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Search for a muon EDM at the Paul Scherrer Institute

Philipp Schmidt-Wellenburg,[a,*] **Ciro Calzolaio,**[a] **Ritwika Chakraborty,**[a] **Anastasia Doinaki,**[a,b] **Chavdar Dutsov,**[a] **Timothy Hume,**[a,b] **Ljiljana Morvaj,**[a] **Angela Papa,**[a,c,d] **Mikio Sakurai**[e] **and the muEDM collaboration**

[a] *Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen, Switzerland*
[b] *ETH Zürich, 8092 Zürich, Switzerland*
[c] *INFN Sezione di Pisa, 56127 Pisa, Italy*
[d] *Universitá di Pisa, 56127 Pisa, Italy*
[e] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom*

E-mail: philipp.schmidt-wellenburg@psi.ch

Electric dipole moments (EDM) of non-degenerate systems with angular momentum violate parity and time symmetry, and by the virtue of the CPT-theorem also the combined symmetry of charge and parity (CP). Although CP violation (CPV) is an established ingredient of the weak sector of the standard model of particle physics (SM), its contribution to an EDM of a fundamental particle is too small to be measured any time soon. Therefore, any discovery of an EDM would be a genuine signal of yet unobserved physics. As the muon is the only accessible probe of the second generation of fermions and the only fermion of which the EDM can be measured on the bare particle, a search for a muon EDM thus uniquely complements more established searches using atoms and neutrons. Here we report on the status of a search for the muon EDM using the frozen-spin technique in a compact storage ring, aiming for an improvement by three orders of magnitude in sensitivity compared to the current best direct limit $d_\mu \leq 1.8 \times 10^{-19}\, e\cdot$cm.

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	μ	d	$\mathbf{s}$	$\mathbf{E}$	$\mathbf{B}$	$-d\,\mathbf{s}\cdot\mathbf{E}$	$-\mu\,\mathbf{s}\cdot\mathbf{B}$
parity	+	+	+	-	+	$(++-)=-$	$(+++)=+$
time	+	+	-	+	-	$(+-+)=-$	$(+--)=+$
charge	-	-	+	-	-	$(-+-)=+$	$(-+-)=+$
charge & parity	-	-	+	+	-	$(-++)=-$	$(-+-)=+$

Table 1: Behavior of the magnetic dipole moment, μ, the electric dipole moment, d, the spin, $\mathbf{s}$, the electric, $\mathbf{E}$, and magnetic field, $\mathbf{B}$, and the non-relativistic Hamiltonians under parity, time, charge and CP transformation.

1. Introduction

The interaction of a fermion with the electromagnetic four-potential A_μ is described by $A_\mu(x)j^\mu(x)$, where $j^\mu(x)$ is the electromagnetic current. The most general representation of the electromagnetic current, using four form factors, $F_{i=1\ldots4}$, and a combination of gauge invariant bilinears, is given by [1]

$$\langle\mathbf{p}'|j^\mu|\mathbf{p}\rangle=\bar{u}(\mathbf{p}')\left[F_1(q^2)\gamma^\mu+\frac{iF_2(q^2)}{2m}\sigma^{\mu\nu}q_\nu+\frac{iF_3(q^2)}{2m}\sigma^{\mu\nu}\gamma^5q_\nu+\frac{F_4}{2m}\gamma^5\left(q^\mu-\frac{q^2}{2m}\gamma^\mu\right)\right]u(\mathbf{p}),\qquad(1)$$

where $u(\mathbf{p}^{(\prime)})$ is the incoming (outgoing) fermion spinor with momentum p (p') and $q^\mu=p^{\mu\prime}-p^\mu$ is the momentum transfer. The form factors F_i are functions of the squared momentum transfer, q^2. For a comprehensive description of the Dirac algebra using γ-matrices we refer the reader to standard textbooks such as [2, 3].

The form factors, or a combination of them, can be interpreted in the non-relativistic limit as the charge $q=F_1(0)$, the magnetic dipole moment $\mu=(F_1(0)+F_2(0))/(2m)$, the electric dipole moment $d=-F_3(0)/(2m)$, and the anapole moment $F_4(0)$ of the fermion interacting with an external electromagnetic field. In this talk we set aside the anapole moment and will have a closer look at the the second and third form factor. The magnetic moment of a charged fermion is $\mu=gq/(4m)$, hence the second form factor,

$$F_2(0)/q=\frac{g-2}{2}=a,\qquad(2)$$

corresponds to the anomalous magnetic moment (AMM) of the fermion. For bare leptons, like the electron and the muon, the form factors result from loop effects involving electromagnetic, weak, and strong interaction. For nucleons, like the neutron and proton, they result primarily from the internal structure due to quarks and the strong interaction. In both cases $F_2(0)$ is measured to a high precision [4–7], while all measurements of electric dipole moments (EDM) of any fermion, and hence of $F_3(0)$, is in agreement with zero and only upper limits have been published so far [8–12]. These results are in agreement with standard model (SM) expectations, although in the case of the muon's anomalous moment the situation is less clear [5, 13, 14]. In turn, this also means that any EDM signal at current sensitivities is a sign of yet unknown physics, as SM-induced EDMs are far beyond today's experimental sensitivities[1].

Taking a closer look at the Hamiltonian of the non-relativistic limit of the EDM term in Eq. (1) coupling F_3 to the electromagnetic four-potential,

$$\mathcal{H}^{\mathrm{NR}}(F_3)=-d\,\mathbf{s}\cdot\mathbf{E},\qquad(3)$$

one can quickly see, c.f. table 1, that the EDM Hamiltonian changes sign under parity and time inversion due to the dot-product of the spin, $\mathbf{s}$, and the vector, $\mathbf{E}$, indicating parity and time symmetry violation and also violation of the combined symmetry of charge and parity (CPV).

[1]The only known source for an EDM of a fermion in the SM is the complex phase of the CKM-matrix in the weak interaction. An additional possible source for EDMs is the Θ-term of the strong interaction, which is considered as unnaturally small and gave rise to axions.

Intriguingly, one can show in an effective field theory approach [15, 16] that the complex phase of the same Wilson coefficient which gives rise to possible BSM contributions of the AMM

$$a_\ell = -\frac{4m_\ell}{e}\mathrm{Re}(c_R^{\ell\ell}), \qquad \text{while} \qquad d_\ell = -\mathrm{Im}(\mathrm{c}_\mathrm{R}^{\ell\ell}) \tag{4}$$

gives rise to the EDM of the fermion. A direct search for a muon EDM is the only way to probe the complex phase of the associated Wilson coefficient, $c_R^{\mu\mu}$, and form factor F_3^μ of the muon without imposing specific assumptions on the structure of new physics.

The most prolific leptonic EDM searches of the past decades have been the search for an EDM of the electron, using paramagnetic atoms or molecules [11] and having recently published the most stringent result of all EDM searches with $d_e < 4.1 \times 10^{-30}\, e\cdot\mathrm{cm}$ at C.L. 90% [8]. As these measurements effectively observe a superposed quantum state within a molecule exposed to a small electric field in the lab, $E_\mathrm{lab} = O(10\,\mathrm{V})$, the extraction of an EDM of the bare electron relies on atomic theory calculations to deduce the effective electric field, $E_\mathrm{eff} = O(100\,\mathrm{GV})$, and the assumption that the pseudoscalar-scalar electron-nucleon coupling $C_S = 0$ [12]. Nevertheless, assuming minimal flavor violation (MFV), as often implemented in BSM scenarios, e.g. within the Minimal Supersymmetric Standard Model (MSSM), the EDM of other leptons can be inferred by simple mass scaling m_ℓ/m_e. This would result in EDM limits for the muon and tau of, $d_\mu^\mathrm{MFV} < 8.5 \times 10^{-28}\, e\cdot\mathrm{cm}$ and $d_\tau^\mathrm{MFV} < 1.4 \times 10^{-26}\, e\cdot\mathrm{cm}$. In comparison, the current best direct limit is $d_\mu < 1.8 \times 10^{-19}\, e\cdot\mathrm{cm}$ at C.L.95% [9] and an assumption-free limit derived from the electron EDM searches suggests $d_\mu < 1.9 \times 10^{-20}\, e\cdot\mathrm{cm}$ [17].

However, MFV is, to some extent, an ad hoc symmetry, required to permit a light particle spectrum within the MSSM while avoiding fine-tuning in the Higgs sector and simultaneously respecting flavor constraints. Contrary to expectations, no light particle spectrum has been found at LHC [18, 19], while many interesting hints in precision measurement of leptonic observables including muons [20, 21] suggest a flavor structure going beyond MFV in the lepton sector [22]. In theories with a flavor structure beyond the MFV assumption, simple mass scaling does not hold, thus allowing, in general, for a sizable EDM of the muon and tau.

In this contribution we present the experimental effort at the Paul Scherrer Institute to directly measure the EDM of the bare positive muon to a precision of better than $6 \times 10^{-23}\, e\cdot\mathrm{cm}$ using the frozen-spin technique [23–25] in a compact solenoid.

2. Experimental techniques

An electric dipole moment of a fermion exposed to an electric field results in a two level system with energy eigenstates

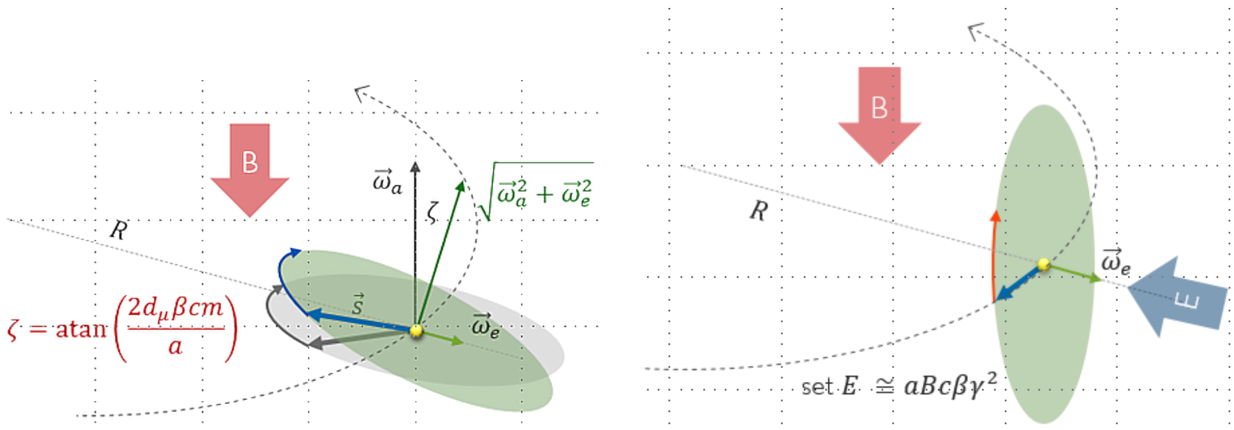
$$E_\pm = \pm dE, \qquad \text{with} \qquad \omega_e = \frac{2dE}{\hbar} \tag{5}$$

the precession frequency proportional to the transition energy between the two states of the Hamiltonian, Eq. (3).

Most experiments searching for an EDM implement Ramsey's method of separated oscillating fields [26] in combination with alternating strong electric fields to measure the EDM frequency. However, exposing muons to a static electric field between two electrodes will result in an acceleration, moving the muon quickly into a region without field, e.g. the surface of one of the electrodes. Instead of using a static electric field in the laboratory, we will use a static magnetic field, $\vec{B}$, in which we store muons with a velocity $\vec{v} = \vec{\beta}c$, where c is the speed of light in vacuum and $0 < \beta < 1$, on a circular orbit. In the rest frame of the muon this results in a static electric field $E^* = \gamma c\beta B = O(1\,\mathrm{GV/m})$.

2.1 Spin motion of muons with an EDM in electromagnetic fields

The relative spin precession $\vec{\Omega}$ of a muon moving with momentum $\vec{p}$, and hence $\vec{\beta} = \vec{v}/c$ and $\gamma = (1-\beta^2)^{-1/2}$, in a storage ring with an electric field $\vec{E}$ and a magnetic field $\vec{B}$ is given by the Thomas-BMT



(a) **(b)**

Figure 1: Spin precession of a muon stored on a circular orbit using a magnetic field $\vec{B}$. (a) Combined precession due to AMM and EDM in storage rings optimized for the search for the $(g-2)$ of the muon [5, 29]. (b) Precession due to the EDM only, in a storage ring using the frozen-spin technique zeroing the AMM precession[24, 25, 30].

equation [27, 28],

$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{6}$$

where $\vec{\Omega}_0$ is the Larmor and $\vec{\Omega}_c$ the cyclotron precession, and a the AMM. The presence of the EDM adds a second term such that

$$\begin{aligned}\vec{\Omega} =& \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \\ &+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{c(\gamma+1)}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right].\end{aligned} \tag{7}$$

The first line in Eq. (7) is the anomalous precession frequency, $\vec{\omega}_\mathrm{a} \parallel \vec{B}$, the difference between the Larmor precession and the cyclotron precession. The second line is the precession $\vec{\omega}_\mathrm{e} \perp \vec{B}$ due to the EDM coupling the spin to the relativistic electric field of the muon moving in the magnetic field $\vec{B}$, oriented perpendicular to $\vec{B}$.

If momentum, magnetic field, and electric field form an orthogonal basis, the scalar products of momentum with the fields, $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$, drop out. In the presence of a muon EDM, the precession plane is tilted out of the orbital plane as illustrated in Fig. 1a. As a consequence, an oscillating longitudinal polarization, $P_e = \sin(\Omega t + \phi)$ with an amplitude $P_e \propto \zeta = 2d_\mu\beta m c/a$ and a frequency Ω, shifted in phase by $\pi/2$ with respect to anomalous oscillation signal, would become observable. The observed precession frequency, $\Omega = \sqrt{\vec{\omega}_\mathrm{a}^2 + \vec{\omega}_\mathrm{e}^2}$, increases due to the EDM.

2.2 The frozen-spin technique

The experimental setup proposed for this dedicated search for a muon EDM is based on the ideas and concepts discussed in Refs. [24, 25, 29–31]. The salient feature of the proposed search for the muon EDM is the cancellation of the effects from the anomalous moment by precisely adjusting a radial electric field E_ρ. In this way the spin is only sensitive to the large electric field $\vec{E}^* = \gamma c\vec{\beta}\times\vec{B}$ in the rest frame of the muon, resulting in a perpendicular precession ($\vec{\omega}_\mathrm{e} \perp \vec{B}$) due to the EDM, as shown in Fig. 1b.

The anomalous precession term in Eq. (7) can be set to zero by applying an electric field such that

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}. \tag{8}$$

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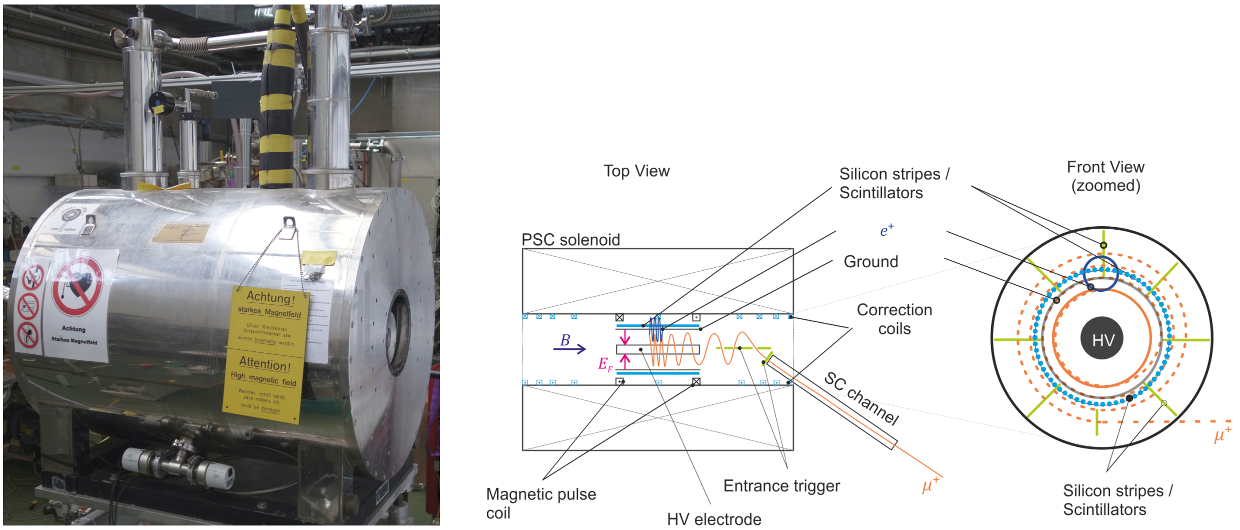

(a) **(b)**

Figure 2: Photo (a) and sketch (b) of the compact superconducting solenoid and the experimental setup for the search for the EDM of the muon. The warm bore of the solenoid has an inner diameter of 200 mm and an outer diameter of about 1000 mm. In the next years we will demonstrate all features of the experiment mentioned on the right.

In the idealized case of $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$, and $\vec{B} \cdot \vec{E} = 0$, we find a required field strength of $E_\mathrm{f} \approx aBc\beta\gamma^2$. By selecting the exact field condition of Eq. (8), the cyclotron precession frequency is modified such that the relative angle between the momentum vector and the spin remains unchanged if $d_\mu = 0$, and hence it is "frozen". In the presence of an electric dipole moment, the change in polarization is described by

$$P(t) = P_0 \sin(\omega_e t) \approx P_0 \omega_e t = 2P_0 \frac{d_\mu}{\hbar} \frac{E_\mathrm{f}}{a\gamma^2} t. \tag{9}$$

From the slope $\mathrm{d}P(t)/\mathrm{d}d_\mu$ multiplied by the mean analysis power of the final polarization, A, we calculate the sensitivity as

$$\sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0 E_\mathrm{f} \sqrt{N} \tau_\mu A} \tag{10}$$

for a search for the muon EDM by replacing t with the mean free laboratory lifetime of the muon in the detector $\gamma\tau_\mu$ and scaling by $1/\sqrt{N}$ for the Poisson statistics of N observed muon decays.

3. Experimental setup

In the next years, we will set up a search for a muon EDM in an existing solenoid, see Fig. 2a. The instrument will be connected to a surface muon beam line at PSI, delivering about $4 \times 10^6\,\mathrm{s}^{-1}$ muons at a momentum of $p = 28\,\mathrm{MeV}/c$ in a transverse phase space of $\epsilon_{xx'} = 192\,\pi\mathrm{mm\,mrad}$ and $\epsilon_{yy'} = 171\,\pi\mathrm{mm\,mrad}$. As the acceptance phase space is tiny, we will use a long copper tube inside a superconducting shield [32] for collimation. Simulations of the collimation show that this reduces the number of muons inside the solenoid to about $1.2 \times 10^5\,\mathrm{s}^{-1}$. Of these, only a small fraction follow close enough to the nominal injection trajectory to be finally stored. These muons passing through the center need to be captured and stored within the weakly-focusing magnetic field by a precisely timed magnetic pulse. For this purpose we will generate a trigger from an anti-coincidence between two scintillators at the exit of the collimation channel. We expect about 800 muons per second to match these conditions, in turn this means that we store only one muon at a time.

During storage, the muon will circulate on a radius, $r = 31\,\mathrm{mm}$, with a cyclotron period of about 2.5 ns until it decays into a positron and muon neutrino. Due to parity violation of the weak decay the positron ejection direction is correlated to the spin orientation. To track the direction of each positron and reconstruct

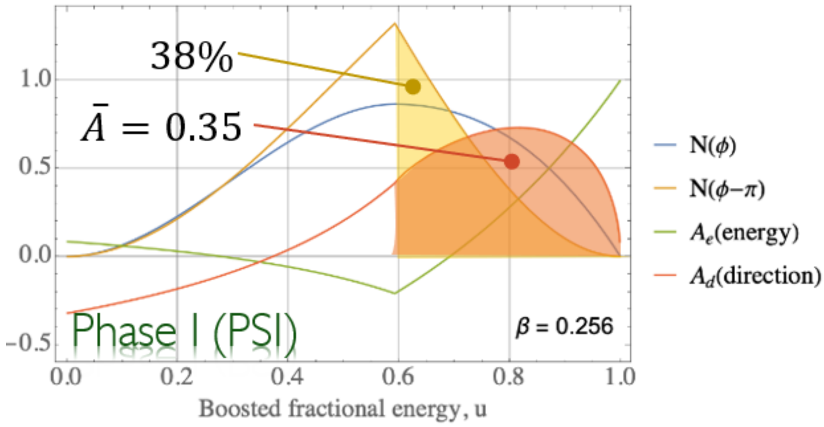

Figure 3: Positron energy distribution for aligned (blue) and anti-aligned (orange) spin with respect to the momentum. The g-2 precession is deduced from the asymmetry (green) between the energy distributions, while the EDM signal is proportional to the directional asymmetry (red).

its momentum, we will use a combination of scintillating fibers and silicon strip detectors. Figure 3 shows the change of the decay positron energy distribution for two extreme spin orientations, along (blue) and opposite to (orange) the muon momentum. The measured positron energy distribution will oscillate between these two extremes as a function of the decay time, allowing the precession frequency, Ω, to be extracted. The frozen-spin condition can then be found by measuring Ω as a function of the radial electric field and interpolating to $\Omega(E) = 0$. In this case the spin will always point opposite to the momentum and we will measure the orange energy distribution.

Once the frozen-spin condition is met and in the case of an EDM, the muon spin will precess out of the orbit plane, c.f. Eq. (7), and start to point along or counter the magnetic field direction. By detecting the decay asymmetry, proportional to the longitudinal polarization $P(t) \propto (N_a - N_c)/(N_a + N_c)$, where N_a and N_c are the numbers of positrons tracked along or counter the B-field direction, we can detect a non-zero EDM. The directional decay asymmetry as a function of positron momentum is depicted in red in Fig. 3. In Phase I, the highest sensitivity to a muEDM is accomplished for a tracking detector sensitive to positron momenta above 40 MeV/c resulting in a mean asymmetry of about $A = 0.35$.

In summary, using Eq. (10) with $\gamma = 1.04$, $P_0 = 0.95$, $E_\mathrm{f} = 3\,\mathrm{MV/m}$ we expect a sensitivity of $\sigma(d_\mu) < 2.8 \times 10^{-16}\, e\cdot$cm per muon, which translates to $\sigma(d_\mu) < 3 \times 10^{-21}\, e\cdot$cm in a year of data taking assuming $N = 300\,\mathrm{s}^{-1}$ positron detections.

4. Outlook and conclusion

In the next few years we will setup an instrument to demonstrate all necessary techniques for the frozen-spin technique and search for a muon EDM with an annual sensitivity of better than $3 \times 10^{-21}\, e\cdot$cm. For Phase II we are designing a hi-fidelity NMR magnet which, when connected to a PSI beamline with muons of $p \approx 125$MeV/c and a flux of more than $1 \times 10^8\,\mathrm{s}^{-1}$, will result in a sensitivity to a muon EDM of better than $6 \times 10^{-23}\, e\cdot$cm. A further increase in sensitivity will require the simultaneous injection of several muons. This will only be possible when the Phase II instrument will be connected to a beamline at similar momentum with similar flux and much smaller lateral phase space, or an accordingly higher muon flux.

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