Precision Muon Physics

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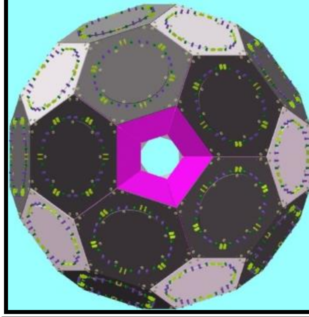
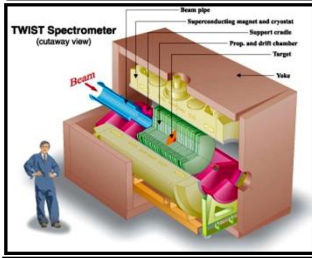
- **Muon primer**

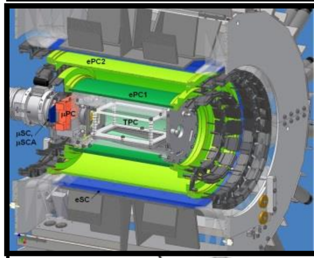
- **Muons in support of the Standard Model**
- **Muons challenging the Standard Model**

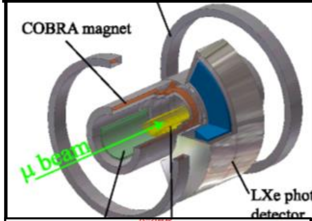
- **Unique, “single purpose” experiments**
  - **Generally, do only 1 thing, but <u>very well</u>**
  - **I will emphasize why this is necessary**

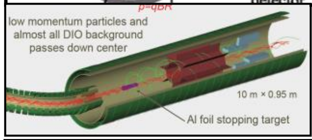
Argonne, April, 2013









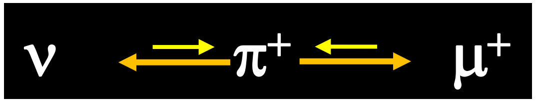


Muon Primer

- **Mass ~ 207 m_e**
  - **$(m_\mu/m_e)^2 \approx 43{,}000$ times more sensitive to "new physics" through quantum loops compared to electrons (taus would be better!)**

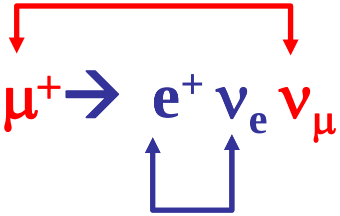
- **Lifetime ~2.2 μs**
  - **High-intensity beams; can stop and study; can possibly collide**

- **Primary production: $\pi^+ \rightarrow \mu^+ \nu_\mu$**
  - **Polarized naturally:**

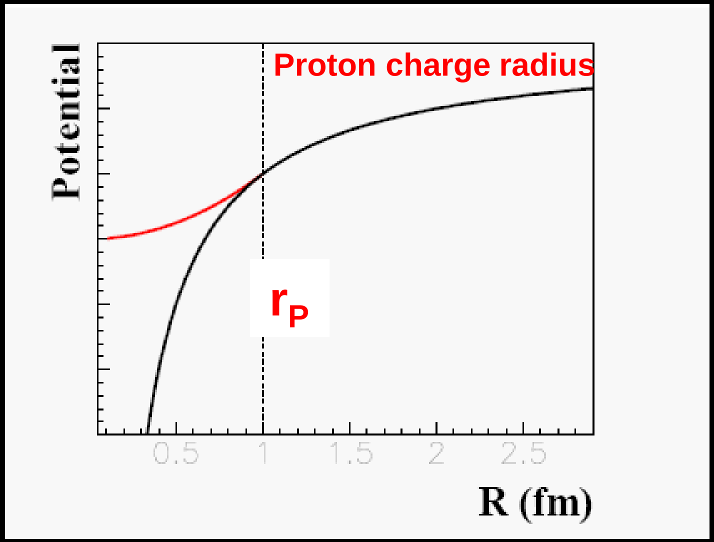


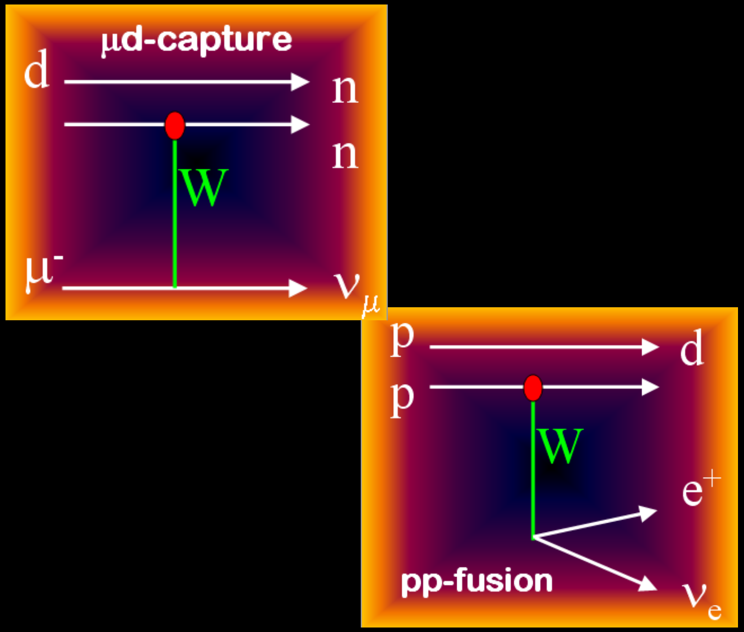
- **Primary decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$**
  - **Purely weak; distribution in θ and *E* reveals weak parameters**

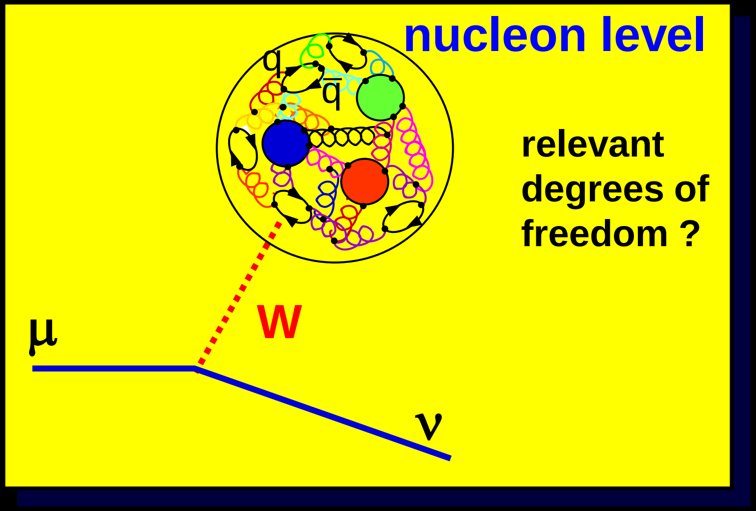
- **Lepton number is conserved**

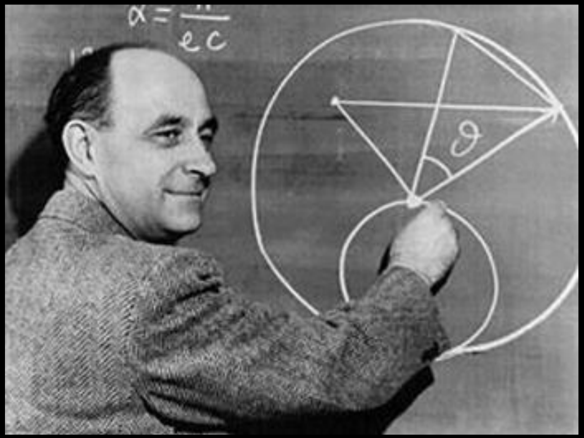


Establishing SM Parameters





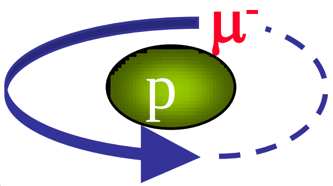


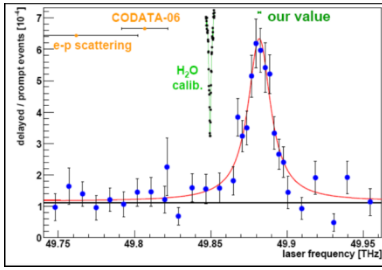


Fermi Constant

Muonic "1-electron hydrogen-like" Atoms

μ^-p, μ^-d, μ^-A





- **Charge radius of proton,**
- **Measure 2S → 2P transition in μ^-p**
- **Which is related to r_p in clean way**

$$\Delta E(2S-2P) = 209.978(5) - 5.226\, r_p^2 + 0.0347\, r_p^3 \quad \text{meV}$$

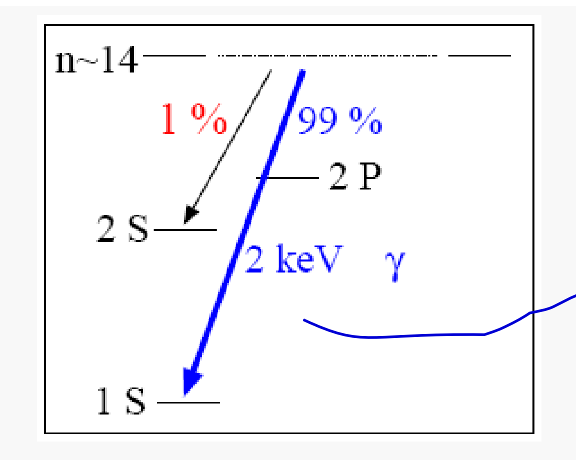
ΔE larger than expected → proton is smaller by 3 – 5 σ.

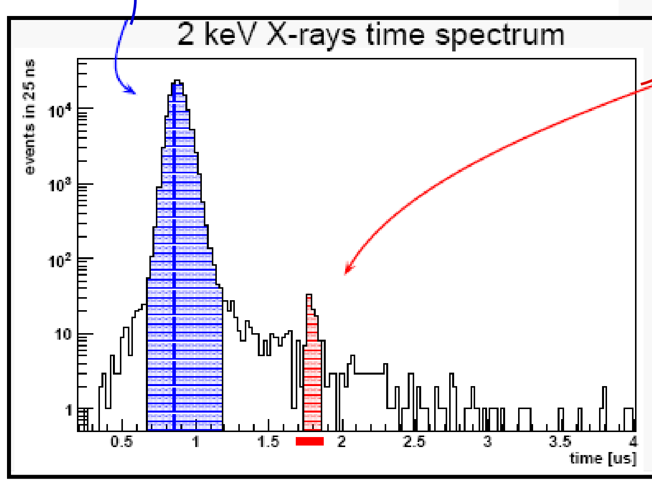
- **μp results wrong**? (no, see next slide)
- **ep scattering results wrong**? (can check)
- **Novel BSM physics** between μ and e interactions ?
  - Possibly related to this puzzle and to g-2, but very constrained

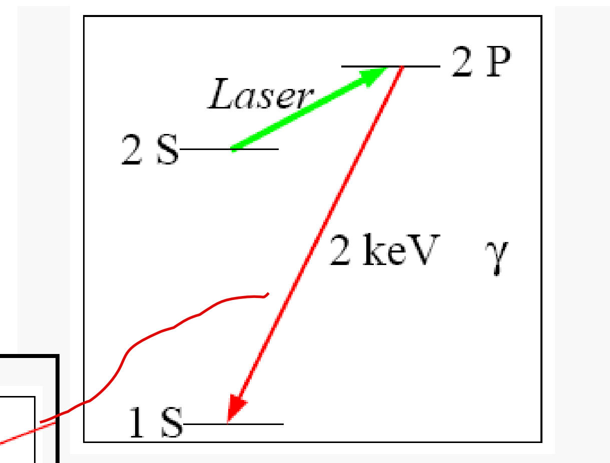
Bottom line: No clear resolution yet

The Muonic Lamb shift method is robust

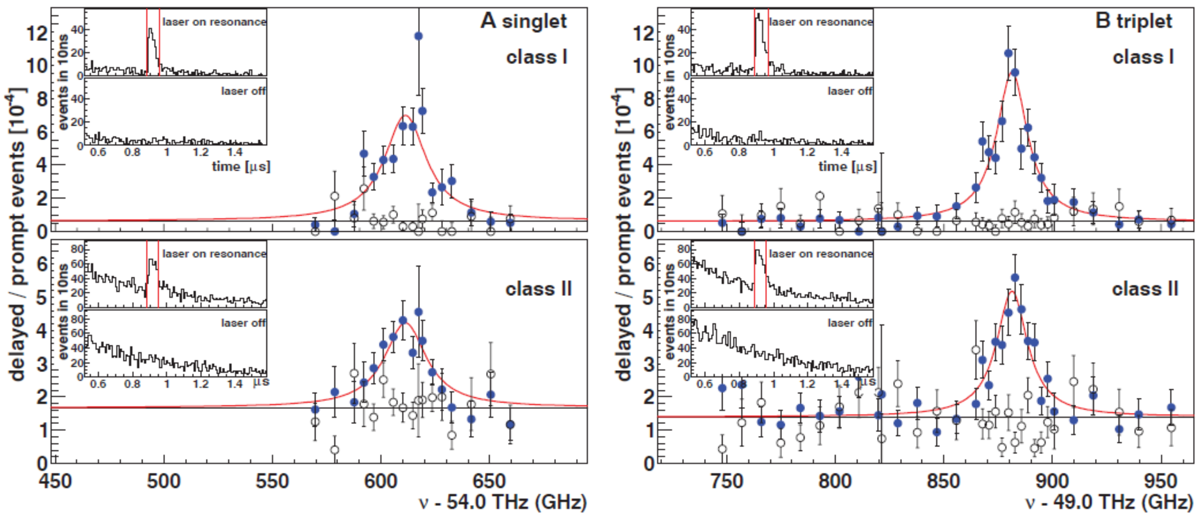
1. Stop μ^- in hydrogen
2. ~1% of μp arrive in 2S atomic state
   … lifetime there ~1 μs
3. Trigger laser to excite 2S → 2P transition
   … occurs only if laser frequency is at correct ΔE
4. 2P de-excites to 1S
   … emits 2 keV X-ray as "tag"







Update: 2013



Additional transitions: ***Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen*** ***Science 25 January 2013:***

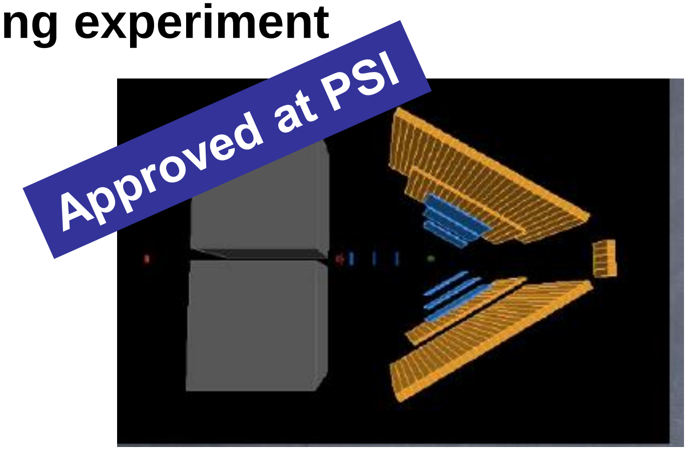
MUSE: µp Scattering at PSI

Direct test of µp versus ep interactions in a scattering experiment

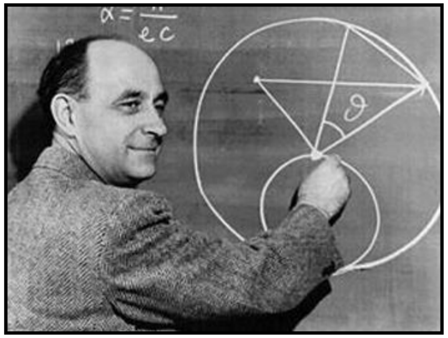
MUSE Test Run Report

The MUon proton Scattering Experiment collaboration (MUSE):

W.J. Briscoe,[1] K. Deiters,[2] E. Downie,[1] R. Gilman,[3] K.E. Myers,[3] E. Piasetzsky,[4] D. Reggiani,[2] P. Reimer,[5] G. Ron,[6] V. Sulkosky,[7] and M. Taragin[8]



Muon Lifetime



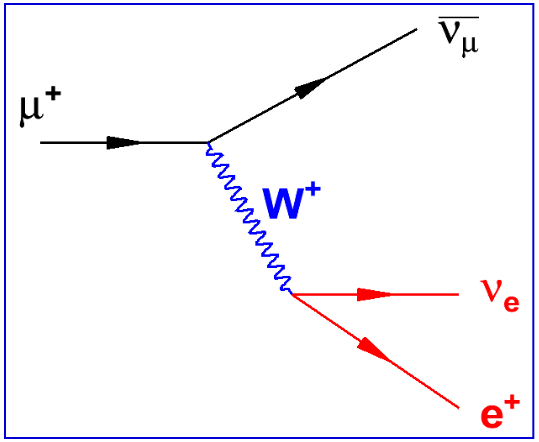
Fundamental electro-weak couplings

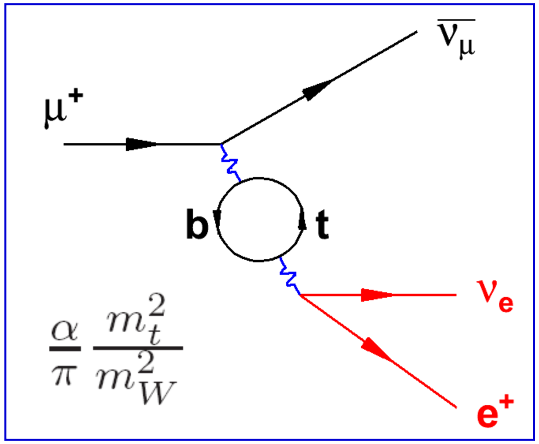
G_F	α	M_Z
9 ppm $\rightarrow$ 0.5 ppm	0.37 ppb	23 ppm

MuLan Collaboration
PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (**2013**)

Implicit to all EW precision physics

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r(m_t, m_H, \ldots)\right)$$

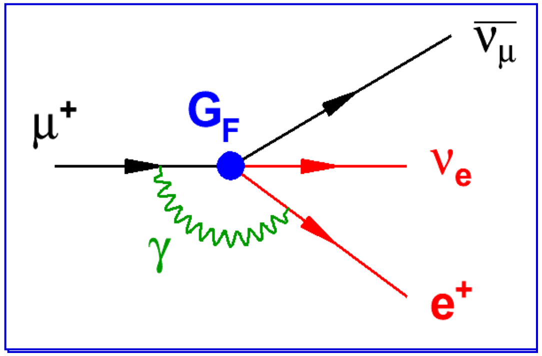




Uniquely defined by muon decay

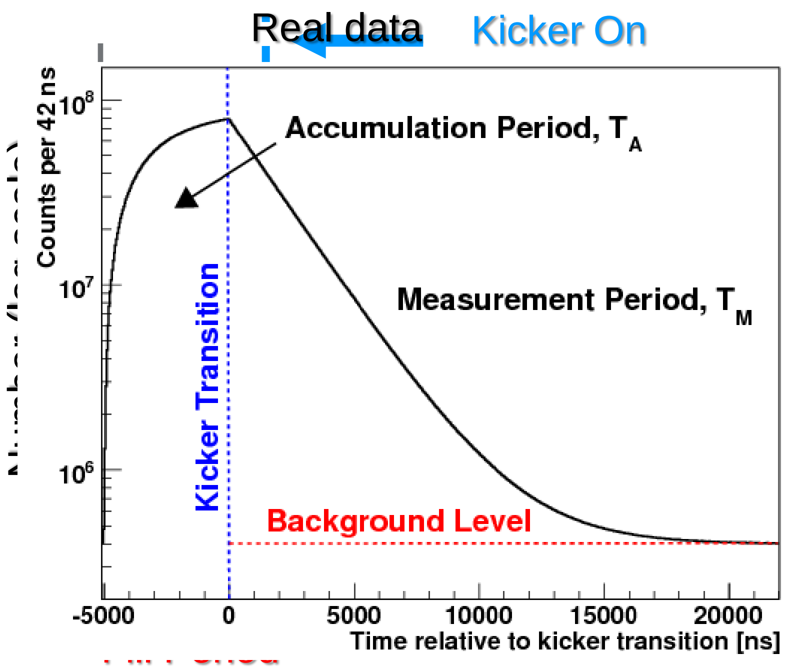
$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}(1 + q)$$

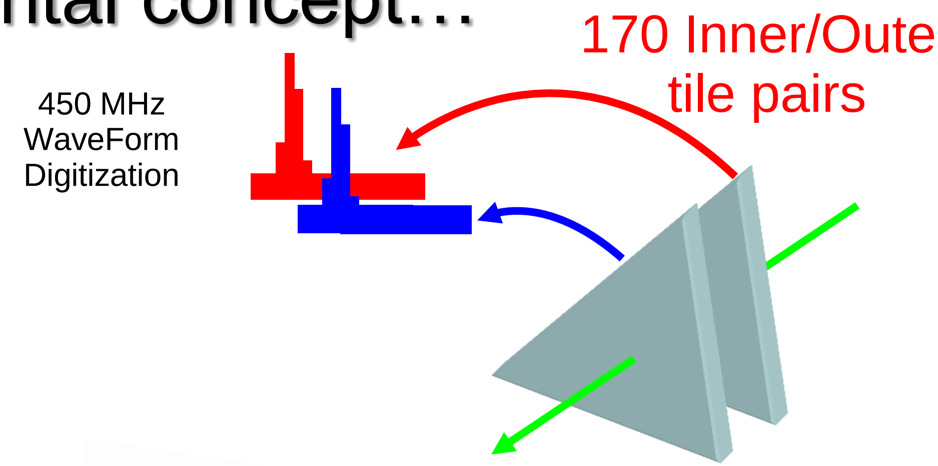
QED

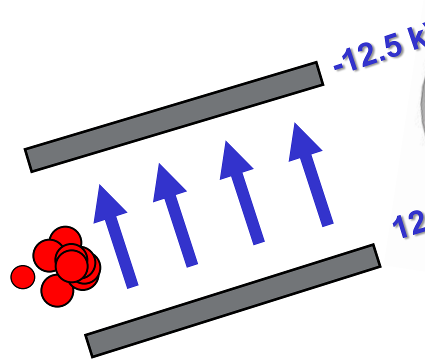


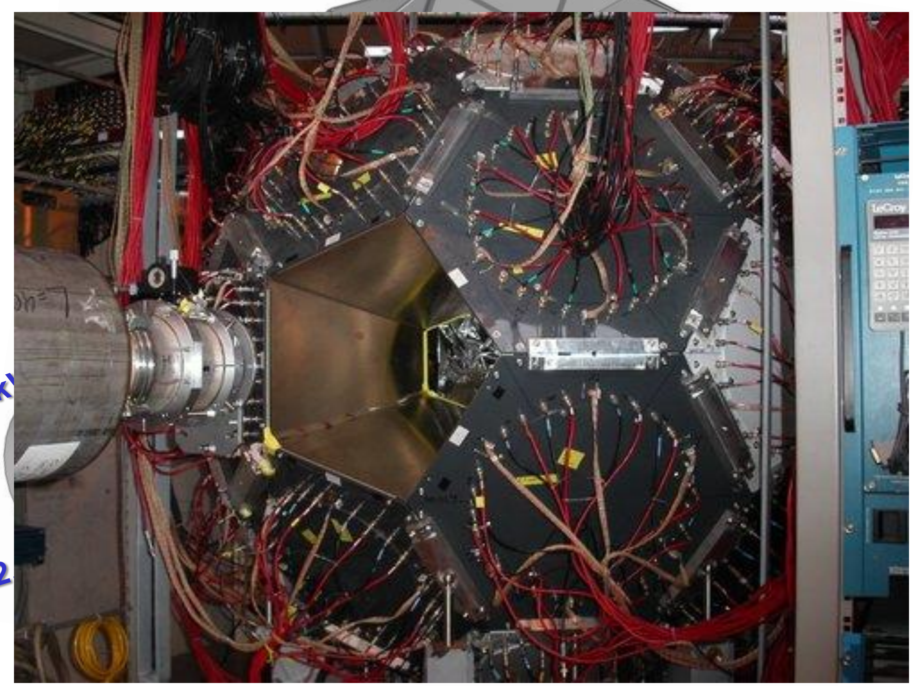
Extraction of G_F from τ_μ :
1999 two-loop calc.
reduced error from
15 to ~0.2 ppm

The MuLan experimental concept…



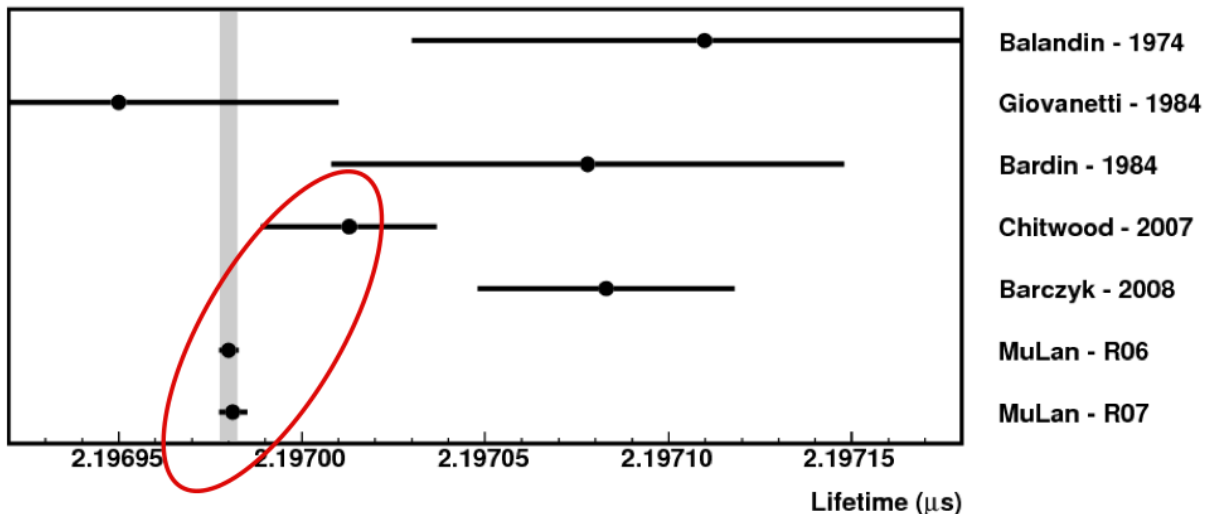






Detector has symmetric design around stops

Muon lifetime / Fermi constant



The most precise particle or nuclear or atomic lifetime ever measured

τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps

τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

τ(Combined) = 2 196 980.3 ± 2.2 ps (1.0 ppm)

$\Delta\tau$(R07 – R06) = 1.3 ps

New G_F (30x improved since 1999 PDG)

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

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Weak Nuclear Force Is Less Weak

New insights from subatomic particles that fly apart.

Jan 12, 2011

By Phillip F. Schewe
Inside Science News Service

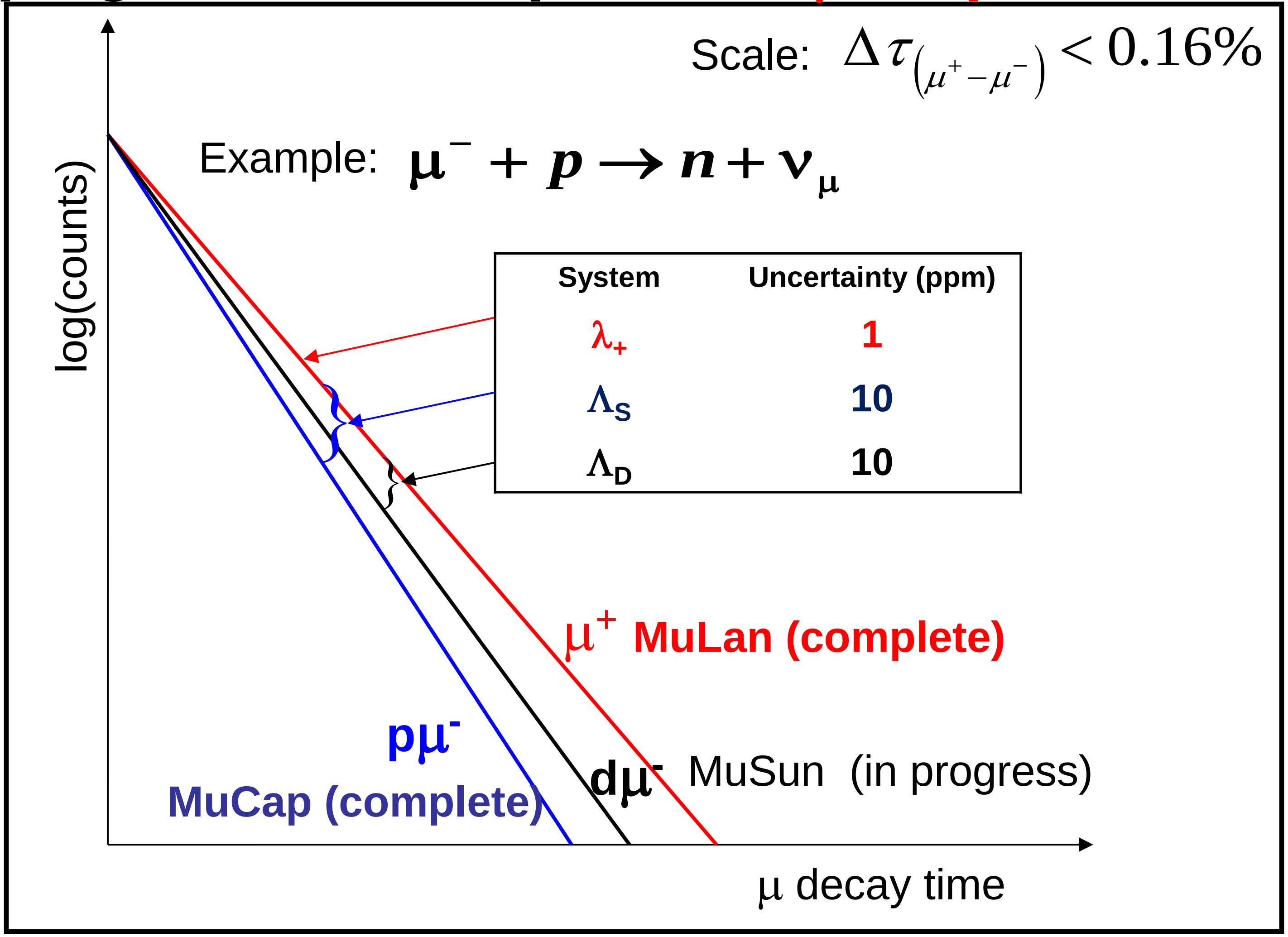
(ISNS) -- The force that governs some of the reactions that keep our sun shining is not quite as weak as scientists had previously thought. As a consequence, our estimation of how energetic the sun actually is just went up by a tiny amount.

The evidence for this weak nuclear force comes from the decay of muons, essentially heavier cousins of the electron, one of the building blocks of atoms.

Just as biologists sometimes study the tiniest and most

View full-size image

The lifetime is also used in a precision "capture" campaign when compared to μ^- in p and d targets,



System	Uncertainty (ppm)
λ_+	1
Λ_S	10
Λ_D	10

e.g: The μp singlet capture rate determines g_P

$$\Lambda_S = \Lambda_{\mu^-} - \Lambda_{\mu^+} = (\tau_{\mu^-})^{-1} - (\tau_{\mu^+})^{-1} \Rightarrow g_P$$

Muon Capture on the proton and Axial Nucleon Structure

$$\mu^- + p \to n + \nu_\mu$$

Capture rate Λ_S :

$$\mathcal{M} = \frac{-iG_F V_{ud}}{\sqrt{2}} \overline{u}(p_\nu)\gamma_\alpha(1-\gamma_5)u(p_\mu)\overline{u}(p_f)\tau_- \left[V^\alpha - A^\alpha\right] u(p_i)$$

Lorentz, T invariance gives these possibilities

$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

How does Λ_S depend on precision of the form factors ?

Well known

$$\left(\frac{\partial\Lambda_S}{\Lambda_S}\right)_{\Delta g_V} = 0.024\%$$

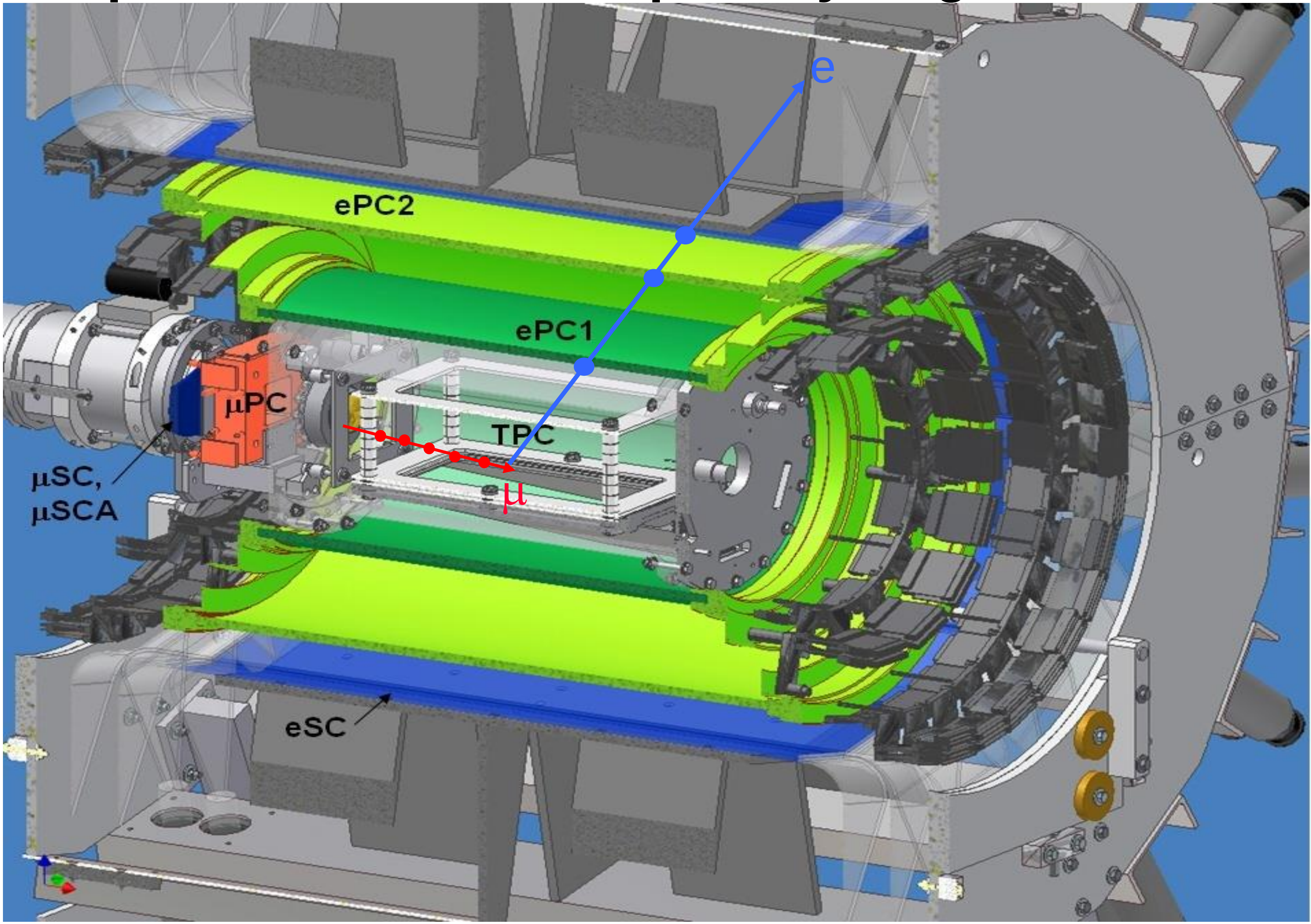
$$\left(\frac{\partial\Lambda_S}{\Lambda_S}\right)_{\Delta g_M} = 0.01\%$$

$$\left(\frac{\partial\Lambda_S}{\Lambda_S}\right)_{\Delta g_A} = 0.38\%$$

$$\frac{\Delta\Lambda_S}{\Lambda_S} = 1\% \quad \Rightarrow \quad \frac{\Delta g_P}{g_P} \approx 6.1\%$$

The least well known is g_P

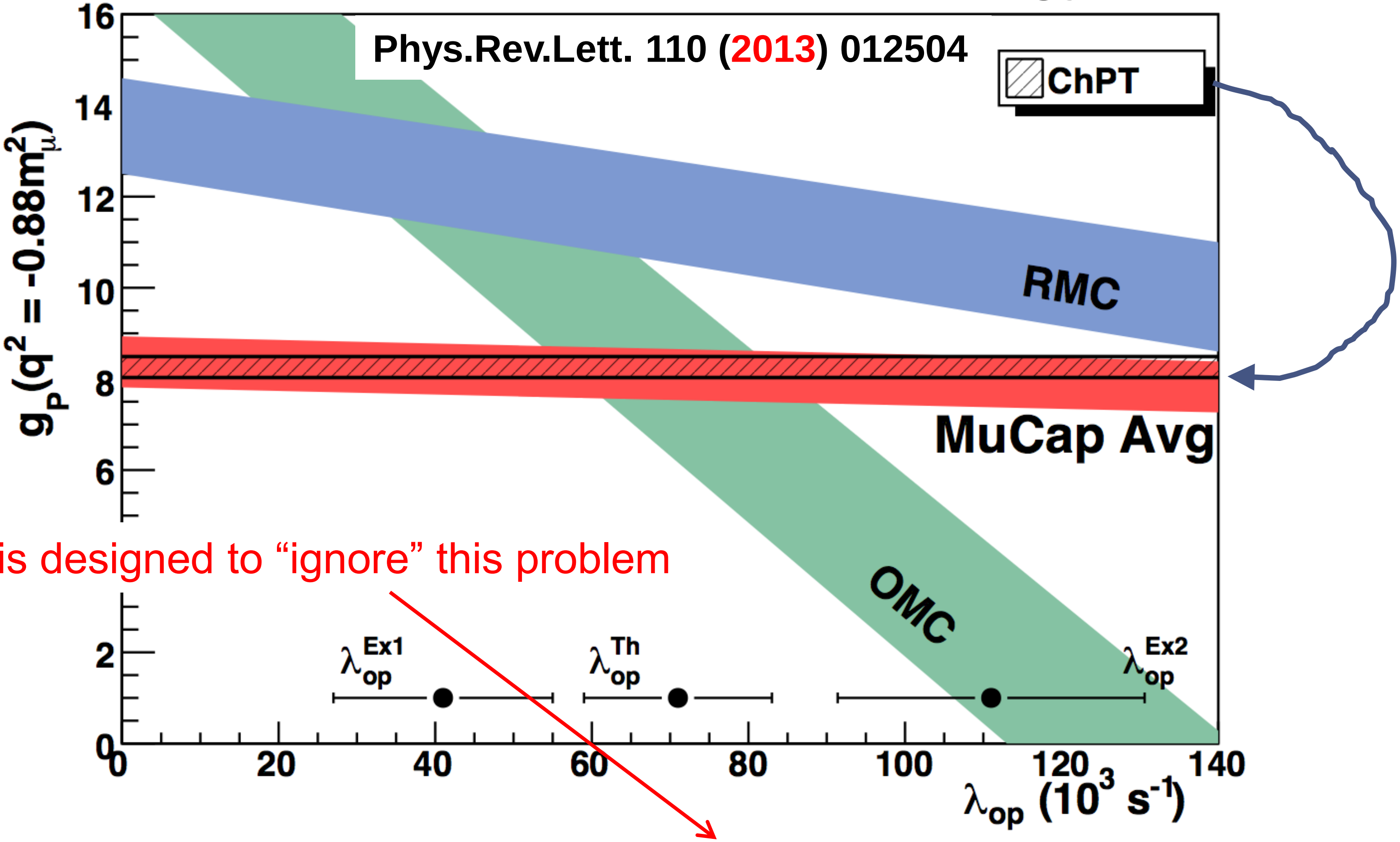
Technique: Lifetime in ultra-pure hydrogen TPC



1st Precise and Unambiguous Result

Verifies Basic Prediction of Low-Energy QCD

Physics Axis



MuCap is designed to "ignore" this problem

Horizontal axis represents some not-well-known Mu-Molecular physics

g_P(MuCap) = 8.06 ± 0.55

g_P(theory) = 8.26 ± 0.23

MuSun: muon capture on the deuteron

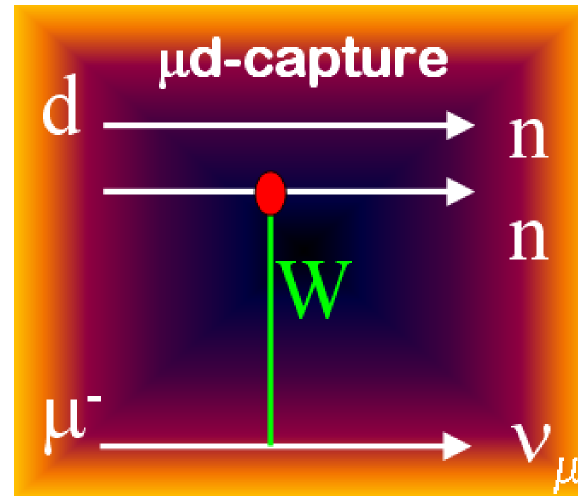
Goal: Measure rate Λ_d from $\mu d(\uparrow\downarrow)$ to < 1.5 %

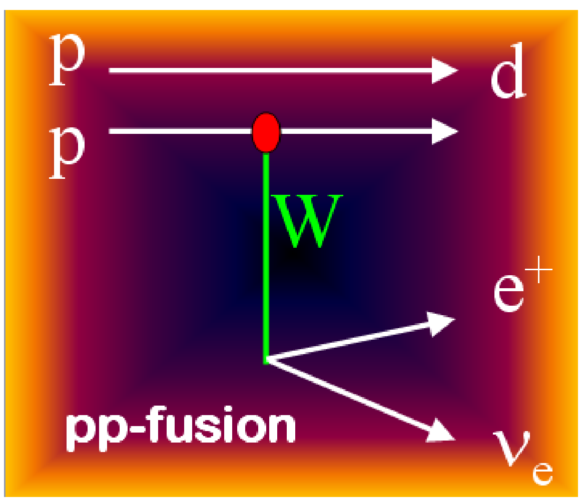
Several fundamental astrophysics processes depend on weak interaction in deuterium

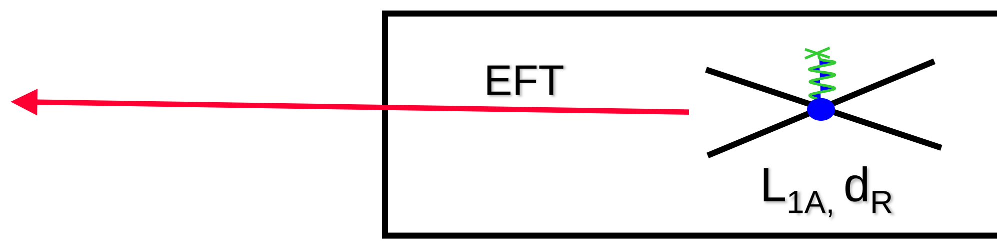
Basic solar fusion: $p + p \rightarrow d + e^+ + \nu$

$\nu_e + d \rightarrow p + p + e^-$ **(CC)**

$\nu_x + d \rightarrow p + n + \nu_x$ **(NC)**

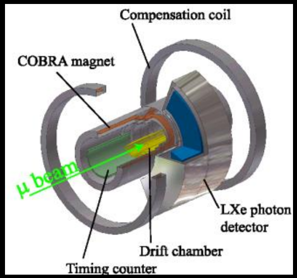






Experiment In Progress at PSI

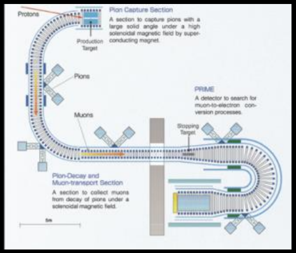
The Muon's Role in Testing the Standard Model



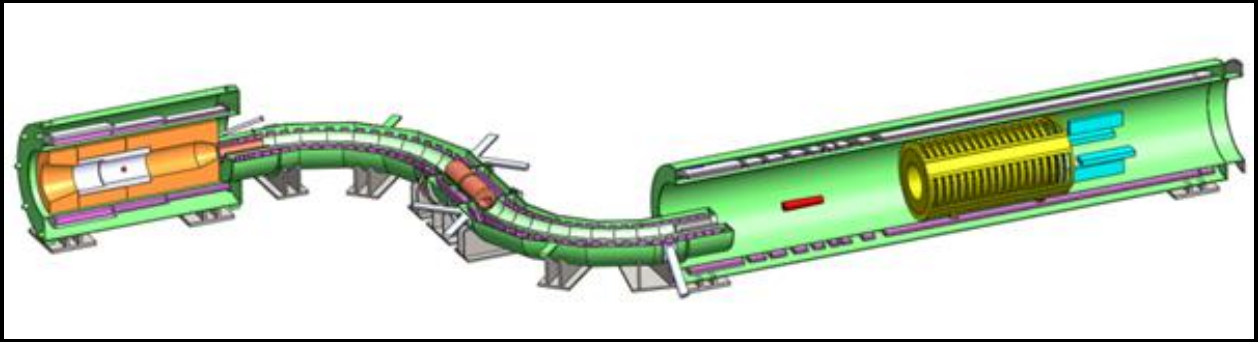
Michel Parameters

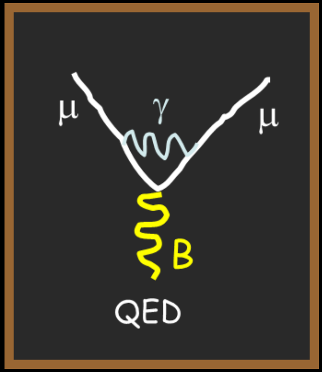
Anomalous Magnetic Moment

Charged Lepton Flavor Violation

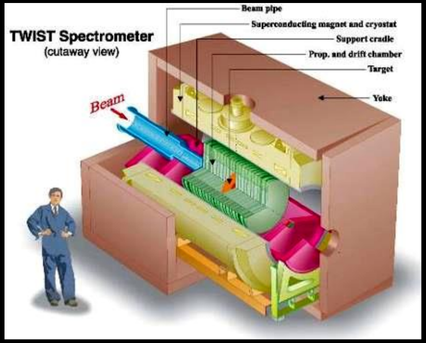


Michel Parameters





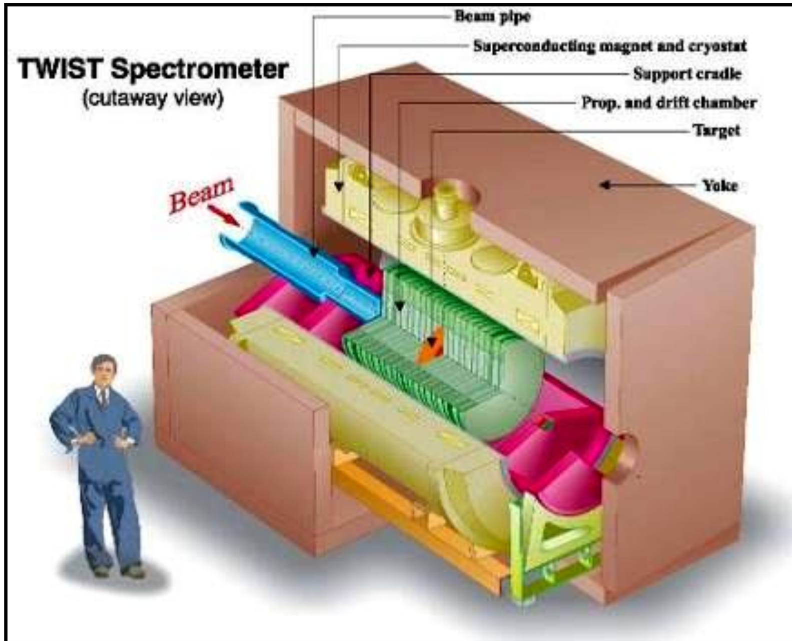
(well) Beyond Schwinger



Final results from *TWIST*

- **Is muon decay purely V-A?**
  - **Sensitive to attractive SM extensions:**
    - **L-R symmetric models, which would permit a W_R**

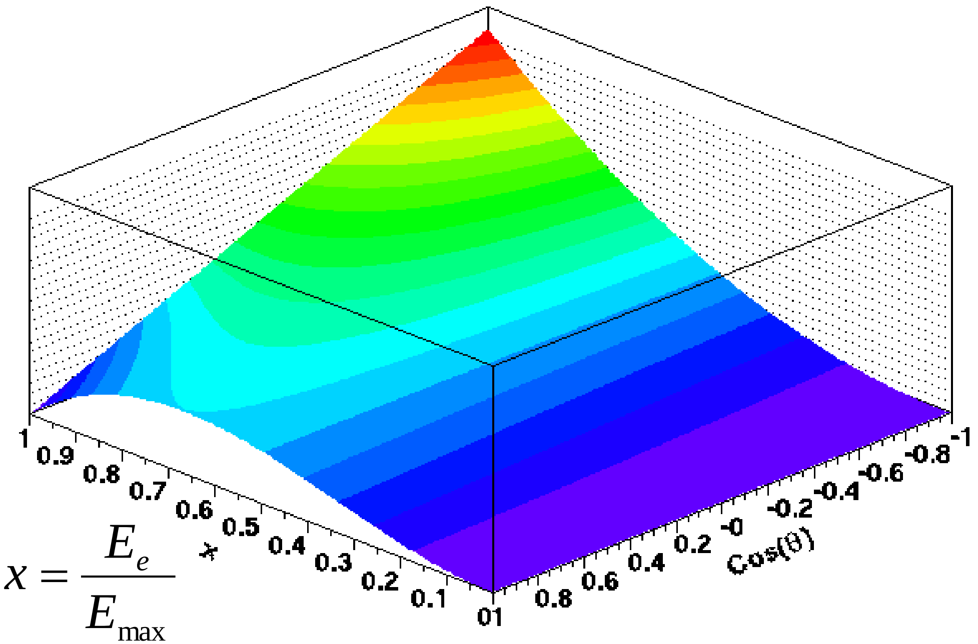
- **Basic idea:**
  - **Measure the energy and angular of e^+ from $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$**
  - **Compare to Monte Carlo**



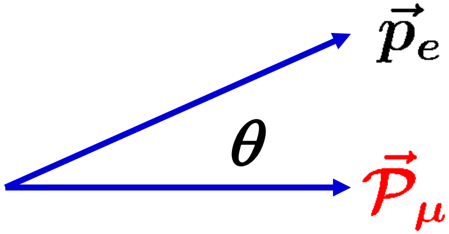
The formalism, "Michel" parameters

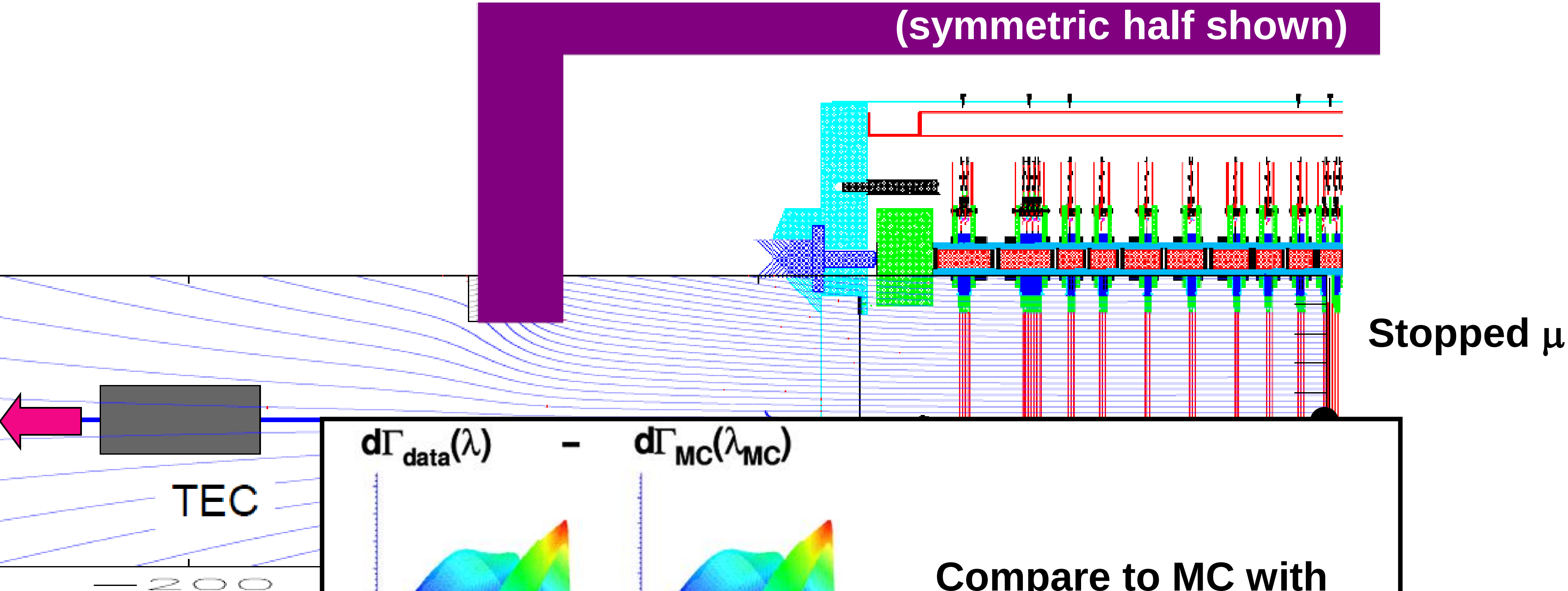
- Muon decay parameters $\rho, \eta, \mathcal{P}_\mu \xi, \delta$
- Differential decay rate *vs.* energy and angle:

$$\frac{d^2\Gamma}{dx\; d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot$$
$$\{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\} + R.C.$$

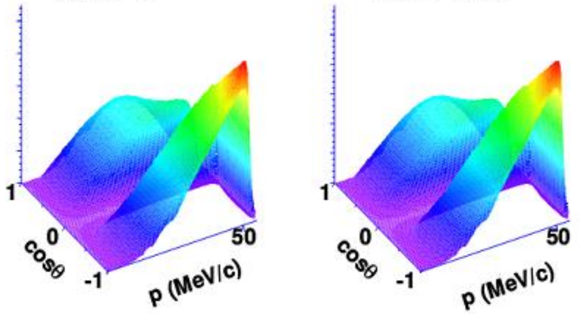


$$x = \frac{E_e}{E_{\max}}$$



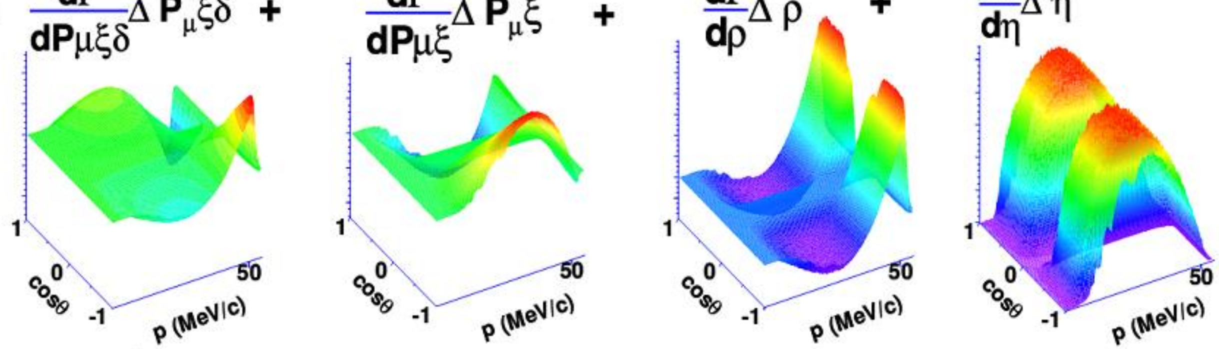


$$d\Gamma_{data}(\lambda) - d\Gamma_{MC}(\lambda_{MC})$$



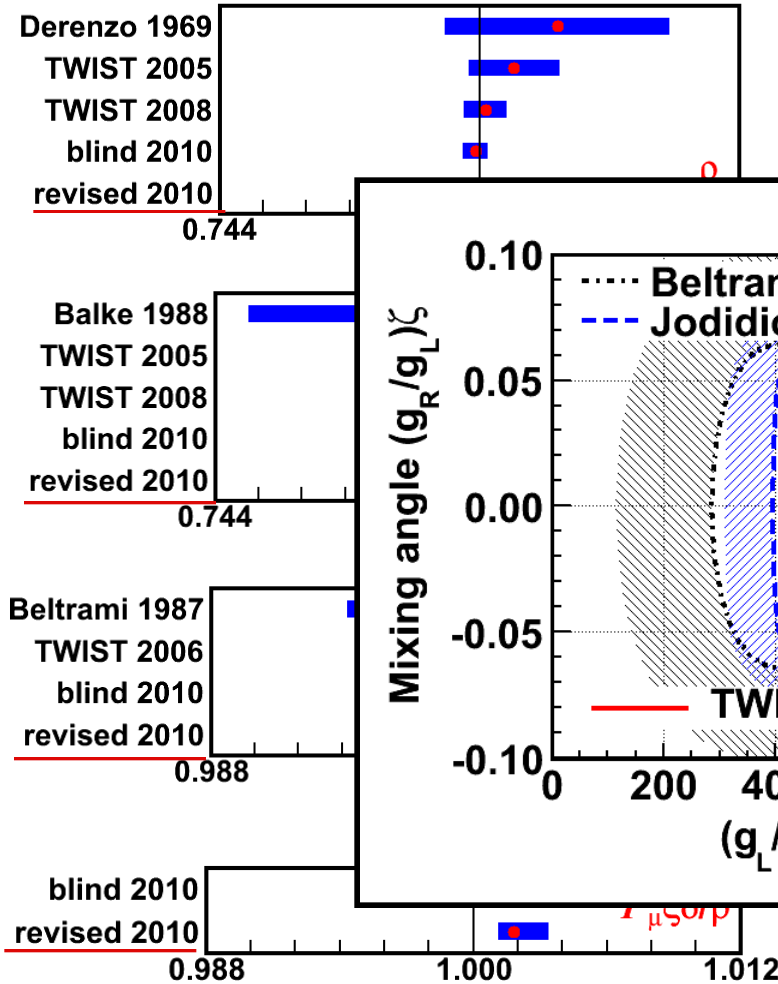
Compare to MC with expectations for non-SM parameters

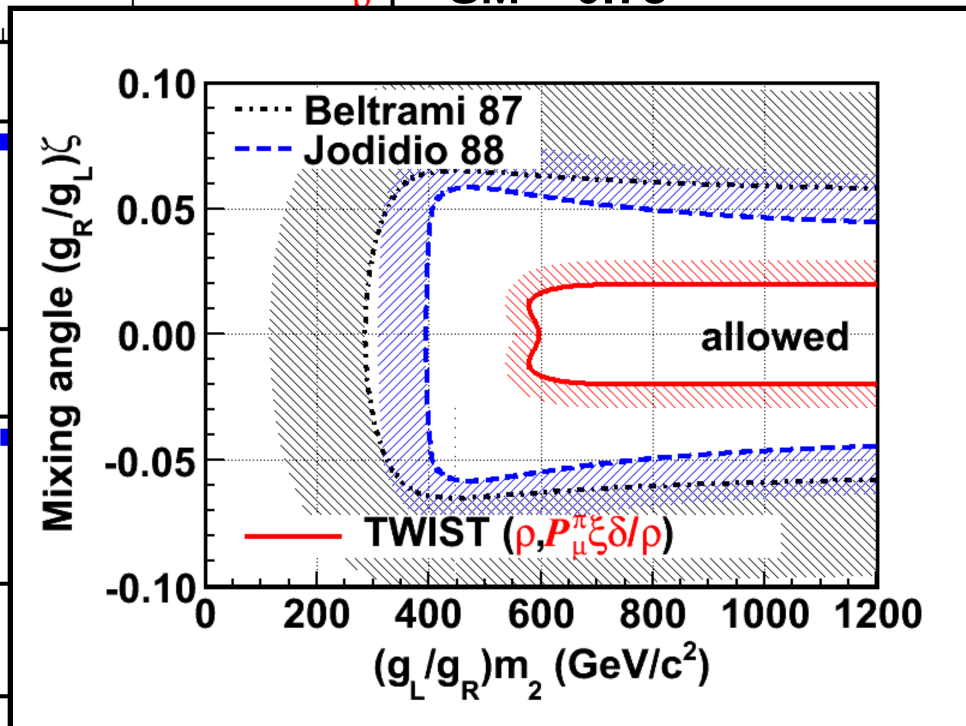
$$= \frac{d\Gamma}{dP_\mu\xi\delta}\Delta P_\mu\xi\delta + \frac{d\Gamma}{dP_\mu\xi}\Delta P_\mu\xi + \frac{d\Gamma}{d\rho}\Delta\rho + \frac{d\Gamma}{d\eta}\Delta\eta$$



Final results: "SM still okay"

Mostly constrains right-handed muon terms





ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

SM = 0.75

stat) ± 0.00027 (syst)

(stat) $^{+0.00165}_{-0.00063}$ (syst)

L)

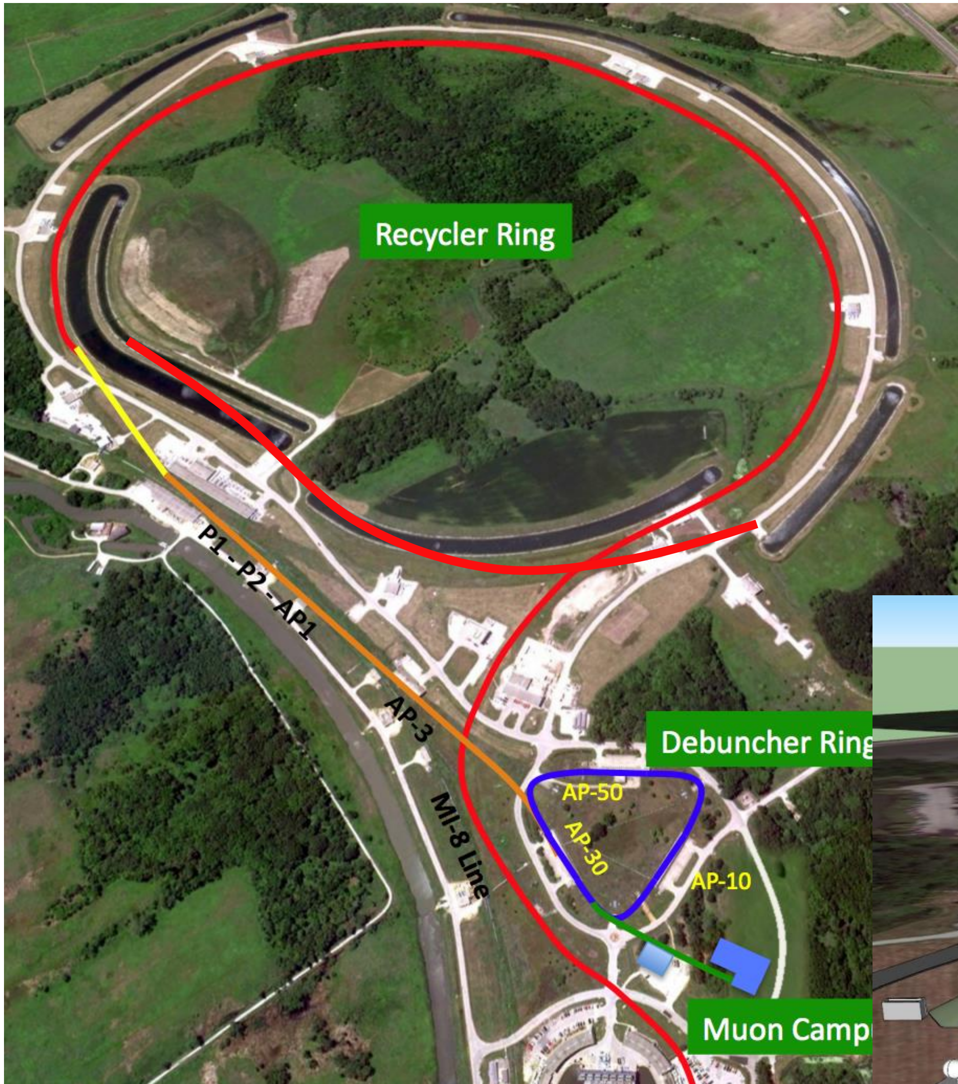
from global analysis

SM = 1.0 (cannot be above 1 in general)

A bit of tension here, but thoroughly investigated

A. Hillairet et al., Phys. Rev. D 85, 092013 (2012)

Flagship efforts being mounted at the new Fermilab Muon Campus: g-2 & Mu2e

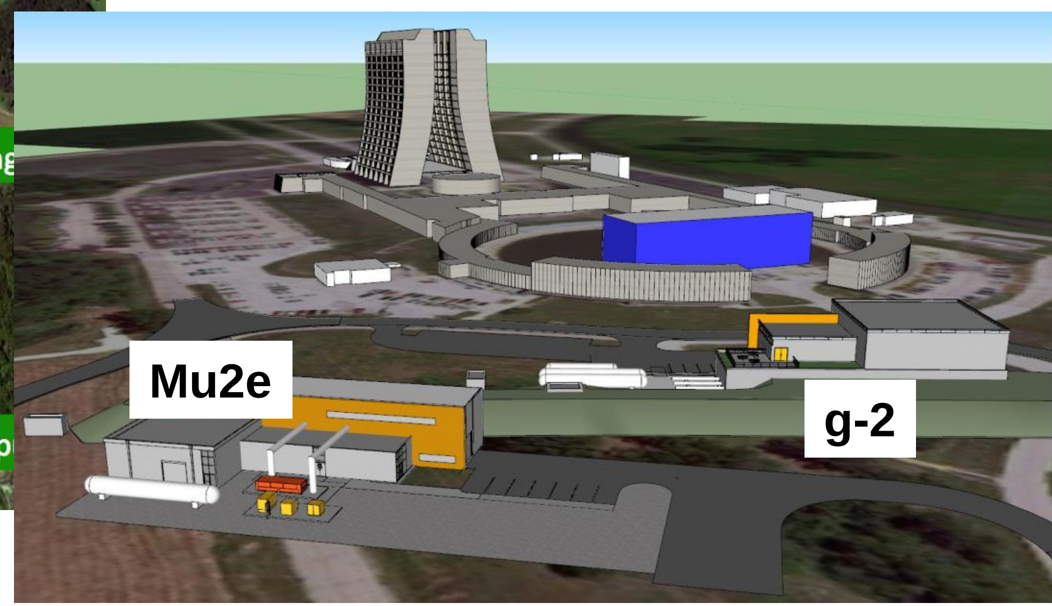


For g-2, achieves

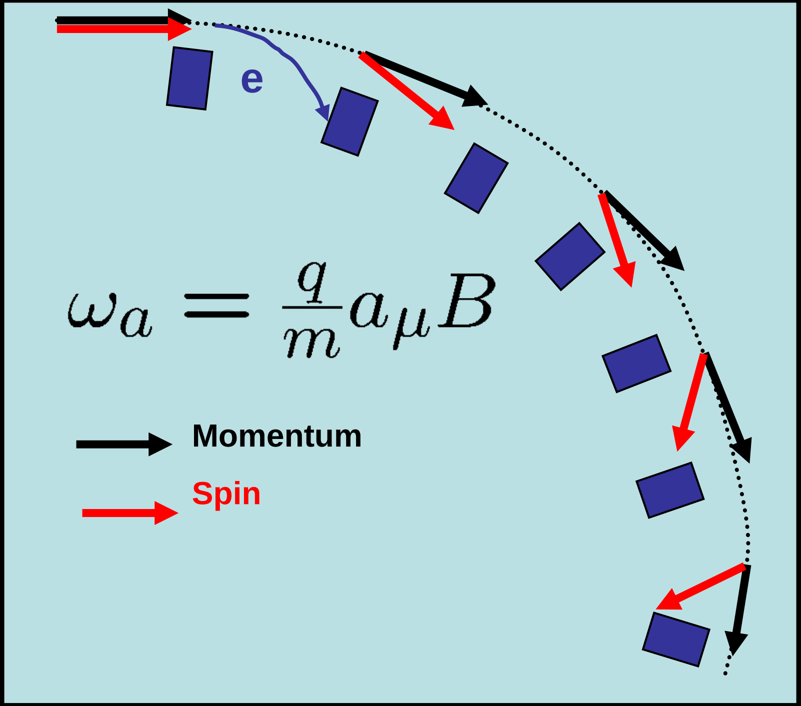
1) Long decay channel
2) Rapid ring cycle
3) No hadronic flash

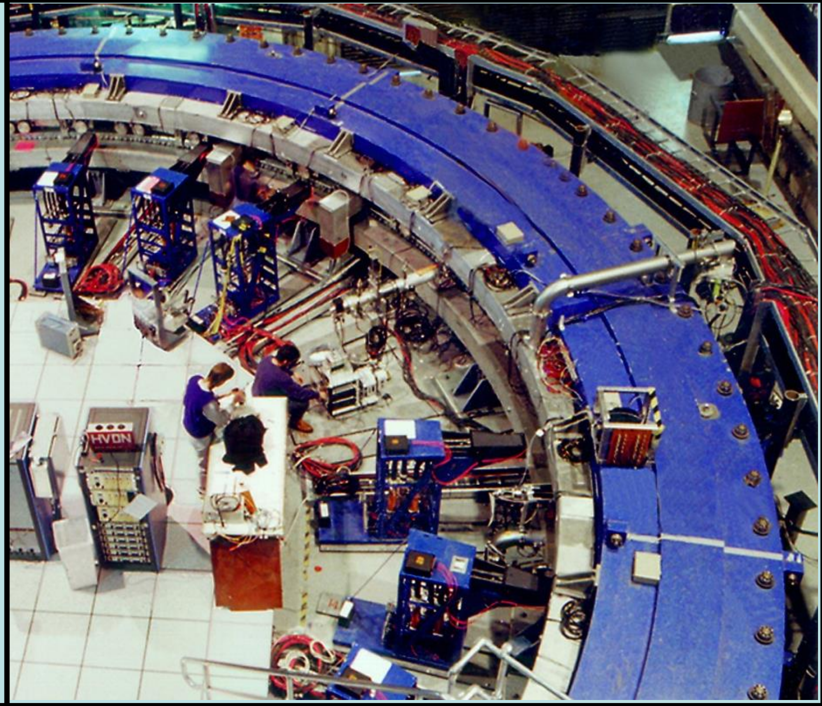
For Mu2e, achieves

1) Ideal proton bunches for mu formation
2) High intensity / Extinction



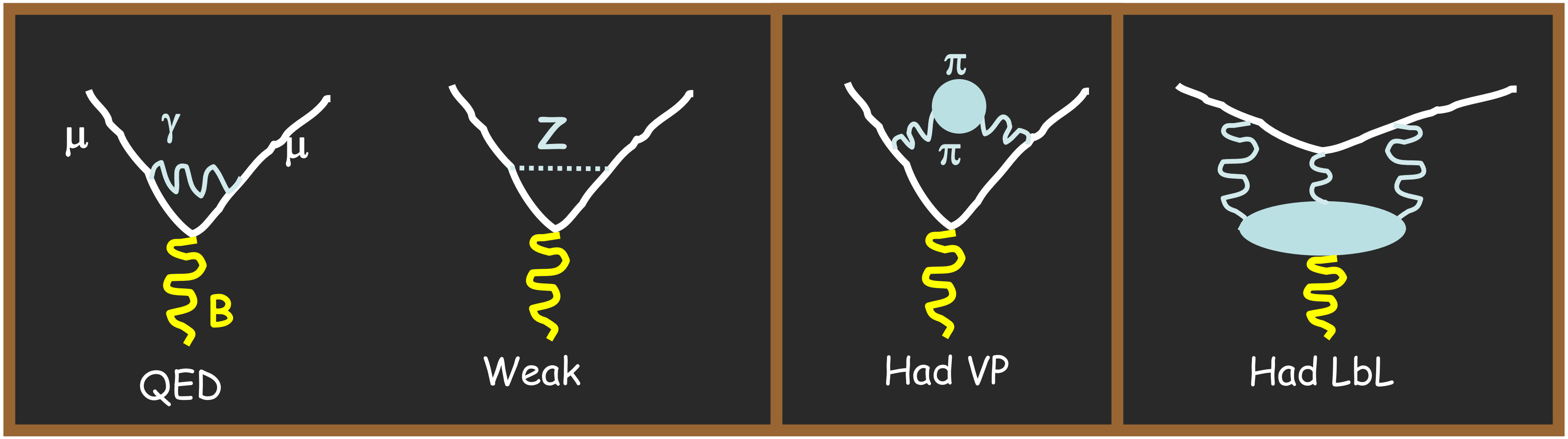
A Case for Challenging the Standard Model: Muon g-2





$$a_\mu(\text{Expt.}) = 116592089(63) \times 10^{-11} \qquad (0.54\ \text{ppm})$$

Summary of Standard Model Contributions



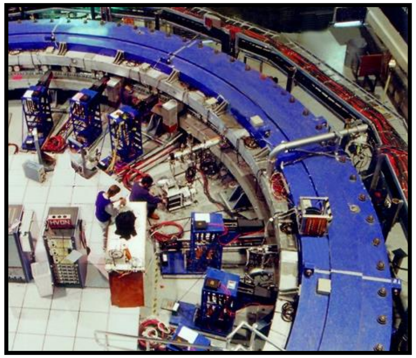
Known well **Theoretical work ongoing**

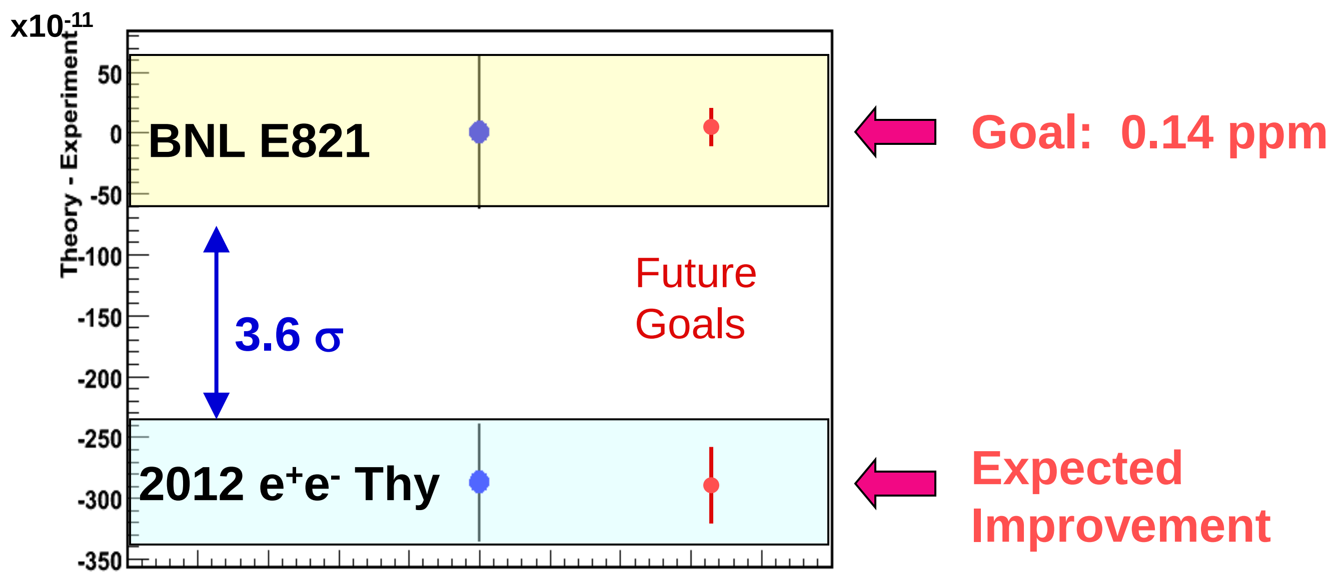
	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_{\alpha}$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)	-98.4 ± 0.7
H-LBL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

Critical (HVP(lo)*, H-LBL)

Δa_{μ}(Expt – Thy) = 297 ± 81 x 10^{-11} 3.6 σ

Three sigma is not enough: Do it better





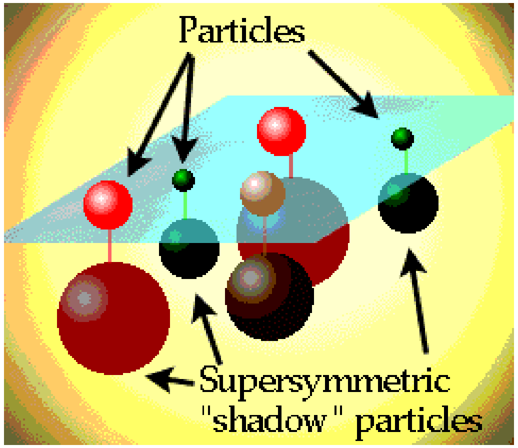
(Would exceed 7 σ even with modest theory improvements and same Δa_μ)

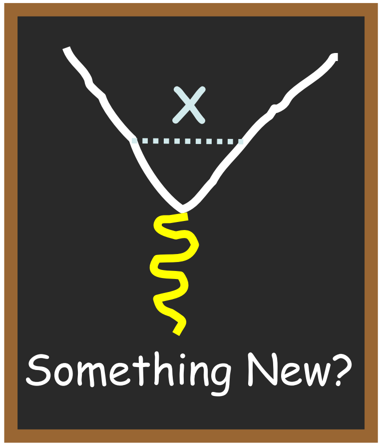
Δa_μ(Expt – Thy) = 297 ± 81 x 10^{-11} 3.6 σ

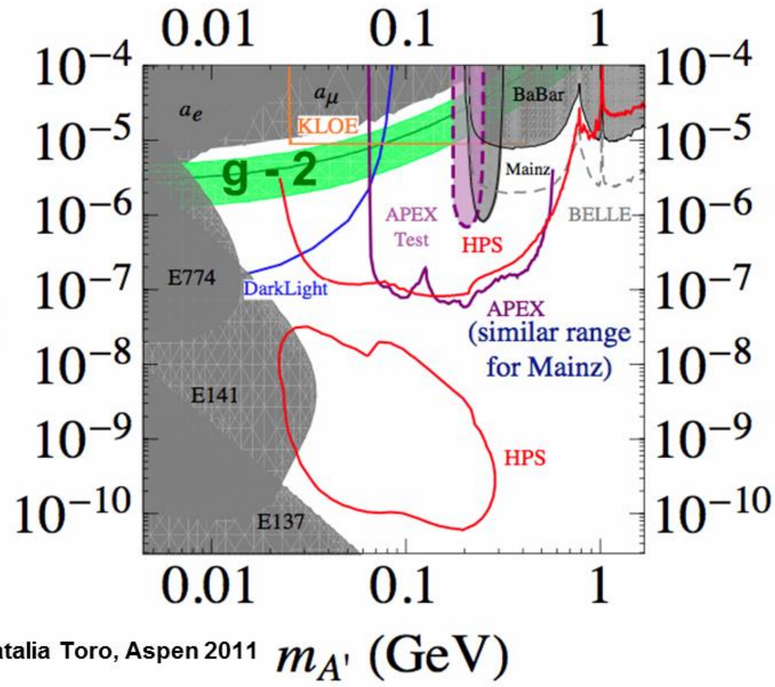
In search of what?

New physics enters through loops

- **Supersymmetry**
  - **Attractive option that fits data well**
- **Universal Extra Dimensions,**
  - **Possible, but ~ 0 for 1 UED**
- **Dark Photons**
  - **Many efforts emerging to test this idea**
- **The Uninvented**
  - **Perhaps the most important of all**





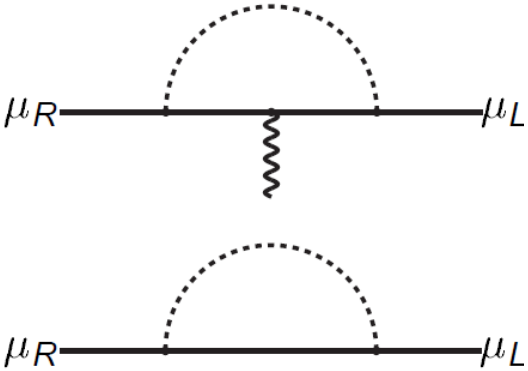


Natalia Toro, Aspen 2011

Chirality flipping interactions for mass and charge (moment) terms

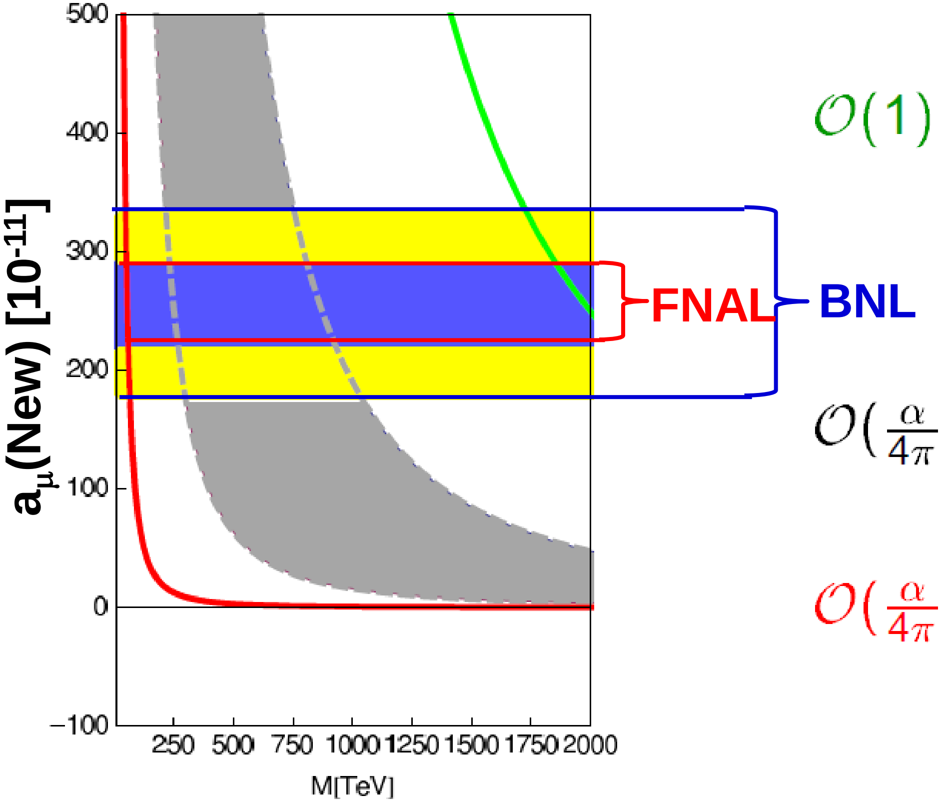
g – 2

m_μ



$$C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}, \quad \delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2$$

The coupling *C* is VERY model dependent



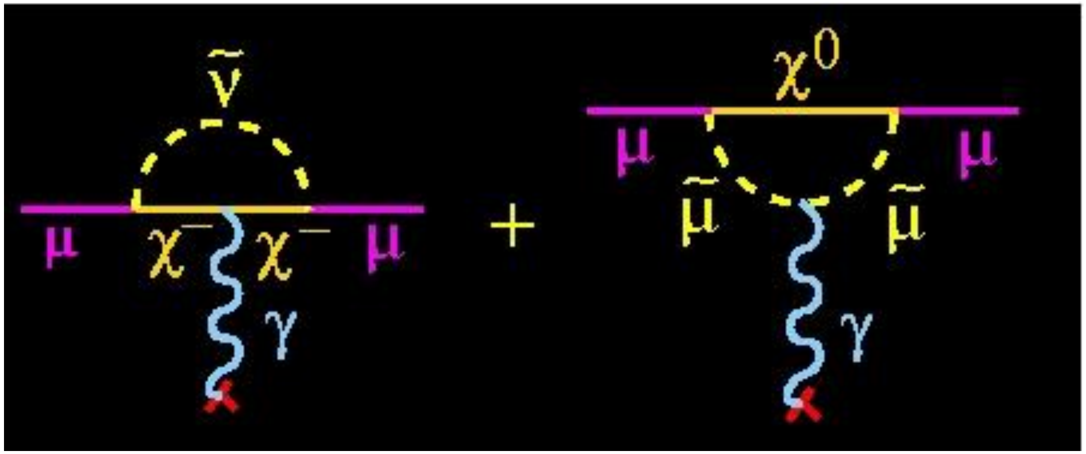
$\mathcal{O}(1)$ **Radiative muon mass generation**

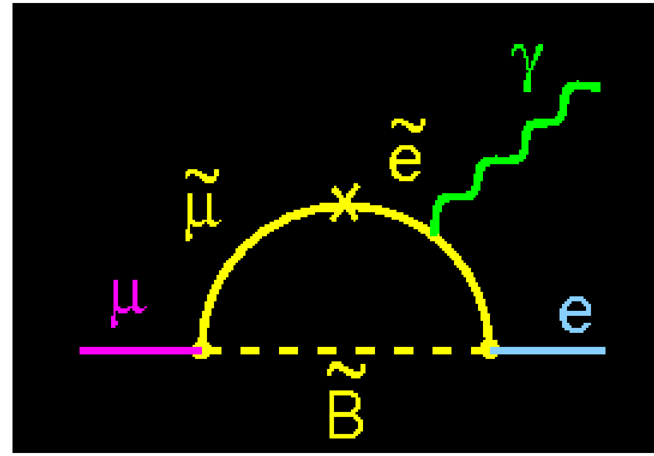
$\mathcal{O}(\frac{\alpha}{4\pi} \ldots)$ **SUSY (tanβ), unparticles**
Extra dimensions (ADD/RS)

$\mathcal{O}(\frac{\alpha}{4\pi})$ **Z', W', UED, Littlest Higgs (LHT) …**

From D. Stockinger (See many of this g-2 presentations about new physics impact)

SUSY contribution to a_μ:





$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}} \right)^2 \tan\beta\ \text{sign}(\mu)$$

Difficulty to measure at the LHC

Related processes in SUSY

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

How have the LHC results affected things?

- No new particles → "SUSY is dead!"
- Wait … lots of new conversations now
- H → $\gamma\gamma$ excess?
  - Connects g-2, dark photons, etc. !
- M_H at 125 GeV… what's compatible
  - Split supersymmetry ?
  - Other models?

Muon g-2 and 125 GeV Higgs in Split-Family Supersymmetry

Masahiro Ibe[(a,b)], Tsutomu T. Yanagida[(b)], Norimi Yokozaki[(b)]

Lots of SUSYs

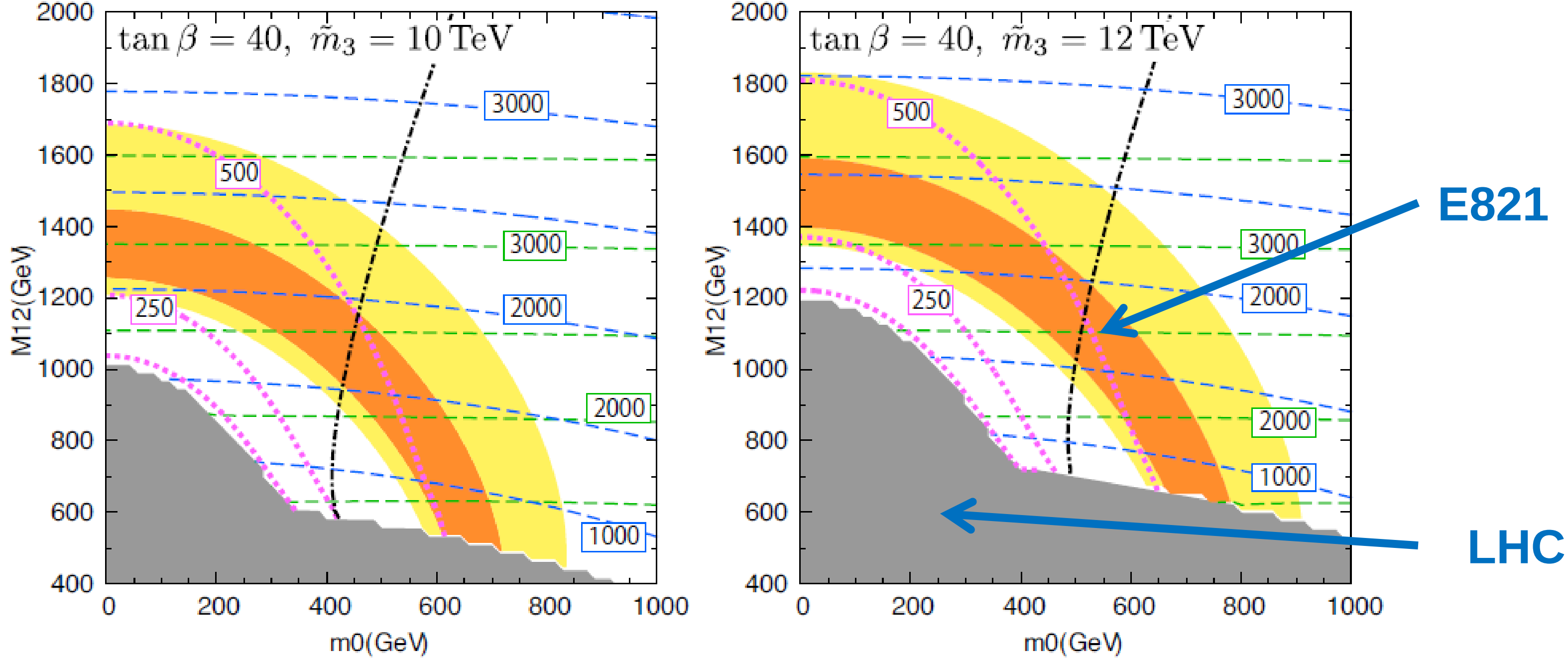
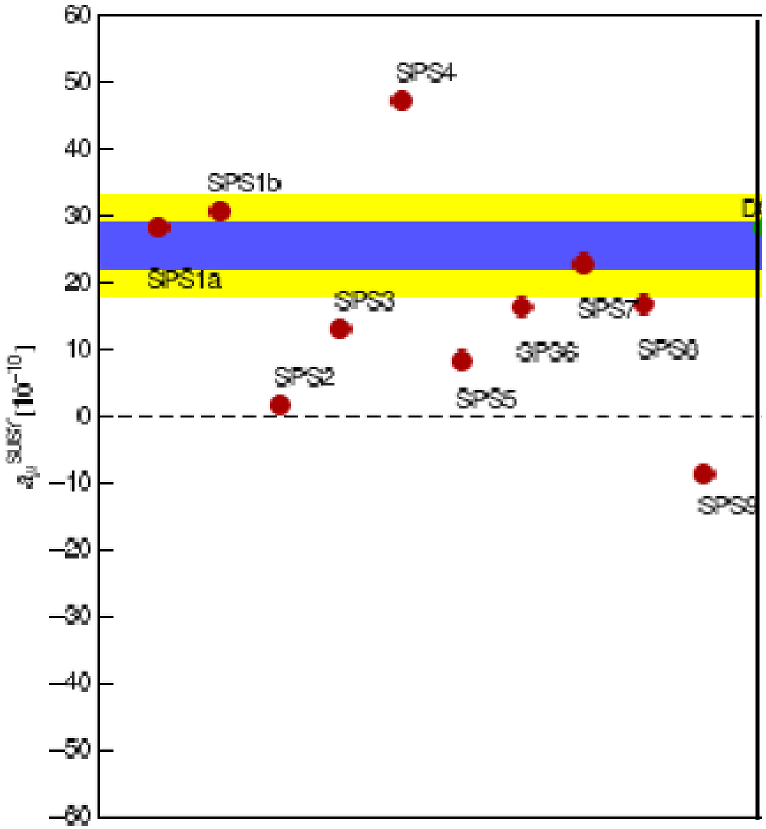


Figure 1: *Contours of δa_μ, the squark mass, the gluino mass, and the lightest slepton mass (the masses are shown in the unit of GeV) on $m_0 - M_{1/2}$ plane. The blue (green) dash-lines correspond to the squark (gluino) masses. The magenta dotted lines show the contours of the lightest slepton masses (from top to bottom, 500 GeV, 250 GeV, 100 GeV). In the orange (yellow) region, δa_μ is explained within 1σ (2σ) level. On the left region of the black dot-dashed line, the LSP is a slepton. The stop mass is $\simeq 8.5\,(10)$ TeV for $m_3 = 10\,(12)$ TeV.*

arXiv:1303.6995v1 [hep-ph] 27 Mar 2013

An older but illustrative study connecting SUSY and g-2: The power to resolve among models and break LHC degeneracies

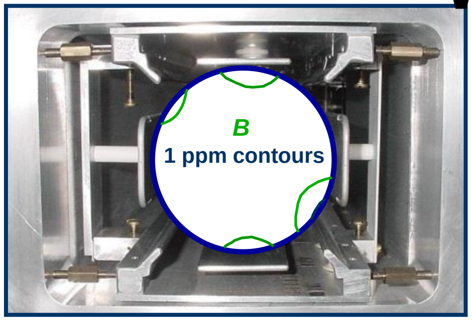


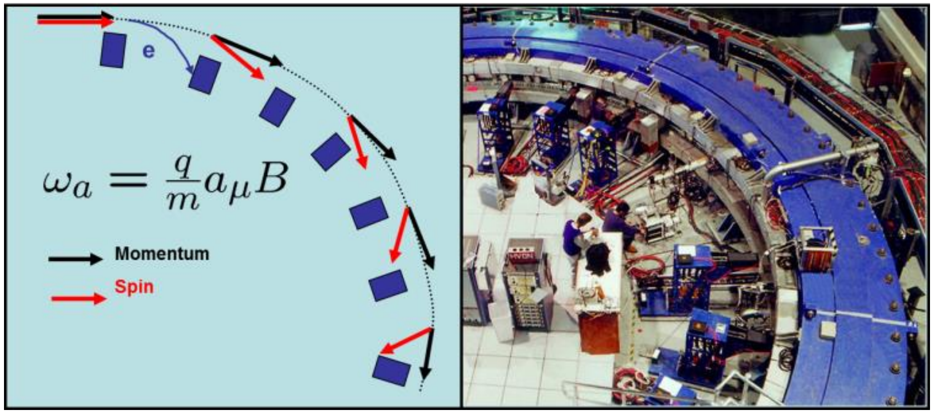
SPS benchmark points

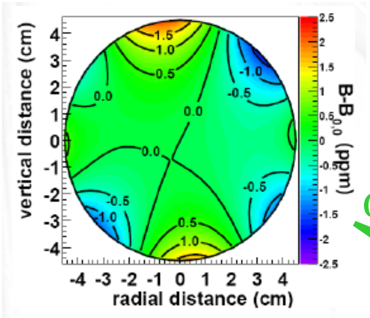
Note: Δa_μ centered at 255 here

Method

The anomaly is obtained from three well-measured quantities

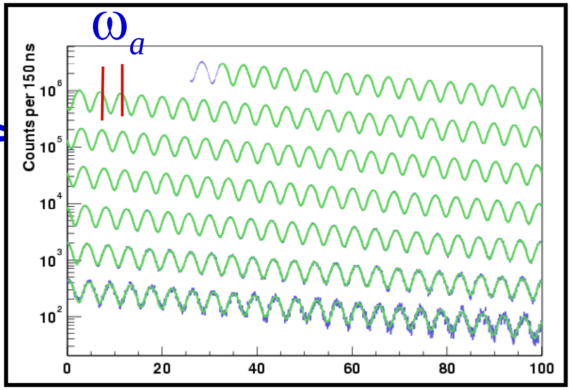


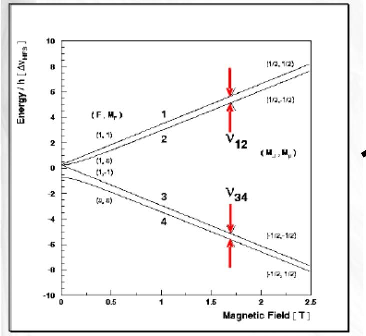




ω_p

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

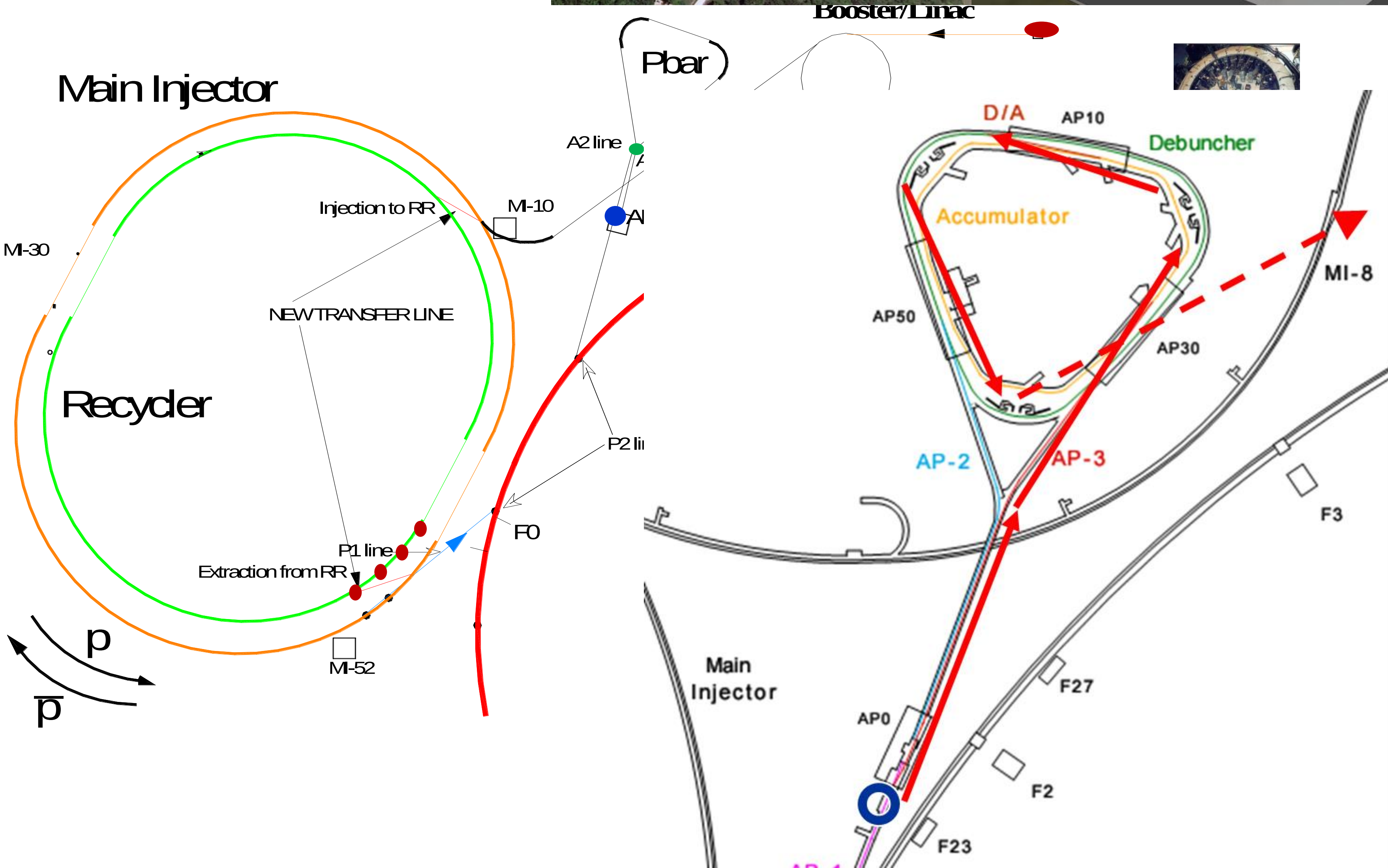




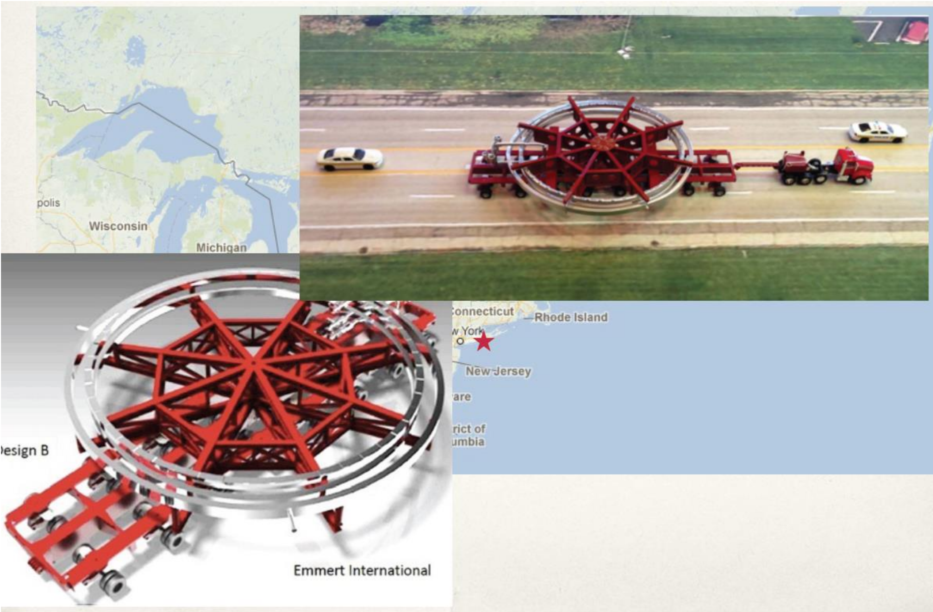
μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

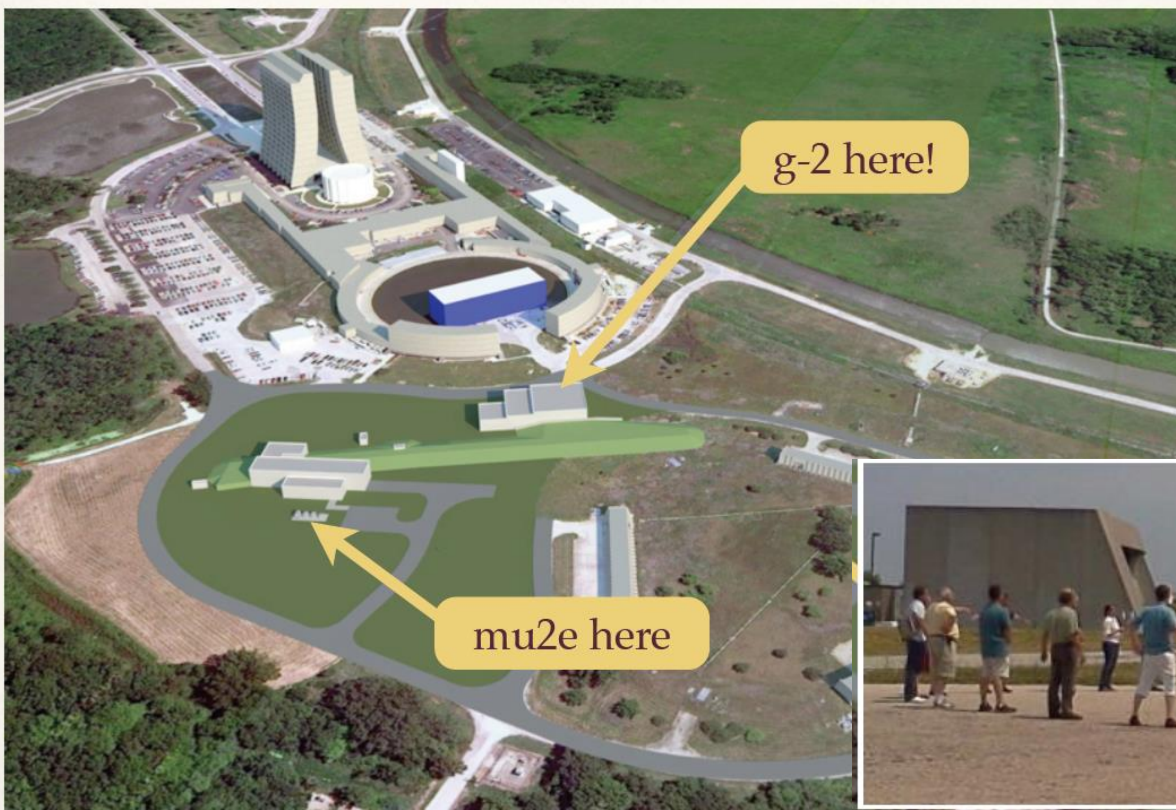
= *3.183 345 39(10) (31 ppb)*

Polarized muons delivered and stored in the ring at the magic momentum, 3.094 GeV/c



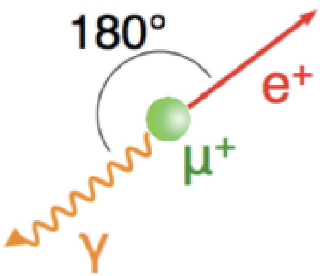
Moving the ring …

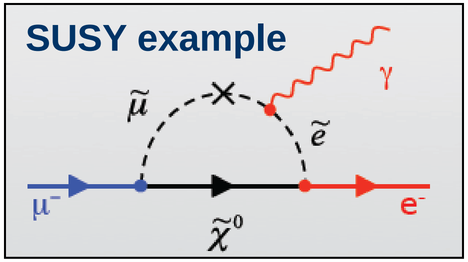




MEG: $\mu \rightarrow e\gamma$ at PSI

The SM theory is clear: Unobservable





Signal is back-to-back 53 MeV γ and e^+ from muons at rest

2013: BR($\mu \rightarrow e\gamma$) < 5.7 x 10^{-13} @ 90%C. … another x4 improvement from 1st results.

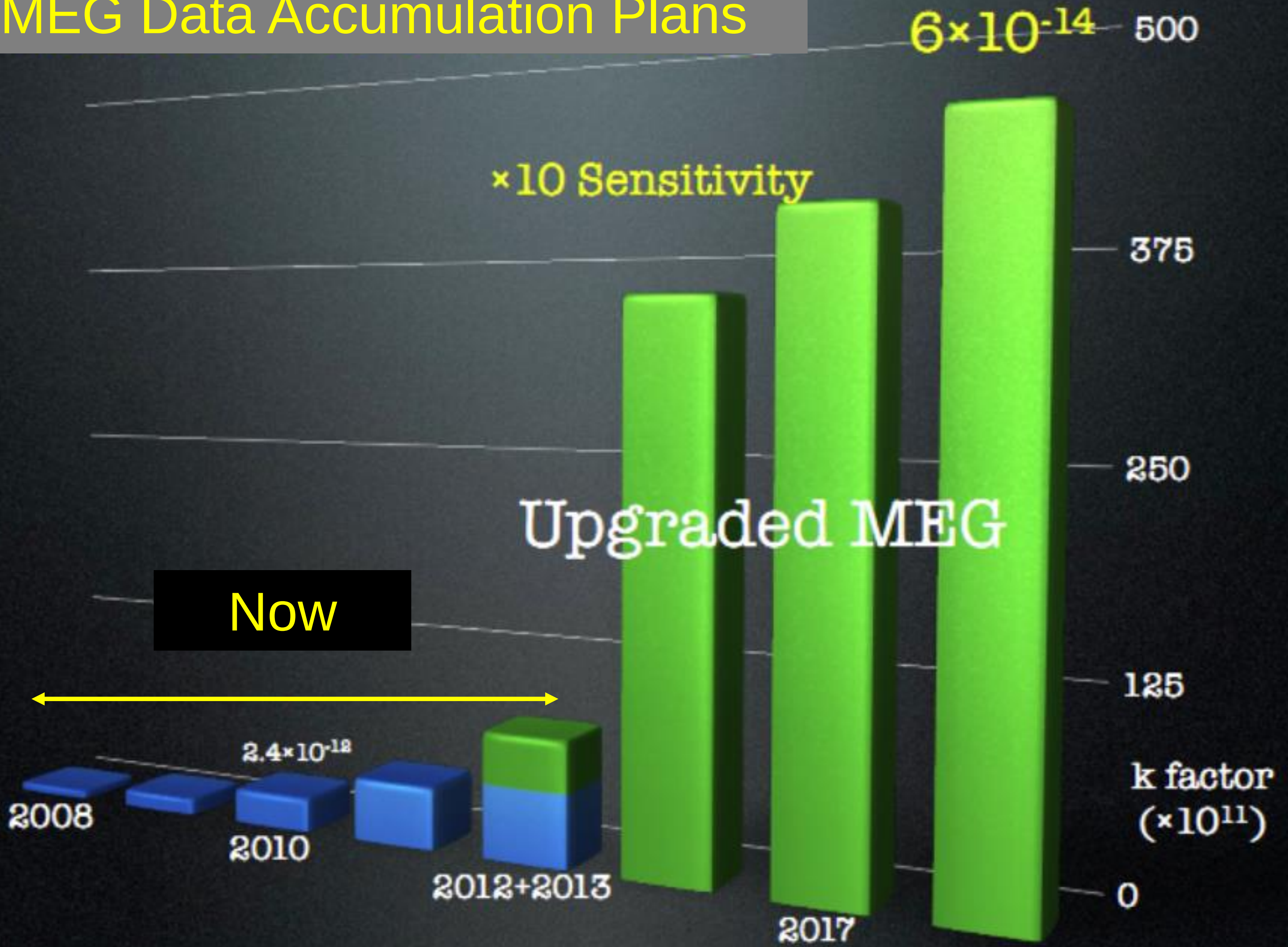
New MEG Upgrade approved: Expect to improve by another factor of 10 !

New constraint on the existence of the $\mu^+ \rightarrow e^+\gamma$ decay

J. Adam,[1,2] X. Bai,[3] A. M. Baldini[a],[4] E. Baracchini,[3,5,6] C. Bemporad[ab],[4] G. Boca[ab],[7] P. W. Cattaneo[a],[7] G. Cavoto[a],[8] F. Cei[ab],[4] C. Cerri[a],[4] A. de Bari[ab],[7] M. De Gerone[ab],[9] T. Doke,[10] S. Dussoni[a],[4] J. Egger,[1] K. Fratini[ab],[9] Y. Fujii,[3] L. Galli[a],[1,4] G. Gallucci[ab],[4] F. Gatti[ab],[9] B. Golden,[6] M. Grassi[a],[4] A. Graziosi,[8] D. N. Grigoriev,[11] T. Haruyama,[5] M. Hildebrandt,[1] Y. Hisamatsu,[3] F. Ignatov,[11] T. Iwamoto,[3] D. Kaneko,[3] P.-R. Kettle,[1] B. I. Khazin,[11] N. Khomotov,[11] O. Kiselev,[1] A. Korenchenko,[12] N. Kravchuk,[12] G. Lim,[6] A. Maki,[5] S. Mihara,[5] W. Molzon,[6] T. Mori,[3] D. Mzavia,[12] R. Nardò,[7] H. Natori,[5,3,1] D. Nicolò[ab],[4] H. Nishiguchi,[5] Y. Nishimura,[3] W. Ootani,[3] M. Panareo[ab],[13] A. Papa,[1] R. Pazzi[ab],[4] G. Piredda[a],[8] A. Popov,[11] F. Renga[a],[8,1] E. Ripiccini,[8] S. Ritt,[1] M. Rossella[a],[7] R. Sawada,[3] F. Sergiampietri[a],[4] G. Signorelli[a],[4] S. Suzuki,[10] F. Tenchini[ab],[4] C. Topchyan,[6] Y. Uchiyama,[3,1] R. Valle[ab],[9] C. Voena[a],[8] F. Xiao,[6] S. Yamada,[5] A. Yamamoto,[5] S. Yamashita,[3] Z. You,[6] Yu. V. Yudin,[11] and D. Zanello[a8]
(MEG Collaboration)

arXiv:1303.0754v1 [hep-ex] 4 Mar 2013

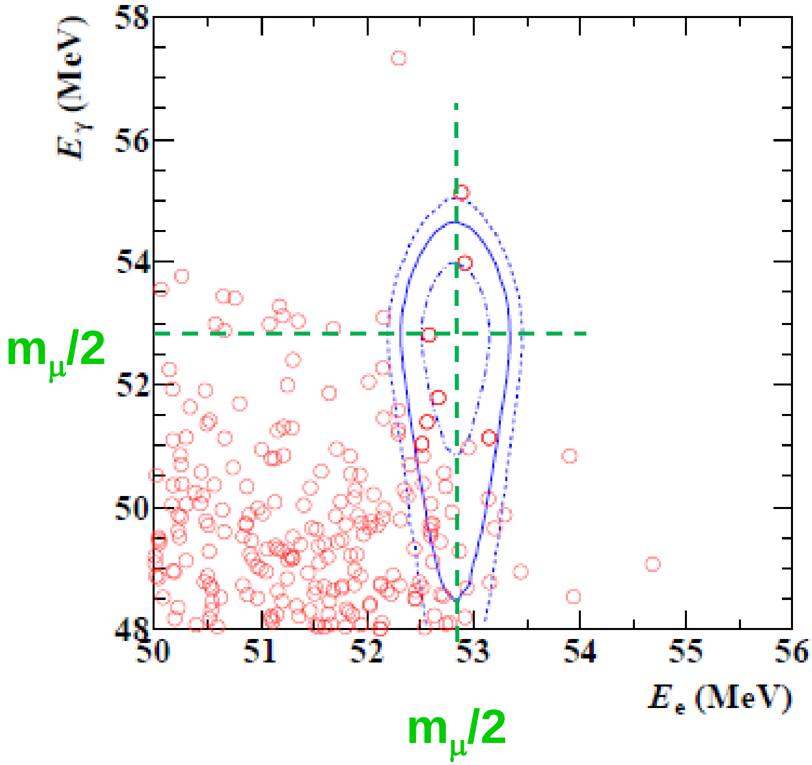
MEG Data Accumulation Plans

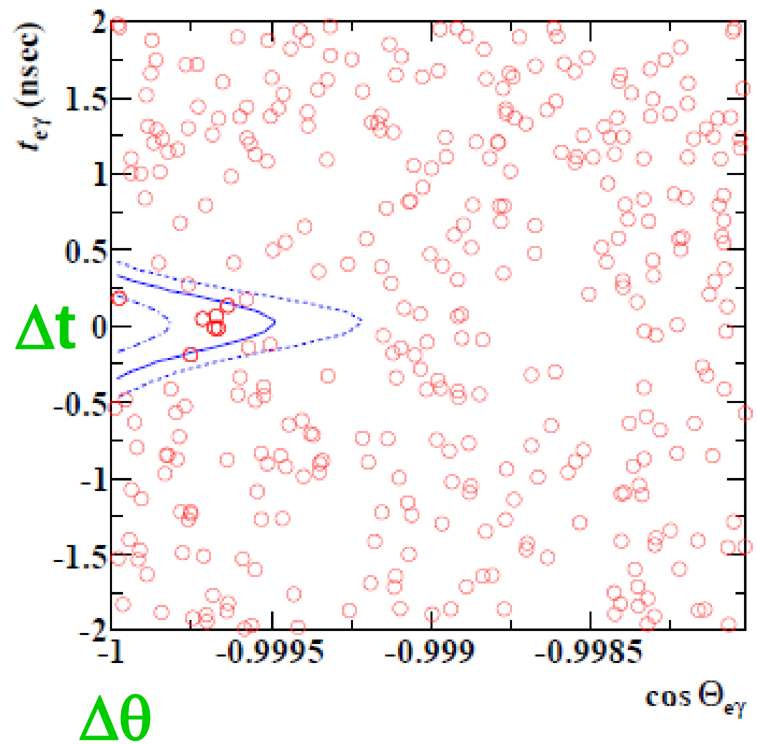


Design for a *unique* signature

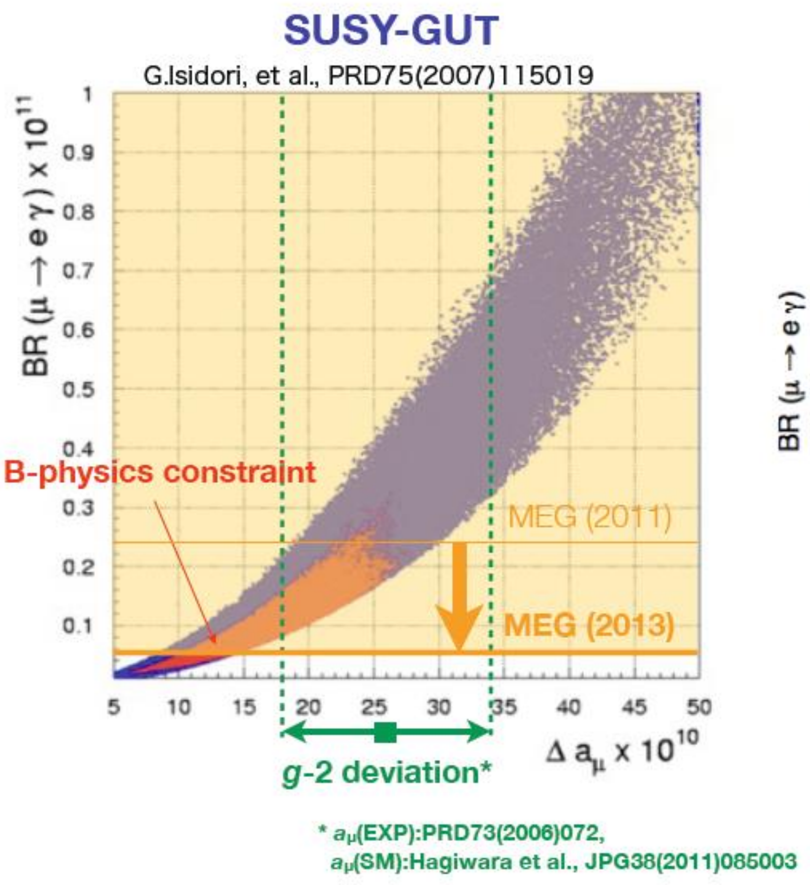
- **e and γ are back-to-back, $\Delta\theta = 180°$**
- **e and γ are simultaneous, $\Delta t = 0$**
- **$E_e = E_\gamma = m_\mu/2$**

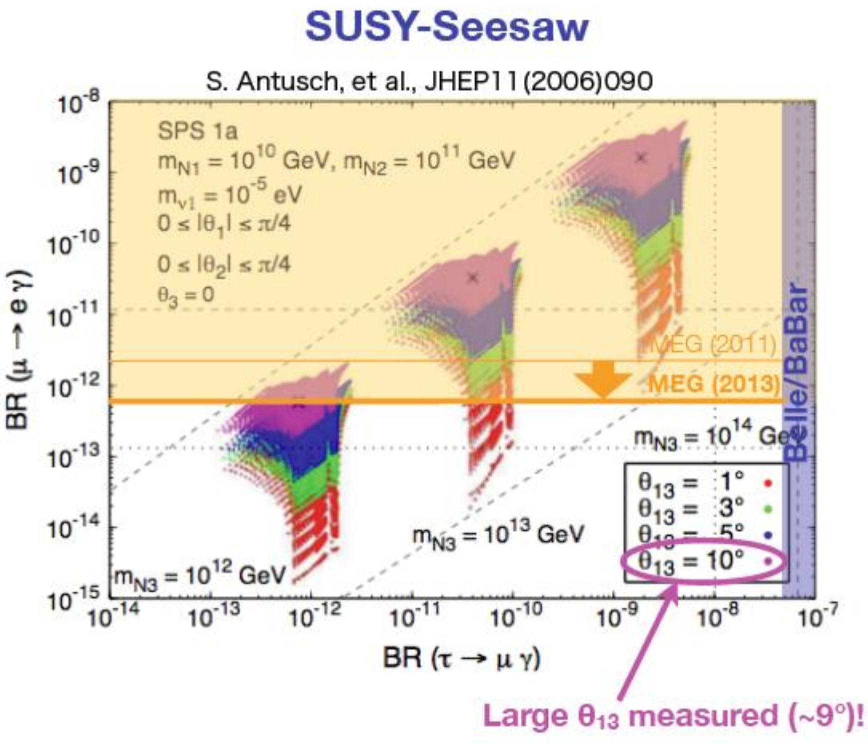
4





Constraints on New Physics

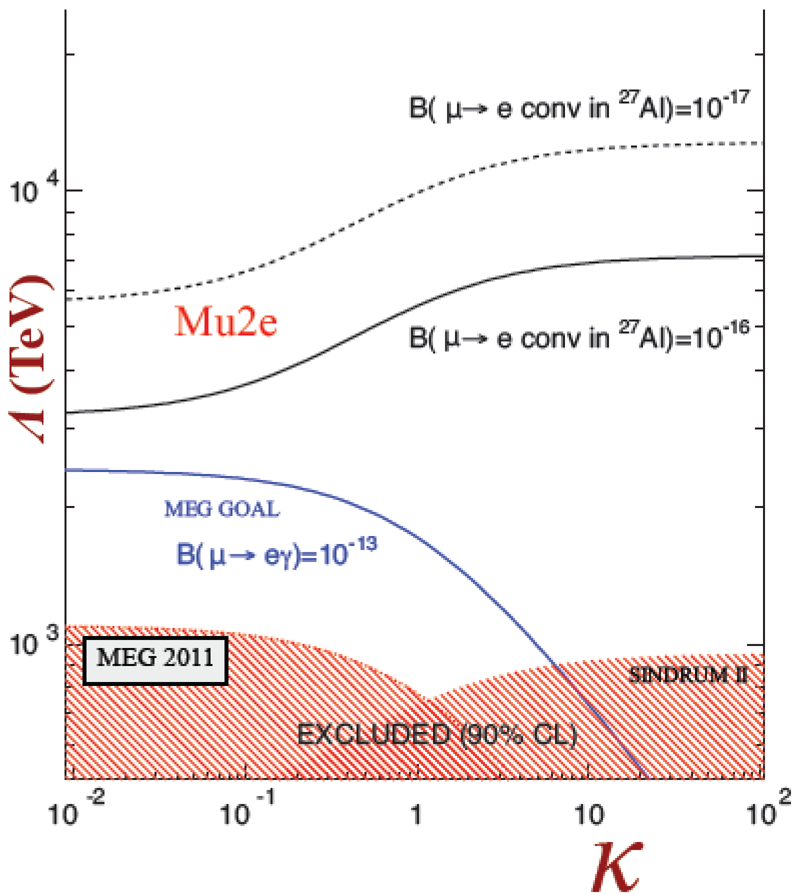




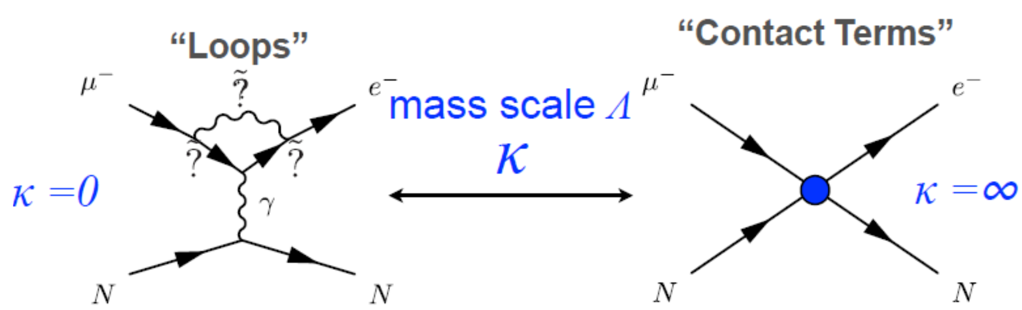
Muon-to-Electron Conversion: Mu2e

The SM theory also clear: Unobservable (BR: 10^{-54})

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$



Vertex correction" vs "4-fermion" operator



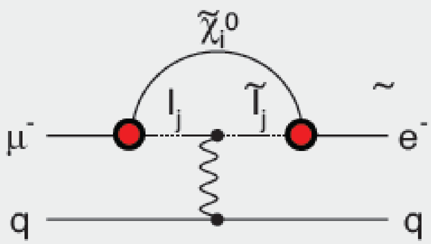
Contributes to μ→eγ

Does not contribute to μ→eγ

Contributions to μe Conversion

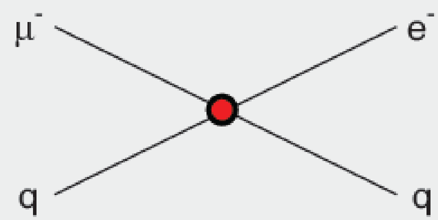
Supersymmetry

Rate ~ 10^{-15}



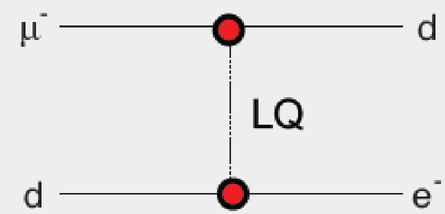
Compositeness

Λ_c ~ 3000 TeV



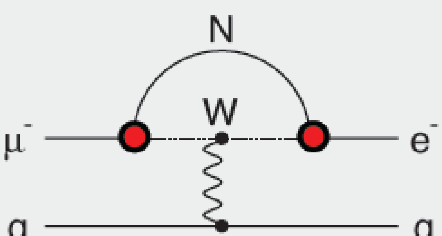
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



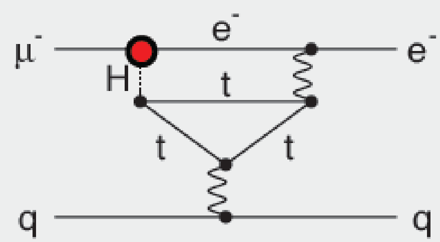
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



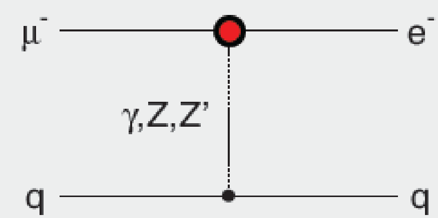
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



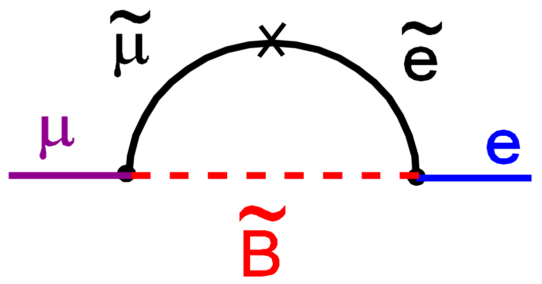
Muon to electron conversion is potentially the most sensitive test for new physics

Images Bernstein

Connection between a_μ, EDM and the charged Lepton Flavor Violating transition moment $\mu \to e$

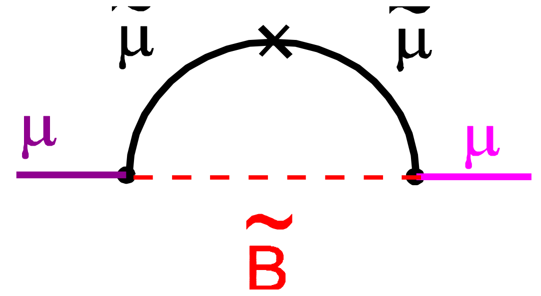
SUSY $\Longrightarrow$ slepton mixing

$\mu \to e$



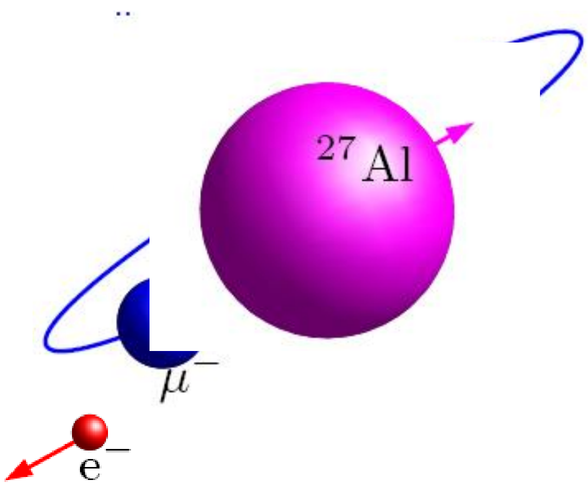
a_μ (real)

EDM (imaginary)



$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

Method and Goal



105 MeV
monoenergetic e-

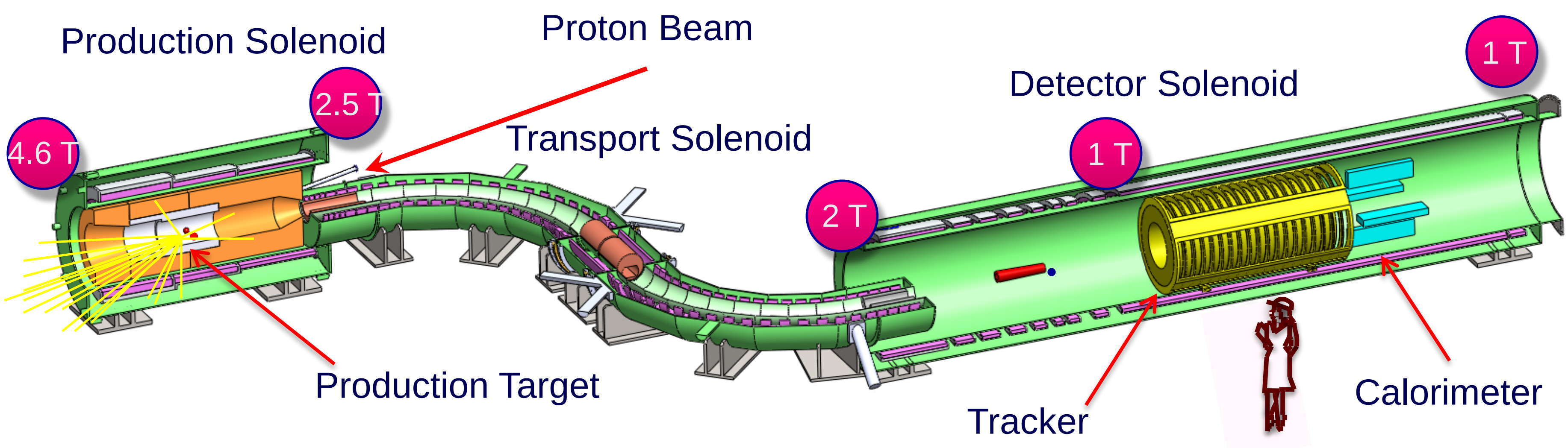
$$\mu^- N \rightarrow e^- N$$

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

- **This signature is quite unique**
- **Goal $R_{\mu\varepsilon}$ to < 6 x 10^{-17} (90% C.L.)**
  - **Present is < 7 x 10^{-13} → So this is very ambitious**

How it is done

- **Need intense pulsed source of low-energy muons**
- **Stop in thin Al target**
- **Form muonic Al atoms.**
- **Observe**
  - **40% will decay “in orbit”;**
  - **60% will capture (hadronic junk emitted)**

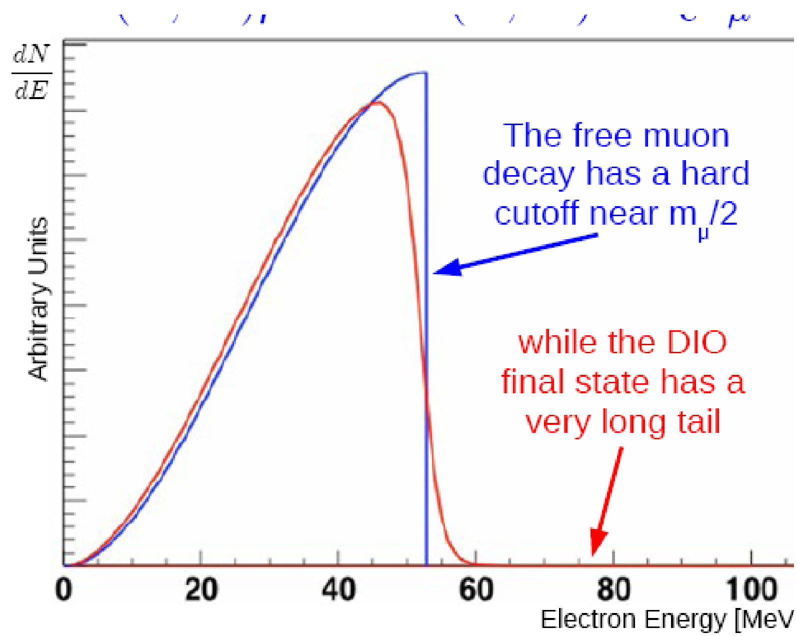


This experiment is in R&D and Pre-Construction Mode with CD1 approval

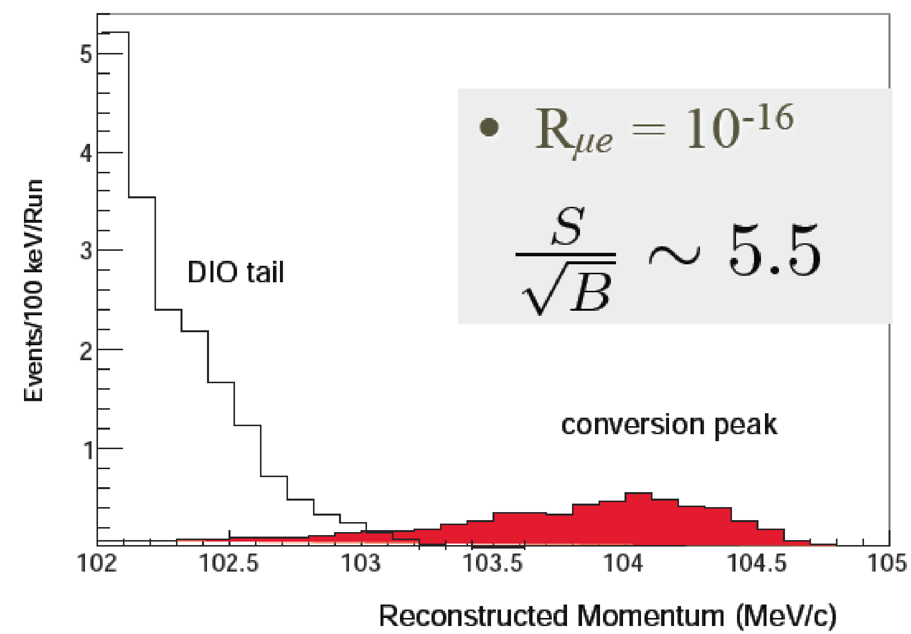
Images: Ray

Start date close to 2020

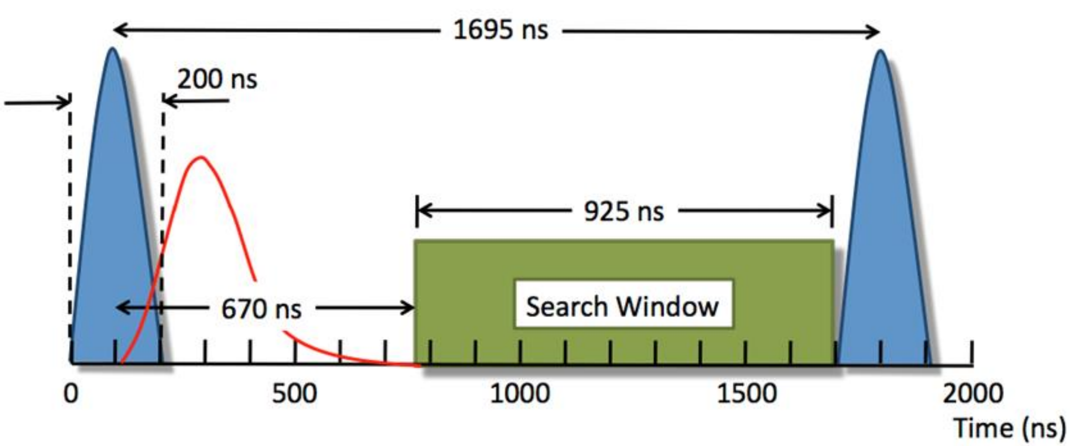
Challenge: find signal above "Decay in Orbit" tail



Resolution and Redundancy critical



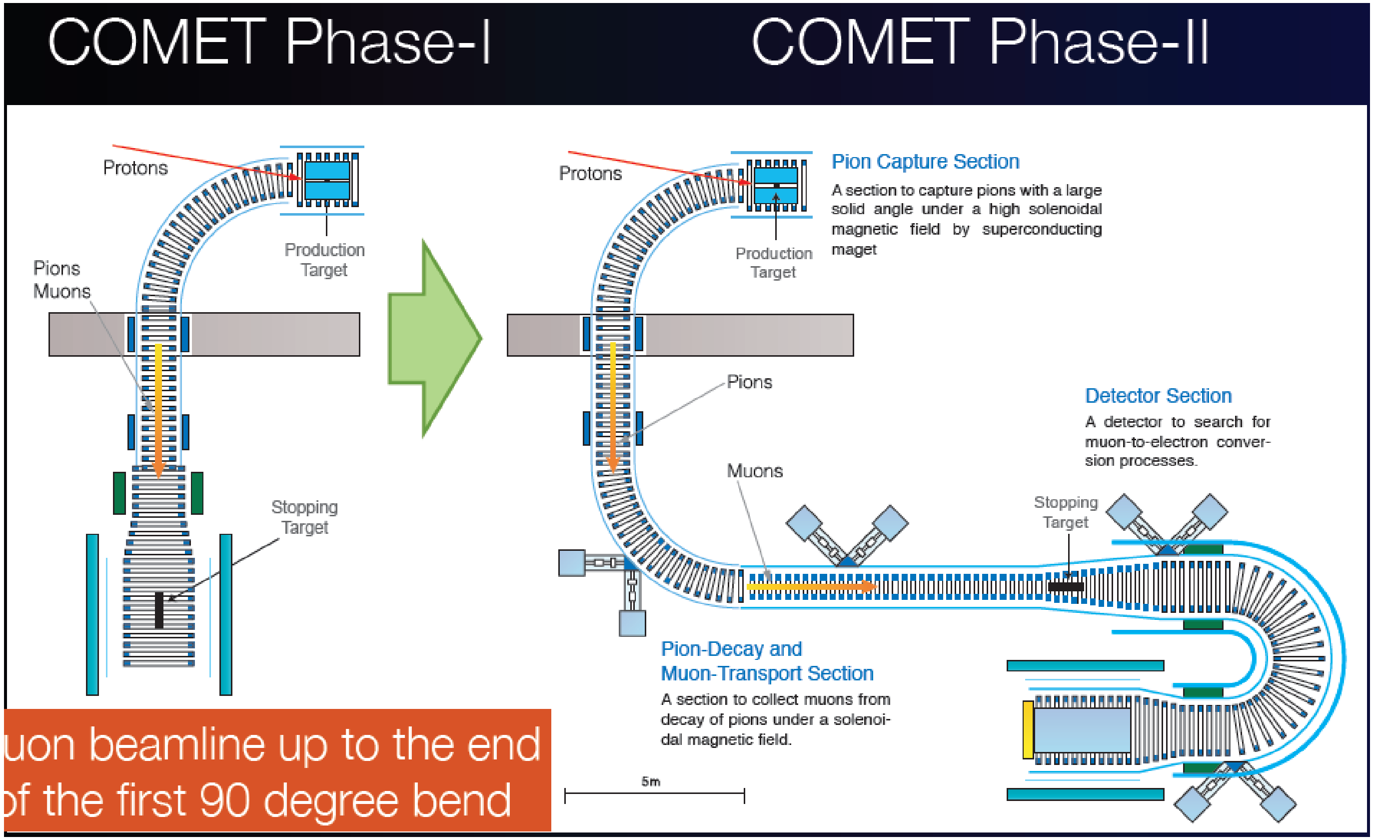
Concept: Only look for events in quiet search window



Avoids prompt backgrounds such as Radiative Pion Capture.

Similar: COMET in Japan

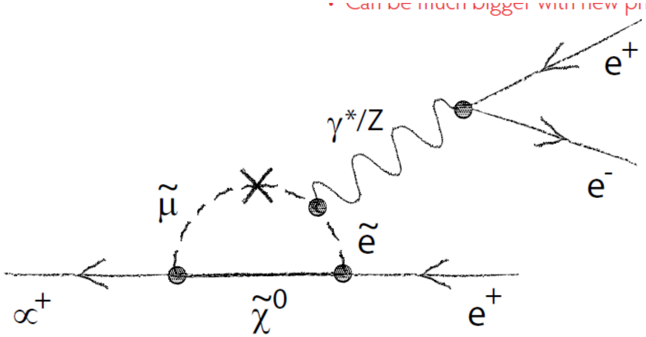
- Staged approach.
- Approved for Phase-1
  - Sensitivity: < **7×10^{-15}**
- Full phase later

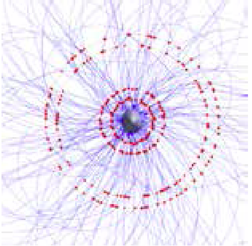


Next-generation: μ → eee

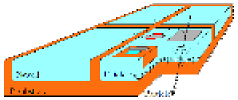
(2013: approved at PSI)

The SM theory still clear: Unobservable (BR: 10^{-50})





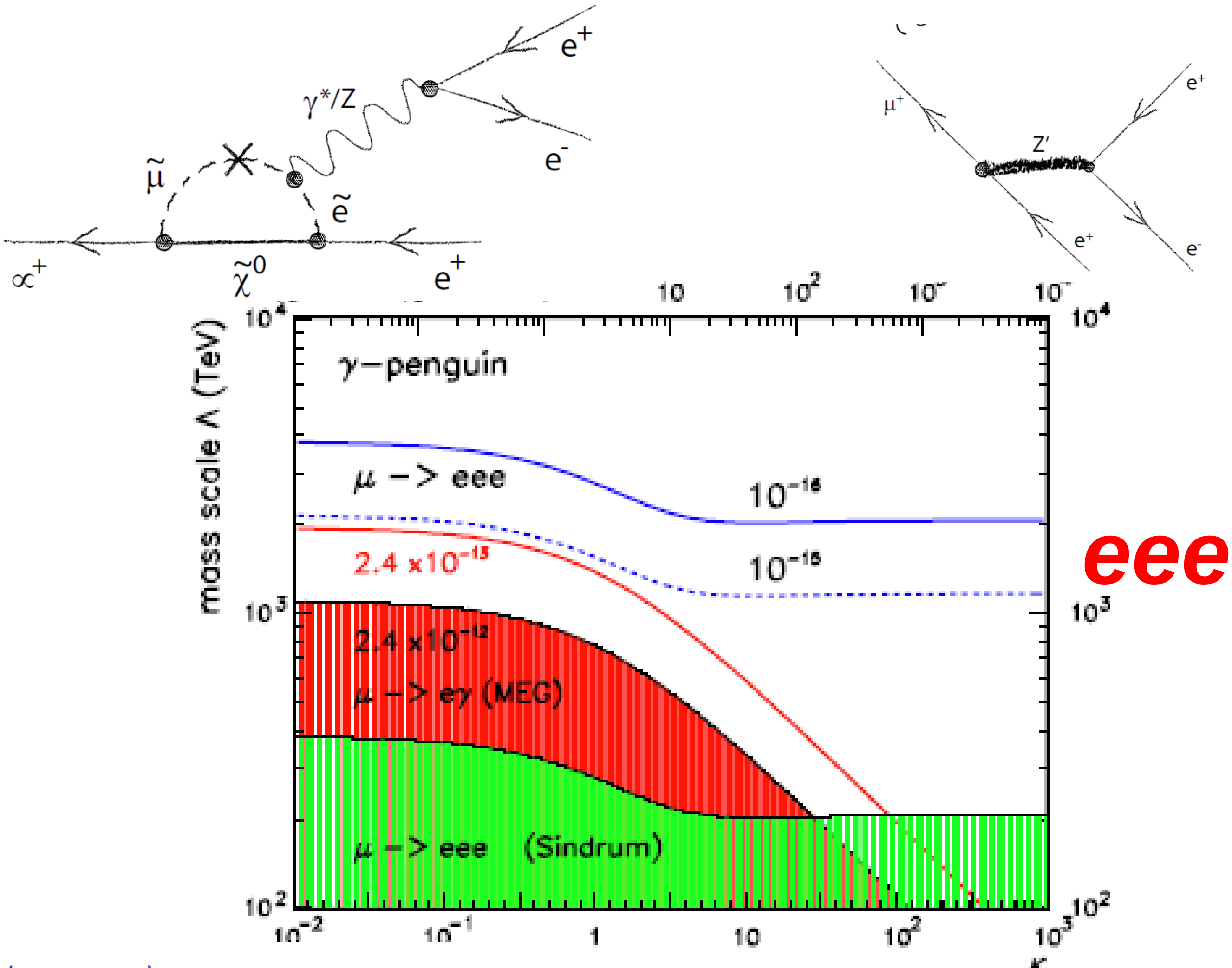
- **Goal:**
  - **Finding 1 in 10^{16} muon decays**



- **Special technique**
  - **High-voltage monolithic active pixel sensors**

- **The detector**
  - **Minimum material, maximum precision**

Compared to other channels …

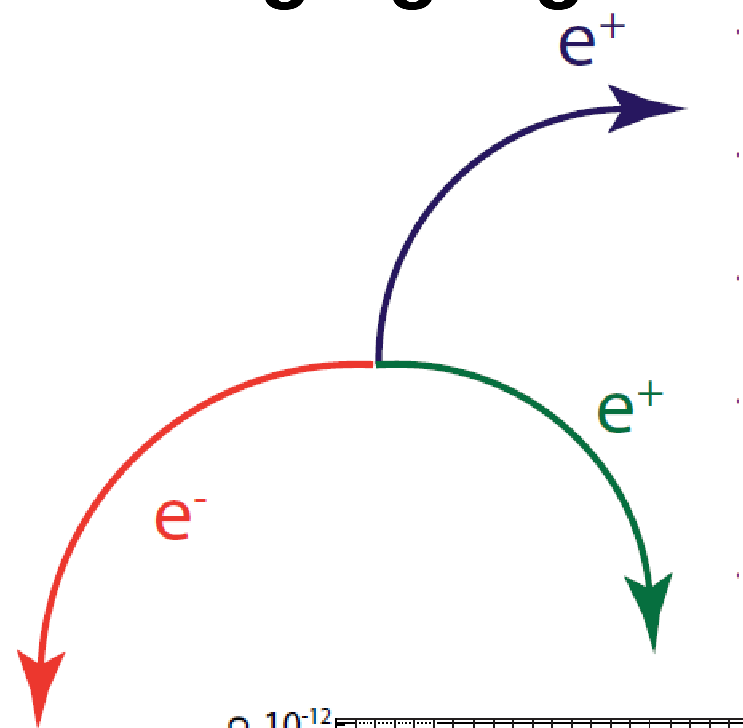


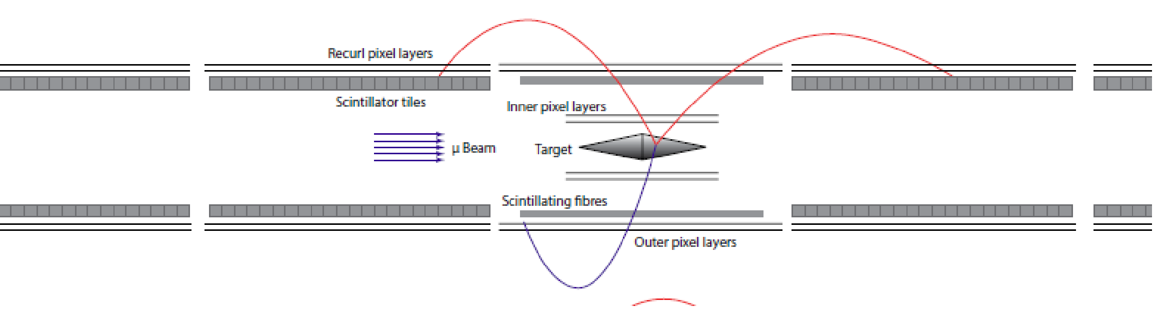
eee

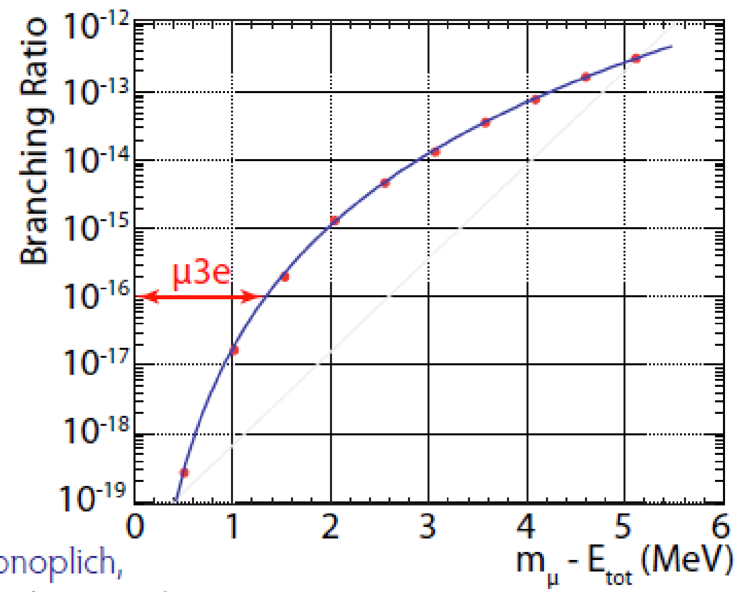
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad \text{(essentially } \alpha_{em}\text{)}$$

Again, a unique and challenging signature

- $2\ e^+$, $1\ e^-$
- Common vertex
- Common time
- Σ energies = m_μ
- No energy > m_μ / 2







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Summary: Muon Experiments

In Support of the Standard Model

- **Lifetime – G_F**
  - **MuLan: 1 ppm lifetime; 0.5 ppm G_F**
- **Capture on protons and deuterons**
  - **MuCap g_P: Unambiguous confirmation of low-energy QCD-based theory**
  - **MuSun L_{1a} Fundamental astrophysics implications**
- **Muonic Atoms**
  - **Lamb shift in hydrogen, r_p proton radius puzzle**
  - **Lamb shift in other light systems in prep**

Physics Beyond the Standard Model Tests

- **Michel parameters**
  - **TWIST $\rho, \delta, \eta, P_\mu \xi$: constrains right handed terms in WI**
- **Anomalous magnetic moment (g-2)**
  - **BNL: a hint of something interesting**
  - **FNAL: Improved precision will provide definitive test**
- **Lepton Flavor Violation**
  - **MEG: $\mu \rightarrow e\gamma$ New limits at … Plans to go to xx**
  - **Mu2e: $\mu \rightarrow e$ conversion in prep to improve by > 3 orders of magnitude**
  - **COMET: Similar long term goal with nearer term intermediate result**
- **EDM –**
  - **Parasitic from g-2 data; can improve by x100**
- **Lorentz / CPT violation test –**
  - **Similar improvements expected from higher statistics data sets**