Sensitivities to feebly interacting particles: public and unified calculations

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A need in public and unified sensitivity estimates

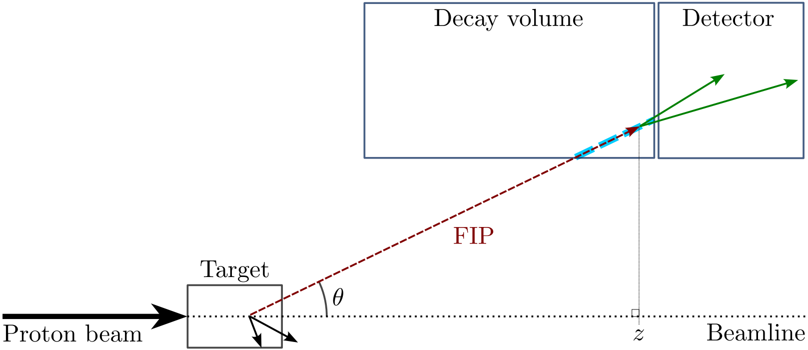
GeV-scale FIPs	Proposed experiments
ALPs, dark photons HNLs, dark scalars Dark pions, spin-2 spin-2, ...	FACET/FASER2/advSND MATHUSLA/ANUBIS/CODEX-b/AL3X SHiP/SHADOWS/HIKE$_{\text{dump}}$ DUNE/DarkQuest/Belle II FCC-hh-based experiments ...

Compare experiments $\leftrightarrow$ compare sensitivities to FIPs. In a perfect world:

1. Unified phenomenology description
2. Explicit control of all the input
3. Control over numerical artifacts
4. Publicity of the sensitivity calculations

How to address these requirements?

Semi-analytic estimates I



– Rough but transparent – toy analytic estimate [1902.06240]:

$$\boldsymbol{N}_{\text{ev}} \approx \boldsymbol{N}_{\text{prod}} \times \langle \boldsymbol{\epsilon}_{\text{FIP}} \rangle \times \langle \boldsymbol{P}_{\text{dec}} \rangle \times \langle \boldsymbol{\epsilon}_{\text{dec}} \rangle \tag{1}$$

Each factor may be qualitatively estimated

Semi-analytic estimates II

– Improved version to gain accuracy:

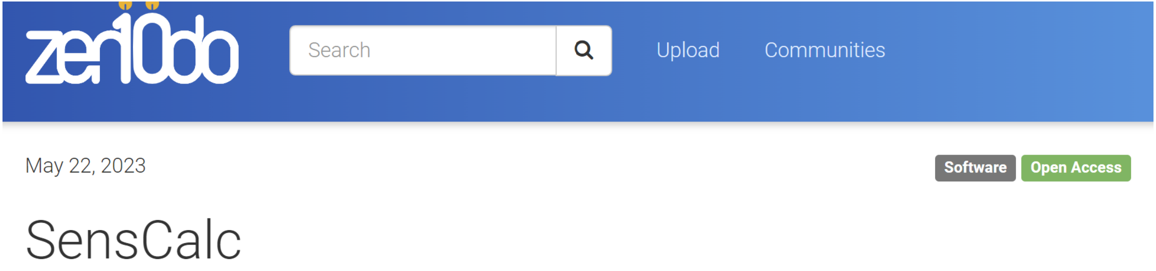
$$\boldsymbol{N_{\text{ev}} = \sum_i N^{(i)}_{\text{prod}} \int dEd\theta dz\ f^{(i)}(\theta, E)\cdot \epsilon_{\text{az}}(\theta, z)\cdot \frac{dP_{\text{dec}}}{dz}\cdot \epsilon_{\text{dec}}(m,\theta,E,z)\cdot\epsilon_{\text{rec}}} \quad (2)$$

- $\boldsymbol{N^{(i)}_{\text{prod}}, f^{(i)}(\theta, E)}$: total number of produced FIPs, $\theta - E$ FIP distribution
- $\boldsymbol{\epsilon_{\text{az}}}$ is the azimuthal acceptance for the FIP to decay inside the decay volume
- $\boldsymbol{\frac{dP_{\text{dec}}}{dz} = \frac{\exp[-z/(\cos(\theta)c\tau\sqrt{\gamma^2-1})]}{\cos(\theta)c\tau\sqrt{\gamma^2-1}}}$ is the differential decay probability for the FIP to decay
- $\boldsymbol{\epsilon_{\text{dec}}}$ is the decay products acceptance
- $\boldsymbol{\epsilon_{\text{rec}}}$ (must be computed externally) is the reconstruction efficiency

– Eq. (2) has been used to estimate sensitivities of various facilities and experiments

Public sensitivity evaluator based on Eq. (2)?

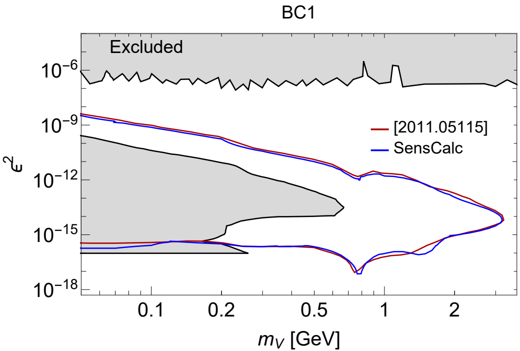
SensCalc I

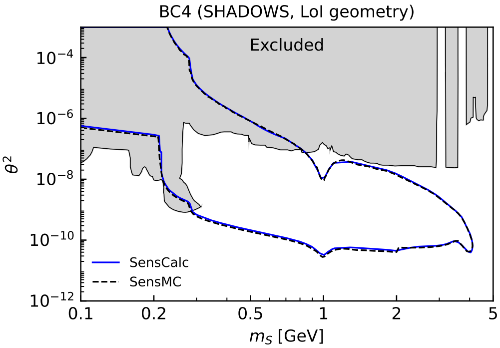


- SensCalc – a `Mathematica`-based sensitivity evaluator
- **Input**: experimental setup (geometry, selection cuts), FIP model (branching ratios, matrix elements, lifetimes), tabulated distributions of mother particles
- **Output**: tabulated number of events $N_{\text{ev}}(m_{\text{FIP}}, g_{\text{FIP-SM}})$ that may be converted into exclusion/discovery limits
- **Limitations**: no detailed event record, only prompt FIPS production (ALPs at FASER are included)

Based on 2305.13383

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)*

What is implemented so far

Implemented experiments:

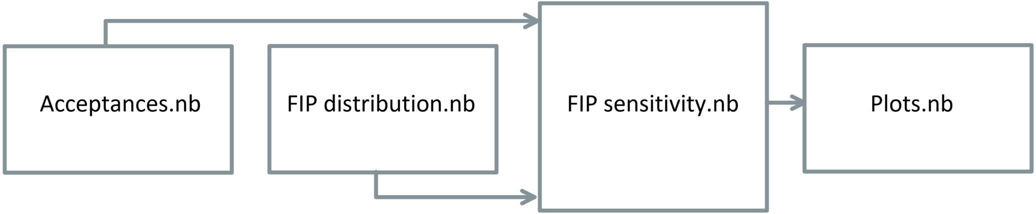
- **SPS**
  - NA62/HIKE$_{\text{dump}}$
  - SHiP
  - SHADOWS
  - CHARM, BEBC
- **Fermilab BD**
  - DUNE/DUNE-PRISM, DarkQuest
- **LHC**
  - FASER/FASER2/FASERν, SND@LHC/advSND,
  - FACET
  - MATHUSLA, Codex-b
- **FCC-hh**
  - Analogs of the LHC-based experiments

Implemented FIPs:

- **Dark photons**
- **Dark scalars** (with mixing and quartic couplings)
- **HNLs** (with arbitrary mixing pattern)
- **ALPs** coupled to
  - gluons
  - photons
  - fermions
- **Anomaly-free mediators** ($B-L$, $B-3L_\mu$,...)

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

Launching I



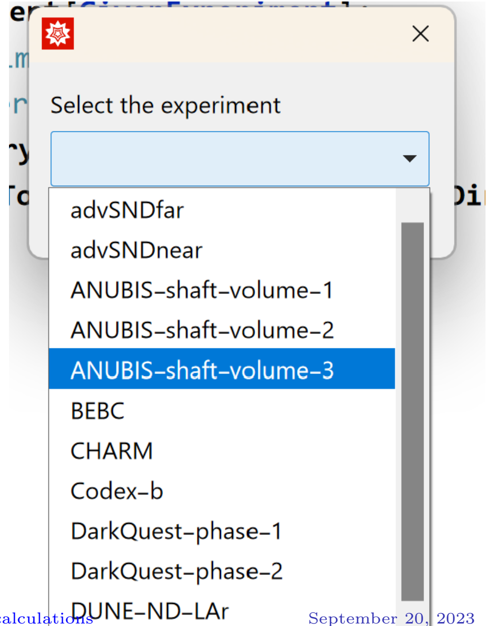
Modular structure:

1. In `Acceptances.nb`, specify the geometry of the experiment and selection criteria for the decay products to produce the tabulated $\epsilon_{\mathrm{az}}, \epsilon_{\mathrm{dec}}$
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

Launching II

- **If the experiment and FIP have already been implemented**: just launch the notebook and pass through dialog windows
- **If something is not implemented**: add by analogy or compute from scratch

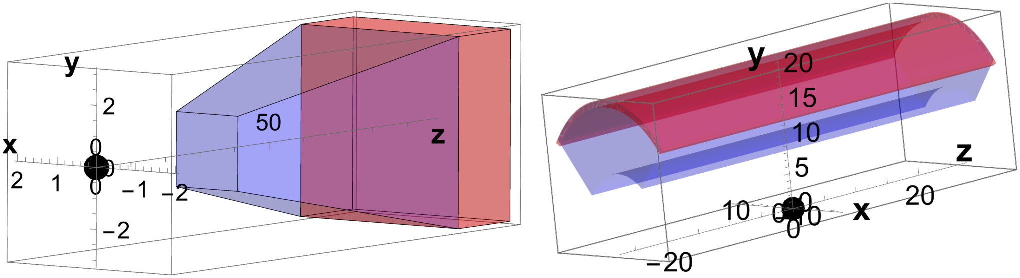
Running time (from scratch): <1 **hour**



`Acceptances.nb`: a bit of details I

`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.)

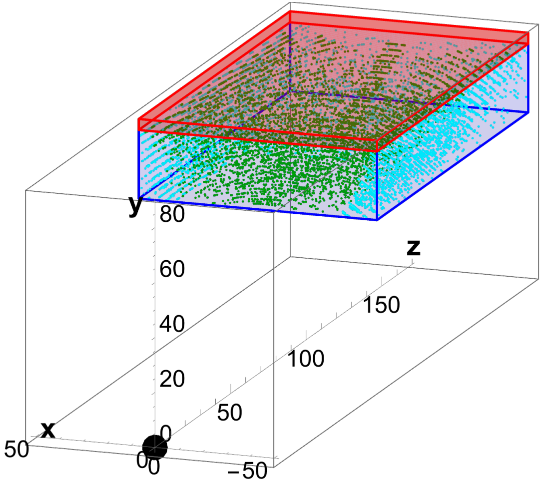


Left panel: SHiP. Right panel: ANUBIS-ceiling. Blue domain: decay volume, red domain: the entire detector

Acceptances.nb: a bit of details II

2. The notebook produces the grid

$$m, \theta, E, z, \phi_{\text{inside decay volume}}, \epsilon_{\text{az}}(\theta, z) \tag{3}$$



MATHUSLA geometry. Green (cyan) points: trajectories of FIPs that point (do not point) to the end of the detector

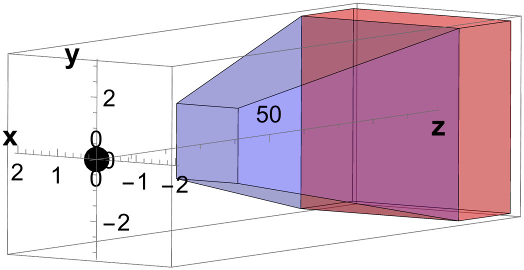
`Acceptances.nb`: a bit of details III

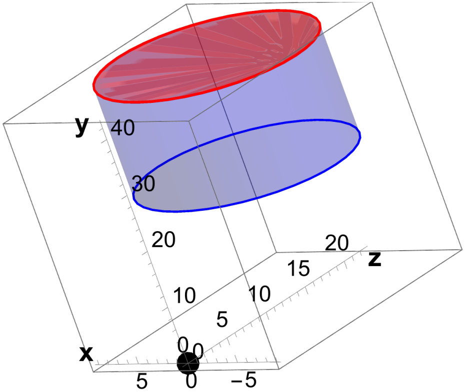
3. The notebook generates

$$\boldsymbol{\epsilon}_{\text{dec}}(\boldsymbol{m},\boldsymbol{\theta},\boldsymbol{E},\boldsymbol{z}) = \langle \boldsymbol{\epsilon}_{\text{dec}}(\boldsymbol{m},\boldsymbol{\theta},\boldsymbol{E},\boldsymbol{z},\boldsymbol{\phi}_{\text{inside decay volume}}, \text{dec. ch.})\rangle_{\text{decay channels},\boldsymbol{\phi}} \quad (4)$$

- For this, it checks whether the decay products point to the end of the detector and satisfy specified kinematic cuts
- The decay phase space: either simulate in-flight (if analytic matrix element exists) or use phase space pre-generated in `MadGraph5+pythia8` (if decays into jets)

Case study: acceptances I





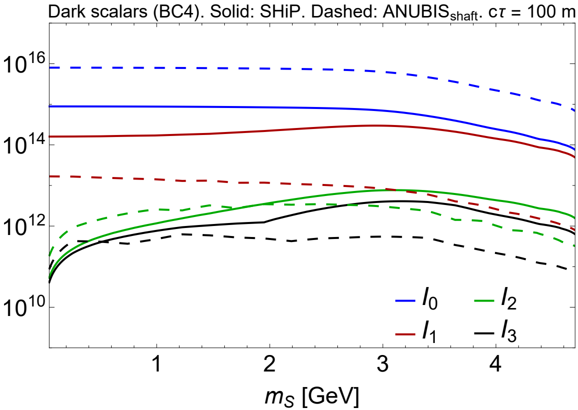
- **SHiP**: on-axis experiment at SPS. **ANUBIS-shaft**: off-axis experiment near ATLAS
- They differ in all possible aspects. How do we understand their sensitivity?

Case study: acceptances II

- $c\tau\langle\gamma\rangle \gg l_{\text{experiment}}$: $c\tau$ factorizes out

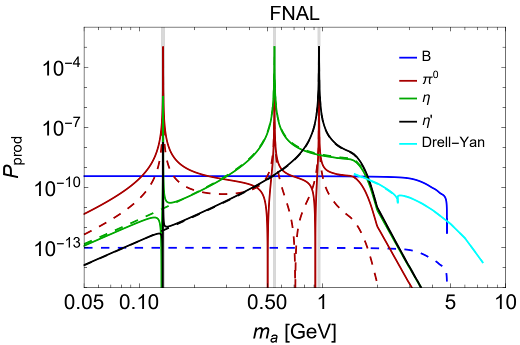
$$N_{\text{ev}} = \sum_i \frac{N^{(i)}_{\text{prod}}}{c\tau} \int \frac{f^{(i)} \cdot \epsilon_{\text{az}} \cdot \epsilon_{\text{dec}}}{\cos(\theta)\sqrt{\gamma^2 - 1}} \quad (5)$$

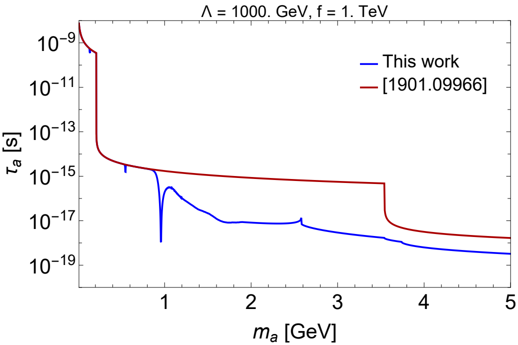
- Easy to study qualitative behavior of the sensitivity: subsequently include the factors in the integral (5)



$\mathcal{I}_0 = N_{\text{prod}}$	Total number of the produced FIPs
$\mathcal{I}_1 = \mathcal{I}_0 \cdot \int f^{(i)} \cdot \epsilon_{\text{az}}/\Delta z_{\text{decay volume}}$	Fraction of FIPs intersecting the decay volume
$\mathcal{I}_2 = \mathcal{I}_0 \cdot \int f^{(i)} \cdot \epsilon_{\text{az}}/\sqrt{\gamma^2 - 1}$	Fraction of FIPs decayed inside the decay volume
$\mathcal{I}_3 = c\tau N_{\text{ev}}$	Fraction of events passing decay products acceptance

Case study: ALPs with fermion coupling I

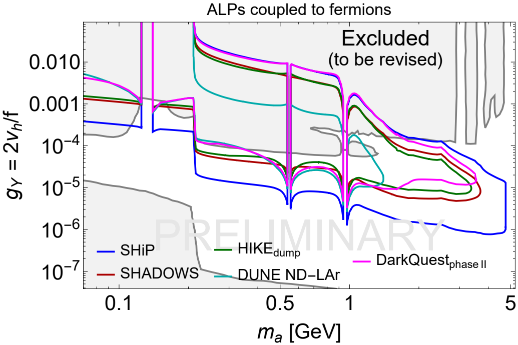


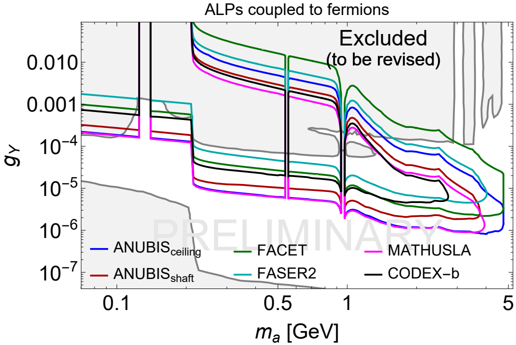


- ALPs with fermion coupling: the widely adopted phenomenology [1901.09966] misses hadronic ALP decays and various production channels
- All sensitivities of future experiments/existing bounds have to be recomputed

F. Kahlhoefer, G.D.V. Garcia, MO, A. Zaporozhchenko, in preparation

Case study: ALPs with fermion coupling II





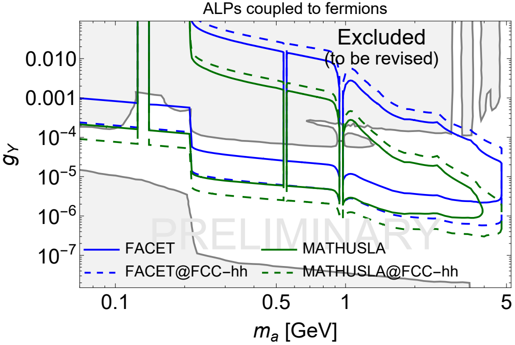
Compared to PBC description:

– Generically, it becomes more complicated to explore the domain of large ALP mass

– Experiments at Fermilab: no significant production from Bs; instead, production from the mixing with light mesons

F. Kahlhoefer, G.D.V. Garcia, MO, A. Zaporozhchenko, in preparation

Case study: ALPs with fermion coupling III



– FCC-hh would improve the reach of LHC-based experiments, but not dramatically (for this model)

See also Rhitaja's talk

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
- We are missing the same approach for cosmology (BBN and CMB)
  In preparation

Backup slides

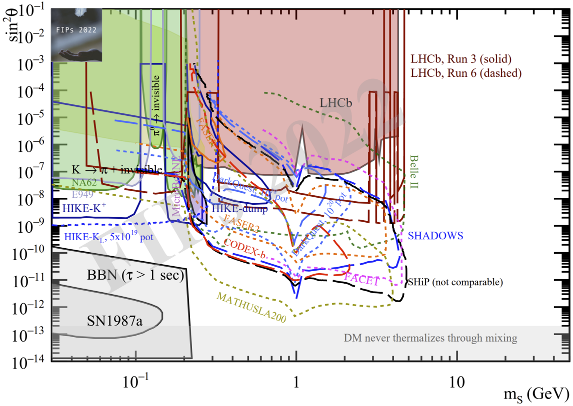
Semi-analytic estimates in the literature

- 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

Different experiments use different FIP's phenomenology I

Example 1 – dark scalars:

1. Some experiments use inclusive production and some exclusive (difference in $\mathrm{Br}(B \to S)$ from a factor 2 to a factor 10 and more)
2. Hadronic decays for $m_S \simeq 1$ GeV suffer from huge theoretical uncertainties, the studies are ongoing (see, e.g., [2303.12847])

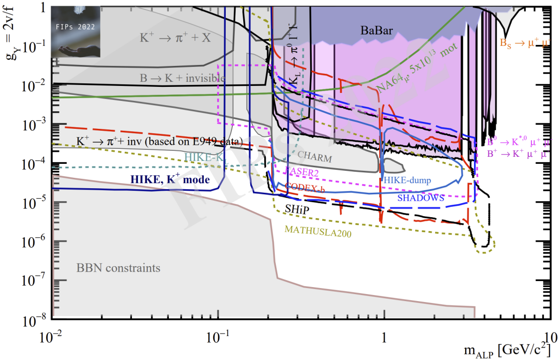


Latest FIPs proceedings

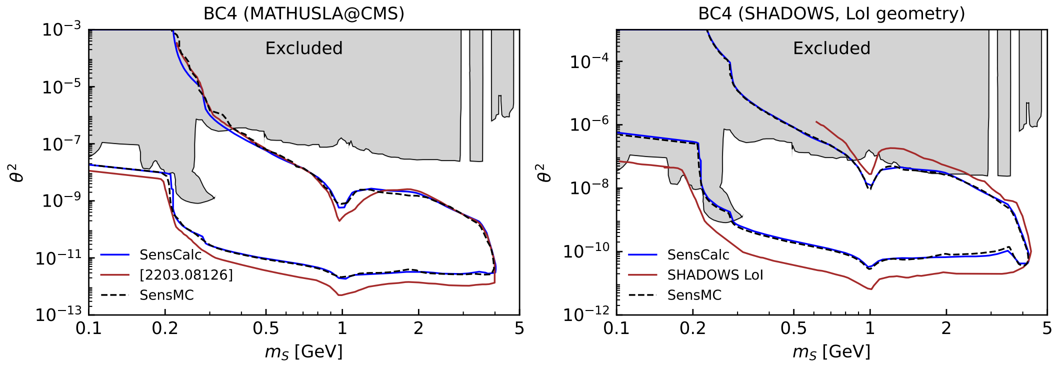
Different experiments use different FIP's phenomenology II

Example 2 – ALPs coupled to fermions:

1. Some experiments include width into hadrons, while others don't
2. Production description does not include important channels (see main slides)



Validation: dark scalars at MATHUSLA and SHADOWS I

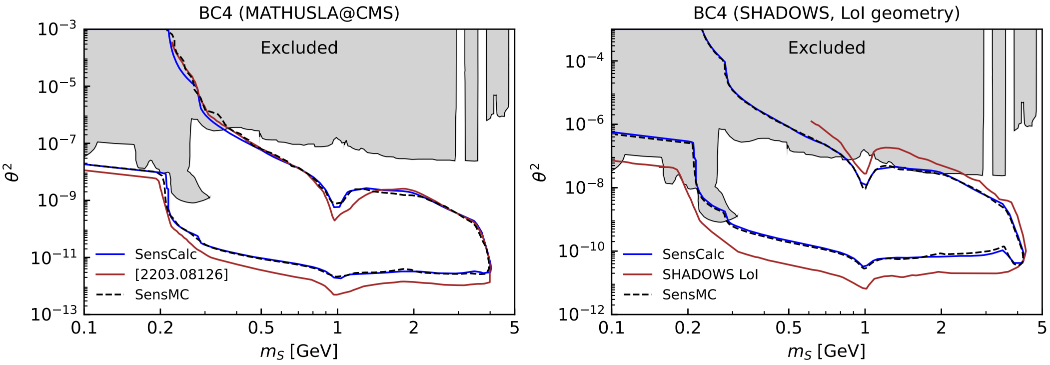


– Setups: taken from the SHADOWS LoI and MATHUSLA Snowmass paper

– Minimal event requirements: scalars must decay inside the decay volume, decay products have to point to the end of the detector

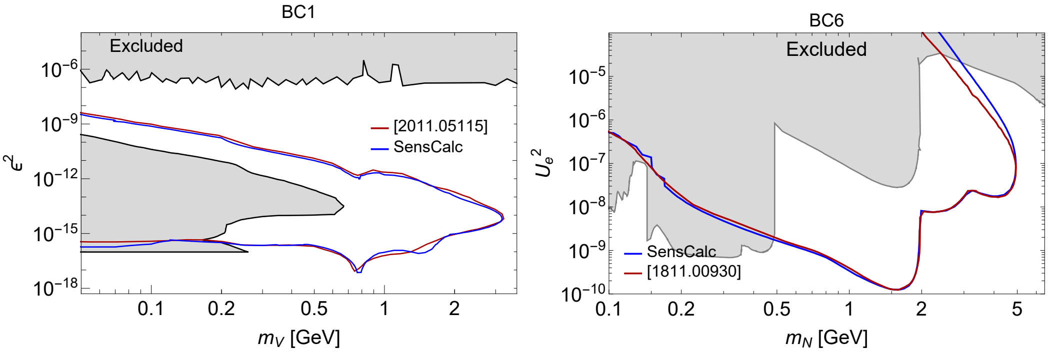
– `SensCalc` predictions cross-checked with a dedicated simulation under the same input

Validation: dark scalars at MATHUSLA and SHADOWS II



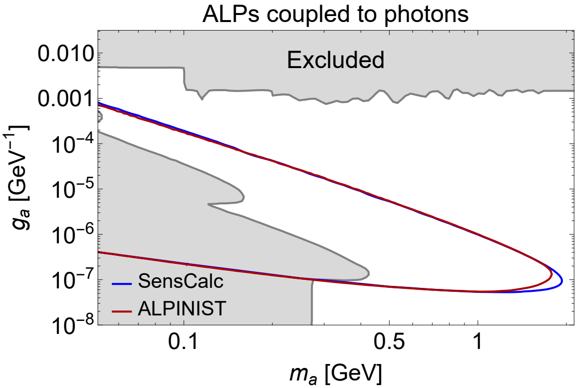
- The sensitivities obtained by SHADOWS and MATHUSLA people: a huge difference
- **Reason 1**: the setups used in the collab. estimates do not match the setups described publicly: $\epsilon_{\text{dec}} = 1$ for MATHUSLA, a larger decay volume (without clearly studied background status) for SHADOWS
-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

Validation: SHiP sensitivity I



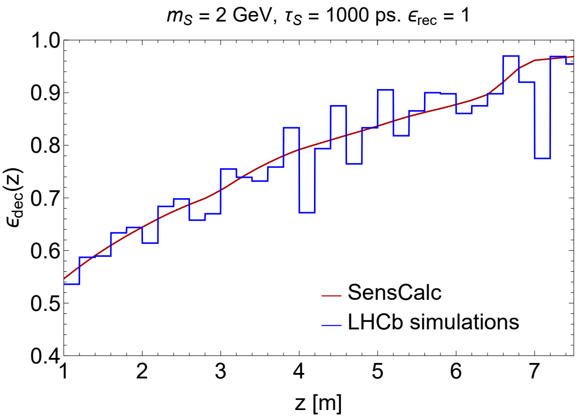
- `SensCalc` predictions agree with FairShip simulations for the ECN4 setup from [1811.00930], [2011.05115]
- Differences: different phenomenology, simplification for the upper bound calculation in [1811.00930]

Validation: ALPINIST



- Comparison with ALPINIST: ALPs coupled to photons at SHiP
- A perfect agreement except for a small domain at large masses

Validation: LHCb simulations



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