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A SEARCH FOR EXOTIC PARTICLES OF CHARGE 5/3 WITH THE CMS DETECTOR

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Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

ABSTRACT

Short summary of the contents in English. . .

ZUSAMMENFASSUNG

Kurze Zusammenfassung des Inhaltes in deutscher Sprache. . .

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— **?** [**?**]

ACKNOWLEDGMENTS

Put your acknowledgments here.

Many thanks to everybody who already sent me a postcard!

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1 Members of GuIT (Gruppo Italiano Utilizzatori di TeX e LaTeX)

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1 THE THEORY OF THE TOP PARTNERS

1.1 THE STANDARD MODEL

The SM is a quantum field theory developed in the 1970s. It describes matter and the electromagnetic, weak and strong nuclear forces in terms of point-like particles.

The most profound insight in the SM is that all of these interactions are determined by symmetry principles, called local gauge symmetries. This idea is connected with the fact that the conserved physical quantities, e. g.electric charge, are conserved at every point in space-time, and not just globally. This connection is given by Nöther's theorem in the lagrangian formalism.

The treatment of one particular property of the particles requires some ingenuity. Mass terms are not allowed in the SM lagrangian, because they break the fundamental symmetry principles. Yet it is obvious from observation that most particles have mass. The Higgs mechanism with spontaneous symmetry breaking was devised to solve this problem, and appears to be close to experimental confirmation at the time of writing.

We will first review the features of the unbroken SM, then introduce the Higgs field and finally present some shortcomings of this theoretical description.

A complete description can be found elsewhere, the following section will highlight the material that is relevant to the problems we are investigating in the rest of our work.

1.1.1 *The unbroken SM*

All of the matter particles in the SM are fermions, and are usually divided in two categories: particles that feel the strong force, called *quarks*, and particles that do not, called *leptons*. Quarks and leptons are grouped into three *families* or *generations*. Particles from different generations have exactly the same properties, except for mass. The origin of this family structure is still unknown.

A force is introduced by requiring the lagrangian for the matter fields to be invariant under a group of space-time dependent transformations, called *gauge* transformations.

The theory of QED was the first succesful gauge theory. It describes the electromagnetic force, with a $U(1)$ gauge invariance. As a consequence, a *gauge boson* has to be introduced to preserve the local symmetry, that is the photon.

The electromagnetic and weak forces are then unified by a gauge group $SU(2)_L \times U(1)_Y$, with the L subscript denoting the fact that the $SU(2)$ gauge transformations only involve the left-handed fermions. The Y subscript is intended to indicate that this $U(1)_Y$ group is not the same as the aforementioned group for QED. The number of gauge bosons must be the same as the dimension of the gauge group, so that we now get four vector bosons: the photon, the $W^{\pm}$ and the Z.

The description of the strong force involves the group $SU(3)$. The charge of the strong force is called *colour*, it is carried by eight bosons called *gluons*. Figure 1 summarizes the particle contents of the unbroken SM.

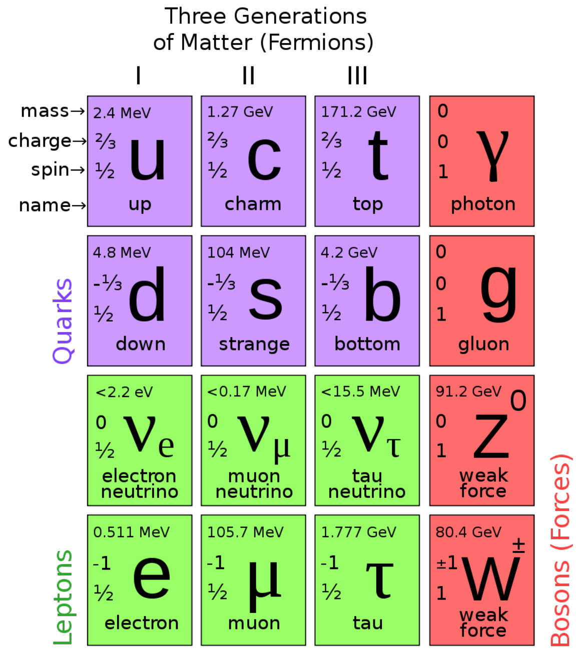

Figure 1: The particles in the unbroken SM.

1.1.2 *Spontaneous simmetry breaking: the Higgs mechanism*

We have only considered massless particles. This is not the case for all the known fermions, and for the Wand Zbosons. A mechanism was proposed to preserve the gauge invariance of the lagrangian, while the vacuum state is no longer a singlet under the action of the gauge group.

Spontaneous symmetry breaking of the local gauge symmetry in the SM provides massive Wand Zbosons and a new boson, called the Higgs boson. In addition, we can obtain massive fermions by coupling them to the Higgs field with Yukawa terms.

1.1.3 *The hierarchy problem*

Recently found evidence for a light Higgs boson, with a mass near 125 GeV, are thought to be an indication of new symmetries and new particles beyond the SM.

The theory predicts that the mass m_H is subject to large radiative corrections from loop diagrams similar to figure 3, that should increase it by a large amount. In the SM, fine tuning is required to prevent this corrections from becoming too large. Theoretical physicists generally dislike this fine tuning on grounds of *naturalness*.

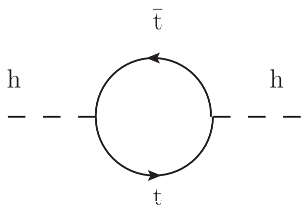

Figure 2: Radiative correction to the Higgs mass from the top quark.

The most notorious example of an extension to the SM that can eliminate this naturalness problem is supersimmetry, where the radiative corrections to the Higgs mass of the SM fermions are canceled by their superpartners.

There exist many theories that do not invoke supersimmetry as the solution to the hierarchy problem. A robust and generic prediction of many of them is the existence of new particles, the top partners, again balancing the largest contribution to m_H coming from the top quark.

1.1.4 *The top partners*

Theoretical developments predicting the existence of top partners stem from the search for a way of introducing gravity in the SM, while solving the hierarchy problem at the same time.

Five-dimensional space-time theories including gravity can be formulated in terms of effective 4-d lagrangians where SM quarks mix with the top partners, which, again from naturalness arguments, should have below or slightly above the TeV scale. The lightest quarks have a small mass, indicating that their mixing with the new particles is small. The top quark, having a very large mass, should have a sizeable mixing with its partner, possibly making deviation from the SM top interactions detectable at the LHC.

We use the top partner model from -REF mrazek wulzer- to describe our signal, with vertices with the vector bosons and the top quark. We study the possibility of observing the top partners in the very clean channel of two same-sign hard leptons. Typical production and decay diagrams are shown in figure **??**.

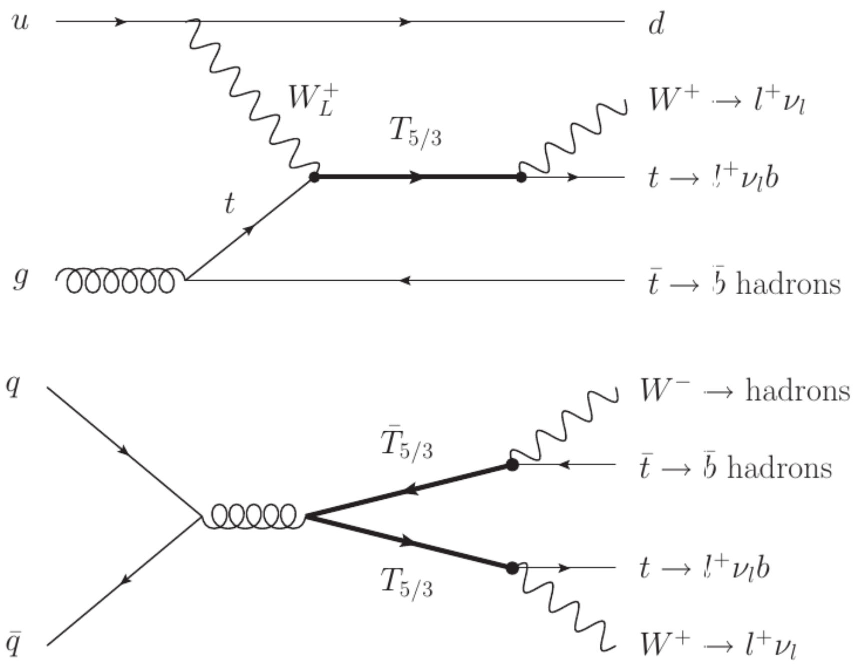

Figure 3: Typical single and pair production the top partner $T_{5/3}$ at the LHC.

2 THE LHC AND THE CMS DETECTOR

2.1 THE LARGE HADRON COLLIDER

The LHC is a ring-shaped proton-proton accelerator with a circumference of 27 km. It is hosted in a tunnel 45 to 170 m below ground at the CERN laboratory in Geneva, Switzerland. In 2011, the LHC accelerated two proton beams up to an energy of 3.5 TeV each and an instantaneous luminosity of up to $3.5 \cdot 10^{33}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The two proton beams are pre-accelerated through four smaller systems before being injected in the LHC:

- the linear accelerator (up to 50 MeV)
- the proton synchrotron booster (up to 1.4 GeV)
- the proton synchrotron (up to 26 GeV)
- the super proton synchrotron (up to 450 GeV)

The protons travel in ultra-high vacuum around 10^{-10} mbar, while different sets of magnets keep them in a circular orbit and provide acceleration and focusing.

Radio frequency cavities in the LHC accelerate the protons, providing an energy increase of 0.5 MeV/turn. Superconducting dipole magnets operate at currents of 11850 A to bend the trajectories of the protons with a magnetic field up to 8.3 T. Quadrupole magnets are employed to focus the beams, thus increasing the probability of an interaction when they collide. The magnets are cooled with superfluid helium at 1.9 K. The beams are made of "bunches" of protons with a time spacing of 75 ns.

At four different interaction points, the two proton beams are brought to collision where the experiments are located: CMS, ATLAS, LHCb and ALICE. The first two are general purpose detectors. LHCb is designed for the study of CP violation in b physics, and ALICE for the analysis of the quark-gluon plasma produced mainly in heavy ion collisions.

2.2 THE COMPACT MUON SOLENOID

CMS is a general purpose detector based on interlocking cylindrical subdetectors in the central *barrel* region, closed by two *endcaps*, all placed coaxially with the beam and centred on the beam interaction point.

2.2.1 *Coordinate convention*

The conventional coordinate system has its origin at the nominal interaction point. The z axis points along the beam direction, the y axis points vertically upwards, and the x axis points towards the centre of the LHC circumference. The xy plane is thus called the *transverse* plane as it is orthogonal to the CMS cylinder.

We define two angles in the transverse plane: the azimuthal φ angle is measured from the x axis, and the polar angle θ, measured from the z axis. *Pseudorapidity* is defined as $\eta = -\log\tan{}^{\theta}/_{2}$.

2.2.2 *Structure of the detector*

A global view and a transverse section of the detector are shown in figures 4 and 5.

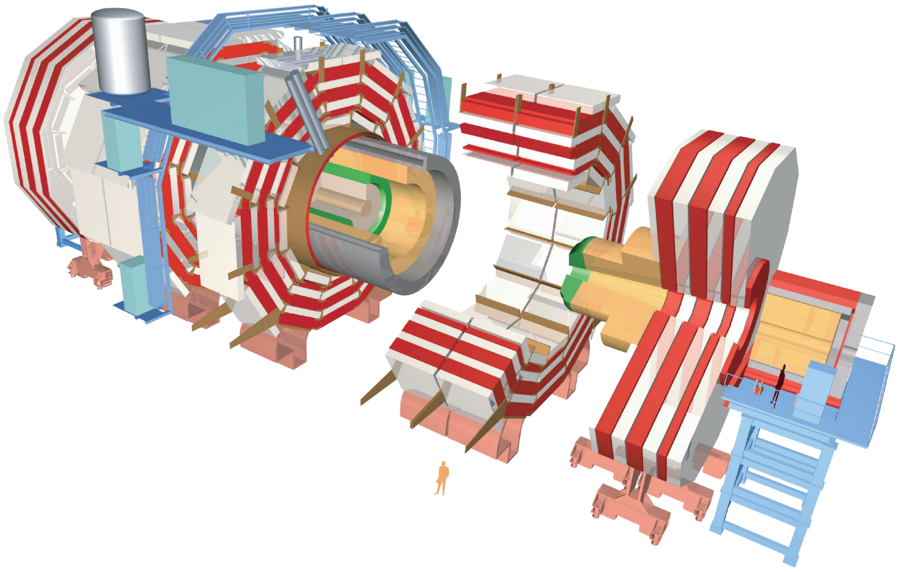

Figure 4: The CMS detector.

A superconducting solenoid 13.5 m and with a diameter of 5.9 m provides a uniform, axial magnetic field of 3.8 T. The return field saturates an iron yoke, which consists of five wheels in the barrel region and three disks in each of the two endcaps. Muon detectors are installed in the return yokes, with four stations of aluminium drift tubes in the barrel and cathode strip chambers with resistive plate chambers in the endcap.

The tracking system and the calorimeters are installed inside the solenoid. The tracker is a cylinder with a diameter of 2.6 m with three layers of pixel detectors, allowing exceptional measurements of the impact parameter of the particles and secondary vertex reconstruction, and ten layers of silicon microstrip detectors. The tracking system is surrounded by the calorimeters, which cover the region

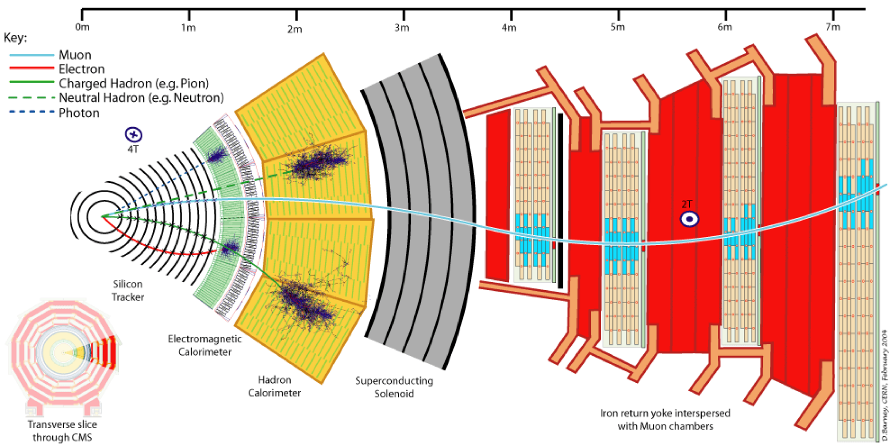

Figure 5: Transverse view of the CMS detector with sample tracks.

with $|\eta| < 3$. There is an electromagnetic calorimeter (ECAL), made of lead tungstate crystals and a brass/scintillator hadron calorimeter (HCAL). A forward calorimeter provides additional coverage up to $|\eta| < 5$.

2.2.3 *The tracking system*

Very high granularity and time resolutions are needed in the tough environment of the LHC experiments, with thousands of particles produced for every interaction. The high spatial resolution is particularly important in the region close to the primary interaction.

For these reasons, silicon detectors where chosen for the whole tracking system of the CMS experiment.

THE PIXEL DETECTOR is made of three cylinders in the barrel and two disks in each of the two endcaps. The spatial resolution on each hit is about 10 µm in r-φ and about 20 µm in z.

THE MICROSTRIP DETECTOR is made of concentrical layers in the barrel region, divided in two systems: the *tracker inner barrel* (TIB) and the *tracker outer barrel* (TOB).

The TIB has four layers in the region with $20\,\mathrm{cm} < r < 55\,\mathrm{cm}$ and $|z| < 65\,\mathrm{cm}$. The sensors are 10 cm long in z, 80 to 120 µm wide and 320 µm thick. The single hit resolution is between 23 and 34 µm in the r-φ plane, and about 230 µm in z.

The TOB module is made of six layers, covering $55\,\mathrm{cm} < r < 116\,\mathrm{cm}$ and $|z| < 116\,\mathrm{cm}$. The sensors have a length of 25 cm, a width of 180 µm and a thickness of 500 µm. The single hit resolution is 35 to 52 µm in the r-φ coordinates, and 530 µm in z.

Two more modules are installed in the endcaps, arranged around the beam line: the *tracker inner disks* (TID) and *tracker outer endcaps* (TEC)

Each TEC module consists of nine disks, while the TID have three smaller disks. Both these modules have strips pointing radially toward the beam line with a thickness of 320 µm to 500 µ m.

2.2.4 *The electromagnetic calorimeter*

The ECAL is the inner calorimeter, made of 61200 lead tungstate crystals in the barrel and 7324 crystals in the endcaps. The base of the crystals is about 2×2 cm in size, with a depth of 23 cm, corresponding to 25 radiation lengths.

The scintillation light is collected by avalanche photodiodes in the barrel and vacuum phototriodes in the endcaps. They have a high gain and are insensitive to the magnetic field of the detector.

The energy resolution of the calorimeter has been measured in $Z \rightarrow ee$ events from the 2011 data [**?**], as shown in figure 6.

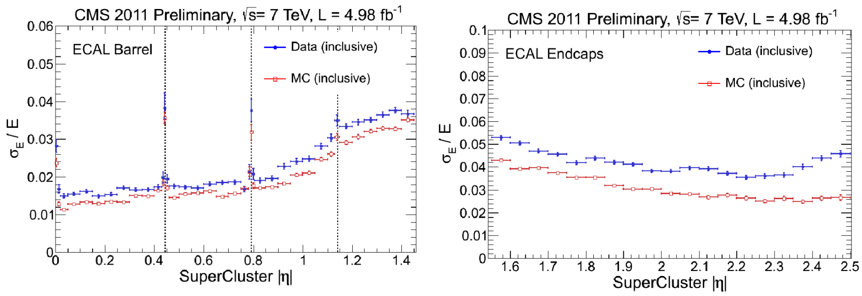

Figure 6: Energy resolution of the ECAL as measured in $Z \rightarrow ee$ events in the 2011 data.

2.2.5 *The hadron calorimeter*

The HCAL surrounds the ECAL and is made of plastic scintillators interleaved with brass layers.