Master Advanced Lab Course
Universität Göttingen – Fakultät für Physik

Report on the experiment KT.HIP

Higgs physics with the ATLAS experiment

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2.1 A summary of the Standard Model

The Standard Model (SM) is the combination of different theories governing three of the four known fundamental forces (electromagnetic, weak and strong interactions), as well as all known elementary particles and their interaction. It consists of 6 quarks making up the hadrons, 6 leptons, as well as 4 gauge bosons acting as force carriers for the interaction between the other particles. The interactions are fixed by the principle of local gauge invariance. The last puzzle piece - the Higgs boson - has recently been found at the LHC. It gives mass to the other particles by the Higgs mechanism, a form of spontaneous symmetry breaking. The Standard model has been a great success, having made predictions for new physics as well as confirming these predictions with great accuracy. An example of this is the theory of quantum-electro-dynamics, which has been confirmed to an astounding precision [cite]. Despite the great success, the Standard Model is a rather ad-hoc combination of different ideas without a unifying underlying theoretical principle. It features 26 free parameters, namely the fermion masses, the coupling strengths of the fundamental forces, mixing angles of quarks and neutrinos and parameters specifying the Higgs mechanism [2, p. 500]. Therefore, it is desired that all four forces would unify into a "Great Unified Theory" (GUT). There are other obvious shortcommings of the SM: Gravity is not part of the SM, meaning that general relativity is not compatible with it, although being much weaker than the other forces, it can be neglected in particle experiments. Furthermore, dark matter is not described by the SM. Furthermore, the mass of the Higgs boson does not have the right mass order of magnitude at very high energy scales due to loop corrections, a problem known as the "hierarchy problem" [2, p. 505].

2.2 Beyond the Standard Model

Several ideas exist for an extension of the SM. Supersymmetry is an attempt to both unify the electroweak and strong force as well as solving the hierarchy problem. In supersymmetry, every elementary particle would have a corresponding super-partner, called a "sparticle". So far, no super-partners have been found [2]. Also, there would be the need for 5 different Higgs bosons. There is also a possibility of extra space-like dimensions that are hidden from us, which would be a possible explanation for the weakness of gravity. A prominent theory of quantum gravity - string theory - predicts these extra dimensions. In an experiment, these extra dimensions could manifest as a large amount of missing energy [3]. Additionally, neutrino masses need to be explained. A prominent idea is that neutrinos are majorana particles, namely particles being their own antiparticles.

2.3 The Higgs mechanism

[2, Ch. 17] The Higgs mechanism is needed in the SM to give rise to massive gauge bosons and fermions in a locally gauge invariant manner. The problem can be illustrated with a simplified toy model. Consider a mass term for a vector boson (e.g. a photon) in the Lagrangian:

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_\gamma A_\mu A^\mu. \tag{2.1}$$

Such a term is not invariant under a local gauge transformation

$$\partial_\mu \to D_\mu = \partial_\mu + igA_\mu \tag{2.2}$$
$$A_\mu \to A'_\mu = A_\mu - \partial_\mu \chi(x). \tag{2.3}$$

One now introduces a complex scalar field $\phi(x)$ with a mexican hat potential $V(\Phi) = \mu^2\phi^2 + \lambda\phi^4$, which is shown in fig. 1. For $\mu^2 < 0$, $\lambda > 0$, the potential minimum shifts from the origin at $\phi = 0$ to a degenerate ring in the complex plane. The ground state thus chooses a new vacuum in an arbitrary direction with nonzero ϕ, a process called "spontaneous symmetry breaking". This ground state can now be expanded around this minimum, choosing a convenient gauge, to describe the system's low energy excitations in this new vacuum. This gives rise to a massless particle called the Goldstone boson, as well a massive scalar particle, called the Higgs boson. The original lagrangian expressed in this gauge around this new minimum now has a mass term for the vector bosons without having broken local gauge invariance. The standard model Higgs has more subtleties arising from the noncommutativity of the SU(2) and SU(3) gauge symmetries, but the general principle stays the same.

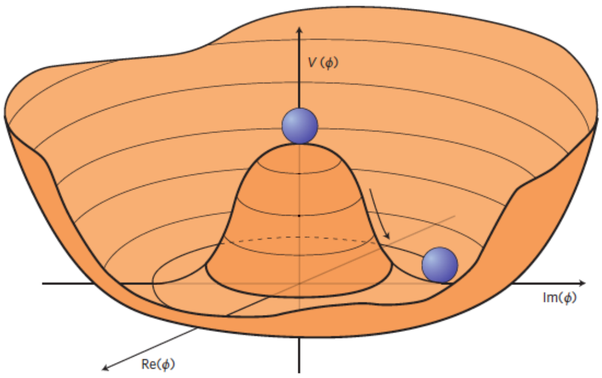

Figure 1: The mexican hat potential for the scalar Higgs boson. The symmetric state at $\phi = 0$ is spontaneously broken and a new vacuum state is chosen in a random direction. For a particular choice of ground state, the low-energy excitations look like a massive scalar field in addition to a massless Goldstone field. After a local gauge transformation, a mass term for the vector bosons becomes visible in the lagrangian [1].

3 Experimental setup and methods

4 Analysis

5 Discussion

References

[1] *Cern website*. `https://cds.cern.ch/record/2012465/files/higgspotential.png`. – Zugriff:2018-04-23

[2] THOMSON, Mark: *Modern Particle Physics*. Cambridge University Press, 2013

[3] ZWIEBACH, Barton: *A first course in string theory*. Cambridge university press, 2004