

# Tracker EDM analysis note: A measurement of the longitudinal magnetic field in Run-1

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## Abstract

This document briefly outlines the methodology of the longitudinal magnetic field,  $B_z$ , measurement using the tracker data in Run-1. The final results for the systematic uncertainty on  $\omega_a$  due to  $B_z$  are presented, and are found to be:  $0 \text{ ppm} < \frac{\Delta\omega_a}{\omega_a} < 4 \text{ ppm}$ .

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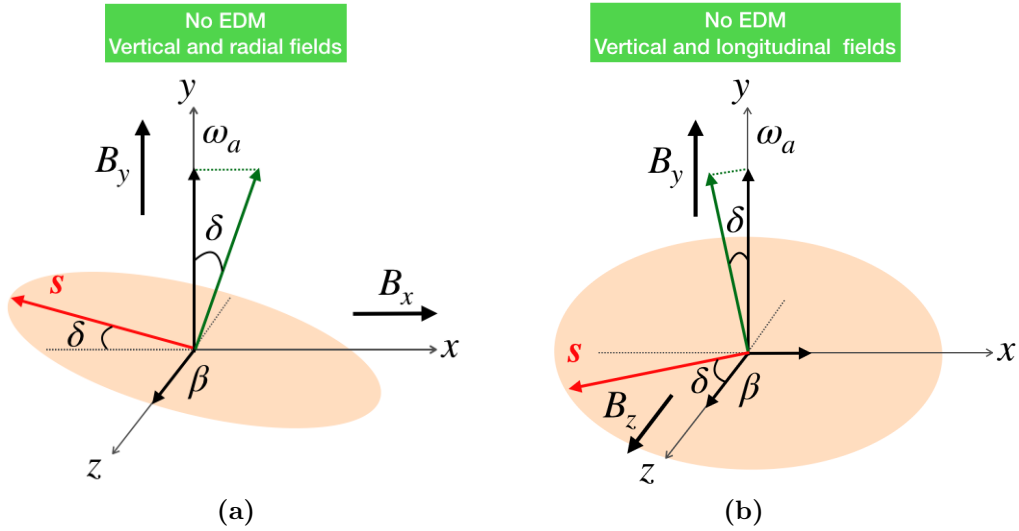
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# 1 Introduction

A presence of a longitudinal field,  $B_z$ , tilts the precession plane of the muon, as shown in Figure 1, and modifies [1] the observed precession frequency according to

$$\omega_a = a_\mu \frac{e}{m_\mu} B \rightarrow \frac{e}{m_\mu} \sqrt{(a_\mu B_y)^2 + \left( \frac{(1 + a_\mu) B_z}{\gamma} \right)^2}. \quad (1)$$

It is therefore imperative to estimate this systematic effect on  $\omega_a$ .



**Figure 1:** The tilt in the precession plane due to field components: a) radial ( $B_x$ ) b) longitudinal ( $B_z$ ). The momentum vector ( $\beta$ ) is along the  $z$ -axis. The tilt due to the radial field - towards the centre of the ring - is analogous to an effect due to an EDM. The longitudinal field, however, would produce a tilt towards the direction of the stored beam, by an angle  $\delta$ .

This tilt due to  $B_z$  can be used in the measurement of the average vertical angle of muon decay as a function of time: an up-down oscillation in-phase with  $\omega_a$  would be indicative of a longitudinal field.

## 2 Methodology

In this study, the measurement of the vertical angle,  $\theta_y$ , is coming from the tracking detector, where for each track a corresponding measurement of track time in a fill is available. This time is used to modulate data by the  $g - 2$  period,  $T_{g-2}$ , to remove any systematic effects that are not periodic with  $T_{g-2}$  (e.g. VBO). This is analogous to the method used in the BNL EDM analysis by M. Sossong [2]. The remaining analysis steps also follow the Sossong's methodology closely, and are presented in detail in DocDB:22201 [3]. These steps include fitting data for the number oscillation

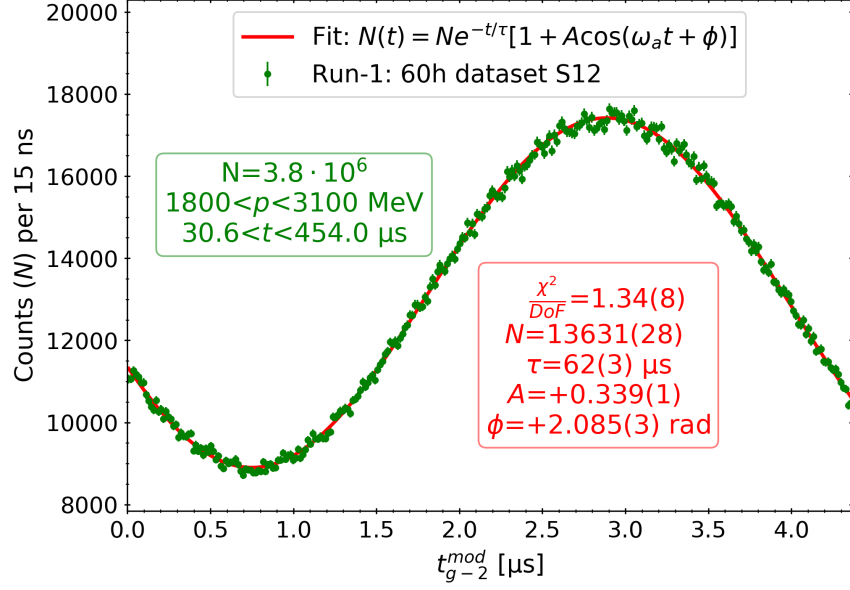
$$N(t) = Ne^{-t/\tau}[1 + A \cos(\omega_a t + \phi)], \quad (2)$$

using a constant value of 1.439 311 MHz for  $\omega_a$ , as measured at the BNL  $g - 2$  [4]. This is shown in Figure 2a. The value of  $\phi$  from Equation (2) is then used in the fit to the vertical angle oscillation

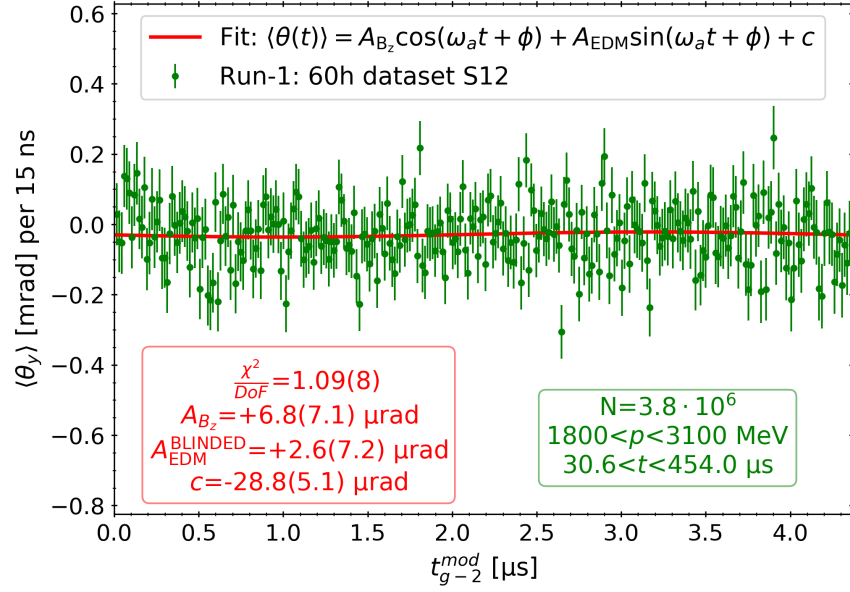
$$\theta(t) = A_{B_z} \cos(\omega_a t + \phi) + A_{\text{EDM}} \sin(\omega_a t + \phi) + c, \quad (3)$$

where  $A_{B_z}$  is the amplitude due to the longitudinal magnetic field,  $A_{\text{EDM}}$  is the EDM amplitude, and  $c$  is the overall offset. This is shown in Figure 2b.  $A_{\text{EDM}}$  is blinded with data, as discussed in DocDB:22201 [3].

Parameter stability scans with fit start time, fit end time, momentum cuts, bin width, and a choice of  $T_{g-2}$  (i.e.  $\omega_a$ ) and  $\phi$  are also presented in DocDB:22201 [3], and are found to be stable.



(a)

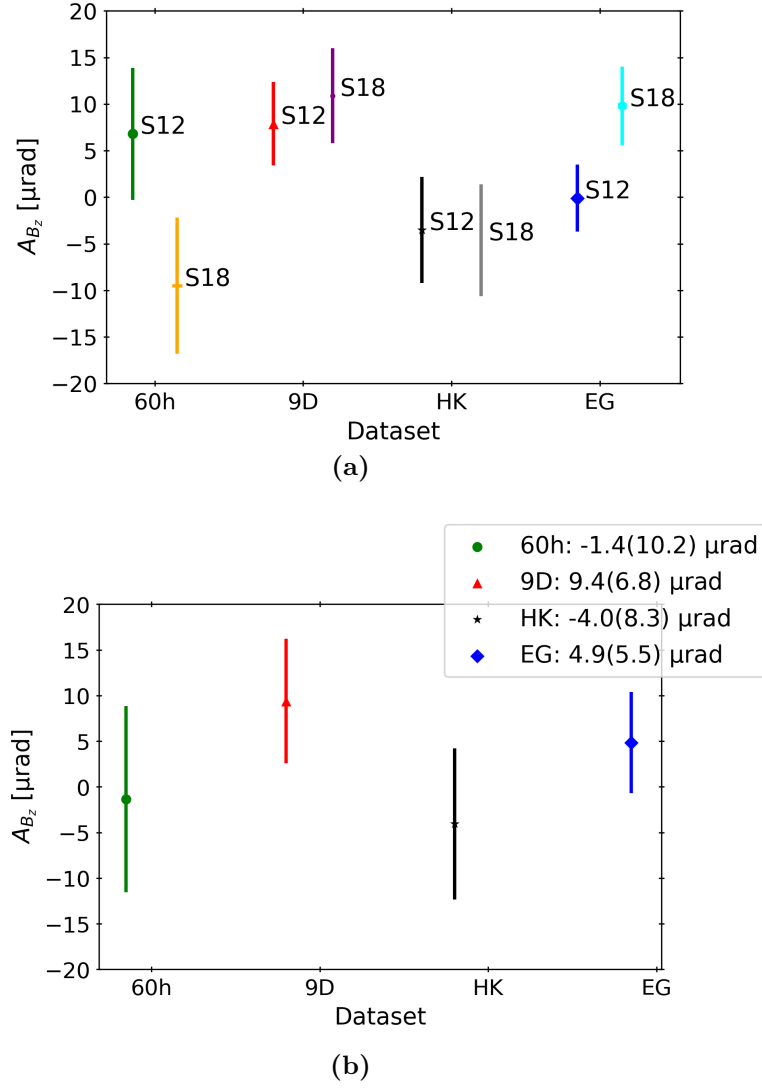


(b)

**Figure 2:** Fitting results in the 60h dataset for S12: a) number oscillation, and b) average vertical angle oscillation.

### 3 Results

The observed (i.e. fitted) amplitudes of the vertical angle oscillation due to  $B_z$  (i.e.  $A_{B_z}$ ) from all the four Run-1 datasets are presented in Figure 3.



**Figure 3:** Fitting results in all Run-1 datasets: a) S12 and S18 separately, and b) mean of the two stations. The individual fit results are summarised in DocDB:22201 [3].

Joe has posted a great and comprehensive note [5], which deals with a conversion from an observed amplitude to an estimated value of  $B_z$ . The conversion steps are as follows. Asymmetry term,  $A = 0.1$ , is connecting the observed amplitude ( $A_{B_z}$ ) with the actual precession plane tilt in the lab frame ( $\delta'$ )

$$A_{B_z} = 0.1\delta'. \quad (4)$$

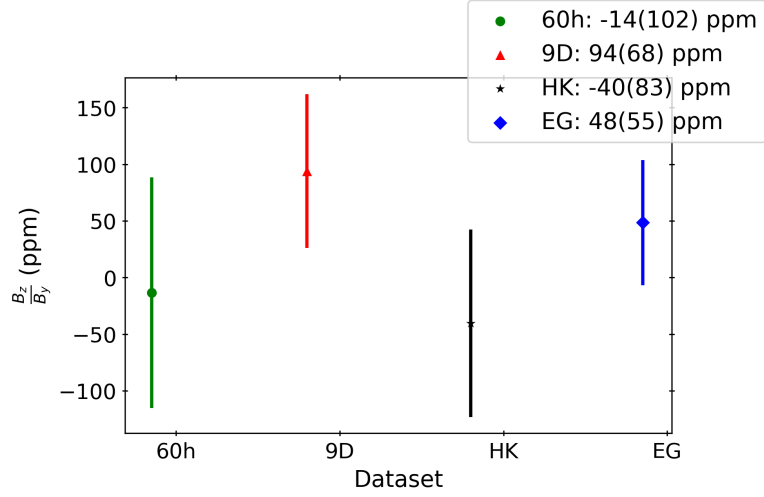
Asymmetry is accounting for the fact that not all positrons are emitted in the direction of polarisation vector [5]. Given that the muon motion is along  $z$  (c.f. Figure 1), there is no Lorentz boost in this direction. Therefore, the estimate of  $B_z$  is directly available from the measured angle in the lab frame, after the asymmetry term is taken into account. Hence,

$$\delta' = \tan\left(\frac{B_z}{B_y}\right) \approx \frac{B_z}{B_y}. \quad (5)$$

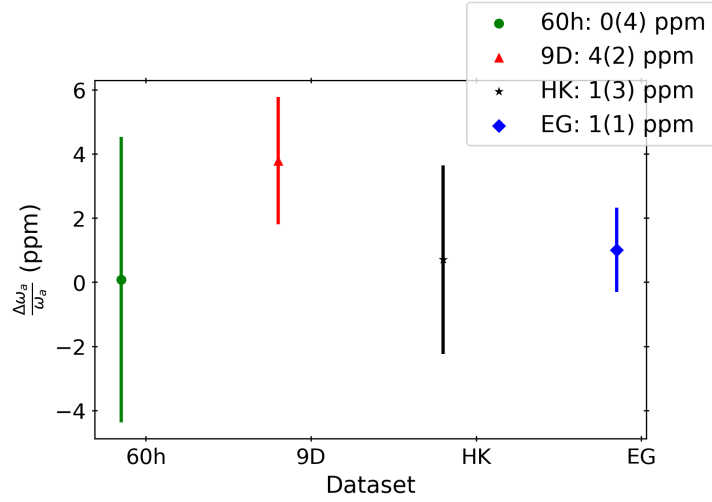
Finally, the corresponding systematic uncertainty on  $\omega_a$  can be estimated using the formula in Bill's note [1]

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{2} \left( \frac{(1 + a_\mu) B_z}{a_\mu \gamma B_y} \right)^2. \quad (6)$$

The final results of the application of Equations (5) and (6) to Run-1 vertical angle oscillation is given in Figure 4.



(a)



(b)

**Figure 4:** Run-1 systematic uncertainty results: a)  $B_z$  in ppm and b)  $\omega_a$  in ppm.

Given the range of values in Figure 4b, the uncertainty spread on  $\omega_a$  can be summarised as

$$0 \text{ ppm} < \frac{\Delta\omega_a}{\omega_a} < 4 \text{ ppm}. \quad (7)$$

## References

- [1] B. Morse, *Traceback and geometric phase systematic error*,  $g - 2$  DocDB:1839 (2014).
- [2] M. Sossong, *A search for an electric dipole moment of the positive muon*, PhD thesis, University of Illinois at Urbana-Champaign (2005).
- [3] G. Lukicov, *EDM: Longitudinal field*,  $g - 2$  DocDB:22201 (2020).
- [4] G. Bennett et al., *Final report of the Muon E821 anomalous magnetic moment measurement at BNL*, Phys. Rev. D **73**, 072003 (2006).
- [5] J. Price, *Note on Gleb's talk (22201)*,  $g - 2$  DocDB:22213 (2020).

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