Searching for Long-Lived Neutralinos & RH Neutrinos

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Recent work together with: **Daniel Dercks (né Schmeier)**
Jordy de Vries
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Martin Hirsch
Zeren Simon Wang
Guanghui Zhou

Previous Work

RPV-Light Neutralino

- KARMEN: Choudhury, HD, Richardson, Sarkar; *Phys.Rev.D* 61 (2000) 095009
- NuTeV: Dedes, HD, Richardson; *Phys.Rev.D* 65 (2001) 015001
- SHiP, ATLAS: de Vries, HD, Schmeier, *Phys.Rev.D 94 (2016) 035006*
- CODEX-b, FASER, MATHUSLA: Dercks, de Vries, HD, Wang; *PRD* 99 (2019) 055039
- AL3X: Dercks, HD, Hirsch, Wang; *Phys.Rev.D* 99 (2019) 5, 055020
- ANUBIS, MoEDAL/MAPP: HD, Günther, ZS Wang; *2008.07539 [hep-ph]*

Right Handed Neutrino

- Many Exps.: de Vries, HD, Günther, Wang, Zhou; *2008.07539 [hep-ph]*

Searches for Long-Lived Particles

- Motivated by dark matter, new experimental proposals: search for light dark sector particles.

- Light neutralinos, briefly: RH neutrinos

Massless Neutralinos

- Drop SUSY GUT assumption relating M_1 and M_2, set determinant of neutralino mass matrix to zero, solve for M_1

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

- 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, EPJ C62 (2009) 547

- For: $0.7\,\mathrm{eV} < M_{\tilde{\chi}_1^0} < 10\,\mathrm{GeV}$ LSP must decay (RPV)

Search for Light Longlived Neutralino

- Mass range we consider here: 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 in (remote) detector

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
  ANUBIS
  MoEDAL-MAPP
- Compare with potential at: **ATLAS**

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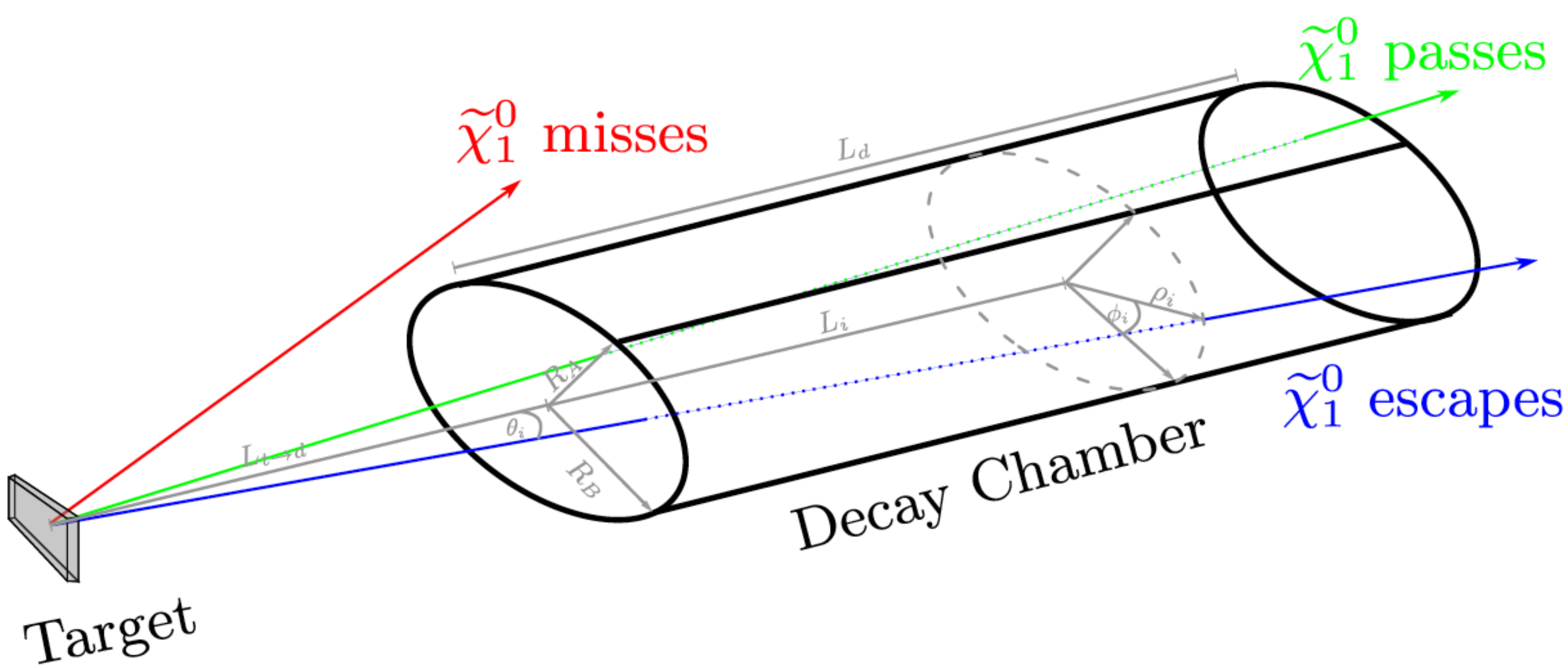
Proposed SHiP Experiment Parameters

$\sqrt{s} = 27\,\mathrm{GeV};$ 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 $\qquad N_{c\bar{c}} = 9 \times 10^{16}$

Pythia, FONLL $\qquad N_{b\bar{b}} = 2 \times 10^{13}$

$n^{c\bar{c}}_{D^\pm}$	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

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

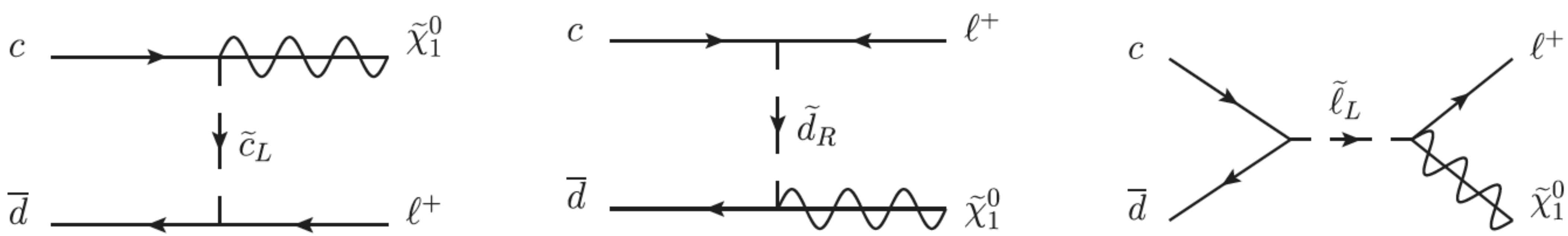
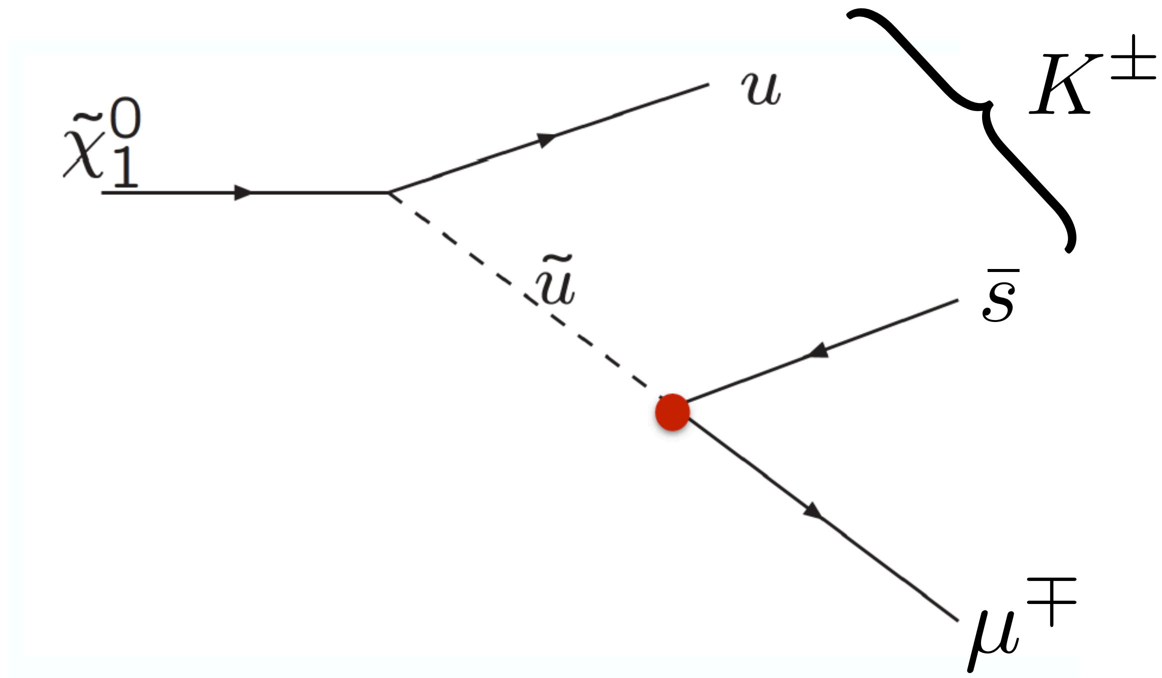


FIG. 1. Relevant Feynman diagrams for $D^+ \to \tilde{\chi}_1^0 + \ell^+$.

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}

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

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

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

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

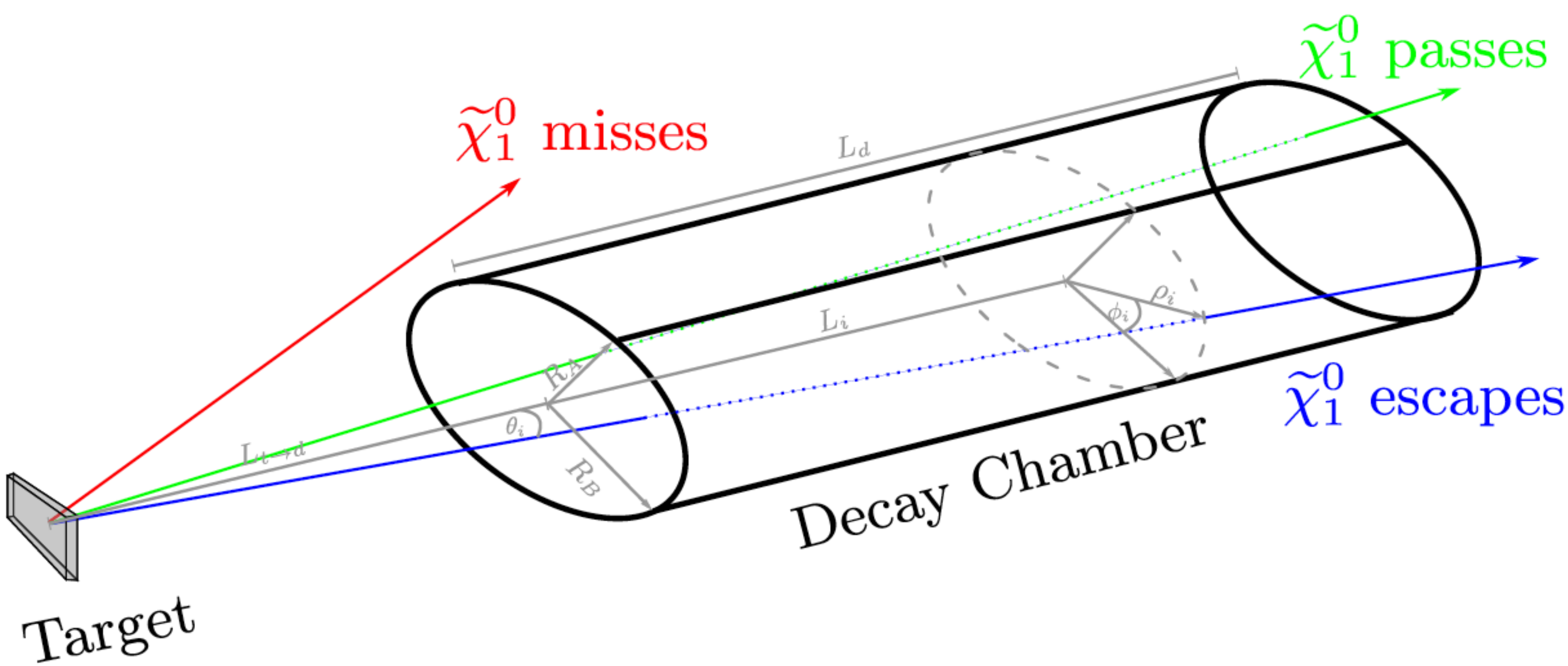
- $\langle P[\tilde{\chi}^0_1 \,{\rm in\, d.r.}]\rangle = \frac{1}{N^{\rm MC}_{\tilde{\chi}^0_1}} \sum_{i=1}^{N^{\rm MC}_{\tilde{\chi}^0_1}} P[(\tilde{\chi}^0_1)_i \,{\rm in\, d.r.}],$

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

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

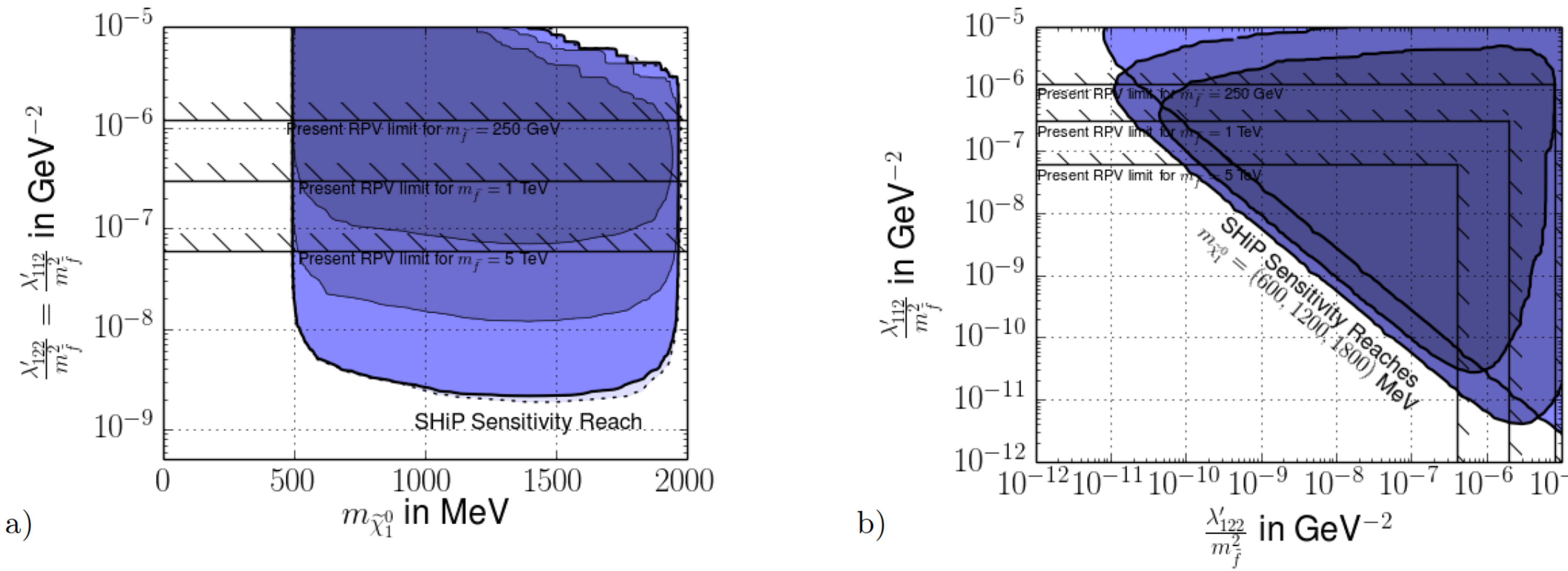
$$\beta^z_i = p^z_i / E_i$$

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



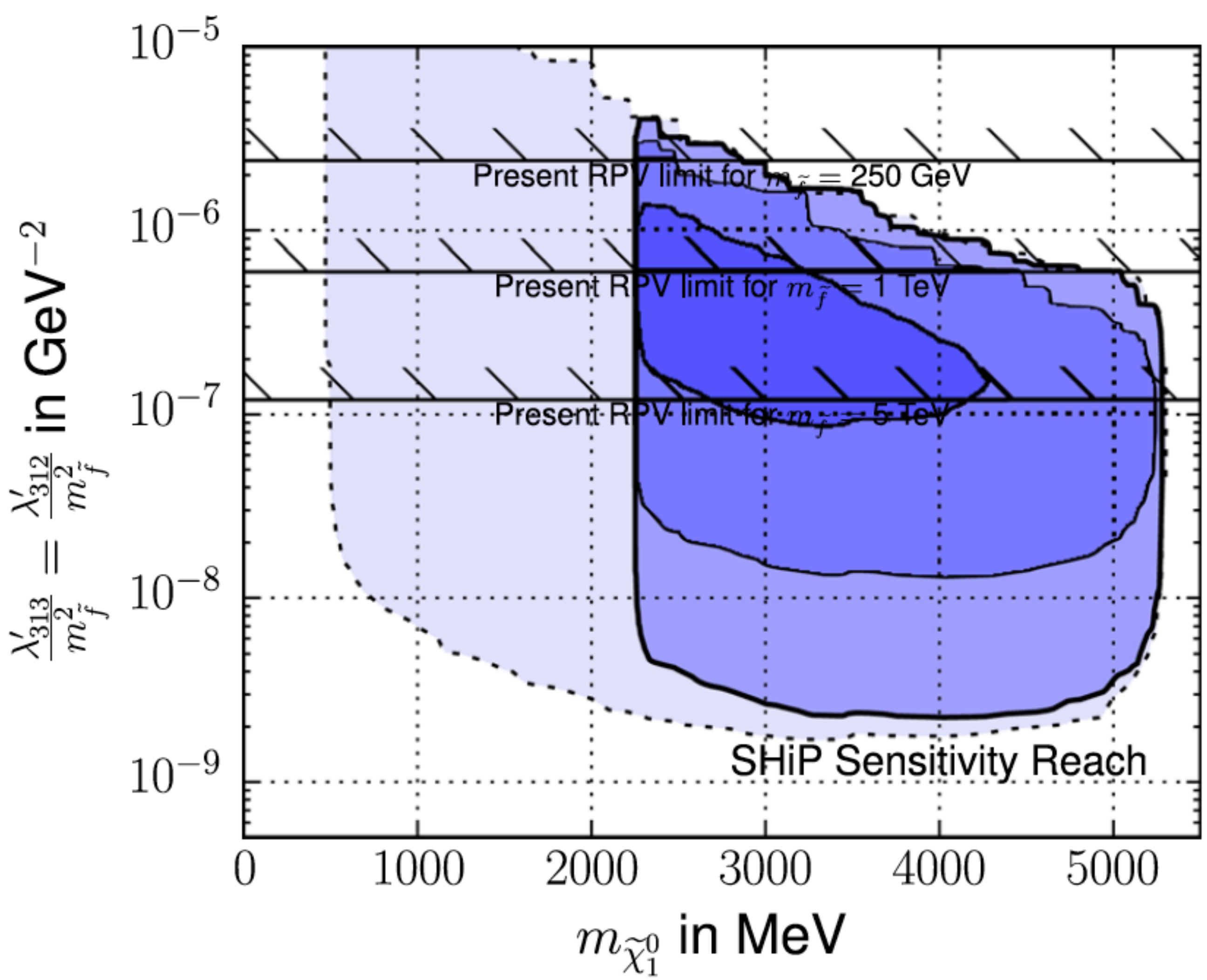
Results: Benchmark II

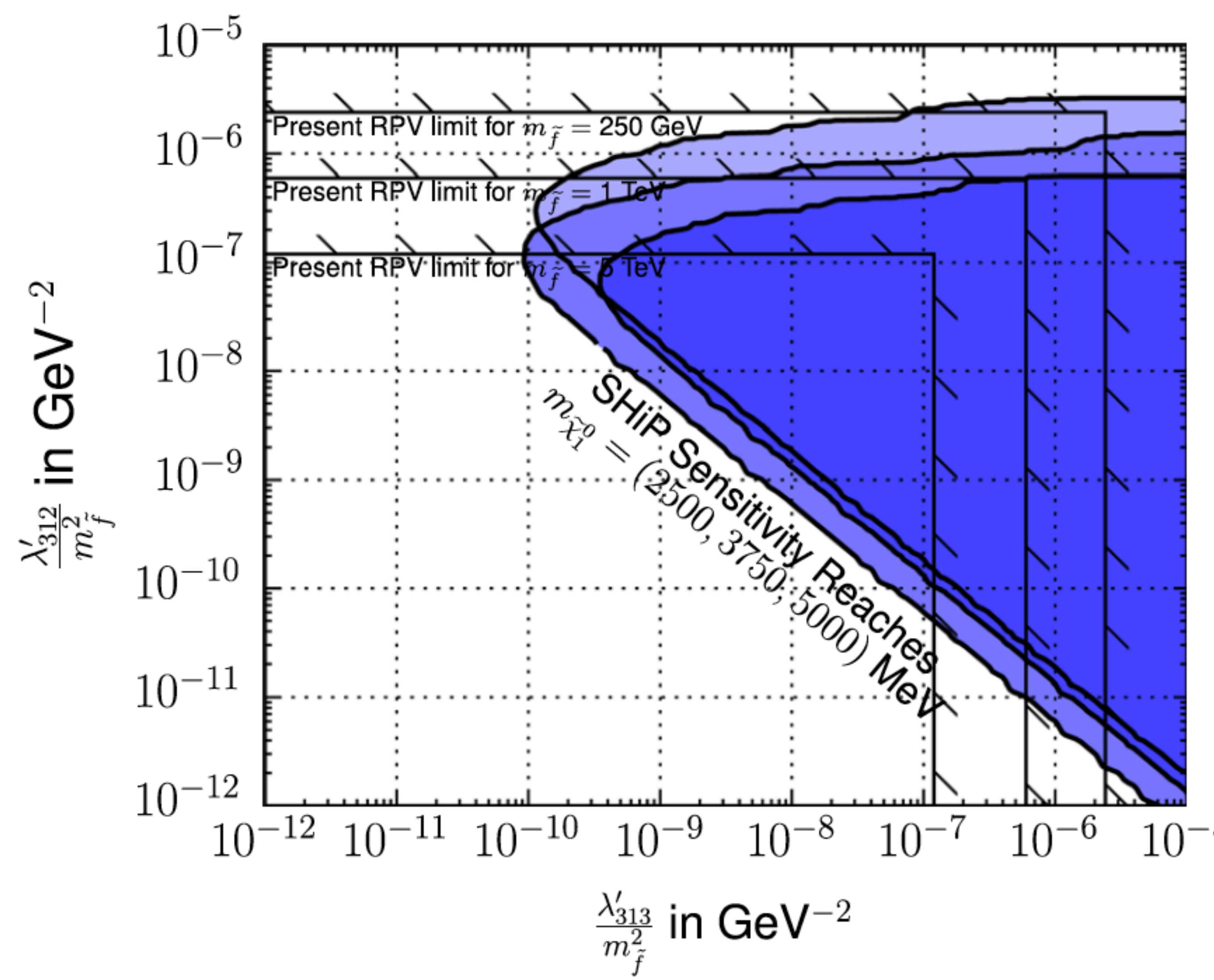
λ'_P for production	λ'_{122}
λ'_D for decay	λ'_{112}
produced meson(s)	D_s
visible final state(s)	$K^{\pm}e^{\mp}, K^{*\pm}e^{\mp}$
invisible final state(s) via λ'_P	$(\eta, \eta', \phi) + (\nu, \bar{\nu})$
invisible final state(s) via λ'_D	$(K_L^0, K_S^0, K^*) + (\nu, \bar{\nu})$



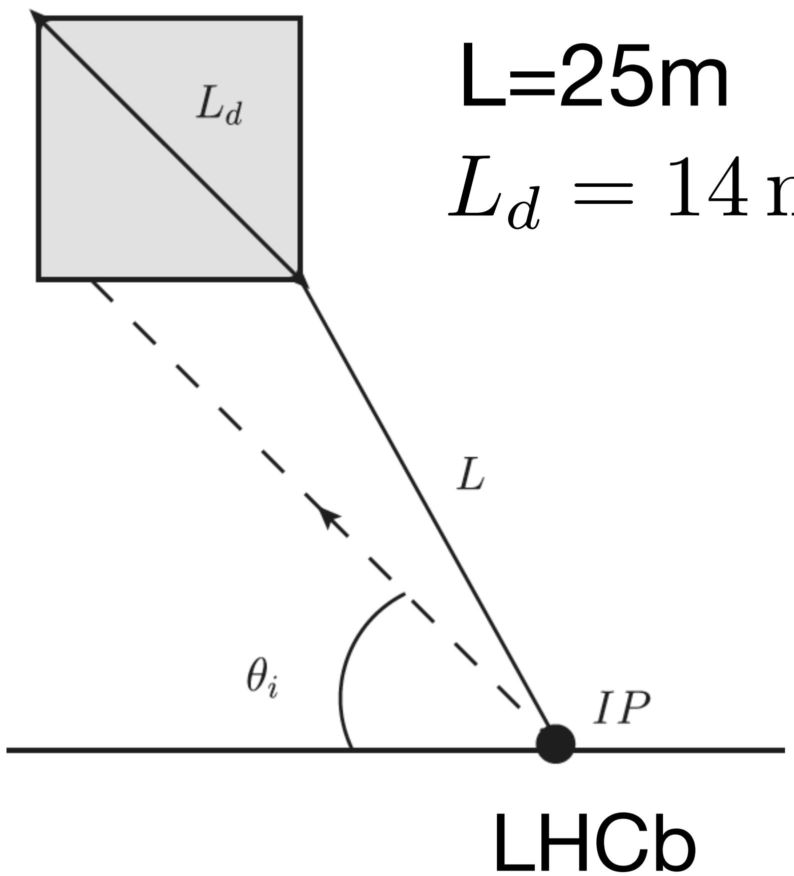
Results: Benchmark V

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	$(K^0_L, K^0_S, K^*) + (\nu, \bar{\nu})$





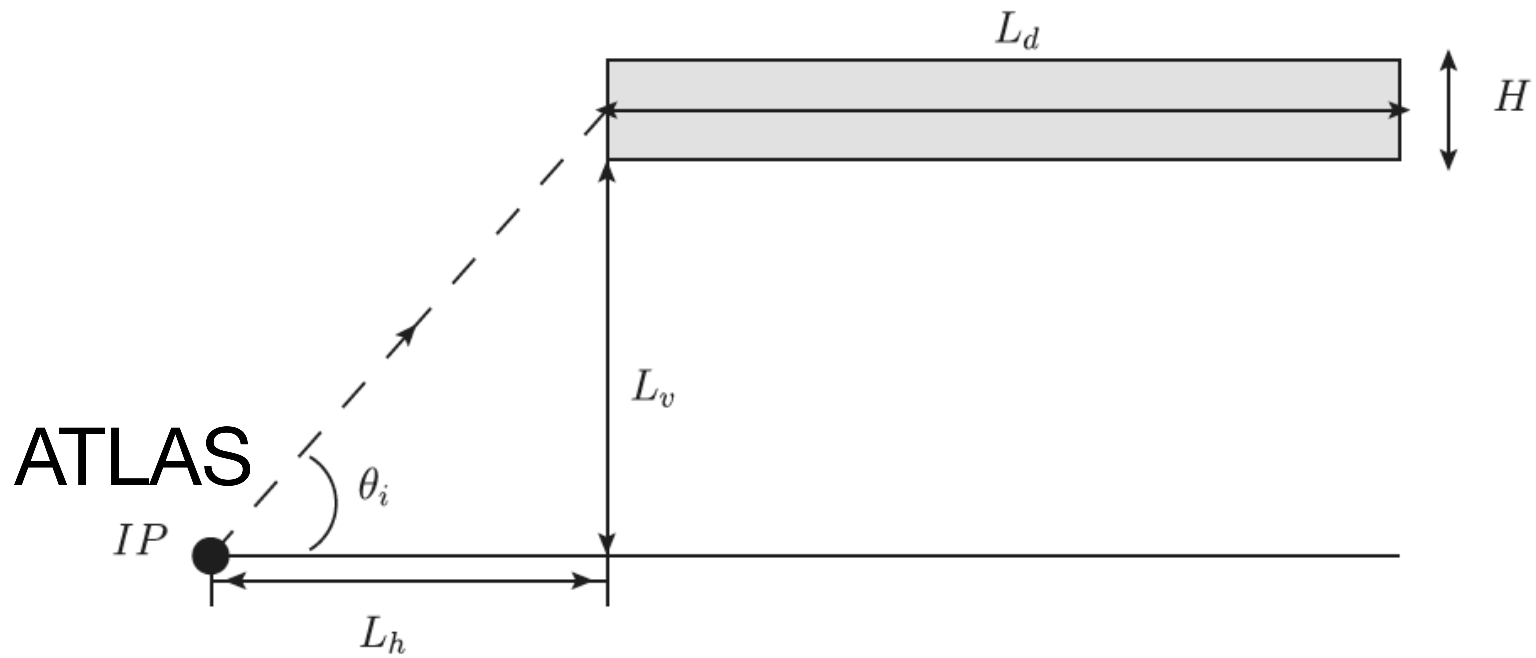
CODEX-b



L=25m

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

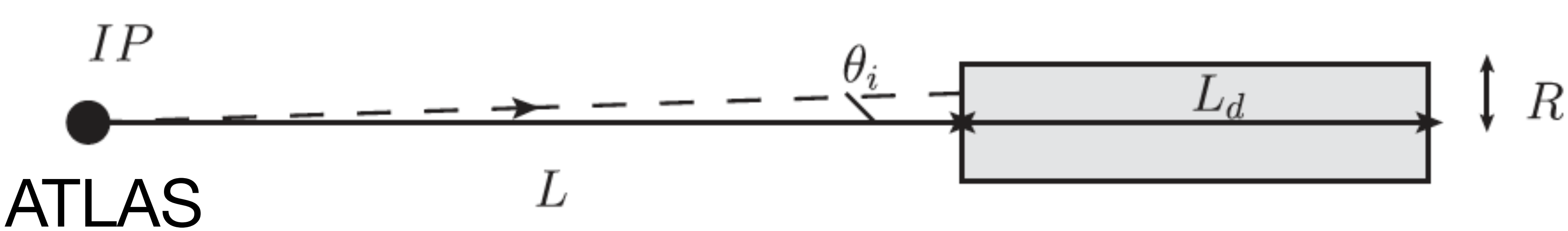
MATHUSLA



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

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

FASER

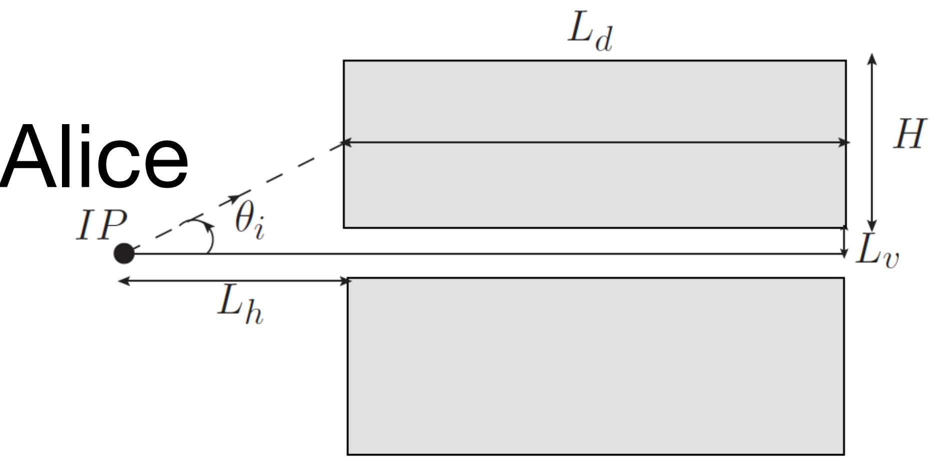


L=470m

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

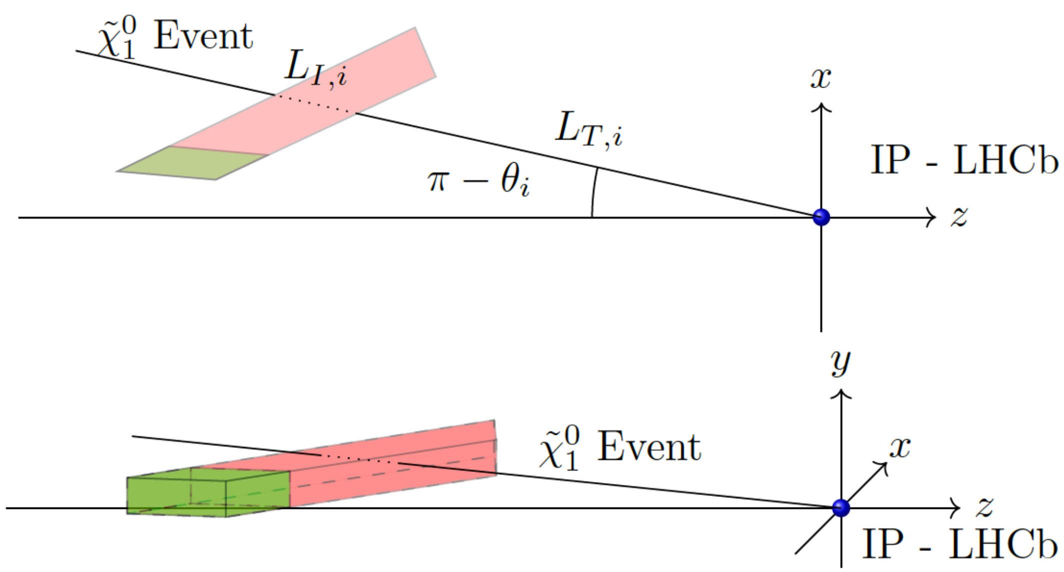
R=1m

AL3X



$$L_d = 12\,\mathrm{m},\;\; L_h = 5.25\,\mathrm{m}$$
$$H = 4.15\,\mathrm{m}$$

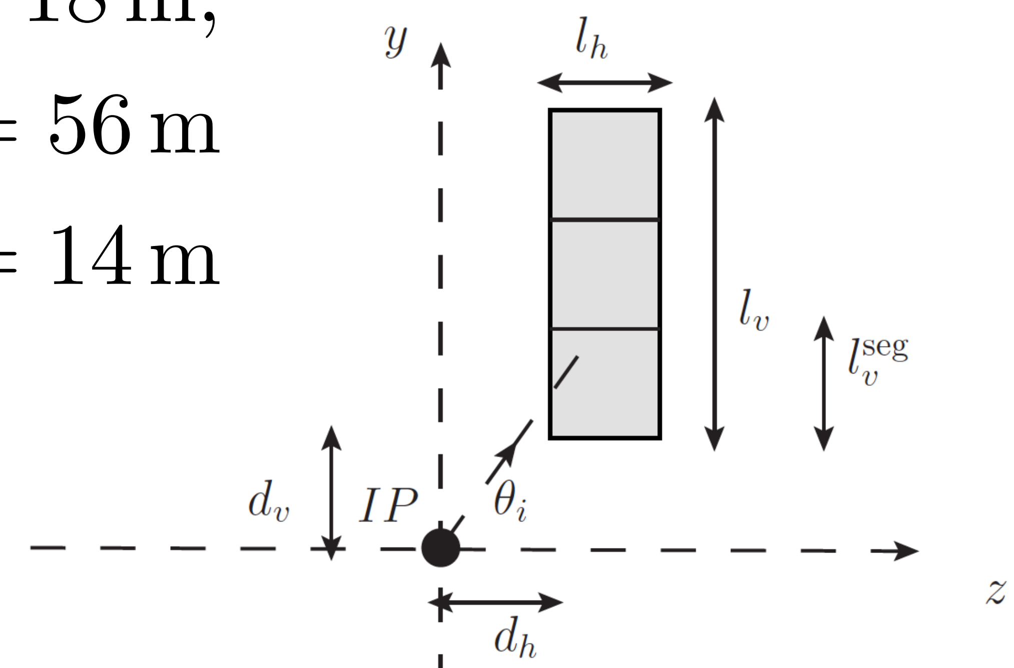
MoEDAL-MAPP

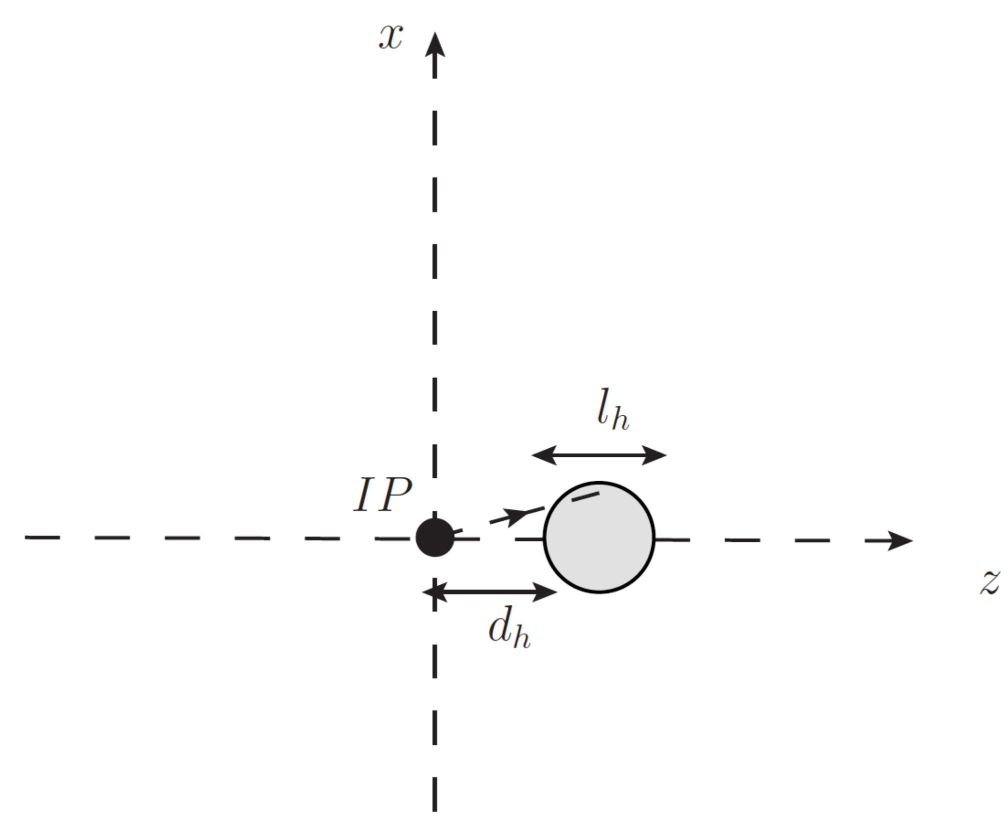


$$L = 55\,\mathrm{m};\quad \theta = 5^\circ$$

ANUBIS (Atlas/CMS)

$$l_h = 18\,\mathrm{m},$$
$$l_v = 56\,\mathrm{m}$$
$$d_h = 14\,\mathrm{m}$$

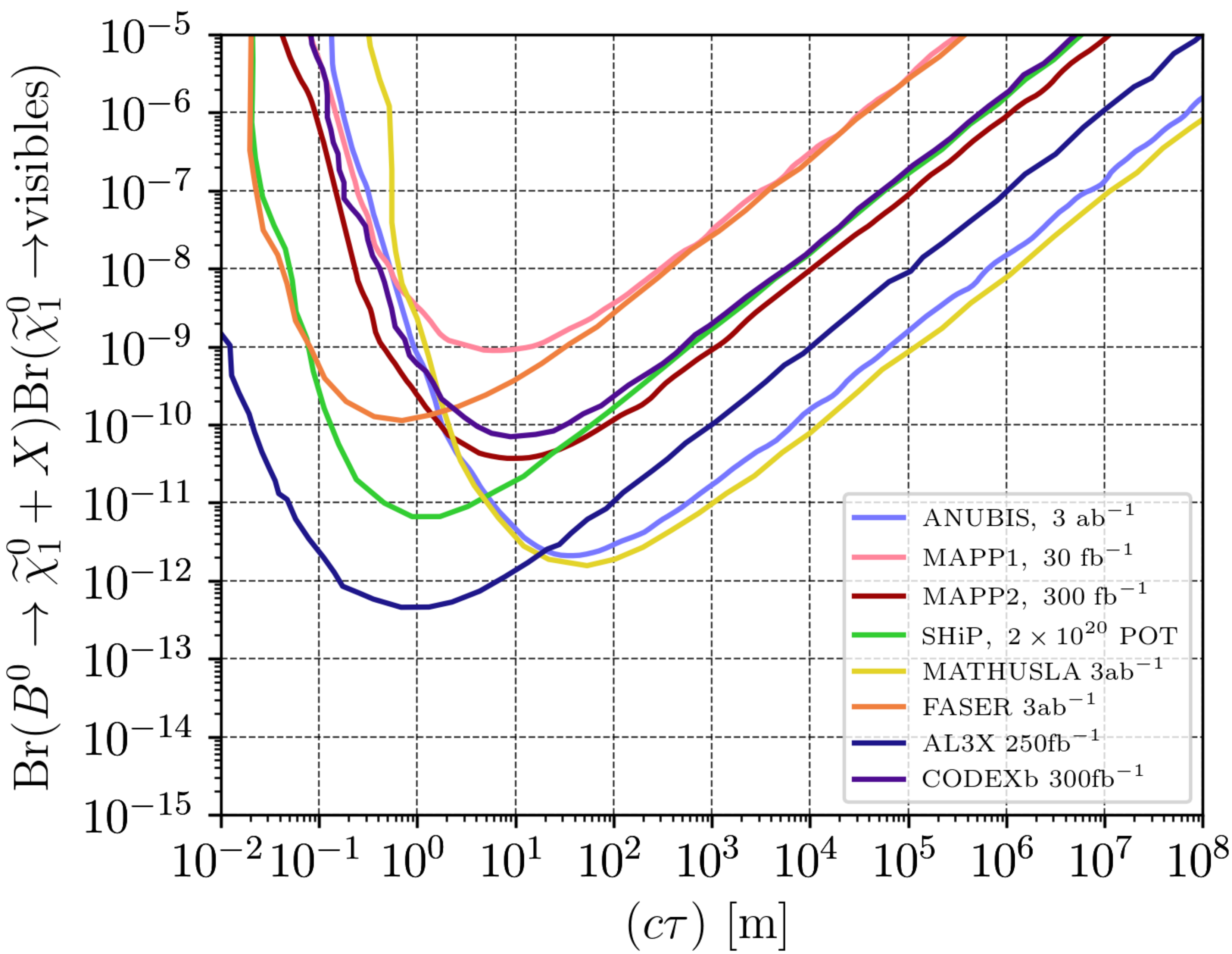


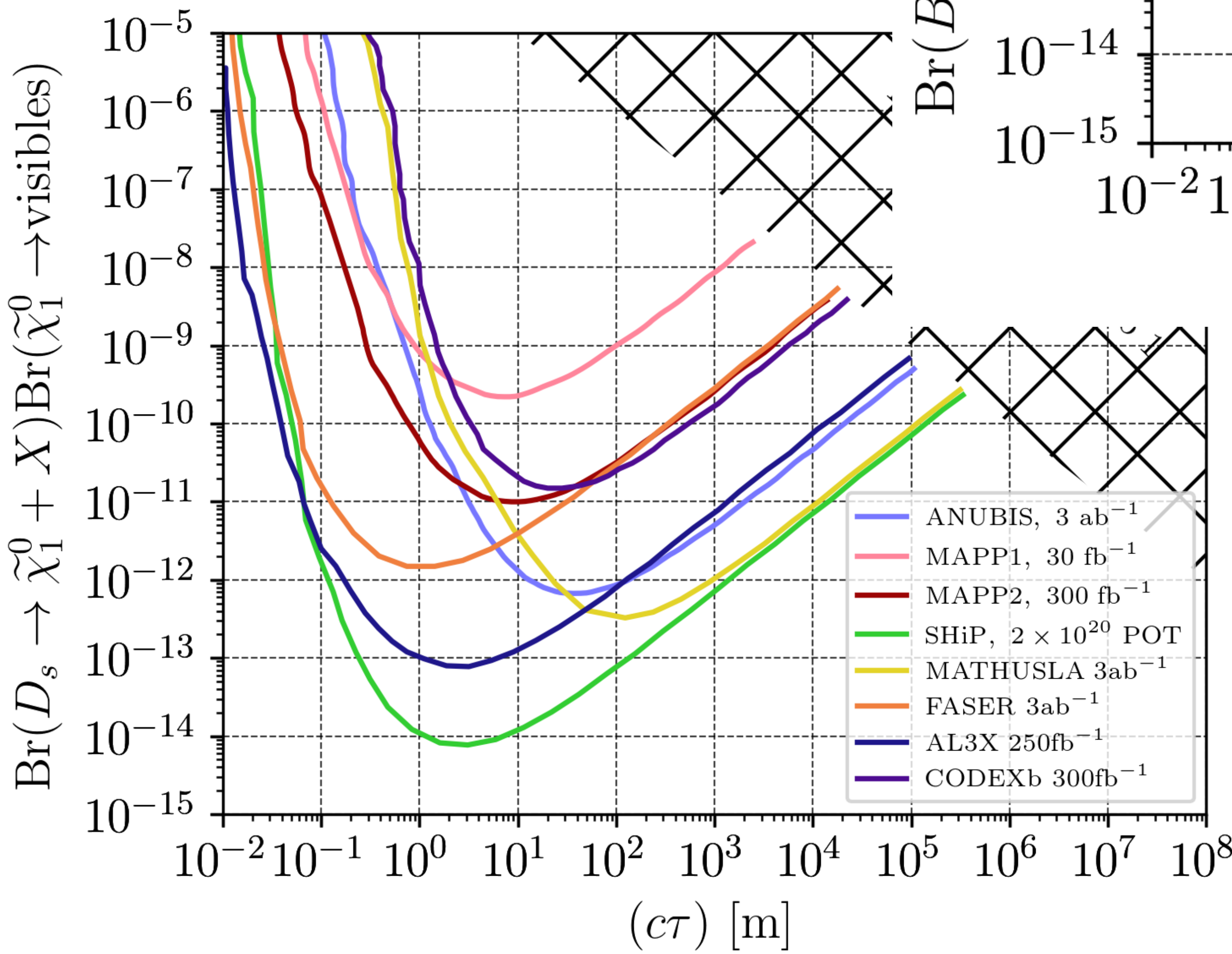


Basic Parameters of Experiments

Experiment	SHiP	ATLAS	AL3X	ANUBIS	CODEX-b
Int. Lumi.	2×10^{20} POT	$3000\ \mathrm{fb}^{-1}$	100 or $250\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$	$300\ \mathrm{fb}^{-1}$
Angular Cov.	0.89%	100%	13.73%	1.79%	1%

Experiment	FASER	FASER2	MAPP1	MAPP2	MATHUSLA
Int. Lumi.	$150\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$	$30\ \mathrm{fb}^{-1}$	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
Angular Cov.	1.1×10^{-8}	1.1×10^{-6}	0.17%	0.68%	3.8%





Herbi Dreiner, IRN, 11/2020

Right Handed Neutrino N

Minimal Scenario

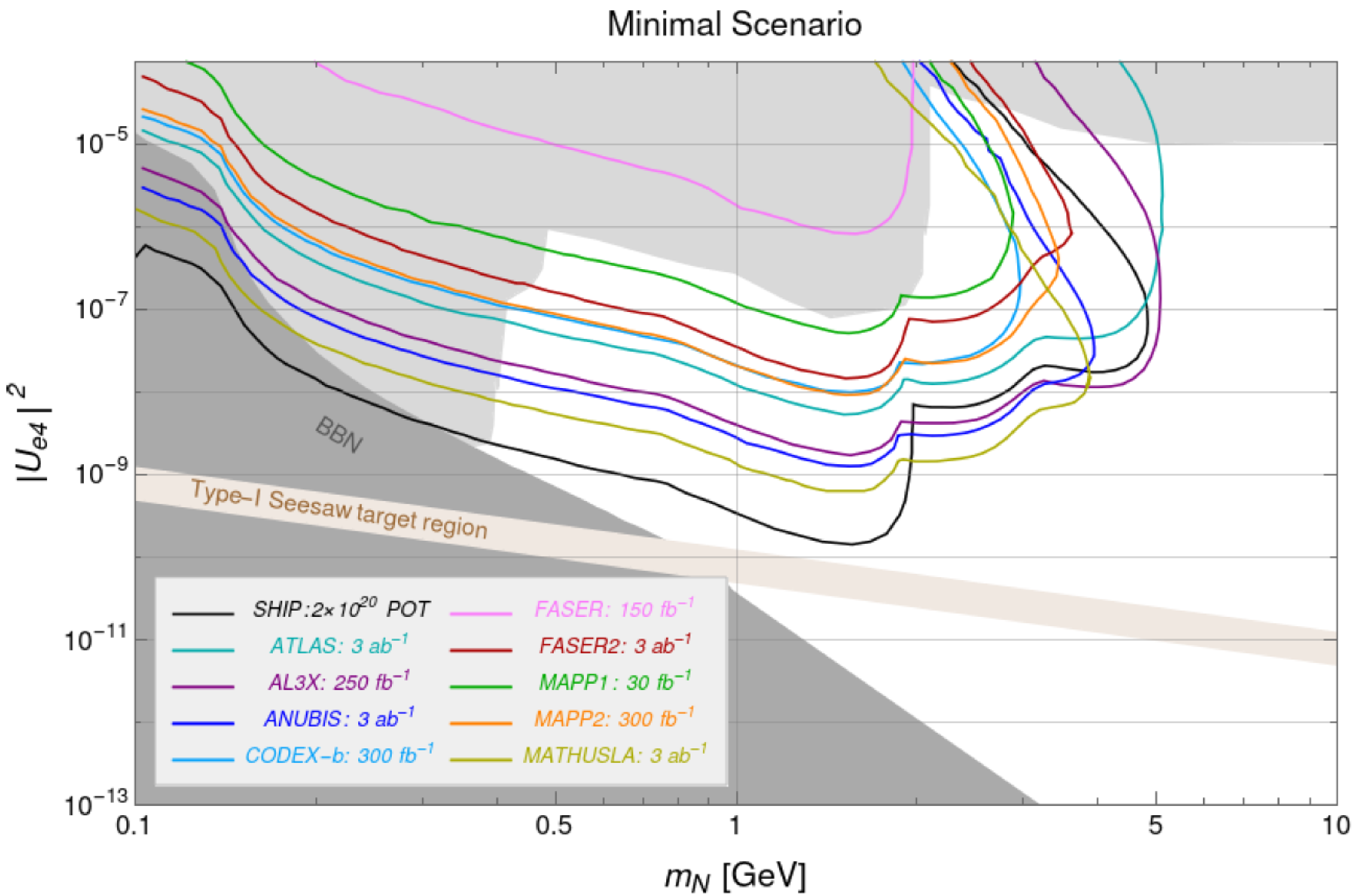
- N mixes with SM neutrinos, replace ν in SM meson decays by N
- Reverse, also to get N decays

Extended EFT Scenarios

- Extra production and decay modes

$$\text{Sterile Neutrino Production Modes}: \begin{cases} (C_{\rm P})_{21}: & D \to N + e\,(+X), \\ (C_{\rm P})_{13}: & B \to N + e\,(+X). \end{cases}$$

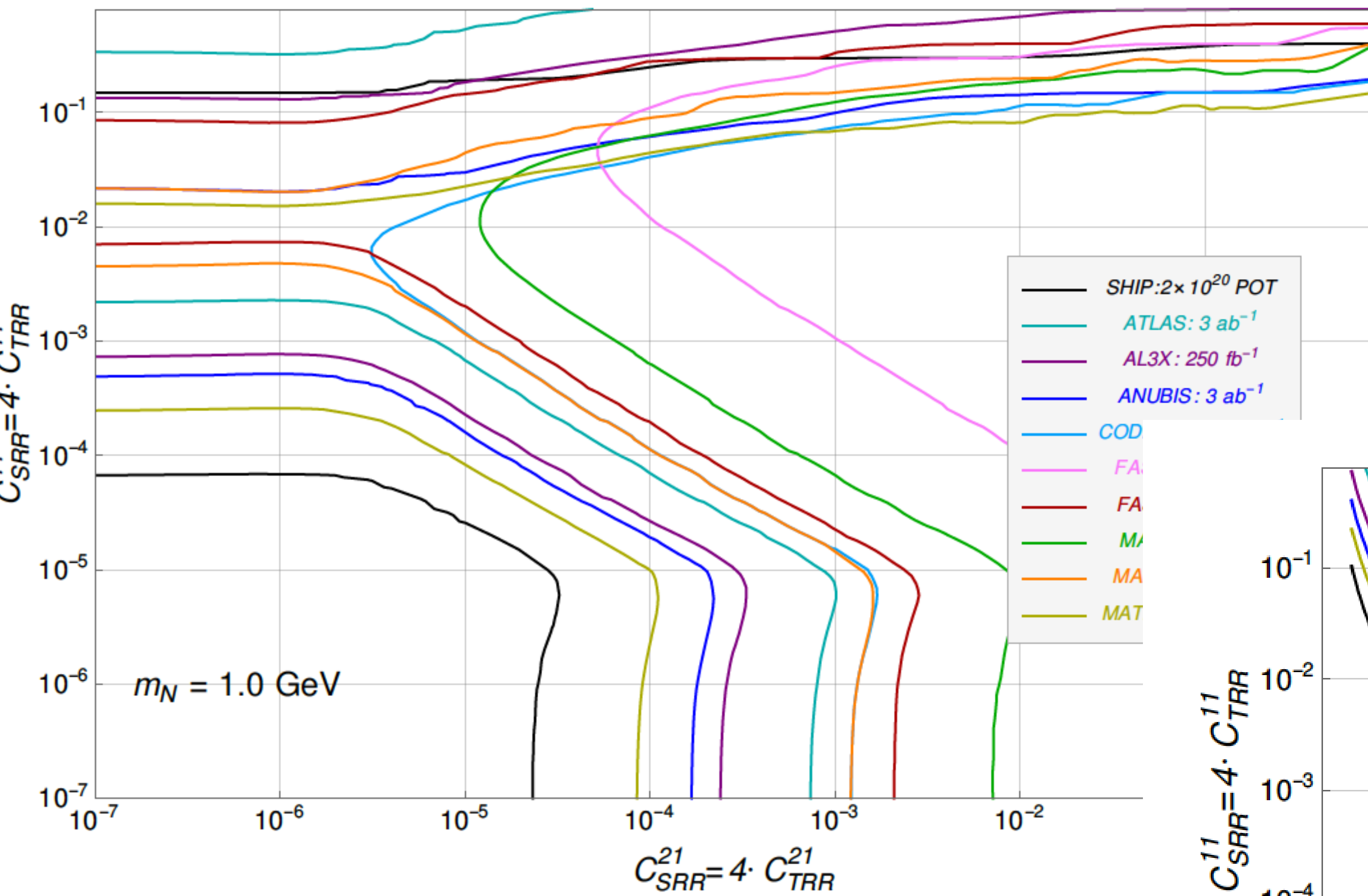
$$\text{Sterile Neutrino Decay Modes}: \begin{cases} (C_{\rm D})_{11}: & N \to \pi^{\pm} + e^{\mp},\ \rho^{\pm} + e^{\mp}\,, \\ (C_{\rm D})_{12}: & N \to K^{\pm} + e^{\mp},\ K^{*\pm} + e^{\mp}\,, \\ (C_{\rm D})_{21}: & N \to D^{\pm} + e^{\mp},\ D^{*\pm} + e^{\mp}\,. \end{cases}$$

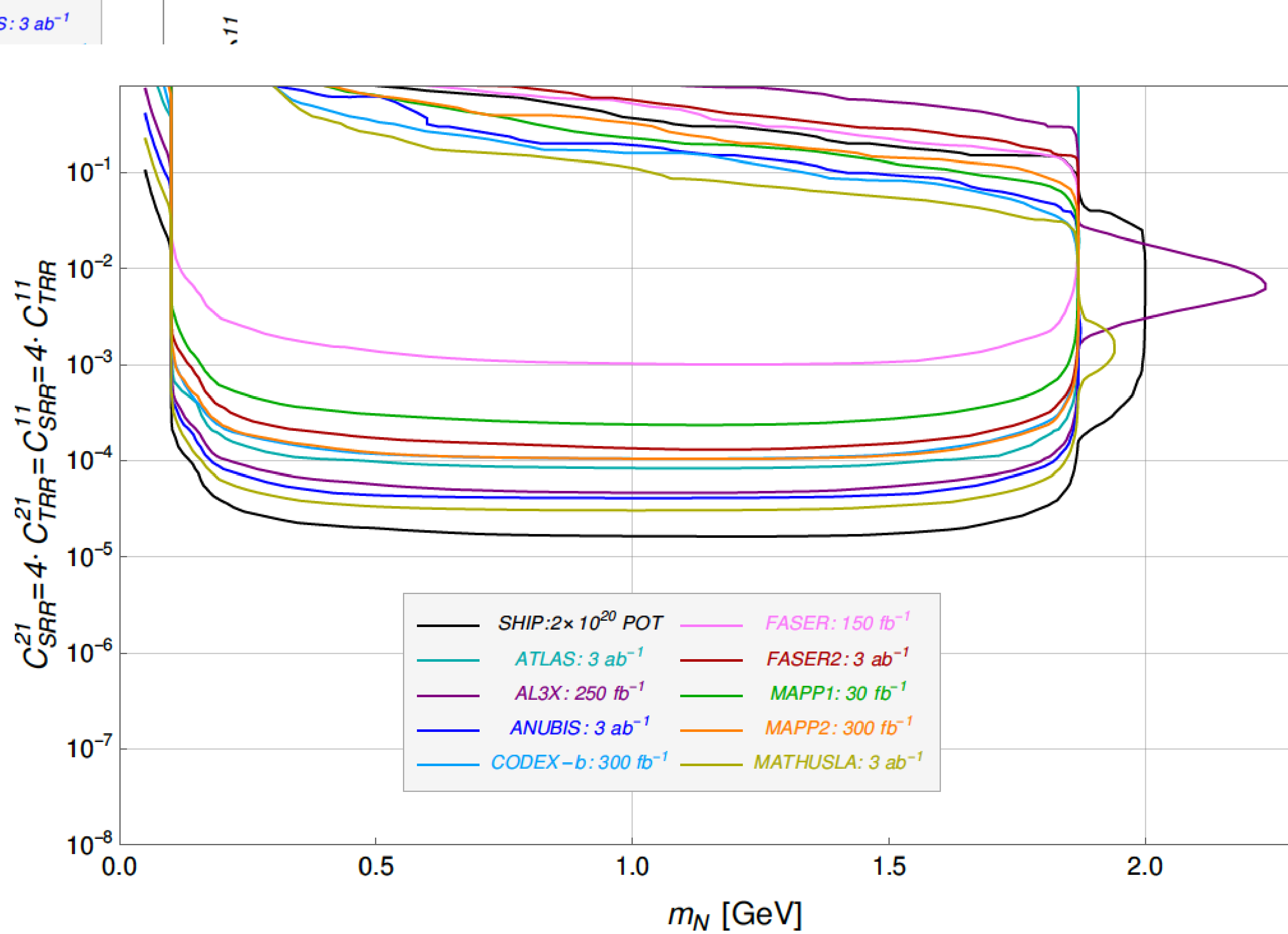


Minimal Scenario
$|U_{e4}|^2$
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
0.1
0.5
1
5
10
m_N [GeV]
BBN
Type-I Seesaw target region
SHIP: 2× 10^{20} POT
ATLAS: 3 ab^{-1}
AL3X: 250 fb^{-1}
ANUBIS: 3 ab^{-1}
CODEX-b: 300 fb^{-1}
FASER: 150 fb^{-1}
FASER2: 3 ab^{-1}
MAPP1: 30 fb^{-1}
MAPP2: 300 fb^{-1}
MATHUSLA: 3 ab^{-1}

Results

	Flavor benchmark 1.2	Flavor benchmark 1.3
production operator: C_{P}	$C^{21}_{\mathrm{SRR}} = 4C^{21}_{\mathrm{TRR}}$	C^{21}_{VLR}
decay operators: C_{D}	$C^{11}_{\mathrm{SRR}} = 4C^{11}_{\mathrm{TRR}}$	C^{11}_{VLR}
production process via C_{P}	$D^{\pm}/D^0/D_s \to N + e^{\pm}(+X)$	
decay process via C_{D}	$N \to \pi^{\pm} + e^{\mp},\ \rho^{\pm} + e^{\mp}$	

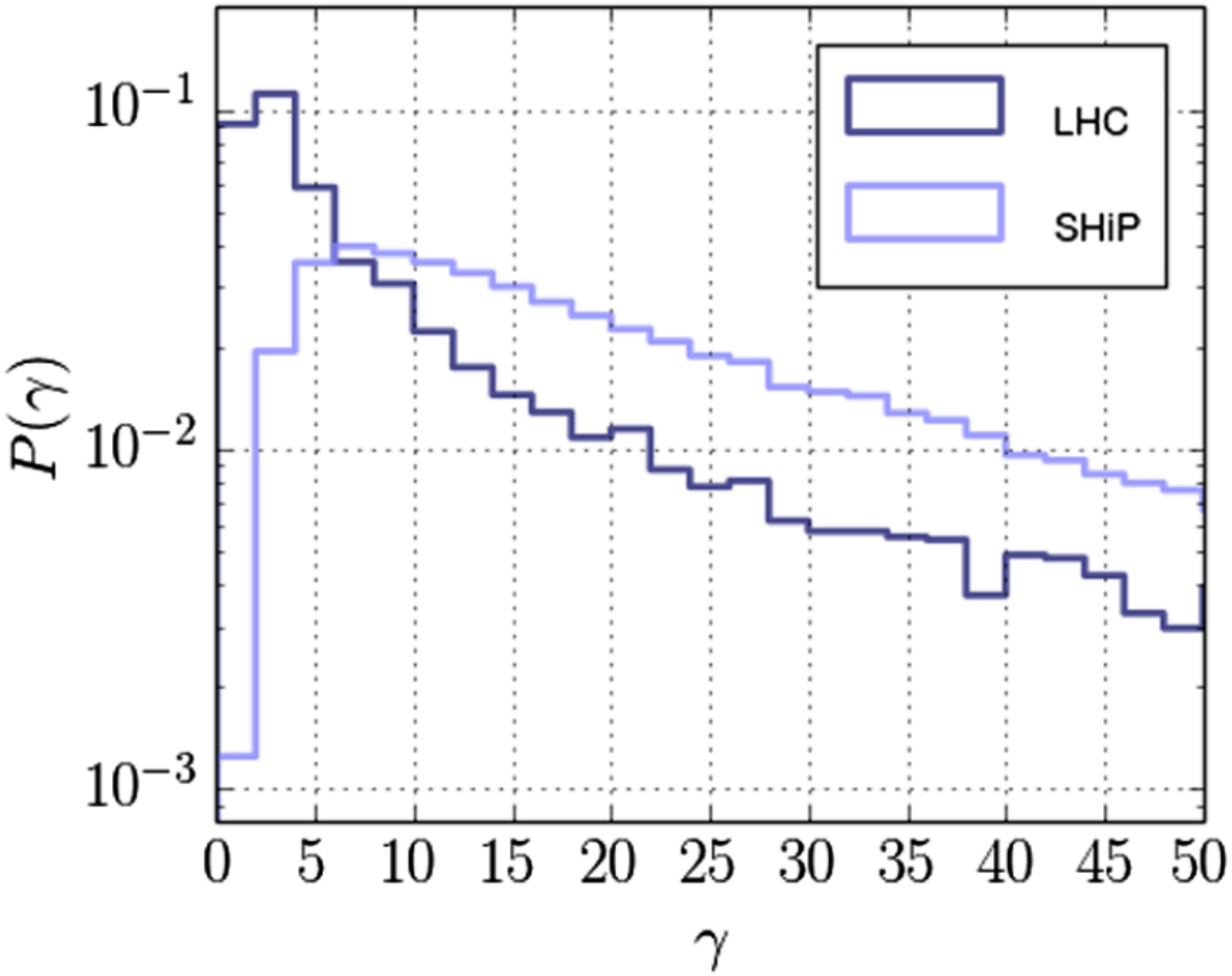


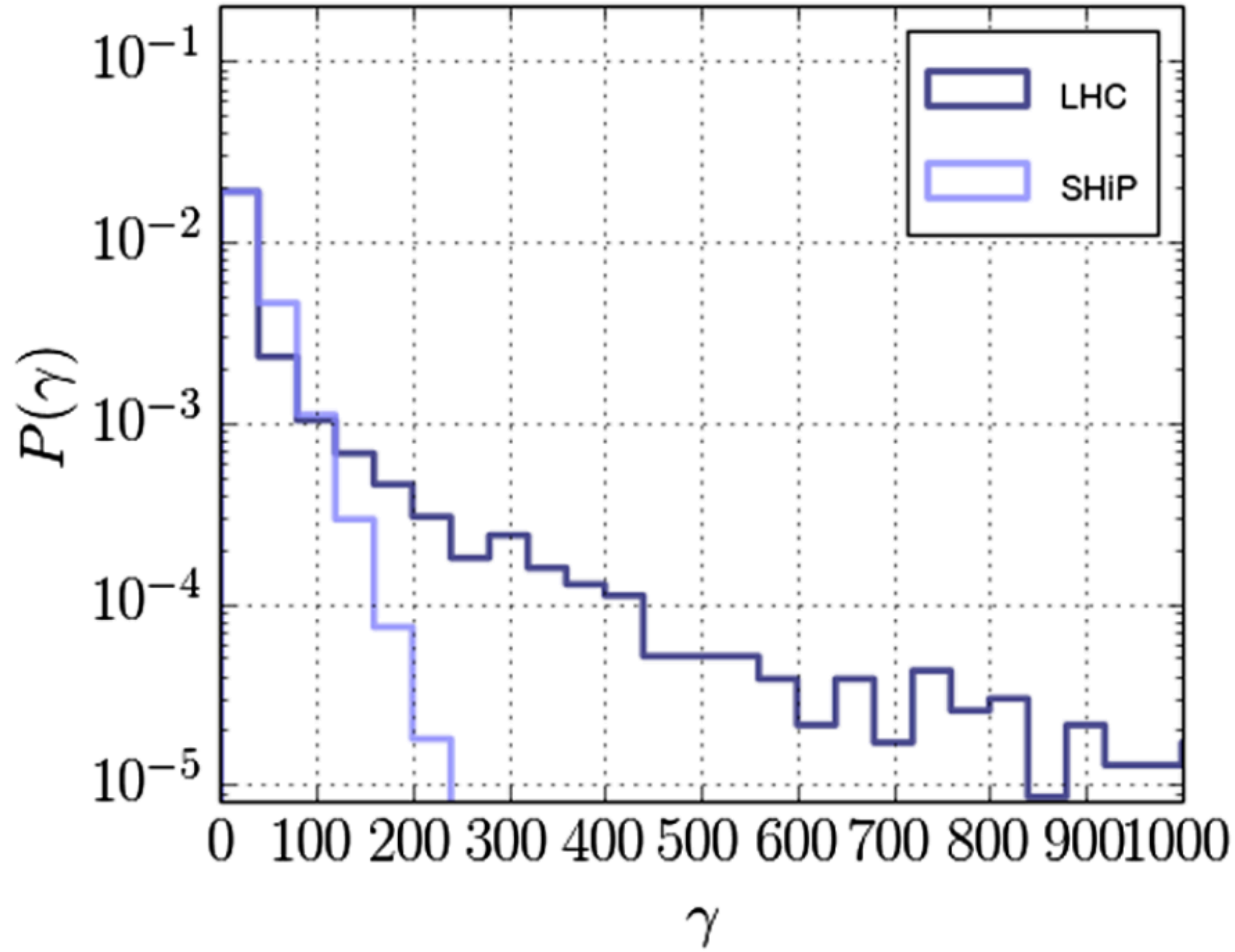


ATLAS

- Much shorter decay length
- high luminosity, high energy
- assumed efficiency: 10^{-3}

Neutralino Boost





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

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

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

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

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	ATLAS
MATHUSLA	ANUBIS
CODEX-b	MoEDAL-MAPP
FASER	AL3X

- Similarly for RH Neutrinos