

# Chapter 1

## CMS-EXO-16-022: a CMS long-lived lepton analysis ( $2.6 \text{ fb}^{-1}$ )

*Jung Chang*

### Abstract

We present the MADANALYSIS 5 implementation and validation of the CMS-EXO-2016-22 analysis, which documents a search for new long-lived particles that decay into electrons and muons. The results are based on a dataset of proton-proton collisions recorded by CMS with a center-of-mass energy of 13 TeV and an integrated luminosity of  $2.6 \text{ fb}^{-1}$ . The validation of our reimplemention is based on a comparison of the expected number of signal event counts in the signal regions with information provided by the CMS collaboration, with signal events corresponding to a benchmark model featuring pair-produced long-lived top squarks.

### 1 Introduction

In this contribution, we summarize the MADANALYSIS 5 [1–3] implementation of the CMS-EXO-16-022 analysis, a search for long-lived particles in  $2.6 \text{ fb}^{-1}$  of LHC proton-proton collision data at a center-of-mass energy of 13 TeV [4], that we present together with its validation. The simulation of the signal events used for the validation relies on a MADANALYSIS 5 tune of DELPHES 3 [5] that has been specifically designed to deal with long-lived particles. It in particular allows for handling neutral long-lived particles that decay into leptons within the volume of the tracker. Reconstruction efficiencies can be applied to displaced tracks and various related parameters can be accessed at the analysis level by means of a dedicated MADANALYSIS 5 version.

In practice, the simulation of the displaced leptons is performed through efficiencies and resolution functions that the user can specify in the DELPHES card. More information is available on the web page <https://madanalysis.irmp.ucl.ac.be/wiki/MA5LongLivedParticle> that also includes a download link to the special version of MADANALYSIS 5 that has to be employed. We have used the reconstruction efficiency depending on the impact parameter  $d_0$  provided in Ref. [6].

For our validation, we have focused on an  $R$ -parity-violating (RPV) supersymmetric scenario featuring a long-lived stop. Relying on the material provided by the CMS collaboration, we have considered four different stop decay lengths fixed to

$$c\tau_{\tilde{t}} = 0.1, 1, 10 \text{ and } 100 \text{ cm}, \quad (1.1)$$

respectively, for a stop mass of  $m_{\tilde{t}} = 700 \text{ GeV}$  in all cases. The stop is then assumed to decay via an RPV channel,

$$\tilde{t} \rightarrow b\ell \quad \text{with} \quad \ell = e \text{ or } \mu. \quad (1.2)$$

For simplicity, lepton universality has been assumed, so that the stop branching fraction into an electron, muon and tau final state equals  $1/3$  in all cases. The benchmark information corresponds to the Snowmass Points and Slopes scenario SPS1a [7] that has been provided by the CMS collaboration.

We have made use of our reimplemention of the CMS-EXO-16-022 analysis to compute MADANALYSIS 5 predictions for the expected number of signal events in the different signal regions defined in the CMS analysis. This has allowed us to validate our reimplemention by comparing our predictions with the official numbers from CMS.

## 2 Description of the analysis

As mentioned above, the CMS-EXO-16-022 analysis investigate new physics in a channel where two displaced leptons, with a transverse impact parameter lying between  $200 \mu\text{m}$  and  $10 \text{ cm}$ , are observed. This analysis is particularly sensitive to RPV supersymmetric signals as they could originate from the production of a pair of long-lived top squarks that decay into a lepton and a  $b$ -jet. While any combination of leptons is theoretically allowed, the analysis focuses on the production of one muon and one electron only.

### 2.1 Object definition and preselection

The analysis preselects events that feature exactly one electron and one muon that are well reconstructed and isolated. Selected events must have passed a dedicated trigger targeting displaced electron-muon pairs where both leptons have a transverse momentum  $p_T^\ell$  satisfying

$$p_T^\ell > 38 \text{ GeV}. \quad (1.3)$$

Both leptons are then required to be central, with a pseudorapidity  $\eta^\ell$  fulfilling

$$|\eta^\ell| < 2.4, \quad (1.4)$$

and with a transverse momentum constrained to satisfy

$$p_T^e > 42 \text{ GeV} \quad \text{and} \quad p_T^\mu > 40 \text{ GeV} \quad (1.5)$$

for electrons and muons respectively. Moreover, both leptons are required to be well separated from each other, in the transverse plane,

$$\Delta R(e, \mu) > 0.5, \quad (1.6)$$

and are required to satisfy the isolation requirements

$$\frac{1}{p_T} \sum_i (p_T)_i < \begin{cases} 0.065 & \text{for } \ell = e \text{ with } 1.57 < |\eta^e| < 2.4 \\ 0.035 & \text{for } \ell = e \text{ with } |\eta^e| < 1.44 \\ 0.015 & \text{for } \ell = \mu \end{cases}, \quad (1.7)$$

where the sum is considered over all reconstructed particles within a  $\Delta R$  cone of 0.3 (electrons) or 0.4 (muons), and where the lepton candidate itself is excluded from the sum. Additionally, the lepton candidates are required to originate from the pixel detector, which is achieved by imposing a threshold on the transverse impact parameter  $d_0^\ell$ ,

$$d_0^\ell < 10 \text{ cm}. \quad (1.8)$$

### 2.2 Signal region selections

The analysis contains three signal search regions whose definition varies according to the values of the transverse impact parameters  $d_0^\ell$  of the two leptons. The tight search region (SR III) requires both leptons to be displaced by more than  $10 \text{ cm}$ ,

$$\text{SR III : } d_0^{\ell_1} > 1000 \mu\text{m} \quad \text{and} \quad d_0^{\ell_2} > 1000 \mu\text{m}, \quad (1.9)$$

while an intermediate signal region SR II allows for smaller displacements,

$$\text{SR II : } d_0^{\ell_1} > 500 \mu\text{m} \quad \text{and} \quad d_0^{\ell_2} > 500 \mu\text{m}. \quad (1.10)$$

Finally, a looser signal region SR I allows for even smaller displaced leptons, featuring

$$\text{SR I : } d_0^{\ell_1} > 200 \mu\text{m} \quad \text{and} \quad d_0^{\ell_2} > 200 \mu\text{m}. \quad (1.11)$$

Overlaps are removed from the signal regions by explicitly excluding the tighter signal regions from the looser. For example, events populating the SR III region are excluded from the SR II and SR I regions, and events populating the SR II region are not allowed to populate the SR I region.

### 3 Validation

#### 3.1 Event Generation

In order to validate the CMS-EXO-16-022 MADANALYSIS 5 reimplementation, we focus on the SPS1a supersymmetric scenario whose parameterization has been provided by the CMS collaboration under the form of an appropriate SLHA file [8]. The stop decay table, mass and width have been modified according to the requirement of the considered benchmark scenarios.

Event generation relies on PYTHIA8 (v 8.226) [9], after making use of the command card provided by the CMS collaboration. This corresponds to the PYTHIA script,

```
SUSY:gg2squarkantisquark = on
SUSY:qqbar2squarkantisquark= on
SLHA:useDecayTable = true
RHadrons:allow = on
1000006:tau0 = 1000 !mm
```

in which we have turned on the RHadrons command to enable stop hadronization and the tau0 attribute of the particle class to set the stop width.

We reweight our events so that the total production rate for stop pair-production in proton-proton collisions at a center-of-mass energy of 13 TeV matches the NLO+NLL predictions [10],

$$\sigma(pp \rightarrow \tilde{t} \tilde{t}^\dagger) \Big|_{m_t=700 \text{ GeV}} = 0.067 \text{ pb.} \quad (1.12)$$

The event weight moreover includes a normalization factor accounting for an integrated luminosity of  $2.6 \text{ fb}^{-1}$ .

The simulation of the response of the detector is achieved via the DELPHES 3 [5] program and its internal use of FASTJET [11] for object reconstruction. Our detector simulation includes reconstruction and selection efficiencies for displaced electrons and muons, as provided on the public CMS webpage

<https://twiki.cern.ch/CMSPublic/DisplacedSusyParametrisationStudyForUser> and presented on Figure 1.1.

#### 3.2 Comparison with official results

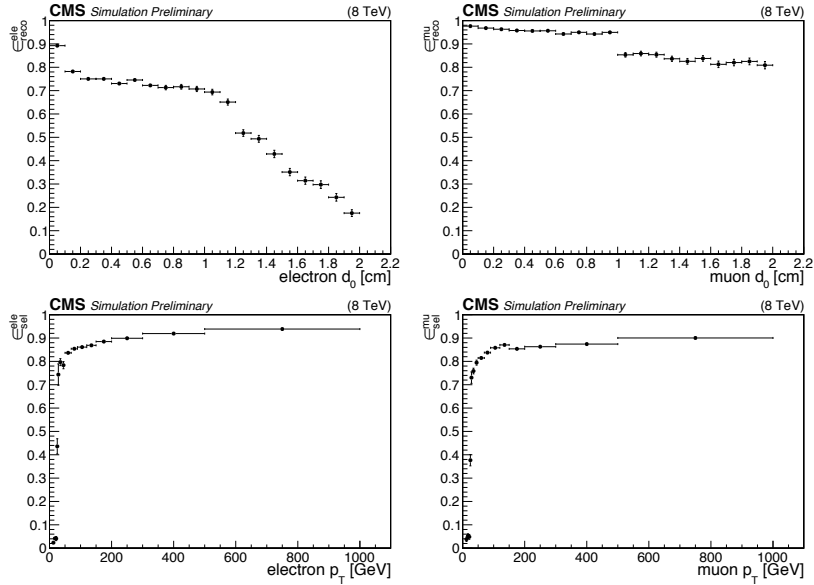
In Table 1.1, we compare our predictions (MA5) with the official results provided by CMS, for the four considered stop lifetimes. The deviations are evaluated relatively to the CMS official results, according to the measure

$$|\text{error}| = \left| \frac{\text{MA5} - \text{CMS}}{\text{CMS}} \right|. \quad (1.13)$$

We obtain a good agreement in most of the case, with the exception of the very long stop lifetime setup ( $c\tau = 100 \text{ cm}$ ) for which very important discrepancies are found. The origins of the discrepancies are connected to the reconstruction and selection efficiencies of Figure 1.1 that have been extracted from 8 TeV data and provided for stop decays lengths of at most 2.2 cm. More information would be necessary to allowing for better modeling of the reconstruction properties of very long-lived stops, as we manually set the efficiency to zero in our DELPHES configuration card. Moreover, the position of the secondary vertex along the collision axis is used in the CMS-EXO-16-022 analysis, so that the dependence of the efficiencies on the longitudinal impact parameter may be important.

### 4 Summary

The MADANALYSIS 5 implementation of the CMS-EXO-2016-22 analysis, a search for long-lived particles decaying into electrons and muons, has been presented. The simulation of signal events needs to be performed using a special tune of DELPHES 3 that has been modified for handling displaced vertex



**Fig. 1.1:** Reconstruction (upper panels) and selection (lower panels) efficiencies associated with displaced electrons and muons, as provided on <https://twiki.cern.ch/CMSPublic/DisplacedSusyParametrisationStudyForUser>.

Region	$c\tau_{\tilde{t}}$ [cm]	MA5	CMS	Difference [%]
<b>SR-I</b>	0.1	3.89	3.8	2.30
	1	4.44	5.2	14.51
	10	0.697	0.8	12.84
	100	0.0610	0.009	> 100%
<b>SR-II</b>	0.1	0.924	0.94	1.71
	1	3.87	4.1	5.61
	10	0.854	1.0	14.58
	100	0.0662	0.03	$\sim$ 100%
<b>SR-III</b>	0.1	0.139	0.16	12.84
	1	6.19	7.0	11.59
	10	4.45	5.8	23.56
	100	0.497	0.27	$\sim$ 100%

**Table 1.1:** Number of events populating the three signal regions of the CMS-EXO-16-022 analysis for the different considered stop decay lengths. We compare the CMS and MADANALYSIS 5 (MA5) results in the second and third column of the table, respectively, and evaluate the difference according to Eq. (1.13) in the last column of the table.

information. A link to a download of this tune is made available on the webpage

<https://madanalysis.irmp.ucl.ac.be/wiki/MA5LongLivedParticle>.

For the considered benchmark scenarios, the calculation of the signal acceptance and efficiency is consistent with predictions given by CMS for proper decay lengths smaller than 10 cm. However, this implementation is not valid and should not be used to constrain models containing particles with proper decay lengths greater than 10 cm. This analysis is thus considered as validated and has been made available from the MADANALYSIS 5 Public Analysis Database and from INSPIRE [12],

<http://doi.org/10.7484/INSPIREHEP.DATA.UFU4.99E3>.

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