Flavor and LHC Searches for New Physics

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Received: date / Revised version: date

Abstract. Uncovering the physics of electroweak symmetry breaking (EWSB) is the raison-d'etre of the LHC. Flavor questions, it would seem, are of minor relevance for this quest, apart from their role in constraining the possible structure of EWSB physics. In this short review article, we outline, using flavor-dependent sleptons as an example, how flavor can affect both searches for supersymmetry, and future measurements aimed at understanding the nature of any new discoveries. If the production cross-sections for supersymmetry are relatively low, as indicated by the fact that it has not revealed itself yet in standard searches, the usual assumptions about the superpartner spectra need re-thinking. Furthermore, one must consider more intricate searches, such as lepton-based searches, which could be susceptible to flavor effects. We start by reviewing the flavor structure of existing frameworks for mediating supersymmetry breaking, emphasizing flavor-dependent models proposed recently. We use the kinematic endpoints of invariant mass distributions to demonstrate how flavor dependence can impact both searches for supersymmetry and the Inverse Problem. We also discuss methods for measuring small-mass splittings and mixings at the LHC, both in models with a neutralino LSP and in models with a charged slepton (N)LSP.

PACS. 12.60.Jv Supersymmetric models – 14.80.Ly Supersymmetric partners of known particles – 11.30.Hv Flavor symmetries

1 Introduction

The subject of this review is the interplay between flavor questions and LHC searches for the origin of electroweak symmetry breaking. The latter is the most pressing problem of the standard model (SM). With just the observed SM particles, this theory fails around the TeV scale, because it predicts W and Z scattering cross-sections above the unitarity bounds. If the W and Z cross section is unitarized by a Higgs scalar, one is still faced with the hierarchy, or fine-tuning, problem. This is of course the raison-d’etre of the LHC, and the main argument for new particles at or below the TeV.

Flavor, too, refers to one of the open issues in the SM. The SM flavor puzzle is the fact that the intricate generation structure of the SM has no fundamental explanation. Both the fermion masses and their couplings to the W bosons involve many small and hierarchical dimensionless parameters with no explanation in the SM. This puzzle is really a question of aesthetics. Not only is there no fine-tuning involved, but the small parameters are technically natural. There is certainly no inherent inconsistency in the SM with its unexplained generation structure. Still, it seems to suggest an underlying flavor theory, one that would naturally generate the observed masses and mixings.

There are several ways in which flavor physics, and the new physics (NP) motivated by electroweak symmetry breaking (which we will refer to simply as NP), are related. We list these here, and will elaborate on each of them in the next sections.

(i) Bounds on flavor violation constrain the NP. The NP could exhibit a non-trivial generation structure. At the very least, if the new states couple directly to the SM fermions, the couplings could a-priori be generation-dependent. Furthermore, the new states could also appear in three copies, corresponding to the three generations of the SM. This is necessarily the case if this NP is the consequence of enlarging the space-time symmetry of the SM, as in supersymmetric and extra-dimension models. The SM matter fields then have new partners that come in three copies, and the masses and couplings of the new states are matrices, or more generally higher-rank tensors, in generation space. If these matrices are arbitrary, and the new states are around the TeV, the stringent bounds on flavor violation would be grossly violated. This greatly con-

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1 The term “flavor” is somewhat vague, and often redundant, since it can usually be replaced by “generation.” The matter fields of the SM carry both gauge indices and generation indices. The latter are often called flavor indices. Flavor-dependence simply means generation-dependence, and flavor parameters refer to the generation-dependent parameters of the SM.

2 For a review of EDM bounds on CP-violating phases, see the article by B. Batell in this chapter.
strains the structure of the NP, and has led to the spreading belief that the NP must be Minimally Flavor Violating (MFV), that is, the only source of generation dependence of the NP can be the SM Yukawas [1].

That this assumption needs rethinking is clear. In the case of supersymmetry for example, the fact that it has not shown up yet at the LHC may hint at possibilities that are markedly different from MFV scenarios. The most drastic possibility, if supersymmetry exists, is that all sfermions, or at least all squarks, are heavy, as in [2,3,4], and beyond the LHC reach. This may imply a certain amount of fine-tuning in the Higgs sector, and would altogether eliminate flavor constraints for scalar masses of 10^4 TeV (see, e.g., [5]). A more moderate possibility is that only the first- and second-generation squarks are heavy, as in More Minimal Supersymmetry Breaking [6,7].

At this stage, however, given the (relatively) low energy of the LHC, the small dataset analyzed so far (1 fb^{-1}), and the simplifying assumptions made in many of the analyses, it is still possible that more mundane supersymmetric models are within LHC reach. Even in this case, as was emphasized in recent years (see e.g., [8,9,10]), there is room for generation-dependent superpartner spectra that are nonetheless consistent with low-energy bounds, and there are natural models that predict such spectra.

(ii) Flavor impacts NP search strategies. The flavor structure of the NP obviously determines its LHC signatures. It is important to bear in mind that most studies of NP at the LHC assume a flavor-blind, or MFV spectrum. In the busy LHC environment, however, if we don’t specifically look for something, it can be easily missed. That More Minimal Supersymmetry may be missed by traditional search techniques is clear (see for example the recent analyses of [11,12]) but the same could hold for more “bread-and-butter” models, especially if only a subset of the superpartners are light enough to be produced.

(iii) Flavor can exacerbate the Inverse Problem. Even if NP is discovered at the LHC, understanding the nature of this NP, and whether and how it is related to EWSB, would be far from trivial (see, e.g., [13,14]). This task would be especially hard if only a few new particles are discovered. In particular, it is well known that different solutions to the hierarchy problem, such as supersymmetry and UED models, have similar LHC signatures, and would therefore be hard to tell apart. This has been called the “Inverse Problem” [14]. This problem can be even more challenging if the NP is generation dependent. We will see an example of this kind in section 4.

(iv) How well can we measure the NP flavor parameters? If NP is discovered at the LHC, one would like to understand its flavor structure. Are the new states single states, with universal couplings to different SM generations? Are they single states with generation-dependent couplings? Are there three copies of new states with different or equal masses and with different couplings to the SM generations? It is therefore important to devise methods for measuring the flavor parameters of the NP. A particularly plausible possibility, given the stringent bounds on flavor violation involving the first and second generations, is that some of the new states are almost degenerate, especially if these states are far from pure flavor states. Such a scenario would be hard to distinguish from having a single state which couples to different SM generations, or from having two degenerate pure flavor states.

(v) The NP flavor parameters would provide information about the underlying NP theory. Thus for example, they could tell us about the mediation mechanism of supersymmetry breaking.

(vi) The NP flavor parameters may provide information about the underlying flavor theory. If the SM generation structure is explained by some flavor theory, this flavor theory may control the generation structure of the NP. The NP flavor parameters will then provide new handles on the flavor theory, whether this theory involves a flavor symmetry, new strong dynamics, or the wave-functions of the matter fields in an extra-dimension.

There is a huge literature on flavor, and it’s impossible to coherently review it within the limited length of this review. We will therefore focus on a very specific example, namely the sleptons of supersymmetry, in order to demonstrate the inter-relations listed above. There are several reasons why sleptons are a useful example. First, as opposed to quarks, (especially the light quarks), the flavor of a lepton—whether it is an electron, a muon, and to a lesser extent, a tau—can be determined very precisely in collider detectors. Second, many frameworks for mediating supersymmetry breaking predict sleptons at the bottom of the spectrum, below colored particles, so that they typically appear at the end of decay chains and will therefore be easier to reconstruct. For the same reason, if colored particles are above LHC reach, we may have to content ourselves with sleptons and electroweak gauginos only. These have much smaller production cross sections, so may still be hiding in LHC data. Finally, the lepton inter-generation mixings, measured in neutrino oscillations, are much larger than the quark inter-generation mixings. These mixings could feed into the slepton inter-generational mixings, resulting in observable lepton flavor-changing processes at the LHC (see, e.g., [15]). It should also be noted that much of the above reasoning in favor of sleptons can be repeated for different lepton partners, such as KK leptons.

2 The mediation of supersymmetry breaking in light of flavor-constraints

Supersymmetry would not have much theoretical appeal if we didn’t have plausible theoretical frameworks for generating the 100 or so soft supersymmetry-breaking terms from a few fundamental parameters. Flavor is an important guiding principle in devising such frameworks, since weak-scale superpartners generically give rise to large loop contributions to flavor changing processes, such as $\mu\rightarrow e\gamma$ or $K^0 - \bar{K}^0$ mixing.

The experimental constraints on flavor violation are usually derived by working in the interaction basis, in which the sfermion-fermion-gaugino coupling is a diagonal matrix in generation space, using the mass-insertion
approximation \[16\].

\[ \delta_{ij}^{MN} = \frac{\Delta \tilde{M}_{ij}^{2,MN}}{m_s^2} \ll 1. \]  

(1)

Here \( M, N = L, R \), with \( L, R \) denoting the sfermion partners of left-handed or right handed-fermions, \( \tilde{M}^{2,MN} \) is the mass squared matrix for the relevant sfermions, and \( m_s^2 \) is the typical sfermion mass squared. The bounded quantities are then the off-diagonal elements in the sfermion mass-squared matrices, which provide useful information for top-down model building. When discussing the collider signatures of superpartners, however, it is more natural to work in terms of the physical observables—the sfermion masses and mixings. These are found by diagonalizing the \( 6 \times 6 \) mass matrix for the three \( L \)-sfermions and three \( R \)-sfermions. The gaugino coupling to a (mass-eigenstate) fermion of generation \( i \) and sfermion \( J \) is then proportional to some mixing matrix \( K_{iJ} \), where \( J = 1, \ldots, 6 \) runs over the six mass eigenstates.

There are several possible approaches to suppressing the superpartner loop contributions to FV processes. Essentially, these follow from the different limits in which the FV contributions vanish. Since we would first like to enumerate different approaches to mediating supersymmetry breaking, it is convenient to phrase the discussion in terms of the theoretical input parameters \( \tilde{M}^{2,MN} \). Often, these contain a few sources of FV and one or two of the approaches below must be combined. Below we list features of the soft terms that lead to reduced FV, starting with the scalars and continuing with the gauginos.

1. Heavy Scalars (often called decoupling): Some diagonal elements of \( \tilde{M}^{2,MN} \) are much larger than a TeV, so that the corresponding scalars are heavy.
2. Alignment: The matrices \( \tilde{M}^{2,MN} \) are approximately diagonal in the fermion mass basis.
3. Universality: \( \tilde{M}^{2,MN} \propto \delta_{L^{3}R^{3}} \).
4. Small \( A \) terms. Penguin-type FV processes like \( \mu \rightarrow e\gamma \) require a helicity flip on the fermion line. If they don’t involve Higgsinos, the diagrams therefore require an insertion of \( \delta_{LR} \). These can be dangerous even if they are not flavor-violating, since multiple insertions involving a flavor-diagonal \( \delta_{LR} \) can dominate over a single insertion.
5. Heavy gauginos: Since the loop diagrams contain both virtual spin-0 sfermions and spin-1/2 gauginos or Higgsinos it suffices to take either the sfermions or the spin-1/2 superpartners to be heavy.
6. Gauginos are Dirac fermions: In this case, Penguin-type diagrams with a helicity flip on the gaugino line are absent.

We can now classify existing models and frameworks according to which of these features they employ:

- Heavy superpartners occur in different scenarios. Indeed, the null results of LHC searches for supersymmetry could indicate that some, or all, scalars are heavy. Models in which all scalars are beyond LHC reach are not relevant for this review. Dirac gauginos \[18\], as in \( R \)-symmetric models \[10\], can be heavier than the scalar superpartners since their effect on the Higgs mass is relatively small. \( R \) symmetric models therefore allow\[4\] for generation-dependent slepton and squark masses \[10\]. Similarly, the first-and second-generation squarks can be heavy with only mild tuning of the Higgs mass \[7\]. This pattern is sometimes called an “Inverted Hierarchy” or “More Minimal Supersymmetry”. The flavor constraints and LHC signatures of this scenario were recently studied in \[11\].

- Universality is achieved if the soft terms are determined solely by the gauge charges of the scalars. This is the case for the soft terms of Gauge Mediated Supersymmetry Breaking (GMSB) \[20\] or Gaugino Mediated Supersymmetry Breaking (gMSB) \[22\] at the scale at which supersymmetry breaking is mediated to the MSSM. The \( A \) terms at the mediation scale are zero in these models. “Minimal SUGRA” (mSUGRA) imposes universality at the mediation scale as an ansatz, and actually assumes that all scalar masses are the same at this scale. In Anomaly Mediated Supersymmetry Breaking (AMS) \[24\], the soft terms at the mediation scale are only approximately universal. They are determined by the anomalous dimensions of the MSSM fields, and therefore involve both the gauge couplings and the Yukawa couplings.

In all these models, the soft terms acquire some Yukawa dependence due to the RG evolution to the weak scale. These models are then “Minimally Flavor Violating” (MFV): the only source of generation dependence is the SM Yukawa couplings \[1\]. The size of the Yukawa dependence is affected by the amount of running, and is therefore the smallest in GMSB models with a low mediation scale.

Alignment can be achieved when the underlying theory responsible for generating the SM fermion mass matrices also controls the soft terms \[25\]. Known examples include models with flavor symmetries \[25\], (or Froggatt-Nielsen symmetries \[26\], and theories in which the SM fields develop large anomalous dimensions through their couplings to a near-conformal theory \[24\].

Small \( A \) terms arise naturally in some of the frameworks mentioned above such as GMSB and gMSB. They are also a feature of \( R \)-symmetric models, since they break \( R \)-symmetry. Other mechanisms for suppressing these include the Higgsophobic supersymmetry breaking of \[28\], which relies on a fifth dimension to separate the supersymmetry-breaking fields from the Higgses.

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3. To better understand these points, one should examine the structure of FV diagrams. See for example eqn. 20 of \[17\].

4. Some of these are actual models, with a well-defined mechanism for generating the soft terms and controlling their structure. Others are simply ansätze, which may have some concrete realization(s).

5. These models have additional features that contribute to the suppression of FV processes, including the absence of \( A \) terms and the Dirac nature of the gauginos (see items 5, 6 above).

6. In gravity mediated models, without additional ingredients, the scalar mass matrices could be arbitrary, so that bounds on FV are not satisfied.
As mentioned above, for the purposes of this review, the parameters of interest are the physical parameters in the slepton mass basis, namely, the maximal mass splittings and mixings consistent with FV bounds. Universality and small $A$ terms result in mass degeneracy. Alignment results in small mixings.

As we saw above, models exhibiting universality are MFV. Since the only order one Yukawa coupling is the top Yukawa (except at large $\tan \beta$, for which the bottom and tau Yukawas can be significant) the charged matter sector of the low-energy supersymmetric models have an approximate $SU(2)_L \times SU(2)_R \times SU(3)_D \times SU(3)_U \times SU(3)_L \times SU(3)_R$ lepton symmetry. To see interesting flavor effects at the LHC, we must therefore go beyond MFV. The models must involve some of the remaining ingredients listed above: alignment, heavy scalars or gauginos, or Dirac gauginos.

To be concrete, let us focus from now on on the sleptons. We can estimate the sizes of the slepton mass matrices using their transformation properties under the $SU(3)_C$ symmetry. To leading order in $Y_L$, the slepton soft terms are then

$$M^L_L = \tilde{m}^2_L \left( 1_{3 \times 3} + Y_L Y^T_L + \ldots \right),$$
$$M^c_c = \tilde{m}^2_c \left( 1_{3 \times 3} + Y_L^T Y_L + \ldots \right),$$
$$A_{LR} = \tilde{m}_{LR} (Y_L + \ldots),$$

where $\tilde{m}^2_L$, $\tilde{m}^2_c$ and $\tilde{m}_{LR}$ are numbers. We then find that, for LHC purposes, the spectrum is almost generation blind. The only potentially observable effect is the stau splitting from the other sleptons, with $\Delta \tilde{m}_{13}/\tilde{m} \sim 10^{-4} \tan^2 \beta$ (with $I = 1, 2$) which for $\tan \beta \sim m_t/m_b$ is roughly 10%. In order to have either slepton mixings, or selectron-smuon mass splittings, we must go beyond MFV.

We now give a few representative examples.

- Flavor constraints satisfied by a combination of universality and alignment: Some examples of this type are based on a dominant universal contribution from GMSB \[3\], or AMSB \[29\] with a sub-dominant non-universal contribution controlled by the flavor symmetry responsible for the structure of the SM fermion masses. This can be realized purely in GMSB models \[29\], with the non-universal contribution coming from superpotential matter-messenger couplings, or in high-scale GMSB \[3\] models which always have sub-dominant but non-negligible gravity-mediated contributions to the soft masses. Such models typically have small LR mixings. The right handed sleptons can have order-one relative mass splittings, with small mixings: $1 - 2$ mixings at the percent level and $2 - 3$ mixings at the ten percent level.\[4\] The left handed sleptons can have relative mass-splittings of order one with negligible mixings, or, at the other extreme, order-one mixings with relative mass splittings of order $10^{-3}$ (such splittings will probably be below LHC sensitivity). Between these two extremes, there are models in which both the relative mass splittings and the mixings are a few percent.

  - $R$-symmetric Models \[10\]. Here FV is suppressed by a combination of having Dirac gauginos (some of which can additionally be heavy—see item 4 above), and the absence of $A$ terms. Ref. \[19\] performed a detailed analysis of the predictions of a class of $R$ symmetric models to $e - \mu$ FV processes, and showed that even for large selectron-smuon mass splittings of 50%, 10% mixings are generically allowed. In small wedges of the parameter space, even $O(1)$ mixings are possible.

  - Supersymmetric 5d models. The SM flavor parameters may be the result of different overlaps of the 5d fermion wave-functions with the Higgs wave function, in either flat or warped 5d models \[31,32\]. Since the hierarchy problem is solved by supersymmetry, the 5d dimension can be very small in this case, thus for example it can be of GUT-scale size. The 5d locations of the matter fields will generically affect the soft terms \[33,34\]. As mentioned above, in Higgsophobic models, the Higgs fields and supersymmetry breaking fields are localized at different points along an extra dimension. In this case, $A$ terms are adequately suppressed. The resulting R-sleptons can then exhibit relative mass splittings of $O(10^{-2})$ between the selectron and smuon, with order one mass splittings from the stau \[28\]. A detailed analysis of flavor in 5D models recently appeared in \[35\]. In these models, the Higgs and the supersymmetry breaking sector are taken to be on the same 4d brane. The $O(1)$ 5d mass-parameters of the matter fields (which determine the wave-functions of these fields) are chosen so that viable fermion masses are obtained. Flavor constraints then imply several allowed superpartner spectra, with all colored superpartners above LHC reach. The lightest superpartners are the $R$-handed sleptons (often the selectron or smuon), with masses that are rather large, around 500-600 GeV and relative mass splittings of roughly 20%, and mixings of order 10%.

To summarize, we have examples of viable models that predict potentially observable generation-dependent slepton spectra at the LHC, with mass splittings of the selectron and smuon of up to tens (or even hundreds, in $R$-symmetric models) of GeV, and with slepton mixings up to order one. Some examples can exhibit selectron and smuon splittings above a few GeV with non-negligible mixings.

\[7\] $SU(3)_C$ is further broken by the neutrino masses. Here, for simplicity, we will neglect the spurions associated with the neutrinos. This is justified if the seesaw scale is higher than the mediation scale. We can then take the charged lepton Yukawa to be a diagonal matrix without loss of generality.

\[8\] As mentioned above, AMSB is not universal but MFV.

\[9\] These small mixings are a generic result of the flavor symmetry.
3 Flavor impacts NP search strategies.

The basic supersymmetry searches rely on jets plus missing $E_T$ and are therefore truly blind to slepton flavor. Searches involving leptons are especially important given the fact that colored superpartners have so far not revealed themselves at the LHC. If squarks and gluinos are beyond LHC reach, and only neutralinos, charginos and sleptons can be produced, lepton-based searches would be essential (see, e.g., [39]). Lepton searches are important even if colored superpartners are within reach, but are very heavy. In this case, the electroweak cross-sections for producing neutralinos, charginos, and sleptons can become comparable to strong SUSY production. Relying on missing $E_T$ is then problematic, since the masses of the pair produced non-colored particles is not as much higher than the top, $W$ and $Z$ masses. The missing $E_T$ carried by a neutralino $\chi_1^0$ that is produced from cascade decays of heavier charginos or neutralinos, is likely to be smaller than the missing energy carried by a neutralino coming from the decay of a much heavier colored object.

Searches involving leptons usually require missing energy, one or more leptons, and possibly some number of jets. The latest ATLAS search of this type, for example, based on $1 \text{ fb}^{-1}$ is described in [40]. Lepton flavor mostly affects the two lepton channels, since these are sensitive to two correlated leptons coming from the decay chain

$$\chi_2^0 \rightarrow t^\pm \bar{t}^\mp \rightarrow \chi_1^0 t^\pm \bar{t}^\mp . \quad (3)$$

Such searches were designed with the assumption that the selectron and smuon are degenerate with no mixing, so that the OS leptons of Eq. (3) are of the same flavor (SF). This assumption is important in even the simplest counting-experiment dilepton searches, since these rely on “flavor subtraction” in order to enhance the SUSY signal over the background (and over the SUSY background of uncorrelated leptons), by measuring

$$N_{\text{flav-sub}} \equiv N(e^+e^-) + N(\mu^+\mu^-) - N(e^+\mu^-) . \quad (4)$$

If the slepton spectrum is generation-independent, the supersymmetric signal contributes in only the first two terms of Eq. (4), while the uncorrelated lepton SM background contributes equally to these and to the third term and therefore drops out. If the slepton spectrum is generation-dependent, $N_{\text{flav-sub}}$ might not be a sensible observable. The relevant slepton states (between the heavier and lighter neutralinos) are in general some combinations of the selectron, smuon and stau, with some mass differences. For simplicity, assume that two of the lightest sleptons are selectron-smuon mixtures, with mixing sin $\theta$, \begin{align*}
\tilde{l}_1 &= \cos \theta \tilde{e} - \sin \theta \tilde{\mu} , \\
\tilde{l}_2 &= \sin \theta \tilde{e} + \cos \theta \tilde{\mu} , \quad (5)
\end{align*}
and with masses $m_1 = m$ and $m_2 = m + \delta m$, such that

$$m_{\chi_1^0} < m < m + \delta m < m_{\chi_2^0} . \quad (6)$$

If the mixing is very small, sin $\theta \ll 1$, flavor subtraction still works. Note however that in this case, flavor constraints allow a substantial slepton mass splitting $\delta m$, and if this splitting is not much smaller than $m_{\chi_2^0} - m$, the branching ratios of $\chi_2^0$ to the different sleptons are different and $N(e^+e^-) \neq N(\mu^+\mu^-)$. If, on the other hand, the mixing is substantial, the leptons in Eq. (4) can have either flavor. In particular, both SF and DF dileptons appear in the decay Eq. (3), and $N_{\text{flav-sub}}$ dilutes the signal.

Another common strategy (also employed in [10], see also [39]) for enhancing the SUSY signal over the background, is to measure the OS dilepton invariant mass distribution. The reason is that the signal distribution has a triangle shape, which peaks at the kinematic endpoint of the dilepton invariant mass $\chi_2^0 \chi_1^0$ for enhancing the SUSY signal over the background, and is constant (at least over some range of the dilepton invariant mass near the endpoint). If the slepton spectrum is generation-independent, $\delta m = 0$ and sin $\theta = 0$, and the dilepton-invariant mass distribution has a single peak, at the endpoint of $m_{\chi_1^0}$,

$$m_{\text{lep}}^2 \equiv \frac{(m_{\chi_2^0}^2 - m_{\chi_1^0}^2)(m_{\chi_1^0}^2 - m_{\tilde{l}_1^0}^2)}{m_{\tilde{l}_1^0}^2} . \quad (7)$$

with identical contributions from the two sleptons. The resulting SF invariant mass distribution has a triangle shape (see Figure 1). With $\delta m \neq 0$, the two sleptons give rise to two separate endpoints, $m_{\chi_1^0}$ and $m_{\chi_2^0}$ [39]. For small $\delta m$, the edge separation is

$$\Delta m_{\chi_1^0} \equiv m_{\chi_2^0} - m_{\chi_1^0} \approx \frac{m_{\chi_2^0}^2 - m_{\chi_1^0}^2}{m_{\tilde{l}_1^0}} \left( \frac{m_{\chi_2^0}^2 - m_{\chi_1^0}^2}{m_{\chi_1^0}^2 - m_{\tilde{l}_1^0}^2} \right) \delta m . \quad (8)$$

\[\text{Fig. 1.} \text{ The } l^+l^- \text{ invariant mass distribution (} l = e, \mu \text{) for degenerate sleptons (dashed) and for sleptons of different masses (solid).}\]
Note that this edge separation can either enhance or suppress the slepton mass difference. In particular, for $m(m + \delta m) \sim m_{\tilde{e}} m_{\tilde{\mu}}$ one finds $\Delta m_{ll} \ll \delta m$, and for $m(m + \delta m)$ very far from this value, $\Delta m_{ll} \gg \delta m$.

Consider first a small slepton mixing $\sin \theta \ll 1$. In this case, the $ee$ distribution is only sensitive to the selectron, and the $\mu \mu$ distribution is only sensitive to the smuon, so flavor subtraction can be used. The $m_{ll}$ distribution of SF dilepton pairs now exhibits two endpoints, separated by $\delta m_{ll}$ (see Figure 1). If $\delta m_{ll}$ is large, the height of the corresponding peaks is smaller than the height of the single peak in the generation-independent model with $\delta m = 0$ (see Figure 1). It would therefore be harder to detect these peaks.

If, on the other hand, $\delta m_{ll}$ is just somewhat above the possible resolution of the experiment, the two endpoints are one or two bins apart. Because of detector effects, the SF distribution will then exhibit a fuzzier peak, which would be harder to observe compared to the single peak of the flavor-blind spectrum.

A non-zero mixing complicates the picture, since now the signal generates both SF and DF dileptons. The two endpoints appear therefore in both the SF and DF $m_{ll}$ distribution, again with heights smaller than the single peak obtained for $\delta m = 0$. As suggested in [50], a better approach in this case would be to consider the flavor-added (i.e., SF+DF) $m_{ll}$ distribution. This distribution contains all the signal contributions to the two endpoints. Furthermore, its shape is independent of the mixing $\sin \theta$. Irreducible backgrounds from uncorrelated lepton pairs are expected to be roughly constant over reasonable ranges of $m_{ll}$, so one should be able to extract them by fitting this distribution.

4 Interpreting the new physics in the presence of generation-dependence

If superpartners are discovered, a lot of work would be required in order to establish that they are indeed the supersymmetric partners of SM particles (see, e.g., [53, 54]). This would entail, beyond the obvious mass measurements, also measuring the sizes of couplings of the new particles, and ultimately their spins. The latter are particularly important since different SM extensions motivated by the hierarchy problem, most notably UED [55], have similar signatures at the LHC [52]. This problem has come to be known as the “Inverse Problem” [13], since it is the inverse of the traditional approach to NP at colliders, whose starting point is a specific NP model. Determining the spins of new particles would typically require measuring angular distributions or other event shape variables.

Supersymmetric models and their look-alikes [52] often have a stable neutral particle at the bottom of the spectrum, with all other new particles decaying to this new lightest particle plus some SM particles. As a result, NP events cannot be fully reconstructed, and some sophisticated methods are required even for mass measurements. The kinematic endpoint of the dilepton invariant mass distribution from Eq. (3) is a well-known tool for extracting superpartner masses [22, 23, 24, 25]. Furthermore, since the $m_{ll}$ distribution depends on the spin of the intermediate particle in the decay, it has been extensively discussed as a useful discriminator between different types of NP [55, 56, 57]. Both applications of the $m_{ll}$ distribution are complicated by having a generation-dependent NP spectrum. Here we focus on its use as a spin discriminator.

The sharp triangle form of the $m_{ll}$ distribution for dileptons from the SUSY decay Eq. (3) follows from the fact that the intermediate slepton is a scalar. In the slepton rest frame, $m_{ll}^2 \propto (1 - \cos \theta)$ where $\cos \theta$ is the angle between the two leptons. Since $d\sigma / dm_{ll}^2$ is constant, $d\sigma / dm_{ll}$ is a straight line. Different NP models give rise to analogs of the decay Eq. (3), with the intermediate particle potentially having a nonzero spin. In that case, the $m_{ll}$ distribution is no longer a straight line. As shown in [53, 54], with a SUSY-like mass spectrum, it would still be hard to differentiate between SUSY and UED models based on this distribution, but other spin combinations can be distinguished. Thus for example, replacing the intermediate slepton by a vector particle results in a very different distribution. For near-degenerate spectra, UED and SUSY can be better differentiated. In any case, distinguishing between SUSY and other frameworks relies on the triangular shape of the SUSY distribution. As we saw in the previous section, in the presence of flavor-dependence, the single triangle shape of the SUSY distribution is replaced by the double triangle of Figure 1. This shape would be smeared by detector effects, so that it would be harder to differentiate from the shapes obtained in other models.

5 NP Flavor measurements: measuring the slepton mass splittings and mixings

If NP is discovered at the LHC, one would want to understand its flavor structure. This question is relevant even if the new particles do not come in three copies corresponding to the three generations of the SM. For any new particle with couplings to the SM fermions, one would like to know whether these couplings are generation dependent. In the case of a chargino or neutralino, this translates to information about the sfermion mixings. At the same time, for any new particle discovered, one would like to establish whether only a single particle is seen, or a few nearly degenerate particles with similar signatures. Thus for example, a supersymmetric model with a neutralino LSP and generation blind slepton spectrum (with degenerate selectrons and smuons), may be hard to distinguish from a model with a single slepton with equal selectron and smuon components. Differentiating between the two involves information on both the mass splittings and mixings. It is important to note that nearly-degenerate particles are a very plausible possibility, given the strong flavor

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\(^{12}\) For early work on the collider signatures of generation-dependent sleptons, focused on lepton flavor violation, see, e.g., [26, 27, 28, 29, 30].
constraints on the first and second generation. As we saw in section 2 these essentially restrict the product of the mass splitting and mixing, so that a small mass splitting is necessary if the mixing is non-negligible.

In the following we will discuss these questions in the context of the first and second generation sleptons, focusing on mixed sleptons as in Eq. (5), with a small mass splitting $\delta m$ of order a few GeV. When discussing mass measurements, one must distinguish between two qualitatively different scenarios. One is supersymmetry with a neutralino LSP, leading to missing energy in each event, and the second is supersymmetry with a charged (N)LSP, such as a slepton, in which most events have no missing energy and are therefore fully reconstructible.

5.1 Neutralino LSP models

As discussed in section 4, the dilepton invariant mass distribution is an important tool for mass measurements in neutralino LSP models. We have already seen that a slepton mass splitting results in a double triangle shape of this distribution, with the separation of the two endpoints being a non-trivial function of the two neutralino masses, $m$ and $\delta m$. This example was studied in detail in [63], and in the following we summarize the results. If the endpoint separation is large, it would be fairly easy to detect the two endpoints, and to infer the presence of two distinct slepton states of different masses. Note, however, that a large endpoint separation is typically obtained when the slepton masses are close to either one of the neutralino masses [recall that when the two slepton masses are close to the geometric mean of the two neutralino masses, the edge separation $\Delta m_{ll} \ll \delta m$, see Eq. (8)]. In this case, one of the sleptons emitted in the decay Eq. (3) is relatively soft, making the endpoint measurement more challenging [62]. Indeed, for this reason, most benchmark points chosen for measurements of the dilepton invariant mass distribution had (degenerate) sleptons far from the two neutralinos.

As discussed in section 3 in the presence of mixing, the decay Eq. (3) contributes both SF and DF dileptons. The flavor-added distribution is then particularly useful, since it does not dilute the signal. Another advantage of the flavor-added distribution is that it is independent of the mixing $\sin \theta$. One can therefore start by extracting the two endpoints from the flavor-added distribution (by fitting it to a double triangle), and then use these endpoints as input to a simultaneous fit of the $ee$, $\mu\mu$, and $e\mu$ distributions. The total numbers of events in these distributions are related by,

$$\frac{N_{FV}(e^+e^-)}{N_{FV}(e^+e^-)} = \frac{2(1 + R) \cos^2 \theta \sin^2 \theta}{\cos^4 \theta + R \sin^4 \theta} \left(1 + \frac{R \sin^4 \theta}{\cos^4 \theta + R \sin^4 \theta}\right),$$

where $R$ is the ratio of phase-space factors in $\chi_0^0$ decays involving the different intermediate sleptons:

$$R \equiv \frac{(m^2_{\tilde{l}_2} - m^2_{\tilde{l}_1})^2}{(m^2_{\tilde{l}_2} - m^2_{\tilde{l}_1})^2}.$$  (10)

Fitting each one of the distributions with a double triangle with the endpoints as input, one can extract the mixing angle. In particular, for $\delta m \ll m_{\chi_0^0} - m$, $R$ is approximately 1, so the fit only depends on the mixing angle. These methods were applied in [61] to an example with $\delta m \sim 3$ GeV, with the endpoints separated by 6 GeV, showing (at a 14 TeV LHC with 10 fb$^{-1}$) that the two endpoints and the mixing can be resolved both for small mixing ($\sin^2 \theta \sim 0.03$) and for large mixing ($\sin^2 \theta \sim 0.6$).

Note that $R$ and the two endpoints contain complementary information about the slepton and neutralino masses. As stressed above, a small endpoint difference $\Delta m_{ll}$ does not necessarily mean a small $\delta m$. If $\Delta m_{ll}$ is small, $R \neq 1$ would indicate an appreciable slepton mass splitting, with the sleptons close to the mean of the neutralino masses.

5.2 Slepton NLSP models

Models with a metastable NLSP charged slepton can be obtained with gauge-mediated supersymmetry breaking [63], and in large regions of the parameter space of gravity-mediated supersymmetry breaking [64]. The NLSP eventually decays to a gravitino, but if this decay occurs outside the detector, the slepton leaves a track in the muon detector, its momentum is measured, and its mass can be determined based on its time-of-flight or energy deposition patterns [65][66][67][68][69].

Supersymmetric events are then not only fully reconstructible, but also virtually background-free.

Measurements of masses and mixings in such models were discussed in [70][71][72][73][74][75][76]. A clean way of extracting the masses is to sequentially reconstruct each particle in a cascade decay by looking for the peak it generates [73]. Consider for example the decay of a heavy slepton

$$\tilde{\ell}_{\text{heavy}} \to \chi_0^0 l_a \to \tilde{l}_{\text{NLSP}} \bar{b} l_a,$$  (11)

where $\tilde{l}_{\text{NLSP}}$ is the metastable slepton. The $\chi_0^0$ can be identified through the peak in the OS lepton-$\tilde{l}_{\text{NLSP}}$ invariant mass distribution. The next superpartner in the chain, $\tilde{\ell}_{\text{heavy}}$, is often hard to detect by looking for a peak in the $ll\tilde{l}_{\text{NLSP}}$ distribution, due to the large combinatorial background. Choosing however only those $\tilde{l}_{\text{NLSP}}$ pairs whose invariant mass is close to the $\chi_0^0$ peak, one can construct a

13 Here and in the following we assume that the mass splitting is much bigger than the slepton decay width. The effect of non-zero width was studied in detail in [61].

14 Apart from [70], these techniques rely on the low slepton speed. Sleptons produced in the decay of heavier particles can have large boosts, and therefore look like fake muons. Such sleptons may be detected by looking for a peak in the muon-lepton invariant mass distribution [71].
sample of $\chi_0^0$ candidates, and then add to each of them another lepton. The resulting lepton-$\chi_0^0$-candidate invariant mass distribution would exhibit a clearer $l_{\text{heavy}}$ peak.

Once the masses are determined, the mixings can be measured by comparing the relative numbers of events contributing to peaks involving different flavor leptons. Thus for example, comparing the number of events in the $\chi_1^0$ peak of the $t_{\text{NLSP}}^l$, $\mu_{\text{NLSP}}^l$, and $\tau_{\text{NLSP}}^l$, resolves the flavor composition of the $t_{\text{NLSP}}$, and similarly for the heavier sleptons.

As explained above, a particularly plausible scenario is that two sleptons are nearly degenerate. If both of these sleptons have observable decays, as would be the case for example for nearly degenerate $l_{\text{heavy}}$'s, one would see two different peaks in the $l_{\text{NLSP}}$ invariant-mass distributions. Whether or not the two peaks can be resolved depends both on the $l_{\text{heavy}}$ masses and on their flavor composition. An even more challenging scenario however is that two (or more) of the lighter sleptons are nearly degenerate. Consider for concreteness a spectrum with a second slepton, $l_2$, a few GeV above the mass of $l_{\text{NLSP}}$, so that $l_2$ decays to $l_{\text{NLSP}}$ via a three-body decay $l_2 \rightarrow l_{\text{NLSP}}X$, where $X$ is a dilepton [77][78]. The two leptons in $X$ are typically soft because of the small slepton mass difference, and will go undetected, so that the $l_2$ decays are invisible. The existence of $l_2$ can then be probed using the “Shifted Peak” method, proposed in [74], which utilizes the hard lepton $l_2$ emitted in association with $l_{\text{NLSP}}$. The neutralino $\chi_1^0$ has two possible decays into sleptons. The first is the direct decay to $l_{\text{NLSP}}$,

$$\chi_1^0 \rightarrow l_{\text{NLSP}}^{\pm} l_{\text{NLSP}}^\mp \, (12)$$

The second is the decay to $l_{\text{NLSP}}$,

$$\chi_1^0 \rightarrow l_2^{\pm} l_2^\mp \, (13)$$

followed by one of the two three-body decays [77][78]

$$l_2^\pm \rightarrow l_{\text{NLSP}}^\mp X^{\pm\mp} \, (14)$$

$$l_2^\pm \rightarrow l_{\text{NLSP}}^{\pm} X^{\mp\pm} \, (15)$$

where $X^{\pm\mp}$ contains two OS leptons, and $X^{\pm\pm}$ contains two SS leptons. Note that the charge-flipping decays of Eq. (15) resulting in SS leptons are possible because the neutralino is a Majorana fermion. SS leptons are also present in models other than supersymmetry when the decay is mediated by a vector boson or a scalar. Thus, the observed particles are the hard lepton from Eq. (12) or Eq. (13), and the long-lived slepton $l_{\text{NLSP}}$ from Eq. (12), Eq. (14), or Eq. (15).

We can thus construct distributions for the following invariant masses-squared:

$$m_{l_1}^2 = (p_1 + p_{l_{\text{NLSP}}^\mp})^2 \, (16)$$

$$m_{l_2}^2 = (p_1 + p_{l_{\text{NLSP}}^{\pm\mp}})^2 \, (17)$$

where the $l_{\text{NLSP}}$ and $l_2$ charges can be either opposite or the same. The distribution Eq. (16) peaks of course at the neutralino mass $m_{\chi_1^0}$, but, because of the missing leptons, Eq. (17) peaks somewhat below this mass, at $m_{\chi_1^0} - E_{\text{shift}}$, with

$$E_{\text{shift}} = \frac{m_{\chi_1^0}}{2m_{\chi_1^0}} \delta m \, (18)$$

The slepton mass difference $\delta m$ can therefore be extracted from the shift $E_{\text{shift}}$ between the two peak locations.

The charge-flipping decays of Eq. (15) provide a useful handle on the shifted peak. A peak in the invariant mass $m_{l_{\text{NLSP}}^\mp}^{l_{\text{NLSP}}^{\pm\mp}}$, formed from events with SS sleptons and leptons, can only come from the decays of Eq. (15) and will therefore exhibit the shift $E_{\text{shift}}$. The analogous OS distribution will contain both types of events specified in Eq. (12) and Eq. (13), and will therefore generically exhibit a double peak structure, with the two peaks separated by $E_{\text{shift}}$.

The identities of $l_1$ and $l_2$ depend, of course, on the flavor composition of $l_{\text{NLSP}}$ and $l_2$. In one extreme case, if these are the left- and right-handed sleptons associated with the same flavor, the two leptons are identical. In the opposite extreme, the two sleptons could be pure states of different flavors. In this case, the leptons $l_1$ and $l_2$ are different flavors, and there is no need to rely on the charges to separate the distributions. More generally, the two sleptons contain both selectron and smuon components, and each of the OS $l_{\text{NLSP}}^l$ and $l_{\text{NLSP}}^\mu$ distributions will exhibit both the true neutralino peak and the shifted peak. Still, the SS distributions will be sensitive to just the $l_2$, and can therefore be used to cleanly determine its flavor composition. In [75], it was shown that mixings of around 5% and mass differences of around 5 GeV can be resolved in this way.

6 Acknowledgments

Research supported in part by the Israel Science Foundation (ISF) under grant No. 1367/11, by the United States-Israel Binational Science Foundation (BSF) under grant No. 2010221.

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