Searching for Supersymmetry with the α_T variable in $p\bar{p}$ collisions with the CMS Detector at the Large Hadron Collider

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Chapter 1

Theoretical Overview

This analysis lies within the framework of particle physics, the study of the fundamental building blocks of our universe and their interactions. The findings of these studies are mathematically described using Quantum Field Theory, in which particles are represented as an excitation in a quantised field, and their interactions are mediated by force-carrying particles called bosons. The hugely popular Standard Model (SM) is the collective name given to the accepted and rigorously tested theories that successfully describe three of the four fundamental forces, the electromagnetic, strong and weak forces. At this time Gravity remains absent from the Standard Model. A quick overview is given in this chapter of the formalism of the SM, along with the motivation for physics Beyond the Standard Model (BSM). Many of the shortcomings of the SM can be explained by the popular theory of Supersymmetry, which provides a framework for the analysis presented in this thesis.

1.1 The Standard Model

The Standard Model (SM) is the collective name given to the theories that successfully describes the known elementary particles and their fundamental interactions with respect to the strong, weak and electromagnetic forces. These theories are formulated mathematically using quantum field theory (QFT), in which particles are thought of as excitations of fields, and the dynamics of a given system are summarised in a function called a Lagrangian. In order to reflect the symmetries observed in nature, measurements of physical properties in the SM must be invariant under local transformations, and this property is called gauge invariance. Therefore the SM is a special case of field theory, called Gauge Theory, and the interactions between particles are described by force-carrying mediation particles known as gauge bosons.

The set of possible transformations is described in the language of Group Theory, and thus we describe the SM as a non-Abelian Yang-Mills type gauge field theory based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The strong interactions described by Quantum Chromodynamics (QCD) are represented by $SU(3)_C$, and the electromagnetic and weak interactions are represented together due to Electroweak Unification by the group $SU(2)_L \times U(1)_Y$. As of yet, the fourth fundamental force Gravity is not included in the Standard Model, but this is seen as of little consequence as gravitational forces are thought to have comparatively little effect on fundamental particles. The current understanding of the theory has been rigorously tested.

The particle content exists in two types, the bosons which carry forces as described above, and the fermions, which are the building blocks for matter. These two sets are distinguished by the property of Spin, the measure of intrinsic angular moment, as the gauge bosons have spin-1 and the fermions spin-1/2 The fermions which make up all visible matter can be described in three families, or "generations", shown in Equation **??**. Within each generation, there are two sets of particles, those on the left are the leptons, which do not feel the strong force, and those on the right are the quarks, which do. In each generation, there are two quarks, which differ by electoral charge - one has +2/3 and the other -1/3 (in units of the electron charge e), a lepton with charge -1 and neutral lepton called a neutrino which is either massless or very light. The three families then are organised in ascending order of mass. The first generation is therefore stable and all ordinary matter is constructed from it, whilst the second and third are liable to decay into particles of the first generation. In addition to each particle detailed here there exists a corresponding antiparticle due to a symmetry in charge and quantum numbers.

$$\begin{bmatrix} \nu_e & u \\ e & d \end{bmatrix}, \begin{bmatrix} \nu_\mu & c \\ \mu & s \end{bmatrix}, \begin{bmatrix} \nu_\tau & t \\ \tau & b \end{bmatrix} \tag{1.1}$$

1.1.1 Guage Theory

QCD

The theory of the strong force and its interactions with quarks through the force-carrier gluons

Electroweak Sector

1.1.2 EWSB and the Higgs Mechanism

In order to give mass to the W and Z bosons we say that $SU(2)_L \times U(1)_Y$ must be spontaneously broken into $U(1)_{em}$, the group of symmetries representing the electromagnetic sector. In order to

1.2 Motivation for Physics Beyond the Standard Model

The standard model has been widely successful, predicting the existence of particles such as the $W^{\pm}$ and Z Bosons, and the t quark, showing impressive agreement with experimental findings. However, there are several signs that it is not a complete theory, motivating the postulation of new theories and extensions. The SM does not currently incorporate the gravitational force, nor does it explain the existence of dark matter and dark energy. Neutrino masses and flavour mixing are also unexplained. In addition, several features of the existing SM are seen as inelegant, as they require some mathematical fine-tuning and thus are unlikely to reflect nature. The main motivations for

1.2.1 The Hierarchy Problem

1.2.2 Dark Matter

1.2.3 Unification of Coupling Constants

At the basis of theoretical particle physics is the observation of the symmetry and simplicity of nature. Unification, where several theories can be combined into one description, has undergone before, first Electricity and magnetism, and then electromagnetism with the weak force. The coupling constants for the electromagnetic and weak forces converge as energies increase but as of yet there is no energy scale where this can be achieved with the strong force PIC.

1.3 Supersymmetry

Supersymmetry is a theory which represents an extension to the Standard Model based around a symmetry between fermions and bosons. Under this symmetry elementary particles in the SM would each have corresponding super-partners, differing by one half unit of spin, such that a fermion has a boson super partner, and vice versa. The transformation of supersymmetry can be seen as a transformation

$$Q|F >= |B >, Q|B >= |F > \tag{1.2}$$

1.3.1 MSSM

Whilst there are money ways to construct mathematically the theory of Supersymmery, it is usual to do it in the way which introduces the least number of new degrees of freedom. This corresponds to the minimal particle contact required to satisfy the core symmetry, which corresponds to one supersymmetric particle, called a super partner, for each SM particle. We call this the Minimal Supersymetric Standard Model.

1.3.2 R-Parity

In order to distinguish the SUSY particles from the SM particles a new quantum number R Parity is born, defined in Equation **??** using the quantum numbers B (baryon number), L (lepton Number) and S (spin). Under this construction, all SM particles carry R_p of +1 and all super partners carry -1.

$$R_P = (-1)^{3(B-L)+2S} \tag{1.3}$$

Whilst terms in the Quantum Field Theory do allow for the possibility of violation of this parity, experimental measurements has excluded this for sparticles with masses on the TeV scale, and therefore those within the reach of the LHC. Thus the majority of searches consider models with a symmetry which forbids this violation and conserves Rp. Several phenomenological consequences arise from this assumption which provide the backbone to SUSY searches at the LHC.

IN over for SUSY particles to be produced at the LHC under this framework, they must be pair produced from SM particles. The heavier particles undergo a decay chain ending in the lightest of the supersymmetric particles, denoted the Lightest Super Partner (LSP), and this particle is by necessity stable and neutral, as it cannot decay into SM particles. This type of particle is called a Weakly Interacting Massive Particle (WIMP), and they will not interact in a detector, leading us to characterise our searches for it by a requirement for large amounts of missing energy.

1.3.3 CMSSM

Current Limits on the CMSSM

1.3.4 Other BSM Models

1.3.5 Production Mechanisms at the LHC

Bibliography

[1] Oliver Sim Brning, Paul Collier, P Lebrun, Stephen Myers, Ranko Ostojic, John Poole, and Paul Proudlock. *LHC Design Report.* CERN, Geneva, 2004.

[2] Thomas Sven Pettersson and P Lefvre. The Large Hadron Collider: Conceptual Design. Technical Report CERN-AC-95-05 LHC, CERN, Geneva, Oct 1995.

[3] The CMS Collaboration. The Compact Muon Solenoid Technical Proposal. *CERN/LHCC*, 94-38, 1994.

[4] K et al. Nakamura. Review of particle physics, 2010-2011. review of particle properties. *J. Phys. G*, 37(7A):075021, 2010. The 2010 edition of Review of Particle Physics is published for the Particle Data Group by IOP Publishing as article number 075021 in volume 37 of Journal of Physics G: Nuclear and Particle Physics. This edition should be cited as: K Nakamura et al (Particle Data Group) 2010 J. Phys. G: Nucl. Part. Phys. 37 075021.

[5] The CMS Collaboration. *The CMS hadron calorimeter project: Technical Design Report.* Technical Design Report CMS. CERN, Geneva, 1997.

[6] Efe Yazgan. The CMS barrel calorimeter response to particle beams from 2-GeV/c to 350-GeV/c. *J. Phys. Conf. Ser.*, 160:012056, 2009.

[7] The CMS Collaboration. *The CMS muon project: Technical Design Report.* Technical Design Report CMS. CERN, Geneva, 1997.

[8] Sergio Cittolin, Attila Rcz, and Paris Sphicas. *CMS trigger and data-acquisition project: Technical Design Report.* Technical Design Report CMS. CERN, Geneva, 2002.