Left-right asymmetries in polarized $e$-$\mu$ scattering

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Abstract

We consider, in the electroweak standard model context, several left-right asymmetries in $\mu e$ elastic scattering at fixed target and collider experiments. For the former case, we show that the muon mass effects are important in a wide energy range. We also show that these asymmetries are sensitive to the electroweak mixing angle $\theta_W$. The effect of an extra $Z'$ neutral vector boson appearing in a 331 model is also considered. The capabilities of these asymmetries in the search of this extra $Z'$ are addressed.

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Several years ago Derman and Marciano \cite{1} considered briefly the left-right asymmetry in $\mu^+e^- \rightarrow \mu^-e^-$, here denoted by $A_{RL}(\mu e)$, with unpolarized muon scattering on polarized electron target. According to them this asymmetry can be measured and the only difference between the high energy $\mu^-e^-$ scattering and the high energy $e^-e^-$ scattering is that in the former we must omit crossed amplitudes. With the attention received by muon colliders nowadays this issue become important \cite{2}. Beside, it has been shown that the mass effect of the muon can not be neglected in muon-muon scattering \cite{3}. Here we will show that at the Born approximation and in the context of the electroweak standard model there are appreciable effects coming from the mass of the muon.

Some advantage to measure $A_{RL}(\mu e)$ were commented in Ref. \cite{1}. The first is that muon beams generally have energies at least one order of magnitude greater than the electron beams. Thus experimentally, since the left-right asymmetry in $ee$ and in $\mu e$ are proportional to $s$, a larger value for the asymmetry in the later case can be obtained. Secondly, in $\mu^-e^-$ scattering the background contribution from $\mu^-N$ scattering is less severe because one could trigger on a single scattered electron which could not have arisen from a $\mu^-N$ collision. The problem arisen by Derman and Marciano was that the experiment requires strictly zero muon polarization, otherwise the purely QED spin-spin effect would totally mask $A_{RL}(\mu e)$. However we will show below that this happens only for low values of $y \equiv \sin^2(\theta/2)$. This problem does not exist in a muon-electron fixed target experiment using the high-energy muon beam M2 of the CERN SPS as in the NA47 experiment \cite{4}. In this case left- and right-handed polarized muon can be scattered off unpolarized electron (see below).

Here we will calculate the $A_{RL}(\mu e)$ asymmetry taking into account the muon mass but neglecting the electron mass. Recently, $\mathcal{O}(\alpha^3)$ purely QED spin-spin effect calculations (with both particles polarized) have been done in these conditions \cite{5}. The fact is that at NA47 typical energies the muon energy is $E_\mu = 190$ GeV, i. e., the invariant $s$ is only 20 times bigger than the muon mass squared and the effects of the muon mass cannot be neglected. Hence, future electroweak radiative corrections to the $A_{RL}(\mu e)$ asymmetry probably will have to take into account the muon mass also.

The left-right asymmetry with one of the particle being unpolarized is defined as

\[ A_{RL}(\mu e \rightarrow \mu e) \equiv A_{RL}(\mu e) = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}, \tag{1} \]

where $d\sigma_{R(L)}$ is the differential cross section for one right (left)-handed lepton $l$ scattering on an unpolarized lepton $l'$. That is

\[ A_{RL}(\mu e) = \frac{(d\sigma_{RR} + d\sigma_{RL}) - (d\sigma_{LL} + d\sigma_{LR})}{(d\sigma_{RR} + d\sigma_{RL}) + (d\sigma_{LL} + d\sigma_{LR})}, \tag{2} \]

where $d\sigma_{ij}$ denotes the cross section for incoming leptons with helicity $i$ and $j$, respectively, and they are given by

\[ d\sigma_{ij} \propto \sum_{kl} |M_{ij,kl}|^2, \quad i, j; k, l = L, R. \tag{3} \]

Notice that since the $\mu e$ scattering is non-diagonal $d\sigma_{RL} \neq d\sigma_{LR}$, so the asymmetry in Eq. (2) is different from the asymmetry defined as $(d\sigma_{RR} - d\sigma_{LL})/(d\sigma_{RR} + d\sigma_{LL})$.

We will consider the process...
\[ e^-(p_1, \lambda) + \mu^-(q_1, \Lambda) \rightarrow e^-(p_2, \lambda') + \mu^-(q_2, \Lambda'), \]

where \( q = p_2 - p_1 = q_2 - q_1 \) is the transferred momentum. As we said before, we will neglect the electron mass but not the muon mass i.e., \( E = |\vec{p}_e| \) for the electron and \( K^2 - |\vec{q}_\mu|^2 = m_\mu^2 \) for the muon. In the non-diagonal elastic scattering in the standard model we have only the \( t \)-channel contribution. The relevant amplitudes are in Appendix A and in the appendices of Ref. B.

We will study here \( A_{RL}(\mu e) \) defined in Eq. (2) in the context of two models: the electroweak standard model (ESM) and in a model having a doubly charged bilepton vector field \( (U^-_\mu) \) and an extra neutral vector boson \( Z' \) C. The latter model has also two doubly charged scalar bileptons but since their contributions cancel out in the numerator of the asymmetry we will not consider them. We identify the case under study by using the \{ESM\}, \{ESM + U\}, and \{ESM + Z'\} labels in cross sections and asymmetries.

First, we will consider the \( \mu e \) elastic scattering in the context of the electroweak standard model. The \( A_{RL} \) asymmetry for \( m_\mu = 0 \) and fixed target experiments is

\[
A_{RL}^{FT;ESM}(\mu e)\big|_{m_\mu=0} = 4\beta_W g_V g_A \frac{y s}{1 + (1 - y)^2}; \quad \beta_W \equiv \frac{G_F}{\sqrt{2}} \frac{8M_W^2}{4\pi\alpha M_Z^2}; \quad y \equiv \sin^2(\theta/2),
\]

which is the expression obtained by Derman and Marciano D. Here we will not shown explicitly the \( A_{RL} \) expression for \( m_\mu \neq 0 \). For \( y = 1/2 \), the above asymmetry is \( A_{RL}^{FT}(\mu e) = -1.643 \times 10^{-6} s \). Although it is a rather small value the cross section still depends on \( m_e^{-1} \) implying a large cross section which can allow to have enough statistics as in the case of \( ee \) scattering D. In fact, from Eq. (E1) we obtain a total cross section of 11.86(3.88) mb for \( E_\mu = 50(190) \) GeV. (In Appendix E we show the differential cross section for \( \mu e \) scattering in the laboratory frame.)

From Eq. (E3) and \( y = 1/2 \), we get \( A_{RL}^{FT;ESM}(\mu e) = -8.216 \times 10^{-8} \) for \( E_\mu = 50 \) GeV (or \( s = 0.05 \) GeV\(^2\)) and \( A_{RL}^{FT;ESM}(\mu e) = -3.122 \times 10^{-7} \) for \( E_\mu = 190 \) GeV (or \( s = 0.19 \) GeV\(^2\)). Taking into account the muon mass we get for the same conditions \( A_{RL}^{FT;ESM}(\mu e) = -5.917 \times 10^{-8} \) and \( A_{RL}^{FT;ESM}(\mu e) = -2.913 \times 10^{-7} \), respectively. Form Fig. 1 and the illustrative values given above we see that for fixed target experiments the muon-mass effects can not be neglected. In fact, taking into account the muon-mass effects in \( A_{RL}^{FT} \) will be crucial to correctly interpret the experimental data. This is due to the high sensitivity of \( A_{RL}^{FT} \) with the electroweak mixing angle as it can be seen in Fig. 2. For instance, for \( E_\mu = 190 \) GeV a 0.5% change in the \( A_{RL}^{FT} \) value corresponds to a 0.04% change in \( \sin^2(\theta_W) \), i.e., a change from 0.2315 to 0.2316. In the NA47 experiment the beam polarization was determined by measuring the cross-section asymmetry for the scattering of polarized muons on polarized atomic electrons. Since the elastic cross section for fixed target experiments is large \( (\sim 4 - 11) \) mb may be it is possible to extract information about the \( A_{RL}^{FT;ESM}(\mu e) \) asymmetry with unpolarized electrons. This parameter is dominated by weak effects.

For collider experiments, that would be feasible if the muon-electron collider is constructed, we have that the asymmetry is large when comparing with the corresponding for fixed target experiments. For instance \( A_{RL}^{CO;ESM}(\mu e) = -0.024 \) for \( E_\mu = 190 \) GeV (\( \sqrt{s} \sim 380 \) GeV) and \( y = 1/2 \), as can be seen from Fig. 3. We show only one curve in Fig. 3 because mass effects are not important in high-energy colliders. We have also verified that \( A_{RL}^{CO;ESM} \)
is as sensitive as $A_{tree}^{FT; ESM}$ to the value of $\sin^2(\theta_W)$. However, for statistical purposes we have to observe that the cross section for colliders is considerably smaller than that of fixed target experiments: $\sigma^{CO} \sim 66 \text{ nb for } \sqrt{s} \sim 380 \text{ GeV}$.

Another interesting possibility is the case when both leptons are polarized. We can define an asymmetry $A_{R;L}$ in which one beam is always in the same polarization state, say right-handed, and the other is either right- or left-handed polarized (similarly we can define $A_{L;R}$):

$$A_{R;L} = \frac{d\sigma_{RR} - d\sigma_{RL}}{d\sigma_{RR} + d\sigma_{RL}}, \quad A_{L;R} = \frac{d\sigma_{LR} - d\sigma_{LL}}{d\sigma_{LL} + d\sigma_{LR}}. \tag{6}$$

In Fig. 4 we show the asymmetry $A_{R;L}$ as a function of $y \equiv \sin^2(\theta/2)$ and we note that the muon–mass effects are relevant for a wide range of $y$-values. For $y = 1/2$ and $E_\mu = 190 \text{ GeV}$ we have $A_{R;L} \approx 0.2844$ while for the same condition the purely QED contribution gives $A_{R;L}^{QED} = 0.5689$. Hence, we see that like in the electron-electron Möller scattering this asymmetry is sensitive to the neutral vector contributions. This is interesting since this asymmetry, as we said before, can already be measured in experiments like the NA47 at CERN showing that it could be useful for doing electroweak studies also. In fact, this experiment has already measured the asymmetry for polarized muon-electron scattering expected in QED: the cross section asymmetry for antiparallel ($\uparrow \downarrow$) and parallel ($\uparrow \uparrow$) \[4\]. This corresponds in our notation to the asymmetry

$$\hat{A}_{R;L}^{FT} = \frac{(d\sigma_{LR} + d\sigma_{RL}) - (d\sigma_{LL} + d\sigma_{RR})}{(d\sigma_{LR} + d\sigma_{RL}) + (d\sigma_{LL} + d\sigma_{RR})}. \tag{7}$$

We have confirmed the value obtained by the SMC Collaboration for this asymmetry i.e., it ranges from 0.01 to 0.05 for low values of $y$ ($\hat{A}_{RL} \approx y$). $A_{R;L}$ ($A_{L;R}$) is not interesting for colliders experiments since it gives $\sim 1$ ($\sim -1$) due to the fact that $d\sigma_{RR}$ ($d\sigma_{LL}$) largely dominates in Eq. (6)

We have also investigated the effect of a doubly charged bilepton vector boson. In some models with vector bileptons like $U^{--}$ the decay $\mu^{-} \rightarrow e^{-} e^{-} e^{+}$ (and similar ones) does occur. The branching ratio for this decay is $\sim 10^{-12}$ \[8\]. This bound strongly limits the $K_{\mu e}$ couplings. The branching fraction for $\mu \rightarrow 3e$ decay is

$$B(\mu \rightarrow 3e) \propto \left( \frac{K_{\mu e} K_{ee}}{M_U} \right)^2 \frac{1}{G_F^2}. \tag{8}$$

For the case $M_U = 300 \text{ GeV}$ and $K_{ee} \sim 1$ the experimental value for the above branching ratio implies $K_{\mu e} \sim 10^{-6}$. Hence, we see that with such a large suppression the $U$-amplitudes given in Eqs. (A3) are negligible. However, since we do not know if the $U$-vector doubly charged bilepton (if it exists) prefers to couple in an almost diagonal way to charged leptons we are free to consider also the case $K_{ee} \sim 10^{-6}$ and $K_{\mu e} \sim 1$. In the first case the $U$-contributions to cross section and asymmetry are negligible and the asymmetry is the same as in the ESM: $A_{R;L}^{CO; ESM} (\mu e) = -0.024$ for $E_\mu = 190 \text{ GeV } (\sqrt{s} = 380 \text{ GeV})$. In the second case we have $A_{R;L}^{CO; ESM + U} (\mu e) = -0.0092$ for the same experimental conditions. In the following we will assume that we are in the first case and so we will not consider the $U$-contribution to the asymmetry.

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In the model there is also a $Z'$ neutral vector boson which couples with the leptons as follows

$$\mathcal{L}_{NC}^{Z'} = -\frac{g}{2c_W} \left[ i a_L \gamma^\mu L_l a_L + i a_R \gamma^\mu R_l a_R + \bar{\nu}_a L \gamma^\mu L_{\nu a L} \right] Z'_{\mu}, \tag{9}$$

with $L_l = L_{\nu} = -(1 - 4s_W^2)^{1/2}/\sqrt{3}$ and $R_l = 2L_l$. The $t$-channel $Z'$-exchange amplitudes are similar to those of the ESM $Z$ given in the Appendix A2 of Ref. [3] but now with the couplings $L$'s and $R$'s given in Eq. (9).

Taking into account the $Z'$ contributions the $A_{RL}(\mu e)$ asymmetry is considerably enhanced as showed in Fig. 5. We see from Fig. 5 that the measurement of the $A_{RL}^{CO}(\mu e)$ asymmetry will be appropriate for searching extra neutral vector bosons with a mass up to 1 TeV. Since in the 331 model the $Z'$ couplings with the leptons are flavor conserving we do not have additional suppression factors coming from mixing. Hence the non-diagonal Møller scattering ($\mu e$) can be very helpful, even with the present experimental capabilities, for looking for non-standard physics effects. We will not consider the $Z'$ contributions to the $A_{RL}$ and $A_{R:RL}$ asymmetries in fixed target experiments because they are very small.

Finally, we would like to stress that other related processes like $\mu^+ e^- \rightarrow \mu^- e^+$ and $e^- e^- \rightarrow \mu^- \mu^- (\tau^- \tau^-)$ deserve a detailed study. In particular the $\mu^+ e^- \rightarrow \mu^- e^+$ collision is interesting, as it was pointed out by Hou [8], because of its connection with $M - \bar{M}$ conversion ($M \equiv \mu^+ e^-$ denote the muonium atom). The effect of resonance production involving lepton flavor violating couplings with hypothetical particles (like doubly charged scalar or vector bileptons, flavor changing neutral scalar bosons) at a $\mu e$ collider have been considered in Ref. [8]. However, Barger et al., have shown that the resonance production of the known particles puts severe limits on the respective cross section [10].

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APPENDIX A: THE AMPLITUDES

For a fixed target experiment $s \approx m^2_\mu + 2m_e E_\mu$ where $E_\mu$ is the muon beam energy. In the center of mass frame $t = m^2_\tau + m^2_e - 2K E + 2[E^2(K^2 - m^2_\mu)^{1/2}] \cos^2 \theta$. ($E$ is the electron total energy and $K$ is the muon kinetic energy.) Up to a $-e^2/q^2$ factor the photon amplitudes are

$$M^\gamma_{RR,RR}(t) = M^\gamma_{LL,LL}(t) = 4E \left[ K \cos^2 \frac{\theta}{2} + (K - m_\mu) \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \left( \cos^2 \frac{\theta}{2} + 2 \sin^2 \frac{\theta}{2} \right) \right],$$

$$\rightarrow 8EK \quad \text{when} \quad m_\mu \rightarrow 0; \quad \tag{A1a}$$

$$M^\gamma_{RR,RL}(t) = M^\gamma_{LR,LL} = M^\gamma_{RL,RR}(t) = M^\gamma_{LL,LR}(t) = 2m_\mu E \sin \theta \rightarrow 0 \quad \text{when} \quad m_\mu \rightarrow 0; \quad \tag{A1b}$$
\[
M_{RL:RL}^\gamma(t) = 4E \left[ K + (K - m_\mu) \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \right] \cos^2 \frac{\theta}{2}
\]
\[
\rightarrow 8EK \cos^2 \frac{\theta}{2} \quad \text{when} \quad m_\mu \rightarrow 0; \tag{A1c}
\]

Up to a factor \(-g^2/(q^2 - M_Z^2)\) the \(Z\) exchange amplitude is

\[
M_{RR:RR}^Z(t) = 2(g_V + g_A)E \left\{ (3g_A + g_V)K - (g_A - g_V)K \cos \theta \right. \\
+ \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} [g_A K - m_\mu g_A + 3g_V K - 3m_\mu g_V + g_A K \cos \theta \\
- m_\mu g_A \cos \theta - g_V K \cos \theta + m_\mu g_V \cos \theta] \right\}, \\
\rightarrow 8KE(g_V + g_A)^2 \quad \text{when} \quad m_\mu \rightarrow 0; \tag{A2a}
\]

\[
M_{LL:LL}^Z(t) = 2(g_V + g_A)E \left\{ (3g_A + g_V)K - (g_A - g_V)K \cos \theta \right. \\
+ \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} [g_A K - m_\mu g_A + 3g_V K - 3m_\mu g_V + g_A K \cos \theta \\
- m_\mu g_A \cos \theta - g_V K \cos \theta + m_\mu g_V \cos \theta] \right\}, \\
\rightarrow 8KE(g_V - g_A)^2 \quad \text{when} \quad m_\mu \rightarrow 0; \tag{A2b}
\]

\[
M_{RR:RR}^Z(t) = M_{RL:RL}^Z(t) = M_{LL:RR}^Z(t) = 2m_\mu E(g_V^2 - g_A^2) \sin \theta \rightarrow 0 \quad \text{when} \quad m_\mu \rightarrow 0; \tag{A2c}
\]

\[
M_{RL:RL}^Z(t) = 4E(g_V^2 - g_A^2) \left[ K + (K - m_\mu) \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \right] \cos^2 \frac{\theta}{2}
\]
\[
\rightarrow 8EK(g_V^2 - g_A^2) \cos^2 \frac{\theta}{2}, \quad \text{when} \quad m_\mu \rightarrow 0; \tag{A2d}
\]

All other amplitudes vanish.

The \(U^-\) vector bilepton contribution to the cross section are small because of the suppression factor \(|K_{\mu\mu}|^2\) in the amplitudes. The cross section of the \(\mu\epsilon\) scattering is dominated by the same fields of the ESM. However, in the \(A_{RL}(\mu\epsilon)\) asymmetry this factor cancel out.

Up to a \(ig^2|K_{\mu\mu}|^2/2(s - M_Z^2)\) factor the s-channel \(U\)-exchange amplitudes are

\[
M_{RR:RR}^U(s) = -M_{RL:RL}^U(s) = M_{LL:RR}^U(s) = M_{LL:LL}^U(s)
\]
\[
= 2E(K - m_\mu) \left[ \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} - 1 \right]^2 \sin^2 \frac{\theta}{2}
\]
\[
\rightarrow 0 \quad \text{when} \quad m_\mu \rightarrow 0; \tag{A3a}
\]

\[
M_{RL:RL}^U(s) = M_{RR:LR}(s) = -M_{RL:RR}(s) = M_{RL:LL}(s)
\]
\[
= -M_{LL:RL}(s) = M_{LL:LR}(s) = -M_{LR:RR}(s) = M_{LR:LL}(s)
\]
\[
= 2Em_\mu \sin \theta, \tag{A3b}
\]
all these amplitudes go to zero when \( m_\mu \to 0 \).

Finally,

\[
M_{RL;RL}^U(s) = -M_{RL;LR}^U(s) = -M_{LR;RL}^U(s) = M_{LR;LL}^U(s) = 2E(K - m_\mu) \left[ \left( \frac{K + m_\mu}{K - m_\mu} \right) + 1 \right]^2 \sin^2 \frac{\theta}{2} \\
\to 4K \sin^2 \frac{\theta}{2} \quad \text{when} \quad m_\mu \to 0.
\] (A3c)

APPENDIX B: DIFFERENTIAL CROSS SECTION FOR MUON-ELECTRON FT EXPERIMENT

In the target frame

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 m_e(E_\mu^2 - m_\mu^2)^{1/2}} \frac{|\vec{q}_2|^2}{(E_\mu + m_e)|\vec{q}_2| - (E_\mu^2 - m_\mu^2)^{1/2} E'_\mu \cos \theta} \quad |M|^2, \quad (B1)
\]

where

\[
|M|^2 = 4 \left[ 4EK \cos^2 \frac{\theta}{2} + 4E(K - m_\mu) \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \cos \frac{\theta}{2} \right]^2 + 16m_\mu^2 \sin^2 \theta E^2 \\
+ 128E(K - m_\mu) \left[ EK \cos^2 \frac{\theta}{2} + E(K - m_\mu) \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \cos^2 \frac{\theta}{2} \right] \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \sin^2 \frac{\theta}{2} \\
+ 2 \left[ 8E(K - m_\mu) \left( \frac{K + m_\mu}{K - m_\mu} \right)^{1/2} \sin^2 \frac{\theta}{2} \right]^2 \], \quad (B2)
\]

and \( |\vec{q}_2|, E'_\mu \) are the momentum and the energy in the target referential frame of the off going muon.
REFERENCES

[1] E. Derman and W. Marciano, Ann. Phys. (N.Y.) **121**, 147 (1979).

[2] J. F. Gunion, *Muon Colliders: The Machine and the Physics*, hep-ph/9707379. See also http://www.cap.bnl.gov/mumu and http://www.fnal.gov/projects/muon collider.

[3] J. C. Montero, V. Pleitez and M. C. Rodriguez, Preprint IFT-P.01/698; hep-ph/9802313.

[4] D. Adams *et al.* (SMC Collaboration), Phys. Rev. D **56**, 5330 (1997).

[5] D. Bardin and L. Kalinovskaya, hep-ph/9712310.

[6] F. Pisano and V. Pleitez, Phys. Rev. D **46**, 410 (1992).

[7] R. M. Barnett *et al.*, (Review of Particle Physics), Phys. Rev. D **54**, 1 (1996).

[8] G. W. S. Hou, Nucl. Phys. **B** (Proc. Suppl.) **51A**, 40 (1996).

[9] S. Y. Choi, C. S. Kim, Y. J. Kwon and S-H. Lee, hep-ph/9707483.

[10] V. Barger, S. Pakvasa and X. Tata, Phys. Lett. **B415**, 200 (1997).
Figure Captions

**Fig. 1** The $A_{RL}(\mu e)$ asymmetry for the ESM in a fixed target experiment as a function of the muon energy with $y = 1/2$ and $\sin^2(\theta_W) = 0.2315$ for $m_\mu = 0$ (continuous line) and $m_\mu = 0.105$ GeV (dashed line).

**Fig. 2** The $A_{RL}(\mu e)$ asymmetry for the ESM in a fixed target experiment with $E_\mu = 190$ GeV and $y = 1/2$ as a function of $\sin^2(\theta_W)$.

**Fig. 3** The $A_{RL}(\mu e)$ asymmetry for the ESM in a collider experiment with $E_\mu = 190$ GeV ($\sqrt{s} = 380$ GeV) and $\sin^2(\theta_W) = 0.2315$ as a function of $y$.

**Fig. 4** The $A_{R,RL}(\mu e)$ asymmetry for the ESM in a fixed target experiment with $E_\mu = 190$ GeV and $\sin^2(\theta_W) = 0.2315$ as a function of $y$ for $m_\mu = 0$ (continuous line) and $m_\mu = 0.105$ GeV (dashed line).

**Fig. 5** The asymmetry $A_{RL}(\mu e)$ for the ESM (dashed line) and for the ESM plus the $Z'$ contribution (continuous line) in a collider experiment with $E_\mu = 190$ GeV ($\sqrt{s} = 380$ GeV), $\sin^2(\theta_W) = 0.2315$, and $y = 1/2$ as a function of $M_{Z'}$. 
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