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 [3, 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” [3, 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 [3]. 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 [4]. 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

[3, 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.

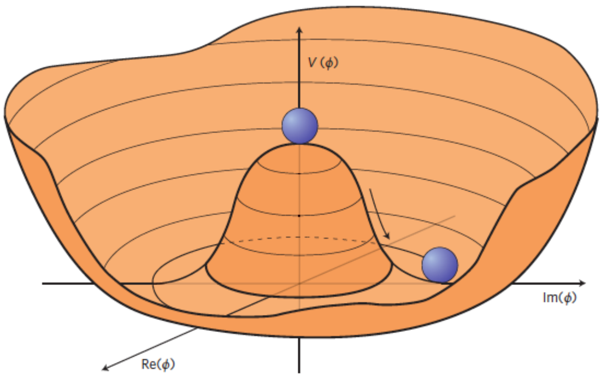

Figure 1: The mexican hat potential for the scalar Higgs boson. The symmetric state at $\phi = 0$ is spontaneously broken and a new vacuum state is chosen in a random direction. For a particular choice of ground state, the low-energy excitations look like a massive scalar field in addition to a massless Goldstone field. After a local gauge transformation, a mass term for the vector bosons becomes visible in the lagrangian [2].

2.4 Higgs decay and production

Apart from maybe neutrinos, whose mass-genertating principle is not yet known, the Higgs boson couples and thus can decay to all SM particles. However, the top quark is too massive to be a real decay product of the Higgs boson. Since the Higgs couples proportionally to the mass of the particle, decays to heavier particles are favoured. The largest decay channels are to bottom quarks (57.8%), W bosons (21.6%) and tau leptons (6,4%). Even though photons are massless, they can be the result of a Higgs decay by means of virtual top quark loops. The Branching ratio to photons is only 0.2%. At the LHC, the two most important Higgs production mechanisms are gluon-gluon fusion and vector boson fusion [3, p. 490f]. Although the former has a significantly higher cross section (10× higher), vector boson fusion is more practical, since the virtual top quark loops lead to QCD radiation from the colour field that makes identifying a Higgs decay more challenging.
Since Higgs decays are hard to seperate from the usual multi jet events at the LHC, decay channels with distinctive final state topologies are favoured. These include $H \to \gamma\gamma$ and $H \to ZZ^* \to l^+l^-l^+l^-$. In this lab, the four lepton states are the most important. These have to be seperated from other four lepton state processes such as $t\bar{t}$ fusion, where each of the two top quarks sends out two W bosons, changing flavour each time. These W's can then each decay into a lepton neutrino pair. Another background four-lepton process is the combination of a Z decaying into two leptons together with a $b\bar{b}$ pair, each decaying into a lepton, neutrino pair via a W boson.

3 Experimental setup and methods

3.1 ATLAS detector

The ATLAS detector is one of four major experiments at the Large Hadron Collider at Cern. It is build for general purpose experiments with propton-proton collisions. Its main goal has been the detection of the Higgs boson, tests of the Standard Model and search for new physics beyond the SM, such as supersymmetry and extra dimensions. The detector itself consists of a inner detector, a calorimeter and the muon spectrometer. The inner detector is a collection of different systems like a pixel detector and semiconductor tracker for measuring the direction, momentum and charge of charged particles, which are brought on a circular path by large magnetic fields parallel to the beam axis. The transition radiation tracker additionally provides information on which type of particle was detected. Next, theelectromagnetic and hadronic calorimeters are designed to absorb as much energy of the produced particles as possble. This yields the direction and energy of particles as well as a means to distinguish leptons from hadrons. Muons however, being a weakly ionising particle mostly flies through these calorimeters. Therefore, the largest part of the detector is the muon spectrometer, which is there to give very precise measurements of the muon momentum.

3.2 ATLAS event display

3.3 trigger?

3.4 Signifikanz????

[1]
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4 Analysis

5 Discussion

References

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

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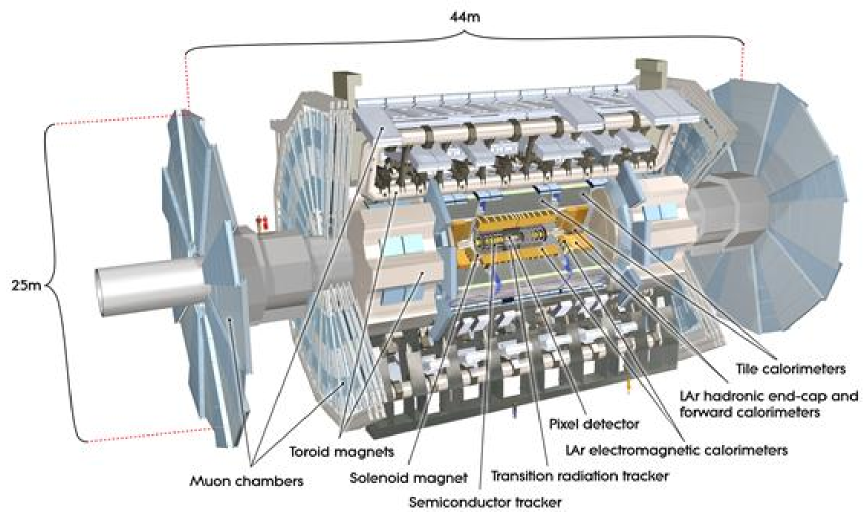
44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Figure 2: <++>