Pauli form factors of electron and muon in nonlocal quantum electrodynamics

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Pauli form factors of electron and muon are studied in nonlocal quantum electrodynamics. We calculate one loop QED correction to their Pauli form factors. The relativistic regulator is generated by the correlation function in the nonlocal interaction. The cut-off parameter \(\Lambda\) in the regulator is determined to get the consistent anomalous magnetic moments of electron and muon at the same level as local QED. When momentum transfer is large, there exists obvious difference between nonlocal and local QED.

I. INTRODUCTION

The anomalous magnetic moments of electron and muon \(a_e\) and \(a_\mu\) are among the most precisely determined observables in particle physics. The most accurate measurement of \(a_e\) so far has been carried out by the Harvard group as \(a_e = 1159652180.73(28) \times 10^{-12}\) [1, 2]. Further improvements for the electron and positron measurements are currently prepared by the Harvard group [3]. For the muon magnetic moment, the E821 measurement at BNL [4], corrected for updated constants [5, 6], is \(a_\mu = 116592089(63) \times 10^{-11}\). Two next generation muon \(g - 2\) experiments at Fermilab in the US and at J-PARC in Japan have been designed to reach a four times better precision from 0.54 ppm to 0.14 ppm [7].

The standard model (SM) values of lepton anomalous magnetic moments are estimated separately by theorists. It has several parts: quantum electrodynamics (QED), electroweak (EW), hadronic vacuum polarization (HVP) and hadronic light-by-light (HLbL). The QED and EW parts are known very well perturbatively. For example, the QED contribution to the anomalous magnetic moment of electron and muon is known up to 5-loop order [8]. The others, being hadronic terms, are less well known and are estimated using various techniques, including data from other experiments [9] and lattice calculations [10, 11].

With the updated theoretical prediction from standard model and the existing experimental measurement, one can get the discrepancy. For example, for electron, the discrepancy is [12, 13]

\[
\Delta a_e = (-87 \pm 36) \times 10^{-14},
\]

(1)

which shows a 2.4\(\sigma\) deviation. For muon, the anomalous magnetic moment \(a_\mu\) has 3.7 \(\sigma\) discrepancy with a positive sign, opposite to the \(a_e\) deviation [10, 14]. The value of \(\Delta a_\mu\) is

\[
\Delta a_\mu = (2.74 \pm 0.73) \times 10^{-9}.
\]

(2)

As standard model predictions almost without exception match perfectly all other experimental information, the deviation in one of the most precisely measured quantities in particle physics remains a mystery and inspires the imagination of model builders. In this paper, we will investigate the anomalous form factors of electron and muon with the nonlocal quantum electrodynamics inspired from the nonlocal effective field theory (EFT).

Nonlocal effective field theory was recently proposed to study hadron physics. Different from the traditional EFT, the interaction is nonlocal which reflects the non-point behavior of hadrons. Therefore, in the nonlocal Lagrangian, there is a correlation function \(F(x - y)\), where the baryon is located at \(x\) and meson at \(y\). If \(F(x - y)\) is chosen to be \(\delta(x - y)\), the Lagrangian will be changed back to the local one. With the correlation function, there is no ultraviolet divergence in the loop integral. The nonlocal EFT has been applied to study the nucleon electromagnetic form factors, strange form factors, parton distributions, etc [15–18].

The nonlocal Lagrangian may be not only the phenomenological method to deal with the divergence, but also the general property for all the physical interactions. In other words, whether there is divergence or not, the nonlocal regulator always exists. Therefore, with the same idea, the interaction between electron and photon could also be nonlocal. In the classical scenario (tree level diagram), the nonlocal effect is certainly negligible for the low momentum transfer. However, for the quantum fluctuation or loop diagram, the internal photon can detect the structure of the physical particle since its momentum can be infinite.

In this paper, we will show the deviation of the lepton Pauli form factors in nonlocal QED from local one. It can be seen that high order QED corrections and hadronic effects do not affect the final conclusion since the deviation is significant, especially at large \(Q^2\). Compared with the observables in hadron physics, where the non-perturbative
FIG. 1: Feynman diagram for the one loop vertex correction to the lepton form factors.

effect is very important, it is a great advantage for the lepton anomalous form factors to serve as the quantities to test standard model. In the following, we will first derive the form factors in nonlocal QED and then show the numerical results.

II. NONLOCAL QED LAGRANGIAN

The nonlocal Lagrangian for quantum electrodynamics is written as

$$\mathcal{L}_{\text{QED}}^{nl} = \bar{\psi}(x)(i\partial - m)\psi(x) - \frac{1}{4}F_{\mu\nu}(x)^2 - e\int d^4a\bar{\psi}(x)A_\mu(x + a)\psi(x)F(a),$$  \hspace{1cm} (3)

where the electron field $\psi(x)$ is located at $x$ and the photon field $A_\mu(x + a)$ is located at $x + a$. $F(a)$ is the correlation function normalized as $\int d^4aF(a) = 1$. If it is chosen to be a $\delta$ function, the nonlocal Lagrangian will be changed back to the local one. The above nonlocal Lagrangian is invariant under the following gauge transformation

$$\psi(x) \to e^{i\alpha(x)}\psi(x), \quad A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \alpha'(x),$$  \hspace{1cm} (4)

where $\alpha(x) = \int d\alpha'(x + a)F(a)$. Different from the nonlocal Lagrangian for EFT, where the gauge link is introduced to guarantee the local gauge invariance, here we need no gauge link since photon is charge neutral.

With the correlation function, the lepton-photon interaction is momentum dependent as $e\gamma_\mu \tilde{F}(q)$, where $\tilde{F}(q)$ is Fourier transformation of the correlation function $F(a)$ and $q$ is photon momentum. Ward-Takahashi identity becomes

$$-iq_\mu\Gamma^\mu(p + q, p) = \tilde{F}(q)(S^{-1}(p + q) - S^{-1}(p)),$$  \hspace{1cm} (5)

where $\Gamma^\mu(p + q, p)$ is the vertex. $S(p + q)$ and $S(p)$ are the lepton propagators with wave function renormalization

$$S(p + q) = \frac{iZ_2}{\not{p} + \not{q} - m}, \quad S(p) = \frac{iZ_2}{\not{p} - m},$$  \hspace{1cm} (6)

where $Z_2$ is lepton wave function renormalization factor. At $q = 0$, $\tilde{F}(q)$ is 1 due to the normalization of $F(a)$ and Eq.(5) can be written as

$$Z_2\Gamma^\mu(p, p) = \gamma^\mu \tilde{F}(0).$$  \hspace{1cm} (7)

The lepton form factors is defined as [19]

$$Z_2\Gamma^\mu(p + q, p) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2).$$  \hspace{1cm} (8)
Therefore, we have $F_1(0) = \tilde{F}(0)$ which is consistent with that the renormalized lepton charge is 1.

The one loop Feynman diagram for the lepton form factors is plotted in Fig. 1. At one loop level, the vertex is written as

$$\bar{u}(p')\Gamma_{\text{loop}}^{\mu}(p',p)u(p) = \bar{u}(p') \int \frac{d^4k}{(2\pi)^4} \tilde{F}(q)\tilde{F}(k)^2(-ie\gamma^\nu) \frac{i}{p' - k - m} \gamma^\mu \frac{i}{p - k - m} (-ie\gamma^\rho) \frac{-ig_{\nu\rho}}{k^2} u(p)$$  \hspace{1cm} (9)

From Eq. (8), one can get

$$F_1^{\text{loop}}(q^2) = \frac{-ie^2\tilde{F}(q^2)}{(4m^2 - q^2)^2} \int \frac{d^4k}{(2\pi)^4} \tilde{F}^2(k^2) \left\{-\frac{2m^2((k \cdot p)^2 + (k \cdot p')^2) + 8m^2k^2(4m^2 - q^2)}{((p' - k)^2 - m^2)(p - k)^2 - m^2)k^2}ight\}$$

$$+ \frac{2(2m^2 - q^2)(4m^2 - q^2)^2 - 4(4m^2 + 2q^2)(k \cdot p)(k' \cdot p') - 4(k \cdot p + k \cdot p')(8m^4 - 6m^2q^2 + q^4)}{((p' - k)^2 - m^2)(p - k)^2 - m^2)k^2}$$ \hspace{1cm} (10)

and

$$F_2^{\text{loop}}(q^2) = \frac{-ie^2\tilde{F}(q^2)8m^2}{q^2(4m^2 - q^2)^2} \int \frac{d^4k}{(2\pi)^4} \tilde{F}^2(k^2) \left\{\frac{(4m^2 + 2q^2)((k \cdot p)^2 + (k \cdot p')^2) - 8m^2q^2(k \cdot p)(k \cdot p')}{((p' - k)^2 - m^2)(p - k)^2 - m^2)k^2}ight\}$$

$$+ \frac{(q^4 - 4m^2q^2)(k \cdot p + k \cdot p' + k^2)}{((p' - k)^2 - m^2)(p - k)^2 - m^2)k^2}.$$ \hspace{1cm} (11)

In the above expressions, the momentum dependent vertexes $\tilde{F}(q)$ and $\tilde{F}(k)$ appear. For $\tilde{F}(q)$, if the external momentum $q$ is much smaller than the scale of electron, the size of electron can be neglected and $\tilde{F}(q) \approx 1$. However, for $\tilde{F}(k)$, the internal momentum $k$ varies from 0 to infinity. The regulator is very important and it makes the loop integral for $F_1$ and $F_2$ both convergent.

For the Dirac form factor $F_1(q^2)$, there is a contribution from tree level as $Z_2\tilde{F}(q^2)$. The wave function renormalization constant $Z_2$ is obtained as [19]

$$Z_2 - 1 = \left. \frac{d\Sigma(p)}{dp} \right|_{p = m}.$$ \hspace{1cm} (12)

where the lepton self-energy is expressed as

$$\Sigma(p) = -\int \frac{d^4k}{(2\pi)^4} \tilde{F}^2(k)(ie\gamma^\nu) \frac{1}{p' - k - m} (-ie\gamma^\rho) \frac{-ig_{\nu\rho}}{k^2}.$$ \hspace{1cm} (13)

It is straightforward to find $\left. \frac{d\Sigma(p)}{dp} \right|_{p = m} = -F_1^{\text{loop}}(0)$. Again, we have $F_1(0) = Z_2 + F_1^{\text{loop}}(0) = 1$.

In the following, we focus on the Pauli form factor $F_2(q^2)$ and $F_2(0)$ gives the anomalous magnetic moment. For the numerical calculation, the regulator $\tilde{F}(k^2)$ is chosen to be a dipole form as

$$\tilde{F}(k^2) = \frac{\Lambda^4}{(k^2 - \Lambda^2)^2}.$$ \hspace{1cm} (14)

The Pauli form factor at one loop level can be obtained as

$$F_2^{\text{nl}}(Q^2) = \frac{\alpha}{2\pi} \tilde{F}(-Q^2) \int_0^1 dx \int_0^{1-x} dy \frac{2\Lambda^8m^2(x+y)(1-x-y)^5}{(Q^2xy + m^2(x+y)^2)(m^2(x+y)^2 + Q^2xy + (1-x-y)\Lambda^2)^4}.$$ \hspace{1cm} (15)

When $\Lambda$ goes to infinity, the local result will be recovered as

$$F_2^{\text{lo}}(Q^2) = \frac{\alpha}{2\pi} \int_0^1 dx \int_0^{1-x} dy \frac{2m^2(1-x-y)(x+y)}{m^2(x+y)^2 + Q^2xy},$$ \hspace{1cm} (16)

which results in the well known anomalous magnetic moment at one loop level $a_1 = F_2^{\text{lo}}(0) = \frac{\alpha}{2\pi}$ [20]. In the above equations, we replaced $q^2$ by $-Q^2$ for convenience. With the results from nonlocal and local QED, we can get the discrepancy between them as $\Delta F_2 = F_2^{\text{lo}} - F_2^{\text{nl}}$. The relative discrepancy is defined as $R = \Delta F_2/F_2^{\text{lo}}$. The loop integral for Pauli form factors are both ultraviolet convergent in local and nonlocal cases. We should mention that
the regulator is not introduced phenomenologically to deal with the divergence. This is different from the original finite-range-regularization [21–36]. The regulator is naturally generated from the nonlocal Lagrangian with the naive idea that the interaction between photon and lepton does not necessary take place at one point. For the ultraviolet divergent integral at local case, the regulator will make the integral convergent. For the integral which is convergent at local case, the regulator also exists and will give obvious deviations from the local result, especially at large momentum transfer.

III. NUMERICAL RESULTS

In the numerical calculation, there is one free parameter \( \Lambda \) in the regulator needs to be determined. \( \Lambda \) is order of 1 GeV for nucleon. For leptons, \( \Lambda \) could be much larger since their sizes are much smaller. Certainly, on the one hand, the smaller the value of \( \Lambda \), the larger the deviation from the standard model. On the other hand, \( \Lambda \) should be large enough and make the nonlocal results consistent with the experiments at the same level as standard model. When \( \Lambda = 0.2 \) TeV, the calculated \( a^\mu_\text{nl} \) in nonlocal QED is 0.00116171491307, which is \( 2.0 \times 10^{-14} \) deviation from the corresponding value in standard model. Considering the experimental accuracy \( 2.6 \times 10^{-13} \) and discrepancy between experiments and SM prediction up to \( 2 \times 10^{-10} \) deviation from that in local case. Comparing with \( \Delta a^\mu_\text{nl} \) is \( 2.7 \times 10^{-9} \), \( \Lambda = 0.2 \) TeV is also fine for muon. Therefore, in the numerical calculation, we show the results with \( \Lambda = 0.2 \) and 0.5 TeV. In principle, QED itself can not determine the form of the regulator and the value of \( \Lambda \). It can only be determined by the experimental data, especially at finite \( Q^2 \). We will show that whatever \( \Lambda \) is, the relative discrepancy between local and nonlocal QED is always significant if momentum transfer \( Q^2 \) is large enough.

In Fig. 2 we plot the Pauli form factor of electron \( F_2^e(Q^2) \) versus momentum transfer \( Q^2 \). The solid, dashed and dotted lines are for \( \Lambda = 0.2 \), 0.5 TeV and local limit, respectively. The small figure is for \( F_2^e(Q^2) \) at low \( Q^2 \) up to 0.001 TeV².

![FIG. 2: Electron Pauli form factor \( F_2^e(Q^2) \) versus momentum transfer \( Q^2 \). The solid, dashed and dotted lines are for \( \Lambda = 0.2 \), 0.5 TeV and local limit, respectively. The small figure is for \( F_2^e(Q^2) \) at low \( Q^2 \) up to 0.001 TeV².](image-url)
both much larger for muon than that for electron. The relative deviation $R$ are almost the same for electron and muon. This can be seen from Eqs. (15) and (16). The lepton mass dependence in the numerator cancels each other for $F_{2l}^n/F_{2l}^o$. The mass in the denominator is much smaller than $\Lambda$ which makes $R$ nonsensitive to the mass. At $Q^2 = 0$, the relative deviation is very small and is order of $10^{-11}$ and $10^{-7}$ for electron and muon. This is more or less the same order for the relative deviation of SM from the experiments. Therefore, to confirm this discrepancy for electron, the experiment should be very accurate to get 10 more effective digits. The relative deviation $R$ increases with the increasing $Q^2$. For example, at $Q^2 = 0.01$ TeV$^2$, $R$ is about 0.37 and 0.08 for $\Lambda = 0.2$ and 0.5 TeV, respectively. When $Q^2$ is larger than 0.1 TeV$^2$, $R$ is larger than 0.5 for both $\Lambda$s. This means the nonlocal value of $F_{2l}^n$ is less than half of the SM value. For even larger $Q^2$, say larger than 0.2 TeV$^2$, $F_{2l}^n$ could be one magnitude smaller than the SM value. We can see though the absolute value of the form factor is small, the relative deviation of nonlocal QED from SM is very large. Even if the experiment can only measure the form factor with one effective digit at finite $Q^2$, one can still conclude whether there is physics beyond SM. Since the deviation is so large at finite $Q^2$, the conclusion is not changed by the high order QED correction or hadronic effect, as we know for both electron and muon, these corrections are less than one percent. In summary, we list the discrepancy between nonlocal QED and SM and the relative deviation at some $Q^2$ for electron and muon in Table I.
IV. SUMMARY

We studied the anomalous form factors of electron and muon in nonlocal QED inspired by the nonlocal effective field theory for hadron physics. The interaction between lepton and photon is describe by the nonlocal QED. The regulator is generated from the correlation function in the nonlocal Lagrangian. For the Dirac form factor of leptons and electromagnetic form factors of nucleon, the ultraviolet divergence of loop integral in local interaction will disappear with the regulator. For the Pauli form factors of electron and muon, the loop integrals are both convergent for nonlocal and local QED. The parameter \( \Lambda \) is chosen to make the nonlocal result of lepton anomalous magnetic effect is less than one percent, the large relative deviation is not affected. If this deviation can be measured, it will definitely indicate new physics beyond SM. It will also imply that nonlocal behavior could be the general property for all the interactions and as a result, we will have to reconsider the regularization and renormalization.

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| \( Q^2 \) (TeV\(^2\)) | 0 | 0.001 | 0.01 | 0.05 | 0.1 | 0.2 |
|----------------|----|--------|------|------|-----|-----|
| \( \Delta F_2^e \) (\( \Lambda = 0.2 \) TeV) | \( 2.03 \times 10^{-14} \) | \( 6.63 \times 10^{-13} \) | \( 5.41 \times 10^{-13} \) | \( 2.55 \times 10^{-13} \) | \( 1.49 \times 10^{-13} \) | \( 8.08 \times 10^{-14} \) |
| \( \Delta F_2^\mu \) (\( \Lambda = 0.5 \) TeV) | \( 3.27 \times 10^{-15} \) | \( 1.10 \times 10^{-13} \) | \( 1.14 \times 10^{-13} \) | \( 9.79 \times 10^{-14} \) | \( 8.03 \times 10^{-14} \) | \( 5.79 \times 10^{-14} \) |
| \( R^e \) (\( \Lambda = 0.2 \) TeV) | \( 1.74 \times 10^{-11} \) | 0.050 | 0.370 | 0.808 | 0.922 | 0.973 |
| \( R^\mu \) (\( \Lambda = 0.5 \) TeV) | \( 2.81 \times 10^{-12} \) | 0.008 | 0.077 | 0.311 | 0.496 | 0.697 |

**TABLE I:** The discrepancy between nonlocal QED and SM and the relative deviation for electron and muon.
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