The Search for Charged Massive Supersymmetric Particles at the LHC

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Contents

1 Abstract

Charged Massive Particles (CHAMPs) are predicted in the Supersymmetry (SUSY) extension of the Standard Model though they have never been observed. We look for CHAMPs in the ALICE Detector at the Large Hadron Collider at CERN. While the main purpose of ALICE is to study Quark-Gluon Plasma, we take advantage of the tracking and time of flight capabilities of several sub-detectors in ALICE to look for signs of CHAMPs. These elusive particles are characterized by their slow velocity, high transverse momentum and therefore heavy mass. Our research found a small handful of candidates among a large sample size but more work is required to confirm their identity and exclude the possibility that they have been misidentified.

2 Introduction

The Standard Model of Particle Physics (SM) is the modern theory describing how fundamental particles interact and behave. It was developed in the second half of the 20th Century after physicist Sheldon Glashow found a way to combine, or unify, the electromagnetic and electroweak forces [7]. In 1973 Glashow's electroweak theory was experimentally confirmed at CERN, the European Organization for Nuclear Research in Geneva, Switzerland, when nuetral currents through the weak nuclear force were measured. Later, in 1983, the particles in these interactions were identified. The Standard Model was used to predict masses of then undiscovered particles which were subsequently measured by experiments to be in full agreement. Since then the Standard Model has had a fantastic track record of being able to make predictions which coincide with experimental results.

Within the last sixty years scientists have used particle accelerators to probe nature at its smallest level, revealing elementary particles, the fundamental building blocks of nature, and their properties. Together these elementary particles including quarks, leptons, and gauge bosons make up the Standard Model. Quarks and leptons make up most of the regular matter in the universe while the gauge bosons, also called the force carriers, mediate the force interactions between the rest of the particles [13]. The photon, which is a particle of light, mediates the electromagnetic force, gluons mediate the strong nuclear force between quarks and the W and Z bosons are exchanged through the weak nuclear force. The fourth fundamental force, gravity, is not included in the Standard Model as the graviton has not been found and no quantum theory of gravity has been successfully theorized. Figure 1 summarizes the particles of the Standard Model.

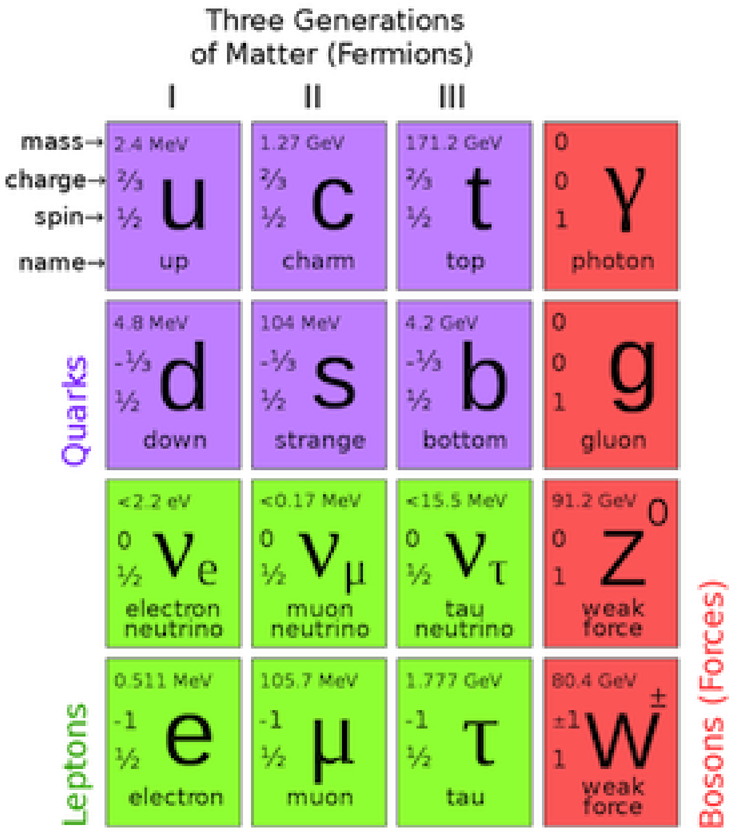

Figure 1: The Standard Model with the force carrying particles in red and the matter constituents in purple and green. Notice the vast range of masses the different particles have. *Source: CERN document server*

The gravity force carrier is not the only thing barring the Standard Model from completion. Another fundamental particle, the Higgs Boson, which is theorized to be responsible for giving the other particles mass has yet to be found experimentally. A lot rests on the Higgs since its existence is crucial in completing the Standard Model. Aside from the so far absent Higgs, the Standard Model has also not yet been able to explain dark matter[1] and the imbalance of matter and antimatter in our universe [4, 13].

[1] Regular matter, which is what makes up all the stuff around us, is a small part of the total matter in the universe. The rest is dark matter which accounts for approximately 83% of total matter. Dark matter does not scatter or emit light so it cannot be seen. Dark matter was proposed to explain the observations of rotation curves of galaxies not matching the distribution of visible matter in them. Additional unseen mass must be responsible for these motions, thus the name “dark” matter.

3 Supersymmetry: An Extension of the Standard Model

The Standard Model (SM) is not yet complete, but has been tremendously successful in matching theoretical predictions with experimental results, solidifying its validity. Assuming that the theory is valid scientists have extended it to make further predictions. One of these extensions, known as Supersymmetry (SUSY), predicts the existence of new particles, the search for which is the subject of this study.

In physics a feature of a system exhibits symmetry if it does not change upon a transformation of the system. One common symmetry in our universe is charge symmetry; a universe in which all particles are swapped with their antiparticles is indistinguishable from ours. In other words the universe is *invariant* under a charge transformation. On subatomic scales a symmetry can be defined as a transformation from one-particle quantum states to other one-particle states. Symmetry is interesting because it relates particles with differing statistics (the particular descriptions and characteristics of particles) and different spins [11, 6]. Supersymmetry is a specific symmetry which relates fermions with bosons[2] and vise-versa. The math behind SUSY is elegant and complex and has very interesting implications. The main prediction is that for every known elementary particle in SM there is at least one other particle, its supersymmetric partner or *sparticle*, which has the exact opposite statistics and differs in spin by $-\frac{1}{2}$. The two are related through a supersymmetrical transformation. Since the transformation changes the particle's spin by $-\frac{1}{2}$ it turns bosons into fermions and vise versa. This means that the Higgs sparticle, the higgsino, is a fermion while the Higgs is a boson and that quark sparticles, or squarks, are bosons while all quarks are fermions [14]. Even though their statistics are opposite one another the physical properties and characteristics of the two are related. If the lowest order SUSY theory is correct, then for each known particle there would be only one supersymmetric partner [11]. This requires there to be twice as many elementary particles as previously thought with just SM. The SUSY theory that predicts order-one symmetry is called the Minimal Supersymmetric Standard Model (MSSM) [5] and is the most commonly studied.

Supersymmetric partners are not simply mirror images of each other. Mass is not invariant under a supersymmetric transformation, making SUSY

[2]Bosons are particles that have integer spin and obey Bose-Einstein statistics which allows them to occupy the same state and space. Fermions have half integer spin, do not obey Bose-Einstein statistics, and are restricted to only one per state and space by Fermi-Dirac statistics.

a broken symmetry[3] [11]. If mass was invariant then the masses of sparticles would be the same as their corresponding particles. The electron sparticle (selectron) would have already been found in the same mass-energy region as the electron. Unfortunately since we do not see selectrons everywhere we see electrons this (through very complex calculations) implies that the masses of sparticles are at least two orders of magnitude higher than the masses of their corresponding particles [11].

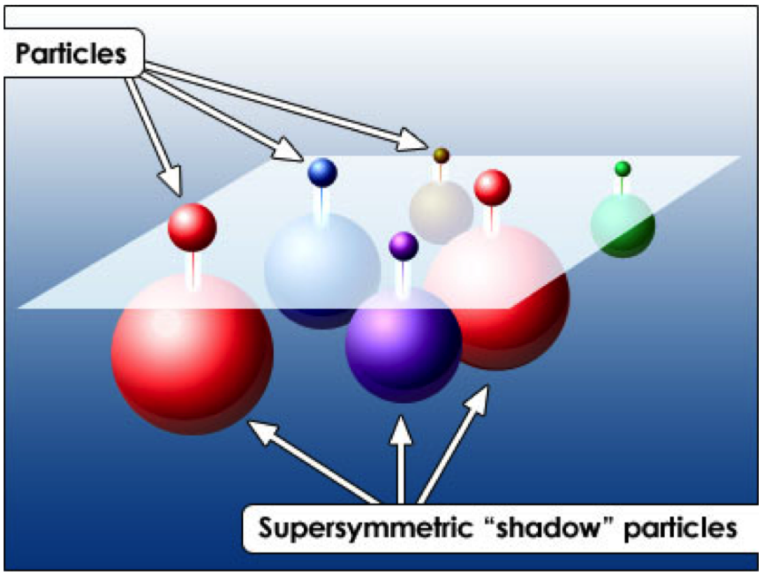

Figure 2: In SUSY each SM particle has a much more massive complementary sparticle. *Source: CERN document server*

SUSY introduces another new concept, R-parity [4, 5, 6]. In SM and SUSY all particles have an R value of 1 and all sparticles have R equal to −1. R-parity is important in explaining the stability of the proton upon the implementation of SUSY; without it, in MSSM, protons would decay in less than a second, while no such decay has been observed. In fact, the proton's lifetime is predicted to be on the order of 10^{34} years. For comparison the universe is in only $14 * 10^9$ years old [17]. R-parity is calculated using the baryon and lepton[4] number and the spin of a (s)particle. It is given by $R = (-1)^{3(B-L)+2S}$. Since the value $B - L$ is conserved it is the $-\frac{1}{2}$

[3]Symmetry breaking is a term to describe the specific choice of one of several possible natural states of a system. Although the underlying system is symmetrical, the choice of specific state forces the system into an apparent asymmetry. In particle physics, symmetries of the fields that describe the force carrying particles “break” at different energy scales [11].

[4]The baryon number is a quantum number found by taking the third of the difference

shift in spin that makes particles have $R = 1$ and sparticles $R = -1$ [5]. The R value is a multiplicative quantum number; instead of being conserved though addition in an interaction, such as charge, it is conserved through multiplication. This immediately restricts how sparticles and particles can decay. To conserve R-parity a particle ($R = 1$) can either decay into two particles ($R = 1 * 1 = 1$) or two sparticles ($R = -1 * -1 = 1$). In the same manner a sparticle ($R = -1$) can only decay into a sparticle and a particle ($R = -1 * 1 = -1$). From that it's concluded that sparticles are made in pairs from particles and that sparticles decay into other sparticles. Since they always decay into more sparticles (and particles) there must be a lightest sparticle (LSP) which is at the end of any possible decay chain and is therefore stable. It is worth noting that even though the LSP is the lightest of all sparticles it would still be much more massive than any regular SM particle. An exception to this exists in more abstract SUSY theories where the gravitino, the graviton's sparticle, whose mass would be on the order of or barely higher in magnitude of regular SM particles [11], is the LSP.

If there is an LSP it would be charge and color[5] neutral and therefore would only interact with matter weakly[6]. LSPs make great candidates for dark matter since dark matter must be charge neutral (or it would scatter light and therefore be visible) and color neutral (to avoid interacting with matter strongly) [4, 14]. In the MSSM, where there is only one symmetry, the LSP is predicted to be the neutralino which is the most favored candidate particle for dark matter. In more complex SUSY theories, ones in which R-parity is violated, the predicted LSP is either the stau or the gravitino, depending on the specific SUSY model [4].

The current search for sparticles predicted in SUSY is led by the experiments at the LHC at CERN and previously at the Tevatron at Fermilab. Both the Tevatron and the LHC are hadron colliders which collide protons or antiprotons so production of squarks and gluinos is predicted to be prevalent since they are made through strong interactions (non color-neutral). At its peak performance the Tevatron collided protons and antiprotons with 1.96 TeV center of mass energy [9, 10]. Squarks and gluinos have specific

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between quarks and antiquarks in a system. The lepton number is simply the difference in the number of leptons and antileptons in a system. e.g. a proton has B=1 and an antiproton has B=-1.

[5]Color charge is a property of quarks and gluons. It is analogous to the property of electric charge but differs because electric charge is either positive or negative while color charge takes on three primary states: red, green, and blue. Each of those has its respected anti-state. The term color is misleading because it has no relation to visual color.

[6]Interacting weakly means only interaction through the weak nuclear force and none of the other fundamental forces.

signatures; when they are produced it is expected that they will result in acoplanar particle jets and missing transverse energy. In the detectors designed to search for them the missing energy is caused by LSPs leaving the detector undetected and without depositing any energy since they are stable and weakly interact with matter [2]. At Fermilab's Tevatron the D0 experiment considered the three possible decay chains for squarks and gluinos but found no candidates. They were able to place a lower limit on the gluino and squark masses at 200 GeV/c^2 [10] and 285 GeV/c^2 [9], respectively.

Once the LHC began colliding particles at the end of 2009 it became the most powerful tool in the search for SUSY sparticles [4]. The general-purpose detectors (CMS and ATLAS) at the LHC are currently being used to test for SUSY. These detectors along with the higher energy and luminosity of the LHC are expected to produce results beyond those reachable at the Tevatron.

So far there is no experimental evidence of SUSY; no supersymmetric particles have been conclusively found yet [11]. Discovering new particles is not an easy task. A signal with a new particle differs very slightly from a signal without it. This combined with the fact that there is always experimental uncertainty requires incredibly large amounts of data to be taken, over a long period of time, to conclusively declare the discovery of a new particle. However discouraging, the search for SUSY is still on-going because it has promising implications. SUSY theories appear to be able to solve some lingering difficulties in the Standard Model. Along with figuring out dark matter SUSY can explain at least part of the 'hierarchy problem', which is the puzzle of why gravity is so much weaker than all the other forces. Gravity's weakness compared to the other forces is daunting; it is 10^{33} times weaker than the *weak* nuclear force [11, 14]. A successful SUSY theory, one that is confirmed with experiment, could play a vital role in unifying gravity with everything else, and could help explain dark matter.

4 CHAMPs

Little is known about the sparticles that could come out of SUSY. Some predictions envision sparticles named CHAMPs or CHArged Massive Particles[7]. Evident by their name these sparticles would have very large masses and have electric charge. This gives CHAMPs very distinct properties that can be sought out in particle accelerator experiments. CHAMPs can have large transverse momenta due to their size but are relatively slow compared to all the less massive SM particles with similar momenta emerging from particle collisions. Although CHAMPs are not restricted to SUSY models

[7]The name is misleading because all CHAMPs would be sparticles.

alone, (some, outside of SUSY, have magnetic charge and non integer electric charge [4]), the CHAMPs that are predicted from SUSY are the ones we are most likely to find at the LHC.

In the Standard Model there are several mechanisms responsible for the stability of particles. Since CHAMPs are part of a theory that derives from SM we are confident that similar mechanisms exist that would make CHAMPs stable and therefore observable [4]. One of these mechanisms is the conservation of quantum numbers. For example, the electron does not decay into anything lighter because there is no way charge could be conserved [5]. It is this mechanism that would require the existence of an LSP as described in the previous section. Another is the lack of phase space for decay, the space in which all possible decay states of a system are represented, like in the case of a bound neutron which will not decay as long as it is bound in a nucleus. [5]. Aside from these mechanisms there could be others that have not been seen in SM but would allow the stability of sparticles.

In MSSM one predicted CHAMP is the chargino, which is a combination of a W boson sparticle and the Higgs sparticle. Theory predicts that charginos decay into charge neutral neutralinos, an electron, and an electron neutrino. This decay happens after a free travel distance on the order of hundreds of meters so it would not decay in any particle detector and hence appear stable [4]. The gluino, the gluon sparticle, is another common possible CHAMP. The gluino is not electrically charged but however is color charged and therefore interacts through the strong nuclear force instead of the electromagnetic force like an electron. The gluino is predicted to be metastable[8] and is commonly considered to be a viable next to lightest sparticle (NLSP) [5].

The fact that CHAMPs are predicted to be exceptionally stable limits the way we can look for them. Since they are stable enough to not decay inside detectors there are no decay signals to look for [3]. One has to look directly for the particle itself by looking for signals with high dE/dx (a particle's energy loss in a detector), high momentum and low velocity.

5 The LHC

The data analyzed in this research was collected in 2010 at the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. The LHC is currently the largest particle accelerator in the world with a 27 kilometer (17 mile) circumference. It sits at an average 100 meters under the French/Swiss border near

[8]A metastable particle is one which is stable on one scale, but may be unstable at much longer times and distances.

Geneva, passing under both countries. The project, which was conceived in the late seventies and realized and built from 1998 to 2008, is a collaborative effort by 100 countries [1]. CERN has a long history of developing new accelerators, including the SPS (Super Proton Synchrotron) through which the masses of the W and Z bosons were measured in the early 1980's [15] and the LEP (Large Electron-Positron Collider) which occupied the giant underground ring before the LHC was built in its place.

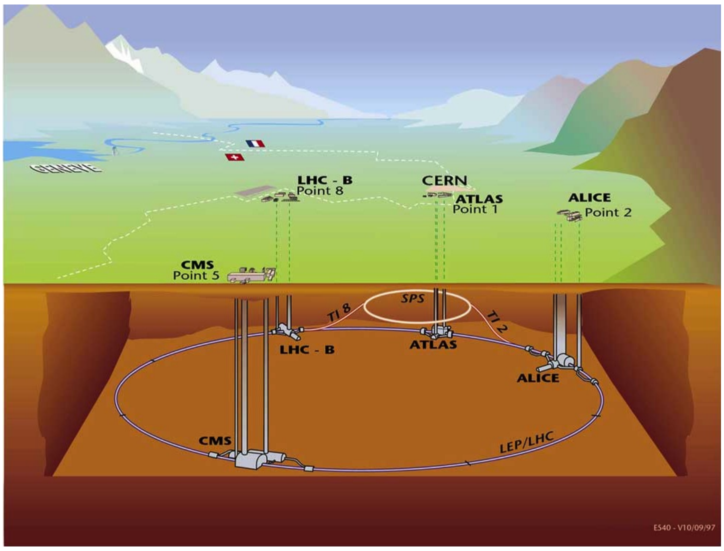


Figure 3: The general structure of the LHC. The major experiments which are situated at beam crossings are ATLAS, CMS, ALICE and LHCb. *Source: ATLAS Document Server*

The LHC accelerates subatomic particles in two parallel counter-circulating beam pipes to velocities incredibly close to the speed of light before colliding them at four different points along the ring, each point being dedicated to a unique detector and experiment. Under nominal conditions, the LHC will accelerate protons to an energy of 7 TeV, making the final collision energy 14 TeV. It uses both electric fields and magnetic fields to accelerate particles. Over one thousand dipole magnets use magnetic fields to turn the particles to keep them along a circular path, while five hundred quadrupole magnets are used to focus and compress the beam down to maximize the number of collisions per intersection [8].

As the particle beam passes through the dipole magnets it can be treated as a current of particles which experiences a force perpendicular to its motion. The force is inward, keeping the beam moving in a circle. The quadrupole magnets which are used to focus the beam are set up such that in the center of the magnetic cavity there is no magnetic force, and as a particle gets farther out from the center there is a strong force pushing it back to the center. Figure 4 shows a single quadrupole set-up and resulting field lines. A single quadrupole magnet can only focus in one plane, the x or y, which means the beam gets focused in one plane while growing away from the center in the other. A series of magnets, each rotated 90 degrees relative to the previous, ensures the beam is focused in both planes. Using these quadrupoles the beams are focused into regions of approximately 90 micrometers in diameter, a size smaller than the thickness of a human hair [8].

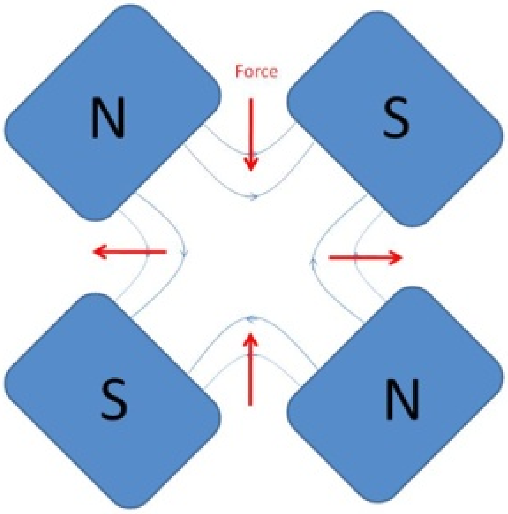


Figure 4: Single quadrupole magnet set-up. In the center particles experience no force from the magnetic fields. *Source: European Coordination for Accelerator Research and Development*

Tremendous $\vec{B}$ fields are required to turn and focus the beams and thus superconducting magnets are required. The magnetic fields in these magnets reach as high as 8 Tesla, 100,000 times stronger than the magnetic field of the earth [12]. To keep the magnets superconducting they sit at a mere 1.9 Kelvin above absolute zero, cooled by tons of liquid helium. This is colder than the vacuum of outer space and makes the LHC the largest cryogenic facility in the world.

As magnetic fields are used to guide particles, electric fields are used to accelerate them. Unlike the $\vec{B}$ field the $\vec{E}$ field accelerates objects in the direction of the field, so the electric field is along the beam path. Along the ring there are Radio Frequency (RF) cavities that deposit energy from radio waves into the beam, accelerating it. As a particle approaches an RF cavity the field is set so that it attracts the particle and when it passes the cavity the polarity is flipped so it repels and pushes the particle along. When the beam starts reaching its peak energy the frequency of the polarity flips reaches into the Gigahertz (GHz) range. The beam pipes that the particles travel through are kept at a tight vacuum to minimize unwanted interactions with gases which scatter the beam off the desired axis.

During the majority of the year the LHC collides protons. These protons start out as hydrogen gas atoms. The electrons are then ionized off of the atoms to get the protons by themselves. Before entering the main accelerator the protons enter a series of lower energy accelerators. Starting off in a linear accelerator which accelerates the particles into the mega-electron volt range (MeV) they are then injected into the first circular accelerator, the Proton Synchrotron Booster (PSB) which boosts them into the low GeV range. Following the PSB they enter the Proton Synchrotron (PS) which boosts their energy to 26 GeV and then they are off into the Super Proton Synchrotron (SPS) where they reach 450 GeV [8]. Finally they are injected into the main ring, alternating which beam pipe they enter so there are two counter-circulating beams. Once inside the main ring, they are brought to their maximum collision energy.

Instead of being a continuous beam of particles the protons are packed into bunches which are injected into the ring. Latest performance had 10^{11} protons per bunch. The amount of bunches in the accelerator depends on the fill scheme but it can be over 2000 bunches per beam. In April of 2012 the LHC reached 1380 bunches per beam which was the planned maximum for 2012 [16]. After the bunches are injected, one by one, into the beam pipes the long process of ramp-up begins. During ramp-up the bunches are slowly accelerated to target energies by the RF cavities. Once the beam is at the desired energy the bunches are timed to collide at the various intersections. After collisions begin the beam slowly starts to deteriorate and lose luminosity as particles are collided. Although there are 10^{11} particles in a bunch each crossing yields few collisions compared to the number of protons in the bunch, due to the cross sectional area of the particles being much smaller than the cross section of the beam (90 micrometers). There are around 40,000 bunch crossing per second but still the beam can last many hours before being dumped due to low luminosity.

Beam dumps can be triggered for many reasons besides low luminosity. The beam dumps shoot the beam out of the beam pipe and into a beam trap absorbing all the beam's energy. This utilizes very powerful kicker magnets to divert the beam out and above the LHC. After a beam dump is triggered and the kicker magnets are told to power up they only take 3 microseconds to reach full strength, a time in which the beam only traverses a thirtieth of the total beam pipe circumference [1]. The beam dumps absorb 380 megajoules (580 during maximum energy and luminosity) of energy per beam. The energy is absorbed in a seven meter long carbon cylinder which is enclosed in a steel cylinder and is surrounded by 750 tons of concrete and iron.

6 The ALICE Detector

The ALICE detector is one of six experiments at the LHC. While most of the other experiments at CERN focus on proton-proton collisions, ALICE focuses on heavy ion collisions, specifically the collisions of lead (Pb) nuclei. During most of the year the LHC collides protons leaving only a month of Pb-Pb runs. However, ALICE is still interested in the proton-proton data as it helps calibrate and provide a reference for when lead nuclei are collided. The ALICE collaboration consists of about 1000 members from over 100 countries, 200 of which are students.

The goal of ALICE is to generate and study an exotic state of matter called Quark-Gluon Plasma which existed in the very early universe when quarks and gluons were deconfined[9]. To do this the detector is composed of many subdetectors, each of which has its own purpose in detecting different types of particles.

[9] Due to the way the strong force works quarks and gluons only exist in nature in bound forms as hadrons such as protons and neutrons. When enough energy is put into separating two quarks it is energetically more favorable to pull a pair/anti-pair for each quark out of vacuum then to keep increasing the distance between them. Hence when quarks and gluons are deconfined in high energy collisions they very quickly undergo hadronization, the process of forming hadrons in directional jets. It is these jets of hadrons that are detected and their origin is traced back to deconfined quarks and gluons.

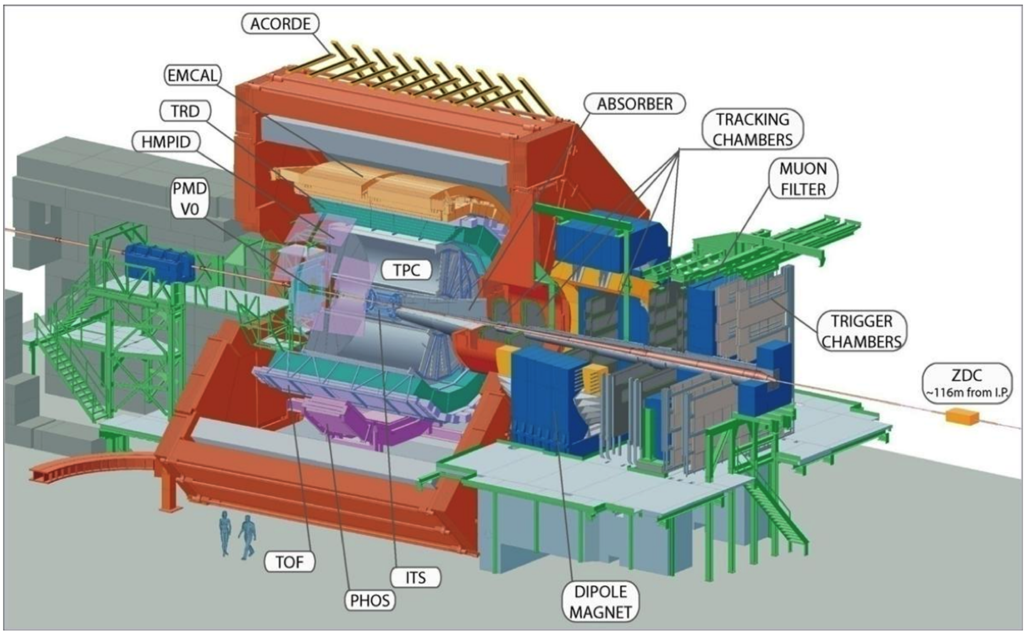


Figure 5: A cross section of ALICE showing all the subdetector systems and size relative to a person. The large L3 magnet enclosing most of the detector is shown in red. *Source: ALICE document server*

The first set of detectors that particles encounter is the Inner Tracking System (ITS) which is composed of three silicon based detectors, the Silicon Strip Detector (SSD), the Silicon Drift Detector (SDD) and the Silicon Pixel Detector (SPD). The main function of these three detectors is to determine the location in space of a collision vertex, the place where the two beam particles collided and emitted other particles which were then detected. The ITS wraps around the 6 cm diameter beam pipe and has a total radius of only 43 cm, making it the smallest detector system in ALICE. The SPD is the innermost detector of ITS and is crucial in determining collision vertices. Following it is the SDD which is responsible for half of the data required for the ITS to identify a particle passing through it. The outermost detector, the SSD, is necessary for matching particle tracks between the ITS and the massive Time Projection Chamber (TPC), the detector that encases the ITS.

The TPC is a large cylindrical detector with a 2.5 meter radius that is the most important tracking detector in ALICE. It is filled with a gas mixture of Carbon Dioxide, Neon and Helium and sits in in a uniform electrostatic field. When charged particles pass through the gas they ionize it and the ionized electrons drift towards the endplates due to the electric field. The readout location on the endplates gives the radial and angular coordinates of the passing particles. Outside the TPC is the Transition Radiation Detector

(TRD) which is used to identify high energy (greater than 1 GeV/c) electrons and positrons. Lower energy electrons are identifiable by the TPC. The Time of Flight (TOF) detector uses the tracking and vertex data from the ITS and TPC to identify particles such as pions, kaons, and protons. It identifies particles by measuring the time it takes them to travel from the collision vertex to the detector surface with a resolution of 100 picoseconds. The detector sits almost 4 meters radially from the beam pipe. The TOF covers 360 degrees around the beam pipe and is 7 meters long. On the outer edges of ALICE are several other detectors, the High Momentum Particle Identification Detector (HMPID), the Photon Spectrometer (PHOS), and the Electromagnetic Calorimeter (EMCal) which studies jet quenching, a crucial phenomenon in understanding Quark-Gluon Plasma. All of these detectors sit inside a giant solenoid magnet left over from the LEP experiment L3. This magnet, which houses all the inner detectors, has a radius over 6 meters, weighs 7800 tons and operates at a tremendous 30,000 Amps [1]. Unlike the magnets in the LHC beam pipes this magnet is not superconducting and has a maximum field strength of 0.75 Tesla. By bending the path of charged particles this magnetic field provides momentum information.

Outside of the LEP L3 magnet are a few other detectors and a dipole magnet which sit adjacent to the L3 along the beam pipe. These are the Muon Spectrometer and the Photon Multiplicity Detector (PMD) which detect muons and measure spatial distribution of produced photons, respectively.

7 Analysis

The two subdetectors that we focus on for this research are the TOF and TPC. Using the data from both the TPC and TOF we can determine the momentum, velocity, charge and mass of particles. Figures 6 and 7 illustrate the way they can be used to identify different particles through their momentum and time of flight. The TPC is also able to measure the energy loss, or dE/dx, of particles in the detector. The two detectors were built to study particles with momenta in the 0-5 GeV/c range but can also be extended to the higher momentum range. TOF is also able to identify large times of flight and those two abilities together give us confidence that these can be used to look for CHAMPs [3].

TOF and TPC are utilized differently than the CMS and ATLAS detectors to search for CHAMPs. Since ATLAS and CMS have 4π solid angle coverage they can look for CHAMPs by inspecting missing energy from collisions. ALICE does not have 4π coverage on all of its detectors; in fact, many of them do not cover the entire cylindrical area around the collision point (2π in azimuth). This causes ALICE to see lots of missing energy because it cannot account for the energy that would have been deposited if the subdetectors had full solid angle coverage. However we can use TOF and TPC to conduct our search because they can measure the time of flight and momenta of particles with great resolution in the areas in which we would expect CHAMPs.

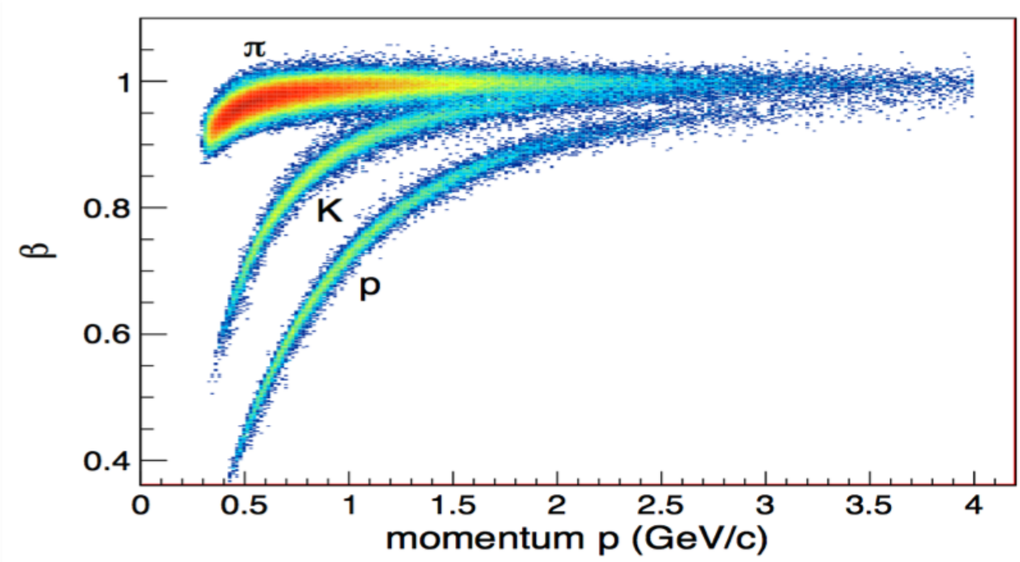


Figure 6: A plot of detected particles' velocity, β (in units of the fraction the speed of light), versus momentum. Each type of particle has its distinct curve and from this we can measure the particle's mass. The color of the graph denotes density of data with red indicating highest density. The particles displayed here are the pion, kaon, and proton. *Source: ALICE Collaboration*

The data in Figure 6 shows a distinct flattening curve because special relativity prohibits particles from having a beta higher than one, even though they can still attain high momenta. SM particles with momenta above about 2 GeV/c are all going near the speed of light as they emerge from the collisions. Since CHAMPs have much slower velocities they should be very easy to discriminate from all the SM particles with beta close to one in higher momentum regions. They should fall in the very empty lower right portion of the plot at even greater momenta ranges of about 50-100 GeV/c.

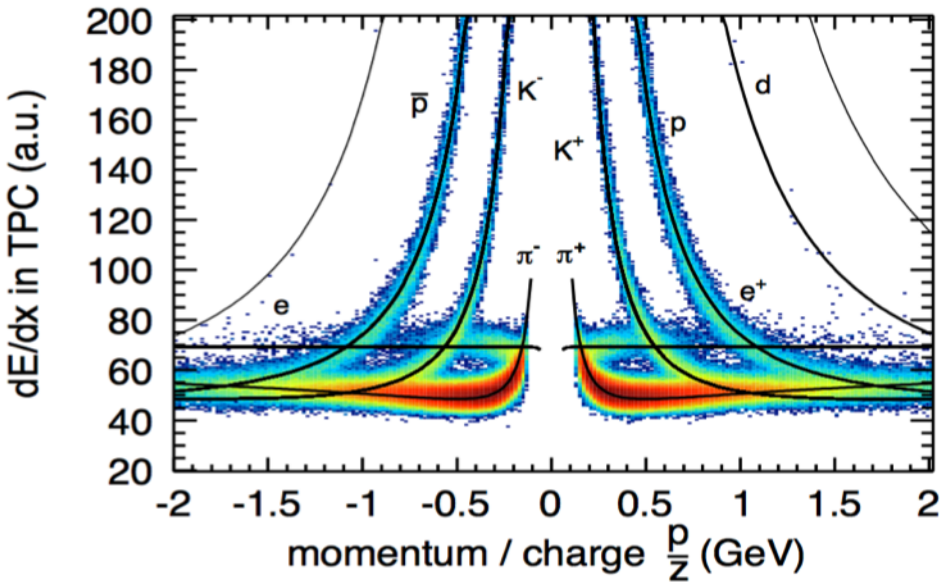


Figure 7: The energy loss of particles in the TPC vs. momentum. The graph is mirrored to display particles of different charge, negatively charged being on the left and positively charged on the right. The distinct curves allow identification of particles. Each particle here is mirrored by its antiparticle. *Source: ALICE Collaboration*

For this paper, a large set of data was analyzed. Specifically, the beta and the time of flight of particles versus their momentum were extracted from three data runs in the heavy ion collision data from 2010. The three runs totaled about 4.5 million events, corresponding to approximately 66 terabytes of data spread over a grid of data centers all over the world. The analysis was conducted by submitting data algorithms to a software management system called AliEn, which is short for ALICE Environment. AliEn retrieves the data from the multiple data centers on the grid and runs our analysis algorithm on its servers, analyzing tremendous amounts of data in parallel in little time.

The analysis algorithm sampled all the reconstructed tracks from the many events in each run and filtered out those that do not meet track quality standards. The tracks that passed these cuts were then sorted according to the track momentum and time of flight. Each entry in the histograms shown in Figures 8 and 9 is one reconstructed track of a particle or sparticle which passed through the ALICE detector after a collision. If the momentum of a track is above a certain threshold that track was flagged for more analysis later.

The two main properties of the particles, their beta and time of flight, are plotted against their transverse momentum. Time of fight is the time in picoseconds which it took the particle to travel from the center of the collision to the TOF detector surface. Knowing the distance to the detector and the time of flight allows us to calculate the particles' velocities. Beta is the ratio of a particle's velocity to the speed of light. Since a large portion of particles are moving near the speed of light when they come out of a collision, we see a lot of particles with beta very close to one. CHAMP candidates should appear in regions of high momentum, low beta and high time of flight.

Given the design of ALICE, the mass range of CHAMPs this analysis is sensitive to is from about 50 GeV/c^2 to 200 GeV/c^2, the smaller limit already being fifty times bigger than the proton, one hundred times bigger than the kaon (mass .497 GeV/c^2) and more than two hundred times bigger than the pion (mass .139 GeV/c^2).

8 Results

Out of the 4.5 million events analyzed, four CHAMP candidates were found. They are enclosed by the red boxes in the regions of high interest of high momentum and high time of flight in Figures 8 and 9.

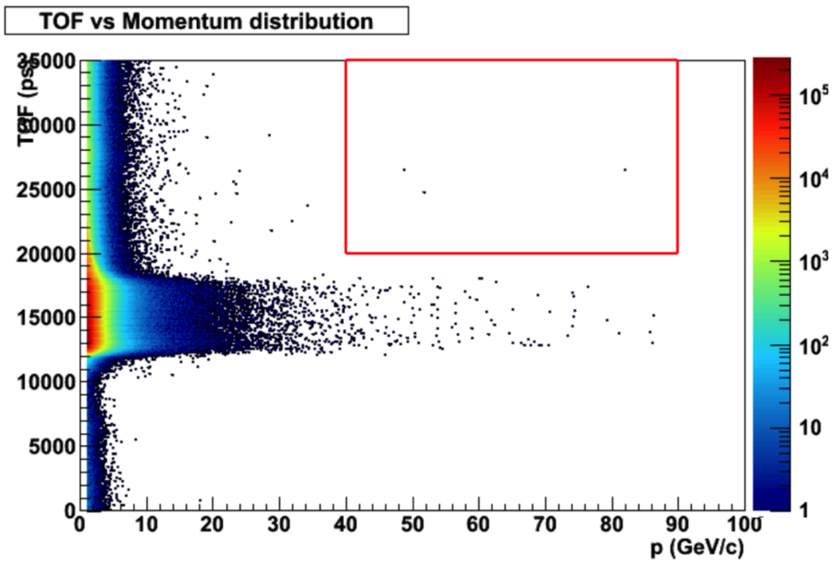


Figure 8: Time of flight vs. momentum for selected tracks from 4.5 million Pb-Pb events. The majority of the data is in the 1-10 GeV/c momentum range. The red box encloses the region of interest; the few particles in that region are CHAMP candidates.

In Figure 8 most of the data is in the 1-10 GeV range and 13-20 thousand picosecond range. This corresponds with light SM particles traveling at or near the speed of light. The tail to high momenta is due to light SM particles. This is why we expect the few particles with high momentum and high time of flight to be super massive SUSY particles. Particles within the red box must have both long time of flight and high momentum corresponding to high mass.

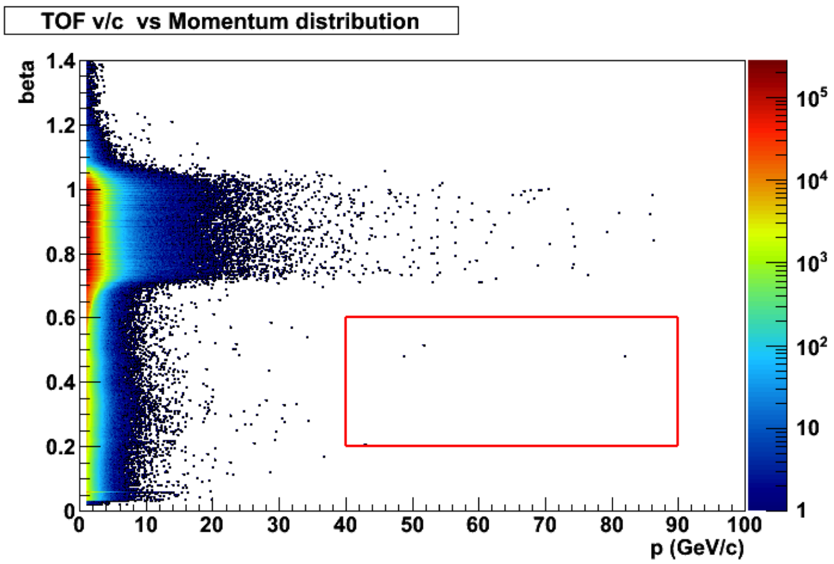
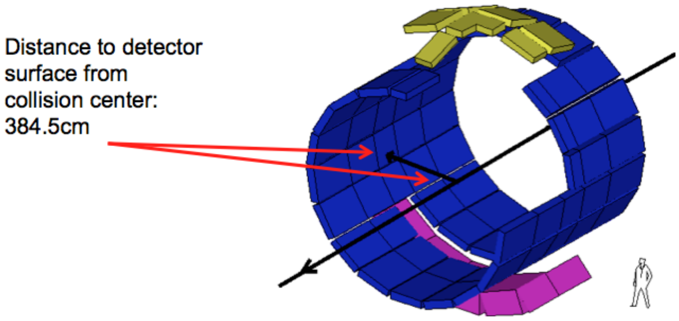


Figure 9: The beta vs. momentum of selected tracks from 4.5 million Pb-Pb events. The region of interest (high momentum and low beta) encloses four CHAMP candidate tracks.

Another way to plot the data is shown in Figure 9. Here, most of the data is represented in the 1-10 GeV range and beta close to 1. Note that there are values above one. Special relativity prohibits anything going above the speed of light so this is erroneous data. This also corresponds with data in the lower end of Figure 8. It is simply not possible to traverse 384.5 centimeters (the distance from the beam pipe to the TOF surface) in less than 13,000 picoseconds.



	Time to Travel 384.5cm		
Velocity	.1c	.5c	.9c
Time (ps)	128,000	25,700	14,300

Figure 10: Distance from the center of the beam pipe to the TOF detector surface and the time it takes in picoseconds to travel that distance at different fractions of the speed of light. *Source: ALICE Collaboration*

The fact that there are unphysical entries in our analysis is an indication of calibration uncertainties in the data. Also note that the scales of our regions of interest (shown by the red boxes) differ between Figures 8 and 9. This results in there being one less candidate than in Figure 9 due to the range of time of flight in Figure 8 not being high enough to show the fourth candidate.

The density of data is represented by color gradient; each red dot represents about 100,000 particles in that momentum/beta or time of flight bin. The dark blue or black dots represent just one. It is clear by the wash of red that the majority of expelled particles are in the 1-5 GeV range and only a few single particles were in the higher momentum ranges. In a sample of over 4 million detected particles, only a small handful of candidates (4) passed our selection cuts. This is a testament to how rare production and or detection of CHAMPs is, at least at these energy ranges. Once the LHC is operating at maximum energy and luminosity the number of candidates may increase.

More work is required to validate the identity of our candidate. There is a decent chance that these stragglers are noise in the data or poor track matches. Even though we made track quality cuts to ensure the integrity of the data there is always the possibility of poor track matching. One way to identify these particles would be to also look at their dE/dx and see if they appear in the high ranges that we would expect for CHAMPs. It is also possible to go back and find these individual events and look at them in an event display monitor and scrutinize them in more detail.

If SUSY were confirmed experimentally, it would have a tremendous impact on physics. Some of the largest unanswered questions in particle physics could be resolved and a whole new era of discovery, both theoretical and experimental, would begin. If the predictions of SUSY do not reveal themselves at the LHC, our Standard Model of the Universe, as elegant and powerful as it has proven to be, will remain an incomplete picture. Where will our explorations take us next? Only time will tell.

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