THE PHYSICS PERFORMANCE OF AND LEVEL 2 TRIGGER FOR THE INNER DETECTOR OF ATLAS

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PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. F.A. van Vught,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op donderdag 29 oktober 1998 te 13:15 uur.

door

Reinier Josephus Dankers

geboren op 24 september 1970
te Tilburg

Dit proefschrift is goedgekeurd door:

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1.1 Particle physics experiments

Particle physics is the scientific discipline studying the fundamental particles that are the building blocks of all matter, their properties and their interactions. Particle physics is also referred to as **H**igh **E**nergy **P**hysics (**HEP**).

Nowadays particle physics experiments are mostly collider experiments. In a collider experiment two charged particle beams are accelerated (for example proton-proton) and brought into collision in a well-defined region. The beams are accelerated with electromagnetic waves in a linear or circular machine. In a circular accelerator the beams are contained on a circular orbit. The main advantages of a circular accelerator compared to a linear accelerator are that the beams can be stored for relatively long periods and that the beams and accelerating elements can be reused because the beams pass the same elements many times. The disadvantage of a circular accelerator is that bending magnets are needed, and that the bending introduces radiation losses (synchrotron radiation).

In the case of an inelastic collision new particles are created. The centre-of-mass energy and the type of the particles brought into collision determine which particles can be created. In general the produced particles are unstable and may decay rapidly into other particles.

Around the interaction point a set-up of dedicated detectors is placed. The task of these detectors is to identify the particles produced in the collision point or their decay products and to measure properties of these particles (energy/momentum and direction of flight).

The total momentum perpendicular to the beam pipe of the incoming beam (total transverse momentum) is zero[1]. The total transverse momentum of the detected particles will in general not add up to zero, a part seems to have disappeared. Neutral particles with very low interaction cross-sections that can not be detected, particles that are not detected due to detector inefficiencies and particles that are not detected due to the fact that the detector is not 100% hermetic carry the missing part.

From the measured properties of the detected particles and the missing transverse momentum, information about the underlying collision process is obtained.

1.2 The standard model of particle physics

1.2.1 Fundamental particles in the standard model

The **S**tandard **M**odel of particle physics (**SM**) is based on the results of many years of particle physics experiments and theoretical developments.

According to the standard model, three types of fundamental particles can be distinguished: **quarks**, **leptons** and **force carrying bosons**. The quarks and leptons are **fermions**, spin ½ particles that follow Fermi-Dirac statistics. They can be grouped intro three families of increasing mass scale. Each family consists of four particles, two leptons and two quarks. Also the antiparticles of these particles exist, with the same mass but opposite quantum numbers.

The known elementary leptons are given in table 1.1, together with the non-zero lepton numbers. The only existing stable leptons in nature are the electron and the neutrinos. The muon is a relatively long living particle and can be detected directly in particle physics experiments.

The known elementary quarks are given in table 1.2. All quarks have baryon number 1/3. The additional non-zero quantum numbers describing the quark **flavour** are also given in table 1.2. The quantum number I_z is called isospin [1]. Each quark has an additional quantum number called **colour**. Three values for the colour are possible.

The leptons can occur freely in space. The quarks occur only in a bound state (all naturally occurring particles are colourless[2]). Bound states exist of three quarks (**baryons**, *qqq*), of three antiquarks (**antibaryons**, $\bar{q}\bar{q}\bar{q}$) and of a quark with an antiquark (**mesons**, $q\bar{q}$). The bound states of quarks are also referred to as **hadrons**. The only existing stable baryon is the proton (*uud*). The neutron (*udd*) is only stable when bound in a nucleus. The mesons are always unstable. The π and K mesons are relatively long living and can be detected directly in particle physics experiments.

[1] In LHC experiments (section 1.3) also the total momentum sum longitudinal to the beam pipe of the two beams is zero.

[2] Colourless means that either the total amount of each colour is zero or all the colours are present in equal amounts.

Table 1.1 *The leptons (spin ½). The antiparticle of the electron is called positron.*

	lepton	name	charge	mass [MeV] [3]	lepton number
first generation	e	electron	-1	0.511	$L_e = 1$
	ν_e	electron neutrino	0	~0	$L_e = 1$
second generation	μ	muon	-1	105.658	$L_\mu = 1$
	ν_μ	muon neutrino	0	< 0.17	$L_\mu = 1$
third generation	τ	tau	-1	1777	$L_\tau = 1$
	ν_τ	tau neutrino	0	< 24	$L_\tau = 1$

Table 1.2 *The quarks (spin ½). The masses of the quarks are not very well defined. The given masses are the so-called "current quark masses" [2], which are relevant for kinematics in hard processes.*

	flavour	name	charge	mass [GeV]	additional non zero quantum numbers
first generation	d	down	-1/3	0.005 – 0.015	$I_z = -½$
	u	up	+2/3	0.002 – 0.008	$I_z = ½$
second generation	s	strange	-1/3	0.1 – 0.3	$S = -1$
	c	charm	+2/3	1.0 – 1.6	$C = 1$
third generation	b	bottom	-1/3	4.1 – 4.5	$B = -1$
	t	top	+2/3	180 ± 12	$T = 1$

The force carrying bosons are spin 1 particles that follow Bose-Einstein statistics. Each of the three forces playing a role in particle physics has it own bosons (table 1.3).

Table 1.3 *The force carrying bosons (spin 1).*

boson	charge	mass [GeV]	force
8 gluons[4] (g)	0	0	strong
$W^\pm$	±1	80.33	weak
Z^0	0	91.19	weak
photon (γ)[5]	0	0	electromagnetic

1.2.2 Interactions in the standard model

The electromagnetic force couples to electric charge and is mediated by the photon. All charged particles are subject to the electromagnetic force. The strong force couples to colour and is mediated by the eight gluons. All coloured particles (quarks and gluons) are subject to the strong force. Due to the strong force, a "sea" of gluons and short living quark-antiquark pairs surround the valence quarks in the bound state of a hadron. The W^+, W^- and Z^0 bosons (**massive vector bosons**) carry the weak force. All leptons and quarks are subject to the weak force.

[3] Throughout this thesis, natural units are used: $\hbar = c = 1$.
[4] The gluons carry colour and do not exist as isolated particles.
[5] The photon plays a somewhat special role because it also exists abundantly as a free particle in nature.

In all interactions the electric charge, colour, baryon number and the lepton number are conserved. The quark flavour is a conserved quantity in the strong and electromagnetic interaction but not in the weak interaction.

In the **G**rand **U**nification **T**heory (**GUT**) it is assumed that the strong, weak and electromagnetic interactions unify at a very high energy scale M_x $O(10^{15}$ GeV). If also the gravitational force (produced by mass) is included in grand unification also this force should be carried by a hypothetical particle of spin 2, the graviton. Until now however the graviton has not been observed.

1.2.3 The Higgs boson

In the standard model at least one extra spin 0 boson (the Higgs boson H^0) is predicted. This Higgs boson is necessary to explain why the massive vector bosons have a mass. Also the cross-sections of simple processes like $W^+ + W^- \rightarrow W^+ + W^-$ theoretically diverge beyond an energy scale of 1 TeV without Higgs boson. This means that at a centre-of-mass energy of the two bosons larger than 1 TeV, the probability that two interacting *W*'s produce two *W*'s is larger than unity. The extra contributions from the Higgs boson can cancel the divergences (figure 1.1).

Until now the Higgs boson has not been detected experimentally. One possible reason is that the Higgs boson may be too heavy to be created with current colliders. If it exists it should however be accessible with the LHC, described in section 1.3.

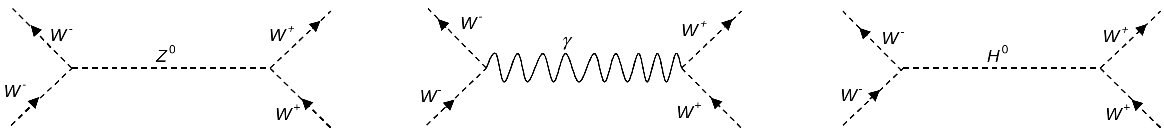

Figure 1.1 *Three possible processes contributing to W^+W^- scattering. In the given diagrams time always flows upward.*

1.2.4 The parameters of the standard model

In the standard model, nineteen parameters are necessary to describe all masses and couplings [3]. Seventeen of these parameters have been determined with varying errors [2]. These are three coupling constants, three leptons and six quarks masses[6], the mass of the Z^0 boson and four parameters describing the mixing between the quark flavour in the weak interaction (Cabbibo-Kobayashi-Maskawa mixing matrix). Of the remaining two parameters, one must be very small. This is a ***CP*-violation**[7] parameter associated with the weak interaction [3]. The other one is the mass of the Higgs boson.

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[6] All neutrinos are massless in the standard model.

[7] *CP*-violation is a violation of the invariance under particle-antiparticle interchange (*C*) and space inversion (*P*). This is equivalent to a violation of time reversal (*T*) invariance, if the *CPT*-theorem is valid. *C*-invariance means that an experiment in a world of antimatter will give identical results as in our world. *P*-invariance in a three-dimensional world means that the mirror image of an experiment yields the same result as the original experiment. *T*-invariance means that the process going backwards in time has exactly the same probability as the original process.

1.3 The LHC Project

1.3.1 Introduction

At CERN a new circular proton-proton collider of 14 TeV centre-of-mass energy, the **LHC** (**L**arge **H**adron **C**ollider) will be built, and should be operational in 2005. LHC will be built in the existing LEP[8] tunnel of 27 km circumference. LHC will have two high luminosity (see below) collision points, and at least two low luminosity collision points. The LHC beams are not continuous but consist of packets of accelerated protons (bunches). The time interval between two LHC bunch-crossings is 25 ns. The length of a bunch is 7.5 cm. The length of the interaction region along the beam axis can be described by a Gaussian distribution with a standard deviation value of 5.6 cm.

The **luminosity** is an important quantity describing the performance of a collider. In the case of a head-on collision, the luminosity is directly proportional to the number of particles in each bunch-crossing (N_1 and N_2) and to the bunch-crossing frequency (f). It is inversely proportional to the overlap area of the bunches at the collision point (A):

$$L[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = \frac{N_1 N_2 f[\mathrm{s}^{-1}]}{A[\mathrm{cm}^2]} \tag{1.1}$$

The number of events collected over a given period of time can be calculated from the production cross-section and the luminosity. For a process with a cross-section σ, the event rate is given by σL, and the number of events N collected over a given period of time t is given by:

$$N(t) = \sigma \int_0^t L(t')\mathrm{d}t' \tag{1.2}$$

LHC is supposed to reach a design luminosity $L_{design} = 10^{34}$ cm^{-2}s^{-1}. The first few years, LHC will run with a lower luminosity $L_{initial} = 10^{33}$ cm^{-2}s^{-1}.

The centre-of-mass energy and the luminosity at LHC will be much higher than the values at the currently most powerful hadron collider, the **TEVATRON** at Fermilab. The TEVATRON is a proton-antiproton collider with a maximum centre-of-mass energy of 1.8 TeV, a luminosity of 10^{31} cm^{-2}s^{-1}, a bunch-crossing interval of 3.5 μs and a bunch length of 50 cm [2]. In 2000 the TEVRATON will have been upgraded. The maximum luminosity will be 10^{32} cm^{-2}s^{-1} at a maximum centre-of-mass energy of 2 TeV.

In circular colliders like the TEVATRON and LHC, it is necessary to use protons (or anti-protons) as beam particles at the energies obtained. The production cross-sections of interesting physics channels are about the same for a proton-proton or proton-antiproton collider in the TeV range. Electrons can not be used anymore because they suffer too much from synchrotron radiation losses. The average energy loss through synchrotron radiation per revolution in a circular machine is proportional to the fourth power of the inverse mass m^{-4}, so this is much more serious for electrons than for protons.

For LHC one has chosen for a proton-proton instead of a proton-antiproton collider because only with two proton beams it is possible to reach the required luminosity. The drawback of this choice is that two separate beam pipes with separate accelerating and bending units are necessary. Only at the interaction points the two beam pipes are brought together.

[8] LEP is an electron-positron collider, currently in use at CERN.

1.3.2 Collisions at LHC

Centre-of-mass energy

Protons as beam particles have as drawback that they are, contrary to for example electrons, composite objects. A proton consists of three valence quarks (*uud*), plus a “sea” of gluons and quarks. When two protons are brought into collision at LHC energies, it is unknown which of the constituents actually collided and which were merely spectators of the event. The individual constituents carry also only an unknown fraction of the total proton energy. This means that the real centre-of-mass energy in quark-quark, quark-gluon or gluon-gluon collision is lower than the total proton centre-of-mass energy, complicating the analysis of proton-proton collisions.

The **parton distribution function** $\mathrm{f}_i^a(x, Q^2)$ parameterises the probability to find a parton i with a fraction x of the beam energy when the beam particle a undergoes a hard scattering at energy scale Q, with the energy scale defined as the square root of the four momentum transferred between the scattering particles (see also section 4.5.4). For the momentum-weighted combination $x\,\mathrm{f}_i^a(x, Q^2)$, the following normalisation condition is valid:

$$\sum_i \int_0^1 x\,\mathrm{f}_i^a(x, Q^2)\mathrm{d}x = 1 \tag{1.3}$$

From this equation it follows that all partons of the beam particle together carry the full beam energy.

LHC bunch structure

In general more than one collision will occur at an LHC bunch-crossing. Most of these collisions are soft hadronic collisions at low parton-parton centre-of-mass energy. At high luminosity ($L = 10^{34}$ cm^{-2}s^{-1}), about 25 soft collisions will accompany each interesting hard collision, taking into account that at LHC approximately 20% of the bunches will be empty [4]. This corresponds to a total cross-section of proton-proton collisions of about 100 mb [5]. These soft collisions are called **minimum bias events** because when an LHC experiment registers collisions without any requirement (bias) on the type of collision, mainly this type of events will be observed. Minimum bias events superimposed on an interesting event are also referred to as **pile-up**. A picture of the LHC bunch structure is given in figure 1.2.

The bunch structure in LHC is such that there will be many successive filled bunches followed by successive empty bunches. This means that an interesting event will usually follow and be followed by bunch-crossings causing pile-up events. Consequently there is the potential for collisions from previous and following bunch-crossings to be observed by the detector, depending on the response of the detector system. In particular, low-p_T charged tracks ($p_T < 500$ MeV) from bunch-crossings prior to the event of interest can spiral in the magnetic field of the detector system for extended periods of time (up to 100 ns [4]) and may be present during the event. Such tracks are referred to as **loopers**.

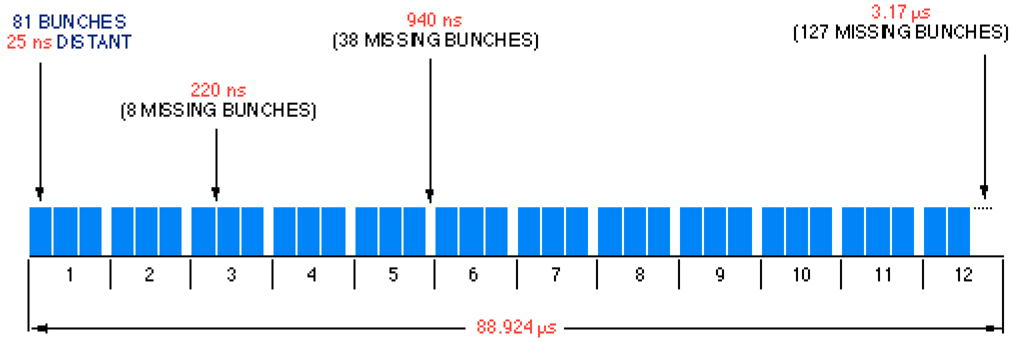

Figure 1.2 *LHC bunch structure.*

1.3.3 LHC co-ordinate system

LHC experiments use the following co-ordinate system: the beam axis is the z-axis. The vertical direction is y. The co-direction of x follows now from the right-handedness of the system (figure 1.3). Positions and directions can also be expressed in cylindrical (ϕ, r, z) co-ordinates or in (ϕ, η, r) co-ordinates, with the radius[9] $r = x \oplus y$, the angle in the (x, y) plane or **azimuth** $\phi = \text{atan}(y/x)$, and the **pseudorapidity** $\eta = \text{asinh}(z/r)$ (or equivalently $\eta = -\ln(\tan(\theta/2))$, with $\tan\theta = r/z$).

The advantage of the (ϕ, η, r) co-ordinate system is that in the final state of an inelastic proton-proton collision the particle density per unit of η and ϕ is on average constant.

The pseudorapidity η of a particle is a different quantity than the **rapidity** ($\text{atanh}(p_z/E)$, with p_z the momentum in z-direction and E the particle energy). For highly energetic particles the pseudorapidity is an approximation of the true rapidity. Only for massless particles the rapidity is equal to the pseudorapidity.

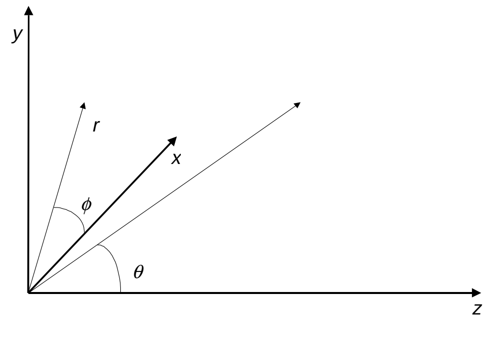

Figure 1.3 *Co-ordinate system in LHC experiments. The origin lies at the average position of the interactions. The direction along the beam is z, the vertical direction is y.*

1.3.4 Experiments at LHC

Four experiments are now planned at LHC. Studies in the context of **ATLAS** [6] (**A** **T**oroidal **L**HC **A**pparatu**S**), are the subject of this thesis and will be described in more detail in the following chapters. The other experiments are: **CMS** [7] (**C**ompact **M**uon **S**olenoid), **ALICE**

[9] Throughout this thesis the following meaning for the $\oplus$ symbol is used: $a \oplus b = \sqrt{a^2 + b^2}$

[8] (**A** **L**arge **I**on **C**ollider **E**xperiment) and **LHC-B** [9]. ATLAS and CMS are general-purpose high-luminosity experiments, studying several physics channels. ALICE is a dedicated heavy ion experiment, using heavy ions (Pb) instead of protons as beam particles. The low-luminosity LHC-B experiment is especially developed for bottom quark physics (B-physics) studies.

1.4 Physics studies at LHC

1.4.1 Introduction

The LHC opens up a new range of centre-of-mass energy. The most important physics study at LHC is the search for and measurement of the properties of the Higgs boson in the mass range from about 80 GeV until about 1 TeV. However apart from the creation of the Higgs boson, also other physics processes of interest can be investigated. The LHC also enables to study the bottom and top quark in great detail. Supersymmetry and other physics models extending the standard models can be tested on their validity.

The physics studies at LHC are shortly described in the following sections. Supersymmetry is described in more detail in chapter 4.

1.4.2 Higgs physics

At LHC the Higgs boson is predominantly produced via gluon-gluon fusion. Other contributing processes are $t\bar{t}$ fusion, *WW* and *ZZ* fusion, and production through *W* or *Z* bremsstrahlung (figure 1.4).

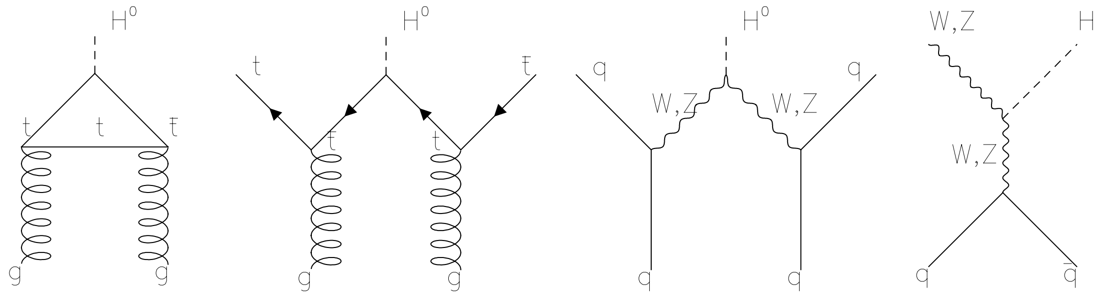

Figure 1.4 *The production of a Higgs boson through four channels: a) gluon-gluon fusion; b) $t\bar{t}$ fusion; c) WW and ZZ fusion; d) W, Z bremsstrahlung.*

The coupling strength of the Higgs particle to other particles depends strongly on the mass of these particles. For this reason the Higgs boson decays preferentially in a particle as heavy as possible. Therefore, the main decay channel depends on the mass of the Higgs boson.

Mass range 80 GeV – 130 GeV

A relatively light Higgs boson in the mass range 80-130 GeV decays for almost 100% in $b\bar{b}$ quarks. The expectation is that the Higgs boson can not be identified from this decay, due to the large background signal.

Background is coming from processes like $WZ \rightarrow l\nu_l b\bar{b}$, with l a charged lepton and ν_l the corresponding (anti)neutrino, and $W +$ jet-jet production, with the jets misidentified as b jets. The first background is **irreducible** because it produces a signal that is in essence indistinguishable from the signal of the Higgs decay. The second background mentioned is **reducible**, because it produces a signal in essence different from the signal of the Higgs decay. Due to experimental restrictions this signal can however be misidentified as a similar signal. For decreasing the reducible background, good particle identification is essential.

The higher order decay $H^0 \rightarrow \gamma\gamma$ is more suited for studying the Higgs boson, although the branching fraction is much smaller. Irreducible background channels are processes like $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$. Reducible backgrounds are processes like jet-jet and γ-jet events, with one or both jets misidentified as photons. Simulations show that several years of data taking at high luminosity are necessary to discover a Higgs boson of mass 80-130 GeV using the $H^0 \rightarrow \gamma\gamma$ channel only [6].

Mass range 130 GeV - 800 GeV

The decay $H^0 \rightarrow ZZ \rightarrow 4l$ gives a clear signature for a Higgs boson in the mass range from about 180 GeV to about 800 GeV ($m_H > 2\ m_Z$). This channel is called the **gold-plated decay**. In the mass range 130 GeV < m_H < 180 GeV ($m_H < 2\ m_Z$), one of the two Z bosons is virtual[10]. The expected signal cross-section is smaller in this case and the signal will be less clear.

The most important background processes are the $Z\gamma, ZZ^* \rightarrow llll$ continuum and the $t\bar{t} \rightarrow llll$ process. The continuous background, mainly produced by Z bosons that are created directly in the proton-proton collision, has a small cross-section, but it is irreducible, since it has the same final state as the signal. The $t\bar{t} \rightarrow llll$ process is the most important reducible background.

For the gold-plated decay channel a good identification of leptons is necessary, together with an accurate measurement of the four-vectors of the particles (so that the error on the measured invariant mass is small).

Mass range 800 GeV - 1 TeV

Above 800 GeV, it is difficult to find the Higgs boson through the gold-plated decay channel only, because the cross-section for Higgs production becomes very low. In this region the statistics can be increased by taking not only into account the Higgs decaying into four charged leptons, but also the decay $H^0 \rightarrow ZZ \rightarrow l^+l^-\nu\bar{\nu}$. This channel benefits from a six times higher rate, but the decay can not be completely reconstructed because of escaping neutrinos. Only the two leptons can be identified, the neutrinos leave nothing but a signal of missing transverse energy. At this very high value of the mass, low backgrounds are expected [6].

1.4.3 Top quark physics

Statistics severely limits the current top quark studies at the TEVATRON. This means that the mass of the top quark can not be determined very accurately. At the LHC, top quarks are produced thousands per day. The mass of the top quark can be measured to an accuracy of about 3%, limited by theoretical uncertainties rather than statistics. Also the decay channels can be studied in detail. The top quark physics studies at LHC are described in more detail in [10].

[10] A virtual particle (marked with ‘*’) is not on its mass shell.

1.4.4 Bottom quark physics

The bottom quarks will be produced at a high rate at LHC. The expected $b\bar{b}$ production cross-section of 500 mbarn leads to a production rate of almost 10^{12} $b\bar{b}$ events per year at low luminosity [9]. The bottom quarks are well suited for the search and measurement of *CP*-violation through the decays of the B mesons:

- $B_d^0 \rightarrow J/\Psi + K_S^0$ ($d\bar{b} \rightarrow c\bar{c} + d\bar{s}$)
- $B_d^0 \rightarrow \pi^+ + \pi^-$ ($d\bar{b} \rightarrow u\bar{d} + d\bar{u}$)
- $B_S^0 \rightarrow J/\Psi + \phi$ ($s\bar{b} \rightarrow c\bar{c} + c_1(u\bar{u} + d\bar{d}) + c_2 s\bar{s}$)

CP-violation will cause an asymmetry in the time-integrated production of for example the decay $B_d^0 \rightarrow J/\Psi K_S^0$ and $\bar{B}_d^0 \rightarrow J/\Psi \bar{K}_S^0$. Other topics are the measurement of B_S^0 mixing, search for rare decays such as $B_d^0 \rightarrow \mu^+\mu^-$ and $B_S^0 \rightarrow \mu^+\mu^-$, the study of bottom baryon decays and the study of rare bottom hadrons.

Bottom physics studies will be experimentally easiest at the initial luminosity $L = 10^{33}\text{cm}^{-2}\text{s}^{-1}$ where pile-up effects are small and detectors close to the collision point are expected to survive for several years. These detectors are used for the reconstruction of secondary vertices and bottom quark identification. Most of the bottom quark studies will thus be performed during the first few years of LHC operation.

1.4.5 Physics beyond the standard model

Several possible extensions of the standard model can be tested on their validity at LHC.

In a supersymmetric extension of the standard model a complete range of new particles is predicted with masses up to 1 TeV. Supersymmetry is based on the idea of a symmetry existing between the fermionic and bosonic degrees of freedom and is described in more detail in chapter 4.

In some minimal extensions of the standard model new neutral Z' or charged W' vector bosons are occurring, with masses up to about 6 TeV. Simulations show that if the charged boson W' exists, its mass could be measured with an accuracy of about 50-100 GeV [6].

In many theoretical models beyond the standard model **leptoquarks** are predicted, inspired by the symmetry between the quark and leptons generations. These particles carry both lepton and baryon quantum numbers and hence couple to both leptons and quarks, making transitions between quarks and leptons possible [11]. Moreover, each fermion generation is associated with a different leptoquark. Simulations show that these leptoquarks could be observed easily at LHC if their mass is below 1 TeV [6].

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