Exotics

Unusual Energy Deposition, Timing, and Tracks

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Signature Keywords: Exotics, CHAMPS, kinks, weird tracks, intermittent tracks, reduced hits, new stable particles, fractional charge

Model Keywords: Supersymmetry (GMSB), Quirks

Disclaimer

This note is still very preliminary. Please use with caution. For more details, MC implementations or updates, please contact one of the authors.

I. INTRODUCTION

This note describes simplified models that lead to an unusual energy deposition ("dE/dx") or timing in the HCAL, ECAL, or muon-chamber, or to weird tracks such as kinks, reduced hits in the tracker, or intermittent tracks. These signatures can all be obtained from minor changes to a small set of simplified models. They can be found in various new physics models, such as gauge-mediated supersymmetry breaking, quirks, supersymmetry (SUSY) with R-parity violation (RPV), split-SUSY, and monopoles (see PDG searches). Since some of these signatures are non-standard, they can also easily be missed at the trigger level.

We are interested in describing several effects. *Timing* is controlled by whether the particle is fast or slow moving[1]. The change in a particle's energy as it traverses the detector,

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[1] The particle does not have to be charged. An unstable particle that does not leave a track (or interact with the detector at all) may decay into two charged/interacting particles. Such a decay may not leave any kink if the mother particle is very slowly moving, but will register as an anomalous timing event. This possibility is also covered by the models below.

dE/dx, is controlled by how fast or slow the particle is moving as well as its charge. *Kinks* are produced when a charged particle decays into a neutral and another charged particle, producing a track with a sharp deviation. We distinguish this case from when a charged particle decays to multiple charged particles. In this case we assume searching for displaced vertices will be sufficient. *Intermittent tracks* are produced by particles that pick up or lose charge as they traverse the detector, and so alternate between being positively charged, neutral, and negatively charged. These tracks disappear and reappear, possibly bending the opposite way. A track with a *reduced number of hits* in the tracker can be caused by a particle that has only a fractional charge and thus has a reduced interaction with the detector. Our models below are aimed at manifesting these different effects.

II. SIMPLIFIED MODEL DEFINITION

We divide the model into **production** and **decay**. The operators responsible for the production of such particles are described below. We try to make that part generic and featureless since the physics we are interested in is not in the production mode. Conversely, we design the details of the particle representations and decay models to cover the full signature space, generating the physics of particles passing and interacting through the detector. We begin with the decay description.

A. Decay

Consider a new particle X, which is either resonantly-produced or pair-produced (the production is described below in §II B). We first consider the case when X is long-lived (stable on detector time-scales), and will below consider the case when X is unstable.

1. Stable X

X can be either colored ($\mathbf{3}$ or $\bar{\mathbf{3}}$ of the color group $SU(3)_c$, like the Standard Model quarks) or uncolored, but charged under the electroweak group. The parameters of the model with a long-lived X are

- σ_X, the production cross-section

- m_X, the mass
- q_X, the charge (can be zero or fractional)

The mass m_X together with the parton distribution functions for the production process control the velocity of X. Due to sharply falling parton distribution functions, the X is usually produced approximately on threshold without much kinetic energy. If X has zero charge, it appears as missing energy, unless it is unstable (see below). If X has a non-zero charge, it is called a "charged massive particle" (CHAMP). The parameter q_X controls the ionization of the particle. Varying the mass and charge can significantly change the resulting signatures. For instance, a slowly moving X, with $q_X = 1$ would be detected by a dE/dx measurement. Conversely, by decreasing the q_X one can mimic a standard dE/dx measurement, in which case timing in the muon chamber or calorimeter (depending on the Standard Model charges of X) would be necessary to measure the mass. Clearly, GEANT would require modifications in order to take into account non-standard charges.

In §III, we will discuss in detail the signatures that different m_X and q_X can produce. However, a larger class of signatures is obtained by considering an unstable particle X.

2. Unstable X

The velocity distribution of X is linked to the production process. In order to consider particles with different velocity distributions, we can consider X to be unstable. This allows the possibility of studying a fast moving CHAMP or late decay of a slowly moving neutral particle. By tuning the mass difference between X and its decay products (which now act as the CHAMPS) the velocity of the CHAMP can be adjusted.

To allow decays into charged particles, we consider the following part of the Lagrangian:

$$\mathcal{L} \supset XYZ \tag{1}$$

Here Y and Z are either neutral under $SU(3)_c$ if X is neutral, or otherwise one of the two must lie in the fundamental representation. We take Z to be massless, and consider the following parameters for this model:

- σ_X, the production cross-section
- $c\tau_X$, the lifetime of X

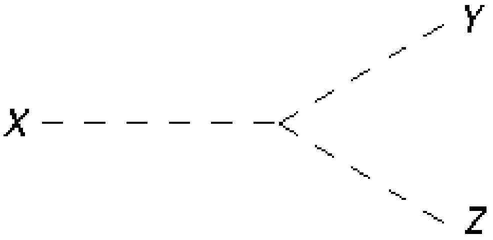

FIG. 1: If X particle decays then this diagram describe this process. The parameters associated with this process are m_X and τ_X (we take $m_Y, mZ \ll m_X$ since the other possibility is already covered by the case of stable X.

- m_X, the mass of X
- m_Y, the mass of Y
- q_X, the charge of X
- q_Y, the charge of Y

The charge of Z is given by $-q_X - q_Y$ and not an independent parameter. The decay diagram is shown in Fig. 1.

The charge of X can take any value, including zero. The case $q_X = 0$ is interesting for an unstable X (a stable neutral X would just appear as missing energy). The charges of Y and Z can take any value (including fractional charges and/or greater than unity). We note that the stable case described above is obtained by simply taking $c\tau_X \to \infty$.

B. Production

We now briefly describe the production mechanism. We want to stress that the production mechanism should not be used to search for these signatures since the interesting physics is in the decay. We give two production modes only in order to illustrate how such states can be produced and to facilitate a concrete Monte Carlo implementation. For the resonant production this model has overlap with the models considered by the *Resonance Working Group*.

If X is a scalar, then for resonance production we consider two possible couplings:

$$\mathcal{L} \supset \lambda q\bar{q}X \qquad \text{and/or} \qquad \mathcal{L} \supset \frac{1}{\Lambda} X \mathrm{tr} G_{\mu\nu} G^{\mu\nu} \tag{2}$$

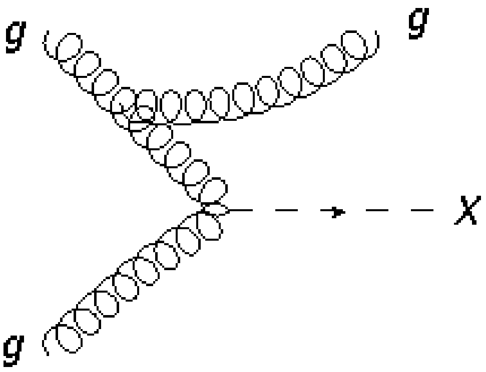

FIG. 2: Resonance production of the X particle with associated initial state radiation (ISR). A similar diagram can be made with quarks ($q\bar{q}$) in the initial state.

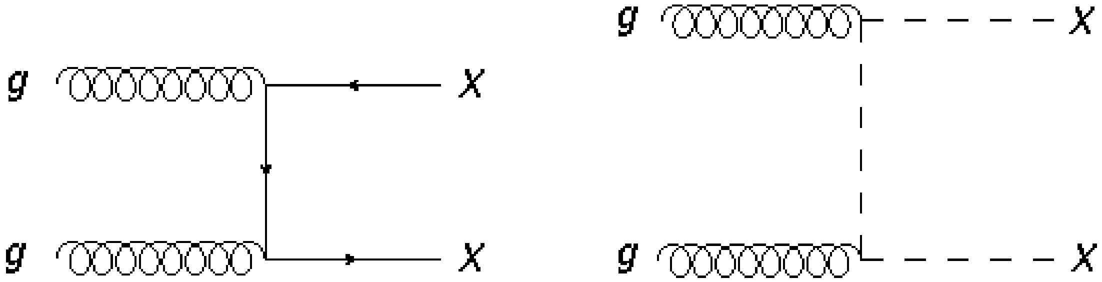

FIG. 3: Pair production of the X particle.

where for completeness we have included λ, an unimportant dimensionless coupling, and Λ, an unimportant mass scale. The fields q and $\bar{q}$ are Standard Model quarks, while $G_{\mu\nu}$ is the gluon field strength. The relevant diagrams are shown in Fig. 2.

For pair production we consider the following operators:

$$\mathcal{L} \supset \lambda\, q\, Q\, X \qquad \text{and/or} \qquad |D_\mu X|^2 \tag{3}$$

where Q is a heavy quark-like object (i.e. a fundamental of $SU(3)_c$), λ is again an unimportant dimensionless coupling, and D_μ is the covariant derivative including the gluon coupling in the case that X is a fundamental of $SU(3)_c$. The diagrams are shown in Fig. 3.

III. MAPPING THE SIMPLIFIED MODELS ON TO SIGNATURES

We summarize the matching of the simplified model on to signatures in Table I.

A. Anomalous dE/dx and Timing

This case is best described by a stable massive X. X can be electrically charged, or electrically neutral and charged under $SU(3)_c$, and accordingly it would be detected in the tracker or in the calorimeter. Typically, a charged X would leave an anomalous dE/dx signature (although, as mentioned above, a fractionally charged slowly moving particle can mimic this signature).

B. Anomalous dE/dx, but Normal Timing

As mentioned above, X typically decays at rest. This means that if we want to model fast-moving CHAMPS, we need to consider particles that come from the decay of X. In this case, X can be electrically charged or neutral and may or may not be charged under $SU(3)_c$. If X decays promptly (or at least within the detector) to Y and Z, with $m_Z = 0$ (as discussed in §II A 2), then Y can be a fast moving CHAMP. It would leave an anomalous dE/dx signature. Timing in the calorimeter or muon chamber can be used, depending on the representation of Y. However, due to the uncertainty in the velocity measurement, it may be difficult to separate Y from certain Standard Model particles using dE/dx and timing alone. For example, a fast moving long-lived slepton can mimic muons.

C. Kinks

The decay $X \to YZ$ in the detector, where X and Y are charged, and Z is neutral, leads to a track with a kink. The track is defined by its length (controlled by the lifetime $c\tau_X$) and by the angle of the tracks produced by X and Y, which is controlled by the masses m_X and m_Y (we have set $m_Z = 0$).

D. Reduced Hits

Reduced hits would occur for fractionally charged particles (FCPs). As with the CHAMPs, either a slowly moving FCP (stable X) or a fast moving FCP (Y with a promptly decaying X) can be considered. Charges to consider are $1/6 \lesssim Q < 1$. In the fast moving case, X may be neutral (in which case Y and Z are FCPs) or have fractional charge.

E. Highly Ionizing Tracks

Other than considering CHAMPs, this can be obviously achieved with $q_X > 1$. This signature is a special case of an anomalous dE/dx signature. A combination of timing and dE/dx measurements may (in some cases) be used simultaneously to establish anomalously large charges.

F. Intermittent Tracks

Finally, one can consider a stable electrically charged particle X that becomes neutral after traversing some length, then charged again after traversing some different length (the sign of the charge can be randomly assigned). While our simplified model does not directly describe this case, one could imagine simulating with GEANT the passage of such a particle through the detector.

IV. MATCHING THE SIMPLIFIED MODEL ON TO THEORIES

We summarize the matching of the simplified model on to theories in Table I.

- *CHAMPS* (see [1, 2] and references therein): These models can have integer or fractional charges. For slowly moving CHAMPs, one therefore considers, $m_X \gtrsim 150\,\mathrm{GeV}$, $c\tau_X \to \infty$, $q_X = 1, 2/3, 1/3, ...$, with an arbitrary cross-section. Similarly, for a fast moving track, $c\tau_X \lesssim 1$ meter, and Y carries similar charge and mass.
- *Quirks* ([3]): Here, close-by tracks produce large ionizing tracks and can therefore be mimicked by taking $m_X > \mathcal{O}(100)\,\mathrm{GeV}$, $c\tau_X \to \infty$ and $q_X \gtrsim 2$.
- *Gauge Mediated Supersymmetry Breaking (GMSB)* ([4, 5]): GMSB with a slepton as the next-to-lightest supersymmetric particle (NLSP) is an example of a CHAMP. In this case, the slepton once produced is long-lived and will reach the detector. We can take $m_X > \mathcal{O}(100)\,\mathrm{GeV}$ and Y as a slepton with $m_Y \gtrsim 100$ GeV to match GMSB. Z acts as the corresponding lepton. The NLSP can also be colored, e.g. squarks $\tilde{q}$ and gluinos $\tilde{g}$, hence acting as colored CHAMPS. These long-lived colored particles can also lead to intermittent highly ionizing tracks, similar to the case in split supersymmetry described below.

Signatures	Simplified Model	Theories
dE/dx + timing (slow)	$m_X \gtrsim 100\,\mathrm{GeV}$, $c\tau_X \to \infty$	Quirks, long-lived sparticles ($\tilde{l}$, $\tilde{t}_1$ ...)
dE/dx + timing (fast)	$m_X \gg m_Y \gtrsim 100\,\mathrm{GeV}$, $c\tau_X \to 0$, $c\tau_Y \to \infty$	same as above
kink	$q_X = q_Y \neq 0$, $q_Z = 0$, $c\tau_X \lesssim \mathcal{O}(1)m$	degenerate chargino/LSP
reduced hits	$1/6 \lesssim q_X < 1$, $c\tau_X \gtrsim \mathcal{O}(1)m$	fracitonally charged particles
Intermittent tracks	$m_X \gtrsim 100\,\mathrm{GeV}$, X color charged	long-lived gluino/squark

TABLE I: Matching simplified models to signatures and theories.

- *Degenerate chargino/LSP in Supersymmetry* ([6, 7]): The chargino NLSP here is long-lived with a lifetime determined by its mass difference with the LSP. It has all the features of a CHAMP, plus the additional signature of a kinky track if it decays inside the tracker. This can be described by the simplified model with $q_X = q_Y \neq 0$, $q_Z = 0$, $c\tau_X \lesssim \mathcal{O}(1)$ meter.

- *RPV*: The situation is similar to the GMSB case.

- *Split Supersymmetry* ([8]): Here, the superheavy squarks lead to a long-lived gluino, which hadronizes with either a gluon or light quark and antiquark to form what is generally referred to as an R-hadron bound state. An R-hadron can charge-exchange with detector material, yielding an intermittent charge exchange associated with a highly ionizing track.

V. RELEVANT VARIABLES/PLOTS

Along with the production mechanism there is an associated cross-section σ_X, which we leave as a free parameter (it is directly connected with the coupling of X to matter).

If X is stable, then the only two parameters are its mass and charge. Its mass, together with the production cross-section and the relevant parton distribution functions determine the velocity distribution of X at production. In general, for heavy X we expect it to be produced more or less on threshold.

If X is allowed to decay then its lifetime, τ_X, is another relevant parameter. Together with X's velocity distribution , the lifetime determines how far in the detector X travels before it decays. The mass splitting between m_X and m_Y determines the speed distribution of Y. In the case where $m_X \gg m_Y$ the mass m_Y only goes into determining the amount of ionization together with q_Y and the velocity of Y.

VI. EXISTING LIMITS

Recent searches for CHAMPS were reported in [1, 2].

A recent search for quirks was reported in [9]. A lower limit of 107 GeV was set on quirks that produce a high transverse momentum track with a large ionization-energy loss rate (dE/dX), together with a jet and missing transverse energy aligned with the track.

VII. POSSIBLE REACH

VIII. MC GENERATION

Monte carlo generation is straightforward, however ultimately useless in many cases. For stable R-hadrons or stau NLSP's, GEANT can handle the output of pythia and simulate a CHAMP in a detector. However, for the cases which do not fall into the category of a slow moving heavily ionizing particle there is no set standard for passing such a particle to GEANT. It would be useful to investigate the study of a fractionally charged particle or a stau NLSP which decayed on moderate distance scales within the detector.

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