Comments on a possible search for the $\mu^+ \to \mathrm{e}^+ + \gamma$ decay with a modified SINDRUM II spectrometer

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Abstract

The possibility of performing a sensitive (two orders of magnitude under the current MEGA[1] limit: 1.2×10^{-11}) although very fast and cheap search for the $\mu^+ \to \mathrm{e}^+\gamma$ decay, by using parts of the SINDRUM II[2] detector (currently taking data) was recently envisaged[3].

We performed extensive Montecarlo calculations to check this idea. It turned out that the cost of such an experiment would not be small and that the sensitivity which could be realistically reached is a only factor ten under the present limit. Although such an experiment would in principle be valid it looses meaning when compared with the planned sensitivity of the project already approved by PSI.

1 Introduction

An experiment[4], which aims at reaching a sensitivity of $\sim 10^{-14}$ in the branching ratio (BR) of the $\mu^+ \to \mathrm{e}^+ + \gamma$ decay, was approved by the PSI scientific committee in July 1999 and is foreseen to enter the experimental πe5 area after 2003. That area is now occupied by the SINDRUM II experiment which is currently taking data in search for $\mu \to$ e conversions by stopping the very intense ($\approx 3 \times 10^8$ muons per second) muon beam in several materials. SINDRUM II should end its data taking within this year.

The idea behind this study is that several components of SINDRUM II could be re-used for a very sensitive (down to a BR of 10^{-13}) search for $\mu^+ \to \mathrm{e}^+ + \gamma$, to be performed over three years. The cost for this operation appeared at first sight to be very low (about one tenth of the cost of the approved $\mu^+ \to \mathrm{e}^+ + \gamma$ project). These features would have been very attractive since this experiment might have explored, in a limited amount of time, most of the parameter space allowed by supersymmetric theories[5].

2 Detector simulation

In order to estimate the sensitivity of the experiment we made extensive use of a GEANT[6] based Montecarlo simulation program.

A longitudinal overview of the detector we envisaged is shown in figure 1. All the detector elements are axially symmetric. The outer elements, namely the scintillator hodoscope SH1, the two drift chambers DC1 and DC2 [7] and the magnet are those parts of the SINDRUM II spectrometer to be used in the new set-up. The new detector elements are:

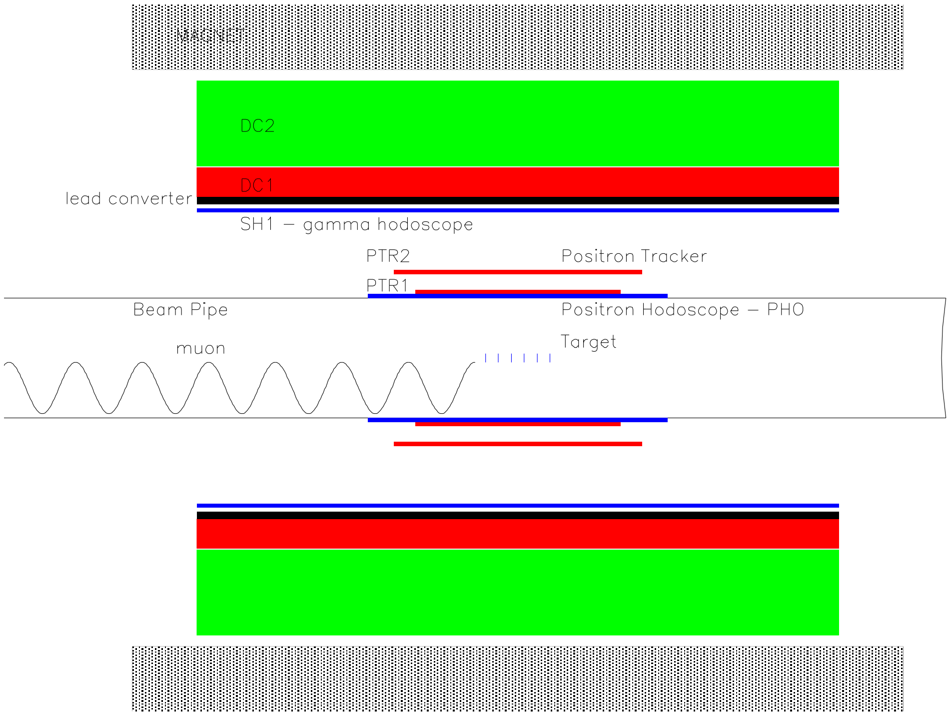

Figure 1: Sketch of the detector (not to scale)

- the target
- the lead converter in front of DC1
- the detectors for the positron tracking, namely the two chambers (PTR1 and PTR2) and the positron scintillating fiber hodoscope (PHO)

In the following paragraphs we give a more detailed description of how the several detector elements were simulated.

2.1 Beam transport, target and magnet

We did not simulate the muon beam transport and stopping process: we just assumed a total decay rate of 10^8 μ/s. This intensity is reduced by a factor three compared to the nominal beam intensity because we were planning to use a method exploiting degraders and collimators for reducing the beam positron contamination by a factor 100 as indicated in reference [8].

The stopping target is made of 6 polyethylene disks with 5 mm radius and 50 μm thickness. These disks are placed perpendicularly to the SINDRUM magnet symmetry axis and centered on the axis. They are spaced by 3 cm, for a total length of 15 cm.

The reason for subdividing the target in this way is that the photon pair spectrometer is able to measure the photon direction and to determine (as we will see in the next section) from which of the 6 targets the photon originated. This implies a reduction in the accidental background since we require photons and positrons to originate in the same target.

The identification of the target element together with the knowledge of the photon conversion point determines very precisely the photon direction.

In our simulation the field of the SINDRUM II magnet was assumed to be uniform, without edge effects (known to be of the order of 10%), with a value of 1.1T.

2.2 The photon detector

The existing drift chambers of SINDRUM II (DC1 and DC2) form, together with the SINDRUM magnet, a pair spectrometer. They have a cylindrical shape: 1.5 m length, DC1 internal radius 37.6 cm, external 44.5 cm, DC2 internal radius 44.9 cm, external 65.0 cm.

DC1 and DC2 were not fully simulated. They were considered just as cylinders filled with the proper gas mixture. The photon momentum was determined from the sum of the momenta (as given by GEANT) of the electron – positron pair entering DC1, therefore assuming the measuring errors, ionization and multiple scattering inside DC1 and DC2 to have a negligible effect when compared with the multiple scattering effects in the materials in front of DC1.

The photon angle with respect to the beam axis is reconstructed in this way with a $\sigma = 75\,\mathrm{mrad}$ (see figure 2a) which corresponds to a resolution of 3.6 cm in determining the origin of the photon at the beam axis.

We further assumed that the photon conversion point can be determined by the tracking in the drift chambers with a σ of 1 mm.

In order to increase the photon conversion efficiency, several configurations of high Z converters at several positions in the apparatus were simulated. Since the photon efficiency does not depend very much (it stays around 1.3% with $\simeq 0.15\%$ variations) on the different configurations, we present here the results we got by adding just one layer of lead, 0.5 mm thick, right in front of DC1.

The distribution of the reconstructed photon energy (for 52.8 MeV photons) is given in figure 2b. This distribution has a 3% FWHM.

The existing scintillator timing counters of SINDRUM II (SH1) provide the photon conversion time by independently measuring the hodoscope crossing time of the e^+ and of the e^-. It consists of 64 scintillators 0.5 cm thick at distance of 34.6 cm from the beam axis.

In figure 3 we show a view, orthogonal to the beam axis, of the simulated detector, with the interaction of a 52.8 MeV photon superimposed.

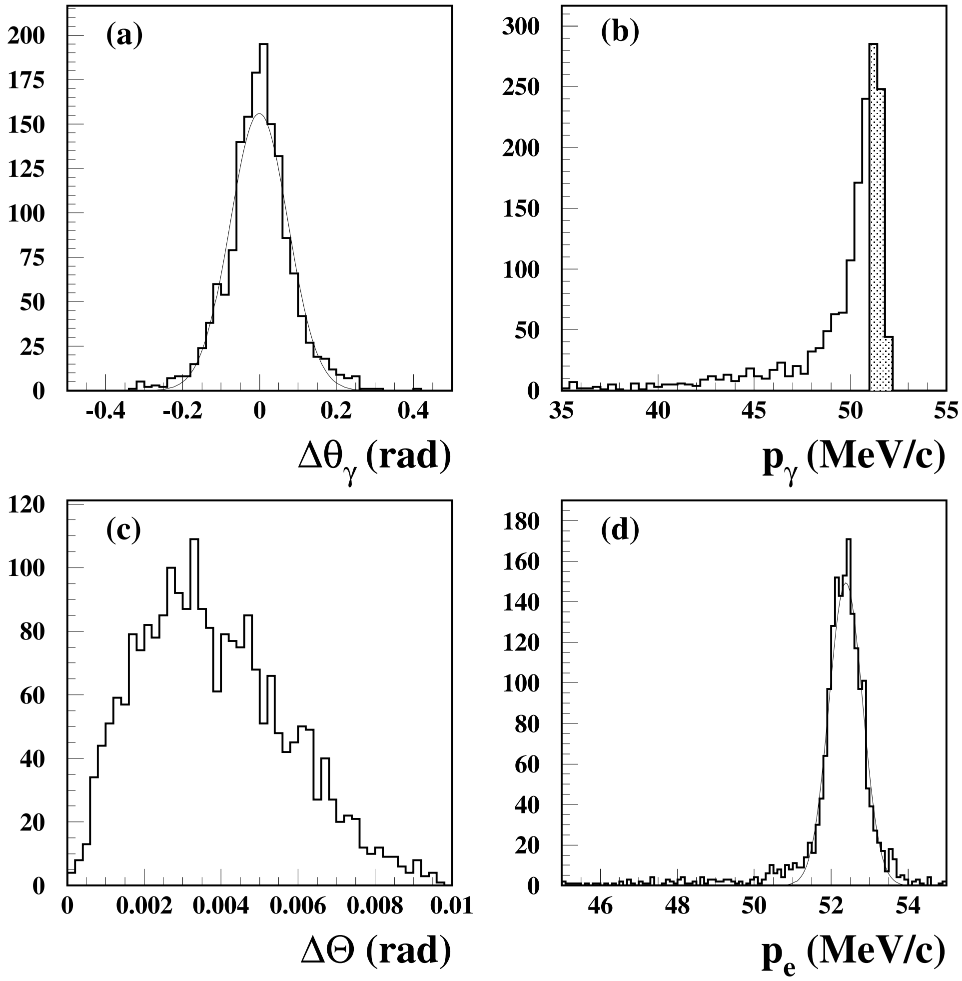

Figure 2: Reconstruction of $\mu^+ \to e^+ + \gamma$ decays a) photon angle with respect to the beam axis; b) photon momentum: the hatched area represents the window for the signal selection (see section 3; c) positron angle with respect to the photon reconstructed direction d) positron momentum

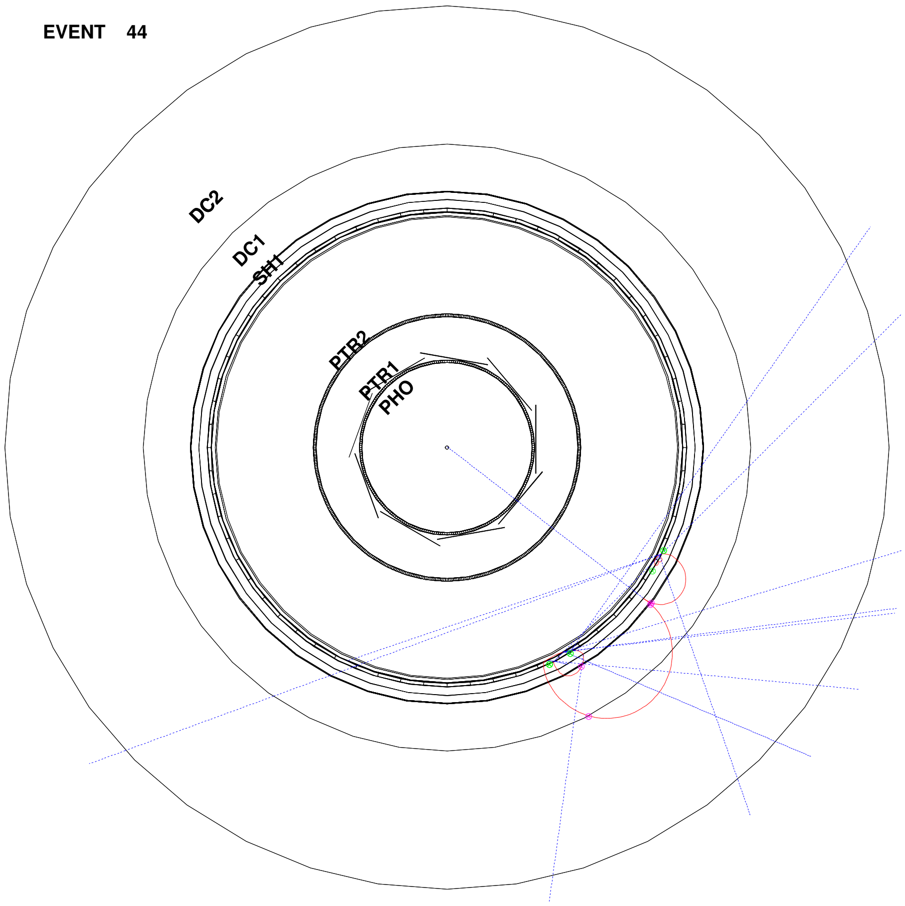

Figure 3: The projective view of the modified SINDRUM II detector. The interaction of a 52.8MeV gamma is also shown. The subdetectors are described in the text.

2.3 The positron detector

Positrons cannot be detected by means of existing parts of the present SINDRUM II detector. All the equipments installed in-between the beam axis and the SH1 hodoscope should be removed to install the positron detector.

After evaluating several positron tracker configurations, including solid state and gaseous trackers at various radial distances from the target, we selected the configuration described here.

A scintillating–fibers hodoscope (PHO), 70 cm long, is placed just outside the vacuum pipe at a radius of 12.5 cm. It is 3 mm thick and it is subdivided in 256 elements for the readout.

Chamber PTR1 is a silicon pad chamber, with $4 \times 4\,\mathrm{mm}^2$ pad dimensions, composed of 9 elements of dimensions $10\,\mathrm{cm} \times 48\,\mathrm{cm} \times 300\,\mu\mathrm{m}$ disposed around the beam axis, tangent to a 13 cm radius circonference, as can be seen in fig. 4 where the trajectory of a 52.8MeV positron is also shown. Chamber PTR2 is a

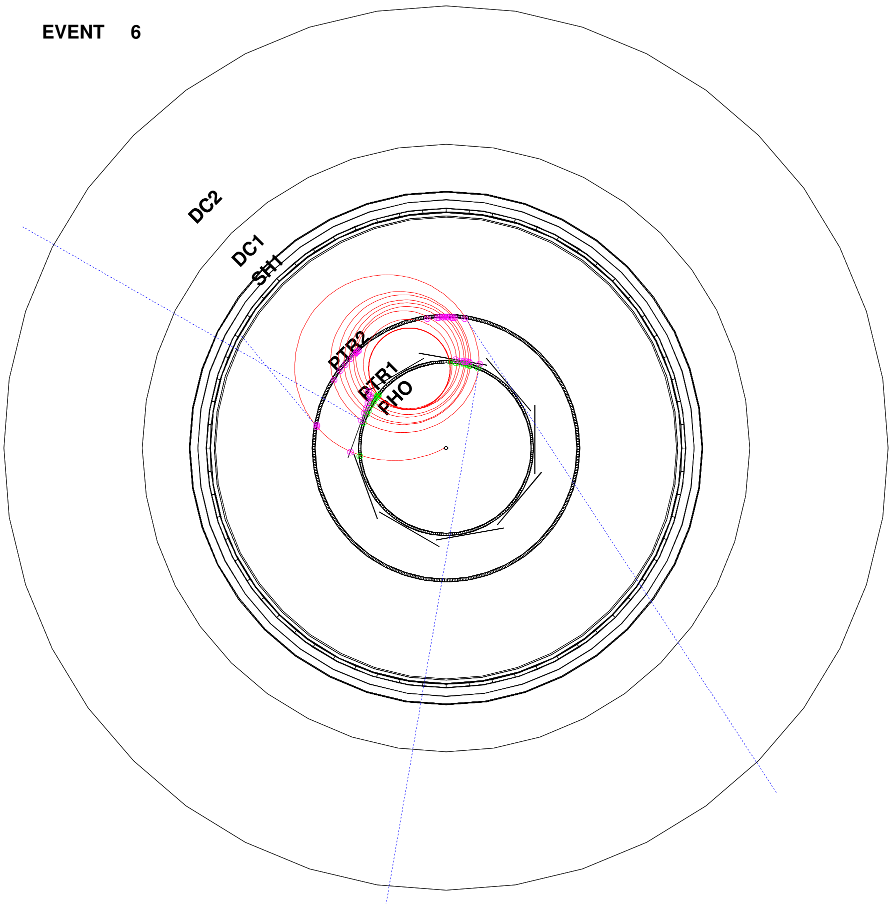

Figure 4: The projective view of the modified SINDRUM II detector. The interaction of a 52.8MeV positron is also shown. The subdetectors are described in the text. Straight lines are secondary photons.

cylindrical proportional wire chamber, 58 cm long, 4 mm thick, with an inner radius of 19.2 cm. It is composed of 512 wires and we assumed that, by reading the induced charge on strips, non collinear with the wires, a flat resolution of 2.5 mm along the beam axis can be obtained.

Positron tracks from $\mu^+ \to e^+ + \gamma$ decays were reconstructed by a helix fit to the crossing points of PHO, PTR1 and PTR2, smeared with the appropriate resolutions and by assuming to be able to measure the ionization loss in PHO with a 10% resolution. The reconstructed positron momentum distribution is shown in figure 2d; it has a 2% FWHM. Figure 2c shows the reconstructed positron direction with respect to that reconstructed for the photon. The half-aperture cone containing 76% of the events in this distribution is $\Delta\Theta = 6.5\,\mathrm{mrad}$.

3 Factors determining the sensitivity of the experiment

The number N_s of $\mu^+ \to e^+ + \gamma$ decays expected in the experiment can be written as:

$$N_s = N_\mu \cdot t \cdot (\Omega/4\pi) \cdot \epsilon_e \cdot \epsilon_\gamma \cdot \epsilon_{cut} \cdot BR_{\mu\to e\,\gamma} \quad (1)$$

where N_μ is the muon stop rate, t is the measuring time, Ω is the detector solid angle, ϵ_e and ϵ_γ are the positron and photon detection efficiencies, ϵ_{cut} is the efficiency of the selection cuts.

The background is assumed to be dominated by accidental coincidences of a positron from the normal muon decay and a high energy photon from the decay $\mu^+ \to e^+\nu\overline{\nu}\gamma$ or produced by an e^+ through external bremsstrahlung or annihilation in flight.

The number of accidental coincidences is given by:

$$\begin{aligned} N_b = {} & N_\mu \cdot f_e \cdot \Omega/4\pi \cdot \epsilon_e \\ & \times N_\mu \cdot f_\gamma \cdot \Omega/4\pi \cdot \epsilon_\gamma \\ & \times f_{angle} \cdot 2\delta t \cdot t \end{aligned} \quad (2)$$

where f_e and f_γ are the e^+ and γ yields per stopped muon, respectively; f_{angle} is the accidental probability for an e^+ and a γ to be collinear within the experimental resolutions and δt is the cut applied on the $e^+ - \gamma$ relative timing.

The values used in this note for determining the experiment sensitivity are shown in table 1.

Table 1: Values used for the factors determininining the sensitivity of the experiment

Factor	value
N_μ	$10^8 \mu/s$
t	$2 \times 10^7 s$
$\Omega/4\pi$	0.44
ϵ_e	0.76
ϵ_γ	.013
ϵ_{cut}	.58
f_e	.04
f_γ	10^{-6}
f_{angle}	2×10^{-5}
δt	$10^{-9}s$

- We assumed to run the experiment for about one year with a $\approx 65\%$ of live time.
- The positron detection efficiency (ϵ_e) stems from the 1 FWHM cut (Δp) we required on the reconstructed momentum around the 52.8 MeV value.

- f_e is computed in [9] to be $2 \times \Delta p/p$.
- For the photon we defined our acceptance window to be 1 MeV from the energy distribution end-point (see figure 2b). This implies $\epsilon_\gamma = .013$ (which takes into account also the conversion probability) and $f_\gamma = 10^{-6}$, which again is evaluated in [9].
- $\delta t_{\rm FWHM}$ is assumed to be 1 ns and we used this cut.
- $\epsilon_{\rm cut}$ is the combined efficiency of the 1 FWHM angular and time selection cuts.
- $f_{\rm angle}$ was evaluated by means of a Montecarlo simulation of the accidental background. It contains also the background reduction effect of the segmented target.

From formula 2 one can compute $N_b = 0.6$. From the currently accepted Feldman and Cousins prescriptions[10] we get that, at 90% C.L., $N_s \leq 2.9$, which in turns, from equation 1, implies that the sensitivity of the experiment is $BR_{\mu\to e\,\gamma} \leq 5.8 \times 10^{-13}$ (90% C.L.).

4 Conclusions

The result of the previous section on the branching ratio does not take into consideration any trigger or pattern recognition efficiency which would certainly worsen the limit obtained. We further computed this limits under some optimistic assumptions (on the resolution of photon conversion point, on the gaussian shape of the distributions etc.). We believe that the BR limit obtained should realistically be multiplied by a factor ≈ 2.

We also believe that, in order not to introduce large dead times in the acquisition, the read-out of the silicon pad chamber PTR1 would be complicate and expensive, since the number of channels of this chamber is very high (27,000).

Finally, even if, in principle, this experiment would be a factor ten more sensitive to the $\mu^+ \to e^+ + \gamma$ than the present best limit, we must consider that an experiment aiming at a better result (although with higher costs and in a longer time) was already approved by PSI.

For these reasons we decided not to go on with this project.

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