Subnuclear Physics: Past, Present and Future
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Achievements in Subnuclear Physics at Fermilab

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Fermilab

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1. Introduction

In such a short presentation, I will be very selective in describing the physics achievements at Fermilab. Of the thousands of papers and results over the four decades of Fermilab's life I will be able to highlight only a few major achievements. I will also project into the future and highlight the plans for Fermilab at the three frontiers of particle physics: the energy frontier, the intensity frontier and the cosmic frontier.

Fermilab is a relatively young laboratory. It was created in 1965 when the University Research Association, a corporation that included a large number of research universities, signed a contract with the Atomic Energy Commission for the creation of Fermilab. Previous AEC laboratories had been mostly regional, dominated by the institutions that managed them, often single universities. Fermilab was to be different: a true national laboratory. The National Accelerator Laboratory (NAL), the first name for Fermilab, would be the home of the highest energy machine in the world by a large margin, more than a factor of 10 higher than the existing machines at the time, the Proton Synchrotron at CERN and the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory.

The original proposal to build a large accelerator had been developed by the Lawrence Berkeley Laboratory. It was for a 200 GeV machine, conservatively designed, based on combined function magnets. The founding director of Fermilab, Robert Wilson scrapped the Berkeley design and led a new design. This design was based on a lattice of separated-function magnets, of smaller aperture, capable of reaching 500 GeV and at the same time more economical than the Berkeley design.

Robert R. Wilson's own recollection of the early years of the laboratory, written in the 1987 URA Annual Report, has been published as a Fermilab "Golden Book"[1]. Robert R. Wilson's imprint on the laboratory was huge: the ambitious design of the accelerator, the establishment of a Fermilab culture to serve the university community, his promotion of international collaborations, the nature of its scientific program, the esthetics of the site, the stewardship of the natural environment, the novel architecture and his own ubiquitous sculptures that are an extraordinary melding of art and science.

The laboratory was built quickly at the current Fermilab site. The land was acquired by the Atomic Energy Commission (AEC) from 56 farming families in what at the time was a rural area in the proximity of Chicago. The aggregation of this farm land yielded a site of 6800 acres, appropriate to be the home of very large accelerators.

Ground-breaking for the Linear Accelerator, the front end of all machines at Fermilab, was in December 1^{st}, 1968, and groundbreaking for the *Main Ring* was on October 3^{rd} 1969; the first 200 GeV beam was achieved on March 1, 1972. A few months later, in December, Fermilab achieved the first 400 GeV beam. Robert Wilson's ultimate goal of 500 GeV was reached on May 14^{th}, 1976. The National Accelerator Laboratory was dedicated to Enrico Fermi on May 14^{th}, 1974 and became the Fermi National Accelerator Laboratory (FNAL) or Fermilab.

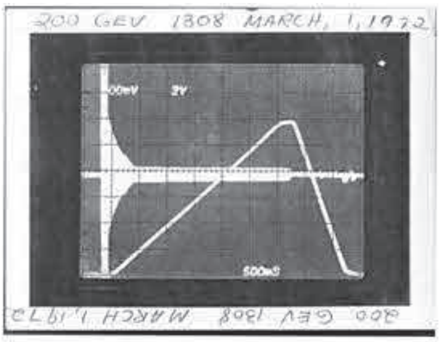

Figure 1: Screen shot and celebration on achieving 200 GeV; March 1, 1972

2.   The early fixed target era: discovery of the bottom quark

During the initial phases of Fermilab, the entire program was based on fix target experiments that spanned a broad range of particle beams: primary proton beams, selected hadron and photon beams and neutrino beams. The program was characterized by a multiplicity of experiments using quite varied techniques: bubble chambers, multi-wire proportional chambers, Cerenkov counters and a variety of scintillation counters. The results of these experiments contributed to the gradual completion of the Standard Model of particle physics.

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The most important experiment of this era was the discovery of the bottom quark by Leon Lederman and his team[2] in 1977. The original proposal had been submitted in 1970 to study single and double leptons from proton interactions. With the discovery of the *J/Psi* at Brookhaven and SLAC in 1974, it became clear that the di-muon channel would be a powerful tool to discover "onium" states beyond charmonium. Ironically, Lederman's early experiment at Brookhaven had detected a shoulder in the di-muon distribution that at the time was left unresolved. It was at the mass where San Ting and his team later discovered the *J*. In 1977 the experiment produced unmistakable evidence for the Upsilon at 9.5 Gev, making it a re-play of the charm discovery three years earlier.

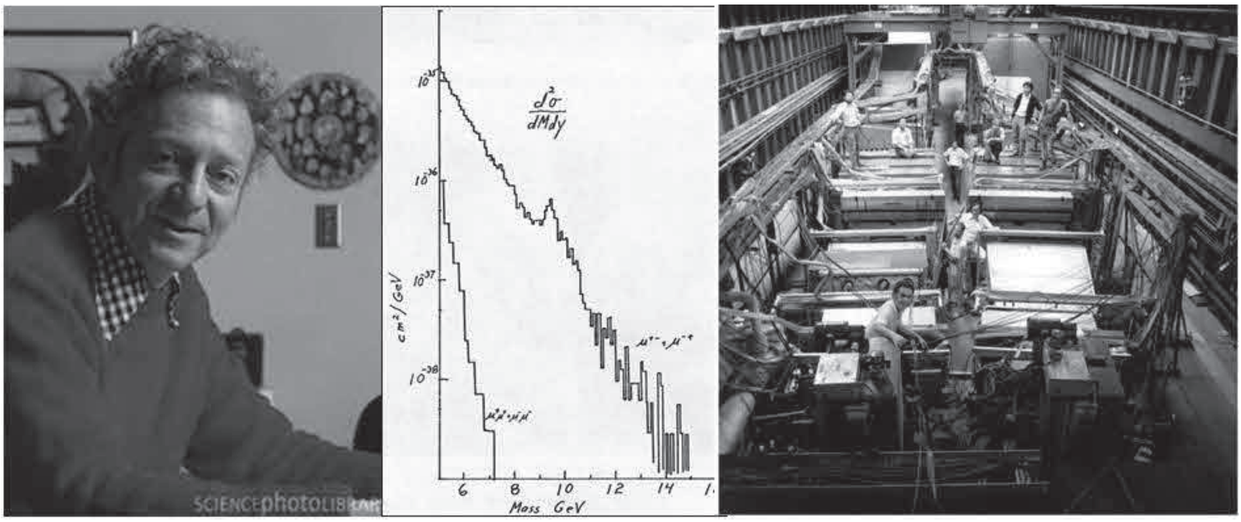


Figure 2: Discovery of the bottom quark: Lederman, data and detector

Another important set of experiments concerned the confirmation of the discovery by Gargamelle of neutral currents, one of the early back-and-forth between experiments at CERN and Fermilab.

3. Fixed target experiments with the *Tevatron*: first observation of the *tau* neutrino

Already during the construction of the *Main Ring*, there was considerable interest in the development of higher energy machines. The key was the development of superconducting magnets. The project initially called the *Energy Doubler/Saver* would double the energy of the main ring and save half the power. The second Director of Fermilab, Leon Lederman, decided to proceed with completing the superconducting ring instead of pursuing a race for the *W* and *Z* bosons by trying for a collider program with the existing *Main Ring*[3].

With the advent of the *Energy Saver/Doubler* (dubbed the *Tevatron*), with its high energy and with both short and long spills, a set of powerful experiments ensued. The results of over 40 experiments were reviewed at a symposium in the year 2000[4]. The fixed target program was quite vast and important covering QCD; the structure of protons, neutrons and mesons; charm and beauty mesons and their properties; hyperons; neutrinos and symmetry tests. For any given topic there was often a sequence of experiments that one could call a program of ever increasing capabilities. These programs led to five Panofsky prizes awarded for work either done entirely in the fixed target program at Fermilab or substantially done there[5]:

1990: Witherell (Charm)
1994: Devlin & Pondrom (Hyperons)
1995: Sciulli (Neutrinos)
2004: Bodek (Neutrinos).
2007: Winstein (Kaons, CP violation)

One of the examples was the series of experiments started with *E691*, in the study of charm. This experiment exploited the advent of silicon detectors to identify vertices and identify charm events. The experiment exploited the very large rates of charm production in a tagged photon beam compared to electron-positron colliders. The experiment produced more than 100 million events while keeping backgrounds under control[6].

A second series of beautiful experiments was the study of direct matter-antimatter symmetry violation (CP violation) in neutral kaon decays, culminating with the *KTeV* experiment[7]. The results of *E731* and *KTeV* at Fermilab and the results of *NA31* and *NA48* at CERN alternated with progressively smaller systematic and statistical errors, ultimately establishing direct CP violation at greater than 5 sigma level. The competition between the two groups was fierce for a number of years and the progression of their results on the measurement of direct CP violation, the primary aim of the experiments, is shown below.

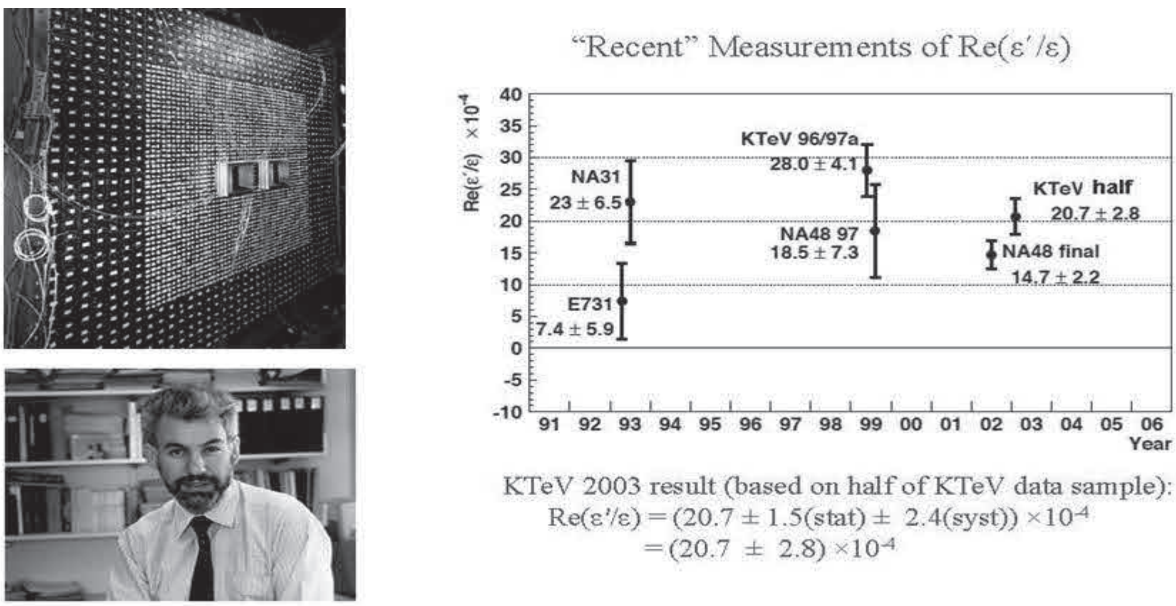
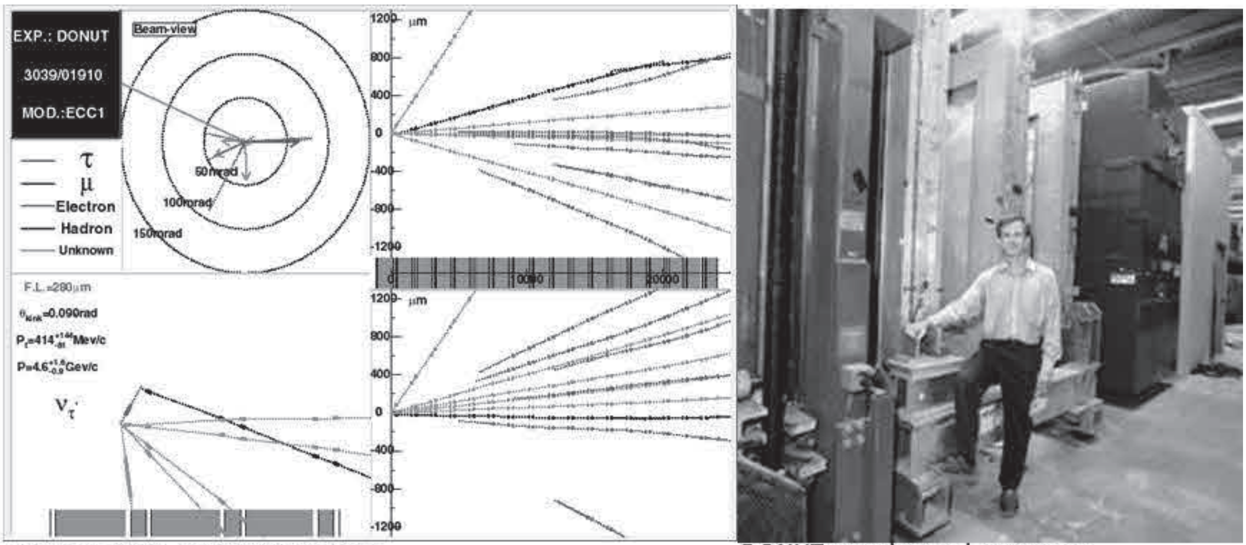


Figure 3: KTeV CsI Calorimeter, Bruce Weinstein and 2003 results

A beautiful example of the high-energy fixed target operation of the *Tevatron* was the first observation of the tau neutrino[8]. The existence of the third generation of quark and leptons was first established at SPEAR with the discovery of the charged tau-lepton. Using the high energy of the *Tevatron*, a high energy beam of neutrinos was used to produce quasi-elastic charged current events in which an outgoing charged tau lepton signaled the presence of an incoming tau neutrino.



Tau neutrino candidate events

DONUT experimental apparatus

Figure 4: the DONUT experiment observes tau neutrino

4. The *Tevatron Collider* era: discovery of the top quark

With the advent of the *Tevatron* in its collider mode, Fermilab became the leader at the energy frontier, a position it maintained from 1985 through the advent of the *Large Hadron Collider* at CERN in 2010. Two very large detectors, the *Collider Detector Facility (CDF)*[9] and the *DZero Detector*[10], each manned by very large international collaborations, defined the scientific program. During the two and a half decades as the forefront facility at the energy frontier the *Tevatron* produced major discoveries and hundreds of publications and Ph.D. thesis.

During the collider era we can distinguish two main periods. The first period takes us from the first collisions in 1985 through the discovery of the top quark in 1995 and is characterized by relatively low luminosities. From the first collisions through the discovery of the top quark the Tevatron integrated less than 0.2 inverse femtobarns. In the second period, with the new injector (the *Main Injector*), various improvements to the cryogenic system to reach 2 TeV CM energy and finally the implementation of electron cooling of antiprotons, the *Tevatron* reached a peak luminosity of $4\ 10^{32}\ cm^{-2}sec^{-1}$ and a total integrated luminosity of 12 inverse femtobarns.

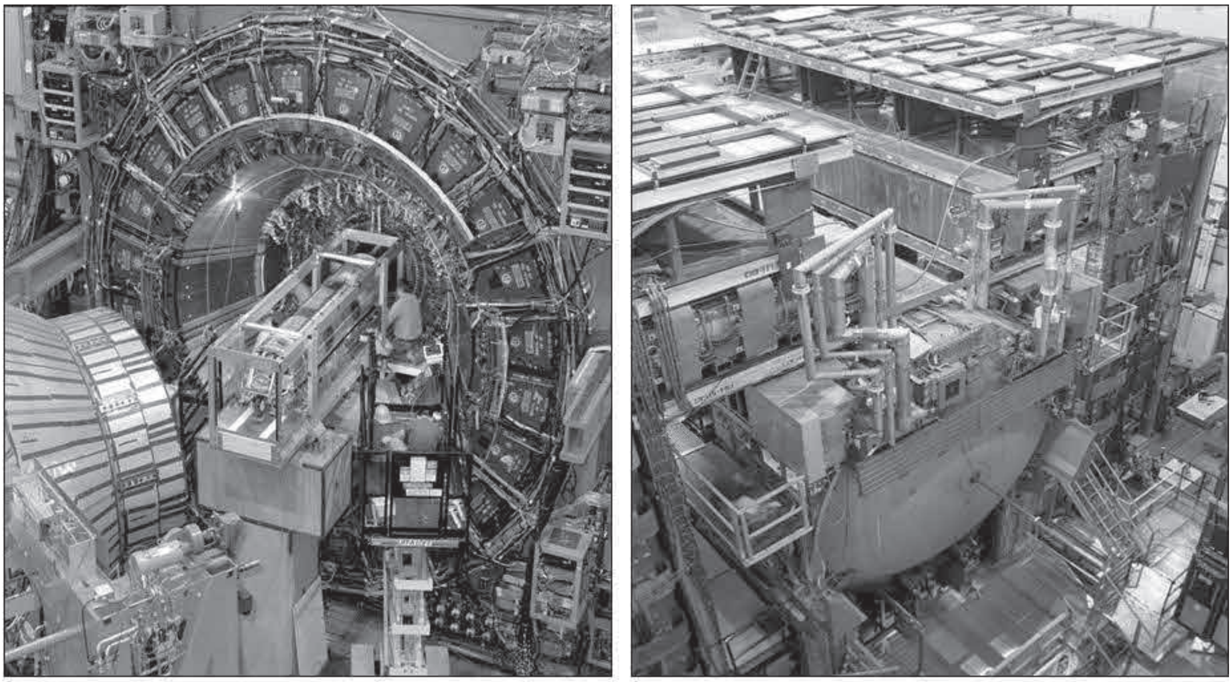


Figure 5: ~10 fb^{-1} recorded to tapes by each CDF and DZero

The discovery of the top quark culminated a world-wide saga where after accelerators fell short of the necessary energy to produce the top quark. In a series of measurements in the early 90s, *CDF* and *DZero* gradually raised the lower limit on the mass of the top. Finally in 1995 both experiments announced the discovery of the top quark[11]. Subsequent to the discovery and for the next 16 years, the *Tevatron* was the only facility capable of producing the top quark and studying its properties. Many measurements confirmed the expectations of the top quark in the Standard Model: QCD predictions for production rate and transverse momentum distributions; its invariant mass; 2/3 charge; and the study of properties of the *tbW* vertex. At the *Tevatron* the mass of the top, was measured to better to about 0.5% (Figure 6) and is an important ingredient in determining the region of mass where the Standard Model Higgs should be. With the increased data samples, studies of *t-tbar* correlations became possible and the two collaborations, *CDF* and *DZero* observed an asymmetry in *t-tbar* production larger than predicted by the standard model, a result that remains unexplained at this date.

The *Tevatron* collaboration explored electroweak physics to an unprecedented level. Precision measurements of the *W* boson mass to four parts in ten thousand were achieved, with millions of events per leptonic channel in each experiment. This together with the top quark measurement limits the mass region for the Standard Model Higgs. All di-boson production *WW, ZZ, WZ Wg Zg* agrees with QCD predictions and their production rates are shown in Figure 7.

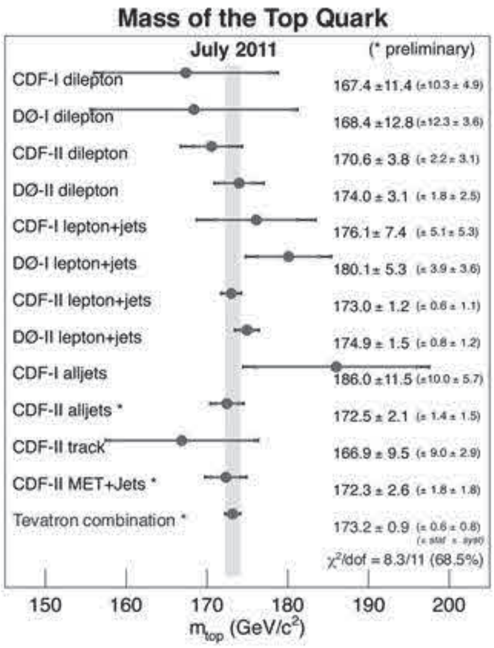


Figure 6: evolution of top-quark mass measurements

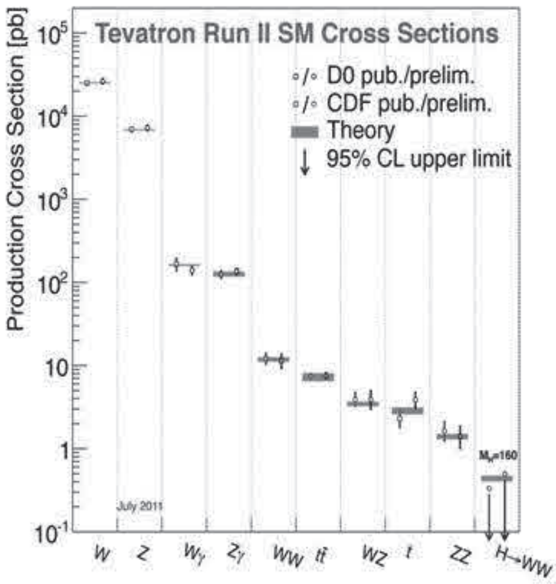


Figure 7: di-boson production

Remarkably enough the *Tevatron* had an impact on the spectroscopy of heavy mesons and baryons, a subject normally associated with electron-positron colliders. All the knowledge about the top quark comes from the *Tevatron*. The discovery of the B_c meson and the measurement of its properties were first done at the *Tevatron*. The Tevatron has contributed to the measurement of masses and lifetimes and observed B mesons and baryons. With the baryons discovered at the *Tevatron* we have a complete picture all the ½ spin baryons containing a *b* quark as shown in Figure 8.

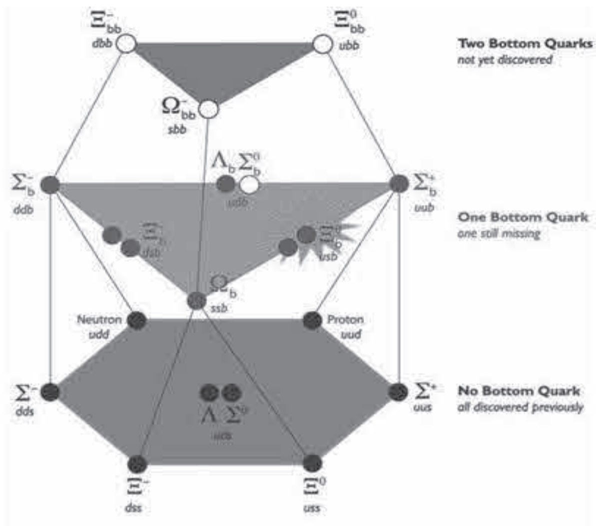


Figure 8: b-baryon spectroscopy

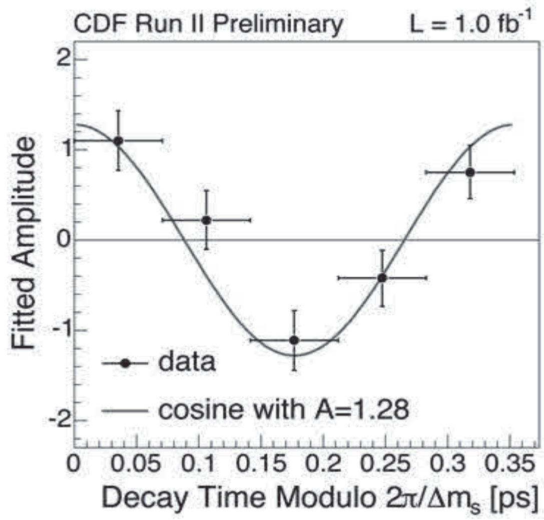


Figure 9: B_s oscillations

One of the most remarkable measurements was the very fast oscillations of the B_s system. After limits first published by *DZero*, *CDF* determined the oscillation frequency of 17.77+- 0.13 ns shown in Figure 9.

The *Tevatron* pushed the kinematic limits over which the strong interaction was tested. QCD was tested over a broad set of transverse momenta. The transverse momentum distributions over many orders of magnitude are shown in Figure 10. Single jet and multijet distributions validate perturbative QCD and have served to tune parameters for the planning of detectors for *LHC*.

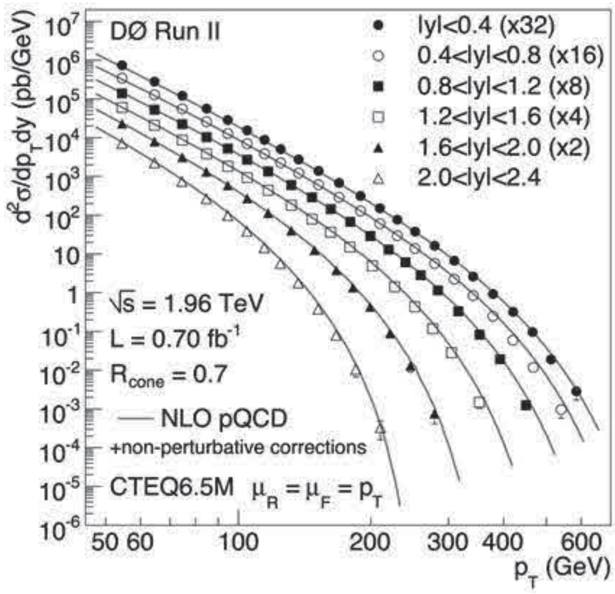


Figure 10: Data and NLO calculations

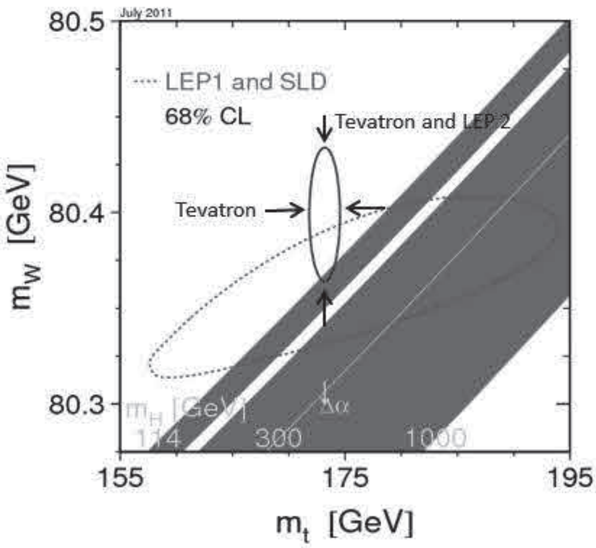


Figure 11: indirect Higgs masss

A large enterprise at the *Tevatron* was the search for phenomena beyond the Standard Model. Searches for extra spatial dimensions, supersymmetry, technicolor, monopoles, new forces of nature and many more yielded no observations. A few results at the 3 standard deviation remain puzzling and will have to be elucidated either with the remaining analysis at the *Tevatron* and more likely with the much more abundant data at the *LHC*.

The search for the *Higgs* has been a principal endeavor of the *Tevatron*. The *Tevatron* excluded new regions of the mass range for the first time since the *LEP* collider. If the *Higgs* is not there, the *Tevatron* has the potential to exclude the *Higgs* at the 95% confidence level from the *LEP* limit of 115 GeV to about 185 GeV. At this point, the regions where the *Tevatron* has enough sensitivity to discover the *Higgs* have been excluded as shown in Figure 12.

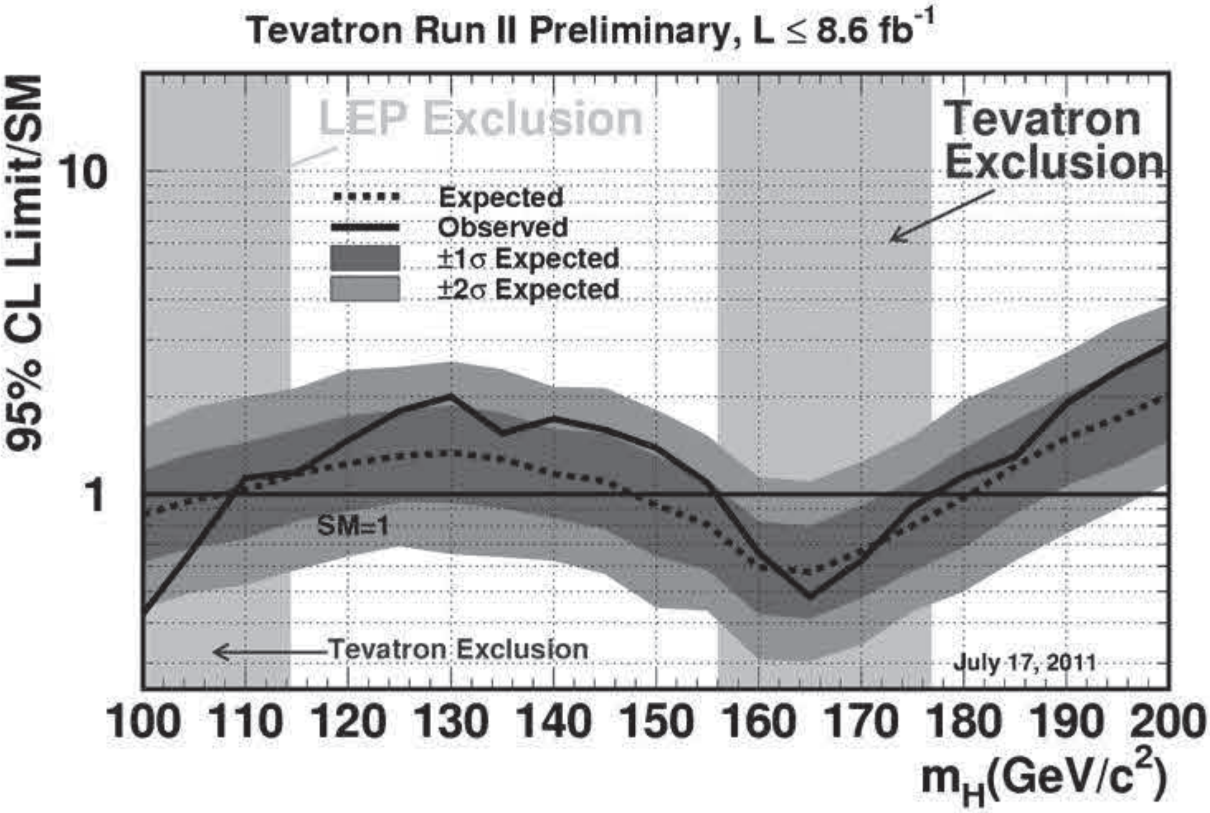


Figure 12: Higgs limits combined CDF and DZero

5. The current neutrino program and future extensions

To achieve the high luminosity of the *Tevatron*, the front end accelerators were developed to achieve high intensity. The 8 GeV booster is a rapid cycling accelerator running at 7 Hertz (with an ultimate capability of 15 Hz) and the *Main Injector* produces 120 GeV beam every 2.3 seconds, relatively rapidly for such a large synchrotron. Using these machines Fermilab developed both a long and a short baseline neutrino programs.

Our understanding of neutrinos lags our understanding of all other known particles. Today we believe in a picture with three generation of neutrinos. Even in this picture many parameters remain to be measured. While we know that neutrinos have a very small mass, we do not know the absolute value of the masses, only the mass differences between pairs of neutrinos. The mass eigenstates of neutrinos are combinations of the different flavor of neutrinos, but in some instances we do not know what those combinations are. Finally we do not know whether neutrinos and anti-neutrinos respect matter-antimatter symmetry. So even if the overall picture we have of neutrinos is correct, there is much to be done in understanding them. Furthermore, we may not have the totally correct picture; additional interactions could exist that affect the neutrino world. In particular, there may be sterile neutrinos that mix with regular neutrinos and would indicate a totally different kind of particle with no standard interactions. The neutrino program at Fermilab aims to study all these different possibilities.

Today the Fermilab short baseline program has two experiments: *MiniBooNE*[12], and *MINERvA*[13]. The *MINERvA* experiment studies neutrino-nucleus interactions and started taking data in 2010. The *MiniBooNE* detector has operated for several years and has investigated the possibility of neutrino oscillations claimed by the *LSND* experiment that do not fit the standard picture. Using a neutrino beam, *MiniBooNE* disproved the oscillations observed by *LSND*. The results of *MiniBooNE* with anti-neutrinos is more ambiguous: they could be consistent with *LSND* but suffer from small statistics. More interestingly *MiniBooNE* has observed a statistically significant excess of events at low energies that may indicate new phenomena. *MiniBooNE* which is based on Cerenkov detector cannot resolve this issue.

To resolve the *MiniBooNE* excess we are building *MicroBooNE*[14], a fine grain detector. Placed in the Fermilab booster beam, the *MicroBooNE* detector will be an approximately 150-ton, liquid Argon Time Projection Chamber (LArTPC). The experiment will measure low energy neutrino cross sections, and investigate the low energy excess events observed by the *MiniBooNE* experiment. The detector serves as the necessary next step in a phased program towards the construction of massive, kiloton range, LArTPC detectors. It will be operational in 2014.

Figure 13: MINERvA Detector

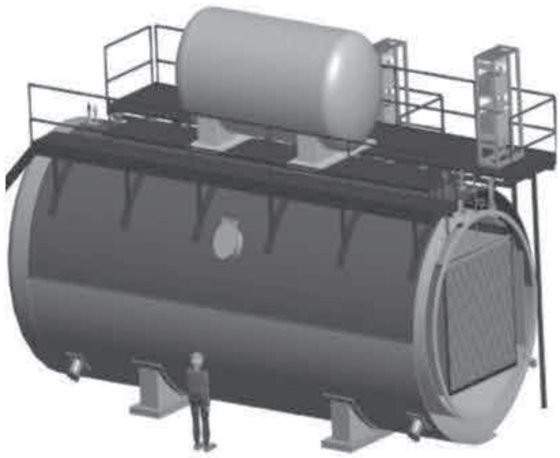


Figure 14: MicroBooNE Detector

The long base line neutrino oscillation experiments used a high energy beam from the *Main Injector* to the Soudan mine in Minnesota. The first of these experiments is the *MINOS*[15]experiment which has produced the most accurate measurement of the mass difference and improved the measurement of the mixing angle in the region of atmospheric neutrinos. The *MINOS* experiment has measured the oscillation parameters of neutrinos and antineutrinos and found them equal within statistics. It has ruled out some models for sterile neutrinos and is in the process to measure the speed of neutrinos to verify the *OPERA* results. It also has set limits on electron appearance.

The *NOvA*[16] detector is under construction and is aimed as studying electron appearance. It is a 15 kton totally active detector. It will measure electron appearance accurately and the mixing angle θ_{13}. It will have some sensitivity to the mass hierarchy and to CP violation. The *NOvA* detector is the next step in understanding the neutrino mixing matrix and verifying the current understanding of neutrinos with three generations of neutrinos.

To fully measure the mass hierarchy and CP violation one needs a longer baseline experiment. This is currently planned for the Homestake mine in South Dakota. The experiment, *LBNE*[17], would be a massive 33 kton liquid argon TPC one mile underground that would not only permit the study of all the oscillation parameters, but also the study of proton decay, atmospheric neutrinos and supernova bursts. The reach in oscillations for the three generation of experiments MINOS → NOvA → LBNE is shown in Figure 15.

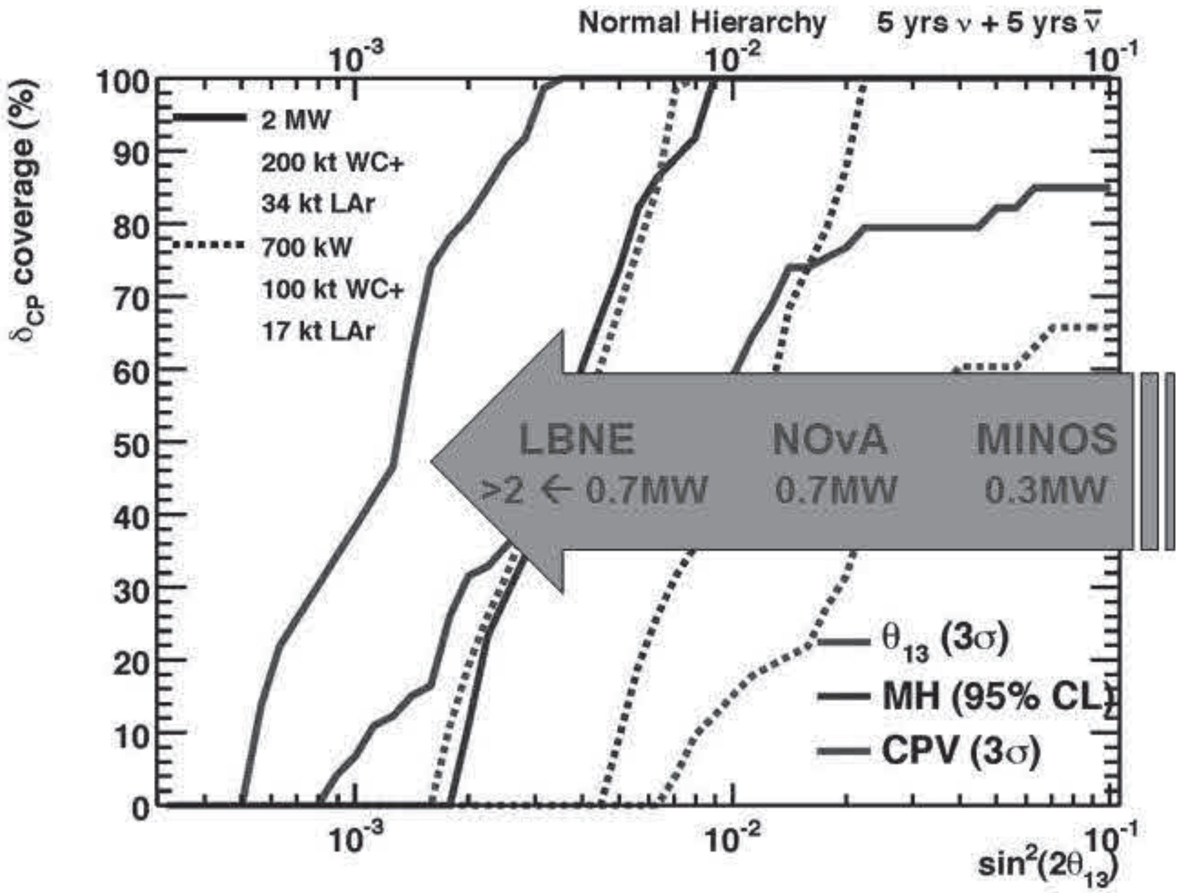


Figure 15: Evolution of sensitivities

6. The future muon campus: *g-2* and *Mu2e*

The measurement of the anomalous magnetic moment of the muon, *g-2*[18], is a classic experiment that has become the "gateway" experiment through which every model of physics beyond the Standard Model has to pass. The Fermilab experiment will have 20 times the previous statistics and reduce the error of the previous Brookhaven National Laboratory experiment by a factor of four to 0.14ppm. The experiment will be based on the storage ring built at BNL for the previous measurement of *g-2*. This storage ring will be moved to Fermilab and housed in the muon campus. The experiment will start operations in the 2016-2017 time frame.

The *Mu2e*[19] experiment will study the conversion of a muon to an electron in the field of the nucleus. This conversion cannot occur in the Standard Model except through neutrino mixing which would be at an infinitesimal rate. Any measured rate is an indication of new physics beyond the Standard Model. Depending on the couplings, indirect sensitivities to masses of 1000 Tev and more can be achieved. If a finite rate is measured, variations in the nuclear target can give information on the nature of the new physics. The experiment is quite complex and involves producing an intense muon beam impinging on a target and a detector to measure the mono-energetic electron produced by this process. The picture of the experiment is shown in Figure 16.

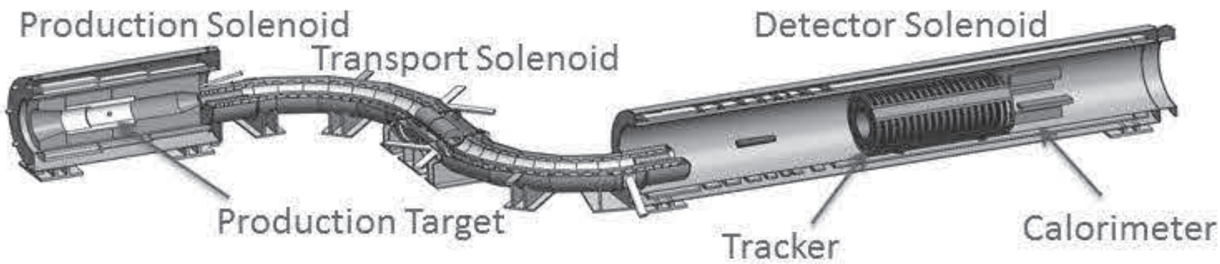


Figure 16: Mu2e experiment

7. *Project X*[20] and its scientific reach

To have a broad program at the intensity frontier, Fermilab has proposed to build a continuous wave (CW) superconducting linac with an energy above kaon threshold. This 3 GeV, 3 MWatt linac would fuel a powerful program of rare muon and kaon decays. It would provide megawatt beams with precisely tailored timing characteristics that would enable experiments of high precision that have not been possible before. In addition megawatt class beams could be delivered to nuclear targets for EDM measurements and also for a specialized station for materials studies and spallation targets.

The 3 GeV CW linac would provide a fraction of the beam to a pulsed superconducting linac for acceleration to 8 GeV, with several hundred kilowatts of power delivered at that energy. Finally acceleration of a fraction of the beam from 8 GeV to 60-120 GeV would provide 2.3 MWatts to the Long Baseline Neutrino Experiment. *Project X* is being planned in such a way that it would serve as the front end for a neutrino factory or a muon collider. A schematic of *Project X* is shown in Figure 17.

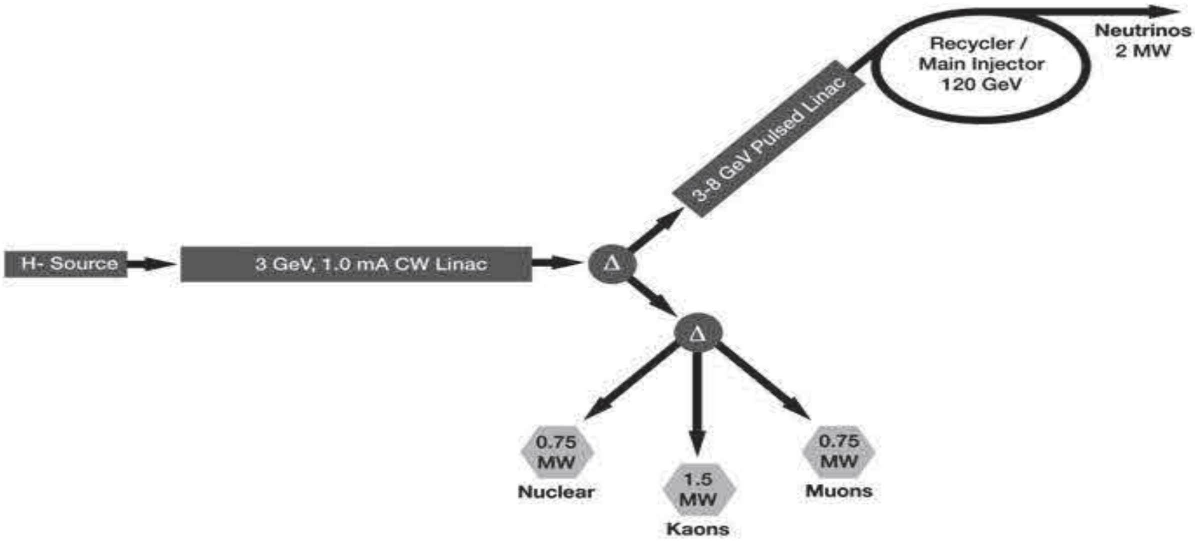


Figure 17: Schematic of Project X

8. Connection to the cosmic frontier

Particle physics is intimately related to cosmology. Fermilab played a leading role in the theoretical underpinnings of this connection with the establishment of one of the earliest groups of theoretical particle astrophysics. It established an experimental program with the *Sloan Digital Sky Survery (SDSS)*, which has an enormous impact on the determination of cosmological parameters. Today Fermilab is carrying out a leading program on the study of dark matter with the *Cold Dark Matter Search (CDMS)* experiment in the Soudan mine, and the development of other techniques to reach background free condition including the *COUPP* detector now being tested at *SNO*.

SDSS observed baryon acoustic oscillations, a powerful component of studying dark energy. Fermilab is following *SDSS* with the *Dark Energy Survey* (*DES*) employing a 0.5 gigapixel camera mounted on the 4m Blanco telescope in CerroTololo, Chile. This experiment should give the first indications on whether the acceleration parameter has been constant or is changing through the expansion of the Universe.

Fermilab has played a leading role in the development of the Pierre Auger Observatory studying the highest energy particles in nature.

9. The follow-up to the *LHC* at the energy front

At the time of this writing the *LHC* is working extremely well and we are at the threshold of discovering if the Standard Model Higgs provides the mechanism of symmetry breaking. The biggest issue in the field today is what should follow the *LHC*.

Fermilab is participating in a major way in the worldwide *ILC* R&D. If the phenomena discovered at the *LHC* are below 1 TeV, then it is likely that there will be an *ILC* somewhere in the world. If on the other hand the phenomena extend well beyond 1 TeV, then different technology will be necessary to explore these phenomena. At Fermilab we are concentrating on demonstrating the feasibility of a muon collider while at CERN there is development of the warm RF *CLIC* linac with high electric field gradients and using a two-beam accelerator.

The muon collider feasibility study requires solving many challenges in the production, capturing and acceleration of muons. The new technologies developed in this enterprise include very high field (40T) magnets, rapid acceleration to TeV energies, high power targets and muon ionization cooling.

The overall future program for Fermilab is shown in Figure 18 in the Appendix.

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16. NOvA: http://www-nova.fnal.gov/
17. LBNE: http://lbne.fnal.gov/
18. g-2: http://gm2.fnal.gov/
19. Mu2e: http://mu2e.fnal.gov/
20. Project X: http://projectx.fnal.gov/

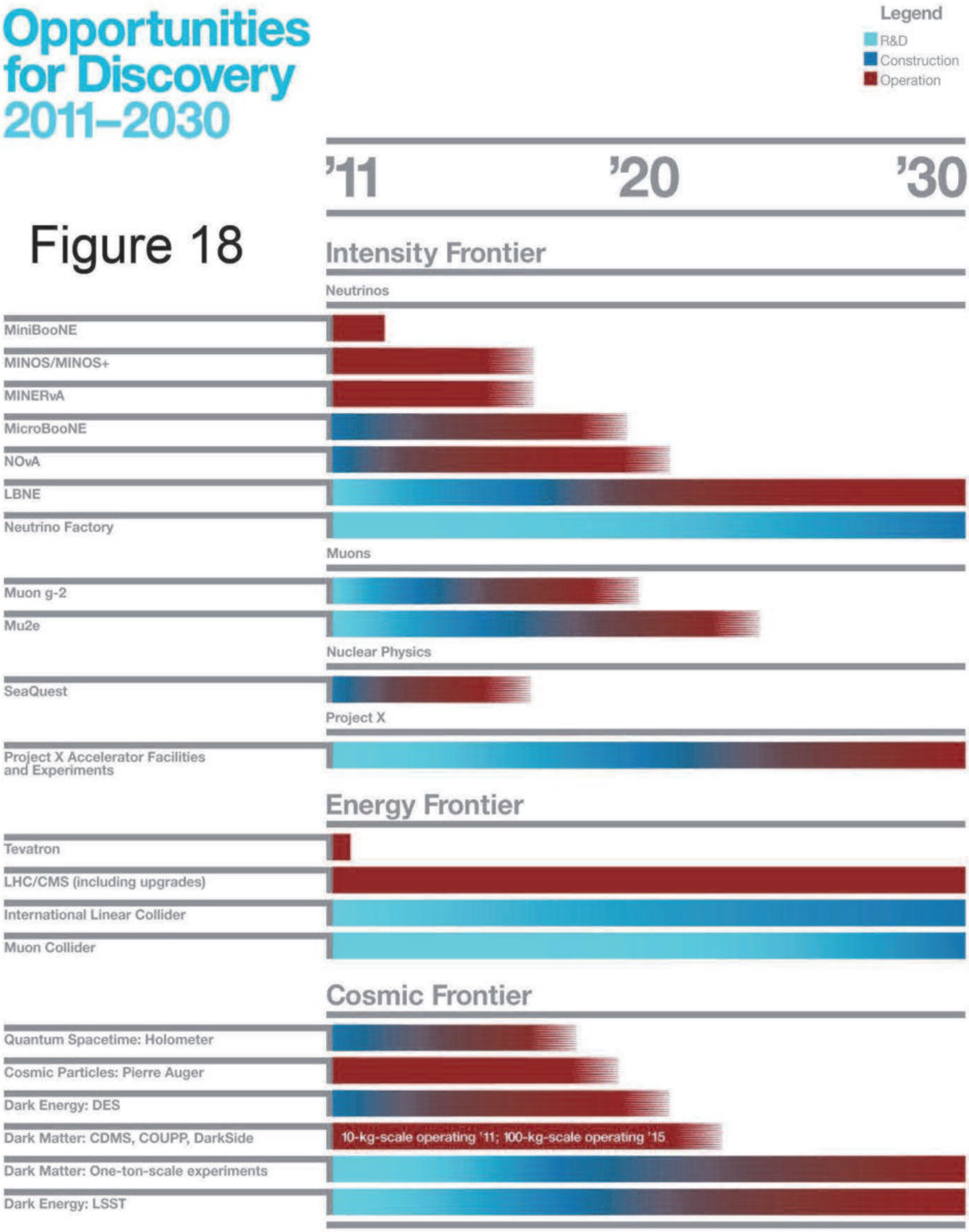

Figure 18

The timeline on this page shows experiments and major accelerators currently in the R&D, construction or operation phases. All experiments currently in the R&D phase require additional levels of approval from the Department of Energy before construction can begin. Construction of a Neutrino Factory or a lepton collider, at Fermilab or at any other worldwide site, would proceed only if discoveries at the LHC or elsewhere point to a need for such a machine.