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EXCELENCIA SEVERO OCHOA

GOBIERNO DE ESPAÑA · MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD · SECRETARÍA DE ESTADO DE INVESTIGACIÓN, DESARROLLO E INNOVACIÓN

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

Jean-Loup Tastet <jean-loup.tastet@uam.es> · Brookhaven Forum · Online · 2023-10-05

Plan

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

Reminder: feebly interacting particle (FIPs)

Class of proposed BSM particles that:

- Address some of the limitations of the SM (ν masses, DM, BAU, ...)
- May be light enough to be produced at current facilities
- Have so far escaped detection due to highly suppressed interactions
- May be so long-lived that they decay outside the current detectors

Examples: dark Higgs, heavy neutral leptons, dark photon, axion-like particles

May 22, 2023

SensCalc

doi.org/10.5281/zenodo.7957784

Maksym Ovchynnikov

Please always switch to the up-to-date version!

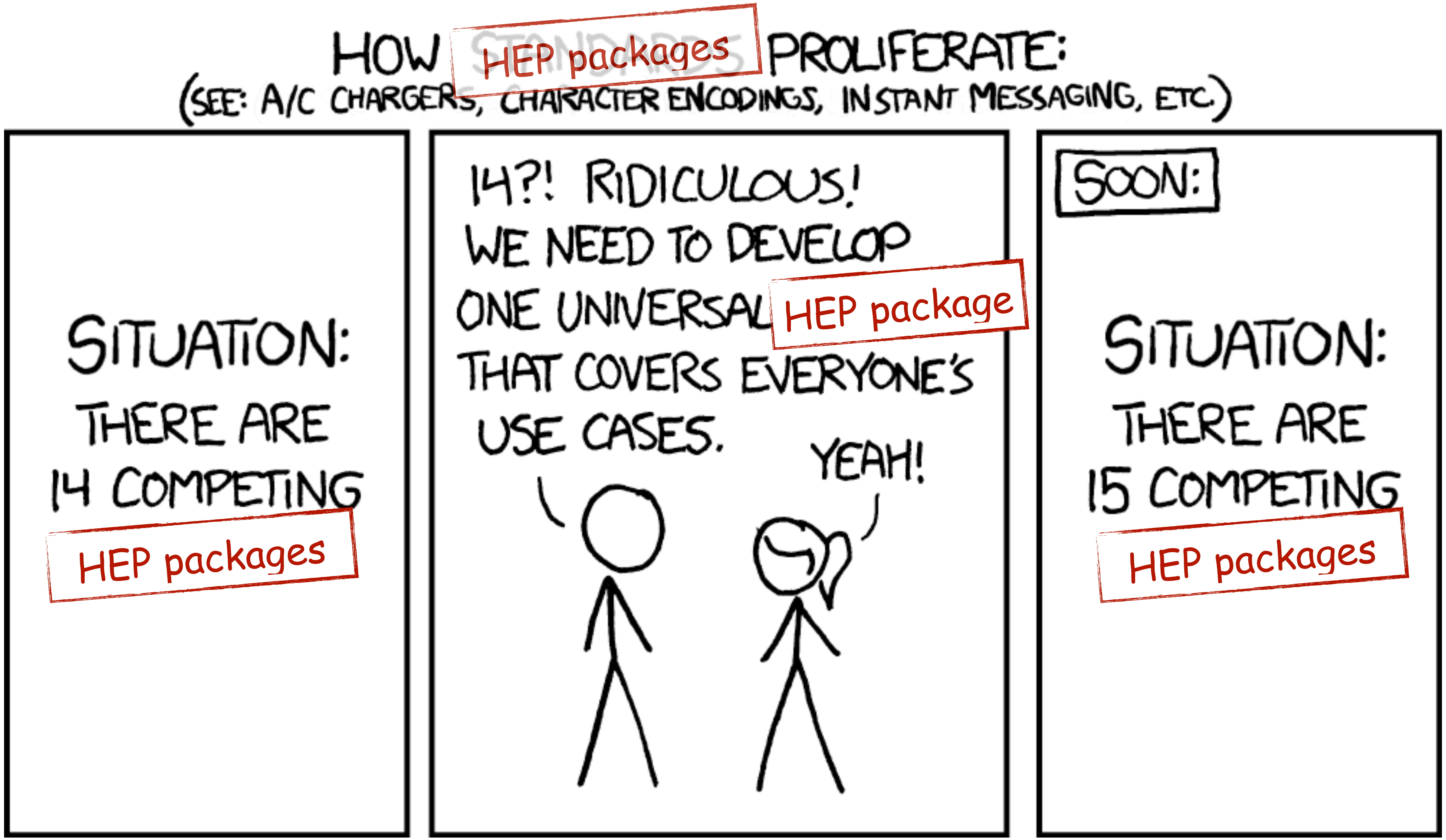
A public and unified evaluator of sensitivities of lifetime frontier experiments to feebly interacting particles. Based on Mathematica. For details, see the accompanying arXiv preprint https://arxiv.org/abs/2305.13383 and the manual included among the files.

Currently, it is a beta version, so there may be bugs. You are very welcome to write about them!

The list of changes compared to the previous version (1.0.4):

- Added the possibility to select the FIP decay channels visible in the given experiment.
- Re-organized the notebook 1. Acceptances.nb. Its structure should now be more transparent.
- Fixed several minor mistakes in the code.
- Added hadronized phase space for all relevant FIP decays into jets

Why one more tool?



https://xkcd.com/927/

Searching for FIPs

A plethora of proposed experiments...

More info here!

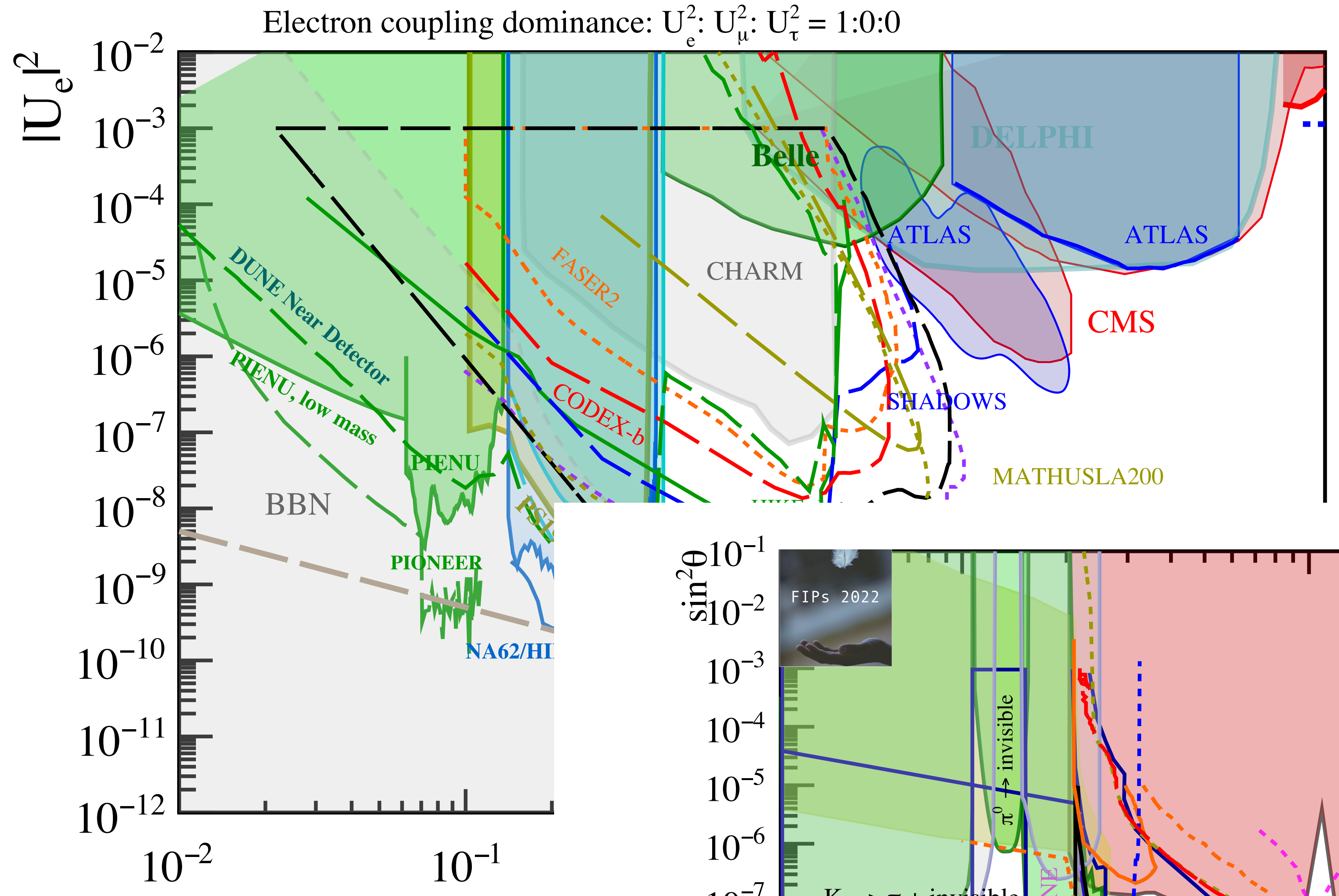
[2305.01715]

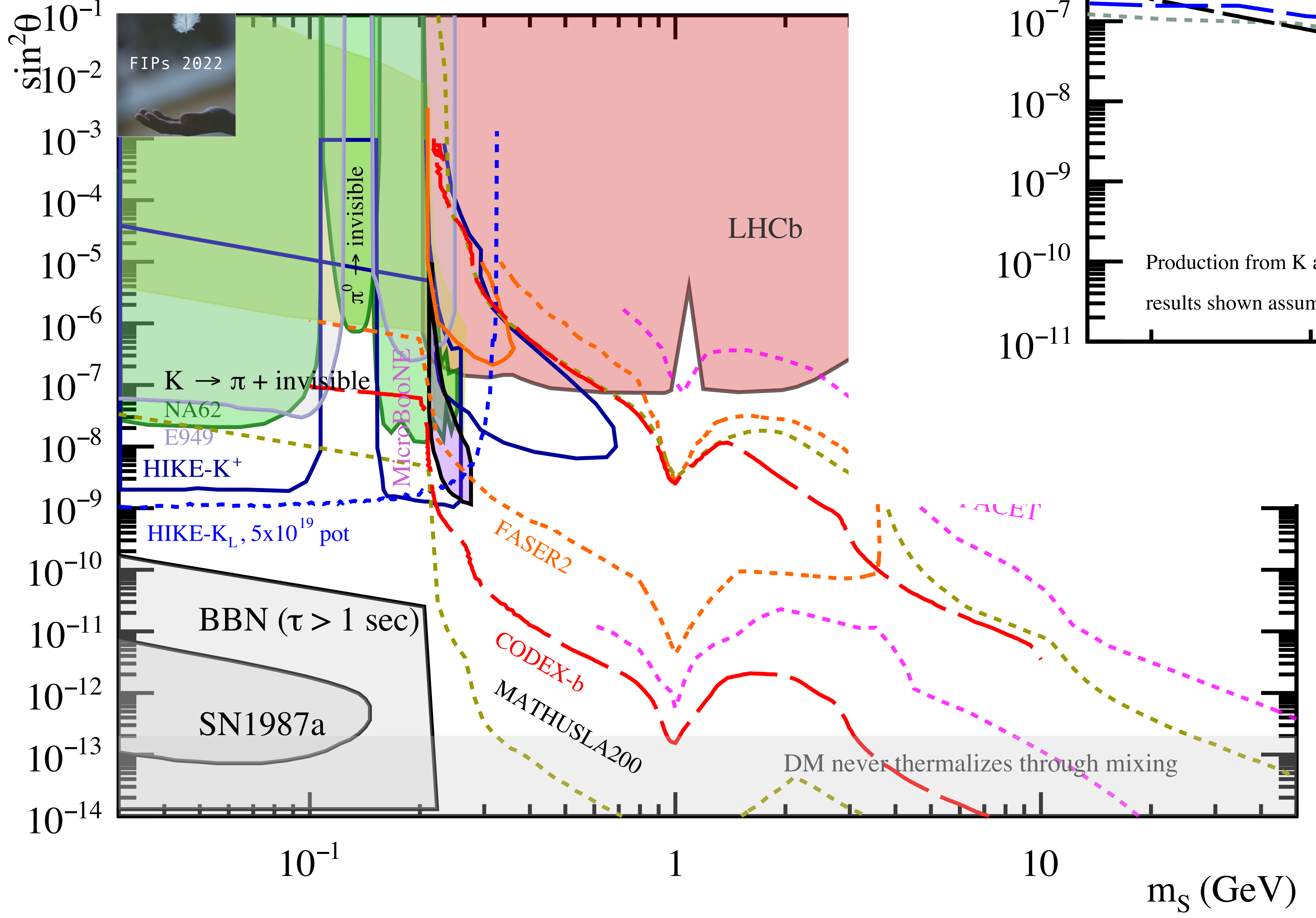
FIPs 2022

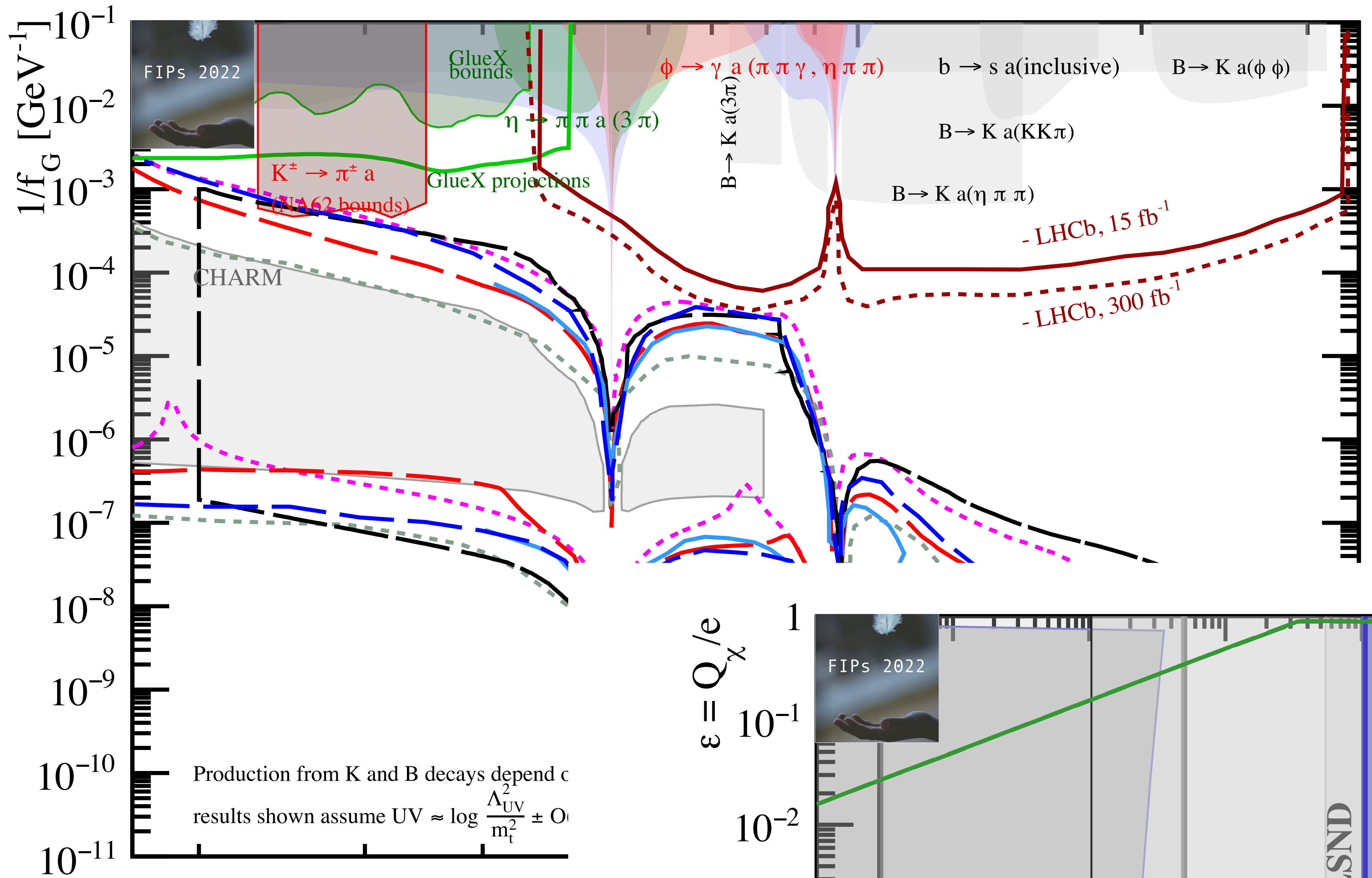
CERN-TH-2023-061
DESY-23-050
FERMILAB-PUB-23-149-PPD
INFN-23-14-LNF
JLAB-PHY-23-3789
LA-UR-23-21432
MITP-23-015

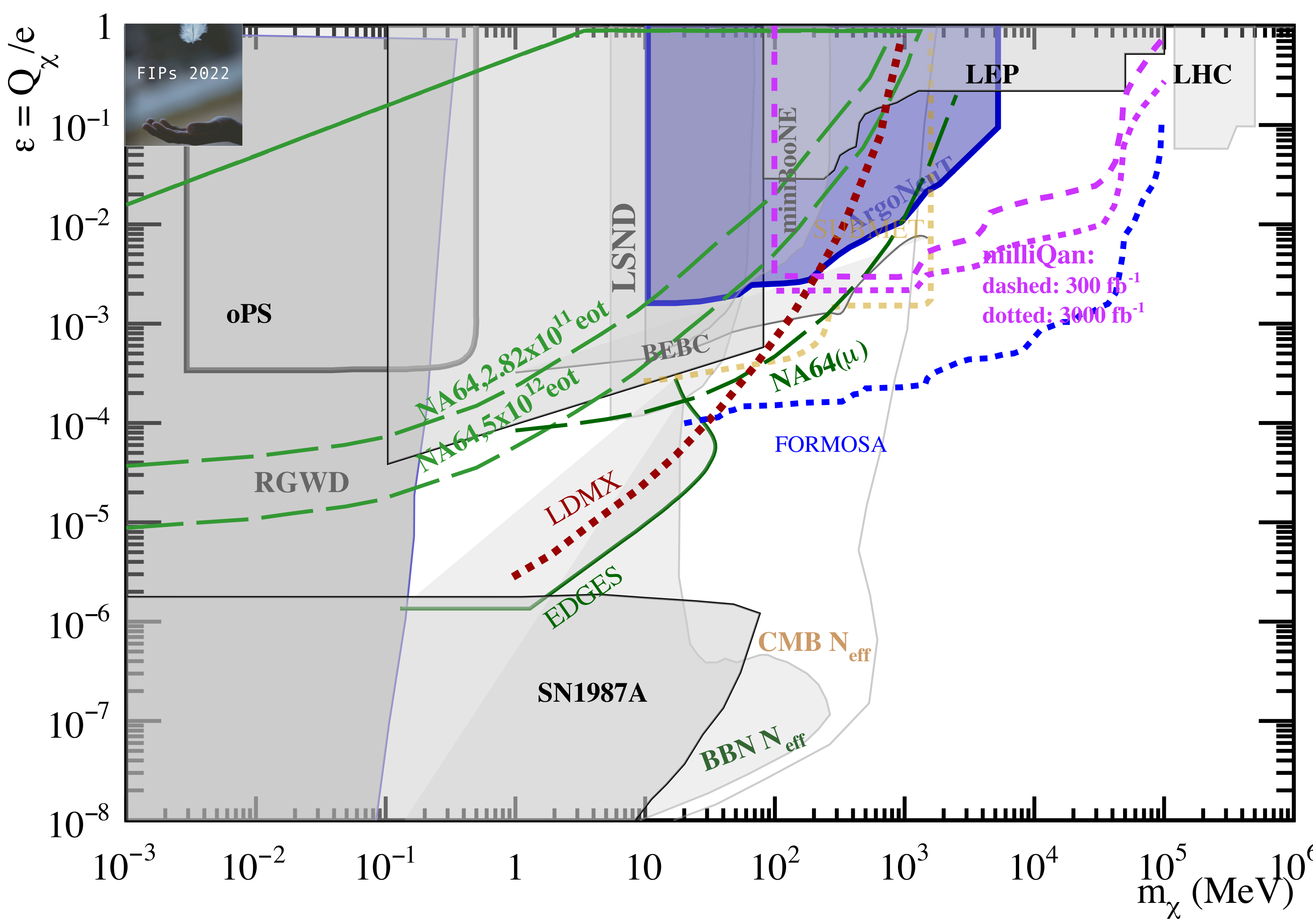
Feebly-Interacting Particles: FIPs 2022 Workshop Report

C. Antel[1], M. Battaglieri[2], J. Beacham[3,a], C. Boehm[4], O. Buchmüller[5], F. Calore[6], P. Carenza[7],
[11], V. Dandoy[12], L. Darmé[13], B. Dey[14], F. F. Deppisch[15],
d[18,a], V. V. Flambaum[19], P. Foldenauer[10], C. Gatti[20],
nzalez-Garcia[22,23,24], S. Gori[25], E. Goudzovski[26],
a[9,30], J. Hajer[31], P. Harris[32], C. Hearty[33], D. Heuchel[34],
r[39], J. Klaric[17,a], F. Kling[34], P. Klose[40], J. Knolle[41],
franchi[20,a,*], L. Li[45], A. Lindner[34], J. Lopez-Pavon[46,a],
Milstead[49], I. Oceano[34], C. A. J. O'Hare[4], A. Paoloni[20],
elov[35,36,37], R. Pöttgen[53], M. Raggi[54], G. Ripellino[55]
er-Rembold[56], J. Shelton[57], N. Song[58], C. Sun[59],
N. Tran[62], N. Trevisani[63], S. Ulmer[64,65], S. Urrea[46],
Y. Y. Wong[19], C. Zorbilmez[69], K. Zurek[18]





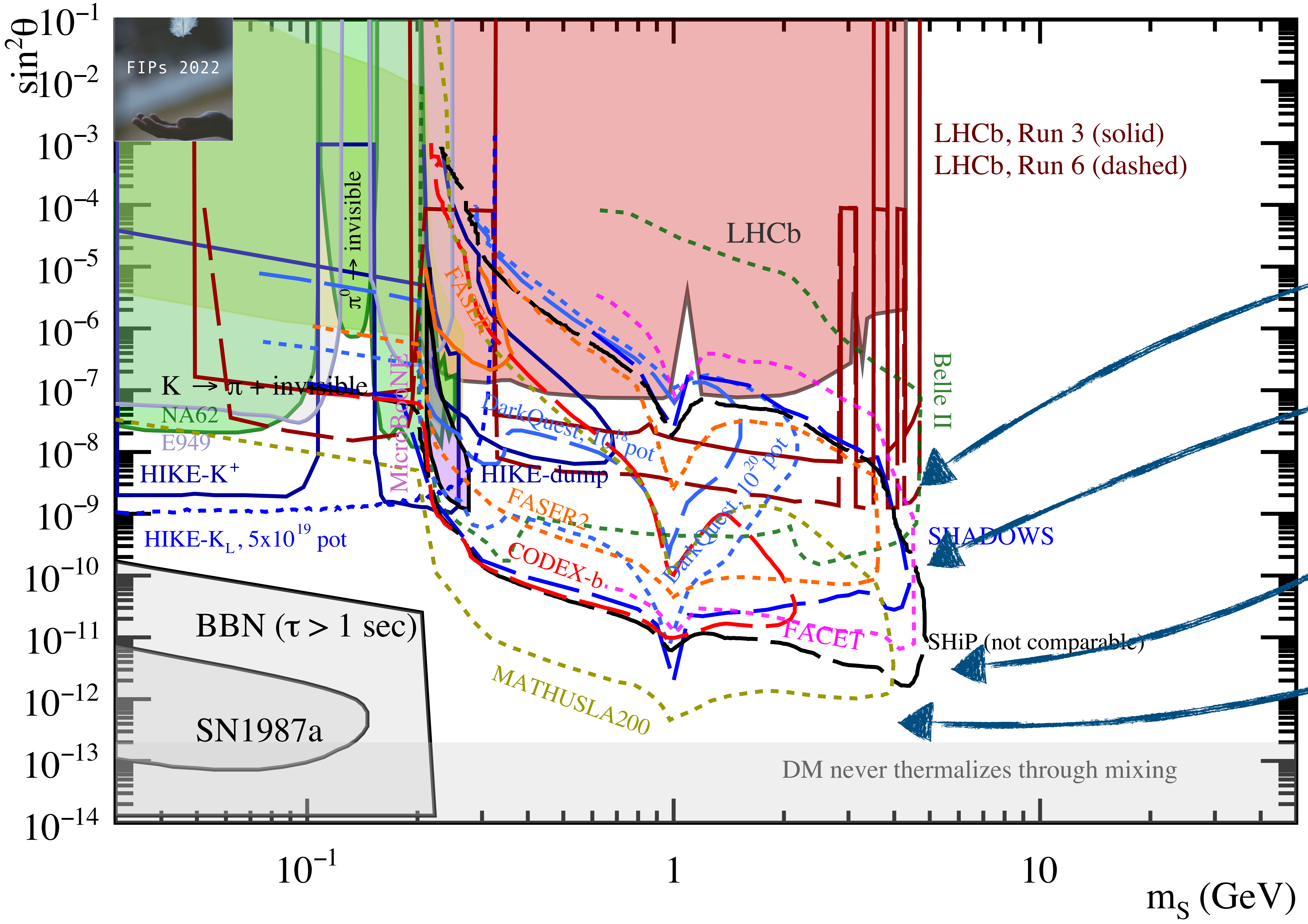




Searching for FIPs

... 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 FIP phenomenologies
- The user retains control over all the inputs
  (SM particle spectra, experiment geometry, selection cuts, ...)
- Public, hackable code based on a transparent, 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/FASERν/FASERν2/ FASER2-FPF, SND@LHC/advSND, FACET, MATHUSLA, CODEX-b, ANUBIS (shaft or ceiling)
- FCC-hh: equivalents of the LHC experiments + DELIGHT, FOREHUNT

Implemented models

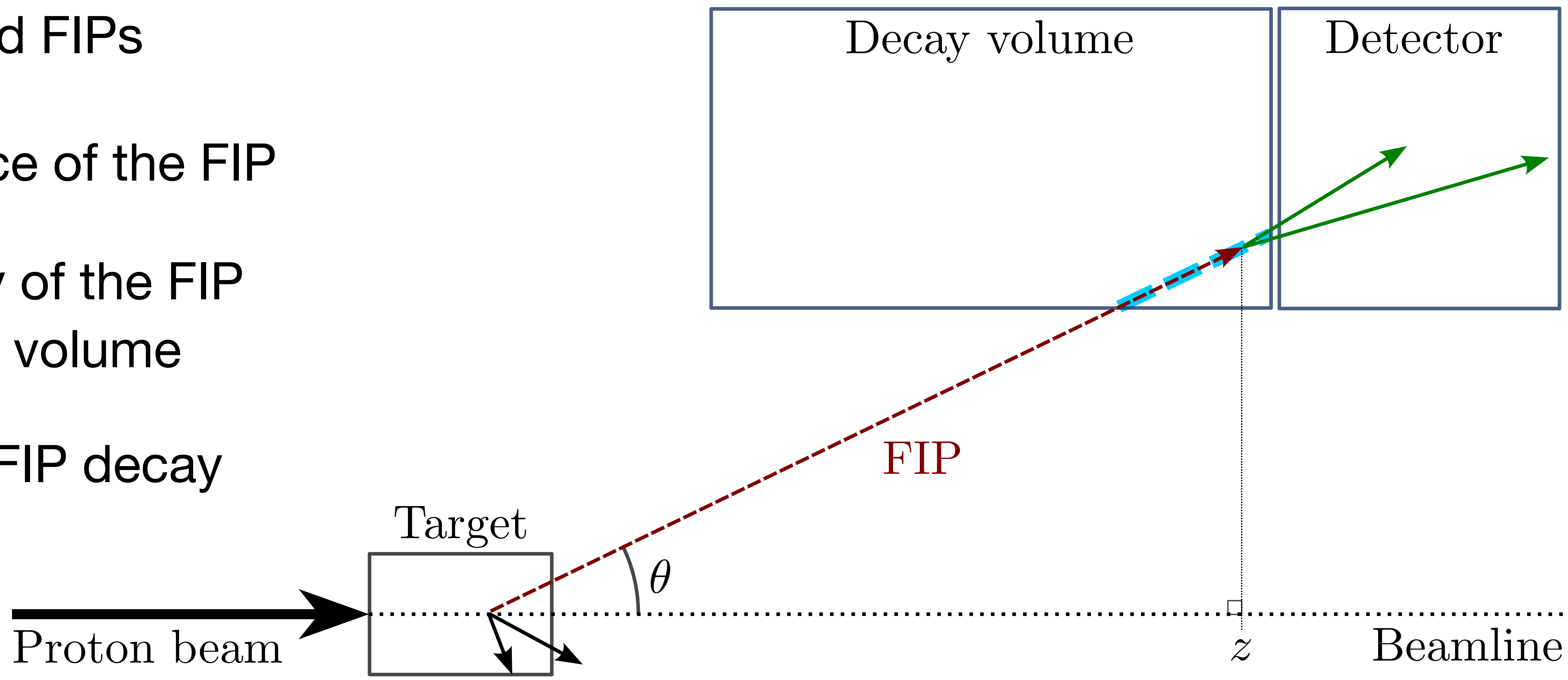
- Dark photons
- Dark scalars (mixing & quartic coupling)
- HNLs (with arbitrary mixing pattern)
- ALPs (coupled to gluons, photons, fermions)
- Anomaly-free U(1) mediators

Semi-analytic estimate

Experimental setup & naive estimate

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

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

Alternatively: integrate using Monte-Carlo for validation

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

Semi-analytical $\longleftrightarrow$ (weighted) Monte-Carlo equivalence

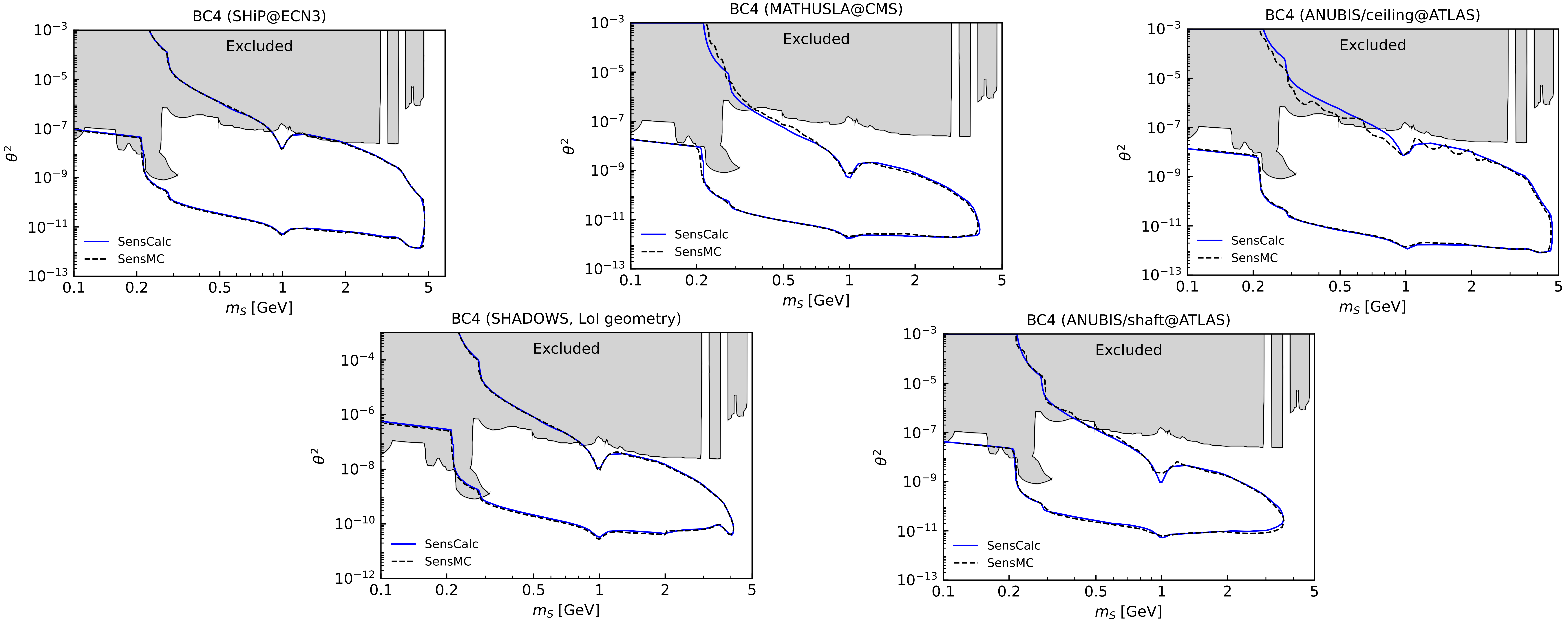
SensCalc
(main package)

SensMC
(for validation only, limited functionality)

Semi-analytical estimate

Validation against SensMC (Monte-Carlo)

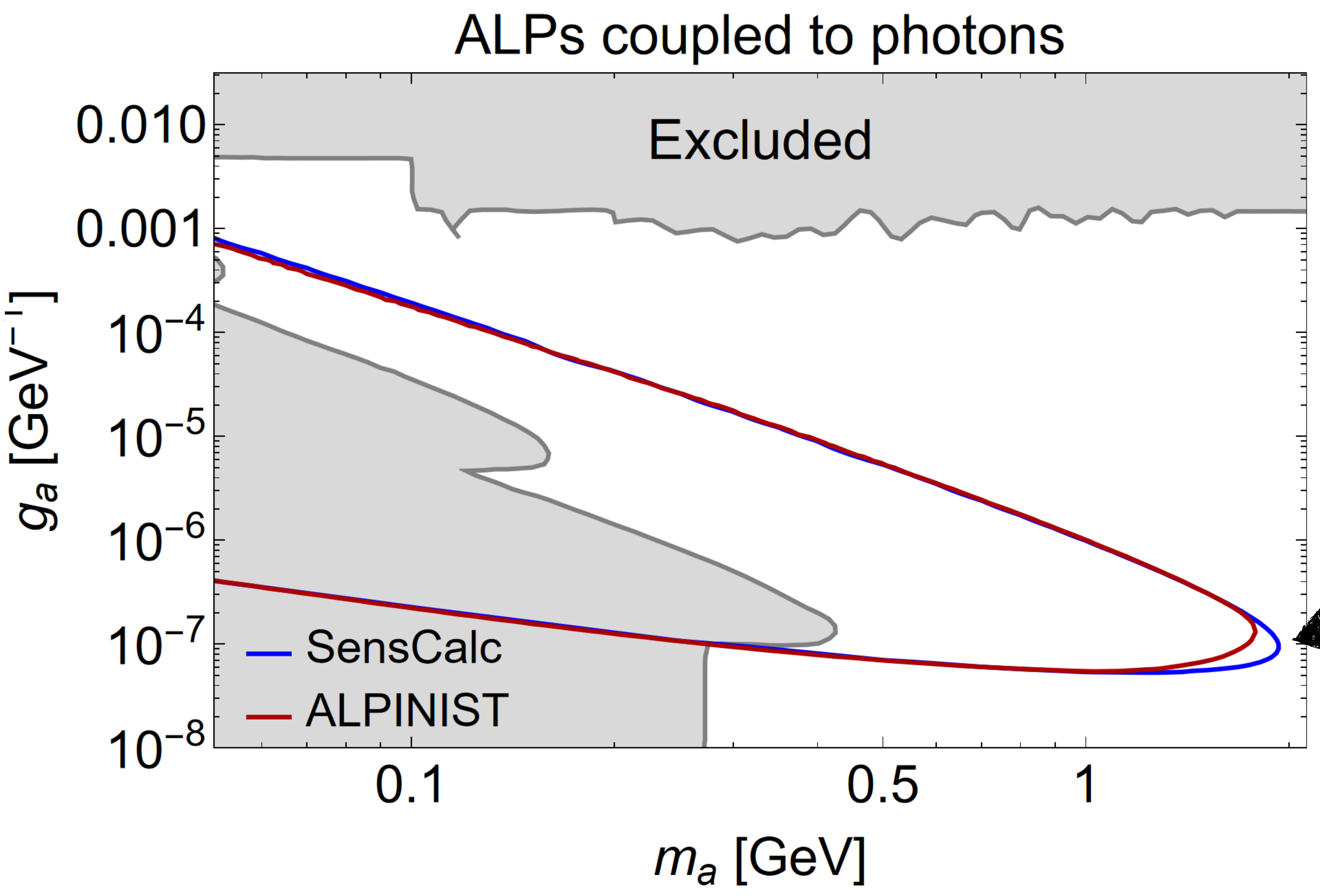
* single-event sensitivity at 90% CL used for validation (i.e. zero background)



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

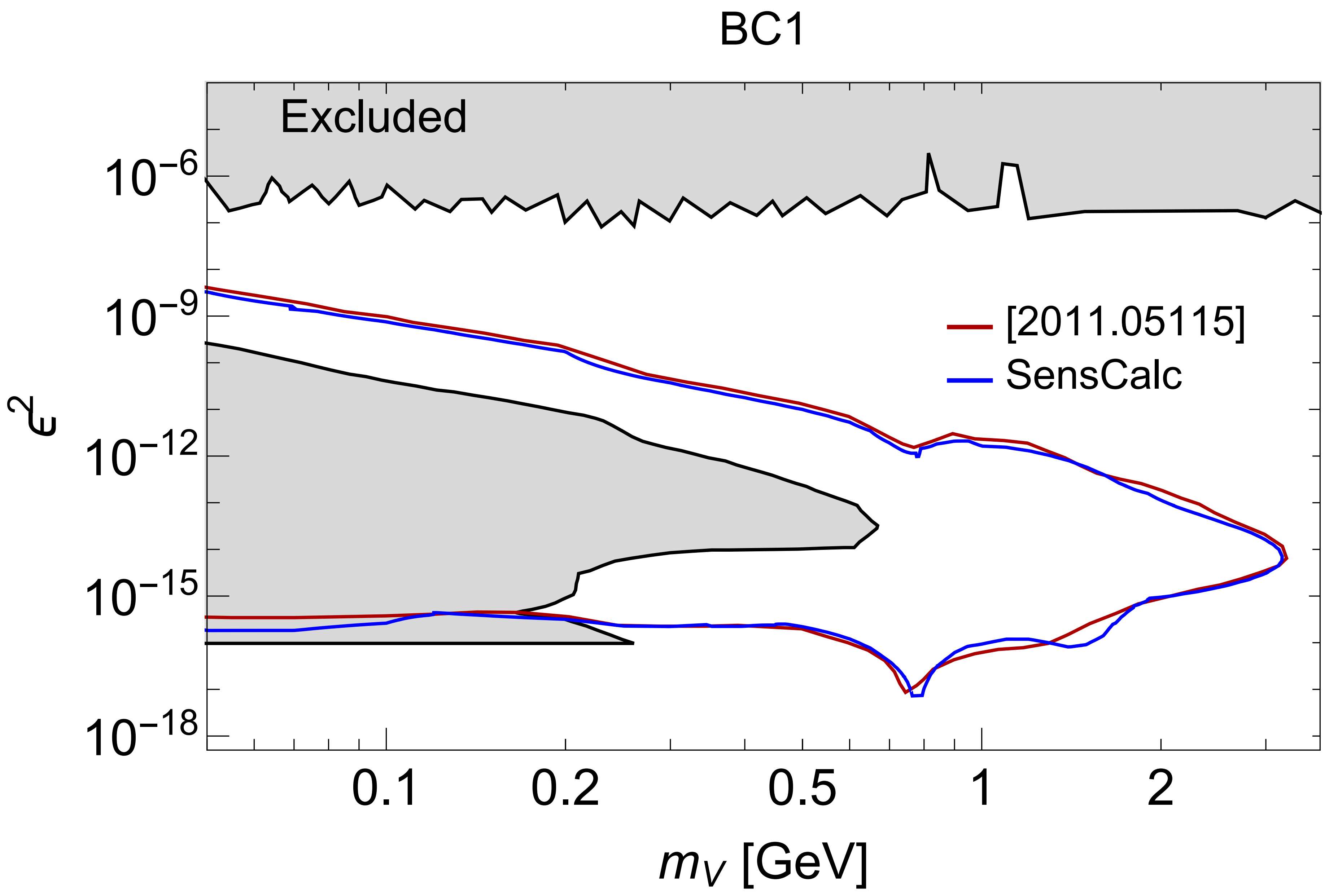


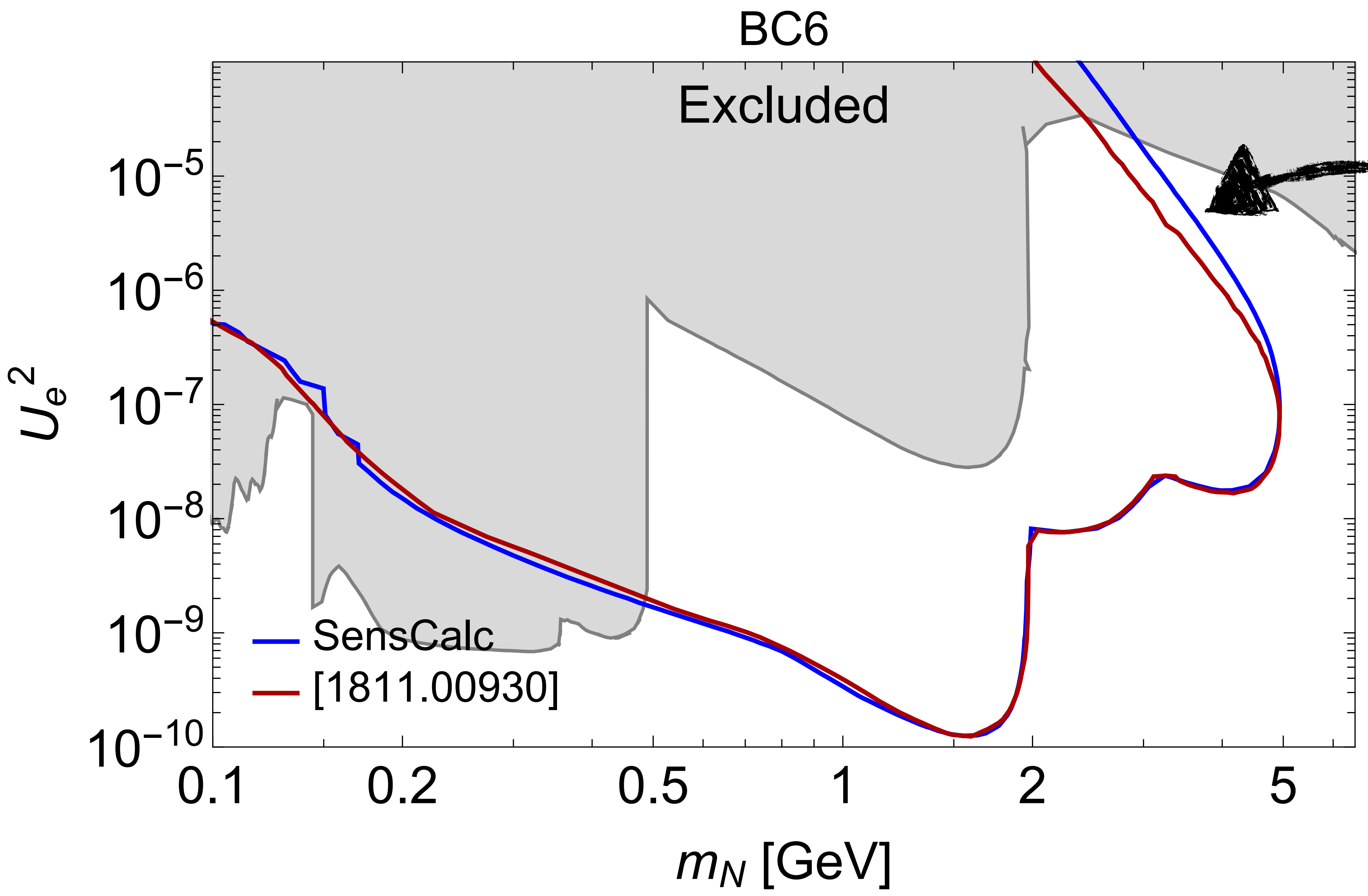
Discrepancy likely caused by slightly different geometries

✔

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

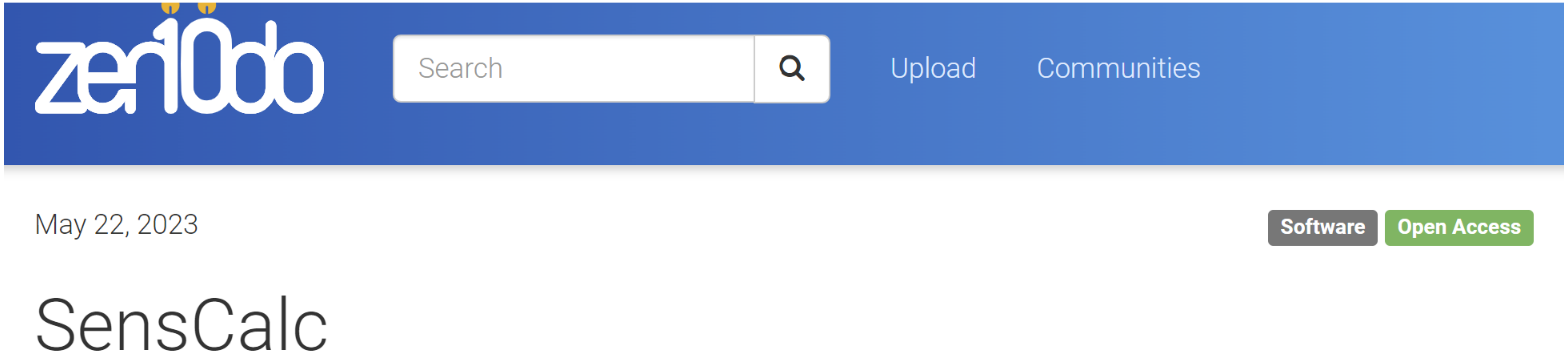
Validation against other packages

And more…

- FORESEE
- The LHCb simulation framework

Running SensCalc

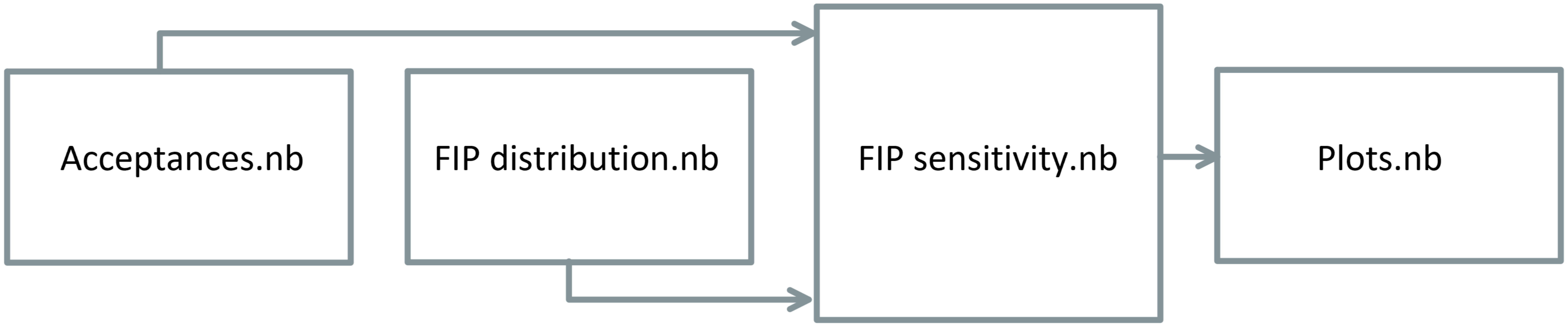
[doi.org/10.5281/zenodo.7957784]



- 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

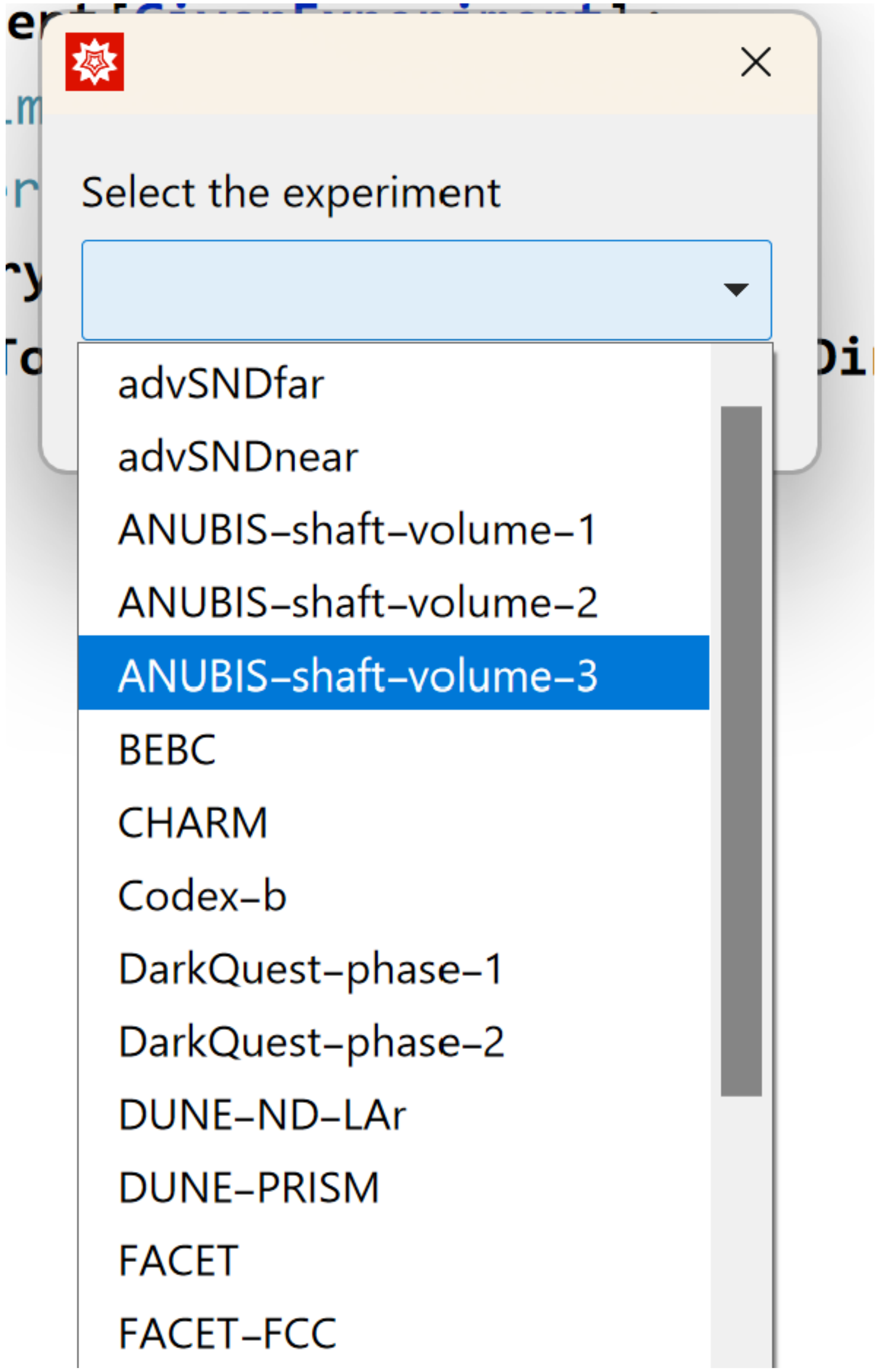


- **Acceptances.nb:** specify the geometry & acceptance criteria $\rightarrow$ $\epsilon_{\text{az}}, \epsilon_{\text{dec}}$
- **FIP distribution.nb:** specify the facility & FIP → FIP distribution
- **FIP sensitivity.nb:** compute the tabulated number of events & sensitivity
- **Plots.nb:** produce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

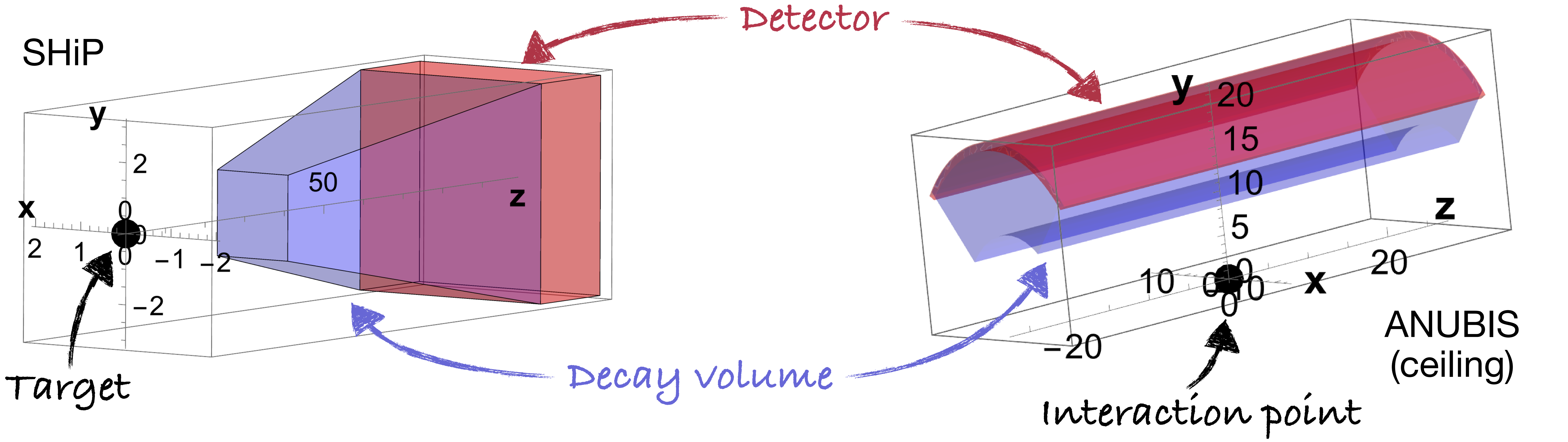
Running SensCalc

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



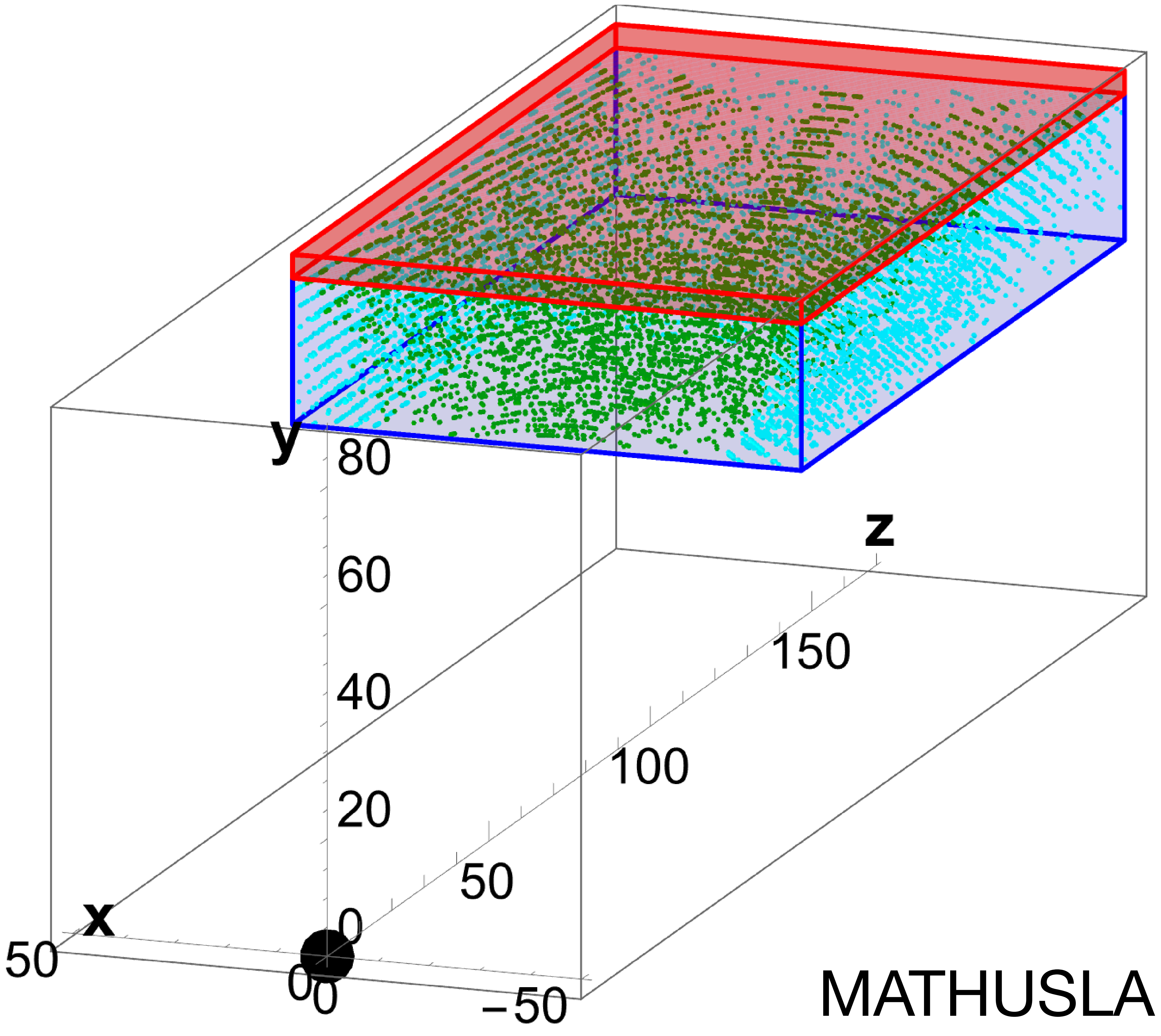
Acceptances.nb



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 $\epsilon_{\text{dec}}(m, \theta, E, z)$ by averaging

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

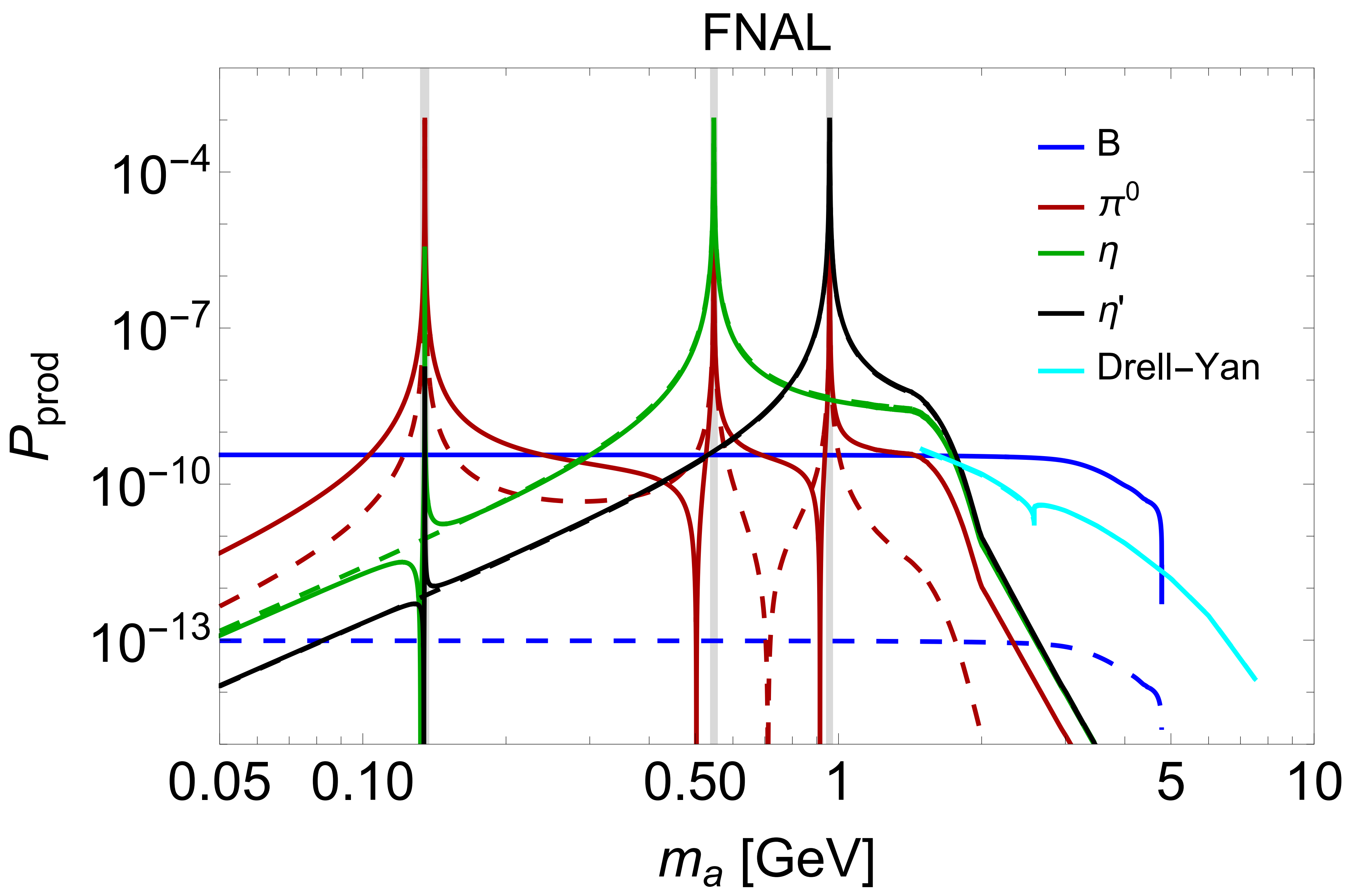
over all decay channels and azimuthal angles ϕ.

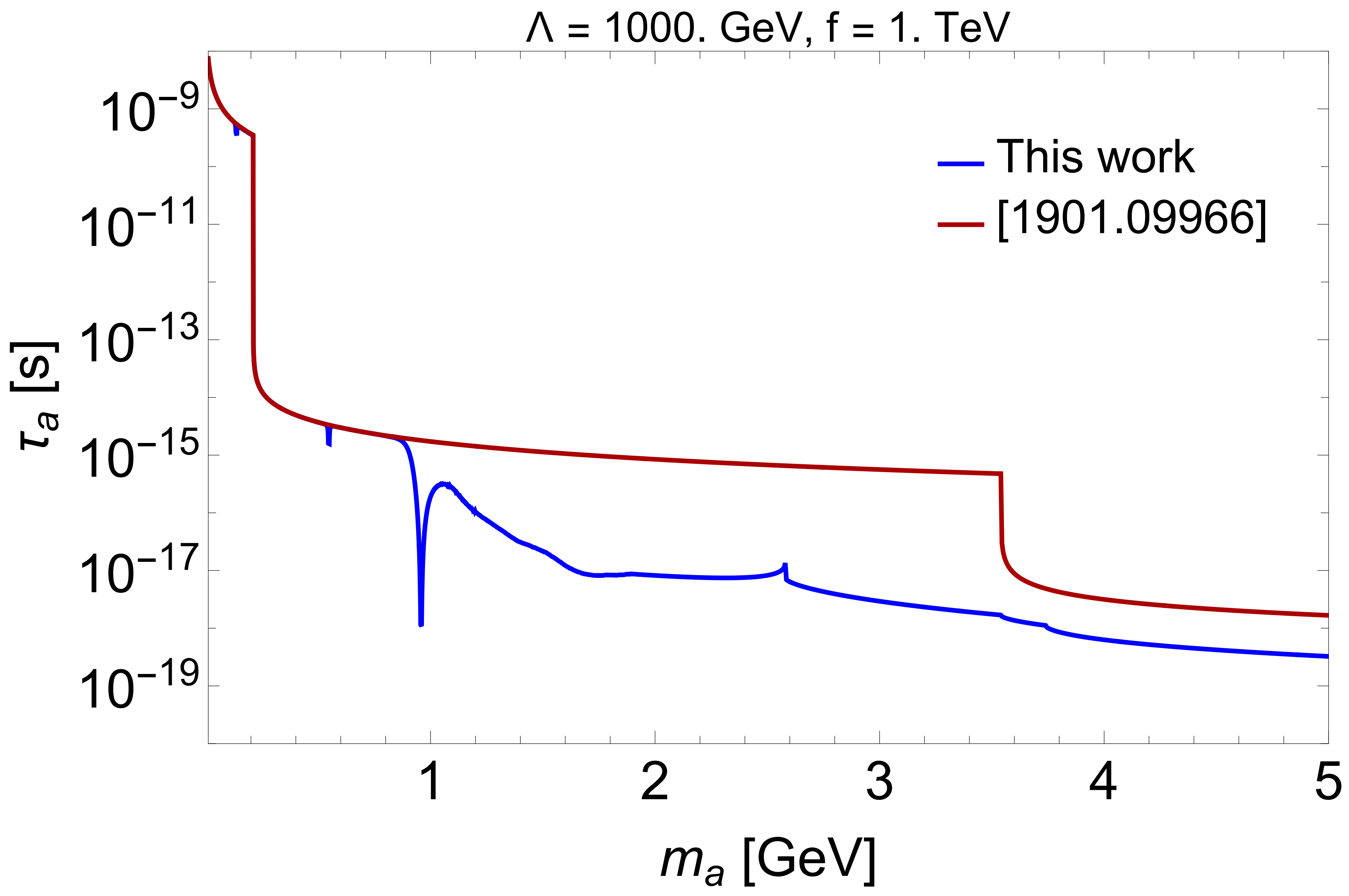
For each channel and angle ϕ, ϵ_{dec} is computed by:

- evaluating the decay phase space using either i) analytic matrix elements or ii) 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 talk yesterday

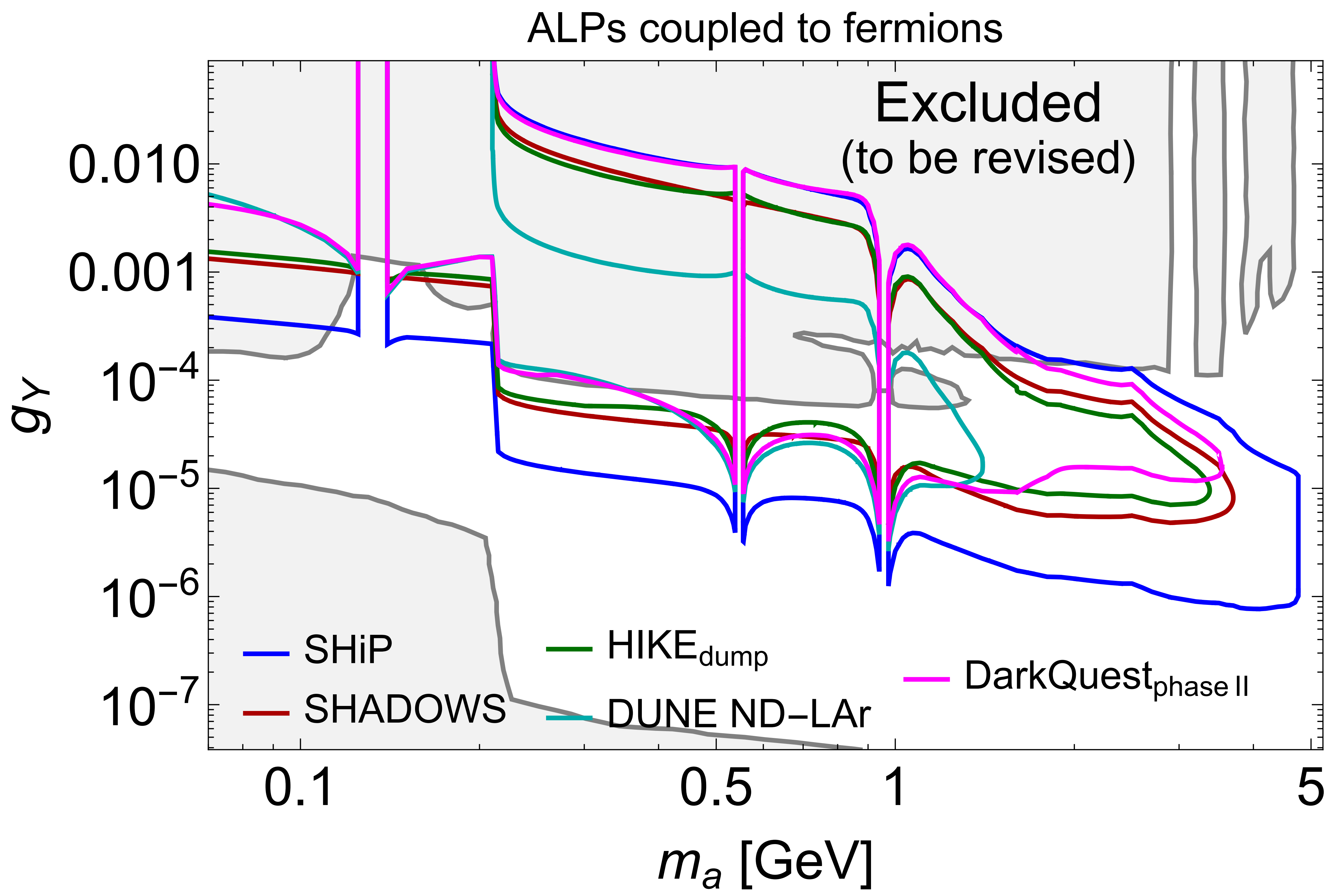


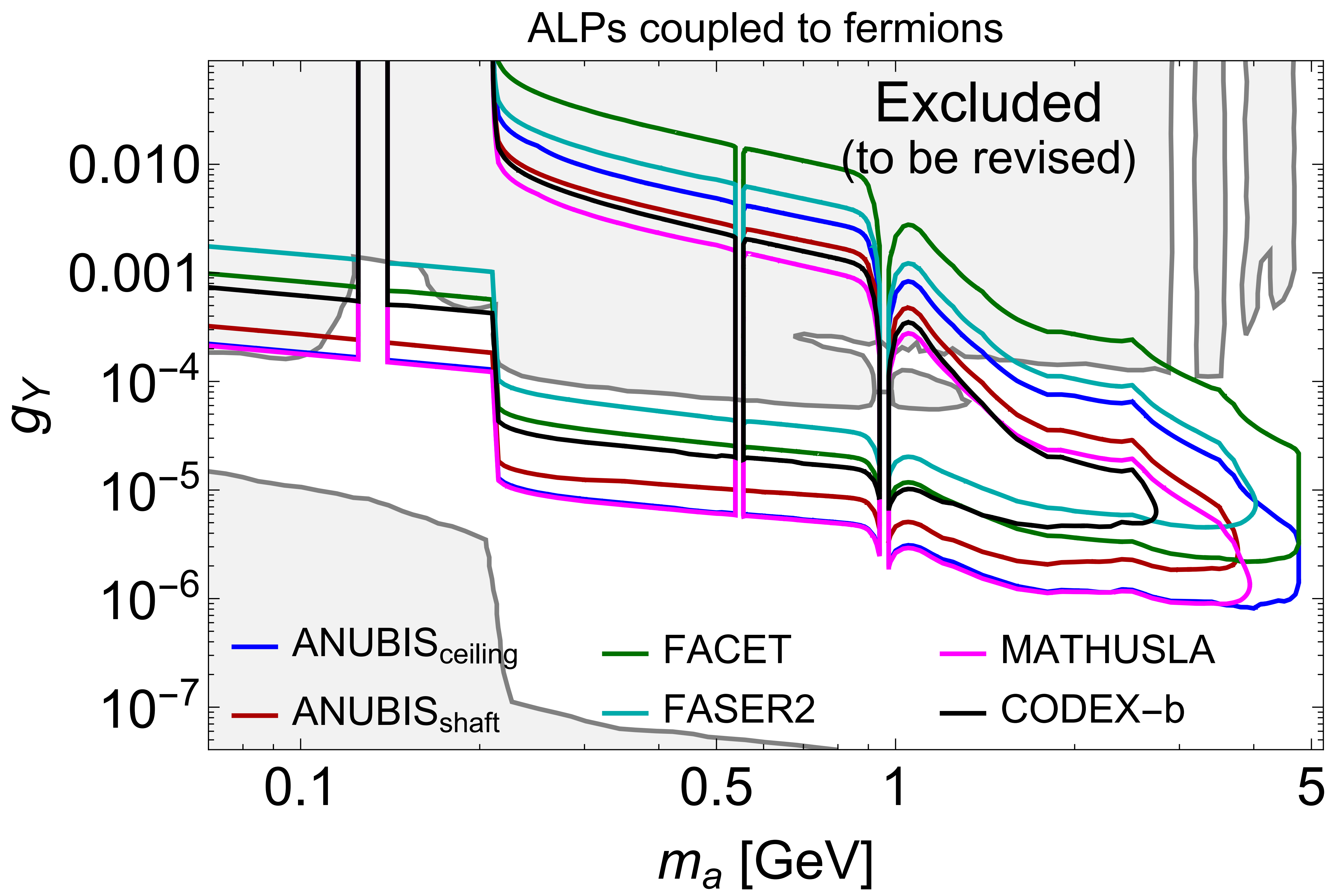


- The widely adopted phenomenology [1901.09966] lacks the hadronic decays of ALPs and various production channels
- All sensitivities of future experiments & existing bounds have to be recomputed! [F. Kahlhoefer, G.D.V. Garcia, M. Ovchynnikov, A. Zaporozhchenko, in preparation]

Case study: ALP with fermion couplings

Cf. Maksym's talk yesterday





Summary plots can be quickly recomputed!

(at least for background-free experiments)

Limitations

- The user is responsible for specifying 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 background
- SensCalc only computes the total number of accepted events (but *not* detailed event records)
  $\rightarrow$ cannot use binned likelihoods, CL_s, etc...

When to use SensCalc?

- Validate your signal model
- Estimate the sensitivity in a counting experiment (single bin)
  In particular, if zero background
- 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)
- Leverage the relative shapes of the signal and background
  (e.g. peak searches)

Conclusion

- Summary plots can give a false illusion of consistency
- Computing sensitivities is a complicated, messy process:
  - Different phenomenologies, different 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...)

FASER2@FPF just added!