

Tau Custodian searches at the LHC

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Abstract

The tau lepton can be more composite than naively expected in models of strong electroweak symmetry breaking with tri-bimaximal lepton mixing. New leptonic resonances required by custodial symmetry, the tau custodians, can then be the first signal of this lepton flavor realization. Tau custodians can be very light, decaying almost exclusively into taus. The LHC reach for these new leptons is up to masses of 240, 480 and 720 GeV for $\sqrt{s} = 14$ TeV and an integrated luminosity of 30, 300 and 3000 fb^{-1} , respectively. Our analysis can be extended to any pair produced particles decaying mostly into taus and Standard Model bosons.

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I. INTRODUCTION

Custodial symmetry [1] is a natural ingredient in models of strong electroweak symmetry breaking (EWSB). The Standard Model (SM) fields can be partly composite in these models [2], i.e. an admixture of elementary and composite states, acquiring a mass from their composite components. Thus, heavier fields are naturally more composite, and also have a sizable mixing with composite states of the strong sector with the same SM quantum numbers. These composite states come, however, in full multiplets of the custodial symmetry, the custodians, which can be relatively light and couple strongly to the partly composite SM field. Then, it is natural to expect, for instance, new light fermionic resonances with a large mixing with the top [3].

The leptonic sector can be similarly realized with an extra global symmetry implying tri-bimaximal mixing [4, 5]. In this case, the tau can be more composite than naively expected from its mass. Tau custodians, the custodial symmetry partners of the composite state mixing with the elementary tau, can then be relatively light, coupling sizably only to the tau [5]. Moreover, these new resonances do not disturb the very precisely measured properties of the tau lepton because its coupling to the Z boson is protected by a subgroup of the custodial symmetry [6, 7].¹

In this letter we investigate the LHC reach for such new leptonic resonances. They can be pair produced with electroweak (EW) strength through the exchange of a SM gauge boson, decaying almost exclusively into taus and a vector or scalar SM boson. This analysis is crucial because signatures with taus in the final state are typically deemed challenging and therefore not the first choice for new physics searches. Such a signature could however very well be the first hint, and maybe the only one for a while, of the explicit realization of the lepton spectrum in models of strong EWSB.² Pair production of these new resonances with the taus subsequently decaying into leptons appears to be the cleanest, model independent channel for these searches. Assuming collinearity and no other source of missing energy we can fully reconstruct the two taus. Equality of the invariant mass of the two reconstructed new leptons then allows to reduce the background and reconstruct the custodian masses.

¹ In a similar way as originally proposed to protect the $Zb_L\bar{b}_L$ coupling [8].

² This is an interesting example in which the mechanism of neutrino mass generation, despite having a large suppression scale, has testable consequences at the LHC.

The outline of the paper is as follows. We review the main features and signatures at the LHC of the tau custodians in section II. The details of the analysis and the results are given in section III and our conclusions in section IV.

II. NEW LEPTON DOUBLETS AT THE LHC

The simplest realization of tau custodians with a protected $Z\tau\bar{\tau}$ coupling consists of two vector-like lepton doublets with hypercharges $-1/2$ and $-3/2$,

$$L_{1L,R}^{(0)} = \begin{pmatrix} N_{L,R}^{(0)} \\ E_{1L,R}^{(0)} \end{pmatrix} \sim (2)_{-\frac{1}{2}}, \quad L_{2L,R}^{(0)} = \begin{pmatrix} E_{2L,R}^{(0)} \\ Y_{L,R}^{(0)} \end{pmatrix} \sim (2)_{-\frac{3}{2}}, \quad (1)$$

respectively. The script (0) indicates the current basis. The relevant part of the Yukawa and mass Lagrangian reads, in the basis with diagonal charged lepton Yukawa couplings,

$$\mathcal{L} = -\frac{m}{v}\bar{l}_L^{(0)}\varphi\tau_R^{(0)} - \frac{m'}{v}\left[\bar{L}_{1L}^{(0)}\varphi + \bar{L}_{2L}^{(0)}\tilde{\varphi}\right]\tau_R^{(0)} - M\left[\bar{L}_{1L}^{(0)}L_{1R}^{(0)} + \bar{L}_{2L}^{(0)}L_{2R}^{(0)}\right] + \text{h.c.} + \dots, \quad (2)$$

where the dots denote kinetic terms and other terms in the Lagrangian not involving the new leptons. φ is the SM Higgs doublet and $\tilde{\varphi} = i\sigma^2\varphi^*$, with σ^2 the second Pauli matrix, $v \approx 174$ GeV is the Higgs vev, and $l_L^{(0)}, \tau_R^{(0)}$ are the third generation SM leptons. In the class of models we consider, the coupling to e, μ or any right-handed neutrino is negligible. After EWSB, the lepton mass matrix

$$\mathcal{M} = \begin{pmatrix} m & 0 & 0 \\ m' & M & 0 \\ m' & 0 & M \end{pmatrix} \quad (3)$$

is diagonalized with the usual bi-unitary rotations, $U_L^\dagger \mathcal{M} U_R = \mathcal{M}_{\text{diag}} = (m_\tau, m_{E_1}, m_{E_2})$, which in our case take the very simple form

$$U_{L,R} = \begin{pmatrix} c_{L,R} & 0 & s_{L,R} \\ -\frac{s_{L,R}}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{c_{L,R}}{\sqrt{2}} \\ -\frac{s_{L,R}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{c_{L,R}}{\sqrt{2}} \end{pmatrix}, \quad (4)$$

where $s_{L,R} \equiv \sin(\theta_{L,R})$, $c_{L,R} \equiv \cos(\theta_{L,R})$. All relevant physics can be parameterized in terms of m, m' and M . However, it is simpler to use as alternative parameters m_τ, s_R and M , where the latter two fully describe the model, with the left-handed mixing parameter

$$s_L = s_R \frac{m_\tau}{M}. \quad (5)$$

In particular, assuming $M \geq 100$ GeV we have $s_L \leq 0.018$, $c_L \geq 0.9998$. (Thus $s_L \approx 0$, $c_L \approx 1$ is an excellent approximation.) The resulting physical spectrum consists of three degenerate leptons with mass M and charges 0, -1 and -2 , respectively

$$m_N = m_{E_1} = m_Y = M, \quad (6)$$

and a heavier charge -1 lepton with mass

$$m_{E_2} = \frac{M}{c_R} \sqrt{1 - s_R^2 \frac{m_\tau^2}{M^2}}. \quad (7)$$

In the physical basis the lepton couplings to the SM gauge bosons and to the Higgs can be written without loss of generality

$$\mathcal{L}^Z = \frac{g}{2c_W} \bar{\psi}_Q^i \gamma^\mu \left[X_{ij}^{QL} P_L + X_{ij}^{QR} P_R - 2s_W^2 Q \delta_{ij} \right] \psi_Q^j Z_\mu, \quad (8)$$

$$\mathcal{L}^W = \frac{g}{\sqrt{2}} \bar{\psi}_Q^i \gamma^\mu \left[V_{ij}^{QL} P_L + V_{ij}^{QR} P_R \right] \psi_{(Q-1)}^j W_\mu^+ + \text{h.c.}, \quad (9)$$

$$\mathcal{L}^H = -\frac{H}{\sqrt{2}} \bar{\psi}_Q^i Y_{ij}^Q P_R \psi_Q^j + \text{h.c.}, \quad (10)$$

where Q runs over the electric charges in the spectrum ($-2, -1, 0$) and $P_{LR} = (1 \mp \gamma^5)/2$ are the chirality projectors. In our case, the neutral gauge couplings read

$$X_L^{(-1)} = \begin{pmatrix} -c_L^2 & s_L & -s_L c_L \\ s_L & 0 & -c_L \\ -s_L c_L & -c_L & -s_L^2 \end{pmatrix}, \quad X_R^{(-1)} = \begin{pmatrix} 0 & s_R & 0 \\ s_R & 0 & -c_R \\ 0 & -c_R & 0 \end{pmatrix}, \quad (11)$$

$$X_L^{(0)} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad X_R^{(0)} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \quad X_L^{(-2)} = X_R^{(-2)} = -1; \quad (12)$$

and the charged ones

$$V_L^{(0)} = \begin{pmatrix} c_L U_{33}^{PMNS} & 0 & s_L U_{33}^{PMNS} \\ -\frac{s_L}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{c_L}{\sqrt{2}} \end{pmatrix}, \quad V_R^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ -\frac{s_R}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{c_R}{\sqrt{2}} \end{pmatrix}, \quad (13)$$

$$V_L^{(-1)} = \left(-\frac{s_L}{\sqrt{2}} \quad -\frac{1}{\sqrt{2}} \quad \frac{c_L}{\sqrt{2}} \right)^T, \quad V_R^{(-1)} = \left(-\frac{s_R}{\sqrt{2}} \quad -\frac{1}{\sqrt{2}} \quad \frac{c_R}{\sqrt{2}} \right)^T, \quad (14)$$

where U_{33}^{PMNS} is the corresponding entry of the PMNS matrix [9]. Finally, the corresponding Yukawa couplings read

$$vY^{(-1)} = \begin{pmatrix} c_R^2 m_\tau & 0 & s_R c_R m_\tau \\ 0 & 0 & 0 \\ s_R c_L M & 0 & \frac{s_R^2}{c_R} c_L M \end{pmatrix}. \quad (15)$$

An explicit example, including numerical values for these couplings in the context of composite Higgs models, can be found in [5]. Note that EW single production of these states in association with a tau lepton is proportional to $s_L \approx 0$ or s_R , and therefore very sensitive to the particular value of the latter. Pair production, on the other hand, is proportional to the electric charge, to $c_L \approx 1$ or to c_R , and then less sensitive to the precise value of s_R unless $s_R \gtrsim 0.5$. The three leptons with mass M always decay into a tau lepton and a SM gauge boson

$$N \rightarrow \tau W^+, \quad E_1 \rightarrow \tau Z, \quad Y \rightarrow \tau W^-, \quad (16)$$

whereas the heavier one always decays to a tau and a Higgs

$$E_2 \rightarrow \tau H, \quad (17)$$

provided $c_R \geq (1 + m_W/M)^{-1}$. For smaller c_R values the corresponding decay channels into another heavy lepton and a gauge or Higgs boson open up. This is an exciting possibility, since it allows for a richer phenomenology but requires a large mixing (for instance, $s_R \geq 0.5$ for $M \approx 720$ GeV). Mixing angles that large require a detailed analysis of indirect constraints to assess the phenomenological viability of the model and we defer it to a future publication. Hence, we restrict ourselves to the case in which all new leptons only decay to tau leptons and a SM scalar or vector boson.

New leptons can be singly produced in association with a tau or pair produced at the LHC. Single production, which may be relevant for the early LHC run $\mathcal{L} \sim 1 \text{ fb}^{-1}$ at $\sqrt{s} = 7$ TeV, is very sensitive to the values of the couplings in the model, as just stressed. The relatively light masses and large couplings that can be tested in this early run not only require an analysis of current EW constraints but a dedicated study of the LHC reach, which will be presented elsewhere. Pair production, on the other hand, is EW and model independent to a large extent. The two heavy leptons then decay into two taus and two SM bosons, which in turn will result in ten fermions in the final state. We are in the best position to beat the background if we consider fully leptonic tau decays. Besides, we will require a Z in the final state decaying into leptons for the same reason. Due to the relatively large mass of the heavy leptons, the two taus are largely boosted and therefore their decay products highly collimated. Assuming full collimation, we can completely reconstruct the two taus despite having four neutrinos in the final state if there is no further source of missing energy.

Thus, we consider the following channels

$$pp \rightarrow \bar{E}_1 E_1 \rightarrow ZZ\bar{\tau}\tau, \quad pp \rightarrow \bar{E}_1 Y \rightarrow ZW^-\bar{\tau}\tau, \quad (18)$$

$$pp \rightarrow \bar{E}_1 E_2 \rightarrow ZH\bar{\tau}\tau, \quad pp \rightarrow \bar{E}_1 N \rightarrow ZW^+\bar{\tau}\tau, \quad (19)$$

together with the conjugated ones. The signature we are interested in is therefore

$$pp \rightarrow l^+ l^- l'^+ l''- jj \cancel{E}_T, \quad \text{with } l, l', l'' = e, \mu. \quad (20)$$

Even though we have to pay an important price due to the leptonic branching ratios $\sim 0.6\%$ [$\text{BR}(Z \rightarrow l^+ l^-) \approx 6.6\%$, $\text{BR}(\tau \rightarrow l \cancel{E}_T) \approx 34\%$], the dramatic reduction of backgrounds overcomes this signal suppression. Besides the multilepton final state, the full reconstruction of the taus decaying leptonically and that the pair produced heavy leptons have the same mass allows us to further reduce the background down to an almost unobservable level.

III. ANALYSIS

As explained in the previous section, we consider pair production of tau custodians for it is model independent. The corresponding branching ratios, together with the energy required to produce two heavy states makes the cross section too small to have a significant number of events in the early LHC run. We thus concentrate on the nominal energy $\sqrt{s} = 14$ TeV. The backgrounds we have considered are

$$Zt\bar{t} + n \text{ jets}, \quad \sigma = 39.6 \text{ fb}, \quad Zb\bar{b} + n \text{ jets}, \quad \sigma = 5.85 \text{ pb}, \quad (21)$$

$$ZZ + n \text{ jets}, \quad \sigma = 2.35 \text{ pb}, \quad ZW + n \text{ jets}, \quad \sigma = 1.76 \text{ pb}. \quad (22)$$

$$t\bar{t} + n \text{ jets}, \quad \sigma = 55 \text{ pb}, \quad ZWW + n \text{ jets}, \quad \sigma = 1.9 \text{ fb}, \quad (23)$$

where σ are the corresponding cross sections. One Z in all channels and both tops in the $t\bar{t}$ channel have been required to decay leptonically and the cross section reported includes the corresponding branching ratios and some minimal cuts. In all cases we have generated up to $n = 2$ jets at the partonic level with ALPGEN V2.13 [10], and used the PGS4 [11] fast detector simulation after passing the events through PYTHIA [12] for hadronization and showering (with the MLM matching algorithm). Our signal events are generated with MADGRAPH/MADEVENT v4 [13] and taus are decayed with TAUOLA [14]. In all cases we have included initial and final state radiation but no pile-up effects. We show in Fig. 1 the

signal production cross section, including the Z leptonic branching ratio but not decaying the tau leptons, as a function of the heavy mass M (and assuming a Higgs mass $m_H = 120$ GeV).

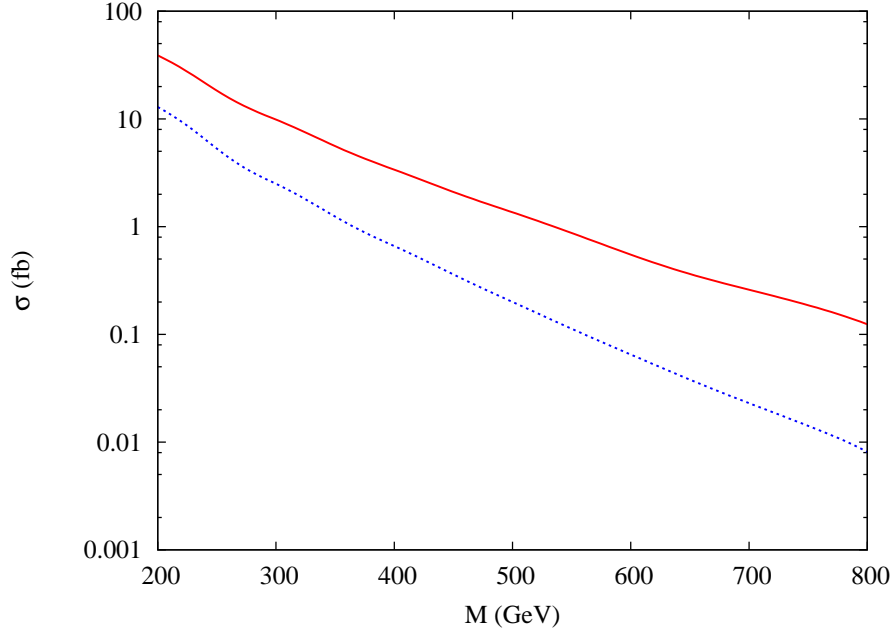


FIG. 1: Heavy lepton pair production cross section (in fb) as a function of the heavy mass M . The dotted (solid) line corresponds to $\sqrt{s} = 7$ (14) TeV. The cross section includes the leptonic Z decay but not the tau decays, i.e. $pp \rightarrow l^+l^- jj\tau^+\tau^-$.

In order to reduce the background we have implemented the following cuts

- **Basic cuts.** We require at least two positively and two negatively charged isolated leptons (electrons or muons), two jets and missing energy with

$$\begin{aligned}
 p_T(l) \geq 10 \text{ GeV}, \quad p_T(j) \geq 20 \text{ GeV}, \quad \cancel{E}_T \geq 20 \text{ GeV}, \\
 |\eta_l| \leq 2.5, \quad |\eta_j| \leq 5, \quad \Delta R_{jj} \geq 0.5, \quad \Delta R_{jl} \geq 0.5.
 \end{aligned}
 \tag{24}$$

We keep the hardest four leptons and two jets if their multiplicity is larger.

- **Leptons.** We require two same flavour, opposite charge leptons to reconstruct a Z , and the other two not to be back to back (so that the two taus can be reconstructed assuming collinearity),

$$|M_{l+l-} - M_Z| \leq 10 \text{ GeV}, \quad \cos(\phi_{l+l-}) \geq -0.95,
 \tag{25}$$

- **M_{jj}**. The two jets in our signal come from the decay of a SM boson. We therefore impose a cut on the invariant mass of the two jets

$$50 \text{ GeV} \leq M_{jj} \leq 150 \text{ GeV}. \quad (26)$$

- **τ reconstruction**. We use the two leptons not reconstructing the Z and the transverse missing energy to infer the tau four-momenta [15]. First, we assume all momenta in the tau decays are aligned

$$p_i^{l'+} = x^+ p_i^{\tau^+}, \quad \not{p}_i^+ = (1 - x^+) p_i^{\tau^+}, \quad (27)$$

$$p_i^{l''-} = x^- p_i^{\tau^-}, \quad \not{p}_i^- = (1 - x^-) p_i^{\tau^-}, \quad (28)$$

where i stands for the spatial components x, y, z and \not{p}_i^\pm denotes the sum of the momenta of the neutrinos coming from the τ^\pm decay. x^\pm are the fraction of τ^\pm momentum taken by $l'^+, l''-$, respectively. They are fixed by momentum conservation in the transverse plane

$$x^+ = \frac{p_y^{l''-} p_x^{l'+} - p_x^{l''-} p_y^{l'+}}{\not{p}_x p_y^{l''-} - \not{p}_y p_x^{l''-} + p_y^{l''-} p_x^{l'+} - p_x^{l''-} p_y^{l'+}}, \quad (29)$$

$$x^- = \frac{p_y^{l'+} p_x^{l''-} - p_x^{l'+} p_y^{l''-}}{\not{p}_y p_x^{l'+} - \not{p}_x p_y^{l'+} + p_y^{l''-} p_x^{l'+} - p_x^{l''-} p_y^{l'+}}. \quad (30)$$

These lie between 0 and 1 if all transverse missing energy, measured with infinite precision, comes from collinear tau decays. Thus, we require $0 \leq x^\pm \leq 1$ and use them to reconstruct the τ^\pm four-momenta

$$p_i^{\tau^+} = \frac{p_i^{l'+}}{x^+}, \quad p_i^{\tau^-} = \frac{p_i^{l''-}}{x^-}, \quad i = x, y, z, \quad (31)$$

$$p_0^{\tau^\pm} = \sqrt{m_\tau^2 + \sum_{i=x,y,z} (p_i^{\tau^\pm})^2}. \quad (32)$$

- **Pair production**. We require the two reconstructed heavy leptons to have the same mass within 50 GeV,

$$|M_{L_1} - M_{L_2}| \leq 50 \text{ GeV}, \quad (33)$$

where M_{L_i} corresponds to the invariant mass of τ^\pm and either l^+l^- or jj . (We select the pairing giving the smaller difference.)

- **Mass reconstruction.** Finally we require the invariant mass of the $\tau l^+ l^-$ pairing to peak around a test mass within 50 GeV.

$$|M_{\tau l^+ l^-} - M_{L^{\text{test}}}| \leq 50 \text{ GeV}. \quad (34)$$

We have applied the analysis described above to the signal, for different values of the custodian mass M , and to the background. In order to estimate the statistical significance of the result we use

$$S_{cL} = \sqrt{2 \left((s+b) \ln(1+s/b) - s \right)}, \quad (35)$$

where s and b are the number of signal and background events, respectively, after all cuts have been imposed [16]. We require a minimum number of 3 signal events and $S_{cL} = 5$ for a 5σ discovery. An example of the efficiency of each cut on the signal and on the main backgrounds for two sample custodian masses $M = 200$ GeV and $M = 400$ GeV is shown in Table I. The required luminosity for a 5σ discovery is 17 and 170 fb^{-1} , respectively. The

14 TeV	$M = 200$ GeV	$M = 400$ GeV	$Zt\bar{t}$		ZZ	
Basic	0.85	0.14	0.49		0.44	
Leptons	0.68 (81%)	0.11 (77%)	0.41(84%)		0.41 (93%)	
M_{jj}	0.49 (72%)	0.063 (59%)	0.15(37%)		0.13 (31%)	
Tau rec.	0.42 (86%)	0.057 (90%)	0.039 (26%)		0.052(40%)	
Pair prod.	0.39 (91%)	0.045 (79%)	0.017(44%)		0.032 (61%)	
Mass rec.	0.37 (96%)	0.041 (91%)	0.008 (48%)	0.0016 (9%)	0.016 (50%)	0.0018 (6%)

TABLE I: Cross sections in fb (and corresponding efficiencies) after cuts for the signal and main backgrounds. The cuts are described in Eqs. (24-34). We show the results for two different values of the custodian masses $M = 200, 400$ GeV. The effect of the last cut on the background depends on the test mass as shown in the last row. The required luminosity to have a 5σ discovery, with 3 or more events, being $\mathcal{L} \approx 17, 170 \text{ fb}^{-1}$, respectively.

corresponding luminosity as a function of the custodian masses is shown in Fig. 2. The expected reach after 30, 300 and 3000 fb^{-1} of integrated luminosity is $M \sim 240, 480$ and 720 GeV, respectively, for a 5σ discovery.

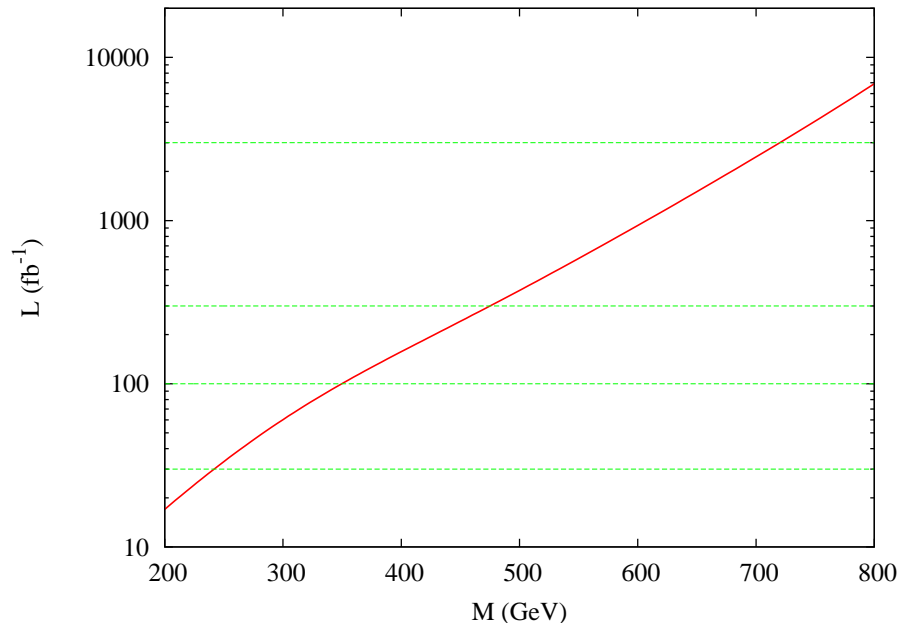


FIG. 2: Luminosity required for a 5σ discovery at the LHC with $\sqrt{s} = 14$ TeV as a function of the custodian mass M .

IV. CONCLUSIONS

New light leptonic resonances related to the tau lepton through custodial symmetry, tau custodians, can be a natural occurrence in models of strong EWSB, if a global symmetry governs the lepton spectrum. Thanks to the custodial symmetry, they can be light and strongly coupled to the tau without conflict with EW precision or flavour data. Pair production of tau custodians provides a clean, model independent channel, that results in two taus and two gauge or Higgs bosons. Requiring at least one Z decaying into electrons or muons, leptonic tau decays and no further source of missing energy, we end up with a final state with four charged leptons (electrons or muons), missing energy and two jets. The large number of leptons allows for a very efficient reduction of the main backgrounds. The relative large mass of the custodians results in highly boosted taus with very collimated decay products. Assuming complete collimation, we can fully reconstruct both taus, despite the presence of four neutrinos in the final state. The requirement of pair production of same mass objects then further enhances the signal, leading to a discovery reach for tau custodians at the LHC with $\sqrt{s} = 14$ TeV of $M = 240, 480$ and 720 GeV for a total integrated

luminosity $\mathcal{L} = 30, 300, 3000 \text{ fb}^{-1}$, respectively.

This analysis is crucial in the context of models of strong EWSB due to the difficulty of observing pair production of tau custodians because they only decay into taus, and this could be the very first experimental signature of the explicit realization of the lepton spectrum in these models. It can be applied to any new particles that are pair produced and decay predominantly into taus and gauge or Higgs bosons. Hadronic tau decays could be also used to search for these new resonances. A rough estimate indicates that they could give a similar sensitivity. However, the a priori larger backgrounds and the need of an efficient tau identification make a full real detector simulation compulsory. What would be also welcome for the analysis presented here.

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