Constraining ν-DM Interactions: Updated Laboratory Limits

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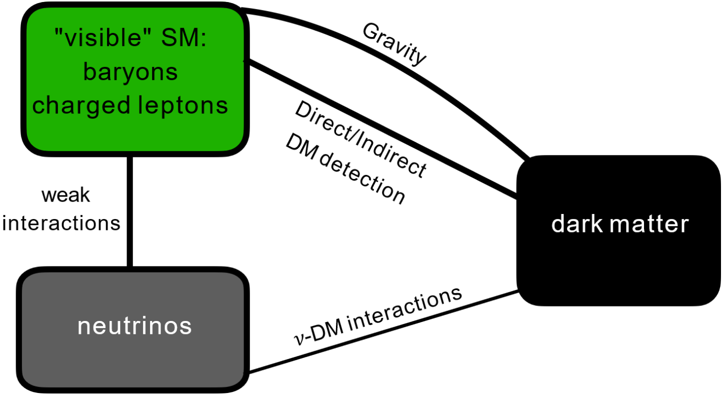
based on

with Bhupal Dev, Doojin Kim, Deepak Sathyan, Kuver Sinha, 2407.12738 & 2410.abcde

Connecting two mostly unknown sectors



"visible" SM:
baryons
charged leptons

weak
interactions

neutrinos

Gravity

Direct/Indirect
DM detection

ν-DM interactions

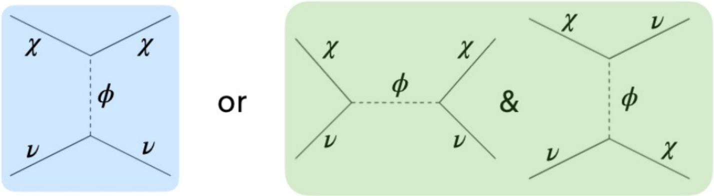
dark matter

Modeling ν-DM interactions

Olivares-Del Campo, Boehm, Palomares-Ruiz & Pascoli '17;

Blennow, Fernandez-Martinez, Olivares-Del Campo, Pascoli, Rosauro-Alcaraz & Titov '19

- Simplified EFT approach.
- Categorizing models into DM and mediator types:
  scalar, fermion, vector.
- t-channel or $s\&u$ (s/u) channel ν-DM scattering, depending on the DM&mediator types.



Only 4 or 3 parameters: DM & mediator masses, coupling(s)

(light) scalar mediators: examples

- Majoron J coupling $J\bar{\nu}i\gamma_5\nu$. Chikashige, Mohapatra & Peccei '81; Gelmini & Roncadelli '81; Schechter & Valle '82
- Mediator-ν-DM coupling $\phi\bar{\chi}\nu$. Boehm & Fayet '04; Barranco, Miranda, Moura, Rashba & Rossi-Torres '11; Farzan, Pascoli & Schmidt '13; Olivares-Del Campo, Boehm, Palomares-Ruiz & Pascoli '18; Ghosh, Khatri & Roy '18; Hagedorn, Herrero-Garcia, Molinaro & Schmidt '18; Hufnagel & Xu '22; Alvarado, Bonilla, Leite & Valle '21; Herms, Jana, K. & Saad '23; Dev, Kim, Sathyan, Sinha & YCZ '24; Bischer, Rodejohann & Xu '18; Herrera & Shoemaker '24;

Relevant to neutrino nonstandard interactions (NSIs)

- Probing neutrino self-interactions via mediators Berryman et al '23
- Probing neutrino interactions with DM via mediators Blennow, Fernandez-Martinez, Olivares-Del Campo, Pascoli, Rosauro-Alcaraz & Titov '19

Limits on ϕ

- low-energy experiments Pasquini & Peres '16; Berryman, De Gouvêa, Kelly & Zhang '18; Kelly & Zhang '19; Brdar, Lindner, Vogl & Xu '20
- high-energy colliders de Gouvêa, Dev, Dutta, Ghosh, Han & YCZ '20; Dev, Dutta, Ghosh, Han, Qin & YCZ '22; Agashe, Airen, Franceschini, Kim, Kotwal, Ricci & Sathyan '24
- astrophysical effects Ng & Beacom '14; Shoemaker & Murase '16; Heurtier & YCZ '17; Das, Dighe & Sen '17; Kelly & Machado '18; Bustamante, Rosenstrom, Shalgar & Tamborra '20; Esteban, Pandey, Brdar & Beacom '21
- cosmological observables Cyr-Racine & K. Sigurdson '14; Archidiacono & Hannestad '14; Huang, Ohlsson & Zhou '18; Barenboim, Denton & Oldengott '19; Blinov, Kelly, Krnjaic & McDermott '19; Lyu, Stamou & Wang '21; Das & Ghosh '21

Simplest case: $\phi\nu\bar{\nu}$

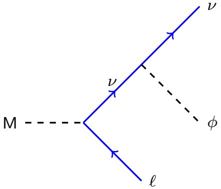
- We study the generic coupling of ϕ with neutrinos in the form of

$$\mathcal{L} = g_\nu \phi \bar{\nu} \nu \, .$$

- Assuming g_ν is flavor-conserving and universal.
- There are some ultraviolet (UV) completions of such effective coupling. Berryman, De Gouvêa, Kelly & Zhang '18; Kelly & Zhang '19; de Gouvêa, Dev, Dutta, Ghosh, Han & YCZ '20

Meson decay $\mathrm{M}^{\pm} \to \ell^{\pm} + \nu + \phi$

Gelmini, Nussinov & Roncadelli '82; Barger, Keung & Pakvasa '82; Glashow & Manohar '85



- Partial width $\Gamma(\mathrm{M}^{\pm} \to \ell^{\pm} + \nu + \phi)$

$$\Gamma^{\rm tree} \simeq \frac{G_F^2 m_{\rm M}^3 f_{\rm M}^2 |V|^2 g_\nu^2}{128\pi^3} \left[-x_{\ell \rm M}(1-x_{\ell \rm M})^2 \log x_{\phi \rm M} + C_2(x_{\ell \rm M}) \right] ,$$

$$C_2(x_2) \simeq -x_2(1+2x_2-x_2^2){\rm arctanh}\frac{1-x_2}{1+x_2} + \frac{1}{6}(1-x_2)\left[2 - 4x_2(4-5x_2) - 3x_2(1-x_2)\frac{x_2}{(1-x_2)^4}\right] .$$

- $\Gamma^{\rm tree}$ has Infrared (IR) divergence $\Longleftarrow$ the term of $x_{\phi \rm M} \equiv m_\phi^2 / m_{\rm M}^2$!

IR divergence & cancellation in QED

Bloch & Nordsieck '37; Schwartz, Quantum Field Theory and the Standard Model '14

- The process $e^+e^- \to \mu^+\mu^-\gamma$, with $\sigma_0(e^+e^- \to \mu^+\mu^-) = e^4/12\pi s$

$$\sigma_{\rm tree} = \frac{e^2}{8\pi^2}\sigma_0 \left[5 - \frac{\pi^2}{3} + 3\log\frac{m_\gamma^2}{s} + \log^2\frac{m_\gamma^2}{s}\right]$$

- The 1-loop (vertex) correction with photon (after removing the UV divergence):

$$\sigma_{\rm loop} = -\frac{e^2}{8\pi^2}\sigma_0 \left[\frac{7}{2} - \frac{\pi^2}{3} + 3\log\frac{m_\gamma^2}{s} + \log^2\frac{m_\gamma^2}{s}\right]$$

- The total cross section for $e^+e^- \to \mu^+\mu^-(\gamma)$:

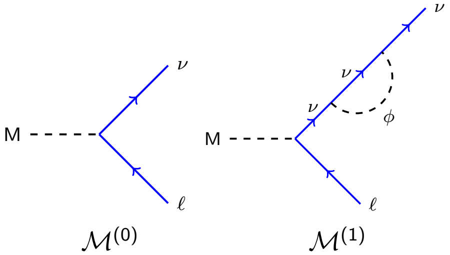
$$\sigma_{\rm tot} = \sigma_0 \left[1 + \frac{3e^2}{16\pi^2}\right] \quad \text{finite!!!}$$

  The IR divergences are cancelled out!

- More general discussions: **Kinoshita-Lee-Nauenberg (KLN) theorem**.

  Kinoshita '62; Lee & Nauenberg '64

Meson decay: 1-loop contribution



- 1-loop contribution is from the interference term of $\mathcal{M}^{(0)}$ & $\mathcal{M}^{(1)}$.
- 1-loop contribution is at the same order of g_ν as the tree-level process:

$$\mathrm{Re}\left[\mathcal{M}^{(0)*}(g_\nu^0)\mathcal{M}^{(1)}(g_\nu^2)\right] \propto g_\nu^2 \,.$$

- 1-loop contribution to $\Gamma(\mathrm{M}^\pm \to \ell^\pm + \nu)$:

$$\Delta\Gamma^{\rm loop} = -\frac{g_\nu^2 G_F^2 m_{\rm M} m_\ell^2 f_{\rm M}^2 |V|^2}{128\pi^3} (1 - x_{\ell \rm M})^2 \left[\frac{5}{2} - \log \frac{x_{\phi \rm M}(1 - x_{\ell \rm M})^2}{16\pi^2}\right] \,.$$

IR divergence cancellation

- IR divergence cancellation in decay $\mathsf{M}^\pm \to \ell^\pm\nu(\phi)$:

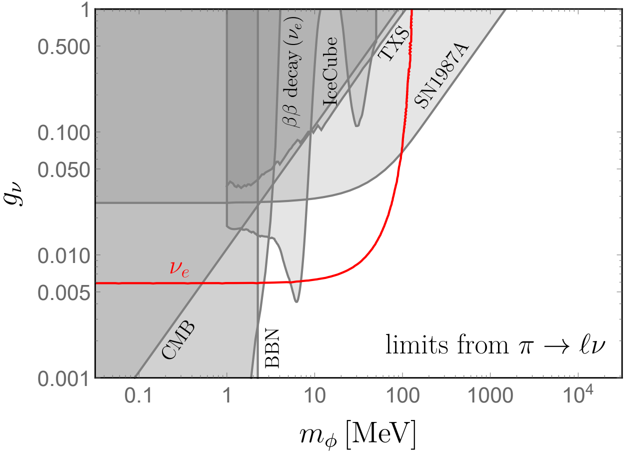
$$\propto \underbrace{-x_{\ell\mathsf{M}}(1-x_{\ell\mathsf{M}})^2 \log x_{\phi\mathsf{M}}}_{\text{tree } \mathsf{M}\to\ell\nu\phi} + \underbrace{x_{\ell\mathsf{M}}(1-x_{\ell\mathsf{M}})^2 \log x_{\phi\mathsf{M}}}_{\text{loop } \mathsf{M}\to\ell\nu} = 0\,.$$

- Dependence of IR divergence (IRD) on charged lepton mass:

$$\begin{aligned} \text{IRD} &\propto -x_{\ell\mathsf{M}}(1-x_{\ell\mathsf{M}})^2 \log x_{\phi\mathsf{M}} \\ &= \frac{m_\ell^2}{m_{\mathsf{M}}^2}\left(1-\frac{m_\ell^2}{m_{\mathsf{M}}^2}\right)^2 \log\frac{m_\phi^2}{m_{\mathsf{M}}^2} \end{aligned}$$

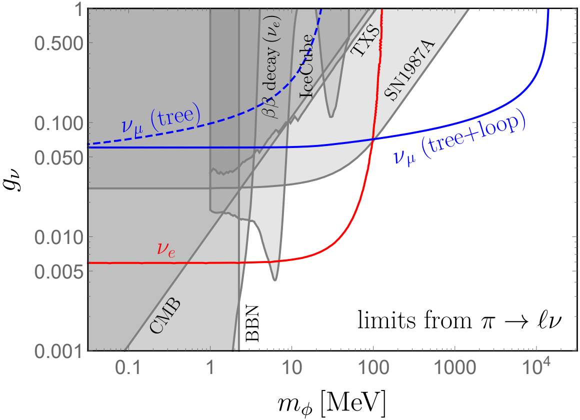
Limits on $\pi^\pm \to e^\pm + \nu + \phi$

- For $\pi^\pm \to e^\pm + \nu + \phi$, IRD is heavily suppressed by m_e^2/m_π^2, thus not important.
  Red line is (almost) flat when $m_\phi \to 0$.
- Current limits from 2203.01955.



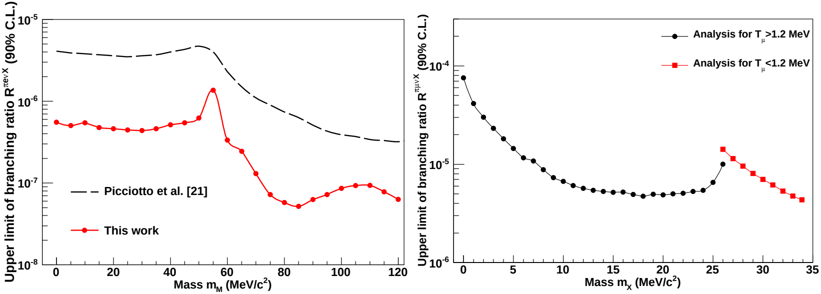
Limits on $\pi^\pm \to \mu^\pm + \nu + \phi$

- For $\pi^\pm \to \mu^\pm + \nu + \phi$, $m_\mu \sim m_\pi$, IRD is important & has to be cancelled. Solid blue line is flat when $m_\phi \to 0$.
- $\pi^\pm \to \mu^\pm + \nu + \phi$ is kinematically forbidden for $m_\phi > m_\pi$. Loop contribution $\pi^\pm \to \mu^\pm + \nu$ exists for $m_\phi > m_\pi$. Solid blue line extends far beyond m_π.



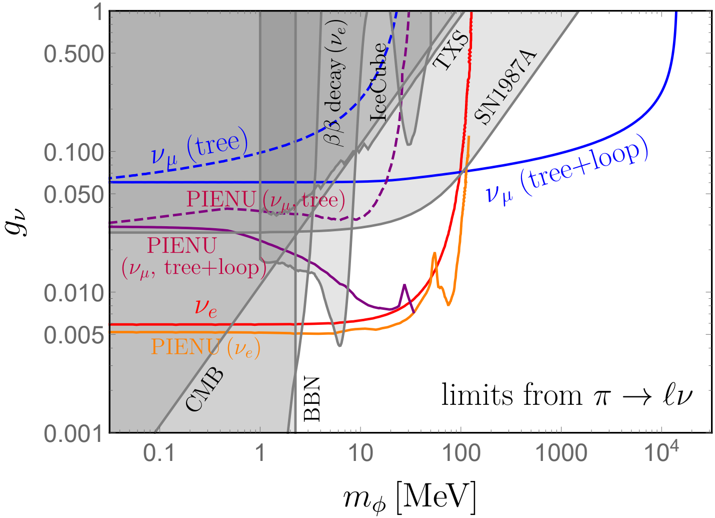
PIENU limits on $\mathrm{BR}(\pi^{\pm} \to \ell^{\pm} + \nu + X)$

PIENU, 2101.07381



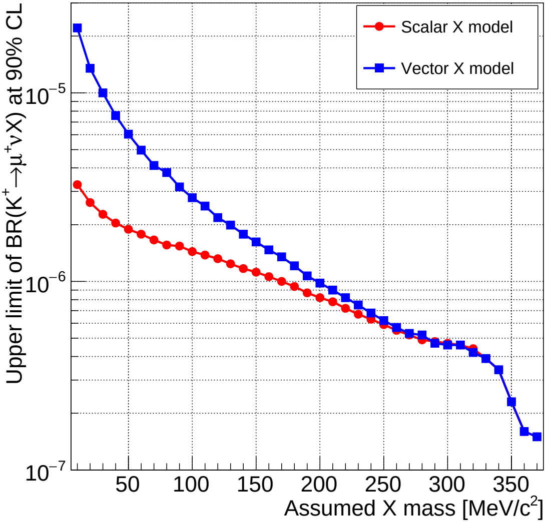
- PIENU provided limits on $\mathrm{BR}(\pi^{\pm} \to \ell^{\pm} + \nu + X)$, depending on the mass m_X.
- The PIENU limits are re-interpreted to get the constraints on m_ϕ & g_ν.

Updated pion limits

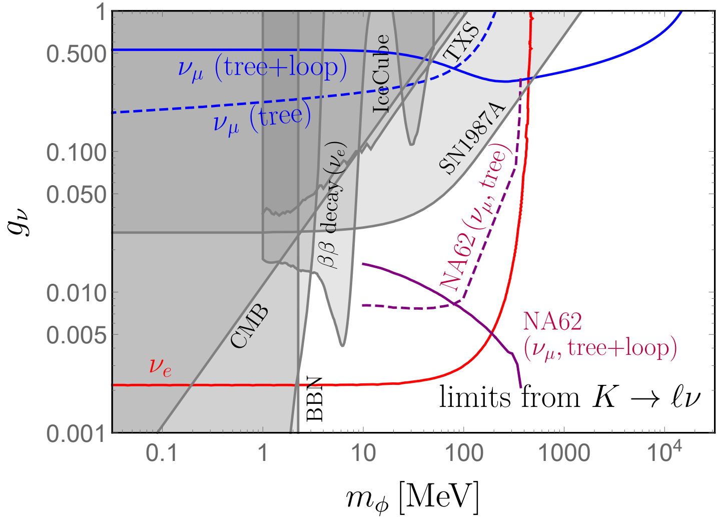


NA62 limits on $\mathrm{BR}(K^{\pm} \to \mu^{\pm} + \nu + X)$

NA62, 2101.12304



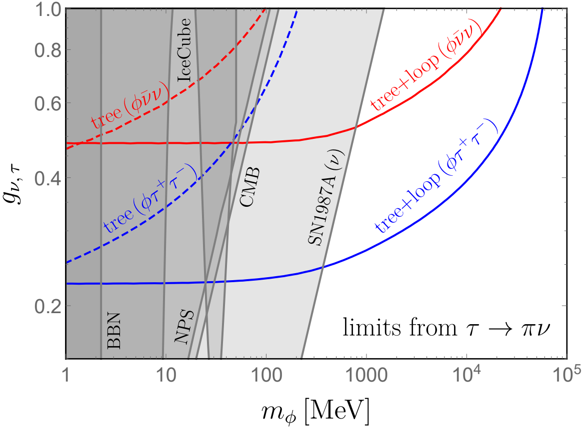
Updated Kaon limits



More meson decay limits

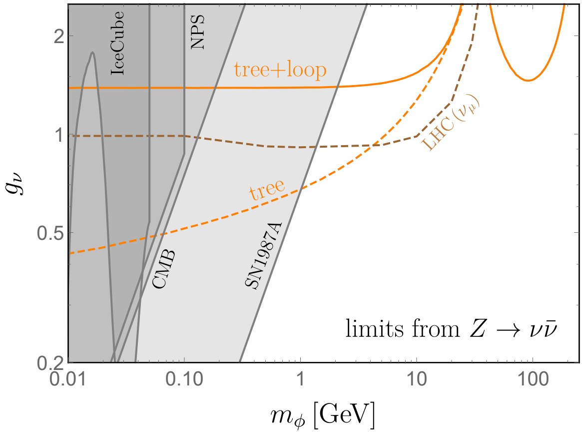
- Pseudoscalar coupling $J\bar{\nu}i\gamma_5\nu$: **No IR divergence!**
- D & B meson decays, e.g. $D^\pm \to \ell^\pm + \nu + \phi$, $B^\pm \to \overline{D}^0 + \ell^\pm + \nu + \phi$, limits are weaker. Berryman, De Gouvěa, Kelly & Zhang '18; de Gouvêa, Dev, Dutta, Ghosh, Han & YCZ '19
- $\Gamma(\mathrm{M}^\pm \to \ell^\pm + \nu + Z')$ is dominated by the term of $m_\mathrm{M}^4/m_{Z'}^2$, much larger than the IR divergent term $m_\ell^2 \log(m_{Z'}^2/m_\mathrm{M}^2)$. Carlson & Rislow '12; Dutta, Kim, Thompson, Thornton & Van de Water '22; Laha, Dasgupta & Beacom '13; Barger, Chiang, Keung & Marfatia '11; Bakhti & Farzan '17

Tau limits



- Consider both $g_\nu \phi\bar{\nu}\nu$ & $g_\tau \phi\tau^+\tau^-$ couplings.
- $g_\tau \phi\tau^+\tau^-$: limit from a_τ measurement by ATLAS: $-0.057 < a_\tau < 0.024 \Longrightarrow g_\tau > 1$. ATLAS, 2204.13478

Updated Z limits



- 1-loop contribution: both $Z\nu\bar{\nu}$ & neutrino self-energy corrections.
- Gap at $\sim$ 30 GeV: cancellation of the tree & loop contributions.
- See also Brdar, Lindner, Vogl & Xu ’20

More W/Z boson decay limits

- W boson decay $W^\pm \to \ell^\pm + \nu + \phi$,
  limits are weaker.

$$\begin{aligned} \Delta\mathrm{BR}(W^\pm \to \ell^\pm + \nu) &\simeq 3.6 \times 10^{-3}\,, \\ \Delta\mathrm{BR}(Z \to \nu\bar{\nu}) &\simeq 7.3 \times 10^{-4}\,. \end{aligned}$$

- Z boson decay $Z \to \nu + \bar{\nu} + Z'$,
  very different from $\mathrm{M}^\pm \to \ell^\pm + \nu + Z'$;
  IR divergence is cancelled out.

Generalization

- M$^{\pm} \to \ell^{\pm} + \chi + \phi$, with $g\phi\bar{\chi}\nu$ coupling, for DM phenomenology.
- M$^{\pm} \to \ell^{\pm} + N + \phi$, with $g\phi\bar{N}\nu$ coupling, for heavy neutrino physics.

Combined ν-DM limits

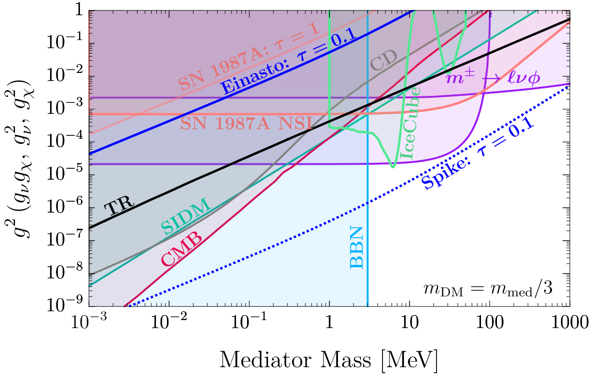


Figure: Preliminary limits for Dirac fermion DM + scalar mediator.

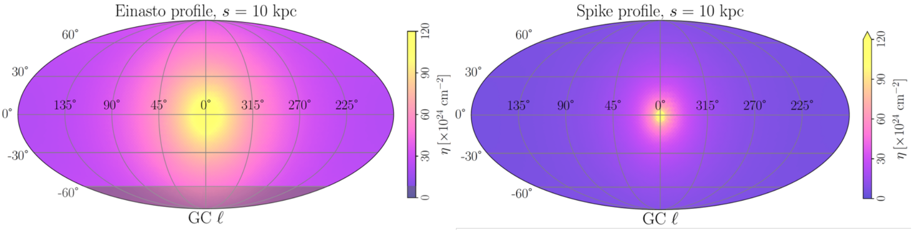
Neutrino flux attenuation

IceCube Collaboration, McMullen, Vincent, Arguelles & Schneider, 2107.11491

- Cascade equation:

$$\frac{\mathrm{d}\Phi(E,\tau)}{\mathrm{d}\eta} = -\sigma(E)\Phi(E,\tau) + \int_E^{E_{\max}} \mathrm{d}\tilde{E}\,\frac{\mathrm{d}\sigma(\tilde{E},E)}{\mathrm{d}E}\Phi(\tilde{E},\tau)$$

- Skymaps of the integrated column density η of DM: galactic supernova at $d = 10$ kpc, galactic coordinates $(\ell, b) = (0, 0)$.

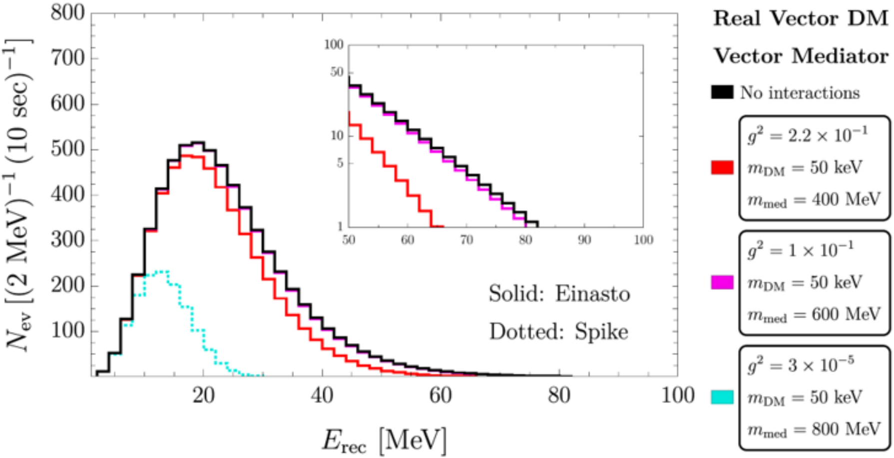


Einasto profile, $s = 10$ kpc

Spike profile, $s = 10$ kpc

Figure: Preliminary plots for Dirac fermion DM + scalar mediator.

Impacts of ν-DM interactions on JUNO events



Effects on DUNE & Hyper-K events are similar.

Conclusion

- The SM is IR finite: the KLN theorem.
  The IR divergence is cancelled out when we include a scalar mediator ϕ.
- Including the 1-loop contributions will also bring new limits in the region of parameter space, in general beyond the kinematically "forbidden" region of the tree-level processes.
- The precision meson data provide the most stringent limits for $m_\phi \gtrsim$ MeV.
- In light of all the constraints, there could be detectable effects in future neutrino experiments, **if DM halo has a spike profile**.

Thank you for your attention!