Signatures of long-lived colored sparticles

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September 28, 2009

Abstract

In this paper an updated Geant-4 simulation toolkit is presented describing the interactions in matter of heavy hadrons containing long-lived squarks and gluinos. Generic signatures are derived that are applicable at the Large Hadron Collider, and the problem of theoretical uncertainties arising from model dependence is addressed. For a more detailed description of the assumptions and techniques used, the reader is referred to ref. [1].

1 Introduction

Stable massive particles (SMPs) are a feature of many models of physics beyond the Standard Model [2, 3]. Exclusively weakly interacting SMPs may be searched for utilising the induced missing transverse energy in events where they are created. Electromagnetically charged SMPs (e.g. sleptons) may be recognized by their ionisation properties as they traverse a detector as well as (depending on their mass) their time of flight. Particles carrying colour charge on the other hand exhibit a phenomenology of somewhat larger complexity. Squarks and gluinos for instance will form hadrons (hereafter termed R-hadrons in accordance with litterature) that will then undergo not only electromagnetic but also hadronic processes in the traversed matter. This work describes an implementation of a Geant-4 toolkit describing scattering of R-hadrons in matter. The toolkit is described in detail in refs. [1, 5] and is based on previous works [6, 7].

2 Scattering of heavy hadrons

When describing the scattering of the heavy hadrons formed by long-lived squarks or gluinos as they traverse a detector, two questions become important:

\footnote{Here taken to mean that the decay length is larger than a typical collider physics experiment.}
What are the stable hadronic states, and what are their scattering properties? Answers to both questions, of course highly model dependent. Previous approaches [7, 6] have employed liberal assumptions with respect to the possible stable states allowing for all combinations of $u$ and $d$ quarks to combine with the heavy sparticle to form hadrons. For this work, a number of different mass calculations have been taken into account [8, 9, 10, 11, 12]. From these calculations a consistent set of masses can be chosen as shown in table 1.

| Heavy Parton | States          | Mass (GeV) |
|-------------|----------------|------------|
| Squark      | $\tilde{q}u, \tilde{q}d$ | $m_{\tilde{q}} + 0.3$ |
|             | $\tilde{q}ud$    | $m_{\tilde{q}} + 0.7$ |
| Gluino      | $\tilde{g}q\tilde{q}, \tilde{g}ud, \tilde{g}d\tilde{u}, \tilde{g}g$ | $m_{\tilde{g}} + 0.7$ |
|             | $\tilde{g}uds$   | $m_{\tilde{g}} + 0.7$ |

Table 1: Assumed stable hadrons formed from squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), together with mass estimates used in this work. The neutral gluino states containing a mixture $u\bar{u}$ and $d\bar{d}$ pairs are generically denoted by $\tilde{g}q\tilde{q}$.

Of particular interest in table 1 is the observation that especially the baryonic states are constrained. For instance there can be no $\tilde{g}uu^{++}$ or $\tilde{g}uuu^{++}$ states.

Turning to the scattering of the particles themselves, the toolkit used was based on that presented in [7]. The software framework and the treatment of nuclear effects such as nuclear evaporation and creation of black track particles was left unchanged. The innovations were the implementation of a theory driven scattering cross section and a different approach to the transmutation of the R-hadrons themselves.

The cross section calculation used stems from the model presented in ref. [13] (the Regge model). It is depicted in figure 1 together with the predictions from the previous model (refs. [6, 7], hereafter referred to as the generic model). For the specific formulae the reader is referred to ref. [1]. Final states in the individual hadronic interaction are chosen randomly among the kinematically allowed processes with the constraint that meson states should turn into baryon states with a 10% probability. Once an $R$-hadron becomes a baryon it cannot turn back into a meson by subsequent hadronic collisions as was first noted in [6].

Another process that must be taken into account is the possibility that neutral squark mesoninos may oscillate into their anti-particle. As mixing of such states would be highly model dependent we allow only for the cases of no mixing and maximal mixing, where there is a 50% probability for any neutral squark mesonino to turn into its anti-particle. These choices correspond to oscillation lengths of zero and infinity, respectively.
3 Signatures deriving from hadronic interactions

The heavy sparticle is typically orders of magnitude heavier than the light quark system (LQS) of the R-hadron. As the scale (i.e. geometric cross section) of a wave function is inversely proportional to the square of the mass [6], any hadronic interaction is assumed to take place between a nucleon and the LQS of the R-hadron. The kinetic energy of the LQS system scaling with $M_{\text{LQS}}^2$, $E_{\text{kin},\text{Total}}$ therefore represents a measure of the available energy in any collision. This is consistent with the observed energy loss per hadronic inter-

Figure 2: Left: Energy loss per hadronic interaction for stop hadrons in iron is shown for the Regge model with and without mixing as well as the generic model. Right: Total energy loss for R-hadrons traversing 2 m of iron action shown in figure 2 (left). Generating gluino pair-production events with Pythia[13] for $pp$ collisions at a centre-of-mass energy of 14 TeV, kinematic distributions were obtained for R-hadrons. R-hadrons were subsequently simulated traversing 2 m of iron to estimate their behaviour in an LHC experiment [15]. The results showed that the different types of R-hadrons would undergo
These observations imply that R-hadrons at the LHC experiments will interact hadronically but that they will not through these interactions give rise to anything that might be interpreted as hard jets.

Using similarly generated kinematics as for the energy loss observations, the distributions of R-hadrons on the different flavours in table 1 were studied as a function of penetration depth in iron. As is shown in figure 3 (left), gluino R-hadrons have a \( \sim 50\% \) probability of being baryons after traversing 2 m of iron. Of the remaining R-mesons, roughly half will be electrically neutral. The stopped fraction of the R-hadrons is on the order of a few percent. Comparing these numbers to the stop and sbottom cases, one needs to consider both squarks and anti-squarks for the minimal and maximal mixing scenarios. This is done in the table in figure 3 (right) where the gluino numbers are also included for comparison. As can be seen, the fraction of stopped R-hadrons is in all cases 3-8\%. Gluino and sbottom hadrons in all scenarios are found to be predominantly neutral while the stop is found to have a charged fraction of roughly 2/3. These observations are not greatly diluted when mixing is enabled.

It turns out that there is little impact on these conclusions by varying the meson/baryon mass splittings in the model. Varying the mass splitting by 1 GeV moves the predictions less than one percent. Varying the hadronic cross section by a factor of 2 produces an effect of O(10\%) in the predictions. The scattering cross section thus remains a key ingredient in the estimation of the theoretical uncertainties for the scattering of heavy hadrons containing coloured sparticles. Should it turn out that more baryonic states of squark or gluino hadrons exists, the prediction of this model would of course also be altered.
4 Acknowledgements

The author wishes to acknowledge his fruitful collaboration with prof. D.A. Milstead, Stockholm University.

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