Lepton Flavor Violation and Dipole Moments in the Muon System at High Intensity Beams

Marco Incagli - INFN Pisa

SPSC meeting - Villars - 27 sep 2004

- Precision Physics as complementary to Frontier Energy Physics
- Precision Measurement relevant if:
  - firm predictions (eventually null) from Standard Model
  - relevant informations on Standard Model or on Standard Model extensions can be extracted
  - *experimentally accessible*
  - *(relatively) low cost*
- Muons satisfy all requirements!

Physics motivations: LFV

- Lepton flavor violation processes (LFV), like $\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ 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

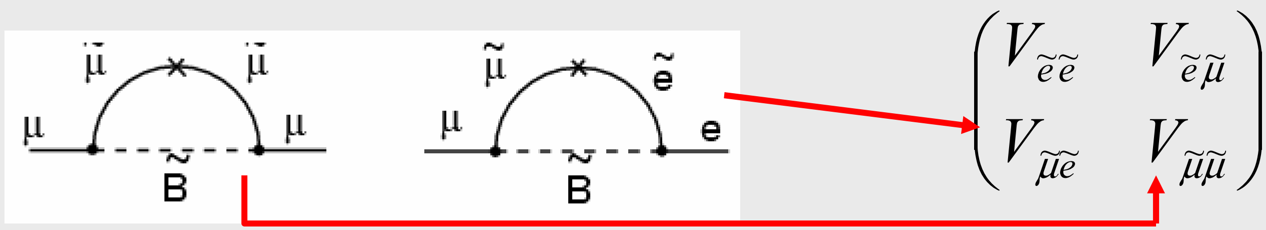
1. **Magnetic Dipole Moment** (*g-2*) :
   - ✓ measured and predicted with very high accuracy (10 ppb in electron; 0.5 ppm in muon), it represents the most precise test of QED ;
   - ✓ most extensions of SM predict a contribution to *g-2* ;
   - ✓ a 2.7 σ discrepancy between theory and experiment has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

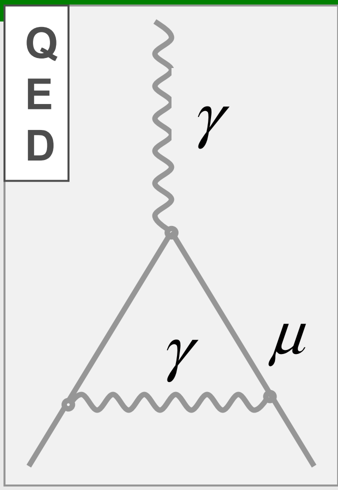
Connection between *LFV* and *μ-moments*

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



- 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* .

The Anomalous Magnetic Moment : a_μ



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

Schwinger 1948
(Nobel price 1965)

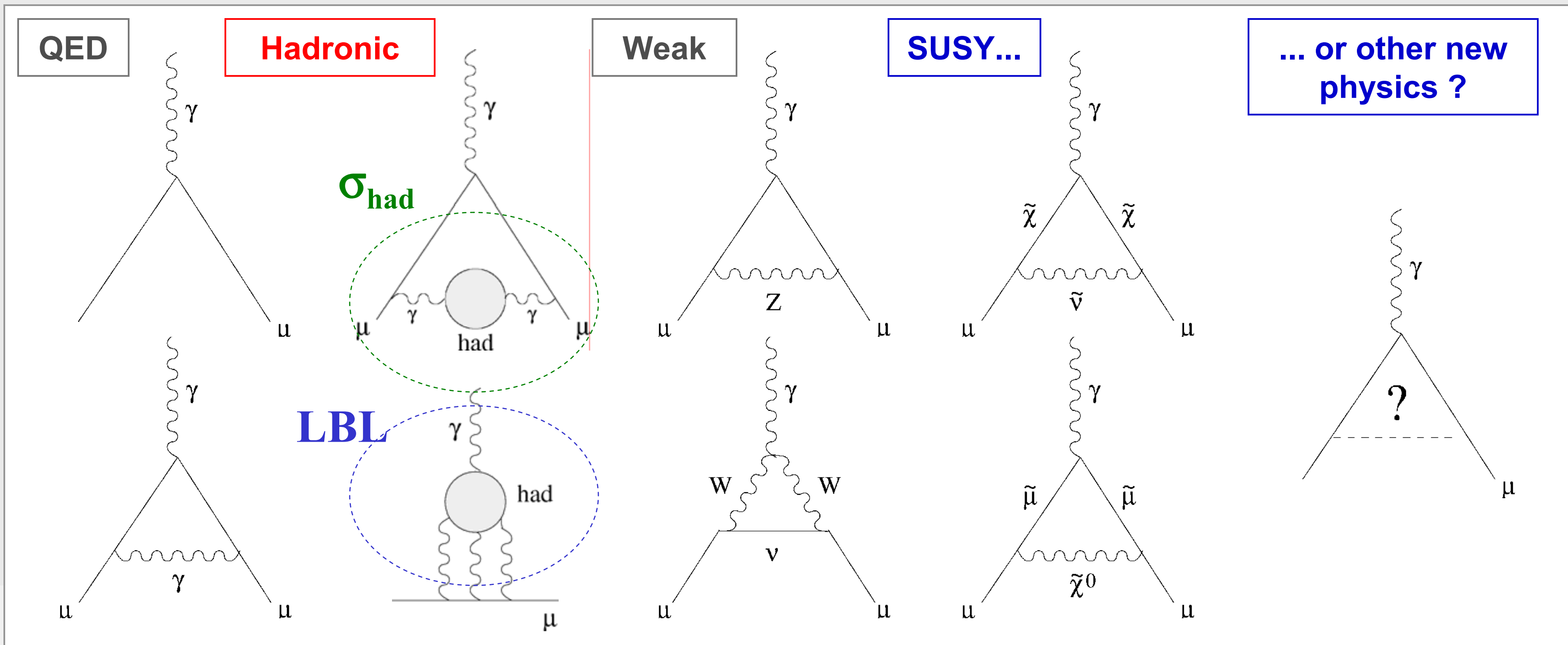
Computed up to 4th order
[Kinoshita *et al.*]
(5th order estimated [Mohr, Taylor])

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

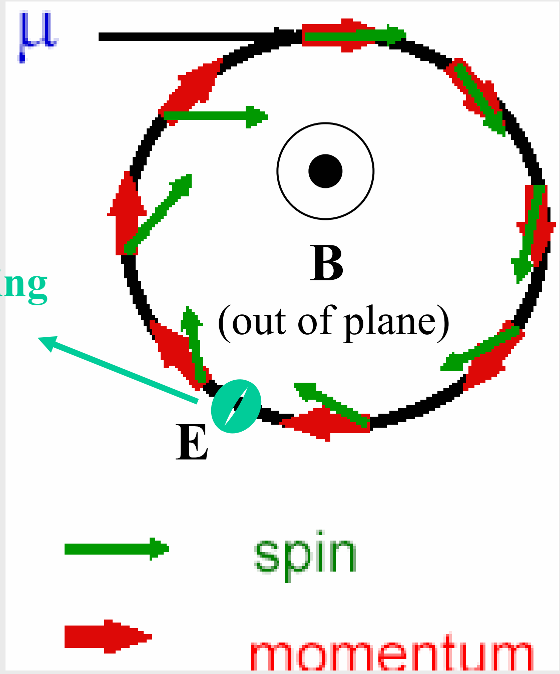
$$a_\mu^{QED} = \sum_{n=1} \left(\frac{\alpha}{\pi}\right)^n \approx \left(\begin{array}{l} 11614098.1 + 41321.8 \\ + \ 3014.2 + 38.1 + 0.6 \end{array}\right) \times 10^{-10}$$

corrected feb 04

Kinoshita-Nio,
hep-ph/0402206



Storage ring to measure a_μ



Precession of *spin* and *momentum* vectors in **E**, **B** fields (in the hyp. **β**·**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

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

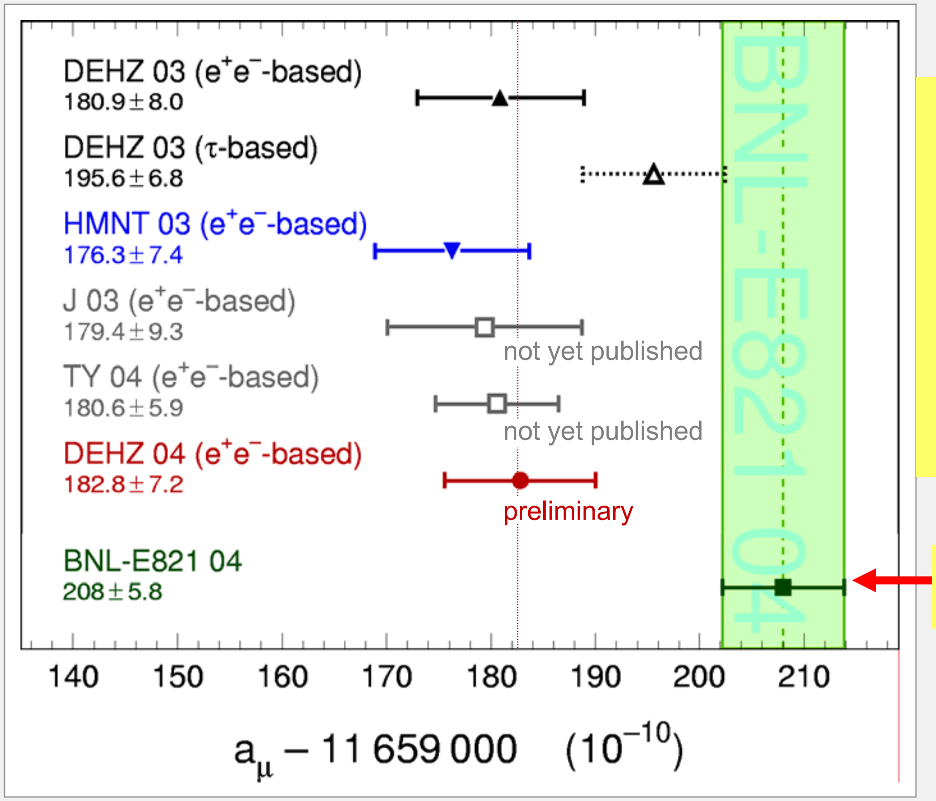
Muon anomaly (from Hoecker's presentation at ICHEP04 - Beijing)

Including **CMD2** and **KLOE** e^+e^- results

Melnikov-Vainshtein, hep-ph/0312226

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

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



Observed Difference with Experiment:

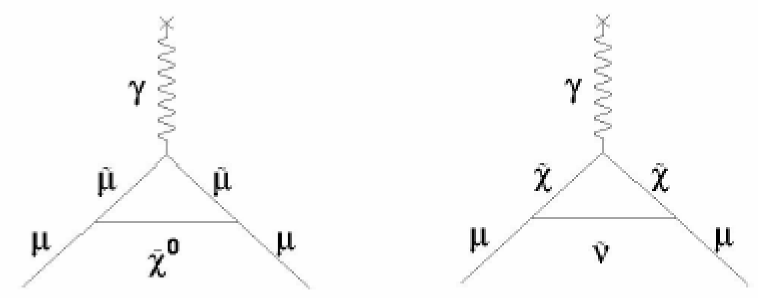
$$a_\mu^{exp} - a_\mu^{SM} = (25.2 \pm 9.2) \times 10^{-10}$$

➡ 2.7 "standard deviations" (using e^+e^- data only)

μ^+ and μ^- data combined together (CPT)

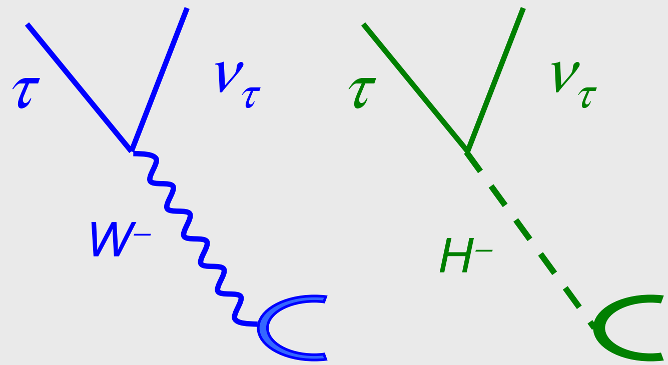
Possible new physics contribution…

- 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



LoI to J-PARC

- ✓ An experiment with sensitivity of 0.05 ppm proposed at J-PARC
- ✓ At the moment, the project is scheduled for Phase2 (>2011)
- ✓ Together with the experiment there must be an improvement on:
  - ➢ evaluation of LBL
  - ➢ experimetal data on σ(had) to cover $m(\pi)<\sqrt{s}<m(\rho)$ and $1<\sqrt{s}<2$ *GeV*

Letter of Intent: An Improved Muon $(g-2)$ Experiment at J-PARC

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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

Intermediate step on g-2 …

- As *intermediate step* between now (~ 0.6 ppm) and a future storage ring (~ 0.05) a proposal of upgrading E821, in order to reach ~ 0.2 ppm, has been submitted to BNL in July 2004 and defended Sep 9 → positive response from PAC

A $(g-2)_\mu$ Experiment to ± 0.2 ppm Precision

BNL P969

New $(g-2)_\mu$ Collaboration: R.M. Carey[1], A. Gafarov[1], I. Logashenko[1], K.R. Lynch[1], J.P. Miller[1], B.L. Roberts[1], G. Bunce[2], W. Meng[2], W.M. Morse[2], Y.K. Semertzidis[2], D. Grigoriev[3], B.I. Khazin[3], S.I. Redin[3], Yuri M. Shatunov[3], E. Solodov[3], Y. Orlov[4], P. Debevec[5], D.W. Hertzog[5], P. Kammel[5], R. McNabb[5],

Fast extracted proton beam to the V-target. 12 or 24 bunches per AGS cycle, 60 TP per cycle, minimum possible AGS cycle time.

Spokespersons:	B. Lee Roberts (roberts@bu.edu, 617-353-2187)
	David W. Hertzog (hertzog@uiuc.edu, 217-333-3988)
Resident-spokesperson:	William M. Morse (morse@bnl.gov, 631-344-3859)

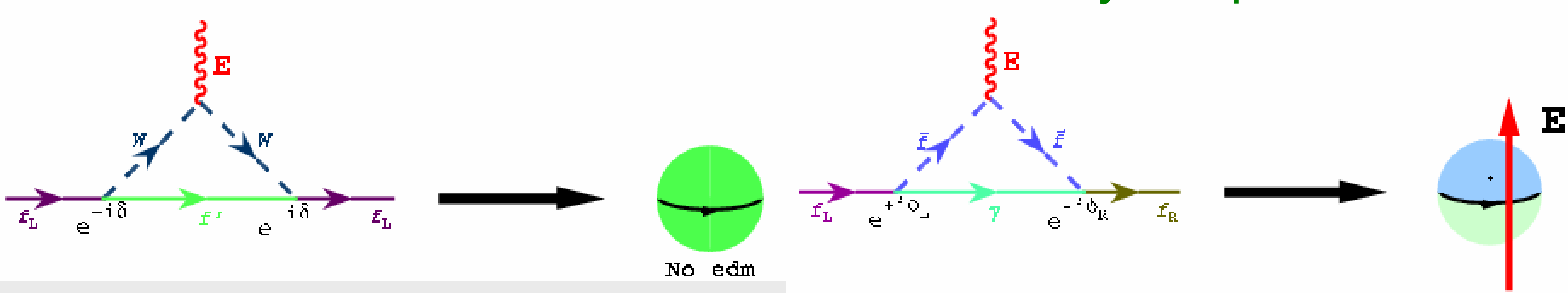
Electric Dipole Moment (EDM)

- 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

- 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

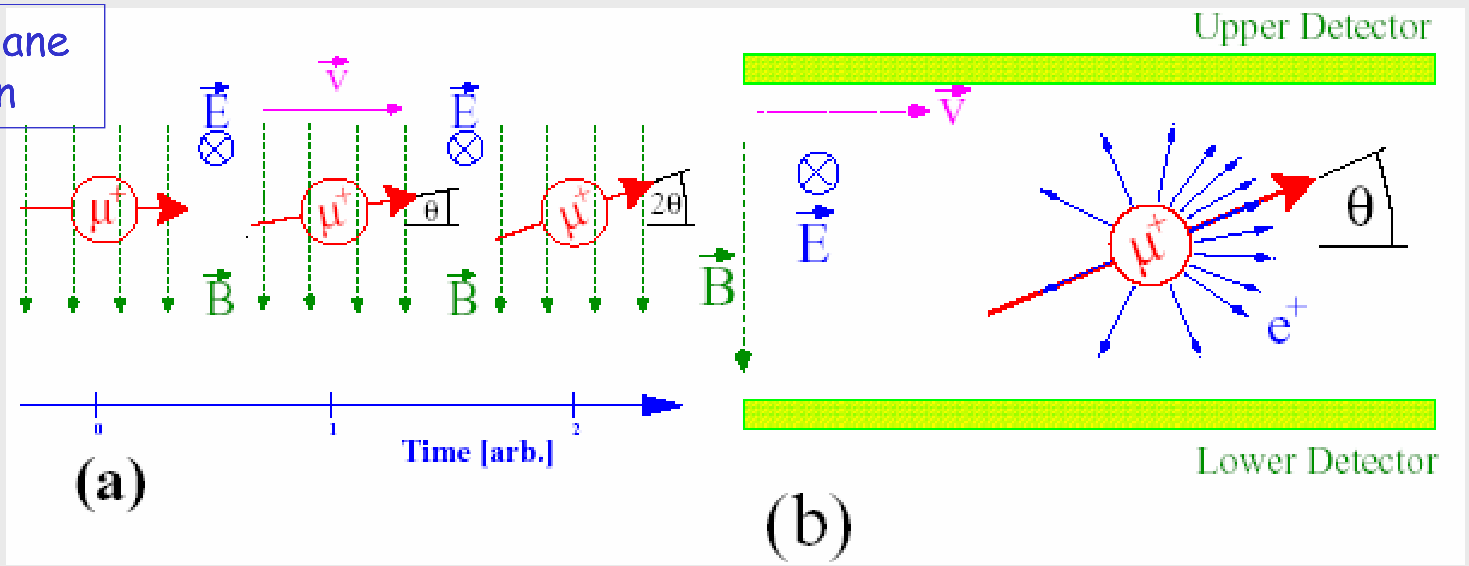
- Muons in storage ring: combination of γ, E, B that cancels out muon spin (g-2) precession (electric field E must be radial and E·β=B·β=0) ; only μEDM precession left .

$$\vec{\omega}_a \propto a_\mu \vec{B} - K(\gamma)\vec{\beta}\times\vec{E} = \left(a_\mu B - K(\gamma)\beta E\right)\hat{z} \equiv 0$$ - precession due to a_μ

$$\vec{\omega}_{EDM} = \frac{e}{mc}\frac{\eta}{2}\left(\vec{E} + \vec{\beta}\times\vec{B}\right) \approx \eta\frac{e}{2mc}\beta B\hat{r}$$ - precession due to μEDM

NO out of plane precession

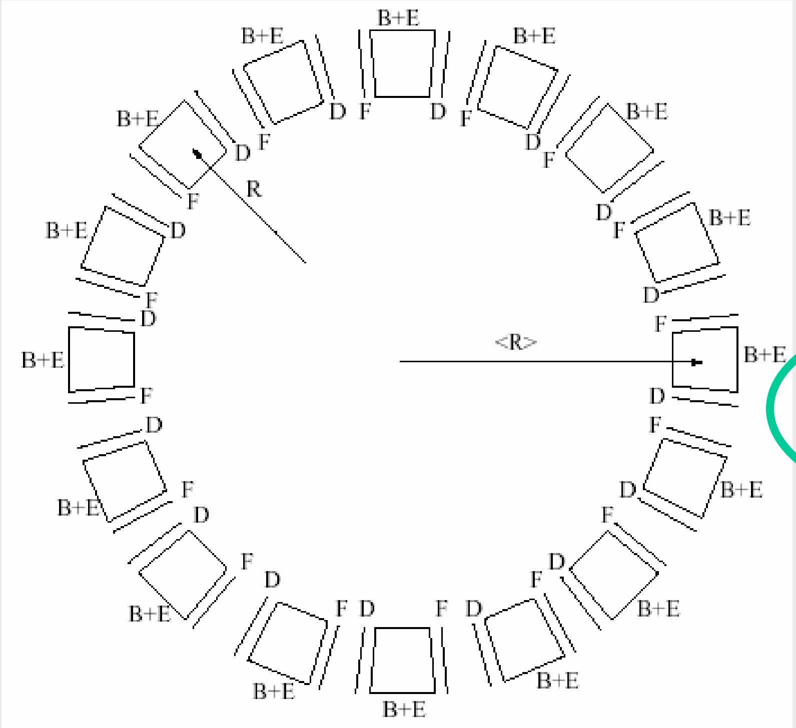
side view



Muon ring for μEDM measurement

LOI to J-PARC with following parameters:

P = 500 MeV/c
B_z = 0.25 T
E_r = 2MV/m
R = 7m
$\langle R \rangle$ = 11m
B+E = 2.6 m
Intervals = 1.7 m
n. elements = 16
circumference ~ 40m



Required statistics:

$$N_\mu \cdot P^2 = 10^{16}$$

P = Beam Polarization

- Optimal momentum choice : p_μ ~ 300-500 MeV
  - Below ~300 MeV the *muon polarization* becomes a concern
  - Above ~500 MeV the *radial electric field* needed to cancel out *g-2* precession is >20kV/cm

Systematics

- Basic idea to fight systematics: compare *clockwise* vs *counter-clockwise* results

~0 due to choice of **β,B,E**

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

Opposite sign — Same sign

cw → ccw
β → -β
B → -B
E → E

- Needs 2 injection points and possibility of changing polarity of dipole magnets (not necessary for quadrupoles)

Summary on μ-moments

- Both g-2 and μEDM are sensitive to new physics beyond the SM *(maybe behind the corner)*
- Unique opportunity of studying *phases of mixing matrix* for SUSY particles
- μEDM first direct probe of d_E on elementary particle
- The experiments are hard but, in particular the μEDM, not impossible
- A *large flux of polarized muons* of energy 3 GeV (g-2) or ~500 MeV (μEDM) is required

Lepton Flavor Violation μ decays

- Three relevant processes :

  $\mu \to e\gamma$ $\mu \to 3e$ $\mu N \to eN$

- Model Indipendent Interactions:

Dipole Transition
$$\mathcal{L} = \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \text{h.c.}$$

e.g. : slepton mixing matrix

Direct violation
$$\mathcal{L} = \frac{1}{\Lambda_F^2} \bar{\mu}_L \gamma^\mu e_L \bar{f}_L \gamma_\mu f_L + \text{h.c.}$$

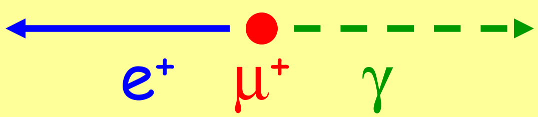
- Relative strength depends upon arbitrary parameters Λ, Λ_F
- In the hyp. $\Lambda/\Lambda_F \ll 1$, as in large class of SUSY-GUT theories:

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

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

signal

$\mu \to e\,\gamma$



$\theta_{e\gamma} = 180°$

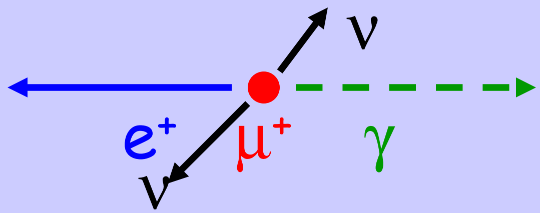
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

correlated

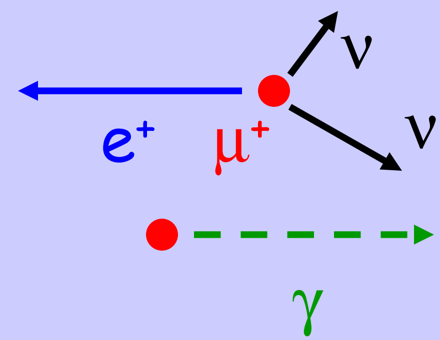
$\mu \to e\,\gamma\,\nu\,\nu$



accidental

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

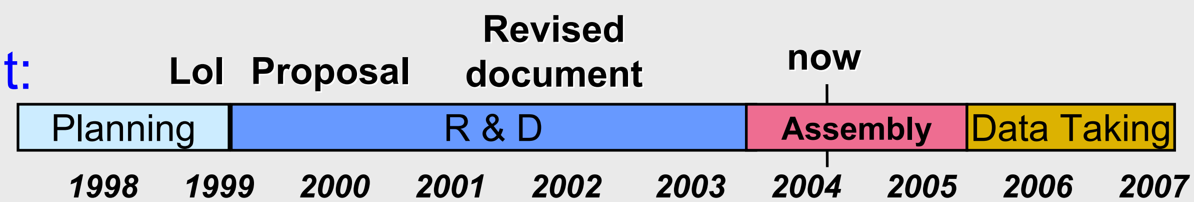
$$\begin{cases} \mu \to e\,\gamma\,\nu\,\nu \\ ee \to \gamma\,\gamma \\ eZ \to eZ\,\gamma \end{cases}$$



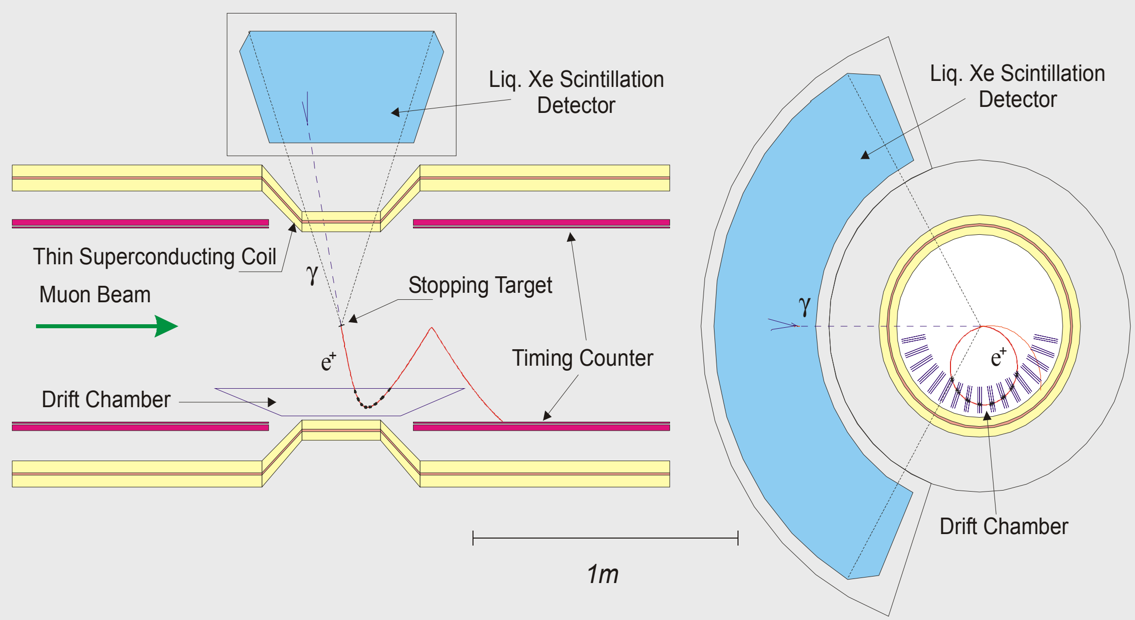
$\mu^+ \to e^+\gamma$: present

Present limit $B(\mu \to e\ ) < 1.2 \times 10^{-11}$ by the MEGA Collab. M.L.Brooks et al. Phys.Rev.Lett. 83(1999)1521

New approved experiment:
MEG @ PSI



- Stopped beam of $>10^7\ \mu$ /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



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

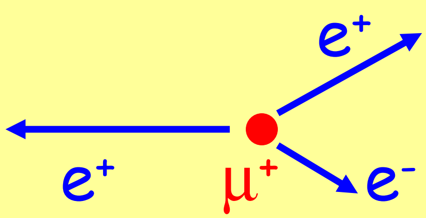
No immediate (next 10 years) need for

a more intense beam

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

signal

$\mu \to eee$



Coplanarity

Vertexing

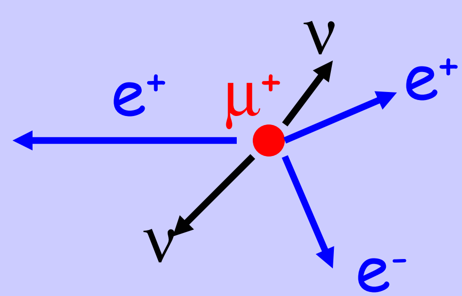
$\Sigma E_e = m_\mu$

Te+ = Te+ = Te-

background

correlated

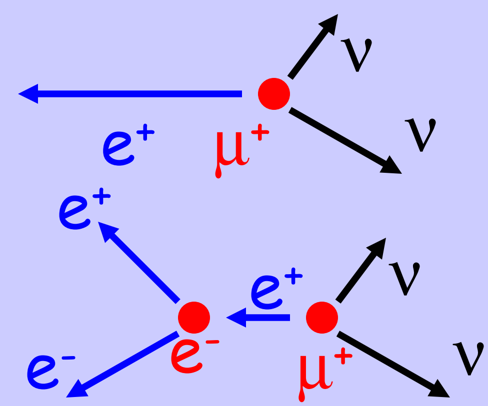
$\mu \to e\ e\ e\ \nu\ \nu$



accidental

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

$\left\{ \begin{array}{l} \mu \to e\ \nu\ \nu \\ e^+e^- \to e^+e^- \end{array} \right.$



$\mu^+ \to e^+e^+e^-$: SINDRUM I

Present limit $B(\mu \to 3e) < 1 \times 10^{-12}$ U.Bellgardt et al. Nucl.Phys. B299(1985)1

No other experimental proposal

SINDRUM I parameters

– beam intensity	$6 \times 10^6\ \mu^+/s$
– μ^+ momentum	25 MeV/c
– magnetic field	0.33T
– acceptance	24%
– momentum resolution	10% FWHM
– vertex resolution	≈ 2 mm^2 FWHM
– timing resolution	≈ ns
– target length	220 mm
– target density	11 mg/cm^2

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

- A new experiment should aim at a sensitivity of $\sim 10^{-15}$, which means to increase beam intensity by 10^3
- Technically not impossible, but uncorrelated background scales *quadratically* with the beam intensity, therefore six orders of magnitude of background reduction, wrt to SINDRUM I, is required

  $\rightarrow$ four orders of magnitude could be achieved … more?

Challenging !

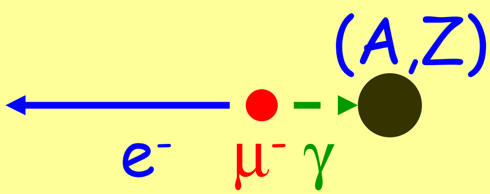
No immediate (next 10 years) need for

a more intense beam

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

signal

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

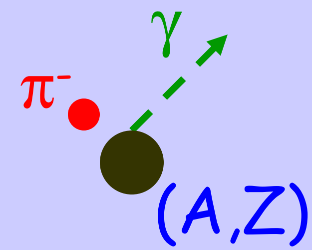


$E_e = m_\mu - E_B$

background

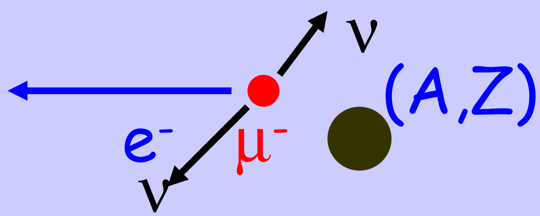
RPC

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



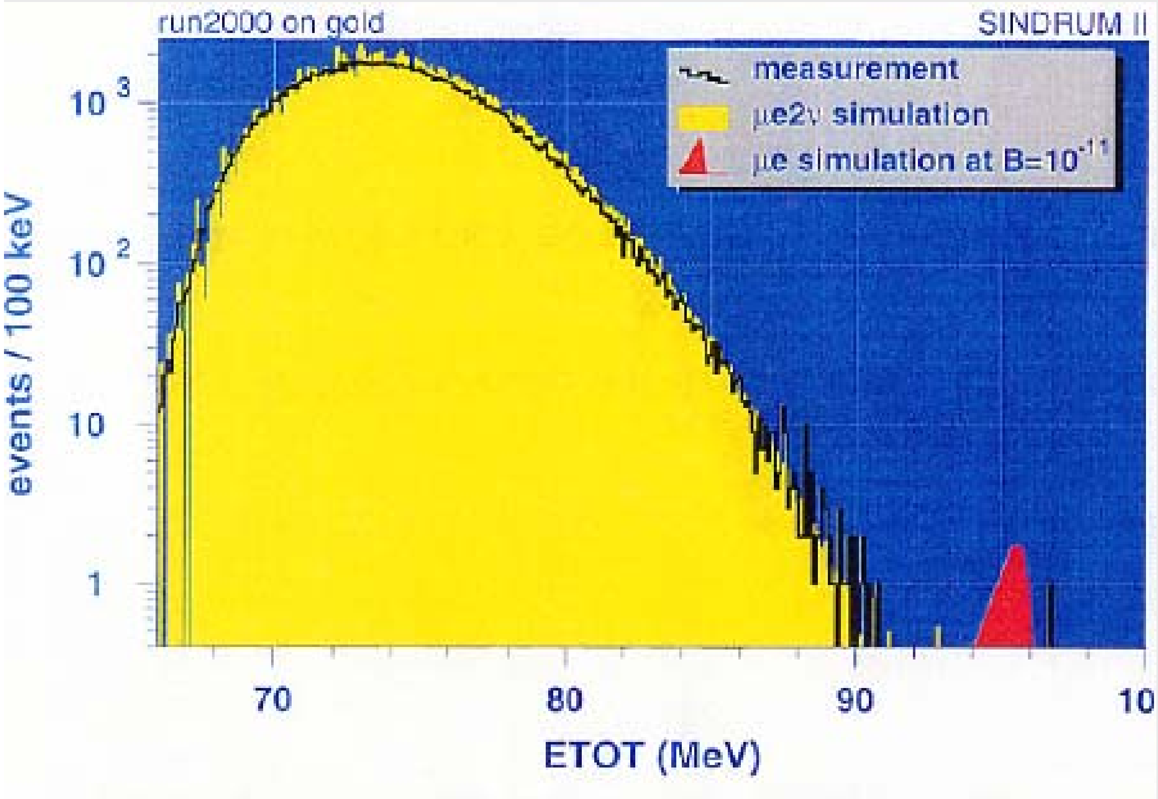
MIO

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



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

Present limit $B(\mu \to e:Au) < 8\times10^{-13}$ SINDRUM II COLLABORATION



SINDRUM II parameters

- beam intensity — $3\times10^7\ \mu^-/s$
- 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

$\mu^- \rightarrow e^-$: future

- Differently from other channels, this one is not limited by *accidentals* but by *RPC*
- Two techinques to improve beam purity proposed for two *next generation* experiments:
  - New approved experiment at BNL:

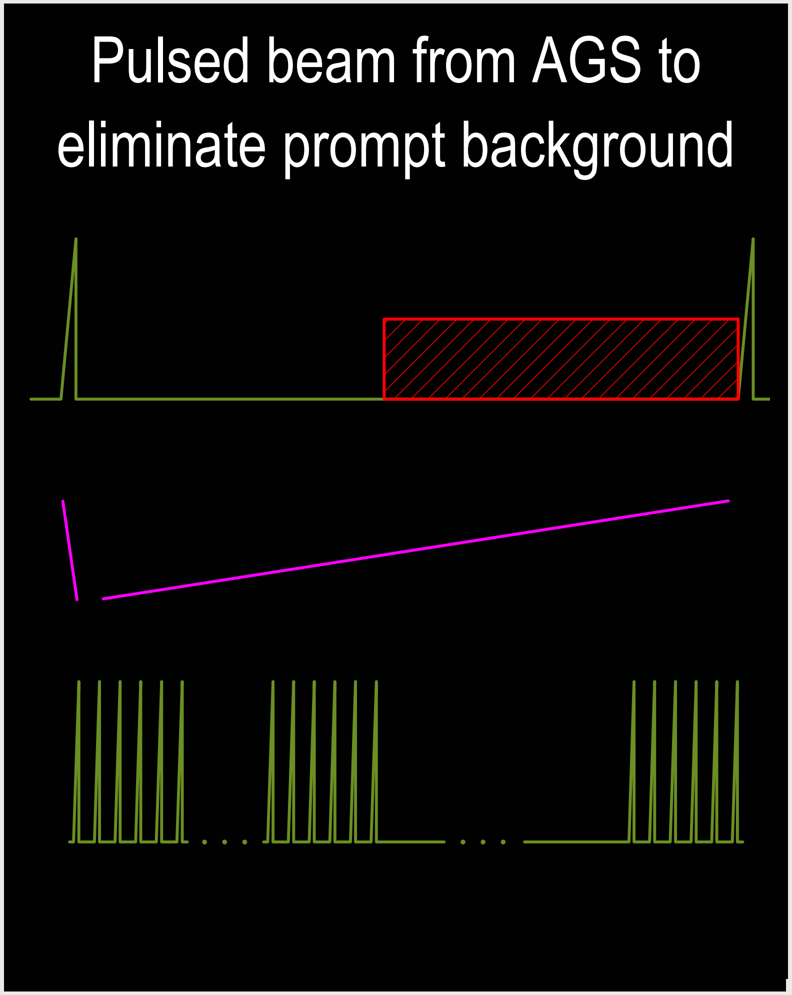
    MECO (E940) BR($\mu \rightarrow e$) < 10^{-16} (2008 ??)
  - New project LOI to J-PARC:

    PRISM/PRIME BR($\mu \rightarrow e$) < 10^{-18} (>2008 ???)

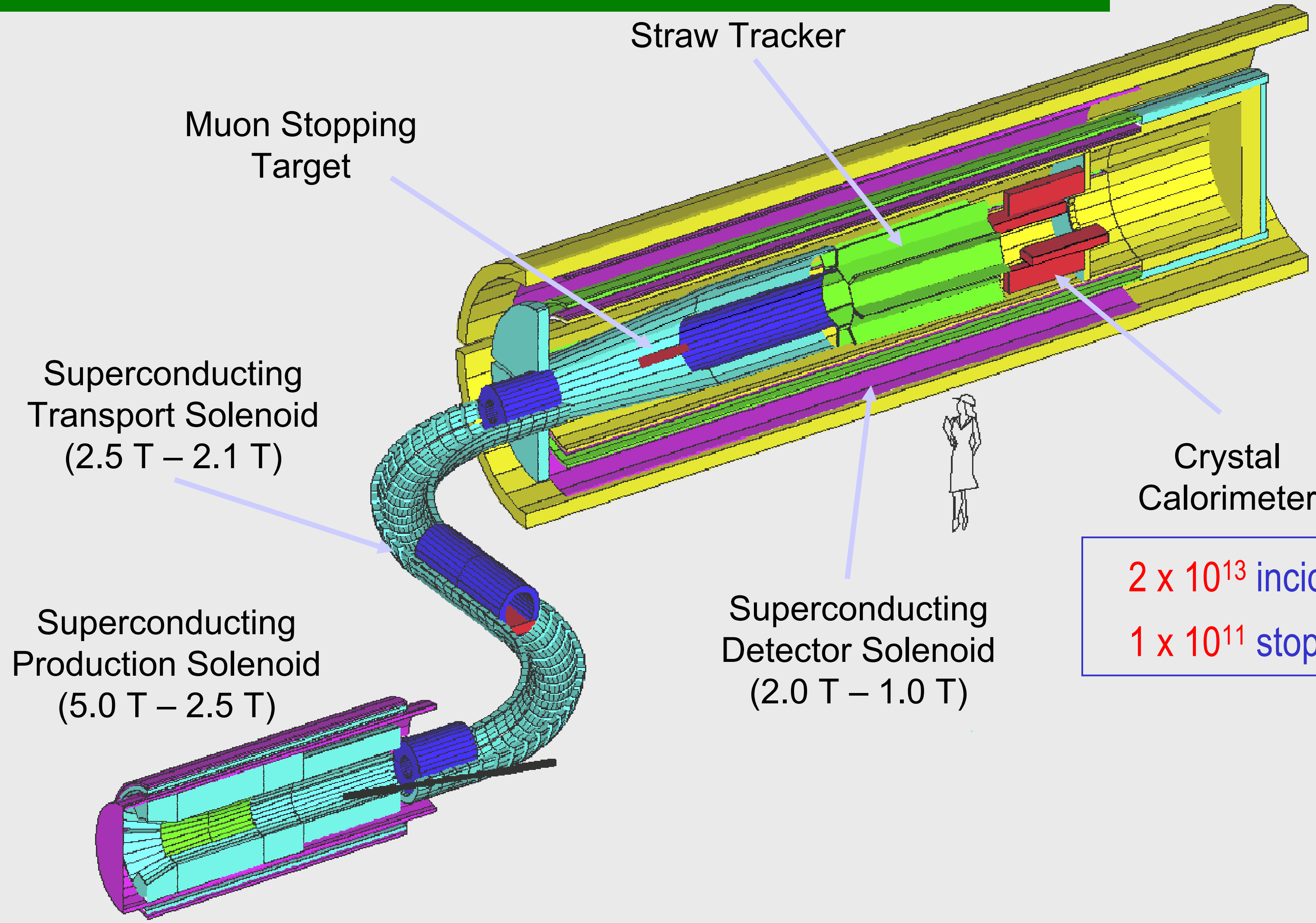
$\mu^- \rightarrow e^-$: beam line for MECO

- **New AGS beam structure:**

1. 2×10^{13} protons/bucket (7×10^{12} for *g-2* experiment)
2. Short pulses of 30nsec with 1.35 μsec separation between pulses (2 per rotation)
3. Extinction between pulses must be >10^9; fast kicker in transport will divert beam from production solenoid



$\mu^- \rightarrow e^-$: MECO detector



2×10^{13} incident p/sec

1×10^{11} stopping μ/sec

~ 5 signal events for 10^7 s (2800 hours) running **if $R_{\mu e} = 10^{-16}$**

~ 0.45 expected bckg events **if extinction factor = 10^{-9}**

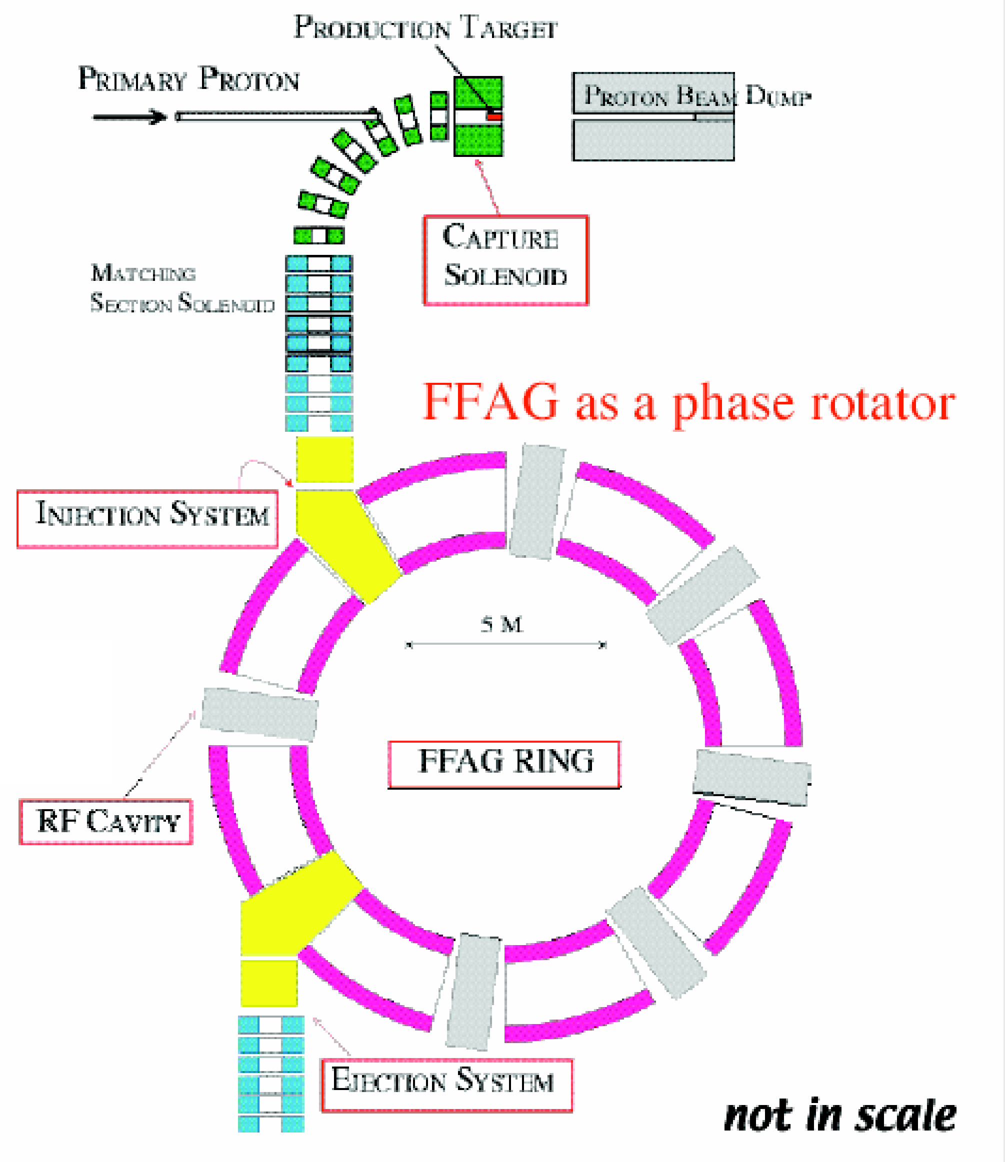
$\mu^- \rightarrow e^-$: PRISM beam

PRISM (Phase Rotated Intense Slow Muon source):

- Pion capture section
- Decay section
- Phase rotation section
- Ejection system

Machine parameters

- Intensity: 10^{11}-10^{12} $\mu^{\pm}$/sec
- Muon momentum : 68 MeV
- Momentum spread : ± 0.5-1.0 MeV
- Beam repetition : ~100 Hz



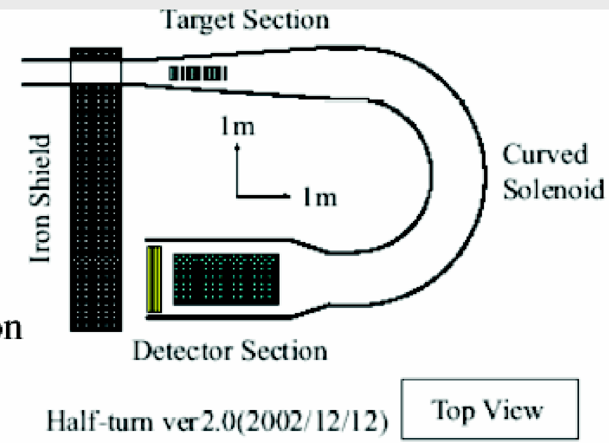
$\mu^- \rightarrow e^-$: PRIME detector

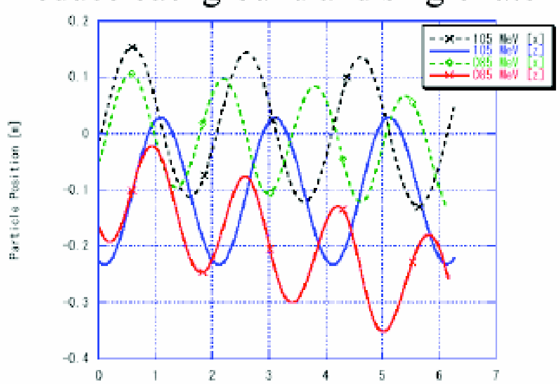
select a charged particle with a desired mom.

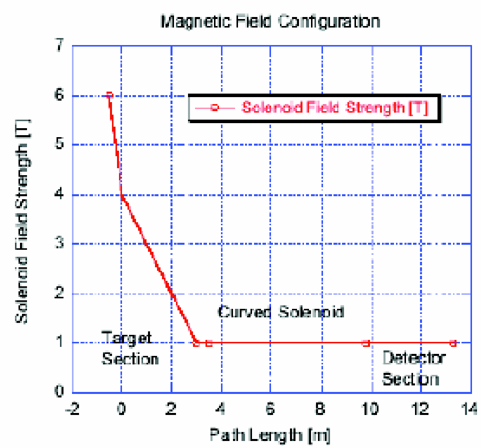
- Extract signal region only
  - Curvature drift

$$D = 1./(0.3B) \times s/R \times \frac{(p_s^2 + 0.5p_t^2)}{p_s}$$

  - impose auxiliary field along the drift direction
  - Block unwanted particles
    - Positive
    - DIO (P<90 GeV/c)
- Reduce background and single rate







- Single event sensitivity : $B(\mu^- + A \rightarrow e^- + A) \sim 6 \times 10^{-19}$

$\mu^- \rightarrow e^-$: summary

- This channel will definitely benefit from an increase in beam intensity

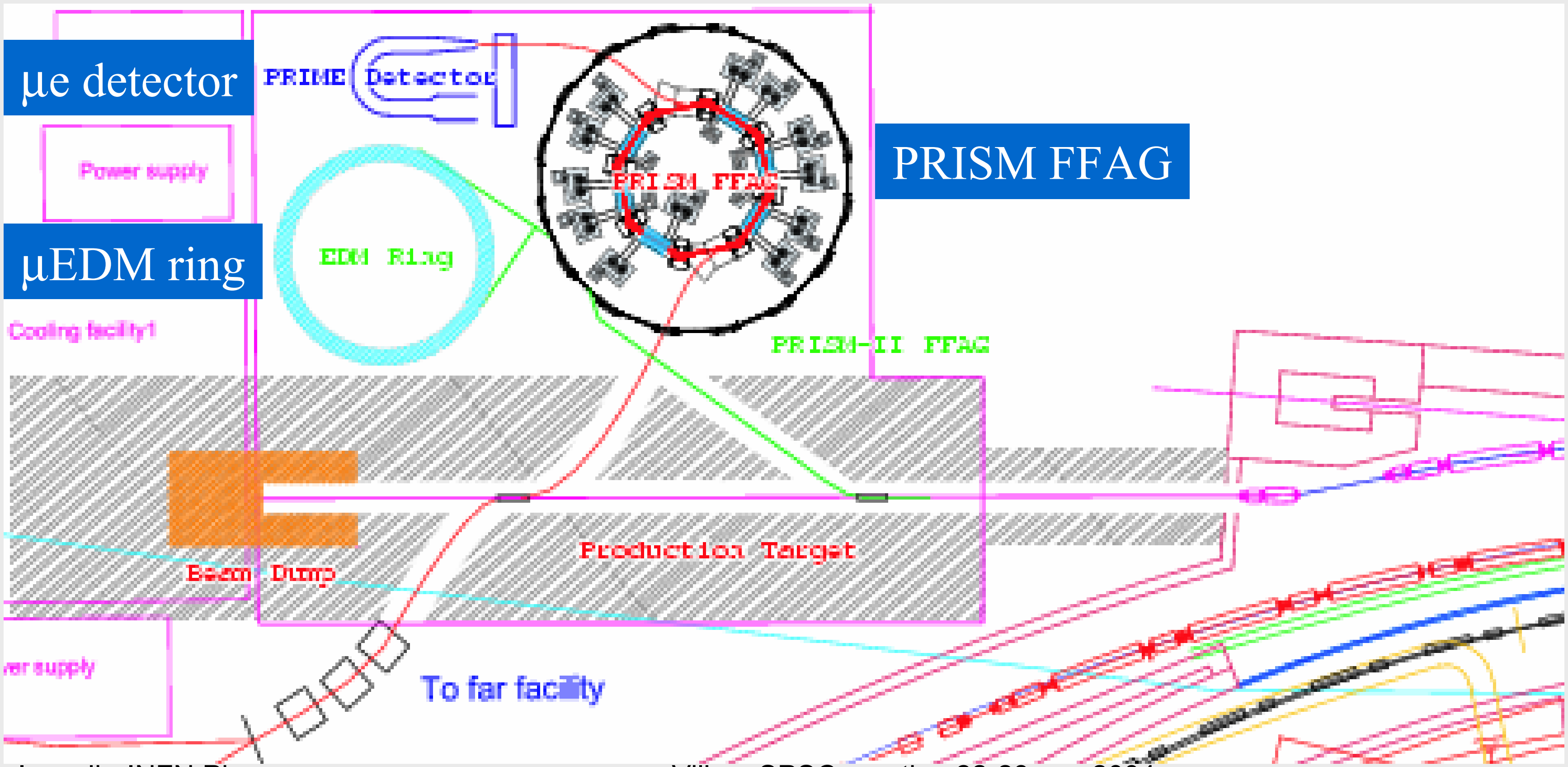
BUT

- The problem of pion contamination of the muon beam is the fundamental issue
- Two proposals :
  - Beam extinction at $<10^{-9}$ level (!) - BNL
  - New kind of muon extraction technique with circular (compact) FFAG - PRISM

Very promising channel !

μEDM and μe conversion with "same" beam?

- In μEDM LOI to J-PARC the possibility of accomodating μEDM and μe in the same hall is prospected
- The FFAG system must be projected with the possibility of providing muons both of ~80 and of ~400 MeV



Summary table and Conclusions

Experiment	N_μ	p_μ(MeV)	$\Delta p_\mu/p_\mu(\%)$	sensitivity	I_{off}/I_{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

- *Muons have historically played a key role in understanding the structure of the Standard Model* (V-A, QED tests, …)
- *Muons are fundamental tools to discover and/or to understand the structure of any physics beyond the SM*
- *All future projects* (J-PARC, Fermilab) *foresee high intensity flux of muons to be used in a storage ring and/or LFV exp.*
- **μe transitions and μEDM (also g-2) seem very promising**
- **Europe (CERN) should not loose this opportunity and aim for a leading role in the field of μ decays and μ moments**