Looking for HNLs via Double Bang signals

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Motivation

- In SM neutrinos are massless.
  - No dirac mass term for neutrinos. No right-handed neutrino.
  - From oscillation experiment ($m_\nu \neq 0$)

- SM can be considered as low energy effective model.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{\mathcal{L}_{d=5}}{\Lambda} + \cdots$$

  - For $d = 5$. Weinberg operator.
  - Type-I seesaw

Motivation

See Jacobo Lopez-Pavon's talk

Type-I seesaw

- Introduce right-handed neutrinos
- Allow L number violation

$$\mathcal{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N^c_R} N_R + h.c.$$

- For $M_R \gg v$

$$m_\nu \sim \frac{Y_\nu^\dagger Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

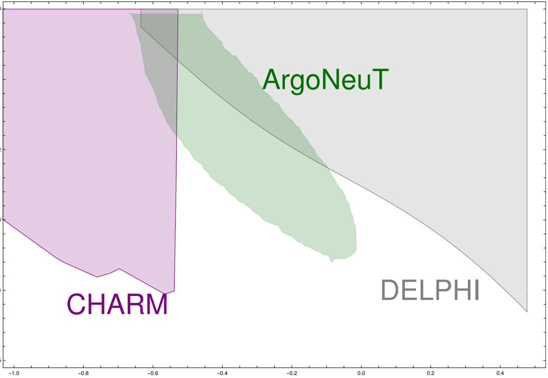
  - Neutrino masses can be smaller than fermion masses
  - Heavy neutrinos can hardly be tested
  - Tight bounds from charged lepton flavor violating experiments

Heavy sterile neutrino

In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m} \nu_{mL} + U_{\alpha 4} N_{4L}$$

In the presence of $\nu - N - Z$ interaction



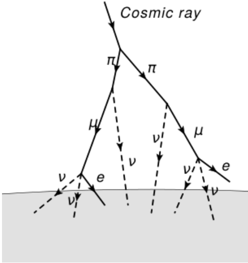
Weaker constraints over $U_{\tau 4}$

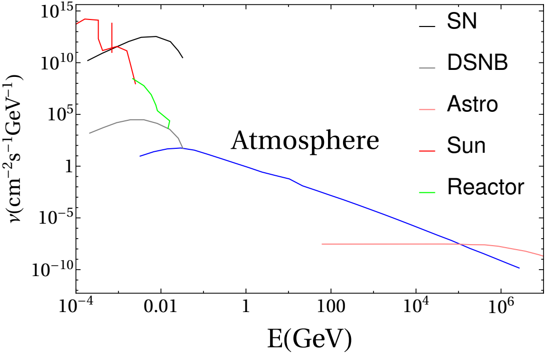
[A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05,030 (2009)]

Sources of ν_τ: Atmosphere

ν_τ are created by the flavor oscillation of the atmospheric neutrinos

- Created in the collisions of cosmic rays with the atmosphere.
- Atmospheric flux covers a wide range of energies ($\phi_\nu \sim E_\nu^{-2.7}$)



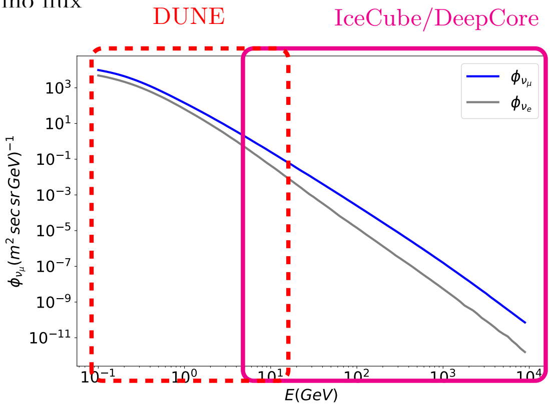


$$\begin{aligned}
\pi^\pm &\rightarrow \mu^\pm + \nu_\mu(\overline{\nu_\mu}) \\
K^\pm &\rightarrow \mu^\pm + \nu_\mu(\overline{\nu_\mu}) \\
\mu^\pm &\rightarrow e^\pm + \nu_e(\overline{\nu_e}) + \nu_\mu(\overline{\nu_\mu})
\end{aligned}$$

See Tyce DeYoung's talk

Sources of ν_τ: Atmosphere

The combination of several experiments will allow exploring the whole energy range of the atmospheric neutrino flux



DUNE

- 40 kton LArTPC
- Measures the neutrino flux from the Sub-GeV
- **Good event topology reconstruction** at low energies

IceCube/DeepCore

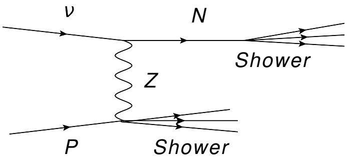
- $\sim 1\text{km}^3$ ice Cherenkov
- Measures the **high energy** part of the flux $E \geq 5$ GeV
- Events sample divided in: cascades and tracks

Observation of HNLs via Double Bang signals

- Heavy neutrinos can travel long distance with low initial energies.
- We will look for double bang signals:

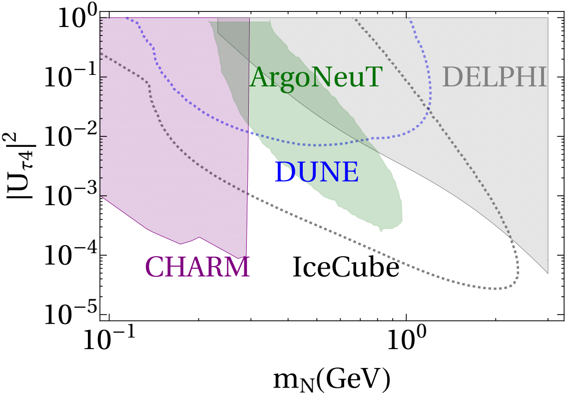
$$\begin{aligned} \nu_\tau + N &\to N_4 + \text{shower} \\ N_4 &\to \text{shower} \end{aligned}$$

- The decay length depends on M_4 and on $|U_{\tau 4}|^2$
- Cross section proportional to mixing parameter $|U_{\tau 4}|^2$



Double Bang signals

Double-Bang signals can be used to search for **HNLs in IceCube and DUNE**

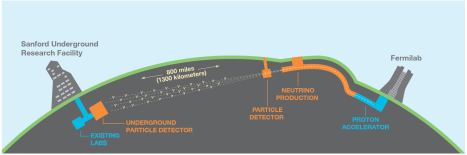


$$L_{\rm lab} = c\tau\gamma\beta \simeq 10\,{\rm m}\,\left(\frac{10^{-2}}{|U_{\tau 4}|^2}\right)\,\left(\frac{0.5\ {\rm GeV}}{m_N}\right)^5\,\left(\frac{E_N}{1\ {\rm GeV}}\right)$$

Coloma, Machado, IMS, Shoemaker (1707.08573)
Atkinson, Coloma, IMS, Rocco, Shoemaker (2105.09357)

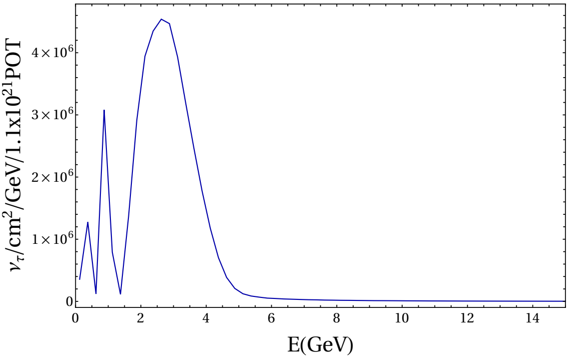
Sources of ν_τ: Beam

LBL experiments can also search for **double bang cascades**.



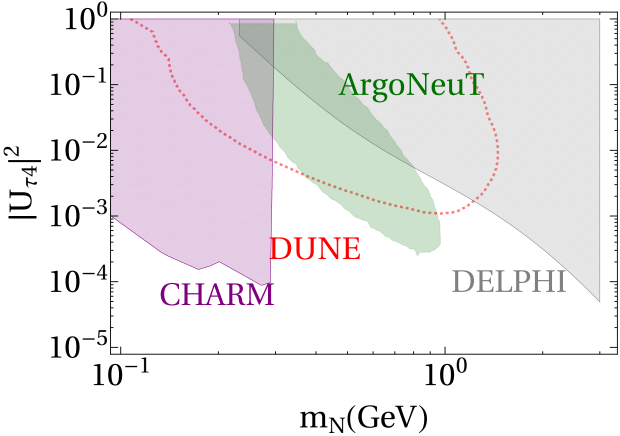
DUNE:

- ν_μ flux that peaks at ~ 2 GeV and propagates ~ 1000 km
- ν_τ flux at the far detector due to the flavor oscillation of ν_μ.



Double Bang signals

The beam can provide a complementary sensitivity to the present bounds.

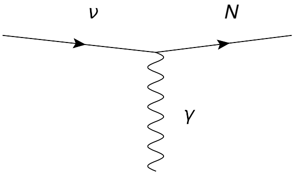


Atkinson, Coloma, IMS, Rocco, Shoemaker (2105.09357)

Transition magnetic moment

Other BSM scenarios can be explored using Double-bang signals

Transition magnetic moment



$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$

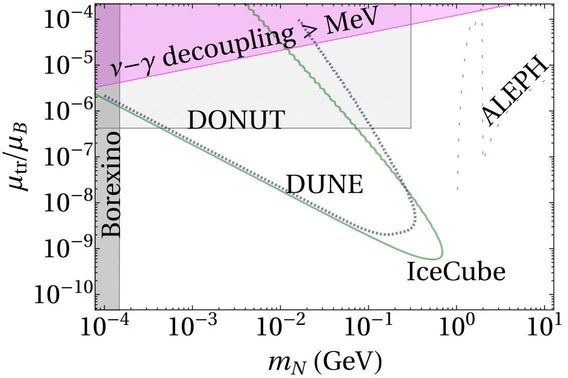
- The main contribution to our signal events comes from DIS on nucleons
- The decay length $N \to \nu_i \gamma$

$$\Gamma = \frac{\mu_\nu^2 M_4^3}{4\pi}$$

See Jing-yu Zhu's talk

Transition magnetic moment

Double-Bang signals can be used to search for neutrino **transition magnetic moments**



$$L_{\rm lab} = c\tau\gamma\beta \simeq 2.5\ \mathrm{m}\ \left(\frac{10^{-8}\ \mu_B}{\mu}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_N}\right)^4 \left(\frac{E_N}{1\ \mathrm{GeV}}\right)$$

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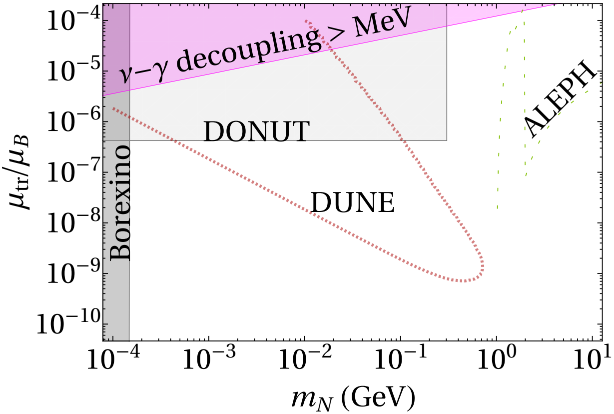
Transition magnetic moment

The **beam** will allow exploring a large region of the transition magnetic moments



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Conclusions

- **Double Bang** signals can probe **new physics**
- **HNLs** via neutral current interaction
  - IceCube and DUNE could increase the current bounds by 1 or 2 orders of mangnitude.
- **Transition magnetic moments**
  Competitive bounds on μ_ν for ν_τ for $m_N \sim 1$ GeV.

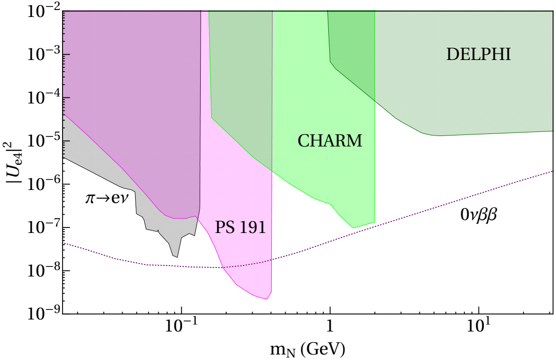
Thank you!

Backup: Heavy sterile neutrino

- Sterile mass mixing with active neutrinos

$$\nu_{\alpha L} = \sum U_{\alpha m}\nu_{mL} + U_{\alpha 4}N_{4L}$$

In the presence of $\nu - N - Z$ interaction



Strongs bounds on U_{e4} and $U_{\mu 4}$

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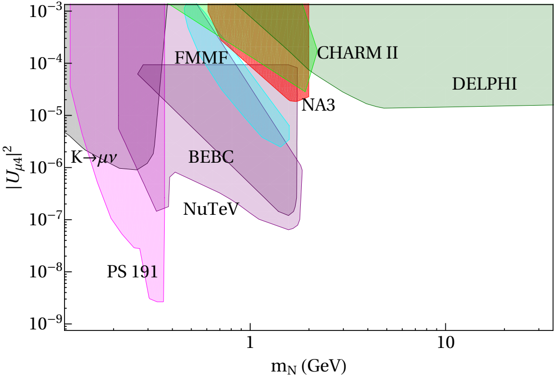

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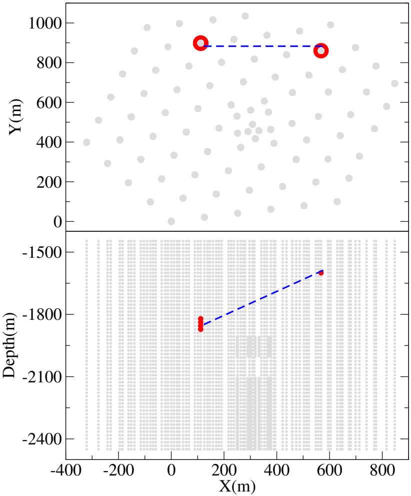
Backup: Heavy sterile neutrino

The number of events in the detector is given by

$$N(L) \propto T\mathcal{B} \int dE d\cos\theta \;\; \phi_{\nu_\alpha} \;\; P_{\alpha\to\tau} \;\; \sigma_{\nu_\tau \nu_4} \;\; P_d \;\; V_{eff}$$

- The largest contribution comes from low energy neutrinos ($\phi \sim E^{-2.7}$)
- $V_{eff}(L, \cos\theta)$ calculated using a montecarlo integration.
- The cascade separation must be $L > 20$ m
- Minimum energy for each cascade $E > 5$ GeV
- $N_{bkg} < 10^{-11} yr^{-1}$

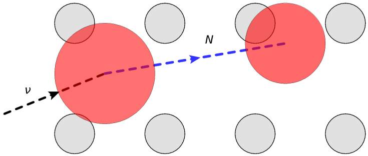
Our Monte Carlo



Backup: Double Bang topology to look for New physics

Double bang signals mediated by right-handed neutrinos

- 1st shower ν interaction
- 2nd shower N decay
- No cherenkov radiation in between



What kind of new physics?

Backup: Transition magnetic moment

$\nu_\mu - N$ transition