Particle Physics Topics

Status of the Field

Herman B. White

Fermi National Accelerator Laboratory

July 25, 2012

ASP2012

Kumasi, Ghana

U.S. DEPARTMENT OF ENERGY

Fermilab

Outline

Particles and the makeup of matter

Symmetry Properties

Anti-Matter

Kaon Physics Experiments

Neutrino Physics Experiments

The Intensity Frontier and Precision Measurements

Charged Lepton Flavor Violation

Mu2e

Physics Drivers

1940's	Basic Nuclear Structures Studies	Cyclotrons
	Nuclear Structure	
		-QED
1950's-60's	Particle and Particle Properties	Synchrotrons
1960's-70's	Substructure	
		-QCD
1980's-2000	Finishing the Standard Model	Lepton Colliders
		SSC, TeV
2000-----	Search for new particles	LHC, TeV
	Symmetries and New Matter Types	

Fixed Target Mode of Experimentation

(a beam of particles and a stationary target)

Colliding Beams Mode of Experimentation

(Counter rotating nearly head-on beam-beam collisions)

Fermilab

- Collider Tevatron
- Collider LHC

- Fixed Target

Using the Early Tevatron

$$E_{CM} \simeq 2E_{beam}$$

$$E_{CM} \simeq \sqrt{2ME_{beam}}$$

- Early Tevatron~1960 GeV
- LHC ~7 TeV

- ~40 GeV

- E_{beam} = 800 GeV

Different advantages in both techniques

Beam-Beam

- About twice the collision energy and luminosity of ~10^{32}/cm^2/sec and slightly higher now
- Close approximation to the interaction site location

Fixed Target

- Many targeting centers and Avagadro’s number
- Mostly limited by the beam energy
- Higher Luminosity (10^{13} Protons/min extracted which leads to ~ 10^{36}/cm^2/sec luminosity)

- In these next two lectures
  - The current status of physics in the fixed target configuration
  - Possible lepton collider beams
  - Exciting research in Hadron Collider beams.

- This focus will include some information on
  - Symmetry properties and Kaon Physics
  - Neutrino Physics
  - B meson physics and its importance

- Symmetry Properties
- P, CP, CPT

Open Questions in Particle Physics

- What is the origin of the mass? (Are we there yet?)
- What is dark matter? What is dark energy?
- Why is there more matter than antimatter in the universe?
- Why are there many different kinds of elementary particles? Do quarks and leptons have substructure?

Conservation laws and symmetries are closely related.

Energy conservation < > Time symmetry

Momentum conservation < > Displacement symmetry

Angular momentum < > Rotational symmetry

Continuous Symmetries

i. Translational (x,y,z >> 3 degrees of freedom)

.........Momentum (P_x, P_y, P_z ....)

ii. Temporal (T>>> 1 degree of freedom)

....Energy (E>>1 degree of freedom)

iii. Rotational (θ_1, θ_2, θ_3 >> 3 degrees of freedom)

For each of these Continuous symmetries there exist a Conservation Law

Dynamical Conservation Laws

I. Conservation of Linear Momentum

II. Conservation of Energy

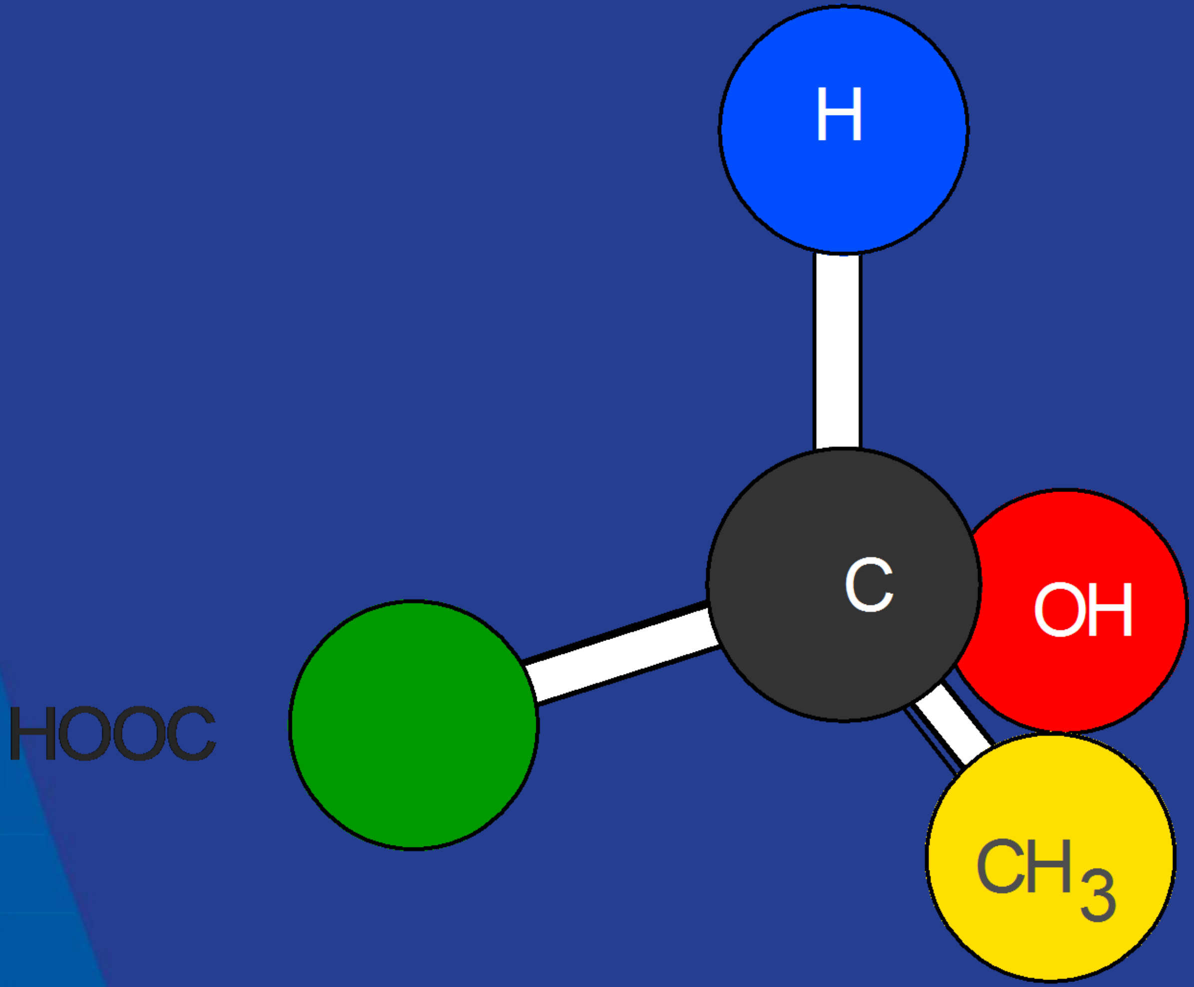
III. Conservation of Angular Momentum

IV. Other Discrete Conservation Laws

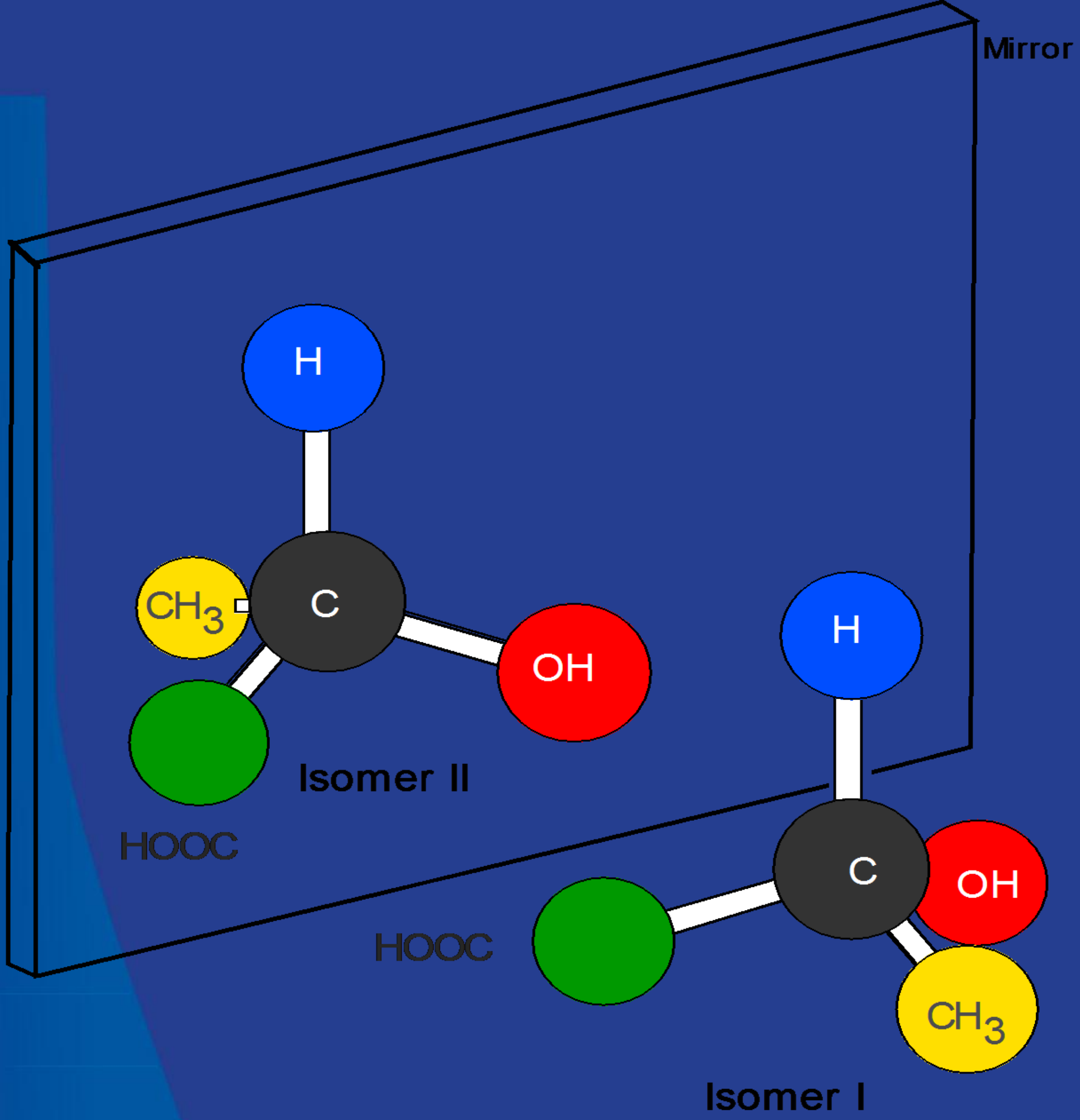
   a. Charge

   b. Baryon and Lepton number

   c. Parity, CP, CPT,……



Isomer I



Lactic Acid

INTRODUCING ANTI-MATTER

In 1929 Paul Dirac formulated a theory with solutions that required the existence of a positive electron or “positron”.

Every “particle” has a partner called an “anti-particle” .

The two have the same mass and the same lifetime (if it decays).

The main difference is that they have OPPOSITE electric charge.

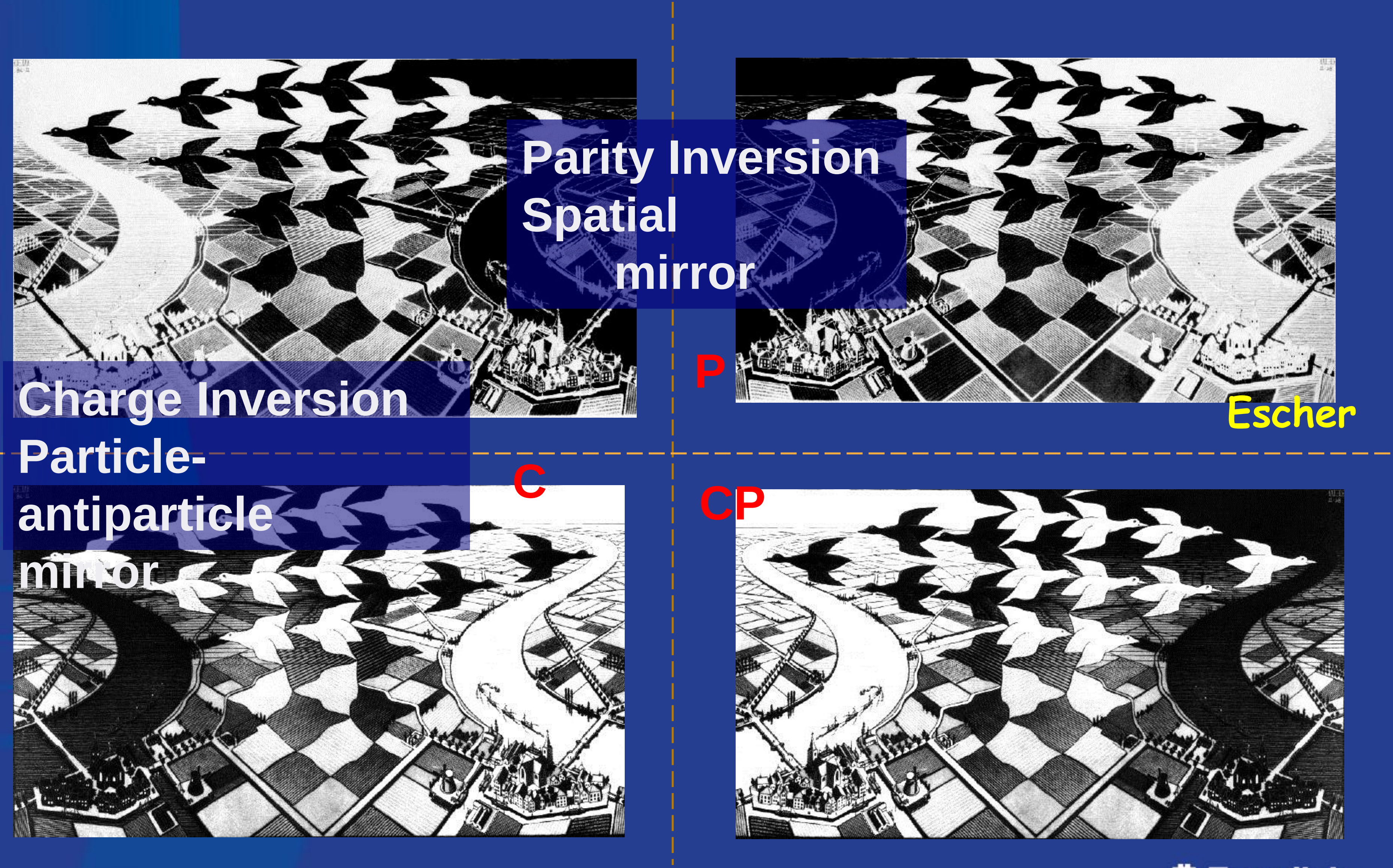
Examples:	Year of discovery
Electron	(1897)
Positron	(1932)
Proton	(1919)
Anti-Proton	(1955)
Neutron	(1932)
Anti-Neutron	(1956)

Fundamental Symmetries of Nature

A Brief Summary

C	**Charge Conjugation**	**(Antimatter World)**
P	**Parity Reversal**	**(Mirror World)**
CP	**C and P Together**	**(Antimatter Mirror World)**
T	**Time Reversal**	**(World Running Backward)**
CPT	**C and P and T**	**(Backward Running Antimatter Mirror World)**

Discrete Symmetries



Parity Inversion
Spatial
mirror

P

Escher

Charge Inversion
Particle-antiparticle
mirror

C

CP

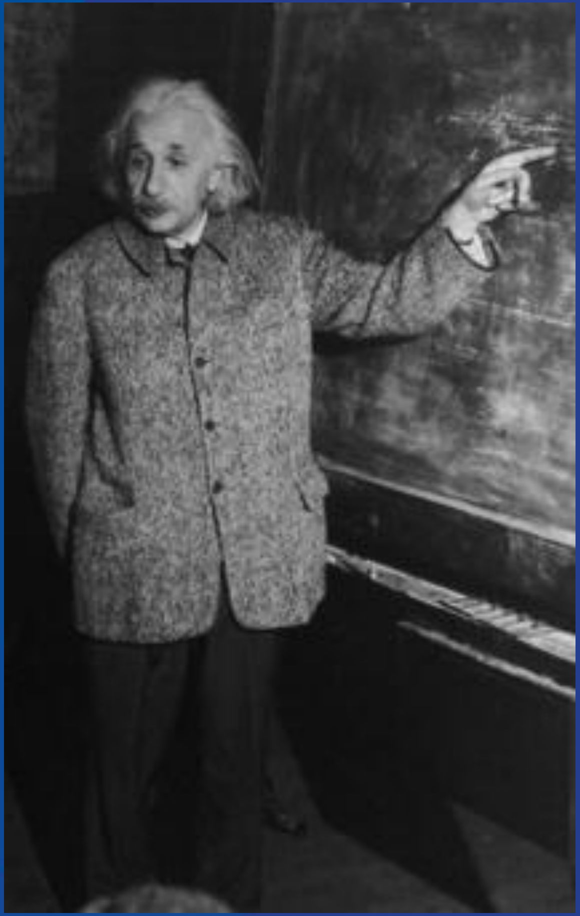
Courtesy: W. Wester, Fermilab

Lincoln University, 1946

Courtesy: Leo Baeck Institute, New York & The Albert Einstein Estate

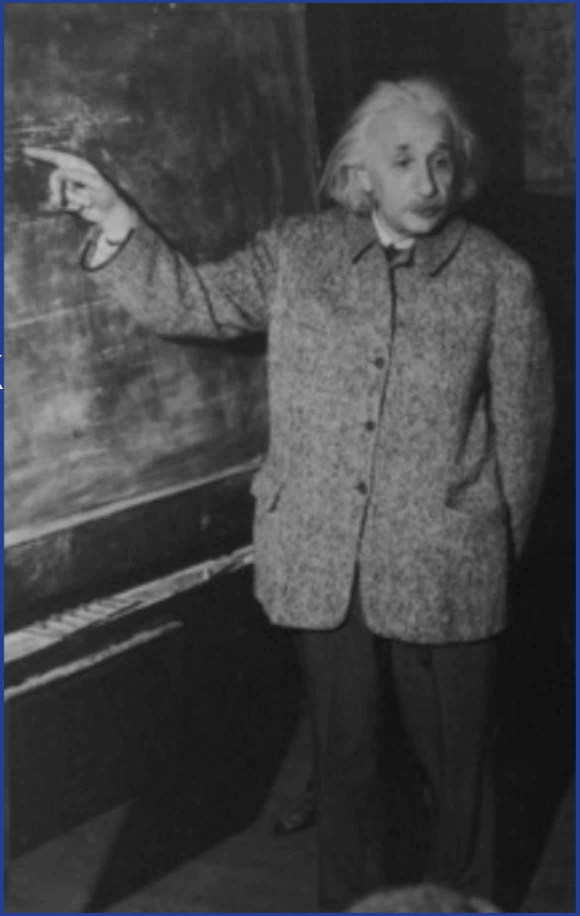
Matter vs. Antimatter

Anti-Albert



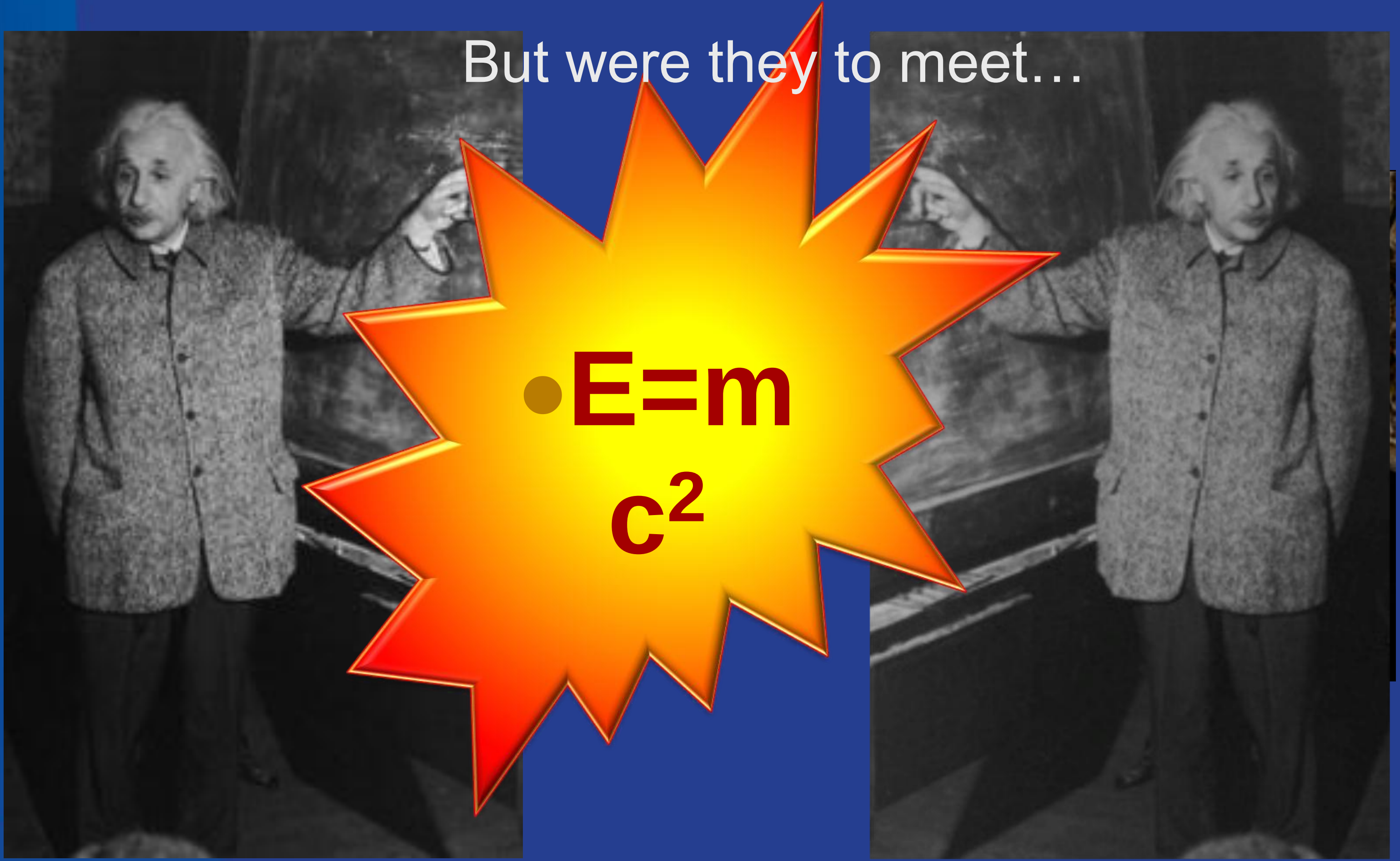
- **Would look very much like**

Albert



Matter vs. Antimatter

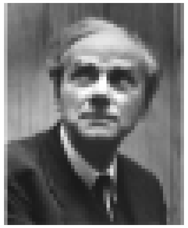
But were they to meet…



- $E=mc^2$

MATTER WITH A BAR MILESTONES IN THE UNDERSTANDING OF ANTIMATTER

Paul Dirac predicts the existence of antimatter.

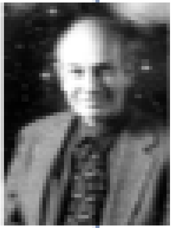


1929

Carl Anderson sees the track of the first antiparticle, the antielectron, or positron, in a cloud chamber at Caltech.

1932

Emilio Segre and Owen Chamberlain observe the antiproton at the Bevatron accelerator at Lawrence Berkeley Laboratory.

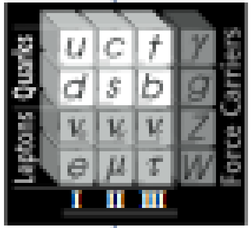


1955

James Cronin and Val Fitch discover CP violation in the mixing of the neutral kaon and its antiparticle (indirect CP violation).

1964

John Ellis, Mary Kay Gaillard, and D. Nanopoulos calculate for the first time the size of ε'/ε in the Standard Model, getting a value of about 0.0022.



1976

Fred Gilman and M. Wise publish the first in long series of refinements to the calculations by many authors, leading to estimates of ε'/ε below 0.001.

1979

Fermilab, Brookhaven and, later, CERN launch experimental efforts to search for CP violation in neutral kaon decays at the level of the Standard Model.

Late 1970s

CERN's NA31 experiment reports first evidence for CP violation in decays of the neutral kaon ($\varepsilon'/\varepsilon = 0.0033$, 3 standard deviations).

1988

Fermilab's E731 experiment reports $\varepsilon'/\varepsilon = 0.00074$, 1.25 standard deviations from zero; CERN reports $\varepsilon'/\varepsilon = 0.0023$, 3.5 standard deviations from zero.

1993

Fermilab (KTeV) and CERN (NA48) begin constructing new, more precise experiments.

1993

KTeV announces a value of 0.00280 for ε'/ε, more than 6 standard deviations from zero, firmly establishing direct CP violation.

1999

Everyone awaits results from CERN's NA48.

1999

- For roughly every billion anti-particles there are one billion and 1 particles.

- This is in effect a broken symmetry, and it is not understood very well.

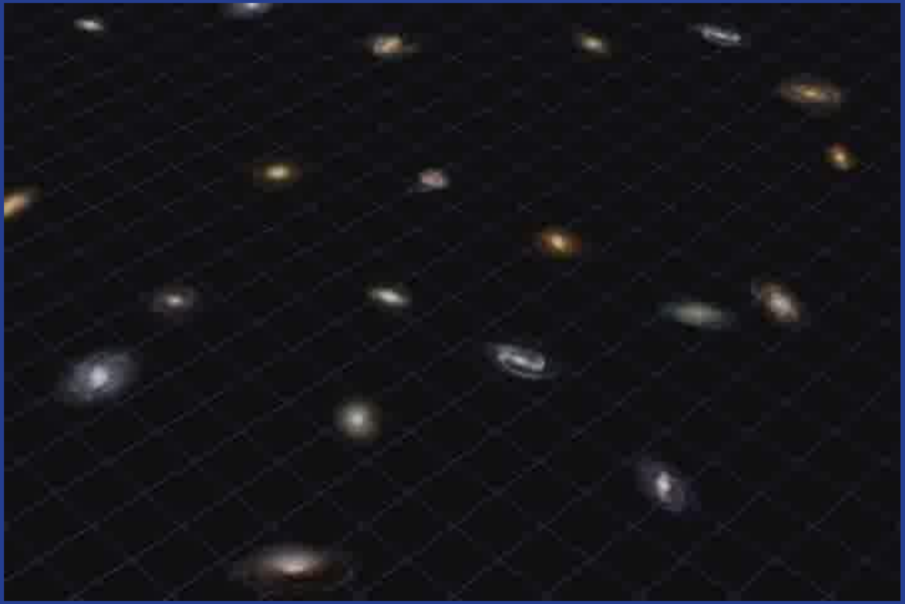
- The cosmic microwave background radiation is the leftover energy from the annihilations.

- Thus as the Universe expands and cools, the pair production stops, and the matter annihilation continues until the anti-matter is depleted (as far as we know).

- The matter left over makes up the matter Universe (Stars, galaxies and Us)

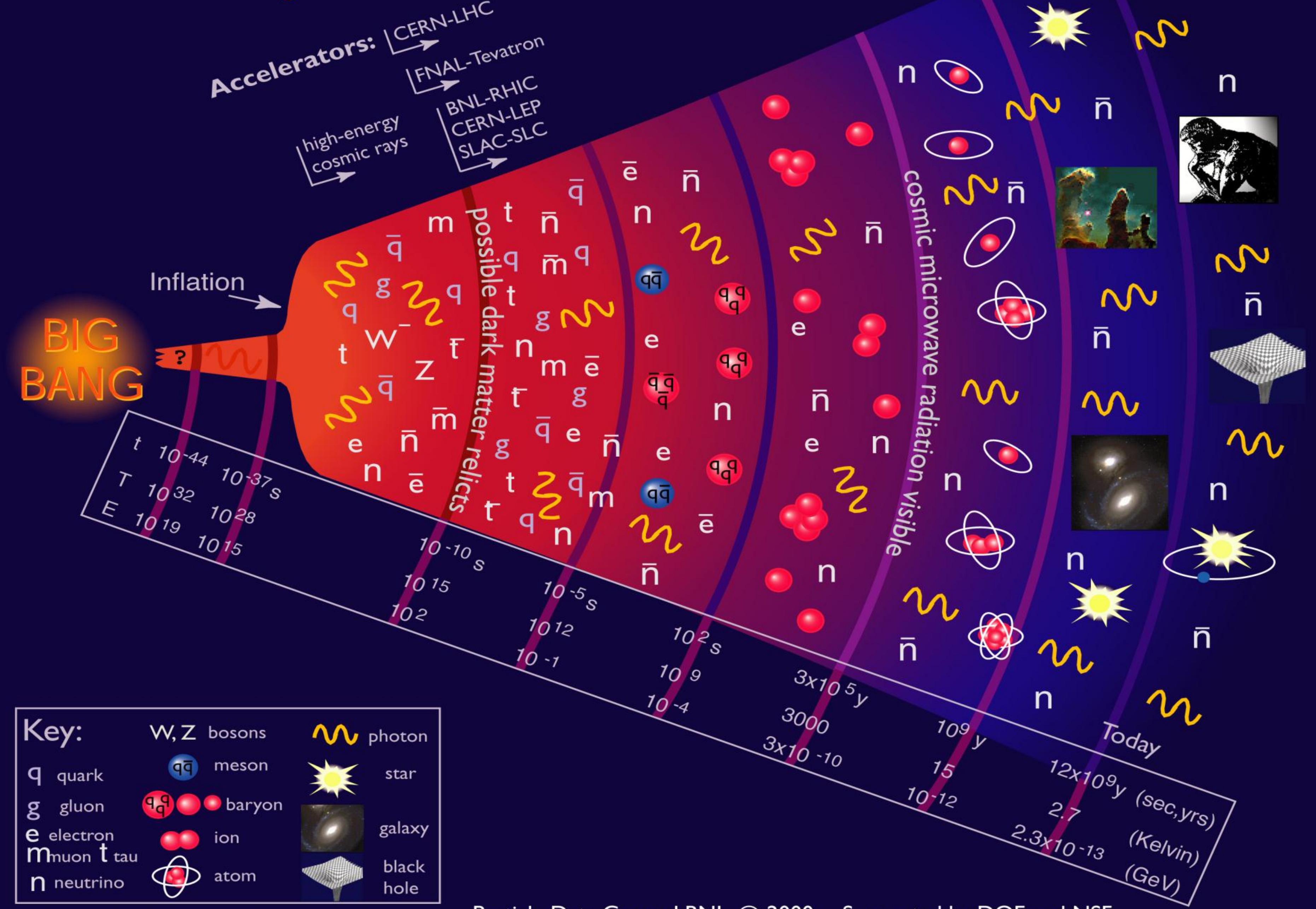
The mystery of antimatter

- We exist because there is almost no antimatter around
- It wasn’t always that way



- NASA/STScI/G.Bacon

History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

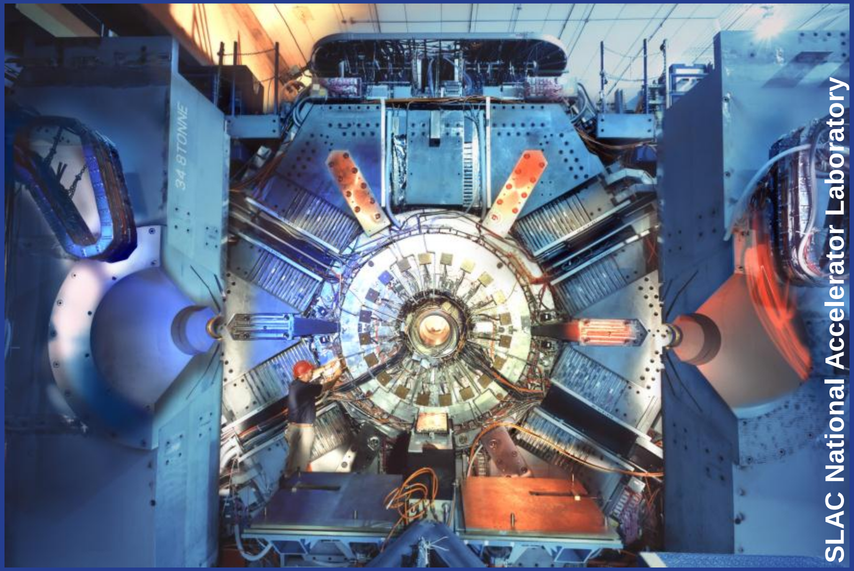
What happened to the antimatter?

- After 40 years of research we know:
- Some particles behave differently from their antiparticles
- The difference is very slight – not enough
- There must be another explanation

Solving the mystery

With quarks

- Particle accelerators produce equal amounts of matter (quarks) and antimatter (anti-quarks)
- So we study the difference between them



SLAC National Accelerator Laboratory

BaBar

Kaon Physics Experimentation

Since the mass and the lifetime for the matter and anti-matter particles are deemed to be the same, we can study the different properties and thus the symmetry of nature by measuring the partial decay rates for these particles.

In nature, symmetry is expected in matter and anti-matter interactions that we can measure, except primarily in the decay of Kaons and B- mesons.

In 1964 the amazing discovery was made that the neutral K^0 and $\overline{K}^0$ decayed differently by about 0.23% !!!

- **Neutral Kaons**

Strangeness Eigenstates :

$$K^0 = \bar{s}d$$

$$\overline{K}^0 = s\bar{d}$$

CP Eigenstates :

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right) \quad (CP + 1)$$

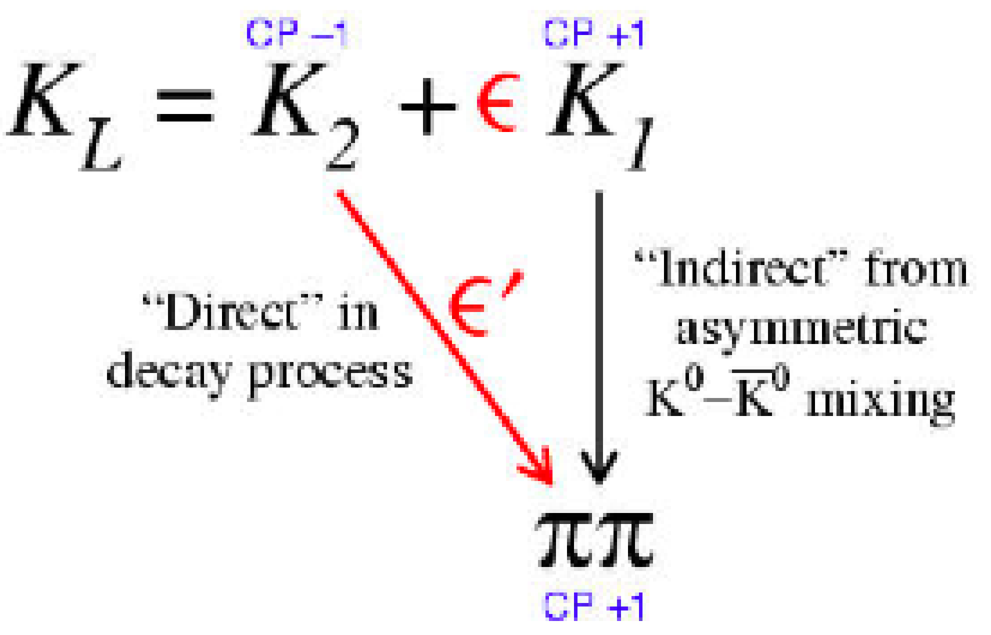
$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right) \quad (CP - 1)$$

CP Violation in Kaon System

Weak Eigenstates :

$$|K_L\rangle \approx |K_2\rangle + \varepsilon |K_1\rangle \qquad (\textit{mostly } CP-1)$$

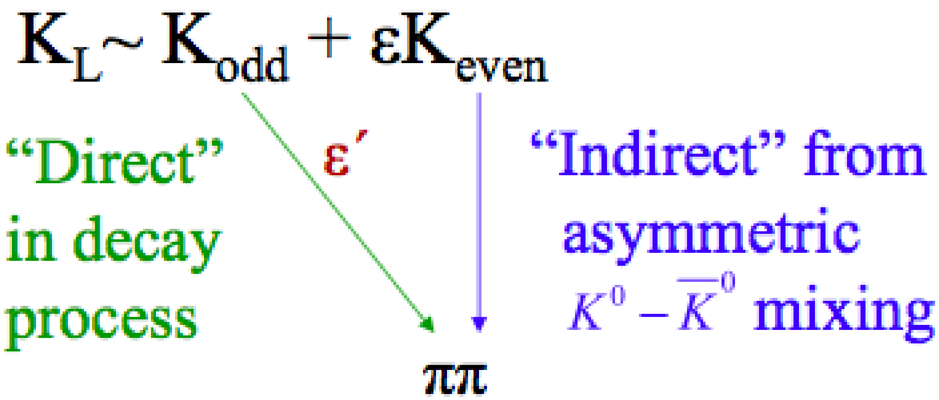
$$|K_S\rangle \approx |K_1\rangle + \varepsilon |K_2\rangle \qquad (\textit{mostly } CP+1)$$



$$K_L = K_2 + \epsilon K_1$$

- CP symmetry can be violated in the mixing and in the decay

ε′/ε : Indirect vs. Direct CP Violation



$K_L \sim K_{odd} + \varepsilon K_{even}$

“Direct” in decay process

ε′

“Indirect” from asymmetric $K^0 - \overline{K}^0$ mixing

ππ

To distinguish between direct and indirect CP violation, compare $K_{L,S} \rightarrow \pi^+\pi^-, \pi^0\pi^0$:

$$\mathrm{Re}(\varepsilon' / \varepsilon) \approx \frac{1}{6}\left[\frac{\Gamma\left(K_L \rightarrow \pi^+\pi^-\right) / \Gamma\left(K_s \rightarrow \pi^+\pi^-\right)}{\Gamma\left(K_L \rightarrow \pi^0\pi^0\right) / \Gamma\left(K_s \rightarrow \pi^0\pi^0\right)} - 1\right]$$

$\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$ ⟹ direct CP violation

$$\Gamma(K^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\overline{K}^0 \rightarrow \pi^+\pi^-)$$

The KTeV Experiments

- KTeV stands for “Kaons at the TeVatron” and consists of two fixed target experiments (E799 and E832) located at Fermilab (on the Neutrino-Muon fixed-target beamline).

- Data was collected in 1996-1997 and 1999-2000; these two runs are referred to as the '97 and '99 runs respectively. (Note: there were modifications to the detector and the Tevatron during the intermediary period.)

- The main purpose of E832 was to measure the direct CP violation parameter Re(ε'/ε) at the 10^{-4} level.

- The goal of E799 was to detect and measure rare K_L decays, especially CP-violating processes.

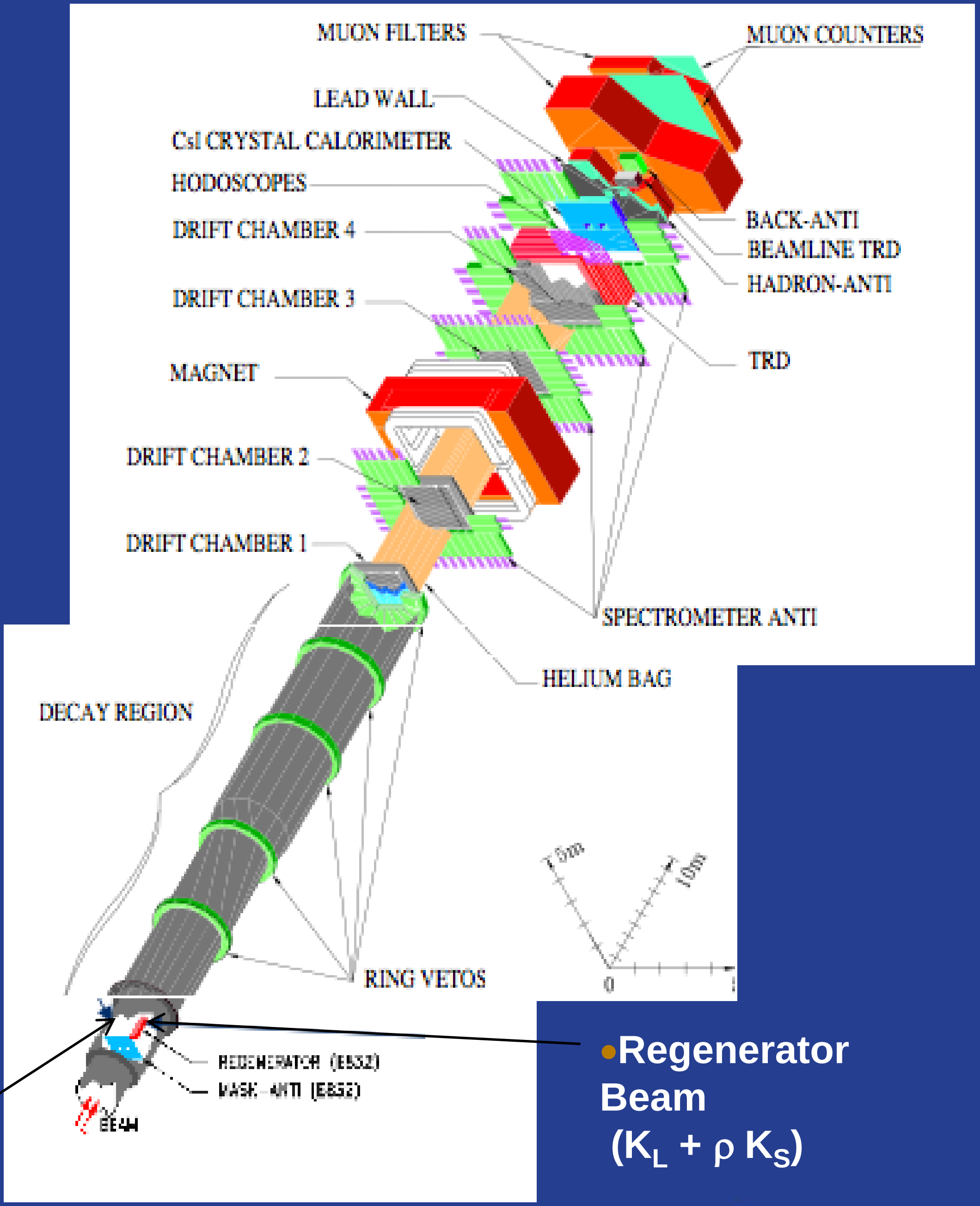
Fermilab

The KTeV Detector

- Movable active regenerator to provide a coherent mixture of K_L and K_S and to veto scattered kaons

- Charged spectrometer to reconstruct $K \rightarrow \pi^+\pi^-$ decays

- CsI calorimeter to reconstruct $K \rightarrow \pi^0\pi^0$ decays

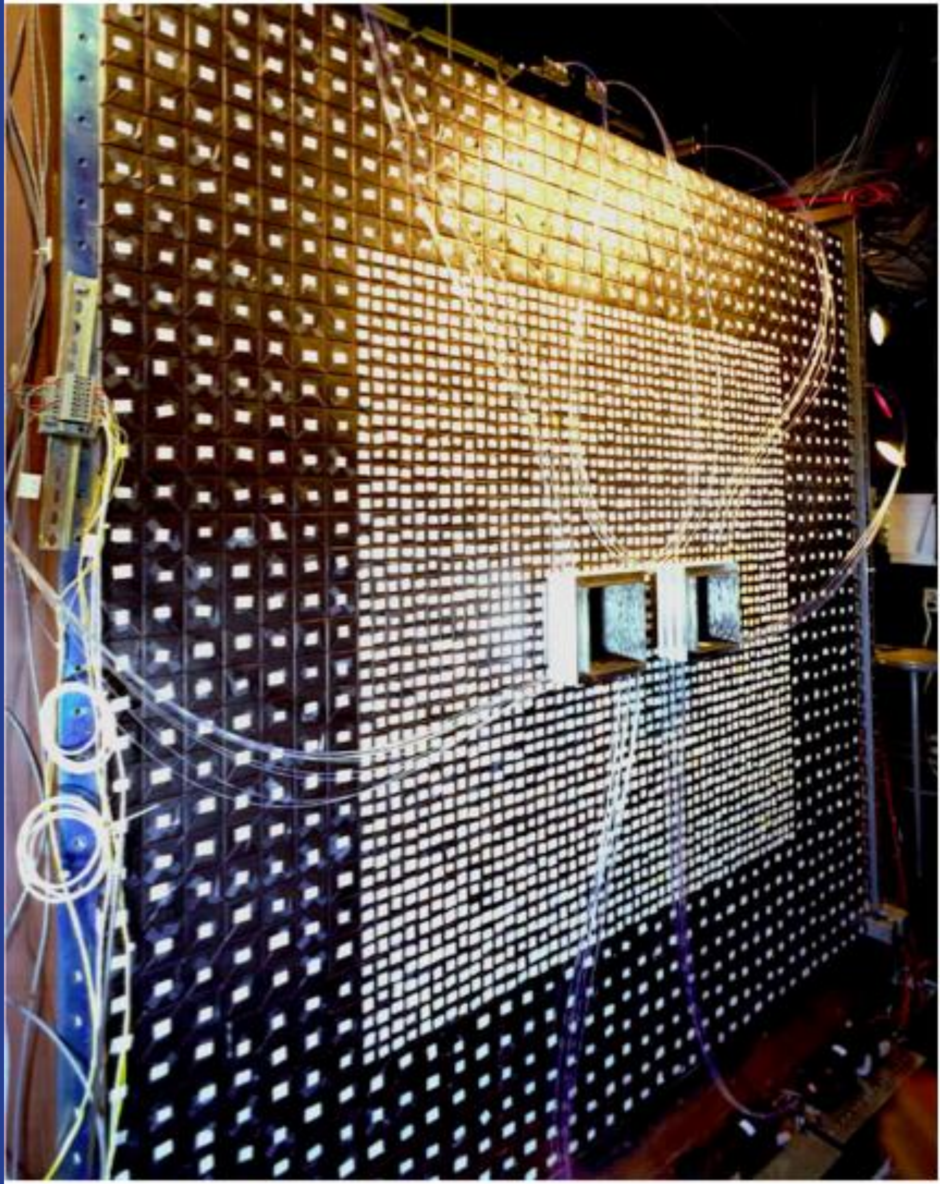


- Regenerator Beam ($K_L + \rho K_S$)

- Vacuum Beam (K_L)

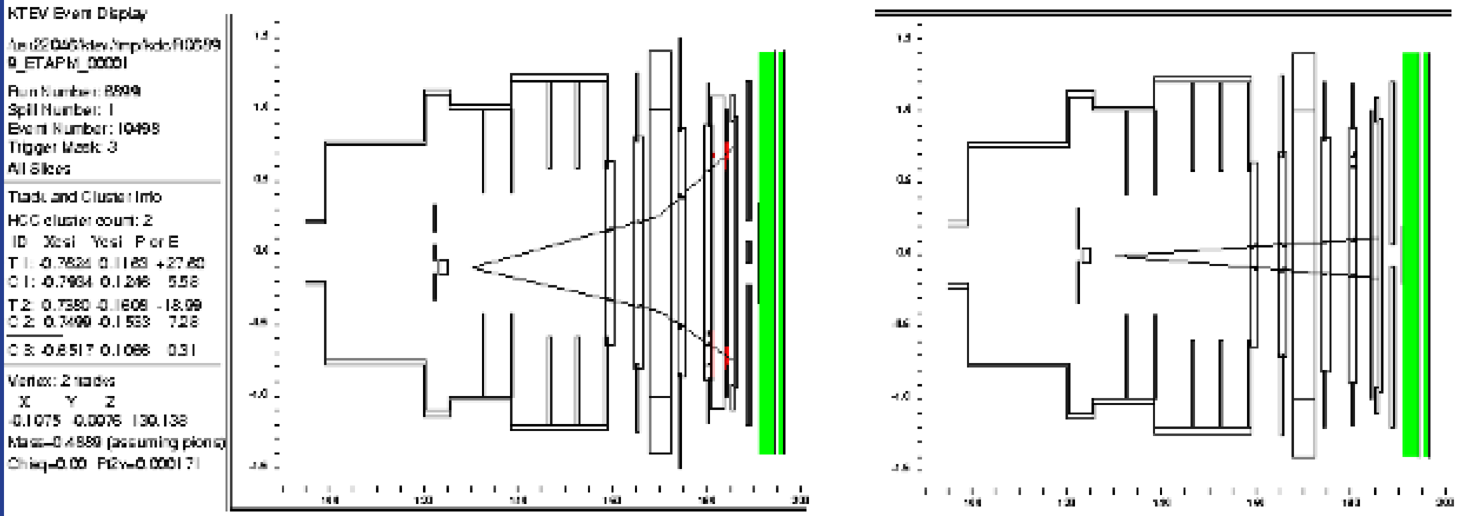
CsI Calorimeter

- **3100 CsI crystals**
  - **–small blocks 2.5 × 2.5 × 50cm^3**
  - **–large blocks 5.0 × 5.0 × 50 cm^3**
- **Calibrated using in-situ laser system and momentum analyzed electrons from K_e3 decays**
  - **–position resolution**
    - **~1.2 mm (small blocks)**
    - **~2.4 mm (large blocks)**
  - **–energy resolution ~0.6%**
  - **–absolute energy scale ~0.05%**



- 2003 result based on ~3 million $K_L \rightarrow \pi^0\pi^0$ decays from 1996 and 1997
- 1999 dataset contains ~3 million $K_L \rightarrow \pi^0\pi^0$ decays

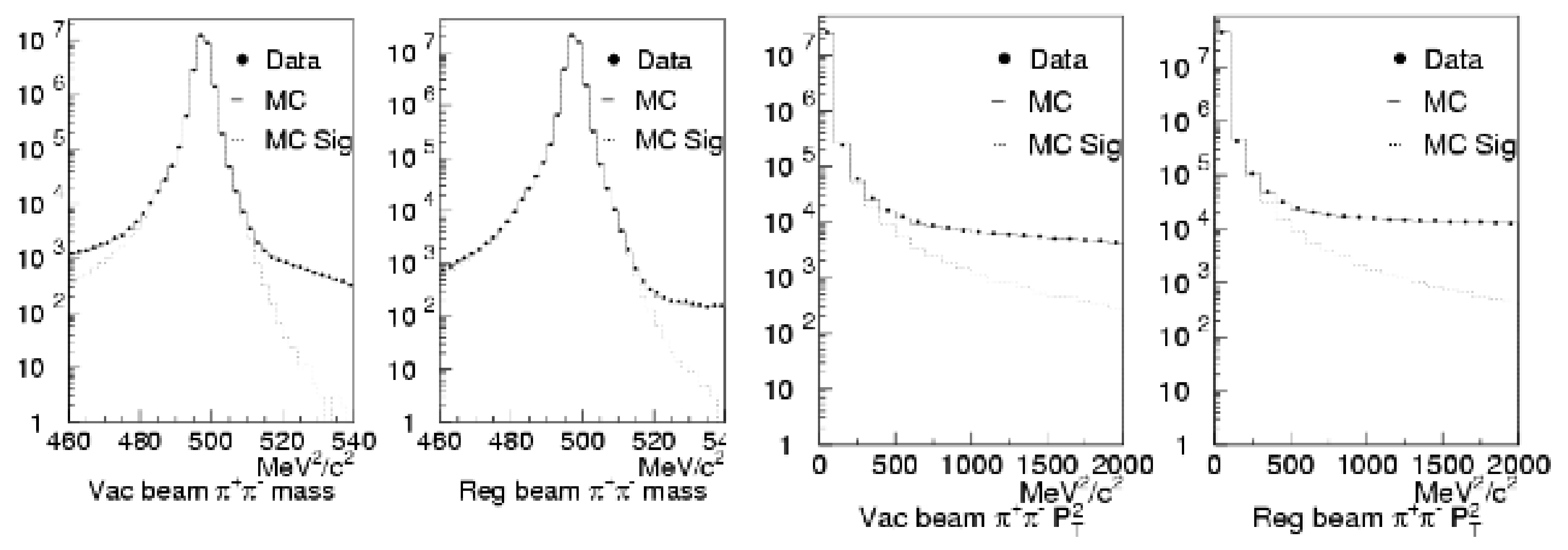
•K → $\pi^+\pi^-$ Event



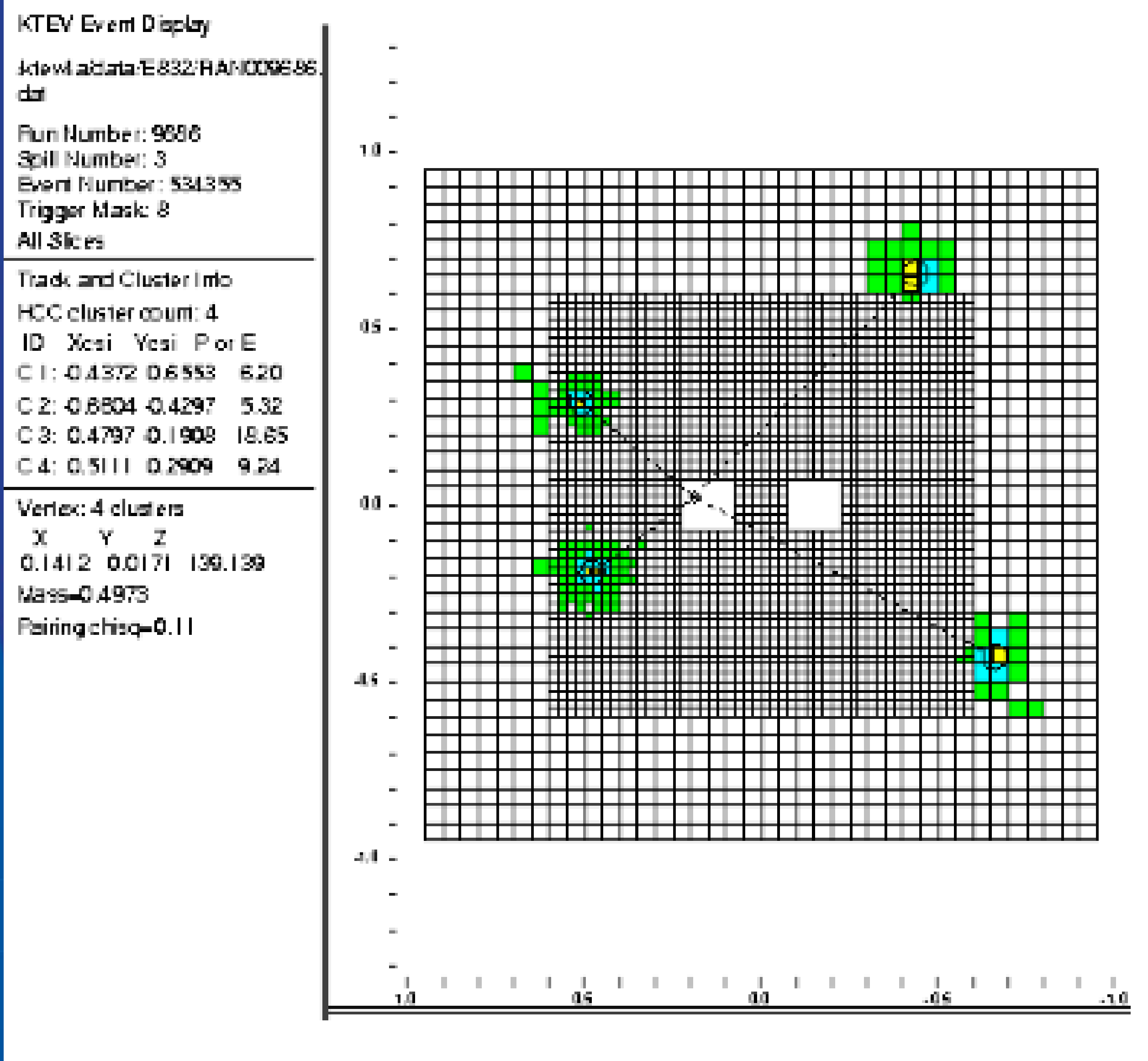
```
KTEV Event Display
/usr22045/ktev/tmp/kdc/R0859
9_ETAPM_00001
Run Number: 8599
Spill Number: 1
Event Number: 10495
Trigger Mask: 3
All Slices
Track and Cluster Info
HCC cluster count: 2
 ID   Xcsi    Ycsi    P or E
T 1: -0.7824  0.1163  +27.80
C 1: -0.7934  0.1246    5.58
T 2:  0.7380 -0.1608  -18.99
C 2:  0.7499 -0.1553    7.28
C 3: -0.8517  0.1066    0.31
Vertex: 2 tracks
  X        Y        Z
-0.1075  -0.0076  130.138
Mass=0.4989 (assuming pions)
Chisq=0.00  Pt2=0.000171
```

X vs Z

Y vs Z



• K → $\pi^0\pi^0$ Events



KTEV Event Display

/ktev4a/data/E832/RAN009686.dat

Run Number: 9686
Spill Number: 3
Event Number: 534355
Trigger Mask: 8
All Slices

Track and Cluster Info

HCC cluster count: 4

ID	Xcsi	Ycsi	P or E
C 1:	-0.4372	0.6553	6.20
C 2:	-0.6504	-0.4297	5.32
C 3:	0.4797	-0.1908	18.65
C 4:	0.5111	0.2909	9.24

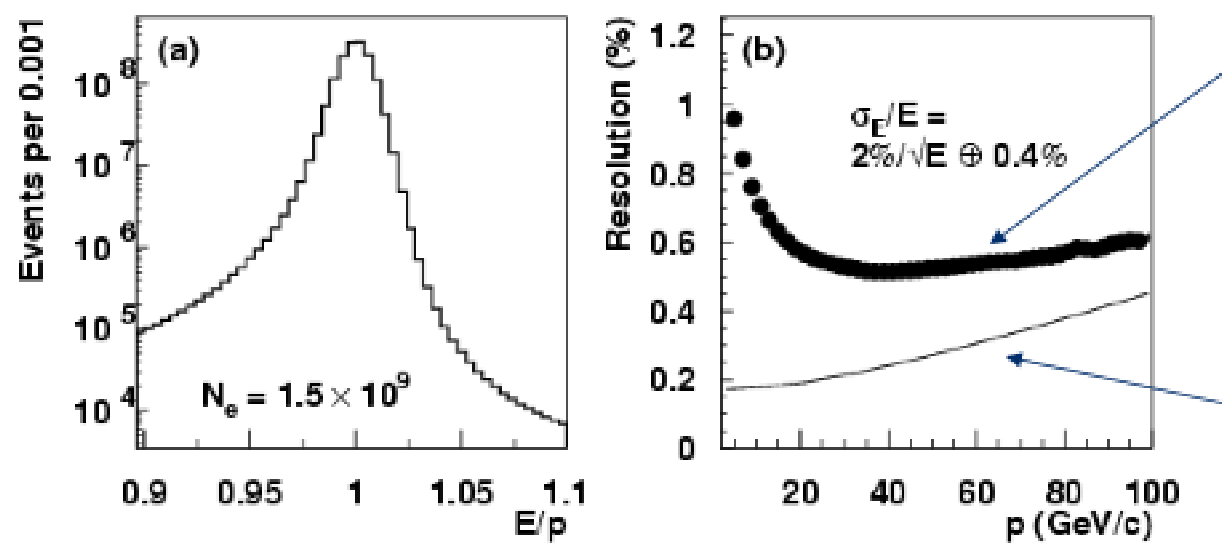
Vertex: 4 clusters

X	Y	Z
0.1412	0.0171	139.139

Mass=0.4973

Pairing chisq=0.11

- CsI Performance



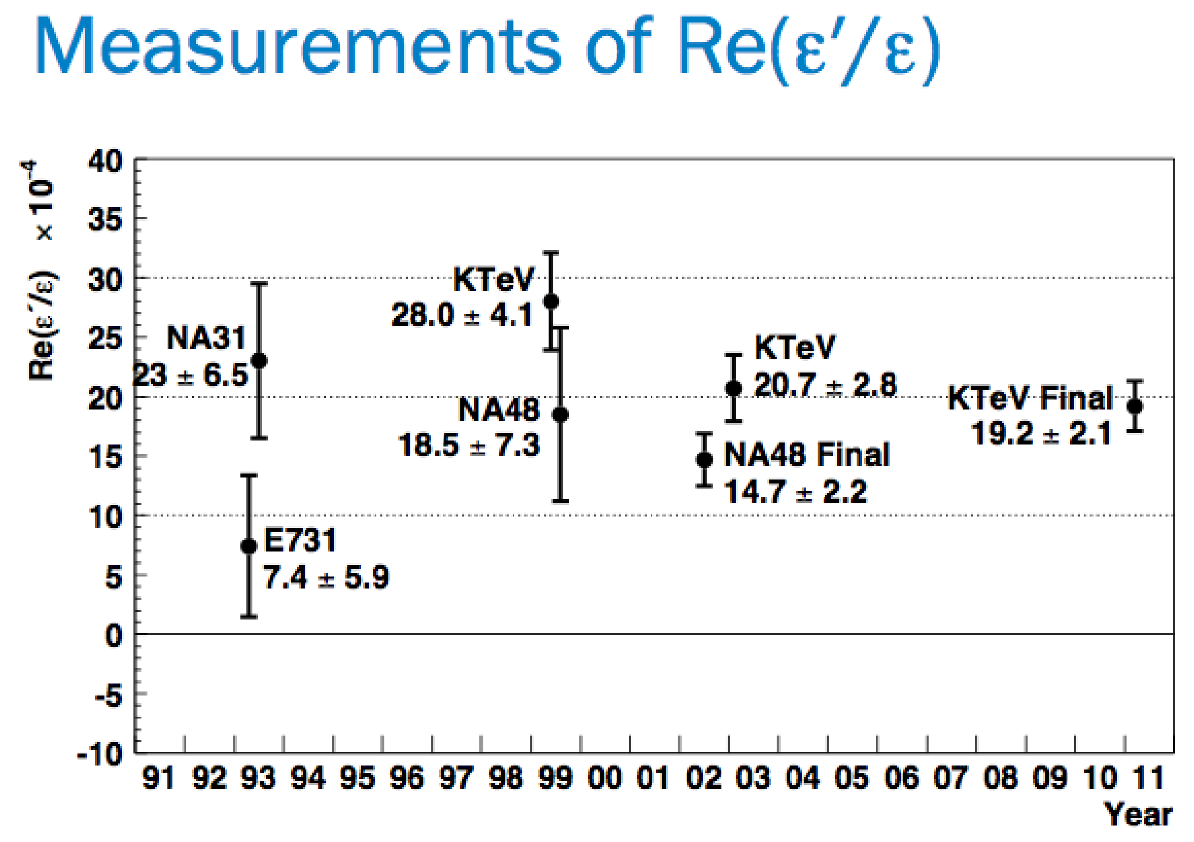
- Energy resolution
- Estimated momentum resolution

- Final E/p resolution after all corrections: ~0.6%

KTeV Result:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})] \times 10^{-4}$$

$$= (19.2 \pm 2.1) \times 10^{-4}$$



Measurements of Re(ε′/ε)

World average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$
(confidence level = 13%)

Significance of the Kaon Experiments

Direct CP violation in the Kaon sector is established.

There is some suggestion that the partial decay asymmetry between particle and anti-particle, could be responsible for the anti-matter deficit in the universe. Perhaps the positive but small observed asymmetry cannot explain the total anti-matter deficit.

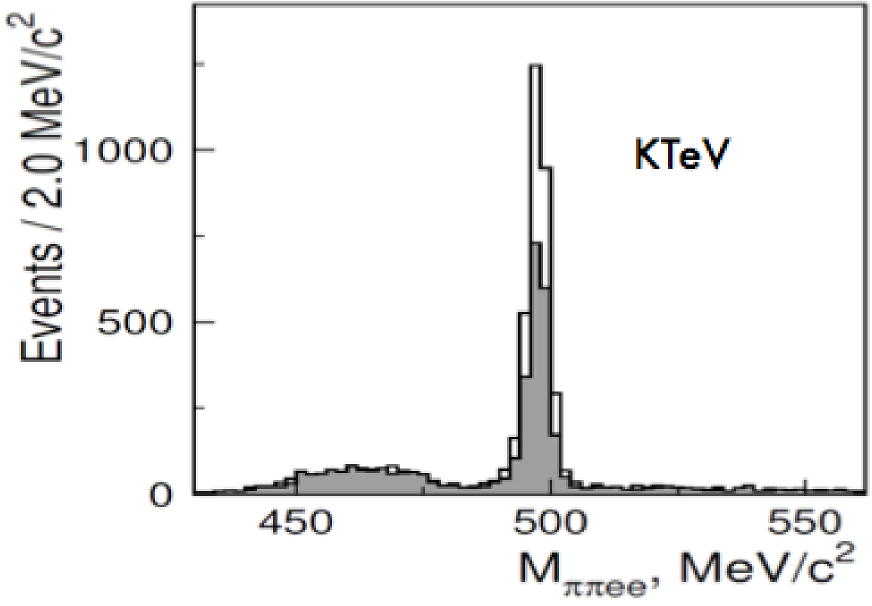
There are a number of other significant observations from this experiment.

KTeV Result

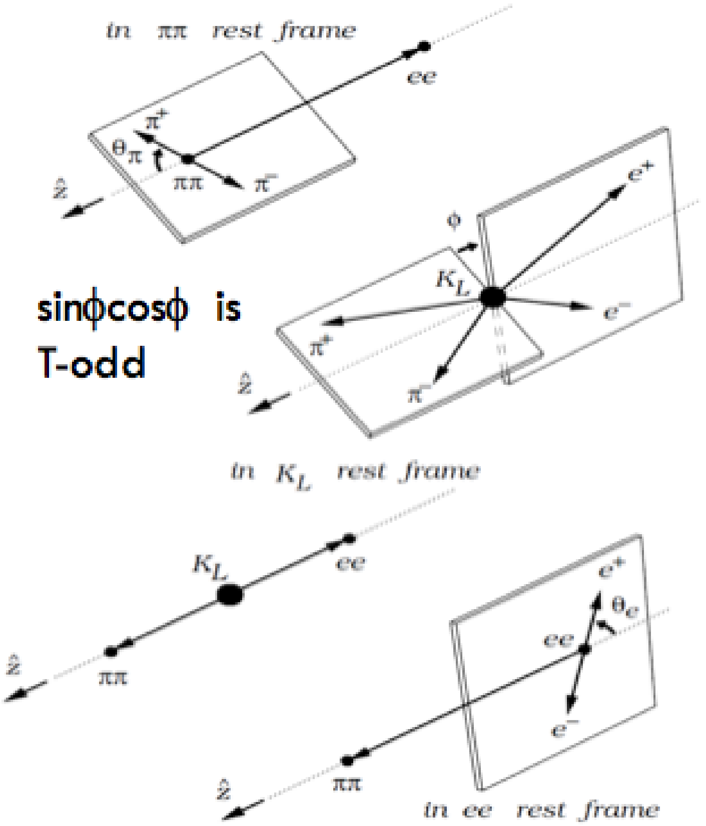
Discovery of $K_L \rightarrow \pi^+\pi^-e^+e^-$

Branching fraction of 4x10^{-7}

Phys. Rev. Lett. 96, 101801 (2006).



Gray: sinφcosφ<0; Clear: sinφcosφ>0



sinφcosφ is
T-odd

- 5000 events observed, sensitivity < 10^{-10}.
- Large T-odd, CP asymmetry observed.

•Courtesy: Heidi Schellman, Northwestern University (Achievements of theTevatron Fixed Target Program)

There are other experiments around the world

that are pursuing related physics:

K_L Decay in flight experiments at KEK (JPARC)

and CERN (NA62)

Storage Ring experiments at Frascati

K^+ Decay at rest experiments BNL, and FNAL

A whole area of physics that focuses on CP violation in B and K meson decays is one of the central topics in particle physics. CP-violating and rare decays of K and B mesons are sensitive to the Standard Model (SM) and its extensions and flavor structure. In your theoretical studies, this context is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

Neutrino Physics measurements

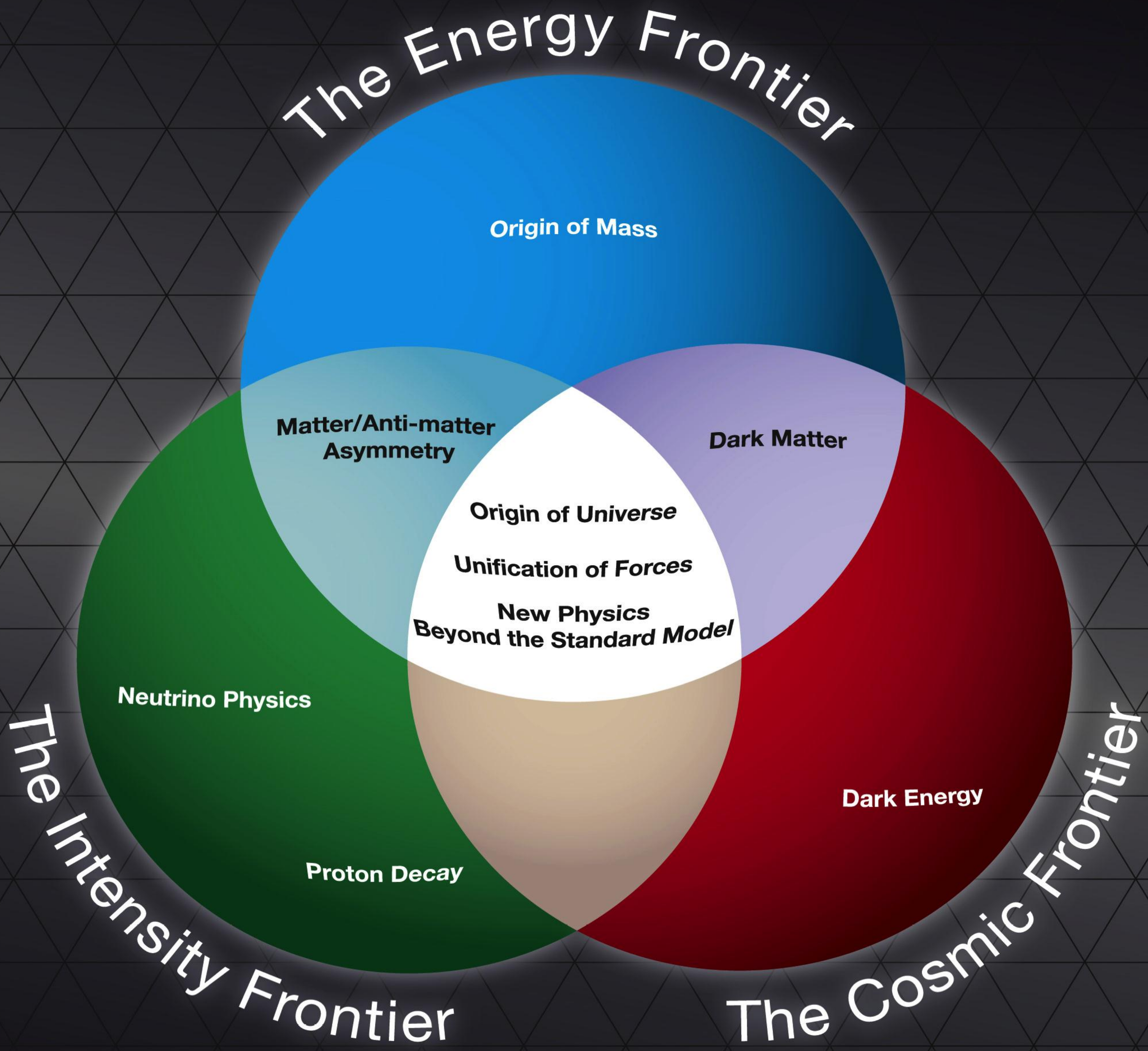
Another way to study matter – antimatter symmetry or asymmetry is the study of neutrino interactions.

The study of neutrino mass, and various flavors of these particles

Neutrinos:

Produced in the sun, supernovas, the earth, cosmic rays, reactors, medical isotopes, and accelerators. About 10^{14} pass through us, and even more through the many miles of the earth thickness every second. Maybe one in 10^5 might interact while passing through the earth.

P5



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

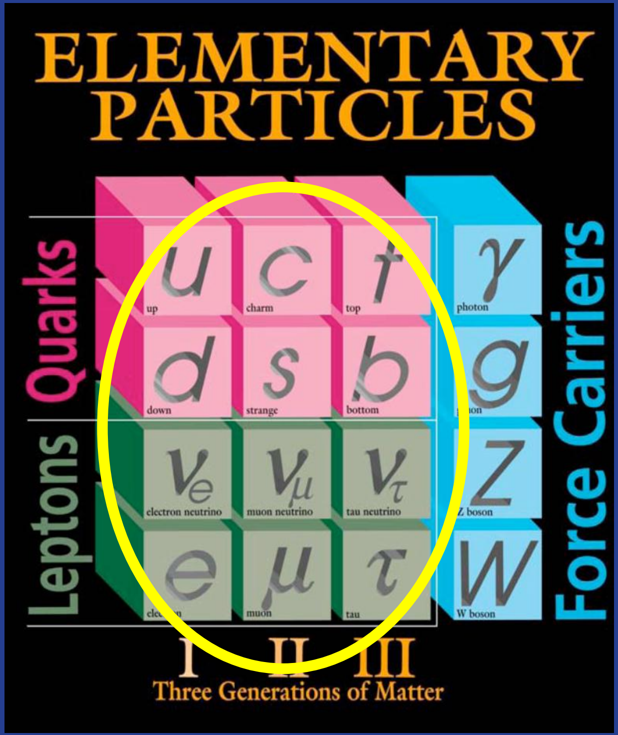
Proton Decay

Dark Energy

The Intensity Frontier

The Cosmic Frontier

The Intensity Frontier



Physics of Flavor

- Flavor phenomena
  - Essential to shaping physics beyond the SM.
- SM is incomplete:
  - Neutrino Masses (flavor)
    - The new physics seen so far in the laboratory
  - Baryon Asymmetry of the Universe (flavor)
  - Dark Matter / Dark Energy
  - One can also probe the properties of the universe by looking for extremely rare processes

Courtesy : Young-Kee Kim

As they move along they change from one flavor to another, such as, $\nu_\mu \rightarrow \nu_\tau$ and back again. Neutrino masses are tiny; their mass is probably no more than one millionth the mass of an electron.

Accelerators are the best way to create and control neutrino particles for study.

The standard and most frequently used neutrino beams, are produced from decays of pions and kaons, with the dominant two-body decays into π and ν_μ providing most of the flux. Neutrinos originating from K decays give a higher energy flux, their energies reaching close to the energy of the parent kaon while the neutrinos from pion decays are limited in the parent pion energy.

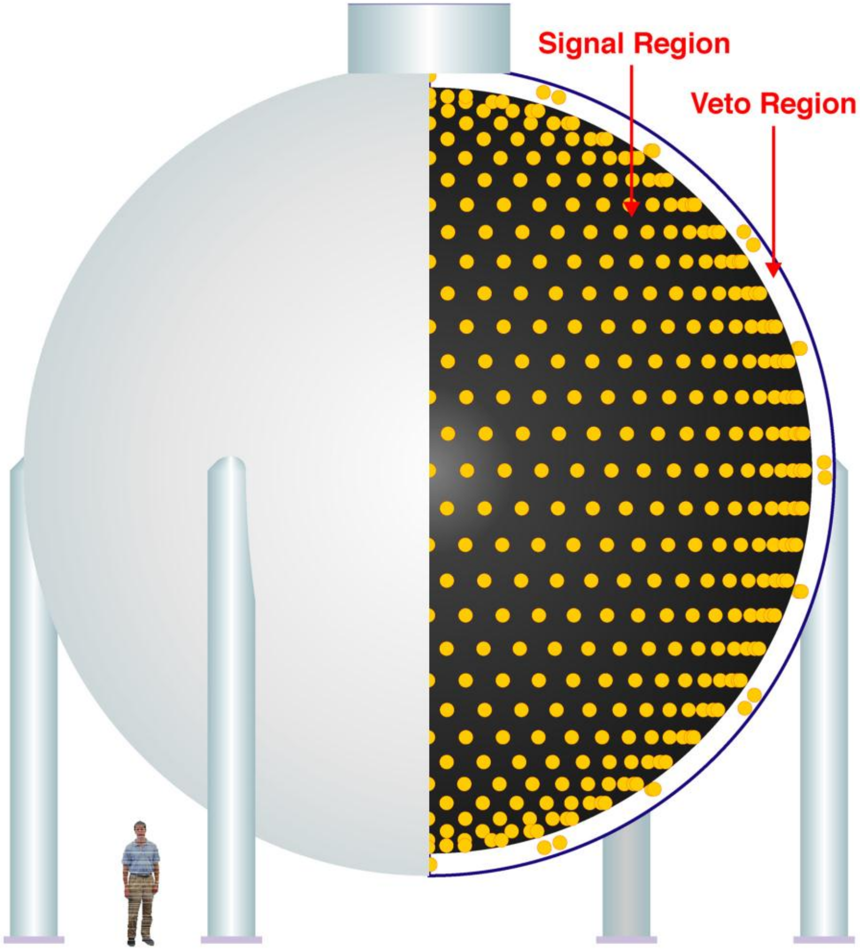
As in the case for the Kaon complex introduced before, the principle behind neutrino oscillations is the fact that if neutrinos have mass, then a generalized neutrino state can be expressed either as a superposition of different mass eigenstates or of different flavor eigenstates. This is mainly a restatement of a well-known quantum mechanics theorem that, in general, several different basis vector representations are possible, these different representations being connected by a unitary transformation such as the CKM matrix. (Ref: Wojcicki Lecture, 1997)

$|\nu_\alpha> = \nu_e, \nu_\mu, \nu_\tau$ $\qquad$ $|\nu_i> = \nu_1, \nu_2, \nu_3$

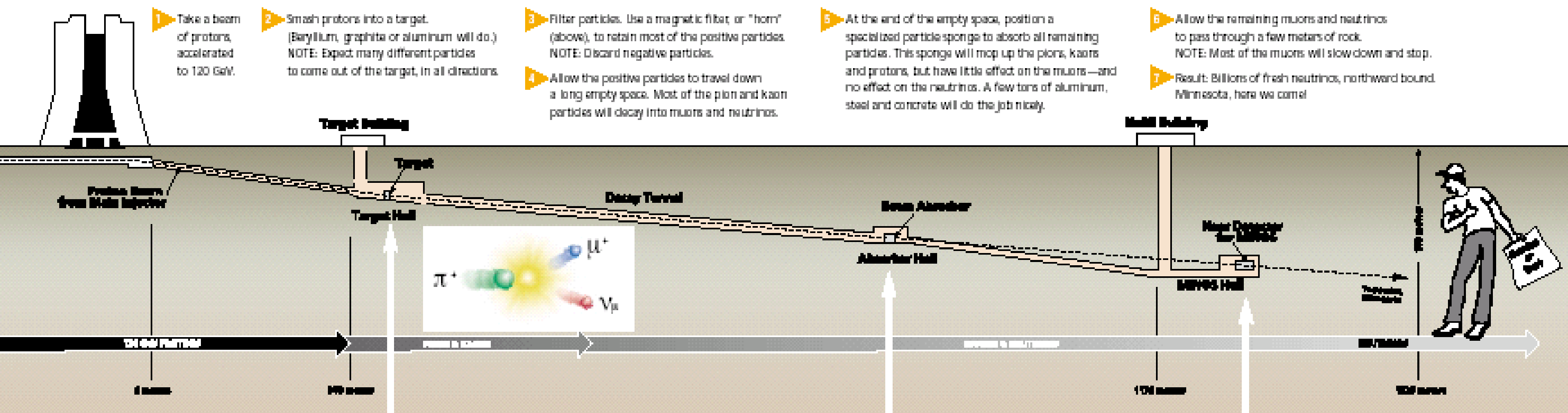
$|\nu_\alpha> = \quad U \; |\nu_i>$ $\qquad$ **Where U is unitary**

$$P(\nu_a \rightarrow \nu_b) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

MiniBooNE Detector



NUMI – Neutrinos at the Main Injector



1 Take a beam of protons, accelerated to 120 GeV.

2 Smash protons into a target. (Beryllium, graphite or aluminum will do.) NOTE: Expect many different particles to come out of the target, in all directions.

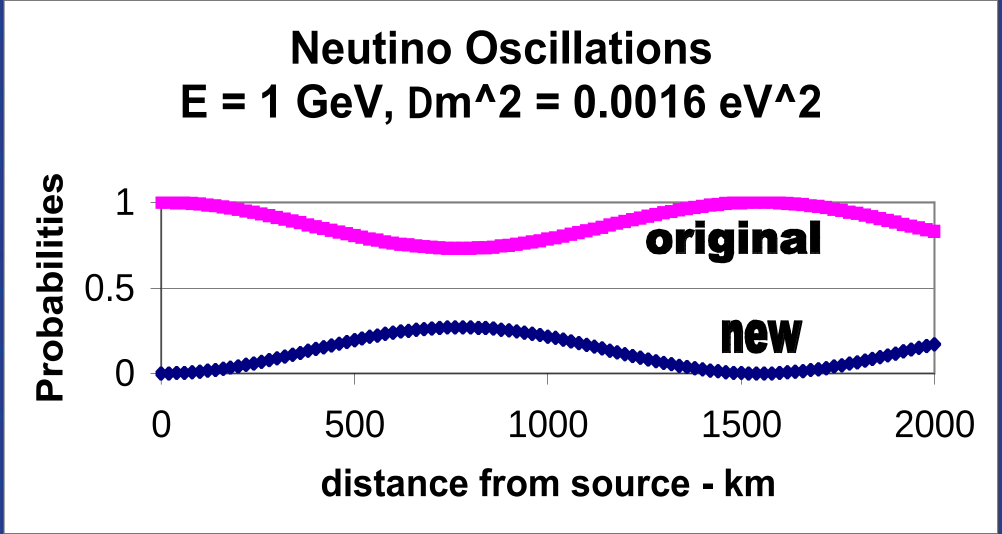
3 Filter particles. Use a magnetic filter, or "horn" (above), to retain most of the positive particles. NOTE: Discard negative particles.

4 Allow the positive particles to travel down a long empty space. Most of the pion and kaon particles will decay into muons and neutrinos.

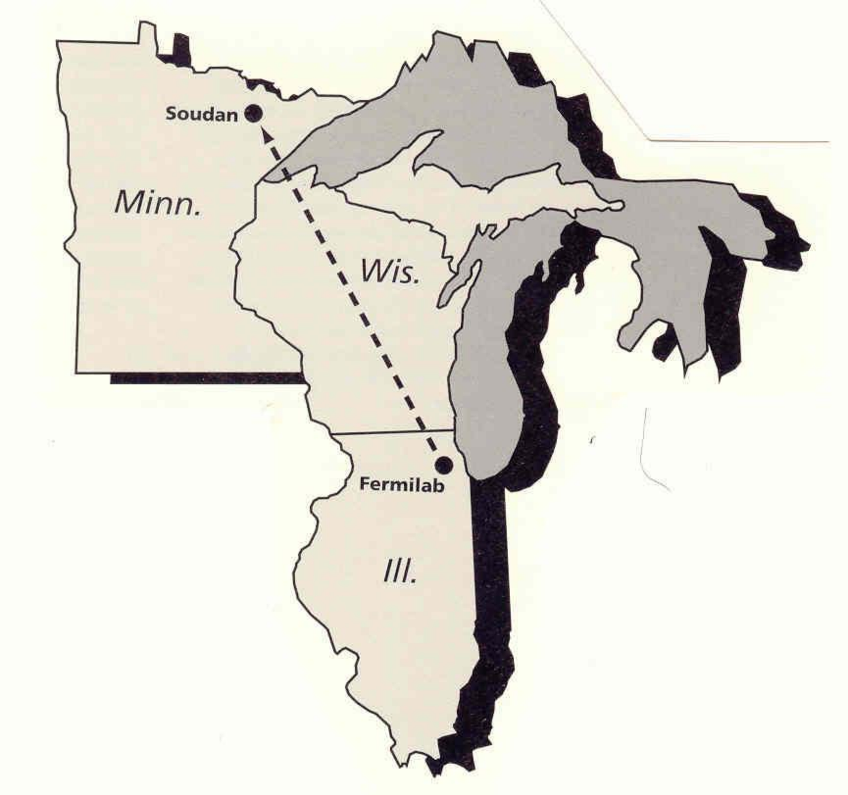
5 At the end of the empty space, position a specialized particle sponge to absorb all remaining particles. This sponge will mop up the pions, kaons and protons, but have little effect on the muons—and no effect on the neutrinos. A few tons of aluminum, steel and concrete will do the job nicely.

6 Allow the remaining muons and neutrinos to pass through a few meters of rock. NOTE: Most of the muons will slow down and stop.

7 Result: Billions of fresh neutrinos, northward bound. Minnesota, here we come!



Neutino Oscillations
E = 1 GeV, Dm^2 = 0.0016 eV^2



735 km long beam, right thru the earth!
10 km deep

NEUTRINO EVENT RATES ⇒

Requirements: protons+target ⇒ pions ⇒ neutrinos
+detector

The number of events will be proportional to: cross-section * detector mass * flux * time

Thus for precise measurement we need:

A large detector mass and a large ν flux (ie. intense proton beam)

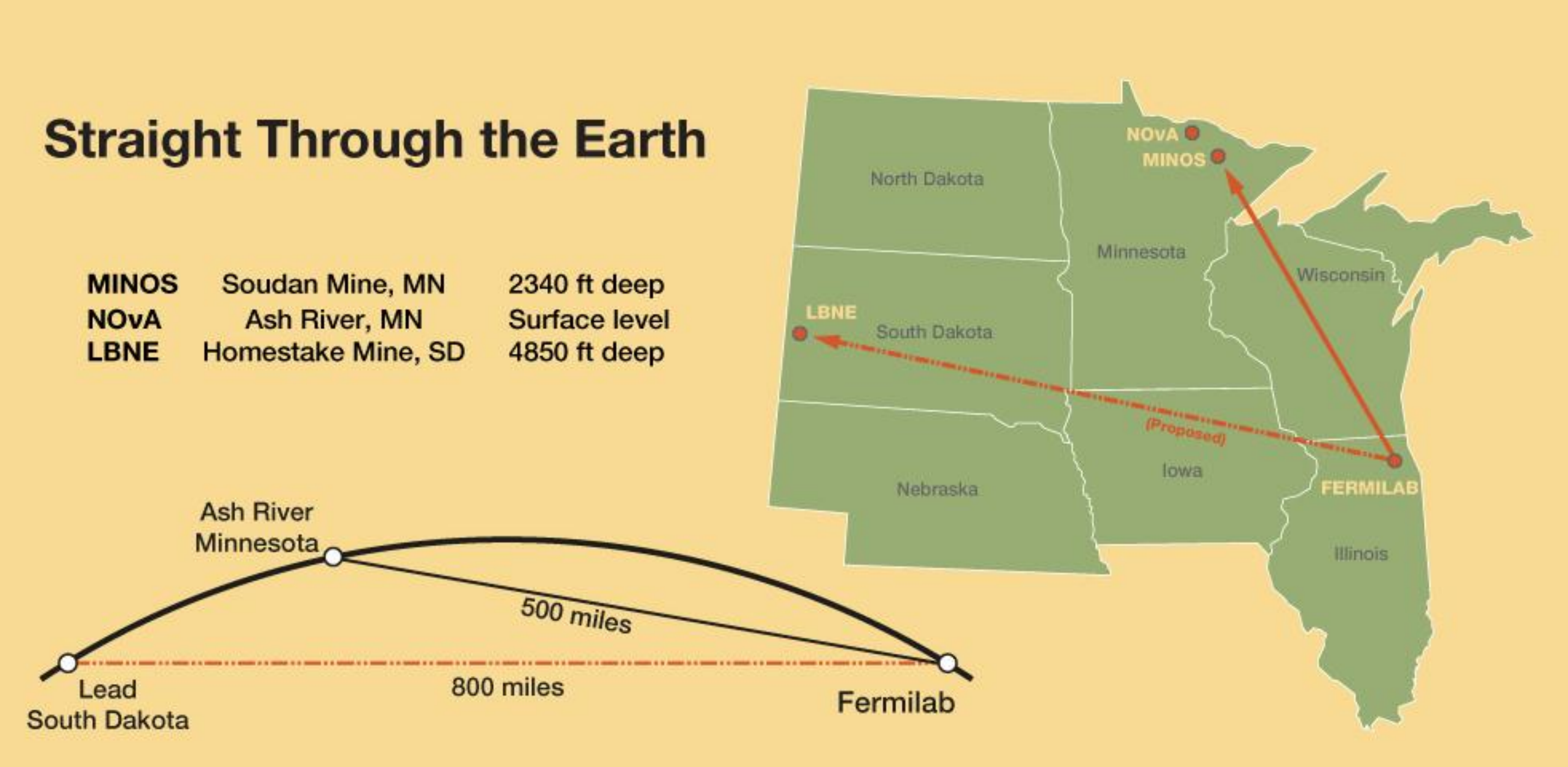
NOvA 14 kt & deep pit of building in “a” football stadium

(wire frame of loading dock in black hangs out over the stands by 30 yards)

14,700 tons, 810 km, expected to start in 2013

Intensity Frontier:

Aiming neutrinos through 500 miles of earth to study their family behavior…



Straight Through the Earth

MINOS	Soudan Mine, MN	2340 ft deep
NOvA	Ash River, MN	Surface level
LBNE	Homestake Mine, SD	4850 ft deep

The neutrino oscillations in the atmospheric domain are dominated by two parameters, the mass squared difference, Δm^2_{13}, and mixing angle $\sin^2(2\theta_{23})$.

Typical experiments looks for disappearance of ν_μs interactions. The formula, in the two-favor approximation, for the ν_μ survival probability, is given by

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E).$$

Ref:(**ACCELERATOR NEUTRINO PHYSICS Å CURRENT STATUS AND FUTURE PROSPECTS**

S. G. Wojcicki Stanford University, Stanford, CA, USA), 2010

Experiments engaged include:

Super-Kamiokande
MINOS
OPERA
K2K, T2K
BOONe
NOvA
LBNE (proposed)

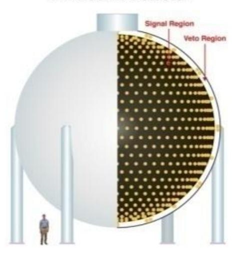
The current focus is mass hierarchy: that is which v is heaviest?

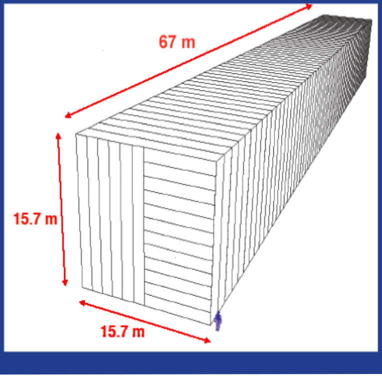
Study of matter-antimatter symmetry

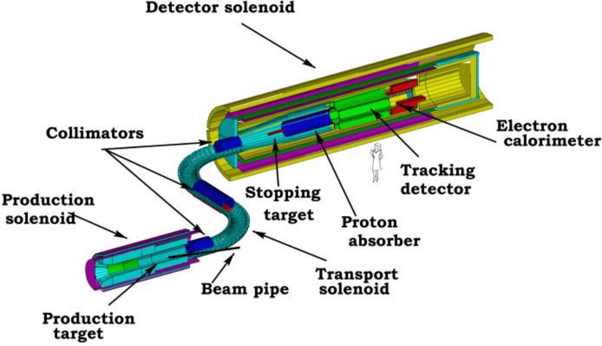
Search for more v’s, if any

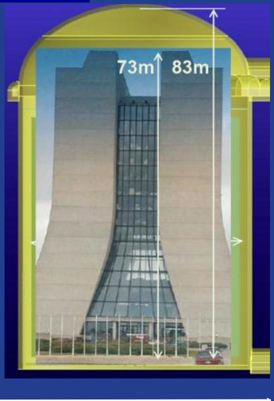
- Physics Laboratories around the world
- Prospects for some future experiments
- Some fixed Target

Present Plan: Intensity Frontier



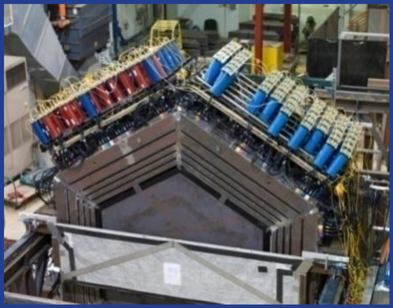


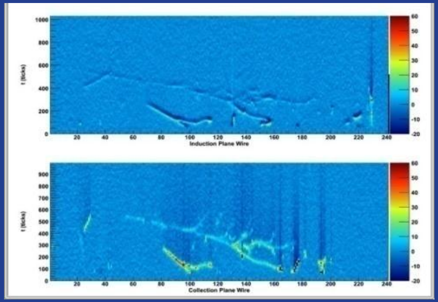


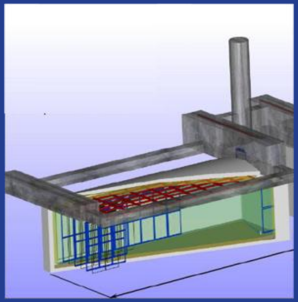


MINOS MiniBooNE MINERvA SeaQuest	NOvA MicroBooNE g-2? SeaQuest	LBNE Mu2e	Project X+LBNE m̦ K, nuclear, ! ! Factory ??

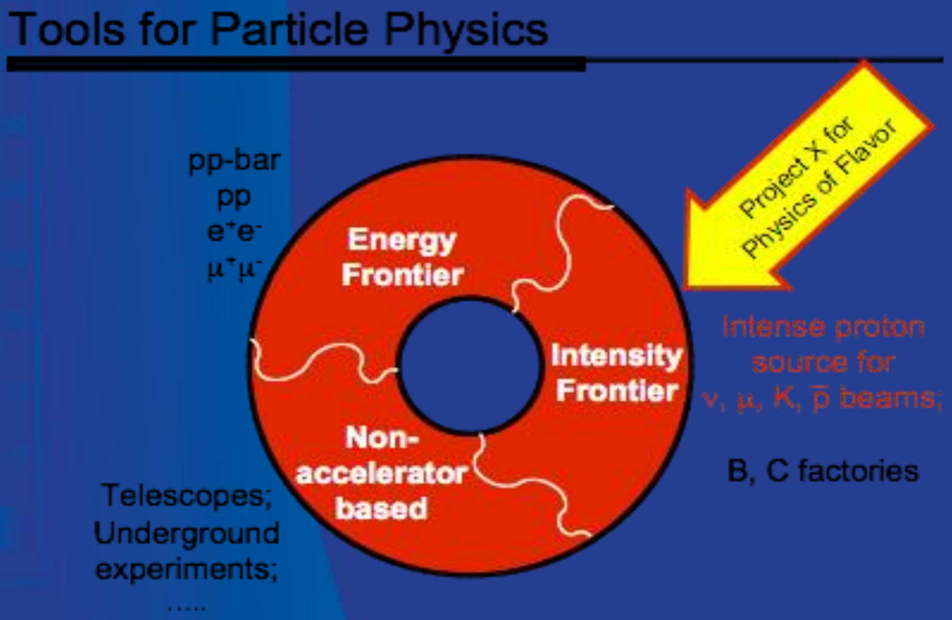
Now 2013 2016 2019 2022







Why Project X?



Tools for Particle Physics

pp-bar
pp
e^+e^-
$\mu^+\mu^-$

Energy Frontier

Intensity Frontier

Non-accelerator based

Telescopes;
Underground experiments;
.....

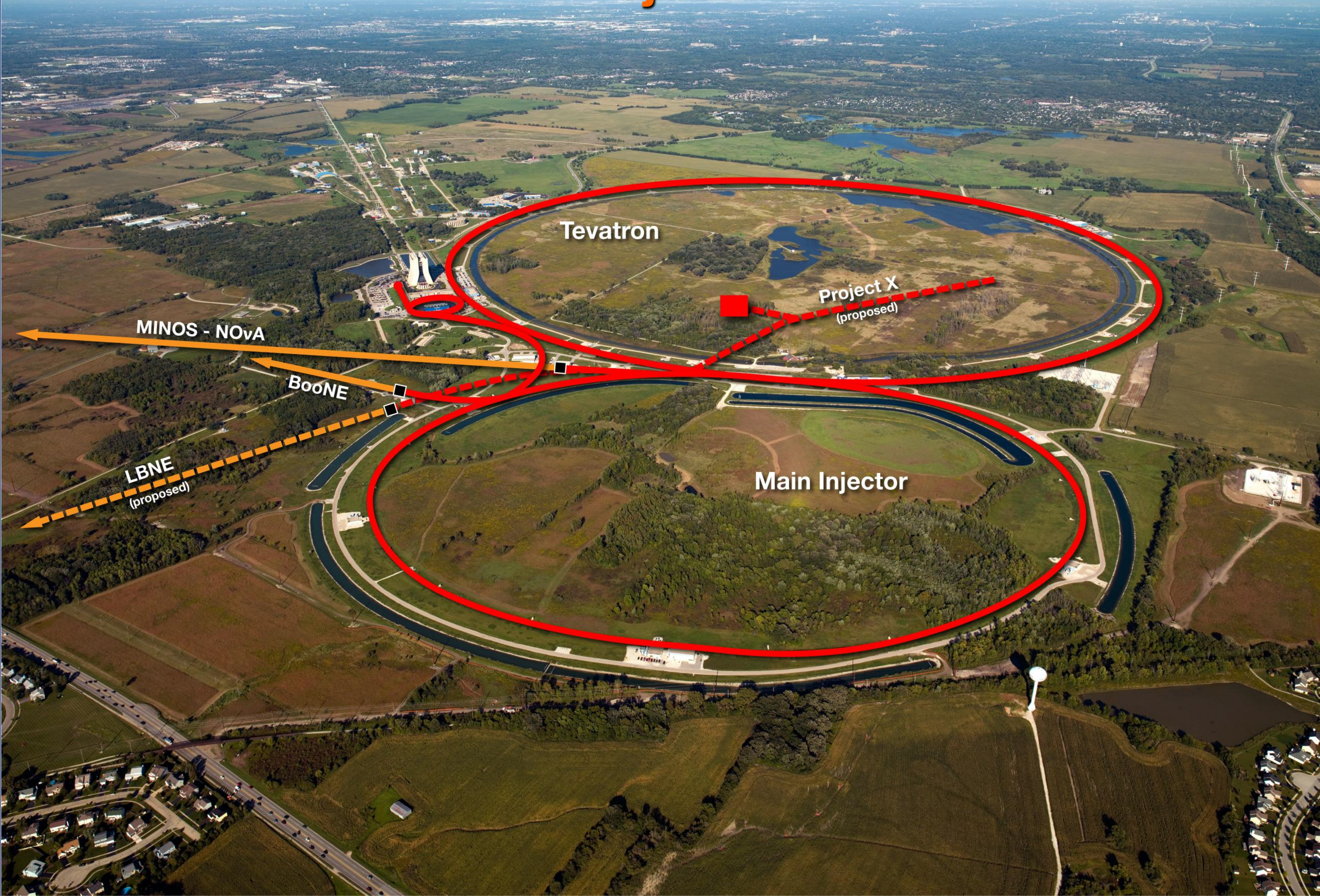
Project X for Physics of Flavor

Intense proton source for ν, μ, K, $\bar{p}$ beams;

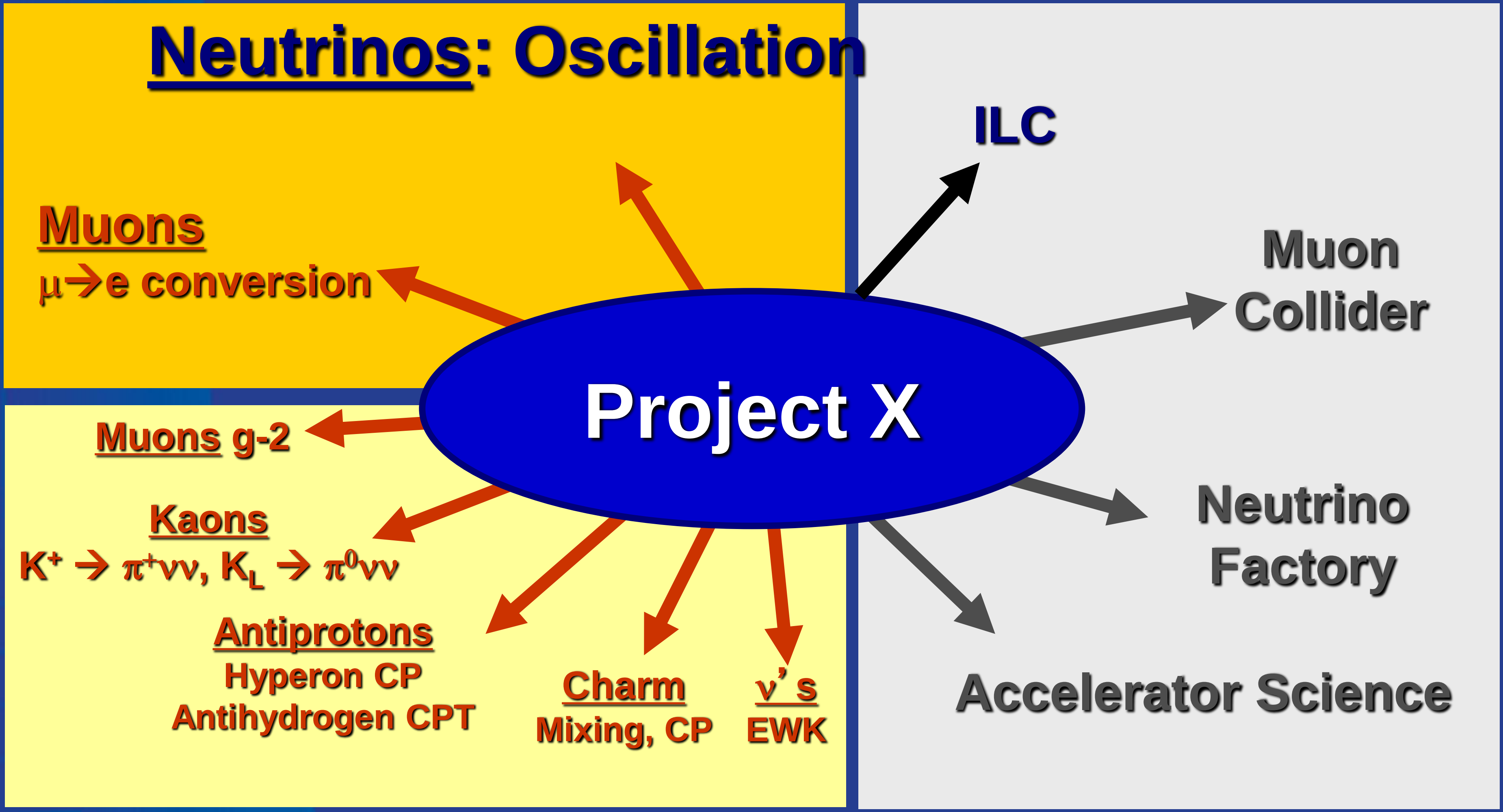
B, C factories

- FNAL Booster cannot provide sufficient intensity for the Intensity Frontier Program: neutrinos, muons, kaons,...

Project X


Tevatron
Project X
(proposed)
MINOS - NOvA
BooNE
LBNE
(proposed)
Main Injector

Opportunities with Project X



Neutrinos: Oscillation

Muons
$\mu \rightarrow e$ conversion

Muons g-2

Kaons
$K^+ \rightarrow \pi^+\nu\nu$, $K_L \rightarrow \pi^0\nu\nu$

Antiprotons
Hyperon CP
Antihydrogen CPT

Charm
Mixing, CP

ν's
EWK

Project X

ILC

Muon Collider

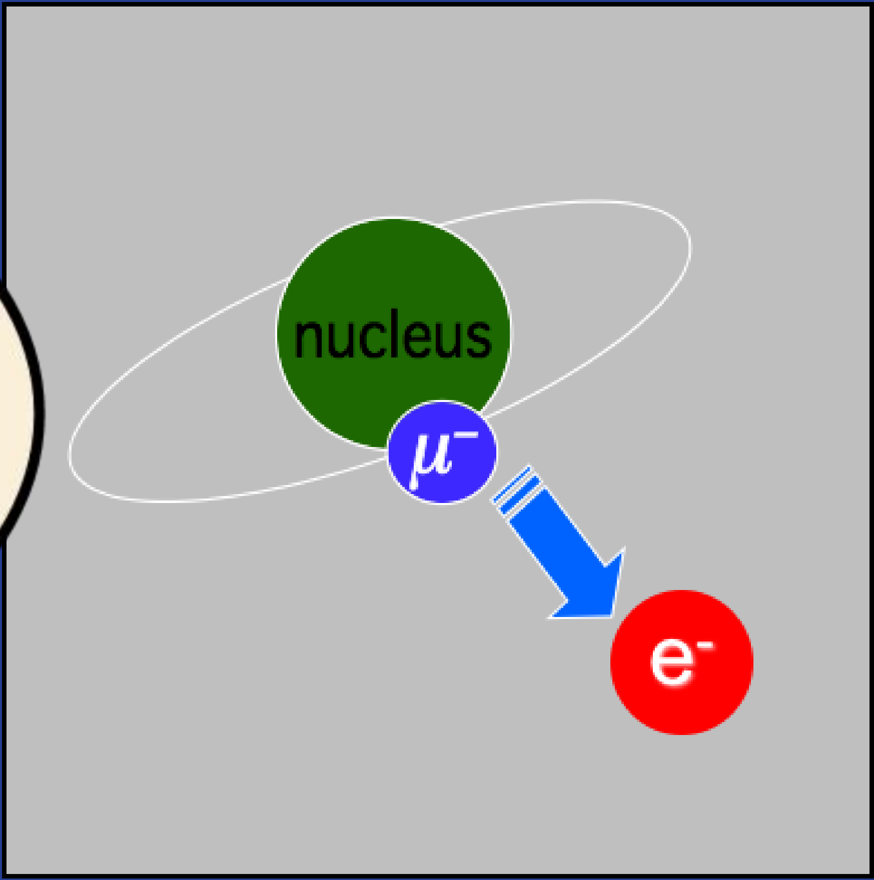
Neutrino Factory

Accelerator Science

US HEP community and International Partners

Muon to Electron Conversion

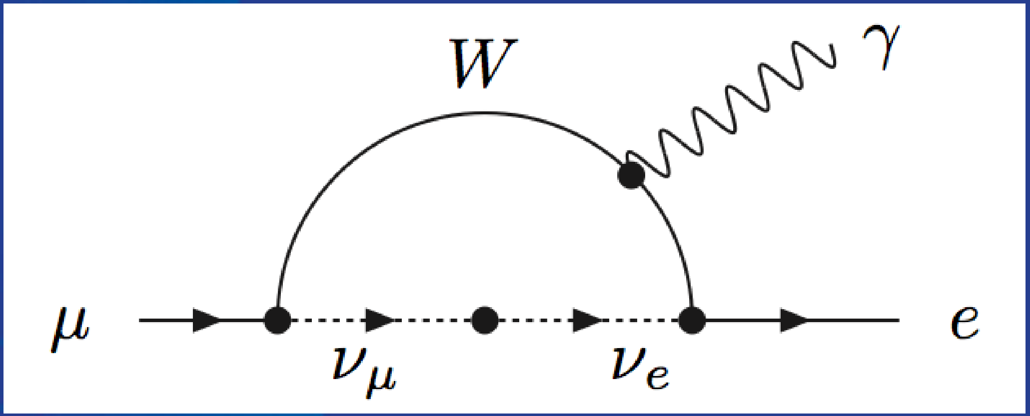
$$\mu^- N \rightarrow e^- N$$



Discovery of $\mu^- N \rightarrow e^- N$ or a similar <u>charged</u> lepton flavor violating (LFV) process will be unambiguous evidence for physics beyond the Standard Model.

This process is basically free of *background* from Standard Model processes.

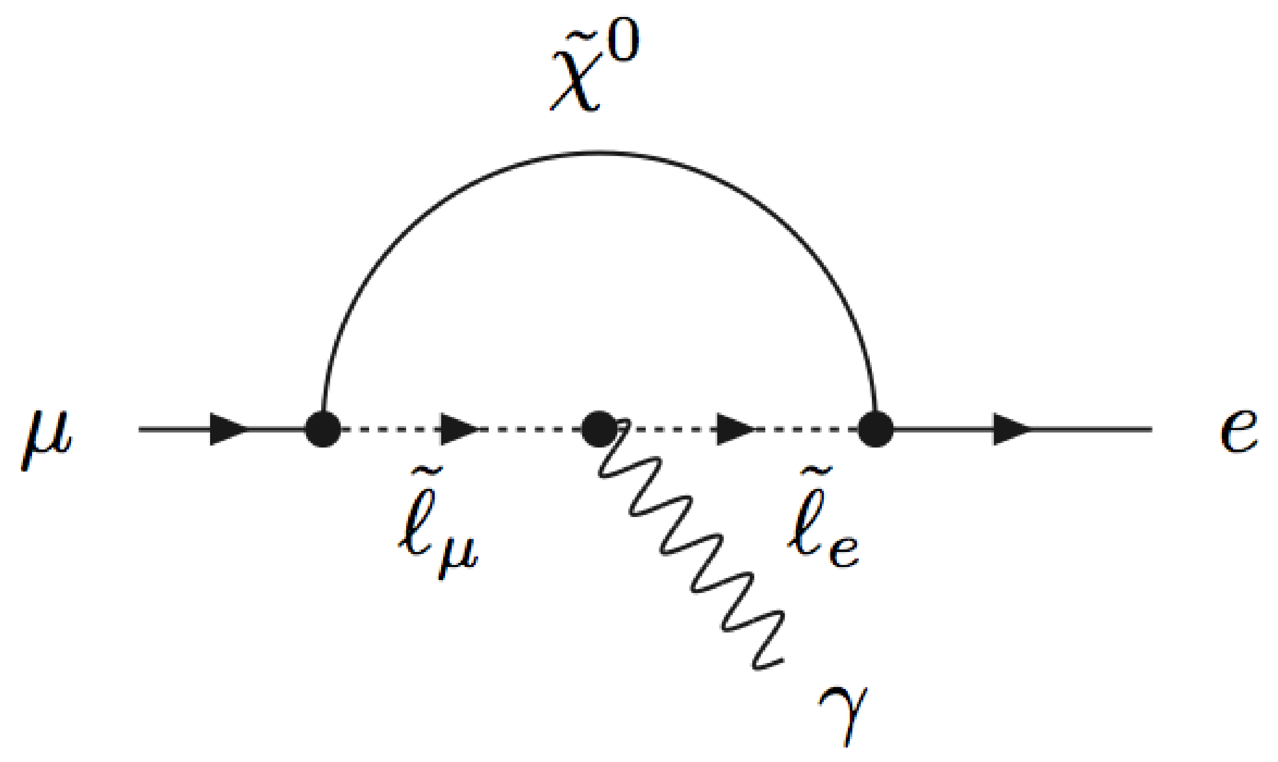
- **Neutrinos have** mass!
    - → *individual lepton numbers are not conserved!*
- Therefore, Lepton Flavor Violation occurs in Charged Leptons!



- **NO PHYSICS BACKGROUND!**
- **Observation is unambiguous sign of new physics!**

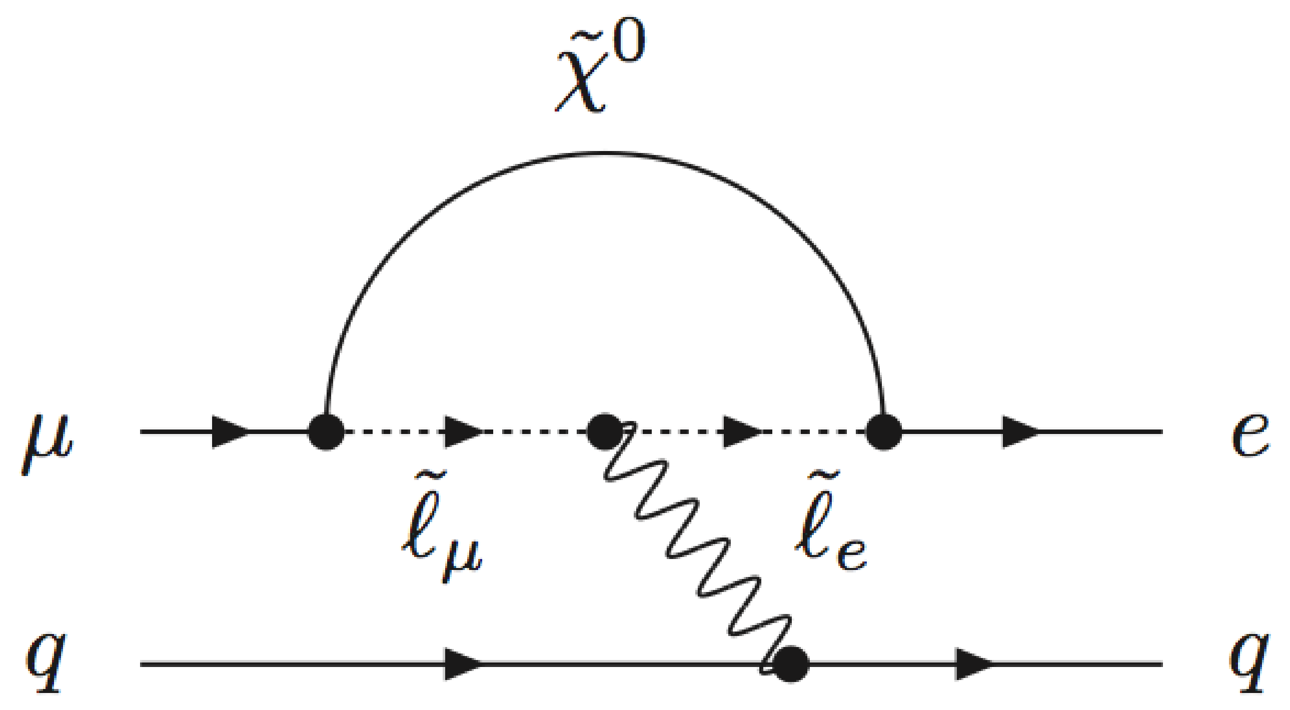
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

Search for muons decaying to an electron plus a photon:



Experiments: MEGA, MEG, and others…

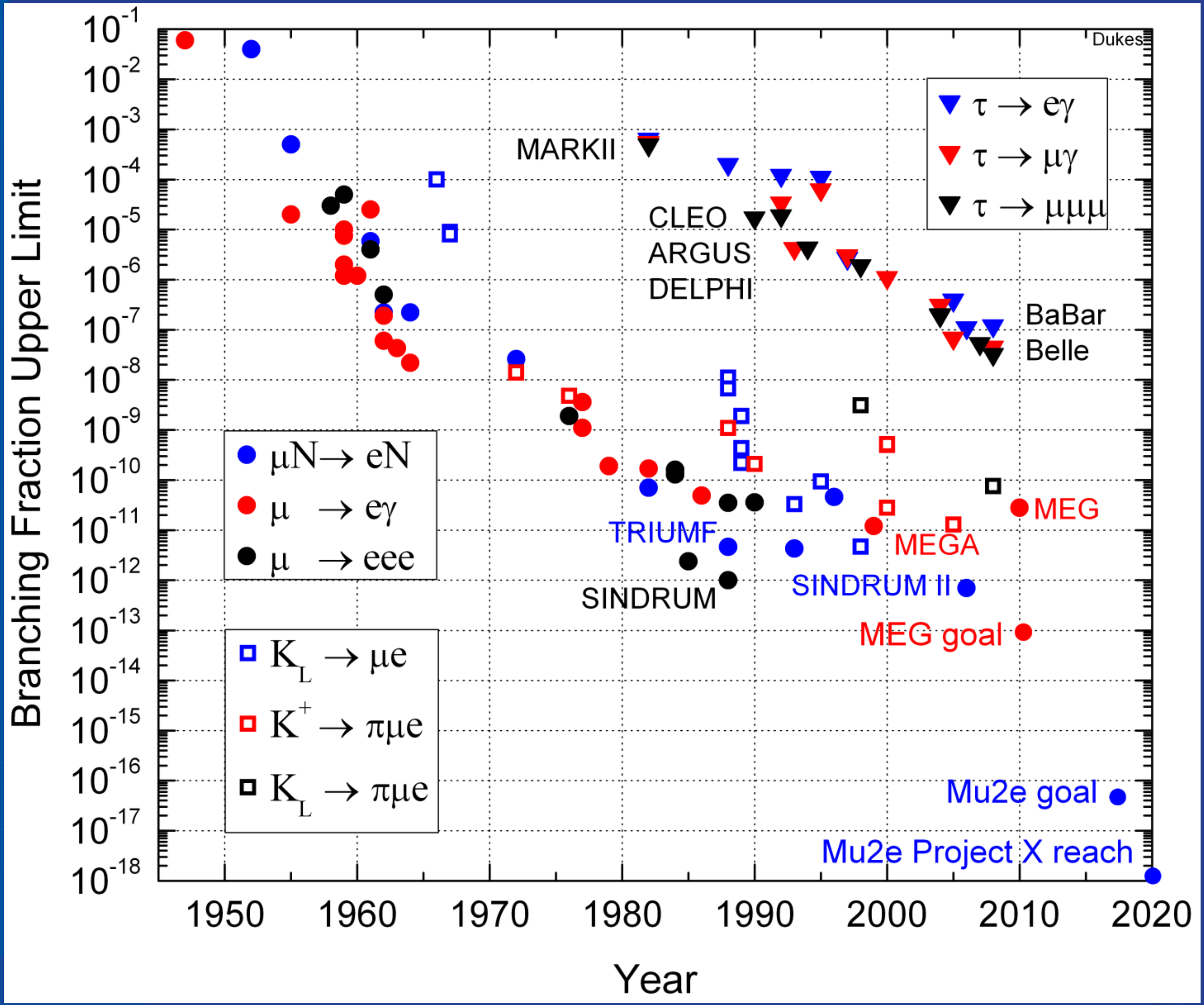
In the presence of a nucleus (N):



The electron is mono-energetic in CM frame!

Experiments: Mu2e, SINDRUM II, TRIUMF, COMET, and others…

History of CLFV Searches



This Experiment has been approved and is proposed to begin data taking about 2018

- **Goal: Search for** $\mu^- N \rightarrow e^- N$
  - **Measure ratio:**

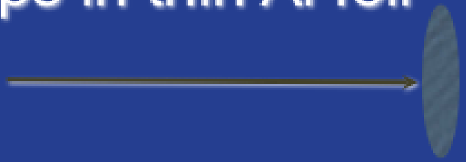
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

  - With high sensitivity to this ratio of about $6\text{x}10^{-17}$
    - → Need more than 10^{17} stopped captured muons.

      This requires bout $3\text{-}4\text{x}10^{20}$ protons on target and a small understood background.

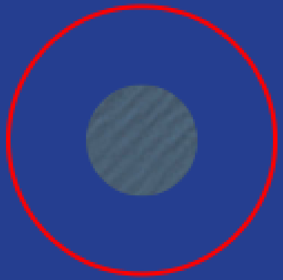
Overview Of Processes

μ^- stops in thin Al foil

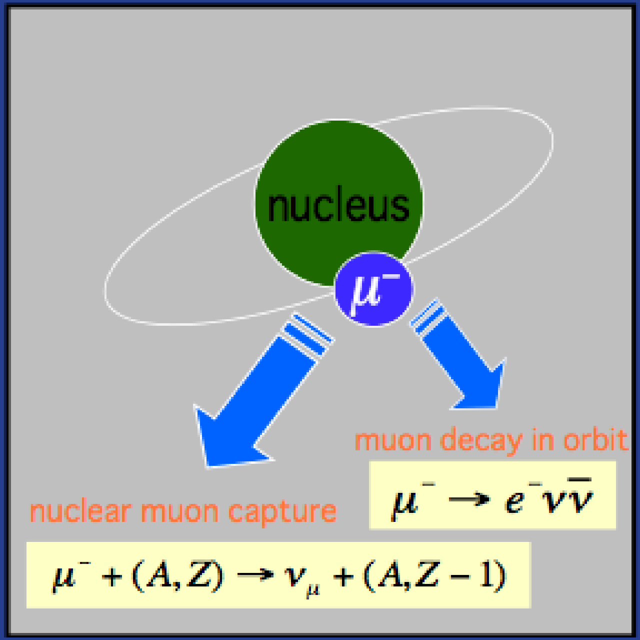


the Bohr radius is ~ 20 fm,
so the μ^- sees the nucleus

μ^- in 1s state



Al Nucleus
~4 fm



$$\mu^- \to e^- \nu \bar{\nu}$$

$$\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$$

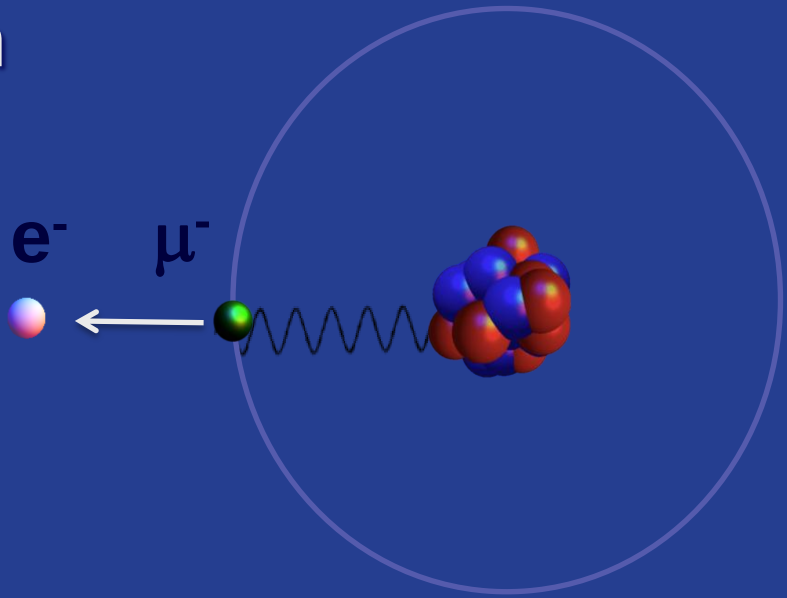
60% capture
40% decay

muon capture,
muon "falls into"
nucleus:
normalization

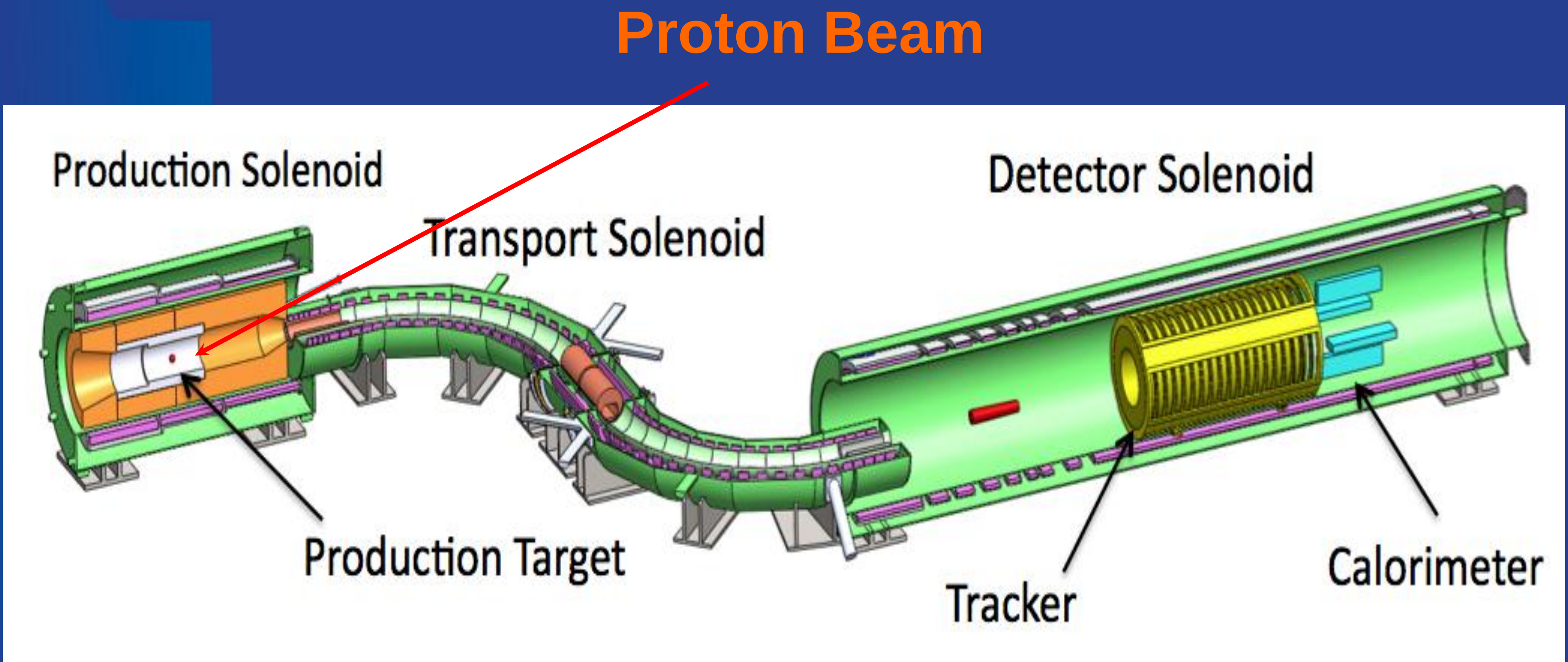
Decay in Orbit:
background

$$\mu^- N \rightarrow e^- N$$

- A single **monoenergetic** electron
- For *N* = Al, E_e = 105. MeV
  - (Electron **E** depends on Z)
- Nucleus coherently recoils off outgoing electron, and no subsequent decay for background



- Signal is a single 105 MeV e-.
- Many possible sources of background events:
  - Muon decay in Coulomb orbit (DIO)
  - Radiative muon/pion capture
  - Beam electrons can scatter in target
  - Muon/pion decay in flight
  - Antiprotons and other late arriving particles
  - Cosmic-ray induced electrons

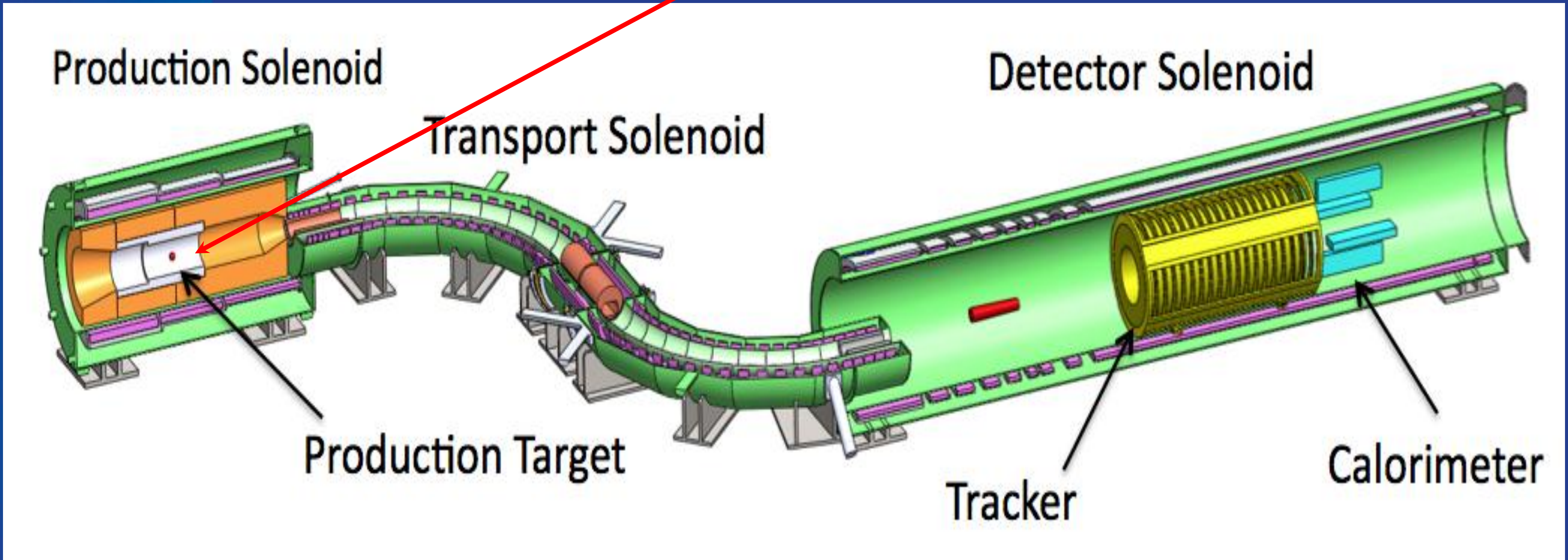


The Proton beam hits a production target in Production Solenoid.

Pions are captured and accelerated toward the Transport Solenoid by a graded field.

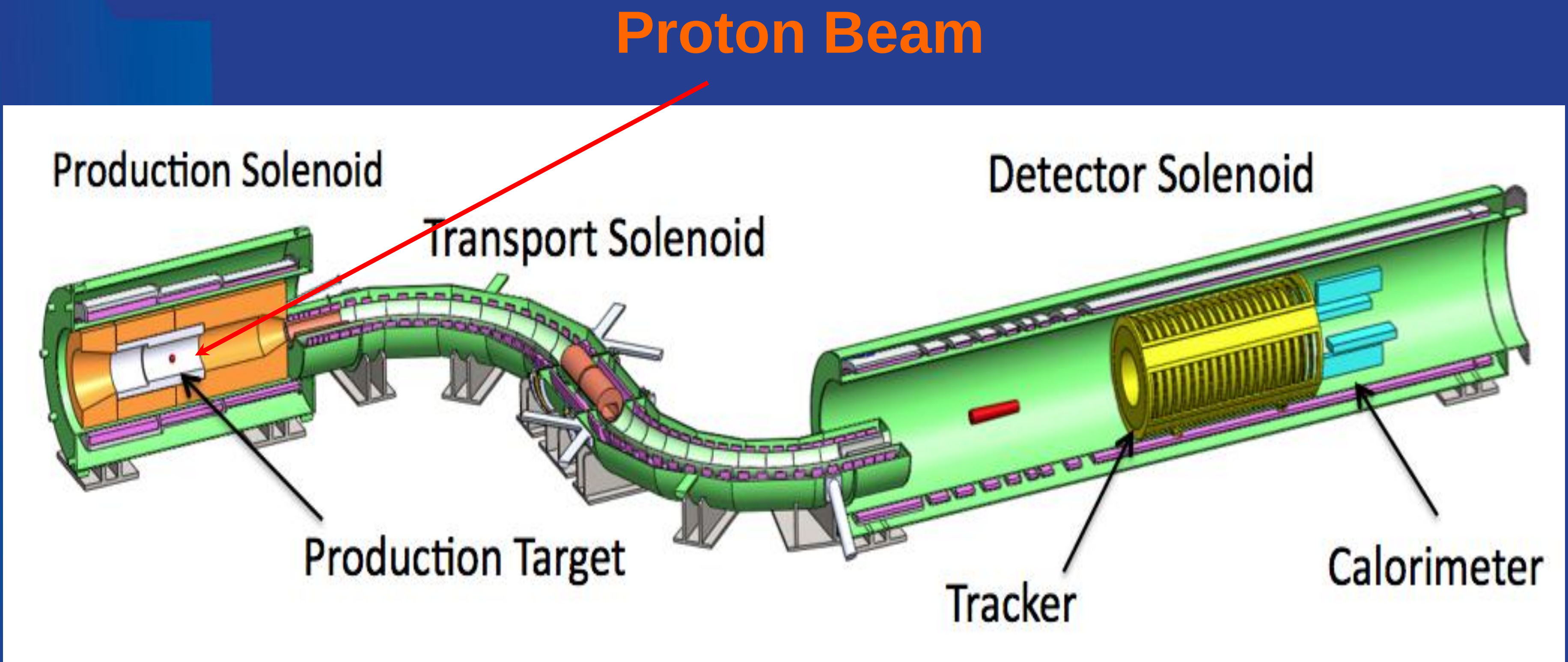
Pions decay producing muons.

Proton Beam



The Transport solenoid performs sign and momentum selection.

High energy negative particles, positive particles and line-of-sight neutrals are eliminated.



Muons are captured in a stopping target.

The conversion electron trajectories are measured in the tracker, and energy in the calorimeter.

Cosmic Ray Veto surrounds the Detector Solenoid.

Conclusions

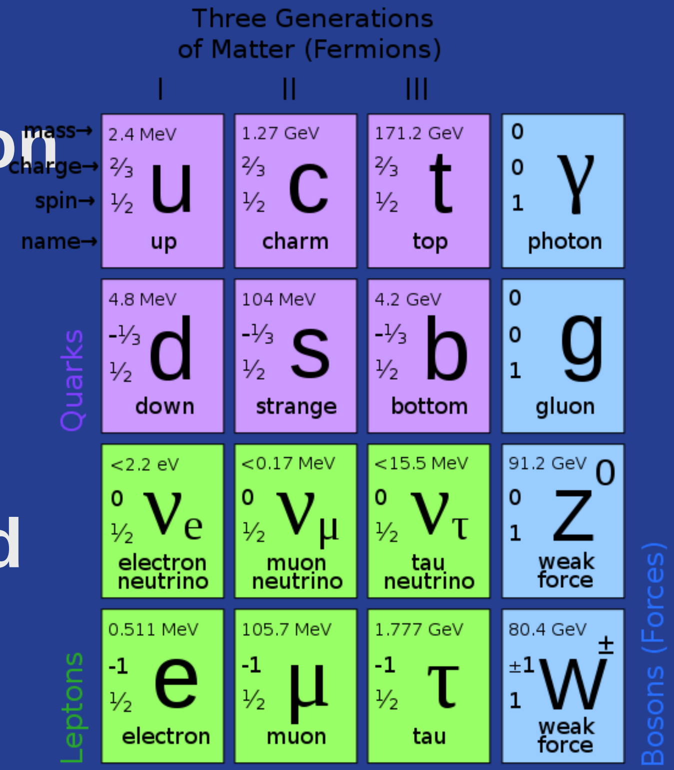
We continue to smash the nuclei that make up our universe and everyday we learn something new!

The Frontiers may merge at some point so

We Should Go Boldly into the Next Frontier

Why Mu2e

- Test SM as a theory
- Charged Lepton Flavor Violation (CLFV) suppressed in SM, allowed in BSM scenarios
- CLFV has never been observed



Three Generations of Matter (Fermions)

		I	II	III	
	mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
Quarks		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
		<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
Leptons		0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Muon Decay

- Rest energy of muon ≈ 105MeV
- Typical muon decay $\mu \rightarrow e^{-} \nu \bar{\nu}$
- Sum of the energy of products = energy of original muon
- In the case of CLFV $\mu \rightarrow e^{-}$, energy of the electron ≈ 105MeV, most is KE

Coherent Conversion of Muon to Electrons ($\mu^- N \rightarrow e^- N$)

- Muons stop in matter and form a muonic atom.
- They cascade down to the 1S state in less than 10^{-16} s.
- They coherently interact with a nucleus (leaving the nucleus in its ground state) and convert to an electron, without emitting neutrinos $\Rightarrow$ $E_e = M_\mu - E_{NR} - E_B$. Coherence gives extra factor of Z with respect to capture process, reduced for large Z by nuclear form factor.
- Experimental signature is an electron with E_e=105.1 MeV emerging from stopping target, with no incoming particle near in time: background/signal independent of rate.
- More often, they are captured on the nucleus: $\mu^-(N,Z) \rightarrow \nu_\mu(N,Z-1)$

  or decay in the Coulomb bound orbit: μ-$(N,Z) \rightarrow \nu_\mu(N,Z)\nu_e$

  (τ_μ = 2.2 μs in vacuum, ~0.9 μs in Al)
- Rate is normalized to the kinematically similar weak capture process:

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N(Z-1))}$$

Goal of new experiment is to detect $\mu^- N \rightarrow e^- N$ if $R_{\mu e}$ is at least 2×10^{-17} with one event providing compelling evidence of a discovery.

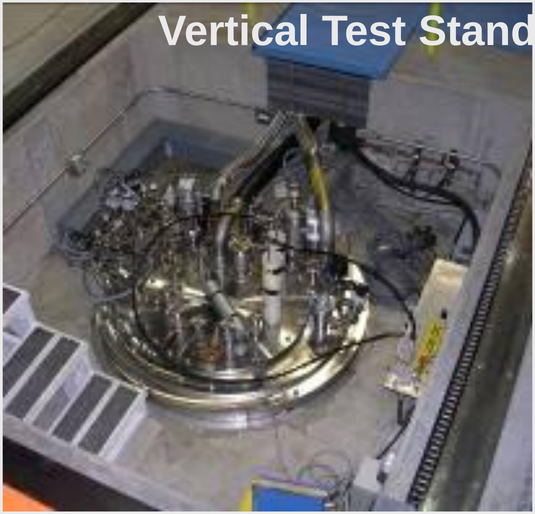
- The intensity frontier and flavor physics may well reveal a sign of exotic physics!
- Mu2e will improve sensitivity by 4 orders-of-magnitude relative to past CLFV searches.
- Mu2e will provide complementary information relative to the LHC and is sensitive to mass scales many orders of magnitude higher than can be directly probed at colliders.
- Lots of interesting work to do. You could help make this fantastic experiment a reality…

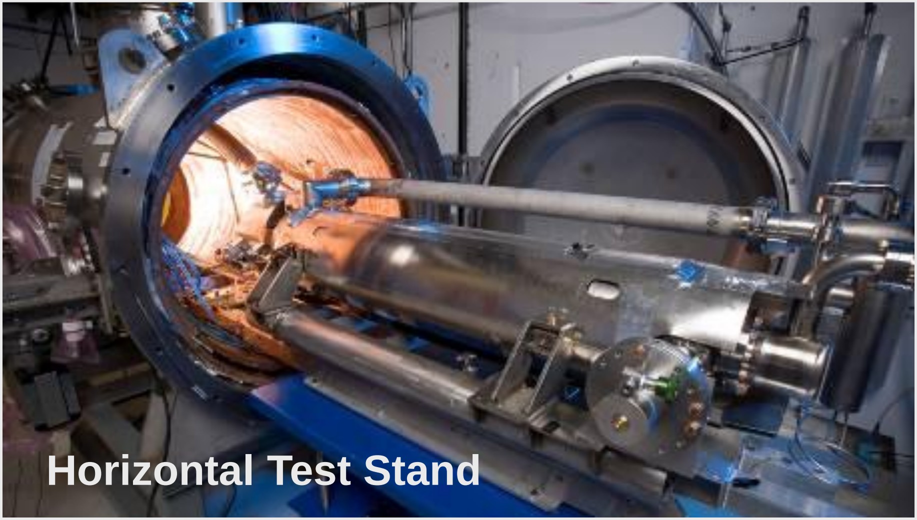
- One can probe the properties of the universe by looking for extremely rare processes
- Complementary alternative to using higher energies
- The medium-term future of accelerator-based particle physics on US soil is the intensity frontier:
    - Neutrino experiments (NOvA, LBNE, MINOS, MINERvA, and others…)
    - Precision measurements (g-2)
    - Rare decays (Mu2e)

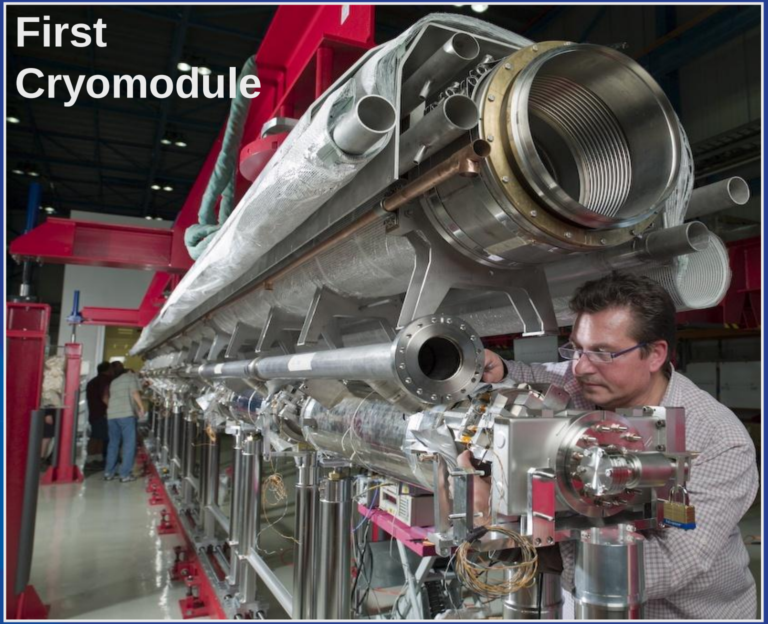
SCRF Tech: Broadly Applicable

at Fermilab


cavities


Vertical Test Stand


Horizontal Test Stand


First Cryomodule


NML Test Facility

The Mu2e Collaboration

- *Boston University*
- *Brookhaven National Laboratory*
- *Cal Tech*
- *University of California, Berkeley*
- *University of California, Irvine*
- *City University of New York*
- *Duke University*
- *Fermilab*
- *University of Houston*
- *University of Illinois, Urbana-Champaign*
- *Institute for Nuclear Research, Moscow*
- *JINR, Dubna, Russia*
- *Lawrence Berkeley National Laboratory*
- *Los Alamos National Laboratory*
- *Northwestern University*
- *INFN Frascati*
- *INFN Pisa, Università di Pisa, Pisa, Italy*
- *University of Massachusettes*

- *INFN Lecce, Università del Salento, Italy*
- *Rice University*
- *Syracuse University*
- *University of Virginia*
- *College of William and Mary*
- *University of Washington, Seattle*

~120 collaborators ..plus

- Mu2e received mission-need approval from DOE in November 2009.
- From our Mission Need Statement:
  - “A muon-to-electron conversion experiment at Fermilab could provide an advance in experimental sensitivity of four orders of magnitude.”
- We have a complete set of requirements designed to meet this goal:

  →Describes what each major system component must achieve
- We have a conceptual design that basically satisfies these requirements.
- Mu2e had a successful Independent Design Review on May 3rd and 4th
- Other reviews are pending

Goal: Approved conceptual design in the next few months

Summary

- A muon-to-electron conversion experiment at sensitivity below 10^{-16} has excellent capabilities to search for evidence of new physics and to study the flavor structure of new physics.

- An appropriate proton beam is being designed for such an experiment at Fermilab with net positive impact on the laboratory program.

- This experiment will complement the neutrino program at Fermilab in the next decade and signal a focus on the Intensity Frontier.

- World best measurement of
- Δm^2 : $2.43 \times 10^{-3} \pm 0.13$ eV^2
- $\sin^2 2\theta > 0.95$