Beyond $E=mc^2$:

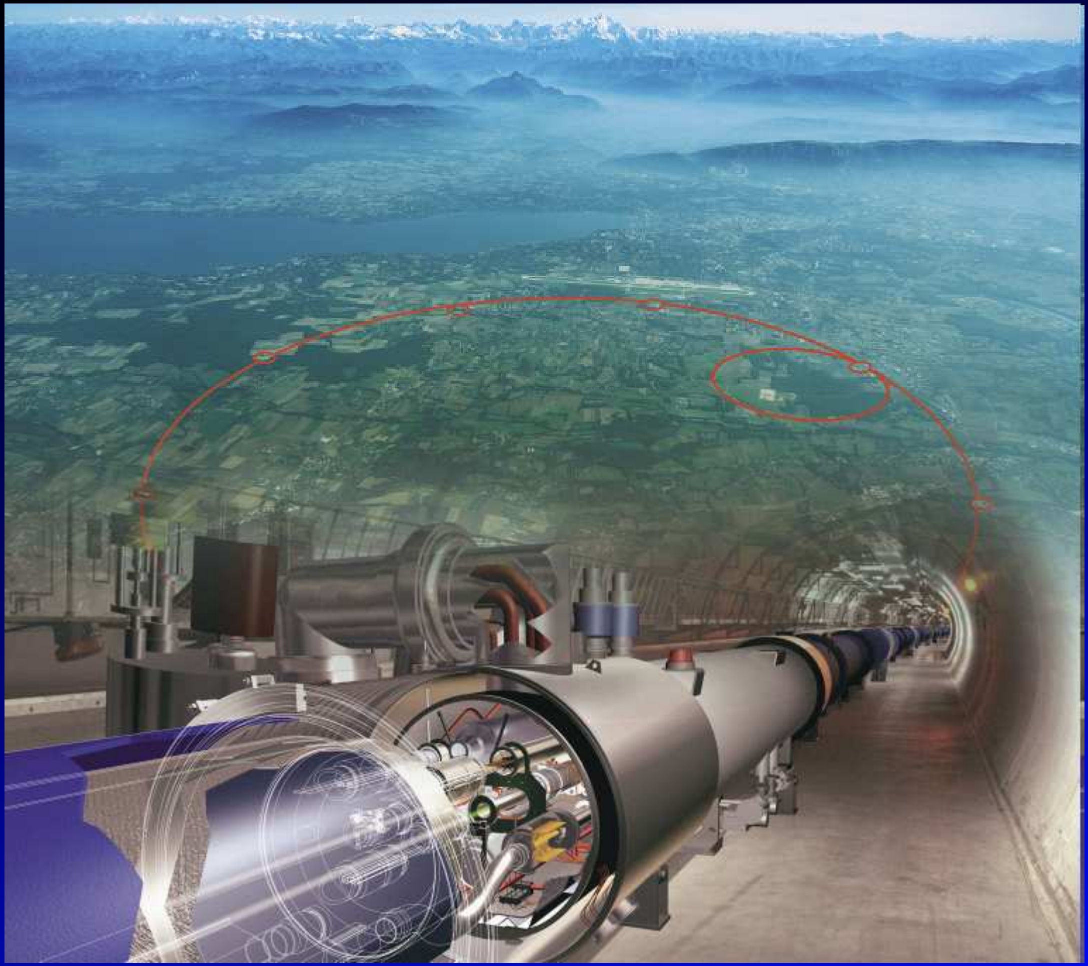
Using Rare Particle Decays to Probe the Energy Frontier

Using Heisenberg's Uncertainty Principle to trump Einstein's $E=mc^2$

E. Craig Dukes
University of Virginia

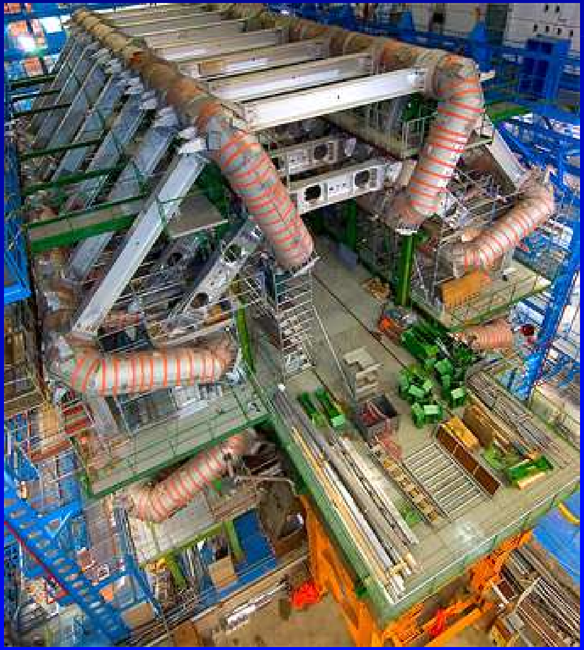
University of Virginia Colloquium

The World Eagerly Awaits the start of the Large Hadron Collider - LHC

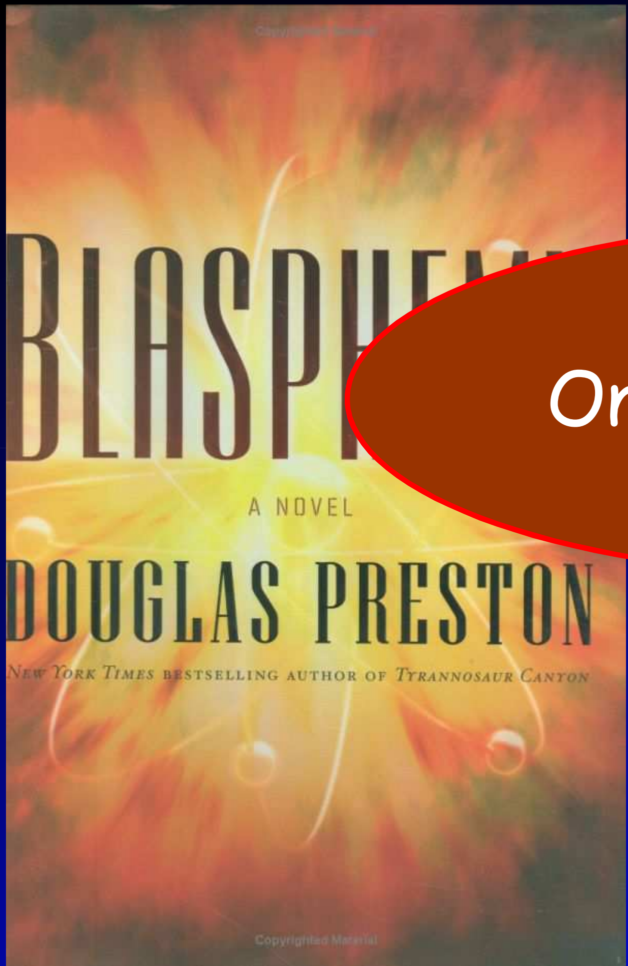


7 trillion (10^{12}) eV proton energy:

7X Fermilab Tevatron



LHC Has Already Had an Impact



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.

On bad literature!

Angels and Demons

The Cause of our Excitement

Theory

- Understanding of the electromagnetic and weak interactions ⇨ Higgs?
- Origin of neutrino mass hierarchy
- Solution to hierarc... p...b... supersy...metr...?

Cosmology

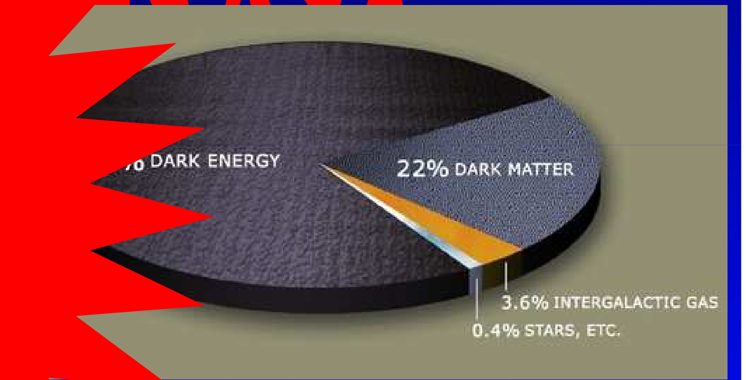
- Matter-... univer...
- Dark m...
- Dark ene...

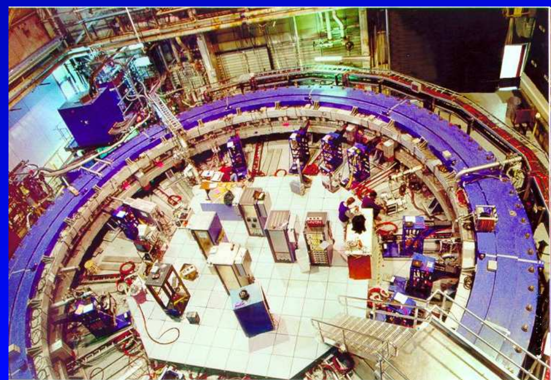
Experiment

- Neut...ino... physics be... ...del
- Weak interac...ion... stu...ie... ⇨ ...iggs?
- Other hints, muon g-2, LSND, NuTeV, CP phases in B_s mixing, D_s decay rates

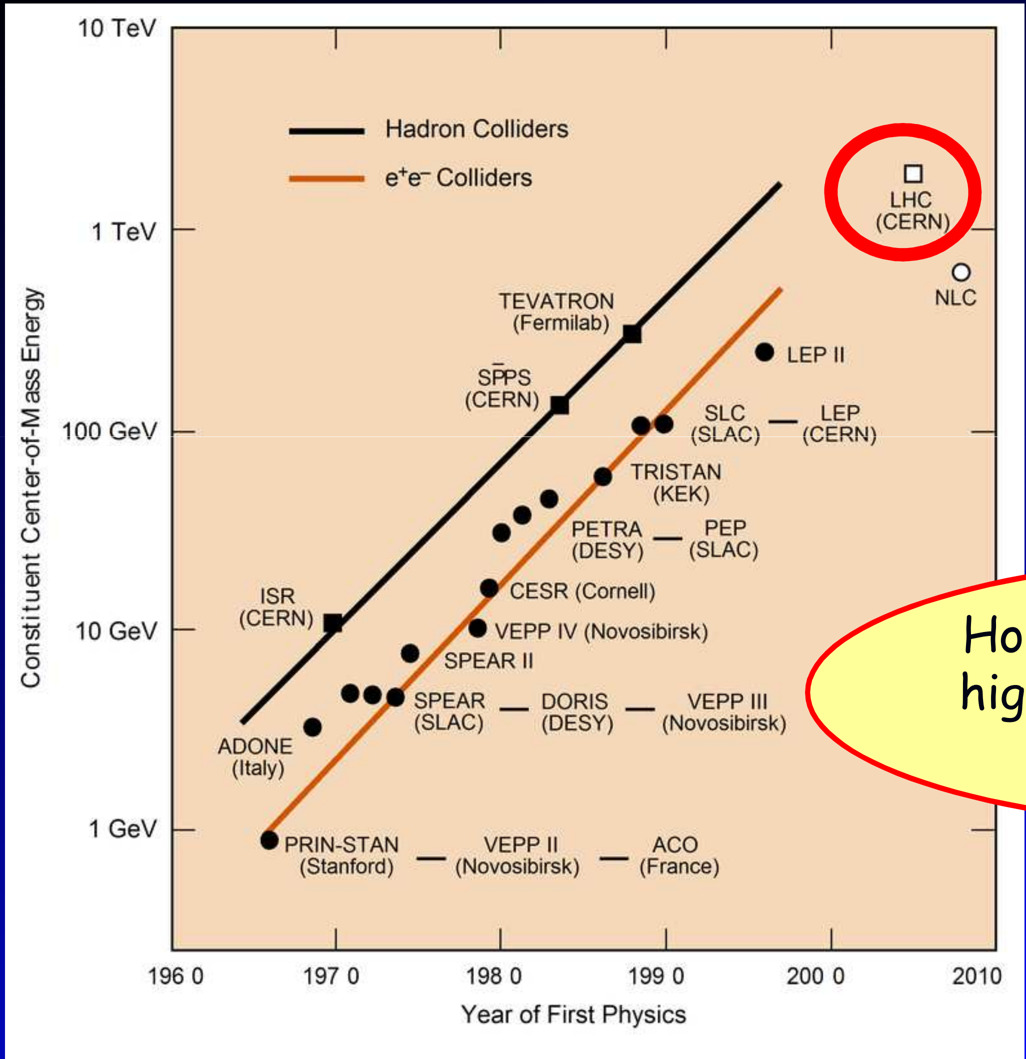
Ne...

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 go probe higher mass scales without higher energies?

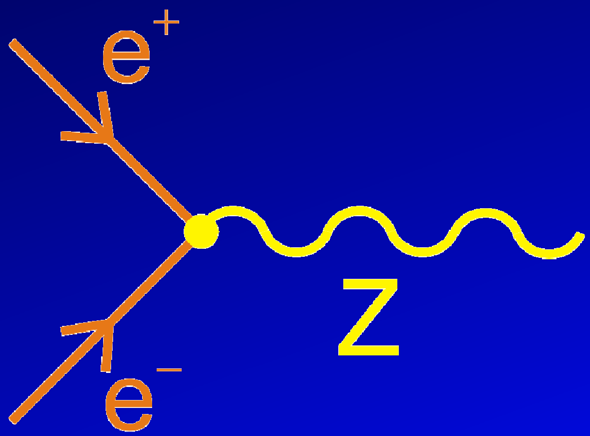
Rather than exploiting Einstein's mass-energy relation, $E=mc^2$, we can exploit Heisenberg's uncertainty principle, $\Delta E \Delta t \gtrsim \hbar/2$

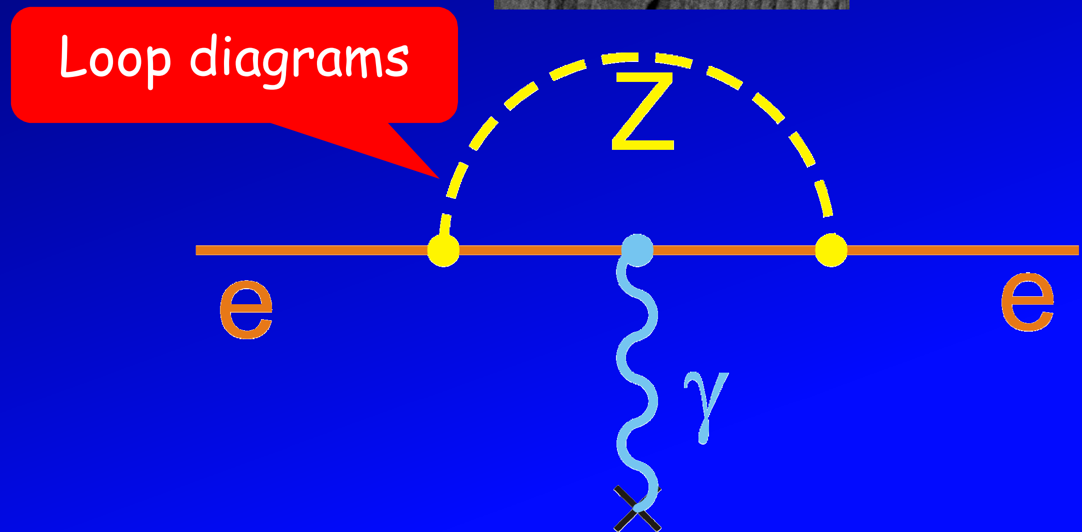
$E=mc^2$
appearance of **real** new particles

Highest energy crucial

$\Delta E \Delta t \gtrsim \hbar$
appearance of **virtual** new particles

Highest intensities crucial

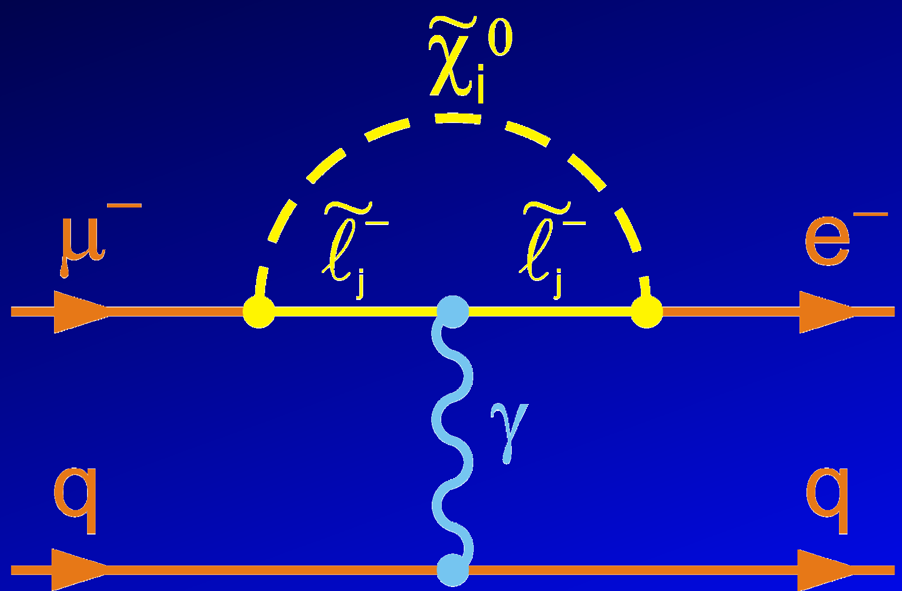




Virtual Particles Can Have Two Effects

They can produce slight deviations from expected properties

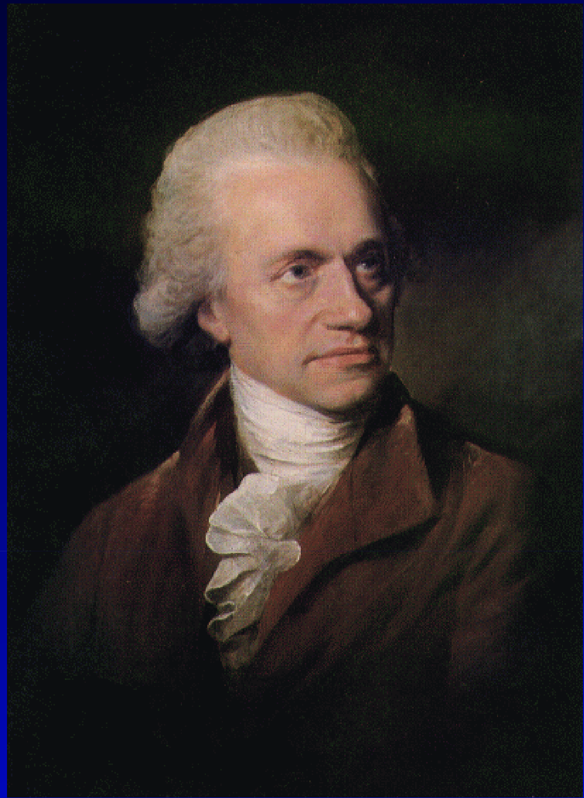
Difficult experiments:
- incredible precisions often needed
- theoretical precision needed too
- precision ∝ √N

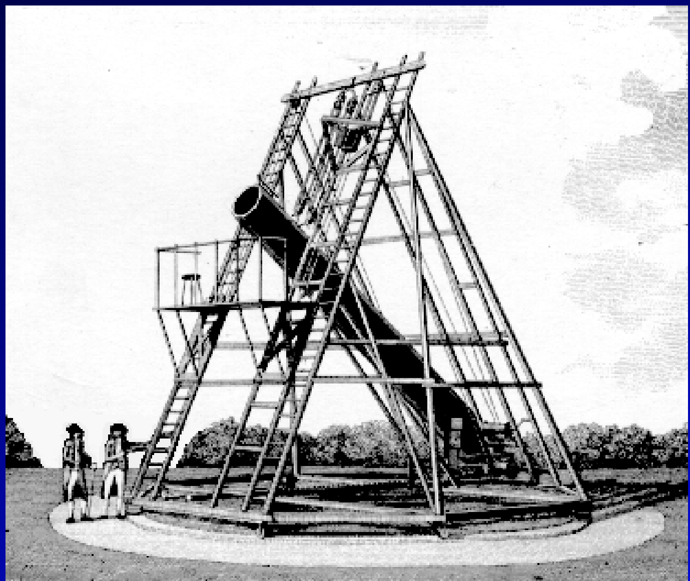


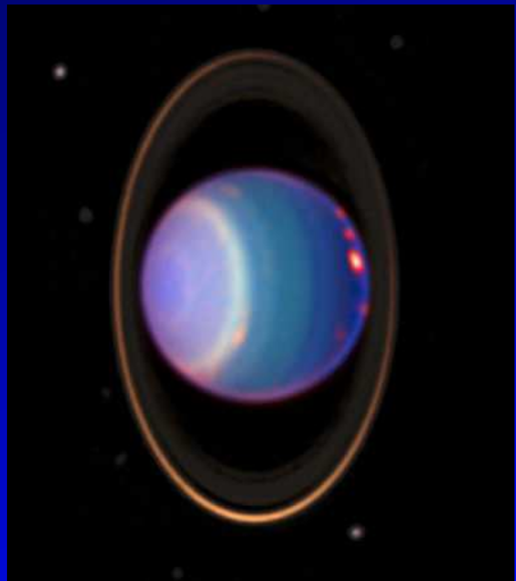
"Easy" search experiments:
- theory ⇨ process is "forbidden"
- one event can be enough
- sensitivity ∝ N

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



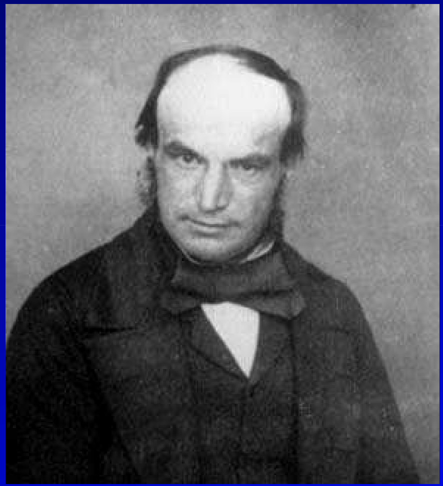




Race to find explanation began

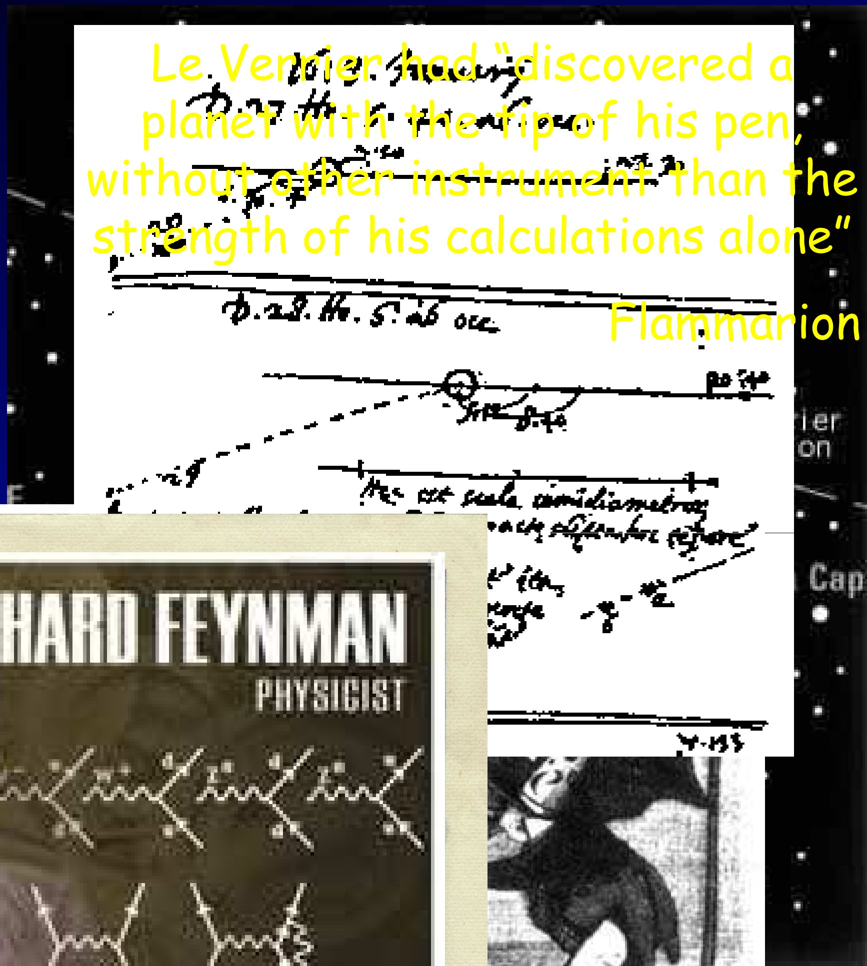
George Airy thought that explanation lied with deviations from Newton's law of gravitation

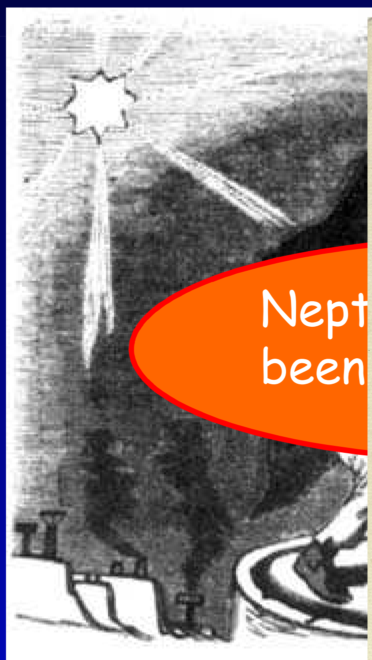
Le Verrier (France) and John Adams (UK) thought that the deviations were due to a hitherto unknown planet

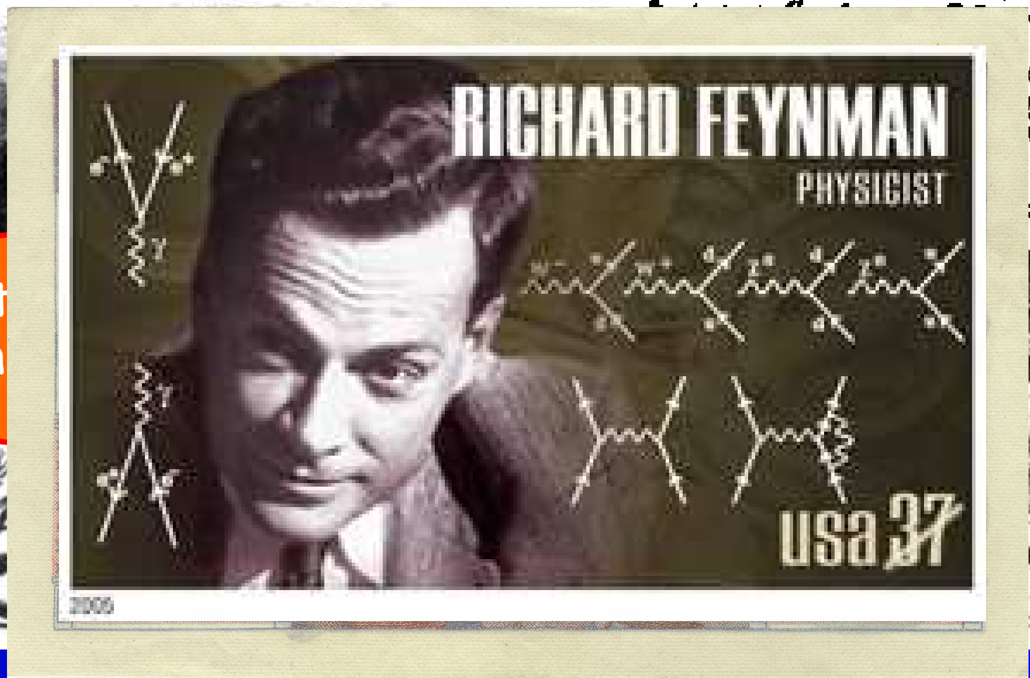


Newton Vindicated

- 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

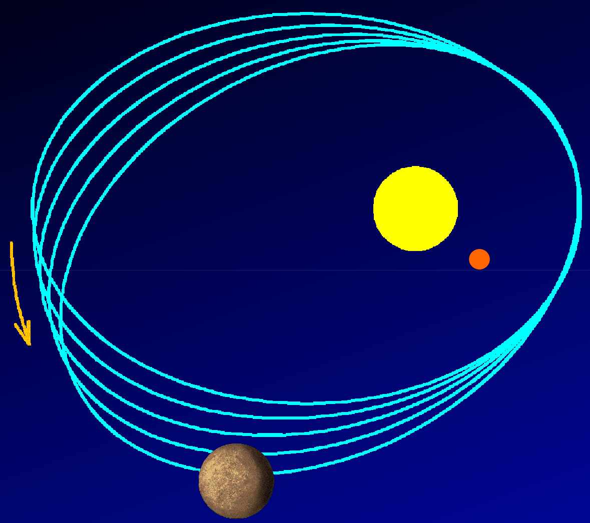






What about Mercury?

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″

L'immense difficulté qu ... ercure a présentée aux anciens astronomes, venait surtout de ce ... planète, plongée durant le jour dans les rayons du Soleil, ne ... ue que le soir ou le matin dans les vapeurs de l'horizon; en sorte ... l'invention et le perfectionnement des lunettes, il était impossible de ... ses élongations. Copernic, empêché par les brouillards de la ... ongue durée des crépuscules en été, ne put jamais parvenir à

..., II, 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 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.

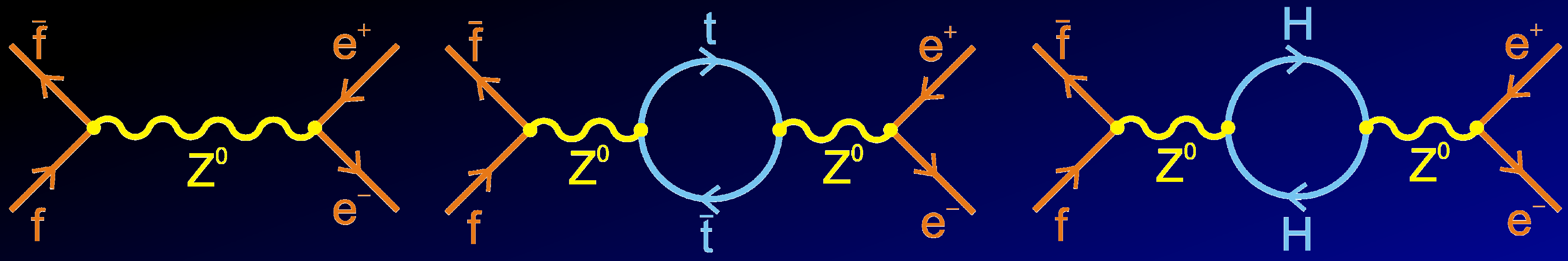
Von A. Einstein.

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

"For a few days I was beside myself with joyous excitement"
Albert Einstein, 18 November 1915

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

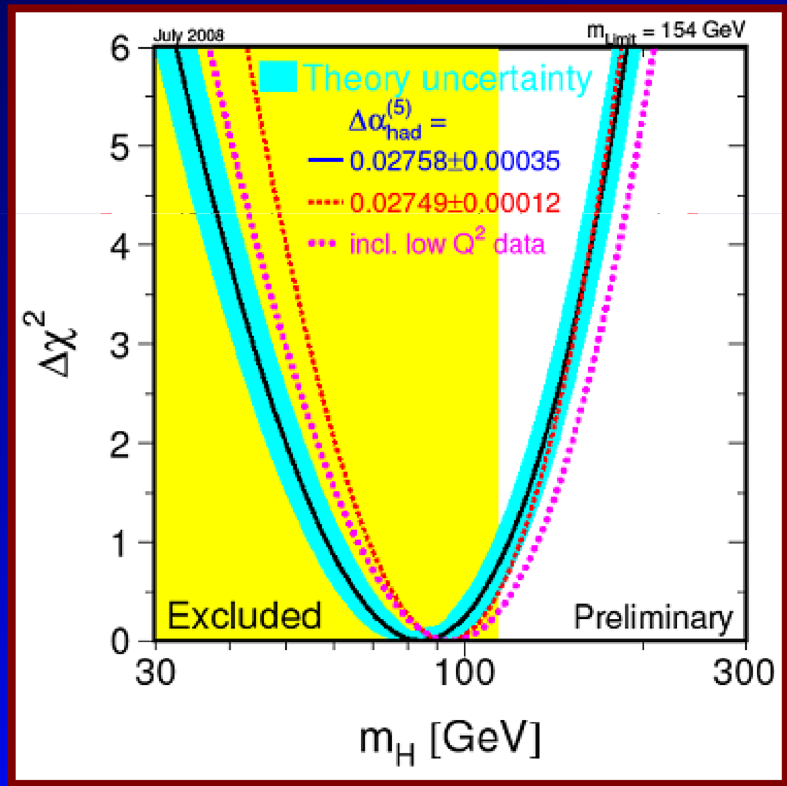
Example: Top and Higgs Masses



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: m_t = 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: $m_H = 84^{+34}_{-26}$ GeV

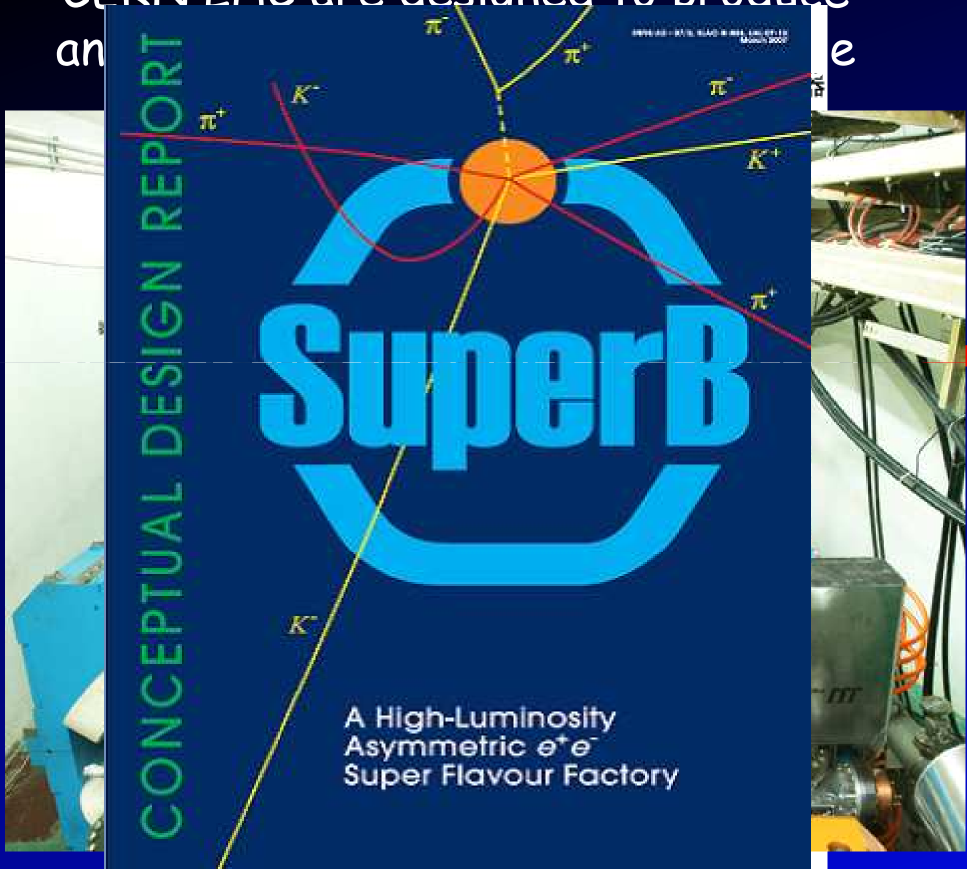


Rare Decays Require Flavor Factories

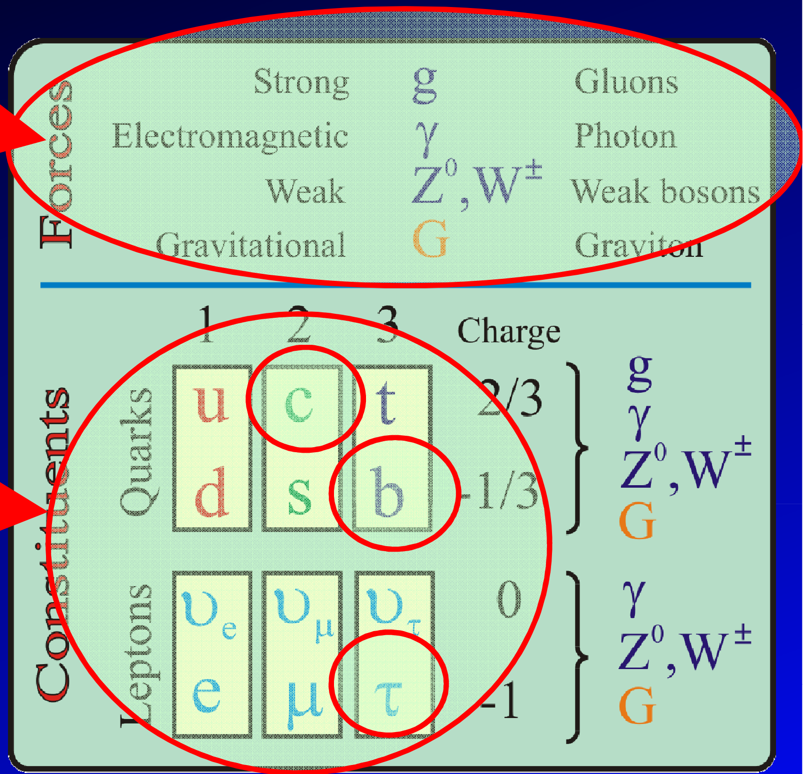
Highest energy particle accelerators, such as the Fermilab Tevatron and the CERN LHC are designed to produce an… e

B-Factories produce bottom/anti-bottom quark pairs

Tau-charm factories produce charm/anti-charm quark and tau/anti-tau lepton pairs



BES-III tau-charm Factory at Beijing, China

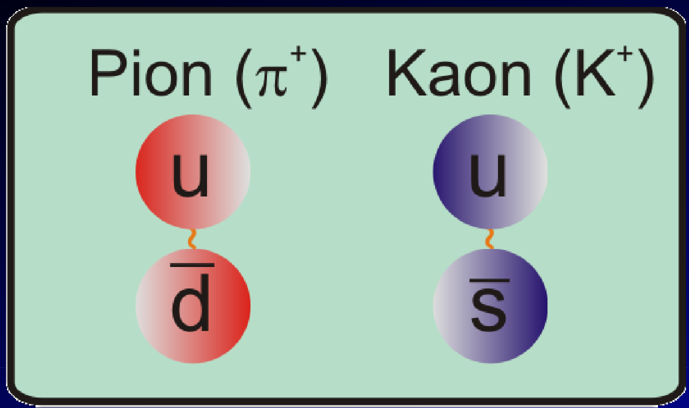


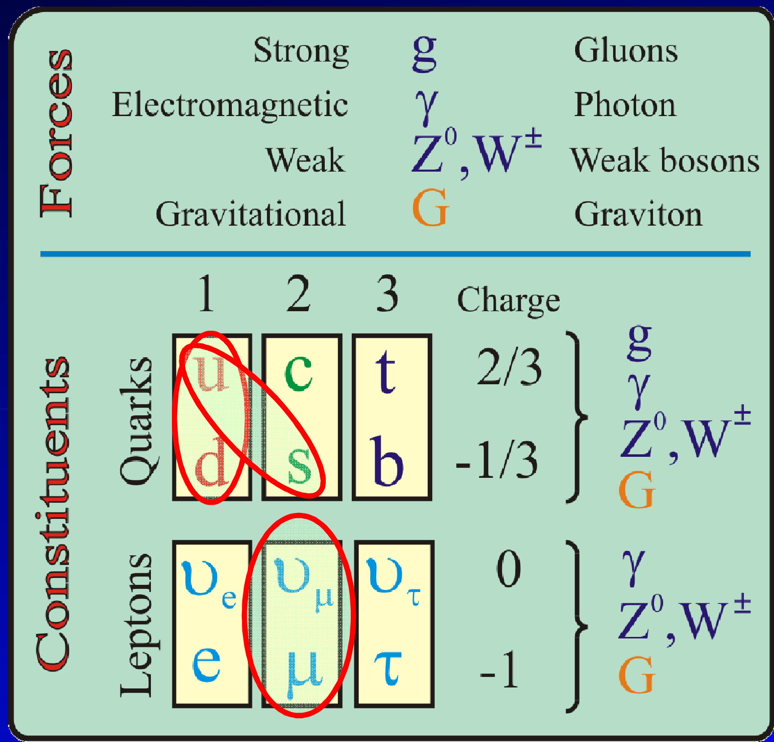
10 billion b/anti-b pairs/yr

10 billion τ/anti-τ 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

$$\left.\begin{aligned} \pi^+ &\rightarrow \mu^+ \nu_\mu \\ K^+ &\rightarrow \mu^+ \nu_\mu \end{aligned}\right\}$$

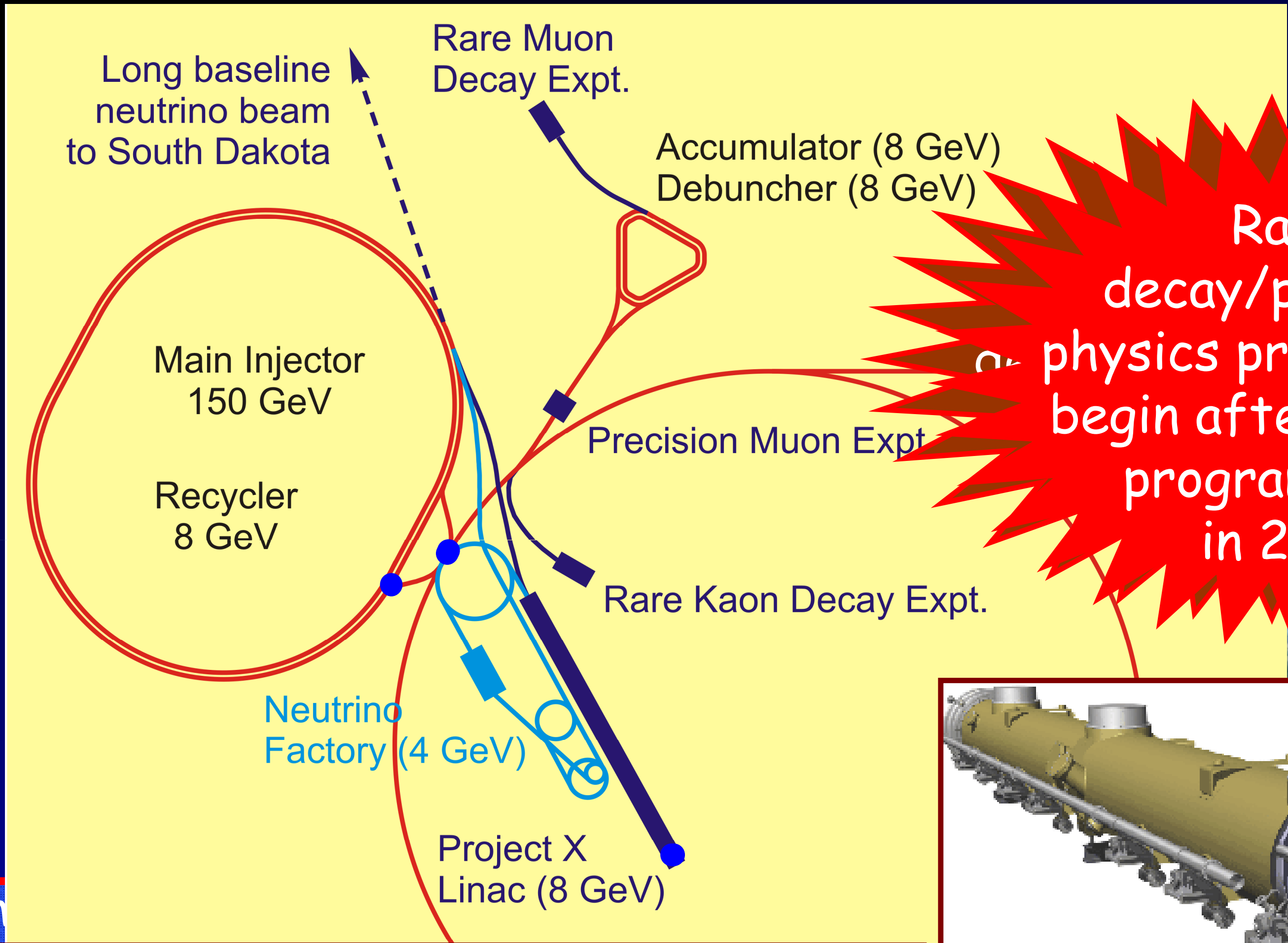
~1-100 billion/s can be produced

Fermilab Pushing Forward on Intensity Frontier

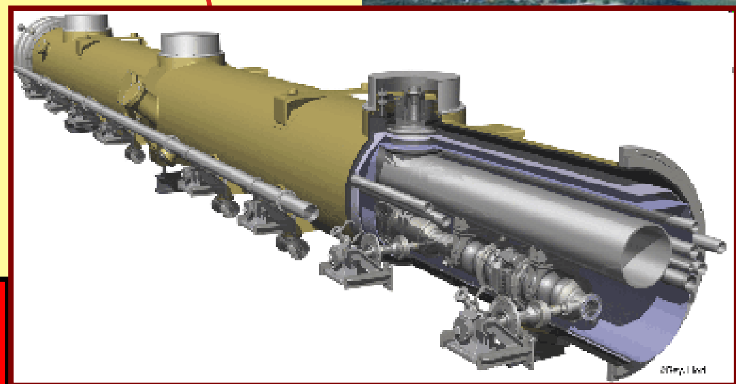
Strategic Plan for the Next Ten Years:

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

Fermilab: Moving from the Present to Project X



Rare decay/precision physics program can begin after collider program ends in 2010!



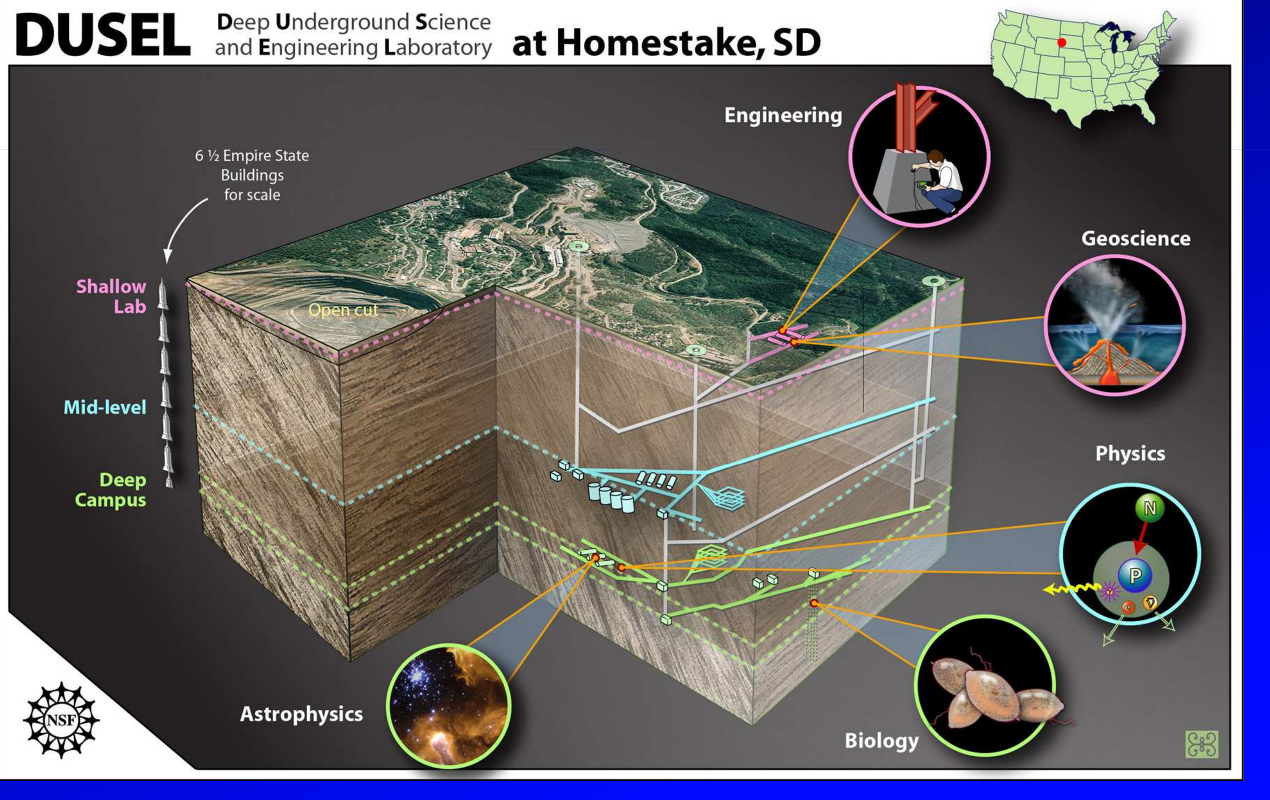
The Project X linear accelerator would feed a high-intensity neutrino and rare decay/high precision physics program

Project X Neutrino Program: DUSEL

- Deep Underground Science and Engineering Laboratory (DUSEL)
  - Longer baseline than NuMI
  - Old Homestake mine
  - Multi-purpose detector possible: proton decay and neutrino physics
- Wide band beam: not off axis like NOvA

U.S. Long Baseline Neutrino Experiment Study (arXiv:0705:4396)

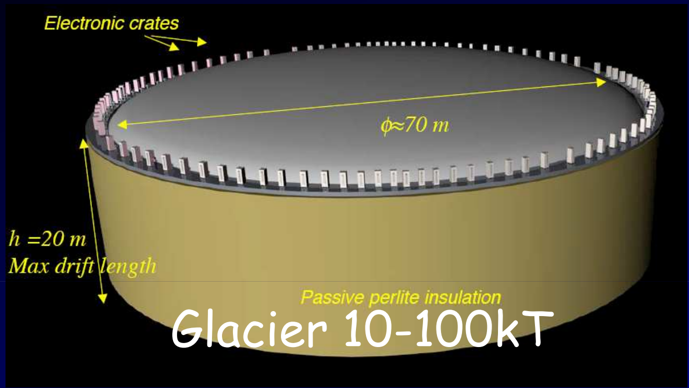
NUSAG Report, July 13, 2007

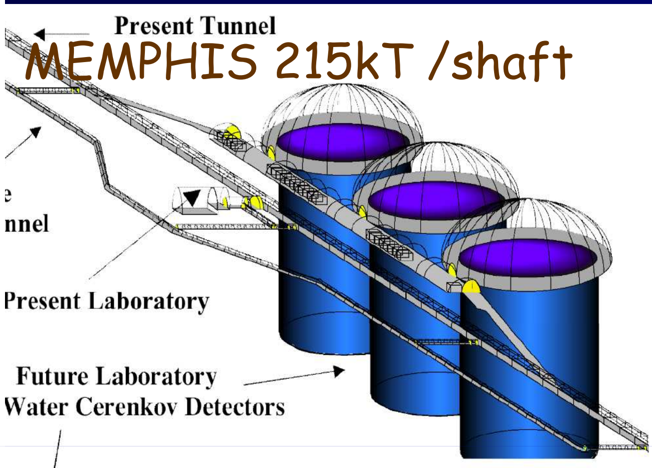


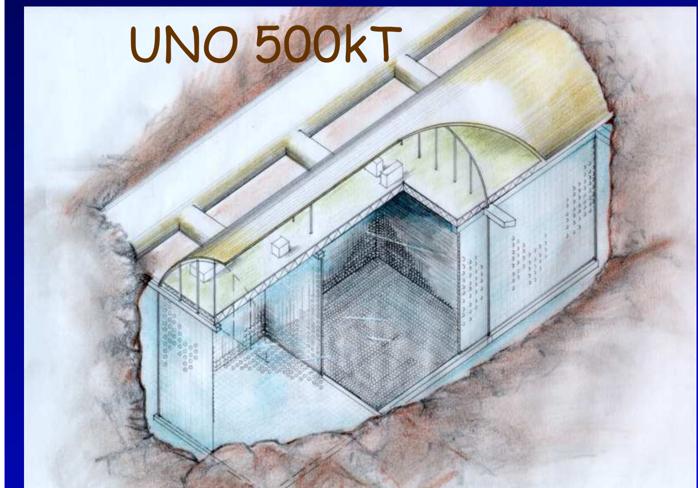
Next Generation Detectors Being Designed

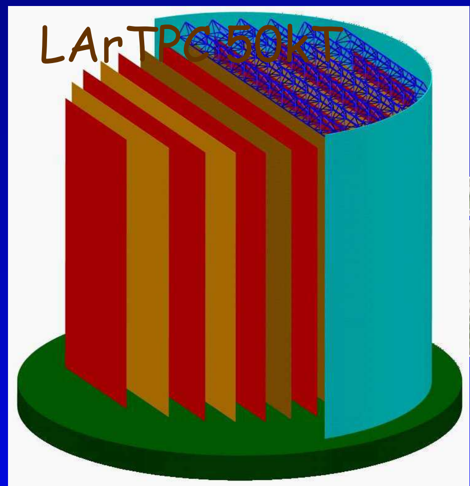
Two favorite technologies

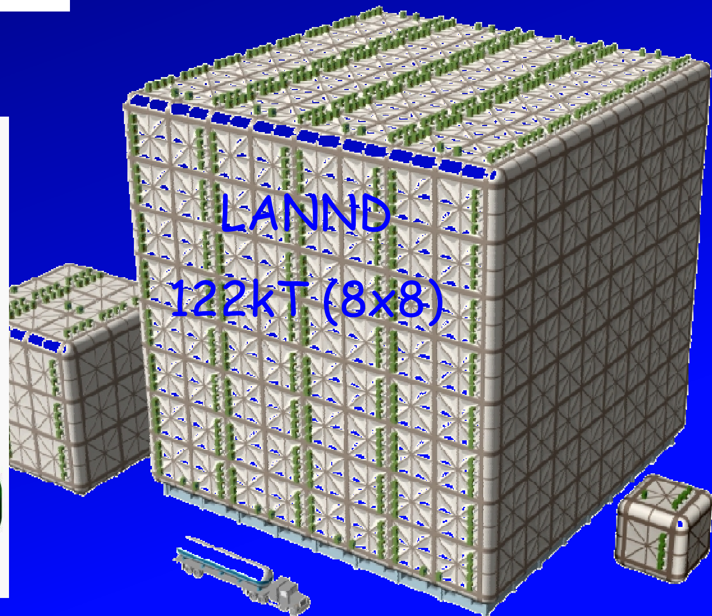
1. Water Cerenkov
2. Liquid Argon











Ultimate Reach: Neutrino Factory

Advantages:

- Large neutrino fluxes
- Little uncertainty in neutrino flux
- Little background if sign of lepton can be determined
- All ν parameters measured from $\nu_e \rightarrow \nu_\mu$ and anti-$\nu_e \rightarrow$ anti-ν_μ
- Δm^2 sensitivity so good that hierarchy may be measurable with θ_{13} = 0!

Disadvantages:

- Need to measure muon sign $\rightarrow$ magnetic detector needed

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \dashrightarrow \mu^-$$

$$\bar{\nu}_\mu \rightarrow \mu^+$$

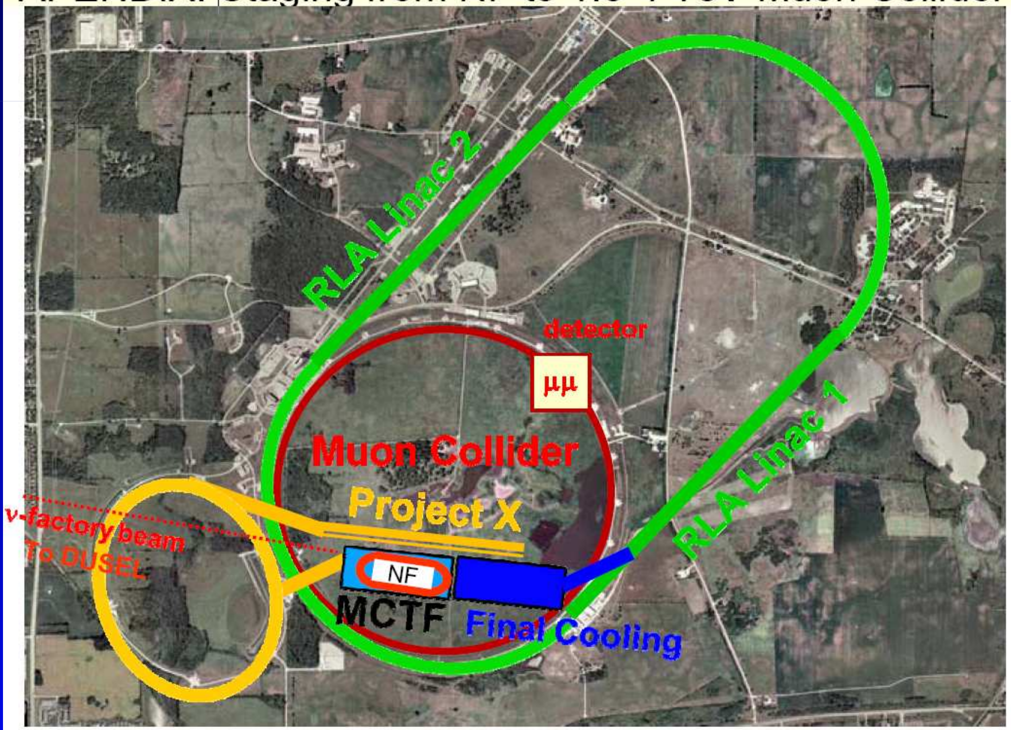
Golden Channel

- Technology unproven: lots of R&D needed that will take time

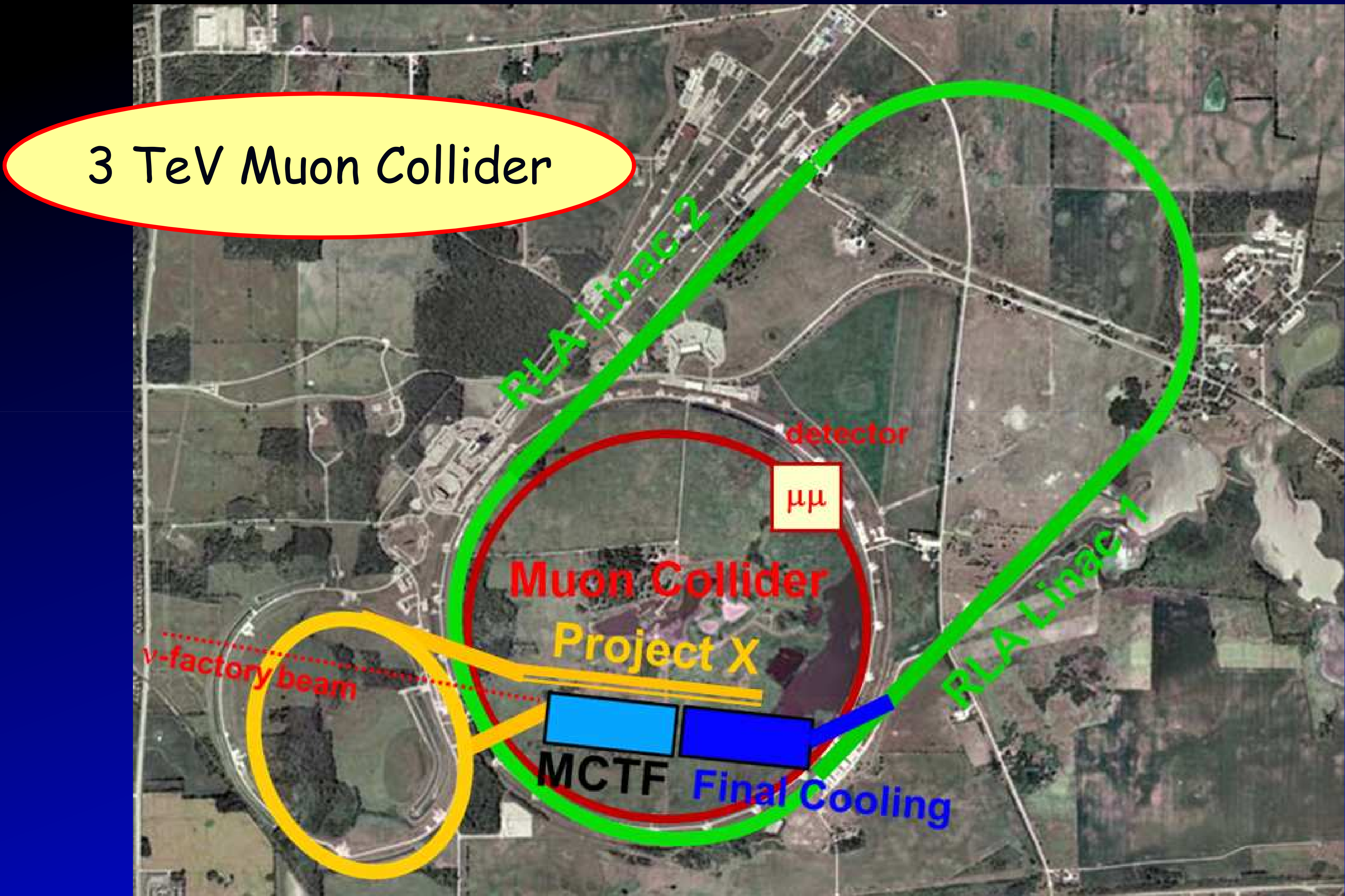
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad 50\% \; \bar{\nu}_e + 50\% \; \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad 50\% \; \nu_e + 50\% \; \bar{\nu}_\mu$$

International Design Study: ZDR by ~2010, RDR by ~2012

APENDIX: Staging from NF to 1.5-4 TeV Muon Collider



Getting Back to the Energy Frontier



Project X Beam Rates Enormous

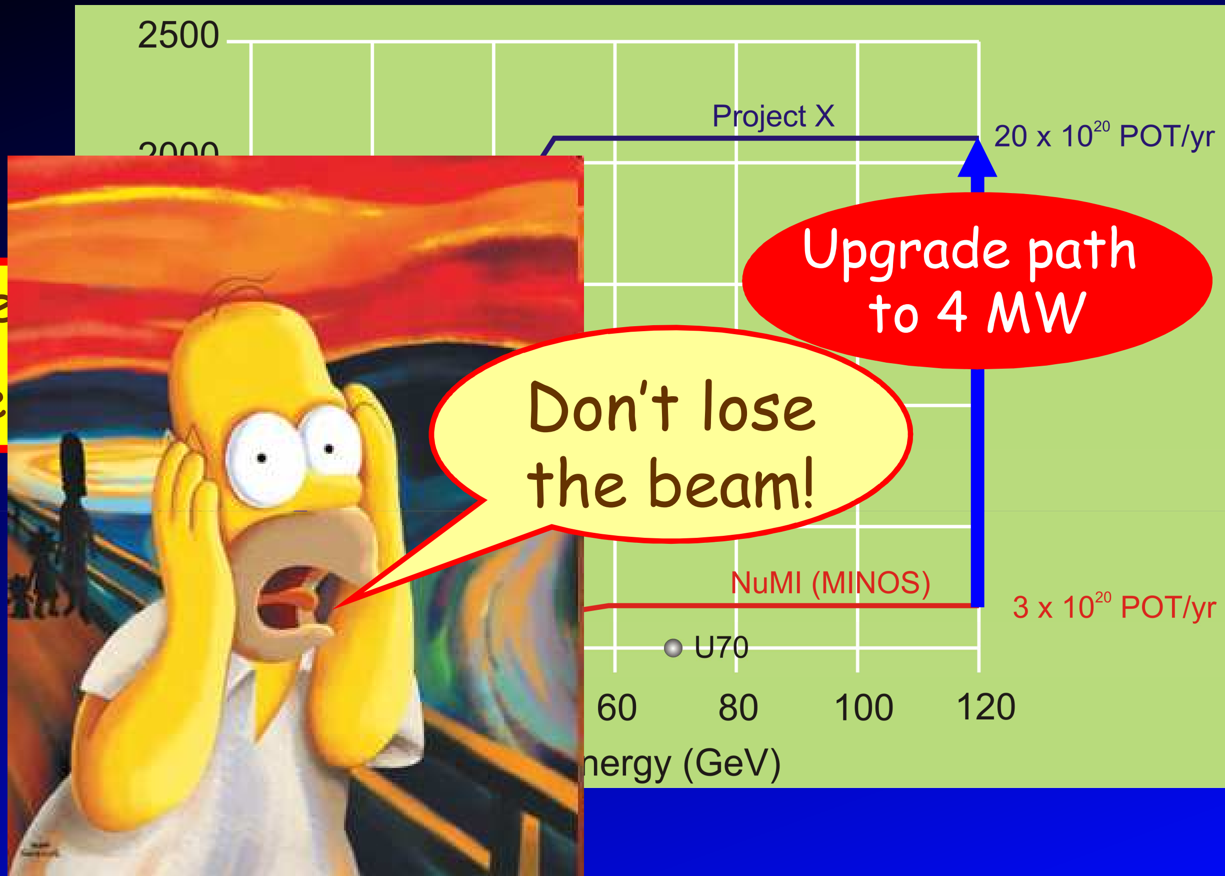
Beam Power

= particles/s x energy

8 GeV: ~20X increase

120 GeV: ~10X increase

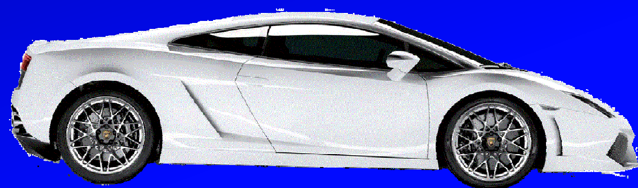
Produce 1,000 billion muons per second!



Upgrade path to 4 MW

Don't lose the beam!

Each beam pulse has energy of Lamborghini Gallardo going 140 mph (226 km/h), with only 1.7 x 10^{-16} the Gallardo's mass!



Great Interest in Project X

Three workshops held at Fermilab on accelerator and experiments

Nov 12-13, 2007

- 174 participants, 25 institutions

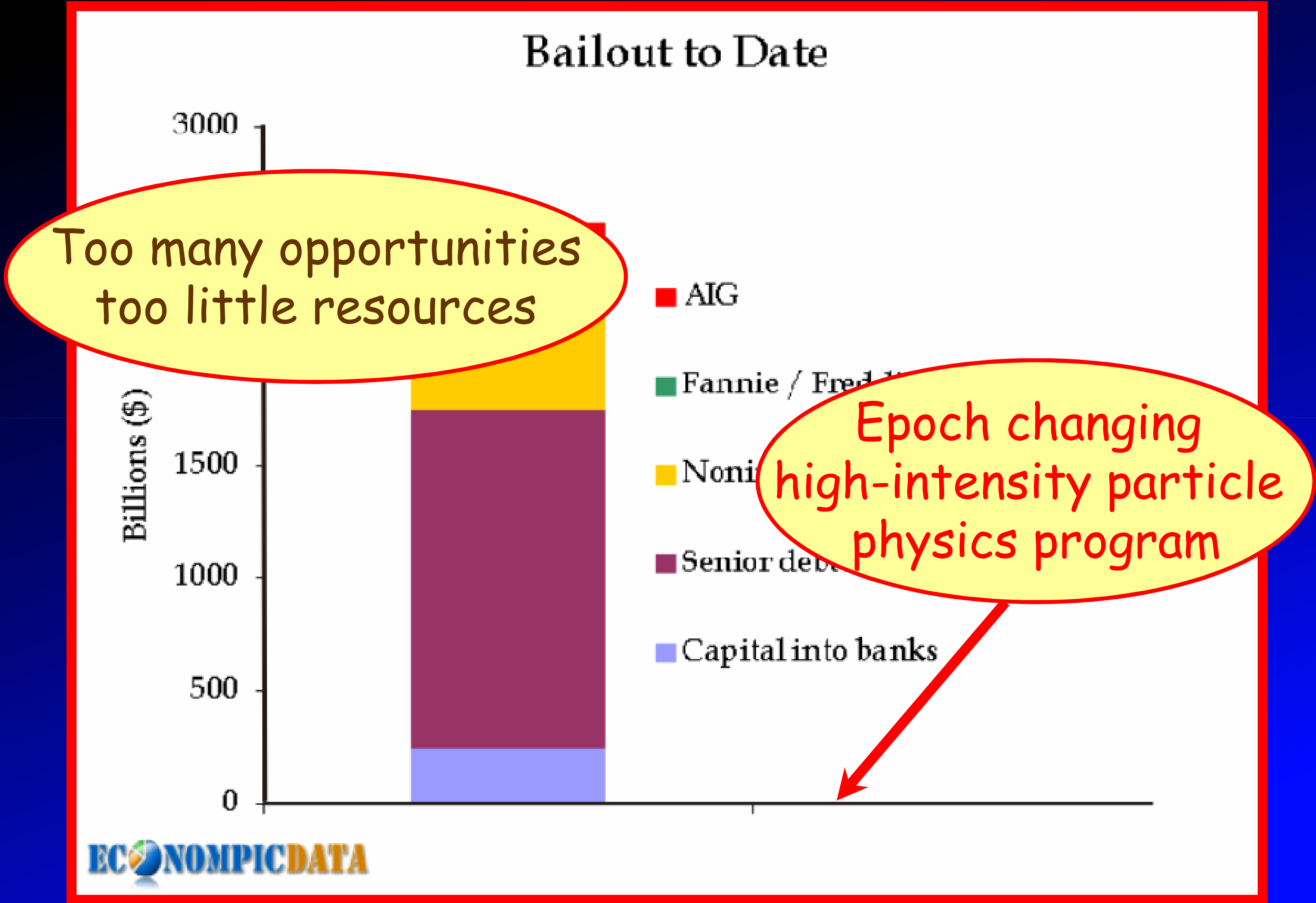
Nov 16-17, 2007

- 250 participants, 78 institutions

Jan 25-26, 2008

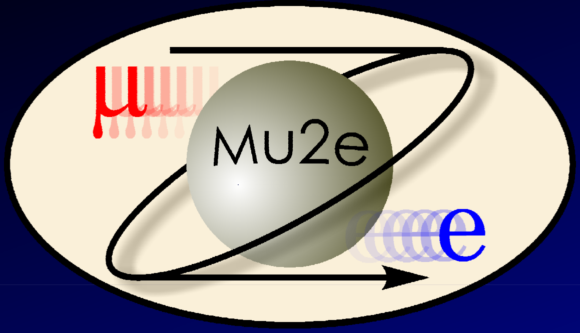
- 200+ participants, 64 institutions

Potential Program Huge

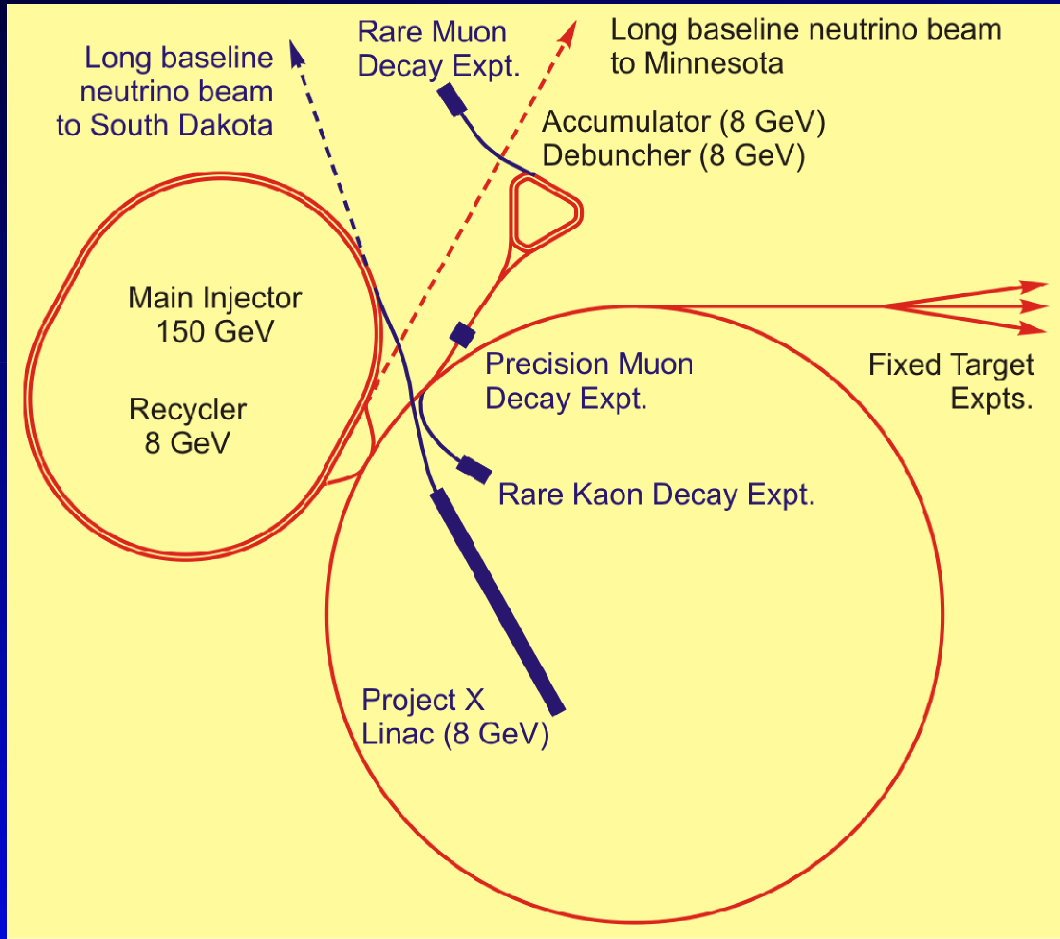


A Snapshot of Two Experiments

Rare muon decay experiment



Precision muon experiment

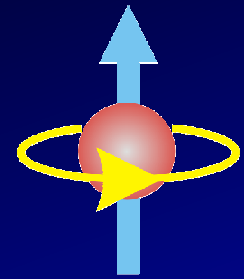


Magnetic Moment of the Muon: Theory

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)

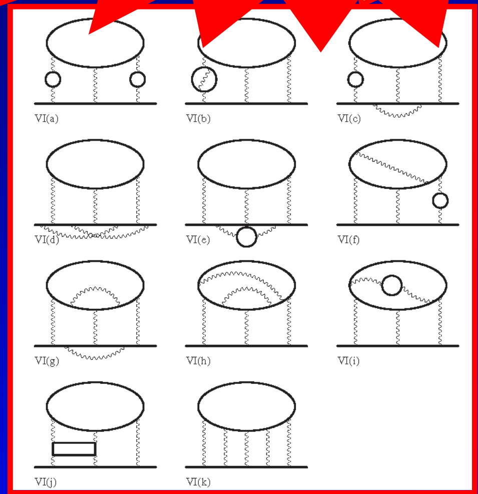


past 40 years by
er's in calculating
ment

Muon's magnetic moment 40,000 times more sensitive than electron's to new physics

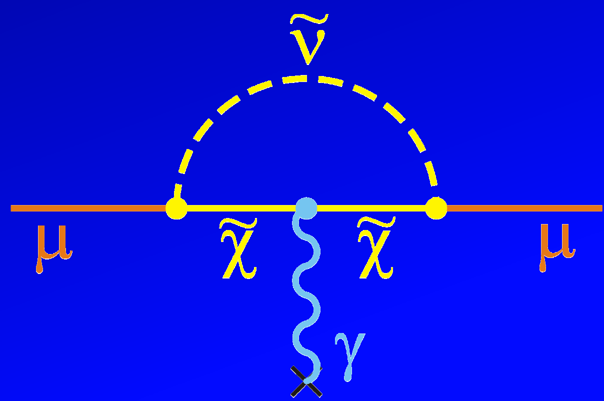
Dirac

$$\mu = \frac{e}{2m_\mu c} +$$



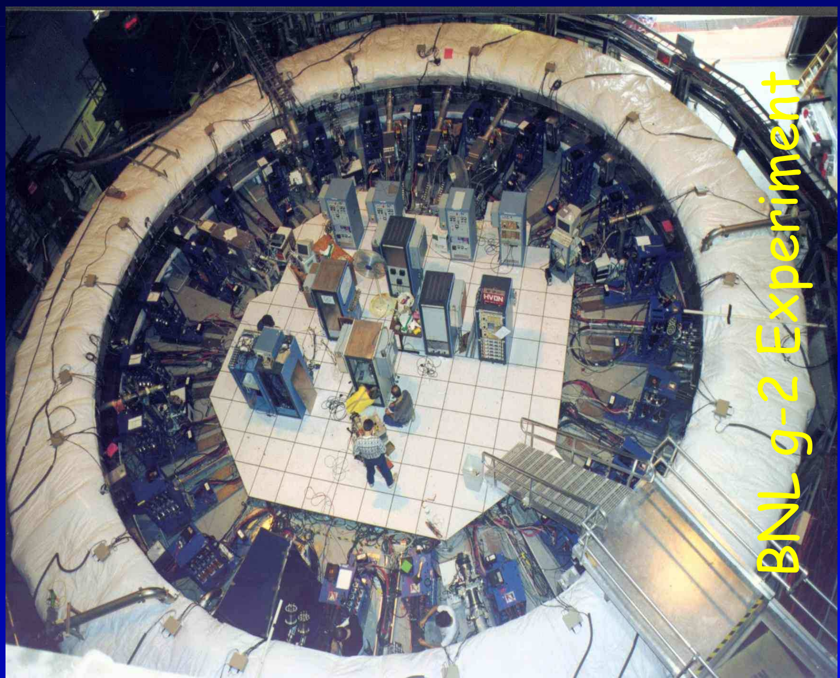
$+$

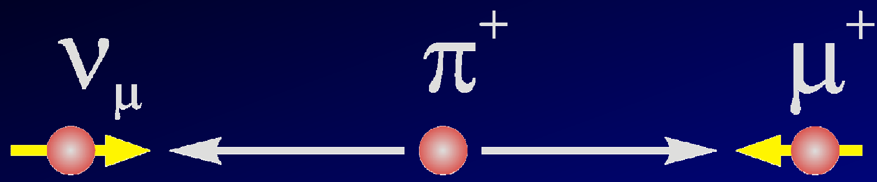
New Physics

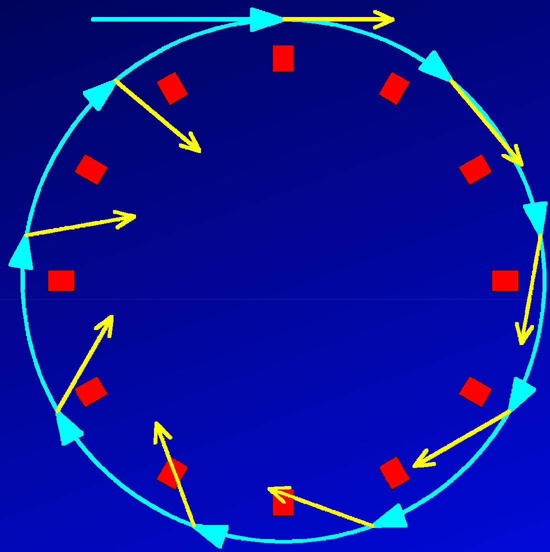


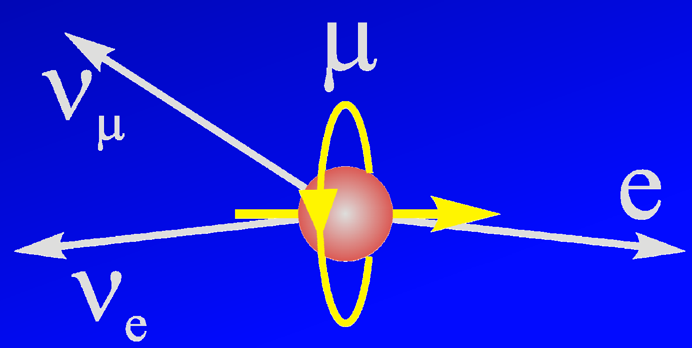
Magnetic Moment of the Muon: Experiment

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

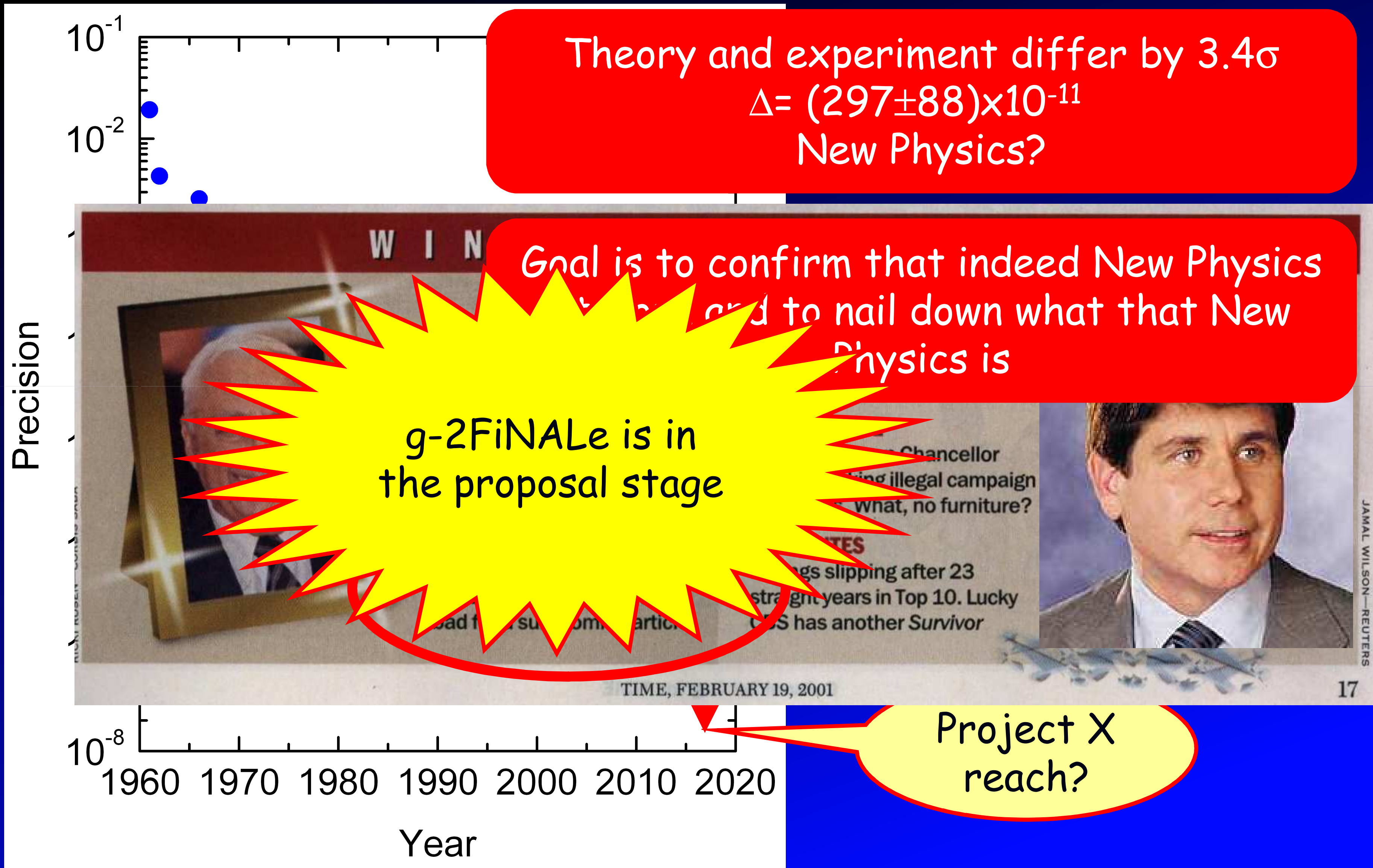








Theory Meets Experiment



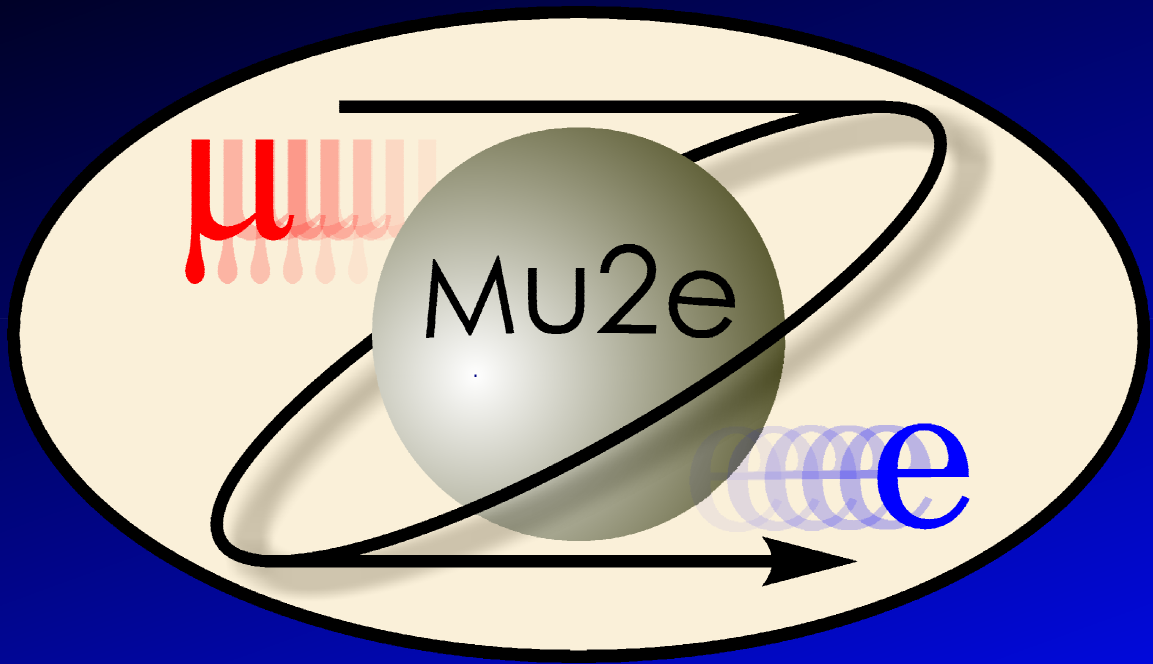
Theory and experiment differ by 3.4σ
$\Delta = (297 \pm 88) \times 10^{-11}$
New Physics?

Goal is to confirm that indeed New Physics ... and to nail down what that New Physics is

g-2FiNALe is in the proposal stage

Project X reach?

Search For Lepton Flavor Violation



Quark and Lepton Alchemy

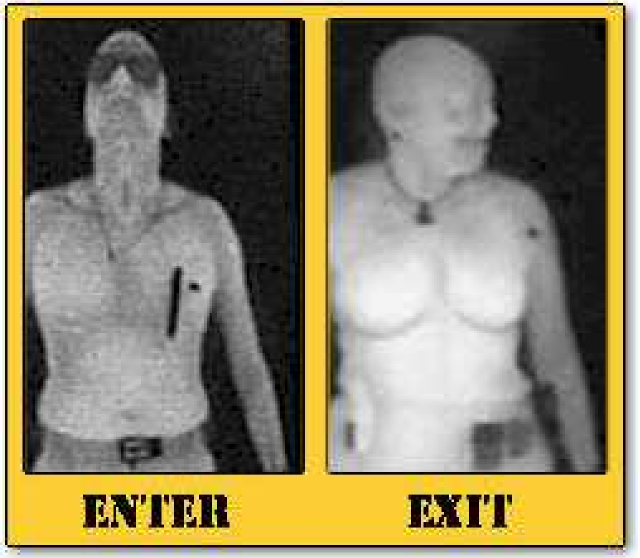
Quarks

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."

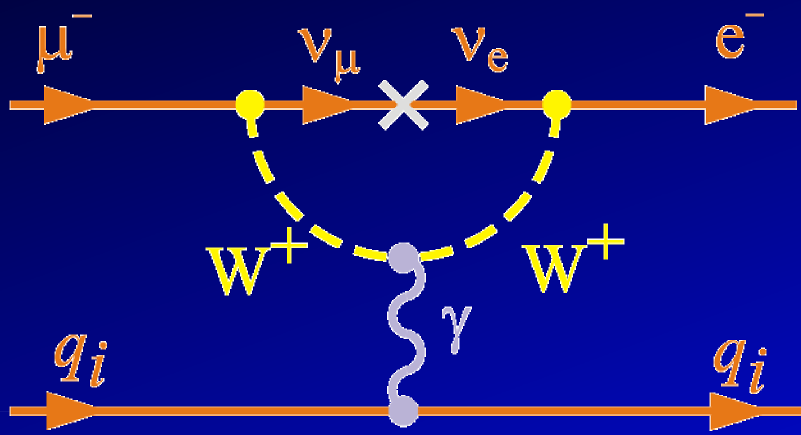
is charged

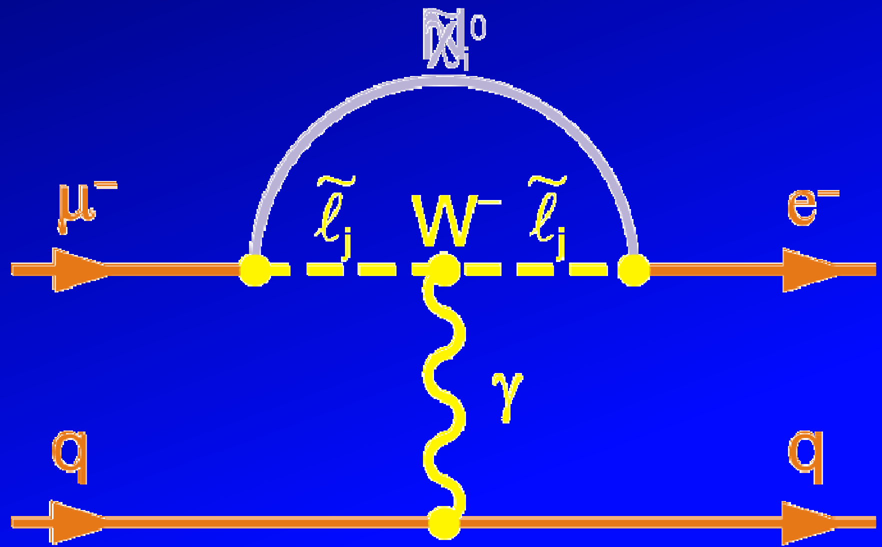
violated?

Why Search for Charged Lepton Flavor Violation?

$$\mu^- N \to e^- N'$$

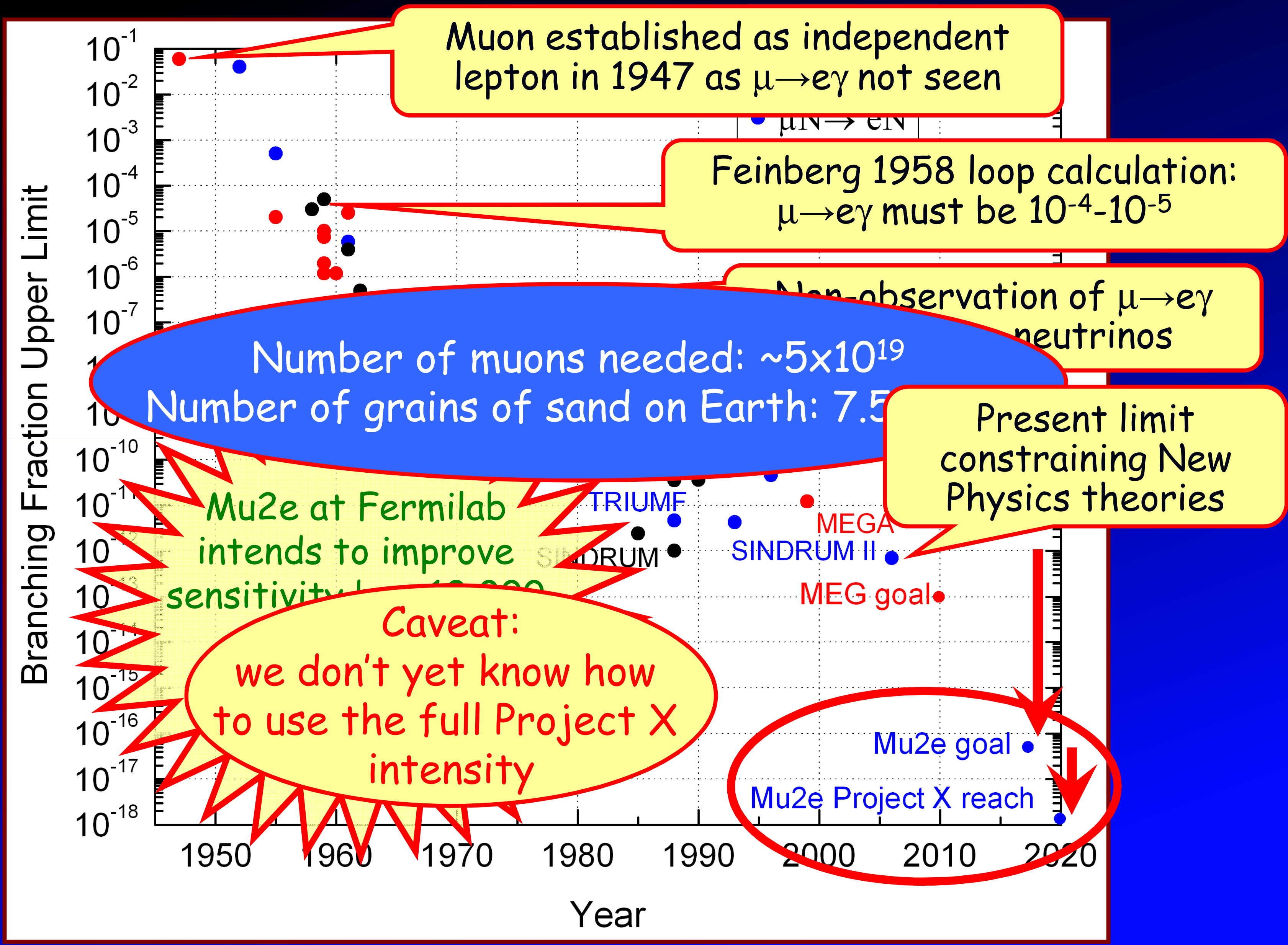
- In Standard Model not there ⇨ neutrino mass discovery implies an unobservable 10^{-52} rate
- Hence, any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally
  - ⇨ sensitivities that allow favored beyond-the-standard-model theories to be tested





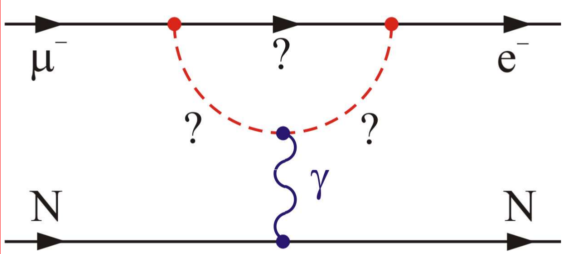
Almost all models explaining the neutrino mass hierarchy produce $\mu^- N \to e^- N$ at levels that will be probed by Project X

History of Lepton Flavor Violation Searches



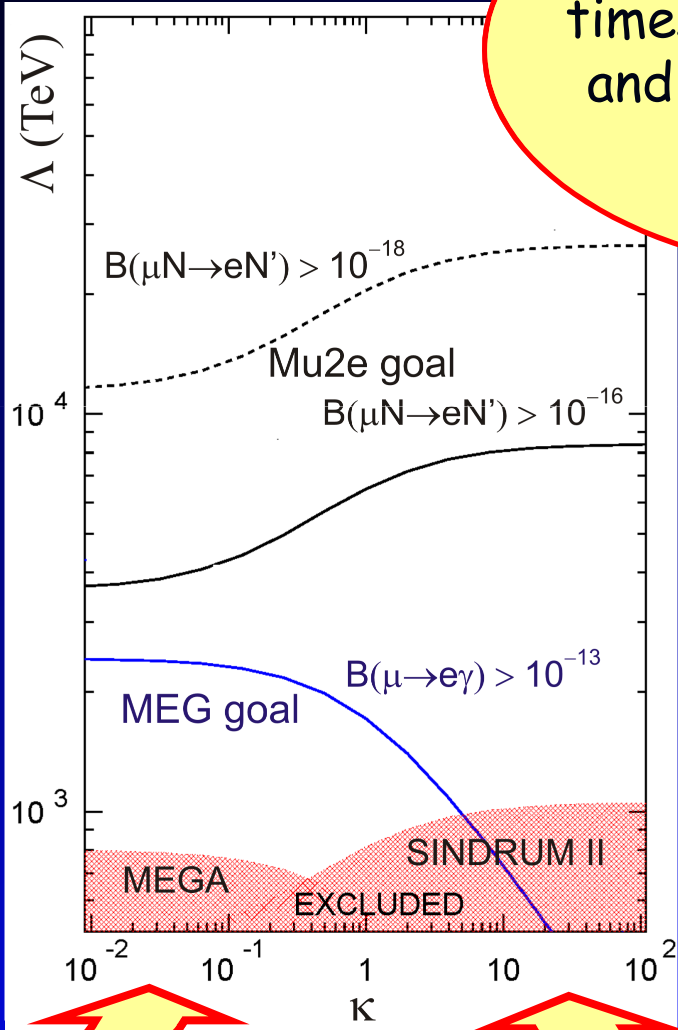
$\mu^+ \to e^+\gamma$ vs $\mu^- N \to e^- N$

Model independent CLFV Lagrangian

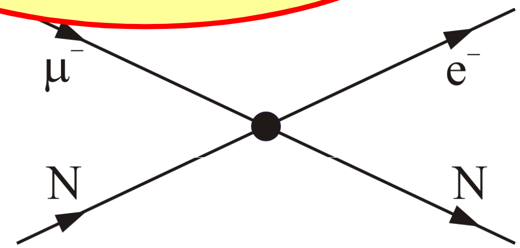


$\kappa \ll 1$
magnetic moment type operator

$\mu \to e\gamma$ rate ~300X $\mu N \to eN$ rate



Mu2e will probe mass scales 10,000,000 times the mass of proton and ~10,000 times that probed directly by LHC



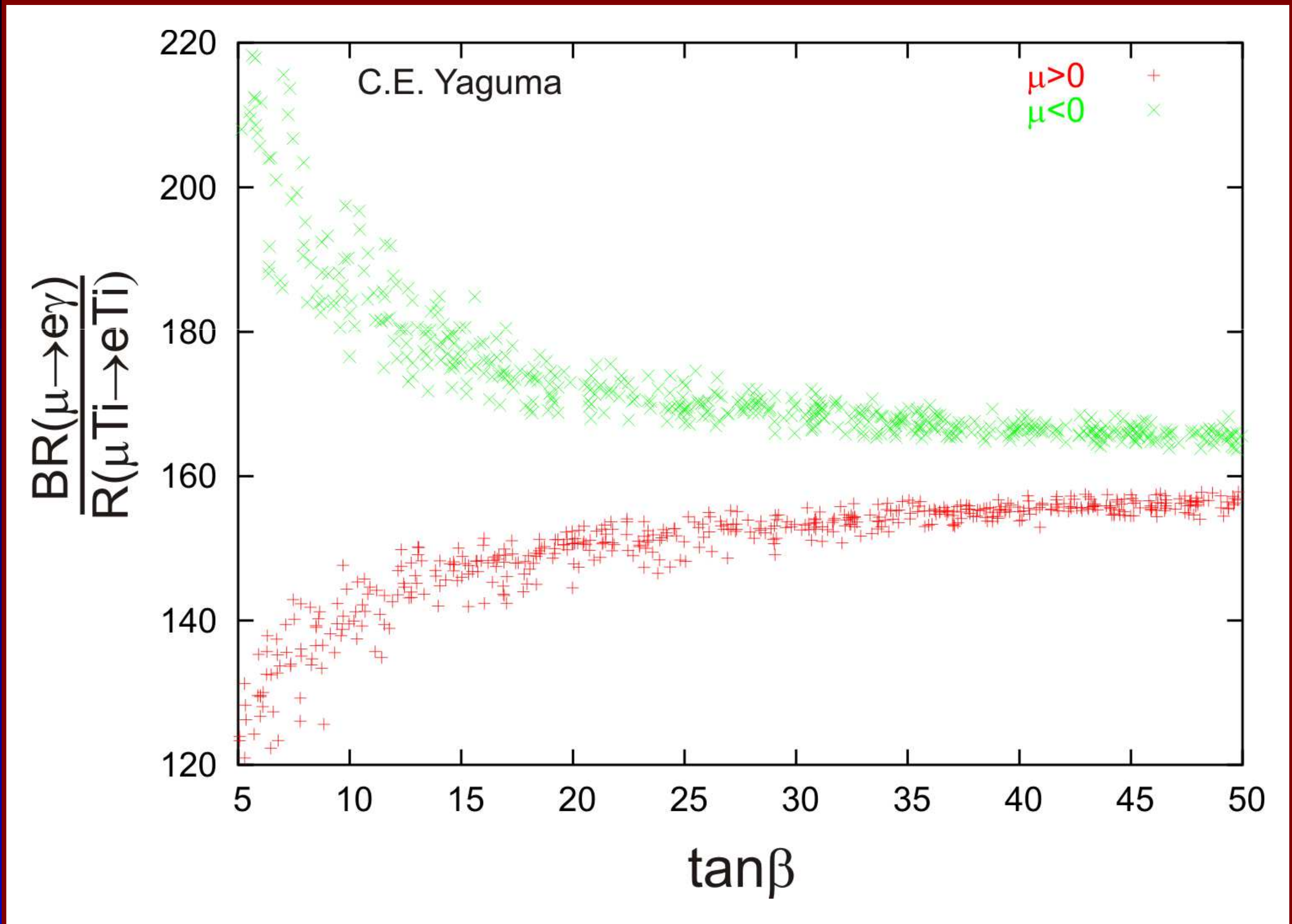
$\kappa \gg 1$
four-fermion interaction

$\mu N \to eN$ rate many orders of magnitude greater than $\mu \to e\gamma$ rate

Two Methods are Complementary

Observation of CLFV in both $\mu^- N \rightarrow e^- N$ and $\mu^+ \rightarrow e^+ \gamma$ could elucidate SUSY parameters

MSSM/msugra/seesaw

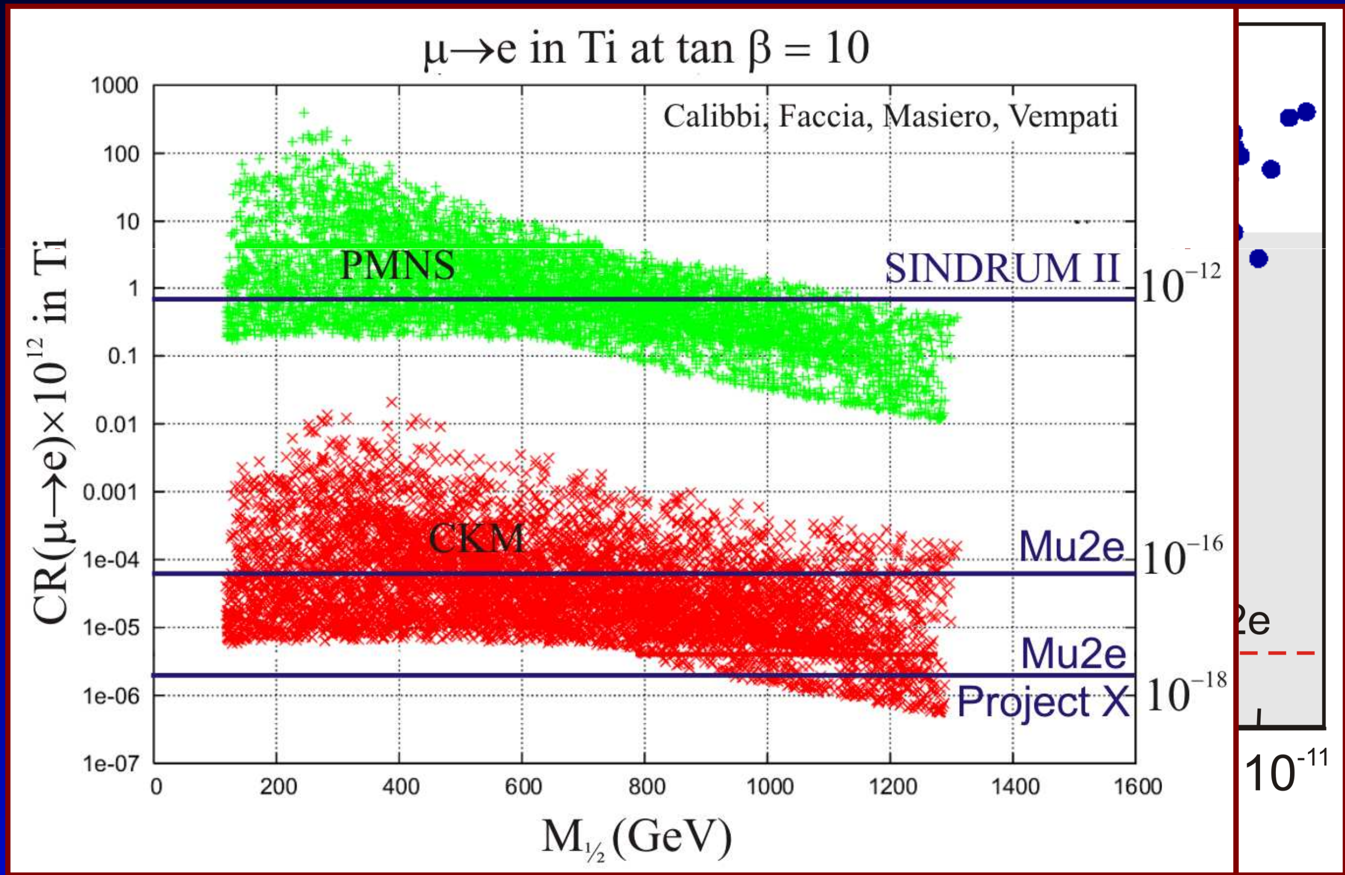


What Sensitivity is Needed?

Present sensitivity already interesting and constraining!

~10^{-16} removes many models

~10^{-18} extremely difficult for theorists to deal with

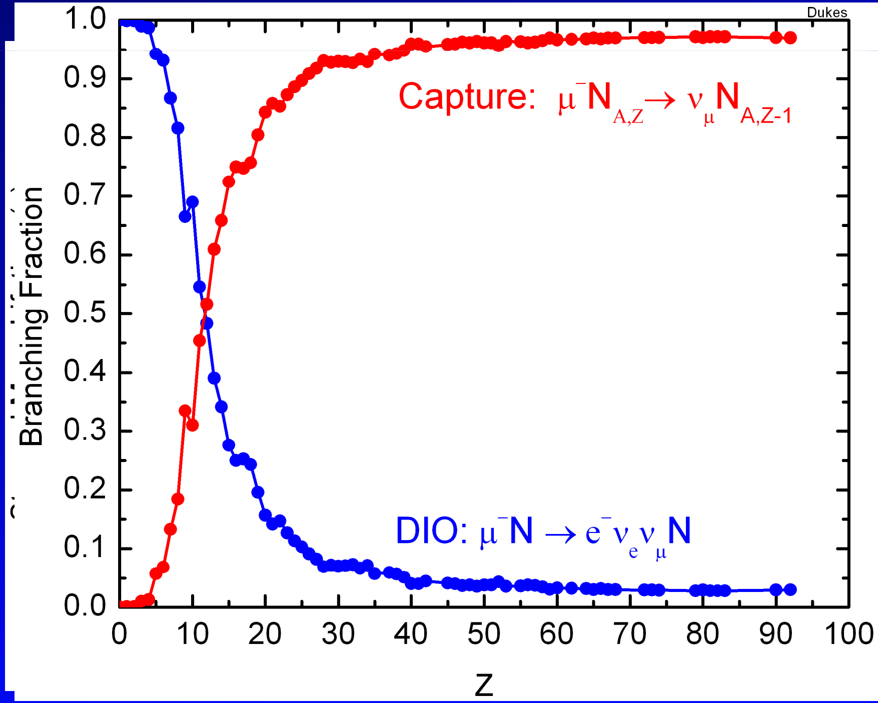


How to Search for $\mu^- N \to e^- N$

- Stop muon in atom
- Muon rapidly (10^{-16}s) cascades to 1S state
- Circles the nucleus for up to ~2 μs
- Two things most likely happen:
  1. muon is captured by the nucleus: $\mu^- N_{A,Z} \to \nu_\mu N_{A,Z-1}$
  2. muon decays in orbit: $\mu^- N_{A,Z} \to e^- \nu_\mu \nu_e N_{A,Z}$
- In $\mu^- N \to e^- N$ the muon coherently interacts with nucleus leaving it in ground state
  - signature single isolated electron
  - $E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)

$$R_{\mu e} = \frac{\Gamma(\mu^- Al \to e^- Al)}{\Gamma(\mu^- Al \to \nu_\mu Mg)}$$

Measure ratio of conversion rate to capture rate



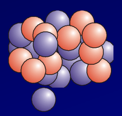
Bunched Beam Technique Needed

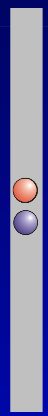
Need ~10^{18} stopped muons

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

- Rate too high for continuous beam: need bunched muon beam: 50×10^9 μ/s
- Need turn off detector for ~ $\tau_{\mu N}$ (~800 ns) while bad stuff (pions, electrons) is around
- Need < 10^{-9} interbunch contamination

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





about 50% of the muons stop in target

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

need to be sure it isn't a scattered electron or π capture electron

look for a delayed 105 MeV electron

Three Types of Backgrounds to $\mu^- N \rightarrow e^- N$

1. Stopped Muon Backgrounds

Muon decay in orbit (DIO):

$$\mu^- N_{A,Z} \rightarrow e^- \nu_\mu \nu_e N_{A,Z}$$

Note: $E_e < mc^2 - E_{NR} - E_b$ not $E_e < \frac{1}{2} mc^2$

- defeated by good energy resolution

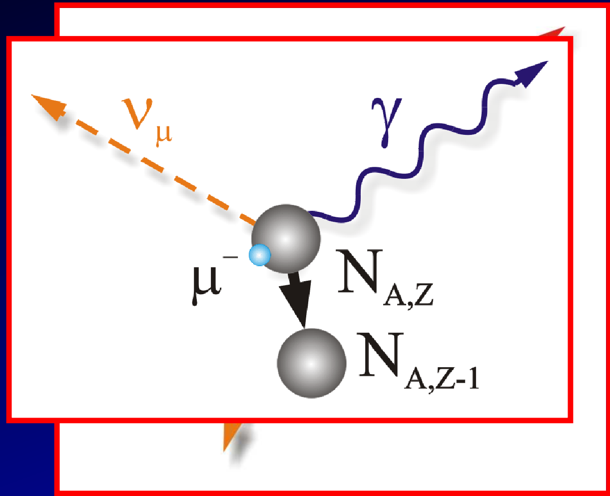
Radiative muon capture (RMC):

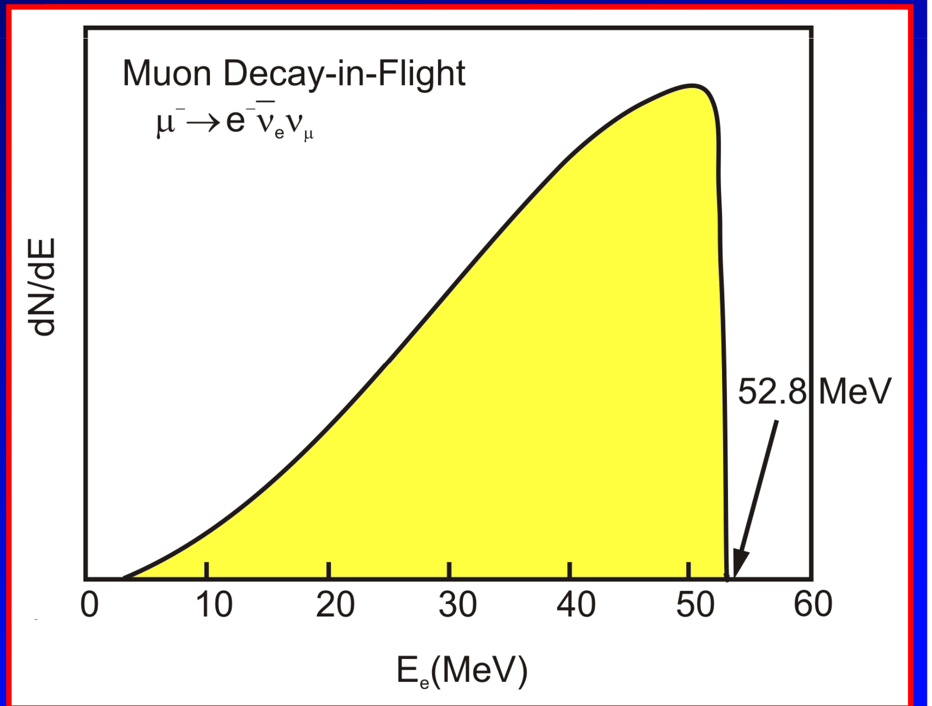
$$\mu^- N_{A,Z} \rightarrow \nu_\mu \gamma N_{A,Z-1},\ \gamma \rightarrow e^+ e$$

Note: $E_{\gamma max}(Al) = 102.5$ MeV

- restricts choice of stopping targets
- defeated by good energy resolution

$m_{Z-1} > m_Z$





Three Types of Backgrounds (continued)

2. Prompt Beam Related Backgrounds

Radiative pion capture (RPC):

$\pi^- N_{A,Z} \rightarrow \gamma N_{A,Z-1}$, $\gamma \rightarrow e^+e^-$

Note: 1.2% have E_γ > 105 MeV

Muon decay in flight:

$\mu^- \rightarrow e^- \nu\nu$

Note: since $E_e < m_\mu c^2/2$, p_μ > 77MeV/c

Beam electrons scattering in target

Pion decay in flight:

$\pi^- \rightarrow e^- \nu_e$

- *Defeated by 10^{-9} interbunch extinction!*

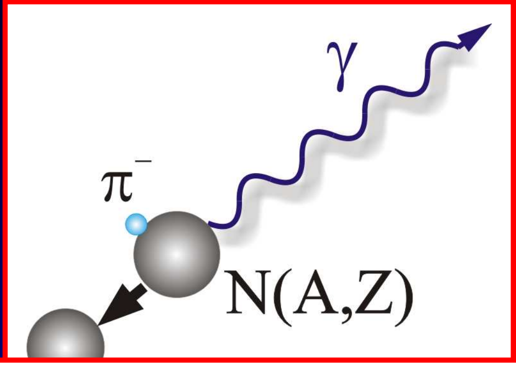
Antiprotons annihilating

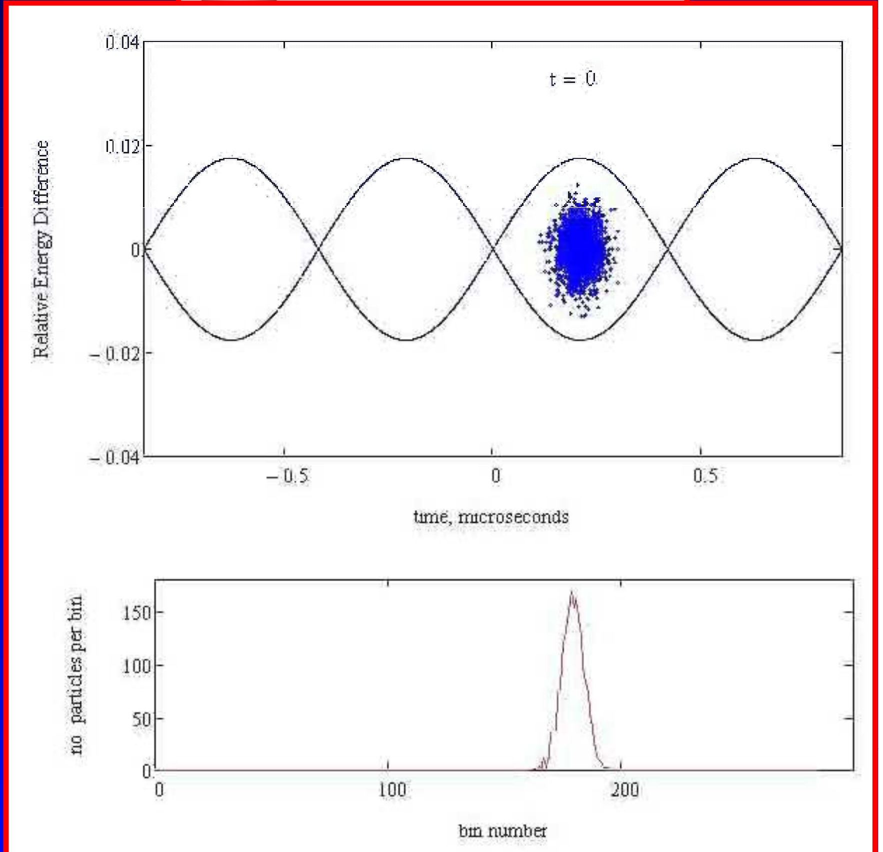
- *Defeated by thin absorber*

3. Time Dependent Backgrounds

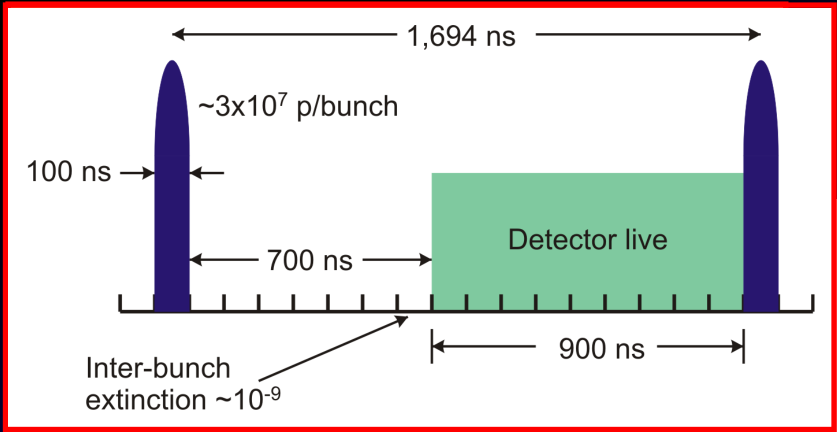
Cosmic Rays

- *Defeated by active+passive shielding*

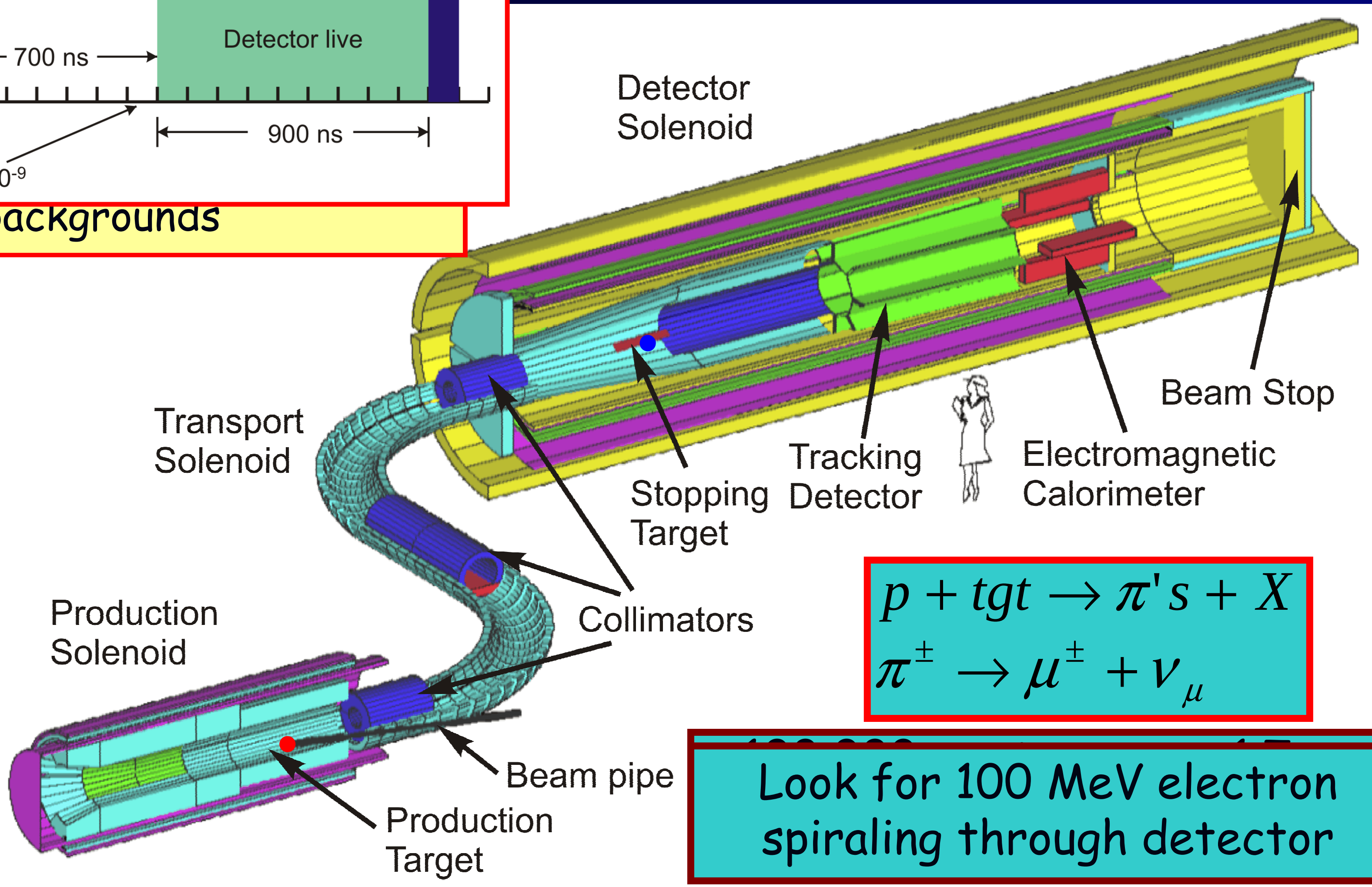




Mu2e: Looking for that Grain of Sand



prompt backgrounds



$$p + tgt \rightarrow \pi's + X$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

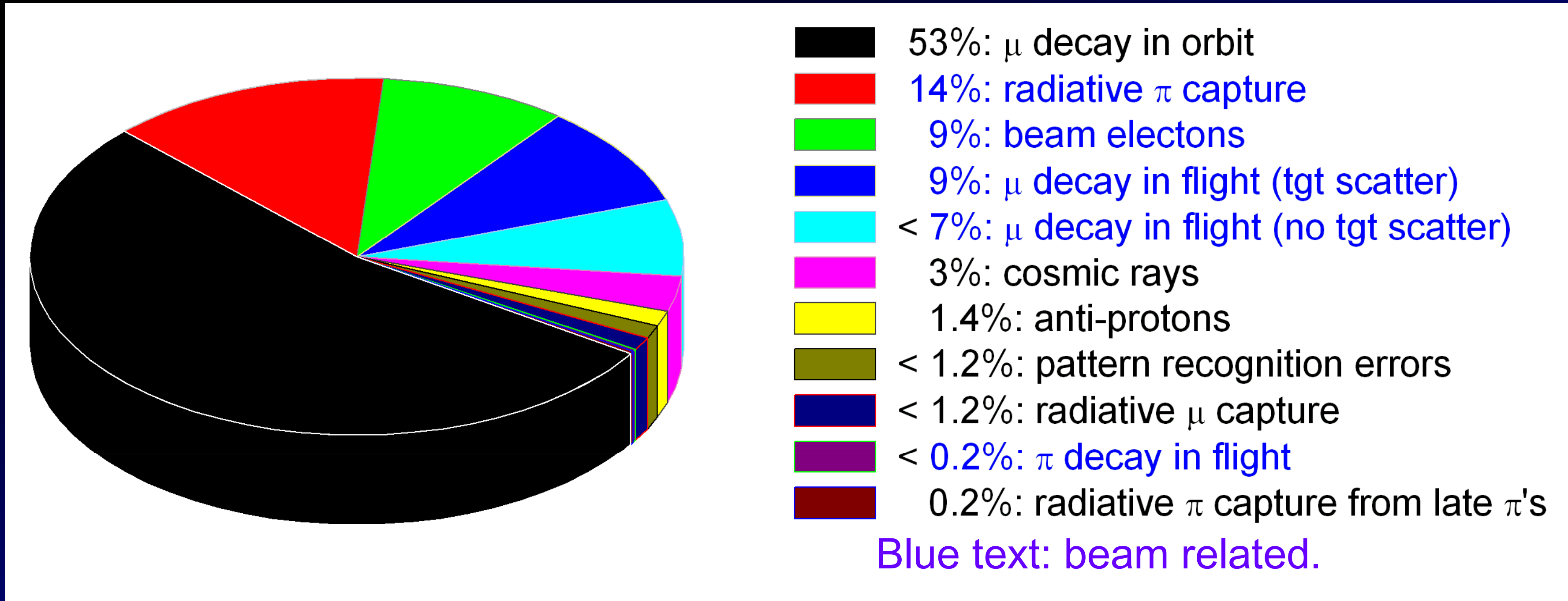
Look for 100 MeV electron spiraling through detector

What we Get (pre-Project X)

$$R_{\mu e} = \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \nu_\mu N^*)} = \frac{N_{\nu e} / N_s \times 1/\varepsilon_{\mu e}}{\Lambda_{\mu\nu} / \Lambda_{tot} (= 0.609)}$$

Proton flux	1.8×10^{13} p/s
Running time	2×10^{7} s
Total protons	3.6×10^{20} p
μ^- stops/incident proton	0.0025
μ^- capture probability	0.61
Time window fraction	0.49
Electron trigger efficiency	0.80
Reconstruction and selection efficiency	0.19
Sensitivity (90% CL)	6×10^{-17}
Detected events for $R_{\mu e} = 10^{-16}$	4

Background Fractions



Roughly half of background is interbunch contamination related

Total background per 3.6×10^{20} protons, 2×10^{7} s: 0.41 events

Signal for $R_{\mu e} = 10^{-16}$: 4 events

Mu2e Collaboration

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Currently:
65 scientists
17 institutions

Mu2e Status

1992	Solenoidal collection scheme fir … osal at Moscow Meson Factory
1997	MECO proposed for the AGS at
1998-2005	Intensive work on MECO techni … sted at $58M, detector at $27M
July 2005	RSVP cancelled for financial re
2006	MECO subgroup + Fermilab phy … nt experiment at Fermilab, keepin
June 2007	Mu2e EOI submitted to Fermil
October 2007	LOI submitted to Fermilab
May 2008	P5 "recommends pursuing the muon-to-electron conversion experiment, subject to approval by the Fermilab PAC, under all budget scenarios considered by the panel."
November 2008	Proposal to be submitted to Fermilab and approved
2011	Start construction
2015	Data taking begins

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.