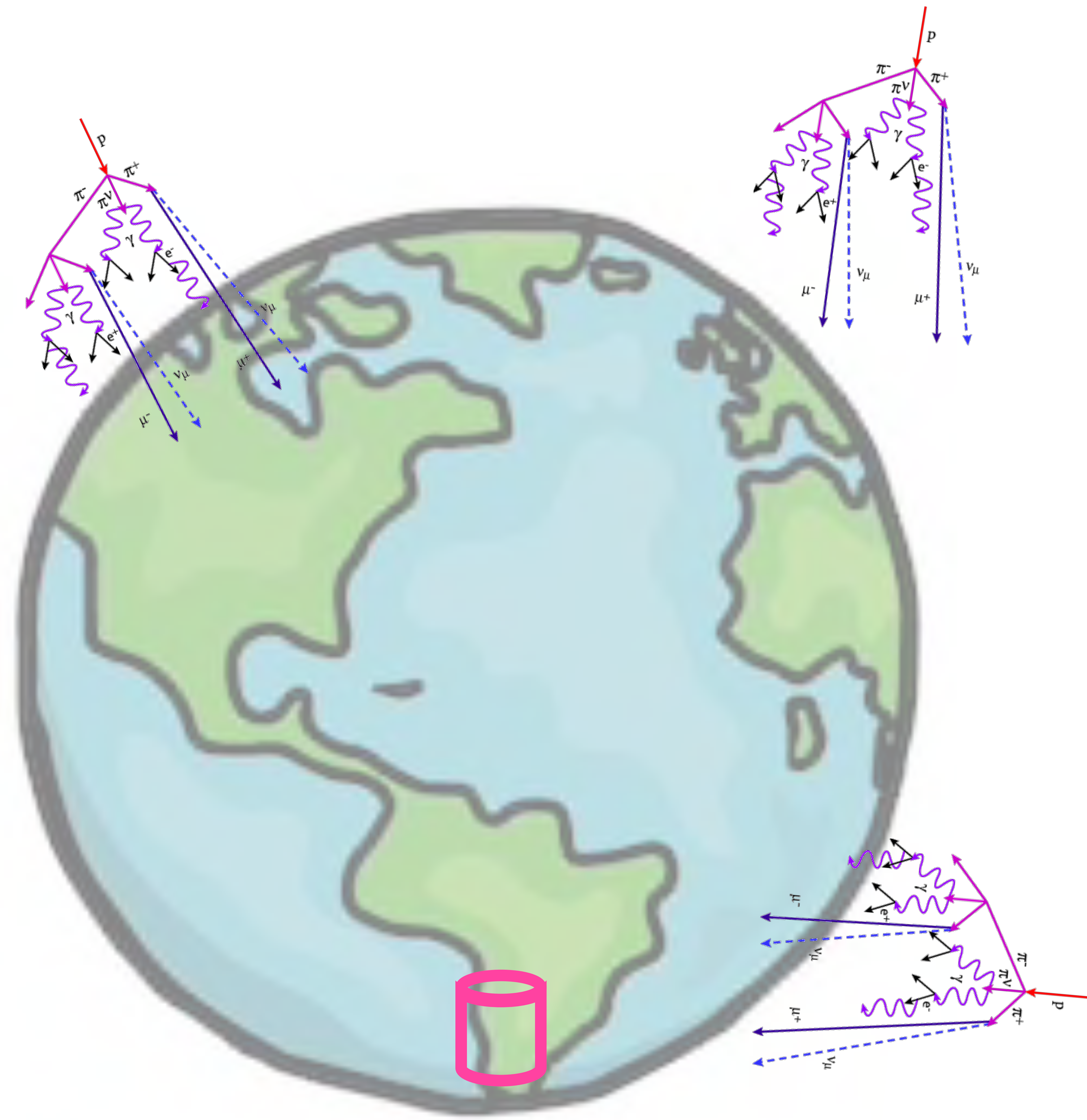
Searches for Atmospheric Long-Lived Particles

Carlos Argüelles

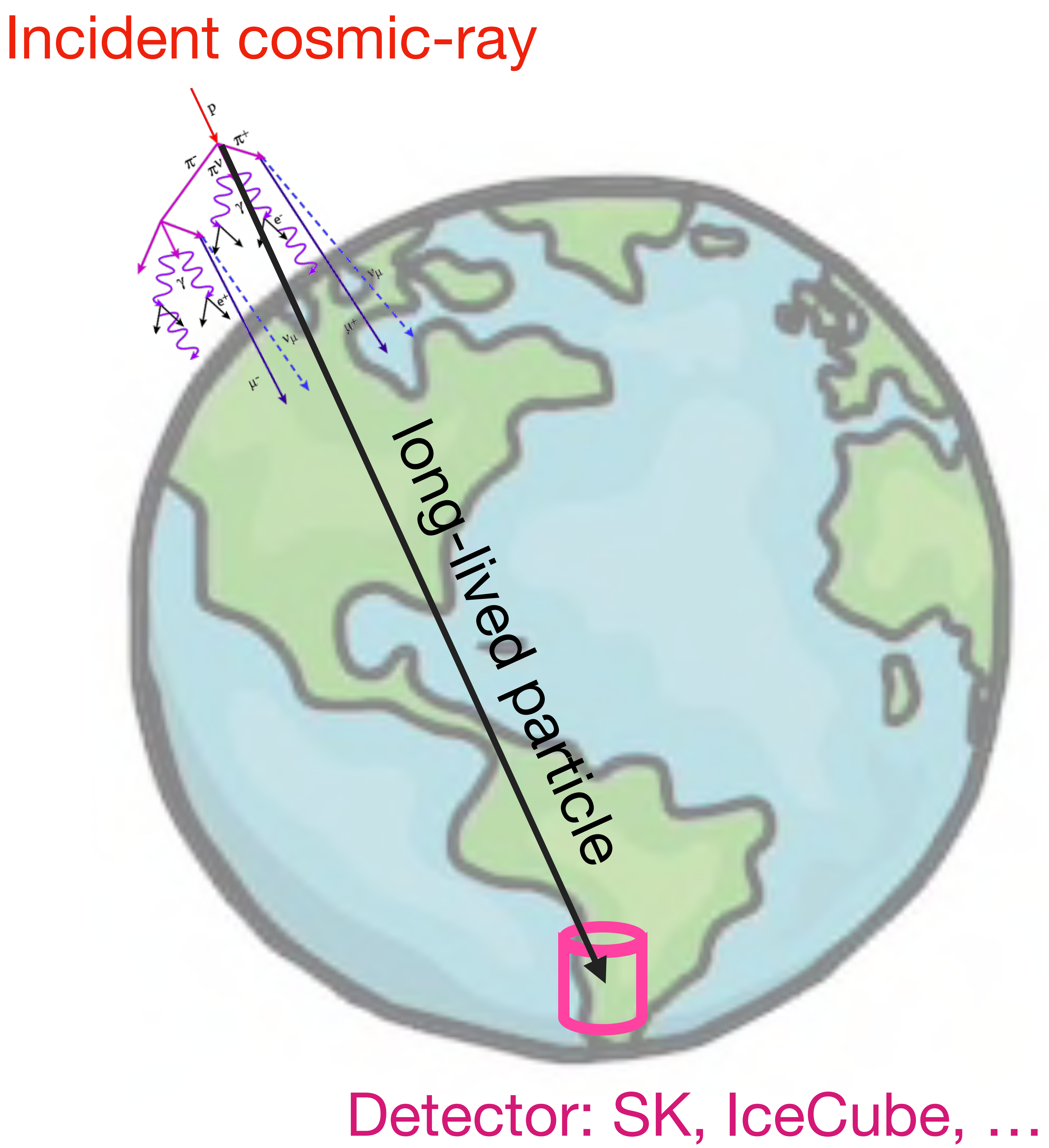
in collaboration with
P. Coloma, P. Hernández, and V. Muñoz

Based on arXiv:1910.12839



Outline

1. Production of long-lived particles (LLP) in cosmic-ray air showers.
2. Signatures and data sets of very large volume neutrino detectors: IceCube and Super-Kamiokande.
3. New constraints in three scenarios: heavy neutral leptons (HNH), dark photons (DP), and a B-L model.



Production of LLP in cosmic-ray showers

Parent distribution

$$\frac{d\Pi_A}{dE\,d\cos\theta\,d\ell} = \sum_{ch}\int_{E_P^{\min}}^{E_P^{\max}} dE_P \frac{1}{\gamma_P\beta_P c\tau_P}\boxed{\frac{d\Phi_P(E_P,\cos\theta)}{dE_P\,d\cos\theta}}\frac{dn_{ch}(E_P,E)}{dE}$$

see *e.g.* Gondolo, Ingleman and Thunman, hep-ph/9505417

$$\frac{d\Phi_A}{dE_A\,d\cos\theta} = \int_0^{\ell_{\max}} d\ell \frac{d\Pi_A}{dE_A\,d\cos\theta\,d\ell}\, e^{-\frac{\ell}{\ell_{\text{decay}}}}$$

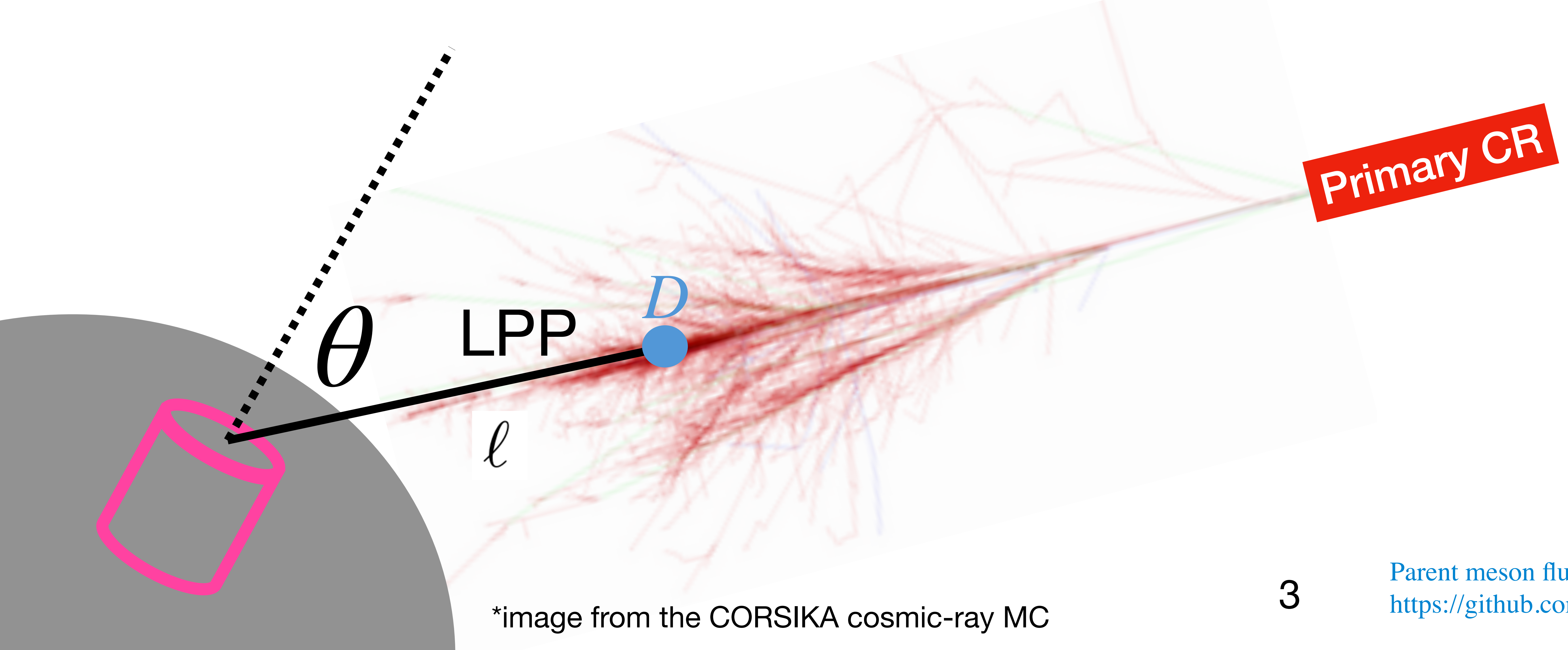
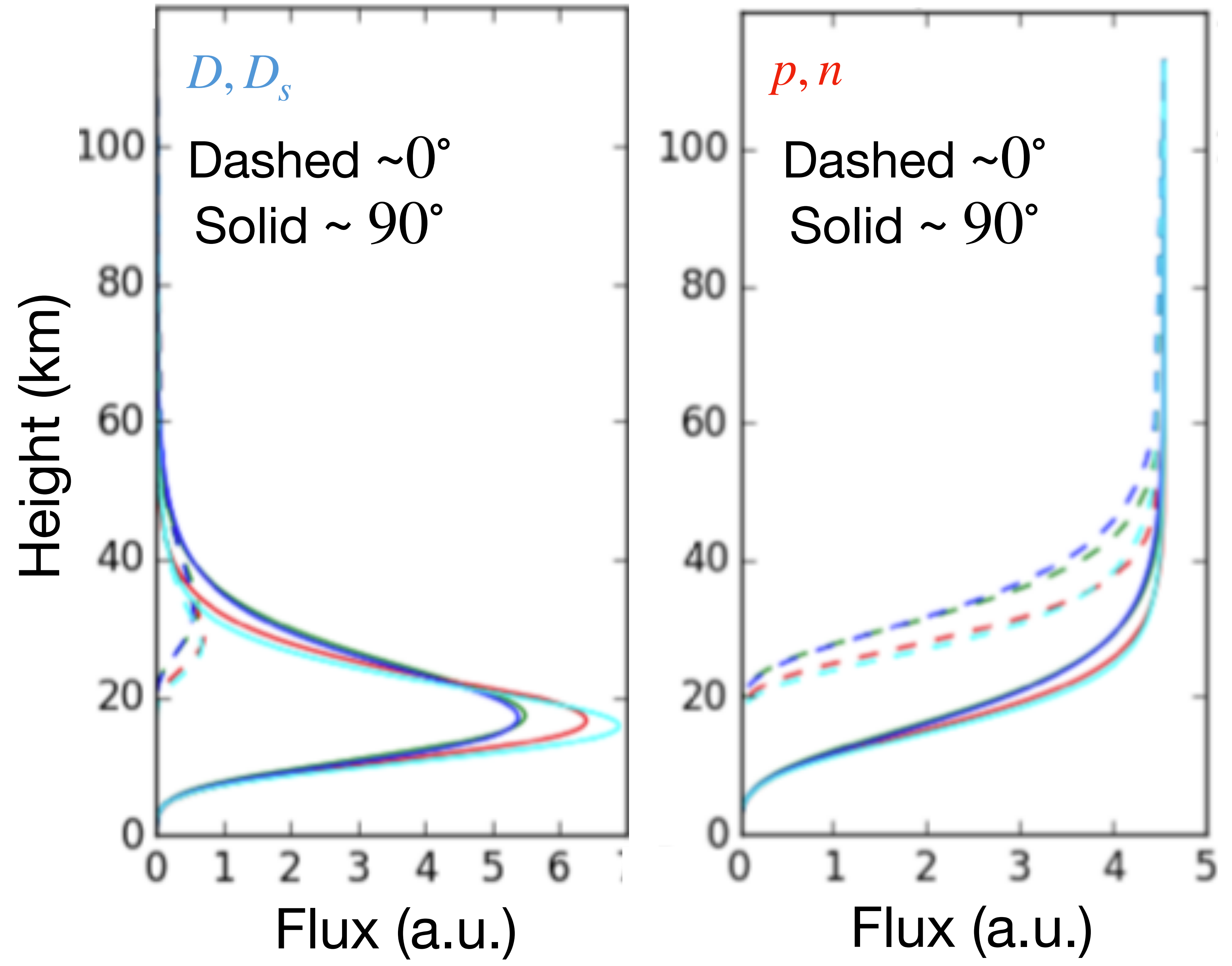


*image from the CORSIKA cosmic-ray MC



Parent meson fluxes extracted from MCEq: https://github.com/afedynitch/MCEq

(Colors of the different lines indicate different seasons and atmospheric models)

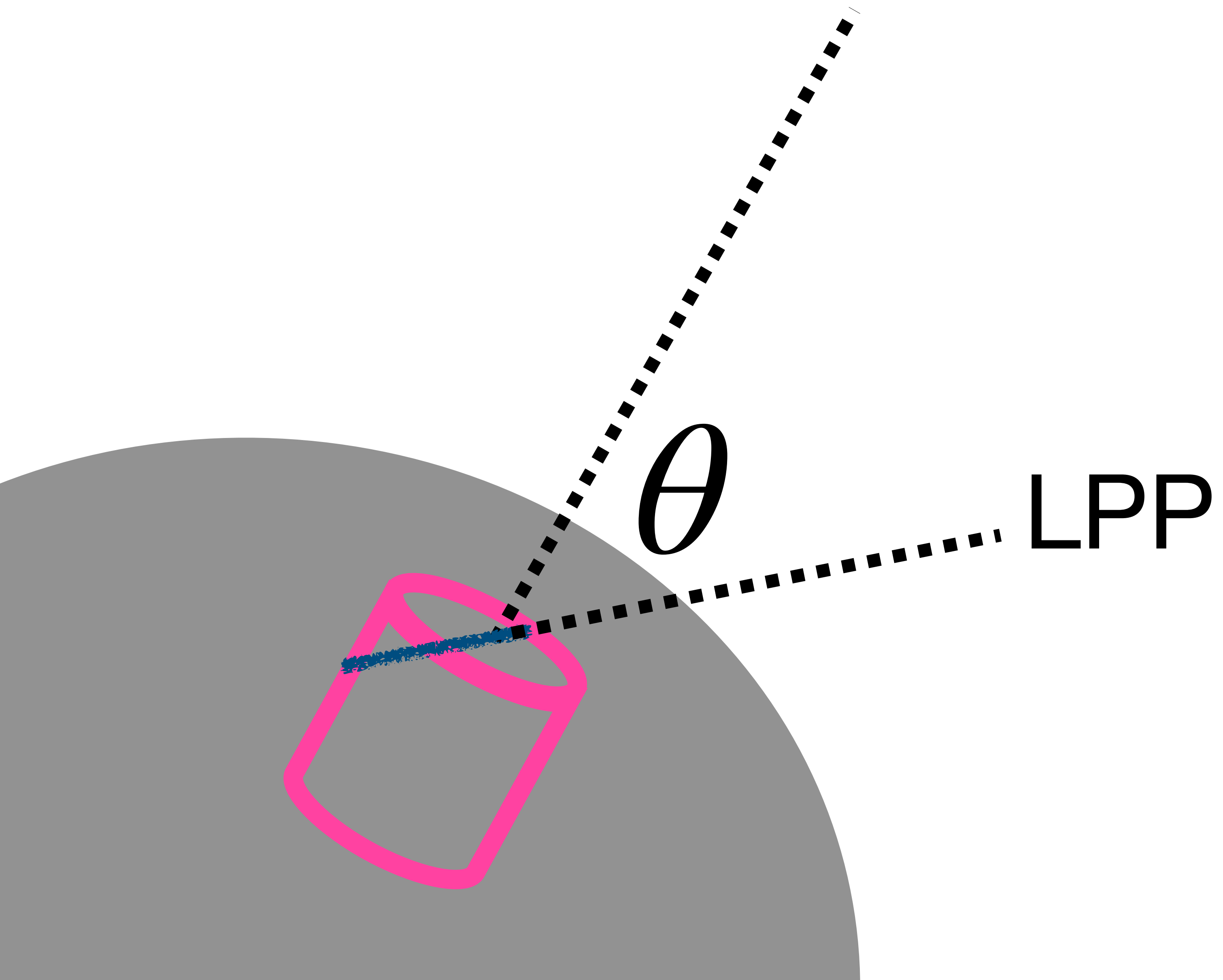
Rates in an underground detector

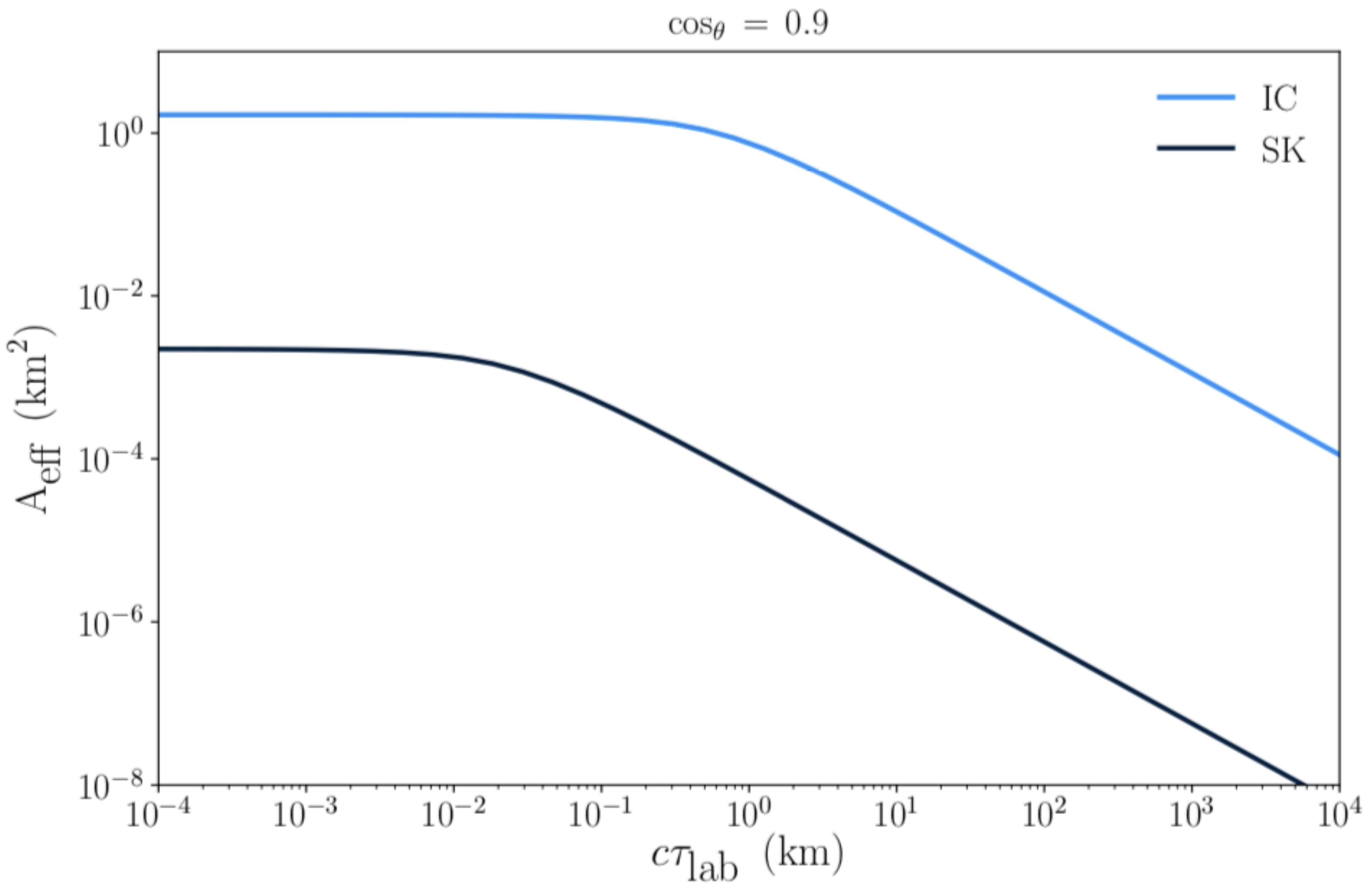
$$\frac{dN_i^\alpha}{dE\,d\cos\theta} \propto \mathrm{Br}(\alpha\text{–like})\;\epsilon^\alpha\;\Delta T\;A^{\rm eff}_{\rm decay}(E,\cos\theta)\,\frac{d\Phi_A}{dE\,d\cos\theta}$$

Detector efficiencies (estimated)

Geometric acceptance

$$A^{\rm eff}_{\rm decay}(E_A,\cos\theta) = \int dS_\perp \left\{1 - \exp\left(-\frac{\Delta\ell_{det}(\cos\theta)}{\ell_{\rm decay}(E_A)}\right)\right\}$$

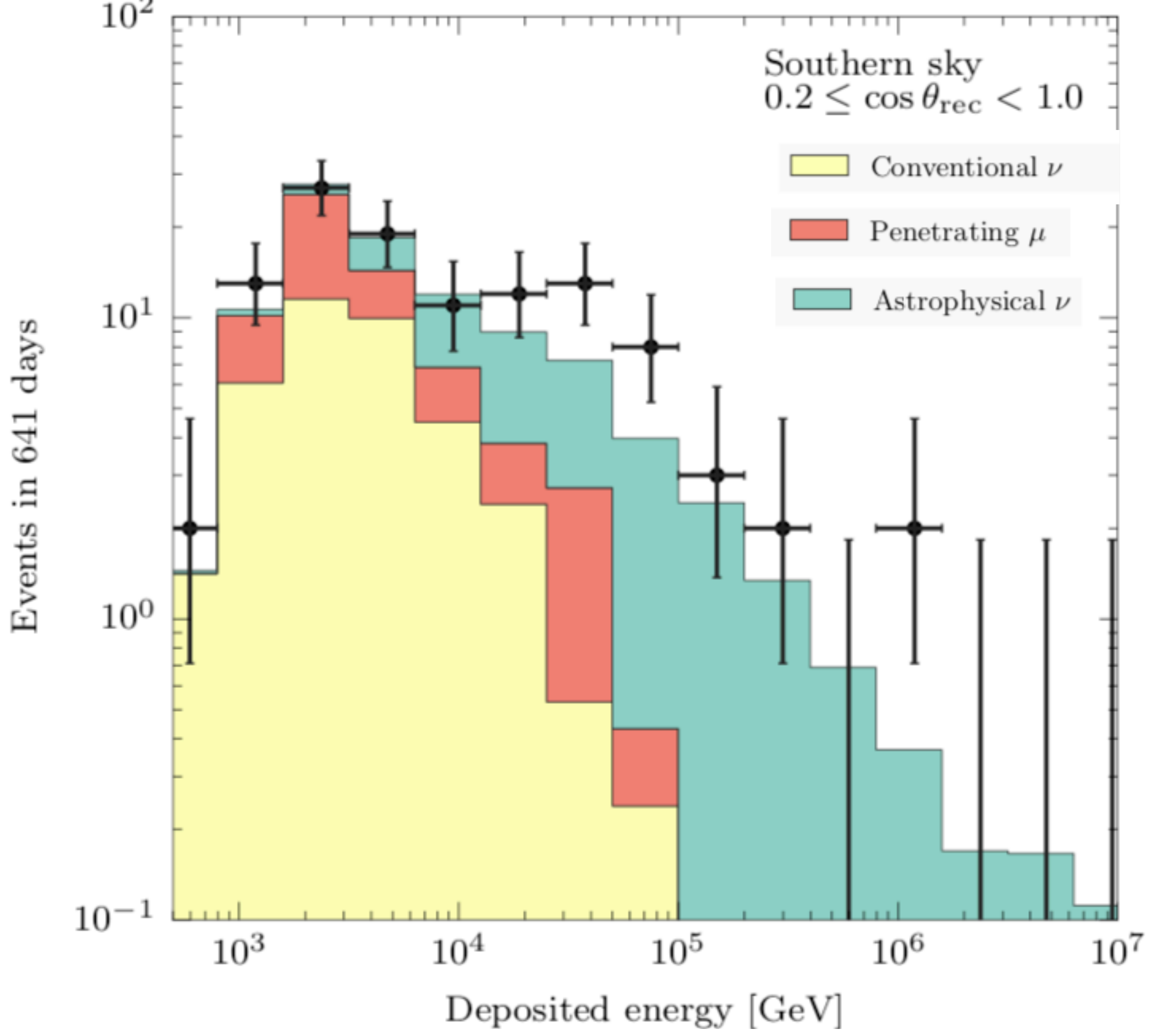


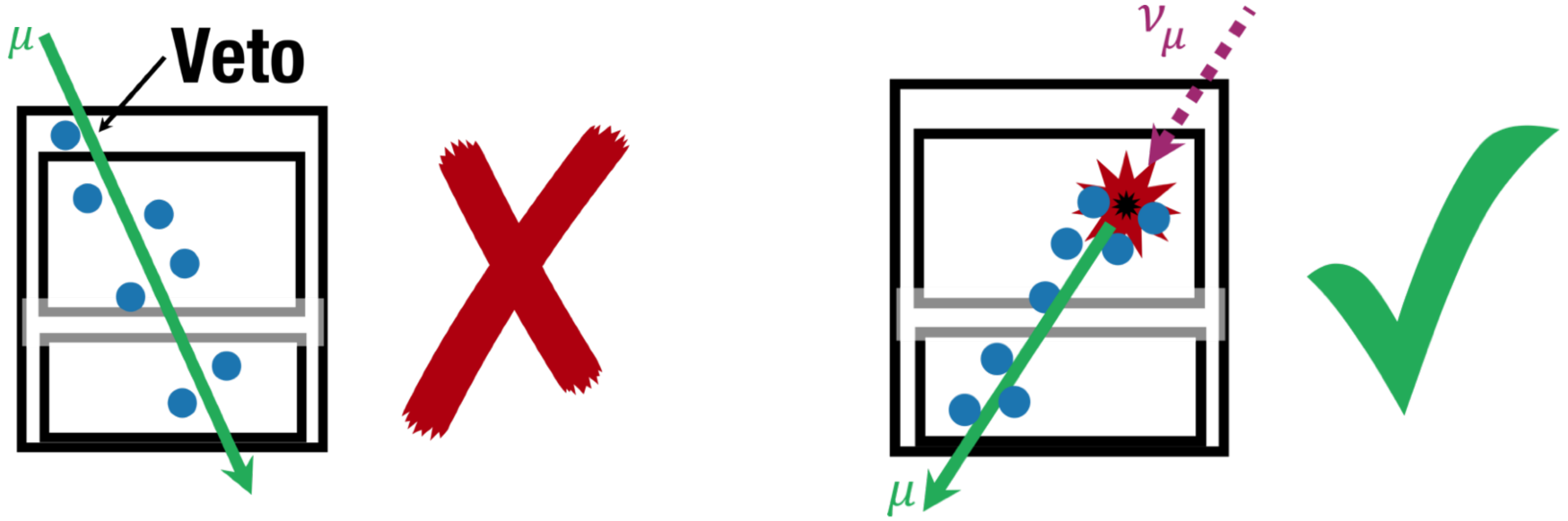


Backgrounds and data sets used

IceCube Medium-Energy Starting Events (MESE) sample

IceCube collaboration 1410.1749



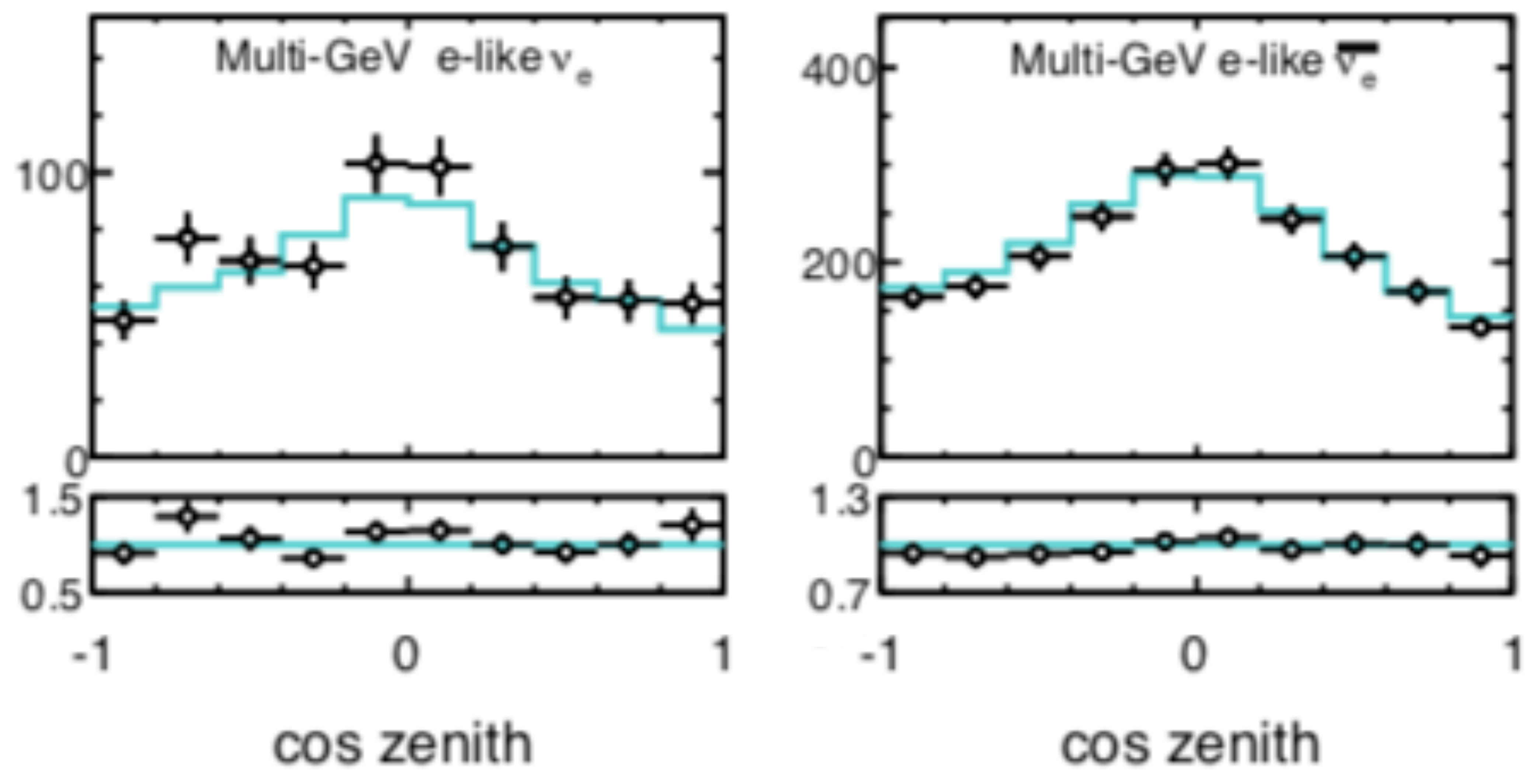


- Selection uses outer part of the detector to remove cosmic-ray muon background.
    - Signal also reduced by muons produced in the same shower triggering the veto. See CA *et al.* arXiv:1805.11003
- Data only available integrated in the Southern sky direction.
- We compare to the reported energy distribution of electromagnetic/hadronic showers.

$$N_i^{\rm IC} = {\rm Br}(A \to e{-}{\rm like}) \int d\cos\theta \int dE_A \; \epsilon_\nu^{\alpha\beta}(E_i, \theta_{\rm rec}; E_A, \theta) \mathcal{P}_{\rm pass}^{{\rm prompt}-\nu_e}(E_A, \theta) \; \frac{dN}{dE_A d\cos\theta}$$

Backgrounds and data sets used

SuperKamiokande I-IV multi-GeV electron-like events



Super-Kamiokande coll. 1710.09126

- Includes the angular distribution, but is integrated in energy.

- We will study LLP producing electromagnetic/hadronic signatures, we assume the efficiency is similar to electron neutrino CC interactions.

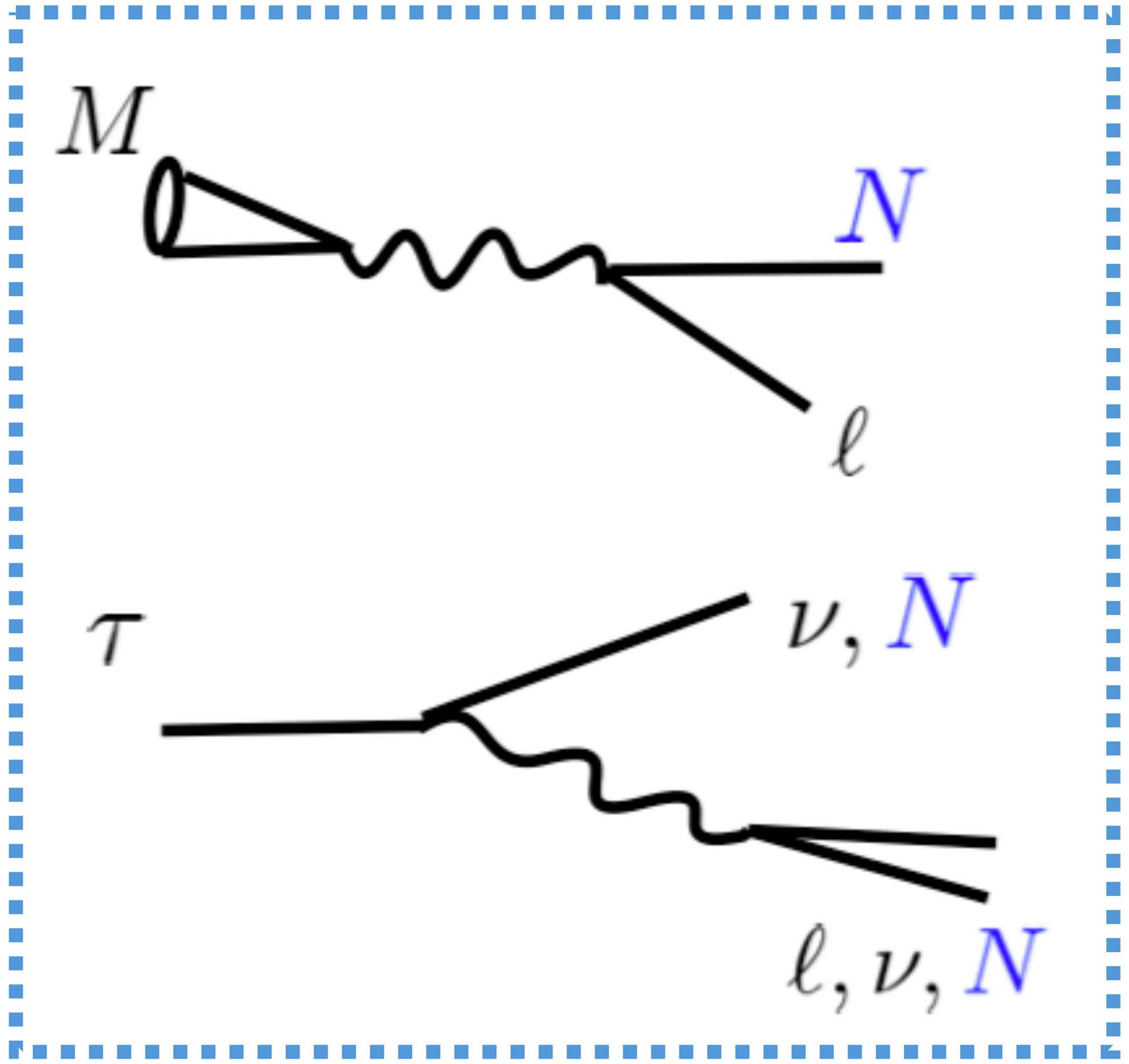
- We compare to the reported angular distribution to derive constraints.

$$N_i^{\rm SK} = {\rm Br}(A, e\text{−like}) \int_{\cos\theta_i^{\rm min}}^{\cos\theta_i^{\rm max}} d\cos\theta \int_{1\ \rm GeV}^{90\ \rm GeV} dE_A \epsilon^{SK} \frac{dN}{dE_A d\cos\theta}$$

Results on HNL

Production and decay

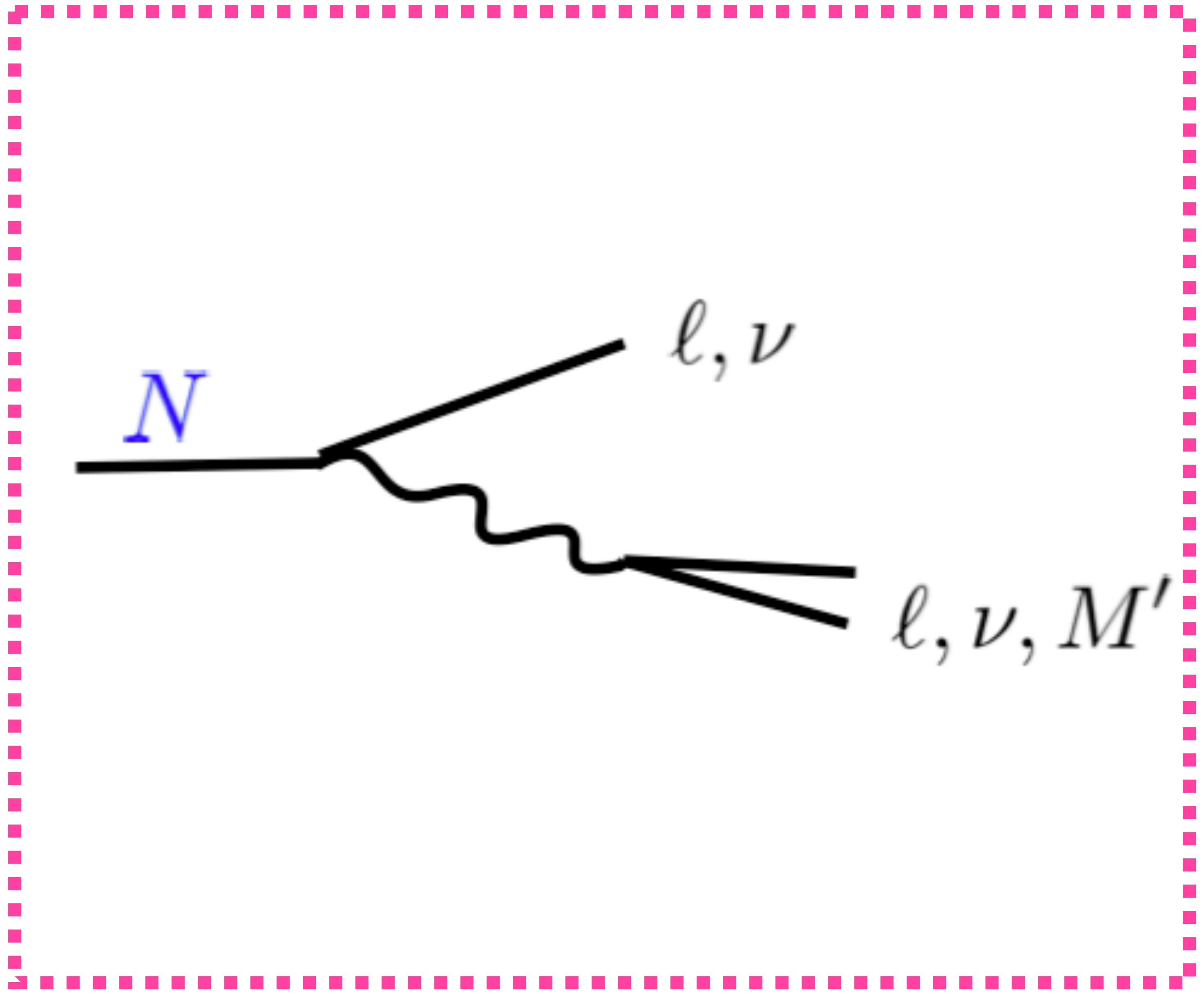
production



$BR(P \to N)$

$+$

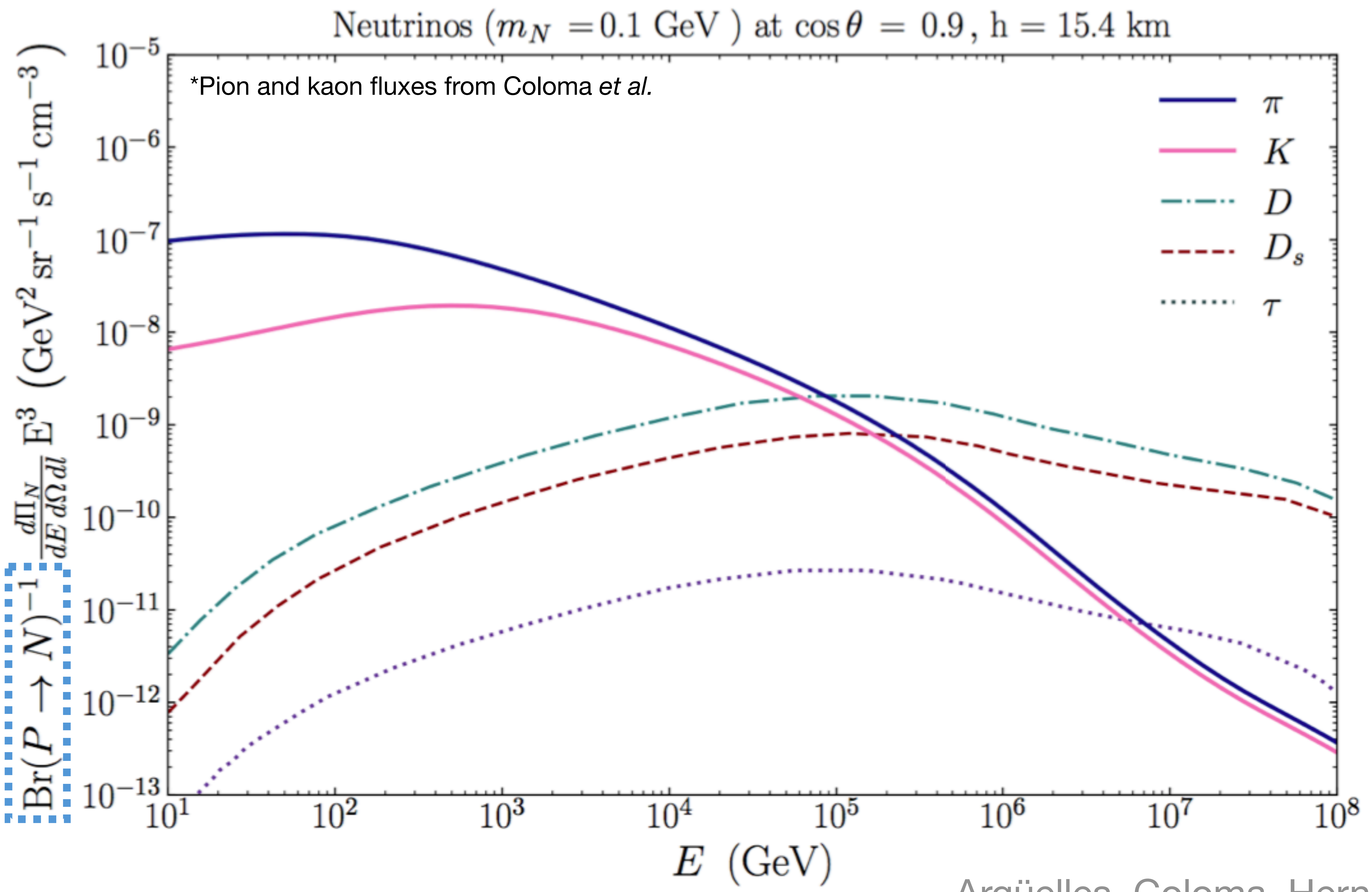
detection



$BR(CC\ e - like)$

Results on HNL

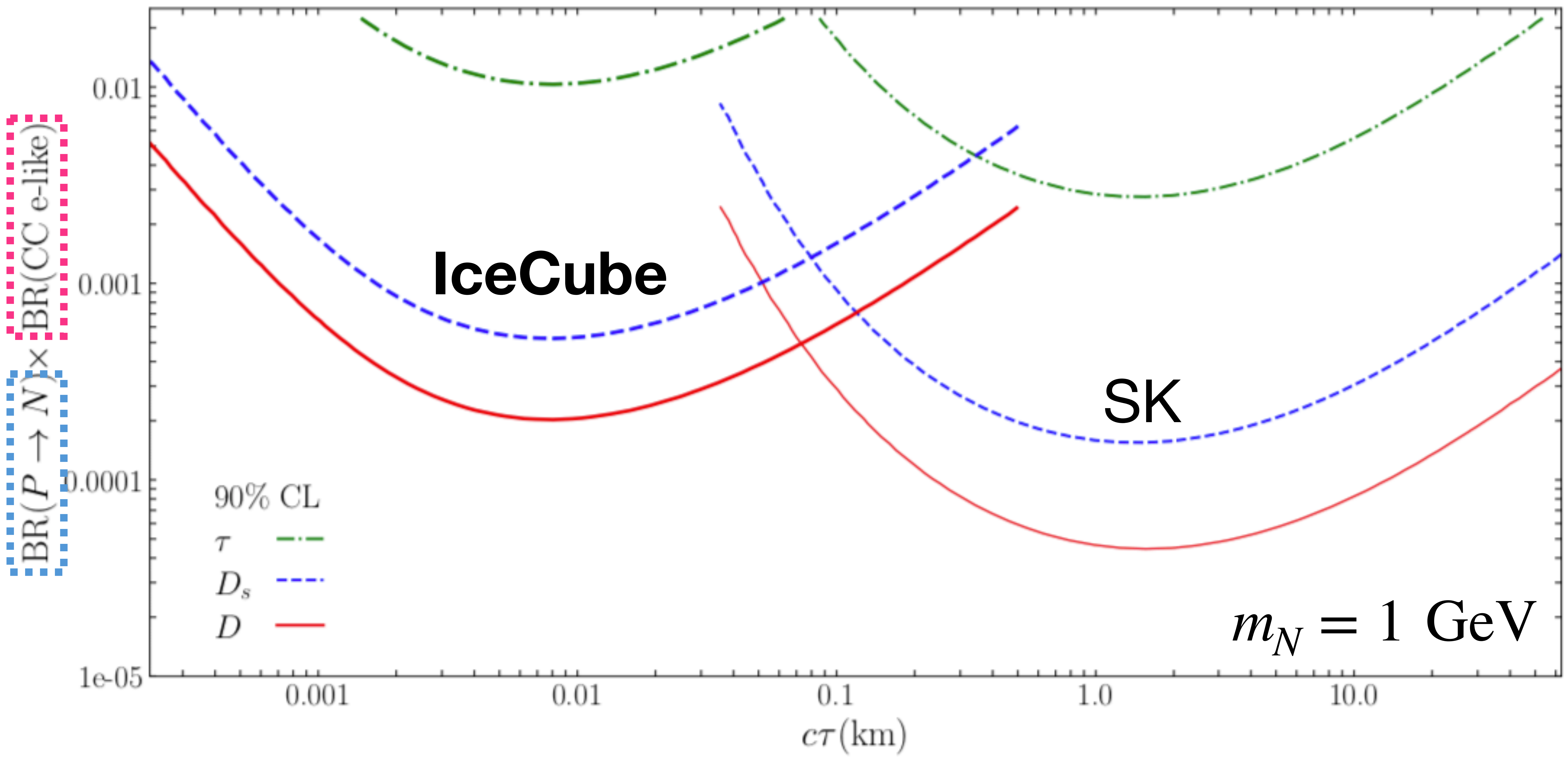
Flux of HNL from the cosmic-ray air showers



Argüelles, Coloma, Hernandez, Muñoz, 1910.12839
Coloma, Hernandez, Muñoz, Shoemaker, 1911.09129

Results on HNL

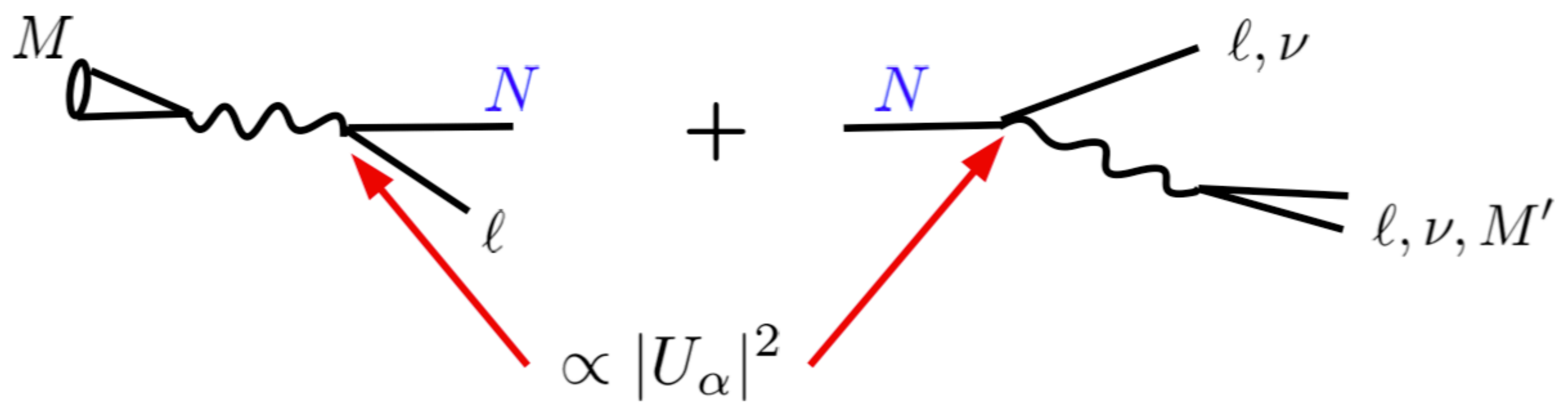
Model independent constraints



Because the shower development height is O(10km), best sensitivity lifetimes of O(10km) in lab frame: translates to two different lifetimes for SK (GeV) and IceCube (TeV).

Results on HNL

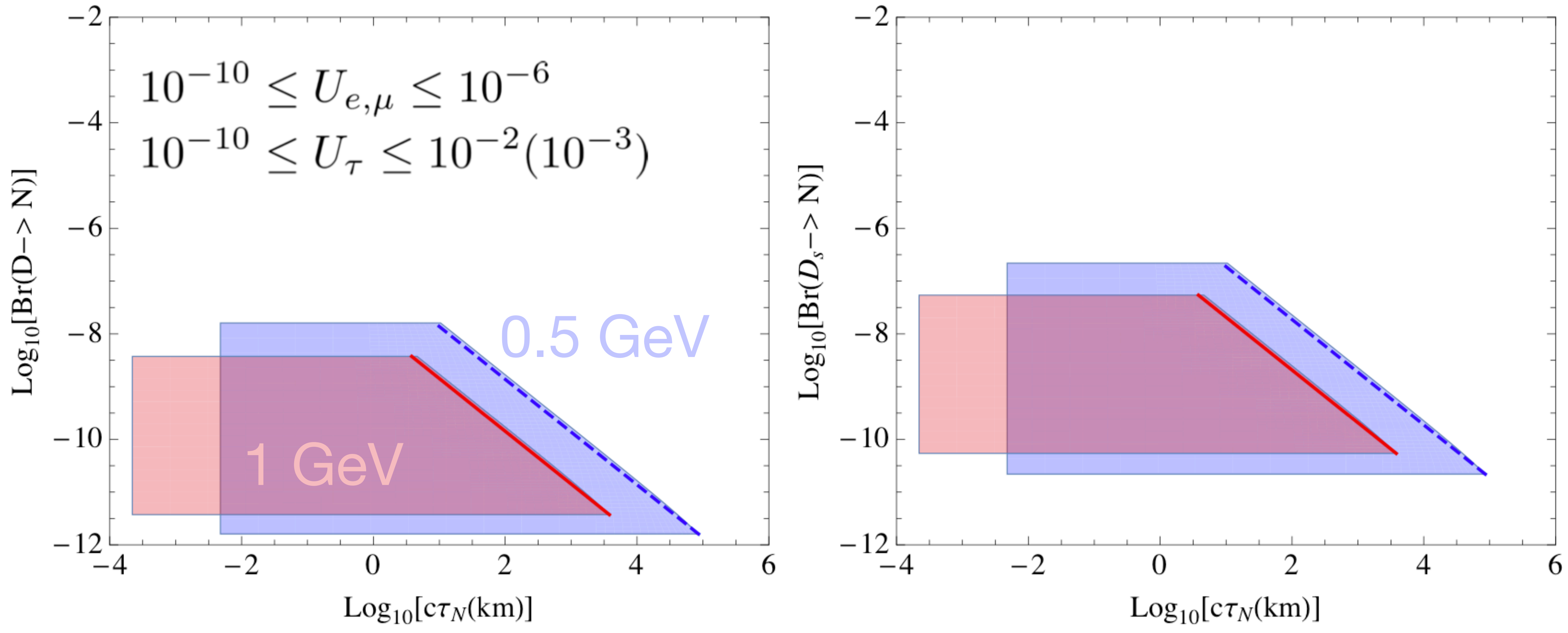
In a minimal scenario: are these bounds competitive?



$$\mathcal{L}_N = \mathcal{L}_{SM} + \sum_j i\bar{N}_j \gamma^\mu \partial_\mu N_j - \left(Y_{\alpha j} \bar{L}_\alpha \tilde{\Phi} N_j + \frac{m_{N_j}}{2} \bar{N}_j N_j^c \right)$$

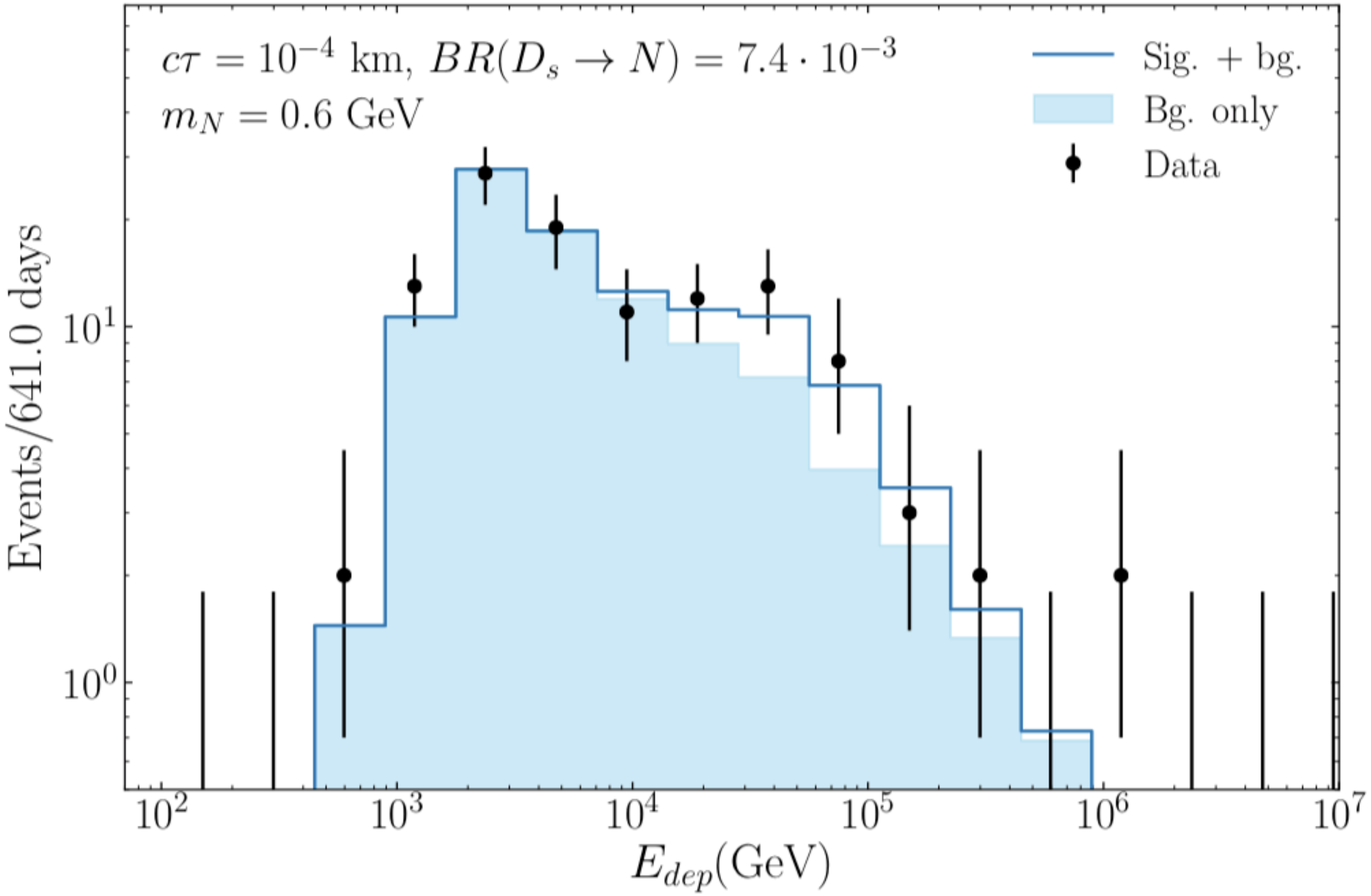
In a minimal scenario production and detection are correlated.

Allowed regions have much branchings than reached sensitivities



Results on HNL

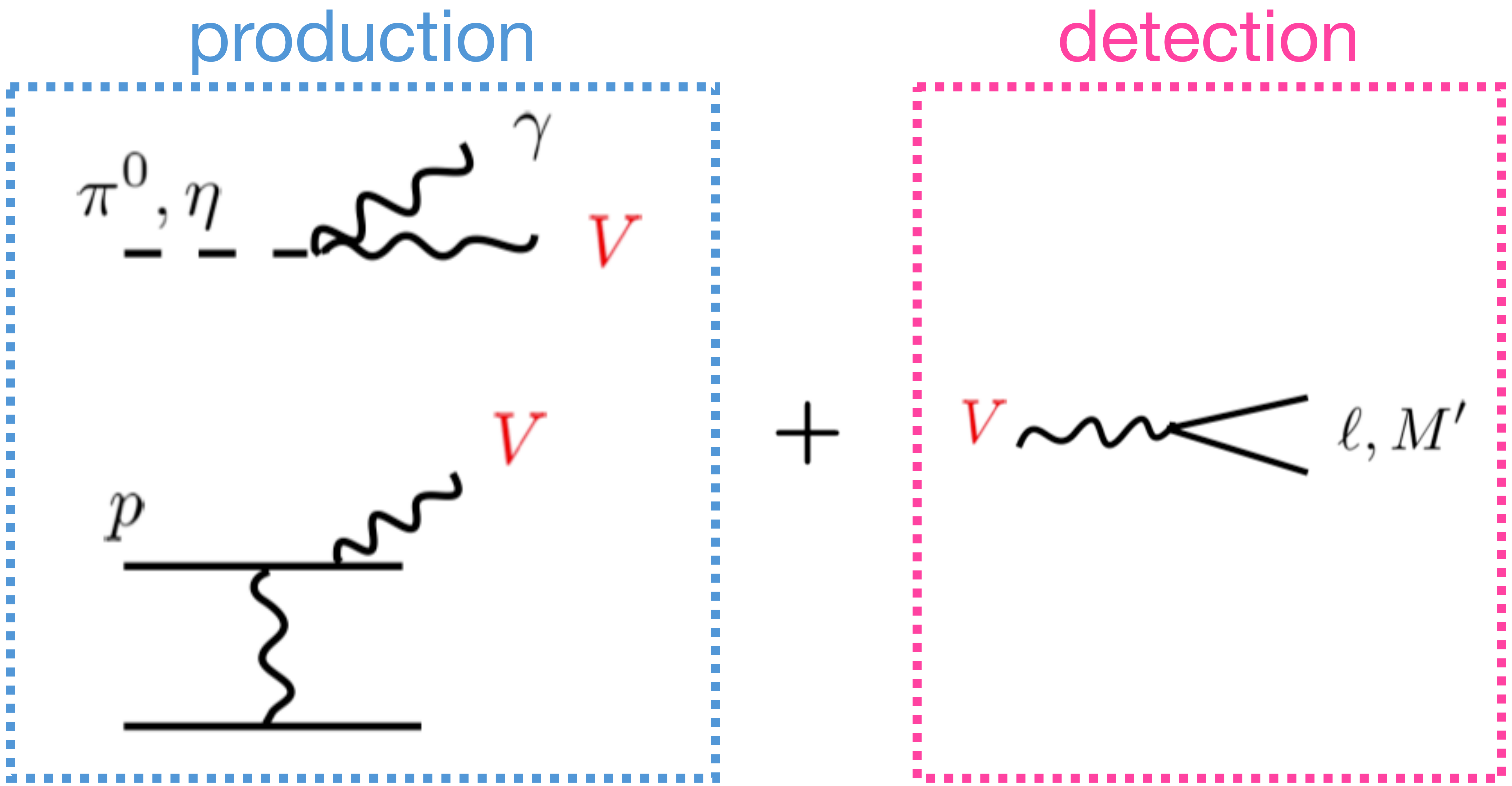
Though, there is something *interesting* in the data …



- In the simplest NHL model the "MESE" bump can't be explained.
- If production and detection mechanisms are uncorrelated, the energy distribution fit can be improved ($\Delta\chi^2 = 7(3dof)$).
- This significance can decrease or increase once: 1) add more data, 2) look at the angular distribution (not public).

Results on dark photons

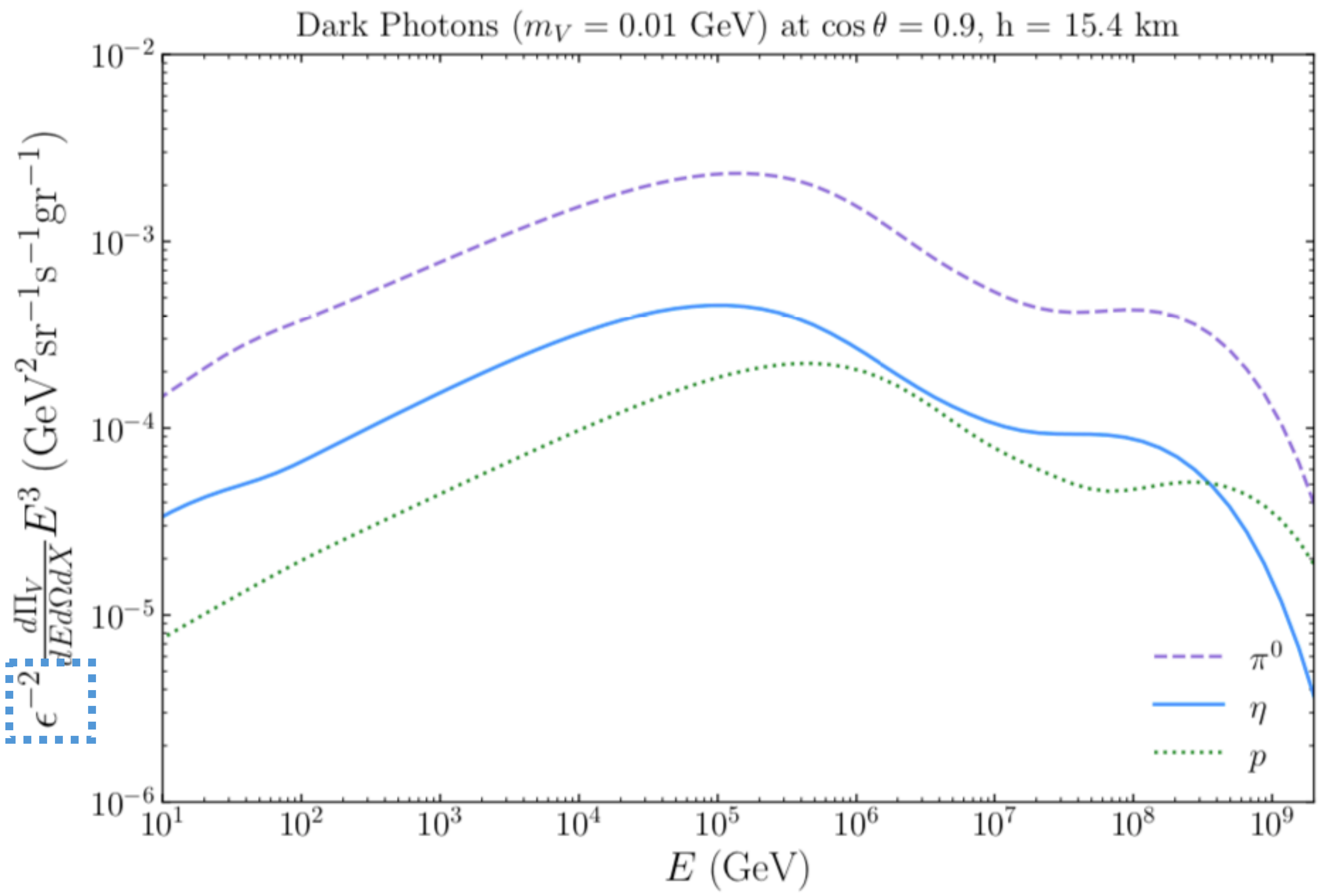
Production and detection produced by kinetic mixing



$$\mathcal{L}_V = \mathcal{L}_{SM} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu$$

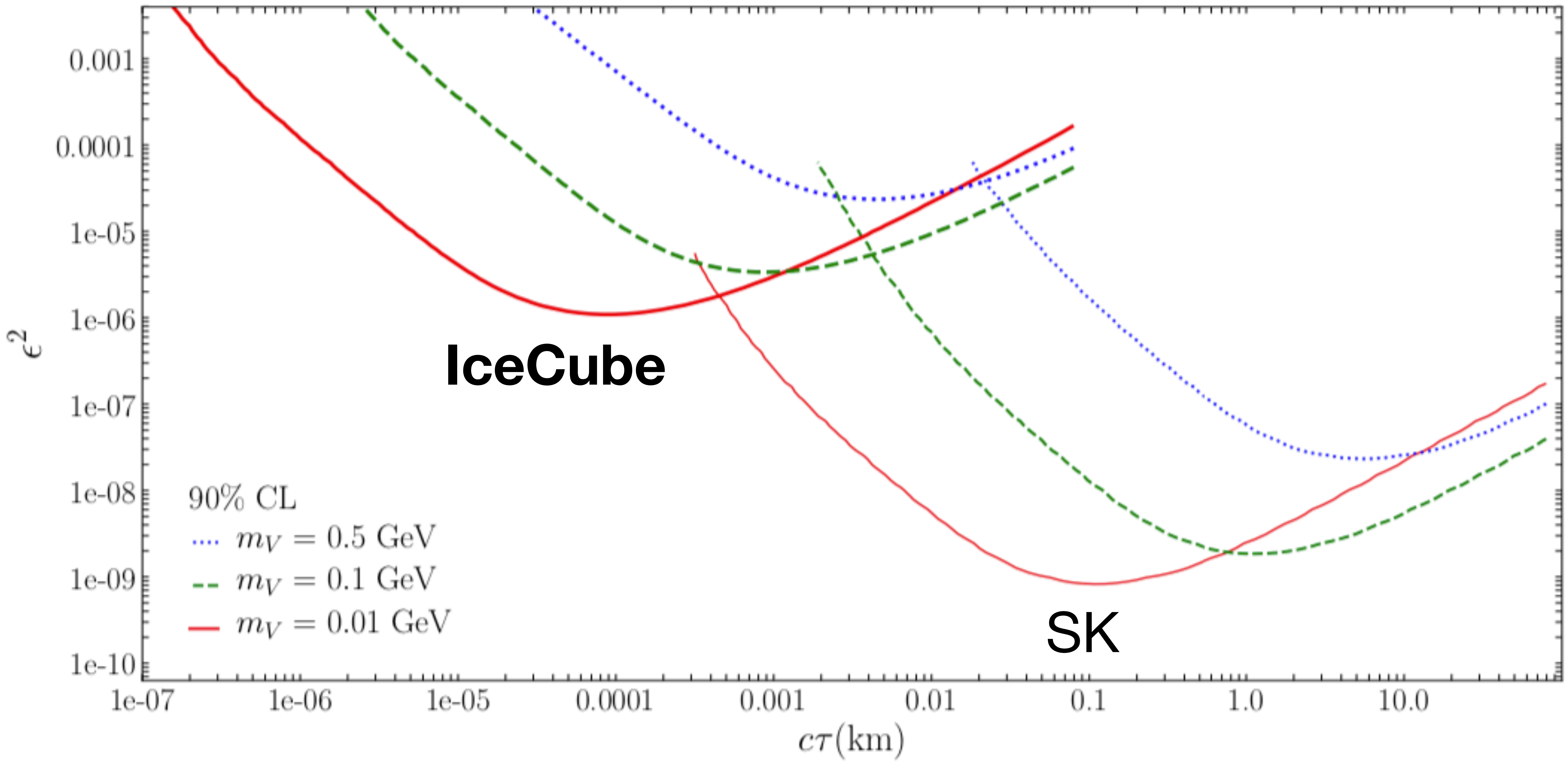
Results on dark photons

Dark photon fluxes in the atmosphere



Results on dark photons

“Model independent” constraints

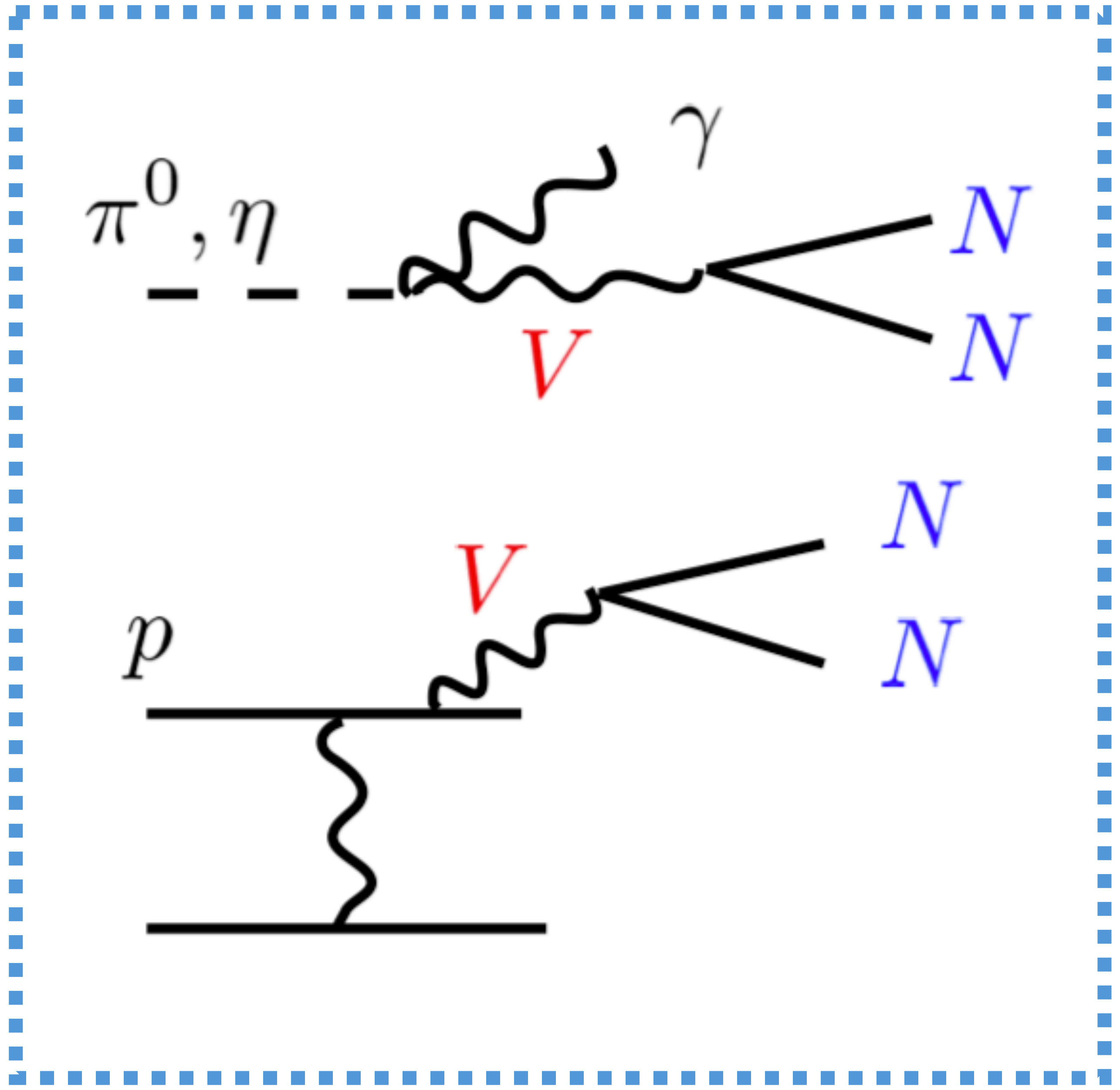


IC results are much weaker than SK compared to the NHL case, due to the steeper light meson atmospheric flux.

Results on dark photons

Production and detection in a B-L model

production



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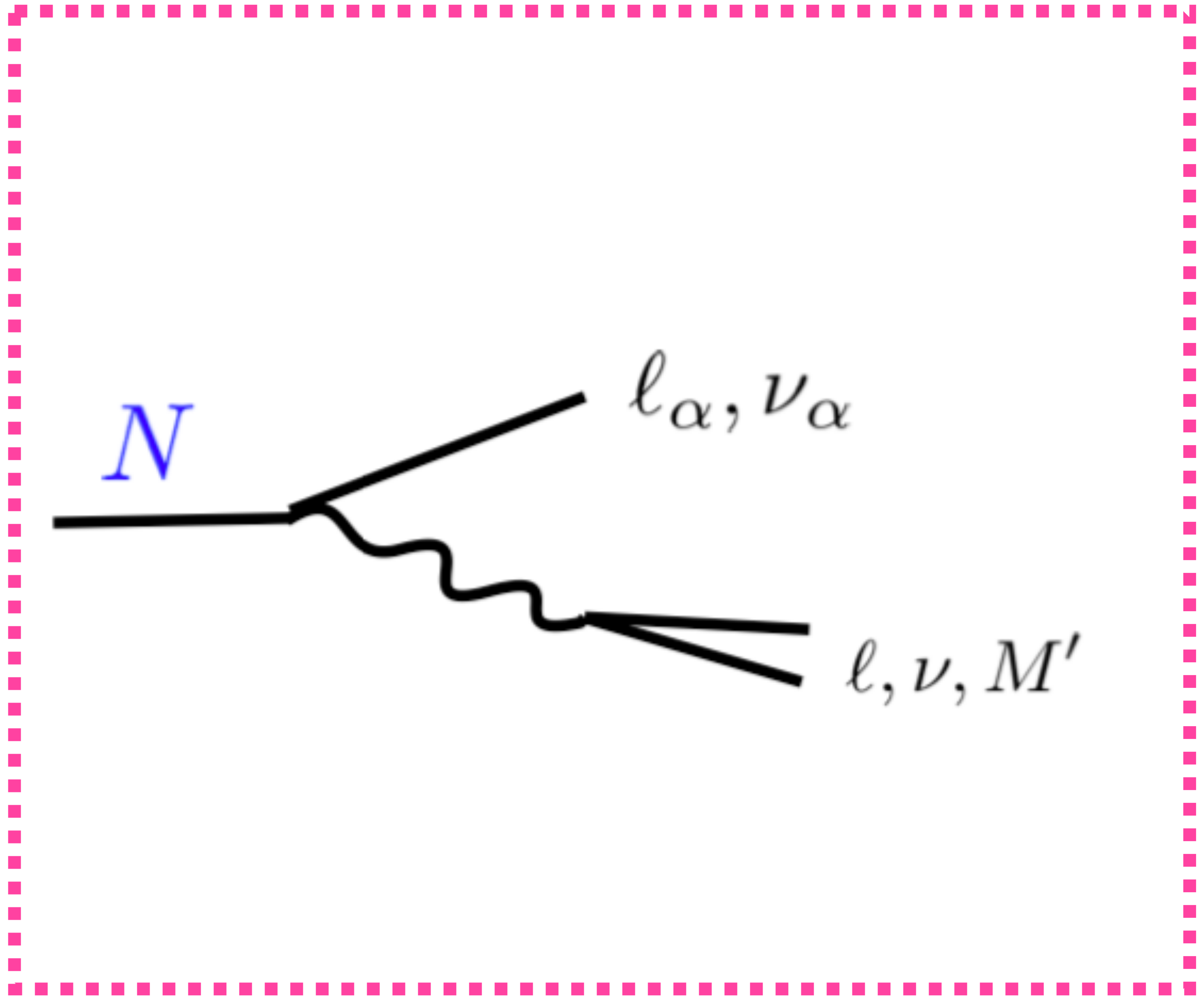
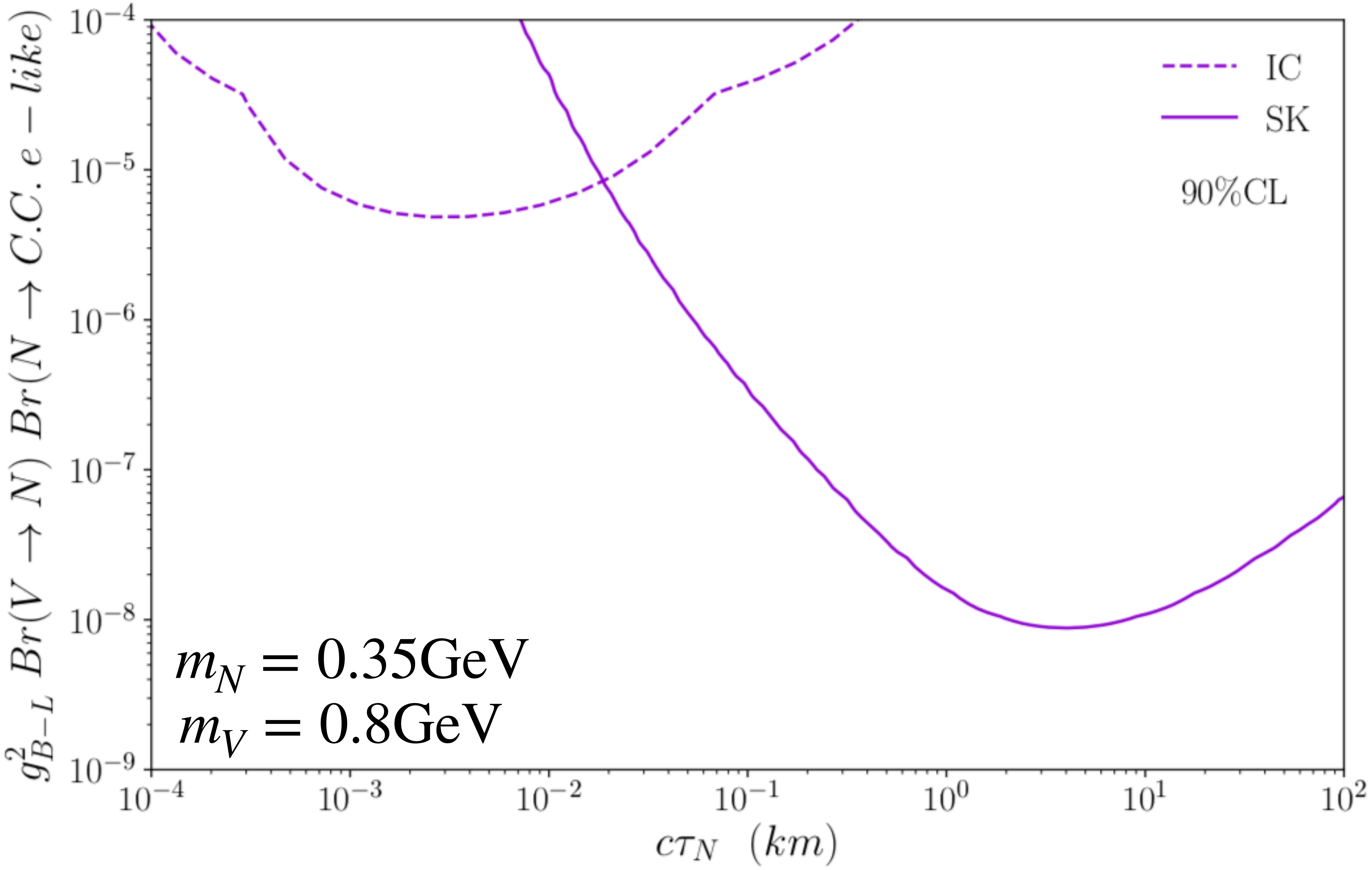
detection



$$\mathcal{L} = \mathcal{L}_N - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu + g_{\mathrm{B-L}}\left(\sum_f Q^f_{B-L}\overline{f}\gamma^\mu f V_\mu - \overline{N}\gamma^\mu N V_\mu\right)$$

Results on dark photons

Constraints for a B-L model

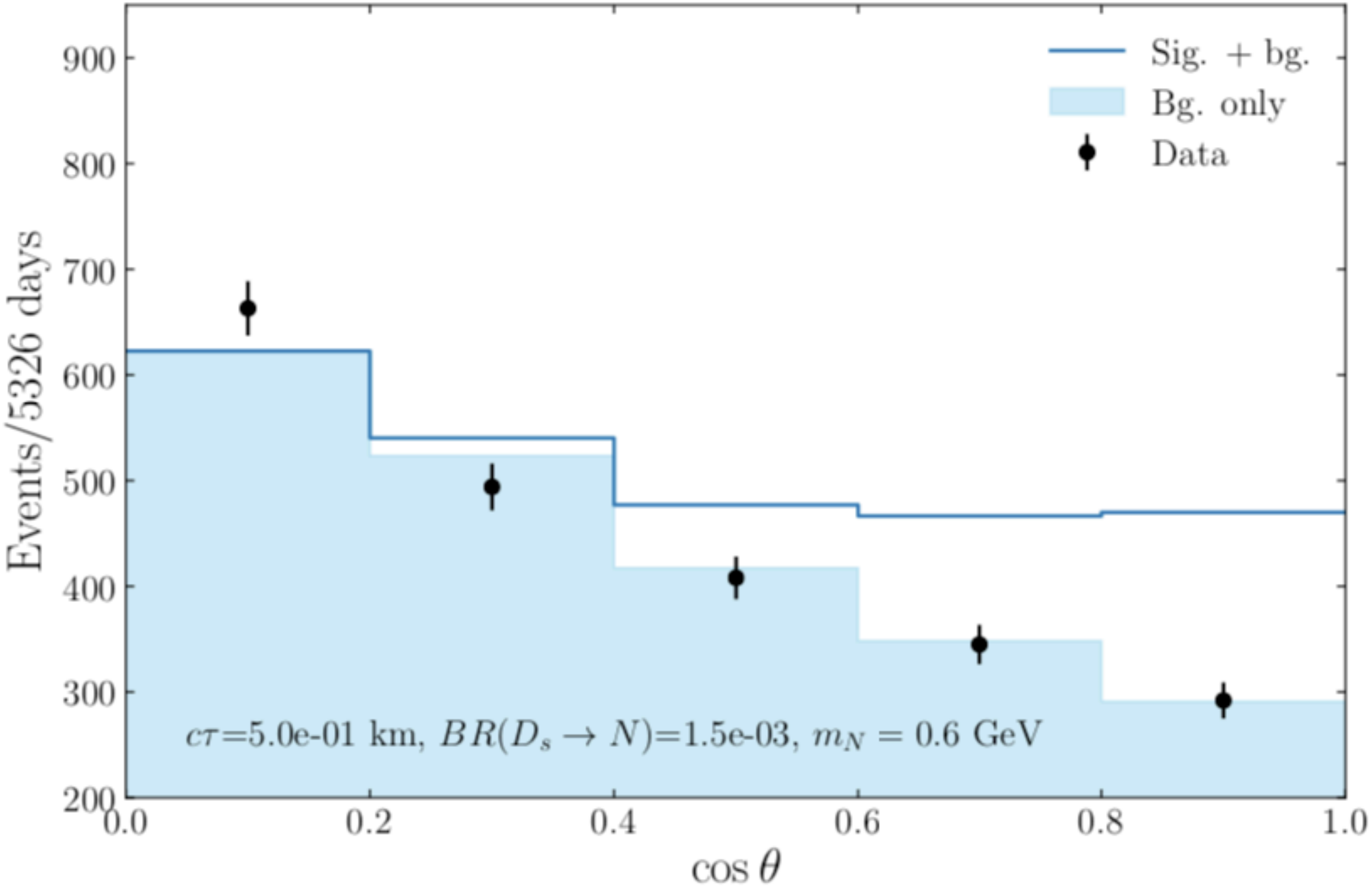


Conclusions and take-home message

- Very large volume neutrino detectors are capable of searching for signatures of long-lived particles produced in cosmic-ray air showers.
- We use public data from SuperKamiokande and IceCube to search for long-lived particles.
    - We study three different scenarios: NHL, dark photons, and a B-L model. Constraints for minimal scenarios are not competitive.
    - We present our constraints in terms of branching and lifetime so they can be reinterpreted in non-minimal scenarios.
    - The MESE “bump” can be accommodated in a non-minimal scenario.
    - Analyses can be improved by using both the energy and angular information; we only used projections.
- See also Coloma, Hernández, Muñoz, Shoemaker 1911.09129 for discussion of lower mass HNL.

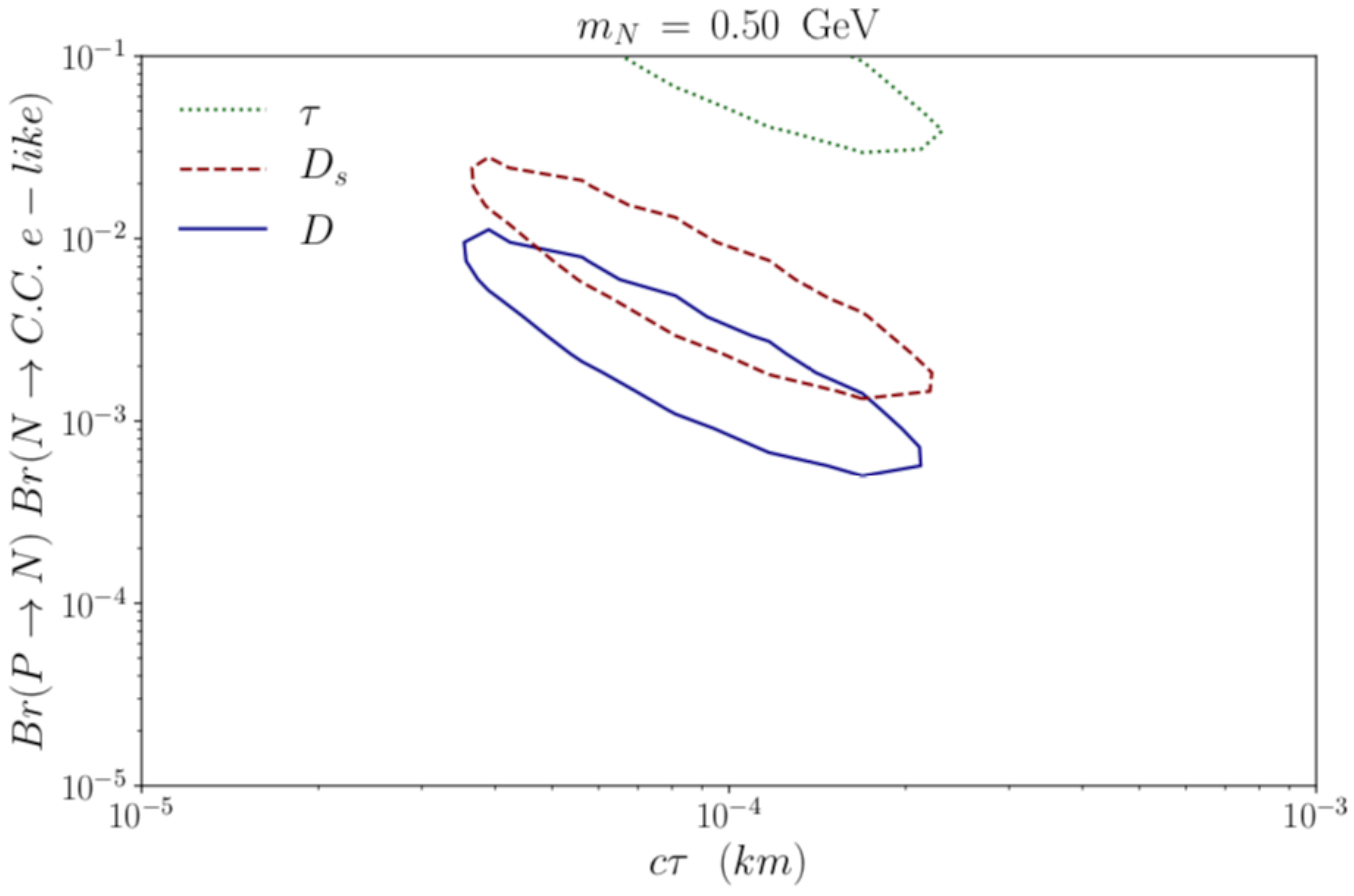
Bonus slides

Example of signal on the SK sample

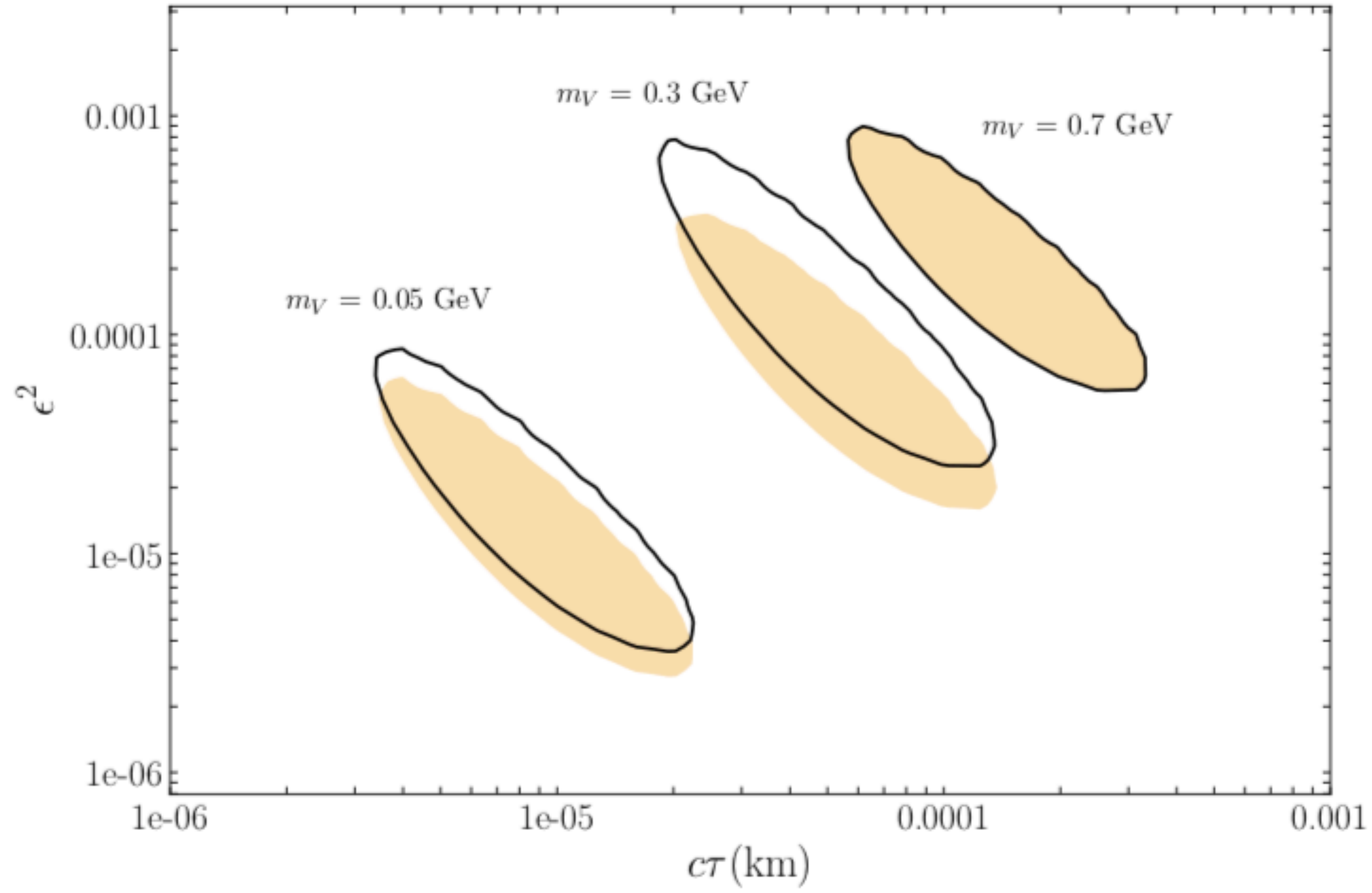


IceCube MESE favored regions

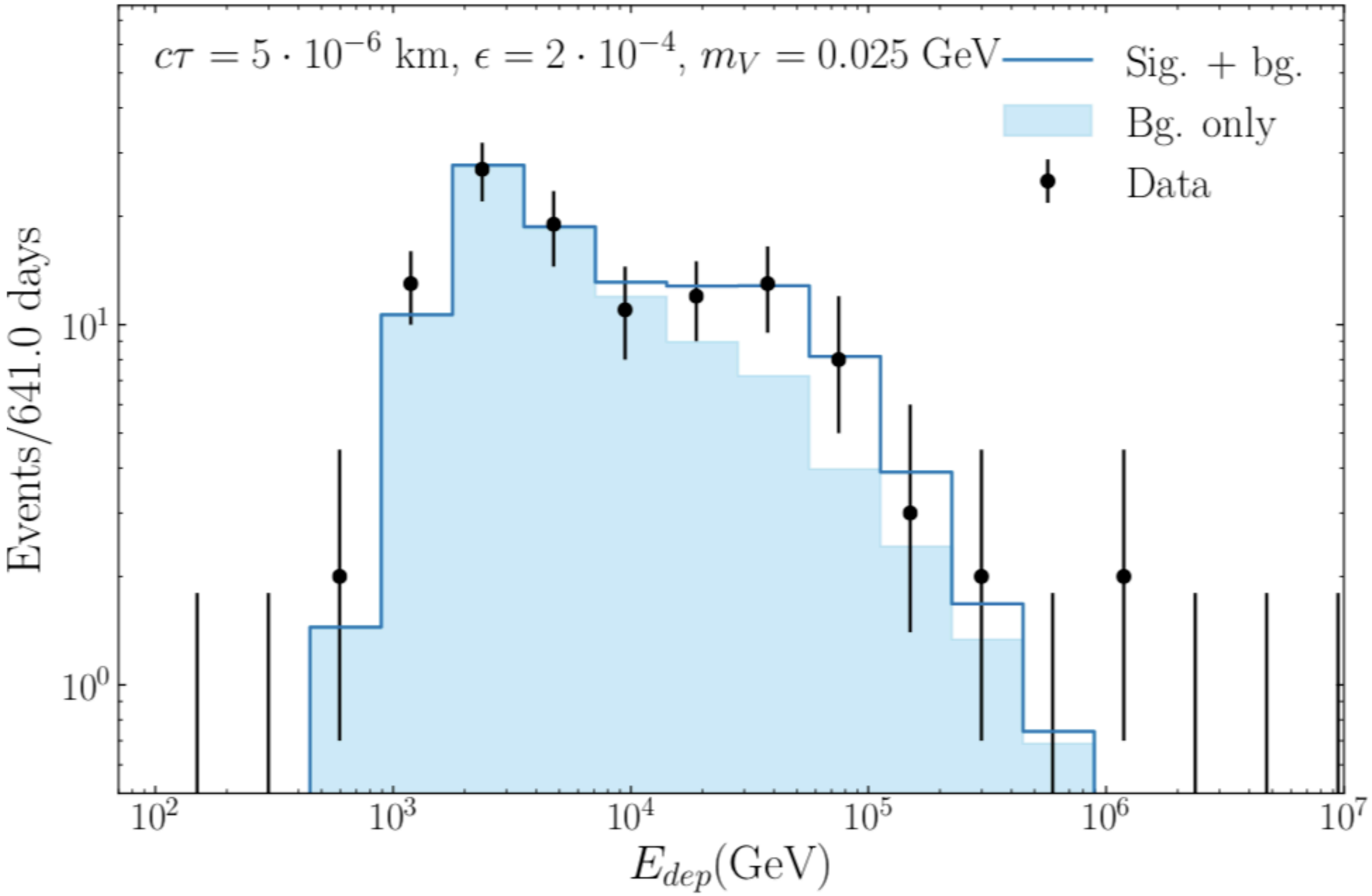
NHL



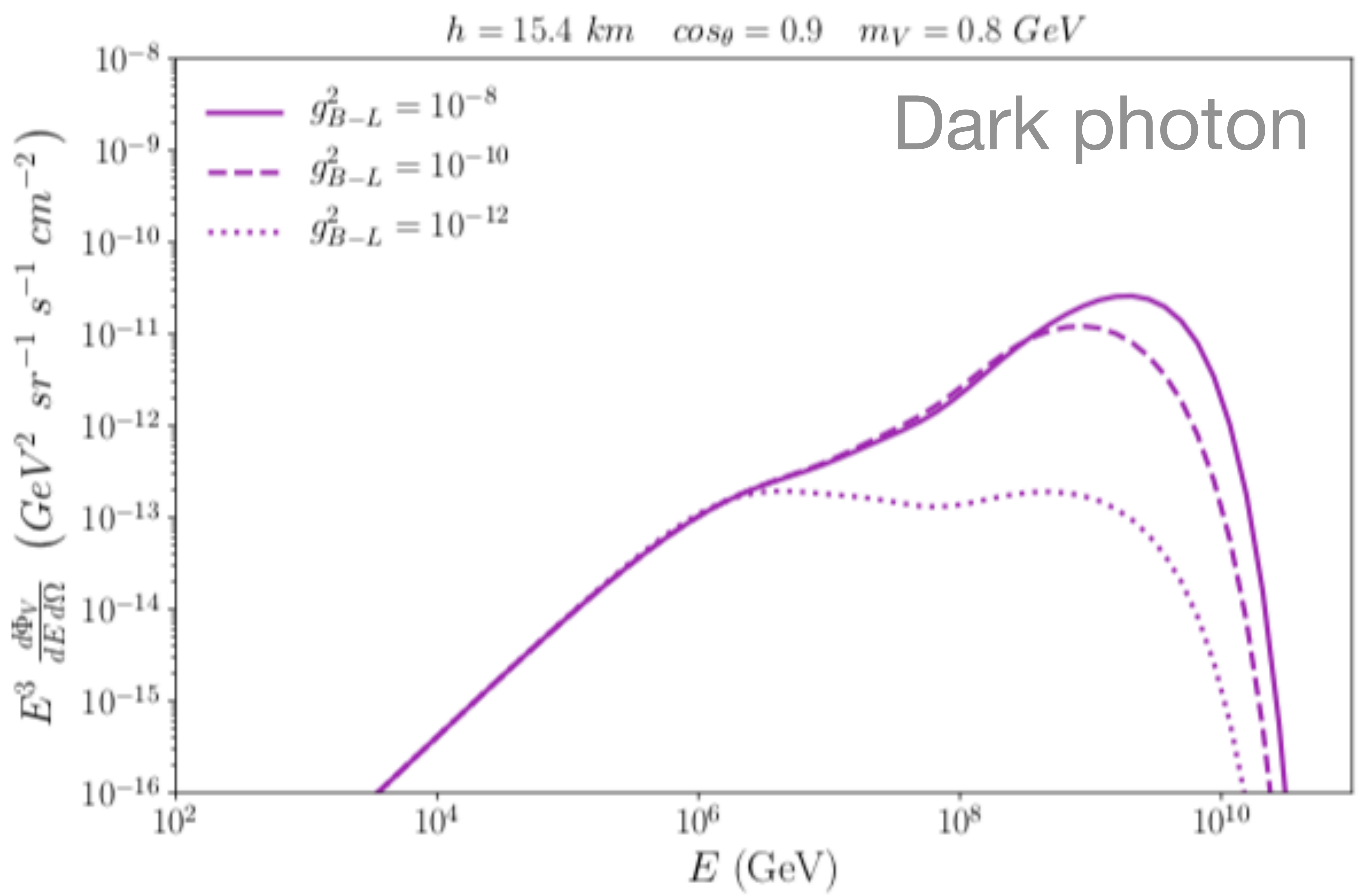
Dark Photon

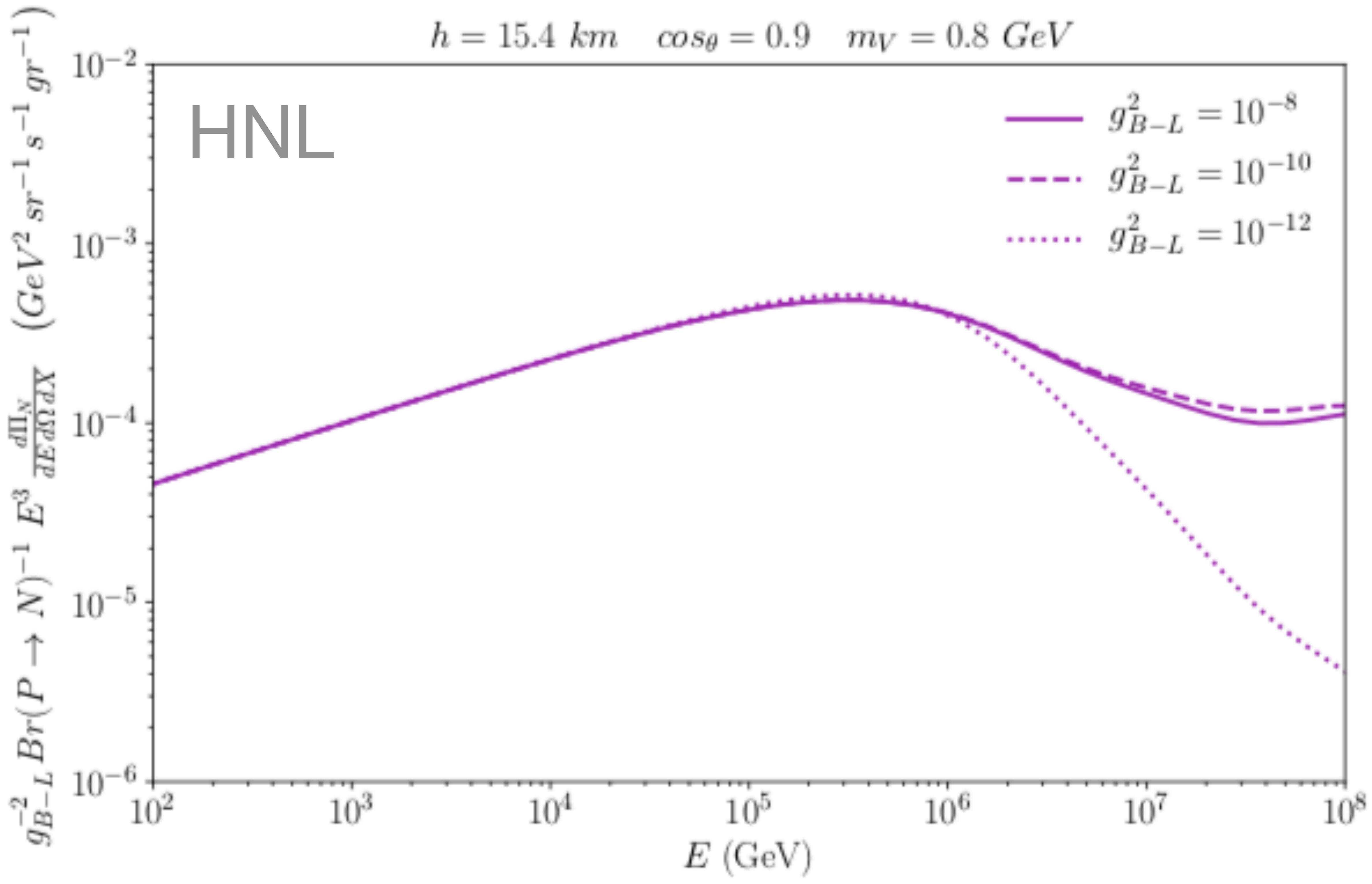


MESE “bump” fitted with the dark photon scenario



B-L atmospheric fluxes





For small couplings the dark photon is also long-lived leading to a compound decay process.