The muon $g-2$ experiment

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Summary. — Measurements of the anomalous magnetic moment of the muon, a_μ, with increased precision are motivated by the ~ 3 standard deviation discrepancy between the most recent measurement performed at the Brookhaven National Laboratory (BNL) by the experiment E821 and the standard model prediction. A brief summary of the current theoretical and experimental status is reported in this proceeding.

1. – Introduction

In the standard model (SM) of particle physics, the muon is described as a point-like spin-1/2 particle with a magnetic dipole moment, $\vec{\mu}$, proportional to its spin, $\vec{s}$: $\vec{\mu} = g(q/2m_\mu)\vec{s}$, with g the gyromagnetic factor, q the electric charge and m_μ the mass of the muon. In the framework of Dirac's relativistic theory g is exactly 2 for muons. However, since Schwinger (1947) addressed the discrepancy between predictions and measurements of the hydrogen hyperfine structure by adding QED-corrections to the Dirac magnetic moment, it is expected $g > 2$ [1]. The fractional deviation of g from 2, $a_\mu = (g-2)/2$, is called muon anomaly.

The comparison between the most recent experimental value, measured at BNL by the experiment E821 (2006), and the SM prediction of a_μ results in a discrepancy of ~ 3 standard deviations [2]. This disagreement might imply physics beyond the standard model: for this reason, both the experimental measurement and the theoretical prediction are being improved.

2. – Current Standard-Model expectation and experimental value

The anomalous magnetic moment of the muon incorporates all the corrections to the Dirac magnetic moment, which include contribution from quantum electrodynamics (a_μ^{QED}), electroweak (a_μ^{EW}) and quantum cromodynamics (a_μ^{Had}) theories.

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TABLE I. – *Current theoretical and experimental values of a_μ. The contributions to the Standard Model expectation are detailed. All terms are defined in the text.*

	Contribution		$a_\mu(\times 10^{-11})$				
QED		a_μ^{QED}	116584718.95	$\pm$	0.08		[3]
EW		a_μ^{EW}	154	$\pm$	1		[3]
Had	HVP (lo)	$a_\mu^{\mathrm{HVP(LO)}}$	6923	$\pm$	42		[3]
Had	HVP (ho)	$a_\mu^{\mathrm{HVP(HO)}}$	-98.4	$\pm$	0.7		[3]
Had	HLbL	a_μ^{HLbL}	105	$\pm$	26		[3]
Total SM	theoretical	a_μ^{SM}	116591802	$\pm$	49	(420 ppb)	[3]
E821 (2006)	experimental	a_μ^{E821}	116592089	$\pm$	63	(540 ppb)	[2]

The largest contribution to the SM value ($\mathcal{O}(10^{-3})$) has the lowest computed uncertainty ($<$ 1 ppb) and comes from the QED theory. The term a_μ^{QED} has been recently calculated up to five loop contribution, including all the loops involving photons and leptons (a total of 12672 Feynman diagrams). The electroweak term a_μ^{EW} ($\mathcal{O}(10^{-9})$), has been calculated out to two loops with a relatively small uncertainty (20 ppb of the total theoretical uncertainty) [3]. The hadronic part (a_μ^{had}) is the dominant contribution on the overall theoretical uncertainty because its computation is based on experimental data or is model-dependent. In particular, its evaluation comes from the sum of three different terms: the hadronic vacuum polarization at leading order (HVP, LO) and at higher orders (HVP, HO), and the hadronic light-by-light (HLbL). The term $a_\mu^{\mathrm{HVP(LO)}}$ has been extracted from measurements performed at the e^+e^- colliders by BESIII, BaBar, CMD2, SND and KLOE collaborations [3], while $a_\mu^{\mathrm{HVP(HO)}}$ is obtained by using a dispersion relation [3]. Finally, a_μ^{HLbL} calculation is model-dependent and uses data from experiments as constraints [3].

The current theoretical expectation of a_μ (a_μ^{SM}) and the values and uncertainties of each contribution are reported in table I together with the experimental result from the BNL experiment E821 (a_μ^{E821}).

The muon $g-2$ experiment at Fermilab is designed to reduce the uncertainty of the BNL experiment by a factor of four, which would result in 5 standard deviations from the SM calculation if the value a_μ^{E821} is confirmed [4]. At the same time an improvement of the theoretical prediction is also expected. The projected theoretical uncertainty goal is 310 ppb, which should be reached by performing a more precise calculation of the hadronic contribution, particularly the term $a_\mu^{\mathrm{HVP(LO)}}$, which at present carries the largest source of uncertainty [3].

3. – The Muon g – 2 experiment

The muon $g-2$ experiment is under construction and assembly at the Muon Campus at Fermilab. The muon beam is provided by the accelerator complex. The 8 GeV protons produced by the Booster are injected into the Recycler ring where they are re-bunched and transported to the target station. The proton beam collides with an Inconel target producing pions which are transferred into the Delivery Ring where they decay into muons and neutrinos. A 3.1 GeV/c polarized and positively-charged muon beam is then extracted and delivered to storage ring. The beam is designed to have higher rate and better quality than the BNL beam, resulting in a projection of a factor of 20 increase in muon statistics with respect to the previous experiment. It follows that the statistical uncertainty expected for the E989 experiment is about 100 ppb. The storage ring, which was transported from BNL to Fermilab, is a superconducting magnet with a diameter of 14 m that provides an highly uniform 1.45 T magnetic field. Injection of the beam into the ring is provided by an inflector, kickers and collimators, while muons are kept focused inside the magnetic ring by electrostatic quadrupoles. The ring is also instrumented with a beam monitoring system and a trolley that travels inside the ring orbit and measures the magnetic field. Muons decay into positrons and neutrinos inside the ring and, positrons curve inwards where 24 highly segmented lead-fluorid electromagnetic calorimeters and 3 straw trackers chambers are positioned to detect them.

The quantities directly measured are the precession frequency, ω_a and the magnetic field ($\vec{B}$) in units of proton Larmor frequency, ω_p. These frequencies are related to the anomaly a_μ via:

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{m_\mu c}{p_\mu}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{1}$$

with $\vec{\omega}_S$ the muon spin precession rate, $\vec{\omega}_C$ the muon cyclotron frequency, m_μ and p_μ the mass and the momentum of the muon, $\vec{\beta}$ the muon velocity in units of the speed of light c and, $\vec{E}$ the electric field. The measurement is performed at a magic momentum of $p_\mu = 3.094$ GeV/c, so the second term term (*i.e.*, the electric field term) cancels out, leaving the relation:

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}, \tag{2}$$

where $\vec{B}$ is expressed in terms of ω_p and μ_μ/μ_p is the muon-to-proton magnetic moment ratio taken from independent measurements on the muonium hyperfine structure. The term ω_a is measured by fitting the rate of the positrons detected by the calorimeters, while ω_p by using nuclear magnetic resonance (NMR) probes.

4. – Conclusions

Precise measurements of the anomalous magnetic moment a_μ will provide an insight into the SM of particle physics and beyond. Currently the uncertainty on the experimental a_μ value is 540 ppb while the uncertainty on the theoretical prediction is 420 ppb. The goal of the Muon $g-2$ experiment at Fermilab (E989) is to reduce the uncertainty on the experimental measurement by a factor 4 (goal of 140 ppb), meanwhile improvements in the theoretical calculation are also expected. The E989 experiment is now at the end of the installation phase and entering the commissioning stage, physics-data taking is expected to start later this year.

REFERENCES

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