A C++ program for estimating detector sensitivities to long-lived particles: **displaced decay counter**

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arXiv:2308.07371 (*Eur. Phys. J. C 84, 642 (2024)*)

GitHub repository of DDC

in collaboration with F. Domingo, J. Günther, and J. S. Kim

May 24$^{\text{th}}$, 2025
30th Mini-workshop on the frontier of LHC

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Motivation

- No concrete evidence so far at the LHC for heavy resonances
- Increasingly more attention given to other signatures e.g. long-lived particles (LLPs)
- LLP: well motivated, predicted in various BSM scenarios
- ATLAS, CMS, etc. performed multiple searches
- LHC far detectors proposed: FASER(2), MATHUSLA, CODEX-b, ANUBIS, MoEDAL-MAPP1(2), etc.
- Need a unified platform for sensitivity estimation at all these experimental setups

$\Rightarrow$ **D**isplaced **D**ecay **C**ounter

What is DDC?

- Main functionality: compute the decay probability of an LLP within a pre-defined detector volume
- Some LHC detector models pre-encoded; an editor for further constructions integrated
- Relies on MC-simulation tools, but not pre-generated tabulated spectra
- Versatility: different experimental facilities, MC-simulation tools, theoretical models, interaction types, detector constructions

General features

- Basic input:
  - PID, mass, lifetime, and 'visible' BR of the LLP
  - MC events in the LHEF or HepMC format, or Pythia8 run card; A total cross section normalizing the set of events
  - Names of the detectors that the user wants to simulate, with their corresponding integrated luminosities
- DDC computes decay probability of the LLPs identified by their PID inside the specified detectors, and then the signal-event number

Modeling the decay probability

- Probability that the particle decays in a detector that comes across its trajectory between distances ℓ_1 and ℓ_2 ($\ell_1 < \ell_2$):

$$P^{\text{dec}}_{\text{lab}}(\ell_1, \ell_2) = \exp[-\frac{\ell_1}{\gamma \|\vec{v}\| \tau}] - \exp[-\frac{\ell_2}{\gamma \|\vec{v}\| \tau}]$$

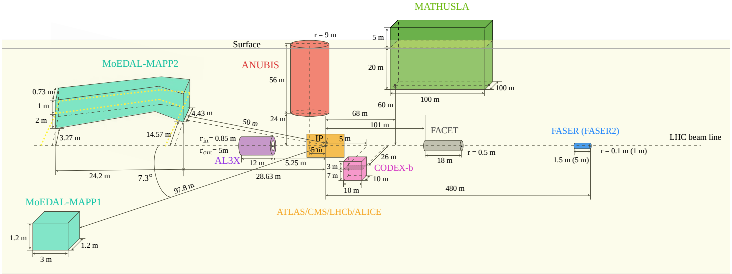
$\Rightarrow$ Geometrical exercise of determining the distances ℓ_1 and ℓ_2

- Additivity: given a volume V with $V = \sqcup_i V_i$,
$\mathcal{P}(\text{decay in } V) = \sum_i \mathcal{P}(\text{decay in } V_i)$

Underlying hypotheses:

1. LLP produced at the IP
2. LLP lifetime not modified by the interactions of this particle with the matter constituting the detector
3. LLP flies in a straight line from the interaction point

LHC far detectors



reproduced from [*2410.19561*] (C.-T. Lu, X. Wang, X. Wei, Y. Wu)

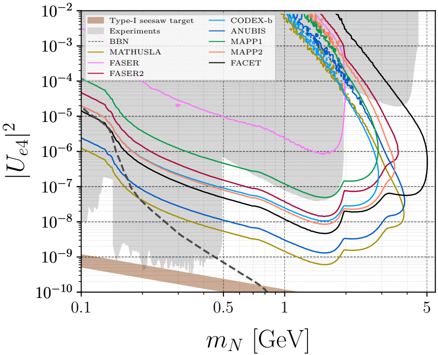
Transverse: ANUBIS, CODEX-b, MoEDAL-MAPP1(2), MATHUSLA
Forward: FACET, FASER(2)

- Mostly background-free; will assume that 3 signal events correspond to exclusion bounds at 95% C.L.

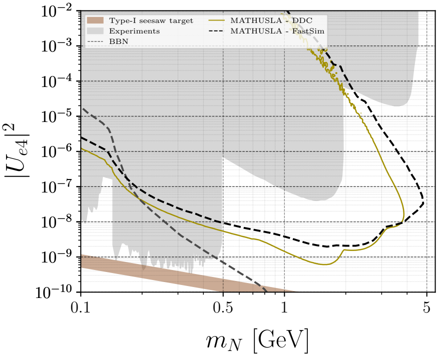
Heavy neutral lepton in the minimal scenario

- Heavy neutral leptons, SM singlet; One N and it mixed with ν_e

$$\mathcal{L} = \frac{g}{\sqrt{2}} \sum_{\alpha,j} U_{\alpha j}\, \bar{\ell}_\alpha \gamma^\mu P_L N_j W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} V^L_{\alpha i} U^*_{\alpha j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$



Sensitivity reach at 95% C.L.



DDC vs. FastSim for MATHUSLA. The FastSim results are extracted from [2308.05860]. General agreement.

Summary

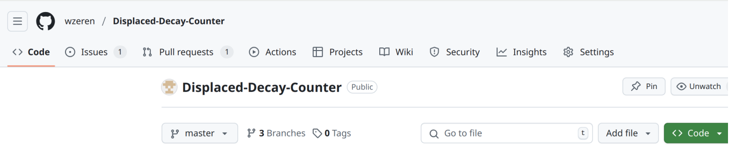
- Displaced Decay Counter (DDC): a C++ program for calculating detector acceptances and signal rates, relying on MC-simulation tools
- Input: MC events in LHEF and HepMC format; or a Pythia8 run card for internal event generation
- Pre-defined far-detector proposals
- Provides the user with an editor for the implementation of further detector models
- Presented benchmark scenarios to illustrate the usage of our tool:
  - Validation of our results with existing ones
  - Validated agreement between DDC and other similar tools
- Not restricted to applications in LHC experiments
- High potential for studying LLP models at colliders

Thank You! 谢谢！

Back-up slides

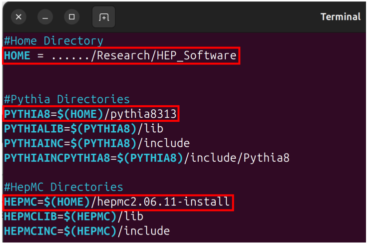
Getting started

- Source code downloaded from https://github.com/wzeren/Displaced-Decay-Counter



- Prerequisites: Pythia8 and HepMC2; a C++17 compiler

- Adjust the paths in DDC/Makefile to the local setup and make -jN



Input

Input files in `json` format:

- `DDC/bin/inputEvents.dat`:
  `{"input":{"input_file_format":"...", "input_file_path":"...", "nMC":..., "sigma":...}}`

- `DDC/bin/inputLLPs.dat`:
  `{"LLP":{"LLPPID":...,"ctau":..., "mass":...,"visibleBR":...}}`

- `DDC/bin/detectors.dat`:
  `{"detector_name":[switch,int_luminosity]}`

Operation and output

- `cd bin/`
  `./main inputEvents.dat inputLLPs.dat results.txt`
- Results saved in `bin/results.txt` and logs (availability of the detectors and summary of the input information) in `bin/Logs/`
- Results include the simulated acceptance and number of signal events for each detector

```
*****************************************************************
**************** WELCOME TO THE RESULT FILE *****************
*****************************************************************

*****************************************************************
        Number of visible LLP events in the detectors.
Detector: simulated acceptance, number of events:
*****************************************************************
AL3X, LLP0:     0.0333148 ,    31.7906
ANUBIS0, LLP0:  0.000384867 ,   4.40712
ANUBIS1, LLP0:  0.000308149 ,   3.52861
CODEXB0, LLP0:  6.88927e-05 ,   0.078889
CODEXB1, LLP0:  7.00049e-05 ,   0.0801626
FACET, LLP0:    0.000392674 ,   4.49651
FASER, LLP0:    1.41389e-07 ,   8.09524e-05
FASER2, LLP0:   2.78528e-05 ,   0.318942
MAPP1, LLP0:    0.000175794 ,   0.0201302
MAPP2, LLP0:    0.000417777 ,   0.478396
MATHUSLA0, LLP0:        0.000232753 ,   2.66526
MATHUSLA1, LLP0:        0.000179199 ,   2.05201
MATHUSLA2, LLP0:        0.000185024 ,   2.11871
```

Sample result file

Code structure

1. Read and interpret the input files
   - Using the `inputInterface` class
   - A class object constructed from the paths to the input files
   - Input extracted and stored using the `json` interface
2. Encode the properties of detector models
   - Characteristics of the detector models stored in objects of the `Detector` class
   - Central property of these detector models rests with their class function computing a probability of decay within the detector
3. Analyze the MC events against the former
   - Analysis of MC events processed within the analysis class
   - Object created in the main routine from the stored input
   - The event file is read (or produced with Pythia)
   - LLPs searched for by their PDG code
   - LLPs checked against a list of detector models
   - Outcome copied in the output file

Doxygen documentation:
https://wzeren.github.io/Displaced-Decay-Counter

Defining detectors in cylindrical geometry

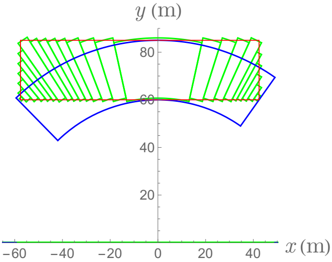
- Detectors designed in a fashion exploiting the cylindrical symmetry (of LLP production) around the beam axis, to minimize the time cost of event simulation
- Detectors constructed from 'shapes' in the cylindrical half-plane –the latter being defined by the beam axis (Oz) and the radial coordinate (Oh) –, to which an angular aperture $\delta\varphi$ is associated
- LLPs emitted at any azimuthal angle used in the calculation of the acceptance
- Saves a factor $\approx 2\pi/\delta\varphi$ in terms of event generation, as compared to a strict three-dimensional modelization

More on the cylindrical definition of detectors

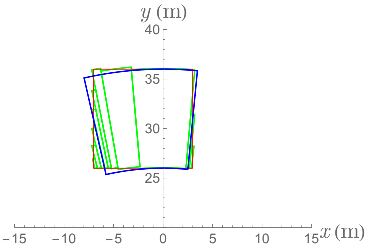
A set of basic objects defined in the program to facilitate the implementation of detectors in cylindrical geometry:

1. Oriented cylindrical segments (`class CylSeg`):
   - (`std::array<double,2> AA=zA,hA;`)
   - A sign representing its orientation (incoming or outgoing): $\varepsilon_{\mathcal{O}} = \pm 1$
   - $\varepsilon_{\mathcal{O}} \exp\left[-\frac{\ell}{\gamma\|\vec{v}\|\tau}\right]$
2. Cylindrical detector layers (`class CylDetLayer`):
   - A list of oriented cylindrical segments (`std::vector<CylSeg> SegList`) with a weighing factor $\mathcal{W}$ (`double`)
   - Sum of decay probabilities for the segments: $\mathcal{W} \cdot \sum_i \varepsilon_{\mathcal{O}} \exp\left[-\frac{\ell_i}{\gamma\|\vec{v}\|\tau}\right]$
   - Weight associated with the detector layer $\mathcal{W}_\varphi = \delta\varphi/2\pi$
   - Constructed from either segments, coordinates and weights, or 'bricks'
3. Detectors (`class Detector`):
   - Combines an identifier (`std::string`), an integrated luminosity (`double`), and a list of cylindrical detector layers (`std::vector<CylDet Layer>`)

Built-in detectors



MATHUSLA (red) vs. MATHUSLA0 (blue) vs. MATHUSLA1 (green)



CODEX-b (red) vs. CODEXB0 (blue) vs. CODEXB1 (green)

- FASER(2): cylindrical detectors aligned with the beam axis in the far-forward region. Respects the cylindrical symmetry ⇒ no difficulty in modeling these detectors with a single detector layer
- Others include AL3X (deprecated), ANUBIS, MAPP1(2), and FACET

Implementing cuts

- Possible to implement cuts on events containing LLPs
- A cut function is attached to each detector in the `DDC/src/Detectors` folder
- By default trivial but can be edited
- The input of this function is a collider event in HepMC format, leaving a maximal flexibility on the possible types of conditions
- To be filled up in a later stage when more experimental detail becomes available

Implementing new detectors

- Possible to implement new detectors: studying new geometries or improving existing ones
- Run `make DetEditor` in the main folder ⇒ `DetEditor` executable created in `DDC/src`
- `DetEditor` can prepare a skeleton code and link it to the rest of the program
- The only needed input is the name of the new detector
- The barebone script is in DDC/src/Detectors

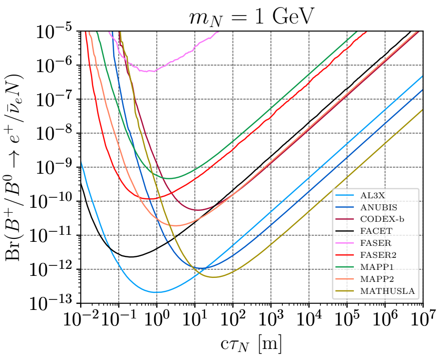
Similar tools

Name	Code & Tool	Process Types	Models
MadDump	plugin for MG5, Python	LLP decays/scattering	Many
FORESEE	Python	LLP decays	Many
ALPINIST	Mathematica–ROOT–Python	LLP decays	ALP only
SensCalc	Mathematica	LLP decays	Many
FastSim	Python	LLP decays	Many
DDC	C++	LLP decays	Many

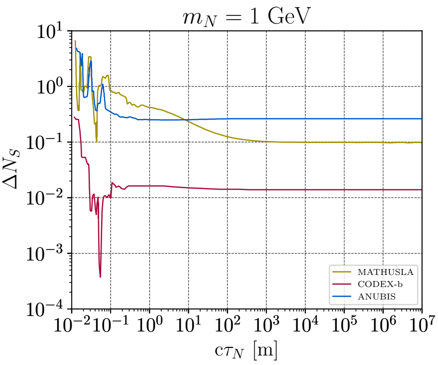
Name	Experiments	Recon. and Effi.	Reference
MadDump	Beam-dump exp. mainly	✗	JHEP05(2019)028
FORESEE	Far detectors	Cut functions ✓, decay-product effi. ✗	Phys. Rev. D 104, 035012 (2021)
ALPINIST	Extracted-beam exp.	Fully reconstructed final states ✓	JHEP07(2022)094
SensCalc	Far detectors	✗	Phys. Rev. D 108, 075028 (2023)
FastSim	Far detectors	Recons. criteria for DVs ✓	Phys. Rev. D 109, 075017 (2024)
DDC	Far detectors	Cut functions ✓	Eur. Phys. J. C (2024) 84:642

Light neutral fermion N produced in bottom decays

- Consider $B^+ \to e^+ N$ or $B^0 \to \bar{\nu}_e N$
- N can be a sterile neutrino, a light bino in the RPV-SUSY, ...



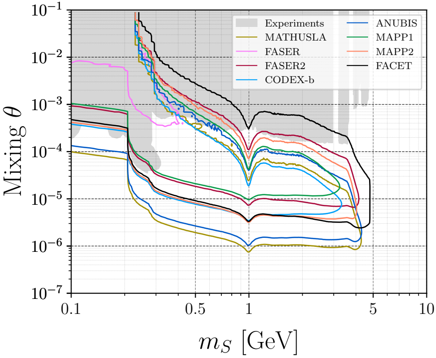
Sensitivity reach at 95% C.L.



$\Delta N_S = |N_S^1 - N_S^0|/N_S^0$
simple approx. vs. sophisticated implem.

Long-lived complex scalar mixed with the SM Higgs boson and produced from B-meson decays

- Focus on $B \to K + S$, ignore trilinear scalar couplings
- Visible final states: $S \to e^- e^+, \mu^- \mu^+, \pi\pi, KK, gg$, and ss



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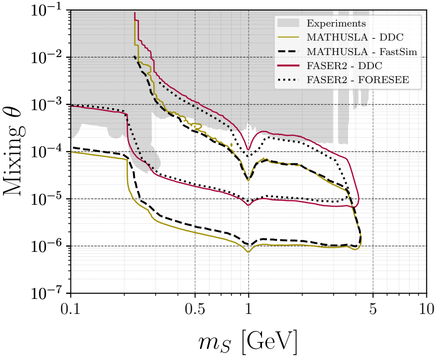
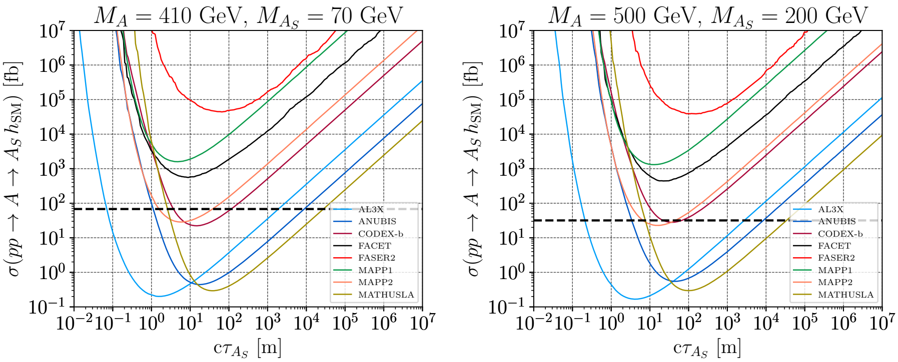


DDC vs. FastSim or FORESEE. FastSim results from [2308.05860] and FORESEE results from GitHub. General agreement

Long-lived scalar in an extended Higgs sector

- New scalar states: H, A, $H^{\pm}$ at about 500 GeV, and a lighter, mostly singlet CP-odd scalar A_S with mass in the 100 GeV range
- $pp \to A \to A_S h_{\text{SM}}$, A_S long-lived
- Configuration discussed in [2203.05049]



Long-lived fermion from a pair of heavy resonances

- $pp \overset{\text{EW}}{\to} \tilde{e}_R\tilde{e}_R$, $(\tilde{e}_R \to e\tilde{\chi}_1^0,\ \tilde{e}_R \to e\tilde{\chi}_1^0)$
- A long-lived light bino $\tilde{\chi}_1^0$ decays via RPV couplings