Sensitivities to feebly interacting particles: public and unified calculations

Maksym Ovchynnikov, Jean-Loup Tastet

June 29, 2023

A need for public and unified sensitivity estimates I

Comparison of the potential of various experiments suffers from several issues:

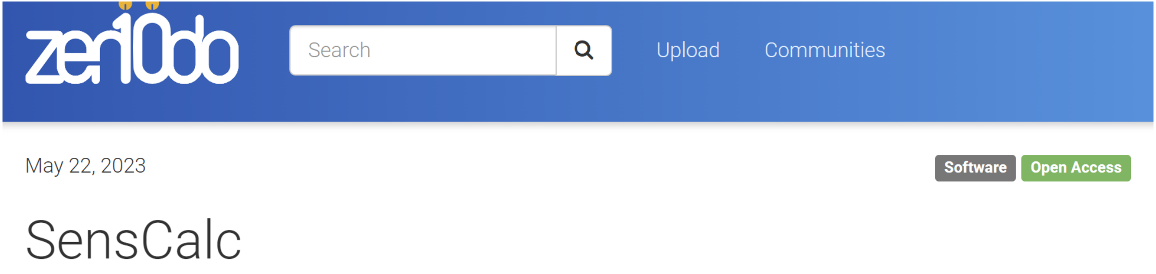
1. (Often) no unique description of the FIP phenomenology
2. Experimental design changes frequently; re-doing simulations requires much time
3. Tools performing sensitivity calculations: black-box and not publicly accessible

How to address these issues?

A public tool is needed:

- Unified FIP phenomenology description
- Explicit control over each stage of the sensitivity evaluation
- Accuracy compared with MC simulations

SensCalc I



- SensCalc (also on github) – a Mathematica-based sensitivity evaluator
- **Input**: experimental setup (geometry, selection cuts) and the tabulated distributions of mother particles
- **Output**: tabulated number of events N_{events} that may be converted into exclusion/discovery limits

Based on [2305.13383]

SensCalc II

– Method used by `SensCalc`: semi-analytic estimates

$$N_{\text{ev}} = \sum_i N^{(i)}_{\text{prod}} \int dE d\theta dz\; f^{(i)}(\theta, E) \cdot \epsilon_{\text{az}}(\theta, z) \cdot \frac{dP_{\text{dec}}}{dz} \cdot \epsilon_{\text{dec}}(m, \theta, E, z) \cdot \epsilon_{\text{rec}} \qquad (1)$$

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

– The approach was extensively used to cross-check SHiP sensitivity simulations [1811.00930]

– Later, for various facilities and experiments:

- Papers: [2209.14870], [2107.14685], [1908.04635], [2204.01622], [2210.13141], [2304.02511]
- Ph.D. theses: 1, 2, 3

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, ANUBIS, CODEX-b
- **FCC-hh**
  - Analogs of the LHC-based experiments

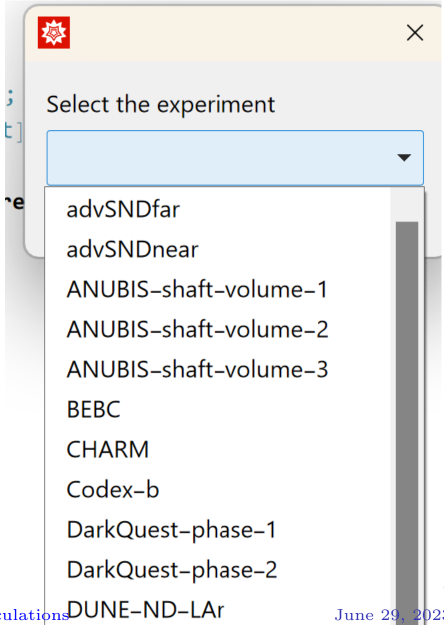
The list of implemented FIPs:

- **Dark photons**
- **Dark scalars** (with mixing and quartic couplings)
- **HNLs** (with arbitrary mixing pattern)
- **ALPs** coupled to
  - gluons
  - photons
  - fermions
- $U(1)$ **mediators coupled to anomaly-free charges** ($B-L, \ldots$)

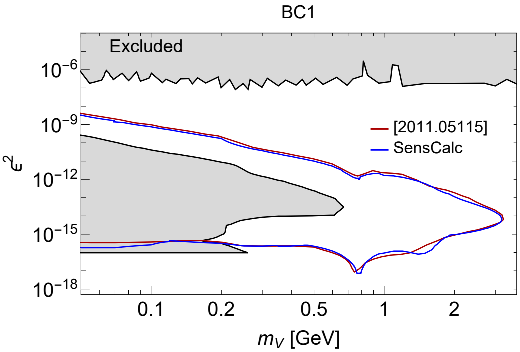
Other FIPs and signatures (e.g., scatterings) will be added in the next releases

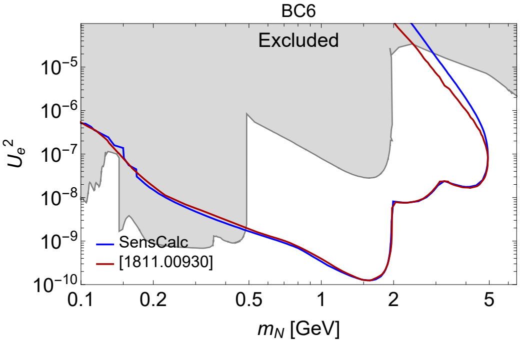
Launching

- `SensCalc` has a modular structure for computing quantities entering Eq. (1)
- **If the experiment and FIP have already been implemented**: just launch the notebook and follow the dialog windows
- **If something is not implemented**: may be added analogously to the implemented examples, or computed from scratch (a complicated geometry or a very exotic FIP phenomenology) *(ANUBIS-ceiling?)*
- Apart from the tabulated N_{events}, it produces many useful quantities: differential number of events, acceptances (Rebeca's talk), etc.



Validation: comparison with SHiP simulations and other codes I





- SensCalc predictions agree with FairShip simulations for the ECN4 setup from [1811.00930], [2011.05115]. Differences are understood and not related to inaccuracies
- SensCalc also agrees with FORESEE and ALPINIST

Validation: an independent public MC estimator SensMC I

Overview

- Simple program to numerically estimate Eq. (1) using Monte-Carlo integration
- Written from scratch in `Julia` to be hackable and retain control over assumptions
- Designed with FIPs in mind:
  $\rightarrow$ extensive use of importance sampling to compensate for small probabilities
- In contrast to `SensCalc`, produces an actual event record
- Available on GitHub and on Zenodo along with SensCalc

Limitations

- Only supports the scalar portal [1904.10447] (and HNLs unofficially...)
- Can only simulate FIPs produced in decays of heavy mesons or EW bosons

Validation: an independent public MC estimator SensMC II

Monte-Carlo integration (See JLT's lecture at the 3rd SHiP Starter Kit for more details)

– Estimate the expectation value of an observable $O(X)$ as:

$$\langle O(X)\rangle = \int \mathrm{d}X \underbrace{P(X)}_{\text{probability}} O(X) \overset{\text{large } N}{\approx} \frac{1}{N}\sum_{k=1}^{N} O(x^{(k)}) \quad \text{where} \quad x^{(k)} \sim P \tag{2}$$

– Divide and conquer to generate $x^{(k)}$: $P(A\cap B\cap C\cap \ldots) = P(A)P(B|A)P(C|A\cap B)\ldots$
$\rightarrow$ follow the chain of events, sampling one conditional probability at a time

– Importance sampling: sample from an easier *importance* distribution, $x^{(k)} \sim Q$:
($Q(X)$ must be nonzero whenever $P(X)O(X)$ is nonzero)

$$\langle O(X)\rangle = \int \mathrm{d}X Q(X)\left(\frac{P(X)}{Q(X)}O(X)\right) \approx \frac{1}{N}\sum_{k=1}^{N} \overbrace{\left(\frac{P(x^{(k)})}{Q(x^{(k)})}\right)}^{\text{weight } w(x^{(k)})} O(x^{(k)}) \tag{3}$$

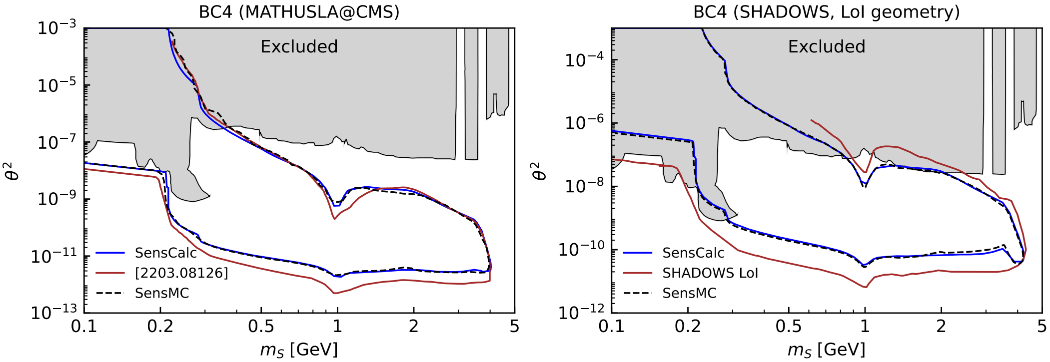
Interesting if $P(X)O(X)$ is zero almost everywhere (e.g. branching ratio to some FIP)

Validation: an independent public MC estimator SensMC III

Event generation

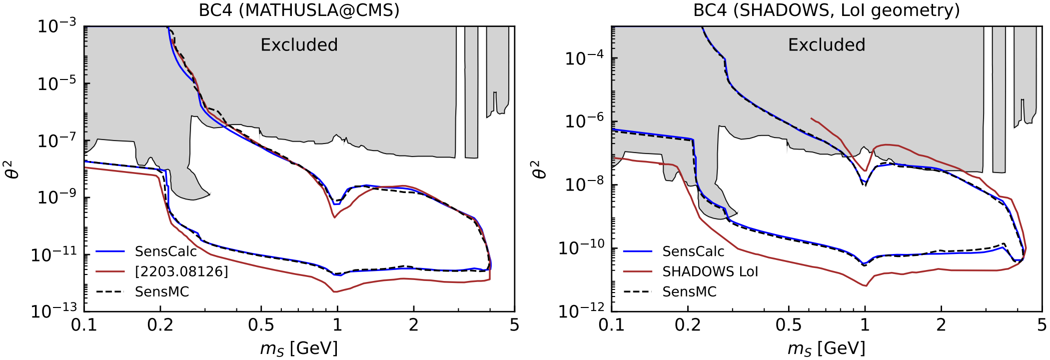
- Only simulates events that involve FIPs (i.e. $O(X)$ must be zero otherwise)
- At each step, sample only among the relevant outcomes
  $\rightarrow$ weight = total probability of such outcomes (the weights multiply at each step)
- Each sample (= event) is generated following these steps:
  1. Sample a meson species and its momentum
  2. Sample a meson decay channel to a FIP, as well as the FIP momentum
  3. Sample the FIP decay vertex along its trajectory (optionally using importance sampling)
  4. Sample the FIP decay channel and the momenta of its decay products
  5. Recursively decay any Standard Model particles, until only metastable particles are left
  6. Evaluate the acceptance criterion specified by the user
  7. Record the final event weight along with its “accepted” status (true=1 or false=0)
- $N_{\mathrm{ev}} = \frac{1}{N_{\mathrm{gen}}} \sum_{k=1}^{N_{\mathrm{gen}}} w(x^{(k)}) \cdot \mathrm{accepted}(x^{(k)})$ (independently of the importance distribution)

Validation: an independent public MC estimator SensMC IV



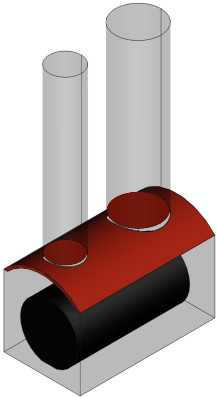
- Setups: taken from the SHADOWS LoI and MATHUSLA Snowmass paper
- Minimal event requirements: scalars must decay inside the decay volume, decay products have to point to the end of the detector
- SensCalc and SensMC agree

Validation: an independent public MC estimator SensMC V

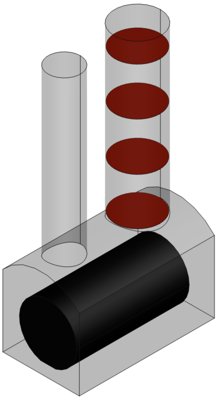


– The sensitivities obtained by SHADOWS and MATHUSLA people: a huge difference. Reasons:
  1. The setups used in the collab. estimates do not match the setups described publicly
  2. Different descriptions of the scalar production
     (In collab. estimates, the inclusive description is used which breaks down at large masses and contradicts PBC recommendations)

ANUBIS: two configurations I



(a) Ceiling geometry

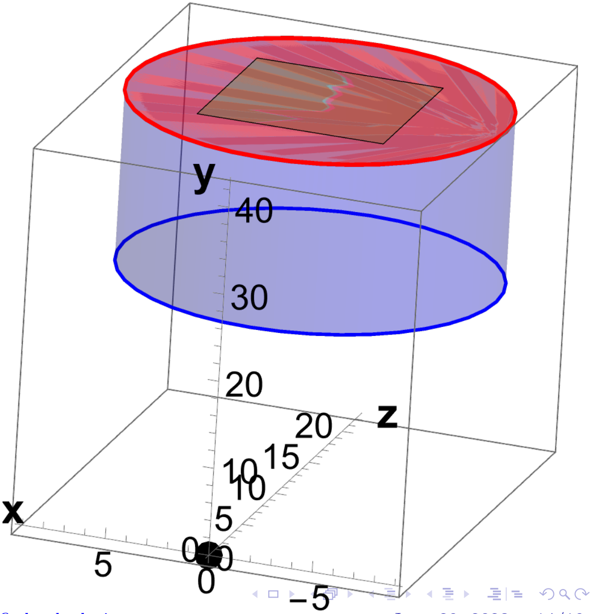


(b) In-shaft geometry

- Ceiling: ATLAS cavern as the decay volume
- Shaft: three decay volumes, with the tracking stations placed on top of each

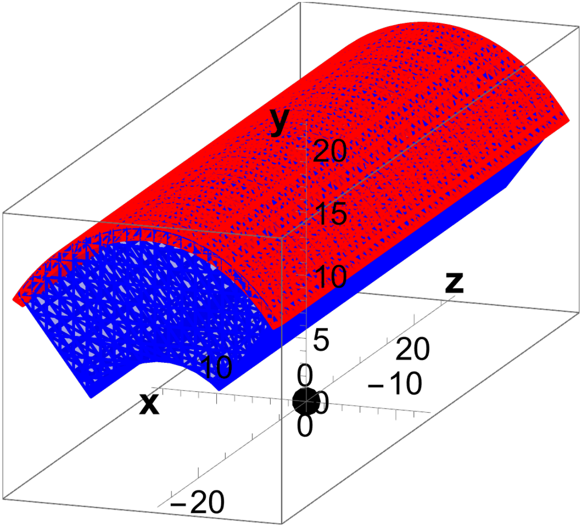
ANUBIS: two configurations II

- Shaft configuration:
  - Each decay volume: cylinders with $h \approx 19$ m and $R = 9$ m beginning at $z = 4.5$ m from the IP
  - The first cylinder has $y_{\text{min}} = 23$ m
  - At least two charged decay products must intersect the detector plane
  - No other cuts

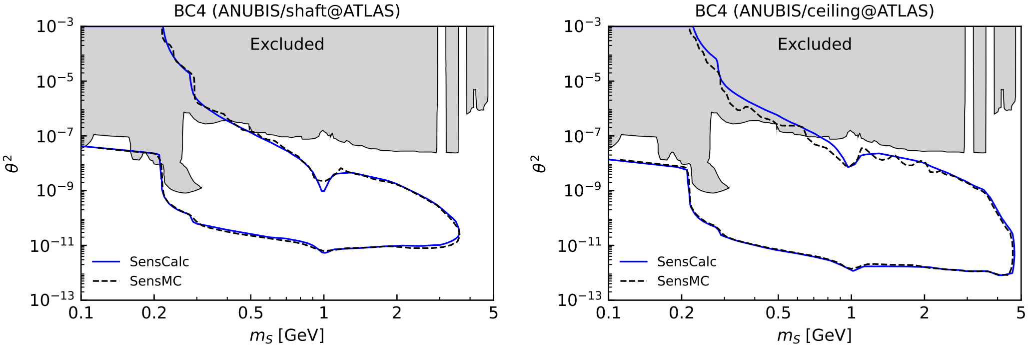


ANUBIS: two configurations III

- Ceiling configuration:
  - `SensCalc`: projective decay volume matching the angular coverage of the detector
  - `SensMC`: the whole cavern (minus the ATLAS detector) is the decay volume
- Expectation: because of the 4-momentum conservation law and the ATLAS volume, the volume outside the projective volume is not expected to contribute

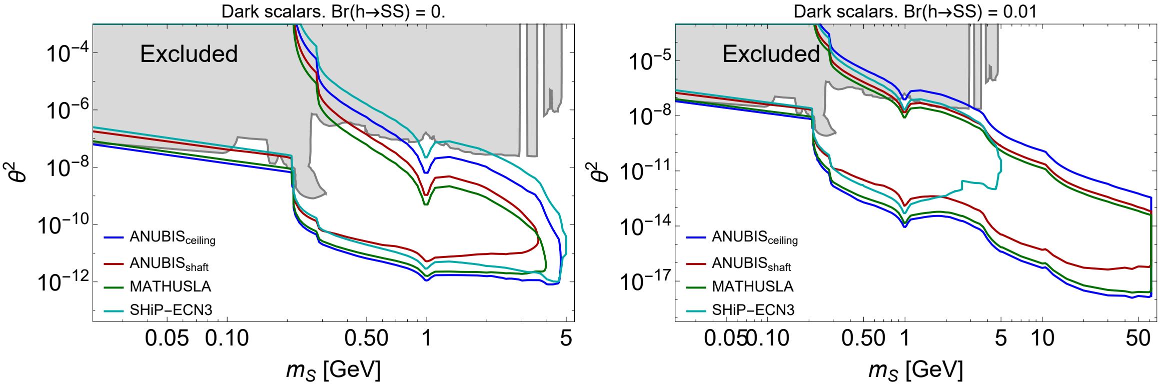


ANUBIS sensitivity to dark scalars (BC4): `SensCalc` vs `SensMC`



- 90% CL assuming zero background and unit reconstruction efficiency ($N_{\text{events}} > 2.3$)
- `SensCalc` and `SensMC` largely agree, up to some minor differences
  - Small disagreements for the shaft configuration are under investigation
  - SensMC suffers from statistical noise at the upper limit

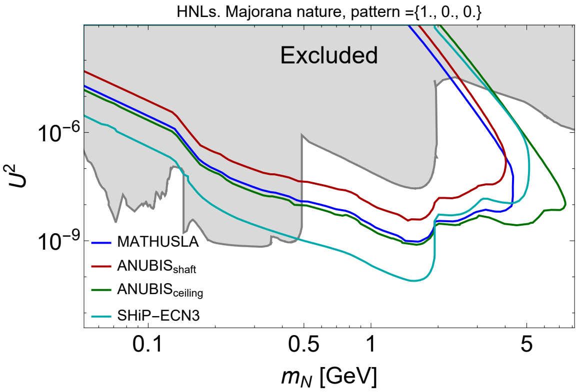
Sensitivity to other models+comparison with other experiments I



– Three models: BC4, BC5 (dark scalars), BC6 (HNLs)

– Domain $m_S \gg 2m_B$: under improvement

Sensitivity to other models+comparison with other experiments II



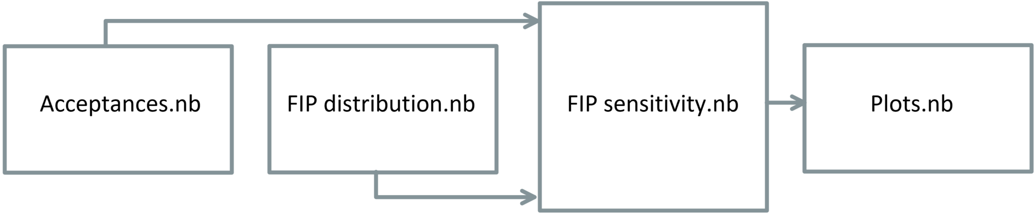
– Three models: BC4, BC5 (dark scalars), BC6 (HNLs)

Summary

- ANUBIS-shaft and ANUBIS-ceiling are implemented in `SensCalc` and `SensMC`
- ANUBIS may be competitive with SHiP and MATHUSLA in the potential to explore the parameter space of FIPs
- Additional questions to study:
  1. Backgrounds *(our estimates assumed a background-free environment)*
  2. What is the impact of, e.g., the energy cut?

Backup slides

How does SensCalc work I



Modular structure:

1. In `Acceptances.nb`, specify the geometry of the experiment and selection criteria for the decay products, in order 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 the sensitivity plots

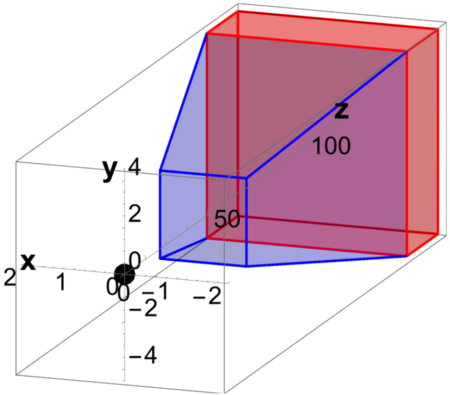
How does SensCalc work II

`Acceptances.nb`:

1. The user specifies the experiment geometry and selection criteria
   Geometry implementation may be easily cross-checked by visualization and characteristic quantities (total volume, $\theta_{min/max}$)
2. The notebook produces the grid

$$m, \theta, E, z, \epsilon_{\mathrm{az}}, \epsilon_{\mathrm{dec}} \tag{4}$$

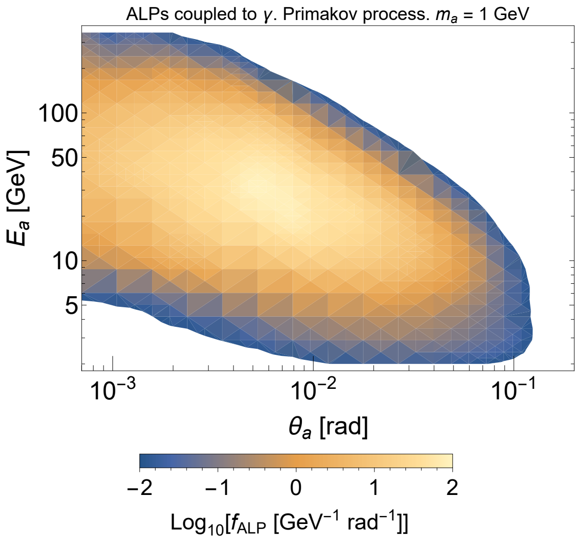
*ϵ_{dec}: decay products are propagated through the detector (possibly affected by the dipole magnet) and selected according to the cuts (**pure MC**)*



How does SensCalc work III

`FIP distribution.nb`:

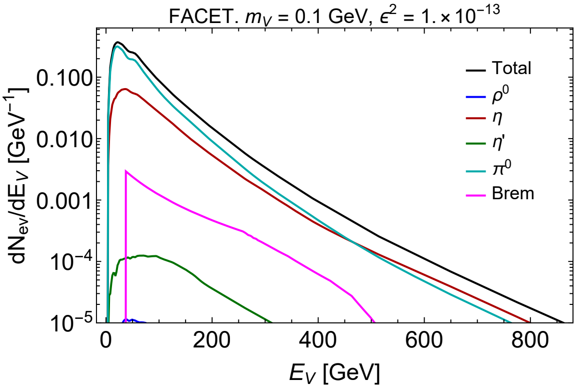
- The user selects the FIP, facility, and production channels
- Afterward, the notebook uses pre-computed distributions of secondary particles (photons, mesons, EW bosons) to compute the distributions of FIPs
- The distributions of FIPs produced by DIS are pre-computed using `FeynRules+MadGraph+PYTHIA 8`



How does SensCalc work IV

`FIP sensitivity.nb`:

- The user selects the FIP and the experiment
- Then, the notebook imports the tabulated acceptances and FIP distributions and evaluates the integral (1) on a grid of mass-coupling
- It also produces a list of useful quantities, such as the angle-energy distributions for the number of events, and acceptances



FIP models

Dark scalars:

- Two models: BC4 (Br($h \to SS$) = 0), BC5 (Br($h \to SS$) = 0.01)
- Production modes (see [1904.10447]):
  - $B \to S + X_s$, exclusive
  - $B \to SS + X_s$, $B_s \to SS$, $h \to SS$ (if Br($h \to SS$) $\neq 0$)
- Decay modes: $ee, \mu\mu, \tau\tau, \pi\pi, KK, DD, BB$

HNLs:

- Reference model: mixing pattern $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 0 : 0$, Majorana nature
- Production modes (see [1805.08567]):
  - $D^{0/+}/D_s \to N + X$ (and anti-modes)
  - $B^{+/0}/B_c \to N + X$
  - $W \to N + e$
- Decay modes: $ll'\nu, \pi e, \rho e, q\bar{q}\nu, q\bar{q}'e$