SensCalc

Public and unified calculations of sensitivities to feebly interacting particles

Based on [2305.13383] by Maksym Ovchynnikov, Jean-Loup Tastet, Oleksii Mikulenko, Kyrylo Bondarenko

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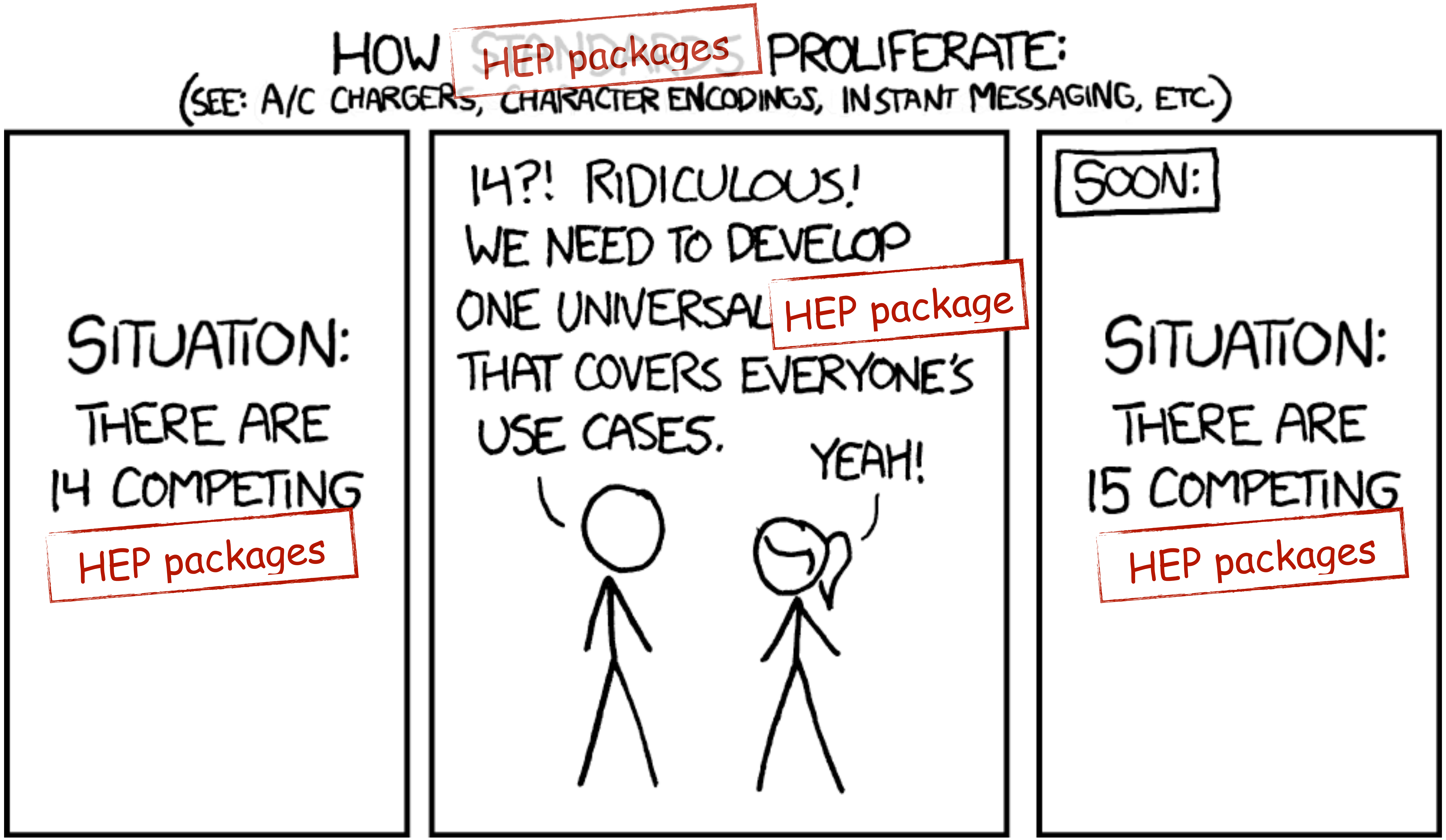
Plan

- Why a new package?
- The semi-analytic estimate behind SensCalc
- How to run SensCalc
- Limitations & conclusion

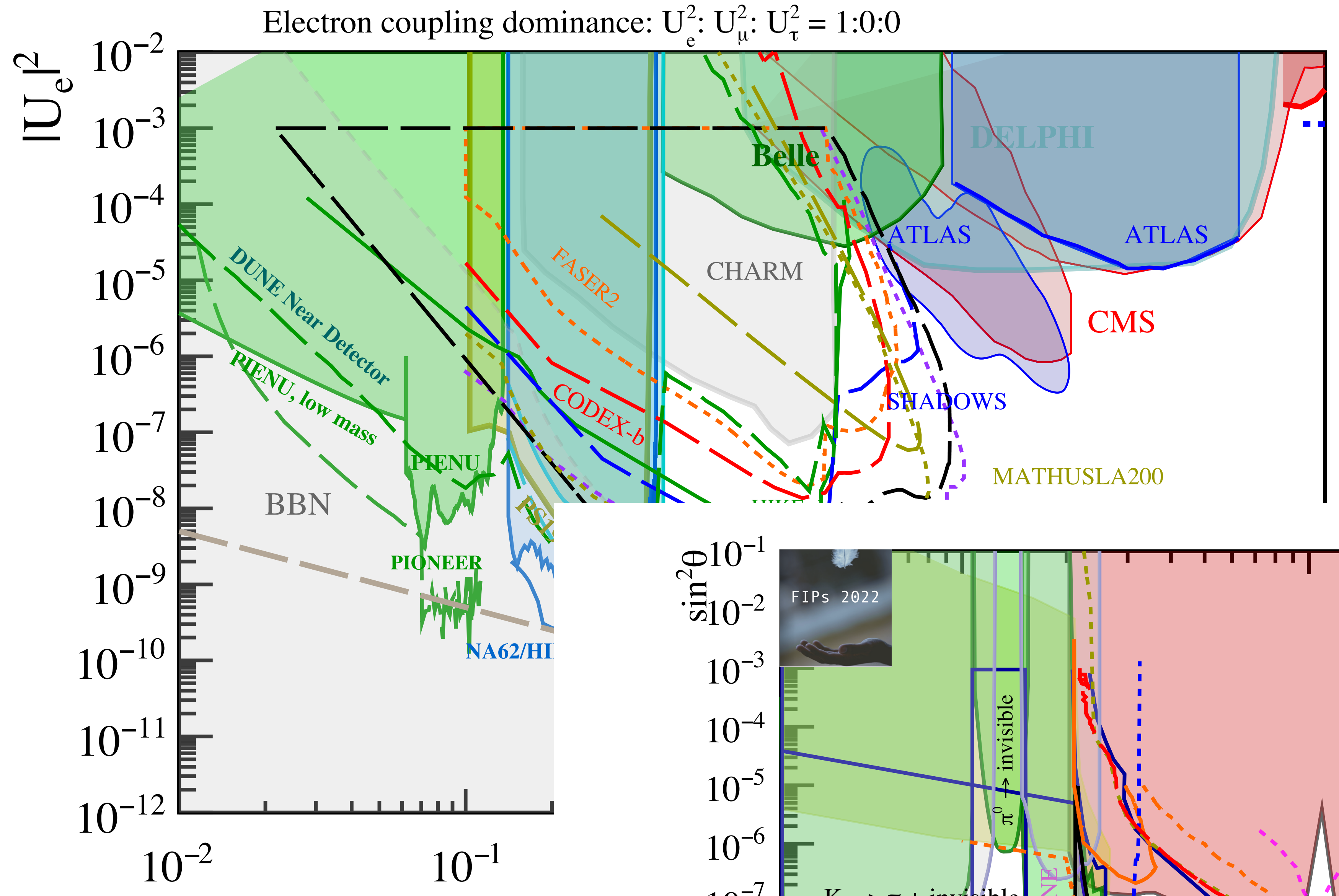
Why one more tool?

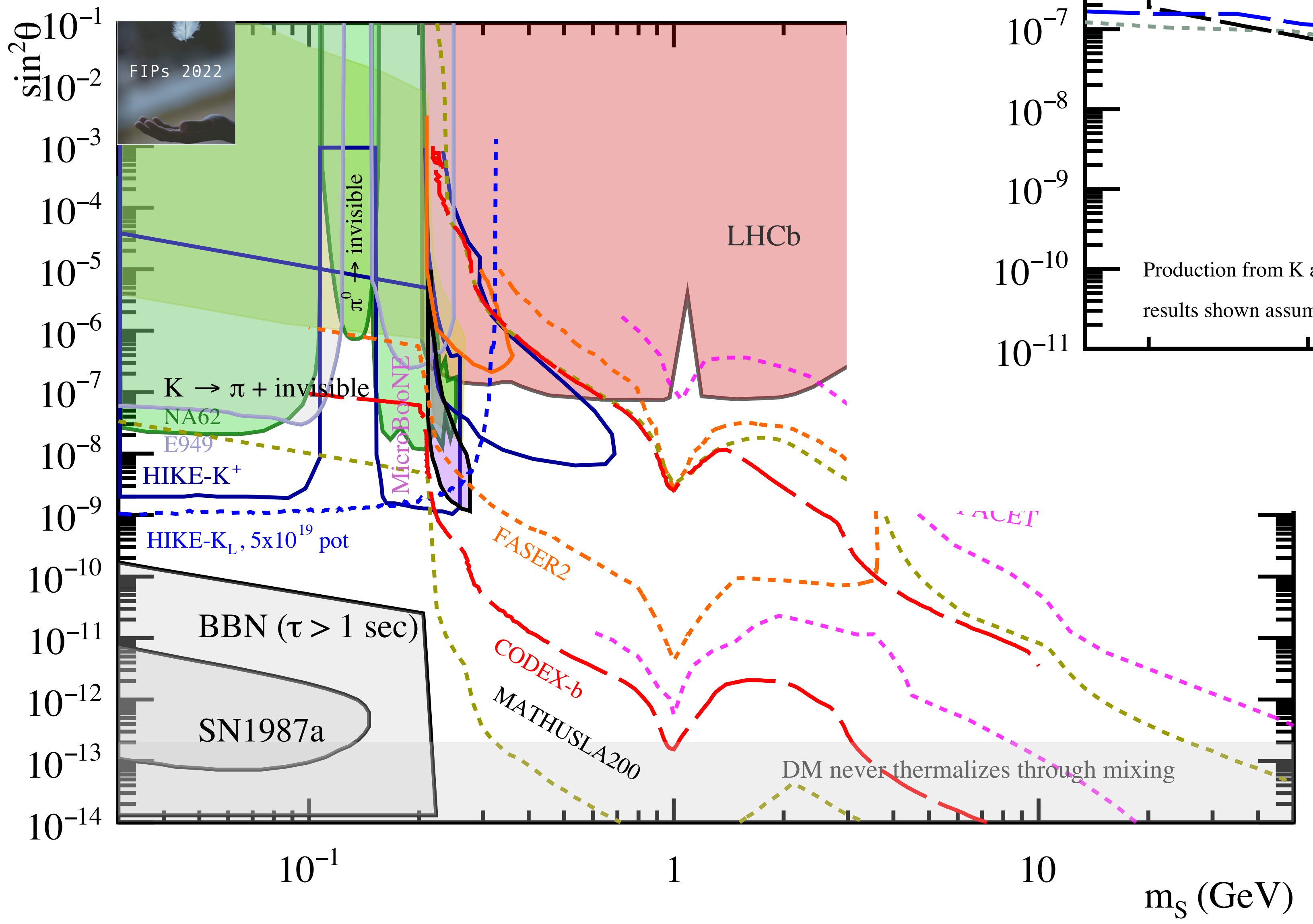


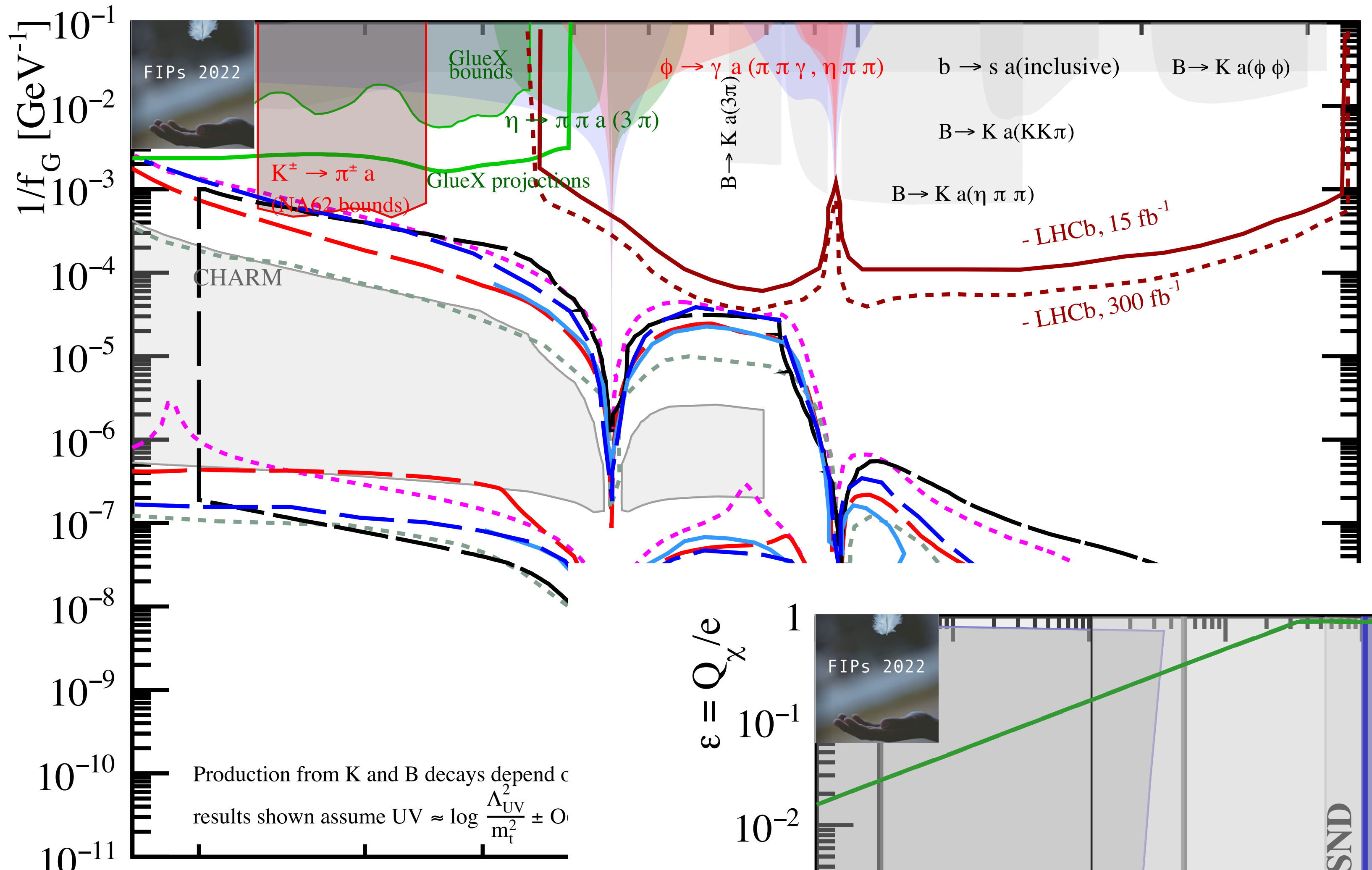
https://xkcd.com/927/

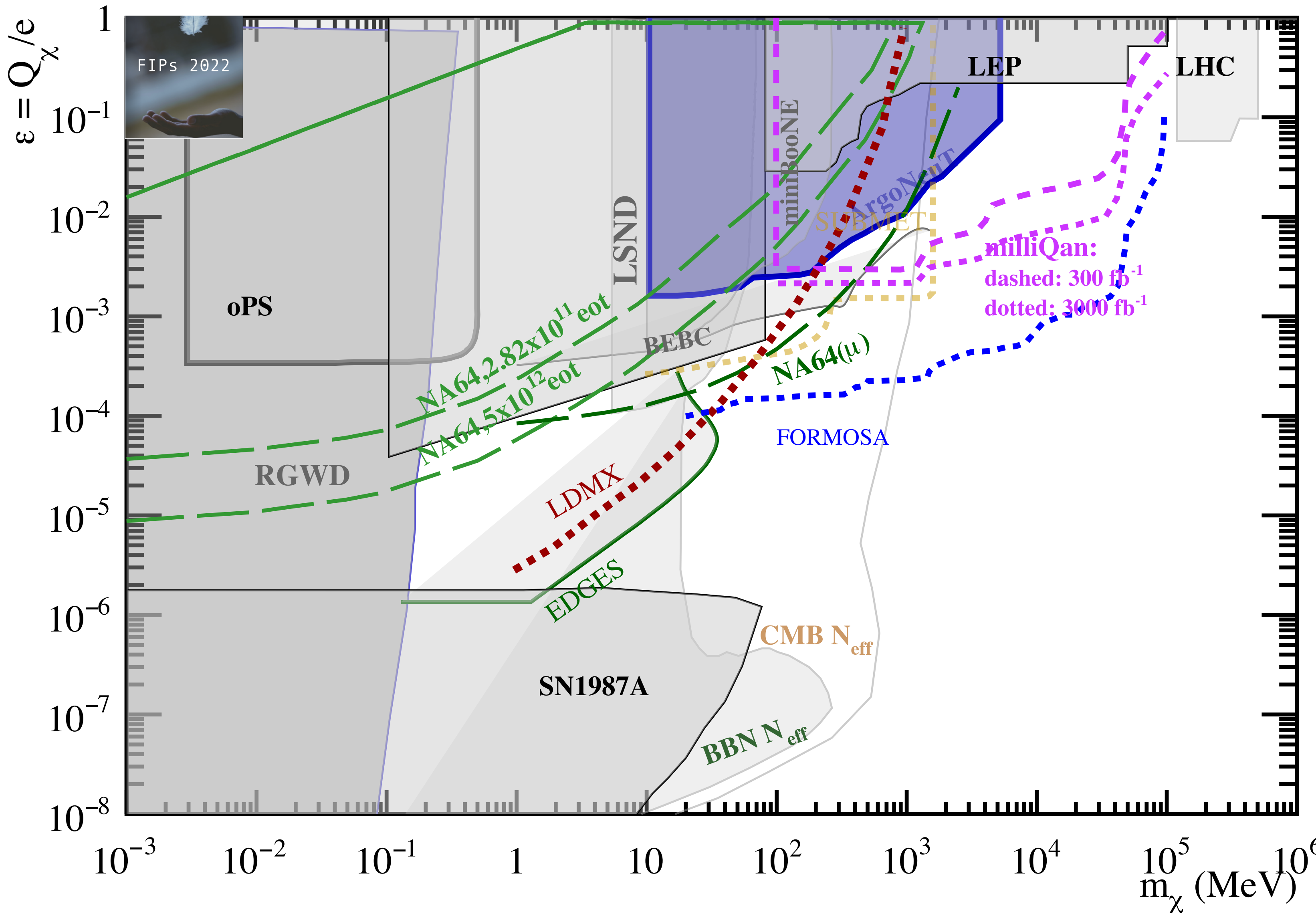
The search for feebly-interacting particles

A plethora of proposed experiments...







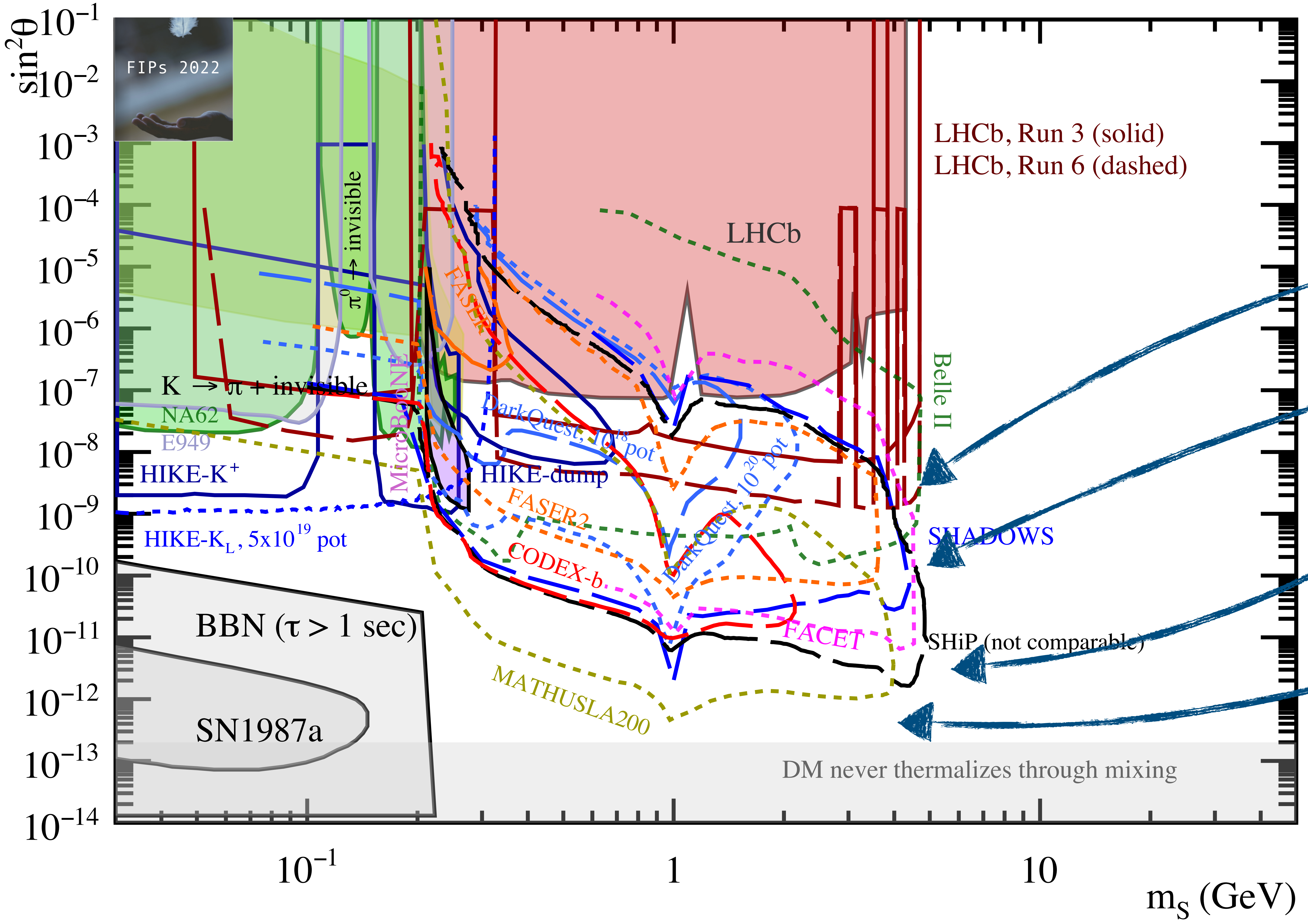


[2305.01715]

The search for feebly-interacting particles

... with one problem

* the specific experiments
don't matter to the discussion



Many discrepancies!

Different formula for decay width

Inclusive description of production

Exclusive description of production

Simplified acceptance

(+ for ALPs: different coupling conventions)

SensCalc

One Mathematica package to rule them all 

- Unified description of the New Physics phenomenology
- Explicit control over all the inputs
  (SM particle spectra, experiment geometry, selection cuts, …)
- Public, hackable code based on a semi-analytical method

SensCalc

One Mathematica package to rule them all 

Implemented facilities & experiments

- SPS: NA62/HIKE (dump), SHiP, SHADOWS, CHARM, BEBC
- Fermilab: DUNE, DUNE-prism, DarkQuest
- LHC: FASER/FASER2/FASERv/FASERv2/ FASER2-FPF, SND@LHC/advSND, FACET, MATHUSLA, CODEX-b, ANUBIS (shaft or ceiling)
- FCC-hh: equivalents of the LHC experiments + DELIGHT, FOREHUNT

Implemented models

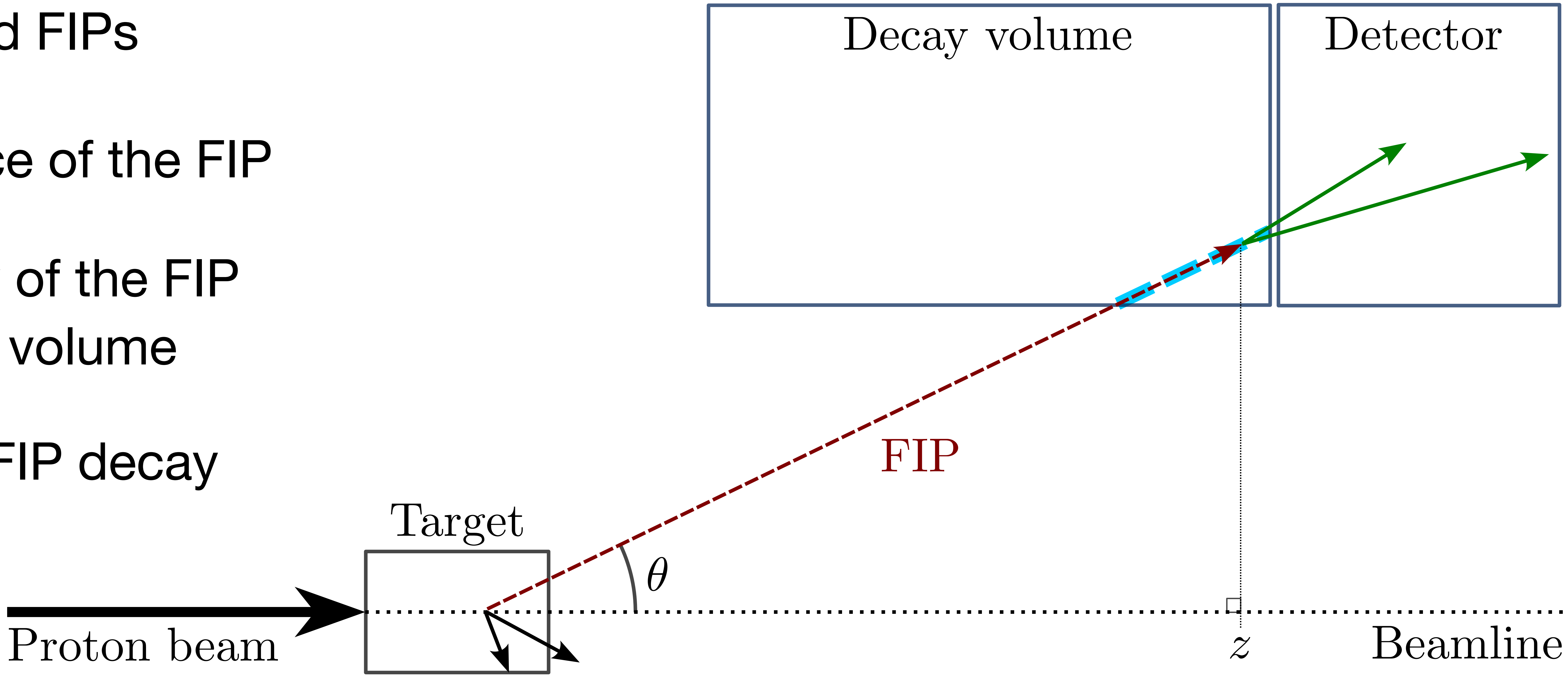
- Dark photons
- Dark scalars (mixing & quartic coupling)
- HNLs (with arbitrary mixing pattern)
- ALPs (coupled to gluons, photons, fermions)
- Anomaly-free U(1) mediators

Semi-analytic estimate

Experimental setup & naive estimate

$$N_{\rm ev} \sim N_{\rm prod} \cdot \epsilon_{\rm FIP} \cdot \langle P_{\rm decay} \rangle \cdot \epsilon_{\rm decay}$$

- $N_{\rm prod}$ = number of produced FIPs
- $\epsilon_{\rm FIP}$ = geometric acceptance of the FIP
- $\langle P_{\rm decay} \rangle$ = mean probability of the FIP decaying within the fiducial volume
- $\epsilon_{\rm decay}$ = acceptance of the FIP decay products



Semi-analytic estimate

Precise estimate

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

- $N_{\text{prod}}^{(i)}, f^{(i)}(\theta, E)$ = total number of produced FIPs & their distribution in $\theta - E$ (for a given production mechanism (i))
- ϵ_{az} = azimuthal acceptance for the FIP to decay within the decay volume
- $\frac{dP_{\text{dec}}}{dz} = \frac{1}{\cos(\theta)c\tau\sqrt{\gamma^2 - 1}} \exp\left[-\frac{z}{(\cos(\theta)c\tau\sqrt{\gamma^2 - 1})}\right]$ = differential decay probability for the FIP
- ϵ_{dec} = acceptance of the FIP decay products
- ϵ_{rec} = reconstruction efficiency (**optional:** must be computed externally)

Semi-analytic estimate

Integrate using Monte-Carlo

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

The integral can be broken down into conditional distributions and computed using Monte-Carlo integration

Semi-analytical $\longleftrightarrow$ Monte-Carlo equivalence

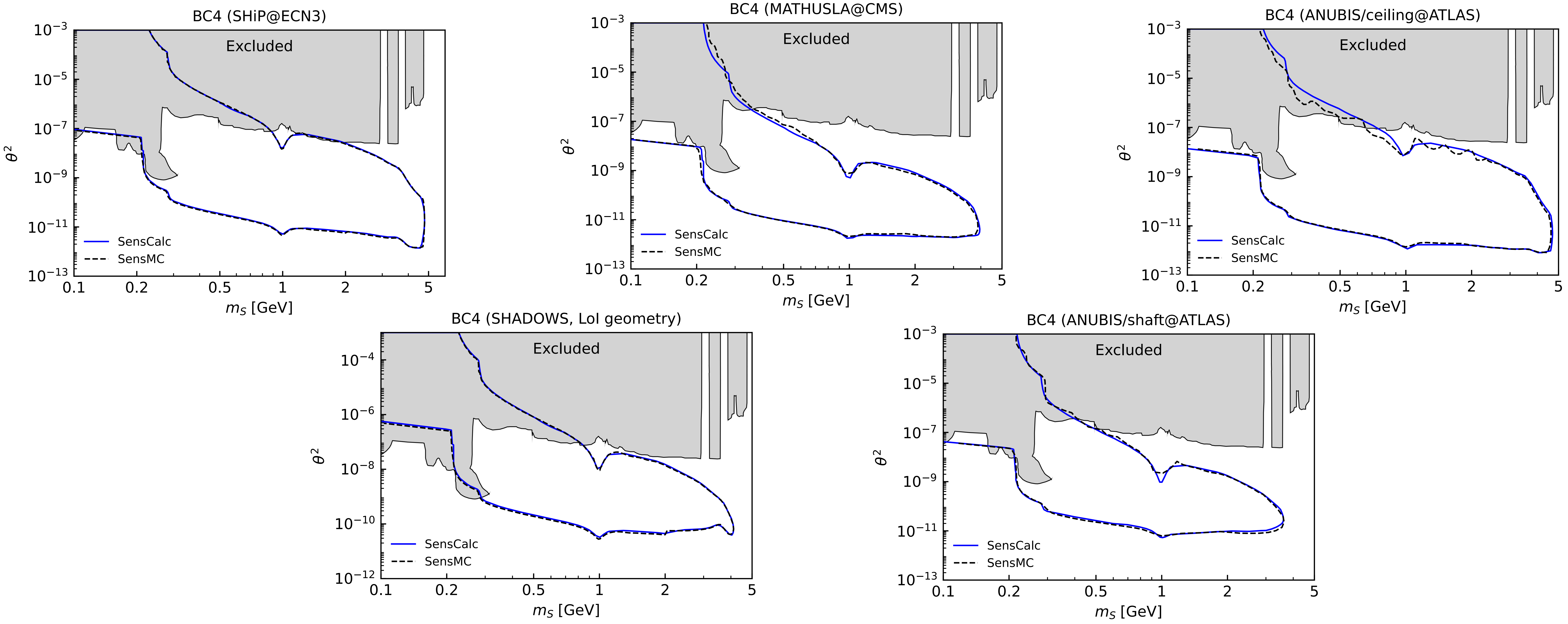
SensCalc
(main package)

SensMC
(for validation, limited functionality)

Semi-analytical estimate

Validation against SensMC (Monte-Carlo)

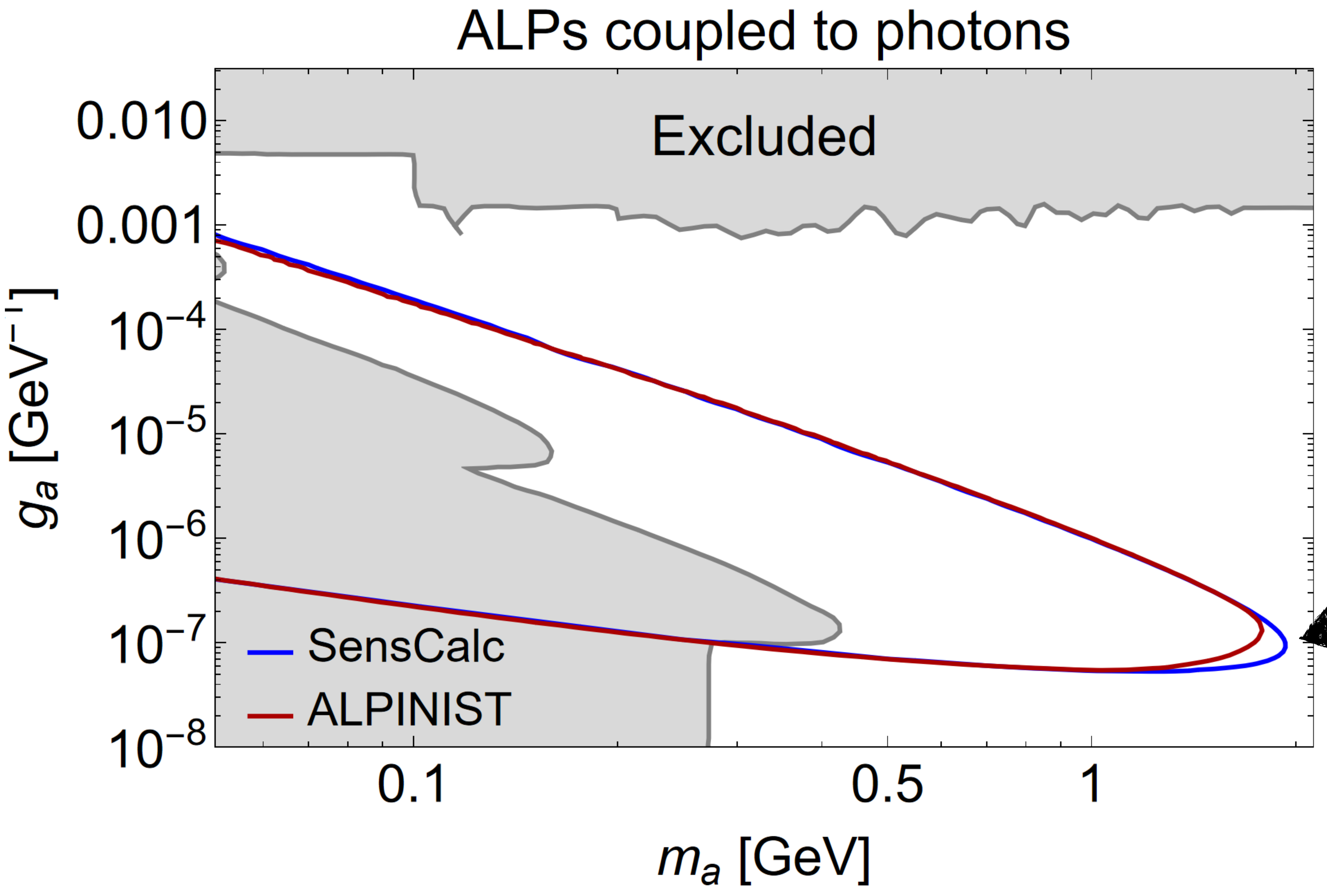
* single-event sensitivity at 90% CL used for validation (i.e. zero background)



Good agreement at the $\sim 10 - 20\,\%$ level despite different code base and inputs

Validation against other packages

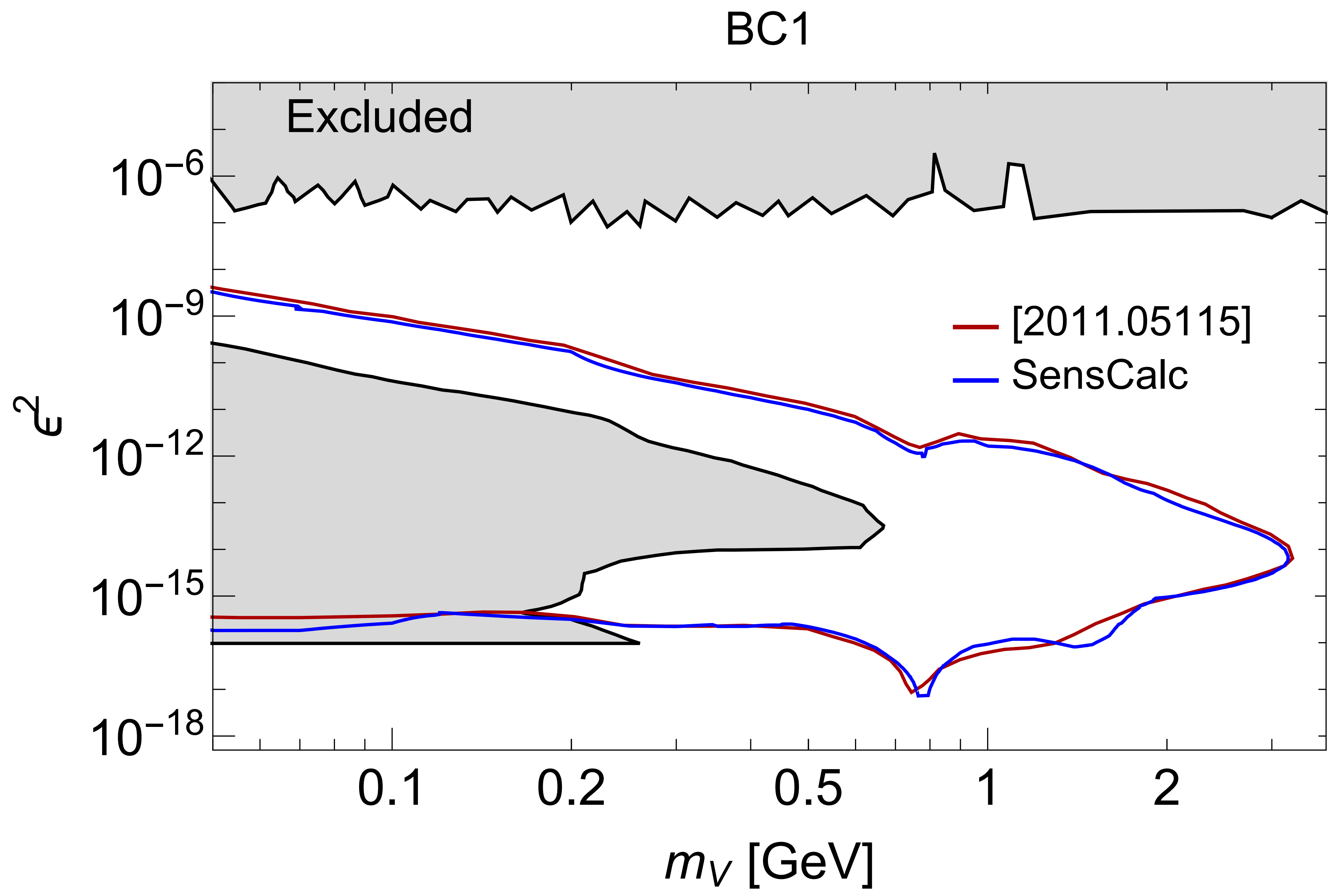
ALPINIST — BC9 (ALPs coupled to photons) — SHiP

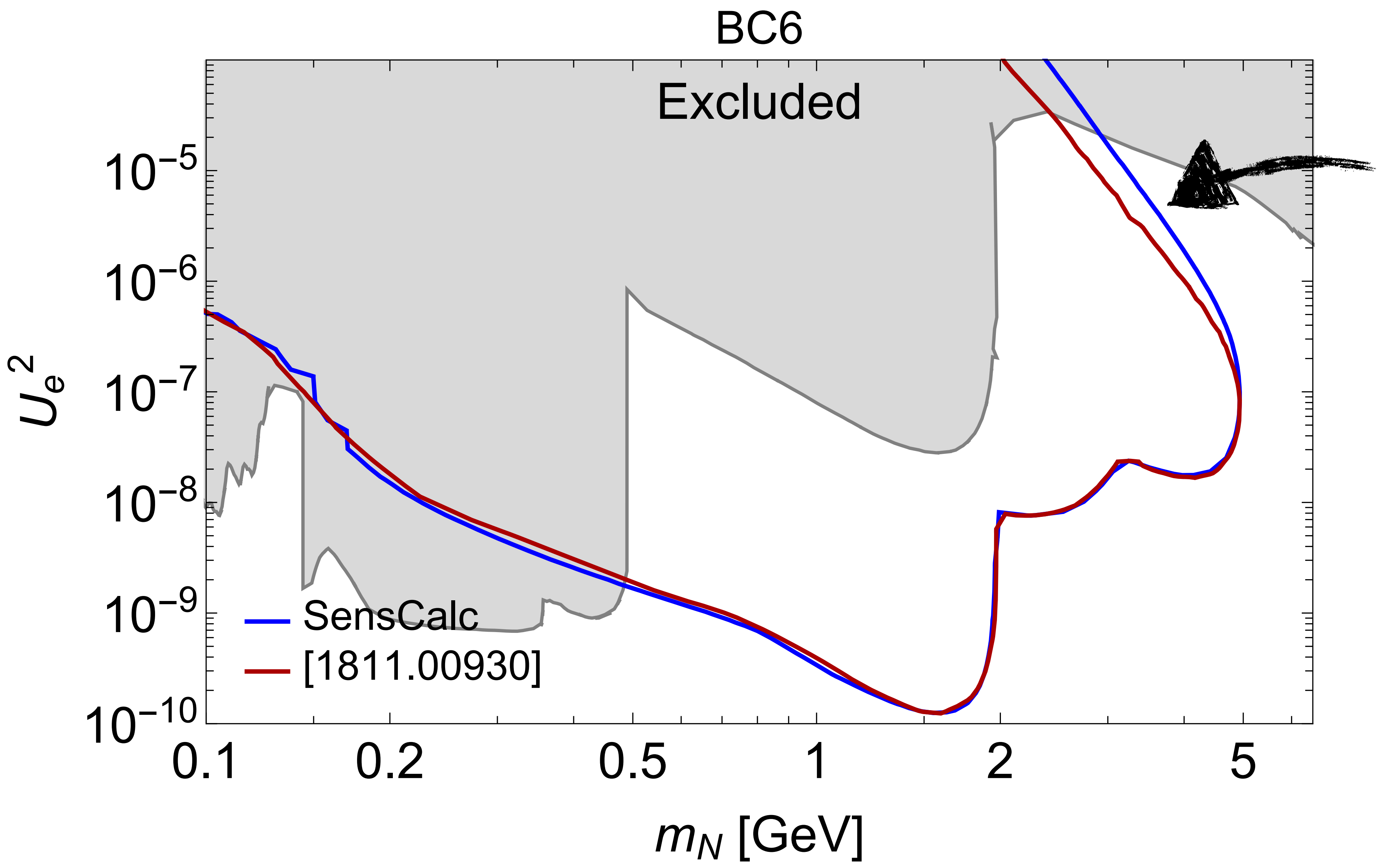


Discrepancy likely caused by slightly different geometries

Validation against other packages

FairShip — BC1 (dark photons) & BC6 (HNLs) — SHiP @ ECN4





Simplified treatment of the upper bound in FairShip

✔

Good agreement despite slightly different phenomenology

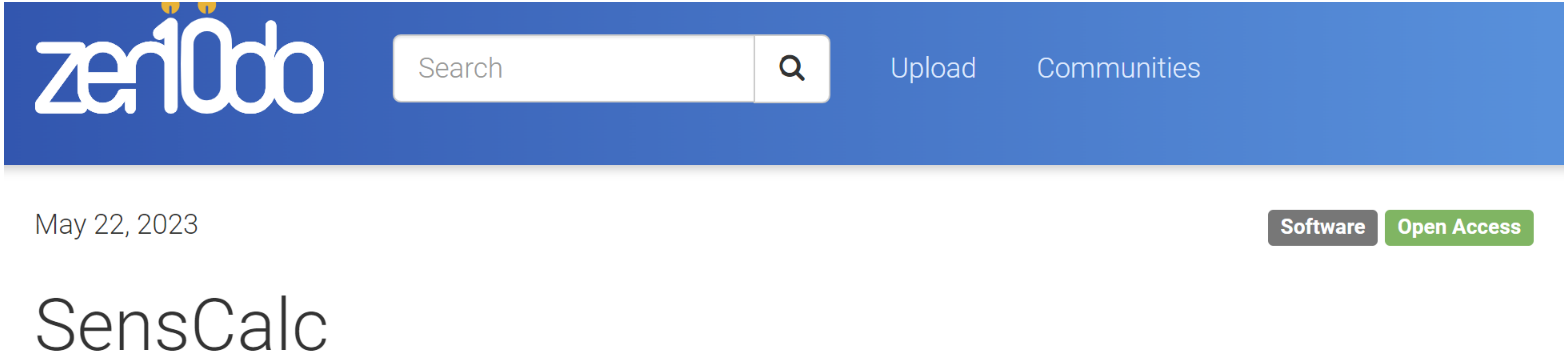
Validation against other packages

And more...

- FORESEE
- The LHCb simulation framework

Running SensCalc

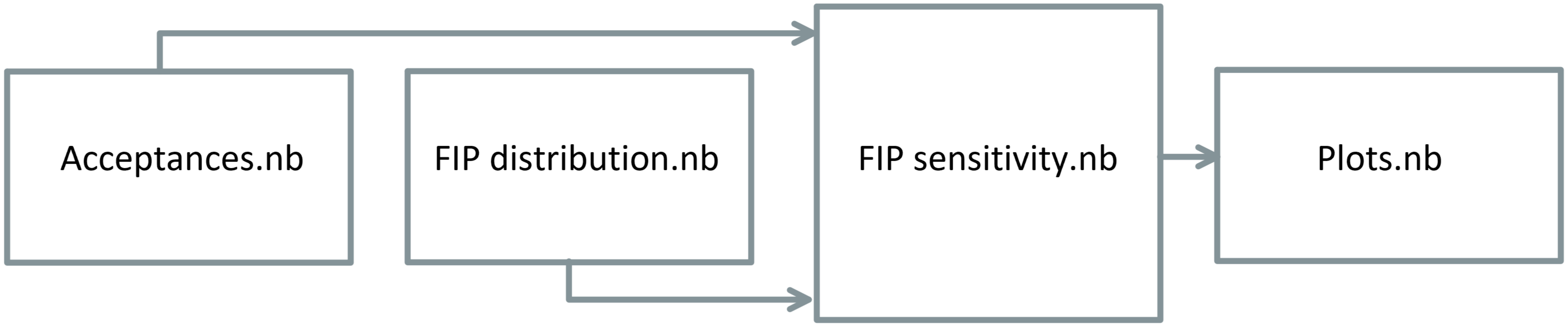
[doi.org/10.5281/zenodo.7957784]



- A set of Mathematica notebooks for computing the signal or sensitivity
- **Input:** experimental setup (geometry, cuts) and distribution of parent particles
- **Output:** tabulated number of events as a function of the mass and coupling (may be converted into exclusion or discovery sensitivities)

Running SensCalc

Modular structure

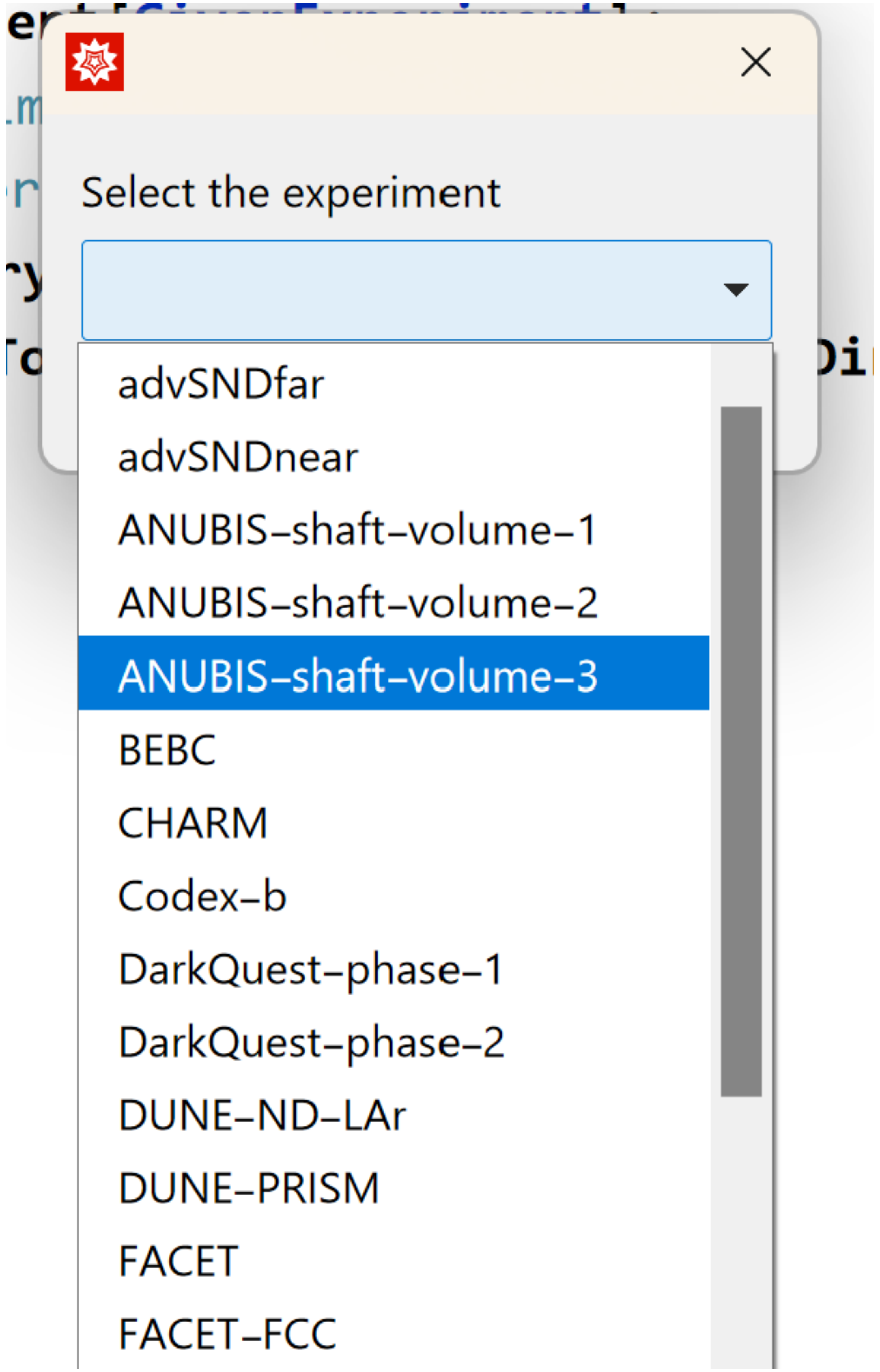


- **Acceptances.nb:** specify the geometry & acceptance criteria $\to \epsilon_{\rm az}, \epsilon_{\rm dec}$
- **FIP distribution.nb:** specify the facility & FIP → FIP distribution
- **FIP sensitivity.nb:** compute the tabulated number of events & sensitivity
- **Plots.nb:** produce the sensitivity plots

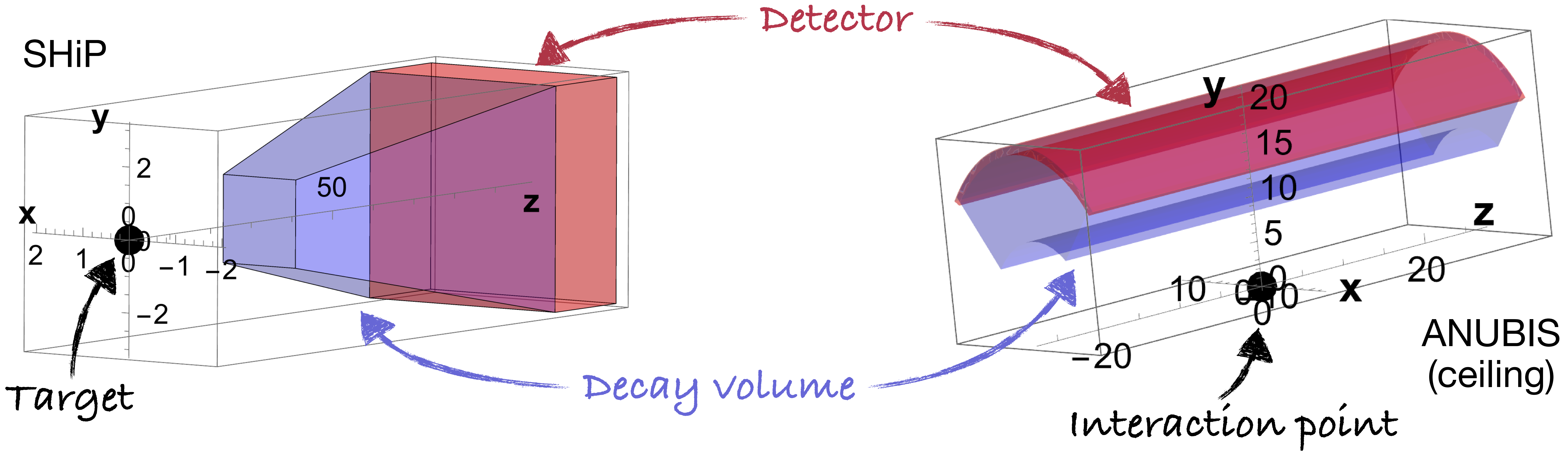
Running SensCalc

Models & experiment selection

- Numerous models & experiments are already implemented and can be easily selected through dialog windows
- New models or geometries can be implemented similarly to the existing ones



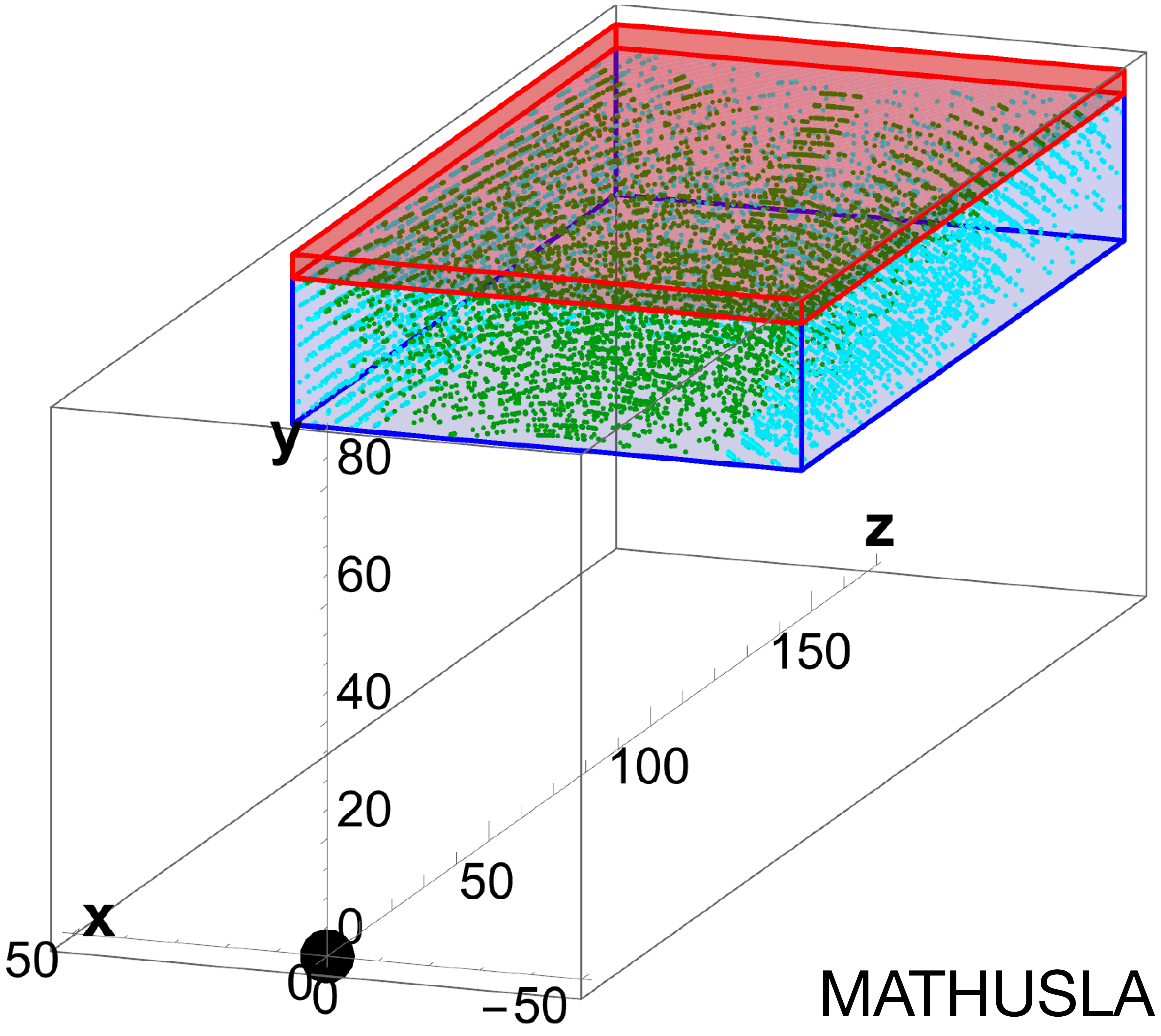
Acceptances.nb



The user specifies:

- the experimental setup (geometry, magnetic field, presence of an EM calorimeter)
- the selection cuts (E, p_{T}, impact parameter, ...)

Acceptances.nb



The notebook produces the grid:

$$m, \theta, E, z, \phi_{\text{inside decay vol.}}, \epsilon_{\text{az}}(\theta, z)$$

FIP trajectories that point:

- (green) towards the end of the detector
- (cyan) elsewhere

Acceptances.nb

The notebook outputs $\epsilon_{\rm dec}(m,\theta,E,z)$ by averaging

$$\epsilon_{\rm dec}(m,\theta,E,z,\phi_{\text{inside decay volume}}, \text{decay channel})$$

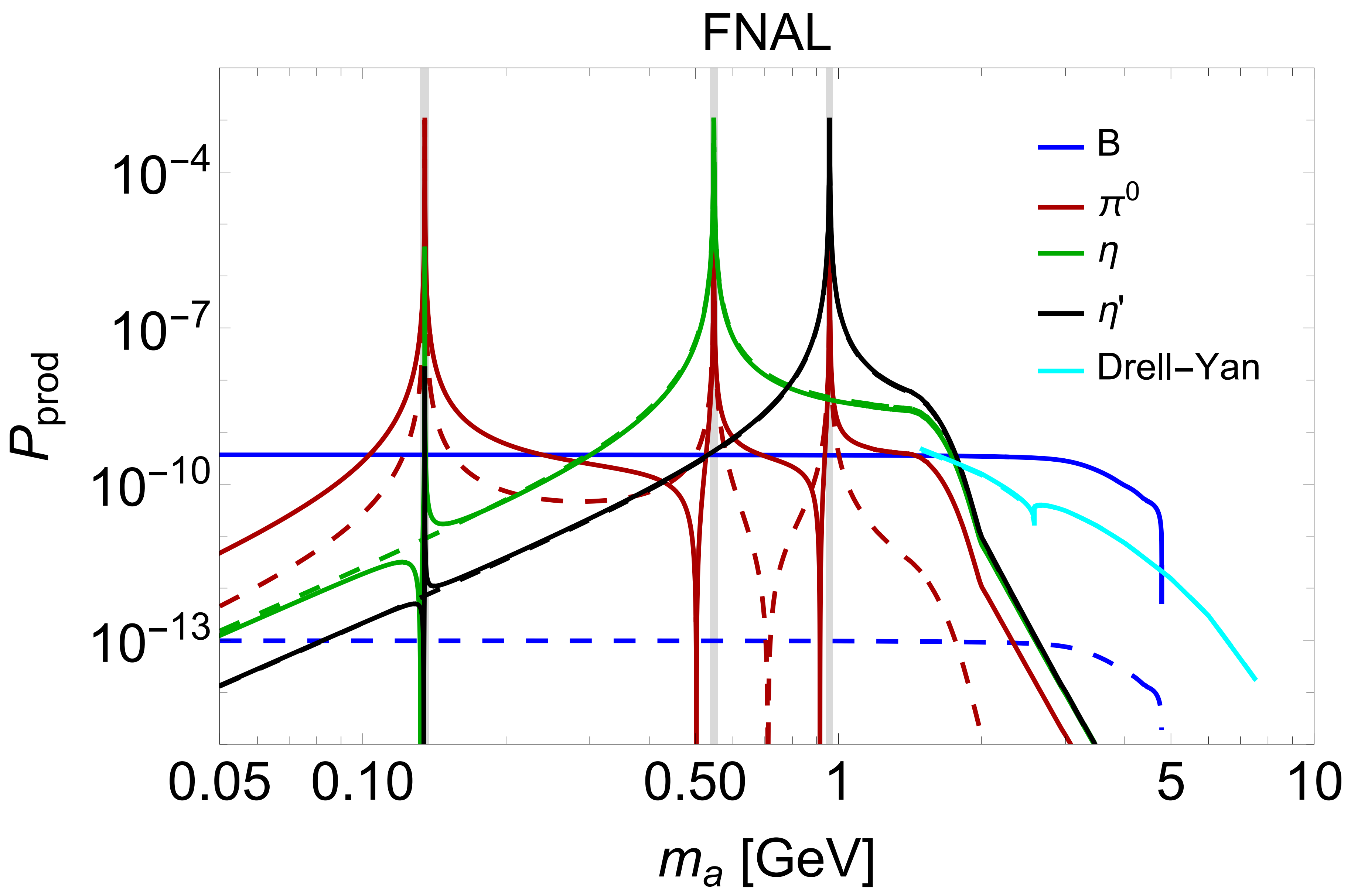
over all decay channels and azimuthal angles ϕ.

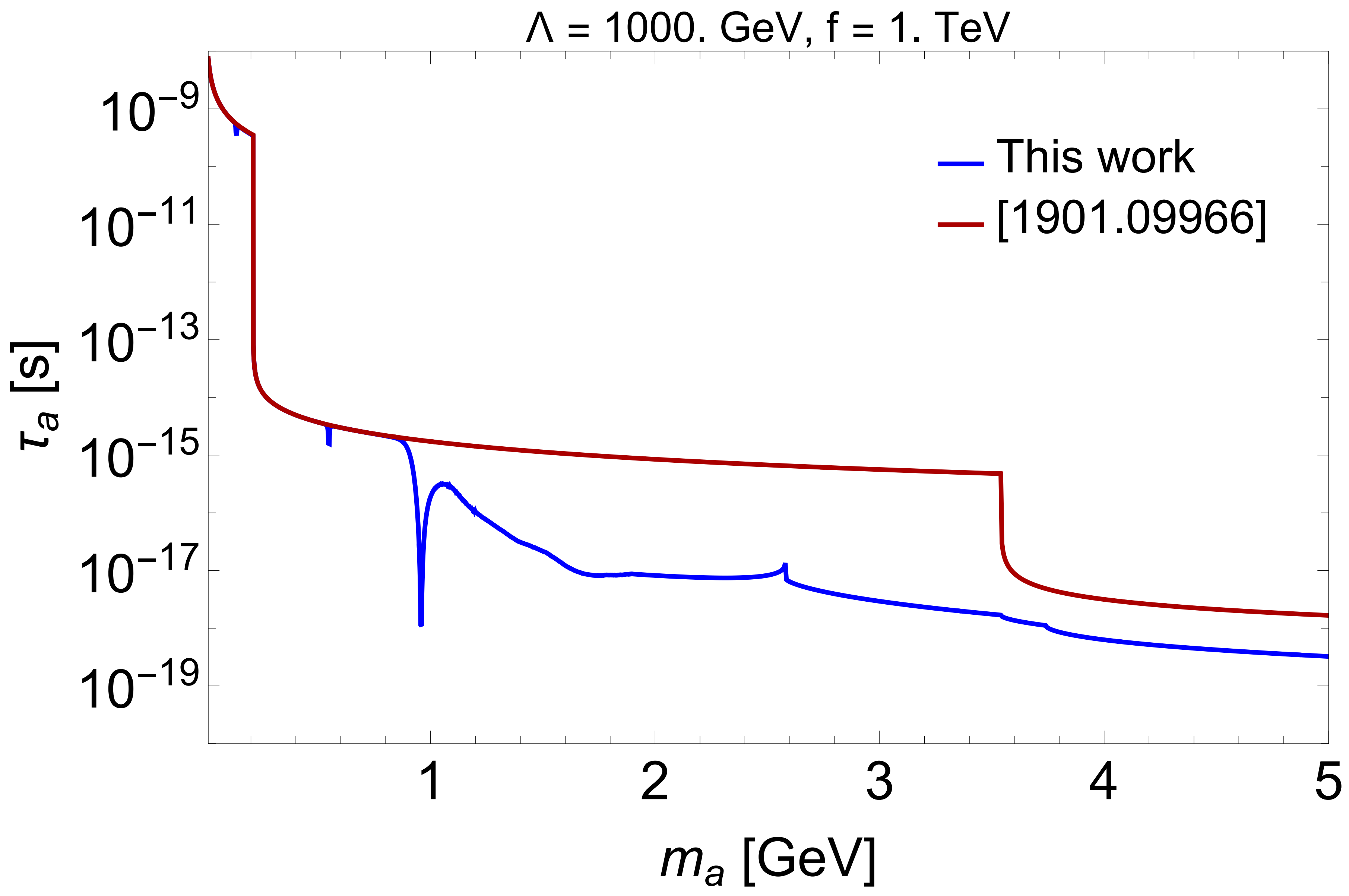
This is done by:

- evaluating the decay phase space using either analytic matrix elements or a phase space pre-generated by MadGraph5_aMC@NLO and Pythia8 (for decays involving jets)
- checking whether the decay products point towards the end of the detector and satisfy the kinematic cuts

Case study: ALP with fermion couplings

Cf. Maksym's upcoming talk at Light Dark World





- 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, M. Ovchynnikov, A. Zaporozhchenko, in preparation]

Case study: ALP with fermion couplings

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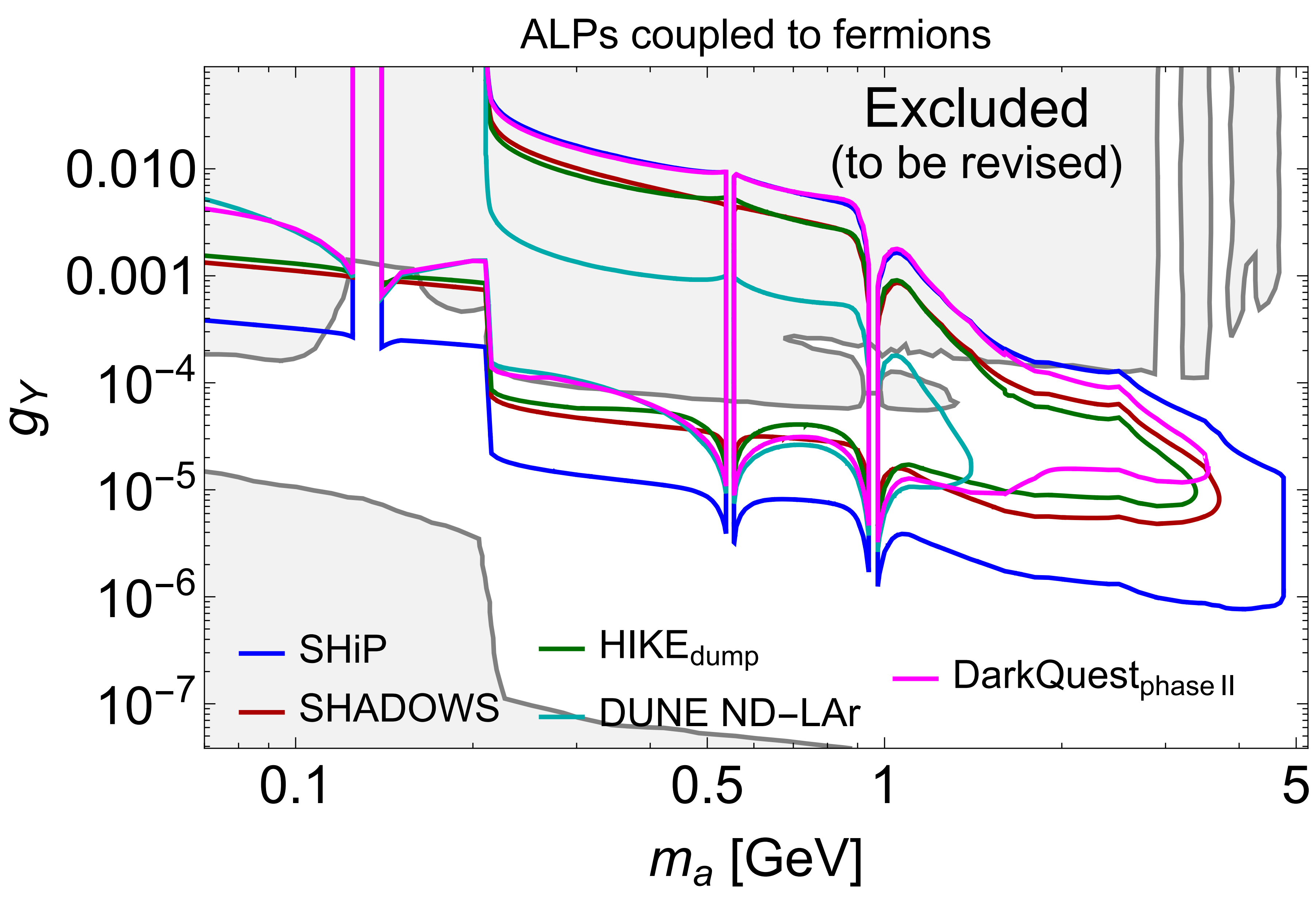

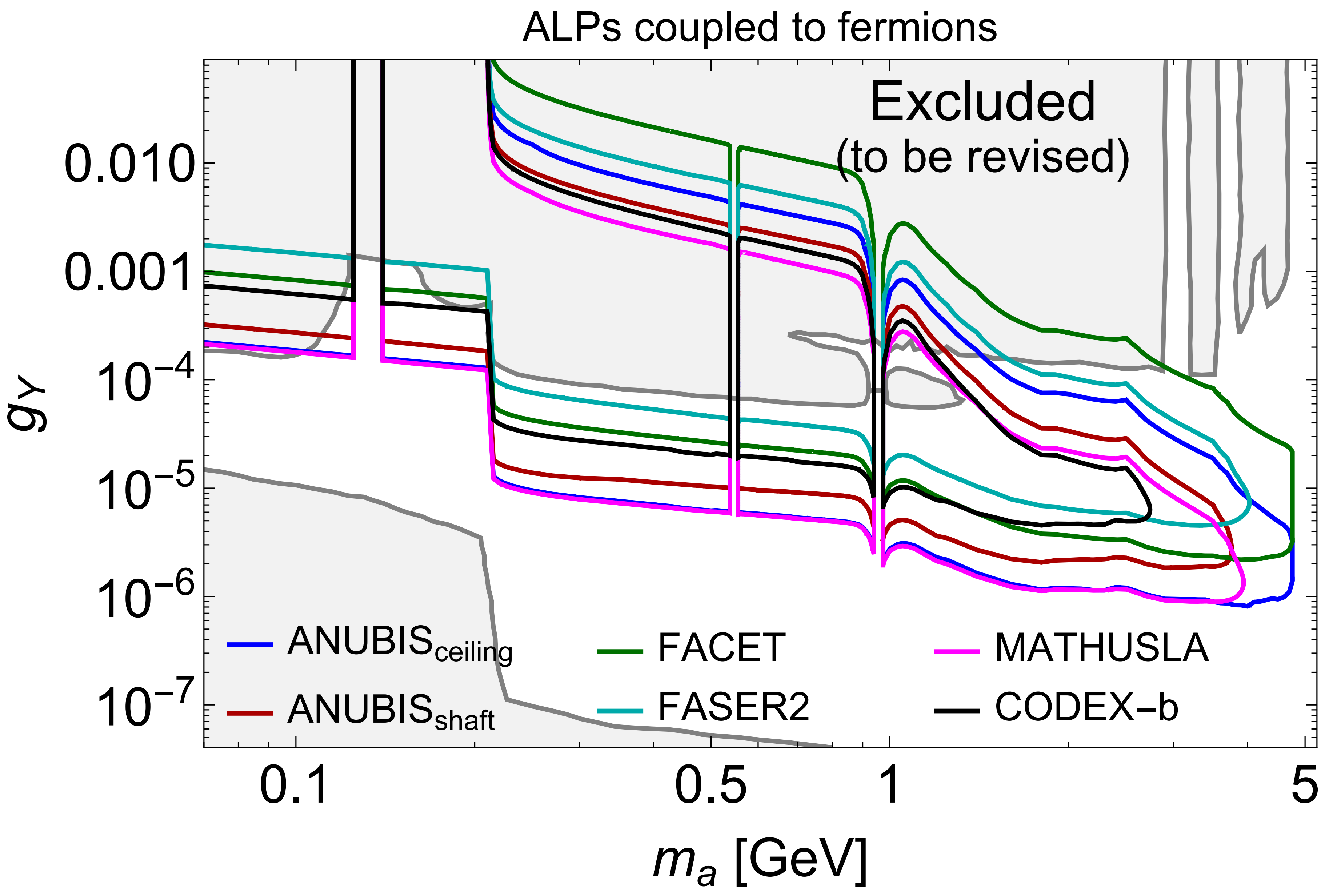

Compared to the PBC description:

- Large ALP masses have become less accessible
- Fermilab experiments feature no significant production from B_s
  Instead, the dominant production mechanism is the mixing with light mesons

Limitations

- The user is responsible for passing the number of signal events corresponding to the desired significance level
  $\rightarrow$ 2.3 for 90% CL, 3 for 95% CL assuming zero background

- SensCalc cannot estimate the expected number of background events

- SensCalc only computes the total number of accepted events
  It does *not* produce detailed event records with the final states
  $\rightarrow$ cannot use binned likelihoods, CL_s, etc...

When to use SensCalc?

✔

- Validate your signal model
- Estimate the sensitivity in a zero-background setting or in a counting experiment (single background bin)
- Consistently compare the sensitivities of multiple experiments
- Compute an optimistic upper bound on your sensitivity

✘

- Produce detailed event records (e.g. to pass to the full simulation)
- Estimate the sensitivity in the background-dominated regime when the shapes of the signal/bkg. matter (e.g. peak searches)

Conclusion

- Summary plots can give a false illusion of consistency and order
- But computing sensitivities is a complicated, messy process:
  - Different phenomenologies and conventions for couplings
  - More-or-less precise signal acceptances and background estimations
- SensCalc helps bring some consistency back
  - Validate your signal model
  - Compare experiments under the same assumptions
  - Regularly updated (new experiments, new ALP phenomenology, etc...)