Sensitivities to feebly interacting particles: public and unified calculations

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August 24, 2023

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A need in public and unified sensitivity estimates I

A proper comparison of the potential of different experiments to search for long-lived new physics particles in a perfect world:

1. Unified description of the phenomenology of new physics
2. Explicit control of all the input: from spectra of SM particles to the experiment geometry and selection cuts
3. Protection against numerical artifacts
4. Publicity of the sensitivity calculations

How to address these requirements?

A need in public and unified sensitivity estimates II

– **Semi-analytic estimates**:

$$N_{\text{ev}} \approx N_{\text{prod}} \times \epsilon_{\text{FIP}} \times \langle P_{\text{dec}} \rangle \times \epsilon_{\text{dec}} \tag{1}$$

Each factor may be qualitatively estimated with control on errors [1902.06240]

– Improved version (z - FIP long. displacement, θ - FIP polar angle, ϕ - az. angle):

$$N_{\text{ev}} = \sum_i N_{\text{prod}}^{(i)} \int dE d\theta dz \; f^{(i)}(\theta, E) \cdot \epsilon_{\text{az}}(\theta, z) \cdot \frac{dP_{\text{dec}}}{dz} \cdot \epsilon_{\text{dec}}(m, \theta, E, z) \cdot \epsilon_{\text{rec}} \tag{2}$$

- $N_{\text{prod}}^{(i)}$, $f^{(i)}(\theta, E)$ are the total number of produced FIPs and the angle-energy distribution for the given channel i
- ϵ_{az} is the azimuthal acceptance for the FIP to decay inside the decay volume
- $\frac{dP_{\text{dec}}}{dz} = \frac{\exp[-z/(\cos(\theta)c\tau\sqrt{\gamma^2-1})]}{\cos(\theta)c\tau\sqrt{\gamma^2-1}}$ is the differential decay probability for the FIP to decay
- ϵ_{dec} is the decay products acceptance
- ϵ_{rec} (may be computed externally) is the reconstruction efficiency

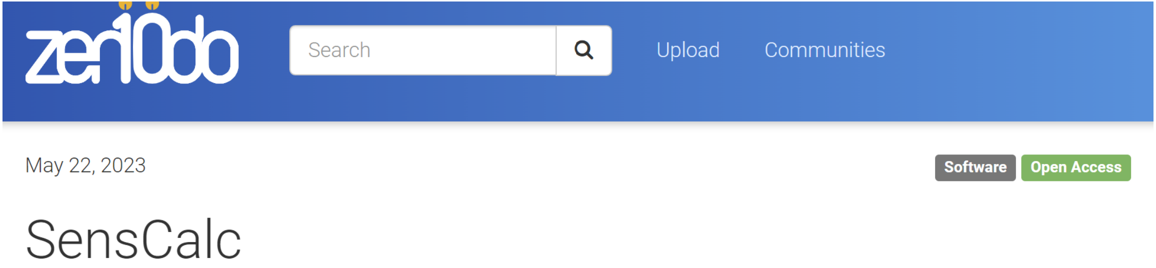
A need in public and unified sensitivity estimates III

- Analytic estimates (1) were extensively used by the SHiP experiment theory group to cross-check SHiP sensitivity simulations
- Later, the estimates based on (2) have been successfully used for various facilities and experiments:
  - Papers: [2209.14870], [2107.14685], [1908.04635], [2204.01622], [2210.13141], [2304.02511]
  - Ph.D. theses: 1, 2, 3

Eq. (2) may be applied to a very wide range of experiments

But one needs a public tool with careful implementation and a cross-check

SensCalc I



- SensCalc – a `Mathematica`-based sensitivity evaluator
- **Input**: experimental setup (geometry, selection cuts) and the tabulated distributions of mother particles
- **Output**: tabulated number of events $N_{\text{events}}(\mathrm{m}_{\text{FIP}}, g_{\text{FIP-SM}})$ that may be converted into exclusion/discovery limits

Based on M. Ovchynnikov et al.

What is implemented so far

The list of implemented facilities:

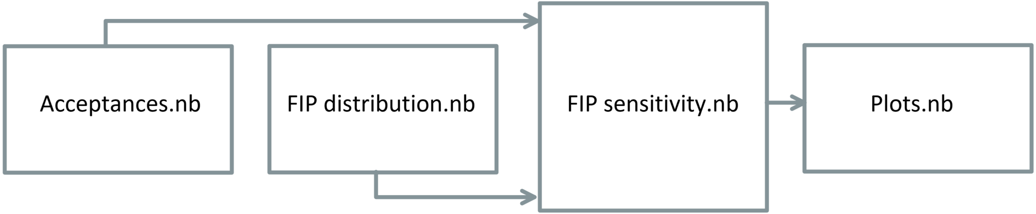
- **SPS**
  - NA62/HIKE$_{\text{dump}}$
  - SHiP
  - SHADOWS
  - CHARM, BEBC
- **Fermilab BD**
  - DUNE/DUNE-PRISM, DarkQuest
- **LHC**
  - FASER/FASER2/FASERν, SND@LHC/advSND,
  - FACET
  - MATHUSLA, Codex-b
- **FCC-hh**
  - Analogs of the LHC-based experiments

The list of implemented FIPs:

- **Dark photons**
- **Dark scalars** (with mixing and quartic couplings)
- **HNLs** (with arbitrary mixing pattern)
- **ALPs** coupled to
  - gluons
  - photons
  - fermions
- $B-L$ **mediator**

Other FIPs and signatures will be added with the next releases. Scattering signature exists in private

Hod does it work I



Modular structure:

1. In `Acceptances.nb`, specify the geometry of the experiment and selection criteria for the decay products to produce the tabulated $\epsilon_{\rm az}, \epsilon_{\rm dec}$
2. In `FIP distribution.nb`, specify the facility and the FIP to generate the distributions of FIPs produced by decays or scatterings
3. In `FIP sensitivity.nb`, compute the tabulated number of events and sensitivity
4. `Plots.nb` produces sensitivity plots

Hod does it work II

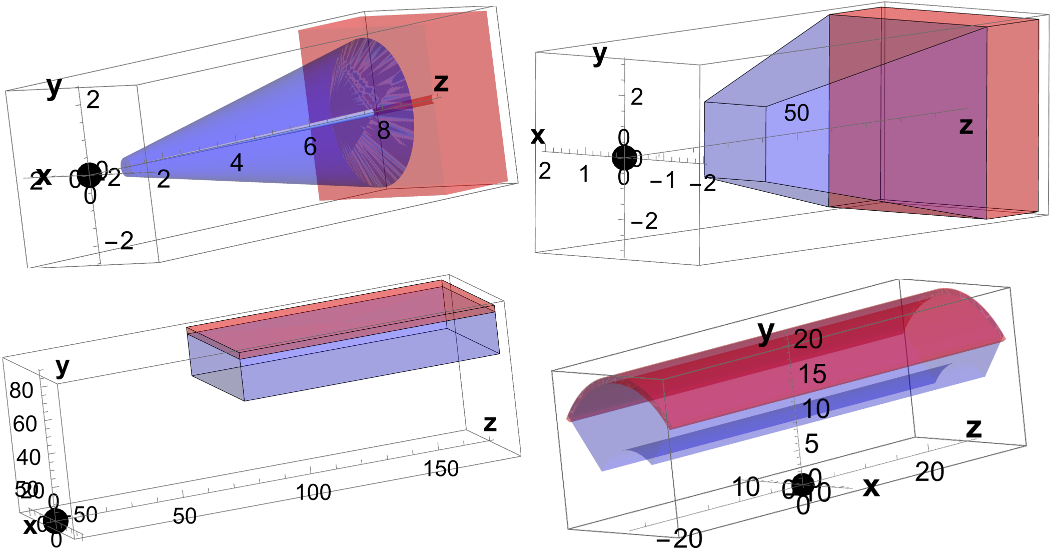
`Acceptances.nb`:

1. The user specifies the experimental setup (geometry, magnetic field of the spectrometer, the presence of the EM calorimeter) and selection criteria (E/p_T/impact parameter cut, etc.)
   Geometry implementation may be easily cross-checked by visualization and characteristic quantities (total volume, $\theta_{min/max}$)
2. The notebook produces the grid

$$m, \theta, E, z, \epsilon_{\text{az}}, \epsilon_{\text{dec}} \tag{3}$$

   ϵ_{dec}: *decay products are propagated through the detector and selected according to the selection (**pure MC**)*

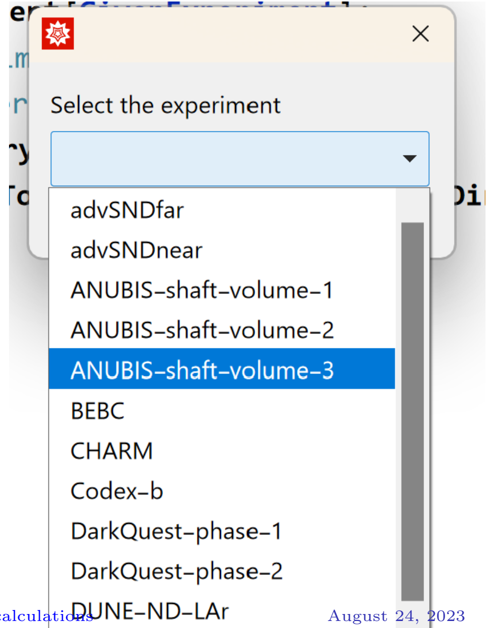
Hod does it work III



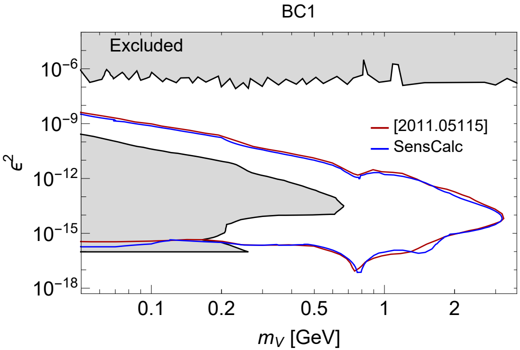
Examples: LHCb-downstream, SHiP, MATHUSLA@CMS, ANUBIS-ceiling

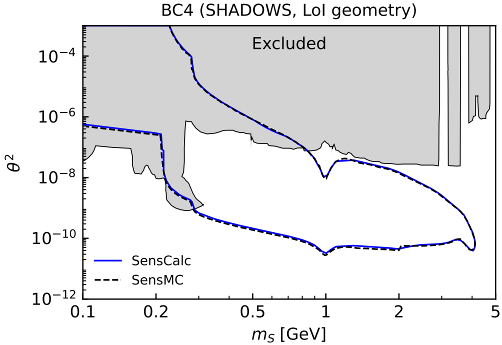
Launching

- **If the experiment and FIP have already been implemented**: just launch the notebook and pass through dialog windows
- **If something is not implemented**: may be added using the analogy with implemented examples, or computed from scratch (a complicated geometry or a very exotic FIP phenomenology)



Validation



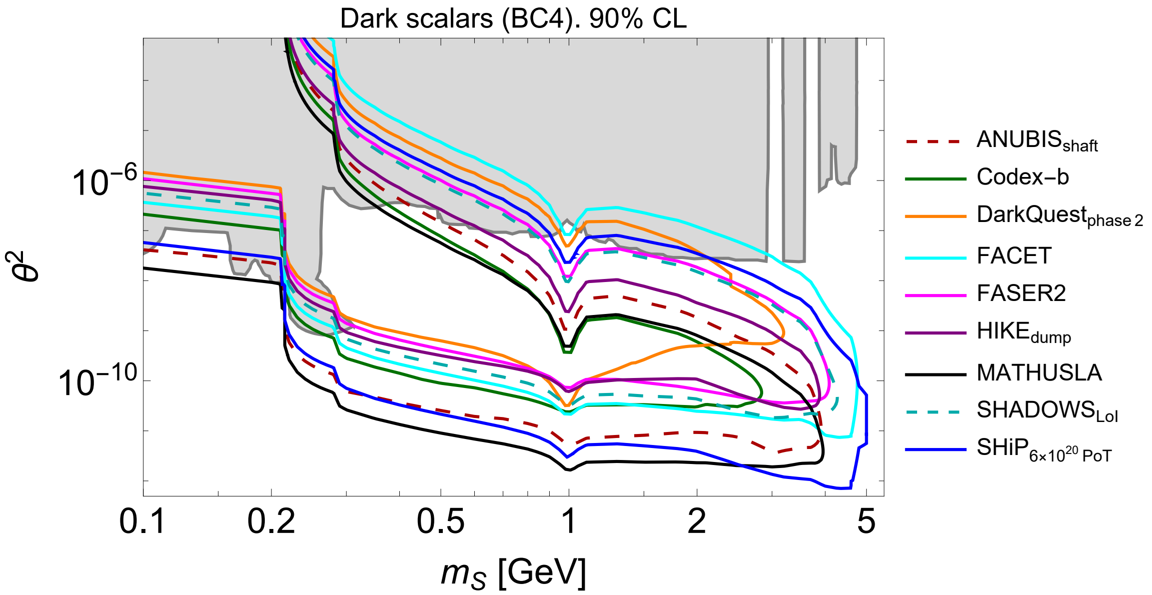


- `SensCalc` has been cross-checked with independent MC codes for experiments at SPS and LHC: `FairShip`, `SensMC`, `FORESEE`, `ALPINIST`, LHCb simulation framework *(see details in backup slides and in the accompanying preprint)*
- It is being used by the SHiP collaboration and for studies of new physics with new algorithms at LHCb

Standard example: dark scalars (BC4) I

- Consider the model of dark scalars
- Problems with previous comparisons (see, e.g., 2305.01715):
  1. The phenomenology description is not unified
     (inclusive/exclusive production via decays of B mesons, different decay widths)
  2. Setups used to calculate the sensitivity differ from those described in the public documents
     (examples include $\epsilon_{dec} = 1$ or a larger decay volume (see, e.g., backup slides)
- Let us use `SensCalc` for improve the comparison. Assumptions:
  - Scalar phenomenology from [1904.10447]
  - Experimental setups from public documents (HIKE$_{\text{dump}}$: phase 2 design)
  - Signature: at two tracks reaching the end of the detector
  - No cuts on decay products except if specified publicly, so estimates are optimistic
  - Zero background has been assumed

Standard example: dark scalars (BC4) II

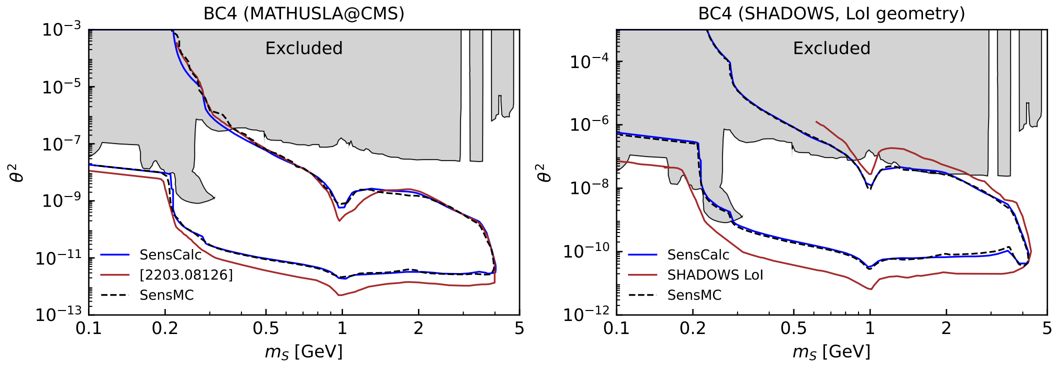


Summary

- Comparison between different experiments in the potential to explore FIPs is far from perfect and has to be revised
- One of the first steps is to have a unified, robust, and public sensitivity estimator
- `SensCalc` is a `Mathematica`-based code which aims to address these issues

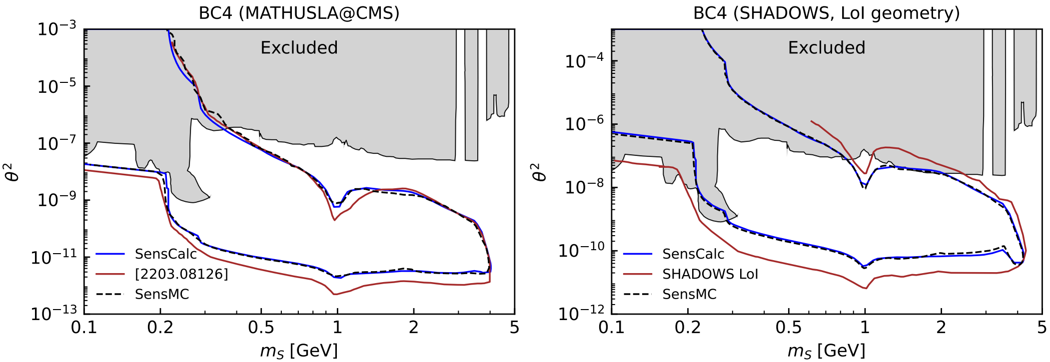
Backup slides

Validation: dark scalars at MATHUSLA and SHADOWS I



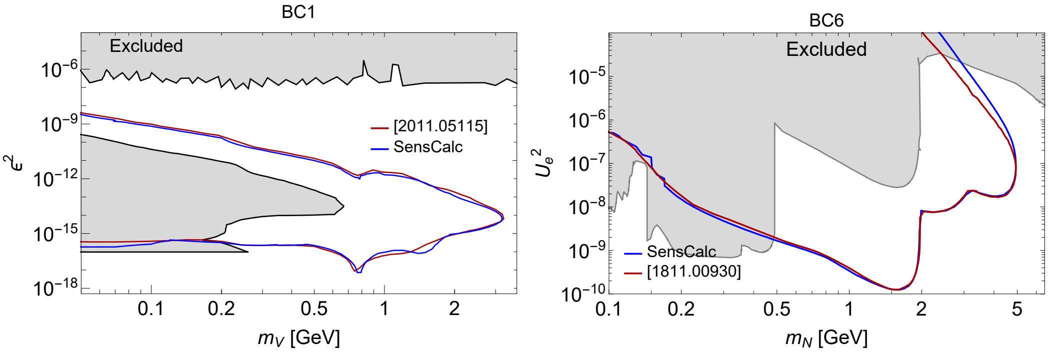
- Setups: taken from the SHADOWS LoI and MATHUSLA Snowmass paper
- Minimal event requirements: scalars must decay inside the decay volume, decay products have to point to the end of the detector
- `SensCalc` predictions cross-checked with a dedicated simulation under the same input

Validation: dark scalars at MATHUSLA and SHADOWS II



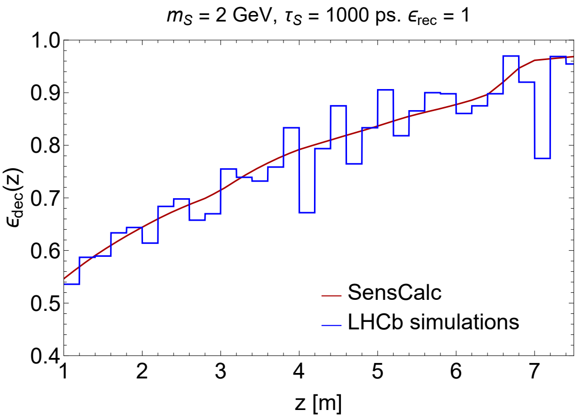
- The sensitivities obtained by SHADOWS and MATHUSLA people: a huge difference
- **Reason 1**: the setups used in the collab. estimates do not match the setups described publicly: $\epsilon_{\text{dec}} = 1$ for MATHUSLA, a larger decay volume (without clearly studied background status) for SHADOWS
- **Reason 2**: different description of the scalar production

Validation: SHiP sensitivity I



- `SensCalc` predictions agree with FairShip simulations for the ECN4 setup from [1811.00930], [2011.05115]
- Differences: different phenomenology, simplification for the upper bound calculation in [1811.00930]

Validation: LHCb simulations



– New physics searches at LHCb using new downstream tracking algorithm (paper in preparation): acceptances perfectly agree with full LHCb simulations

Problems with FIP phenomenology used as input

FIPs 2022 proceedings, FIPs models BCXX:

- **BC4, BC5** (Higgs-like scalars): some (most) of the experiments use inclusive description of the scalar production, which is wrong at large masses $m_S \gtrsim 3$ GeV
- **BC10** (ALPs coupled to fermions): most of the experiments use a completely wrong phenomenology (missing important production and decay channels)[1]; some of them include hadronic width, while most of them don't
- **BC11** (ALPs coupled to gluons): different definition of the coupling to SM particles is used by different experiments

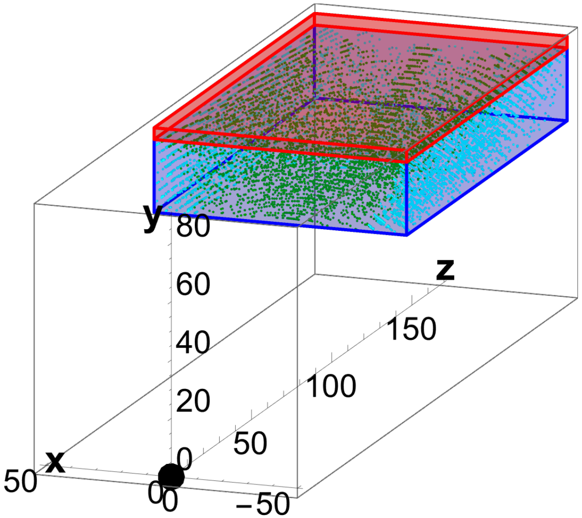
[1] M. Ovchynnikov et al., in progress

Calculating acceptances I

1. Provide geometry input (decay volume, detector)
2. Find a grid $\theta_{\text{FIP}}(z_{\text{FIP}}), \phi_{\text{FIP}}(z_{\text{FIP}})$ for which the FIP is inside the decay volume $\Rightarrow \epsilon_{\text{az}}(\theta_{\text{FIP}}, z_{\text{FIP}})$

   Simple verifications:

   - *checking $\theta_{min/max}$ belonging to the decay volume*
   - *visualization of the points $\{z_{FIP}, \theta_{FIP}, \phi_{FIP}\}$ – they must belong to the decay volume*
   - *the integral of ϵ_{az} gives the total volume of the decay volume*



Calculating acceptances II

3. Consider a grid $m_{\text{FIP}}, E_{\text{FIP}}, \theta_{\text{FIP}}, z_{\text{FIP}}, \phi_{\text{FIP}}$, where $\{\theta, \phi\}$ belong to the decay volume
4. Generate phase space of the decay products at rest and boost them given $E_{\text{FIP}}, \theta_{\text{FIP}}, \phi_{\text{FIP}}$
   - Exclusive decay channels (where analytic expression for the matrix element exists): simulating phase space with the weight given by squared matrix element
   - Inclusive decays (into jets/jets+leptons): either simulating decay into jets in `Mathematica`, or using pre-computed phase space of a typical hadronized final state obtained using `pythia`
5. Require at least two decay products with zero total charge to point to the end of the detector (may be changed to requiring all the decay products to be within the acceptance). Additionally, require some other cuts if needed (the energy cut, the p_T cut, etc.). This gives ϵ_{dec}

Averaging ϵ_{dec} over ϕ: reasonable since other quantities (such as dP_{dec}/dz, f_{FIP}) are ϕ-independent