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High-precision calculations of electroweak radiative corrections for polarized Møller scattering at one loop and beyond

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Summary. — Parity-violating Møller scattering measurements are a powerful probe of new physics effects, and the upcoming high-precision experiments will require a new level of accuracy for electroweak radiative corrections (EWC). First, we perform the updated calculations of one-loop EWC for Møller scattering asymmetry using two different approaches: semi-automatic, precise, with FeynArts and FormCalc as base languages, and “by hand”, with reasonable approximations. In addition, we provide a tuned comparison between the one-loop results obtained in two different renormalization schemes: on-shell and constrained differential renormalization. As the last step, we discuss the two-loop EWC induced by squaring one-loop diagrams, and show that the significant size of this partial correction indicates a need for a complete study of the two-loop EWC in order to meet the precision goals of future experiments.

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1. – Introduction

Møller scattering is a very clean process with well-known kinematic and extremely suppressed backgrounds, and any inconsistency with the Standard Model will signal new physics. The next-generation experiment to study electron-electron scattering, MOLLER [1], planned at JLab following the 11 GeV upgrade, will offer a new level of sensitivity and measure the parity-violating asymmetry in the scattering of longitudinally polarized electrons off an unpolarized target to a precision of 0.73 ppb, and allow a determination of the weak mixing angle with an uncertainty of about 0.1%, a factor

of five improvement over the measurement by E-158 [2]. Obviously, before we can extract reliable information from the experimental data, it is necessary to take into account EWC. EWC to the parity-violating (PV) Møller scattering asymmetry were addressed in the literature earlier ([3-5]) and were shown to be large. A more detailed literature review can be found in [5], our first work on the topic. In [5], we calculated a full gauge-invariant set of the one-loop EWC and found the total correction to be close to -70% , with no significant theoretical uncertainty coming from the hadronic contributions to the vacuum polarization or other uncertain input parameters. Since it is possible that a much larger theoretical uncertainty may come from two-loop corrections, we investigated the importance of two-loops contribution in [6], by comparing corrections calculated in two different renormalization schemes (RS), on-shell and constrained differential renormalization (CDR, [7]), and found a difference to be about 11%. That means that the two-loop EWC may be larger than previously thought and cannot be dismissed, especially in the light of precision promised by MOLLER. We divide the two-loop EWC into two classes: Q-part induced by quadratic one-loop amplitudes, and T-part the interference of Born and two-loop diagrams. In [8], we calculated the Q-part exactly and found that it can reach 4%. Here, we provide a brief review of our calculations done at the one-loop level [5], show details of comparison between corrections evaluated in on-shell and CDR schemes [6], and outline some of our calculations of higher order corrections.

2. – Born and one-loop corrections

The asymmetry between left/right longitudinally polarized electrons can be constructed in the following way:

$$(1) \quad A_{LR} = \frac{\sigma_{LL} + \sigma_{LR} - \sigma_{RL} - \sigma_{RR}}{\sigma_{LL} + \sigma_{LR} + \sigma_{RL} + \sigma_{RR}} = \frac{\sigma_{LL} - \sigma_{RR}}{\sigma_{LL} + 2\sigma_{LR} + \sigma_{RR}},$$

enhancing the contributions induced by PV electroweak interactions. The term $\sigma \equiv \frac{d\sigma}{d\cos\theta}$ stands for the differential cross section defined in the center of mass reference frame of incoming electrons. At the Born level (leading order (LO)), asymmetry is

$$(2) \quad A_{LR} = \frac{s}{2m_W^2} \frac{y(1-y)}{1+y^4+(1-y)^4} \frac{1-4s_W^2}{s_W^2}, \quad y = -\frac{t}{s},$$

where $s_W^2 \equiv \sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \sim 0.24$. As one can see from eq. (2), the asymmetry is highly sensitive to θ_W so any deviation from the SM value will signal new physics. Obviously, before we can extract reliable information from the experimental data, it is necessary to include EWC. The cross section including one-loop matrix elements is

$$(3) \quad \sigma = \frac{\pi^3}{2s} |M_0 + M_1|^2 = \frac{\pi^3}{2s} (M_0 M_0^\dagger + 2 \operatorname{Re} M_1 M_0^\dagger + M_1 M_1^\dagger) = \sigma_0 + \sigma_1 + \sigma_Q,$$

where $\sigma_1 = \sigma_1^{BSE} + \sigma_1^{Ver} + \sigma_1^{Box} \propto \alpha^3$ is an interference term between the Born and one-loop amplitudes (NLO), and the cross section $\sigma_Q \propto \alpha^4$ is a quadratic term of the same order as two-loops contribution (NNLO). To make sure that our calculations at the one-loop level are error-free, we evaluate EWC using two different methods. Our first method, “by hand”, is to derive the compact analytic expressions for the leading one-loop correction (see [5]) manually using appropriate approximations for $\sqrt{s} \ll 30 \text{ GeV}$ and

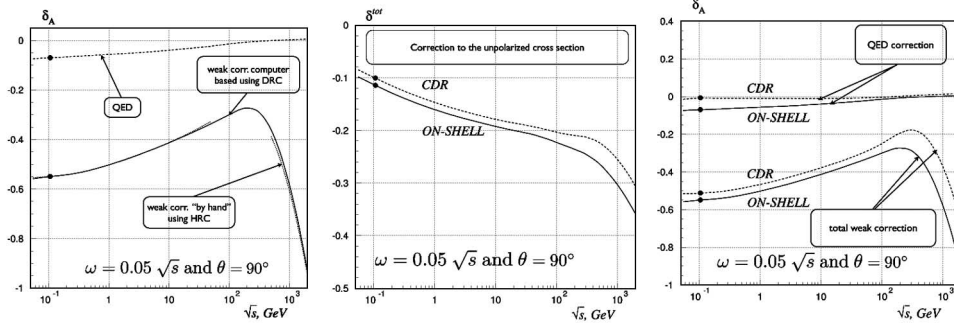


Fig. 1. – a) Weak and QED ($\omega = 0.05 \cdot \sqrt{s}$) corrections to the PV asymmetry in Møller scattering at $\theta = 90^\circ$ (left plot). b) Total correction to the cross section in OS and CDR schemes (middle plot). c) Correction to the PV asymmetry in OS and CDR schemes (right plot).

$\sqrt{s} \gg 500$ GeV. Our second method, semi-automated, is to consider a full set of graphs with no approximations using computer-based algebra packages [9,10] and [11]. To make sure that we calculate a gauge-invariant set of graphs, we use two sets of renormalization conditions (RC): RC by Hollik (HRC) introduced in [12] for our “by hand” approach, and RC proposed by Denner (DRC) in [13] for our semi-automated method. The infrared divergences (IR) are treated by the soft and hard-photon bremsstrahlung (see [5]). We choose our input parameters to be the fine structure constant ($\alpha = 1/137.03599$), mass of the W boson ($m_W = 80.398$ GeV) and mass of the Z boson ($m_Z = 91.1876$ GeV). A relative correction to the PV asymmetry is defined as $\delta_A^C = (A_{LR}^C - A_{LR}^0)/A_{LR}^0$, with the superscript in δ_A^C corresponding to the various contributions: “weak”—no IR-divergent graphs and “QED”—only IR divergent graphs treated by bremsstrahlung contribution. In order to see how our results compare to the literature [4], we compare $\delta_A^{weak}([5]) = -0.2790$ for the $\sqrt{s} = 100$ GeV and $\delta_A^{weak}([4]) = -0.2787$ using the same input parameters as in [4] and obtained an excellent agreement. A comparison of results evaluated by two methods can be seen in fig. 1(a). To establish if the higher-order (NNLO) contributions in a given RS are important (see [14]), we compare results in two RS: on-shell (OS) and CDR. Figure 1(b) shows the total correction to the unpolarized cross section $\delta^{tot} = (\sigma^{tot} - \sigma^0)/\sigma^0$ calculated in OS and CDR schemes. In the low-energy region, the correction to the cross section is dominated by the QED contribution, and the difference between the two schemes is almost constant and rather small (~ 0.01), but it grows at $\sqrt{s} \geq m_Z$ as the weak correction becomes comparable to QED. As a result (see fig. 1(c)), the difference between OS and CDR corrections to the PV asymmetry can reach as much as 10% so contribution from two-loop corrections could become important.

3. – Two-loops corrections (Q-part)

The higher-order corrections ($\propto \alpha^4$) to the electroweak Born cross section can be divided into two classes, Q-part and T-part. The Q-part is induced by the quadratic one-loop amplitude ($\sim M_1 M_1^\dagger$) (third term in eq. (2)) and the T-part is an interference term between the Born and two-loops amplitudes: $\sigma_T = \frac{\pi^3}{s} \text{Re} M_2 M_0^\dagger \propto \alpha^4$ (fig. 2). The T-part still needs to be evaluated in the future, but we can provide some results for the Q-part in this paper. The cross section for the Q-part can be divided into two

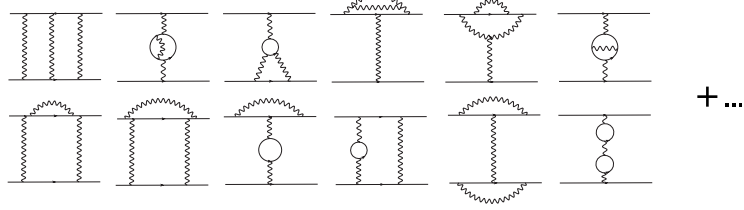


Fig. 2. – Representative two-loops graphs for the Møller scattering.

terms: $\sigma_Q = \sigma_Q^\lambda + \sigma_Q^f$. The first term, σ_Q^λ , is an IR-divergent and regularized part of the cross section and the second term $\sigma_Q^f = (\frac{\alpha}{\pi})^2 \delta_1^f \cdot \sigma_0$ is a finite contribution. The IR-divergent part has the following structure:

$$(4) \quad \sigma_Q^\lambda = \frac{\pi^3}{2s} M_1^{\lambda\dagger} (M_1^\lambda + 2M_1^f) = \frac{1}{4} \left(\frac{\alpha}{\pi} \right)^2 \text{Re} \left[\delta_1^{\lambda*} (\delta_1^\lambda + 2\delta_1^f) \right] \cdot \sigma_0,$$

where $\delta_1^\lambda = 4 \ln \frac{\lambda}{\sqrt{s}} (\ln \frac{tu}{m^2 s} - 1 + i\pi)$. Since the Q-part contains terms of order $\propto \ln^2 \frac{\lambda}{\sqrt{s}}$ it deserves a special attention. To treat the IR divergences, we have to account not only for photon emission from one-loop diagrams but also include a complete treatment of the two-photons emission (fig. 3). A half of the bremsstrahlung contribution in fig. 3(a) and (b) is responsible for the treatment of IR divergence in the Q-part and an other half for the T-part. We take the maximum energy of the emitted soft photon to be $\omega = 0.05 \cdot \sqrt{s}$. The bremsstrahlung cross section for Q-part is derived from fig. 3(a) as

$$(5) \quad \sigma_Q^\gamma = \frac{1}{2} \sigma^\gamma = \frac{1}{2} \left(\frac{\alpha}{\pi} \right)^2 \text{Re} [(-\delta_1^\lambda + R_1)^* (\delta_1^\lambda + \delta_1^f)] \cdot \sigma_0,$$

$$R_1 = -4 \ln \frac{\sqrt{s}}{2\omega} \left(\ln \frac{tu}{m^2 s} - 1 + i\pi \right) - \ln^2 \frac{s}{em^2} + 1 - \frac{\pi^3}{3} + \ln^2 \frac{u}{t}.$$

Here, σ^γ is the total photon emission cross section and σ_Q^γ is the one-photon bremsstrahlung term from the Q-part. The two-photons emission for the Q-part ($\sigma_Q^{\gamma\gamma}$) is derived from fig. 3(b):

$$(6) \quad \sigma_Q^{\gamma\gamma} = \frac{1}{2} \sigma^{\gamma\gamma} = \frac{1}{4} \left(\frac{\alpha}{\pi} \right)^2 \left(|-\delta_1^\lambda + R_1|^2 - \frac{8}{3} \pi^2 \left| \ln \frac{tu}{m^2 s} - 1 + i\pi \right|^2 \right) \cdot \sigma_0.$$

Combining eqs. (4), (5) and (6) gives the final result for $\sigma_Q^\lambda + \sigma_Q^\gamma + \sigma_Q^{\gamma\gamma}$ free from non-physical parameters with the regularization parameter λ cancelled analytically. Detailed calculations can be found in [8]. As one can see from fig. 4(a), the correction induced by the Q-part ($\Delta_A = (A_{LR}^{1-loop+Q} - A_{LR}^{1-loop})/A_{LR}^0$) can reach as much as $\sim 4\%$ at 90° . The energy dependence (fig. 4(b)) is nearly constant for $\sqrt{s} < m_Z$ but increases rapidly after weak interactions become comparable to QED.

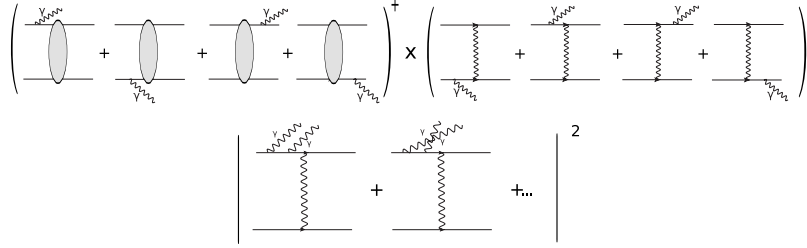


Fig. 3. – Bremsstrahlung treatment of IR divergences in the Q-part. The top plot represents interference between emission from one-loop (shaded bubble) and Born graphs. The bottom plot is the two-photons emission amplitude squared.

4. – Conclusion

With the one-loop corrections now under control, it is worth considering the EWC corrections at the two-loop level. One way to find some indication of the size of higher-order contributions is to compare results that are expressed in terms of quantities related to different renormalization schemes (RS), and our tuned comparison between the results obtained in on-shell and CDR RS show a difference of about 11%. Although an argument can be made that the two-loop corrections are suppressed by a factor of $\alpha\pi$ relative to the one-loop corrections, we believe that they can no longer be dismissed, especially in the light of 2% uncertainty to asymmetry promised by the MOLLER experiment. At the MOLLER kinematic conditions, the part of the quadratic correction considered here can increase the asymmetry up to $\sim 4\%$. For the high-energy region $\sqrt{s} \sim 2$ TeV, a contribution from the quadratic correction can reach +30%. It is impossible to say at this time if the Q-part will be enhanced or cancelled by other two-loop radiative corrections, but we believe that the large size of the Q-part demands detailed and consistent consideration of two-loop corrections (T-part), which is the current task of our group.

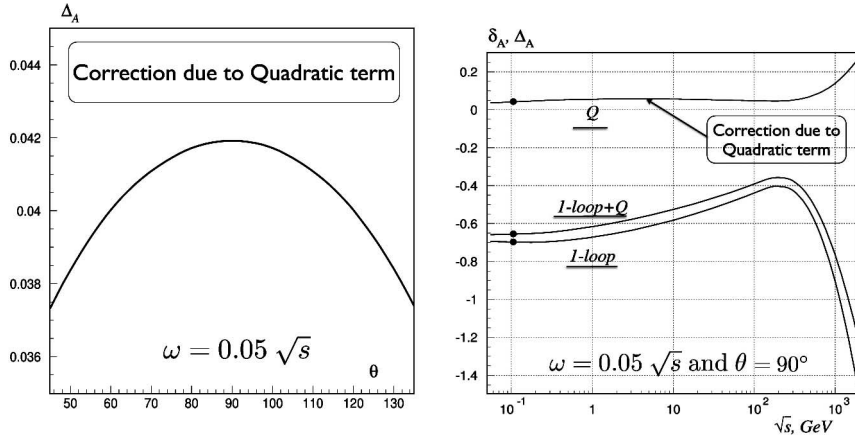


Fig. 4. – Left plot (a) shows the angular dependence of the correction induced by quadratic part only (Δ_A) and the right plot (b) shows “one-loop”, “one-loop + Q-part” and quadratic corrections energy dependence.

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