

ACD-5791

INVO. M.S.A - 7/2/98

EXACT CALCULATION OF THE FLAVOUR-CHANGING QUARK-HIGGS VERTEX

BY

TAN BOK HOOI
DEPARTMENT OF PHYSICS
FACULTY OF SCIENCE
UNIVERSITI MALAYA

Perpustakaan Universiti Malaya



A507469681

DISSERTATION PRESENTED FOR THE
DEGREE OF MASTER OF SCIENCE

UNIVERSITI MALAYA

KUALA LUMPUR

1997

Dimikrofiskan pada.....

No. Mikrofis.....

Jumlah Mikrofis.....

16.09.2000

14456

2

HAMSIH BT. MOHAMAD ZAHARI

UPR

UNIT REPROGRAFI
PERPUSTAKAAN UTAMA
UNIVERSITI MALAYA

ABSTRAK

Fungsi verteks $q_i q_j H$ di mana indeks i dan j merujuk kepada jenis kuark bawah dan H pula merujuk kepada zarah Higgs telah dikira dalam konteks model Glashow-Weinberg-Salam (GWS). Pengiraan dibuat dengan menggunakan cara 't Hooft-Feynman. Jisim kuark luaran diabaikan dalam pengiraan ini. Bahagian pengiraan yang menyebabkan sifat infiniti boleh dihapuskan dengan menggunakan satu cara renormalisasi yang terdiri daripada gambarajah pengurangan satu zarah. Cara renormalisasi ini berbeza dengan beberapa pengarang lain yang menggunakan pendekatan Ward-Takahashi. Bagaimana fungsi verteks bergantung kepada jisim zarah Higgs juga disiasat. Apabila jisim zarah Higgs diambil kira dalam pengiraan, faktor bentuk fungsi verteks akan terdiri daripada bahagian nyata dan khayalan. Apabila julat jisim zarah Higgs diambil sebagai $0 \leq m_H \leq 250$ GeV wujud dua titik utama pada $k^2 = 4m_j^2$ dan $k^2 = 4M_W^2$ untuk bahagian nyata dan khayalan. Bahagian khayalan adalah bertanggungjawab terhadap asimetri kadar pereputan. Tanpa mengambil kira jisim zarah Higgs, kadar pereputan $q_i \rightarrow q_j H$ dan $q_i \rightarrow q_j e^+ e^-$ dikira. Pereputan zarah Higgs kepada pasangan kuark-antikuark ($H \rightarrow q_i \bar{q}_j$) juga disiasat. Siasatan ke atas asimetri pelanggaran-CP untuk proses pereputan zarah Higgs kepada pasangan kuark-antikuark iaitu $H \rightarrow s\bar{d}$ dan $H \rightarrow d\bar{s}$, $H \rightarrow b\bar{d}$ dan $H \rightarrow d\bar{b}$ serta akhirnya $H \rightarrow b\bar{s}$ dan $H \rightarrow s\bar{b}$ juga dijalankan.

ABSTRACT

The vertex function of $q_i q_j H$ where the indices i and j refers to the down type of quarks and H refers to the virtual Higgs boson is calculated within the framework of the Glashow-Weinberg-Salam (GWS) model. The calculation is done in the 't Hooft-Feynman gauge where the external quark masses and the mass of the Higgs boson have been neglected. The divergence in the vertex function is eliminated by using a renormalization scheme which consists of one-particle reducible diagrams. The renormalization scheme differs from several other authors who used the Ward-Takahashi approach. The dependence of the vertex function with respect to the mass of the Higgs boson is also investigated. When the mass of the Higgs boson is taken into consideration, the form factors of the vertex function will consist of the real and imaginary parts. When the range of the mass of Higgs boson is taken to be $0 \leq m_H \leq 250$ GeV there exist two thresholds at $k^2 = 4m_j^2$ and $k^2 = 4M_W^2$ for the real and imaginary parts. The imaginary part is responsible for the decay rate asymmetry. Without taking the mass of Higgs into consideration, the decay rate of $q_i \rightarrow q_j H$ and $q_i \rightarrow q_j e^+ e^-$ are calculated. The Higgs boson decaying into quark-antiquark pair ($H \rightarrow q_i \bar{q}_j$) is also investigated. The investigation of the CP-violating asymmetry for the process of Higgs decay into quark-antiquark pair where $H \rightarrow s\bar{d}$ and $H \rightarrow d\bar{s}$, $H \rightarrow b\bar{d}$ and $H \rightarrow d\bar{b}$ and finally $H \rightarrow b\bar{s}$ and $H \rightarrow s\bar{b}$ are also carried out.

ACKNOWLEDGEMENT

I would like to take this great opportunity to express my gratitude to my supervisor, Professor Chia Swee Ping for his detailed supervision, constant encouragement and understanding. A billion thanks for being a wonderful friend.

A million thanks to the Head of Physics Department, Associate Professor Muhammad Rasat Muhammad for his encouragement and also the use of the facilities in the department.

I would like to thank Associate Professor Kurunathan Ratnavelu for his stimulating discussions.

My sincere thanks to Dr. Benardine Wong for his enlightening and keenly-pursued discussions.

I am also thankful to a whole lot of people, which includes:

- Bee Ean, for her tremendous and unselfish moral support when I was down in the dumps.
- Pooi Fun, for her enlightening company and not forgetting the small little kick in the butt that she gave which provoked an immediate comprehension of my delicate situation.
- Daisy, for whatever lessons in life that I chose to ignore but eventually learned them all, the hard way.

- Tiem Leong, for his unselfish act in allowing me to engage in a time-consuming intellectual struggle with his portable computer as an unwilling guinea-pig.
- Weng Lee, for his willingness to demonstrate the vast and hidden capabilities of the computing machine which left me totally devastated but full of admiration, not forgetting, consumed by a certain degree of guilt regarding my own ignorance of this wonderful but sometimes unpredictable machine.
- Wee Seong, for his over enthusiasm in giving me the green light to continue my epic struggle with the high-tech but sometimes unreliable product of the scientific world, the machine which we now called the computer, in a totally new and refreshing environment.
- Wai Leong, or better known as Hilbert, for his over abundance supply of good quality papers which has become an important and essential necessity just to cater for my calculations, the degree of complexity which can sometimes be totally shocking and unimaginable.
- The rest of the so-called Feynman group or gang or even brothers, whichever one deemed appropriate, Sashi, Rajesh and Chong for their company, support and lively but sometimes nonsensical discussion not only about research but includes just about everything there is to be discussed and talked about.

- Mr. Soo, for his readiness to provide me with a back-up supply of computing papers just in case my long-winded and seemingly endless technical calculations need to swallow extra bundles of good quality papers.
- Ms. Ng Lee Leng, for her last-minute acceptance to type my thesis and indirectly accepting the challenge to peruse my extremely intricate handwriting and to bear with my fickle-mindedness and the burning obsession for perfection.
- And last but not least, Quek, Chin, Yap, Heng and Foo for their continued presence in the department which provide an electrically-charged atmosphere for stimulating discussions and scientific research, without which, an otherwise mundane and monotonous atmosphere would have prevailed.

To my parents, for their undivided love, total support and their comprehension that I am the master of my own destiny.

And my sisters, Bee Yee, Bee Eu and Bee Chin, for their undisputed love, moral support, infinite patience and profound understanding that I am trying my very best to fulfill my seemingly natural obligations.

LIST OF FIGURES

Fig. 3.1 a)	The flavour-changing quark self-energy resulting from the emission and reabsorption of a W boson	26
b)	The flavour-changing quark self-energy due to the emission and reabsorption of a charged unphysical Higgs scalar	
Fig. 3.2	Feynman diagram for the $\bar{s}dH$ vertex function	31
Fig. 3.3	One-particle reducible diagrams for the $\bar{s}dH$ vertex function	38
Fig. 3.4	Real part of the form factors vs. k (GeV) where solid (dashed) line is $\text{Re}(C_t)$ ($\text{Re}(C_c)$)	55
Fig. 3.5	Imaginary part of the form factors vs. k (GeV) where solid (dashed) line is $\text{Im}(C_t)$ ($\text{Im}(C_c)$)	56
Fig. 4.1	Total decay rate $\Gamma(s \rightarrow dH)$ vs. m_H (GeV)	63
Fig. 4.2	Total decay rate $\Gamma(b \rightarrow dH)$ vs. m_H (GeV)	64
Fig. 4.3	Total decay rate $\Gamma(b \rightarrow sH)$ vs. m_H (GeV)	65
Fig. 4.4	Total decay rate $\ln \Gamma(s \rightarrow de^+e^-)$ vs. m_H (GeV)	71
Fig. 4.5	Total decay rate $\ln \Gamma(b \rightarrow de^+e^-)$ vs. m_H (GeV)	72
Fig. 4.6	Total decay rate $\ln \Gamma(b \rightarrow se^+e^-)$ vs. m_H (GeV)	73
Fig. 4.7	Decay rate $\Gamma(H \rightarrow d\bar{s})$ vs. m_H (GeV) when $\text{Re}(\lambda_u \lambda_c^*) = -4.412 \times 10^{-2}$	81
Fig. 4.8	Decay rate $\Gamma(H \rightarrow d\bar{b})$ vs. m_H (GeV) where solid (dashed) line is for $\text{Re}(\lambda_u \lambda_c^*) = 2.385 \times 10^{-5}$ (-2.385×10^{-5})	82
Fig. 4.9	Decay rate $\Gamma(H \rightarrow s\bar{b})$ vs. m_H (GeV) where solid (dashed) line is for $\text{Re}(\lambda_u \lambda_c^*) = 2.635 \times 10^{-5}$ (-2.635×10^{-5})	83

Fig. 5.1	Decay rate asymmetry parameter, $a(sd)$ vs. m_H (GeV) when $\text{Re}(\lambda_u \lambda_c^*) = -4.412 \times 10^{-2}$	102
Fig. 5.2	Decay rate asymmetry parameter, $a(bd)$ vs. m_H (GeV) where solid (dashed) line is for $\text{Re}(\lambda_u \lambda_c^*) = 2.385 \times 10^{-5}$ (-2.385×10^{-5})	103
Fig. 5.3	Decay rate asymmetry parameter, $a(bs)$ vs. m_H (GeV) where solid (dashed) line is for $\text{Re}(\lambda_u \lambda_c^*) = 2.635 \times 10^{-5}$ (-2.635×10^{-5})	104
Fig. 5.4	Decay rate asymmetry parameter, $a(bd)$ vs. $ \lambda_u ^2$ when $k = 150.0$ GeV where solid (dashed) line is for $10a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = 2.385 \times 10^{-5}$ ($a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = -2.385 \times 10^{-5}$)	105
Fig. 5.5	Decay rate asymmetry parameter, $a(bd)$ vs. $ \lambda_c ^2$ when $k = 150.0$ GeV where solid (dashed) line refers to $10a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = 2.385 \times 10^{-5}$ ($a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = -2.385 \times 10^{-5}$)	106
Fig. 5.6	Decay rate asymmetry parameter, $a(bd)$ vs. $\text{Re}(\lambda_u \lambda_c^*)$ when $k = 150.0$ GeV	107
Fig. 5.7	Decay rate asymmetry parameter, $a(sd)$ vs. $ \lambda_c ^2$ when $k = 100.0$ GeV and $\text{Re}(\lambda_u \lambda_c^*) = -4.412 \times 10^{-2}$	108

LIST OF TABLES

TABLE I	Real part of the form factors for the u , c and t quarks with respect to k	53
TABLE II	Imaginary part of the form factors for the u , c and t quarks with respect to k	54
TABLE III	Decay rate, Γ of $s \rightarrow dH$	60
TABLE IV	Decay rate, Γ of $b \rightarrow dH$	61
TABLE V	Decay rate, Γ of $b \rightarrow sH$	62
TABLE VI	Decay rate, Γ of $s \rightarrow de^+e^-$	68
TABLE VII	Decay rate, Γ of $b \rightarrow de^+e^-$	69
TABLE VIII	Decay rate, Γ of $b \rightarrow se^+e^-$	70
TABLE IX	Decay rate, Γ for $H \rightarrow d\bar{s}$ when $\text{Re}(\lambda_u\lambda_c^*) = -4.412 \times 10^{-2}$	78
TABLE X	Decay rate, Γ for $H \rightarrow d\bar{b}$ when $\text{Re}(\lambda_u\lambda_c^*) = \pm 2.385 \times 10^{-5}$ where $\Gamma(H \rightarrow d\bar{b})_m$ refers to $\text{Re}(\lambda_u\lambda_c^*) = +2.385 \times 10^{-5}$ and $\Gamma(H \rightarrow d\bar{b})_n$ refers to $\text{Re}(\lambda_u\lambda_c^*) = -2.385 \times 10^{-5}$	79
TABLE XI	Decay rate, Γ for $H \rightarrow s\bar{b}$ when $\text{Re}(\lambda_u\lambda_c^*) = \pm 2.635 \times 10^{-5}$ where $\Gamma(H \rightarrow s\bar{b})_m$ refers to $\text{Re}(\lambda_u\lambda_c^*) = +2.635 \times 10^{-5}$ and $\Gamma(H \rightarrow s\bar{b})_n$ refers to $\text{Re}(\lambda_u\lambda_c^*) = -2.635 \times 10^{-5}$	80
TABLE XII	Decay rate asymmetry parameter for $H \rightarrow b\bar{d}$ and $H \rightarrow d\bar{b}$ when $\text{Re}(\lambda_u\lambda_c^*) = 2.385 \times 10^{-5}$	89
TABLE XIII	Decay rate asymmetry parameter for $H \rightarrow b\bar{s}$ and $H \rightarrow s\bar{b}$ when $\text{Re}(\lambda_u\lambda_c^*) = 2.635 \times 10^{-5}$	90
TABLE XIV	Decay rate asymmetry parameter for $H \rightarrow s\bar{d}$ $H \rightarrow d\bar{s}$ when $\text{Re}(\lambda_u\lambda_c^*) = -4.412 \times 10^{-2}$	91

TABLE XV	Decay rate asymmetry parameter for $H \rightarrow b\bar{d}$ and $H \rightarrow d\bar{b}$ when $\text{Re}(\lambda_u \lambda_c^*) = -2.385 \times 10^{-5}$	92
TABLE XVI	Decay rate asymmetry parameter for $H \rightarrow b\bar{s}$ and $H \rightarrow s\bar{b}$ when $\text{Re}(\lambda_u \lambda_c^*) = -2.635 \times 10^{-5}$	93
TABLE XVII	Decay rate asymmetry parameter $a(sd)$ when $\text{Re}(\lambda_u \lambda_c^*)$ is -4.412×10^{-2}	94
TABLE XVIII	Decay rate asymmetry parameter $a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = \pm 2.385 \times 10^{-5}$ where $a(bd)_m$ refers to the decay rate asymmetry parameter when $\text{Re}(\lambda_u \lambda_c^*) = +2.385 \times 10^{-5}$ and $a(bd)_n$ refers to the decay rate asymmetry parameter when $\text{Re}(\lambda_u \lambda_c^*) = -2.385 \times 10^{-5}$	95
TABLE XIX	Decay rate asymmetry parameter $a(bs)$ when $\text{Re}(\lambda_u \lambda_c^*) = \pm 2.635 \times 10^{-5}$ where $a(bs)_m$ refers to the decay rate asymmetry parameter when $\text{Re}(\lambda_u \lambda_c^*) = +2.635 \times 10^{-5}$ and $a(bs)_n$ refers to the decay rate asymmetry parameter when $\text{Re}(\lambda_u \lambda_c^*) = -2.635 \times 10^{-5}$	96
TABLE XX	Decay rate asymmetry parameter vs. $ \lambda_u ^2$ when $k = 150.0$ GeV where $a(bd)_m$ refers to $a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = +2.385 \times 10^{-5}$ and $a(bd)_n$ refers to $a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = -2.385 \times 10^{-5}$	97
TABLE XXI	Decay rate asymmetry parameter vs. $ \lambda_c ^2$ when $k = 150.0$ GeV where $a(bd)_m$ refers to $a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = +2.385 \times 10^{-5}$ and $a(bd)_n$ refers to $a(bd)$ when $\text{Re}(\lambda_u \lambda_c^*) = -2.385 \times 10^{-5}$	98
TABLE XXII	Decay rate asymmetry parameter vs. $\text{Re}(\lambda_u \lambda_c^*)$ for $H \rightarrow b\bar{d}$ and $H \rightarrow d\bar{b}$ when $k = 150.0$ GeV	99
TABLE XXIII	Decay rate asymmetry parameter vs. $ \lambda_c ^2$ when $k = 100.0$ GeV for $H \rightarrow s\bar{d}$ and $H \rightarrow d\bar{s}$ when $\text{Re}(\lambda_u \lambda_c^*) = -4.412 \times 10^{-2}$	100
TABLE XXIV	Decay rate asymmetry parameter vs. $\text{Re}(\lambda_u \lambda_c^*)$ for $H \rightarrow s\bar{d}$ and $H \rightarrow d\bar{s}$ when $k = 100.0$ GeV	101

CONTENTS

ABSTRAK	i
ABSTRACT	ii
ACKNOWLEDGEMENT	iii
LIST OF FIGURES	vii
LIST OF TABLES	ix
CHAPTER 1 INTRODUCTION	1
CHAPTER 2 THE STANDARD $SU(2) \times U(1)$ GLASHOW-WEINBERG-SALAM MODEL	6
2.1 Introduction	6
2.2 Historical Development of the Model of Weak Interaction	6
2.3 The Glashow-Weinberg-Salam Model of Electroweak Interaction	12
2.4 Extension to the Quark Sector	19
2.5 Feynman Rules in the 't Hooft-Feynman Gauge	22
CHAPTER 3 THE FLAVOUR-CHANGING QUARK-HIGGS VERTEX	25
3.1 Introduction	25
3.2 The Flavour-Changing Quark Self-Energy	25
3.3 Calculation of the $\bar{s}dH$ Vertex Function	30
3.4 Renormalization	37
3.5 The On-Shell $\bar{s}dH$ Vertex Function	40
3.6 $\bar{s}dH$ Vertex Function Without Neglecting k^2	43

CHAPTER 4	APPLICATIONS	57
4.1	Introduction	57
4.2	Decay Rate for the Process $q_i \rightarrow q_j H$	57
4.3	Decay Rate for the Process $q_i \rightarrow q_j e^+ e^-$	66
4.4	Decay Rate for Flavour-Changing Decays of Higgs	74
CHAPTER 5	CP VIOLATION	84
5.1	Introduction	84
5.2	Calculation of the Decay Rate Asymmetry Parameter	84
CHAPTER 6	CONCLUSION	109
APPENDIX A	Dirac Algebra and Loop Momentum Integration in n Dimension	116
APPENDIX B	Momentum Integrals for One-Loop Diagram	118
APPENDIX C	Romberg Integration	119
APPENDIX D	Fortran Program	123
APPENDIX E	The KM Mixing Matrix	129
REFERENCES		131