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Measuring supersymmetry at the large hadron collider

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Abstract. The large hadron collider (LHC) should have the ability to detect supersymmetric particles if low-energy supersymmetry solves the hierarchy problem. Studies of the LHC detection reach, and the ability to measure properties of supersymmetric particles are currently underway. We highlight some of these, such as the reach in minimal supergravity space and correlation with a fine-tuning parameter, precision measurements of edge variables, anomaly- or gauge-mediated supersymmetry breaking. Supersymmetry with baryon-number violation seems at first glance more difficult to detect, but proves to be possible by using leptons from cascade decays.

Keywords. MSSM; R-parity violation; fine tuning.

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1. Introduction

The so-called technical hierarchy problem of the standard model (SM) refers to an aesthetic difficulty originating in radiative corrections to the masses of fundamental scalars. The Higgs field, used in the SM to break the electroweak symmetry and provide masses for quarks, leptons, and W and Z bosons, is a fundamental scalar and is therefore vulnerable to this difficulty. One-loop diagrams in the Higgs self-energy lead to quadratic divergences [1]. Viewing the SM as an effective theory, we consider an ultra-violet cut-off Λ of the order of highest energy scale of new physics in the theory. When the theory is renormalised, the Higgs mass receives corrections of the order of a loop factor multiplied by Λ, caused by some particle with a mass of that order running around the loop. Because we at least expect some new physics scale associated with gravity, or the Planck scale, $\sim 10^{19}$ GeV. The one-loop correction to the Higgs bare mass is then huge, but we know that in order to preserve perturbative unitary of WW scattering [2], the renormalised Higgs mass must be less than 1 TeV. We are therefore faced with cancelling a huge $O(10^{17})$ GeV radiative correction with a very large bare mass to leave a result of order 1 TeV or less. Thus, once the other masses in the high-scale theory are fixed, the bare Higgs mass must be set to cancel their radiative corrections to 15 decimal places. Since, on the face of it, the bare Higgs mass is not connected to the other masses of order Λ, this appears very unnatural and constitutes the technical hierarchy problem.

One possibility for new physics beyond the standard model that solves the technical hierarchy problem is low-energy supersymmetry (SUSY). If fermionic generators are added to the bosonic generators of the Lorentz group to form a graded Lie algebra, the new space-time symmetry is supersymmetry. As a result of exact supersymmetry, all particles have a partner of equal mass but opposite spin-statistics. The couplings of these 'superpartners' are constrained by supersymmetry to be identical to those of the originals, except for the space-time structure associated with spin. When self-energy corrections to the SM Higgs mass is calculated, the quadratically divergent piece cancels between particles and their superpartners [1], solving the technical hierarchy problem.

Since partners of SM particles with identical masses have not been observed, SUSY must be a broken symmetry if it exists in nature. The scale at which supersymmetry is broken, $M_{\rm SUSY}$, is the typical mass of the as-yet undiscovered superpartners of the standard model particles and represents the scale at which this new physics becomes relevant. Of course, we must be careful when breaking supersymmetry not to re-introduce the technical hierarchy problem, which was the main motivation for invoking supersymmetry. If we choose $m_{\tilde{\rm f}}^2 = m_{\rm f}^2 + \delta^2$, where $m_{\rm f}$ is the mass of the heaviest fermion in the theory and $m_{\tilde{\rm f}}$ is the mass of its superpartner, we obtain radiative corrections to the Higgs mass of the order of a loop factor multiplied by δ^2 (plus other terms logarithmically dependent upon masses). Thus, as long as $\delta < 1$ TeV or so, the Higgs mass is protected against radiative corrections from *arbitrarily heavy particles*. If typical values of δ are at or below the TeV scale, then supersymmetric particles will almost certainly be discovered at the large hadron collider, being built at CERN.

The LHC accelerator is a proton–proton collider that will be installed in the tunnel previously used by the LEP electron–positron collider at CERN. Protons intersect at four points where experiments are placed. Two of these are high luminosity regions and house the ATLAS and CMS detectors. The expected data samples are 30 (300) fb^{-1} per year in low (high) luminosity mode. The LHC can be thought of as a parton–parton collider with beams of partons of indefinite energy. The effective luminosity of these collisions is proportional to the pp luminosity and falls rapidly with the centre of mass energy of the parton–parton system. The combination of the higher energy and luminosity of the LHC compared to the highest energy collider currently operating, the Tevatron, implies that the accessible energy range is extended by approximately a factor of ten.

Though they differ in most details, the ATLAS and CMS detectors share some common features: lepton identification and precision measurement over $|\eta| < 2.5$, multi-layer silicon pixel tracker systems for heavy flavour tagging and large $|\eta| < 5$ calorimetric coverage in order to obtain the required missing transverse energy resolution, very important for many supersymmetry signals.

The simplest possible SUSY extension of the standard model, with a superpartner for each standard model particle, and the addition of a second Higgs scalar doublet, is called the minimal supersymmetric standard model (MSSM). The MSSM has received much attention in the literature, but supersymmetric phenomenology is so complicated that even this model still requires many studies of how to pin its parameters down in a more model-independent way. We will specialise to this model for the rest of the talk. Search capabilities of the CMS and ATLAS have been recently reviewed in the excellent article of ref. [3], which has some overlap with this talk.

2. Detection reach in minimal supergravity

The most studied sub-category of the MSSM is minimal supergravity, mSUGRA. Supergravity, where supersymmetry is a local, rather than a global symmetry, at one time mo-

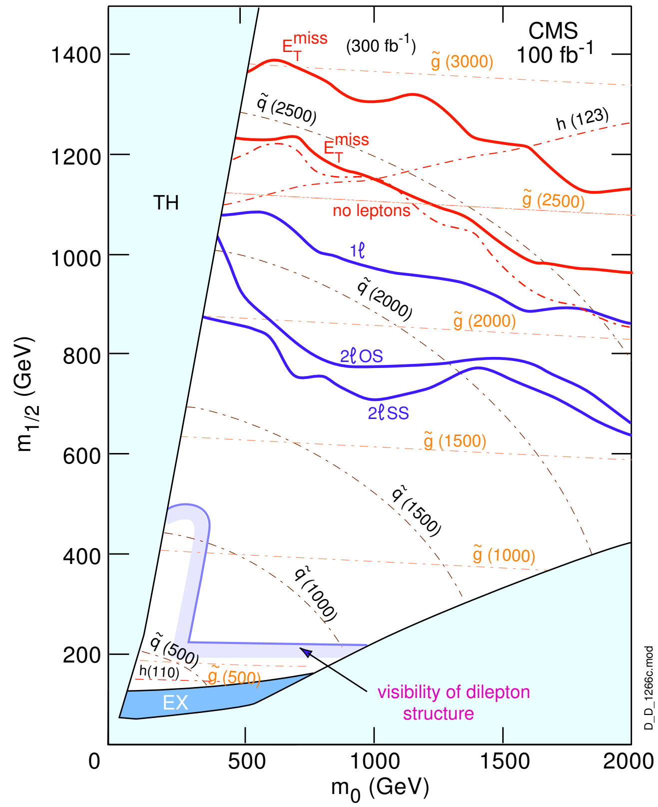

Figure 1. Plot of 5σ reach in mSUGRA model for $\tan\beta = 35$ and $\mu = +$ at LHC with 100 for inclusive, with no leptons, plus one lepton (1ℓ), opposite sign (2ℓOS) and same sign (2ℓSS) dileptons, and multi-leptons (3ℓ,4ℓ) channels. The region where a dilepton edge is visible is indicated. The regions filled in light-blue are ruled out. Contours of gluino, squark and higgs mass have been superimposed (from ref. [4]).

tivated unification assumptions amongst the MSSM SUSY breaking parameters, reducing the number of parameters, from the hundred or so of the MSSM, to just four, plus one sign. Currently, the suppression of flavour changing neutral currents, not supergravity, is the main motivator for these assumptions. The theory is specified by the following parameters: a common scalar mass m_0, a common gaugino mass $m_{1/2}$ and common trilinear coupling A_0, the ratio of the neutral Higgs vacuum expectation values $\tan\beta$, the sign of the μ parameter together with SM couplings.

Gluinos and squarks usually dominate the LHC SUSY production cross-section, which is of order 10 for masses around 1 TeV. Since these are strongly produced, it is easy to separate SUSY from standard model backgrounds provided only that the SUSY decays are distinctive. In the mSUGRA model these decays produce from the missing plus multiple jets and varying numbers of leptons from the intermediate gauginos. Figure 1 shows the 5σ reach in this model at the LHC for 100 [4]. The reach is not very sensitive to the fixed parameters (A_0 and $\tan\beta$). The figure shows that discovery of supersymmetry for $m_{1/2} < 1$

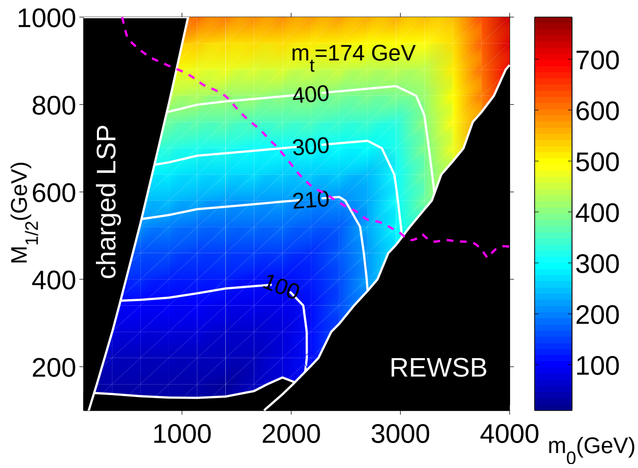

Figure 2. Naturalness reach at the LHC for $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, $m_t = 174$ GeV in mSUGRA. The fine-tuning is represented by the background density, as measured by the bar on the right. White contours of fine-tuning are also presented. The dashed line is the LHC expectation SUSY discovery contour for a luminosity of $\mathscr{L} = 10$ fb^{-1}. The excluded regions are filled black (from ref. [8]).

TeV and $m_0 < 2$ TeV is possible in the inclusive missing E_T channel, i.e., even where the strongly interacting sparticles are heavy.

At tree-level, in the MSSM, the Z boson mass is determined to be [5]

$$\frac{1}{2}M_Z^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \tag{1}$$

by minimising the Higgs potential. In mSUGRA, m_{H_2} has the same origin as the superpartner masses (m_0). Thus as search limits put lower bounds upon superpartners' masses, the lower bound upon m_0 rises, and consequently so does $|m_{H_2}|$. A cancellation is then required between the terms of eq. (1) in order to provide the measured value of $M_Z \ll |m_{H_2}|$. Various measures have been proposed in order to quantify this cancellation [6].

The definition of naturalness c_a of a 'fundamental' parameter a employed in ref. [7] is

$$c_a \equiv \left| \frac{\partial \ln M_Z^2}{\partial \ln a} \right|, \tag{2}$$

where $\{a_i\} = \{m_0, M_{1/2}, \mu(M_{\text{GUT}}), A_0, B(M_{\text{GUT}})\}$. $M_{\text{GUT}} \sim O(10^{16})$ GeV denotes the grand unification scale, usually defined to be the scale at which the MSSM electroweak gauge couplings $g_{1,2}$ unify.

Figure 2 shows the reach in mSUGRA space for a generic LHC experiment (without including detector effects) as a function of the naturalness parameter max(c_a) for the jets, missing transverse energy and one observed lepton channel [8]. The figure shows that a fine-tuning up to 210 can be ruled out by this channel at the LHC. It would be interesting to compare the fine-tuning reach for other experiments and SUSY-breaking models to this number.

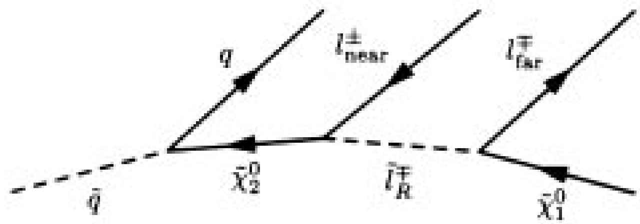

Figure 3. Example of sequential sparticle decay cascade.

3. Measurement of edge variables

The LHC can make certain precise measurements of sparticle mass parameters. Initially produced sparticles decay through a cascade and if one selects cascades with leptons, whose momenta can be accurately measured, endpoints in their kinematical distributions can provide a precise inference of mass parameters. For example, one can study the 'sequential' decay mode $L \to q \to^{\mp}_{R} l^{\pm}_{\rm near} q \to l^{\mp}_{\rm far} l^{\pm}_{\rm near} q$ (see figure 3).

The kinematic edges used in [9] to identify particle masses at LHC mSUGRA point S5 ($m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan\beta = 2.1$, sgn$\mu = +$) contain:

- ll edge: This picks out, from the 'sequential' decays, the position of the very sharp edge in the dilepton invariant mass spectrum caused by $\chi^0_2 \to l$ followed by $\to l\chi^0_1$. The fit error in the edge position [10] at S5 is 0.1%.
- llq edge: In 'sequential' decays, the llq invariant mass spectrum contains a linearly vanishing upper edge due to successive two-body decays. The fit error in the edge position is 0.6%.
- llq threshold: This is the non-zero minimum in the 'sequential' llq invariant mass spectrum, for the subset of events in which the angle between the two leptons (in the centre of mass frame of the slepton) is greater than $\pi/2$. The fit error in the edge position is 2.4%.
- hq edge: Governed by $\tilde{q} \to q\chi^0_2 \to qh\chi^0_1$, followed by the lightest CP-even Higgs decay $h \to bb$. The position of this edge in m_{bbq} is again determined by two-body kinematics. The fit error in the edge position is 1.3%.

These kinematic variables can also be useful at other points in parameter space, where similar fit errors can often be obtained. We take the example of the dilepton edge endpoint, which measures

$$\sqrt{\frac{(M^2_{\chi^0_2} - M^2_{\tilde{l}})(M^2_{\tilde{l}} - M^2_{\chi^0_1})}{M^2_{\tilde{l}}}}. \qquad (3)$$

Figure 4 shows the dilepton mass distribution after cuts, using a particular flavour subtraction combination in order to remove backgrounds from two independent decays. If a supersymmetric signal is found, the kinematic endpoints will be only one of several quantities used to help constrain the sparticle spectrum, for example, cross-sections (and therefore branching ratios) and p_T spectra could also be used.

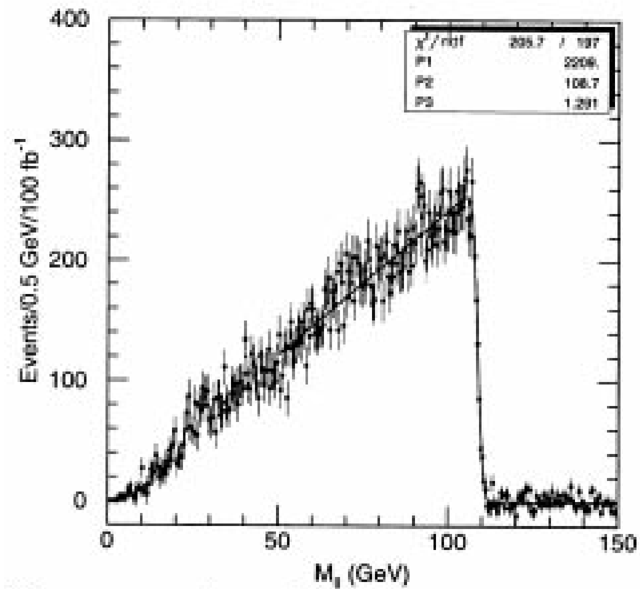

Figure 4. Plot of $e^{+}e^{-} + \mu^{+}\mu^{-} - e^{\pm}\mu^{\mp}$ mass distribution for for LHC mSUGRA Point 5 with $\chi_2^0 \to \tilde{l}^{\pm}\ell^{\mp} \to \chi_1^0 l^+ l^-$ in ATLAS (from ref. [9]).

4. Anomaly- and gauge-mediated supersymmetry breaking

Instead of gravity mediating supersymmetry breaking to the MSSM from some hidden sector, as is supposed to be the case in mSUGRA, there is also the possibility that gauge interactions could provide the dominant terms [11]. Alternatively, if the gravitino $\tilde{G}$ mass is tens or hundreds of TeV, a quantum anomaly (in the super-Weyl conformal symmetry) could dominate [12].

The impact on the resulting phenomenology is potentially large: in the gauge-mediated case, the gravitino is very light and is the LSP, still providing the missing energy signature. If the next-to-lightest sparticle is a bino-like neutralino, $\chi_0 \to \tilde{G}\gamma$ provides hard isolated photons in addition to the more familiar mSUGRA final state signatures of jets, missing transverse energy and leptons. This provides new endpoints such as in the $ll\gamma$ invariant mass (from, for example, $\chi_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \chi_1^0 l^+ l^- \to \tilde{G} l^+ l^- \gamma$). Since the gravitino is essentially massless compared to other sparticles, the χ_i^0 and slepton masses can be determined unambiguously from (for example), ll, $ll\gamma$ and $l\gamma$ endpoints. See figure 5 for an example taken from the aforementioned decay chain.

The interactions of the gravitino, while being suppressed by $M_P \sim 10^{19}$ GeV, are enhanced by a factor $1/m_{\tilde{G}}$ in the $m_{\tilde{G}} \to 0$ limit. Depending upon $m_{\tilde{G}}$, the LSP can have a significant lifetime and decay outside the detector. If it is uncharged, an LSP signature is then a hard isolated photon that does not match up to other tracks or the interaction point. On the other hand, a charged LSP could lead to heavily ionising tracks with $\beta < 1$, leading to the possibility of using time-of-flight measurements in the muon system [13].

If one applies anomaly-mediated supersymmetry breaking to the MSSM, the spectrum depends upon only the gravitino mass and $\tan\beta$. However, the sleptons are tachyonic,

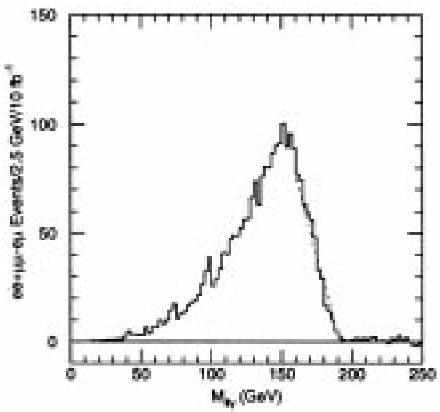

Figure 5. $l^+l^-\gamma$ mass distribution for a gauge-mediated point with prompt neutralino decays. The dashed line shows the fitted (linear) edge (from ref. [9]).

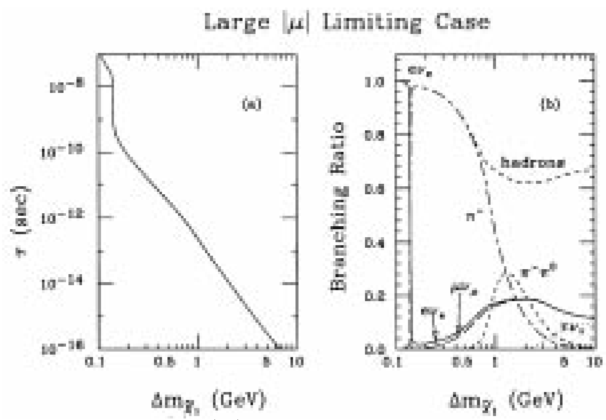

Figure 6. Large $|\mu|$ limiting case of chargino lifetime and decays, where $\Delta m_{\tilde{\chi}_1} = M_{\chi_1^\pm} - M_{\chi_1^0}$ (from ref. [14]).

a problem which must be solved. Solutions to this problem bring in additional model dependence and parameters. The most common assumption is that there is a universal positive contribution to all scalar mass squared values at M_{GUT}. At the electroweak scale, the gauginos satisfy

$$M_1 : M_2 : M_3 \approx 2.8 : 1 : 7.1 \tag{4}$$

in anomaly mediation. The light wino mass parameter implies that the $\chi_1^\pm$ is quasi-degenerate with the χ_1^0 LSP, providing the most parameter independent potential signature for anomaly mediation. The lifetimes and decay modes of the $\chi_1^\pm$ are shown in figure 6. The mass splitting is usually around the 0.1–0.3 GeV region for anomaly-mediated models, implying that $\chi_1^\pm \to \pi^\pm\chi_1^0$ dominates the lightest chargino's decays. The soft pion will be difficult to detect at the LHC, but some of the charginos may decay beyond the vertex detectors, particularly if the mass splitting is small (as can be seen from figure 6). Whereas

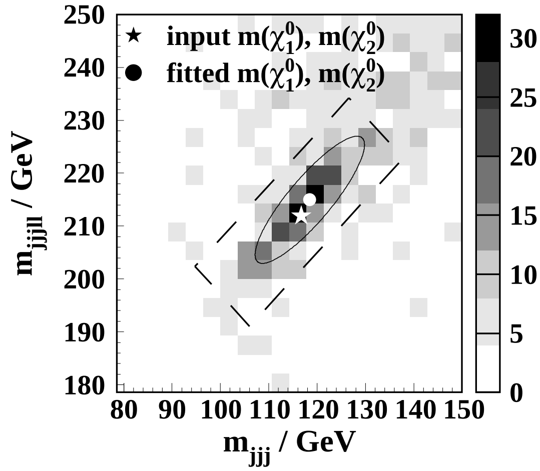

Figure 7. The χ_1^0 (m_{jjj}) and χ_2^0 ($m_{jjj\ell\ell}$) candidates for a coupling of $\lambda''_{212} = 0.005$ at the mSUGRA point $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan\beta = 10$, $\mu > 0$. The number of jet combinations passing the cuts per 30 fb^{-1} is given by the key. The circle and the ellipse show the peak and standard deviation of a 2-d Gaussian fitted to the data contained in the dashed box. The star shows the input masses (from ref. [17]).

chargino detection looks problematic in anomaly mediation, heavier sparticles are more amenable to the usual mSUGRA-type analyses [15].

5. Baryon number violation

R-parity violation has several important phenomenological consequences for the MSSM. In general, the MSSM must not possess both significant baryon-number and lepton-number violating terms, because then [16] the proton would decay much too fast compared with observations. As long as the R-parity violating couplings are larger than $O(10^{-6})$, an LSP produced at the LHC typically decays within the detector. With one type (LLE) of lepton-number violating coupling, a neutralino LSP decays to 2 leptons plus missing energy. With the other (LQD), the LSPs decay to either a visible lepton plus 2 jets or to missing energy plus 2 jets. The production of additional leptons in this manner makes a lepton-number violating MSSM typically easier to measure and detect than the R-parity conserving case.

However, if the MSSM perturbatively violates baryon number only, a neutralino LSP would decay to 3 jets, raising concerns about the possibility for detection and measurement in a hadron-rich environment. It has been shown [17] however, that by examining cascade decay chains involving leptons, it is possible to make quite precise measurements. Such a decay chain would be, for example, $\tilde{q}_L \to \chi_2^0 q \to \tilde{l}_R lq \to \chi_1^0 llq$. After the hadronic decays of two χ_1^0s, there are typically around 10 jets per event for squark production. The difficulty then is beating down combinatoric background in order to specify which jets the neutralino decays into, so that its mass may be reconstructed. This is achieved (after some cuts), by examining the invariant mass of three-jet χ_1^0 candidates and an opposite-sign same family dilepton pair. This is correlated with the three-jet invariant mass of the χ_1^0 candidate as in figure 7. Background is approximately flat in this plane.

Examining the events contained within the peak of the figure allows a measurement of the $\tilde{l}_R$ and $\tilde{q}_L$ masses by finding peaks in m_{jjjl} (with reconstructed χ_1^0 closest to a lepton) and m_{jjjllj} (by combining each χ_2^0 candidate with the harder jets). For the parameter point examined in the figure, one obtains statistical (systematic) errors of 3 (3), 3 (3), 0.3 (4) and 5 (12) GeV respectively for the masses of the χ_1^0, χ_2^0, $\tilde{l}_R$ and $\tilde{q}_L$, with an integrated luminosity of 30 fb^{-1}. These masses are better determined than in the R-parity conserving case, mainly because the lack of missing transverse energy allows reconstruction of all of the particles. In many cases, it is even possible to discern the flavour structure of the baryon-number violating coupling [18] by examining the distribution of secondary vertex tags and muons produced by heavy-quark jets.

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