Muon Physics with Project X: Experiment

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November 8, 2010

What can we do with lots of muons from Project X?

- Muon to electron conversion
- $\mu \rightarrow 3e$, $\mu \rightarrow e\gamma$
- Muon EDM
- $\mu^+e^- \rightarrow \mu^-e^+$ (muonium-antimuonium conversion)
- Muon Lifetime

Current and Proposed Limits on CLFV Muon Processes

mode	**Current Limit**	**Proposed Limit in Current or Planned Experiment**	**Project X Limit**
$\mu\rightarrow e\gamma$	$1.2x10^{-11}$	10^{-13}	10^{-15}
$\mu\rightarrow eee$	$1.0x10^{-12}$	---	10^{-16}
$\mu^{+}e^{-}\rightarrow\mu^{-}e^{+}$	$8.3x10^{-11}$	---	$5x10^{-15}$
$\mu^{-}\mathrm{Au}\rightarrow e^{-}\mathrm{Au}$	$7x10^{-13}$	$6x10^{-17}$	$3 \text{ x } 10^{-19}$

μ to e Conversion

A muon converts to electron in the presence of a nucleus, with no neutrinos being produced

$$\underset{\substack{\uparrow \\ \ell_e = 0 \\ \ell_\mu = +1}}{\mu^-} + A(Z,N) \rightarrow \underset{\substack{\uparrow \\ \ell_e = +1 \\ \ell_\mu = 0}}{e^-} + A(Z,N)$$

The muon are in atomic 1S orbits around the nucleus- this conserves E and p and also allows for exchanges of heavy new particles in the interaction

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

- Charged Lepton Flavor Violation (CLFV)

Muon to Electron Conversion

Current limits: $R_{\mu e} = \dfrac{\mu^- Au \rightarrow e^- Au}{\mu^- Au \rightarrow \text{capture}} < 7\text{x}10^{-13}$ (SINDRUM II)

Also: $R_{\mu e} = \dfrac{\mu^- Ti \rightarrow e^- Ti}{\mu^- Ti \rightarrow \text{capture}} < 4.3\text{x}10^{-12}$ (SINDRUM II)

$R_{\mu e} = \dfrac{\mu^- Ti \rightarrow e^- Ti}{\mu^- Ti \rightarrow \text{capture}} < 4.6\text{x}10^{-12}$ (TRIUMF)

New Mu2e/COMET proposals:

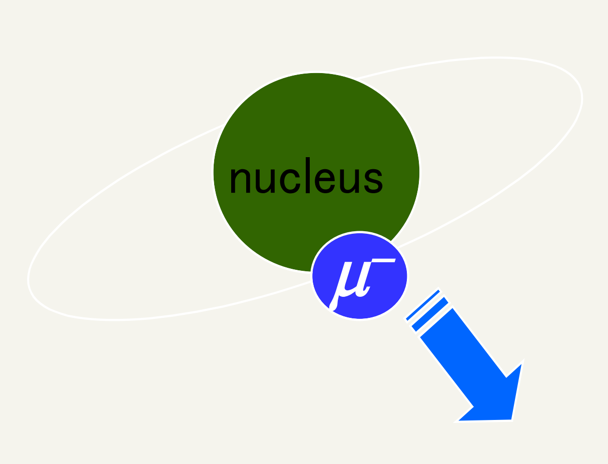
$$R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow \text{capture}} < 6\text{x}10^{-17} \text{ (90\% c.l.)}$$

x10000 improvement over current limit

Project X: another 2 orders of magnitude, to few x 10^{-19}

The Mu2e Measurement Method

- Stop negative muons in an aluminum target
- The stopped muons form muonic atoms
  - Bohr r=$n^2/(m_\mu Z)$, E =$m_\mu Z^2/n^2$: 2500x smaller r, 35000x more BE than e^- in Al–>well inside electron orbits → hydrogen-like atom
  - hydrogenic 1S Al: Bohr r ~20 fm, BE~500 keV
  - muon and nuclear wavefunctions overlap
  - Muon lifetime in 1S orbit of aluminum ~864 ns (40% decay, 60% nuclear capture), compared to 2.2 μsec in vacuum (capture is roughly sum of reactions with protons in nucleus: $\mu^- + p \to \nu_\mu + n$



Look for a monoenenergetic electron from the neutrinoless conversion of a muon to an electron:

$$\mu^- + {}^{27}_{13}Al \to {}^{27}_{13}Al + e^- \qquad \text{Electron energy}{\sim}105\text{ MeV}$$

- What is actually measured and quoted:

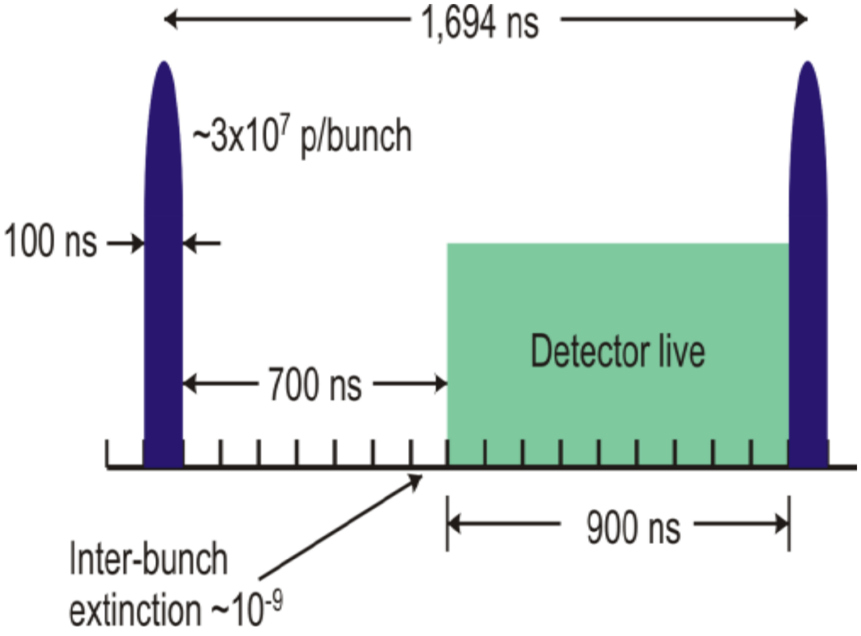
$$R_{\mu e} = \frac{\mu^- + {}^{27}_{13}Al \to {}^{27}_{13}Al + e^-}{\mu^- + {}^{27}_{13}Al \to X + \nu_\mu (capture)}, \text{ where X=A(N,Z)+neutrons, protons,...}$$

- Goal: $R_{\mu e} < 6\text{x}10^{-17}$, 90% c.l. x10000 better than current limit

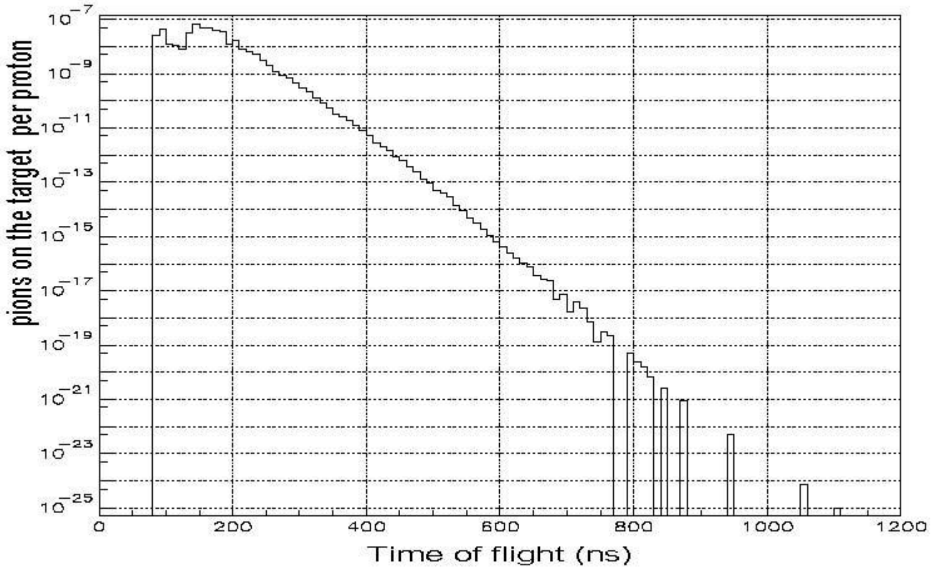
Dealing with radiative pion capture background

Use pulsed proton beam

Well-matched to 864 ns muonic Al lifetime



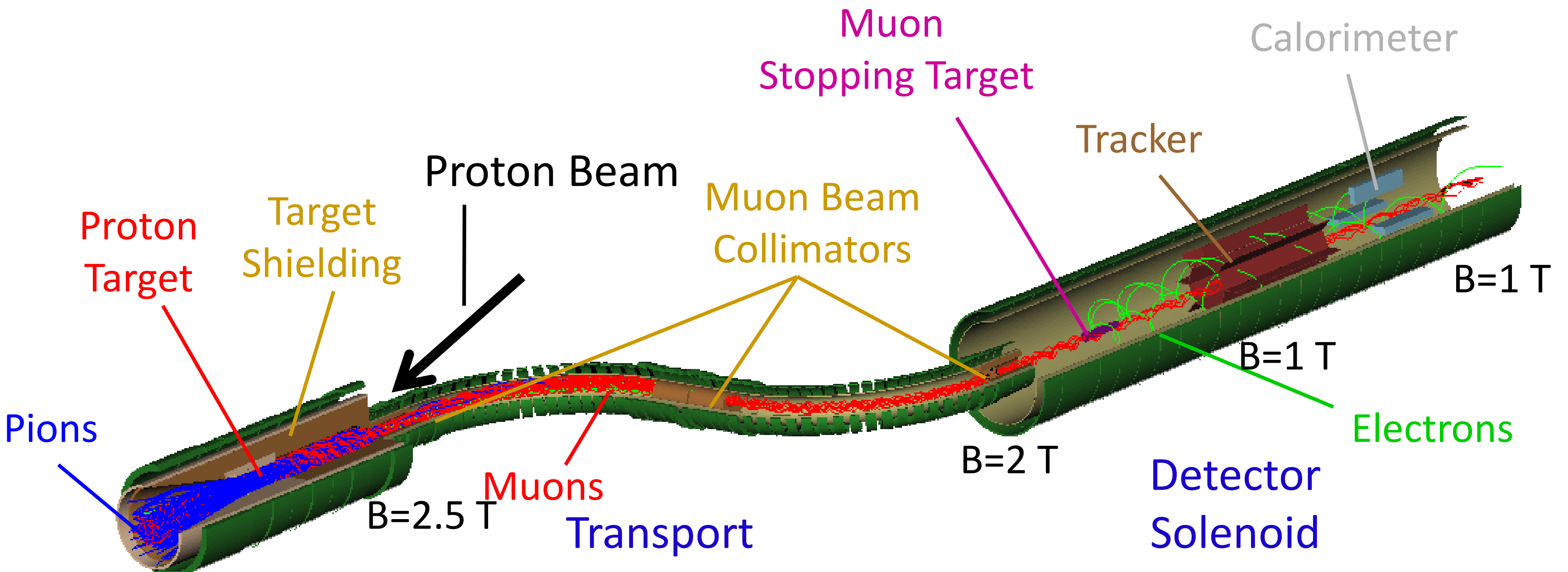
Simulation Time distribution of pions arriving at target after proton strikes the production target



- Wait ~700 ns to start measurement, pion stopping rate is reduced by ~10^{11} → ~0.0007 events background, compared to ~4 events signal at $R_{\mu e}=10^{-16}$
- Extinction (=between-pulse proton rate) < 10^{-9} gives ~0.07 counts
- Recognized and studied by time dependence, presence of e+

Mu2e Muon Beamline

Muons are collected, transported, and detected in superconducting solenoidal magnets



Production Solenoid

Transport Solenoid

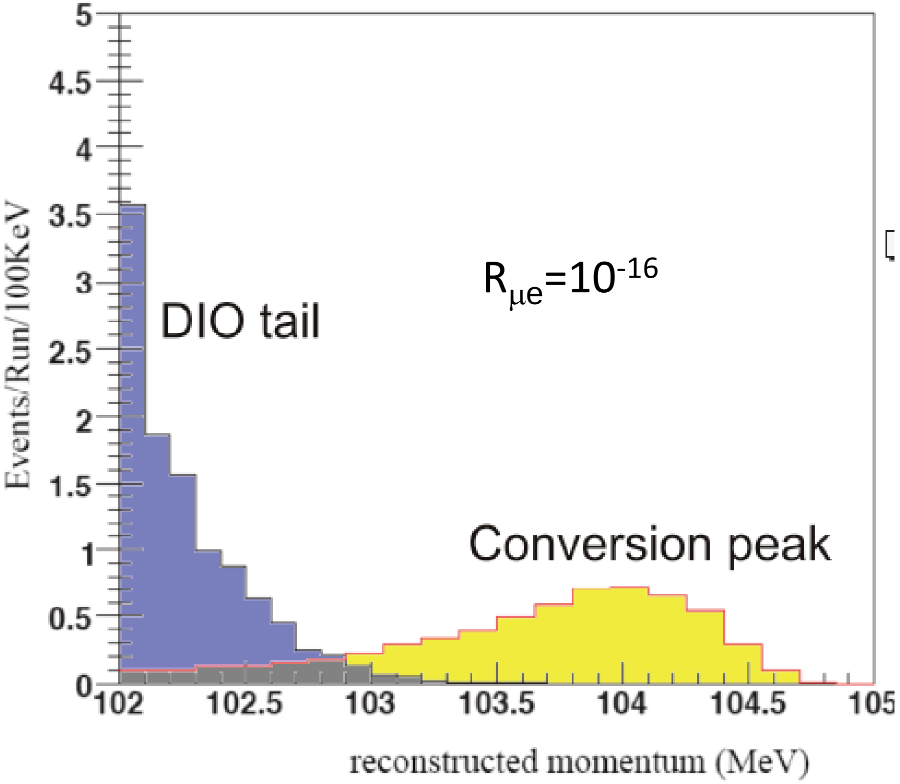
- Selects low momentum μ^-
- Avoids straight line from production target to detectors

Detector Solenoid

Delivers 0.0025 stopped muons per 8 GeV proton

Signal to DIO Background

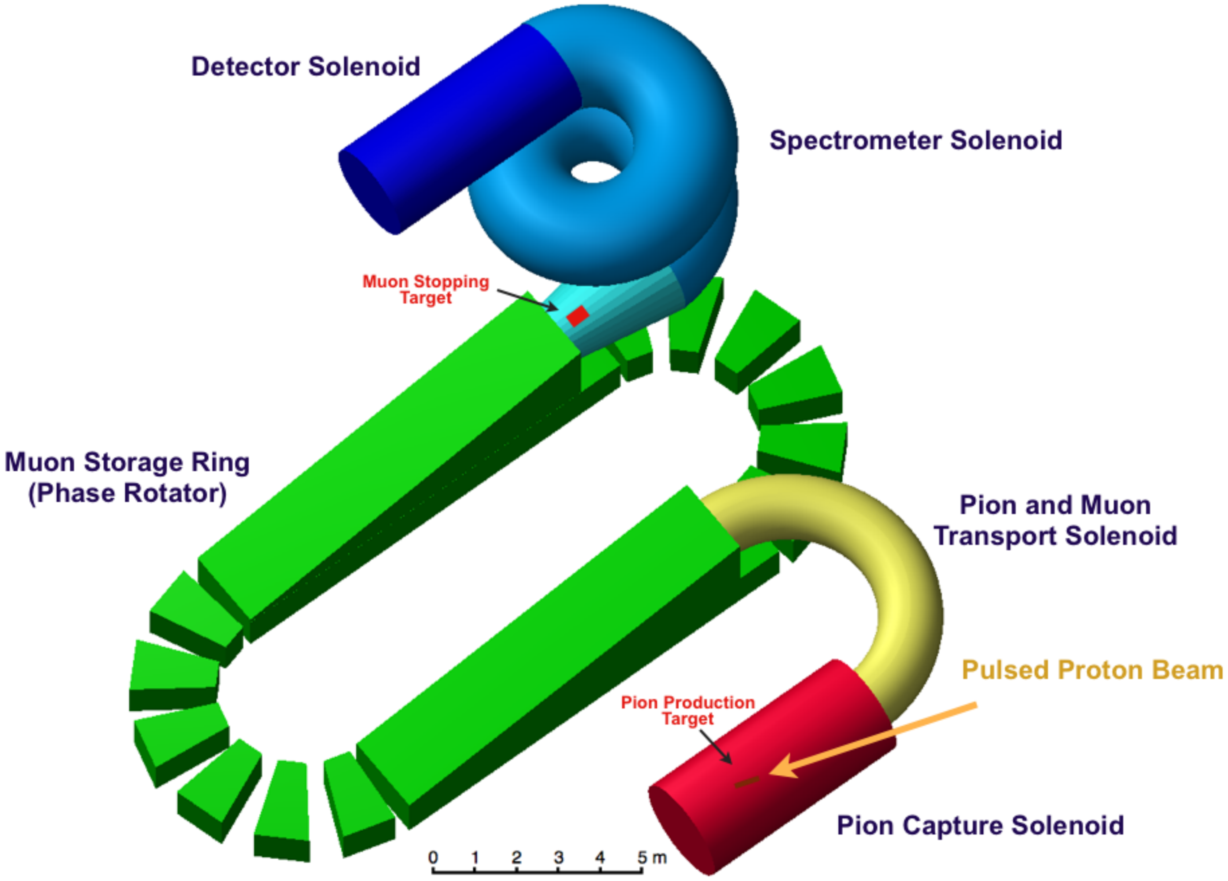
- Simulated DIO (electrons from Muon Decay in Orbit) tail + signal, assuming 1 MEV (FWHM) resolution on electrons around 105 MeV
- If geometry can be arranged to eliminate low energy electrons, the rate in the detector is quite low.
- If the energy resolution is good enough, the DIO electron background can be made negligible.
- Need to also eliminate pions and low energy noise from n,p, γ emanating from stopping target.
- Conceivable to go to very high rates—very different from most experiments!



Muon to Electron Conversion at Project X

- We will need a new detector design to handle Project X rates
  - Improved suppression of low energy n,p,gamma noise
- Strategy depends on results of Mu2e or COMET
- Do we see a signal at 10^{-16} ?
  - If yes, measure Z-dependence of conversion rate (nature of interaction depends on Z) with good statistics..
    - To measure high-Z targets, need beam which clears pions more quickly due to short muonic atom lifetime, many more muons to establish magnitude of CLFV in several nuclei with precision
  - If no, go for few x 10^{-19} sensitivity in Al or Ti.
    - Need better energy resolution, may need better cosmic ray rejection
- Pulsed Beam
  - 10 ns wide pulse, 3×10^{12} Stopped muons/s, 10^{-11} extinction, 2 MW if no improvements in collection efficiency of muons

Concept for the Project X μ→e Conversion Experiment



Muon ring: rotate phase (narrow t, wide p)→(wider t, narrow p)

Narrow p beam stops in thin target

Ring also eliminates pion and other backgrounds.

Pulsed Beam, 100x more flux than Mu2e, 1000 Hz, 10 ns wide

Detector/Spectrometer which greatly suppresses backgrounds (e.g. DIO)

Y. Kuno will explain the new concept detail

$\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+ e^+ e^-$

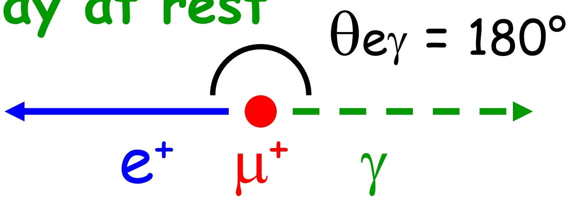
- Both decays require coincidence measurements
  - DC beam may be best, but…
  - A pulsed beam with spacing <~ muon lifetime would be OK, maybe even beneficial if there are prompt particles (π,e,..) in the beam which dissipate quickly with time
  - Accidentals will limit maximum allowable beam: in each case the final particles are sitting in a sea of electron and positron backgrounds at similar energies- contrast with μ->e
  - $\mu^+ \rightarrow e^+ e^+ e^-$ is the most promising for better precision
  - Sufficient DC beam is available at PSI for 10^{-14} limits but not 10^{-15}

$\mu^+ \rightarrow e^+\gamma$

- MEG Experiment now under way at PSI plans a 10^{-13} measurement (current limit 1.2×10^{-11})
- Stop positive muons in thin target
- Detect back-to-back 53 MeV e^+ and γ
- But the background of e^+ from $\mu \rightarrow e^+\nu\nu$ peaks at 53 MeV, leading to significant accidentals. Presents huge challenge to improving limit.
- Cut background with superior resolution on
  - Angle between e^+ and γ
  - Energies of e^+ and γ
  - Vertex position
  - $t_e=t_\gamma$
  - MEG: Rate dependence of background limits stop rate to <few x 10^7 Hz

MEG detection technique

μ^+ decay at rest

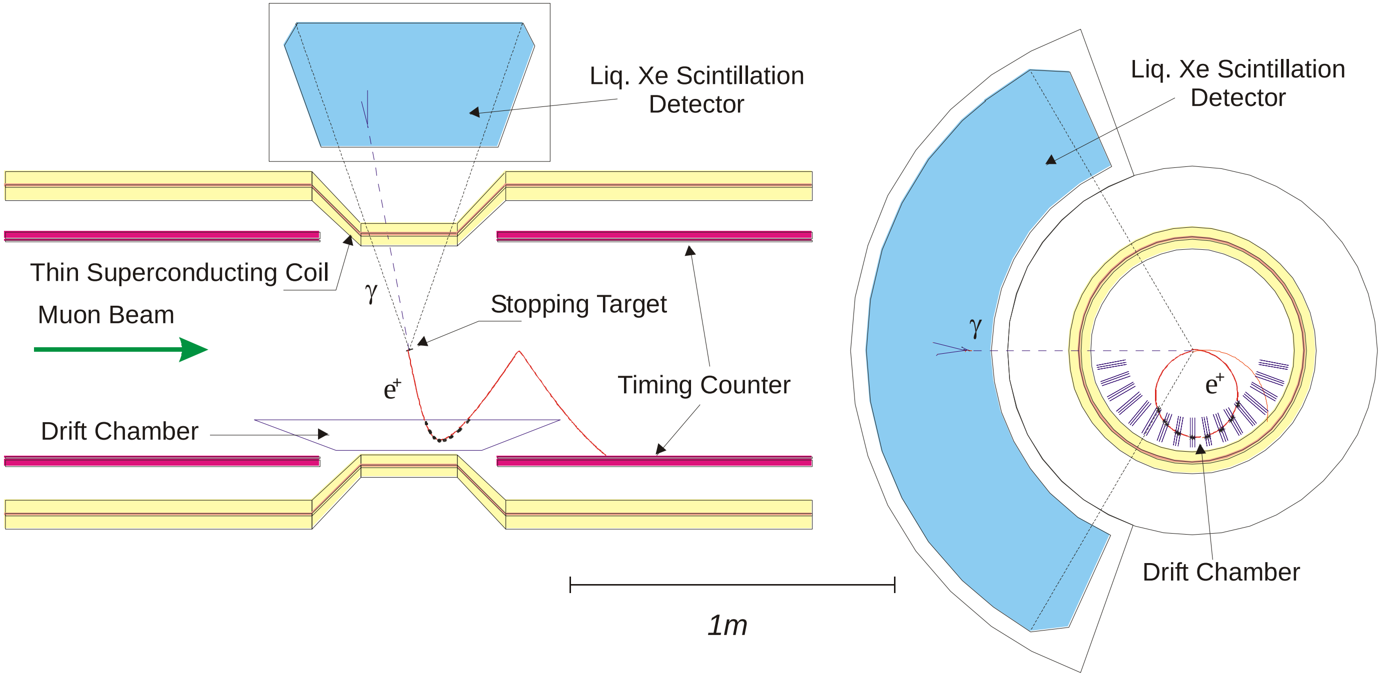


$E_e = E_\gamma$ = 52.8 MeV

Stopped beam of 3×10^7 μ/sec in a 150 μm target

Liquid Xenon calorimeter for γ detection (scintillation):

- fast: 4 / 22 / 45 ns
- high LY: ~ 0.8 * NaI
- short X_0: 2.77 cm



Solenoid spectrometer (COBRA) & drift chambers for e+ momentum measurement

Scintillation counters for e+ timing

MEG Experiment Status

- First result, BR<2.8x10^{-11} (90% c.l.)

(Compare MEGA, 1.2x10^{-11})

- Ultimate goal ~ 10^{-13}

$\mu^+ \rightarrow e^+\gamma$ at Project X

- Goal 10^{-15}
  - More muons would be needed; very challenging because of accidental backgrounds at high rates
  - Background proportional to Rate x $\sigma_{E\gamma}^2$ x σ_{Ee} x σ_t x σ_θ^2
  - Use large area target to improve selectivity of vertex cut against accidentals
  - Thinner target to reduce multiple scattering, background pair production in target
  - Improve energy, angle resolutions (Increase distance of calorimeter and tracker from target, thin close-in tracker to improve vertex location, go to LYSO array or pair spectrometer for photon…)
  - A pulsed beam is acceptable provided pulse spacing is not much larger than the muon lifetime. Pulsing may be beneficial if there are prompt beam-related backgrounds, from pions or beam positrons for example.
  - May be possible to handle a stopping rate up to 5×10^8 , with a detection probability of 0.1, can get to 10^{-15} in one year.

$\mu^+ \rightarrow e^+ e^+ e^-$

- No gamma to detect: makes it ‘easier’ than $\mu^+ \rightarrow e^+\gamma$
- Current BR limit 1×10^{-12}, background ~1×10^{-13}, beam 6×10^6 Hz
- Proposed Limit 1×10^{-16} , background ~1×10^{-16}, beam 1×10^{10} Hz

(“Physics at a future Neutrino Factory & super-beam facility”, hep-ph/0710.4947)

  - Main background: accidental e^+e^- from Bhabha scattering of e^+ from ordinary decay or from pair production in the target
  - Make target thinner (narrow p distribution or throw away muons)
  - Background scales as (vertex resolution)/(target area)
    - Vertex resolution dominated by scattering in first layer of detector
      - Bring the detector closer to the target, make it thinner: x10
    - Greatly increase the area of the target x10
  - Accidental rate scales as (momentum resolution)^2
    - 10% (previous expt) → 1% gives x100
  - Reduction from collinearity requirement on e^+ with e^+e^- pair : x100
  - Dramatic background reduction: require each e^+e^- pair combination have an opening angle of at least 30 degrees
    - But this will reduce sensitivity to some physics channels.

Muon EDM

- A non-vanishing permanent EDM in an elementary particle is a violation of both T and P symmetries.
- In the SM, predicted EDMs are extremely small→ *any* EDM is a sign of new physics
- Assuming CPT invariance, a non-vanishing EDM implies CP violation.
- The currently known extent of CP violation does not explain baryon asymmetry of the universe.
- Searching for EDM’s is one of the most promising ways to look for CP violation→ Many high-priority efforts to measure EDM’s of neutron, proton, electron, ions
- The muon is by far the best candidate outside the first generation of particles for improvement of EDM measurement.

Muon EDM

- Present limit on muon EDM determined parasitically in muon g-2 storage ring experiment, E821: $d_\mu < 1.8x10^{-19}$ e-cm
- Assuming lepton-universality, $d_e < 2.2x10^{-27}$ e-cm implies $d_\mu \simeq (\frac{m_\mu}{m_e})2.2x10^{-27} < 5x10^{-25}$ e-cm
- Many models predict an EDM well above naïve scaling, up to ~10^{-22} e-cm.
- A measurement bettering this limit is called for.

Muon EDM Experimental Approach

- In a storage ring, the spin precession rate depends on E and B:

$$\boldsymbol{\omega} = \boldsymbol{\omega}_{\mathbf{e}} + \boldsymbol{\omega}_{\mathbf{a}}$$

$$\boldsymbol{\omega}_{\mathbf{e}} = \frac{\eta}{2}\frac{e}{m}(\boldsymbol{\beta}\mathbf{x}\mathbf{B} + \mathbf{E}), \qquad \boldsymbol{\omega}_{\mathbf{a}} = \frac{e}{m}\left[a\mathbf{B} - (a - \frac{1}{\gamma^2 - 1})\mathbf{E}\right]$$

η is EDM analogue of g for MDM, $d_\mu \simeq \eta x 4.7 x 10^{-14}$ e-cm

$a = (g-2)/2$ is the magnetic anomaly

- Choose γ^2, E, B so that $\omega_a=0$ → “Frozen spin method”
- Trap muons in a circular storage ring, with initial polarization directed along or opposite the momentum, for several muon lifetimes
- With $\omega_a=0$, only ω_e acts on the spin. βxB dominates, ω_e is directed radially, the polarization vector acquires a vertical component which increases linearly with time. This will lead to a difference in the number of decay electrons going up compared to down.

Muon EDM Sensitivity

- Small ring: p_μ=125 MeV/c, B =1 T, E=0.64 MV/m, R=0.42 m, P=0.9, A=0.3 (see Adelman, et al., hep-ex/0606034)

$$E \simeq aB\beta\gamma^2$$

$$\sigma_{d_\mu} = \frac{\sqrt{2}\hbar a\gamma}{4\tau EAP\sqrt{N}} = \frac{1.1x10^{-16} \text{ e-cm}}{\sqrt{N}}$$

- At PSI, continuous beam, one muon at a time→$2x10^5$/s=$4x10^{12}$/year→

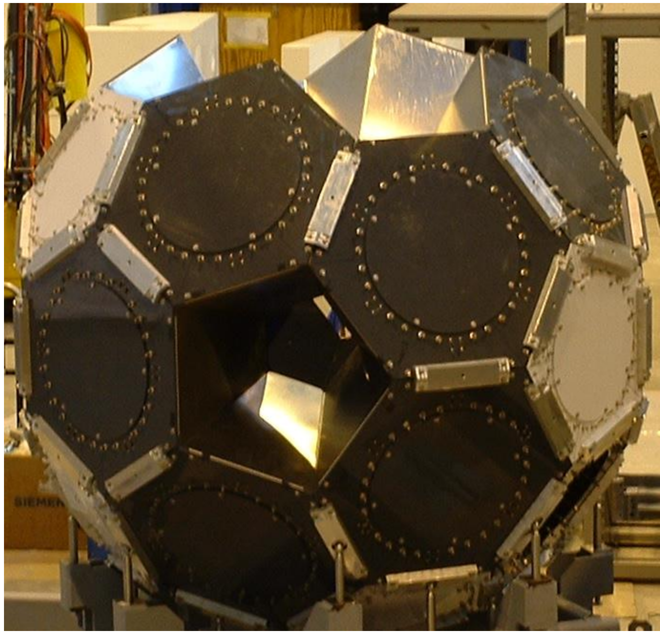
$$\sigma_{d_\mu} = 5x10^{-23} \text{ e-cm}$$

- Statistics Limited
- Pulsed beam, ~$5x10^{10}$ Hz, →Stat error $\sigma_{d_\mu} = 1x10^{-25}$ e-cm
- Use resonant injection: in small ring, need beam pulses timed to multiple of cyclotron frequency, followed by measurement period of ~10μs
- Need highly polarized muons

Muon Lifetime Experiment

- MuLan, at PSI has just published the best measurement of the muon lifetime, to 1 ppm uncertainty.
- Gives the best value for the Fermi constant G_F (0.6 ppm)

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q)$$



- Δq contains well-known phase space and both QED and hadronic radiative corrections
- G_F is one of the fundamental constants of the SM

Muon Lifetime: Main Sources of Uncertainty in MuLan

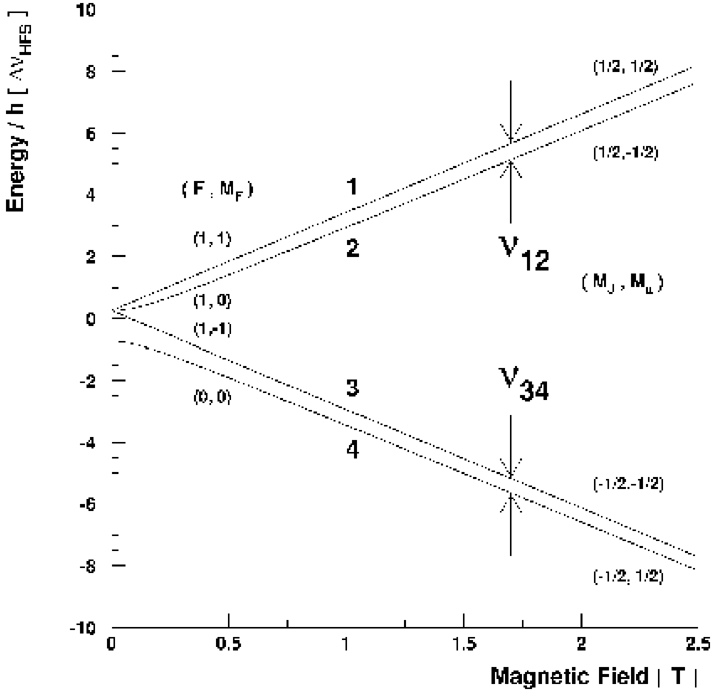
Effect uncertainty in ppm	R06		R07
Kicker stability	0.20		0.07
Spin precession / relaxation	0.10		0.20
Pileup		0.20	
Gain stability		0.25	
Upstream muon stops		0.10	
Timing stability		0.12	
Clock calibration		0.03	
Total systematic	0.42		0.42
Statistical uncertainty	1.14		1.68

- Dominated by statistical uncertainty- more muons, go to pulsed beam
- With pulsed beam and good extinction, eliminate kicker
- Spin precession: $N = N_0 e^{-\lambda t}(1 + A\sin(\omega t + \phi))$
  - Add equal contribution from segment on opposite side of detector to cancel- could be improved with bigger array, more careful balancing
  - Eliminate with unpolarized beam
- Pileup: increased segmentation on detector
- Gain and time stability: can be improved
- Put whole detector in vacuum, eliminate beam pipe in path of decay positrons.
- Project X goal: at least x10 in lifetime measurement

Muonium (M) Production

- Muonium, M: Atomic bound state of μ^+ and e^-
- Like hydrogen atom, but no strongly interacting particles; two *point* particles
- Thermal M produced near surface of SiO_2 powder in vacuum, few x0.1% efficiency.
- Most measurements using M are statistics limited

Muonium Hyperfine Structure and 1s-2s Interval



- Ground state HFS (LAMPF, RAL, KEK):
  - $(F,M_F),(M_J,M_\mu)$ 1: (1,1), (1/2,1/2)
    2: (1,0),(1/2,-1/2)
    3: (1,-1),(-1/2,-1/2)
    4: (0,0), (-1/2,1/2)
  - ν_{12} and ν_{34} involve muon spin flip.
- $\nu_{12}-\nu_{34}$ gives μ_μ
- $\nu_{12}+\nu_{34}$ gives HFS at B=0. Comparison with theory gives one of the most stringent tests of QED: gives value of α with bound state QED to compare with free QED from the electron magnetic anomaly.
- Intrinsic linewidth limited by muon lifetime- won't help to cool
  - LAMPF experiments used 'Old Muonium' to get ~factor two improvement in linewidth- need a pulsed beam
- 1s-2s transition energy gives m_e/m_μ and q_e/q_m (KEK and RAL)

Muonium to Antimuonium Conversion

$$M \rightarrow \bar{M}$$

- $\mu^+e^- \rightarrow \mu^-e^+$ $|\Delta L_i|=2$
  - PSI Experiment: Total of 5.7×10^{10} Muonium atoms → probability $<8 \times 10^{-11}/S_B$ probability (90% c.l.)
    - S_B~1 is a theory-dependent correction for magnetic field which splits energy of M-Mbar
    - Detect both energetic e^- from μ^- decay and low energy e^+, reconstruct vertex, and look for e^+ annihilation gamma
    - Signal amplitude $= \sin^2 \frac{\delta t}{2\hbar} e^{-\lambda_\mu t} \approx \left(\frac{\delta t}{2\hbar}\right)^2 e^{-\lambda_\mu t}$: wait ~2 lifetimes

      so that beam-related accidental backgrounds decrease by x10:

      use pulsed beam!
  - At least two orders of magnitude improvement in rate is possible before background becomes an issue:
    - $\mu \rightarrow 3e2\nu$
    - μ^+ decays to e^+, e^+ transfers energy to e^-
  - At least a factor of 10000 improvement in rate can be achieved at Project X- an experiment must be designed to handle the rate.

What Kind of Beams Do we Need?

- Muon to electron conversion
  - Very low momentum negative muons,(p<70 MeV/c), or very narrow momentum range, in order to stop in a thin target
  - Polarization not needed
  - Pulsed proton beam, pulse time width as narrow as possible, pulse width<<(lifetime muonic atom). 80 ns<(lifetime muonic atom)<1000 ns (depends on Z). Very high extinction: 10^{-11} or 10^{-12}
  - Minimum beam pulse spacing at least 2 times muonic atom lifetime: 500 ns<(beam spacing)<2000 ns (depends on Z). Extinction of beam between pulses 10^{12}
  - For FFAG muon ring, kickers limit repetition rate to ~1000 Hz, need beam width<10 ns
  - No pions in beam line, no late-arriving high momentum muons
  - No high energy electrons (>100 MeV), or other particles which could produce high energy electrons, in beam line
  - Average intensity x100 compared to Mu2e run plan (20kW →2 MW)
  - Mu2e: $3\text{x}10^{10}$ Hz stopping rate→Project X: $3\text{x}10^{12}$ Hz

What Kind of Beams Do we Need?(2)

- Muon EDM: Muon Storage Ring
  - Highly polarized muons, both signs, momentum ~100 MeV/c-600 MeV/c, momentum range 1%, phase space well-matched to the storage ring
  - Pulsed beam, beam pulse width may have to be narrow to inject properly into storage ring
  - Pulses may have to be spaced closely (tens ns) for resonant injection into storage ring
  - Load storage ring every ~10 μs (may need to be larger, depending on injection scheme into EDM storage ring). Extinction during measurement periods $<10^{-5}$
  - Very large flux of muons needed for precision experiment, take all the beam available.
  - For planned 10^{-25} e-cm limit, 5×10^{10}Hz, $NP^2 = 1 \times 10^{18}$ total polarized muons.
  - Effective rate will depend on polarization of beam.

More about Beams(3)

- Muon Lifetime
  - Unpolarized muons
  - Positive muons, no pions or positrons
  - Pulsed beam, pulse width ~1 μs or less, pulse spacing ~ 20 μs, excellent extinction (better than 10^6) between pulses
  - Stop in thin target: Narrow muon beam momentum, or very low momentum
  - Muon flux several x 10^9 Hz would give 0.1 ppm, could do this with 25 kW available from Booster now, but the required beam structure is not available.
- Muonium
  - Polarized positive muons, very low energy and/or very narrow momentum range to stop efficiently in a very thin target; could be surface muons
  - Production is inefficient, only few tenths % of incident surface muons make M
  - Most experiments could use at least 100x more muonium rate
  - Most experiments could benefit from pulsed beams: width ~ 100 ns, pulse spacing ~ 10 muon lifetimes.

More about Beams(4)

- $\mu^+ \rightarrow e^+\gamma$
  - Needs μ^+, very low p or narrow p spread μ^+ to stop in a very thin target
  - DC beam is best for this coincidence experiment
  - MEG(PSI) has a DC surface μ^+ beam that can deliver 10^8 Hz muons.

sensitivity goal (MEG)	10^{-14}
running time	10^7 s
detection efficiency	0.1
macro duty cycle	1
stop rate	10^8

  - To get to 10^{-15}, 10^9 Hz muons are needed; PSI may be able to upgrade their beam line
  - A pulsed beam at Project X, with pulse spacing ~muon lifetime, would suffice to replace the DC beam.

More about Beams(5)

- $\mu^{+} \rightarrow e^{+}\, e^{+}\, e^{-}$
  - Needs μ^{+}, very low p or narrow p spread to stop in a very thin target. Polarization not necessary
  - DC beam is best for this coincidence experiment
  - No proposals are on the table at this time

sensitivity goal	10^{-16}
running time	10^{7} s
detection efficiency	0.1
macro duty cycle	1
stop rate	10^{10}

  - Could PSI upgrade their beam line to 10^{10}?
  - A pulsed beam at Project X, with pulse spacing ~muon lifetime, would suffice to replace the DC beam.

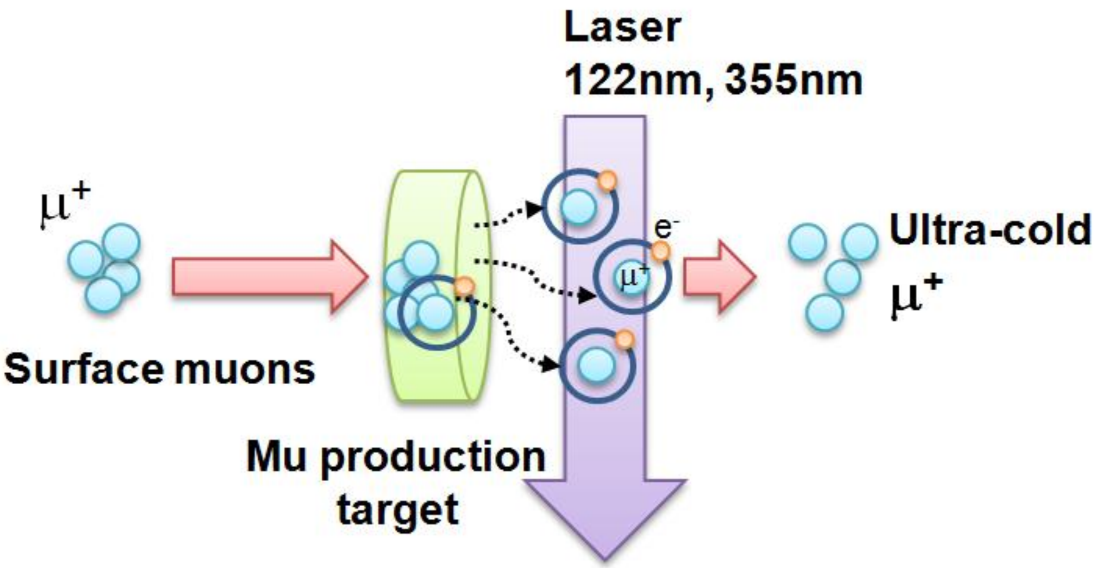
Approaches to Delivering Muon Beam to μ to e Conversion Experiment

- Muon storage ring (Y. Kuno):
  - Solenoid collection around production target (Mu2e scheme)
  - Solenoid transport
  - Injection into FFAG
    - Rotate phase space to get narrow momentum distribution
    - Eliminate pion background
    - Limits on maximum kicker rates may limit pulse repetition rate to ~1000 Hz
- Cooled RF and ionization beams (C. Ankenbrandt)
  - Combination of RF acceleration and degrading of energy in material.
  - Likely have advantage of high duty factor
  - May get larger flux because of collection of forward pions
  - Will produce a muon with little pion, electron, …background.

Conclusions

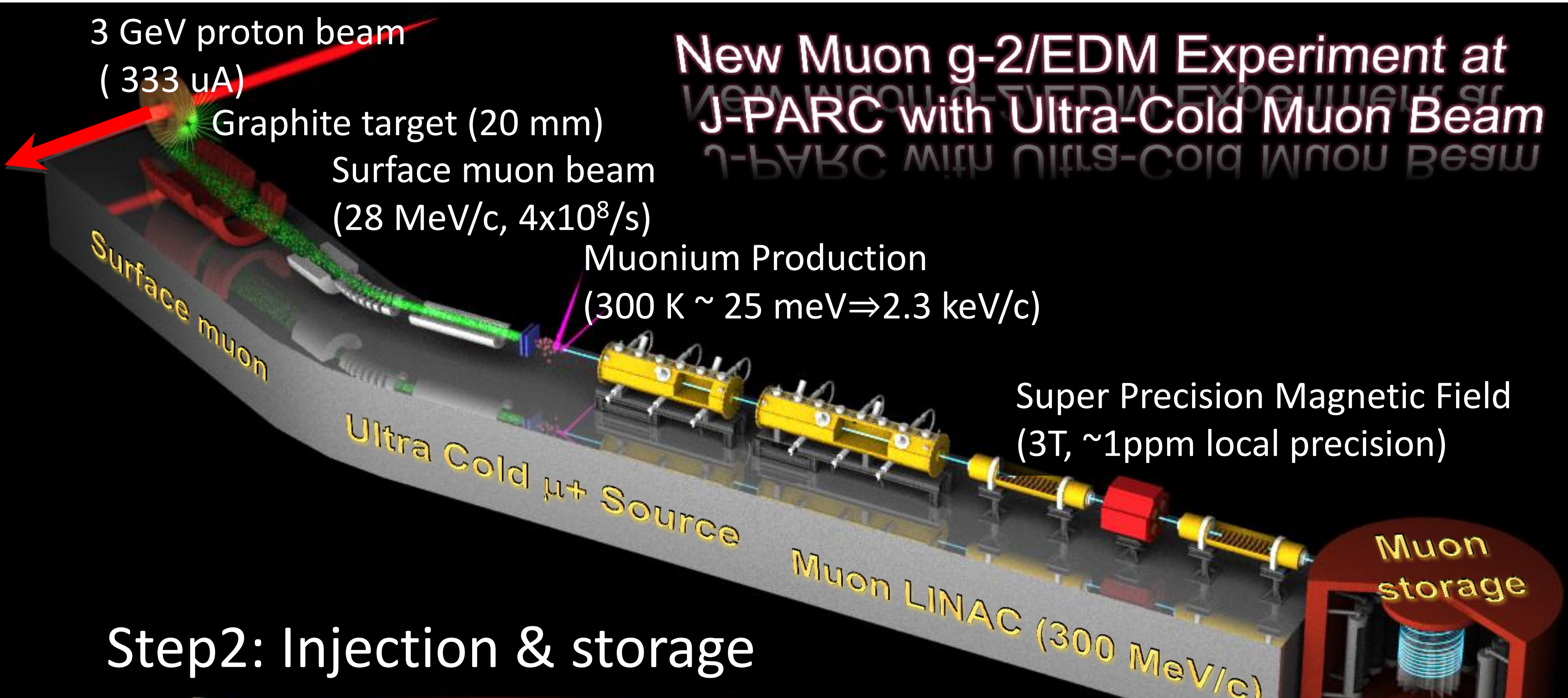
- An intense pulsed muon beam as proposed in Project X is ideally suited to dramatically increase sensitivities:
  - Stopped muon experiments requiring very low energy, narrow momentum muons
    - μ–, muon to electron conversion-especially good fit to Project X
    - μ+, M-Mbar
    - μ+, muon lifetime
  - muon EDM- requires polarized μ+ and μ-, 125-600 MeV/c
- It is less clear whether $\mu \rightarrow e\gamma$ or $\mu \rightarrow 3e$ can benefit
- A pulsed beam is superior to a DC beam for most applications.
- For stopping experiments, muons with very low momenta or narrow momentum spread are needed so that muons stop in thin targets
- High muon polarization is needed for Muon EDM and M-Mbar, irrelevant for CLFV experiments, and undesirable for the muon lifetime measurement
- High duty factor is usually desired if the kickers which deliver beam to the different applications can handle it.
- Low duty factor may be needed for some kicker schemes, e.g. PRISM

Cold Muon Production



Part of proposed JPARC g-2 Experimental Approach
Predicting 1 cold muon per 2x10^5 surface muons
Beam should be pulsed

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam


3 GeV proton beam
(333 uA)

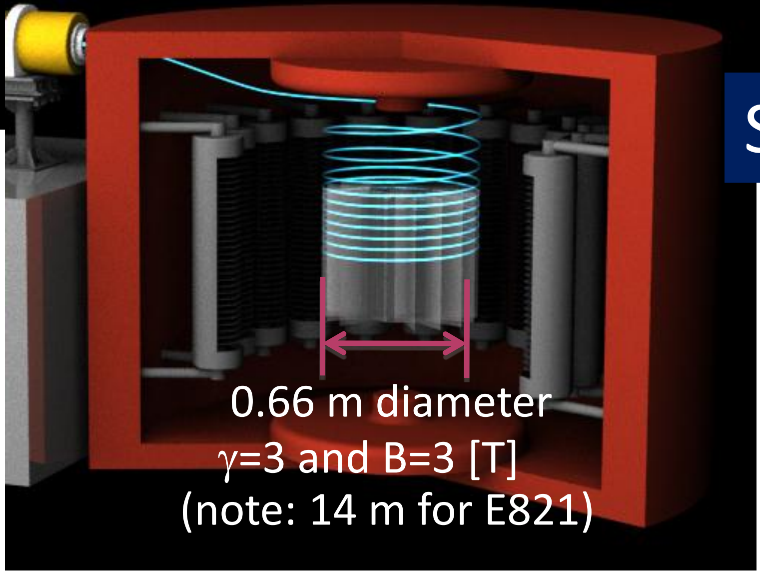
Graphite target (20 mm)

Surface muon beam
(28 MeV/c, 4x10^8/s)

Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)

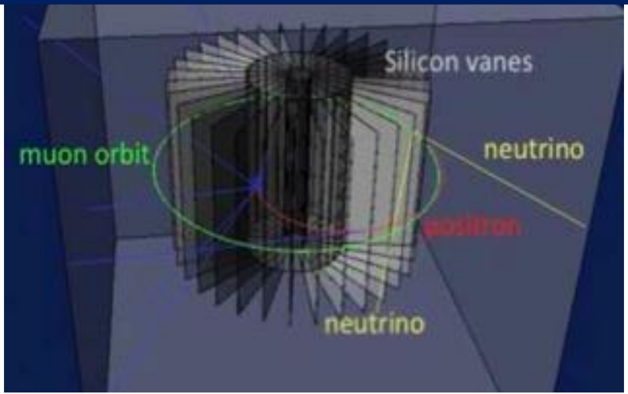
Super Precision Magnetic Field
(3T, ~1ppm local precision)

Step2: Injection & storage


μ^+ beam

0.66 m diameter
γ=3 and B=3 [T]
(note: 14 m for E821)

Step3: Detect decay e$^+$



MEG Experiment

- Uncertainty in angles between γ and e^+
  - $\sigma_\theta = 18$ mrad, $\sigma_\phi = 10$ mrad
- Uncertainty in photon first interaction position
  - $\sigma_x = 5$ mm, $\sigma_y = 6$ mm
- Uncertainty in t_γ
  - 148 ps
- Uncertainty in gamma energy
  - $\sigma_{E\gamma} \sim 1$ MeV
- Backgrounds
  - RMD: $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu + \gamma$
  - Accidentals between e+ from $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$ and photons from
    - RMD
    - Positrons annihilating in flight
    - Bremsstrahlung
  - Rate and therefore sensitivity limited by accidental backgrounds
    - Background proportional to Rate x $\sigma_{E\gamma}^2$ x σ_{Ee} x σ_t x σ_θ^2
    - MEG: Rate dependence of background limits stop rate to <few x 10^7 Hz