Understanding Our Asymmetric Universe

NIU's Experimental Program at Fermilab
1986-2018

David Hedin
Department of Physics
April 2018

Symmetries vs Asymmetries

- Ancient scientists (e.g. Archimedes): Universe is made from perfectly symmetric objects like circles and spheres → wrong models of the orbits of the planets

- Now know: "perfect" symmetry gives a lifeless Universe → it is the asymmetries that give it complexity

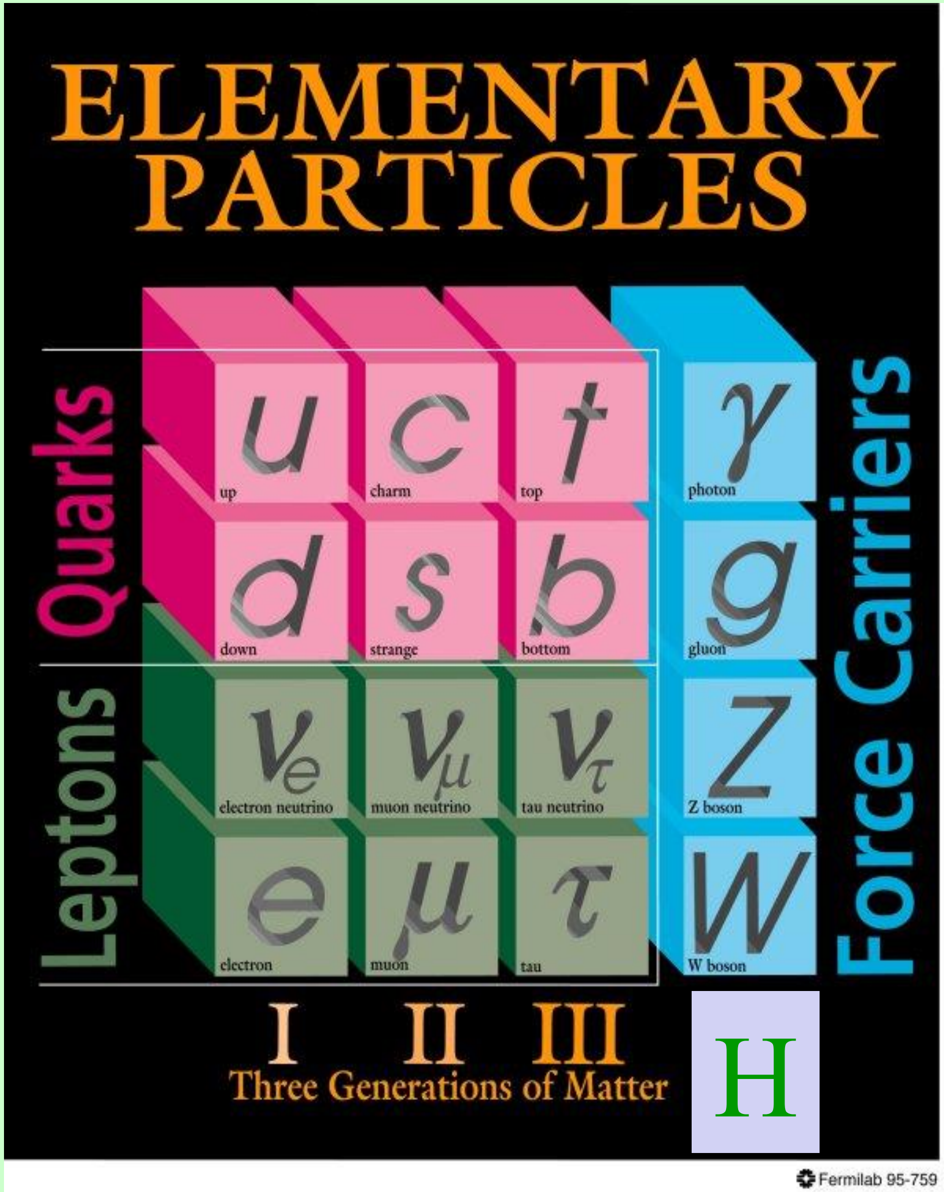
- Differences in DNA (you vs me, humans vs clams)

- Difference in particle properties: neutron mass is larger then proton mass → n decays while p is stable

→ **we exist**

- matter is slightly different than antimatter

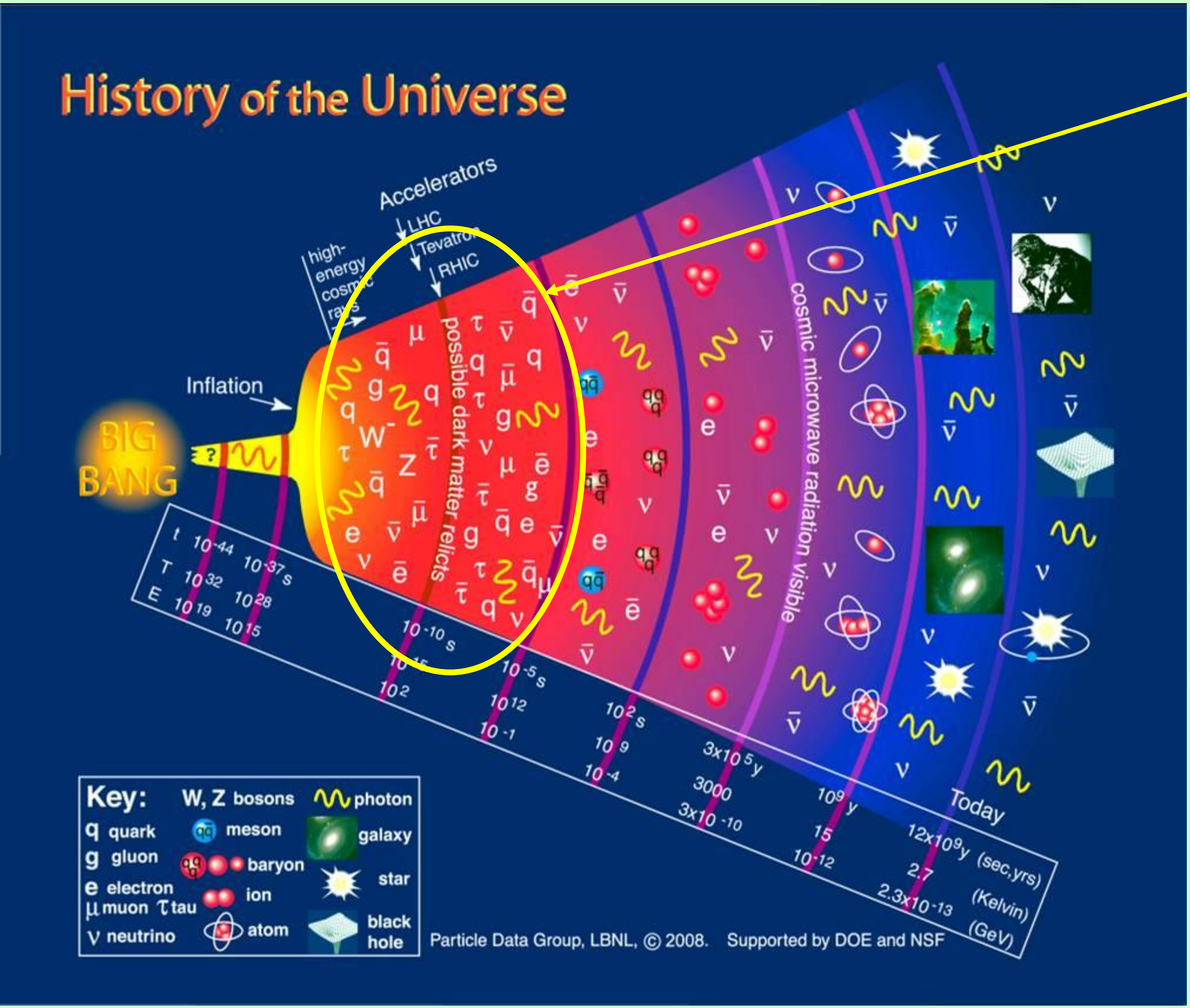
→ **we exist**



•Have antiparticles for quarks and leptons
electron vs positron
proton (uud) vs antiproton

• II and III generations decay to I generation through Weak interactions
muon → electron + 2 neutrinos

• These intergenerational decays give rise to matter-antimatter differences



early Universe was hot enough to make particle-antiparticle pairs:

$$\gamma \rightarrow b + \bar{b}$$

$$g \rightarrow b + \bar{b}$$

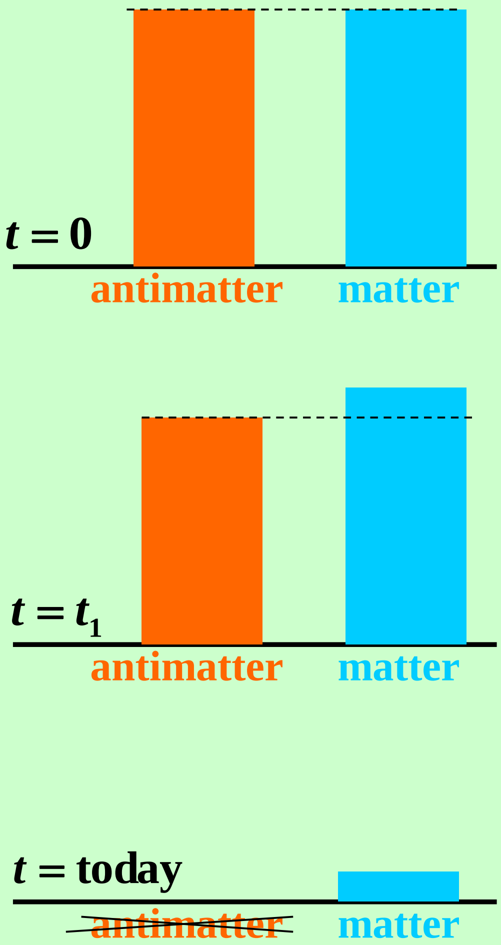
$$\gamma \rightarrow \mu^+ + \mu^-$$

$$\gamma \rightarrow e^+ + e^-$$

etc

Matter – Antimatter Asymmetry

- early universe: very hot, makes matter-antimatter
- For some reason matter becomes more abundant in the early stages of Universe
- Antimatter completely annihilated
- Hence we're left only with matter today:
  (0.25 protons, ~10^9 photons, ~10^8 neutrinos+antineutrinos)/m^3
- Fossil evidence from early Universe
- One of major challenges of particle physics – explain the dominance of matter in our Universe



Matter-Antimatter Difference = CP Violation

- In particle physics matter-antimatter differences are called “CP Violation”

- C   changes particle to antiparticle
- P   operator flips space (mirror image)
- T   time reversal   t → -t

CP Violation: Observations 50 Years ago

1 Universe is mostly matter, need CP violation in very early Universe. Andrei Sakharov

2 CP violation observed in the decays of strange quark eigenstates. Jim Cronin and Val Fitch

3 CP violation observed in electron and muon charge asymmetries in strange quark decays. Mel Schwartz

Sakharov, 1975 Nobel Peace Prize

Cronin and Fitch, 1980 Nobel Prize for Physics

Schwartz, 1988 Nobel Prize for Physics (for discovering the muon type neutrino)

CP Violation: Observation vs Matter in Universe

All observations of CP violation in heavy quark decay BEFORE 2018 are much, much lower than the amount needed in the first instance of creation to explain the amount of matter in the Universe, the matter-antimatter asymmetry

→ Many experiments since 1970 have looked for larger effects

→Need something new.

Best current bet: look at lepton sector: neutrinos, electrons, muons

Note: 8 authors on 1979 proposal

A Study of Direct CP Violation in the Decay of the Neutral Kaon via a Precision Measurement of $|\eta_{oo}/\eta_{+-}|$

R. Bernstein, J.W. Cronin, and B. Winstein

University of Chicago, Enrico Fermi Institute, Chicago, Illinois

B. Cousins, J. Greenhalgh, and M. Schwartz

Stanford University, Department of Physics, Stanford, California

D. Hedin and G. Thomson

University of Wisconsin, Department of Physics, Madison, Wisconsin

CP violation in strange quark decay

Fermilab proposal 617 January 1979

wrong. very small effect. new physics must come from somewhere else

ABSTRACT

In this proposal, we describe an experiment to measure the ratio R of the CP violating amplitudes $|\eta_{oo}|$ and $|\eta_{+-}|$ to a precision of better than 1% thereby improving the present results by about one order of magnitude. If the CP violation is confined to the mass matrix, R = 1.0 exactly. Recent theoretical considerations which unify the CP violating interaction with the CP conserving weak and electromagnetic interactions among six quarks predict R differing from 1.0 by sizable amounts.

NIU Fermilab Experiments

D0   1986-2018   data collection ended 2011

Faculty: DH, Dan Kaplan, Sue Willis, Jim Green, Jerry Blazey, Mike Fortner, Dhiman Chakraborty, Mike Eads, Vishnu Zutshi

11 scientists, 124 NIU students, 19 MS+PhD degrees

Mu2E 2011-2018   data collection 2022-2025

Faculty: DH, Nick Pohlman, Jerry Blazey, Vishnu Zutshi

7 scientists, 32 NIU students, 9 MS degrees

Muon g-2   2012-2018   data collection 2017-2019

Faculty: Mike Eads, Nick Pohlman, Mike Fortner, Mike Syphers, Swapan Chattopadhyay

2 scientists, 15 NIU students, 8 MS degrees plus 5 high school students and 35 engineering design students

DUNE 2016-2018   data collection 2026 – ∞

Faculty: Vishnu Zutshi, Mike Eads, Jerry Blazey, Swapan Chattopadhyay

2 scientists, 2 NIU students

Total: 173 employed students (DOE, NSF, Fermilab

D0 Timeline

Large Angle Particle D0 Group

1982 Proposal. 6 institutions, 31 physicists (6 remain on D0 in 2013)

M.R. Adams,[s] L. Ahrens,[a] S. Aronson,[a] J. Callas,[b], D. Cutts,[b]
R. Dixon,[f] R. Engelmann,[s] D. Finley,[f] G. Finocchiaro,[s]
P. Franzini,[c] B. Gibbard,[a] M.L. Good,[s] P.D. Grannis,[s] M. Harrison,[f]
D. Hedin,[s] J. Horstkotte,[s] H. Jostlein,[f] T. Kafka,[s] J. Kirz,[s]
R.E. Lanou,[b] J. Lee-Franzini,[s] M. Marx,[s] P. Mazur[f] R.L. McCarthy,[s]
B.G. Pope,[p] C. Rad,[f] R.D. Schamberger,[s] T. Shinkawa,[b] P. Tuts,[s]
H. Weisberg,[a] P. Yamin[a]

(Brookhaven[a] - Brown[b] - Columbia[c] - Fermilab[f] -
Princeton[p] - Stony Brook[s] Collaboration)

1982 Initial proposals

1985 Approved for construction

1986 NIU joins D0

1992-1996 Data Collection I

1993 First top-antitop quarks observed

1995 Top quark discovery published

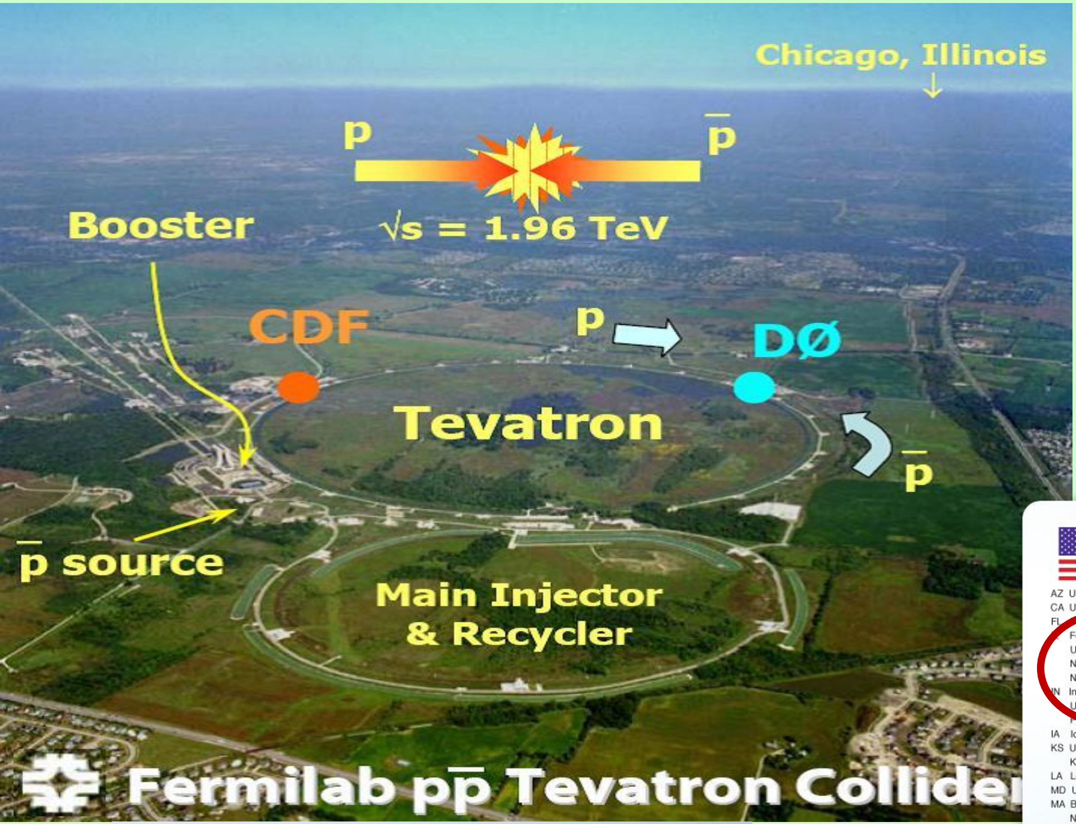
1996-2001 Rebuild detector

2001-2011 Data Collection II

2002-2006 Jerry Blazey D0 spokesperson

2010-2012 D0 observes possible large matter-antimatter asymmetry, sees "evidence" for Higgs boson with discovery at CERN

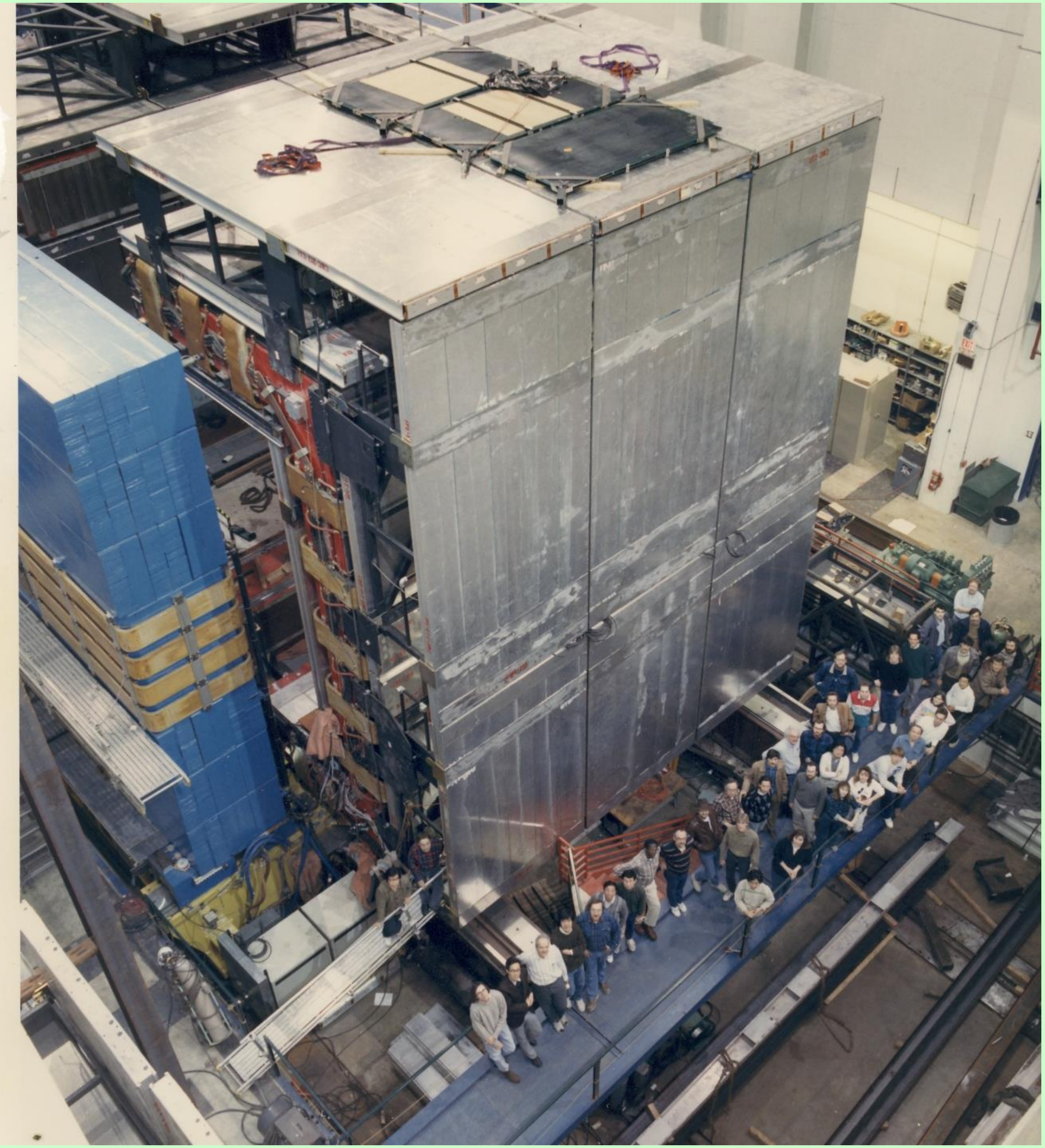
D0 Collaboration



82 institutions

19 countries

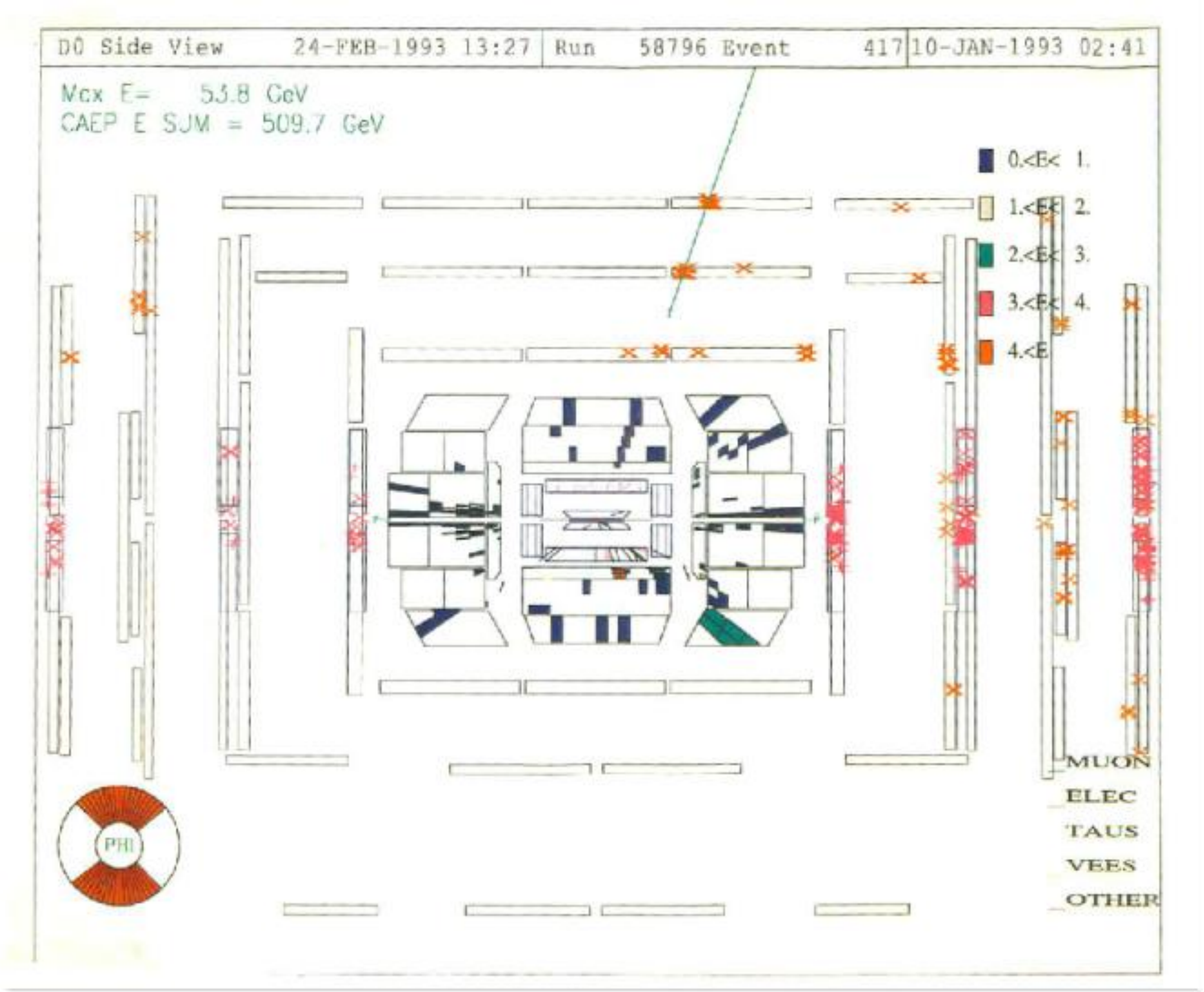
~500 physicists



D0 Detector

muon system under construction
January 1990
13 from NIU in photo
In 1990 the NIU HEP group had 25 members: 18 on D0 and 7 on a fixed target experiment. The size was due to the strong support from D0 and Fermilab (Paul Grannis, Gene Fisk, Ernie Malamud) to provide funds to support NIU students. NIU support from Jim Norris and Jerry Zar helped to initiate

D0 is now a museum with 2-5 tour groups/week visiting the detector, control room, and Tevatron tunnel



First observed top-antitop quark event

Jan 10, 1993

Muon event display software written by NIU biology major Carol Francis and NIU research associate Tami Kramer

That muon track is a straight line which indicates it is very high energy. Red deposition in calorimeter is a high energy electron

1995: Top Quark Discovery


VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B.S. Acharya,[43] I. Adam,[10] D.L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[36] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[38] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[7] J. Bendich,[20] S.B. Beri,[31] I. Bertram,[34] V.A. Bezzubov,[32] P.C. Bhat,[12] V. Bhatnagar,[31] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] A. Boehnlein,[12] N.I. Bojko,[32] F. Borcherding,[12] J. Borders,[35] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[28] V.S. Burtovoi,[32] J.M. Butler,[12] D. Casey,[35] H. Castilla-Valdez,[9] D. Chakraborty,[38] S.-M. Chang,[27] S.V. Chekulaev,[32] L.-P. Chen,[20] W. Chen,[38] L. Chevalier,[36] S. Chopra,[31] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[38] A.R. Clark,[20] W.G. 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Gibbard,[3] M. Glaubman,[27] V. Glebov,[35] S. Glenn,[5] J.F. Glicenstein,[36] B. Gobbi,[28] M. Goforth,[13] A. Goldschmidt,[20] B. Gomez,[1] P.I. Goncharov,[32] H. Gordon,[3] L.T. Goss,[42] N. Graf,[3] P.D. Grannis,[38] D.R. Green,[12] J. Green,[28] H. Greenlee,[12] G. Griffin,[6] N. Grossman,[12] P. Grudberg,[20] S. Grünendahl,[35] J.A. Guida,[38] J.M. Guida,[3] W. Guryn,[3] S.N. Gurzhiev,[32] Y.E. Gutnikov,[32] N.J. Hadley,[21] H. Haggerty,[12] S. Hagopian,[13] V. Hagopian,[13] K.S. Hahn,[35] R.E. Hall,[6] S. Hansen,[12] R. Hatcher,[23] J.M. Hauptman,[17] D. Hedin,[28] A.P. Heinson,[7] U. Heintz,[12] R. Hernández-Montoya,[9] T. Heuring,[13] R. Hirosky,[13] J.D. Hobbs,[12] B. Hoeneisen,[1,§] J.S. Hoftun,[4] F. Hsieh,[22] Ting Hu,[38] Tong Hu,[16] T. Huehn,[7] S. Igarashi,[12] A.S. Ito,[12] E. James,[2] J. Jaques,[30] S.A. Jerger,[23] J.Z.-Y. Jiang,[38] T. Joffe-Minor,[29] H. Johari,[27] K. Johns,[2] M. Johnson,[12] H. Johnstad,[39] A. Jonckheere,[12] H. Jöstlein,[12] S.Y. Jun,[29] C.K. Jung,[38] S. Kahn,[3] J.S. Kang,[18] R. Kehoe,[30] M. Kelly,[30] A. Kernan,[7] L. Kerth,[20] C.L. Kim,[18] S.K. Kim,[37] A. Klatchko,[13] B. Klima,[12] B.I. Klochkov,[32] C. Klopfenstein,[38] V.I. Klyukhin,[32] V.I. Kochetkov,[32] J.M. Kohli,[31] D. Koltick,[33] A.V. Kostritskiy,[32] J. Kotcher,[3] J. Kourlas,[26] A.V. Kozelov,[32] E.A. Kozlovski,[32] M.R. Krishnaswamy,[40] S. Krzywdzinski,[12] S. Kunori,[21] S. Lami,[38] G. Landsberg,[12] R.E. Lanou,[4] J-F. Lebrat,[36] J. Lee-Franzini,[38] A. Leflat,[24] H. Li,[38] J. Li,[41] Y.K. Li,[29] Q.Z. Li-Demarteau,[12] J.G.R. Lima,[8] D. Lincoln,[22] S.L. Linn,[13] J. Linnemann,[23] R. Lipton,[12] Y.C. Liu,[29] F. Lobkowicz,[35] S.C. Loken,[20] S. Lökös,[38] L. Lueking,[12] A.L. Lyon,[21] A.K.A. Maciel,[8] R.J. Madaras,[20] R. Madden,[13] I.V. Mandrichenko,[32] Ph. Mangeot,[36] S. Mani,[5] B. Mansoulié,[36] H.S. Mao,[12,†] S. Margulies,[15] R. Markeloff,[28] L. Markosky,[2] T. Marshall,[16] M.I. Martin,[12] M. Marx,[38] B. 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Vorobiev,[32] H.D. Wahl,[13] J. Wang,[12,†] L.Z. Wang,[12,†] J. Warchol,[30] M. Wayne,[30] H. Weerts,[23] W.A. Wenzel,[20] A. White,[41] J.T. White,[42] J.A. Wightman,[17] J. Wilcox,[27] S. Willis,[28] S.J. Wimpenny,[7] J.V.D. Wirjawan,[42] Z. Wolf,[39] J. Womersley,[12] E. Won,[35] D.R. Wood,[12] H. Xu,[4] R. Yamada,[12] P. Yamin,[3] C. Yanagisawa,[38] J. Yang,[26] T. Yasuda,[27] C. Yoshikawa,[14] S. Youssef,[13] J. Yu,[35] Y. Yu,[37] Y. Zhang,[12,†] Y.H. Zhou,[12,†] Q. Zhu,[26] Y.S. Zhu,[12,†] Z.H. Zhu,[35] D. Zieminska,[16] A. Zieminski,[16] A. Zinchenko,[17] and A. Zylberstejn[36]

(D0 Collaboration)

402 authors from D0
15 from NIU:
1995: Mike Fortner, Jim Green, Dave Hedin, Rich Markeloff, Vladimir Sirotenko, Sue Willis
After 1995: Pushpa Bhat (adjunct), Jerry Blazey, Dhiman Chakraborty, Mary Anne Cummings, Guilherme Lima, Arthur Maciel, Manuel Martin
Former NIU students: Ray Brock, Jim McKinley

CDF co-published discovery

In 2010 the D0 experiment showed evidence that there is a 4.2σ difference between the number of observed $\mu+$ and observed $\mu-$ events in $6x10^{14}$ proton-antiproton collisions with over 2 billion observed muons. Larger than what is expected. Lots of media attention but so far not confirmed by other experiments

The New York Times
A New Clue to Explain Existence

TIME
Big News About Small Particles. And Why You Care

SCIENTIFIC AMERICAN
Fermilab Finds New Mechanism for Matter's Dominance over Antimatter

FORTE
Teadlased avastasid aine ja antiaine ebasümmeetria

HABERCİNİZ
Haber: Evrendeki Dengelere Yeni Denklem

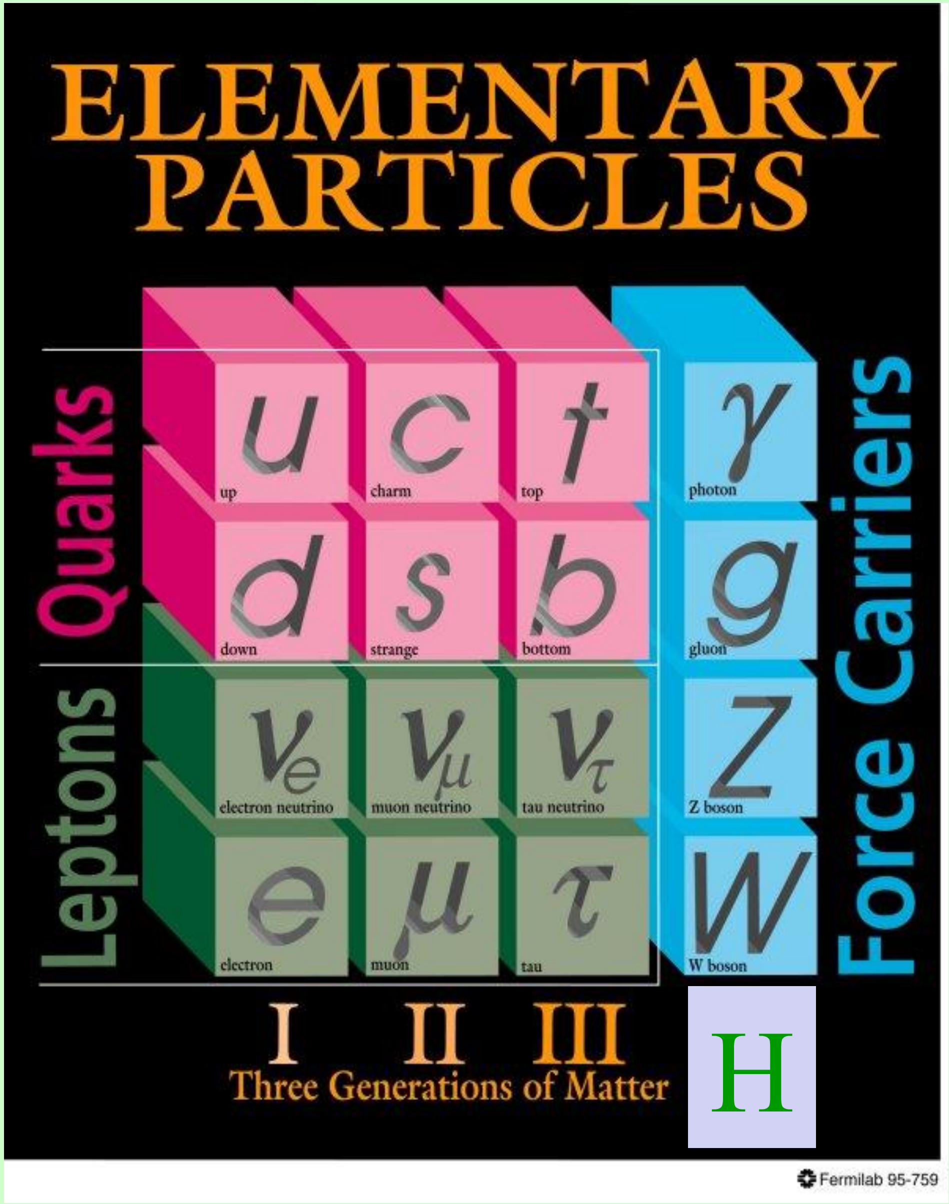
RL Romania libera.ro
Noi descoperiri în misterul antimateriei

Telegraph
Atom smasher offers new clue to mystery of universe's formation

САМАРА сегодня
Почему мы существуем: как материя побеждает антиматерию

中国新闻网
WWW.CHINANEWS.COM.CN
宇宙何以充斥物质而不是反物质？

europapress.es
El Tevatrón halla una pista para entender la composición del Universo



- matter-antimatter differences in quark sector (using s and b quark transitions to lighter quarks) are not large enough to account for the amount of matter in the Universe
- How about the lepton sector?
- Neutrinos oscillate, change from one type to another. Is there a difference between neutrino and antineutrino oscillations?
- Are there new effects in the muon-electron system?

Electron first particle to be discovered, 1897. muon first second generation particle to be discovered, 1936. New studies of e,μ may help explain

DUNE: Deep Underground Neutrino Experiment

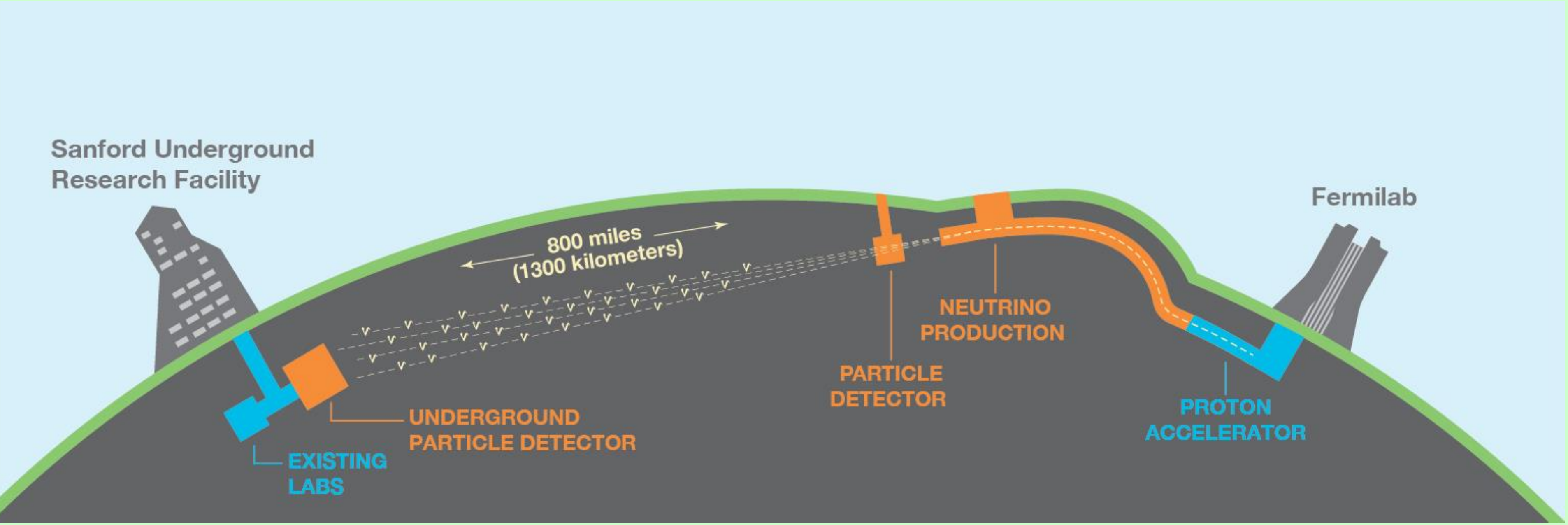
176 institutions with >1,100 scientists
From NIU: Vishnu Zutshi, Jerry Blazey, Swapan Chattopadhyay, Nathan Dille, Sasha Dychkant, Mike Eads, Kurt Francis, Logan Rice

Beams of muon-type neutrinos and anti-neutrinos can change (oscillate) to electron-type or tau type

$\nu_\mu \rightarrow \nu_\tau , \nu_e$

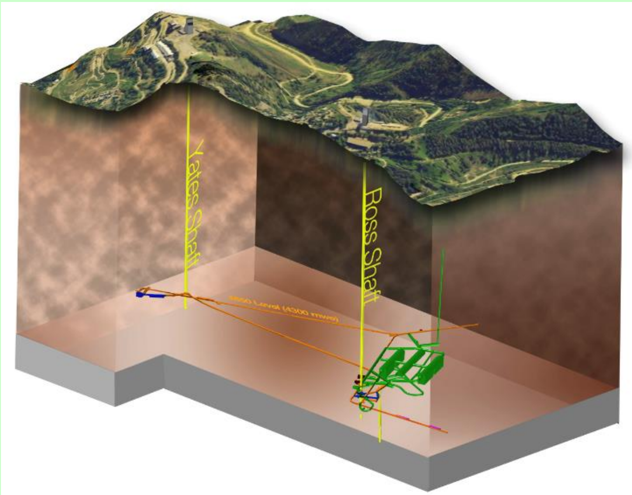
Long distance increases probability to oscillate

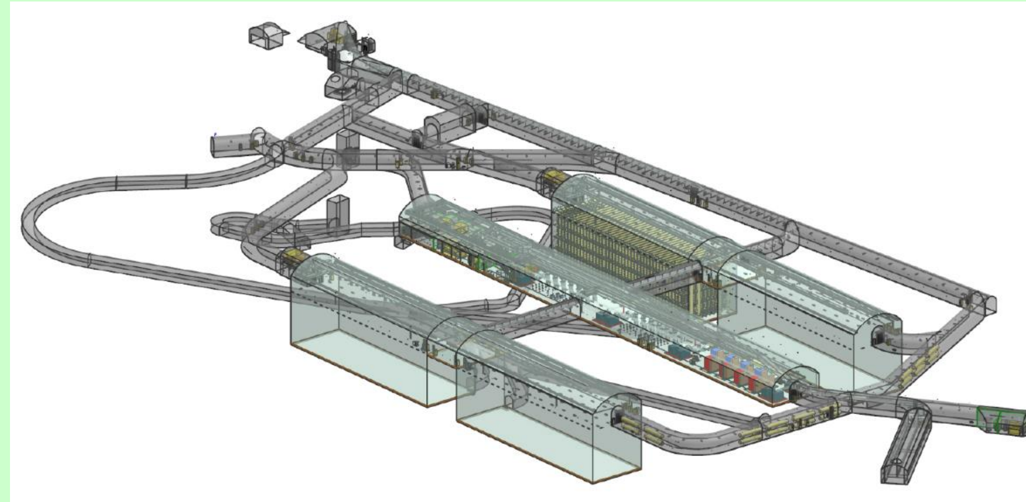
DUNE: Deep Underground Neutrino Experiment



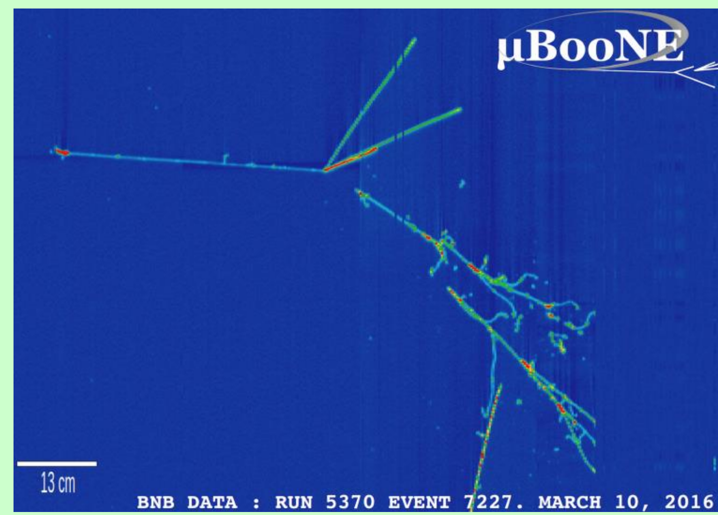
Long Baseline Neutrino Facility (LBNF) at Fermilab will produce the beams of muon-type neutrinos and antineutrinos. Particle detectors made from instrumented tanks of liquid Argon will be sited at Fermilab and South Dakota. Beam energy and 1300 km distance optimizes the ability to look for neutrino-antineutrino oscillation differences

DUNE: Deep Underground Neutrino Experiment





The detectors in South Dakota will be installed 1,475 m underground to reduce backgrounds from cosmic rays. 68,000 tons of liquid Argon will be contained in 4 cryostats with wire chambers and silicon photodetectors used to detect the particles produced by the neutrino interactions in the Argon.



Muon g-2 and Mu2e Experiments

Muon g-2

Mu2e

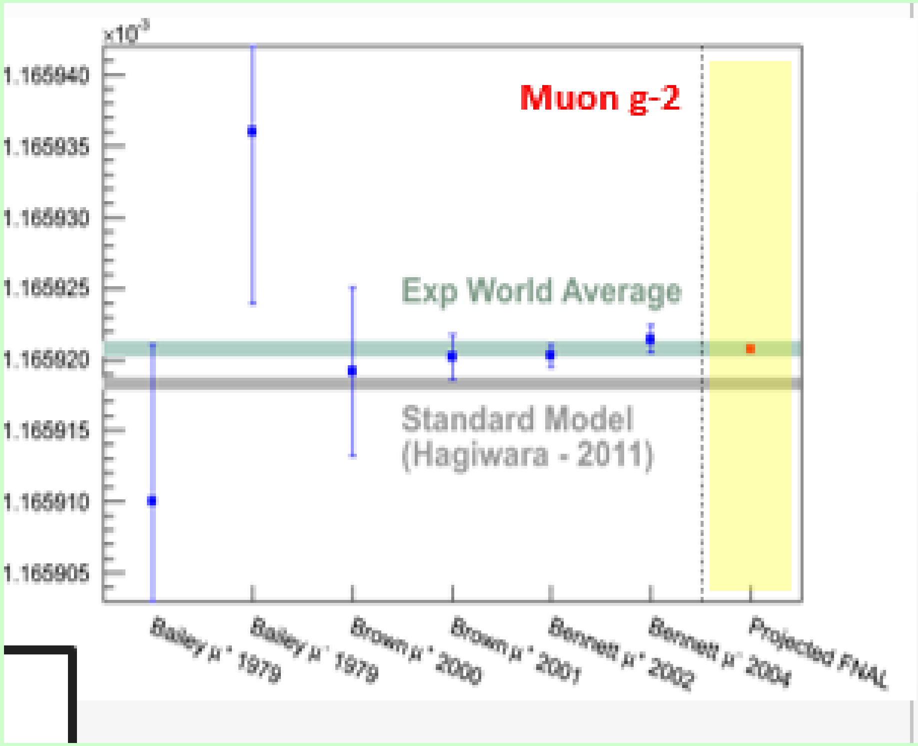
Observing large CP violations in neutrino oscillations will point to the source of the Universe's matter-antimatter differences. Studies of muons may point to the underlying mechanisms. Fermilab's Muon Campus will provide high intensity proton beams which are used to make muons for new experiments: muon g-2 and Mu2e

Muon g-2 Experiment

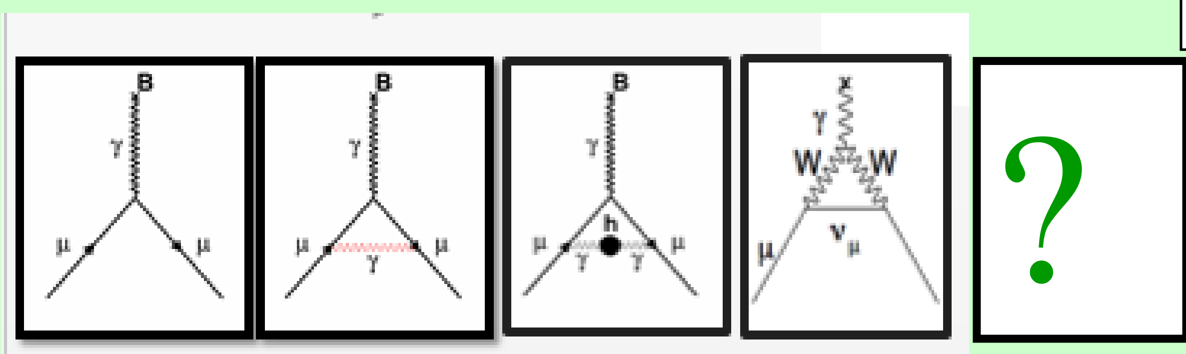
Measure the magnetic moment of the muon using a magnet moved from Long Island

From NIU: Mike Eads, Dan Boyden, Swapan Chattopadhyay, Gavin Dunn, Nick Pohlman, Mike Syphers

Muon g-2 Experiment



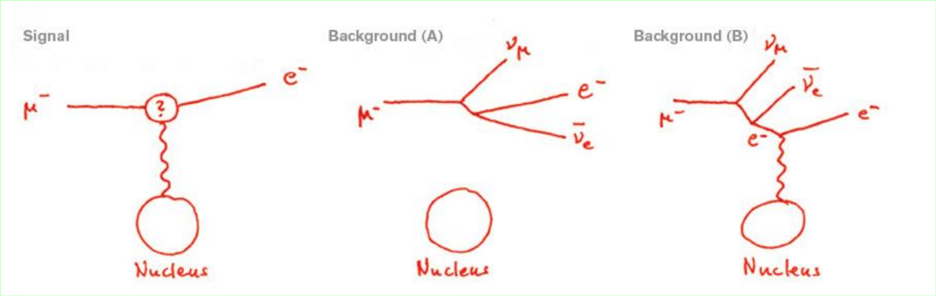
Current measurement of the muon's magnetic moment disagrees with the expected value which depends on the masses of the known particles. Goal of the Fermilab experiment is to improve the precision.



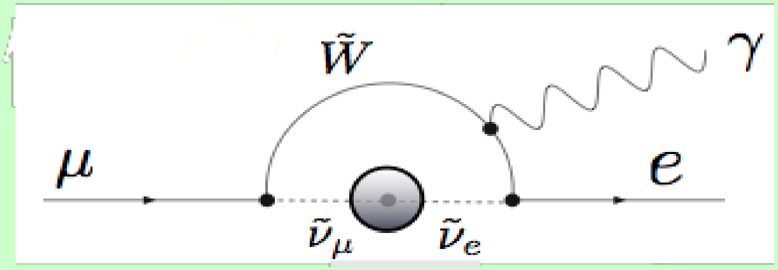
Mu2e Experiment

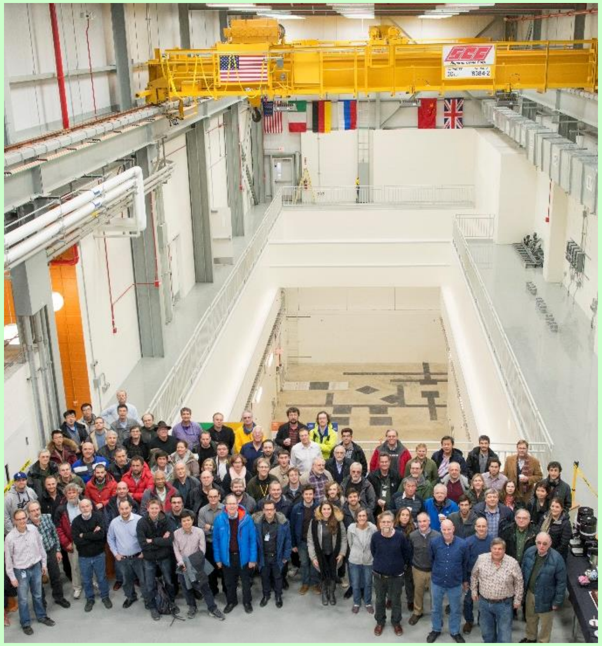
$$\mu^- + \mathbf{Al} \rightarrow e^- + \mathbf{Al}$$

Stop muons in Aluminum and measure the rate of directly converting to an electron. Usually muon decay produces 2 neutrinos which conserve "lepton" number



Sensitive to many new mechanisms: this show supersymmetry but also leptoquarks…

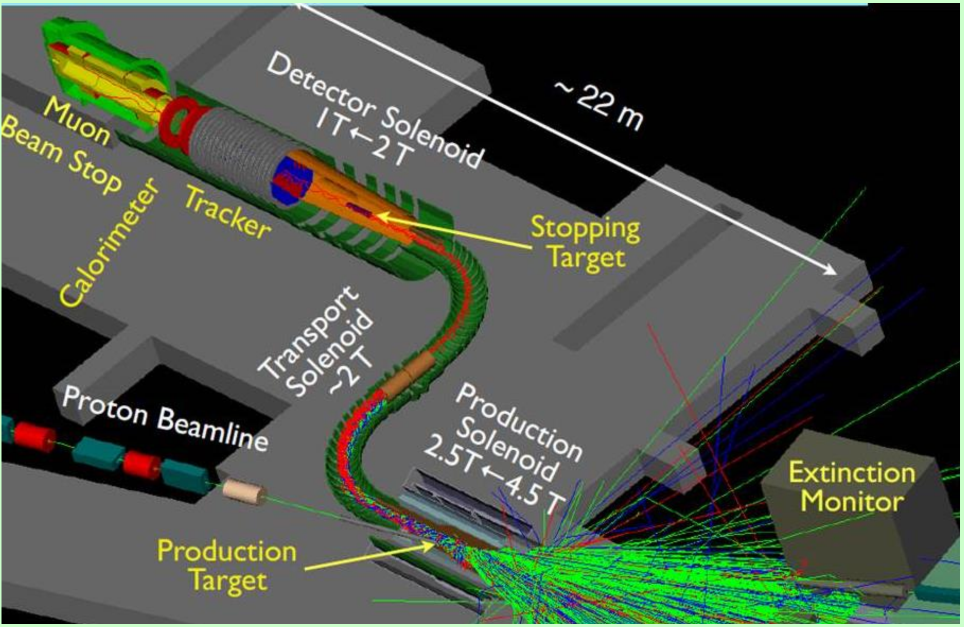




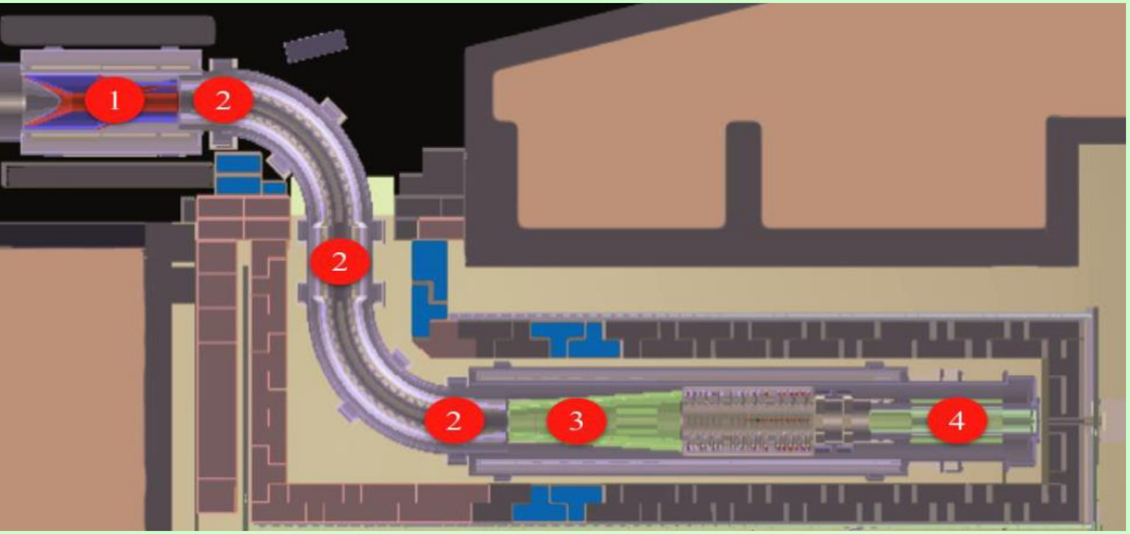
34 institution, 273 collaborators

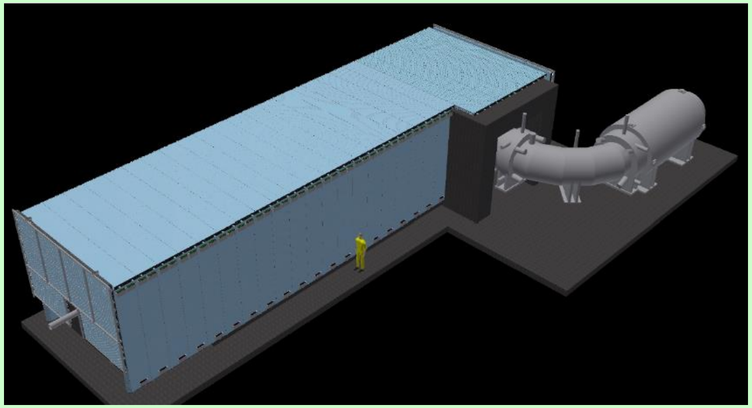
From NIU: DH, Jerry Blazey, Jake Colston, Dayne Coveyou, Nathan Dille, Sasha Dychkant, Kurt Francis, Jacob Kalnins, Nathan Luptak, Colin Naurig, Nick Pohlman, Jaime Serrano, Sergey Uzunyan, Vishnu Zutshi

Mu2e Experiment



Protons hit the target (1), pions move through solenoid (2) producing low energy muons which stop in the Aluminum (3) with electrons from their decays detected in the tracker and calorimeter. About ½ the muons stop in the Muon Beam Stop. The detector is surrounded by the Cosmic Ray Veto with concrete shielding needed to minimize CRV rate. Goal: 10,000 better current, sensitivity of 10^{-18}





Cosmic Ray Veto

Conclusion

- We live in a matter-dominated world (plus dark matter and dark energy but that's another talk)
- Related to CP violation and quark or lepton mixing but the physics is not yet well-understood
- Something new is needed. Next generation of Fermilab neutrino and muon experiments will look for new mechanisms that may, at least partially, answer some of these questions
- The NIU Fermilab-based particle physics group is contributing to three of these new projects which will continue beyond the next decade

(last slide)(very early promo) **STEMfest**

Saturday October 27, 2018 10 am to 5 pm
Convocation Center – free event