Universidad Autónoma de Madrid

Instituto de Física Teórica
UAM-CSIC

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> · CPAN · Santander · 2023-10-03

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

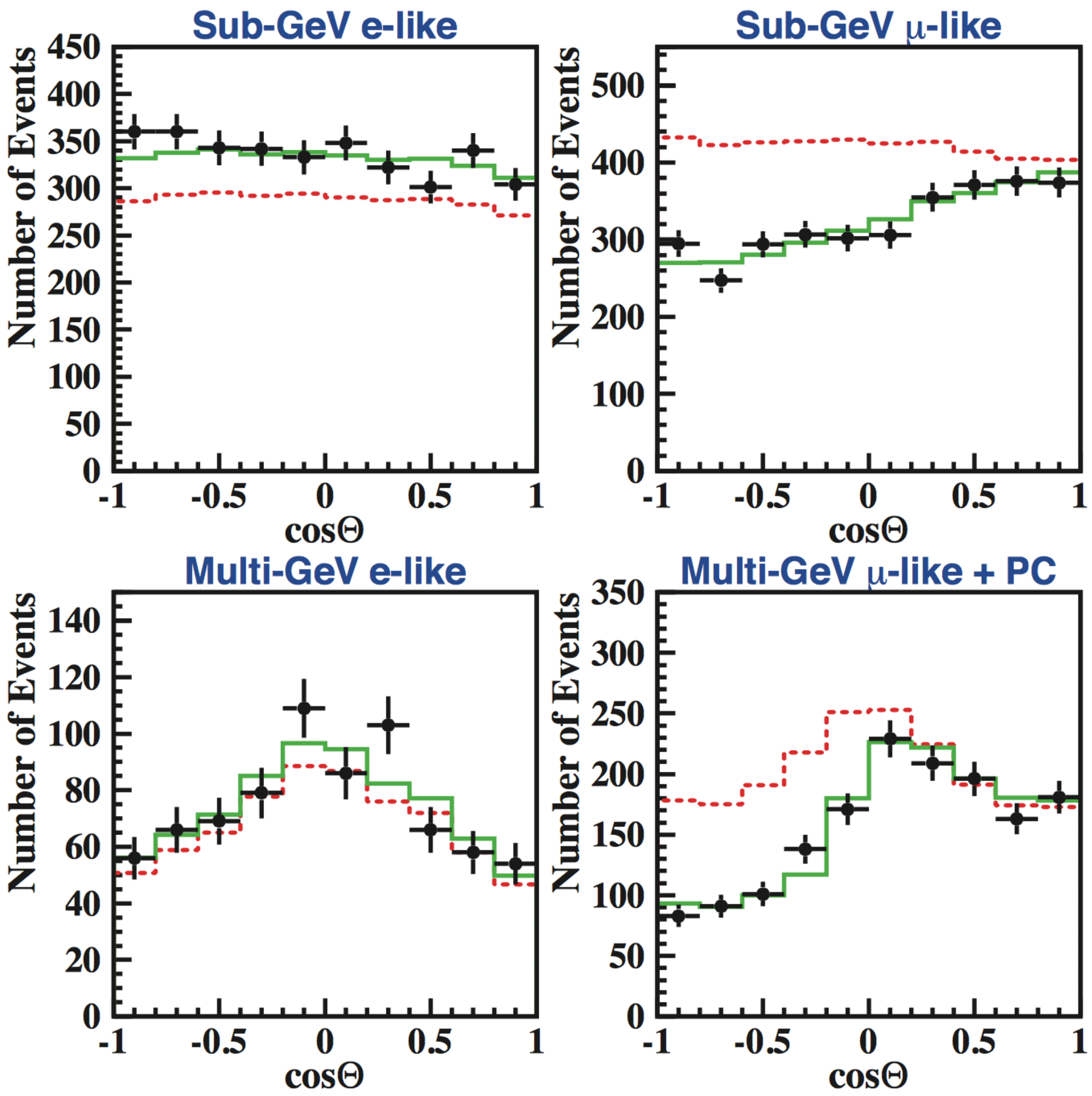
Limitations of the SM

Observational limitations

Limitations of the SM

Observational limitations

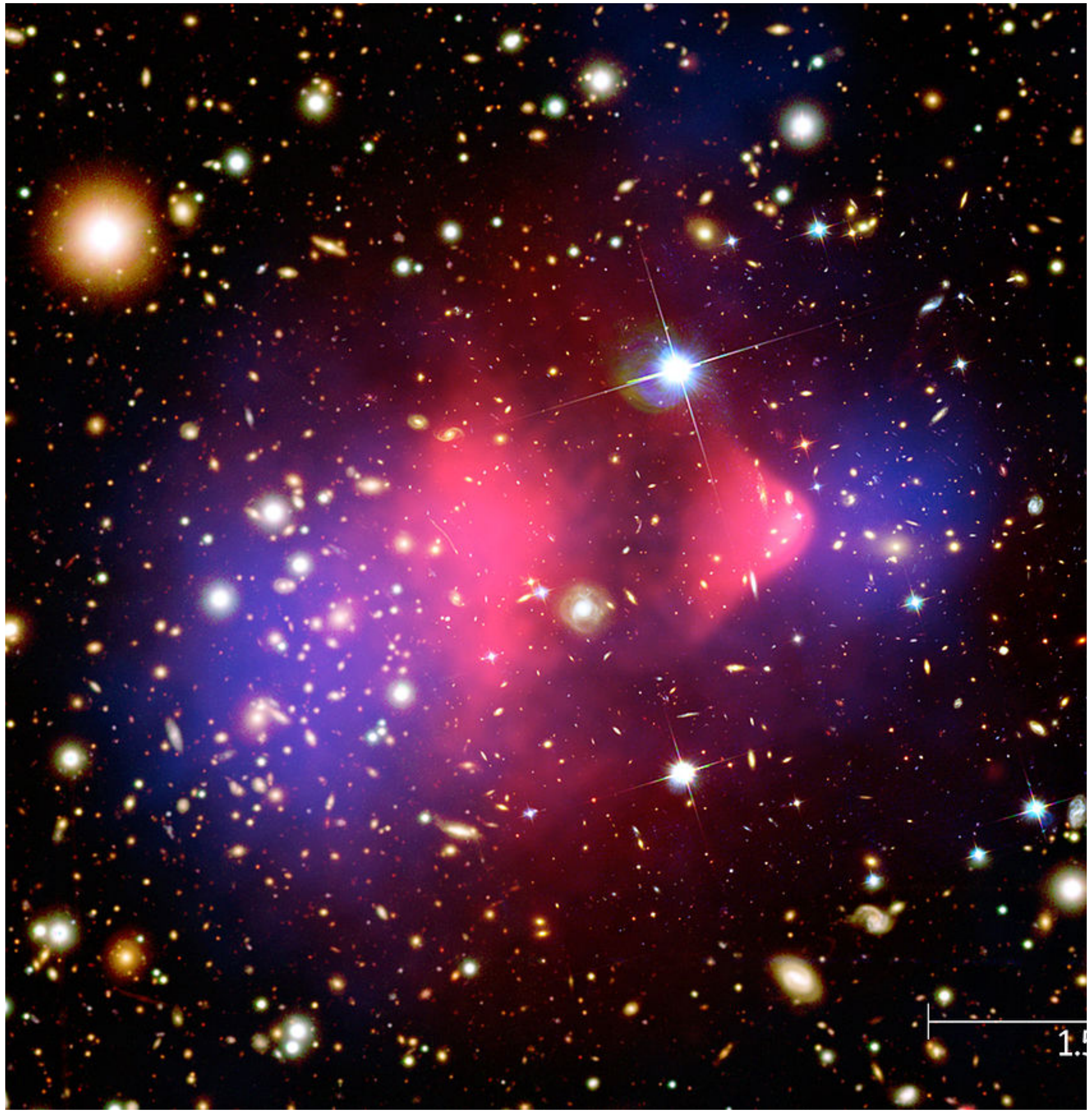
- Massless neutrinos
  $\Longrightarrow$ no oscillations



Limitations of the SM

Observational limitations

- Massless neutrinos
  $\implies$ no oscillations
- No dark matter



Limitations of the SM

Observational limitations

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

Limitations of the SM

Limitations of the SM

Theoretical limitations

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Theoretical limitations

- Higgs naturalness

Limitations of the SM

Theoretical limitations

- Higgs naturalness
- Strong CP problem

Limitations of the SM

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- Higgs naturalness
- Strong CP problem
- Flavour puzzle

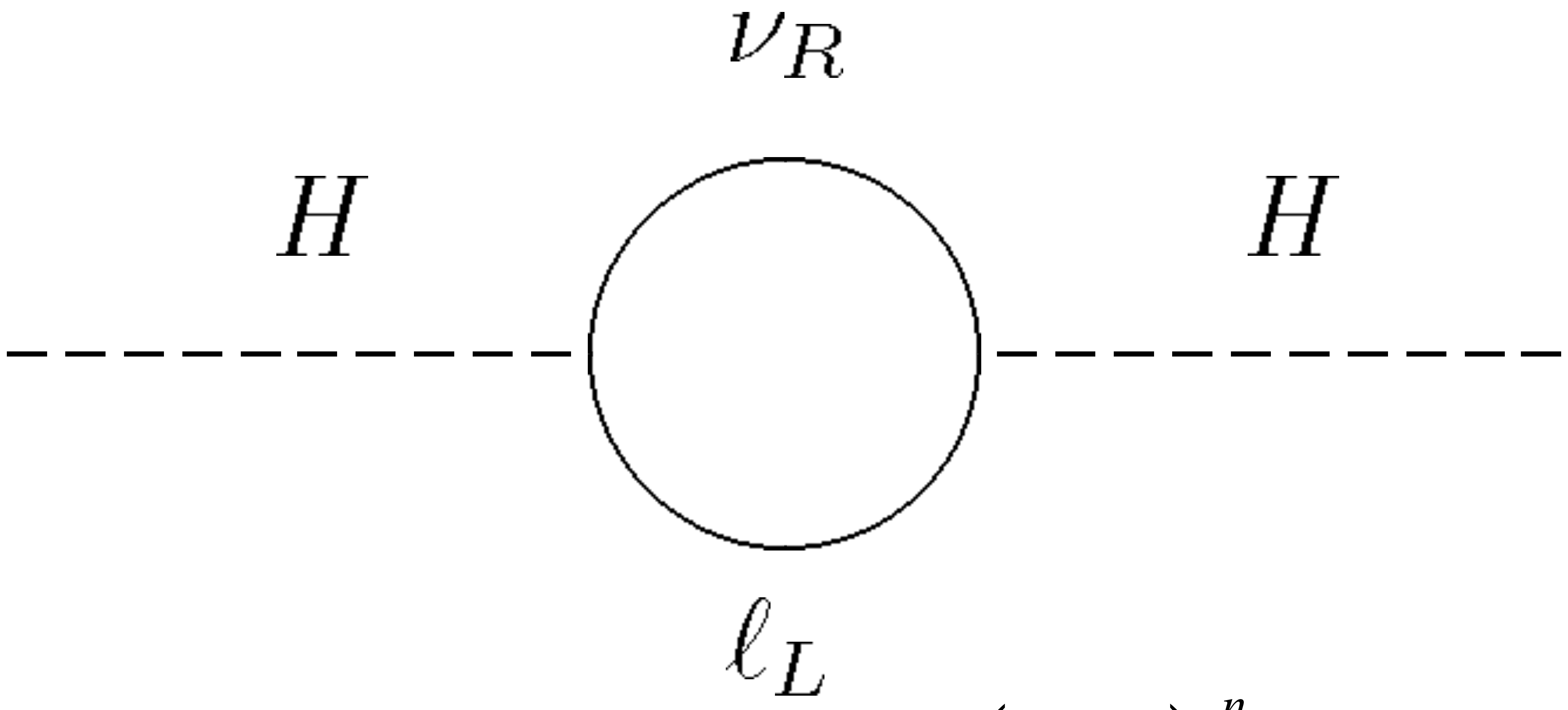
Limitations of the SM

Theoretical limitations

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

Limitations of the SM

- Higgs naturalness



Threshold correction $\delta\mu^2 \sim \left(\frac{g^2}{16\pi^2}\right)^n M^2$

(n = loop order at which the new particle appears)

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

The 5 portals

$d = 4$

- Scalar portal / dark Higgs S: $\mu_{\mathrm{HS}} S\phi^\dagger\phi$, $\lambda_{\mathrm{HS}} S^2\phi^\dagger\phi$
- Heavy neutral lepton / right-handed neutrino ν_R: $-Y^\nu_\alpha (L^\dagger_\alpha \cdot \tilde{\phi})\nu^\dagger_R$
- Vector portal / dark photon A': $\epsilon F'_{\mu\nu}F^{\mu\nu}$ (kinetic mixing with the SM photon)
- Millicharged particle χ: $\epsilon\bar{\chi}\not{A}\chi$ (coupled to very light dark photon)

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$d = 5$

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

The 5 portals

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Example: Heavy neutral leptons (HNLs)

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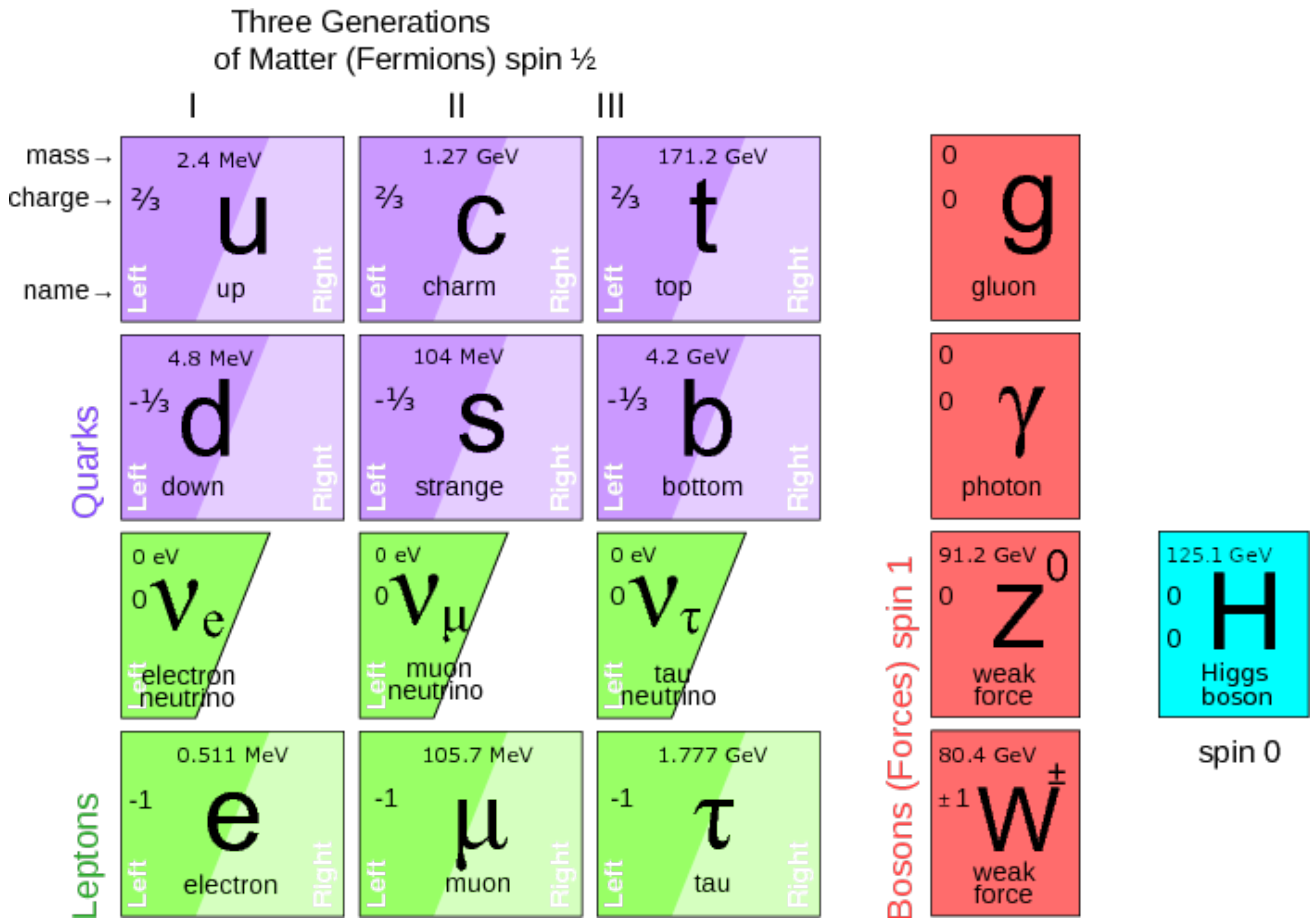
- No $SU(2)_L$ singlet ν_R in the SM



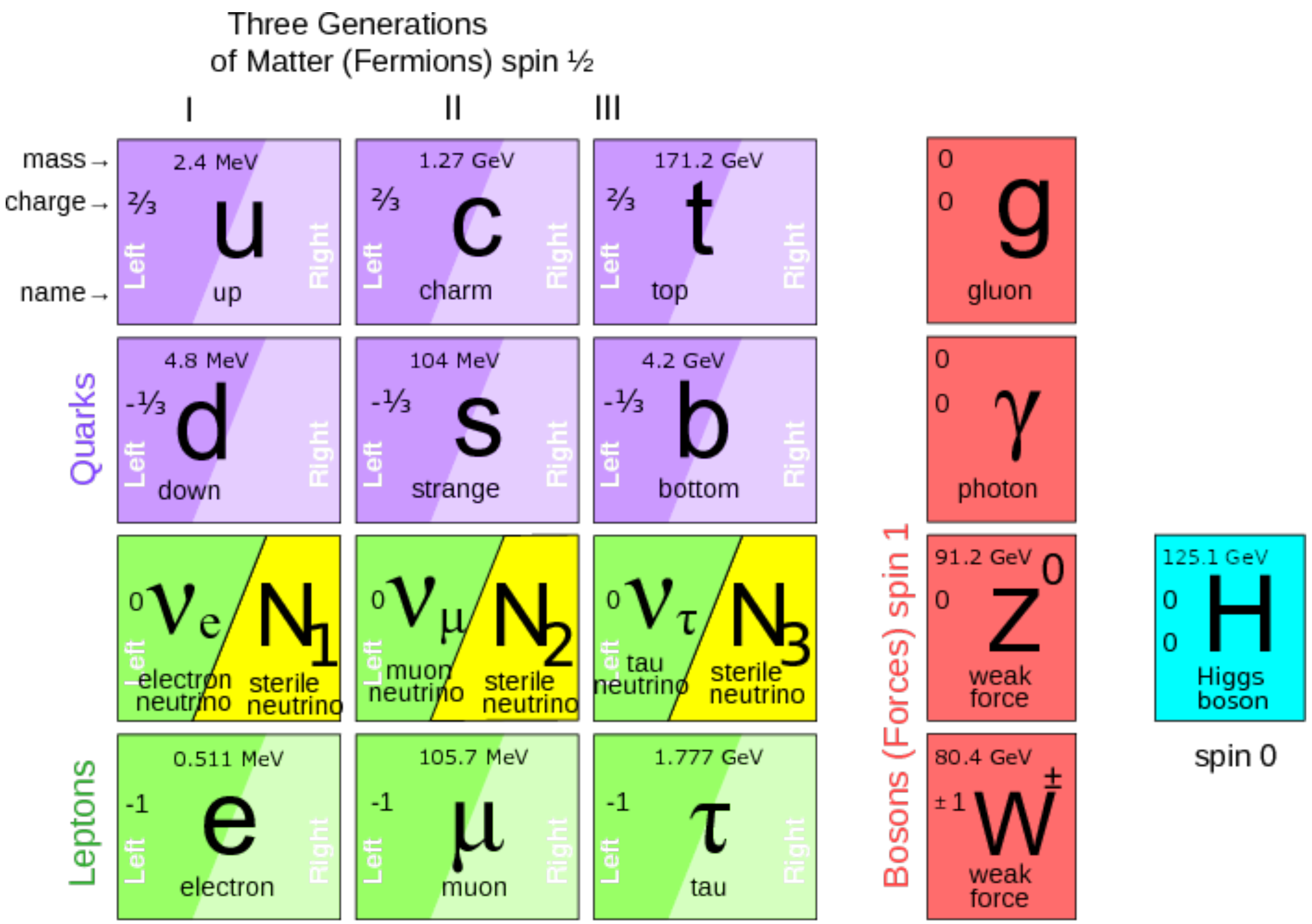
Example: Heavy neutral leptons (HNLs)

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

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

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

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



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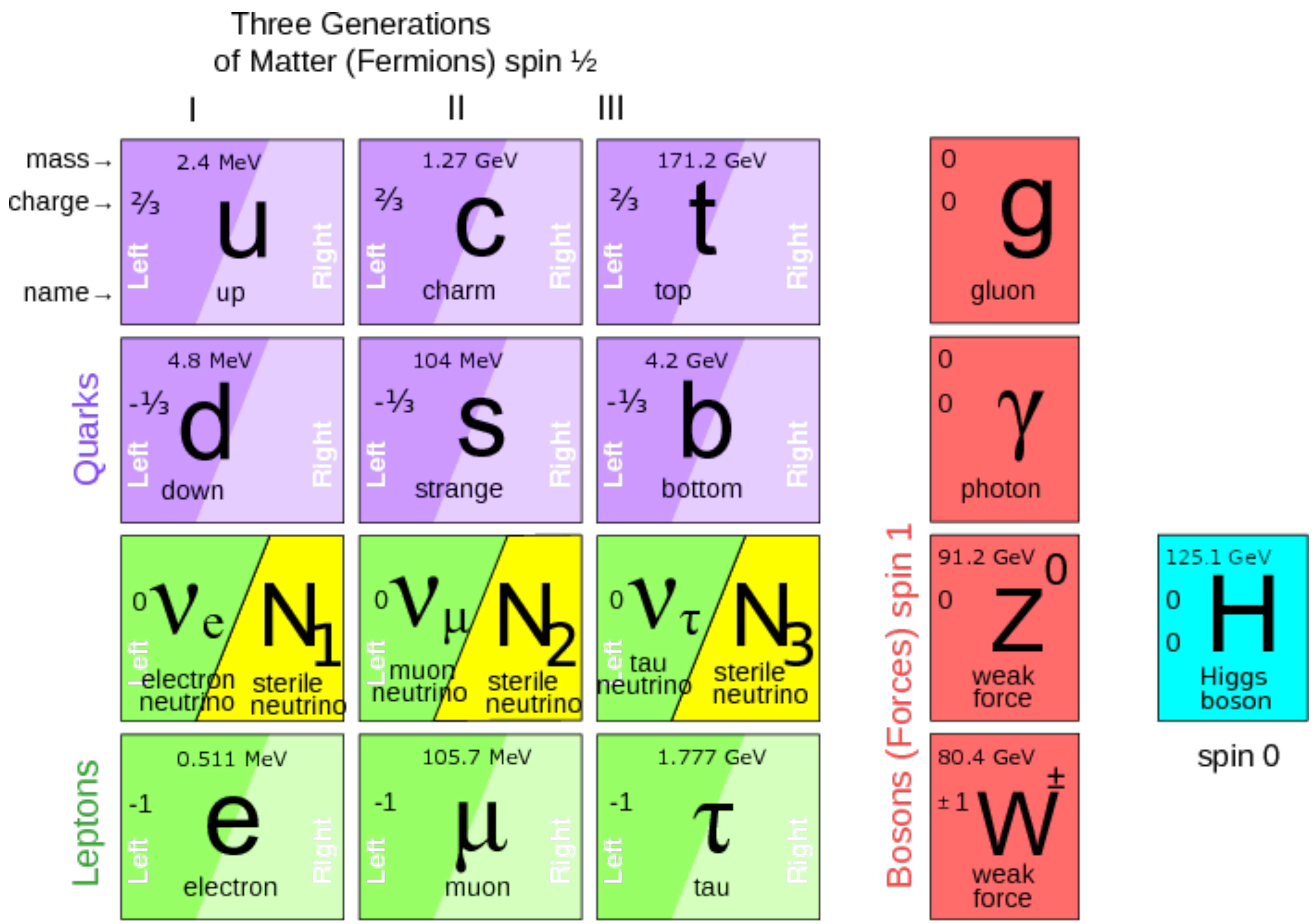
(where $\alpha = e, \mu, \tau$, $I = 1,2,\ldots,N_{\mathrm{HNL}}$)

- SM singlets can have a Majorana mass:

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



Example: Heavy neutral leptons (HNLs)

The see-saw mechanism

- Both mass terms are allowed: $-\frac{1}{2}\begin{pmatrix}\nu_L^T & \nu_R^T\end{pmatrix}\begin{pmatrix}0 & m_D^T \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix} + \mathrm{h.c.}$

- Mass diagonalisation leads to mixing: $\nu_{L,\alpha} \cong U^{\mathrm{PMNS}}_{\alpha,i}\nu_i + \Theta_{\alpha,I}\nu_{R,I}$

- 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:

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

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

How to search for FIPs

Feeble interactions lead to:

- Suppressed production rate

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Solution

- High intensity / luminosity
- Low background

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- A possibly long lifetime:
  the particle may travel a long
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- Low background

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

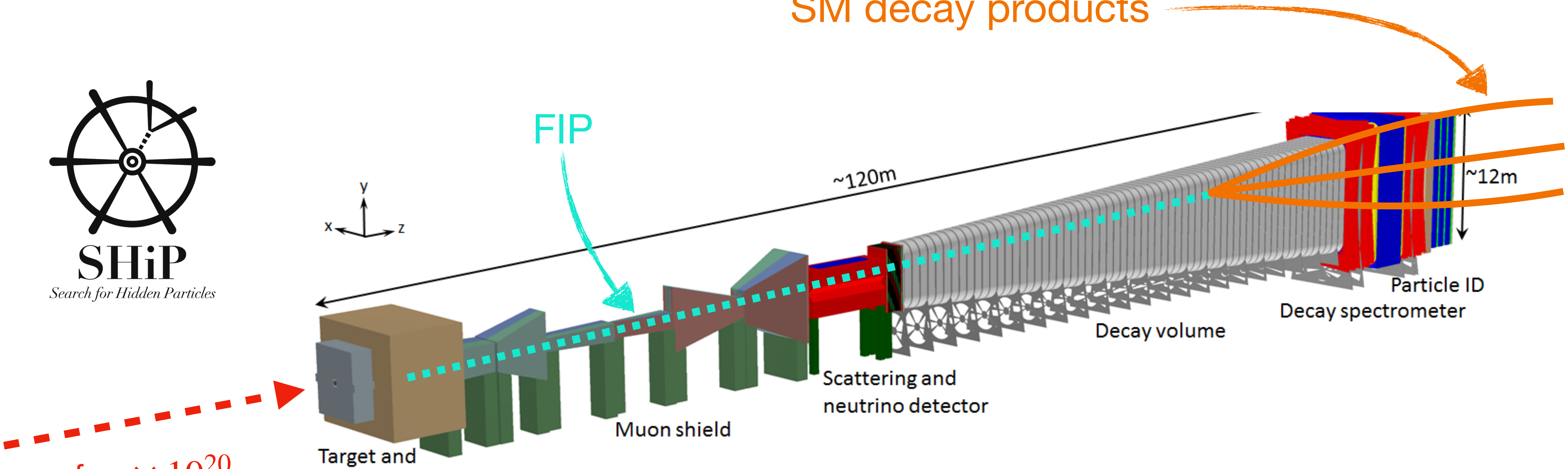
Solution

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

Example: SHiP

(Search for HIdden Particles)

SHiP
Search for Hidden Particles

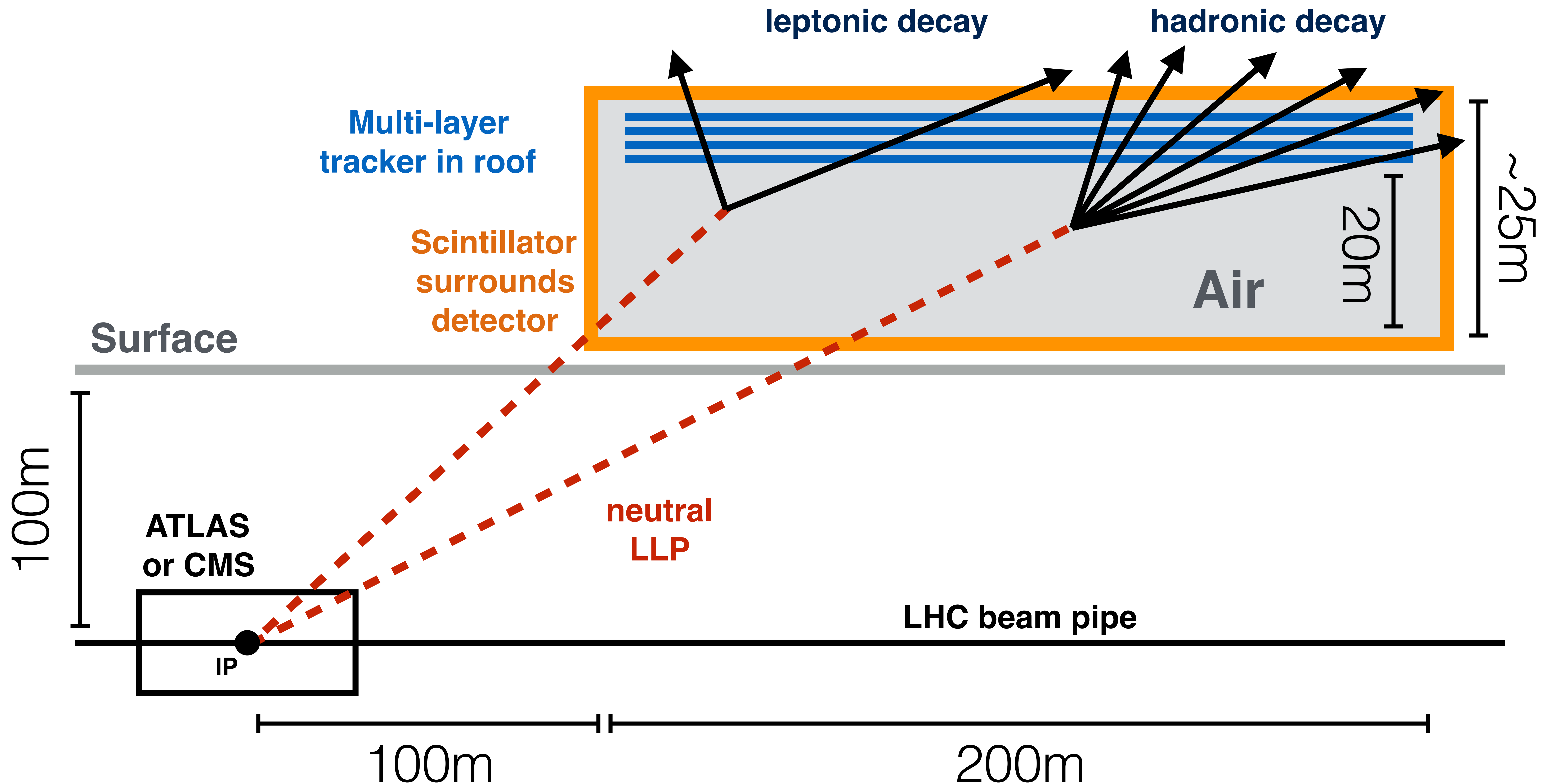

SM decay products

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

[1504.04956, 1504.04855, 2112.01487]

Example: MATHUSLA

(Massive Timing Hodoscope for Ultra Stable neutraL pArticles)

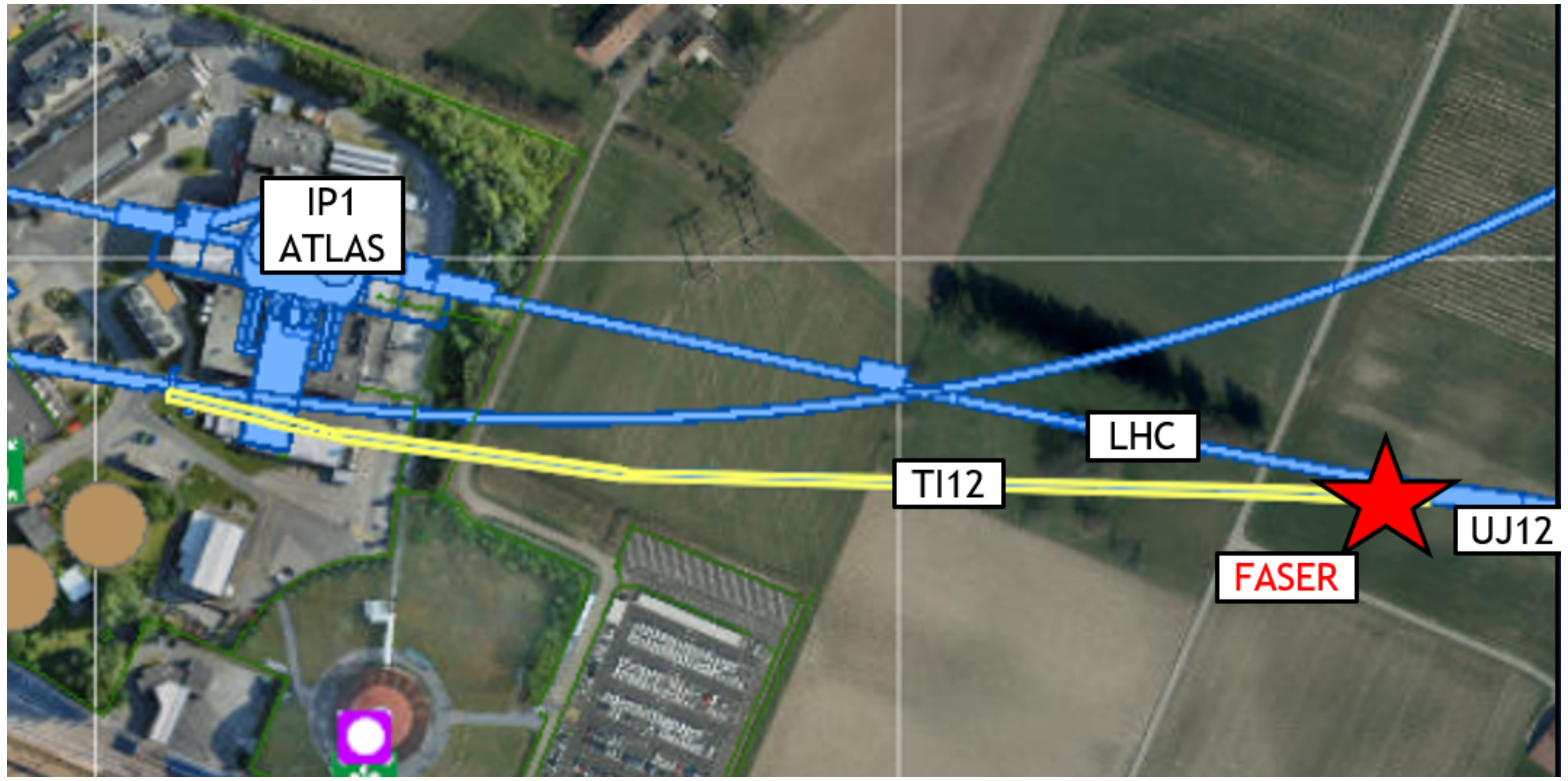


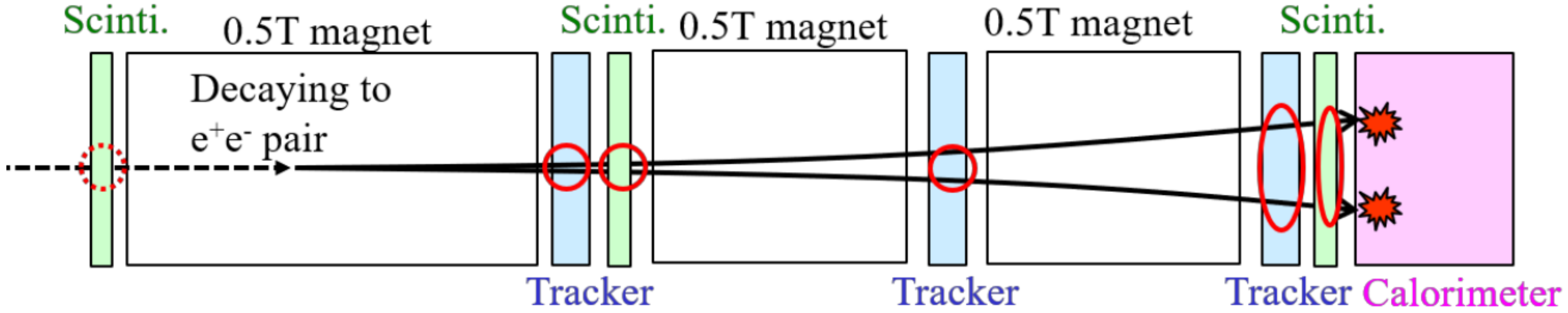
[1606.06298, 1806.07396, 1811.00927]

Example: FASER

(Forward search experiment at the LHC)

First physics results!
[2303.14185]



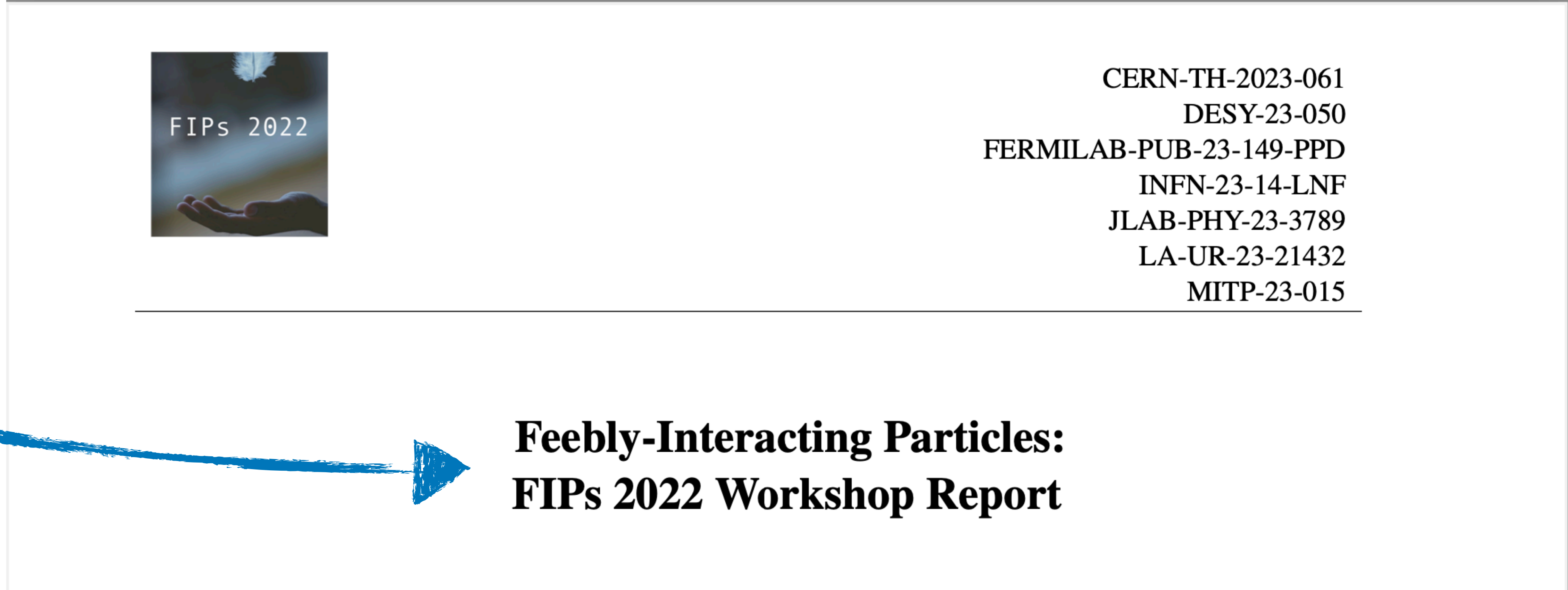


[1811.10243, 1812.09139]

And more!

A plethora of proposed experiments

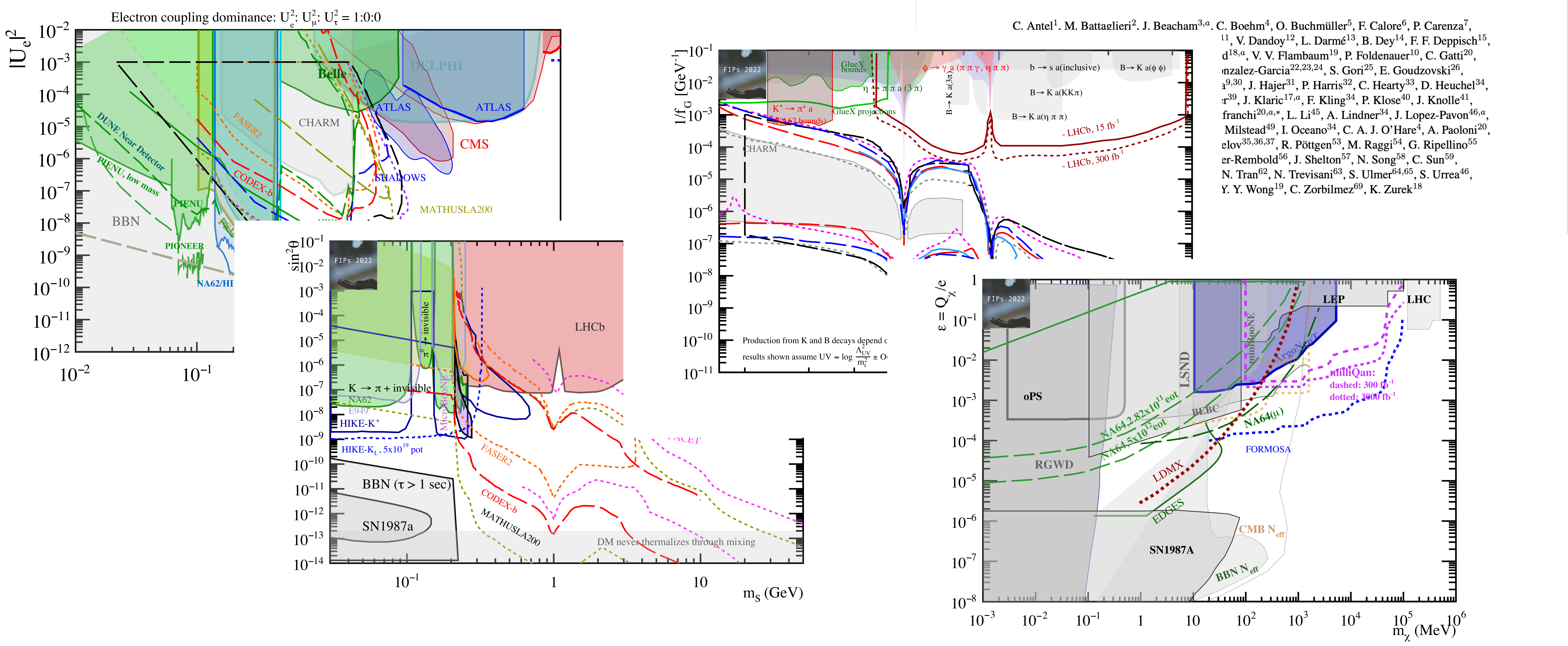
More info here!
[2305.01715]



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

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]



May 22, 2023

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!

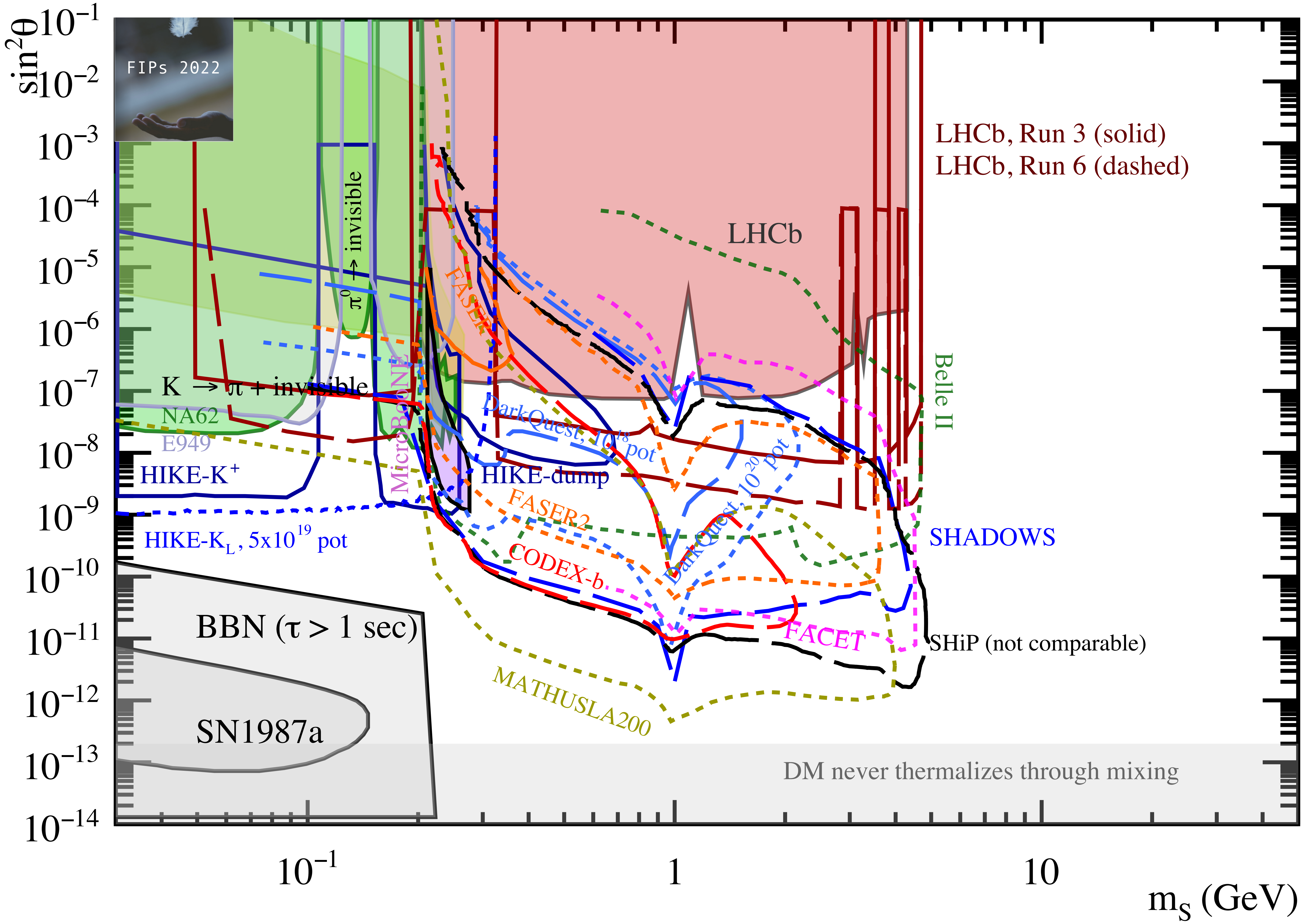
The list of changes compared to the previous version (1.0.4):

- 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?

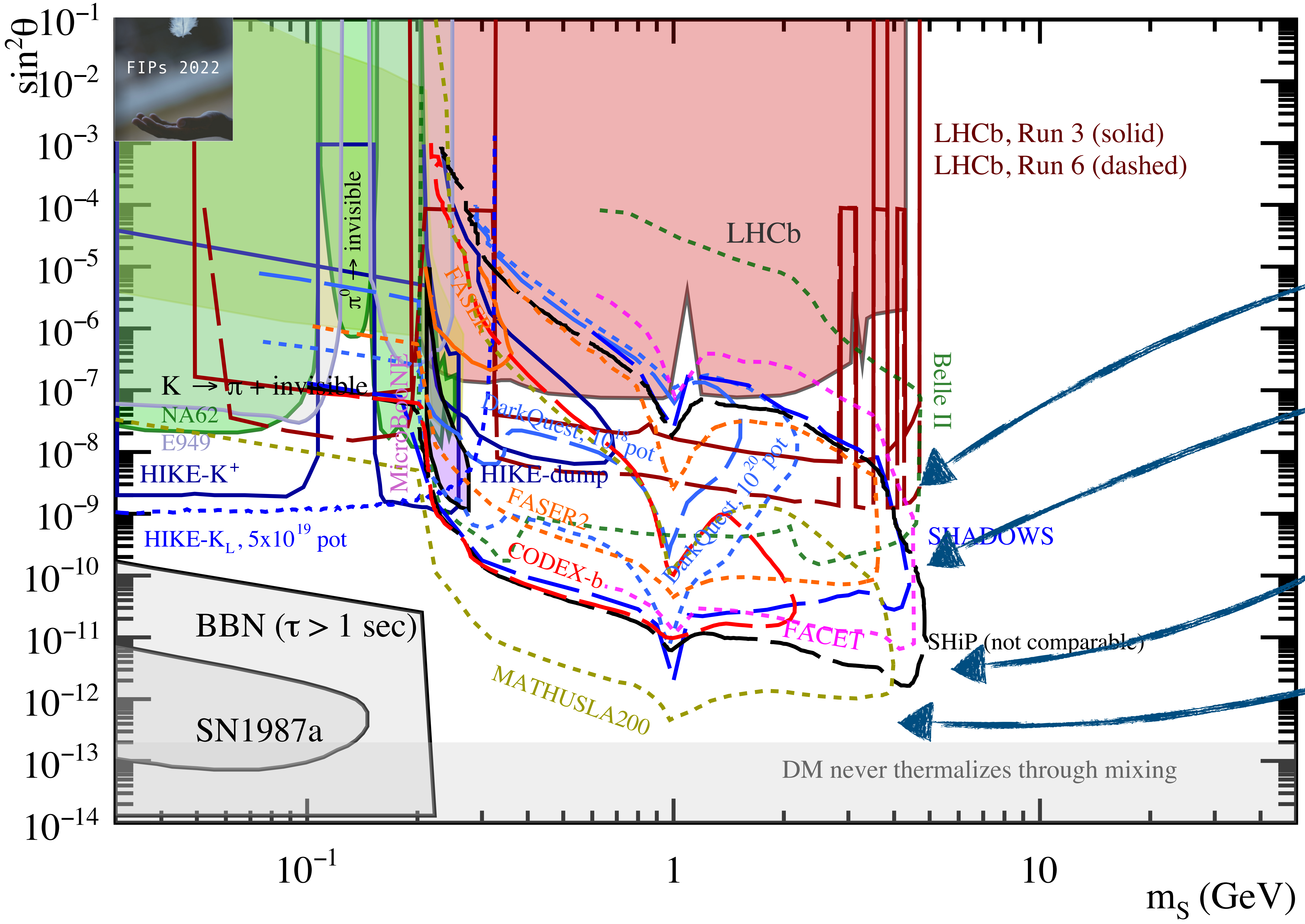
https://xkcd.com/927/

The problem


FIPs 2022
$\sin^2\theta$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-1}
1
10
m_S (GeV)
LHCb, Run 3 (solid)
LHCb, Run 6 (dashed)
LHCb
Belle II
$\pi^0 \to$ invisible
$K \to \pi$ + invisible
NA62
E949
HIKE-K^+
MicroBooNE
FASER
DarkQuest, 10^{18} pot
DarkQuest, 10^{20} pot
HIKE-dump
FASER2
HIKE-K_L, 5×10^{19} pot
CODEX-b
SHADOWS
FACET
SHiP (not comparable)
MATHUSLA200
BBN ($\tau > 1$ sec)
SN1987a
DM never thermalizes through mixing

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

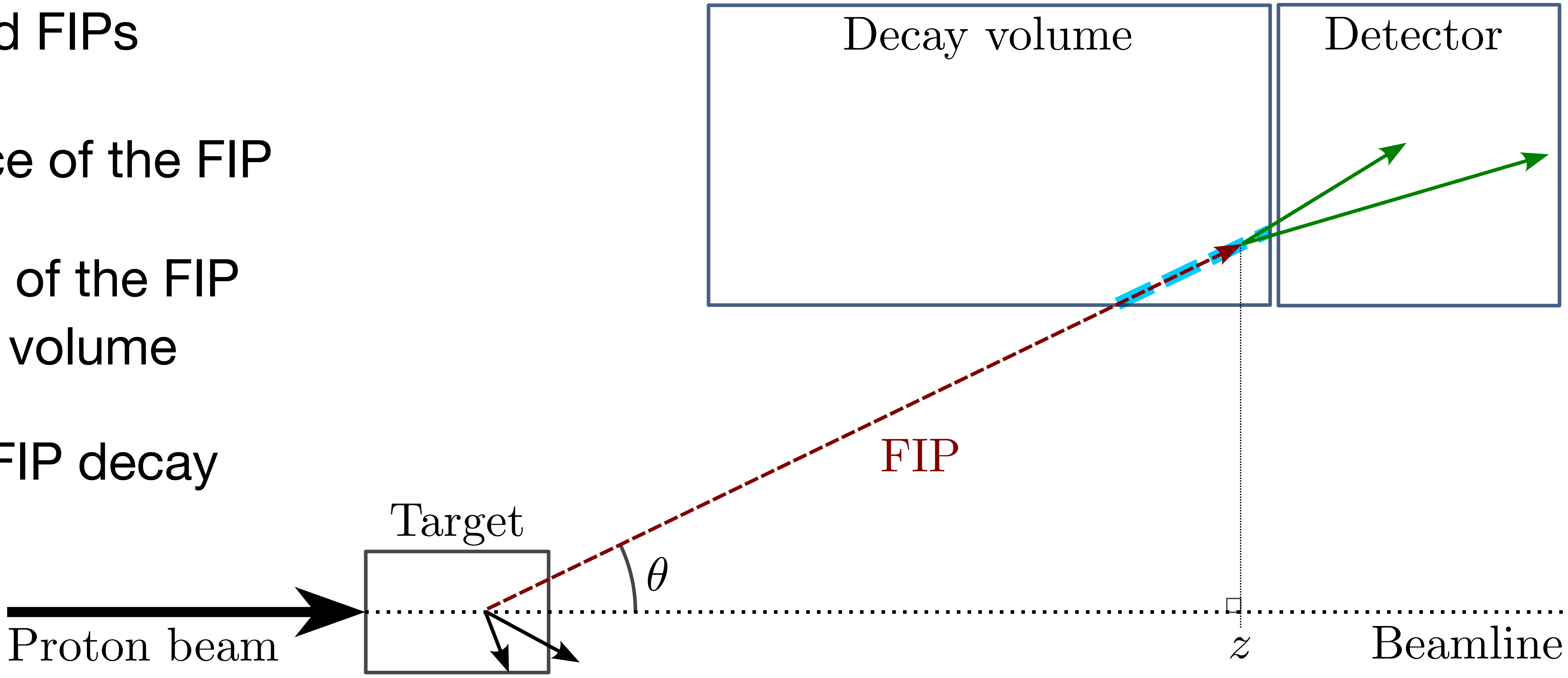
- Dark photons
- Dark scalars (mixing & quartic coupling)
- HNLs (with arbitrary mixing pattern)
- ALPs (coupled to gluons, photons, fermions)
- Anomaly-free U(1) mediators

Semi-analytic estimate

Experimental setup & naive estimate

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

- 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

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

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

Semi-analytical ⟷ Monte-Carlo equivalence

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 ⟷ Monte-Carlo equivalence

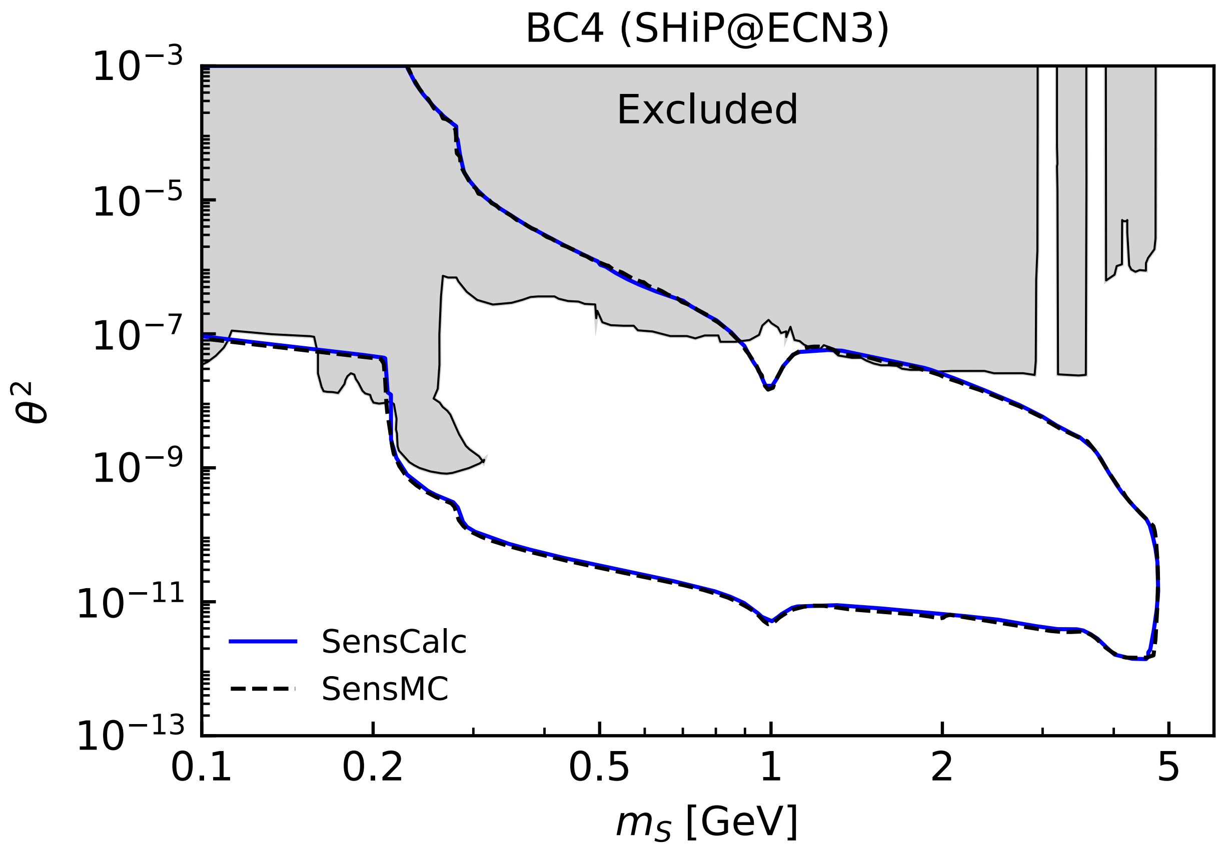
SensCalc
(main package)

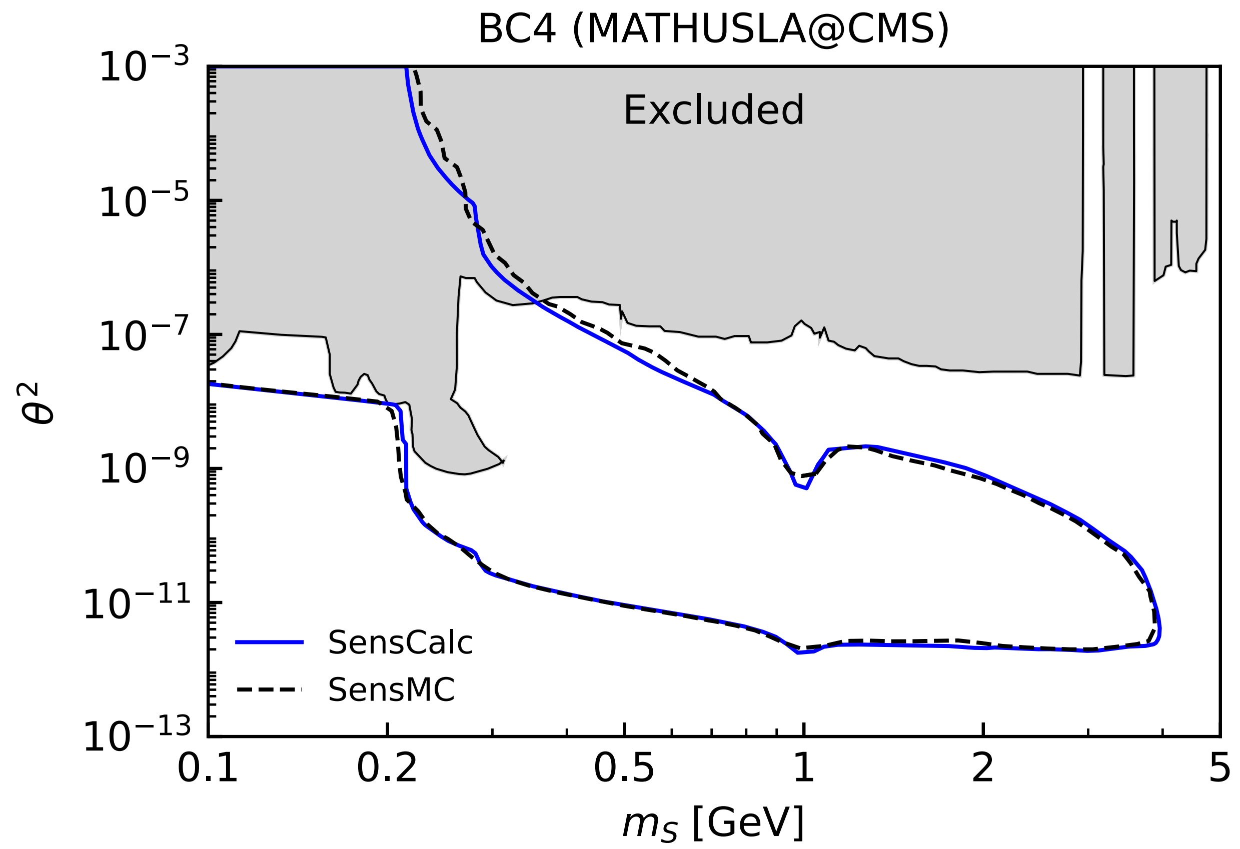
SensMC
(for validation, limited functionality)

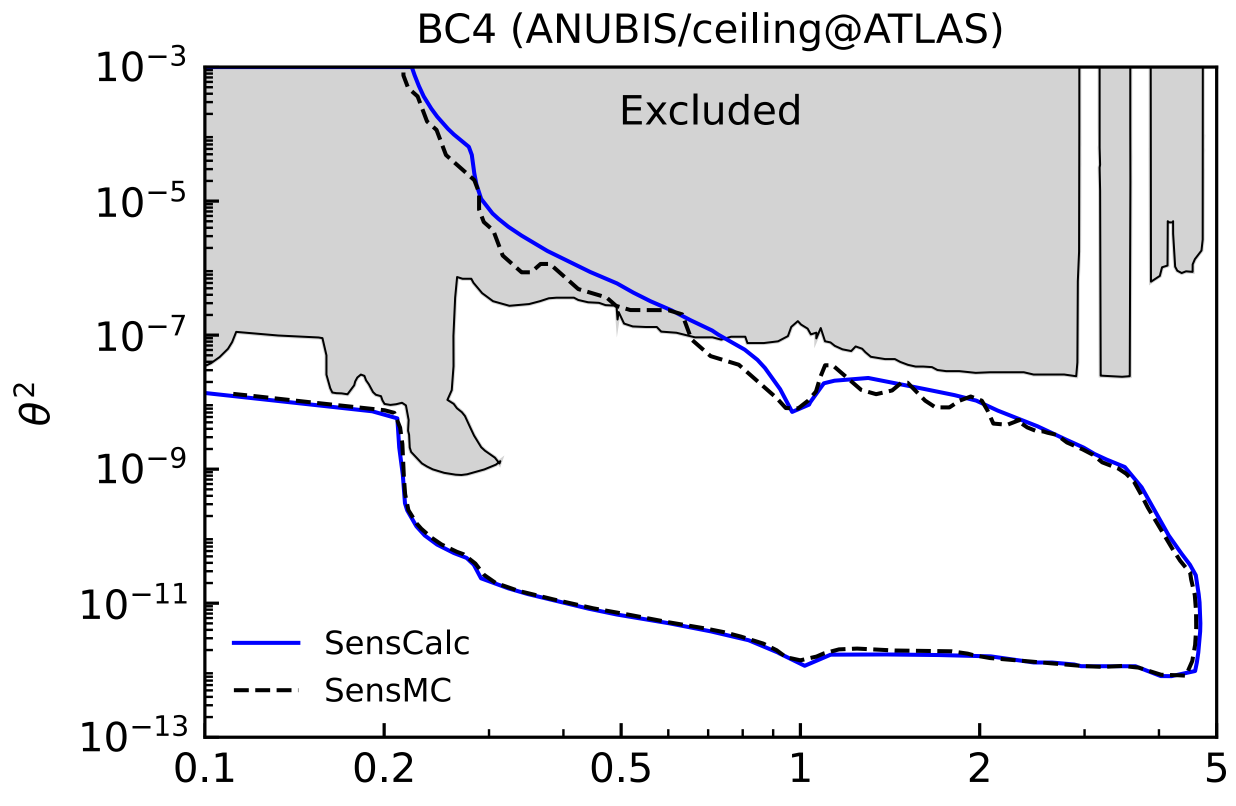
Semi-analytical estimate

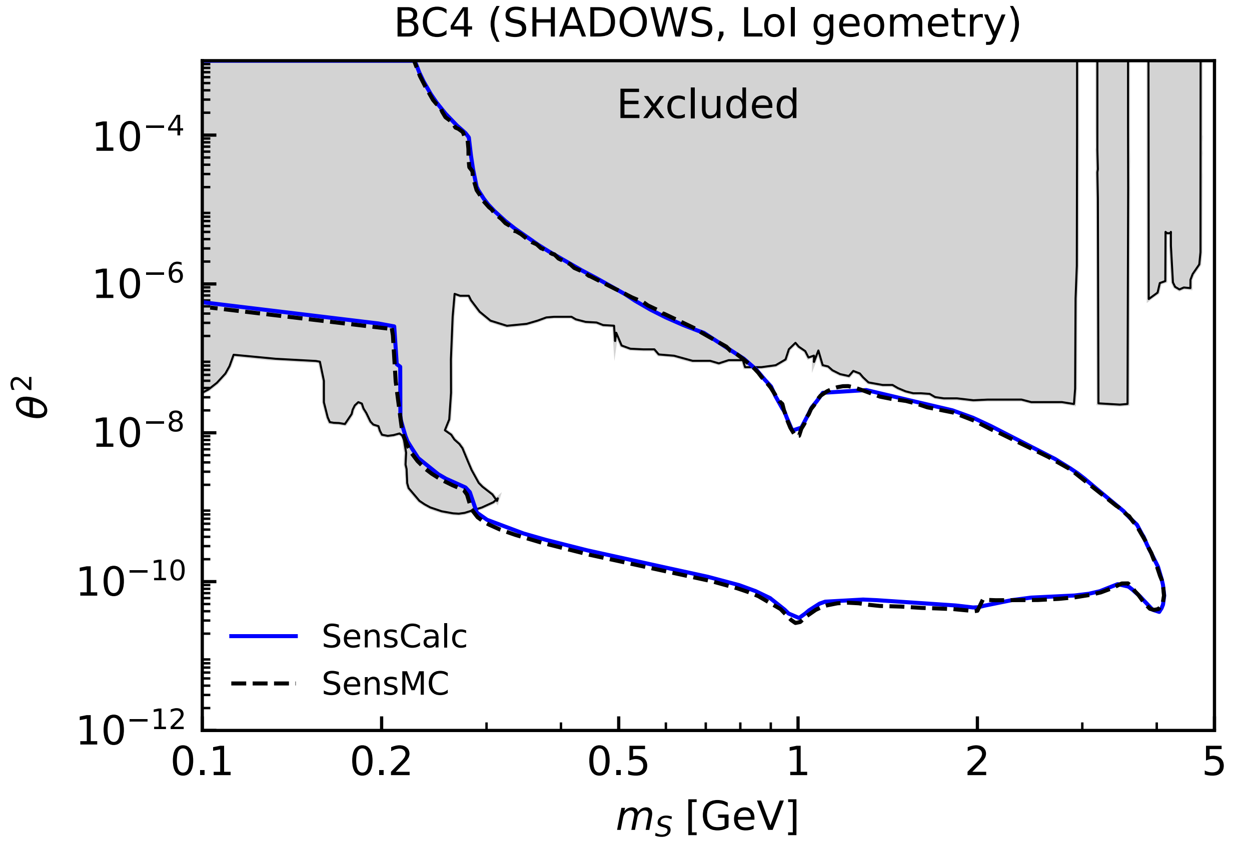
Validation against SensMC (Monte-Carlo)

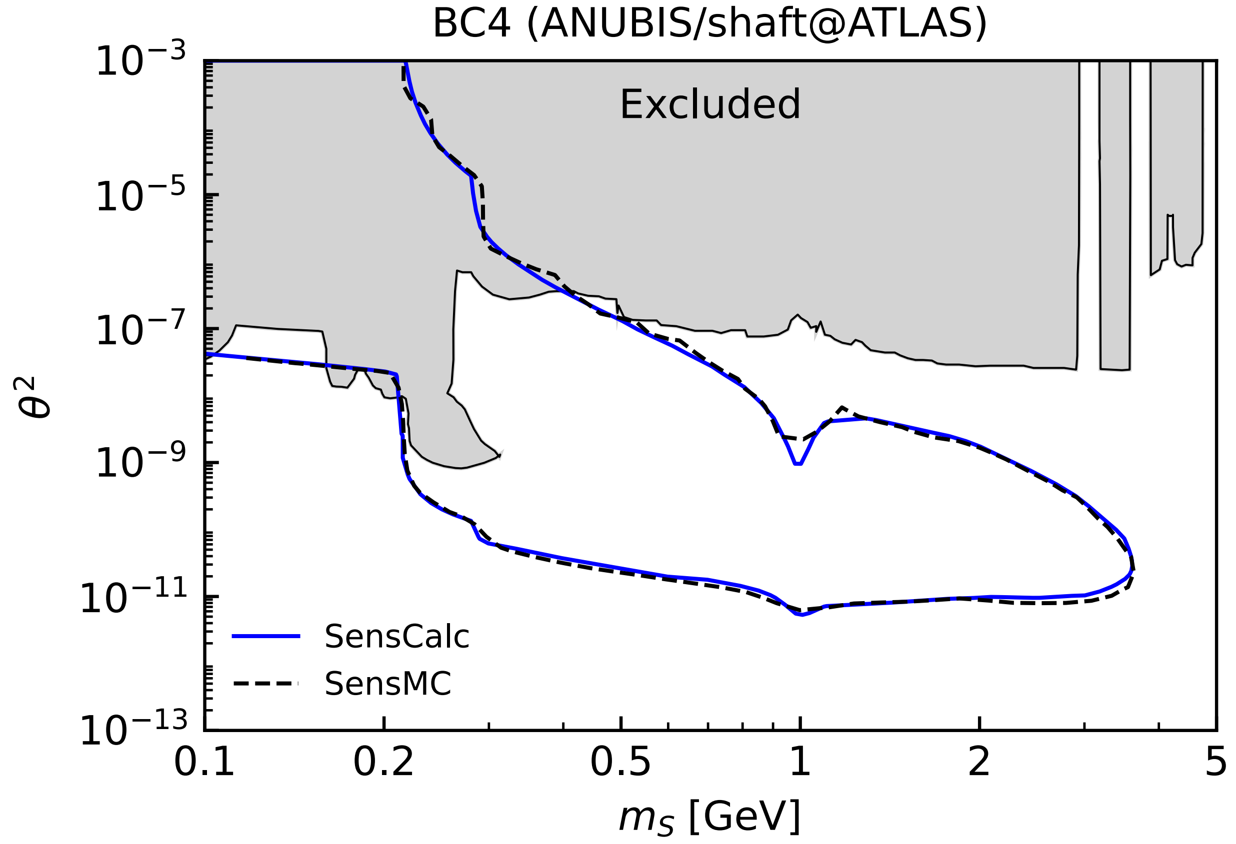
* single-event sensitivity at
90% CL used for validation
(i.e. zero background)







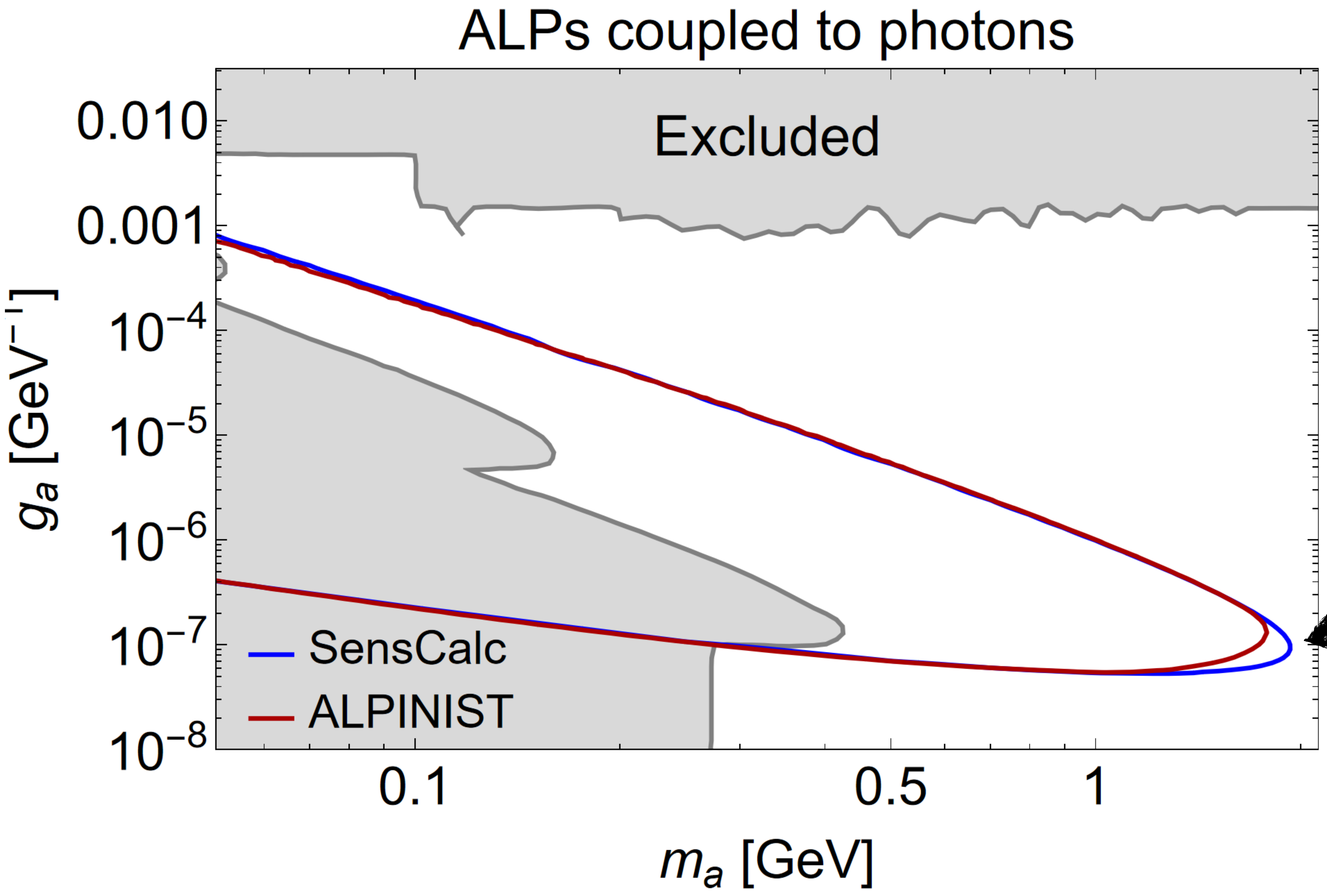




Good agreement at the $\sim 10 - 20\,\%$ level despite different code base and inputs

Validation against other packages

ALPINIST — BC9 (ALPs coupled to photons) — SHiP

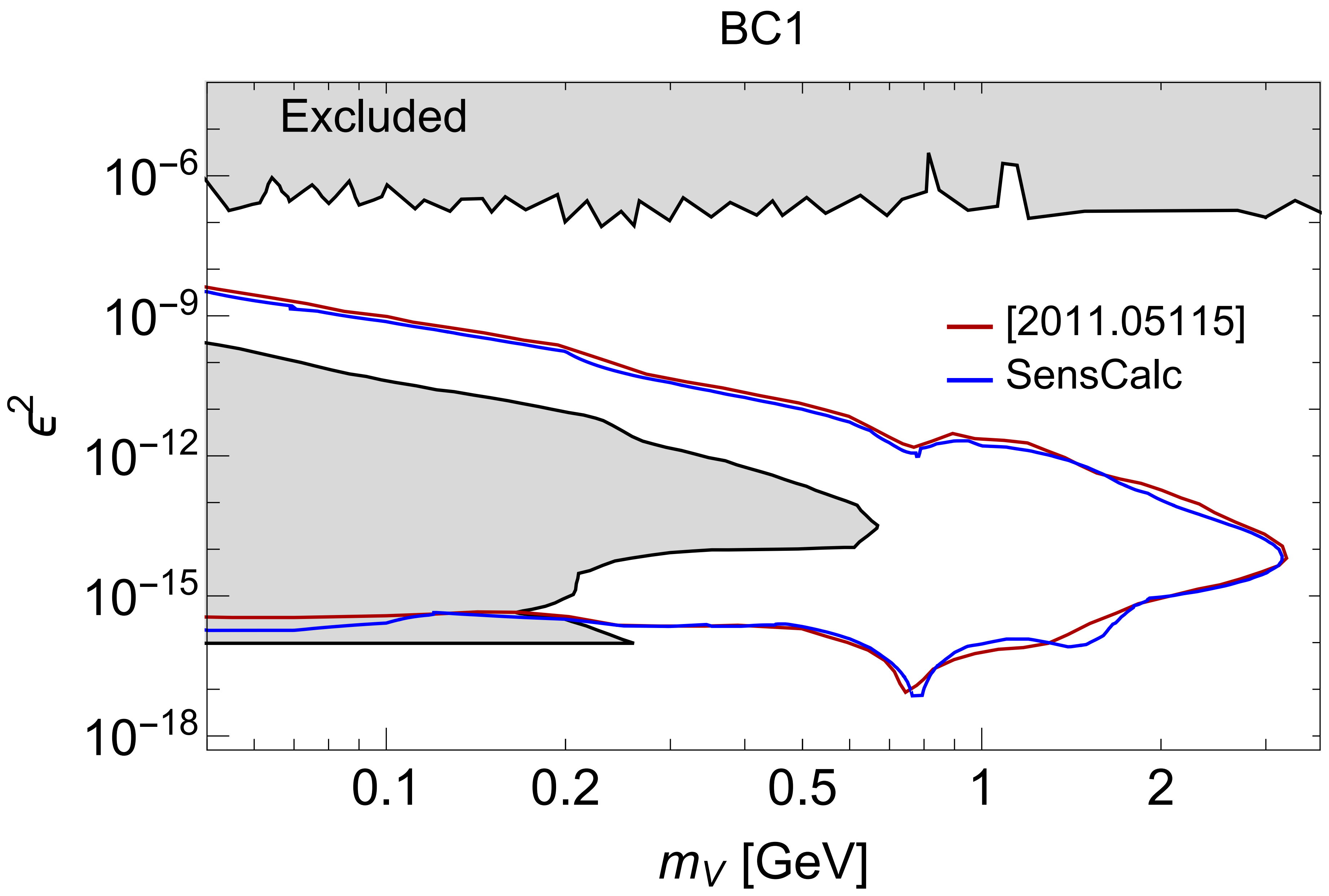


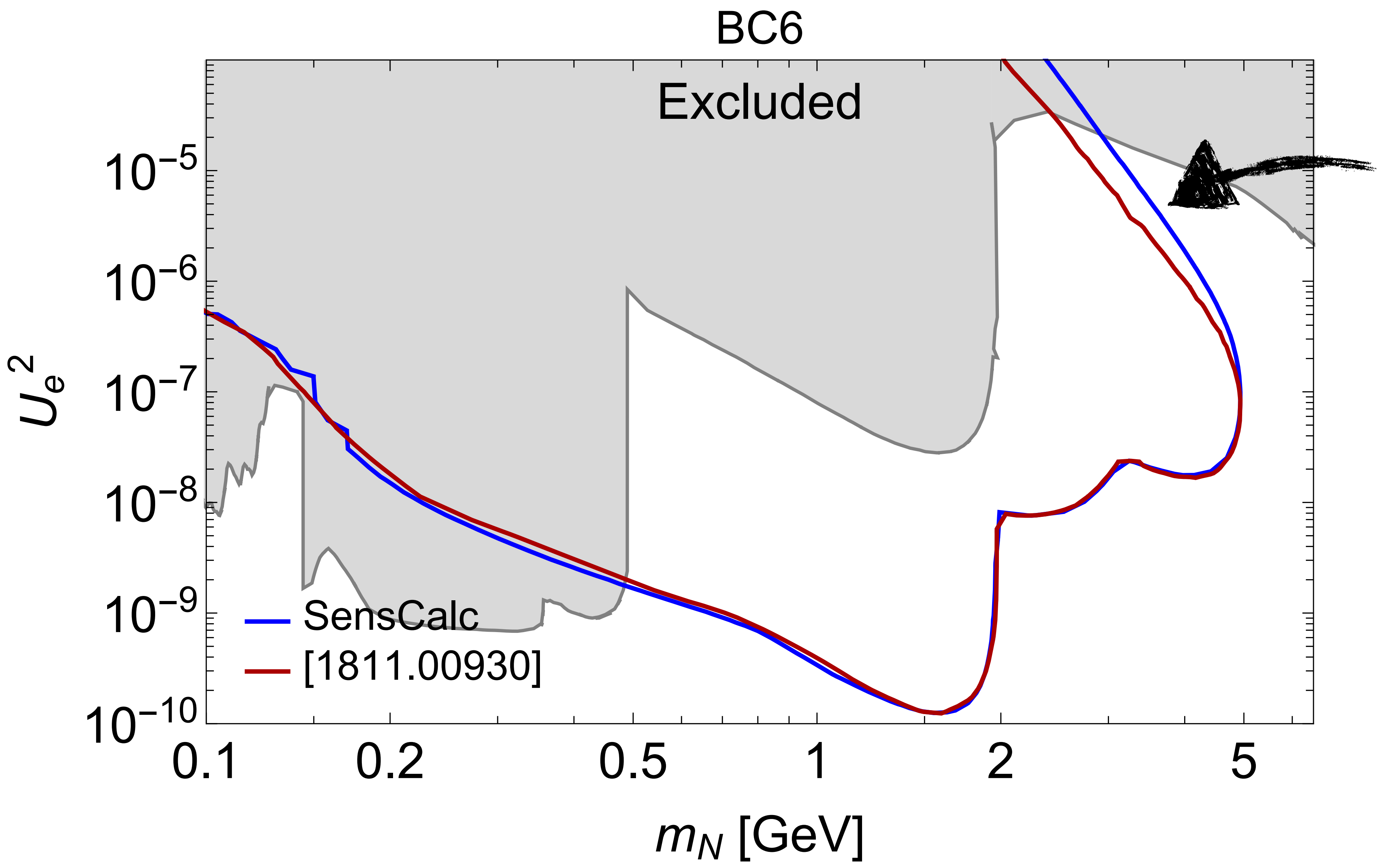
Discrepancy likely caused by slightly different geometries

✓

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

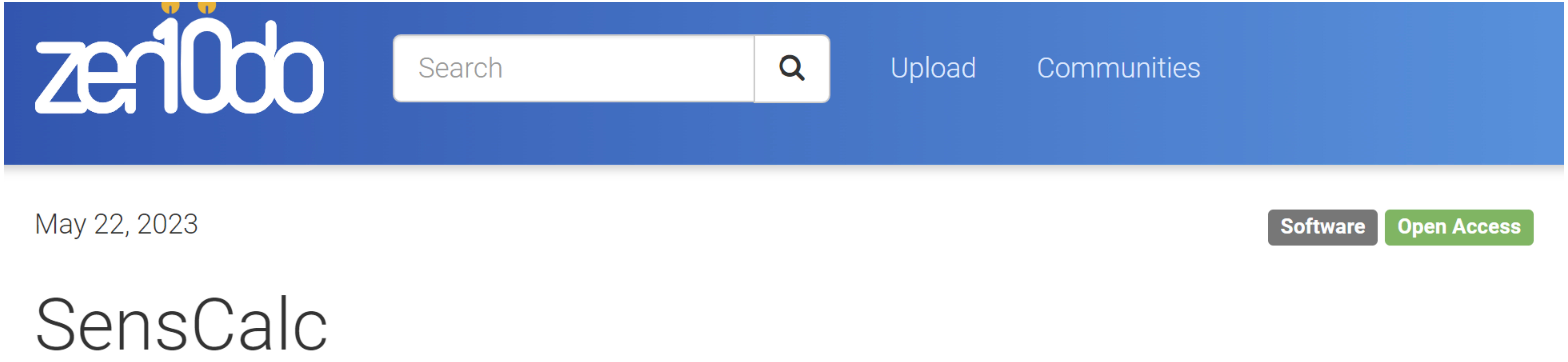
And more...

- FORESEE
- The LHCb simulation framework

✓

Running SensCalc

[doi.org/10.5281/zenodo.7957784]



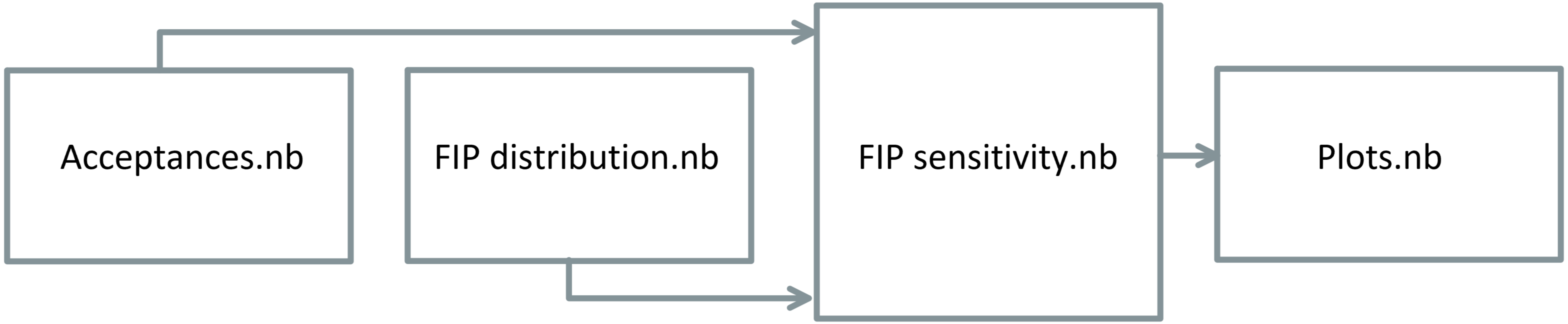
May 22, 2023

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

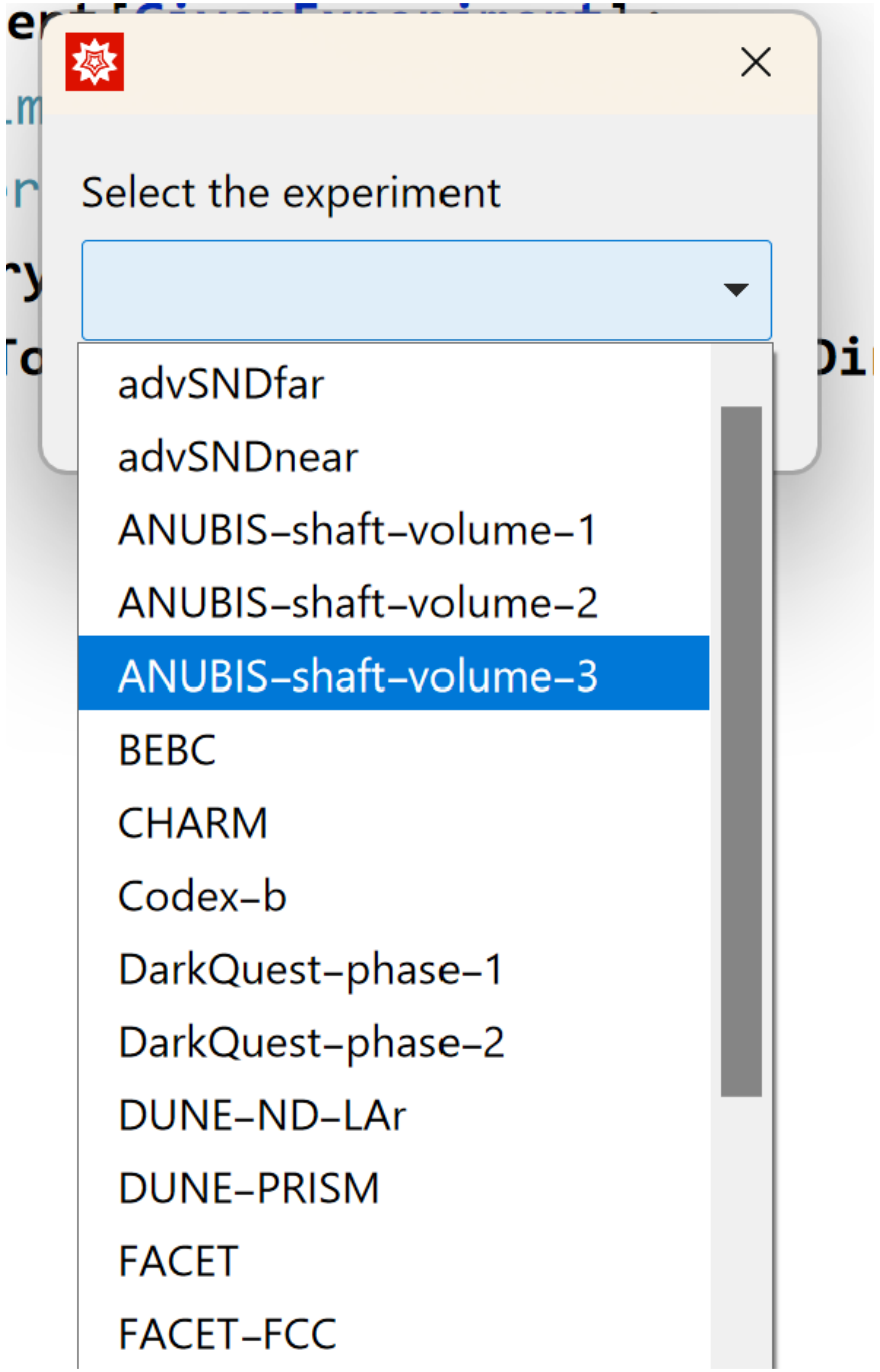


- **Acceptances.nb:** specify the geometry & acceptance criteria → $\epsilon_{\rm az}, \epsilon_{\rm dec}$
- **FIP distribution.nb:** specify the facility & FIP → FIP distribution
- **FIP sensitivity.nb:** compute the tabulated number of events & sensitivity
- **Plots.nb:** produce the sensitivity plots

Running SensCalc

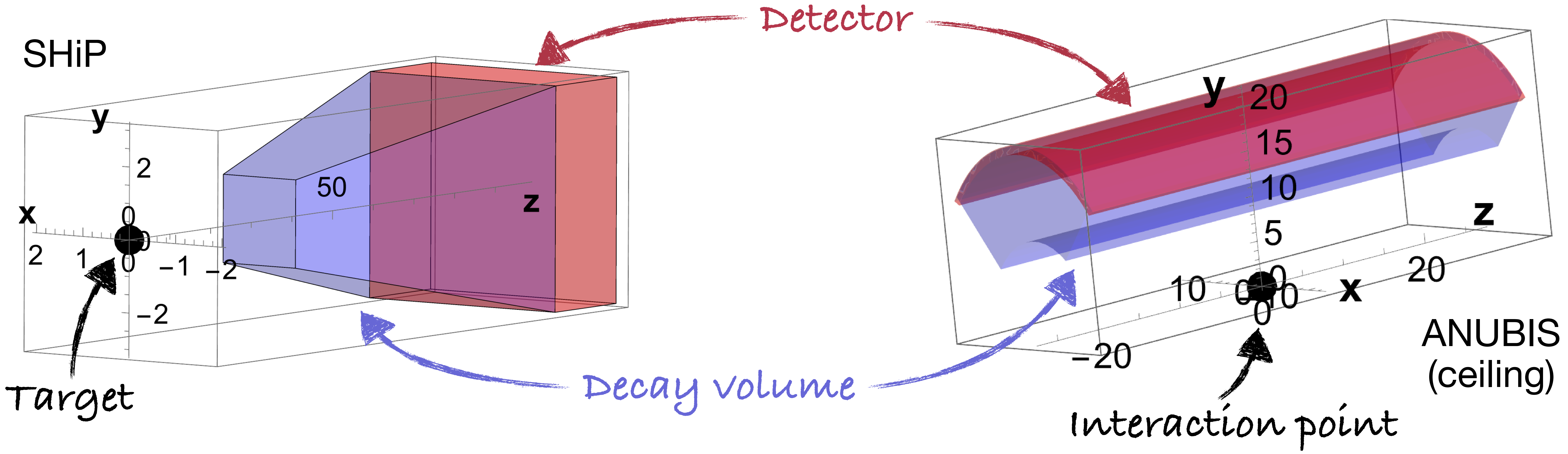
Models & experiment selection

- 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



Select the experiment

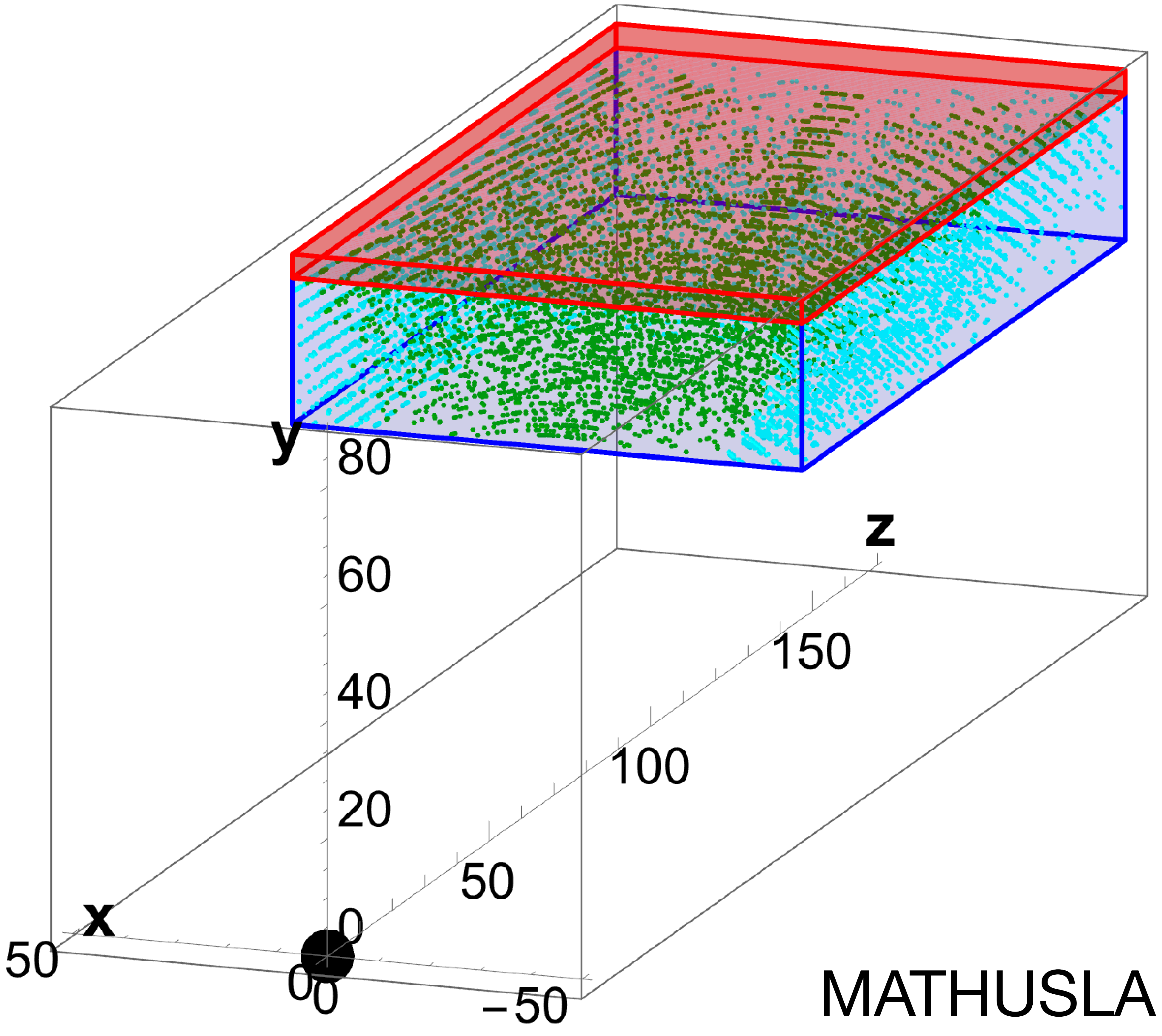
Acceptances.nb



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

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

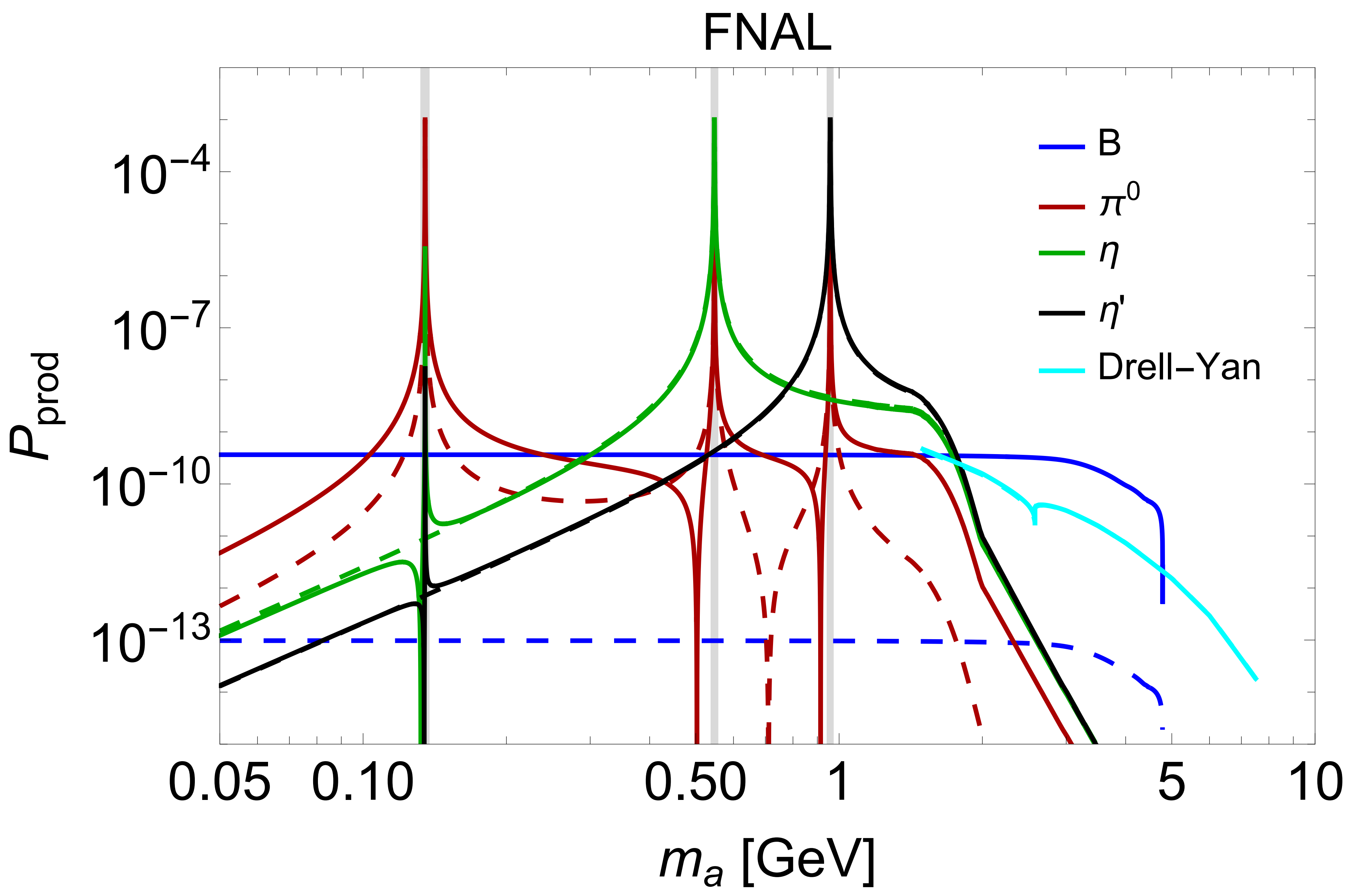
over all decay channels and azimuthal angles ϕ.

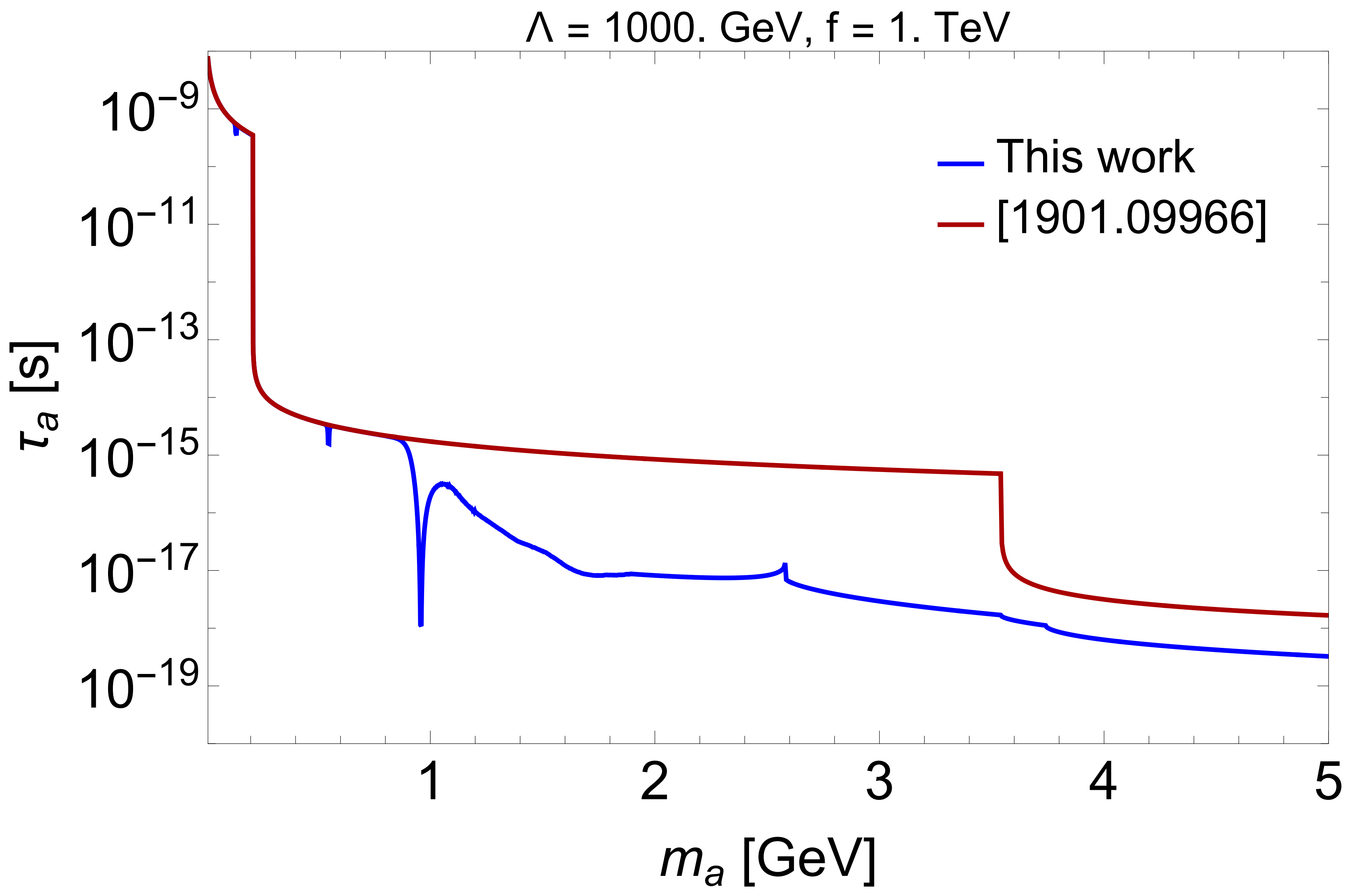
This is done by:

- 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. Ovchynnikov, A. Zaporozhchenko, in preparation]

Case study: ALP with fermion couplings

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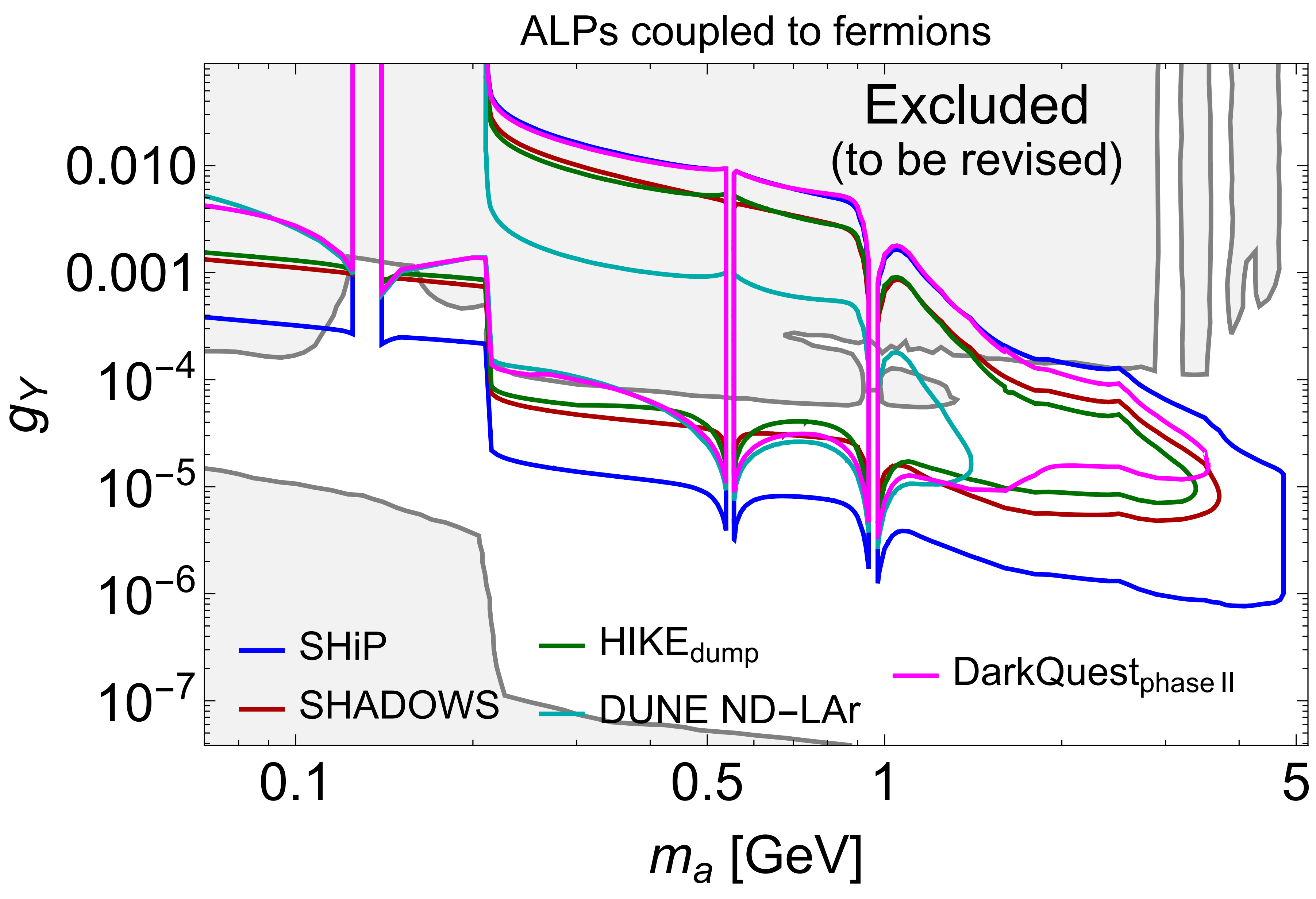

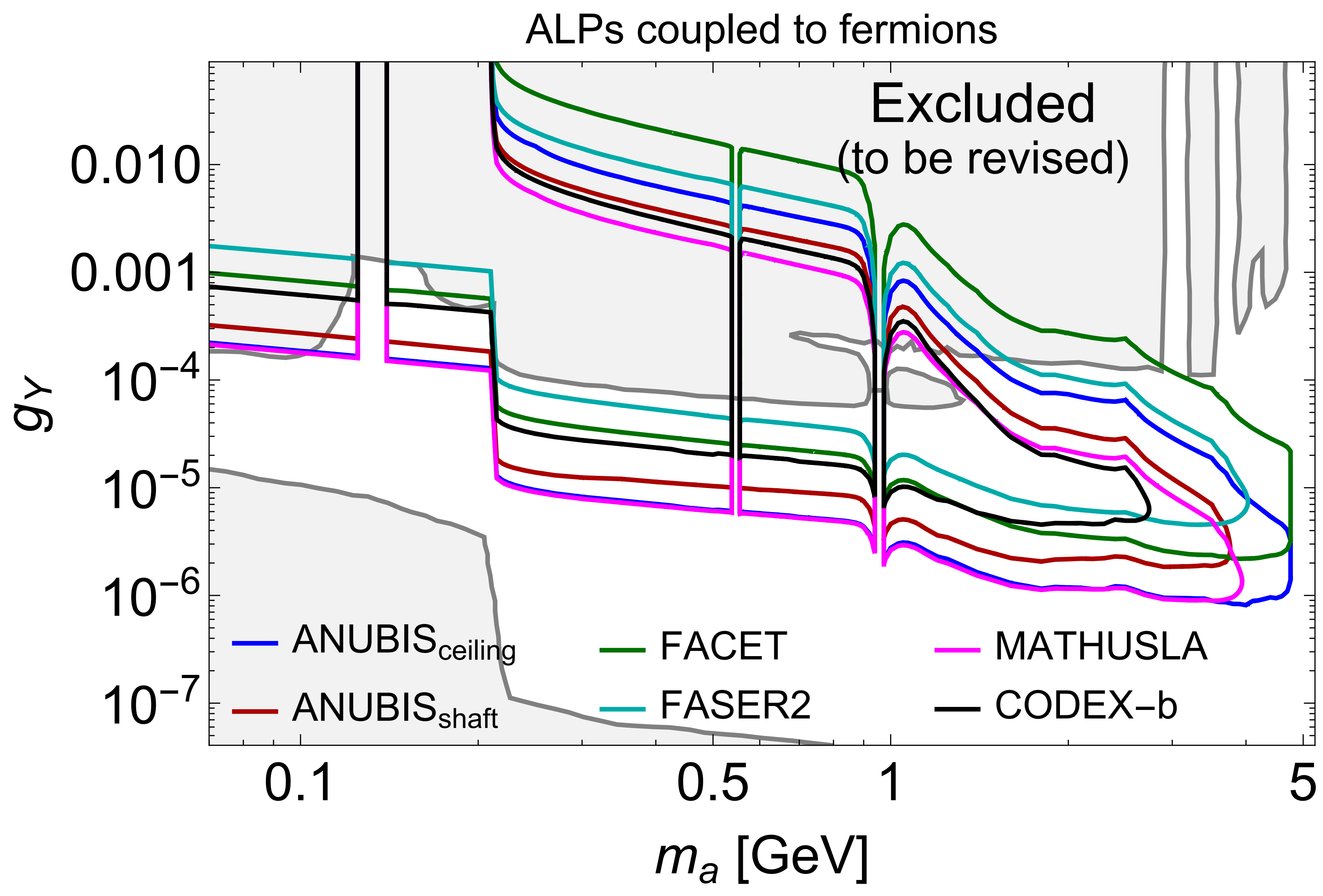

Compared to the PBC description:

- 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
  → 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!