



SensCalc

Public and unified calculations of sensitivities to feebly interacting particles

Based on [\[2305.13383\]](#) by Maksym Ovchynnikov, Jean-Loup Tastet, Oleksii Mikulenko, Kyrilo Bondarenko

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Plan

- The search for feebly interacting particles (FIPs)
- Why a new package?
- The semi-analytic estimate behind SensCalc
- How to run SensCalc
- Limitations & conclusion

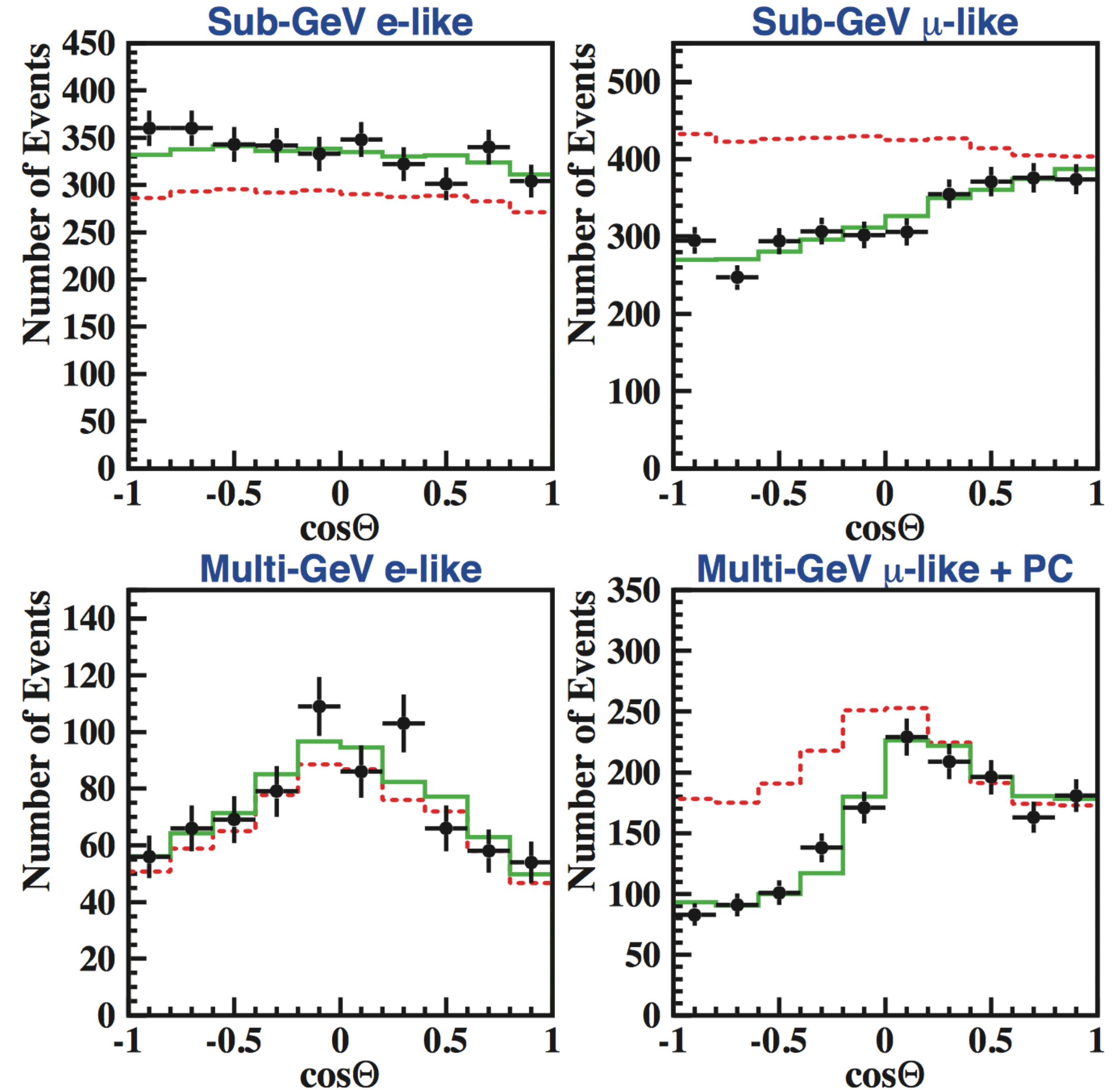
The search for feebly interacting particles (FIPs)



Limitations of the SM

Observational limitations

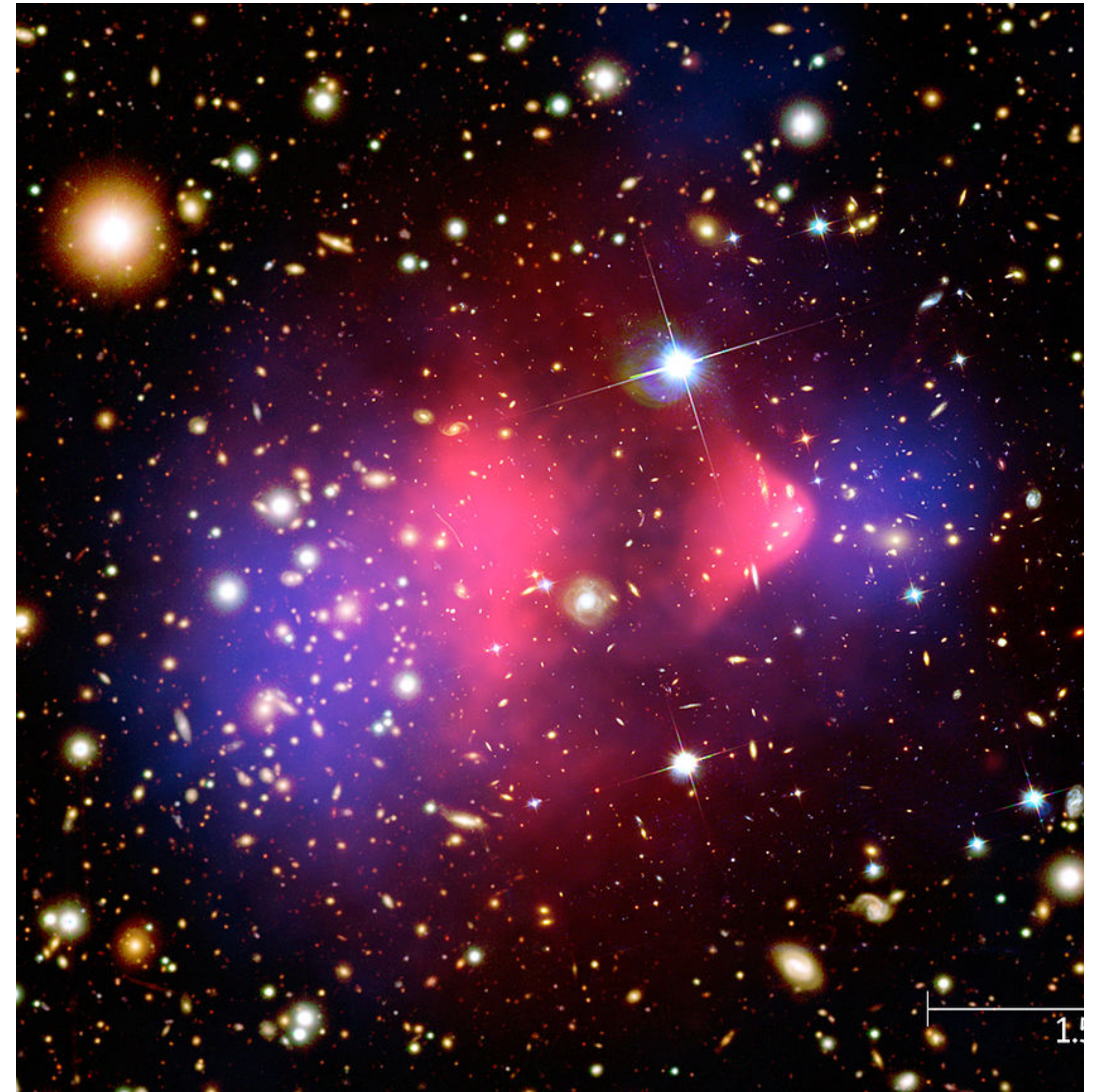
- Massless neutrinos
⇒ no oscillations



Limitations of the SM

Observational limitations

- Massless neutrinos
⇒ no oscillations
- No dark matter



Limitations of the SM

Observational limitations

- Massless neutrinos
⇒ no oscillations
- No dark matter
- No matter ($\eta = 0$)

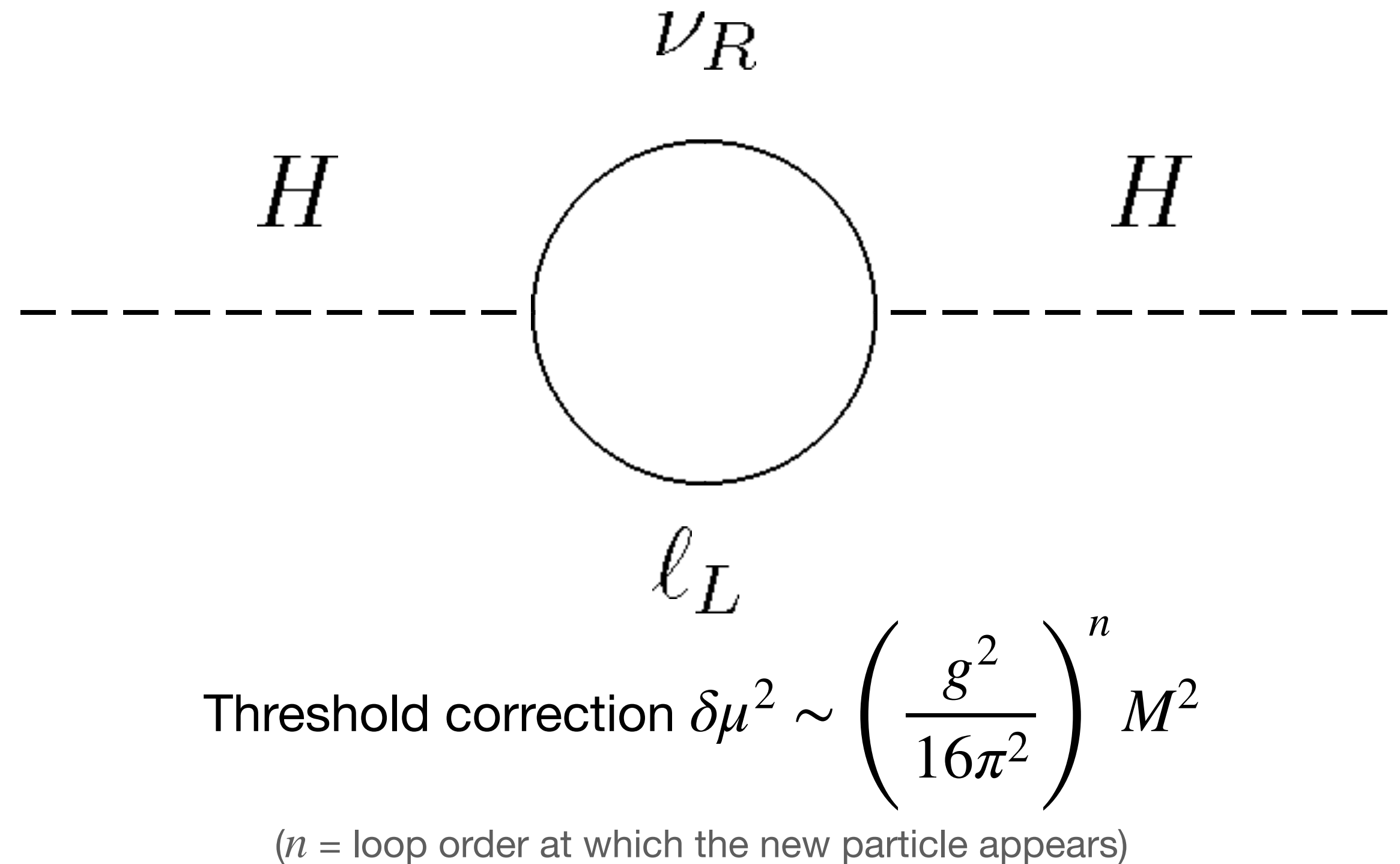
Limitations of the SM

Theoretical limitations

- Higgs naturalness
- Strong CP problem
- Flavour puzzle
- And more...

Possible solution:

New particles are light and/or feebly coupled to the Higgs



How could a light particle have evaded searches?

- Must be a Standard Model singlet, i.e. a $(\mathbf{1}_c, \mathbf{1}_L, Y = 0)$ representation
- Interacts through **mass mixing, kinetic mixing, $d > 4$ operators, ...**
- In the absence of additional interactions, is typically long-lived
(with the notable exception of "rich" dark sectors, where it can decay to lighter particles)
- The simplest examples are the so-called "portals":
Add a new degree of freedom, with the **lowest-dimensional interactions**, and suppressed by a **small coupling**.

The 5 portals

$d = 4$

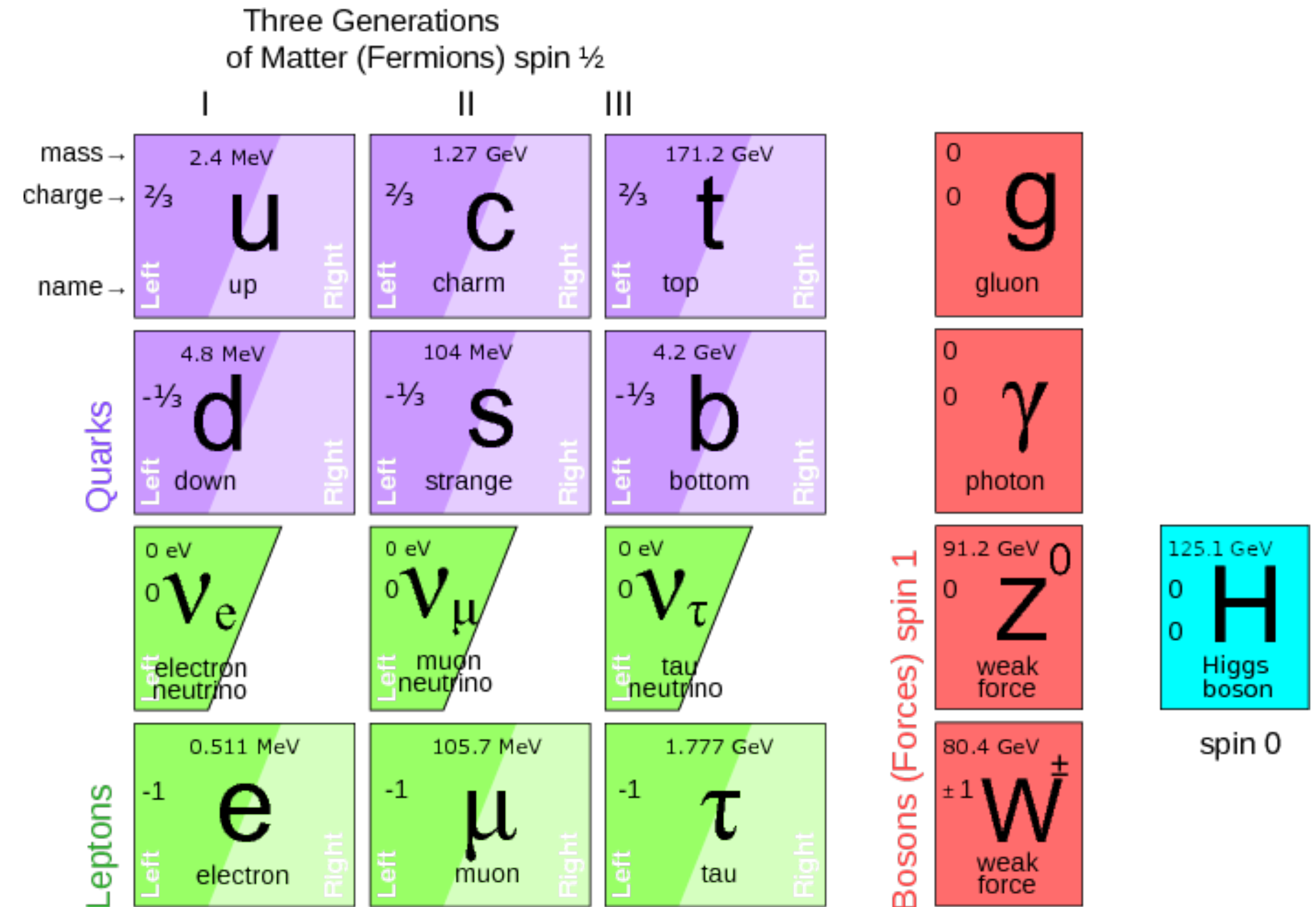
- Scalar portal / dark Higgs S : $\mu_{\text{HS}} S \phi^\dagger \phi$, $\lambda_{\text{HS}} S^2 \phi^\dagger \phi$
- Heavy neutral lepton / right-handed neutrino ν_R : $-Y_\alpha^\nu (L_\alpha^\dagger \cdot \tilde{\phi}) \nu_R^\dagger$
- Vector portal / dark photon A' : $\epsilon F'_{\mu\nu} F^{\mu\nu}$ (kinetic mixing with the SM photon)
- Millicharged particle χ : $\epsilon \bar{\chi} A \chi$ (coupled to very light dark photon)

$d = 5$

- Axion-like particle a : $\frac{c_{a\gamma\gamma}}{f_a} a F \tilde{F}$, $\frac{c_{agg}}{f_a} a G \tilde{G}$, $\frac{c_\psi}{f_a} \partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$

Example: Heavy neutral leptons (HNLs)

- No $SU(2)_L$ singlet ν_R in the SM



Example: Heavy neutral leptons (HNLs)

- No $SU(2)_L$ singlet ν_R in the SM
- Simplest addition which can give a mass to neutrinos:

$$-(Y_{\alpha I}^\nu)^*(L_\alpha \cdot \tilde{\phi}^\dagger)\nu_{R,I} \longrightarrow (m_D)_{\alpha I}\nu_{L,\alpha}\nu_{R,I}$$

with the Dirac mass $m_D = \frac{v}{\sqrt{2}}(Y_{\alpha I}^\nu)^*$

(where $\alpha = e, \mu, \tau, I = 1, 2, \dots, N_{\text{HNL}}$)

- SM singlets can have a Majorana mass:

$$-\frac{M_I}{2}(\nu_{R,I}\nu_{R,I} + \nu_{R,I}^\dagger\nu_{R,I}^\dagger)$$

Three Generations of Matter (Fermions) spin 1/2

	I	II	III		
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0	0
charge →	2/3	2/3	2/3	0	0
name →	Left u Right up	Left c Right charm	Left t Right top	g gluon	
Quarks	4.8 MeV	104 MeV	4.2 GeV	0	0
	-1/3	-1/3	-1/3	0	0
	Left d Right down	Left s Right strange	Left b Right bottom	γ photon	
0	0	0	91.2 GeV	0	125.1 GeV
Left ν_e Right electron neutrino	Left ν_μ Right muon neutrino	Left ν_τ Right tau neutrino	Z ⁰ weak force	H Higgs boson	
Left ν₁ Right sterile neutrino	Left ν₂ Right sterile neutrino	Left ν₃ Right sterile neutrino	80.4 GeV	±1	spin 0
Leptons	0.511 MeV	105.7 MeV	1.777 GeV	W [±] weak force	
-1	-1	-1			
Left e Right electron	Left μ Right muon	Left τ Right tau			

Example: Heavy neutral leptons (HNLs)

The see-saw mechanism

- Both mass terms are allowed: $-\frac{1}{2} \begin{pmatrix} \nu_L^T & \nu_R^T \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + \text{h.c.}$
- Mass diagonalisation leads to **mixing**: $\nu_{L,\alpha} \cong U_{\alpha,i}^{\text{PMNS}} \nu_i + \Theta_{\alpha,I} \nu_{R,I}$
- Neutrinos are light if HNLs are heavy, i.e. $M_R \gg m_D$ (or $\Theta \ll 1$)
Their masses are given by the **see-saw formula**:

$$m_{\alpha\beta}^{\text{light}} \approx - \sum_I \frac{(m_D)_{\alpha I} (m_D)_{\beta I}}{M_I} \approx - \sum_I M_I \Theta_{\alpha I} \Theta_{\beta I}$$

Example: Heavy neutral leptons (HNLs)

Phenomenology

- HNLs have mass $M_N \approx M_R \longrightarrow$ heavy neutrinos
- Same interactions as light neutrinos, but suppressed by the mixing angle Θ
- Lifetime $\tau_N \propto \Theta^{-2} \longrightarrow$ potentially long-lived particle (LLP)

Prototypical example of a feebly interacting particle (FIP)

How to search for FIPs

Feeble interactions lead to:

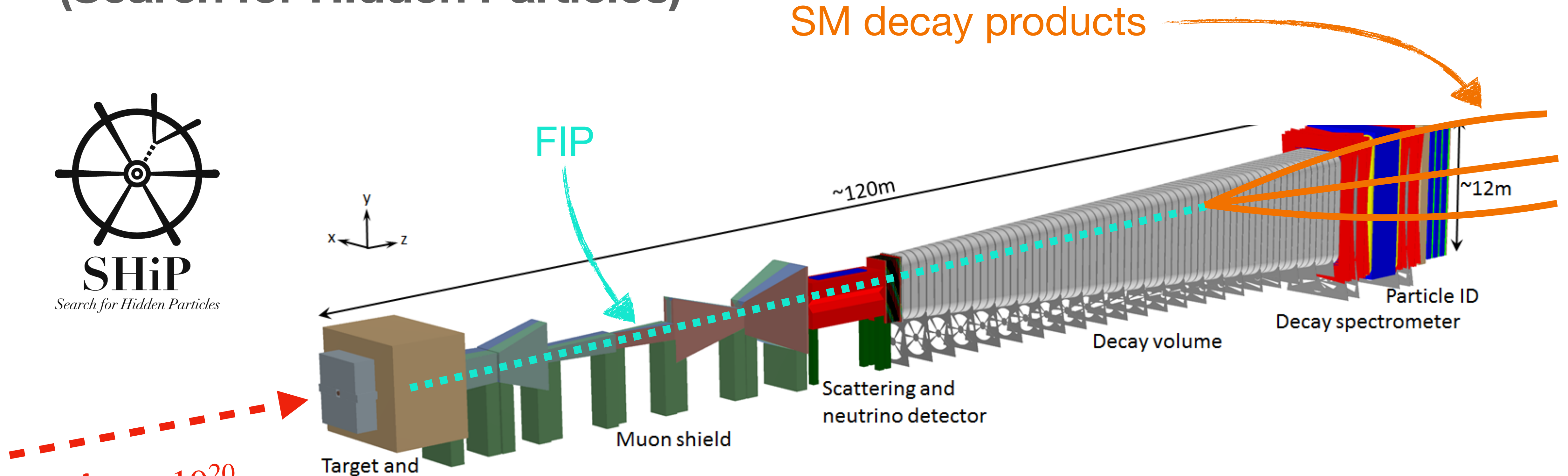
- Suppressed production rate
- A possibly long lifetime:
the particle may travel a long distance before decaying

Solution

- High intensity / luminosity
- Low background
- Displaced detector
- Large detector volume

Example: SHiP

(Search for Hidden Particles)

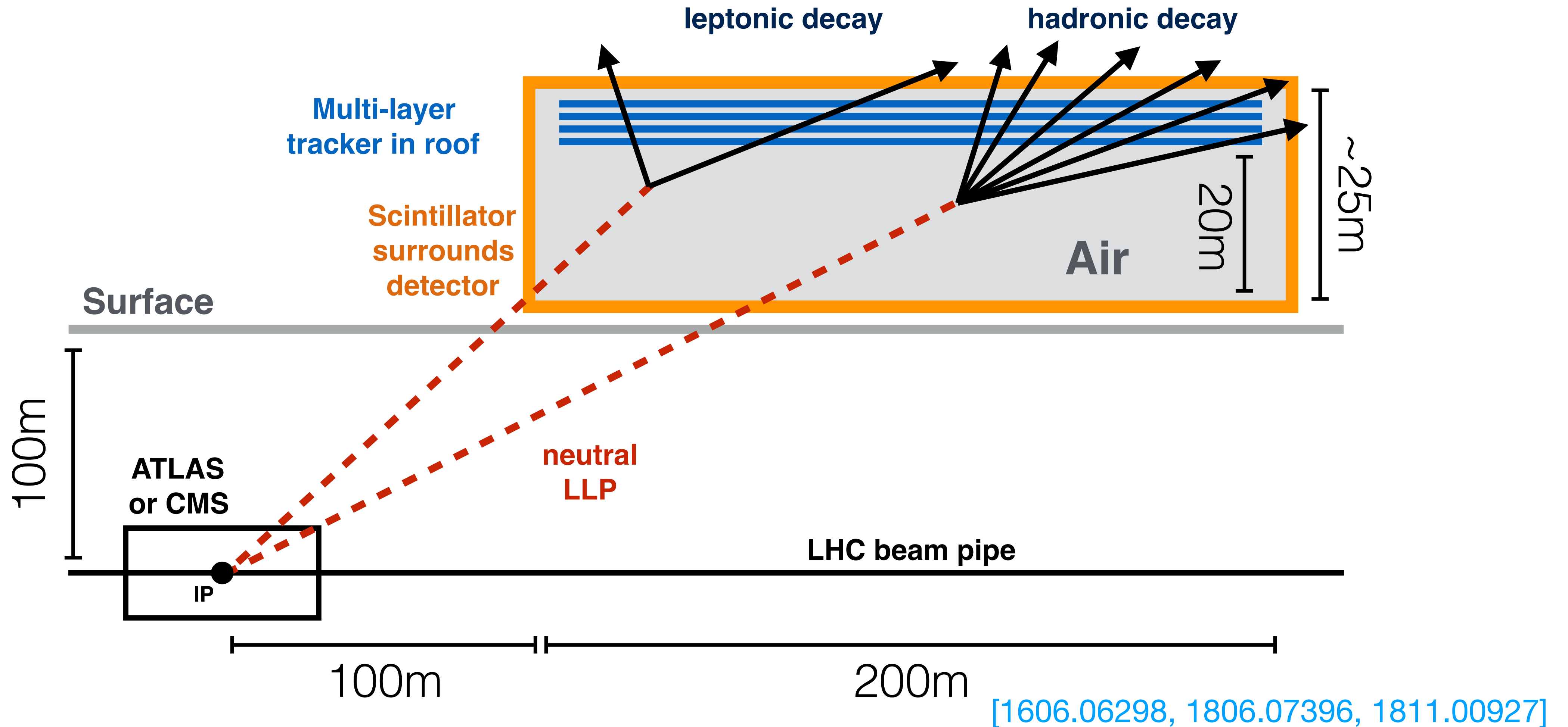


few $\times 10^{20}$
protons-on-target
/ 5 years
@ 400 GeV

[1504.04956, 1504.04855, 2112.01487]

Example: MATISIA

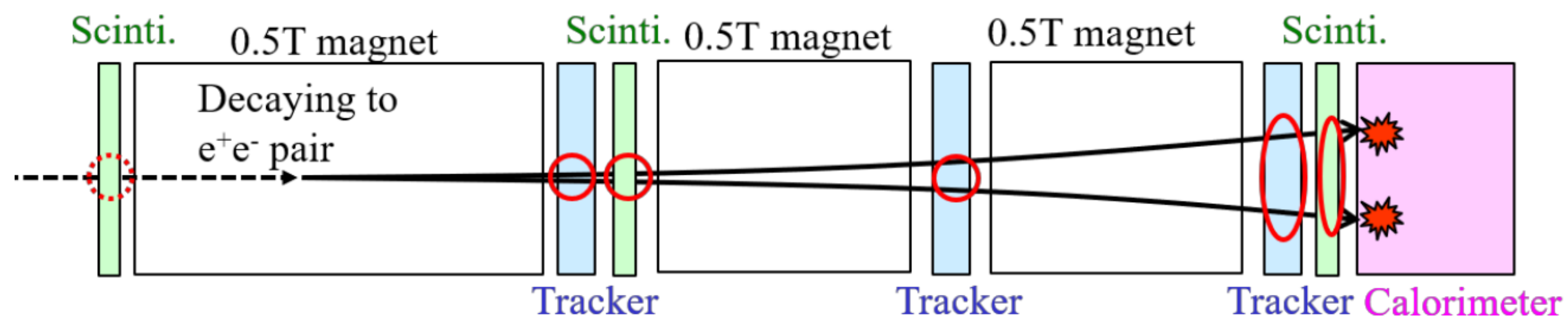
(Massive Timing Hodoscope for Ultra Stable neutral LLP)



Example: **FASER**

(Forward search experiment at the LHC)

First physics results!
[2303.14185]



[1811.10243, 1812.09139]

More info here!
[2305.01715]

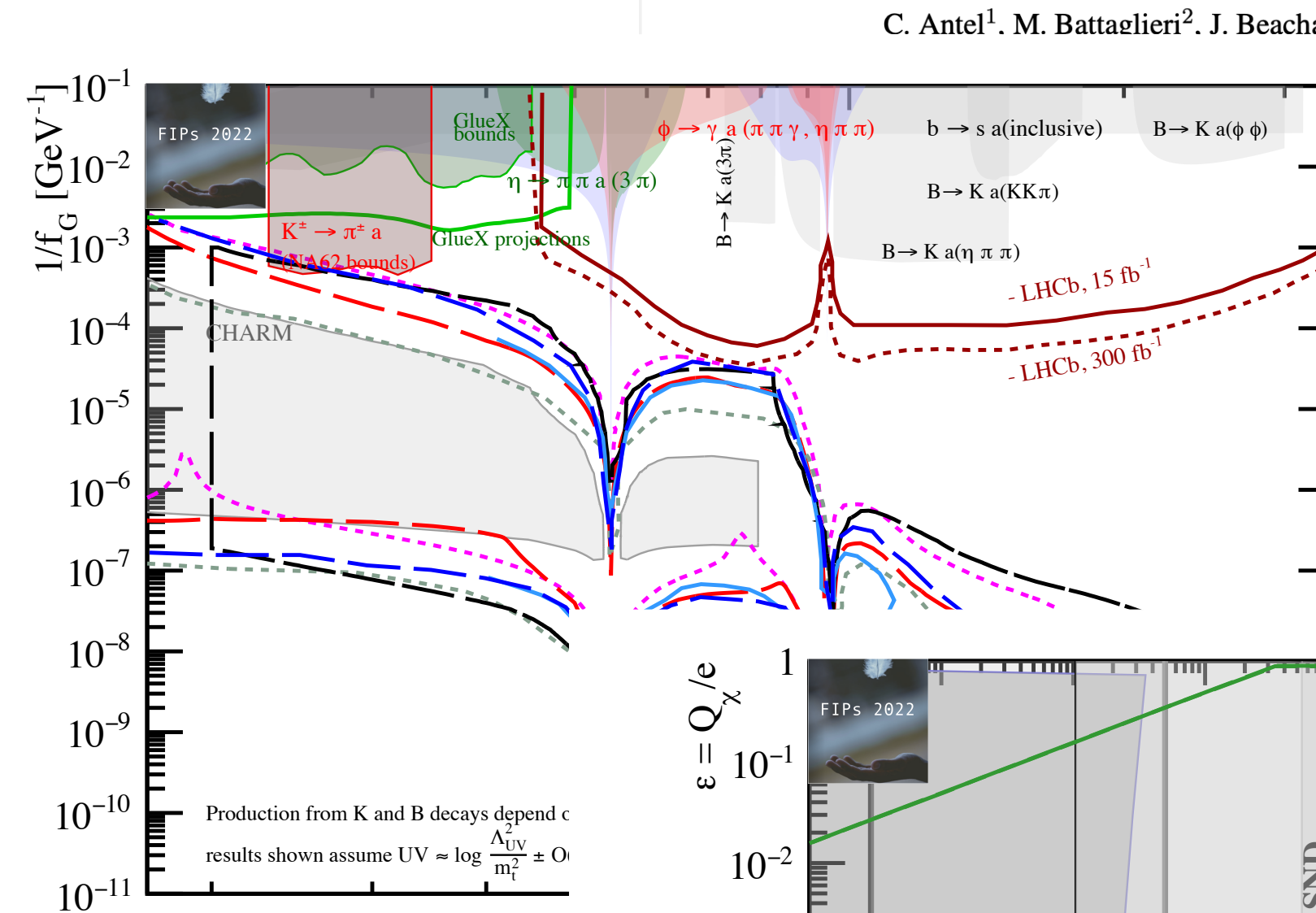
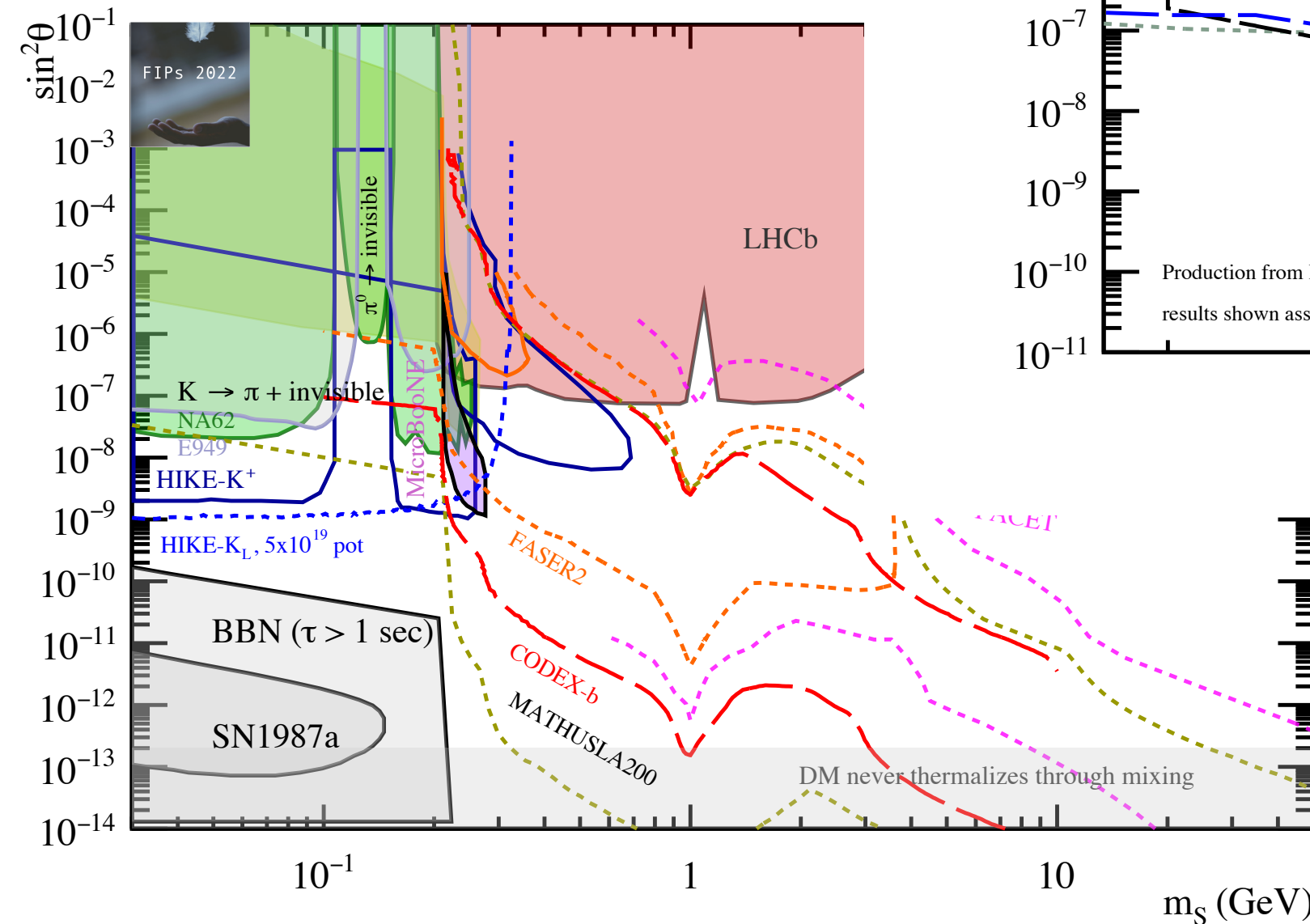
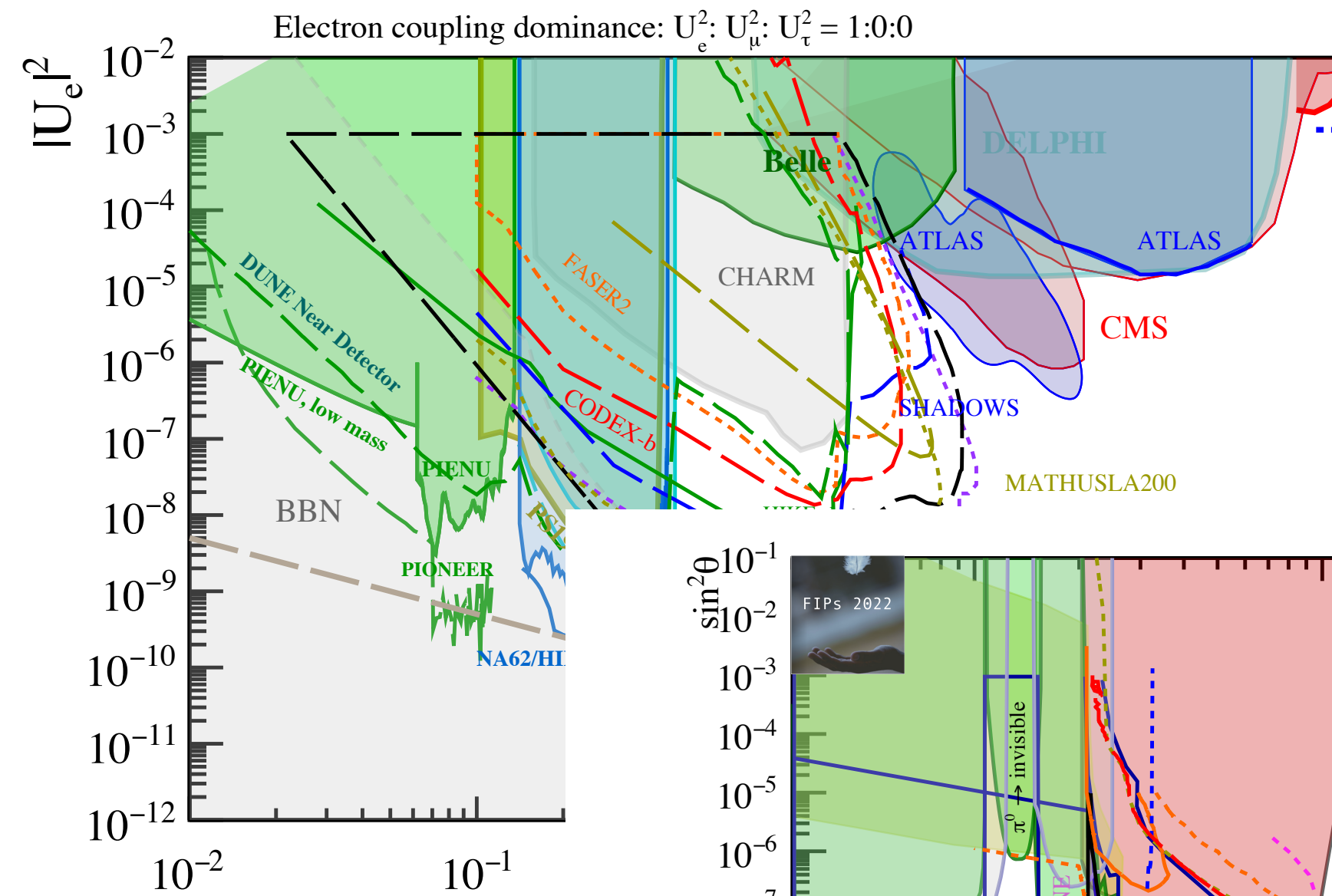


CERN-TH-2023-061
DESY-23-050
FERMILAB-PUB-23-149-PPD
INFN-23-14-LNF
JLAB-PHY-23-3789
LA-UR-23-21432
MITP-23-015

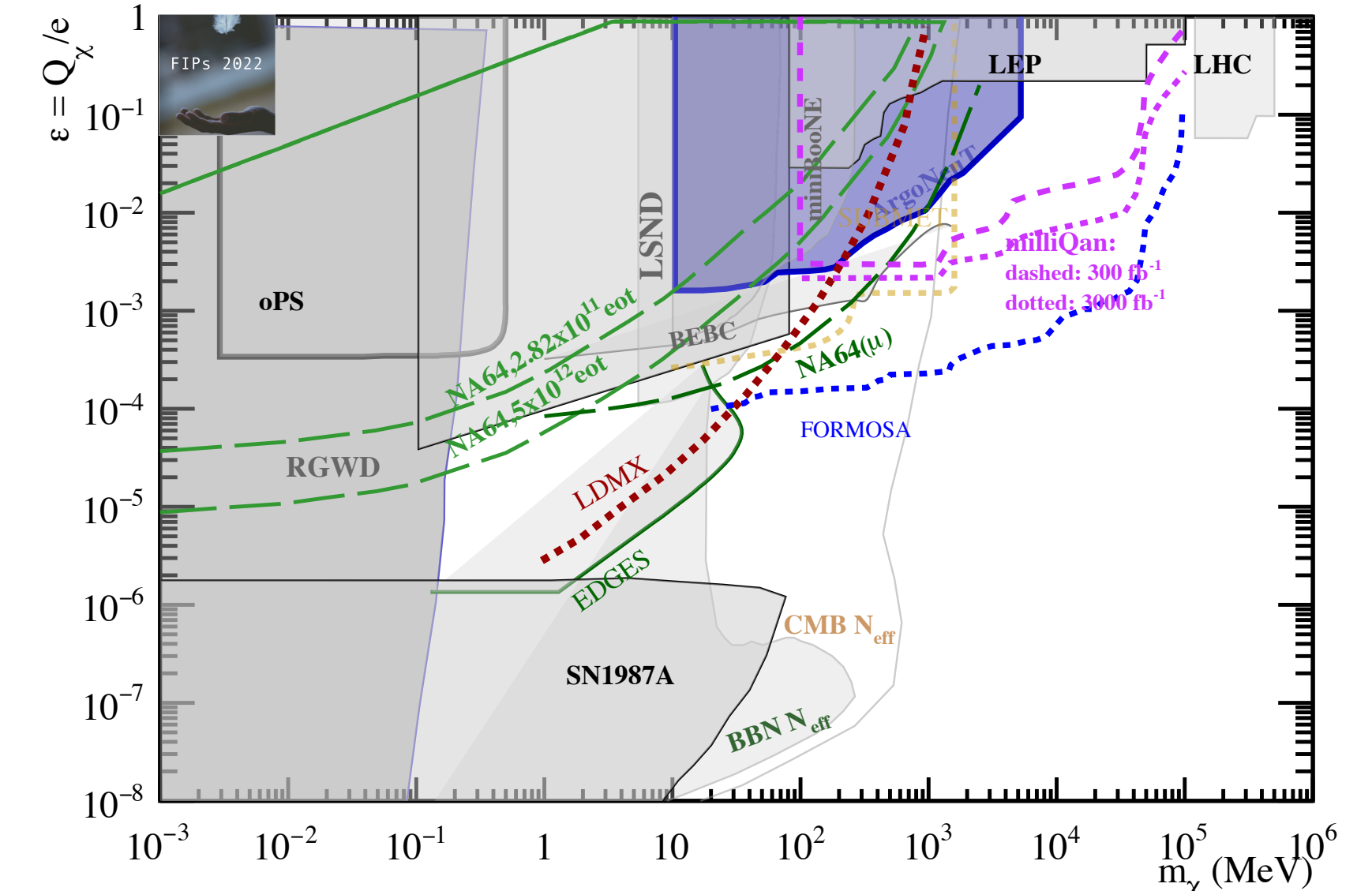
And more!

A plethora of proposed experiments

Feebly-Interacting Particles:
FIPs 2022 Workshop Report



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May 22, 2023

Software

Open Access

SensCalc

 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.

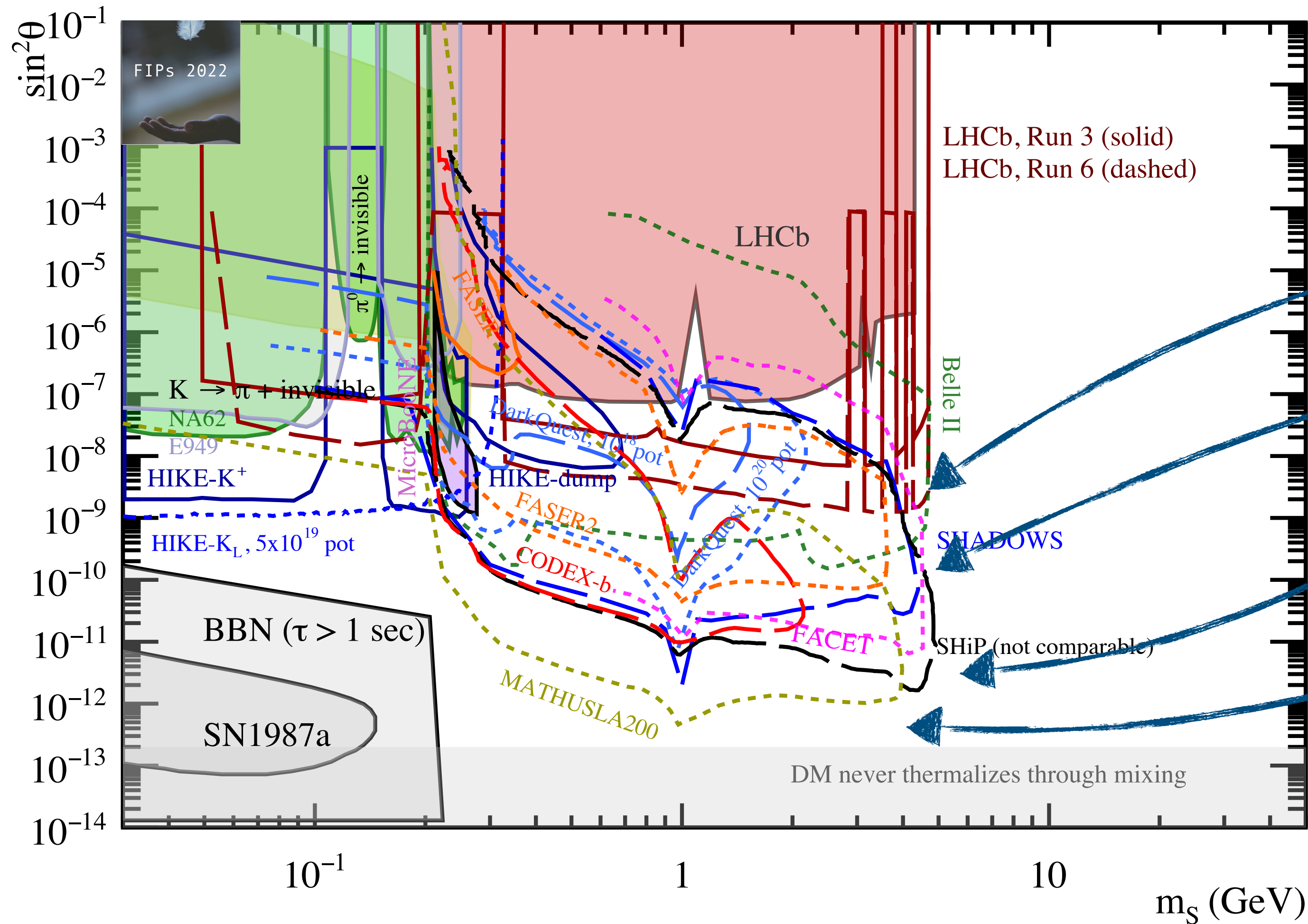
Why a new software package?

HOW **STANDARDS** PROLIFERATE:
(SEE: A/C CHARGERS, **HEP packages**, CHARACTER ENCODINGS, INSTANT MESSAGING, ETC.)



The 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
- 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

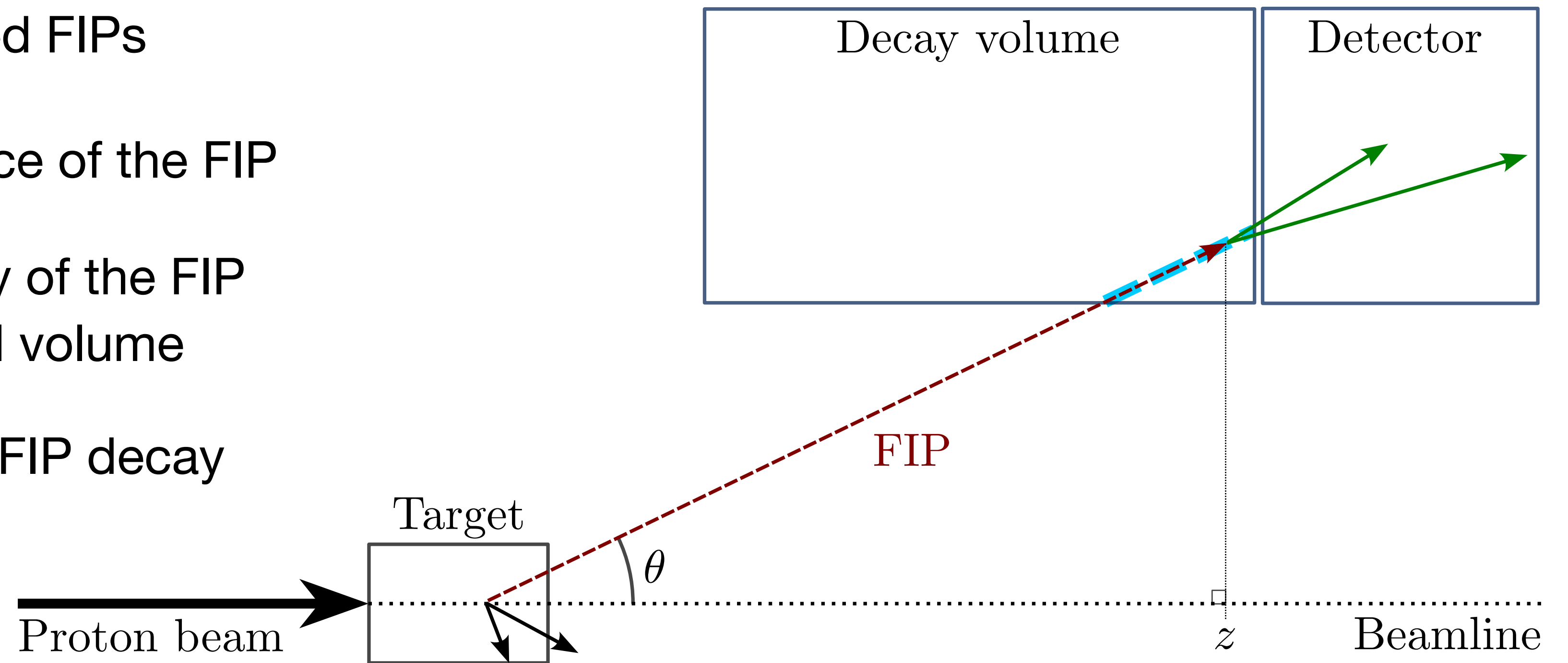
- Dark photons
- Dark scalars (mixing & quartic coupling)
- HNLs (with arbitrary mixing pattern)
- ALPs (coupled to gluons, photons, fermions)
- Anomaly-free U(1) mediators

Semi-analytic estimate

Experimental setup & naive estimate

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

- 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

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

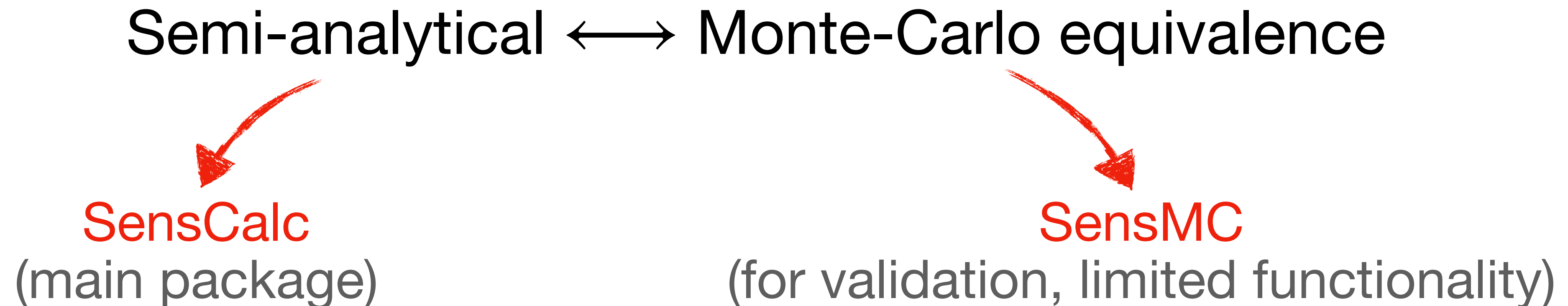
- $N_{\text{prod}}^{(i)}, f^{(i)}(\theta, E)$ = total number of produced FIPs & their distribution in $\theta - E$ (for a given production mechanism (i))
- ϵ_{az} = azimuthal acceptance for the FIP to decay within the decay volume
- $\frac{dP_{\text{dec}}}{dz} = \frac{1}{\cos(\theta)c\tau\sqrt{\gamma^2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

Integrate using Monte-Carlo

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

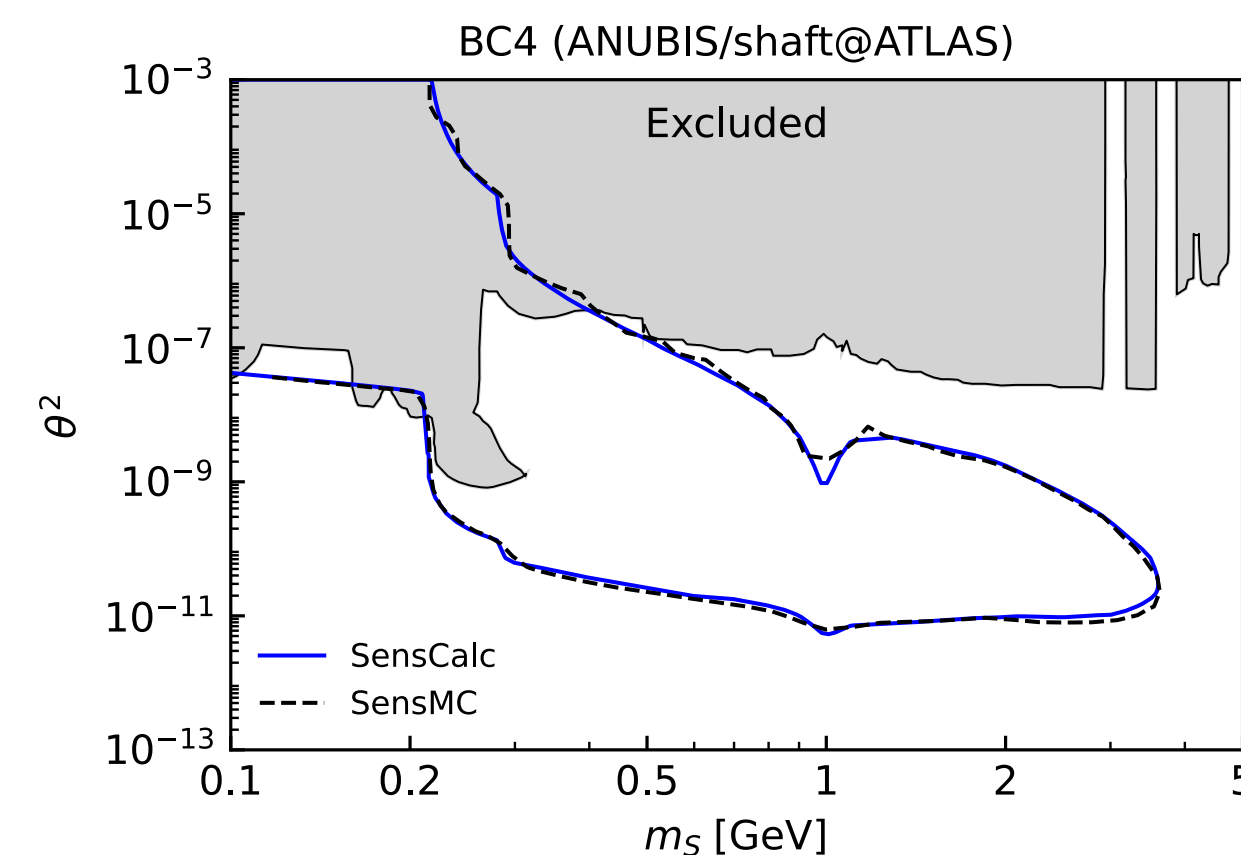
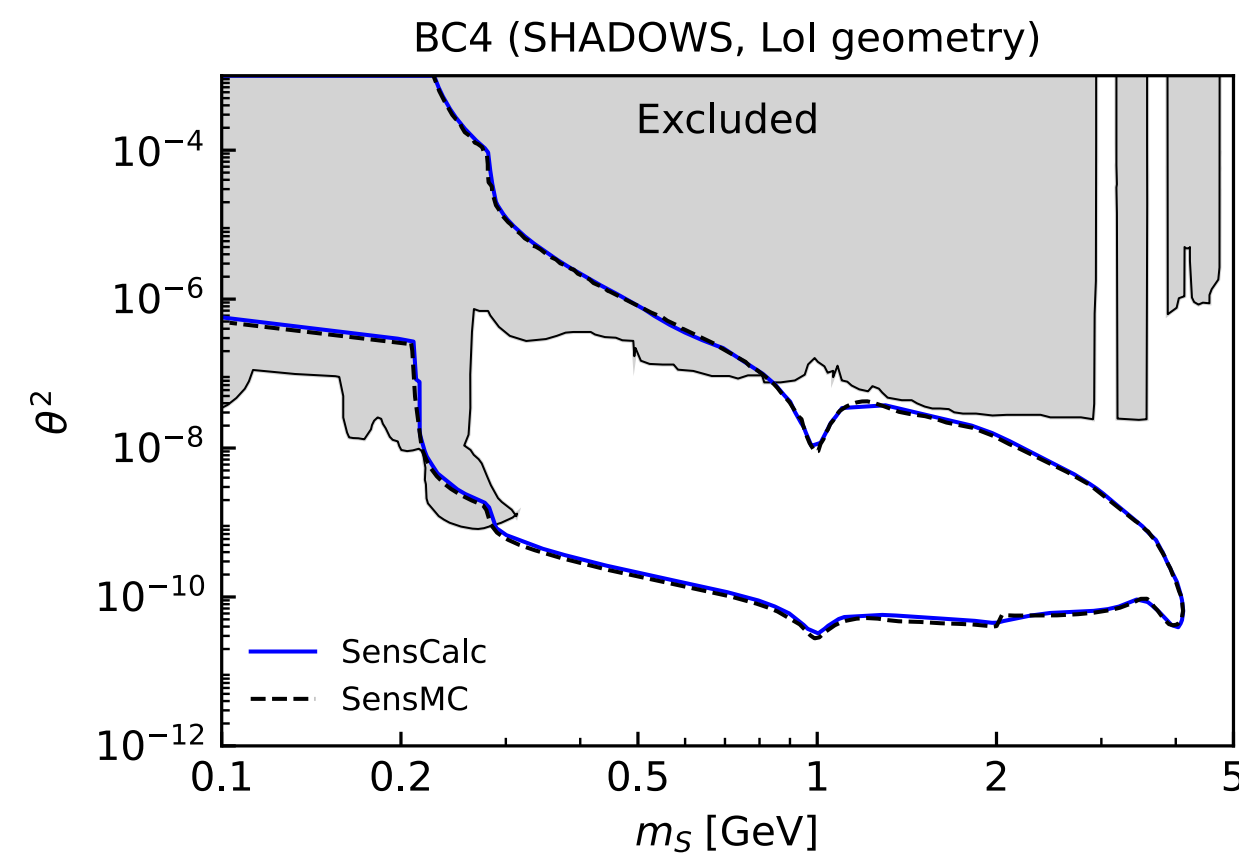
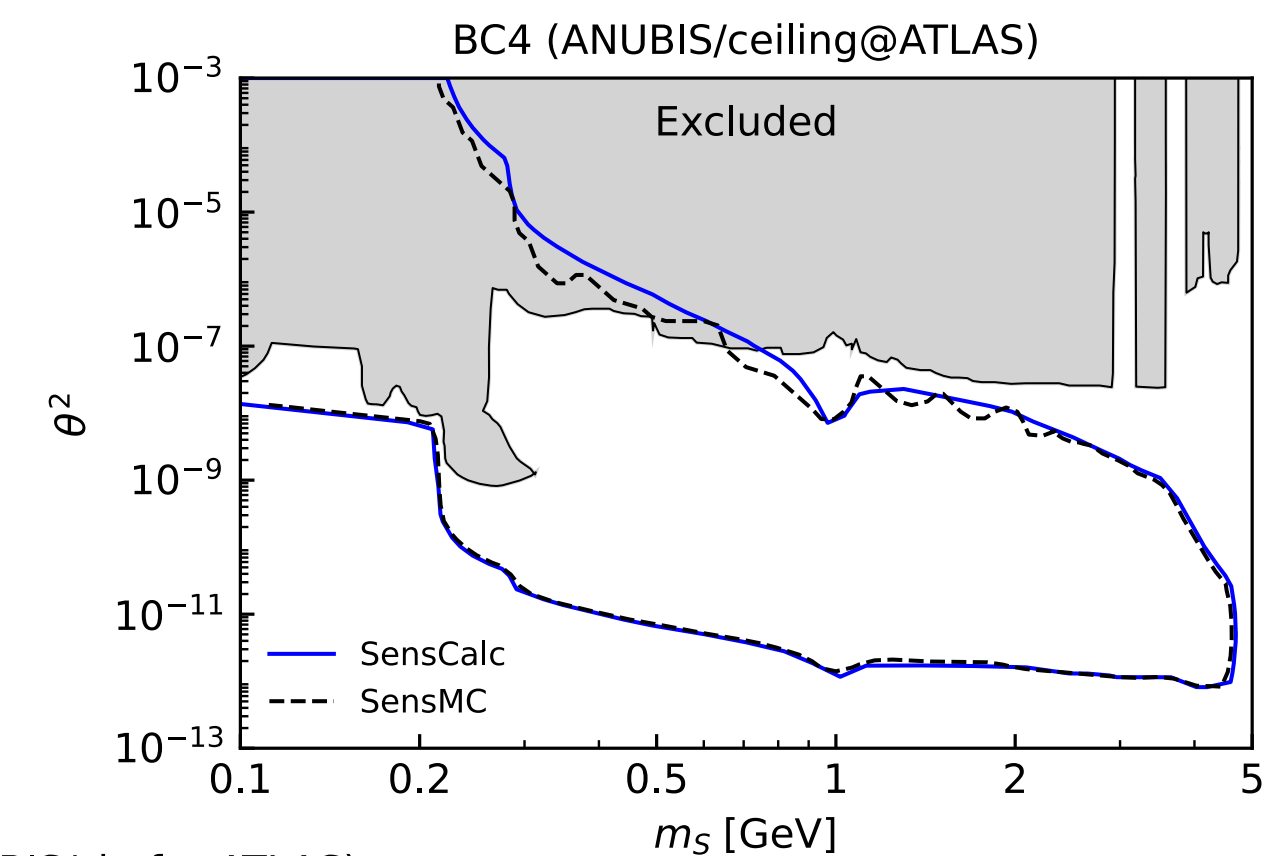
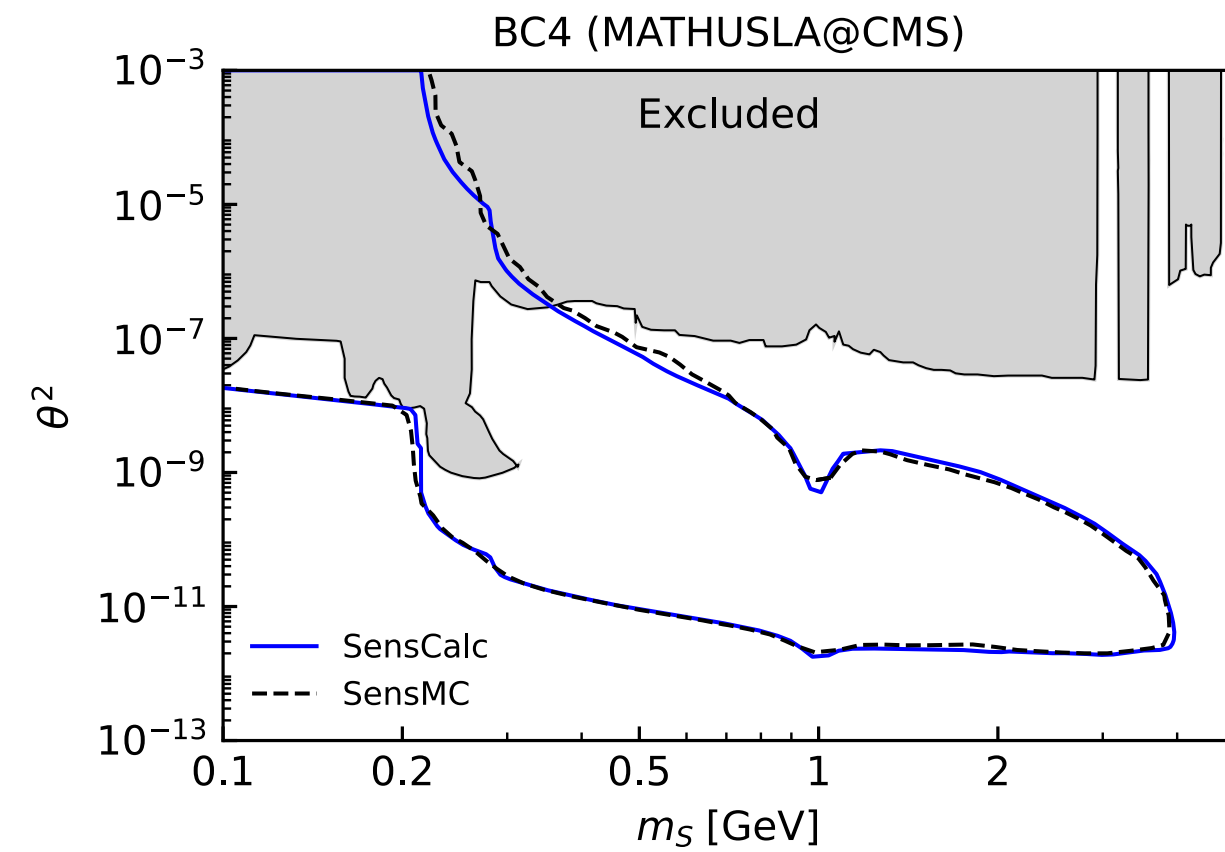
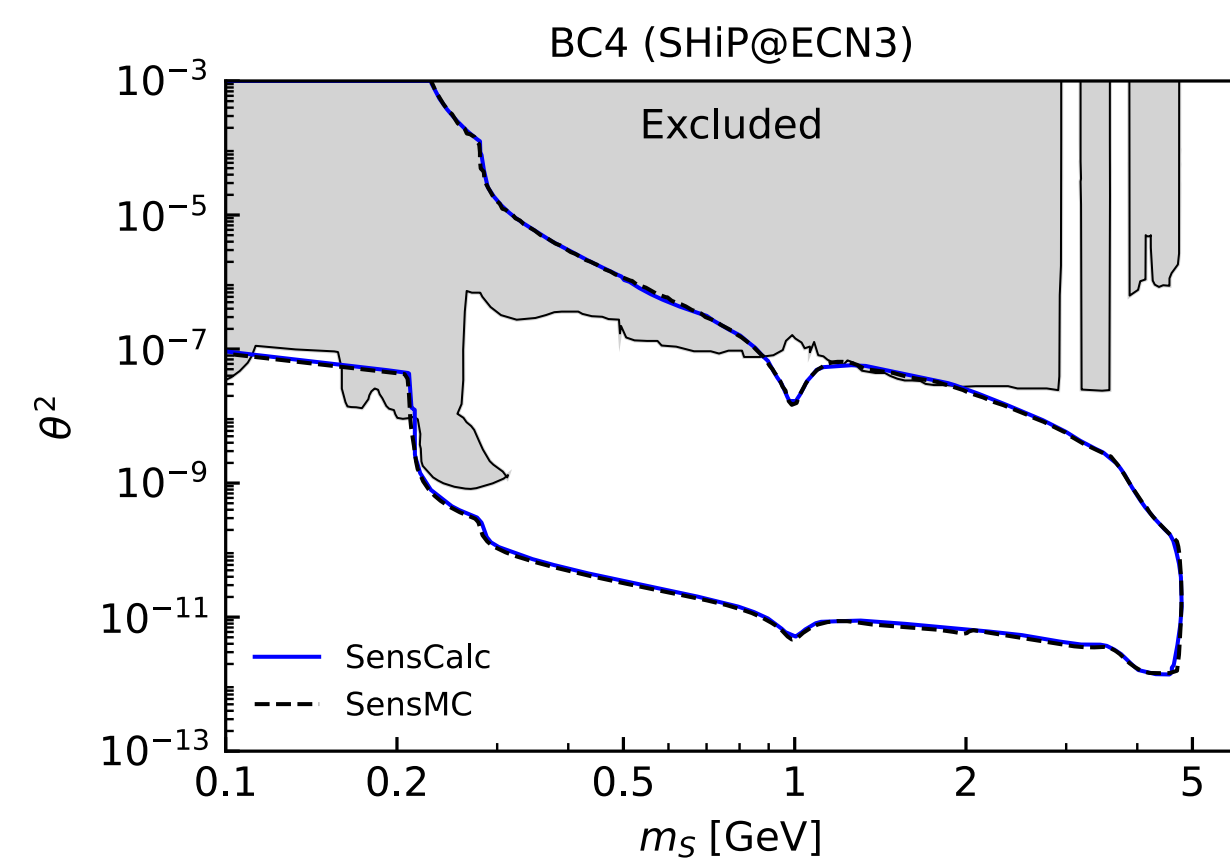
The integral can be broken down into conditional distributions and computed using **Monte-Carlo integration**



Semi-analytical estimate

Validation against SensMC (Monte-Carlo)

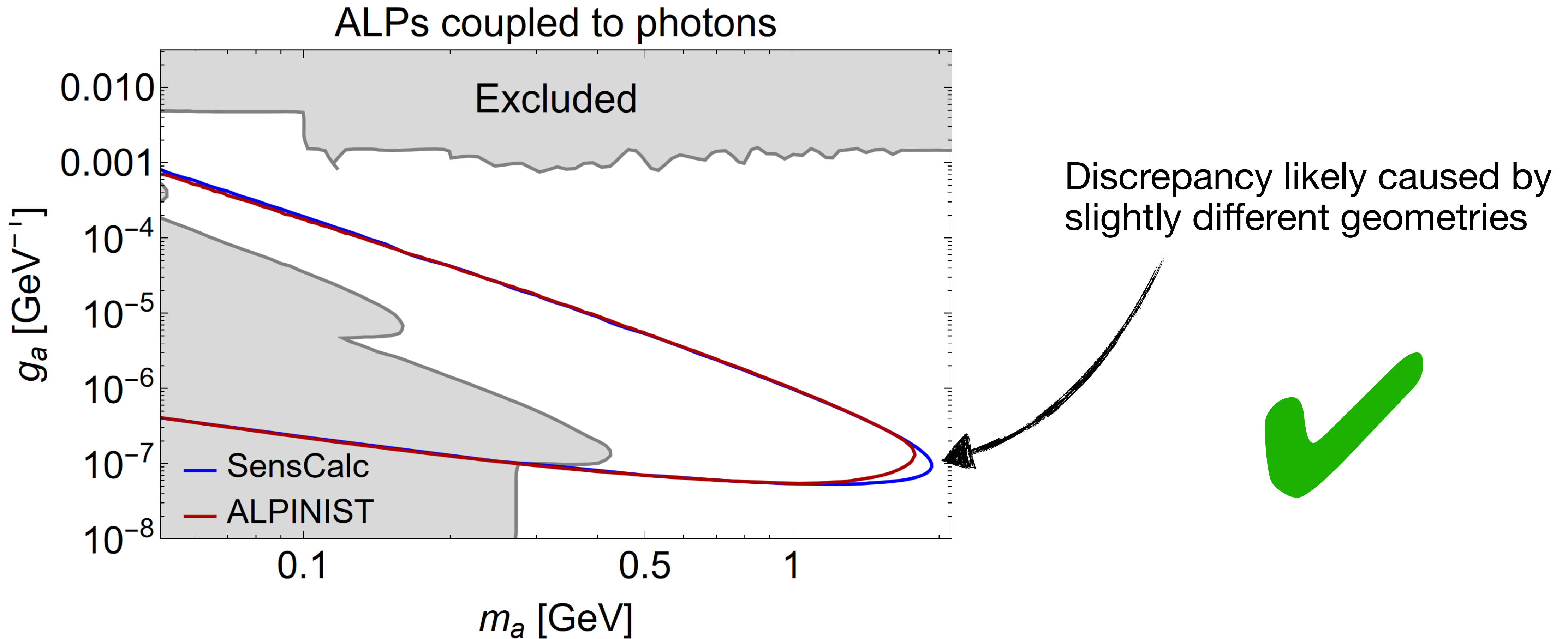
* single-event sensitivity at 90% CL used for validation (i.e. zero background)



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

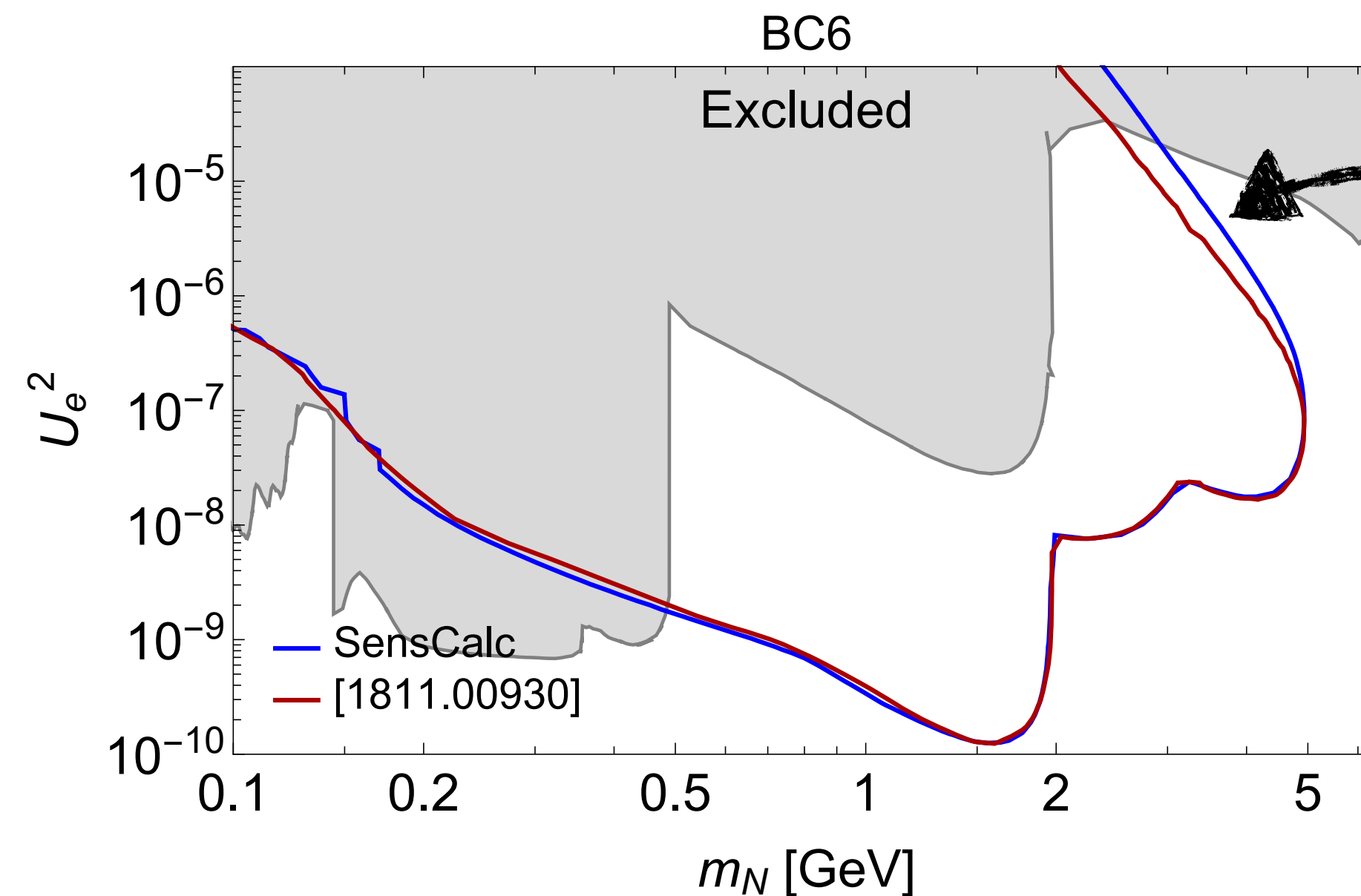
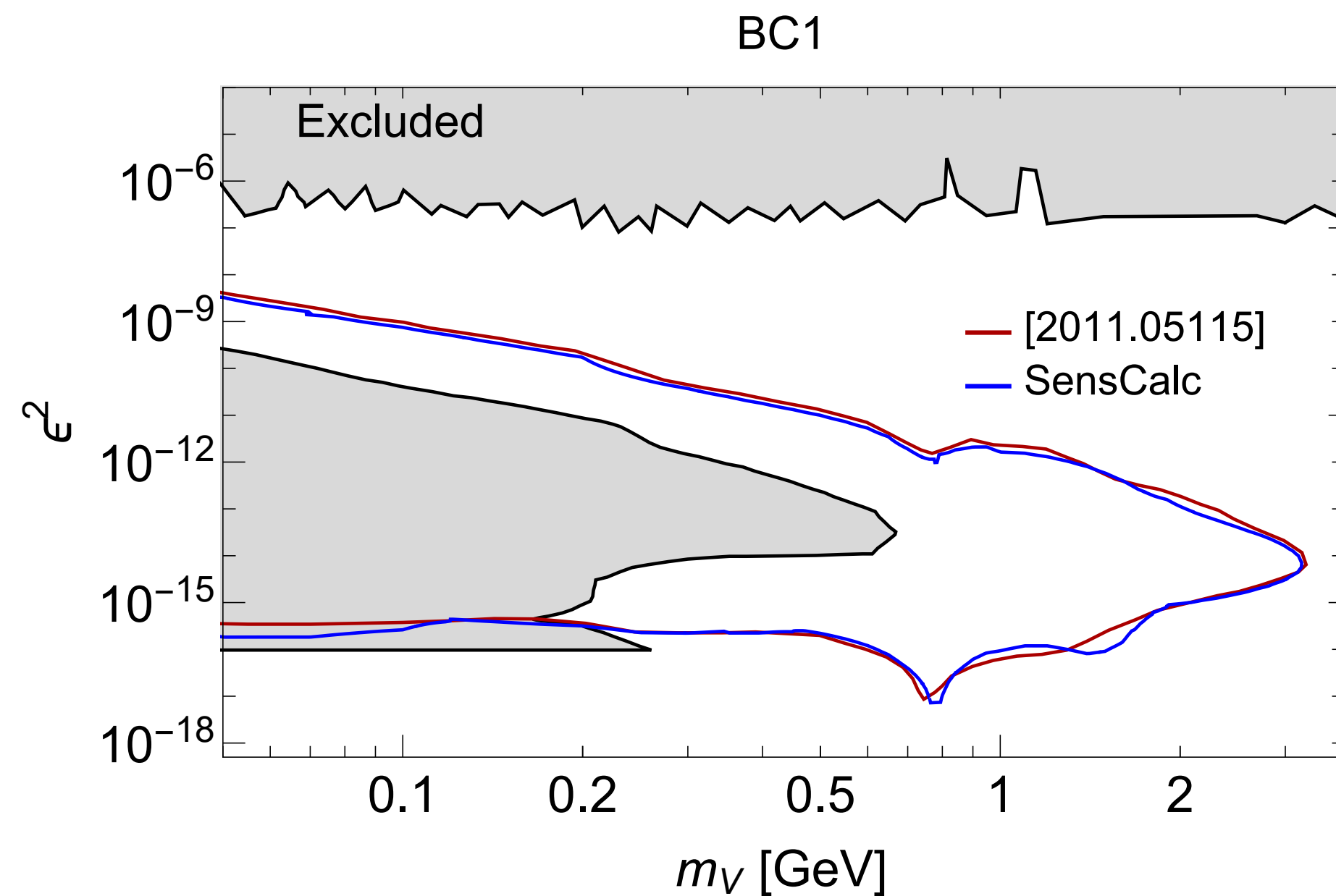
Validation against other packages

ALPINIST – BC9 (ALPs coupled to photons) – SHiP



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

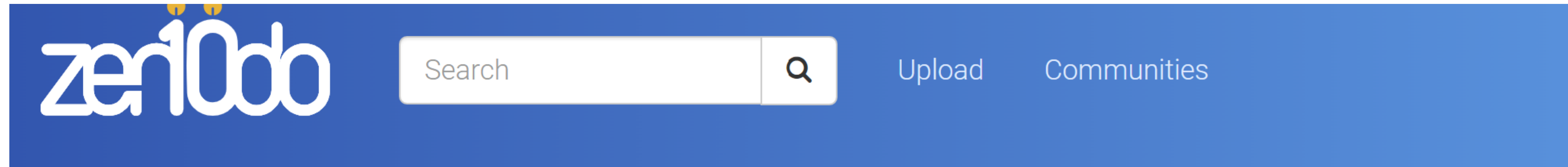
And more...

- FORESEE
- The LHCb simulation framework



Running SensCalc

[\[doi.org/10.5281/zenodo.7957784\]](https://doi.org/10.5281/zenodo.7957784)



May 22, 2023

Software

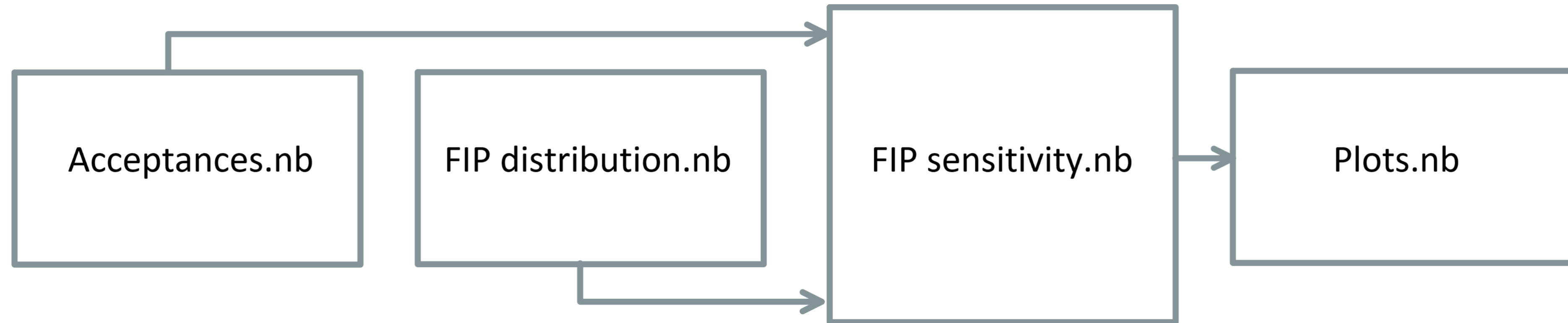
Open Access

SensCalc

- 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

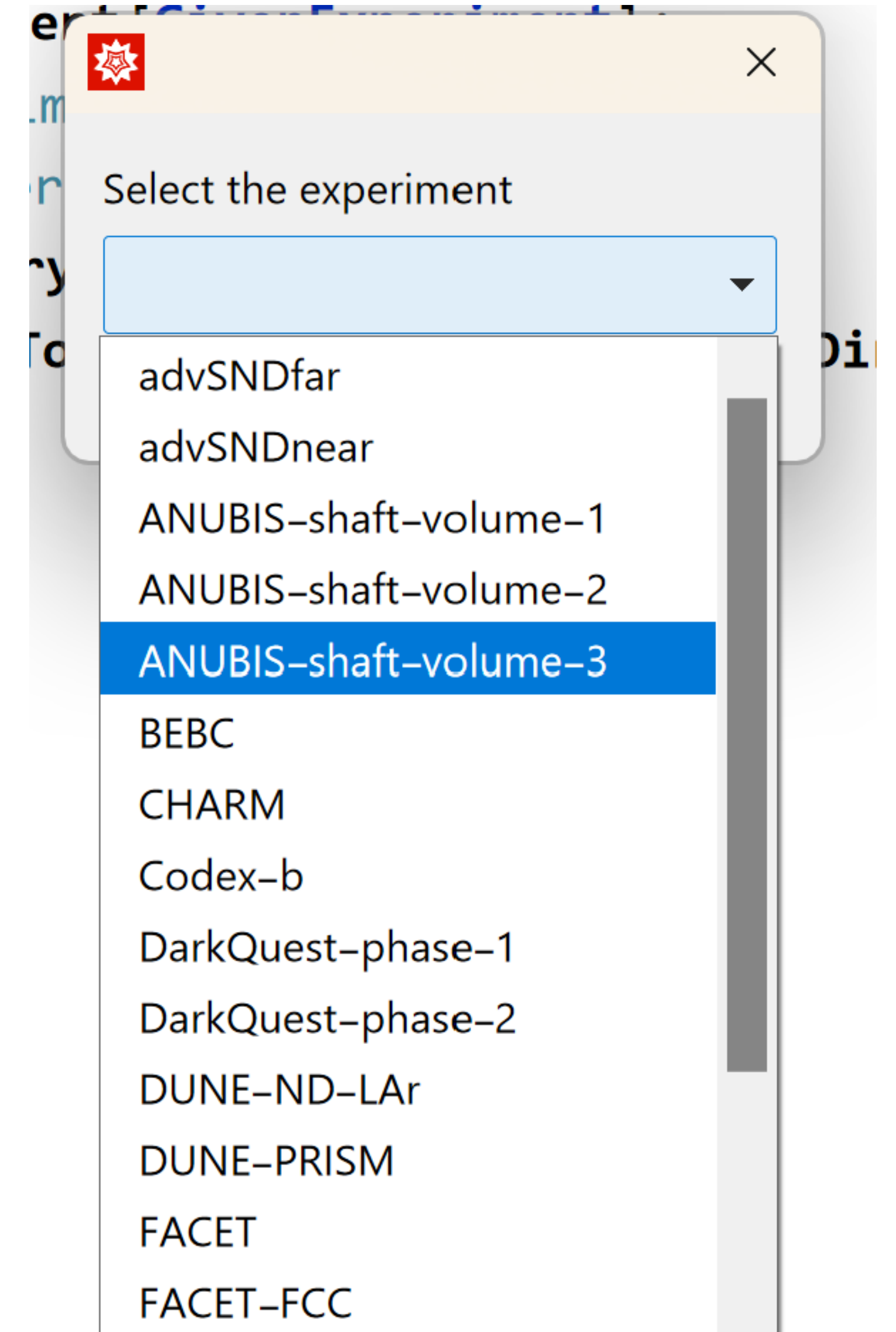


- **Acceptances.nb:** specify the geometry & acceptance criteria $\rightarrow \epsilon_{az}, \epsilon_{dec}$
- **FIP distribution.nb:** specify the facility & FIP \rightarrow FIP distribution
- **FIP sensitivity.nb:** compute the tabulated number of events & sensitivity
- **Plots.nb:** produce the sensitivity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

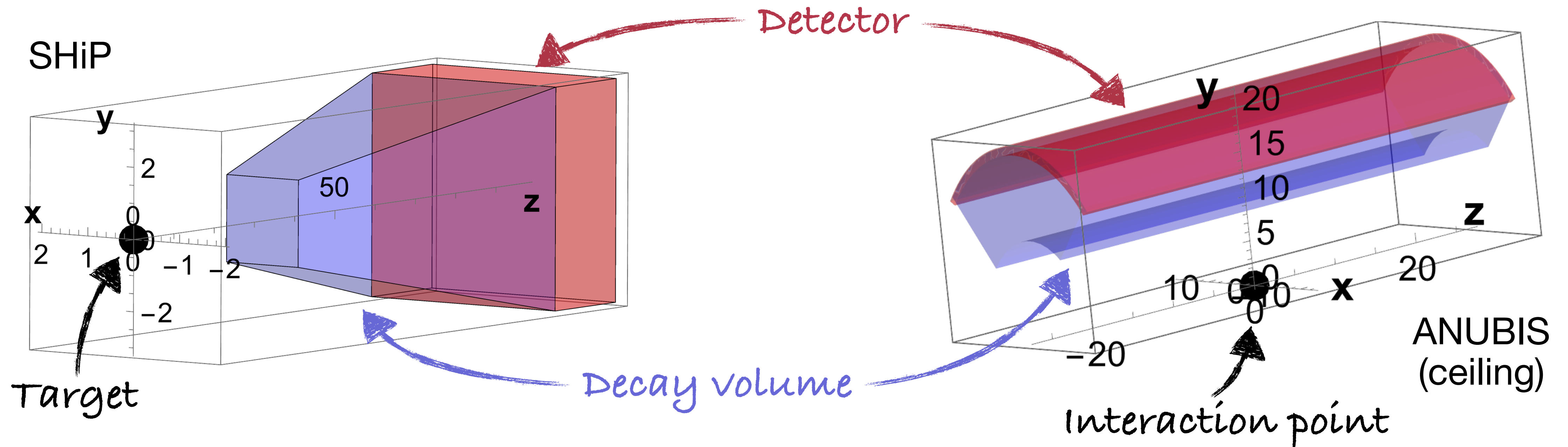
Running SensCalc

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



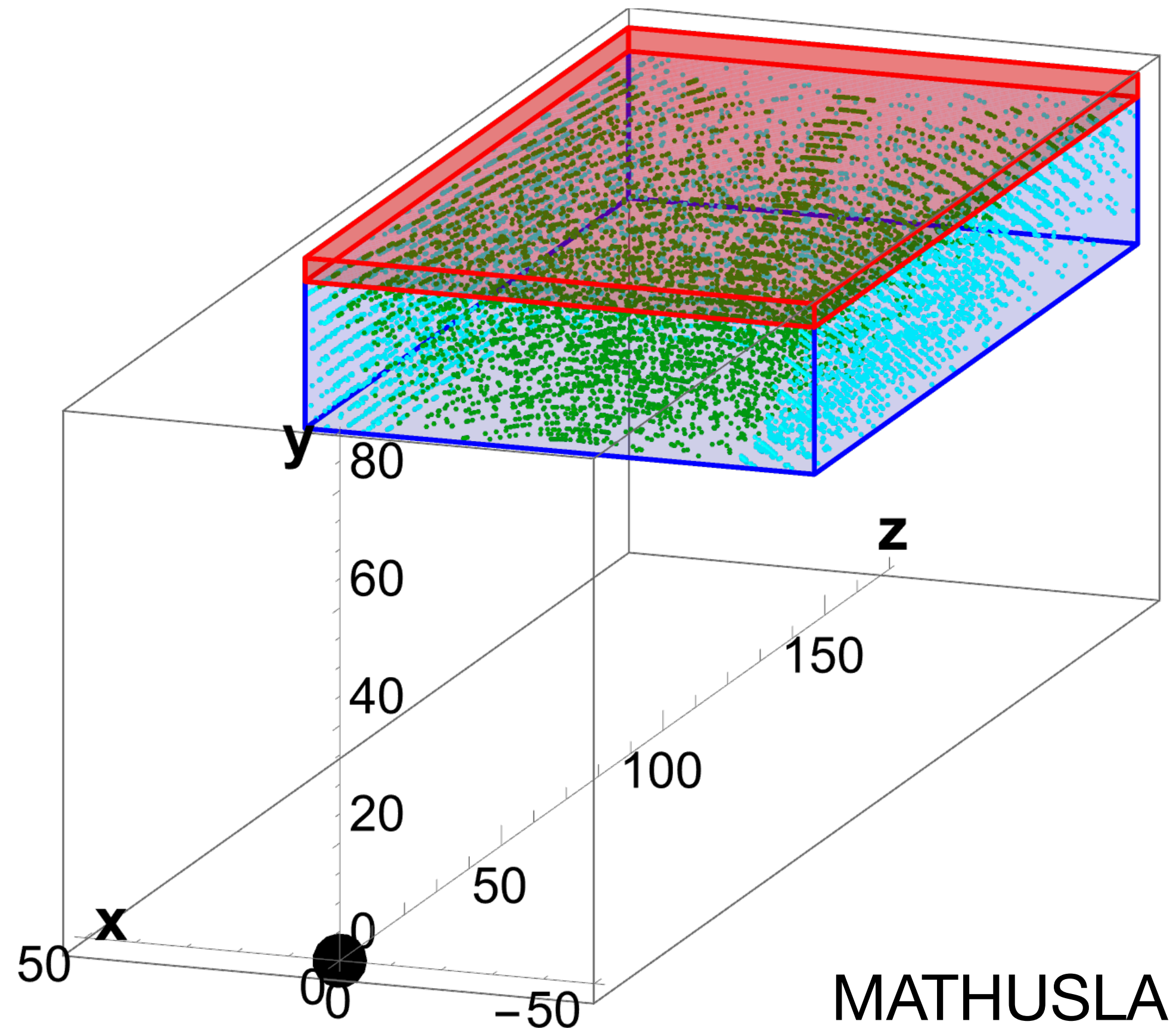
Acceptances.nb



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, θ, E, z, ϕ inside decay vol., $\epsilon_{az}(\theta, z)$

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

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

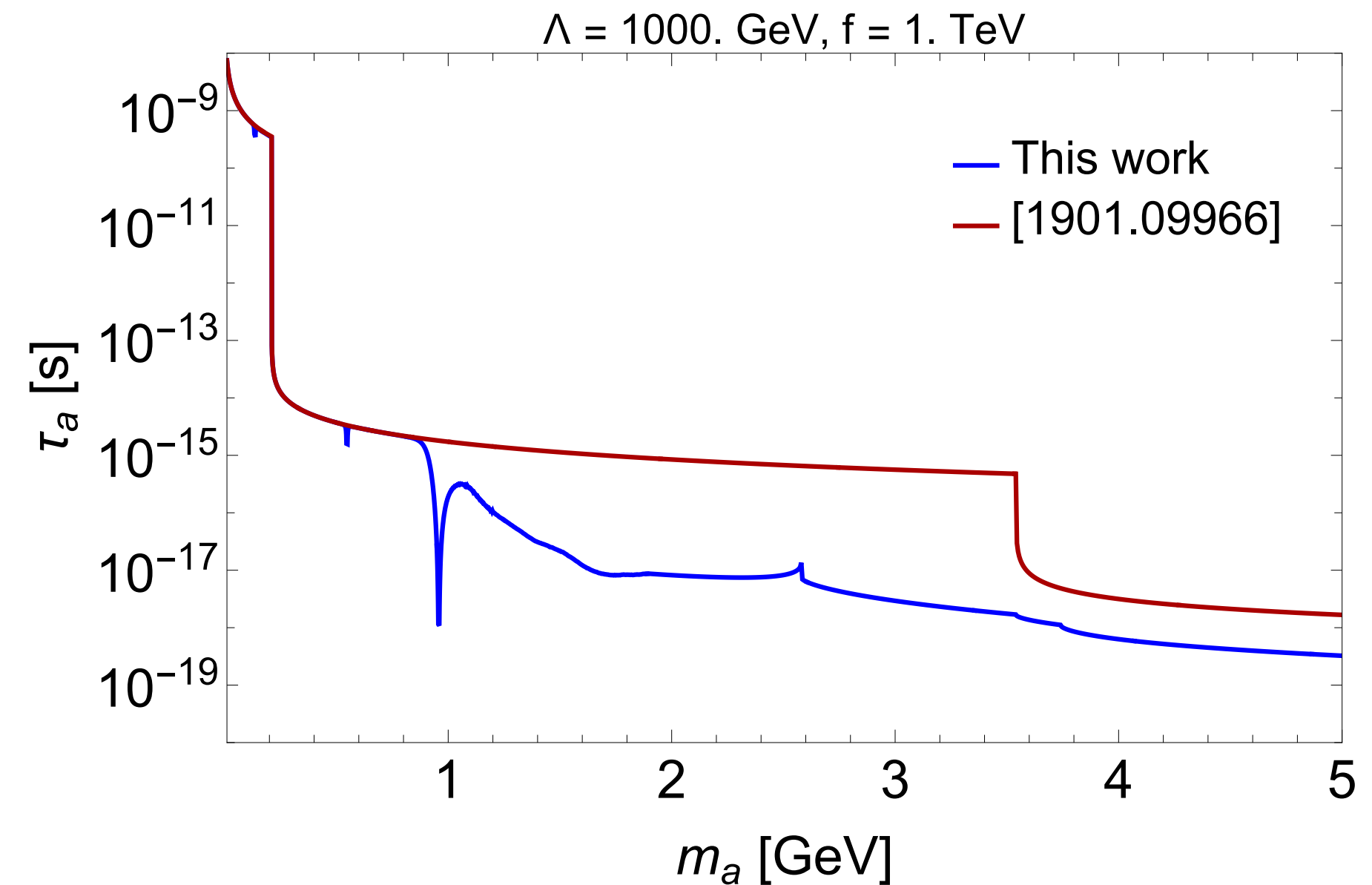
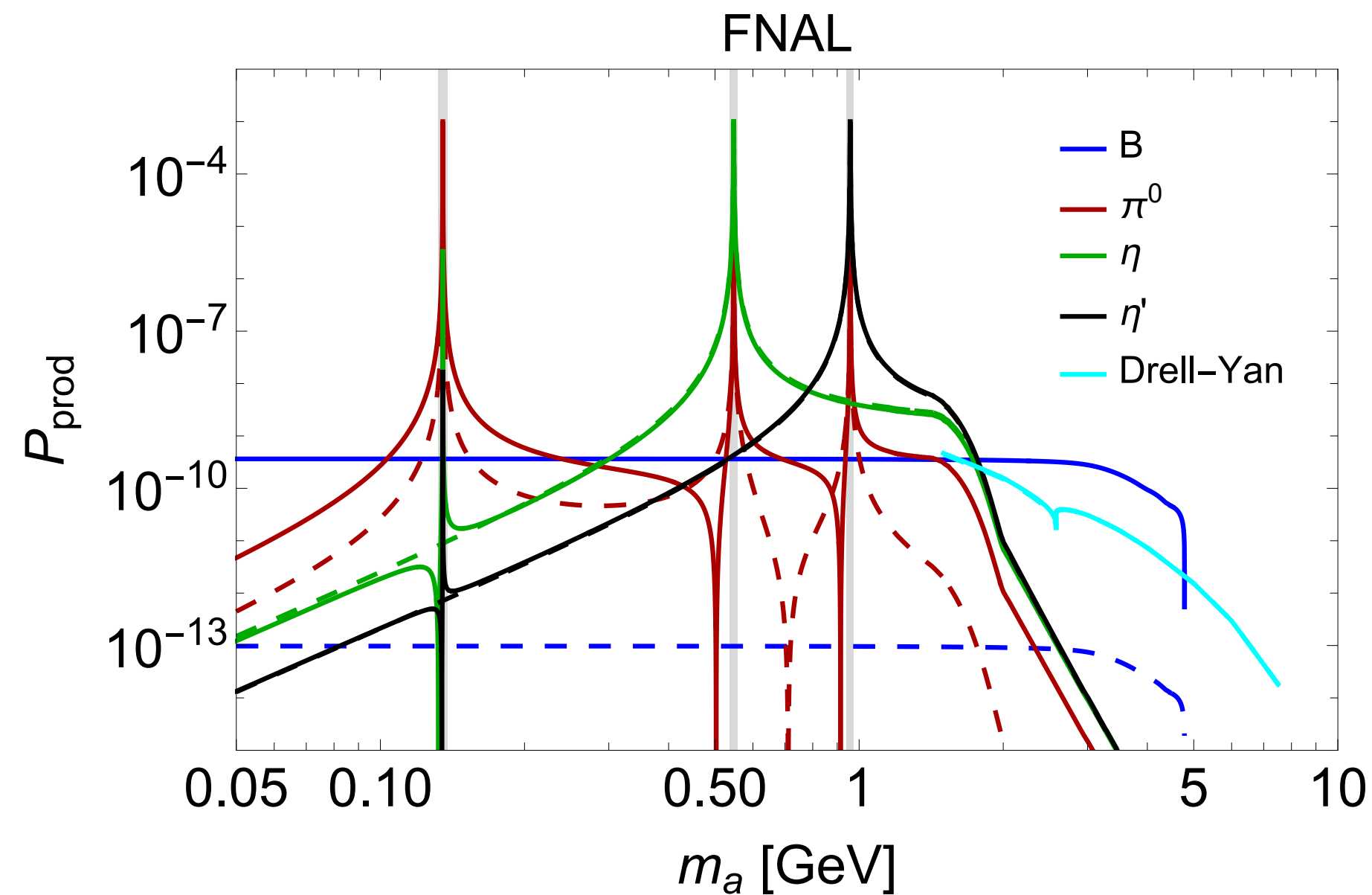
over all decay channels and azimuthal angles ϕ .

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

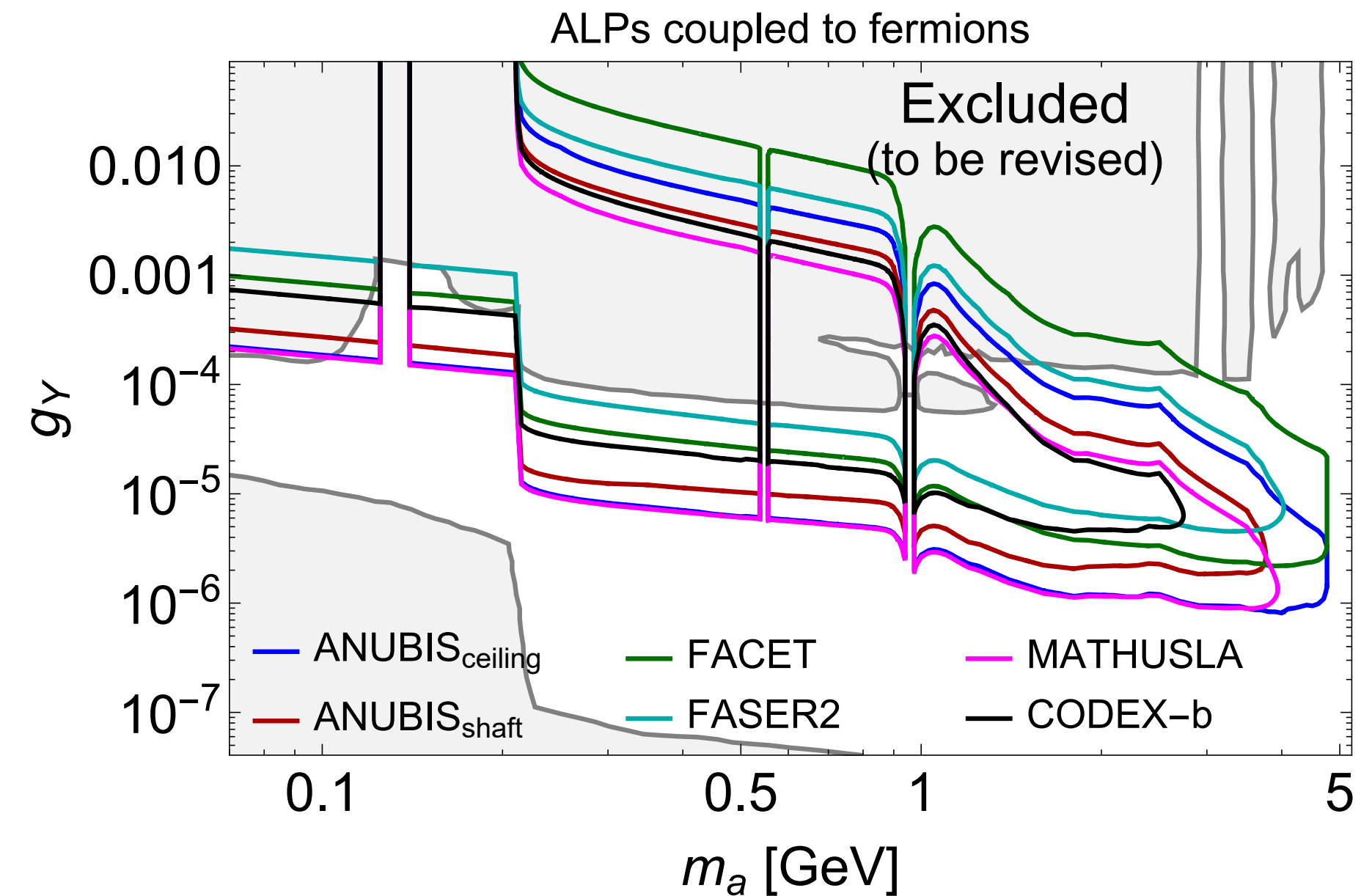
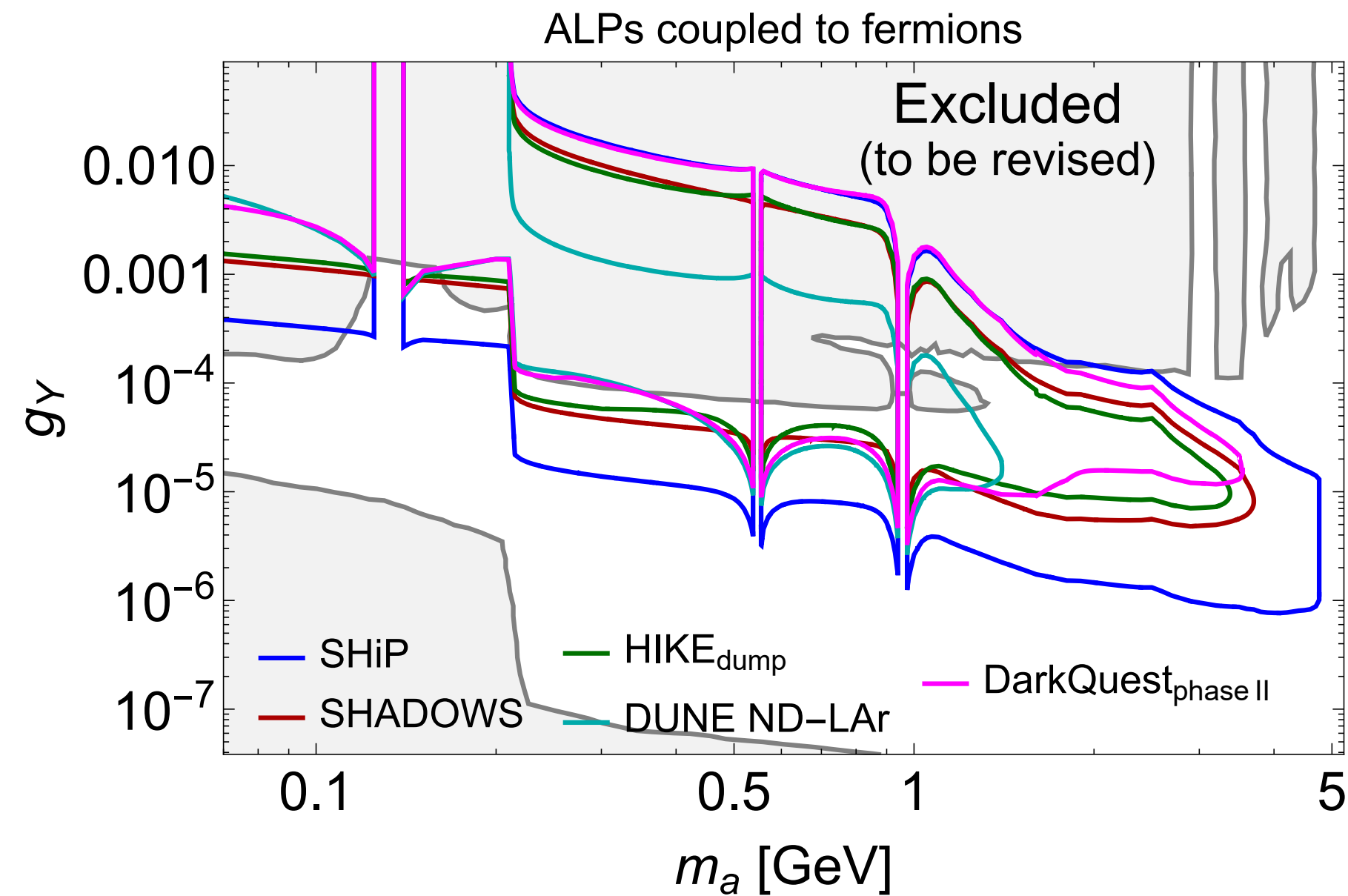
cf. Maksym's talks at [Light Dark World](#) and the [Brookhaven Forum](#) (tomorrow, online)



- 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!** [\[F. Kahlhoefer, G.D.V. Garcia, M. Ovchinnikov, A. Zaporozhchenko, in preparation\]](#)

Case study: ALP with fermion couplings

cf. Maksym's talks at [Light Dark World](#) and the [Brookhaven Forum](#) (tomorrow, online)



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
→ 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
→ 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...)

FASER2@FPF just added!