The $(g-2)_\mu$ data and the lightest Higgs boson in 2HDM(II)

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The present limits on the lightest Higgs boson in 2HDM (II) in light of the new E821 measurement of $g - 2$ for the muon are discussed.

The precision measurement of $g - 2$ for the muon is expected to shed light on "new physics". Here we discuss constraints on the lightest neutral Higgs boson in 2HDM (II) which can be derived from the new E821 measurement based on 1999 data. A current mean of experimental results for $(g - 2)_\mu$ is (from 6)

$$a^{exp}_\mu \equiv (g - 2)_\mu^{exp}/2 = 11659203(15) \cdot 10^{-10},$$

where the accuracy of this result (in parentheses) approaches the size of electro-weak contribution, $a^{EW}_\mu$. The ultimate accuracy of the E821 experiment is $4 \cdot 10^{-10}$. The Standard Model prediction for $a_\mu$ consists of the QED, hadronic and EW contributions:

$$a^{SM}_\mu = a^{QED}_\mu + a^{had}_\mu + a^{EW}_\mu.$$ Both the QED and EW contributions to $a^{SM}_\mu$ are well under control. The predictions for the hadronic contribution, $a^{had}_\mu$, differ considerably among themselves. Its uncertainty is presently of order $(7 - 10) \cdot 10^{-10}$, with the dominant error coming from the leading vacuum polarization contribution (see discussions in 3, also 4). A new controversy of the light-by-light scattering contribution (a sign !) has appeared recently 7.

The difference between the experimental data, $a^{exp}_\mu$, and the Standard Model (SM) prediction, $a^{SM}_\mu$, defines the room for "new physics". Obviously the uncertainties of the hadronic contributions influence the estimation of a size of new effects. To illustrate the present situation we calculate 95% CL intervals ($\lim$(95%)) for an allowed new contribution, $\delta a_\mu$, using two representative SM predictions 3: one based on the calculation of leading vacuum polarization diagrams by Davier and Höcker (DH) 5 and the other by Jegerlehner (J2000) 6, with a smaller and larger $a^{had}_\mu$ (and its uncertainty), respectively.

The obtained intervals we apply to constrain the parameters of the non-supersymmetric, CP conserving 2HDM (Model II) 8. This model, based on the two doublets of complex scalar fields, predicts existence of five Higgs particles: two neutral Higgs scalars $h$ and $H$, one neutral pseudoscalar $A$, and a pair of charged Higgses $H^\pm$. In this model one light neutral Higgs boson, $h$ or $A$, with mass even below 20 GeV is still allowed by the LEP 11,12 and low energy experiments 13,14 in contrast to the SM Higgs boson which should be heavier than 114.1 GeV (95% CL) 8. Previous (CERN) data and the SM prediction(s) for $a_\mu$ were used by us to derive the constraints (based on the one-loop calculation 15) for $h$ or $A$ in 2HDM (II) 8,16. A very small improvement with comparison to the LEP limits were obtained. In this paper we use new E821 data and apply the two-loop approach 17 to derive tight constraints on the Yukawa couplings to muon of $h$ and $A$ (similar results are in 18, see also 19,20 for one-loop results). Next we combine these constraints with other limits to derive current constraints for the lightest Higgs boson in 2HDM(II).

We study separately case A and case B based on the DH and J2000 calculation of the leading vacuum polarization diagram, respectively. The contributions differ by the higher hadronic corrections and the light-on-light scattering are taken from 18 and 20, respectively. In the table below we collect, following 3, the corresponding SM contributions (and their uncertainties). From $\Delta a_\mu$, the difference of the central values $a^{exp}_\mu - a^{SM}_\mu \equiv \Delta a_\mu$, and the error for this quantity, $\sigma$, one can calculate an allowed at chosen confidence level (CL) interval of an additional contribution. We estimate $\sigma$ by adding in quadrature $\sigma^{exp}_\mu$ and $\sigma^{tot}_\mu$. Assuming a Gaussian distribution we calculate in both cases, A and B, the allowed at 95% CL $\delta a_\mu$ regions, symmetric around $\Delta a_\mu$ (see table below).

| case | A [in 10^{-11}] | B [in 10^{-11}] |
|------|----------------|----------------|
| QED  | 116 584 706 (3) | 116 584 706 (3) |
| had  | 6 739 (67)      | 6 803 (114)    |
| EW   | 152 (4)         | 152 (4)        |
| tot  | 116 591 597 (67)| 116 591 661 (114)|
| $\Delta a_\mu(\sigma)$ | 426(165) | 362(189) |
| $\lim$(95%) | 102 $\leq \delta a_\mu \leq$ 750 $- 8.65 \leq \delta a_\mu \leq 733$ |

We see that at 95 %CL the more conservative estimation of the hadronic contribution to $a^{SM}_\mu$ (case B) leads to both the negative and positive $\delta a_\mu$, while in case A $\delta a_\mu$ is of a positive sign only. As a consequence, the 95 %CL
interval leads in case A to an allowed positive contribution (an allowed band) and at the same time to the exclusion of the negative contribution. For the case B, the positive (negative) contribution is only bounded from above (below) (upper limits for the absolute value of the new contribution). This reflects the fact that the SM prediction lies within the 95% CL interval for case B, while for case A it is outside the corresponding interval.

\[
\gamma_{h,A}^{+} \mu \mu
\]

One- and two-loop diagrams. The \( W^+ \) and \( H^+ \) loops contribute only for a \( h \) exchange.

We apply the obtained intervals \( \delta a_{\mu} \) to constrain parameters of the 2HDM (II) using a simple approach, where only one neutral Higgs boson, \( h \) or \( A \), contributes. In the one-loop calculation (based on the one-loop diagram, see above) a light scalar scenario leads to the positive, whereas the one with a light pseudoscalar to the negative contribution to \( a_{\mu} \), independently of mass. In the two-loop analysis, based on a sum of the one- and two-loop (fermionic and bosonic) diagram contributions, the situation changes drastically. Now the positive (negative) contribution can be ascribed to a scalar \( h \) with mass below (above) 5 GeV or a pseudoscalar \( A \) with mass above (below) 3 GeV. For \( h \) we assumed \( \chi_0^h = 0 \), so the \( W \)-loop does not contribute. A \( H^+ \) loop, for \( M_{H^+} = 400, 800 \) GeV and infinity (and with parameter \( \mu = 0 \) in the \( hH^+H^- \) coupling), is included in the analysis.

Our results are presented in Fig. 1 and Fig. 2 (tick lines) together with current upper limits from the Yukawa process (ALEPH, DELPHI and OPAL results) and lower limits from the \( Z \to h(A)\gamma \) [10]. In addition the upper 90% CL limits from the \( \Upsilon \) decay (K,N), rescaled by a factor 2, and from the TEVATRON [21] are presented. Constraints on case B lead to an improvement of the existing upper limits for \( h \) for mass above 10 GeV (Fig. 1(left)) and for \( A \) above 50 GeV (Fig. 2(left)). For case A our results are in the form of allowed regions for mass below 5 GeV for \( h \) (Fig. 1(right)) and for mass above 3 GeV for \( A \) (Fig. 2(right)) (see also [17]).

This two-loop analysis based on new \((g - 2)_\mu\) data and on the DH estimation of \( a_{\mu}^{had} \) (case A) if combined with constraints from other experiments allows in the 2HDM (II) for an existence of a pseudoscalar with mass between \( \sim 25 \) GeV and 70 GeV, and \( \tan \beta \) above 30. A light scalar is excluded. This latter result is in agreement with a conclusion of theoretical analysis [22].

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FIG. 1: The 95% CL upper and lower limits for the Yukawa coupling $\chi_h^d$ for a scalar $h$ ($\chi_h^d = \tan \beta$ for vanishing coupling to gauge bosons $\chi^V = 0$) as a function of mass. Left: The tick lines "$g-2(B)$" give upper limits in case B. Line 1 (2,3) is obtained for mass of $H^+$ equal to infinity (800, 400 GeV). Right: Similar results for case A, allowed region between upper tick line B/A (which coincides with case B) and lower tick line A.

FIG. 2: As in Fig.1 for a pseudoscalar $A$ ($\chi_A^d = \tan \beta$).