# Beyond E = mc2
# Using Rare Particle Decays to Probe the Energy Frontier

## Exploiting Heisenberg's Uncertainty Principle to trump Einstein's E=mc2

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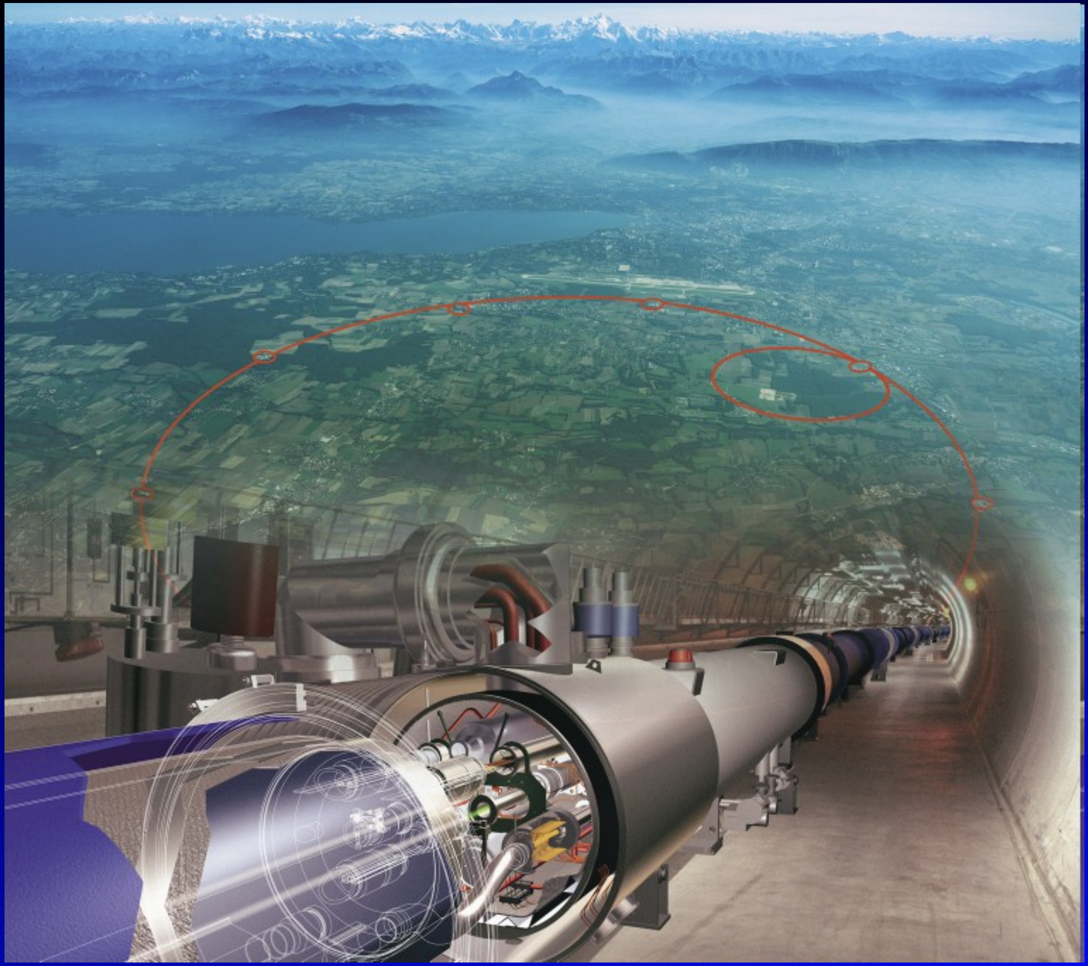
University of Virginia
BCVSPIN 2011
July 27, 2011

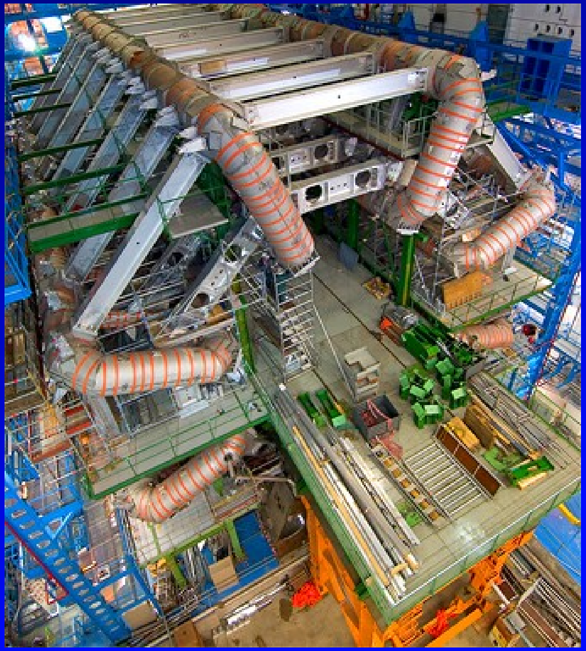
Elementary Particle Physics
University of Virginia
Antimatter Asymmetry Group
at the University of Virginia

# The World Eagerly Awaits Physics from the LHC

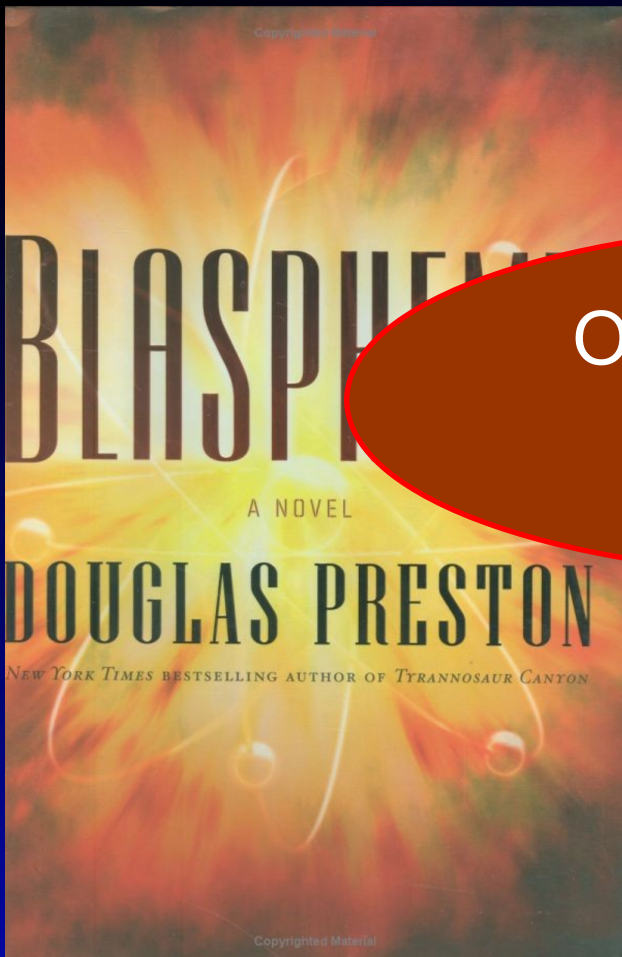


7 trillion (1012) eV proton energy:

7X Fermilab Tevatron



# LHC Has Already Had a Profound Impact




On bad literature!

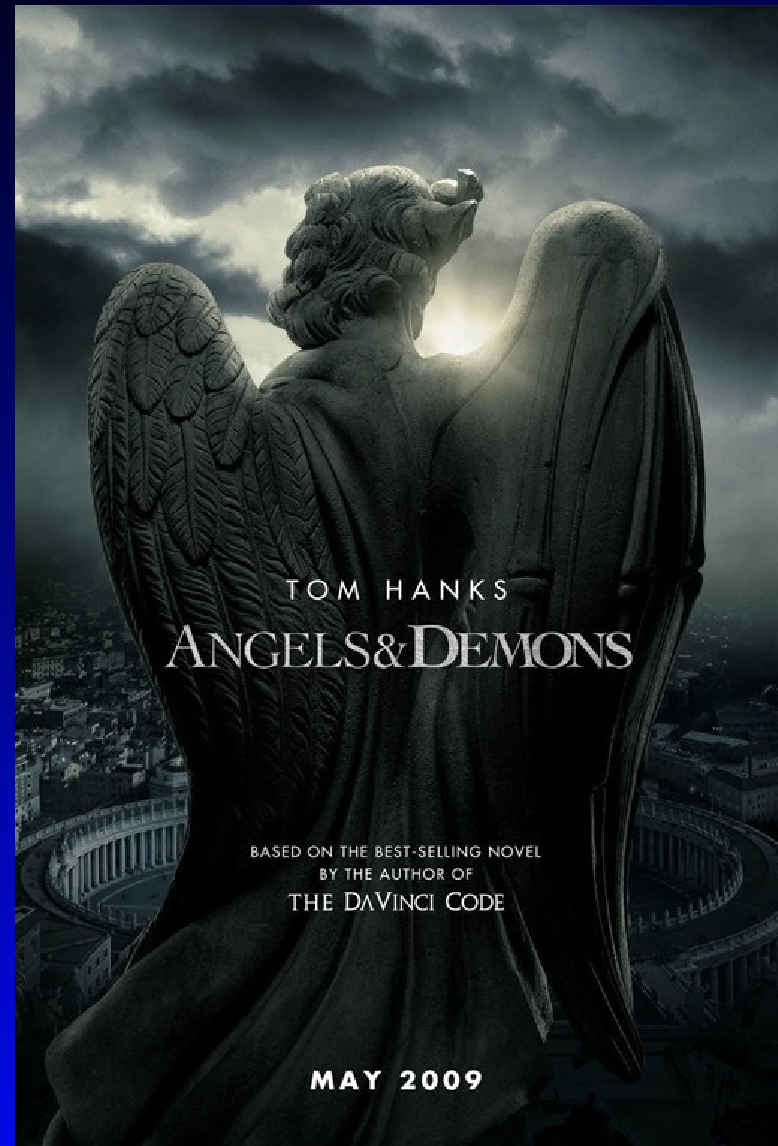
JULY

KEN DOLBY STOOD BEFORE HIS WORKSTATION, his smooth, polished fingers caressing the controls of Isabella. He waited, savoring the moment, and then he unlocked a cage on the panel and pulled down a small red bar.

…thing to indicate that the most expensive …d on. Except that, two hundred …slightly.

…the fine vibration of her …a woman, and in his more …what she looked like—tall and …the desert night, beaded with sweat. Isabella. He had shared these feelings with no one—no point in attracting ridicule. To the rest of the scientists on the project, Isabella was an "it," a dead machine built for a specific purpose. But Dolby had always felt a deep affection for the machines he created—from when he was ten years old and constructed his first radio from a kit. Fred. That was the radio's name. And when he thought of Fred, he saw a fat carroty-haired white man. The first computer he had built was Betty—who looked in his head like a brisk and efficient secretary. He couldn't explain why his machines took on the personalities they did—it just happened.

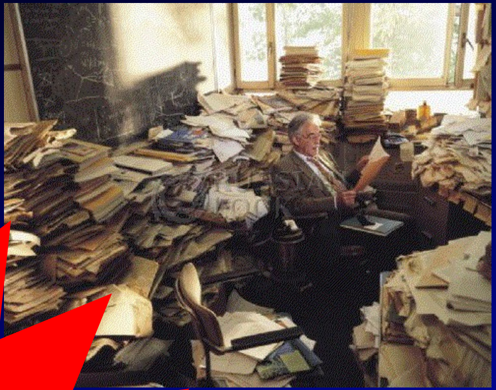
# Angels and Demons

# The Cause of our Excitement

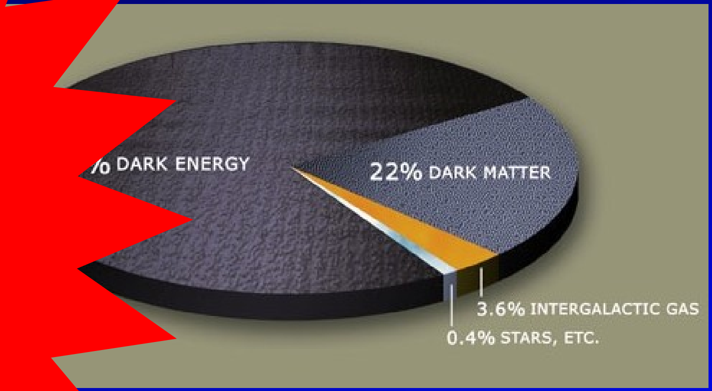
Theory

- Understanding of the electromagnetic and weak interactions ¿ Higgs?
- Origin of neutrino mass hierarchy
- Solution to hierarchy pr... supersym...e...ry?



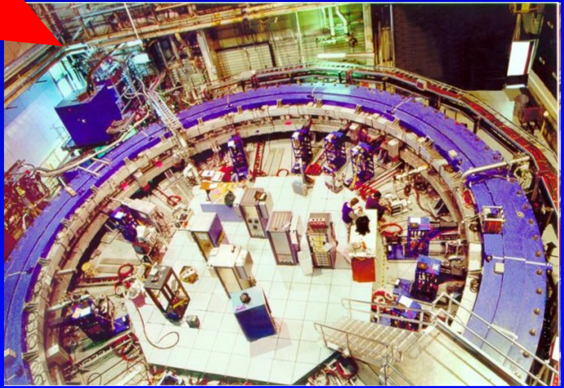
Cosmology

- Matter-antimat... universe
- Dark matte...
- Dark energ...




Experiment

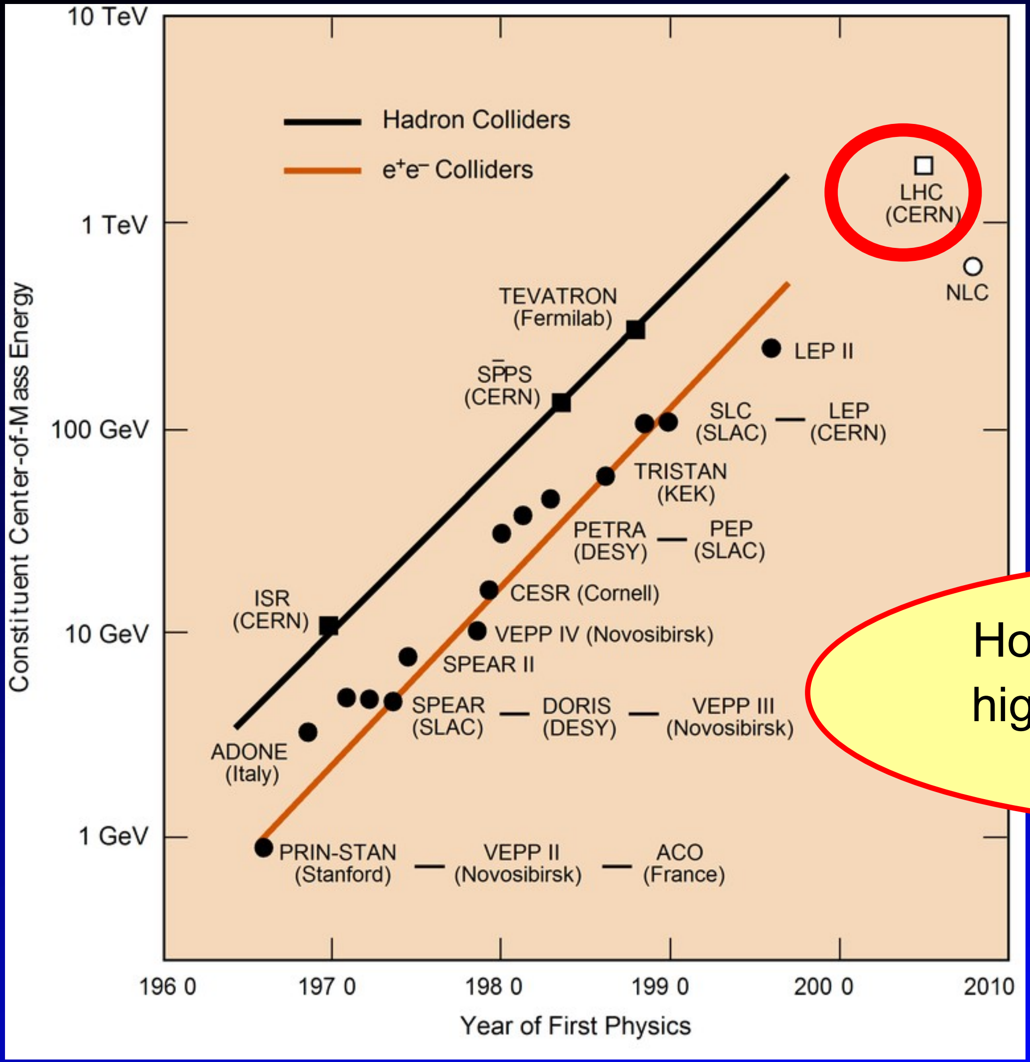
- Neutrino mass... physics be...ond...
- Weak interaction studi... ¿ ...igg...?
- Other hints, muon g-2, NuTeV, CP phases in Bs mixing, Ds decay rates, W+jets, Top AFB



No...

**Some of this New Physics may appear at energies too high for the LHC**

# Is the Large Hadron Collider the Last in a Long Line of ever Higher Energy Particle Accelerators?



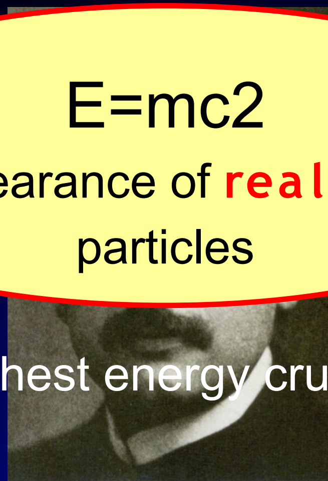

Presently there are no concrete plans for an accelerator to probe the next energy regime

How are we going to probe higher mass scales without higher energies?

# Rather than exploiting Einstein's mass-energy relation, E=mc2, exploit Heisenberg's uncertainty principle, ΔEΔt≳ħ/2

E=mc2

appearance of **real** new particles

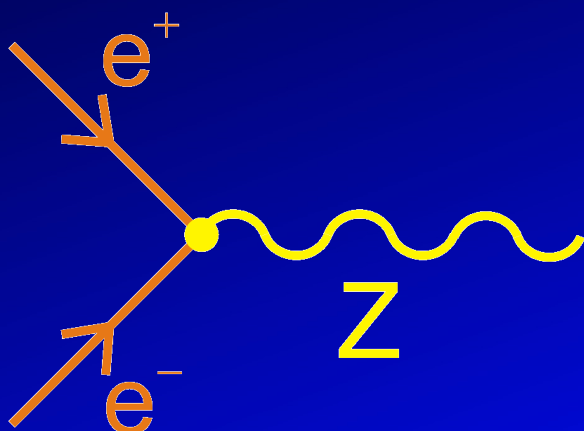


Highest energy crucial

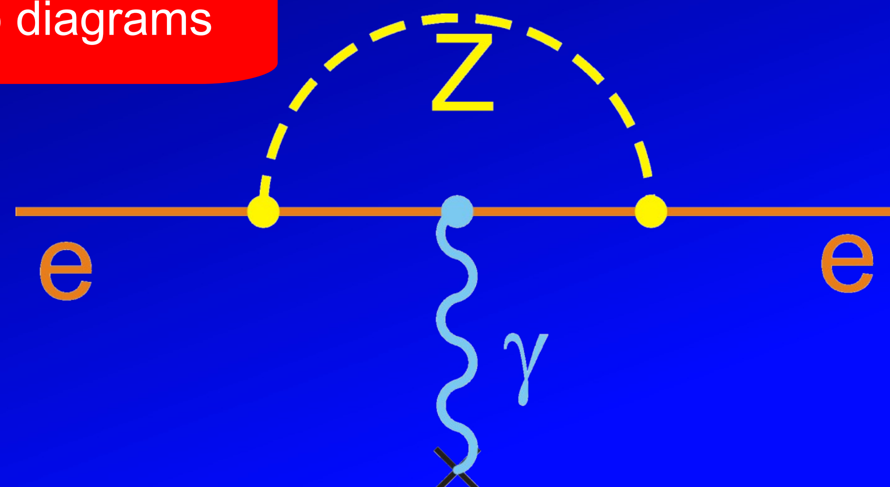
ΔEΔt ≳ ħ

appearance of **virtual** new particles

Highest intensities crucial



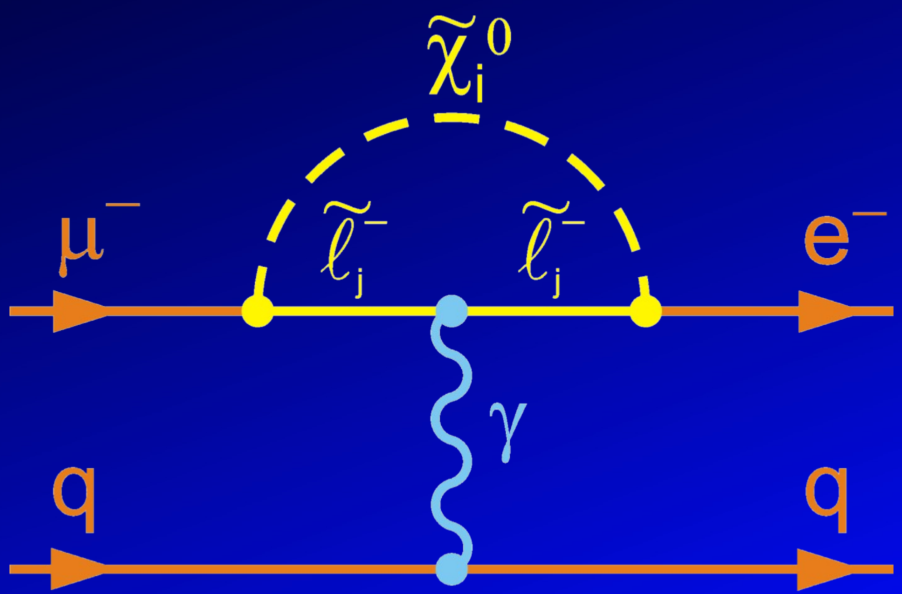

Loop diagrams



# Virtual Particles Can Have Two Effects

They can produce slight deviations from expected properties

Difficult experiments:
- incredible precisions often needed
- theoretical precision needed too
- precision ¿ 1/√N



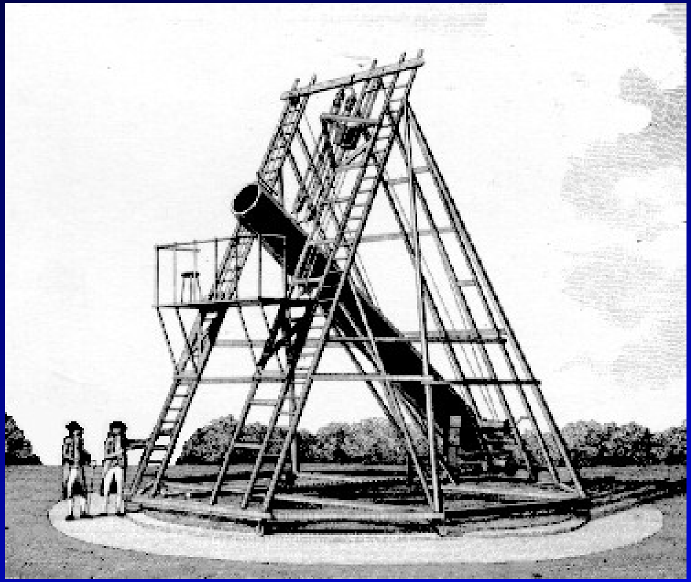


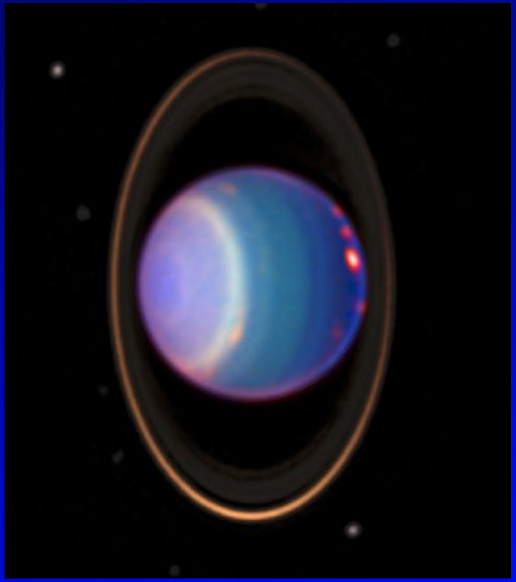
Th ... es,

"Easy" search experiments:
- theory ¿ process is "forbidden"
- one event can be enough
- sensitivity ¿ 1/N

# This Indirect Approach has a Distinguished Past

- Starts with William Herschel's discovery Uranus in 1781
- Uranus was the first planet to be discovered – all others were known to the ancients
- Soon a problem appeared ¿ orbit of Uranus was found to deviate from predictions from Newton's Laws

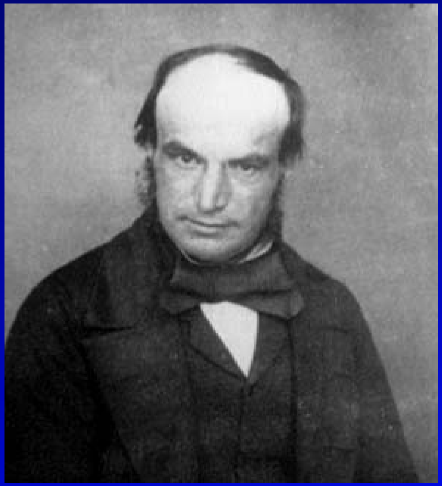




# Race to find explanation began

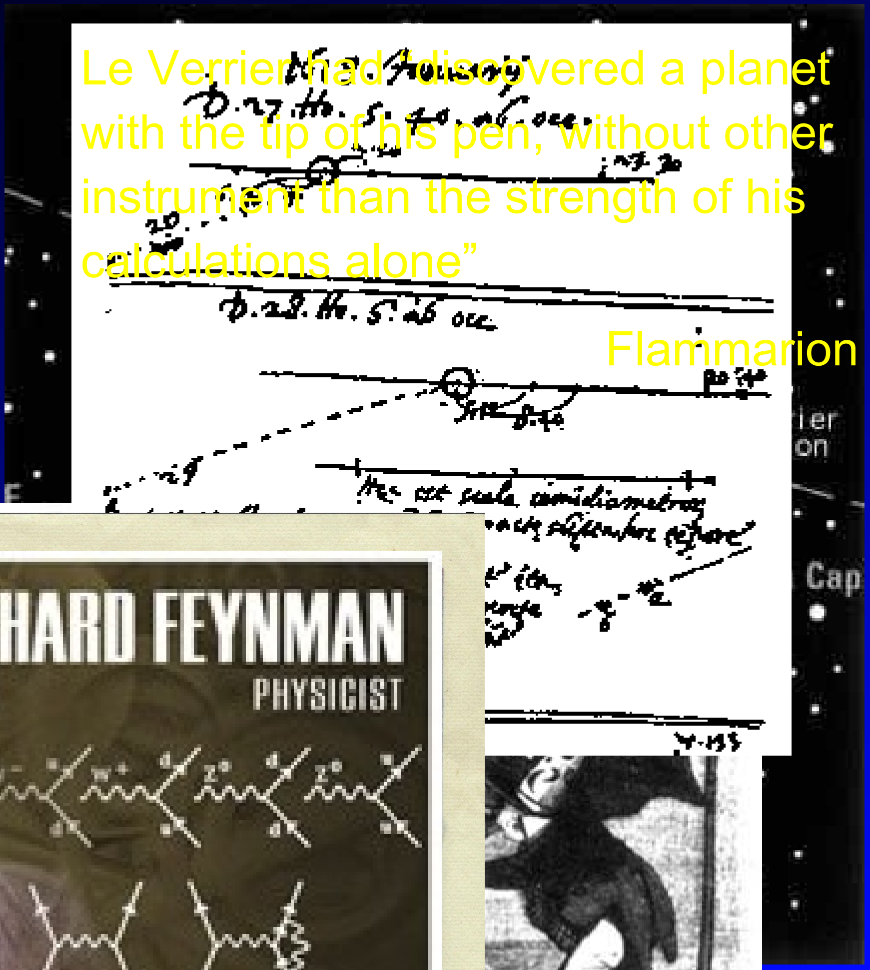
George Airy thought that explanation lied with deviations from Newton's law of gravitation

Le Verrier (France) and John Adams (UK) thought that the deviations were due to a hitherto unknown planet



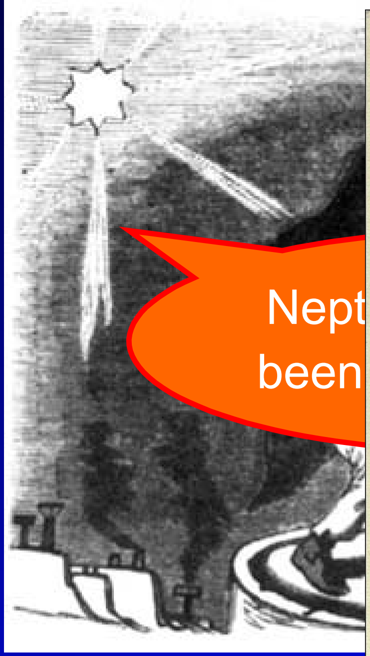
# Newton Vindicated

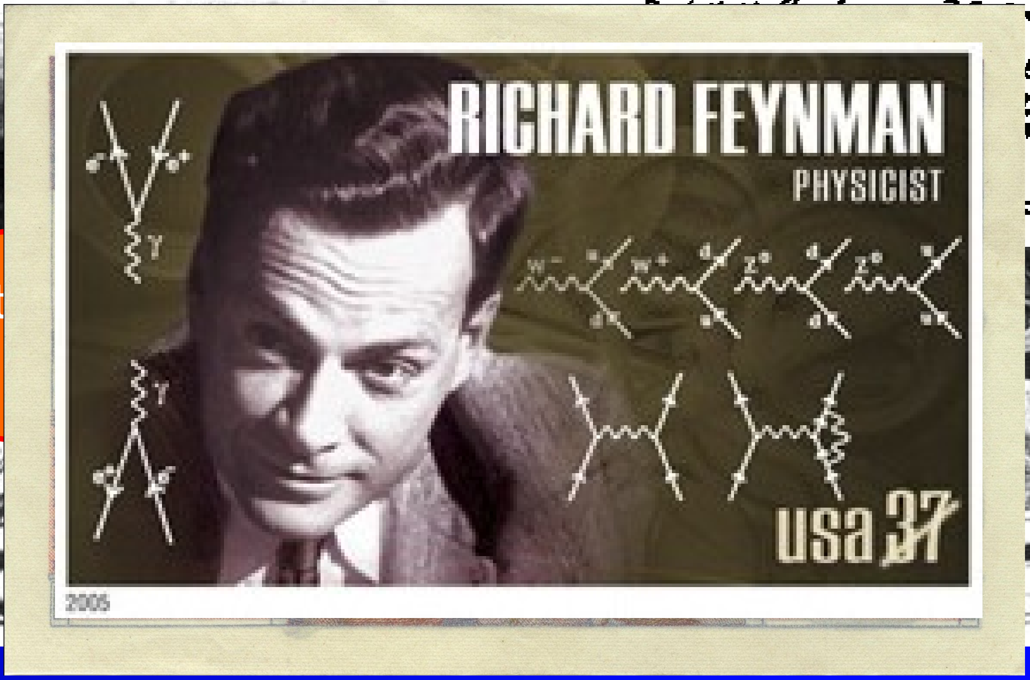
- Le Verrier won:  September 18, 1846 he wrote a letter asking Johann Galle at the Berlin Observatory if he might have a look
- On September 23 Galle in Berlin found Le Verrier’s planet



Le Verrier had discovered a planet with the tip of his pen, without other instrument than the strength of his calculations alone”

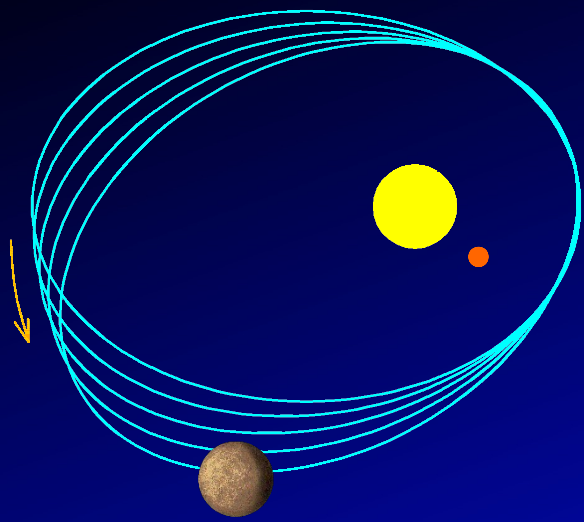
Flammarion



# What about Mercury?

Le Verrier turned his formidable talents to the orbits of the planets and found a discrepancy in the precession of the perihelion of Mercury



The race to find planet Vulcan had begun!

| Effect of the planets on the precession of Mercury's perihelion | |
|---|---|
| Venus | 280.6″ |
| Earth | 83.6″ |
| Mars | 2.6″ |
| Jupiter | 152.6″ |
| Saturn | 7.2″ |
| Uranus | 0.1″ |
| Total per century: | 527″ |
| Observed: | 527″+38″ |

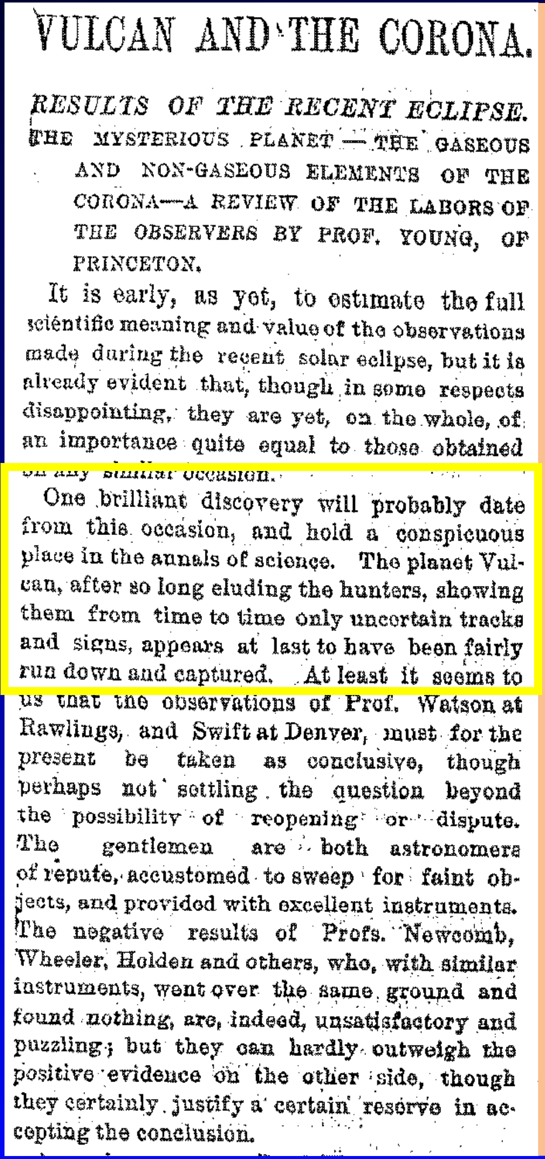
ne pouvait être vue que le soir ou le matin dans les vapeurs de l'horizon; en sorte qu'avant l'invention et le perfectionnement des lunettes, il était impossible de l'observer hors de ses élongations. Copernic, empêché par les brouillards de la ... ue durée des crépuscules en été, ne put jamais parvenir à

..., III et IV.

In 1859 he found a discrepancy of 1/10,000 of a degree per year!

# Race to Find Vulcan

- Vulcan was seen many times, but never confirmed
- “Dark matter” near the sun was invoked as a solution
- A modification of Newton’s law of gravity was another: $1/r^{2.00000016}$
- The problem remained outstanding at the beginning of the 20th century



VULCAN AND THE CORONA.

*RESULTS OF THE RECENT ECLIPSE.*

THE MYSTERIOUS PLANET—THE GASEOUS AND NON-GASEOUS ELEMENTS OF THE CORONA—A REVIEW OF THE LABORS OF THE OBSERVERS BY PROF. YOUNG, OF PRINCETON.

It is early, as yet, to estimate the full scientific meaning and value of the observations made during the recent solar eclipse, but it is already evident that, though in some respects disappointing, they are yet, on the whole, of an importance quite equal to those obtained on any similar occasion.

One brilliant discovery will probably date from this occasion, and hold a conspicuous place in the annals of science. The planet Vulcan, after so long eluding the hunters, showing them from time to time only uncertain tracks and signs, appears at last to have been fairly run down and captured. At least it seems to us that the observations of Prof. Watson at Rawlings, and Swift at Denver, must for the present be taken as conclusive, though perhaps not settling the question beyond the possibility of reopening or dispute. The gentlemen are both astronomers of repute, accustomed to sweep for faint objects, and provided with excellent instruments. The negative results of Profs. Newcomb, Wheeler, Holden and others, who, with similar instruments, went over the same ground and found nothing, are, indeed, unsatisfactory and puzzling; but they can hardly outweigh the positive evidence on the other side, though they certainly justify a certain reserve in accepting the conclusion.

New York Times, Aug. 16, 1878

# Vulcan not Found but General Relativity is

Einstein calculates the perihelion of Mercury using his new theory of General Relativity and recovers the missing 38”/century found by le Verrier 56 years earlier!

**Erklärung der Perihelbewegung des Merkur aus der allgemeinen Relativitätstheorie.**

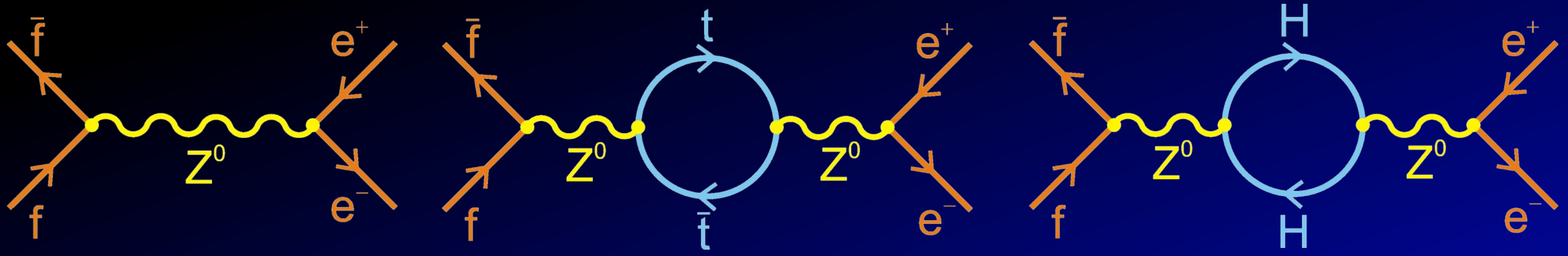
Von A. Einstein.

*Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1915): 831-839.

Three weeks later he admitted in a letter to Sommerfeld that he had been critical of the “*pedantic accuracy of astronomy*”.

“*For a few days I was beside myself with joyous excitement* .”
Albert Einstein, 18 November 1915

# Example: Top and Higgs Masses

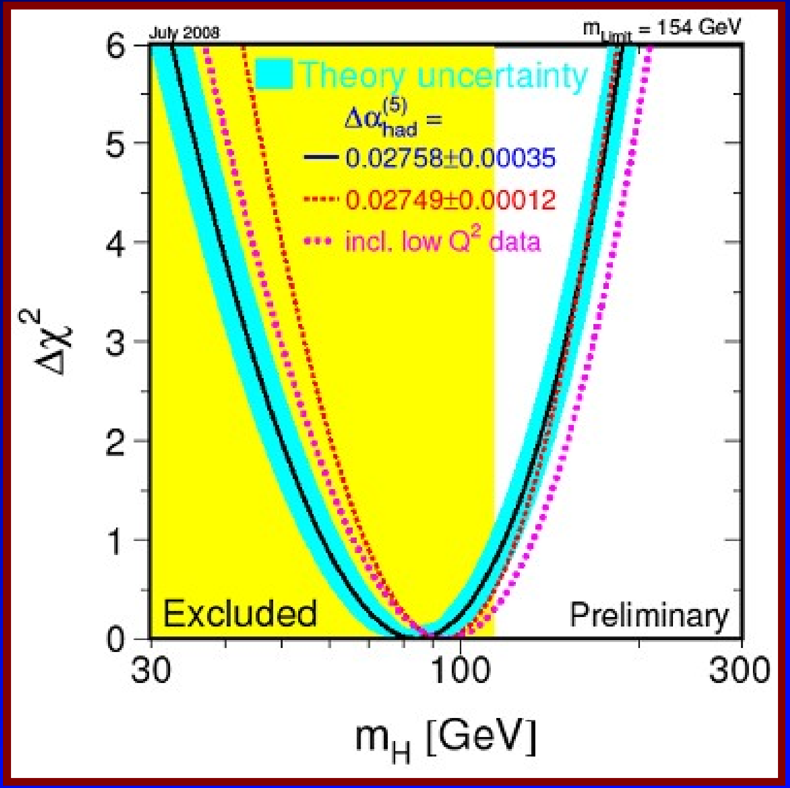



Virtual particles relate the properties of the weak force carriers (W, Z), and the masses of the top quark and Higgs

Top quark mass “predicted” by precision electroweak measurements before it was directly discovered by CDF and DØ at Fermilab: mt = 162±9 GeV (Ellis, Fogli, Lisi, 1994).

Now that top quark mass is known the same game is being played to predict the Higgs mass

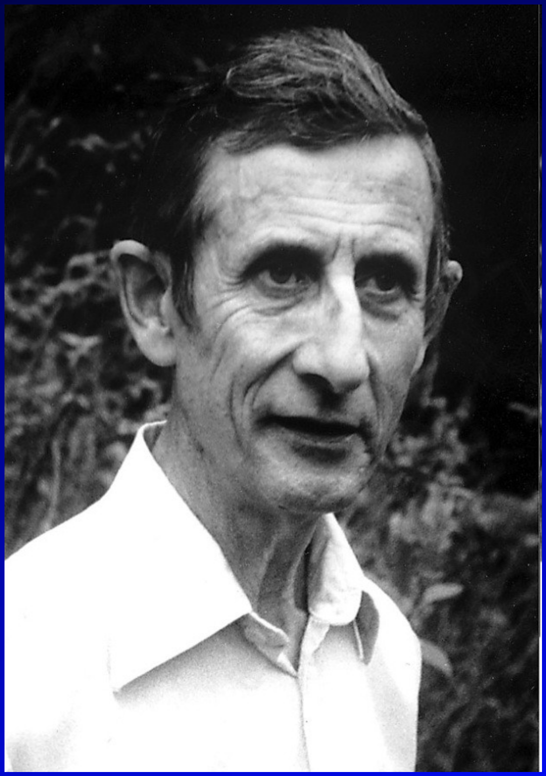
most probable value:



# Rare and Precision Physics has a Distinguished Past

"The results of my survey are then as follows: four discoveries on the energy frontier, four on the rarity frontier, eight on the accuracy frontier. Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier. For making important discoveries, high accuracy was more useful than high energy."

Freeman Dyson, review of *The Lightness of Being*, F. Wilczek



# Rare Decays Require Flavor Factories

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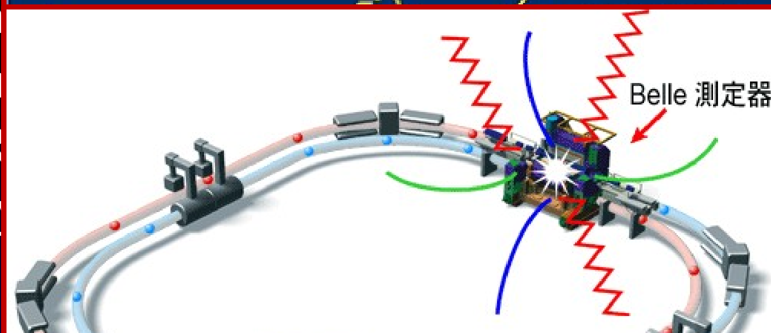



BES-III tau-charm
Factory at Beijing, China

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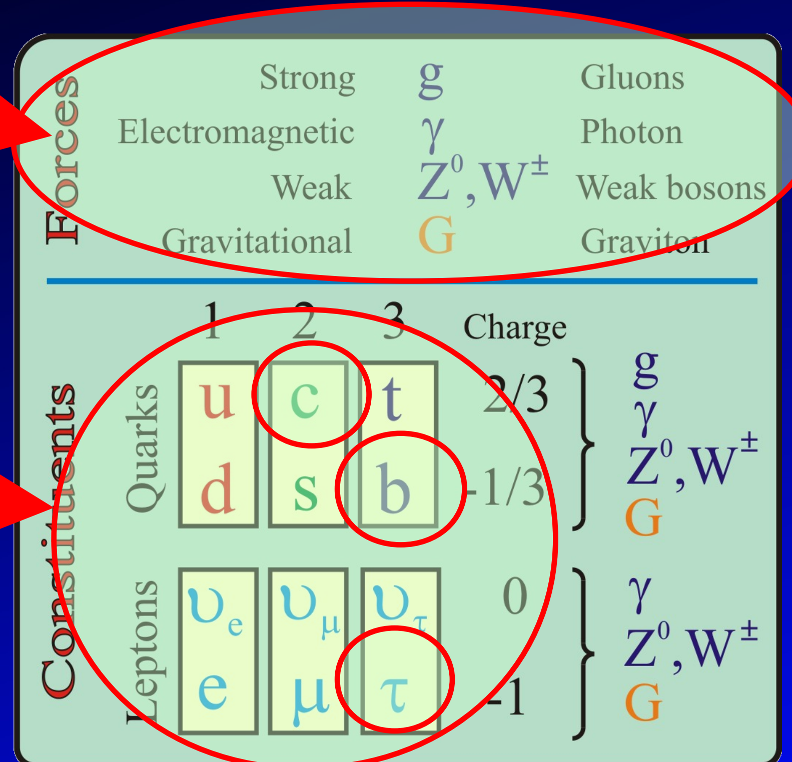
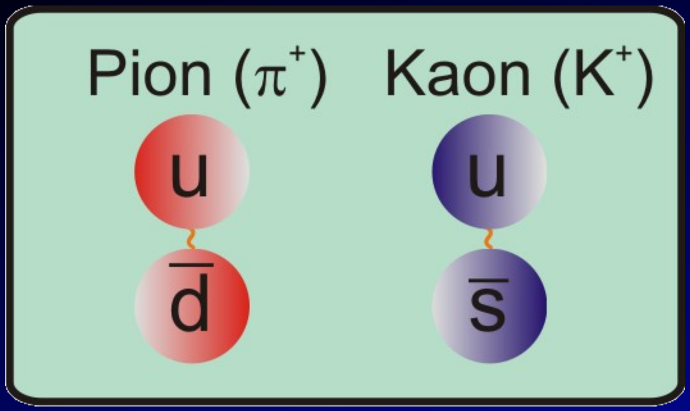



10 billion b/anti-b pairs/yr

10 billion $\tau$/anti-$\tau$ pairs/yr

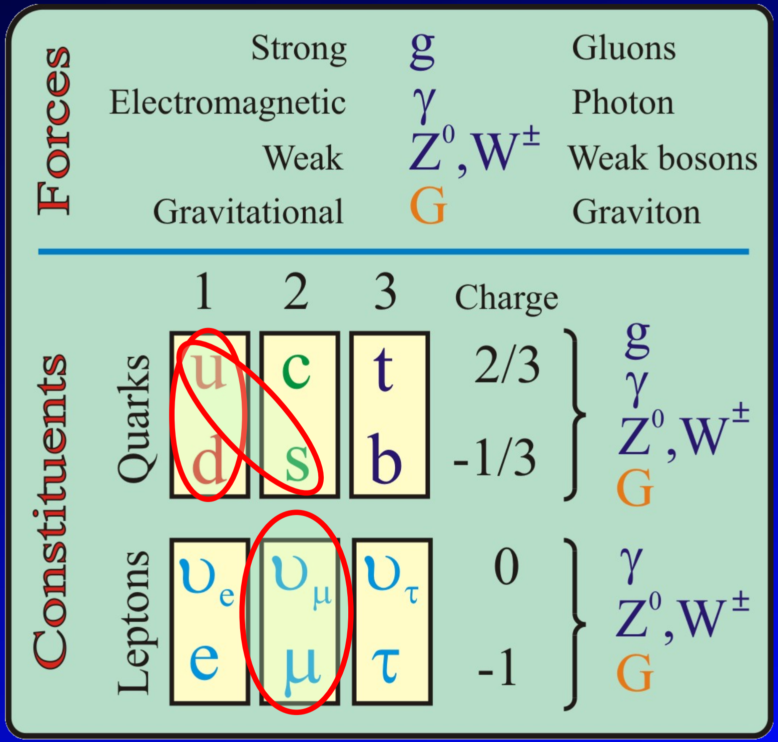
# Proton Accelerators are General Purpose Flavor Factories

Produce beams of pions and kaons




Which in turn produce beams of muons and muons neutrinos

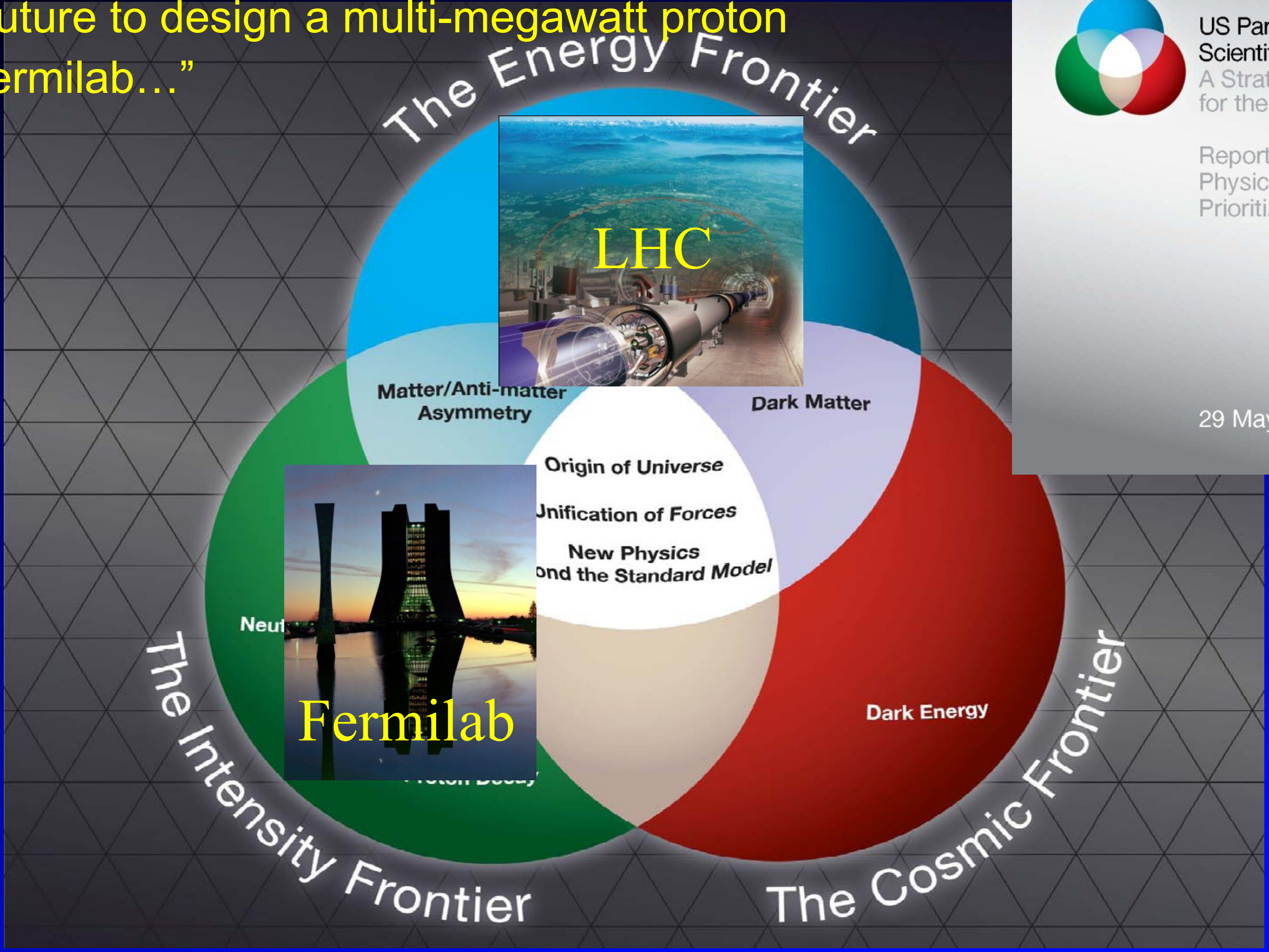
~1-100 billion/s can be produced

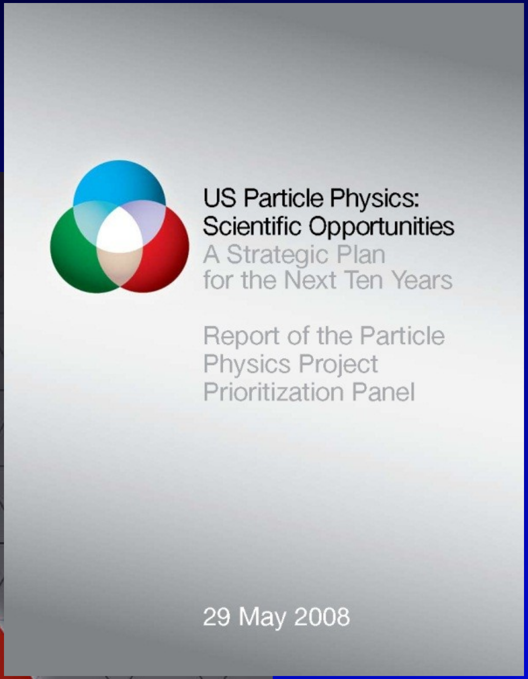


# Fermilab Pushing Forward on Intensity Frontier

Strategic Plan for the Next Ten Years:

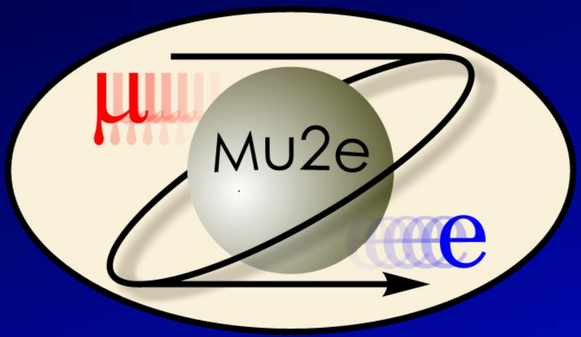
"The panel recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab…"



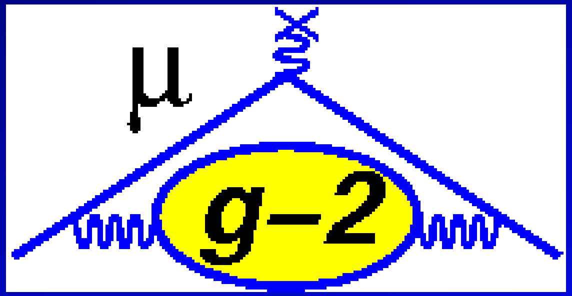



# A Snapshot of Two Intensity Frontier Experiments

Rare muon decay experiment



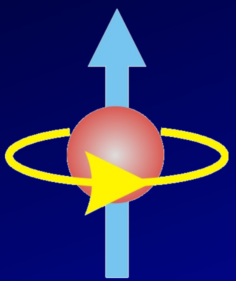

Precision muon experiment



# Magnetic Moment of the Muon: Theory

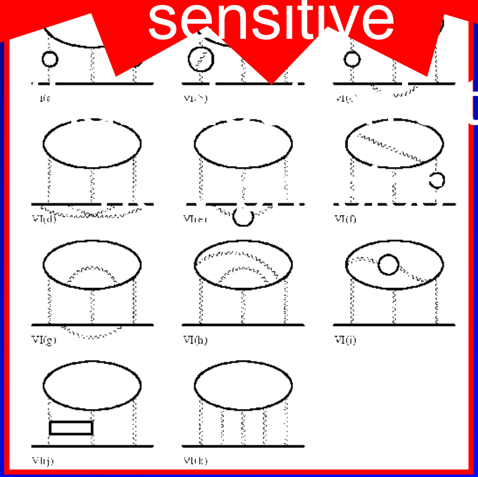
Measuring magnetic moments of fundamental particles has long and productive history

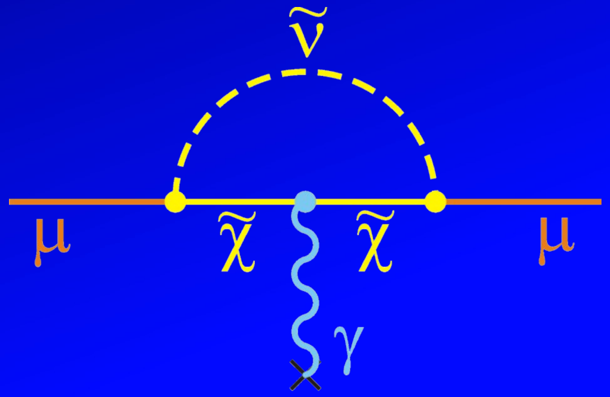
- anomalous magnetic moments of protons and neutrons implied substructure ¿ quarks
- Most precise test of quantum electrodynamics (QED)



...ation over past 40 years by ...errier's in calculating ...etic moment

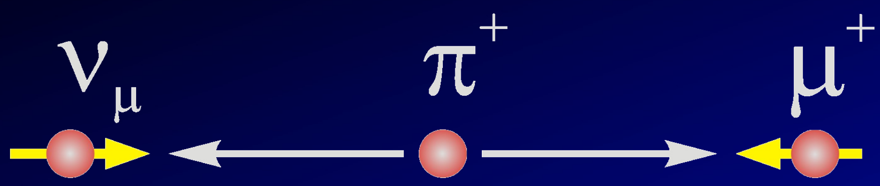
Muon's magnetic moment
40,000 times more sensitive

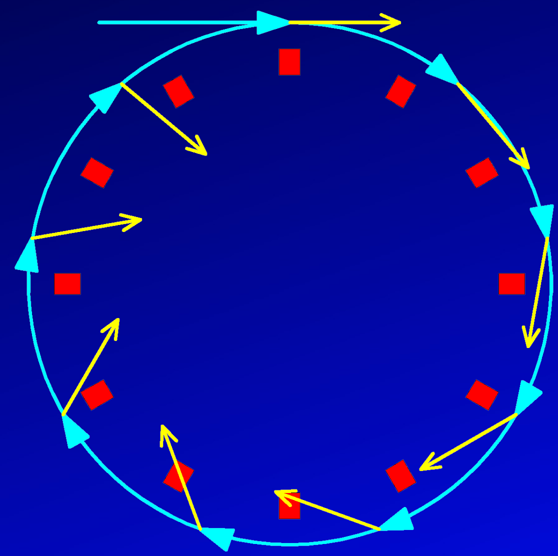
Dirac +  to + New Physics

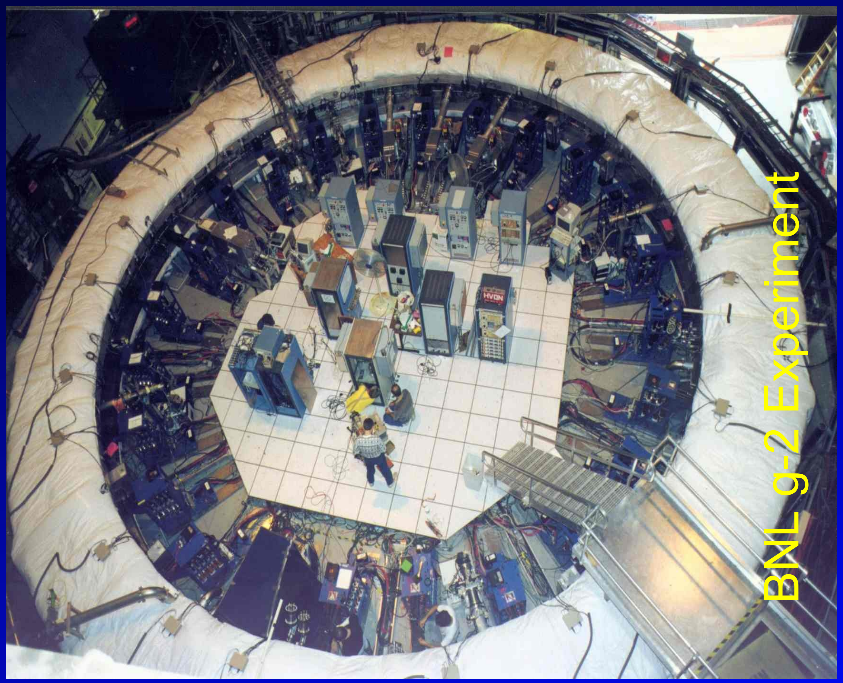


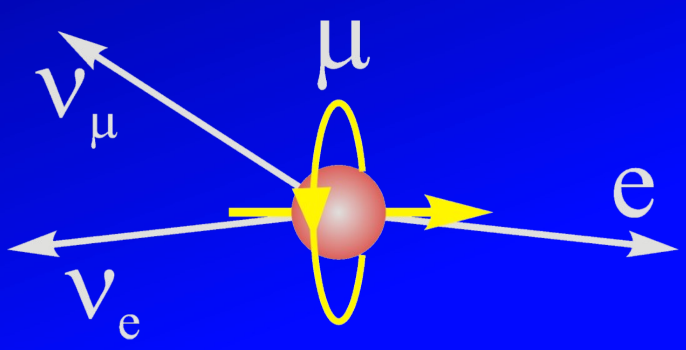
# Magnetic Moment of the Muon: Experiment

1. Pion decay produces polarized muons
2. Precession in magnetic field proportional to anomalous magnetic moment
3. Parity-violating decay of muons reveals precessed magnetic moment direction





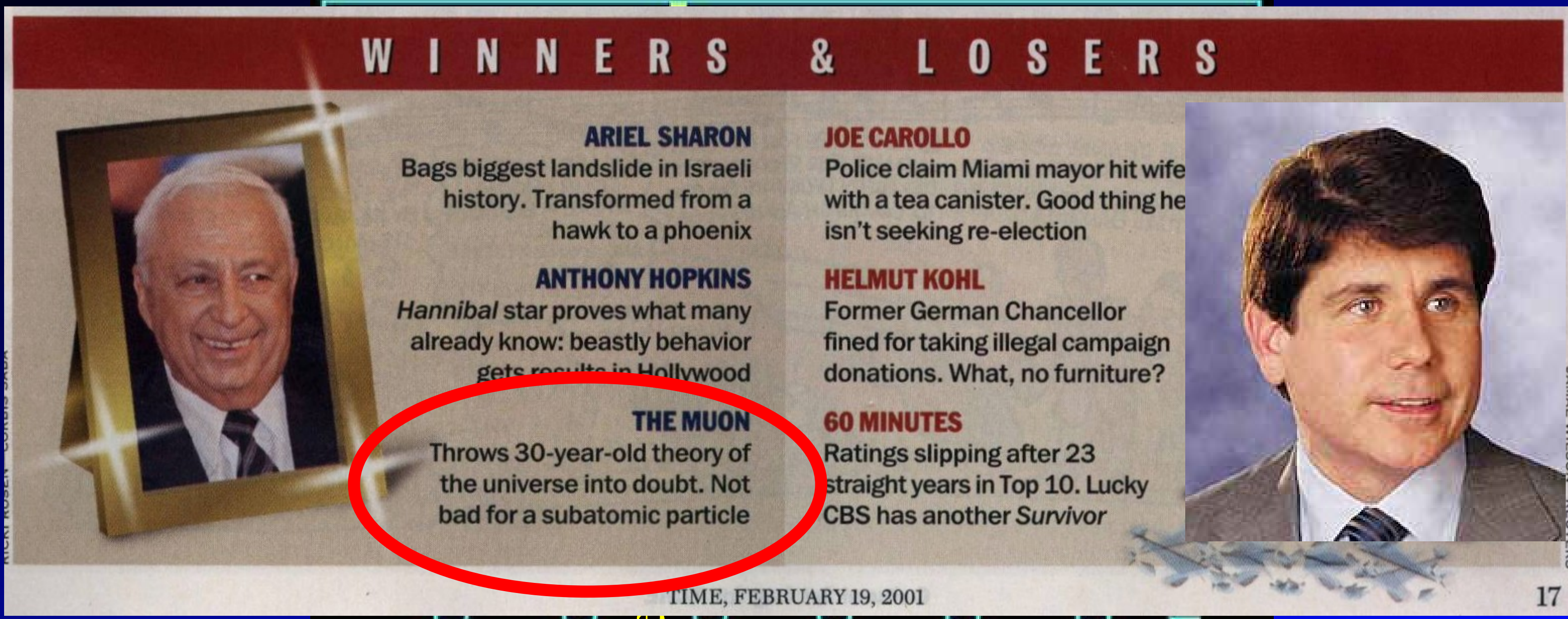



# Theory Meets Experiment

Theory and experiment differ by > $3\sigma$

$\Delta$= (296¿ 81)x10-11

New Physics?

WINNERS & LOSERS

**ARIEL SHARON**
Bags biggest landslide in Israeli history. Transformed from a hawk to a phoenix

**ANTHONY HOPKINS**
*Hannibal* star proves what many already know: beastly behavior gets results in Hollywood

**THE MUON**
Throws 30-year-old theory of the universe into doubt. Not bad for a subatomic particle

**JOE CAROLLO**
Police claim Miami mayor hit wife with a tea canister. Good thing he isn't seeking re-election

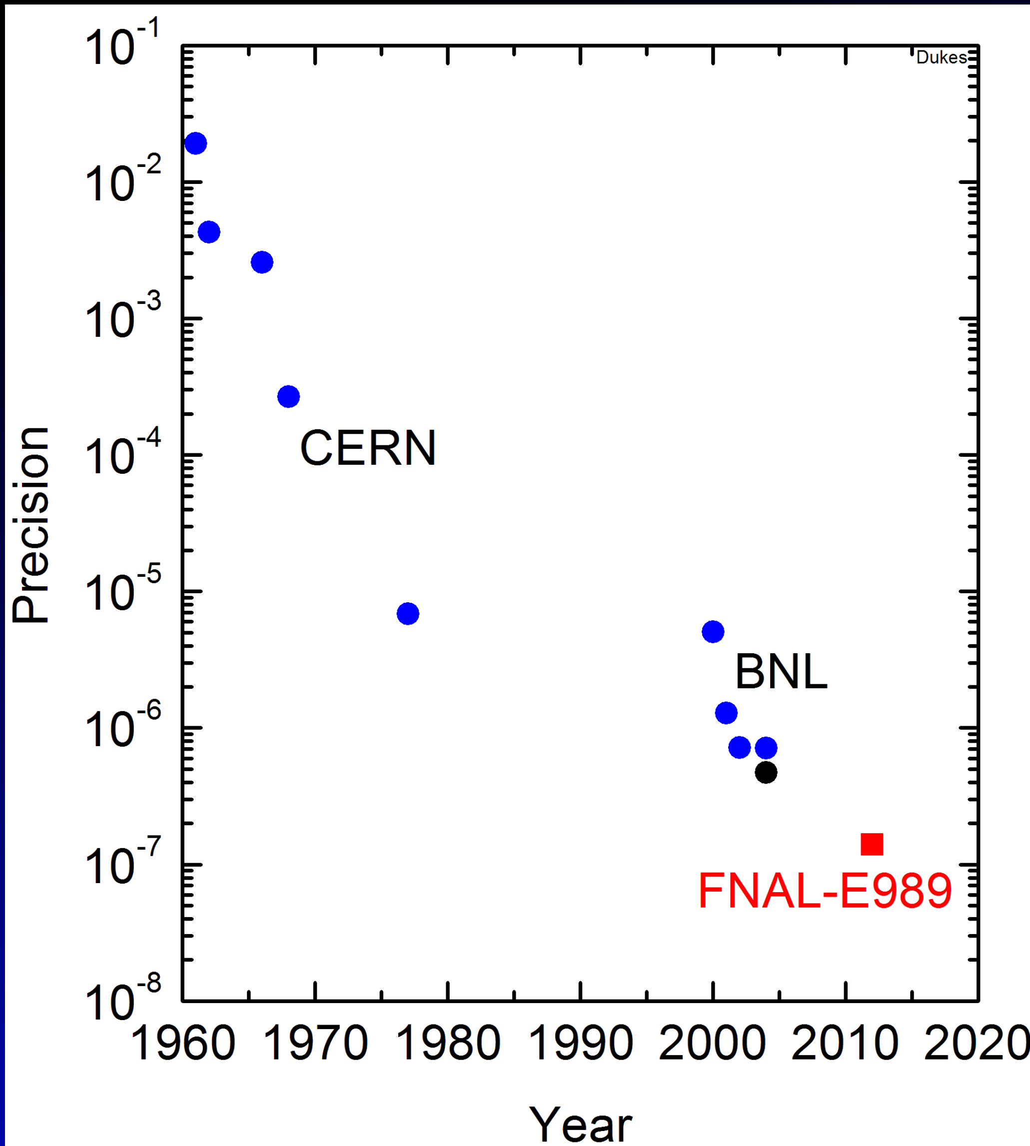
**HELMUT KOHL**
Former German Chancellor fined for taking illegal campaign donations. What, no furniture?

**60 MINUTES**
Ratings slipping after 23 straight years in Top 10. Lucky CBS has another *Survivor*

JAMAL WILSON—REUTERS

TIME, FEBRUARY 19, 2001 17

# Pushing the Precision at Fermilab: E989



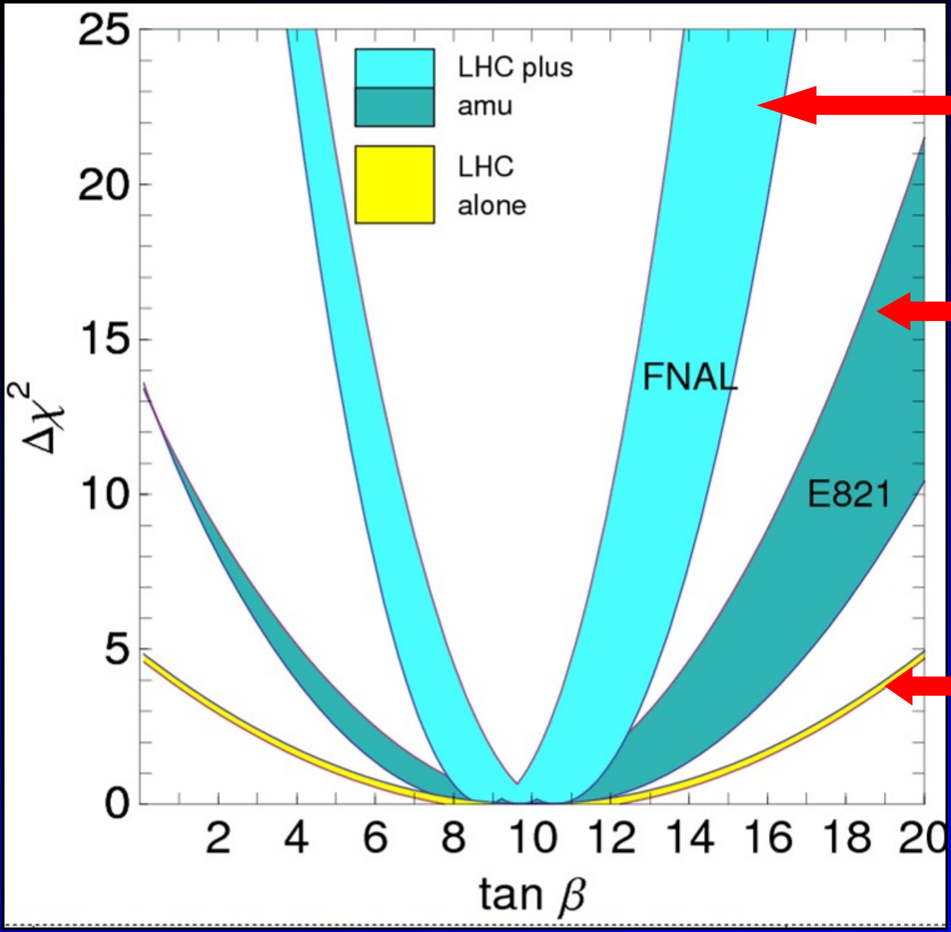

Approved
February 2011

| Error Budget (ppm) | | | |
|---|---|---|---|
| | BNL | | Fermilab |
| Statistical | 0.46 | → | 0.10 |
| Systematic | 0.18 | → | 0.07 |
| Total: | 0.54 | → | 0.14 |

- 20X more beam
- Better calorimeter/DAQ
- Longer beamline

# Moving the BNL Magnet to Fermilab

# SUSY Meets Muon g-2




FNAL

BNL

LHC (Sfitter)

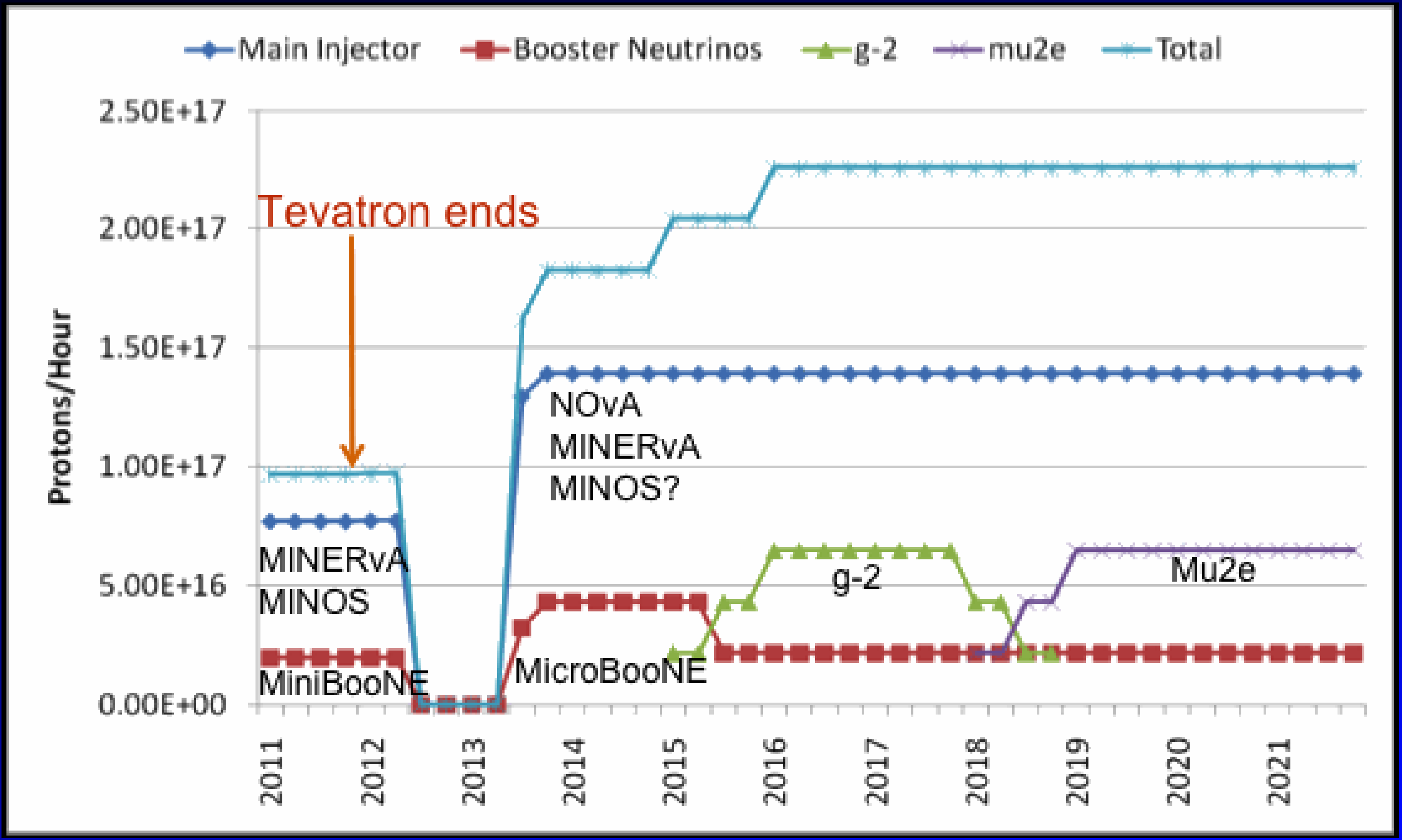
SPS1a: 100 fb-1, 14 TeV

"g-2 is the most important constraint (for SUSY), even more important than dark matter"

Fittino-collaboration, arXiv:0907.2589

# Proposed Schedule

- E989 approved in Feb. 2011
- Data taking in 2016



# Search for Charged Lepton Flavor Violation

# Quark and Lepton Alchemy

Quarks

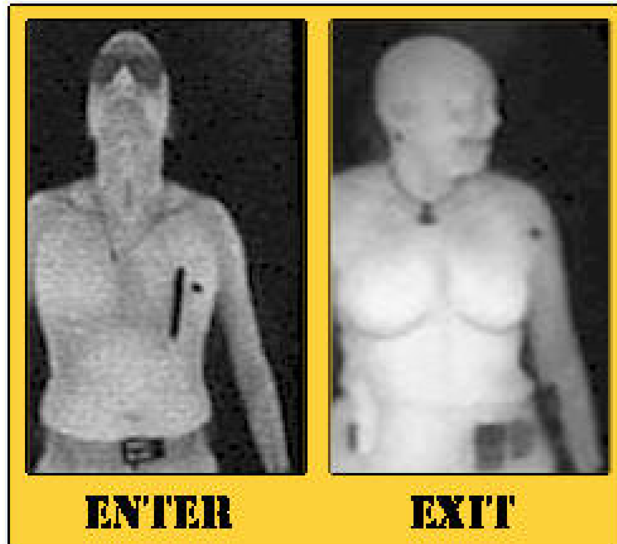
Leptons

1 September 2005

## Passenger sues TSA over "instant" sex change

### Agency blames malfunctioning X-ray scanner

DALLAS, Texas -- An American Airlines passenger who was passing through a newly installed X-ray machine here got more than scanned this past month. In a freak accident during a thunderstorm at the Dallas/Fort Worth International Airport, a lightning strike caused a surge in power just as the passenger entered the device. According to Dr. Sanjay McMurphy, a physician who happened to be at the scene during the incident, "the momentary increase in voltage apparently caused the instantaneous mutation of the passenger's hormonal structure, instantly changing him from a man into a woman."




In response to the incident, Rhoda Prindabble, a spokesperson for the Transportation Security Administration (TSA) said, "While we have had reports of people aging significantly while passing through the body scanners, this is the first we've heard of the machines contributing to a sex change. The TSA has opened an investigation, the results of which should be known before the devices are widely deployed."

$e^-$

$e^-$

vert to one

ton flavor

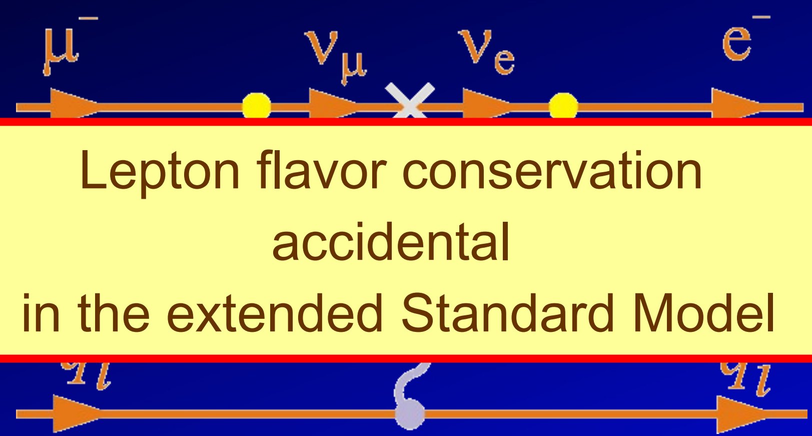
# Why Search for Charged Lepton Flavor Violation?

- In Standard Model not there ¿ neutrino mass discovery implies an unobservable 10-52 rate
- Hence, any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally
  - sensitivities that allow favored beyond-the-standard-model

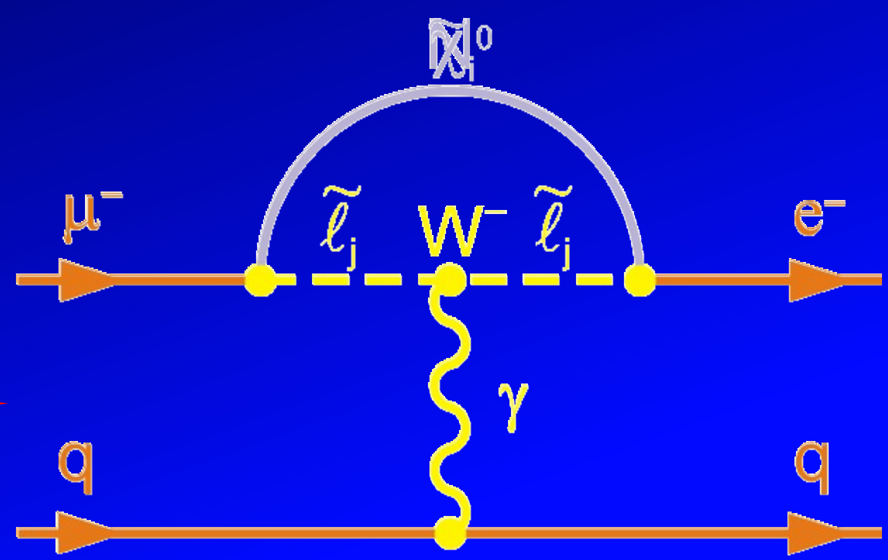
Almost all models explaining the

Supersymmetry

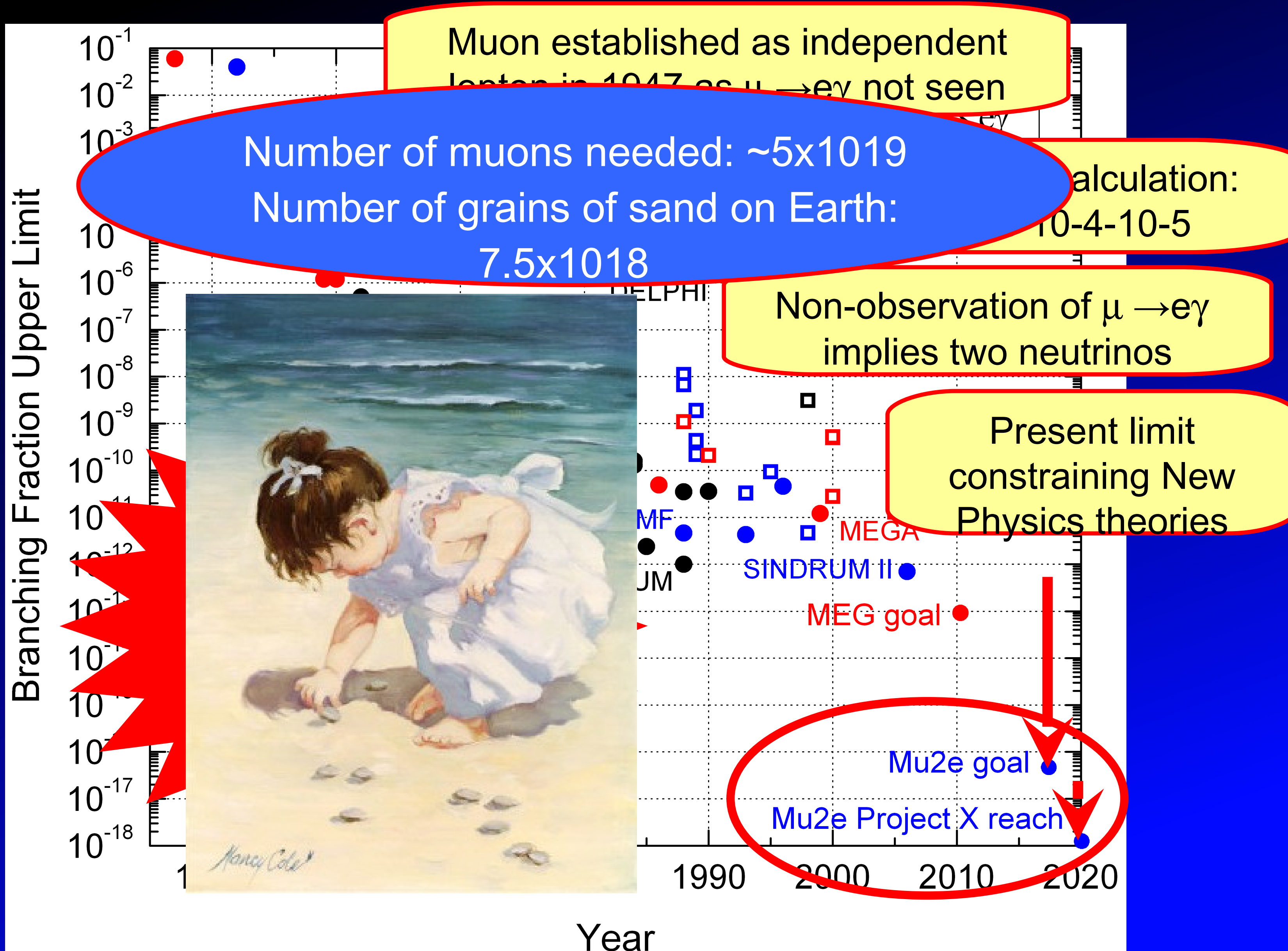
$\mu^- N \rightarrow e^- N$ at levels that will be probed by Mu2e




Lepton flavor conservation accidental
in the extended Standard Model

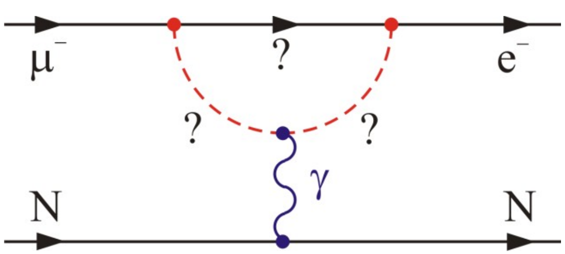


# Incomplete History of Lepton Flavor Violation Searches



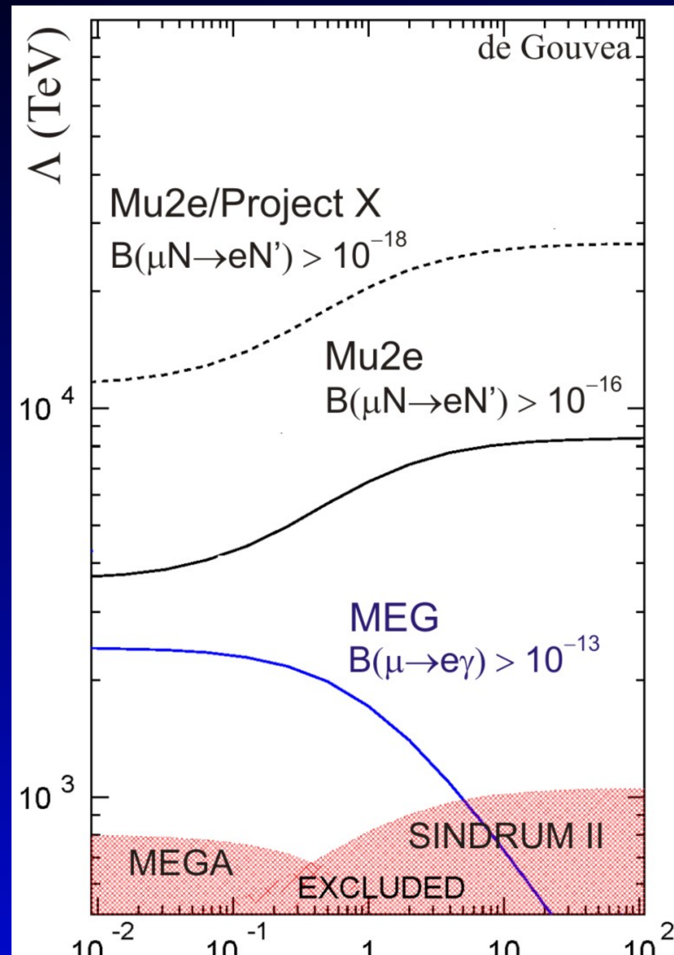
# CLFV in μ+→e+γ and μ-N→e-N

Model independent effective CLFV Lagrangian

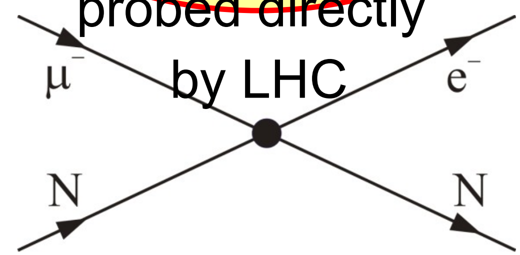



κ << 1
magnetic moment type operator

μ → eγ rate ~300X μ N → eN rate




Mass scales probed ~10,000 times that probed directly by LHC

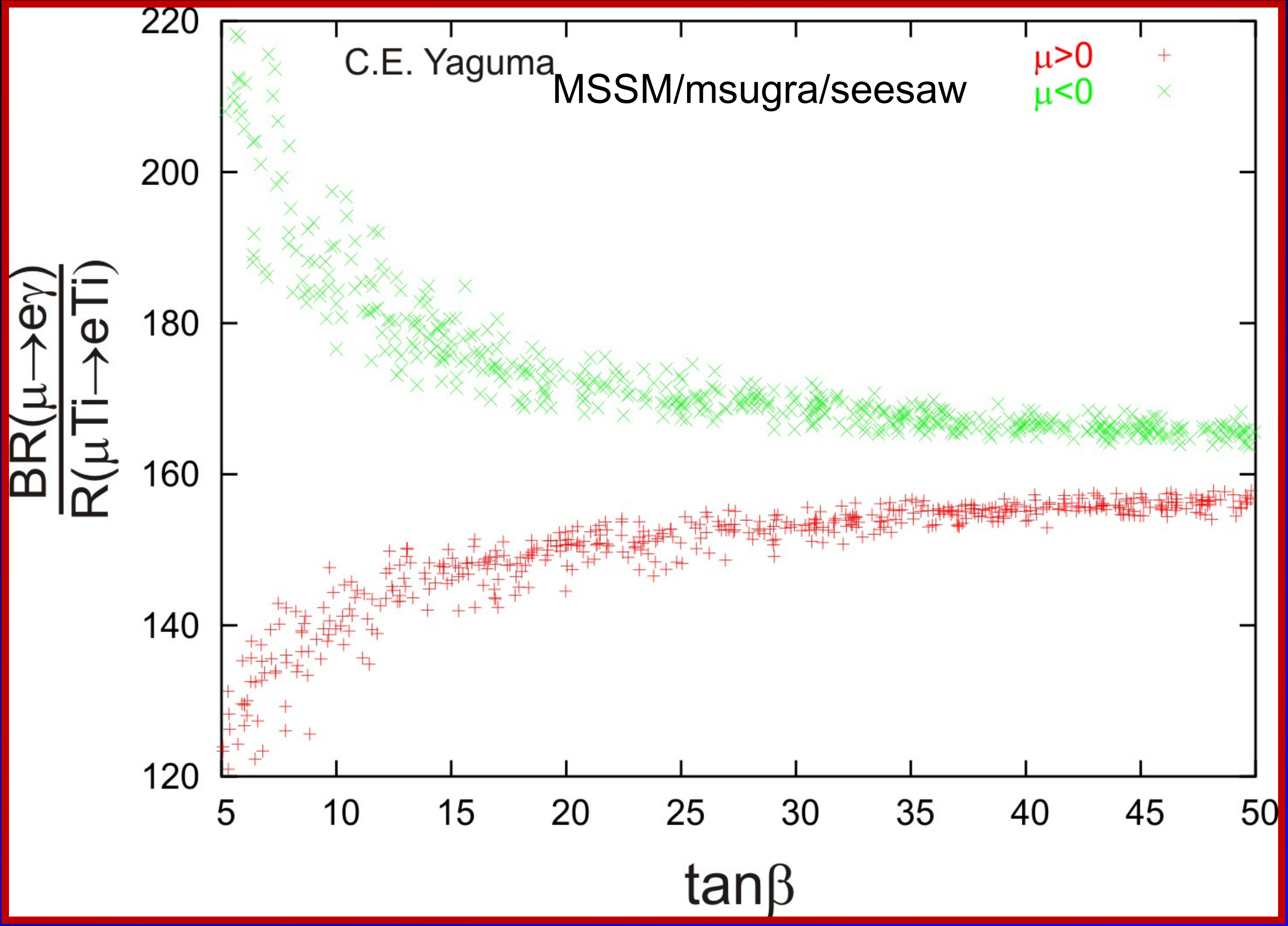



κ >> 1
four-fermion interaction

μ N → eN >> μ → eγ rate

# Two Methods are Complementary

Observation of CLFV in both μ -N→e-N and μ +→e+γ could elucidate SUSY parameters

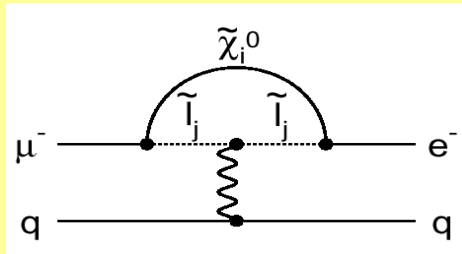



μ = mass term mixing 2 Higgs doublets

tanβ = ratio of 2 vacuum values of 2 neutral Higgs

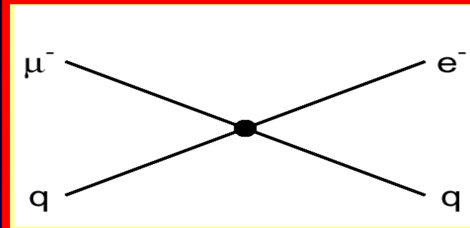
# CLFV Sensitive to Many Sources of New Physics

Supersymmetry

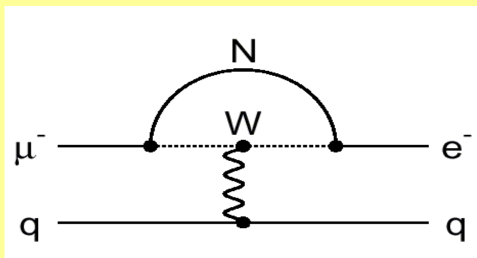



Predictions at 10-13

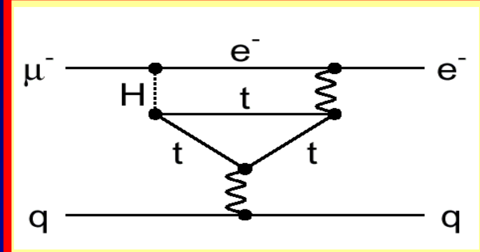
Compositeness



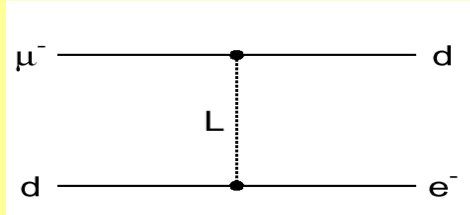

Heavy Neutrinos



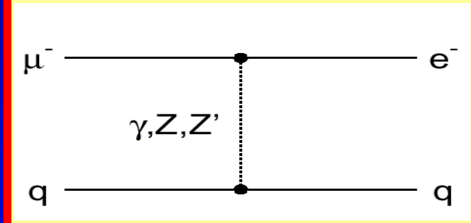

Second Higgs doublet




Leptoquarks




Heavy Z'
Anomalous Z coupling




New physics probed by $\mu N \rightarrow eN$ (Marciano)

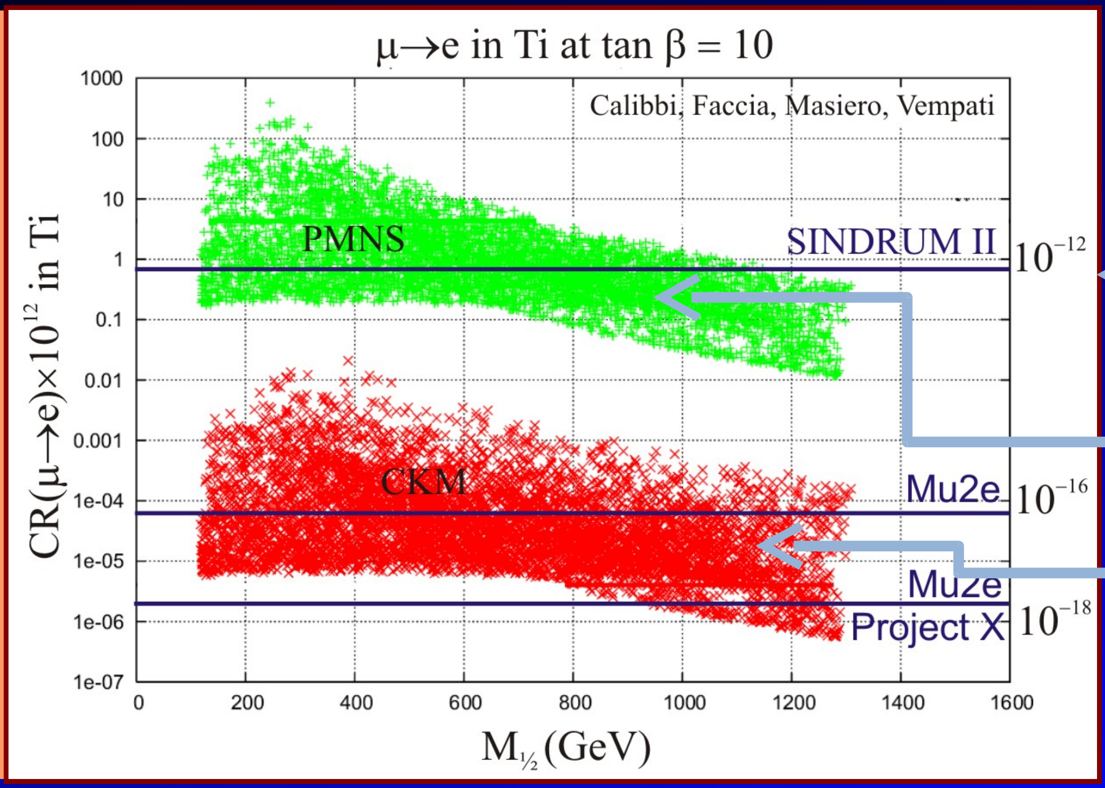
# What Sensitivity is Needed?

Present sensitivity already interesting and constraining!

~10-16 removes many models

~10-18 extremely difficult for theorists to deal with

SUSY GUT w Seesaw




Current limit

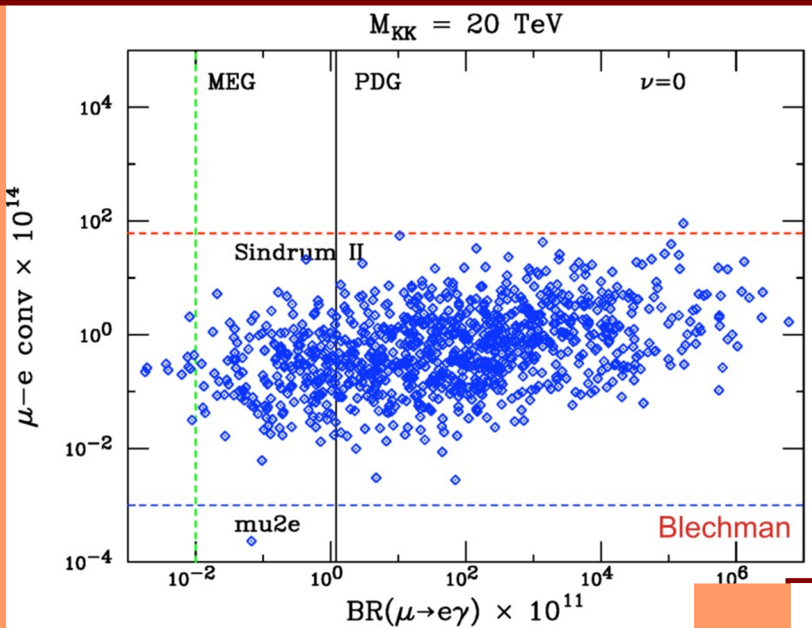
PMNS: neutrino-like mixing

CKM: minimal flavor violation

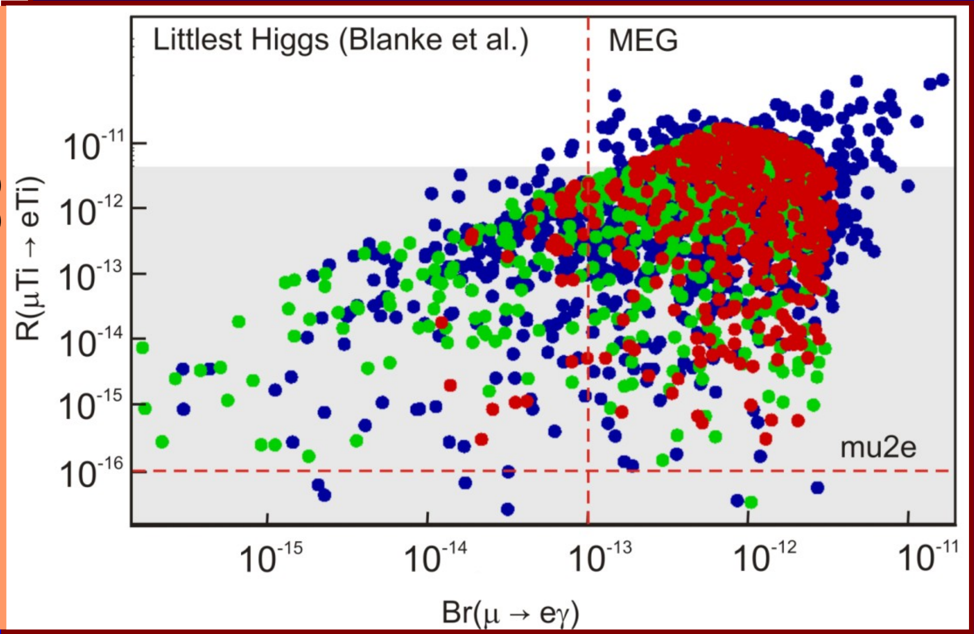
M1/2 = gaugino mass

# What Sensitivity is Needed?

Randall-Sundrum

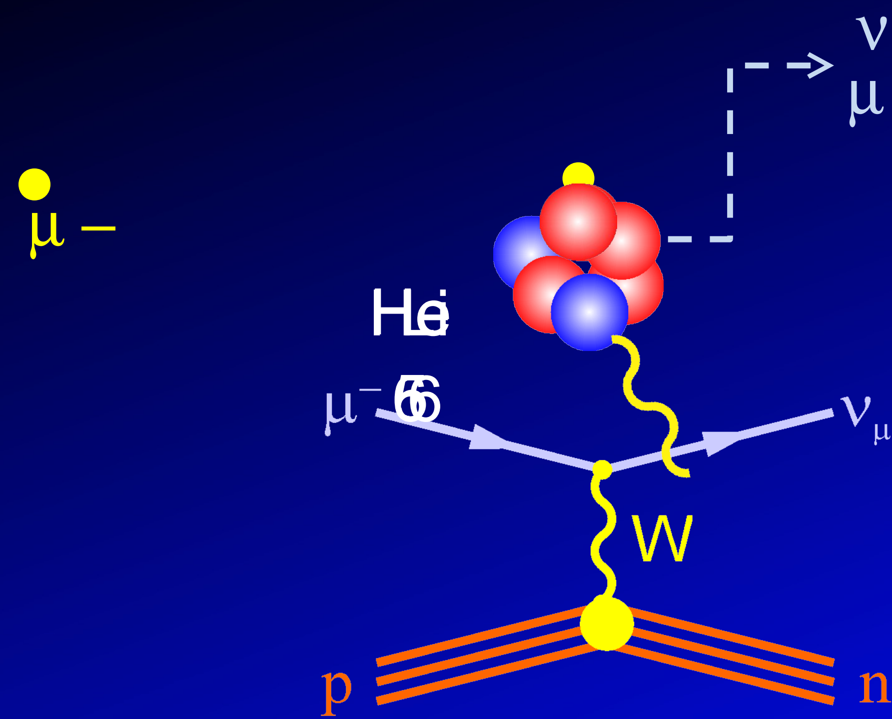


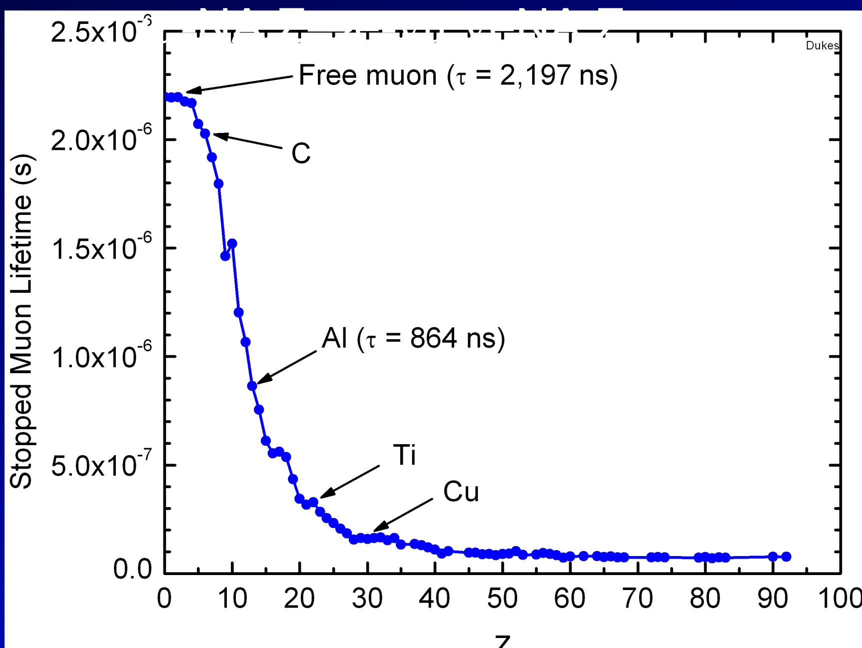

Littlest Higgs



# How to Search for μ -N→e-N

- Stop muon in atom
- Muon rapidly (10-16s) cascades to 1S state
- Circles the nucleus for up to ~2 μ s
- Two things most likely happen:
  1. muon is captured by the nucleus: μ -NA,Z→νμ NA,Z-1
  2. muon decays in orbit:




Muon Capture

- New nucleus (NA,Z-1) "de-excites" emitting neutrons, protons, and gammas
- Al: 1.3 n + 0.1 p + 2γ
- These particles can produce "noise" in the detector

# How to Search for $\mu$-N→e-N

- Stop muon in atom
- Muon rapidly (10-16s) cascades to 1S state
- Circles the nucleus for up to ~2 $\mu$ s
- Two things most likely happen:
  1. muon is captured by the nucleus: $\mu$ -NA,Z→$\nu\mu$ NA,Z-1
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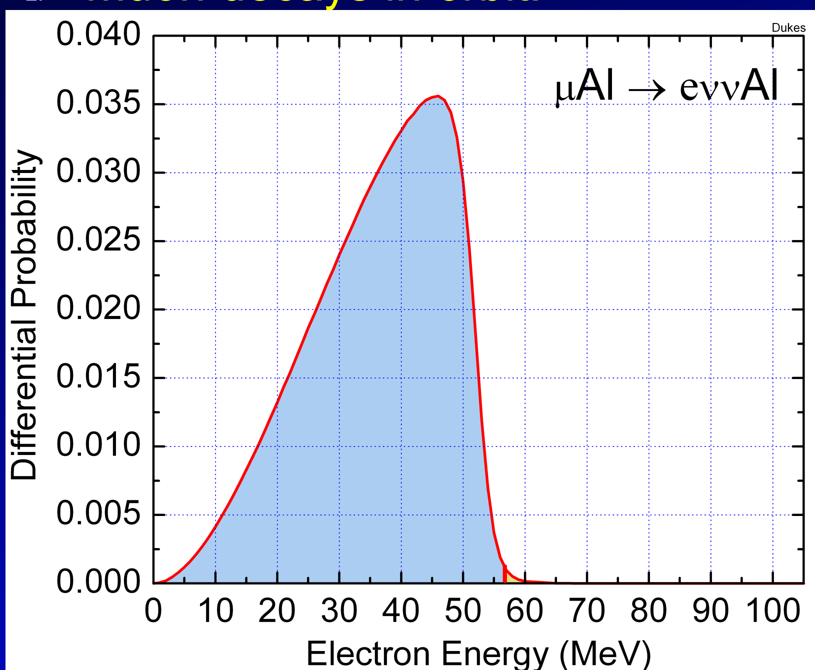
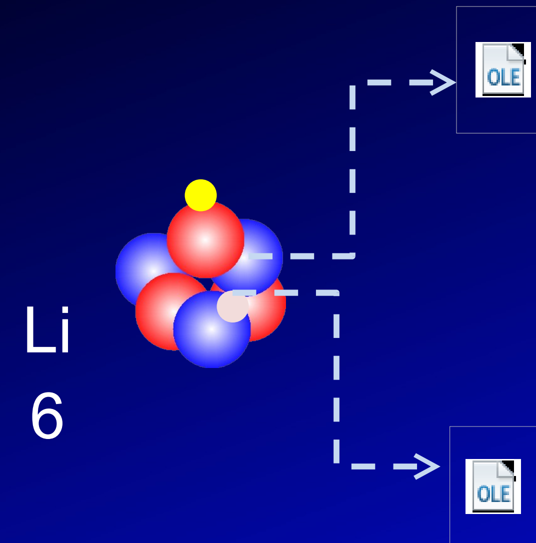
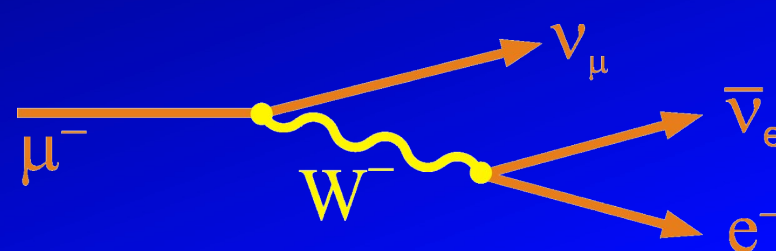


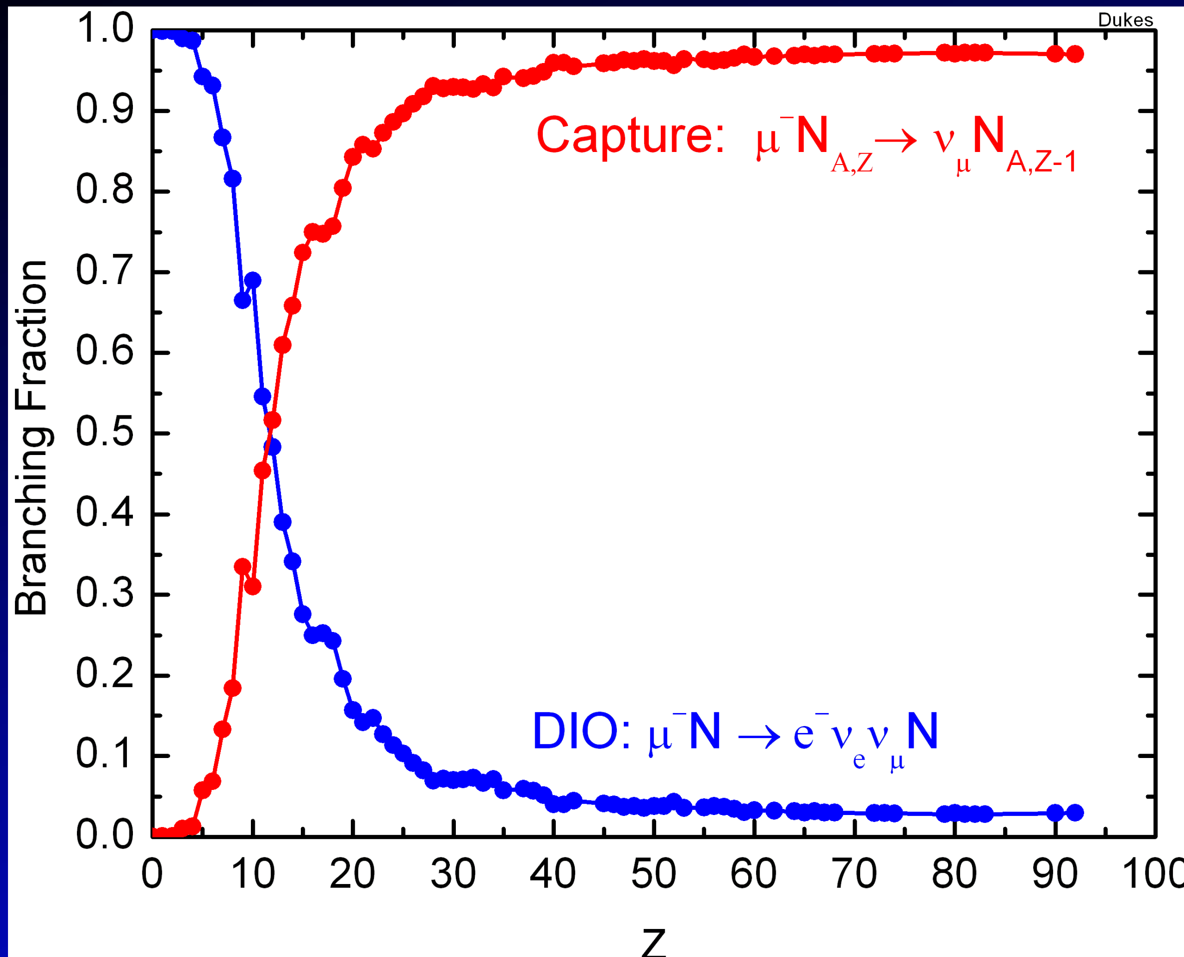

Note: tail not present in free decay due to recoil of nucleus

e-




Muon Decay-in-Orbit

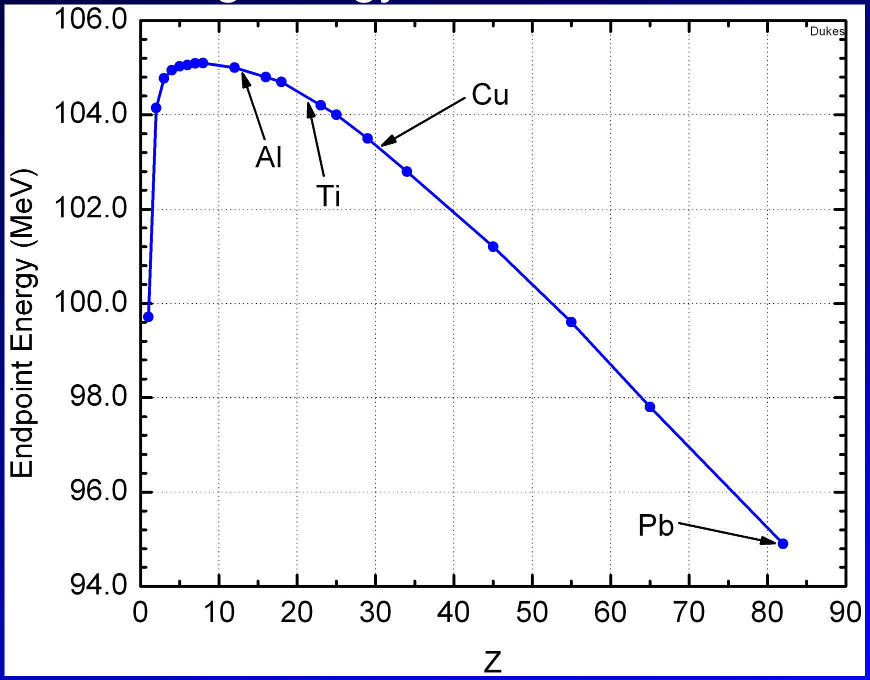
# Relative Rate of Capture to DIO Depends on Target Z



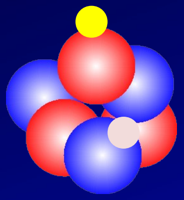
# MuZe Searching for a Third Process: $\mu^-N \to e^-N$

In $\mu^-N \to e^-N$ the muon coherently interacts with nucleus leaving it in ground state

- signature single isolated electron
- Electron energy given by the rest mass of the muon minus the nucleus recoil energy and the binding energy:




Li 6



e-

Measure ratio of conversion rate to capture rate

# Bunched Beam Technique Needed

Need ~1018 stopped muons

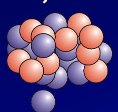
Signal: 105 MeV electron coming from the target, ~1 μ s after the μ is stopped in the foils

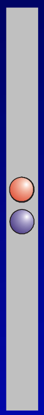
·Rate too high for continuous beam: need bunched muon beam: 50x109 μ /s

·Need gate off detector for ~ tmN (~800 ns) while bad stuff (pions, electrons) is around

·Ne

Bunched beam arrives with μ 's, π's, and electrons



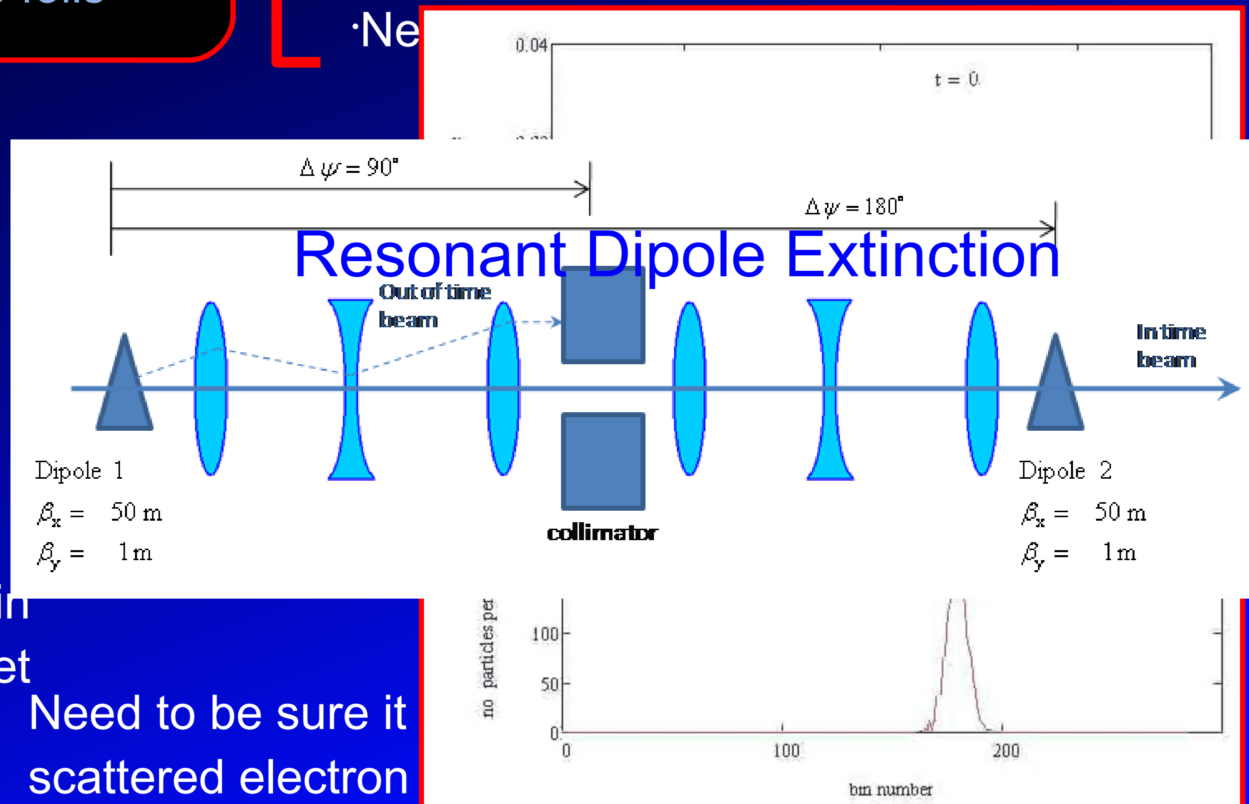


A huge amount of stuff comes off the target from scatters, captures etc.

About 50% of the muons stop in target

Stopping target

Resonant Dipole Extinction

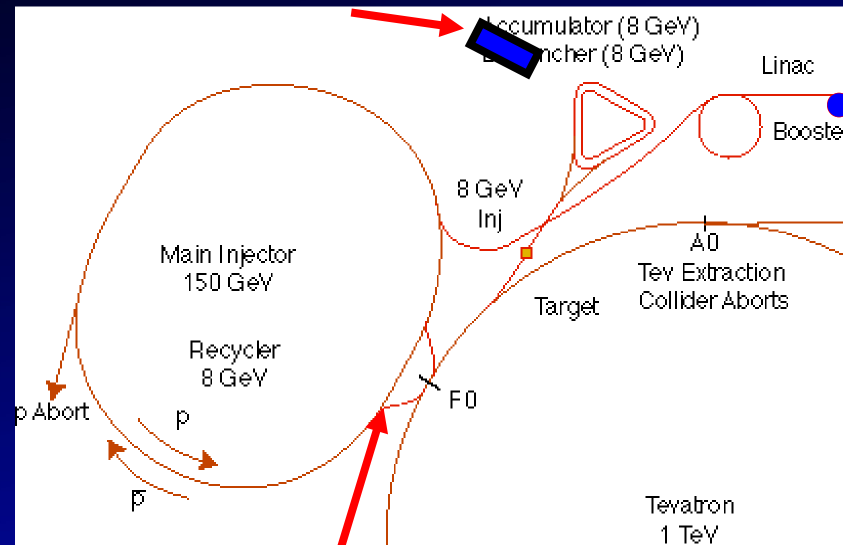



Need to be sure it scattered electron electron

# Producing ~1018 Bunched Muons

- Energy: 8 GeV Booster beam optimal
- Structure: need bunch spacing on order of muon lifetime ~1 μ s ¿ orbit period of Accumulator/Debuncher optimal at 1.7 μ s
- Use Recycler as a transfer line
- Stack in Accumulator; bunch in Debuncher
- Slow spill extraction: 90% duty factor

new detector hall and beamline




One of several possible schemes

Mu2e cannot take any protons away from the neutrino program

…07

Mu2e … er batches NOvA cannot use during Main Injector cycle

# New Beamline and Detector Hall to be Built

# Backgrounds, Backgrounds, Backgrounds . . .

## 1. Stopped Muon Backgrounds

**Muon decay in orbit (DIO):**

$\mu$ -NA,Z$\to$e-$\nu\mu$ $\nu$eNA,Z

- *defeated by good energy resolution*

**Radiative muon capture (RMC):**

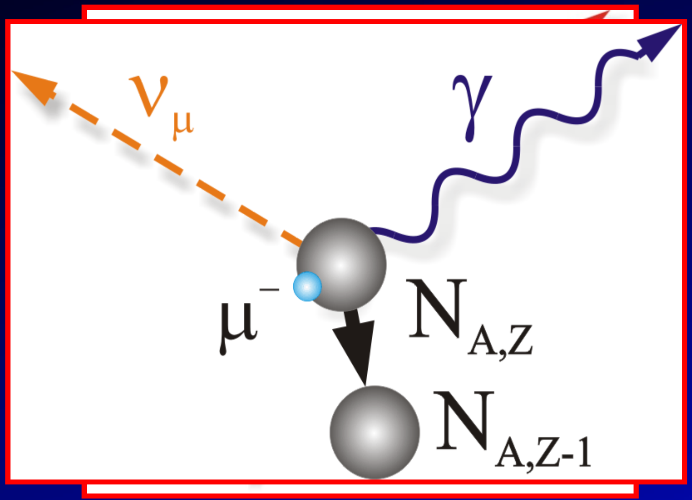
$\mu$ -NA,Z$\to\nu\mu$ $\gamma$NA,Z-1, $\gamma\to$e+e-

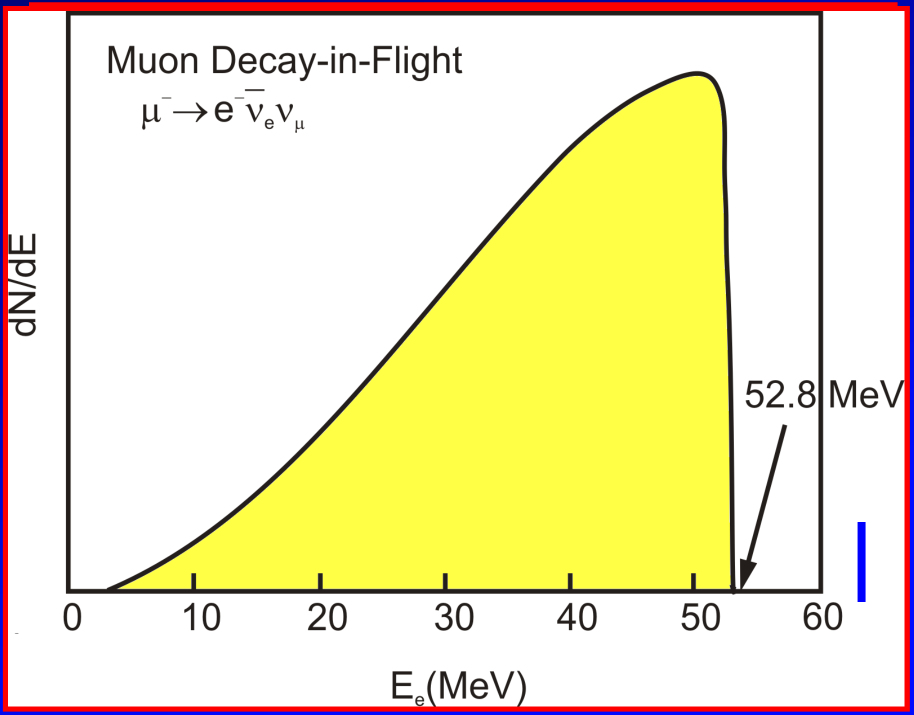
- *defeated by mZ < mZ-1*
- *defeated by good energy resolution*

**Muon capture:**

$\mu$ -NA,Z$\to\nu\mu$ N'A',Z' + 1.3n + 0.1p + 2$\gamma$

- *Note: does not produce a physics background, but detector "noise"*
- *defeated by proton absorber*



# Backgrounds, Backgrounds, Backgrounds . . .

## 2. Prompt Beam Related Backgrounds

**Radiative pion capture (RPC):**

$\pi$-NA,Z$\rightarrow\gamma$NA,Z-1 , $\gamma\rightarrow e+e-$

Note: 1.2% have E$\gamma$ > 105 MeV

**Muon decay in flight:**

$\mu - \longrightarrow e - \nu\nu$

Note: p$\mu$ > 77 MeV/c

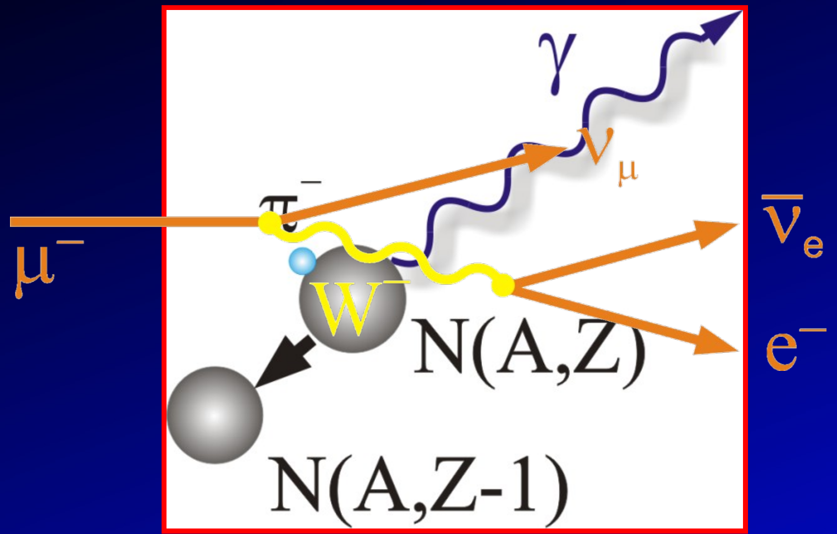
**Pion decay in flight:**

$\pi - \longrightarrow e - \nu e$

**Beam electrons scattering in target**

- *Defeated by 10-10interbunch extinction*
- *Defeated by hard cuts on momentum*

**Antiprotons annihilating**

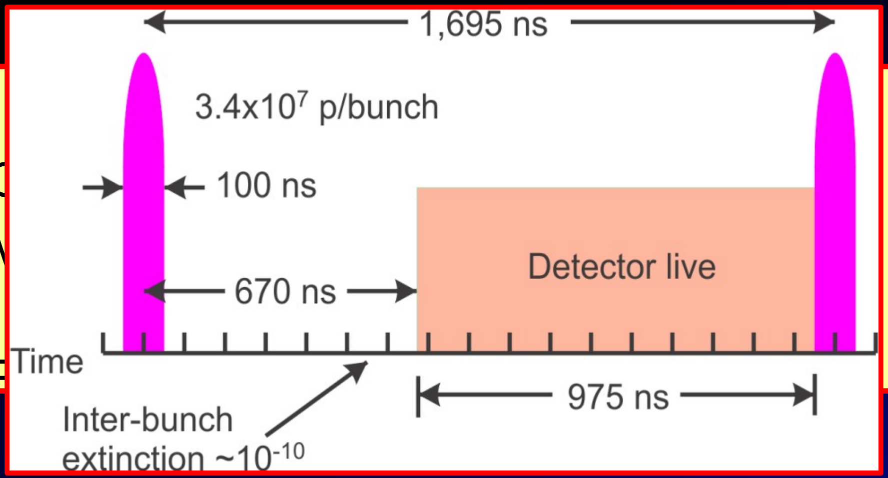


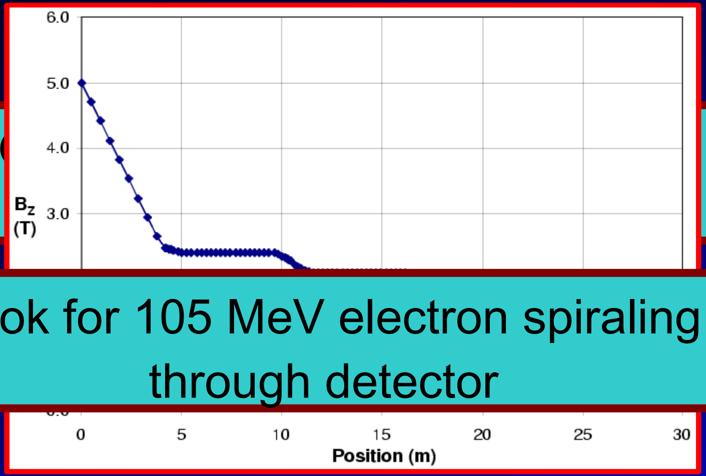

## 3. Time Dependent Backgrounds

**Cosmic Rays**

- *Defeated by active shield*

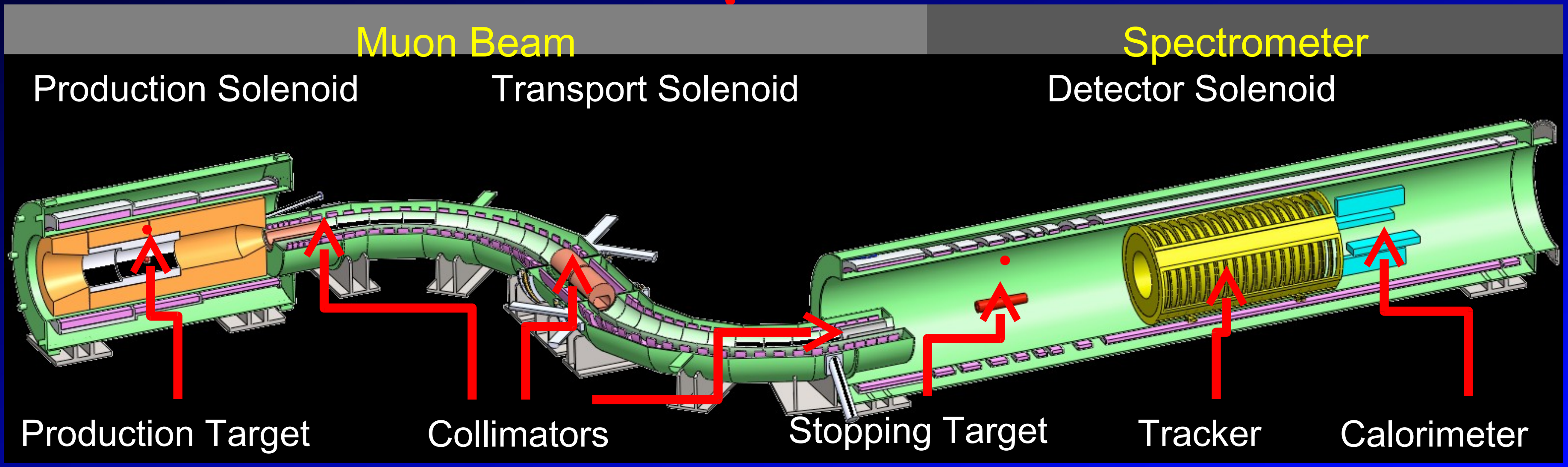
# Mu2e Apparatus




8 (

Look for 105 MeV electron spiraling through detector

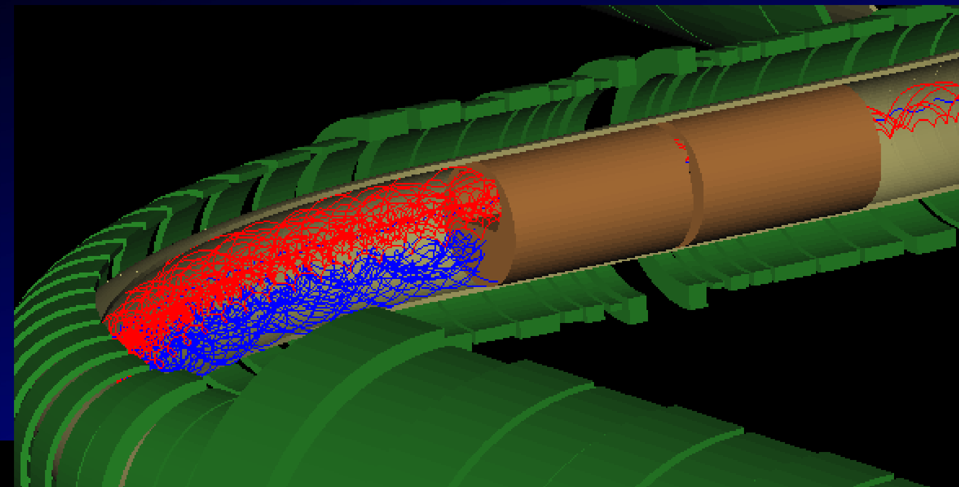


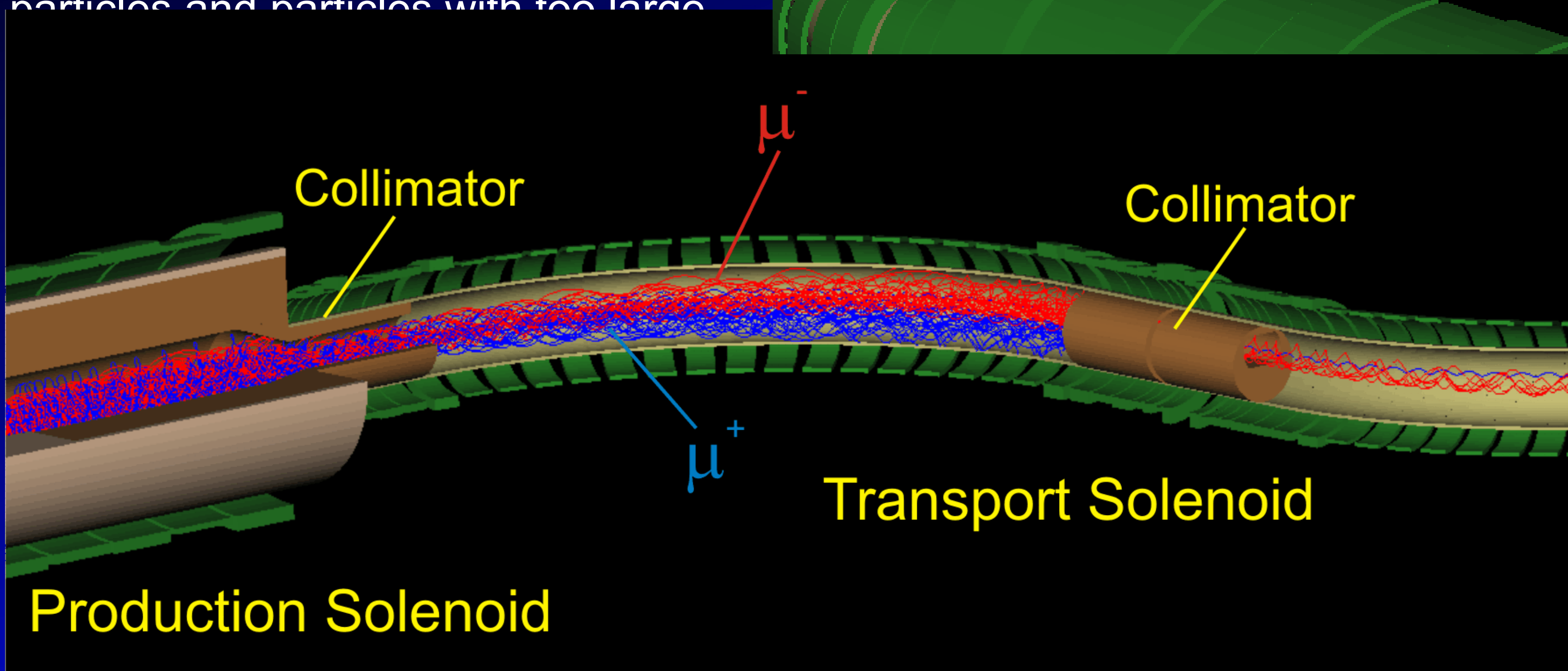

85,000 μ –stop every 1.7 μ s

50 billion μ –stops/second

# Transport Solenoidal Magnet

- Curved solenoid:
  1. separates charges by charge sign
  2. reduces line-of-sight transport of neutrals
- Collimators eliminate wrong-sign particles and particles with too large

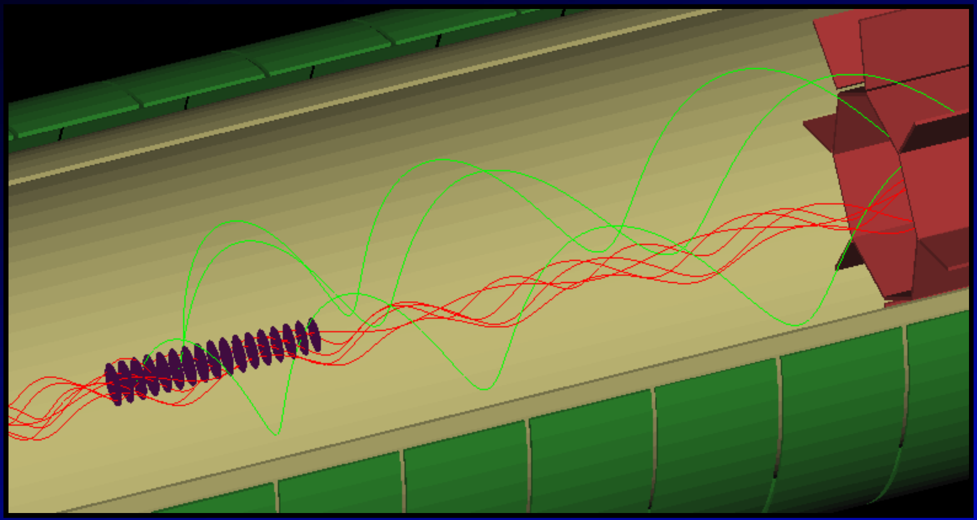


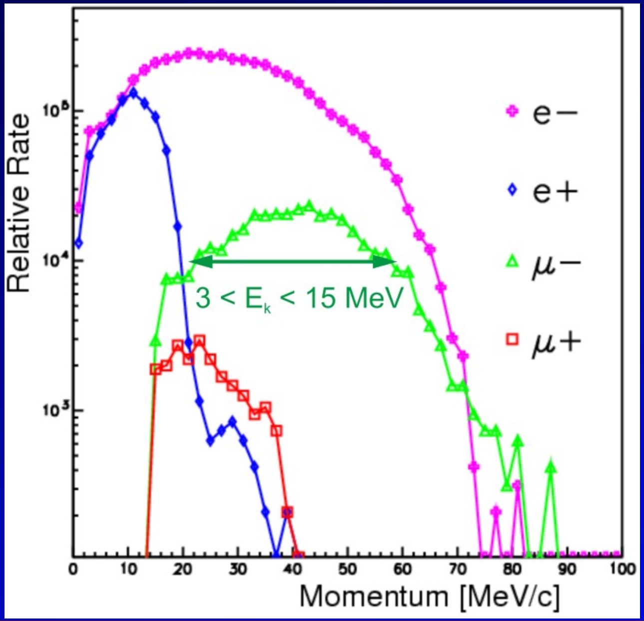


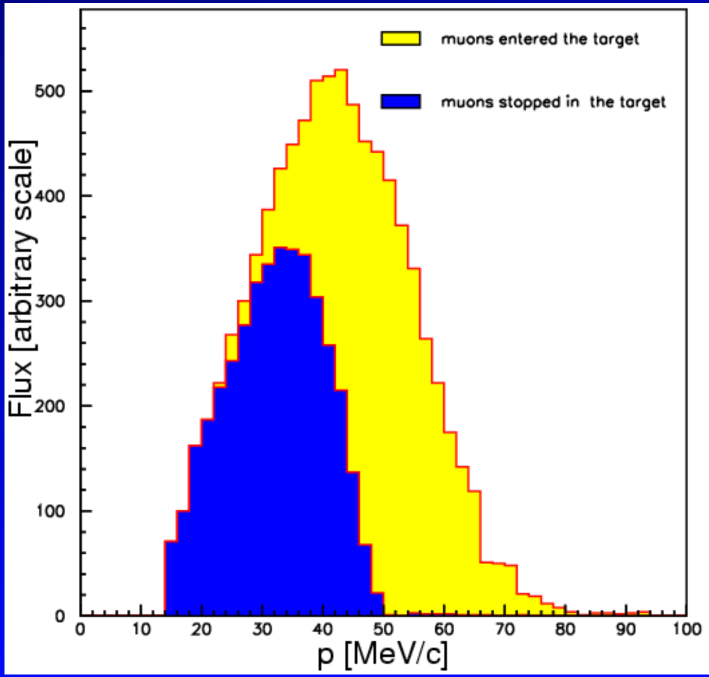
# What we get at the Stopping Target

- 17 Al disks
- each 200 μ m thick
- 83 mm to 65 mm radius
- in graded magnetic field

- 1/230 incident protons produce a muon at the stopping target
- 58% of muons stop in target
- 50x109 μ  stops per spill second
- 85,000 μ  stops per microbunch

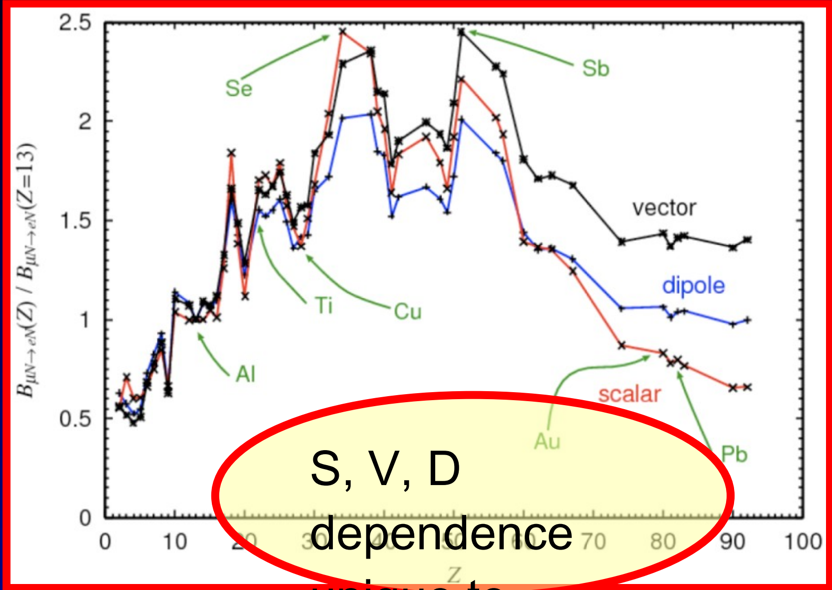


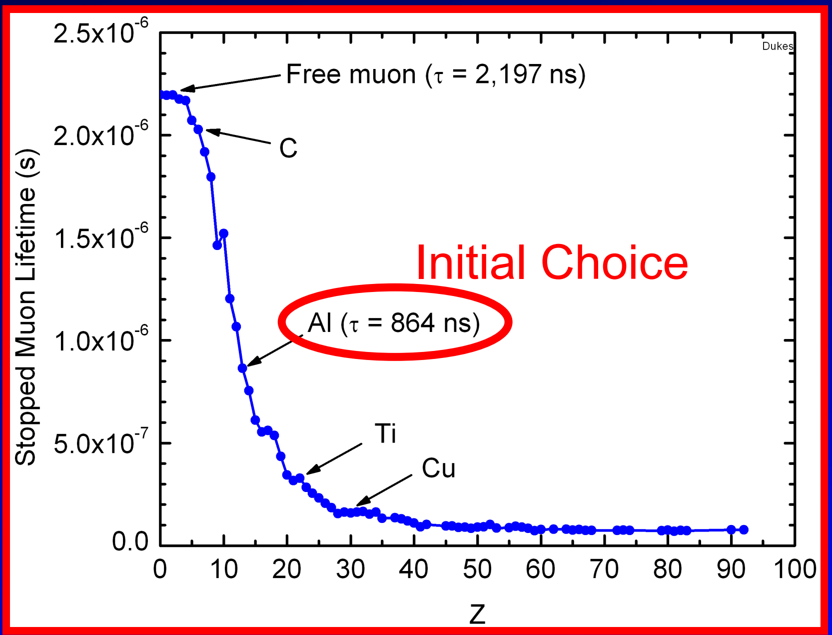


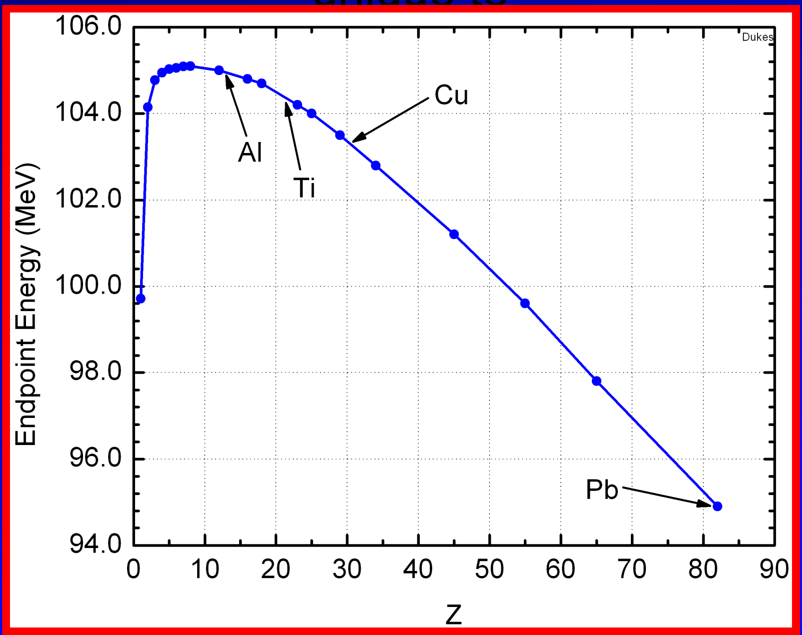



# Choice of Stopping Target Material

- Large Z:
  - rate ¿ Z|Fn|2 (Fn is the form factor)
  - can reveal nature of interaction
- Small Z:
  - longer lifetime
  - higher endpoint energy
- Note: Need mZ-1 > mZ to place max. energy of radiative capture muons below signal electrons



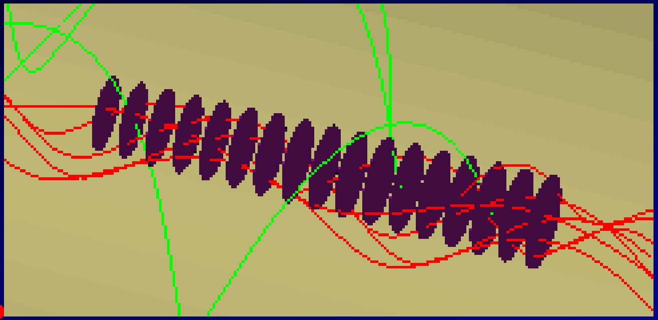



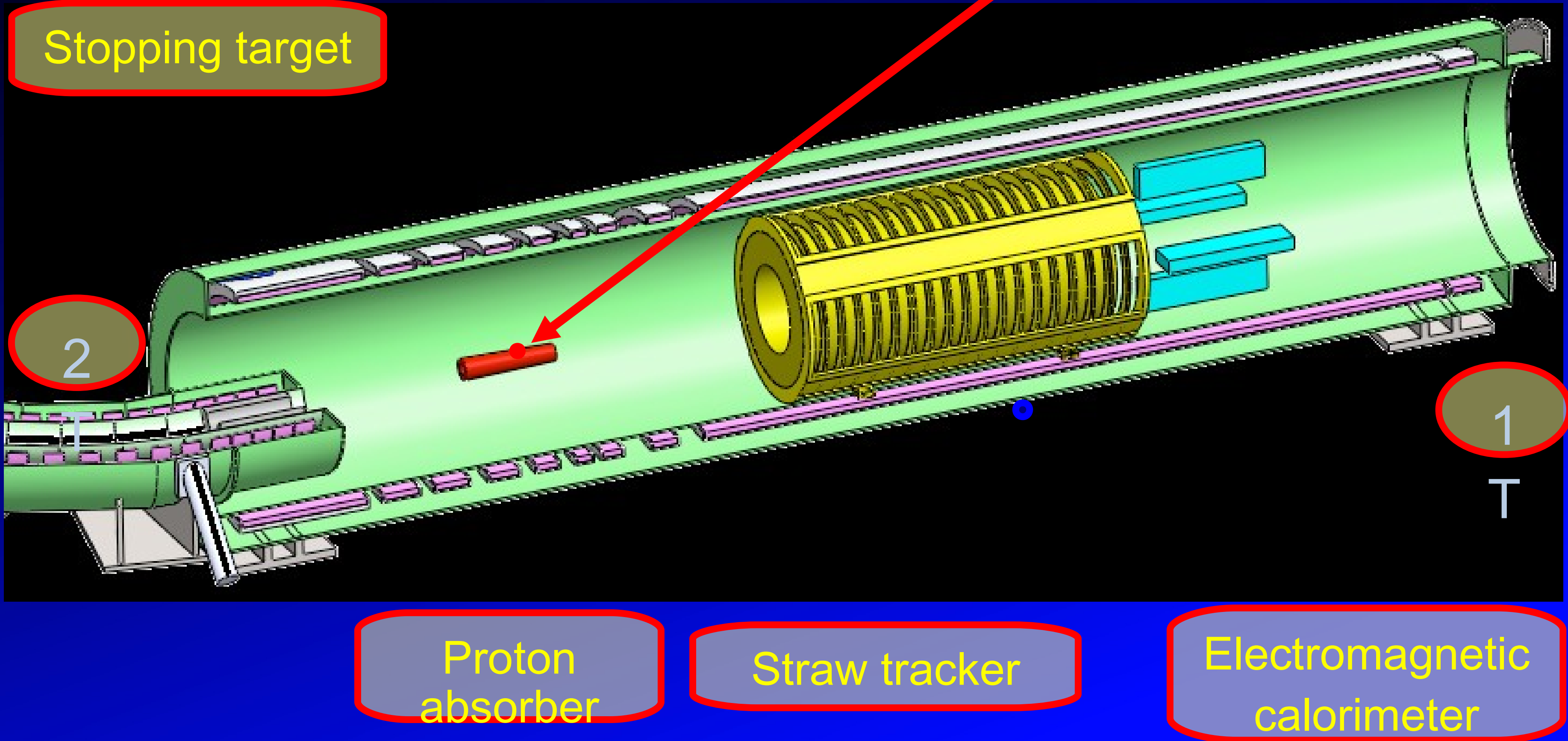



# Mu2e Spectrometer

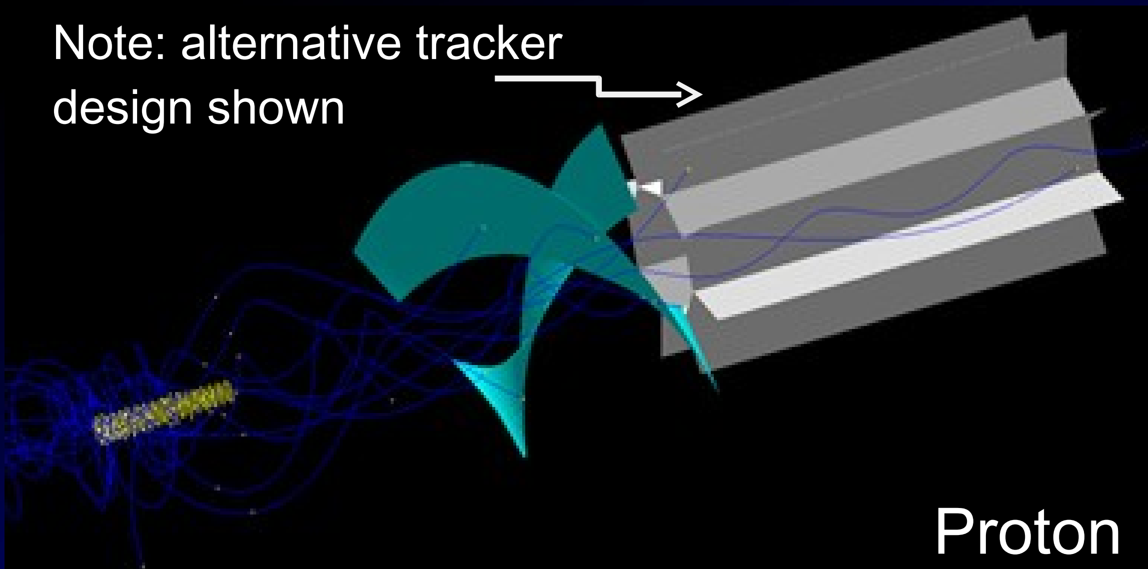
## Salient Features

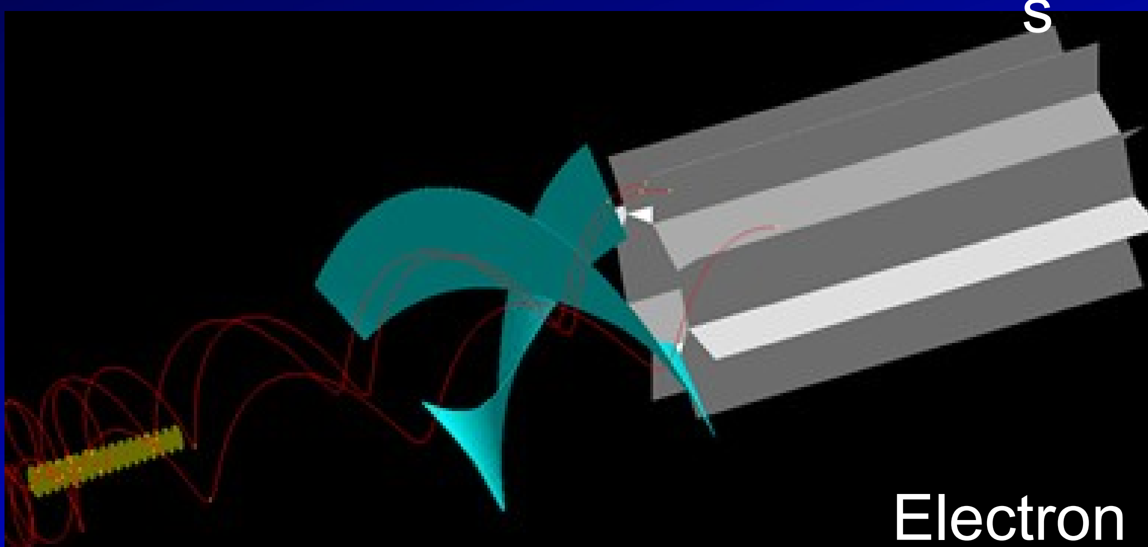
- No detector element in region of transported beam
- Small acceptance for DIO electrons
- Minimal amount of material ¿ detector elements in vacuum





# Helical Proton Absorber

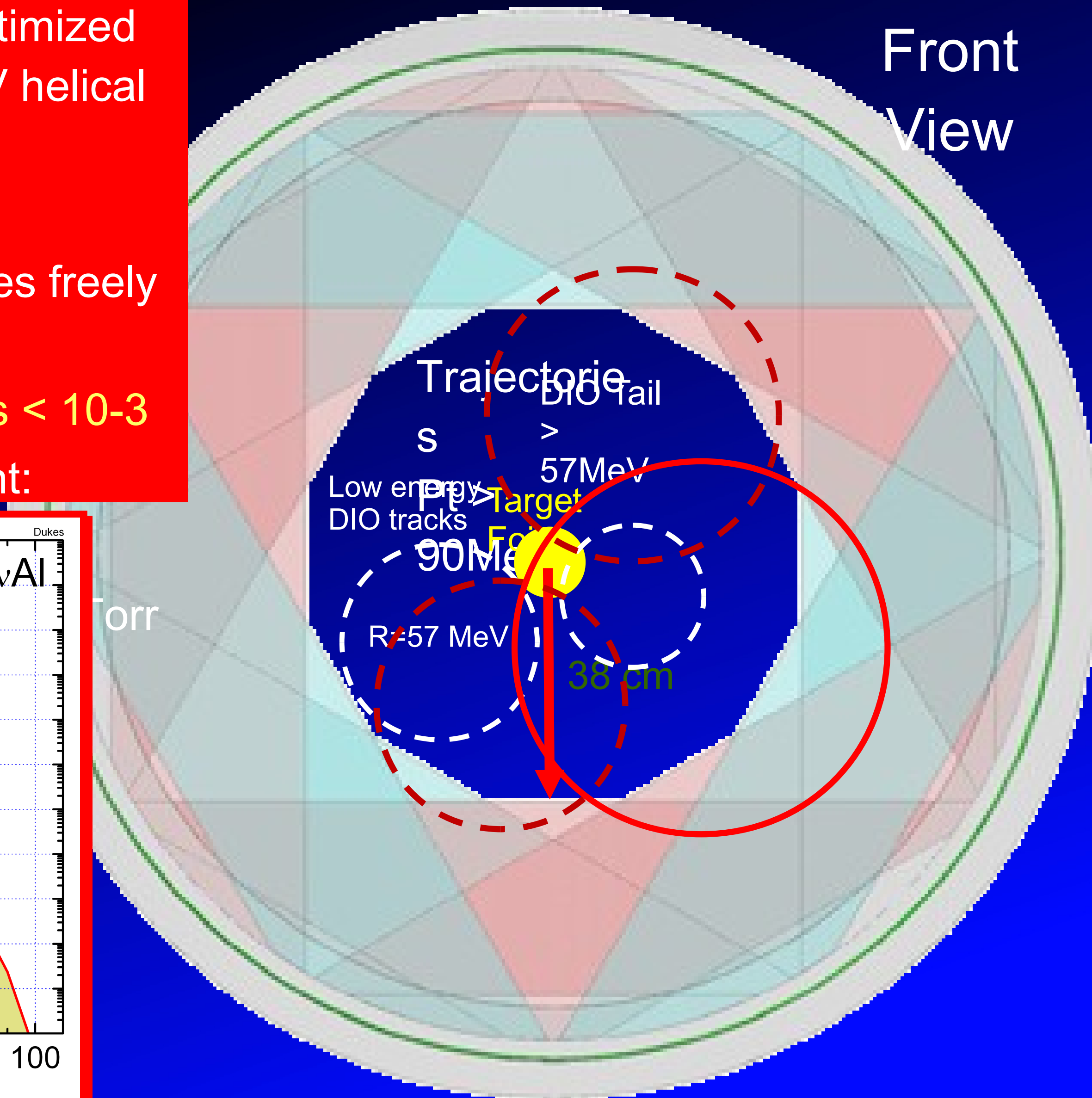


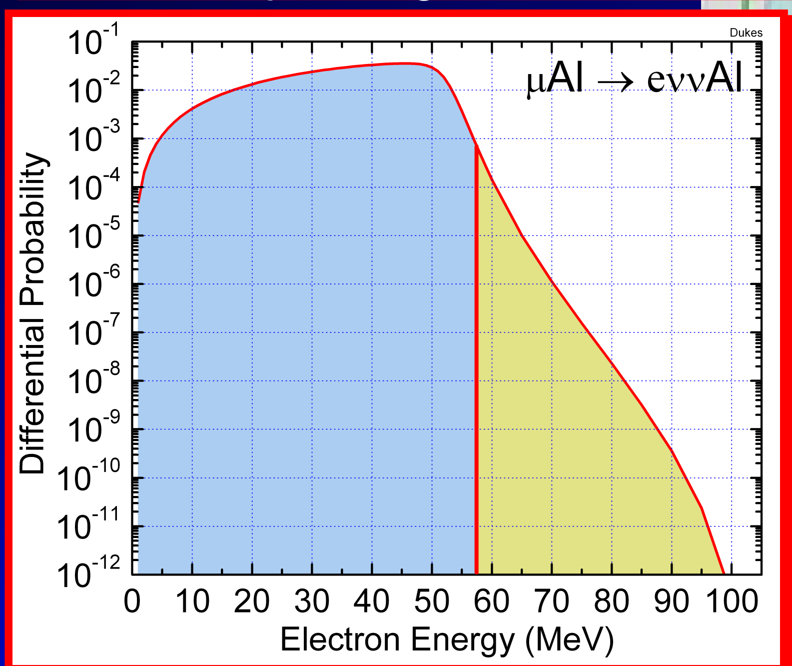




- Needed to beat down rate of muon capture protons: ~0.1 per capture: ~3 x 109/s
- Note: capture proton s not relativistic: KE and momentum not the same!
- Geometry exploits different helical trajectories of protons and electrons
- Material: 0.5 mm polyethylene
- Absorbers 93% of protons from muon capture
- Only 13% of the electrons impact absorber
- FWHM energy loss: 0.33 MeV

# Heart of the Spectrometer: Straw Tracker

- Octagonal vane geometry optimized for reconstruction of 105 MeV helical trajectories
- Center beam region empty:
  - Intense muon beam passes freely through
  - Acceptance for DIO tracks < 10-3
- Severe operating environment:

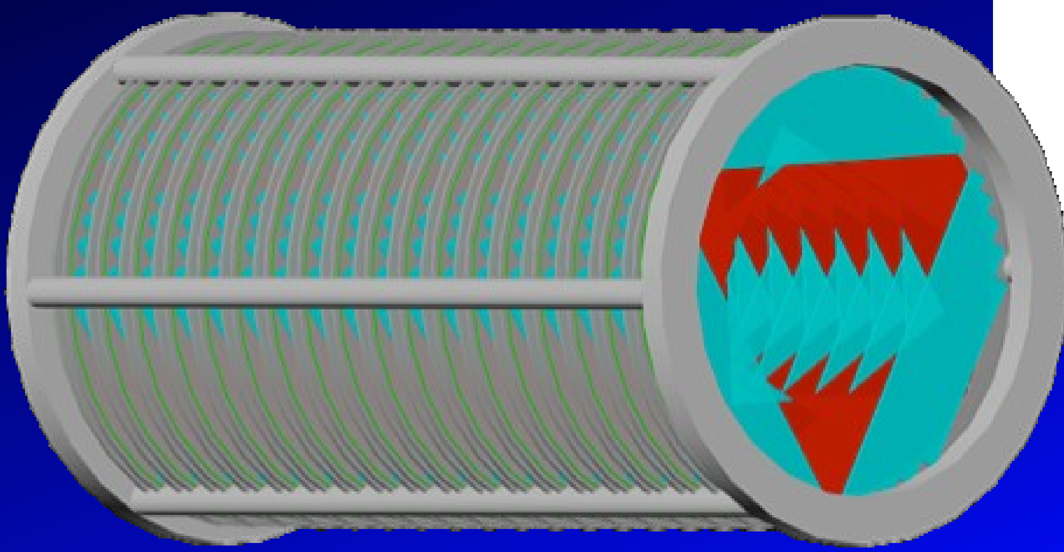


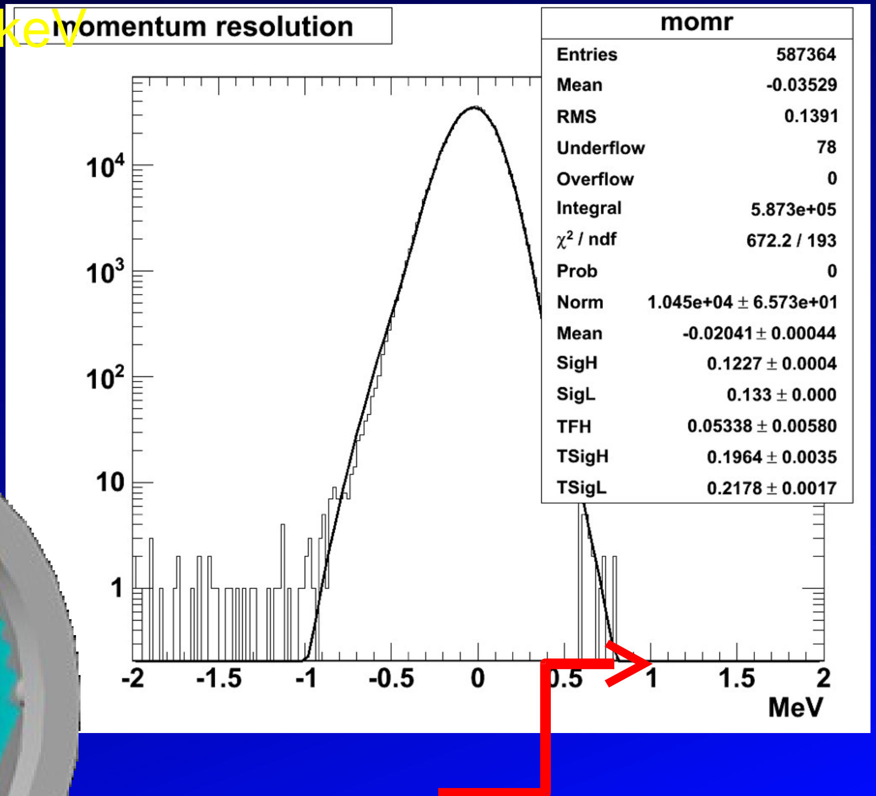



# Tracker Performance

Large acceptance: 50% (90°±30°)
Intrinsic energy resolution: $\sigma$= 140 keV

- 5 mm diam. Straws
- 18 stations:
  - 24 planes each
  - 50 straws/plane
- 21,600 straws total
- ArCO2 80:20
- ADC/TDC readout: 100 $\mu$ m resolution



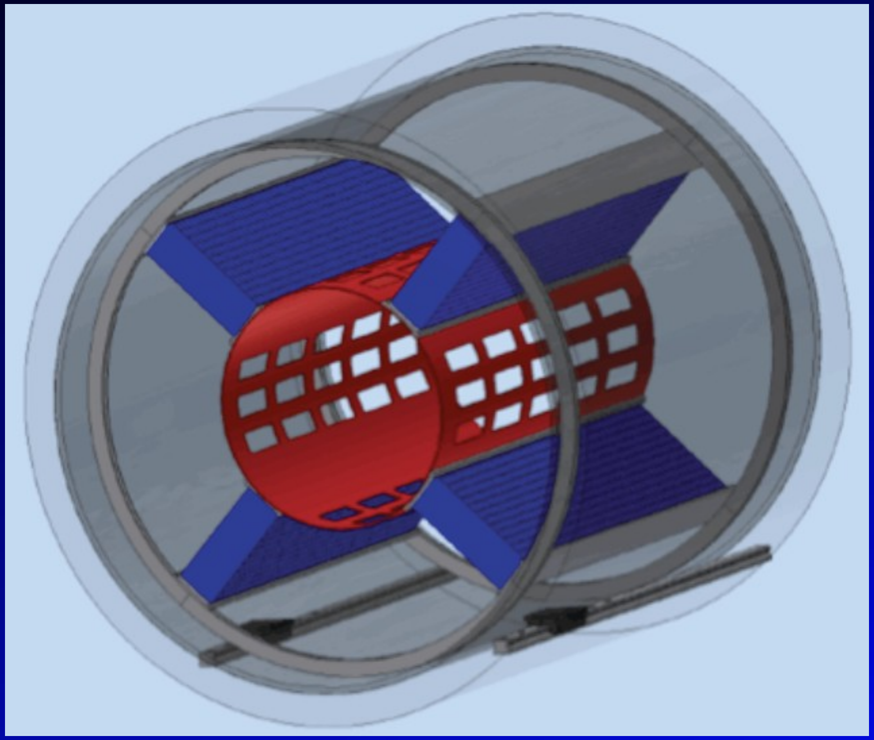



No high-side tail!

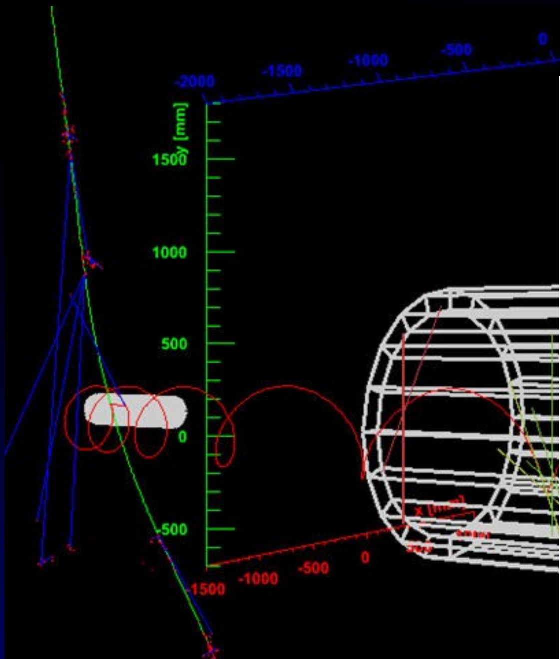
# Electromagnetic Calorimeter

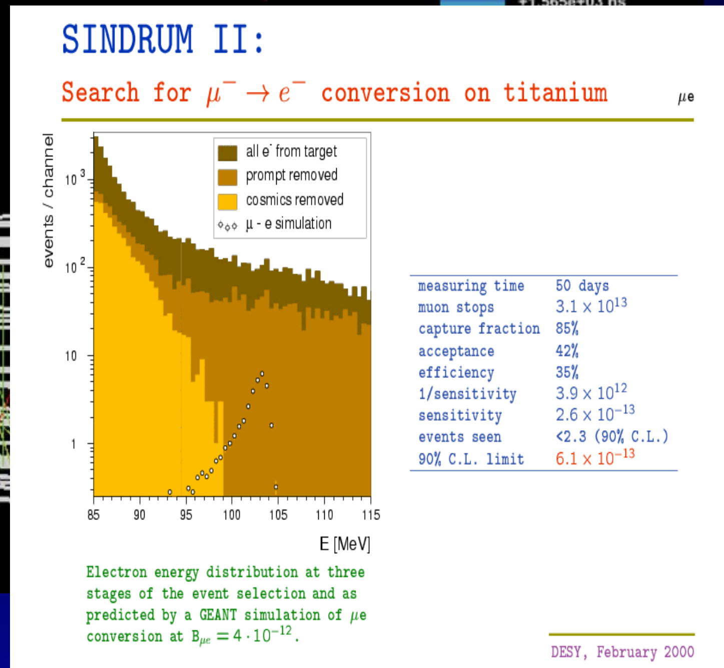
- Needed for:
  - trigger: 5% energy resolution → 1,000 triggers/s
  - Timing
  - Confirmation of the electron energy measurements of the straws
- Note: must operate in 160 Gy/yr
- 2112 3x3x13cm3 LYSO crystals
- Dual APD readout
- $\sigma/E \sim$ 2-3%
- $\sigma t \sim$ 0.1 ns

} @ 100 MeV



# Cosmic Ray Veto



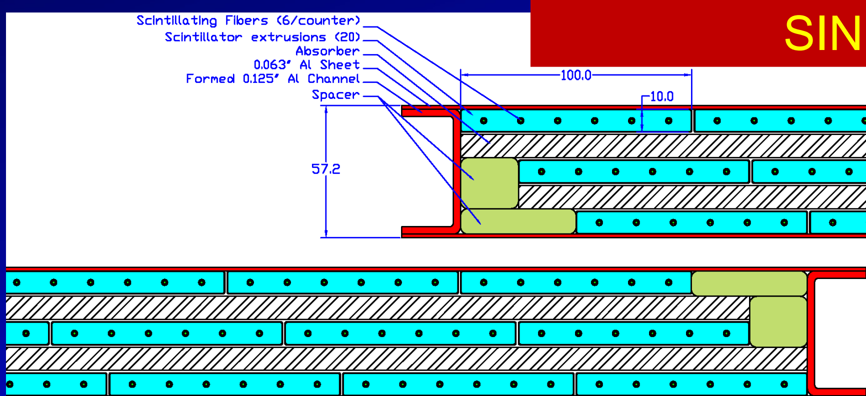



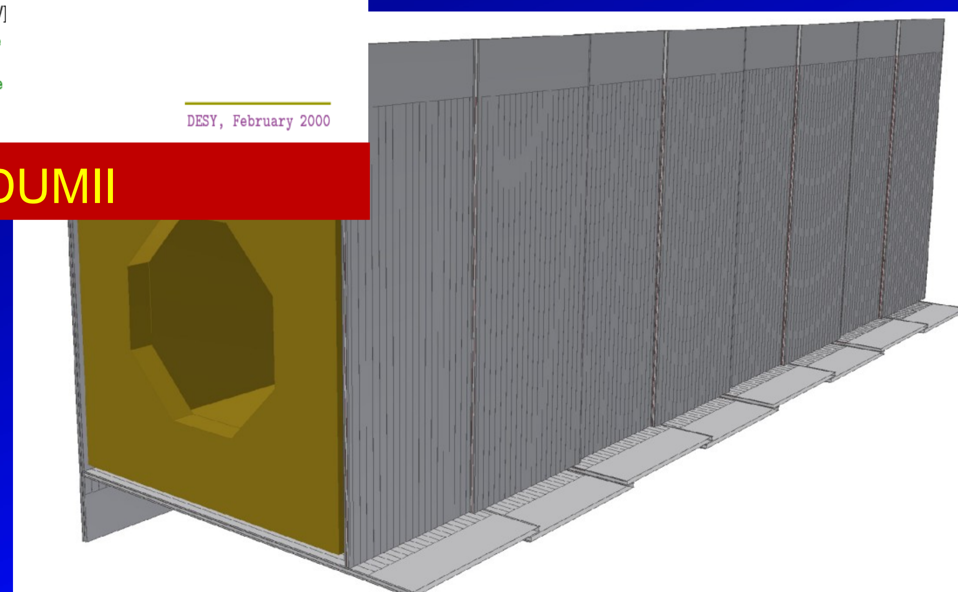

SINDUMII

MC studies show 416 fake 105 MeV conversion electrons from cosmic-ray muons

Hence need 10-4 Inefficiency

Surround Detector Solenoid by 3 layers of



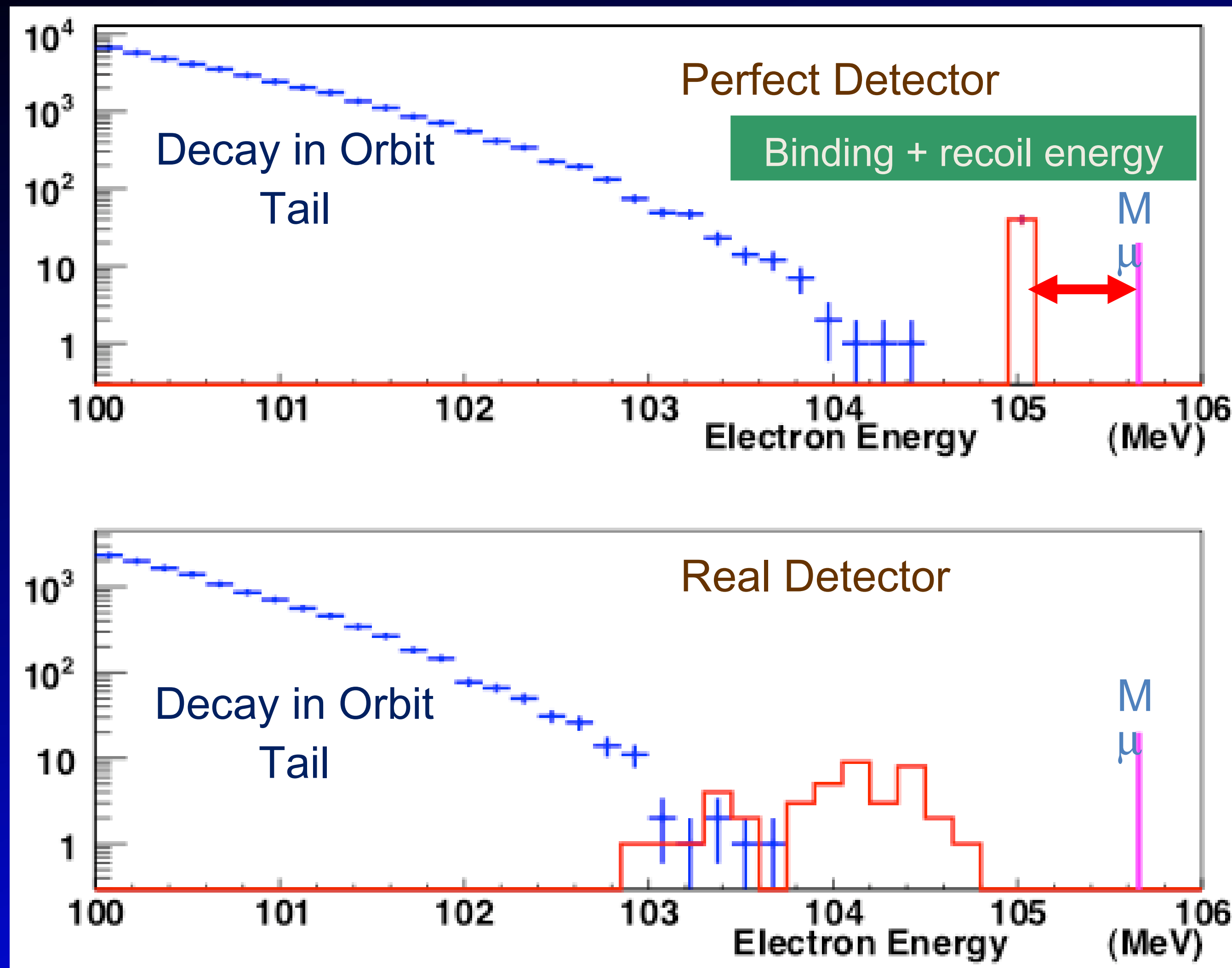
# What we Get

Intrinsic tracker energy resolution:

$\sigma(E)$ ¿ 150 keV

Average energy loss due to spectrometer material:

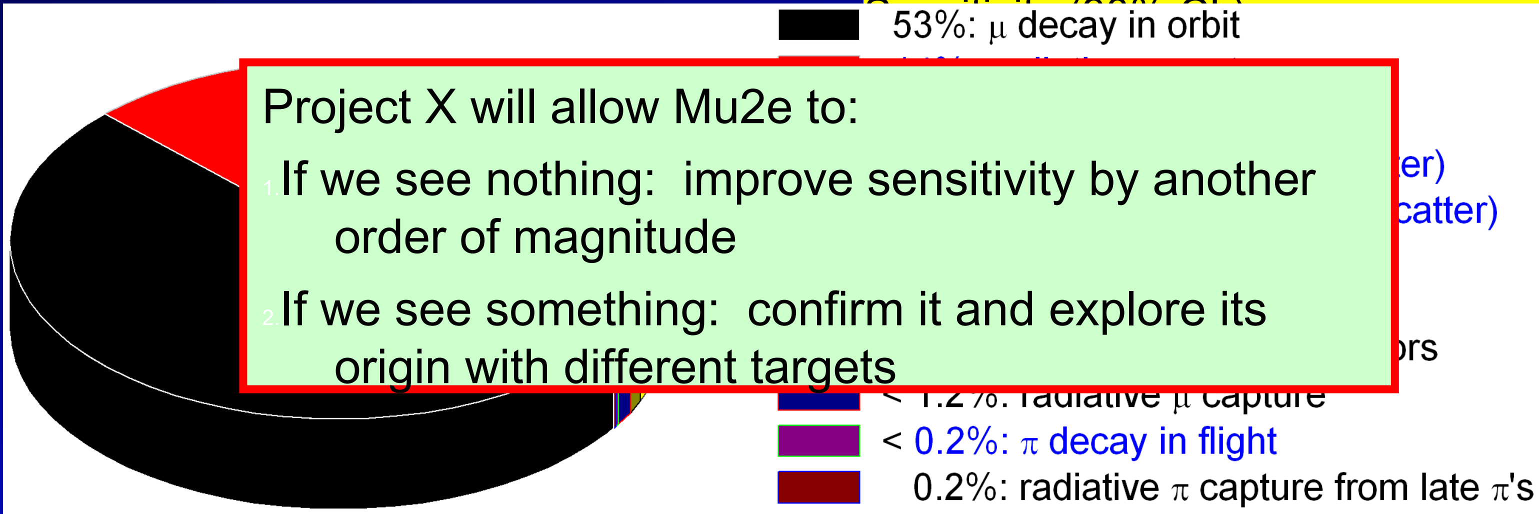
E(shift) ¿ 1 MeV



# Mu2e Sensitivity

| | |
|---|---|
| Proton flux | 1.8x1013 p/s |
| Running time | 2x107 s |
| Total protons | 3.6x1020 p |
| μ - stops/incident proton | 0.0025 |
| μ - capture probability | 0.61 |
| Time window fraction | 0.49 |
| Electron trigger eff. | 0.80 |
| Reconstruction and selection eff. | 0.19 |
| Sensitivity (90% CL) | 6x10-17 |
| [illegible] | 4 |
| [illegible] | 0.4 |

Roughly half of background is interbunch contamination related




Project X will allow Mu2e to:

1. If we see nothing: improve sensitivity by another order of magnitude
2. If we see something: confirm it and explore its origin with different targets

# Mu2e Collaboration

| | |
|---|---|
| *Boston University* | R. Carey, V. Jorjadze, V. Khalatian, J. Miller*, B. Roberts |
| *Brookhaven National Laboratory* | W. Marciano, V. Polychronakos, Y. Semertzidis, P. Yamin |
| *Caltech* | D. Hitlin, F. Porter, R.-Y. Zhu |
| *University of Califon* | |
| *University of Cal* | |
| *City University* | |
| | |
| *Fermi National A* | eJongh, N. petz, R. ee, S. rebys, V. White, K. |
| | S. Rella, G. |
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| *Institute for Nucle* | |
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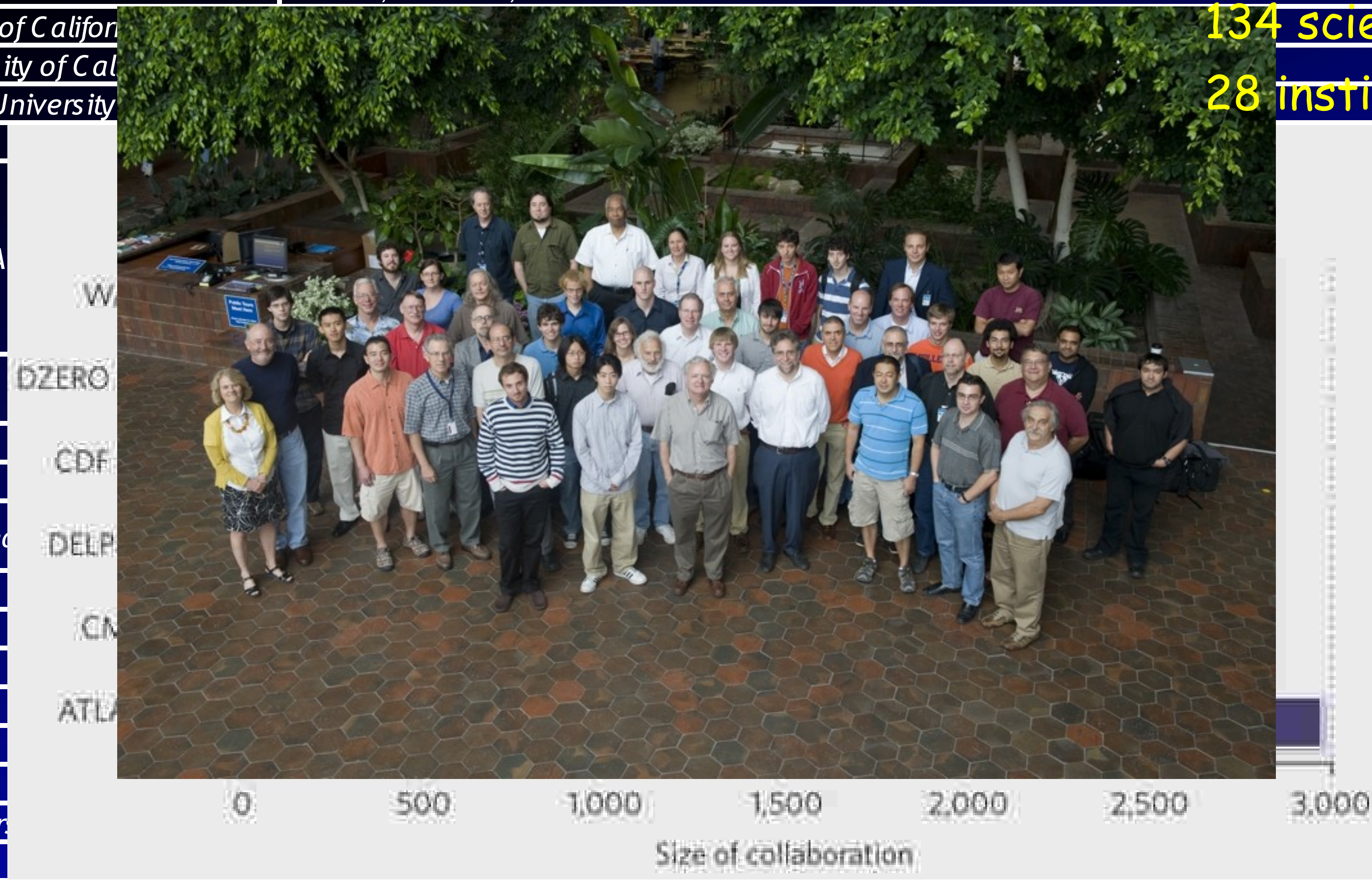
| *Univers* | |
| | oshikawa |
| *Northern Illinois University* | D. Hedin, A. Dychkant |
| *Northwestern University* | A. deGouvea |
| *INFN Pisa, Universitua Di Pisa* | F. Cervelli, R. Carosi, M. Incagli, T. Lomtadze, L. Ristori, F. Scuri, C. Vannini |
| *Rice University* | M. Corcoran |
| *Syracuse University* | R.S. Holmes, P.A. Souder |
| *Universita di Udine* | D. Cauz, G. Pauletta |
| *University of Virginia* | M. Bychkov, E.C. Dukes, R. Ehrlich, M. Frank, E. Frlez, C. Group, R. Hirosky, P.Q. Hung, Y. Oksuzian, K. Paschke, D. Pocanic |

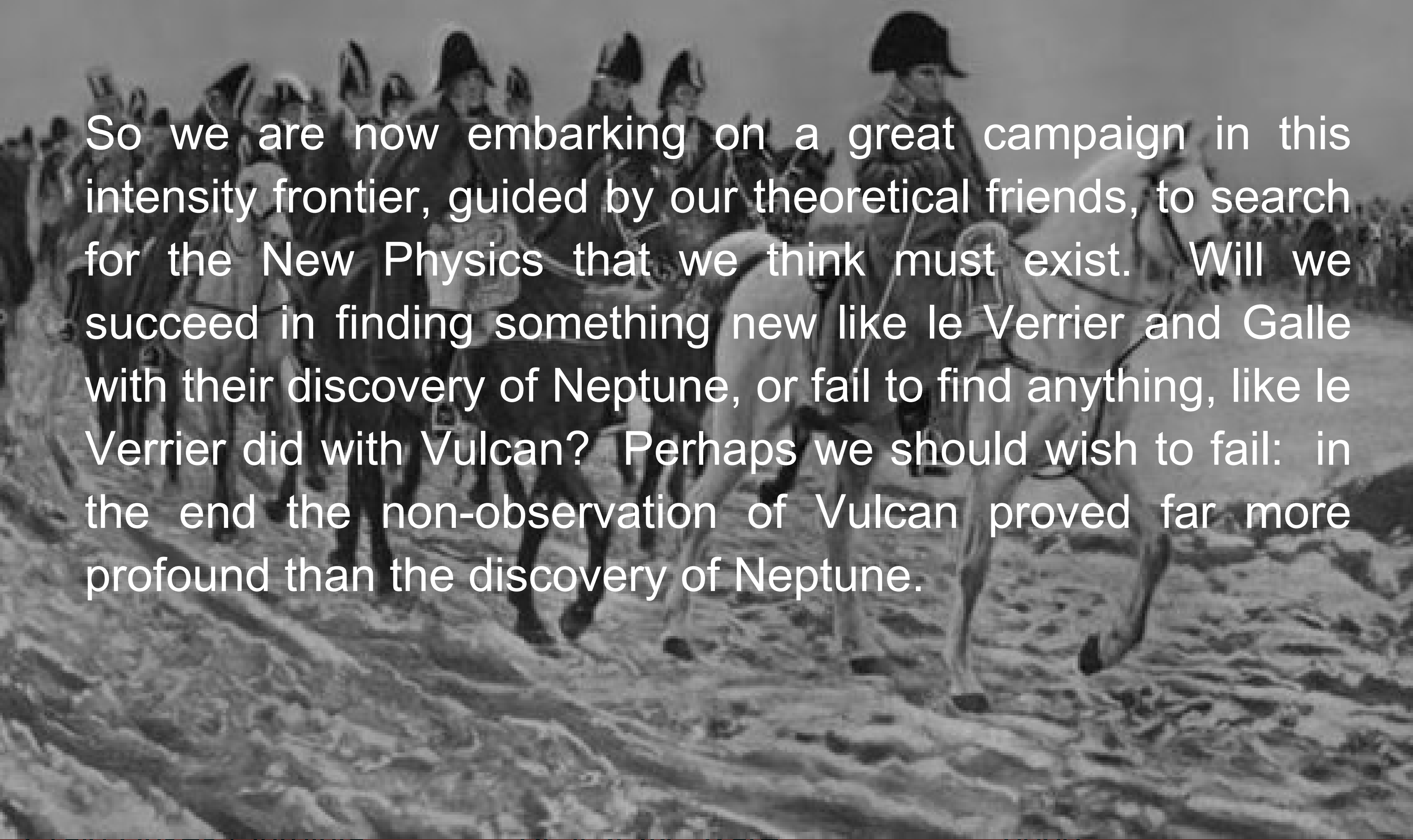



Currently:
134 scientists
28 institutions

# Mu2e Status

| | |
|---|---|
| 1992 | Solenoidal collection scheme first propos Moscow Meson Factory |
| 1997 | MECO proposed for the AGS at Brookha |
| 1998-2005 | Intensive work on MECO technical desigr $58M, detector at $27M |
| July 2005 | RSVP cancelled for financial reasons not |
| 2006 | Steering committed set up to work out me Fermilab, keeping detector the same |
| June 2007 | Mu2e EOI submitted to Fermilab |
| October 2007 | LOI submitted to Fermilab |
| May 2008 | P5 "recommends pursuing the muon-to-e subject to approval by the Fermilab PAC, considered by the panel." |
| Fall 2008 | Proposal submitted to Fermilab and receives Stage I approval. Total project cost estimated at $180M |
| November 2009 | Approval of mission need by DOE (CD-0) granted ($145M - $205M) |
| FY2010 | Mu2e receives $4M in R&D funding ($10M FY2011, $20M FY2012) |
| Fall 2011 | Approval of preliminary baseline range by DOE (CD-1) |
| 2014 | Start of Construction (CD-3) |

# The End



So we are now embarking on a great campaign in this intensity frontier, guided by our theoretical friends, to search for the New Physics that we think must exist. Will we succeed in finding something new like le Verrier and Galle with their discovery of Neptune, or fail to find anything, like le Verrier did with Vulcan? Perhaps we should wish to fail: in the end the non-observation of Vulcan proved far more profound than the discovery of Neptune.