Introduction and Disclaimer

These mock examination questions span diverse disciplines and are designed for your practice in preparation for the International Research Olympiad (IRO) 2024. Endeavor to answer them to the best of your ability, utilizing this opportunity to enhance your skills and knowledge. For additional practice, it is advisable to engage in extensive reading of various papers; such efforts will contribute to a more comprehensive and nuanced understanding of the subject matter.

Try your best, and good luck! -International Research Olympiad 2024

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb−1 collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb−1 at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels H→ ZZ(∗)→ 4ℓ, H→ γγ and H→ WW(∗)→ eνμν in the 8 TeV data are combined with previously published results of searches for H→ ZZ(∗) , WW(∗) , bb¯ and τ + τ − in the 7 TeV data and results from improved analyses of the H→ ZZ(∗)→ 4ℓ and H→ γγ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10−9 , is compatible with the production and decay of the Standard Model Higgs boson.

Key Terms

- GeV - unit of measure (giga-electronvolts)
- TeV - unit of measure (tera-electronvolts)
- Muon - similar to an electron, but with greater mass
- |η| - Pseudorapidity measure; Pseudorapidity describes the angular distribution of particles produced in high energy collisions, in this case within the Large Hadron Collider
- ℓ - symbol for muon/electron

Paper

The Standard Model (SM) of particle physics has been tested by many experiments over the last four decades and has been shown to successfully describe high energy particle interactions. However, the mechanism that breaks electroweak symmetry in the SM has not been verified experimentally. This mechanism, which gives mass to massive elementary particles, implies the existence of a scalar particle, the SM Higgs boson. The search for the Higgs boson, the only elementary particle in the SM that has not yet been observed, is one of the highlights of the Large Hadron Collider (LHC) physics programme.

The ATLAS detector is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a straw-tube transition radiation tracker (TRT). The ID is surrounded by a thin superconducting solenoid which provides a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimetry. The electromagnetic calorimeter is divided into a central barrel (pseudorapidity2 $|\eta| < 1.475$) and end-cap regions on either end of the detector ($1.375 < |\eta| < 2.5$ for the outer wheel and $2.5 < |\eta| < 3.2$ for the inner wheel). In the region matched to the ID ($|\eta| < 2.5$), it is radially segmented into three layers. The first layer has a fine segmentation in η to facilitate e/γ separation from π 0 and to improve the resolution of the shower position and direction measurements. In the region $|\eta| < 1.8$, the electromagnetic calorimeter is preceded by a presampler detector to correct for upstream energy losses. An iron-scintillator/tile calorimeter gives hadronic coverage in the central rapidity range ($|\eta| < 1.7$), while a LAr hadronic end-cap calorimeter provides coverage over $1.5 < |\eta| < 3.2$. The forward regions ($3.2 < |\eta| < 4.9$) are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large air-core superconducting magnets providing a toroidal field, each with eight coils, a system of precision tracking chambers, and fast detectors for triggering. The combination of all these systems provides charged particle measurements together with efficient and precise lepton and photon measurements in the pseudorapidity range $|\eta| < 2.5$. Jets and E miss T are reconstructed using energy deposits over the full coverage of the calorimeters, $|\eta| < 4.9$.

The data are selected using single-lepton or dilepton triggers. For the single-muon trigger, the pT threshold is 18 GeV for the 7 TeV data and 24 GeV for the 8 TeV data, while for the single-electron trigger the transverse energy, ET, threshold varies from 20 GeV to 22 GeV for the 7 TeV data and is 24 GeV for the 8 TeV data. For the dielectron triggers, the thresholds are 12 GeV for both electrons. For the dimuon triggers, the thresholds for the 7 TeV data are 10 GeV for each muon, while for the 8 TeV data the thresholds are 13 GeV. An additional asymmetric dimuon trigger is used in the 8 TeV data with thresholds 18 GeV and 8 GeV for the leading and sub-leading muon, respectively.

Muon candidates are formed by matching reconstructed ID tracks with either a complete track or a track-segment reconstructed in the MS [84]. The muon acceptance is extended with respect to Ref. using tracks reconstructed in the forward region of the MS ($2.5 < |\eta| < 2.7$), which is outside the ID coverage. If both an ID and a complete MS track are present, the two independent momentum measurements are combined; otherwise the information of the ID or the MS is used alone. Electron candidates must have a well-reconstructed ID track pointing to an electromagnetic calorimeter cluster and the cluster should satisfy a set of identification criteria that require the longitudinal and transverse shower profiles to be consistent with those expected for electromagnetic showers. Tracks associated with electromagnetic clusters are fitted using a Gaussian-Sum Filter, which allows for bremsstrahlung energy losses to be taken into account.

Each electron (muon) must satisfy pT > 7 GeV (pT > 6 GeV) and be measured in the pseudorapidity range $|\eta| < 2.47$ ($|\eta| < 2.7$). All possible quadruplet combinations with same-flavour opposite-charge lepton pairs are then formed. The most energetic lepton in the quadruplet must satisfy pT > 20 GeV, and the second (third) lepton in pT order must satisfy pT > 15 GeV (pT > 10 GeV). At least one of the leptons must satisfy the single-lepton trigger or one pair must satisfy the dilepton trigger requirements. The leptons are required to be separated from each other by ΔR = p ($\Delta\eta$) 2 + ($\Delta\varphi$) 2 > 0.1 if they are of the same flavour and by $\Delta R > 0.2$ otherwise. The longitudinal impact parameters of the leptons along the beam axis are required to be within 10 mm of the reconstructed primary vertex. The primary vertex used for the event is defined as the reconstructed vertex with the highest P p 2 T of associated tracks and is required to have at least three tracks with pT > 0.4 GeV. To reject cosmic rays, muon tracks are required to have a transverse impact parameter, defined as the distance of closest approach to the primary vertex in the transverse plane, of less than 1 mm.

The same-flavour and opposite-charge lepton pair with an invariant mass closest to the Z boson mass (mZ) in the quadruplet is referred to as the leading lepton pair. Its invariant mass, denoted by m12, is required to be between 50 GeV and 106 GeV. The remaining sameflavour, opposite-charge lepton pair is the sub-leading lepton pair. Its invariant mass, m34, is required to be in the range mmin < m34 < 115 GeV, where the value of mmin depends on the reconstructed four-lepton invariant mass, m4ℓ. The value of mmin varies monotonically from 17.5 GeV at m4ℓ = 120 GeV to 50 GeV at m4ℓ = 190 GeV and is constant above this value. All possible lepton pairs in the quadruplet that have the same flavour and opposite charge must satisfy mℓℓ > 5 GeV in order to reject backgrounds involving the production and decay of J/ψ mesons. If two or more quadruplets satisfy the above selection, the one with the highest value of m34 is selected. Four different analysis sub-channels, 4e, 2e2μ, 2μ2e and 4μ, arranged by the flavour of the leading lepton pair, are defined. Non-prompt leptons from heavy flavour decays, electrons from photon conversions and jets mis-identified as electrons have broader transverse impact parameter distributions than prompt leptons from Z boson decays and/or are non-isolated. Thus, the Z+jets and tt¯background contributions are reduced by applying a cut on the transverse impact parameter significance, defined as the transverse impact parameter divided by its uncertainty, d0/σd0 . This is required to be less than 3.5 (6.5) for muons (electrons). The electron impact parameter is affected by bremsstrahlung and thus has a broader distribution.

The search for the SM Higgs boson through the decay H → ZZ(∗) → 4ℓ, where ℓ = e or μ, provides good sensitivity over a wide mass range (110- 600 GeV), largely due to the excellent momentum resolution of the ATLAS detector. This analysis searches for Higgs boson candidates by selecting two pairs of isolated leptons, each of which is comprised of two leptons with the same flavour and opposite charge. The expected cross section times branching ratio for the process H → ZZ(∗) → 4ℓ with mH = 125 GeV is 2.2 fb for √ s = 7 TeV and 2.8 fb for √ s = 8 TeV.

The largest background comes from continuum (Z (∗) /γ*)(Z (∗) /γ*) production, referred to hereafter as ZZ(∗) . For low masses there are also important background contributions from Z + jets and tt¯production, where charged lepton candidates arise either from decays of hadrons with b- or c-quark content or from misidentification of jets.

The 7 TeV data have been re-analysed and combined with the 8 TeV data. The analysis is improved in several aspects with respect to Ref. to enhance the sensitivity to a low-mass Higgs boson. In particular, the kinematic selections are revised, and the 8 TeV data analysis benefits from improvements in the electron reconstruction and identification. The expected signal significances for a Higgs boson with mH = 125 GeV are 1.6 σ for the 7 TeV data (to be compared with 1.25 σ in Ref.) and 2.1 σ for the 8 TeV data.

The mass of the observed new particle is estimated using the profile likelihood ratio λ(mH) for H→ZZ(∗)→ 4ℓ and H→γγ, the two channels with the highest mass resolution. The signal strength is allowed to vary independently in the two channels, although the result is essentially unchanged when restricted to the SM hypothesis μ = 1. The leading sources of systematic uncertainty come from the electron and photon energy scales and resolutions. The resulting estimate for the mass of the observed particle is 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV.

In order to test which values of the strength and mass of a signal hypothesis are simultaneously consistent with the data, the profile likelihood ratio λ(μ, mH) is used. In the presence of a strong signal, it will produce closed contours around the best-fit point $(\hat{\mu}, \hat{m}_H)$, while in the absence of a signal the contours will be upper limits on μ for all values of m_H.

Paper 4: High Energy Physics

Question 1

Question: The ATLAS experiment at the Large Hadron Collider was crucial in the observation of a new particle. What is the primary role of the ATLAS detector in this context?

a.) To detect and measure the energy of particles resulting from proton-proton collisions.

b.) To generate high-energy proton beams for collision experiments.

c.) To provide theoretical predictions for particle interactions.

d.) To focus on astrophysical observations outside the LHC.

Question 2

Question: In the search for the Higgs boson, one of the key concepts is its ability to endow other particles with mass. Based on the paper, what property of the Higgs boson makes it unique compared to other elementary particles?

a.) It is the only particle with an infinite mass.

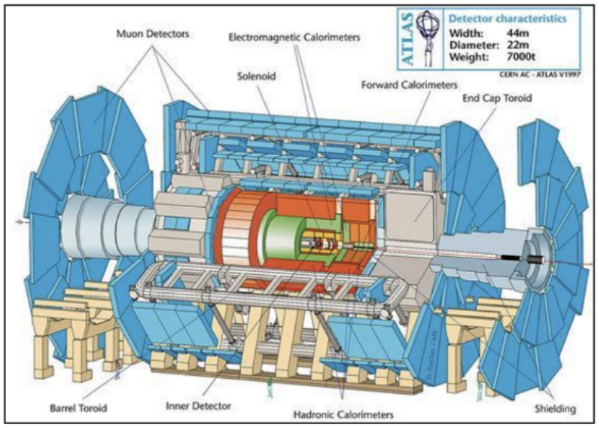
b.) It is the only particle that interacts with the gravitational force.

c.) It has no spin, electric charge, or color charge.

d.) It is the smallest particle known to exist.

Question 3

Question: The ATLAS detector, used in this experiment, is a complex apparatus designed to observe a variety of particle interactions. If a schematic diagram of the ATLAS detector was provided, which component is responsible for measuring the momentum of charged particles?



a.) The inner detector system, utilizing layers of sensors.

b.) The calorimeters, designed to measure the energy of particles.

c.) The magnet system, primarily for bending particle trajectories.

d.) The outer muon spectrometer, for identifying muons specifically.

Question 4

Question: In the paper, the data visualization of the decay channels of the new particle plays a critical role. Suppose you are shown a graph depicting the decay of this particle into two photons. What does this specific decay channel signify about the properties of the new particle?

a.) It suggests the particle is a type of quark.

b.) It indicates the particle has a strong interaction with electromagnetic forces.

c.) It shows the particle has a direct interaction with dark matter.

d.) It implies the particle is primarily involved in gravitational interactions.

Question 5

Question: The discovery of the new particle required complex statistical analysis to differentiate signal from background noise. If a new statistical method were introduced that could double the sensitivity of such experiments, which of the following predictions about future particle physics experiments is most supported?

a.) They would require half the amount of data to achieve similar results.

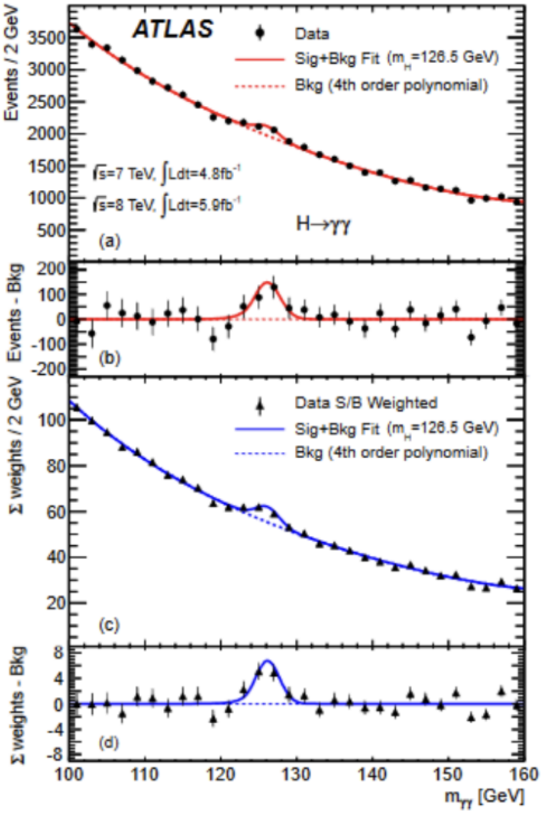
b.) They would exclusively focus on higher energy collisions, ignoring lower energy ones.

c.) They would be able to confirm the existence of particles with even shorter lifetimes.

d.) They would render the Large Hadron Collider obsolete.

Question 6

Question: The paper discusses the significance of the mass of the newly observed particle in confirming its identity as the Higgs boson. Imagine you are shown a plot displaying the invariant mass distribution of a number of particle decay events. The plot shows a distinct peak at around 125 GeV. What does this peak in the distribution signify in the context of the Higgs boson search?



a.) It represents the collective mass of all particles produced in the LHC.

b.) It indicates the energy level at which quarks are formed from gluons.

c.) It signifies a common mass value where a significant number of events cluster, hinting at the mass of the new particle.

d.) It shows the maximum energy level achieved by the LHC during the experiments.