SHIFT: sensitivity to low-mass new physics with fixed-target at the LHC

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Abstract

SHIFT is a newly proposed fixed-target experiment at the Large Hadron Collider (LHC) designed to investigate long-lived particles (LLPs), which may decay after travelling long distances. This study explores the sensitivity of SHIFT to various models of low-mass (< 10 GeV) LLPs using the recently developed SensCalc framework. SensCalc enables direct comparisons between SHIFT and other proposed or ongoing experiments. The findings demonstrate that SHIFT exhibits strong sensitivity to dark photons, particularly within a mixing and mass range that remains largely unexplored.

Contents

1 Introduction

Many BSM (Beyond the Standard Model) models have been proposed to explain some of the unanswered questions and gaps of the Standard Model (SM), such as experimental deviations from SM predictions, the existence of dark matter, the neutrino masses or the matter-antimatter asymmetry in our universe for instance. These models of new physics, which may solve many of the actual problems of the SM, predict the existence of feebly interacting particles (FIPs) that interact with SM particles. Examples include dark photons, heavy neutral leptons (HNLs), axion-like particles (ALPs), and dark scalars, among others. Detecting these particles is a major goal in contemporary particle physics.

SHIFT, which stands for "SHIFTted interaction on a Fixed Target", is an experiment designed to investigate these models [1]. The primary concept involves placing a fixed target approximately 160 meters downstream from the CMS detector within the LHC facility [1].

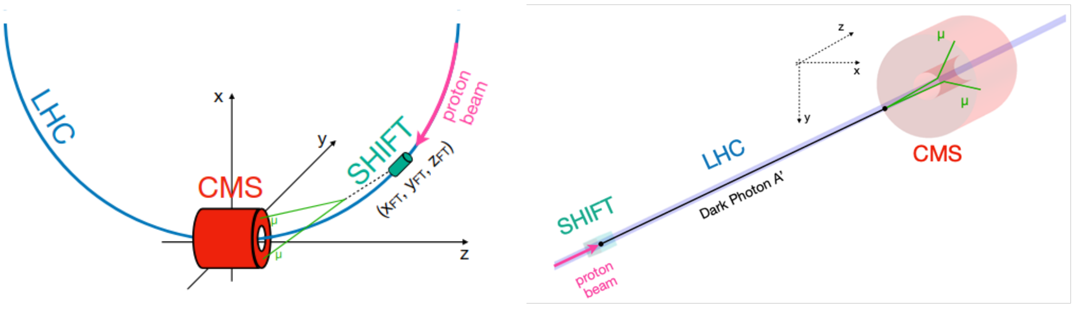
Our objective is to study the lower mass range, specifically below 10 GeV. For this purpose, we employed SensCalc [2], a Mathematica-based framework for computing and comparing experimental sensitivities, which already includes many experiments and models. SensCalc uses a semi-analytical method for calculating sensitivities, an approach that has proven accurate for other experiments such as SHiP[7], MATHUSLA[8], SHADOWS[9], and FASER[10].

The primary aim of this project is to understand the workings of SensCalc, model and integrate SHIFT into SensCalc, and ultimately use SensCalc to calculate the SHIFT sensitivity to various models.

1.1 SHIFT

SHIFT is a proposed experiment that utilizes a gas fixed target, such as hydrogen or helium, positioned 160 meters downstream from the CMS detector at the LHC. When the LHC proton beam interacts with the hydrogen target, collisions occur at a center-of-mass energy of approximately 113 GeV, which is calculated using relativistic kinematics with a beam energy of 6.8 TeV. The majority of the resulting particles are produced in the forward direction, and these particles, or their decay products, would travel through the intervening rock and materials, potentially reaching the CMS detector where they could be detected. This setup enables the exploration of otherwise inaccessible regions of parameter space at a relatively low cost, as it leverages existing infrastructure and eliminates the need to construct a new detector.

[1] This setup has been optimized for particles with masses ranging from 11 to 70 GeV by studying the expected number of events reaching the detector. The distance is a critical factor, as a greater distance allows more particles to decay within the detector's range, but fewer prompt decays are detected due to the reduced solid angle coverage.



(a) (b)

Figure 1: (a) General layout of SHIFT within LHC ring and CMS detector. Taken from [1] (b) Expected event scheme where a Dark Photon is generated, travels in the forward direction and finally decays into two muons which are detected. Taken from [1]

The overall layout of SHIFT, the LHC ring, and the CMS detector is illustrated in Fig. 1 (a) [2]. While the exact positioning of the target can be adjusted, a distance of approximately 100-200 meters typically optimizes the number of particles from BSM interactions that reach CMS. This is because, in the asymmetric system, **most particles are produced at a forward rapidity of around $\eta \approx 5$**, from which an appropriate distance can be inferred. In Fig.1 (b) a detectable event is depicted where a dark photon is produced and travels a significant distance before decaying into a pair of muons, which subsequently reach the detector.

Since the particles reaching CMS from SHIFT are not produced in the typical collider mode, they will primarily be detected as hits in the CMS muon system, with many occurring in the endcaps (at the sides of the detector). The trajectories of these muons may differ significantly from those of muons produced in standard collider mode, making them easier to identify. Additionally, non-muonic particles will generate showers in the muon system's endcaps, producing detectable signals distinct from those in normal collider mode.

While SHIFT may generate numerous forward-directed muons from SM processes, many of these muons are unlikely to traverse the material. The majority of muons come from pion decays, but pions would typically be stopped in the material before decaying or would lose nearly all their energy, resulting in muons that are produced at any angle related to the initial forward direction and with lower energy, so their chance to reach the detector is reduced.

[2]The actual distance between SHIFT and CMS is 160 meters, placing it within the Long Straight Section (LSS) of the LHC, which spans 230 meters. Therefore, there is no curvature in this section.

1.2 SensCalc

SensCalc is a Mathematica-based program that allows one to calculate sensitivities of lifetime frontier experiments to Long-Lived Particles (LLPs)[2]. The framework takes basically the following inputs:

- **Phenomenology of the Model**: This includes the branching ratios for production and decay channels, the corresponding squared matrix elements, and tabulated lifetimes for the LLPs.
- **Tabulated Distributions of Mother Particles**: This refers to distributions of light mesons (such as η, η', ρ, π^0, etc.) and other production channels (e.g., Drell-Yan processes) that may generate LLPs at the specified facility.
- **Experimental Setup**: This encompasses the geometry (dimensions, distances, and shape of the detector, alignment with the beamline, etc.) and selection criteria for LLP decay products (including requirements on energy and transverse momentum), as well as facility parameters such as total and partial cross sections, integrated luminosity or number of protons on target.

The SensCalc framework enables the generation of plots for an experiment in approximately 30 minutes, depending on computational power. However, it has some limitations. SensCalc assumes a **background-free** environment, which is nearly valid for many proposed experiments, but for SHIFT the background amounts are nontrivial. Additionally, it does not directly account for **interactions with the material**, which are crucial for non-muons or low-energy muons that may be stopped by the material. To address these issues, slight modifications to SensCalc will be necessary, as detailed in the implementation section. Finally, although it is possible to extend the **mass range** beyond 5 GeV, current simulations of phase space for LLPs are only available up to 5 GeV. This limitation restricts the study for SHIFT and should be addressed by producing new files to cover a broader mass range.

The framework's code structure is straightforward, consisting of four primary notebooks and several secondary ones for specific tasks or storing variable values.

1.2.1 The experiments notebook

The experiments notebook is one of the secondary notebooks which has particular significance. This notebook establishes the complete geometry of the experiments and is referenced by the main notebooks to retrieve various parameter values. Key aspects defined in the experiments notebook include:

- **Decay Volume:** Specifies the region within which an LLP can decay and be considered in subsequent calculations. LLPs decaying outside this volume are deemed non-detectable.

- **Detector:** Describes the geometry and characteristics of the detector, including components such as the magnet and calorimeter.
- **Target:** Outlines parameters related to the target material, including its composition, cross-sectional area, and the number of protons present.
- **Facility parameters:** Values for cross sections and average multiplicities are set.

1.2.2 Main notebooks structure

The four main notebooks are:

1. **Acceptances notebook**: With the geometry of the experiment and selection criteria for the decay products, this notebook produces the tabulated distributions:
   - $\epsilon_{az}(\theta, E)$: Fraction of particles which decay inside the decay volume.
   - $\epsilon_{dec}(m, \theta, E, z)$: Fraction of detectable decay products which point into the detector and satisfy the various selection criteria provided.
2. **LLP distribution notebook**: This notebook evaluates the angle-energy distribution of LLPs at the facility housing the given experiment, $f^{(i)}(\theta, E)$. For that purpose, it loads all the pregenerated files from SM distributions and other input files for direct production modes.
3. **Sensitivity notebook**: This notebook integrates the input distributions and calculates the tabulated number of events (eq: 1) with decays of LLPs at the given experiment, and then the sensitivity based on the input (such as expected background and the number of proton collisions).
4. **Plots notebook**: This final notebook simply creates sensitivity plots with the previous output files.

In Fig. 2, the flow of information through SensCalc is represented. `Acceptances.nb` and `LLP distribution.nb` produce the outputs necessary for computing the sensitivity in `LLP sensitivity.nb` and finally producing the plots in `Plots.nb`.

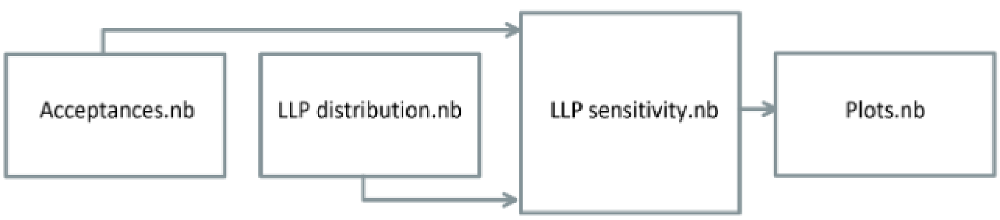


Figure 2: Description of the modular structure of SensCalc. Taken from [2]

To obtain the final number of expected signal events for a certain model, SensCalc uses this equation:

$$N_{ev} = \sum_i N_{prod}^{(i)} \int dEd\theta dz f^{(i)}(\theta, E) \cdot \epsilon_{az}(\theta, E) \cdot \frac{dP_{dec}}{dz} \cdot \epsilon_{dec}(m, \theta, E, z) \tag{1}$$

Let $N_{prod}^{(i)}$ denote the total number of LLPs produced through a given production channel. The function $f^{(i)}(\theta, E)$ represents the distribution of angles and energies produced by that channel. The acceptance factor $\epsilon_{az}(\theta, E)$ quantifies the ratio of events where the LLP decays within the decay volume, while $\epsilon_{dec}(m, \theta, E, z)$ describes the ratio of events where the decay products are directed towards the detector and meet the necessary criteria. The term $\frac{dP_{dec}}{dz}$ represents the differential probability of an LLP decaying at a distance z. In summary, the procedure involves taking the number of initially produced LLPs and applying three factors:

1. The ratio of LLPs decaying within the decay volume ϵ_{az}.
2. The differential decay probability of the LLP $\frac{dP_{dec}}{dz}$.
3. The ratio of decay products that are registered by the detector ϵ_{dec}.

To calculate the total expected number of events N_{ev} for a given model, SensCalc performs the following steps:

- Integrates over the energy, angle, and distance of the LLPs.
- Sums over all the available production channels.

In Fig. 3 there is an example of the results of this calculation and the final sensitivity contour obtained. With eq. 1 SensCalc calculates the expected number of events in the phase space of the plot (a). Once this is calculated, the contour of plot (b) is created by requiring a minimum number of events inside the region enclosed by the contour.

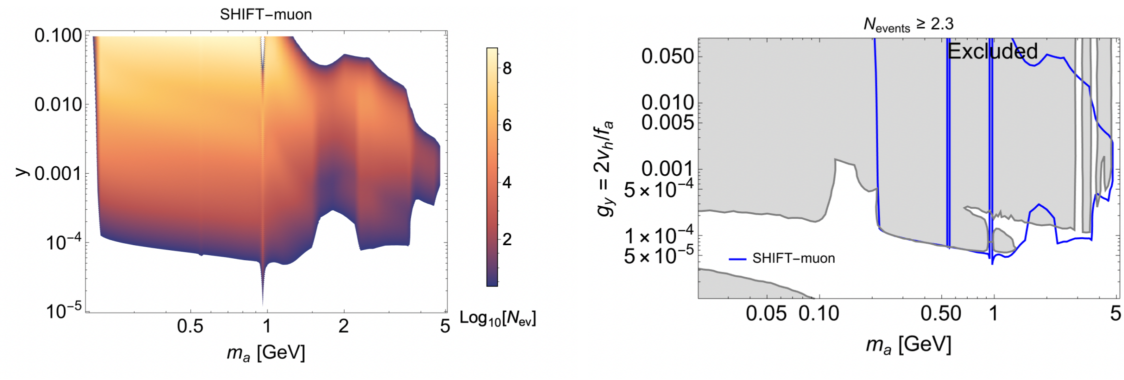
This minimum number of events is calculated accordingly to a 90% of confidence level (CL) assuming zero background and a Poisson distribution for the number of events:

$$P(n; \mu) = \frac{\mu^n e^{-\mu}}{n!} \tag{2}$$

where n is the actual number of observed events and μ is the expected number of events.

Assuming zero background events, we want to find the number of signal events such that the probability of observing no events is 10% (90% of CL). Thus,

$$P(0; \mu) = e^{-mu} = 0.1 \quad \longrightarrow \quad \boxed{\mu \approx 2.3 \text{ events}} \tag{3}$$



(a) (b)

Figure 3: (a) Number of expected events as a function of the mass of the particle (on the x-axis) and the strength of interaction constant (on the y-axis) (b) Example of a sensitivity plot, contour which encloses the required number of events to exclude the model with a 90% CL.

For SHIFT, the background should be considered, so a method for including background was implemented in the code and is available in the code documentation [5]. The main idea is to define the significance level as:

$$S = \frac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}}$$

.

We typically use a significance level corresponding to $S = 1.28$, which is the one-tailed standard normal value [3] corresponding to 90% CL. Thus,

$$N_{\text{signal}} \geq \sqrt{N_{\text{background}}} \times 1.28 \tag{4}$$

Finally, $N_{\text{background}}$ can be computed and modeled as a function of mass, allowing for the calculation of N_{signal}, which then also becomes a function of mass.

In this project, background contributions were not included due to the absence of a reliable estimation. However, once an accurate estimation of $N_{\text{background}}$ is obtained, it can be readily fitted and incorporated into the existing code.

[3]Despite signal and background are governed by Poisson statistics, due to the Central Limit Theorem the significance can be approximated by a standard normal distribution for enough background events.

2 Implementation

The implementation of SHIFT in SensCalc involved defining numerous parameters, generating external files, and modifying routines within the original code. In this report, we will list some of the routines with the greatest influence on the results that were adapted for SHIFT. For a complete description of the changes, refer to the code documentation [5]. Firstly, we will discuss the definition of the parameters, which are categorized into the following groups:

- **Facility Parameters:** Collision mode (fixed target), target material, number of protons on target, maximum available energy, cross sections, average multiplicities, fragmentation fractions, etc. The Facility Parameters are described in Section 2.1.
- **Experiment Parameters:** Coordinates and size of the detector and Decay Volume, list of detectable particles, and selection criteria, etc. The Experiment Parameters are described in Section 2.2.

Although the SHIFT experiment would be conducted at the LHC, the facility description needs to be adjusted for a fixed-target experiment, so not all parameters already set for the LHC in SensCalc can be used. Instead, we created a different facility named `"LHC-fixed-target"` for this purpose.

The following subsections will discuss most of these parameters. For a better understanding of each step in the implementation, one should consult the project documentation available in [5].

2.1 Facility parameters for "LHC-fixed-target"

For the correct definition of a new facility, a list of parameters should be provided, and they are listed in Tab. 1. The majority of these values had been computed using Pythia [11].

One important parameter from the list is the number of protons on target, `NPOTexperiment`, which represents the effective number of protons that are directed onto the fixed target over a period of time. It is calculated internally assuming 1% of the HL-LHC luminosity would be collected by SHIFT:

$$\text{NPOT} = \text{luminosity} \times \text{cross section} = \frac{1}{100} \cdot \text{LHChighLumi} \times \sigma\text{ppInpbFacility} \tag{5}$$

Additionally, SensCalc needs externally computed input files that depend on the facility, which were also externally computed using Pythia:

1. **Angle and energy distributions for mesons and bosons**: `.txt` files located in the folder `spectra/SM particles` of SensCalc.

2. **Drell-Yan distributions**: `.m` files located in `spectra/New physics particles/LLP/Pregenerated`.

3. **Drell-Yan cross sections**: `.txt` files located in `phenomenology/LLP/Production probabilities`.

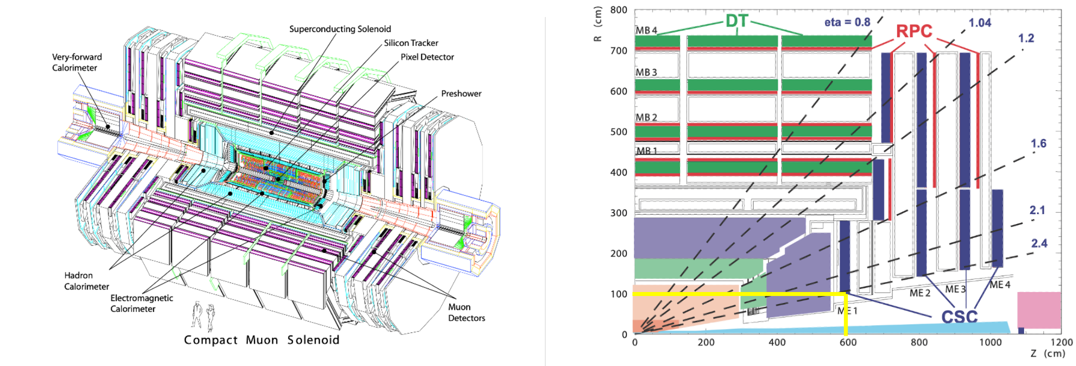
	Facility parameters	
Cross sections (pb)	σppInpbFacility	$42.5 \cdot 10^9$
	σppTobbInpbFacility	$2.878 \cdot 10^5$
	σppToccInpbFacility	$3.924 \cdot 10^7$
	σppTohInpbFacility	0
	σppToWInpbFacility	1.34
Average multiplicities	PppToπ0Facility	12.148
	PppToη0Facility	1.391
	PppToηprFacility	0.170
	PppToρ0Facility	1.705
	PppToω0Facility	1.649
	PppToJpsiFacility	0.00026
	PppToUpsilonFacility	0
	PppToPhiFacility	0.074
Fragmentation fractions	fctod0	0.593
	fctodplus	0.287
	fctods	0.086
	fbtobplus	0.4
	fbtob0	0.4
	fbtobc	0
	EmaxFacility (GeV)	7000
	NPOTexperiment	$1.275 \cdot 10^{15}$
	AtargetExperiment	1
	CascadeFactorbb	1
	CascadeFactorcc	1
	kfactorNLO	1

Table 1: Facility parameters defined for SHIFT in SensCalc. Cross sections and average multiplicities are defined in `experiments.nb` while fragmentation fractions are defined in `LLP distribution.nb`. All of the last few parameters are defined in `experiments.nb` execpt for `kfactorNLO` which is defined in `DP sensitivity.nb`.

2.2 Experiment parameters for SHIFT

2.2.1 Geometry of detector and decay volume

We will model our detector as a cylinder with a cylindrical hole inside. This is a simplified picture of CMS, but accurate enough for our purposes. We calculated the internal radius of the cylinder by taking the nearer distance of the endcaps of the muon system, which could detect pp collider mode particles with $\eta \approx 2.4$. (see figure 4)



(a) (b)

Figure 4: (a) The layout of the real CMS detector. (b) The layout of the different stations is plotted, and the corresponding particle paths for different η. The limit taken for our model is $R_{in} = 1$ m which corresponds to the endcaps of the muon system.

We also added a mean magnetic field that takes into account the residual field of the CMS magnet in the muon system.

The decay volume is modeled as a cylinder of the same outer radius. The impact of selecting a bigger radius has been analyzed and it was found to be irrelevant, as there is no scattering or interaction with material inside or in the surroundings of the decay volume. The length of this cylinder may vary, but in principle, it starts just after the interaction point and ends when the detector starts. But we will see in the next section that in SensCalc, where no stopping power or material between the target and detector are implemented, we will have to modify the decay volume for a more realistic approach.

2.2.2 Modes

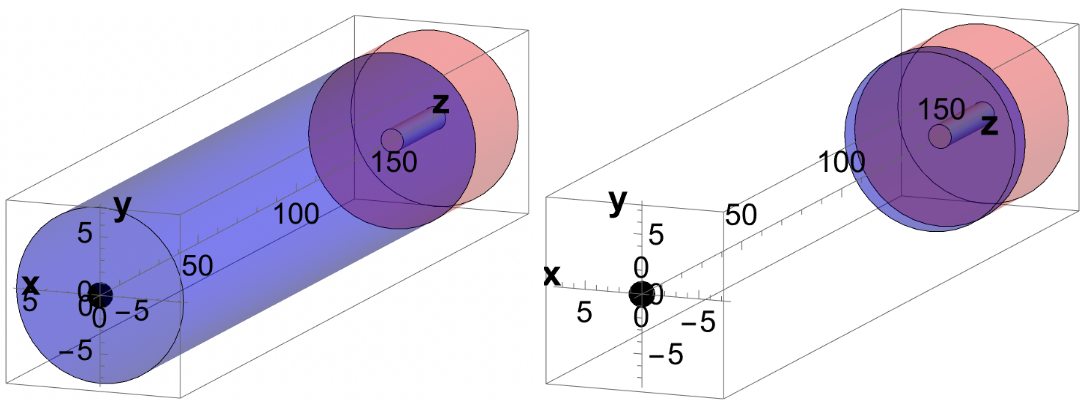
To implement SHIFT in SensCalc, we created 3 separate modes:

- **"SHIFT-empty-decay-volume"**: This was the first attempt at implementing SHIFT, and we kept it as a reference, best-case scenario, despite not being realistic. In this mode, it is assumed that all the products from the LLPs that decay inside the decay volume can reach the detector (i.e., if the decay volume was empty, while in reality there is material between the target and detector).

- **"SHIFT-muon"**: In this mode, the full decay volume is kept, as in the previous mode, but the particles detected can only be muons with at least $E > 20$ GeV (we assume that muons with such energy can transverse the material).
- **"SHIFT-non-muon"**: In this mode, we kept all the other detectable particles except muons, but we modified the decay volume to a 5 m length cavern in front of CMS (so we assume that any particle which decays outside of the cavern is undetectable). We also implemented an $E > 2$ GeV requirement to account for the minimum energy needed to detect a particle in CMS. While this threshold is somewhat conservative, it ensures that the detection criteria are effective for various charged particles.

All the events need **at least 2 particles pointing into the detector** to be counted as detected events. By defining these "muon" and "non-muon" modes we have a realistic evaluation of the sensitivity. Sufficiently energetic muons produced between the target and detector can potentially be detected, and only non-muon particles that are produced in the cavern next to CMS can be detected. It must be noticed also, that by creating these two modes, we are eliminating events where the final products are $\mu + X$, which are important inside the cavern of CMS (before the cavern the X particle would not reach the detector), where we are setting muons as non-detectable. This must not have a large impact on the results, because they are only a small fraction of the total events, but it should be kept in mind as a factor that makes our results slightly conservative.

In Fig. 5, we can see a geometrical visualization of our experimental layout for the different modes, which is produced in Acceptances.nb to check that everything is correct.



(a) (b)

Figure 5: (a) layout for "SHIFT-empty-decay-volume" and "SHIFT-muon" modes. (b) Layout for "SHIFT-non-muon" mode.

In table 2, all the geometrical and detector parameters are listed for each mode.

Some of the more influencing parameters, related to distances and dimensions are:

- **zToDecayVolume (zToDetectorCenterExperiment)**: Which are the distance between the collision point and the start of the decay volume (or center of the detector). The value for the first one can not be directly zero so it is set to the smallest possible value (this occurs also for the inner radius of the detector).
- **xToDecayVolumeCenterExperiment (xToDetectorCenterExperiment)**: They are important for off-axis experiments, here we assume that the collision point, decay volume, and detector are aligned.
- **xLongMuonPlaneExperiment (xLongNonMuonPlaneExperiment)**:
  - These variables are crucial as they define a distance that sets a plane towards which muons (or non-muons) must point to be detected. Most experiments configure these planes at the final detection plane of the detector. However, in CMS, detecting a muon typically requires only a few hits across various stations. Therefore, we positioned these planes in the middle of CMS.
  - This choice is quite conservative; in reality, muons could be detected with planes set at just 1/3 or 1/4 of the CMS depth.

	"SHIFT-empty-decay-volume" and "SHIFT-muon"	**"SHIFT-non-muon"**
zToDecayVolume (m)	0.0001	144.2
dzDecayVolumeExperiment (m)	149.1999	5
xToDecayVolumeCenterExperiment (m)	0	0
yToDecayVolumeCenterExperiment (m)	0	0
RinnerDecayVolumeExperiment (m)	0.0000001	0.0000001
RouterDecayVolumeExperiment (m)	7.5	7.5
dzDetectorExperiment (m)	21.6	21.6
xToDetectorCenterExperiment (m)	0	0
yToDetectorCenterExperiment (m)	0	0
zToDetectorCenterExperiment (m)	160	160
RinnerDetectorExperiment (m)	1	1
RouterDetectorExperiment (m)	7.5	7.5
zMagnetMinExperiment (m)	149.2	149.2
zMagnetMaxExperiment (m)	170.8	170.8
MagneticFieldExperiment (T)	1	1
ECALoptionExperiment	"False"	"False"
xLongMuonPlaneExperiment (m)	160	160
xLongNonMuonPlaneExperiment (m)	160	160

Table 2: List of parameters related to the experimental setup for SHIFT.

3 Results

The results of this project can be categorized into several distinct areas:

- Integration of SHIFT into the Dark Photons (DP) plot.
- Analysis of how various parameters affect the sensitivity of SHIFT when using Dark Photons as the model.
- Incorporation of SHIFT into plots for Heavy Neutral Leptons (HNLs), Dark Scalars, and Axion-Like Particles (ALPs) coupled to fermions. [4].

3.1 SHIFT for Dark Photons

This was the main model used while updating many routines and parameters in SensCalc, so we studied their influence on the curve of the sensitivity plot for SHIFT.

Fig. 6 shows the final results for Dark Photons (DPs). SHIFT covers a new region, extending to masses ranging from 0.25 to 5 GeV and mixing constants between 10^{-14} and 10^{-6}, which corresponds to the region covered by the "SHIFT-muon" mode.

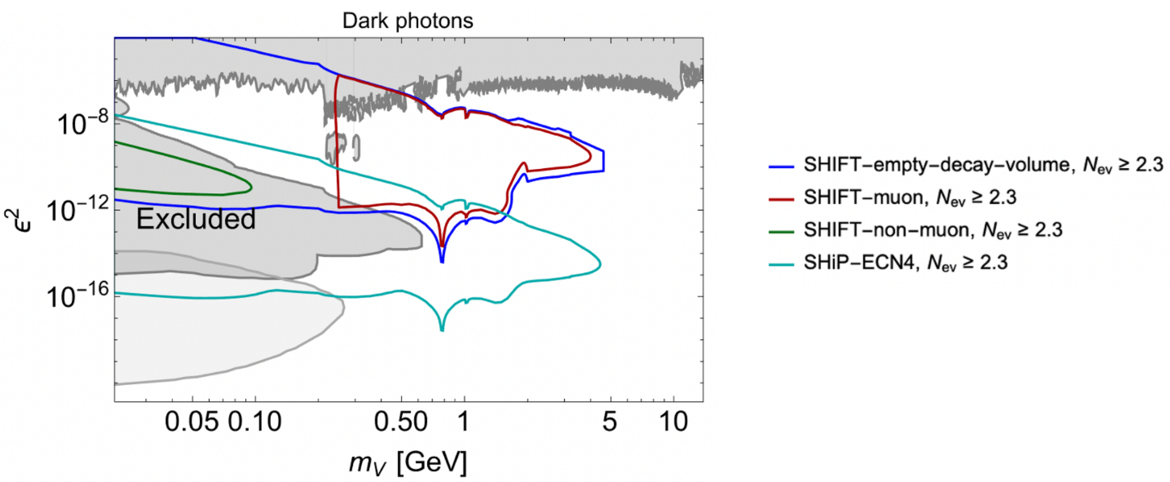


Figure 6: Dark Photon sensitivity plot generated using SensCalc, displaying the three distinct modes for SHIFT. The plot also includes the sensitivity contour for SHiP, the primary competitor to SHIFT for this model, which has already been approved by CERN.

For the **"SHIFT-muon"** mode, we see a limit for lower masses which, corresponds to the dimuon mass threshold.

[4]These models were not explored as extensively as Dark Photons.

The **"SHIFT-non-muon"** mode is influenced by the limited statistics of particles decaying within the decay volume. Comparing it with the "SHIFT-empty-decay-volume" mode reveals the impact of reducing the decay volume to the 5-meter cavern of CMS. In this scenario, the top of the sensitivity contour is significantly reduced, as many particles decay close to the target. Additionally, the lower limit is also slightly decreased.

Several parameters influence the general shape and limits of the sensitivity curves across different regions:

- **Top of the Contour**:
  - Generally, the existence of an upper boundary of the contour for beam dump experiments arises because larger mixing constants lead to prompt decays, and consequently, the decay products may be reabsorbed by the target material.
  - However, in SensCalc, reabsorption in the target material is not implemented. The upper boundary of the sensitivity contour arises in SensCalc due to the finite distance between the collision point and the beginning of the decay volume. Particles that decay before reaching the decay volume are considered undetectable. Thus, for sufficiently large mixing constants, nearly all particles decay immediately after production, resulting in a minimum number of detectable events in those regions of the phase space.
  - For SHIFT, where the target is hydrogen or helium, this upper limit is not physically meaningful. It represents a numerical limitation of SensCalc, which requires a minimum distance of 0.0001 meters between the collision point and the decay volume.
  - Additionally, the insufficient density in the longitudinal distance grid for small distances used in the acceptance calculation results in inaccurate interpolations during sensitivity integration. This contributes to the observed decreasing slope at the top of the contour (see [5]). Although increasing the grid density for very small distances could reduce these effects, it significantly increases the computational time required to run the notebooks.
- **Bottom of the Contour**: This lower boundary is primarily governed by the available luminosity (or the number of protons on target). As couplings get smaller, fewer events are observed. Increasing the luminosity will lead to more collisions and potentially more detectable events (see Appendix B.3).
- **Resonances**: It is also noticeable that the shapes of the SHiP and SHIFT curves are quite similar. In addition to the previously mentioned factors, characteristic peaks and shapes are observed between masses of 0.5 and 3 GeV. These features correspond to meson resonances and the sharp onset of Drell-Yan production at 1.5 GeV, as illustrated in Fig. 7.

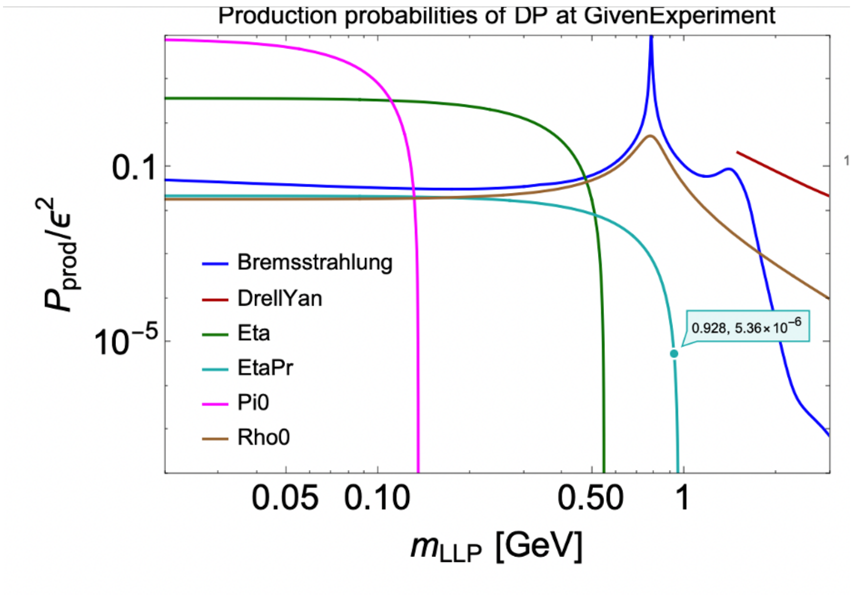


Figure 7: Probability of production divided by the mixing constant as a function of mass for different production channels.

3.1.1 Parameters dependence

Apart from the luminosity and the distance between the target and decay volume, we also studied a list of parameters that may modify the results.

- **Distance between Target and Detector** (see Appendix A):
  - While increasing this distance had no effect within this framework, it might influence the results in reality, as additional material would need to be traversed to reach the detector, and many particles would be stopped.
  - Shorter distances yielded poorer results, likely because many particles decay after passing through the detector, while others decay before reaching the detector but their decay products go through the CMS cylindrical hole (which is present in our detector model due to the lack of muon detectors within that volume).
- **Average Multiplicities**:
  - Altering the average multiplicities by a factor of two resulted in very similar outcomes, indicating that they have minimal impact.
- **Inner Radius of the Decay Volume**:
  - Results remained consistent for inner radii below 0.01 meters. For larger radii, a smaller region was obtained, so we maintained the radius as small as possible, noting that in reality there is no actual hole in the decay volume.

- **Meson Distributions**:
  - Initially, we used meson distributions from SPS before generating those for the LHC with the fixed target setup. The results were similar, but slightly better for the LHC setup due to its higher center-of-mass energy.

3.2 SHIFT for Axion-Like particles (ALPs) coupled to fermions

The final step of the project involved extending the implementation to additional models. The geometry and facility parameters remain consistent with those used for Dark Photons. The only exception is Drell-Yan production, which necessitates external computation. Currently, we are utilizing SPS distributions. Our observations indicated that for DPs the results obtained using SPS distributions were quite comparable to those produced with LHC distributions under a fixed target setup, particularly since this production mechanism primarily influences masses above 1.5 GeV. As a result, we keep the same approach for other models.

In Fig. 8, the results for ALPs are presented. These results are less favorable compared to those for Dark Photons (DPs). To obtain more reliable results, it is necessary to extend the mass range over 5 GeV and calculate the actual Drell-Yan distributions.

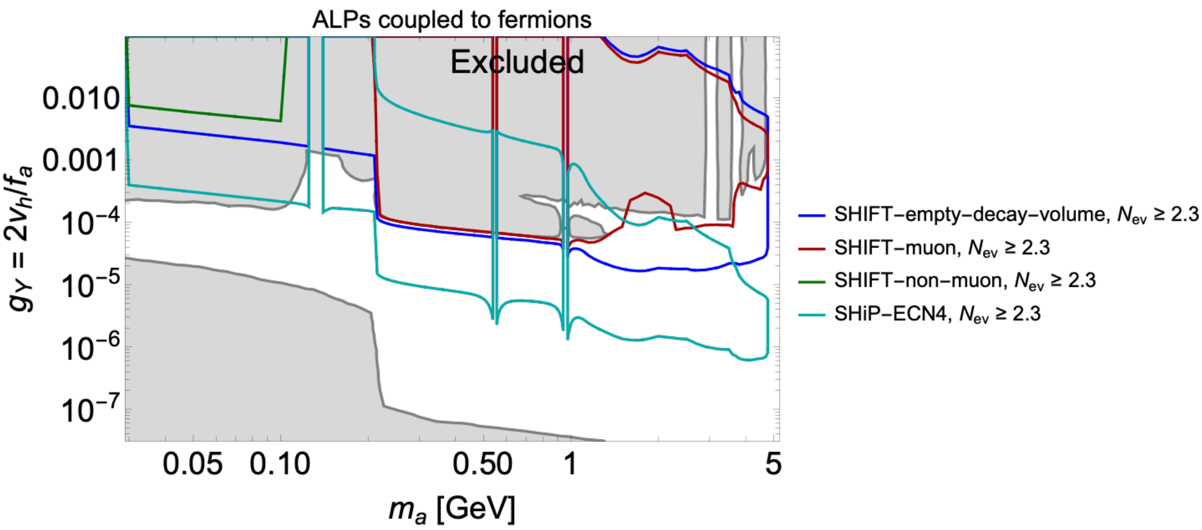


Figure 8: ALPs coupled to fermions sensitivity plot generated using SensCalc, displaying the three distinct modes for SHIFT. The plot also includes the sensitivity contour for SHiP, which is also the primary competitor to SHIFT for this model.

Although plots for other models, such as Dark Scalars or Heavy Neutral Leptons (HNLs), have not yet been generated for the current version of SHIFT, the code implementation for these models has been completed and is available in [6]. Nevertheless, some plots for these models were produced during the project and can be reviewed in Appendix B.1.

4 Conclusions

In this project, the **sensitivity** of **SHIFT**, a novel fixed-target experiment designed to search for **new physics** at the LHC, is evaluated within the **low-mass range (< 10 GeV)** for various long-lived particle (LLP) models. The analysis employed **SensCalc**, a framework developed for sensitivity studies of feebly interacting particles in the low-mass range, which enables direct comparisons between SHIFT and other existing or proposed experiments. The results reveal that **SHIFT demonstrates significant sensitivity to dark photons**, particularly **in a region of the parameter space (mixing constant and mass) that remains unexplored** by current and other proposed experiments, including SHIFT's main competitors.

While further improvements are necessary, such as incorporating realistic background estimations and extending the mass range beyond 5 GeV in the analyses, the results are highly significant. SHIFT's ability to explore previously uncharted regions of the parameter space marks a **significant advancement for its future implementation at the LHC**. To fully leverage this potential, additional models should be evaluated for SHIFT to provide stronger validation of its value.

References

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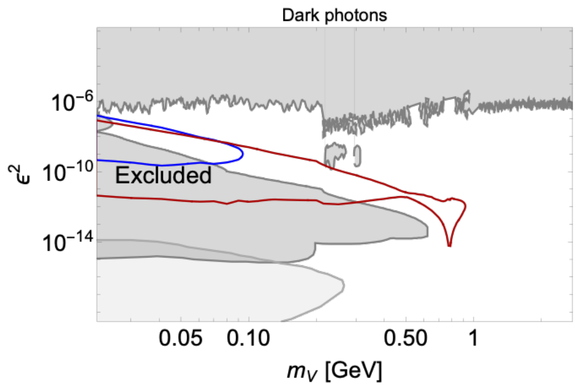
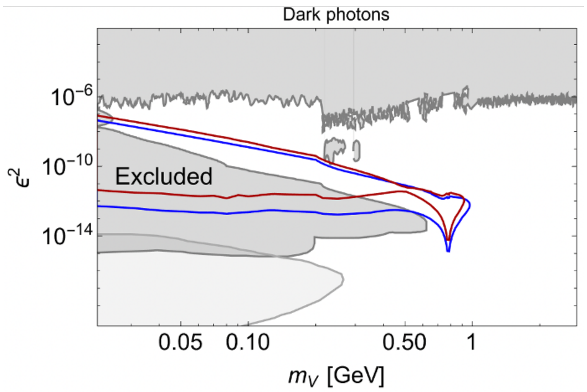
A Plots of distance dependence

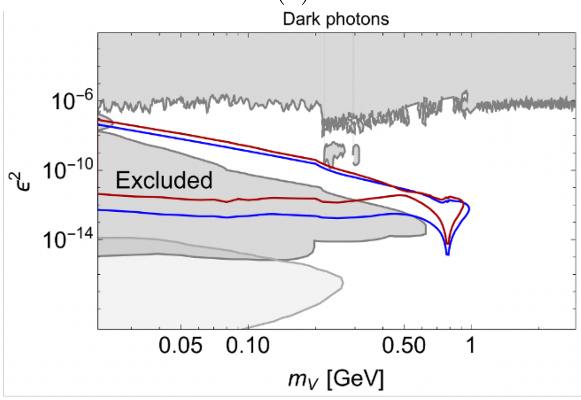
These plots were generated using an initial implementation of SHIFT, where the longitudinal grids (which influence the top of the contour and mass coverage) were not properly defined. However, this version was useful for studying the dependence on distance.



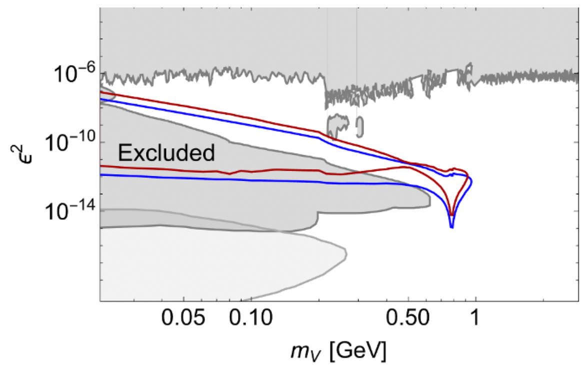
(a)



(b)



(c)



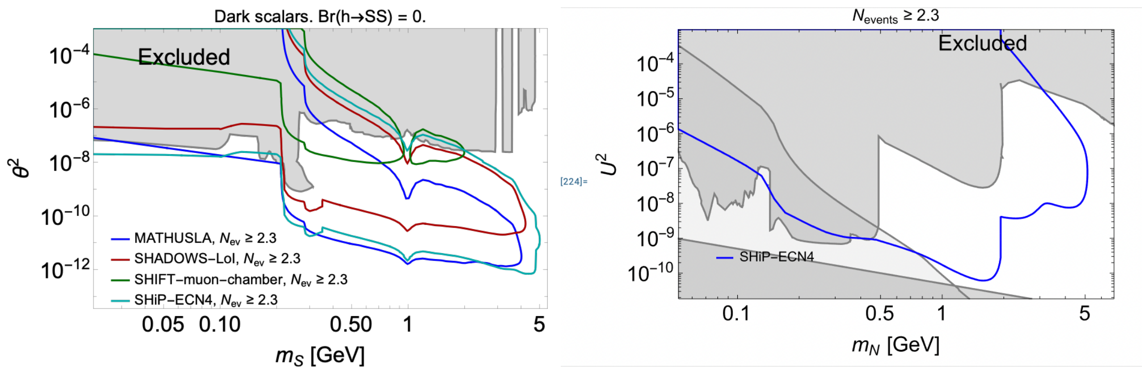
(d)

Figure 9: **Blue curve:** (a) Distance of 30 m between target and detector (b) Distance of 300 m between target and detector (c) Distance of 1 km between target and detector (d) Distance of 10 km between target and detector. **Red curve:** Distance of 160 m between target and detector (default configuration).

B Various additional plots

B.1 Dark Scalars and HNLs

These plots represent an initial attempt to work with these models. For Dark Scalars, a preliminary implementation of SHIFT is included. However, for HNLs we did not add SHIFT to the plot yet but we successfully reproduced the plot for SHiP, as shown in [3].



(a) (b)

Figure 10: (a) Sensitivity plot for the Dark Scalars model with an initial version of SHIFT included (empty decay volume for all detectable particles). The parameters used for SHIFT in this plot are preliminary, leading to a smaller covered region, particularly at the top of the contour and for higher masses, due to the longitudinal grid not being updated when this plot was generated. modes. (b) Sensitivity plot for HNLs for SHiP. The options for only electron mixing and Majorana particles were selected in the SensCalc popups.

B.2 FASER

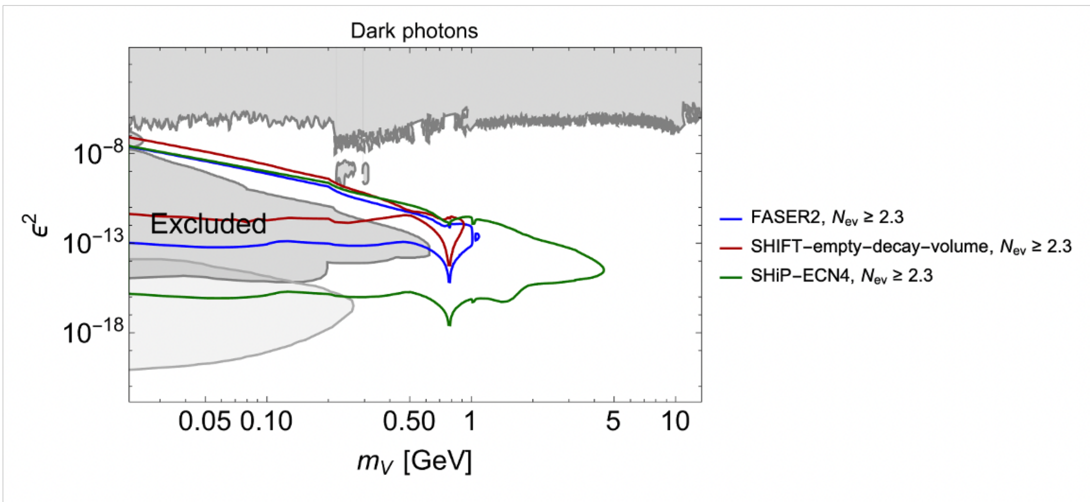


Figure 11: Sensitivity plot for Dark Photons with FASER included. The influence of luminosity is evident. Despite FASER's smaller decay volume located just before the detector, it covers a region similar to the first implementation of SHIFT, primarily due to its higher luminosity.

B.3 Luminosity and decay volume length

This plot was generated to study the influence of higher luminosity on the results and to determine whether a higher luminosity combined with a smaller decay volume could still cover a similar region. The results showed that, despite the increased luminosity, the smaller decay volume affected negatively the results and SHIFT did not cover the same region.

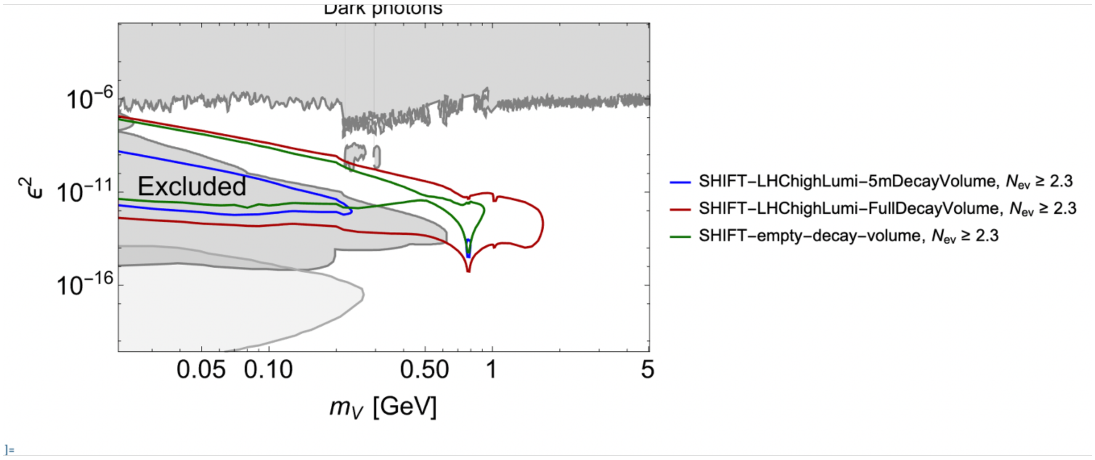


Figure 12: Dependence on luminosity for SHIFT. **Green line:** SHIFT with a default luminosity and an empty decay volume of 160 m. **Blue line:** SHIFT with a 100 times more luminosity and an empty decay volume of 5 m before CMS. **Red line:** SHIFT with a 100 times more luminosity and an empty decay volume of 160 m before CMS.

B.4 Implementation of CMS collider mode

We attempted to implement the CMS normal collider mode to verify if SensCalc functions correctly for non-beam-dump experiments. We observed that the bottom of the contour covers a smaller region compared to beam-dump experiments, which is expected since particles with small mixing constants may decay outside the detector. Additionally, we noted that the top of the contours has limits in SensCalc, whereas in reality, the region for the CMS normal collider mode should extend further upward and not exhibit a decreasing slope at the top. This discrepancy highlighted the influence of the previously mentioned longitudinal grid.

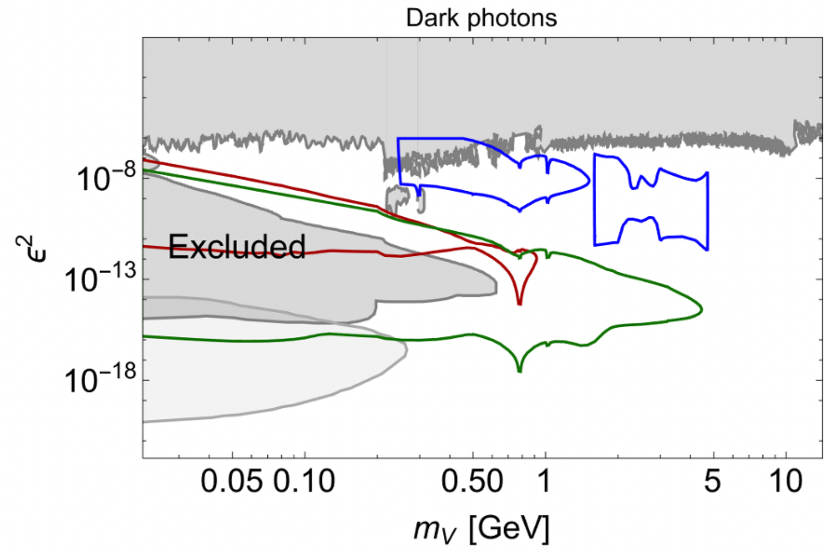


Figure 13: Implementation of CMS in normal collider mode (blue contour), for muons with E, p > 10 GeV.