Looking for Fundamental principles and basic building blocks

The Standard Model of Particle Physics

Mathematical framework:
Quantum field theory



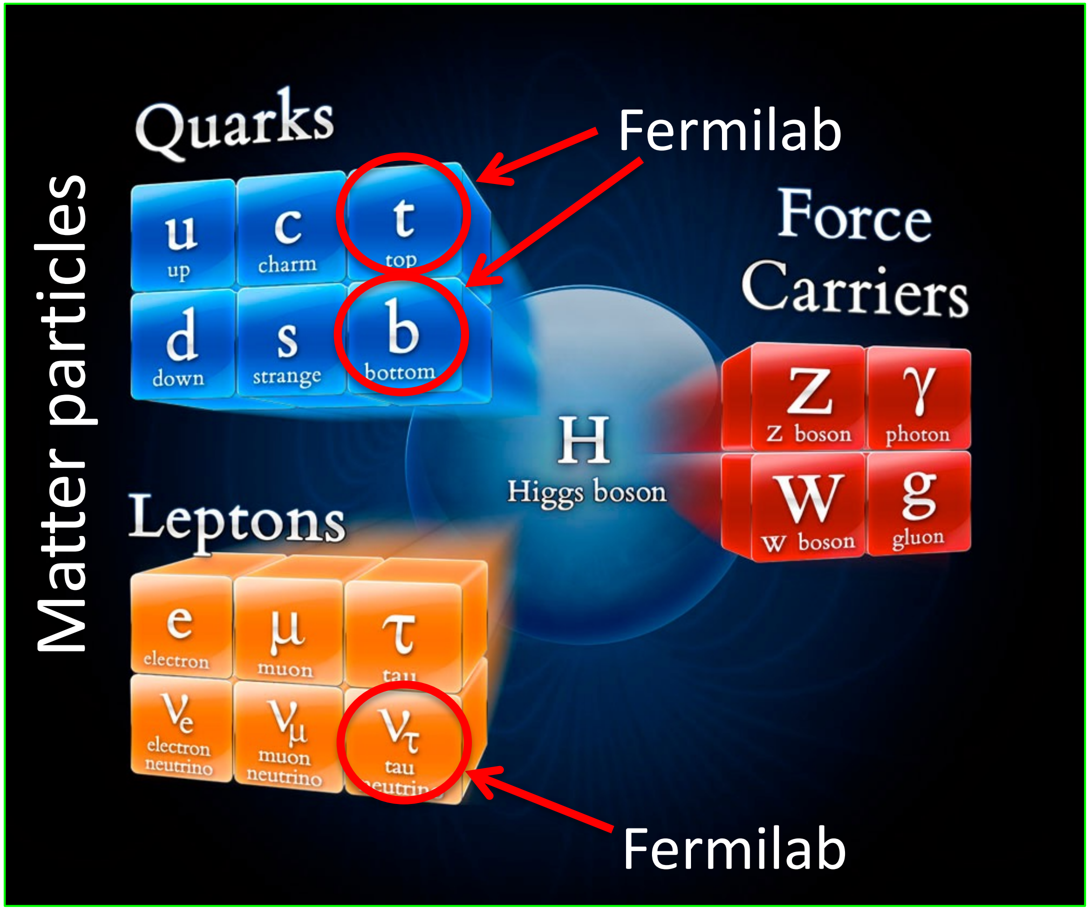
Quarks & Leptons
are Fermions (spin ½)
Named after Enrico Fermi
(Italian American physicist, namesake of Fermilab)

Force Carrier Particles
(mediate strong, weak, electromagnetic interactions)
are called Bosons (spin 1)
Named after Satyen Bose
(Indian physicist)

Higgs boson (spin 0)
(named for Peter Higgs)

Basic building blocks of matter and their interactions

The Standard Model of Particle Physics

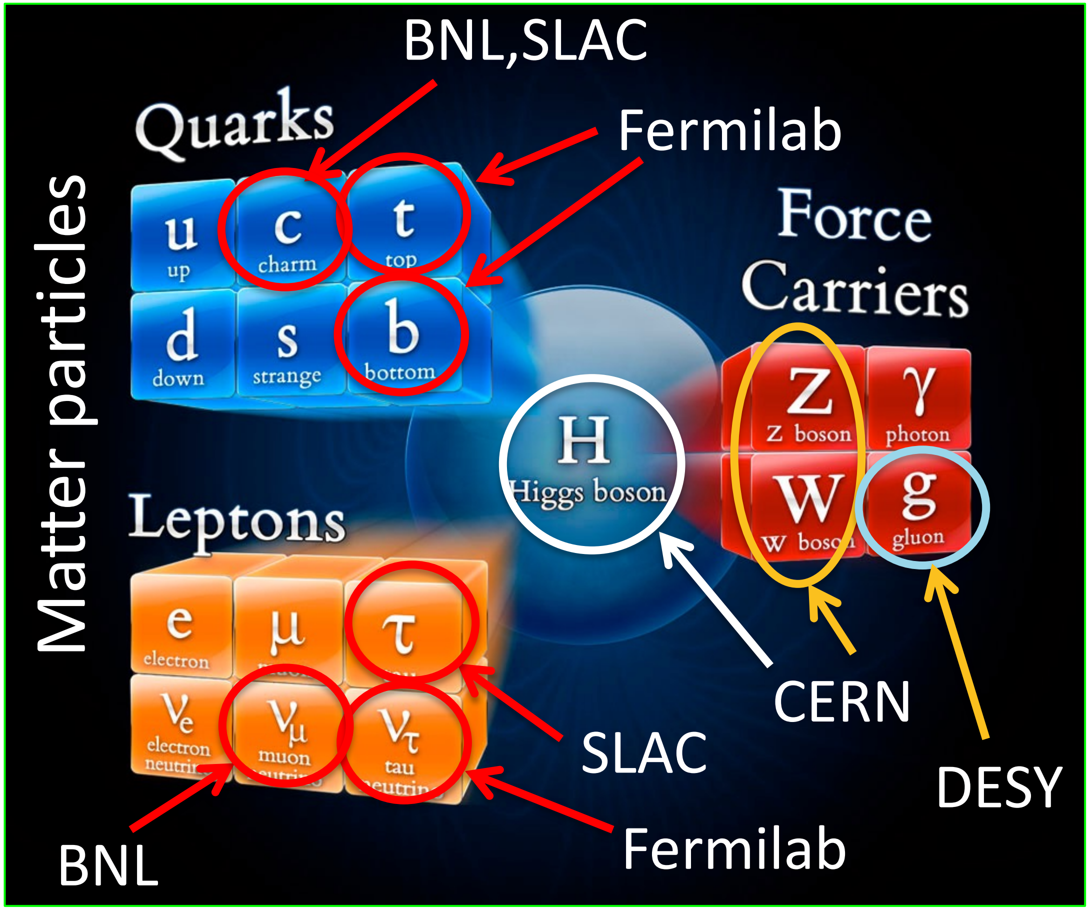


Three particles were discovered at Fermilab:

b-quark 1977
t-quark 1995
ν_τ (tau neutrino) 2000

Hints for the Higgs: 2012

The Standard Model of Particle Physics

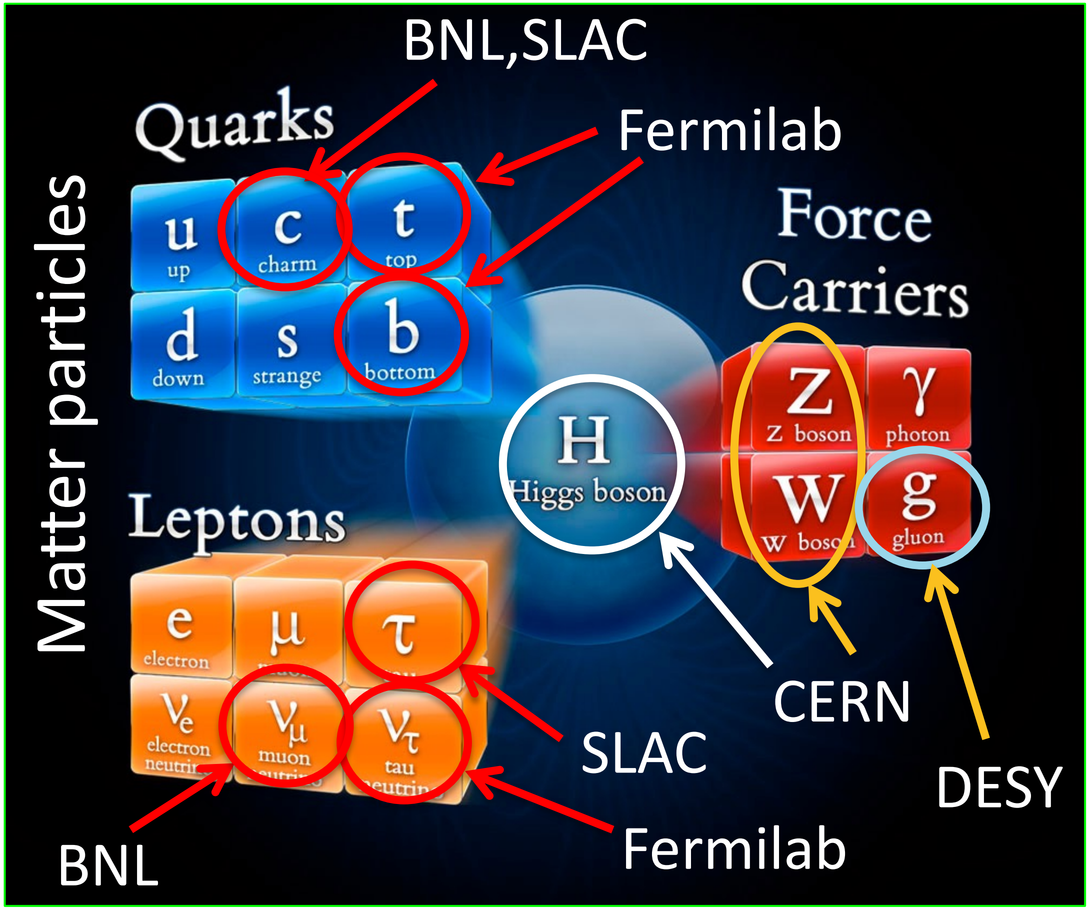


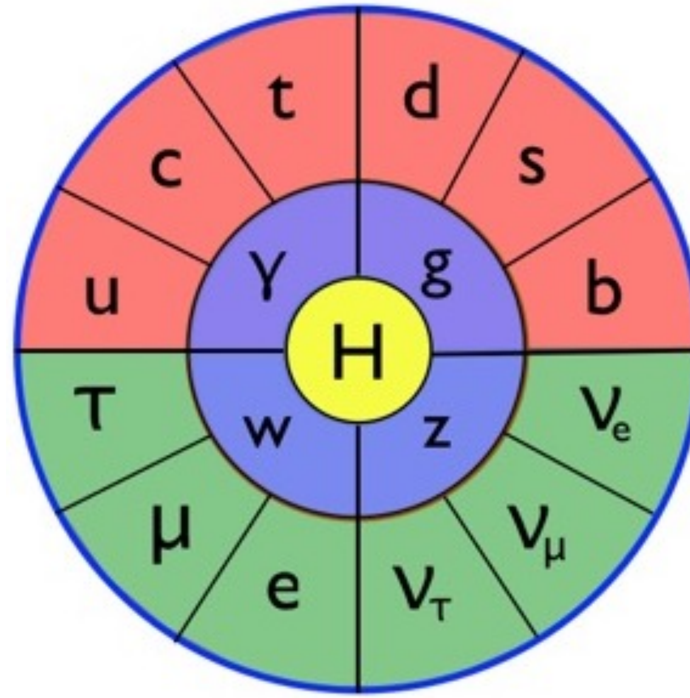
- Progress in particle physics over the past 50 years have mainly come from discoveries at successively more powerful particle accelerators, particularly at colliders
  - Charm quark (1974) e+e-, pN
  - Tau lepton (1975) e+e-
  - bottom quark (1977) pN
  - Gluon (1978/79) e+e-
  - W,Z bosons (1983) **ppbar**
  - Top quark (1995) **ppbar**
  - Tau neutrino (2000) pN
  - Higgs boson (2012) **pp**

Interesting to note:
All fermions discovered in the U.S.
All bosons discovered in Europe

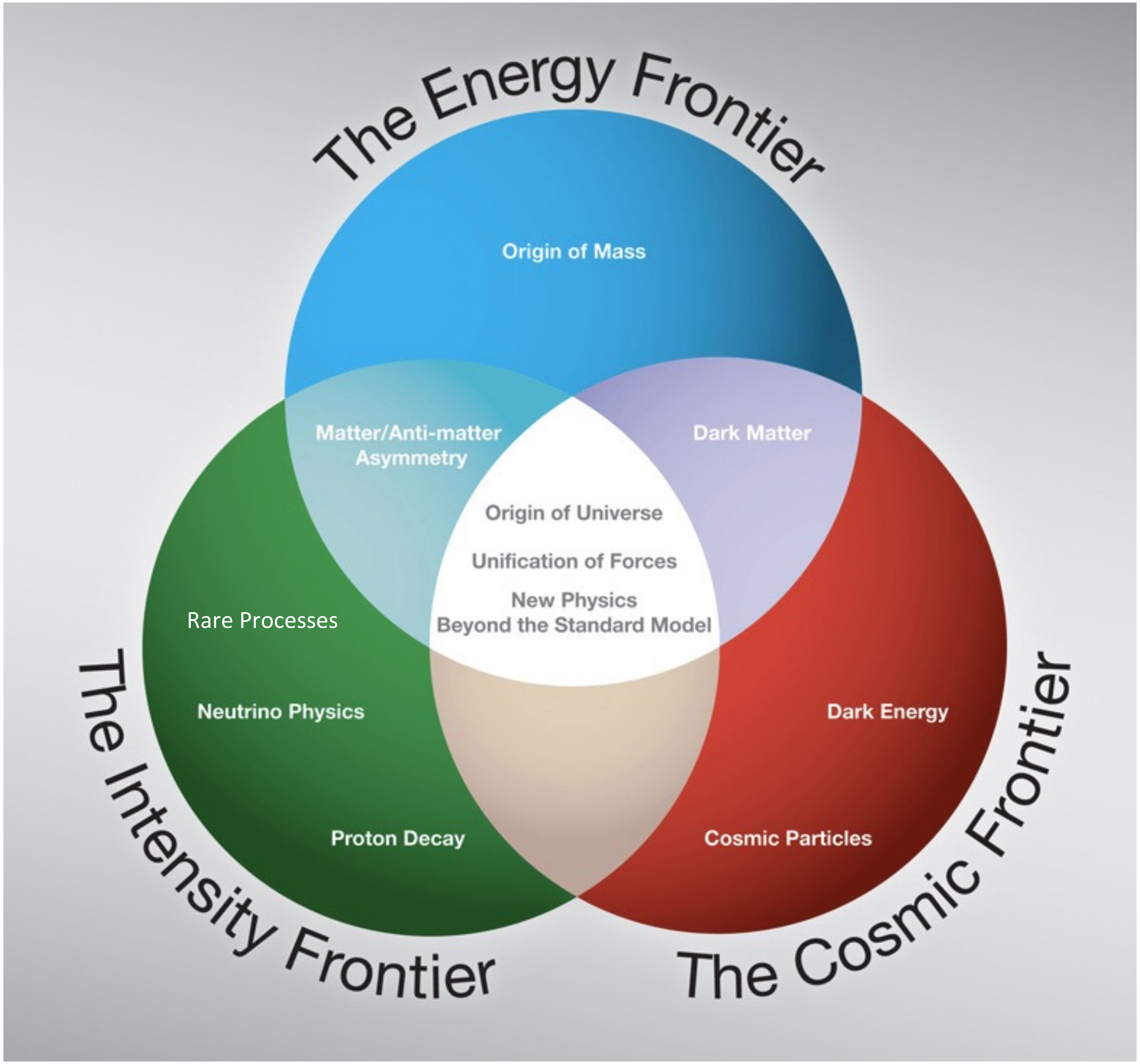
The Standard Model of Particle Physics

Developed and validated over the past five decades

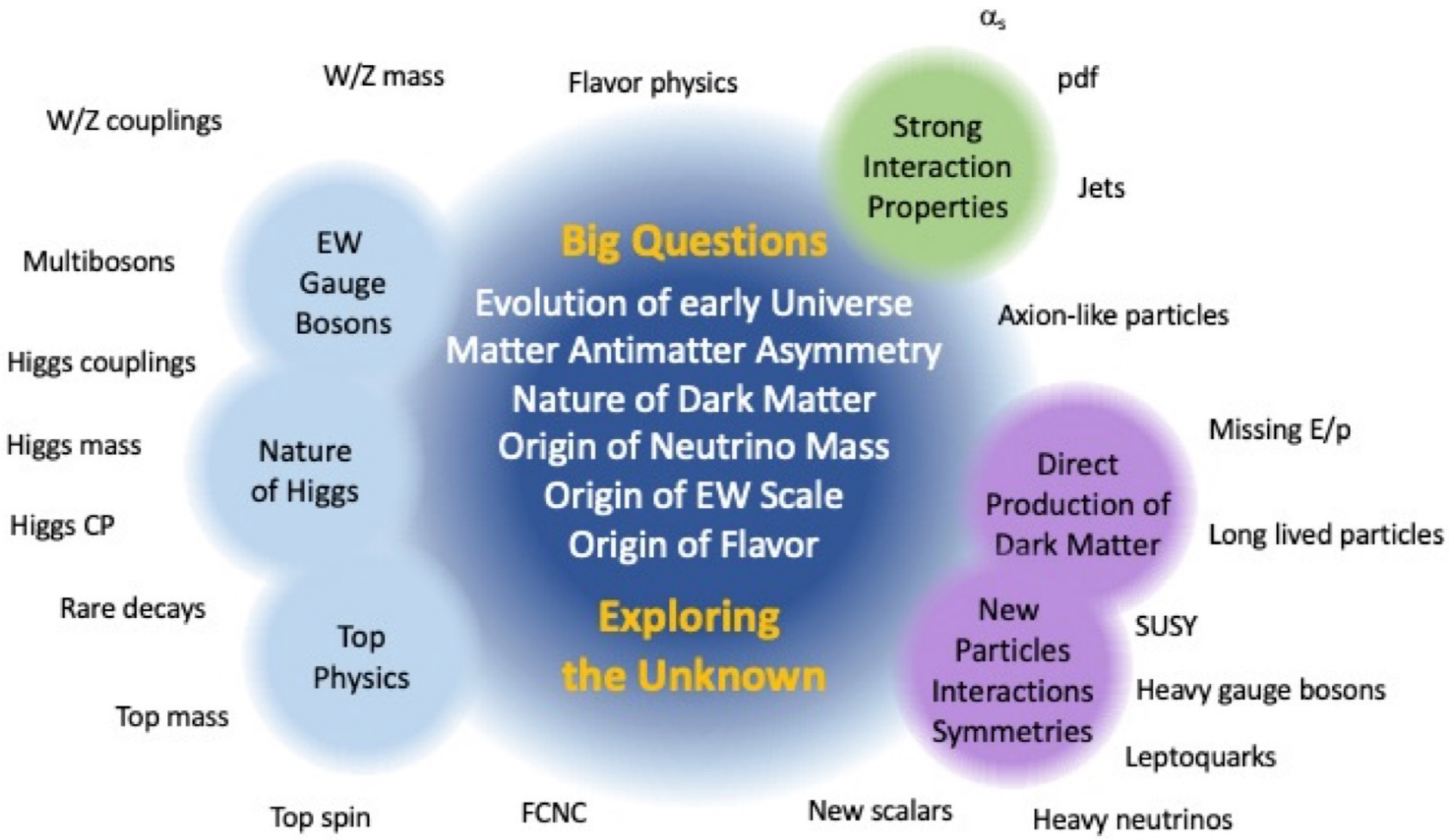




17 particles/fields that appear to be elementary.


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Rare Processes
Neutrino Physics
Dark Energy
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

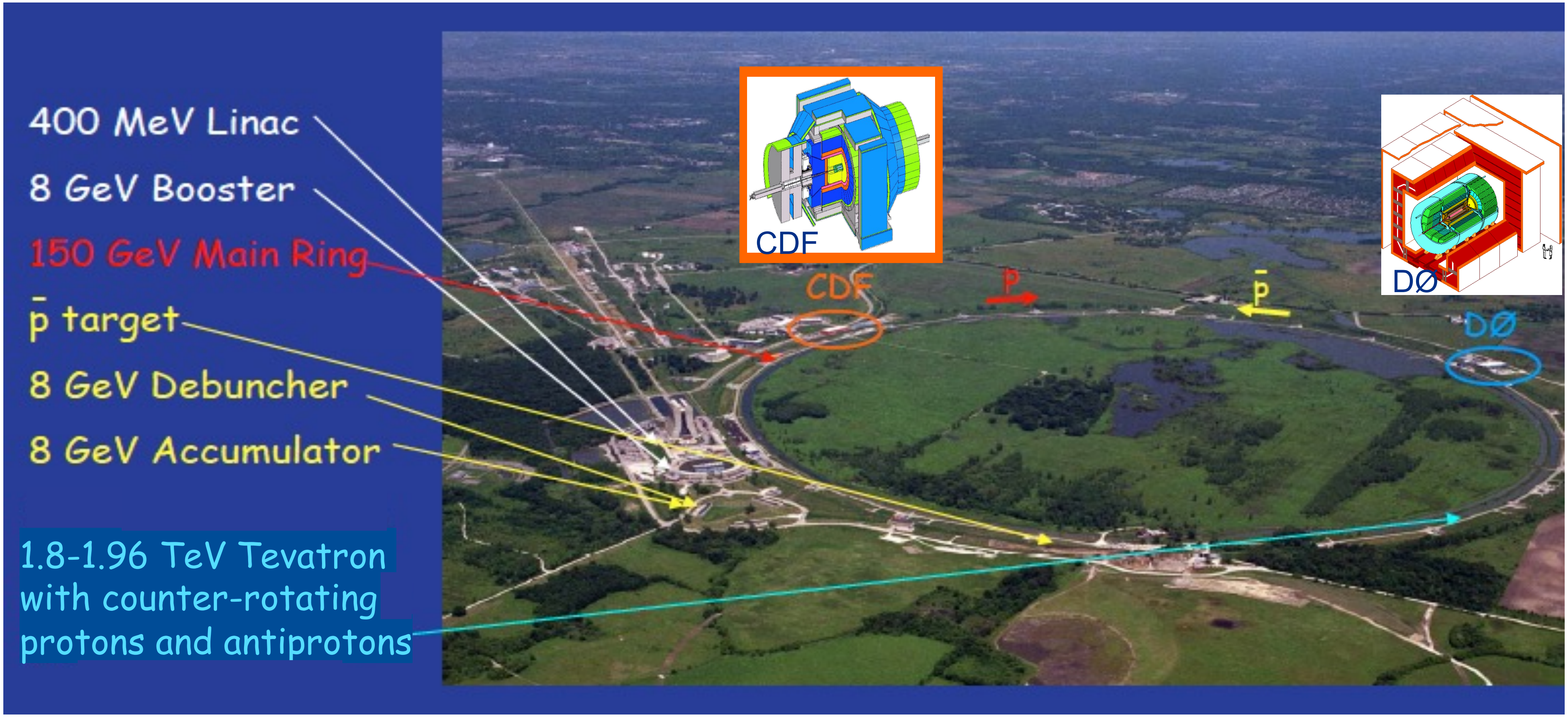
Big Questions



Snowmass Energy Frontier Report, 2022

Tevatron Collider Complex (1985-2011)

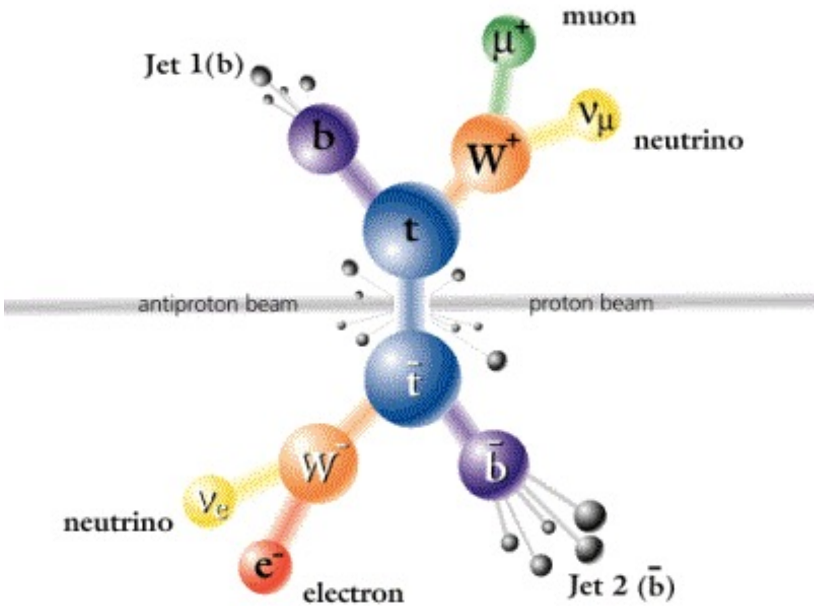
The Tevatron was at the **Energy Frontier** for ~25 years



The Tevatron Collider and the experiments

Until 2011, Fermilab hosted the highest energy hadron collider in the World producing proton-antiproton collisions at center of mass-energy of 1.96 TeV

Discovery of top quark in 1995



top-pair production
and decay (lepton+jets)

Cutting-edge detector technology and advanced analysis techniques were critical for discovery!

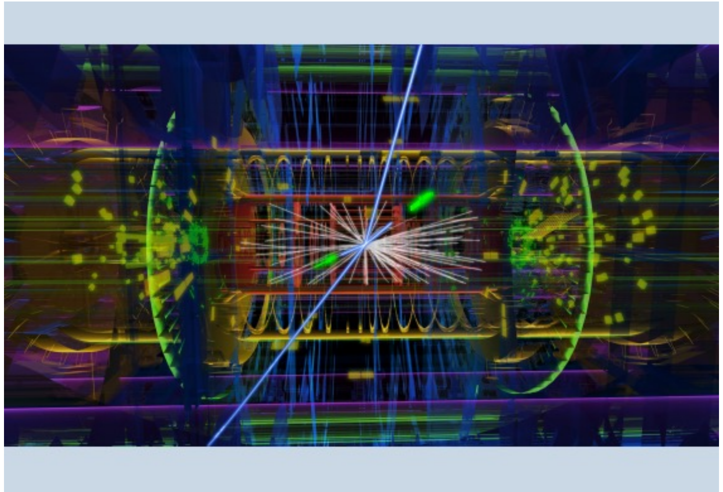
CDF and D0 at the Tevatron discovered the top quark in 1995, after decades of search at other machines around the world.

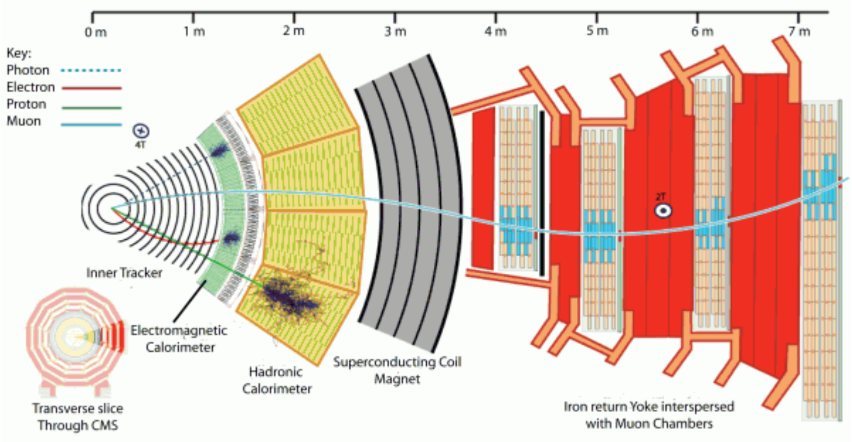
Mass of the Top Quark ~ 173 GeV

March 2, 1995 at Ramsey Auditorium

Creation, Detection and Discovery

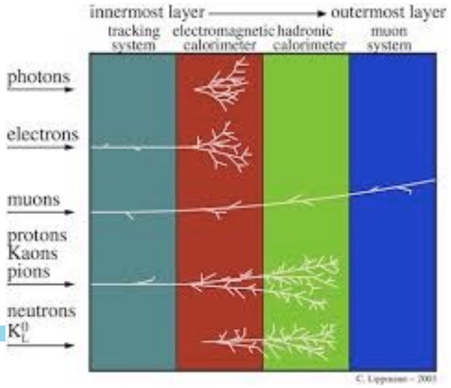
- Particle collisions at very high energies can create lots of all sorts of particles (via $E=mc^2$) and some extraordinary ones, such as the top quark or the Higgs boson!
- Particle detectors track, identify and "measure" particles produced in collision "events".





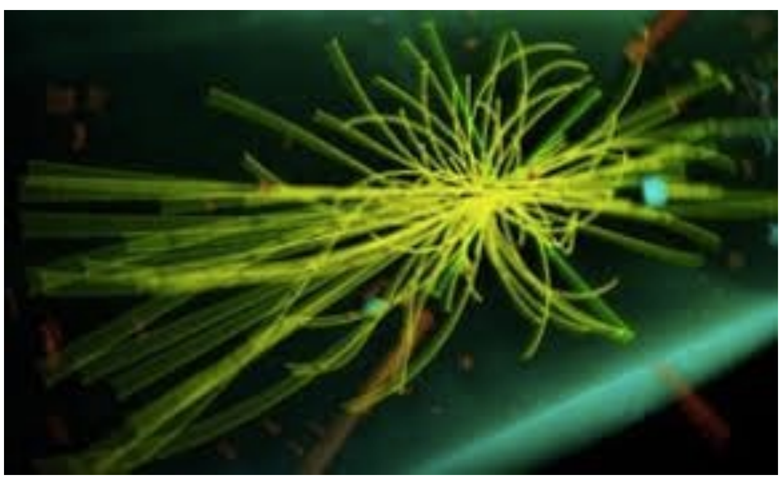
➢ Detectors are large, multi-layered, multi-system devices surrounding the collision region

➢ Have millions of electronic readout channels, have multi-tiered data-acquisition systems

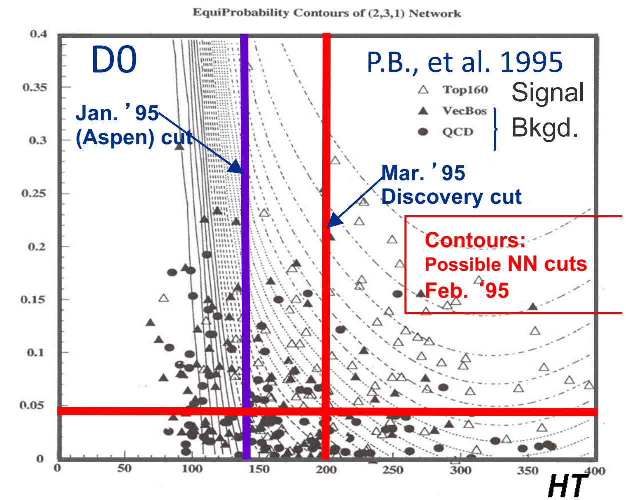


How do we find new particles?

Search for particles/events with expected (or unexpected) characteristics of new particles; compare with background

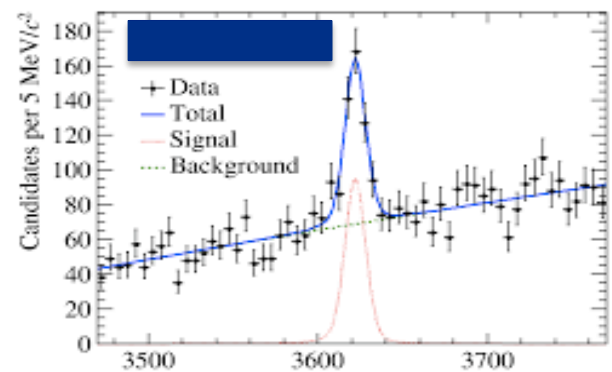


Look for excess events in distributions



Look for a bump/peak in a distribution of a quantity

[redacted]



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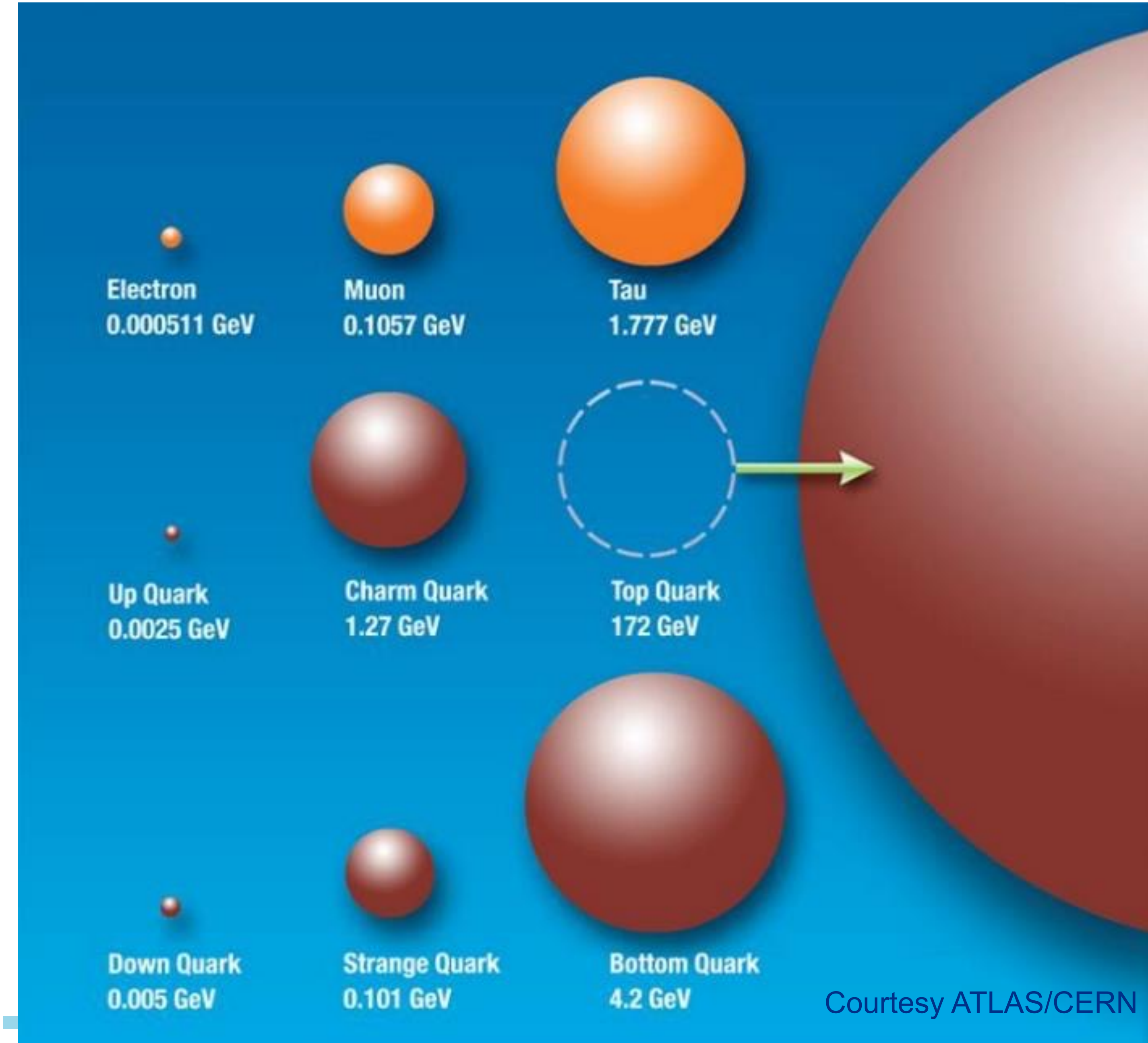


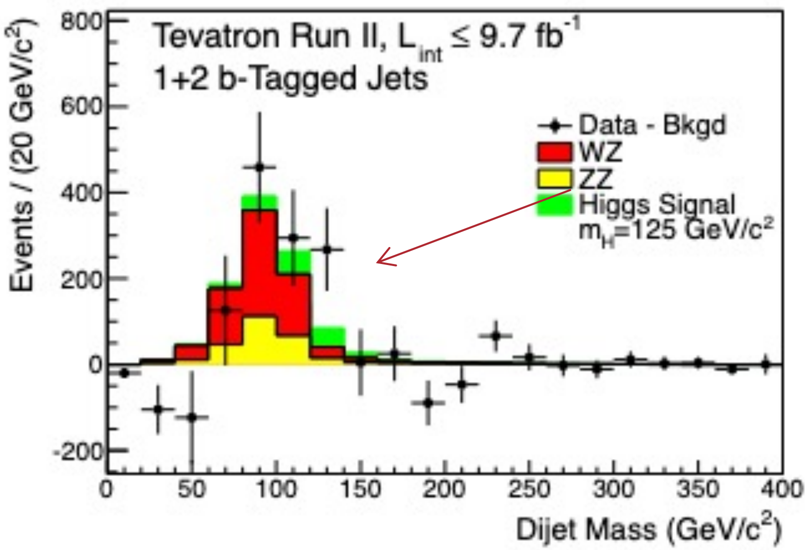
Top quark turned out to be much heavier than anticipated.

172x more massive than a proton.

After the top (and ν_τ) discovery, Higgs boson was the only missing piece in the Standard Model!

Searching for the SM Higgs Boson
at the Tevatron

- **Fermilab upgraded the Tevatron collider complex for Run II, to accumulate large amounts of data, hoping to find the Higgs before the LHC! Still fell short for the discovery.**
- Using **neural networks** provided same reach with a factor of 2 less luminosity w.r.t. conventional analysis (See e.g., P.B. et al. Phys. Rev. D **62**, 074022 (2000))
- Improved bb mass resolution & b-tag efficiency

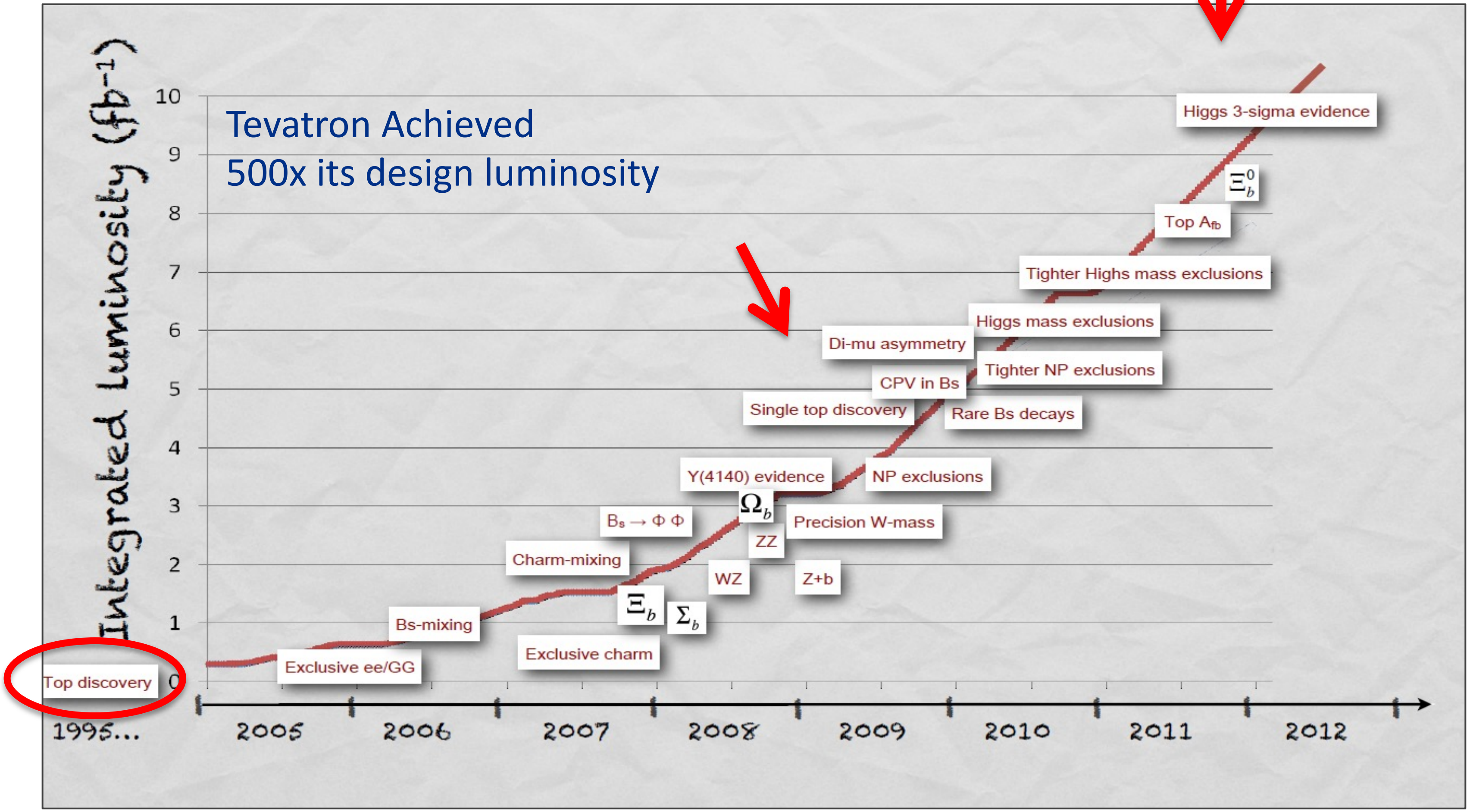


Tantalizing excess of events between 120 – 135 GeV/c^2

Significance of 3.1 σ global

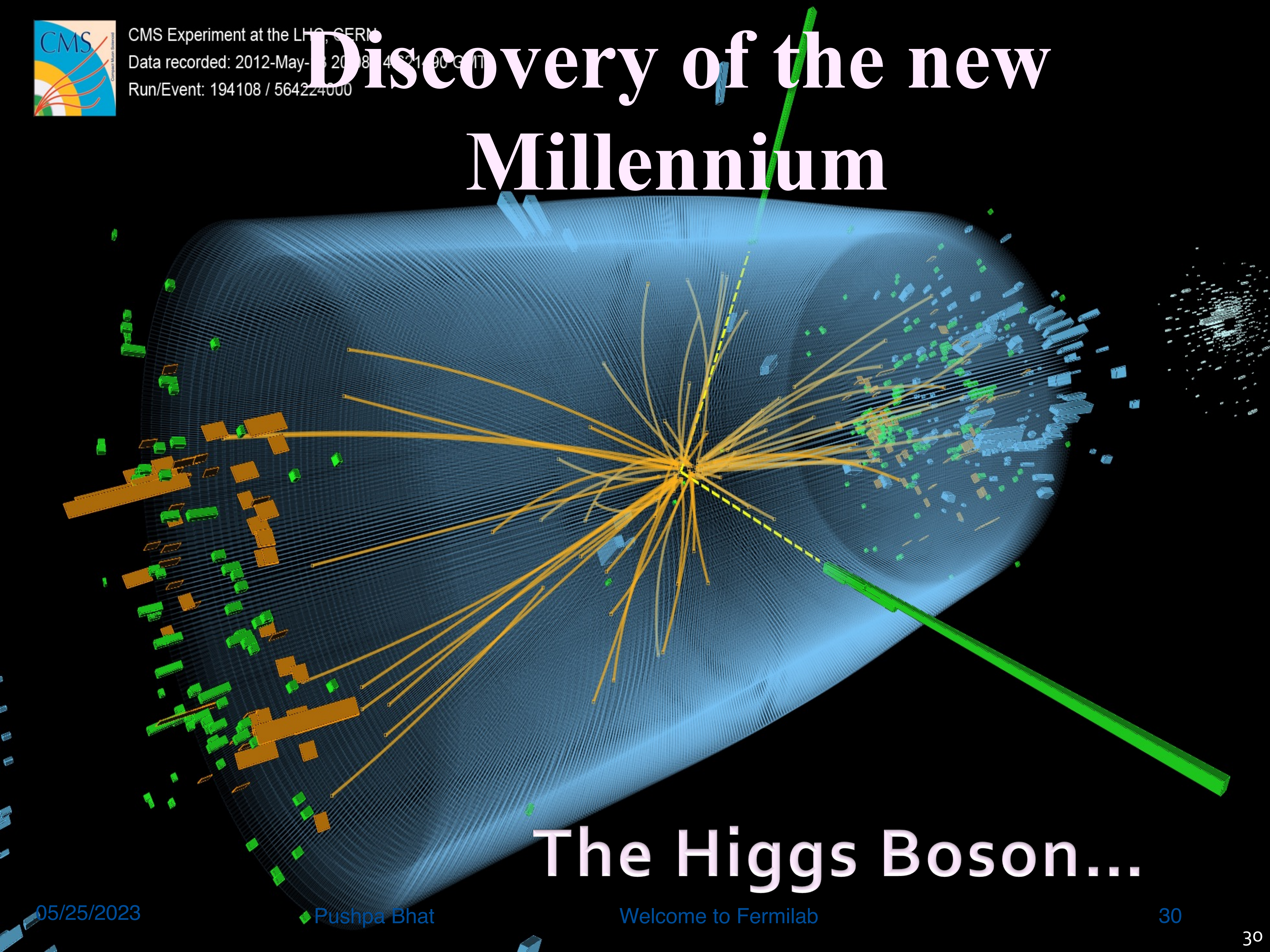
July 2, 2012

Beyond the Top Discovery at the Fermilab Tevatron



- **CDF and DØ went on to make more discoveries and measurements**
- **Machine Learning has had a "Deep Learning" revolution and its use has become ubiquitous!**

Discovery of the new Millennium



The Higgs Boson…

The Large Hadron Collider at CERN

Geneva, Switzerland

The LHC is a proton-proton collider in an underground 27 km ring straddling the Swiss-French border

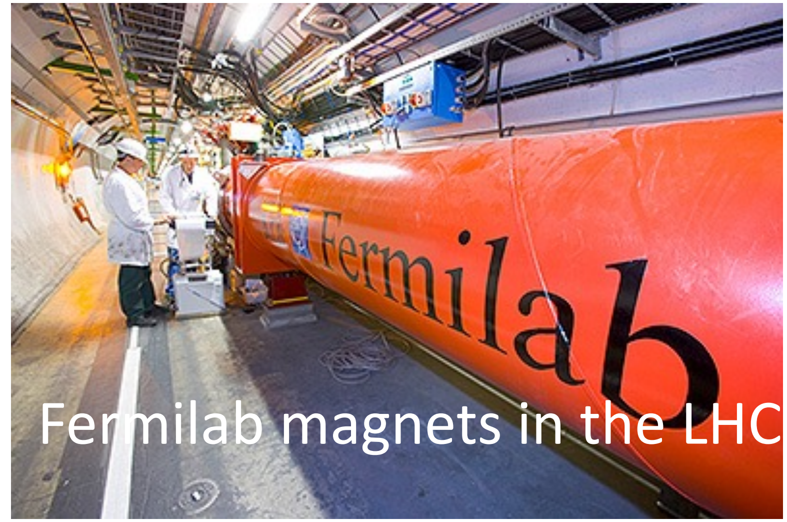
Two proton beams colliding with a kinetic energy > 7,000 times their rest mass

100 billion protons per bunch

Bunches collide 40 million times per second

The Large Hadron Collider @ CERN

A scientific & technological marvel!



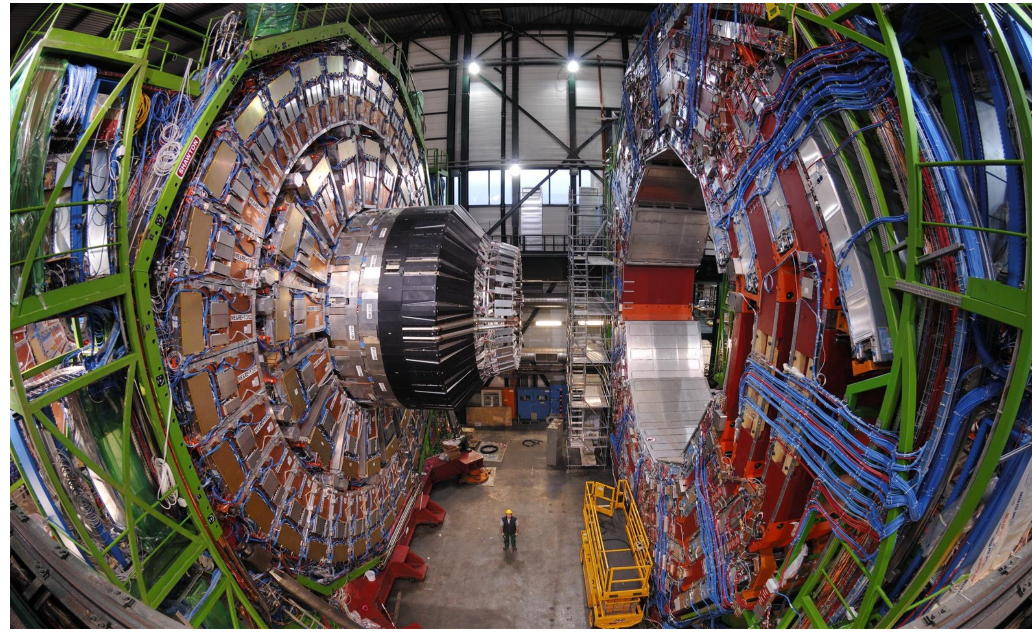
- ~ 27 km circumference
- >10,000 Magnets
- Largest cryogenic system in the world
- Magnets cooled by superfluid helium to 1.9^{o}K (523^{o}F below RT)

Fermilab at the LHC/CMS

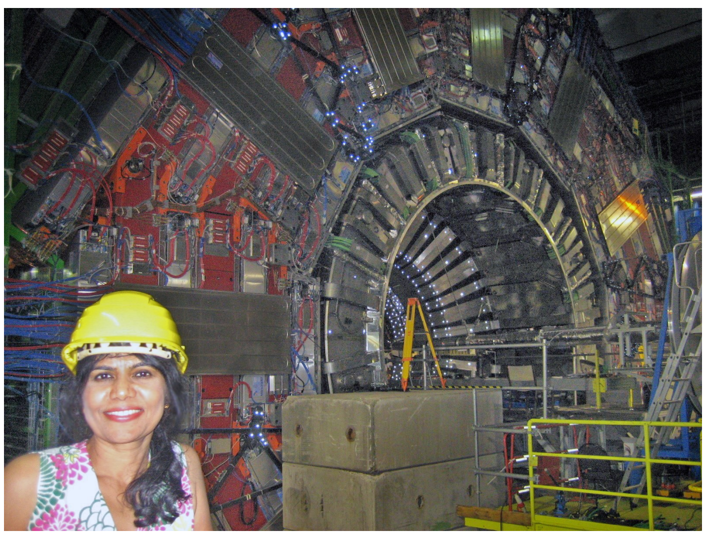
- Fermilab is the "host" laboratory for US CMS
  - Leveraged CDF and D0 experience and expertise at the Tevatron
    - Detectors: CMS all-Si tracker (FPIX, TOB; HCAL/HB); Muon endcap (ME) chambers and steel
    - Software & computing: data storage, management (grid computing), analysis computing
    - Operations: LHC/CMS Remote operations center (Wilson Hall 1st floor)
    - Data analysis: LHC Physics Center @ Fermilab (Multivariate, machine learning analysis methods used in top discovery, measurements and new particle searches).
- Superconducting accelerator experience
    - LHC Accelerator Research Program
    - Magnet expertise – responsible for LHC "low-beta" quadrupoles (Tevatron experience).

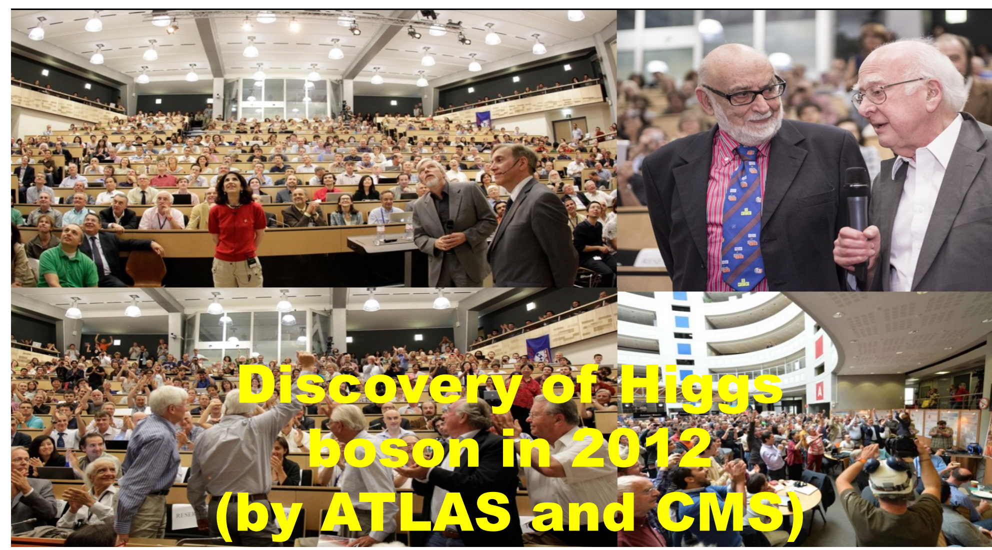
LHC Remote operations center @Fermilab

The CMS detector



- 14,000 tons of sensors with 100 million channels of readout (40M events readout per second!)
- World's largest superconducting solenoid magnet
- World's largest active Si Tracker detector
  - *Building on the legacy of the collider experiments at the Tevatron*

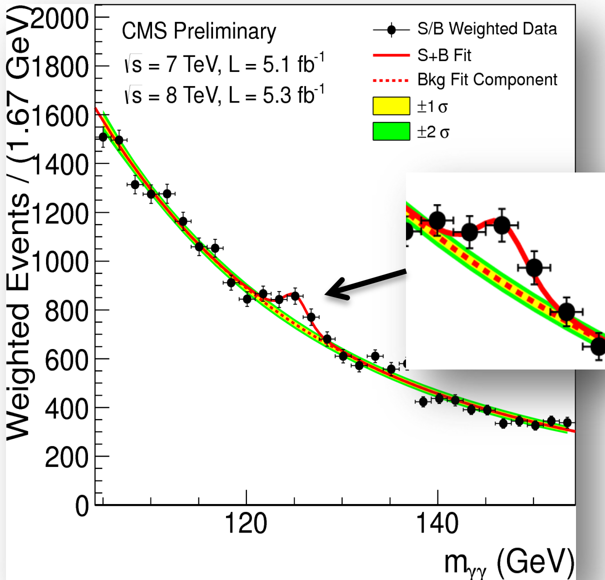


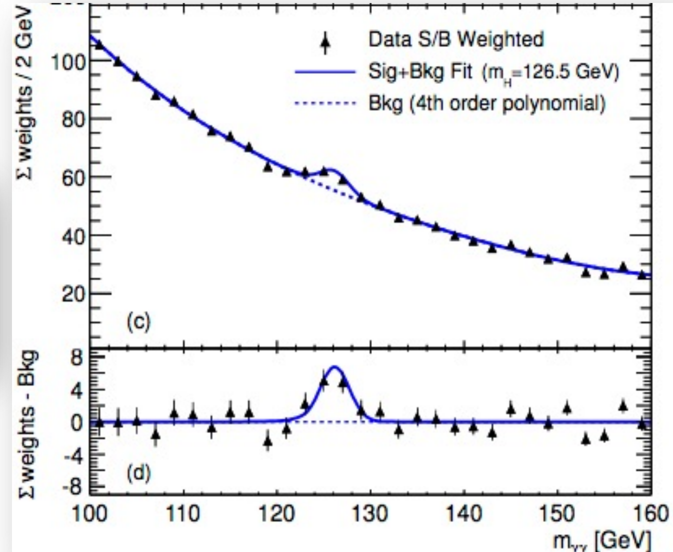


Higgs Discovery

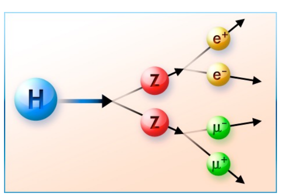
Data from ~10^{15} Collisions

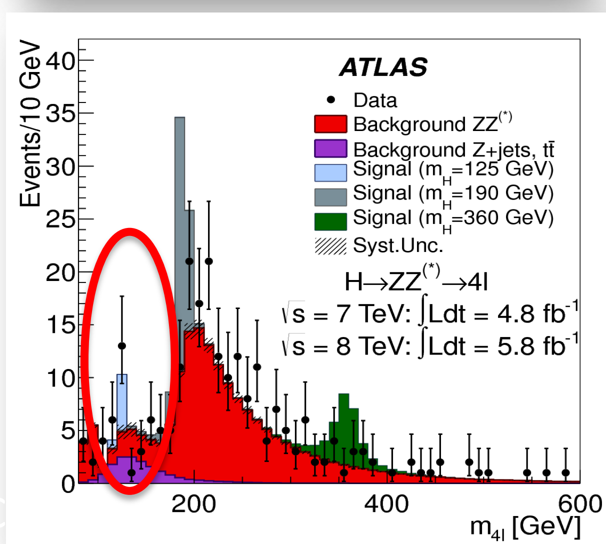
$H \rightarrow \gamma\gamma$

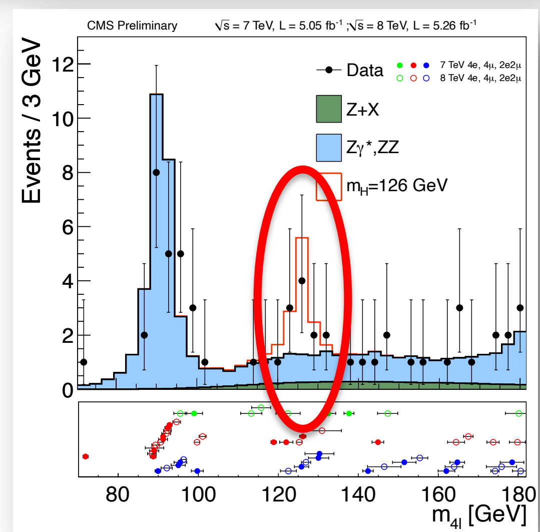




$H \rightarrow ZZ \rightarrow 4\ell$

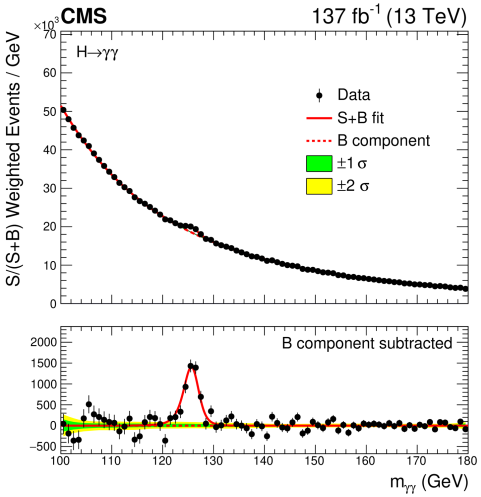


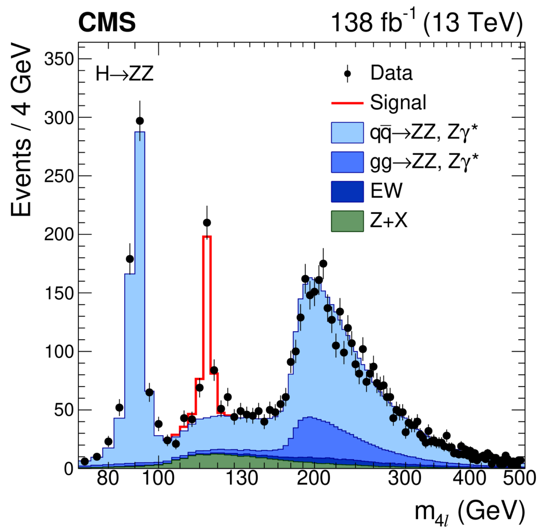


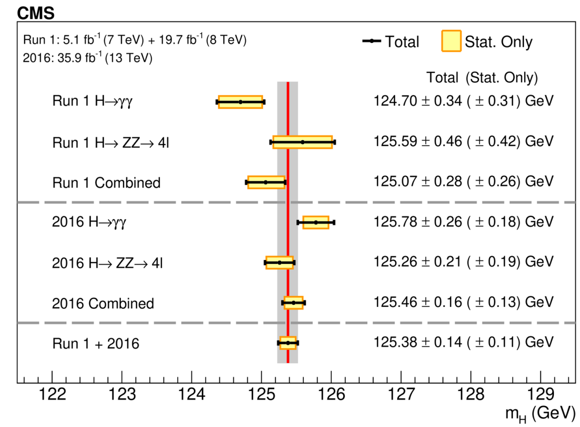


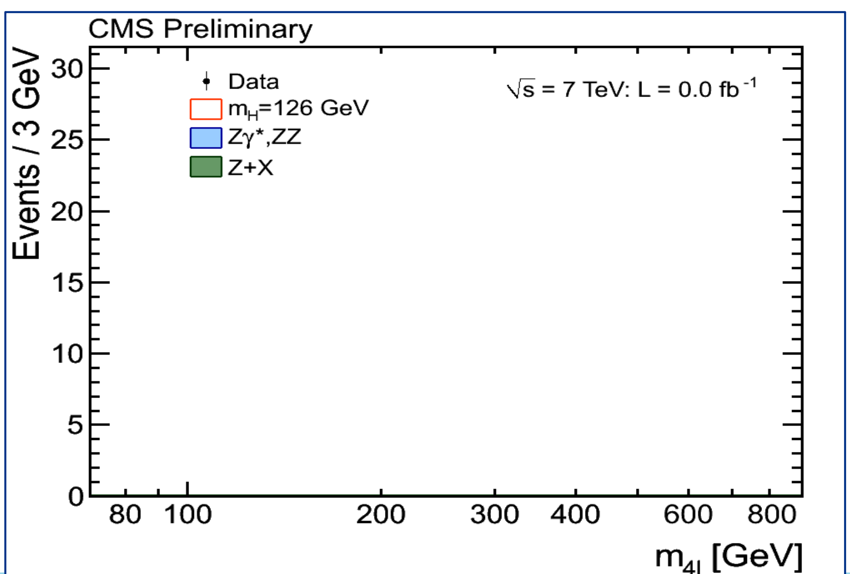
Fermilab

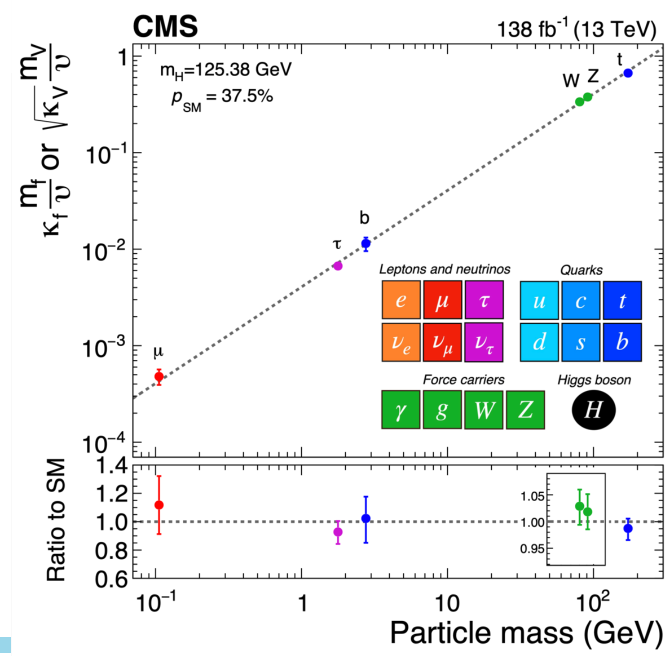
Higgs Boson Properties











Higgs Boson Celebrated on Capitol Hill
November 20, 2013

Many members of congress attended and spoke

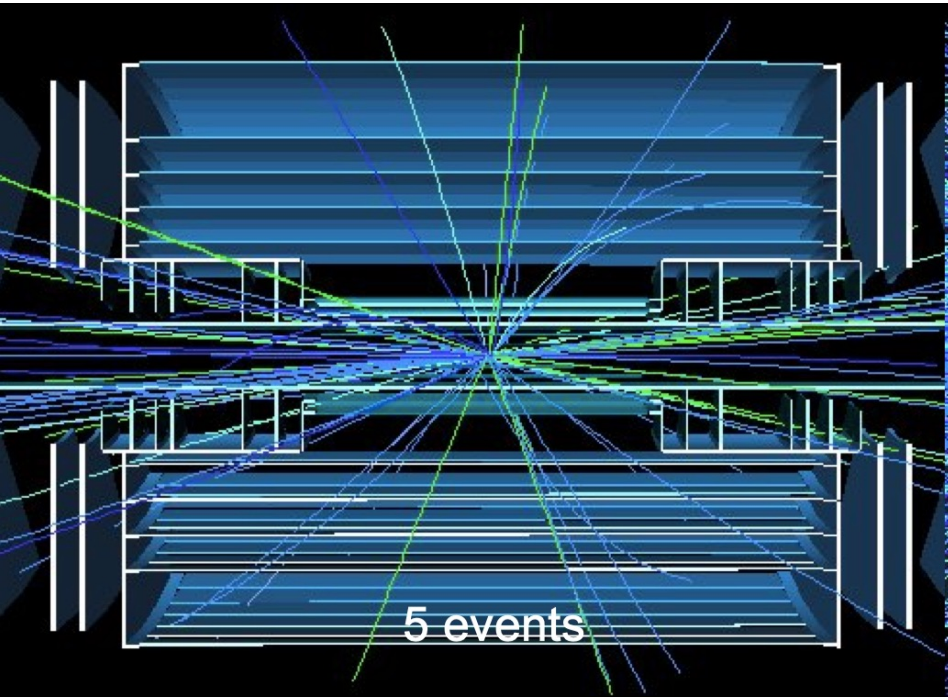
CMS @ Fermilab

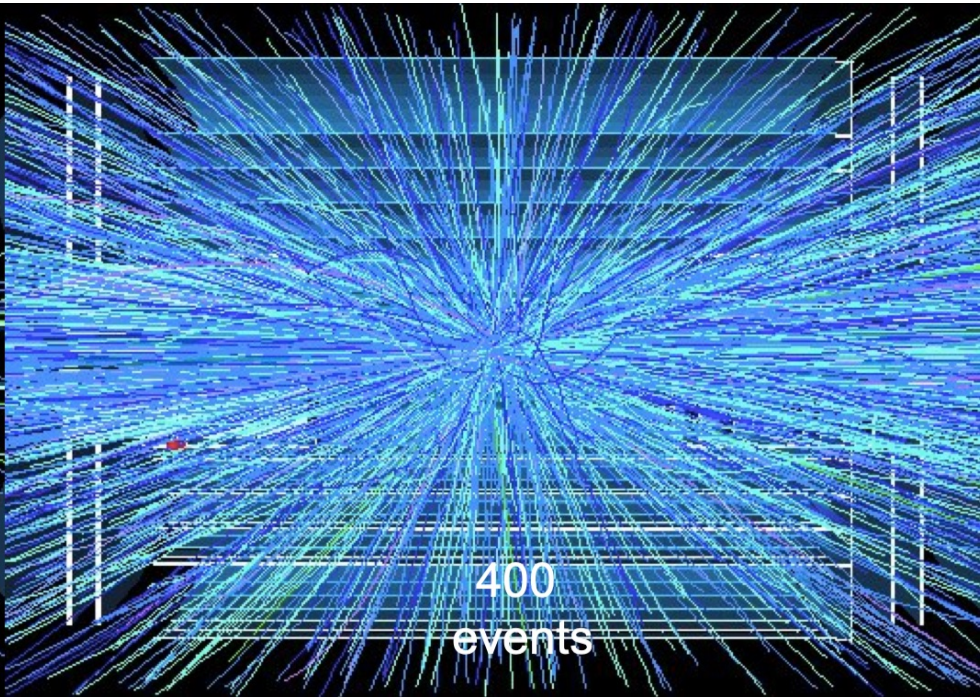
LHC will operate for a couple of more decades.
Only about 5% of the data collected so far.

The HL-LHC Environment

"Typical" LHC collision event at the time of the Higgs discovery

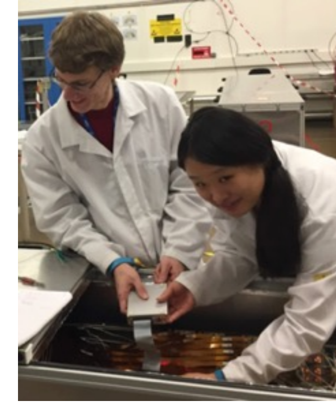
HL-LHC collision event has as many as 400 proton-proton collisions at once



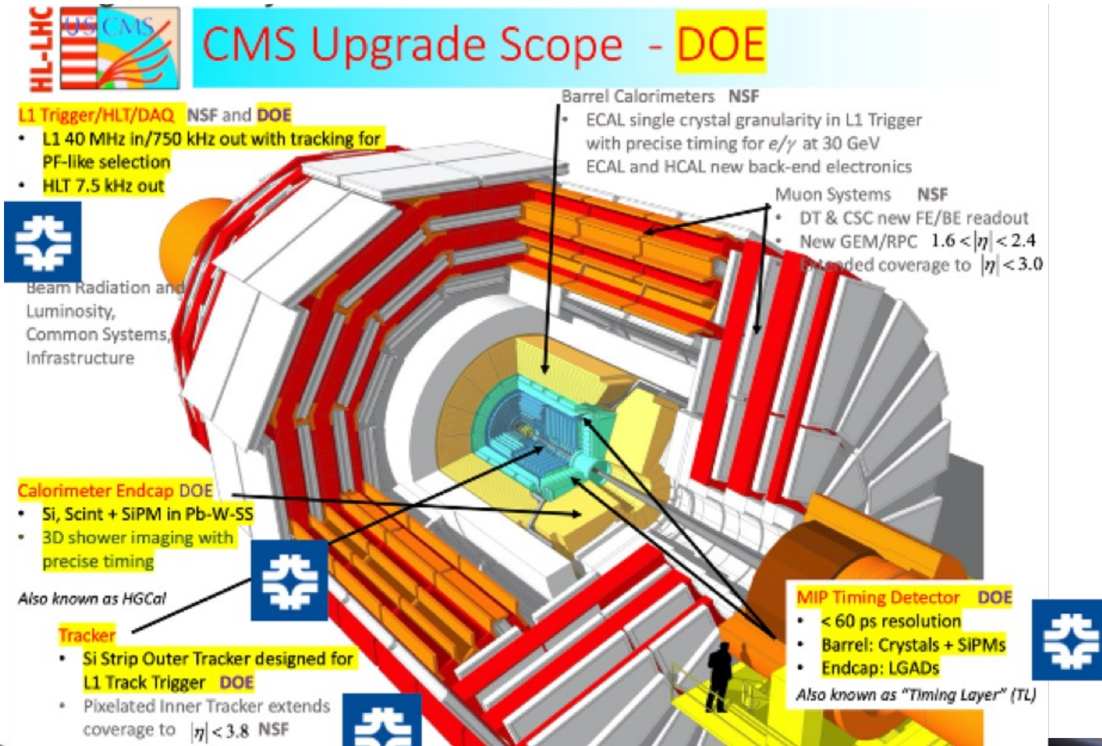


Need major upgrades of the detectors to make sense of these kind of events

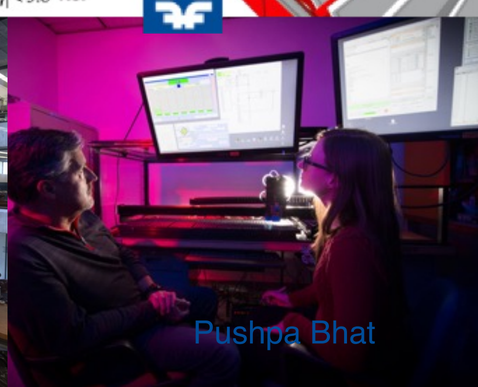
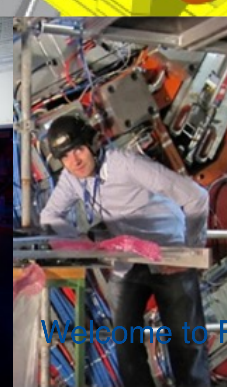
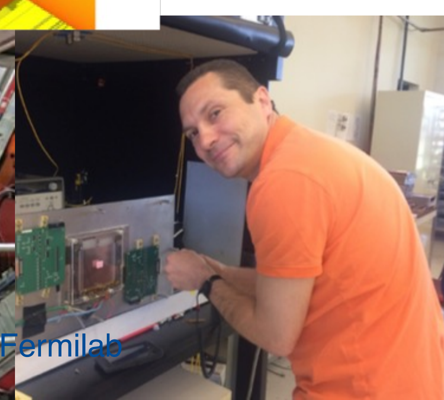
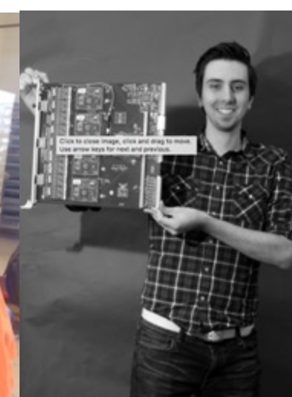
Fermilab and CMS Upgrades



Innovation and cutting edge technologies to maximize the discovery potential of the LHC and HL-LHC

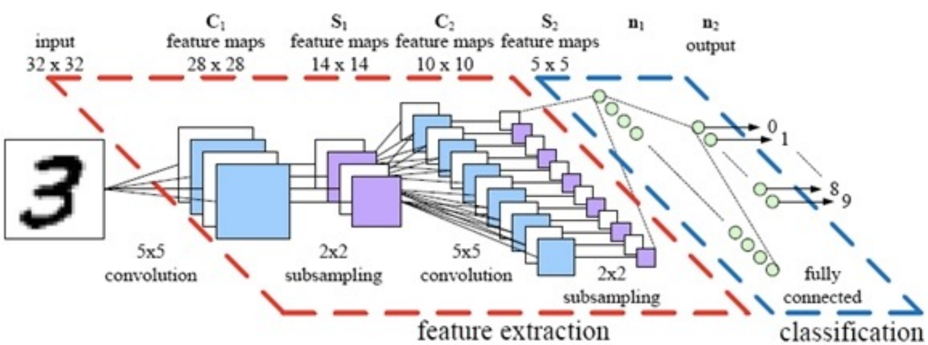


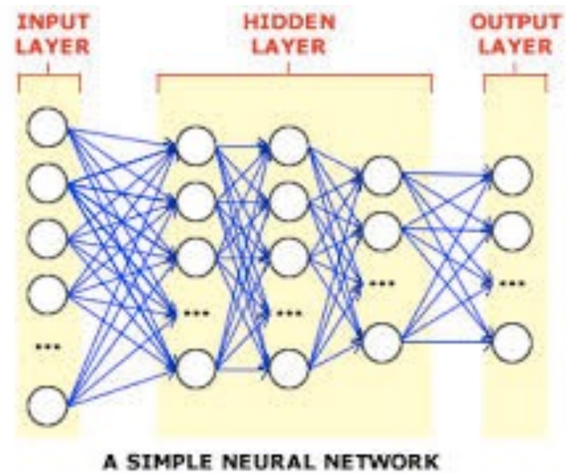
- **Over 2B channels!**
- **Tracker measuring momentum at 40MHz**
- **Calorimeter with imaging capabilities**
- **Timing detector with 15ps resolution**


Machine Learning (and Artificial Intelligence)

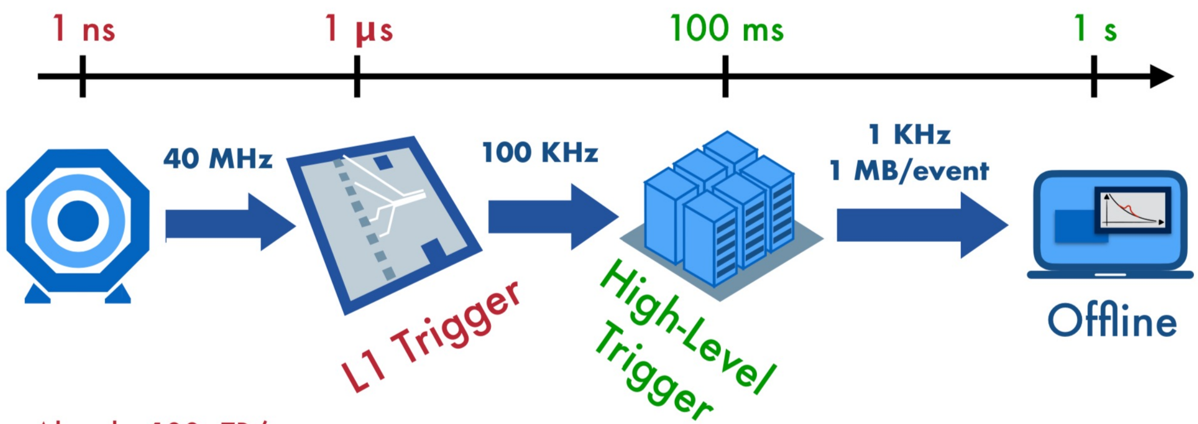
- Machine learning (ML) was used at Fermilab starting in 1990 in top quark searches and measurements and later in Higgs searches and studies
  - See P.C. Bhat, Annu. Rev. Nucl. Part. Sci. Vol. 61 (2011) 281-309
- Now the buzz is about **DEEP LEARNING**





- Energy, Intensity and cosmic Frontier experiments all use ML now.
- Fermilab is deploying ML in analysis software, hardware and in operations and accelerator control systems

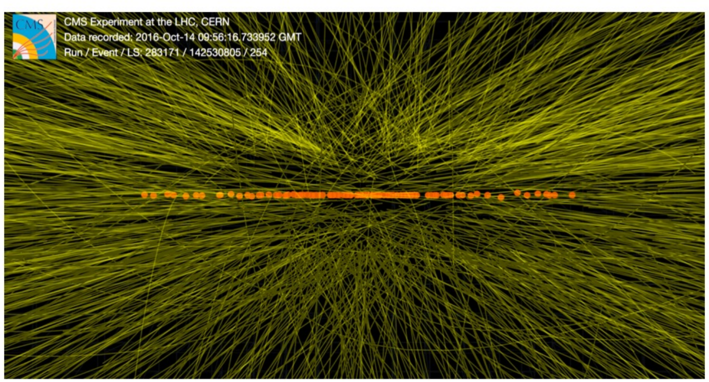
ML to meet the big data challenge



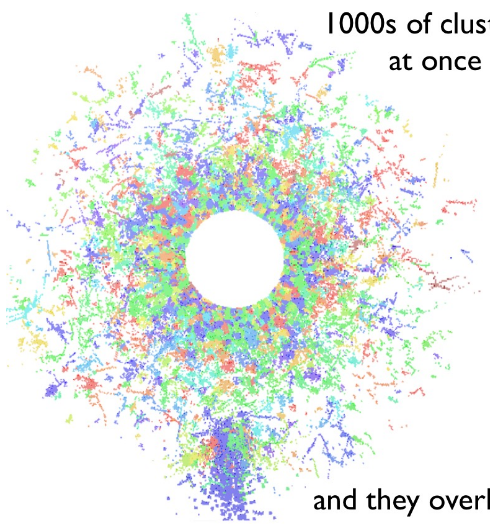
Absorbs 100s TB/s
Trigger decision to be made in O(µs)
Latencies require all-FPGA design
99.75% events rejected!

- We are leading the development of the world's fastest AI
- Machine learning inference in ~15 microseconds using FPGA/ASIC based architectures

1000s of tracks at once

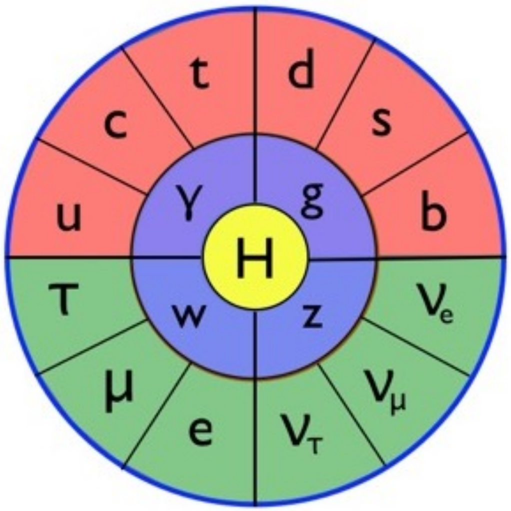


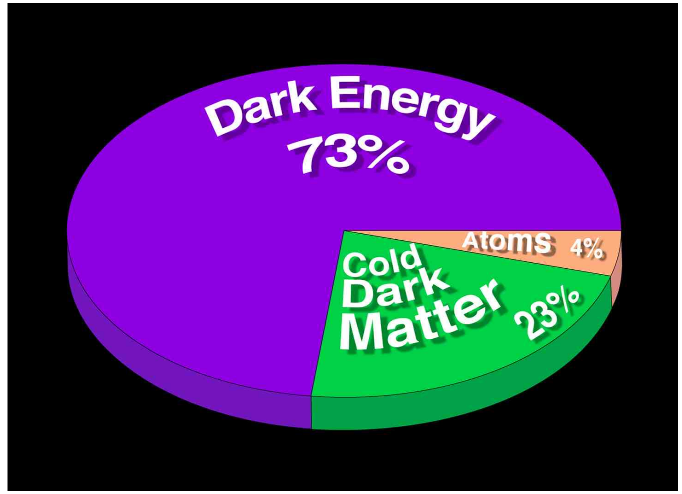
1000s of clusters at once

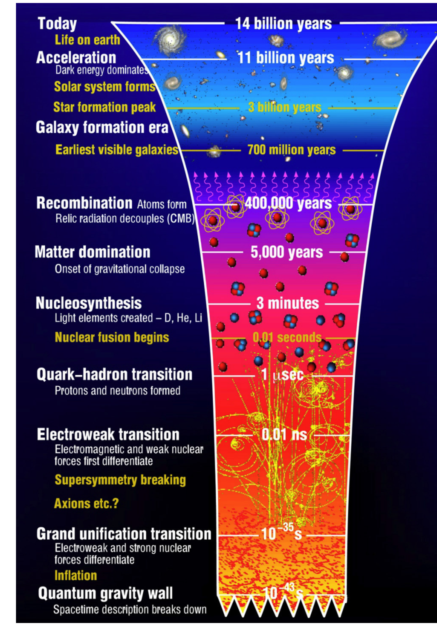


and they overlap :-)

Beyond Colliders







To solve the mysteries of matter, energy, space and time for the benefit of all. Fermilab strives to:

- lead the world in n**eutrino physics** with particle accelerators
- Carry out **precision measurements of rare processes**
- lead the nation in the development of particle accelerators and colliders and their use for scientific discovery
- advance particle physics through measurements of the **cosmos**

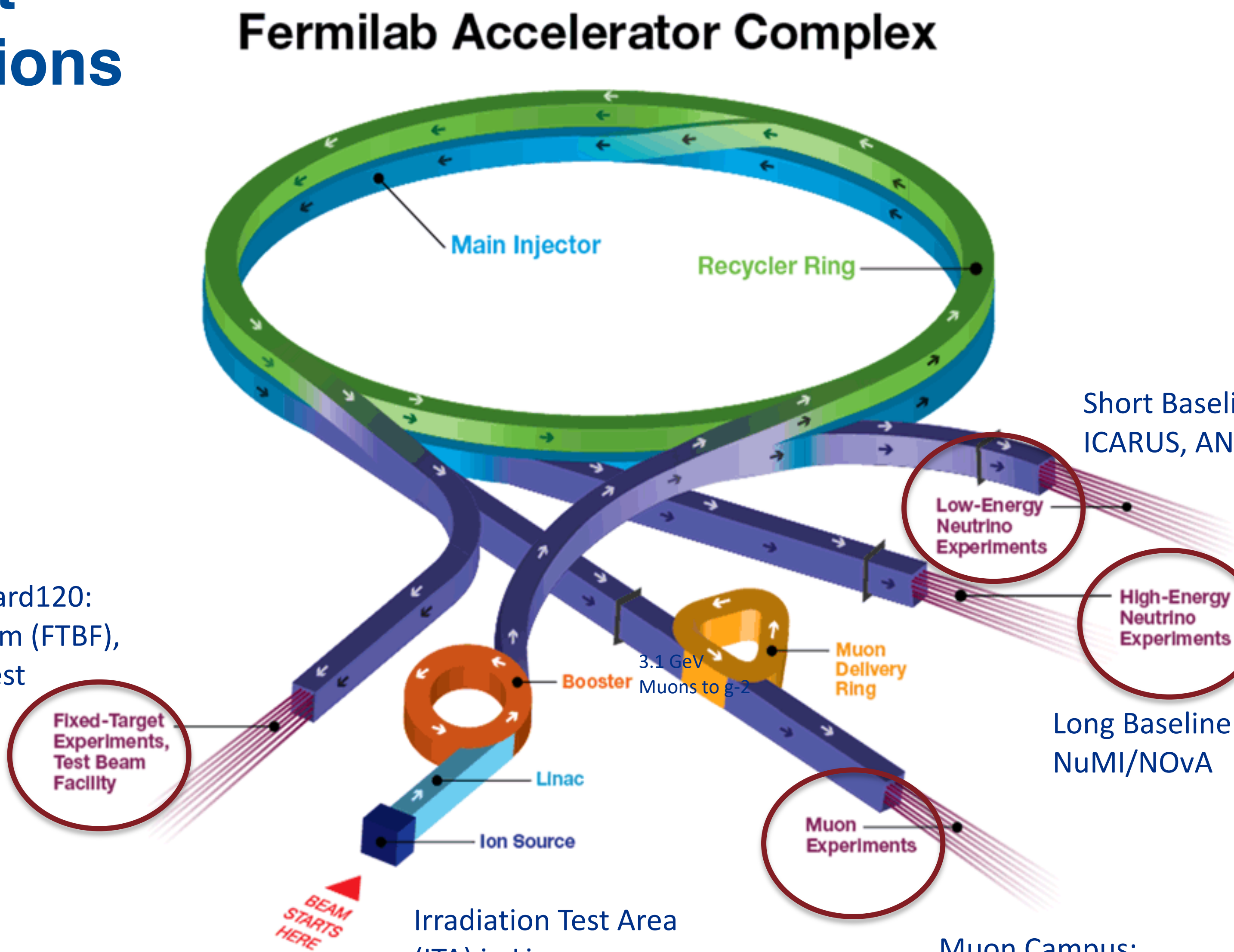
P5/USHEP Science Drivers

- 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

2013 P5 Report
"Building for Discovery"

A new US Particle Physics Community Study completed last summer to develop strategy and vision for the next couple of decades

Current Operations



Short Baseline Neutrino: ICARUS, ANNIE, SBND

SwitchYard120: test beam (FTBF), SpinQuest

Long Baseline Neutrino: NuMI/NOvA

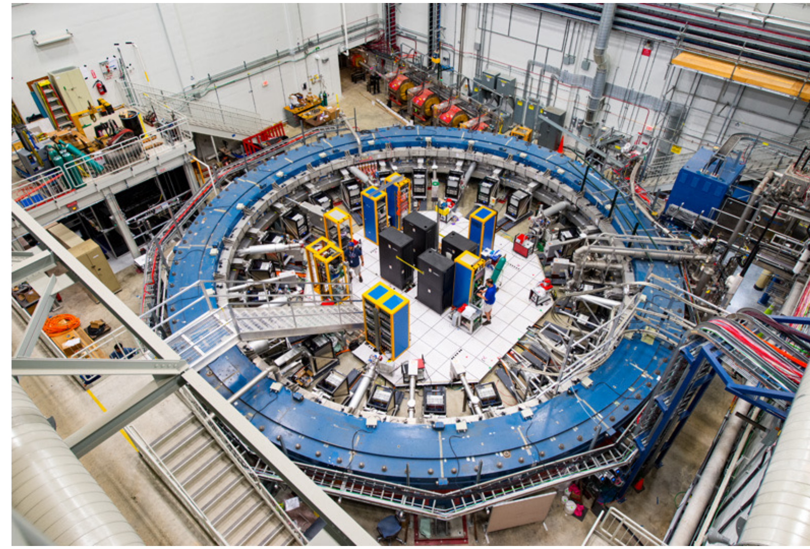
Irradiation Test Area (ITA) in Linac

Muon Campus:
g-2 (completing this year),
Mu2e (commissioning)C

A Chain of Accelerators

Muon g-2 Experiment

- The Fermilab Muon g-2 experiment measures the anomalous magnetic moment of the muon with unprecedented precision (goal:140 parts billion), by studying the precession of muons in an applied magnetic field.
- The measurement is sensitive to virtual particles that pop in and out of existence in the quantum vacuum and can affect the measured g-2. Standard Model (SM) predicts the value with high precision and so deviations could indicate existence of new particles or forces not yet observed.
- Recent result, a 4.2 s deviation from SM, has caused a buzz!



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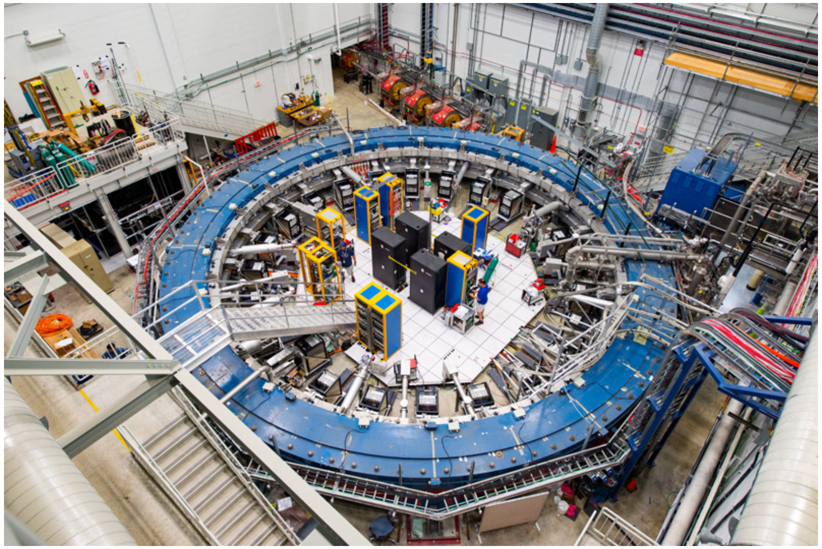
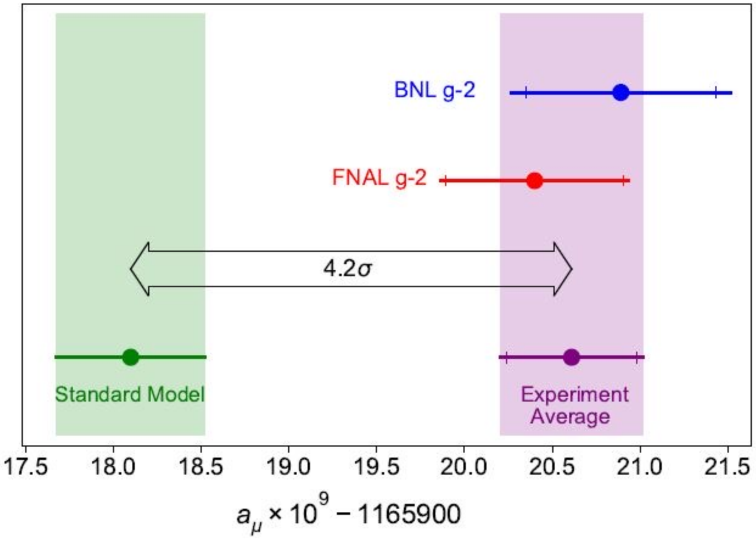
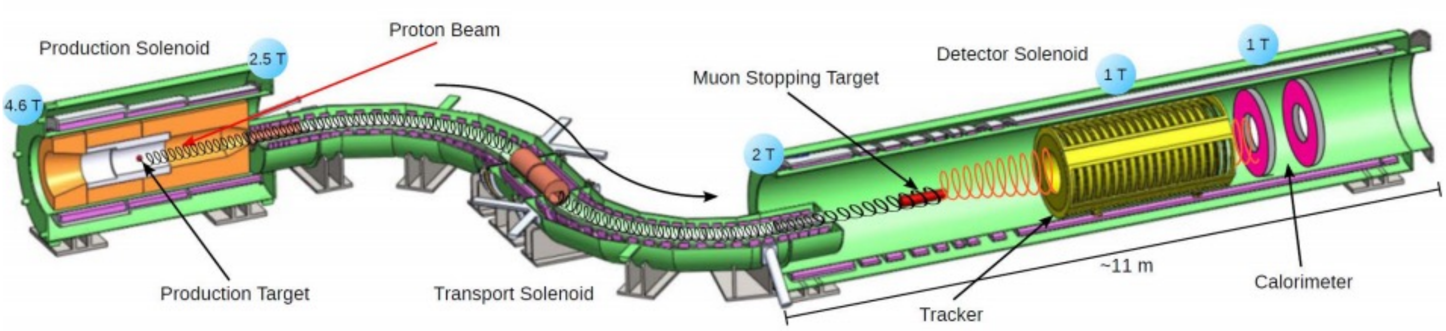


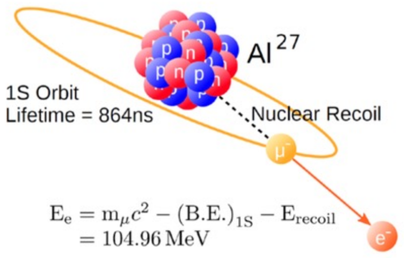


Charged Lepton Flavor Violation (Mu2e)

- The Mu2e experiment at Fermilab will look for evidence of a muon changing to an electron and nothing else. (Tiny in the SM)
- Observing $\mu \rightarrow e$ conversion will signal new physics beyond the standard model, existence of new particles and/or forces.
- It is an indirect search for new particles and interactions and can reach energy scales far beyond LHC's reach in direct searches.



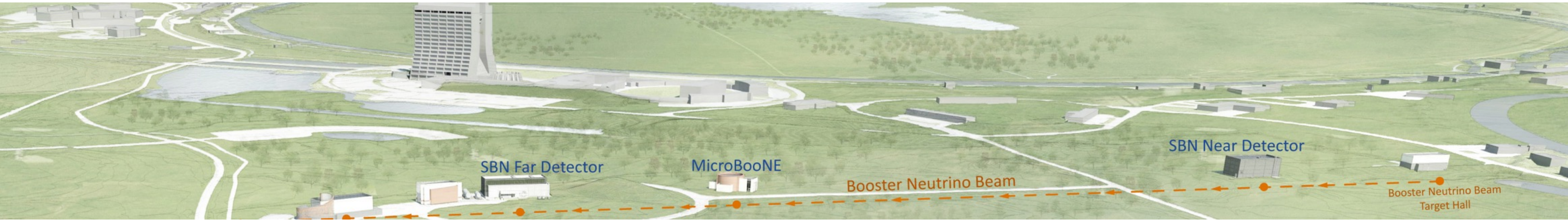
- Three sophisticated superconducting solenoid magnets
- Intense beam of low-energy muons directed on to a thin aluminum stopping target.
- The largest solenoid also houses detectors that measure momenta and energy of particles produced.
- 75' wide, 10' tall



The mesmerizing history of the mysterious neutrinos

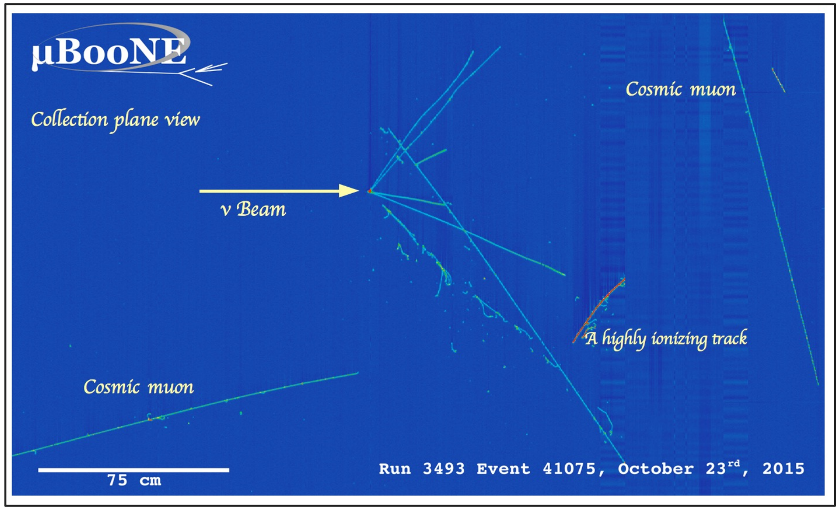
- 1930: Pauli proposes existence of a very light, neutral particle to explain conservation of energy in ^{14}N beta decay.
- 1934: Fermi develops a theory of beta decay; calls the particle ”neutrino”, the “little neutral one”.
- 1956: Reines and Cowan detect neutrinos (ν_e) with a massive detector placed near nuclear reactor at the Savannah River nuclear plant. 
- 1962: Second flavor of neutrinos (ν_μ) detected at an experiment at BNL by Lederman, Schwartz, Steinberger, et al.  in 1988.
- 1968: Neutrinos from the Sun detected at the Homestake mine in South Dakota by Ray Davis, et al.  2002
- 1987: Neutrinos from supernova 1987A detected; Koshiba  2002 (with Davis)
- 1990: LEP experiments show 3 families of neutrinos from Z width
- 1998: Oscillations observed in atmospheric neutrinos 
- 2000: Observation of ν_τ at Fermilab
- 2001: Solar ν oscillations observed at SNO  (2015)
- 2011: $\nu_\mu \rightarrow \nu_e$ oscillations at T2K  (2015)
- ….

Short Baseline Program at Fermilab

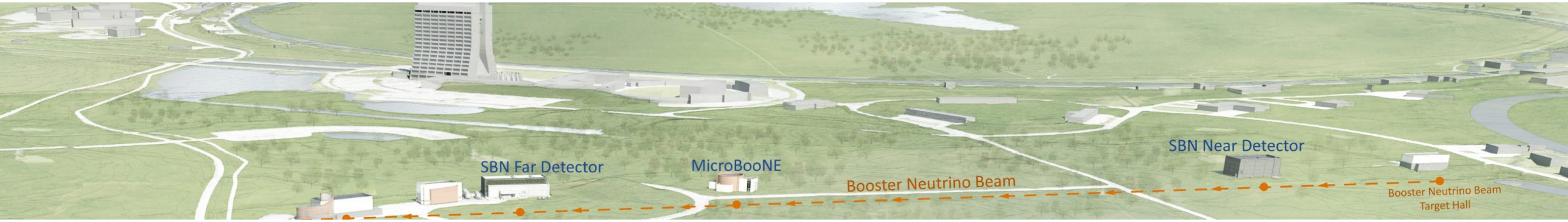


- On Fermilab site are experiments with short baseline -- MicroBooNE, ICARUS & SBN Far and Near Detector, using Booster neutrino beams
- Probing the mysteries of neutrinos: neutrino interactions, sterile neutrino search, ..
- Advancing the technology for neutrino detection

MicroBoone 170-ton liquid-argon time projection chamber (LArTPC)



Short Baseline Program at Fermilab



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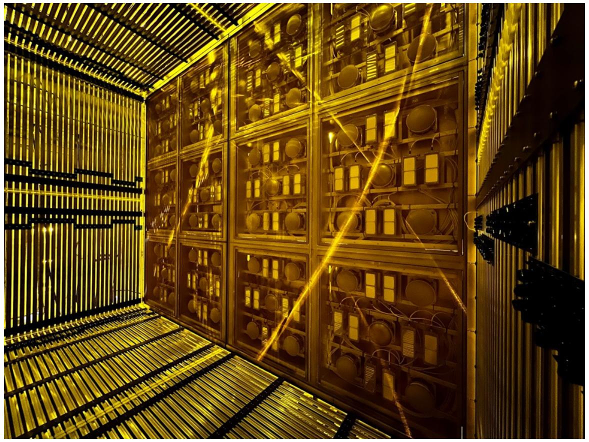
- Advancing the technology for neutrino detection

ICARUS (Far) 500-ton active volume

SBND 112-ton active volume

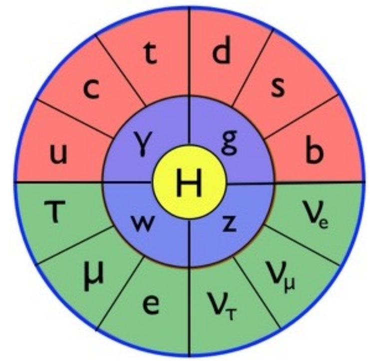


SBND will record over a million neutrino interactions per year.

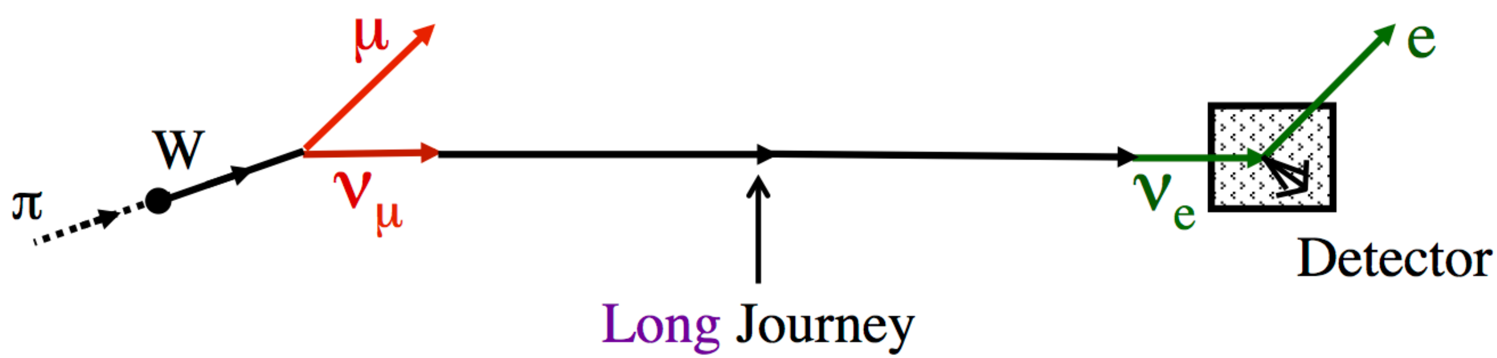
Neutrino oscillations

Each type of neutrino, e.g. muon-flavored neutrino in a neutrino beam is a **quantum superposition** of three different neutrino mass eigenstates

$$|\nu_\mu\rangle = \theta_{\mu 1}|\nu_1\rangle + \theta_{\mu 2}|\nu_2\rangle + \theta_{\mu 3}|\nu_3\rangle$$



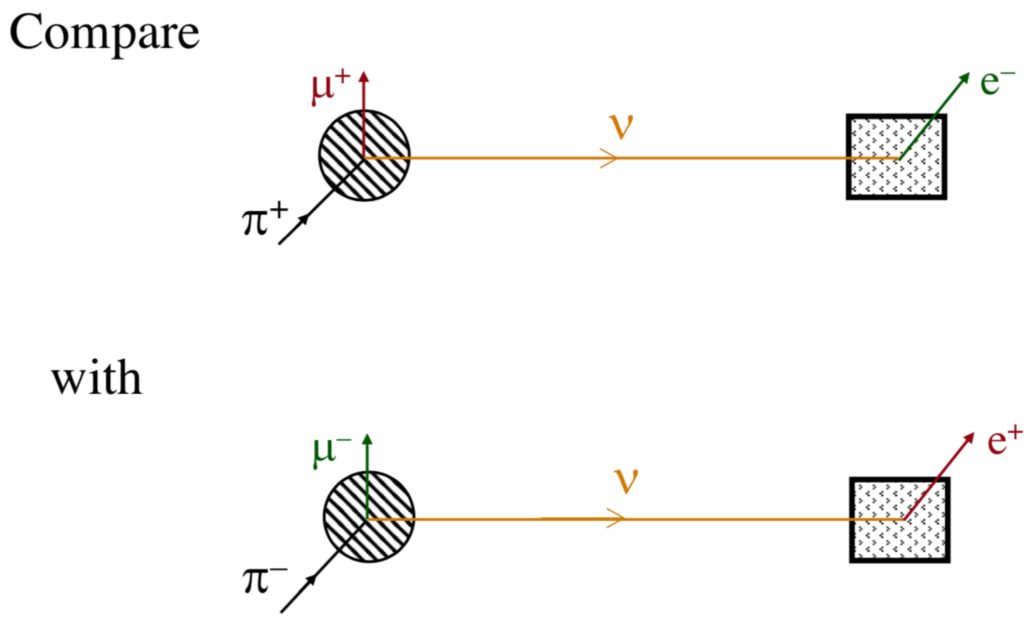
After traveling some distance, this superposition will change because of the different phase factors



Thus even though the neutrino did not interact, there is some chance to detect it later **as a different flavor**

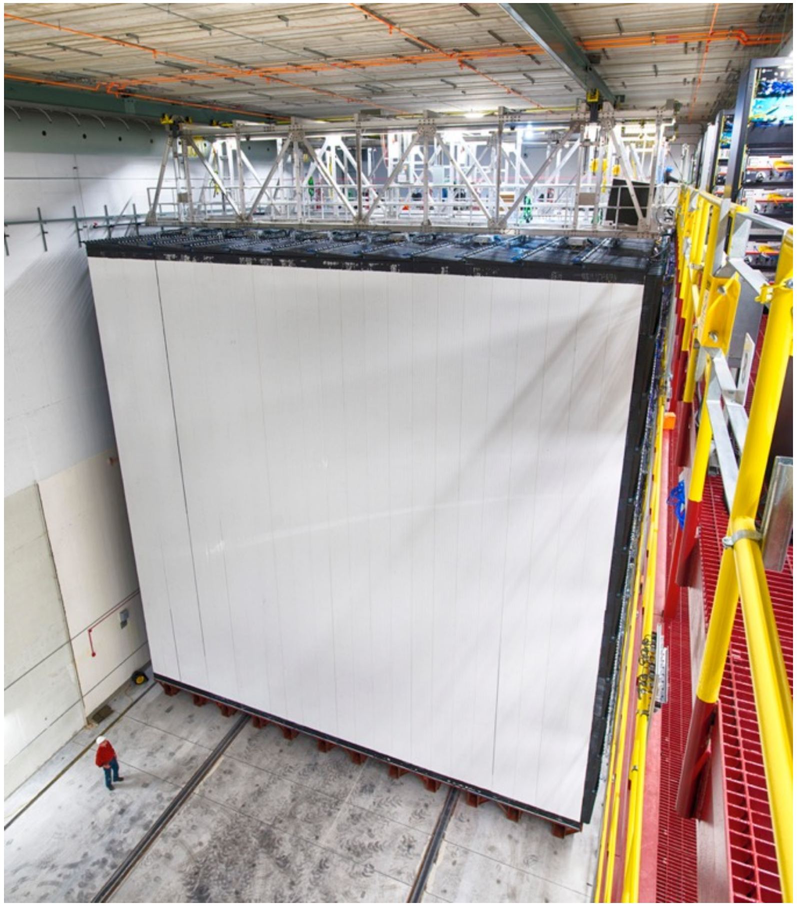
Neutrino oscillations and CP violation

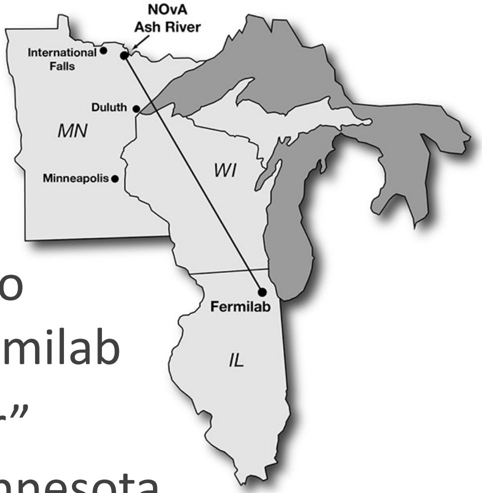
- Because the masses of neutrinos are so small, this **neutrino flavor oscillation** is seen on large distance scales ~ **hundreds of kilometers**
- We are especially interested in comparing these two processes that **interchange the roles of matter and antimatter**



- If they are not the same, then neutrinos violate CP
- This could be the reason why we exist

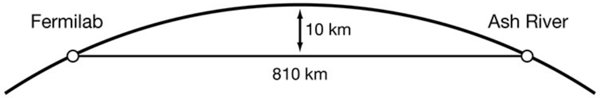
NOvA neutrino oscillation experiment

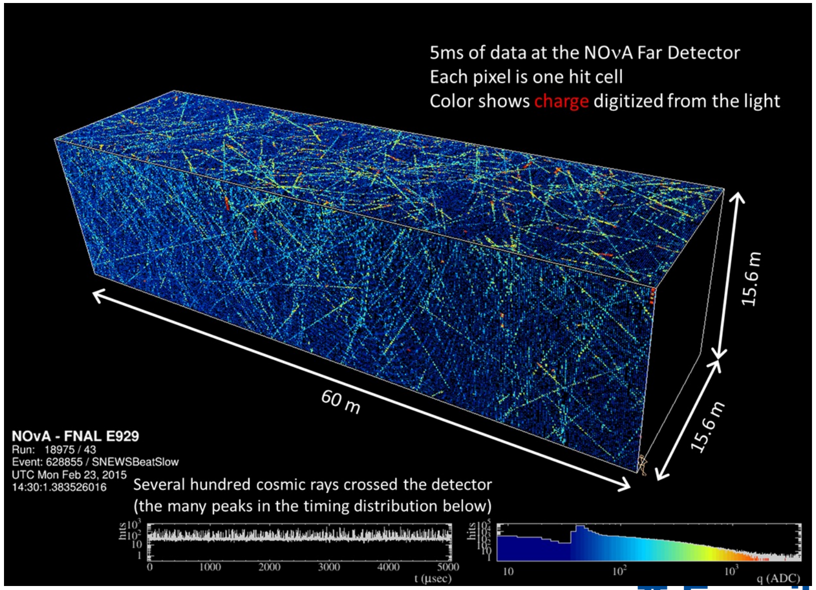




"near" neutrino detector at Fermilab

14,000 ton "far" detector in Minnesota

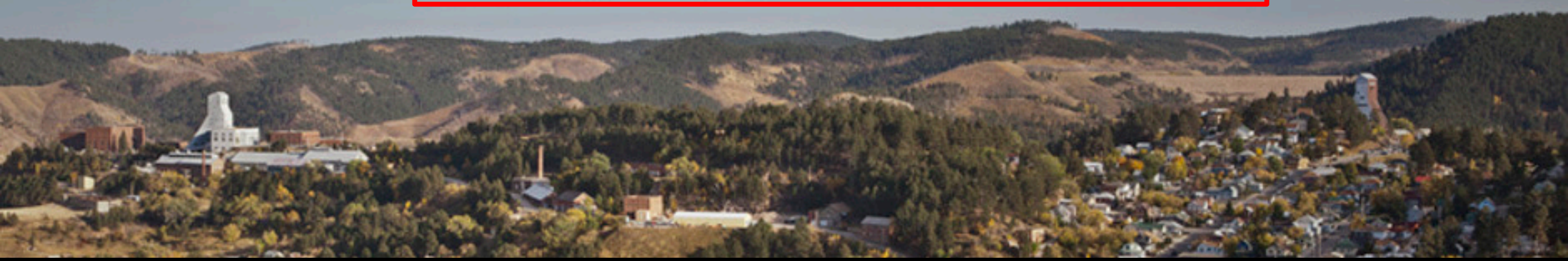




NoVA's research goals are to study Neutrino oscillations, ordering of neutrino masses, and matter-antimatter symmetry

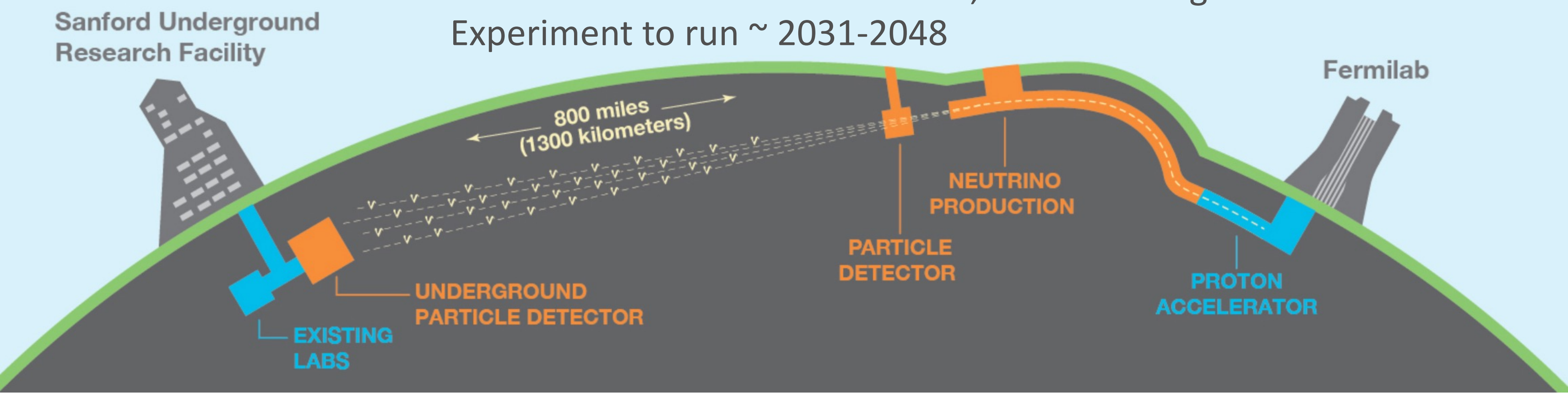
Future Flagship Neutrino Oscillations Experiment

A Megascience International Project



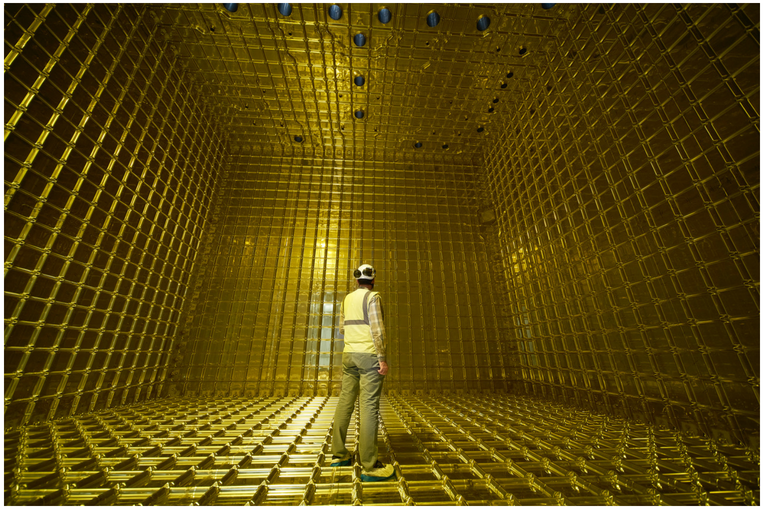
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

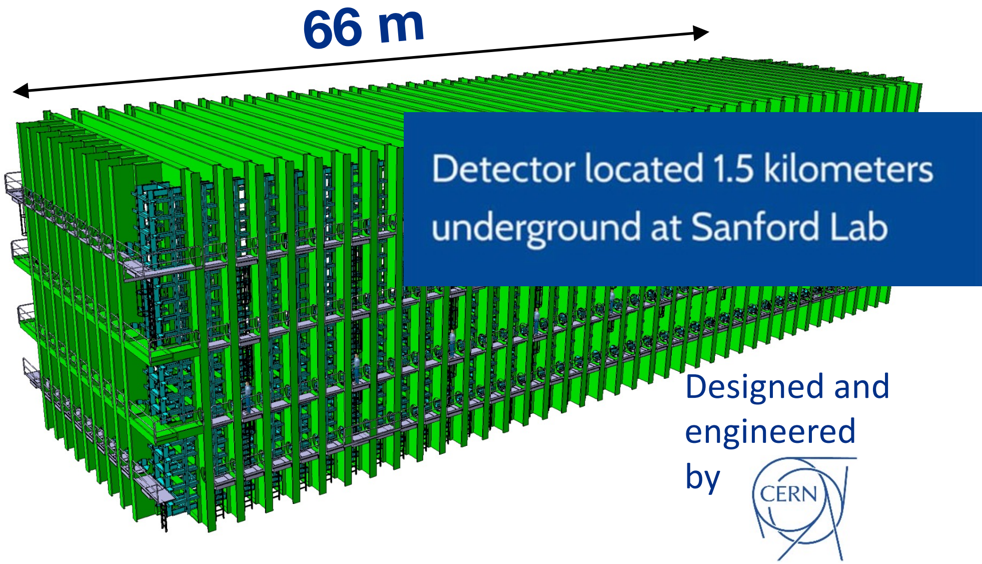
Build the world's most powerful neutrino beam at Fermilab
Send neutrinos 1300 km through the Earth to South Dakota
Detect them in the massive neutrino detectors, a mile underground
Experiment to run ~ 2031-2048

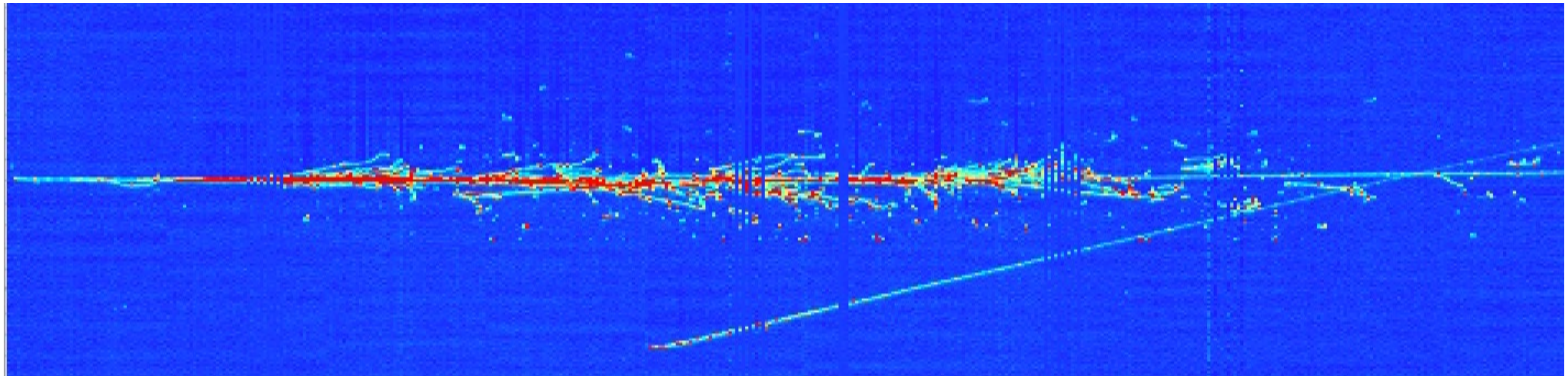


= four 70 kton Cryogenic Liquid Argon Detectors

A 1/20 scale prototype has successfully run at CERN







DUNE Science Goals

Search for the origin of matter

- Observation of CP violation

Look for fundamental underlying symmetries of the Universe

- Measurement of mixing and mass ordering

Unification of forces

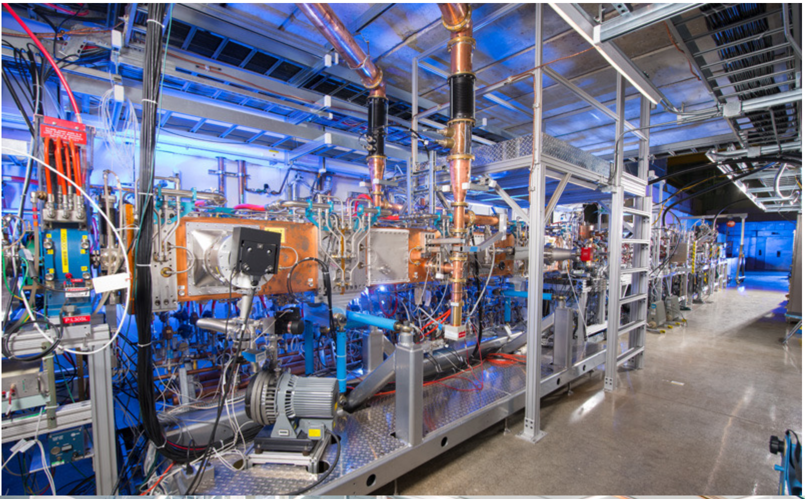
- Search for proton decays

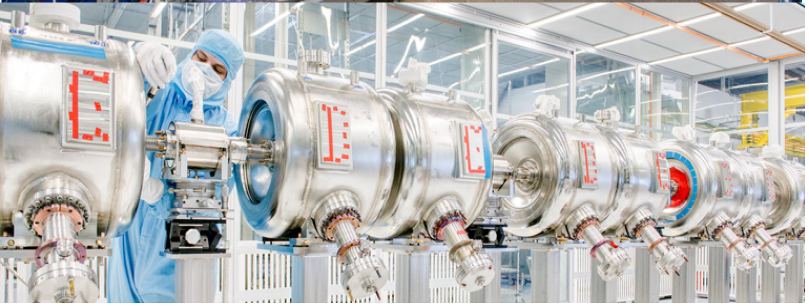
Learn about neutron stars and black holes and thus evolution of the Universe

- Detection of neutrinos emitted by exploding stars

PIP-II accelerator

PIP-II will deliver the world's most intense beam of neutrinos to the international LBNF/DUNE project, and enable a broad physics research program, powering new discoveries for decades to come.

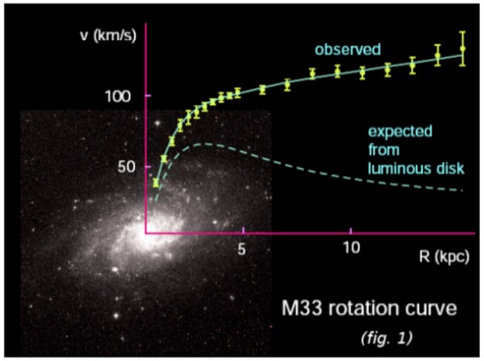


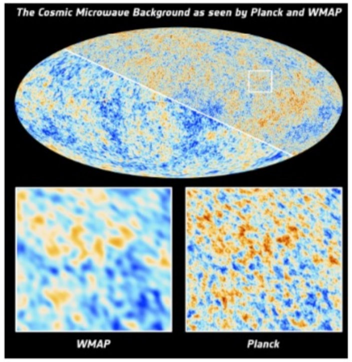


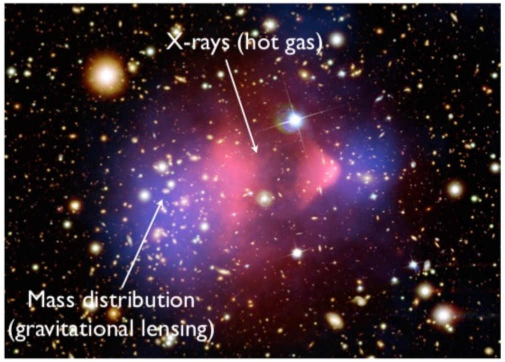
Fermilab, World's leader in SRF cavities, at the core of PIPII

The Future of Dark Matter

- Dark Matter exists, awaiting for discovery



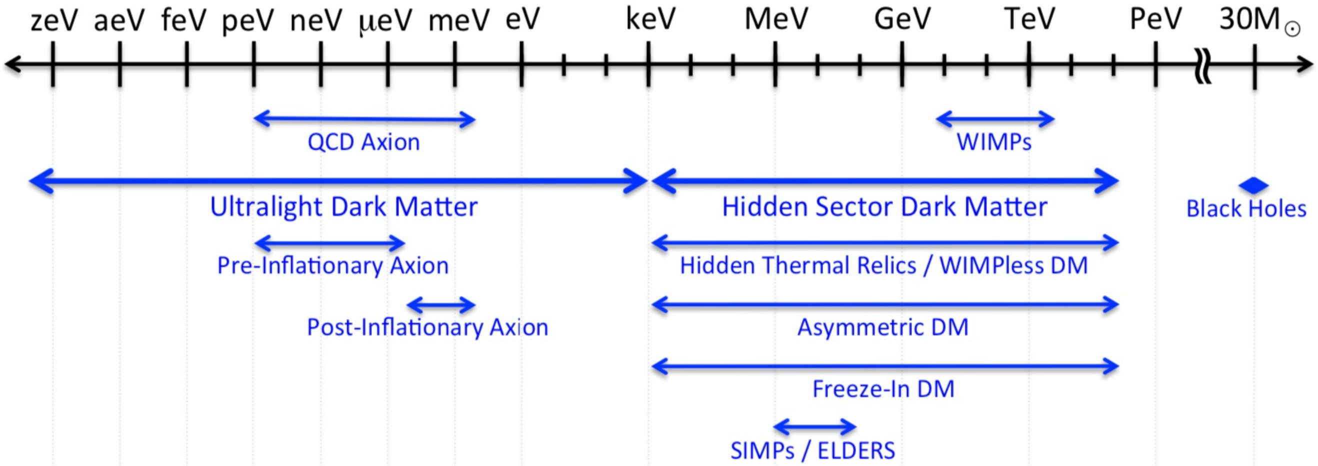




European Strategy Update

Dark Matter Candidates: Very little clue on mass scales

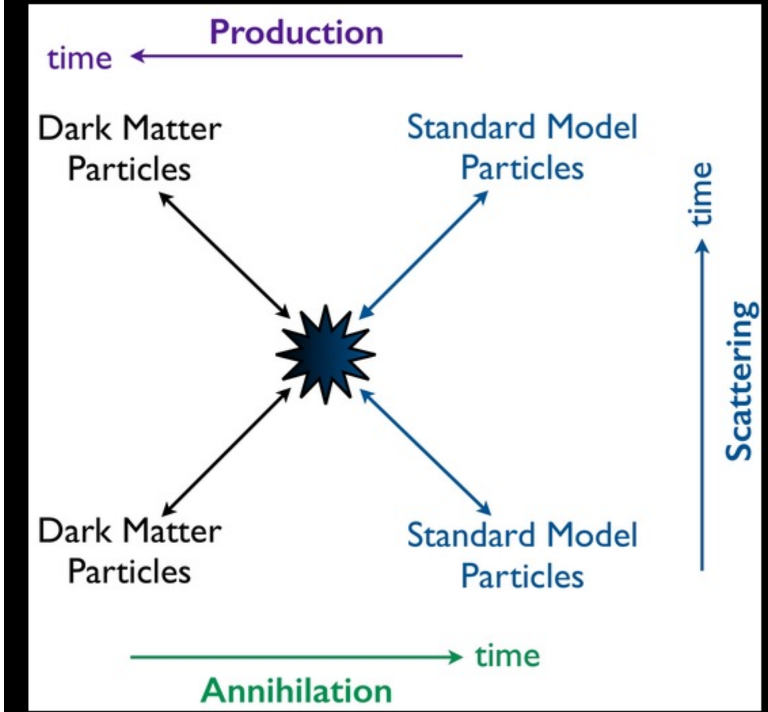
Too small mass ⇒ won't "fit" in a galaxy!



From MACHOs searches

Detecting Dark Matter

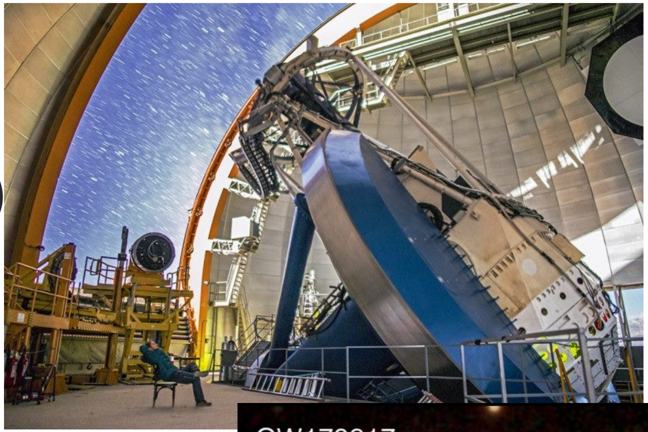
- **Production** of dark matter particles in SM particle interactions (e.g., in LHC collisions
- **Indirect detection:** Dark Matter annihilating to produce SM particles. (Fermi telescope looking for anomalous gamma ray signals)
- **Direct detection:** DM scattering off of SM particle



A diagram showing possible dark matter detection methods.

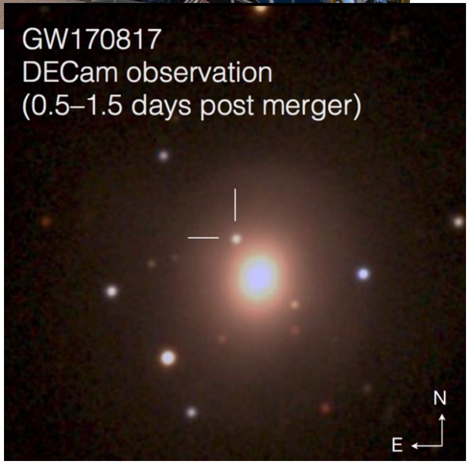
Dark Matter Experiments
- Axion Dark Matter Experiment (ADMX)
- LZ experiment, targeting WIMPs
- SuperCDMS
- SENSEI (Sub-electron-noise skipper-CCD)
- …

Cosmic Frontier Experiments



Dark Energy Survey (DES)

- One of the world's largest digital camera(570 MP) (telescope in Chile); took data 2013-19
- In each snapshot, >100k galaxies up to 8B light-years away
- Surveyed >300 million galaxies
- Most detailed map of dark matter
- Detected gravitational wave source!



Dark Energy Spectroscopic Instrument (DESI)

- To obtain the optical spectra of tens of millions of galaxies and quasars and build a 3D map of Universe up to 11B light-years
- Measure impact of DE on Universe expansion

LSST/Vera Rubin Observatory (Led by LBL)

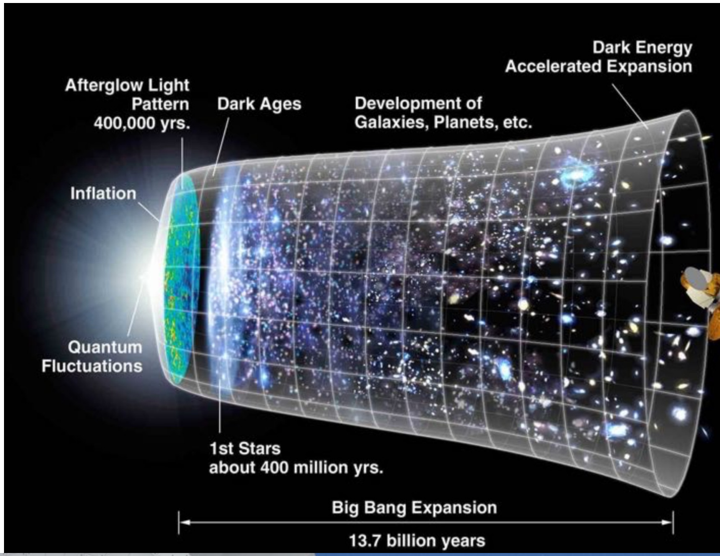
- Science running starts 2023
- Will survey >30 billion galaxies

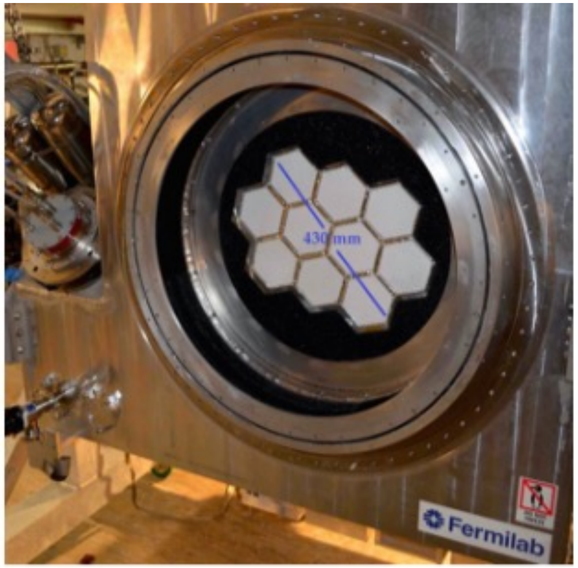
SPT-3G

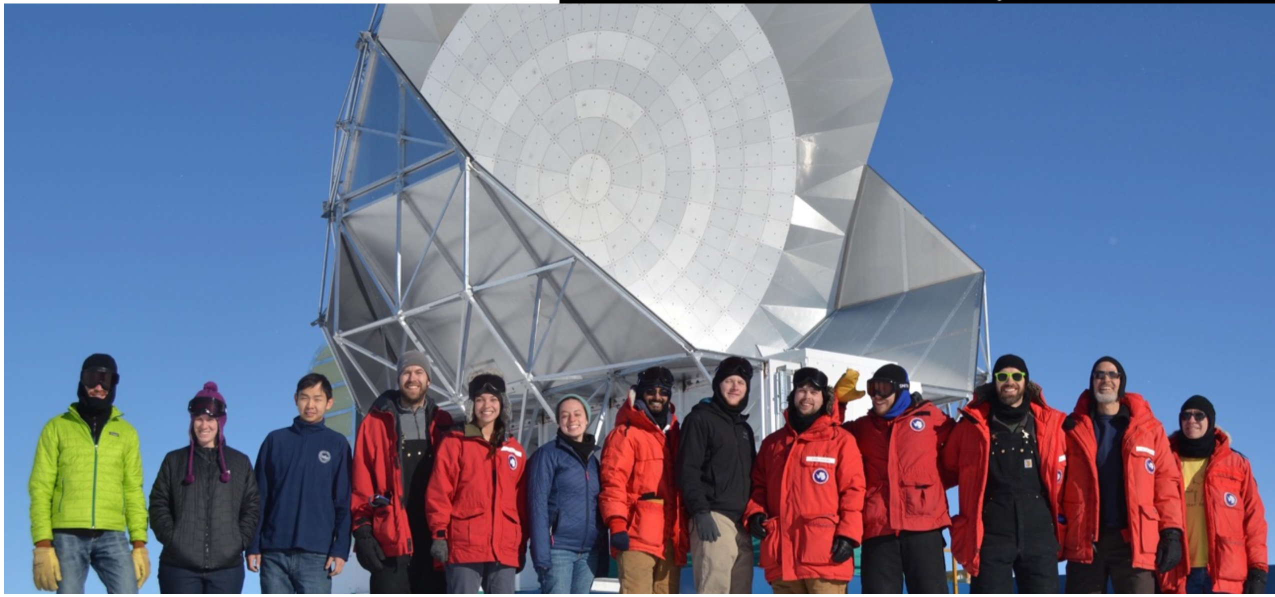
- a 10 meter microwave telescope with an array of 16,000 cryogenic transition-edge sensors

SPT-3G: Looking at the cosmos from the South Pole

- SPT-3G is a 10 meter microwave telescope with an array of 16,000 cryogenic transition-edge sensors
- Probes fine details of the Cosmic Microwave Background
- Sensitive to effects of cosmic inflation, neutrinos, and dark energy
- The next gen experiment CMB-S4 will have 500,000 sensors



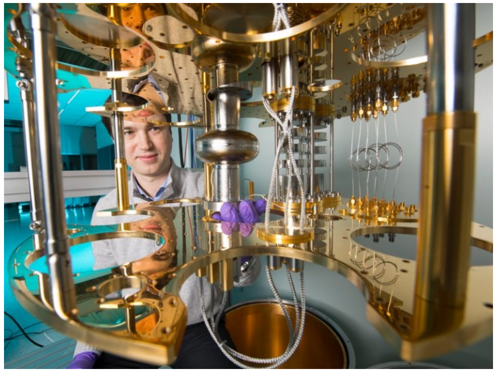


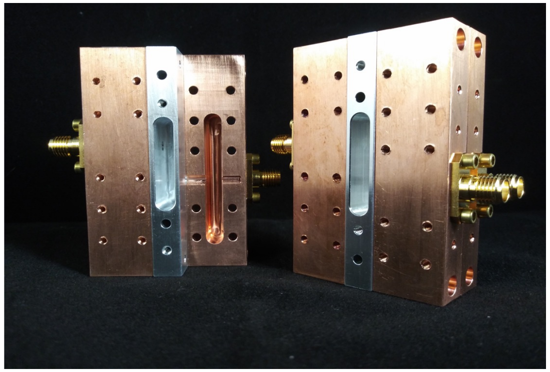


Fermilab Quantum S&T program

- Fermilab is collaborating with 22 universities and other national labs on quantum science and technology
- The very challenging science goals of HEP, e.g. laboratory detection of dark matter, are now driving advances in quantum technologies; these advances will eventually have broad impact beyond HEP
- Fermilab is leveraging infrastructure and HEP expertise for the development of new quantum devices, and for the challenges of scaling up quantum systems; successes here will impact quantum computing, sensing, and communications
- The research leveraging superconducting cavities has already demonstrated significant gains in qubit coherence time
- MAGIS-100 experiment to explore dark matter, gravitational waves and Quantum Science

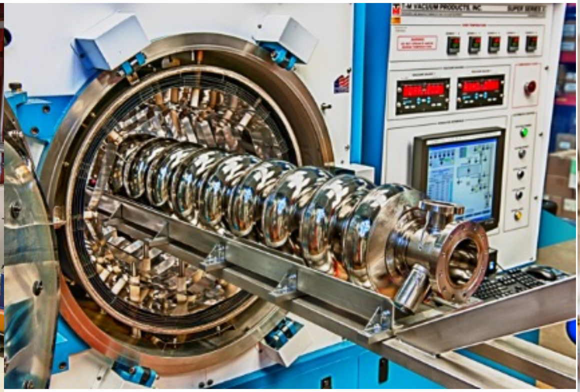
Dark Photon Experiment





Fermilab's pioneering accelerator technology

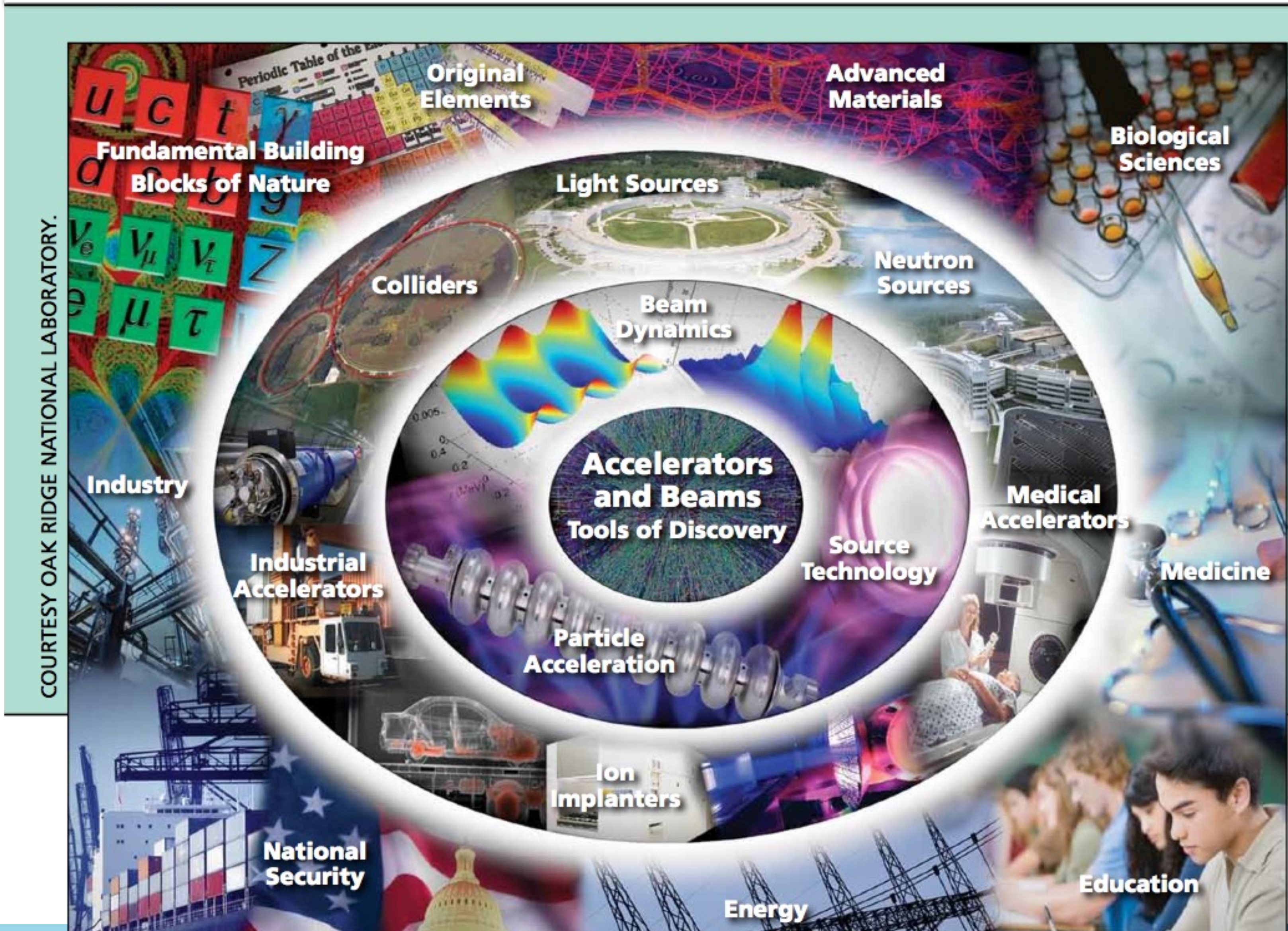
- Superconducting RF Cavities/Cryomodules
- Superconducting magnets



Fermilab Accelerator Science and Technology Research

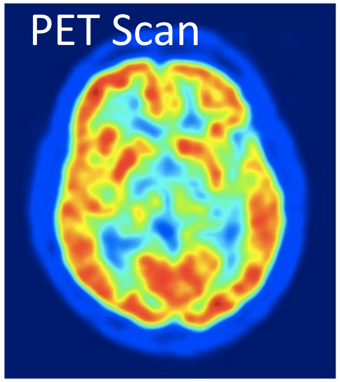
- Particle beam research facility based on superconducting RF technology
- A test bed for cutting edge accelerator R&D
  - High intensity beams via integrable optics (IOTA)
  - Novel radiation sources

Applications of Accelerators



Applications of Accelerators

- Medical Applications
  - Radiation Therapy: X-rays, neutrons, protons, ions
  - Production of radioisotopes for tracers, treatment
  - Equipment sterilization (e- beams)
  - Imaging/diagnostics: X-rays, PET, CT
  - SC magnet used to build compact MRI machines
- Industry
  - Ion implantation in semiconductors (electronics)
  - Treatment of products with e- beam to improve properties
    - Wire cable tubing, ink curing, shrink film, tires,…
- Agriculture
  - Food pasteurization so that it is safe; irradiation of seeds, …
  - Sealing your milk cartons, potato chip bags, …
- National Security: Screening cargo
- Accelerators have transformed research in chemistry, biology, materials
  - Real time movie of chemical reactions, drug design, new materials design, ..



Future Accelerators/Colliders

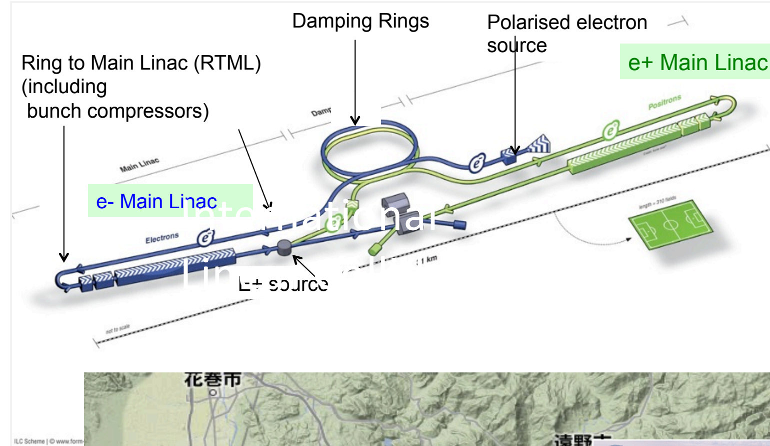
New accelerators/colliders will be needed to support intensity and energy frontier research in the coming decades.

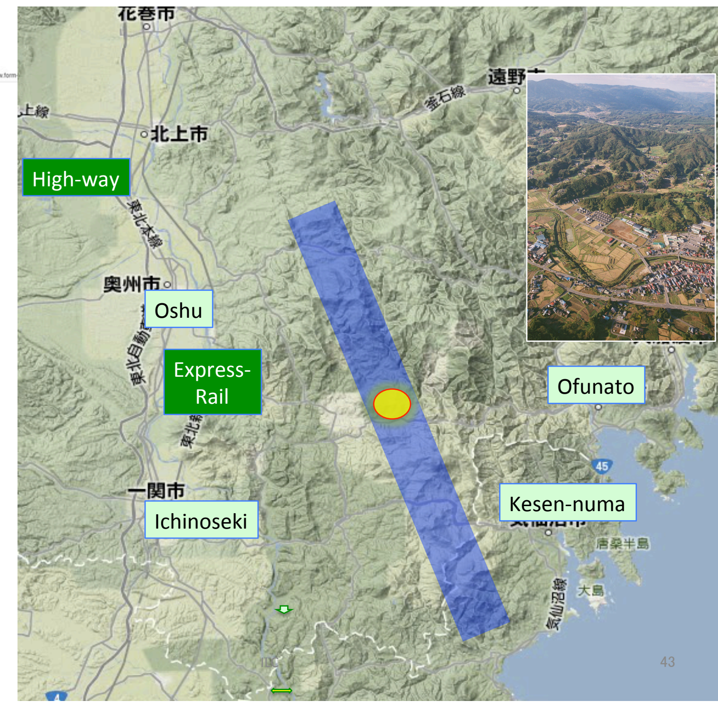
Future Colliders

- The United States has a rich history in particle accelerators and colliders, which enabled major discoveries in particle physics and establishing of the Standard Model.
- Fermilab is a pioneer in technologies that are critical for building powerful accelerators and colliders.
- Recent HEP community study (2020-22) provided a great opportunity to explore the status of the field and study how to shape the future of the field.
- The following strategic vision has been put forth:
  - For precision studies of the Higgs, build an e+e- Higgs factory ASAP. "Use the Higgs boson as a new tool for discovery"
  - For exploration of higher mass scales than will be accessible at the HL-LHC, build a multi-TeV muon collider or a ~100 TeV pp collider

Future Colliders under consideration abroad in Europe/CERN/Asia

Japan

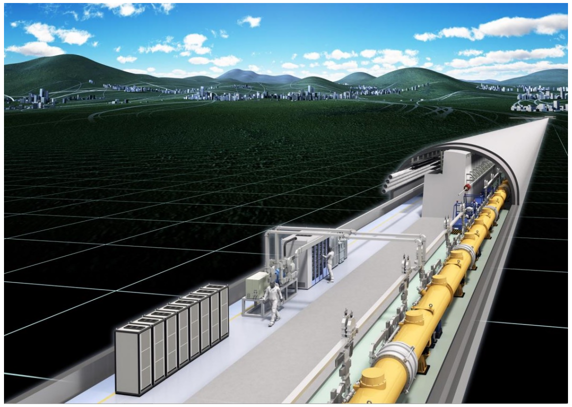




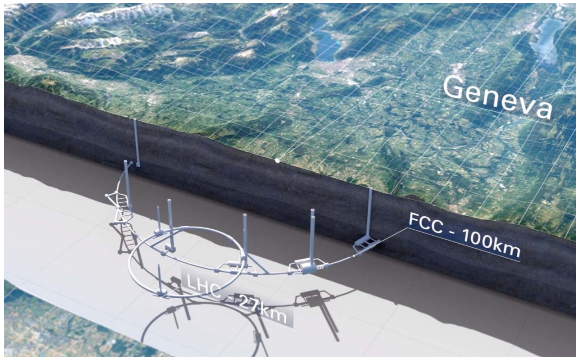
CepC China

Global Collider Projects under Study

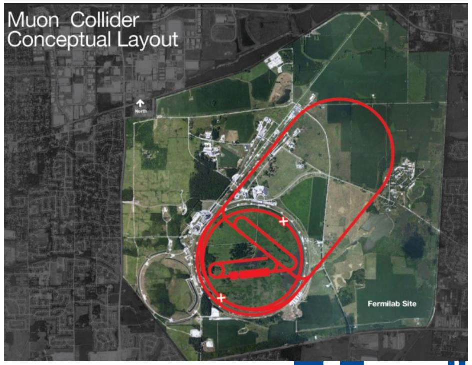
- The International Linear Collider (ILC)
  - e+e- 250 GeV Higgs Factory
  - Fermilab led the technical design (TDR 2013)
  - Fermilab pioneers in critical Superconducting RF (SRF) technology
  - **ILC being considered for construction in Japan**



- Future Circular Colliders (FCC-ee/hh)
  - FCC-ee: e+e- 90-350 GeV
  - ~100 km in circumference
  - Feasibility study report by ~2026
  - To be built around **CERN/Geneva**
  - Similar facilities being considered **in China**



- Muon Collider
  - $\mu+\mu-$ 3 -10 TeV
  - Previous Studies and R&D led by Fermilab
  - Currently being studied by the **International Muon collider Collaboration at CERN** and Muon Collider Forum in the US



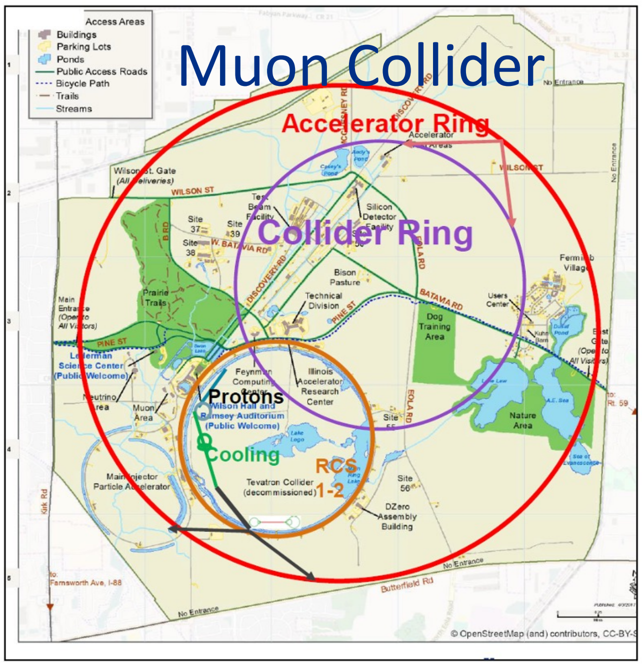
Future Collider Options for the US

Explored as part of the US HEP community study

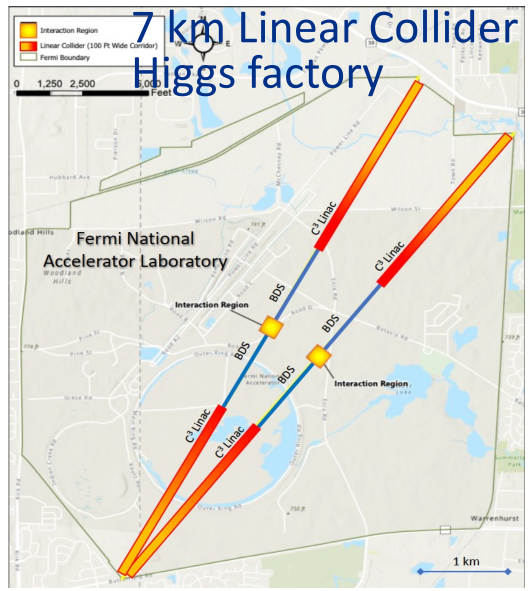
Future Collider Options for the US

P. C. Bhat,* S. Jindariani,† G. Ambrosio, G. Apollinari, S. Belomestnykh, A. Bross, J. Butler, A. Canepa, D. Elvira, P. Fox, Z. Gecse, E. Gianfelice-Wendt, P. Merkel, S. Nagaitsev, D. Neuffer, H. Piekarz, S. Posen, T. Sen, V. Shiltsev, N. Solyak, D. Stratakis, M. Syphers, G. Velev, V. Yakovlev, K. Yonehara, A. Zlobin

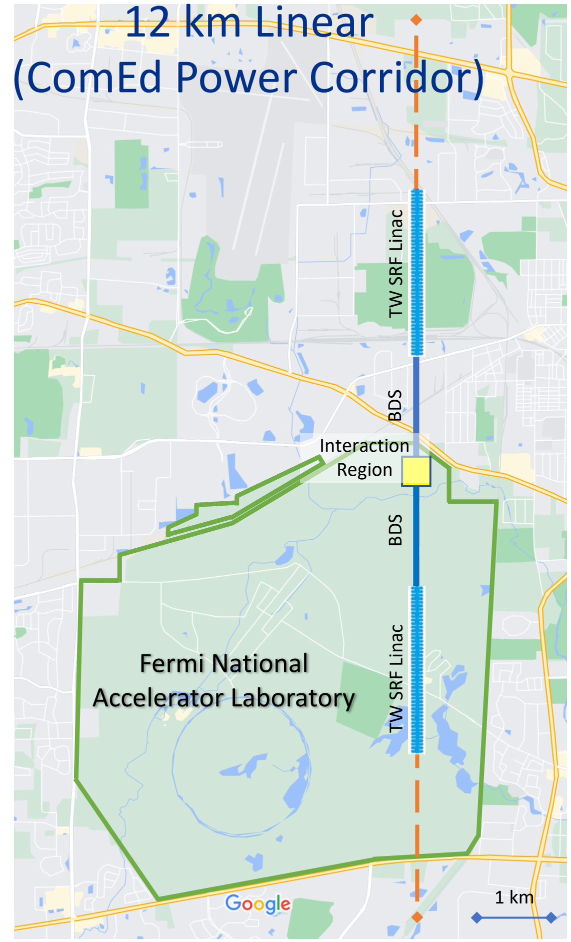
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA



Muon Collider, 6-10 TeV

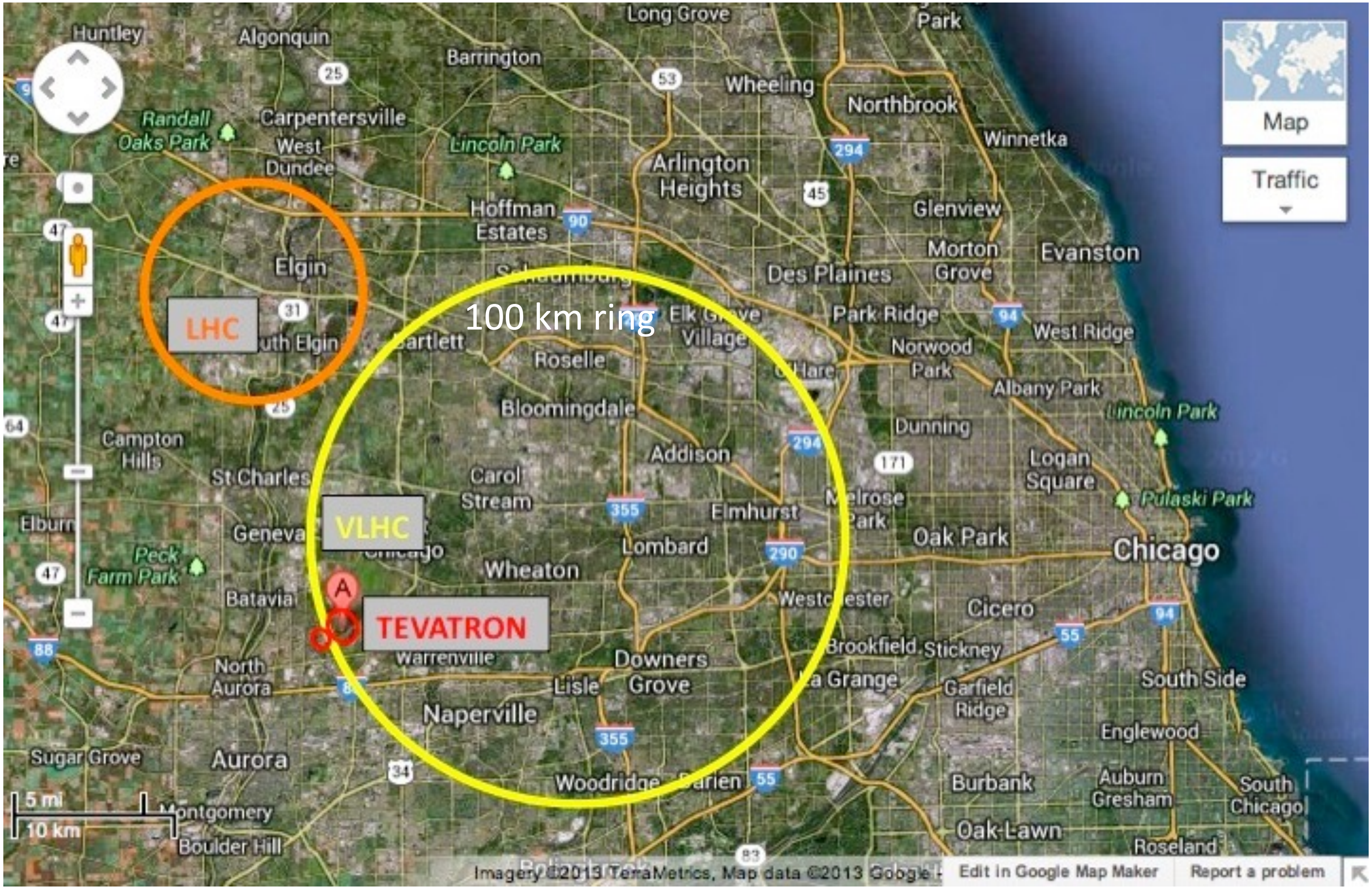


e^+e^- 250 GeV
(C3, HELEN)



e^+e^- 250 - ≥550 GeV
(C3, HELEN,…)

A Very Large Hadron Collider in Chicagoland?



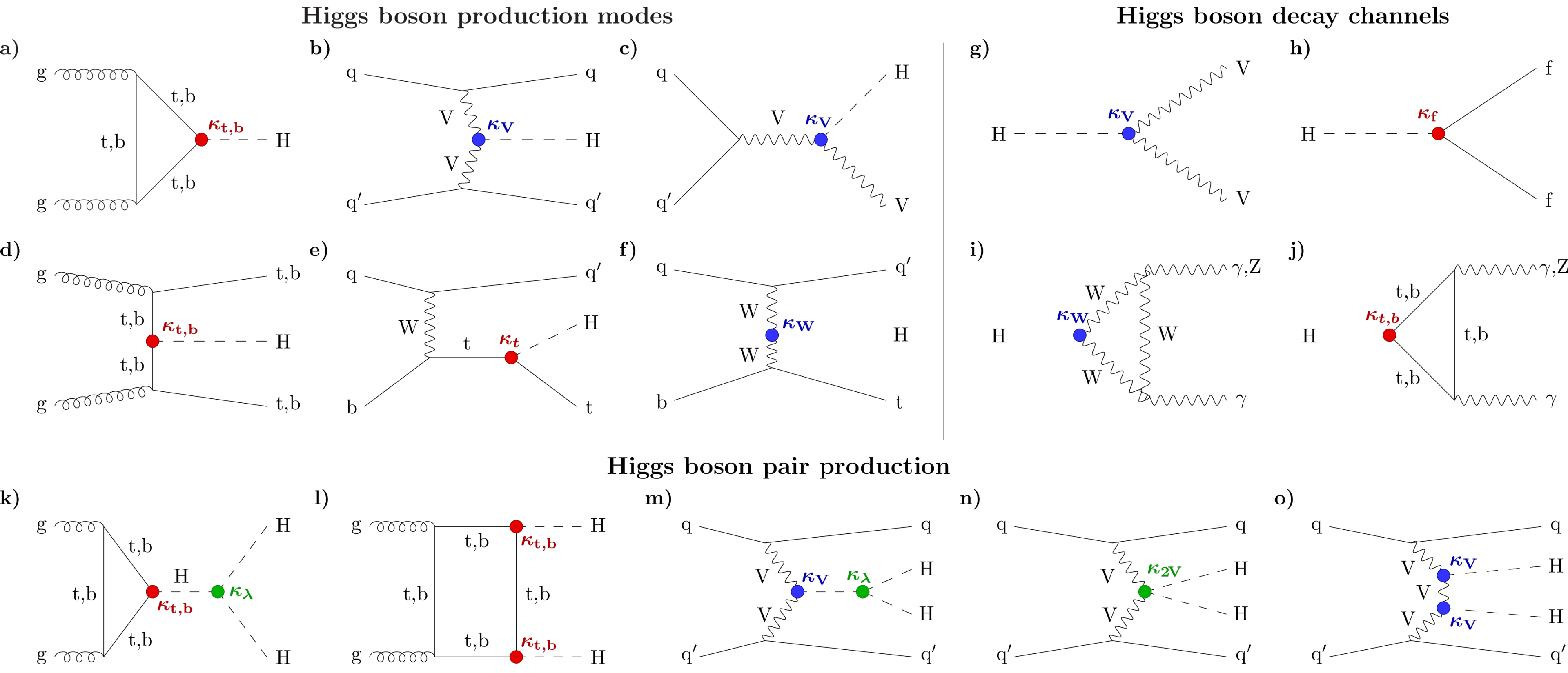
Fermilab is pursuing research at the frontiers of physics with neutrinos, muons, CMS at the LHC, of the cosmos, and carrying out technology R&D for the future.

Good luck with engaging in this cutting-edge research this summer!

Welcome to Fermilab!

Extra Slides

Higgs Boson Production and Decays



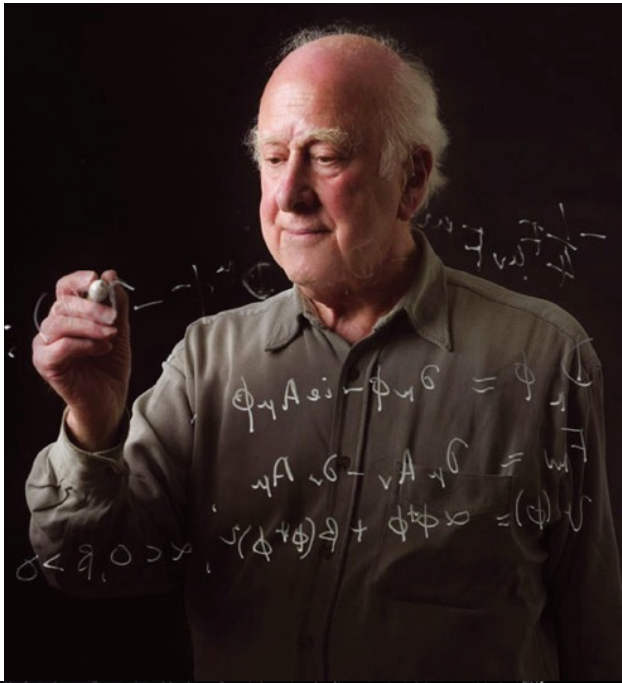
Fermilab

What does the Standard Model explain?

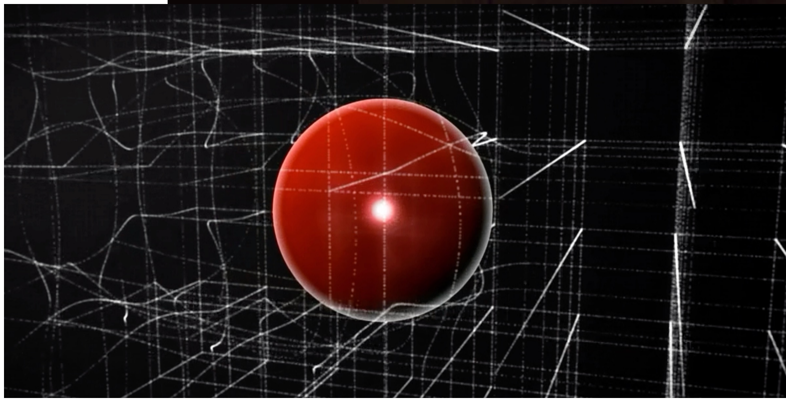
Some properties of the quantum vacuum

The Higgs field has the remarkable feature that (unlike electromagnetic fields) it can source itself.

The SM predicts that the Higgs field turned itself on everywhere in the universe in the first moments of the Big Bang (the electroweak phase transition)



Once this happened, at least 10 of the other kinds of SM particles acquired mass



What does the Standard Model NOT explain?

How do neutrinos get mass?

Why there is more matter than antimatter left over from the Big Bang

What is dark matter made of and how does it interact with ordinary matter

What caused a period of cosmic inflation in the first instants of the Big Bang

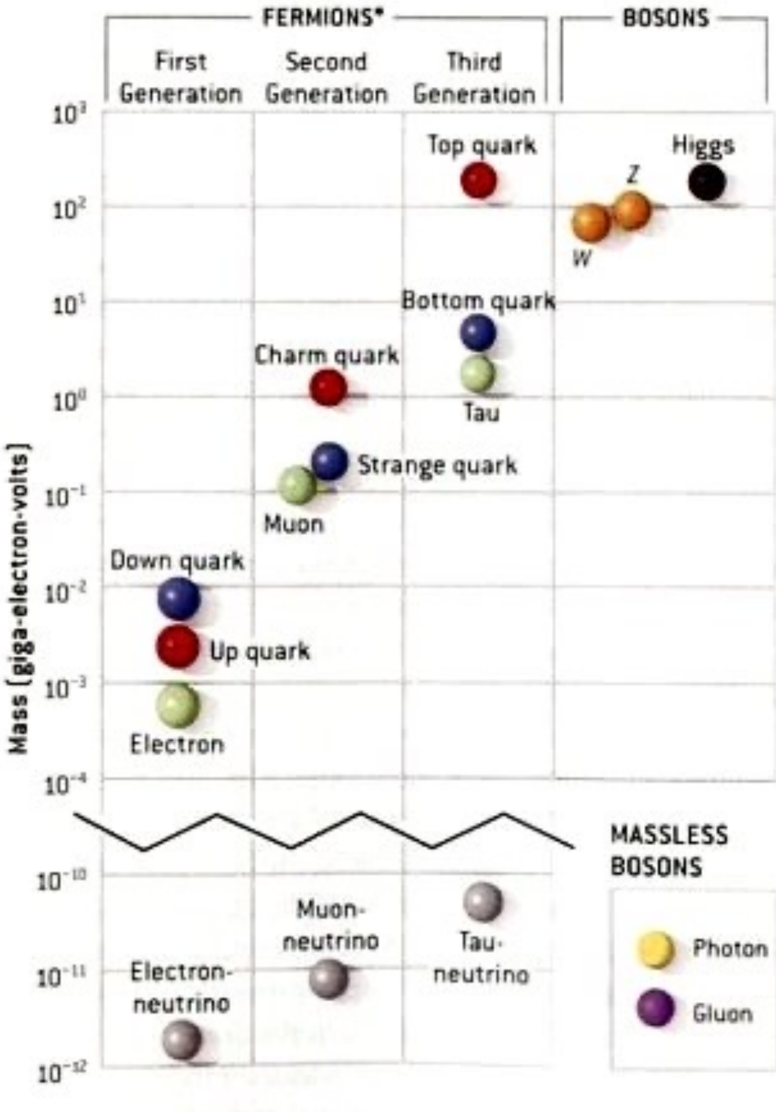
What is dark energy

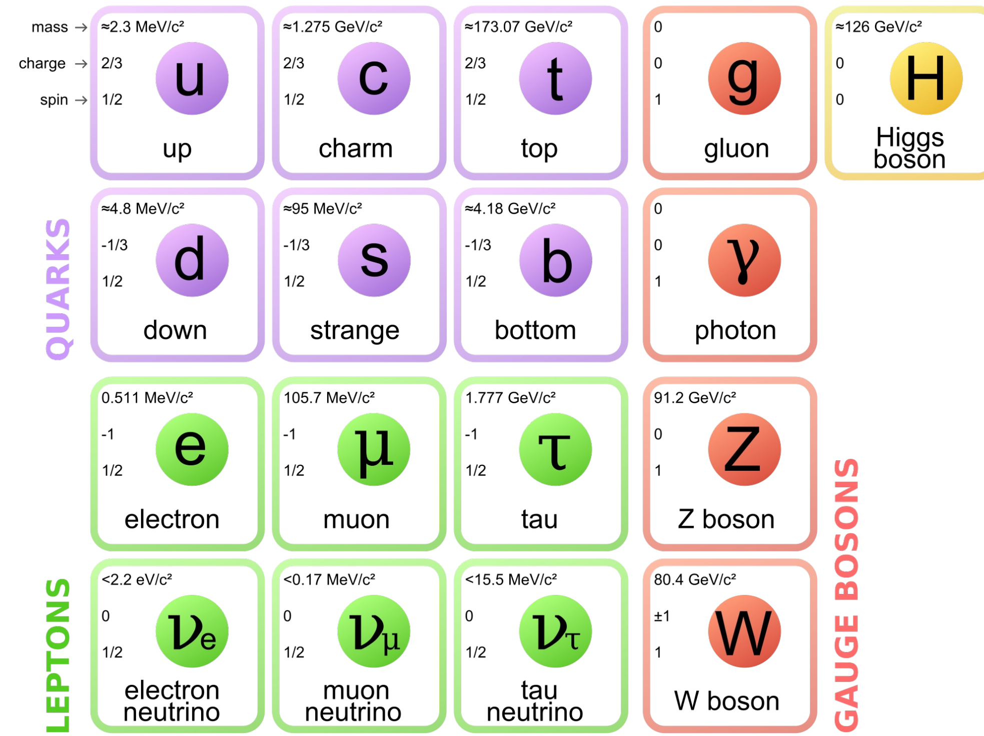
Why are the interactions of the Higgs tuned to make the quantum vacuum metastable

What are the quantum properties of gravity, space, and time

And more …

Fermilab's mission is to answer these fundamental questions


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
Mass (giga-electron-volts)
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

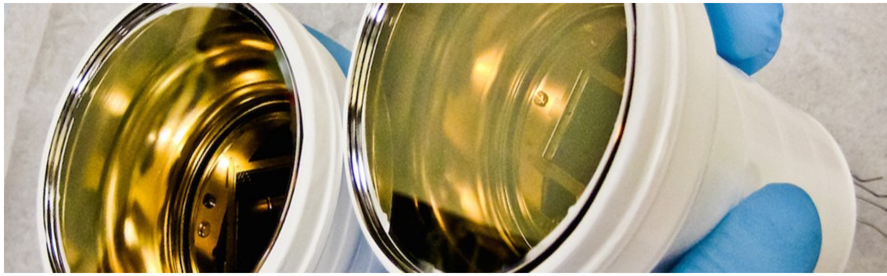

mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
LEPTONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS

Dark Matter Experiments

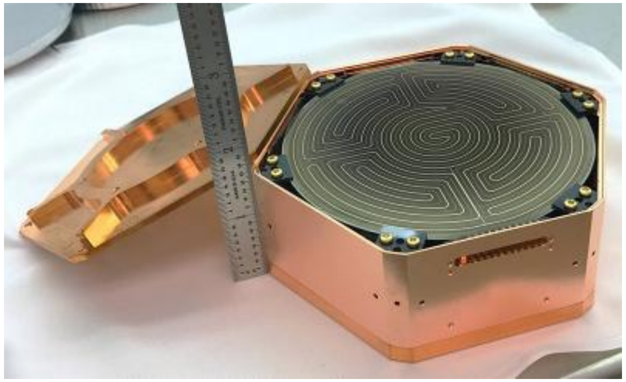
Axion Dark Matter Experiment (ADMX)

Low noise tunable receiver

Axions can convert into photons inside a cold, dark, reflective box subject to magnetic field



LZ experiment, targeting WIMPs: 10 tons of liquid xenon to detect interactions between dark matter and ordinary matter.



SuperCDMS

Super Cryogenic Dark Matter Search, targeting WIMPs

Germanium and Silicon crystal to detect phonons and charge from DM-nuclei elastic collisions

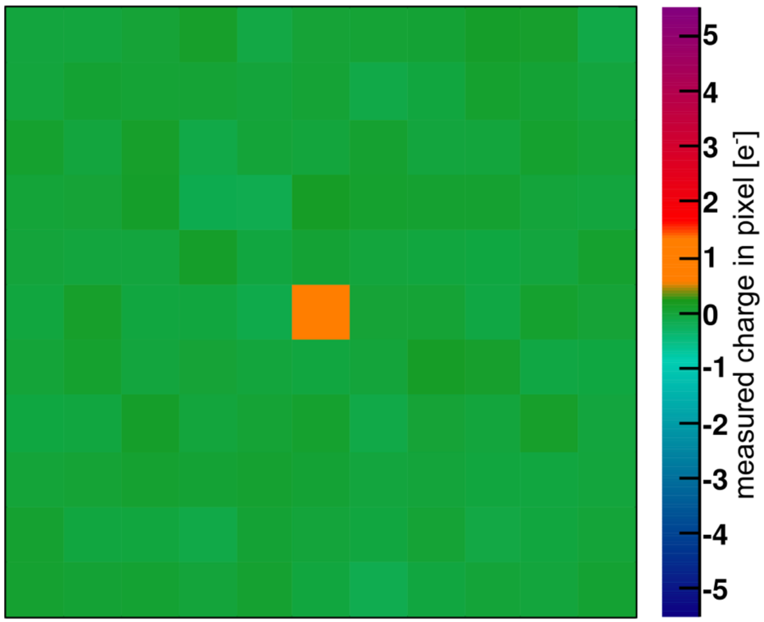
Dark Matter Experiments

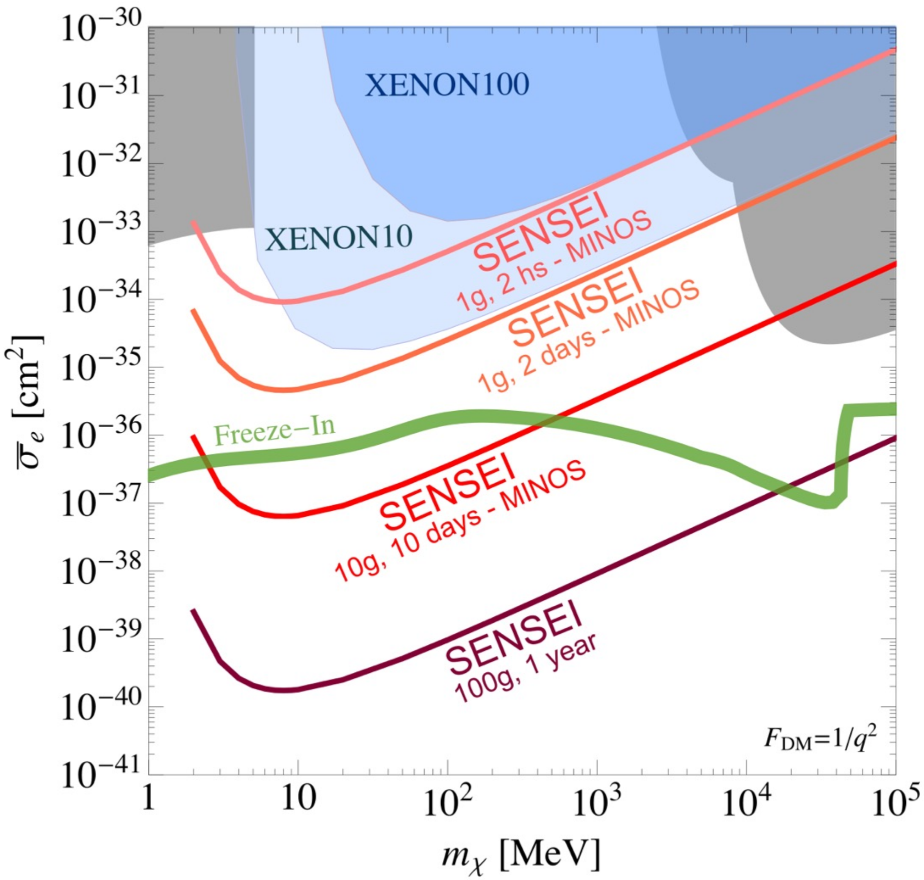
SENSEI Sub-electron-noise skipper-CCD experimental instrument

Breakthrough technology developed by FNAL and LBL

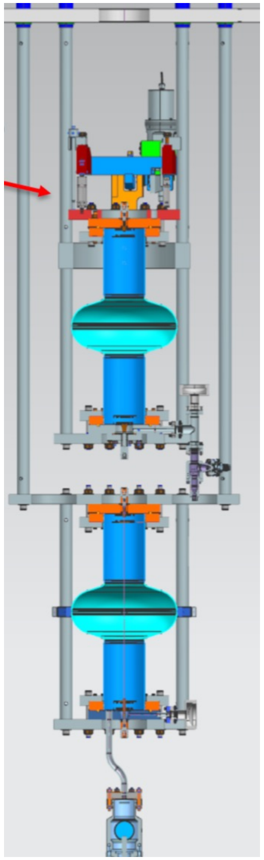
To precisely count each individual electron in each pixel of a large CCD with millions of pixels

Image taken with SENSEI individual e⁻ are resolved





Fermilab Dark Photon Experiment

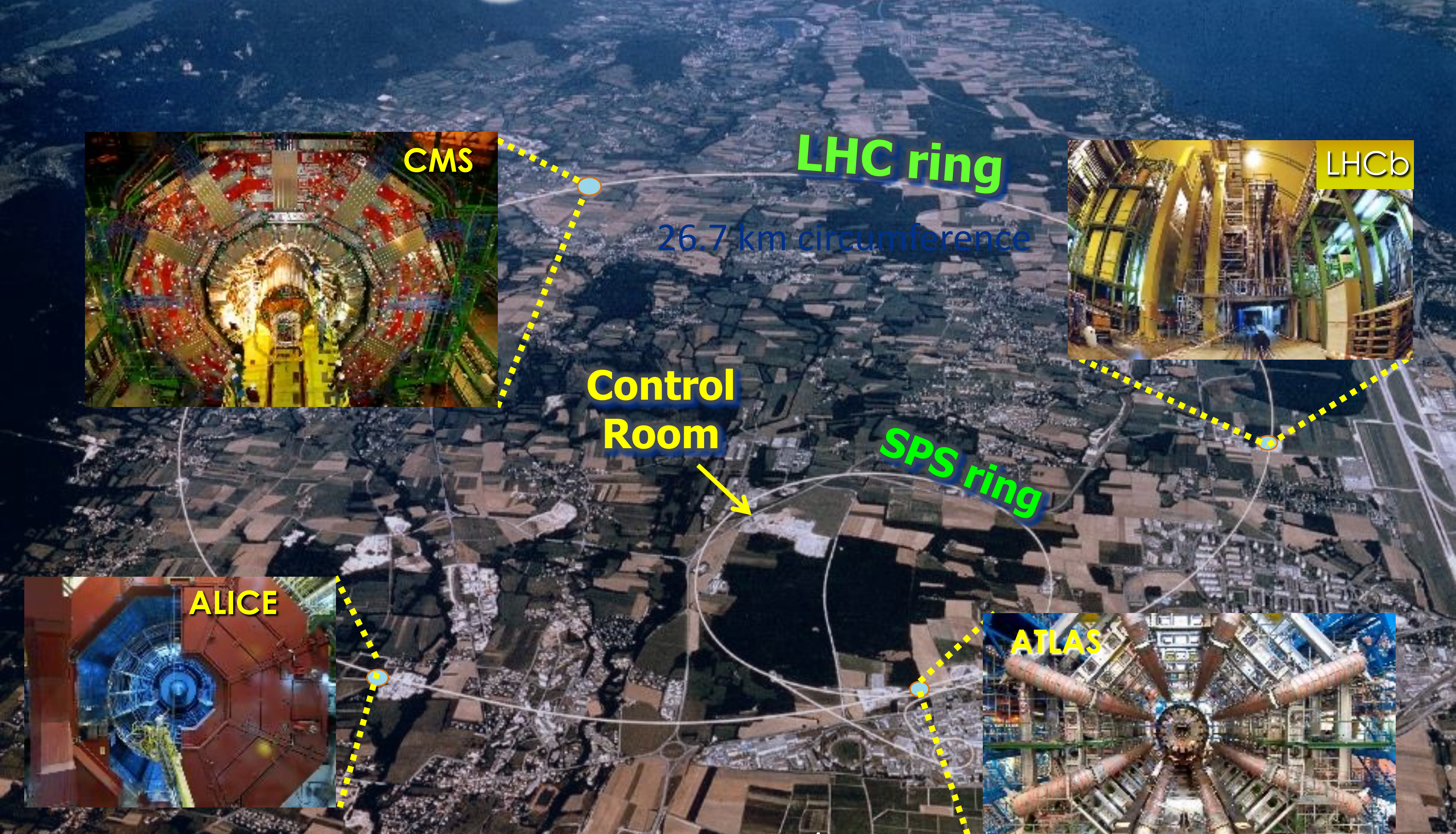


Tunable powered “Emitter” cavity and quiet “Receiver” cavity

Dark SRF experimental apparatus ready for testing

Fermilab Vertical Test Stand used for liquid helium tests of accelerator SRF cavities

The Large Hadron Collider



Beams circulate 11,245 times/sec
100 million collisions/sec in CMS, ATLAS