Low-energy searches for New Physics

Advances in Computational Particle Physics
Durbach, September 16, 2014

Andrzej Czarnecki · University of Alberta

Outline

Three promising directions in low-energy searches:

* anomalous magnetic moments (muon vs electron)

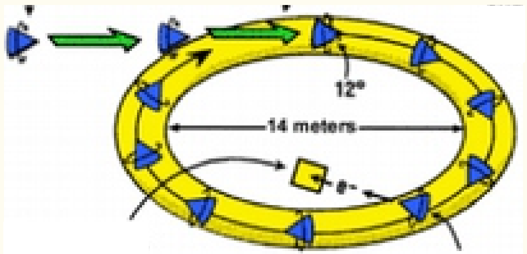
* electric dipole moments (electron)

* lepton flavor violation (muon --> electron)

Anomalous magnetic dipole moments

The puzzle of the muon magnetic moment

The 3.6 sigma discrepancy persists,



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

PRD 86, 095009 (2012)

Much work done in the SFB/TR9, mainly the crucial hadronic contribution:

* Kurz, Liu, Marquard, Steinhauser
* Baikov, Chetyrkin, Kühn, Sturm, Maier

perturbative, up to six loops!

* Burger, Feng, Hotzel, Jansen, Petschlies, Renner: lattice

Ken Wilson Lattice Award

* Kühn, Czyż, Rodrigo, Melnikov, et al: radiative return method

The puzzle of the muon magnetic moment

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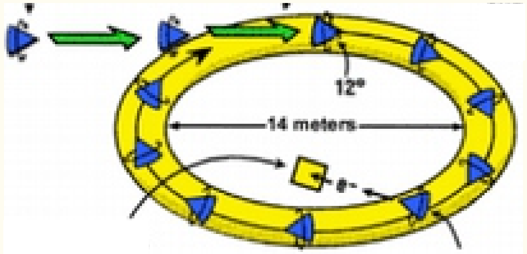


$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287(80) \times 10^{-11}$$

PRD 86, 095009 (2012)

This is rather large when compared with other bounds on New Physics:

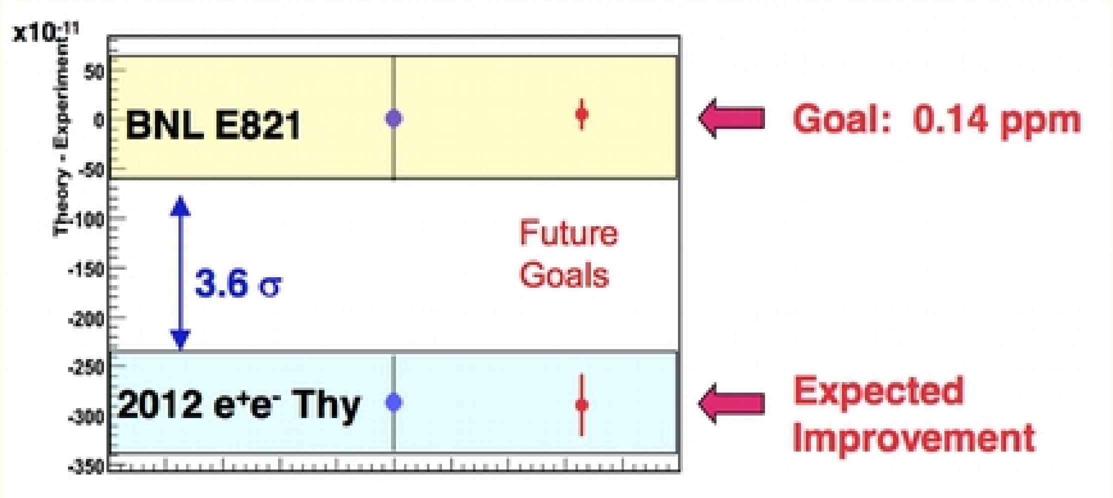
Muon MDM $$d_\mu \sim \frac{e}{2m_\mu} a_\mu^{\rm NP} \sim 3 \cdot 10^{-22}\, e \cdot {\rm cm}$$

Muon-electron transition moment $$|d_{\mu\to e}| < 4 \cdot 10^{-27}\, e \cdot {\rm cm}$$ MEG 2013

Electron EDM $$|d_e| < 8.7 \cdot 10^{-29}\, e \cdot {\rm cm}$$ ACME 2013

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

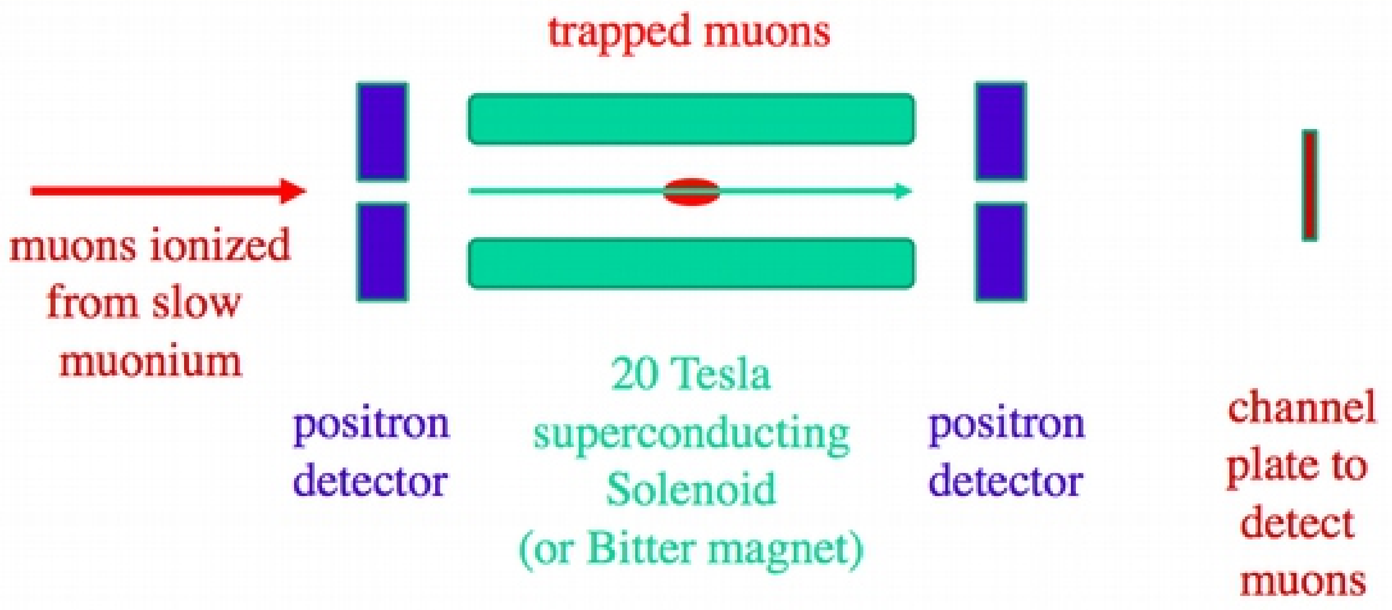
$$\gamma \simeq \sqrt{\frac{2\pi}{\alpha}}$$

From N. Saito

(Futuristic?) approach to g_μ-2

USM2013 Gabrielse

Measure Muon Magnetic Moment in a Trap



Advantages: Use muons to measure the magnetic field in situ
Less expensive
Different systematics

Challenge: 2.2 microsecond muon lifetime

Thanks to A. Mills for helpful conversations

Magnetic moment of the electron

$$a_e = \frac{g_e - 2}{2}$$

Measured with relative error $25 \cdot 10^{-11}$

Phys. Rev. Lett. 100, 120801 (2008)

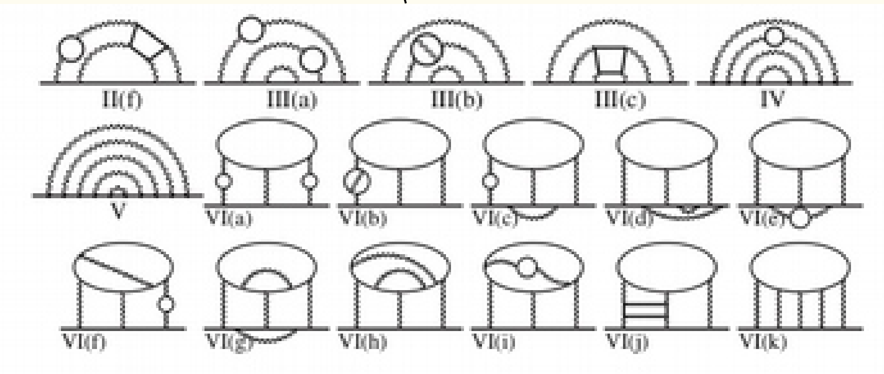
Provides the fine structure constant with the same precision,

$$\alpha^{-1}(a_e) = 137.035\,999\,1736\,(331)\,(86)$$

Phys. Rev. Lett. 109, 111807 (2012)

Experimental error dominates (for now)

Numerical errors from 4- and 5-loop diagrams



Kinoshita

How to use g_e-2 to check g_μ-2?

If the muon anomaly is due to New Physics, the expected effect for the electron is likely smaller by $\frac{m_e^2}{m_\mu^2} \sim \frac{1}{43000}$

$$\Delta a_\mu \sim 287 \cdot 10^{-11} \rightarrow \Delta a_e \sim 7 \cdot 10^{-14}$$

This means relative uncertainty $\frac{\Delta a_e}{a_e} \sim 7 \cdot 10^{-11}$

and requires a factor of 4 improvement of the latest measurement.

In addition, an independent determination of the fine structure constant is needed, with matching precision.

How to use g_e-2 to check g_μ-2?

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

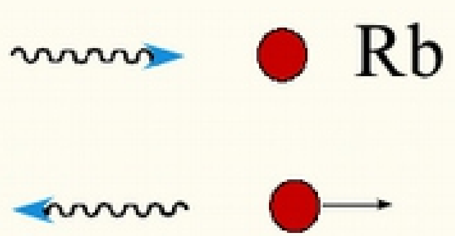
The second best determination of alpha:
from atomic spectroscopy

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

Needed precision:

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

- α^2: $14 \cdot 10^{-11}$
- $\frac{R_\infty}{2}$: $7 \cdot 10^{-12}$ (but is it for sure?)
- $\frac{u}{m_e}$: $8 \cdot 10^{-11}$ NEW Nature 2014 Sturm et al
- $\frac{M_X}{u}$: $12 \cdot 10^{-11}$ for Rb (better for He)
- $\frac{h}{M_X}$: $124 \cdot 10^{-11}$ improvement needed by factor ~10

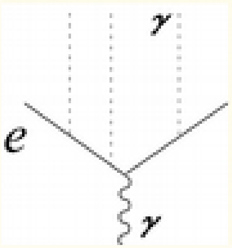


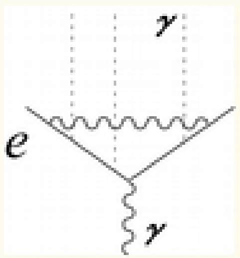
gives h/m

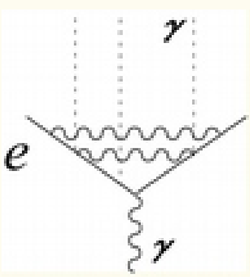
$$\alpha(\mathrm{Rb}) = 1/137.035\,999\,049(90) \quad [66 \cdot 10^{-11}]$$

PRL 106, 080801 (2011)

Bound-electron g-2: theory needed for u/m_e







$$g = 2 - \frac{2\,(Z\alpha)^2}{3} - \frac{(Z\alpha)^4}{6} + \ldots$$

$$+\frac{\alpha}{\pi}\left[1 + \frac{(Z\alpha)^2}{6} + (Z\alpha)^4\,(a_{41}\ln Z\alpha + a_{40}) + \ldots\right]$$

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

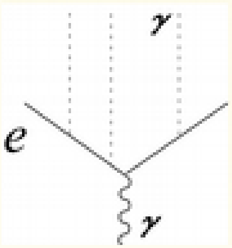
two-loop corrections

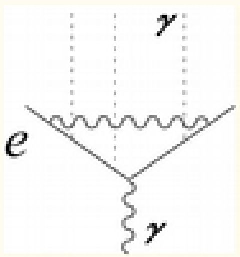
$$b_{41} = \frac{28}{9}$$

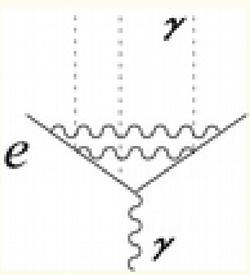
$$b_{40} = -16.4$$

Pachucki,
AC
Jentschura,
Yerokhin

Bound-electron g-2: theory needed for u/m_e







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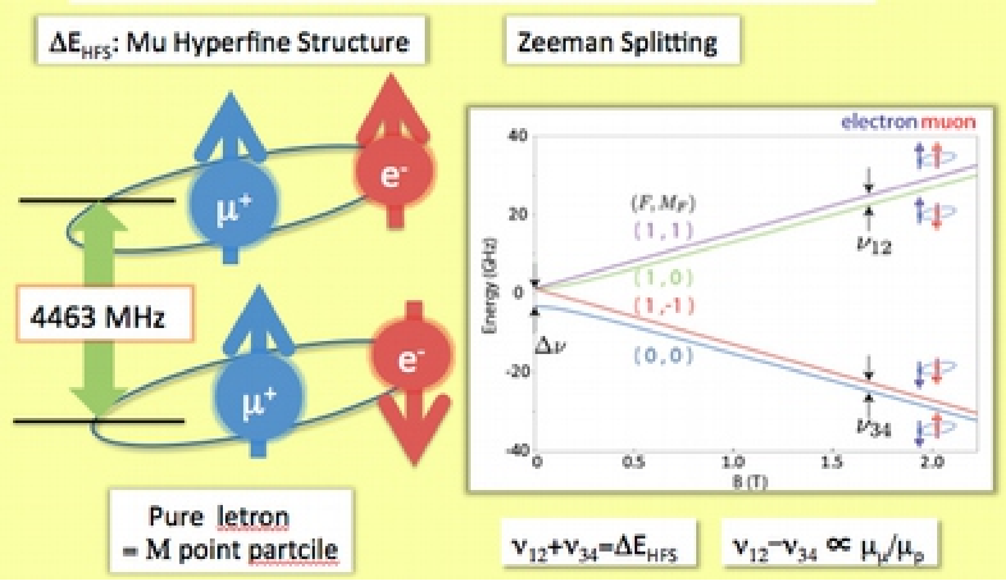
With Matt Dowling and Jan Piclum,
we are now computing a_{50} and b_{50},
using many tools developed in SFB/TR9:
q2e, exp, MATAD, FIRE, FIESTA
and of course FORM

Steinhauser, Smirnov
Vermaseren

talk by Takahiro Ueda

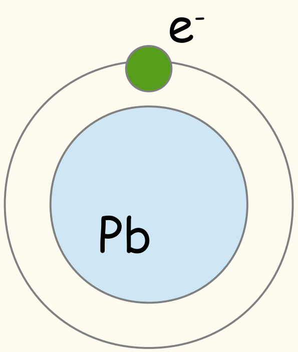
Similar binding corrections needed for the muonium: input to g-2



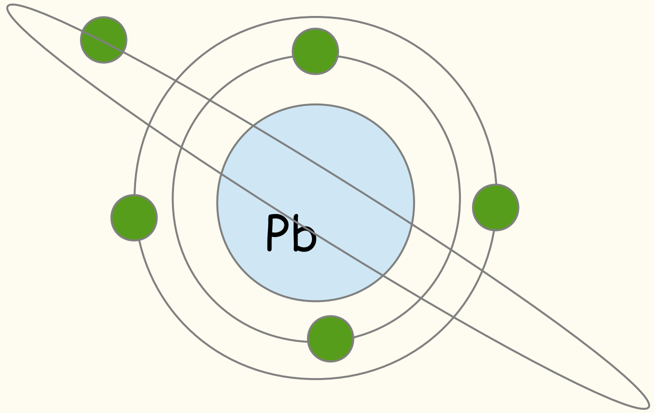
Another source of alpha: highly-charged ions

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

large Z favorable



Hydrogen-like lead



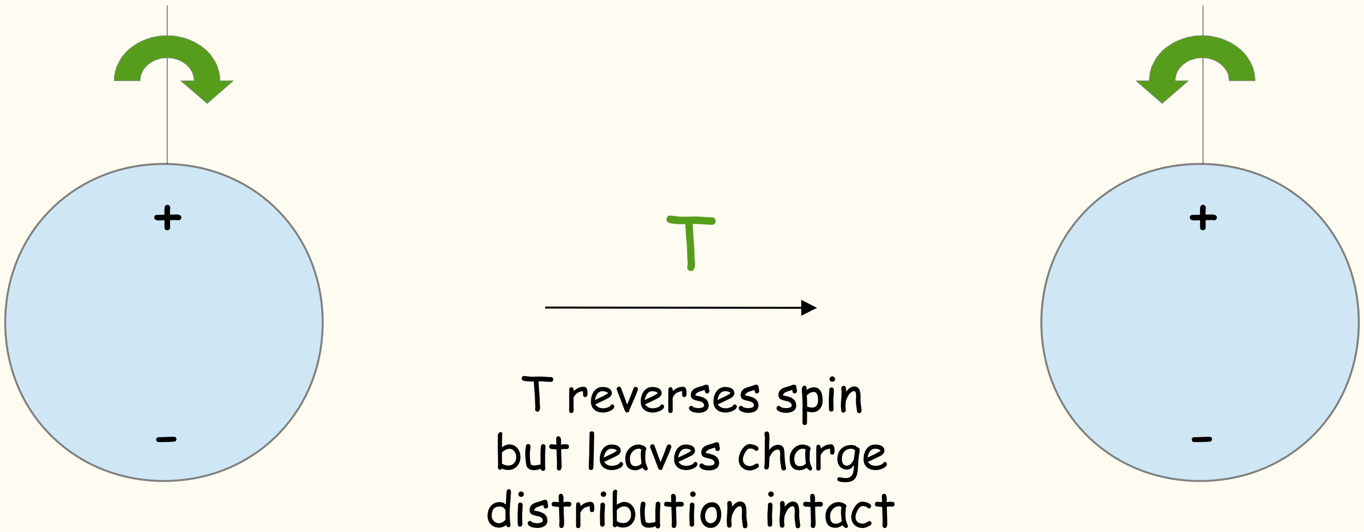
Boron-like lead

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.

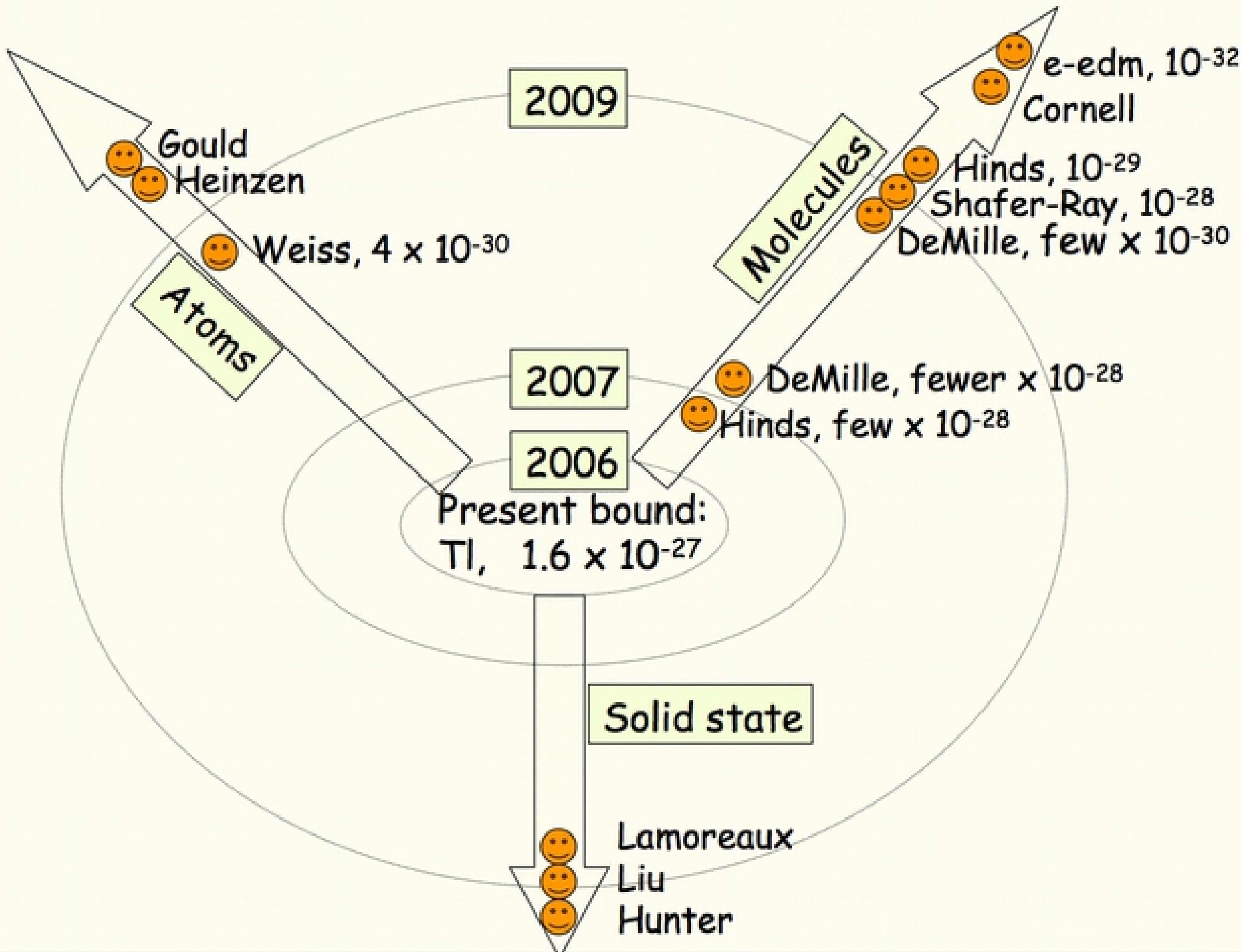
Much interesting theoretical work remains to be done!

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

Electron electric dipole moment



Electron EDM: what used to be expected (2006)



Recent great progress

2011: YbF @ Imperial $|d_e| < 10.5 \times 10^{-28} e\,\text{cm}$

LETTER

doi:10.1038/nature10104

Improved measurement of the shape of the electron

J. J. Hudson[1], D. M. Kara[1], I. J. Smallman[1], B. E. Sauer[1], M. R. Tarbutt[1] & E. A. Hinds[1]

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2014: ThO by ACME $|d_e| < 8.7 \times 10^{-29}\ e \cdot \mathrm{cm}$

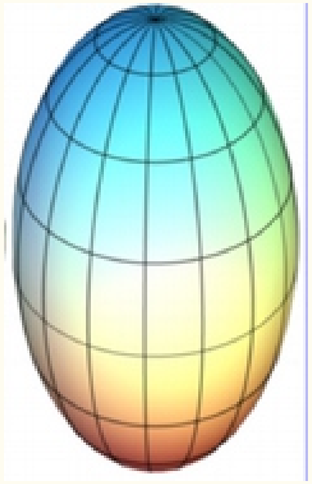
Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration,* J. Baron,[1] W. C. Campbell,[2] D. DeMille,[3]† J. M. Doyle,[1]† G. Gabrielse,[1]† Y. V. Gurevich,[1]‡ P. W. Hess,[1] N. R. Hutzler,[1] E. Kirilov,[3]§ I. Kozyryev,[3]|| B. R. O'Leary,[3] C. D. Panda,[1] M. F. Parsons,[1] E. S. Petrik,[1] B. Spaun,[1] A. C. Vutha,[4] A. D. West[3]

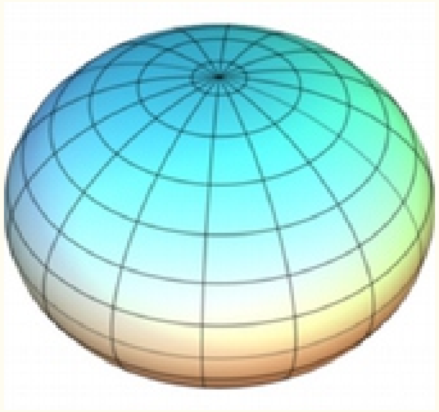
What will be on the cover when d_e discovered?

Analogous discussion about the shape of the earth (18th century):
which theory of gravity is correct?

Descartes:



Newton:



When will we get there? Plans for d_e:

	Near future	Ultimate goal	
Molecular ion	< ACME	$< 10^{-29}$	Ye Cornell
Atoms in an optical lattice	< ACME	$\text{few} \cdot 10^{-30}$	Weiss
YbF	10^{-29}	$\sim 10^{-30}$	Sauer
Future ACME	10^{-29}	$< 10^{-30}$	DeMille Gabrielse

Remarks on d_e

Molecules: great new player; but enhancement factors very tricky
One way to check: hyperfine structure (YbF)

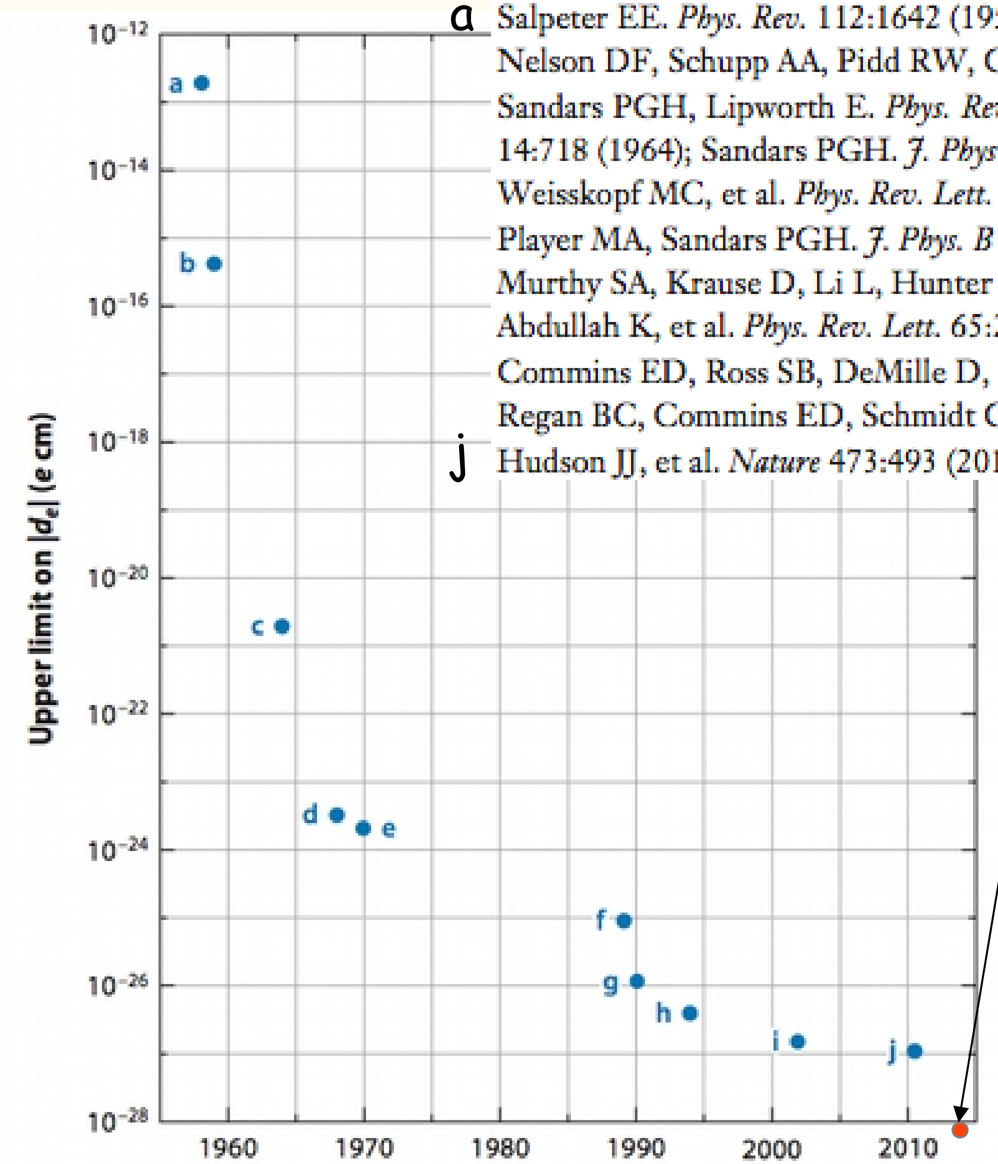
Molecules are a very new field; many improvements possible (sources!)

An even newer field: molecular ions.

Challenge for theorists: "enhancement factors": this is a new frontier for quantitative studies in molecules.

History of the electron EDM

a Salpeter EE. *Phys. Rev.* 112:1642 (1958)
Nelson DF, Schupp AA, Pidd RW, Crane HR. *Phys. Rev. Lett.* 2:492 (1959)
Sandars PGH, Lipworth E. *Phys. Rev. Lett.* 13:529 (1964); Sandars PGH, Lipworth E. *Phys. Rev. Lett.* 14:718 (1964); Sandars PGH. *J. Phys. B* 1:494 (1968); Sandars PGH. *J. Phys. B* 1:511 (1968)
Weisskopf MC, et al. *Phys. Rev. Lett.* 19:741 (1967); Weisskopf MC, et al. *Phys. Rev.* 174:125 (1968)
Player MA, Sandars PGH. *J. Phys. B* 3:1620 (1970)
Murthy SA, Krause D, Li L, Hunter LR. *Phys. Rev. Lett.* 63:965 (1989)
Abdullah K, et al. *Phys. Rev. Lett.* 65:2347 (1990)
Commins ED, Ross SB, DeMille D, Regan BC. *Phys. Rev. A* 50:2960 (1994)
Regan BC, Commins ED, Schmidt CJ, DeMille D. *Phys. Rev. Lett.* 88:071805 (2002)
j Hudson JJ, et al. *Nature* 473:493 (2011)

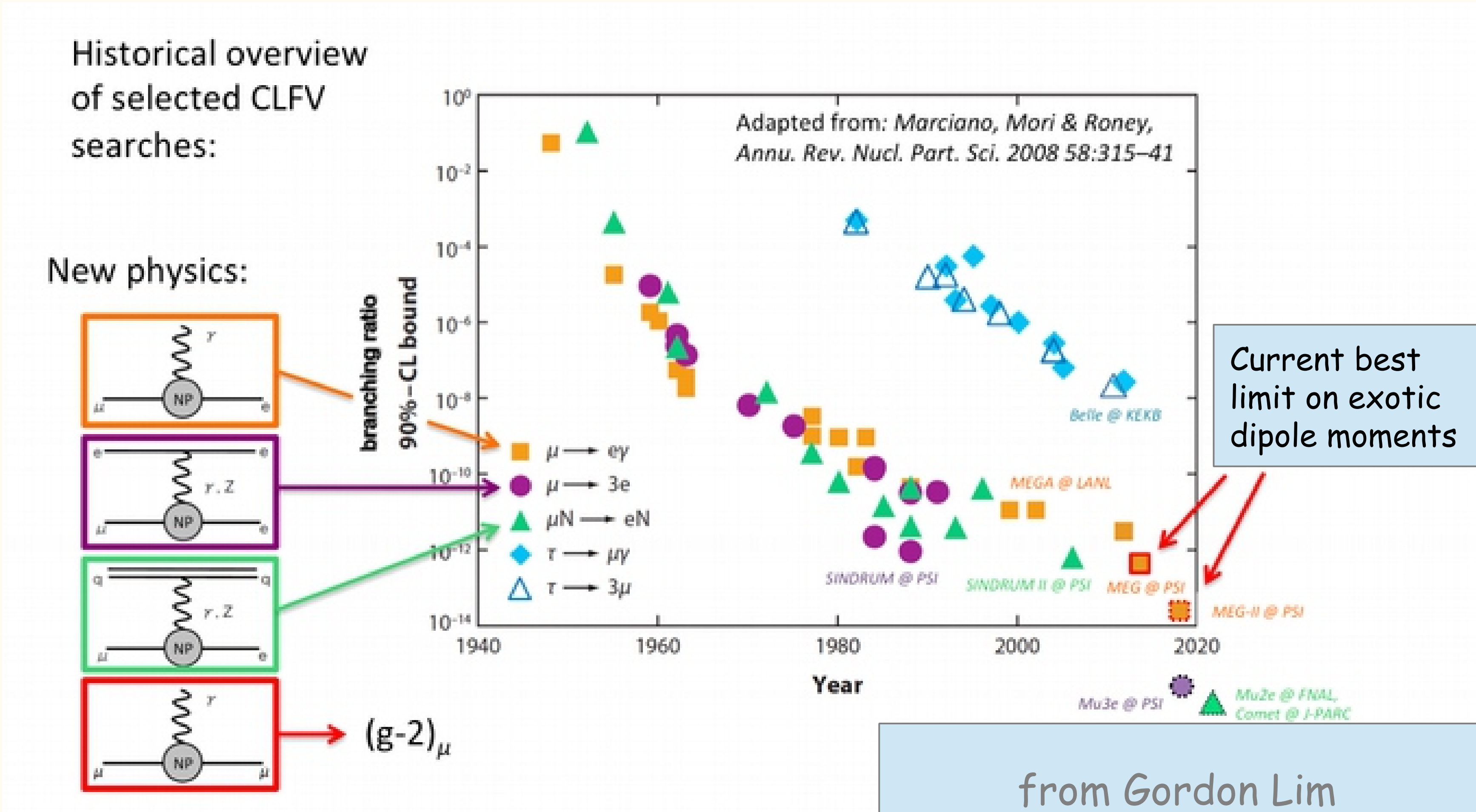


Baron et al. Science 343:269 (2014)

from Commins: Electron spin and its history

Lepton flavor violation

Efforts in LFV searches



Current best limit on exotic dipole moments

from Gordon Lim

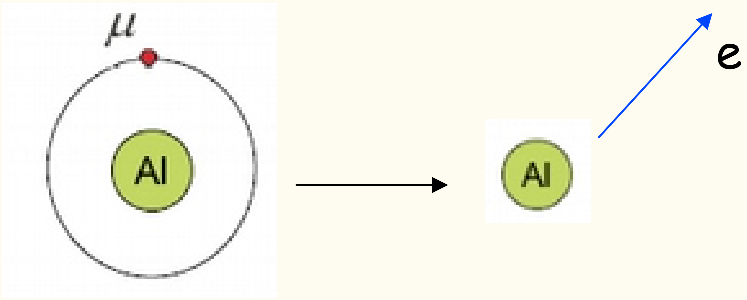
Conversion: probes also non-dipole interactions

So far, we have only talked about dipole interactions.
There are also vectors and scalars.

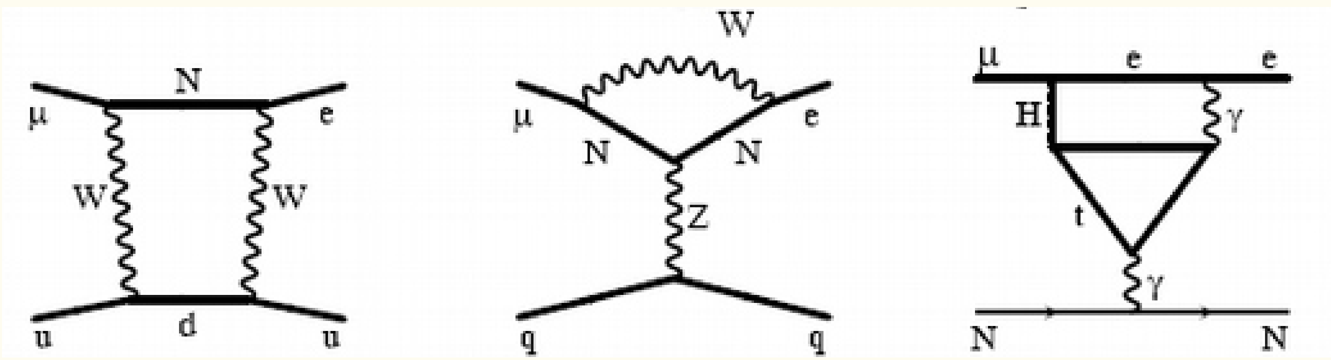
They are not (directly) probed by processes with external photons,
by gauge invariance requirements.

New process: muon-electron conversion

(as well as mu --> eee)

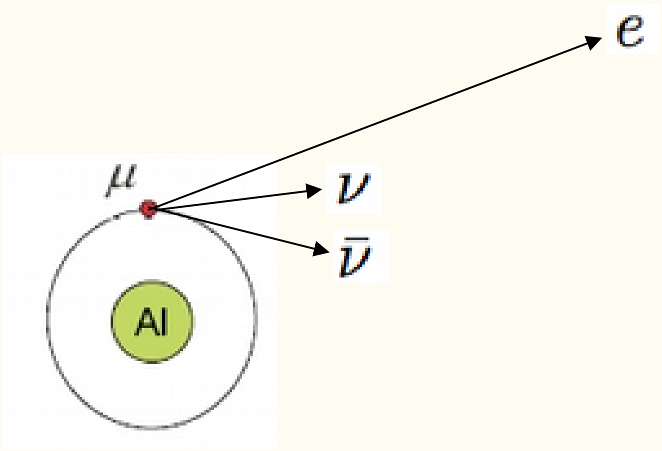


Variety of mechanisms:



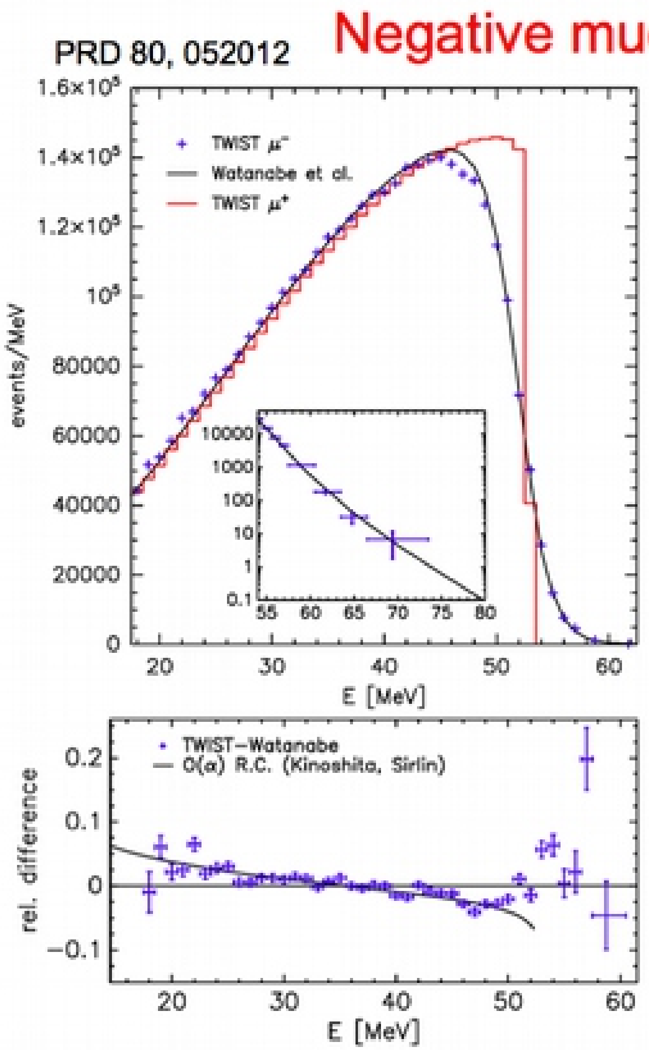
Background for the conversion search

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



Spectrum has to be well understood.

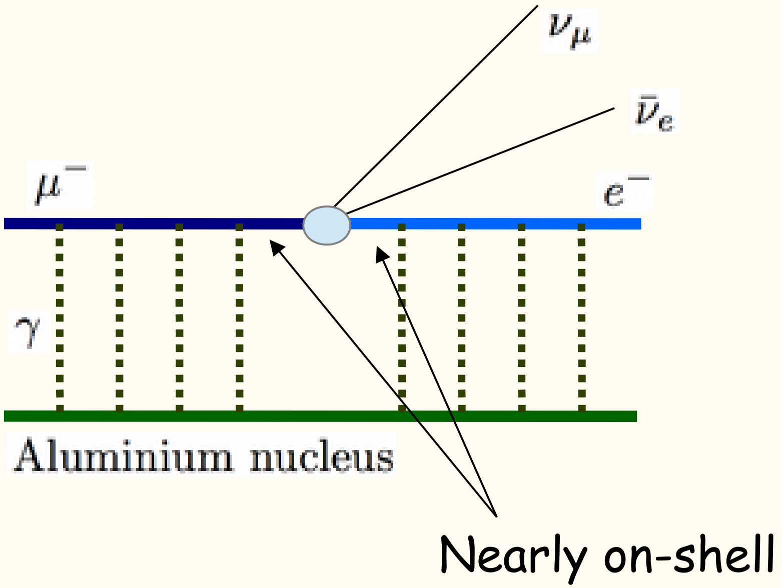
Bound muon decay has been measured: TWIST/TRIUMF



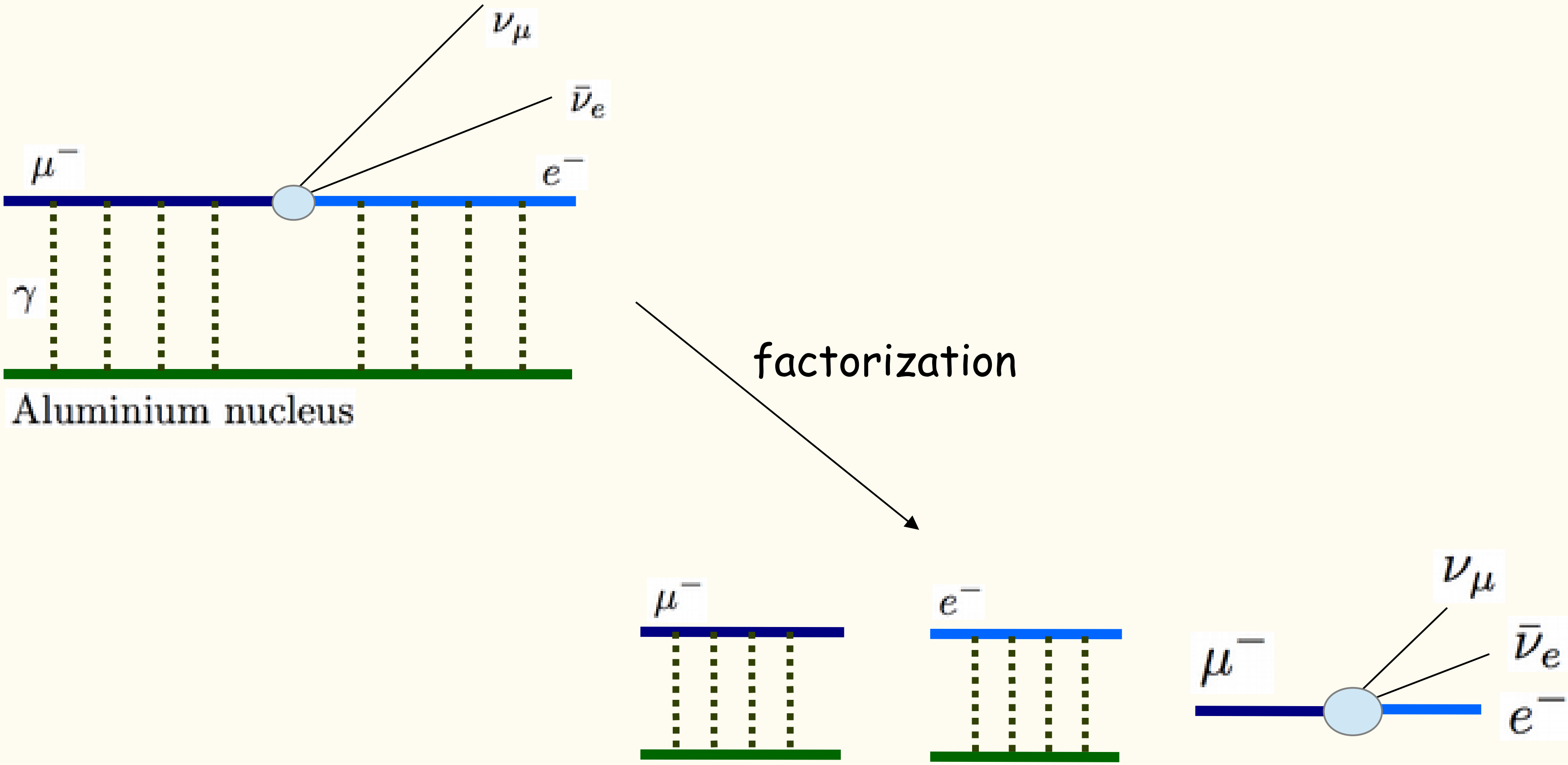
- Future $\mu \rightarrow e$ conversion experiments plan to study negative muons bound to Al
- Most precise measurement ever of the muon decay-in-orbit spectrum
- Theoretical predictions include higher-order contributions from the muon+nucleus potential
- Need to include the $O(\alpha)$ radiative corrections that arise from the interaction between the muon and the outgoing electron

From Carl A. Gagliardi/TWIST

Decay of a muon bound in aluminium



Decay of a muon bound in aluminium



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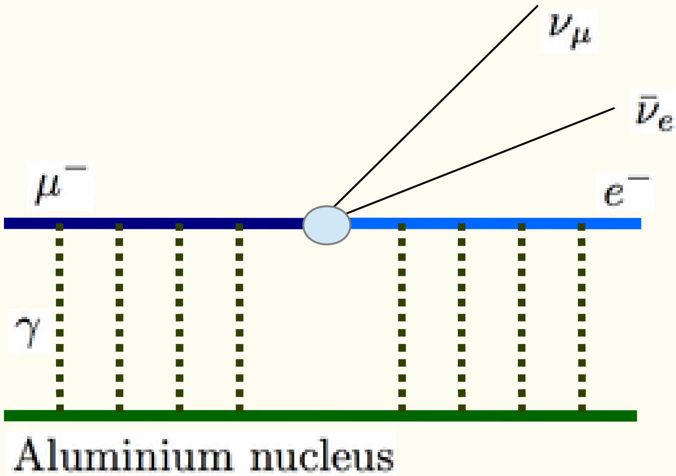
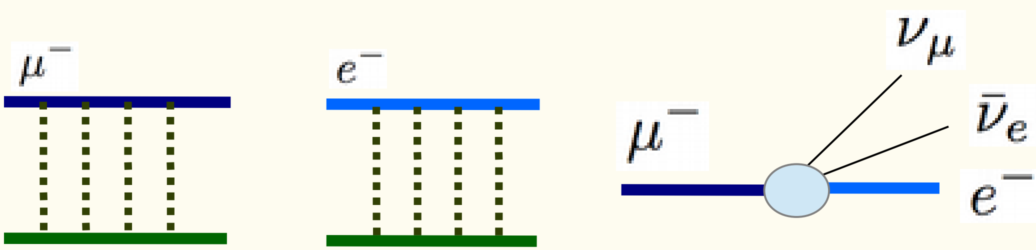


factorization



Free muon decay rate, with all corrections!

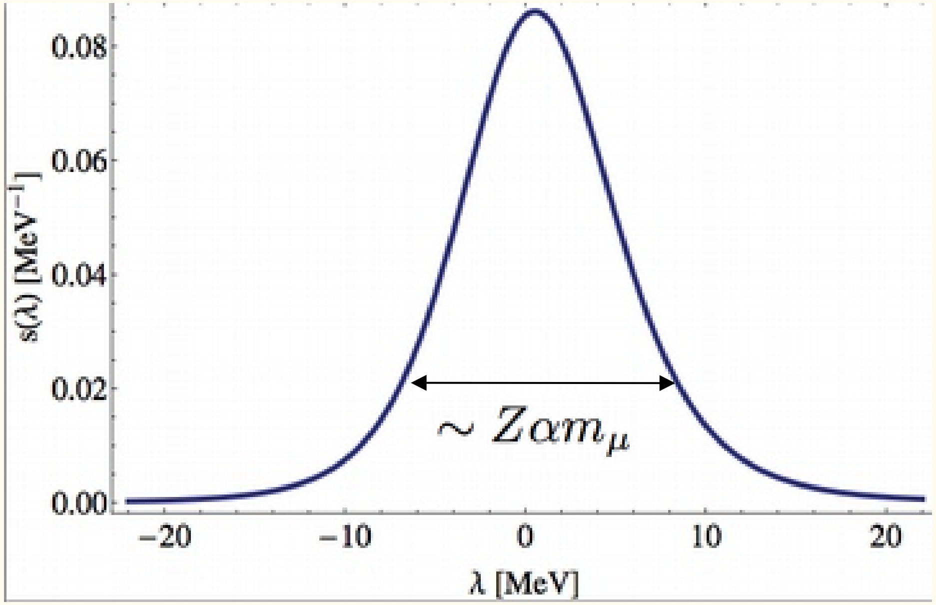
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \int \mathrm{d}\lambda \, s(\lambda) \frac{\mathrm{d}\Gamma_{\text{free}}}{\mathrm{d}z} \frac{\mathrm{d}z}{\mathrm{d}E_e}\bigg|_{z \to z(\lambda)}$$

$$z(\lambda) = \frac{2(E_e + \lambda) + (Z\alpha)^2 m_\mu}{m_\mu + \lambda}$$

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

Shape function

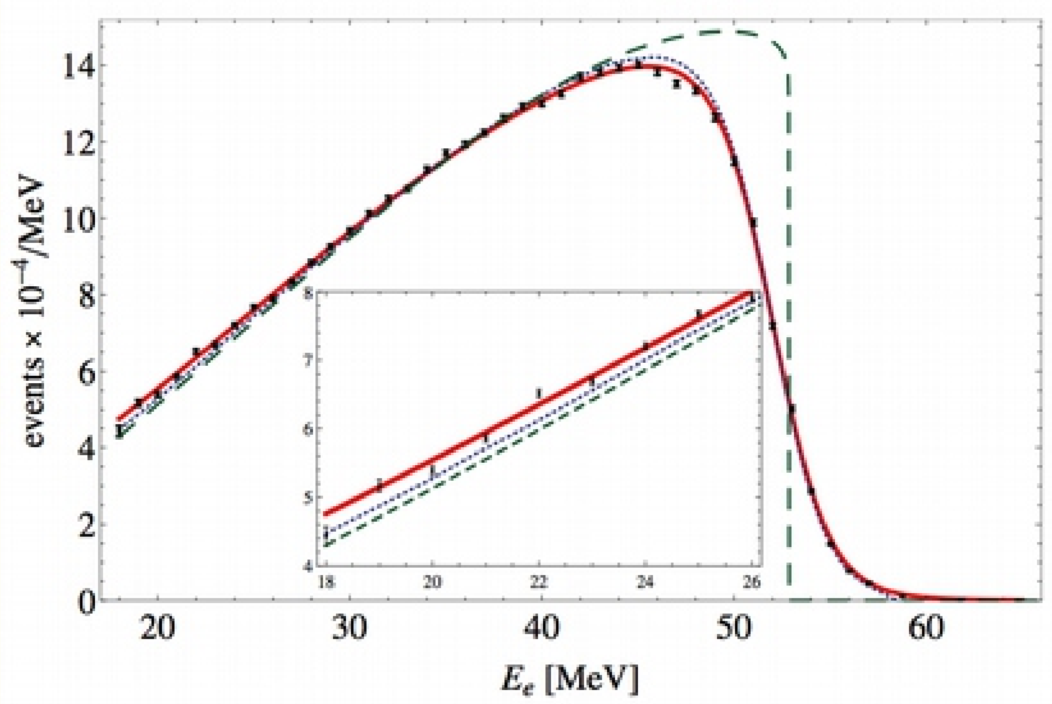
$$s(\lambda) = \int \frac{d^3k}{(2\pi)^3} \psi_g^\star\left(\vec{k}\right) \delta(\lambda + \vec{n}\cdot\vec{k}) \psi_g\left(\vec{k}\right)$$



Previously used in heavy mesons, where it cannot be computed from first principles, but can be experimentally accessed.
Mannel, Neubert, Bigi, Shifman, Uraltsev, Vainshtein

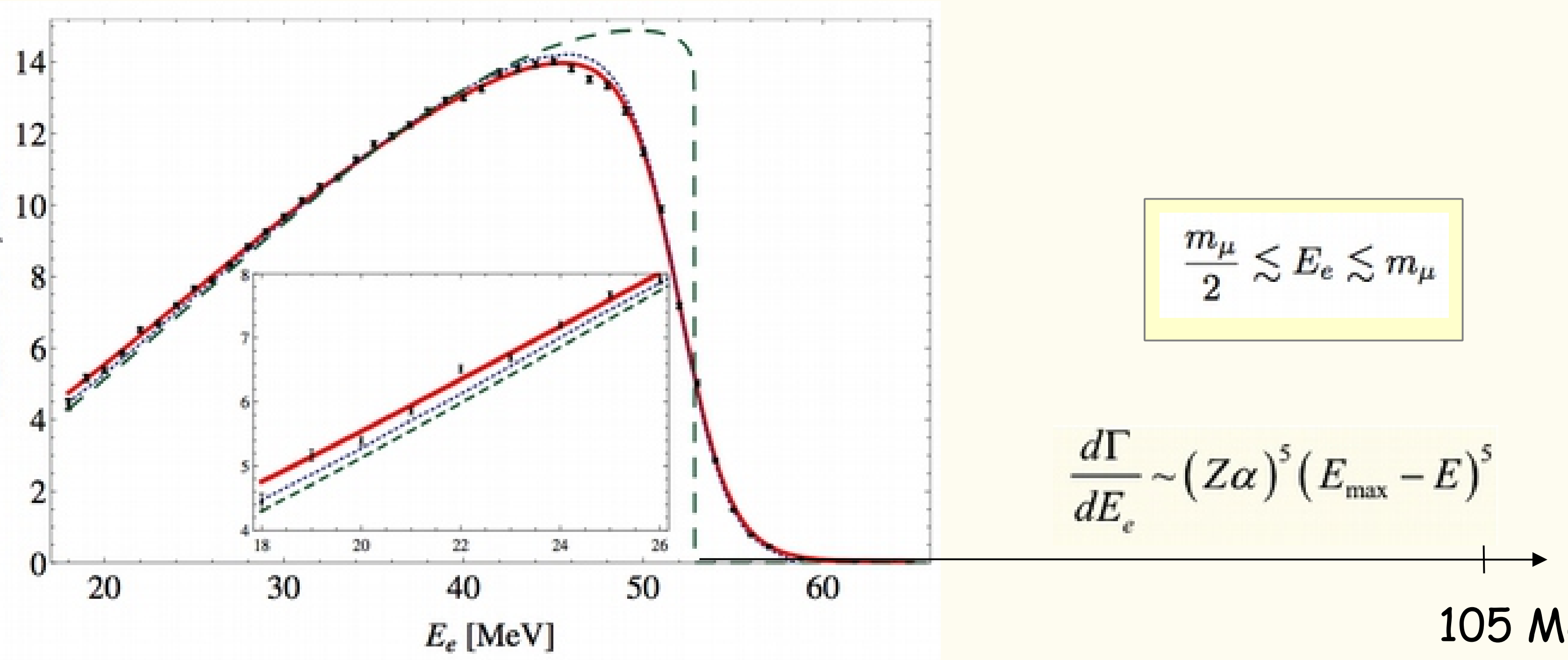
AC, M. Dowling, X. Garcia i Tormo, W. Marciano, R. Szafron

Result: spectrum of the bound muon decay



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

What about the upper half of the spectrum?

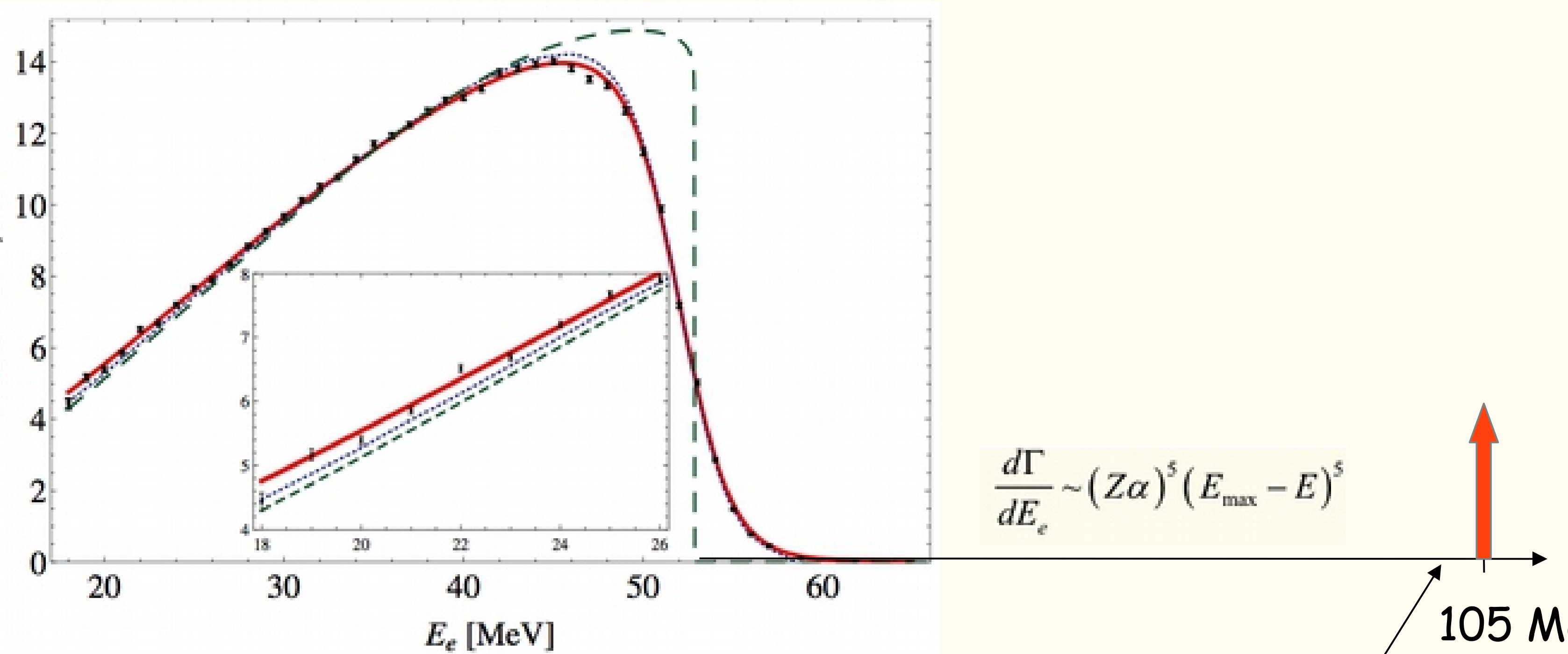


$$\frac{m_\mu}{2} \lesssim E_e \lesssim m_\mu$$

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

It seems to be VERY suppressed; so who cares?

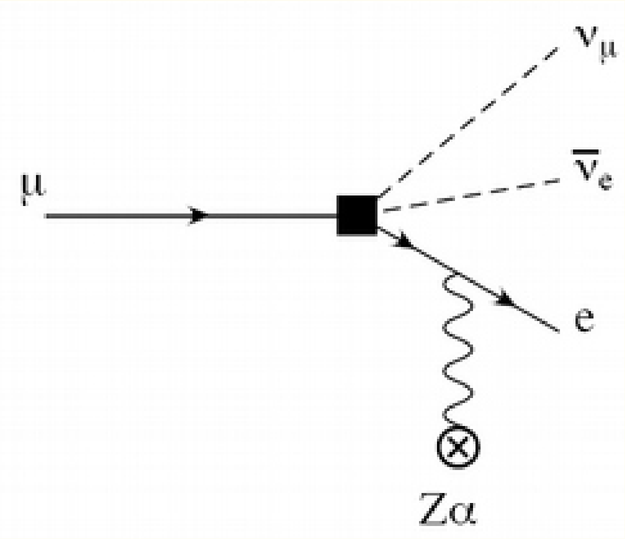
What about the upper half of the spectrum?



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

It is the main background for the expected conversion signal

Next step: radiative corrections to the electron spectrum

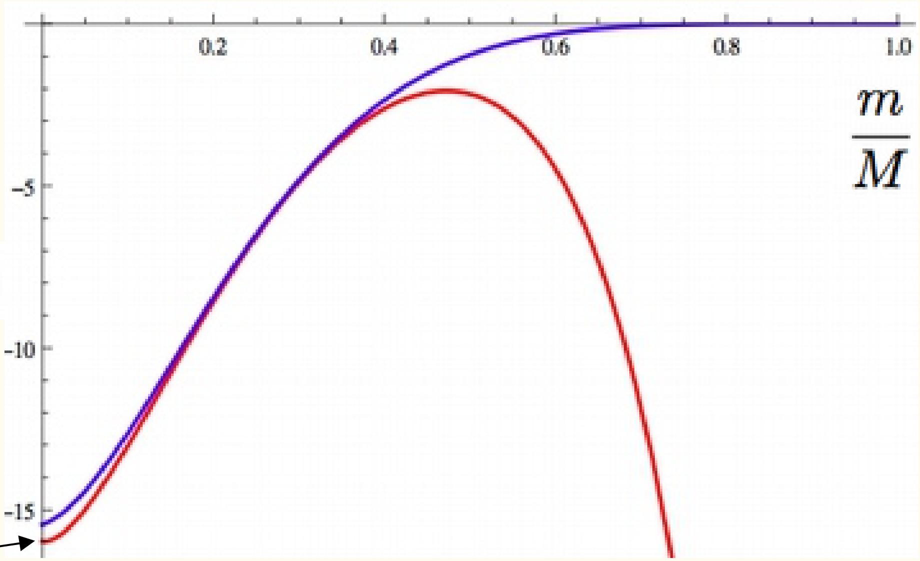


Competing effects:
- vacuum polarization in the hard photon; and
- self-energy and real radiation

Ultimate goal: smooth matching of all energy regions, from the bound electron at low energy to the end-point.

Free muon lifetime

α^2 correction to
$\Gamma\left(\mu(M) \to e\,(m)\,\nu\bar{\nu}\right)$



exact

Note: the blue curve is designed for m ~ M,
but is good even for m << M.

So we want to exploit the expansion around m = M to get α^3

M. Dowling, with J. Piclum, AC, M. Czakon

Conclusions

Great opportunities for precise theoretical studies in low-energy physics:

- bound electron *g*-factor: complements a vigorous experimental program in Mainz, Heidelberg and GSI Darmstadt

- muon decay: background for μ-e conversion searches; theoretically interesting

- many atomic/molecular structure studies needed, eg for electric dipole searches