LFV muon decays and muon dipole moments

Fenomenologia delle Interazioni Elettrodeboli

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Supersymmetry (SUSY)

Supersymmetry is a hypothetical symmetry of nature which relates fermions and bosons. We postulate the existence of operators which change bosons into fermions

$$Q|b\rangle = |f\rangle$$

with a conjugate operator going the the opposite way.

Q leaves all other quantum numbers unchanged.

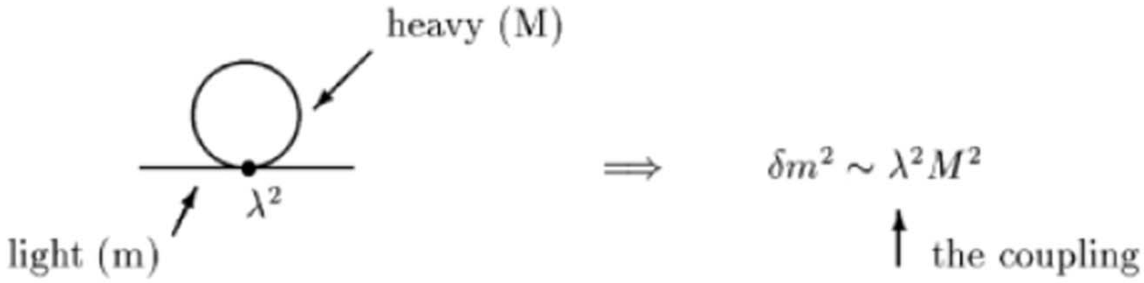
If the SM were part of a supersymmetric theory, with the symmetry not broken, each of the fermions and gauge bosons would have a supersymmetric partner generated by Q (or its conjugate operator) that differed in spin but otherwise identical.

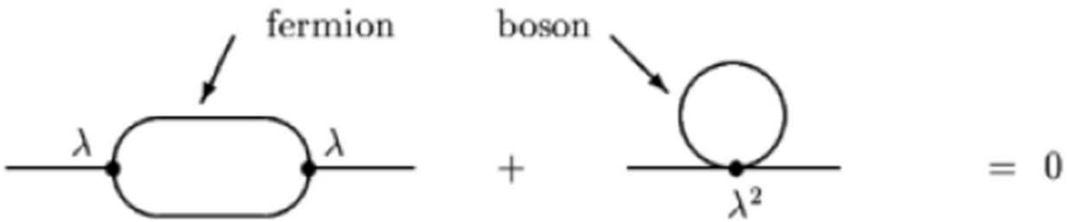
Why do we need SUSY ?

- All attempts to make general relativity consistent with quantum field theory require a new symmetry.
- Mass hierarchy problem
- Coupling constant unification

Mass Hierarchy Problem

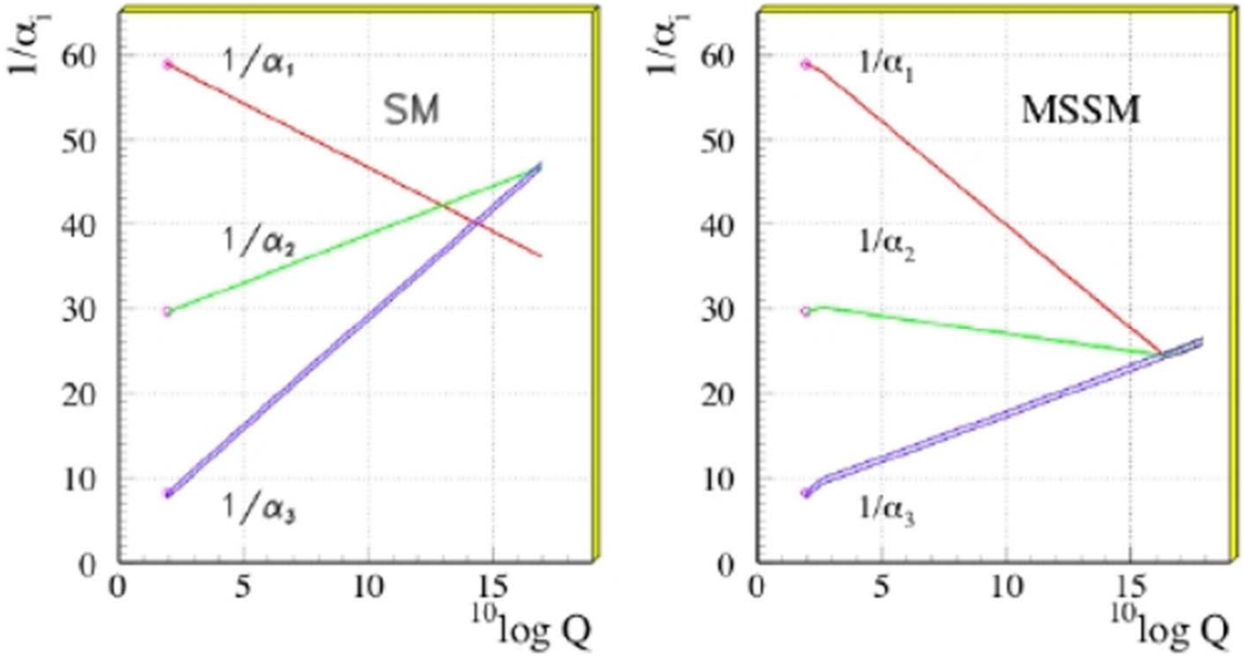
The electroweak scale if of the order of 100 GeV, but radiative corrections in the SM point to a scale which is many orders of magnitude larger, around the Planck scale. A supersymmetric version of the SM is able to stabilize these radiative corrections and solve the hierarchy problem, provided that the new particles have masses of less than a few TeV.





Coupling Constant Unification

In the past few years the values of the three coupling constants have been measured with great accuracy and it is now clear that they cannot unify at any scale unless many new particles are added to the theory.



Minimal Supersymmetric Standard Model (MSSM)

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u\ \ H^0_u)$	$(\widetilde{H}^+_u\ \ \widetilde{H}^0_u)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H^0_d\ \ H^-_d)$	$(\widetilde{H}^0_d\ \ \widetilde{H}^-_d)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

Physics motivations: LFV

- Lepton flavor violation processes (LFV), like $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu \rightarrow e$ conversion , are negligibly small in the extended Standard Model (SM) with massive Dirac neutrinos (BR $\approx 10^{-50}$)
- Super-Symmetric extensions of the SM (SUSY-GUTs) with right handed neutrinos and see-saw mechanism may produce LFV processes at significant rates

μ-LFV decays are therefore a clean (no SM contaminated) indication of New Physics

and

they are accessible experimentally

Physics motivations : μ moments

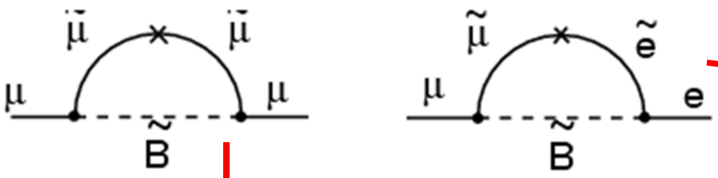
1. **Magnetic Dipole Moment** (***g-2***) :
   - ✓ measured and predicted with very high accuracy (10 ppb in electron; 0.5 ppm in muon), it represents the most precise test of QED ;
   - ✓ most extensions of SM predict a contribution to ***g-2*** ;
   - ✓ a 2.7 σ discrepancy between theory and experiment has raised a lot of interest (and publications) .

2. **Electric Dipole Moment** (**μEDM**) :
   - ✓ Like LFV processes, a positive measurement of μ Electric Dipole Moment (μEDM) would be a signal of physics beyond the SM

Both experiments need a new high intensity muon source for the next generation of measurements

Connection between *LFV* and *μ-moments*

- In SUSY, g-2 and EDM probe the diagonal elements of the *slepton mixing matrix*, while the LFV decay $\mu \to e$ probes the off-diagonal terms



$$\begin{pmatrix} V_{\tilde{e}\tilde{e}} & V_{\tilde{e}\tilde{\mu}} \\ V_{\tilde{\mu}\tilde{e}} & V_{\tilde{\mu}\tilde{\mu}} \end{pmatrix}$$

- In case SUSY particles are observed at LHC, measurements of the LFV decays and of the μ-moments will provide one of the cleanest measarements of *tanβ* and of the *new CP violating phase* .

Momenti Magnetici dei Leptoni

Un fermione puntiforme di Dirac possiede un momento magnetico pari a un magnetone di Bohr. Se *e* ed *m* sono carica e massa del leptone:

$$\mu_B = \frac{e}{2m}$$

In generale, per un fermione di spin $\vec{s}$:

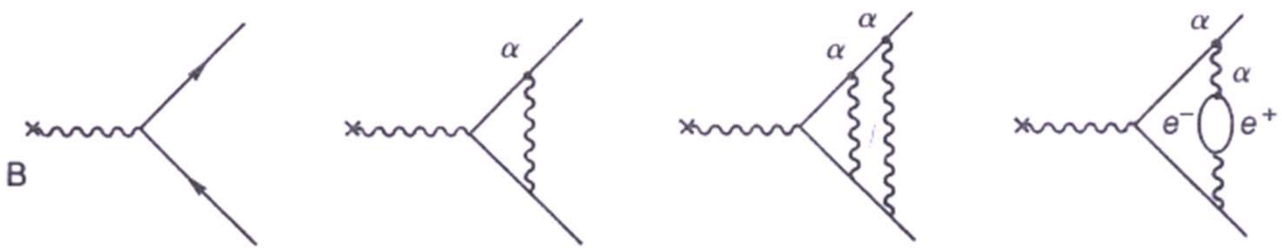
$$\vec{\mu} = g\mu_B\vec{s}$$

Dove g è il fattore di Landé e $g\mu_B$ il rapporto giromagnetico.
Per elettrone e muone $|\vec{s}|=½$ e la teoria di Dirac prevede g=2.
Sperimentalmente si trova che i fattori di Landé per elettrone e muone differiscono dal valore g=2 di circa lo 0.2 %.
La teoria di Dirac secondo la quale l'elettrone e il muone sono particelle puntiformi (prive di struttura interna) ha quindi bisogno di correzioni.

Il momento magnetico di una particella carica dipende dalle distribuzioni spaziali di carica e massa. Per una particella di spin ½ un valore $g \neq 2$ segnala la presenza di processi che modificano la distribuzione relativa di carica e massa. Per esempio, per il protone $g=5.59$, a causa della sua struttura interna.

L'elettrone, il μ, il τ sono costituiti da un oggetto puntiforme circondato da una nuvola di γ virtuali che vengono continuamente emessi e riassorbiti. Questi γ si prendono parte della massa del leptone, per cui il rapporto e/m (e quindi il momento magnetico) cambia.

In termini di QED:



Il fattore di Landé si può scrivere come una serie perturbativa in (α/π).

All'ordine più basso:

$$g = 2 \qquad \vec{\mu} = -\frac{e}{2m}\vec{\sigma}$$

All'ordine successivo: $g = 2 + \frac{\alpha}{\pi}$ $\qquad \vec{\mu} = -\frac{e}{2m}\left(1+\frac{\alpha}{\pi}\right)\vec{\sigma}$

Si può definire l'anomalia: $a \equiv \frac{g-2}{2}$

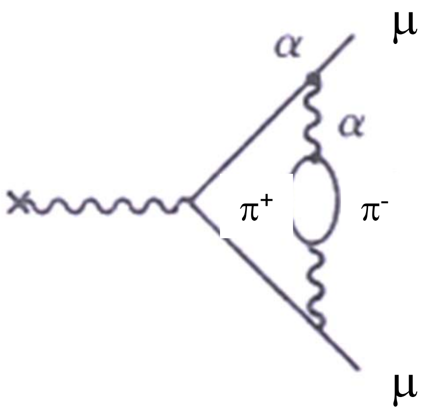
$$a_e \equiv \left(\frac{g-2}{2}\right)_e^{QED} = 0.5\left(\frac{\alpha}{\pi}\right) - 0.32848\left(\frac{\alpha}{\pi}\right)^2 + 1.19\left(\frac{\alpha}{\pi}\right)^3 + \cdots$$

$$= (1159652140 \pm 28)\times 10^{-12}$$

$$a_\mu \equiv \left(\frac{g-2}{2}\right)_\mu^{QED} = 0.5\left(\frac{\alpha}{\pi}\right) - 0.76578\left(\frac{\alpha}{\pi}\right)^2 + 24.45\left(\frac{\alpha}{\pi}\right)^3 + \cdots$$

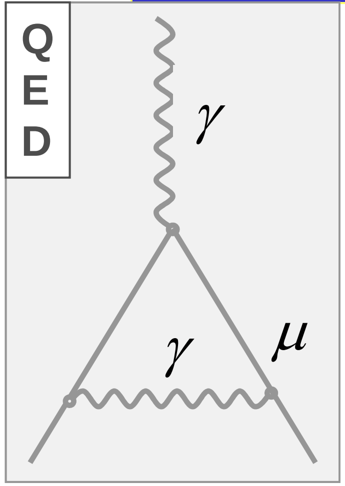
$$= (1165847008 \pm 18 \pm 28)\times 10^{-12}$$

Il valore dell'anomalia che si misura per il μ differisce di circa 9 deviazioni standard dal calcolo di QED. Questo è dovuto al fatto che per il μ ci sono ulteriori correzioni ad a_μ che derivano dalle interazioni forte e debole.
Gli adroni non si accoppiano direttamente al μ, ma si possono accoppiare al fotone. Ci aspettiamo quindi dei contributi adronici alla polarizzazione del vuoto del tipo:



Questo contributo, di per sè piccolo a causa della elevata massa del π, è amplificato dalla presenza di risonanze del sistema $\pi\pi$ (risonanze vettoriali).

The Anomalous Magnetic Moment : a_μ



QED Prediction: $\Gamma_\mu = e\gamma_\mu + a_\ell \dfrac{ie}{2m}\sigma_{\mu\nu}q_\nu$

Schwinger 1948
(Nobel price 1965)

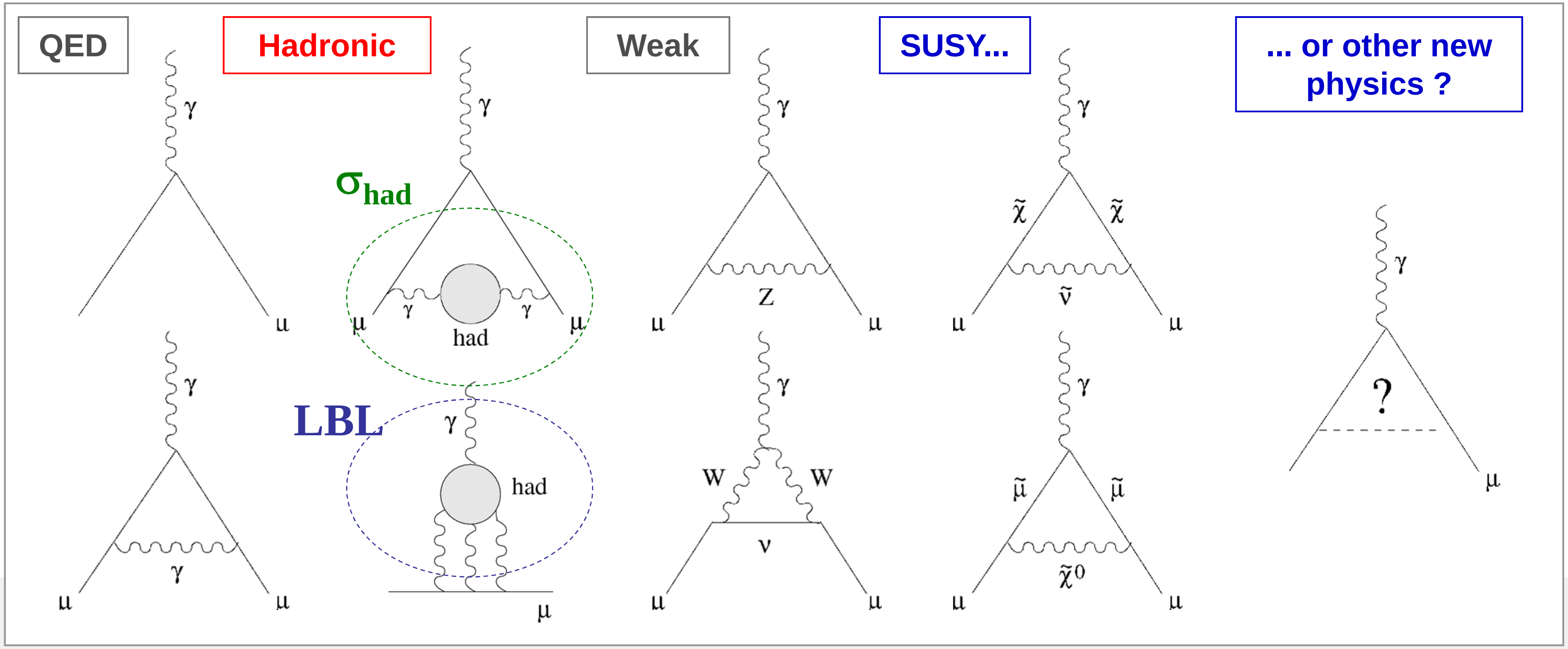
Computed up to 4th order
[Kinoshita *et al.*]
(5th order estimated [Mohr, Taylor])

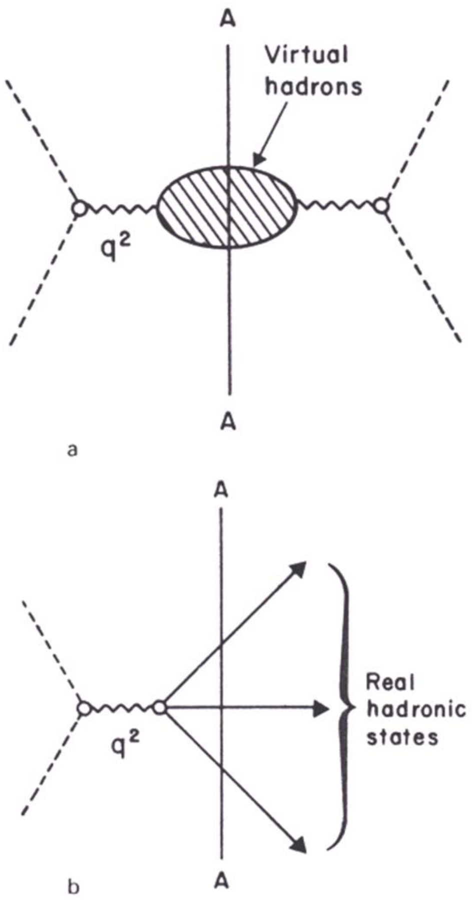
$$a_\ell = \frac{\alpha}{2\pi} = 0.001161\ldots$$

$$a_\mu^{\rm QED} = \sum_{n=1}\left(\frac{\alpha}{\pi}\right)^n \approx \begin{pmatrix} 11614098.1 + 41321.8 \\ + 3014.2 + 38.1 + 0.6 \end{pmatrix} \times 10^{-10}$$

corrected feb 04

Kinoshita-Nio,
hep-ph/0402206





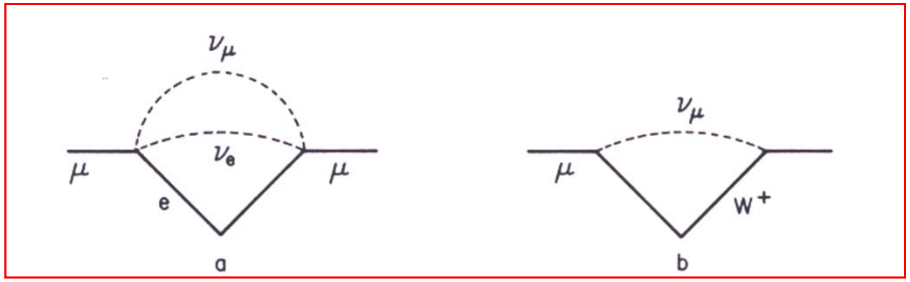
Il contributo forte all'anomalia si può calcolare a partire dalla sezione d'urto (misurabile) per il processo

$e^+e^- \rightarrow$ adroni

Infatti, tramite relazioni di dispersione, è possibile mettere in relazione tra loro i due grafici a sinistra.

$$\Delta a_\mu(\,forte) = \frac{m_\mu^2}{12\pi^3}\int_0^\infty \frac{\sigma\left(e^+e^- \rightarrow adroni\right)}{s}ds$$

Contributi deboli



Misura di g-2 per il μ

Consideriamo una particella polarizzata longitudinalmente che si muove in un campo magnetico statico $\vec{B}$. L'impulso ruota alla frequenza di ciclotrone:

$$\omega_c = \frac{eB}{mc}$$

Lo spin compie un moto di precessione con la frequenza:

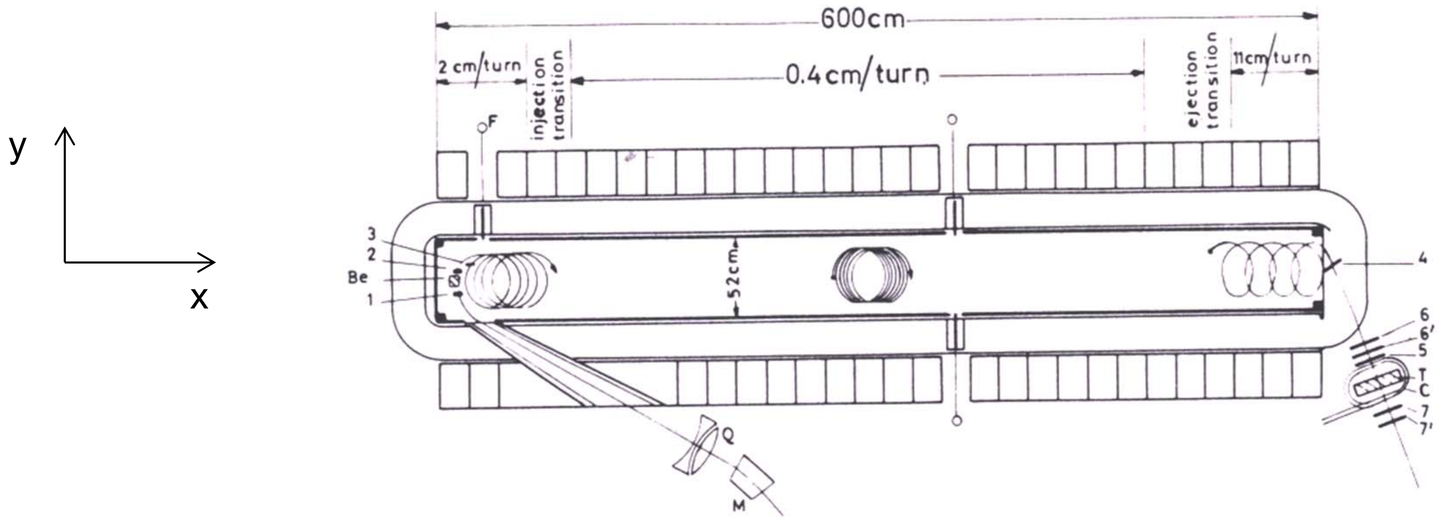
$$\omega_s = g\,\frac{eB}{2mc} = (1 + a_\mu)\frac{eB}{mc}$$

Se g=2, cioè a_μ=0, ω_s=ω_c e la particella rimarrà sempre polarizzata longitudinalmente.

Se invece g>2 (a_μ>0), ω_s>ω_c, lo spin ruota più velocemente dell'impulso. La frequenza ω_a di rotazione dello spin rispetto all'impulso è data da:

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

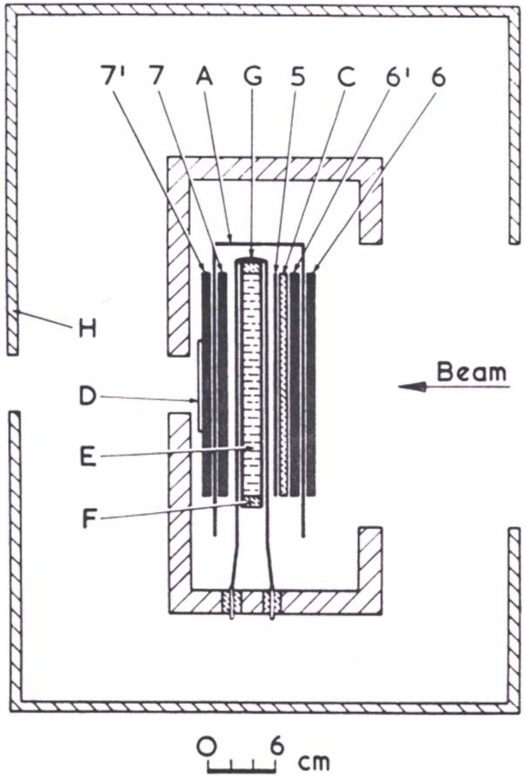
Il principio di misura di a_μ è quindi il seguente: si fa ruotare i muoni in un campo magnetico B, si misura l'angolo tra spin e impulso in funzione del tempo e da qui si ricava a_μ .
Poichè $a_\mu \approx 1/800$, il muone deve compiere circa 800 giri perchè lo spin ne faccia 801 e la polarizzazione cambi di 2π.



I muoni compiono circa 2000 giri nel campo magnetico. Il gradiente del campo sposta l'orbita verso destra. Alla fine un elevato gradiente fa uscire i muoni, che si fermano nell'analizzatore di polarizzazione.

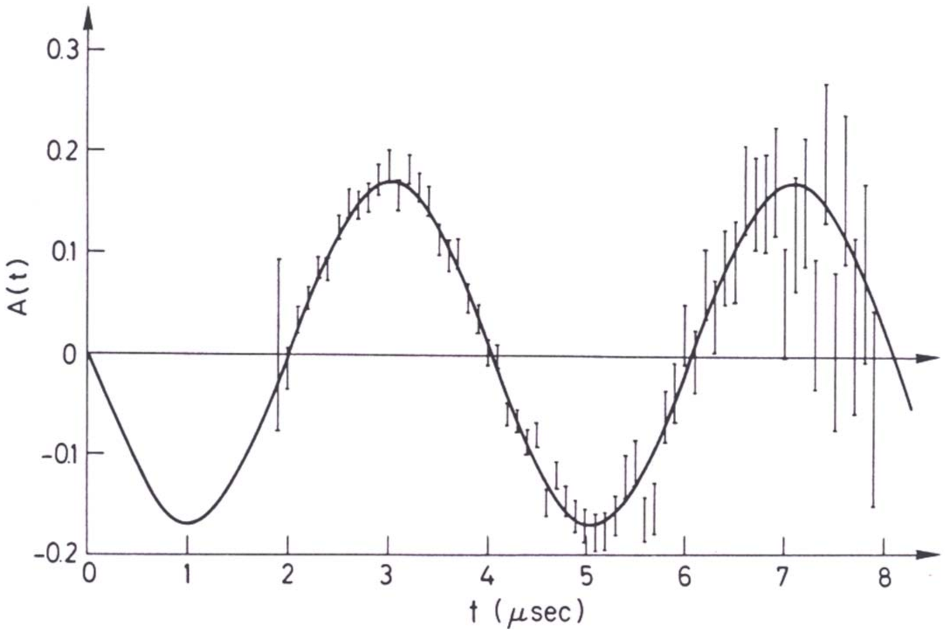
$$B_z = B_0\left(1 + ay + by^2\right)$$

$$B = 1.6\,T \qquad p_\mu \approx 90\ MeV/c \qquad t \approx \tau_\mu = 2.2\ \mu s$$



Analizzatore di polarizzazione. Quando un muone si ferma nel metilene liquido (E) un impulso di corrente nella bobina G rovescia lo spin di $\pm 90^0$. Gli elettroni di decadimento dei muoni sono rivelati dalle coincidenze 66′ (all'indietro) e77′ (in avanti). L'asimmetria dei conteggi in funzione del tempo è data da:

$$A \equiv \frac{c_+ - c_-}{c_+ + c_-} = A_0 \sin\theta_s$$

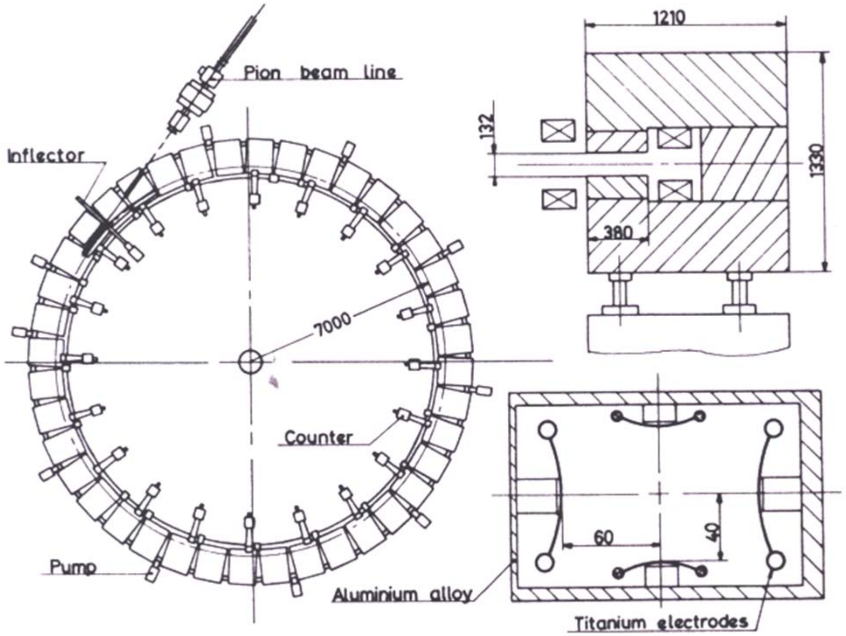


$$A = A_0 \sin\left\{ a_\mu \left(\frac{e}{mc} \right) Bt + \phi \right\}$$

Con questo metodo l'anomalia a_μ fu misurata con precisione 0.4 %

$$a_\mu = (1162 \pm 5) \times 10^{-6}$$

Muon Storage Ring



Per migliorare la precisione nella misura era necessario aumentare il numero di cicli, aumentando B e/o il tempo di immagazzinamento.
L'utilizzo di un campo elettrico per la focalizzazione verticale permetteva di utilizzare un campo magnetico uniforme.
Per la precessione dello spin in campi elettrico e magnetico:

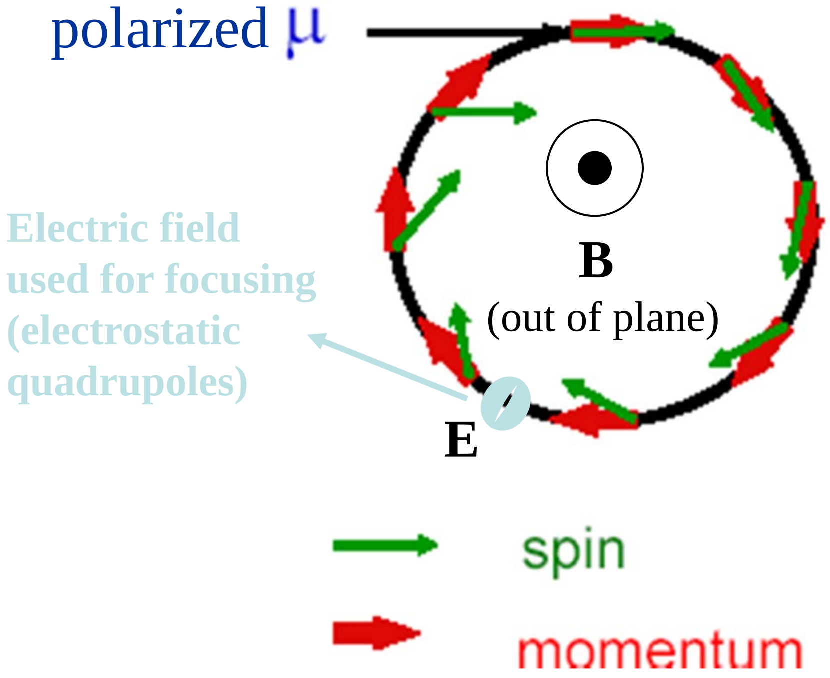
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right]$$

Per γ=29.3 (*magic* γ) il coefficiente del secondo termine si annulla e la precessione è di nuovo $\propto a_\mu$.

Questo metodo ha consentito di migliorare notevolmente la precisione nella misura di a_μ.

$$a_\mu = (1165924 \pm 9)\times 10^{-9}$$

Storage ring to measure a_μ



Precession of *spin* and *momentum* vectors in **E**, **B** fields (in the hyp. $\beta \cdot \mathbf{B}=0$) :

$$\begin{cases} \vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_m = \dfrac{e}{mc}\left(a_\mu \vec{B} - K\vec{\beta}\times\vec{E}\right) \\ K = a_\mu - \dfrac{1}{\gamma^2 - 1} \end{cases}$$

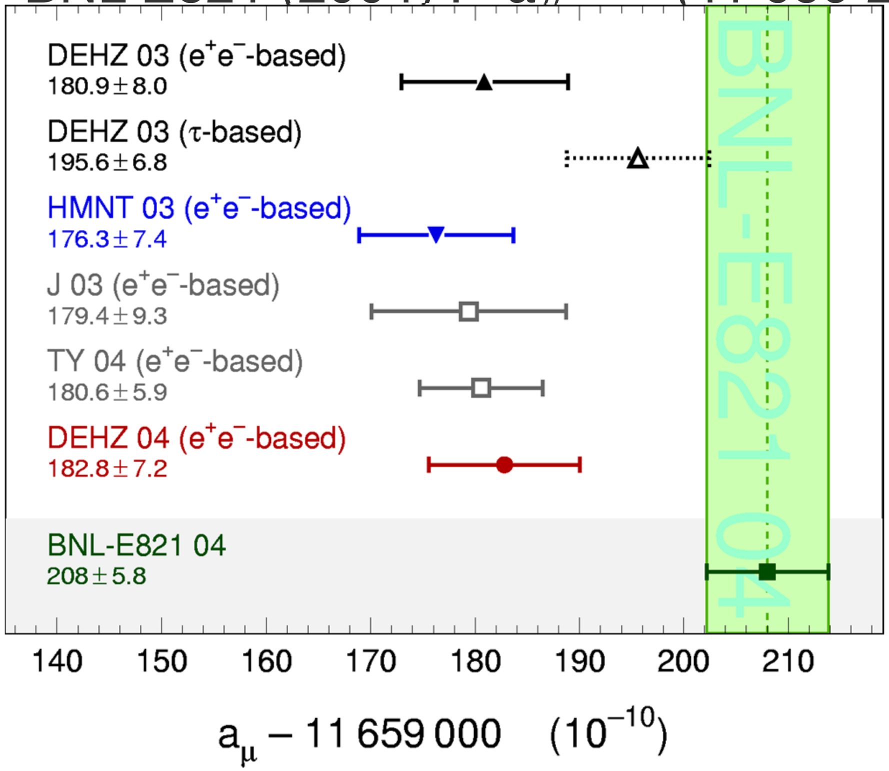
- At γ_{magic} = 29.3, corresponding to E_μ=3.09 GeV, K=0 and precession is directely proportional to a_μ

$$a_\mu \approx \omega_a / B$$

Situazione Attuale per a_μ

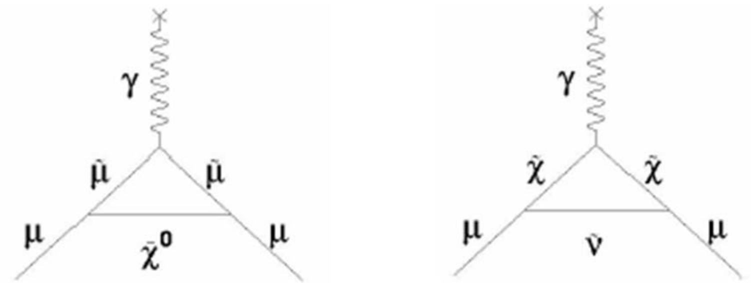
$a_\mu^{SM}[e^+e^-] = (11\ 659\ 182.8 \pm 6.3_{had} \pm 3.5_{LBL} \pm 0.3_{QED+EW}) \times 10^{-10}$

BNL E821 (2004) : $a_\mu^{exp} = (11\ 659\ 208.0 \pm 5.8)\ 10^{-10}$



$$\boxed{a_\mu^{exp} - a_\mu^{SM} = (25.2 \pm 9.2) \times 10^{-10}}$$

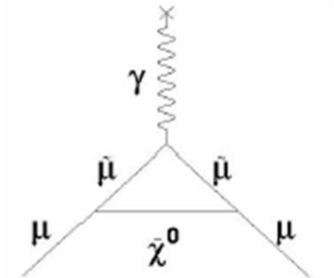
La discrepanza tra teoria ed esperimento è di 2.7 deviazioni standard.

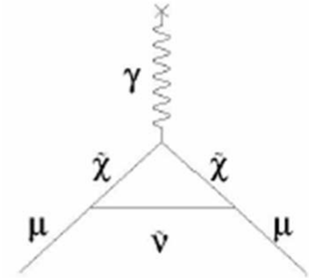


$$\Delta a_\mu^{SUSY} \approx 1.1\,\mathrm{ppm} \times \left(\frac{100\ GeV}{\tilde{m}}\right)^2 \tan\beta$$

Possible new physics contribution…

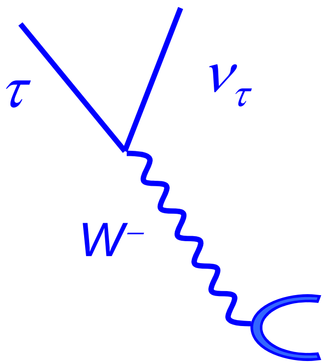
- New physics contribution can affect a_μ through the muon coupling to new particles
- In particular SUSY can easily predict values which contribute to a_μ at the ~1ppm level
- τ data can be affected differently than e^+e^- data by this new physics
- In particular H^- exchange is at the same scale as W^- exchange, while $m(H^0) >> m(\rho)$

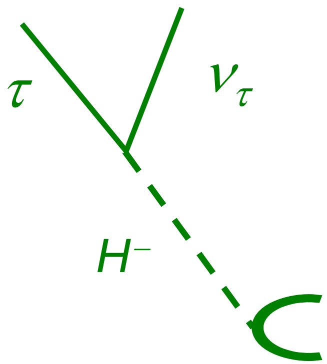




$$\Delta a_\mu^{SUSY} \approx 1.1\,\mathrm{ppm} \times \left(\frac{100\ GeV}{\tilde{m}}\right)^2 \tan\beta$$

Marciano + others





New proposal - statistics

- The new experiment aims to a precision of 0.1-0.05 ppm, which needs a factor of 25-100 more muons
- This can be achieved by increasing the …

1. … number of primary protons on target $\rightarrow$ target must be redisigned
2. … number of bunches
3. … muon injection efficiency which, at E821, was 7%
4. … running time (it was 7months with μ^- at BNL)

- The J-PARC proposal is mostly working on items 2 (go from 12 $\rightarrow$ 90 bunches) and 3

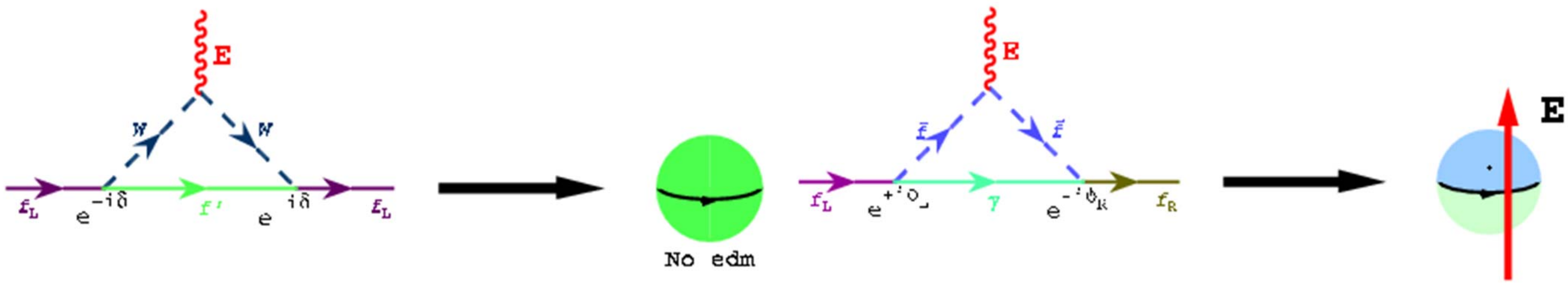
Electric Dipole Moment (EDM)

- The electromagnetic interaction Hamiltonian of a particle with both magnetic and electric dipole moment is:

g-2 term

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} \quad \text{where} \quad \begin{cases} \vec{d}_M \equiv \vec{\mu} = g\dfrac{e\hbar}{2mc}\vec{s} = \dfrac{g}{2}\mu_0\vec{\sigma} \\ \vec{d}_E \equiv \vec{d} = \eta\dfrac{e\hbar}{2mc}\vec{s} = \dfrac{\eta}{2}\mu_0\vec{\sigma} \end{cases}$$

- The existence of d_E, in SM, is suppressed because
  - d_E violates both P and T (and also CP in the CPT hyp.)
  - only one weak phase exist in CKM
- This is not the case for SUSY where many CP phases exist



Limits on EDM

- Electron EDM estimated in the framework of the SM:

$$d_e \cong -1.5\times10^{-38}\, e\cdot cm$$

- No evaluation for muon EDM, but is should scale with mass:

$$d_\mu \cong -1.5\times10^{-36}\, e\cdot cm$$

- For the EDM measurement the particle must be in an electric field which exerts a torque on the electric dipole, inducing precession
- Up to now EDMs have been measured only on:
  1. Neutrons
  2. Heavy paramagnetic/diamagnetic atoms/molecules (Tl,Hg,YbF)
- Electron EDM extracted from (2.) : **$d_E(e)<2\times10^{-27}$ e·cm**
- New idea to measure directly the EDM on an elementary particle : *muons in storage ring*

New approach to μEDM

Muons in storage ring: combination of γ, **E**, **B** that cancels out muon spin (g-2) precession (electric field **E** must be radial and $\mathbf{E}\cdot\beta=\mathbf{B}\cdot\beta=0$) ; only μEDM precession left .

$$\vec{\omega}=\frac{e}{m}\left[a_\mu\vec{B}-\left(a_\mu-\frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}+\frac{\eta}{2}\left(\frac{\vec{E}}{c}+\vec{\beta}\times\vec{B}\right)\right]$$

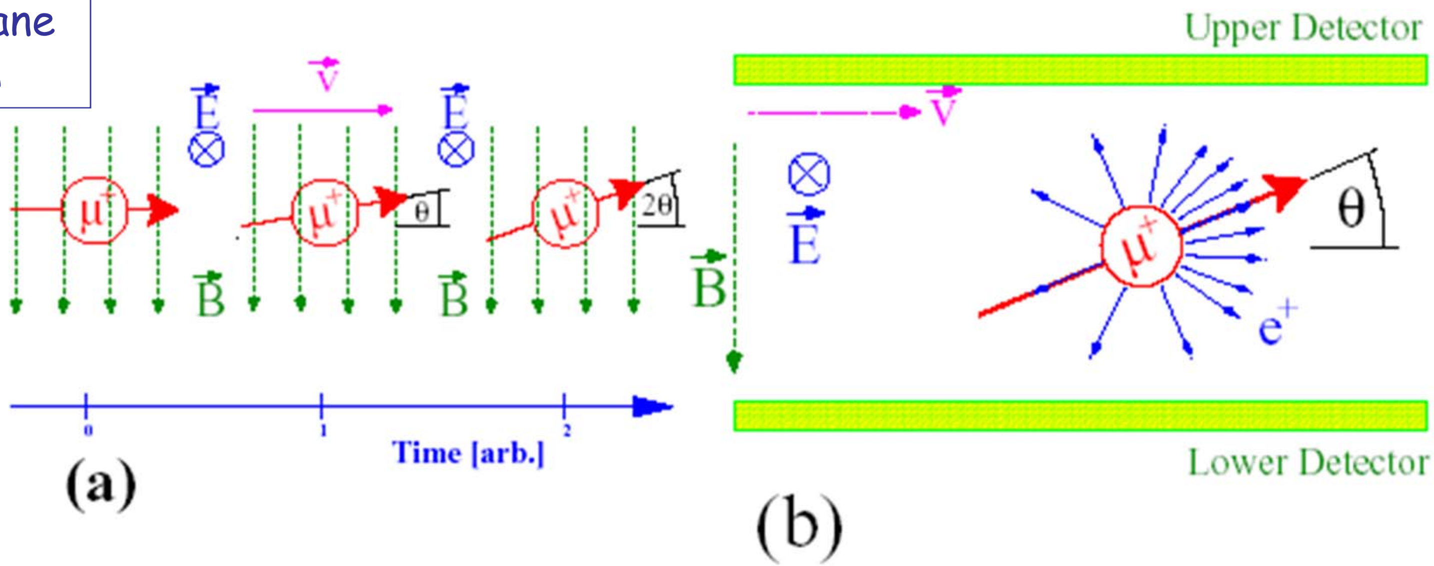
Choose radial electric field $E \sim aBc\beta\gamma^2$ such that:

$$a_\mu\vec{B}-\left(a_\mu-\frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}=0$$

$$\boxed{\vec{\omega}=\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c}+\vec{\beta}\times\vec{B}\right)\right]\cong\frac{e}{m}\frac{\eta}{2}\vec{\beta}\times\vec{B}}$$

NO out of plane precession

side view



Measure vertical asymmetry A of decay electrons. Statistical precision:

$$\sigma = \frac{\sqrt{2}}{\gamma\tau \frac{e}{m} \beta BAP\sqrt{N}}$$

P = muon polarization

A = measured asymmetry

N = number of detected electrons

Present EDM Limits

Particle	*Present EDM limit* (e-cm)	*SM value* (e-cm)
n	6.3×10^{-26}	10^{-31}
e^-	$\sim 1.6 \times 10^{-27}$	10^{-38}
μ	$< 10^{-18}$ (CERN) $\sim 10^{-19}$ * (E821) *projected	10^{-35}
future μ exp	10^{-24} to 10^{-25}	

LFV Muon Decays

Lepton Flavor Violation μ decays

- Three relevant processes :

$$\mu \rightarrow e\gamma \qquad \mu \rightarrow 3e \qquad \mu N \rightarrow eN$$

- Forbidden in SM (they violate lepton number conservation), allowed in extensions of standard model to explain, e.g. neutrino oscillation. However, due to the smallness of the neutrino mass, BRs are unmeasurably small, e.g.

$$B(\mu^{\pm} \rightarrow e^{\pm}\gamma) \sim 10^{-54}$$

- On the other hand SUSY-GUT theories these processes can occur with measurable branching ratios:

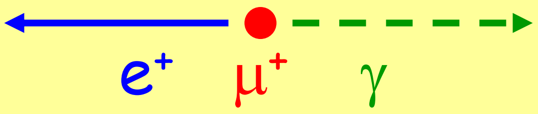
$$BR(\mu\text{-}e\ conv) \approx 10^{-3}\, BR(\mu \rightarrow e\gamma) \qquad BR(\mu \rightarrow 3e) \approx 10^{-2}\, BR(\mu \rightarrow e\gamma)$$

$$BR(\mu \rightarrow e\gamma) \sim 10^{-11} - 10^{-15}.$$

$\mu^+ \to e^+\gamma$

signal

$\mu \to e\,\gamma$



$\theta_{e\gamma} = 180°$

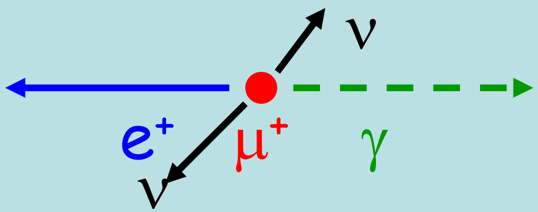
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

correlated

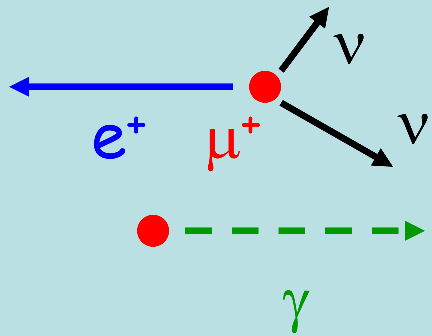
$\mu \to e\,\gamma\,\nu\,\nu$



accidental

$\mu \to e\,\nu\,\nu$

$$\left\{\begin{array}{l} \mu \to e\,\gamma\,\nu\,\nu \\ ee \to \gamma\,\gamma \\ eZ \to eZ\,\gamma \end{array}\right.$$



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

Present limit $B(\mu \rightarrow e\ ) < 1.2\times10^{-11}$ by the MEGA Collab. M.L.Brooks et al. Phys.Rev.Lett. 83(1999)1521

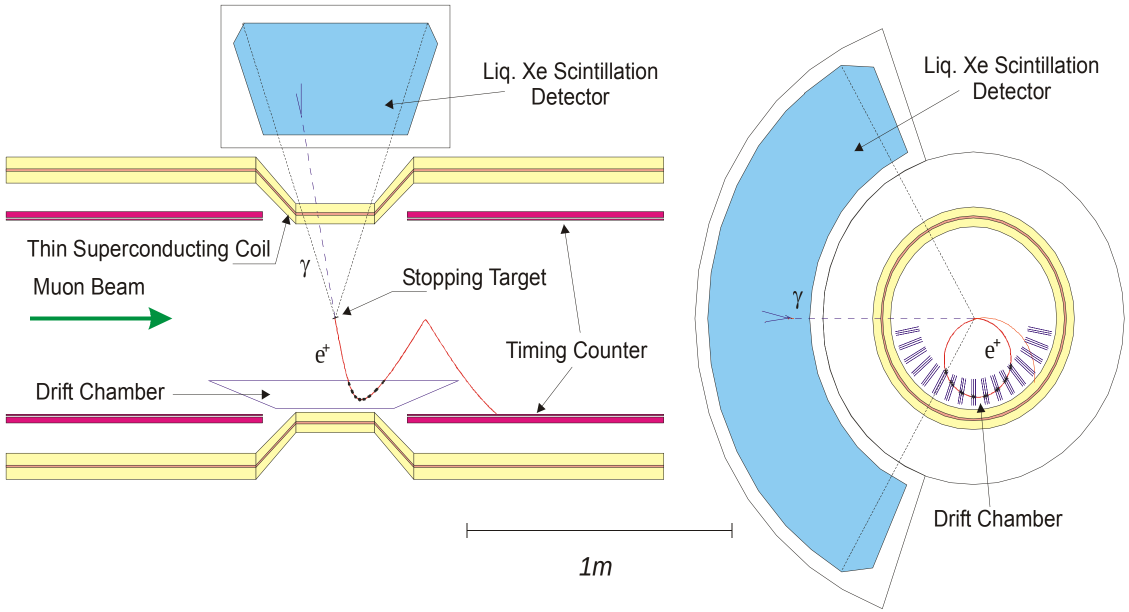
New approved experiment:
MEG @ PSI

LoI · Proposal · Revised document · now

Planning	R & D	Assembly	Data Taking

1998 · 1999 · 2000 · 2001 · 2002 · 2003 · 2004 · 2005 · 2006 · 2007

- Stopped beam of $>10^7$ μ /sec in a 150 μm target
- Liquid Xenon calorimeter for γ detection (scintillation)
- Solenoid spectrometer & drift chambers for e^+ momentum
- Scintillation counters for e^+ timing



$\mu^+ \to e^+\gamma$: future

- MEG sensitivity : 10^{-13} with 10^7 μ^+/s
- The PSI πE5 can deliver up to 3×10^8 μ^+/s
- The MEG sensitivity is accidental background limited
- With better detector resolutions a BR of 10^{-14} would be possible

but...

Challenging !

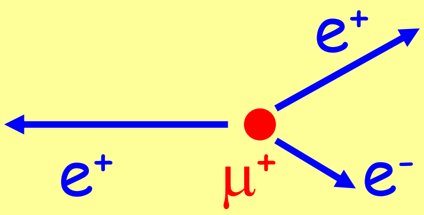
No immediate (next 10 years) need for

a more intense beam

$\mu^+ \to e^+ e^+ e^-$

signal

$\mu \to eee$



Coplanarity

Vertexing

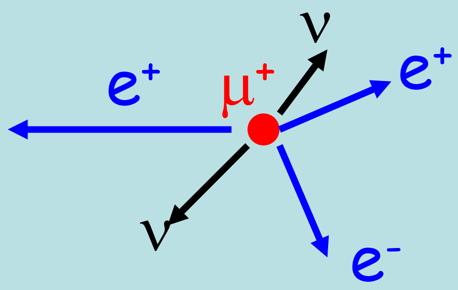
$\Sigma E_e = m_\mu$

Te+ = Te+ = Te-

background

correlated

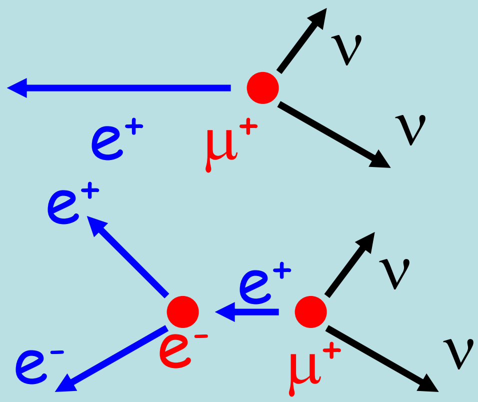
$\mu \to e\ e\ e\ \nu\ \nu$



accidental

$\mu \to e\ \nu\ \nu$

$$\begin{cases} \mu \to e\ \nu\ \nu \\ e^+e^- \to e^+e^- \end{cases}$$

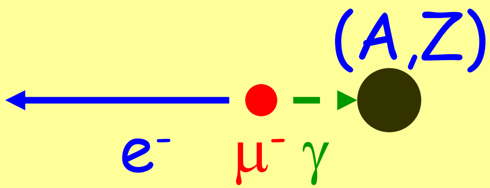


Present limit $B(\mu \to 3e) < 1\times10^{-12}$ No other experimental proposal

$\mu^- \to e^-$ conversion

signal

$\mu\,(A,Z) \to e\,(A,Z)$

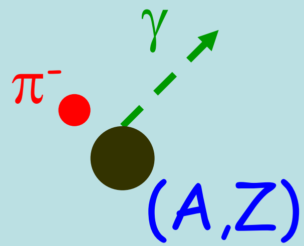


$E_e = m_\mu - E_B$

background

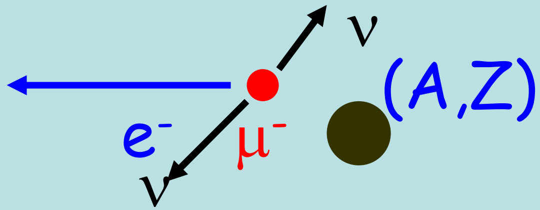
RPC

$\pi\,(A,Z) \to \gamma\,(A,Z\text{-}1)$



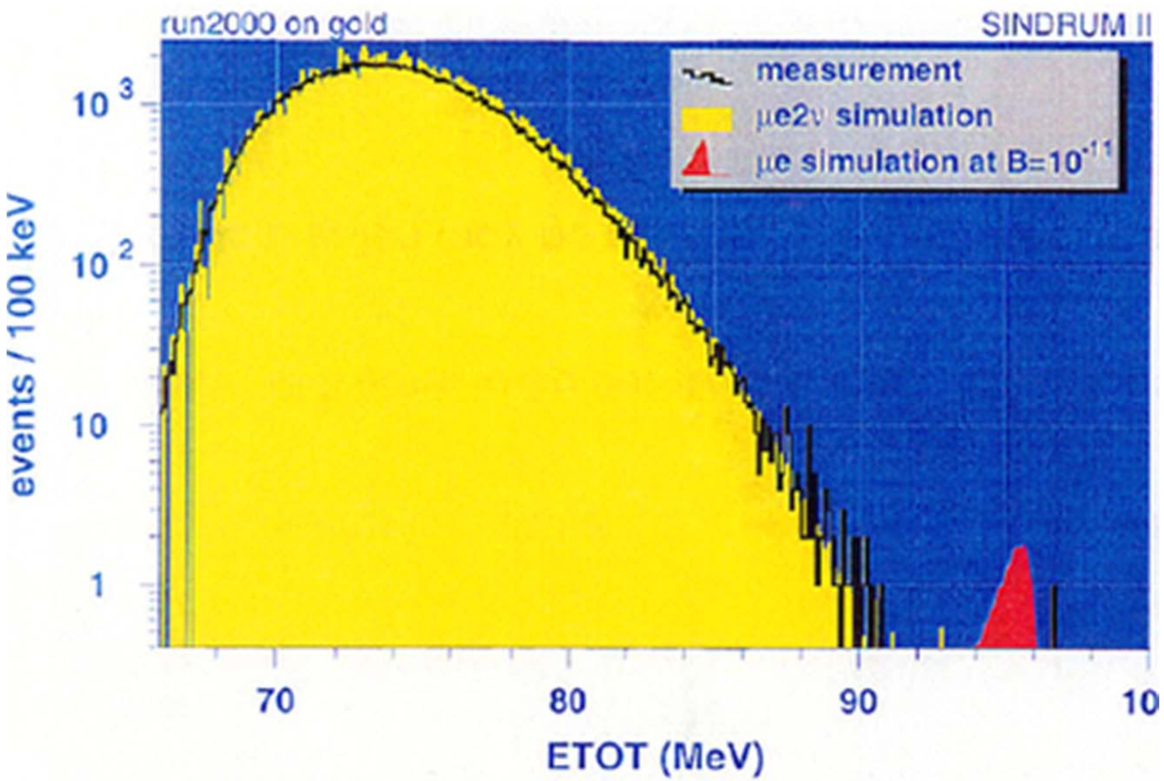
MIO

$\mu\,(A,Z) \to e\,\nu\,\nu\,(A,Z)$



$\mu^- \to e^-$: present limit

Present limit $B(\mu \to e:Au) < 3x10^{-13}$ SINDRUM II COLLABORATION



SINDRUM II parameters

- beam intensity — $3x10^7\ \mu^-/s$
- μ^- momentum — ~~53 MeV/c~~
- magnetic field — 0.33T
- acceptance — 7%
- momentum res. — 2% FWHM

Main background : *Radiative Pion Capture (RPC)*

✸ suppressed with an 8mm carbon absorber at the entrance of the solenoid

Summary on muons

- Both g-2 and μEDM are sensitive to new physics behind the corner
- Unique opportunity of studying phases of mixing matrix for SUSY particles
- Historically, limits on d_E have been strong tests for new physics models
- μ EDM would be the first tight limit on d_E from a second generation particle
- The experiments are hard but, in particular the μEDM, not impossible
- A large muon polarized flux of energy 3GeV (g-2) or 0.5GeV (μEDM) is required

Experiment	N_μ	$p_\mu(\mathrm{MeV})$	$\Delta p_\mu/p_\mu(\%)$	sensitivity	$\mathrm{L_{off}}/\mathrm{L_{on}}$, δT, ΔT
$\mu^+ \to e^+e^-e^+$	10^{17}	< 30	< 10	BR=10^{-15}	DC beam
$\mu^+ \to e^+\gamma$	10^{17}	< 30	< 10	BR=10^{-15}	DC beam
$\mu^- - e^-$ pulsed	10^{21}	< 80	< 5	BR=10^{-19}	10^{-10}, < 100ns, $> 1\mu s$
$\mu^- - e^-$ continuos	10^{20}	< 80	< 5	BR=10^{-19}	DC beam
μEDM	$10^{16}/P^2$	$300 - 500$	< 5	$10^{-24}\,e\,cm$	pulsed beam
$g - 2$	10^{16}	3100	< 2	< 0.1ppm	pulsed beam