On The Possible Detection Of Massive Stable Exotic Particles At The LHC

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Abstract

The possible detection of massive quasi-stable exotic particles at the high luminosity hadronic colliders is discussed. In the coming ten years the LHC, now under preparation, has the best opportunity to observe them at the TeV scale. The present design of the ATLAS detector, that has been almost irreversibly decided, may turn out to be flexible enough to allow the detection of this interesting class of exotic particles. The trigger acceptance, the track reconstruction and the particle identification are studied. The necessity of a good measurement of the ionization loss in the muon sector of the detectors is recommended.

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1 Introduction

In the next years the Large Hadron Collider (LHC) will be the main instrument potentially capable of producing new particles beyond the Standard Model over a wide mass range around the TeV scale.

There are a lot of possible extensions of the Standard Model, like SUSY, compositeness, grand unification, left-right symmetric models etc., that foresee a specific enlargement of the known particle spectrum with exotic not yet observed states. The physics for LHC beyond the Standard Model has been extensively studied at the LHC workshop (Aachen 1990)[1] and there is also an excellent review of this subject in the proceedings of the workshop for the SSC (Berkeley 1987)[2].

In this article we consider an interesting, wide-ranging, class of exotic particles that are characterized by a few model independent common features:

a) they have large masses and are produced with $\beta < 1$ at the collider;
b) they are stable or quasi-stable, i.e. their life-time must be larger than $10^{-7}$ s, so that they decay outside the detector;
c) they have electric charge either integer or fractional multiple of the proton charge.

Actually, several theories beyond the Standard Model foresee charged particles, both hadrons and leptons, with large masses and, although many exotic particles are unstable, often the lowest (or the next-to-the lowest) lying state may be stable or quasi-stable[3][4]. Throughout this article we call them Massive Stable Exotic (MSE) particles.

Here we briefly review some of the results of the most recent searches based on this philosophy. One example of MSE is given by heavy quarks belonging to higher representations of $SU(3)_C$[5]. Recently a color sextet of quarks $Q$ has been proposed in order to explain the dynamical breaking of the electroweak symmetry [6]. The quark sextet, taking the role of a condensate, forms a doublet of weak $SU(2)_L$ (U D) with mass range: $300 < m_U, m_D < 400$ GeV/$c^2$. The lightest state of these quarks may be stable or it may decay into normal quark and long-lived leptons after being hadronized in an exotic colorless hadron.

The cross-section of this exotic reaction, which has been calculated in the gluon fusion model in ref. [6], turns out to be around one order of magnitude greater than the top quark production cross-section because of the larger color factors of the sextet.
The CDF collaboration at the TEVATRON has published several analyses setting upper limits on the MSE particles cross-sections, see ref. [7] and references therein. The theoretical cross-sections have been used by CDF to set bounds on the mass of fermionic color triplets, sextets, etc. In particular, at the Warsaw Conference [7], CDF has presented a search for particles with low velocity, \( \beta \gamma < 0.65 \), with \( p_T > 30 \text{ GeV}/c \) and \( dE/dx \geq 1.8 \) (2.5) times larger than expected for a particle at minimum in the central tracker (silicon tracker). The non-observation of MSE particles is used preliminarily to set a lower limit of 190 GeV/c\(^2\) on the mass of a stable color triplet quark.

Other examples of MSE particles come from SUSY. In ref. [8] the production of MSE particles at the hadronic colliders has been examined and also the production cross-sections for different types of SUSY MSE particles together with a detailed study of their experimental signatures has been reported. For these channels, the value of the cross-sections are lower than the top quark pair cross-section but there is still a large range of the parameters for which the reaction is potentially visible at LHC.

In some realizations of SUSY, there can be charged, long-lived supersymmetric particles like charginos or staus that behave like MSE particles.

At LEP1, searches for MSE particles were performed [9] obtaining the limit (ALEPH) on the production cross-section of \( \sim 1.5 \text{ pb} \) at 95% CL in the mass range \( 34 \div 44 \text{ GeV}/c^2 \). At LEP2, both ALEPH [10] and DELPHI [11] have searched for MSE particles up to \( \sqrt{s} = 172 \text{ GeV} \). DELPHI gives upper limits at 95% CL on the cross-section of pair-produced MSE particles in the range of \( 0.4 \div 2.3 \text{ pb} \) for masses from 45 to 84 GeV/c\(^2\) and electric charge \( \pm e \) and \( \pm 2/3 e \). ALEPH gives a model independent at 95% CL upper limit on the production cross-section of \( 0.2 \div 0.4 \text{ pb} \) for masses between 45 and 86 GeV/c\(^2\). All these (unsuccessful) searches could only establish the upper limits we reported.

These results imply, when converted in limits on SUSY particles, that long-lived charginos are excluded for masses below 86 GeV/c\(^2\) and long-lived left-handed (right-handed) smuons and staus below 68(65) GeV/c\(^2\).

The energy loss in matter of an MSE particle has been carefully studied in ref. [8] (see also ref. [3]). As far as the energy loss for ionization is concerned, for \( \beta > \frac{1}{2} \) and for particles with \( M > 100 \text{ GeV}/c^2 \) the range in iron exceeds several meters and increases with \( M \). Moreover, for strongly interacting MSE particles the penetration length in matter does not change significantly for \( \beta \leq 0.7 \) and \( M = 100 \text{ GeV}/c^2 \).
Nevertheless, it is important to note that an MSE particle, because of its low $\beta$ value, produces an anomalous energy loss for ionization in matter that can be used as a distinctive feature for its identification.

This discussion supports the statement that an MSE behaves like a massive muon with a velocity considerably lower than $c$ and consequently with high energy losses in matter. Therefore the selection and identification of an MSE particle may naturally be done measuring the time of flight, the momentum and the ionization of a particle that is able to escape from hadronic calorimeter. Following these lines two of us have already discussed, in a previous note [12], the problems connected with the detection of MSE particles at LHC with the air-core apparatus ATLAS. In particular in that paper it has been suggested to add to the apparatus a specialized "window" devoted to the observation of MSE particles.

At the present stage of the design of the LHC detectors, the complexity of the structures makes it unthinkable to add specific sectors inside the detectors and anyhow we leave these windows to the rather distant future. Here and in the rest of this article we focus the discussion on the case of the ATLAS detector. For the sake of completeness we have shown in Figs. 1 the present design of the ATLAS detector [13].

Nevertheless, we believe that it is important and still possible to maintain in LHC the capacity to search for exotic particles like MSE, undertaking some final decisions on the MDT detector and using suitable off-line algorithms for the event reconstruction.

In this paper we analyse the present design of ATLAS in order to verify how its structures could allow the detection of MSE particles taking into account the specific qualities we have stated before, and without altering the hardware design. As we have already stated, this is the main point of this note.

2 Trigger Acceptance of MSE Particles

First of all we have to check the possibility that an MSE particle can be accepted by the trigger. At LHC the bunch crossing rate of 25 ns and the high luminosity set stringent limits on the trigger.

The ATLAS trigger [13] is organized in three sequential levels which must
reduce the initial input rate of 40 MHz to the first level trigger progressively to a rate of $\sim 100$ Hz; that is the maximum input rate of the data storage system and corresponds to an acquisition of $\sim 100$ MB/s.

In the following we will ascertain the possibility that an MSE particle is accepted by the first level trigger that is the most rapid and almost completely hard-wired. We consider the implications of the higher trigger levels a less severe problem, which can be addressed in the future.

Assuming that an MSE particle is similar to massive muon, we now study the possibility that the first level muon trigger may allow the detection of an MSE particle.

In ATLAS, the muon trigger is composed by 3 stations each made of 2 RPCs (Resistive Plate Chambers) read out in the 2 orthogonal views, located at $\sim 7.0 \sim 7.5 \sim 10.5$ m (we call them station 1, 2, 3 respectively) from the beam line. The RPCs are the most rapid detectors of the apparatus: they have a typical gaussian time resolution $\sigma = 1.5$ ns. Taking into account the signal delay along the collecting strips, the muon trigger system assigns a temporal gate that is, in one of the possible choices, of 18 ns to each RPC in order to allow an efficient temporal coincidence of the innermost and the outermost trigger stations to the crossing of a high energy muon. After that, the event is stored in pipe-line memories, inside the apparatus, waiting for the decision of the first level trigger. If the track gets a valid identification, the event is taken and the data go to the second level trigger, otherwise the event is lost. The decision to acquire the data from the pipe-line must be taken in a maximum time of $2.5 \mu s$ that is the latency time of the first level trigger.

The RPCs (and all the other part of the apparatus) are locally synchronized with the LHC clock of 25 ns taking into account the relativistic delay among different parts due to the relative distance. This fact is a potential source of rejection of an MSE particle with $\beta < 1$. However the temporal gate of 18 ns provides a window large enough for the detection of MSE particles as we will show.

We distinguish two muon trigger schemes: one is the same trigger proposed for high luminosity ($\sim 10^{34} cm^{-2}s^{-1}$) and high $p_T$ ($\geq 20$ GeV/c) muons in which all the three stations of RPC are in coincidence. The second is the trigger proposed for low $p_T$ ($\geq 6$ GeV/c) muons and low luminosity ($\sim 10^{33} cm^{-2}s^{-1}$) in which only the two inner stations (1 and 2) are in coincidence (see Fig. 1).
We call these two trigger schemes trigger A and trigger B respectively. In both cases the first level trigger accepts the event when a coincidence is obtained among the three (or two in the scheme B) temporal windows of 18 ns. In this case the data taken from the RPCs are labelled by a bunch crossing number which identifies the event, this number is the same for the data of the same event coming from the other detectors of the apparatus.

In Fig. 2 we give an estimate, based on the parameters explained above, of the trigger efficiency for schemes A and B, normalized to the trigger efficiency for an ultra-relativistic muon, as a function of $\beta$ for particles coming out of the inner detector. We see that, for the trigger A, at $\beta = 0.5$ we still have a good efficiency ($\sim 50\%$) that decreases rapidly and approaches 0 at $\beta \sim 0.35$. This is due to the fact that the trigger does not require the bunch crossing time as a further coincidence. The main coincidence is then between station 1 and 3 that are at a distance of $\sim 3$ m; in this case 18 ns is a large enough time to accept MSE particles with $\beta \geq 0.5$.

For the sake of completeness in Figs. 3A and 3B we have shown the main features of an MSE particle coming out from the central calorimeter with velocity $\beta c$. In Fig. 3A we have reported the delay (ns/m) of an MSE particle with respect to an ultra-relativistic particle, and in Fig. 3B we have plotted the energy loss rate normalized to its minimum value. In the case of trigger B, because of the small distance ($\sim 0.5$ m) between the two RPC stations, the efficiency remains high over a larger region, and goes down at a very low $\beta$ value: $\beta \sim 0.15$. We must note that trigger B can be used only when LHC runs at low luminosity, because it does not guarantee the necessary background rejection in the case of high luminosity.

On the other hand, due to the very fast increase of the energy loss with decreasing $\beta$ values, the MSE particle may stop inside the hadronic calorimeter. In Fig. 4 we have shown the range of an MSE particle in iron as a function of $\beta$ for $M = 0.2, 0.6$ and 1 TeV/$c^2$. Considering that the inner calorimeter system corresponds to about 2 m of iron, we see that only MSE particles with masses $M \geq 1$ TeV/$c^2$ could escape off the calorimeter when $\beta \leq 0.25$. An MSE particle stopped inside the calorimeter is typically lost because the kinetic energy deposited into the calorimeter is, in almost every case, below the threshold of the hadron calorimeter trigger. In any case the calorimeter system will contribute to the MSE identification with the measurements of the energy deposition, particularly in the more external layer.
3 MSE Particle Identification

The track identification of an MSE particle escaping the hadronic calorimeter in the high $p_T$ muon region is the natural task of the ATLAS specialized structure of precision chambers, composed of MDTs (Monitored Drift Tubes), which are dedicated to determining, with a good precision, the position of a charge particle.

We recall that in this region an air-core toroidal superconducting magnet generates a magnetic field of about 0.5 T to allow the measurements of particle momentum. The precision chambers are composed by two multilayers, and each of them is composed of three (four in the inner station) MDT layers. A typical track goes through about twenty MDTs before escaping from the apparatus. A single MDT is a cylindrical counter of 3 cm diameter; it is basically filled with Argon at 3 atmosphere absolute pressure. It has a typical spatial resolution $\sigma = 80 \, \mu\text{m}$ and a maximum drift time of 500 ns. The resulting spatial resolution for the single particle is about $30 \, \mu\text{m}[14]$.

When an event has been accepted by the first level trigger, all the data coming from the MDTs for the following 500 ns are labelled with the bunch crossing number and are extracted from the pipe-line memories. The track reconstruction for an MSE particle will be done by taking into account in the hit analysis the delay along the track due to $\beta < 1$. Note that there is the possibility (depending on the position of the crossing point respect to the MDT wire) that the more delayed hits could be associated with the following bunch crossing number. This is a problem that must be faced in a more complete analysis. Here we want to note that due to the large MDT drift time (500 ns) this effect should be very small.

In order to estimate the mass measurement accuracy of an MSE particle, it is necessary to know the error in the measurement of the $\beta$ value that is connected to the MDT intrinsic space resolution and to the maximum drift time.

By combining the time measurements available from MDTs and RPCs along the particle trajectory we get a conservative estimate for the $\beta$ accuracy:

$$\frac{\Delta \beta}{\beta} \simeq 0.1 \cdot \beta .$$

The measurement of the mass $M$ of the MSE particle is obtained using
the relation \( M = P/\beta \gamma \), and the error is given by

\[
\Delta M/M = \sqrt{(\Delta p/p)^2 + (\Delta \beta \gamma/\beta \gamma)^2}.
\]

The term \( \Delta \beta \gamma/\beta \gamma \) satisfies the relation

\[
\frac{\Delta \beta \gamma}{\beta \gamma} = \gamma^2 \frac{\Delta \beta}{\beta} \simeq 0.1 \cdot \gamma^2 \beta
\]

and dominates, over a large range of \( \beta \), the term \( \Delta p/p \simeq 0.025 \div 0.10 \) for the ATLAS muon spectrometer\textsuperscript{[13]}. Therefore we conclude that the MSE mass can be measured with a resolution of the order of 10%.

Besides the strong signature of the delay needed to reconstruct the track, a MSE particle is identified by the energy loss for ionization that can be much higher than that of muon at minimum. We see, from Fig. 3B, that already at \( \beta \simeq 0.6 \) the energy loss is around twice the minimum and of course it increases rapidly for a lower value of \( \beta \). Already with a specific ionization of twice the minimum, the deposit of primary charge into the twenty MDTs through which the MSE particle passed will be statistically recognizable. Therefore the signature of high energy loss is a powerful physical quantity that must be considered to make a clear identification of an MSE particle.

Up to now, the MDT front-end electronics is not completely settled. A feasibility study to achieve a measurement of charge in the MDTs front end equipment is under way\textsuperscript{[14]}. We know that the economical convenience to measure the charge in each channel is still under discussion. This measurement is important from the general point of view to distinguish real muon tracks from the background of neutron and gamma hits. We underline here that the measurement of \( dE/dx \) in the MDTs is also fundamental to any future hope to observe MSE particles.

4 Conclusion

We believe that there are excellent reasons for looking for MSE particles. It is important that this search be done at the LHC accelerator, which will keep the energy and luminosity supremacy for many years. As we said, the range of MSE particles with a remarkable ionization loss may be quite high.
We have seen that the first level muon trigger allows the gathering of MSE particle data over a large space of the MSE particle parameters (mass and $\beta$).

For the runs at low luminosity, the muon trigger made by two RPC layers provides a larger window. The track reconstruction of an MSE particle must take into account the temporal delay of these particles, and this delay is the first strong signature of an MSE particle. The measure of the ionization losses in the MDTs which is, in our opinion, of great importance, will strongly improve the identification of MSE particles in the muon system. The inner detector and the hadronic calorimeter can complete the track reconstruction.

The present analysis of this problem is far from being complete. In fact the higher levels of the muon trigger ought to be studied and the track reconstruction for an MSE particle should be evaluated with the necessary accuracy. We think also that other methods could be followed in the research of MSE particles with the ATLAS detector.

The aim of this note is to point out that the strategy of searching for MSE particles is an important field of study which can be investigated at the LHC with the present ATLAS detector.

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6 Figure Captions

Fig. 1:
Side view of a quarter of the ATLAS detector showing the locations of different subsystems (taken from ref.[13]). In the innermost part of the apparatus is visible the inner tracker (IT); the electromagnetic and hadron calorimeter are indicated respectively by EM and HC. The muon system in the barrell extends from about 5 to 10 m in radius and is composed by three tracking stations and three trigger stations indicated respectively MDT and RPC Stations 1, 2, 3. The barrell region extends over $|\eta| \leq 1.05$. In the figure the layout of the forward muon system is also shown.

Fig. 2:
Estimate of the (muon) trigger efficiency (normalized to the efficiency of an ultra-relativistic muon) as a function of the $\beta$ values of an MSE particle escaping the central calorimeter. The curves (A) and (B) refer to trigger scheme A and B respectively.

Fig. 3:
A) Delay per meter of a particle as a function of $\beta$.
B) Energy loss rate normalized to the value at the minimum as a function of $\beta$. The scale in $\beta\gamma = \beta/\sqrt{1-\beta^2}$ is also shown.

Fig. 4:
Range of an MSE particle in iron as a function of $\beta$ for three different mass values. Note that the central calorimeter corresponds to about 2 m of iron. The scale in $\beta\gamma$ is also shown.
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