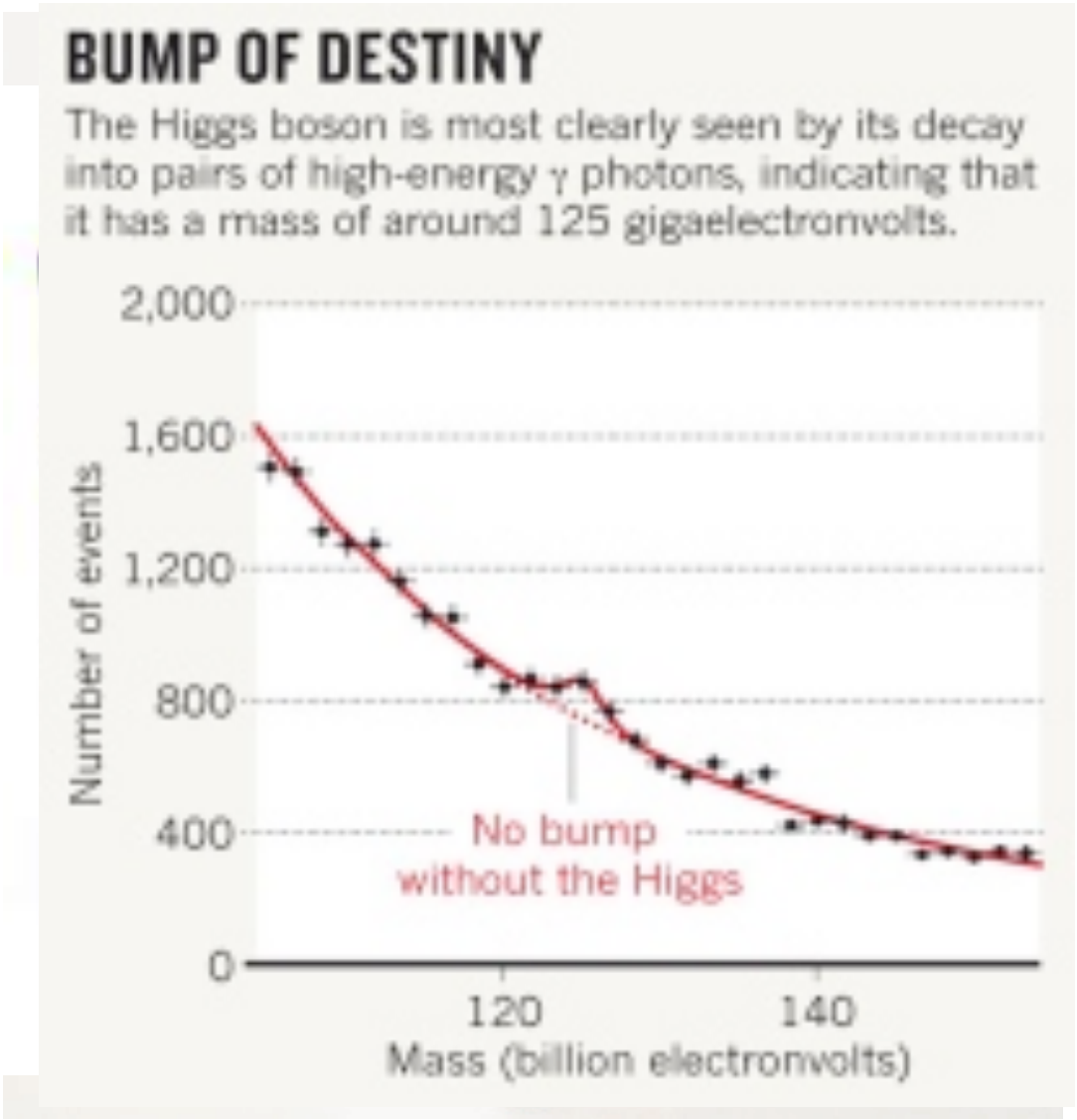
MUON PHYSICS AT NuFACT 2012 (WG4)

Opening Summary

RHB, G. Signorelli, N. Saito

Purpose: Solve this Puzzle

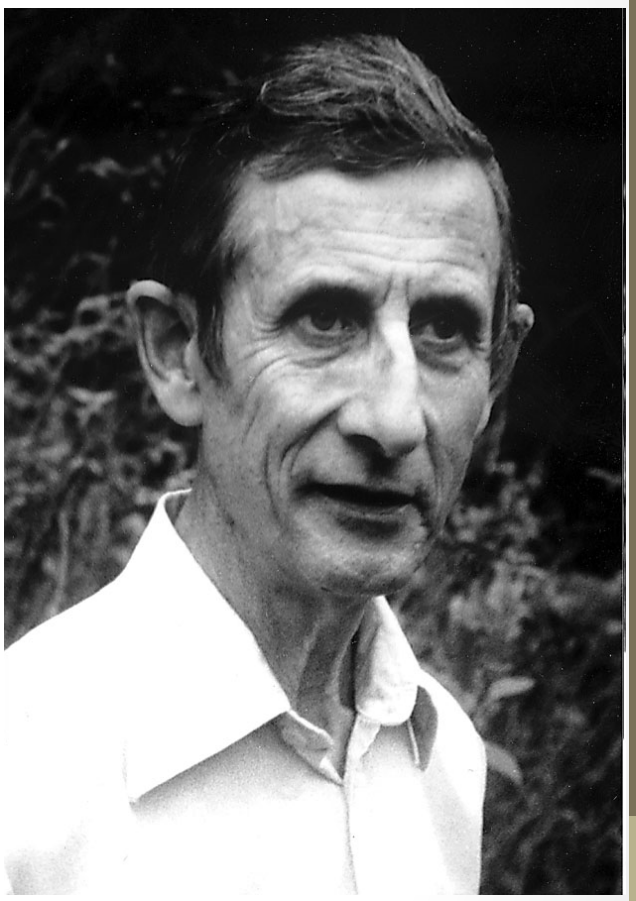


μ

Precision Experiments Are Important! (at least from a survey of Nobel Prizes)

"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



http://www.nybooks.com/articles/archives/2009/apr/09/leaping-into-the-grand-unknown/

Muons WG4: Goals

- **What upcoming measurements would benefit from the muon flux at a neutrino factory?**
  - cLFV and non-cLFV
    - $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu N \rightarrow eN$ conversion, g-2
  - Proton radius/Lamb shift
  - Muonium HFS

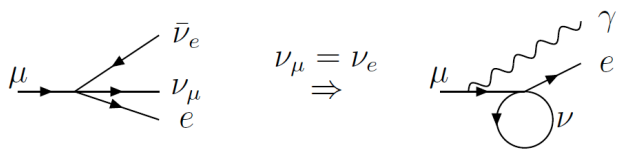
- **How good should the measurements be?**
  - "If you can measure something an order of magnitude better, you should just do it"
    – Jim Cronin
  - Most funding agencies and committees are not as smart as Cronin
    - Therefore we need theory guidance on what to try for!

    - Less flippantly, the large value of θ_{13} is telling us something. We know cLFV and neutrino oscillations are connected, and both are connected to kaons and taus and *g-2* and EDMs. So we will hear about those too
    - (Calibbi, Gardner, Semertzidis in a joint WG1/2 Session Thursday AM)

- **What technologies do we need and how are they related to NuFACT?**

Basic cLFV muon experiments

- Muon Decays: μ→eγ and : μ→3e
- Muon Conversion: μN→eN
  - Coherent process off nucleus, enhancement ∝ Z, monoenergetic electron
- These have been studied since the muon was identified, starting with Pontecorvo. One would expect μ→eγ to be of order 10^{-4} from this process where the neutrino goes around a loop



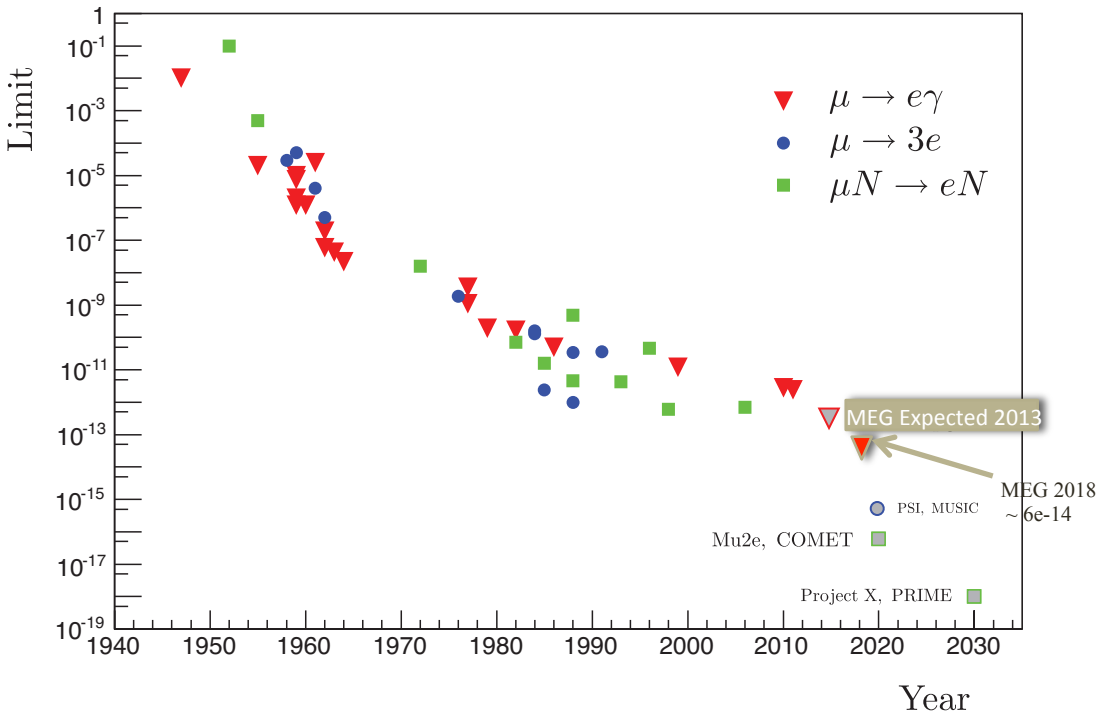
[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$. Feinberg, 1958

- This problem led directly to the 1962 Lederman/Schwartz/ Steinberger et al. two-neutrino experiment, so you can see cLFV and neutrinos are closely related

cLFV Experiments

- cLFV in the Muon System

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



10^4 improvement followed by additional X100 followed by…

Shameless Plug for *my* cLFV experiment

- Mu2e Gets CD-1!

Critical Decision 1, Approve Alternative Selection and Cost Range for the Muon to Electron Conversion Experiment (Mu2e) Project

Approval:

Based on the information presented above and at this review, Critical Decision-1, Approve Alternative Selection and Cost Range, is approved and authorization is provided to proceed to initial construction.

W. F. Brinkman
Director, Office of Science

7/11/12
Date

CD Process

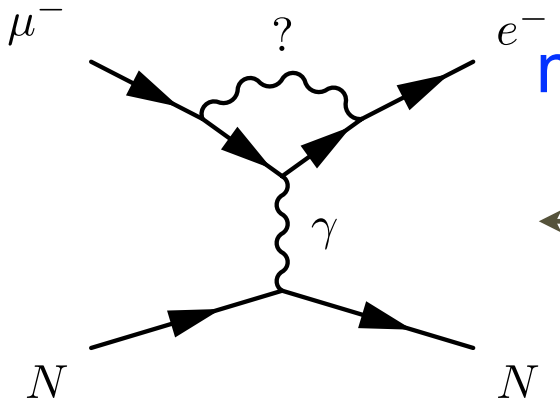
- With LBNE and g-2 to follow shortly

cLFV for Dummies

- Very generically, "loops" and contact-terms

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_{\mathrm{L}}F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

"Loops"



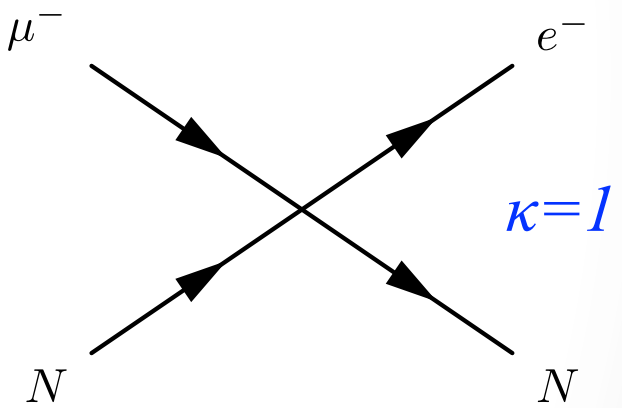
Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

mass scale Λ

κ

"Contact Terms"



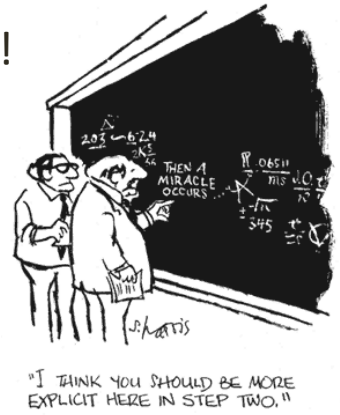
New Particles at High Mass Scale (leptoquarks, heavy Z,...)

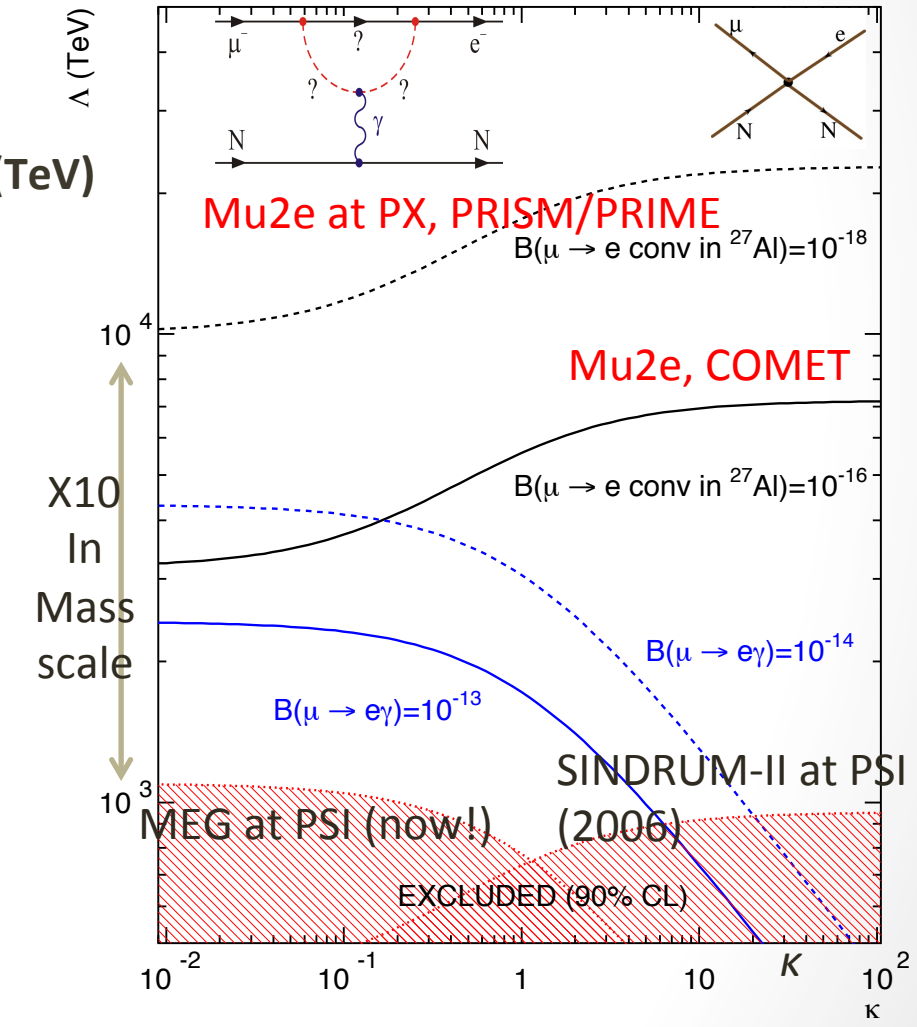
Does not produce μ→eγ

Why Do we Need More than One Experiment?

New version, A. de Gouvea

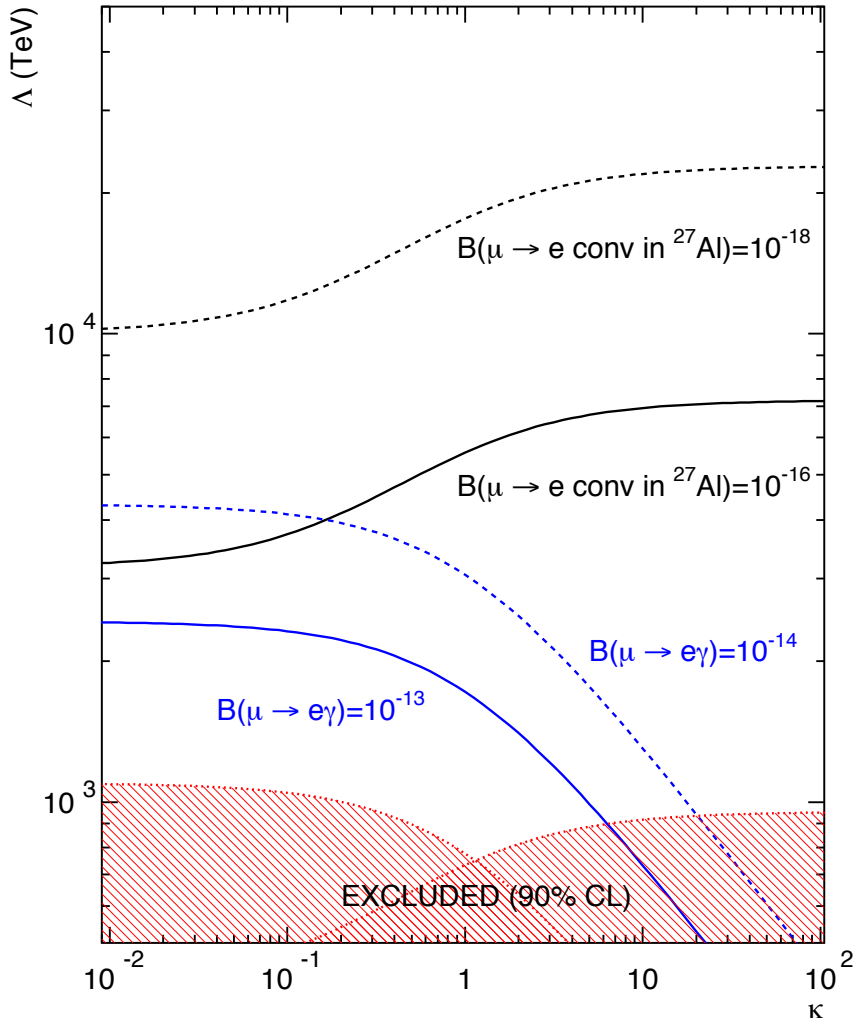
- Note μ→eγ and μe (Mu2e)conversion (and μ→3e) are complementary
- Suppose:
  - Mu2e/3e, but not μ→eγ
    - Contact! NP at a very high mass scale
  - Both
    - Loop!
  - Neither

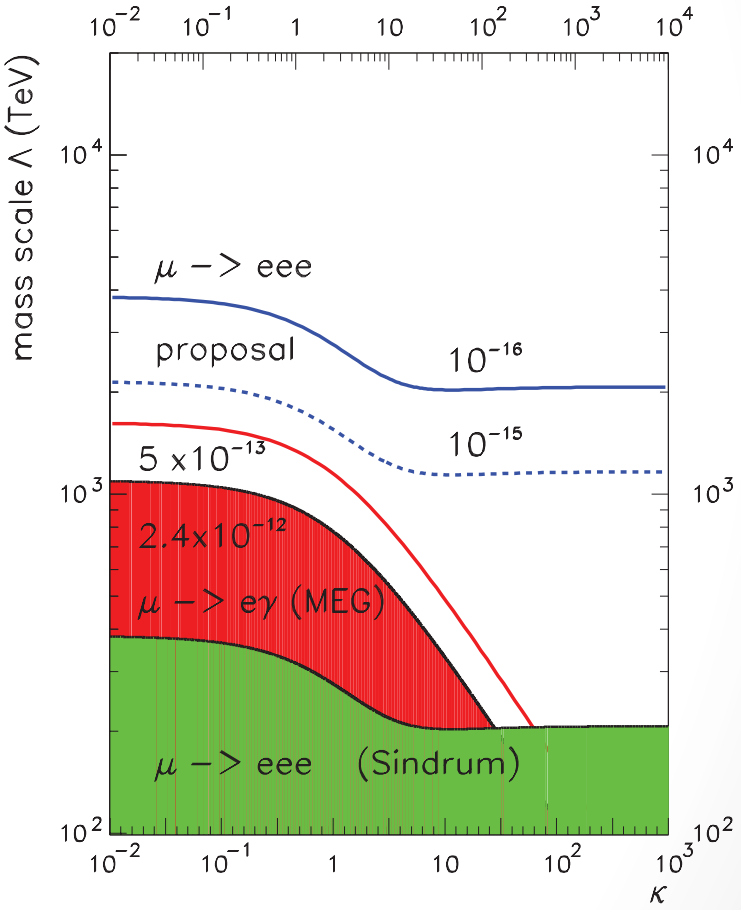




μ→ 3e, μ→ eγ and μe conversion

- All are probing >1000 TeV/c^2 mass scales





cLFV Talks

- *What is the State of the Art and How Can We Advance It?*
  - μ→eγ How far can MEG be advanced?
    - What are the right methods?
      - Convert the photon?
        - Better resolution, lower rate
      - Use EM Calorimetry
        - Worse resolution than tracking
  - μ→3e
  - PSI LOI: active pixel tracker surrounding a target. Very similar reach to Mu2e but sensitivity to physics different!

- Baracchini, Tuesday 2PM and DeJongh, Wed 5PM

- Wiedner, Tuesday 5PM

A novel experiment searching for the lepton flavour violating decay μ → eee

http://www.physi.uni-heidelberg.de/Forschung/he/mu3e/documents/LOI_Mu3e_PSI.pdf

cLFV Talks, continued

- μN→eN
  - Growing program in US and Japan:
    - Mu2e at FNAL
    - MUSIC/COMET
    - Intermediate Experiments: DeeMe and COMET Phase I
    - "Extinction" in muon-electron conversion: "bursts and nothing in-between" at 10^{-10} or better
      - Need to improve for future experiments: neutrino factory or FNAL Project X beams
  - For additional x100 beyond, require new muon beams with small momentum bite
  - To reduce pion contamination, technology of FFAGs or HCC or…
- *And in the tau system: competitive and getting more so: BELLE-II and SuperB*

- Hungerford, 2:35 Tuesday
- Sato, 3:30 Tuesday
- Aoki, Wed 3:00PM
- Kasper, 3:10 Tuesday
- Ankenbrandt, 9:00 AM Wed
- Luo, Blackmore, Pasternak Joint WG1/4 Wed AM
- Hayasaka, 2PM Wed

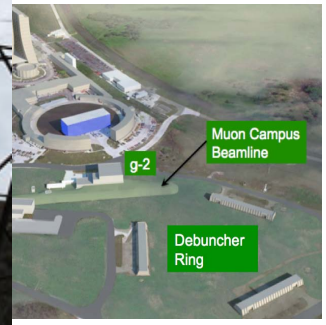
Future Facilities for Muon Physics

- Project X at FNAL: 1->3->8 GeV proton beams
  - Enough protons for cLFV program with multiple experiments running simultaneously with neutrinos and kaons
  - Also see Project X Summer Study: https://indico.fnal.gov/conferenceDisplay.py?confId=5276
- Tschirhart, Thursday 2:30 PM

- J-PARC Program
  - Many similar physics topics to Project X
  - Will hear about several experiments discussed throughout NuFACT
- Ikedo, Tuesday 5:30 PM

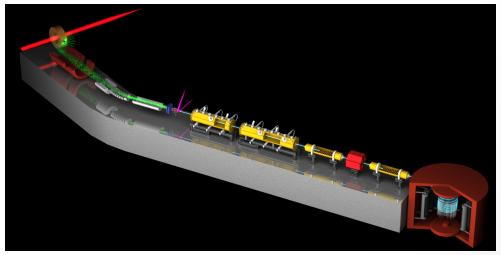
- PSI has upgrades planned as well, will hear about upgrades in mu->3e talk
- Wiedner, Tuesday 5PM

g-2: what's next?



- Progress
- Current e
  - Uncert of 0.46
  - Propos
    - An Stu
- Status and plans: run at FNAL in next 3 years (Miller, Wed 3:30)
  - What can be done next?
  - Run negatives (systematics and CPT?)
- Different, innovative method: cold g-2: (Tomono, wed 5:45)
  - Input: MuHFS: (Mibe, Wed 4:30)
  - Different systematics!

Surface muon beam for cold g-2



Next-Generation *Muon EDM*

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \qquad \vec{\mu}, \vec{d} \parallel \vec{\sigma}$$

	E	B	μ or *d*
P	-	+	+
C	-	-	-
T	+	-	-

$$\vec{d} = \eta \frac{q}{2mc} \vec{s} \qquad \vec{\mu} = g \frac{q}{2m} \vec{s}$$

$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2}$$

$$\vec{\omega}_{\alpha\eta} = -\frac{Qe}{m}\left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p}\right)^2\right)\frac{\vec{\beta} \times \vec{E}}{c}\right] - \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \beta \times \vec{B}\right]$$

- Assuming CPT, a non-zero *d* implies non-CKM CP violation
  - Huge physics payoff
- Current muon limit ~ 2 x 10^{-19}
- Need a new method ("frozen-spin")
- Choose radial E field to cancel all but η term, and spin will precess -> EDM to 10^{-24} e-cm

Gardner, Thurs 9:30 joint WG1

Proton Charge Radius

- Charge Radius of Proton Extracted from Muonic Hydrogen:
  - R. Pohl et al., Nature 466, 213 (2010)
- Radius 5σ from the measurement in regular hydrogen

	r^E_p (fm)	Error
Muonic Lamb Shift	0.84184	0.00067
Electron Lamb Shift	0.8768	0.0069
Electron scattering	0.879	~0.008

- Electrons agree, muons disagree
  - How good is the extraction from scattering measurement? Paz and Hill, http://arxiv.org/pdf/1008.4619.pdf
- New forces? (Hill, Tuesday 12:30 PM)
- Low energy muon beams in scattering experiments and/or muonic atoms, both natural territory for PX

Electron Lamb Shift: J. C. Bernauer et al. [A1 Collaboration], Phys. Rev. Lett.105, 242001(2010).

Scattering: P. J. Mohr, B.N. Taylor and D. B. Newell, Rev. Mod.Phys. 80, 633 (2008)

Other Physics

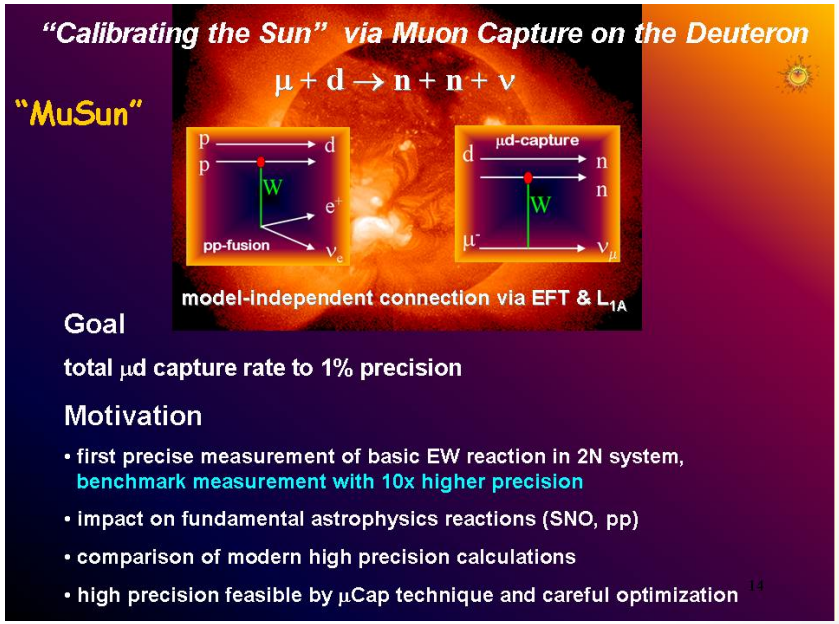
- MuSun: measure the rate

$$\mu^- + d \rightarrow \nu_\mu + n + n$$

to better than 1.5%, x10 better than existing

- Part of the MuLan, MuCap series at PSI

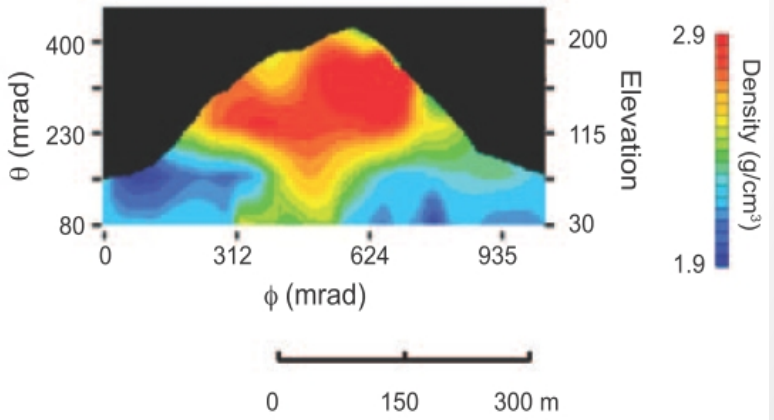
- Carey, 12:00 PM Tuesday



Other Physics

- Muon Tomography
- Looking for minerals: (Bryman, Tuesday 11:00AM)
- Looking inside volcanoes with muons (Miyamoto, Tuesday 11:30 AM)

Using your PhD
for more than running ntuples



Beams and Solenoids

- What is the status of cooling and how does the technology enable non-muon collider experiments?
  - PRISM/PRIME/HCCs/Other
- Would a next-generation muon-to-electron conversion experiment work with current technology?
  - Examine Mu2e design
  - Examine simulations of radiation damage to superconductors in Mu2e context
    - What can we learn, or not learn, from Mu2e studies?

- Berg, Roblin, Stratakis, Maloney, Friday AM (Joint WG3)

- Lamm, Friday 10 AM
- Pronskikh, Friday 10:30 AM (Joint WG3)

Summary

- Muon experiments can address some of the most interesting questions in our field;
- We need more intense muon beams of the sort that could be provided at a neutrino factory;
- There is much overlap in the technologies of neutrino factories, muon colliders, and experiments discussed at this workshop. Upcoming experiments are already helping to develop the technology;
- The worldwide muon program is gathering momentum and becoming stronger; at least the 1st and 2nd derivatives are positive!