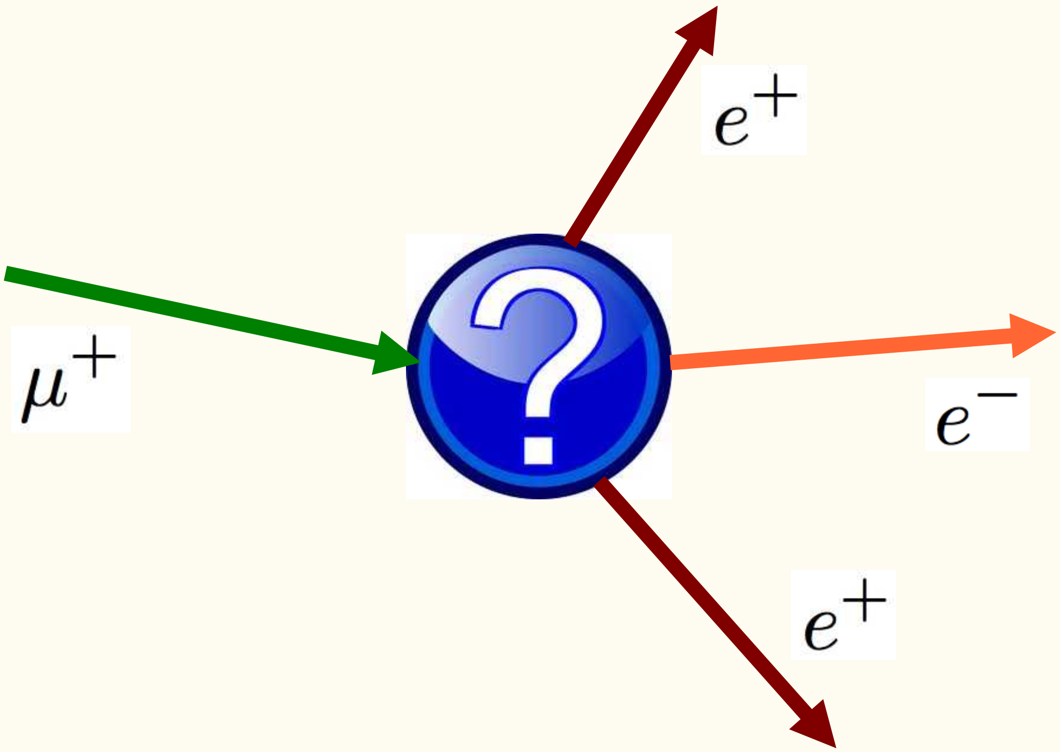
Fundamental physics with muons



Physics of Fundamental Symmetries and Interactions

PSI, September 9, 2013

Andrzej Czarnecki University of Alberta

Outline

Muon g-2, muonium HFS

Transition moments and Lepton Flavor Violation
comparison of the muon decays and conversion

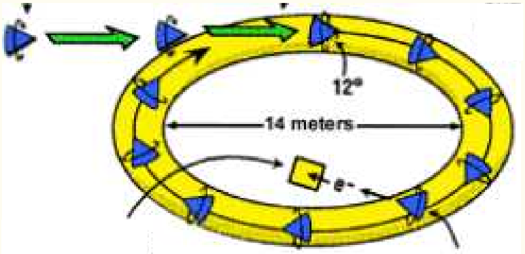
Free muon decay

Muonic atoms: spectroscopy and nuclear capture

Side theme: development of new theoretical tools, due to experimental progress

Muon anomalous magnetic dipole moment

The 3.6 sigma discrepancy persists,



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

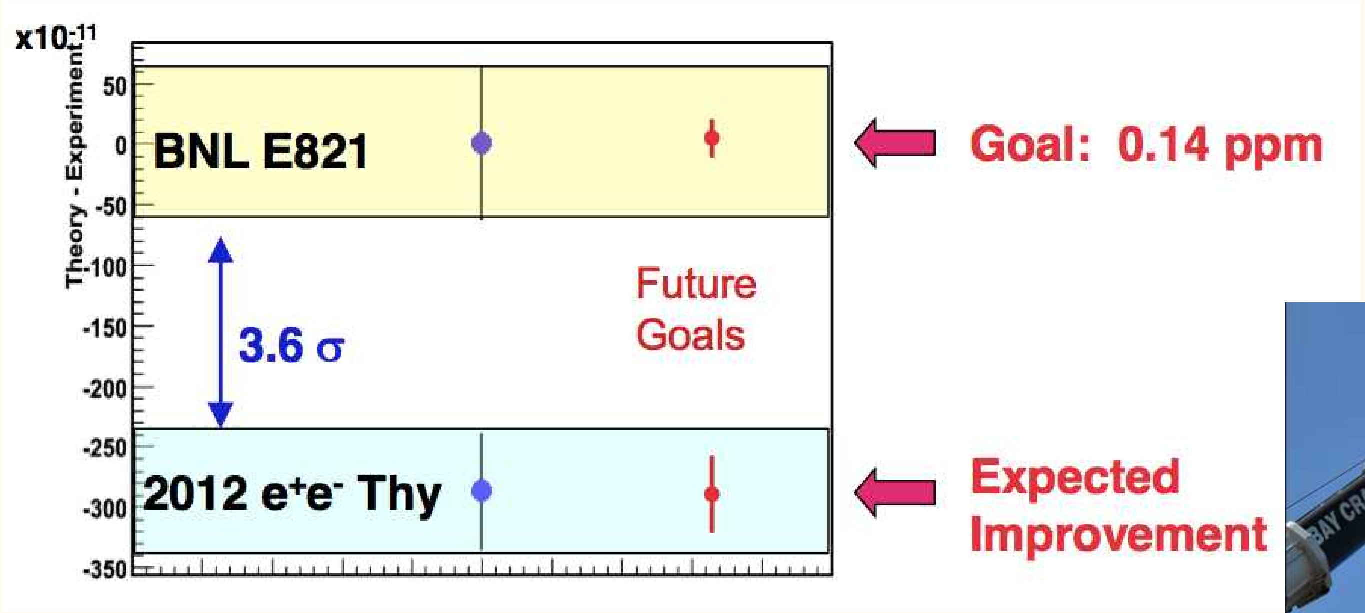
PRD 86, 095009 (2012)

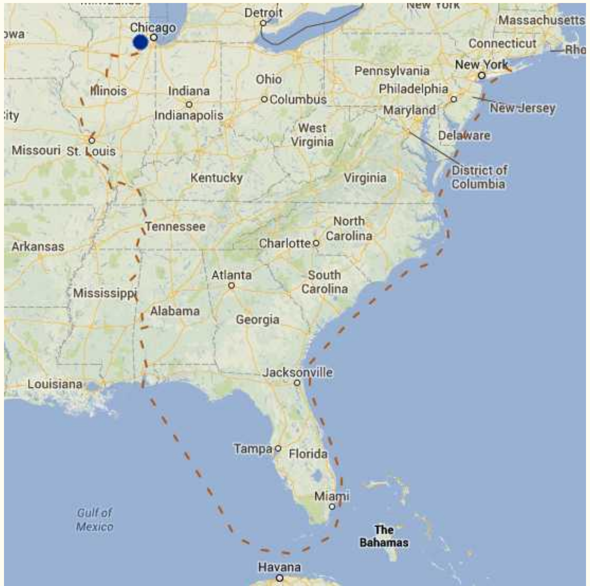
Is it due to New Physics? The dipole moment is relatively large,

$$d_\mu \sim \frac{e}{2m_\mu} a_\mu^{\rm NP} \sim 300 \cdot 10^{-11} \frac{e}{200\,{\rm MeV}} \sim 3 \cdot 10^{-22}\, e \cdot {\rm cm}$$

New g-2 experiment in Fermilab

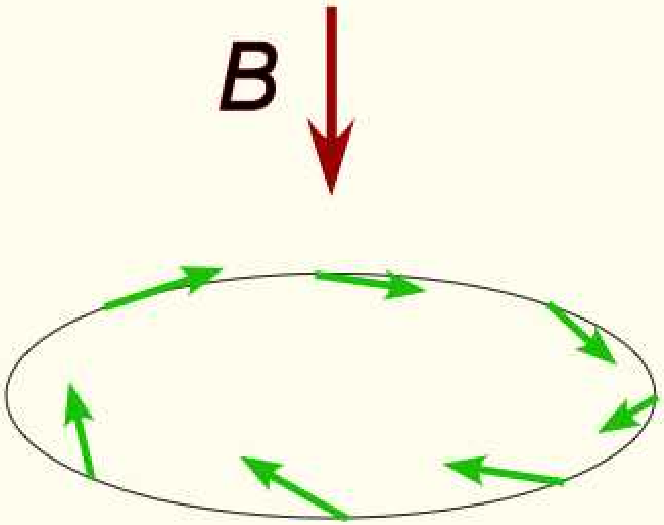
talk by Gibbons later today;
g-2 @ PSI poster: Taqqu





How the g-2 is determined

Measure $$\omega_a = \frac{g-2}{2}\frac{e}{m_\mu}B$$



B from NMR: $$\omega_p = \frac{2\mu_p B}{\hbar}$$

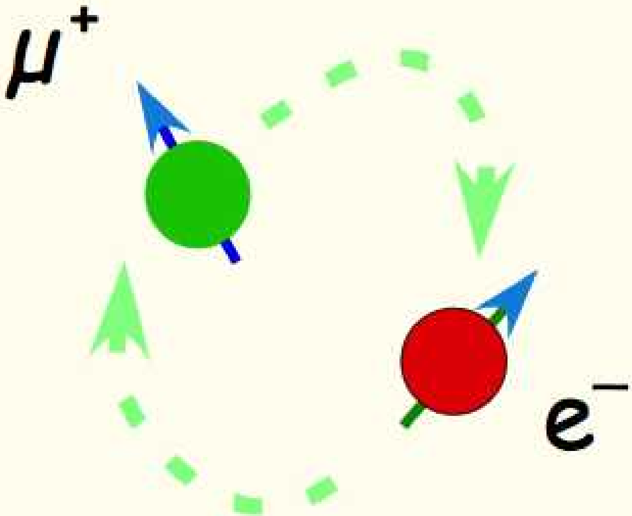
$\frac{e}{m_\mu}$ from $$\mu_\mu \equiv g\frac{e\hbar}{4m_\mu}$$

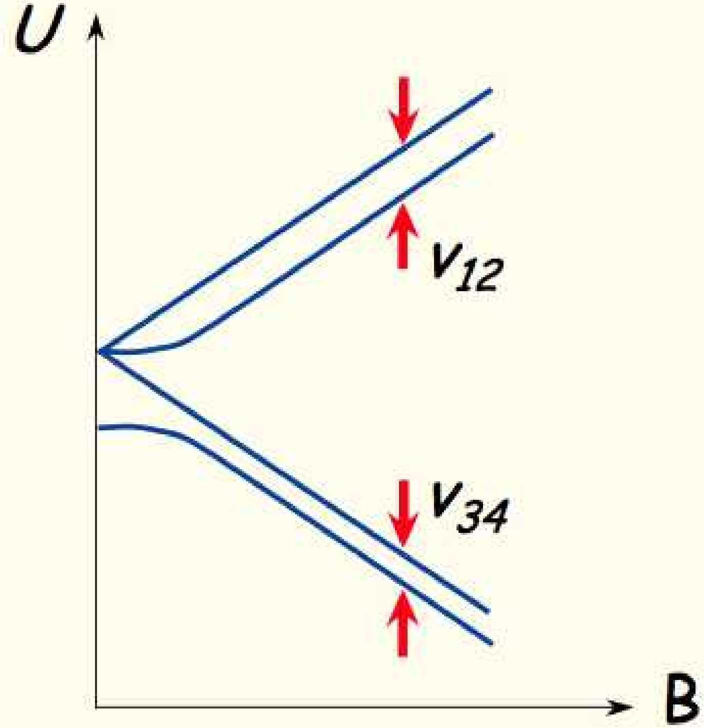
Master formula: $$\frac{g-2}{2} = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Measured by E821

From muonium

Muonium spectrum determines μ_μ/μ_p





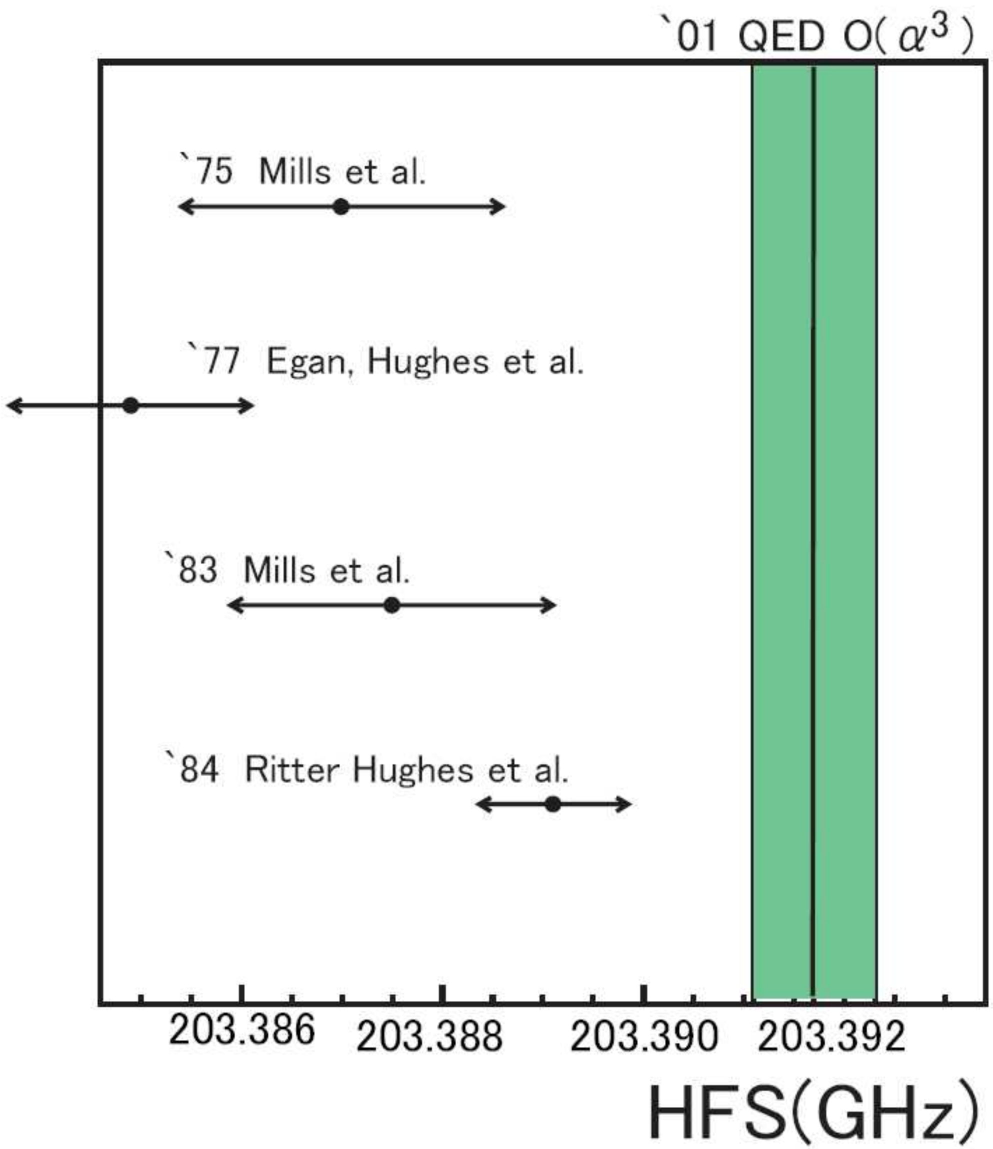
$$\nu_{34} - \nu_{12} \sim \mu_\mu B \quad \Rightarrow \quad \mu_\mu / \mu_p$$

Measured to relative 0.12 ppm (like $14 \cdot 10^{-11}$ in a_μ)

Should be improved for the next generation g-2 (FNAL goal: 0.14 ppm)

Talk by Kanda

Muonium vs positronium HFS: a comment



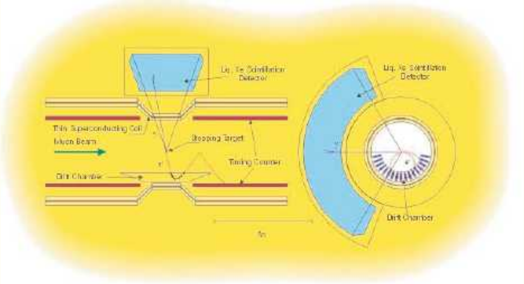
3.4σ difference in positronium HFS between measurements and QED

New experiment ongoing in Tokyo;
Related effort in Zurich: Crivelli

There are also flavor-off-diagonal dipole moments: muon decay to an electron and photon, $\mu \to e\gamma$

Until recently (MEGA @ Los Alamos): $BR(\mu \to e\gamma) < 10^{-11}$

New bound (MEG @ Paul Scherrer Institute)



$< 5.7 \cdot 10^{-13} \quad (2013)$

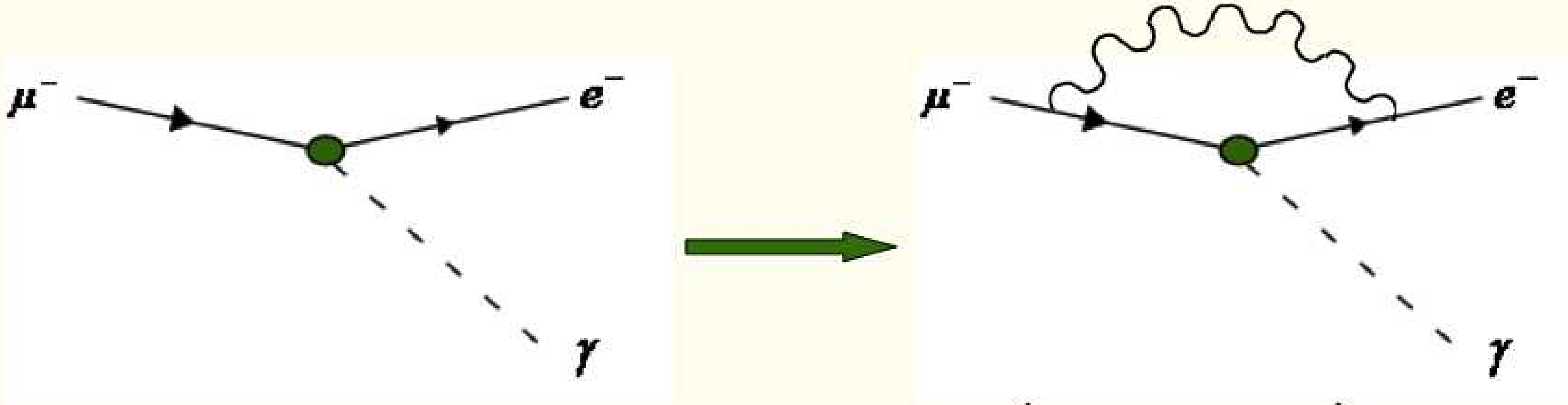
This corresponds to the transition dipole moment

$$d_{\mu \to e} \simeq 4 \cdot 10^{-27}\, e \cdot \mathrm{cm}$$

Talk by Voena
Posters Kanako, Pruna

similar to the best electron EDM, $<10^{-27}$! Nature 473, 493 (2011)

QED suppression of the decay $\mu \to e\gamma$



$$\sigma_{\alpha\beta} q^{\beta} \left(E - M\gamma_5 \right) A^{\alpha} \qquad \times \left(1 - \frac{4\alpha}{\pi} \ln \frac{\Lambda}{m_\mu} \right)$$

AC and Jankowski,
PRD 65, 113004 (2002)

This is the largest known QED correction to a decay rate;
15 percent for $\Lambda \sim 250$ GeV. In general, $\sim 2\ln(\Lambda/m_\mu)$ percent.

For comparison, correction for the normal muon decay is 0.4 percent.

New Physics scales probed by dipole moments

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

Electron EDM $$|d_e| < 10^{-27}\, e \cdot \mathrm{cm}$$

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

These moments are expected to scale with the New Physics mass like

$$d_f \sim \frac{m_f}{\Lambda^2}$$

The transition moment probes the highest mass scales,

$$\frac{\Lambda_{\mu \to e}}{\Lambda_{\mathrm{eEDM}}} \sim \sqrt{\frac{m_\mu}{4m_e}} \simeq 7$$

Bravo MEG!

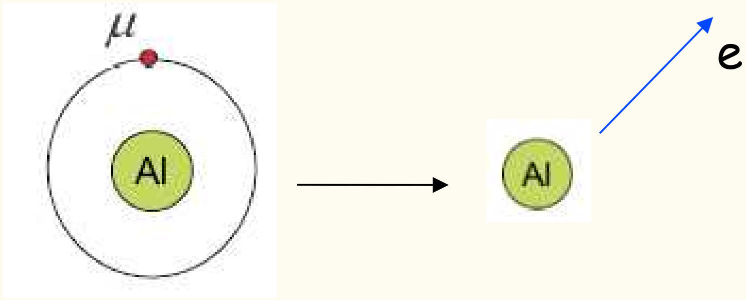
What about non-tensor interactions?

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.

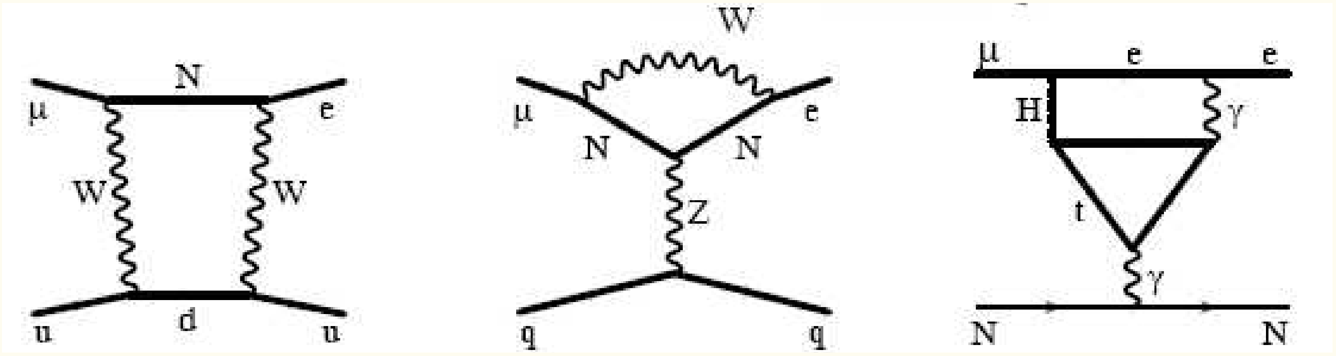
Probed by muon-electron conversion

as well as mu --> eee



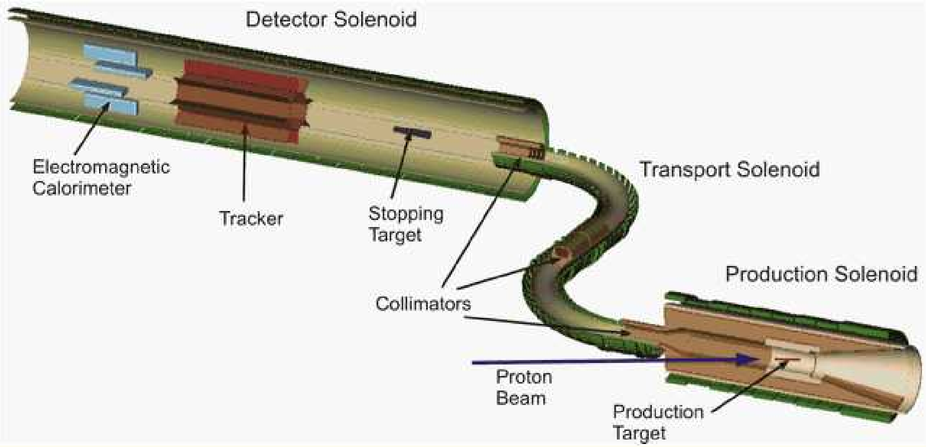
Talks by Gaponenko, Schoening
Poster by Nishiguchi

Variety of mechanisms:



Muon-electron conversion

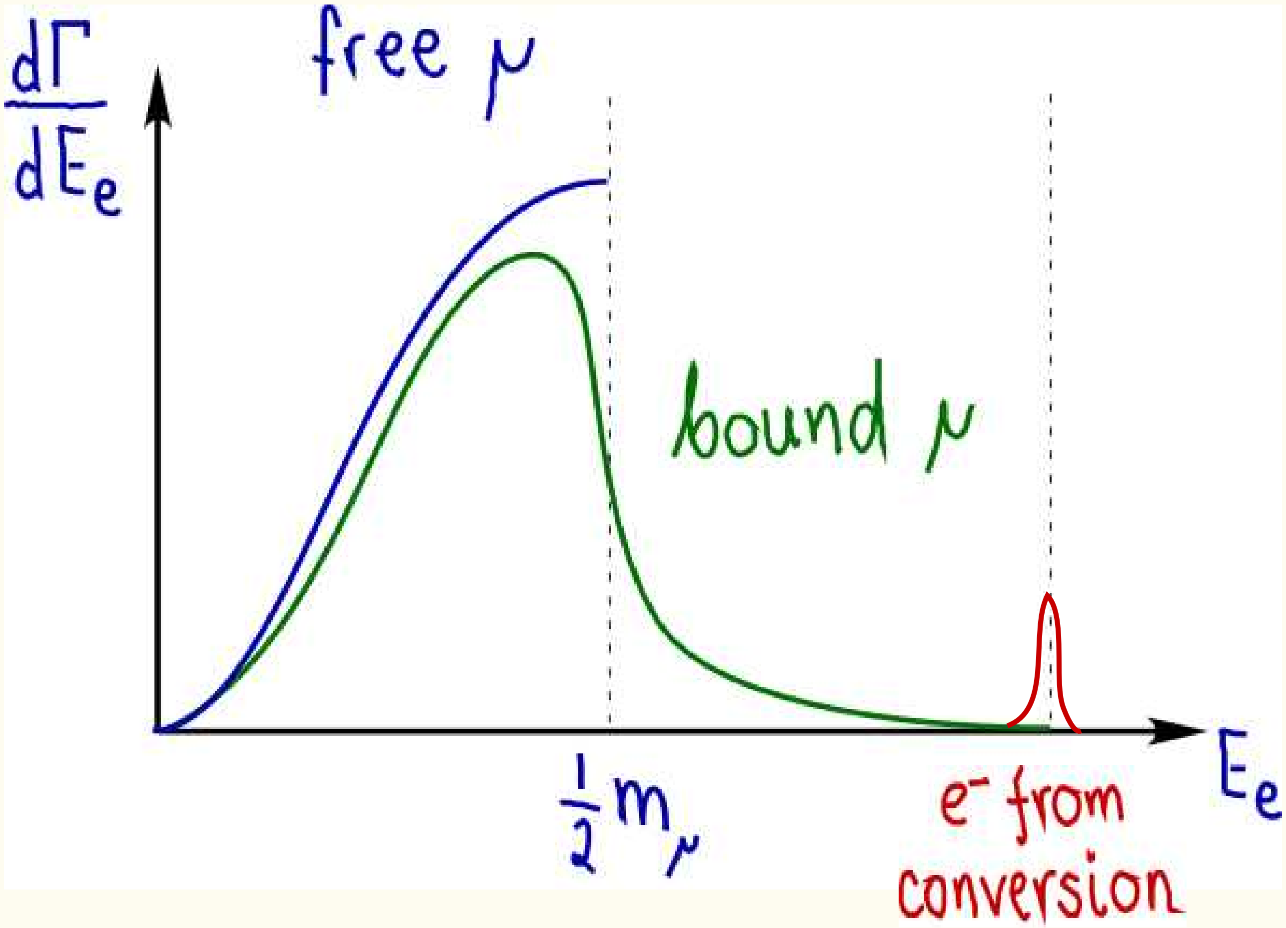
No accidental bkgd
(single monochromatic e^-);
$\sim 10^{-17}$ sensitivity envisioned



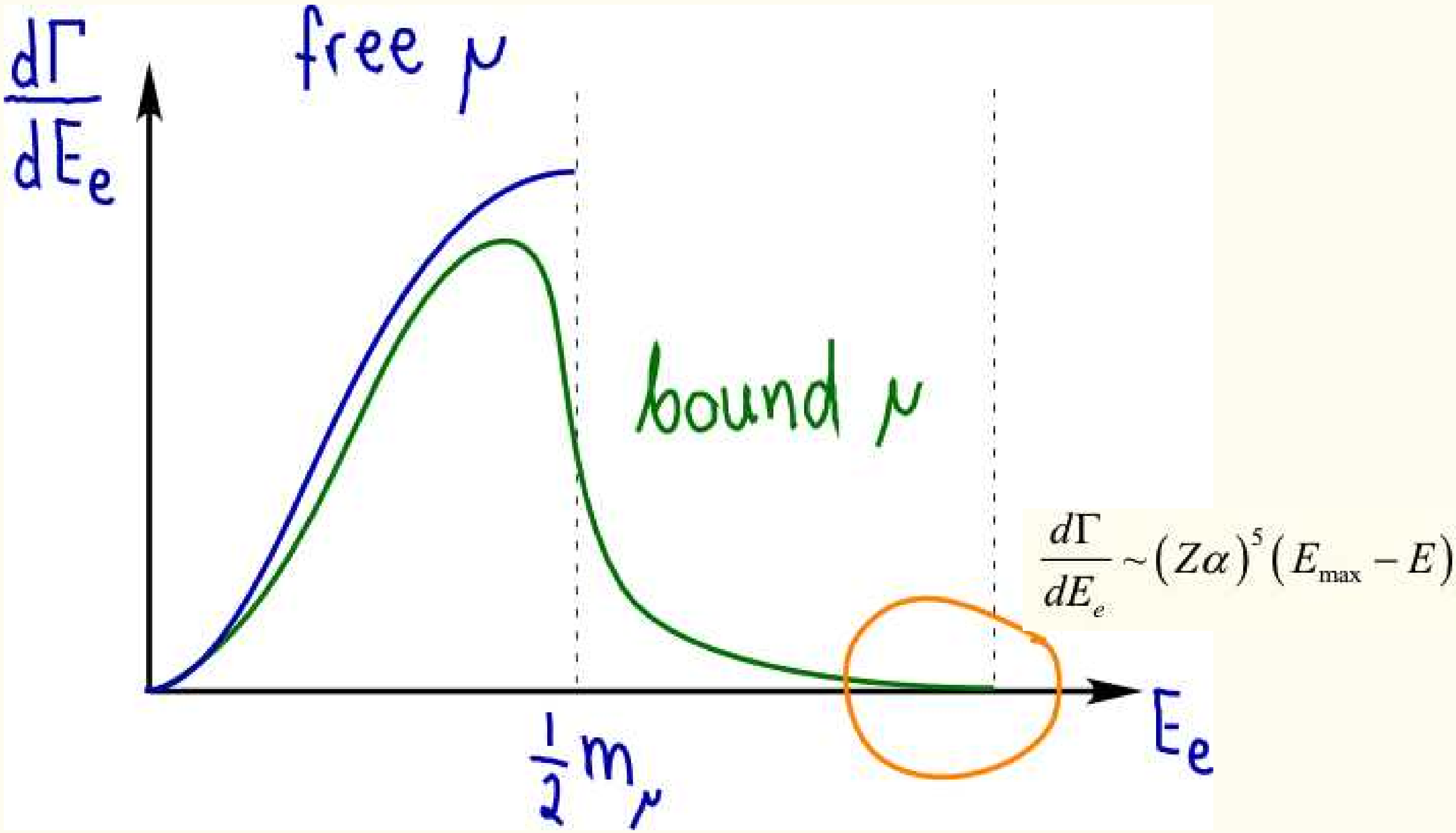
Analogy to fixed-target experiments with a luminosity ~ $10^{50} / (\mathrm{cm}^2 \cdot \mathrm{s})$

A year of HL-LHC integrated luminosity collected here every nanosecond!!

Background from the standard muon decay



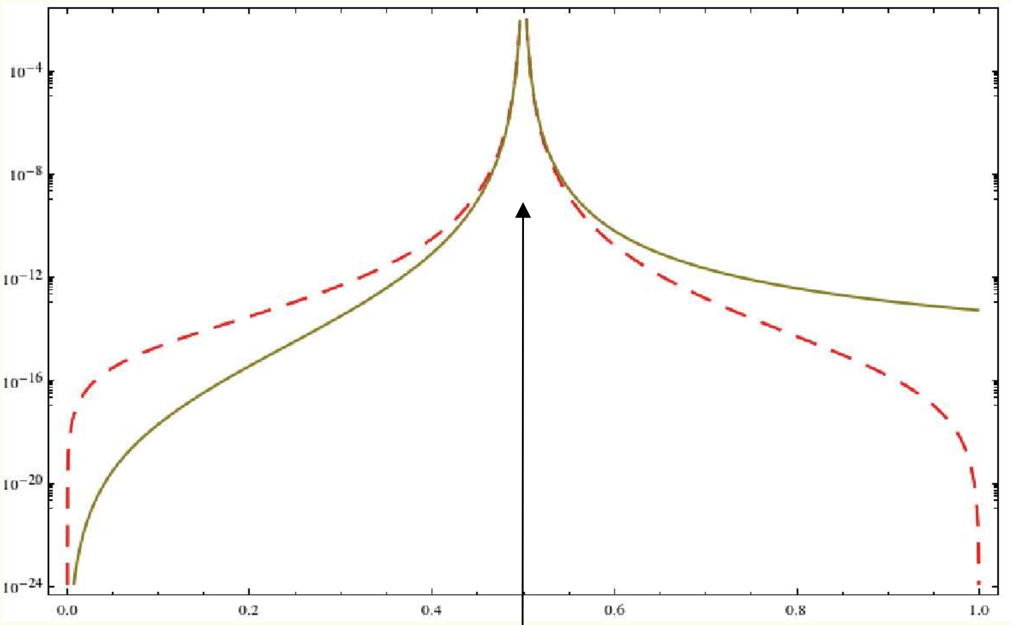
End point spectrum must be well understood



AC, X. Garcia i Tormo, W. J. Marciano PRD84,013006,2011

Results: electron spectrum in $\mu \rightarrow e+J$

Robert Szafron



without binding effects,
the electron spectrum is
monochromatic,
concentrated here
at half muon mass

Summary of LFV muon decays

	Present limit	Planned sensitivity
$\mu \to e\gamma$	$5.7 \cdot 10^{-13}$	$5 \cdot 10^{-14}$
$\mu \to eee$	10^{-12}	10^{-16}
$\mu N \to eN$	$7 \cdot 10^{-13}$ (Au)	$2 \cdot 10^{-17}$

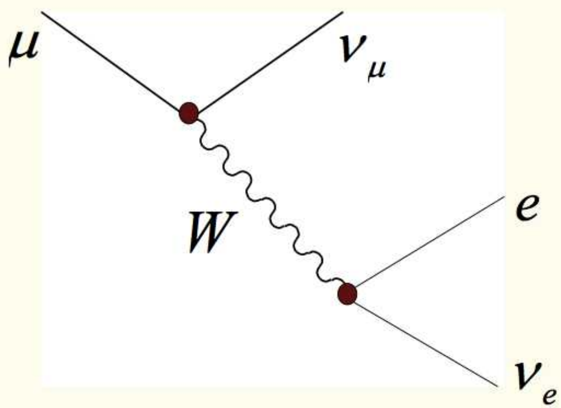
If dipole operators dominate,

$$B(\mu \to e\gamma) : B(\mu \to ee^+e^-) : R(\mu^- \mathrm{Al} \to e^- \mathrm{Al}) :: 389 : 2.3 : 1$$

If all experimental goals are achieved, in the long term

$$B(\mu \to e\gamma)^{\exp} : B(\mu \to ee^+e^-)^{\exp} : R(\mu^- \mathrm{Al} \to e^- \mathrm{Al})^{\exp} :: \frac{1}{6} : \frac{1}{2} : 1$$

Free muon decay



A model process in particle physics
(tools for quark decays)

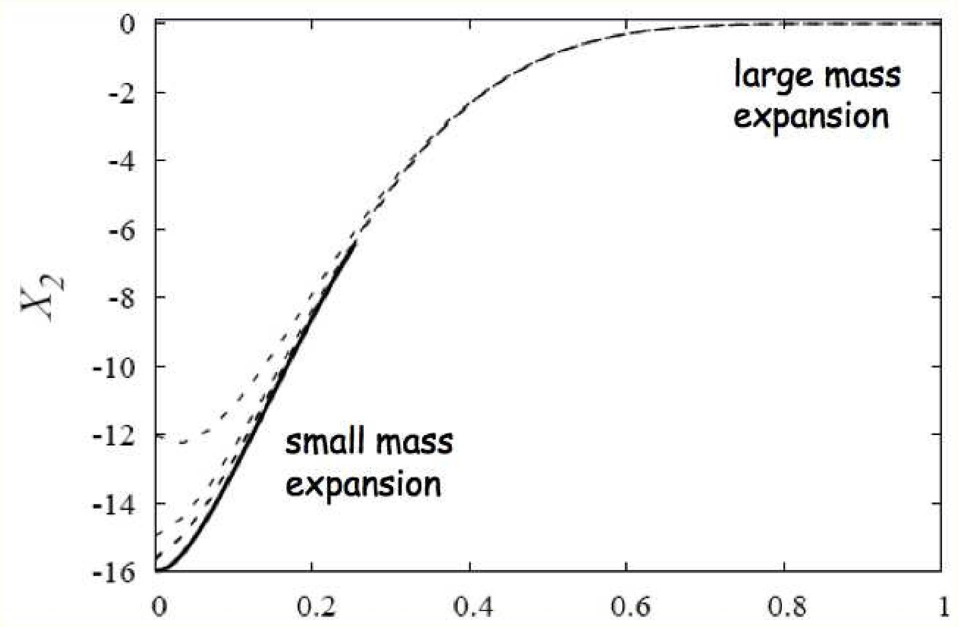
The first decay process known with one- and two-loop QED effects.

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

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.



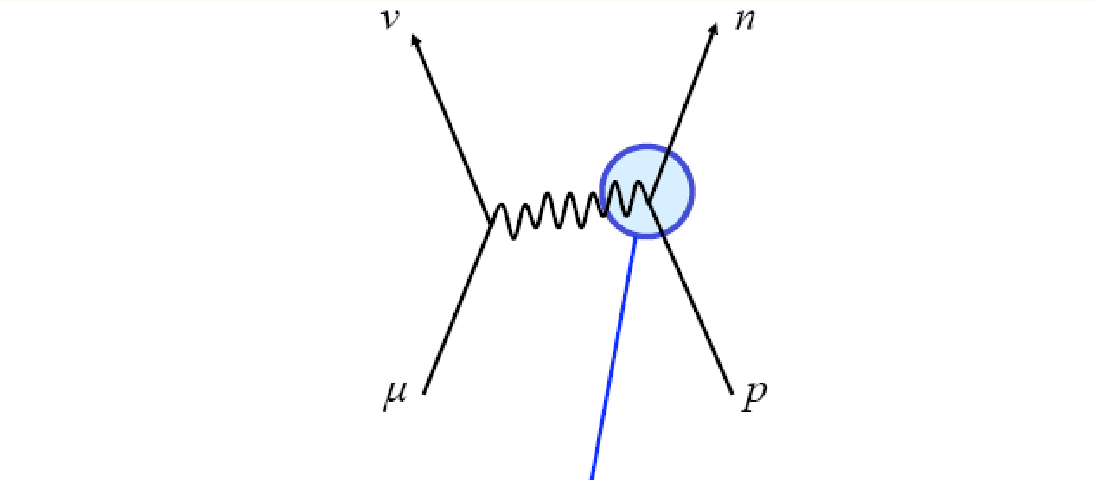
"Electron to muon" mass ratio

From Dowling, Piclum, AC

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

Muon capture

Talks by Kammel, Viviani, Murray



$$\langle n | (\gamma_\alpha) g_V + (i\sigma_{\alpha\beta} q^\beta) g_M + (\gamma_\alpha \gamma_5) g_A + (q_\alpha \gamma_5)\, g_P \,| p \rangle$$

Theory and experiment agree, after years of confusion.

Average of HBChPT calculations of Λ_S:

$$(687.4\ \mathrm{s}^{-1} + 695\ \mathrm{s}^{-1})/2 = 691.2\ \mathrm{s}^{-1}$$

Apply new rad. correction (2.8%):

$$(1 + 0.028) 691.2\ \mathrm{s}^{-1} = 710.6\ \mathrm{s}^{-1}$$

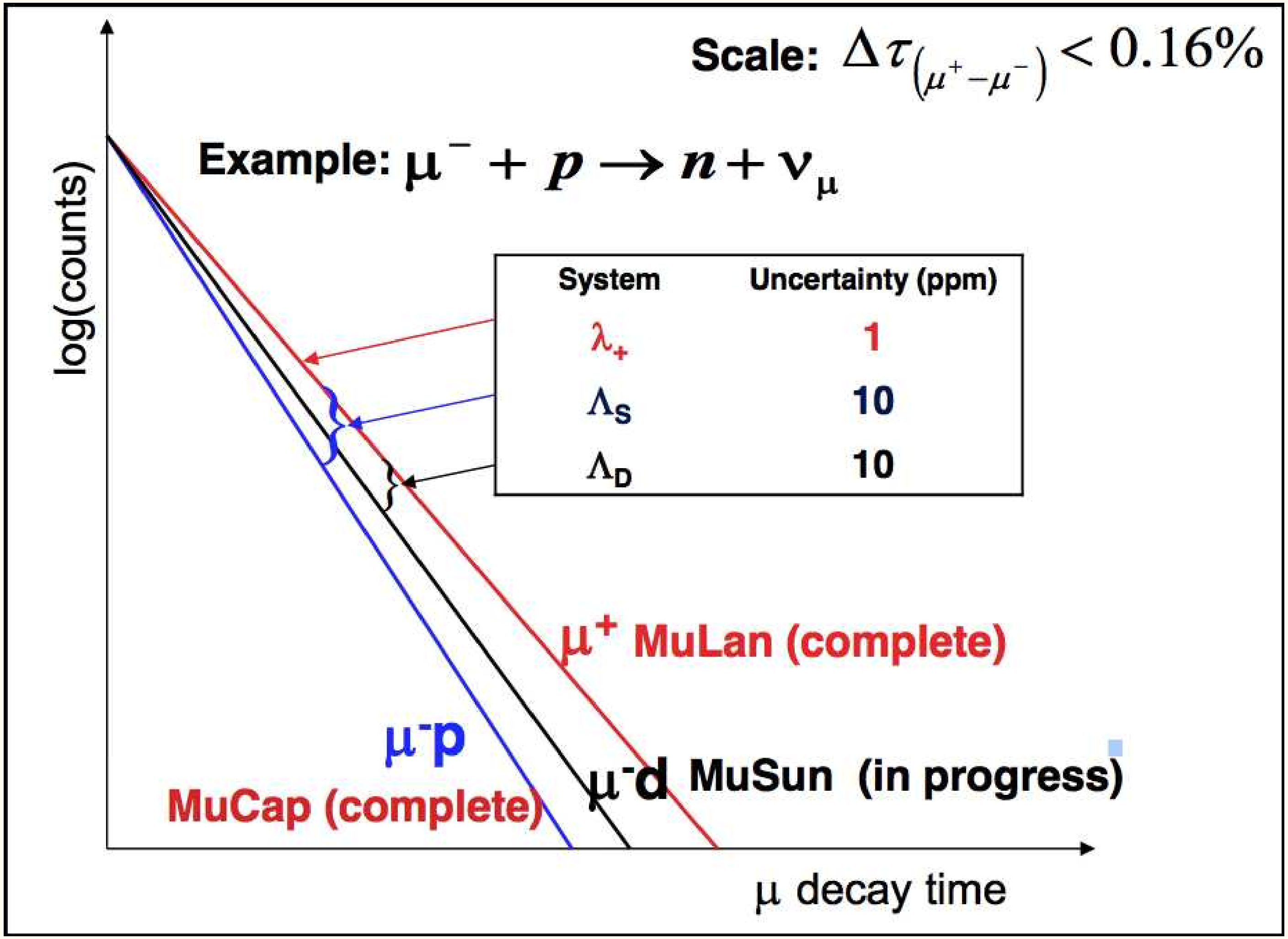
further sub percent theory required

Λ_S^{Theory} = **710.6 s^{-1}**

PRL **99**, 032001 (2007)

Λ_S^{MuCap} = **725.0 ± 13.7$_{stat}$ ± 10.7$_{sys}$ s^{-1}**

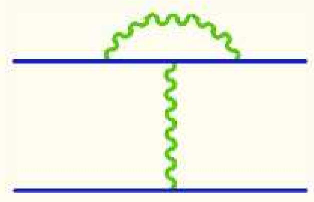
Lifetimes of muons vs antimuons

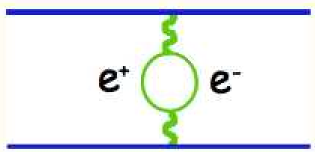


$$\frac{1}{\tau} = \Lambda_{total} = \Lambda_{decay} + \Lambda_{capture}$$

Spectroscopy of muonic atoms: μp Lamb shift

Origins of Lamb shift:

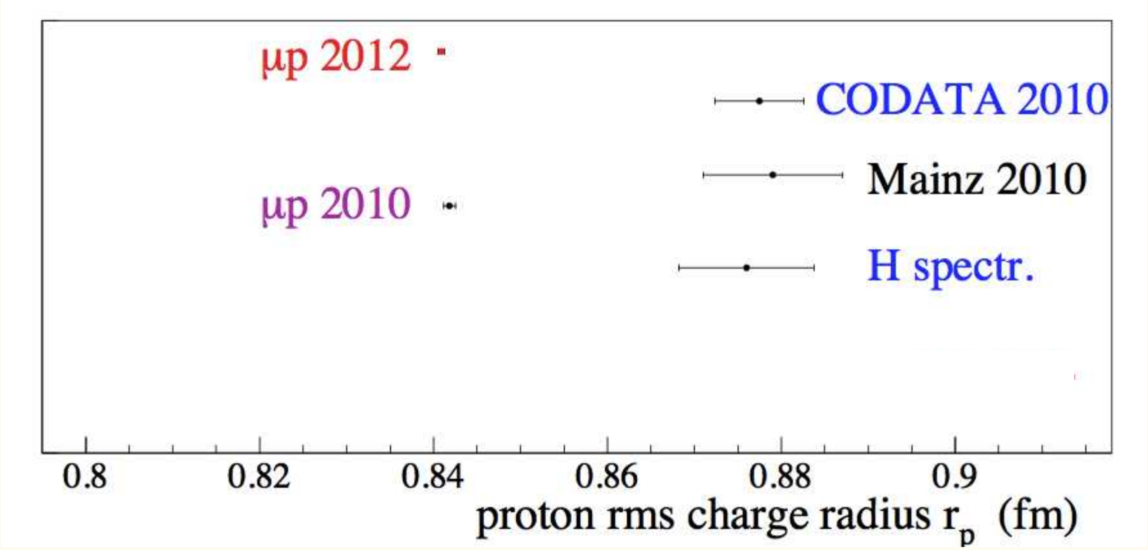




Smeared nuclear charge

If the loops are correctly evaluated (talk by Pachucki)
and the Lamb shift measured (talk by Pohl),
the smearing (proton radius) can be extracted.

Dramatic results:



Difficult to explain with New Physics.
New proposals: search for parity violation with muons (McKeen, Pospelov '12)

Summary

Currently, Paul Scherrer Institute is the world capital of muon physics.
Fermilab, J-PARC planning complementary experiments.

Talk by Tschirhart,
posters by Kawamura, Khaw, Knecht

Low energy experiments are excellent probes for New Physics.

Pushing the limits of experimental and theoretical techniques.

Exciting future prospects at PSI, Fermilab, J-PARC, among others.