A.M. Baldini - INFN Pisa

(particle) physics with a new high intensity low energy muon source

Layout of this talk

A community of physicists is performing/designing and proposing experiments with low energy muons

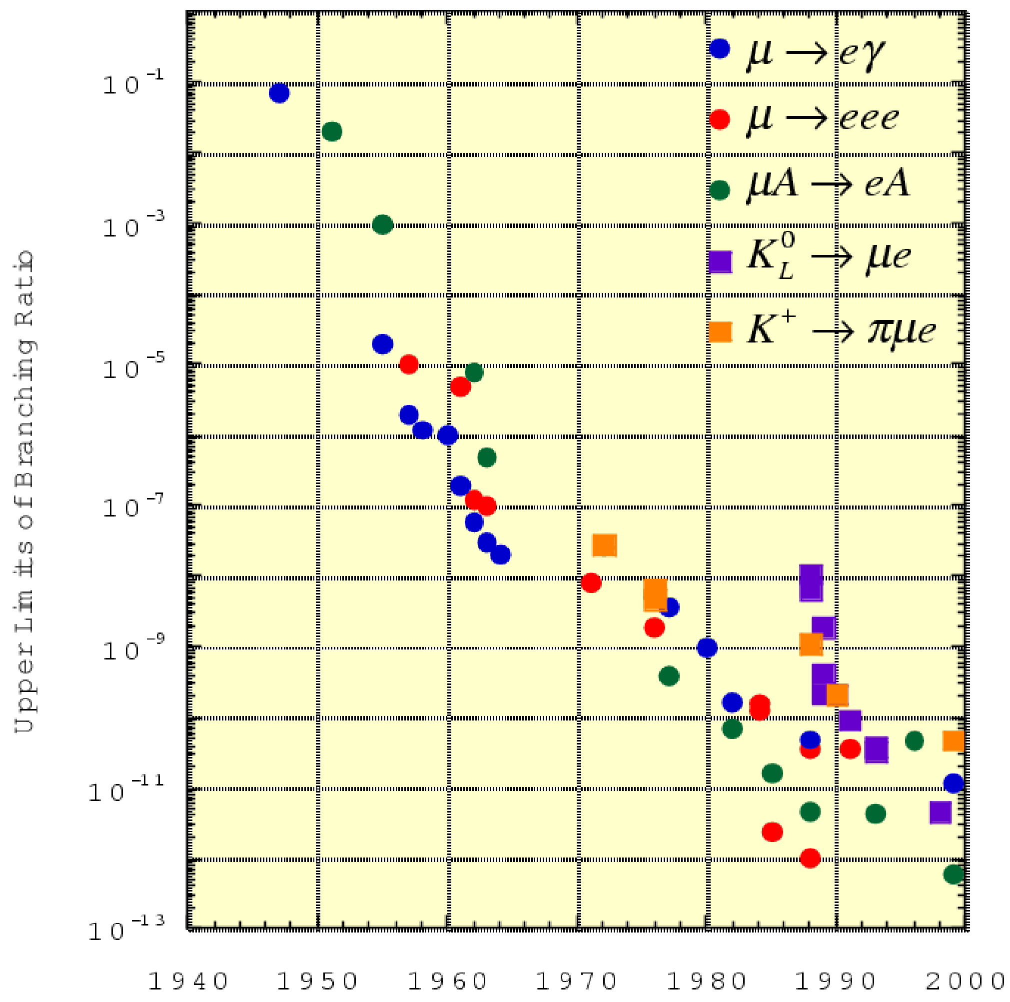
The aims:

- (C)LFV experiments (muon rare decays mainly)
- Precise measurements of muon lifetime (G_F)
- High precision experiments mesuring the carachteristics of the normal muon decay
- g-2 and EDM

What can be gained with a new high intensity muon source ? Statistics vs systematics

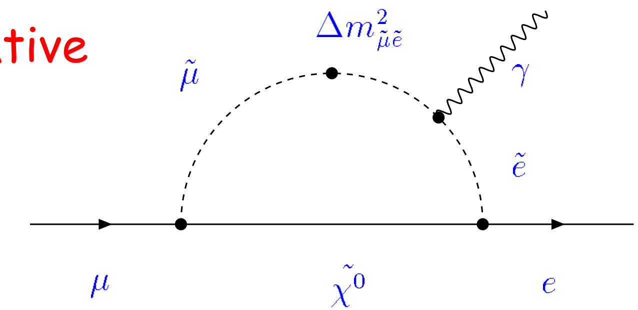
J. Aysto et al., CERN-TH/2001-231

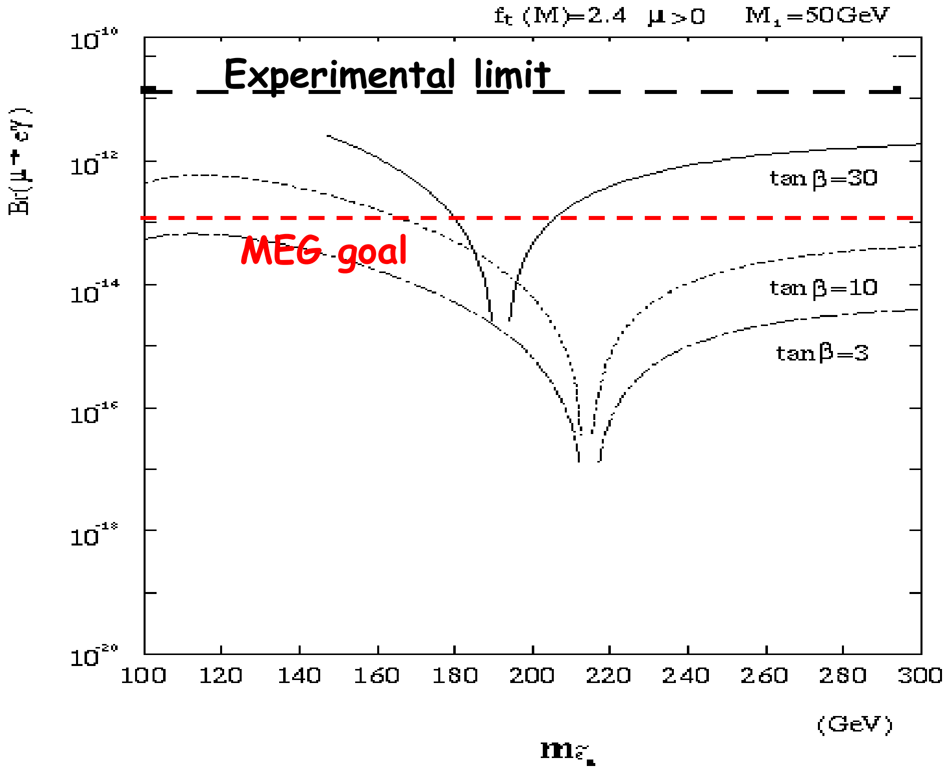
3. (C)LFV: History of rare decays searches



μ→eγ: SUGRA indications

LFV induced by finite slepton mixing through radiative corrections (big top yukawa coupling)





- SUSY SU(5) predictions

  BR (μ→eγ) ≈ $10^{-14} \div 10^{-13}$

- SUSY SO(10) predictions

  $BR_{SO(10)} \approx 100\ BR_{SU(5)}$

R. Barbieri *et al.*, Phys. Lett. B338(1994) 212

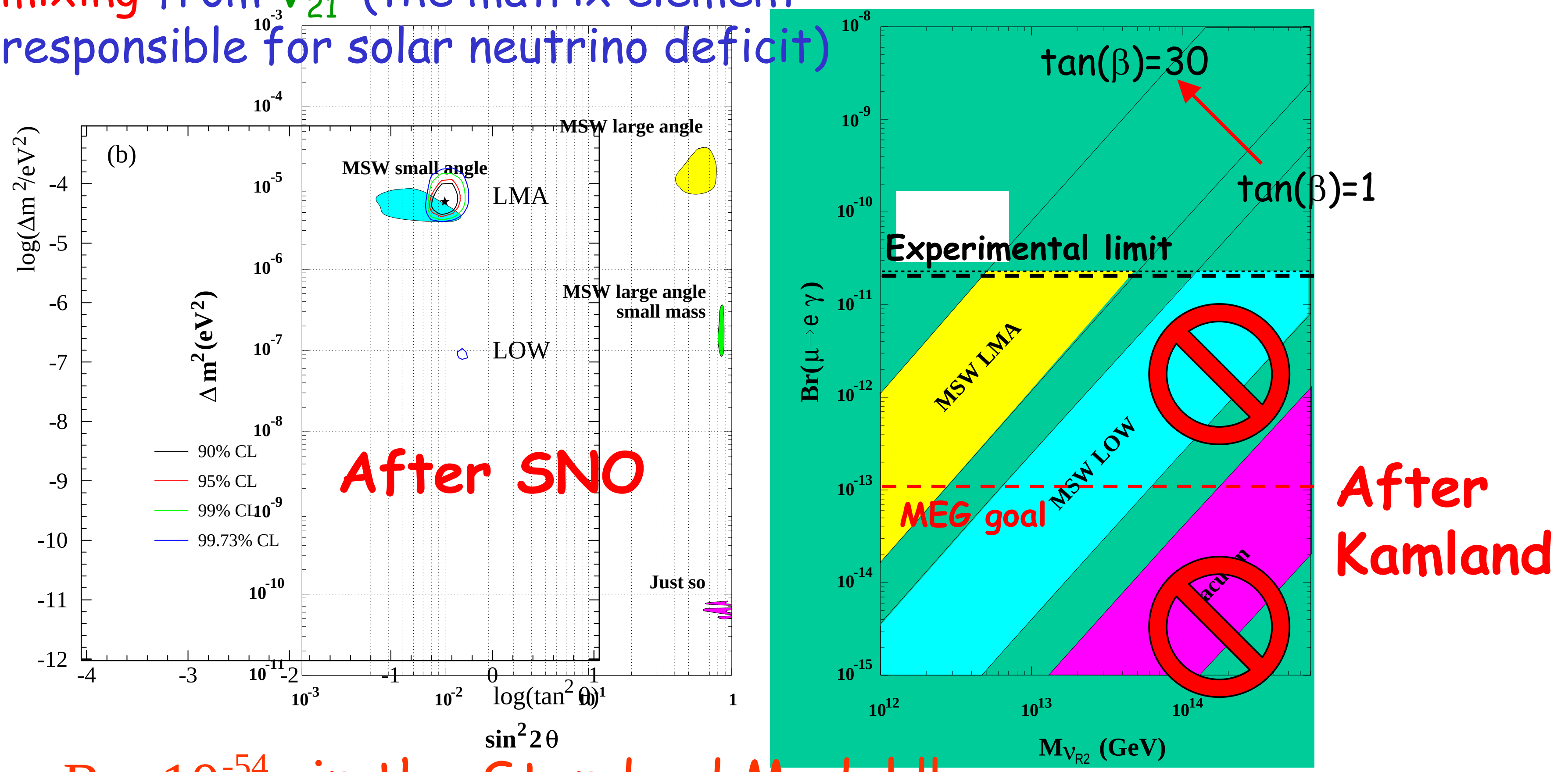
R. Barbieri *et al.*, Nucl. Phys. B445(1995) 215

combined LEP results favour tanβ>10

Connection with ν-oscillations

Additional contribution to slepton mixing from V_{21} (the matrix element responsible for solar neutrino deficit)

J. Hisano, N. Nomura, Phys. Rev. D59 (1999)

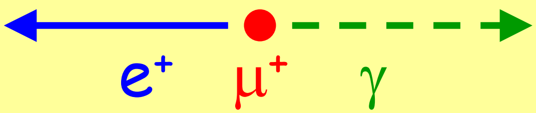


➡ $R \approx 10^{-54}$ in the Standard Model !!

Signal and background

signal

$\mu \rightarrow e\,\gamma$



$\theta_{e\gamma} = 180°$

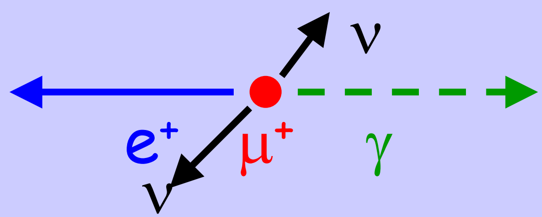
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

physical

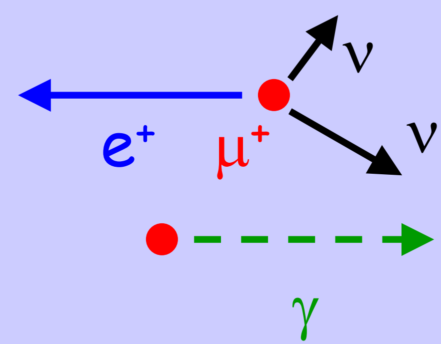
$\mu \rightarrow e\,\gamma\,\nu\,\nu$



accidental

$\mu \rightarrow e\,\nu\,\nu$

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



Required Performances

Even with the best possible detectors the sensitivity is limited by the by the accidental background

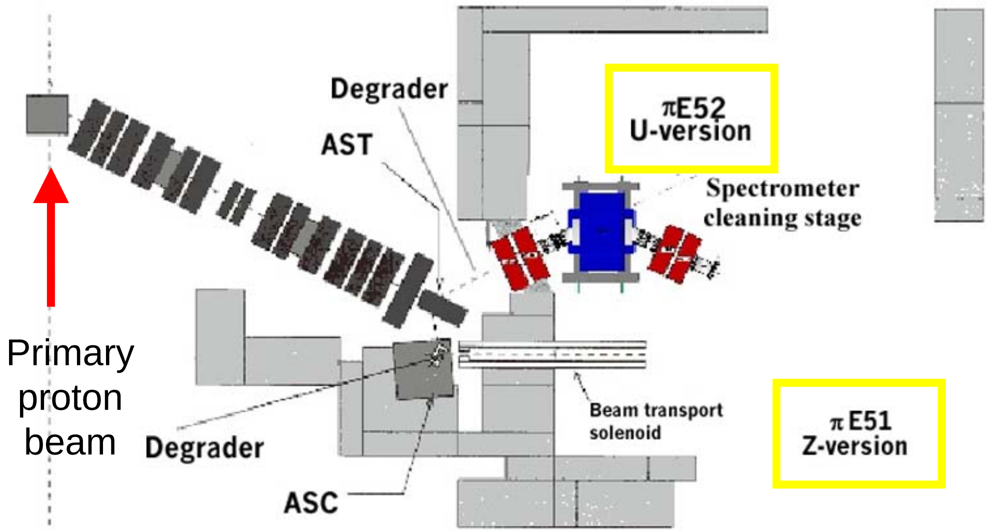
The $BR_{acc} \propto R_\mu \times \Delta E_e \times \Delta E_\gamma^2 \times \Delta\theta_{e\gamma}^2 \times \Delta t_{e\gamma} \approx 3\times10^{-14}$

FWHM

Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5×10^5	100	3.6×10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2×10^5	100	1×10^{-9}
LANL	1979	8.8	8	1.9	37	2.4×10^5	6.4	1.7×10^{-10}
Crystal Box	1986	8	8	1.3	87	4×10^5	(6..9)	4.9×10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5×10^8	(6..7)	1.2×10^{-11}
MEG	2007	0.8	4	0.15	19	2.5×10^7	100	1×10^{-13}

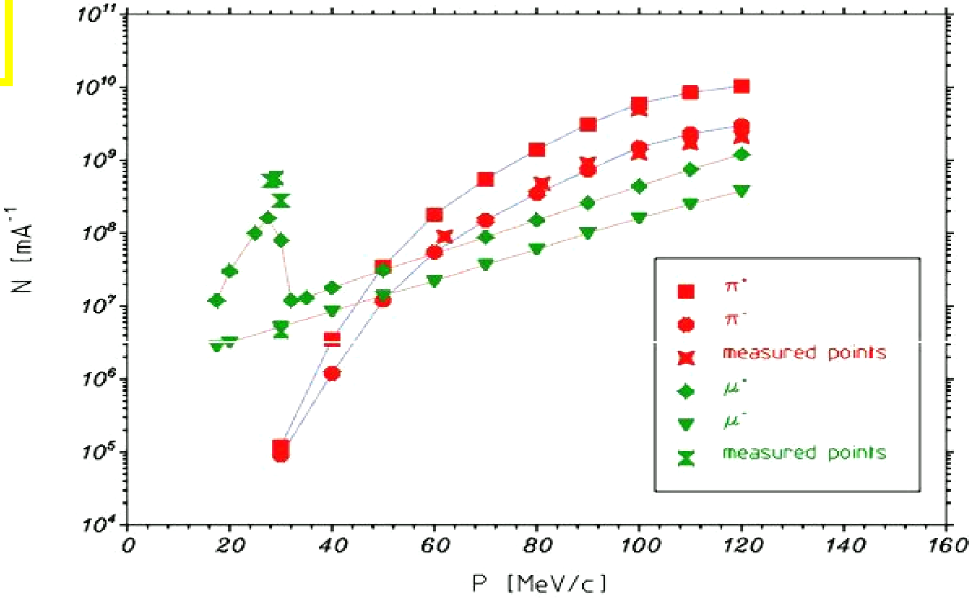
Need of a DC beam

The PSI πE5 surface muon beam



The layout of πE5

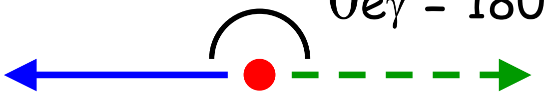
- 1.8 mA of 590 MeV/c protons (1.1 MW)
- 30 MeV/c muons from π stop at rest
- DC beam (≈ 10^8 μ/s)



The MEG experiment at PSI

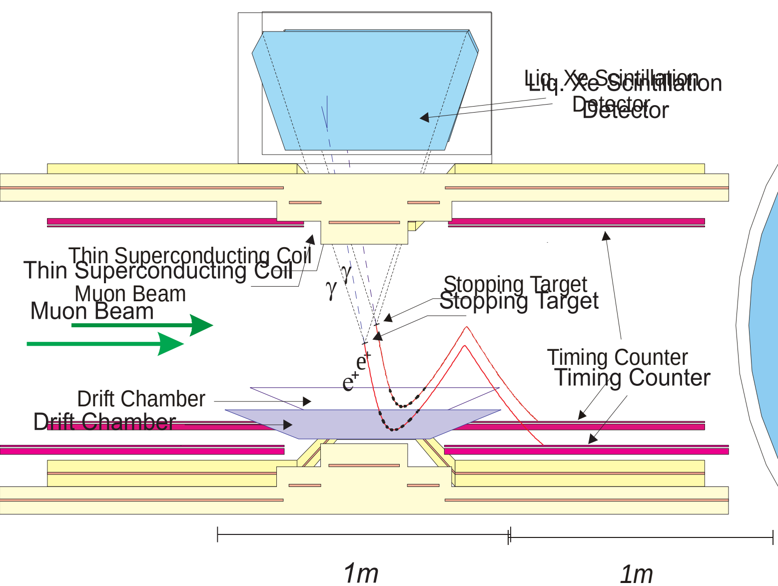
Easy signal selection with μ^+ at rest

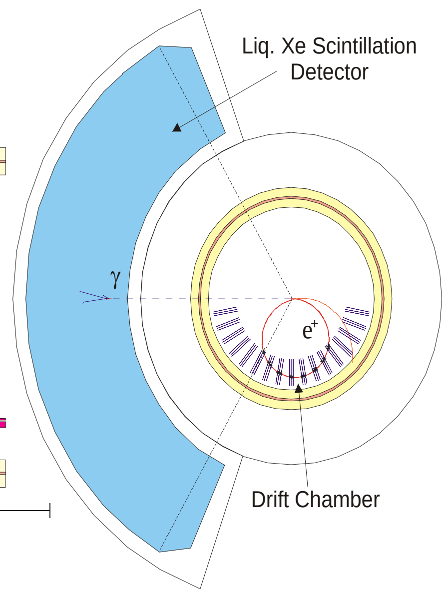
$\theta_{e\gamma}$ = 180°



e^+ μ^+ γ

$E_e = E_\gamma$ = 52.8 MeV





Detector outline

- Stopped beam of $>10^7$ μ /sec in a 150 μm target
- Liquid Xenon calorimeter for γ detection (scintillation)
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- Solenoid spectrometer & drift chambers for e^+ momentum
- Scintillation counters for e^+ timing

$\mu^+ \to e^+\gamma$: MEG sensitivity summary

Detector parameters $T = 2.6 \cdot 10^7\, s \qquad R_\mu = 0.3 \cdot 10^8\, \mu/s \qquad \frac{\Omega}{4\pi} = 0.09$

$\varepsilon_e \approx 0.9 \qquad \varepsilon_{sel} \approx (0.9)^3 = 0.7 \qquad \varepsilon_\gamma \approx 0.6$

Cuts at 1,4×FWHM

Signal $N_{sig} = BR \cdot T \cdot R_\mu \cdot \frac{\Omega}{4\pi} \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel}$

Single Event Sensitivity $SES = 1 \Big/ T \cdot R_\mu \cdot \frac{\Omega}{4\pi} \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_{sel} \approx 4 \times 10^{-14}$

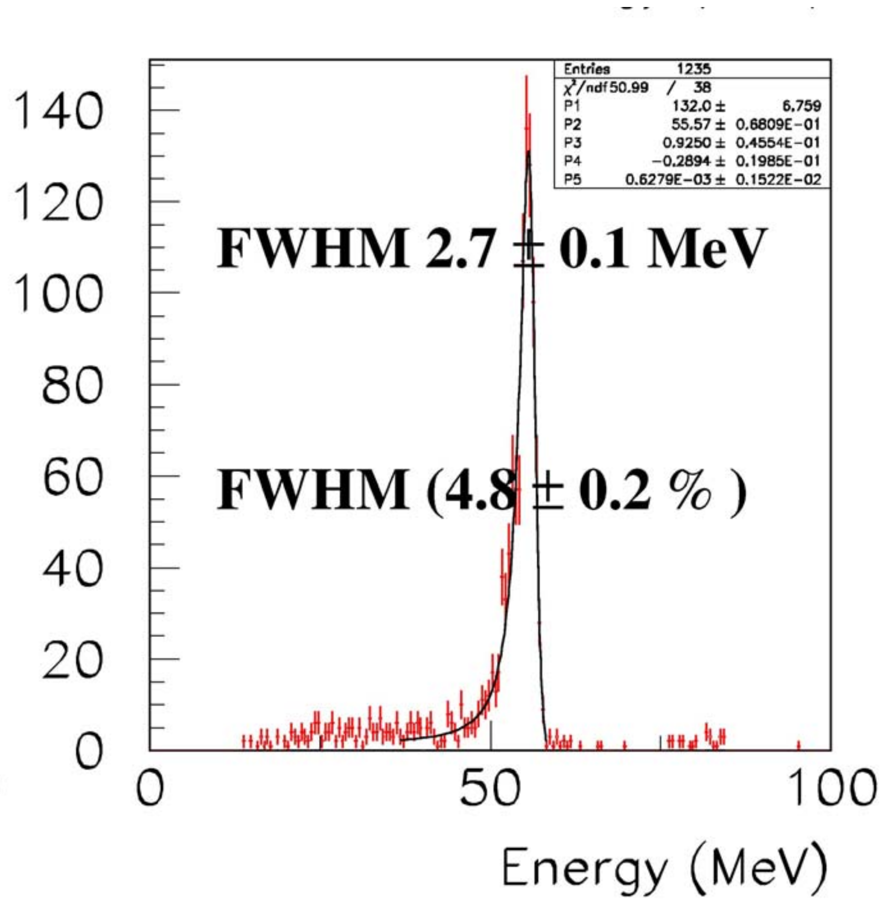
Backgrounds $BR_{acc} \propto R_\mu^2 \times \Delta E_e \times \Delta E_\gamma^2 \times \Delta\theta_{e\gamma}^2 \times \Delta t_{e\gamma} \approx 3 \times 10^{-14}$

$BR_{corr} \approx 3 \times 10^{-15}$

Upper Limit at 90% CL $BR\,(\mu \to e\gamma) \approx 1 \times 10^{-13}$

Discovery 4 events (P = 2×10^{-3}) correspond $BR = 2 \times 10^{-13}$

MEG recent e.m. calorimeter result



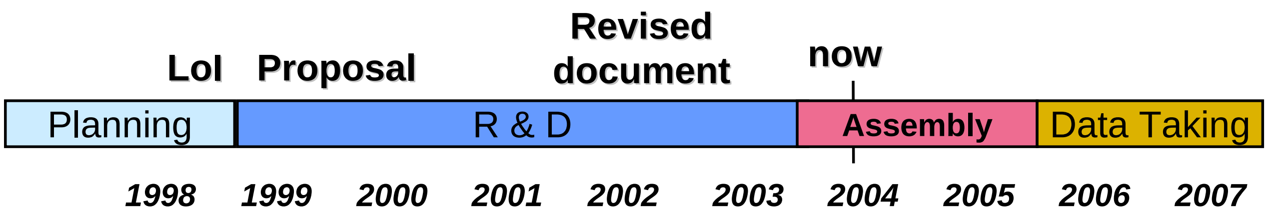
$\pi^- p \rightarrow \pi^0 n$ **and** $\pi^0 \rightarrow \gamma\,\gamma$

4.8 % FWHM

with: R < 1.5 cm

D from wall > 3 cm

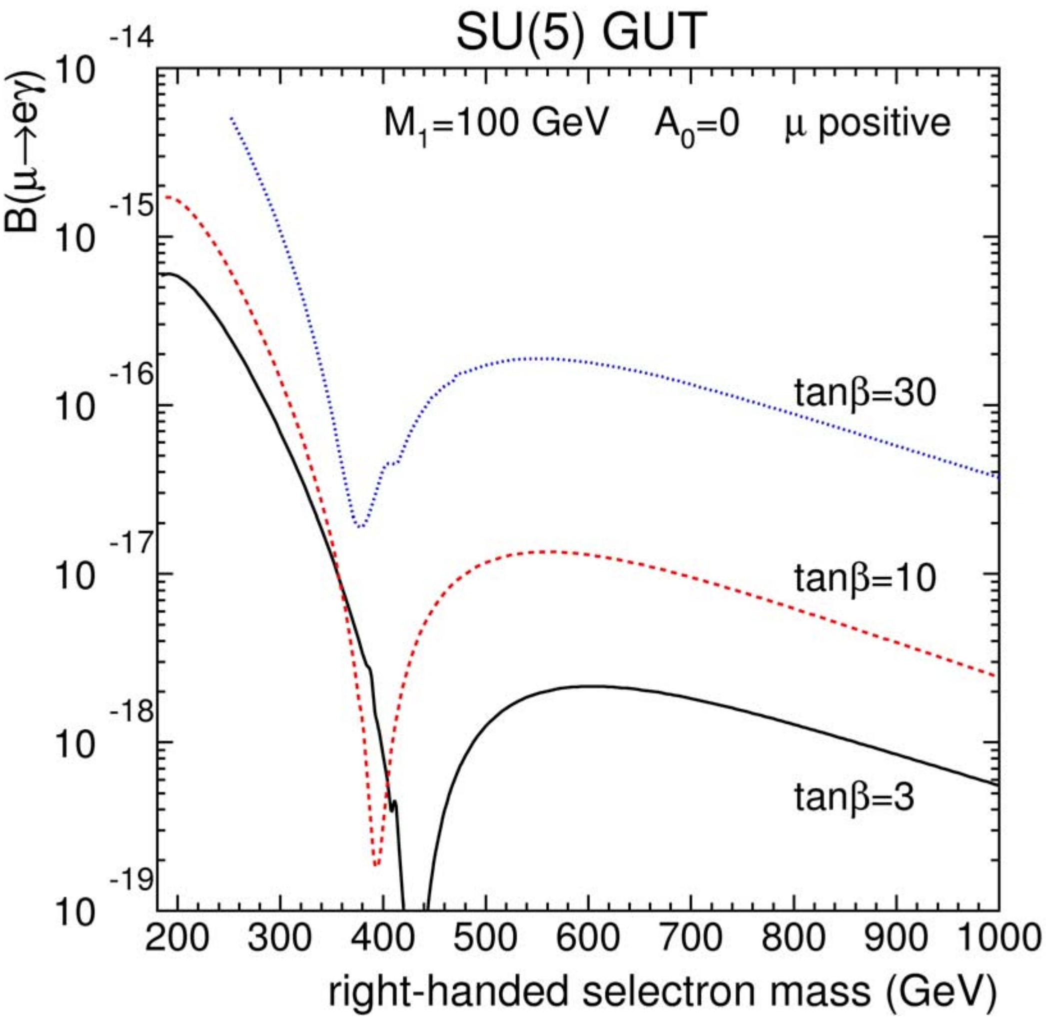
$\mu^+ \to e^+ \gamma$: MEG time profile



More details at

http://meg.psi.ch
http://meg.pi.infn.it
http://meg.icepp.s.u-tokyo.ac.jp

It would (obviously) be nice to explore lower BRs !



Accidental background limited ➔ Sensitivity is not improved by a simple muon intensity increase

(same thing for μ➔3e)

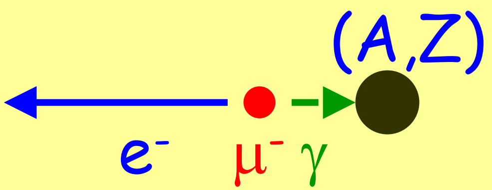
Need of much better detectors to reach a

10^{-15} sensitivity

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

signal

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



$E_e = m_\mu - E_B$

main backgrounds

MIO

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

RPC

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

Beam related background

Calculation of $B_{\mu^- e}/B_{\mu\to e\gamma}$

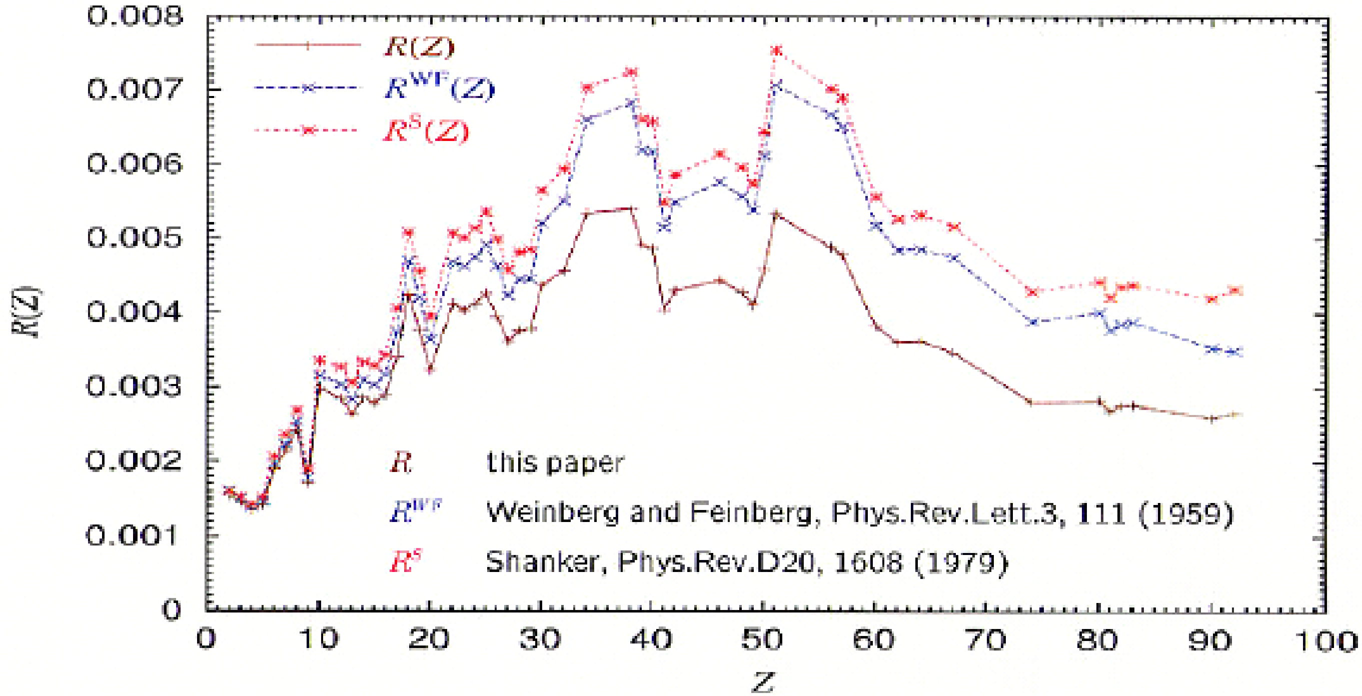
the nuclear dependence

Phys.Rev.D**66**, 096002 (2002)

Ryuichiro Kitano, Masafumi Koike, and Yasuhiro Okada:

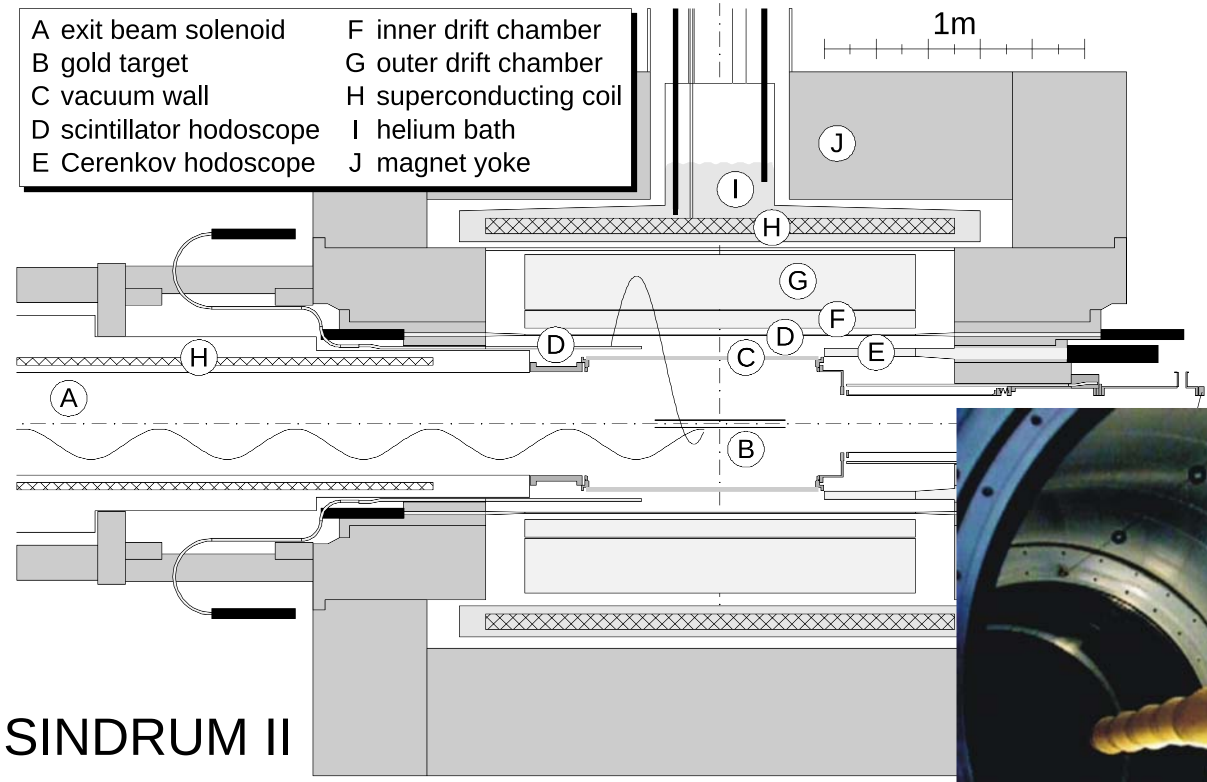
Detailed calculation of lepton flavor violating muon-electron conversion rate for various nuclei

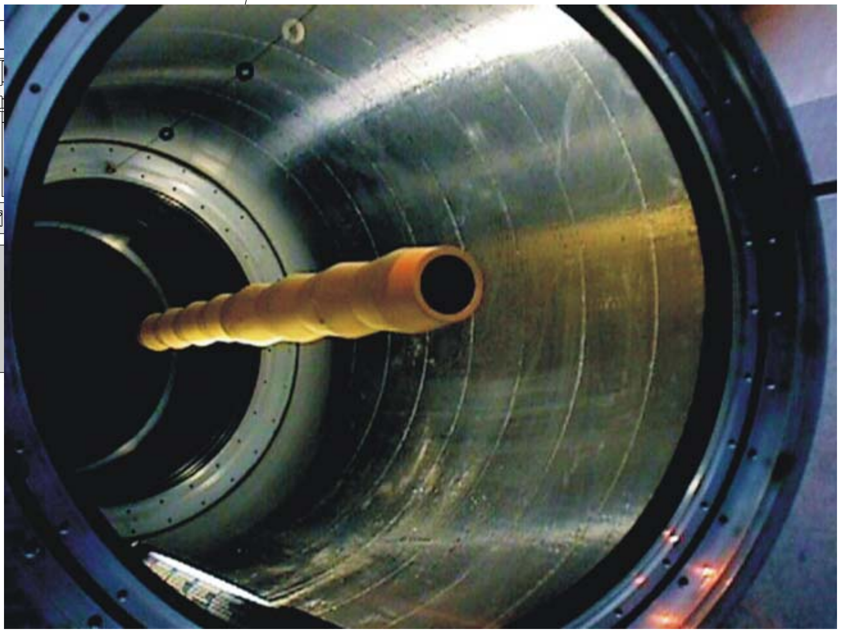
$R \equiv B_{\mu e}/B_{\mu\to e\gamma}$



These results are valid for a photonic dipole operator as found in many SUSY models.

$\mu^- \rightarrow e^-$: SINDRUM II detector





Beam related background

strategies against beam-related background

1985	TRIUMF	beam counter
1993	PSI μE1	beam counter
2000	PSI πE5	beam quality ←
2006	BNL AGS	pulsed beam
2010	ν-factory (PRISM)	pulsed/quality

Moderator: range π about $\frac{1}{2}$ range μ

beam quality means:

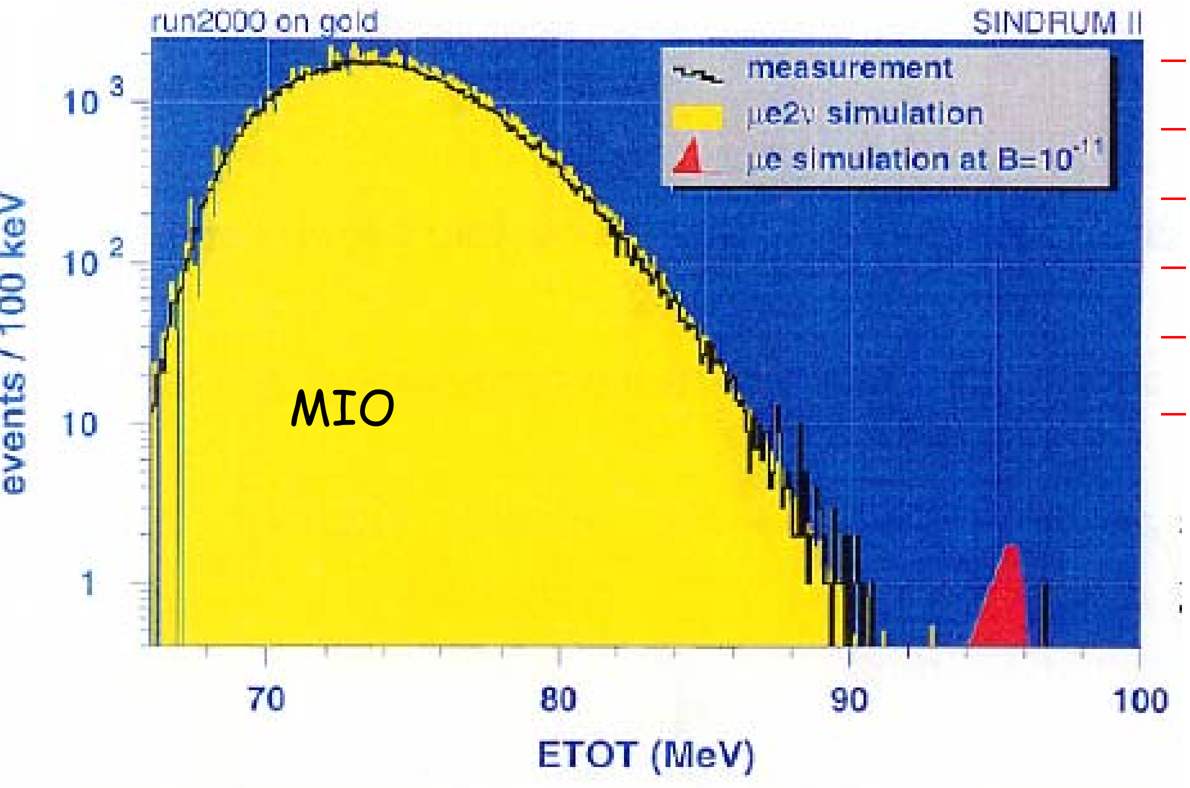
- radiative π^- capture followed by $\gamma \to e^+e^-$ conversion

  at most 10^5 pions may stop in the target during the full measurement

- μ^- decay in flight

  beam momentum has to be below 60 MeV/c

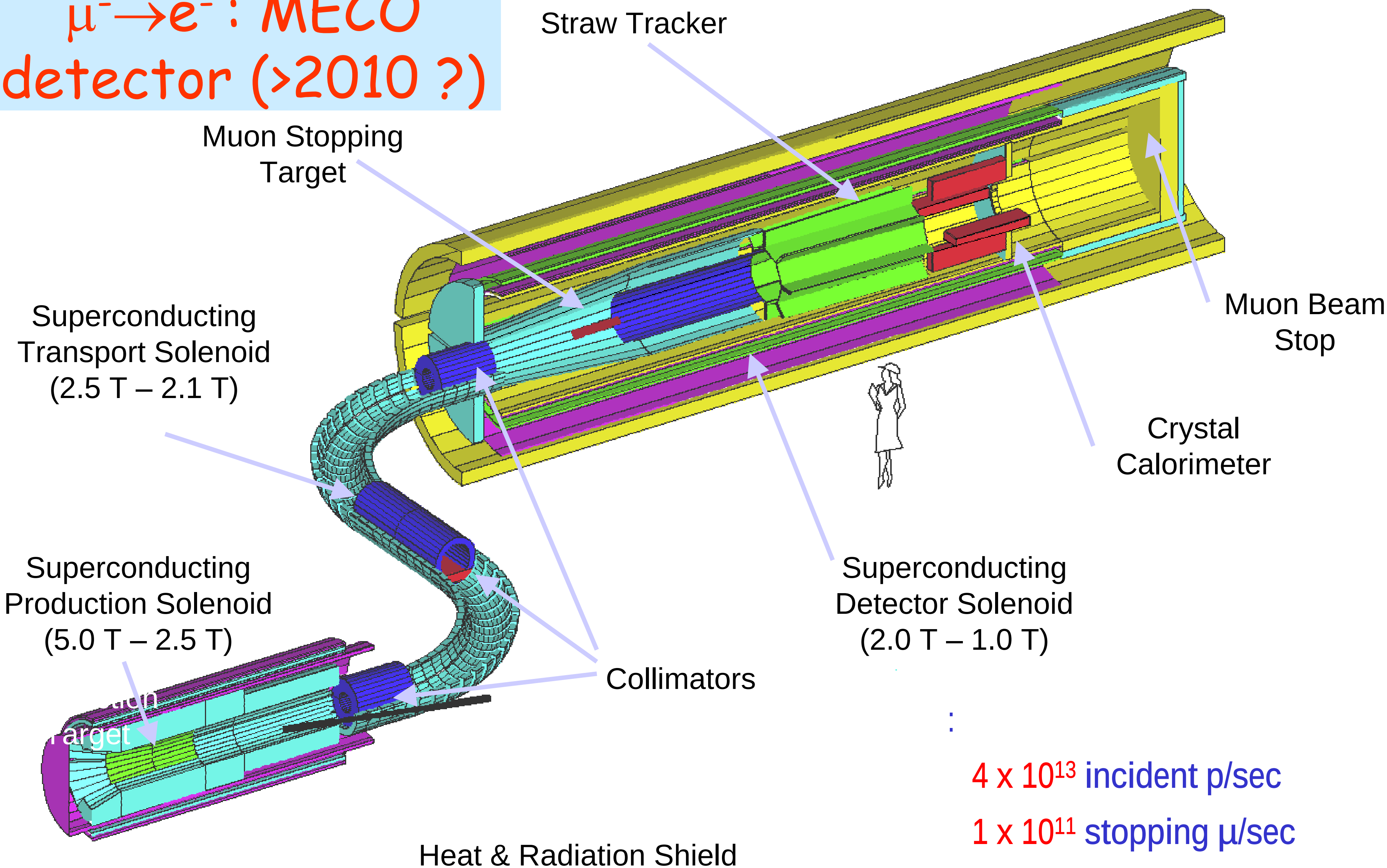
$\mu^- \rightarrow e^-$: SINDRUM II result



SINDRUM II parameters

- beam intensity — $3 \times 10^7\ \mu^-/s$
- μ^- momentum — 53 MeV/c
- magnetic field — 0.33T
- acceptance — 7%
- momentum res. — 2% FWHM
- S.E.S — 3.3×10^{-13}
- $B(\mu \rightarrow e{:}Au)$ — 8×10^{-13}

$\mu^- \rightarrow e^-$: MECO detector (>2010 ?)



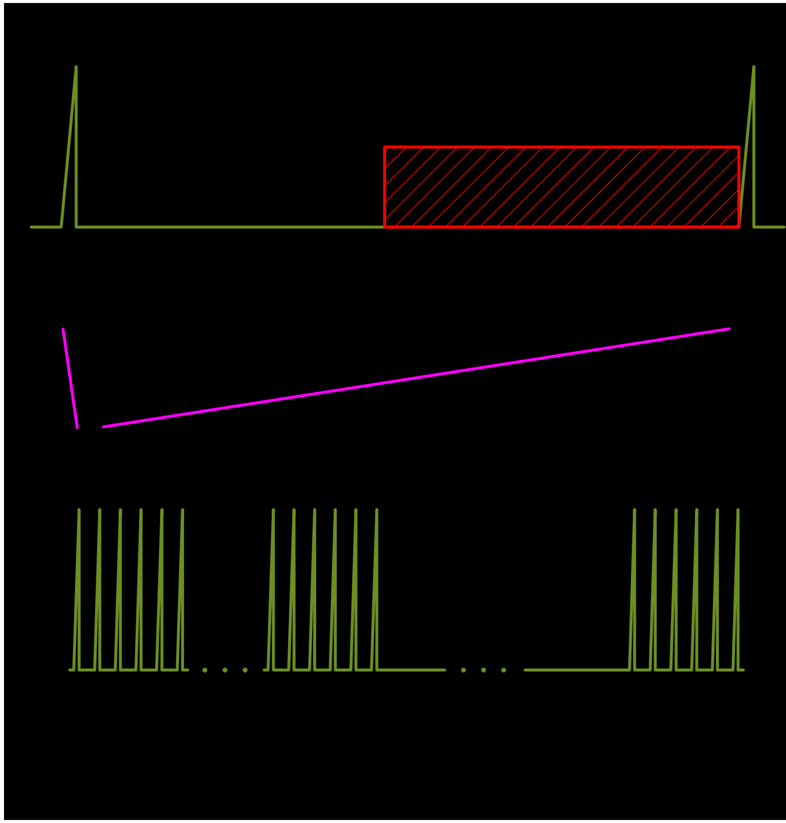
4×10^{13} incident p/sec

1×10^{11} stopping μ/sec

$\mu^- \rightarrow e^-$: MECO Proton Beam

Pulsed beam from AGS to eliminate prompt backgrounds

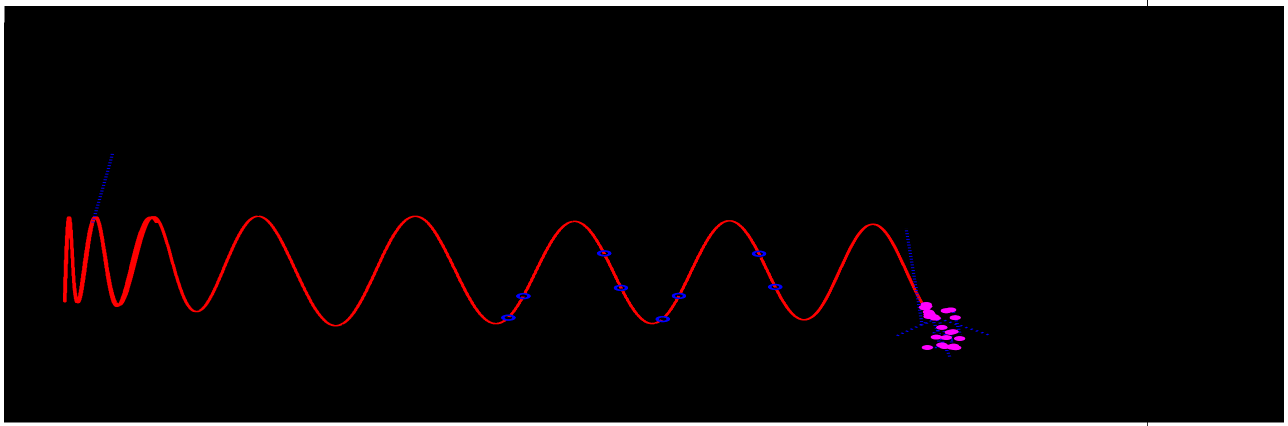
1.35 μsec separation between pulses for a 2.7 μsec rotation time. AGS cycle time is 1 sec.

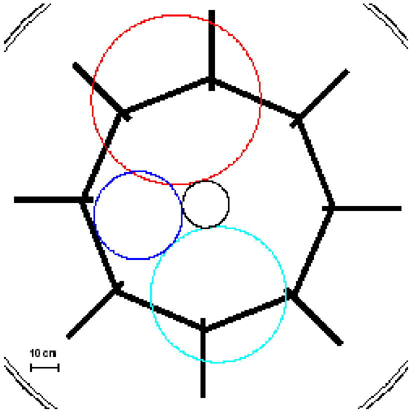


Extinction must be $>10^9$; fast kicker in transport will divert beam from production solenoid

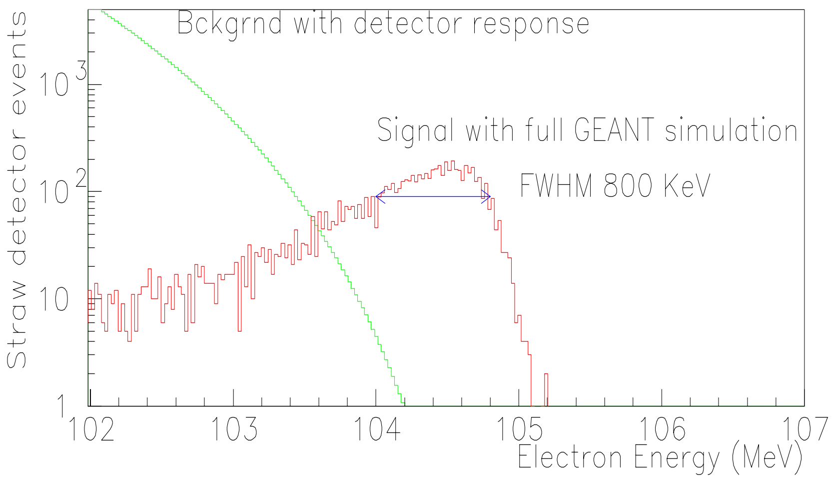
Work to be done. 2 10^{13} protons/bucket is twice the present AGS bunch intensity. In preliminary tests, extinction of ~ 10^7 has been achieved.

Spectrometer Performance





55, 91, & 105 MeV e^- from target



- Performance calculated using Monte Carlo simulation of all physical effects
- Resolution dominated by multiple scattering in tracker
- Resolution function of spectrometer convolved with theoretical calculation of muon decay in orbit to get expected background.

$\mu^- \to e^-$: MECO background

~ 0.45 background events for 10^7 s running time

sensitivity of ~ 5 signal events for $R_{me} = 10^{-16}$

Source	Events	Comments
μ decay in orbit	**0.25**	S/N = 20 for $R_{\mu e} = 10^{-16}$
Tracking errors	< 0.006	
Radiative μ decay	< 0.005	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	Without scattering in stopping target
μ decay in flight	**0.04**	With scattering in stopping target
π decay in flight	< 0.001	
Radiative π capture	**0.07**	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	Assuming 10^{-4} CR veto inefficiency
Total Background	0.45	Assuming 10^{-9} inter-bunch extinction

PRISM/PRIME (FFAG financed. Ready in 2007)

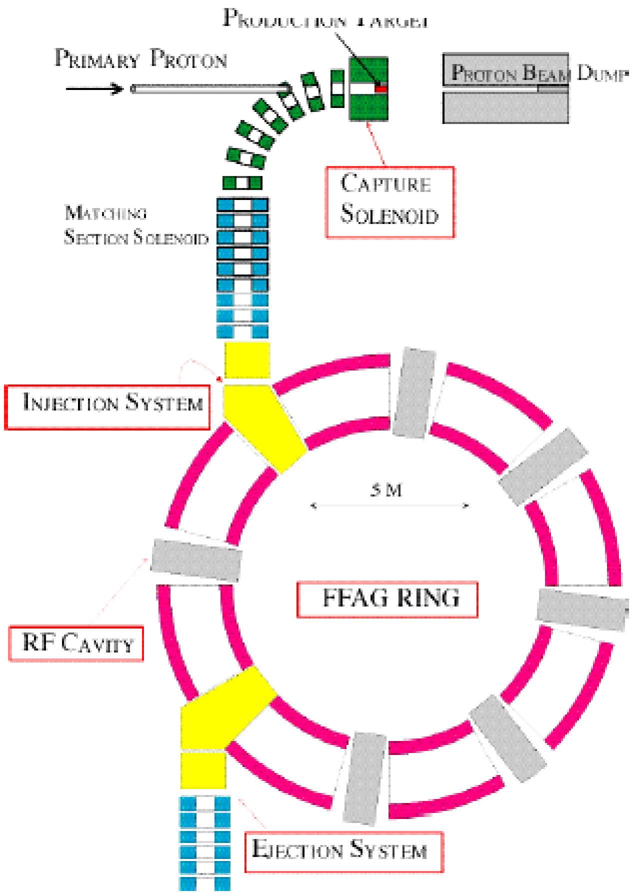


Fig.2 Schematic PRISM Layout

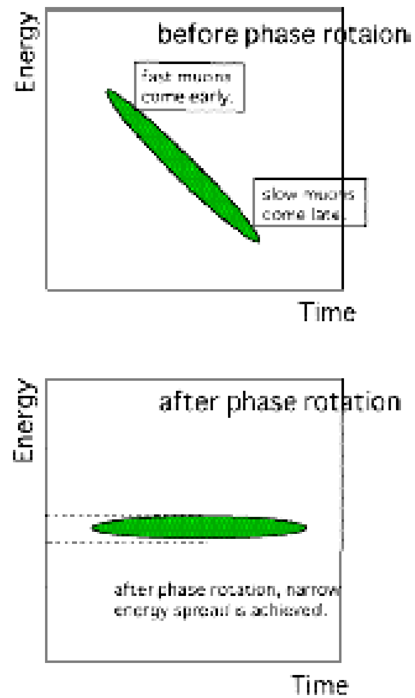


Fig.1 Phase Rotation

- High intensity pulsed proton beam
- Pion capture solenoid
- Pion decay section
- Phase rotation (muon energy spread reduction) by means of an rf field
- Very similar to the front end of the proposed neutrino factories (Staging strategy)

PRISM/PRIME (2)

- Intensity ≈10^{12} muons/s (pion cleaned)
- 68 MeV/c
- Narrow energy spread (few % FWHM)

The last characteristic is essential to stop enough muons in thin targets. If the electron momentum resolution can be kept below 350 KeV (FWHM) the experiment can be sensitive to μe conversion down to **10^{-18}**

Preliminary, rough, estimates for a possible SPL pulsed muon beam

- Macro duty cycle: 1.2 ms every 20 ms (6% duty cycle)
- By the help of a chopper 40 mA of protons in bursts of 200 ns can be provided every 2 μs (good microstructure for mu-e conv)
- This corresponds to 1.5×10^{15} p/s @2.2 GeV (0.5 MW)
- An extinction factor of 10^8 might be within reach (difficult to be measured): confirmation in 2007

R.G.

- An additional 10^3 might be added to the extinction factor by using a veto counter active only between the p bursts
- By using GHEISHA to scale #π/p from 8 to 2.2 GeV (HARP results needed) ➔ 10^{12} μ/s (tungsten target) Sensitivity down to $B=10^{-18}$
- Heat power release about 100 KW (tungsten would melt)
- Need of precise design/estimates
- μ-community

Continuous beam

- The new design of the SPL is not compatible with a CW operation
- Thin production target in the accumulator (not liked because of safety/shielding problems) should be better investigated

2. Orther items: measurements of muon lifetime (G_F)

- G_F is one of the three parameters of the standard model bosonic sector

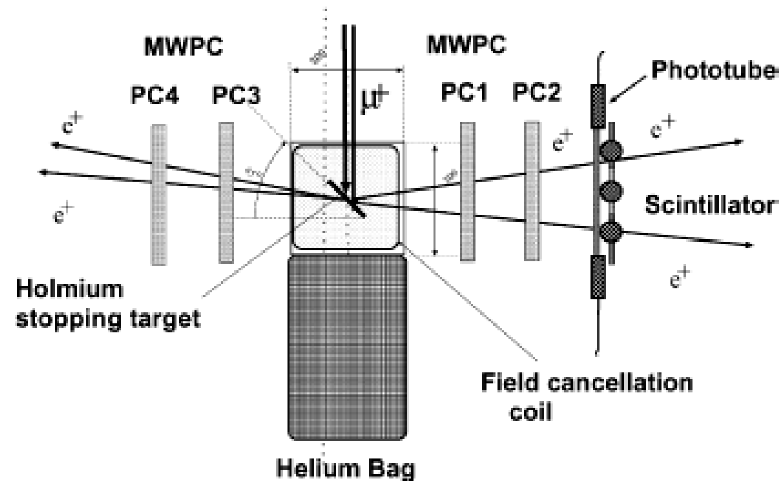
  α (0,045 ppm), M_Z (23 ppm), G_F (9 ppm)

- The accuracy is dominated by the knowledge of the muon lifetime (theoretical uncertainty <1ppm)

  (True in pure V-A and Electroweak fits depend on $G_F M^2_Z$)

Experiments

RAL



- 3 experiments going-on (2 at PSI and one at RAL)

Need to depolarize the muons (limited Ω coverage)

Detector segmented (MWPC+scint.) to avoid pile-up

Benefits from pulsed structure of the beam (time)

But repetition rate too low (50 Hz) -> statistically limited to 10^4 events/s to avoid pile-up

In order a 1 ppm accuracy 10^{12} events are needed

50 Hz ->50 KHz

muLan at PSI

- Scintillator tiles + PMTs
- symmetric detector to reduce polarization effects
- Beam structure created artificially at PSI
- 20 muons of the DC beam are used every 10 muon lifetimes
- 10^{12} events collection

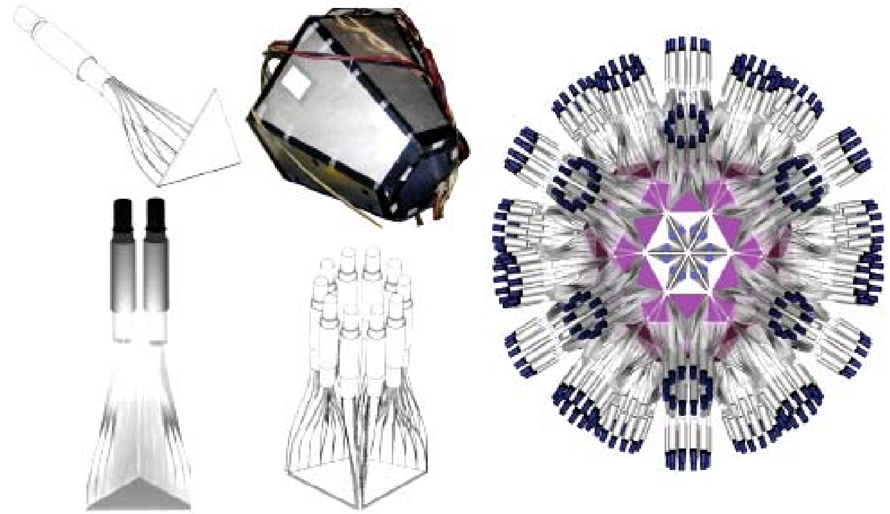


Fig. 4. The μLan detector elements. Individual scintillator element, lightguide and PMT (top left); tile pair (bottom left); pentagon cluster of tiles (bottom middle); hex-house complete structure (top middle); μLan ball (right).

This class of experiments could gain an additional order of magnitude snsitivity by an increase of the muon rate if pile-up and detector timing stability are kept under control

Precise measurements of the muon decay parameters: TWIST (E614) at TRIUMF

Precise measurement of the Michel spectrum

$$\frac{d\Gamma}{\varepsilon^2 d\varepsilon d\Omega} \propto 3(1-\varepsilon) + \frac{2}{3}\rho(4\varepsilon - 3) \pm P_\mu \xi \cos\theta [1 - \varepsilon + \frac{2}{3}\delta(4\varepsilon - 3)]$$

$$\varepsilon = E_e / E_{\max}\ ; \text{neglected terms} \propto m_e / m_\mu (\text{fourth parameter } \eta)$$

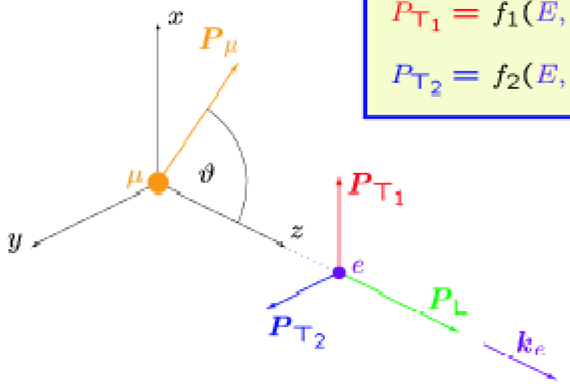
	Accepted Value	Standard Model Value	TWIST Precision
ρ	0.7518 ± 0.0026	$\frac{3}{4}$	± 0.0001
δ	$0.7486 \pm 0.0026 \pm 0.0028$	$\frac{3}{4}$	± 0.00014
$P_\mu \xi$	$1.0027 \pm 0.0079 \pm 0.0030$	1	± 0.00013
η	-0.007 ± 0.013	0	± 0.003

T-violation experiment at PSI

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g^{\gamma}_{\varepsilon\mu} \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle \bar{\nu}_m | \Gamma_\gamma | (\mu)_\mu \rangle$$

The index γ labels the type of interaction:

Γ^S = 4-scalar
Γ^V = 4-vector
Γ^T = 4-tensor



$P_{T_1} = f_1(E, \vartheta, \eta, \eta'')$
$P_{T_2} = f_2(E, \vartheta, \frac{\alpha}{A}, \frac{\beta}{A})$

P_{T_1}: Precise determination of Fermi coupling constant $G_F(\eta)$

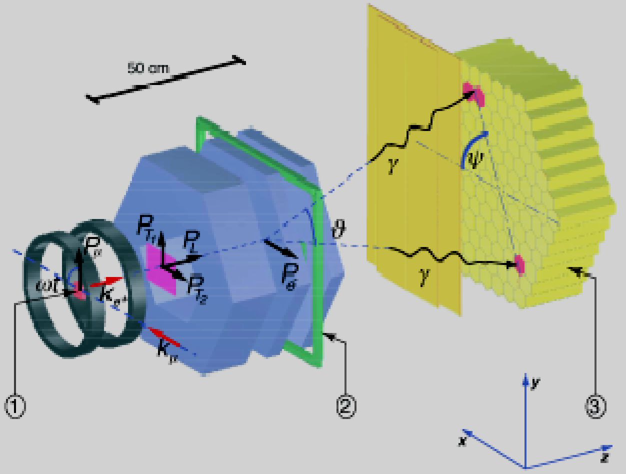
P_{T_2}: Test of time reversal invariance

Improve precision of previous experiment [1] by almost one order in magnitude to:

$\Delta < P_{T_1} > = 0.004$
$\Delta < P_{T_2} > = 0.004$

Observable	Method
P_T	Time dependence of annihilation
φ	Remnant μSR effect
P_L	Spatial dependence of annihilation

Setup of the Experiment and Principle of Measurement :



①: Beryllium stop target within spin precession magnet

②: magnetized Vacoflux foil within iron return yoke

③: calorimeter consisting of 127 BGO crystals

- Highly polarized μ^+ beam at μE1 area of PSI: (91%)
- Muon stop rate in Be target: $(20-80)\times 10^6\ s^{-1}$

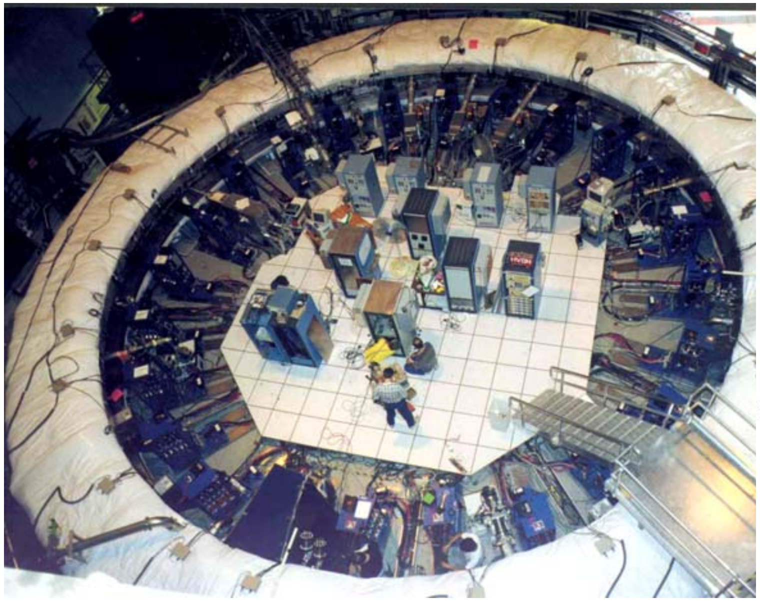
T-violation: principle of the measurement

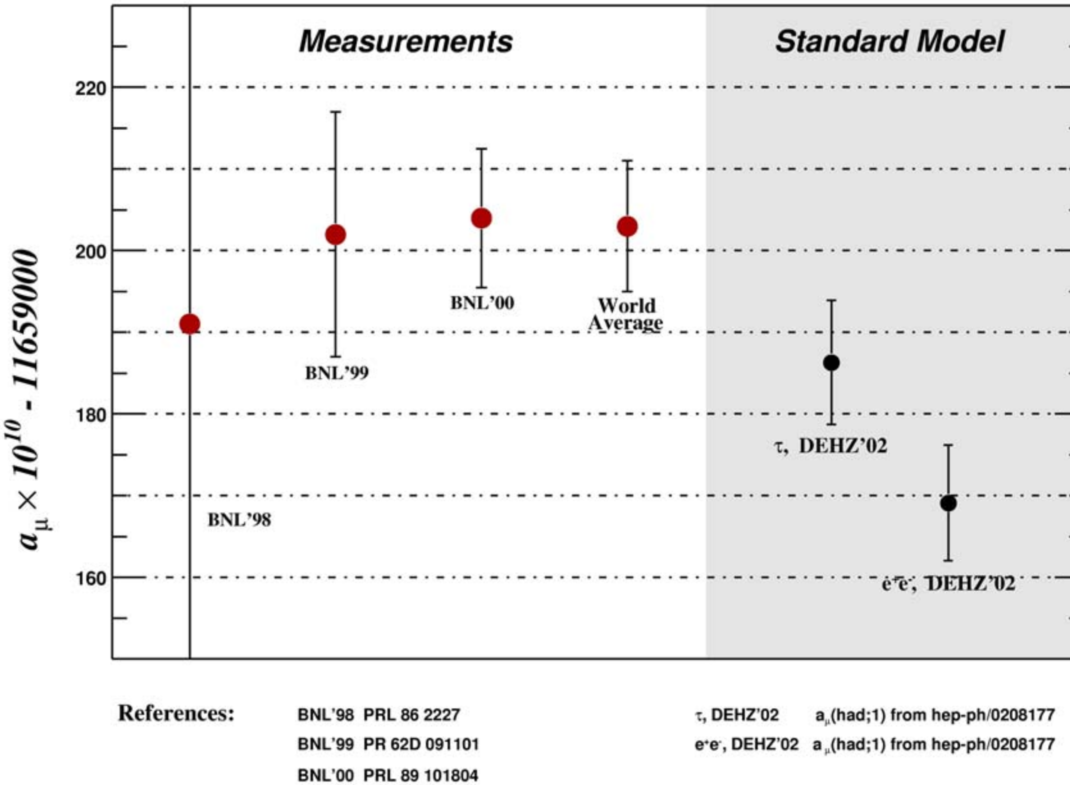
•sensitivity limited in both cases by systematic effects

- Precession in homogeneous $\boldsymbol{B}$ field; precession frequency = cyclotron frequency (50.8 MHz)
- Burst width 3.9 ns (FWHM)

  $\Rightarrow$ 80% muon polarization in Be stop target
- Positron tracking with drift chambers
- Annihilation with polarized e^-
- Detection of annihilation quanta with 127 BGO crystals

g-2





a_μ = 11 659 204(7)(5) x 10^{-10} (0.7 ppm)

a_μ for negative muons (CPT test)

μ edm

- P and T violating
- Best limit from g-2 CERN experiment: $3.7 \pm 3.4 \times 10^{-19}$ e·cm
- Letter of intent (Jan 2003) for a dedicated experiment ->10^{-24} e·cm level
- Disentangle the EDM effect from the g-2 precession by means of a radial electric field
- High intensity dedicated beam of 0.5 GeV/c polarized muons: new PRISM; PRISMII

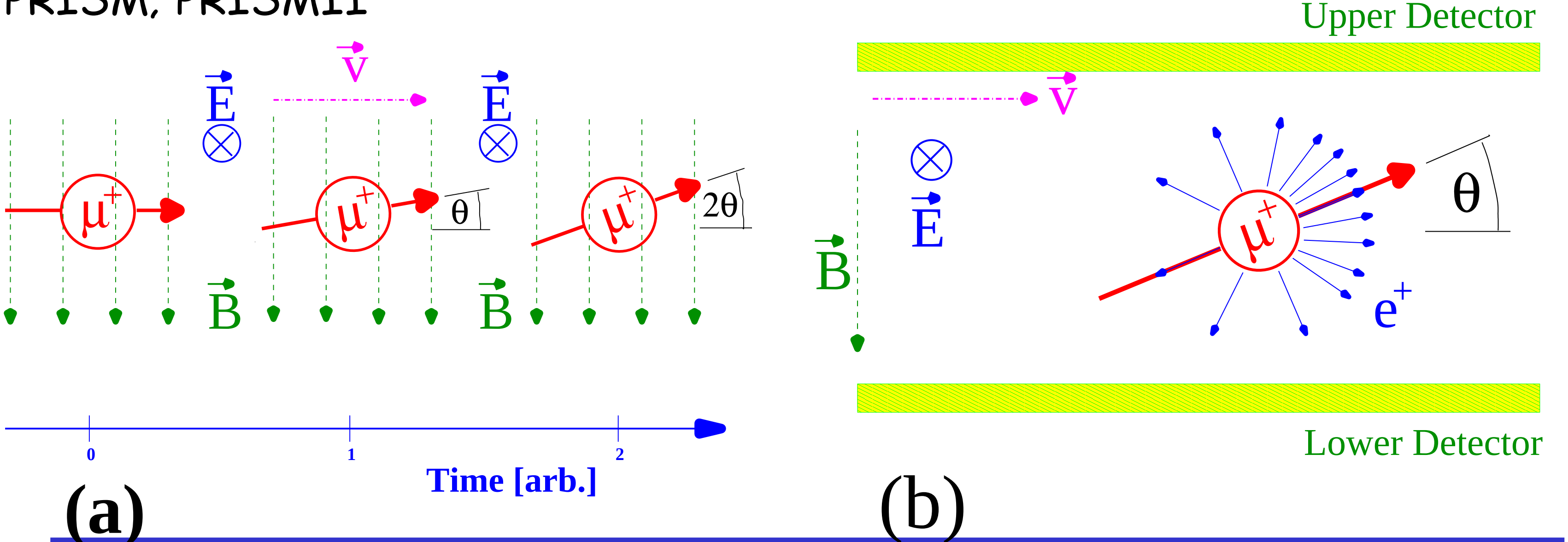


Illustration of the beam needs for the different kinds of experiments

Experiment	q_μ	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{21}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{20}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu \to eee$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1...10
transvers. polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	$\leq$1000	$\leq 10^{-3}$

Conclusions

- Muons are sensitive probes of physics beyond the standard model: SUGRA theories need (C)LFV not too far from the existing limits
- Many other searches can benefit from an increase of the muon flux at a New Low Energy Muon Facility
- In some cases better experiments should be conceived; (challenge for the field of detectors R&D)
- The effort is worthwhile: new physics could be not so far...