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IMPLEMENTATION OF THE CMS-EXO-17-009 ANALYSIS IN THE MADANALYSIS 5 FRAMEWORK

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We present the implementation in MadAnalysis 5 of CMS-EXO-17-009, a search for the pair production of first-generation scalar leptoquarks, and detail the validation of this implementation. This CMS analysis targets scalar leptoquarks decaying promptly to a quark and either an electron (with branching fraction β) or a neutrino (with branching fraction $1-\beta$) using $\mathcal{L} = 35.9\,\text{fb}^{-1}$ of proton-proton (pp) collisions at the LHC at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$. The search is conducted in two final states, one with two electrons and at least two jets and the other with one electron, multiple jets, and significant missing transverse momentum. We validate our implementation of this search by simulating scalar leptoquark pair production, followed by the decays appropriate for each channel, and comparing the observed and expected limits at 95% confidence level after the full selections to those provided by CMS. This manner of validation is the best available given the limited material (*i.e.*, no detailed cut-flows) provided by CMS. We find good agreement with the official limits and consider this implementation validated.

Keywords: Leptoquarks, multijet events

1. Introduction

The excellent performance of the LHC, alongside increasingly sophisticated analysis by the ATLAS and CMS collaborations, offers an unprecedented opportunity to explore physics beyond the Standard Model (bSM). One promising class of extensions to the Standard Model features one or more new bosons carrying both lepton number and baryon number and therefore coupling to some SM lepton-quark pair(s). These *leptoquarks* are motivated not only by well established top-down ideas, including grand unified theories,[1] technicolor models,[2] and the ongoing search for dark matter;[3] but also by modern phenomenological considerations, most notably lepton flavor university violation.[4,5] A variety of searches for both scalar and vector leptoquarks, both of which should produce distinctive signatures with jets and and leptons, have been conducted by the ATLAS and CMS collaborations using both Run 1 and Run 2 data,[6] significantly extending limits from LEP, HERA, and the Tevatron.[7–10]

One such search, conducted by the CMS Collaboration and designated as CMS-EXO-17-009, targets pair-produced scalar leptoquarks decaying exclusively to first-generation Standard Model fermions using $\mathcal{L} = 35.9\,\text{fb}^{-1}$ of Run 2 ($\sqrt{s} = 13\,\text{TeV}$)

data.[11] This search consists of two channels, each targeting a specific possible final state following the decays of the leptoquarks. In particular, one channel targets charged-lepton decays and requires at least two electrons and at least two jets resulting from the hadronization of up quarks, whereas the other part of the analysis supposes that one leptoquark instead decays to a neutrino and requires exactly one electron, multiple jets, and sizable missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$). In the absence of a discovery, CMS excludes first-generation scalar leptoquarks lighter than 1435 (1270) GeV, assuming a branching fraction to electron + jet (ej) of $\beta = 1$ (0.5), using the CLs prescription.[12]

Given the wide variety of well motivated models with scalar and vector leptoquarks, and certain other models predicting signatures with multiple jets and multiple leptons,[13,14] it is in the community's interest to be able to interpret this analysis in models not considered by CMS. The MadAnalysis 5 framework, which provides a platform to emulate each step of an LHC analysis from detector simulation and object reconstruction to event selection, makes this goal achievable.[15–17] At the time of writing, however, there is a surprising deficit of leptoquark-related analyses implemented for public reinterpretation in MadAnalysis 5 and similar platforms. In this note, we describe how we have implemented the CMS-EXO-17-009 analysis in this framework in order to apply it to arbitrary models of new physics.

This note is organized as follows. In Section 2, we reproduce the salient details of the CMS-EXO-17-009 analysis, including object definitions and event selection, and we explain how we have emulated this analysis in the MadAnalysis 5 framework. We present the validation of our implementation in Section 3, describing the simulation of scalar leptoquark pair production and decay(s), and computing limits at 95% CL for comparison to those published by the CMS Collaboration. We demonstrate acceptable agreement between our results and the official limits. We summarize this note in Section 4.

2. Description of the analysis

CMS-EXO-17-009 looks for pair-produced scalar leptoquarks decaying to first-generation Standard Model fermions. The leptoquark (LQ) for which this search is optimized has SM quantum numbers $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$, which are shared by the right-chiral SM quarks; its most general renormalizable interactions with first-generation SM fermions can be expressed as

$$\mathcal{L}_{\mathrm{LQ}} = \Phi_{\mathrm{LQ}}^{\dagger i} \left[y_{\mathrm{L}} \overline{U^{c}_{ia}} \mathrm{P_L}\, \varepsilon^{ab} E_b + y_{\mathrm{R}} \overline{u^{c}_{i}} \mathrm{P_R} e \right] + \text{H.c.}, \tag{1}$$

where $\{U, E\}$ are the first-generation quark and lepton $\mathrm{SU(2)_L}$ doublets with indices $a, b \in \{1, 2\}$, and $\{u, e\}$ are the corresponding weak singlets. (Superscripts $^{\mathrm{c}}$ denote charge conjugation and $\mathrm{P_{L,R}}$ are the chiral projectors.) The operator (1) permits LQ to decay according to LQ $\to ej$, with j an up quark seen as a hadronic jet, or LQ $\to j + p_{\mathrm{T}}^{\mathrm{miss}}$, with missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}} \equiv |\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}|$ associated with a neutrino. For the interpretation of the results (*viz.* Section 3), CMS assigns constant

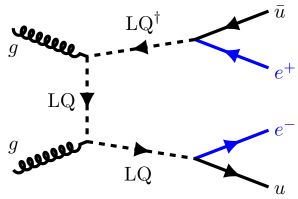

Fig. 1: Representative diagram for first-generation leptoquark pair production and decay, which generates a potentially sizable $eejj$ signal at LHC.

values to the branching fractions $\beta(\text{LQ} \to ej)$ and $\beta(\text{LQ} \to \nu j) \equiv 1 - \beta(\text{LQ} \to ej)$. A representative diagram for the pair production and fully visible decay ($\text{LQ} \to e^- u$) of these first-generation LQs is displayed in Figure 1, and other pair-production diagrams can be found in Figure 1 of CMS-EXO-17-009.

In view of the two decay channels available to this leptoquark, CMS conducts this search in two final states: in the $eejj$ channel, CMS requires at least two electrons and two high-p_{T} jets in order to target pairs of leptoquarks both decaying to ej (with total branching fraction β^2); in the $e\nu jj$ channel, CMS looks for exactly one electron, two high-p_{T} jets, and sizable isolated $p_{\text{T}}^{\text{miss}}$, which corresponds to one ej decay and one νj decay with total branching fraction $2\beta(1-\beta)$. In both channels, CMS vetoes isolated muons in order to restrict the search to first-generation leptoquarks. Each channel moreover includes a set of cuts on some kinematic criteria that generally escalate with increasing leptoquark mass m_{LQ} in order to optimize the sensitivity of the search. Here we discuss these criteria in some more detail and offer notes about our implementation of this analysis in MadAnalysis 5.

2.1. *Object definitions*

As mentioned above, CMS-EXO-17-009 consists of two channels, one targeting scalar leptoquarks decaying only to ej and the other looking for mixed decays to an $e\nu jj$ final state. We have implemented both channels of the analysis in MadAnalysis 5. The signal object candidates are common to both channels; they are required to satisfy several kinematic and isolation criteria. The most important preselection criteria are summarized in Table 1, but we comment more on particle reconstruction here.

Electrons are identified by matching charged-particle tracks to clusters of energy deposits in the electromagnetic calorimeter (ECAL) of the CMS detector. They are required to have transverse momentum $p_{\text{T}} > 50\,\text{GeV}$ and $|\eta| < 2.5$ and must furthermore not inhabit the barrel-endcap transition region between $|\eta| > 1.4442$ and $|\eta| < 1.5660$. Electrons must be isolated from hadronic activity according to calorimeter and track measurements. The scalar sum of p_{T} from ECAL clusters in a cone of radius $\Delta R = 0.3$ centered on any electron candidate must be less than 0.03

Criterion	Electrons	Muons	Jets
p_{T} [GeV]	> 50	> 35	> 50
$\|\eta\|$	< 2.5 and $\notin (1.4442, 1.5660)$	< 2.4	< 2.4
Isolation	$E_{\mathrm{cal},0.3} < 0.03\, p_{\mathrm{T}}(e)$ $E_{\mathrm{track},0.3} < 5\,\mathrm{GeV}$	$E_{\mathrm{track},0.3} < 0.1\, p_{\mathrm{T}}(\mu)$	$\Delta R(j, \{e, \mu\}) > 0.3$

Table 1: Summary of preselection criteria, reproduced in part from Section 4 of CMS-EXO-17-009.[11]

of the electron p_{T}. (ATLAS uses a standard definition of angular distance,

$$\Delta R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2} \quad \text{with} \quad y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z},$$

in which the rapidity y is defined in terms of the energy E and component p_z of momentum along the beam direction, and ϕ is the azimuthal angle about the beam (z) axis.) We denote the aforementioned scalar p_{T} sum by $E_{\mathrm{cal},0.3}$ in Table 1. The scalar p_{T} sum of all tracks in the same cone, which we denote by $E_{\mathrm{track},0.3}$, must be less than 5 GeV.

Muons are vetoed in both channels of the analysis but are used to define a control region to estimate the $t\bar{t}$ background. Muon candidates must have $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ and $|\eta| < 2.4$. Muons eligible to be vetoed in the common selection must satisfy a track-based isolation criteria of $E_{\mathrm{track},0.3} < 0.1\, p_{\mathrm{T}}(\mu)$. In order to distinguish between muons created in pp collisions and those associated with cosmic rays, muon candidates must have a transverse impact parameter $|d_z| < 5\,\mathrm{mm}$ and a longitudinal impact parameter $|d_{xy}| < 2\,\mathrm{mm}$.

Jets are reconstructed using the anti-k_t algorithm[18] with radius parameter $R = 0.4$. They must have $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and pseudorapidity $|\eta| < 2.4$. In order to account for pileup interactions, tracks originating from pileup vertices are discarded and a correction is applied to mitigate surviving spurious energy deposits.[19] Remaining jets are removed if they lie closer than $\Delta R = 0.3$ to any electron or muon.

The missing transverse momentum, $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, is defined as the negative vector sum of the transverse momenta of all objects (electrons, muons, and jets) satisfying the preselection criteria discussed above:

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_i \left[\vec{p}_{\mathrm{T}}(e_i) + \vec{p}_{\mathrm{T}}(\mu_i) + \vec{p}_{\mathrm{T}}(j_i)\right].$$

The scalar missing transverse momentum, $p_{\mathrm{T}}^{\mathrm{miss}}$, is defined as the magnitude of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$.

2.2. *Event selection*

Requirements on the electron and jet multiplicities, and the isolation and total momentum of the final-state objects, are imposed by both channels of CMS-EXO-

Selection criterion	Requirements	
	$eejj$ channel	$e\nu jj$ channel
Electron multiplicity, N_e	≥ 2	1
Muon multiplicity, N_μ	0	
Jet multiplicity, N_{jet}	≥ 2	
Special kinematic cuts	$m_{ee} > 50\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$
	$\lvert\vec{p}_{\mathrm{T}}(e_1) + \vec{p}_{\mathrm{T}}(e_2)\rvert > 70\,\mathrm{GeV}$	$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\, j_1\ [e]) > 0.5\ [0.8]$
		$\lvert\vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}}(e)\rvert > 70\,\mathrm{GeV}$
		$m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, e) > 50\,\mathrm{GeV}$
Total scalar p_{T}, S_{T}	$\geq 300\,\mathrm{GeV}$	

Table 2: Summary of common selection criteria, reproduced in part from Section 4 of CMS-EXO-17-009.[11]

17-009. These common criteria are summarized in Table 2. As mentioned above, the $eejj$ analysis requires at least two electrons and at least two jets satisfying the preselection criteria. No charge requirements are imposed on the electrons. No isolated muons are permitted. The invariant mass m_{ee} of the two (or two highest-p_{T}) electrons $\{e_1, e_2\}$ must exceed 50 GeV. The p_{T} of the system for which m_{ee} is calculated must furthermore exceed 70 GeV. The observable

$$S_{\mathrm{T}} = p_{\mathrm{T}}(e_1) + p_{\mathrm{T}}(e_2) + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2),$$

with $\{j_1, j_2\}$ the two highest-p_{T} jets, must be at least 300 GeV. The $e\nu jj$ channel, meanwhile, requires exactly one electron, at least two jets, and missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$. No isolated muons are permitted. CMS attempts to discriminate between genuine missing transverse momentum and $p_{\mathrm{T}}^{\mathrm{miss}}$ due to instrumentation by requiring angular isolation of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ from the electron and leading jet; namely,

$$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, j_1) > 0.5 \quad \text{and} \quad \Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, e) > 0.8.$$

The p_{T} of the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$-electron system must then exceed 70 GeV in analogy with the ee system in the $eejj$ analysis. The transverse mass of the same system, which is defined for any two objects with transverse momenta $\vec{p}_{\mathrm{T}1}, \vec{p}_{\mathrm{T}2}$ as

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}1}p_{\mathrm{T}2}[1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}1}, \vec{p}_{\mathrm{T}2})]},$$

must exceed 50 GeV. Finally, a different S_{T} is defined for the $e\nu jj$ analysis as

$$S_{\mathrm{T}} = p_{\mathrm{T}}(e) + p_{\mathrm{T}}(j_1) + p_{\mathrm{T}}(j_2) + p_{\mathrm{T}}^{\mathrm{miss}}$$

and must be at least 300 GeV.

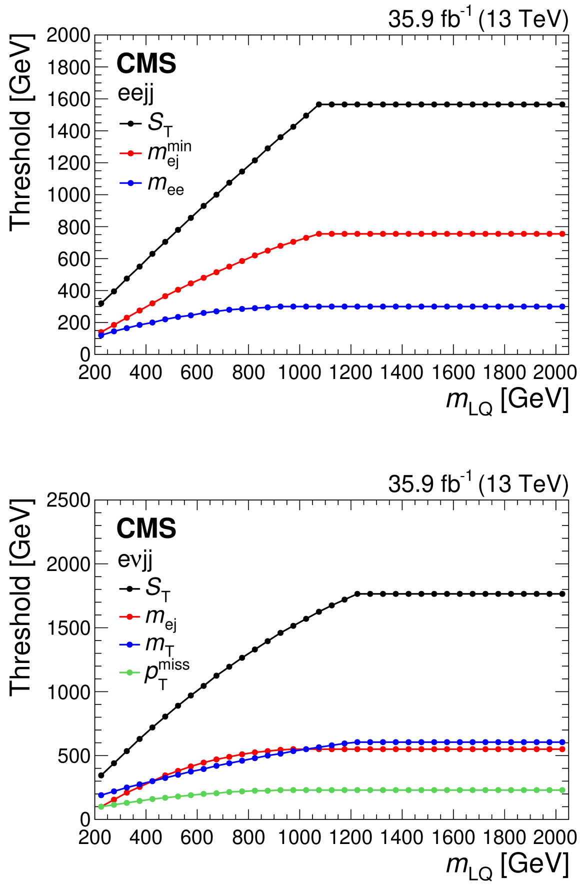

FIG. 2: Optimized selections as functions of leptoquark mass m_{LQ} for (top) the $eejj$ channel and (bottom) the $e\nu jj$ channel of CMS-EXO-17-009.[11] These figures appear as Figure 2 in the original analysis.

In each channel of CMS-EXO-17-009, following these common selections, a set of final selections is chosen for each hypothetical leptoquark mass $m_{\mathrm{LQ}} \in [200, 2000]$ GeV so as to maximize the Punzi criterion for observation of a signal at a significance of five standard deviations. In the $eejj$ channel, the final cuts are on the dielectron invariant mass m_{ee}, the total scalar transverse momentum S_{T}, and m_{ej}^{min}. The latter observable is the smaller of the two electron-jet invariant masses obtained after choosing the ej pairings to minimize the difference between the invariant masses of the two leptoquark candidates. The requirements on these three quantities generally rise with leptoquark mass until $m_{\mathrm{LQ}} = 1050\,\mathrm{GeV}$, after which large background uncertainties make further optimization impossible. The final selections are available in the left panel of Figure 2 of CMS-EXO-17-009, which we have copied to our Figure 2 (top) for convenience. In the $e\nu jj$ channel, the optimized selections are instead imposed on $p_{\rm T}^{\rm miss}$, $m_{\rm T}(\vec{p}_{\rm T}^{\rm miss}, e)$, $S_{\rm T}$ (the one defined for this channel, not for $eejj$), and finally on m_{ej}, the invariant mass of the electron-jet pair chosen to minimize the difference between transverse masses of leptoquark candidates. Again the optimized selections rise with $m_{\rm LQ}$ until $m_{\rm LQ} = 1200\,{\rm GeV}$, after which further optimization is beyond reach. The final selections are available in the right panel of Figure 2 of CMS-EXO-17-009, which we have copied to our Figure 2 (bottom).

We have written code in C++ that can be run in the reconstruction (`-R`) mode of MadAnalysis 5 to emulate the analysis described above and allow us to apply it to new event samples. We have implemented the optimized cuts discussed in the previous paragraph, and displayed in Figure 2, as non-overlapping *signal regions* in our code. Either for the purpose of validation, which is discussed in Section 3, or in order to analyze different models, we provide as input to MadAnalysis 5 some sample of hard-scattering events that have been matched to parton showers and hadronized. These showered and hadronized events are first passed by MadAnalysis 5 to Delphes 3 version 3.4.2[20] and FastJet version 3.3.3,[21] which respectively model the response of the CMS detector and perform object reconstruction. For this implementation, we use the Delphes 3 card for the CMS detector, including pileup corrections, that is shipped with MadAnalysis 5. The reconstructed events are then analyzed by our reimplementation code, after which MadAnalysis 5 computes the acceptance of the event sample by the emulated selection criteria. With the acceptance(s) in hand, MadAnalysis 5 can use the CLs prescription[12] to compute the expected and observed upper limits at 95% confidence level (CL) on the number of signal events given the official numbers of expected background events and observed events. It can also extrapolate these limits to higher integrated luminosities, assuming no excess is found, with multiple approaches to background error propagation available to the user.[17]

3. Validation

While CMS does not provide detailed yields after each individual selection cut, it does offer the expected yields for the leading backgrounds and leptoquark signals corresponding to a range of masses $m_{\rm LQ} \in [200, 2000]\,{\rm GeV}$ in Tables 2 and 3 of CMS-EXO-17-009. Based on the expected and observed yields, CMS computes the expected and observed limits at 95% confidence level (CL) and compares them to a benchmark scenario appropriate for each search channel. Their results are presented in Figure 8 of CMS-EXO-17-009. We validate our implementation by generating event samples according to CMS' specifications and comparing the limits computed by MadAnalysis 5 to those reported by CMS.

3.1. *Event generation*

In order to validate our implementation, we produce samples of 2.5×10^4 leptoquark signal events in close correspondence with the simulated signals described in CMS-EXO-17-009. Following CMS' approach, we produce a set of samples with leptoquarks decaying only to electrons and a set with one electron decay and one neutrino decay. To ease the computing expense, we use intervals of $\Delta m_{\text{LQ}} = 100\,\text{GeV}$ instead of CMS' choice of $\Delta m_{\text{LQ}} = 50\,\text{GeV}$, though we have implemented the final selections for all m_{LQ} considered by CMS. We implement the interactions (1) in FeynRules version 2.3.43 and produce a UFO module[22] suitable for use in MadGraph5_aMC@NLO (MG5_aMC) version 3.3.1.[23,24] In accordance with the experimental analysis, we simulate the full events including ej and/or νj decays at leading order (LO), using the NNPDF 2.3 LO parton distribution functions,[25] and use the NLO normalizations[26] used by CMS and displayed in Figure 8 of CMS-EXO-17-009. We shower and hadronize the events using Pythia 8 version 8.244[27] and use these showered samples as input for the reconstruction mode of MadAnalysis 5.

3.2. *Comparison with official results*

The resulting observed and expected limits at 95% CL are displayed in Figure 3 alongside the official results. Following the CMS analysis, we report the limits derived from the final selections optimized for each m_{LQ}. As a sanity check, we note that the *best signal region* designated by MadAnalysis 5 corresponds in all cases either to m_{LQ} or to $m_{\text{LQ}} \pm 50\,\text{GeV}$, as one would expect if indeed the final selections optimize the sensitivity of the search to each hypothetical m_{LQ} signal. (Recall that the signal regions in this implementation correspond to each set of optimized selections for each m_{LQ}; *viz.* Section 2.2.) In both channels, we find good agreement between the results, especially in the regions where the signals are excluded. In the $eejj$ channel, the discrepancy between excluded m_{LQ} is roughly 50 GeV or 3.5%; our implementation of the $e\nu jj$ channel has negligible error in the analogous region. Elsewhere, our implementation exhibits a few fairly small fluctuations away from the official results, which we expect would diminish with improved statistics. In the absence of detailed cut-flows, it is not possible to identify a particular culprit for any genuine errors in our implementation; our first suggestion is discrepancies between electron reconstruction in Delphes and Geant4,[28] further study of which we delay to possible future work. At any rate, we consider the agreement between our results and those of CMS good enough to claim validation.

4. Conclusions

We have presented the implementation in MadAnalysis 5 of CMS-EXO-17-009, a search for the pair production of scalar leptoquarks decaying only to first-generation Standard Model quarks and leptons. This analysis consists of two channels, $eejj$ and $e\nu jj$, which correspond to two possible final states resulting from decays of pair-produced leptoquarks. Each channel of this analysis can be used as a template for recasting conceptually similar leptoquark searches, or to constrain other models of new physics involving final states with multiple leptons and multiple high-p_{T} jets. We have validated our implementation by simulating the pair production of scalar leptoquarks decaying promptly to up quarks (hadronic jets) and electrons or

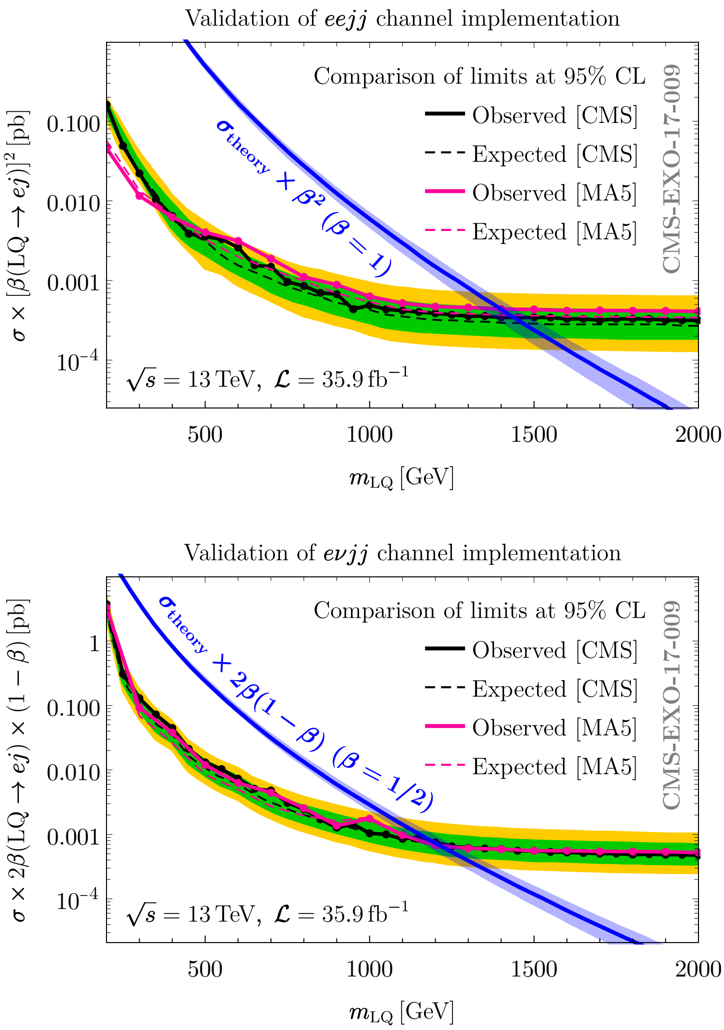

FIG. 3: Comparison between official CMS[11] limits at 95% CL and those obtained in MadAnalysis 5 using our implementation of CMS-EXO-17-009 for (top) the $eejj$ channel and (bottom) the $e\nu jj$ channel of the analysis.

(electron) neutrinos, and comparing the expected and observed limits at 95% CL in MadAnalysis 5 to those reported by CMS. We find acceptable agreement between our results and the CMS limits and consider our implementation to be validated. The Delphes (detector simulation) and MadAnalysis recasting cards, along with materials corresponding to a sample produced in MadGraph5_aMC@NLO to validate the $eejj$ analysis, are available on the MadAnalysis 5 Public Analysis Database (PAD).

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