Muon Experiments at PIP-II

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PIP-II Collaboration Meeting

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Disclaimer

- This is an overview and way too simplistic
- I will discuss this as an experimenter
- So therefore everything will not be even close to exactly right and all the definitions and boundaries are blurry.

Physics Goals

- What Experiments Do We Want To Do?
  - primarily charged lepton flavor violation (CLFV), muons changing into electrons without neutrino emission

Kyle has talked about Mu2e

$$\mu^- N \to e^- N \text{ and } \mu^- N \to e^+ N(Z-2)$$

$$\mu^+ \to e^+\gamma \text{ and } \mu^+ \to e^+ e^+ e^-$$

$$\mu^+ e^- \to \mu^- e^+$$

this comes "for free"

Outline

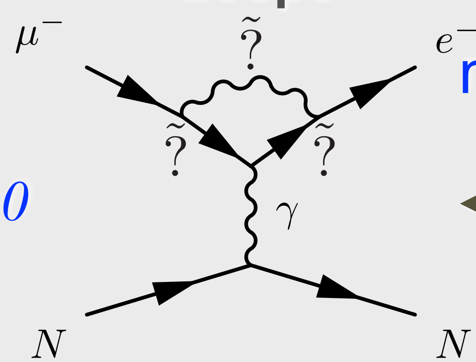
- Why more than muon-electron conversion?
  - compare and contrast to isolate source of new physics
- What would you need to do a significantly more powerful new search in a decade?
  - changing landscape. want to be first-class no matter what.

“Model-Independent” Lagrangian

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

“Loops”

$\kappa = 0$



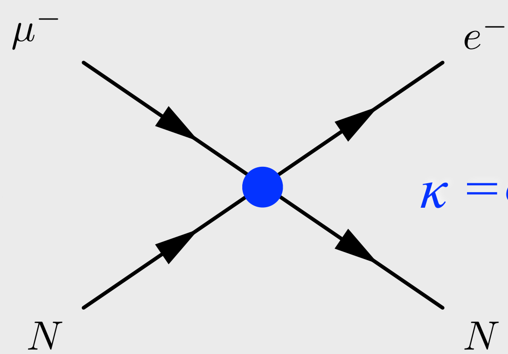
Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ
(just imagine the photon is real)

mass scale Λ

κ

“Contact Terms”



$\kappa = \infty$

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

Does not produce μ→eγ

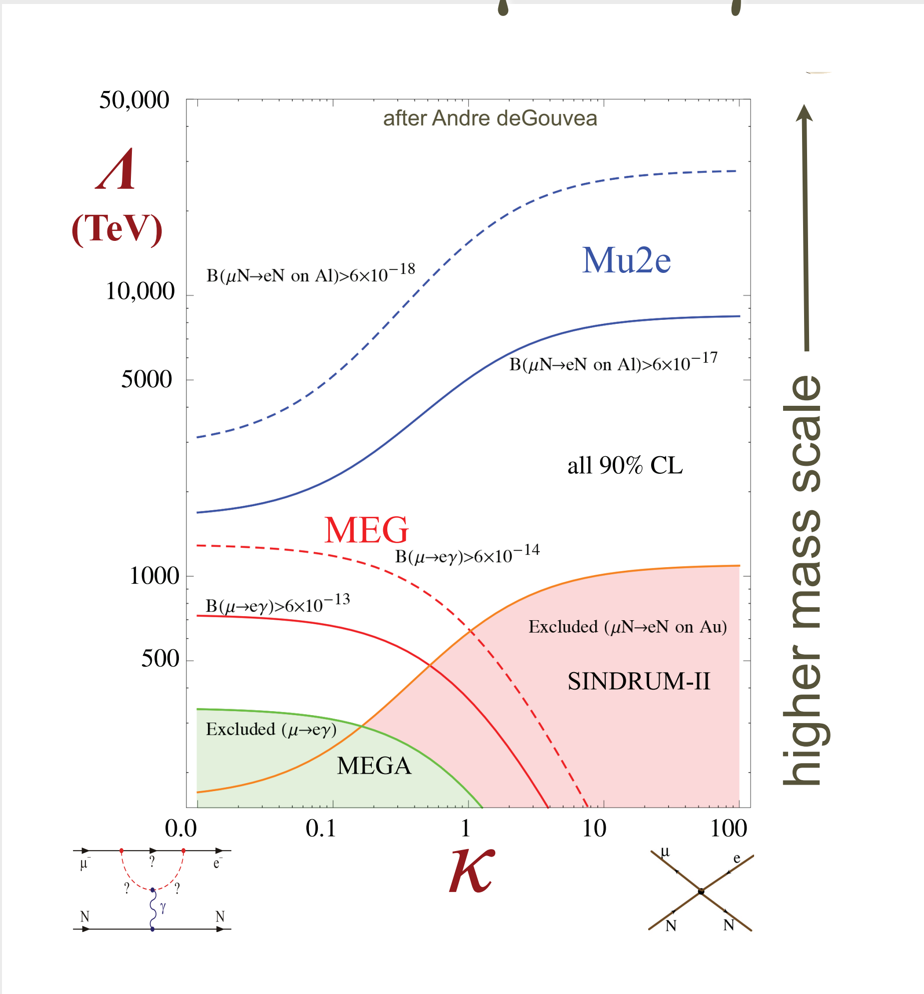
μe Conversion and μ⟶eγ

CLFV:

probes masses up to 10^4 TeV/c^2

next generations are discovery experiments

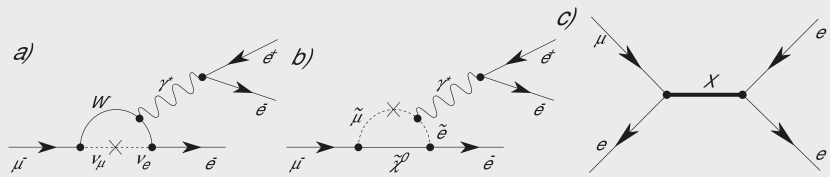
new beams can build rich program



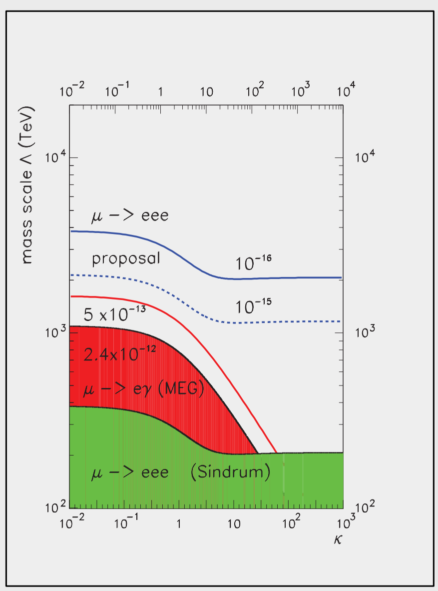
$\mu \rightarrow 3e$

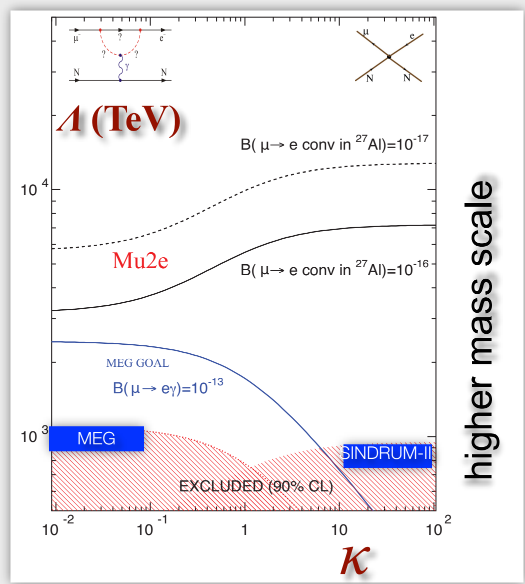
Hisano

$$L_{\text{eff}} = \frac{m_\mu}{\Lambda^2}\bar{e}(\sigma^{\mu\upsilon}F^{\mu\nu})\mu + \frac{1}{\Lambda_F^2}\bar{e}\Gamma_A e\,\bar{e}\Gamma_A\mu + \frac{1}{\Lambda_F'^2}\bar{q}\Gamma_A q\,\bar{e}\Gamma_A\mu$$



- "Sister" process to $\tau \rightarrow 3l$
- The meaning of κ is not the same since the underlying diagrams are different, but still indicative
- *reaching "ultimate" sensitivity is a combination of resolution and statistics; can't easily overpower backgrounds with cuts*

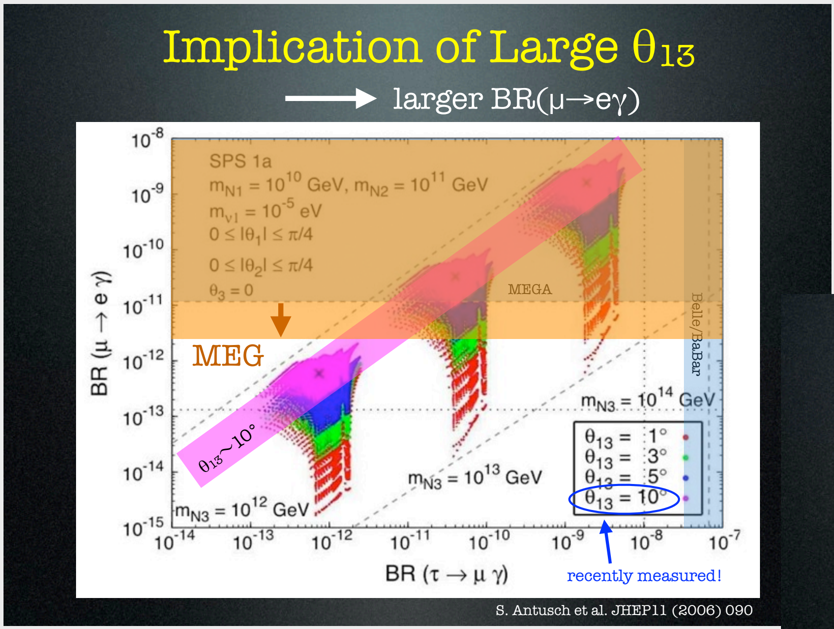


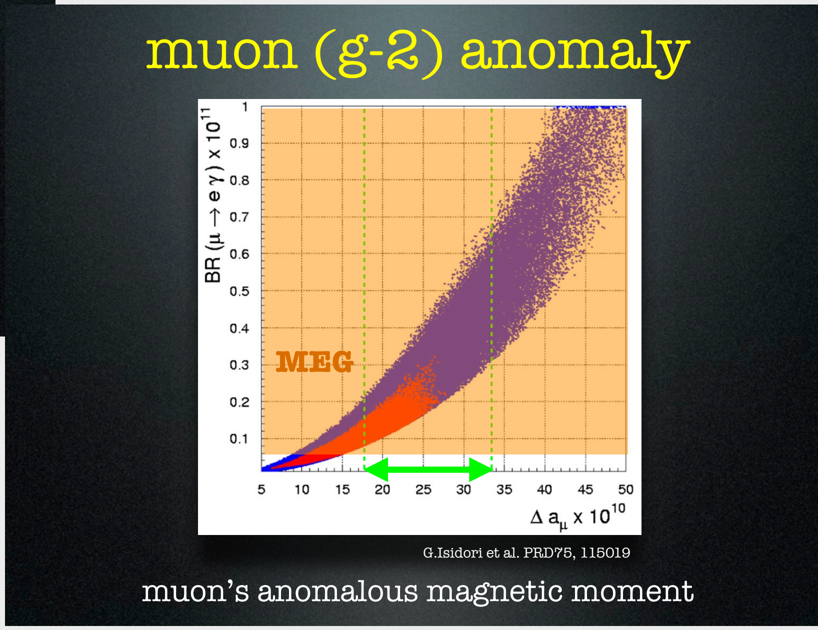


Specific Examples

Combining MEG at PSI

with $\tau \to \mu\gamma$





with BNL821 g-2

Surface Muon Beams

"Arizona Beam"

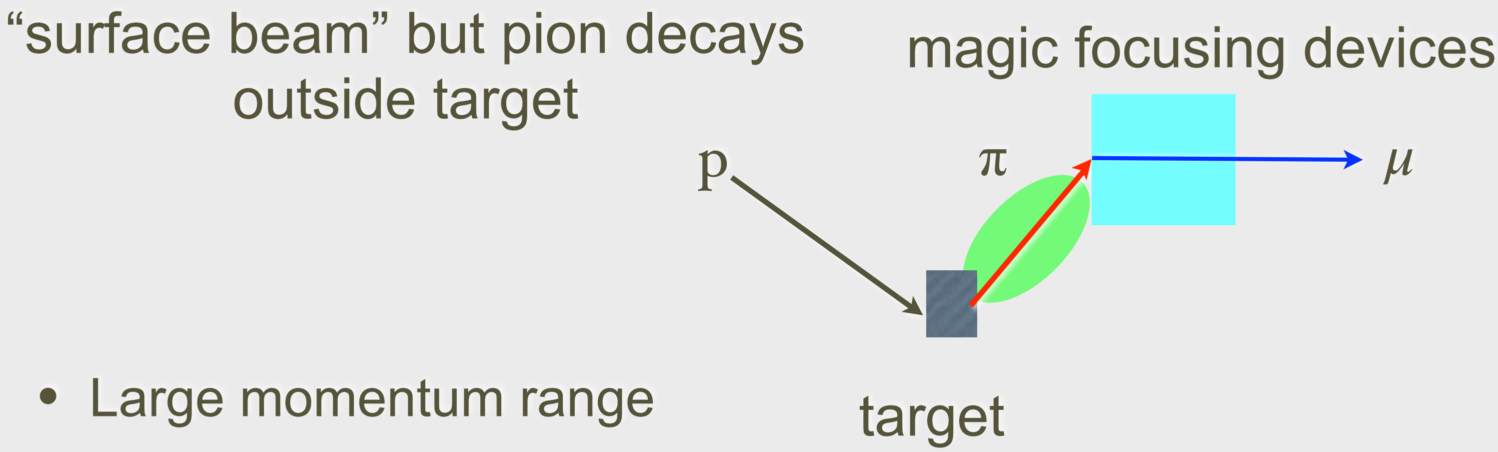
A. Pifer et al., NIM 135, 39.

$$\mathrm{p} \longrightarrow \pi \longrightarrow \mu$$

- Pions range out and decay close to the surface of a target and yield muons at 29.8 MeV/c (MEG may go slightly sub-surface; see below eqn.)
  - Source is very well defined
  - Polarization (pion stopped) near 100%
  - μ^{+} only since π^{-} would be captured on nuclei
    - positron contamination

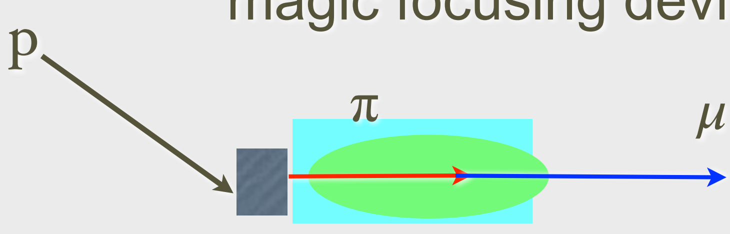
$$R_{\mu} \sim p^{3.5} \sqrt{\left(3.5 \frac{\Delta p}{p}\right)^{2} + \left(\Delta R_{\text{straggling}}\right)^{2}}$$

Cloud Muon Beams



- Large momentum range
- Source bigger than production target
- Contamination of both charges of pions and electrons
- Low Polarization

Decay Muon Beams



- Source much bigger than production target
- Polarization high; by using pion lifetime, contamination low
- Very flexible
  - neutrino horn beams
  - many deep-inelastic scattering experiments

"cloud beam" but select pion momentum

Experiments

- Reorder the experiments into beam type:
  - two stopped muon processes: *stopped→+*

$$\mu^+ \to e^+\gamma \text{ and } \mu^+ \to e^+e^+e^-$$

  - two captured muon processes in clouds *captured→-*

$$\mu^- N \to e^- N \text{ and } \mu^- N \to e^+ N(Z-2)$$

  - muonium-antimuonium oscillation and muonium HFS from cloud beam

$$\mu^+ e^- \to \mu^- e^+$$

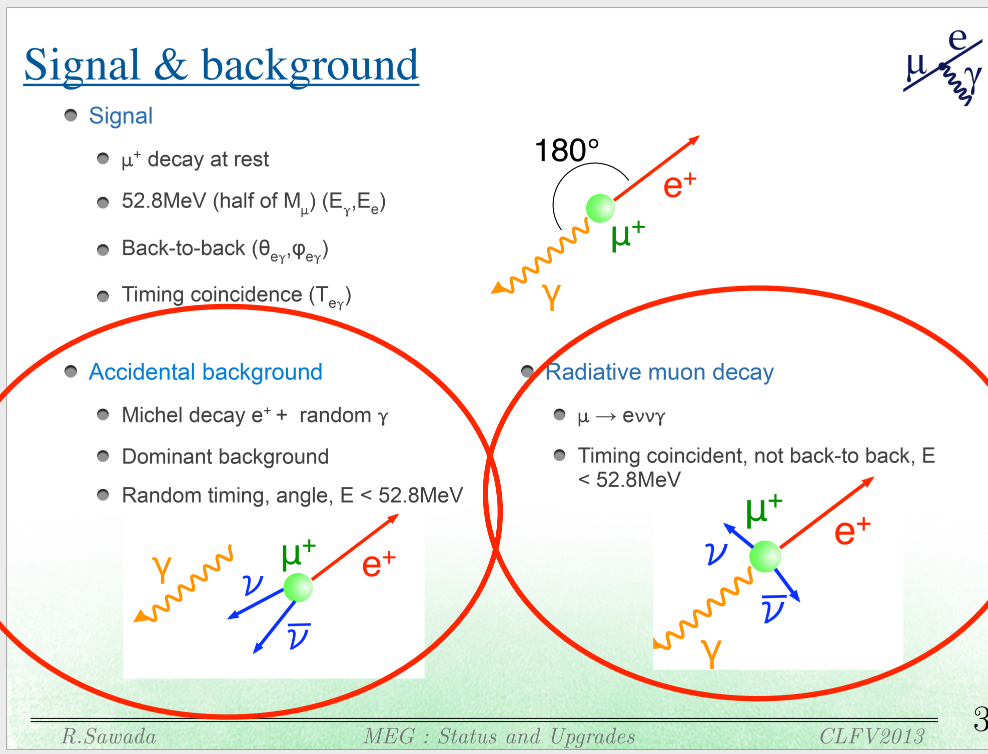
MEG: $\mu \rightarrow e\gamma$

- Measurement: < 5.7 x 10^{-13} @ 90%CL

J. Adam et al., arXiv:1303.0754

  - stopped muons at PSI

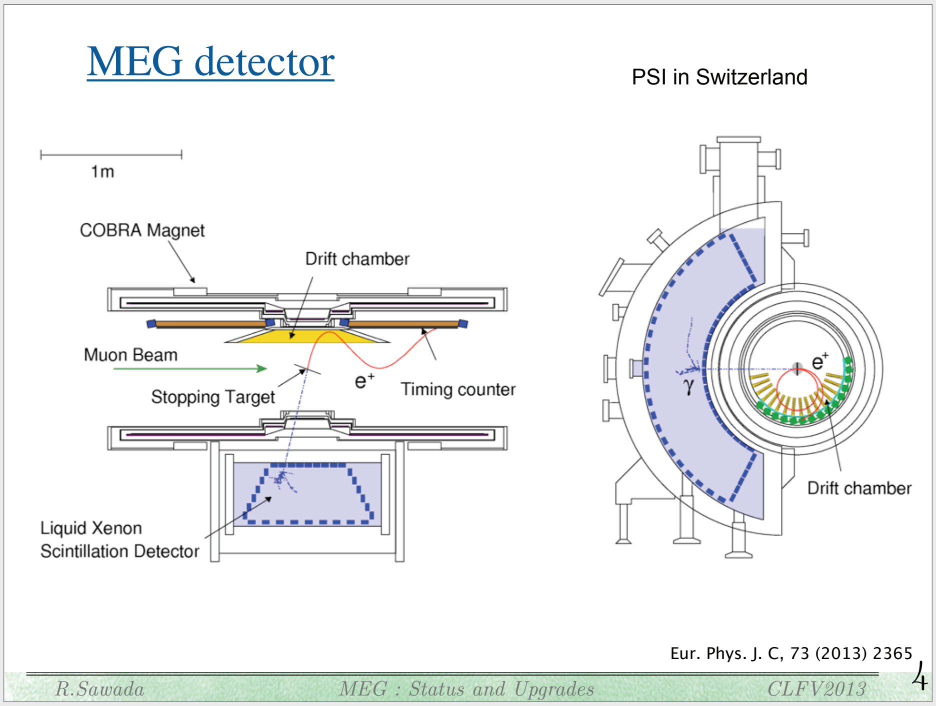
accidental, rate limiting



background, resolution limiting

MEG: $\mu \rightarrow e\gamma$ J. Adam et al., arXiv:1303.0754

- LXe on one side
- Tracker on the “other” (not 180 because positron curls first)



MEG and Upgrades

closely related experimentally to $\mu^+ \rightarrow e^+ e^+ e^-$

- MEG: $\mu^+ \rightarrow e^+ \gamma$

PSI: ~51 MHz , 300 psec wide bursts

  - need to stop muons and let them decay
  - signal is back-to-back photon and electron

why DC

why well-defined stop

$$\mathcal{B} \quad \propto \quad (\frac{R_\mu}{D})(\Delta t_{e\gamma}) \frac{\Delta E_e}{m_\mu/2} \left(\frac{\Delta E_\gamma}{15 m_\mu/2} \right)^2 \left(\frac{\Delta \theta_{e\gamma}}{2} \right)^2$$

  - R/D term is rate over duty cycle: want DC beam as constant as possible over macroscopic time: duty factor critical
  - $\Delta\theta_{e\gamma}$ is vertexing: surface muons, well-defined stop location

MEG Upgrade Plan

http://arxiv.org/pdf/1301.7225v2.pdf

1. Increasing the number of stopping muons on target;
2. Reducing the target thickness to minimize the material traversed by photons and positrons on their trajectories towards the detector;
3. Replacing the positron tracker, reducing its radiation length and improving its granularity and resolutions;
4. Improving the positron tracking and timing integration, by measuring the e+ trajectory to the TC interface; *(scintillation timing counter)*
5. Improving the timing counter granularity for better timing and reconstruction;
6. Extending the gamma ray detector acceptance;
7. Improving the gamma ray energy, position and timing resolution for shallow events *(conversion near entrance)*
8. Integrating splitter, trigger and DAQ while maintaining a high bandwidth.

What Do They Have Now?

should regard this as a challenge

A. The MEG beam line and muon target

A schematic of the MEG beam line and the $\pi E5$ channel is show in Fig. 11. Driven by the world's most intense DC proton machines at the Paul Scherrer Institut's high-intensity proton accelerator complex HIPA, it constitutes the intensity frontier in continuous muon beams around the world (c.f. Table II) and as such, is capable of delivering more than $10^8\ \mu^+/s$ at 28 MeV$/c$ to the MEG experiment. The surface muon beam has distinct advantages over a conventional 2-step pion decay-channel.

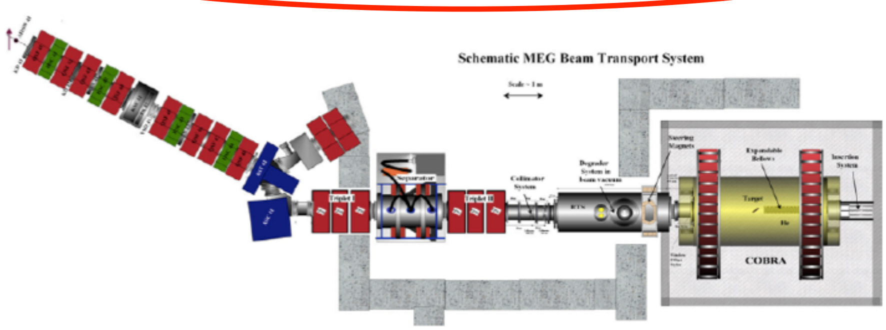


FIG. 11: (Left-part) shows the $\pi E5$ channel, connecting the production target E to the $\pi E5$ area. The MEG beam line starts from the extraction element Triplet I exiting the wall, followed by a Wien-filter, Triplet II and a collimator system, used to eliminate the beam contamination. The final range adjustment and focusing is performed by a superconducting solenoid BTS, before the muons are stopped in an ultra-thin target placed at the centre of the COBRA positron spectrometer.

What Would We do Next?

- How Do We Progress?
  - approved MEG upgrade is x10 from existing: beyond that?
- This is pure speculation and my personal opinion:
  - convert the photon and use tracking
  - resolution on electrons from tracking far better than from calorimetry
- But you lose a lot of rate, since converter must be thin or experiment will suffer from multiple scattering

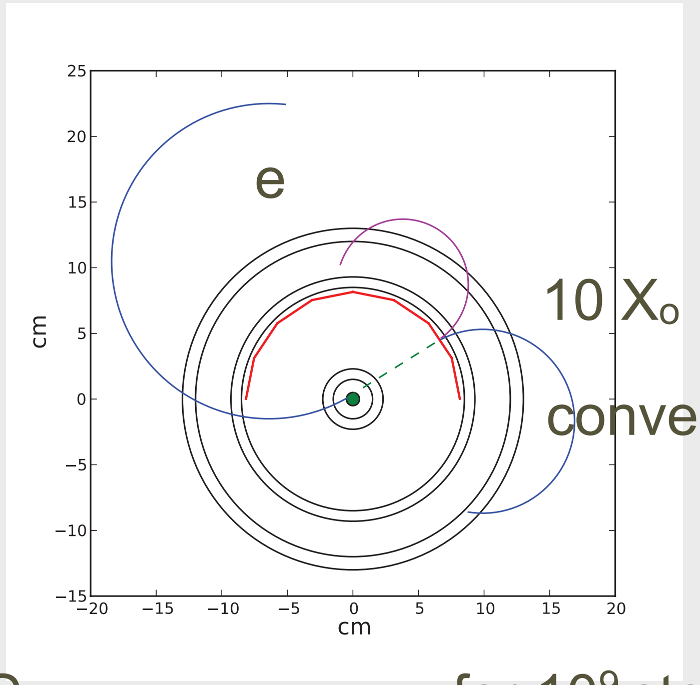
Rough Guesses

- 10^9 stopped muons/sec
- surface or sub-surface positive muon beam
  - recall $R \sim p^{3.5}$ so small drop in momentum is big change in range, helps with constraining vertex
- as continuous as possible (10-20 nsec rep rate probably fine)
- proton energy? depends on complex, but stopped beam is needed
- duty factor as high as feasible

Thoughts At Snowmass

- Conversion over π in azimuth

1311.5278



MEG:
3.6 x 10^{14} stopped muons,
5.7x 10^{-13}; upgrade to 6 x 10^{-14}

for 10^{9} stopped muons/sec,
3 DAQ years,
~1.6 x 10^{-14}

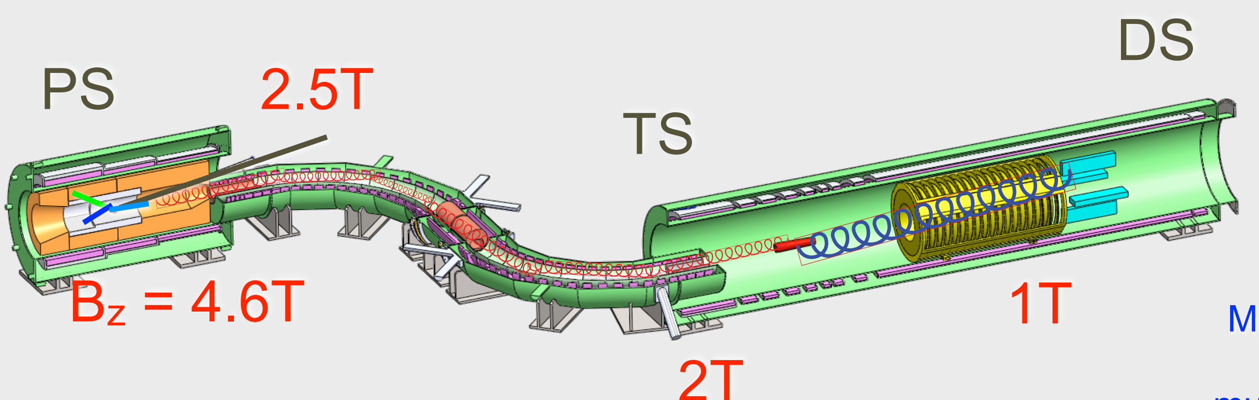
Two Takeaways

- Duty Factor (qualitative)
  - recall accidental background scales as 1/D
  - run times increases with D
  - so experiment gets more difficult as $1/D^2$
- Machine Energy
  - what's important is stopped muons
  - lower energy beams that can be stopped in small range are better

$$R_\mu \sim p^{3.5}\sqrt{\left(3.5\frac{\Delta p}{p}\right)^2+\left(\Delta R_{\text{straggling}}\right)^2}$$

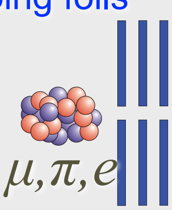
Mu2e Muon Beam: Three Solenoids and Gradient

4.6T ⟶ B-field gradient ⟶ 1T



- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

Muon Momentum ~ 50 MeV/c: muons range out in stopping foils



To Pulse or Not To Pulse?

- Pulses:
  - width of pulse
  - time between pulses
  - shape of pulse
  - “extinction”: suppress beam between pulses
- In general (but NOT a fine line)
  - stopped muon experiments want as DC a beam as possible to keep instantaneous rates low
  - capture muon experiments want varying pulse width and separation depending on lifetime in capture atom

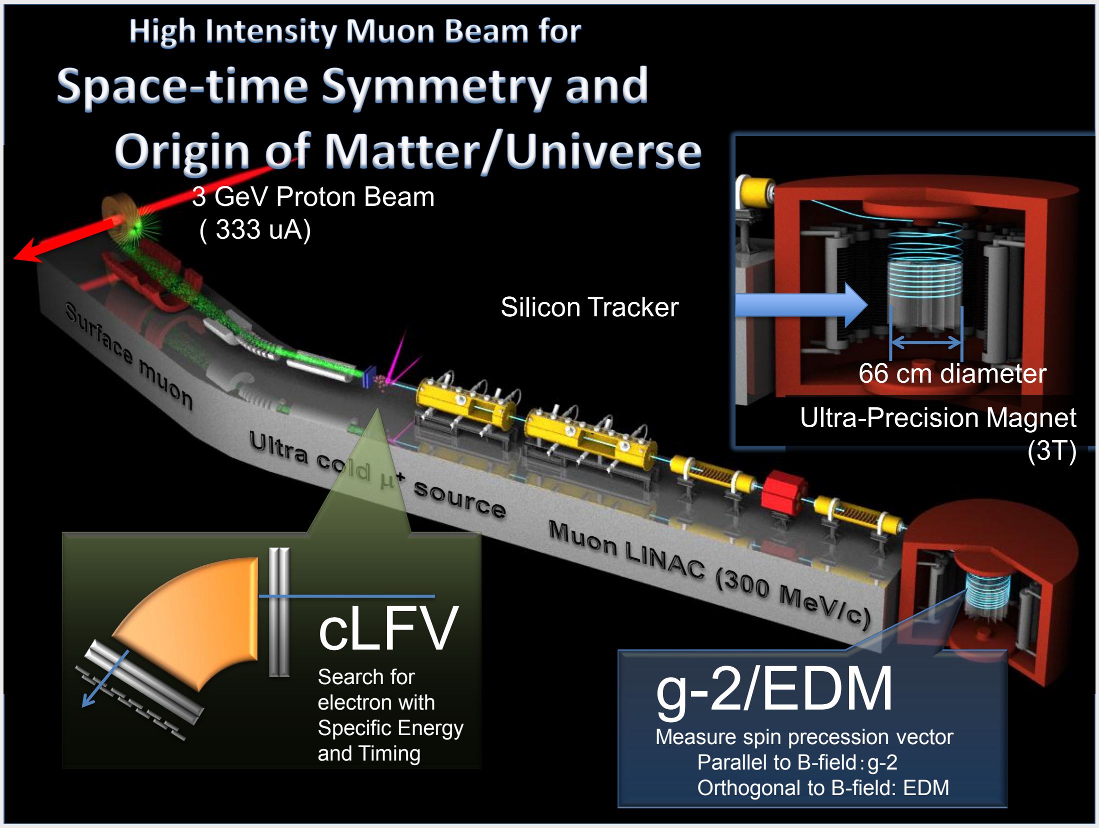
What Exists?

http://arxiv.org/pdf/1301.7225v2.pdf

Laboratory / Beam line	Energy / Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	″	$4 \cdot 10^8$	
πE 5	″	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10}(\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	″	$3 \cdot 10^7$	
MUSE U-line	″		$4 \cdot 10^8(\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11}(\mu^-)$ (2019/20)
PRIME /PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12}(\mu^-)$ (> 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10}(\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12}(\mu^-)$ (> 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	″	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	″	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8(\mu^+)$ (2012) means> 10^{11} per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

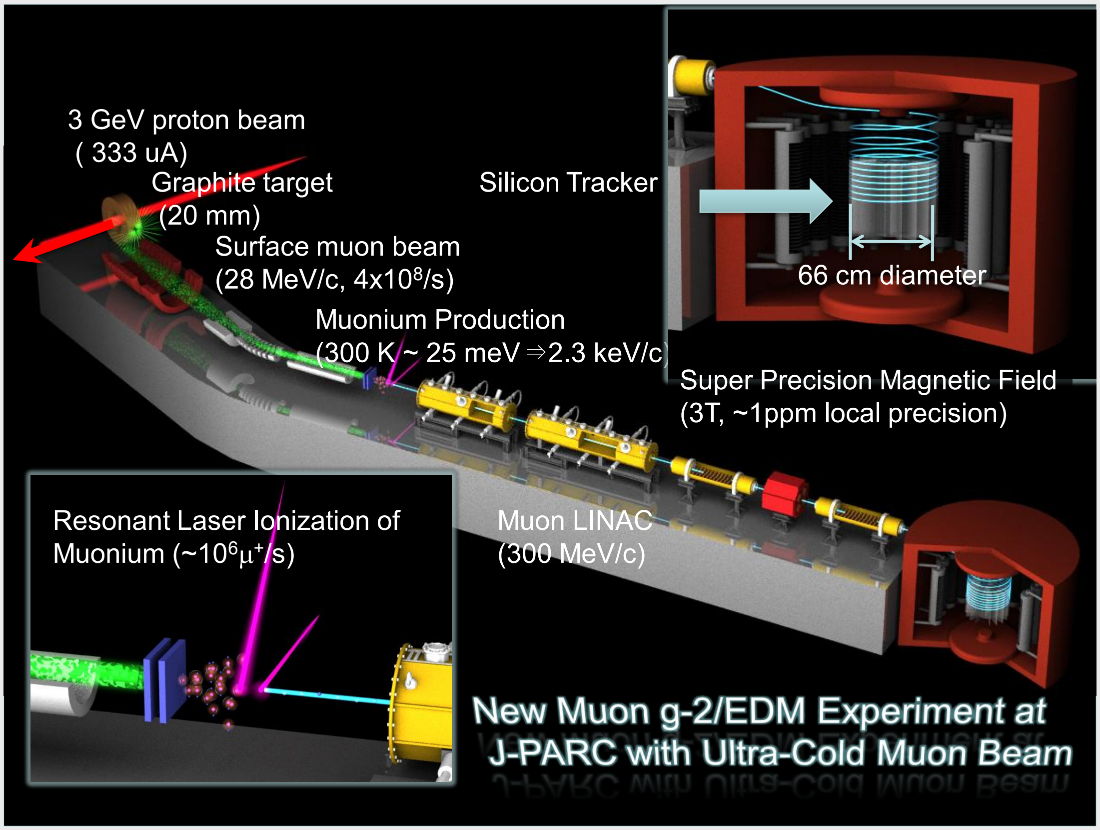
Japanese Plans

- different g-2 technique
  - “cold g-2”, not magic momentum
- CLFV: DeeMe, separate from COMET and x100 less sensitive
- and EDMs



Status: Much to Work On!

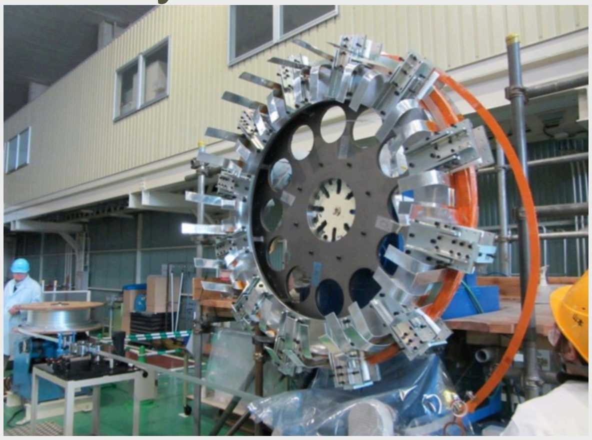
- yield of muonium too low to be useful; precise numbers hard to get
- surface muon rate way too low for competitive next-gen expt in CLFV



U.S losing in pretty picture department

Mu2e: Status

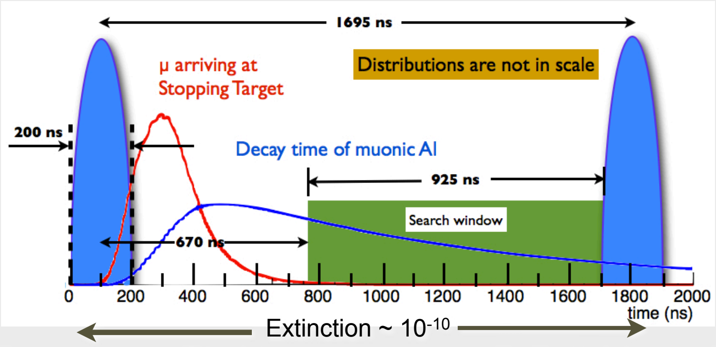
- US Mu2e at CD1 planning for CD2 this year
- Data ~2020
- See Knoepfel talks



Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_μ^{Al} , pulse separation ≈ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7μsec , ~x2 τ_μ^{Al}
- Extinction between pulses < 10^{-10} needed

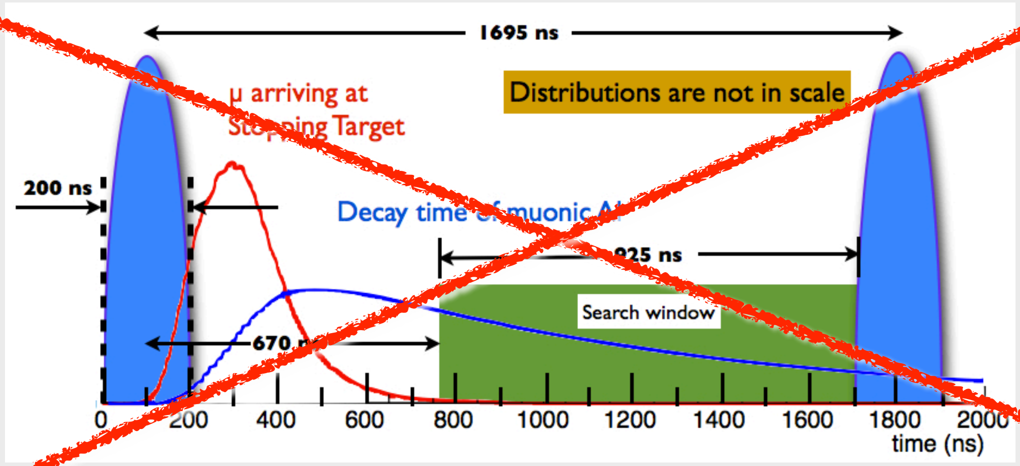
  = # protons out of pulse/# protons in pulse



- 10^{-10} based on simulation of prompt backgrounds and beamline

What Has to Change?

- If we see a signal, need to go to higher *Z*
- Lifetime of the captured muon decreases with higher *Z*
- For Au, lifetime = 72.6 nsec: *inside beam pulse*



Beyond Mu2e-II?

- You saw from Knoepfel that backgrounds are starting to be a problem for x10 better
- Can’t have pbars; radiative pion capture within pulse; decay-in-orbit becoming significant; cosmic rays growing with running time
- technique hard to push on limits past Mu2e-II
  - if signal, need 5% measurement to split Al/Ti
  - but going to higher Z is problematic

Different Muon Beams

http://www.sciencedirect.com/science/article/pii/S0920563211005330

- Would like to let all pions decay and then extract muons: no background, no extinction...
- Would be even better if muons nearly monochromatic: tightly controlled stopping location
  - PRISM/PRIME idea at J-PARC
    - FFAG kicker not on mass shell yet
  - Other ideas?
    - need some generic muon storage ring.

PRISM=Phase Rotated Intense Slow Muon source

http://iopscience.iop.org/1742-6596/408/1/012080/pdf/1742-6596_408_1_012080.pdf

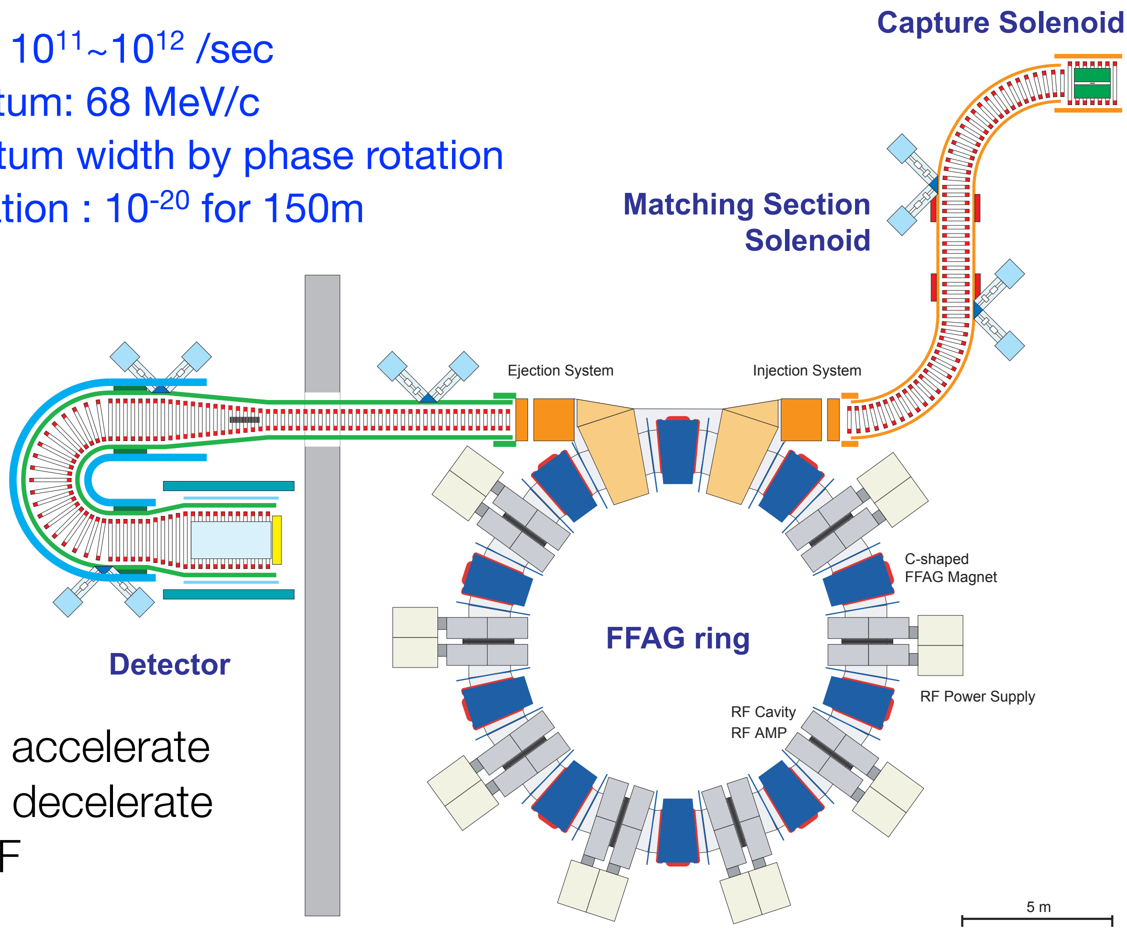
PRISM

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m

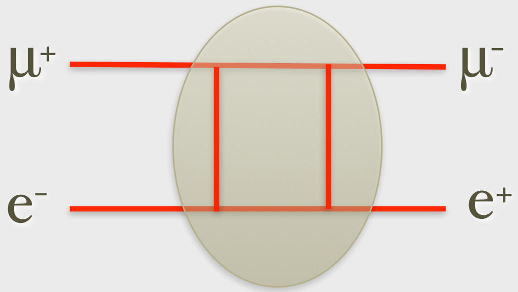
Table 1
Accelerator Parameters of the PRISM system.

Proton Beam	
Beam power	0.75 - 2 MW
Beam Kinetic Energy	2-8 GeV
Bunch length at the target	15 ns total
Repetition rate	1 KHz
Target & π/μ transport	
Target Type	Solid
Capture Elements	Solenoid 4-10 T
Transport System	solenoidal channel & FFAG transport line
Beam Polarity	Negative
PRISM ring	
Machine type	FFAG
Momentum Acceptance	±20 %
Reference muon momentum	40-50 MeV/c
Acceptance (H/V)	(3.8/0.57) πcm rad
Harmonic number	1
RF Voltage per turn	5.5 MV
RF frequency	3-6 MHz
Injection/extraction type	single turn
Extraction Kicker Rise Time	50-60 ns
Repetition Rate	1 KHz
Initial momentum spread	±20 %
Final momentum spread	±2%
No. of turns	6
Synchrotron oscillations	$\frac{1}{4}$ or $\frac{3}{4}$



Phase rotation = accelerate slow muons and decelerate fast muons by RF

Muonium/AntiMuonium



V-A new physics: coupling

$$G_{\mathrm{Mu}\overline{\mathrm{Mu}}}$$

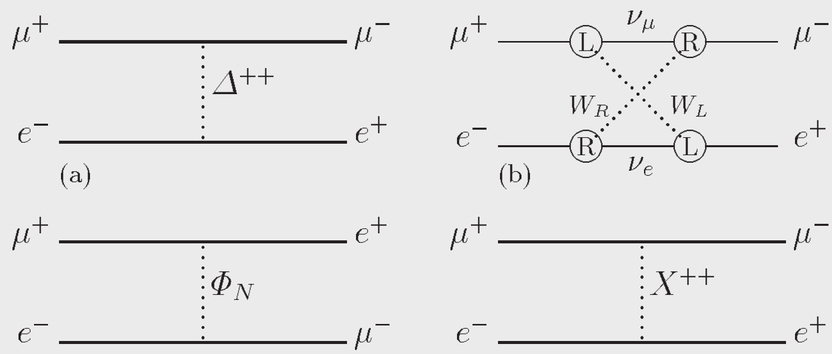
- World's best limit from PSI : (Willmann, L., Jungmann, K. et al.(1999), Phys. Rev. Lett. 82, 49)

$$\Delta L = 2$$

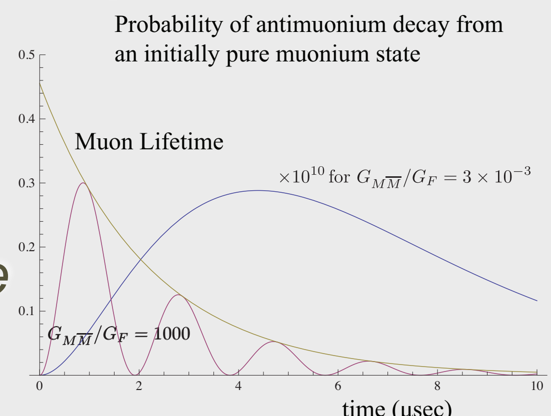
$$\mathrm{G}_{\mathrm{Mu}\overline{\mathrm{Mu}}} < 3 \times 10^{-3} \mathrm{G}_{\mathrm{F}} \text{ (Probability of spon. transition } < 8.2 \times 10^{-11})$$

- Wide variety of Beyond Standard Model Physics
- Could be improved x100 with better resolution and pulsed beam, so ~ $10^{-5} G_F$

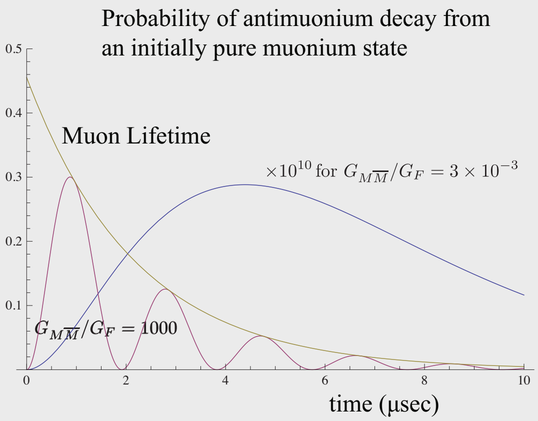
Muonium-Antimuonium



- Number of models
  - doubly charged Higgs, heavy Majorana neutrinos, ...
  - oscillates like $K^0 - \bar{K}^0$
  - *but damped by muon lifetime*



Time-Behavior



- Prepare muonium
- Look for positrons vs. time
  - the positron in antimuonium left behind after negative muon decay at “1s” energy of 13.5 eV
- But there’s a muon decay background:
  - $\mu^- \to e^+ e^- e^+ \nu_\mu \bar{\nu}_e$
  - positron has low KE, electron detected

So Pulse Beam to Suppress Muon Decay

- Wait enough muon lifetimes to suppress decays
- Want pulses (somewhat arbitrary) five muon lifetimes apart
- then the rest is the detector resolution
- should be able to do x100 better(from discussions with people who did last generation)
- muonium yield requirement not as stringent as cold g-2, should be manageable

Summary

- One accelerator? Multiple Accelerators?
  - that's for you to decide
- Sociological Comment: in neutrino world, get a big advantage from multiple neutrino experiments at one site; similar constructive interference between g-2 and Mu2e
  - grad student/post-doc pipeline
  - easier to build a program
  - well-demonstrated at PSI

Conclusions: Beam Requirements

- Wide variety of beams required
  - pulse rates, muon energy, etc. vary
- Flexibility, Power, and High Duty Factor are needed

Physics Process	Continuous/Pulsed	Capture /Stopped	$\sim$ # Muons	Muon KE
$\mu \to 3e$	continuous	stopped	$\mathcal{O}(10^{18})$	surface
$\mu \to e\gamma$	continuous	stopped	$\mathcal{O}(10^{18})$	surface
$\mu^- N \to e^- N$	pulsed	capture	$\mathcal{O}(10^{23})$	≤ 50 MeV
$\mu^- N \to e^+ N(A, Z-2)$	pulsed	capture	$\mathcal{O}(10^{21})$	≤ 50 MeV
$\mu^+ e^- \to \mu^- e^+$	pulsed	stopped	$\mathcal{O}(10^{15})$	surface

these are very rough numbers