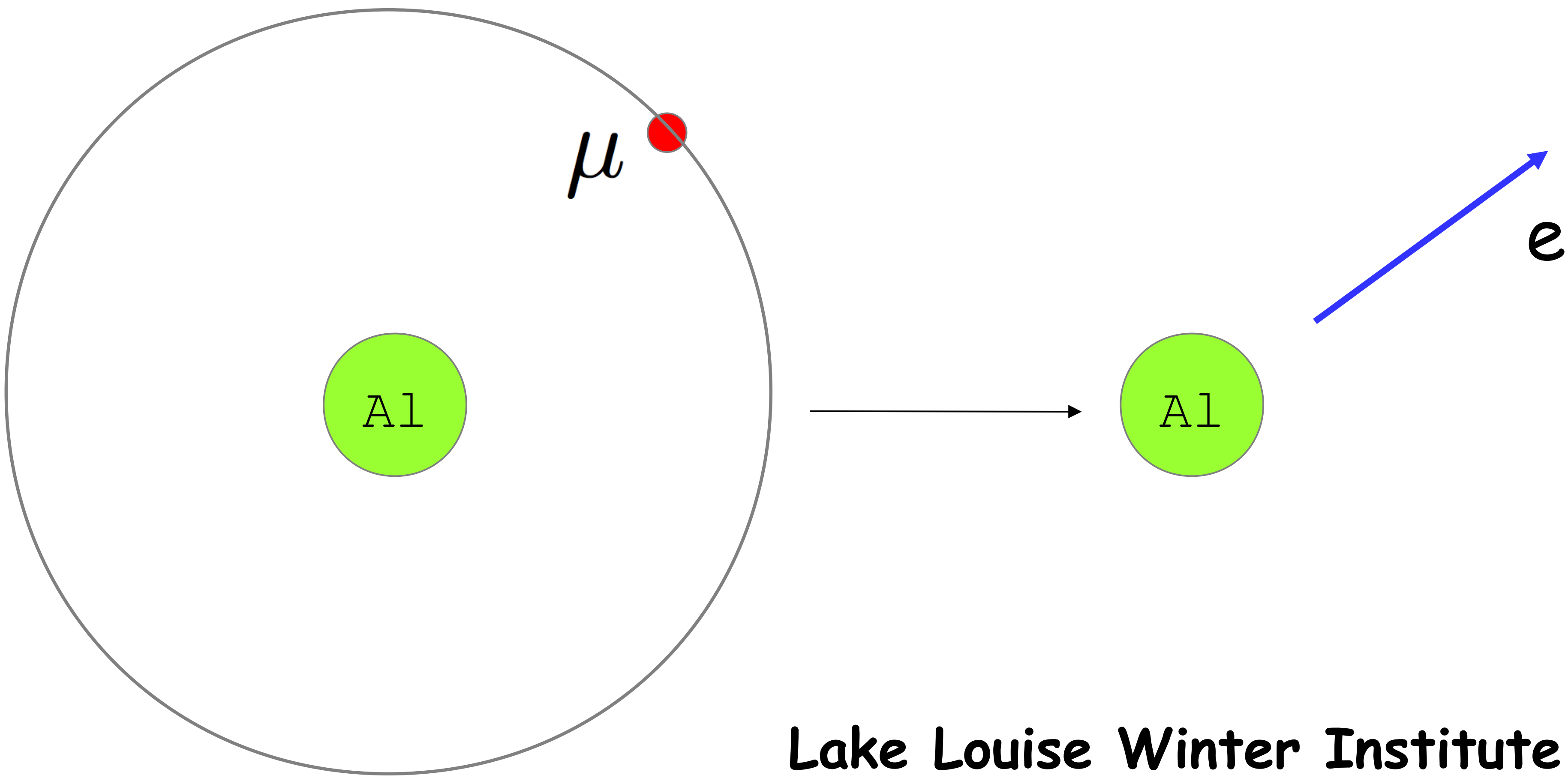
Looking for New Physics with muons



Lake Louise Winter Institute
February 22, 2016

Andrzej Czarnecki — University of Alberta

with M. Dowling, J. Piclum, R. Szafron

Outline

Muon decay

New era of experiments with muons

Muon-electron conversion: the rarest decay

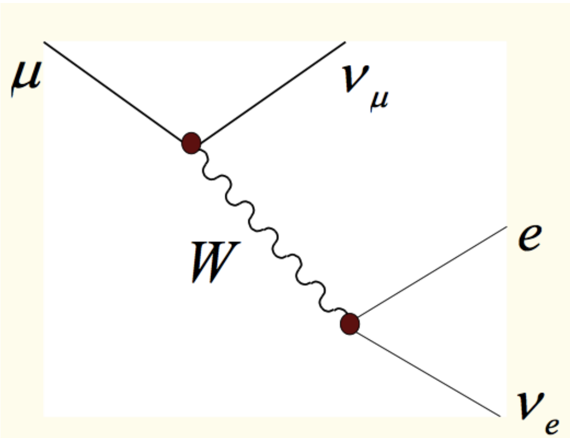
Muon decay in orbit: background for conversion

- approaches to radiative corrections

g-factor of a muon and of a bound electron

- binding effects at a new level

Free muon decay



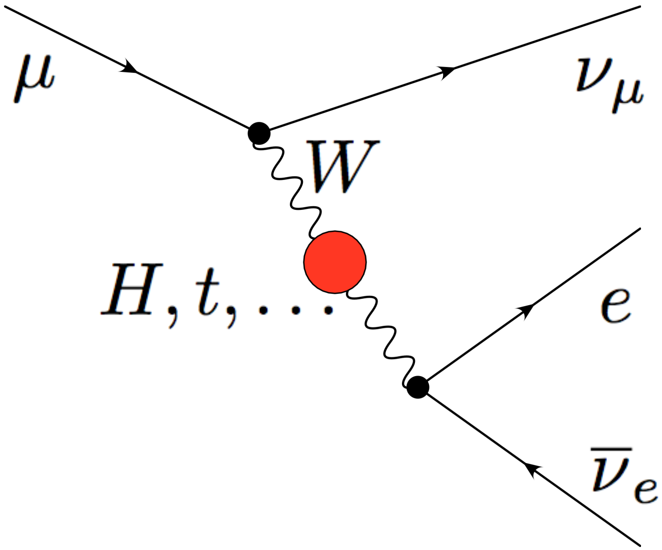
A model process in particle physics
(tools for quark decays:
charm in b-decays, Nir 1989)

The first decay process known with one- and two-loop QED effects.

Anastasiou, Melnikov, Petriello, JHEP 0709 (2007) 014
van Ritbergen + Stuart, PRL 82 (1999) 488
Pak + Czarnecki, PRL 100 (2008) 241807

Also very thoroughly studied experimentally; most recently
* decay distributions ("Michel parameters") TWIST PRD 85 (2012) 092013
* total rate (1 ppm!) MuLan PRL 106 (2011) 041803

Fermi constant and tests of the SM

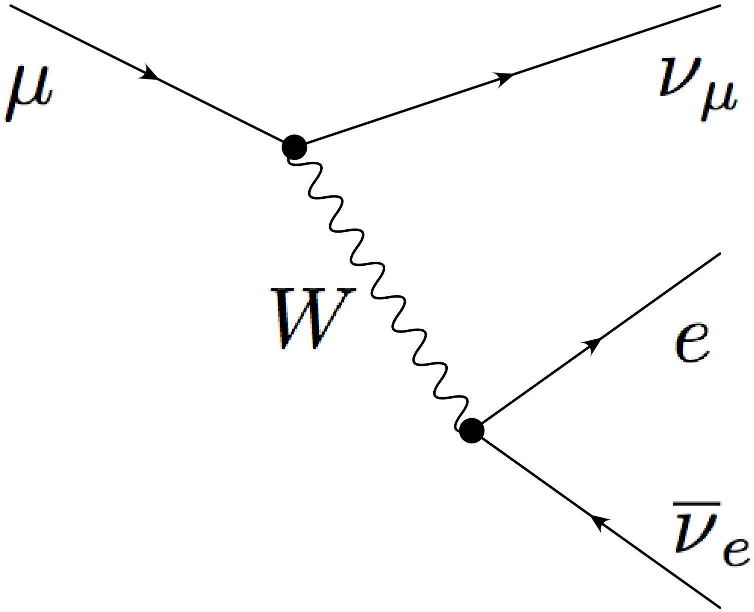


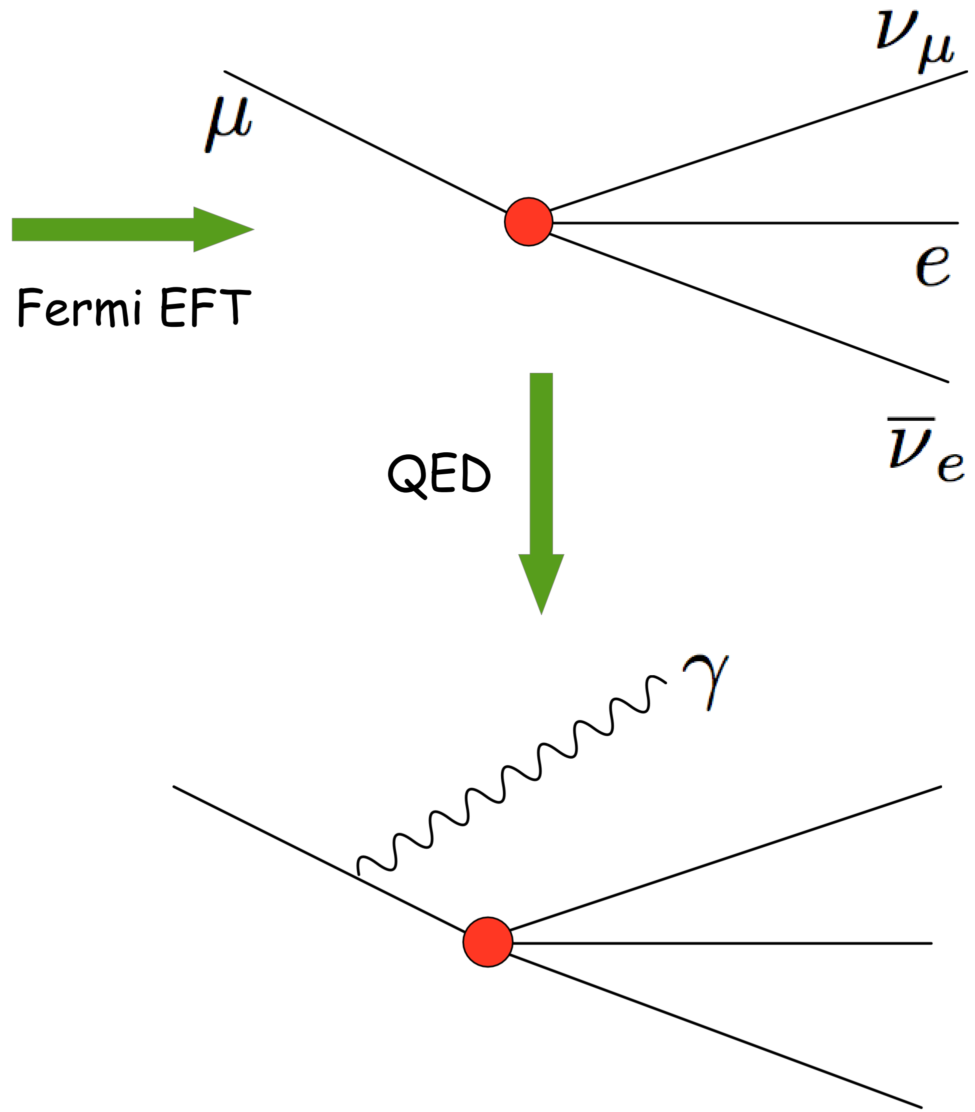
$$G_F \sim \frac{\alpha}{M_W \left(1 - \frac{M_W^2}{M_Z^2}\right)} (1 + \Delta r)$$

$$\Delta\alpha_{\text{had}} - c m_t^2 + c' \ln M_H + \ldots$$

One of the pillars of electroweak precision tests.

Determination of the Fermi constant (convention)





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

Finite m_e and QED corrections in Fermi EFT

Radiative effects in Fermi EFT

1956 one-photon, with finite m_e — Behrends, Finkelstein, Sirlin

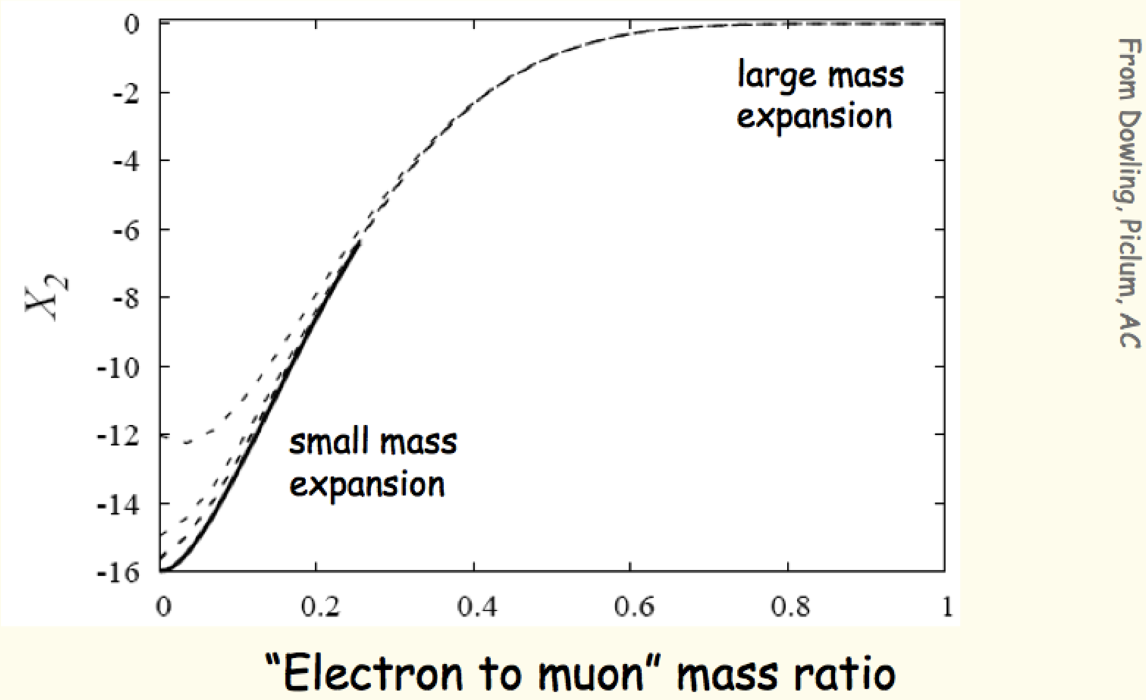
1999 two-photon, with $m_e=0$ — Stuart, van Ritbergen

2007 two-photon, spectrum of E_e — Anastasiou, Melnikov, Petriello

2008 two-photon, with finite m_e — Pak, AC

Can one go further: to three loops?

We have found an interesting way while checking the two-loop result: the calculation would be easier if the electron was very heavy, almost as heavy as the decaying muon.



Note: the plot actually for QCD.
QED given by a subset of QCD results.

Lepton Flavor Violation

New era of experiments with muons

PSI (Switzerland):

- muonic atoms
- mu -> e + gamma
- mu + p scattering
- mu -> eee

Fermilab (USA):

- g-2
- Mu2e

J-PARC (Japan):

- g-2
- DeeMe
- COMET
- muonium HFS

Muons are indeed a great tool for New Physics searches:
long-lived, just massive enough, easy to produce, with convenient spin properties.

They are also mysterious. Some precise measurements disagree with expectations:
g-2, proton radius, B-decays.

$$B^0 \to K^{*0}\mu^+\mu^-$$

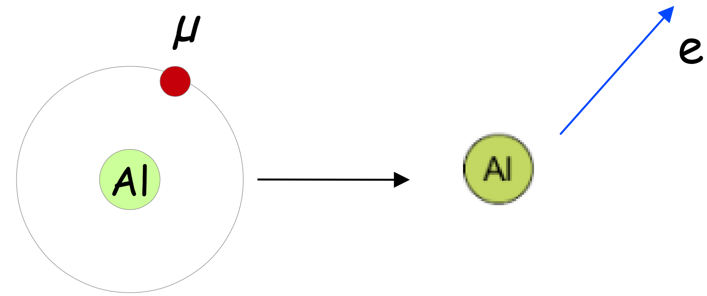
$$R_K = \mathrm{BR}(B^+ \to K^+\mu^+\mu^-)/\ \mathrm{BR}(B^+ \to K^+e^+e^-)$$

Muon-electron conversion: probes various types of interactions

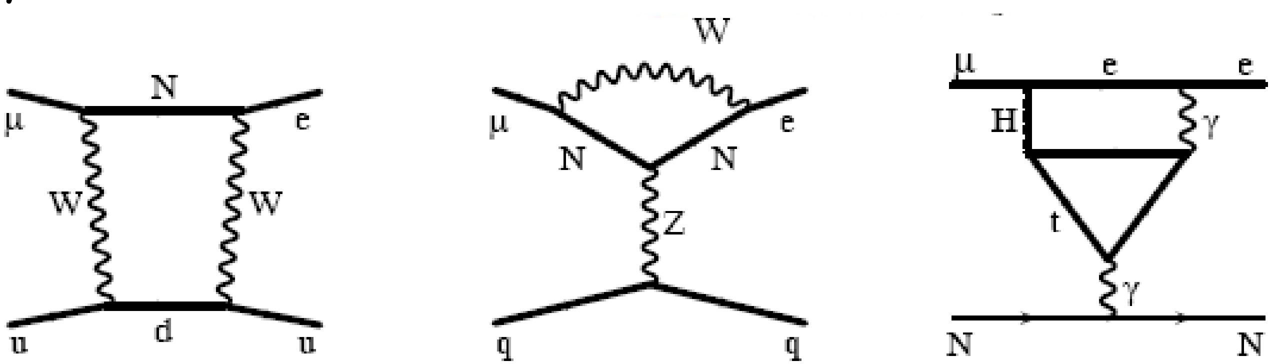
Non-dipole interactions are not (directly) probed by processes with external photons, by gauge invariance requirements.

New process: muon-electron conversion

(as well as mu --> eee)

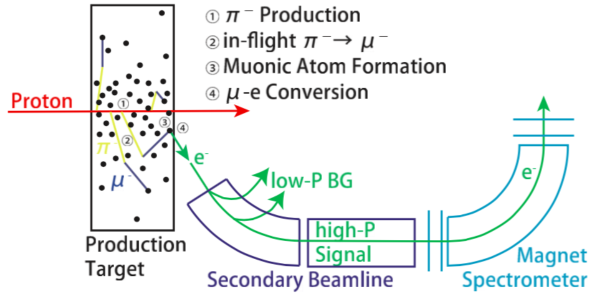


Variety of mechanisms:



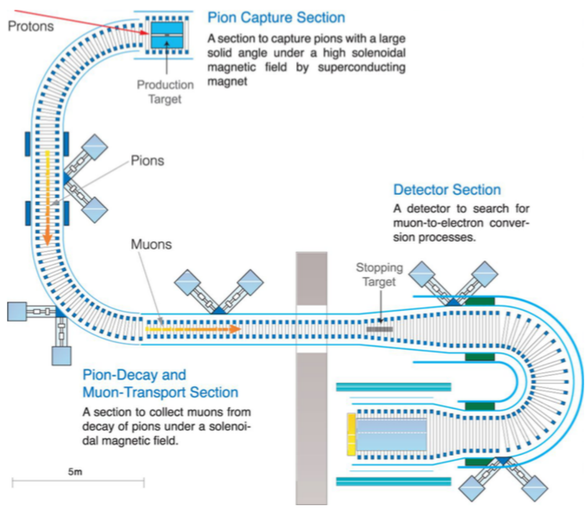
Muon-electron conversion plans
(The Next Big Thing in muon physics)

DeeMe
J-PARC



starts 2016;
aims for 1e-13 (graphite target),
followed by 1e-14 (SiC target)

COMET
Phase 1
J-PARC

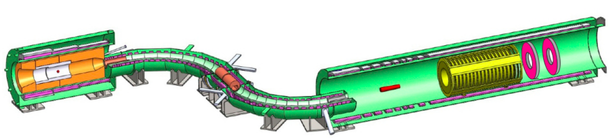


7e-15

COMET
Phase 2
J-PARC

2.6e-17

Mu2e
Fermilab

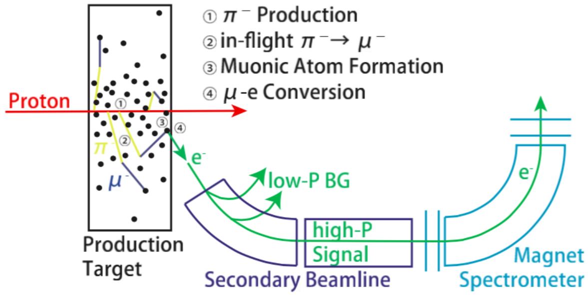


2e-17

from Hiroaki Natori JPS Conf. Proc. 8, 025017 (2015)

Muon-electron conversion plans (The Next Big Thing in muon physics)

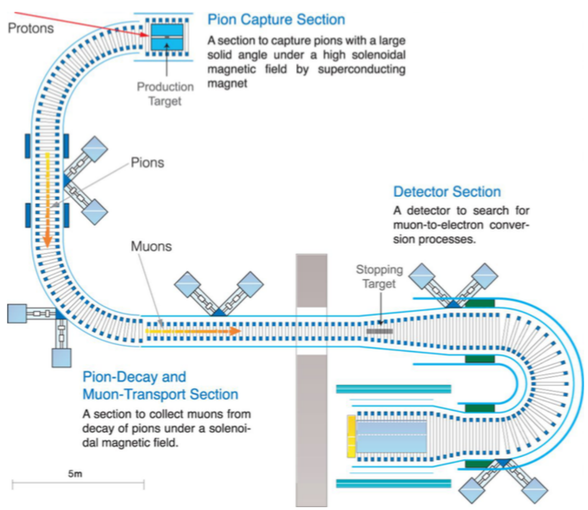
DeeMe
J-PARC



starts 2016;
aims for 1e-13 (graphite target),
followed by 1e-14 (SiC target)

For comparison,

$BR(\mu \to e\gamma) <$ 4e-13



COMET
Phase 1
J-PARC

7e-15

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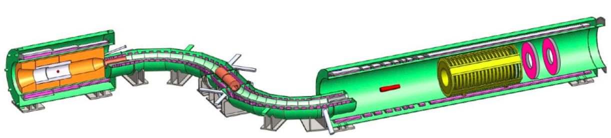


2e-17

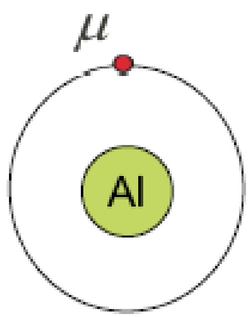
from Hiroaki Natori JPS Conf. Proc. 8, 025017 (2015)

Comparison with scattering experiments

Highest luminosity in fixed-target experiments

$$\sim 10^{37\ldots38}/\left(\mathrm{cm}^2\cdot\mathrm{s}\right)$$

In a single muonic atom



$$\begin{aligned}\mathrm{flux} &= \mathrm{density}\times\mathrm{velocity}\\ &= \left|\psi\left(0\right)\right|^2\times Z\alpha = \frac{m_\mu^3 Z^4\alpha^4}{\pi}\sim Z^4\times 4\cdot 10^{39}/\left(\mathrm{cm}^2\cdot\mathrm{s}\right)\end{aligned}$$

Comparison with scattering experiments

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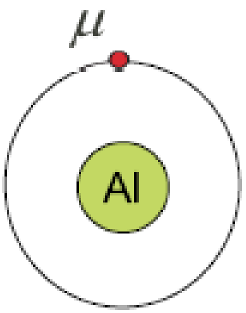
$$\sim 10^{37\ldots38} / \left(\mathrm{cm}^2 \cdot \mathrm{s}\right)$$

In a single muonic atom



$$\text{flux} = \text{density} \times \text{velocity}$$

$$= |\psi(0)|^2 \times Z\alpha = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} \sim Z^4 \times 4 \cdot 10^{39} / \left(\mathrm{cm}^2 \cdot \mathrm{s}\right)$$

Many atoms are studied in parallel: ~10^{11} muons stopped per second; each lives about 10^{-6} seconds: 10^5 atoms present:

$$\boxed{\sim 10^{49} / \left(\mathrm{cm}^2 \cdot \mathrm{s}\right)}$$

What does the conversion rate mean?

Three fates of a bound muon:

- decay in orbit (dominates for Z < 11)

- nuclear capture (most likely for Z > 11)

- muon-electron conversion (less that 4.3e-12 cases)

$$\Gamma(\mu^- \mathrm{Ti} \to e^- \mathrm{Ti})/\Gamma(\mu^- \mathrm{Ti} \to \mathrm{all}) < 4.3 \times 10^{-12}$$ PDG

On the other hand, for free muons: $\Gamma(\mu \to e\gamma)/\Gamma(\mu \to \mathrm{all}) < 4.2 \times 10^{-13}$

Which of these bounds is “better”?

Two types of operators contribute to LFV

$$O_L^D = e\, m_\mu \left(\bar{e}\sigma^{\mu\nu} P_L \mu\right) F_{\mu\nu}$$

$$O_{ff}^{V\,LL} = \left(\bar{e}\gamma^\mu P_L \mu\right)\left(\bar{f}\gamma_\mu P_L f\right)$$

$$O_{ff}^{V\,LR} = \left(\bar{e}\gamma^\mu P_L \mu\right)\left(\bar{f}\gamma_\mu P_R f\right)$$

...

$$P_{L/R} = \left(\mathbb{I} \mp \gamma^5\right)/2$$

connects opposite chiralities of e, mu

equal chiralities

Crivellin, Davidson, Pruna, Signer 1702.03020.

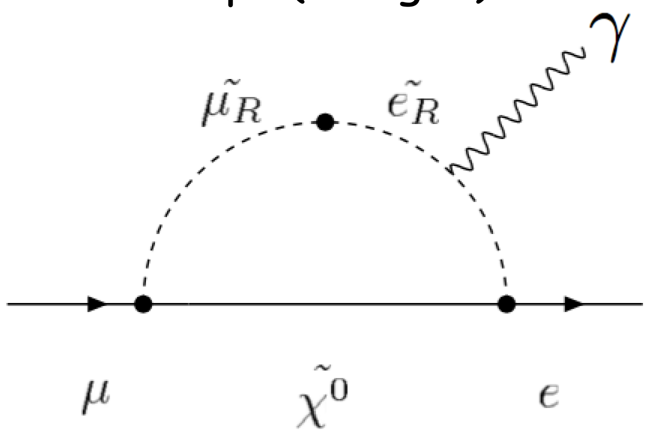
Only the chirality-flipping operators O^D_L and O^D_R contribute to $\mu \to e\gamma$

All operators contribute to the muon-electron conversion (because there are no external photons -> no gauge constraints).

Take-home message #1: conversion probes a broader range of physics.

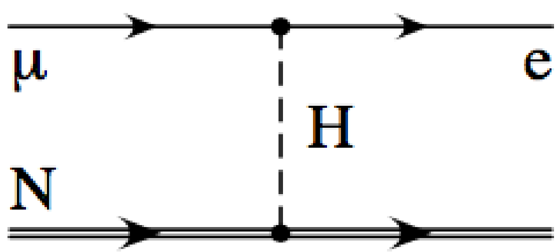
Examples of New Physics scenarios

Dipole operators: closed SUSY loops (like g-2):



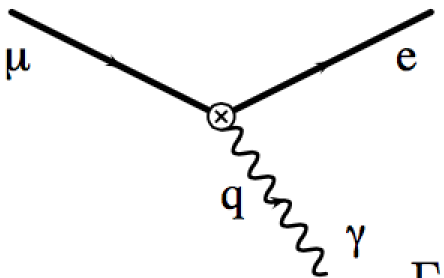
Kuno, Okada
RMP 73, 151

Scalar four-fermion operator, in case of a flavor-offdiagonal Higgs coupling



Contributes mainly to the conversion

How fast is the conversion induced by dipoles?

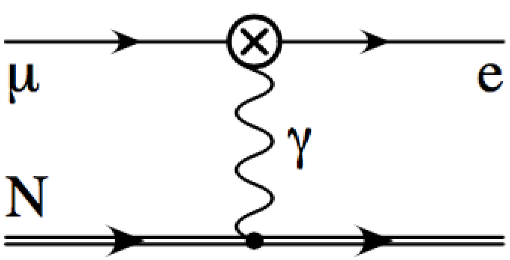


$$= \bar{e}\, \sigma^{\mu\nu} (f_M + f_E \gamma_5)\, \mu \cdot q_\mu A_\nu$$

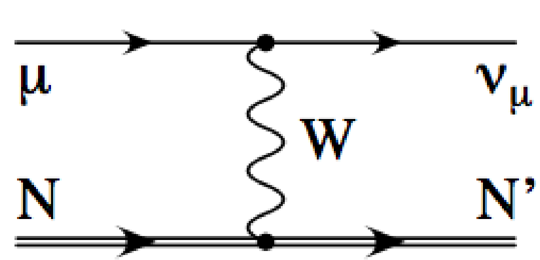
$$\Gamma(\mu \to e\gamma) = \frac{m_\mu^3}{8\pi} \left(|f_M|^2 + |f_E|^2 \right) \equiv \frac{m_\mu^3 f^2}{8\pi}$$

$$BR(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to \text{all})} \simeq \frac{m_\mu^3 f^2}{8\pi} \cdot \frac{192\pi^3}{G_F^2 m_\mu^5} = 24\pi^2 \left(\frac{f}{G_F m_\mu} \right)^2$$

The same operator induces conversion, competing with capture:



$$\sim \frac{m_\mu f}{m_\mu^2}$$



$$\sim G_F$$

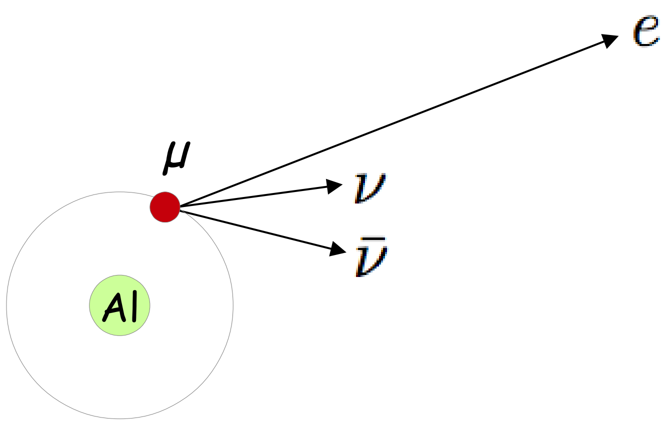
Take-home message #2: in case of dipole operators,

$$BR(\text{conversion}) \sim \frac{BR(\mu \to e\gamma)}{200(\text{Ti}) - 400\,(\text{Al, Pb})}$$

Czarnecki, Marciano, Melnikov

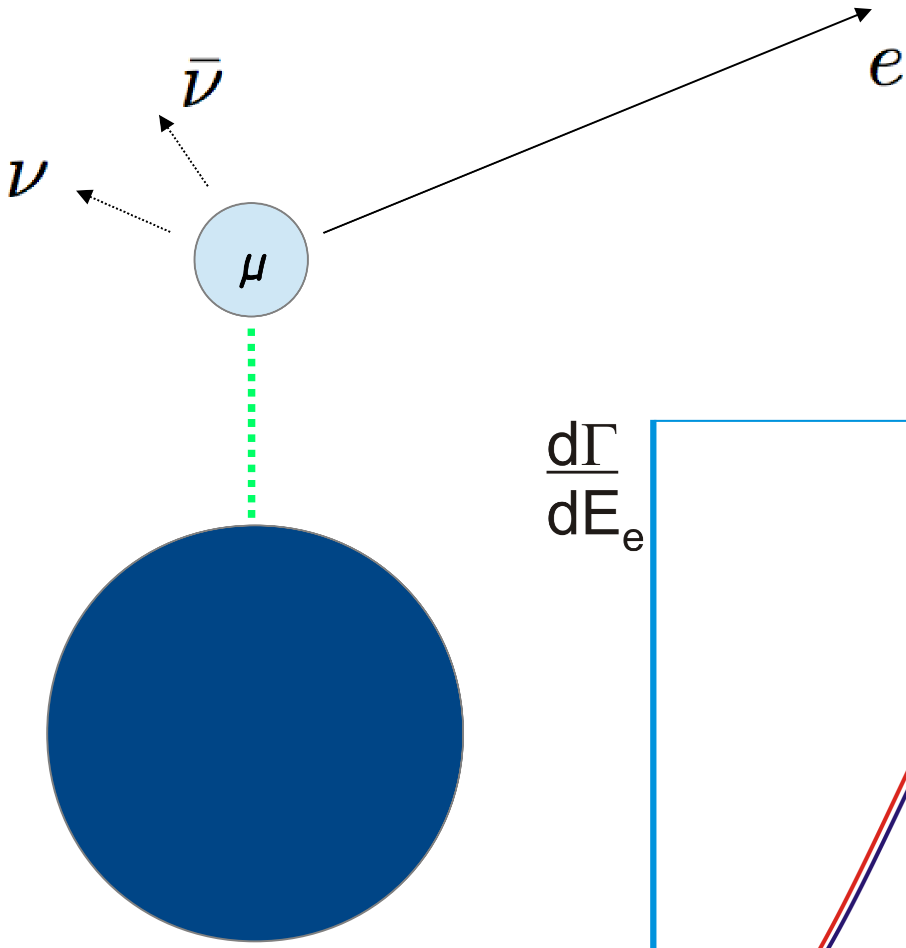
Background for the conversion search

Normal decay of the muon bound in the atom
can produce high-energy electron,

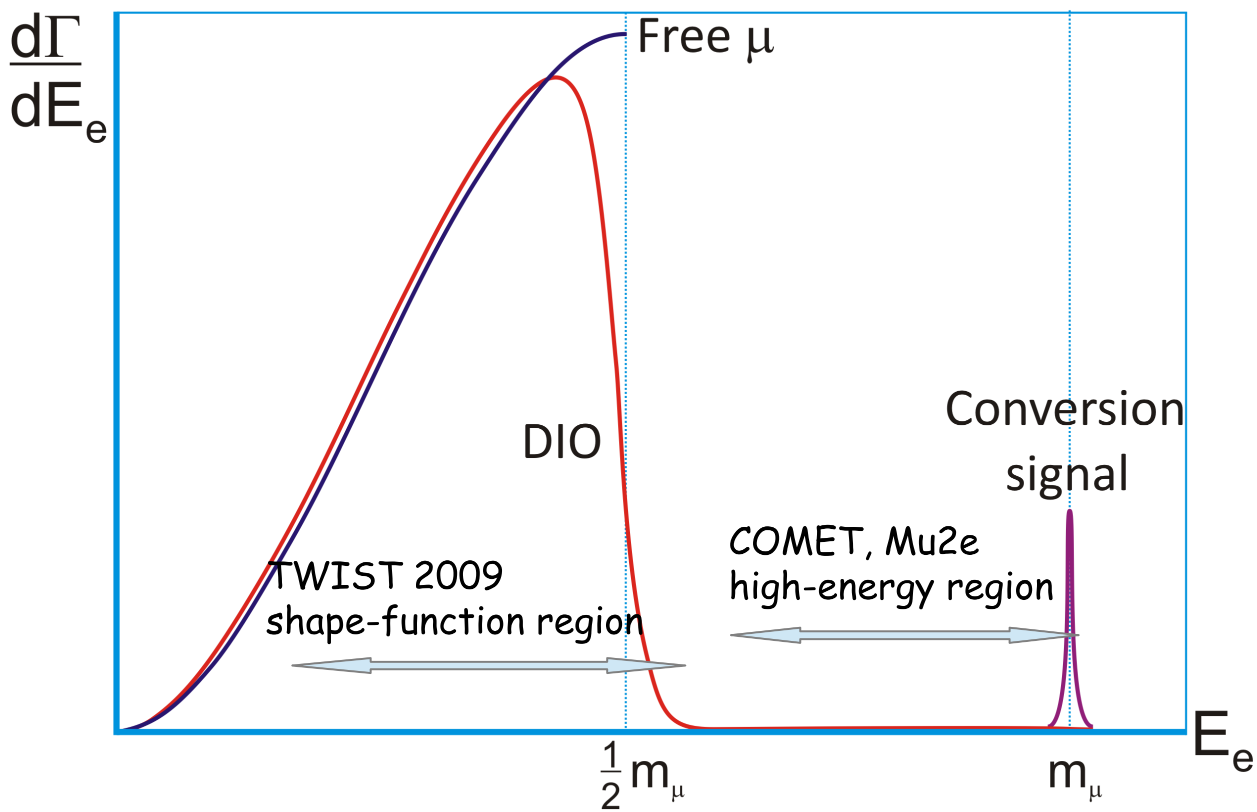


Spectrum has to be well understood.

Electron spectrum in a bound muon decay



Electron energy can be as large as the whole muon mass

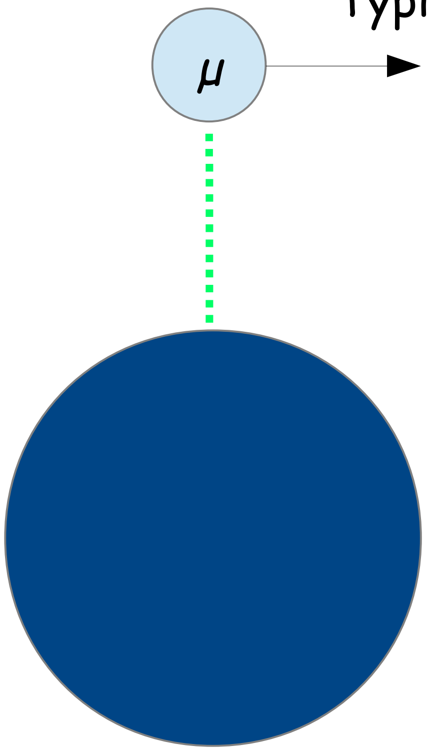


Muon decay-in-orbit spectrum:
the shape-function region

Experiment: TWIST

Two effects: muon motion & Coulomb attraction

Typical velocity $\sim Z\alpha$



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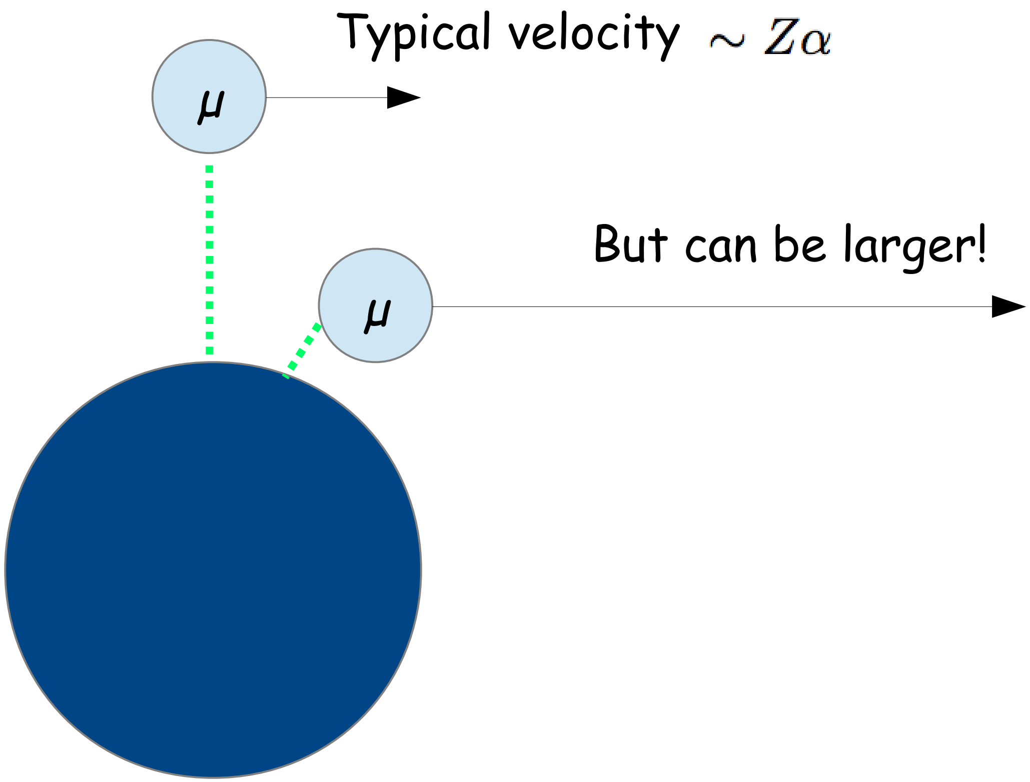

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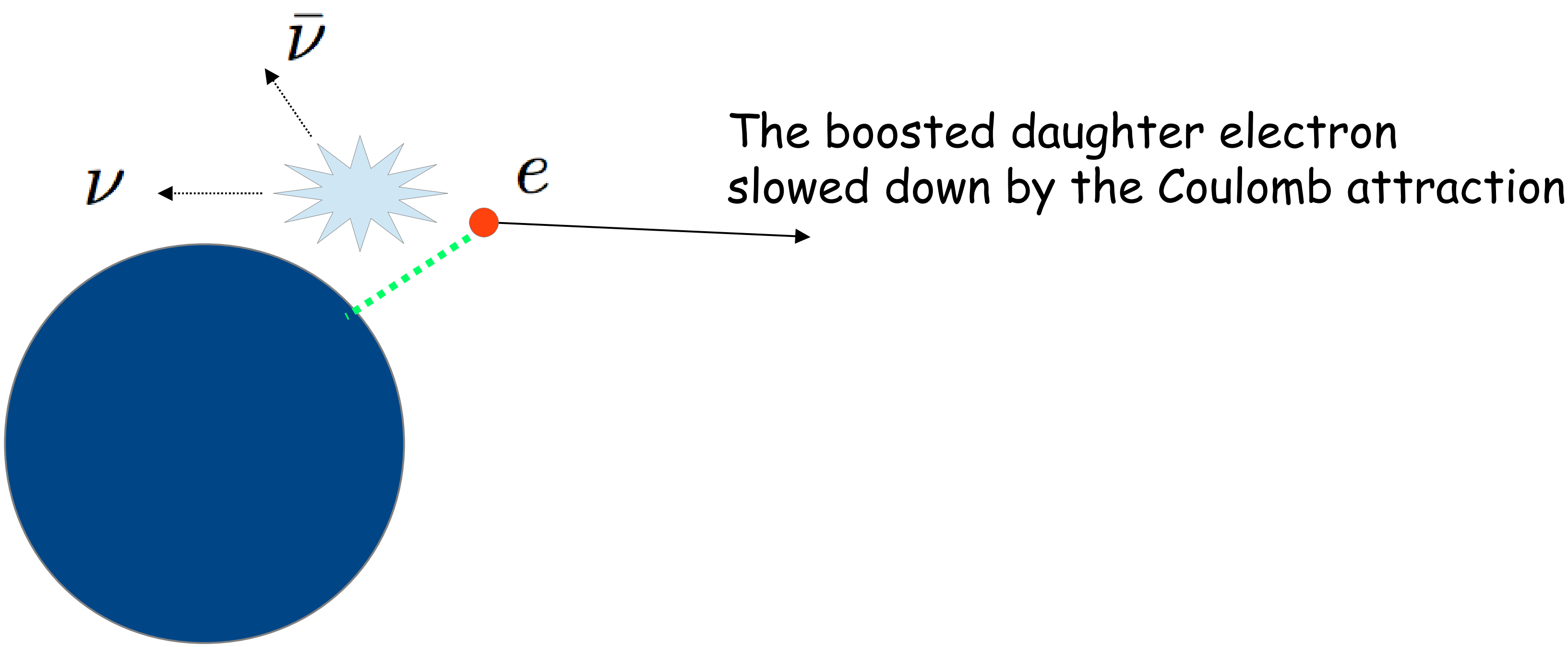
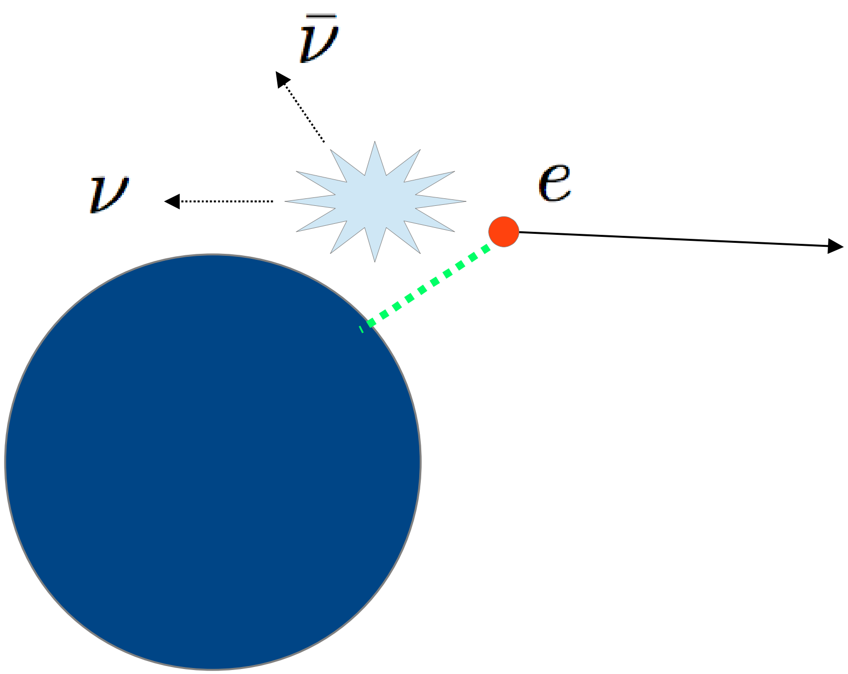


Two effects: muon motion & Coulomb attraction

Net effect:
- In the decay rate: almost none;
  only time dilation

$$\Gamma \to \left(1 - \frac{(Z\alpha)^2}{2}\right)\Gamma$$

Überall, Phys. Rev. 119, 365 (1960)



Two effects: muon motion & Coulomb attraction

Szafron, AC, PRD 92 (2015) 053004

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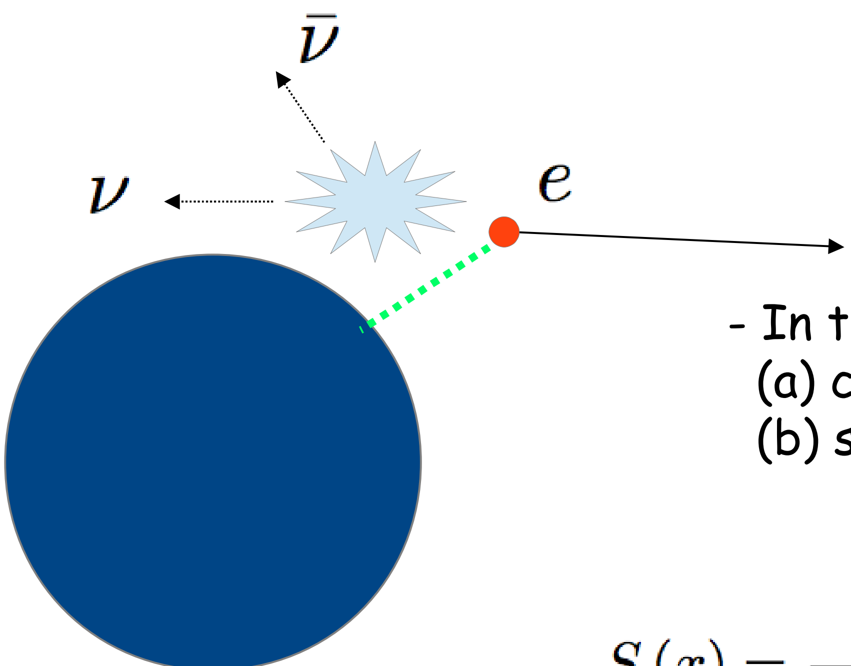
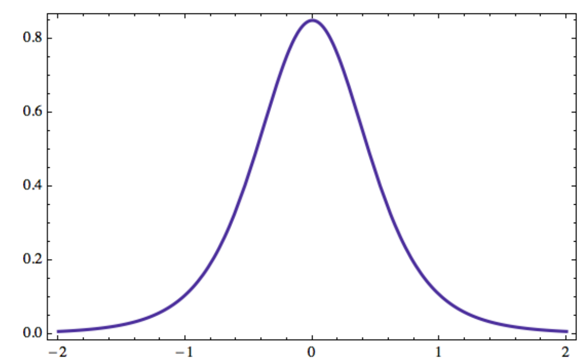


- In the electron energy spectrum:
  (a) computable shift
  (b) smearing -> “shape function”

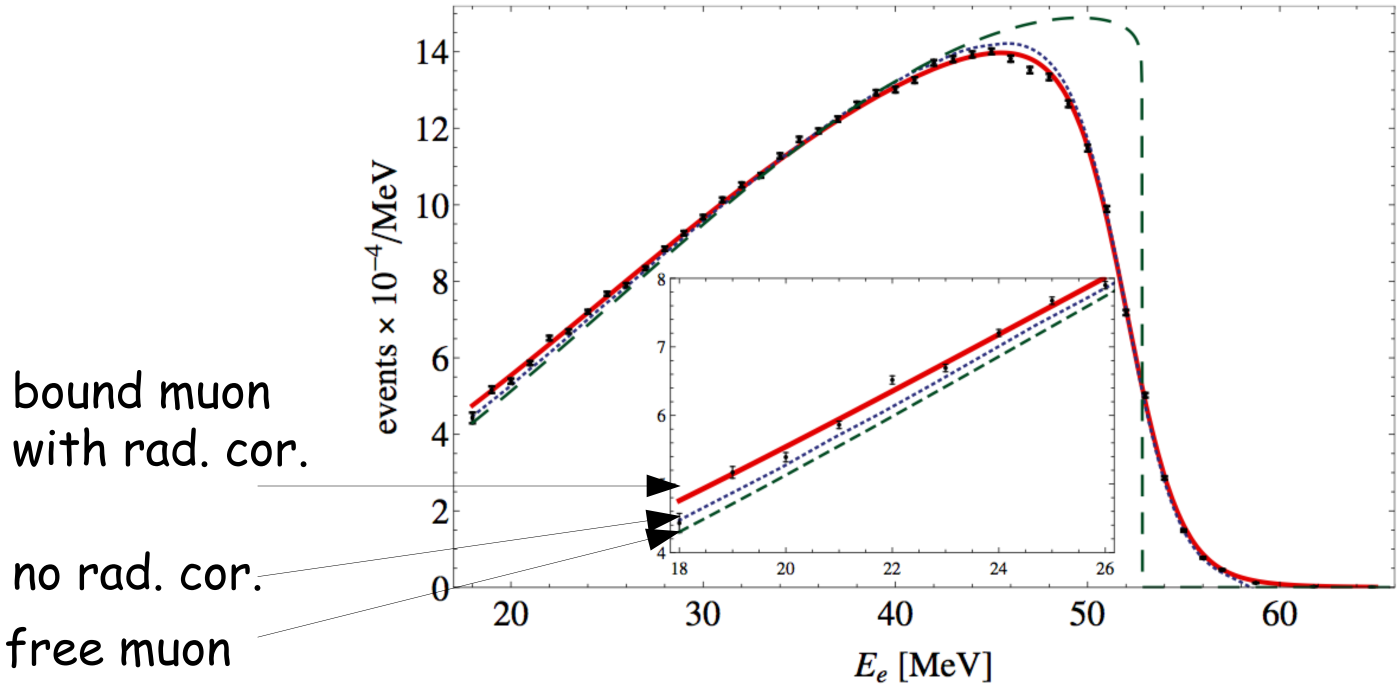
$$S(x) = \frac{8}{3\pi\left[1+x^2\right]^3}$$



Previously used in heavy mesons, where it cannot be computed from first principles, but can be experimentally accessed.

Mannel, Neubert,
Bigi, Shifman, Uraltsev, Vainshtein

Comparison with measurement: TWIST

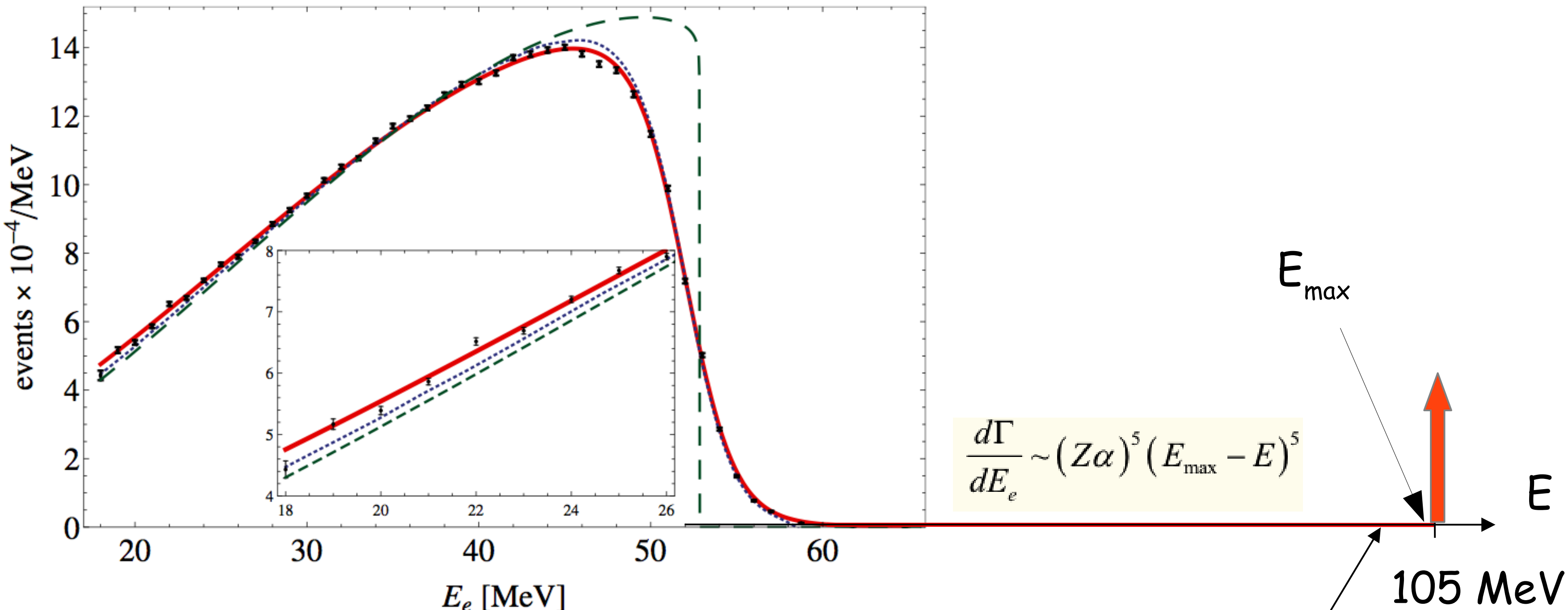


The spectrum is modified very significantly: effects ~ 1/Zα

Muon decay-in-orbit spectrum:
the high-energy region

Experiments: Mu2e and COMET

Spectrum of the bound muon decay



$$\frac{d\Gamma}{dE_e} \sim (Z\alpha)^5 (E_{\max} - E)^5$$

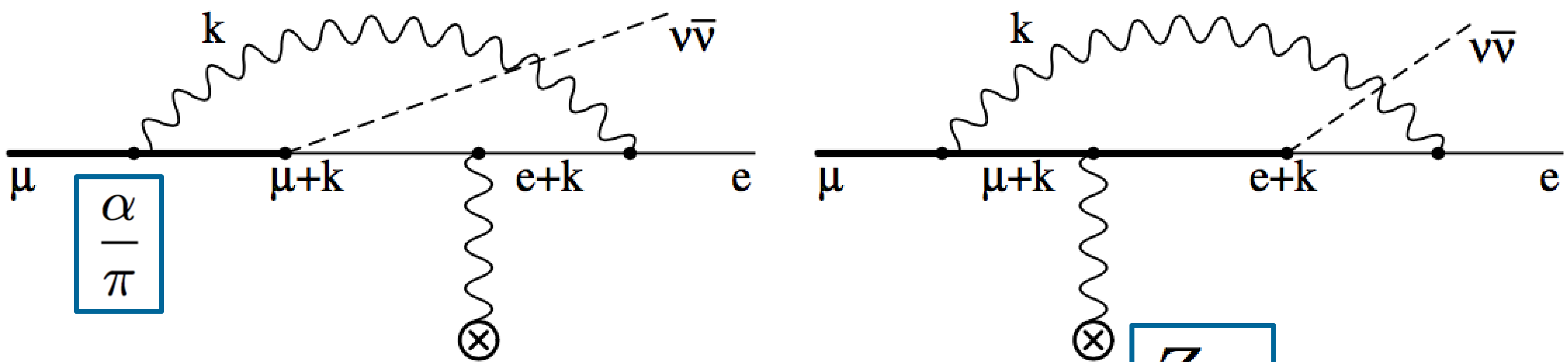
Main background for the conversion signal

AC, M. Dowling, X. Garcia i Tormo, W. Marciano, R. Szafron
R. Szafron, AC

Radiative corrections to the electron spectrum

Expansion near the end-point $\frac{m_\mu}{\Gamma_0}\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \sum_{ijk} B_{ijk}\Delta^i(\pi Z\alpha)^j\left(\frac{\alpha}{\pi}\right)^k$

Three "small" parameters: $\Delta = \frac{E_{\max} - E}{m_\mu}$



$$B_{550} + \frac{\alpha}{\pi}B_{551} \to B_{550}\left[\Delta^{\frac{\alpha}{\pi}\delta_S} + \frac{\alpha}{\pi}\delta_H\right]$$

$$\delta_S = 10.1$$

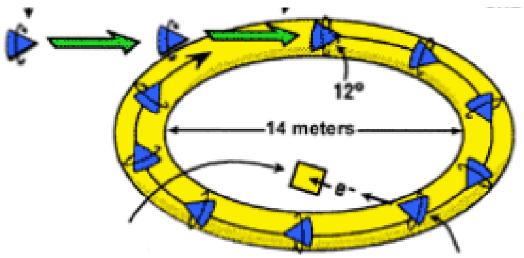
number of electrons in the end-point bin of 1 (0.1) MeV is reduced by 11% (16%)

Szafron, AC, PLB753, 61 (2016)

Anomalous magnetic moment

The puzzle of the muon magnetic moment

The 3.6 sigma discrepancy,



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

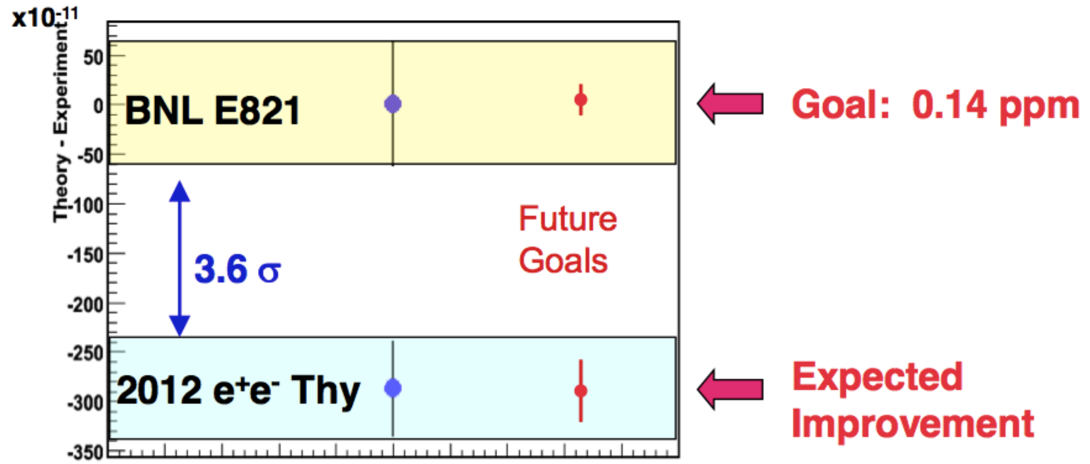
PRD 86, 095009 (2012)

0.7 ppm

is rather large when compared with other bounds on New Physics.

How can g_μ-2 be checked?

New experiment at Fermilab



New experimental concept at J-PARC

Can we use g_e-2?

New approach to g_μ-2 at J-PARC

Slower muons 300 MeV (instead of the "magic" 3.1 GeV)

Ultracold muons; no electric focusing!

Smaller ring r = 33 cm (instead of 7 m)

$$r\,[\text{in meters}] \simeq \frac{\gamma}{3B\,[\text{in Tesla}]}$$

Strong, very precisely controlled magnetic field.

~ 10 times more muons than at Fermilab (compensates shorter lifetime).

	Brookhaven	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

$$\simeq \sqrt{\frac{2\pi}{\alpha}}$$

From N. Saito

How to check g_μ-2?

Electron *g*-2 is likely sensitive to the same New Physics; but at present it is used to determine the fine-structure constant.

A new source of alpha is needed.

How to check g_μ-2?

Nature 442, 516 (2006)
PRA 89, 052118 (2014)

The second best determination of alpha:
from atomic spectroscopy

$$R_\infty = \frac{m_e c \alpha^2}{2h}$$

Needed precision:

$$\alpha^2 = \frac{2R_\infty}{c} \cdot \frac{u}{m_e} \cdot \frac{M_X}{u} \cdot \frac{h}{M_X}$$

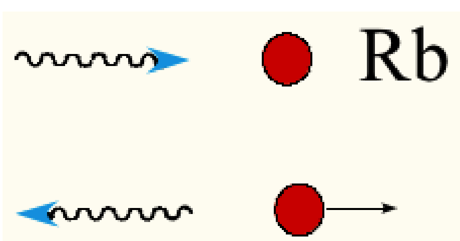
$14 \cdot 10^{-11}$ → α^2

$7 \cdot 10^{-12}$ (but is it for sure?) → $\frac{2R_\infty}{c}$

$8 \cdot 10^{-11}$ Nature 2014 Sturm et al → $\frac{u}{m_e}$

$12 \cdot 10^{-11}$ for Rb (better for He) → $\frac{M_X}{u}$

$124 \cdot 10^{-11}$ improvement needed by factor ~10 → $\frac{h}{M_X}$

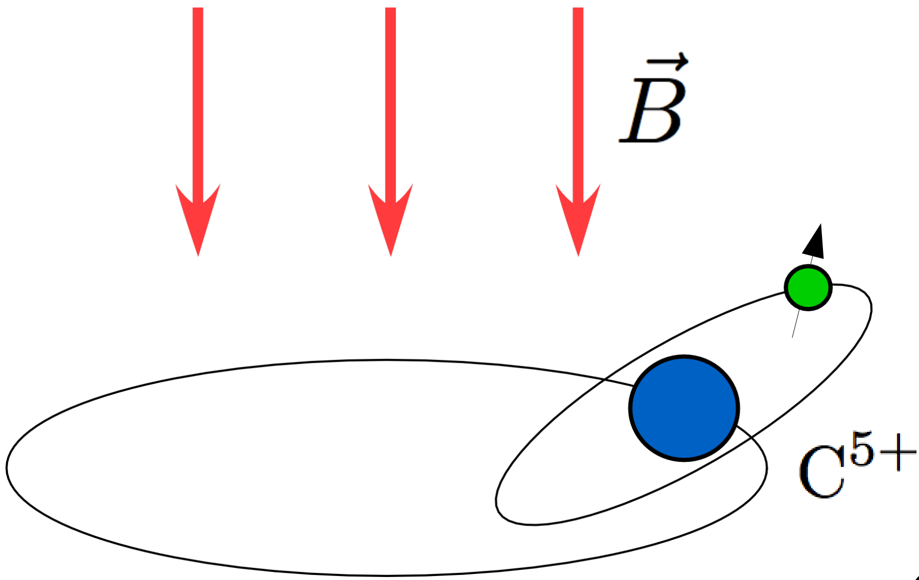


gives h/m

$$\alpha(\mathrm{Rb}) = 1/137.035\,999\,049(90) \quad [66 \cdot 10^{-11}]$$

PRL 106, 080801 (2011)

Fine structure constant from bound-e g-factor



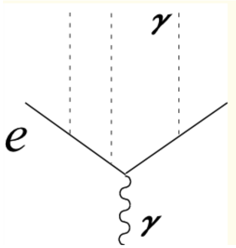
Larmor frequency $\omega_L = \frac{geB}{2m_e}$

Cyclotron frequency $\omega_{\text{cycl}} = \frac{ZeB}{M}$

$$m_e = \frac{g}{2Z} \frac{\omega_{\text{cycl}}}{\omega_L} M$$

Bound-electron g-2: the leading effect

Breit 1928: energy correction due to magnetic field
in the hydrogen ground state.

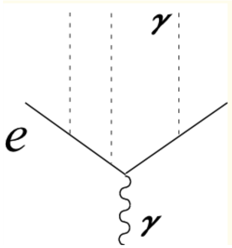


$$\delta E = e \int d^3x f^2 v^* \left[1 - i\gamma \boldsymbol{\Sigma} \cdot \hat{\boldsymbol{r}} \gamma^5\right] \gamma^5 \boldsymbol{A} \cdot \boldsymbol{\Sigma} \left[1 + i\gamma \boldsymbol{\Sigma} \cdot \hat{\boldsymbol{r}} \gamma^5\right] v$$

$$g = 2 \cdot \frac{1}{3}\left(1 + 2\sqrt{1-(Z\alpha)^2}\right) \simeq 2\left(1 - \frac{(Z\alpha)^2}{3}\right)$$

Bound-electron g-2: the leading effect

Breit 1928: energy correction due to magnetic field
in the hydrogen ground state.

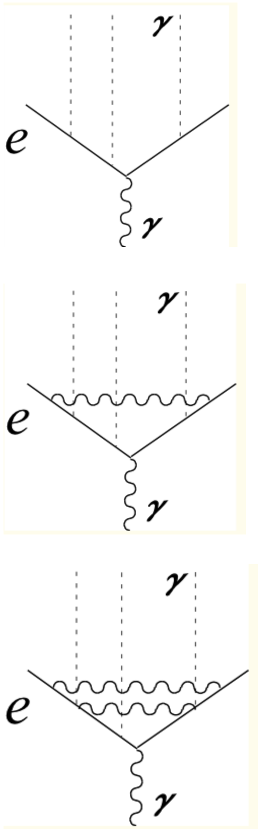


$$\delta E = e \int d^3x f^2 v^* \left[1 - i\gamma \boldsymbol{\Sigma} \cdot \hat{\boldsymbol{r}} \gamma^5\right] \gamma^5 \boldsymbol{A} \cdot \boldsymbol{\Sigma} \left[1 + i\gamma \boldsymbol{\Sigma} \cdot \hat{\boldsymbol{r}} \gamma^5\right] v$$

$$g = 2 \cdot \frac{1}{3}\left(1 + 2\sqrt{1 - (Z\alpha)^2}\right) \simeq 2\left(1 - \frac{(Z\alpha)^2}{3}\right)$$

Important: dependence
on alpha; may be exploited
to determine its value.
(Use ions with various Z)

Bound-electron g-2: theory

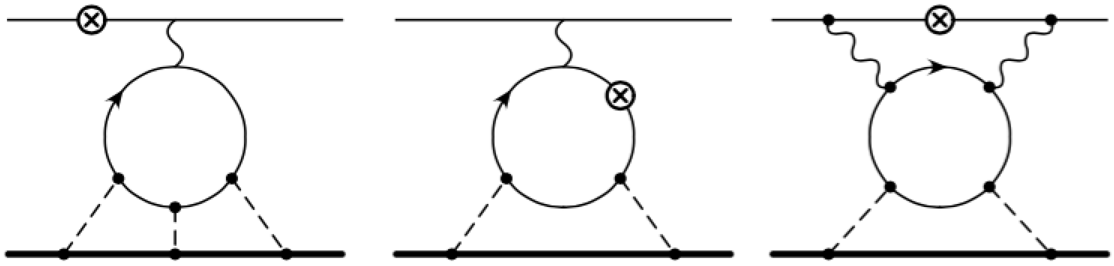


$$g = 2 - \frac{2\,(Z\alpha)^2}{3} - \frac{(Z\alpha)^4}{6} + \ldots$$
$$+ \frac{\alpha}{\pi}\left[1 + \frac{(Z\alpha)^2}{6} + (Z\alpha)^4\,(a_{41}\ln Z\alpha + a_{40}) + \ldots\right]$$
$$+ \left(\frac{\alpha}{\pi}\right)^2\left[-0.65..\left(1 + \frac{(Z\alpha)^2}{6}\right) + (Z\alpha)^4\,(b_{41}\ln Z\alpha + b_{40}) + \ldots\right]$$

Pachucki,
AC
Jentschura,
Yerokhin

Next goal: $\alpha^2(Z\alpha)^5$ corrections to g

Examples:

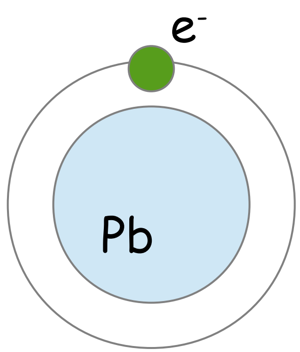


More than 300 contributions.

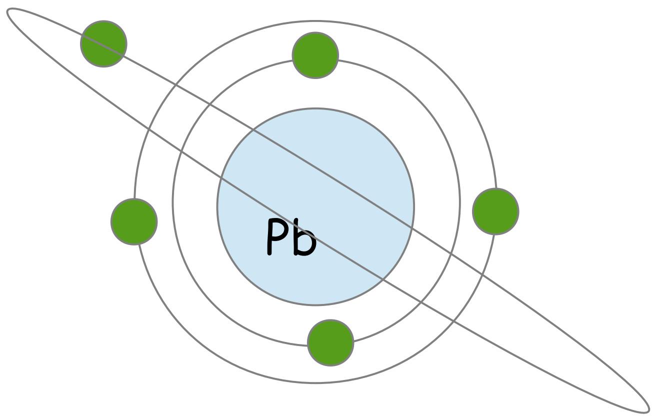
A new source of alpha: highly-charged ions

$$g \simeq 2 - \frac{2\,(Z\alpha)^2}{3} \longrightarrow \frac{\delta\alpha}{\alpha} \sim \frac{1}{(\alpha Z)^2}\sqrt{(\delta g_{\rm exp})^2 + (\delta g_{\rm th})^2}$$

large Z favorable



Hydrogen-like lead



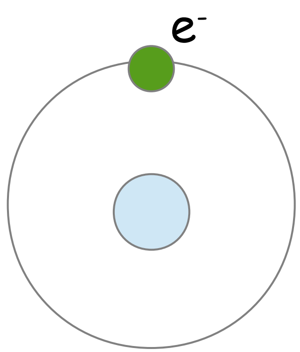
Boron-like lead

There is a combination of g-factors in both ions where the sensitivity to the nuclear structure largely cancels, but the sensitivity to alpha remains.

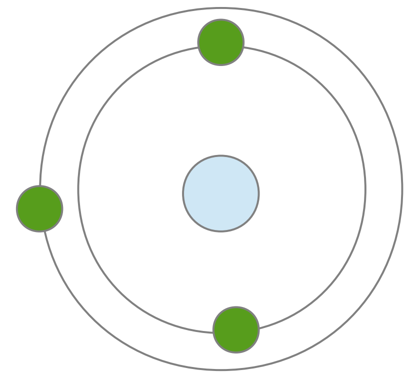
Shabaev, Glazov, Oreshkina, Volotka, Plunien, Kluge, Quint

New idea: medium-charged ions

$$g \simeq 2 - \frac{2\,(Z\alpha)^2}{3}$$



Hydrogen-like ion



Lithium-like ion

Combine H-like and Li-like to remove nuclear dependence;
then combine with a different nucleus, to remove free-g dependence!

Much interesting theoretical work remains to be done!

Yerokhin, Berseneva, Harman, Tupitsyn, Keitel: PRL (2016)

Summary

* New era of muon studies just starting

* Muon-electron conversion will probe very high mass scales

* Binding modifies the muon decay and the electron g-factor

* Theory of both effects: more fun than for free particles

* Synergy with beautiful experiments: lepton-flavor violation, mass of the electron and, in future, the fine structure constant.

* For g: $\alpha(Z\alpha)^5$ effects almost finished; $\alpha^2(Z\alpha)^5$ hopefully soon.

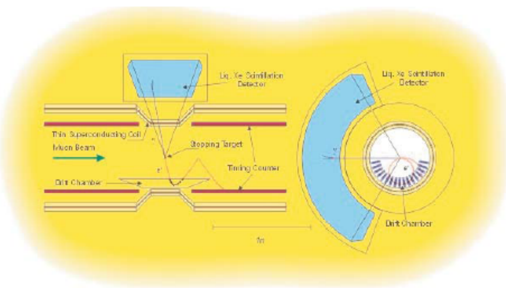
* Opportunities for more theoretical improvement...

Lepton flavor violation: $\mu \rightarrow e\gamma$

New bound (MEG @ Paul Scherrer Institute)

$$\mathrm{BR}\,(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$$

arXiv:1605.05081



This corresponds to the transition dipole moment

$$d_{\mu\to e} \lesssim 3.5 \cdot 10^{-27}\ e \cdot \mathrm{cm}$$

Sensitive to the heaviest "new physics"

For comparison: electron EDM $d_e < 0.87 \cdot 10^{-28}\, e \cdot \mathrm{cm}$ 10.1126/science.1248213

muon g-2 $d_\mu < 3 \cdot 10^{-22}\, e \cdot \mathrm{cm}$