Scalar mesons and the muon anomaly

Stephan Narison

Laboratoire de Physique Mathématique et Théorique, Université de Montpellier II, Case 070, Place Eugène Bataillon, 34095 - Montpellier Cedex 05, France.
E-mail: qcd@lpm.univ-montp2.fr

We evaluate systematically some new contributions of the QCD scalar mesons, including radiative decay-productions, not considered with a better attention until now in the evaluation of the hadronic contributions to the muon anomaly. The sum of the scalar contributions to be added to the existing Standard Model predictions \(a_{\mu}^{SM}\) are estimated in units \(1 \times 10^{-10}\) to be \(a_{\mu}^{SM} = 1.0(0.6)\) [TH based] and 13(11) [PDG based], where the errors are dominated by the ones from the experimental widths of these scalar mesons. PDG based results suggest that the value of \(a_{\mu}^{SM}\) and its errors might have been underestimated in previous works. The inclusion of these new effects leads to a perfect agreement (\(\leq 1.1\sigma\)) of the measured value \(a_{\mu}^{exp}\) and \(a_{\mu}^{SM}\) from \(\tau\)-decay and implies a \((1.5 \sim 3.3)\sigma\) discrepancy between \(a_{\mu}^{exp}\) and \(a_{\mu}^{SM}\) from \(e^+e^- \rightarrow \) hadrons data. More refined unbiased estimates of \(a_{\mu}^{SM}\) require improved measurements of the scalar meson masses and widths. The impact of our results to \(a_{\mu}^{SM}\) is summarized in the conclusions.

1. INTRODUCTION

Improved accurate experimental measurement \(\tau\) and recent theoretical estimates of the muon anomaly \(2\,3\,4\,5\) are now available. The theoretical accuracy in \(2\,3\) is mainly attributed to the use of the new CMD-2 \(6\) around the \(\rho\) mass and on BES data \(7\) around the \(J/\Psi\) region. The impact of the former data on the determination of the muon anomaly is intuitively more important due to the low-energy dominance of the anomaly kernel function \(3\). However, what is more intriguing within this increasing precision is the discrepancy between the results from \(e^+e^-\) and \(\tau\)-decay data \(2\,3\), which was not the case in the previous determinations using preliminary data \(1\). In this short note, we study some other sources of contributions, not considered with a better attention until now, from the scalar mesons. These scalar \((qq, \text{gluonia},...)\) are conceptually fundamental consequences of QCD. Though their existence is not precisely confirmed, there are increasing evidences of their findings in different \(e^+e^-\) and hadronic experiments \(10\).

2. ISOSCALAR SCALAR MESONS

The interest in these \(I = 0\) scalar mesons are that they cannot be obtained from usual ChPT approaches. They are related to the QCD scale anomaly:

\[
\theta^\mu = \frac{1}{4} \beta(\alpha_s) G^2 + \sum_i [1 + \gamma_m(\alpha_s)] m_i \bar{\psi}_i \psi_i ,
\]

where \(G_{\mu\nu}^a\) is the gluon field strengths, \(\psi_i\) is the quark field; \(\beta(\alpha_s)\) and \(\gamma_m(\alpha_s)\) are respectively the QCD \(\beta\)-function and quark mass-anomalous dimension. In this case, arguments based on \(SU(2)\) symmetry or its violation used to estimate some processes like e.g. radiative processes cannot be applied \(11\). Using QCD spectral sum rules (QSSR) \(12\,13\) and low-energy theorems (LET) for estimating the mass and its width, it has been shown in \(14\,15\) that the wide \(\sigma(0.60)\) meson is the best candidate meson (gluonium) associated to the previous interpolating current (see also \(10\)). Its mass is due to the gluon component and its large width into \(\pi\pi\) is due to a large violation of the OZI rule \(^2\) (analogue of the \(\eta'\)-meson of the \(U(1)_A\) sector \(17\)). The observed

\(^1\)Though agreeing in the total sum, the results from these two estimates differ in each energy region.

\(^2\)This feature also implies that lattice calculations of the gluonium mass in pure Yang-Mills or quenched approximation are bad approximations and might miss this “unusual” glueball.
σ(0.60) and f₀(0.98) can be explained by a “maximal quarkonium-gluonium mixing scheme” \[14\], \[15\]. In the following, we study the σ and other scalar mesons contributions to the muon anomaly.

3. THE e⁺e⁻ → Sγ PROCESSES

Using analytic properties of the photon propagator, the general contribution to the muon anomaly from the process:

\[ e^+e^- \rightarrow \gamma \rightarrow \text{hadrons} \]  \( \text{(2)} \)

can be written in a closed form as \[8\]:

\[ a_{l}^{l,l}(l,m) = \frac{1}{4\pi^{3}} \int_{4m} d_{t} K_{i}(t) \sigma_{H}(t), \]  \( \text{(3)} \)

where:

- \( K_{i}(t \geq 0) \) is the QED kernel function \[9\]:

\[ K_{i}(t) = \int_{0}^{t} d_{x} x^{2} (1 - x) \left( \frac{x^{2} - 1}{2} + (1 - z_{i})^{2} \times \right) \]

\[ \left( 1 + \frac{1}{z_{i}} \right) \log(1 + z_{i}) - z_{i} \]

\[ + \frac{z_{i}^{2}}{2} \left( 1 + \frac{1}{z_{i}} \right) z_{i}^{2} \log z_{i}, \]  \( \text{(5)} \)

with:

\[ y_{i} = \frac{t}{4m_{i}^{2}}, \quad z_{i} = \frac{1 - v_{i}}{1 + v_{i}}, \quad \text{and} \quad v_{i} = \sqrt{1 - \frac{4m_{i}^{2}}{t}}. \]  \( \text{(6)} \)

\( K_{i}(t) \) is a monotonically decreasing function of \( t \). For large \( t \), it behaves as:

\[ K_{i}(t > m_{i}^{2}) \simeq \frac{m_{i}^{2}}{3t}, \]  \( \text{(7)} \)

which will be an useful approximation for the analysis in the large \( t \) regime. Such properties then emphasize the importance of the low-energy contribution to \( a_{l}^{l,l}(l,o) \) \( (l \equiv e, \mu) \), where the QCD analytic calculations cannot be applied.

- \( \sigma_{H}(t) \equiv \sigma(e^+e^- \rightarrow \text{hadrons}) \) is the \( e^+e^- \rightarrow \text{hadrons} \) total cross section which can be related to the hadronic two-point spectral function \( \text{Im}\Pi(t)_{em} \) through the optical theorem:

\[ R_{e^+e^-} = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 12\pi \text{Im}\Pi(t)_{em}, \]  \( \text{(8)} \)

where:

\[ \sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^{2}}{3t}. \]  \( \text{(9)} \)

Here,

\[ \Pi_{em}^{\mu\nu} = i \int d^{4}x \ e^{iqx} \langle 0| T J_{\mu}^{em}(x) (\bar{J}_{\nu}^{em}(x))^{\dagger} | 0 \rangle \]

\[ = - (g^{\mu\nu} q^{2} - q^{\mu} q^{\nu}) \Pi_{em}(q^{2}) \]  \( \text{(10)} \)

is the correlator built from the local electromagnetic current:

\[ J_{\mu}^{em}(x) = \frac{2}{3} \bar{u} \gamma_{\mu} u - \frac{1}{3} \bar{d} \gamma_{\mu} d - \frac{1}{3} \bar{s} \gamma_{\mu} s + \ldots \]  \( \text{(11)} \)

Using Vector Meson Dominance Model (VDM) in a Narrow Width Approximation (NWA), one obtains \[13\]:

\[ a_{\mu}^{VDM}(l,o) \simeq \frac{3}{\pi} K \left( \frac{M_{l}^{2}}{m_{l}^{2}} \right) \frac{\Gamma_{V \rightarrow e^+e^-}}{M_{V}} \frac{\Gamma_{V \rightarrow all}}{\Gamma_{V \rightarrow all}}. \]  \( \text{(12)} \)

The \( V \rightarrow \gamma X \) \( (X \equiv \sigma, f_{0}) \) coupling has been estimated from the \( X\gamma\gamma \) one given in \[14\], \[15\] and in the PDG data \[19\] and using the VDM relation:

\[ g_{X\gamma V} \simeq \frac{\sqrt{2} \gamma_{e}}{e} g_{X\gamma\gamma}, \]  \( \text{(13)} \)

where \( e \) is the electric charge and we use the normalization \( \gamma_{e} \sim 2.51 \pm 0.02. \) For the scalar mesons, we use:

\[ M_{\sigma} \simeq (0.6 \sim 0.8) \text{ GeV}, \]

\[ \Gamma_{\sigma \rightarrow \gamma\gamma} \simeq (0.2 \sim 0.3) \text{ keV QSSR} \]  \[14\], \[15\] \( \simeq (3.8 \pm 1.5) \text{ keV PDG} \]  \[19\], \[20\],

\[ \Gamma_{f_{0}(1.4) \rightarrow \gamma\gamma} \simeq (0.7 \sim 5.) \text{ keV}, \]  \( \text{(14)} \)

The ones of the other \( \omega \) and \( \phi \) radiative widths come from PDG \[19\]. We also use in MeV units \[19\]:

\[ \Gamma_{\omega(1.42) \rightarrow e^+e^-} \simeq 0.08 \times 10^{-3}, \quad \Gamma_{\omega \rightarrow all} \simeq 174(59) \]

\[ \Gamma_{\rho(1.45) \rightarrow e^+e^-} \simeq 0.44 \times 10^{-3}, \quad \Gamma_{\rho \rightarrow all} \simeq 310(60) \]

\[ \Gamma_{\phi(1.68) \rightarrow e^+e^-} \simeq 0.48 \times 10^{-3}, \quad \Gamma_{\phi \rightarrow all} \simeq 150(50) \],

\( \text{(15)} \)

We deduce the results in Table \[11\] where the first set of values corresponds to \( \Gamma_{\sigma \rightarrow \gamma\gamma} \) from QSSR and the second set of values to the \( \sigma \) width from PDG. It is clear from Table \[11\] that the results are very sensitive to the value of the \( \sigma \) mass and \( \gamma\gamma \) width. Though, in the “maximal quarkonium-gluonium mixing scheme” of the \( \sigma \) meson, one favours a small \( \gamma\gamma \) width \[14\], \[15\], the PDG data \[19\], \[20\] and some other QCD models still allow higher values. For a conservative and unbiased estimate, we translate the total sum in Table \[11\] into:

\[ a_{\mu}^{V} \times 10^{10} = 0.45(0.13) \text{ QSSR} \]

\[ = 7.30(5.60) \text{ PDG}. \]  \( \text{(16)} \)

In order to include this result into the one in \[2\], and for avoiding an eventual double counting, we “de-rescale” their result on the top of the \( \omega \) by 0.88 and on the \( \phi \) by the factor 0.984 used there for taking into account the missing modes. In this way, we obtain the corresponding “pure” hadronic decay:

\[ a_{\mu}(\omega + \phi \rightarrow 3\pi + K\bar{K}) = 67.04(1.50) \times 10^{-10}, \]  \( \text{(17)} \)

Using the \( \omega \) and \( \phi \) into \( \eta\gamma \) and \( \pi^{0}\gamma \) radiative decay widths from \[19\], we deduce:

\[ a_{\mu}(\omega + \phi \rightarrow \eta\gamma + \pi^{0}\gamma) = 4.36(0.16) \times 10^{-10}. \]  \( \text{(18)} \)
Table 1
$e^+e^- \rightarrow$ scalar+$\gamma$ contributions to $a^\text{had}_\mu$.

| Processes | $a^\text{had}_\mu \times 10^{10}$ |
|-----------|-----------------------------------|
|           | QSSR | PDG         |
| $\rho \rightarrow \sigma\gamma$ | $\sim 0.$ | $\sim 0.05$ |
| $\omega \rightarrow \sigma\gamma$ | $\sim 0.$ | $\sim 0.07$ |
| $\phi \rightarrow \sigma\gamma$ | $0.03 \sim 0.15$ | $1. \sim 10.$ |
| $\phi \rightarrow f_0(98)\gamma$ | PDG | $0.01 \pm 0.00$ |
| $\phi \rightarrow a_0(98)\gamma$ | PDG | $0.03 \pm 0.01$ |
| $\rho(1.45) \rightarrow \sigma\gamma$ | $0.01 \sim 0.02$ | $0.06 \sim 0.42$ |
| $\omega(1.42) \rightarrow \sigma\gamma$ | $0.10 \sim 0.17$ | $0.1 \sim 0.7$ |
| $\phi(1.68) \rightarrow \sigma\gamma$ | $0.14 \sim 0.20$ | $0.17 \sim 1.17$ |
| $\phi(1.68) \rightarrow f_0(1.4)\gamma$ | - | - |
| Total     | $0.45 \pm 0.13$ | $7.3 \pm 5.6$ |

*) For completeness, we also include the contribution of the isovector $a_0(980)$.

4. NEW CONTRIBUTIONS OF THE SCALAR MESON TO $a_\mu$

Here, we study the effect of scalar mesons via a Higgs-like triangle diagram shown in Fig. 1. This new hadronic contribution to $a^\text{had}_\mu$ cannot be estimated using the usual electromagnetic spectral function associated to one virtual photon. The evaluation of this diagram gives the contribution (see e.g. [24]):

$$a^\text{SU}_\mu = \frac{|q_F|^2}{16\pi^2} \int_0^1 dx \frac{x^2(2-x)}{x^2 + (M_S^2/m_{\mu}^2)(1-x)},$$

where $M_S$ is the scalar mass and $q_F$ is the “effective” $S\ell^+\ell^-$ coupling. However, the coupling of these scalar mesons to $e^+e^-$ is not known, and in the case of the isoscalar, the naïve argument based on chiral symmetry (Higgs-type coupling) may not be applied due to the presence of gluon fields in the $U(1)_V$ dilaton current given in Eq. (1). Note that these scalar mesons might also be produced in the $s$-channel in $e^+e^-$ experiments, most probably via two-photon exchange, which should differ from the usual spectral function of a one photon exchange used to estimate $a^\text{had}_\mu(l,o)$, and therefore prevent from some eventual double counting of the $e^+e^- \rightarrow$ hadrons data. However, we are not also aware of existing analyses of the angular distribution which can differentiate a scalar from a vector meson in the low-energy $e^+e^-$ region concerned here [22], while present LEP limits on electroweak scalar particles (sleptons, squarks) given in [23] may not be applied here. If one estimates this coupling from the experimental bound on the $S \rightarrow e^+e^-$ width [19] and, use the positivity of the contribution, one gets the result in Table 2 where an universal coupling to $l^+l^- (l \equiv e, \mu)$ has been assumed [5]. In order to see the strength of this experimental bound, one may assume that the

3For the $\tau$-decay data, we use the average of the results (in units of $10^{-10}$) 709.0(5.9) [2] and 703.6(7.6) [3]. For the $e^+e^-$ data, we use the average of the most recent estimates 684.0(6.5) [2] and 683.1(6.2) [2], which are however lower by about 1.4$\sigma$ than the previous estimates in [19] based on preliminary data.

4Note that the difference $a^\text{exp}_\mu - a^\text{SM}_\mu = (34.9 \pm 28.4) \times 10^{-12}$ from the electron anomaly [23] leads to a weaker upper bound.

5The bound is weaker for a Higgs-type coupling.
Table 2: Contribution of Fig. 1 to $a_\mu$ using the upper bound on the leptonic widths compiled by PDG [19].

| $a_\mu \times 10^{10}$ | $\Gamma_{S\rightarrow e^+e^-}$ [eV] |
|-------------------------|----------------------------------|
| $\sigma (0.60)$         | $0. \sim 8.9$                   | $\leq 20$ *) |
| $f_0 (0.98)$            | $0. \sim 1.1$                   | $< 8.4$      |
| $a_0 (0.98)$            | $0. \sim 0.2$                   | $\leq 1.5$   |
| $f_0 (1.37)$            | $0. \sim 1.1$                   | $< 20$       |
| Total                   | $0. \sim 11.4$                  |              |

*) Due to the non-available experimental leptonic width of the $\sigma$ and the unclear separation between the $\sigma$ and the $f_0(1.37)$, one can safely assume that the bounds for the $\sigma$ and for the $f_0(1.37)$ are about the same.

coupling of the scalar to $l^+l^-$ is dominated by the one through two photons. Therefore, an alternative rough estimate of this effect can be obtained by relating it to the light-by-light (LL) scattering diagram contribution [25], where we obtain [6]:

$$a_\mu^{SLL} \approx e^2 a_\mu^{LL} \approx (0.1 \sim 1.0) \times 10^{-10}, \quad (22)$$

where we have considered the uncertainties to be about one order of magnitude in order to have a conservative estimate. This result indicates that the present experimental upper bound in Table 2 might be very weak, and needs to be improved. We translate the results given in Eqs. (22) and Table 2 into (in units of $10^{-10}$):

$$a_\mu^{SLL} = 0.55(0.45) \text{ TH}$$
$$= 5.7(5.7) \text{ PDG.} \quad (23)$$

Adding the results in Eqs. [19] and [23], one finally deduces the sum of the additional contributions due to scalar mesons in units of $10^{-10}$:

$$a_\mu^{S} = 1.0(0.6) \text{ TH}$$
$$= 13(11) \text{ PDG}, \quad (24)$$

to be added to the SM predictions $a_\mu^{SM}$. One should notice that the present theoretical estimate based on QCD spectral sum rules (QSSR) differs by about an order magnitude to the one based on the PDG data for the $\sigma\gamma\gamma$ and scalar meson leptonic widths. The QSSR estimate of the $\sigma\gamma\gamma$ width is based on the picture where the observed $\sigma$ meson emerges from a maximal mixing between a gluonium and $\bar qq$ states, which then implies a much smaller $\gamma\gamma$ width. On the other, the theoretical estimate of the leptonic width is based on an intermediate $\gamma\gamma$ coupling of the scalar meson to the lepton pair explaining again the relative suppression of a such width. A progress in improving the accuracy of the scalar meson contributions needs solely improved measurements of the scalar mesons $\gamma\gamma$ and leptonic widths. In addition, such a program is also necessary to clarify the exact nature of the scalar mesons which, at present, is, experimentally, poorly known.

5. CONCLUSIONS

The inclusion of the scalar meson contribution in Eq. [19] modifies the recent estimate of $a_\mu^{had}(l.o)$ from [23] into the one in Eq. [20], while the direct exchange of the scalar meson shown in Fig. 1 gives the new contribution in Eq. [21]. The total sum of the scalar contributions is given in Eq. [21]. Adding our result in Eqs. [20] and [23], we deduce in units of $10^{-10}$:

\[
\begin{align*}
a_\mu^{had} &= a_\mu^{had}(l.o) + a_\mu^{SLL} \\
&= 707.4(6.8)(0.6) \left[ \tau - \text{TH} \right], \\
&= 719.4(6.8)(11) \left[ \tau - \text{PDG} \right], \\
&= 684.6(6.4)(0.6) \left[ e^+e^- - \text{TH} \right], \\
&= 696.6(6.4)(11) \left[ e^+e^- - \text{PDG} \right], \quad (25)
\end{align*}
\]

where the first error is the ones from [23] and the second one comes from the present analysis. Our results (especially the one using PDG data) suggest that the value and errors of the hadronic contributions to $a_\mu^{SM}$ might have been underestimated in the previous determinations. From the above results, we deduce our final estimate of the muon anomaly in units of $10^{-10}$:

\[
\begin{align*}
a_\mu^{SM} &= 11 659 191.6(6.8) \left[ \tau - \text{TH} \right], \\
&= 11 659 203.6(12.9) \left[ \tau - \text{PDG} \right], \\
&= 11 659 169.2(6.4) \left[ e^+e^- - \text{TH} \right], \\
&= 11 659 181.2(12.7) \left[ e^+e^- - \text{PDG} \right], \quad (26)
\end{align*}
\]

compared with the recent data [1]:

\[
\begin{align*}
a_\mu^{exp} &= 11 659 204.0(8.6) \times 10^{-10}. \quad (27)
\end{align*}
\]

Then, we deduce in units of $10^{-10}$:

\[
\begin{align*}
\frac{a_\mu^{exp} - a_\mu^{SM}}{a_\mu^{SM}} &= 12.4(11.0) \left[ \tau - \text{TH} \right], \\
&= 0.4(15.5) \left[ \tau - \text{PDG} \right], \\
&= 34.8(10.7) \left[ e^+e^- - \text{TH} \right], \\
&= 22.8(15.3) \left[ e^+e^- - \text{PDG} \right]. \quad (28)
\end{align*}
\]

One can see that the inclusion of these new effects due to scalar mesons improves the agreement between $a_\mu^{exp}$ and $a_\mu^{SM}$: though a such agreement is quite good from $\tau$-decay (less than 1.1 $\sigma$), there still remains some disagreement (1.5 to 3.3 $\sigma$) between $a_\mu^{SM}$ from $e^+e^-$ and $a_\mu^{exp}$. More refined estimates of $a_\mu^{SM}$ require improved measurements of the
masses and widths of the scalar mesons, which are, at present, the major obstacles for reaching a high-precision value of $a^{SM}_\mu$. These new measurements are also necessary for making progresses in our QCD understanding of the nature of scalar mesons, which play a vital role on our understanding of the symmetry breaking in QCD. In addition to some problems mentioned in [2] (absolute normalization of the cross-section, radiative corrections, $SU(2)$ breakings,...), the discrepancy between the $\tau$-decay and $e^+e^-$ data should stimulate improvements of the data and experimental searches for new and presumably tiny effects not accounted for until now. We plan to come back to this point in a future work.

ACKNOWLEDGEMENTS

Stimulating exchanges with William Marciano and Simon Eidelman are gratefully acknowledged.

REFERENCES

1. C.S. Ozben et al., [hep-ex/0211044], G.W. Bennett et al., Phys. Rev. Lett. 89 (2002) 1001804.
2. M. Davier et al., Eur. Phys. Lett. J. C 27 (2003) 497.
3. K. Hagiwara et al., Phys. Lett. B 557 (2003) 69.
4. S. Narison, Phys. Lett. B 513 (2001) 53; Erratum 526 (2002) 414; [hep-ph/0108065].
5. J.F. de Trocóniz and J.F. Ynduráin, Phys. Rev. D 65 (2001) 093001.
6. The CMD-2 collaboration, R.R. Akhmetshin et al., Phys. Lett. B 527 (2002) 161.
7. The BES collaboration, J.Z. Bai et al., Phys. Rev. Lett. 84 (2000) 594; 88 (2002) 101802.
8. C. Bouchiat and L. Michel, J. Phys. Radium 22 (1961) 121; M. Gourdin and E. de Rafael, Nucl. Phys. B 10 (1969) 667.
9. B.E. Lautrup and E. de Rafael, Phys. Rev. 174 (1968) 1835.
10. L. Montanet, Nucl. Phys. (Proc. Suppl.) B 86 (2000) 381; U. Gastaldi, Nucl. Phys. (Proc. Suppl.) B 96 (2001) 234; I. Bediaga, Nucl. Phys. (Proc. Suppl.) B 96 (2001) 225; Possible existence of $\sigma$ meson and its implications, Kyoto KEK Proceedings 2000-4, ed. Ishida et al.
11. V.A. Novikov et al., Nucl. Phys. B 165 (1980) 67; J. Ellis and M.S. Chanowitz, Phys. Lett. B 40 (1972) 397; Phys. Rev. D 7 (1973) 2490; R.J. Crewther, Phys. Rev. Lett. 28 (1972) 1421.
12. M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B 147 (1979) 385, 448.
13. S. Narison, QCD as a Theory of Hadrons Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. 17 (2002) 1 [hep-ph/0205006]; QCD Spectral Sum Rules. World Sci. Lect. Notes Phys. 26 (1989) 1.
14. S. Narison and G. Veneziano, Int. Mod. Phys. A 4 (1989) 2751; A. Bramon and S. Narison, Mod. Phys. Lett. A4 (1989) 1113.
15. S. Narison, Nucl. Phys. B 509 (1998) 312; Nucl. Phys. A 675 (2000) 54c; Nucl. Phys. Proc. Suppl. B 96 (2001) 244; [hep-ph/0009108].
16. W. Ochs and P. Minkowski, [hep-ph/0209225].
17. E. Witten, Nucl. Phys. B 156 (1979) 269; G. Veneziano, Nucl. Phys. B 159 (1979) 213; G.M. Shore, S. Narison and G. Veneziano, Nucl. Phys. B 546 (1999) 235; Nucl. Phys. B 433 (1995) 209.
18. S. Narison, Thèse de Doctorat 3ème cycle, Marseille (1976).
19. PDG02, K. Hagiwara et al., Phys. Rev. D 66 (2002) 010001 and references quoted therein.
20. G. Mennessier, Z. Phys. C 16 (1983) 241 and private communications.
21. J. Calmet et al., Rev. Mod. Phys. 49 (1977) 21.
22. Private communications from Jacques Layssac and Fernand Michel Renard.
23. L3 collaboration, M. Acciarri et al., Phys. Lett. B 414 (1997) 373. I thank Jean Loïc Kneur for bringing this paper to my attention.
24. W.J. Marciano and T. Kinoshita, World Sci. Advanced Series on Directions in High Energy Physics, Vol 7 (1990); A. Czarnecki and W.J. Marciano, Nucl. Phys. (Proc. Suppl.) B 76 (1999) 245.
25. M. Knecht and A. Niffeler, Phys. Rev. D 65 (2002) 073034; M. Knecht et al., Phys. Rev. Lett. 88 (2002) 071802; M. Hayakawa and T. Kinoshita, [hep-ph/0112102].
26. J. Bijnens et al., Nucl. Phys. B 626 (2002) 410.