Searching for Long-Lived Neutralinos

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Searches for Long-Lived Particles

- Motivated by the problem of dark matter, several new experimental proposals to search for light dark sector particles.

- This talk is about a well motivated supersymmetric scenario, which can be searched for in these experiments

Supersymmetry:

- Neutralinos: mixture of bino, wino and higgsinos

$$\chi^0_{i=1,2,3,4}$$

Very Light Neutralinos

SUSY GUTs: $$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \approx \frac{1}{2} M_2$$

Chargino search at LEP-II: $$M_{\chi_1^+} > 94\,\mathrm{GeV}$$

$$\mu,\ M_2 \gtrsim 100\,\mathrm{GeV}$$

$$M_1 \gtrsim 50\,\mathrm{GeV}$$

PDG Neutralino Bound: $$\boxed{M_{\chi_1^0} \gtrsim 46\,\mathrm{GeV}}$$

Massless Neutralinos

- Drop SUSY GUT assumption, set determinant of neutralino mass matrix to zero:

$$M_1 = \frac{M_2 M_Z^2 \sin(2\beta)\sin^2\theta_W}{\mu M_2 - M_Z^2 \sin(2\beta)\cos^2\theta_W}.$$

- Always has a solution (for real parameters)

- Light neutralino dominantly bino, avoid inv. Z-decay constraint

- In fact massless neutralino consistent with all data.

HD, Heinemeier, Kittel, Langenfeld, Weber, Weiglein, EPJC62(2009)547

Cosmological Bounds

excluded for stable χ_1^0:

$$0.7 \text{ eV} < M_{\tilde{\chi}_1^0} < 24 \text{ GeV}$$

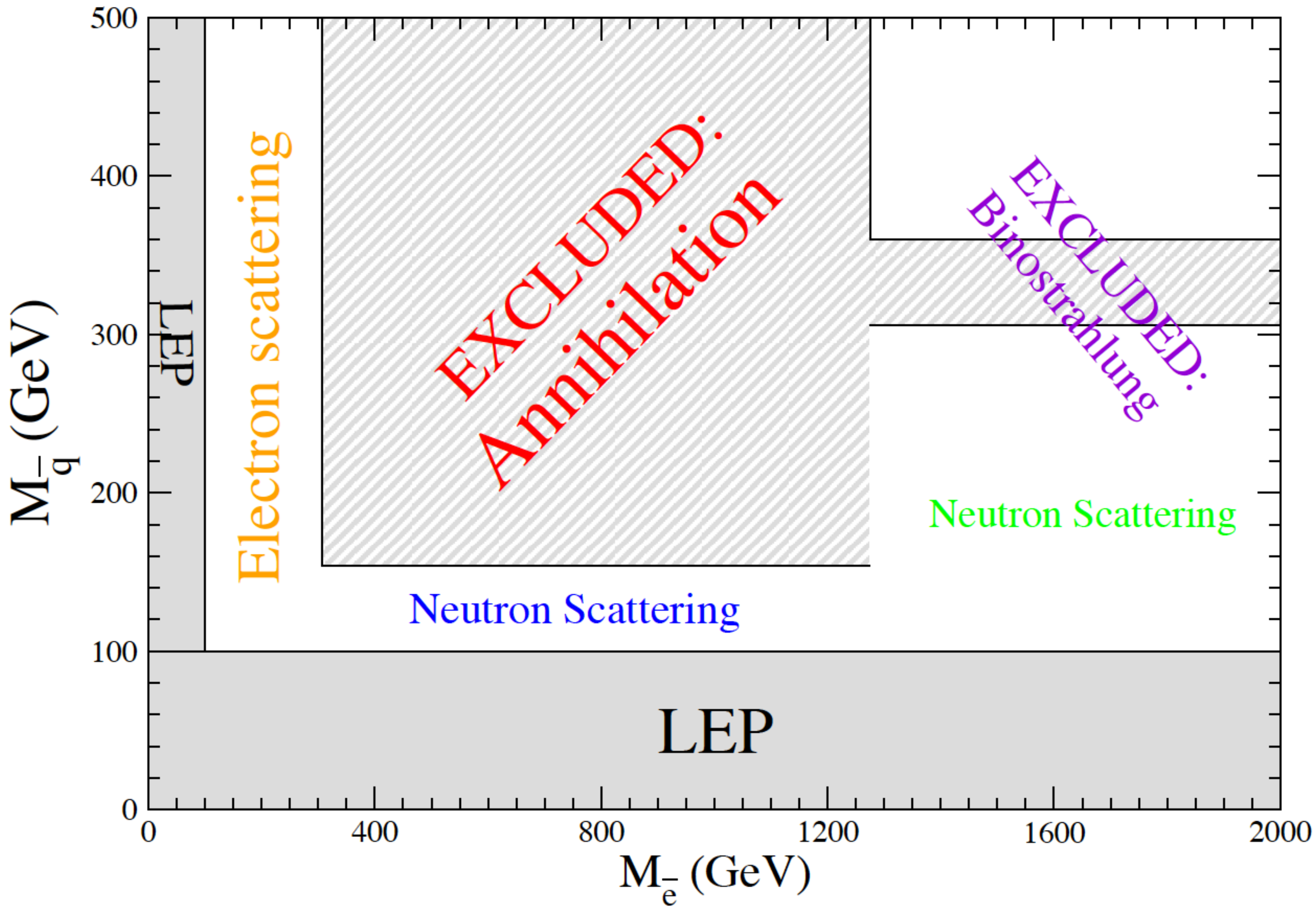
Cowsik-McClelland

Lee-Weinberg

- In this range χ_1^0 must decay, R-Parity Violation

$$W_{\text{RPV}} = \kappa_i L_i H_u + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c,$$

Supernova Cooling Constraints



Search for Light Longlived Neutralino

- Mass range MeV - few GeV

- Production: similar to neutrino experiments

- Produce a meson via strong interaction in hadronic collision

  * $p + p \to D^{\pm} + X$

- Consider rare decays of meson to light neutralino

  * $D^{\pm} \to K^{\pm} + \chi_1^0$

- Search for decays of long-lived neutralino

Search for Light Long-Lived Neutralino

- Have analyzed these scenarios in various experimental set-ups
- Proposed fixed-target exp.: **SHiP**
- Proposed new detectors at the LHC: **CODEX-b**

  FASER

  MATHUSLA

  AL3X
- Compare with potential at: **ATLAS**

Search for Light Long-Lived Neutralino

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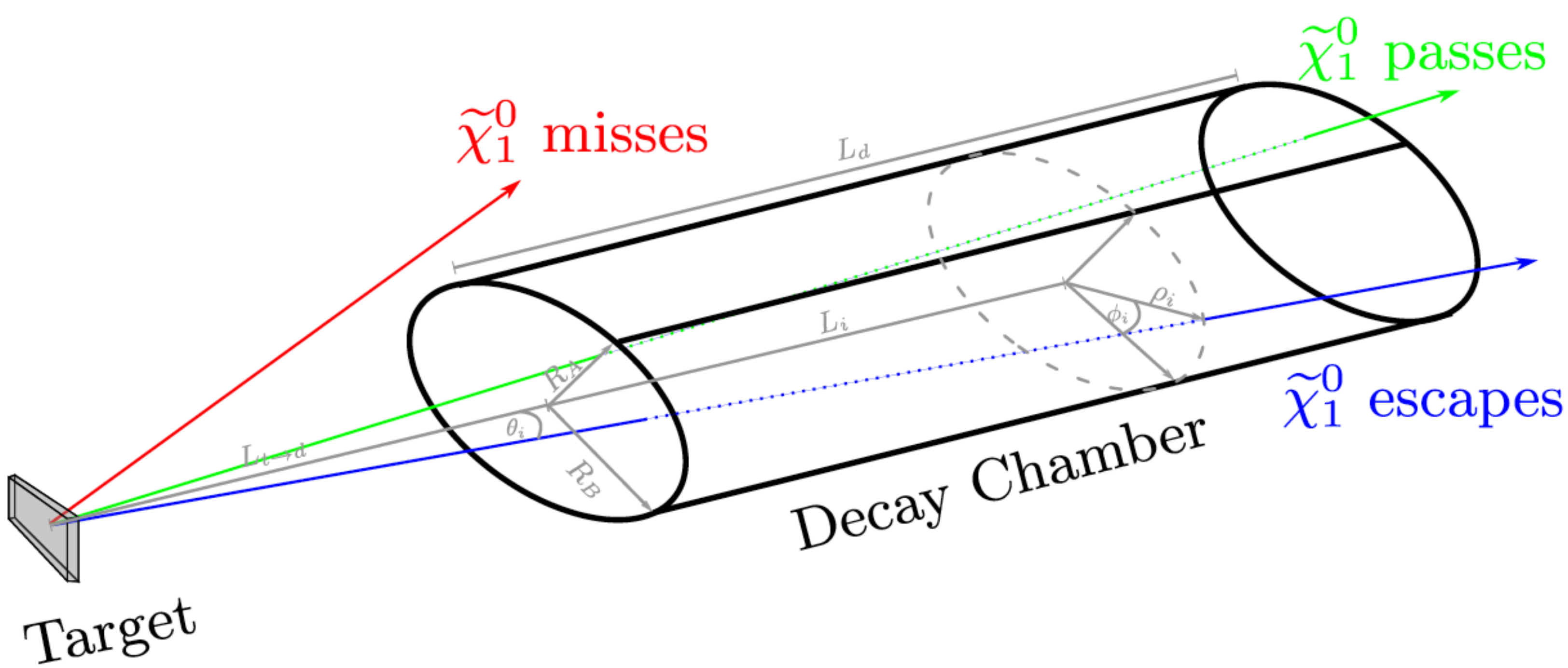
Proposed SHiP Experiment Parameters

$\sqrt{s} = 27\,\mathrm{GeV};$ integrated luminosity: 10^{20} protons on target

distance to detector: 68.8m; detector length: 60m

$R_A = 2.5\,\mathrm{m}; \quad R_B = 5\,\mathrm{m}$



Neutralino Production via Rare Meson Decay

- At SHiP energies large charm and bottom production rates

HardQCD:hardccbar

Pythia

$$N_{c\bar{c}} = 9 \times 10^{16}$$

$$N_{b\bar{b}} = 2 \times 10^{13}$$

$n^{c\bar{c}}_{D^\pm}$	0.53
$n^{c\bar{c}}_{D_s^\pm}$	0.074
$n^{b\bar{b}}_{B^\pm}$	0.83
$n^{b\bar{b}}_{B^0}$	0.80
$n^{b\bar{b}}_{B_s^0}$	0.14

$$N_\chi^{\rm prod} = \sum_M N_M \cdot \Gamma(M \to \tilde{\chi}_1^0 + l) \cdot \tau_M .$$

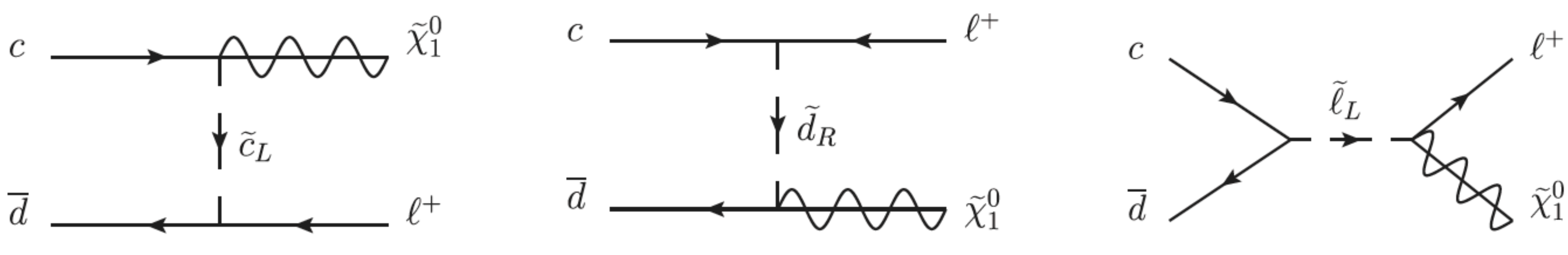
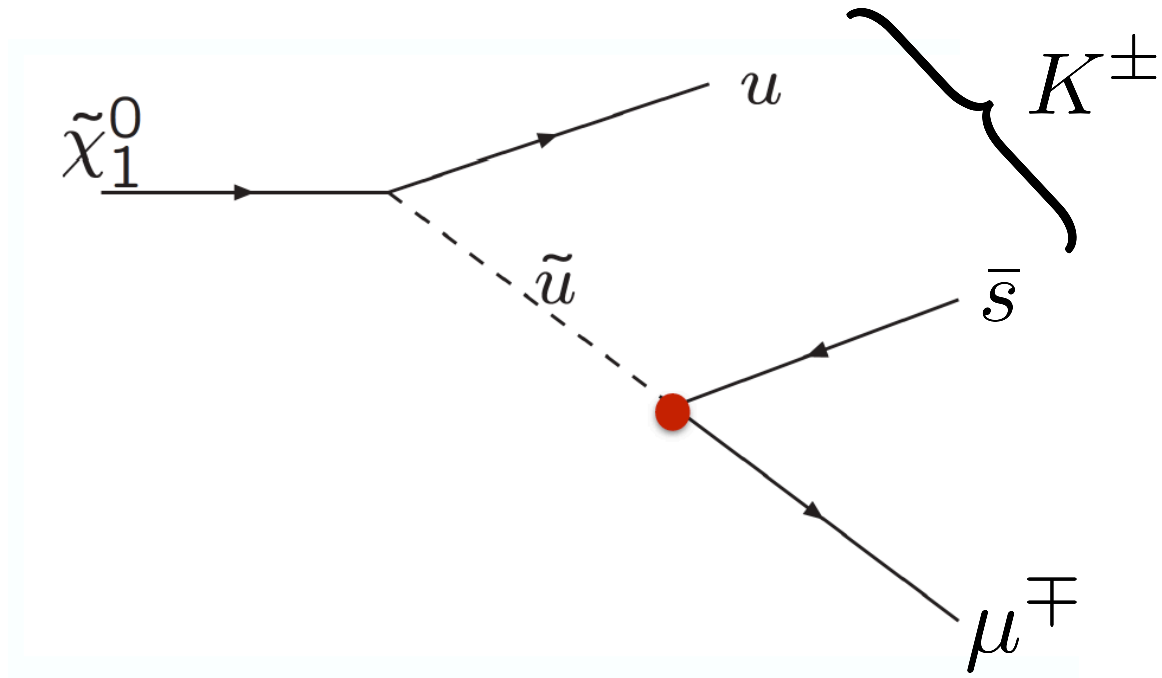


FIG. 1. Relevant Feynman diagrams for $D^+ \to \tilde{\chi}_1^0 + \ell^+$.

Neutralino Decay

- Light neutralino will decay via LQD to meson + lepton



$L_2 Q_1 \bar{D}_2$

- Depending on $M_{\chi_1^0}$ and dominant $L_i Q_j \bar{D}_k$ neutralino will decay to various mesons

- Only one coupling which allows prod. **and** decay: λ'_{112}

$$K^0_{L/S} \to \tilde{\chi}_1^0 \nu, \qquad \tilde{\chi}_1^0 \to K^\pm \ell^\mp.$$

$\Delta m \approx 4\,\mathrm{MeV}$

Possible Scenarios

$$\lambda'_{i11} \to \begin{cases} (u\bar{d}) = (\pi^+, \rho^+) \\ (d\bar{d}) = (\pi^0, \eta, \eta', \rho, \omega), \end{cases}$$

$$\lambda'_{i12} \to \begin{cases} (u\bar{s}) = (K^+, K^{*+}) \\ (d\bar{s}) = (K_L^0, K_S^0, K^{*0}), \end{cases}$$

$$\lambda'_{i13} \to \begin{cases} (u\bar{b}) = (B^+, B^{*+}) \\ (d\bar{b}) = (B^0, B^{*0}), \end{cases}$$

$$\lambda'_{i21} \to \begin{cases} (c\bar{d}) = (D^+, D^{*+}) \\ (s\bar{d}) = (K_L^0, K_S^0, K^{*0}), \end{cases}$$

$$\lambda'_{i22} \to \begin{cases} (c\bar{s}) = D_s^+, D_s^{*+} \\ (s\bar{s}) = \eta, \eta', \phi \end{cases}$$

$$\lambda'_{i23} \to \begin{cases} (c\bar{b}) = B_c^+, B_c^{*+}, \\ (s\bar{b}) = B_s^0, B_s^{*0} \end{cases}$$

$$\lambda'_{i31} \to (b\bar{d}) = B^0, B^{*0}$$

$$\lambda'_{i32} \to (s\bar{b}) = B_s^0, B_s^{*0}$$

$$\lambda'_{i33} \to (b\bar{b}) = \eta_b, \Upsilon.$$

- Kinematically must also take lepton mass into account

Geometry of the Decay

- $N^{\text{obs}}_{\tilde{\chi}^0_1} = N^{\text{prod}}_{\tilde{\chi}^0_1} \cdot \langle P[\tilde{\chi}^0_1 \text{in d.r.}] \rangle \cdot \text{BR}(\tilde{\chi}^0_1 \rightarrow \text{charged})$

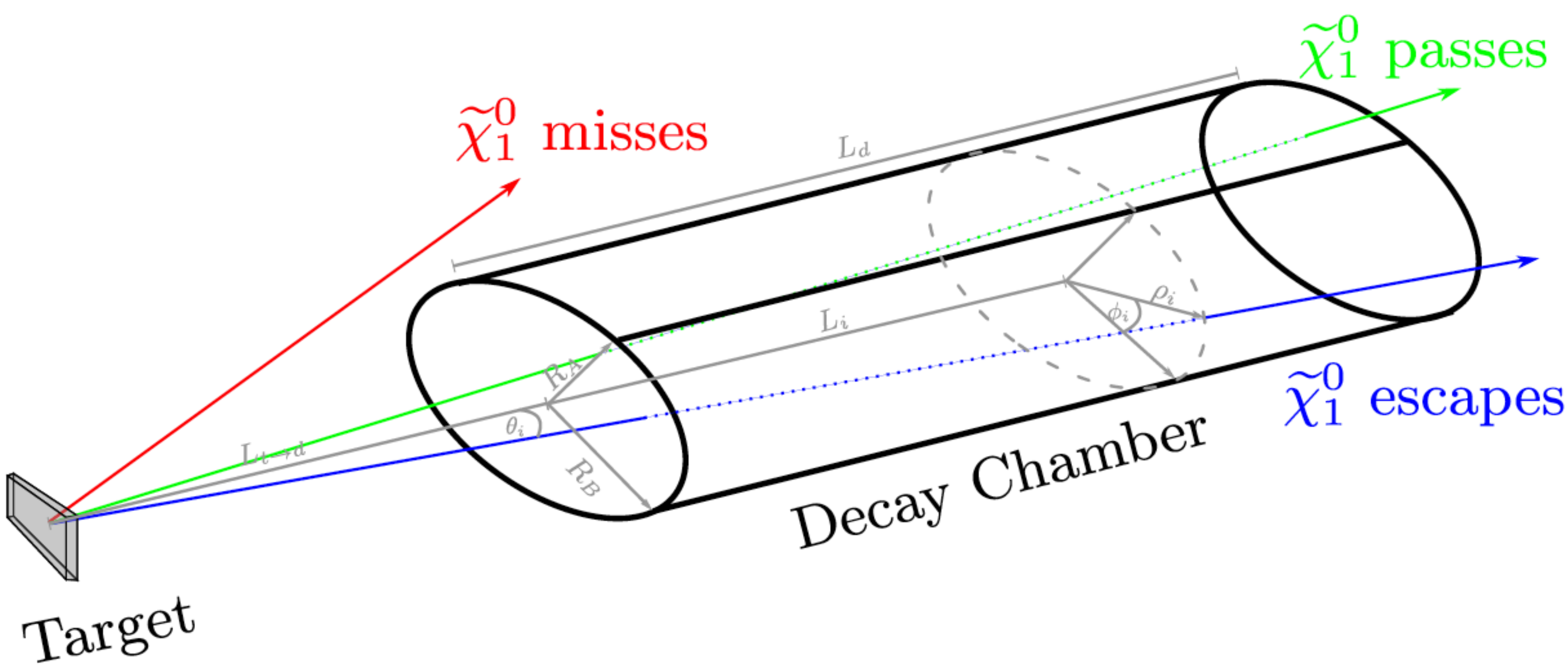
- $\langle P[\tilde{\chi}^0_1 \text{ in d.r.}] \rangle = \frac{1}{N^{\text{MC}}_{\tilde{\chi}^0_1}} \sum_{i=1}^{N^{\text{MC}}_{\tilde{\chi}^0_1}} P[(\tilde{\chi}^0_1)_i \text{ in d.r.}],$

- $P[(\tilde{\chi}^0_1)_i \text{ in d.r.}] = e^{-L_{t\rightarrow d}/\lambda^z_i} \cdot (1 - e^{-L_i/\lambda^z_i}).$

$$\lambda^z_i = \beta^z_i \gamma_i / \Gamma_{\text{tot}}(\tilde{\chi}^0_1),$$

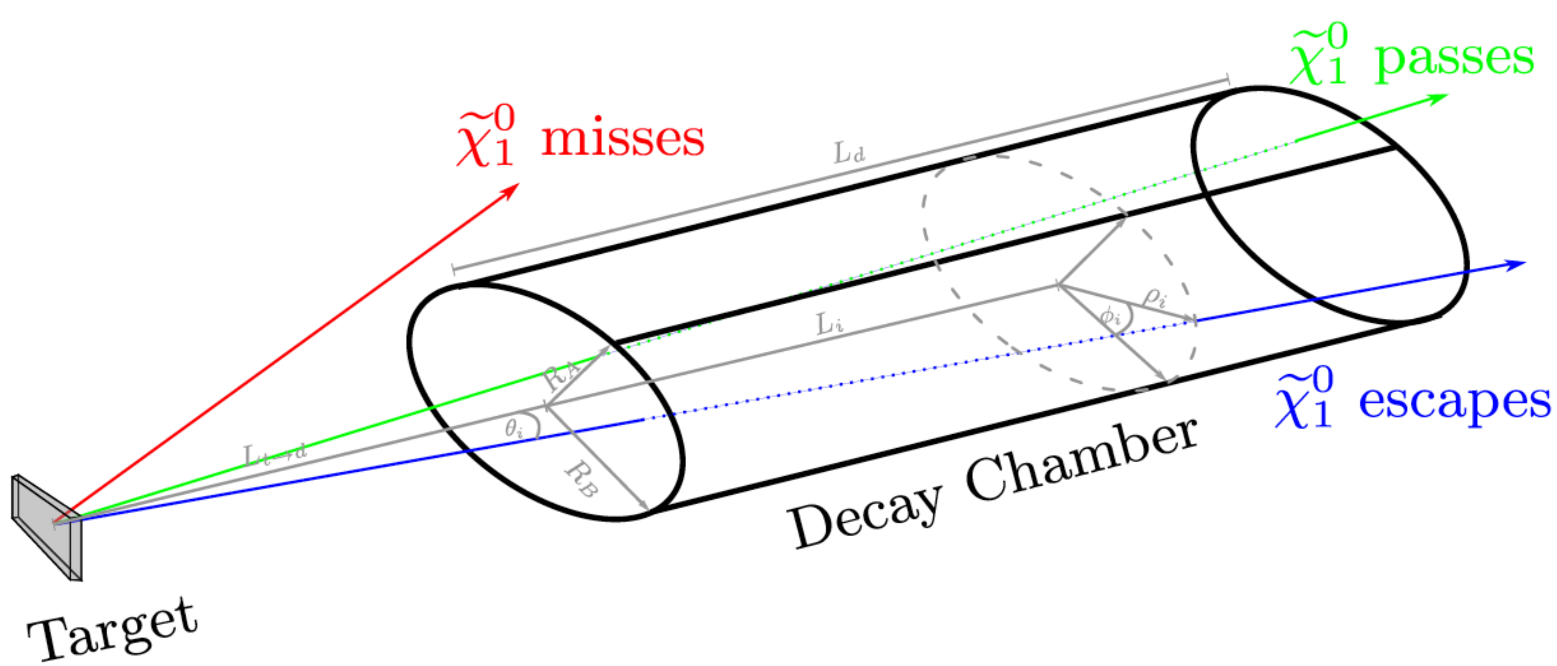
$$\beta^z_i = p^z_i / E_i$$

$$\gamma_i = E_i / m_{\tilde{\chi}^0_1}$$



$$L_i = \begin{cases} 0 & \text{if } \rho_i \cot\theta_i < L_{t\to d}, \\ L_d & \text{if } \rho_i \cot\theta_i > L_{t\to d} + L_d, \\ \rho_i \cot\theta_i - L_{t\to d} & \text{else,} \end{cases}$$

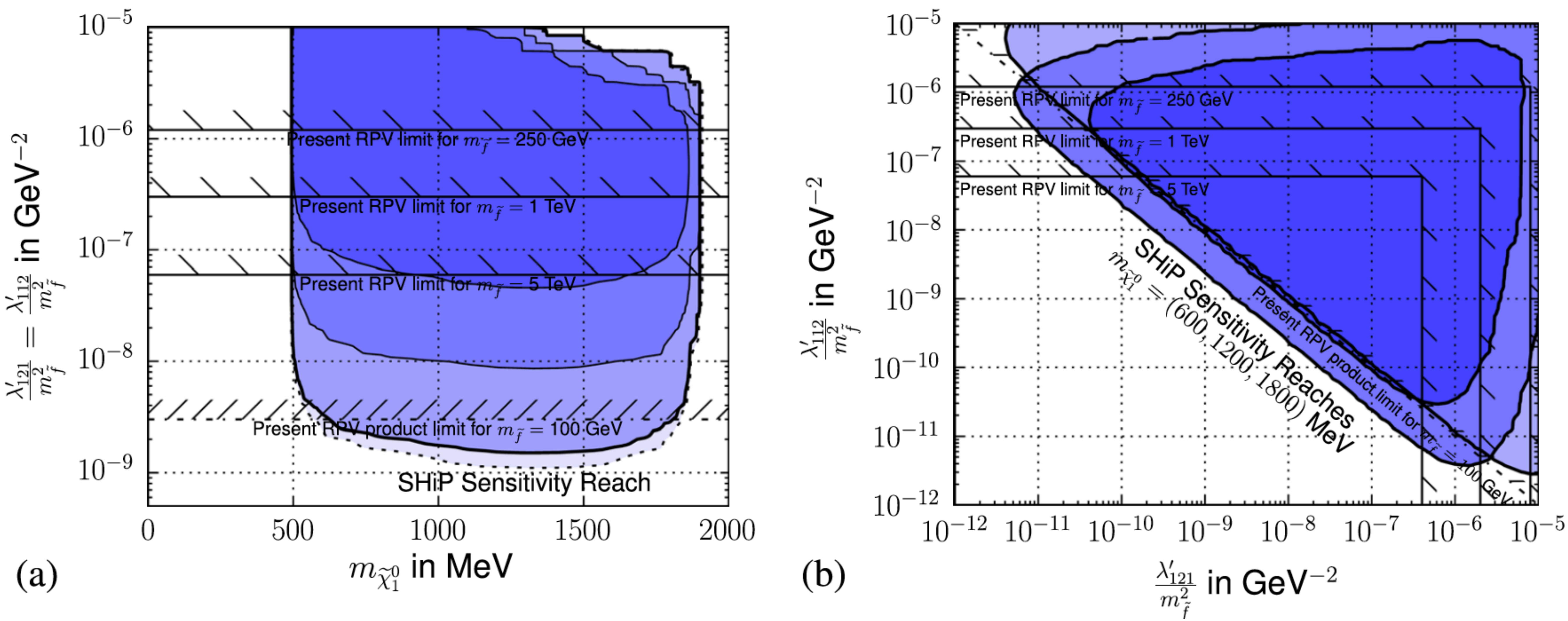
$$\rho_i = R_A R_B / \sqrt{(R_B \cos\phi_i)^2 + (R_A \sin\phi_i)^2}.$$



Herbi Dreiner, Corfu, 9/2019

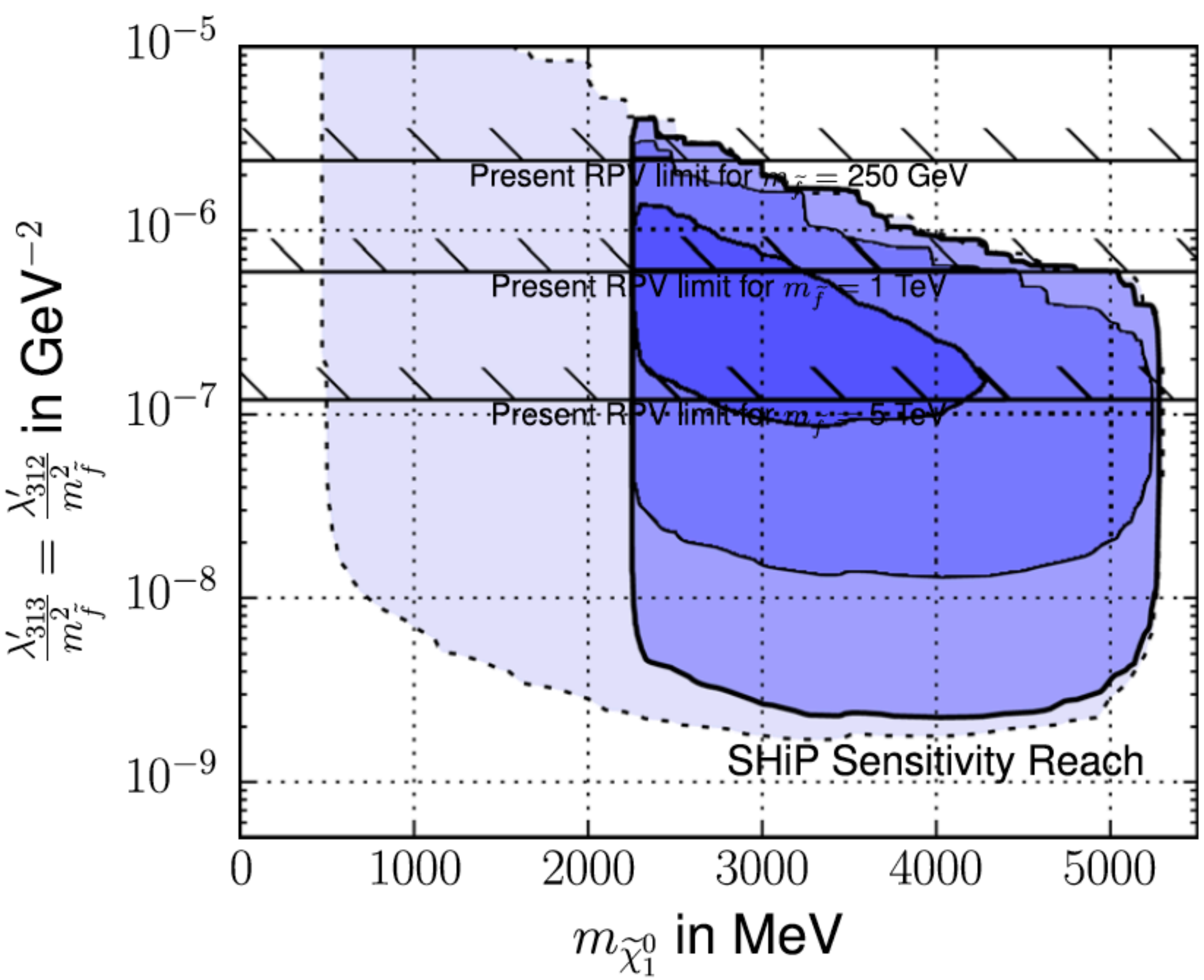
Results: Benchmark I

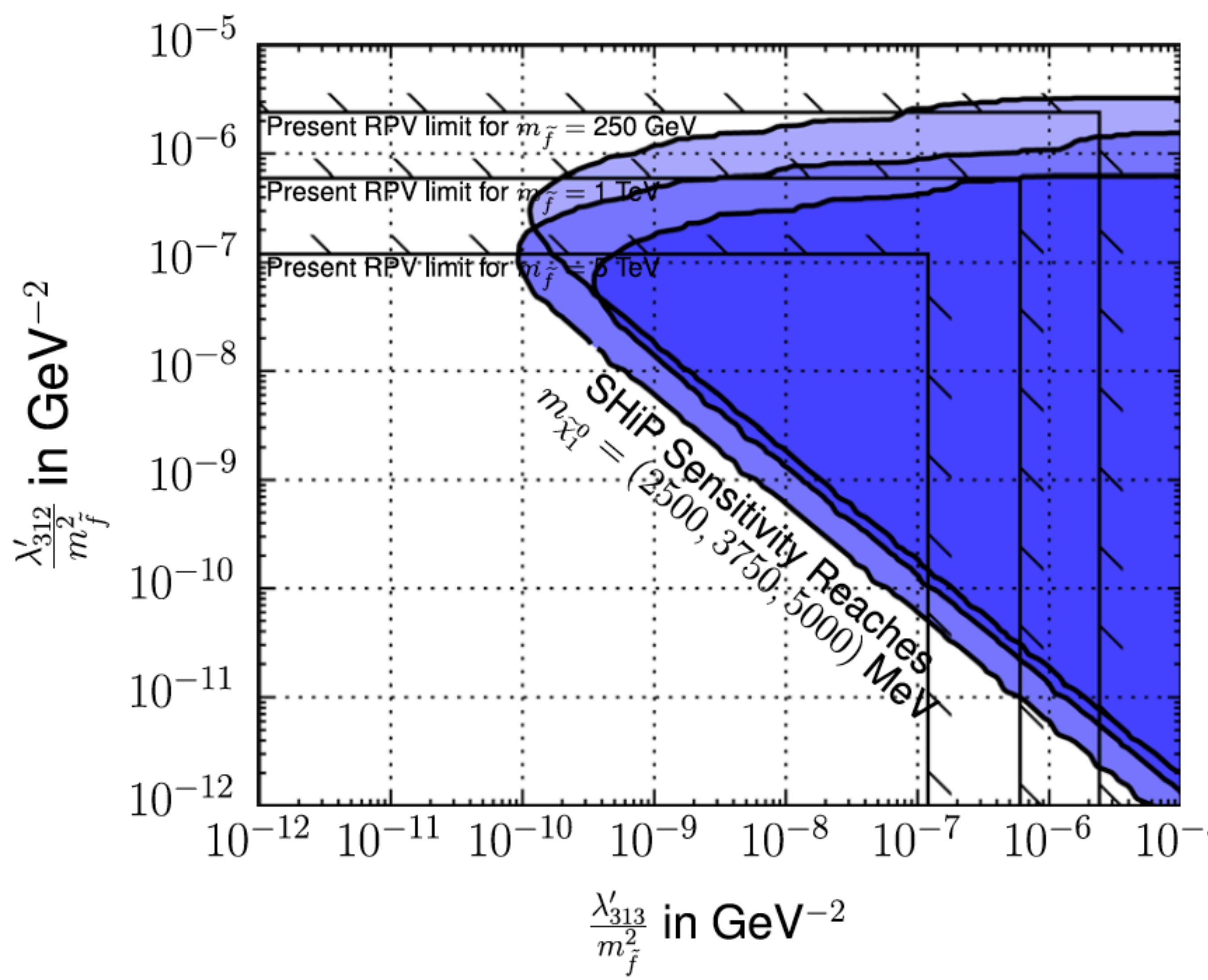
λ'_P for production	λ'_{121}
λ'_D for decay	λ'_{112}
Produced meson(s)	$D^\pm$
Visible final state(s)	$K^{(*)\pm}e^\mp$
Invisible final state(s) via λ'_P	$(K^0_L, K^0_S, K^*) + (\nu, \bar{\nu})$
Invisible final state(s) via λ'_D	$(K^0_L, K^0_S, K^*) + (\nu, \bar{\nu})$



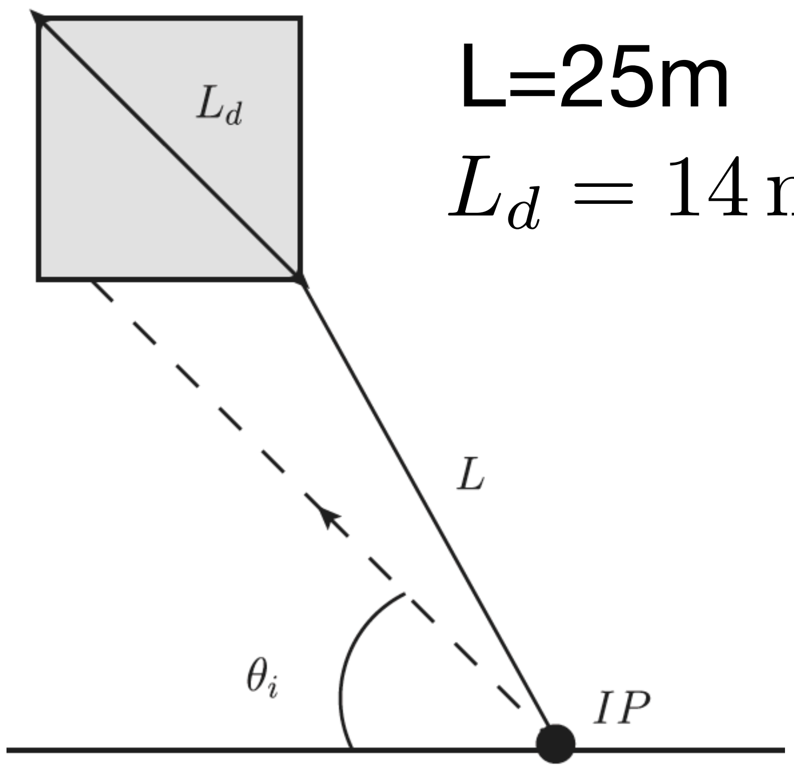
Results: Benchmark V

λ'_P for production	λ'_{313}
λ'_D for decay	λ'_{312}
Produced meson(s)	$B^0, \bar{B}^0, B^\pm(+\tau^\mp)$
Visible final state(s)	$K^\pm\tau^\mp, K^{*\pm}\tau^\mp$
Invisible final state(s) via λ'_P	None
Invisible final state(s) via λ'_D	$(K^0_L, K^0_S, K^*) + (\nu, \bar{\nu})$





CODEX-b

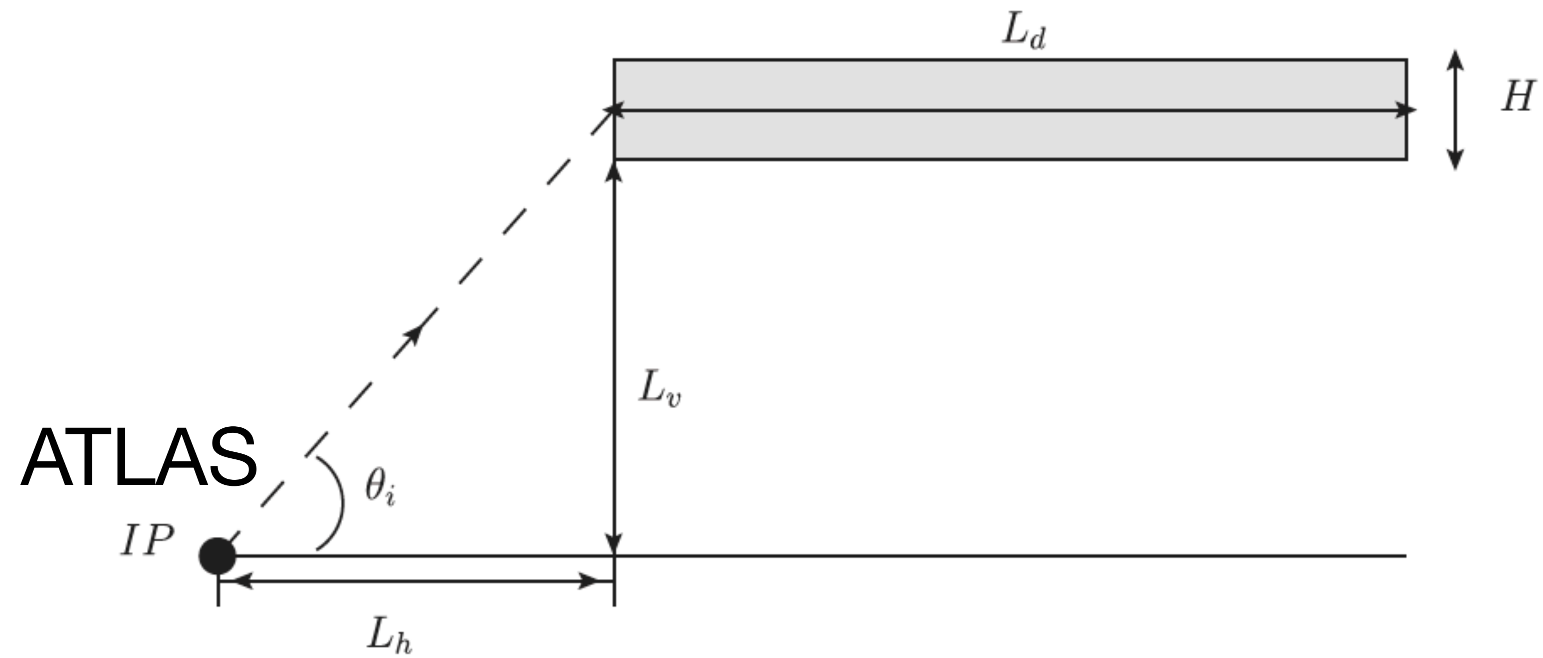


LHCb

L=25m

$L_d = 14\,\mathrm{m}$

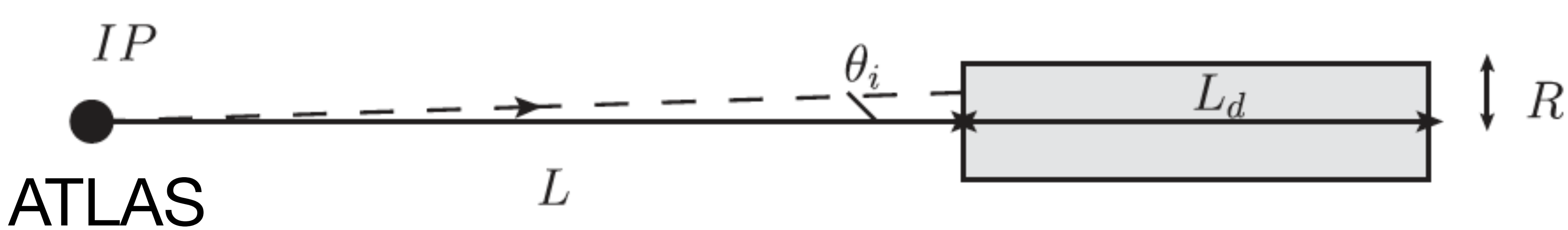
MATHUSLAH



$L_d = 200\,\mathrm{m}$

$L_v = L_h = 100\,\mathrm{m}$

FASER

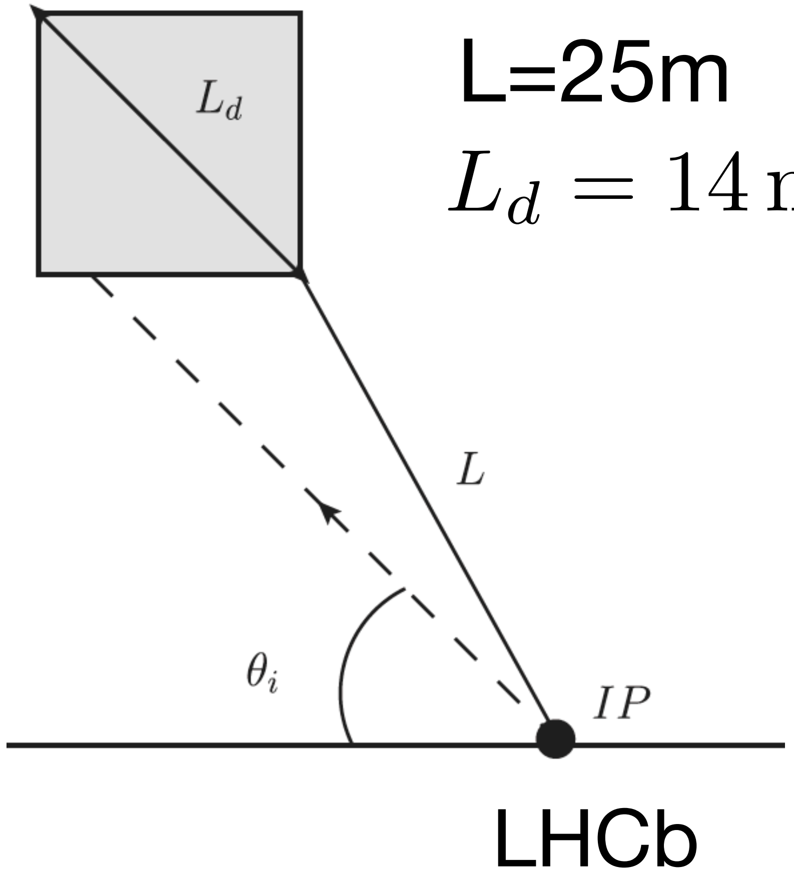


L=470m

$L_d = 10\,\mathrm{m}$

R=1m

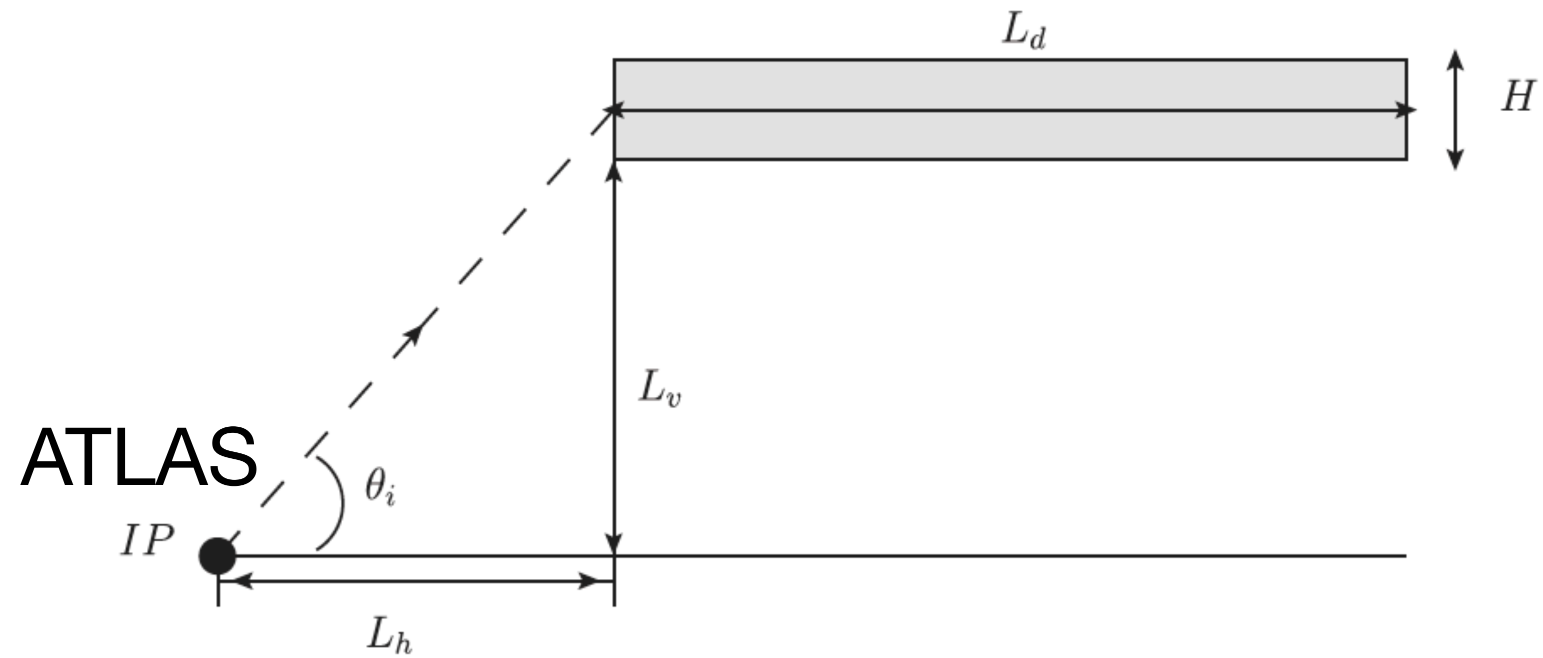
CODEX-b



L=25m

$$L_d = 14\,\mathrm{m}$$

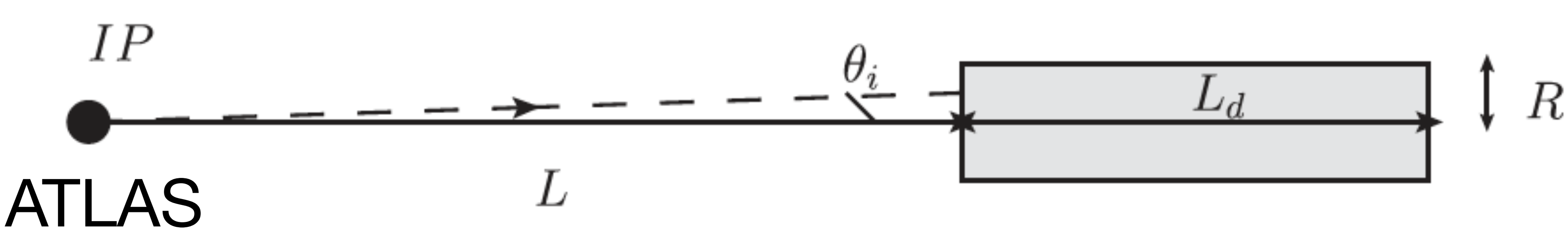
MATHUSLAH



$$L_d = 200\,\mathrm{m}$$

$$L_v = L_h = 100\,\mathrm{m}$$

FASER



L=470m

$$L_d = 10\,\mathrm{m}$$

R=1m

7/3/2019 FASER approved

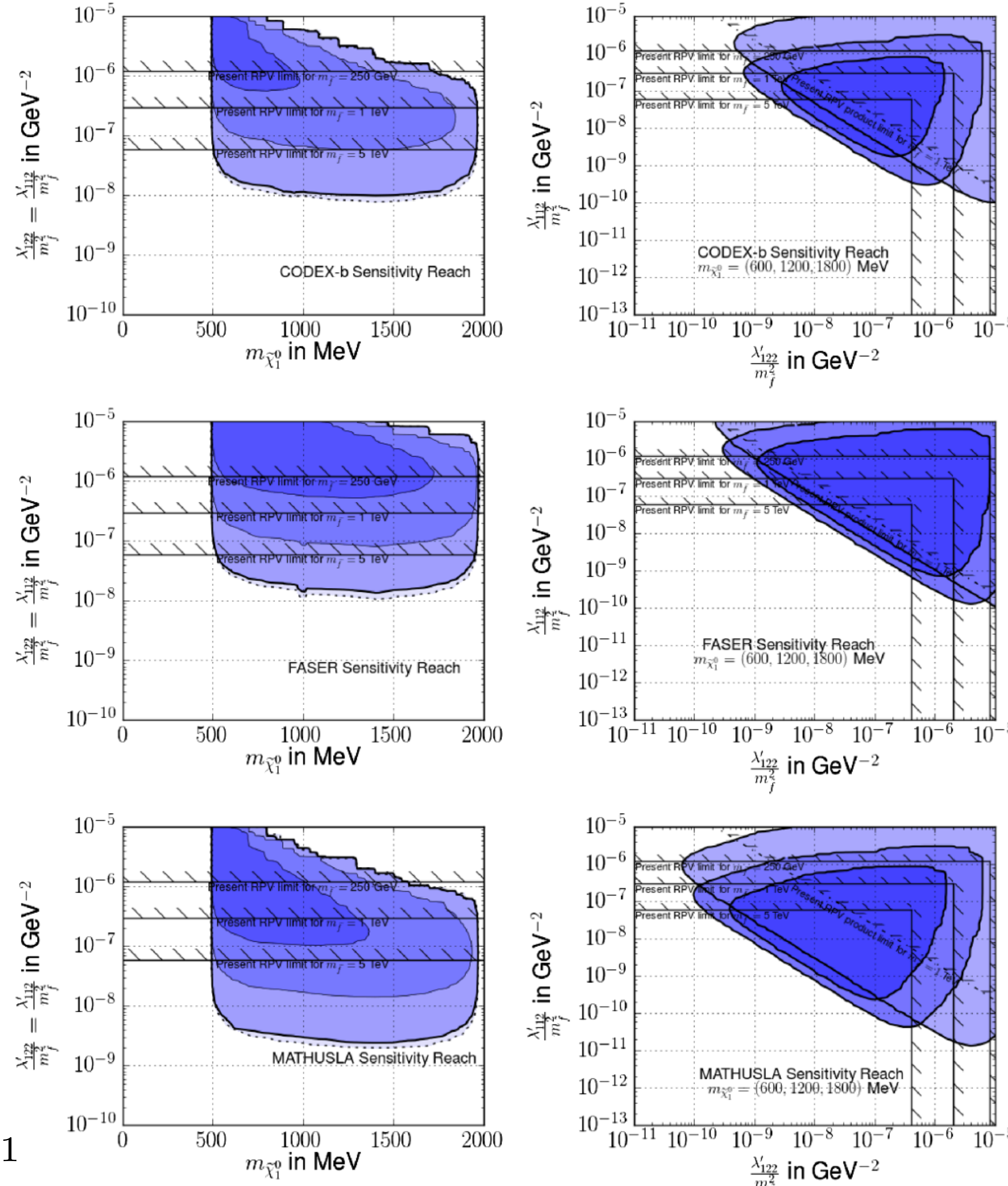
MATHUSLAH: Chou, Curtin, Lubatti. PLB 767 (2017) 29

CODEX-b: Gligorov, Knapen, Nachman, Papucci, Robinson.

PRD 97 (2018) 015023

FASER: Feng, Galon, Kling, Trojanowski. PRD 97 (2018) 035001

Benchmark I



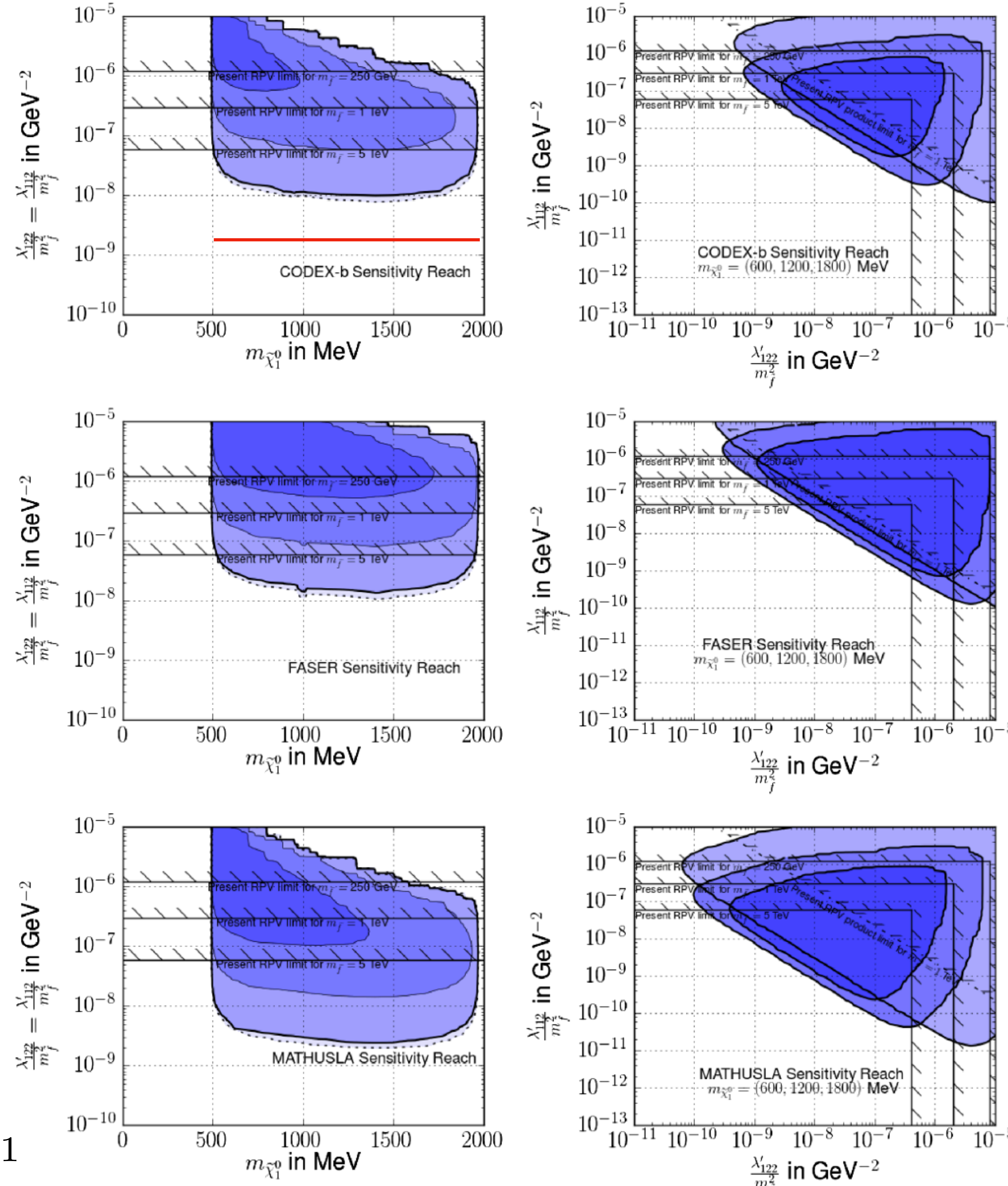
CODEX-b

FASER

MATHUSLAH

$\mathcal{L} = 3\,\mathrm{ab}^{-1}$

Benchmark I



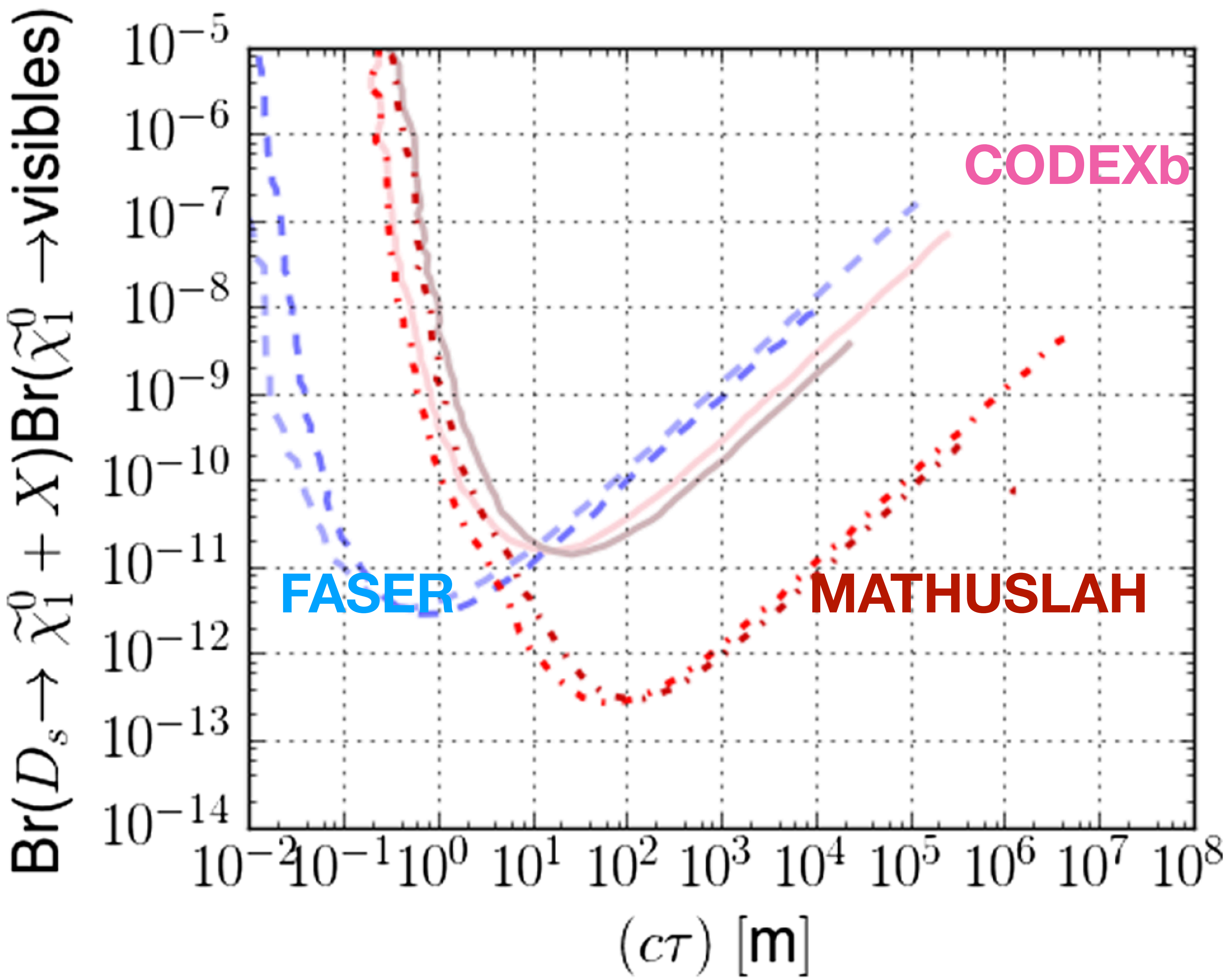
CODEX-b

FASER

MATHUSLA

$\mathcal{L} = 3\,\mathrm{ab}^{-1}$

Benchmark I



max. sensitivity when: $\langle \beta\gamma \rangle c\tau \approx \langle L \rangle,$

$$\langle \beta\gamma \rangle c\tau \approx \langle L \rangle,$$

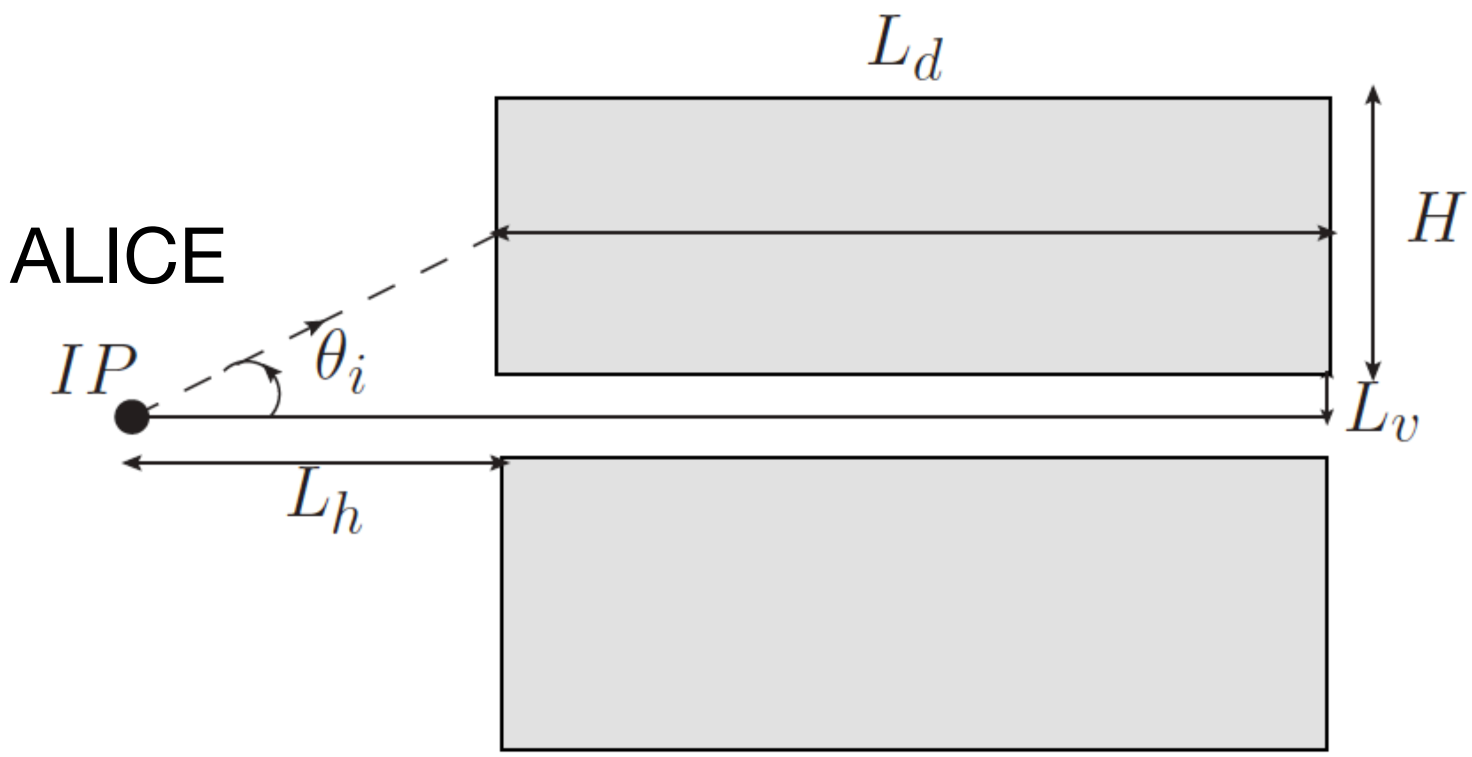
Benchmark Sc.	$m_{\tilde{\chi}_1^0}$ (MeV)	$\langle \beta\gamma \rangle_{\texttt{CODEX-b}}$	$\langle \beta\gamma \rangle_{\texttt{FASER}}$	$\langle \beta\gamma \rangle_{\texttt{MATHUSLA}}$
1 (D_s)	1200	1.64	560	2.87
2 ($D^{\pm}$)	1200	1.50	682	2.90
3 (B^0 & $\bar{B}^0$)	1000	4.07	793	7.32
4 (B^0 & $\bar{B}^0$)	2000	2.22	391	3.88
5 (B^0 & $\bar{B}^0$)	2500	1.88	308	3.36
5 ($B^{\pm}$)	2500	1.55	358	2.95

$$\langle L \rangle = \begin{cases} 30.0 \text{ m} & \text{for } \texttt{CODEX-b}, \\ 475 \text{ m} & \text{for } \texttt{FASER}, \\ 223 \text{ m} & \text{for } \texttt{MATHUSLA}. \end{cases}$$

$$(c\tau)_{\text{max sensitivity}} = \begin{cases} 18.3 \text{ m} & \text{for } \texttt{CODEX-b}, \\ 0.85 \text{ m} & \text{for } \texttt{FASER}, \\ 77 \text{ m} & \text{for } \texttt{MATH} \end{cases}$$

AL3X

Gligorov, Knapen, Nachman, Papucci, Robinson
arXiv:1810.03636



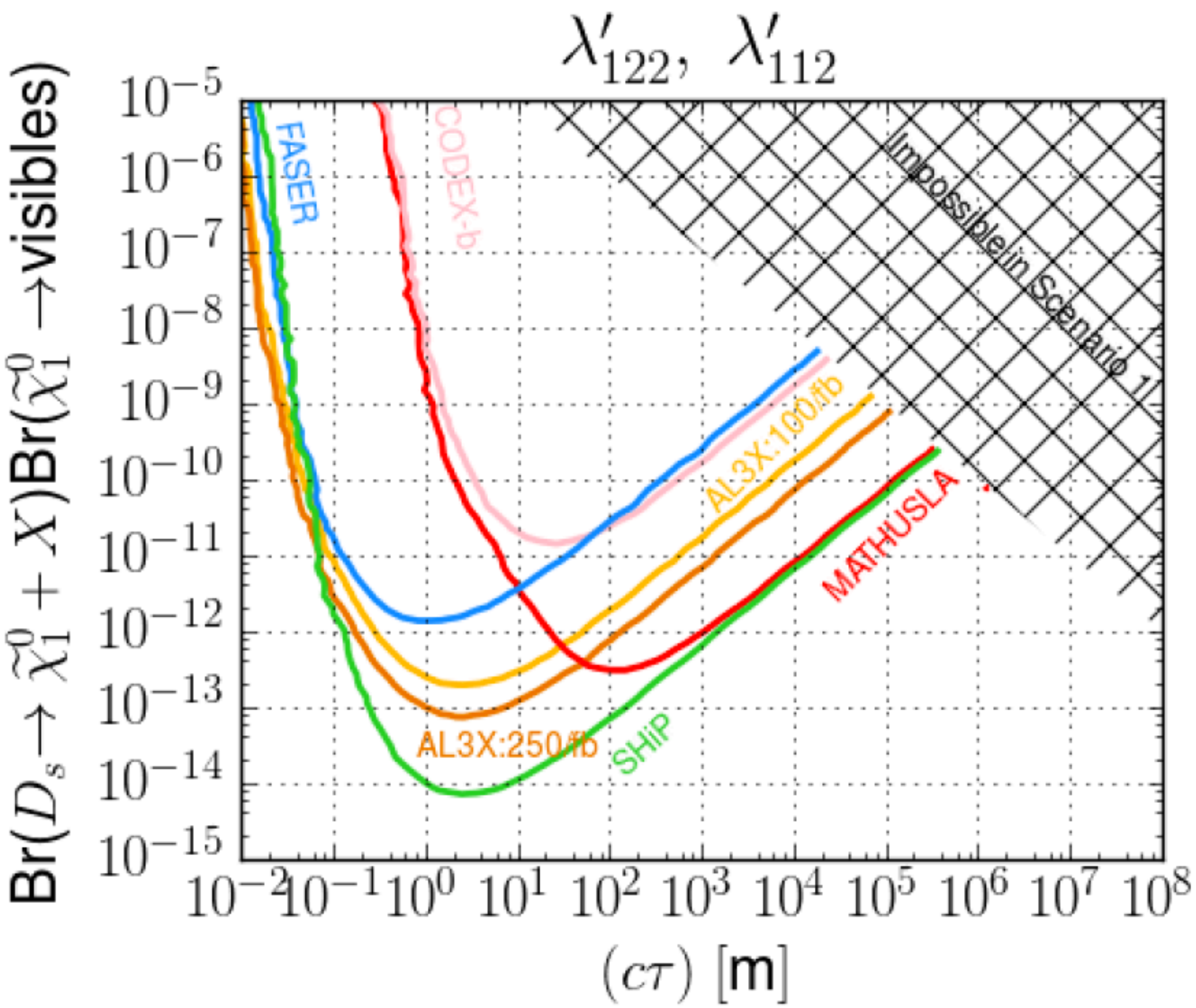
$$L_h = 5.25\,\mathrm{m}$$

$$L_d = 12\,\mathrm{m}$$

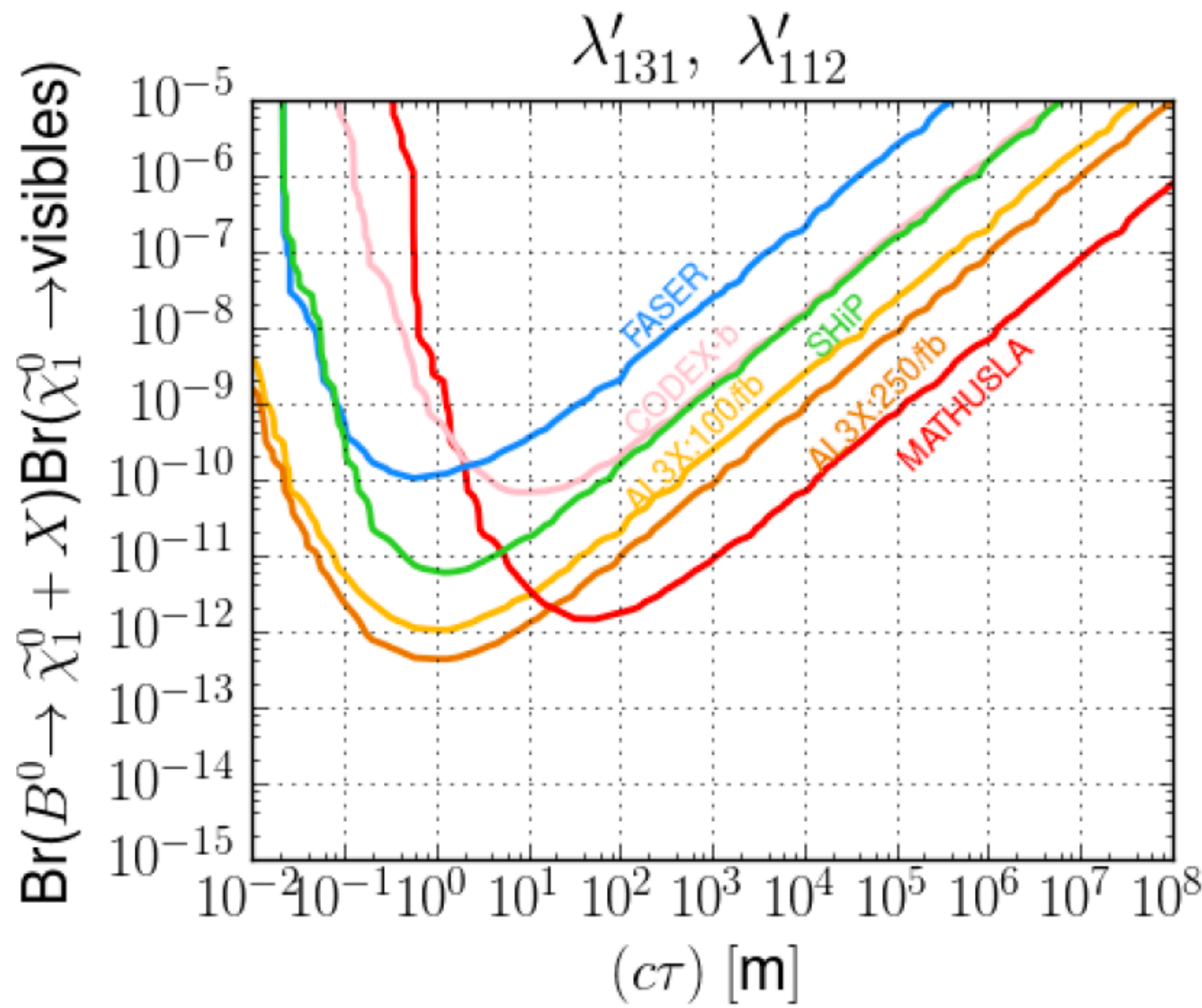
$$H = 5\,\mathrm{m}$$

$$L_v = 0.85\,\mathrm{m}$$

AL3X

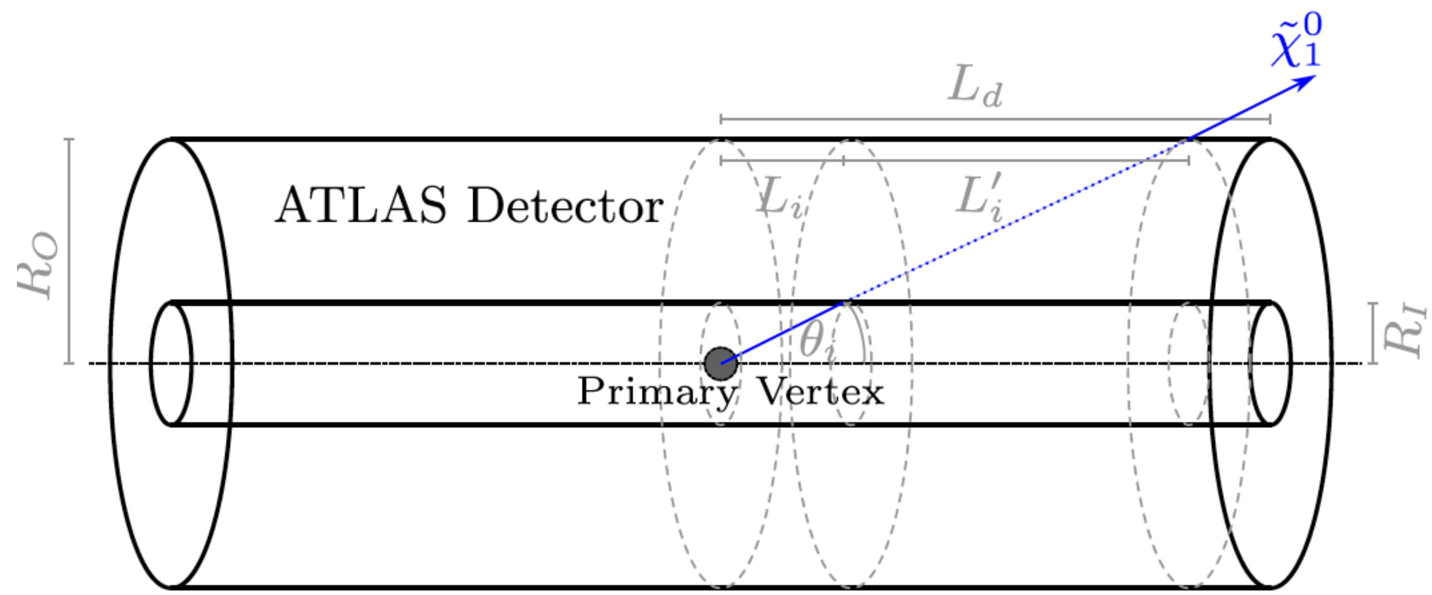


$\lambda'_{122},\ \lambda'_{112}$
$\mathrm{Br}(D_s \to \tilde{\chi}_1^0 + X)\mathrm{Br}(\tilde{\chi}_1^0 \to \mathrm{visibles})$
$(c\tau)$ [m]
FASER
CODEX-b
Impossible in Scenario 1
AL3X:100/fb
AL3X:250/fb
MATHUSLA
SHiP



$\lambda'_{131},\ \lambda'_{112}$
$\mathrm{Br}(B^0 \to \tilde{\chi}_1^0 + X)\mathrm{Br}(\tilde{\chi}_1^0 \to \mathrm{visibles})$
$(c\tau)$ [m]
FASER
CODEX-b
SHiP
AL3X:100/fb
AL3X:250/fb
MATHUSLA

ATLAS

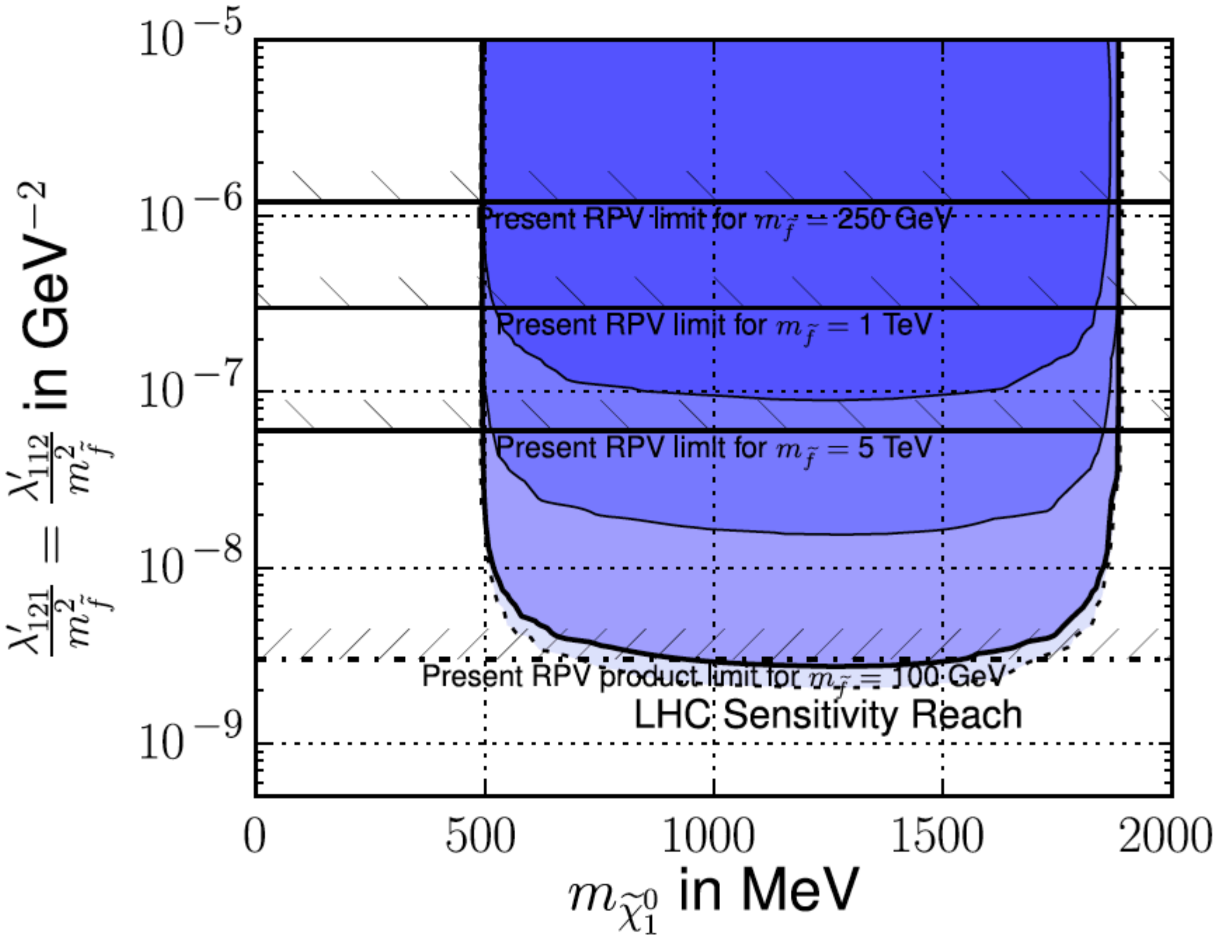


- Assumptions:
  - $\mathcal{L} = 250\,\mathrm{fb}^{-1}$
  - Detectable region between:

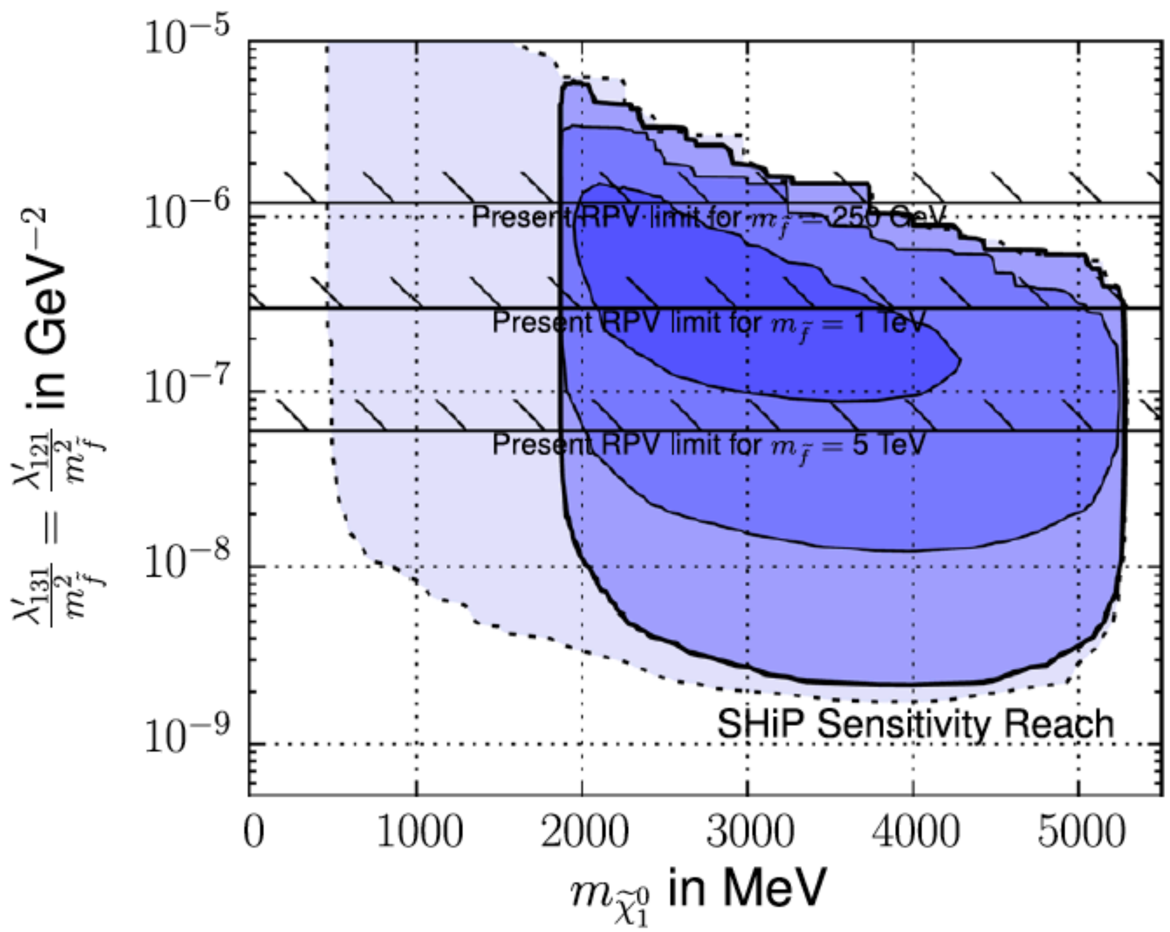
    $R_I = 0.0505\,\mathrm{m}$ and $R_O = 11\,\mathrm{m}$
  - $L_d = 21.5\,\mathrm{m}$

Benchmark I

ATLAS

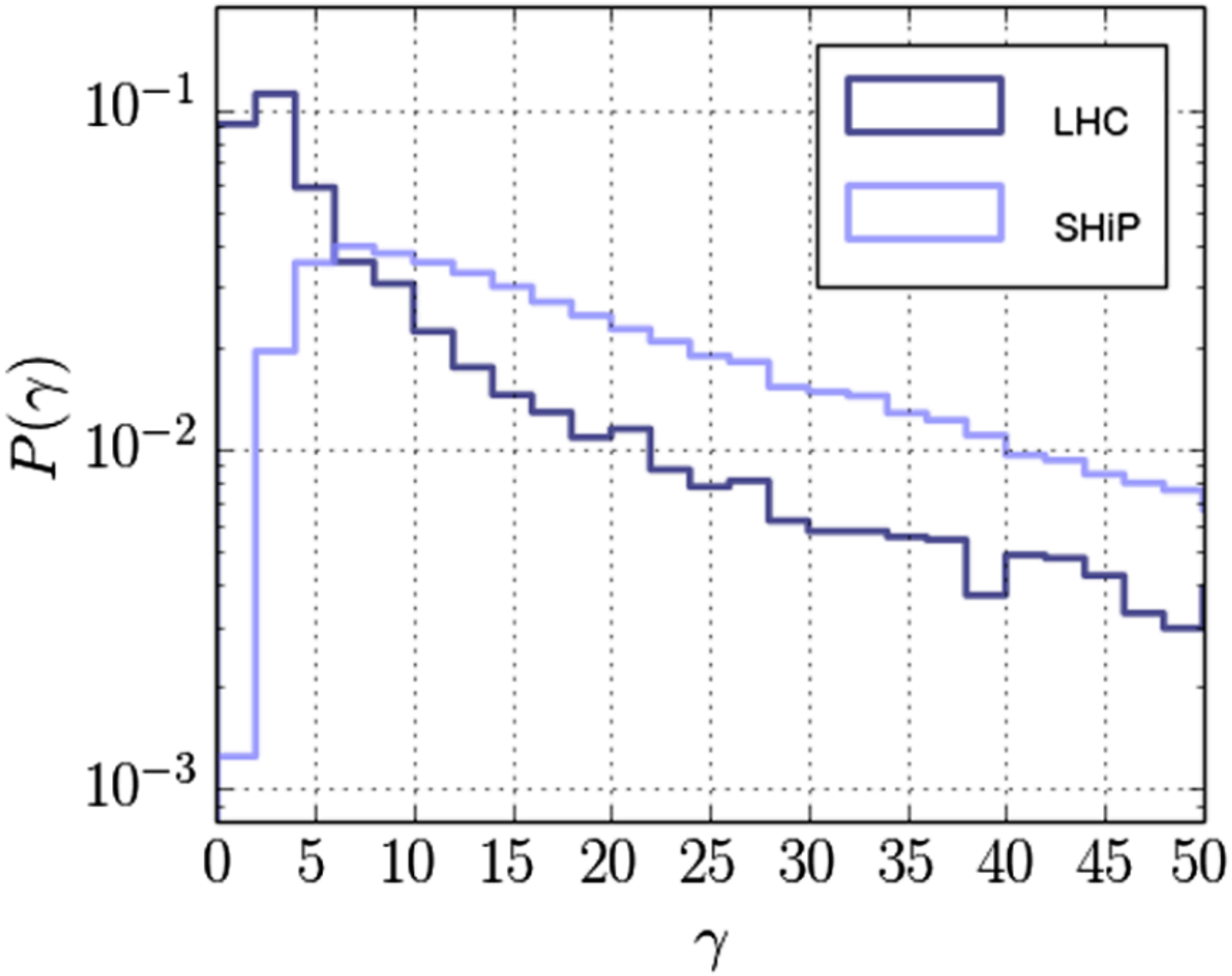


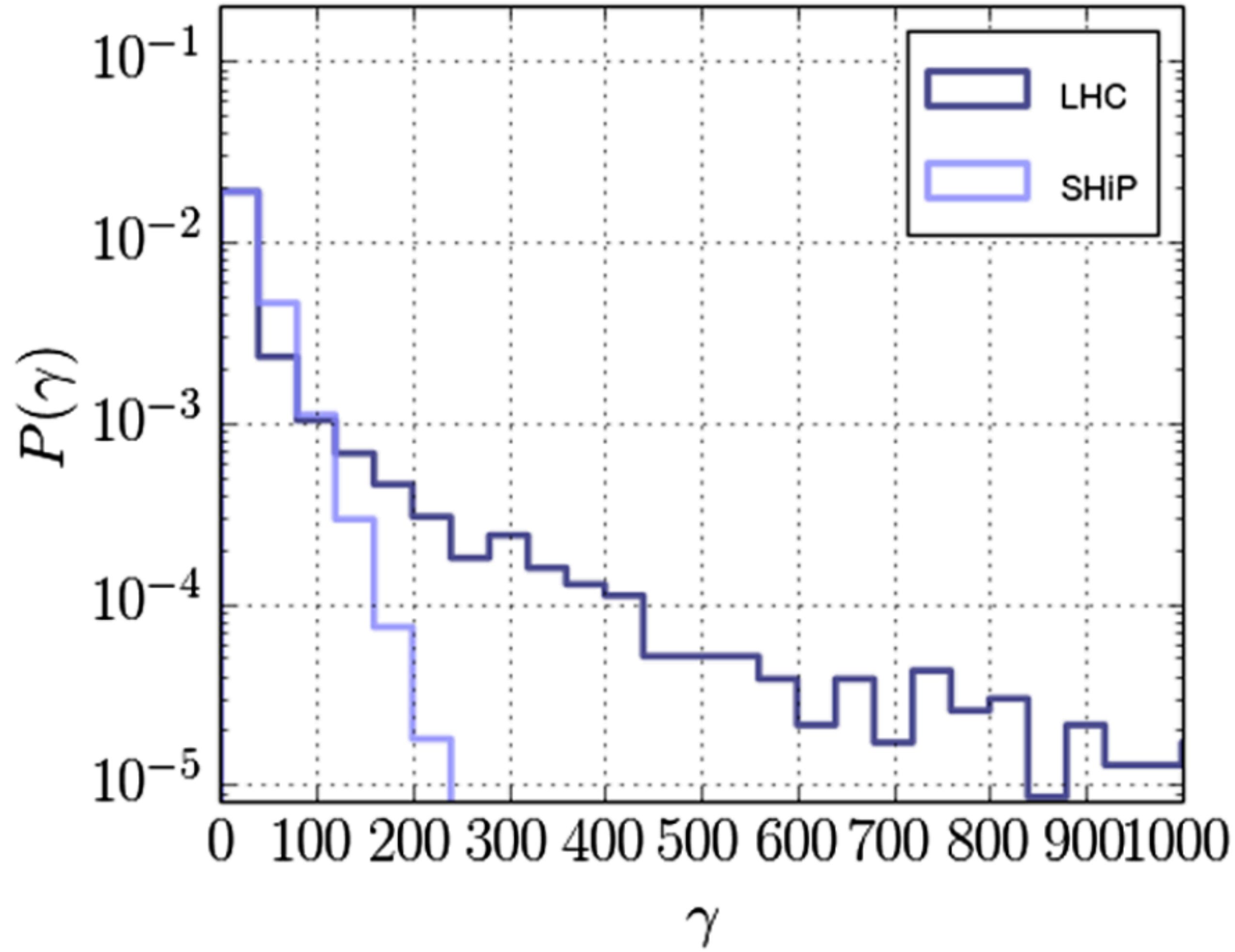
SHiP



- SHiP more sensitive by a factor of 2 in coupling. Why?
- $N_{c\bar c}(\mathrm{SHiP}) = 100 \times N_{c\bar c}(\mathrm{ATLAS})$, correspondingly more χ^0_1
- ATLAS has higher angular acceptance

Neutralino Boost





$$\langle\gamma\rangle_{\rm SHiP} = 30 \qquad \langle\gamma\rangle_{\rm ATLAS} = 55$$

$$\gamma^{\rm max}_{\rm SHiP} = 7.5 \qquad \gamma^{\rm max}_{\rm ATLAS} = 2.5$$

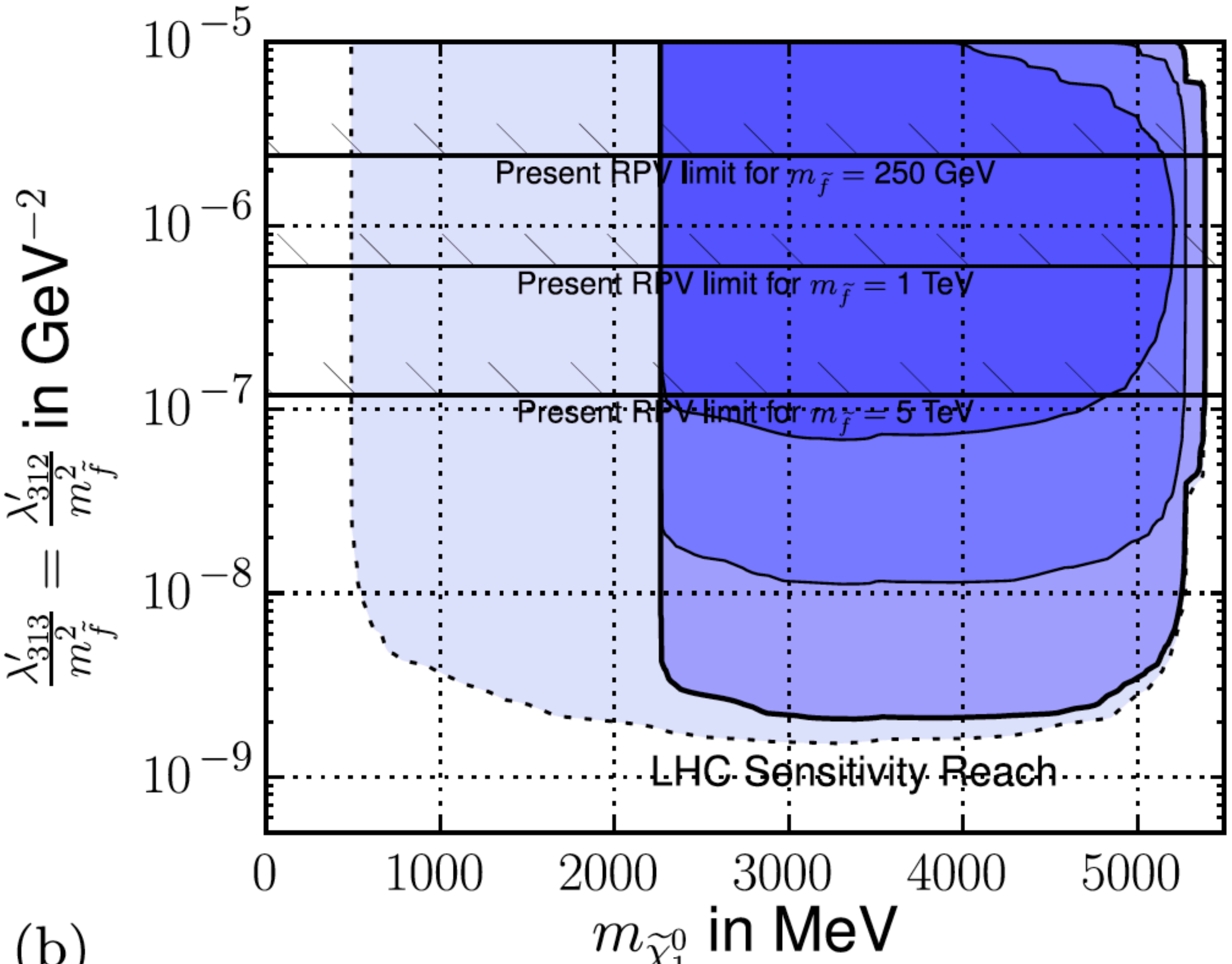
$$\langle P[\tilde{\chi}^0_1 \text{in d.r.}]\rangle_{\rm SHiP} = 25 \times \langle P[\tilde{\chi}^0_1 \text{in d.r.}]\rangle_{\rm ATLAS}$$

$$\sqrt[4]{25} \approx 2.2$$

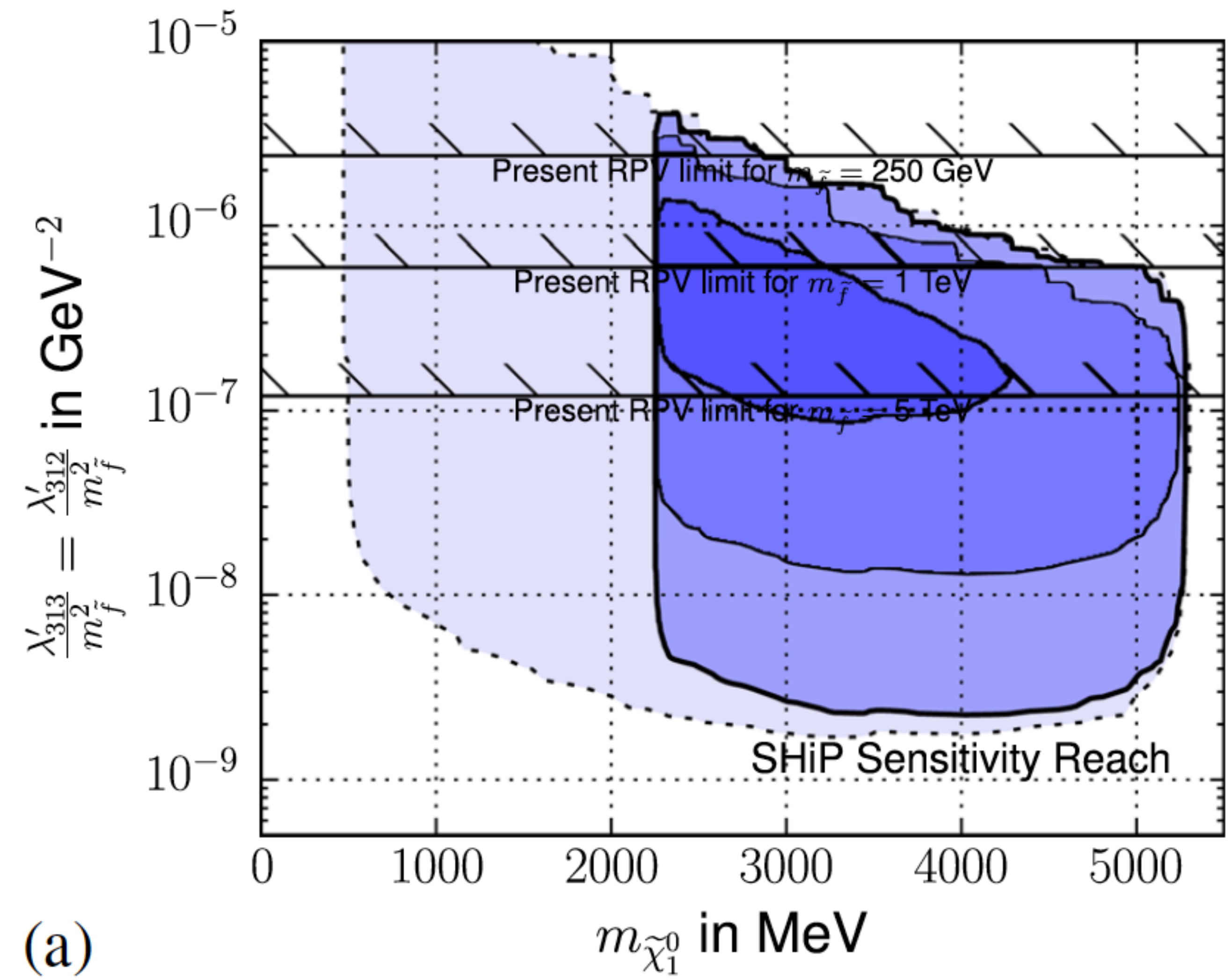
Benchmark V

- In Benchmark V, relying on B-meson production, the expected sensitivity at atlas is the same (10% better)

ATLAS



SHiP



Conclusions

- A light neutralino is a well-motivated supersymmetric scenario
- It is typically long-lived
- Have studied the potential for various experiments to search for it

SHiP

MATHUSLA

CODEX-b

FASER

ATLAS