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Muon $g-2$ update

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We present an update of the theoretical prediction of the muon $g-2$. Mainly new BaBar data and a new measurement of $\sigma^{\pi\pi}$ by KLOE required a new update of the hadronic contribution, although no substantial change of previous estimates results. We also include a new calculation of the hadronic light-by-light contribution in the large-N_c framework. We find $a_\mu^{\rm the} = 116\,591\,795.4(65.2)$ or $a_\mu^{\rm the} - a_\mu^{\rm exp} = -284.6 \pm 90.7$ $(3.1\ \sigma)$. The new measurement of the τ spectral–function by Belle confirms the pattern of deviations observed between e^+e^-– and isospin rotated and corrected τ–data.

1. HADRONIC VP: e^+e^-–DATA UPDATES

For the evaluation of the hadronic contribution to the muon $g-2$ in terms of $e^+e^- \to$ hadrons cross–sections, the most important new measurement is the one of $\sigma^{\pi\pi}$ by KLOE [1]. The new result for $a_\mu^{\pi\pi} \times 10^{10}$ for the range $[0.35, 0.95]$ GeV^2 is $389.2 \pm 0.6 \pm 3.9$ in good agreement with the published $388.7 \pm 0.8 \pm 4.9$ which was updated to $384.4 \pm 0.8 \pm 4.6$ due to a change in the normalizing Bhabha generator. For the interval $[630, 958]$ MeV, a comparison of $a_\mu^{\pi\pi} \times 10^{10}$ between CMD-2 $361.5 \pm 1.7 \pm 2.9$, SND $361.0 \pm 2.0 \pm 4.7$ and KLOE $358.0 \pm 0.6 \pm 3.4$ is well within errors. While the integrated cross sections are in good agreement, observed deviations as a function of energy are less satisfactory. The actual status in the low energy region is displayed in Fig. 1. The existing problems will have to be settled by ongoing and/or future experiments and a better understanding of the radiative corrections involved. Important new data also have been published by BaBar [2]. They mainly help to improve the situation in the problematic range between 1 and 2 GeV. While data for the channels $K^+K^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ have changed substantially towards lower cross sections, the new channels $K^+K^-\pi^0\pi^0$, $\pi^+\pi^-\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-\eta$, $K^+K^-\pi^+\pi^-\pi^0$ and $K^+K^-\pi^+\pi^-\eta$ yield a small additional contribution only. Integrals (int) and averages (ave) for inclusive (incl) and exclusive (excl) data for the interval $[1.4, 2.0]$ GeV yield values $a_\mu^{\rm had} \times 10^{10}$:

data	result	stat	syst
int of incl	34.93	0.27	5.26
int of excl	33.62	0.27	4.01
ave of int	34.11	0.19	3.19
int of ave	34.03	0.20	3.84

Again we observe a reasonable agreement for the integrated cross sections while large differences in the energy dependence of added up exclusive versus inclusive measurements are confirmed by the BaBar data. The large systematic errors here remain a main source of the hadronic uncertainties.

2. UPDATES FOR $a_\mu^{\rm had}$

Updated results for the hadronic vacuum polarization (VP) contribution based on the direct integration of all relevant e^+e^-–data available are given in Table 1. Thereby the well known basic

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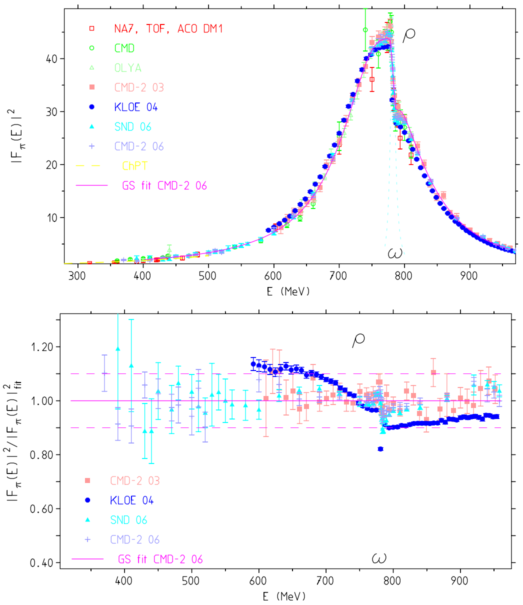

Figure 1. Status of low energy pion form factor measurements. New KLOE data not yet included.

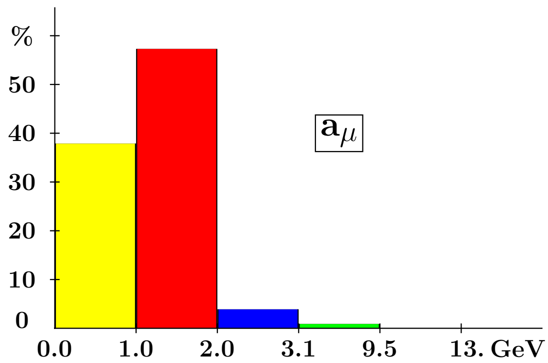

Figure 2. Error profile for a_μ.

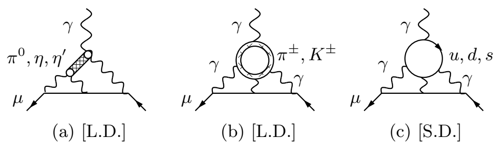

Figure 3. Hadronic light–by–light scattering diagrams representing long distance [L.D.] and short distance [S.D.] contributions.

integral

$$a_\mu^{\rm had} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} {\rm d}s \, \frac{R(s)\,\hat{K}(s)}{s^2} \qquad (1)$$

has been evaluated using $R(s)$–data up to $\sqrt{s} = E_{cut} = 5.2$ GeV and for the Υ resonance–region between 9.46 and 13 GeV and perturbative QCD from 5.2 to 9.46 GeV and for the high energy tail above 13 GeV. The result obtained is

$$a_\mu^{\rm had} = (691.04 \pm 5.29) \times 10^{-10} \qquad (2)$$

and the error profile in shown in Fig. 2.

3. EVALUATION OF $a_\mu^{\rm LbL}$ IN THE LARGE-N_c FRAMEWORK

Besides the established major calculations [4–7] of the hadronic light–by–light scattering contributions (see Fig. 3) more recently Knecht and Nyffeler [8] and Melnikov and Vainshtein [9] were reevaluating the leading π^0–exchange contribution by using the pion-pole approximation together with large-N_c QCD $\pi^0\gamma\gamma$–formfactors. This pion-pole approximation was criticized later in [10,11]: using at the external vertex, either $\mathcal{F}_{\pi^0\gamma^*\gamma}(m_\pi^2,-Q^2,0)$ [KN] (for which experimental data from CLEO [12] are avaliable, which largely confirm the Brodsky-Lepage $2F_\pi/Q^2$ asymptotic behavior [13]) violates four-momentum conservation, while $\mathcal{F}_{\pi^0\gamma\gamma}(0,0,0)$ [MV] (the experimentally well known real $\pi^0 \to \gamma\gamma$ constant, given by the Wess-Zumino effective Lagrangian [14]) fails to have the right off-shell high-energy behavior. What one needs in any case is $\mathcal{F}_{\pi^{0*}\gamma^*\gamma}(-Q^2,-Q^2,0)$ at the external vertex. In a new evaluation together with A. Nyffeler [15] [JN] we relax from sticking to the pole approximation and are using the off-shell LDM+V formfactor [16]

$$\mathcal{F}_{\pi^{0*}\gamma^*\gamma^*}(p_\pi^2,q_1^2,q_2^2) = \frac{F_\pi}{3}\,\frac{\mathcal{P}(q_1^2,q_2^2,p_\pi^2)}{\mathcal{Q}(q_1^2,q_2^2)} \qquad (3)$$

where $\mathcal{P}(q_1^2,q_2^2,p_\pi^2) = h_7 + h_6\,p_\pi^2 + h_5\,(q_2^2+q_1^2) + h_4\,p_\pi^4 + h_3\,(q_2^2+q_1^2)\,p_\pi^2 + h_2\,q_1^2\,q_2^2 + h_1\,(q_2^2+q_1^2)^2 + q_1^2\,q_2^2\,(p_\pi^2+q_2^2+q_1^2))$ and $\mathcal{Q}(q_1^2,q_2^2) = (q_1^2 - M_1^2)\,(q_1^2 - M_2^2)\,(q_2^2 - M_1^2)\,(q_2^2 - M_2^2)$ which, for appropriate choices of the constants h_i, allows

Table 1
Results for $a_\mu^{\rm had} \times 10^{10}$ (updating [3])

final state	range (GeV)	*res* (stat) (syst) [tot]	rel	abs
ρ	(0.28, 0.99)	501.07 (1.64) (2.54)[3.02]	0.7%	39.4%
ω	(0.42, 0.81)	36.96 (0.44) (1.00)[1.09]	3.0%	3.8%
ϕ	(1.00, 1.04)	34.42 (0.48) (0.79)[0.93]	2.7%	2.8%
J/ψ		8.51 (0.40) (0.38)[0.55]	6.5%	1.0%
Υ		0.10 (0.00) (0.01)[0.01]	6.7%	0.0%
had	(0.99, 2.00)	67.12 (0.27) (3.86)[3.87]	5.8%	48.1%
had	(2.00, 3.10)	22.13 (0.15) (1.22)[1.23]	5.6%	4.9%
had	(3.10, 3.60)	4.02 (0.08) (0.08)[0.11]	2.8%	0.0%
had	(3.60, 9.46)	13.89 (0.04) (0.07)[0.08]	0.6%	0.0%
had	(9.46,13.00)	1.30 (0.01) (0.08)[0.09]	6.6%	0.0%
pQCD	(13.0,∞)	1.53 (0.00) (0.00)[0.00]	0.1%	0.0%
data	(0.28,13.00)	689.51 (1.84) (4.96)[5.29]	0.8%	0.0%
total		691.04 (1.84) (4.96)[5.29]	0.8%	100.0%

to satisfy all known constraints from low energy as well as from high energy QCD [evaluated via the operator product expansion (OPE)] [8,15,16]. Eq. 3 incorporates vector meson dominance type $\rho-\gamma$ mixing and $V_{1,2}$ are identified with ρ and ρ'. A new constraint applied is $h_3+h_4 = 2\,c_{VT}$ [16], where c_{VT} can be estimated in the chiral limit. Indeed $c_{VT} = M_{V_1}^2\, M_{V_2}^2\, \chi/2$ is determined by the magnetic susceptibility χ and has been evaluated by various groups (see [15] and references therein). Adopting $\chi = (-3 \pm 1)$ GeV^{-2}, and varying $h_3 \in [-10,10]$ GeV^{-2} yields

$$a_\mu^{{\rm LbL};\pi^0} = (72 \pm 11) \times 10^{-11} \qquad (4)$$

for the leading π^0 exchange contribution. Our short distance constraint agrees qualitatively with the one of [9] but with a constant which is only about 1/3 of the one advocated in [9]. The other LbL contributions read:

X	$a_\mu({\rm LbL};X) \times 10^{11}$	Ref.
π^0, η, η'	97±15	[15]
a_1, f_1', f_1	22± 5	[9]*
a_0, f_0', f_0	−7± 2	[5,7]*
π, K loops	−19±13	[5,7]
quark loops	21± 3	[5,7]

The asterisk indicates values which I have reevaluated independently within the given uncertainties. The complete hadronic LbL term thus reads [15]

$$a_\mu({\rm LbL}) \simeq (114 \pm 38) \times 10^{-11}\,. \qquad (5)$$

The new evaluations of the hadronic contributions slightly modify ths SM prediction of a_μ. Updated values of the different contributions are collected in Table 2. The $3.1\,\sigma$ deviation between theory and experiment

$$\delta a_\mu^{\rm NP?} = a_\mu^{\rm exp} - a_\mu^{\rm the} = (285 \pm 91)\, 10^{-11}\,, \qquad (6)$$

could be a hint for new physics. At the same time this very precise BNL measurement severely constrains possible deviations from the SM (see also [23,24]).

4. REMARKS ON τ VS. e^+e^- DATA

The new precise hadronic τ–decay spectral data for the $\pi\pi$ channel from Belle [25] bring back into focus the τ vs. e^+e^- data discrepancy [26], which may be illustrated as in Fig. 4. Known isospin violation effects [27] have been accounted for. Note the good agreement below 800 MeV, while between 800 and 1200 MeV τ data appear enhanced by 10 to 20% and show a pronounced dip at about 1500 MeV. Apart from possible experimental problems (e.g. clean separation of different channels), reasons for the observed deviations could be not yet accounted isospin breakings, inappropriate treatment of interferences or

Table 2
Standard model theory and experiment comparison for a_μ [in units 10^{-11}]

Contribution		Value	Error	Reference
QED incl. 4-loops+LO 5-loops		116 584 718.1	0.2	[17–19]
Leading hadronic vacuum polarization		6 910.4	52.9	Table 1
Subleading hadronic vacuum polarization		-100.3	2.2	[3]
Hadronic light–by–light		114.0	38.0	new evaluation [15]
Weak incl. 2-loops		153.2	1.8	CMV [20]
Theory		116 591 795.4	65.2	[15]
Experiment		116 592 080.0	63.0	BNL [21,22]
The. - Exp.	3.1 standard deviations	-284.6	90.7	–

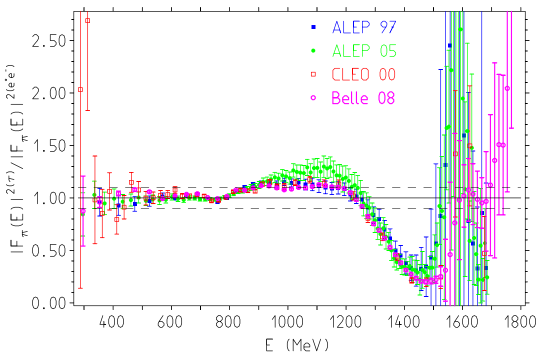

Figure 4. The ratio $|F_\pi(E)|^2(\tau)/|F_\pi(E)|^2_{\rm fit}(e^+e^-[I=1])$ illustrates the missing consistency of the τ–data relative to a CMD-2 fit. Dashed horizontal lines mark $\pm$ 10% (see also [25]). $|F_\pi(E)|^2(\tau)$ is the modulus square of the $I=1$ pion form factor extracted from $\tau^\pm \to \nu_\tau \pi^\pm \pi^0$.

radiative corrections of the hadrons involved:

• Unknown / unaccounted isospin violations in masses $m_{\rho^+} \neq m_{\rho^0}, m_{\rho'^+} \neq m_{\rho'^0}, m_{\rho''^+} \neq m_{\rho''^0}$, widths, mixing parameters, which are largely not established (theoretically and experimentally). Note that the Cottingham formula, determining $m^2_{\pi^-} - m^2_{\pi^0}$ very successfully, suggests $\Delta m^2_\rho = \Delta m^2_\pi \Rightarrow m_{\rho^+} - m_{\rho^0} \simeq 0.81$ MeV ~ 1 MeV, a non–negligible positive result. Also the width **must** show a neutral vs charged difference $\Gamma_{\rho^0} = \left(\frac{m_{\rho^0}}{m_{\rho^-}}\right)^3 \left(\frac{\beta^0}{\beta^-}\right)^3 \Gamma_{\rho^-} + \Delta\Gamma_{\rm em}$, which amounts to $\Gamma_{\rho^-} - \Gamma_{\rho^0} \simeq 2.1 \pm 0.5$ MeV. The latter effect usually is taken into account (see [26,25]), but other isospin breakings in $\Gamma_{\rho^-} - \Gamma_{\rho^0}$ are expected. Parameter shifts usually are fitted using a Gounaris-Sakurai formula including ρ, ρ' and ρ'' and their mixing (see e.g. [28,25]). The new Belle fit parameters agree rather well with earlier determinations [29,30] (see also [31]). For the first time Belle is able to determine all parameters in **one** fit of their data. For mass and width of the ρ: $m_{\rho^-} = 774.6 \pm 0.5[775.0 \pm 0.6]$ and $\Gamma_{\rho^-} = 148.1 \pm 1.7[149.5 \pm 1.1]$ for Belle[ALEPH].

• What we need is the photon VP as it is measured in e^+e^-, namely $|A_{I=1}(s) + A_{I=0}(s)|^2$ in terms of isospin amplitudes, which is lower than $|A_{I=1}(s)|^2 + |A_{I=0}(s)|^2$. Evaluations including τ–data as $|A^\tau_{I=1}(s)|^2 + |A^{e^+e^-}_{I=0}(s)|^2$ in general overestimate the effects. For the $\pi\pi$ channel the $A^{e^+e^-}_{I=0}(s)$ component usually is accounted for as the $\rho - \omega$ mixing term $[\varepsilon_{\rho\omega}]$ on the amplitude level (see e.g. [25]). Benayoun et al. performing a calculation of the ρ–ω–ϕ mixing effects, including self-energy corrections due to pion and kaon loops within the HLS low energy effective model, suggest that the large diminution of e^+e^- relative to τ may be due to interferences [32] beyond the $\rho - \omega$ mixing usually accounted for.

• Isospin violating hadronic final state photon radiation (FSR) is not under full quantitative control. In τ–decay there is an enhanced short distance sensitivity (UV-log modeled by quark parton model, rest by sQED). Also in the neutral channel FSR is usually modeled by sQED [model dependent], but at least it does not exhibit a large UV-log (subleading short distance sensitivity).

Table 3
Comparison of $a_\mu^{\rm had}(2\pi, I=1)$ from τ data corrected for known isospin violations according to [27] and e^+e^- data for the different ranges. FSR is not included.

Data/Range	[0.318, 0.80]	[0.80, 1.20]	[1.20, 1.675]	[0.318, 1.675]
ALEPH '97	392.95 (3.51)	100.56 (0.85)	2.27 (0.10)	495.77 (4.04) (5.60)
ALEPH '05	398.52 (2.52)	100.36 (0.67)	2.23 (0.06)	501.11 (2.64) (4.80)
CLEO '00	404.90 (3.85)	99.48 (0.67)	2.01 (0.05)	506.39 (3.97) (4.23)
Belle '08	409.59 (1.20)	99.55 (0.18)	2.03 (0.01)	511.17 (1.28) (4.20)
e^+e^-(I=1)	403.86 (1.76)	94.49 (0.90)	2.12 (0.12)	500.48 (1.85) (4.05)
e^+e^-(I=1,0)	408.86 (1.76)	92.13 (0.47)	2.11 (0.02)	503.11 (1.85) (4.06)

I think that the missing detailed understanding of the origin of the large differences observed do not allow us to include isospin rotated τ–data in calculations of $g-2$.

Nevertheless, it is interesting to compare the I=1 $\pi\pi$ contribution to $a_\mu^{\rm had}$. In Ref. [25] the comparison reported for $a_\mu^{\rm had}(2\pi, 2\pi\gamma, I=1.0)[2m_\pi, M_\tau] \times 10^{10}$ (res) is

Data	res	exp	Br.	iso
ALEPH, CLEO	519.1±	1.5±	2.6	± 2.5
BELLE	520.1±	2.4±	2.7	± 2.5
CMD2,SND	504.6±	3.1	–	± 0.9

An integration for different data sets for the different ranges yields the results in Table 3. By I=1,0 I denote e^+e^- data (VP and FRS subtracted) and the I=1 component is extracted using the Gounaris-Sakurai parametrization by switching off the ω component. The substantially larger value obtained by Belle is due to the tilt seen in Fig. 9 of [25] and the $1/E^4$ enhancement of the low energy contributions. Belle data are slightly higher in region below 800 MeV. Note that the substantial enhancement in the ALEPH 05 data does not affect the result for $a_\mu^{\rm had}$ as much, since we are at higher energies and in a region where the cross–section by itself is lower.

5. OUTLOOK

Very likely a new muon $g-2$ experiment will happen in not too far future. Considerations aim at $\sim 15 \times 10^{-11}$ experimental precision. The BNL storage ring would remain the key element. Different options are discussed for Brookhaven and for Fermilab in the USA and for JPARC in Japan [22].

On the theory side new progress is expected by new techniques and more automated calculations in 4–loop and 5–loop QED [17,19].

The main problems remain the hadronic effects. For the hadronic vacuum polarization improving hadronic cross section measurements are mandatory and fortunately are in progress [33–35]. According to Table 1 if for each entry [energy domains] we could reach a 1% precision we would be able to reduce the uncertainty in $a_\mu^{\rm had}$ to 31×10^{-11}, where the dominating error again would come from the low energy $\pi\pi$ channel. Here more theory input as discussed by Colangelo [36] would allow further improvements, provided the deviations between different measurements would get under better control.

The persisting problem in the compatibility of the τ–decay data, corrected for isospin violations, with the e^+e^-–data after the results from Belle, makes it unlikely that the τ–data will help to lower the hadronic uncertainty. As a possibility one also may consider the case that the τ–data based evaluation of $a_\mu^{\rm had}$ is the more reliable one. It would improve the agreement between theory and experiment for a_μ to the 1 σ level. However, using the τ–data would also affect the effective $\alpha(M_Z)$ and in fact increase the "gap" between a too low value of indirect Higgs mass determinations in comparison with the known direct lower bound. This does certainly not support the idea that the τ–data based evaluation is more likely to be the correct choice [37].

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