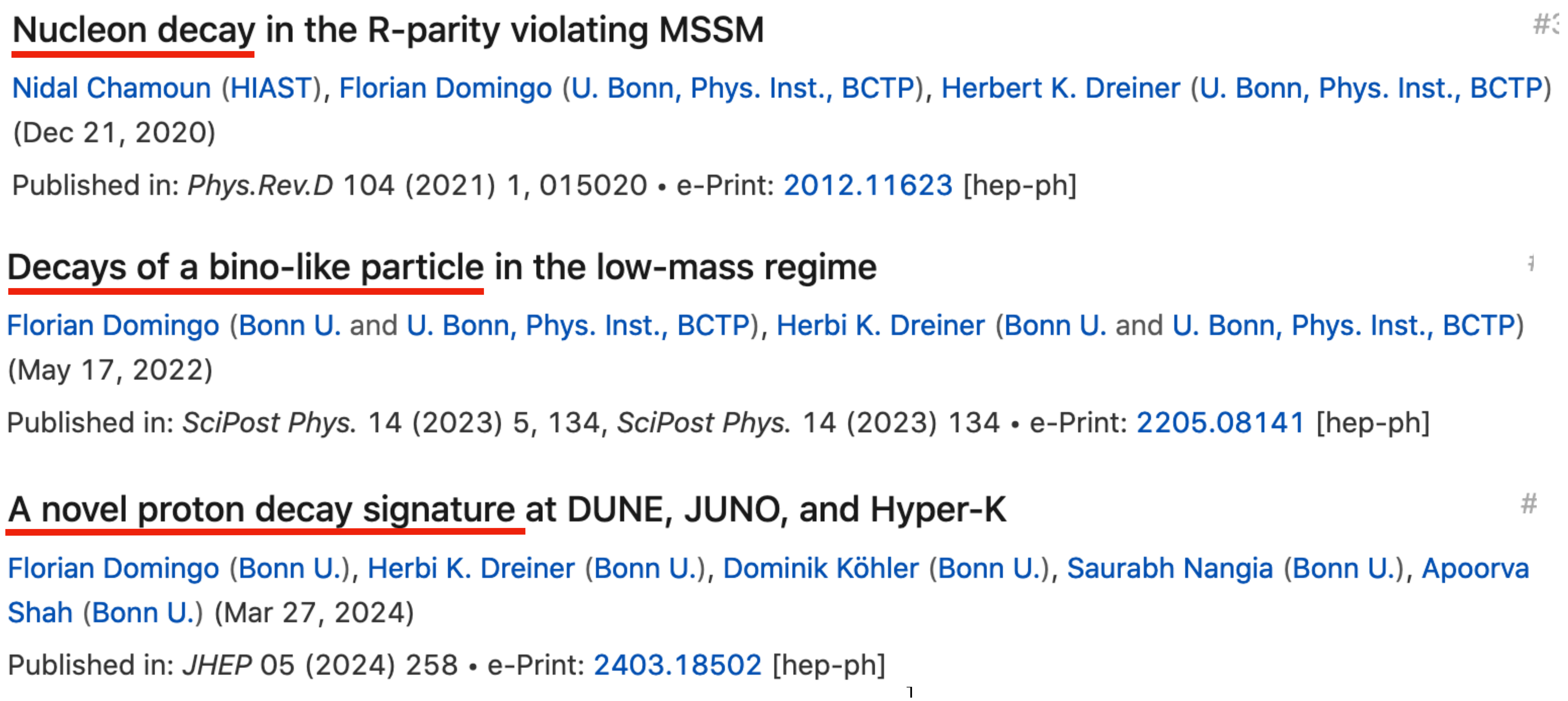
Novel Proton Decay in Supersymmetry

BLV-24
11.10.2024

Herbi Dreiner — University of Bonn



Nucleon decay in the R-parity violating MSSM #

Nidal Chamoun (HIAST), Florian Domingo (U. Bonn, Phys. Inst., BCTP), Herbert K. Dreiner (U. Bonn, Phys. Inst., BCTP)
(Dec 21, 2020)

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Decays of a bino-like particle in the low-mass regime

Florian Domingo (Bonn U. and U. Bonn, Phys. Inst., BCTP), Herbi K. Dreiner (Bonn U. and U. Bonn, Phys. Inst., BCTP)
(May 17, 2022)

Published in: *SciPost Phys.* 14 (2023) 5, 134, *SciPost Phys.* 14 (2023) 134 • e-Print: 2205.08141 [hep-ph]

A novel proton decay signature at DUNE, JUNO, and Hyper-K #

Florian Domingo (Bonn U.), Herbi K. Dreiner (Bonn U.), Dominik Köhler (Bonn U.), Saurabh Nangia (Bonn U.), Apoorva Shah (Bonn U.) (Mar 27, 2024)

Published in: *JHEP* 05 (2024) 258 • e-Print: 2403.18502 [hep-ph]

Light Neutralino

Spin-0 $\xleftrightarrow{\text{SUSY}}$ Spin-½ $\xleftrightarrow{\text{SUSY}}$ Spin-1

(Photon, Z-boson; Higgs-1, Higgs-2) $\xrightarrow{\text{SUSY}}$ $(\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0)$ Neutralinos

(Spin-1) (Spin-0) (Spin-½)

lightest neutralino

mostly Bino

no tree-level coupling to Z

Light Neutralino: mass constraints

- LEP searches: $\boxed{M_{\chi_1^0} \gtrsim 46\,\mathrm{GeV}}$ (PDG)

- However, this is based on chargino searches, and assumption:

SUSY GUTs:

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

- If I drop this assumption, and set determinant of neutralino mass matrix to 0

$$\boxed{M_1 = \frac{M_2 M_Z^2 \sin(2\beta)\sin^2\theta_\mathrm{W}}{\mu M_2 - M_Z^2 \sin(2\beta)\cos^2\theta_\mathrm{W}}.}$$

always has solutions $M_{\tilde{\chi}_1^0} = 0$

Is such a light neutralino allowed?

Light neutralino: mass constraints

- Constraints: invisible Z-width
- Radiative corrections

avoided, since neutralino **dominantly bino**

- Massless neutralino consistent with all constraints:

HKD, Heinemeyer, Kittel (Granada), Langenfeld, Weber, Weiglein: *Eur.Phys.J.C* 62 (2009) 547

- Strictest constraint from Supernova and White Dwarf cooling:

$$m_{\tilde{q}} > 600\,\mathrm{GeV}$$

$$m_{\tilde{e}} > 1100\,\mathrm{GeV}$$

C. Hanhart, HKD, et al: *Phys.Rev.D* 68 (2003) 055004
HKD, J. Fortin, L. Ubadi; *Phys.Rev.D 88 (2013) 043517*

Cosmology: dark matter?

excluded for stable χ_1^0 :

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

Cowsik-McClelland

Lee-Weinberg

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

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

- Neutralino no longer dark matter candidate — axino

Lightest Neutralino can be arbitrarily light

Summary:

Mass Bounds on a Very Light Neutralino

Herbi K. Dreiner (Bonn U.), Sven Heinemeyer (Cantabria Inst. of Phys.), Olaf Kittel (Granada U., Theor. Phys. Astrophys.), Ulrich Langenfeld (DESY, Zeuthen), Arne M. Weber (Munich, Max Planck Inst.) et al. (Jan, 2009)

Published in: *Eur.Phys.J.C* 62 (2009) 547-572 • e-Print: 0901.3485 [hep-ph]

Proton Decay

- **1954** first experimental proton decay search: Reines, Cowan & Goldhaber
- PDG quotes limits on

$$p \to \begin{cases} 1 \ \text{(anti)lepton} + \text{meson(s)}, \\ 1 \ \text{antilepton} + \text{photon(s)}, \\ 1 \ \text{antilepton} + \text{single massless particle}, \\ 3 \ \text{or more leptons} \end{cases}$$

- Our proposal:

$$p \to K^+ + X^0,$$

$$X^0 \to \{\pi^\pm + \mu^\mp, \ \pi^0 + \nu_\mu, \ \pi^0 + \bar{\nu}_\mu\} \, .$$

$$m_{X^0} \leq m_p - m_{K^+} \approx 445 \, \mathrm{MeV}$$

- Here $X^0 = \tilde{\chi}_1^0$, but could also have heavy neutral lepton, for example

Neutralino Decays

$$\left.\begin{array}{ll} L_i L_j \bar{E}_k : & \tilde{\chi}_1^0 \to \ell_i^{\pm} \ell_k^{\mp} \nu_j \\ L_i Q_j \bar{D}_k : & \tilde{\chi}_1^0 \to \ell_i^{\pm} + 2\,\mathrm{jets} \\ & \tilde{\chi}_1^0 \to M_{jk}^{\pm} + \ell_i^{\mp}, \quad M_{jk}^0 + \nu_i \end{array}\right\}$$

for both, for j=k:

$$\tilde{\chi}_1^0 \to \gamma + \nu_i$$

$$\bar{U}_i \bar{D}_j \bar{D}_k : \quad \tilde{\chi}_1^0 \to 3\,\mathrm{jets}$$

$$\tilde{\chi}_1^0 \to M_a B_b$$

$$M_i \in \{\pi^0, \pi^+, \pi^-, K^0, \bar{K}^0, K^+, K^-, \eta_8^0\}$$

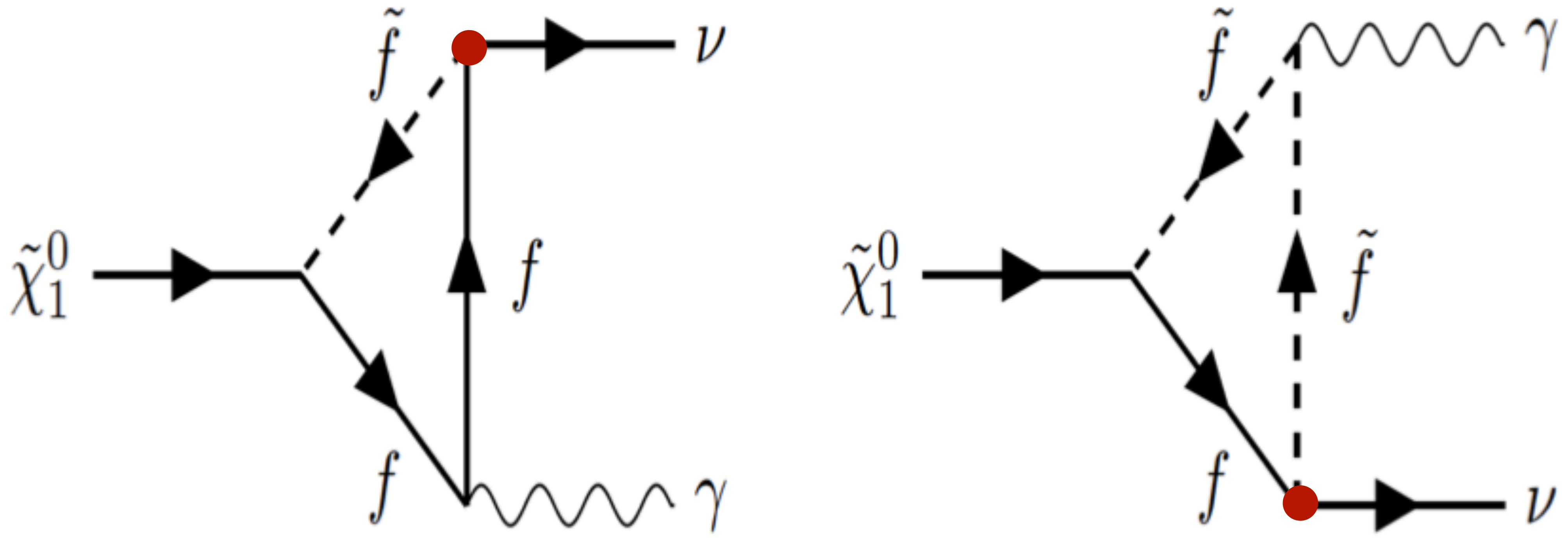
$$B_j \in \{\Sigma^0, \Sigma^+, \Sigma^-, n^0, \Xi^0, p^+, \Xi^-, \Lambda^0\}$$

(neutralino can mix with baryon octet)

Radiative Neutralino Decay

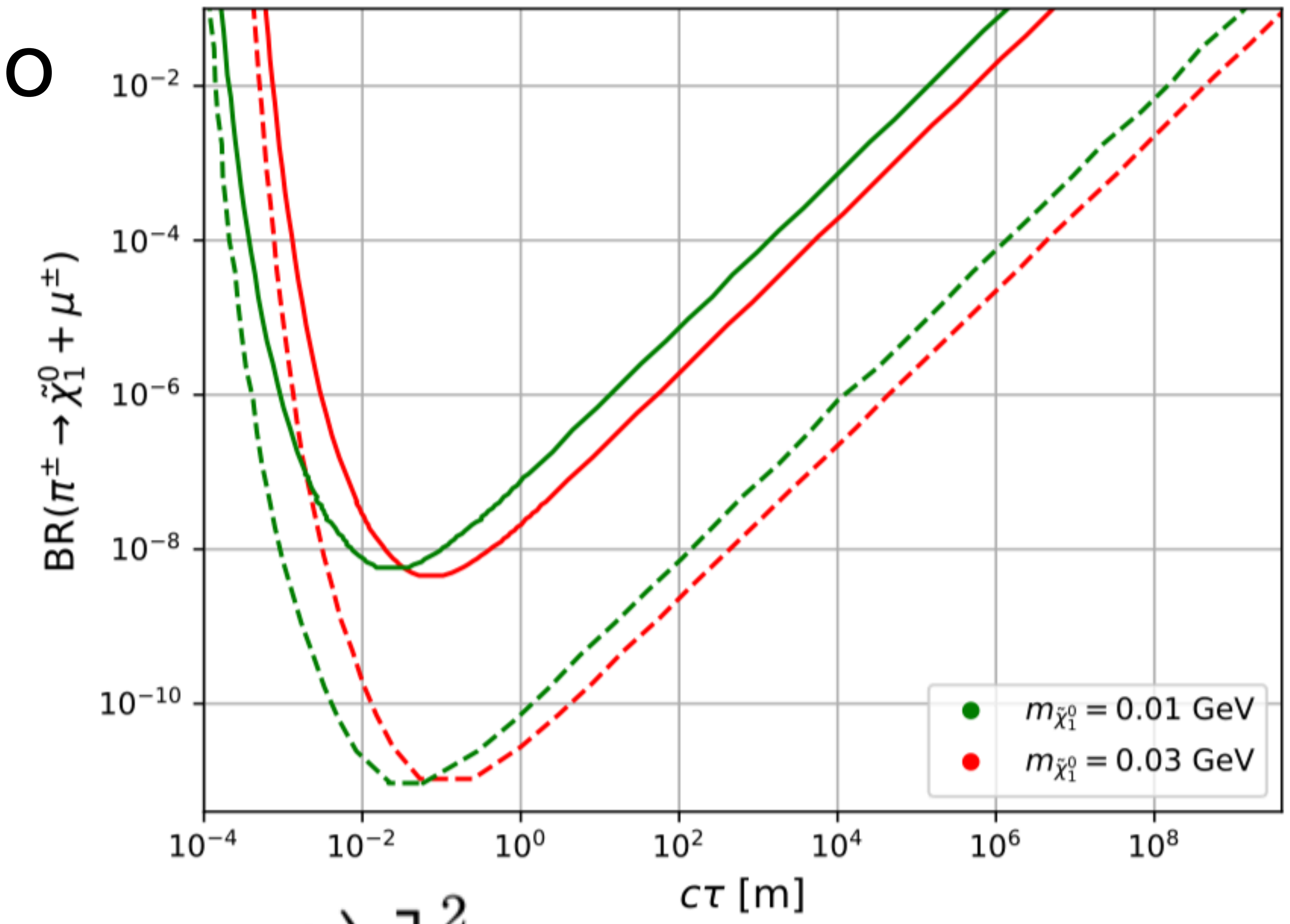
Köhler, Nangia, Wang, HD: *JHEP* 02 (2023) 120

- Novel single photon signature:



- Plus: scenarios with an even lighter neutralino

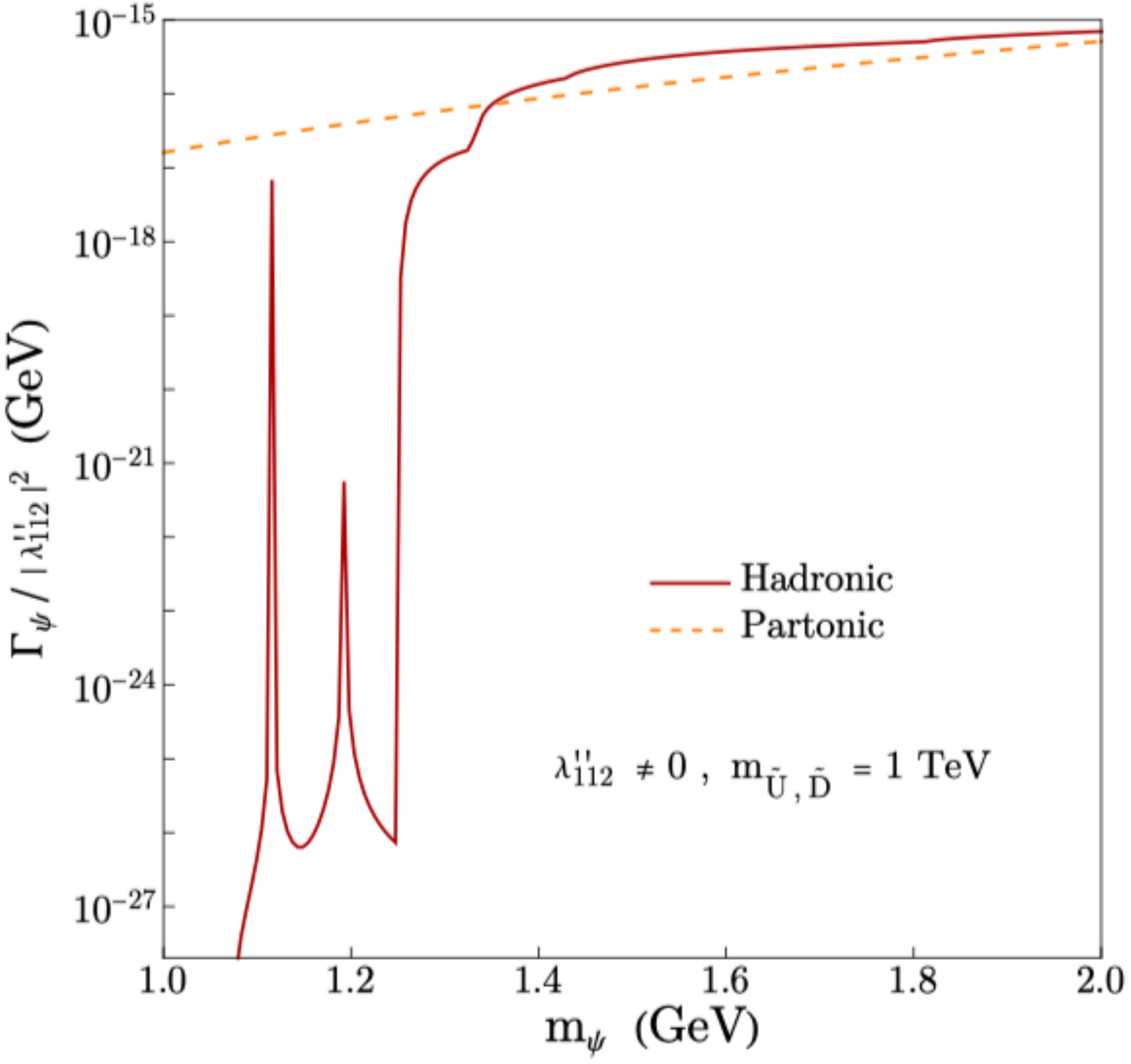
$$\pi^+ \to \ell^+ + \tilde{\chi}_1^0; \qquad \tilde{\chi}_1^0 \to \gamma + \nu$$



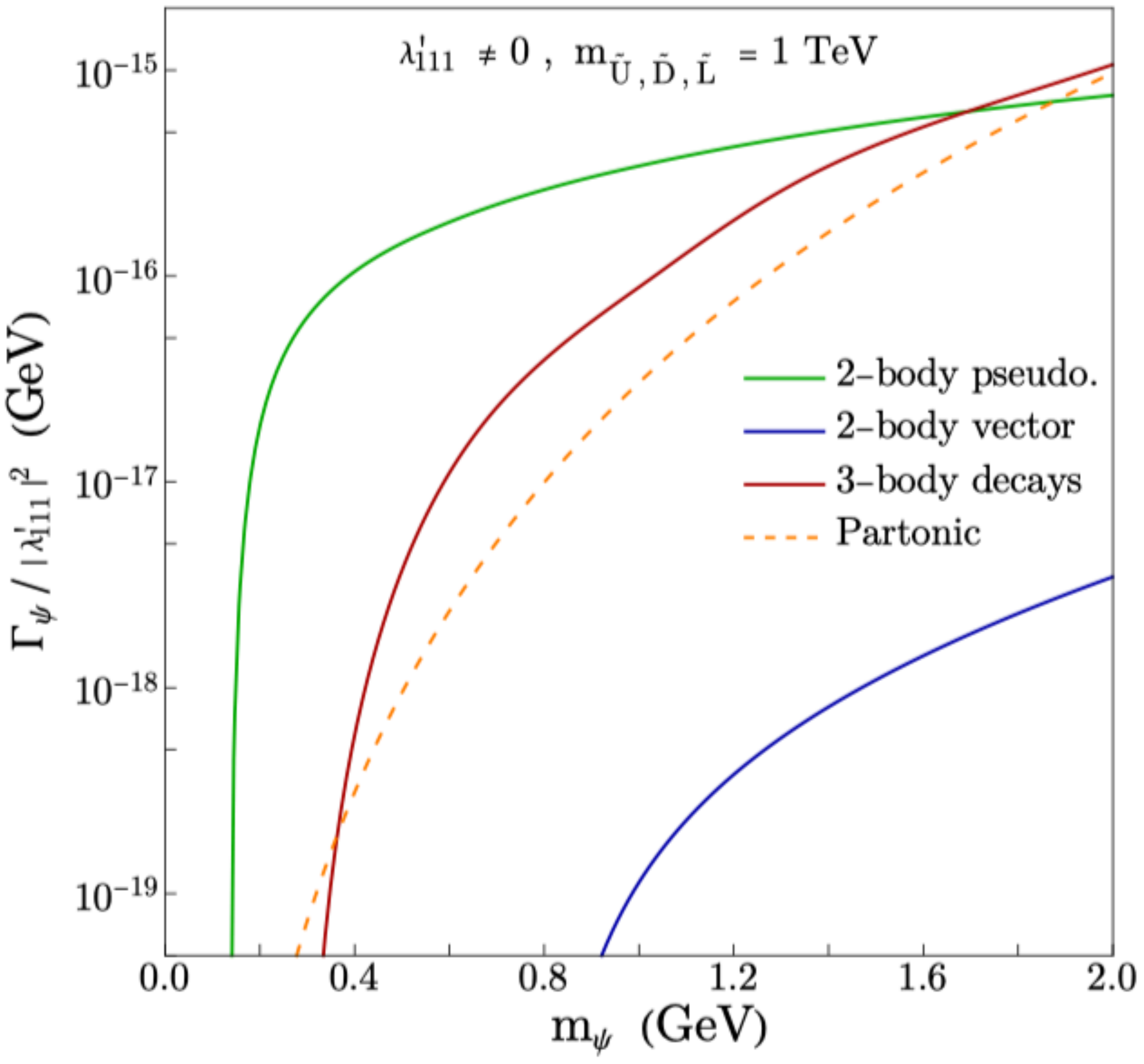
$$\Gamma(\tilde{\chi}_1^0 \to \gamma + \nu_i) = \frac{\lambda^2 \alpha^2 m_{\tilde{\chi}_1^0}^3}{512\pi^3 \cos^2\theta_W} \left[\sum_f \frac{e_f N_c m_f \left(4e_f + 1\right)}{m_{\tilde{f}}^2} \left(1 + \log \frac{m_f^2}{m_{\tilde{f}}^2}\right) \right]^2$$

Neutralino Decays

UDD $\tilde{\chi}_1^0 \to p + M^-$

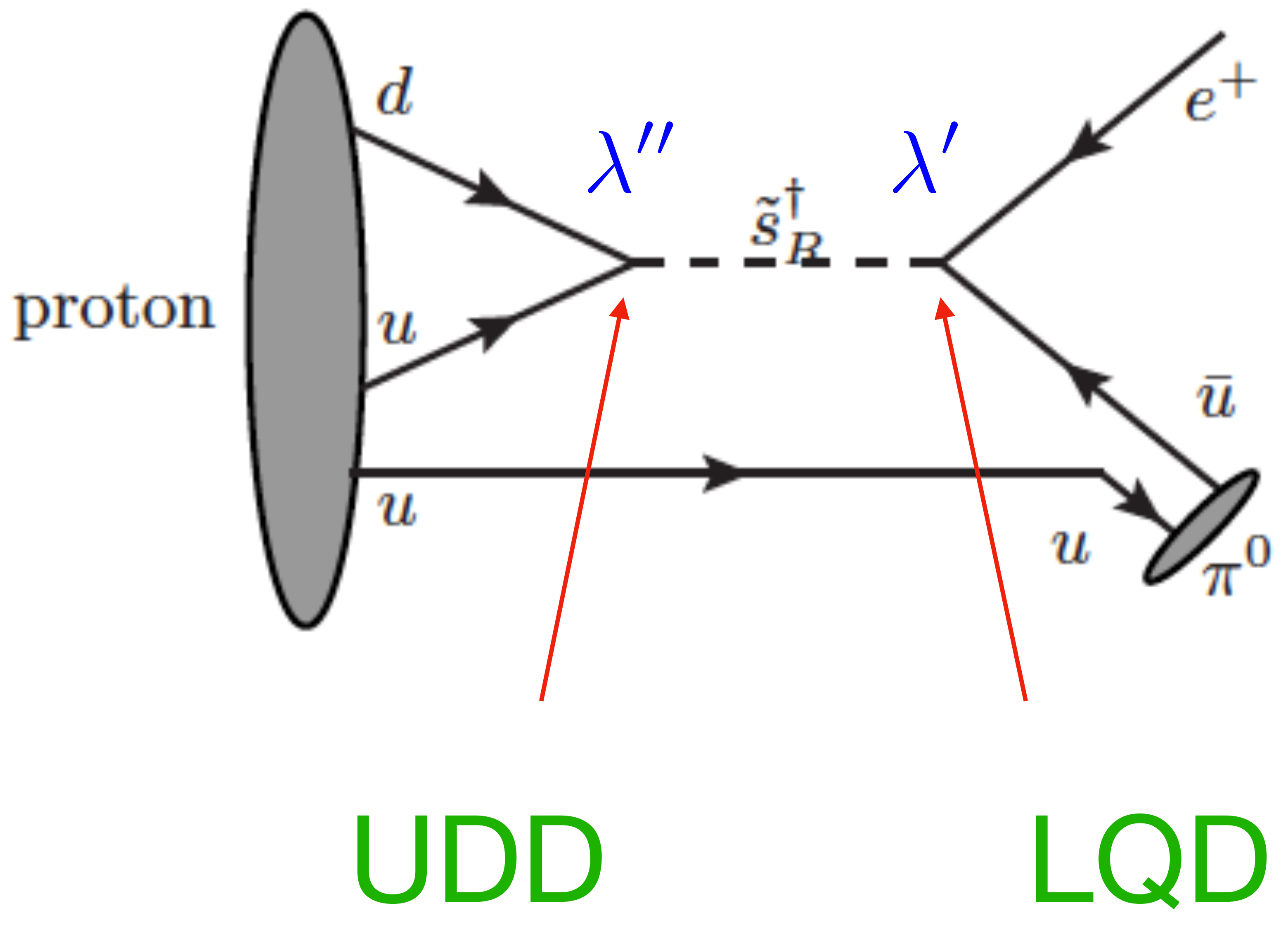


LQD $\tilde{\chi}_1^0 \to M^\pm + \ell^\mp$



Nucleon Decay

- Proton decays in R-parity Violating Supersymmetry

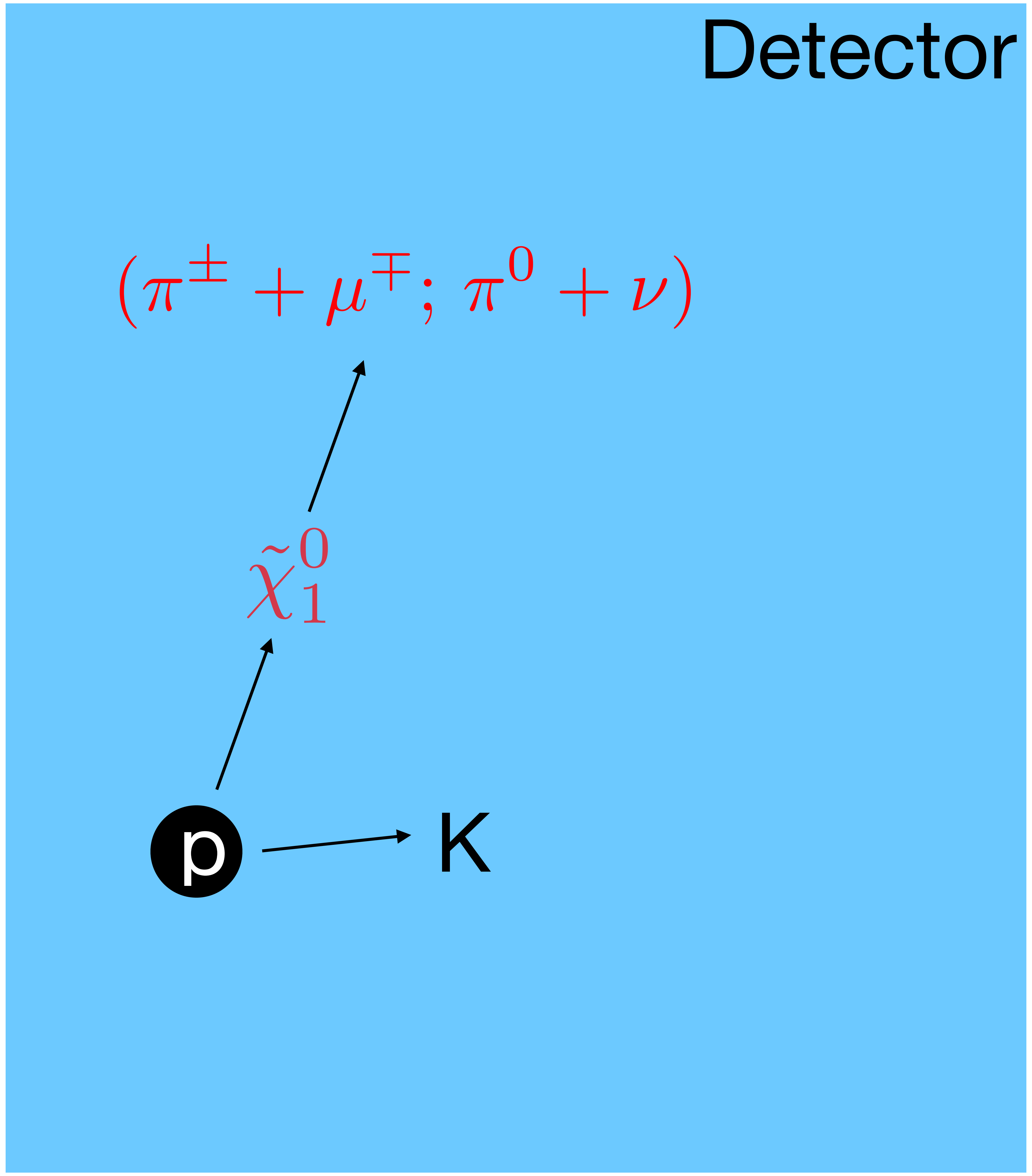


- Get strict bounds on the product: $\dfrac{\lambda'' \cdot \lambda'}{M^2_{\text{SUSY}}}$

- Reanalyzed these bounds, taking into account recent lattice results
  - Nucleon decay in the R-parity violating MSSM

    Nidal Chamoun, Florian Domingo, HKD; PRD. 104 (2021) 015020

Proton Decay - Novel Decay Signature



Detector

$(\pi^{\pm} + \mu^{\mp}; \pi^0 + \nu)$

$\tilde{\chi}_1^0$

p

K

- With: Florian Domingo, Apoorva Shah, Saurabh Nangia, Dominik Köhler: JHEP 05 (2024) 258

Upcoming Detectors

	Super-K	Hyper-K	JUNO	DUNE
Location	Japan	Japan	China	USA
Geometry	Cylinder 42m height×39m diameter	Cylinder 60m height×74m diameter	Sphere 35.4m diameter	Cuboid (4 modules) 58.2m×14.0m×12.0m
Detector Material	Water	Water	LABs	Liquid Argon
Working Principle	Cherenkov	Cherenkov	Scintillation	Scintillation
Fiducial Mass	22.5kt	187kt	20kt	40kt
Approx. Start Year	-	2025	2024	2026

Table 1: Upcoming detectors for proton decay detection.

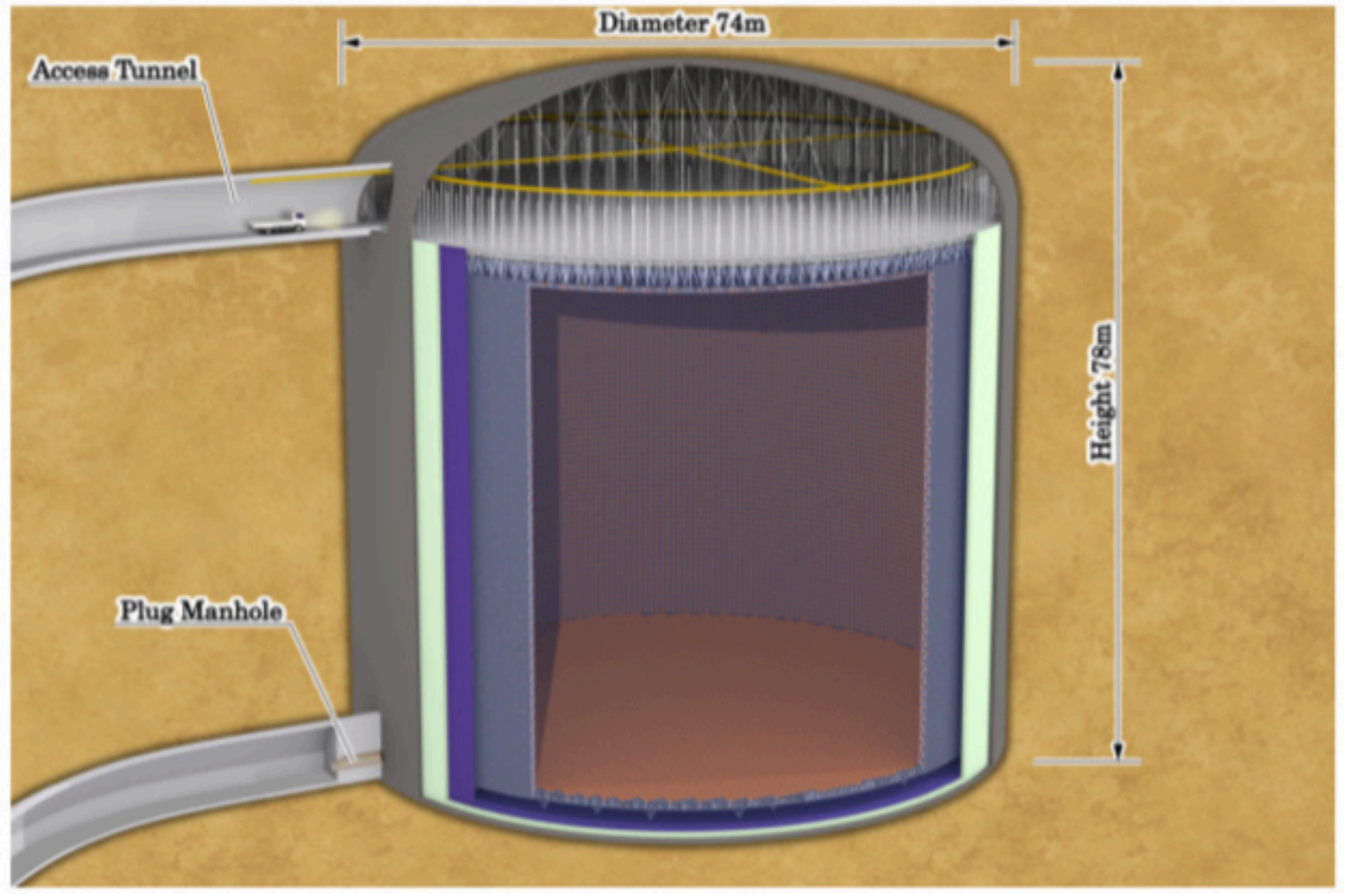


Figure 1: Hyper-K

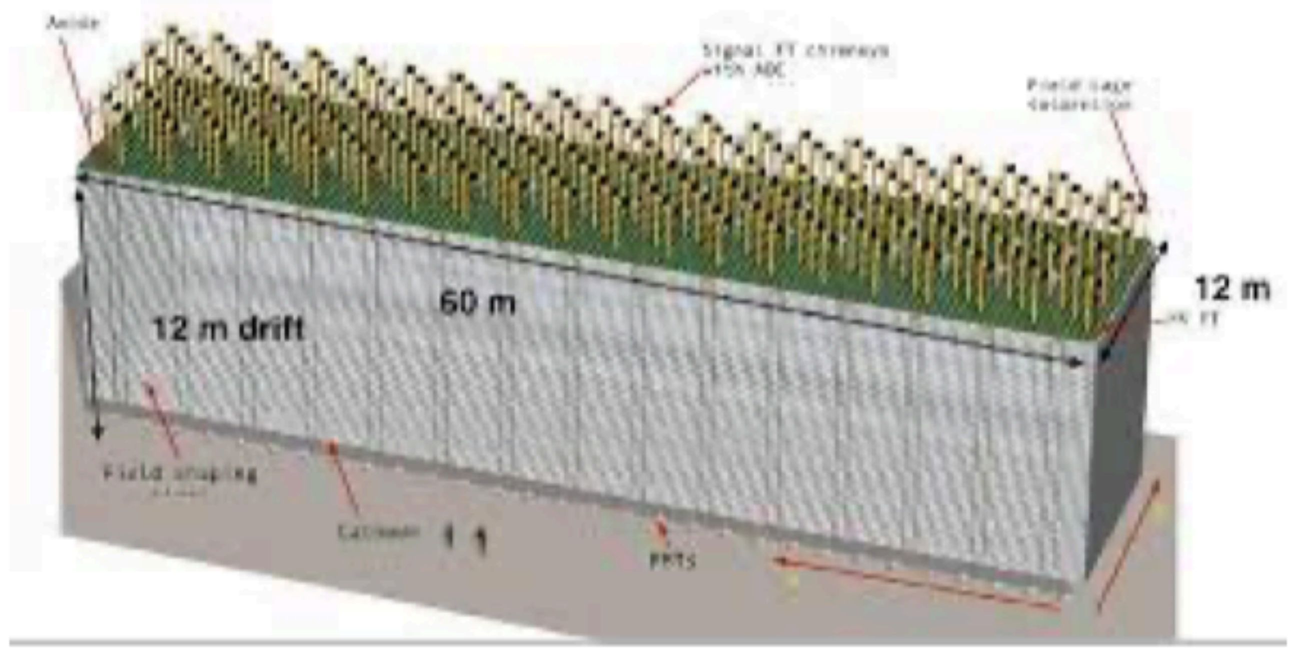


Figure 2: DUNE

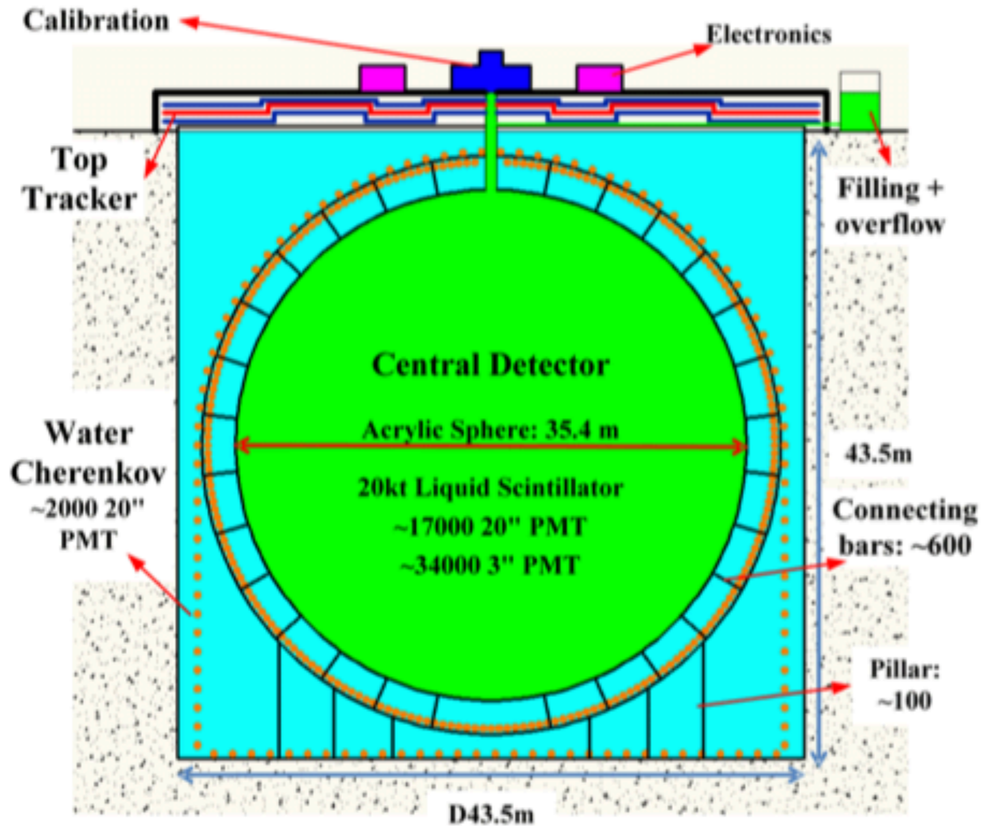


Figure 3: JUNO

includes CAS

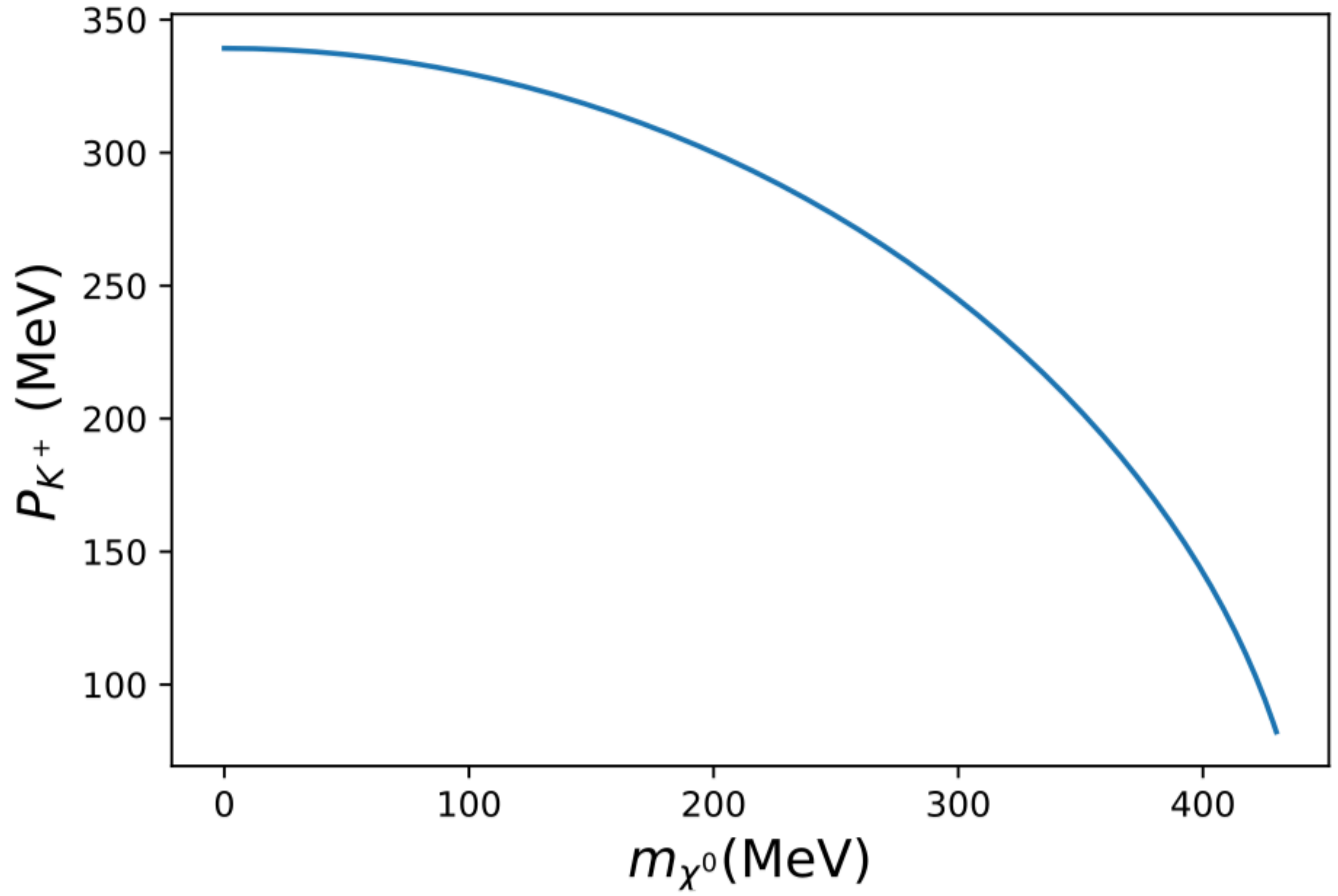


Figure 4: Kaon momentum as a function of neutralino mass.

- The momentum of the Kaon is straightforward from kinematics. → two-body decay
- For the neutrino, $P_{K^+} \sim 330\text{MeV}$
- P_{K^+} is always lower than Cherenkov limit of water → Hyper-K can only detect subsequent decays of Kaons.
- DUNE and JUNO can detect Kaons directly via scintillation.

- From Super-K limit, the number of proton decays/10 years is:
  -Hyper-K: ~ 106
  -DUNE: ~ 18
  -JUNO: ~ 11

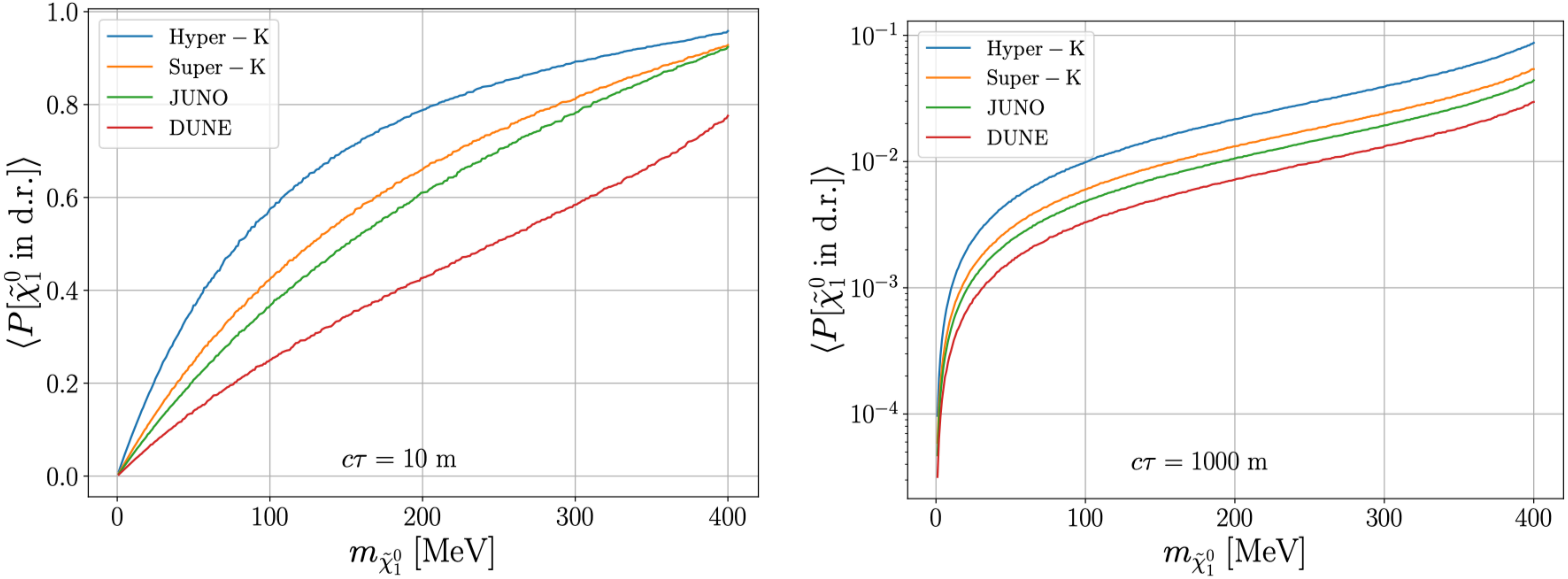
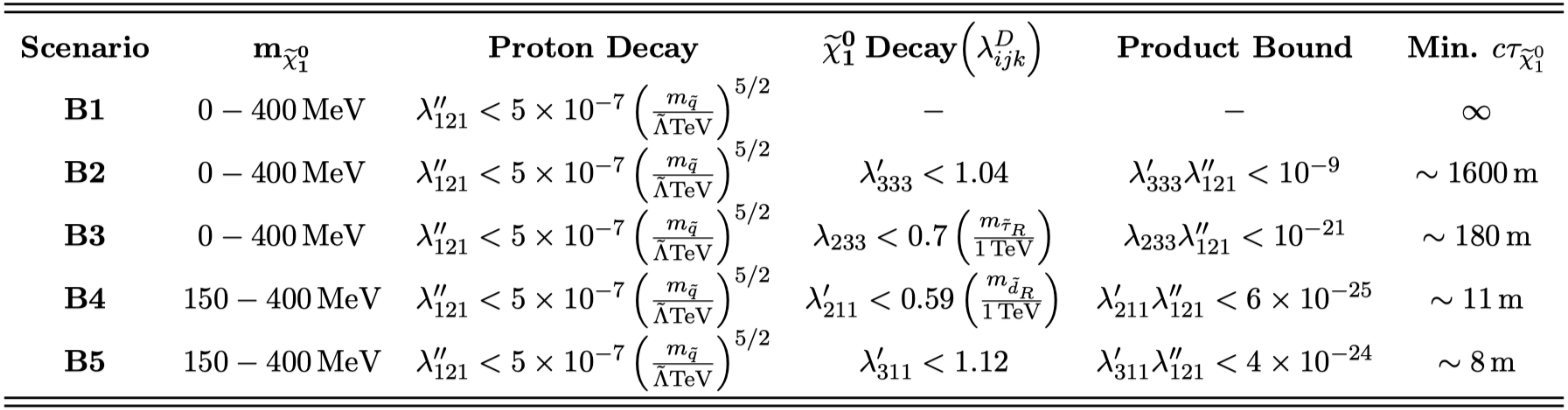


Figure 4: Average neutralino decay probabilities as a function of the neutralino mass for fixed neutralino decay length: $c\tau = 10\,\text{m}$ (left) and $c\tau = 1000\,\text{m}$ (right). These plots have been generated with a sample size $N^{\text{MC}}_{\tilde{\chi}_1^0} = 10,000$.

Proton Decay Benchmarks



Scenario	$m_{\tilde{\chi}_1^0}$	Proton Decay	$\tilde{\chi}_1^0$ Decay $\left(\lambda^D_{ijk}\right)$	Product Bound	Min. $c\tau_{\tilde{\chi}_1^0}$
B1	$0-400\,\mathrm{MeV}$	$\lambda''_{121} < 5\times 10^{-7}\left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^{5/2}$	–	–	∞
B2	$0-400\,\mathrm{MeV}$	$\lambda''_{121} < 5\times 10^{-7}\left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^{5/2}$	$\lambda'_{333} < 1.04$	$\lambda'_{333}\lambda''_{121} < 10^{-9}$	$\sim 1600\,\mathrm{m}$
B3	$0-400\,\mathrm{MeV}$	$\lambda''_{121} < 5\times 10^{-7}\left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^{5/2}$	$\lambda_{233} < 0.7\left(\frac{m_{\tilde{\tau}_R}}{1\,\mathrm{TeV}}\right)$	$\lambda_{233}\lambda''_{121} < 10^{-21}$	$\sim 180\,\mathrm{m}$
B4	$150-400\,\mathrm{MeV}$	$\lambda''_{121} < 5\times 10^{-7}\left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^{5/2}$	$\lambda'_{211} < 0.59\left(\frac{m_{\tilde{d}_R}}{1\,\mathrm{TeV}}\right)$	$\lambda'_{211}\lambda''_{121} < 6\times 10^{-25}$	$\sim 11\,\mathrm{m}$
B5	$150-400\,\mathrm{MeV}$	$\lambda''_{121} < 5\times 10^{-7}\left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^{5/2}$	$\lambda'_{311} < 1.12$	$\lambda'_{311}\lambda''_{121} < 4\times 10^{-24}$	$\sim 8\,\mathrm{m}$

B1: no $\tilde{\chi}_1^0$ -decay

B2: $\tilde{\chi}_1^0 \to \gamma + \nu$

B3: $\tilde{\chi}_1^0 \to \gamma + \nu$

B4: $\tilde{\chi}_1^0 \to (\pi^\pm + \mu^\mp,\ \pi^0 + \nu_\mu)$ $\quad m_{\pi^-} + m_\mu \le M_{\tilde{\chi}_1^0} < m_p - m_{K^+}$

B5: $\tilde{\chi}_1^0 \to \pi^0 + \nu_\mu$ $\quad m_{\pi^0} \le M_{\tilde{\chi}_1^0} < m_p - m_{K^+}$

B1

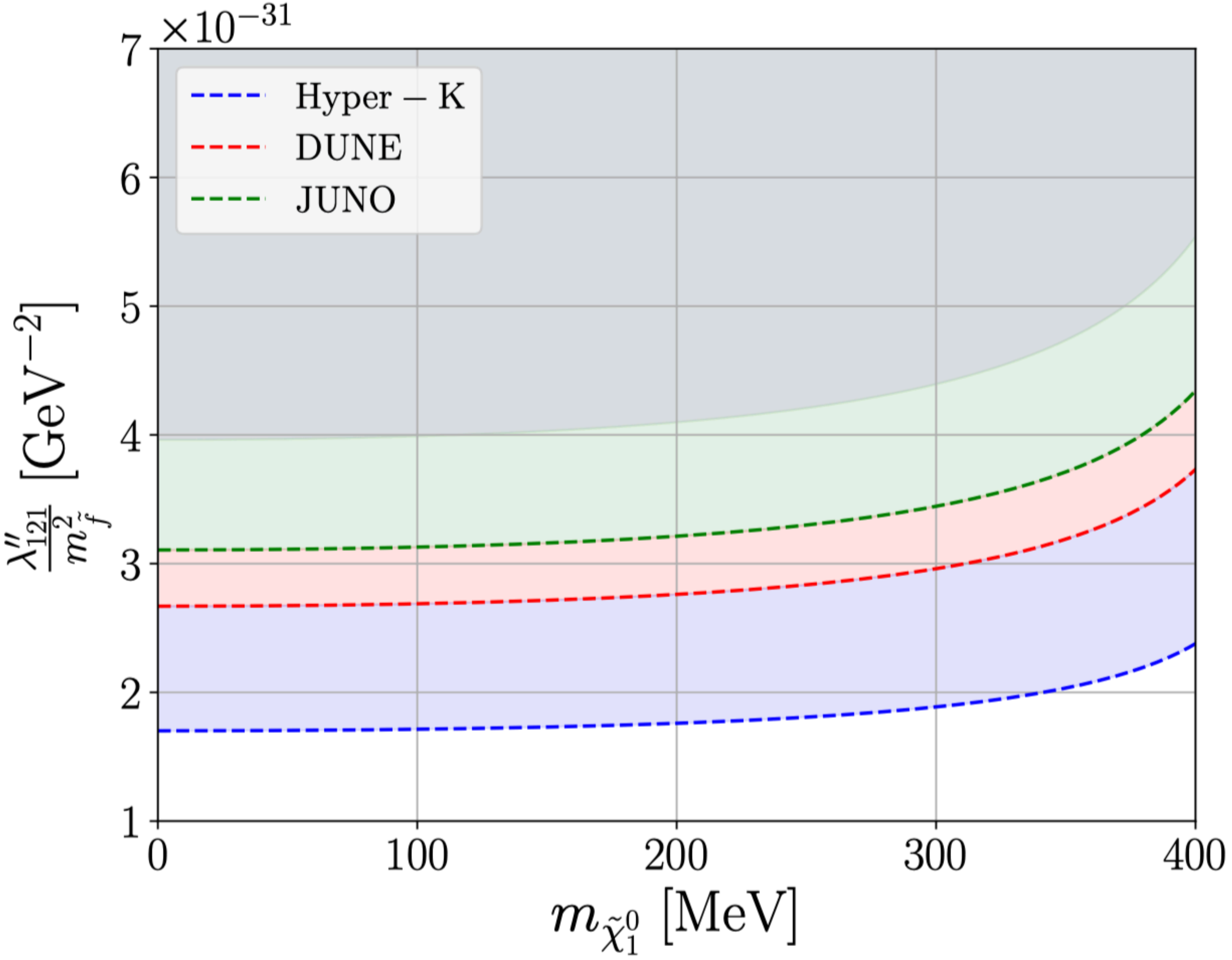


Figure 5: Sensitivity reach for the single coupling scenario of benchmark **B1**. The reinterpreted bound from `Super-K` is shown in gray. The bound from Table 2 lies above the scale of the plot. The results for `Hyper-K`, `DUNE`, and `JUNO` are for a run-time of 10 years.

B3 $\tilde{\chi}_1^0 \to \gamma + \nu$ $c\tau_{\tilde{\chi}_1^0} \sim 180\,\mathrm{m}$

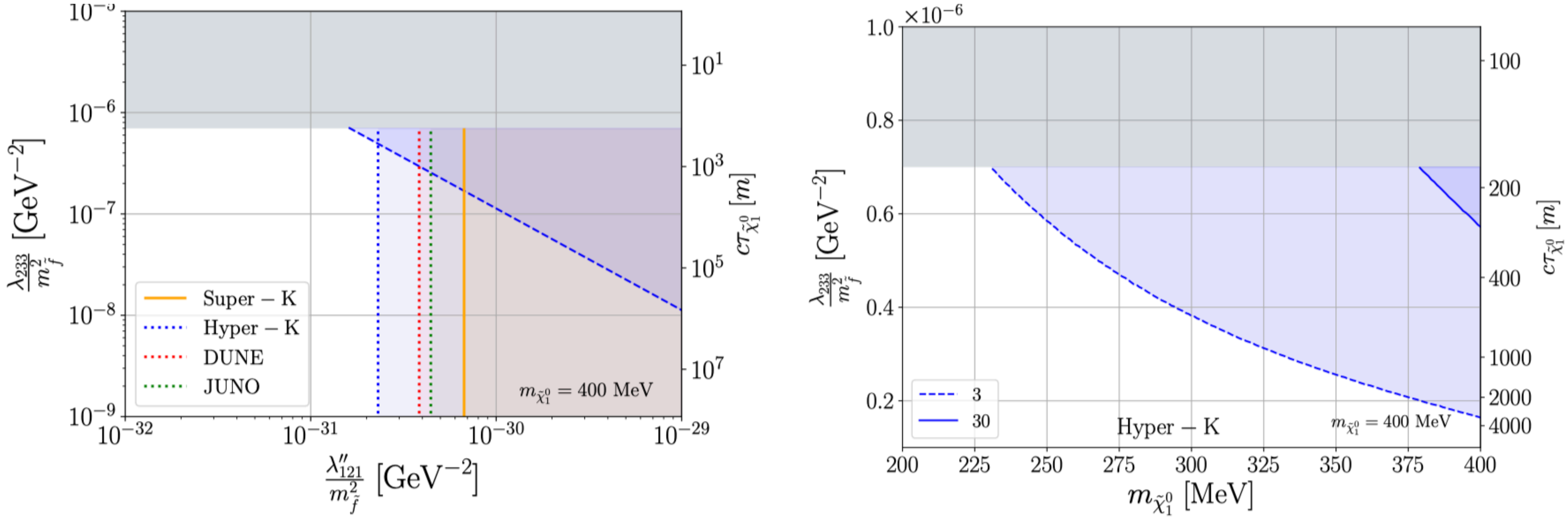
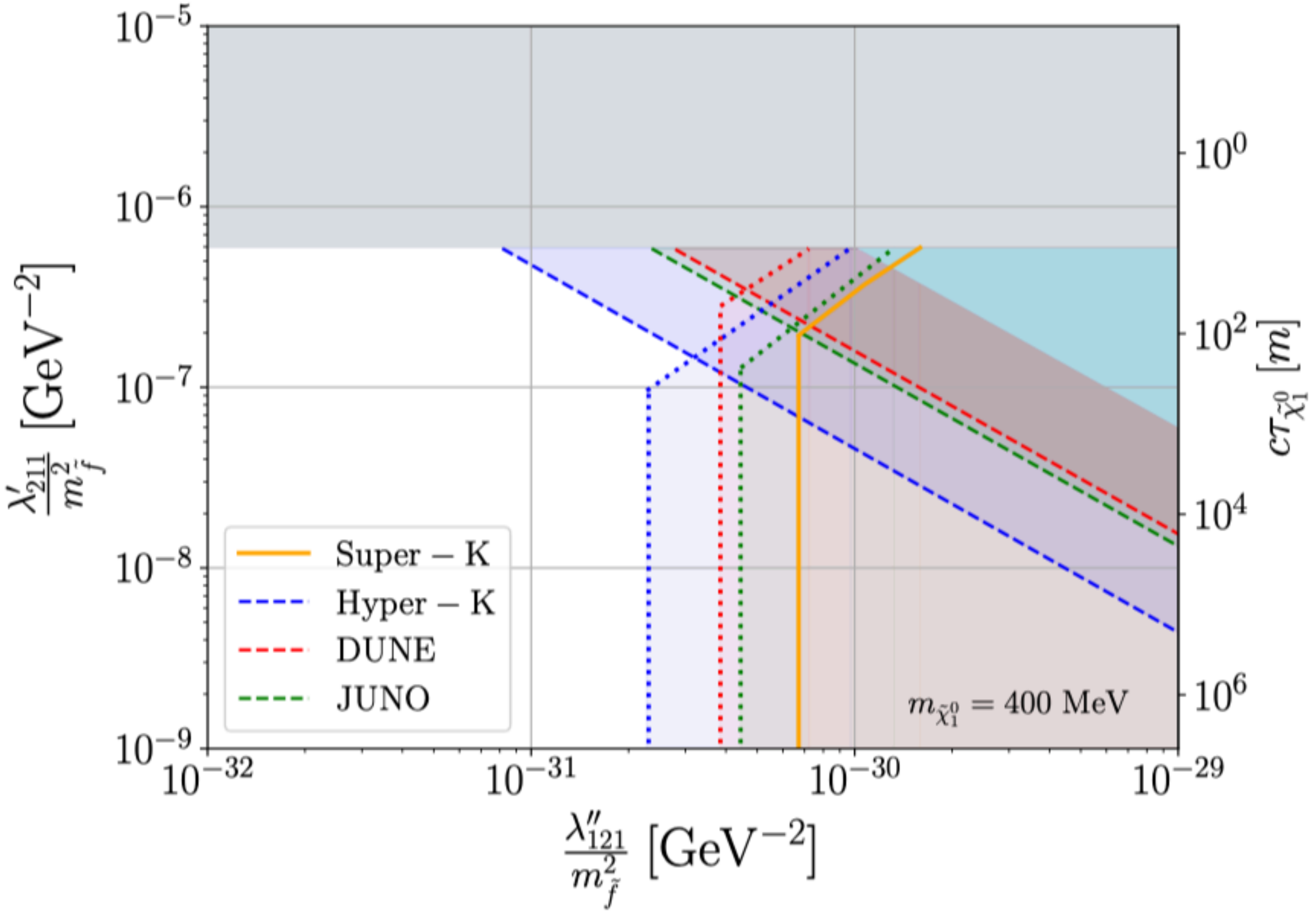


Figure 7: Sensitivity reach/`Super-K` limit for benchmark **B3**. The existing single-bounds from Table 2 are shown in gray

B4 $\tilde{\chi}_1^0 \to (\pi^\pm + \mu^\mp,\ \pi^0 + \nu_\mu)$ $c\tau_{\tilde{\chi}_1^0} \sim 11\,\mathrm{m}$



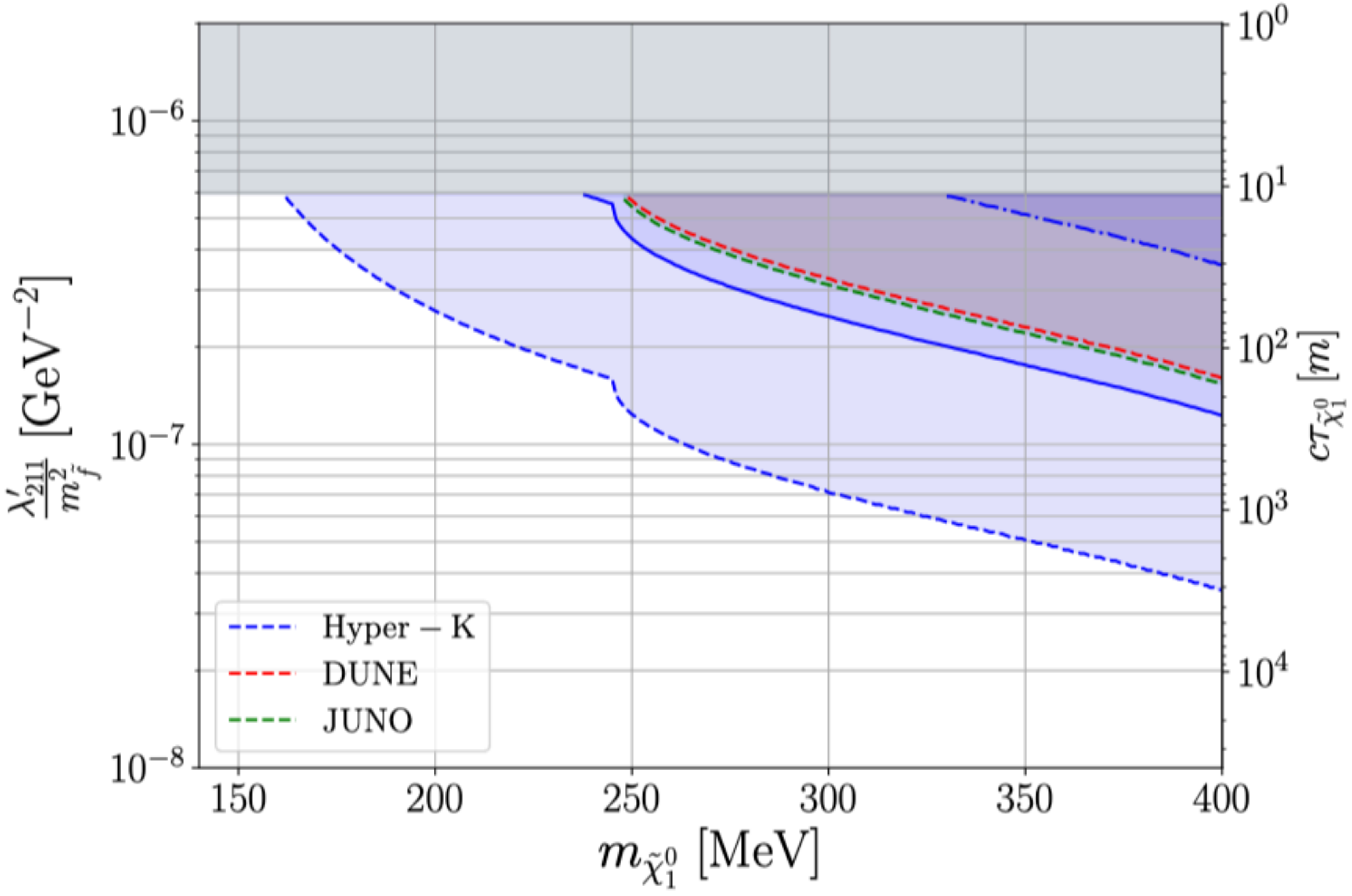


Figure 8: Sensitivity reach/`Super-K` limit for benchmark **B4**. The existing single-bound on λ'_{211} from Table 2 is shown in gray, the product-bound is in light blue (both with $m_{\tilde{f}} = 1\,\text{TeV}$), while the bound on λ''_{121} lies outside the scale of the plot. *Left:* As in left plot of Fig. 6 but for benchmark **B4**. *Right:* As in right plot of Fig. 5 but for benchmark **B4**. The dashed, solid, and dot-dashed lines correspond to 3-, 30- and 90-event isocurves, respectively. An interesting thing to note is the kink in sensitivity in the right figure around $m_{\tilde{\chi}_1^0} \sim 240\,\text{MeV}$, which is due to the modes $\tilde{\chi}_1^0 \to \pi^\pm + \mu^\mp$ being kinematically allowed, thus increasing the total decay width.

B4 $\tilde{\chi}_1^0 \to (\pi^\pm + \mu^\mp,\ \pi^0 + \nu_\mu)$ $c\tau_{\tilde{\chi}_1^0} \sim 8\,\mathrm{m}$

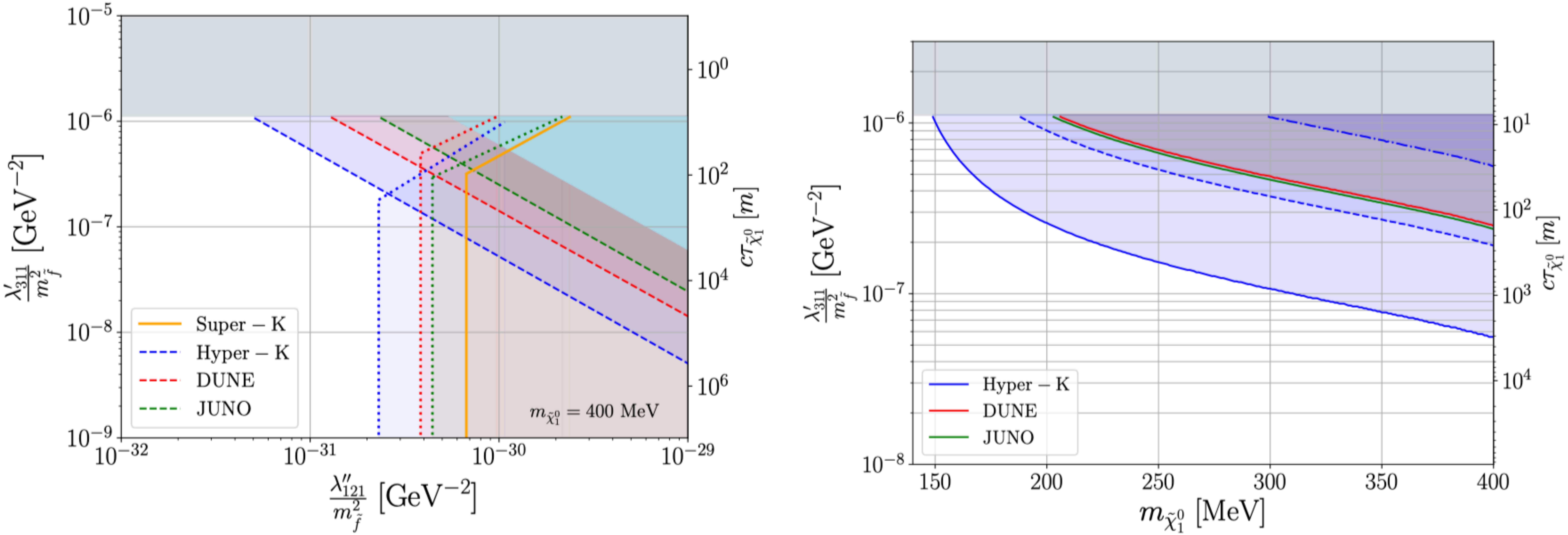


Figure 9: Sensitivity reach/**Super-K** limit for benchmark **B5**. The existing single-bound on λ'_{311} from Table 2 is shown in gray, the product-bound is in light blue (both with $m_{\tilde{f}} = 1\,\mathrm{TeV}$), while the bound on λ''_{121} lies outside the scale of the plot. *Left:* As in left plot of Fig. 6 but for benchmark **B5**. *Right:* As in right plot of Fig. 5 but for benchmark **B5**. The dashed, solid, and dot-dashed lines correspond to 3-, 30- and 90-event isocurves,

Conclusions

- A very light neutralino is consistent with all current data
- It leads to a novel possible proton decay mode
- Determined the search sensitivity at JUNO, DUNE and Hyper-K

P.S. **Please talk to me if you are interested in tests of locality and/or entanglement at colliders.**

Testing locality at colliders via Bell's inequality?

S.A. Abel (Oxford U.), M. Dittmar (UC, Riverside), Herbert K. Dreiner (Oxford U.)

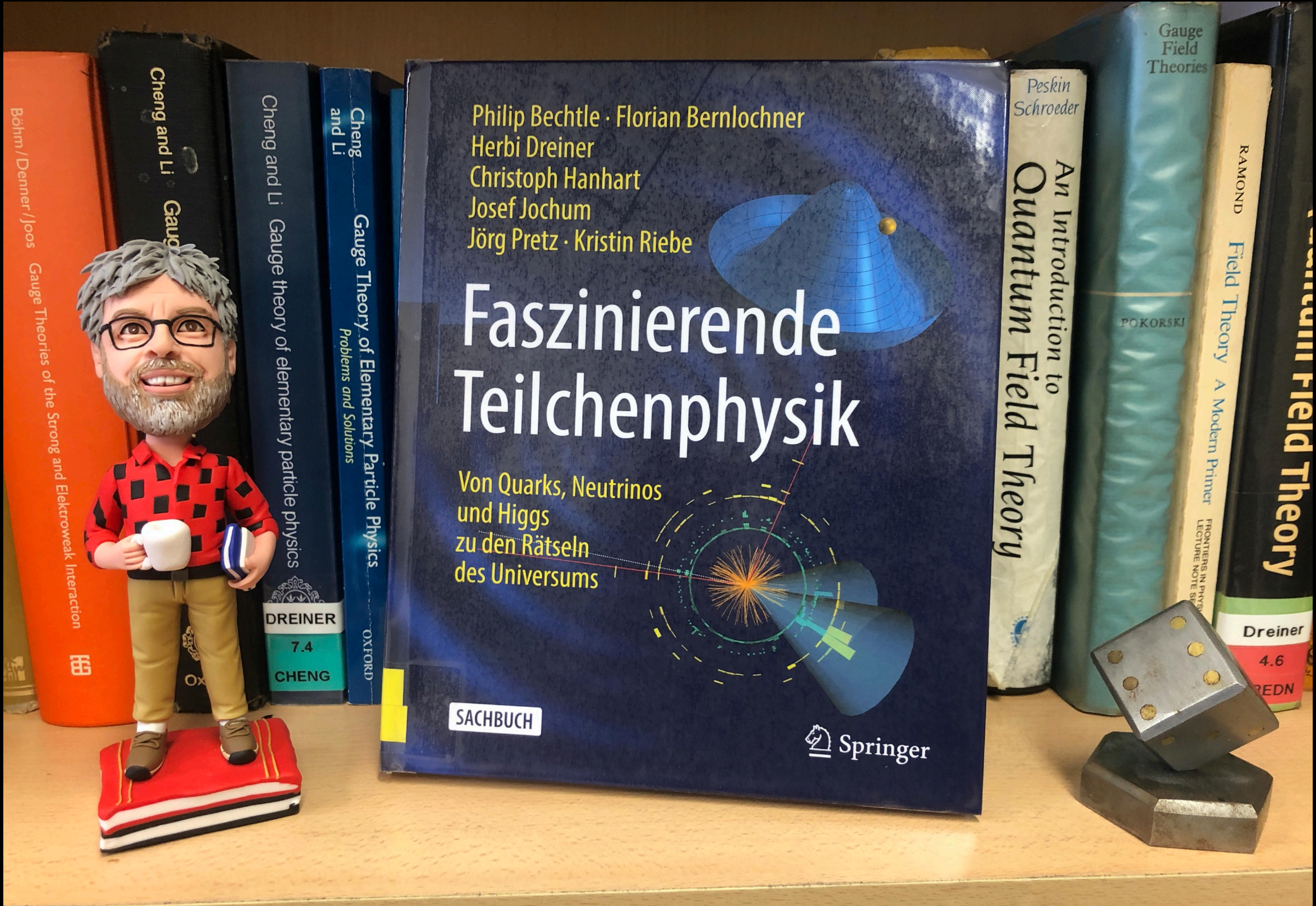
Published in: *Phys.Lett.B* 280 (1992) 304-312

New Show: Far From Home

Bonn Sept. 2023

Tübingen (3/2023)

Fascinating Particle Physics: a Popular Book Project



B4 $\tilde{\chi}_1^0 \to (\pi^\pm + \mu^\mp,\ \pi^0 + \nu_\mu)$ $c\tau_{\tilde{\chi}_1^0} \sim 8\,\mathrm{m}$

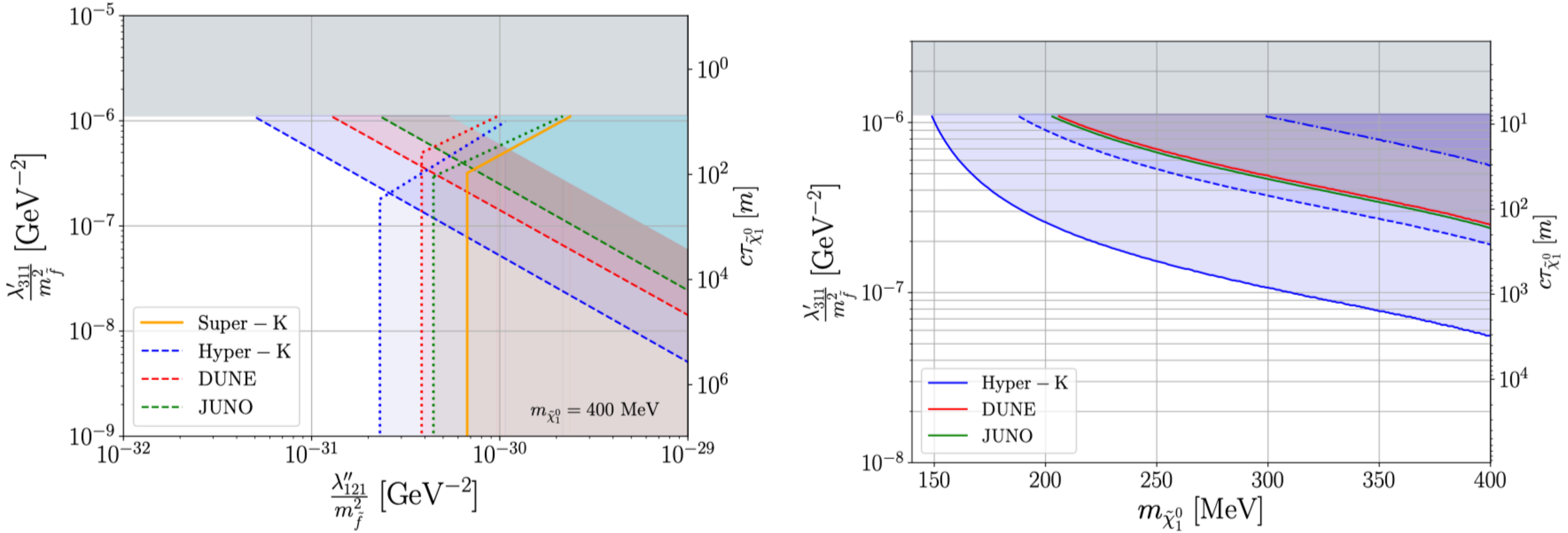


Figure 9: Sensitivity reach/`Super-K` limit for benchmark **B5**. The existing single-bound on λ'_{311} from Table 2 is shown in gray, the product-bound is in light blue (both with $m_{\tilde{f}} = 1\,\mathrm{TeV}$), while the bound on λ''_{121} lies outside the scale of the plot. *Left:* As in left plot of Fig. 6 but for benchmark **B5**. *Right:* As in right plot of Fig. 5 but for benchmark **B5**. The dashed, solid, and dot-dashed lines correspond to 3-, 30- and 90-event isocurves,

Back-Up Slides

Decay of Light Neutralinos (MeV - range)

- Systematic study of light neutralino (Bino) decays

Decays of a bino-like particle in the low-mass regime

Florain Domingo, HKD; arXiv:2205.08141 [hep-ph] (50p)

- General superpotential

$$W_{\mathrm{RpV}} = \mu_i \hat{H}_u \cdot \hat{L}_i + \frac{1}{2}\lambda_{ijk}\hat{L}_i \cdot \hat{L}_j (\hat{E}^c)_k + \lambda'_{ijk}\hat{L}_i \cdot \hat{Q}_{j\alpha}(\hat{D}^c)^{\alpha}_k + \frac{1}{2}\lambda''_{ijk}\varepsilon_{\alpha\beta\gamma}(\hat{U}^c)^{\alpha}_i(\hat{D}^c)^{\beta}_j(\hat{D}^c)^{\gamma}_k,$$

neutralinos and
neutrinos mix

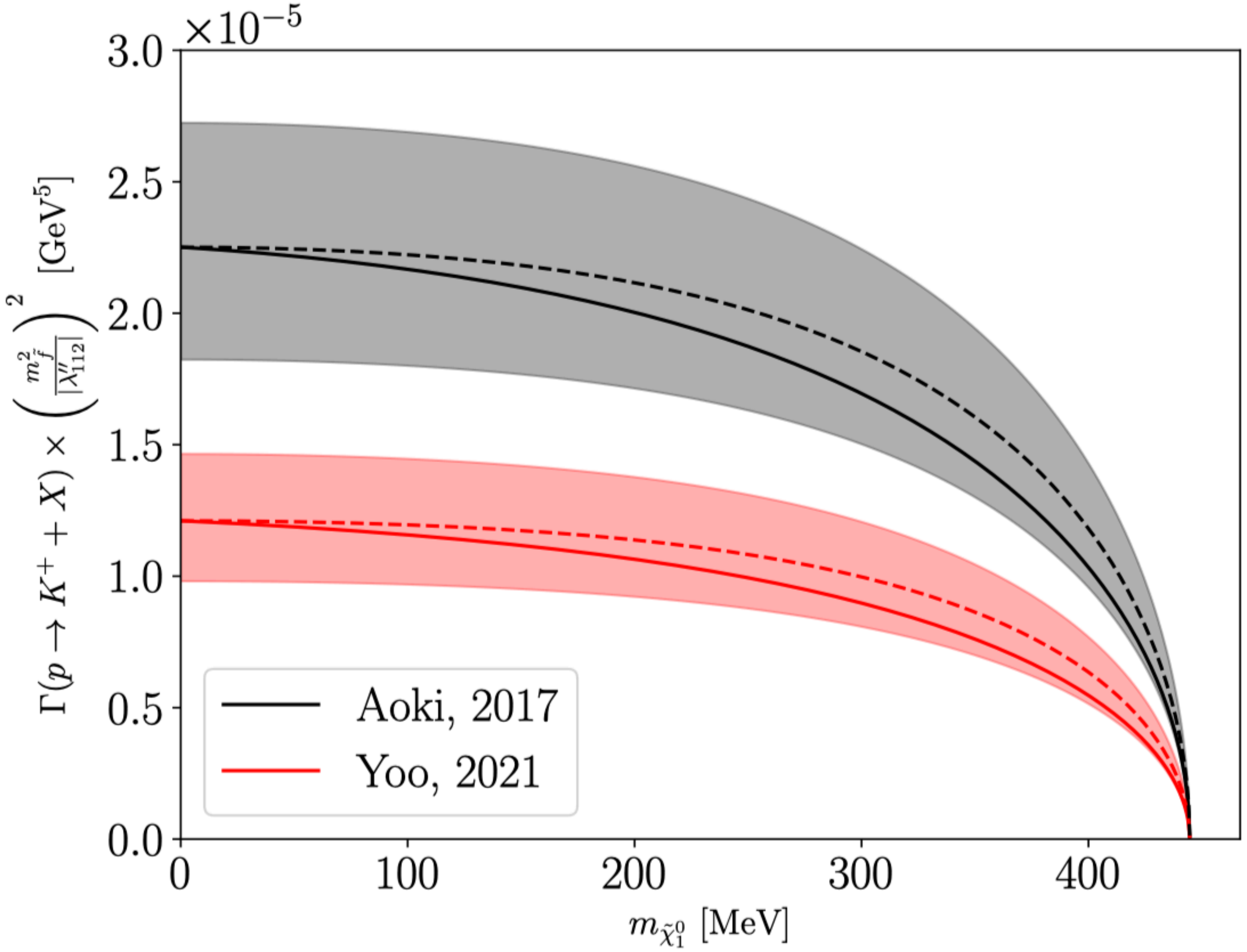
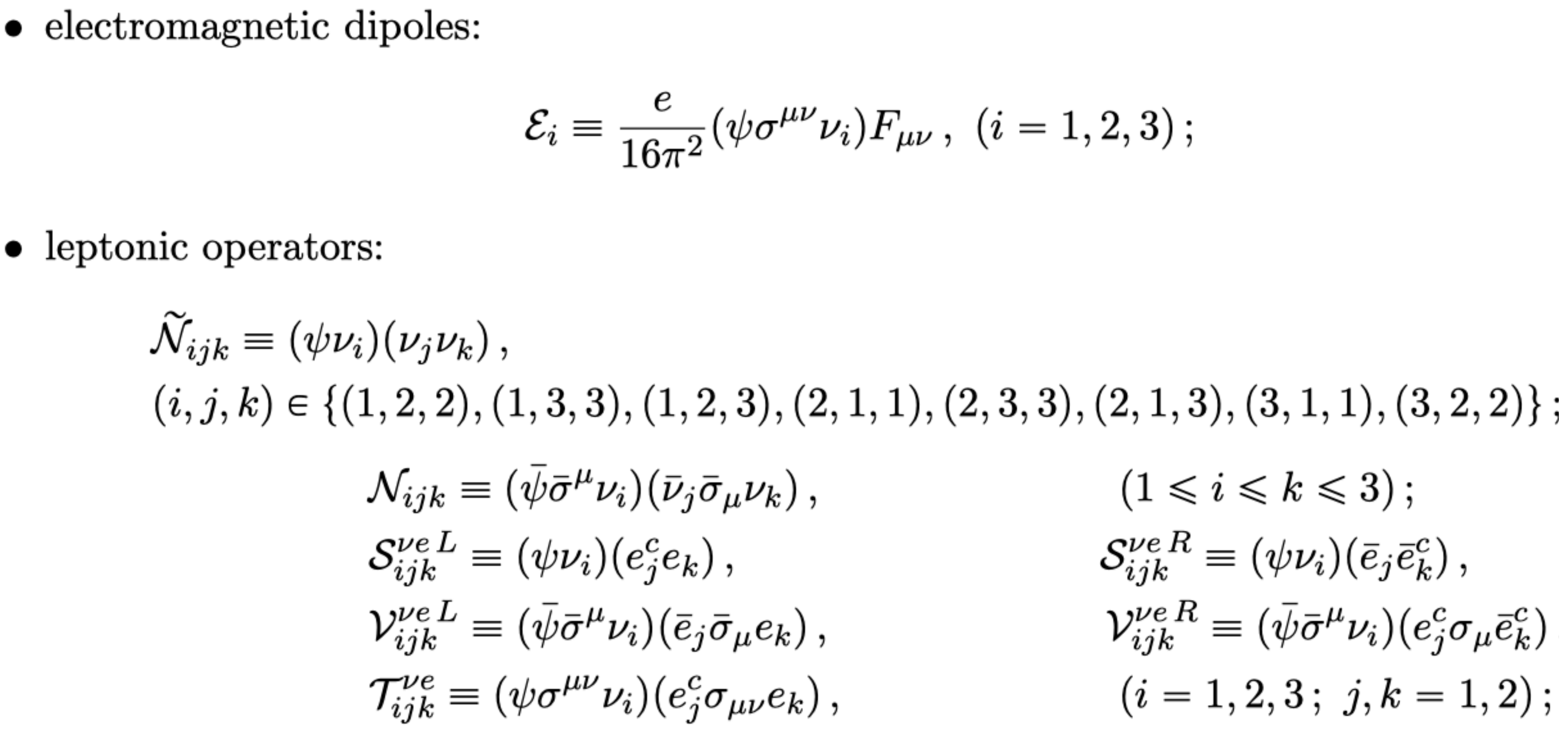


Figure 2: Proton decay width normalised to $|\lambda''_{112}|^2/m_{\tilde{f}}^4$, where $m_{\tilde{f}}$ represents a universal value for the squark masses. Two different lattice evaluations are used for the numerical values of the form factors: from Aoki, 2017 [84] and Yoo, 2021 [85]. The dashed line represents the case where lattice form-factors at $q^2 = 0$ are used, whatever the neutralino mass, while the solid lines represent results with form factors determined according to chiral perturbation theory [83]. The bands around the dashed lines denote the approximate error in the lattice calculation of the form factors.

- Derive effective field theory
- dimension-6 operators



- electromagnetic dipoles:

$$\mathcal{E}_i \equiv \frac{e}{16\pi^2}(\psi\sigma^{\mu\nu}\nu_i)F_{\mu\nu}\,, \quad (i=1,2,3)\,;$$

- leptonic operators:

$$\widetilde{\mathcal{N}}_{ijk} \equiv (\psi\nu_i)(\nu_j\nu_k)\,,$$
$$(i,j,k) \in \{(1,2,2),(1,3,3),(1,2,3),(2,1,1),(2,3,3),(2,1,3),(3,1,1),(3,2,2)\}\,;$$

$$\begin{aligned}
&\mathcal{N}_{ijk} \equiv (\bar\psi\bar\sigma^\mu\nu_i)(\bar\nu_j\bar\sigma_\mu\nu_k)\,, && (1\leqslant i\leqslant k\leqslant 3)\,;\\
&\mathcal{S}^{\nu e\,L}_{ijk} \equiv (\psi\nu_i)(e^c_j e_k)\,, && \mathcal{S}^{\nu e\,R}_{ijk} \equiv (\psi\nu_i)(\bar e_j \bar e^c_k)\,,\\
&\mathcal{V}^{\nu e\,L}_{ijk} \equiv (\bar\psi\bar\sigma^\mu\nu_i)(\bar e_j\bar\sigma_\mu e_k)\,, && \mathcal{V}^{\nu e\,R}_{ijk} \equiv (\bar\psi\bar\sigma^\mu\nu_i)(e^c_j\sigma_\mu\bar e^c_k)\\
&\mathcal{T}^{\nu e}_{ijk} \equiv (\psi\sigma^{\mu\nu}\nu_i)(e^c_j\sigma_{\mu\nu}e_k)\,, && (i=1,2,3;\ j,k=1,2)\,;
\end{aligned}$$

$$\tilde\chi^0_1 \to \gamma + \nu$$

(1-loop)

$$\tilde\chi^0_1 \to \ell^\pm_1 + \ell^\mp_2 + \nu$$
$$\tilde\chi^0_1 \to \nu_1 + \nu_2 + \nu_3$$

- semi-leptonic operators:

$$
\begin{aligned}
\mathcal{S}^{eq\,LL}_{ijk} &\equiv (\psi e_i)(d^c_j u_k)\,, & \mathcal{S}^{eq\,LR}_{ijk} &\equiv (\psi e_i)(\bar{d}_j \bar{u}^c_k)\,, \\
\mathcal{S}^{eq\,RL}_{ijk} &\equiv (\bar{\psi}\bar{e}^c_i)(d^c_j u_k)\,, & \mathcal{S}^{eq\,RR}_{ijk} &\equiv (\bar{\psi}\bar{e}^c_i)(\bar{d}_j \bar{u}^c_k)\,, \\
\mathcal{V}^{eq\,LL}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^\mu e_i)(\bar{d}_j \bar{\sigma}_\mu u_k)\,, & \mathcal{V}^{eq\,LR}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^\mu e_i)(d^c_j \sigma_\mu \bar{u}^c_k)\,, \\
\mathcal{V}^{eq\,RL}_{ijk} &\equiv (\psi\sigma^\mu \bar{e}^c_i)(\bar{d}_j \bar{\sigma}_\mu u_k)\,, & \mathcal{V}^{eq\,RR}_{ijk} &\equiv (\psi\sigma^\mu \bar{e}^c_i)(d^c_j \sigma_\mu \bar{u}^c_k)\,, \\
\mathcal{T}^{eq\,L}_{ijk} &\equiv (\psi\sigma^{\mu\nu} e_i)(d^c_j \sigma_{\mu\nu} u_k)\,, & \mathcal{T}^{eq\,R}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^{\mu\nu} \bar{e}^c_i)(\bar{d}_j \bar{\sigma}_{\mu\nu} \bar{u}^c_k)\,, \\
& & & (i,j = 1,2\,,\ k = 1)\,; \\[1em]
\mathcal{S}^{\nu u\,L}_{ijk} &\equiv (\psi \nu_i)(u^c_j u_k)\,, & \mathcal{S}^{\nu u\,R}_{ijk} &\equiv (\psi \nu_i)(\bar{u}_j \bar{u}^c_k)\,, \\
\mathcal{V}^{\nu u\,L}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^\mu \nu_i)(\bar{u}_j \bar{\sigma}_\mu u_k)\,, & \mathcal{V}^{\nu u\,R}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^\mu \nu_i)(u^c_j \sigma_\mu \bar{u}^k_k)\,, \\
\mathcal{T}^{\nu u}_{ijk} &\equiv (\psi\sigma^{\mu\nu} \nu_i)(u^c_j \sigma_{\mu\nu} u_k)\,, & & (i = 1,2,3\,,\ j,k = 1)\,; \\
\mathcal{S}^{\nu d\,L}_{ijk} &\equiv (\psi \nu_i)(d^c_j d_k)\,, & \mathcal{S}^{\nu d\,R}_{ijk} &\equiv (\psi \nu_i)(\bar{d}_j \bar{d}^c_k)\,, \\
\mathcal{V}^{\nu d\,L}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^\mu \nu_i)(\bar{d}_j \bar{\sigma}_\mu d_k)\,, & \mathcal{V}^{\nu d\,R}_{ijk} &\equiv (\bar{\psi}\bar{\sigma}^\mu \nu_i)(d^c_j \sigma_\mu \bar{d}^k_k)\,, \\
\mathcal{T}^{\nu d}_{ijk} &\equiv (\psi\sigma^{\mu\nu} \nu_i)(d^c_j \sigma_{\mu\nu} d_k)\,, & & (i = 1,2,3\,,\ j,k = 1,2)\,;
\end{aligned}
$$

$$
\boxed{
\begin{aligned}
&\tilde{\chi}^0_1 \to \mathrm{M}^\pm + \ell^\mp \\
&\tilde{\chi}^0_1 \to \mathrm{M}^0 + \nu
\end{aligned}
}
$$