UNIVERSITY OF CAMBRIDGE

PHD THESIS

This is the very exciting title of my thesis something to do with $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime.

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supervised by
Dr Marc Olivier Bettler
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Something about the date

Declaration

Here I shall say the appropriate lines that are needed to say that this thesis is actually mine.

Hannah Evans
May 2016

Abstract

Here is the abstract for my PhD

Acknowledgements

Here are all the people I would like to thank, it may be a longish list

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Introduction

Here I shall eloquently introduce what CERN, the LHC and LHCb are and outline what I an presenting in this thesis.

Chapter 1

CERN, the LHC and LHCb

The European Organisation for Nuclear Research (CERN) was founded in 1954 and began with 12 member states as a organisation to encourage European collaboration and the study of nuclear physics. Since it's foundation the collaborative nature of CERN allowed for large-scale expensive experiments and machines to be built. The Proton Synchrotron was CERN's flagship accelerator, operational in 1959 it had a circumference of 628m and accelerated protons to XXX GeV the highest energy at that time. Now 62 years since it's foundation CERN has grown to include 21 member states [1] and it's latest accelerator, the Large Hadron Collider (LHC), is most energetic particle accelerator ever built, with a 27km circumference the LHC was designed to protons at 14 TeV. This chapter shall discuss the LHC and the LHC beauty experiment, one of the experiments that uses collisions provided by the LHC.

1.1 The LHC

Introduction of what the LHC is and what it was designed to do > The Large Hadron Collider was conveived in 1980 with the purpose to test the SM, look for the Higgs and the capabilities to allow for probbing beyond the SM > it was built in the LEP tunnel for cost reasons - therefore 27km long > It is a synchrotron > It accelerates and collides protons and also lead ions > Two main things to consider for a accelerator are the lumi and energy, explain what lumi is > The LHC was degined to run at an energy of 14 TeV and $10^34cm-2s-1lumiand25nsbuncheswXXXprotonsperbunch$

> the are 4 interaction points where where the LHC makes it's beams collides and the results of these collisions are studied

[1] about the other types of countries involved.

How does the LHC work, acheive it's objectives > The LHC gets its protons from a chain of other accelerators > The PS and SPS have been modified several times over the years to provide for larger accelerators > The linac 2 was designed just to get stuff for other experiments > The LHC accelerates it's protons with RF cavities, bends with dipole magnets and focus with quadrapole magnets > There are 2 beams that rotate in oposite directions > in order to get the 14TeV 8T magnets had to be used - this limits the lead energy to 2.76 TeV > collisions occur

OR

> LHC is a synchrotron to look at SM, Higgs and BSM > is was built in the LEP tunnel > The LHC was designed to collide hadrons - protons at 14TeV with 4 interaction points with lumi of $10^34cm-2s-1 > lumiisXXXXandisacheivedbythenumberofprotonsinthebunchesandtimebetweenthebunch$ $ThisishowisworksRFaccelerate, dipolesbend(havetobe8.3Tfor27kmand14TeV)quadrapolesfocusforthein$ $Butwheredoesitgettheprotonsfrom, Linac2, PSB, PS, SPS > althoughthereisspaceintheLHCforXbunches -$ $therecanonlybeYduetotheacceleratorchain > ItcanalsocollideleadionsbutI'mnotinterestedinthis(soit'snotco$

What has happened at the LHC so far > It ran from 2010 - 2013 had LS2 then started up again in 2015 at a higher energy > What I am interested in for this thesis

What looks at the collisions > ATLAS - A Totally Ludicrous AparatuS > CMS - Crap Muon Solenoid, sorry what solenoid > TOTEM - TOTally umEMportant > LHCf - LHC forgotten > MoEDAL - > ALICE - > LHCb - where the b is clearly for best!

Then power on to LHCb

Start > Introduces LHCb briefly > explain what the coordinated I shall use are > mention LS2 and Run 2 and stuff

Tracking

PID

Trigger

Stripping

Runs for LHCb

1.2 The LHC Machine

The Large Hadron Collider (LHC) [**?**] is a two beams collider predominately designed to collide protons at an energy of 14 TeV but the accelerator can also study collisions of heavy ions. It has been built on the Franco-Swiss border in the tunnel previously used for the LEP machine at CERN[2] with the aim of studying predictions of the Standard Model of particle physics and looking for New Physics beyond the Standard Model. The LHC is the last element of an accelerator complex shown in Fig. 1.1: accelerators previously used at CERN have

[2]CERN is the European Organisation for Nuclear Research.

been modified in order to supply the LHC with high density proton bunches. Protons are first accelerated in the Linac 2 to an energy of 50MeV, the then pass through the Proton Synchrotron Booster, Proton Synchrotron and the Super Proton Synchrotron reaching and energy of 450 GeV before injection into the LHC where they are accelerated up to final energy.

The LHC began taking data in December 2009, most of the data has been acquired during the runs in 2011 and 2012 at center of mass energies of 7 TeV and 8 TeV, respectively, with 50 ns between proton bunches. It is currently in downtime undergoing upgrades and shall resume operation 2015 colliding proton bunches with a spacing of 25 ns at a center of mass energy of 13 TeV.

1.3 The Experiments

There are four detectors at the LHC, ATLAS, CMS, ALICE and LHCb, placed where the two beams cross over. The ATLAS [**?**] and CMS [**?**] detectors are general purpose detectors with 4π angular acceptance and have been designed to perform general searches for New Physics and the Higgs boson.[3] The ALICE [**?**] detector is specialised to study heavy ion collisions in order to investigate strongly interacting matter and quark-gluon plasmas. The LHCb [**?**] detector is a single-arm spectrometer designed for the study of B-hadron decays.

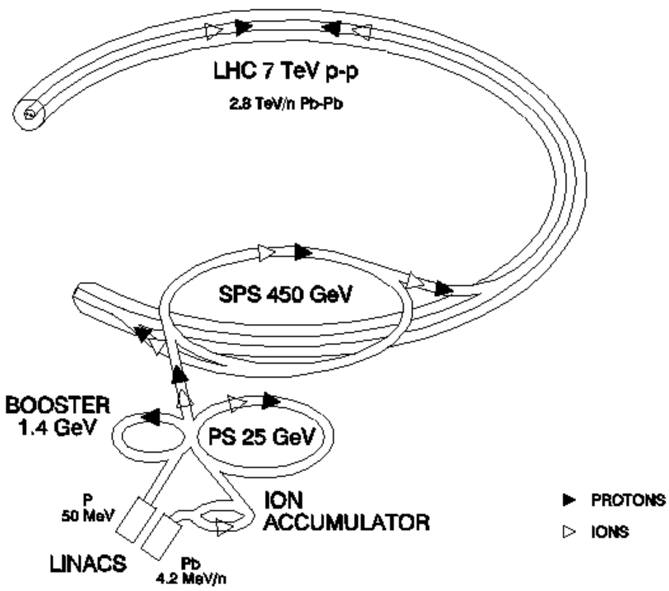

Fig. 1.1 The LHC and adjoining accelerator chain at CERN [**?**]

[3] ATLAS and CMS both discovered a possible candidate for the Standard Model Higgs in 2013 [**? ?**].

1.4 The LHCb Experiment

The LHCb detector is designed specifically to study *CP* violation and rare decays of *b*-hadrons and *c*-hadrons building on work done a the B factories and the Tevatron. At the high energies the LHC operates at $b\bar{b}$ pairs are produced together at low polar angles in either the forwards or backwards cone along the beam direction. The detector is designed as a single-arm spectrometer to take advantage of this behaviour.

A cross-section of the detector layout is shown in Fig. 1.2.

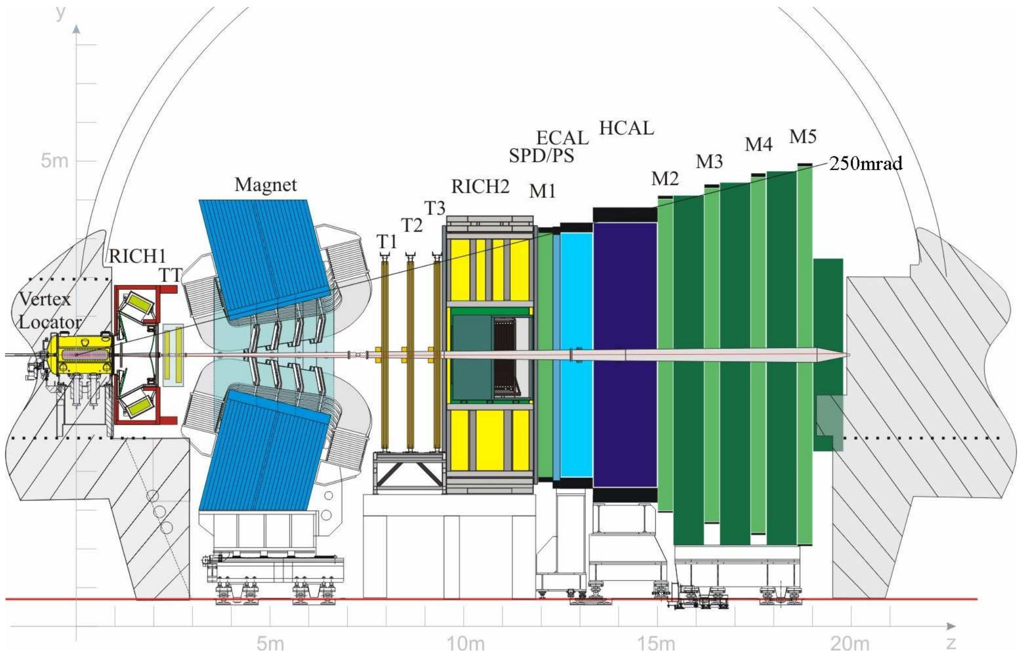

Fig. 1.2 Cross-section of the LHCb detector the the z-axis is along the beam pipe and the y-axis is the vertical direction [**?**].

The LHCb detector is composed of sub-detectors with different design purposes. The vertex locator (VELO) and the tracking stations (TT, T1, T2 and T3) are key for tracking charged particles travelling through the detector. The RICH detectors, calorimeters (ECAL, HCAL, PS and SPD) and the muon stations (M1-5) are necessary for particle identification. The dipole magnet in the detector is used alongside the tracking stations in order to measure particle charge and momentum.

The VELO is the tracking detector closest to the interaction point. It is designed to locate primary and secondary decay vertices. Secondary vertices occur within the VELO due to the short lifetime of *b*-hadrons, whereas primary vertices do not occur in the VELO but tracks in the VELO are extrapolated backwards to determine the vertex location. The VELO is a silicon micro-strip detector which give good resolution of tracks and decay vertices.

The T1-3 tracking station consist of the Inner Tracker (IT) and the Outer Tracker (OT). The IT is a silicon micro-strip detector and makes up the inner sections of the stations closest to the beam pipe. The OT is a straw-tube drift-chamber and covers the outer sections of the T1-3 stations. Silicon micro-strip detectors are needed in the IT due to high particle occupancy however the particle flux is lower at large polar angles from the beam pipe allowing straw tubes to be used in the OT as the occupancy is lower. The Tracker Turicensis (TT) is also a silicon micro-strip detector upstream of IT and OT, it spans the full acceptance of the LHCb detector. The TT, IT and OT work together with the dipole magnet to measure charge and momentum of particles travelling through the detector. Obtaining good momentum resolution is vital because the momentum resolution directly affect the invariant mass resolution of reconstructed particles.

Distinguishing between e, μ, p, K, π and photons is important for accurately reconstructing particle decays. Each sub-detector related to particle identification is specialised for different particles. The sub-detectors for particle identification are the two RICH detectors, the Preshower detector (PS), Scintillating Pad Detector (SPD), the electromagnetic calorimeter (ECAL), the hadronic calorimeter (HCAL) and the muon tracking stations (M1-5).

The particle identification detectors closest to the interaction point are the RICH 1 and RICH 2. These detectors are ring imaging Čerenkov detectors, designed to separate charged pions and kaons which are produced in large number from b-hadron decays. In LHCb, high momentum particles are produced at small polar angles and lower momentum particles at larger polar angles, therefore two RICH detectors are needed to cover the full momentum and acceptance range. The RICH 1 is composed of an areogel and C_4F_{10} gas radiator, it is sensitive to particles with momentum between 1 and 60 GeV/c. The RICH 2 is a CF_4 gas radiator and is sensitive to particles with momentum between 15 and 100 GeV/c.

The SPD distinguishes charged and neutral particles such as photons and electrons which leave the same signals in the ECAL. The PS detector distinguishes electrons and charged pions by utilising their different interaction lengths in matter.

Downstream of the SPD and the PS is the ECAL, a lead-scintillator sampling detector. Electrons and photons interact within the lead producing electromagnetic showers, the scintillator absorbs photons produced by the showers and emits photons at different wavelengths so that photomultiplier tubes detect them. The energy of an incident particle is measured from the energy of the shower which is proportional to the light produced in the shower. Showers produced by photons can be distinguished from those produced by electrons because photons leave no hits in the tracking detectors or the SPD. Hadrons will pass though the ECAL to be detected by the HCAL. The HCAL is composed of lead and scintillator tiles and measure the energy hadronic showers produced inside it. The HCAL works in the same way as the

ECAL however the lead absorber is more suited to producing hadronic showers rather than electromagnetic ones.

Muon identification is key for the analysis of several important CP violating decays and rare decays, including $B_s \to \mu^+\mu^-$. The ECAL and the HCAL absorb most particles produced in collisions. However, the high penetration power of muons allows then to pass through the ECAL and HCAL therefore the muon stations can be the in furthest part of the detector. The muon stations are multi-wire proportional chambers except the inner part of the M1 station which is a gas electron multiplier due to the high particle occupancy.

Muon identification is not only important for offline analysis but, together with information from the ECAL and HCAL, the muon system triggers events which are saved for offline analysis. The LHCb has been designed to operate at a lower instantaneous luminosity than the running of the LHC, the trigger takes the 10 MHz of data visible in the LHCb and reduces it to 5 kHz which can be stored offline. There are two levels to the trigger the Level 0 (L0) and the High Level Trigger (HLT). The L0 operates at the same time as the bunch crossings and reduced the rate to 1 MHz by using transverse momentum information from the ECAL, HCAL and the muon stations. The HLT further reduces the rate to 5 kHz, running asynchronously with the bunch crossings on a processor farm. The HLT takes events that have been triggered by the L0 and confirms them by reconstructing the events more fully using information from the VELO and other tracking stations. Once the data has been stored there are further offline selections which aim to further reduce the background and enhance the signal for particular decays. The trigger is optimised so when it is combined with the offline selection it can give the best signal and best background rejection. Since the LHCb studies many different decays there are various different triggers that are used for different analyses.

Chapter 2

Theory

Here I shall explain some theory stuff The weak decays $B^0_{(s)} \to \mu^+\mu^-$ occur via flavour changing neutral currents (FCNC) in the Standard Model and are highly suppressed.

$B^0_s \to \mu^+\mu^-$ was outlined as one of six important studies to be done at the LHCb [**?**] due to the sensitivity of the branching fraction to contributions from new physics models. Previously these rare decays have been studied at B factories and the Tevatron, and the current measurements for the branching fractions from the LHCb are $\mathscr{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$ at 4.0 σ significance and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL.

In this section I shall introduce the Standard Model (Section 4.1) and outline how $B^0_{(s)} \to \mu^+\mu^-$ occurs within the Standard Model (Section 4.2). The calculation of the branching fractions for the decays is explained (Section 4.3) and finally, the current status for the search and measurements of $B^0_{(s)} \to \mu^+\mu^-$ reviewed and future aims at the LHCb (Section 4.5).

2.1 The Standard Model

The Standard Model (SM) is a quantum field theory which describes matter and its interactions at a fundamental level. In the SM there are 12 fundamental spin-$\frac{1}{2}$ fermions; six quarks and six leptons. The six quarks form three families; up and down, strange and charm, top and bottom. Quarks have both electric and colour charge and combine into composite particles either as a quark anti-quark pair to make a meson or as three quarks to make a baryon.[1] Similarly leptons form three families each containing a charged and a neutral particle: e^- and ν_e, μ^- and ν_μ, τ^- and ν_τ, however leptons have no colour charge.

[1] The Z(4430) is neither a meson or a baryon, it was first observed at Belle [**?**] and recently confirmed at the LHCb [**?**] with a high statistical significance. It is composed of four quarks and is the the first exotic particle to be observed at a high statistical significance.

Quarks and leptons interact through the strong force, weak force and electromagnetic force. The strong force is described by a symmetry group of $SU(3)_C$ colour charge, quarks are the only coloured particles therefore the strong force acts only between quarks and anti-quarks. The strong force is mediated by 8 massless coloured gluons and its strength increases as distance between quarks increases.

The electromagnetic force describes interactions between electrically charged particles. The gauge boson mediating the electromagnetic force is the photon, since the photon is massless the force has in infinite range. The weak force allows interactions between all fermions in the SM, it allows flavour changing to occur between quarks or between charged leptons and their associated neutrinos. These interactions are mediated by massive gauge bosons; the $W^{\pm}$ and the Z^0. The weak and electromagnetic forces can be unified into a $SU(2) \otimes U(1)$ symmetry group. However is a broken symmetry because the gauge bosons have different masses for the two interactions. The Higgs mechanism accounts for this symmetry breaking, interactions of the electroweak bosons with the Higgs field causes symmetry breaking creating the massive $W^{\pm}$ and Z^0 and the massless photon.

The SM has evolved over time into what it is today, with discoveries prompting new theories and theoretical predictions motivation experimental searches. All fermions and bosons predicted in the SM have been discovered, the latest of these being the Higgs boson for which the ATLAS and CMS experiments discovered a possible candidate in 2013 [**? ?**]. However there are several shortcomings of the SM and observed phenomena that it does not explain, a few examples are outlined below;

- matter anti-matter asymmetry - as the universe was created matter and anti-matter would have been created in equal amounts, however the universe today is matter dominated. One process that can cause this asymmetry is *CP* violation, this effect enters the SM via the CKM matrix, however the effect is too small to account for the observed imbalance.

- neutrinos have been observed to oscillate [**? ? ?**], in order for neutrinos to oscillate they must be massive particles but in the SM neutrinos are massless. However the SM can be adapted to include massive neutrinos without any fundamental changes.

- gravity is not explained by the SM

- astronomical observations have revealed that the rotational speed of galaxies does not match up with the speed expect from the amount of matter visible in the universe [**? ? ?**]. If General Relativity is correct then there must be invisible matter which interacts via gravity to produce the extra mass. There is no candidate to explain this dark matter in the SM.

Therefore despite the successes of the SM there must be New Physics beyond the SM that will explain its shortcomings.

2.1.1 $B^0_{(s)} \to \mu^+\mu^-$ in the Standard Model

$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ occur by flavour changing neutral currents (FCNC), they are highly suppressed decays in which quark flavour but not quark charge change. Flavour changes in quarks are allowed in the SM via the CKM matrix. The CKM matrix relates mass and flavour quark eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

where the amplitude for an up quark to change flavour to a bottom quark is proportional to the CKM matrix element $|V_{ub}|^2$. The numerical magnitudes of the CKM matrix elements are given in Eq. (2.1) [**?**], it is clear that some flavour changes are probably than other, e.g. a bottom quark will change into a top quark with a much greater amplitude than to any other quark.

$$V_{CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{0.00031} & 0.0404^{+0.0011}_{0.0005} & 0.999146^{+0.000021}_{0.000046} \end{pmatrix} \tag{2.1}$$

All interactions in the CKM matrix are mediated by $W^{\pm}$, and are flavour and charge changing. The decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ do not change charge and therefore cannot occur at tree level. A $\mu^+\mu^-$ pair can be produced from a Z^0, γ or H^0 which the constituent quarks of the B^0 and B^0_s cannot create. Therefore these decays occur via loop diagram such as Z^0 penguins or box diagrams. Figure 2.1 shows the dominant Feynman diagrams for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$. The intermediate quark in the loop diagrams is the top quark, contributions from other quarks are negligible due to very small coupling to the b quark in the CKM matrix.

The decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are not only suppressed because they are FCNC events they are also suppressed by a factor of

$$\left(\frac{m_\mu}{m_{B^0_{(s)}}} \right)^2$$

due to helicity. The B hadron has zero spin therefore requiring the muons to have the same helicity.

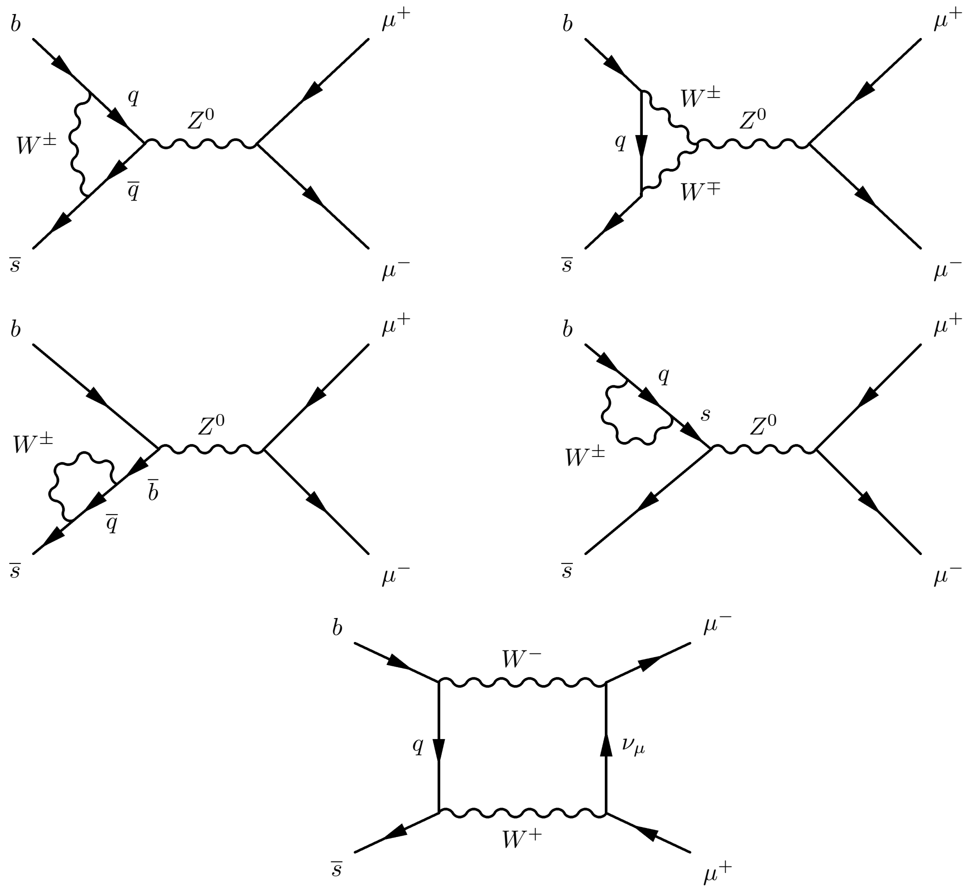

Fig. 2.1 Feynman diagrams dominant in the SM for $B_s^0 \to \mu^+\mu^-$ [**?**].

2.2 Branching Fraction of $B^0_{(s)} \to \mu^+\mu^-$

Weak decays such as $B^0_{(s)} \to \mu^+\mu^-$, can be described using a quantum field theory technique known at the Operator Product Expansion (OPE) [**?** **?**] to produce an effective Hamiltonian. The effective Hamiltonian divides the process into interactions on different distance scales and has the following form [**?**]

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} \mathscr{C}(\mu)_i \mathscr{Q}(\mu)_i$$

where G_F is the Fermi constant, $\mathscr{C}(\mu)_i$ are Wilson coefficients and $\mathscr{Q}(\mu)_i$ are local operators. The energy scale μ separates the interaction into two distance scales. Wilson coefficients describe short scale processes, for energies greater than μ, they incorporate contributions from internal loops and subsequently depend on $W^\pm$, Z^0, H^0 and top quark masses. Perturbation theory can be used to calculate Wilson coefficients due to asymptotic freedom in QCD. The local operators $\mathscr{Q}_i$ describe long distance processes at energies smaller than μ, they link initial and final decay states. These operators cannot be computed using perturbation theory and therefore have the greatest theoretical uncertainty in the in the Hamiltonian in many weak hadron decays. The final Hamiltonian must be independent of μ because it is given an arbitrary size, often chosen as the mass of the decaying particle.

The effective Hamiltonian is a useful formalism for studying effects of new physics on weak decay because new physics contributions can enter the Hamiltonian though Wilson coefficients.

For the decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ the effective Hamiltonian can be written as in [**?**]

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{tq} \left[\sum_{i=1}^{10} \mathscr{C}_i \mathscr{Q}_i + \mathscr{C}_P \mathscr{Q}_P + \mathscr{C}_S \mathscr{Q}_S + \mathscr{C}'_P \mathscr{Q}'_P + \mathscr{C}'_S \mathscr{Q}'_S \right] \tag{2.2}$$

where q corresponds to the other composite quark of B-hadron depending on whether is it B^0 or B^0_s being considered in the Hamiltonian. The terms proportional to $V_{tb}V^*_{uq}$ and $V_{cb}V^*_{cq}$ are omitted from H_{eff} because their contribution is negligible compared to the CKM couplings to the top quark.

The only operators that have non-zero contributions in the decay amplitude for $B^0_{(s)} \to \mu^+\mu^-$ are

$$\mathscr{Q}_{10} = \frac{e^2}{16\pi^2} (\bar{q}\gamma^\mu P_L b)(\bar{l}\gamma_\mu\gamma_5 l) \tag{2.3}$$

$$\mathscr{Q}_S = \frac{e^2}{16\pi^2} m_b (\bar{q} P_R b)(\bar{l}l) \tag{2.4}$$

$$\mathscr{Q}_P = \frac{e^2}{16\pi^2} m_b (\bar{q} P_R b)(\bar{l}\gamma_5 l) \tag{2.5}$$

$$\mathscr{Q}'_S = \frac{e^2}{16\pi^2} m_q (\bar{q} P_L b)(\bar{l} l) \tag{2.6}$$

$$\mathscr{Q}'_P = \frac{e^2}{16\pi^2} m_q (\bar{q} P_L b)(\bar{l}\gamma_5 l) \tag{2.7}$$

all other operators in equation (2.2) are zero due to the leptonic final states in $B^0_{(s)} \to \mu^+\mu^-$.

The dominant contribution in the SM Hamiltonian come from $\mathscr{C}_{10}$ which contains the contributions from Z^0 penguins and W-box diagrams. Contributions from $\mathscr{C}_{\mathscr{S}}$ and $\mathscr{C}_{\mathscr{P}}$, corresponding to Higgs-penguins, are negligible in the SM and can be ignored. However these contributions can be substantially increased by new physics processes. The branching fraction can therefore be written as [**?**]

$$\mathscr{B}(B_{(s)} \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{16\pi^3 \sin^4(\theta_W)} |V_{tb}V^*_{tq}|^2 \tau_{B_{(s)}0} m_{B_{(s)}0} f^2_{B_{(s)}0} m^2_\mu \sqrt{1 - \frac{4m^2_\mu}{m^2_{B_{(s)}0}}} \mathscr{C}^2_{10}$$

where $f_{B_{(s)}0}$ is the B-hadron decay factor, $\tau_{B_{(s)}0}$ it's lifetime and $m_{B_{(s)}0}$ it's mass. The SM predictions for the branching fractions are [**?**]

$$\mathscr{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\mathscr{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

The branching fraction for $B^0 \to \mu^+\mu^-$ is smaller than $B^0_s \to \mu^+\mu^-$ due to the CKM matrix contributions $\frac{|V_{tb}V^*_{td}|^2}{|V_{tb}V^*_{ts}|^2} \sim 0.044$ and larger helicity suppression, therefore although B^0 are produced in greater numbers at the LHC far fewer are observed. This has made the study of $B^0_s \to \mu^+\mu^-$ a greater priority at the LHCb.

References