The Muon: Particle Physics from Precision Measurements

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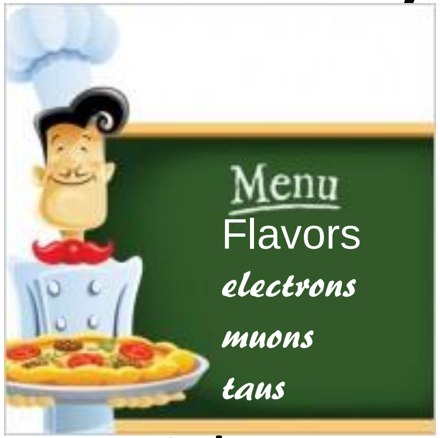
Outline

- Introduction to the muon
- Lepton Flavor Violation
- Magnetic and electric dipole moments
- Muon decays
- Muonium
- Summary and conclusions.

With apologies for areas left out

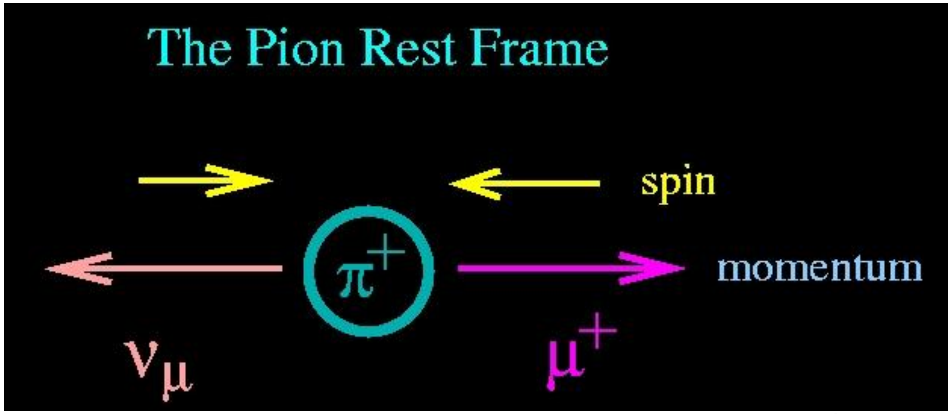
See parallel muon sessions for detailed talks on many of these issues

The Muon ("Who ordered that?")



- 2^{nd} generation lepton
- Lifetime ~2.2 μs, practically forever
- m_μ/m_e = 206.768 284 3(51)
- No internal structure seen so far → point particle
- Looks like a heavy electron in every way except for mass and lepton flavor
- produced easily and polarized

For decay in flight, "forward" and "backward" muons are highly polarized.



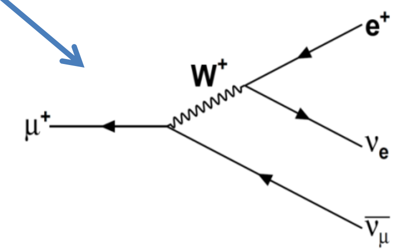
Lepton Number Conservation

- We have found empirically that lepton number is conserved in muon decay and in beta decay.
  - e.g. Muon and electron numbers are separately conserved

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

$$\uparrow \qquad\qquad \uparrow$$

$$\ell_e = 0 \qquad \ell_e = 0$$
$$\ell_\mu = +1 \qquad \ell_\mu = +1$$



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

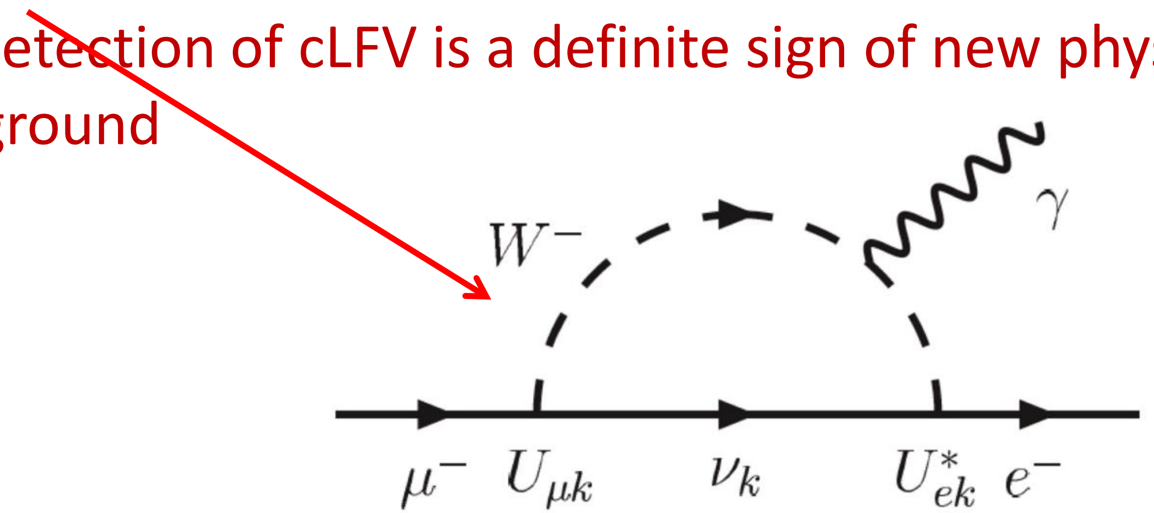
- What about $\mu^+ \rightarrow e^+ + e^+ + e^-$
- cLFV $\mu^- + (nucleus) \rightarrow e^- + (nucleus)$

Lepton Number Violation Only Observed in Neutrino Oscillations...

- Although none of the cLFV trio have been observed to date, Neutrinos *do* oscillate to different lepton generations*:*

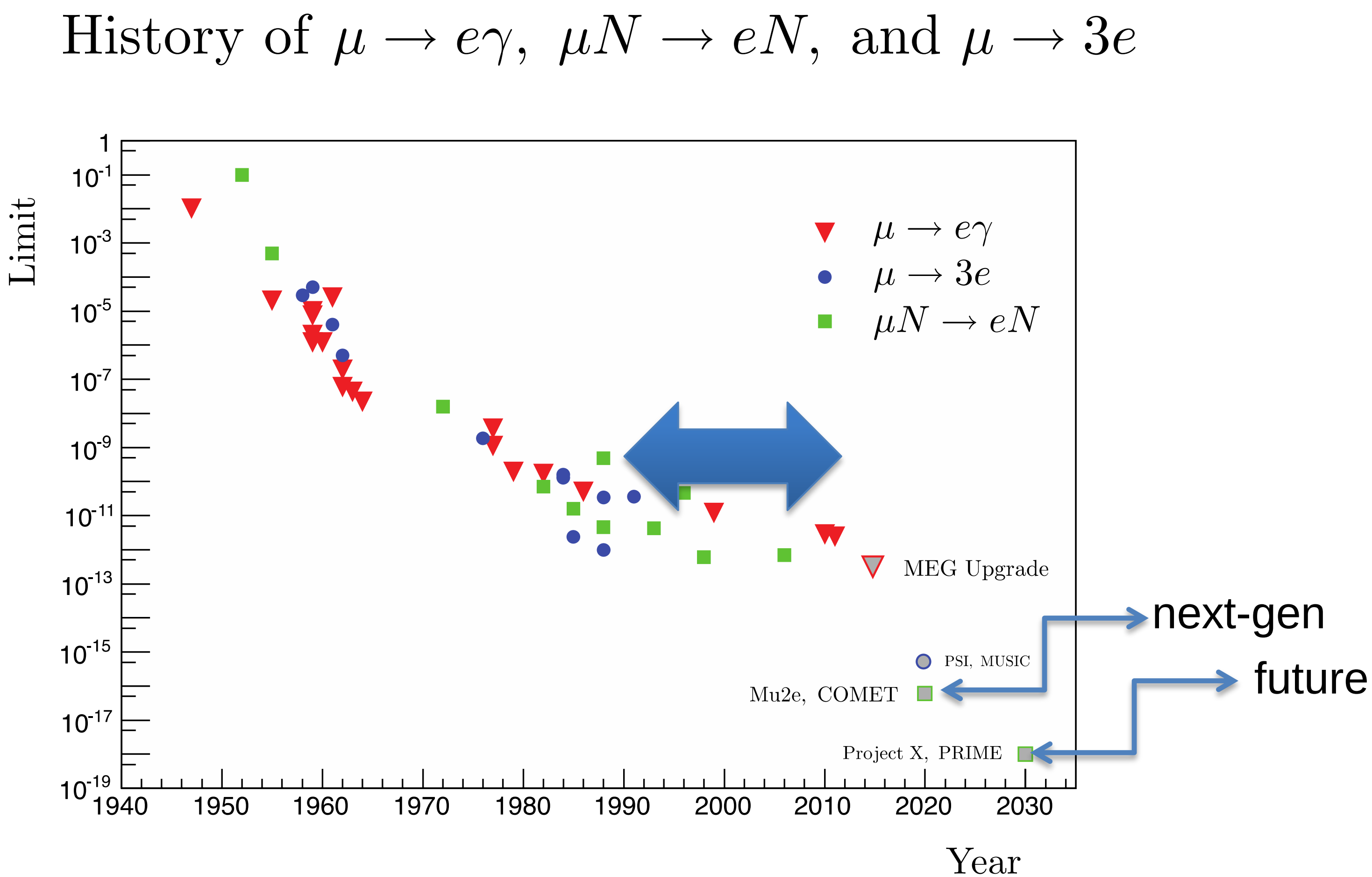
  e.g. $\nu_\mu \rightarrow \nu_\tau$

- This implies that muons and taus should violate lepton number in their decays too, but the predicted Standard Model BR is too tiny to see it experimentally.
- BR<10^{-54} for $\mu \rightarrow e\gamma$! Way below any experimental capability...
- Any detection of cLFV is a definite sign of new physics- no SM background

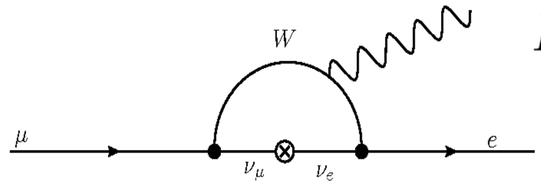


History: Muon cLFV Experiments

- cLFV in the Muon System improved steadily for many years, then leveled out

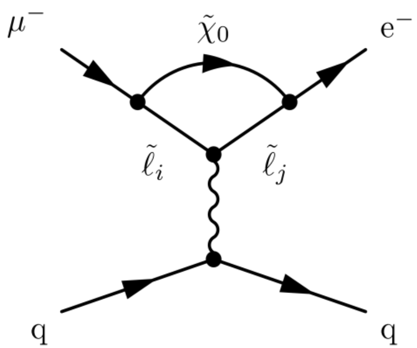


In SM:

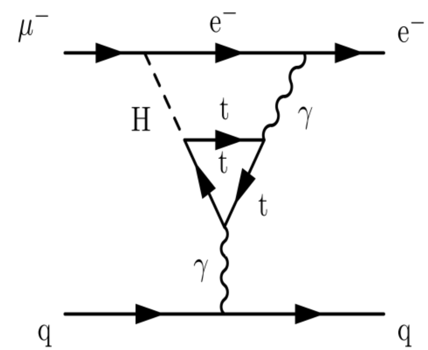


$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W} \right|^2 \lesssim 10^{-54}$$

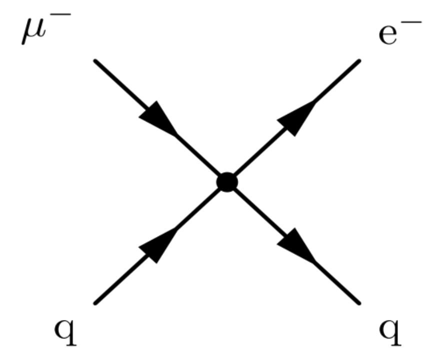
Muon Conversion Arises in Many New Physics Scenarios



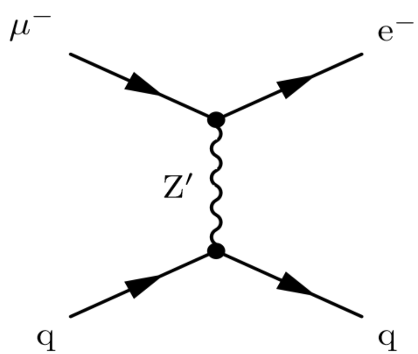
SUSY



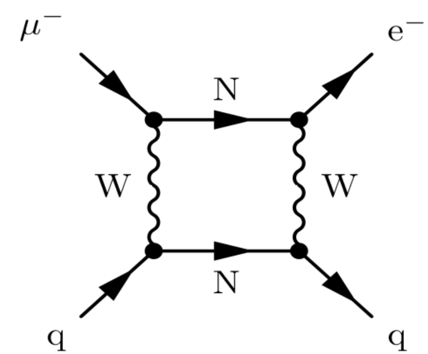
Second Higgs Doublet



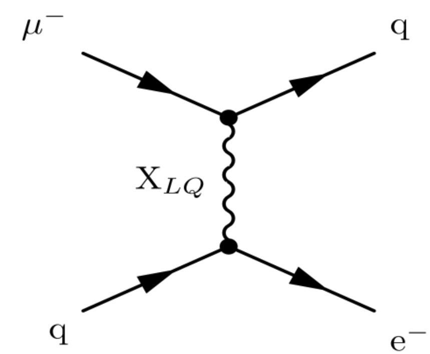
Compositeness



Heavy Gauge Bosons



Heavy Neutrinos



Leptoquarks

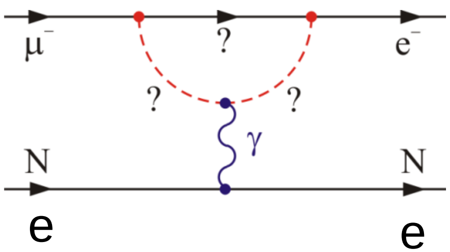
From W. Marciano

The discovery of Weak scale SUSY at LHC would imply observable cLFV rates

cLFV in $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- N \rightarrow e^- N$

Model independent effective cLFV Lagrangian

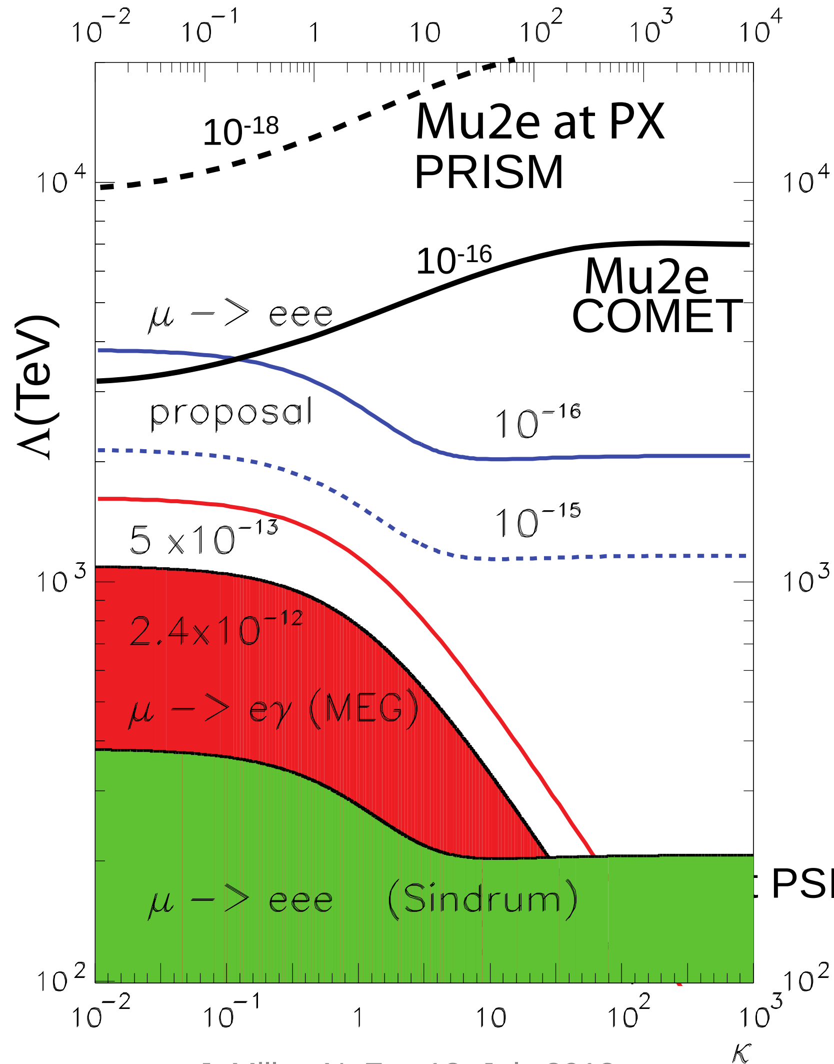
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$

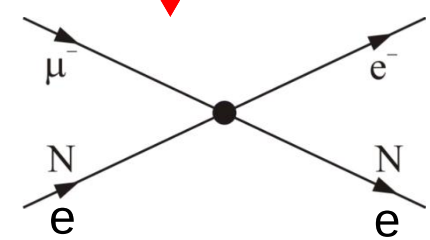


$\kappa << 1$

magnetic moment type operator

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





$\kappa >> 1$

Contact interaction

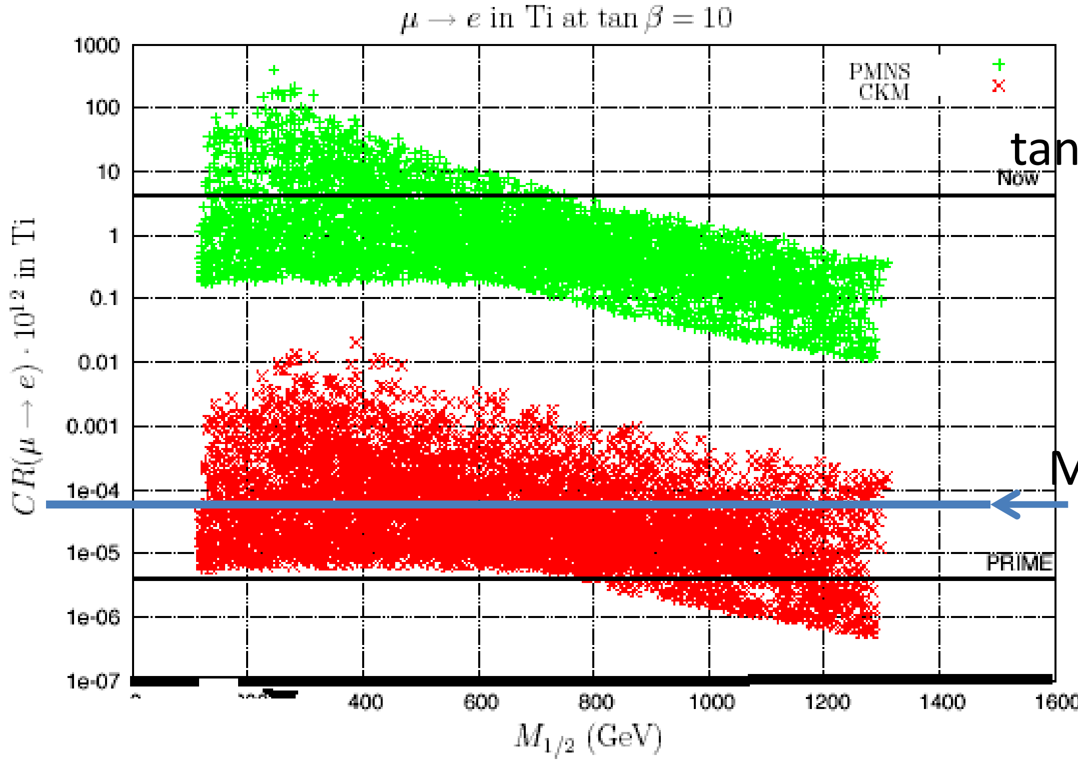
$\mu N \rightarrow eN$ rate many orders of magnitude greater than $\mu \rightarrow e\gamma$ rate

From A. deGouvea

Muon-Electron Conversion in SUSY

Neutrino-Matrix Like (PMNS) — Minimal Flavor Violation (CKM)

$BR(\mu Ti \rightarrow Ti) \times 10^{12}$



tan(β)=10

Mu2e/COMET

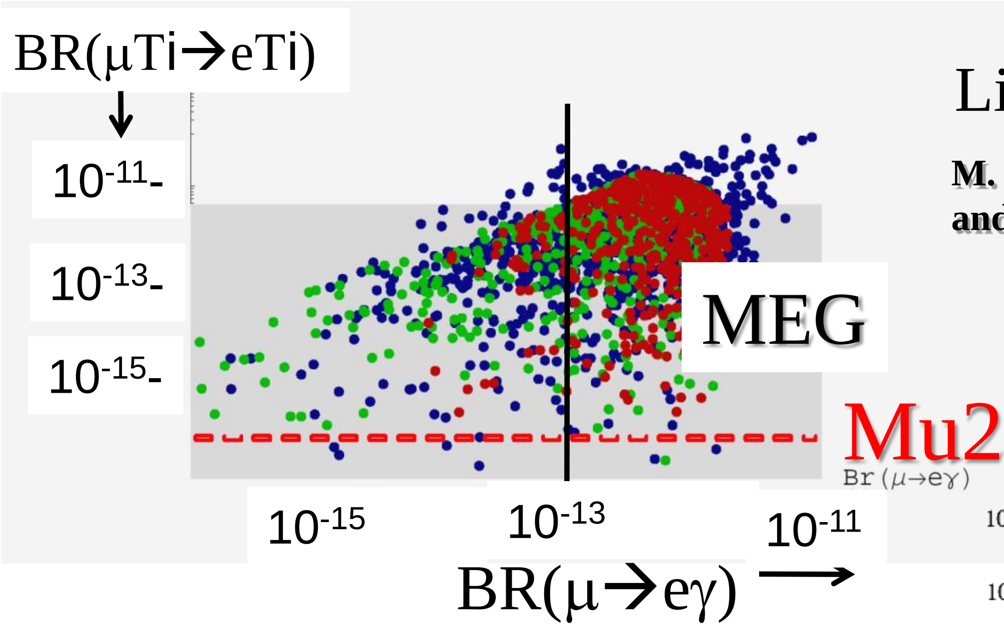
Measurement
Can distinguish
between PMNS
And MFV

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

BR(μN→eN) x10^{12} vs $M_{1/2}$ for tanβ=10

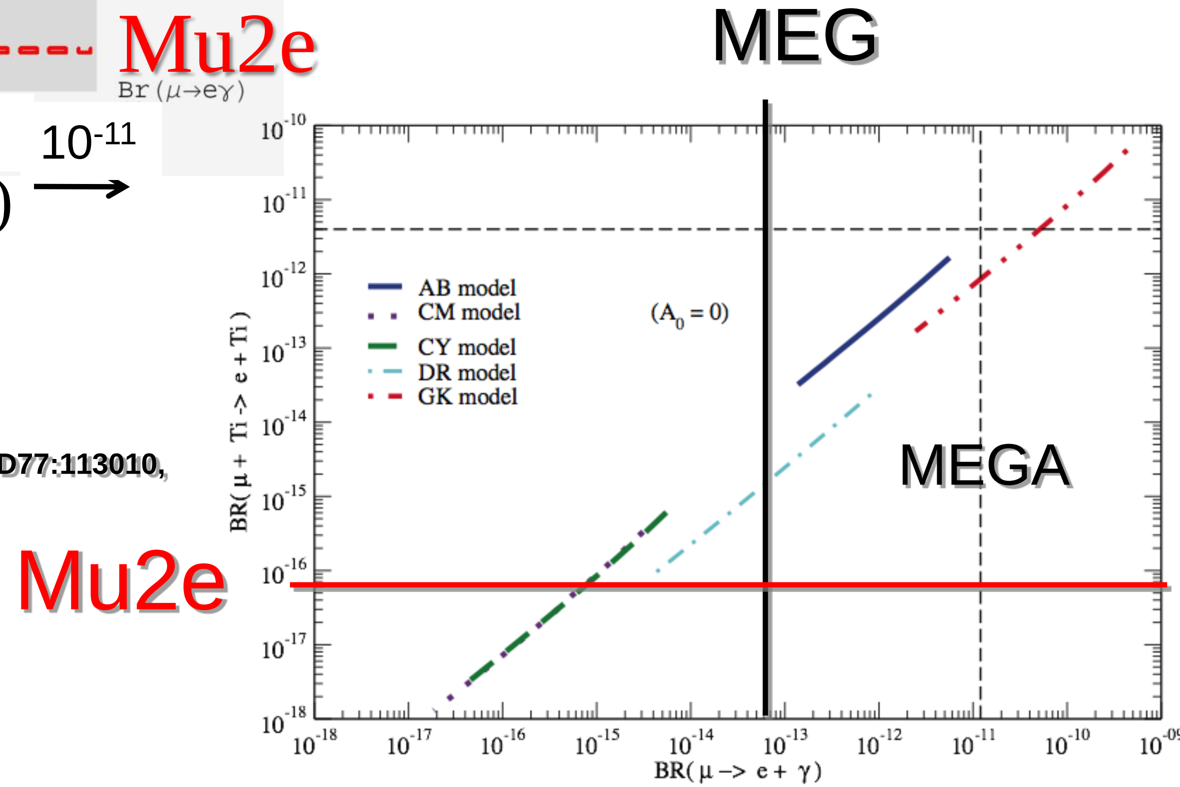
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139: neutrino mass via the see--saw mechanism,analysis in SO(10) SUSY-GUT framework

μ→e Conversion versus μ→eγ



Little Higgs Model w/T parity

M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).

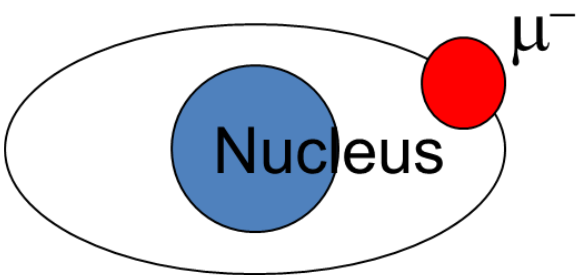


Constrained Minimal SUSY SO(10) models

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

μ^-+N→e^-+N Measurement in a Nutshell

- Make a lot of very low energy negative muons
- Stop them in a suitable thin target material (e.g. Mu2e/COMET choice is aluminum)
- Muonic atoms spontaneously produced (1S)



Bohr orbits: $r = \frac{n^2h^2}{mZke^2}$ $\quad E = -\frac{1}{2}\frac{mZ^2ke^4}{n^2h^2}$

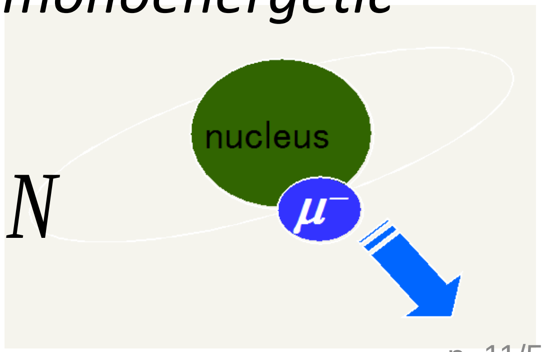
For given n and Z, $\frac{E_\mu}{E_e} = \frac{m_\mu}{m_e} = 207$ and $\frac{r_\mu}{r_e} = \frac{m_e}{m_\mu} = \frac{1}{207}$

For 1S level of muonic aluminum, r~20 fm, E~475 keV

- muon and nuclear wavefunctions overlap significantly
  - Short-range forces can act
- Look for the conversion of a muon to a *monoenergetic* electron

  (E_e =105 MeV in Al):

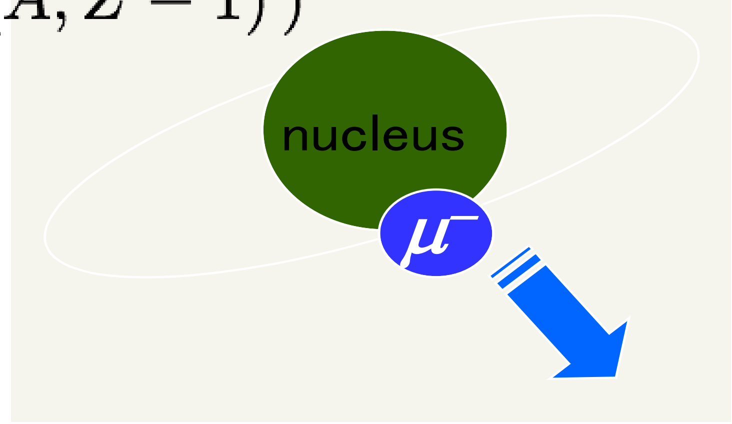
$$\mu^- + N \rightarrow e^- + N$$



The Measurement Method

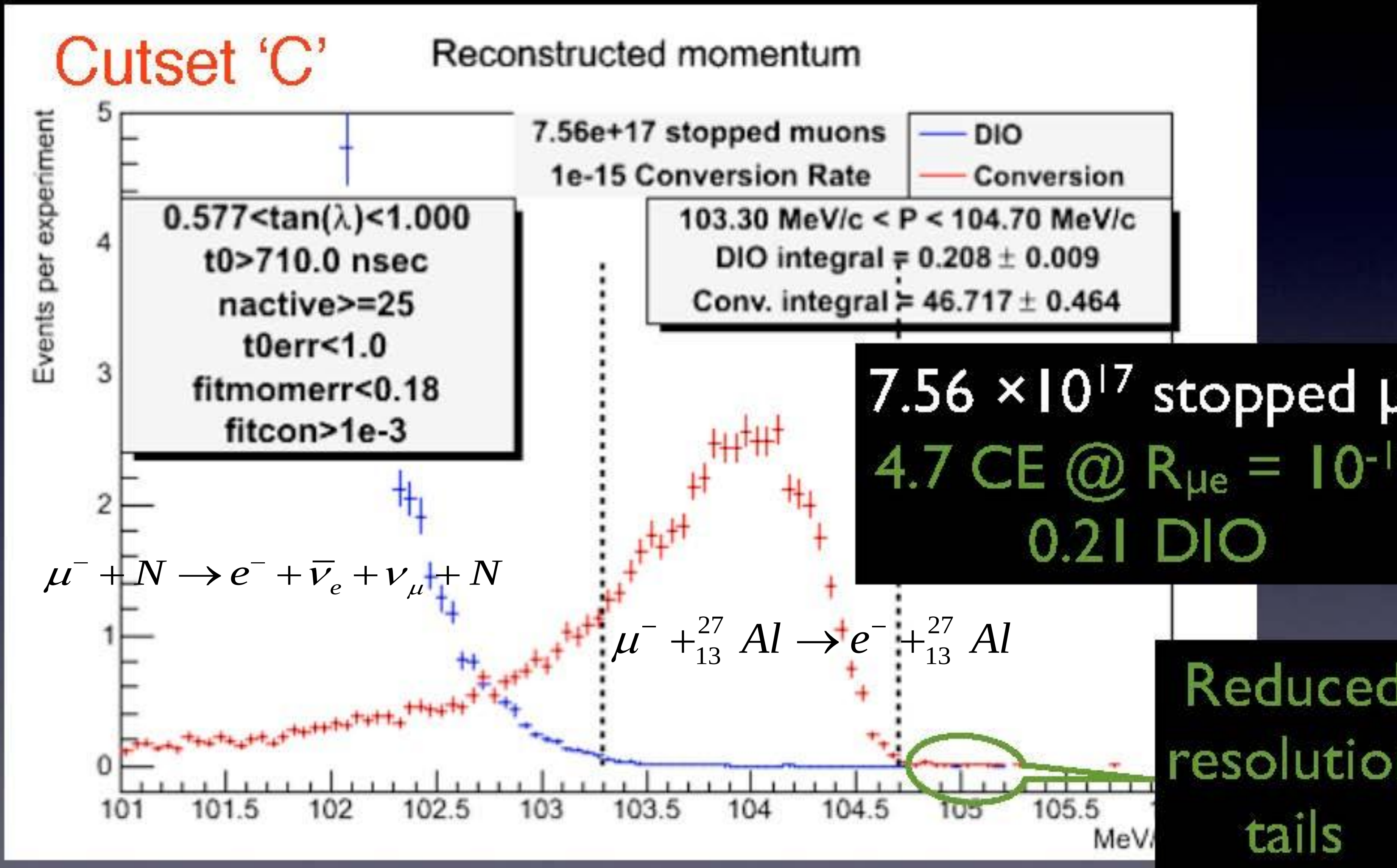
- Three main things can happen when the muon is in the 1S atomic orbital:
  - Bound muon decays(DIO) (40%): $\mu^- + N \rightarrow e^- + \bar{\nu}_e + \nu_\mu + N$
  - Muon captures on the nucleus (60%): $\mu^- + {}^{27}_{13}Al \rightarrow X + \nu_\mu (capture)$
  - Muon to electron conversion: $\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al$
- Muon lifetime in 1S orbit of aluminum ~864 ns, reduced from 2.2 μsec in vacuum because of captures

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



Mu2e simulation
from D. Brown

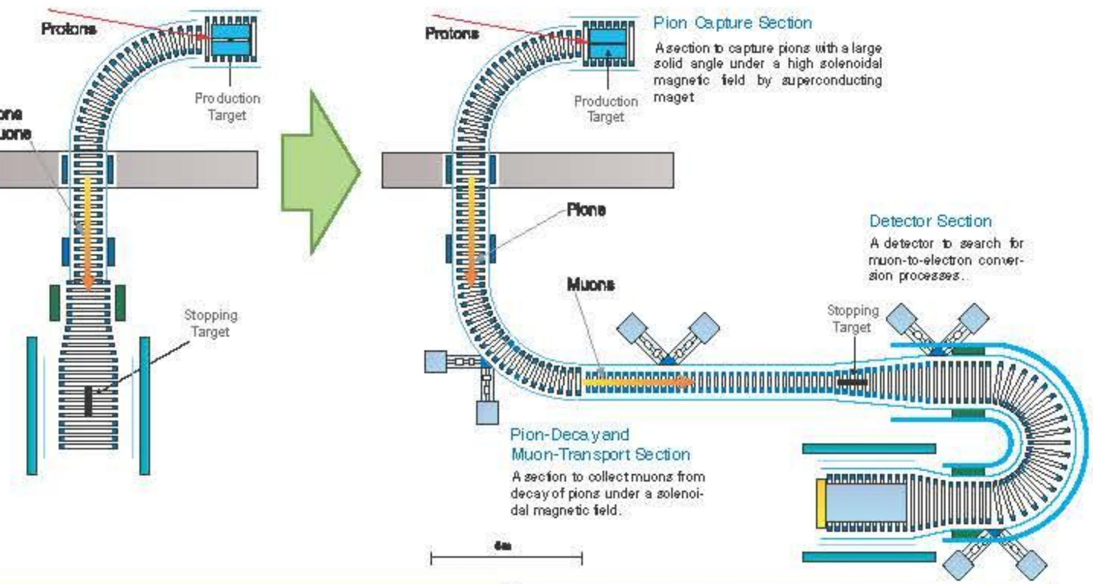
CE and DIO yield

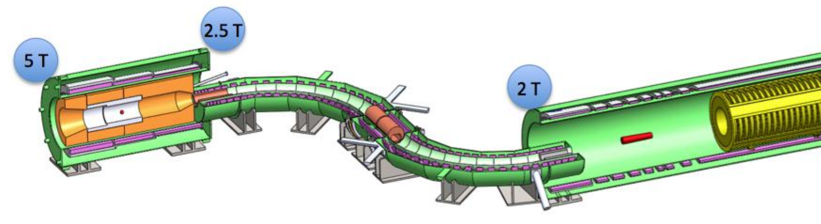


COMET and Mu2e

COMET @J-PARC

Mu2e @FNAL





COMET Phase-I :

physics run 2017-

BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL

*8GeV-3.2kW proton beam, 12 days

*90deg. bend solenoid, cylindrical detector

*Background study for the phase2

COMET Phase-II :

physics run 2019-

BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL

*8GeV-56kW proton beam, 2 years

*180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter

Mu2e :

physics run 2019-

BR(μ+Al→e+Al)<7x10^{-17} @ 90%CL

*8GeV-8kW proton beam, 3 years

*2x90deg. S-shape bend solenoid, straw tracker+calorimeter

- Both COMET Phase-I and Mu2e experiments are now optimizing their parameter get the final design. MUSIC at Osaka : proof of principle at low power, ~10^8 μ/s @ 40

Status and Schedule: Mu2e and COMET

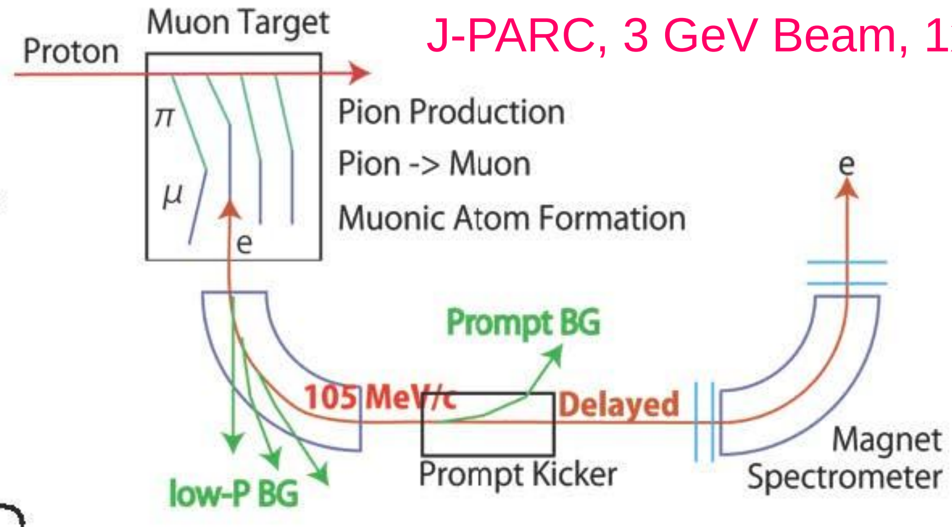
- Mu2e $B(\mu + Al \rightarrow e + Al) < 6 \times 10^{-17}$ @ 90% CL (×10000 better than current)
  - Full Fermilab approval
  - Just received CD1 level approval from DOE- Design Stage
  - Significant preliminary design on magnets and beam lines
  - Extensive detector performance and background simulations
  - Will run concurrently with neutrino program
  - Begin data-taking 2019- schedule driven mainly by time needed to build muon beamline solenoids.

- COMET Phase I $B(\mu + Al \rightarrow e + Al) < 7 \times 10^{-15}$ @ 90% CL (×100 better than current)
  - Begin data-taking ~2016-2017 with full J-PARC ring
  - Received strong recommendation from J-PARC PAC after March 2012 PAC
  - J-PARC plans to submit request for $20M for construction of muon and proton beam lines over next 5 years
  - COMET is preparing a full proposal to J-PARC PAC for submission shortly
- COMET Phase 2
  - Begin data-taking 2019 $B(\mu + Al \rightarrow e + Al) < 6 \times 10^{-17}$ @ 90% CL

A Different approach to mu to e conversion

DeeMe

J-PARC, 3 GeV Beam, 1×10^{-14}



- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
– A single mono-energetic electron
  - 105 MeV
  - Delayed : ~1μS
- No accidental backgrounds
- Physics backgrounds
– Muon Decay in Orbit (DIO)
  - $E_e > 102.5$ MeV (BR:10^{-14})
  - $E_e > 103.5$ MeV (BR:10^{-16})
– Beam Pion Capture
  - $\pi^- + (A,Z) \rightarrow (A,Z\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1)$
    $\gamma \rightarrow e^+ e^-$
  - Prompt timing

- Low Energy main part:
  suppressed by the beamline.
- High Energy tail:
  Magnet Spectrometer ($\Delta p < 0.3\%$)
- Main pulse:
  Kicker to reduce the detector rate.
- after-protons:
  Suppressed owing to the extremely small after-protons from J-PARC/RCS: $R_{AP} < 10^{-17}$.

From M. Aoki

Funding has been recommended

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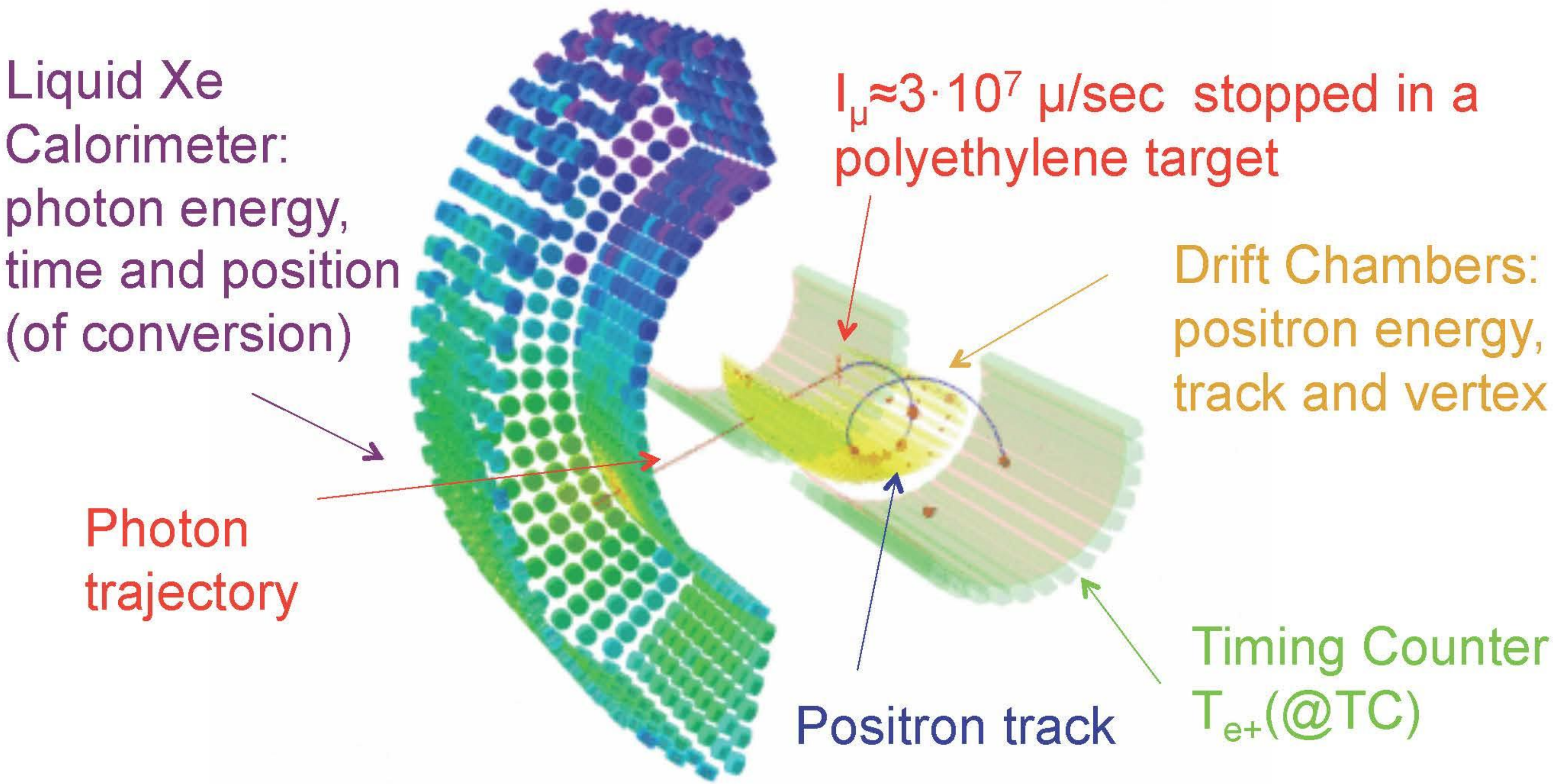
11年10月11日火曜日

Detector Concept: MEG Search for $\mu \rightarrow e\gamma$

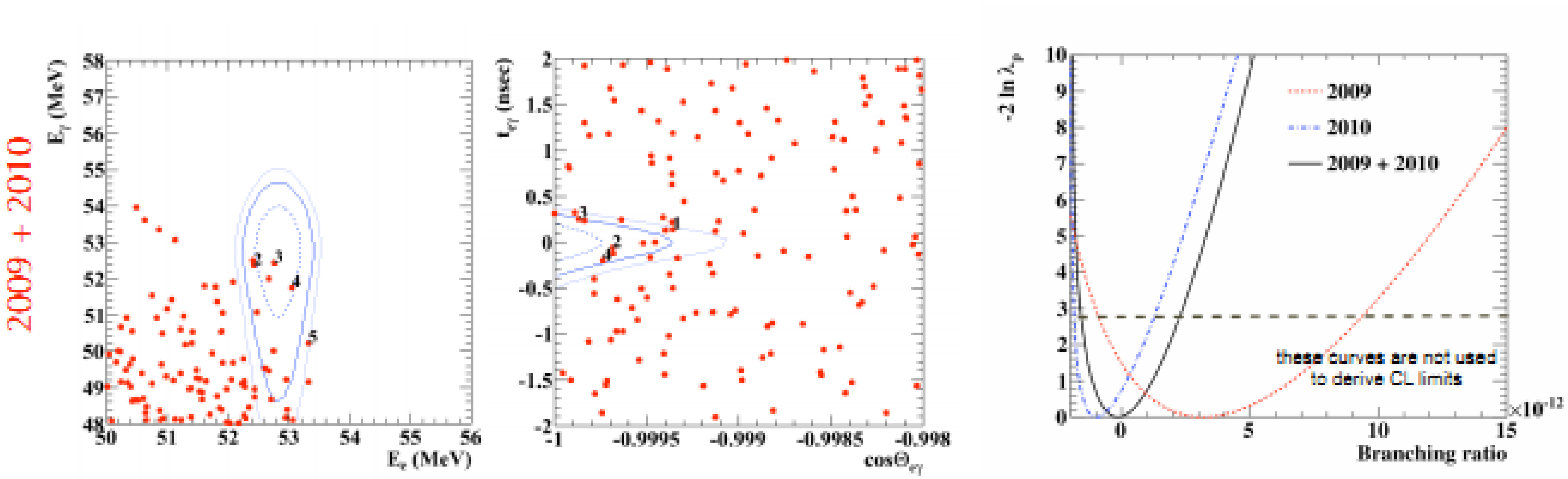


Signal: simultaneous back-to-back μ and γ with $E_\gamma = E_{e+} = 52.8$MeV

Backgrounds:

1) Accidental: e^+ from Michel muon decay and a γ (dominant)
2) Radiative muon decay

MEG: Combined 2009 + 2010

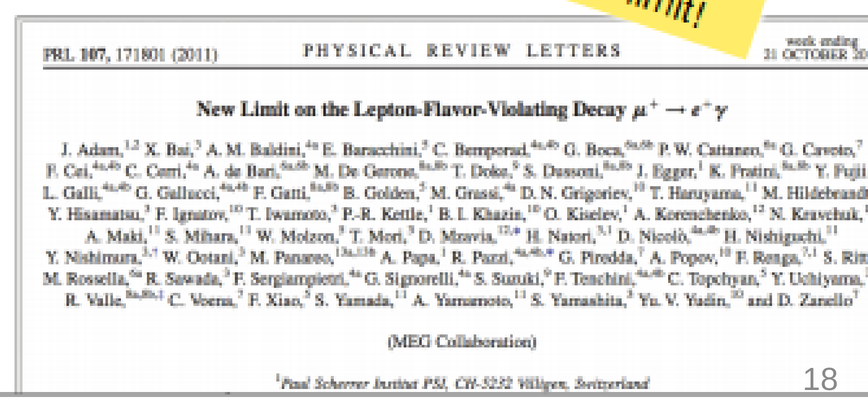


- 90% C.L. Feldman-Cousins upper limit

$$\frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \leq 2.4 \times 10^{-12}$$

5 times better than previous limit!

Data set	$\mathcal{B}_{\rm fit}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12}


PRL 107, 171801 (2011) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2011

New Limit on the Lepton-Flavor-Violating Decay $\mu^+ \to e^+\gamma$

J. Adam, X. Bai, A. M. Baldini, E. Baracchini, C. Bemporad, G. Boca, P. W. Cattaneo, G. Cavoto, F. Cei, C. Cerri, A. de Bari, M. De Gerone, T. Doke, S. Dussoni, J. Egger, K. Fratini, Y. Fujii, L. Galli, G. Gallucci, F. Gatti, B. Golden, M. Grassi, D. N. Grigoriev, T. Haruyama, M. Hildebrandt, Y. Hisamatsu, F. Ignatov, T. Iwamoto, P.-R. Kettle, B. I. Khazin, O. Kiselev, A. Korenchenko, N. Kravchuk, A. Maki, S. Mihara, W. Molzon, T. Mori, D. Mzavia, H. Natori, D. Nicolò, H. Nishiguchi, Y. Nishimura, W. Ootani, M. Panareo, A. Papa, R. Pazzi, G. Piredda, A. Popov, F. Renga, S. Ritt, M. Rossella, R. Sawada, F. Sergiampietri, G. Signorelli, S. Suzuki, F. Tenchini, C. Topchyan, Y. Uchiyama, R. Valle, C. Voena, F. Xiao, S. Yamada, A. Yamamoto, S. Yamashita, Yu. V. Yudin, and D. Zanello

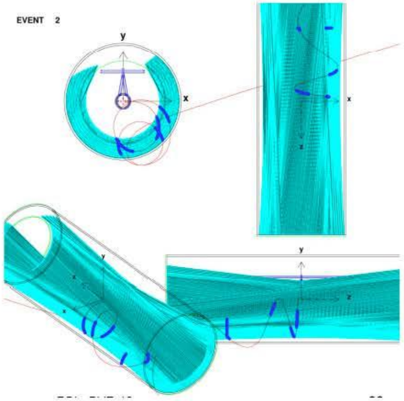
(MEG Collaboration)

[1]Paul Scherrer Institut PSI, CH-5232 Villigen, Switzerland

Toward an Upgrade of MEG

- The collaboration is considering possible upgrades to improve sensitivity by one order of magnitude (5×10^{-14})

$$Accidentals \propto R_\mu \times \Delta t_{e\gamma} \times \Delta\theta^2_{e\gamma} \times \Delta E_e \times \Delta E^2_\gamma$$



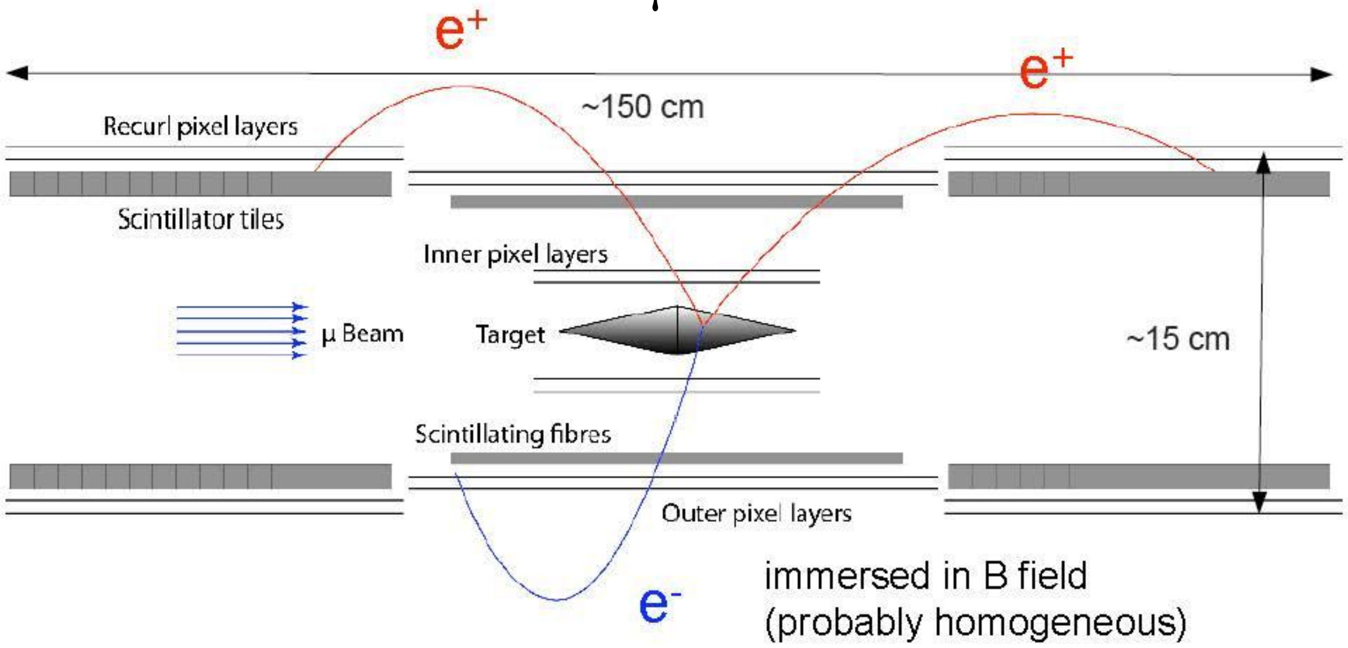
- New Drift Chamber system
  cylinidrical DC, a la Kloe,
  possibly with cluster timing capabilities
- Replacement of inner face PMTs of calorimeter with smaller ones or MPPC
- Active target with scintillating fibers
- Other solutions are also under study (e.g. new Timing counter with scintillating tiles)

- Timescale: 2 years RD + 2-3 years of running

Also, separately, studies to go to 1×10^{-16} under way (F. DeJongh)

The Mu3e Baseline Design at PSI

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



- Tracker: Silicon pixel sensors
- Scintillating fibers and tiles
  - Unambigous assigment of silicon hits

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The Mu3e Timeline

- The collaboration presented a letter of intent to PSI in february 2012

Letter of Intent for an Experiment to Search for the Decay $\mu \rightarrow eee$

A. Blondel, A. Bravar, M. Pohl
Département de physique nucléaire et corpusculaire, Université de Genève, Genève

S. Bachmann, N. Berger, A. Schöning, D. Wiedner
Physikalisches Institut, Universität Heidelberg, Heidelberg

P. Fischer, I. Perić
Zentralinstitut für Informatik, Universität Heidelberg, Mannheim

M. Hildebrandt, P.-R. Kettle, A. Papa, S. Ritt
Paul Scherrer Institut, Villigen

G. Dissertori, Ch. Grab, R. Wallny
Eidgenössiche Technische Hochschule Zürich, Zürich

P. Robmann, U. Straumann
Universität Zürich, Zürich

January 23rd, 2012

- A detailed resarch proposal will be presented to PSI in early 2013
  - 2 phases are forseen
    - Phase 1: Run with present or little upgraded PSI muon beam: $2\text{x}10^{8}\mu/s$ sufficient to reach sensitivity of 10^{-15} in 3 years 2014-2017
    - Phase 2: $2\text{x}10^{9}$ μ/s needed to reach ultimate goal (significant upgrade of PSI muon beam line needed) > 2017 $\rightarrow 10^{-16}$

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Current <1.0e-12 at 90% CL:
Bellgardt et al., Nuclear Physics B 299 (1998)

Experimental Advantages of Muon to Electron Conversion

$\tau \rightarrow \mu\gamma$
$\tau \rightarrow e\gamma$
$\tau \rightarrow 3\mu$
$\tau \rightarrow 3e$

LFV amplitudes typically larger for taus than muons, but production rates dramatically favor muons.

$$10^{11}\,\mu/\mathrm{s} \gg 10^{10}\,\tau/\mathrm{yr}$$

Huge background: ordinary decays, radiative decays

$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ and $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu\gamma$

$$\mu^\pm \rightarrow \mathrm{e}^\pm\gamma$$

MEG at PSI

$$\mu^\pm \rightarrow \mathrm{e}^\pm\mathrm{e}^+\mathrm{e}^-$$

The signal kinematics lie in a sea of background from ordinary muon decay.

$$\mu^- A(Z,N) \rightarrow \mathrm{e}^- A(Z,N)$$

COMET/PRISM at JPARC
Mu2e at FNAL

There is no such kinematic limitation for the conversion process.

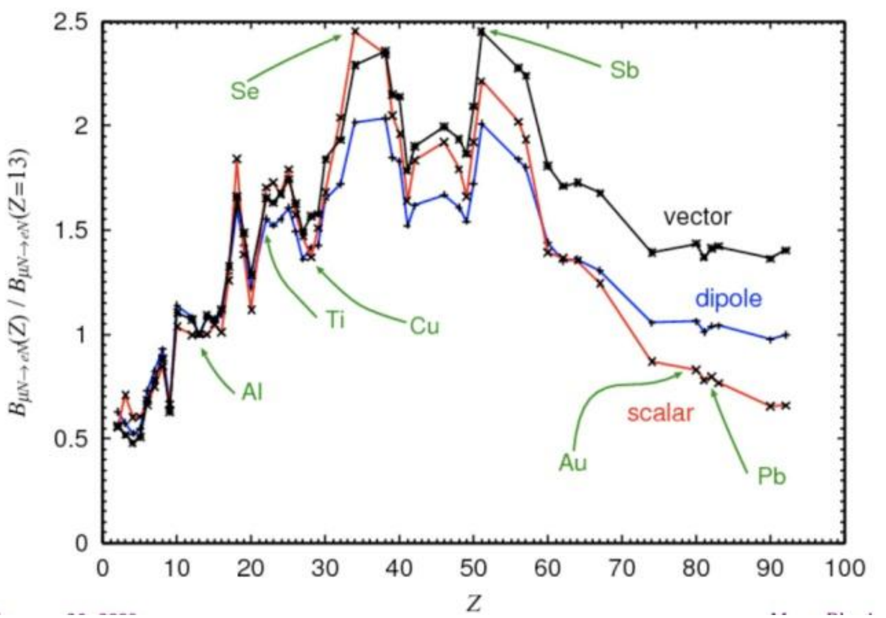
5

Upgrade path to 10^{-18}

Beyond Mu2e and COMET

- Need x100 pulsed beam and/or more efficient muon collection
- Path of upgrade → results of "Round 1"
  - Lessons learned from 10^{-16} measurement
  - If signal seen
    - If signal small, establish signal with high statistics
    - Go to high Z targets: structure of interaction will affect BR vs Z

    Need to start Meas. Period much sooner: eliminate beam pions, electrons…
  - If no signal seen
    - Go to x100 higher statistics on Al or Ti
      - Eliminating background from electrons from muon decays in orbit may require higher detector resolution
      - go to narrower muon momentum distribution to get a thinner target, less multiple scattering.
      - Requires detector configuration capable of handling much higher low energy background rates. (PRISM, cooled beams...)



Muon (g-2)

For the muon magnetic anomaly, $a_\mu=(g-2)/2$,
SM expected value (2009): 116 591 802(49)x10^{-11}
BNL-E821 (2004) measured value: 116 592 089(63) x10^{-11}
Δa_μ=287(80) x10^{-11}=(expt) – (SM)
About 3.6 s.d. difference
2 future experiments (Fermilab, J-PARC) being devloped to sharpen comparison between theory and experiment

Magnetic Dipole Moments

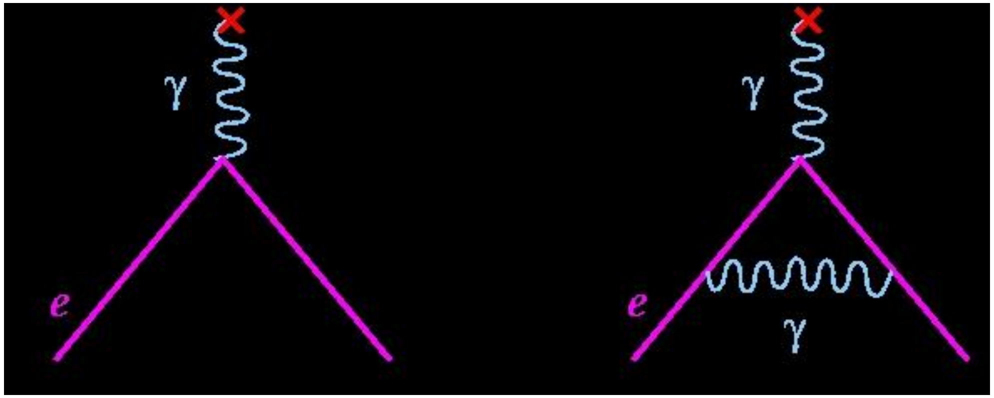
$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}$$

Dirac Equation Predicts g=2

$$i\hbar\frac{\partial\psi}{\partial t} = [\frac{p^2}{2m} - \frac{e}{2m}(\vec{L}+2\vec{S})\cdot\vec{B}]\psi$$

$$a = \frac{(g-2)}{2}$$

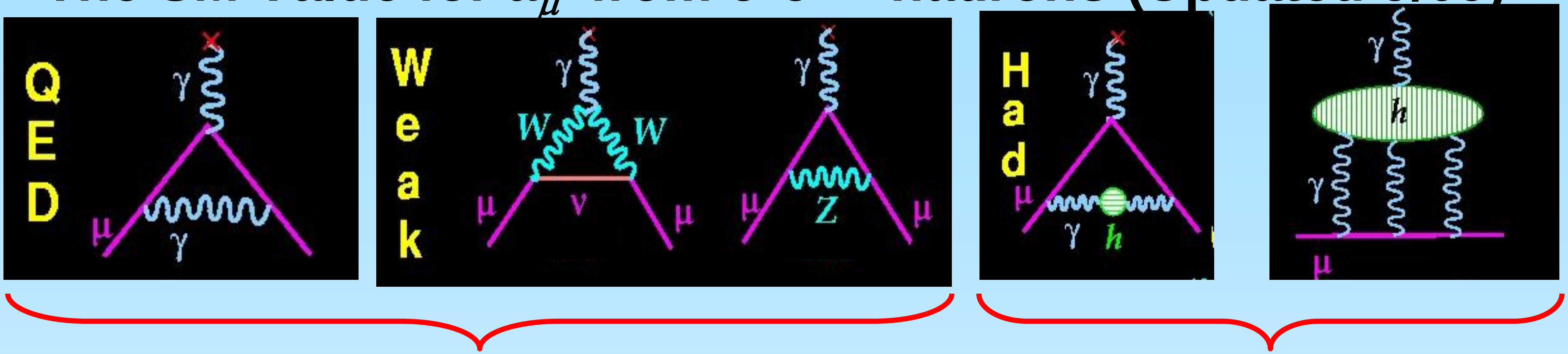
Radiative corrections change g



$$a = \frac{\alpha}{2\pi} = 0.001161$$

New virtual particles that couple to muons also add to *a*→ sensitive to new physics!

The SM Value for a_μ from $e^+e^- \to$ *hadrons* (Updated 9/09)



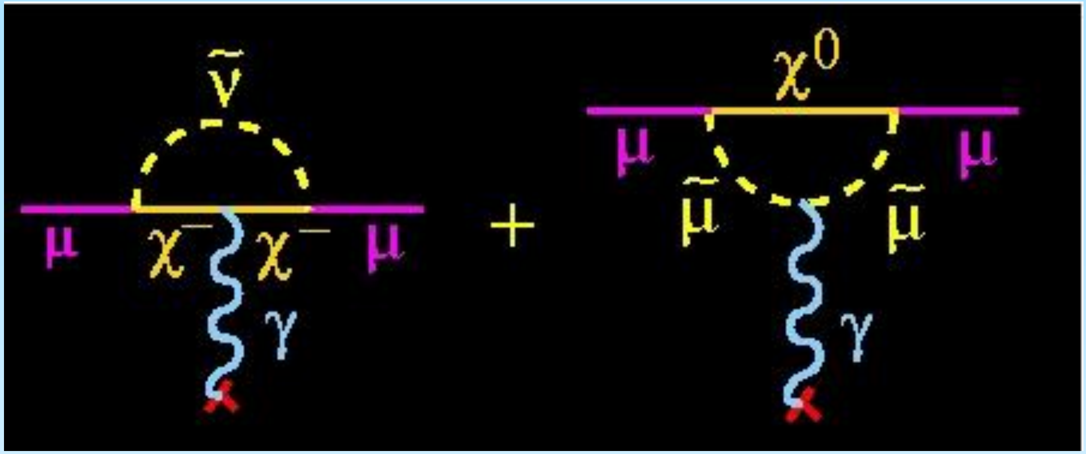
	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)	-98.4 ± 0.7
H-LBL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

*Davier et al, Eur. Phys. J. C (2011) 71:1515

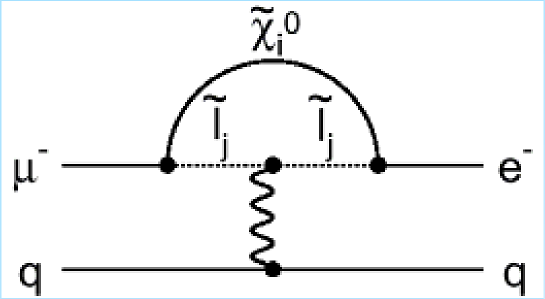
$\sigma_{\text{exp}} = \pm 63$

$\Delta a_\mu = 287(80) \times 10^{-11}$

a_μ is sensitive to a wide range of new physics, e.g.SUSY



Compare μ→e conversion



$$a_\mu(\mathrm{SUSY}) \simeq (\mathrm{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

Related processes in SUSY

$$\mu^+ \to e^+\gamma;\ \mu^- + \mathcal{N} \to e^- + \mathcal{N}$$

Experimental Determination of a_μ (BNL)

Measure muon spin precession rate in a magnetic storage ring

The magnetic, electric dipole moments $\vec{\mu} = \frac{ge}{2m}\vec{s}, \quad \vec{d} = \frac{\eta e}{2mc}\vec{s}; \quad a_\mu = \frac{g-2}{2}$

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

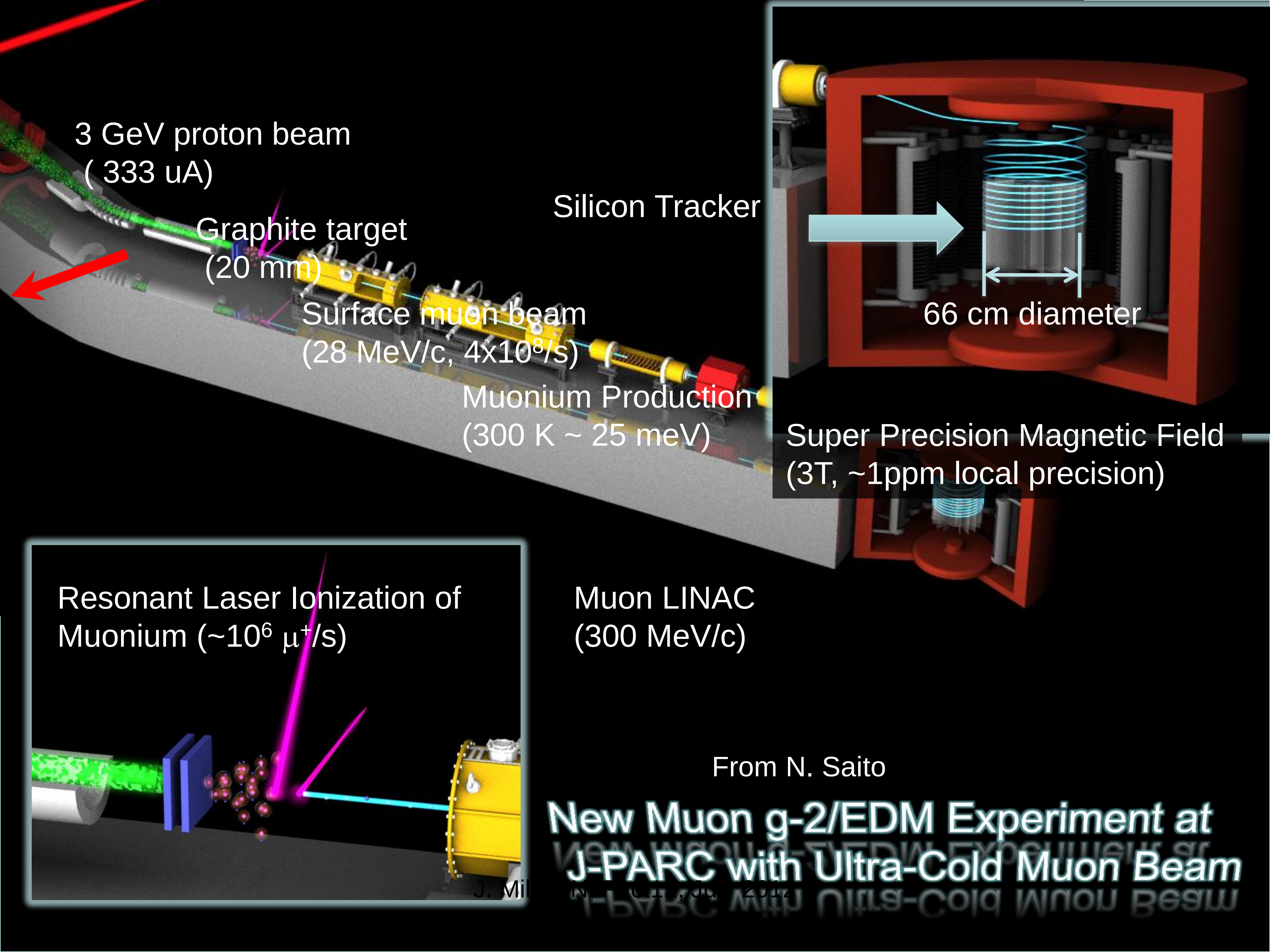
For E=0 and zero EDM $\quad \vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m} a_\mu \vec{B}$

- Precession does not depend on momentum
- Uniform B highly desirable
  - all particles precess at same rate regardless of trajectory or momentum- but then no focusing to hold muons in storage ring
- BNL Solution: uniform B with quadrupole E fields, choose 'magic gamma':

Choose p such that: $a_\mu - \frac{m^2}{p^2} = 0 \rightarrow \ p = \frac{m}{\sqrt{a_\mu}} = 3.096 \text{ GeV/c}$

- Correlation between electron and spin directions causes the number of high energy decay electrons to oscillate at the precession frequency

muon (g-2) storage ring at BNL→Fermilab


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)
Silicon Tracker
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10^6 μ^+/s)
Muon LINAC
(300 MeV/c)
From N. Saito
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

Muon g-2/JPARC- at FNAL

- There appears to be > 3 s.d. difference between experiment and theory
- Very promising beginning points to new experiments
  - FNAL
    - will improve on E821(BNL) by at least X4 using magic p=3.1 GeV/c
    - CD0 soon, building construction starting late 2012
    - plan to relocate the storage ring from BNL to FNAL in 2013
    - Data taking 2016
  - JPARC
    - will follow a very different path- complementary to FNAL
    - Similar sensitivity goals
    - In particular, will not use magic momentum
    - technically challenging new ideas
    - Has first stage approval at J-PARC

Muon EDM

- A non-vanishing EDM signals violations of T and P symmetries
- Assuming CPT this implies CP violation
- New sources of CPV sought to help explain BAU
- Muon EDM is the only measureable EDM outside the first generation
- SM predicts scaling w/r electron proportional to mass, $<10^{-38}$ e-cm
- Lepton universality, current e limit → $d_{\mu} < 5 \times 10^{-25}$ e-cm
- Some new physics models predict muon EDM: few x 10^{-22} while at the same time keeping the electron EDM small (Babu, Barr, Dorsner, 2001)

Present EDM Limits

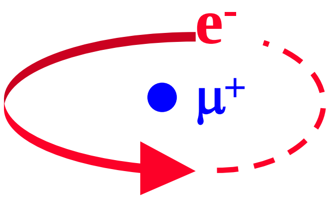
Particle	*Present EDM limit* (e-cm)	*SM value* (e-cm)
n	$<2.9\times10^{-26}$	$10^{-32} - 10^{-31}$
e^{-}	$<1.05\times10^{-27}$	$< 10^{-41}$
μ	$<10^{-18}$ (CERN g-2) $<1.8\times10^{-19}$ (BNL g-2)	$< 10^{-38}$
future exp μ	**10^{-20} to 10^{-25} ?** **x10-100** **(g2@FNAL,JPARC)**	

Dedicated Muon EDM Measurements

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

- *Frozen spin method:*
- In a storage ring, apply radial E-field so that terms in red add to zero
- Effect of EDM accumulates with time- much enhanced signal
  - Spin vector, initially aligned with the momentum, acquires a
  - vertical component proportional to the EDM
- Proposal to J-PARC (2003), Ring: r=7 m, B=0.25 T, E=2.2 MV/m, p=125MeV/c → $d_\mu < 1 \times 10^{-24}$ e-cm
- See also Adelman, et al., hep-ex/0606034v3 (2009): Ring: r=0.42 m, B=1 T, E=0.64 MV/m, p=125MeV/c → $d_\mu < 5 \times 10^{-25}$ e-cm
- Likely limited by number of muons- A natural for future high intensity machines.

Muonium (M)

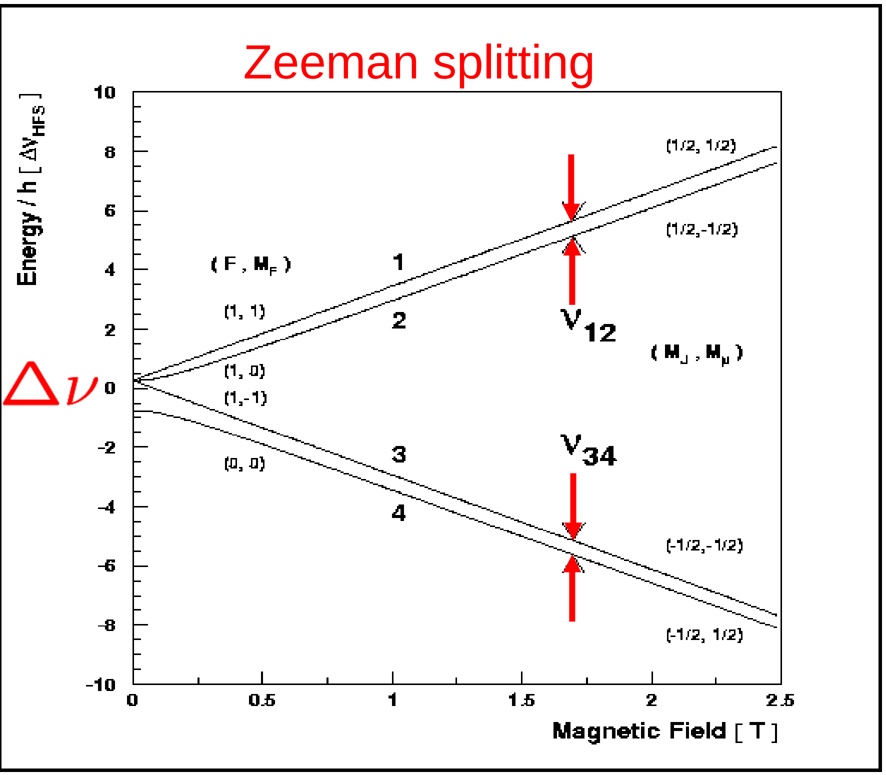


- 'M' consists of an electron bound in atomic orbit around a μ^+
  - Hydrogen-like atom
  - Unlike hydrogen atom, has no strong interaction- gives really clean look at EM and weak effects
- To make it: Low momentum μ^+ are stopped in an appropriate material
  - R&D under way at PSI and Japan to improve M production

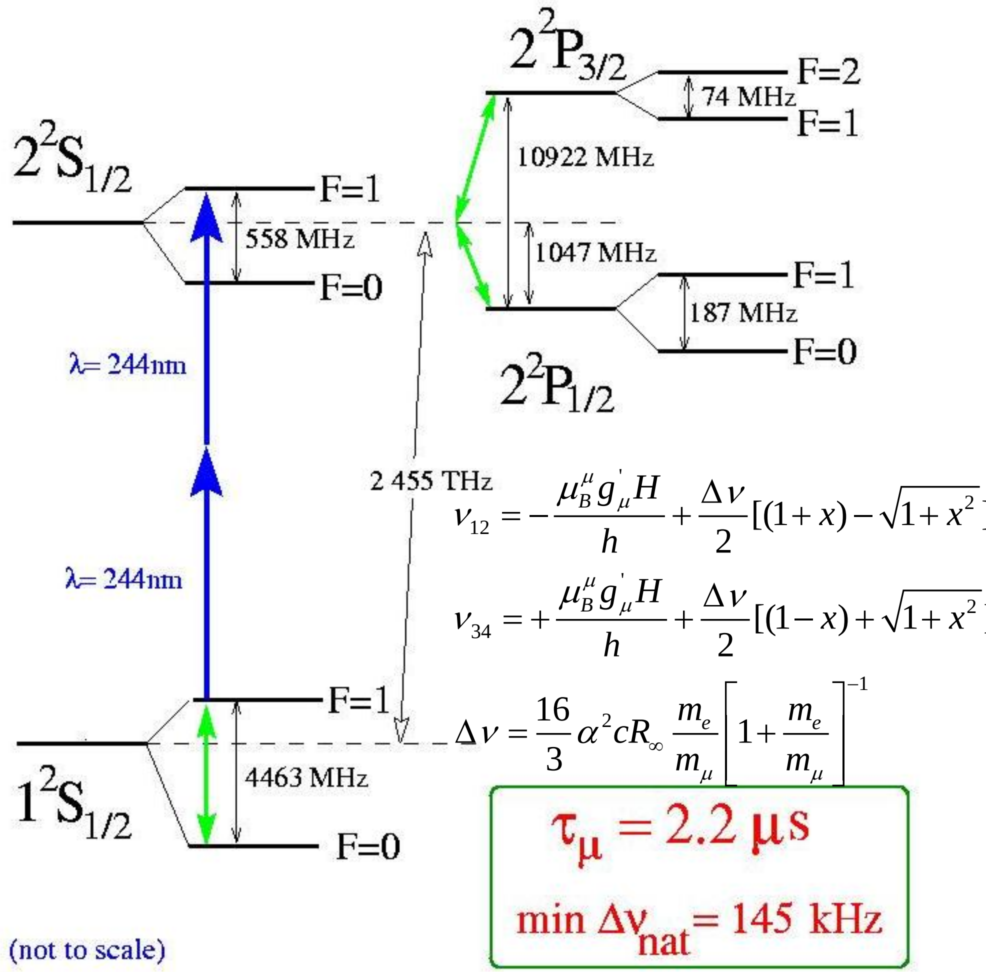
Muonium

$\mu^+ e^-$

Hydrogen (without the proton)



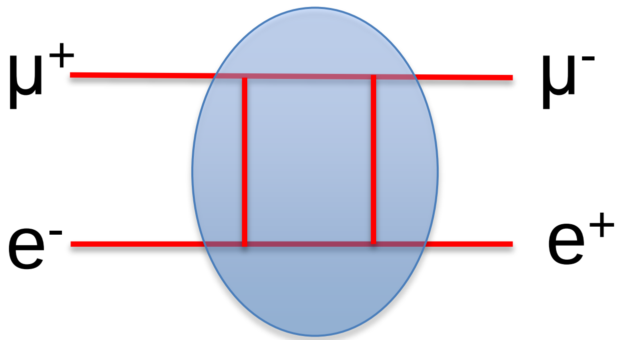
Muonium (M=μ^+e^-) Energy Levels n=1 and n=2

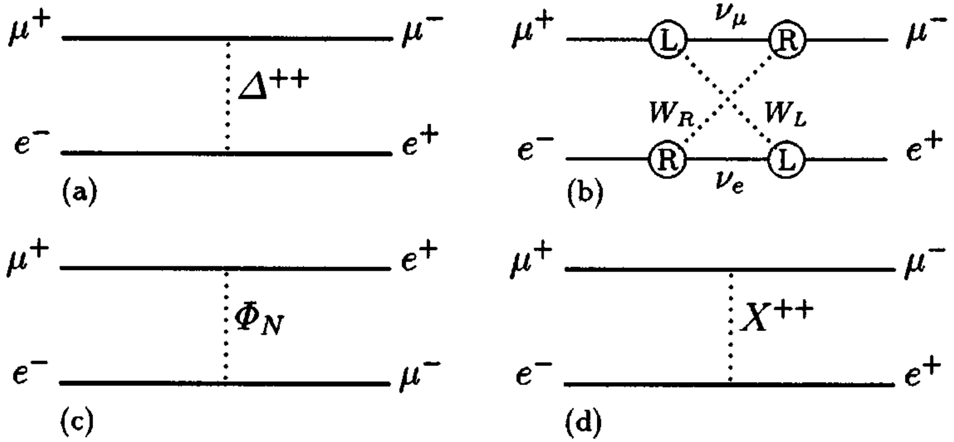


μ_μ/μ_p = 3.183 345 24(37) (120 ppb) Liu, et al., PRL 82(1999)711, CODATA 2010

Also, hfs experiments help produce best value of muon mass.

cLFV: Muonium to Anti-muonium Conversion





a) Higgs, b) heavy Majorana neutrinos
c) neutral scalar, d) bileptonic gauge boson

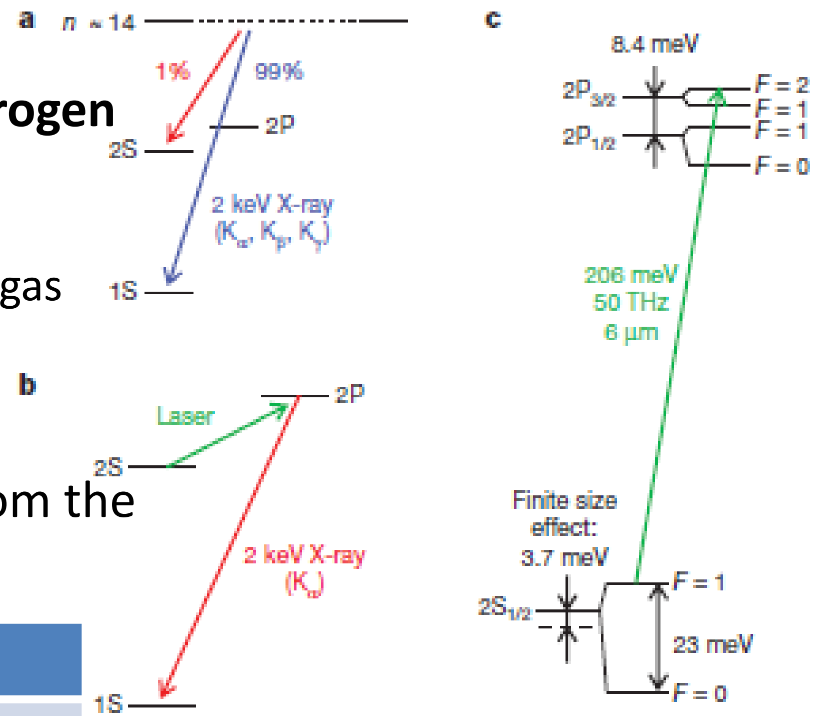
- World's best limit from PSI : (Willmann, L., Jungmann, K. et al.(1999), Phys. Rev. Lett. 82, 49)

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

- Leads to best mass bounds on X++
- Could be improved x100 with better resolution and high intensity pulsed muonium source, to *~ $10^{-5} G_F$*
  - priv. comm. with Klaus Jungmann

Proton Charge Radius

- Charge Radius of Proton from **Muonic Hydrogen**
  - μ^- in 2S atomic orbital around proton
  - R. Pohl et al., Nature 466, 213 (2010)
  - μ^- stopped in 0.001 Atmosphere Hydrogen gas
  - Large overlap of muon 2S w.f. with nucleus
    - sensitive to nuclear size
    - $\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3$
- Radius much more precise, differs by 5σ from the electron measurements 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

49881.88(76) GHz

- 2 electrons measurements agree, muon disagrees
- New forces? Problems related to bound state QED, proton structure, 5 ppm shift in Rydberg...?

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

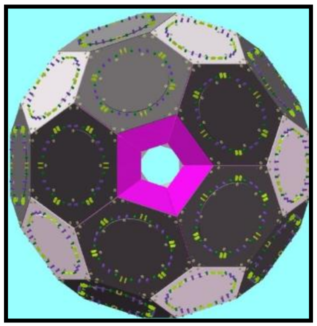
Scattering: P. J. Mohr, B.N. Taylor and D. B. Newell, Rev. Mod. Phys. 80, 633 (2008)

MuLan at PSI: Positive muon lifetime motivation: Predictive power of the SM depends on well-measured input parameters

G_F

9 ppm

0.6 ppm

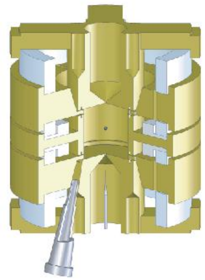


MuLan Collaboration
PRL **106**, 041803 (2011)

$$\frac{1}{\tau_\mu} \propto G_F^2$$

α

0.37 ppb

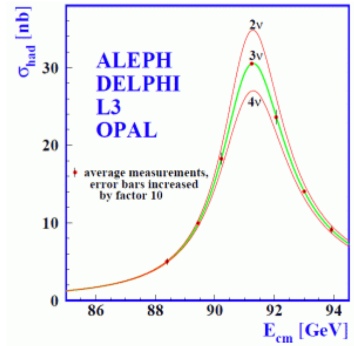


Hanneke, Fogwell, Gabrielse PRL **100,** 120801 (2008)

α^{-1} = 137.035 999 084 ± 0.000 000 051

M_Z

23 ppm



Phys.Rept.427:257-454,2006

At PSI
Muon(+) lifetime: 2196980.3 +/- 2.2 ps
G_F = 1.1663788(7) x 10^{-5} Gev $^{-2}$ +/- 0.6 ppm

M_Z = 91.1875 ± 0.0021 GeV

From D. Hertzog

In 1999, van Ritbergen and Stuart completed full 2-loop QED corrections reducing the uncertainty in G_F from theory to < 0.3 ppm (it was the dominant error before)

MuSun at PSI

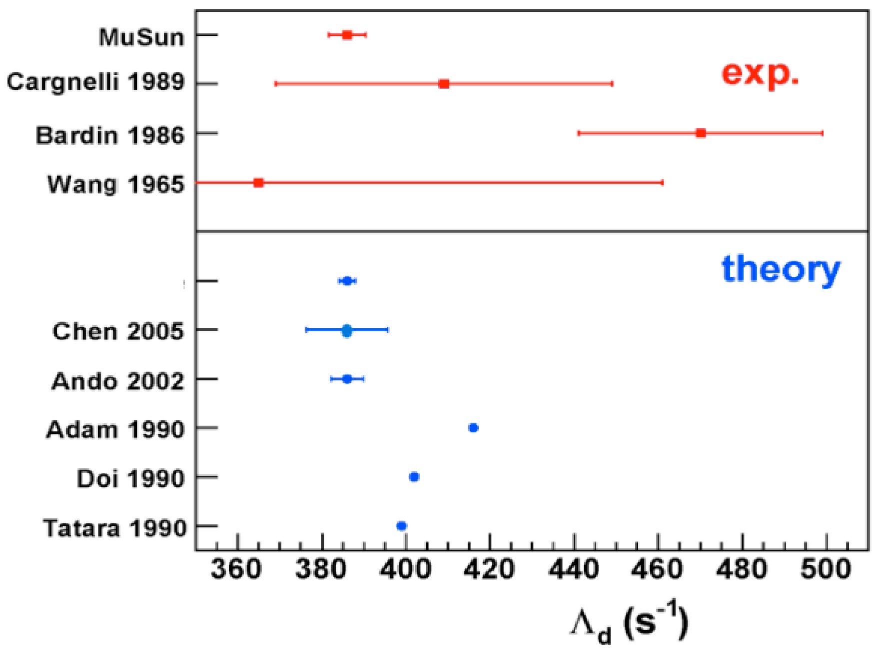
Underway now

τ_{μ^-} capture on deuteron

Measure the Nuclear Capture Rate of μ^- on Deuterium to 1.5 % (10 ppm on muon disappearance rate).

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

Weak interaction on a two-nucleon system



Important for calculations of:

Solar fusion: $p + p \rightarrow d + \nu_e + e^+$

Neutrino oscillation expts (SNO):

$\nu_e + d \rightarrow p + p + e^-$

Muon Decay Spectrum:TWIST Experiment

Standard Model, muon decay is a V-A interaction
Spectral shape, avg over electron helicity and neutrino degrees of freedom, characterized in terms of 4 parameters plus the muon polarization:

$$rate \sim x^2\left[3-3x+\frac{2}{3}\rho(4x-3)+3\eta x_0\left(\frac{1-x}{x}\right)+P_\mu\xi\cos\theta_e\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

$$E_e^{\max}\equiv\frac{m_\mu^2+m_e^2}{2m_\mu}\qquad \mathrm{x}_0\equiv\frac{m_e}{E_e^{\max}}\qquad \mathrm{x}\equiv\frac{E_e}{E_e^{\max}}\qquad \theta \text{ is angle between } \vec{\mathrm{p}}_e \text{ and muon spin}$$

$$\text{Standard Model(exp. before TWIST), } \rho=\frac{3}{4}(0.7518\pm0.0026), \delta=\frac{3}{4}(0.7486\pm0.0038),$$

$$\xi=1(1.00270.0026), \eta=0(-0.007\pm0.013), P_\mu\frac{\xi\delta}{\rho}=1(>0.99682, 90\%C.L.)$$

Recent TWIST Experiment at TRIUMF goal: measure e+ momentum and angular distribution to obtain ρ, ξ, δ to ~$2\mathrm{x}10^{-4}$: test of SM

Results

Final TWIST measurement

$$\rho = 0.74991 \pm 0.00009\ \text{(stat)} \pm 0.00028\ \text{(sys)}$$

$$\delta = 0.75072 \pm 0.00016\ \text{(stat)} \pm 0.00029\ \text{(sys)}$$

$$P_\mu \xi = 1.00083 \pm 0.00035\ \text{(stat)}^{+0.00165}_{-0.00063}\ \text{(sys)}$$

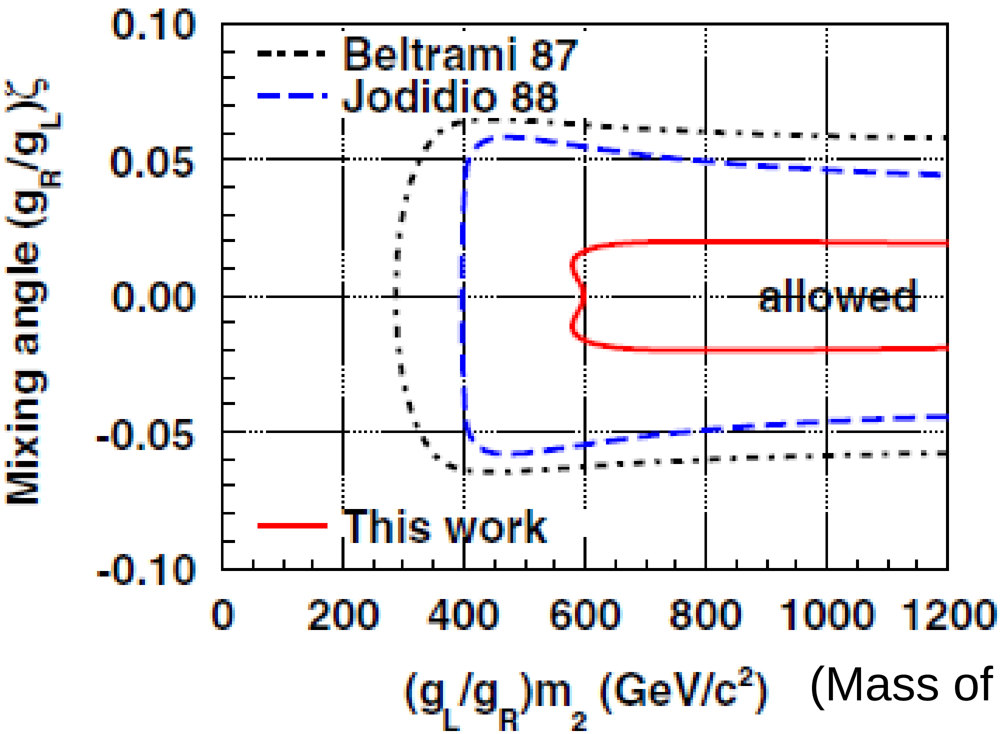
	Improvement over pre-TWIST	Deviation from SM
ρ	$\times$ 8.7	0.3 σ
δ	$\times$ 11.5	2.2 σ
$P_\mu \xi$	$\times$ 11.7	1.2 σ

Left-Right Symmetric Models

In Left-Right Symmetric Models, the (V+A) is suppressed but not zero. The left and right gauge boson fields are given by

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta$$

$$W_R = e^{i\omega}(-W_1 \cos\zeta + W_2 \cos\zeta)$$



(Mass of W_2)

Based on final TWIST results plus other existing muon decay data, e.g. electron helicity data

Intense Muon Sources

- Next generation of muon experiments need very high intensity, collimated, narrow momentum distributions
- Also for Muon Collider: accelerate to CM energies > 1 TeV
- Require intense source of cold muons
  - but muons are born witwid momentum spread and the beams are spread out
  - big challenge to cool them and reduce their size

Beam ionization cooling studies by MICE(UK), Fermilab, MuonsInc, MuCool Test Area to study cooling ideas

See WG4 parallel sessions...there are also talks on muon tomography, ProjectX,... which time prevents discussing

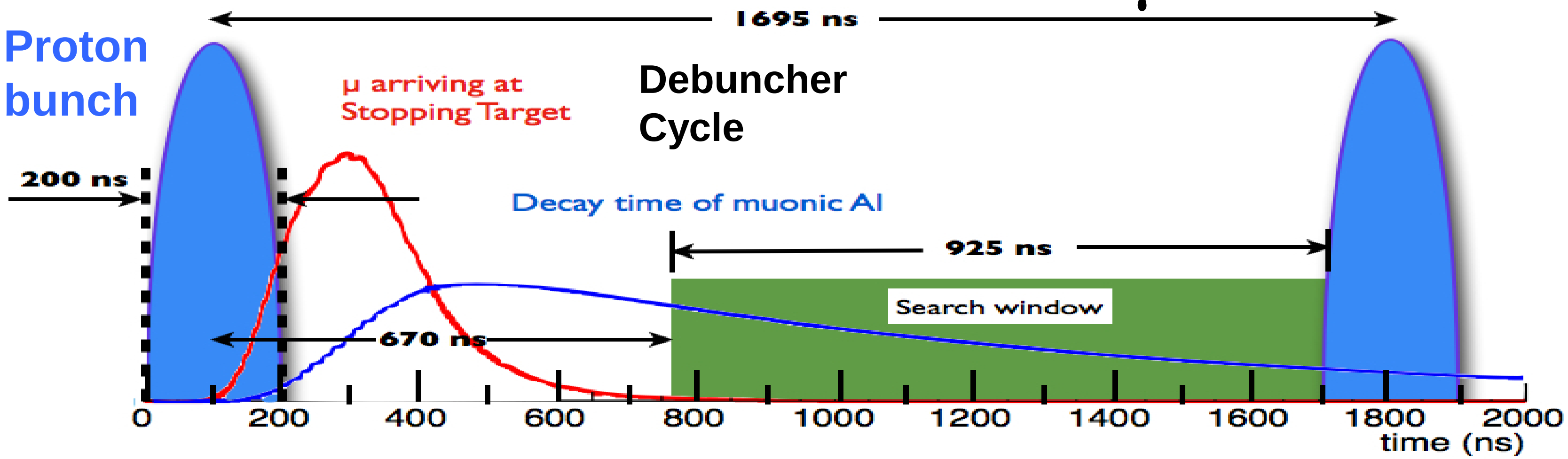
Summary

There has been and will continue to be a very active program of muon expts.
The muon has provided us with extensive knowledge of weak and EM interactions and hints of new physics
New experiments on the horizon will continue this tradition

- Results from muon experiments over the past few years test SM
  - More precise values for muon mass, lifetime, proton capture rate, (g-2) and magnetic moment, EDM, decay parameters, proton radius, cLFV(MEG: $\mu \rightarrow e\gamma$),...
- Puzzles- in addition to the basic questions, what are muons and lepton flavor?
  - Proton radius from muonic hydrogen disagrees with e scattering
  - Muon (g-2) experiment disagrees with SM prediction by > 3 s.d.
- Substantial program of Planned Experiments
  - MEG upgrade $\mu \rightarrow e\gamma$ $5\mathrm{x}10^{-14}$
  - Muon to electron conversion(Mu2e (Fermilab), DeeMe and COMET (J-PARC)0
  - Muon g-2 and EDM (Fermilab, J-PARC)
  - Muon capture on experiments (PSI), Muonum hfs...
  - Muon tomography
- Future high intensity sources (Project X, Muon Collider, ...)
  - Muon to electron conversion to 10^{-18}?
  - Muon EDM to $<10^{-25}$?
  - x100 improvement in limit Muonium- Antimuonium conversion?
  - $\mu \rightarrow e\gamma$ to 10^{-16}?
  - Challenges of muon cooling and acceleration

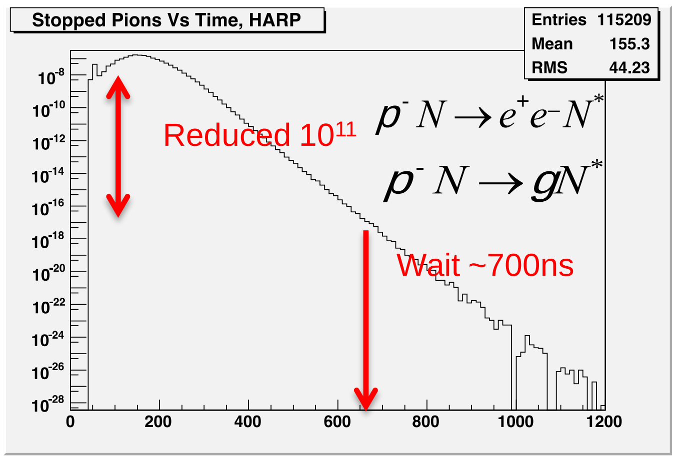
END

Pulsed beam structure for μ→e



- Cycle: narrow pulse of protons, wait ~700 ns for backgrounds (primarily pions) to decay, begin measurement period.

- Muon lifetime in Al is enough that many remain in measurement period.(864 ns)



Extinction level of 10^{-10} between bunches is crucial!

(Mu2e Experiment shown, COMET similar)