Welcome and Introduction to Fermilab

Pushpa Bhat, Fermilab

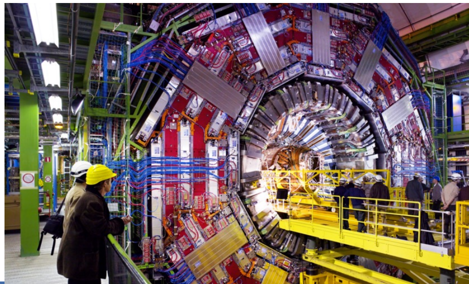
Summer Lecture Series
May 26, 2022

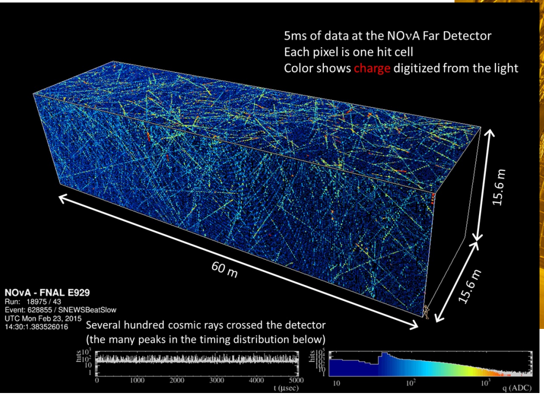
Welcome to Fermilab

The Premier US Lab for Frontier Physics

Fermilab at a glance

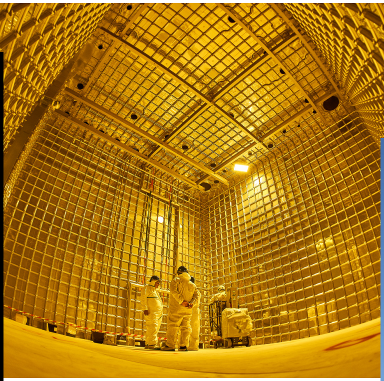
- The premier DOE national laboratory for **high energy particle physics & particle accelerators**
- Conducting fundamental science research to unlock the mysteries of matter, energy, space and time for the benefit of all.
- 6,800 acres of federal land including restored prairie
- About 1,800 staff, 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

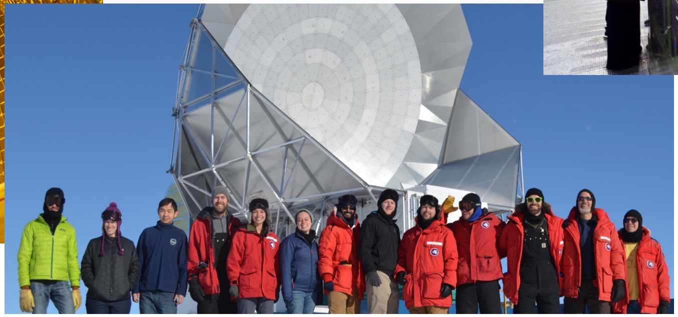




5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)





A Few Words about the History of the Lab

"Utopian laboratory […] environmental beauty, architectural grandeur, cultural splendor" (Wilson)

WESTON IL 1968

AEC ANNOUNCES SITE ON DEC. 16 1966

FIRST BISONS

SEPTEMBER 1969

May 11, 1974

Fermilab

Director Robert Wilson offers a toast to celebrate the milestone.

< 5 years from start of the new Lab

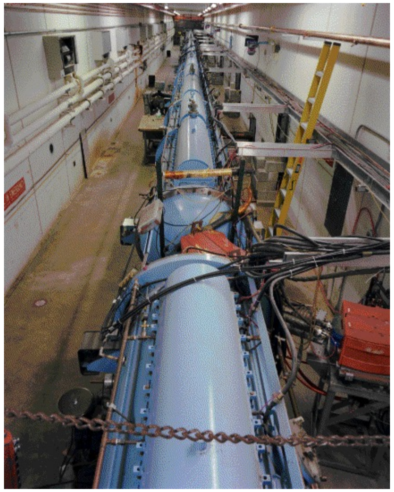
1 March 1972

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.

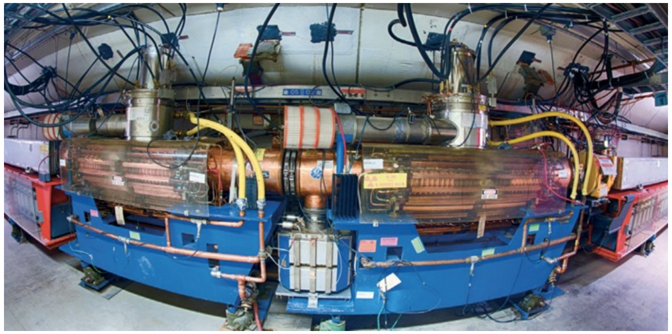
Accelerators built 1968-71

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

The Prairie and the Bisons

Wilson’s Legacy

Restoring and Preserving Nature

Wilson’s Legacy

Flora and Fauna

An International Laboratory

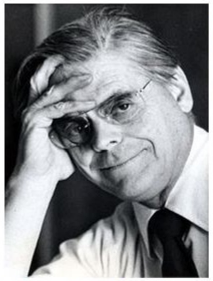
50 Years of Discovery

50th Anniversary
Celebrated in 2017

Fermilab science drives technology innovation

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

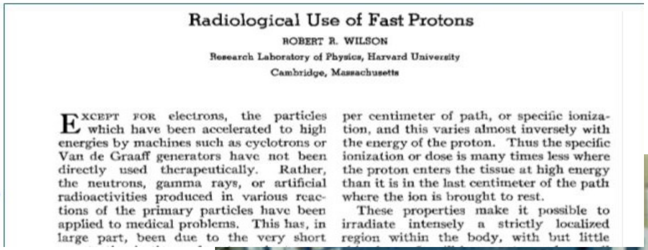
MRI machines from GE and Siemens USA



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

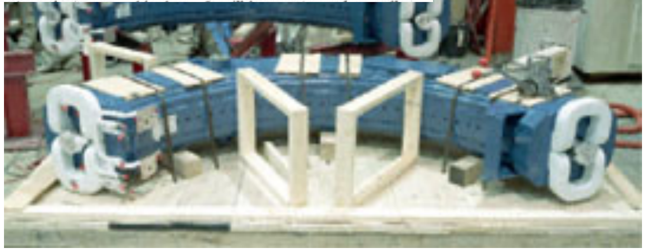
ROBERT R. WILSON

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

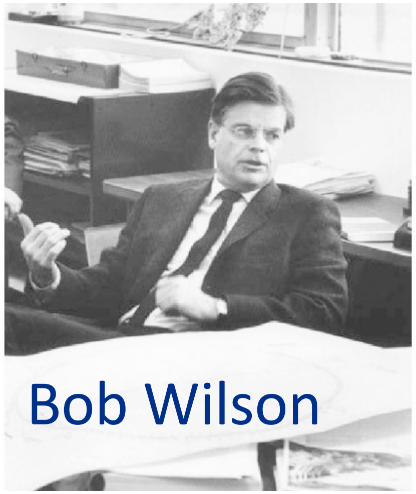


Invented by Fermilab Director, first working system built here

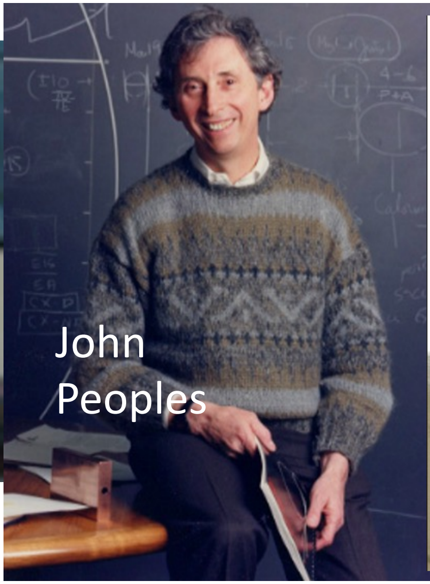
Loma Linda proton cancer therapy

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

Fermilab Directors since inception


Bob Wilson


Leon Lederman


John Peoples


Mike Witherell


Pier Odonne


Nigel Lockyer


current

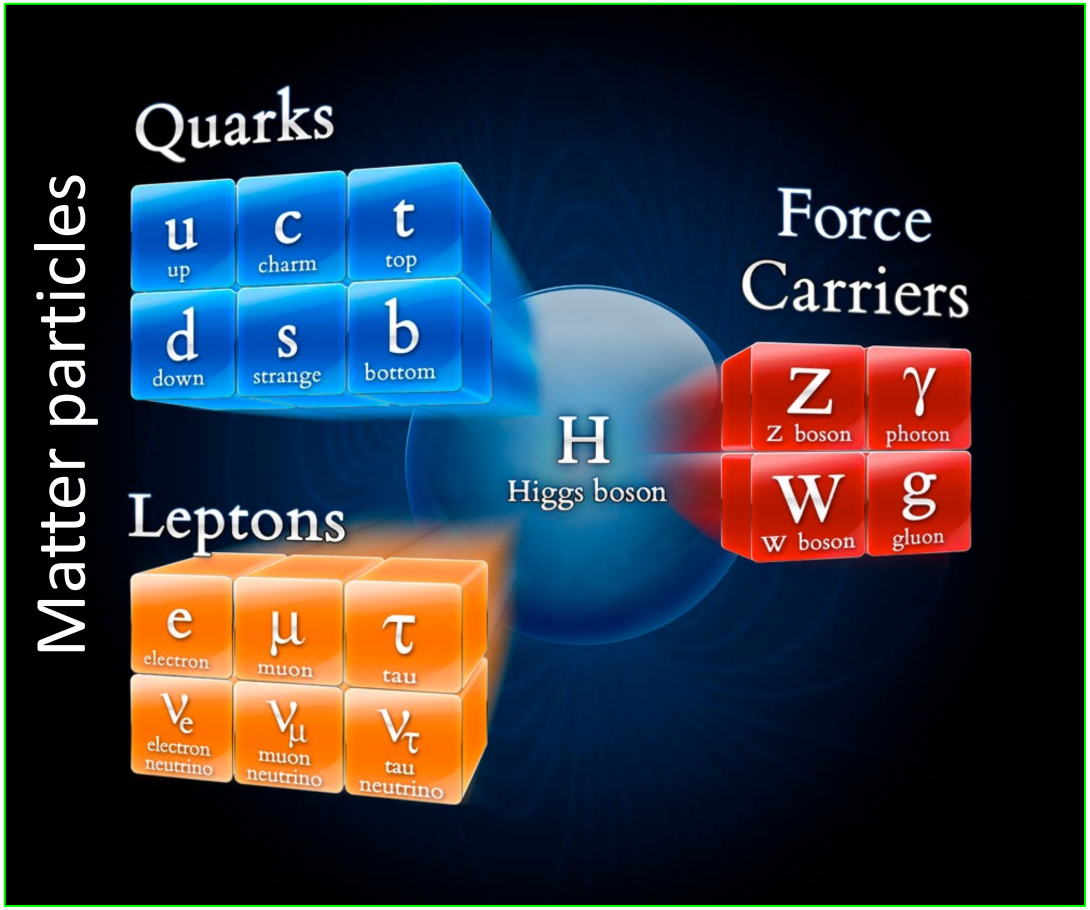
Lia Merminga

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



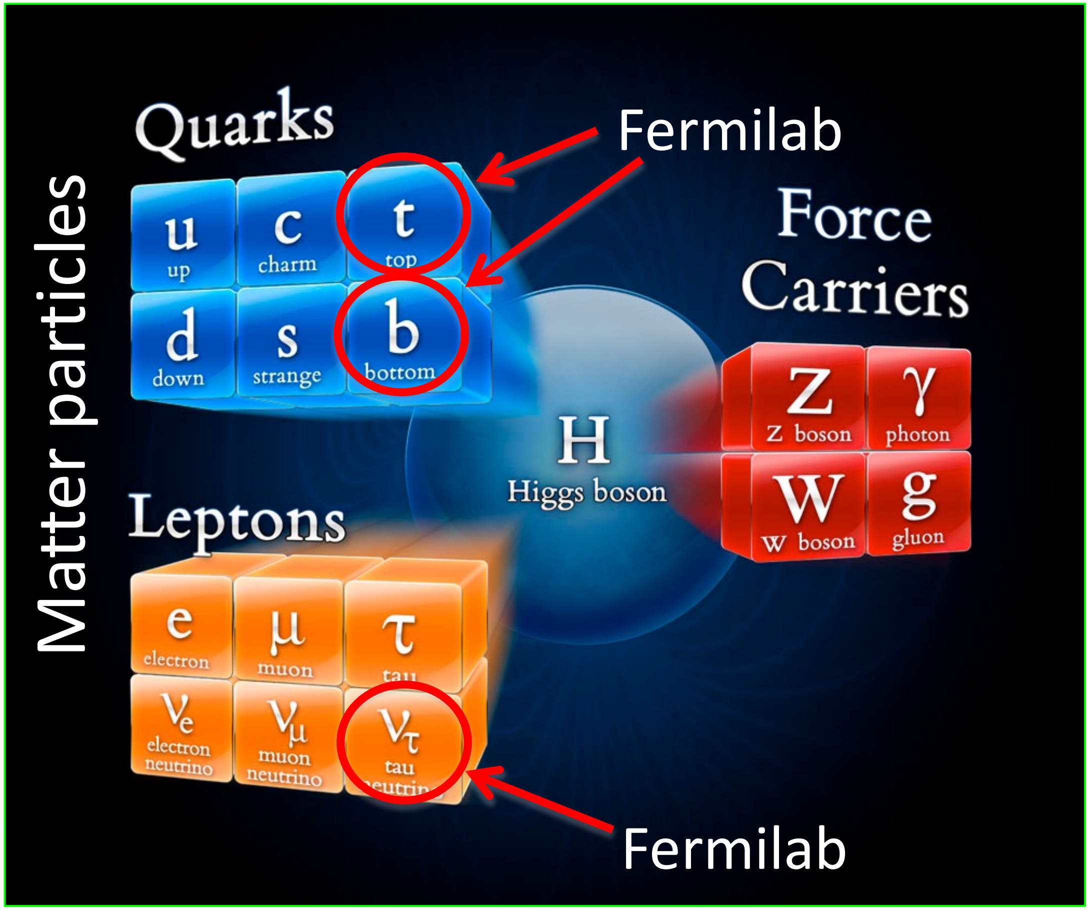
Quarks & Leptons
are Fermions (spin ½)
Named after Enrico Fermi
(Italian American physicist,
namesake of Fermilab)

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

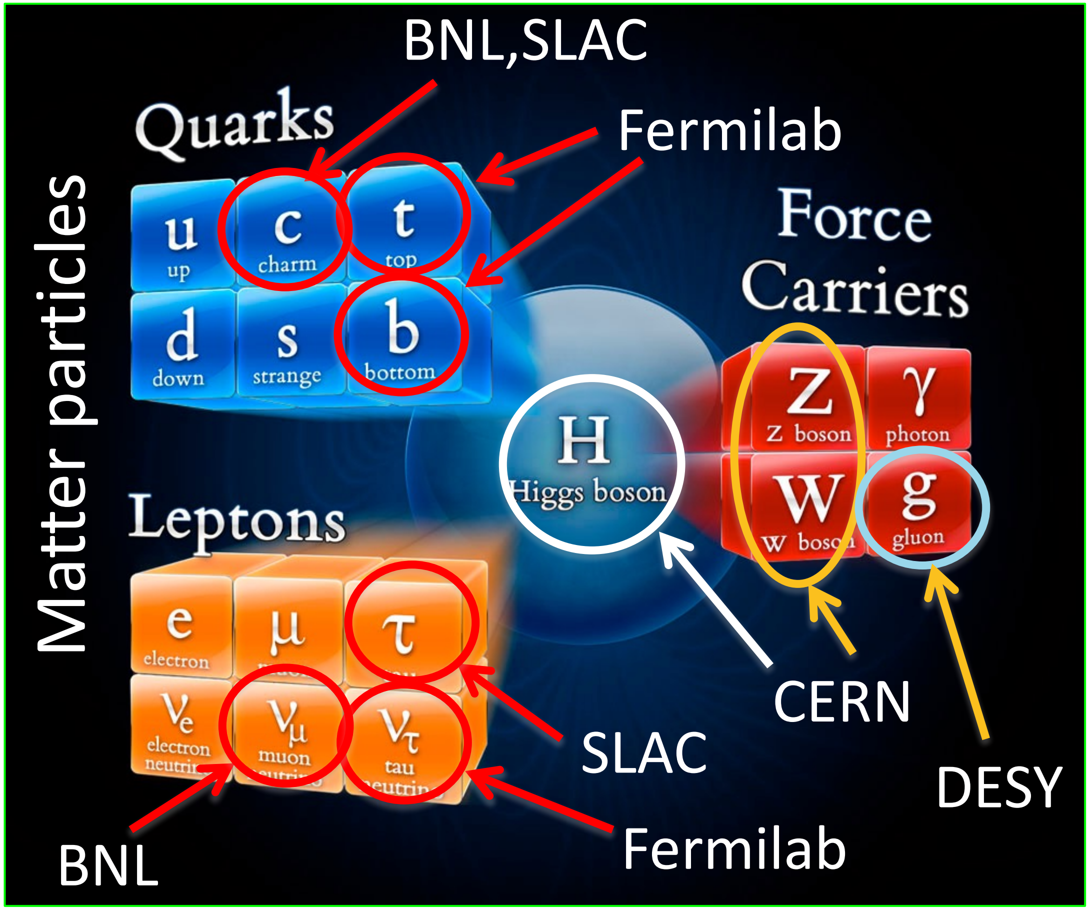


Three particles were discovered at Fermilab:

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

Hints for the Higgs: 2012

The Standard Model of Particle Physics

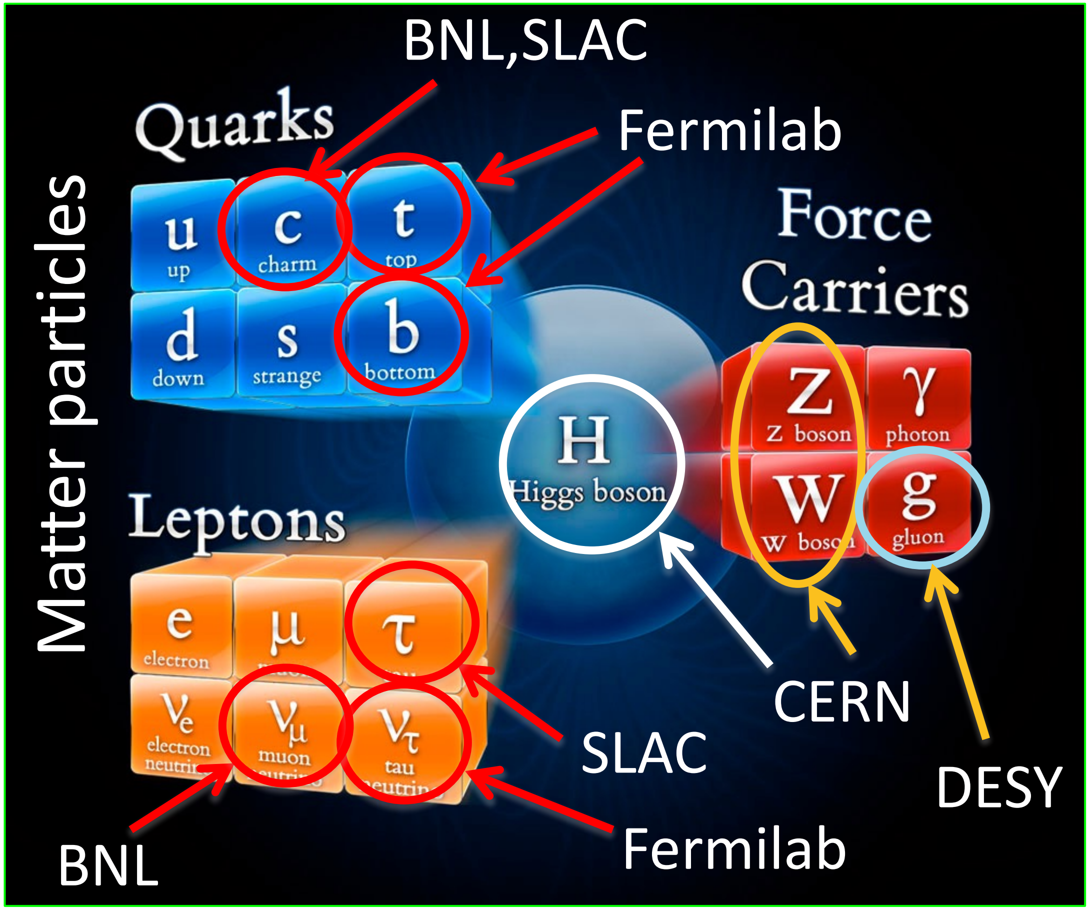


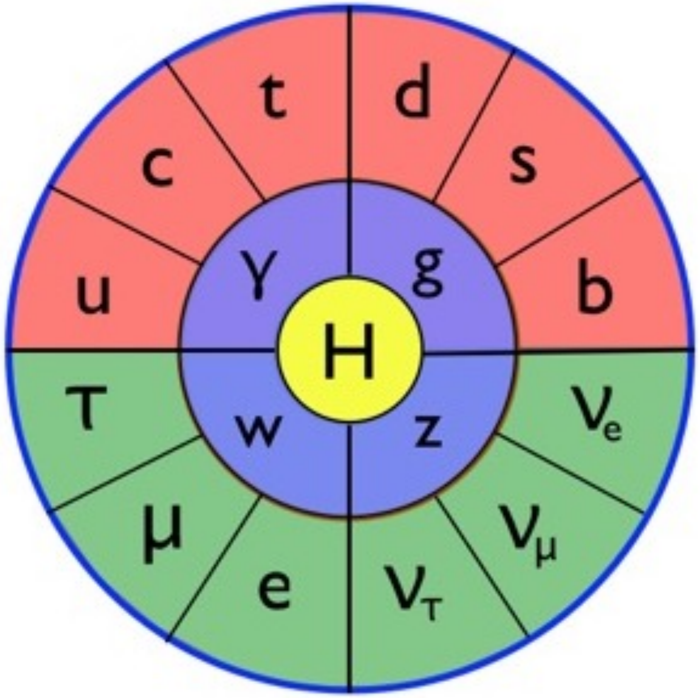
- Progress in particle physics over the past 50 years have mainly come from discoveries at successively more powerful particle accelerators, particularly at colliders
  - Charm quark (1974) e+e-, pN
  - Tau lepton (1975) e+e-
  - bottom quark (1977) pN
  - Gluon (1978/79) e+e-
  - W,Z bosons (1983) **ppbar**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

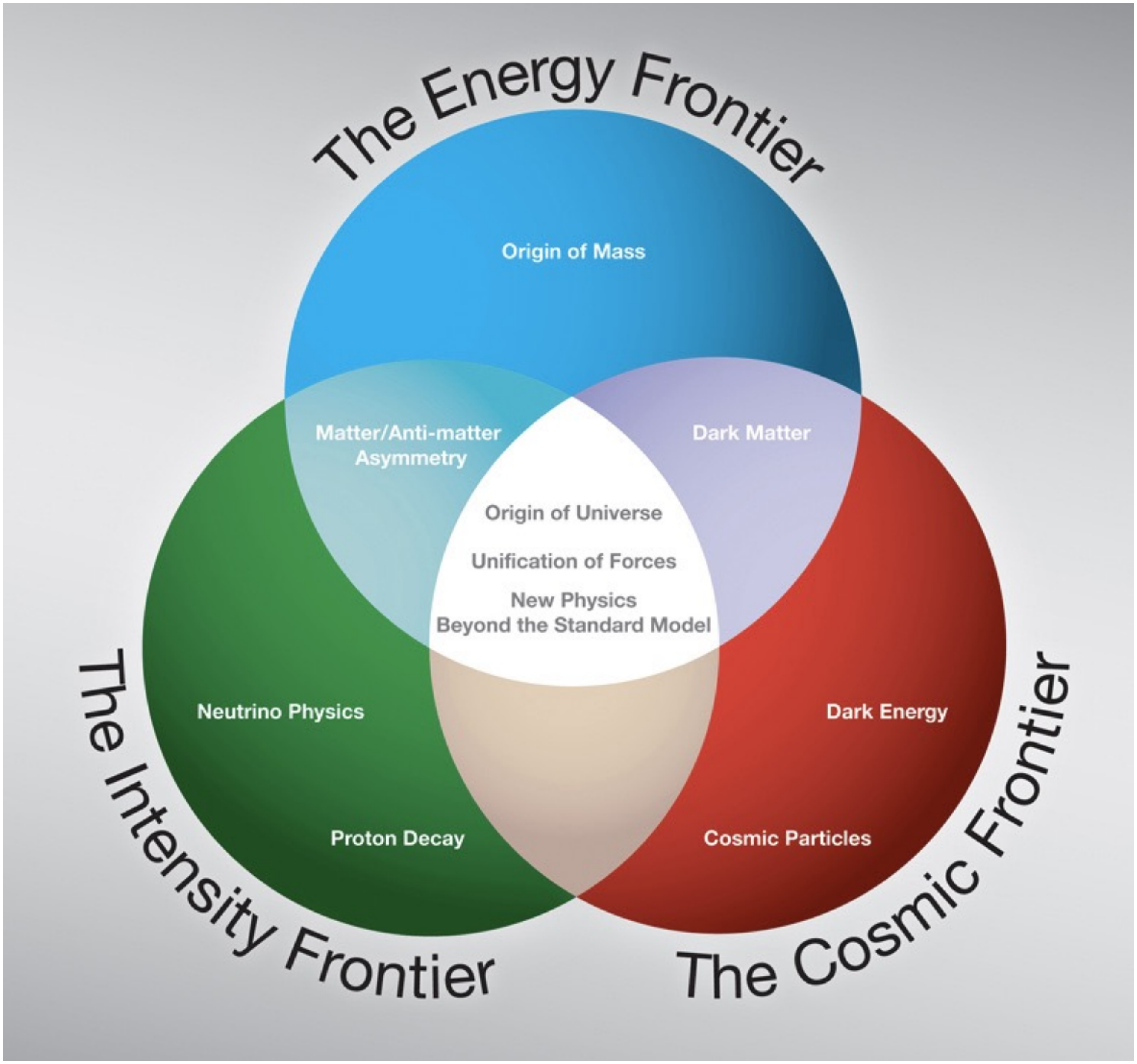
The Standard Model of Particle Physics

Developed and validated over the past five decades

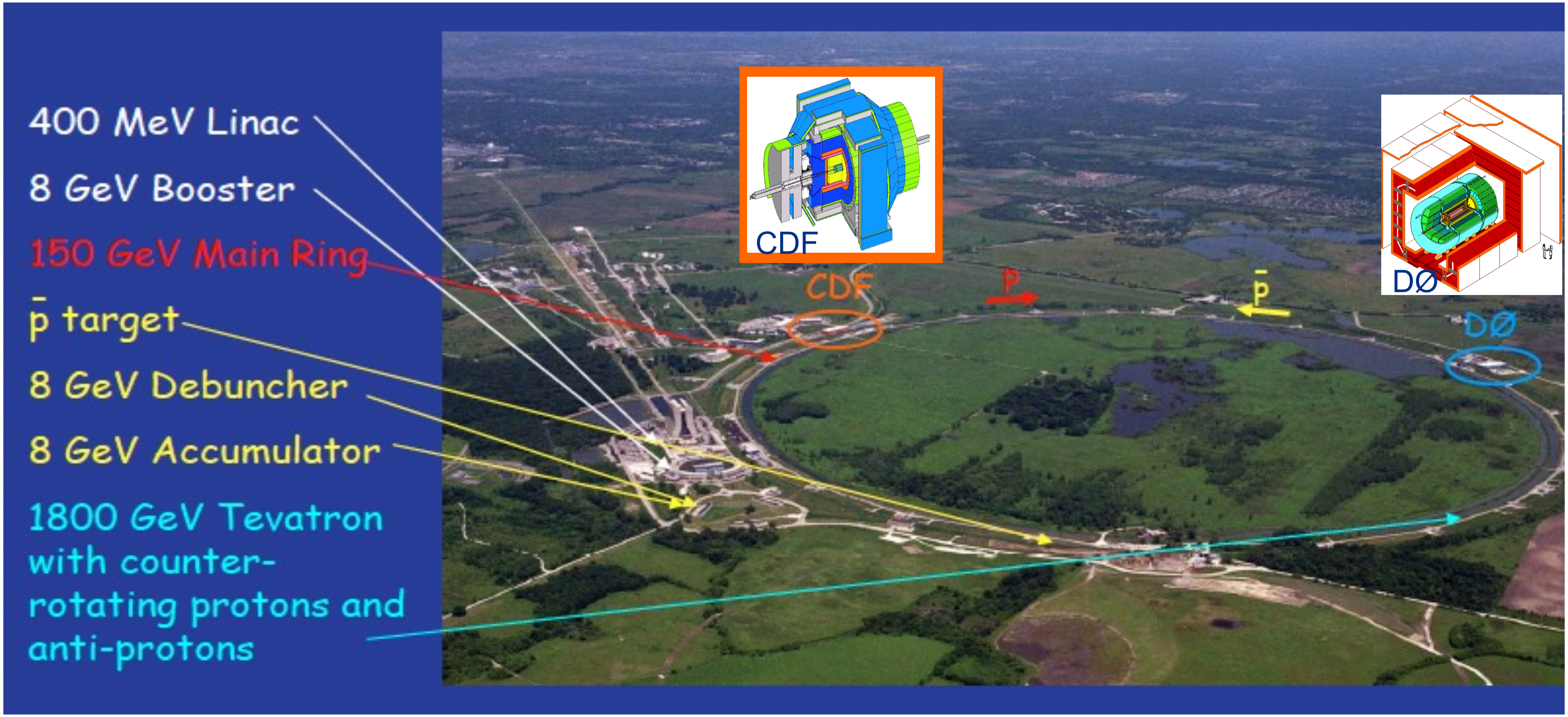




17 particles/fields that appear to be elementary.

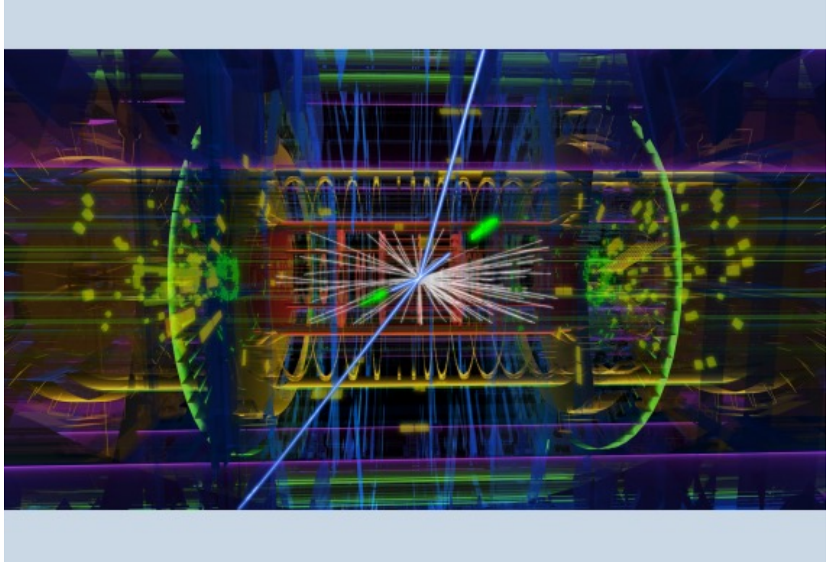

The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

Tevatron Collider Complex (1985-2011)



Creation, Detection and Discovery

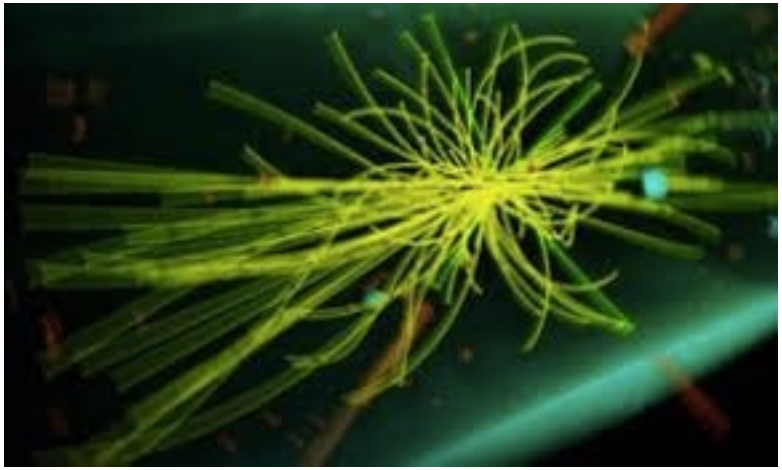
- Particle collisions at very high energies can create lots of all sorts of particles (via $E=mc^2$) and some extraordinary ones, such as the top quark or the Higgs boson!
- Particle detectors track, identify and “measure” particles produced in collision “events”.



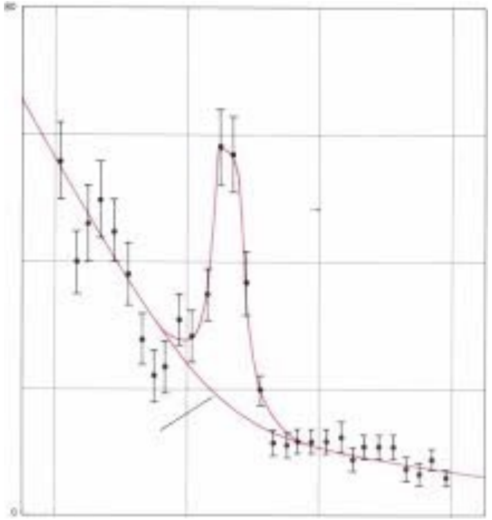
- ➢ Detectors are large, multi-layered, multi-system devices surrounding the collision region
- ➢ Many storeys high, ~ thousands of tons each, millions of electronic readout channels, have multi-tiered data-acquisition systems
- ➢ Produce photographic-like pictures of each collision event

How do we find new particles?

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



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



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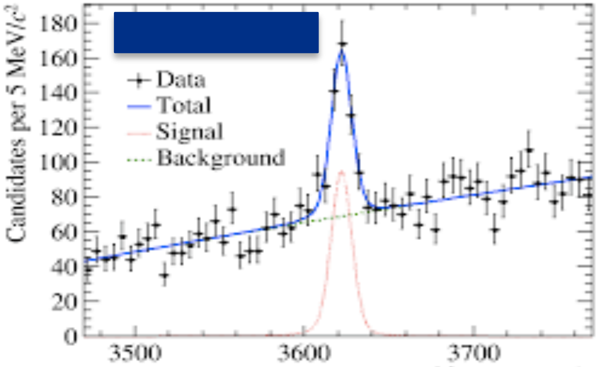


[redacted]

[redacted]

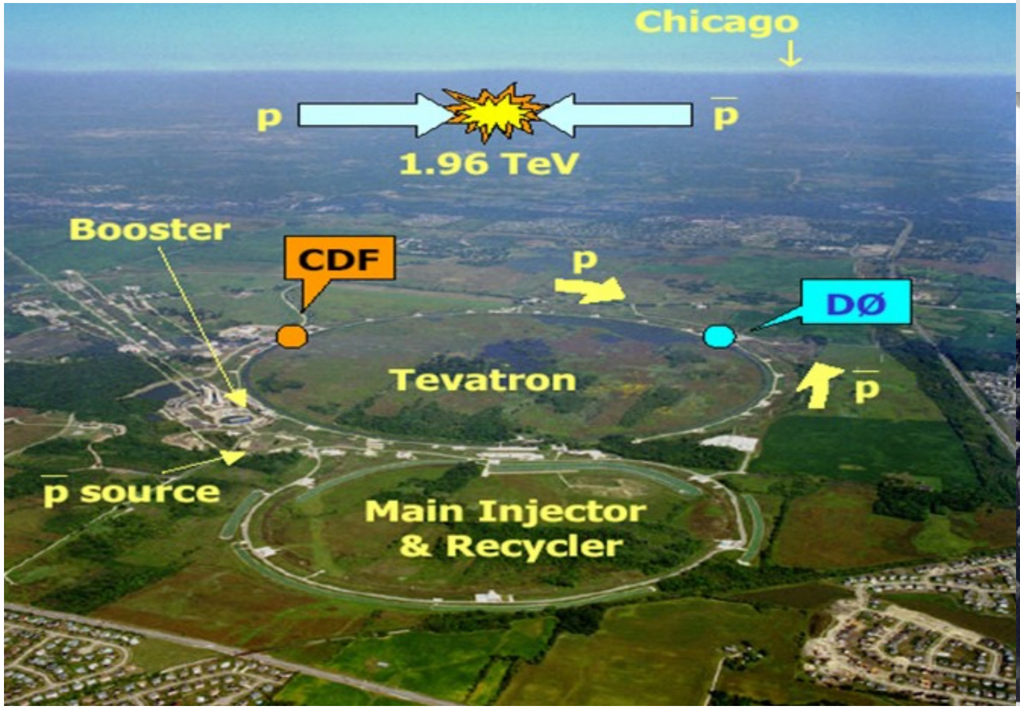
[redacted]

The Tevatron Collider

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

6.5 km in circumference

Superconducting magnets
774 dipoles
240 quadrupoles

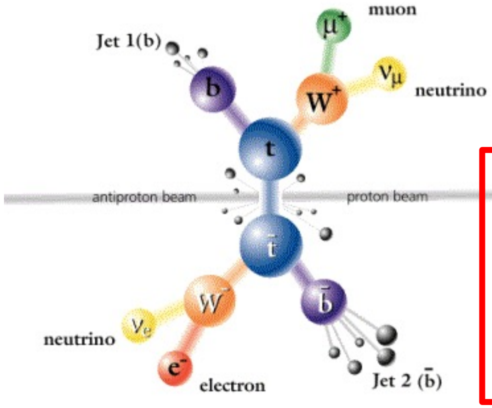


Discovery of top quark in 1995

The CDF detector

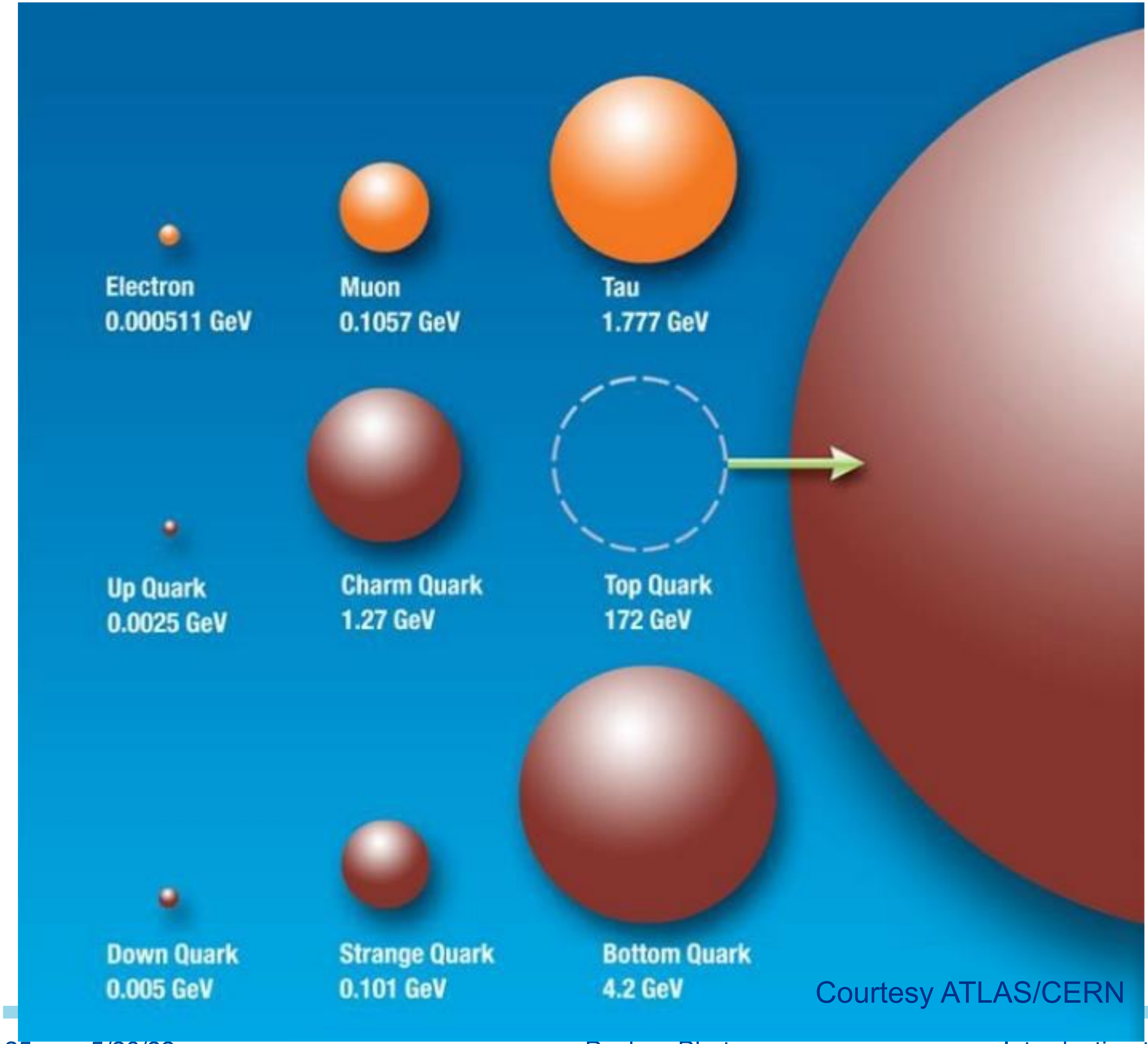
CDF and D0 at the Tevatron discovered the top quark in 1995, after decades of search at other machines around the world.

The D0 Detector



top-pairproduction
and decay (lepton+jets)

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



Courtesy ATLAS/CERN

Top quark turned out to be much heavier than anticipated.

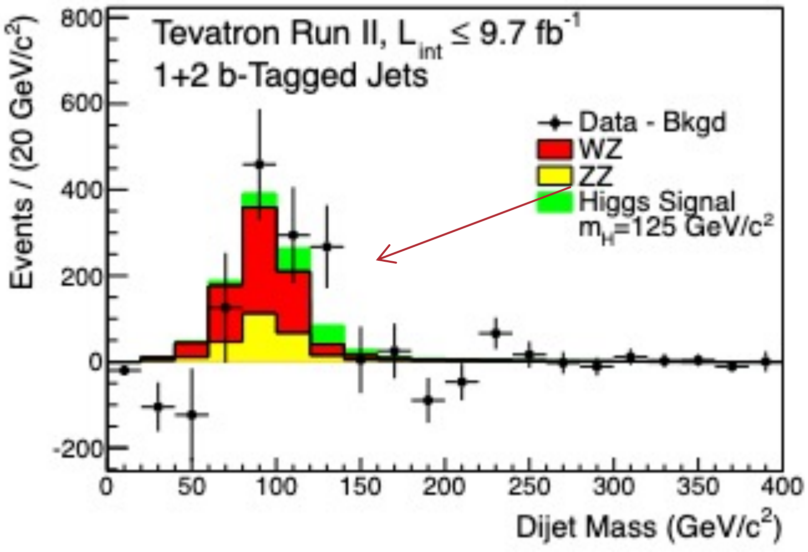
172x more massive than a proton.

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
- Improved bb mass resolution & b-tag efficiency

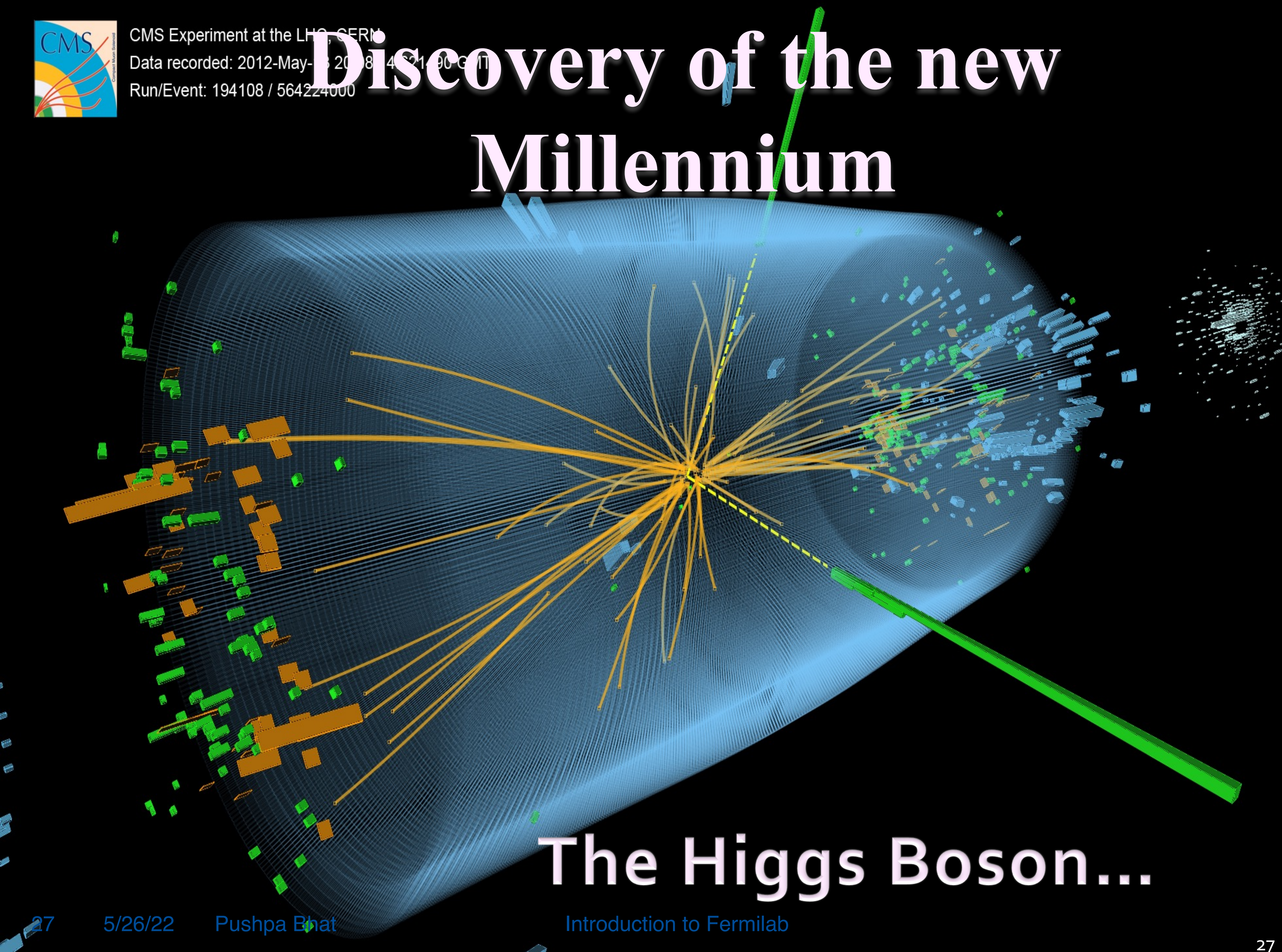


Excess of events between 120 – 135 GeV/c^2

Significance of 3.1 σ global

July 2, 2012

Discovery of the new Millennium



The Higgs Boson…

The Large Hadron Collider at CERN

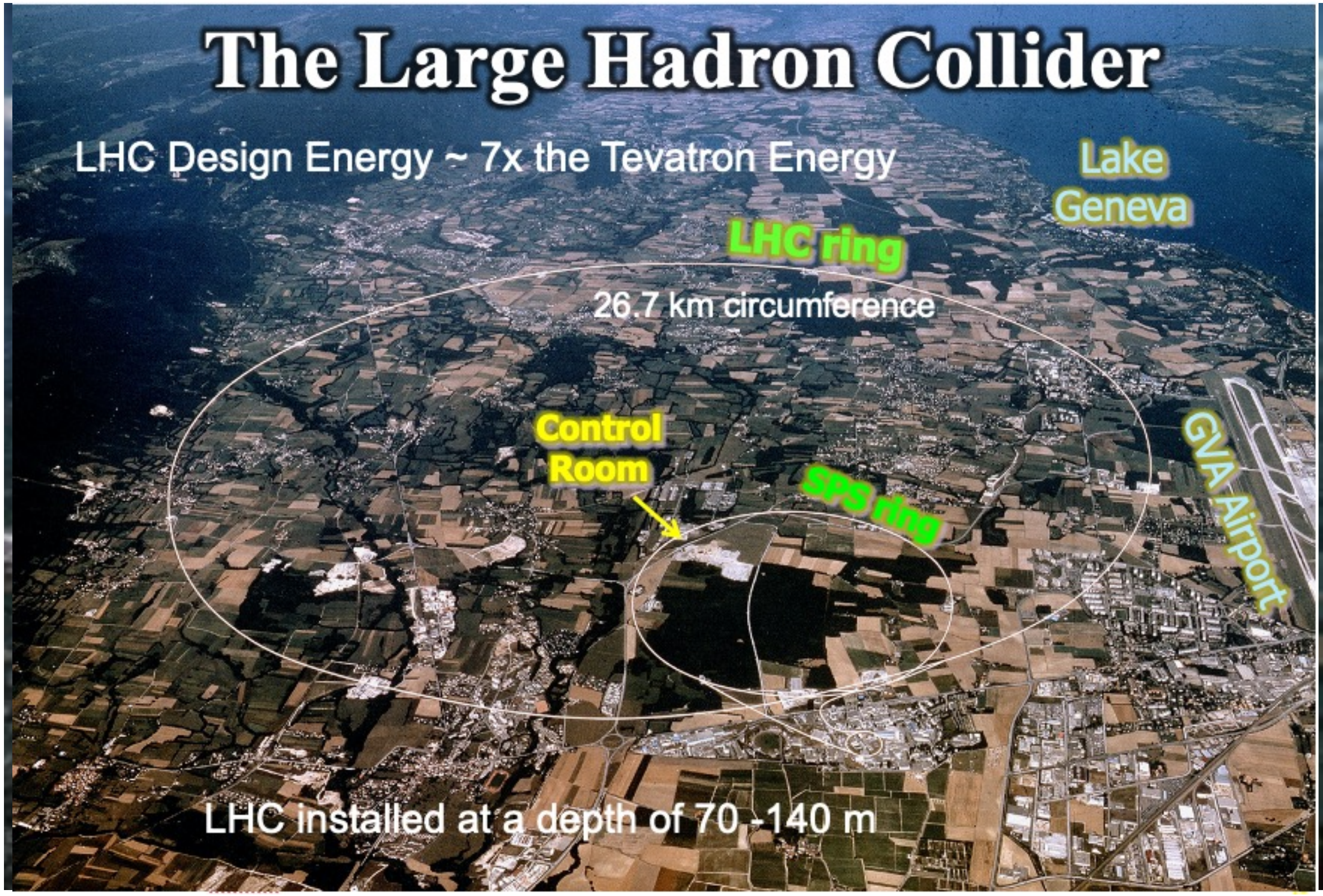
Geneva, Switzerland

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

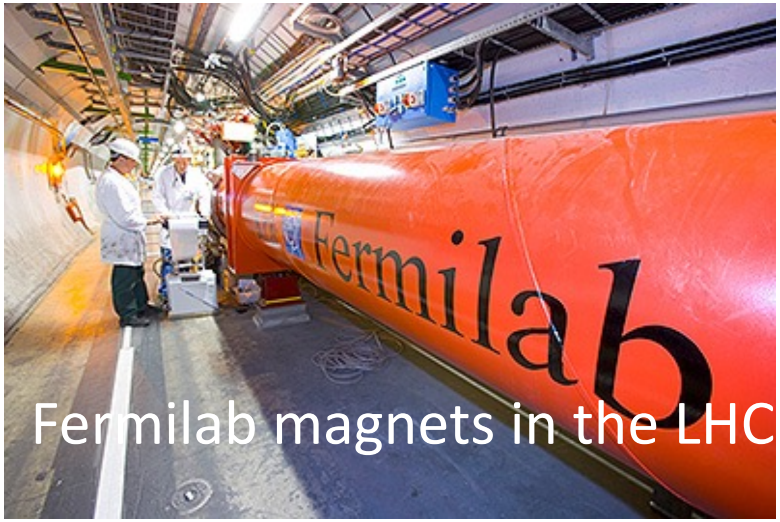
100 billion protons per bunch

Bunches collide 40 million times per second



The Large Hadron Collider @ CERN

A scientific & technological marvel!



Fermilab magnets in the LHC

LHC Control Room @CERN

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

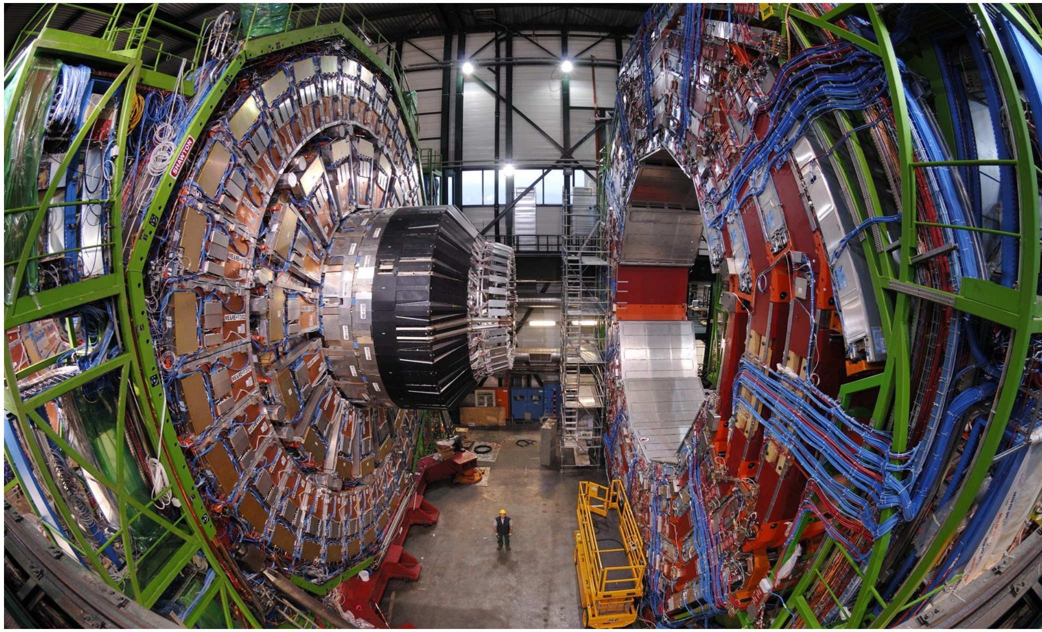
Fermilab at the LHC/CMS

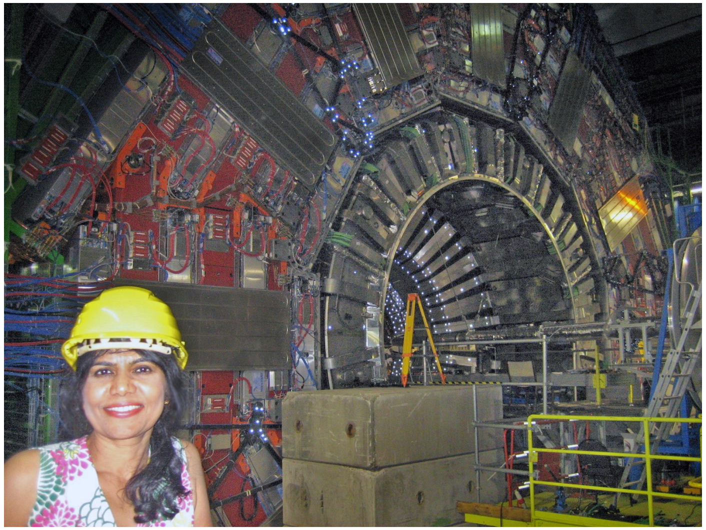
- Fermilab is the "host" laboratory for US CMS
  - Leveraged CDF and D0 experience and expertise at the Tevatron
    - Detectors: CMS all-Si tracker (FPIX, TOB; HCAL/HB); Muon endcap (ME) chambers and steel
    - Software & computing: data storage, management (grid computing), analysis computing
    - 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*



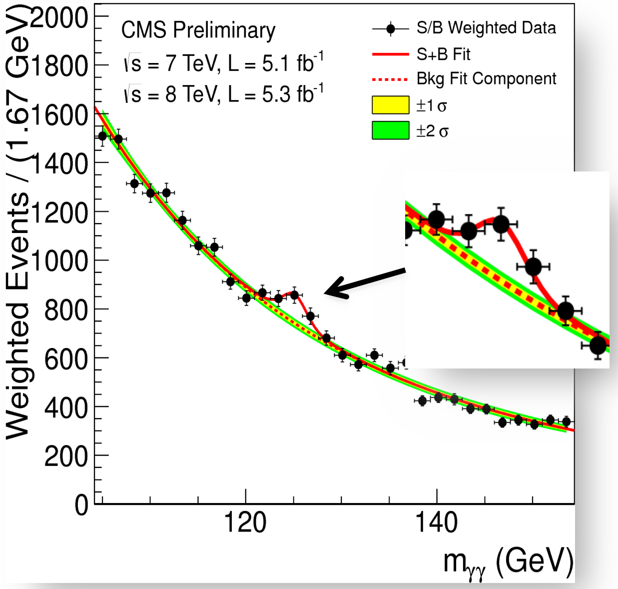


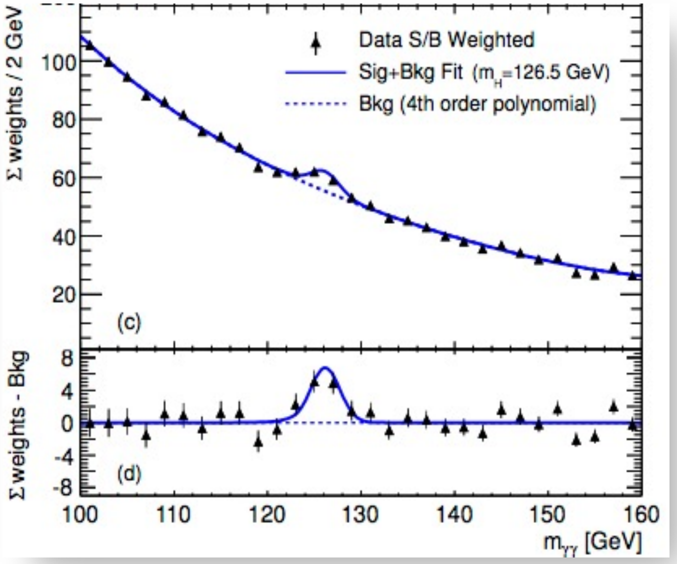
Discovery of Higgs boson in 2012 (by ATLAS and CMS)

Higgs Discovery

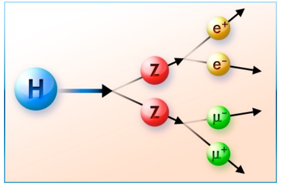
Data from ~10^{15} Collisions

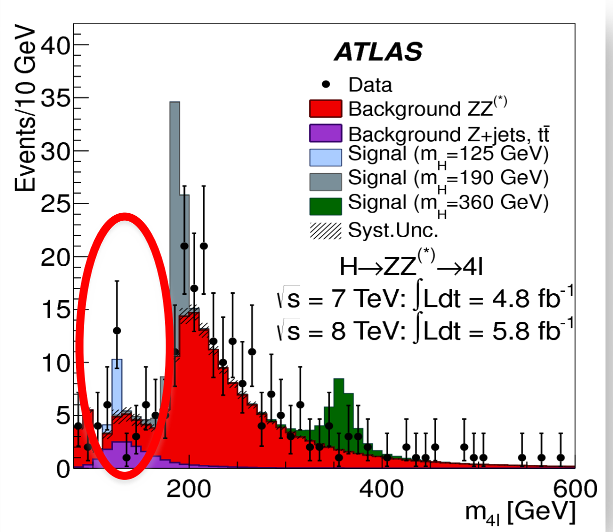
H→ γγ

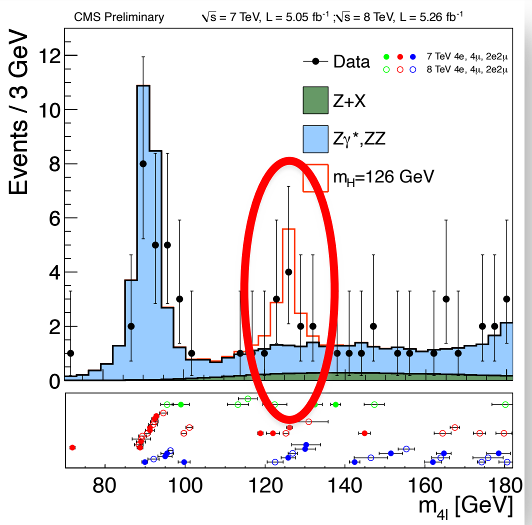




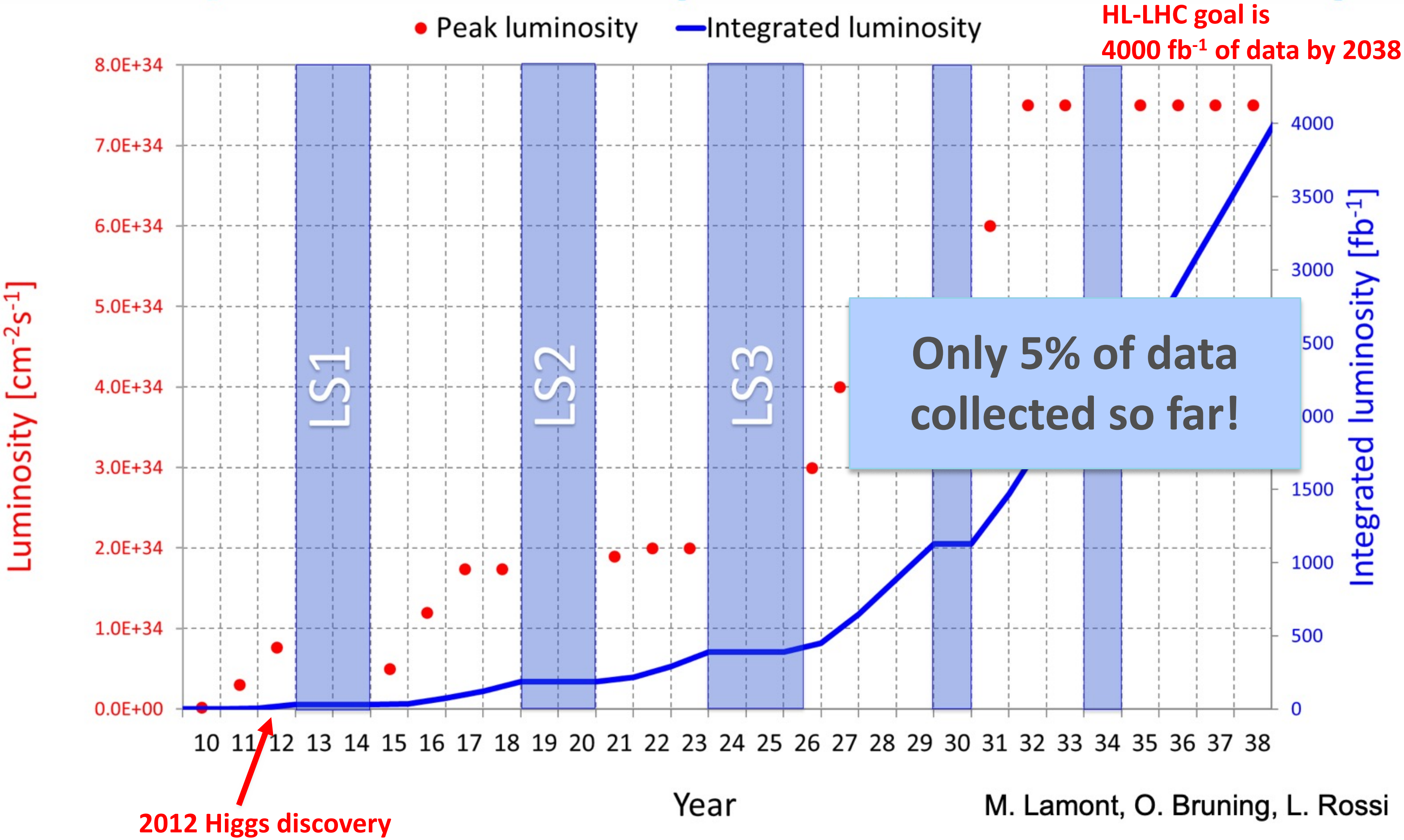
H→ ZZ→4ℓ







From LHC to HL-LHC: data, data, data



M. Lamont, O. Bruning, L. Rossi

HL-LHC goal is 4000 fb^{-1} of data by 2038

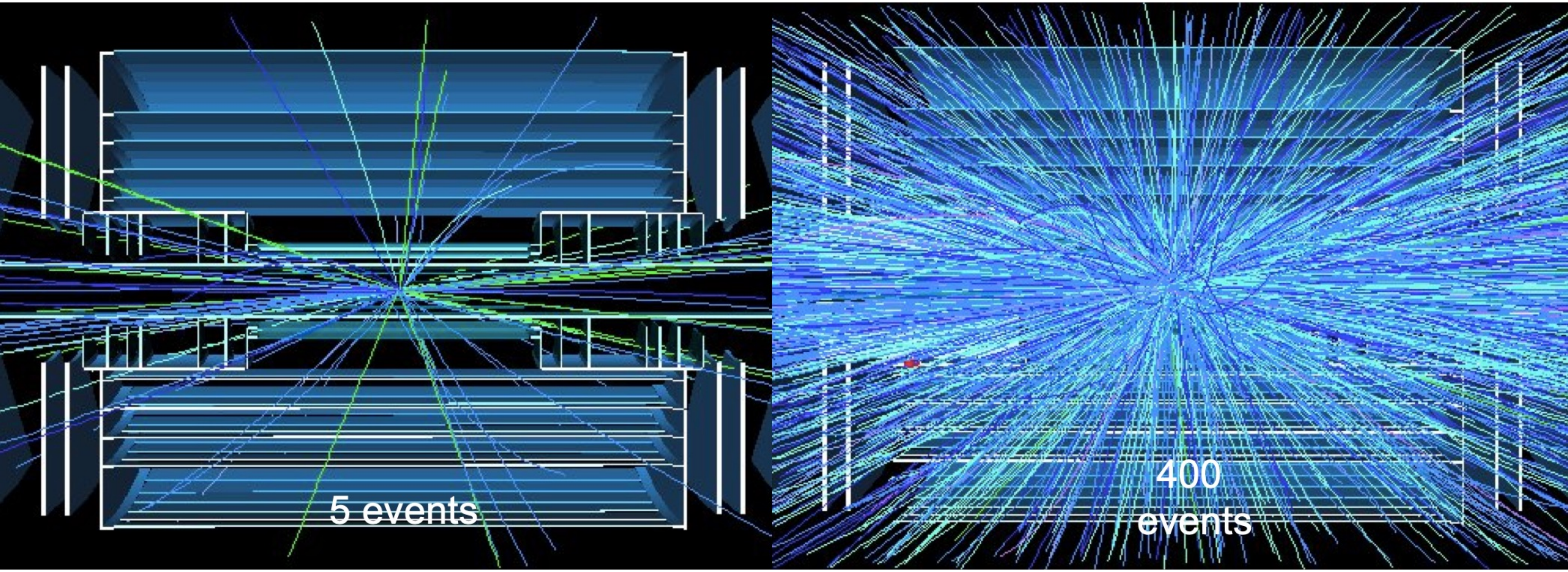
Only 5% of data collected so far!

2012 Higgs discovery with 11 fb^{-1} of data

The HL-LHC Environment

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

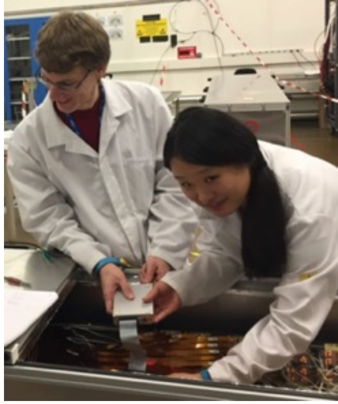
HL-LHC collision event has as many as 400 proton-proton collisions at once



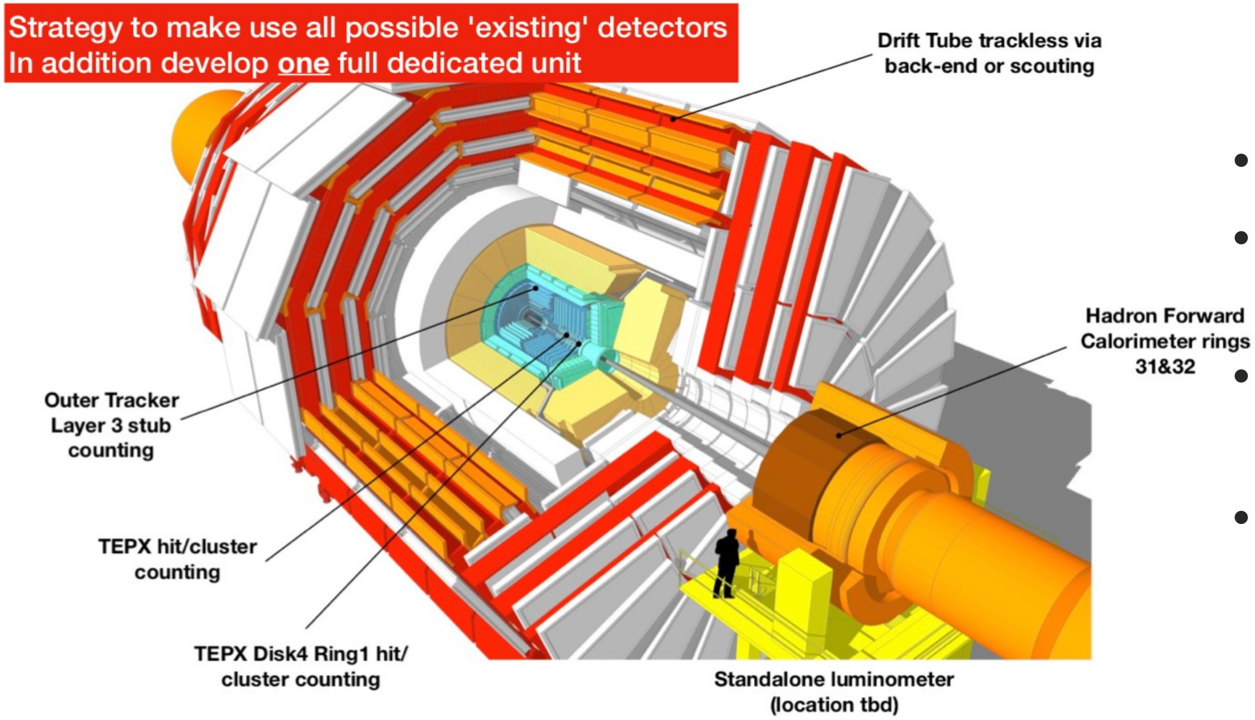
Need major upgrades of the detectors to make sense of these kind of events

Fermilab and CMS Upgrades

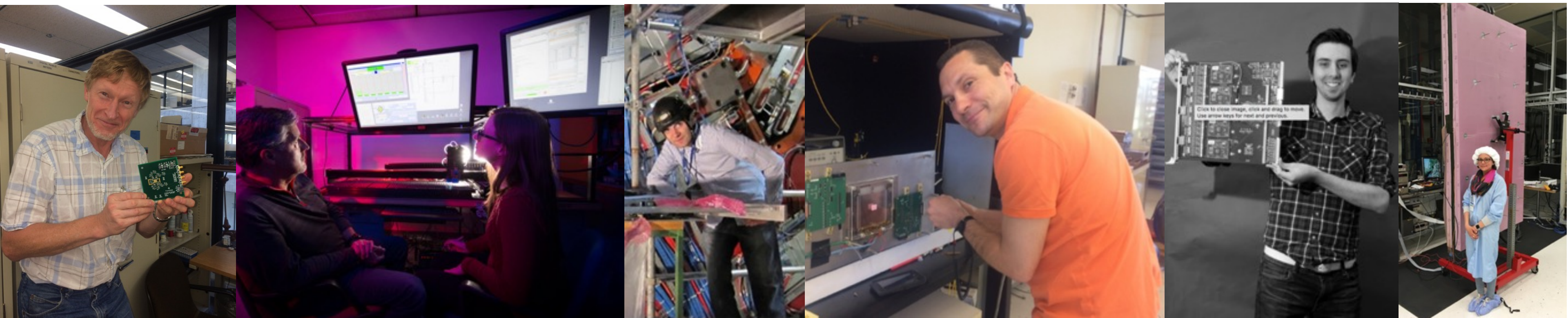
Innovation and cutting edge technologies to maximize the discovery potential of the LHC and HL-LHC



Strategy to make use all possible 'existing' detectors
In addition develop <u>one</u> full dedicated unit

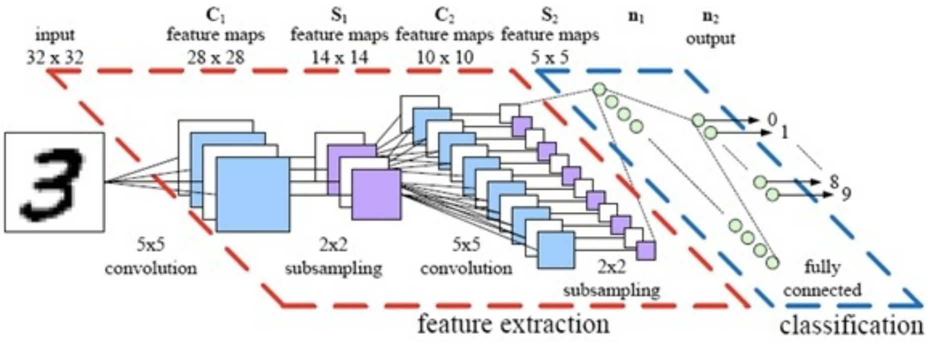


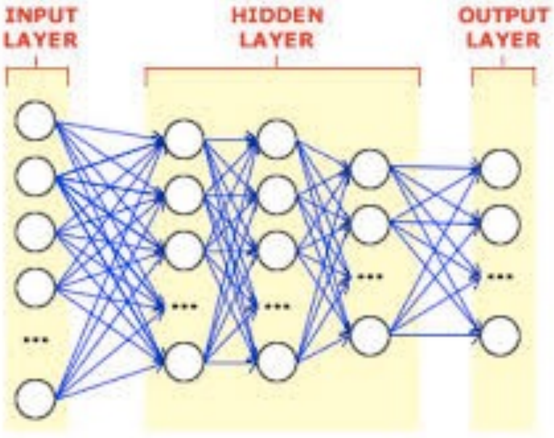
- Over 2B channels!
- Tracker measuring momentum at 40MHz
- Calorimeter with imaging capabilities
- Timing detector with 15ps resolution



Machine Learning and Artificial Intelligence

- Machine learning and AI were 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**

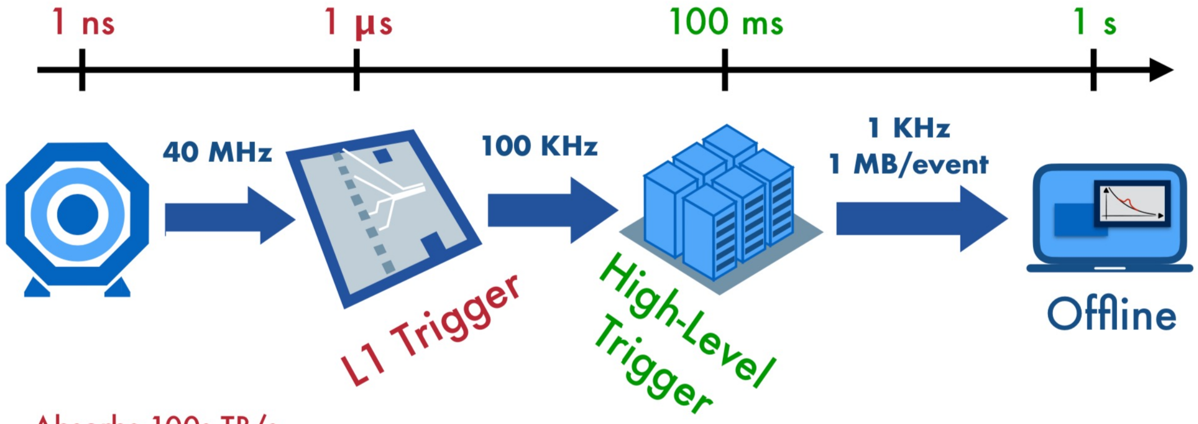




A SIMPLE NEURAL NETWORK

- 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

Fermilab and the big data challenge



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

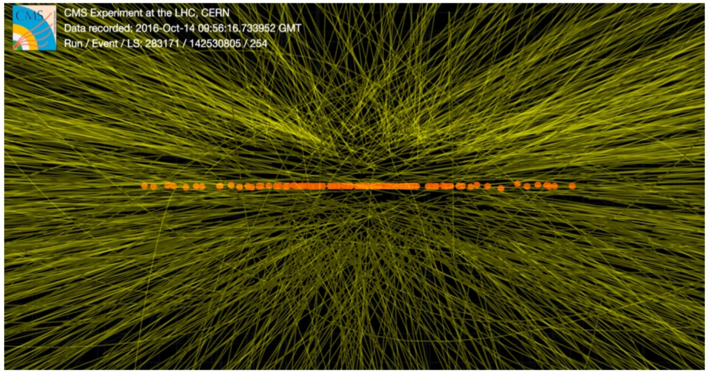
Absorbs 100s TB/s

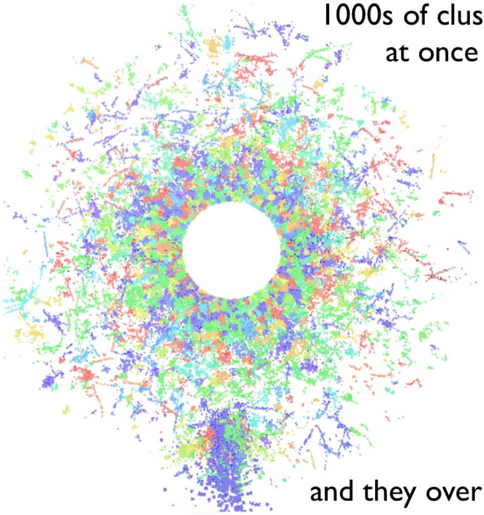
Trigger decision to be made in O(µs)

Latencies require all-FPGA design

99.75% events rejected!

↓ 1000s of tracks at once





1000s of clusters at once

and they overlap :-)

Fast Machine Learning

September 10-13, 2019 at Fermilab

Sept. 10-11
IRIS-HEP Blueprint Meeting

Sept. 12-13
Developer Bootcamp

Accelerating ML in science:

Ultrafast on-detector inference and real-time systems

Acceleration as-a-service

Hardware platforms

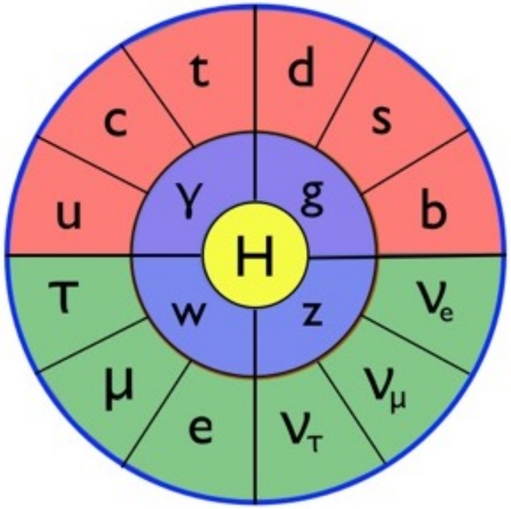
Coprocessor technologies (CPU/GPU/TPU/FPGAs)

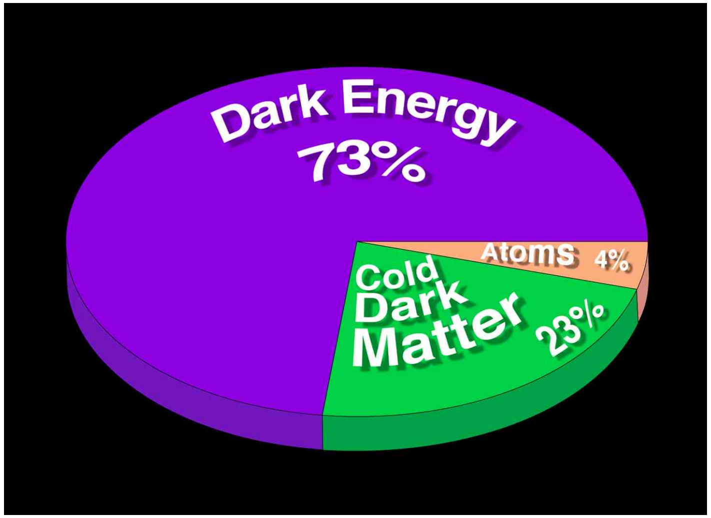
Distributed learning

Local Organization:
Gabriele Benelli (Brown U.)
Javier Duarte (Fermilab)
Lindsey Gray (Fermilab)
Mia Liu (Fermilab)
Kevin Pedro (Fermilab)
Alexx Perloff (CU Boulder)
Zhenbin Wu (U. Illinois Chicago)

Scientific Organization:
Phil Harris (MIT)
Burt Holzman (Fermilab)
Shih-Chieh Hsu (U. Washington)
Sergo Jindariani (Fermilab)
Maurizio Pierini (CERN)
Mark Neubauer (U. Illinois Urbana-Champaign)
Nhan Tran (Fermilab)

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

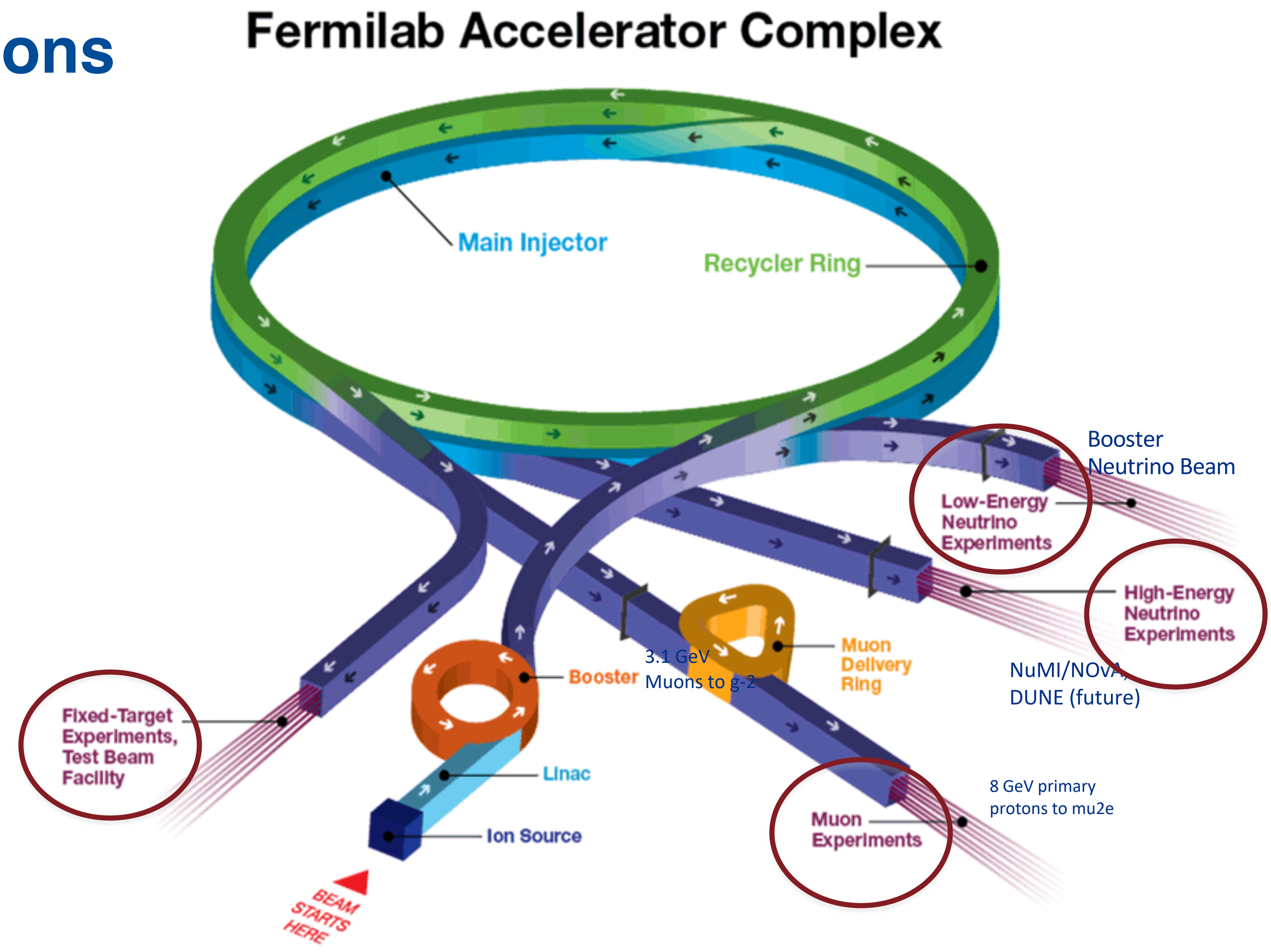
P5/USHEP Science Drivers

- 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 is now in progress to develop strategy and vision for the next couple of decades

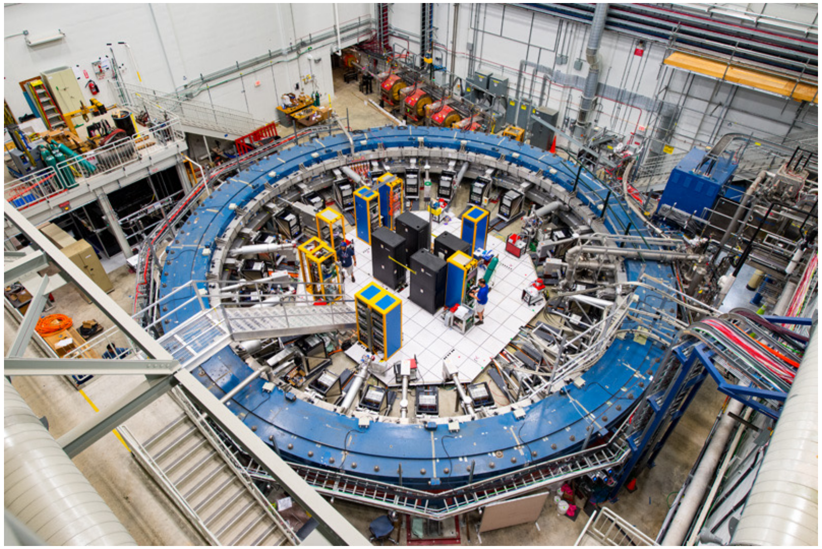
Current Operations

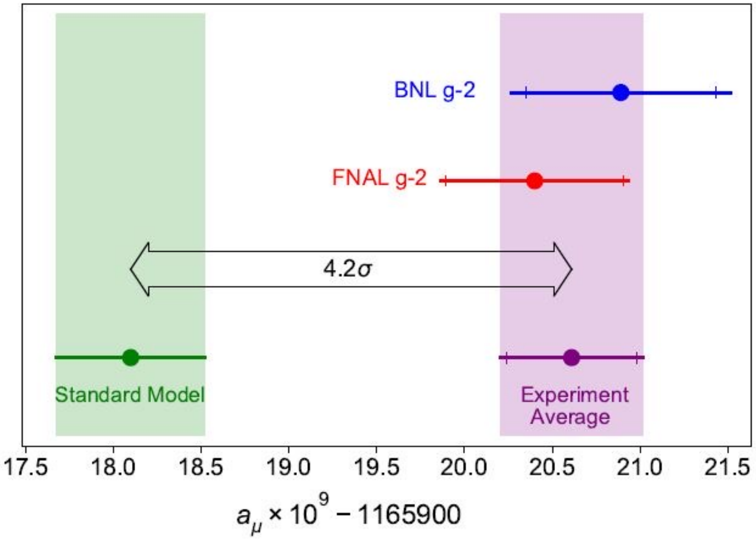


A Chain of Accelerators

Muon g-2 Experiment

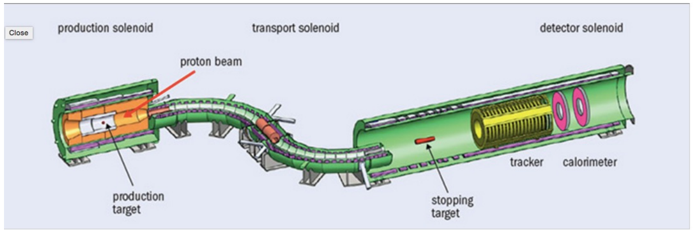
- The Fermilab Muon g-2 experiment measures the anomalous magnetic moment of the muon with unprecedented precision (goal:140 parts billion), by studying the precession of muons in an applied magnetic field.
- The measurement is sensitive to virtual particles that pop in and out of existence in the quantum 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!





Charged Lepton Flavor Violation (Mu2e)

- The Mu2e experiment at Fermilab is looking 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.

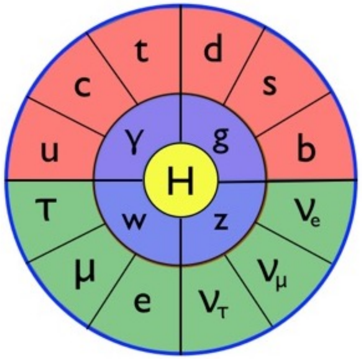


- ➢ Three sophisticated superconducting solenoid magnets
- ➢ Intense beam of low-energy muons directed on to a thin aluminum stopping target.
- ➢ The largest solenoid also houses detectors that measure momenta and energy of particles produced.
- ➢ 75’ wide, 10’ tall

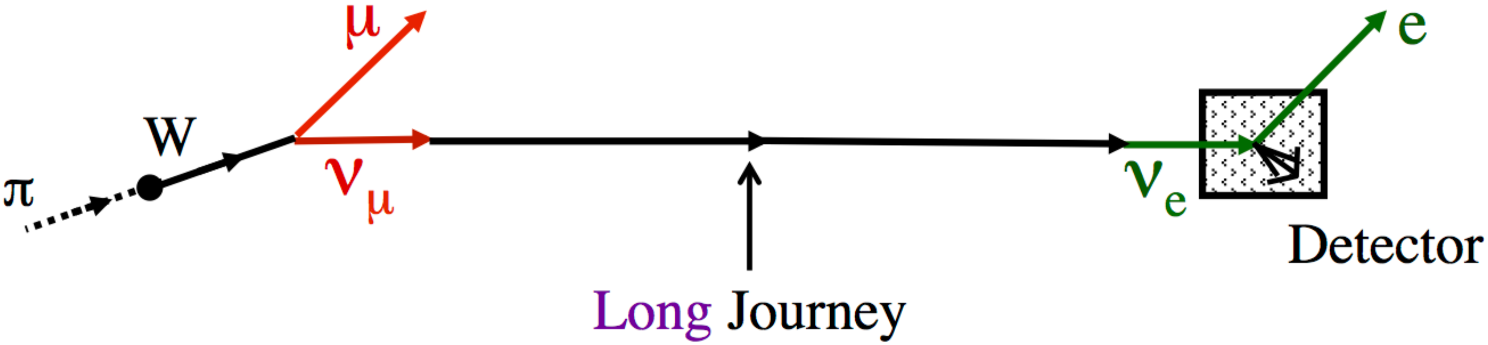
Neutrino oscillations

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

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



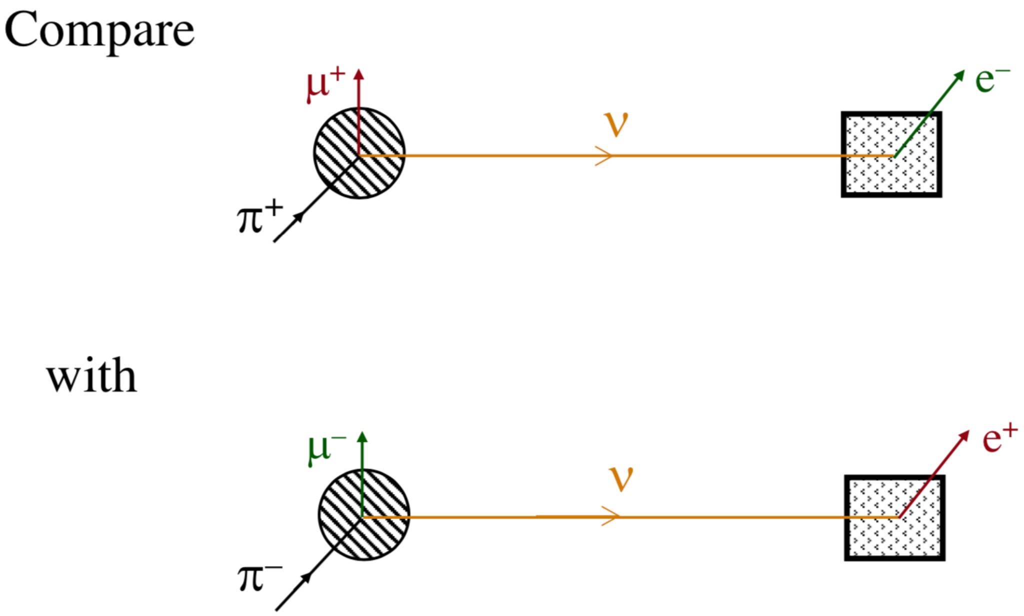
After traveling some distance, this superposition will change because of the different phase factors



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

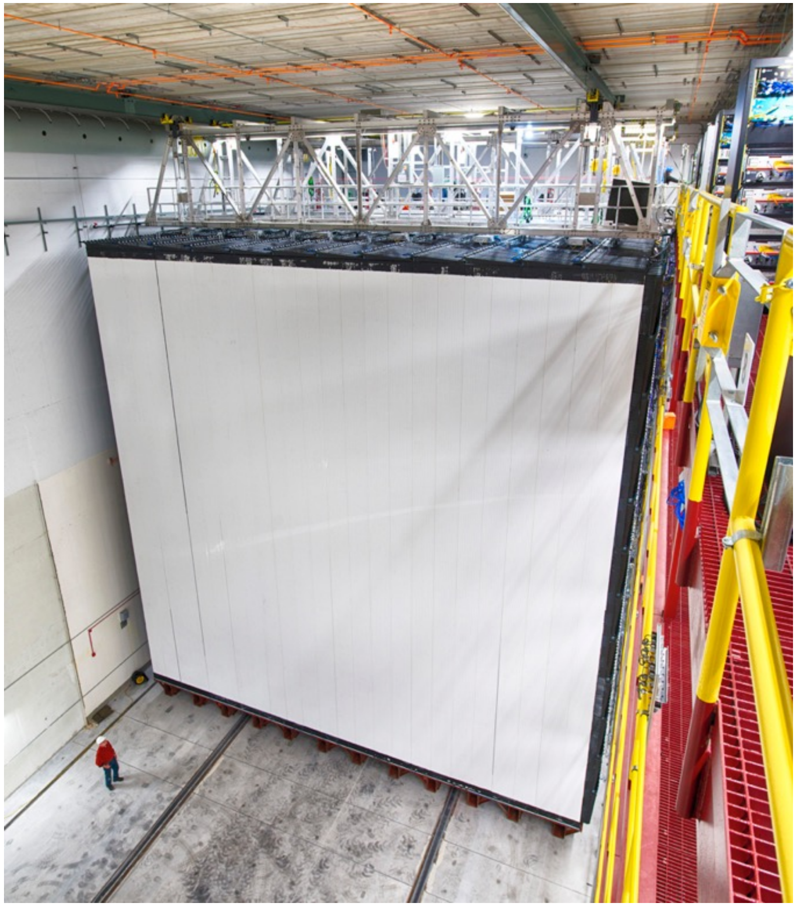
Neutrino oscillations and CP violation

- 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**



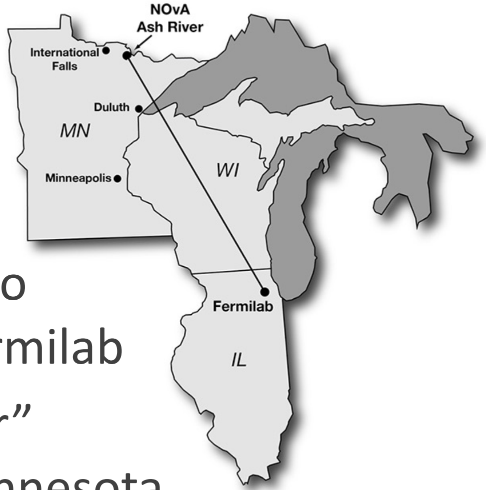
- If they are not the same, then neutrinos violate CP
- This could be the reason why we exist

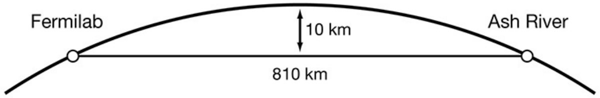
NOvA neutrino oscillation experiment

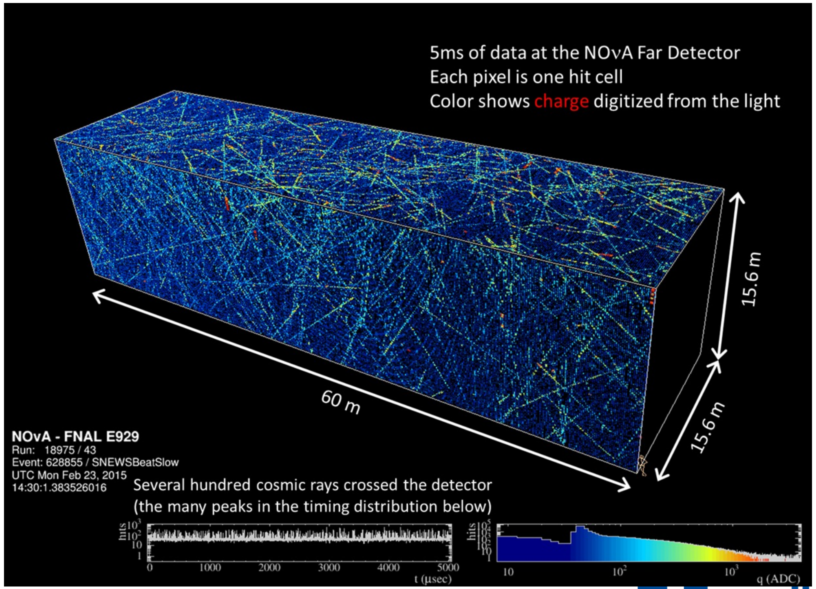


"near" neutrino detector at Fermilab

14,000 ton "far" detector in Minnesota







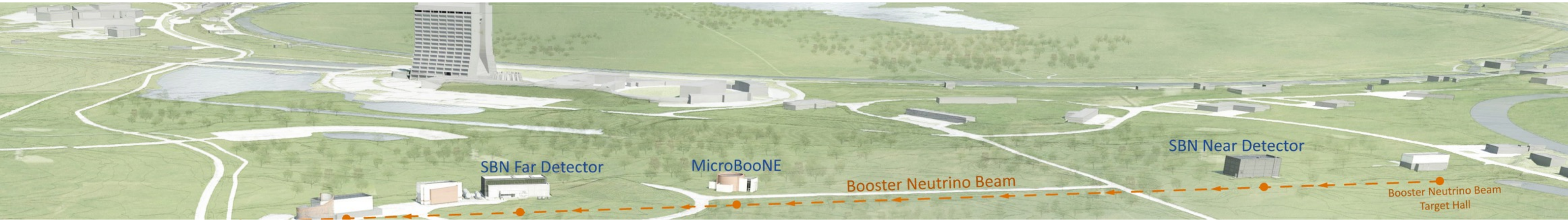
5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

NOvA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)

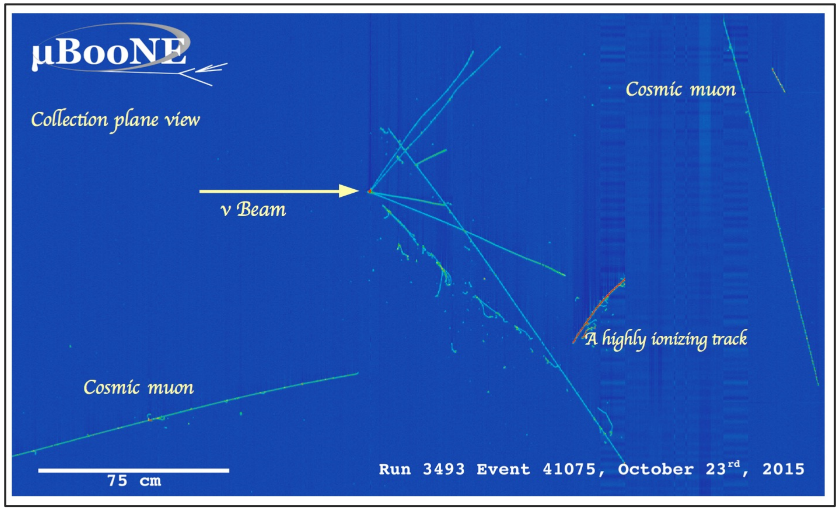
NoVA's research goals are to study Neutrino oscillations, ordering of neutrino masses, and matter-antimatter symmetry

Short Baseline Program at Fermilab

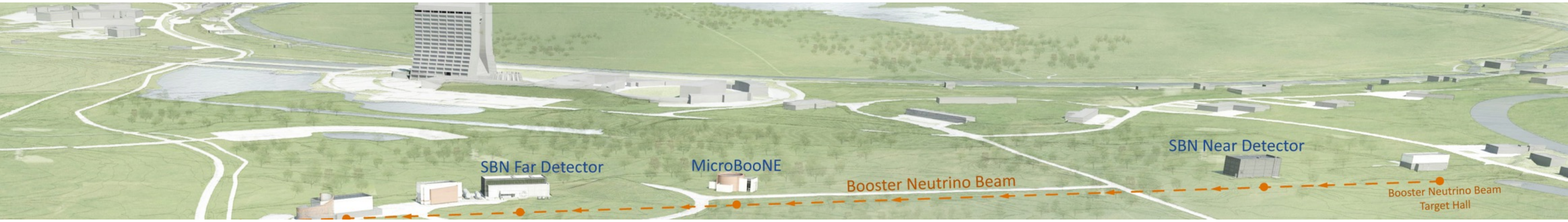


- On Fermilab site are experiments with short baseline -- MicroBooNE, ICARUS & SBN Far and Near Detector, using Booster neutrino beams
- Probing the mysteries of neutrinos: neutrino interactions, sterile neutrino search, ..
- Advancing the technology for neutrino detection

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



Short Baseline Program at Fermilab



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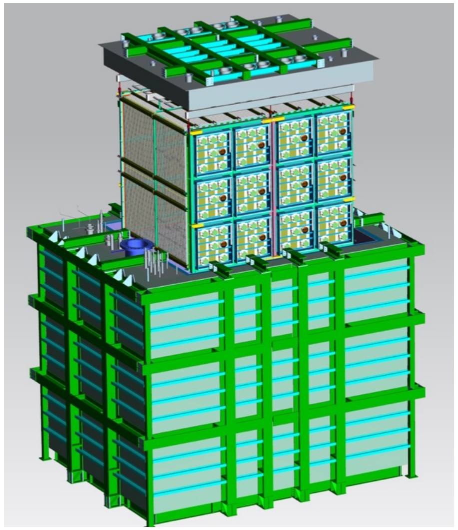
ICARUS (Far) 500-ton active volume

SBND 112-ton active

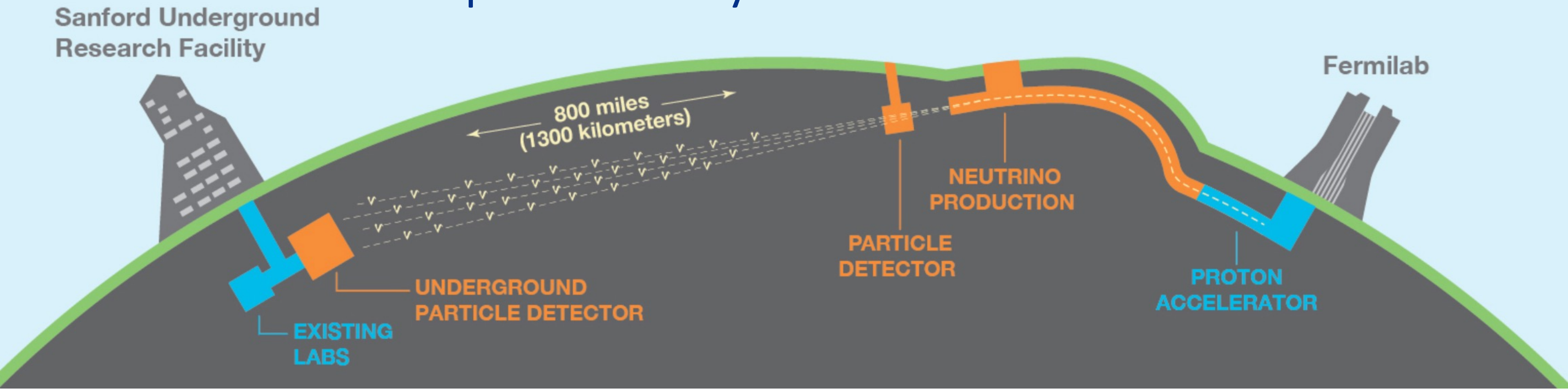


SBND will record over a million neutrino interactions per year.

Future Flagship Neutrino Oscillations Experiment

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

A Megascience International Project
to probe the mysterious neutrinos



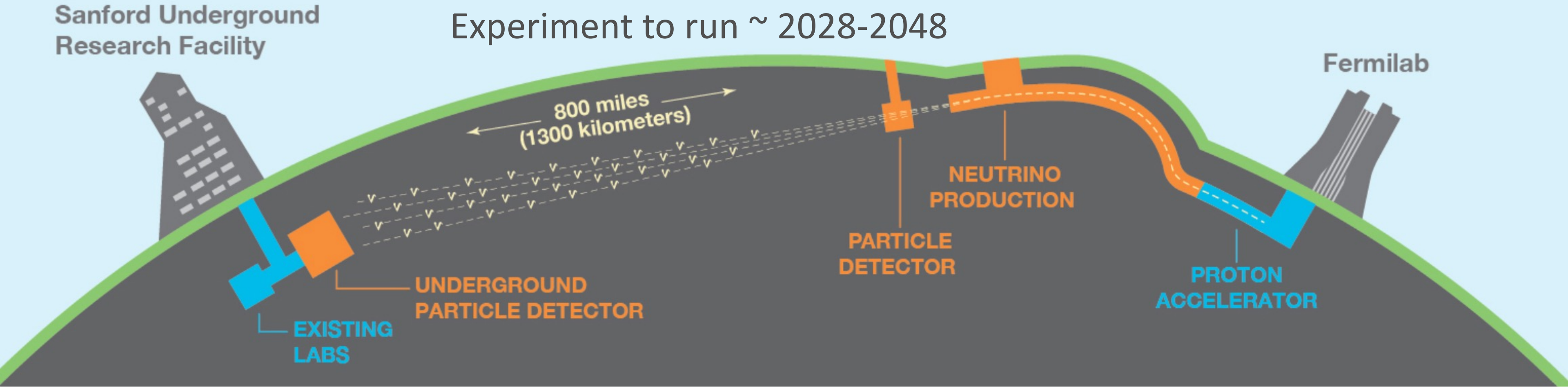
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Build the world’s most powerful neutrino beam at Fermilab

Send neutrinos 1300 km through the Earth to South Dakota

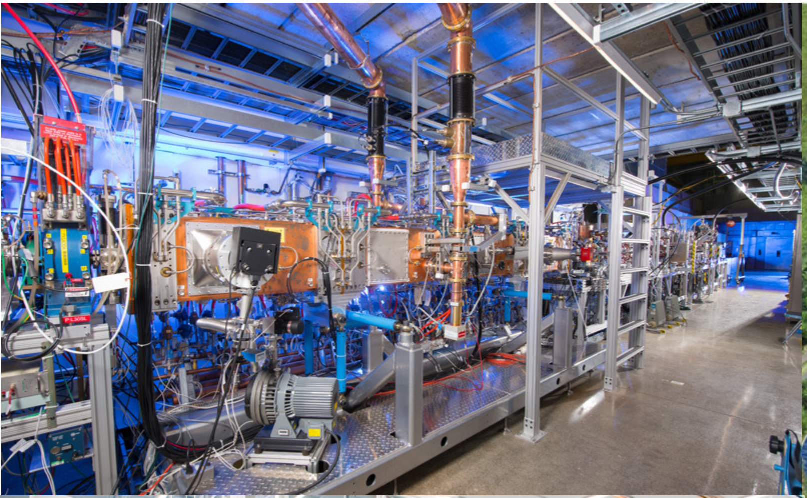
Detect them in the massive, sophisticated neutrino detectors, a mile underground

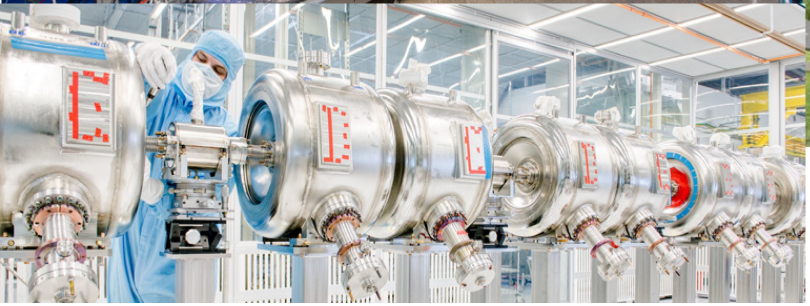
Experiment to run ~ 2028-2048



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.

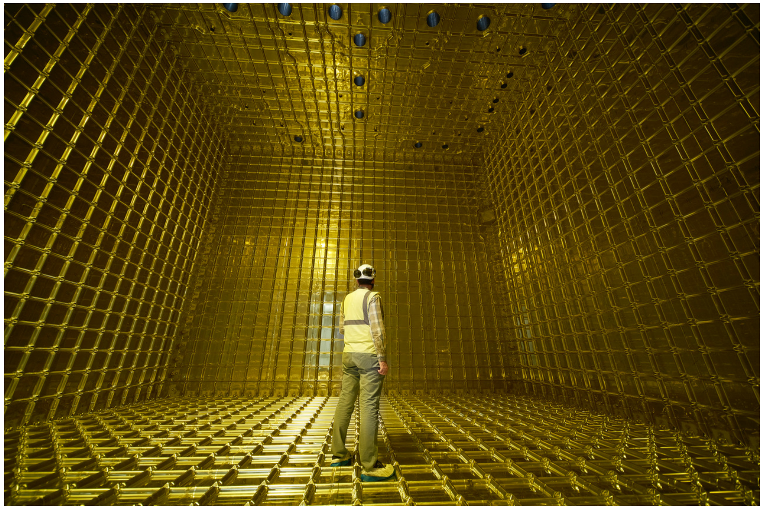


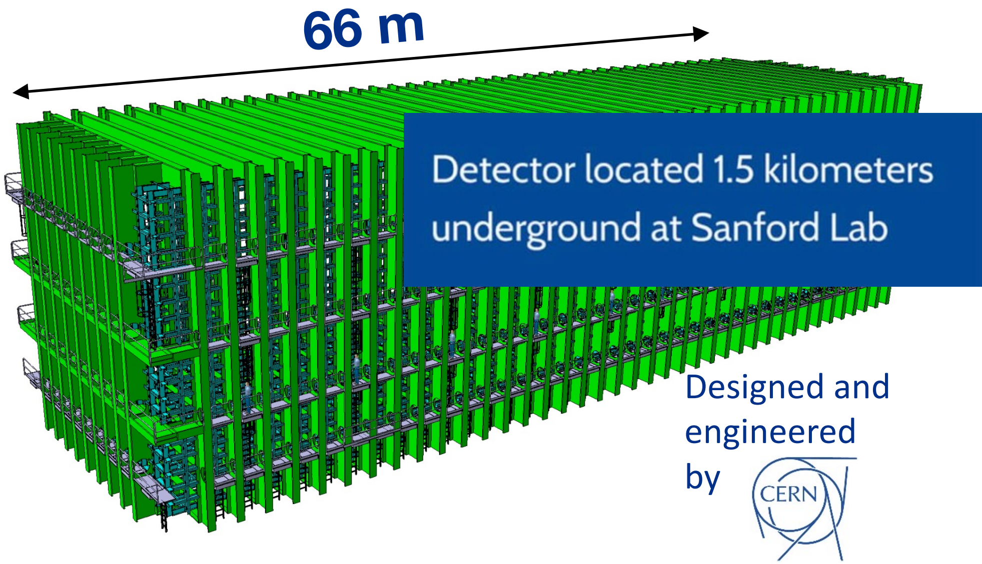


Fermilab, World’s leader in SRF cavities, at the core of PIPII

DUNE = four 70 kton Cryogenic Liquid Argon Detectors

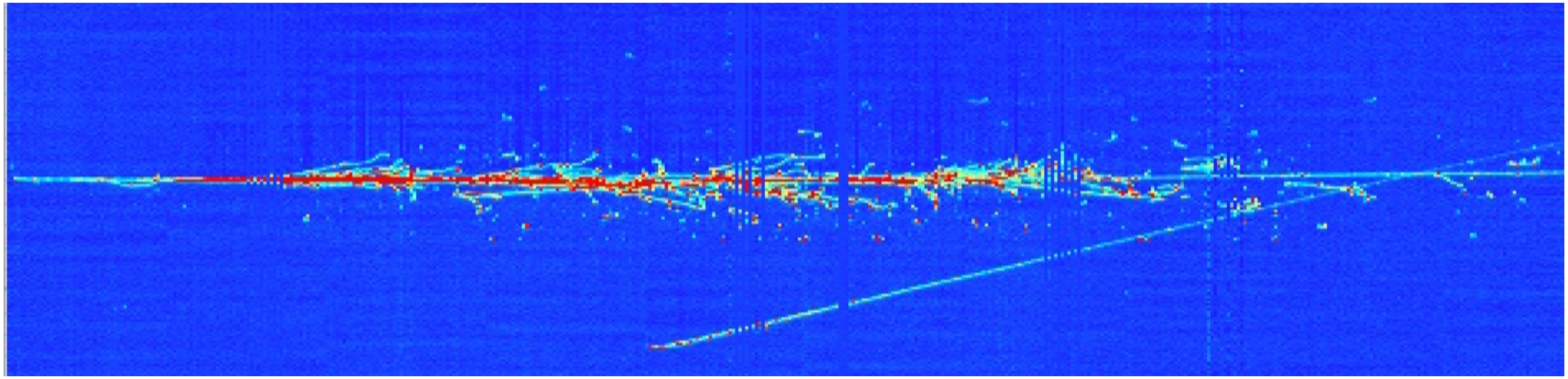
A 1/20 scale prototype has successfully run at CERN





Detector located 1.5 kilometers underground at Sanford Lab

Designed and engineered by 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

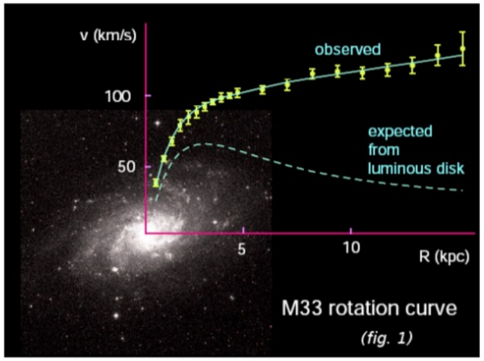
- Search for proton decays

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

- Detection of neutrinos emitted by exploding stars

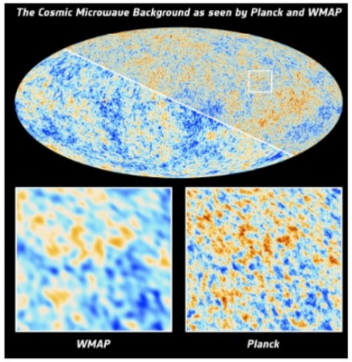
The Future of Dark Matter

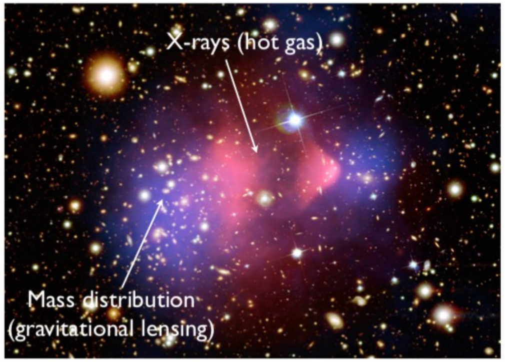
- Dark Matter exists, awaiting for discovery



M33 rotation curve

(fig. 1)

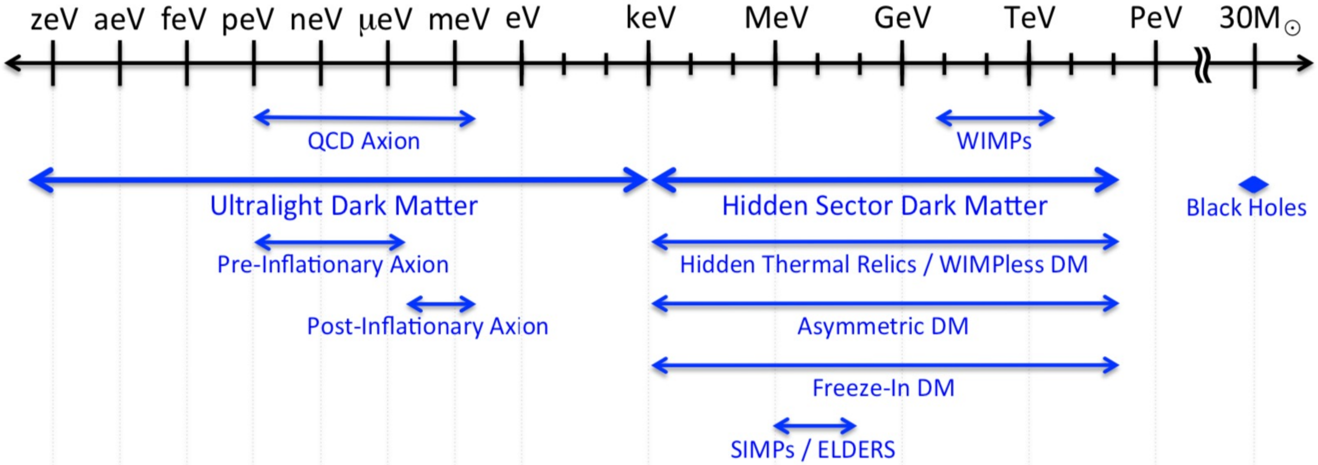




European Strategy Update

Dark Matter Candidates: Very little clue on mass scales

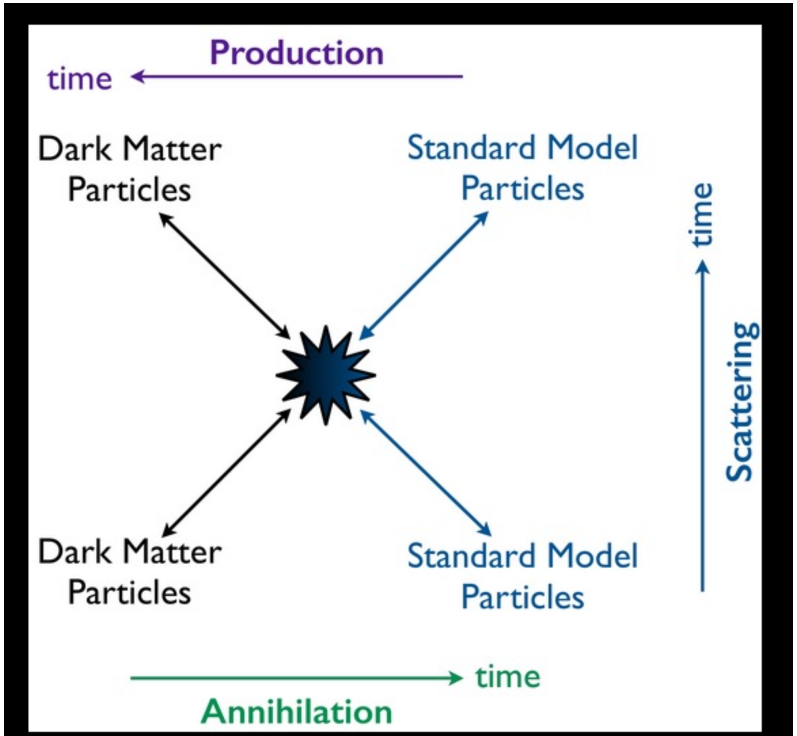
Too small mass
⇒ won't "fit"
in a galaxy!



From MACHOs
searches

Detecting Dark Matter

- **Production** of dark matter particles in LHC collisions → Searches at the LHC
- **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 (LZ, CDMS, ..)



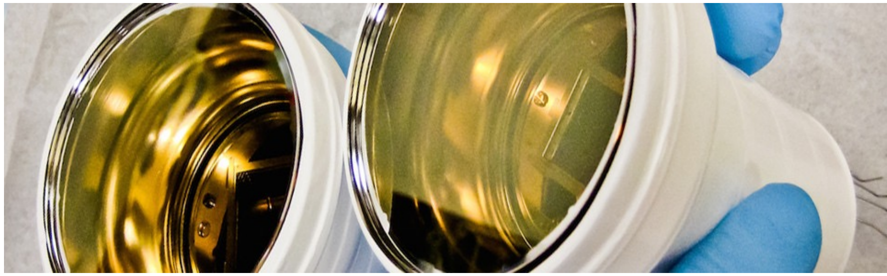
A diagram showing possible dark matter detection methods.

Dark Matter Experiments

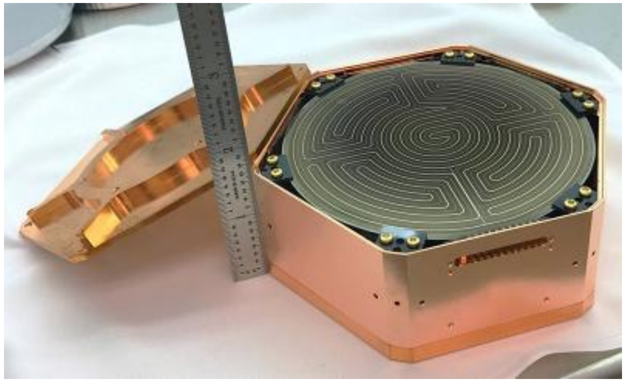
Axion Dark Matter Experiment (ADMX)

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

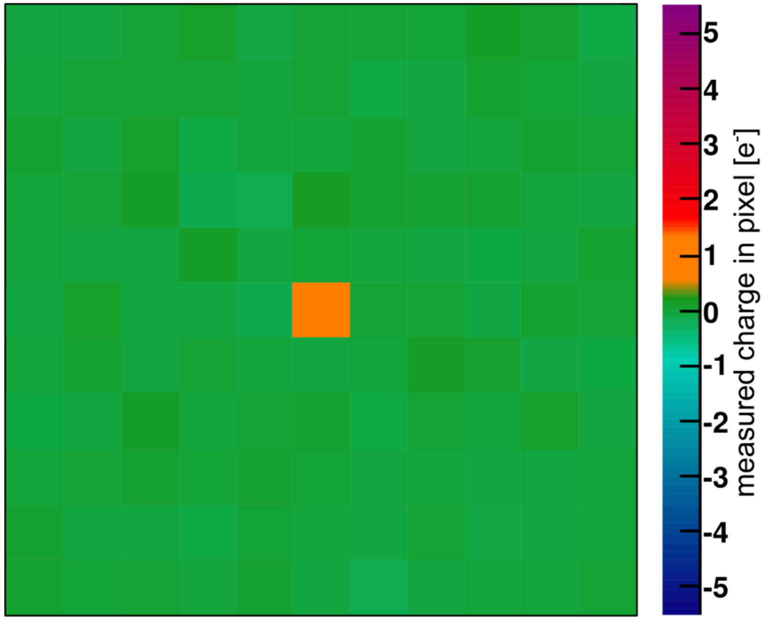
Dark Matter Experiments

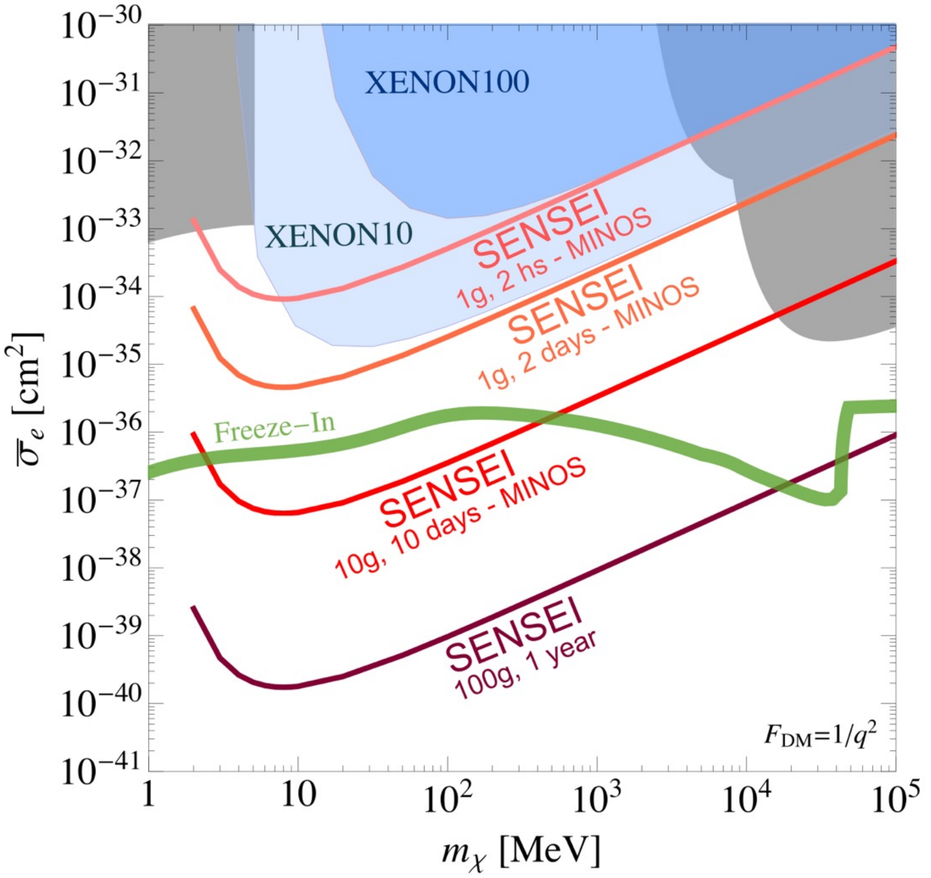
SENSEI Sub-electron-noise skipper-CCD experimental instrument

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





Cosmic Frontier Experiments

Dark Energy Survey (DES)

- One of the world’s largest digital camera (telescope in Chile)
- 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!

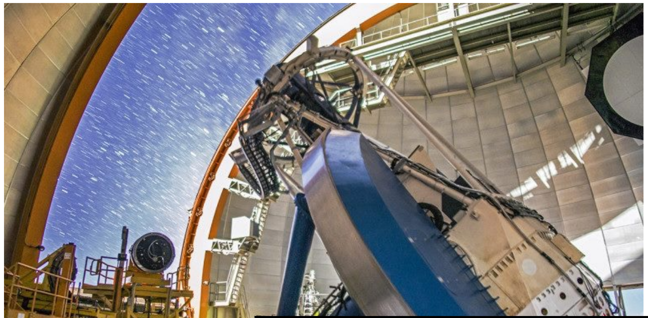
Dark Energy Spectroscopic Instrument (DESI)

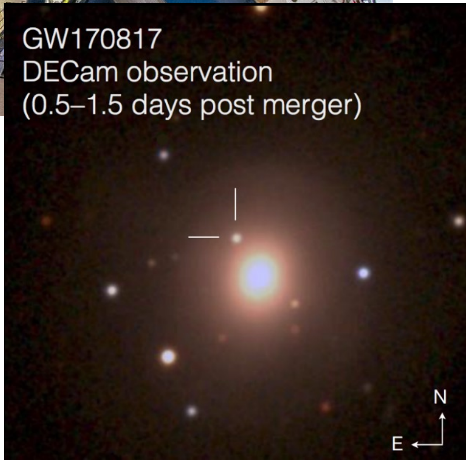
- To obtain the optical spectra of tens of millions of galaxies and quasars and build a 3D map of Universe up to 11B light-years
- Measure impact of DE on Universe expansion

LSST

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

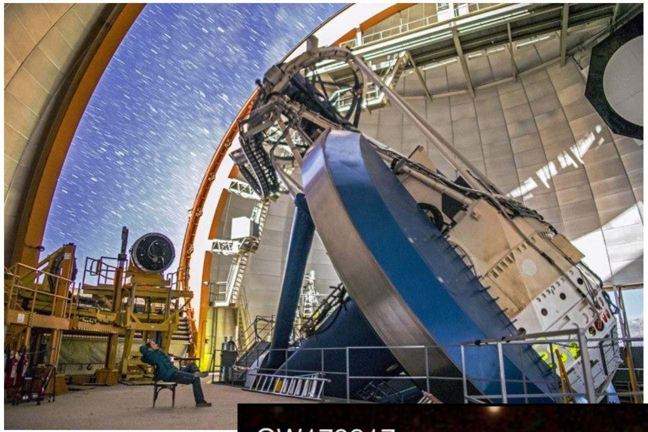
a 10 meter microwave telescope with an array of 16,000 cryogenic transition-edge sensors





GW170817
DECam observation
(0.5–1.5 days post merger)

Cosmic Frontier Experiments



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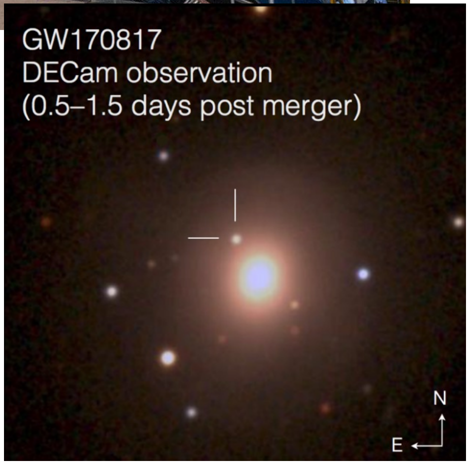
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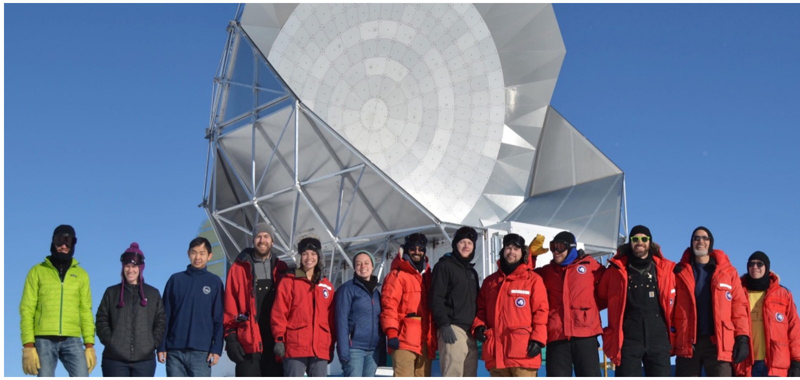
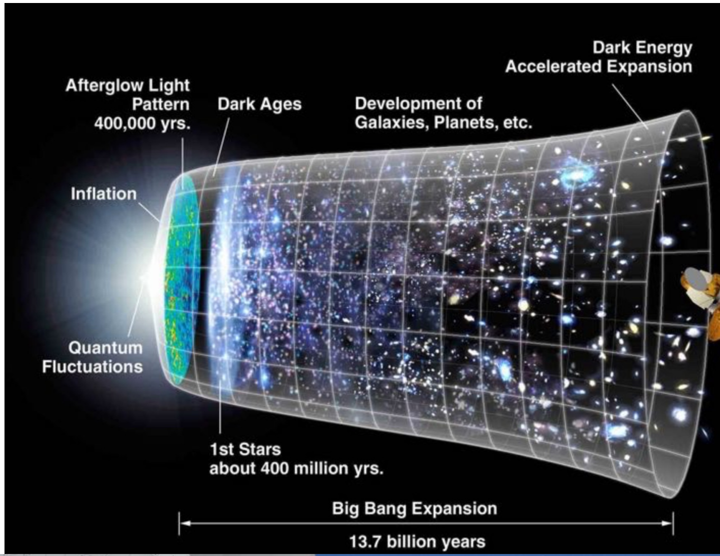
SPT-3G

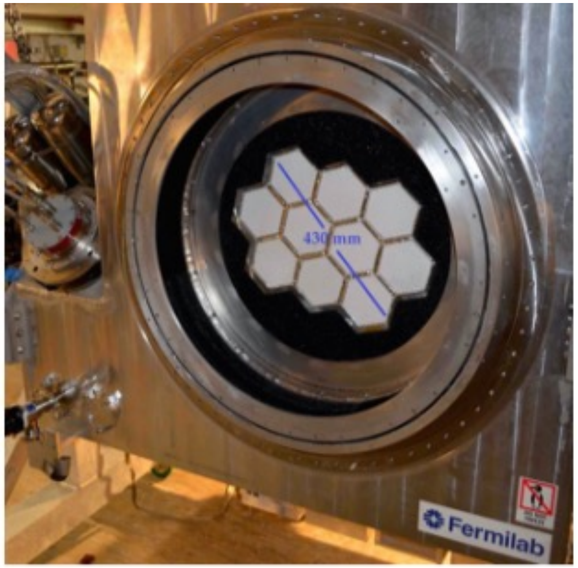
- a 10 meter microwave telescope with an array of 16,000 cryogenic transition-edge sensors

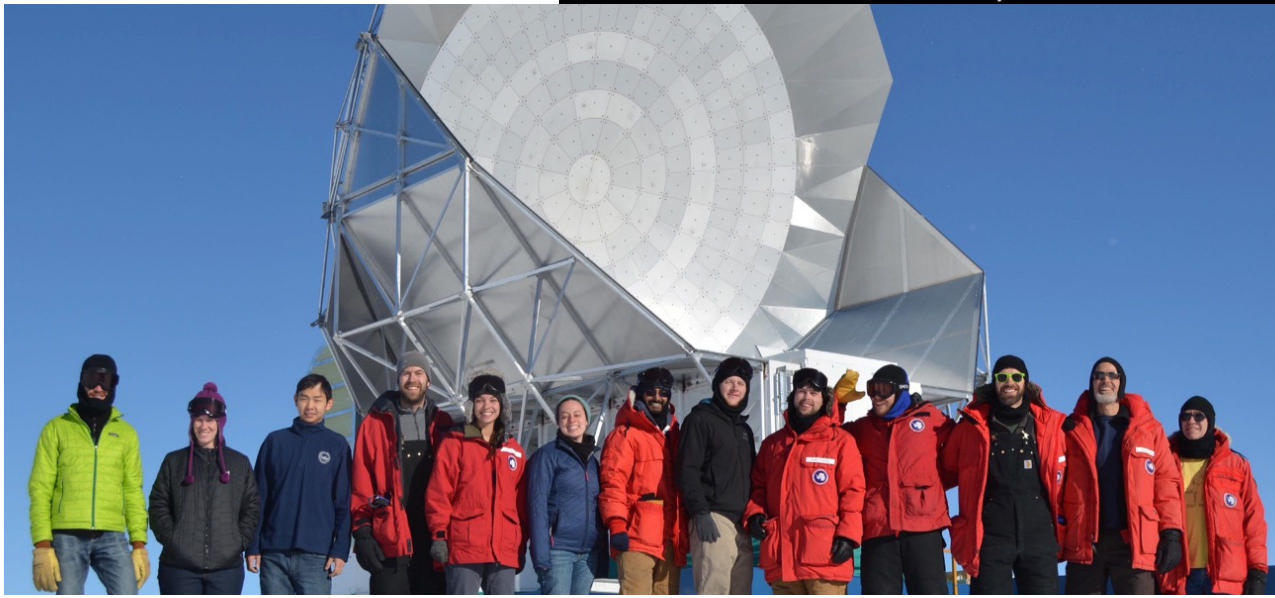


SPT-3G: Looking at the cosmos from the South Pole

- 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

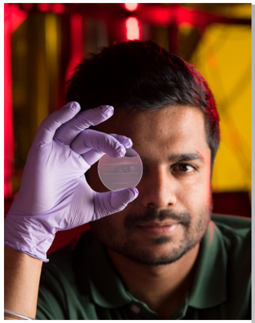


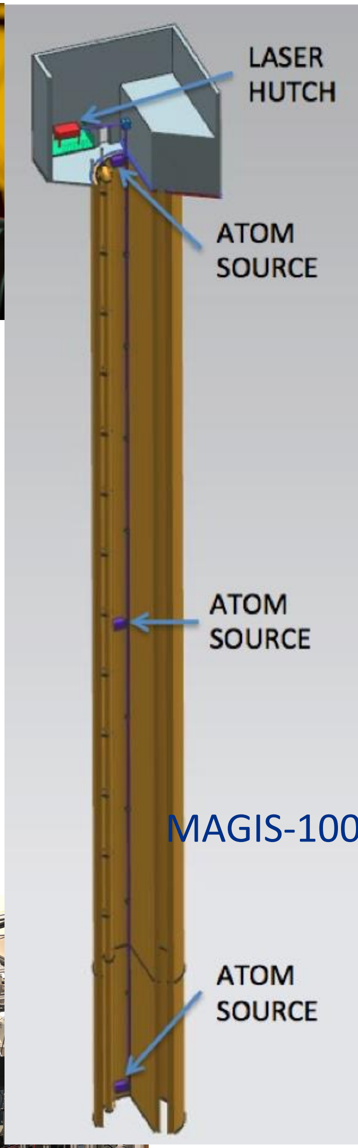


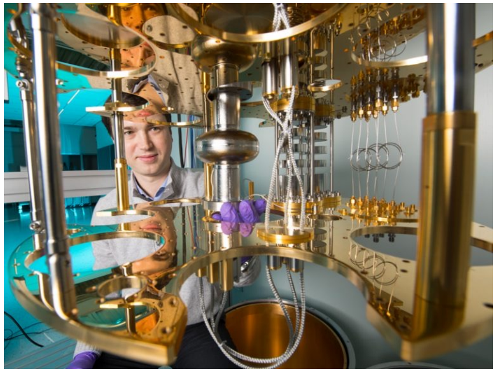


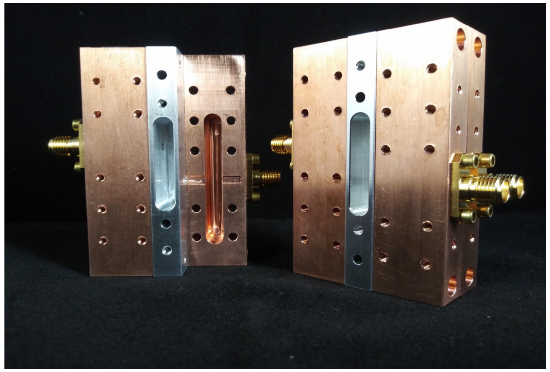
Fermilab quantum program

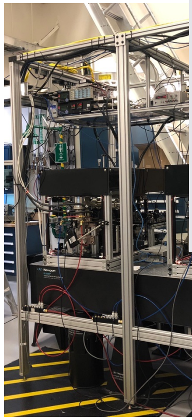
- Fermilab is collaborating with 22 universities and other labs on quantum science and technology
- The very challenging science goals of HEP, e.g. laboratory detection of dark matter, are now driving advances in quantum technologies; these advances will eventually have broad impact beyond HEP
- Fermilab 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



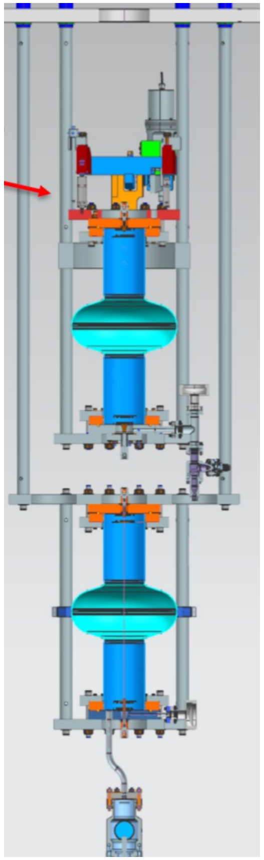








Fermilab Dark Photon Experiment



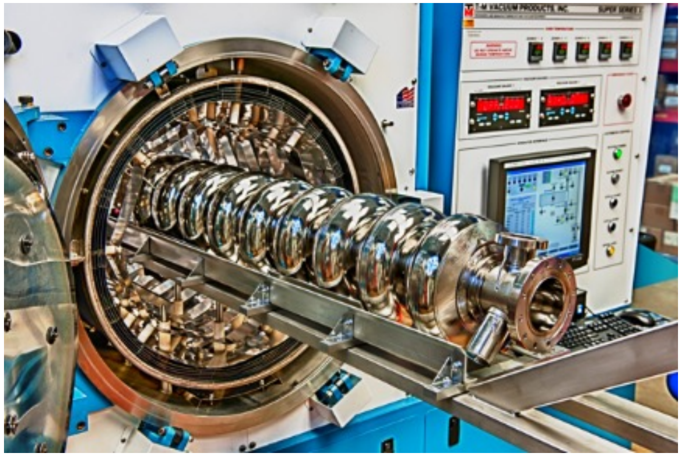
Tunable powered “Emitter” cavity and quiet “Receiver” cavity

Dark SRF experimental apparatus ready for testing

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

Fermilab's pioneering accelerator technology

Assembly and testing of cryomodules for the LCLS-II XFEL accelerator



Fermilab Accelerator Science and Technology Research

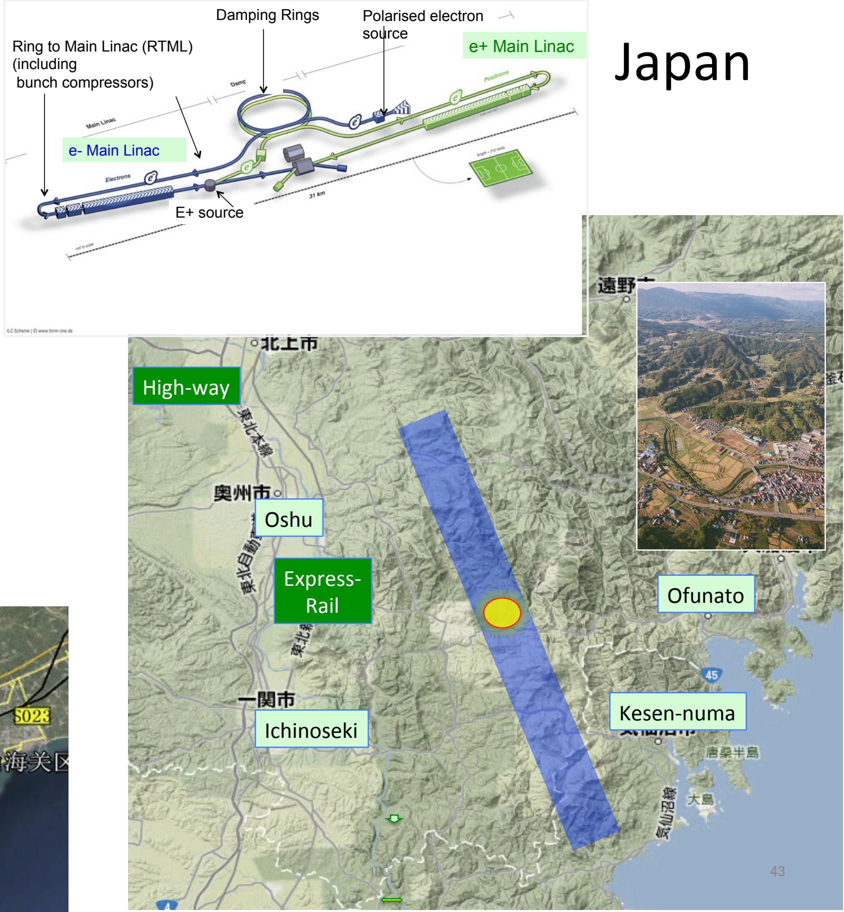
- Particle beam research facility based on superconducting RF technology
- A test bed for cutting edge accelerator R&D
  - High intensity beams via integrable optics (IOTA)
  - Novel radiation sources

Future Accelerators/Colliders

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

Future Colliders under consideration abroad in Europe/CERN/Asia

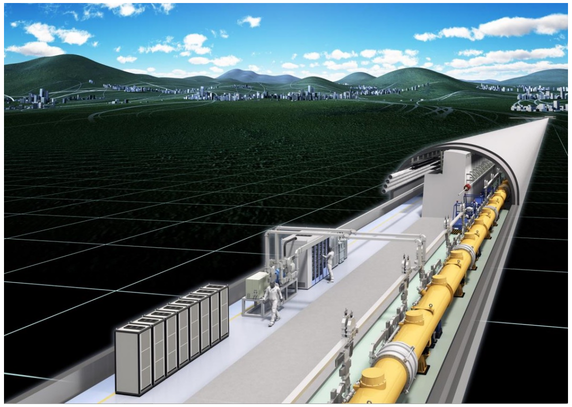
Japan



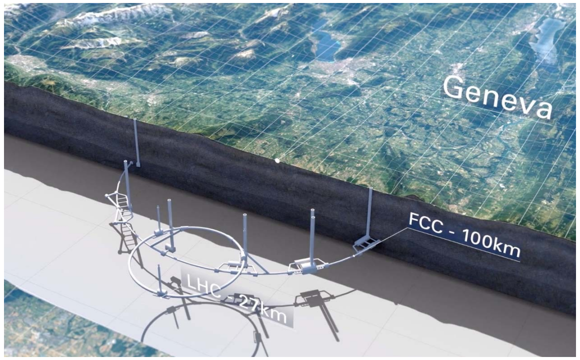
CepC China

Global Collider Projects under Study

- The International Linear Collider (ILC)
  - Fermilab was the headquarters for developing the technical design of the ILC
  - Fermilab is the pioneer in the critical Superconducting RF (SRF) technology
  - **ILC being considered for construction in Japan**



- Future Circular Colliders (FCC-ee/hh)
  - ~100 km in circumference
  - CERN performing feasibility studies; results and conceptual design report by ~2026
  - To be built around **CERN/Geneva**
  - Similar facilities being considered **in China**

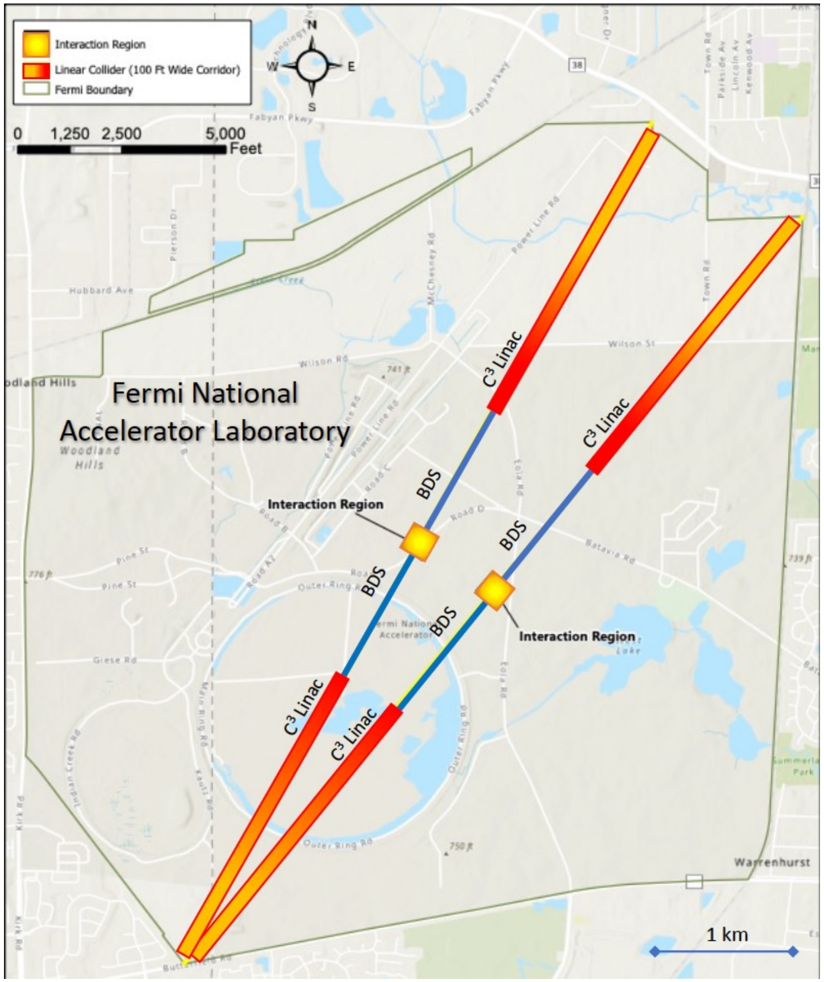


- Muon Collider
  - Studies and R&D performed in the past two decades in the US, led by Fermilab
  - Currently being studied by the **International Muon collider Collaboration at CERN** and Snowmass Muon Collider Forum for the US

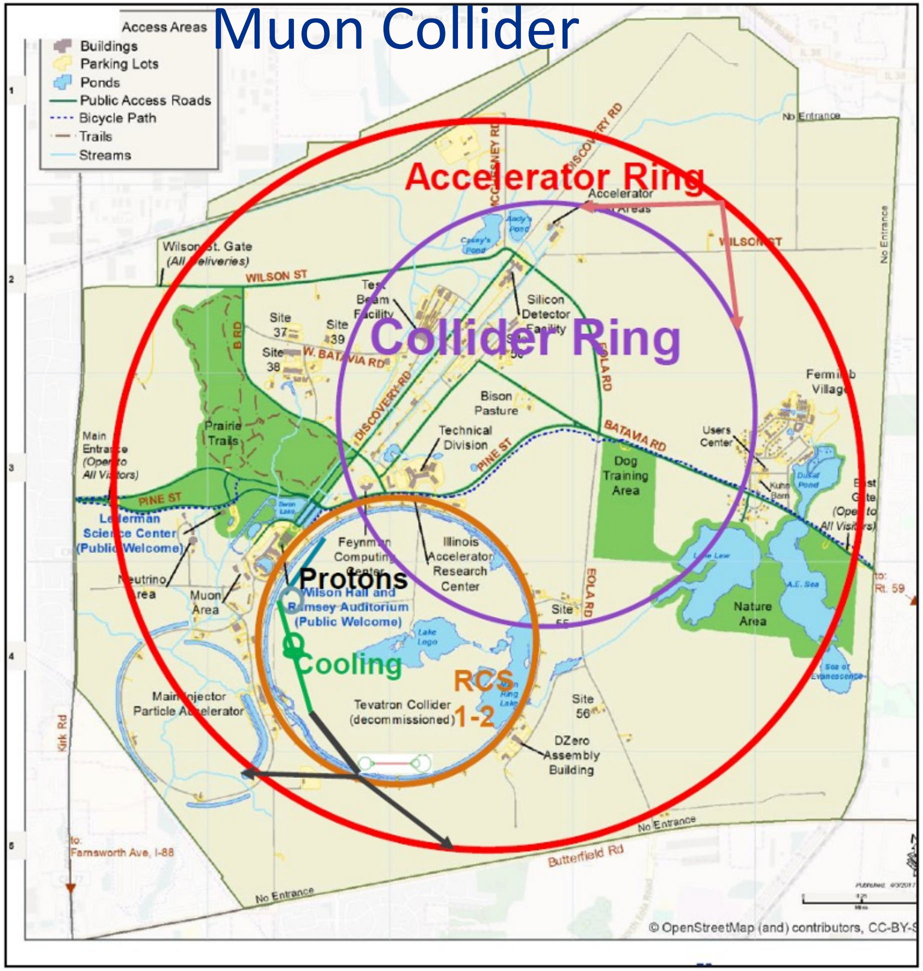
What about the US?

Future Collider options are being explored as part of the US HEP community study

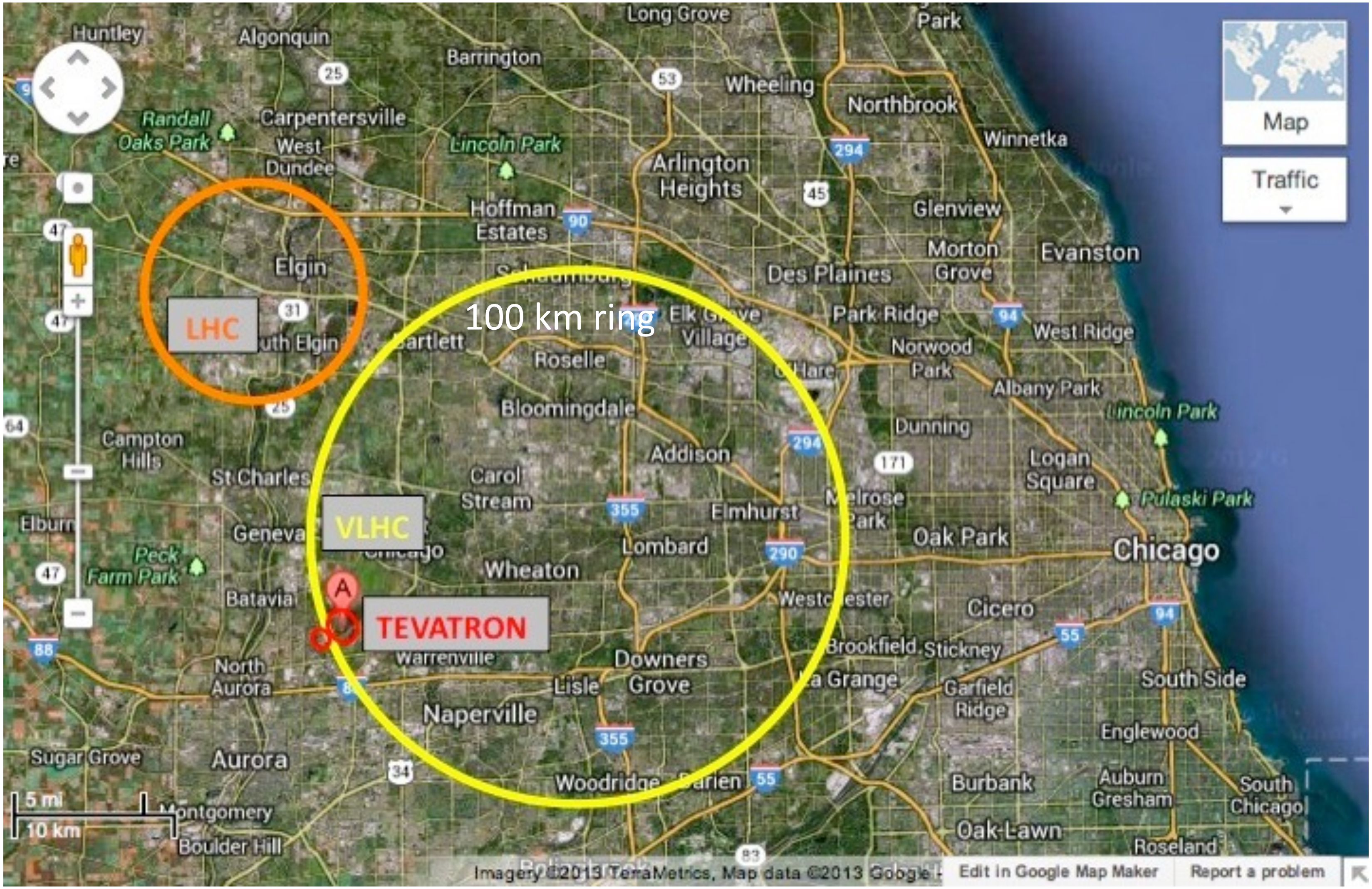
Linear Collider Higgs Factory



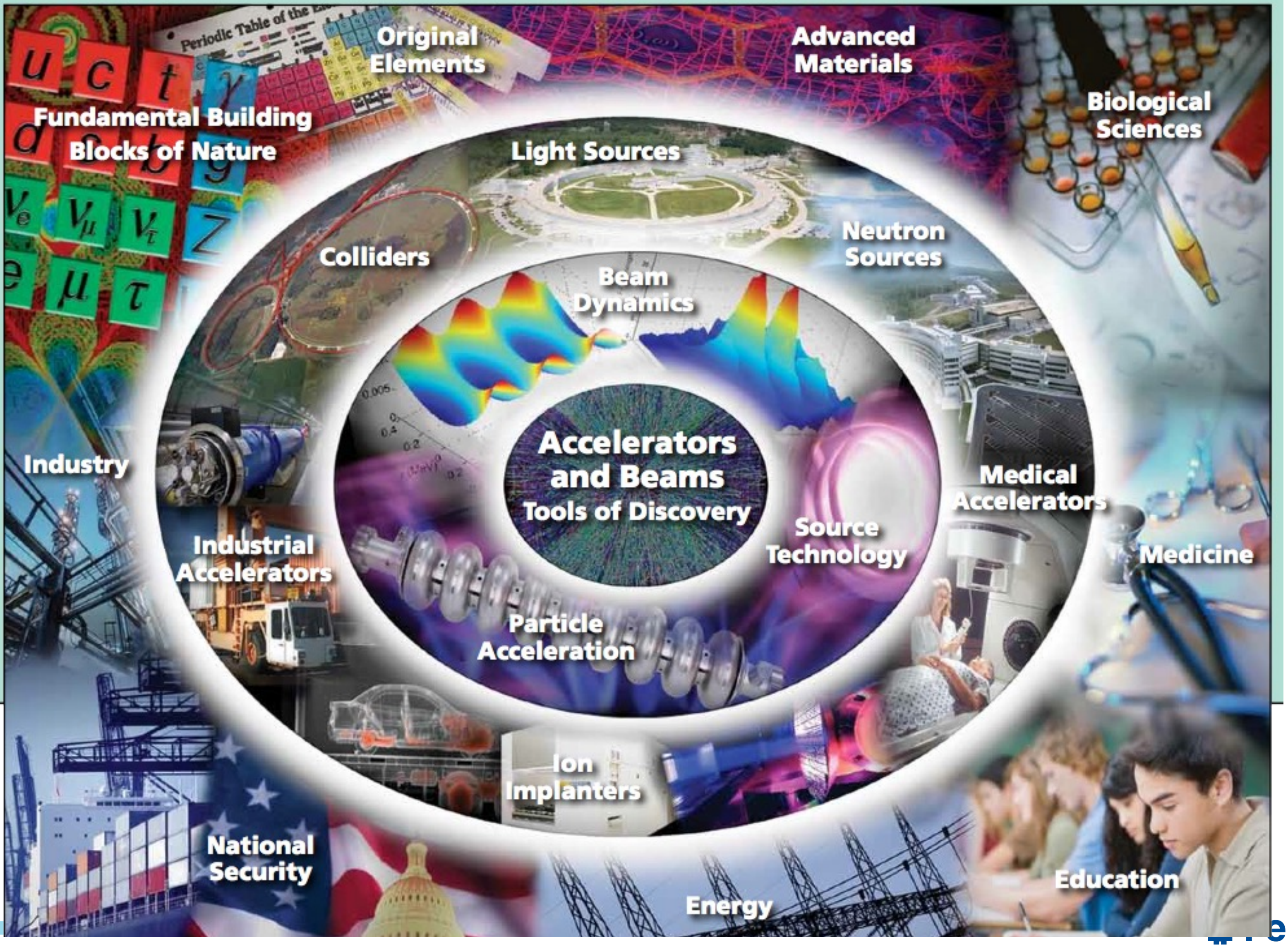
Muon Collider



A Very Large Hadron Collider in Chicagoland?

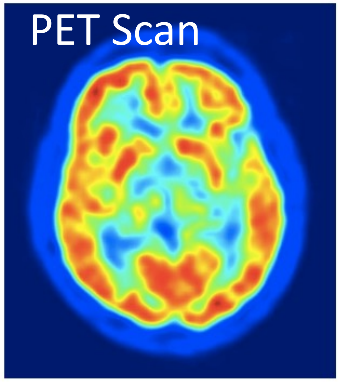


Applications of Accelerators



COURTESY OAK RIDGE NATIONAL LABORATORY.

Applications of Accelerators


PET Scan


MRI

- 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, ..

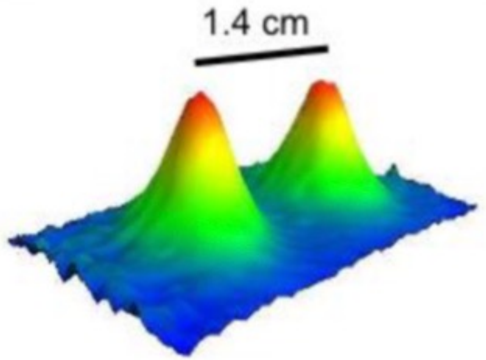



Welcome to Fermilab!
Good luck with your summer research!

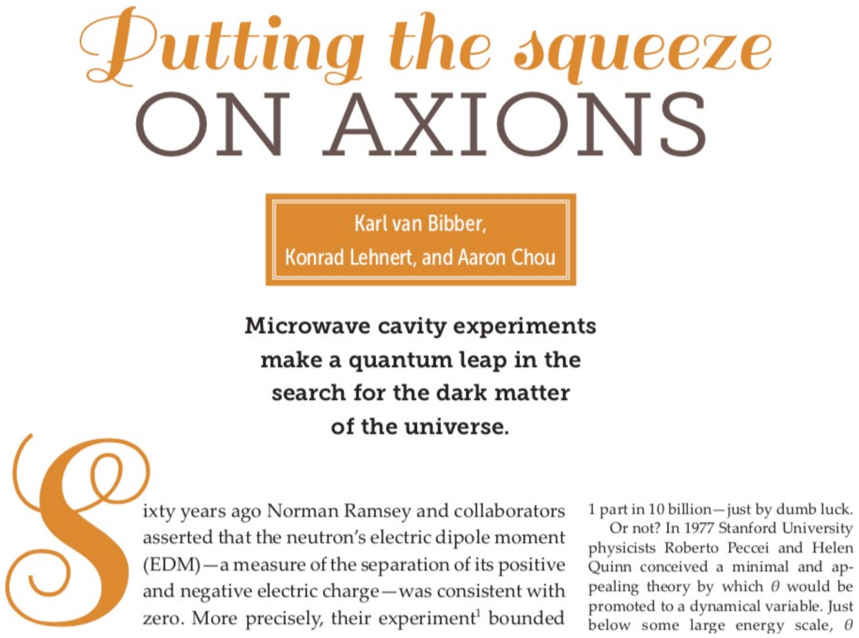
Extra Slides

Much more we could not talk about today!

MAGIS-100 a quantum measuring device enabled by quantum coherence over distances of several meters and times of several seconds



Data from Stanford setup showed single atoms in quantum superposition at world-record separations up to 54 cm



Putting the squeeze
ON AXIONS

Karl van Bibber,
Konrad Lehnert, and Aaron Chou

Microwave cavity experiments make a quantum leap in the search for the dark matter of the universe.

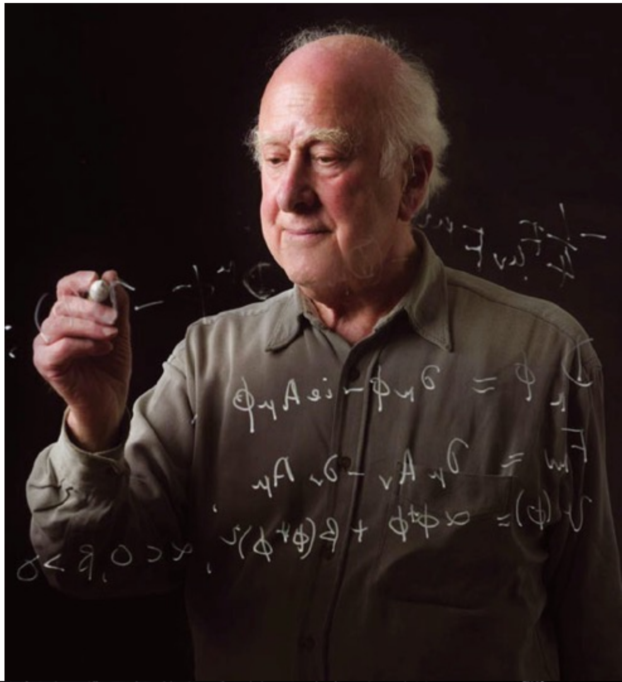
Sixty years ago Norman Ramsey and collaborators asserted that the neutron's electric dipole moment (EDM)—a measure of the separation of its positive and negative electric charge—was consistent with zero. More precisely, their experiment[1] bounded 1 part in 10 billion—just by dumb luck.

Or not? In 1977 Stanford University physicists Roberto Peccei and Helen Quinn conceived a minimal and appealing theory by which θ would be promoted to a dynamical variable. Just below some large energy scale, θ

- Axion dark matter searches are already limited by quantum noise
- new quantum sensing techniques are needed to make further progress towards higher mass axions.

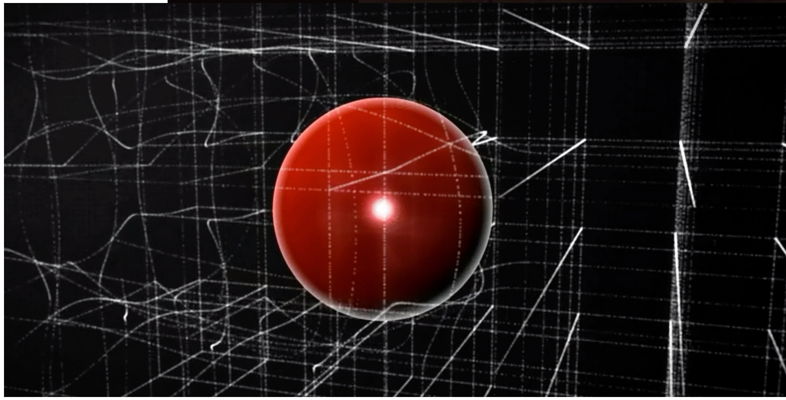
What does the Standard Model explain?

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 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

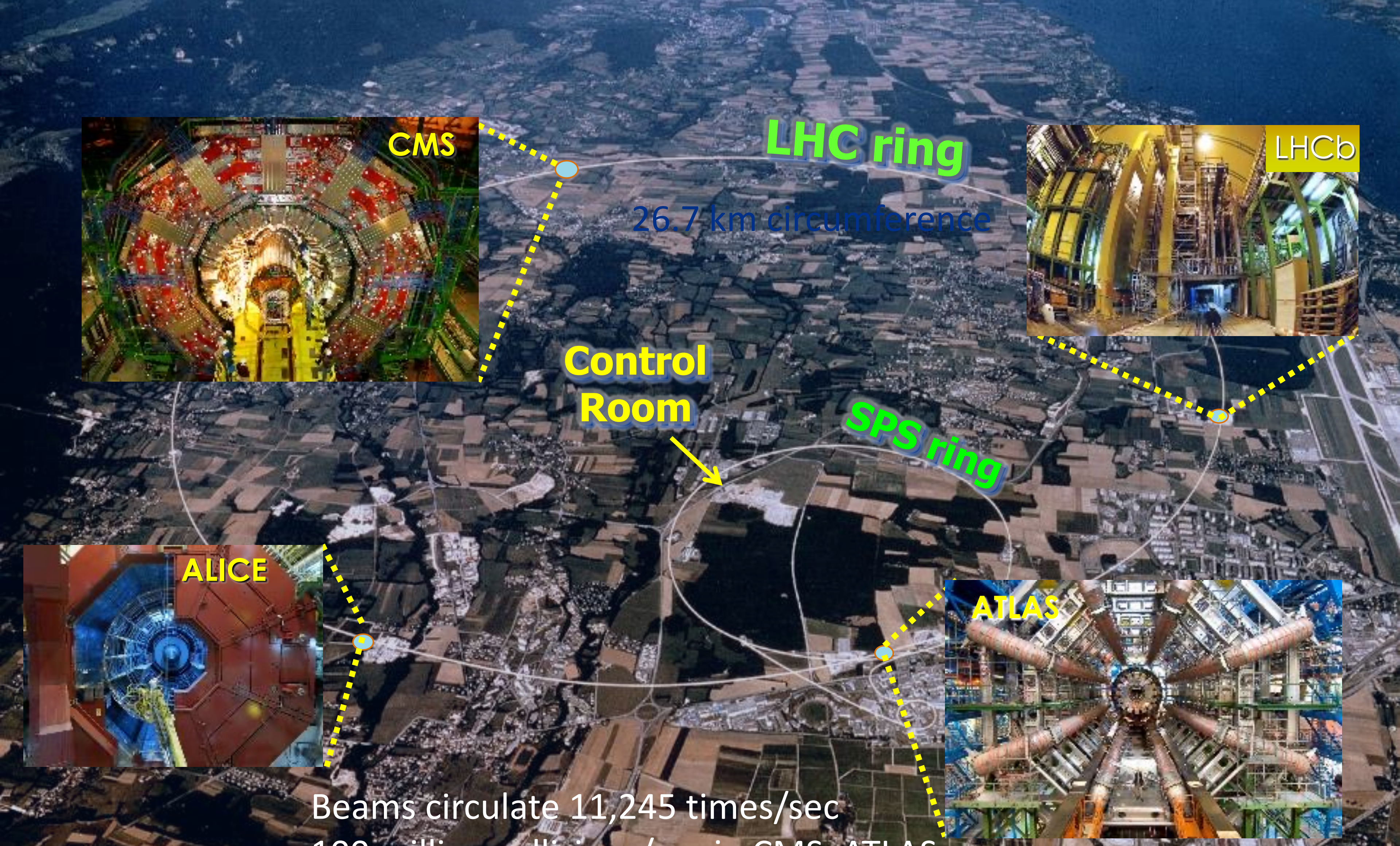
What are the quantum properties of gravity, space, and time

And more …

Fermilab's mission is to answer

these fundamental questions

The Large Hadron Collider



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