Searching for light long-lived neutralinos at Super-Kamiokande

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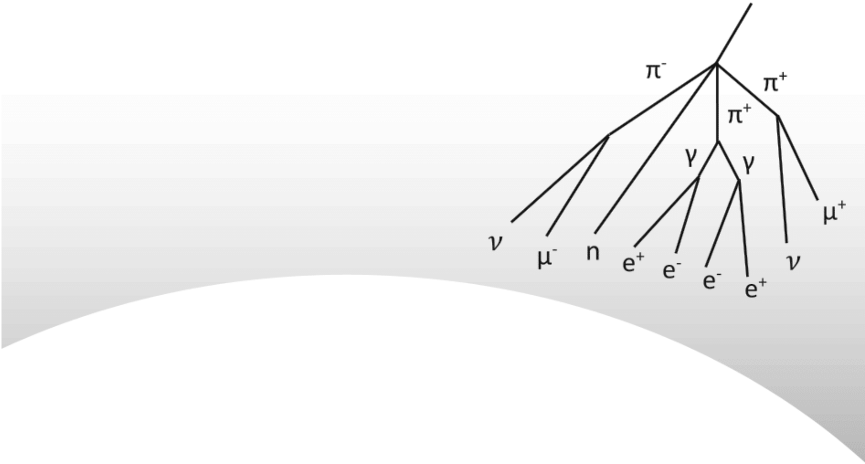
Based on
P. Candia, G. Cottin, A. Méndez, V. Muñoz, Phys.Rev.D 104 (2021) 5, 055024

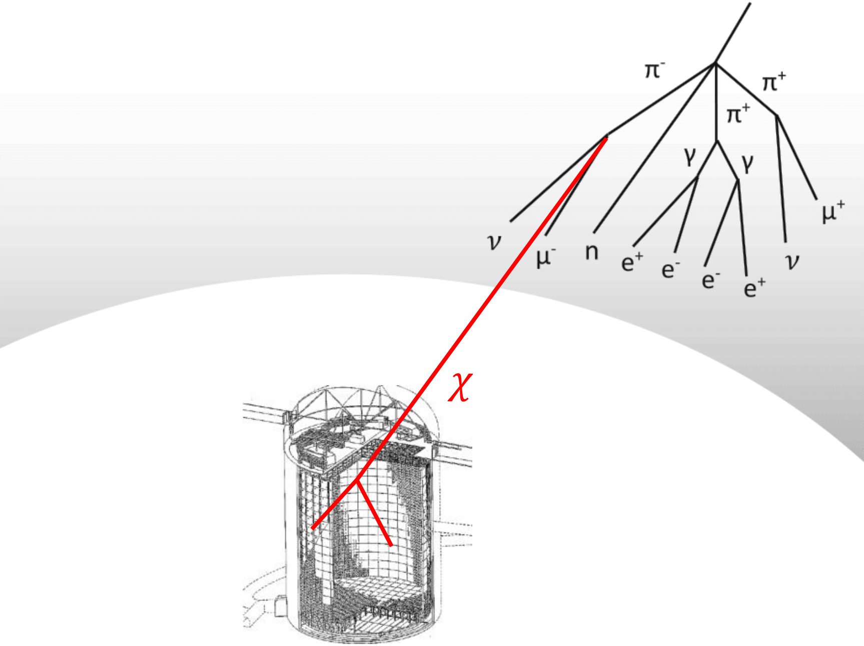
Cosmic-ray air showers

- The earth is constantly being bombarded with cosmic rays
- These cosmic rays collide with air nuclei producing a big amount of unstable hadrons
- These hadrons decay into other particles that form part of the atmospheric shower
- Atmospheric neutrino experiments look at neutrinos that are produced in these showers



BSM particles in air showers

- Hypothetical long-lived particles **could be produced in cosmic ray air showers**
- The particles could travel and decay inside the detection volume of atmospheric neutrino detectors
- This would result in an **excess of events**
    - ❖ Kusenko, Pascoli, Semikoz, JHEP 11 (2005) 028 (Sterile neutrinos at SK)
    - ❖ Asaka, Watanabe, JHEP 07 (2012) 112 (Sterile neutrinos at SK)
    - ❖ Argüelles, Coloma, Hernandez, Muñoz, JHEP 02 (2020) 190 (HNL and dark photons at SK and IC)
- Advantages:
    - ➢ Long lifetimes
    - ➢ There is data **already available**!



Case study: Long-lived light neutralino

- We apply this strategy to search for **long-lived light neutralinos in Super-Kamiokande**
- Light neutralinos are allowed in the **RPV MSSM.** We consider the term

$$W = \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k$$

- The widths are parametrised by λ'_{ijk} (if they are smaller, it lives longer)
- Some studies:
  - **SHiP, ATLAS:** de Vries, HD, Schmeier, PRD 94 (2016) 035006; Gorbunov, Timiryasov, PRD 92 (2015) 7, 075015
  - **CODEX-b, FASER, MATHUSLA:** Dercks, de Vries, Dreiner, Wang; PRD 99 (2019) 055039

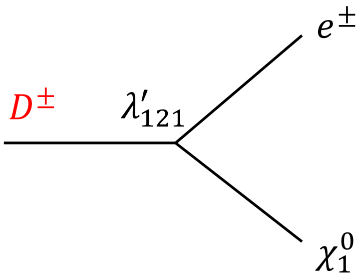
…

- We focus on production from **meson decays** and **degenerate sfermion masses**. Specifically, we choose λ'_{121}, λ'_{112} and λ'_{111}

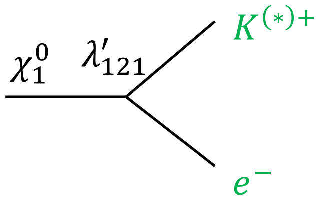
Neutralino production and decay

Benchmark 1: $\lambda'_{121}, \lambda'_{112}; \quad m_{\chi_1^0} \in (m_{K^\pm}, m_{D^\pm})$

Production

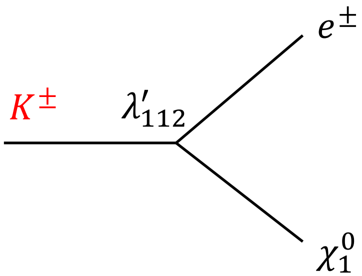


Decay

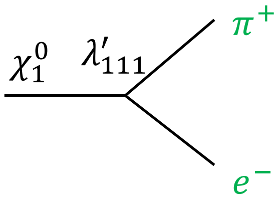


Benchmark 2: $\lambda'_{112}, \lambda'_{111}; \quad m_{\chi_1^0} \in (m_{\pi^0}, m_{K^\pm})$

Production

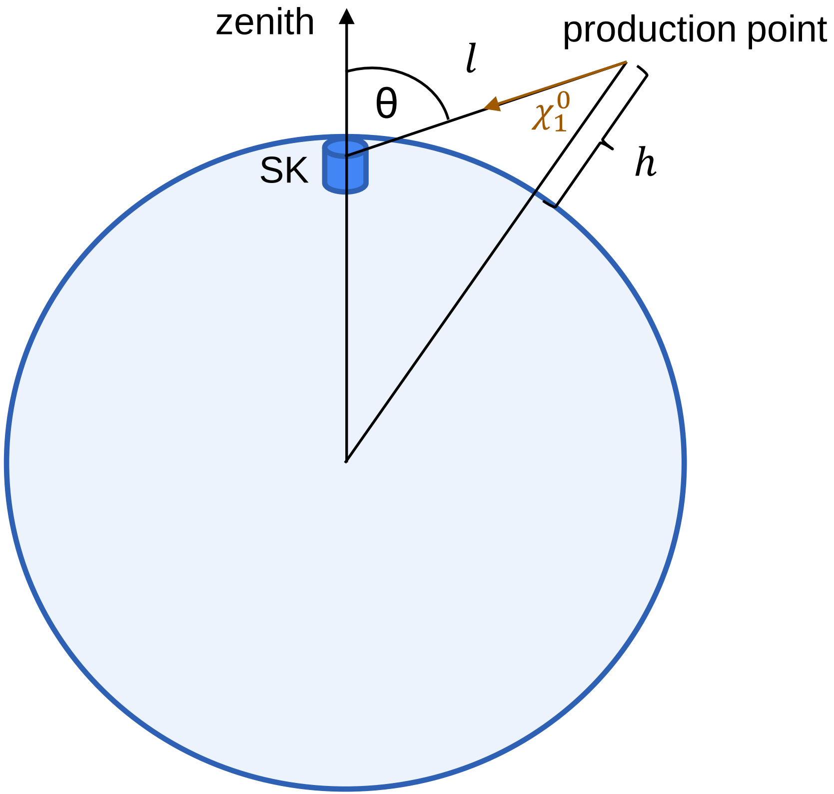


Decay



We are looking at showering final states

Neutralino trajectories



The following coordinates are relevant for the production of the neutralino:

- l: Distance between the production point and the detector
- θ: zenith angle of the trajectory of the neutralino
- h: height at which the neutralino is produced

Column depth: $X = \int \rho(h, l) dl$

Cascade equations and event rate

Cascade equation

$$\frac{d\Phi_{\chi_1^0}}{dE_{\chi_1^0} d\Omega dX} = \sum_M \int dE_M \frac{1}{\rho \lambda_M} \frac{d\Phi_M}{dE_{\chi_1^0} d\Omega} \frac{dn}{dE_{\chi_1^0}}$$

Differential neutralino production rate

from MCEq
https://github.com/afedynitch/MCEq

ρ : atmospheric density at depth X

λ_M : decay length of the meson

$\frac{d\Phi_M}{dE_{\chi_1^0} d\Omega}$: production rate of the parent meson

$\frac{dn}{dE_{\chi_1^0}}$: distribution of neutralinos produced in meson decays

Differential event rate

Probability of decay in the detector volume

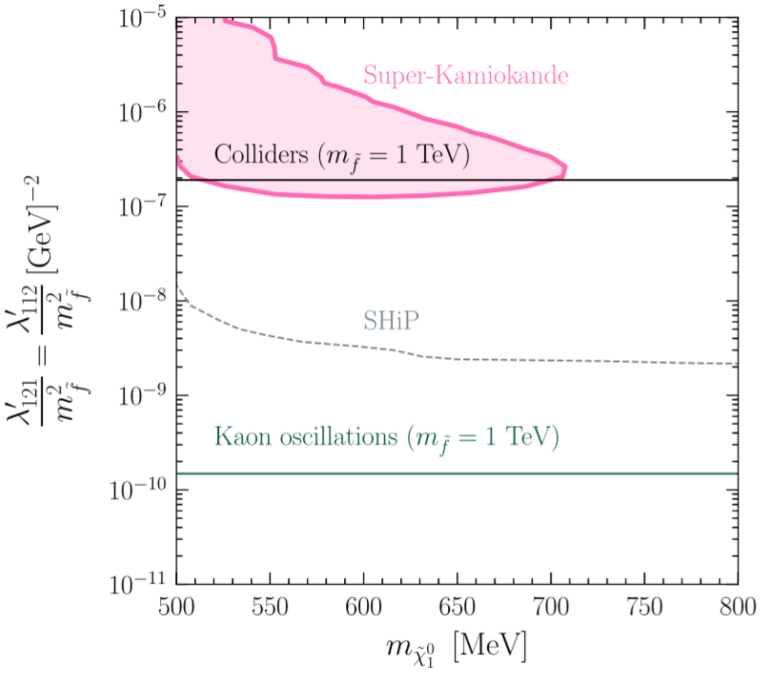
$$\frac{dN}{dE_{\chi_1^0} d\Omega} = \int dS_\perp \int dX \frac{d\Phi_{\chi_1^0}}{dE_{\chi_1^0} d\Omega dX} e^{-l/\lambda_{\chi_1^0}} \left(1 - e^{-\Delta l_{det}/\lambda_{\chi_1^0}}\right)$$

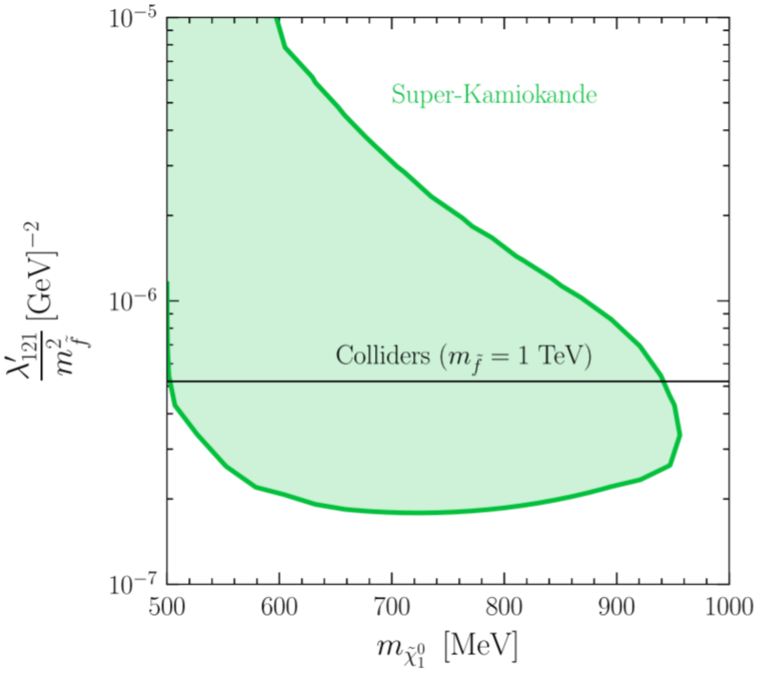
Depends on neutralino lifetime $\lambda_{\chi_1^0}$

The differential event rate can be multiplied by the **exposure time** and integrated to get the **expected number of events**

Results for benchmark 1

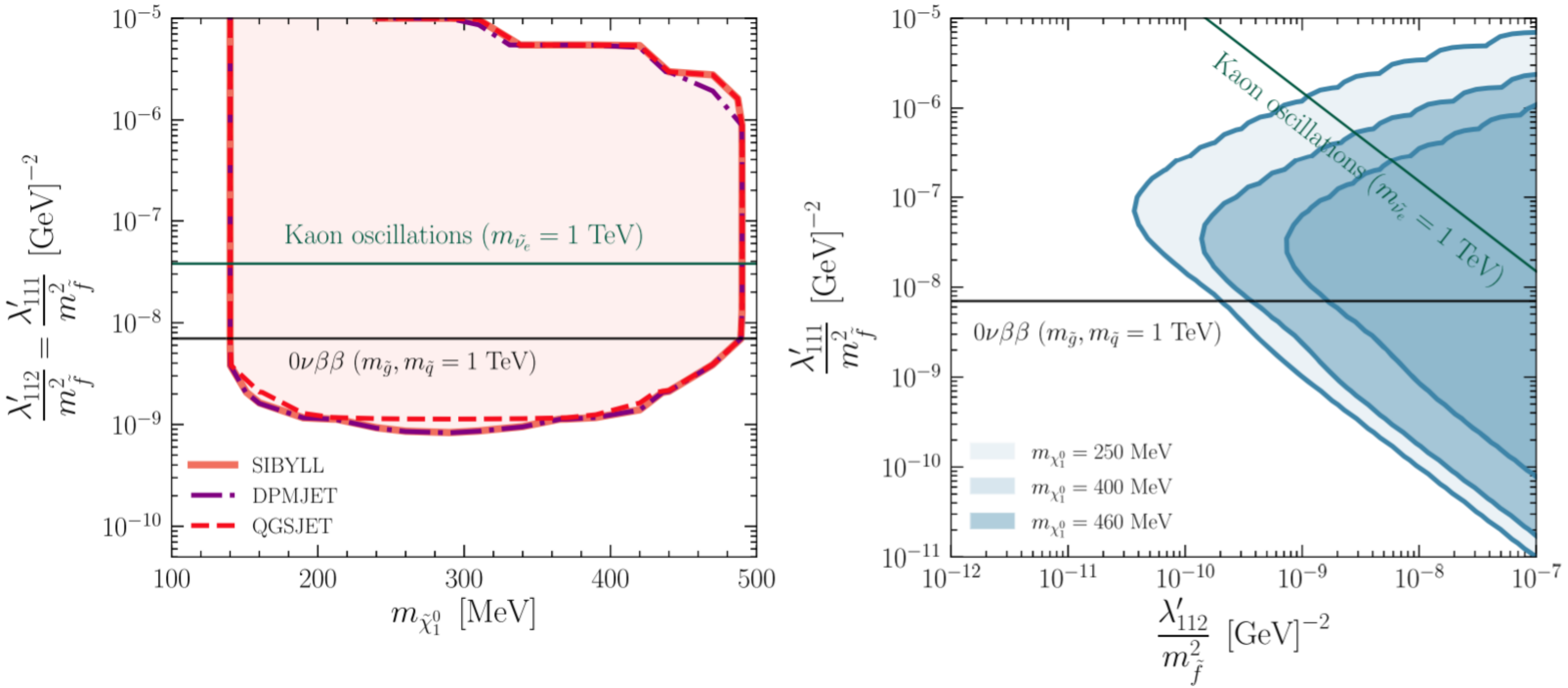
Production from *D* mesons decays



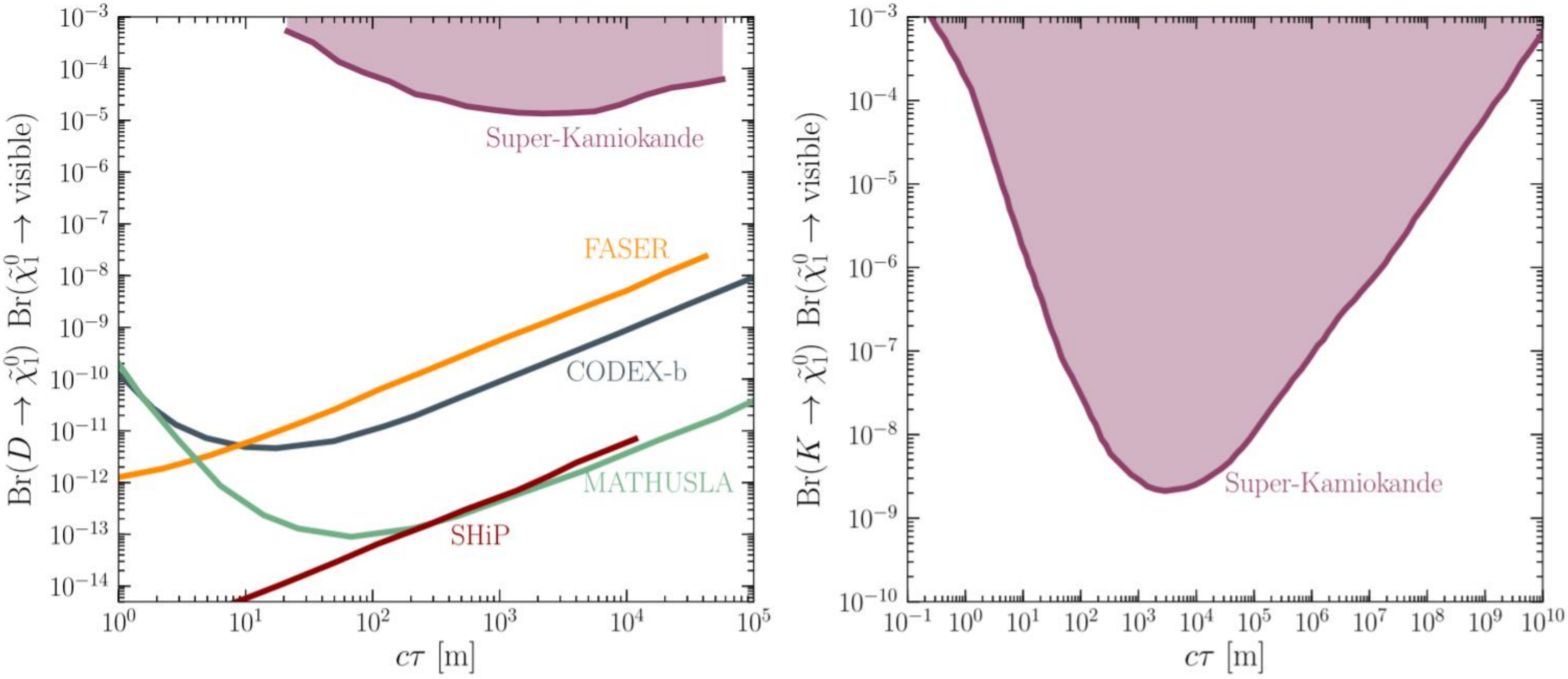


Results for benchmark 2

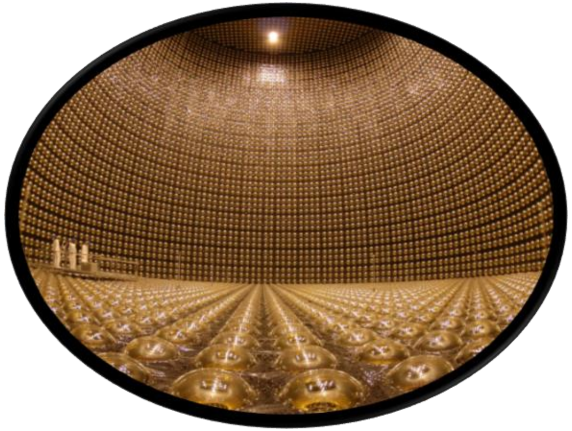
Production from kaon decays

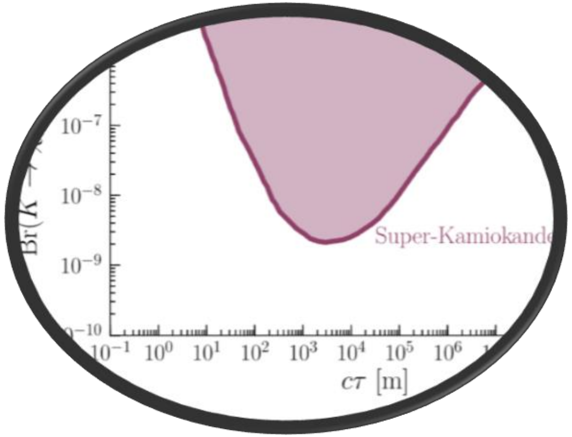


Results in the Br vs. $c\tau$ plane



To summarise





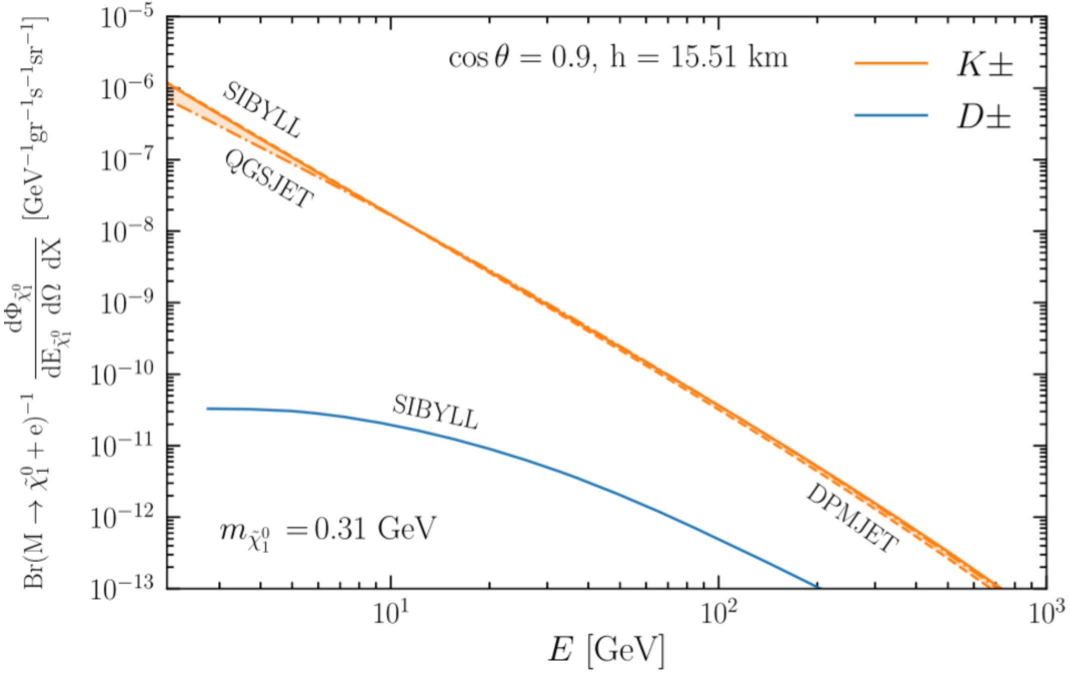
Water Cherenkov detectors can be good at searching for atmospheric long lived particles from meson decays

This search can probe a wide range of lifetimes (peaking at order 1 km)

Many possible directions to follow from here!

BACK-UP SLIDES

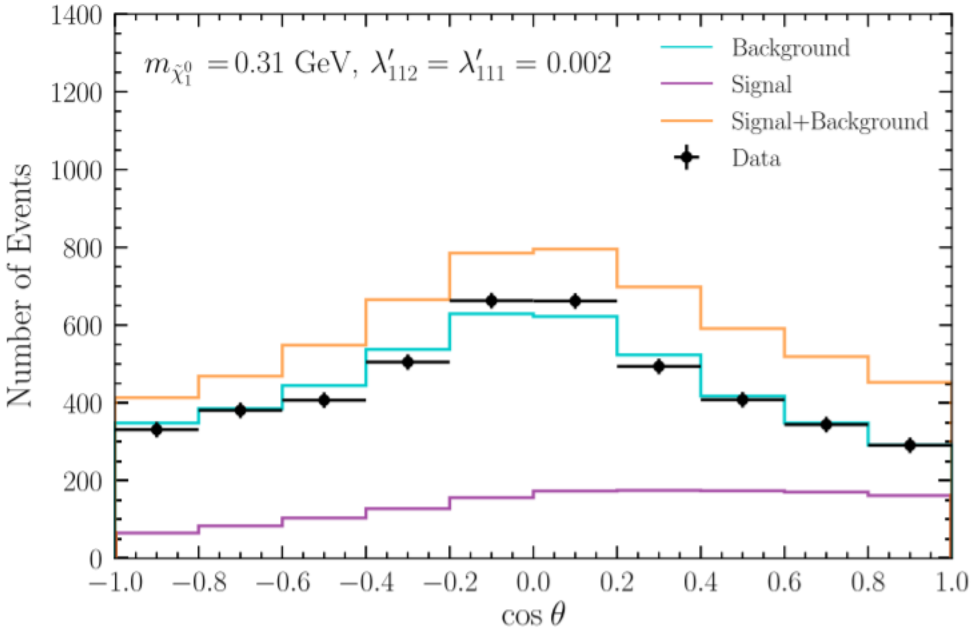
Neutralino production rate



Super-K e-like events dataset

Super-K runs I-IV (5326 days)

**Data obtained from [1710.09126]*



The number of events can be calculated as

$$N_{c_i} = Br(\chi_1^0 \to e - like) \int d\cos\theta \int dE \frac{dN}{dE_{\chi_1^0} d\cos\theta}$$

Production and decay channels

	RPV coupling	Production	Decay mode
B1	$\lambda'_{121}, \lambda'_{112}$	$D^{\pm} \xrightarrow{\lambda'_{121}} e^{\pm} + \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{121}} K_S^0 + \nu_e$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{121}} K^{*0} + \nu_e$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K^{(*)+} + e^-$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K_S^0 + \nu_e$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K^{*0} + \nu_e$
B2	$\lambda'_{112}, \lambda'_{111}$	$K^{\pm} \xrightarrow{\lambda'_{112}} e^{\pm} + \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{111}} \pi^+ + e^-$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{111}} \pi^0 + \nu_e$

Bounds on RPV parameters

Kaon oscillations

$$|\lambda'_{112}\lambda'_{121}| \leq 2.2 \times 10^{-8} \left(\frac{m_{\tilde{\nu}_e}}{1\ \text{TeV}}\right)^2$$

$$|\lambda'_{111}\lambda'_{112}| \leq 1.5 \times 10^{-3} \left(\frac{m_{\tilde{\nu}_e}}{1\ \text{TeV}}\right)^2$$

Colliders

$$\lambda'_{112} \leq 0.16 \frac{m_{\tilde{s}_R}}{1\ \text{TeV}} + 0.030$$

$$\lambda'_{121} \leq 0.34 \frac{m_{\tilde{q}}}{1\ \text{TeV}} + 0.18$$

$0\nu\beta\beta$

$$\lambda'_{111} \leq 2.2 \times 10^{-3} \left(\frac{m_{\tilde{q}}}{1\ \text{TeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{1\ \text{TeV}}\right)^{1/2}$$