Introduction to the Energy Frontier At Fermilab: Past, Present & Future

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Fermilab

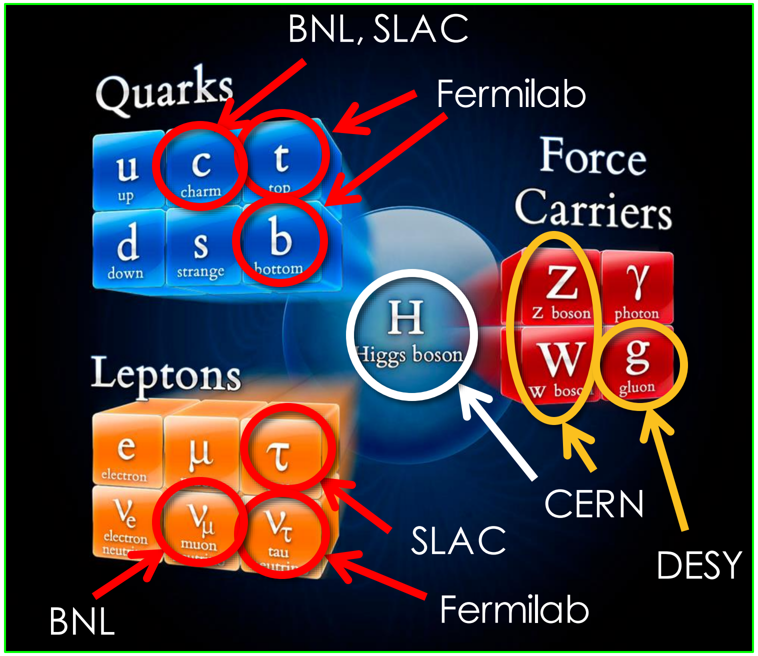
53rd Annual Users' Meeting
August 10-13, 2020

The Energy Frontier

- The ambitious goal of understanding Nature at the most fundamental level has driven us to develop successively more powerful particle accelerators!
- High energy particle beams from accelerators allow us to
  - Probe structure of matter and study physics at very short distance scales.
  - Create new & exotic particles that existed in the early universe by converting energy into matter
- Higher the energy, greater the reach, as to how deep we can look, how far back in the universe's history can we see, and how massive or exotic the particles we can create!
- Each generation of high energy experiments have also been grander in scale than previous – more powerful, more complex, and versatile.
- The lure and the power of the frontier has been exalting!

The Standard Model

- The emergence of particle accelerators as tools to understand the mysteries of matter and energy also accelerated theoretical development.
- Over the second half of the last century, the Standard Model (SM) of Particle Physics, a quantum field theory that describes fundamental particles and their interactions was developed.

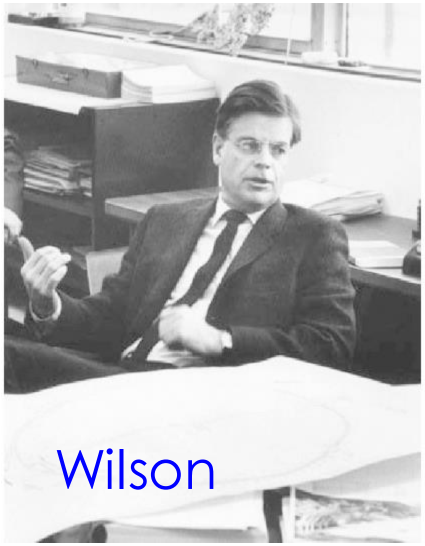


- Fermilab has played a significant role in the establishment of the SM

Our Glorious Past

Creation of Fermilab

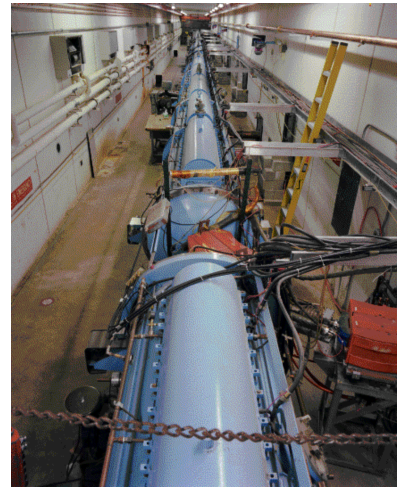
- The National Accelerator Laboratory was created in 1967, to open a new frontier in the exploration of the deepest mysteries of matter and energy.
  - ❖ Desire in the US HEP community for 100-1000 GeV machine (to be at the Energy Frontier)
    - ➢ 1960: 33 GeV Alternating Gradient Synchrotron (AGS) on Long Island, at BNL; 28 GeV Proton Synchrotron (PS) at CERN
  - ❖ April 1963, Ramsey Panel recommends a 200 GeV proton synchrotron
- Robert Wilson was named the first director of the Lab on February 28, 1967.
- The Lab was renamed "Fermilab" in 1974, to honor Enrico Fermi, a quintessential physicist, who had ushered in the Nuclear Age through his seminal experiment on nuclear fission, at the University of Chicago in 1942.



Accelerators built 1968-71

Four Accelerators in Four Years!

Cockroft-Walton
720 keV



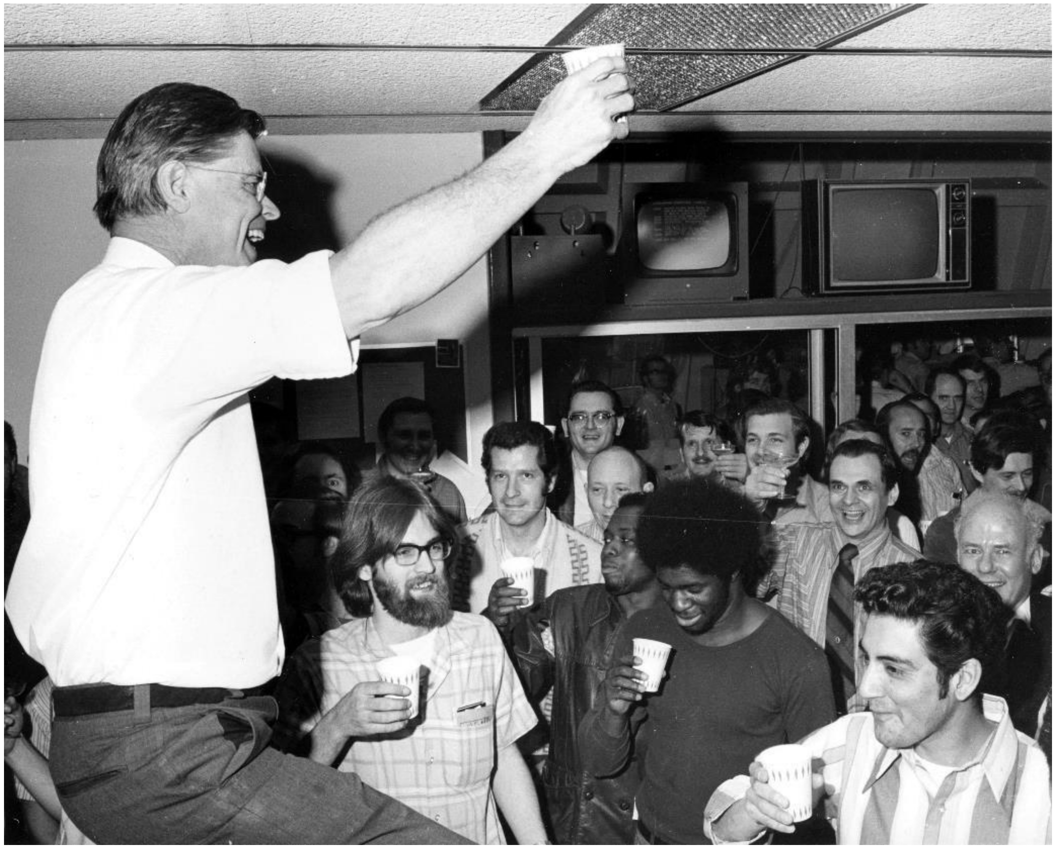
Linac
170 m long
200 MeV

Groundbreaking:
December 1, 1968

Booster 8 GeV
Rapid-cycling synchrotron
0.5 km circumference

Main Ring Accelerator
6.4 km circumference
200 – 400 GeV

Accelerator Reaches Design Energy and beyond!!!



Accelerator at 200 GeV March 1, 1972

400 GeV by Dec. 1972

5 years from start of the brand new Lab

Accelerator project completed
- Ahead of time!
- $10M below budget!
- Double the design energy!

Wilson receives National Medal of Science 1973

Dr. Robert R. Wilson receiving National Medal of Science from President Nixon on Wednesday, October 10, 1973 at The White House. Citation read: '...for his unusual ingenuity in designing experiments to explore the fundamental particles of matter and in designing and constructing the machines to produce the particles, culminating in the world's most powerful particle accelerator.'

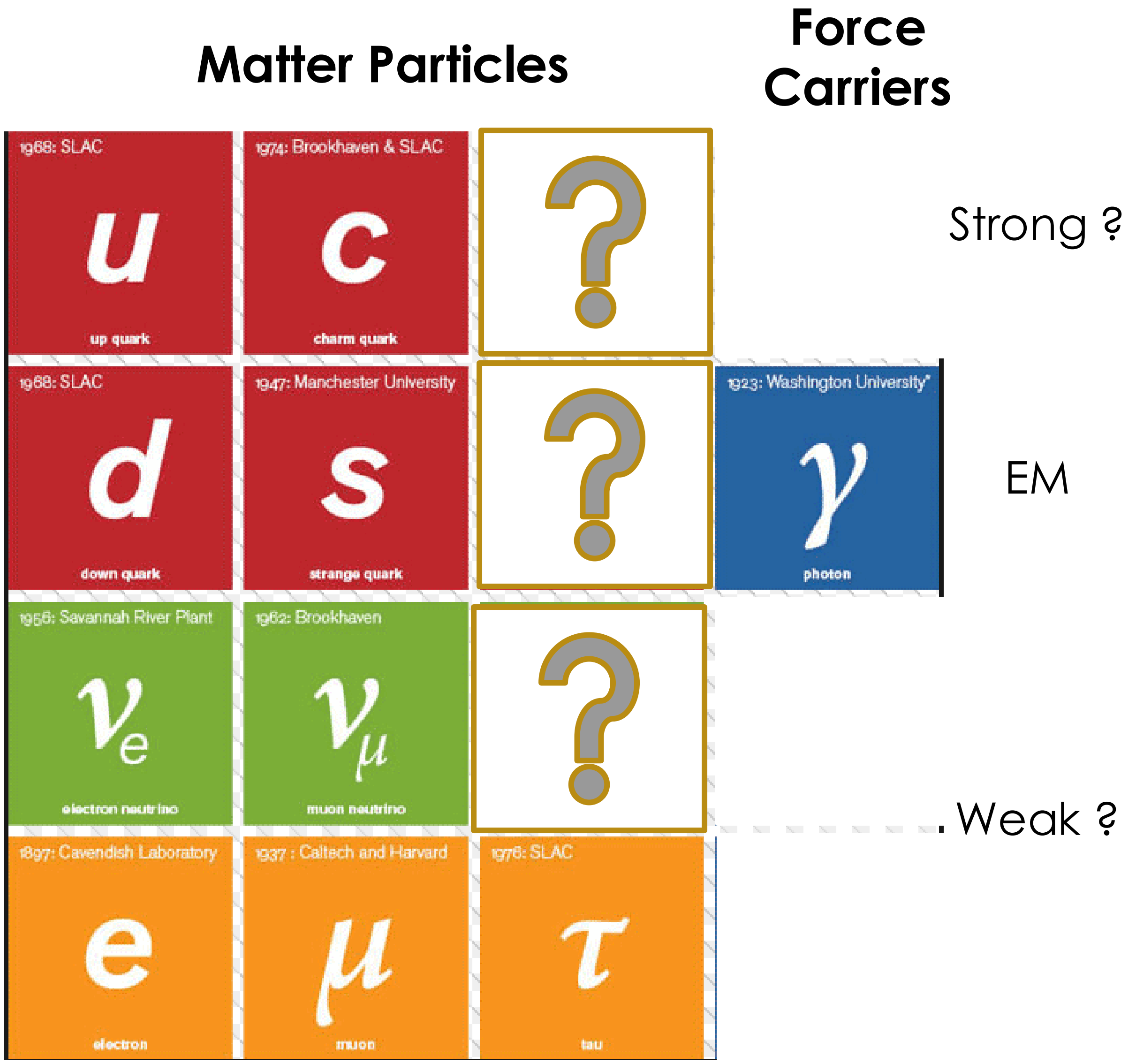
CLOSE ✕

Enrico Fermi Award in 1984; Served as APS President 1985

Initial Fixed Target Experiments

- A diverse suite of experiments
  - K decays and CP violation
  - The Hyperon program (baryon magnetic moments)
  - General explorations of strong interaction
    - Multi-particle production
    - 30” bubble chamber to study hadron-nuclear interactions
  - A broad Neutrino program
    - 15 ft Bubble Chamber to study in detail low energy ν-interactions
    - Two other large detectors studying deep inelastic ν-scattering and study of structure functions.

Standard Model circa 1975



PURSUING BEAUTY AND TRUTH

PHYSICS AT THE ENERGY FRONTIER

E-288 Proposal (Lederman 1974)

NAL PROPOSAL # 288

Scientific Spokesman:

L. M. Lederman
Physics Department
Columbia University
New York, New York 10027

FTS/Off-net: 212 - 460-0100
280-1754

A Study of Di-Lepton Production in Proton Collisions at NAL

J. A. Appel, M. H. Bourquin, D. C. Hom, L. M. Lederman,
J. P. Repellin, H. D. Snyder, J. K. Yoh (Columbia
University); B. C. Brown, P. Limon, T. Yamanouchi (NAL).

(Formerly #70 Phase III)

February 1974

AARS581

Search for structure in the above spectrum, publish these and become famous

A Study of Di-Lepton Production in Proton Collisions at NAL

1. Observe and measure the spectrum of virtual photons emitted in p-nucleon collisions via the mass distribution of e^+e^- pairs: $p + p \rightarrow e^+ e^- +$ anything. (1)
Study characteristics, e.g. parity violation, $p_\perp$ behavior.

2. Search for structures in the above spectrum, publish these and become famous, e.g. $W°$, $B°$.

3. Qualitatively study the mass spectrum of hadron pairs ($\pi\pi$, πp, etc). This is an interesting background for (1). It uses a crude hadron calorimeter, also required for hadron rejection in (1).

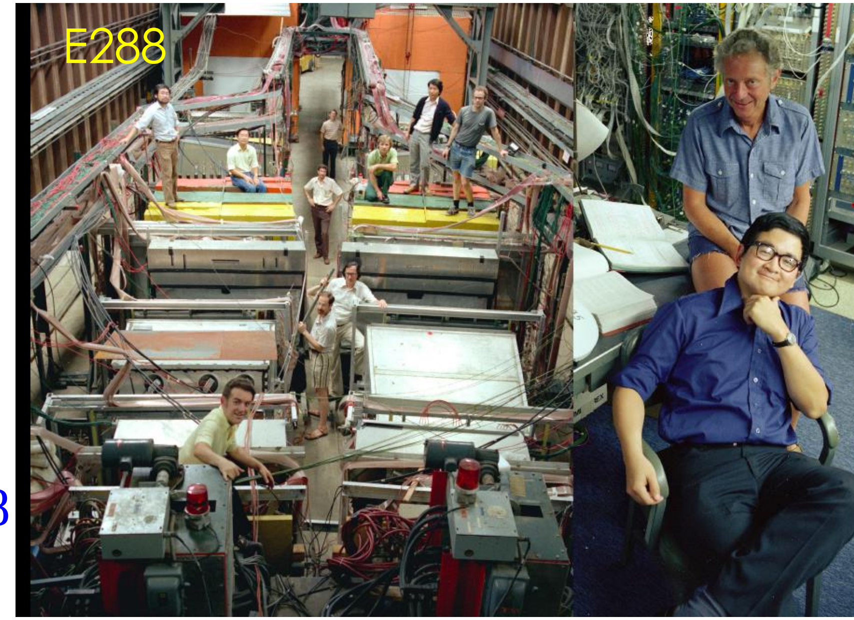
4. Check μe universality by looking, in the same arrangement but with the addition of a pion filter, at $\mu^+\mu^-$ pairs.

5. Extend the Experiment #70 study of single leptons in the double arm arrangement, i.e. $W^\pm$ etc. Publish these and become famous.

6. Look at $\pi°\pi°$ pairs by double conversion of $\pi°- \gamma$'s in thin aluminum radiators. This data comes free since one adds 0.1 radiation length to enable an extrapolation to zero target thickness in (1).

Discovery of the Bottom Quark

- ◆ Lederman and his group discover the b-quark in 1977
  - ❖ There *is* a third generation of quarks!
  - ❖ A top quark and tau-neutrino are required to complete the quark and lepton doublets.
- ◆ (Leon Lederman won a Nobel prize in 1988 for muon-neutrino discovery (BNL Expt.))



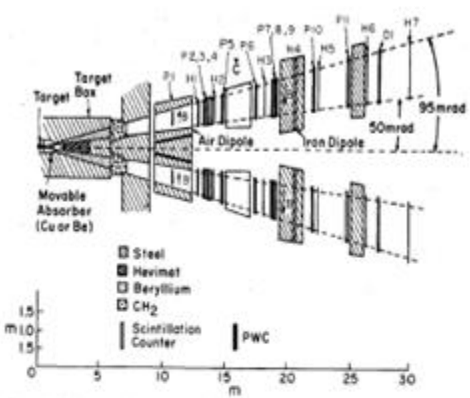


Figure 11a. Plan view of the apparatus. Each spectrometer arm includes 11 PWC's P1-P11, 7 scintillating counter hodoscopes H1-H7, a drift chamber D1, and a gas-filled threshold Cerenkov counter C.

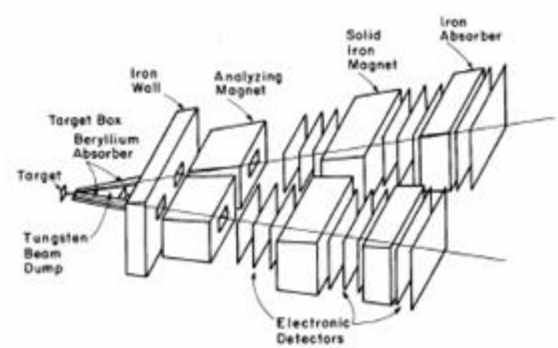


Figure 11b. Schematic sketch of Fermilab dimuon experiment which led to the discovery of the Upsilon particle.

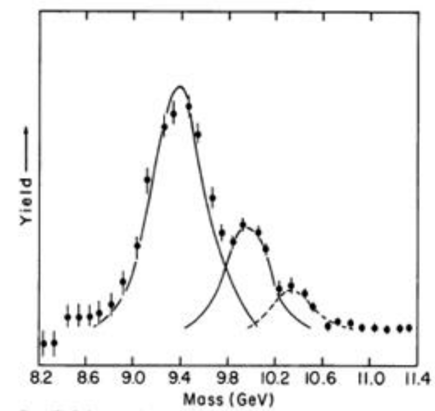
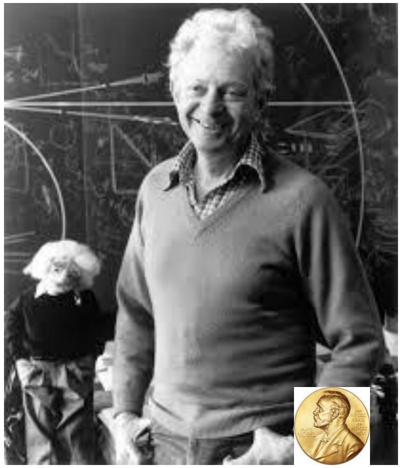


Figure 12b. Peaks with continuum subtracted.

The Tevatron

- ◆Even as the Main Ring was being built, Wilson had plans for a superconducting synchrotron in the same tunnel.
- ◆In 1978, decision was made to build the Tevatron to ramp the energy to 1 Trillion Electron Volts (TeV).
  - ❖Superconducting magnet technology was developed and industrialized (774 dipoles and 240 quads)
  - ❖The "Energy Doubler" (Tevatron) completed in 1983.
  - ❖Total cost of the Tevatron I Project: $137 M
- ◆Feb. 16, 1984: First beams at 800 GeV



Leon Lederman, director from 1978-1989, executed the Energy Doubler project

Helen Edwards signs installation of the last Tevatron magnet

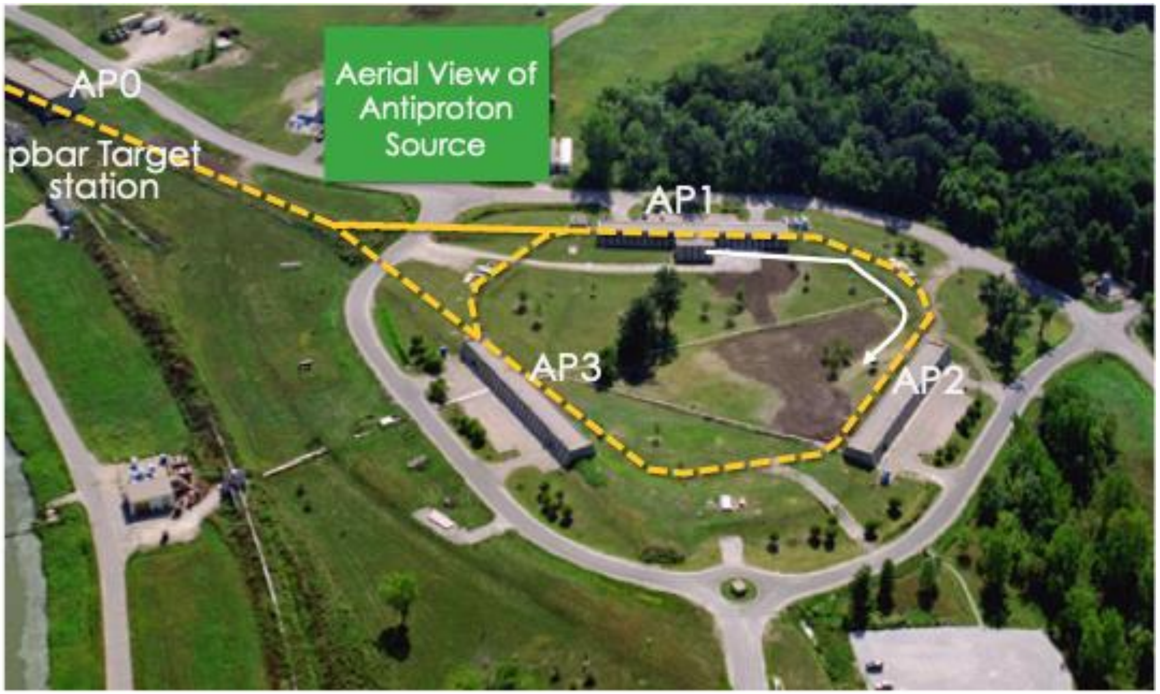
Main Ring (top), Tevatron (bottom)

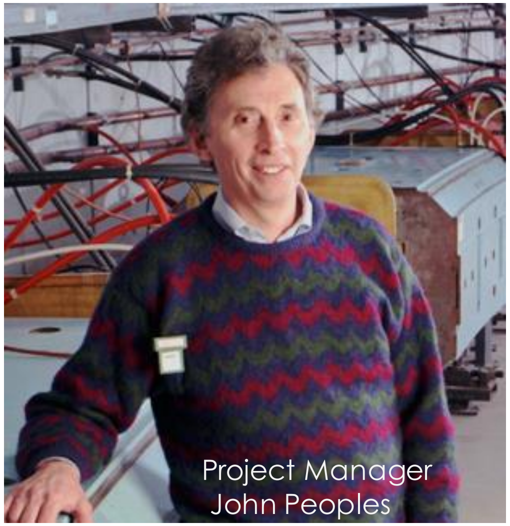
Lundy, Orr, Edwards, Tollestrup, Receving National Medal of Technology (1989)

The Antiproton Source

- Antiproton Source: Initiated in 1981 and completed in 1985.
- Three components
  - Pbar Target station
  - Debuncher Ring (8 GeV synchrotron)
  - Accumulator Ring (8 GeV synchrotron)

- Accumulator Ring (AR) used stochastic cooling technique invented by Simon van der Meer at CERN in 1972.
- Stochastic cooling demonstrated at CERN ISR ($\sqrt{s}$=62 GeV) ; also used in pbar cooling for SPS ppbar collider program (UA1/UA2).

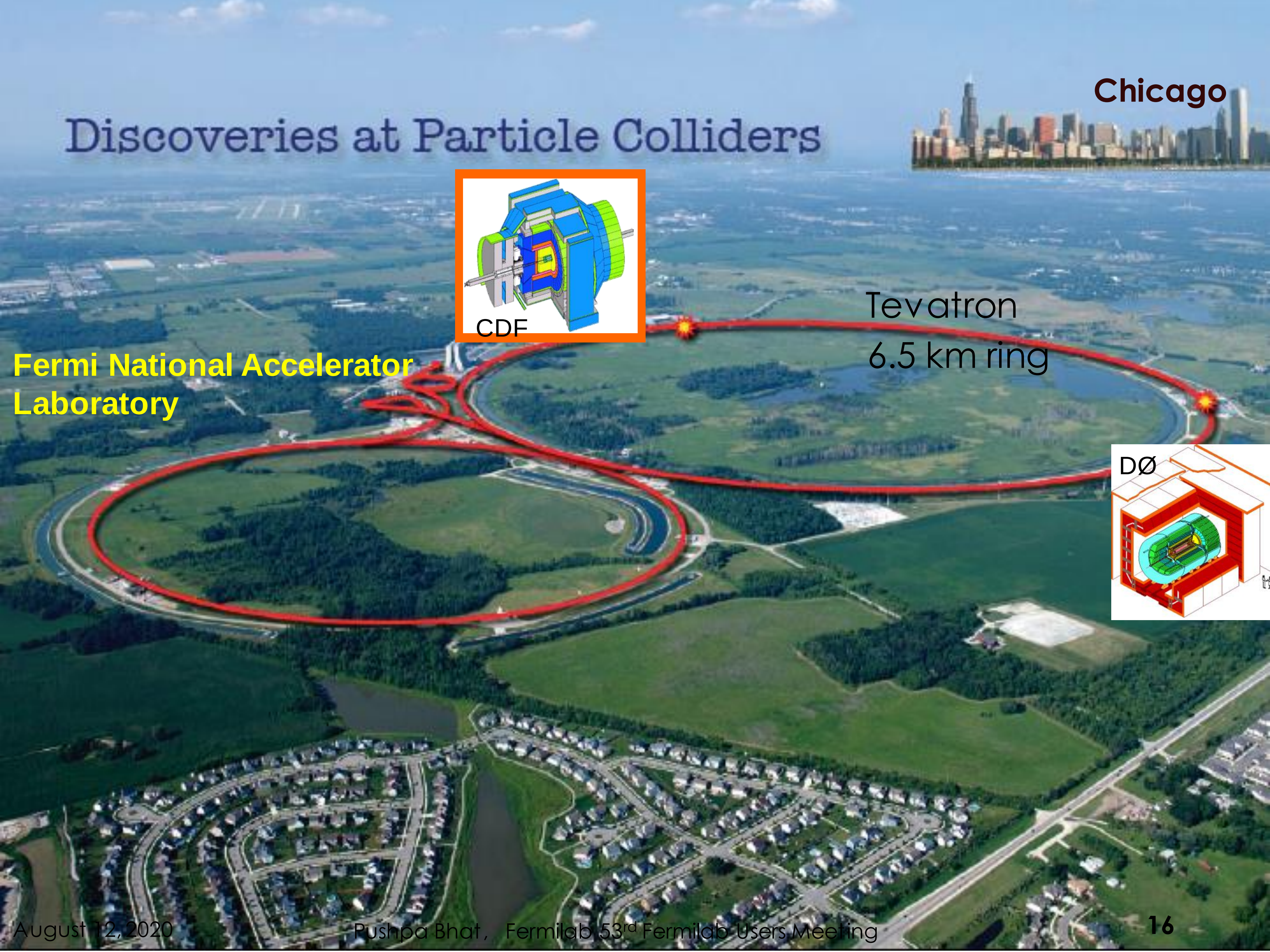




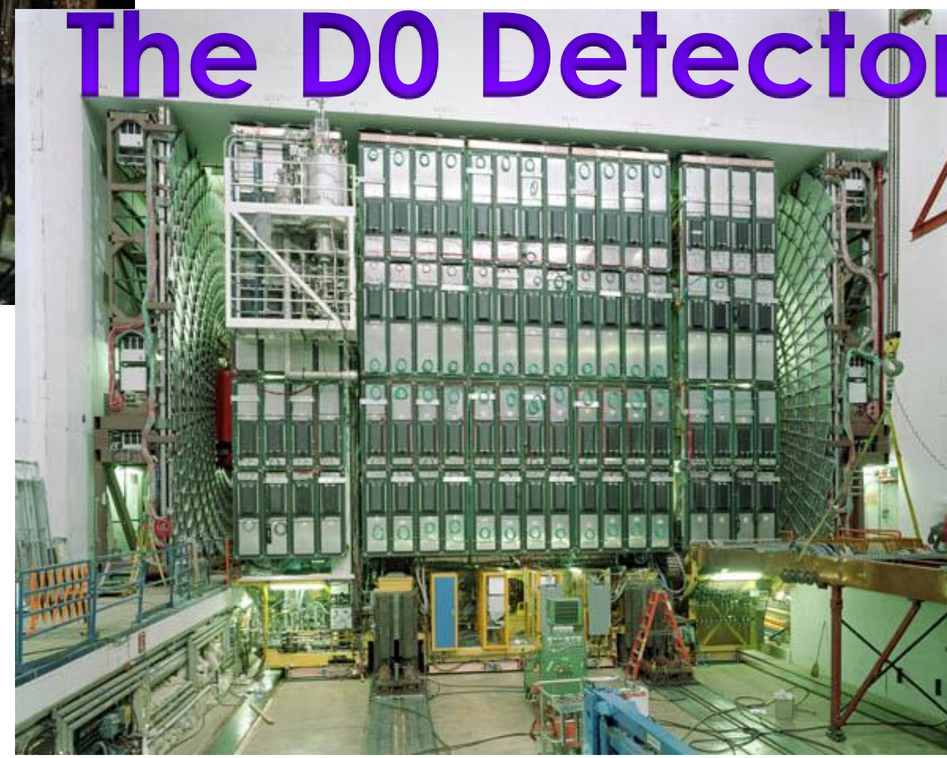
The Top Quark must exist!

Note: Silver Jubilee special in this session at 9:30 AM!

Discoveries at Particle Colliders



Detectors emphasizing different technologies and strengths



- ◆1st collisions @1.6 TeV (at CDF) Oct. 13, 1985; 1.8 TeV Nov. 30, 1986.
- ◆ First physics results from CDF in 1988
- ◆E-735 (C0) took data from 1987-1989
- ◆1992: DØ joins CDF for the historic collider Run 1.

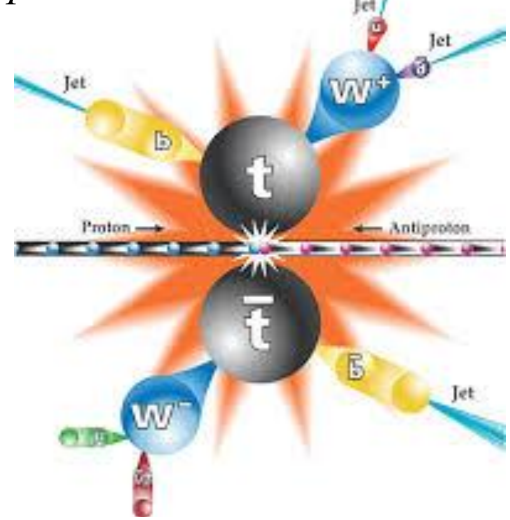
The Top Quark

18 years after The b-quark discovery

- ◆After the b-quark discovery, the hunt for the top quark had gone on at SLAC, DESY and then CERN.
- ◆The top quark turned out to be too heavy for those machines.
- ◆Healthy competition between CDF and D0.

Top-antitop pair production

$$p\bar{p} \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$$



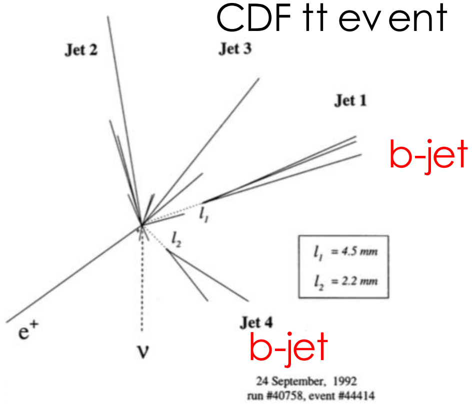
Very heavy (~173 GeV)

Extremely short-lived!

Lifetime ~ 10^{-25} s!

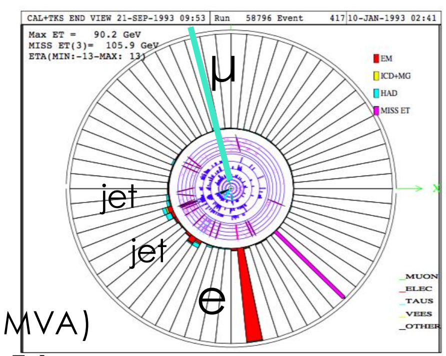
Early Candidate Events

CDF tt event



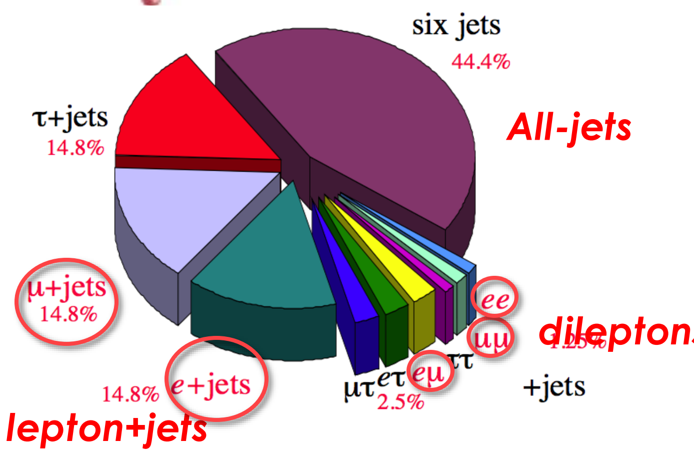
m_t = 170±10 GeV

D0 tt event



S/B (from MVA)
= 10 w.r.t. Z→ττ
= 18 w.r.t. WW
P. B. DPF '94

m_t = 163±37 GeV
(Prosper)

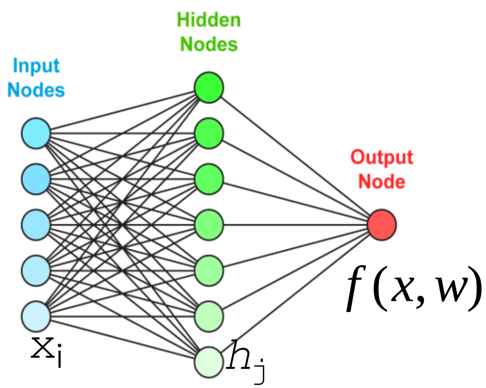


Top Quark Discovery March 2, 1995

Revolutions in Data Analysis

◆Multivariate Analysis Methods, Machine learning

- ❖There was a renaissance in neural networks (NN) in the late 1980s when effective algorithms for training artificial NN was rediscovered.
- ❖CDF had the advantage of silicon vertex detectors to tag b-jets better; CDF eff: ~53%, D0:20%. DØ benefitted from advanced analysis techniques.
- ❖Use of Neural Networks @DØ, since 1990.



$$f(\mathbf{x},\mathbf{w}) = g(\sum_j w_j h_j + \theta) = p(s\,|\,\mathbf{x})$$

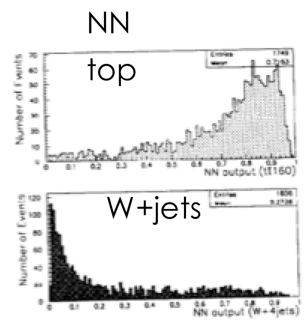
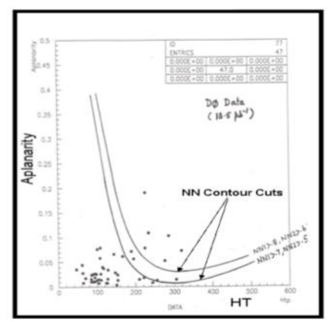
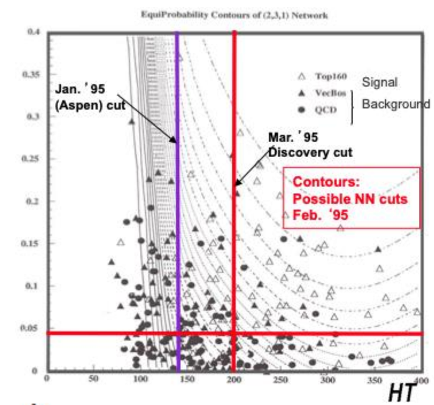
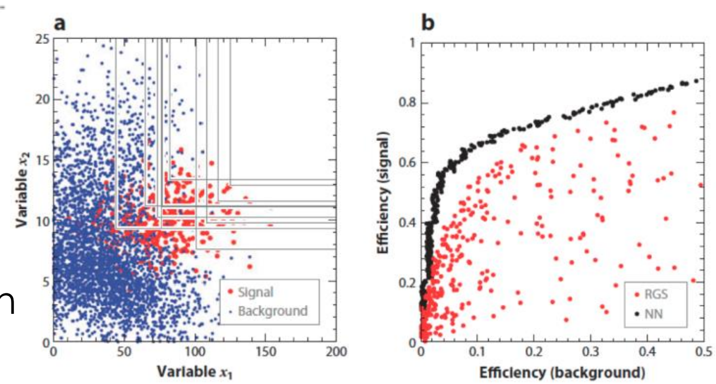


Fig. 4. Distributions of output from network-1 trained on $t\bar{t}160$ and W + jets events





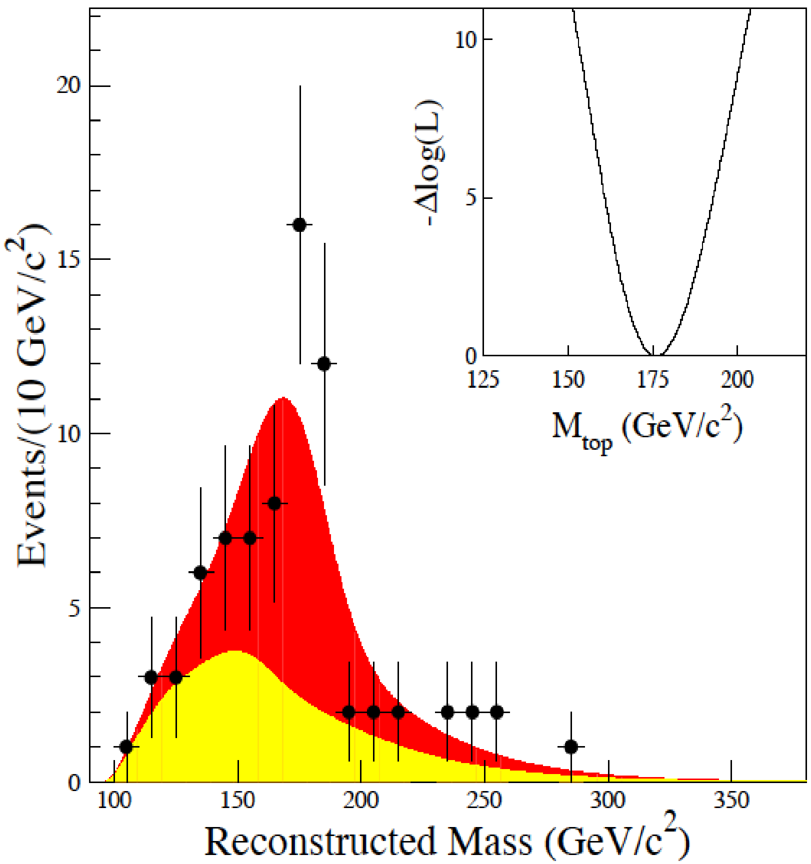
Random Grid Search
For cur optimization



Precision Measurements of the Top quark mass

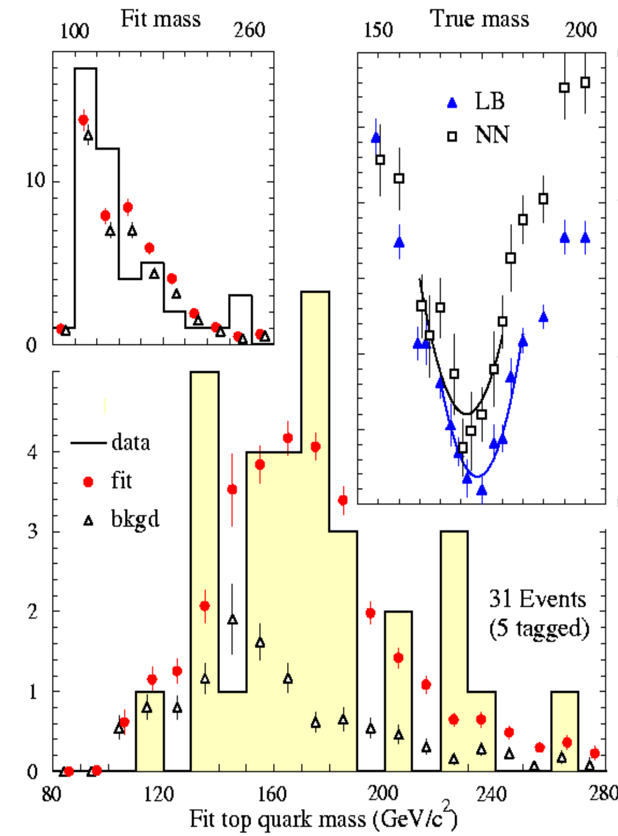
1997-98

CDF



m_t = 175.9 ± 4.8(stat.) ± 4.4 (syst.) GeV/c^2

DØ

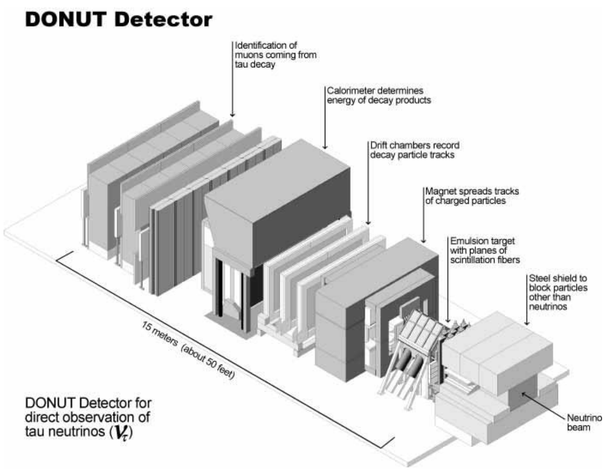


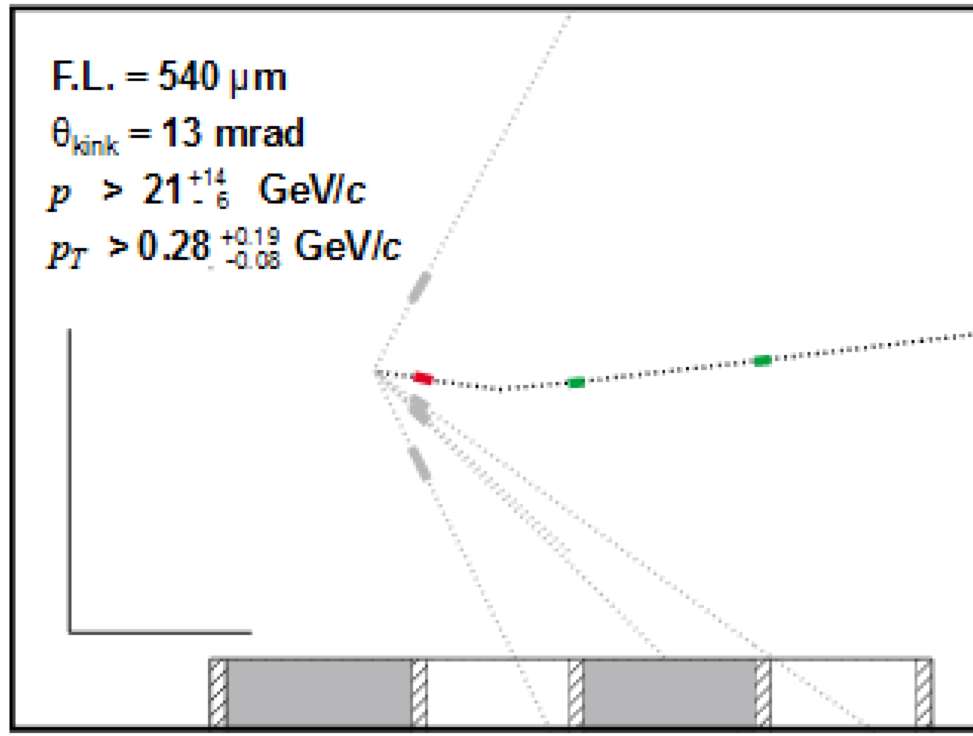
m_t = 173.3 ± 5.6(stat.) ± 6.2 (syst.) GeV/c^2

D0 used MVA/neural networks
for signal/background discrimination

Observation of the Tau Neutrino

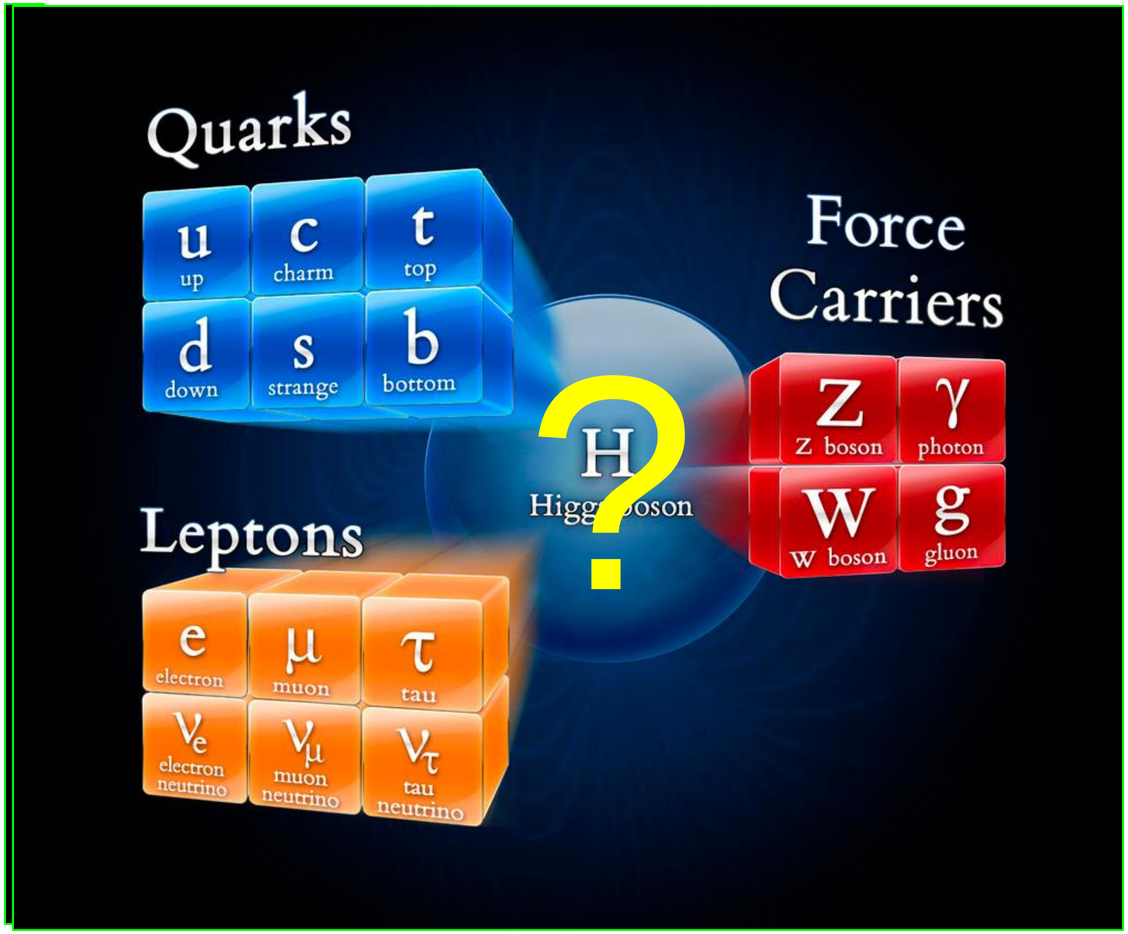
- Detected in emulsions at the Fermilab DONUT experiment in 2000.
- Used a beam dump to form a very "short baseline" ν_τ beam.





Byron Lundberg and Regina Rameika in front of the DONUT detector.

Standard Model circa 2000



- The Standard Model requires the **"Higgs field"** to break electroweak symmetry, giving masses to W,Z bosons
- Quarks/leptons also get masses from the Higgs field
- **Fermilab upgrades the Tevatron for Run II, hoping to find the Higgs before the LHC!**

Run 2 at the Tevatron

- ◆Main Injector and Recycler were added to the Tevatron Complex
- ◆Experimenters (and theorists) pursuing strategies to observe single top production, Higgs boson and new physics beyond the SM

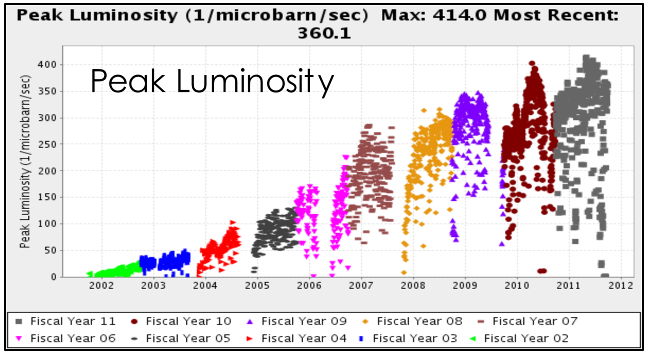
S Holmes,
Project Manager

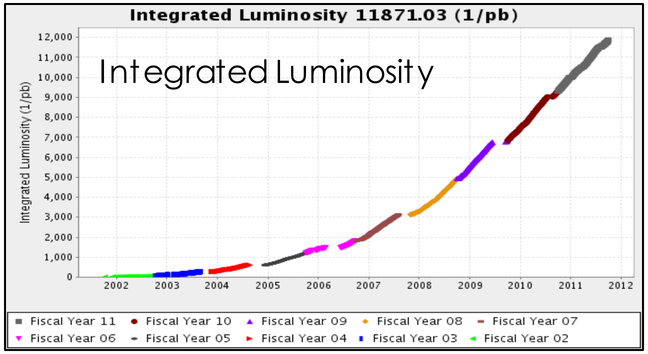
Jackson
Foster

Run 2 Luminosity and Reliability Upgrades

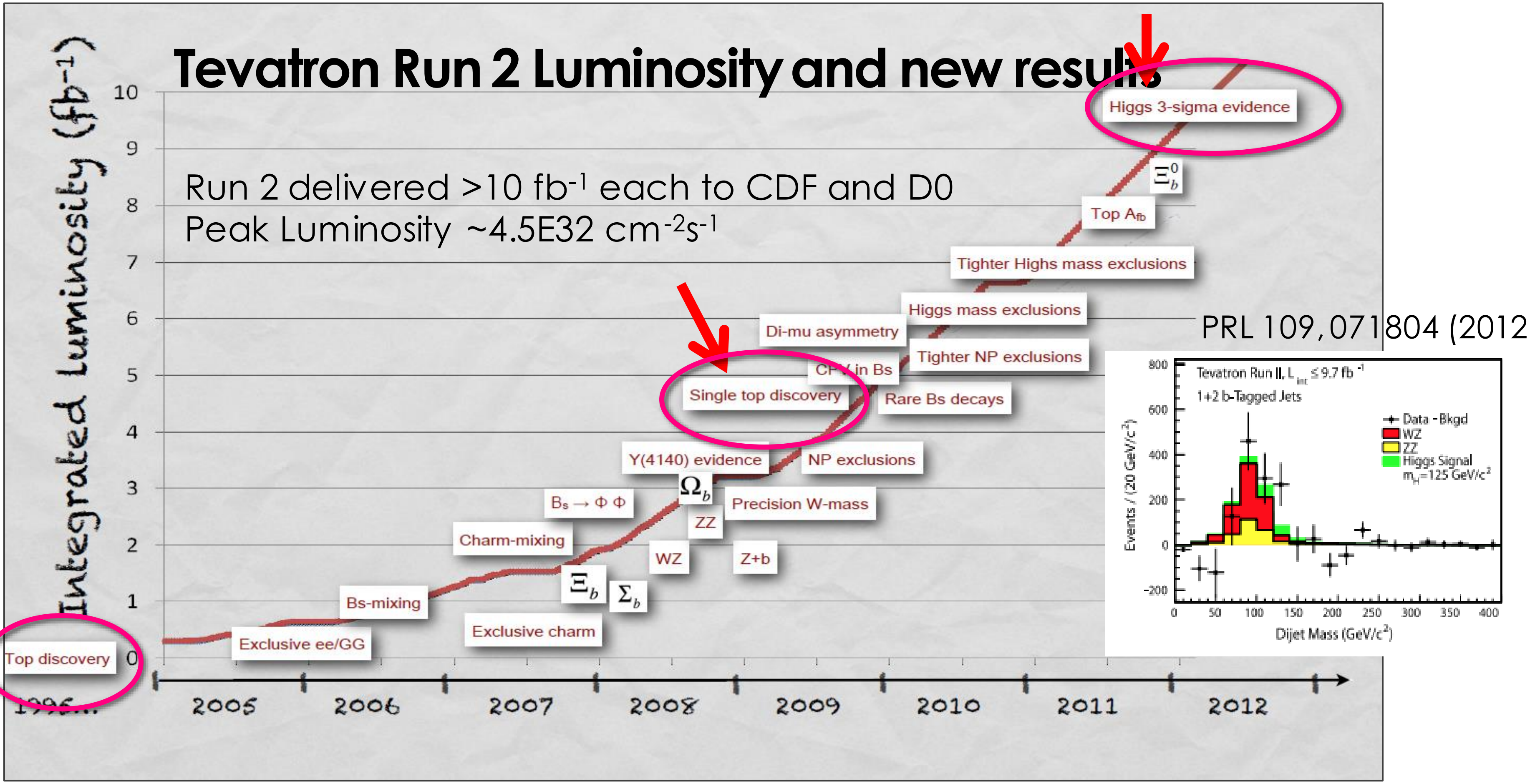
Project Managers: J. Spalding, P. Bhat, J Sims

- ◆Upgrades implemented in accelerators throughout the complex (2002-07)
  - ❖Beam diagnostics
  - ❖LINAC reliability
  - ❖RF upgrades and Slip stacking in the MI
  - ❖Digital dampers
  - ❖Tevatron alignment, helical separators
  - ❖Pbar target, Li-lens, aperture, rapid transfers
  - ❖Recycler commissioning , e-cooling of pbars, momentum mining
  - ❖Mixed-mode operation



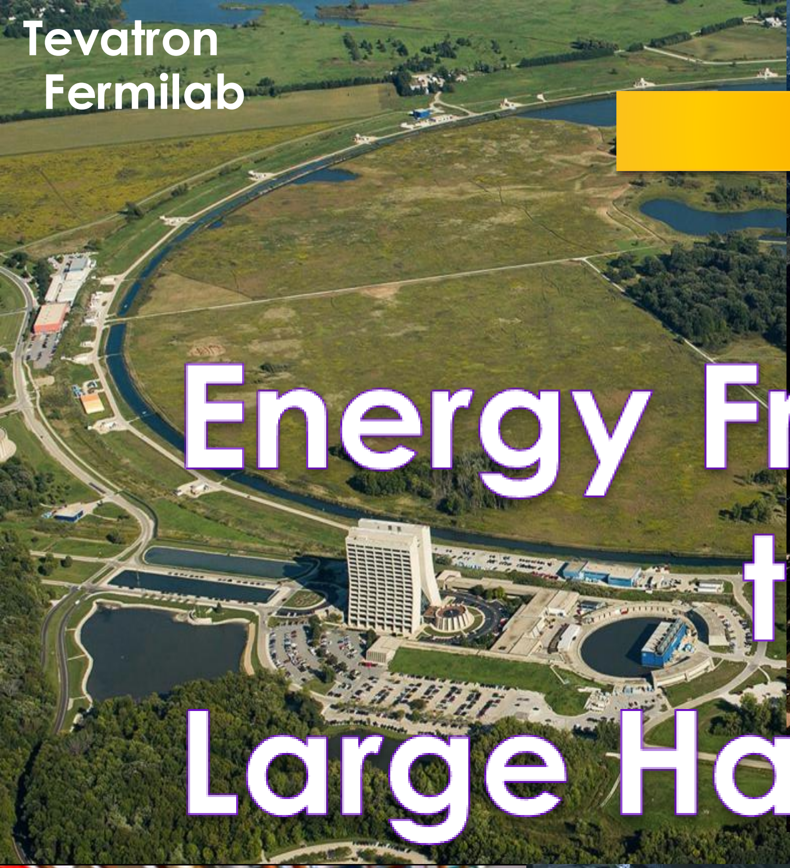


Bountiful Results from Tevatron Run 2



New observations and measurements as more luminosity was accumulated. From the discovery of the top quark, B_s oscillations, new family of b-baryons and multiple new phenomena exclusions to the evidence for the Higgs boson

Energy Frontier moves to the Large Hadron Collider at CERN



Our Pragmatic Present

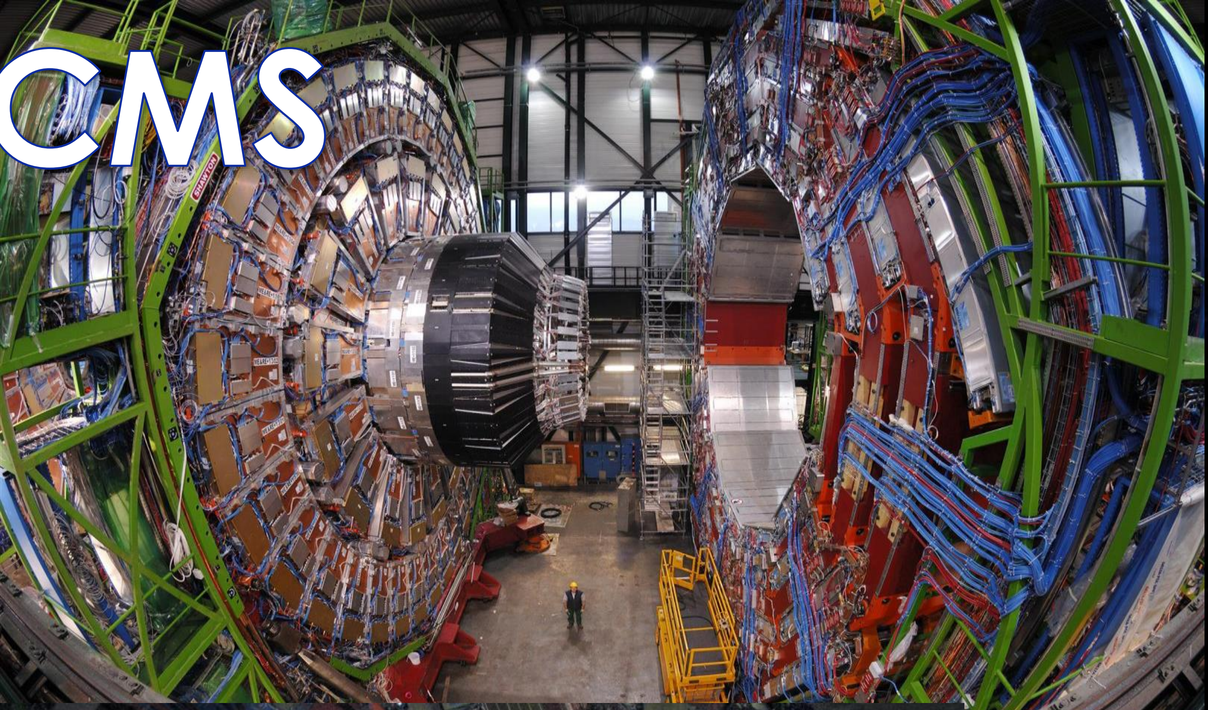
International Partnerships

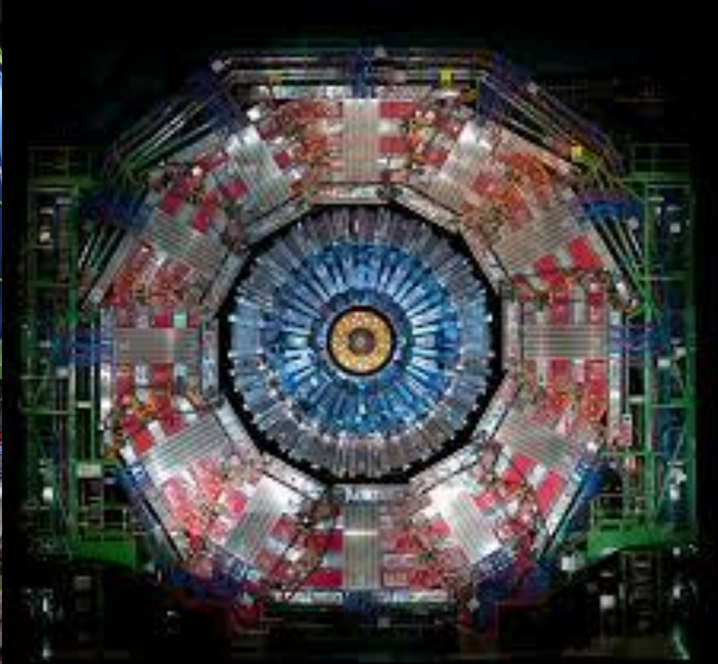
See next talk on CMS for exciting ongoing work

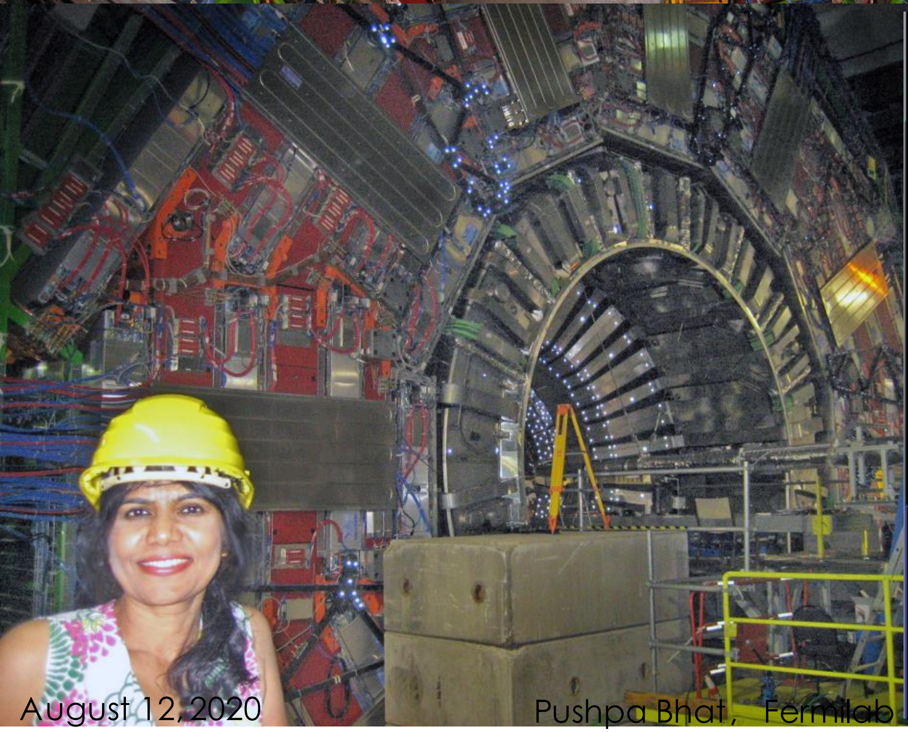
Fermilab at the LHC

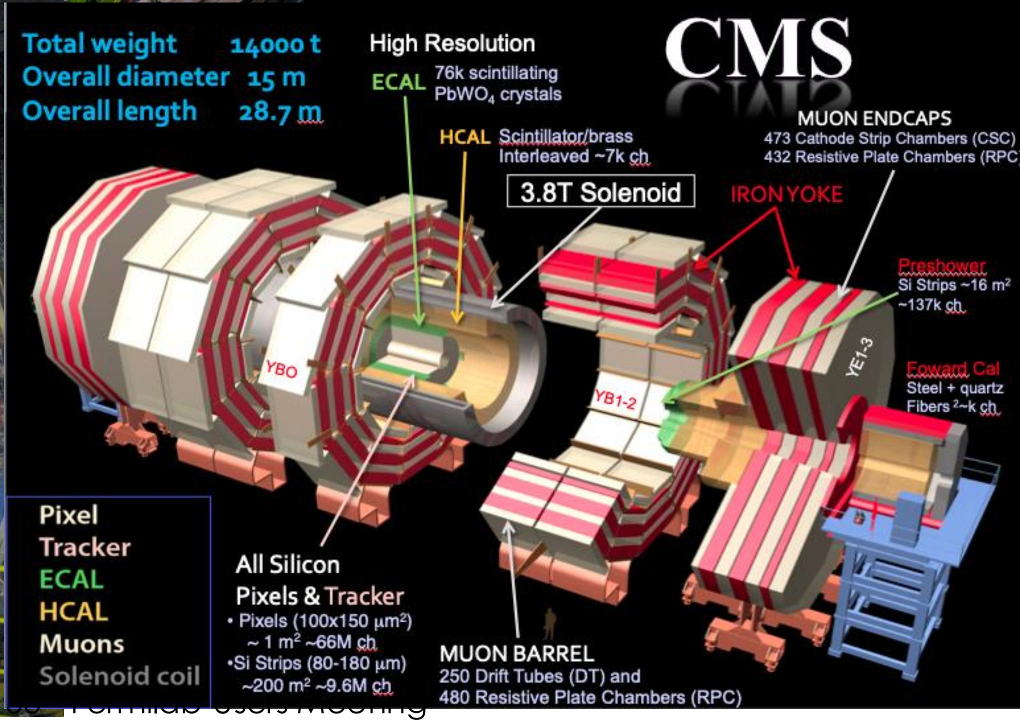
- The United States joined the LHC endeavor back in 1997 (after SSC cancellation,1993); US-CERN agreements signed in 1997 and 2015.
  - Fermilab became the "host" laboratory for US CMS
    - Manage the US contributions to the LHC accelerator and CMS detector
    - US/Fermilab in major leadership roles in CMS
      - Dan Green, Joe Incandela, Joel Butler, Patty McBride, Harrison Prosper
  - Leverage Tevatron experience on detectors, computing & analysis
    - US contributed a third of the original CMS detector
      - The forward (Si) pixel detector; Si Tracker Outer Barrel; Hadronic Barrel Calorimeter (HCAL/HB), forward end-cap muon chambers; front-end electronics, trigger electronics and DAQ systems for HCAL and end-cap muon system
      - LHC Physics Center, Remote Operation Center, Tier-1 computing
  - US LHC Accelerator Construction Project ($200M)
    - Fermilab (+ BNL and LBNL) build interaction region SC quadrupole and dipole magnets, cryo-systems
    - US Industry provided ~$90M worth of materials

CMS



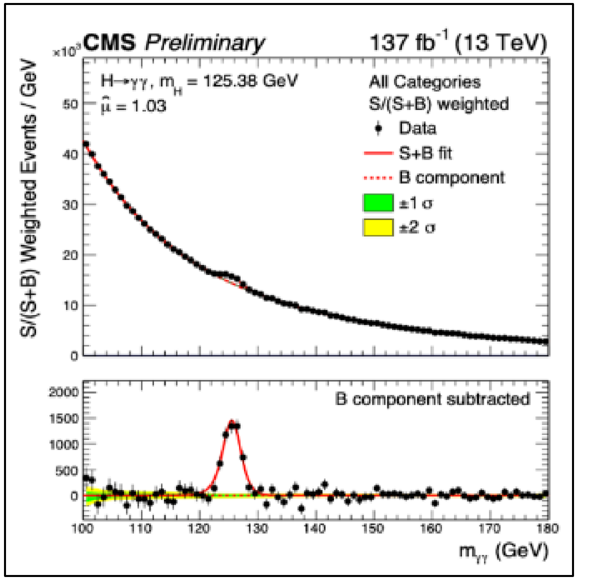





Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
High Resolution
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
CMS
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
3.8T Solenoid
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers ^{2}~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
All Silicon
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

The Higgs Boson (“God Particle”) Emerges

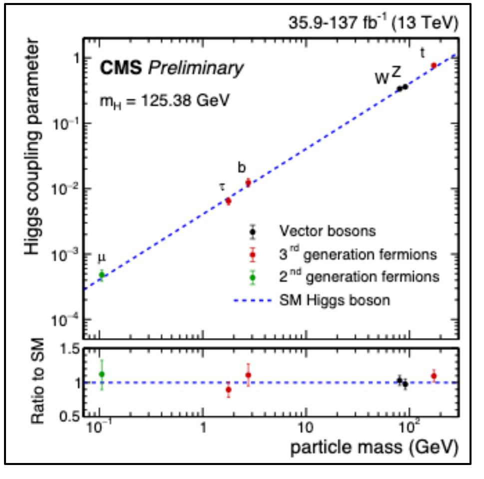
- ◆Hints at the Tevatron; Clear signal at the LHC
- ◆Discovery of the Higgs Boson at the LHC announced on July 4, 2012
- ◆Higgs has been observed in decay channels $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$ $H \rightarrow \tau\tau$, $H \rightarrow bb$
- ◆Most recently $H \rightarrow \mu\mu$, has been seen with 3σ significance.

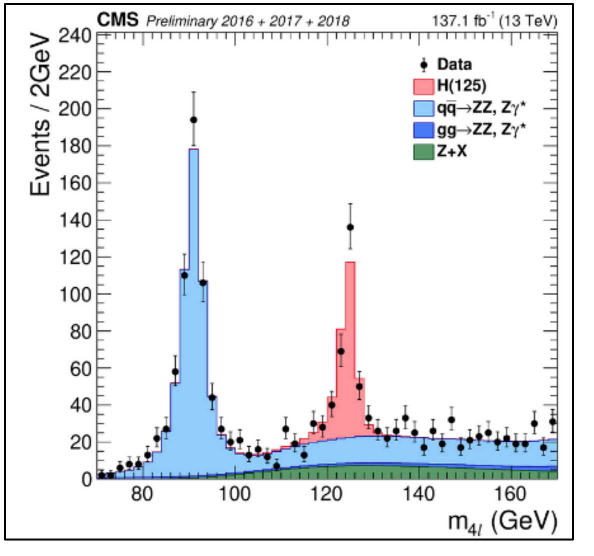


Questions:

- Is the Higgs elementary or composite?
- Are there more Higgses?
- Does it fully account for EWSB?
- Are the couplings as expected in the SM?
- …?

Couplings





Defining the Decade (2015-26?)

- The previous US community-wide "Snowmass" study and P5 report came after the Higgs discovery.
- Five science drivers were identified
  - Use the Higgs Boson as a New Tool for Discovery
  - Pursue the Physics associated with Neutrino Mass
  - Identify the New Physics of Dark Matter
  - Understand Cosmic Acceleration : Dark Energy and Inflation
  - Explore the Unknown : New Particles, Interactions, and Physical Principles
- Fermilab's flagship program at present is the neutrino physics program
  - **NOvA, SBN, LBNF/DUNE**
  - **PIP-2** to support the neutrino physics program
- At the LHC, we continue precision studies of top, Higgs, and the rest of the SM. Searches for dark matter, searches for new physics (SUSY, extra dimensions, etc.) beyond the SM are in full swing.
- Fermilab and US CMS working on accelerator and detector upgrades and looking forward to physics at the High Luminosity LHC (HL-LHC)
- See next talk on CMS.

Our Vibrant Future!

It is ours to create!

"What you think, you become
What you imagine, you create."
- Buddha

Future Colliders with Compelling Physics

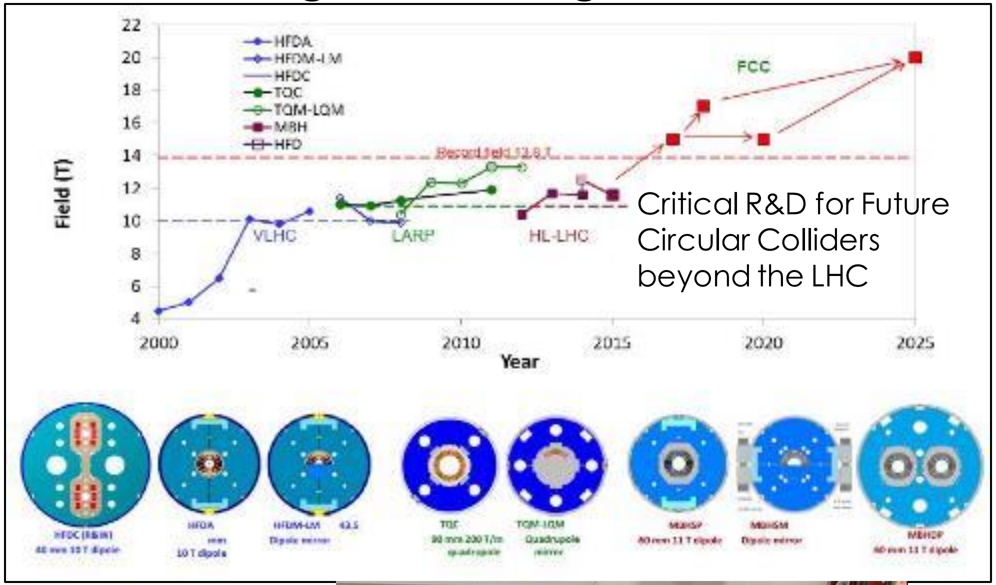
- Colliders of great interest:
  - "Higgs factory" – a collider (e^+e^-) with a center of mass energy of ~250 GeV and above for precision studies of the Higgs Boson
    - Candidates: ILC, CLIC, FCC-ee, CcpC,…
  - A post-LHC pp collider (~2xLHC or above) to search for new particles/phenomena beyond the Standard Model, reaching mass-scales in the range of tens of TeV
    - A 100 TeV collider could "close the book" on electroweak scale, test for compositeness of SM particles, substantial increase in reach for new gauge bosons, ...
    - Candidates: HE-LHC, FCC-pp, SppC, VLHC,..
  - Muon collider
    - Synergy with intensity frontier; nuSTORM, Higgs Factory, multi-TeV collider.

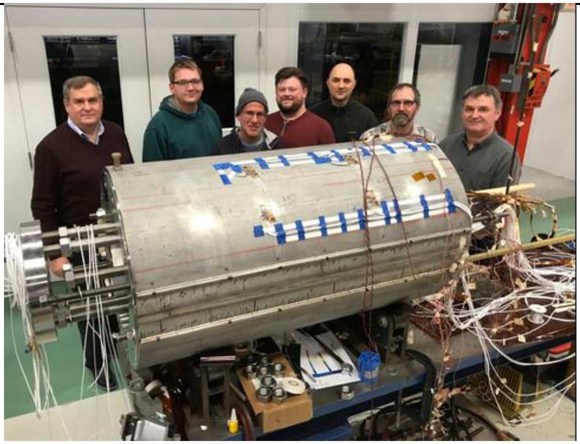
Fermilab’s Leadership in Enabling Technology

Superconducting RF Cavities

- ◆Fermilab is a world leader in superconducting RF (SCRF) and magnet technologies.
- ◆SCRF cavities with gradient ~50 MV/m has been achieved while the original ILC design calls for 31.5 MV/m.

High Field Magnets





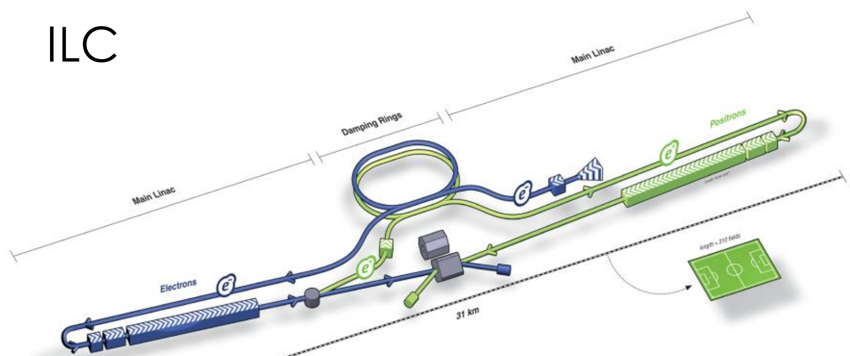
Critical R&D for PIP-II, ILC

Defining the Next Decade and Beyond

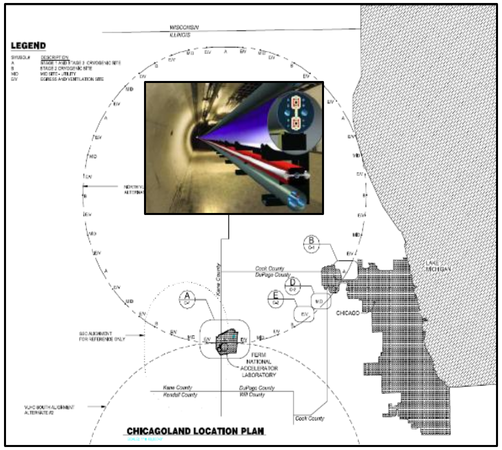
- We are successfully executing our previous P5 plan for US particle physics with due diligence.
- A new round of U.S. Community wide study, the "Snowmass" process has just begun.
  - European strategy for particle physics just updated. Feasibility studies for FCC to follow. CERN has a 70-year road-map!
  - We all recognize that particle physics is a global enterprise!
- Now is a great time to define and investigate scenarios for future large-scale facilities in the US!
  - Planning has to start decades in advance of construction
- The United States, the most powerful and richest country in the world, **should host such a facility at home**, in addition to participating in global facilities abroad (such as ILC, FCC).
- Breakthroughs in enabling technologies, e.g., advanced acceleration techniques could be game changers for the longer term future.

Future Collider Options

ILC



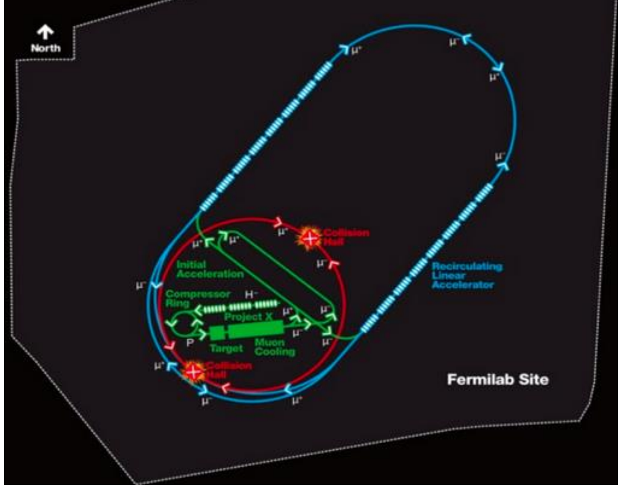
ILC 250 GeV proposed in Japan.
ICFA announced an international development team to prepare for pre-Lab.
Consider in US if Japan doesn't proceed

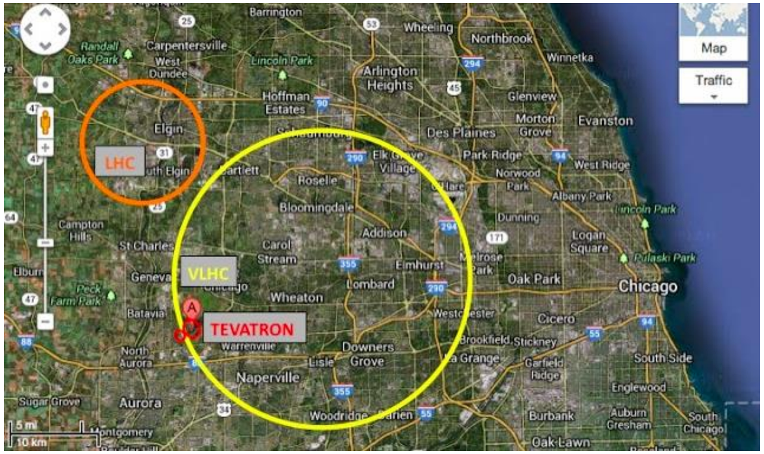


◆VLHC-233 (Foster et. al.)

- Stage 1: 40 TeV (2T Magnet)
- Stage 2: 175 TeV (9.8T Magnets

Renewed interest in the community.
4 TeV collider fits on site



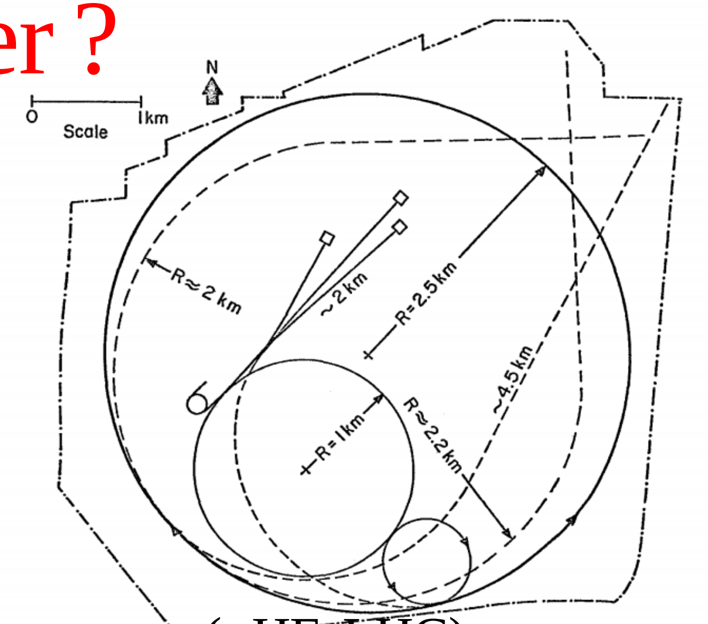


◆VLHC-100 (Bhat et. al., arXiv:1306.2369

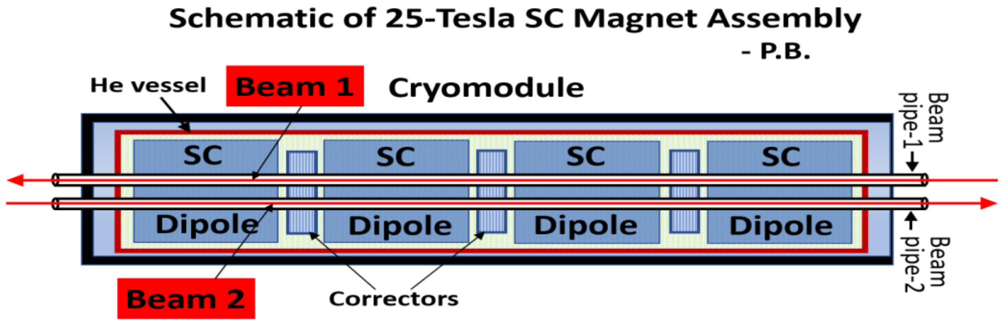
- 100 TeV @ 16T

A Compact Circular Collider ?

- A 10 TeV (5 on 5) ppbar site filler collider was first proposed in 1978 by Bob Wilson.
  - Fantasies of future Fermilab facilities, Rev. Mod. Phys. 51, 259 (1979)
  - **Wilson's dream machine?**



- Site-filler pp collider HE-FNAL
  - Requires 20-25 T magnets for **>25 TeV** collision energy (~HE-LHC)
  - Aggressive R&D on HTS magnets; innovative integrated design of (smaller size) dipoles and quadrupole/multipole corrector elements; novel lattice design
  - Aggressive R&D on Iron-based superconductors ← cheaper and robust magnets



The magnet assembly can possibly incorporate integrable optics.

- Also consider feasibility of a site-filler Higgs Factory with novel ideas

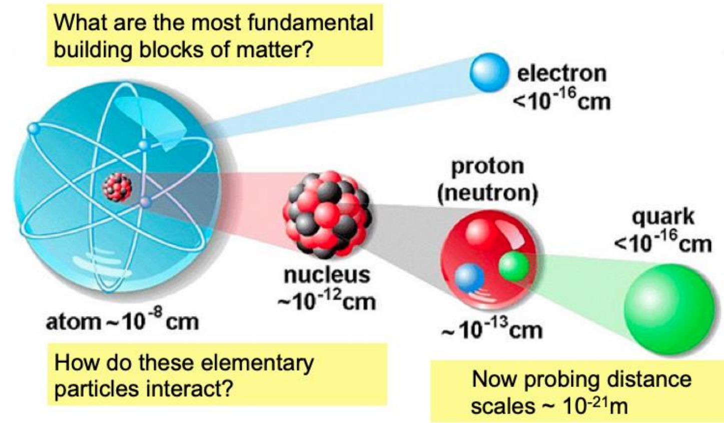
Conclusions

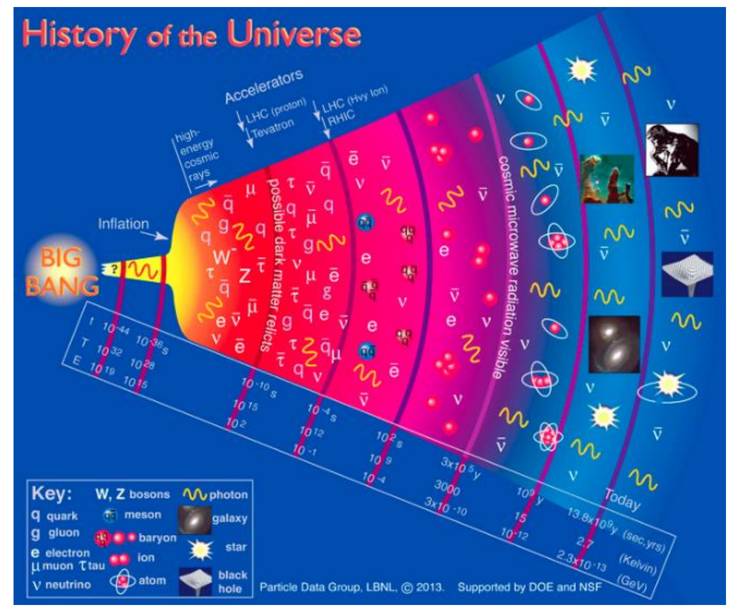
- ◆Fermilab has had a glorious past at the Energy Frontier. Given its history, it is the ideal place in the US for a next generation energy frontier machine.
- ◆The Higgs boson needs to be studied with exquisite precision at a Higgs factory.
- ◆The exploration of the Terascale that began at the Tevatron, now continuing at the LHC requires a post LHC hadron collider at higher energies.
- ◆An HE-FNAL or a VLHC or another energy frontier machine at Fermilab will advance scientific knowledge, accelerate technological progress, spur innovation, and attract bright young people to the science enterprise in the US.

“We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, … that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win.” - JFK

The Energy Frontier

- ◆High energy particle beams from accelerators allow us to
  - ❖Probe structure of matter and study physics at very short distance scales.
  - ❖Create new & exotic particles that existed in the early universe by converting energy into matter
- ◆Higher the energy, greater the reach, as to how deep we can look, how far back in the universe's history can we see, and how massive or exotic the particles we can create!

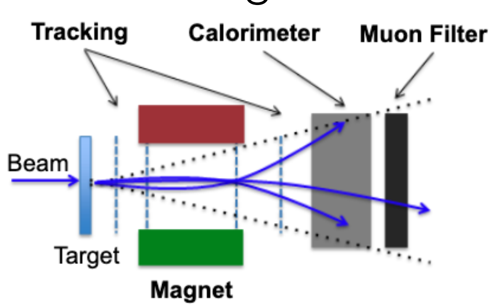


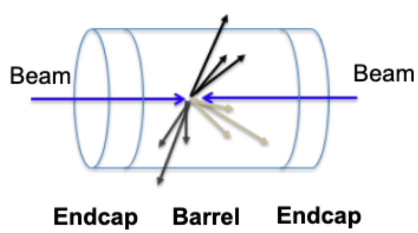


Two Kinds of HEP Experiments

Fixed Target

Collider



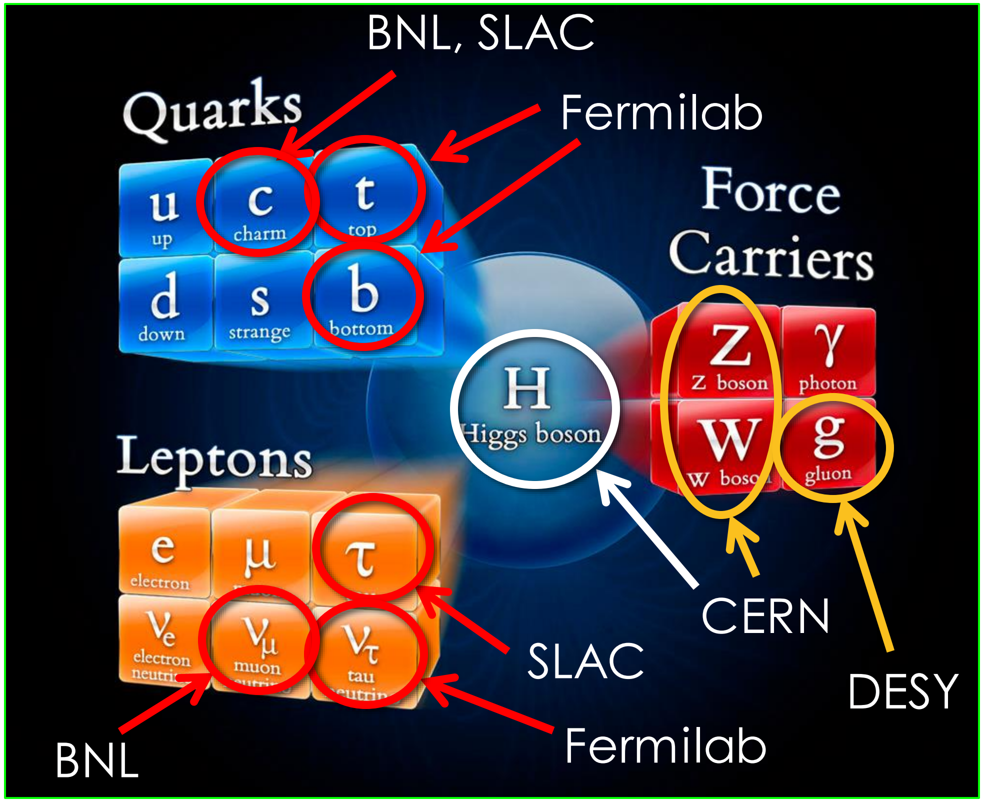


$$E_{CM} = \sqrt{2m_T E_b}$$

$$E_{CM} = E_{b1} + E_{b2}$$

The Standard Model

All Fermions discovered in the US
And bosons discovered in Europe!



Fermilab has played a significant role in the establishment of the SM

◆The Standard Model (SM) of Particle Physics is quantum field theory that describes fundamental particles and interactions between them. Particle accelerators have played a critical role in its development.

- ❖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**

The power of accelerators, especially colliders evident!