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รายงานการวิจัย

ผลของความแปลกต่อฟอร์มแฟกเตอร์แม่เหล็กไฟฟ้า ของนิวคลีออน

(Strangeness contribution to electromagnetic form factors of nucleons)

ได้รับทุนอุดหนุนการวิจัยจาก

มหาวิทยาลัยเทคโนโลยีสุรนารี

ผลงานวิจัยเป็นความรับผิดชอบของหัวหน้าโครงการวิจัยแต่เพียงผู้เดียว

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Strangeness contribution to electromagnetic form factors of nucleons

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บทคัดย่อ

ในโครงการวิจัยนี้ ผลกระทบของกลุ่มหมอกของมีซอนและความแปลกต่อฟอร์มแฟกเตอร์เชิงแม่เหล็กไฟฟ้าของบาริออนชุดแปดได้ถูกศึกษาโดยใช้แบบจำลองควาร์กเชิงไคแรลเพอร์เทอร์เบชัน ซึ่งฟังก์ชันคลื่นของควาร์กได้ถูกกำหนดไว้ล่วงหน้า โดยที่ฟังก์ชันคลื่นของควาร์กเชิงสัมพัทธภาพสามารถคำนวณได้จากการนำผลการคำนวณเชิงทฤษฎีของฟอร์มแฟกเตอร์เชิงประจุของโปรตอนเปรียบเทียบกับผลการทดลอง จากการศึกษาวิจัยนี้ พบว่ากลุ่มหมอกของมีซอนมีผลต่อฟอร์มแฟกเตอร์เชิงแม่เหล็กและเชิงประจุของบาริออนเพียง 10 % นอกจากนี้ผลของมีซอนชนิด K มีความสำคัญต่อโมเมนต์แม่เหล็กของไฮเปอร์รอนชนิดเบา แต่ทว่าไม่มีผลกระทบจากมีซอนชนิด η เนื่องจากการควบคู่ระหว่างกระแสควาร์กชนิดเอสและ η มีค่าน้อย

ABSTRACT IN ENGLISH

Meson cloud and strangeness contributions to the EM form factors of octet baryons are studied in the perturbative chiral quark model (PCQM) with the predetermined quark wave functions, in which the relativistic quark wave functions are extracted by fitting the theoretical results of the proton charge form factor to the experimental data. It is found that the meson cloud contributes about 10% to the magnetic and charge form factors of charged baryons. The K meson contributions to the magnetic moments of the light hyperons are important, but the contribution from the η meson is negligible due to the weak coupling between the s current quark and η meson.

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Chapter 1

Introduction

The study of the nucleon electromagnetic (EM) form factors is a very important first step in understanding internal structure of nucleon. Experimentally, EM form factors and related properties (magnetic moments, charge and magnetic radii) of the nucleon have been measured precisely. Recently, EM form factors have been studied in cloudy bag model [1, 2], chiral perturbation theory [3], various relativistic quark models [4–6], Lattice-QCD [7, 8], in which the theoretical results are comparable with experimental data. In our previous work [9], the EM form factors of octet baryons have been studied in the PCQM with the more reasonable quark wave functions as shown in Fig. 1.1, which have been extracted by fitting the PCQM theoretical result of the proton charge form factor to the experimental data. Our results on the Q^2-dependence of the theoretical EM form factors based on the determined wave functions in the region $Q^2 \leq 1$ GeV^2 are consistent with experimental data. More details could be found in Ref. [9]. In this work we focus on investigating meson cloud and the strangeness contributions to the EM form factors.

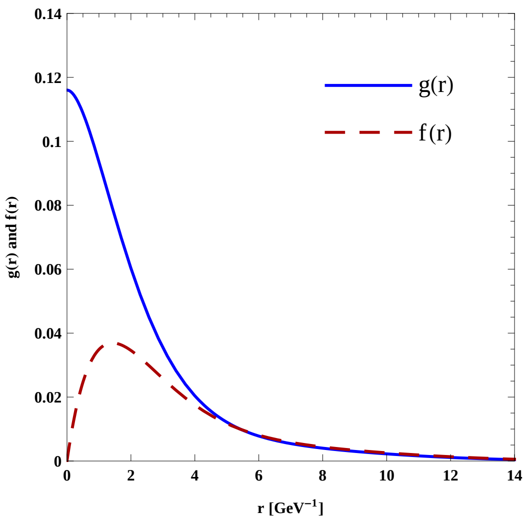

Figure 1.1: Normalized radial wave functions of the valence quarks for the upper component $g(r)$ and the lower component $f(r)$ with the central values of the expansion coefficients, which are determined by fitting the theoretical results of proton charge form factor to the experimental data.

Chapter 2

EM form factors in the PCQM

In the PCQM, the charge and magnetic form factors of octet baryons in the Breit frame are defined by

$$\chi^{\dagger}_{B'_s}\chi_{B_s}G^B_E(Q^2) = {}^B\langle\phi_0|\sum_{n=0}^{n}\frac{i^n}{n!}\int\delta(t)d^4xd^4x_1\cdots d^4x_n e^{-iq\cdot x} \times T[\mathcal{L}^W_I(x_1)\cdots\mathcal{L}^W_I(x_n)j^0(x)]|\phi_0\rangle^B_c, \tag{2.1}$$

$$\chi^{\dagger}_{B'_s}\frac{i\vec{\sigma}\times\vec{q}}{m_B+m'_B}\chi_{B_s}G^B_M(Q^2) = {}^B\langle\phi_0|\sum_{n=0}^{n}\frac{i^n}{n!}\int\delta(t)d^4xd^4x_1\cdots d^4x_n e^{-iq\cdot x} \times T[\mathcal{L}^W_I(x_1)\cdots\mathcal{L}^W_I(x_n)\vec{j}(x)]|\phi_0\rangle^B_c. \tag{2.2}$$

Here, $G^B_E(Q^2)$ and $G^B_M(Q^2)$ are the charge and magnetic form factors of octet baryons. m_B is the mass of baryons. χ_{B_s} and $\chi^{\dagger}_{B_{s'}}$ are the baryon spin wave functions in the initial and final states, $\vec{\sigma}$ is the baryon spin operator, and j^μ is the electromagnetic current

$$j^\mu = j^\mu_\psi + j^\mu_\Phi + j^\mu_{\psi\Phi} + \delta j^\mu_\psi, \tag{2.3}$$

where

$$\begin{aligned}
j^\mu_\psi &= \bar{\psi}\gamma^\mu \mathcal{Q}\psi, && (2.4)\\
j^\mu_\Phi &= \left[f_{3ij} + \frac{f_{8ij}}{\sqrt{3}}\right]\Phi_i \partial^\mu \Phi_j && (2.5)\\
j^\mu_{\psi\Phi} &= \left[f_{3ij} + \frac{f_{8ij}}{\sqrt{3}}\right]\frac{\Phi_j}{2F}\bar{\psi}\gamma^\mu\gamma^5\lambda_i\psi, && (2.6)\\
\delta j^\mu_\psi &= \bar{\psi}\big(Z-1\big)\gamma^\mu \mathcal{Q}\psi, && (2.7)
\end{aligned}$$

where $\mathcal{Q}$ is the quark charge matrix $\mathcal{Q} = \mathrm{diag}\{2/3, -1/3, -1/3\}$, and the renormalization constants $\hat{Z}$ and $\hat{Z}_s$ are defined as

$$\begin{aligned}
\hat{Z} &= 1 - \frac{3}{4(2\pi F)^2}\int_0^\infty dk k^4 F_I^2(k^2)\left[\frac{1}{\omega_\pi^3(k^2)} + \frac{2}{3\omega_K^3(k^2)} + \frac{1}{9\omega_\eta^3(k^2)}\right], && (2.8)\\
\hat{Z}_s &= 1 - \frac{1}{(2\pi F)^2}\int_0^\infty dk k^4 F_I^2(k^2)\left[\frac{1}{\omega_K^3(k^2)} + \frac{1}{3\omega_\eta^3(k^2)}\right], && (2.9)
\end{aligned}$$

We recall interaction Lagrangian of PCQM, it reads,

$$\begin{aligned}
\mathcal{L}_I^W(x) &= \frac{1}{2F}\partial_\mu \Phi_i(x)\bar{\psi}(x)\gamma^\mu\gamma^5\lambda^i\psi(x)\\
&+ \frac{f_{ijk}}{4F^2}\Phi_i(x)\partial_\mu\Phi_j(x)\bar{\psi}(x)\gamma^\mu\lambda_k\psi(x). && (2.10)
\end{aligned}$$

The Feynman diagrams contributing to the EM form factor of octet baryons in accordance with the $\mathcal{L}_I^W(x)$ in Eq. (2.10) and the EM current j_i^μ in Eq. (2.4)-(2.7) are shown in Fig. 2.1. The corresponding analytical expressions for the relevant diagrams are derived as follows:

(a) Three-quark core leading-order diagram (LO)

$$\begin{aligned}
G_E^B(Q^2)\big|_{LO} &= a_1^B G_E^p(Q^2)\big|_{LO}^{3q}, && (2.11)\\
G_M^B(Q^2)\big|_{LO} &= b_1^B \frac{m_B}{m_N} G_M^p(Q^2)\big|_{LO}^{3q}, && (2.12)
\end{aligned}$$

where

$$\begin{aligned}
G_E^p(Q^2)\big|_{LO}^{3q} &= 2\pi\int_0^\infty dr \int_0^\pi d\theta r^2 \sin\theta [g(r)^2 + f(r)^2] e^{iQr\cos\theta}, && (2.13)\\
G_M^p(Q^2)\big|_{LO}^{3q} &= \frac{4\pi i m_N}{Q}\int_0^\infty dr \int_0^\pi d\theta r^2 \sin(2\theta) g(r) f(r) e^{iQr\cos\theta}. && (2.14)
\end{aligned}$$

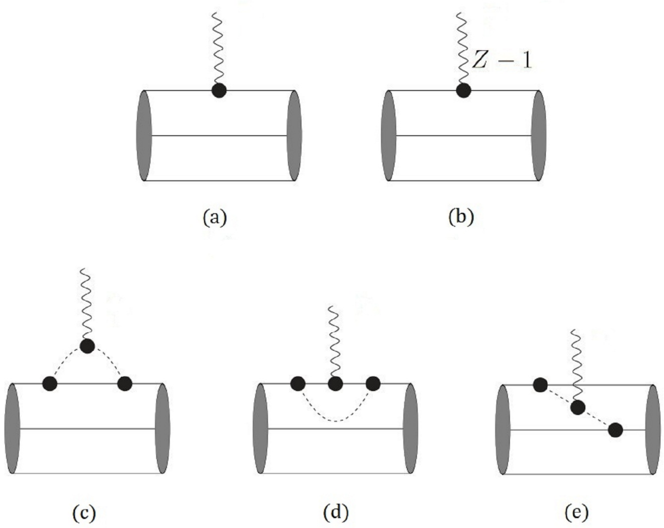

Figure 2.1: Diagrams contributing to the electromagnetic form factors of the baryon octet: three-quark diagram (a), three-quark counterterm diagram (b), meson cloud diagram (c), vertex correction diagram (d), and meson-in-flight diagram (e).

(b) Three-quark core counterterm diagram (CT)

$$G_E^B(Q^2)\big|_{CT}^{3q} = \big[a_2^B(\hat{Z}-1) + a_3^B(\hat{Z}_s-1)\big] G_E^p(Q^2)\big|_{LO}^{3q}, \tag{2.15}$$

$$G_M^B(Q^2)\big|_{CT}^{3q} = \big[b_2^B(\hat{Z}-1) + b_3^B(\hat{Z}_s-1)\big] \frac{m_B}{m_N} G_M^p(Q^2)\big|_{LO}^{3q}. \tag{2.16}$$

(c) Meson-cloud diagram (MC)

$$G_E^B(Q^2)\big|_{MC} = \frac{1}{2(2\pi F)^2}\int_0^\infty dk \int_{-1}^1 dx k^2(k^2+kQx) F_I(k) F_I(k_+) t_E^B(k^2,Q^2,x)\big|_{MC} \tag{2.17}$$

$$G_M^B(Q^2)\big|_{MC} = \frac{5m_B}{6(2\pi F)^2}\int_0^\infty dk k^4 \int_{-1}^1 dx(1-x^2) F_I(k) F_I(k_+) t_M^B(k^2,Q^2,x)\big|_{MC} \tag{2.18}$$

where

$$t_E^B(k^2,Q^2,x)\big|_{MC} = a_4^B C_\pi(k^2,Q^2,x) + a_5^B C_K(k^2,Q^2,x), \tag{2.19}$$

$$t_M^B(k^2,Q^2,x)\big|_{MC} = b_4^B D_\pi(k^2,Q^2,x) + b_5^B D_K(k^2,Q^2,x), \tag{2.20}$$

$$C_\Phi(k^2, Q^2, x) = \frac{1}{\omega_\Phi(k^2)\omega_\Phi(k_+^2)[\omega_\Phi(k^2) + \omega_\Phi(k_+^2)]}, \quad (2.21)$$

$$D_\Phi(k^2, Q^2, x) = \frac{1}{\omega_\Phi^2(k^2)\omega_\Phi^2(k_+^2)}, \quad (2.22)$$

$$k_+ = \sqrt{k^2 + Q^2 + 2k\sqrt{Q^2}x}. \quad (2.23)$$

(d) Vertex-correction diagram (VC)

$$G_E^B(Q^2)\big|_{VC} = \frac{1}{2(2\pi F)^2}\int_0^\infty dk k^4 F_I^2(k) G_E^p(Q^2)\big|_{LO}^{3q}\left[\frac{a_6^B}{\omega_\pi^3(k^2)} + \frac{a_7^B}{\omega_K^3(k^2)} + \frac{a_8^B}{\omega_\eta^3(k^2)}\right], \quad (2.24)$$

$$G_M^B(Q^2)\big|_{VC} = \frac{1}{2(2\pi F)^2}\int_0^\infty dk k^4 F_I^2(k) G_M^p(Q^2)\big|_{LO}^{3q}\left[\frac{b_6^B}{\omega_\pi^3(k^2)} + \frac{b_7^B}{\omega_K^3(k^2)} + \frac{b_8^B}{\omega_\eta^3(k^2)}\right] \quad (2.25)$$

(e) Meson-in-flight diagram (MF)

$$G_E^B(Q^2)\big|_{MF} \equiv 0, \quad (2.26)$$

$$G_M^B(Q^2)\big|_{MF} = \frac{m_B}{(2\pi F)^2}\int_0^\infty dk \int_{-1}^1 dx k^4(1-x^2)F_I(k)F_I(k_+)t_M^B(k^2, Q^2, x)\big|_{MF}, \quad (2.27)$$

where

$$t_M^B(k^2, Q^2, x)\big|_{MF} = b_9^B D_\pi(k^2, Q^2, x) + b_{10}^B D_K(k^2, Q^2, x). \quad (2.28)$$

Table 2.1: The constants a_i^B for the octet baryon charge form factors $G_E^B(Q^2)$.

	p	n	Σ^+	Σ^0	Σ^-	Λ	Ξ^0	Ξ^-
a_1	1	0	1	0	−1	0	0	−1
a_2	1	0	4/3	1/3	−2/3	1/3	2/3	−1/3
a_3	0	0	−1/3	−1/3	−1/3	−1/3	−2/3	−2/3
a_4	1	−1	2	0	−2	0	1	−1
a_5	2	1	1	0	−1	0	−1	−2
a_6	1	2	0	1	2	1	0	1
a_7	−2	−2	−2/3	−2/3	−2/3	−2/3	2/3	2/3
a_8	1/3	0	0	−1/3	−2/3	−1/3	−2/3	−1

The constants a_i^B and b_i^B, which depend on the spin and flavor of baryons, are listed in Table 2.1 and Table 2.2, respectively.

Table 2.2: The constants b_i^B for the octet baryon magnetic form factors $G_M^B(Q^2)$.

	p	n	Σ^+	Σ^0	Σ^-	Λ	Ξ^0	Ξ^-
b_1	1	$-2/3$	1	$1/3$	$-1/3$	$-1/3$	$-2/3$	$-1/3$
b_2	1	$-2/3$	$8/9$	$2/9$	$-4/9$	0	$-2/9$	$1/9$
b_3	0	0	$1/9$	$1/9$	$1/9$	$-1/3$	$-4/9$	$-4/9$
b_4	1	-1	$4/5$	0	$-4/5$	0	$-1/5$	$1/5$
b_5	$4/5$	$-1/5$	1	$3/5$	$1/5$	$-3/5$	-1	$-4/5$
b_6	$1/18$	$-2/9$	0	$-1/9$	$-2/9$	0	0	$1/18$
b_7	$1/9$	$1/9$	$5/27$	$5/27$	$5/27$	$-1/9$	$-5/27$	$-5/27$
b_8	$-1/18$	$1/27$	$-2/27$	$-1/27$	0	$-2/27$	$1/9$	$5/54$
b_9	1	-1	0	0	0	0	0	0
b_{10}	0	0	1	1	1	-1	-1	-1

Chapter 3

Strangeness contribution to EM form factors

The results listed in Table 3.1 are the numerical values for the magnetic moments with the baryon chiral mass $m_B = 1.039$ GeV [10]. It is found that the theoretical results for the octet baryon magnetic moments are consistent with the experimental data in Ref. [11]. The theoretical results reveal that the meson cloud plays an important role in μ_p and μ_n, contributing about 10% and 20% respectively, as shown in Table 3.1. However, the meson cloud contributions to the light hyperons are very limited.

In order to analyze the strangeness effects, we have compiled the π, K and η mesons contributions to the magnetic moments separately in Table 3.2. It is found that the π meson contribution to the nucleon magnetic moments dominates over the ones from the K and η mesons. The K meson contributions to the magnetic moments of the light hyperons are important, but the contribution from the η meson is negligible due to the weak coupling between the s current quark and η meson. We have also listed the strange sea quark (K and η meson clouds) contributions of different diagrams to the magnetic moments μ_B in Table 3.3. Based on Eqs. (2.11)-(2.27), we may point out the fact that the η meson contributes to the VC diagram only while the K meson participates in all loop processes. The results listed in Table 3.3 reveal that the strange sea quark contributions of CT and MC diagrams to the μ_p counteract each other, but the combined contribution of CT and MC

Table 3.1: Numerical results for the octet baryon magnetic moments μ_B (in units of the nucleon magneton μ_N) with chiral mass $m_B = 1.039$ GeV, where the uncertainties are from the fitting errors of the quark wave functions. The experimental data are taken from [11].

	3q LO	Meson loops CT+MC+VC+MF	Total	Exp. [11]
μ_p	2.458	0.277	2.735±0.121	2.793
μ_n	−1.639	−0.317	-1.956 ± 0.103	-1.913
μ_{Σ^+}	2.458	0.079	2.537±0.201	2.458±0.010
μ_{Σ^0}	0.819	0.019	0.838±0.091	—
μ_{Σ^-}	−0.819	−0.042	-0.861 ± 0.040	−1.160±0.025
μ_Λ	−0.819	−0.048	-0.867 ± 0.074	−0.613±0.004
μ_{Ξ^0}	−1.639	−0.051	-1.690 ± 0.142	−1.250±0.014
μ_{Ξ^-}	−0.819	−0.021	-0.840 ± 0.087	−0.651±0.080

diagrams to the μ_n is still sizable. For the light hyperons, the strangeness quark contributions of the CT and MC diagrams are in the same order but with different signs except for the μ_{Σ^-}. The contributions of the MF process to the magnetic moments of light hyperons are considerable. Due to the weak coupling between the s current quark and η meson, the η meson contribution is suppressed for the octet baryons.

We present in Fig. 3.1 the individual contributions of various processes shown in Fig. 2.1 to the charge form factors of octet baryons. As shown in the upper panel

Table 3.2: Contribution of π, K and η mesons to the magnetic momets g_A^B.

	Meson loops π	K	η
μ_p	0.281	0.002	−0.006
μ_n	−0.339	0.018	0.004
μ_{Σ^+}	0.032	0.055	−0.008
μ_{Σ^0}	−0.039	−0.062	−0.004
μ_{Σ^-}	−0.109	0.068	0
μ_Λ	0	−0.052	0.004
μ_{Ξ^0}	−0.008	−0.055	0.012
μ_{Ξ^-}	−0.027	−0.058	0.010

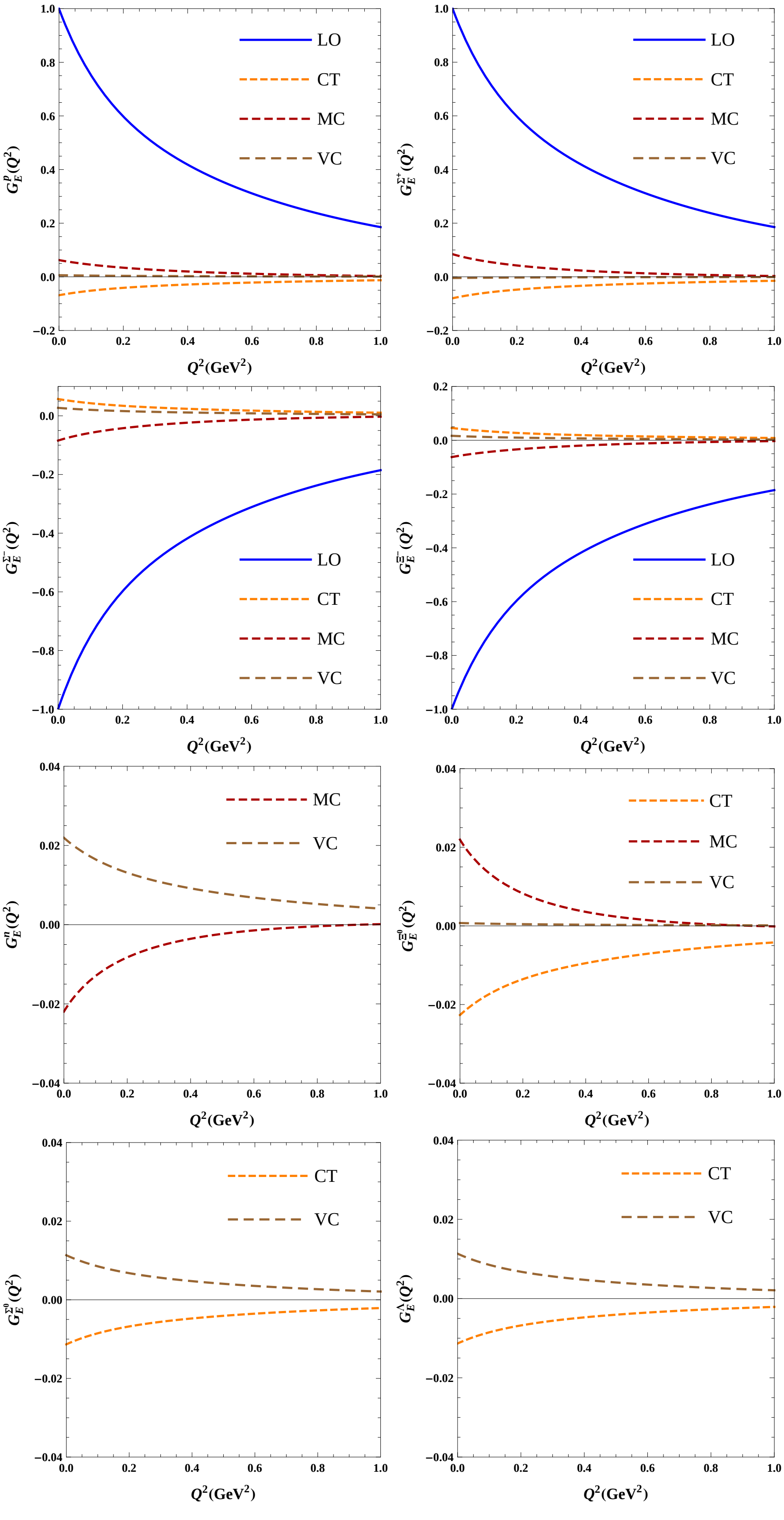

Figure 3.1: The individual contributions of the different diagrams of Fig. 2.1 to the charge form factors of octet baryons.

Table 3.3: Strange sea quark contributions of the individual loop diagrams of Fig. 2.1 to the magnetic moments μ_B.

	CT	MC	VC	MF
μ_p	-0.0378	0.0312	0.0021	0
μ_n	0.0252	-0.0078	0.0047	0
μ_{Σ^+}	-0.0431	0.0390	0.0041	0.0468
μ_{Σ^0}	-0.0178	0.0234	0.0051	0.0468
μ_{Σ^-}	0.0074	0.0078	0.0061	0.0468
μ_Λ	0.0283	-0.0234	-0.0057	-0.0468
μ_{Ξ^0}	0.0462	-0.0390	-0.0031	-0.0468
μ_{Ξ^-}	0.0336	-0.0312	-0.0036	-0.0468

of Fig. 3.1, the LO diagram dominates the charge form factors of charged baryons (p, Σ^+, Σ^- and Ξ^-), contributing over 90% while the contributions of the loop diagrams (CT, MC and VC) are rather small. Among the loop diagrams, the VC process is negligible. The meson cloud is the sole contributor to the neutral baryon (n, Ξ^0, Σ^0 and Λ) charge form factors as presented in the lower panel of Fig. 3.1.

Shown in Fig. 3.2 are the individual program contributions to the octet baryon magnetic form factors. The LO diagram dominates the magnetic form factors of octet baryons while the loop diagrams contribute about 10% to the EM form factors. Notice that the η meson contribution is rather small due to the weak coupling between the s current quark and η meson.

Finally, we may summarize the fact that the meson cloud contributes about 10% to the magnetic and charge form factors of charged baryons. The K meson contributions to the magnetic moments of the light hyperons are important, but the contribution from the η meson is negligible due to the weak coupling between the s current quark and η meson.

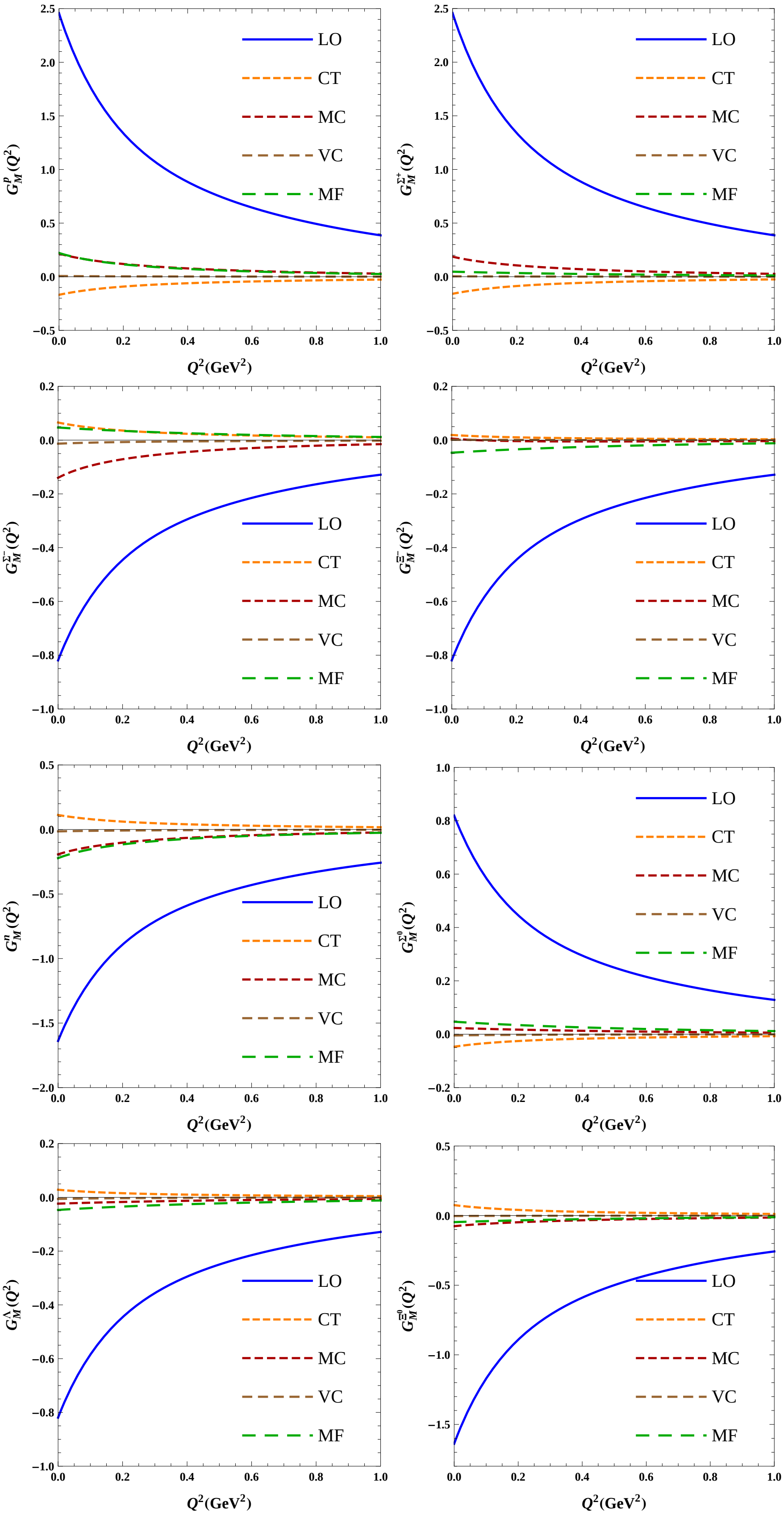

Figure 3.2: The individual contributions of the different diagrams of Fig. 2.1 to the magnetic form factors of octet baryons.

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Appendices

Appendix A

Gell-Mann and Low theorem

The Gell-Mann and Low theorem was proved by Murray Gell-Mann and Francis E. Low in 1951. It is a theorem in quantum field theory that allows one to relate the ground (or vacuum) state of an interacting system to the ground state of the corresponding non-interacting theory. We consider a system described by the Hamiltonian H which might be written as

$$H = H_0 + H_I \tag{A.1}$$

where H_0 and H_I are respectively the free and interaction parts of the Hamiltonian. Let $|\psi_0\rangle$ and $|n\rangle$ be the eigenstates of the free and full Hamiltonian, respectively. One has

$$\begin{aligned} H|n\rangle &= E^{(n)}|n\rangle, \\ H_0|\psi_0\rangle &= E_0|\psi_0\rangle, \end{aligned} \tag{A.2}$$

hence

$$\begin{aligned} e^{-\mathrm{i}Ht}|\psi_0\rangle &= \sum_n e^{-\mathrm{i}E^{(n)}t}|n\rangle\langle n|\psi_0\rangle \\ &= e^{-\mathrm{i}Et}|\psi\rangle\langle\psi|\psi_0\rangle + \sum_{n\neq 0} e^{-\mathrm{i}E^{(n)}t}|n\rangle\langle n|\psi_0\rangle, \end{aligned} \tag{A.3}$$

here we have rewritten ground eigenstate $|0\rangle$ and ground eigenvalue $E^{(0)}$ in the above equation respectively as $|\psi\rangle$ and E, that is

$$H|\psi\rangle = E|\psi\rangle. \tag{A.4}$$

Multiplying the above equation by $e^{\mathrm{i}E_0 t}$, one derives

$$e^{\mathrm{i}E_0 t}e^{\mathrm{i}Ht}|\psi_0\rangle = e^{\mathrm{i}(E-E_0)t}|\psi\rangle\langle\psi|\psi_0\rangle + \sum_{n\neq 0} e^{-\mathrm{i}(E^{(n)}-E_0)t}|n\rangle\langle n|\psi_0\rangle. \tag{A.5}$$

Since $E^{(n)} > E$ for all $n \neq 0$, we can get rid of all the $n \neq 0$ terms in the series by sending t to ∞ in a slightly imaginary direction $t \to \infty(1-\mathrm{i}\varepsilon)$. Then the exponential factor $e^{-\mathrm{i}(E-E_0)t}$ dies slowest and we have

$$\begin{aligned} |\psi\rangle &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{e^{\mathrm{i}H(-t)}e^{-\mathrm{i}H_0(-t)}|\psi_0\rangle}{e^{-\mathrm{i}(E-E_0)t}\langle\psi|\psi_0\rangle} \\ &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{U(0,-t)|\psi_0\rangle}{e^{-\mathrm{i}(E-E_0)t}\langle\psi|\psi_0\rangle}. \end{aligned} \tag{A.6}$$

here we have used

$$U(t_0, t) = e^{\mathrm{i}H(t-t_0)}e^{-\mathrm{i}H_0(t-t_0)}. \tag{A.7}$$

In the same way, we can derive

$$\langle\psi| = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,0)}{e^{-\mathrm{i}(E-E_0)t}\langle\psi_0|\psi\rangle}. \tag{A.8}$$

Now we evaluate the expectation value of the operator $O(x) \equiv O(x^0, \vec{x})$ in the state $|\psi\rangle$

$$\begin{aligned} \langle\psi|O(x^0,\vec{x})|\psi\rangle &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,0)U^\dagger(x^0,0)O_I(x)U(x^0,0)U(0,-t)|\psi_0\rangle}{e^{-\mathrm{i}(E-E_0)t}\langle\psi_0|\psi\rangle e^{-\mathrm{i}(E-E_0)t}\langle\psi|\psi_0\rangle} \\ &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,x^0)O_I(x)U(x^0,-t)|\psi_0\rangle}{e^{-2\mathrm{i}(E-E_0)t}|\langle\psi_0|\psi\rangle|^2}. \end{aligned} \tag{A.9}$$

To get rid of the denominator in the equation, one may divide it by 1 in the form

$$1 = \langle\psi|\psi\rangle = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,0)U(0,-t)|\psi_0\rangle}{e^{-2\mathrm{i}(E-E_0)t}|\langle\psi_0|\psi\rangle|^2}. \tag{A.10}$$

Then finally we derive

$$\langle\psi|O(x^0,\vec{x})|\psi\rangle = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,x^0)O_I(x)U(x^0,-t)|\psi_0\rangle}{\langle\psi_0|U(t,-t)|\psi_0\rangle}. \tag{A.11}$$

The above equation holds for a product of arbitrarily many operators, for example, for two operators

$$\langle\psi|T[O(x)P(x)]|\psi\rangle = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|T\{O_I(x)P_I(x)\exp[-\mathrm{i}\int_{-t}^{t} dz H_I(z)]\}|\psi_0\rangle}{\langle\psi_0|T\{\exp[-\mathrm{i}\int_{-t}^{t} dz H_I(z)]\}|\psi_0\rangle}. \tag{A.12}$$

Appendix B

Calculation of the diagrams for the charge form factor

In the framework of the PCQM, the charge form factors of octet baryons in the Breit frame are defined by

$$\begin{aligned}\chi^{\dagger}_{B'_s}\chi_{B_s}G^B_E(Q^2) &= {}^B\langle\phi_0|\sum_{n=0}^{2}\frac{i^n}{n!}\int\delta(t)d^4xd^4x_1\cdots d^4x_n\mathrm{e}^{-\mathrm{i}q\cdot x} \\ &\quad\times T[\mathcal{L}^W_I(x_1)\cdots\mathcal{L}^W_I(x_n)j^0(x)]|\phi_0\rangle^B_c,\end{aligned} \tag{B.1}$$

where χ_{B_s} and $\chi^{\dagger}_{B_{s'}}$ are the baryon spin wavefunctions in the initial and final states. We assume they are spin-up states, so

$$\chi^{\dagger}_{B'_s}\chi_{B_s} = 1. \tag{B.2}$$

In calculation, the quark wave function is expanded into a completed basis of Sturmian functions in Eq. (**??**). We employ the fermion and boson Feymann propagators as following:

$$\begin{aligned}\overbracket{\psi(x)\bar{\psi}}(y) &= \langle\phi_0|T\{\psi(x)\bar{\psi}(y)\}|\phi_0\rangle \\ &= u_0(\vec{x})u_0(\vec{y})\exp[-i\mathcal{E}_0(x_0-y_0)]\theta(x_0-y_0),\end{aligned} \tag{B.3}$$

$$\begin{aligned}\overbracket{\Phi_i(x)\Phi_j}(y) &= \langle 0|T\{\Phi_i(x)\Phi_j(y)\}|0\rangle \\ &= \delta_{ij}\int\frac{d^4k}{(2\pi)^4i}\frac{\exp[-ik(x-y)]}{M^2_{\Phi}-k^2-i\epsilon},\end{aligned} \tag{B.4}$$

here the fermion propagator is restricted on the ground state only.

B.1 Leading Order Diagram (LO)

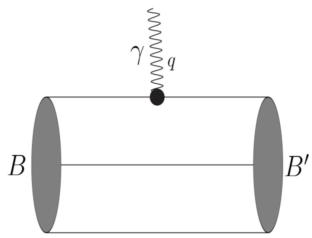

Figure B.1: Leading order diagram

$$
\begin{aligned}
G_E^B(Q^2)\big|_{LO} &= {}^B\langle\phi_0|\mathcal{Q}\int \delta(t)d^4xe^{-\mathrm{i}qx}j^0_\psi(x)|\phi_0\rangle^B \\
&= {}^B\langle\phi_0|\mathcal{Q}\int \delta(t)d^4xe^{-\mathrm{i}qx}\bar\psi(x)\gamma^0\psi(x)|\phi_0\rangle^B \\
&= {}^B\langle\phi_0|b_0^\dagger\mathcal{Q}\int d^3xe^{\mathrm{i}\vec{q}\cdot\vec{x}}\bar u_0(x)\gamma^0u_0(x)b_0|\phi_0\rangle^B \\
&= a_1^BG_E^p(Q^2)|_{3q}^{LO}, \qquad \text{(B.5)}
\end{aligned}
$$

where

$$
G_E^p(Q^2)\big|_{LO} = 2\pi\int_0^\infty dr\int_0^\pi d\theta r^2\sin\theta[g(r)^2+f(r)^2]e^{\mathrm{i}Qr\cos\theta}, \qquad \text{(B.6)}
$$

$$
\begin{aligned}
a_1^B &= {}^B\langle\phi_0|b_0^\dagger\chi_{f'}\sum_{i=1}^3\mathcal{Q}(i)\chi_fb_0|\phi_0\rangle^B \\
&= \langle B\uparrow|\sum_{i=1}^3\mathcal{Q}(i)|B\uparrow\rangle. \qquad \text{(B.7)}
\end{aligned}
$$

B.2 Counterterm Diagram (CT)

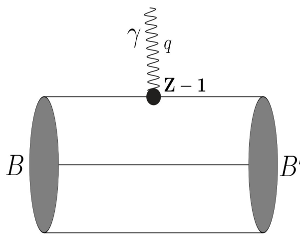

Figure B.2: Counterterm diagram

$$\begin{aligned} G_E^B(Q^2)\big|_{CT} &= {}^B\langle\phi_0|\mathcal{Q}\int\delta(t)d^4xe^{-iqx}\delta j_\psi^0(x)|\phi_0\rangle^B \\ &= {}^B\langle\phi_0|\mathcal{Q}\int\delta(t)d^4xe^{-iqx}\bar\psi(x)(Z-1)\gamma^0\psi(x)|\phi_0\rangle^B \\ &= \left[a_2^B(\hat Z-1)+a_3^B(Z_s-1)\right]G_E^p(Q^2)|_{3q}^{LO}, \end{aligned} \tag{B.8}$$

where

$$\begin{aligned} a_2^B &= {}^B\langle\phi_0|b_0^\dagger\chi_{f'}\sum_{i=1}^3\hat{\mathcal{Q}}(i)\chi_f b_0|\phi_0\rangle^B \\ &= \langle B\uparrow|\sum_{i=1}^3\hat{\mathcal{Q}}(i)|B\uparrow\rangle, \end{aligned} \tag{B.9}$$

$$\begin{aligned} a_3^B &= {}^B\langle\phi_0|b_0^\dagger\chi_{f'}\sum_{i=1}^3\mathcal{Q}_s(i)\chi_f b_0|\phi_0\rangle^B \\ &= \langle B\uparrow|\sum_{i=1}^3\mathcal{Q}_s(i)|B\uparrow\rangle, \end{aligned} \tag{B.10}$$

$$\hat{\mathcal{Q}} = \begin{pmatrix} 2/3 & 0 & 0 \\ 0 & -1/3 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \tag{B.11}$$

$$\mathcal{Q}_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1/3 \end{pmatrix}. \tag{B.12}$$

B.3 Meson Cloud Diagram (MC)

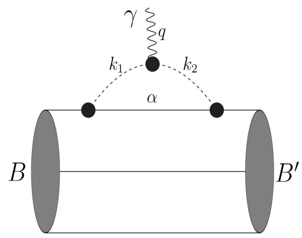

Figure B.3: Meson Cloud Diagram

$$
\begin{aligned}
& G_E^B(Q^2)\big|_{MC}^{\alpha} \\
= \;& {}^B\langle\phi_0|\frac{\mathrm{i}^2}{2!}\int\delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx}T\big[\mathcal{L}_I^W(x_1)\mathcal{L}_I^W(x_2)j_\Phi^0(x)\big]|\phi_0\rangle^B \\
= \;& 4\,{}^B\langle\phi_0|\frac{-1}{2}\int\delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx} \\
& \times N\Big\{\Big[\frac{1}{2F}\partial_\mu\Phi_i\bar\psi\gamma^\mu\gamma^5\lambda_i\psi\Big]_{x_1}\Big[(f_{3kl}+\frac{f_{8kl}}{\sqrt3})\Phi_k\frac{\partial}{\partial t}\Phi_l\Big]_x\Big[\frac{1}{2F}\partial_\nu\Phi_j\bar\psi\gamma^\nu\gamma^5\lambda_j\psi\Big]_{x_2}\Big\} \\
& \times|\phi_0\rangle^B \\
= \;& \frac{-i}{2F^2(2\pi)^8}\,{}^B\langle\phi_0|b_0^\dagger\int d^3x_1d^3x_2d^4k_1d^4k_2\frac{e^{-i\vec k_1\cdot\vec x_1}}{M_\Phi^2-k_1^2-i\epsilon}\frac{e^{-i\vec k_2\cdot\vec x_2}}{M_\Phi^2-k_2^2-i\epsilon} \\
& \times(f_{3ij}+\frac{f_{8ij}}{\sqrt3})\bar u_0(x_1)\gamma^\mu k_{1\mu}\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\gamma^\nu k_{2\nu}\gamma^5k_2^0\lambda_ju_0(x_2) \\
& \times\int dtdt_1dt_2\delta t\Theta(t_1-t_2)e^{-iqt}e^{-i\varepsilon_0(t_2-t_1)}e^{-i\varepsilon_\alpha(t_1-t_2)}e^{-ik_1^0(t_1-t)}e^{-ik_2^0(t-t_2)} \\
& \times\int d^3xe^{-i(\vec k_1-\vec k_2-\vec q)\cdot\vec x}b_0|\phi_0\rangle^B \\
= \;& -\frac{(f_{3ij}+\frac{f_{8ij}}{\sqrt3})}{2F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3x_1d^3x_2d^3k_1d^3k_2\delta(\vec k_1-\vec k_2-\vec q) \\
& \times\int dk_1^0dk_2^0\frac{\delta(k_1^0-k_2^0)}{[\omega_\Phi(k_1^2)-(k_1^0)^2-i\epsilon][\omega_\Phi(k_2^2)-(k_2^0)^2-i\epsilon][\Delta\varepsilon_\alpha+k_1^0-i\epsilon]} \\
& \times\big[(k_2^0)^3\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2) \\
& -(k_2^0)^2\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2) \\
& -(k_2^0)^2\bar u_0(x_1)\vec\gamma\cdot\vec k_1\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2) \\
& +k_2^0\bar u_0(x_1)\vec\gamma\cdot\vec k_1\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)\big]b_0|\phi_0\rangle^B \\
= \;& \frac{i}{4F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\int d^3k_2\frac{f_{3ij}+\frac{f_{8ij}}{\sqrt3}}{[\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)][\omega_\Phi(k_2'^2)+\Delta\varepsilon_\alpha][\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha]} \\
& \times\Big\{\big[\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)+(\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2))\Delta\varepsilon_\alpha\big] \\
& \times\int d^3x_1\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\int d^3x_2\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2} \\
& -\Delta\varepsilon_\alpha\int d^3x_1\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\int d^3x_2\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2} \\
& -\Delta\varepsilon_\alpha\int d^3x_1\bar u_0(x_1)\vec\gamma\cdot\vec k_2'\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\int d^3x_2\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2} \\
& -\int d^3x_1\bar u_0(x_1)\vec\gamma\cdot\vec k_2'\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\int d^3x_2\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2}\Big\} \\
& \times b_0|\phi_0\rangle^B \\
= \;& \frac{i}{4F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\int d^3k_2 \\
& \times\frac{1}{[\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)][\omega_\Phi(k_2'^2)+\Delta\varepsilon_\alpha][\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha]} \\
& \times\Big\{\big[\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)+(\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2))\Delta\varepsilon_\alpha\big]F_{I\alpha}(k_2')F_{I\alpha}^\dagger(k_2) \\
& -\Delta\varepsilon_\alpha F_{I\alpha}(k_2')F_{II\alpha}^\dagger(k_2)-\Delta\varepsilon_\alpha F_{II\alpha}(k_2')F_{I\alpha}^\dagger(k_2)-F_{II\alpha}(k_2')F_{II\alpha}^\dagger(k_2)\Big\} \\
& \times(f_{3ij}+\frac{f_{8ij}}{\sqrt3})[(\vec\sigma\cdot\vec k_2')\lambda_i]_{0,\alpha}[(\vec\sigma\cdot\vec k_2)\lambda_j]_{\alpha,0}\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B
\end{aligned}
\tag{B.13}
$$

where $\Delta\varepsilon_\alpha = \varepsilon_\alpha - \varepsilon_0$, $\vec{k}_2' = \vec{k}_1 + \vec{q}$ and $\omega_\Phi(k^2) = \sqrt{M_\Phi^2 + k^2}$,

$$\int d^3x \bar{u}_0(x)\gamma^0\gamma^5\lambda_i u_\alpha(x) e^{i\vec{k}\cdot\vec{x}} = F_{I\alpha}(k)\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger[\vec{\sigma}\cdot\vec{k}\lambda_i]_{0,\alpha}\chi_s\chi_f\chi_c, \tag{B.14}$$

$$\int d^3x_1 \bar{u}_0(x)\vec{\gamma}\cdot\vec{k}\gamma^5\lambda_i u_\alpha(x) e^{i\vec{k}\cdot\vec{x}} = F_{II\alpha}(k)\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger[\vec{\sigma}\cdot\vec{k}\lambda_i]_{0,\alpha}\chi_s\chi_f\chi_c, \tag{B.15}$$

with

$$F_{I\alpha}(k) = \int_0^\infty drr[g_0(r)f_\alpha(r) - f_0(r)g_\alpha(r)]\frac{\partial}{\partial k}\int_\Omega d\Omega e^{ikrcos\theta}\mathcal{C}_\alpha Y_{l_\alpha 0}(\theta,\phi), \tag{B.16}$$

$$\begin{aligned} F_{II\alpha}(k) &= \int_0^\infty drr^2[g_0(r)g_\alpha(r) - f_0(r)f_\alpha(r)]\int_\Omega d\Omega e^{ikrcos\theta}\mathcal{C}_\alpha Y_{l_\alpha 0}(\theta,\phi) \\ &\quad -2i\frac{\partial}{\partial k}\int_0^\infty drrf_0(r)f_\alpha(r)\int_\Omega d\Omega\cos\theta e^{ikr\cos\theta}\mathcal{C}_\alpha Y_{l_\alpha 0}(\theta,\phi). \end{aligned} \tag{B.17}$$

We define $x = \cos\theta = \frac{\vec{q}\cdot\vec{k}_2}{|\vec{q}||\vec{k}_2|}$, $k = |\vec{k}_2|$, $Q = |\vec{q}|$ and

$$k_\pm = |\vec{q} \pm \vec{k}_2| = \sqrt{k^2 + Q^2 \pm 2kQx}, \tag{B.18}$$

$$\int d^3k_2 = \int_0^\infty dkk^2\int_{-1}^1 dx\int_0^{2\pi} d\phi. \tag{B.19}$$

We obtain the expression of $G_E^B(Q^2)\big|_{MC}^\alpha$ as

$$\begin{aligned} G_E^B(Q^2)\big|_{MC}^\alpha &= -\frac{1}{2(2\pi F)^2}\int_0^\infty dk\int_{-1}^1 dxk^2(k^2 + kQx) \\ &\quad \times\Big\{\big[\omega_\Phi(k_+^2)\omega_\Phi(k^2) + (\omega_\Phi(k_+^2) + \omega_\Phi(k_2^2))\Delta\varepsilon_\alpha\big]F_{I\alpha}(k_+)F_{I\alpha}^\dagger(k) \\ &\quad -\Delta\varepsilon_\alpha F_{I\alpha}(k_+)F_{II\alpha}^\dagger(k) - \Delta\varepsilon_\alpha F_{II\alpha}(k_+)F_{I\alpha}^\dagger(k) - F_{II\alpha}(k_+)F_{II\alpha}^\dagger(k)\Big\} \\ &\quad \times\frac{{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\frac{-i}{2}(f_{3ij} + \frac{f_{8ij}}{\sqrt{3}})\lambda_i\lambda_j\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B}{[\omega_\Phi(k_+^2) + \omega_\Phi(k^2)][\omega_\Phi(k_+^2) + \Delta\varepsilon_\alpha][\omega_\Phi(k^2) + \Delta\varepsilon_\alpha]}. \end{aligned} \tag{B.20}$$

In our calculation, the quark propagator is restricted on the ground state only, i.e. $\alpha = 0$. Hence, we have $\Delta\varepsilon_\alpha = 0$, $F_{I0}(k^2) = 0$ and

$$F_{II}(k) = 2\pi\int_0^\infty dr\int_0^\pi d\theta r^2(g_0(r)^2 + f_0(r)^2\cos2\theta)\sin\theta e^{ikr\cos\theta}, \tag{B.21}$$

Finally

$$
\begin{aligned}
G_E^B(Q^2)\big|_{MC} &= \frac{1}{2(2\pi F)^2}\int_0^\infty dk \int_{-1}^{1} dx k^2(k^2+kQx) \\
&\quad \times F_{II}(k)F_{II}(k_+)[a_4^B C_\pi(k^2,Q^2,x) + a_5^B C_K(k^2,Q^2,x)],
\end{aligned}
\tag{B.22}
$$

where

$$
C_\Phi(k^2,Q^2,x) = \frac{1}{\omega_\Phi(k^2)\omega_\Phi(k_+^2)[\omega_\Phi(k^2)+\omega_\Phi(k_+^2)]}, \tag{B.23}
$$

$$
\begin{aligned}
a_4^B &= \sum_{i,j=1}^{3} {}^B\langle\phi_0|b_0^\dagger\chi_{f'}^\dagger - \frac{i}{2}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i\lambda_j\chi_f b_0|\phi_0\rangle^B \\
&= \sum_{i,j=1}^{3}\langle B|\sum_{k=1}^{3} -\frac{i}{2}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i(k)\lambda_j(k)|B\rangle,
\end{aligned}
\tag{B.24}
$$

$$
a_5^B = \sum_{i,j=4}^{7}\langle B|\sum_{k=1}^{3} -\frac{i}{2}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i(k)\lambda_j(k)|B\rangle. \tag{B.25}
$$

B.4 Vertex Correction Diagram (VC)

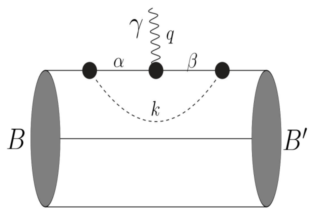

Figure B.4: Vertex Correction Diagram

$$
\begin{aligned}
&G_E^B(Q^2)\big|^{\alpha}_{VC} \\
&= {}^B\langle\phi_0|\frac{\mathrm{i}^2}{2!}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx}T\left[\mathcal{L}_I^W(x_1)\mathcal{L}_I^W(x_2)j^0_\psi(x)\right]|\phi_0\rangle^B \\
&= 2\,{}^B\langle\phi_0|\frac{-1}{2}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx} \\
&\quad \times N\Big\{\Big[\frac{1}{2F}\partial_\mu\Phi_i\bar\psi\gamma^\mu\gamma^5\lambda_i\psi\Big]_{x_1}\Big[\bar\psi\gamma^0\mathcal{Q}\psi\Big]_x\Big[\frac{1}{2F}\partial_\nu\Phi_j\bar\psi\gamma^\nu\gamma^5\lambda_j\psi\Big]_{x_2}\Big\}|\phi_0\rangle^B \\
&= \frac{i}{4F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^3x_2d^4ke^{i\vec q\cdot\vec x}\frac{e^{i\vec k\cdot(\vec x_1-\vec x_2)}}{M_\Phi^2-k^2-i\epsilon} \\
&\quad \times\bar u_0(x_1)\gamma^\mu k_\mu\gamma^5\lambda_i u_\alpha(x_1)\bar u_\alpha(x)\gamma^0\mathcal{Q}u_\beta(x)\bar u_\beta(x_2)\gamma^\nu k_\nu\gamma^5\lambda_i u_0(x_2) \\
&\quad \times\int dtdt_1dt_2\delta t\Theta(t_1-t)\Theta(t-t_2)e^{-iqt}e^{-i\varepsilon_0(t_2-t_1)}e^{-i\varepsilon_\alpha(t_1-t)} \\
&\quad \times e^{-i\varepsilon_\beta(t-t_2)}e^{-ik_0(t_1-t_2)}b_0|\phi_0\rangle^B \\
&= \frac{-i}{4F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger d^3xd^3x_1d^3x_2d^3ke^{i\vec q\cdot\vec x}e^{i\vec k\cdot(\vec x_1-\vec x_2)} \\
&\quad \times\int dk_0\frac{1}{[\omega_\Phi(k^2)-(k_0)^2-i\epsilon][k_0+\Delta\varepsilon_\alpha-i\eta][k_0+\Delta\varepsilon_\beta-i\eta]} \\
&\quad \times\bar u_0(x_1)(\gamma^0k_0-\vec\gamma\cdot\vec k)\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x)\gamma^0\mathcal{Q}u_\beta(x) \\
&\quad \times\bar u_\beta(x_2)(\gamma^0k_0-\vec\gamma\cdot\vec k)\gamma^5\lambda_iu_0(x_2)b_0|\phi_0\rangle^B \\
&= \frac{G_E^p(Q^2)\big|^{\alpha}_{LO}}{8F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\int d^3k\frac{1}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]^2} \\
&\quad \times\big[\omega_\Phi^2(k^2)F_{I\alpha}(k)F^\dagger_{I\alpha}(k)-\omega_\Phi(k^2)F_{I\alpha}(k)F^\dagger_{II\alpha}(k)-\omega_\Phi(k^2)F_{II\alpha}(k)F^\dagger_{I\alpha}(k) \\
&\quad +F_{II\alpha}(k)F^\dagger_{II\alpha}(k)\big][(\vec\sigma\cdot\vec k)\lambda_i]_{0,\alpha}\mathcal{Q}_{\alpha\alpha}[(\vec\sigma\cdot\vec k)\lambda_i]_{\alpha,0}\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B, \qquad \text{(B.26)}
\end{aligned}
$$

where

$$
\int d^3x\bar u_\alpha(x)\gamma^0\mathcal{Q}u_\beta(x)e^{i\vec q\cdot\vec x}=\delta_{\alpha\beta}G_E^p(Q^2)\big|^{\alpha}_{LO}\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\mathcal{Q}_{\alpha\beta}\chi_s\chi_f\chi_c. \qquad \text{(B.27)}
$$

Finally, we have

$$
\begin{aligned}
G_E^B(Q^2)\big|_{VC}^{\alpha} & \\
= & \frac{1}{4(2\pi F)^2} G_E^p(Q^2)\big|_{LO}^{\alpha} \int dk k^4 \big[\omega_\Phi^2(k^2) F_{I\alpha}(k) F_{I\alpha}^\dagger(k) \\
& -\omega_\Phi(k^2) F_{I\alpha}(k) F_{II\alpha}^\dagger(k) - \omega_\Phi(k^2) F_{II\alpha}(k) F_{I\alpha}^\dagger(k) + F_{II\alpha}(k) F_{II\alpha}^\dagger(k)\big] \\
& \times \frac{{}^B\langle\phi_0|b_0^\dagger \chi_c^\dagger \chi_f^\dagger \chi_s^\dagger \lambda_i \mathcal{Q} \lambda_i \chi_s \chi_f \chi_c b_0|\phi_0\rangle^B}{\omega_\Phi(k^2)[\omega_\Phi(k^2) + \Delta\varepsilon_\alpha]^2}. \qquad \text{(B.28)}
\end{aligned}
$$

For the case $\alpha = 0$, we obtain

$$
\begin{aligned}
G_E^B(Q^2)\big|_{VC} &= \frac{1}{4(2\pi F)^2} G_E^p(Q^2)\big|_{LO} \int_0^\infty dk k^4 F_{II}^2(k) \\
&\times \left[\frac{a_6^B}{\omega_\pi^3(k^2)} + \frac{a_7^B}{\omega_K^3(k^2)} + \frac{a_8^B}{\omega_\eta^3(k^2)}\right], \qquad \text{(B.29)}
\end{aligned}
$$

where

$$
\begin{aligned}
a_6^B &= {}^B\langle\phi_0|b_0^\dagger \chi_c^\dagger \chi_f^\dagger \chi_s^\dagger \lambda_i \mathcal{Q} \lambda_i \chi_s \chi_f \chi_c b_0|\phi_0\rangle^B \\
&= \sum_{i=1}^{3} \langle B| \sum_{k=1}^{3} [\lambda_i \mathcal{Q} \lambda_i]^{(k)} |B\rangle \\
a_7^B &= \sum_{i=4}^{7} \langle B| \sum_{k=1}^{3} [\lambda_i \mathcal{Q} \lambda_i]^{(k)} |B\rangle, \\
a_8^B &= \langle B| \sum_{k=1}^{3} [\lambda_8 \mathcal{Q} \lambda_8]^{(k)} |B\rangle. \qquad \text{(B.30)}
\end{aligned}
$$

Appendix C

Calculation of the diagrams for the magnetic form factor

The diagrams contributing to the magnetic form factor are the same ones as for the case of the charge form factor and the meson-in-flight diagram in addition.

C.1 Leading Order Diagram (LO)

$$\chi^\dagger_{B'_s}\tfrac{i\vec{\sigma}\times\vec{q}}{m_B+m'_B}\chi_{B_s}G^B_M(Q^2)\big|_{LO}$$

$$\begin{aligned}
&= {}^B\langle\phi_0|\mathcal{Q}\int\delta(t)d^4xe^{-\mathrm{i}qx}\vec{j}_\psi(x)|\phi_0\rangle^B \\
&= {}^B\langle\phi_0|b_0^\dagger\mathcal{Q}\int d^3xe^{\mathrm{i}\vec{q}\cdot\vec{x}}u_0^\dagger(x)\gamma^0\vec{\gamma}u_0(x)b_0|\phi_0\rangle^B \\
&= 2\frac{\partial}{\partial q}\int d^3xe^{\mathrm{i}\vec{q}\cdot\vec{x}}\frac{g(r)f(r)}{r}\,{}^B\langle\phi_0|b_0^\dagger\chi^\dagger_{c'}\chi^\dagger_{f'}\chi^\dagger_{s'}\mathcal{Q}(\vec{\sigma}\times\hat{q})\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B
\end{aligned} \tag{C.1}$$

here we restrict initial and final spin states to be in the same states, and define $\hat{q}=\hat{j}$, $\vec{\sigma}\times\hat{q}=-\sigma_3\hat{i}+\sigma_1\hat{k}$, we have

$$\chi^\dagger_{c'}\chi^\dagger_{f'}\chi^\dagger_{s'}\mathcal{Q}(\vec{\sigma}\times\hat{q})\chi_s\chi_f\chi_c=-\chi^\dagger_{c'}\chi^\dagger_{f'}\chi^\dagger_{s'}\mathcal{Q}\sigma_3\chi_s\chi_f\chi_c\hat{i} \tag{C.2}$$

and

$$\chi^\dagger_{B'_s}\frac{i\vec{\sigma}\times\vec{q}}{m_B+m'_B}\chi_{B_s}=-\frac{Q}{2m_B}\chi^\dagger_{B'_s}\sigma_3\chi_{B_s}\hat{i}. \tag{C.3}$$

Finally, the leading order of magnetic form factor can be obtained as

$$G_M^B(Q^2)\big|_{LO} = b_1^B \frac{m_B}{m_N} G_M^p(Q^2)\big|_{LO}, \tag{C.4}$$

where

$$G_M^p(Q^2)\big|_{LO} = \frac{4\pi \mathrm{i} m_N}{Q} \int_0^\infty dr \int_0^\pi d\theta r^2 \sin(2\theta) g(r) f(r) e^{\mathrm{i}Qr\cos\theta}, \tag{C.5}$$

$$\begin{aligned} b_1^B &= {}^B\langle\phi_0|b_0^\dagger \chi_{c'}^\dagger \chi_{f'}^\dagger \chi_{s'}^\dagger \mathcal{Q}\sigma_3 \chi_s \chi_f \chi_c|\phi_0\rangle^B \\ &= \langle B\uparrow|\sum_{k=1}^{3}[\mathcal{Q}\sigma_3]^{(k)}|B\uparrow\rangle. \end{aligned} \tag{C.6}$$

C.2 Counterterm Diagram (CT)

$\chi_{B_s'}^\dagger \frac{i\vec{\sigma}\times\vec{q}}{m_B+m_B'} \chi_{B_s} G_E^B(Q^2)\big|_{CT}$

$$\begin{aligned} &= {}^B\langle\phi_0|\mathcal{Q}\int \delta(t) d^4x e^{-\mathrm{i}qx} \delta\vec{j}_\psi(x)|\phi_0\rangle^B \\ &= {}^B\langle\phi_0|b_0^\dagger \mathcal{Q}\int d^3x e^{\mathrm{i}\vec{q}\cdot\vec{x}} u_0^\dagger(x)(Z-1)\gamma^0\vec{\gamma} u_0(x) b_0|\phi_0\rangle^B, \end{aligned} \tag{C.7}$$

then

$$G_E^B(Q^2)\big|_{CT} = \left[b_2^B(\hat{Z}-1) + b_3^B(Z_s-1)\right] \frac{m_B}{m_N} G_M^p(Q^2)\big|_{LO}, \tag{C.8}$$

where

$$\begin{aligned} b_2^B &= {}^B\langle\phi_0|b_0^\dagger \chi_{c'}^\dagger \chi_{f'}^\dagger \chi_{s'}^\dagger \sum_{k=1}^{3}[\hat{\mathcal{Q}}\sigma_3]^{(k)} \chi_s \chi_f \chi_c b_0|\phi_0\rangle^B \\ &= \langle B\uparrow|\sum_{k=1}^{3}[\hat{\mathcal{Q}}\sigma_3]^{(k)}|B\uparrow\rangle, \end{aligned} \tag{C.9}$$

$$b_3^B = \langle B\uparrow|\sum_{k=1}^{3}[\mathcal{Q}_s\sigma_3]^{(k)}|B\uparrow\rangle. \tag{C.10}$$

C.3 Meson Cloud Diagram (MC)

$$G_M^B(Q^2)\big|^{\alpha}_{MC}$$

$$\begin{aligned}
=&\ {}^B\langle\phi_0|\frac{\mathrm{i}^2}{2!}\int\delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx}T\big[\mathcal{L}_I^W(x_1)\mathcal{L}_I^W(x_2)\vec{j}_\Phi(x)\big]|\phi_0\rangle^B\\
=&\ 4\,{}^B\langle\phi_0|\frac{-1}{2}\int\delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx}\\
&\times N\Big\{\Big[\frac{1}{2F}\partial_\mu\Phi_i\bar\psi\gamma^\mu\gamma^5\lambda_i\psi\Big]_{x_1}\Big[(f_{3kl}+\frac{f_{8kl}}{\sqrt3})\Phi_k(-\vec\nabla\Phi_l)\Big]_x\Big[\frac{1}{2F}\partial_\nu\Phi_j\bar\psi\gamma^\nu\gamma^5\lambda_j\psi\Big]_{x_2}\Big\}\\
&\times|\phi_0\rangle^B\\
=&\ \frac{-i}{2F^2(2\pi)^8}\,{}^B\langle\phi_0|b_0^\dagger\int d^3x_1d^3x_2d^4k_1d^4k_2\frac{e^{-i\vec k_1\cdot\vec x_1}}{M_\Phi^2-k_1^2-i\epsilon}\frac{e^{-i\vec k_2\cdot\vec x_2}}{M_\Phi^2-k_2^2-i\epsilon}\\
&\times(f_{3kl}+\frac{f_{8kl}}{\sqrt3})\bar u_0(x_1)\gamma^\mu k_{1\mu}\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\gamma^\nu k_{2\nu}\gamma^5\vec k_2\lambda_ju_0(x_2)\\
&\times\int dtdt_1dt_2\delta t\Theta(t_1-t_2)e^{-iq_0t}e^{-i\varepsilon_0(t_2-t_1)}e^{-i\varepsilon_\alpha(t_1-t_2)}e^{-ik_1^0(t_1-t)}e^{-ik_2^0(t-t_2)}\\
&\times\int d^3xe^{-i(\vec k_1-\vec k_2-\vec q)\cdot\vec x}b_0|\phi_0\rangle^B\\
=&\ -\frac{(f_{3ij}+\frac{f_{8ij}}{\sqrt3})}{2F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3x_1d^3x_2d^3k_1d^3k_2\vec k_2\delta(\vec k_1-\vec k_2-\vec q)\\
&\times\int dk_1^0dk_2^0\frac{\delta(k_1^0-k_2^0)}{[\omega_\Phi(k_1^2)-(k_1^0)^2-i\epsilon][\omega_\Phi(k_2^2)-(k_2^0)^2-i\epsilon][\Delta\varepsilon_\alpha+k_1^0-i\eta]}\\
&\times\big[(k_2^0)^2\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2)\\
&-k_2^0\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)\\
&-k_2^0\bar u_0(x_1)\vec\gamma\cdot\vec k_1\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2)\\
&+\bar u_0(x_1)\vec\gamma\cdot\vec k_1\gamma^5\lambda_iu_\alpha(x_1)\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)\big]b_0|\phi_0\rangle^B\\
=&\ \frac{i}{4F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\int d^3k_2\vec k_2\frac{f_{3ij}+\frac{f_{8ij}}{\sqrt3}}{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)[\omega_\Phi(k_2'^2)+\Delta\varepsilon_\alpha][\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha]}\\
&\times\Big\{-\frac{\Delta\varepsilon_\alpha\omega_\Phi(k_2^2)\omega_\Phi(k_2'^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)}\int d^3x_1\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\\
&\times\int d^3x_2\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2}-\frac{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)}\\
&\times\int d^3x_1\bar u_0(x_1)\gamma^0\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\int d^3x_2\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2}\\
&-\frac{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)}\int d^3x_1\bar u_0(x_1)\vec\gamma\cdot\vec k_2'\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\\
&\times\int d^3x_2\bar u_\alpha(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2}+\frac{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)}\\
&\times\int d^3x_1\bar u_0(x_1)\vec\gamma\cdot\vec k_2'\gamma^5\lambda_iu_\alpha(x_1)e^{i\vec k_2'\cdot\vec x_1}\int d^3x_2\bar u_\alpha(x_2)\vec\gamma\cdot\vec k_2\gamma^5\lambda_ju_0(x_2)e^{-i\vec k_2\cdot\vec x_2}\Big\}\\
&\times b_0|\phi_0\rangle^B
\end{aligned}$$

$$
\begin{aligned}
= \quad & \frac{i}{4F^2(2\pi)^3} {}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger \int d^3k_2\vec{k}_2 \\
& \times \frac{1}{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)[\omega_\Phi(k_2'^2)+\Delta\varepsilon_\alpha][\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha]} \\
& \times \Big\{ -\frac{\Delta\varepsilon_\alpha\omega_\Phi(k_2^2)\omega_\Phi(k_2'^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{I\alpha}(k_2')F_{I\alpha}^\dagger(k_2) \\
& + \frac{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{I\alpha}(k_2')F_{II\alpha}^\dagger(k_2) + \frac{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{II\alpha}(k_2')F_{I\alpha}^\dagger(k_2) \\
& + \frac{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{II\alpha}(k_2')F_{II\alpha}^\dagger(k_2) \Big\} \\
& \times (f_{3ij} + \frac{f_{8ij}}{\sqrt{3}})[(\vec{\sigma}\cdot\vec{k}_2')\lambda_i]_{0,\alpha}[(\vec{\sigma}\cdot\vec{k}_2)\lambda_j]_{\alpha,0}\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B \\
= \quad & -\frac{5i}{12(2\pi F)^2}\int_0^\infty dk \int_{-1}^1 dx k^4(1-x^2) \\
& \times \Big\{ -\frac{\Delta\varepsilon_\alpha\omega_\Phi(k_2^2)\omega_\Phi(k_2'^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{I\alpha}(k_2')F_{I\alpha}^\dagger(k_2) \\
& + \frac{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{I\alpha}(k_2')F_{II\alpha}^\dagger(k_2) + \frac{\omega_\Phi(k_2'^2)\omega_\Phi(k_2^2)}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{II\alpha}(k_2')F_{I\alpha}^\dagger(k_2) \\
& + \frac{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)+\Delta\varepsilon_\alpha}{\omega_\Phi(k_2'^2)+\omega_\Phi(k_2^2)} F_{II\alpha}(k_2')F_{II\alpha}^\dagger(k_2) \Big\} \\
& \times \frac{{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger \frac{-3i}{10}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i\lambda_j\sigma_3\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B}{\omega_\Phi(k_+^2)\omega_\Phi(k^2)[\omega_\Phi(k_+^2)+\Delta\varepsilon_\alpha][\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]}, \qquad \text{(C.11)}
\end{aligned}
$$

When the quark propagator is restricted on the ground state, we obtain

$$
\begin{aligned}
G_M^B(Q^2)\big|_{MC} \quad = \quad & \frac{5}{6(2\pi F)^2}\int_0^\infty dk \int_{-1}^1 dx k^4(1-x^2) \\
& \times F_{II}(k)F_{II}(k_+)[b_4^B D_\pi(k^2,Q^2,x) + b_5^B D_K(k^2,Q^2,x)],
\end{aligned}
$$

(C.12)

where

$$
D_\Phi(k^2,Q^2,x) = \frac{1}{\omega_\Phi^2(k_+^2)\omega_\Phi^2(k^2)}, \qquad \text{(C.13)}
$$

$$
\begin{aligned}
b_4^B \quad &= \quad \sum_{i,j=1}^{3} {}^B\langle\phi_0|b_0^\dagger\chi_{f'}^\dagger\chi_{s'}^\dagger - \frac{3i}{10}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i\lambda_j\sigma_3\chi_s\chi_f b_0|\phi_0\rangle^B \\
&= \quad \sum_{i,j=1}^{3}\langle B\uparrow|\sum_{k=1}^{3}[-\frac{3i}{10}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i\lambda_j\sigma_3]^{(k)}|B\uparrow\rangle, \qquad \text{(C.14)} \\
b_5^B \quad &= \quad \sum_{i,j=4}^{7}\langle B\uparrow|\sum_{k=1}^{3}[-\frac{3i}{10}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\lambda_i\lambda_j\sigma_3]^{(k)}|B\uparrow\rangle. \qquad \text{(C.15)}
\end{aligned}
$$

C.4 Vertex Correction Diagram (VC)

$$
\begin{aligned}
&G_M^B(Q^2)\big|_{VC}^{\alpha\beta} \\
&= {}^B\langle\phi_0|\frac{\mathrm{i}^2}{2!}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx}T\left[\mathcal{L}_I^W(x_1)\mathcal{L}_I^W(x_2)\vec{j}_\psi(x)\right]|\phi_0\rangle^B \\
&= 2\,{}^B\langle\phi_0|\frac{-1}{2}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx} \\
&\quad\times N\Big\{\Big[\frac{1}{2F}\partial_\mu\Phi_i\bar{\psi}\gamma^\mu\gamma^5\lambda_i\psi\Big]_{x_1}\Big[\bar{\psi}\vec{\gamma}\mathcal{Q}\psi\Big]_x\Big[\frac{1}{2F}\partial_\nu\Phi_j\bar{\psi}\gamma^\nu\gamma^5\lambda_j\psi\Big]_{x_2}\Big\}|\phi_0\rangle^B \\
&= \frac{i}{4F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^3x_2d^4ke^{i\vec{q}\cdot\vec{x}}\frac{e^{i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)}}{M_\Phi^2-k^2-i\epsilon} \\
&\quad\times\bar{u}_0(x_1)\gamma^\mu k_\mu\gamma^5\lambda_iu_\alpha(x_1)\bar{u}_\alpha(x)\vec{\gamma}\mathcal{Q}u_\beta(x)\bar{u}_\beta(x_2)\gamma^\nu k_\nu\gamma^5\lambda_iu_0(x_2) \\
&\quad\times\int dtdt_1dt_2\delta t\Theta(t_1-t)\Theta(t-t_2)e^{-iqt}e^{-i\varepsilon_0(t_2-t_1)}e^{-i\varepsilon_\alpha(t_1-t)} \\
&\quad\times e^{-i\varepsilon_\beta(t-t_2)}e^{-ik_0(t_1-t_2)}b_0|\phi_0\rangle^B \\
&= \frac{-i}{4F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger d^3xd^3x_1d^3x_2d^3ke^{i\vec{q}\cdot\vec{x}}e^{i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)} \\
&\quad\times\int dk_0\frac{1}{[\omega_\Phi(k^2)-(k_0)^2-i\epsilon][k_0+\Delta\varepsilon_\alpha-i\eta][k_0+\Delta\varepsilon_\beta-i\eta]} \\
&\quad\times\bar{u}_0(x_1)(\gamma^0k_0-\vec{\gamma}\cdot\vec{k})\gamma^5\lambda_iu_\alpha(x_1)\bar{u}_\alpha(x)\vec{\gamma}\mathcal{Q}u_\beta(x) \\
&\quad\times\bar{u}_\beta(x_2)(\gamma^0k_0-\vec{\gamma}\cdot\vec{k})\gamma^5\lambda_iu_0(x_2)b_0|\phi_0\rangle^B \\
&= \frac{G_M^p(Q^2)\big|_{LO}^\alpha}{8F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\int d^3k\frac{1}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]^2} \\
&\quad\times\big[\omega_\Phi^2(k^2)F_{I\alpha}(k)F_{I\alpha}^\dagger(k)-\omega_\Phi(k^2)F_{I\alpha}(k)F_{II\alpha}^\dagger(k)-\omega_\Phi(k^2)F_{II\alpha}(k)F_{I\alpha}^\dagger(k) \\
&\quad+F_{II\alpha}(k)F_{II\alpha}^\dagger(k)\big]\lambda_i\mathcal{Q}_{\alpha\alpha}\lambda_i(\vec{\sigma}\cdot\vec{k})(\vec{\sigma}\times\vec{k})(\vec{\sigma}\cdot\vec{k})\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B \\
&= \frac{q\hat{i}}{4(2\pi F)^2}G_M^p(Q^2)\big|_{LO}^\alpha\int_0^\infty dkk^4\big[\omega_\Phi^2(k^2)F_{I\alpha}(k)F_{I\alpha}^\dagger(k)-\omega_\Phi(k^2)F_{I\alpha}(k)F_{II\alpha}^\dagger(k) \\
&\quad-\omega_\Phi(k^2)F_{II\alpha}(k)F_{I\alpha}^\dagger(k)+F_{II\alpha}(k)F_{II\alpha}^\dagger(k)\big] \\
&\quad\times\frac{{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\lambda_i\mathcal{Q}_{\alpha\alpha}\lambda_i\sigma_3\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]^2},
\end{aligned}
\tag{C.16}
$$

where

$$
\int d^3x\bar{u}_\alpha(x)\vec{\gamma}u_\beta(x)e^{i\vec{q}\cdot\vec{x}}=\delta_{\alpha\beta}G_E^p(Q^2)\big|_{LO}^\alpha. \tag{C.17}
$$

For the case $\alpha=0$, we obtain

$$
\begin{aligned}
G_M^B(Q^2)\big|_{VC} &= \frac{1}{2(2\pi F)^2}G_M^p(Q^2)\big|_{LO}\int_0^\infty dkk^4F_{II}^2(k^2) \\
&\quad\times\Big[\frac{b_6^B}{\omega_\pi^3(k^2)}+\frac{b_7^B}{\omega_K^3(k^2)}+\frac{b_8^B}{\omega_\eta^3(k^2)}\Big].
\end{aligned}
\tag{C.18}
$$

where

$$
\begin{aligned}
a_6^B &= {}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\lambda_i\mathcal{Q}\lambda_i\sigma_3\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B \\
&= \sum_{i=1}^{3}\langle B\uparrow|\sum_{k=1}^{3}[\lambda_i\mathcal{Q}\lambda_i\sigma_3]^{(k)}|B\uparrow\rangle \\
a_7^B &= \sum_{i=4}^{7}\langle B\uparrow|\sum_{k=1}^{3}[\lambda_i\mathcal{Q}\lambda_i\sigma_3]^{(k)}|B\uparrow\rangle, \\
a_8^B &= \langle B\uparrow|\sum_{k=1}^{3}[\lambda_8\mathcal{Q}\lambda_8\sigma_3]^{(k)}|B\uparrow\rangle. \qquad \text{(C.19)}
\end{aligned}
$$

C.5 Meson-in-Flight Diagram (MF)

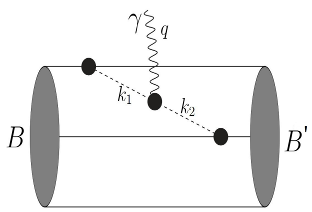

Figure C.1: Meson-in-flight diagram

$$
\begin{aligned}
& G_E^B(Q^2)\big|_{MF} \\
= \; & {}^B\langle\phi_0|\frac{\mathrm{i}^2}{2!}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx}T\big[\mathcal{L}_I^W(x_1)\mathcal{L}_I^W(x_2)\vec{j}_\Phi(x)\big]|\phi_0\rangle^B \\
= \; & 2\,{}^B\langle\phi_0|\frac{-1}{2}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx} \\
& \times N\Big\{\Big[\frac{1}{2F}\partial_\mu\overbrace{\Phi_i\bar{\psi}\gamma^\mu\gamma^5\lambda_i\psi\Big]_{x_1}\Big[(f_{3kl}+\frac{f_{8kl}}{\sqrt{3}})\Phi}_k(-\vec{\nabla}\overbrace{\Phi_l)\Big]_x\Big[\frac{1}{2F}\partial_\nu\Phi}_j\bar{\psi}\gamma^\nu\gamma^5\lambda_j\psi\Big]_{x_2}\Big\} \\
& \times|\phi_0\rangle^B \\
= \; & \frac{-i}{4F^2(2\pi)^8}\,{}^B\langle\phi_0|b_0^{m\dagger}b_0^{n\dagger}\int d^3x_1d^3x_2d^4k_1d^4k_2\vec{k}_2\frac{e^{i\vec{k}_1\cdot\vec{x}_1}}{M_\Phi^2-k_1^2-i\epsilon}\frac{e^{-i\vec{k}_2\cdot\vec{x}_2}}{M_\Phi^2-k_2^2-i\epsilon} \\
& \times(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})\bar{u}_0(x_1)\gamma^\mu k_{1\mu}\gamma^5\lambda_i u_0(x_1)\bar{u}_0(x_2)\gamma^\nu k_{2\nu}\gamma^5\lambda_j u_0(x_2) \\
& \times\int dtdt_1dt_2\delta te^{-iqt}e^{-ik_1^0(t_1-t)}e^{-ik_2^0(t-t_2)}\int d^3xe^{-i(-\vec{k}_1-\vec{k}_2-\vec{q})\cdot\vec{x}}b_0^nb_0^m|\phi_0\rangle^B \\
= \; & -\frac{(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})}{2F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^{m\dagger}b_0^{n\dagger}\int d^3x_1d^3x_2d^3k_1d^3k_2\vec{k}_2\delta(\vec{k}_1-\vec{k}_2-\vec{q}) \\
& \times\int dk_2^0\frac{1}{[\omega_\Phi(k_1^2)-(k_1^0)^2-i\epsilon][\omega_\Phi(k_2^2)-(k_2^0)^2-i\epsilon][k_1^0-i\epsilon]} \\
& \times\big[(k_2^0)^2\bar{u}_0(x_1)\gamma^0\gamma^5\lambda_iu_0(x_1)\bar{u}_0(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2) \\
& -k_2^0\bar{u}_0(x_1)\gamma^0\gamma^5\lambda_iu_0(x_1)\bar{u}_0(x_2)\vec{\gamma}\cdot\vec{k}_2\gamma^5\lambda_ju_0(x_2) \\
& -k_2^0\bar{u}_0(x_1)\vec{\gamma}\cdot\vec{k}_1\gamma^5\lambda_iu_0(x_1)\bar{u}_0(x_2)\gamma^0\gamma^5\lambda_ju_0(x_2) \\
& +\bar{u}_0(x_1)\vec{\gamma}\cdot\vec{k}_1\gamma^5\lambda_iu_0(x_1)\bar{u}_0(x_2)\vec{\gamma}\cdot\vec{k}_2\gamma^5\lambda_ju_0(x_2)\big]b_0^nb_0^m|\phi_0\rangle^B \\
= \; & -\frac{i}{4F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^{m\dagger}b_0^{n\dagger}\chi_c^{m\dagger}\chi_c^{n\dagger}\chi_f^{m\dagger}\chi_f^{n\dagger}\chi_s^{m\dagger}\chi_s^{n\dagger}\int d^3k_2\vec{k}_2F_{II}(k_2')F_{II}(k_2) \\
& \times\frac{(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})[(\vec{\sigma}\cdot\vec{k}_2')\lambda_i][(\vec{\sigma}\cdot\vec{k}_2)\lambda_j]}{\omega_\Phi^2(k_2'^2)\omega_\Phi^2(k_2^2)}\chi_s^n\chi_s^m\chi_f^n\chi_f^m\chi_c^n\chi_c^mb_0^nb_0^m|\phi_0\rangle^B \\
= \; & \frac{-iq}{2(2\pi F)^2}\int_0^\infty dk\int_{-1}^1 dxk^4(1-x^2)F_{II}(k_2')F_{II}(k_2) \\
& \times\,{}^B\langle\phi_0|b_0^{m\dagger}b_0^{n\dagger}\chi_c^{m\dagger}\chi_c^{n\dagger}\chi_f^{m\dagger}\chi_f^{n\dagger}\chi_s^{m\dagger}\chi_s^{n\dagger}\frac{1}{4}(f_{3ij}+\frac{f_{8ij}}{\sqrt{3}})
\end{aligned}
$$

$$\times \frac{[\lambda_i\sigma_1]^{(k)}[\lambda_j\sigma_2]^{(l)}}{\omega_\Phi^2(k_2'^2)\omega_\Phi^2(k_2^2)}\chi_s^n\chi_s^m\chi_f^n\chi_f^m\chi_c^n\chi_c^m b_0^n b_0^m|\phi_0\rangle^B, \tag{C.20}$$

Finally, we have

$$\begin{aligned} G_M^B(Q^2)\big|_{MF} &= \frac{m_B}{(2\pi F)^2}\int_0^\infty dk\int_{-1}^1 dx k^4(1-x^2)F_{II}(k)F_{II}(k_+) \\ &\times[b_9^B D_\pi(k^2,Q^2,x)+b_{10}^B D_K(k^2,Q^2,x)], \end{aligned} \tag{C.21}$$

where

$$\begin{aligned} b_9^B &= \sum_{i,j=1}^3\langle B\uparrow|\sum_{\substack{k,l=1\\k\neq l}}^3[\lambda_i\sigma_1]^{(k)}[\lambda_j\sigma_2]^{(l)}|B\uparrow\rangle \\ b_{10}^B &= \sum_{i,j=4}^7\langle B\uparrow|\sum_{\substack{k,l=1\\k\neq l}}^3[\lambda_i\sigma_1]^{(k)}[\lambda_j\sigma_2]^{(l)}|B\uparrow\rangle. \end{aligned} \tag{C.22}$$

Appendix D

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