Chapter 1

Particle Physics

1.1 Fundamental Particles

Current knowledge tells us that matter is made of fundamental particle called *fermions*, which are spin $\frac{1}{2}$ particles. Our world is composed of two kinds of fermions: leptons and quarks. Both of these can be grouped into three families. Electron and the electron neutrino, ν_e, make up the first family, whereas μ, τ and their associated neutrinos, ν_μ, ν_τ, compose the second and third family, respectively, for leptons. Each family is an identical copy of each other, except with different masses.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

We also have six kinds of quarks. As is the case for leptons, these six quarks are also grouped into three families.

Table 1.1: Charge, Mass and Isospin of the Six Leptons.

Lepton	Symbol	Charge	Mass (Mev/c^2)	weak isospin
electron	e^-	-1	0.511	1/2
muon	μ^-	-1	105.7	1/2
tau	τ^-	-1	1777	1/2
electron neutrino	ν_e	0	$< 7.0 \times 10^{-6}$	-1/2
muon neutrino	ν_μ	0	< 0.27	-1/2
tau neutrino	ν_τ	0	< 31	-1/2

Table 1.2: Charge, Mass and Isospin of the Six Quarks.

Quark	Symbol	Charge	Mass (Gev/c^2)
Up	u	2/3	0.004
Down	d	-1/3	0.007
Charm	c	2/3	0.3
Strange	s	-1/3	1.3
Beauty	b	2/3	4.8
Top	t	-1/3	174

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

The masses and charges of the fermions can be summarized in Table 1.1 for leptons and in Table 1.1 for quarks.

99% of our world is made up of leptons and quarks in the first family. Leptons and quarks in the second and third families are largely produced at machines built for high energy experiments.

Table 1.3: Table of the Four Fundamental Forces

Force	Boson	Symbol	Charge	Mass (Gev/c^2)
Gravitation	graviton	g	0	0
Electromagnetic	photon	γ	0	0
Weak	W	$W^{\pm}$	± 1	80.3
	Z	Z^0	0	91.2
Strong	Gluon	g	0	0

Table 1.4: Theory Corresponds to the Four Fundamental Forces

Force	theory	source	typical lifetime
Gravitation	general relativity	Masses	
Electro-magnetic	Quantum Electrodynamics	electric charge	10^{-26}
Weak	Quantum Flavor-dynamics	"Weak charge"	10^{-8}
Strong	Quantum Chromodynamics	"color charge"	10^{-23}

1.2 Fundamental Forces

These fundamental particles interact with each other by exchanging *intermediate vector bosons*, field quanta with integral spin. Such processes give rise to the fundamental forces. Our understanding is that we have four kinds of fundamental forces: two long range interactions: gravitational and electromagnetic forces; and two forces with short range: weak and strong interactions.

There is a physical theory to each of those forces. The theory describing gravitation is Einstein's General Theory of Relativity. A completely satisfactory quantum theory of gravity has not yet been worked out, and it is too weak to account for any important effects in particle physics.

The electromagnetic, weak and strong forces account for the interactions in particle physics. The character of the field quanta in the four forces is summarized in Table 1.2. In Table 1.2 we list the corresponding theories to describe them.

The fundamental particles described in the previous section experience different forces according to what kinds of "charges" they carry. The quarks are subject to electromagnetic, weak, and strong interactions. The $e-$, $\mu-$, and $\tau-$ leptons are involved in both the electromagnetic and weak interactions, while the neutrinos, $(\nu_e, \nu_\mu, \nu_\tau)$, interact only through the weak interaction.

1.3 Standard Model

The Standard Model (SM) provides a general description of fundamental particles and forces in a way that is accessible with modern high energy physics experiments. The theory is based on the gauge group, $SU(3)_{color} \times (SU(2)_L \times U(1)_Y)_{electroweak}$. The quarks and leptons are grouped into left-handed weak isospin doublets and right-handed singlets.

$$\left(\begin{array}{c} \nu_e \\ e \end{array}\right)_L, \left(\begin{array}{c} \nu_\mu \\ \mu \end{array}\right)_L, \left(\begin{array}{c} \nu_\tau \\ \tau \end{array}\right)_L, e_R, \mu_R, \tau_R$$

$$\left(\begin{array}{c} u \\ d^{'} \end{array}\right)_L, \left(\begin{array}{c} c \\ s^{'} \end{array}\right)_L, \left(\begin{array}{c} t \\ b^{'} \end{array}\right)_L, u_R, c_R, t_R, d^{'}_R, s^{'}_R, b^{'}_R$$

Each of the $d^{'}$, $s^{'}$ and $b^{'}$ is the combination of d, s, b quark states and will be explained in the next section. The $SU(2)_L \times U(1)_Y$ portion of the gauge group introduces four massless gauge bosons: $W^1_\mu, W^2_\mu, W^3_\mu$ for $SU(2)_L$, B_μ for $U(1)_Y$. The four gauge bosons coupled with a scalar Higgs field through a *spontaneous symmetry breaking* mechanism to become the massive W^+, W^-, Z^0 bosons and a massless γ.

The relationships between the four massless field quanta and the intermediate vector bosons are:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \pm iW_\mu^2)$$

$$Z_\mu = W_\mu^3 cos\theta_w - B_\mu sin\theta_W$$

$$A_\mu = W_\mu^3 sin\theta_w + B_\mu cos\theta_W$$

The θ_W is the *Weinberg Angle* in electroweak theory, which relates electromagnetic coupling and weak coupling strength. θ_W is about 28.7°[3].

The dynamics of the interacting particles can be described in the Standard Model Lagrangian:

$$L^{total} = L_d^f + L_d^b + L_{cp}^{f,h} + L_{cp}^{b,h} + L_{int}^f$$

where:

- L_d^f is the dynamic term of the fermions. For example: $\bar{f}\gamma^\mu \partial_\mu f_L$.
- L_d^b is the dynamic term of the gauge vector bosons: $W_\mu^\pm, Z_0, \gamma$. For example: $(-\frac{1}{4}W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$.
- $L_{cp}^{f,h}$ is the fermions coupling with Higgs to give fermions mass. For example: $(G_1 \bar{L}\phi R + G_2 \bar{L}\phi_c R + h.c)$.
- $L_{cp}^{b,h}$ is the vector boson-Higgs coupling term which gives gauge bosons mass. For example: $|(\imath\partial_\mu - g\frac{1}{2}\tau \cdot W_\mu - g'\frac{Y}{2}B_\mu)\phi|^2 - V(\phi)$.
- L_{int}^f is the interaction term for the fermions coupled with the intermediate vector bosons and/or the colored gluons. For example, $\bar{f}_L\gamma^\mu(\imath\partial_\mu - g\frac{1}{2}\tau \cdot W_\mu - g'\frac{Y}{2}B_\mu)f_L$.

We are interested in the interaction term, L^f_{int}, which gives the strong and electroweak interactions:

$$\begin{aligned} L^f_{int} = L^{ew}_{int} \quad + & \quad L^{strong}_{int} \\ L^{ew}_{int} \quad = & \quad L^{ec}_{int} + L^{cc}_{int} + L^{nc}_{int} \end{aligned}$$

where,

- L^{ew}_{int} is the Lagrangian for electroweak interaction.
    - L^{em}_{int} is the *electromagnetic current* Lagrangian.
    - L^{cc}_{int} is the *weak charge current* interacting Lagrangian.
    - L^{nc}_{int} is the *weak neutral current* interacting Lagrangian.
- L^{strong}_{int} is the strong color force Lagrangian.

The individual form of those interacting Lagrangian can be written as follows:

$$\begin{aligned} L^{em}_{int} &= \sum_{f=\ell,q} eQ_f(\bar{f}\gamma^\mu f)A^\mu \\ L^{cc}_{int} &= \frac{e}{sin\theta_w\sqrt{2}}[\sum_{f=\ell,q}(\bar{L}\gamma^\mu L)W^+_\mu + (Hermition.Conjugate)] \\ L^{nc}_{int} &= \frac{e}{sin\theta_w cos\theta_w}\sum_{f=\ell,q}[\bar{f}_L\gamma^\mu f_L(T^3_f - Q_f sin^2\theta_w) + \bar{f}_R\gamma^\mu f_R(-Q_f sin^2\theta_w)]Z_\mu \\ L^{st}_{int} &= \frac{g_3}{2}\sum_{f=q}\bar{f}_\alpha\gamma^\mu\lambda^a_{\alpha\beta}f_\beta G^a_\mu \end{aligned}$$

1.4 Weak Interaction

Weak Interaction is the primary reason why we divide these fundamental particle species into three families for leptons and quarks. The lepton generations were grouped in the way that its three families are orthogonal to each other in weak eigenspace. There is no weak interaction involving leptons from different families under current experimental limits. However, weak eigenspace and strong eigenspace does not coincide with each other. For the case of the quarks, which not only interact weakly but also experience the strong interaction, such effects lead to the phenomenon that a quark could decay into another quark in another family through weak interaction. This is not seen in leptons. The reason for quark "cross-family" decay is that quarks were grouped as an eigenvector in the strong Hamiltonian, H_{strong}, but not in the weak Hamiltonian, H_{weak}, where $[H_{strong}, H_{weak}]$ does not commute. For this purpose, a matrix materializing the cross-family quark decays called the **Cabibbo-Kobayashi-Maskawa** (CKM) Matrix is devised. The $d^{'}$, $s^{'}$,$b^{'}$ in our previous section can be written:

$$\begin{pmatrix} d^{'} \\ s^{'} \\ b^{'} \end{pmatrix} = V_{CKM} \times \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The V_{CKM} is:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM matrix can be parameterized in terms of the four rotation angle θ_1,θ_2,θ_3 and δ as:

$$V_{CKM} = \begin{pmatrix} c_1 & c_3 s_1 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + c_3 s_2 e^{i\delta} \\ s_1 s_2 & -c_1 c_3 s_2 - c_2 s_3 e^{-i\delta} & -c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix}$$

where $c_i = cos\theta_i$, $s_i = sin\theta_i$ [1] and the phase, δ, is within the range 0 - 2π. A popular approximation to the CKM matrix is given by Wolfenstein [2] in the following:

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The strength of the quark coupling between generations can be understood in terms of the power of $\lambda \simeq 0.22$. As can be seen from above, the coupling strengths for quark mixing in the $1^{st}-2^{nd}$, $2^{nd}-3^{rd}$ and $1^{st}-3^{rd}$ families are given by $\lambda, \lambda^2, \lambda^3$, respectively.

Assuming the unitarity of CKM matrix, the measured values of the elements within the CKM matrix up to date are [3]:

$$V_{CKM} = \begin{pmatrix} 0.9745-0.9760 & 0.217-0.224 & 0.0018-0.0045 \\ 0.217-0.224 & 0.9737-0.9753 & 0.036-0.042 \\ 0.004-0.013 & 0.035-0.042 & 0.9991-0.9994 \end{pmatrix}$$

The electroweak interaction Hamiltonian H_{int} can be obtained through the weak interaction Lagrangian terms, L_{int}^{cc} and L_{int}^{nc}, as follows:

$$H_{int}^{W} = \frac{\partial L_{int}^{W}}{\partial(\partial_0\phi)}\partial^0\phi - L_{int}^{W}$$

$H_{int}^{W} = H_{int}^{cc} + H_{int}^{nc}$. where,

- $H_{int}^{cc} = -i\frac{g}{\sqrt{2}}(J^\mu W_\mu^+ + J^{\mu\dagger}W_\mu^-)$
- $H_{int}^{nc} = -i\frac{g}{\cos\theta_w}\bar{\phi}_f\gamma^\mu[\frac{1}{2}(1-\gamma^5)T^3 - \sin^2\theta_w Q]\phi_f Z_\mu$

The charged current in leptonic sector, J_{lepton}^{μ}, can be written as:

$$\begin{pmatrix} \bar{\nu_e} & \bar{\nu_\mu} & \bar{\nu_\tau} \end{pmatrix} \frac{1}{2}\gamma^\mu(1-\gamma^5)\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

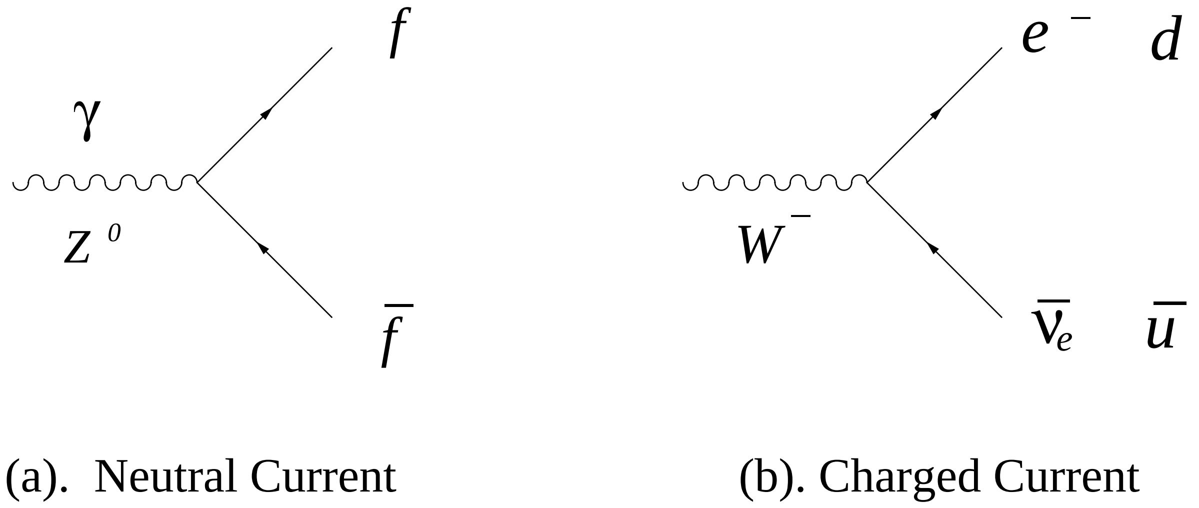

Figure 1.1: The Electroweak currents

The charged current for quarks is similar, except for the additional factor of V_{CKM}. J^{μ}_{quark} is:

$$\begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \frac{1}{2}\gamma^{\mu}(1-\gamma^5)V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Figure 1.1 shows the electroweak currents. Figure 1.1(a) shows the photon and Z boson carrying the neutral current between a fermion and its anti-fermion. Figure 1.1(b) demonstrates the W boson as the charged current carrier. We are studying the charged weak current in this analysis.

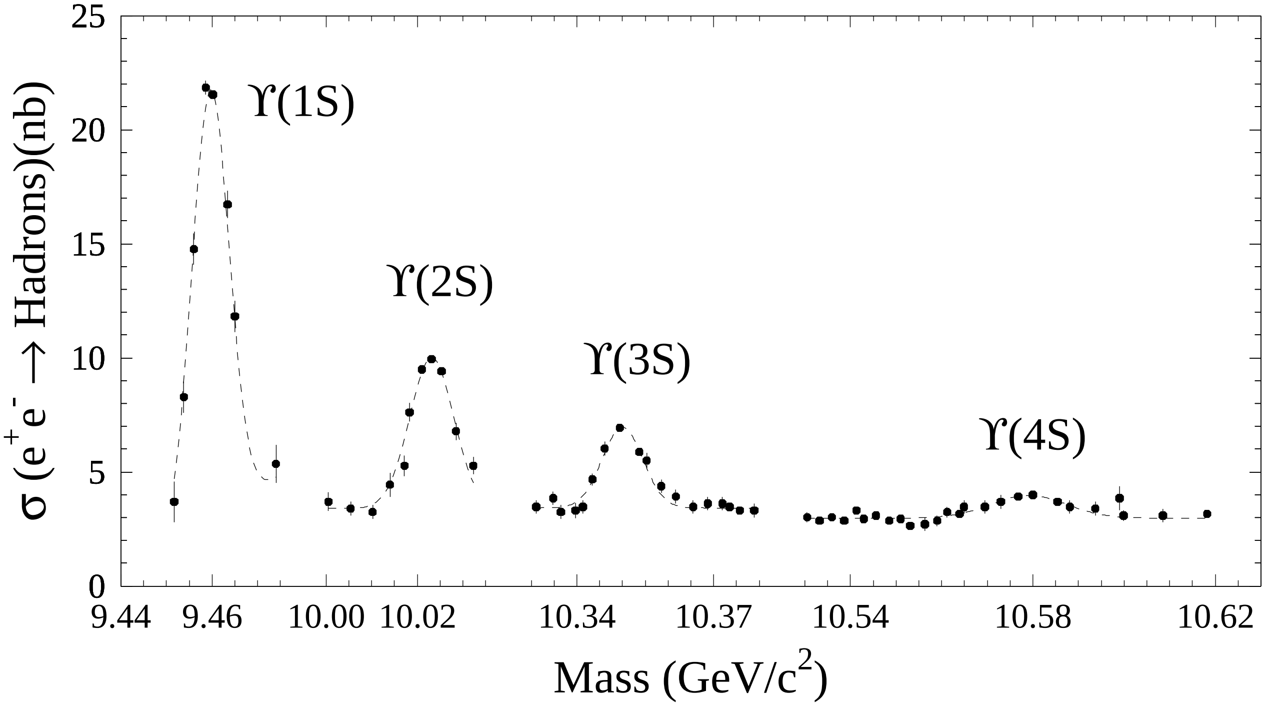

Figure 1.2: The cross section of ϒ(1S) to ϒ(4S) state

1.5 B Meson

The b quark was discovered in 1977 where the narrow $\Upsilon(1S)$ resonance, a $b\bar{b}$ state, was detected [6, 7] at Fermilab by the Columbia-Fermilab-Stony Brook collaboration. The B meson was discovered through the establishment of the $\Upsilon(4S)$ resonance ($J^{pc} = 1^{--}$) in CLEO [8] and CUSB [9] collaboration at CESR storage ring. Its charge assignment favored $-1/3$. With the discovery of the τ lepton in 1975 [10, 11], the quark content within the Υ resonance was assigned as the bottom quark.

The $\Upsilon(4S)$ sits right above the mass threshold of the two lightest B mesons: $\bar{B}^0(b\bar{d})$ and $B^-(b\bar{u})$. In addition to $\Upsilon(4S)$, there are other $b\bar{b}$ resonances (bottomonion) from e^+e^- collisions at lower energy regions: $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. In Figure 1.2 we can see the cross section of the different $\Upsilon(1S)$ to $\Upsilon(4S)$ states.

$\Upsilon(4S)$ has a broader resonance compared with other lower Υ resonant states. This is the sign of B meson production that is not existent from $\Upsilon(1S)$ to $\Upsilon(3S)$. B mesons are produced in pairs in $\Upsilon(4S)$ decay. The mass spectrum of B meson can be seen at Figure 1.3.

Besides B_d^0 and B_u^+ mesons, b quark can combine with a heavier anti-quark (or vice versa) to form other kinds of B meson. $\bar{B}_s$ meson, a b$\bar{s}$ quark-anti-quark pair, has been discovered at a higher energy experiment at LEP [4]. Up to now, B_c meson, a $b\bar{c}$ quark pair, has not yet been seen. The following discussion will focus on $\bar{B}^0$ and B^- produced at the CLEO experiment.

In CLEO, B meson pairs are produced at the $\Upsilon(4S)$ resonance from the collision of e^+e^- at center-of-mass energy 10.58 GeV/c.

$$e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(4S) \rightarrow \bar{B}^0 B^0, B^- B^+$$

Under the $\Upsilon(4S)$ energy region, there are other processes in addition to the B meson production. It can also decay into other lighter quark-antiquark pair:

$$e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}, s\bar{s}, d\bar{d}, u\bar{u}$$

The above production is referred as *continuum*. CLEO runs the experiment approximately 2/3 of its time atop the $\Upsilon(4S)$ energy region (*On* resonance) and 1/3 of its time at an energy about 60 MeV below the resonance (*Off* resonance) to simulate the *continuum* production.

B mesons can decay through the weak interaction of the b quark: $b \rightarrow cW^-$ or a more suppressed $b \rightarrow uW^-$ channel. We will discuss some of these findings in the next chapter.

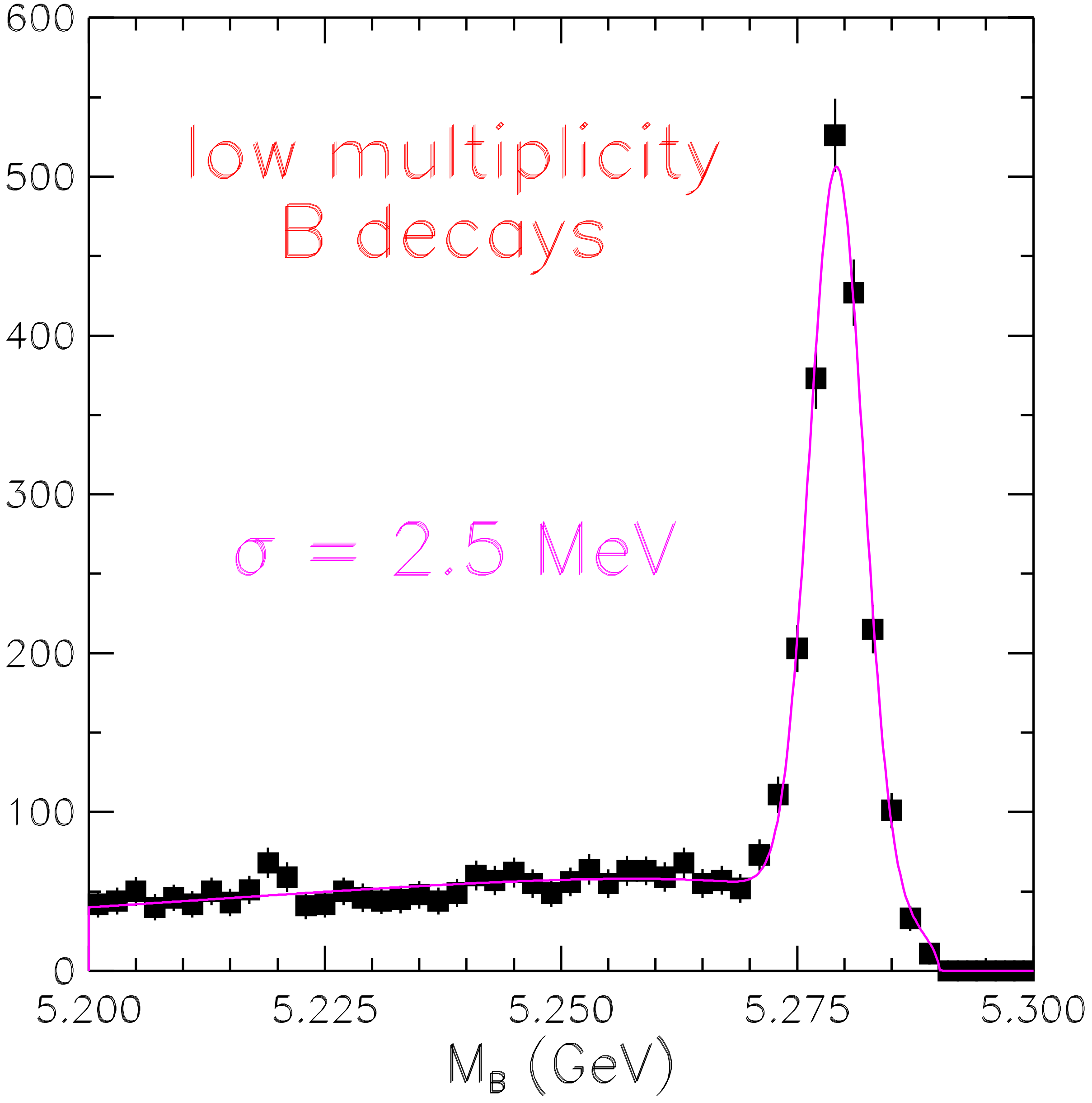

Figure 1.3: The B meson mass spectrum