Reinterpreting the results of the search for long-lived charged particles in the pMSSM and other BSM scenarios

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Abstract

The CMS search for long-lived charged particles in pp collisions at $\sqrt{s} = 7$ and 8 TeV sets the most stringent limits existing to date on long-lived leptons. It is challenging to reinterpret these results under different model assumptions due to the complex dependence of the signal acceptance on the kinematic properties of the long-lived particles predicted by these models. This note presents a reinterpretation technique that overcomes this challenge by estimating the signal acceptance using tabulated efficiency values that are a function of the kinematics of individual long-lived particles. The proposed technique is used to extend a previous CMS pMSSM reinterpretation to the case of long-lived charginos.
1 Introduction

Long-lived charged particles are predicted by various extensions of the standard model (SM) [1–3], such as supersymmetry (SUSY) [4], theories with extra dimensions [5, 6], and several others. If such particles have a mass lighter than a few TeV/c² they could be produced at the Large Hadron Collider (LHC). The energy available at the LHC would allow particles with mass $\gtrsim 100$ GeV/c² and lifetime greater than $\sim 1$ ns to be detected with the Compact Muon Solenoid (CMS) detector [7] as high momentum tracks with anomalously large rate of energy loss through ionization ($dE/dx$). A fraction of these highly penetrating particles are also expected to be able to reach the CMS muon system, which could therefore be used to identify them and measure their time-of-flight (TOF).

This unique signature is heavily exploited in a recent CMS search [8], which has set the most stringent limits to date on a number of representative models containing massive long-lived charged particles such as the inclusive and pair production of long-lived staus and the pair-production of long-lived exotic leptons among others.

In this note we present a new method for reinterpreting the results of searches for long-lived charged particles in pp collisions at $\sqrt{s} = 7$ and 8 TeV [8] within the context of other new physics scenarios predicting singly charged lepton-like long-lived particles. This method does not require running a full simulation of the CMS detector, but allows the signal acceptance for a model with long-lived particles to be computed using the generator-level kinematical properties of the particles and the tabulated efficiency values reported in this note which are given at the level of individual particles.

The method is used to evaluate sensitivity to the phenomenological minimal supersymmetric standard model (pMSSM) [9] by extending a previous CMS pMSSM reinterpretation [10] to the case of long-lived particles. This reinterpretation makes use of a pMSSM sub-space covering particle masses up to about 3 TeV/c². In this sub-space we consider the region with long-lived charginos ($\tilde{\chi}_1^\pm$) with $ct > 50$ cm.

2 Estimation of model acceptance

The reinterpretation of the results presented in Ref. [8] in terms of limits on other beyond the standard model (BSM) theories would require the evaluation of the signal acceptance for the specific model to be tested. This acceptance can then be used to constrain the BSM model.

The acceptance can only be accurately computed by fully simulating and reconstructing signal events through the CMS detector and by applying the same selection criteria as adopted in Ref. [8]. Such an evaluation is necessary because of the possibility of significant differences in signal acceptance between the models investigated in Ref. [8], for which these acceptance values are published, and the model to be tested. These differences are caused by the fact that the $dE/dx$ and TOF measurements are affected by several subtle detector effects, such as amount of traversed material and positions and orientation within the CMS detector. The combination of such effects with the differences in the kinematical properties between models can result in large differences in signal acceptance. Moreover, determining the signal acceptance using the full simulation and reconstruction software of the CMS detector can be challenging from the point of view of computing resources when a large parameter space needs to be explored.

A faster but accurate method, which only requires information at the event generator level for the BSM model to be tested, can be proposed in some cases. The method is applicable if the model is such that the efficiency for triggering, identifying and selecting events with massive
long-lived particles can be expressed in terms of probability functions associated with each individual particle. Models with lepton-like massive long-lived particles fall in this category, because the event selection adopted in Ref. [8] imposes requirements on measurements performed on individual particles, and one can safely assume that the measurements associated with different particles are independent of each other.

The selection requirements of Ref. [8] are expressed in terms of measured transverse momentum ($p_T$), $dE/dx$, TOF and mass. Such requirements allow the probabilities that the $j^{th}$ long-lived particle in the $i^{th}$ event passes the online or offline selection requirements adopted in Ref. [8] to be expressed as a function of the true particle kinematic properties ($k_j^i$): velocity ($\beta$), transverse momentum and pseudo-rapidity ($\eta$). The pseudo-rapidity also serves the purpose of identifying the only space coordinate for which the assumption of detector symmetry does not hold. Any other equivalent set of kinematical and directional variables could also be used to express this dependence. The offline selection of Ref. [8] has fixed values for $p_T$, $dE/dx$, and TOF thresholds but uses different reconstructed mass thresholds depending on the model being tested. The offline probability must therefore be computed for different values of this threshold ($M_{\text{req}}$).

Assuming that these probability functions are made available, the acceptance $\epsilon$ for a BSM model to pass the online and offline selections can be computed with a Monte Carlo technique, i.e. by generating a large number $N$ of events such that

$$\epsilon = \frac{1}{N} \sum_i P^{\text{on}}(k_1^i, k_2^i, ..., k_M^i) \times P^{\text{off}}(M_{\text{req}}, k_1^i, k_2^i, ..., k_M^i),$$

(1)

where $P^{\text{on}}(k_1^i, k_2^i, ..., k_M^i)$ is the probability that an event containing $M$ long-lived particles with true kinematical properties $k_1^i, k_2^i, ..., k_M^i$ passes the online selection and $P^{\text{off}}(M_{\text{req}}, k_1^i, k_2^i, ..., k_M^i)$ is the probability that the event with the same kinematical properties passes the offline selection with mass threshold $M_{\text{req}}$ after having passed the online selection.

In the case where only one long-lived particle is present in each event the probabilities have the simplest functional form $P^{\text{on}}(k)$ and $P^{\text{off}}(M_{\text{req}}, k)$. If each event contains two long-lived particles, the probability functions can be expressed using the probability functions for events with a single long-lived particle:

$$P^{\text{on}}(k_1^i, k_2^i) = P^{\text{on}}(k_1^i) + P^{\text{on}}(k_2^i) - P^{\text{on}}(k_1^i) \times P^{\text{on}}(k_2^i)$$

$$P^{\text{off}}(M_{\text{req}}, k_1^i, k_2^i) = P^{\text{off}}(M_{\text{req}}, k_1^i) + P^{\text{off}}(M_{\text{req}}, k_2^i) - P^{\text{off}}(M_{\text{req}}, k_1^i) \times P^{\text{off}}(M_{\text{req}}, k_2^i)$$

(2)

Expressions for events with a larger number of long-lived particles per event can also be worked out and will always be expressed using the functions $P^{\text{on}}(k)$ and $P^{\text{off}}(M_{\text{req}}, k)$.

The probability functions $P^{\text{on}}(k)$ and $P^{\text{off}}(M_{\text{req}}, k)$ are computed using samples of single long-lived particles generated with a flat distribution in $\eta$ and $\beta$. Twenty samples of one million particles each were produced for the following true long-lived particle masses: 100, 126, 156, 200, 247, 308, 370, 432, 494, 557, 651, 745, 871, 1029, 1200, 1400, 1600, 1800, 2000 and 2500 GeV/$c^2$. Each event was then passed through the full CMS simulation and reconstruction software. The selection requirements adopted by the so called ‘tracker+TOF’ analysis described in Ref. [8] were then applied. This analysis, where tracks are required to be reconstructed in both the inner tracker and the muon system, is expected to be the most sensitive to signals with lepton-like long-lived particles. The probability values were evaluated in bins of $\eta$, $\beta$ and $p_T$ with the following boundaries:
Figure 1 shows the distribution of the number of generated long-lived particles in each bin of the chosen kinematical space. Figures 2, 3 and 4 show the values taken in the chosen kinematical space by $P_{\text{on}}(k)$, $P_{\text{off}}(0 \text{ GeV}/c^2, k)$, and $P_{\text{off}}(300 \text{ GeV}/c^2, k)$, respectively. The complete evaluation of $P_{\text{on}}(k)$ and $P_{\text{off}}(M_{\text{req}}, k)$ for the bin ranges previously described is available in Ref. [11].

The technique outlined above can be applied with two caveats:

- The offline event selection used in the search for long-lived charged particles includes two track isolation requirements. The first is defined by $\sum p_T < 50 \text{ GeV}/c$ where the sum is over all tracks (except the candidate’s track) within a cone about the candidate track $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.3$ radians where $\phi$ is the polar angle that defines the particle direction in the plane transverse to the LHC beams. The second requirement is that $E/p < 0.3$ where $E$ is the sum of energy deposited in the calorimeter towers within $\Delta R < 0.3$ (including the candidate’s energy deposit) and $p$ is the candidate track momentum reconstructed from the inner tracker. The functions $P_{\text{on}}(k)$ and $P_{\text{off}}(M_{\text{req}}, k)$ are estimated with single particle events and are therefore agnostic to the particle isolation in the considered BSM model. For this reason the method presented in this document will not be accurate for models where the long-lived particles are often produced close to each other in the $\eta$-$\phi$ space or in which they are accompanied by non-negligible activity compared to the isolation requirements described above. It will be demonstrated in Sec. 3 and Sec. 4 that this caveat is not an issue for the BSM models discussed in this document. However the situation might be different in BSM models where long-lived particles are created through the long decay chain of massive particles.

- The online selection in Ref. [8] uses a missing transverse energy ($E_T^{\text{miss}}$) trigger in combination with the single muon trigger. The efficiency of this $E_T^{\text{miss}}$ trigger cannot be described accurately in terms of single particle kinematical properties. The assumption that the $E_T^{\text{miss}}$ trigger adds negligibly to the event selection performed by the muon trigger must therefore be satisfied with good approximation for the models under test. Deviations from this assumption would result in underestimated model acceptance values and therefore inaccurate limits on the production cross-section. For this reason, models with production of colored long-lived particles, such as stops or gluinos, are not addressed by the technique presented in this document because their full treatment would require the evaluation of the missing transverse energy trigger efficiency. The latter, contrary to what happens in models with lepton-like long-lived particles, contributes significantly to the overall signal acceptance.

The probability functions $P_{\text{on}}(k)$ and $P_{\text{off}}(M_{\text{req}}, k)$ are computed with simulated stable particles, but the method is easily extended to the case of particles with finite lifetimes. To this aim, these functions are corrected for the probability that the long-lived particle, with mass
Figure 1: Number of generated single long-lived particles as a function of true particle $p_T$, $\beta$ and $|\eta|$. It should be noted that the binning in these figures is coarser than the granularity of the maps discussed in this document.
Figure 2: Values taken by the function $P^{on}(k)$ as a function of true particle $p_T$, $\beta$ and $|\eta|$. It should be noted that the binning in these figures is coarser than the granularity of the maps discussed in this document.
Figure 3: Values taken by the function $P_{\text{eff}}(0, k)$ as a function of true particle $p_T$, $\beta$, and $|\eta|$. It should be noted that the binning in these figures is coarser than the granularity of the maps discussed in this document.
Figure 4: Values taken by the function $P^{\text{eff}}(300\text{GeV}/c^2,k)$ as a function of true particle $p_T$, $\beta$ and $|\eta|$. It should be noted that the binning in these figures is coarser than the granularity of the maps discussed in this document.
$M$, lifetime $\tau$, and momentum $p$, travels at least the distance required to produce the minimum number of track measurements in the CMS muon system, as required in Ref. [8]. The probability that a particle travels at least a distance $x$ is given by:

$$P(\tau > x, M, p) = \exp\left(-\frac{Mx}{c\tau p}\right)$$  \hspace{1cm} (3)

The function $P_{\text{on}}(k)$ is therefore scaled down by this probability. The offline probability $P_{\text{off}}(M_{\text{req}}, k)$ being defined with respect to the candidates that already passed the online selection doesn’t need to be modified. The effect of the ionization energy loss on the momentum or on the survival probability is negligible for the particle passing the search selection. The value of the parameter $x$ is defined as a function of the particle pseudo-rapidity:

$$x = \begin{cases} 
7.0 & 0.0 \leq |\eta| \leq 0.3 \\
8.0 & 0.3 \leq |\eta| \leq 0.5 \\
9.5 & 0.5 \leq |\eta| \leq 0.8 \\
10.0 & 0.8 \leq |\eta| \leq 1.1 \\
11.0 & 1.1 \leq |\eta| 
\end{cases}$$  \hspace{1cm} (4)

These values of $x$ ensure that the particle crosses the entire muon system before decaying. This choice guarantees that the estimate of the model acceptance is conservative since it does not account for candidates that may decay before reaching the end of the muon detector but still pass the selection. It will be shown in the following sections that this conservative choice leads to an underestimation of the acceptance of less than 15% for decay lengths $< 5$ m.

3 Validation

The proposed technique is validated by comparing the estimated model acceptance values with those obtained with the full simulation and reconstruction of the events. The comparison is made for three different models with lepton-like long-lived particles: pair production of staus, inclusive production of staus in the context of a gauge mediated symmetry breaking (GMSB) model, and pair production of long-lived leptons with a null isospin. These three models have significantly different kinematical properties and were well studied in Ref. [8].

The signal acceptance obtained with the two methods is shown in Figures 5 and 7 for the considered benchmark models and for different thresholds, $M_{\text{req}}$, on the reconstructed mass. In most of the cases, an agreement at the level of 10% between full simulation and the technique presented in this document is observed. The agreement is worse when the mass threshold gets closer to the true mass of the long-lived particle. This behavior is a consequence of the finite size of the bins used for the probability maps and because the reconstructed mass is highly dependent on the particle $p_T$ and $\eta$. This is different from Ref. [8] where the reconstructed mass threshold for optimal model sensitivity is always $\leq 60\%$ of the true long-lived particle mass in order to preserve a large signal efficiency and account for potential bias and resolution effects related to the mass reconstruction. The hatched area on the plots of the figure indicates the interval of reconstructed mass thresholds for which this condition is not satisfied. Away from this region the signal acceptance estimates is always compatible at the level of 10% with the full simulation results.

Since no significant excess of events was observed over the predicted backgrounds in Ref. [8], cross section limits can be placed at 95% confidence level (CL) using the CL$_s$ approach [12, 13]
Figure 5: Signal acceptance for a mass requirement of 0 (left) and 300 GeV/c² (right). First and second rows are for the pair and inclusive production of staus, respectively. The panel below each figure shows the ratio between the estimated acceptance and the acceptance predicted by the full simulation of the detector. It must be noted that only the points with an agreement better than 25% are shown in this panel.
Validation

Figure 6: Signal acceptance for a mass requirement of 0 (left) and 300 GeV/$c^2$ (right). The tested model is the pair-production of leptons with a null Isospin. The panel below each figure shows the ratio between the estimated acceptance and the acceptance predicted by the full simulation of the detector. It must be noted that only the points with an agreement better than 25% are shown in this panel.

where $p$-values are computed with a hybrid bayesian-frequentist technique [14] that uses a lognormal model [15, 16] for the nuisance parameters. The latter are the expected background in the signal region, the integrated luminosity and the signal acceptance. The expected background and the integrated luminosity as well as the uncertainty on these values are provided in Ref. [8]. The signal acceptance is estimated using the technique previously described, while the uncertainty on this value is taken as the upper bound ($\leq 31\%$) coming from Table 4 of Ref. [8] augmented by 10% to account for the level of agreement achieved by the fast estimation of the acceptance compared to the full simulation results. A signal acceptance uncertainty of 40% is thus assumed for all signal models.

The limits for the pair and inclusive production of staus in the context of the GMSB model are shown in Fig. 7. The marginal difference in limits between the proposed fast technique and the full simulation results is only due to the residual 10% difference in the signal acceptance computed with the two different techniques, as well as the additional 10% uncertainty assigned to the fast technique acceptance in order to cover for this difference. The larger difference seen between these two results and the results of the search is mostly explained by the much larger systematic uncertainty used for the signal acceptance. In the CMS search for long-lived particles [8] the uncertainties are estimated model by model while we are using here an upper bound on this value. The worsening of the limit is also due to the usage of suboptimal mass requirements. In Ref. [8], the mass requirement was optimized in steps of 10 GeV/$c^2$, while we used 100 GeV/$c^2$ steps here since background prediction results are only provided in steps of 100 GeV/$c^2$ in Ref. [8]. Another, less significant, cause of the difference in the limits related to the use of a $E_T^{\text{miss}}$ trigger in combination with the single muon trigger. This results in slightly higher acceptance values in Ref. [8] compared to what is presented in this document.
Figure 7: Observed limits on the cross-section for the pair (left) and inclusive (right) production of staus. The ratio between the full-simulation (red) and fast technique (blue) is also shown.

4 Reinterpretation in the pMSSM model

The phenomenological MSSM [9] model is a 19-dimensional realization of the MSSM which captures most of the phenomenological features of the R-parity conserving MSSM. The free parameters of the model, in addition to the SM parameters, are the following:

- the gaugino mass parameters $M_1$, $M_2$, and $M_3$;
- the ratio of the Higgs vacuum expectation values (VEV) $\tan \beta = v_2 / v_1$;
- the higgsino mass parameter $\mu$ and the pseudo-scalar Higgs mass $m_A$;
- 10 sfermion mass parameters $m_{\tilde{F}}$, where $\tilde{F} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{E}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3$ (imposing degeneracy of the first two generations $m_{\tilde{Q}_1} \equiv m_{\tilde{Q}_2}, m_{\tilde{L}_1} \equiv m_{\tilde{L}_2}$, etc.), and
- the trilinear couplings $A_t, A_b$ and $A_\tau$.

To minimize theoretical uncertainties in the Higgs sector, these parameters are conveniently defined at the scale, $M_{\text{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, often also referred to as the electroweak symmetry breaking (EWSB) scale.

In the pMSSM, all MSSM parameters are allowed to vary freely, subject to the requirement that the model is consistent with some basic constraints: first, the sparticle spectrum must be free of tachyons and cannot lead to color or charge breaking minima in the scalar potential. We also require that the electroweak symmetry breaking be consistent and that the Higgs potential be bounded from below. Finally, in this study, we also require the lightest supersymmetric particle to be the lightest neutralino ($\tilde{\chi}_1^0$).

Furthermore, due to practical considerations, we limit our study to the pMSSM sub-space chosen to cover sparticle masses up to about $3 \text{ TeV}/c^2$. This sub-space is defined by the following...
entities on the 19 model parameters:

\[-3 \text{ TeV} \leq M_1, M_2 \leq 3 \text{ TeV}\]
\[-3 \text{ TeV} \leq \mu \leq 3 \text{ TeV}\]
\[-3 \text{ TeV} \leq M_3 \leq 3 \text{ TeV}\]
\[-3 \text{ TeV} \leq m_A \leq 3 \text{ TeV}\]
\[2 \leq \tan \beta \leq 60\]
\[0 \leq \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \leq 3 \text{ TeV}\]
\[-7 \text{ TeV} \leq A_t, A_h, A_T \leq 7 \text{ TeV},\] (5)

The sensitivity of CMS to this pMSSM sub-space was already assessed in [10], but only the region of the parameter-space that does not predict long-lived charginos were considered. The technique described in section 2 is an appropriate tool to extend these results to regions of the parameter-space leading to long-lived particles.

We start from the 20 million points sampled in [10] from a prior probability density function for the pMSSM parameters that encodes results from indirect SUSY searches and pre-LHC searches. From this set we randomly select 7205 points with a Higgs mass \( m_h \) in the range \( 120 \leq m_h \leq 130 \text{ GeV}/c^2 \) and predicting long-lived \((c\tau > 50 \text{ cm})\) charginos. Tightening further the mass window to \( 123 \leq m_h \leq 128 \text{ GeV}/c^2 \) in order to reflect the most recent constraints on the Higgs mass measurements [17, 18] reduces the size of the subset by 45% but does not constrain any further the chargino mass nor lifetime. We, therefore, use the same Higgs mass window as in Ref. [10] in order to ease the comparison between the results presented here with the ones of that reference which are based on a subset defined by \( 120 \leq m_h \leq 130 \text{ GeV}/c^2 \) and short \((c\tau < 10 \text{ mm})\) chargino decay length.

For each of the points entering this subset, we have generated 10000 events using \textsc{Pythia} v6.426 [19]. Only the direct pair-production of chargino was considered for this exercise given that the inclusive SUSY productions of charginos may lead to significant hadronic energy surrounding the long-lived particles and may therefore not fulfill the isolation caveat of the proposed acceptance estimation technique. Finally, the generated events have been used to evaluate the signal acceptance of the search for long-lived charged particles given the chargino kinematics predicted by \textsc{Pythia} for the pMSSM sub-space considered.

Several points of this subset have also been fully simulated, as described in Ref. [8], in order to validate further the fast estimation of the acceptance in the context of pMSSM. The acceptance measured using the full simulation prediction and the proposed method prediction was compared in Fig. 8 for points leading to almost stable \((c\tau > > 10 \text{ m})\) charginos. An agreement at the level of 10% was also found in this specific case. Furthermore, similar checks are shown in Fig. 9 for pMSSM models where the charginos decay inside the detector in order to also validate the decay in flight approximation developed in section 2. As mentioned above, the acceptance in this case is underestimated by up to 15% for decay lengths \(< 5 \text{ m}\).

Given that the fast technique can be used to obtain either acceptance in good agreement with the full simulation prediction in the case of long-lived particles, or conservative values of the acceptance in the case of particles with moderate lifetimes, the predicted acceptance was used to compute 95% confidence level limits on the 7205 pMSSM parameter points considered. The mass requirement used to compute the offline acceptance is 0, 100, 200, 300 GeV$/c^2$ for true chargino masses \( M \leq 166, M \leq 330, M \leq 500, M \geq 500 \text{ GeV}/c^2 \) respectively. A parameter point is considered excluded if the obtained limit on the cross-section is less than the theoretical prediction at leading order. Figure 10 shows the fraction of parameter points excluded as a
Figure 8: Signal acceptance for a mass requirement of 0 (left) and 300 GeV/c^2 (right) on a few representative pMSSM points predicting quasi-stable (τ ≥ 100 m) charginos. The panel below each figure shows the ratio between the estimated acceptance and the acceptance predicted by the full simulation of the detector. It must be noted that only the points with an agreement better than 25% are shown in this panel.

Figure 9: Signal acceptance as a function of the chargino lifetime for benchmark samples predicting chargino of mass 100 (left) and 700 GeV/c^2 (right), with a mass requirement of 0 and 300 GeV/c^2 respectively. The panel below each figure shows the ratio between the estimated acceptance and the acceptance predicted by the full simulation of the detector. It must be noted that only the points with an agreement better than 25% are shown in this panel.
5 Conclusions

A technique for reinterpreting the results of the CMS search for long-lived charged particles has been presented. The technique was validated on a few benchmark BSM models: pair production of staus, inclusive production of staus in the context of the GMSB model, pair production of long-lived leptons with a null isospin and pair production of charginos in the context of the pMSSM. A 10% agreement is obtained on the model acceptance between the proposed technique and the acceptance estimated by a full simulation and reconstruction of the CMS detector. The technique was used to constrain the long-lived sector of a sub-space of the pMSSM chosen to cover particle masses up to about 3 TeV/c². We conclude that 98.9% (97.4%) of the considered sub-space predicting long-lived charginos with a decay length $c\tau \geq 10$ m (50 cm) is

Figure 10: Left: Number of pMSSM points of the phase-space excluded at 95% C.L. as a function of the chargino average decay length. Right: Zoom of the long-lived region. The SUS-12-030 search [10] only considered points with $c\tau < 10$ mm. The bottom panel shows the fraction of parameter points excluded by the SUS-12-030 search [10] (blue) or by reinterpreting the long-lived particle search [8] (red). A few points with $c\tau \geq 1$ km are not excluded despite a signal acceptance of about 50% because of their theoretical cross section being at the level of $\sim 0.1$ fb.

Figure 11 shows the number of parameter points predicted, excluded by Ref. [10], excluded by reinterpreting the results of Ref. [8] and not excluded by any of those searches as a function of the chargino mass and the mass difference between the chargino and the neutralino. The Figure 12 shows the same information as a function of the chargino mass and chargino decay length.
Figure 11: Parameter points of pMSSM that are expected (top left), excluded by reinterpreting the search for long-lived charged particles [8] (top right), excluded by the SUS-12-030 search [10] (bottom left) and that are not yet excluded by any of these searches (bottom right). The SUS-12-030 search [10] only considered points with $c\tau < 10$ mm.
Figure 12: Parameter points of pMSSM that are expected (top left), excluded by reinterpret-
ing the search for long-lived charged particles [8] (top right), excluded by the SUS-12-030 search [10] (bottom left) and that are not yet excluded by any of these searches (bottom right). The SUS-12-030 search [10] only considered points with $c\tau < 10$ mm.
excluded by the CMS search for long-lived charged particles [8].
References


