Probing new physics with displaced vertices: muon tracker at CMS

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Long-lived particles can manifest themselves at the LHC via “displaced vertices” – several charged tracks originating from a position separated from the proton interaction point by a macroscopic distance. Here we demonstrate a potential of the muon trackers at the CMS experiment for displaced vertex searches. We use heavy neutral leptons and Chern-Simons portal as two examples of long-lived particles for which the CMS muon tracker can provide essential information about their properties.

I. INTRODUCTION

The Standard model (SM) of particle physics is very successful in describing known elementary particles and their interactions. However, it is not a complete theory, since it does not explain a number of observations in particle physics and cosmology: neutrino oscillations, generation of baryon asymmetry of the Universe, the nature of dark matter. These phenomena imply that new particles beyond the Standard Model should exist. Many extensions of the SM, providing explanations of these phenomena, introduce new particles that have macroscopic decay lengths ($ct > 1$ cm) [1–22]. Such particles are often called long-lived particles (LLPs).

LLPs can be copiously produced at colliders. Their decays present a distinct experimental signature – the position of an LLP decay vertex is highly displaced from its production vertex (PV), see Fig. 1. Therefore, in order to probe the parameter space of the LLPs, experiments searching for the displaced vertices (DVs) must have large length of the decay volume.

![Schematic diagram of an LLP search at particle physics experiments. The LLP X produced at the production vertex (PV) travels a macroscopic distance and then gives rise to a displaced decay vertex (DV).](image)

Figure 1. Schematic diagram of an LLP search at particle physics experiments. The LLP X produced at the production vertex (PV) travels a macroscopic distance and then gives rise to a displaced decay vertex (DV).

Searches for the DV events have been performed at the LHC in the past, including searches for displaced hadronic jets [23–27], dimuon vertices [28–30] and decays into specific final states (for example, the process $B^\pm \rightarrow \mu^\pm \mu^\pm \pi^\mp$ with one prompt and one displaced muon at LHCb [31]). In this paper, we propose a scheme for DV searches exploiting the muon trackers of the CMS experiment. Its advantage is large length of the decay volume, which is essential to probe the parameter space of the LLPs with the decay lengths about 1 meter or larger.

This paper is organized as follows. In Sec. II we discuss the scheme, selection criteria and conditions for an LLP model under which the scheme is the most efficient. In Sec. III we discuss the potential of the scheme to probe particular models — the neutrino portal and the Chern-Simons vector portal, with the new particles being a heavy neutral lepton and an $X$ boson correspondingly. Finally, in Sec. IV we provide conclusions.

II. DISPLACED VERTICES WITH THE MUON TRACKER

Description of the scheme. CMS (compact muon solenoid) is a beam line azimuthally symmetric detector consisting of a solenoid generating the 3.8 T magnetic field, the inner trackers that allow to reconstruct the momentum of particles produced in the pseudorapidity range $|\eta| < 2.5$ (where $\eta = -\log[\tan(\theta/2)]$ and $\theta$ is the polar angle with respect to the anticlockwise-beam direction) and the muon trackers located outside the solenoid [32].

The muon system is located outside the solenoid and covers the range $|\eta| < 2.4$. It is a set of gaseous detectors sandwiched among the layers of the steel flux-return yoke. This allows for a muon to be detected along the track path at multiple points [33]. The magnetic field in the muon system is not uniform, and goes from $2$ T in the innermost part down to almost $0$ T in the outer part [34]. Schematic drawing of the muon detector is shown in Fig. 2.

For the LHC Run 2, new reconstruction of muons has been introduced [36], so-called displaced standalone muon reconstruction. This reconstruction is specifically designed to address cases when a muon is produced in decays far away from the production vertex. New algorithm achieves an almost 100% reconstruction efficiency for the muon production radius up to about 3 m. This is a significant gain in the efficiency compared to the reconstruction which uses also inner tracker information, but at the same time, the momentum resolution deteriorates by about factor of 10 and is in the range 10–60%.
The muon tracker can use two muon tracks to reconstruct a displaced vertex originating from the decay $X \rightarrow \mu\mu$. The reconstructed DV, together with the production vertex that can be tagged by prompt decays products, e.g. a prompt lepton, and an underlying event produced together with the $X$ particle, is identified as a DV event. Because of large positions of the decay vertices that can be reconstructed we will call this scheme the “the long DV” scheme. The scheme is presented in Fig. 3.

The sources of the background for the long DV scheme are decay events of the SM particles into single muons, which give rise to combinatorial two-muon events, and two-muon decays of the SM particles (for example, $J/\psi, \rho, \omega$ mesons and the $Z$ boson). This background can be significantly reduced if one requires the position of the displaced vertex to be as far as $l_{DV} > 2$ cm from the beam collision point, since the most of the SM particles decay before reaching this displacement [37]. Because of the position of the muon trackers, the muon events can be reconstructed at the distances $l_{PV} < 3$ m. The muons can be reconstructed with high efficiency and low misidentification probability if each of them has the transverse momentum $p_T > 5$ GeV [38, 39].

To summarize, a DV event in the long DV search scheme should satisfy the following selection criteria:

- A prompt electron with $|\eta| < 2.5$, $p_T > 30$ GeV or a prompt muon with $|\eta| < 2.4$, $p_T > 25$ GeV, which are required for an event to be recorded by the single lepton triggers;
- The minimal transverse displacement of the DV from the PV is $l_{\min,\perp} = 2$ cm; the maximal transverse and longitudinal displacements are $l_{\max,\perp} = 3$ m, $l_{\max,\parallel} = 7$ m;
- Two displaced muon tracks, each with $|\eta| < 2.4$, $p_T > 5$ GeV.

The requirement of a large displacement of a DV from the PV helps to significantly reduce the background from SM processes which lead to two muons originating from the same vertex, as e.g. decays of heavy flavor mesons. Therefore, even in the region with the invariant mass of two muons below 5 GeV ($m_{\mu\mu}$) the SM background is considered to be negligible.

An event with prompt $\tau$ lepton can be tagged by its leptonic decays $\tau \rightarrow l\nu l\nu\tau$, where the leptons $l = e/\mu$ satisfy the criteria for prompt leptons presented above. We do not consider the reconstruction of $\tau$ leptons by their hadronic decay products since the trigger threshold for $p_T$ of hadronic decay products is too high for efficient reconstruction. However, in the future it is wise to invest into the development of a dedicated multi-object trigger which would allow to bring down the prompt tau $p_T$ by including additional displaced leptons in the event.

Ref. [30] previously explored a potential of the CMS muon chambers alone to reconstruct dimuon DV. This search has been constructed to be much more general, and hence could not profit from the presence of a prompt lepton in the event. This necessarily implied much more stringent cuts on $p_T$ of either of the two muons in the muon tracker since these muons were used to record an event by a trigger, and therefore lower sensitivity.

The combination of the search strategies presented here and of the DV searches with the CMS inner detector have been previously investigated in Ref. [40] and later in [29]. In the latter paper a similar search scheme was discussed albeit with less restrictive selection criteria $l_{\min,\perp} = 0.5$ cm, $l_{\max,\perp} = 4$ m, and $|\eta| < 4$ for leptons. A wider range of muon pseudorapidity leads to the enlargement of the selection efficiency, while a smaller displacement between a DV and the PV lifts up the upper

\footnote{Current trigger threshold is $p_T > 180$ GeV.}
\footnote{After the HL-LHC upgrade the CMS will extend its pseudorapidity range to $|\eta| < 4$.}
bound of the sensitivity and hence increases the maximal mass reach. However, we caution that the background-free hypothesis for the region with smaller DV displacements adopted in [29] has not been tested. Nevertheless, to demonstrate potential improvement from considering lower displacements we provide sensitivity for two scenarios: “realistic” for the selection criteria outlined above, and “optimistic”, defined according to [29].

Estimation of the number of events. The number of decay events of a new particle $X$ that pass the selection criteria is

$$N_{\text{events}} = N_{\text{parent}} \cdot \text{Br}_{\text{prod}} \cdot \text{P}_{\text{dec}} \cdot \epsilon,$$

where
- $N_{\text{parent}}$ is the total number of parent particles that produce a particle $X$ at the LHC;
- $\text{Br}_{\text{prod}}$ is the branching fraction of the production of a particle $X$ in decays of the parent particle;
- $\text{P}_{\text{dec}}$ is the decay probability,

$$\text{P}_{\text{dec}} = \int d\theta \frac{dP_{\text{X}}}{d\theta} f(p_{\text{X}}, \theta_{\text{X}}) \times \left( e^{-l_{\text{min}}/\tau_{\text{X}} \gamma_{\text{X}}} - e^{-l_{\text{max}}/\tau_{\text{X}} \gamma_{\text{X}}} \right),$$

with $\tau_{\text{X}}$ being the proper lifetime of the particle $X$, $\gamma_{\text{X}}$ is its $\gamma$ factor, and $f(p_{\text{X}}, \gamma_{\text{X}})$ is the distribution function of the $X$ particle whose decay products satisfy the selection criteria;
- $\epsilon$ is the overall efficiency — the fraction of all decays of the $X$ particle that occurred in the decay volume between $l_{\text{min}}$ and $l_{\text{max}}$, have passed the selection criteria, and were successfully reconstructed.

The efficiency is a combination of several factors:

$$\epsilon = \epsilon_{\text{sel}} \cdot \epsilon_{\text{rec}} \cdot \text{Br}_{X \rightarrow \mu \mu},$$

where $\epsilon_{\text{sel}}, \epsilon_{\text{rec}}$ are the efficiencies of the selection and subsequent reconstruction of an event correspondingly, and $\text{Br}_{X \rightarrow \mu \mu}$ is the branching ratio of the decay of the $X$ particle into two muons. Clearly, $\epsilon_{\text{rec}}$ does not depend on the nature of LLP. The reconstruction efficiency for leptons is well above 95% for muons with $p_T > 5$ GeV [33, 36, 38] and for electrons with $p_T > 30$ GeV [41]. Therefore, for simplicity the reconstruction efficiency is taken to be equal to 1 ($\epsilon_{\text{rec}} = 1$) in what follows.

The sensitivity curve is determined by the condition $N_{\text{events}} \approx 3$ (95% confidence limit).

Potential of the scheme. The main advantage of the long DV scheme is the large length of the fiducial decay volume $l_{\text{max}}$, which exceeds the lengths of the decay volumes of other DV search schemes at the LHC (see, e.g., [31, 42]) by $\approx 10$ times. This has a benefit when searching for new particle with large decay lengths,

$$l_{\text{dec}} \equiv \epsilon \tau_{\text{X}} \gamma_{\text{X}} \gg l_{\text{max}}$$

Indeed, in this case the decay probability (2) is in the "linear regime", $P_{\text{dec}} \approx l_{\text{max}}/l_{\text{dec}}$, and as a result the number of events (1) is proportional to $l_{\text{max}}$. For decay lengths that do not satisfy the condition (4) the decay probability does not depend on $l_{\text{max}}$, and the improvement is lost (see Fig. 4).

In order to probe the domain (4) there must be sufficient production of the $X$ particles, i.e.

$$N_{\text{prod}} \cdot \text{Br}_{X \rightarrow \mu \mu} > 3,$$

where $N_{\text{prod}} = N_{\text{parent}} \cdot \text{Br}_{\text{prod}}$. The parameter space defined by the conditions (4), (5) is optimal for being probed by the long DV scheme. A toy example of the parameter space is given in Fig. 5.
III. EXAMPLES OF PROBED MODELS

A. HNLs

Consider the model of heavy neutral lepton (HNL), which introduces a Majorana fermion singlet $N$ coupled to the gauge invariant operator $LH$, where $L$ is the left lepton doublet and $H = i \sigma_2 H^*$ is the Higgs doublet in conjugated representation. This coupling introduces the mass mixing between the HNL and active SM neutrino $\nu_l$ parametrized by the mixing angle $U_l$. We adopt the phenomenology of the HNLs from [43]. The main production channel of the HNLs with masses in the range $m_N \gtrsim 5$ GeV is the decay of the $W$ bosons. We use the value $\sigma_W \approx 190$ nb for the total production cross-section of the $W$ bosons at the LHC [44]. To estimate the parameter space defined by (4) and (5), we calculated the energy spectrum and geometric acceptance $\epsilon_{\text{geom}}$ of the HNLs in the pseudorapidity range $|\eta| < 2.5$, see Appendix A. We found $\epsilon_{\text{geom}} \approx 0.5$ for the mass range $m_N \lesssim 20$ GeV and $E_N \approx 80$ GeV.

In Fig. 6 we show the parameter space for the HNLs mixing with $\nu_\mu$ that can be optimally probed by the long DV scheme (see Sec. II). We see that the domain where the long DV scheme has good potential corresponds to the masses $m_N < 10$ GeV and the mixing angles $U^2 \gtrsim 10^{-9}$.

Simulations. To find the efficiency for the HNLs mixing with $\nu_e/\mu$, we used MadGraph5 [45] with the models HeavyN [46]. For simulating decays of $\tau$ lepton, we used taudecay_UFO model [47]. For the mixing with $\nu_e/\mu$ we simulated the process $p + p \to W$, $W \to l + N$, where $l = e$ for the mixing with $\nu_e$ and $l = \mu$ for the mixing with $\nu_\mu$, with subsequent decay $N \to \mu^+ + \mu^- + \nu_\tau$. In the case of the mixing with $\nu_\tau$, we simulated the process $p + p \to W, W \to \tau + N$ with subsequent decays $N \to \mu^+ + \mu^- + \nu_\tau + \nu_\tau$ and $\tau \to l + \bar{\nu}_\tau + \nu_\tau$, where $l = e/\mu$.

Using the selection criteria for the long DV scheme, in the case of HNLs mixing with $\nu_e, \nu_\mu, \nu_\tau$ in the realistic (optimistic) scenario we obtained $\epsilon_{\text{sel}} \approx 0.16 (0.26), 0.17 (0.31)$ and $7 \times 10^{-3} (3.2 \times 10^{-2})$ correspondingly, almost independently on the mass of the HNL in the mass range $1$ GeV $< m_N < 15$ GeV. The suppression of the efficiency for mixing with $\nu_\tau$ is due mainly to the reconstruction of the prompt $\tau$ event. Indeed, the amount of the leptons produced in the decay $\tau \to l \bar{\nu}_\tau \nu_\tau$ and passing the $p_T$ selection criterion for the prompt leptons is $\approx 0.1$.

For the average momentum we found $p_N \approx 70$ GeV and $p_N \approx 180$ GeV for the realistic and optimistic estimates correspondingly.

Comparison with other schemes. Let us compare the sensitivity of the long DV search scheme to the HNLs with a scheme from [42, 48] that uses inner trackers at ATLAS to search for DVs events (c.f. [40]). Owing to its smaller transverse displacement $l_{\text{max}} \approx 0.3$ m we call it the “short DV scheme”. For the estimation of the sensitivity of the short DV scheme we use parametrized efficiencies $\epsilon(m_N, U^2)$ provided by the authors of [42]. The comparison of the sensitivities is given in Fig. 7. We show both optimistic and realistic estimate of the sensitivity of the long DV scheme. We also show the sensitivity of the SHiP experiment from [49] that serves for an illustration of the sensitivity reach of Intensity Frontier experiments.

The long DV scheme allows to search for HNLs in the unexplored region of the parameter space that is not accessible to other Intensity Frontier experiments or other LHC searches. Its difference in the sensitivity with the short DV scheme is due to three reasons. First, for masses $m_N \lesssim 10$ GeV the decay probability for both the schemes is in the linear regime (see Sec. II), and therefore the long DV scheme gets the benefit from the 10 times larger length of the decay volume $l_{\text{max}}$. Second, for the masses $5$ GeV $\lesssim m_N \lesssim 10$ GeV there is a drop of the overall efficiency for the short DV scheme. This is caused by the selection criteria on the reconstructed invariant mass of the $DV$, $m_{\text{DV}} > 5$ GeV, and the charged tracks, $N_{\text{trk}} > 4$, that are needed to remain in the background free region [24]. Third, because of absence of the hadronic background the long DV scheme can probe the parameter space $m_N \lesssim 5$ GeV, which is not reachable by the short DV scheme.

Nevertheless, both the schemes are complementary to each other and provide a cross-check in the mass region $5$ GeV $< m_N < 15$ GeV.

B. Chern-Simons portal

Chern-Simons portal introduces a vector particle $X$ interacting with pseudo-Chern-Simons current of the SM gauge bosons [50, 51]:

$$L_{CS} = c_W e^{\mu\nu\lambda\rho} X_\mu W_\nu \partial_\lambda W_\rho + c_\gamma \cos \theta_W e^{\mu\nu\lambda\rho} X_\mu Z_\nu \partial_\lambda \gamma_\rho + c_Z \sin \theta_W e^{\mu\nu\lambda\rho} X_\mu Z_\nu \partial_\lambda Z_\rho$$

(6)
We can add the interaction of the $X$ boson with SM leptons in the form

$$\mathcal{L}_{X_{\mu\mu}} = c_W g_{Xl} X^{\nu} \sum_{l=e,\mu,\tau} \bar{l}_l \gamma_5 \gamma_{\nu} l,$$

(7)

where $g_{Xl}$ is a dimensionless constant.\(^3\)

Let us consider the case when $c_\gamma, c_Z \ll c_W$. Then the production of the $X$ particle in $pp$ collisions goes through the $XWW$ vertex, while the decay goes through the vertex (7) down to very small couplings $g_{Xl}^2 \approx 10^{-7}$ for the $X$ bosons as heavy as $m_X \approx 40$ GeV, see Appendix B. These vertices are parametrically independent, and for particular values of $g_{Xl}$ it is possible to probe the parameter space in the optimal domain for the long DV scheme. The process of interest is

$$W \rightarrow X + l + \bar{\nu}_l, \quad X \rightarrow \mu^+ + \mu^-$$

(8)

The lepton $l$ produced in the $W$ decay can be triggered as a prompt lepton, while the muon pair from the decay of the $X$ boson can be reconstructed as displaced muons, which meets the selection criteria of a DV event within the long DV scheme.

The sensitivity to the Chern-Simons portal is shown in Fig. 8. We conclude that the long DV scheme can probe masses up to $m_X \approx 30$ GeV and couplings down to $c_W^2 \approx 10^{-9}$. We note that the probed parameter space is well below the current experimental bound on $c_W$, which is $c_W^2 \lesssim 10^{-3}(m_X/1 \text{ GeV})^2$ [51].

\(^3\)The coupling $g_{Xl}$ can be generated effectively by the interaction (6) or be an effect of new physics.
IV. CONCLUSION

In this paper we proposed a new method of searching for long-lived particles at LHC (“the long DV scheme”) that utilizes the muon tracker at the CMS experiment. It uses a prompt lepton and a displaced muon pair to reconstruct a displaced vertex event. The scheme is optimal for probing the parameter space of the LLPs with the decay lengths $l_{\text{dec}} \gtrsim 3 \text{ m}$. We demonstrated the potential of the scheme using two exemplary models: heavy neutral lepton (HNL) and Chern-Simons portal. For the HNLs we made a comparison between the long DV scheme and other planned searching schemes at ATLAS/CMS, using the scheme [42] as an example of the latter.

Our conclusions are the following:

- For the HNLs, the long DV scheme can probe the parameter space in the mass range $m_N \lesssim 20 \text{ GeV}$ and up to mixing angles $U^2 \sim 10^{-8}$;
- The long DV scheme has unique opportunity to probe the LLPs that decay predominantly into leptons, which is demonstrated on the example of Chern-Simons portal;
- Under an assumption of low SM background, the long DV scheme allows to probe the parameter space of the LLPs with the masses $m \lesssim 5 \text{ GeV}$, which is unavailable for DV search schemes at the LHC that look for hadronic decay products. In the case of HNLs this gives a possibility to search the parameter space that can not be probed neither by old experiments nor the planned Intensity Frontier experiments.

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Appendix A: Production of the HNLs from $W$ bosons

We estimate the number of the HNLs flying in the direction of the ATLAS and CMS experiments in the following way:

$$N_{\text{prod}} = \sigma_W \times \mathcal{L} \times \epsilon_{\text{geom}}, \quad (A1)$$

where $\sigma_W$ is the total production cross-section of the $W$ at the LHC (we use $\sigma_W \approx 193 \text{ nb}$ [44]) and $\epsilon_{\text{geom}}$ is the geometric acceptance (i.e. the fraction of the HNLs that are produced in the pseudorapidity range of CMS, $|\eta| < 2.5$).

We estimate the momentum spectrum of the $W$ bosons $dN_W/dp_W$ by performing the leading order simulation of the process $p + p \rightarrow W + X$ in MadGraph5 [45]. Using it, we obtained $\epsilon_{\text{geom}}$ and the average HNL energy $\langle E_N \rangle$ by calculating the distribution of the HNLs in the energy and the angle $\theta_N$ between the direction of motion of the HNL and the $W$ bosons (whose momenta are found to be collinear to the proton beam direction in the simulations):

$$\frac{d^2N_N}{dE_Nd\theta_N} = \int dp_W \frac{dN_W}{dp_W} \times \frac{d^2\text{Br}_{W \rightarrow N + l}}{d\theta_N dE_N} \times P(\theta_N) \quad (A2)$$

Here

$$\frac{d^2\text{Br}_{W \rightarrow N + l}}{d\theta_N dE_N} = \frac{1}{\Gamma_W} \frac{|M_{W \rightarrow l + N}|^2}{8\pi} \times \delta(m_N^2 + m_W^2 - 2E_NE_W + 2p_{NWP} \cos(\theta_N)) \quad (A3)$$

is the differential production branching ratio, and $P(\theta_N)$ is a projector which takes the unit value if $\theta_N$ lies inside the range $|\eta| < 2.5$ and zero otherwise.

The resulting angular and energy distributions of the HNLs at ATLAS are shown in Fig. 9. For the mass range $m_N \lesssim 30 \text{ GeV}$ we obtained $\langle E_N \rangle \approx 80 \text{ GeV}$ and $\epsilon_{\text{geom}} \approx 0.5$ with the accuracy $\sim 20\%$.

Appendix B: Chern-Simons portal

Decay width of the $W$ boson into $X$ boson. The matrix element of the process shown in Fig. 10 is

$$\mathcal{M}_{W \rightarrow X + f + f'} = \frac{g_{\mathcal{CW}}}{2\sqrt{2}} \varepsilon_{\mu\alpha\beta} \epsilon_{\mu}(p)(2p + k_X)_{\nu} \epsilon^{\alpha}(k_X) \times \nonumber$$

$$\times D_{\beta\gamma}(k_f + k_{f'})\bar{u}(k_f)\gamma^\gamma(1 - \gamma_5)v(k_{f'}), \quad (B1)$$

where $\epsilon(p)$ is the polarization vector. In the limit $m_{X,f,f'} \ll m_W$ the decay width is

$$\Gamma_{W \rightarrow X + f + f'} \approx c_W^2 \frac{\alpha_W m_W^3}{432\pi^2 m_X^3} \quad (B2)$$
Figure 9. Left panel: the angular distribution of the HNLs produced in the decays of the W bosons. By the red dashed lines we show the values of the angle that correspond to $\eta = \pm 2.5$. Right panel: the energy distribution of the HNLs flying in the direction of the ATLAS inner tracker. The HNL mass $m_N = 20$ GeV is used. The peak around $E_N \approx M_W/2$ is caused by the contribution of the W bosons produced at with very low $p_T$, so that all of the HNLs have the same energy equal to the half of the W boson mass.

Figure 10. The diagram of the W boson decay into the X boson that goes through the XWW vertex in (6).

Using this decay width, for the branching ratio of the process $W \to X + l + \nu_l$, where $l = e, \mu$ we obtain

$$\text{Br}_{W \to X + l + \nu_l} \approx 2.9 \left( \frac{1 \text{ GeV}}{m_X} \right)^2 c_W^2 \quad \text{(B3)}$$

**Tree-level decays generated by $c_W$ coupling.** The vertex $c_W$ generates the tree level decay process $X \to f f' f'' f'''$. Based on dimensional grounds, we can estimate the corresponding decay width as

$$\Gamma_{X \to f f' f'' f'''} \sim c_W^2 \frac{\alpha_W}{(2\pi)^3} \frac{m_X^9}{m_W^8} \quad \text{(B4)}$$

For the ratio of this decay width to the decay width into two muons, $\Gamma_{X \to \mu \mu} \sim c_W^2 g_{X\mu\mu} m_X/ (2\pi)$, we have

$$\frac{\Gamma_{X \to f f' f'' f'''}}{\Gamma_{X \to \mu \mu}} \approx \left( \frac{\alpha_W}{2\pi g_{X\mu\mu}} \right)^2 \frac{m_X^8}{m_W^8} \approx \frac{10^{-7}}{g_{X\mu\mu}^8} \left( \frac{m_X}{40 \text{ GeV}} \right)^8 \quad \text{(B5)}$$

which means that for $m_X \lesssim 40$ GeV the process $X \to f f' f'' f'''$ is not relevant for $g_{X\mu\mu}^8 > 10^{-7}$.

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