Remarks about left-right asymmetries in polarized lepton-lepton scattering

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The goal of this article is to outline the advantages of the measurement of left-right asymmetries in lepton-lepton ($l^-l^- \to l^-l^-$) scattering. The measurement of these asymmetries provide opportunities for both, precision measurement of $\sin^2\theta_W$ and discovery of "new physics".

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I. INTRODUCTION

It is well known that the observables in the lepton-lepton scattering have less uncertainties than in the lepton-hadron or hadron-hadron cases. This is because gauge models only specify the lepton-quark or quark-quark vertices, and some parton model assumptions of hadron structure, not present in the lepton-lepton case, must be invoked to relate the lepton-quark and quark-quark interactions with the lepton-hadron and hadron-hadron ones, and this implies in introducing some uncertainties in the calculation. In particular, the appealing features for studying the parity-violating asymmetries between the scattering of left- and right-handed polarized electrons on a variety of fixed targets ($e^-e^-, e^-\mu^-$) were pointed out some years ago by Derman and Marciano [1] and they were systematically studied, in both fixed target and collider experiments in lepton-lepton scattering for $e^-e^-, e^-\mu^-$ and in colliders for $\mu^-\mu^-$, in Refs. [2–5].

The left-right asymmetry is defined as

$$A_{RL}(ll \to ll) = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}, \tag{1}$$

where $d\sigma_{R(L)}$ is the differential cross section for one right (left)-handed lepton l scattering on an unpolarized lepton l. Another interesting possibility is the case when both leptons are polarized. We can define an asymmetry $A_{R;RL}$ 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 $A_{L;LR}$):

$$A_{R;RL} = \frac{d\sigma_{RR} - d\sigma_{RL}}{d\sigma_{RR} + d\sigma_{RL}}, \qquad A_{L;RL} = \frac{d\sigma_{LR} - d\sigma_{LL}}{d\sigma_{LL} + d\sigma_{LR}}. \tag{2}$$

We can define also an asymmetry when one incident particle is right- handed and the other is left-handed and the final states are right- and left or left- and right-handed:

$$A_{RL;RL,LR} = \frac{d\sigma_{RL;RL} - d\sigma_{RL;LR}}{d\sigma_{RL;RL} + d\sigma_{RL;LR}}, \tag{3}$$

or similarly, $A_{LR;RL,LR}$. All of these asymmetries can be calculated for both fixed target and colliders experiments. For more details on the notation see Ref. [3].

The appealing features of this type of measurement, following [1], are: (**1**) The asymmetry is manifestly parity violating: therefore its measurement determines the electron's parity violation weak neutral current interaction with the target or with the other beam in the case of colliders. (**2**) Because the effect investigated is due to the interference between the weak and electromagnetic amplitudes, the asymmetry is proportional to G_F and hence larger than the usual weak interaction effects which are $\mathcal{O}(G_F^2)$. (**3**) Since the asymmetry is a ratio, uncertainties (theoretical and experimental) which are common to both the numerator and denominator cancel out and therefore we can use them to perform precision measurement in the context of the standard model [6] (see section II). (**4**) Finally, this kind of interference measurements determines the relative sign between the weak and electromagnetic interactions. Unified gauge theories give unique predictions for this algebraic sign; therefore their determination provides an additional check on various models- i.e. some models may predict the correct magnitude for the asymmetries, but the wrong sign! (see section III). For fixed target experiments, in e^-e^- scattering a very intense polarized electron beam inciding on an unpolarized hydrogen target while in $e^-\mu^-$ scattering it is considered an inciding unpolarized muon beam on polarized electron target.

There are some advantages in considering asymmetries in e^-e^- and $e^-\mu^-$ scattering. Firstly, although in fixed target experiment the value of A_{RL} asymmetry is small (see below), the cross sections of these processes are large allowing for a good statistic and on the other hand in collider experiments the asymmetry is large but cross sections are small. Secondly, in $e^-\mu^-$ scattering the background contribution from μ^-N scattering is less severe because one could trigger on a single scattered electron which could not have arisen from a μ^-N collision. Besides in the $e^-\mu^-$ case that muon beams generally have energies at least one order of magnitude greater than the electron beams. We would like to point out that these asymmetries could be already measured in existing fixed target experiments like E158 [7] and NA47 [8].

On the other hand, we have being interested in these asymmetries in collider experiments since in the future we hope that colliders like the so called Next Linear Collider (NLC) [9] or the International Linear Collider (ILC) [10] could work in the e^-e^- mode and the First Muon Collider (FMC) [11] could work in $\mu^-\mu^-$ modes and hybrid collider could do well in $e^-\mu^-$.

This paper is organized as follows. Precision measurements in colliders experiments are discussed in section II; while "new physics" in section III. Our conclusion are given in the last section, IV.

II. DETERMINATION OF $\sin^2\theta_W$

In the standard electroweak model the $A_{RL}(e^-e^-)$ asymmetry at the tree level in fixed target experiment is given by:

$$A_{RL}^{\mathrm{FT;SM}}(ee) \approx -\frac{G_F Q^2}{\sqrt{2}\pi\alpha}\,\frac{1-y}{1+y^4+(1-y)^4}\,(1-4\sin^2\theta_W), \tag{4}$$

where $Q^2 = -y(2m_e^2 + 2m_e E_{\mathrm{beam}})$, $y = \sin(\theta/2)$, and the other constants are the well know α, G_F and $\sin^2\theta_W$. In the Eq. (4) the approximation $m_e^2 \ll Q^2 \ll M_Z^2$ was used, and if $E_{\mathrm{beam}} = 50$ GeV, $\theta \approx 90^o$ ($y = 1/2$) we obtain the following value [1,3]

$$A_{RL}^{\mathrm{FT;SM}}(ee) \approx -3\times 10^{-7}. \tag{5}$$

Marciano and Czarnecki, Ref. [12] have calculated the one loop electroweak radiative corrections and found a rather substantial $40\pm 3\%$ reduction of the tree level prediction.

We have also verified that $A_{RL}(e^-\mu^-)$, in fixed target experiments, is sensitive to the value of $\sin^2\theta_W$. In this case the A_{RL} asymmerty, for $m_\mu = 0$, is given by [1,4]:

$$A_{RL}^{FT;SM}(\mu e)\Big|_{m_\mu=0} = 4\frac{G_F}{\sqrt{2}}\frac{8M_W^2}{4\pi\alpha M_Z^2}g_V g_A\frac{ys}{1+(1-y)^2}(4\sin^2\theta_W - 1). \tag{6}$$

If we consider a fixed target experiment with $E_\mu = 190$ GeV, E_μ is the muon beam energy, a 0.5% change in the $A_{RL}(e^-\mu^-)$ value corresponds to a 0.04% change in $\sin^2(\theta_W)$, *i.e.*, a change from 0.2315 to 0.2316 [4]. This fact show that it could be useful for doing very precise electroweak studies in this kind of experiment too.

More recently it was pointed out in Ref. [2] that the asymmetry $A_{RL}(e^-e^-)$ in colliders experiments can be used to measure $\sin^2\theta_W$ rather precisely. Here we will briefly discuss the A_{RL} asymmetry for colliders experiments, for more details see Refs. [3,4]. In Fig. 1 we plot the A_{RL} as function of $\sin^2\theta_W$ to both e^-e^- and $e^-\mu^-$ colliders. The results for other values of E_{CM} are shown in Table I. We see that the weak mixing angle is more sensitive to that asymmetry for the $e^-\mu^-$ scattering.

It is clear that in the e^-e^- we need to measure A_{RL} with more precision than in the case $e^-\mu^-$ to have the same variation in $\sin^2\theta_W$ at the energies $\sqrt{s} = 1.0\ \ TeV, 1.5\ \ TeV$ and 2 TeV. In the case of $\sqrt{s} = 0.5$ TeV we need the same precision in both experiments. We should stress that the results to $\mu^-\mu^-$ is the same as in the case of e^-e^- [13].

As we have shown on this section the standard model implies a predictable degree of parity violation in lepton-lepton scattering, ranging from low energy phenomena to high energy, and we can use them to do very precise tests of the model. Of course, such sensitivity implies that a measurement of A_{RL} is also a good probe of "new physics" if it really exists, as we will show on the next section.

III. NEW PHYSICS

The standard model is exceedingly successful in describing leptons, quarks and their interactions, it is in excellent agreement with the worldwide data [14]. However, the necessity to go beyond it, from the experimental point of view, comes at the moment only from neutrino data [15]. If neutrinos are massive then new physics beyond the standard model is needed.

On the other hand, any extension of the standard model implies necessarily the existence of new particles. We can have a rich scalar-boson sector if there are several Higgs-boson multiplets [16] or have more vector and scalar fields in models with a larger gauge symmetry as in the left–right symmetric [17] and in 3-3-1 models [18], or we also can have at the same time more scalar, fermion, and vector particles as in the supersymmetric extensions of the standard model [19], or in the supersymmetric 3-3-1 model [20].

Recently Dimopoulos and Kaplan [21] take up again the Weinberg's idea [22] that the observed value of the weak mixing angle $\sin^2\theta_W = .231$ suggests indeed an $SU(3)$ symmetry at the 1 TeV scale. The point is that in such models $\sin^2\theta_W(M) = 1/4$, where M is an energy scale related with new physics or extra dimension. They implemented an $SU(3)_c \otimes SU(3)_W$ model embedded in a model of the Pati-Salam type [23] with gauge symmetry $SU(4)_c \otimes SU(2)'_L \otimes SU(2)'_R \otimes SU(3)'$ with quarks transforming only through the first three factors. There is a first symmetry breakdown to $SU(3)_c \otimes SU(2)'_L \otimes U(1)'$ and finally, to $SU(2)_L \otimes U(1)_Y$. Another interesting way to solve the introduction of quarks is to consider $SU(3)_c \otimes SU(3)_W$ models in 5 dimensions [24]. Independently of this interesting fact, we recall that the symmetry among the lightest particles i.e., e^-, e^+ and ν_e could be the last symmetry involving the known leptons. If we impose this symmetry on the electron sector we must also to impose it upon all the other particles and if we do not want to introduce extra dimension we must introduce extra quarks. In this case it is also possible to have anomaly cancellation only with three (or a multiple of three) families [18]. Any way, all those sort of models involve doubly charged vector bosons. Our consideration here will be model independent.

In general there will be several particles contributing to all observables, and for this reason it will be very difficult to identify their contributions in the usual and exotic processes. In some models [18,20,25] the contributions of the scalar-bosons can not be suppressed by the fermion masses and they can have the same strength of the fermion–vector-boson coupling. However, for e^-e^- and $\mu^-\mu^-$, in the s-channel there is no contribution to the A_{RL} asymmetry of doubly charged scalars, like H^{--} hence these parity violating asymmetries are only sensitive to the doubly charged vector bosons. In view of this, we will discuss in this section the role of A_{RL} asymmetry in finding signal for "new physics" [26].

In Ref. [3] it was noted that the left-right asymmetries in the lepton–lepton diagonal scattering are quite sensible to doubly-charged vector field contributions. While in [13] it was done an extended analysis by considering a detailed study of the bilepton U^{++} for the case $e^-e^- \to e^-e^-$ and $\mu^-\mu^- \to \mu^-\mu^-$. The main result obtained is

$$A_{R;RL}^{\mathrm{CO;ESM+U}}(l^-l^- \to l^-l^-) \approx -A_{R;RL}^{\mathrm{CO;ESM}}(l^-l^- \to l^-l^-), \tag{7}$$

where $l = e, \mu$.

In the model of the Ref. [18] there is also a Z' neutral vector boson which couples with the leptons. It was shown in Ref. [4] that for the non-diagonal scattering $(e^-\mu^-)$ the asymmetries are sensible to the existence of an extra neutral vector-boson Z', because

$$A_{RL}^{\mathrm{CO;ESM}}(e^-\mu^- \to e^-\mu^-) \neq A_{RL}^{\mathrm{CO;ESM+Z'}}(e^-\mu^- \to e^-\mu^-). \tag{8}$$

Hence, both U^{++} and Z' vector bosons can be potentially discovered in these sort of processes by measuring the left-right asymmetries. Here we should stress that although the results about the U^{++} and Z' were got in the context of the 3-3-1 model they are still valid in the supersymmetric version of the latter model [20]. The reason is that the lagrangian of the interaction between leptons and gauge bosons are the same in both models [27].

Finally, we want to stress that the e^-e^- collider is ideal for discovering and studying selectrons. This will allow to do precise measurements of the neutralino mass and the opportunity to observe and analyze cascade decays of the selectron [28,29].

IV. CONCLUSIONS

We should remember that left-right asymmetries have played key roles in establishing the validity of the standard model. They will continue to provide valuable tools during the next generation of colliders doing precision studies of the standard model and even more exciting is the possible direct detection of new phenomena such as bileptons, Z's, supersymmetry, and others. Here in this work we have reviewed how the asymmetries, defined in Ref. [3] can be used to perform this kind of study.

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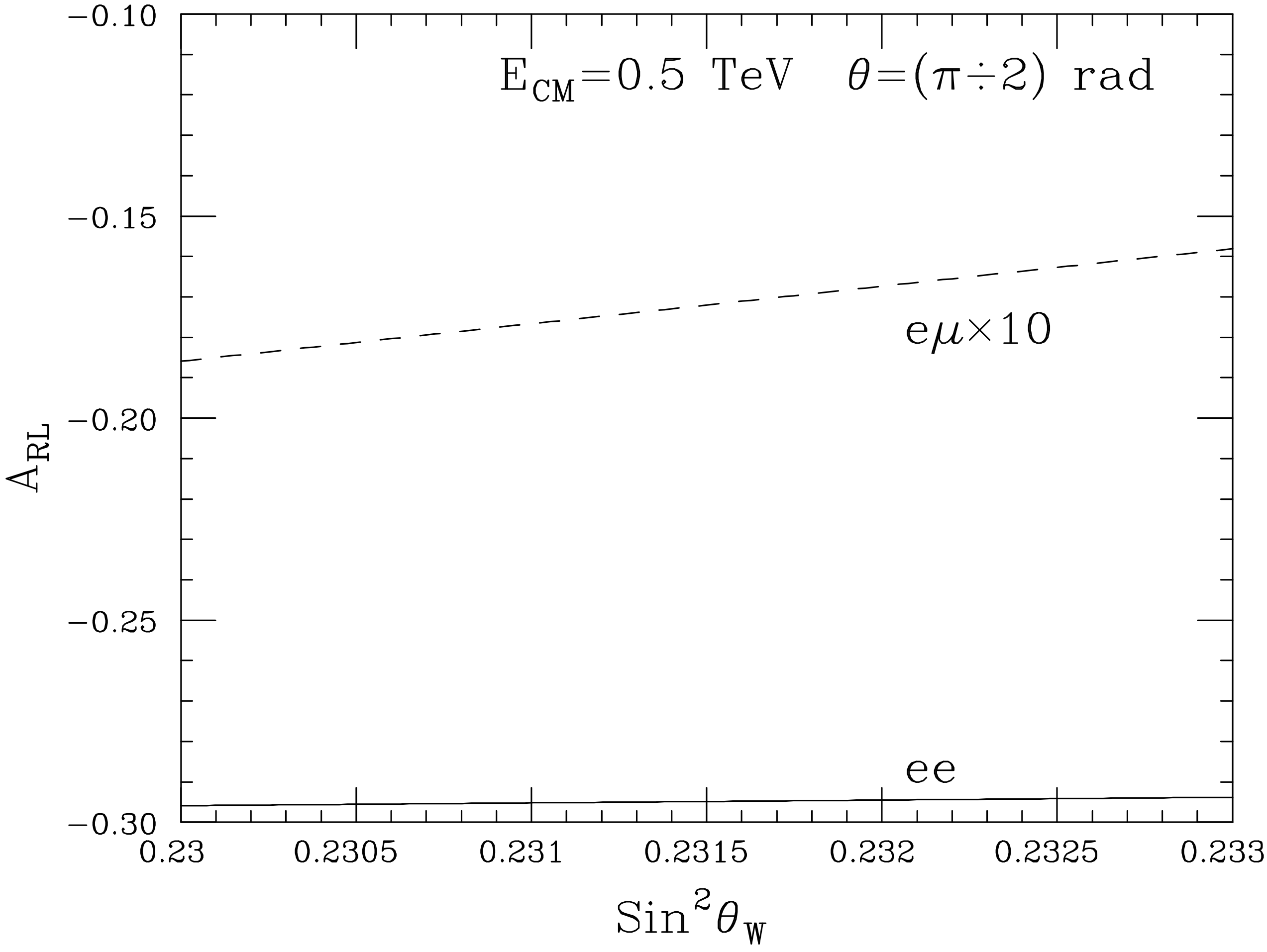

FIG. 1. The A_{RL} asymmetry as a function of $\sin^2\theta_W$ for e^-e^- and $e^-\mu^-$ collider experiments and $E_{\rm CM}=\sqrt{s}=0.5$TeV.

TABLE I. Dependece of the A_{RL} asymmetry on the $\sin^2\theta_W$.

$\sin^2\theta_W$	$A_{RL}^{CO;ESM}(e^-e^-)$	$A_{RL}^{CO;ESM}(e^-\mu^-)$
	$E_{CM} = 0.5$ TeV	
0.23073	-0.29536	-0.01789
0.23063	-0.29545	-0.01801
	$E_{CM} = 1.0$ TeV	
0.23073	-0.33309	-0.01977
0.23063	-0.33319	-0.01989
	$E_{CM} = 1.5$ TeV	
0.23073	-0.34786	-0.02016
0.23063	-0.34796	-0.02028
	$E_{CM} = 2$ TeV	
0.23073	-0.35574	-0.02030
0.23063	-0.35583	-0.02043