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The calculation of the muon g-2 and $\Delta\alpha(M_Z^2)$

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The current status of the Standard Model prediction of the anomalous magnetic moment of the muon is presented and compared with the experimental value. The determination of the effective electromagnetic coupling constant at the scale of the Z mass is also briefly reviewed.

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1. Introduction

During the last few years, in a sequence of increasingly precise measurements, the E821 Collaboration at Brookhaven has determined $a_\mu = (g_\mu - 2)/2$ with a fabulous relative precision of 0.5 parts per million (ppm) [1–3], serving as an invaluable tool to test all sectors of the Standard Model (SM) and to scrutinize viable alternatives to this theory [4]. The impressive results of the E821 experiment are still limited by statistical errors. A new experiment, E969, has been approved (but not yet funded) at Brookhaven in 2004 [3, 5]. Its goal is to reduce the present experimental uncertainty by a factor of 2.5 to about 0.2 ppm. A letter of intent for an even more precise $g-2$ experiment was submitted to J-PARC with the proposal to reach a precision below 0.1 ppm [6]. This note provides a brief summary of the present status of the three contributions into which the SM prediction a_μ^{SM} is usually split – QED, electroweak and hadronic – and a comparison with the current experimental value.

Among the three basic input parameters of the electroweak (EW) sector of the SM – the fine-structure constant α, the Fermi coupling constant G_F and the mass of the Z boson – α is by far the most precisely known, determined mainly from the anomalous magnetic moment of the electron with an amazing relative precision of 3.3 parts per billion (ppb). However, physics at nonzero squared momentum transfer q^2 is actually described by an effective electromagnetic coupling $\alpha(q^2)$ rather than by the low-energy constant α itself. The shift of the fine-structure constant from the Thomson limit to high energy involves non-perturbative effects which can be studied with methods similar to those employed for the evaluation of the leading hadronic contribution to a_μ.

2. The anomalous magnetic moment of the muon

The QED contribution to a_μ arises from the subset of SM diagrams containing only leptons (e, μ, τ) and photons. The lowest-order contribution is $a_\mu^{QED}(1 \text{ loop}) = \alpha/(2\pi)$ [7]. Also the two- and three-loop QED terms are known analytically – see [8] for an update and a review of these contributions. The four-loop term has been evaluated numerically, a formidable task first accomplished by Kinoshita and his collaborators in the early 1980s [9]. The latest analysis appeared in [10]. Note that this four-loop contribution is about six times larger than the present experimental uncertainty of a_μ! The evaluation of the five-loop QED contribution is in progress [11]. Adding up these terms, using the latest CODATA [12] recommended value $\alpha^{-1} = 137.035\,999\,11\,(46)$ [3.3 ppb], one obtains $a_\mu^{QED} = 116\,584\,718.8\,(0.3)\,(0.4) \times 10^{-11}$ [8]. The first error is mainly due to the uncertainty of the $O(\alpha^5)$ term, while the second one is caused by the uncertainty of the fine-structure constant.

The EW contribution to a_μ is suppressed by a factor $(m_\mu/M_W)^2$ with respect to the QED effects. The one-loop part was computed in 1972 by several authors [13]: $a_\mu^{EW}(1 \text{ loop}) = 194.8 \times 10^{-11}$. The two-loop EW contribution to a_μ, computed in 1995 [14], is not negligible because of large factors of $\ln(M_{Z,W}/m_f)$, where m_f is a fermion mass scale much smaller than M_W [15]. The proper treatment of the contribution of the light quarks was addressed in [16, 17]. These refinements significantly improved the reliability of the fermionic part (that containing closed fermion loops) of a_μ^{EW}(two loop) leading, for $M_H = 150$ GeV, to $a_\mu^{EW} = 154(1)(2) \times 10^{-11}$ [17]. The first error is due to hadronic loop uncertainties, while the second one corresponds to an allowed range of $M_H \in [114, 250]$ GeV, to the current top mass uncertainty, and to unknown three-loop effects. The leading-logarithm three-loop contribution to a_μ^{EW} is extremely small [17, 18]. The results of [19] for the two-loop bosonic part of a_μ^{EW}, performed without the large M_H approximation previously employed, agree with the previous evaluation [14] in the large Higgs mass limit. Work is also in progress for an independent recalculation based on the numerical methods of [20].

The evaluation of the hadronic leading-order contribution a_μ^{HLO}, due to the hadronic vacuum polarization correction to the one-loop diagram, involves long-distance QCD for which perturbation theory cannot be employed. However, using analyticity and unitarity, it was shown long ago that this term can be computed from hadronic e^+e^- annihilation data via the dispersion integral $a_\mu^{HLO} = (1/4\pi^3)\int_{4m_\pi^2}^\infty ds K(s)\sigma^{(0)}(s) = (\alpha^2/3\pi^2)\int_{4m_\pi^2}^\infty ds K(s)R(s)/s$ [21], where $\sigma^{(0)}(s)$ is the total cross section for e^+e^- annihilation into any hadronic state, with extraneous QED corrections subtracted off, and $R(s) = \sigma^{(0)}(s)/(4\pi\alpha^2/3s)$. The kernel function $K(s)$ decreases monotonically for increasing s. A prominent role among all e^+e^- annihilation measurements is played by the precise data collected in 1994-95 by the CMD-2 detector at the VEPP-2M collider in Novosibirsk for the $e^+e^- \to \pi^+\pi^-$ cross section at values of $\sqrt{s}$ between 0.61 and 0.96 GeV [22] (quoted systematic error 0.6%, dominated by the uncertainties in the radiative corrections). At this Conference [23] the CMD-2 Collaboration released its 1996-98 measurements for the same cross section in the full energy range $\sqrt{s} \in [0.37, 1.39]$ GeV. The part of these data for $\sqrt{s} \in [0.61, 0.96]$ GeV (quoted systematic error 0.8%) agrees with the earlier result of ref. [22]. Also the SND Collaboration (at the VEPP-2M collider as well) recently presented its analysis of the $e^+e^- \to \pi^+\pi^-$ process for $\sqrt{s}$ between 0.39 and 0.98 GeV, with a systematic uncertainty of 1.3% (3.2%) for $\sqrt{s}$ larger (smaller) than 0.42 GeV [24]. A hint of discrepancy, at the level of the combined systematic error, occurs between the CMD-2 and SND measurements (the contribution to a_μ^{HLO} of the SND data is a bit higher than the corresponding one from CMD-2) [23]. Further significant progress is expected from the new e^+e^- collider VEPP-2000 under construction in Novosibirsk [23, 25]. In 2004 the KLOE experiment at the DAΦNE collider in Frascati presented a precise measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ via the initial-state radiation (ISR) method at the ϕ resonance [26]. This cross section was extracted for $\sqrt{s}$ between 0.59 and 0.97 GeV with a systematic error of 1.3% and a negligible statistical one. There are some discrepancies between the KLOE and CMD-2 results (KLOE's data lying higher than the CMD-2 fit below the ρ peak, and lower on the peak and above it), although their integrated contributions to a_μ^{HLO} are similar [23]. The data of KLOE and SND disagree above the ρ peak, where the latter are significantly higher. The study of the $e^+e^- \to \pi^+\pi^-$ process via the ISR method is also in progress at BABAR [27] and BELLE [28]. On the theoretical side, analyticity, unitarity and chiral symmetry provide strong constraints for the pion form factor in the low-energy region [29]. The evaluations of the dispersive integral based on the CMD-2 analysis of ref. [22] are in good agreement, as it can be seen from the first four entries in the first column of Table 1 (the fifth and the sixth will be discussed below; [33] quotes two values). Reference [30] updates [34] and already includes KLOE's results. The recent data of CMD-2 [23] and SND [24] are not yet included.

The authors of [35] pioneered the idea of using vector spectral functions derived from the study of hadronic τ decays [36, 37] to improve the evaluation of the dispersive integral. The latest analysis with ALEPH, CLEO, and OPAL data [38] yields $a_\mu^{HLO} = 7110\,(50)_{exp}(8)_{rad}(28)_{SU(2)} \times 10^{-11}$[34]. Isospin-breaking corrections were applied [39]. Information from τ decays was also included in one of the analyses of [33], leading to $a_\mu^{HLO} = 7027\,(47)_{exp}(10)_{rad} \times 10^{-11}$. Although the precise CMD-2 $e^+e^- \to \pi^+\pi^-$ data [22] are consistent with the corresponding τ ones for energies

[Ref]	$a_\mu^{HLO} \times 10^{11}$	$a_\mu^{SM} \times 10^{11}$	$\Delta \times 10^{11}$	σ	
[30]	$6934\,(53)_{exp}(35)_{rad}$	116 591 845 (69)	235 (91)	2.6	$\langle 3.0\rangle$
[31]	$6948\,(86)$	116 591 859 (90)	221 (108)	2.1	$\langle 2.5\rangle$
[32]	$6924\,(59)_{exp}(24)_{rad}$	116 591 835 (69)	245 (91)	2.7	$\langle 3.1\rangle$
[33]	$6944\,(48)_{exp}(10)_{rad}$	116 591 855 (55)	225 (81)	2.8	$\langle 3.2\rangle$
[34]	$7110\,(50)_{exp}(8)_{rad}(28)_{SU(2)}$	116 592 018 (63)	62 (87)	0.7	$\langle 1.3\rangle$
[33]	$7027\,(47)_{exp}(10)_{rad}$	116 591 938 (54)	142 (81)	1.8	$\langle 2.3\rangle$

Table 1: Muon anomalous magnetic moment: Standard Model versus measurement.

below ~ 0.85 GeV, they are significantly lower for larger energies. KLOE's $\pi^+\pi^-$ spectral function confirms this discrepancy with the τ data; on the contrary, the recent SND results are compatible with them [24]. This discrepancy could be caused by inconsistencies in the e^+e^- or τ data, or in the isospin-breaking corrections which must be applied to the latter [30, 40].

The hadronic higher-order contribution can be divided into two parts: $a_\mu^{HHO} = a_\mu^{HHO}(\mathrm{vp}) + a_\mu^{HHO}(\mathrm{lbl})$. The first one is the $O(\alpha^3)$ contribution of diagrams containing hadronic vacuum polarization insertions [41]. Its latest value is $a_\mu^{HHO}(\mathrm{vp}) = -97.9\,(0.9)_{exp}(0.3)_{rad} \times 10^{-11}$ [32], obtained using e^+e^- annihilation data; it changes by $\sim -3\times 10^{-11}$ if hadronic τ-decay data are used instead [42]. The second term, also of $O(\alpha^3)$, is the hadronic light-by-light contribution; as it cannot be determined from data, its evaluation relies on specific models. In 2001 the authors of [43] uncovered a sign error in earlier evaluations of its dominating pion-pole part. Their estimate, based also on previous results for the quark and charged-pions loop parts [44], is $a_\mu^{HHO}(\mathrm{lbl}) = 80\,(40) \times 10^{-11}$ [45]. A higher value was obtained in 2003 including short-distance QCD constraints: $a_\mu^{HHO}(\mathrm{lbl}) = 136\,(25) \times 10^{-11}$ [46]. Further independent calculations would provide an important check of this result for $a_\mu^{HHO}(\mathrm{lbl})$, a contribution whose uncertainty may become the ultimate limitation of the SM prediction of the muon $g-2$.

The second column of Table 1 shows the values obtained for $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLO} + a_\mu^{HHO}$, derived with $a_\mu^{HHO}(\mathrm{lbl}) = 136\,(25) \times 10^{-11}$ [46]. Errors were added in quadrature. The present world average experimental value for the muon $g-2$ is $a_\mu^{EXP} = 116\,592\,080\,(60) \times 10^{-11}$ (0.5 ppm) [2]. The differences $\Delta = a_\mu^{EXP} - a_\mu^{SM}$ are listed in the third column of the Table, while the numbers of "standard deviations" (σ) appear in the fourth one. Higher discrepancies, shown in angle brackets, are obtained if $a_\mu^{HHO}(\mathrm{lbl}) = 80\,(40) \times 10^{-11}$ [45] is used instead of $136\,(25) \times 10^{-11}$ [46].

3. The effective fine-structure constant

The effective fine-structure constant at squared momentum transfer $q^2 = M_Z^2$ can be defined by $\alpha(M_Z^2) = \alpha/[1-\Delta\alpha(M_Z^2)]$, where $\Delta\alpha(M_Z^2) = 4\pi\alpha\,\mathrm{Re}[\Pi_{\gamma\gamma}^{(f)}(0) - \Pi_{\gamma\gamma}^{(f)}(M_Z^2)]$ and $\Pi_{\gamma\gamma}^{(f)}(q^2)$ is the fermionic part of the photon vacuum polarization function. The measurement at LEP of the running of the electromagnetic coupling was discussed at this Conference in [47]. Even if the atomic physics parameter α is known with great accuracy, the evaluation of the denominator $\mathrm{Re}[\Pi_{\gamma\gamma}^{(f)}(0) - \Pi_{\gamma\gamma}^{(f)}(M_Z^2)]$ involves long-distance QCD dynamics in the contribution $\Delta\alpha_{\mathrm{had}}^{(5)}$ of the five light quarks (u, d, s, c, and b) for which perturbation theory cannot be employed. Indeed, a dramatic loss of accuracy, by several orders of magnitude, occurs moving from the value of α at vanishing momentum transfer to that at $q^2 = M_Z^2$. The shift $\Delta\alpha(M_Z^2)$ can be split into three parts: $\Delta\alpha(M_Z^2) = \Delta\alpha_{\rm lep}(M_Z^2) + \Delta\alpha_{\rm top}(M_Z^2) + \Delta\alpha_{\rm had}^{(5)}(M_Z^2)$. The leptonic and top-quark contributions are calculable in perturbation theory, and known up to three-loops: $\Delta\alpha_{\rm lep}(M_Z^2) = 3149.7686 \times 10^{-5}$ [48] and $\Delta\alpha_{\rm top}(M_Z^2) = -7.0\,(0.5) \times 10^{-5}$ [49]. The hadronic contribution $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$ can be computed from hadronic e^+e^- annihilation data via the dispersion relation [50]

$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = -\left(\frac{\alpha M_Z^2}{3\pi}\right) {\rm Re} \int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}.$$

This integral is very similar to the one we encountered earlier for the leading hadronic contribution to a_μ. There, however, the weight function in the integrand gives a stronger weight to low-energy data. In the 1990s, detailed evaluations of this dispersive integral have been carried out by several authors [51, 35, 49]. More recently, some of these analyses were updated to include new e^+e^- data – mostly from CMD-2 and BES [52] – obtaining: $\Delta\alpha_{\rm had}^{(5)} = 2761\,(36) \times 10^{-5}$ [53], $\Delta\alpha_{\rm had}^{(5)} = 2757\,(36) \times 10^{-5}$ [54], $\Delta\alpha_{\rm had}^{(5)} = 2755\,(23) \times 10^{-5}$ [32], and $\Delta\alpha_{\rm had}^{(5)} = 2749\,(12) \times 10^{-5}$ [33]. The reduction, by a factor of two, of the uncertainty quoted in the first article of ref. [51] (70×10^{-5}), with respect to that in [54] (36×10^{-5}), is mainly due to the data of BES. The latest update, $\Delta\alpha_{\rm had}^{(5)} = 2758\,(35) \times 10^{-5}$ [55] (June 2005), includes also the measurements of KLOE (see above), although, contrary to the case of a_μ^{HLO}, the influence of these recent low-energy data turns out to be very small. The simple formulae of refs. [56], relating EW observables with $\Delta\alpha_{\rm had}^{(5)}$ and other experimental inputs, allow to set bounds on the mass of the Higgs boson. The uncertainty in $\Delta\alpha_{\rm had}^{(5)}$ has a non-negligible impact on this determination. The influence of $\Delta\alpha_{\rm had}^{(5)}$ on the global EW fit and the importance of a reduced value of its uncertainty were discussed also at this Conference [57].

4. Conclusions

The SM determinations of the muon anomalous magnetic moment and the effective electromagnetic coupling constant at the scale M_Z are limited by the evaluation of the hadronic vacuum polarization. The latest determinations of the contribution $\Delta\alpha_{\rm had}^{(5)}$ of the five light quarks (u, d, s, c and b) were briefly reviewed in the previous section.

Recent SM predictions of the muon $g-2$ were presented in Table 1. The leading-order hadronic contribution to a_μ depends on which of the two sets of data, e^+e^- collisions or τ decays, are employed. The puzzling discrepancy between the $\pi^+\pi^-$ spectral functions from e^+e^- and isospin-breaking-corrected τ data could be caused by inconsistencies in the e^+e^- or τ data, or in the isospin-breaking corrections applied to the latter. Indeed, disagreements occur between e^+e^- data sets, requiring further detailed investigations. On the other hand, the connection of τ data with the leading hadronic contribution to a_μ is less direct, and one wonders whether all possible isospin-breaking effects have been properly taken into account [30, 40]. The discrepancies between recent SM predictions of a_μ and the current experimental value vary in a very wide range, from 0.7 to 3.2 σ, according to the values chosen for the hadronic contributions. Using only e^+e^- data, this range narrows to 2–3 σ.

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