EventCalc: An Event Generator for the SHiP Experiment at CERN

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Abstract

This report presents the development of `EventCalc`, an event generator for the recently approved SHiP experiment at CERN. The generator is designed to produce events for hypothetical long-lived particles (LLPs) based on the output of the `SensCalc` tool, which is used by the SHiP collaboration to compute SHiP sensitivities to LLPs. By leveraging the phenomenology of long-lived particles already implemented in `SensCalc`, the generator produces detailed event simulations that can be used for kinematic reconstructions and background discrimination, which are crucial for analyzing the sensitivity of SHiP to LLPs. The generator has been developed in `Python` and is designed to interface with `FairShip` for further event reconstruction.

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Sincerely,
Josué

1 Introduction and motivation

The SHiP (Search for Hidden Particles) experiment at CERN [1, 2] aims to search for new physics in the form of long-lived particles (LLPs) that are predicted by several extensions of the Standard Model [3, 4]. It provides unique capabilities to explore particles in the mass range $m \lesssim 5$ GeV in the wide range of couplings, covering the decay lengths $c\tau\gamma$, where τ is the LLP's lifetime, and γ is its mean γ factor at the experiment, in the range $\mathcal{O}(0.1) - 10^5$ m and larger.

Currently, the sensitivities of SHiP to such hypothetical LLPs are obtained using the tool `SensCalc` [5]. It uses a semi-analytic approach by presenting the number of events as the integral of the product of several differential quantities: the angle-energy distribution, decay probability, and the acceptance of decay products. This way, `SensCalc` computes the sensitivity to LLPs by averaging over all possible events. The phenomenology input is described, and its predictions for the event rates has been tested across various computational tools, starting from lightweight traditional Monte-Carlo codes and ending with full simulation frameworks of SHiP and LHCb.

While `SensCalc` provides valuable information about the likelihood of LLP production, it does not generate individual event data. For a complete analysis, it is necessary to simulate these events, enabling detailed studies such as kinematic reconstruction and background discrimination. This necessitates the creation of an event generator that can utilize the output from `SensCalc` to simulate events with LLPs in the SHiP detector.

1.1 Objective

The primary goal of this project is to develop `EventCalc`, a Python-based event generator that uses `SensCalc` as its input.

The event generator will:

- Use the phenomenology of LLPs from `SensCalc`, ensuring that no new physics models need to be implemented from scratch.
- Produce event data that can be cross-checked with `SensCalc` at every stage.
- Interface directly with the `FairShip` software to enable further event reconstruction.

2 The SHiP Experiment

The Search for Hidden Particles (SHiP) experiment at CERN is designed to explore new physics beyond the Standard Model, specifically targeting LLPs in the mass range below 5 GeV/c^2 [1, 2]. SHiP operates at the Beam Dump Facility (BDF) in the ECN3 high-intensity beam facility at the CERN SPS. This experiment aims to produce LLPs through the interaction of an intense 400 GeV proton beam with a high-Z target, followed by a detailed investigation of the resulting decays within a low-background environment. The SHiP complex includes several critical components: a high-intensity proton beam, a target system, a hadron absorber, a muon shield, and the SHiP detectors – SND@SHiP, aiming to search for scattering of neutrinos and hypothetical light dark matter particles, and the Hidden Sector Decay Spectrometer (HSDS). These components work in tandem to maximize the detection potential for rare decays of LLPs while minimizing background events.

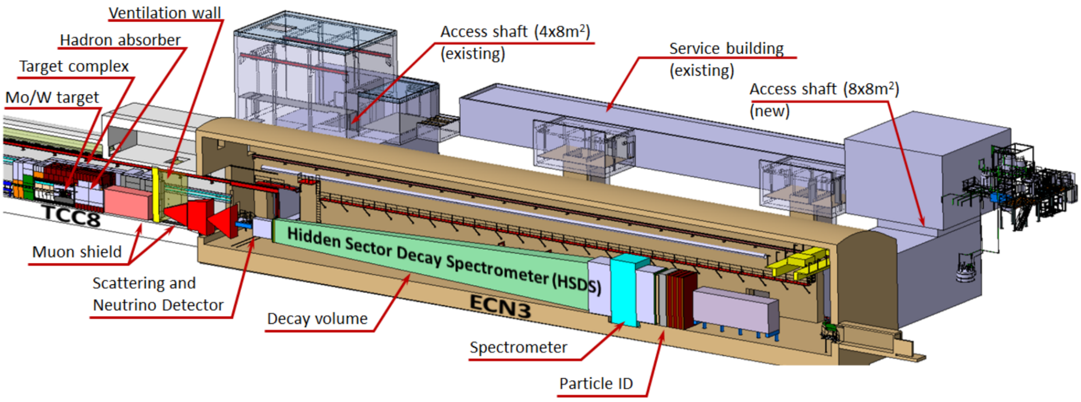

Figure 1: Overview of the SHiP experimental facility at the CERN SPS, showing the proton beam, target system, hadron absorber, muon shield, and detector complex. The figure is taken from [1].

2.1 HSDS

The Hidden Sector Decay Spectrometer (HSDS) is a key element of the SHiP experiment, designed to detect and reconstruct the decay of LLPs. The HSDS is positioned on-axis with respect to the proton beam, taking advantage of the high forward production rate of particles. Its design is optimized to cover a wide range of possible decay angles, ensuring comprehensive detection capabilities. A combination of advanced background suppression techniques, including hadron absorption, muon deflection, and the use of veto systems (SBT and UBT), is employed to achieve a background-free environment for the LLP searches within the HSDS. These methods, along with the projective geometry of the HSDS, make the SHiP experiment uniquely capable of probing previously unexplored regions of the LLP parameter space.

The HSDS has been meticulously designed with dimensions that strike a balance between angular coverage and spatial resolution. The projective design ensures that the detector elements are aligned with the expected decay paths of particles, reducing the need for complex tracking algorithms and minimizing the impact of background noise. This alignment is crucial for accurately reconstructing the decay vertices of LLPs and other particles of interest.

In addition, as it has been shown in [6], the design of the HSDS is close to optimal in terms of maximizing the event rate for LLP decays. This is particularly important given the low production cross-sections and large lifetimes of many LLPs, which make efficient detection strategies essential.

2.2 Background Suppression Techniques

The SHiP experiment employs a comprehensive set of methods to ensure that searches within the HSDS are conducted in a background-free environment. The main sources of background at SHiP include muon-induced events, neutrino interactions, and combinatorial background from random coincidences. The hadron absorber plays a crucial role in attenuating hadrons and photons that could lead to background events. The muon shield deflects high-energy muons away from the detector's acceptance region, significantly reducing the muon-induced background. Next, all the possible background surviving after these systems may be reduced by applying kinematic pre-selection, which is optimized to

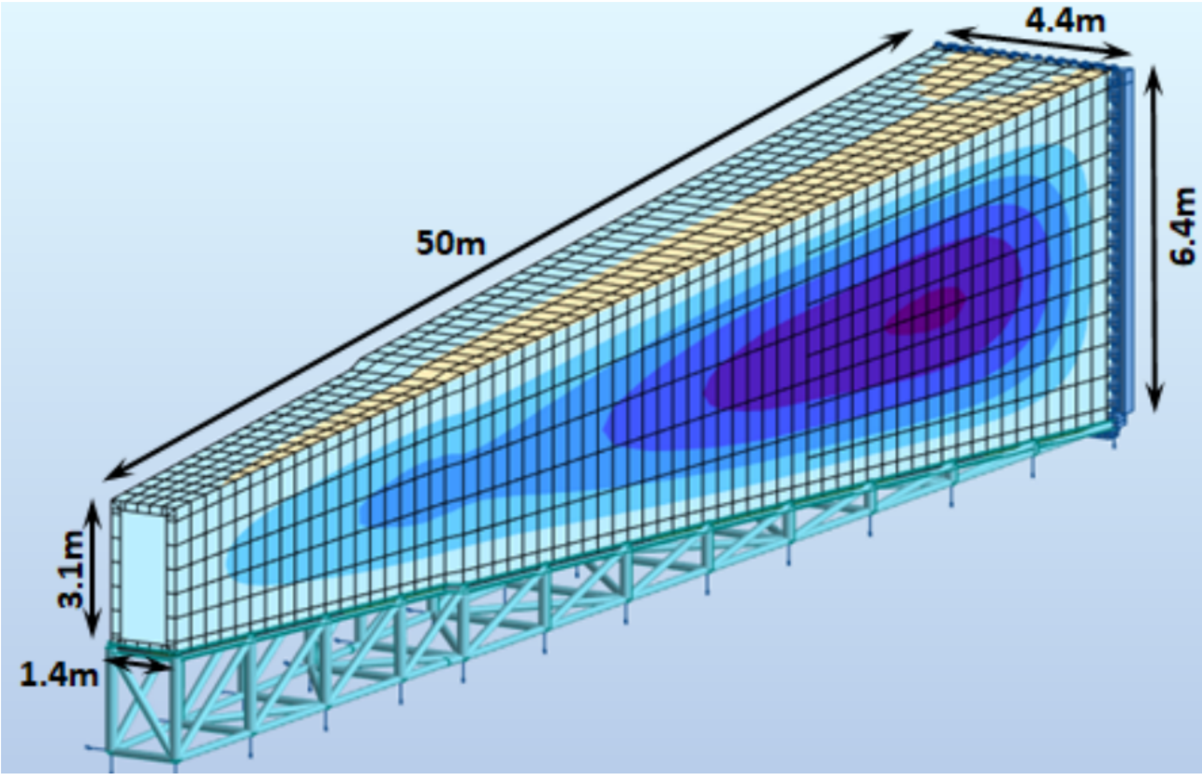

Figure 2: Schematic of the Hidden Sector Decay Spectrometer (HSDS) showing its pyramidal frustum design, which maximizes angular coverage and optimizes the detection of LLP decays. Taken from [1].

keep the yield with LLPs maximal but heavily affects the typical background topologies. Finally, the Surrounding Background Tagger (SBT) and Upstream Background Tagger (UBT) are used to veto any residual background particles that could mimic the signal of a LLP decay.

The combination of these suppression techniques is designed to achieve a background level of less than one event over the entire operational period of the experiment, even with an expected 6×10^{20} protons on target. However, given the experimental complexities and potential budgetary constraints, it is crucial to continue refining these strategies to ensure the experiment's success. The ongoing studies and tools being developed as part of this project are vital for assessing and improving the background suppression in SHiP, thereby ensuring the robustness of the HSDS in searching for new physics.

3 EventCalc: Design and Implementation

3.1 Overview

`EventCalc` is designed to generate events for LLPs by following a series of algorithmic steps. The main idea is to simulate the production and decay of LLPs within the SHiP detector and compute the corresponding event weights that account for production probabilities, geometric acceptance, and decay probabilities.

The event generator starts by selecting an LLP and its production and decay modes, sampling its four-momentum, generating its decay vertex, and finally simulating the decay

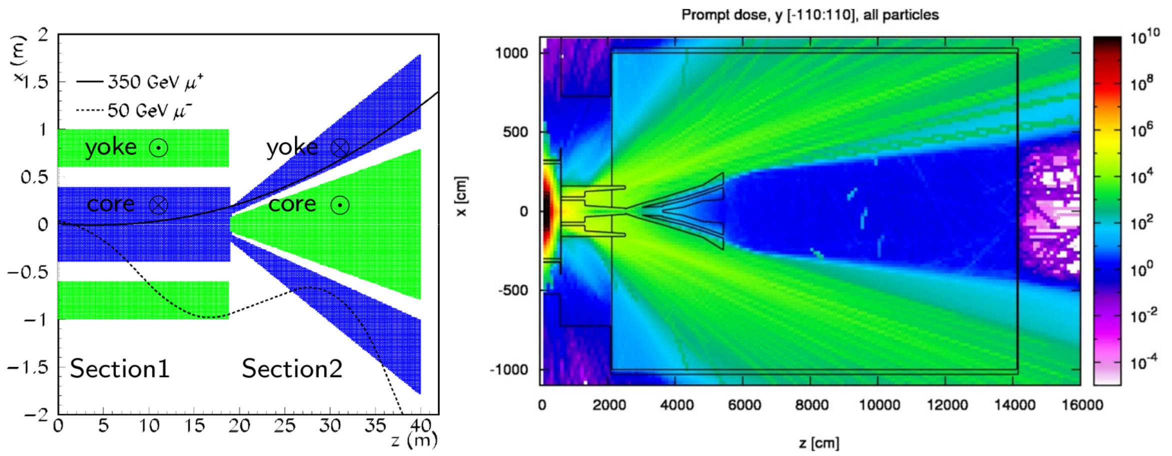

Figure 3: Diagram showing the magnetic field polarity of the muon shield in the SHiP experiment, which deflects high-energy muons to reduce the background in the HSDS. The figure is taken from [1].

products. The following sections provide a detailed breakdown of these steps.

3.2 Algorithm Steps

3.2.1 Selection of LLPs and Decay Modes

The first step is to select an LLP from the list of particles implemented in `SensCalc`. This includes specifying the production and decay modes for the selected particle. The relevant quantities that are obtained from `SensCalc` include:

- The total production probability $P_{\text{pp}\to\text{LLP}}(m_{\text{LLP}}, g_{\text{LLP}})$, which depends on the LLP's mass m_{LLP} and coupling g_{LLP}.
- The tabulated angle-energy distribution of the produced LLPs $\{m_{\text{LLP}}, \theta, E, f\}$, which is available for a limited set of masses.
- The lifetime of the LLP, τ_{LLP}, which depends on its mass and coupling.
- Information on the LLP's decay channels, including the list of channels, branching ratios, and matrix elements for n-body decays.

3.2.2 Sampling of LLP Four-Momentum

Once the LLP is selected, the next step is to sample its four-momentum in the direction of the SHiP detector. This involves the following substeps:

- Generate the angle-energy distribution for the given LLP mass using interpolation methods.
- Sample the LLPs' polar angles and energies using importance sampling.
- Calculate the geometric acceptance, ϵ_{geom}, which represents the fraction of particles produced within the SHiP detector's acceptance.

3.2.3 Decay Vertex Generation

For each generated four-momentum, the decay vertex of the LLP is sampled using the inverse transform sampling method. The decay probability for each event is computed as:

$$P_{\text{decay}}^{\text{event}} = \exp\left[-\frac{32\text{ m}}{\cos(\theta_{\text{event}})c\tau_{\text{LLP}}\sqrt{\gamma_{\text{event}}^2 - 1}}\right] - \exp\left[-\frac{82\text{ m}}{\cos(\theta_{\text{event}})c\tau_{\text{LLP}}\sqrt{\gamma_{\text{event}}^2 - 1}}\right] \quad (1)$$

- θ_{event}: The angle between the particle's trajectory and the reference direction. This angle affects the effective distance the particle travels before decaying.
- c: Speed of light, ensuring consistent units for distance and time.
- τ_{LLP}: Lifetime of the Long-Lived Particle (LLP) in its rest frame.
- $\sqrt{\gamma_{\text{event}}^2 - 1}$: Relativistic factor, where $\gamma_{\text{event}} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ is the Lorentz factor.

This allows for sampling of the decay points solely inside the SHiP decay volume.

3.2.4 Calculation of Event Weights

The number of simulated events must be related to the number of expected physical events. This is done by calculating the event weight ω_{event} for each simulated event, which takes into account the total number of produced LLPs per sampled event, the geometric acceptance, and the decay probability. The total number of expected decay events is then given by the sum of the event weights.

3.2.5 Decay Product Sampling

Once the decay vertex has been generated, the next step is to simulate the phase space of the LLP's decay products. This involves:

- Simulating the decay of the LLP at rest.
- Using matrix elements from `SensCalc` for exclusive decays, such as LLP $\to 3\pi/4\pi$, $2e$, 2γ, and $\eta\pi\pi$.
- Sampling the kinematics of partons for inclusive decays (e.g., LLP $\to u\bar{u}$).
- Boosting the decay products to the laboratory frame based on the LLP's four-momentum.

3.2.6 Output and Interface to FairShip

The final output of `EventCalc` consists of two tables:

- A table with LLP weights ($P_{\text{decay}}^{\text{event}}, \epsilon_{\text{geom}}$) and decay vertices.
- A table with the kinematics of the decay products.

This output can be passed to `FairShip` for further event reconstruction.

4 Current Status

As of the current development stage, `EventCalc` has successfully implemented event generation for heavy neutral leptons (HNLs) and Higgs-like scalars. The implementation of other models is straightforward and can be completed by analogy with the existing particles.

The event generator has been designed with a modular structure, which allows for easy extension and maintenance. The code is written in Python and leverages several well-known packages to improve both performance and usability.

The key Python packages utilized include:

- `numpy`, `scipy`, and `sympy` for numerical and symbolic calculations.
- `pandas` for efficient data management and manipulation.
- `numba` to significantly improve the performance of the code by just-in-time compiling numerical functions.

The full source code and documentation are available in the GitHub repository: https://github.com/josuejaramillo/summer_school_2024_SHiP.

4.1 Launching the Event Generator

To launch the event generator, simply run the main Python file. The code will then prompt the user to select the desired long-lived particle (LLP), specify its mass, lifetime, and the relevant coupling patterns (if applicable). Below is an example of how to interact with the program:

```
python simulate.py

Particle selector

1. Dark_photons
2. Higgs_like_scalars
3. HNL
Select particle: 3

LLP mass: 1 GeV/c^2

Life time c*tau: .2 m

Ue2: 1

Umu2: 1

Utau2: 0
```

This user-friendly interface allows for straightforward customization of the simulation parameters according to the specific LLPs under investigation.

5 Validation

The validation of `EventCalc` has been conducted by comparing the generated event distributions with the expected behavior from theoretical models and previous studies. The following examples demonstrate the successful validation of the generator:

5.1 Example 1: Angular-Energy Distribution

The shape of the tabulated angle-energy distribution is accurately reproduced by the angle-energy sampler. The generated distribution matches the theoretical expectations based on `SensCalc`, confirming that the angle and energy sampling methods are working correctly. Figure 4 shows a comparison between the expected and generated angular-energy distribution of LLPs.

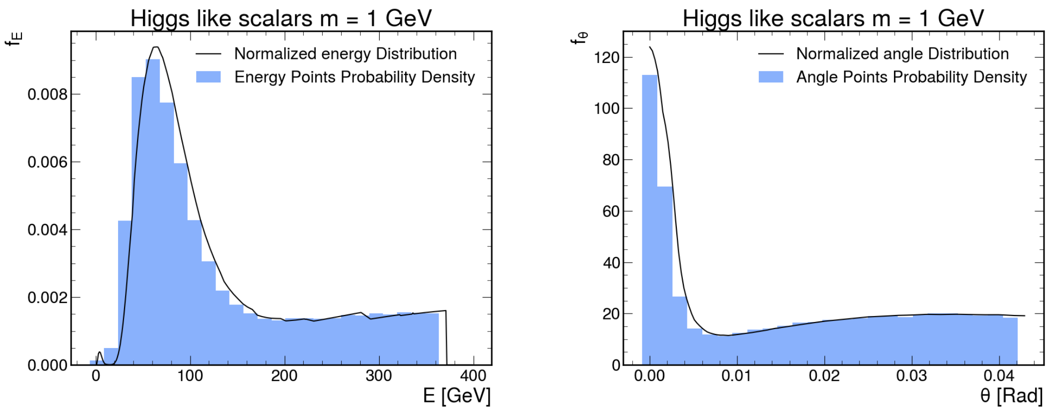

Figure 4: Energy and angular distribution of LLPs generated by `EventCalc`.

5.2 Example 2: Energy Distribution of Decaying LLPs for Various Lifetimes

The energy distribution of LLPs with different lifetimes follows the expected qualitative behavior. Shorter lifetimes favor higher energies since those LLPs decay closer to the production point, while longer lifetimes result in a shift towards lower energies as the particles have more time to lose energy before decaying. Figure 5 illustrates this behavior, showing the energy distribution of LLPs for two different lifetimes.

5.3 Example 3: Distribution of Decay Vertices

The distribution of decay vertices for LLPs is another key validation metric. For short-lived particles, the decay vertices are concentrated near the production point, resulting in a distribution that peaks at small angles and is relatively focused. In contrast, longer-lived particles exhibit a more isotropic distribution of decay vertices as they travel further from the production point before decaying. This behavior is confirmed in Figure 6, which shows the decay vertex distribution for a set of Higgs-like scalar LLPs with different lifetimes.

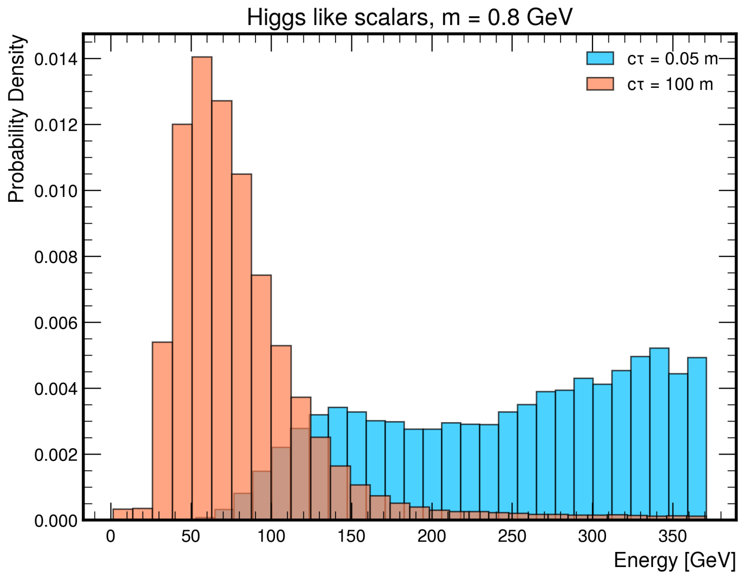

Figure 5: Energy distribution of LLPs for various two lifetimes, showing the expected shift towards lower energies for long lifetimes, while for short lifetimes, the distribution shifts to the right, favoring higher energies.

These validations confirm that `EventCalc` correctly generates the expected distributions for various LLP properties, ensuring its reliability for event simulation in the SHiP experiment.

6 Future Work

Future developments will focus on refining the decay simulations for specific LLP models, improving computational efficiency, and integrating `EventCalc` directly with the `FairShip` framework for automatic reconstruction of generated events. Additionally, further validation with real SHiP data is planned once the experiment begins taking data.

7 Conclusion

`EventCalc` provides a powerful tool for generating event-level simulations of long-lived particles for the SHiP experiment at CERN. By utilizing existing phenomenology from `SensCalc`, it ensures consistency in sensitivity studies while enabling more detailed kinematic reconstructions. The tool will be essential in studying background discrimination and optimizing the detector design in preparation for data collection.

Figure 6: Decay vertex distribution for Higgs-like scalars with mass 0.8 GeV. (Left) $c\tau = 0.02$ m: vertices are concentrated at the beginning of the decay volume and at small angles. (Right) $c\tau = 10$ m: vertices exhibit a more isotropic distribution.

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