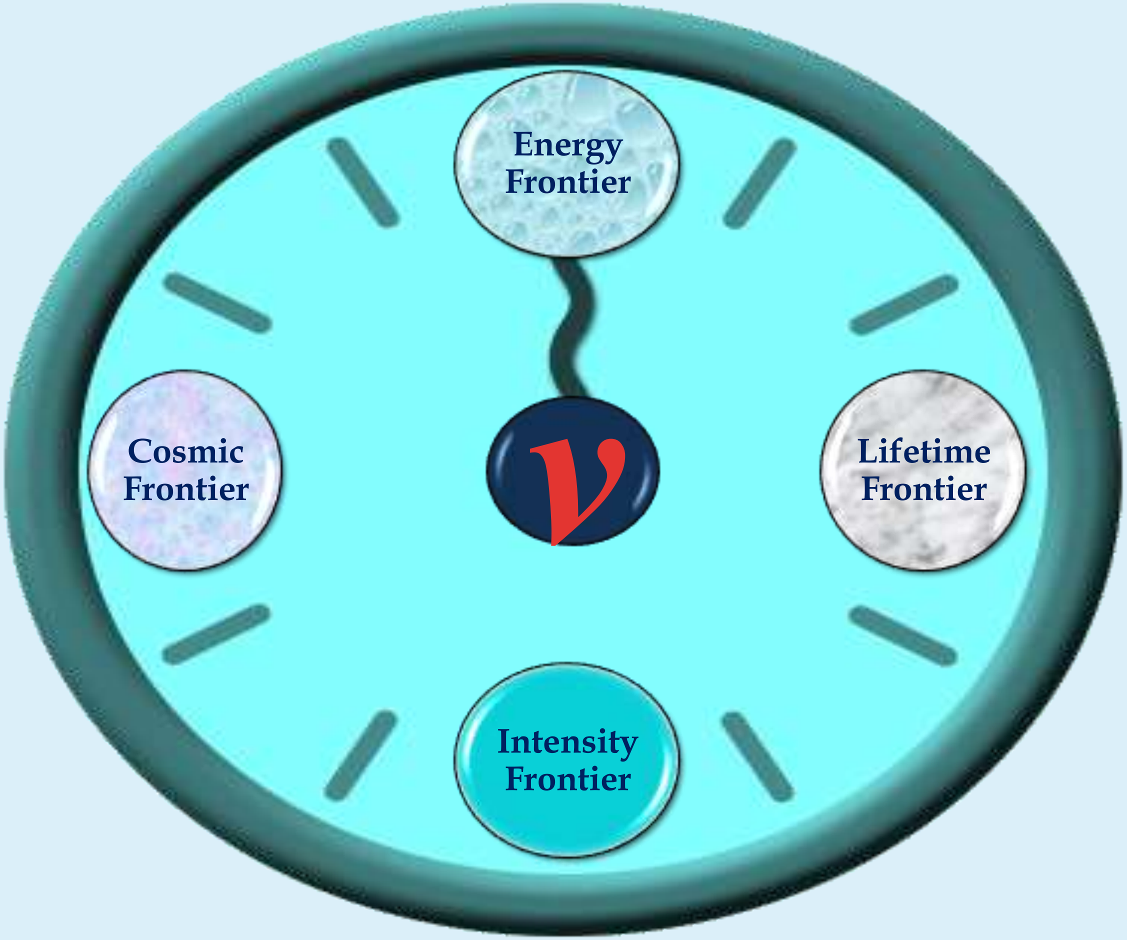
Neutrino as a gateway to new physics

Sudip Jana

Max-Planck-Institut für Kernphysik

Particle and Astroparticle Theory Seminar
MPIK
8th June, 2020

Outline


Energy Frontier
Cosmic Frontier
Lifetime Frontier
Intensity Frontier
ν

Neutrino Oscillations

- Neutrino flavor oscillations have been firmly established from:
  - Solar neutrinos (Homestake, SAGE, GALLEX, Kamiokande, Super-Kamiokande, SNO, Borexino,...)
  - Atmospheric neutrinos (Super-Kamiokande, IceCube,..)
  - Reactor antineutrinos (KamLand, DayaBay, RENO, DoubleChooz,..)
  - Accelerator neutrinos (T2K, MINOS, NOνA...)
- Oscillations can happen only if neutrinos have non-zero masses

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i, \qquad \alpha = (e, \mu, \tau)$$

U is assumed to be unitary (Needs experimental checks!)

- For two neutrino flavors, oscillation probability in vacuum is:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right), \quad \Delta m^2 = m_2^2 - m_1^2$$

Neutrino Oscillations

- For three neutrino flavors, the unitary matrix is parametrized as:

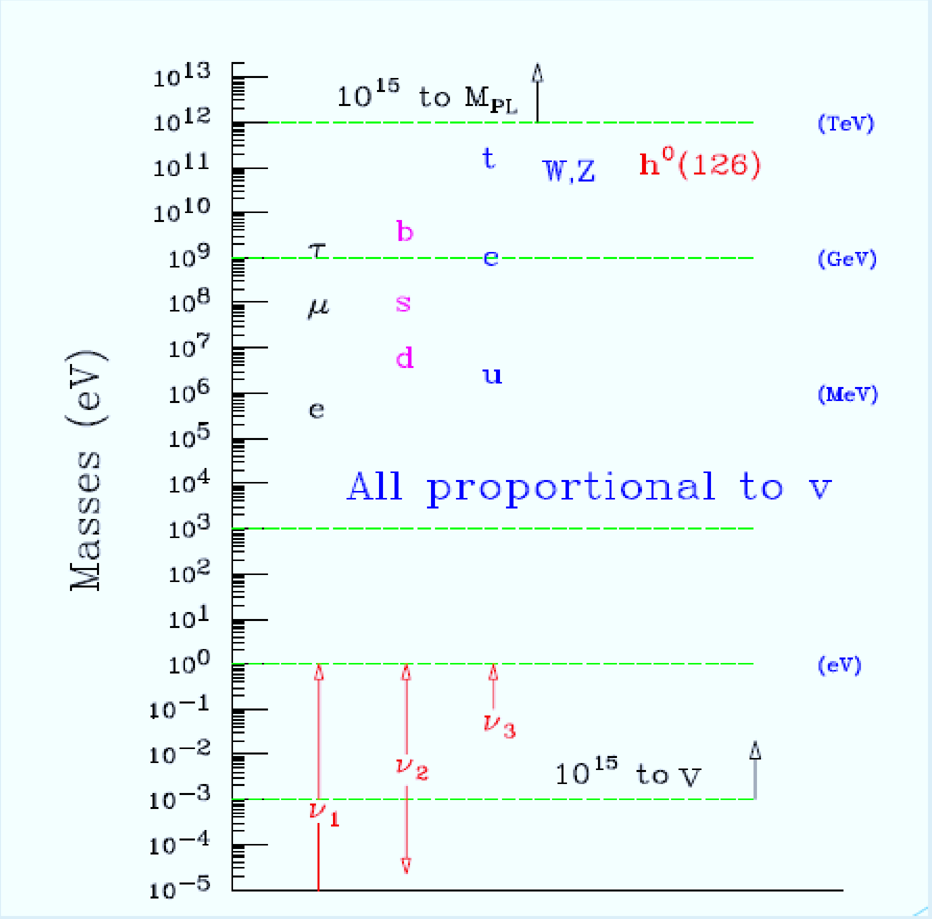
$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \cdot P$$

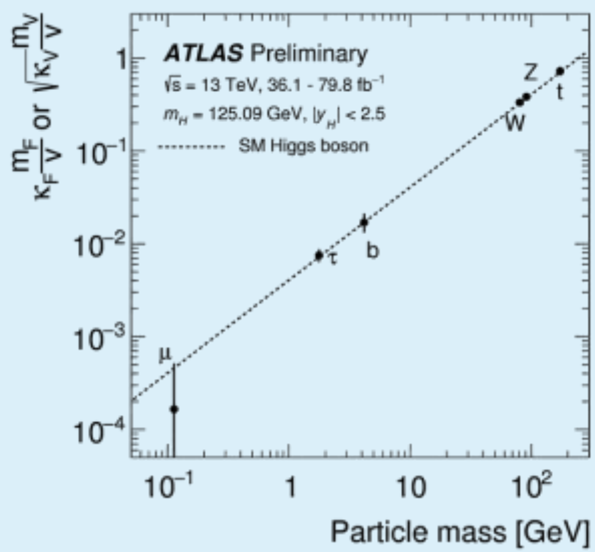
$$s_{ij} \equiv \sin(\theta_{ij}),\ c_{ij} \equiv \cos(\theta_{ij}),\ P = diag.\{e^{i\alpha}, e^{i\beta}, 1\}$$

- "Majorana phases" (α, β) do not affect oscillation probabilities, while the single "Dirac phase" δ does
- All three mixing angles and two mass splittings have been measured with few percent precision
- Currently CP phase δ is unknown

  T2K result (Nature, 2020): $\delta_{CP} = -1.89^{+0.70}_{-0.58}$
- There is a mass ordering ambiguity, normal ordering versus inverted ordering (sign of Δm^2_{31} is currently unknown)
- Unitarity of U_{PMNS} remains to be tested

Neutrino masses and mixings: New physics beyond the SM





$$m_\nu \sim y_\nu^{eff}\ v$$

$$y_\nu^{eff} < 10^{-12}$$

Neutrino Mass Generation

- "Technically natural" in t'Hooft sense. Small values are protected by symmetry. At a cut-off scale Λ :
  "natural" - $\delta m_f \sim g^2/(16\pi^2)\, m_f \ln(\Lambda^2/m_f^2)$
  "unnatural" - $\delta m_H^2 \sim -\ y_t^2/(8\pi^2)\, \Lambda^2$

- **Two ways to generate small values naturally :**

- Suppression by integrating out heavy states :
  the higher dimension $1/\Lambda^n$, the lower Λ can be.

- Suppression by loop radiative generation:
  the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.

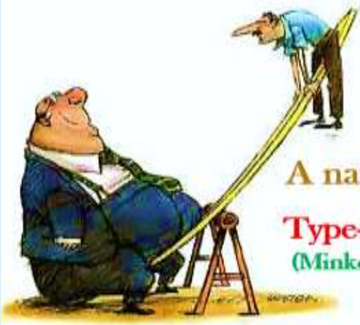
Neutrino Mass Generation

- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

Weinberg, PRL43 (79) 1566

- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ★ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ★ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ★ Type-III Foot, Lew, He, Joshi (89), Ma (98)
    - ★ Linear, Inverse, etc ...
  - Loop-induced:
    - ★ 1-loop Zee (80), Ma (99)
    - ★ 2-loop Babu (88)

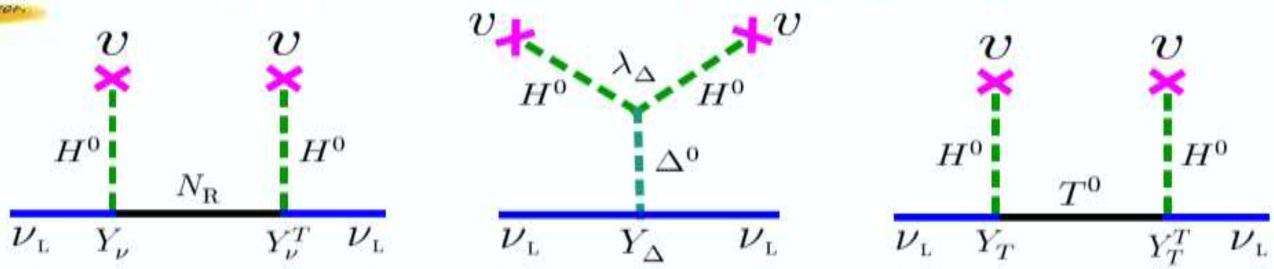
Seesaw Model



A natural theoretical way to understand why 3 ν-masses are very small.

Type-I: SM + 3 right-handed Majorana ν's

(Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)



$$\boxed{M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T} \qquad \boxed{M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}} \qquad \boxed{M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T}$$

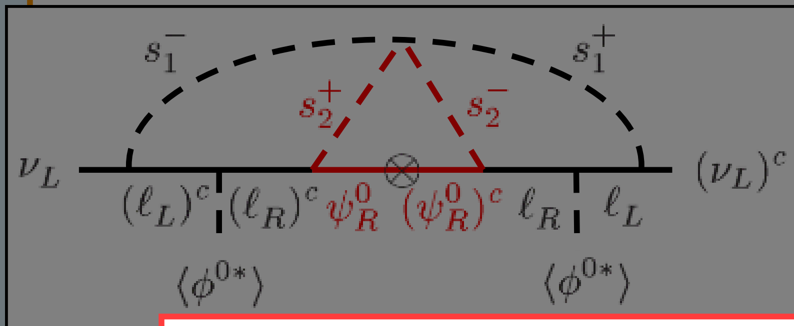
Type-II: SM + 1 Higgs triplet

(Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

Type-III: SM + 3 triplet fermions

(Foot, Lew, He, Joshi 89)

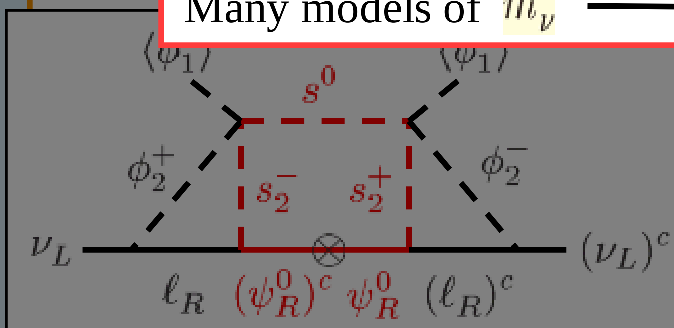
Higher−loop models with DM



Krauss−Nasri−

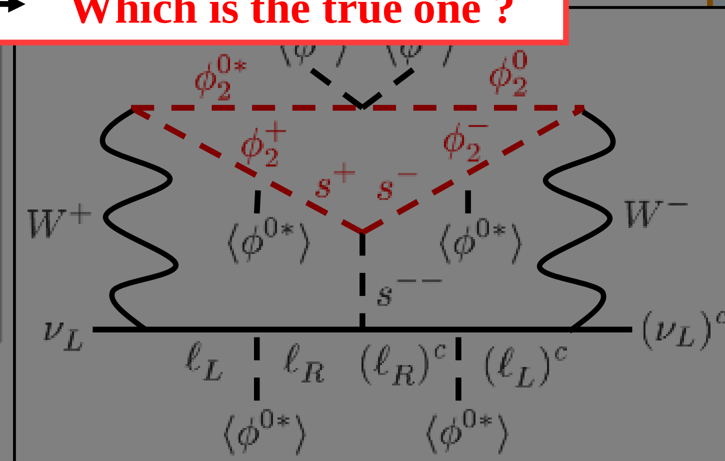
M.L. Krauss, S. Nas

Many models of m_ν $\longrightarrow$ **Which is the true one ?**



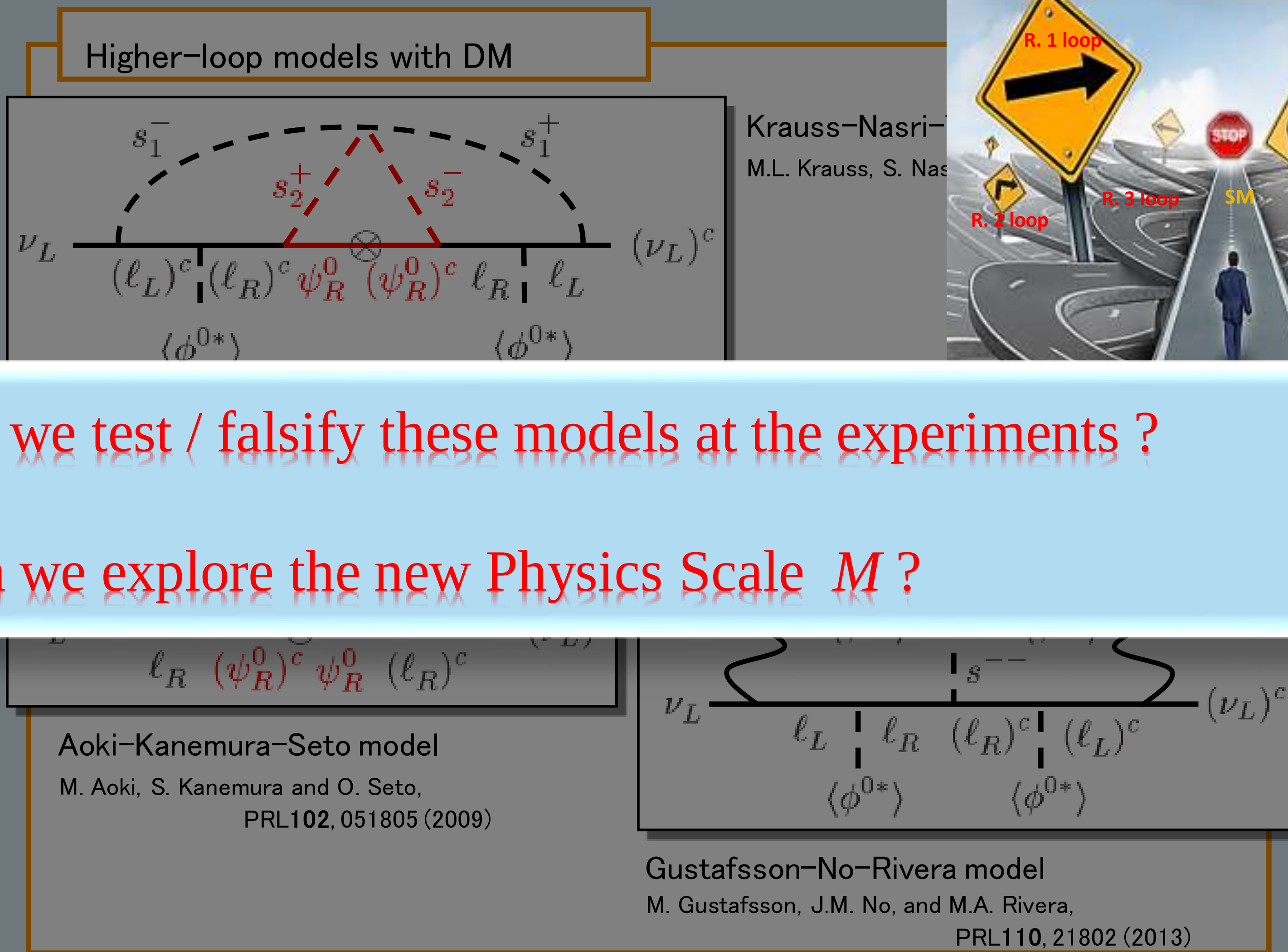
Aoki−Kanemura−Seto model

M. Aoki, S. Kanemura and O. Seto, PRL**102**, 051805 (2009)



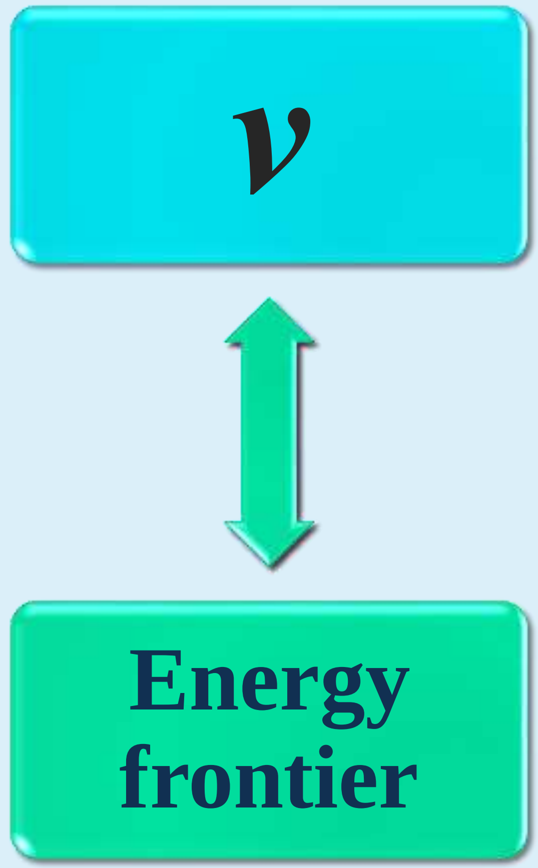
Gustafsson−No−Rivera model

M. Gustafsson, J.M. No, and M.A. Rivera, PRL**110**, 21802 (2013)



1. Can we test / falsify these models at the experiments ?

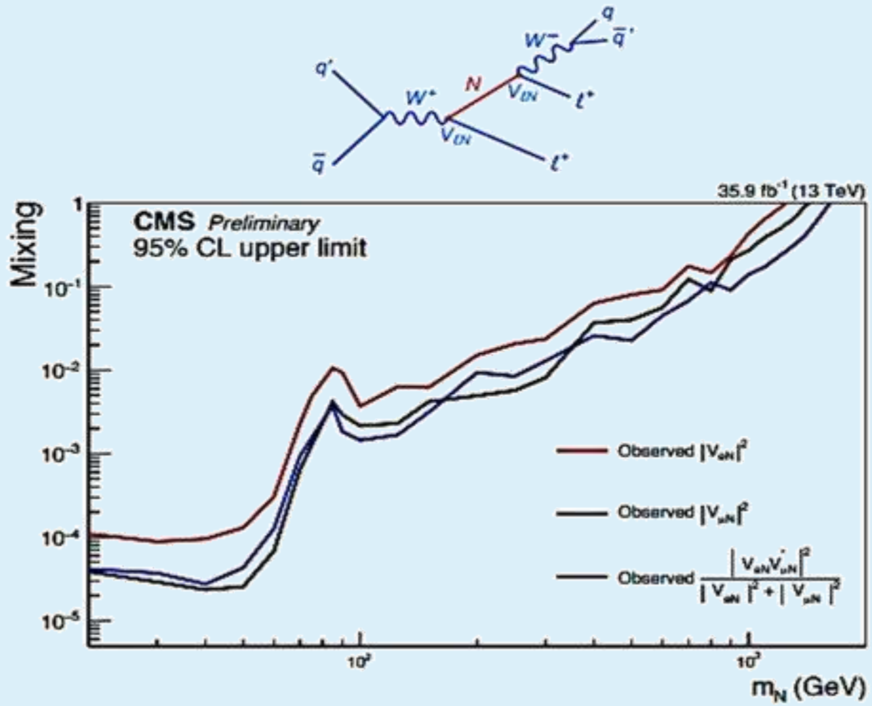
2. Can we explore the new Physics Scale M ?


ν
Energy frontier

Testing type-I Seesaw at LHC

[Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Panella, Cannoni, Carimalo, Srivastava (PRD '02);
Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); Atre, Han, Pascoli, Zhang (JHEP '09)]

Same-sign dilepton plus jets (without $\not{E}_T$)

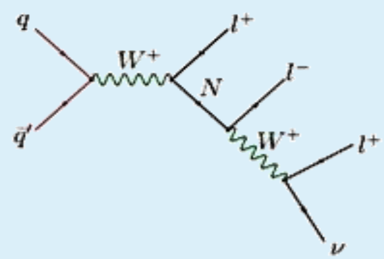


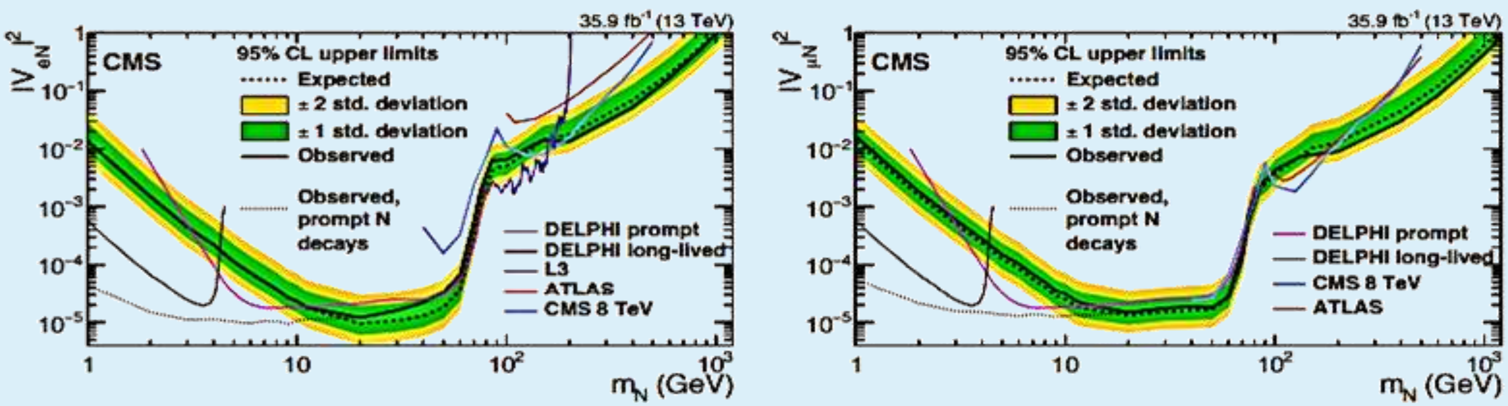
[CMS PAS EXO-17-028]

Testing Inverse Seesaw at LHC

[del Aguila, Aguilar-Saavedra (PLB '09; NPB '09); Chen, BD (PRD '12); Das, Okada (PRD '13); Das, BD, Okada (PLB '14); Izaguirre, Shuve (PRD '15); Dib, Kim (PRD '15); Dib, Kim, Wang (PRD '17; CPC '17); Dube, Gadkari, Thalapillil (PRD '17)]

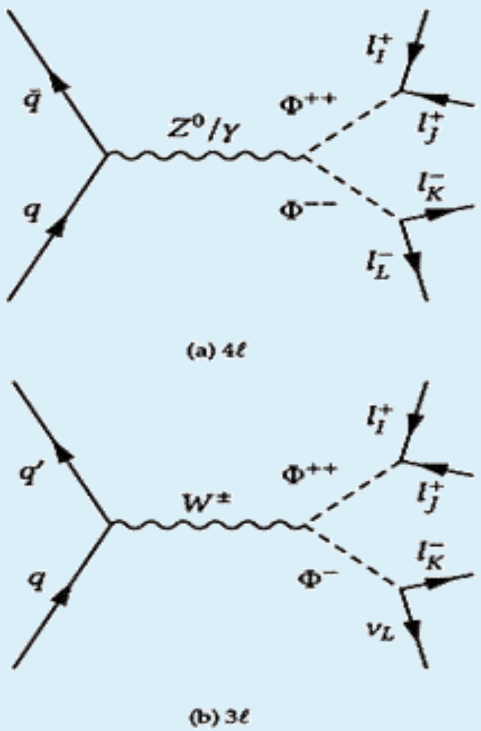
Trilepton plus $\not{E}_T$

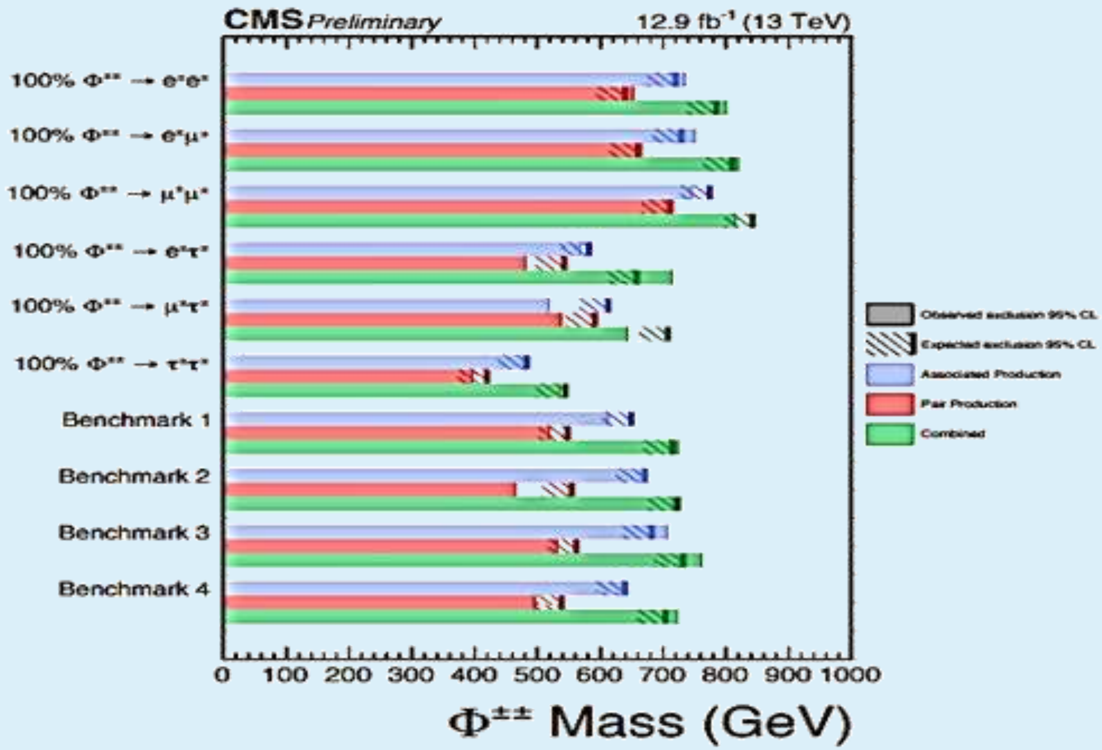




[CMS Collaboration, Phys. Rev. Lett. **120**, 221801 (2018)]

Testing type-II Seesaw at LHC





[CMS-PAS-HIG-16-036]

Rizzo (1982); Huitu, Maalampi, Pietila, Raidal (1997); Gunion, Loomis, Pitts (1996); Akeryod, Aoki (2005); Han, Mukhopadhyaya, Ci, Wang (2005), N. Sahu, Uma Sankar (2005); Sarma, Devi, Singh (2007); Chao, Luo, Xing, Zhao (2007); Perez, Han, Huang, Li, Wang (2008); McDonald, Sahu, Sarkar (2008); Chiang, Nomura, Tsumura (2012); Dev, D. Ghosh, Okada, Saha (2013); Nayak, Parida (2015); Cai, Han, Ruiz (2017), Babu , SJ (2017)……

1 • **Radiative Neutrino Mass Model**
(Babu 88; Zee 80)

2 • **Type II Seesaw Model** (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

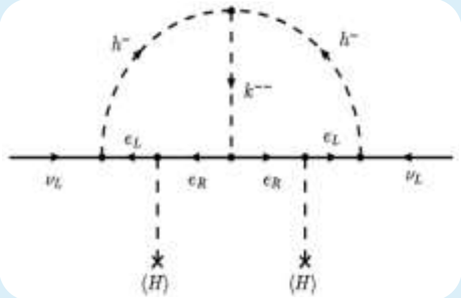
3 • **Left Right Symmetric Model** (Pati, Jogesh C. et al. (74), Mohapatra (75), Senjanovic, (75))

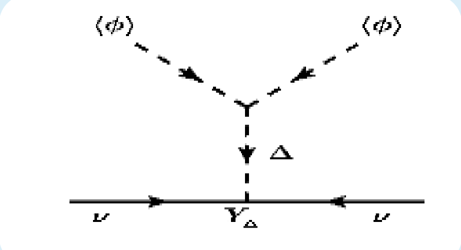
4 • **Little Higgs Model**
(Arkani-Hamed, N. (2002))

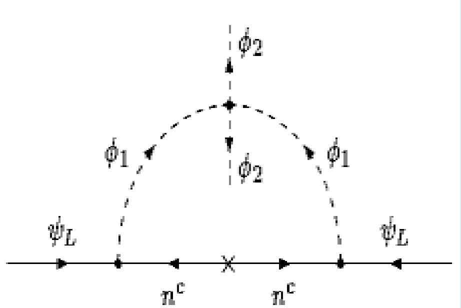
5 • **Dimension 7 Neutrino Mass Model**
(Babu, Nandi (2009), Nandi, SJ (2018))

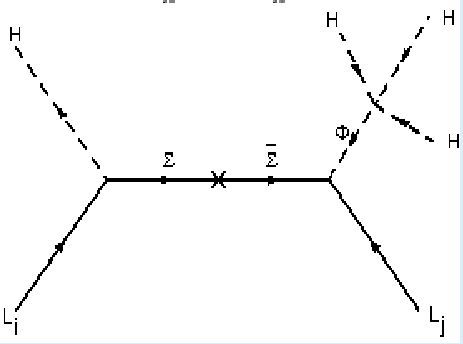
6 • **Georgi-Machacek Model**
(Georgi, Howard et al.(85))

7 • **Other Models**
(Gunion (90), etc.)



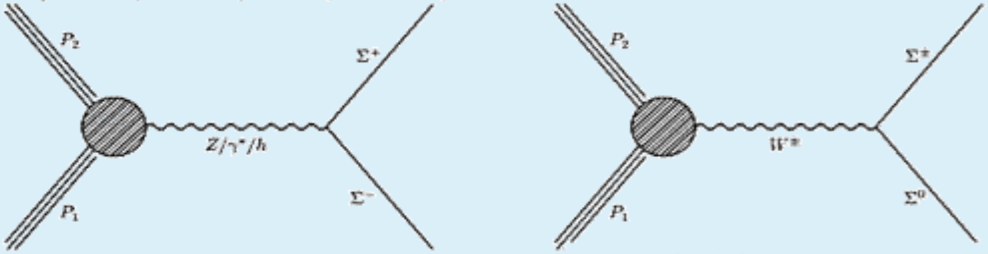


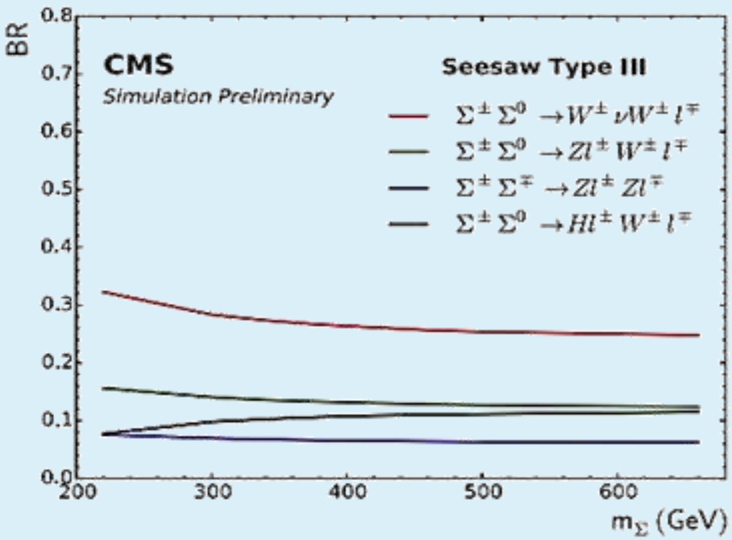


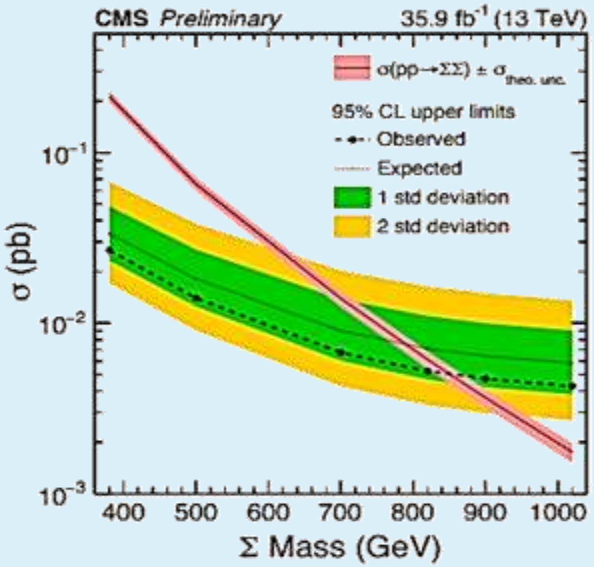


Testing type-III Seesaw at LHC

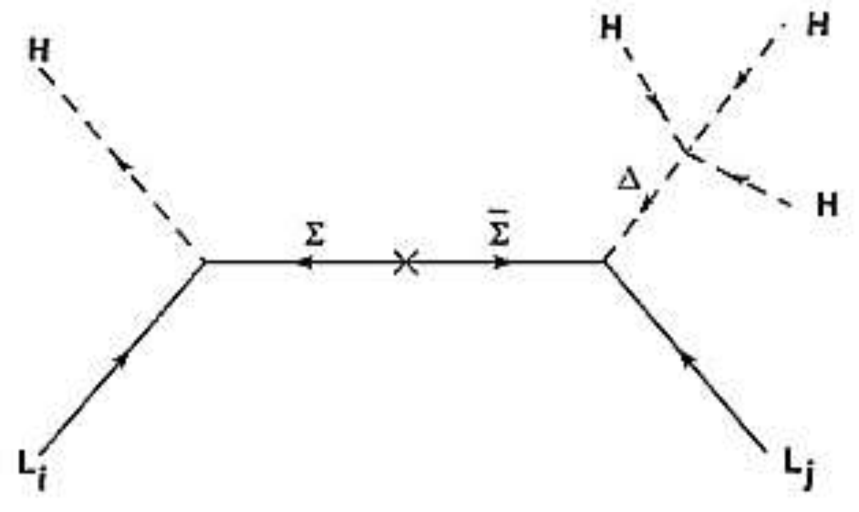
- Multi-lepton signatures. Franceschini, Hambye, Strumia (PRD '08); Li, He (PRD '09); Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović (PRD '10); Ruiz (JHEP '15) , **SJ**, Okada and Raut (2019)





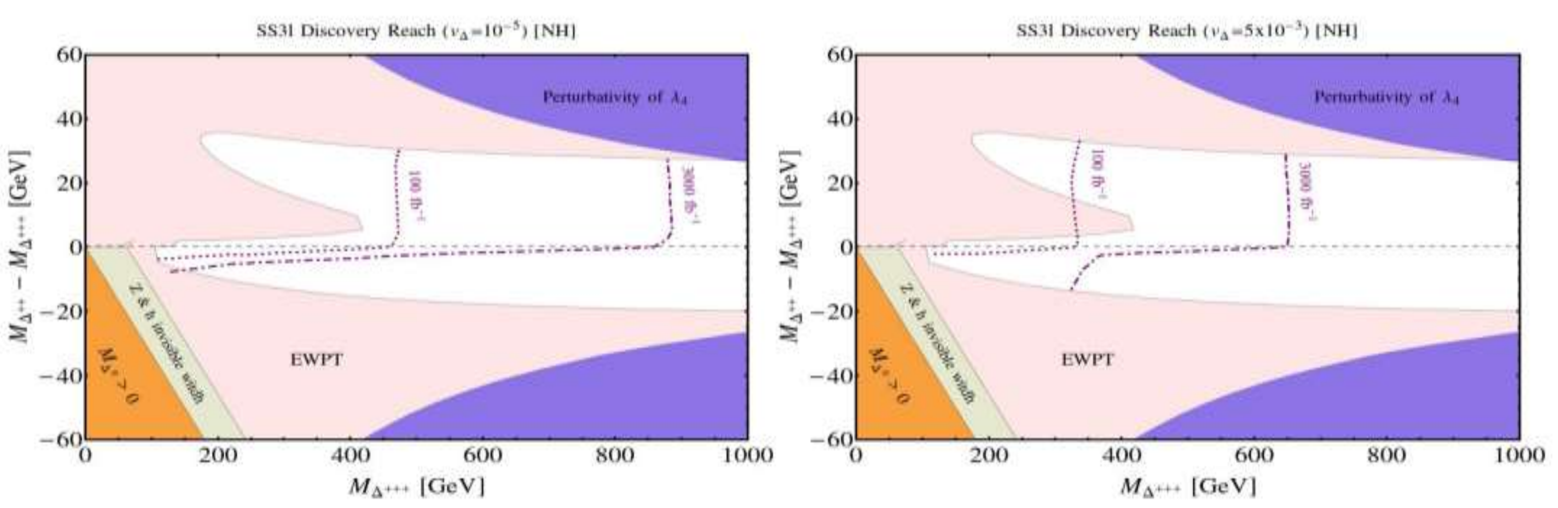


Testing Seesaw with *d=7* operator at the LHC



Babu, Nandi, Tavartkiladze (2009)
T. Ghosh, SJ, Nandi (2018),
K. Ghosh, SJ, Nandi (2017)

Testing Seesaw with dim=7 operator at the LHC



- Discovery potential upto 450 (950) GeV at 100 (3000) fb^{-1} for llW dominated region Discovery potential upto 500 (950) GeV at 100 (3000) fb^{-1} for llW dominated region
- Discovery potential upto 350 (700) GeV at 100 (3000) fb^{-1} for WWW dominated region
- Covers the whole area available for $\Delta M > 0$ scenarios
- Similar results for NH and IH

T. Ghosh, SJ, Nandi (2018),
K. Ghosh, SJ, Nandi (2017)

ν

$\updownarrow$

Lifetime frontier

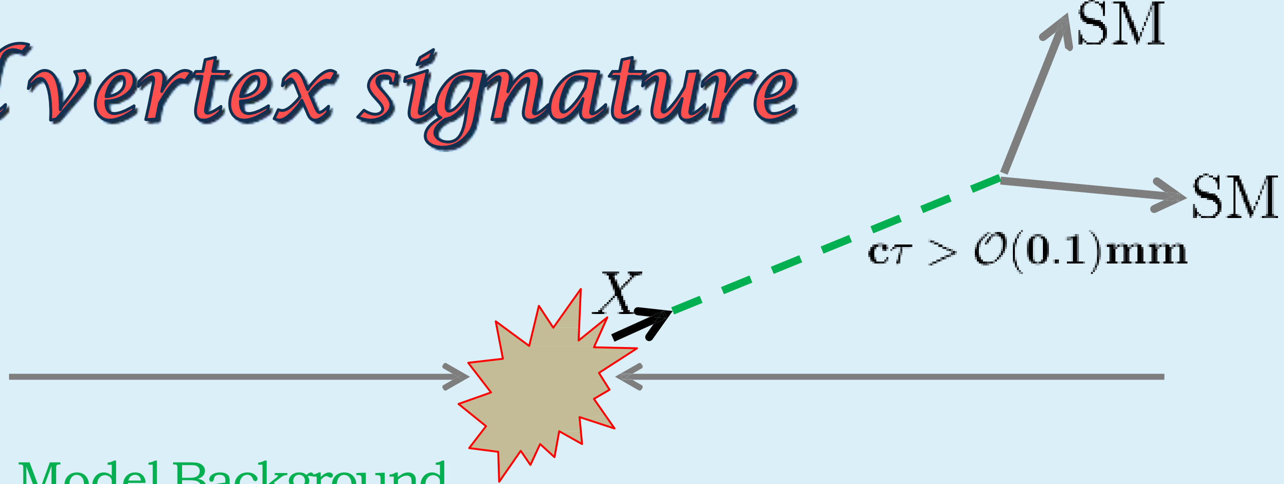
Probe of Seesaw Mechanism at lifetime frontier

- Is it really sufficient to search for new physics scale behind neutrino mass generation by looking at prompt signatures?

- If new particles are completely singlet under the SM gauge group, it can naturally explain the null search results at the LHC because SM singlet particles cannot be directly produced at the LHC through the SM interactions. Such particles may be produced through new interactions and/or rare decay of the SM particles.

- However, if a new particle is long-lived, it can leave a displaced vertex signature at the collider experiments. Since the displaced vertex signatures are generally very clean, they allow us to search for such a particle with only a few events at the LHC or future colliders.

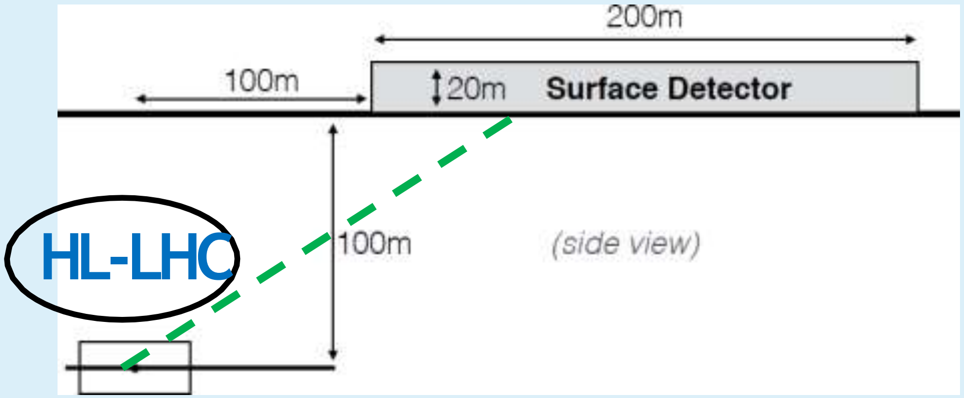
Displaced vertex signature



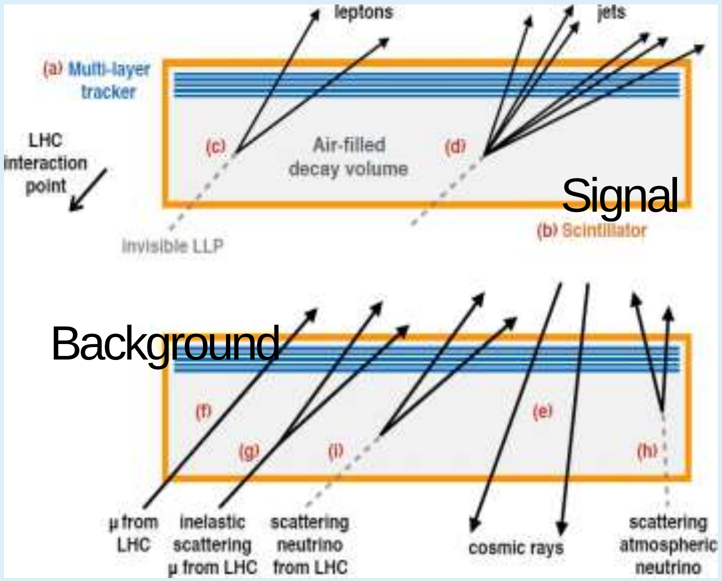
- Low Standard Model Background
- Ideal for new physics searches

Future Displaced Vertex Searches at LHC

MATHUSLA

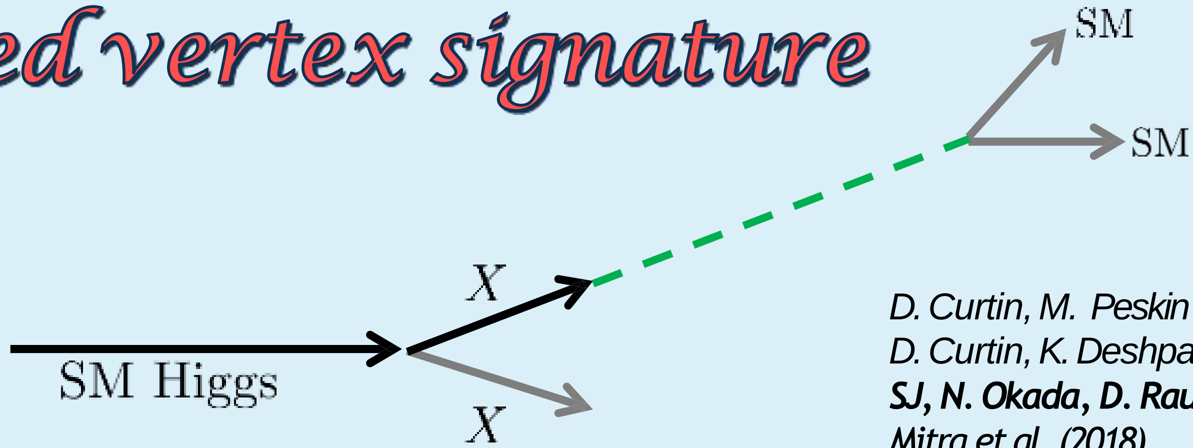


J. Chou, D. Curtin, H. Lubatti
arXiv: 1606.06298



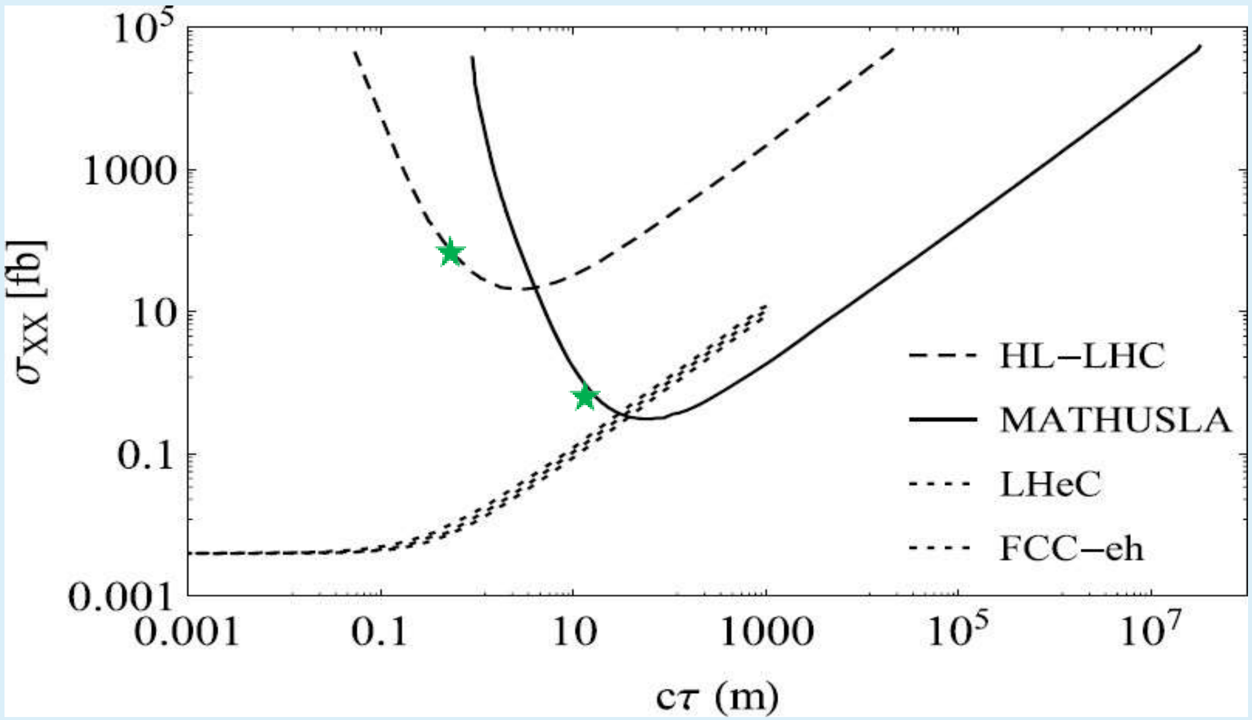
MATHUSLA

Displaced vertex signature



$$m_X = 20 \text{ GeV}$$

*D. Curtin, M. Peskin **(2017)***
*D. Curtin, K. Deshpande, et.al **(2017)***
SJ, N. Okada, D. Raut (2018)
Mitra et al. (2018)



Displaced vertex signature In type-I Seesaw

- *Minimal gauged B-L extension of SM*

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
N_R^i	**1**	**1**	0	-1
φ	**1**	**1**	0	$+2$

Table 1: New Particle content.

- ➢ Anomaly Free:
- ➢ Seesaw Mechanism :
- ➢ N_i can be long-lived !!

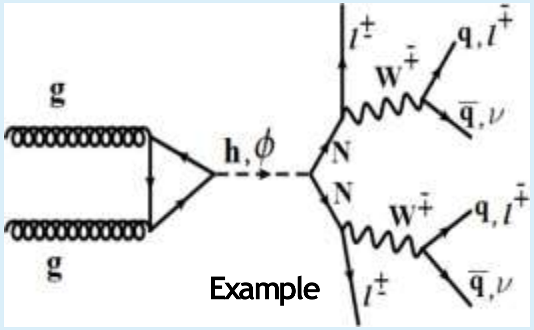
$$\mathcal{L}_Y \supset - \sum_{i,j=1}^{3} Y_D^{ij} \overline{\ell_L^i} H N_R^j - \frac{1}{2} \sum_{k=1}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k$$

3 generation of right handed Neutrinos (N_i)
N_i are SM singlet and can have Majorana mass

Heavy Neutrino production from Higgs decay

- ➢ NN production
- ➢ Higgs Mixing

$$\begin{bmatrix} h \\ \phi \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \phi_{SM} \\ \phi_{BL} \end{bmatrix}$$



SJ, N. Okada, D. Raut (2018)

Displaced vertex signature In type-I Seesaw

- Heavy Neutrino Decay into SM particles

$$\Gamma(N^i \to W/Z + \mathrm{SM}) \propto \sum_{\alpha=1}^{3} |R_{\alpha i}|^2 \times \Gamma_{\mathrm{N^i}}, \qquad \Gamma_{\mathrm{N^i}} = \frac{G_F^2}{192\pi^3} m_{N^i}^5$$

➢ Degenerate Case:

Decay length is independent of U_{MNS}

$$\sum_{\alpha=1}^{3} |R_{\alpha i}|^2 = \frac{m_i}{m_N}$$

➢ m_i is the mass of the light neutrino

➢ Lightest light neutrino mass fixes light neutrino mass spectrum

Normal Hierarchy (NH) : $(m_1 < m_2) < m_3$: $m_1 = m_{lightest}$

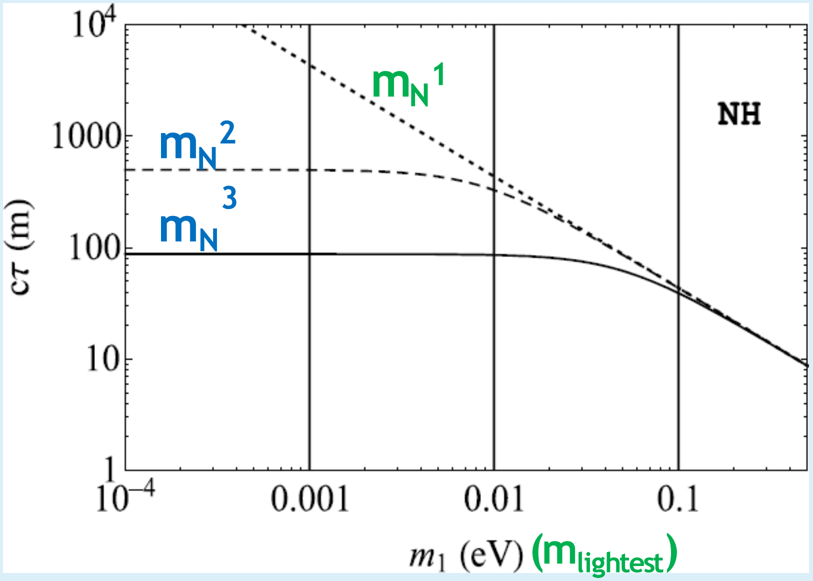
Inverted Hierarchy (IH) : $m_3 < (m_1 < m_2)$: $m_3 = m_{lightest}$

SJ, N. Okada, D. Raut (2018)

Displaced vertex signature In type-I Seesaw

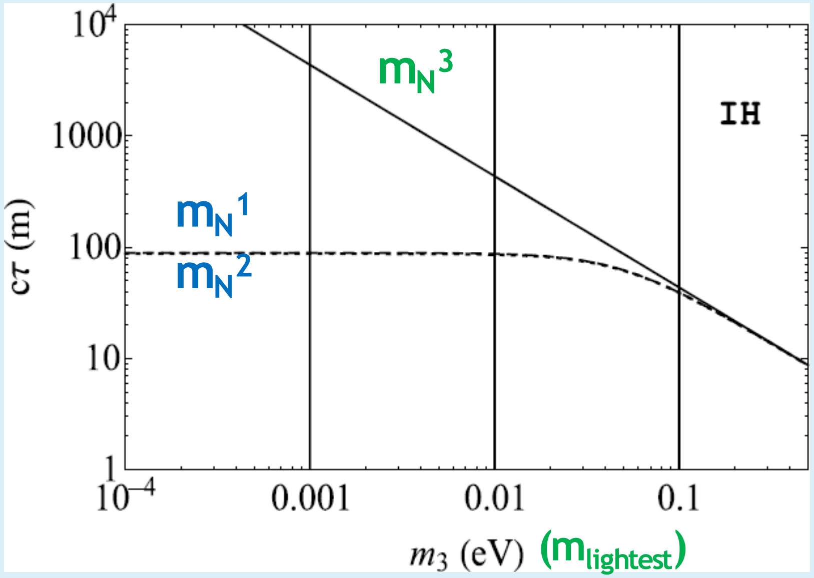
- Decay Length: $c\tau_i = \frac{1}{\Gamma_{N^i}} \propto \frac{1}{m_N^4 \, m_i}$

Normal Hierarchy (NH) : $(m_1 < m_2) < m_3$



$$m_{N^{1,2,3}} = m_N = 20 \text{ GeV}$$

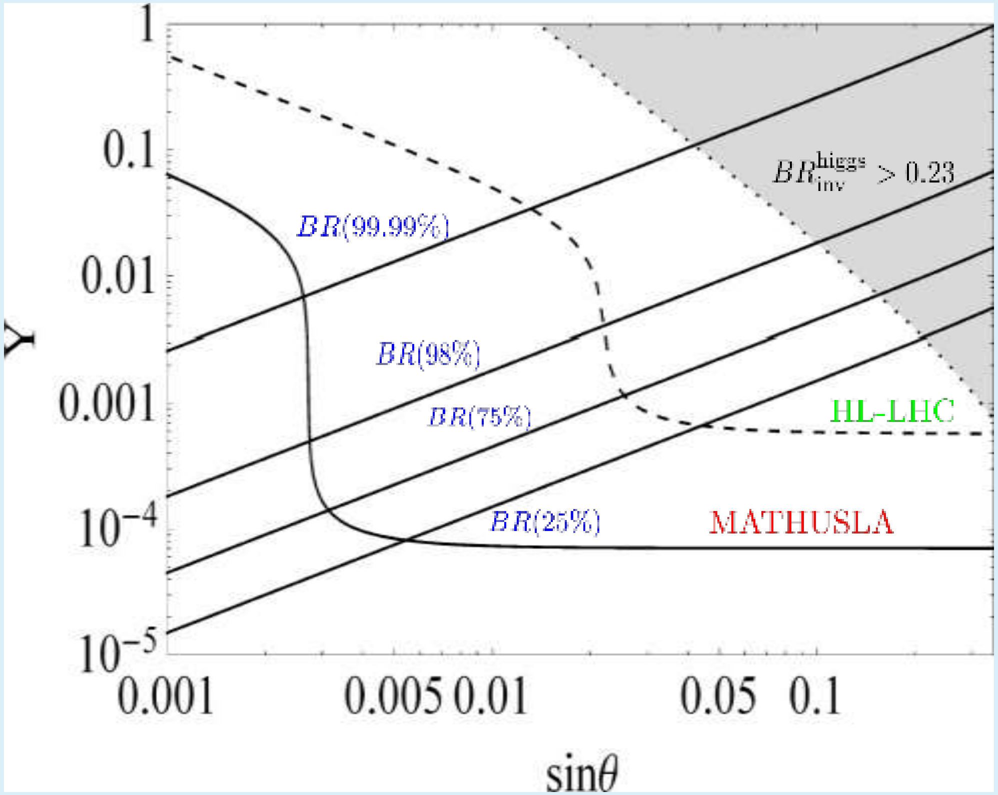
Inverted Hierarchy (IH) : $m_3 < (m_1 < m_2)$



SJ, N. Okada, D. Raut (2018)

Displaced vertex signature In type-I Seesaw

$$\begin{aligned}\sigma_{NN}(min) &= \sigma(pp\to\phi\to NN)+\sigma(pp\to h\to NN)\\ &\simeq \left[\sin^2\theta\times BR(\phi\to NN)+\cos^2\theta\times BR(h\to NN)\right]\sigma_h(m_h).\end{aligned}$$



Displaced vertex and disappearing signature in type-III Seesaw

- *Lagrangian*

hyperchargeless triplet(s) of fermions: $\Sigma^+, \Sigma^0, \Sigma^-$

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

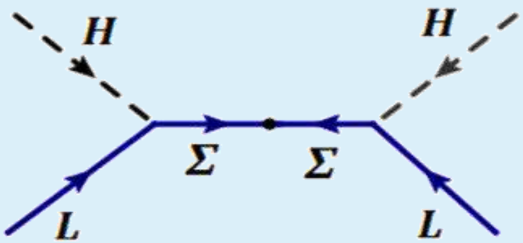
$$\mathcal{L} = \mathcal{L}_{SM} + Tr[\overline{\Sigma} i \not{D} \Sigma] - \frac{1}{2} Tr[\overline{\Sigma} M_\Sigma \Sigma^c + \overline{\Sigma^c} M_\Sigma^* \Sigma] - \tilde{\phi}^\dagger \overline{\Sigma} \sqrt{2} Y_\Sigma L + h.c.$$

Majorana mass term

kinetic term: interactions with W and Z bosons

Yukawa interactions

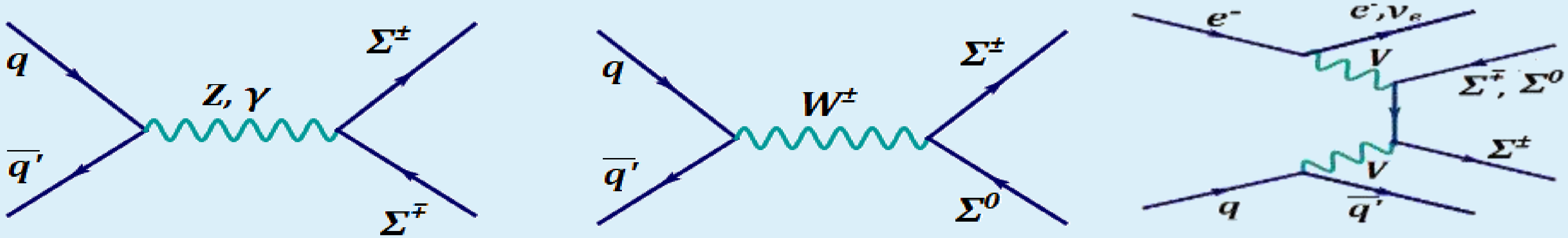
- *Neutrino Mass Generation:*

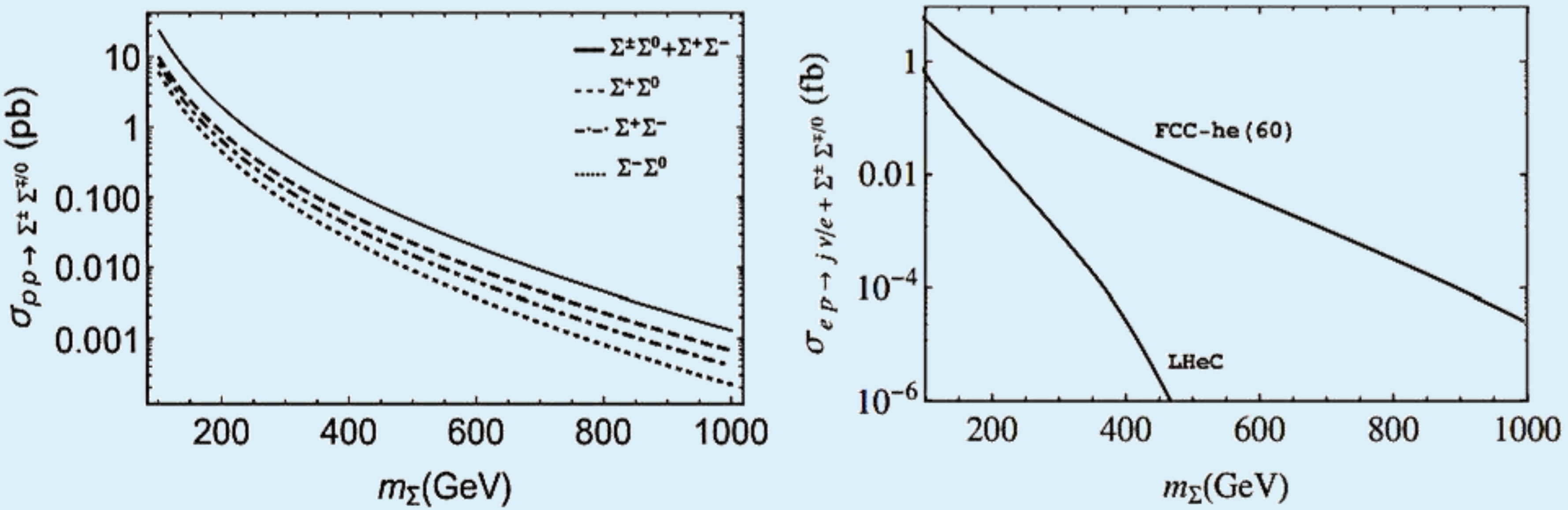


$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Displaced vertex and disappearing signature in type-III Seesaw

- *Production:*

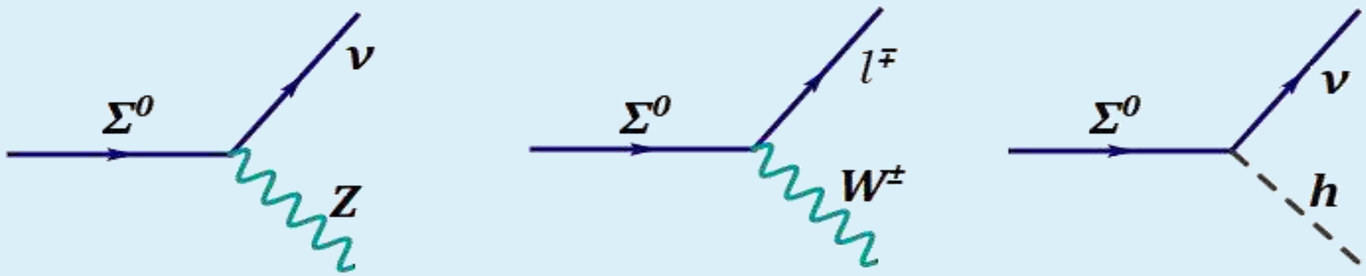




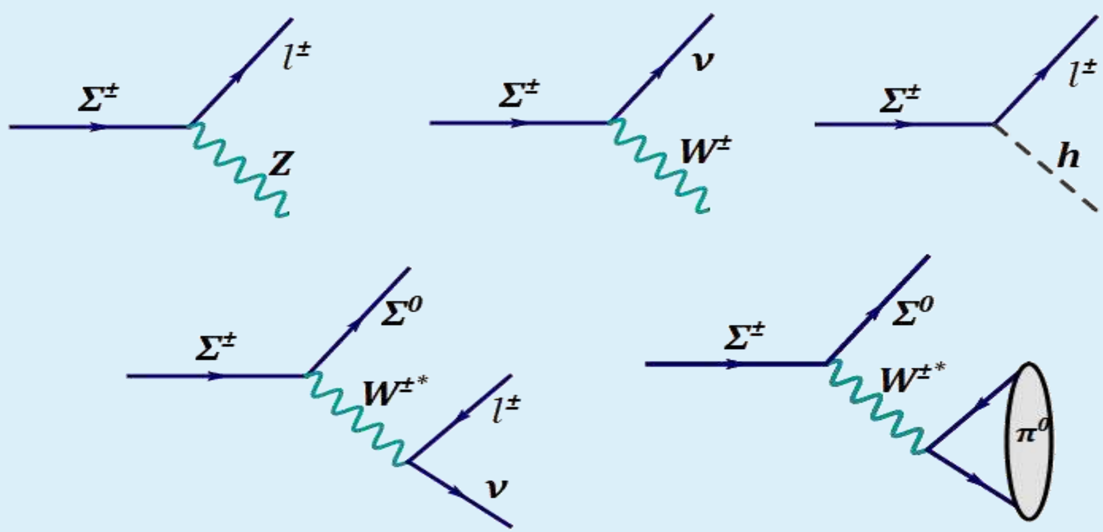
SJ, N.Okada and D.Raut (2019)

Displaced vertex and disappearing signature in type-III Seesaw

- Decay modes of neutral fermion :



- Decay modes of charged fermion :



Displaced vertex and disappearing signature in type-III Seesaw

❖ Connection with neutrino parameters

- *Light neutrino mass matrix:* $m_\nu \simeq m_D \left(M_\Sigma\right)^{-1} m_D^T$
- *Neutrino flavor eigenstate:* $\nu \simeq \mathcal{N}\nu_m + \mathcal{R}N_m,$

$$\mathcal{R} = m_D(M_\Sigma)^{-1},\ \mathcal{N} = \left(1 - \tfrac{1}{2}\mathcal{R}^*\mathcal{R}^T\right)U_{\rm MNS} \simeq U_{\rm MNS}$$

- *Diagonalization of neutrino mass matrix:* $U_{\rm MNS}^T m_\nu U_{\rm MNS} = D_\nu = {\rm diag}(m_1, m_2, m_3)$

$$U_{\rm MNS} = \begin{pmatrix} c_{12}c_{13} & c_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\rho_1} & 0 \\ 0 & 0 & e^{-i\rho_2} \end{pmatrix}$$

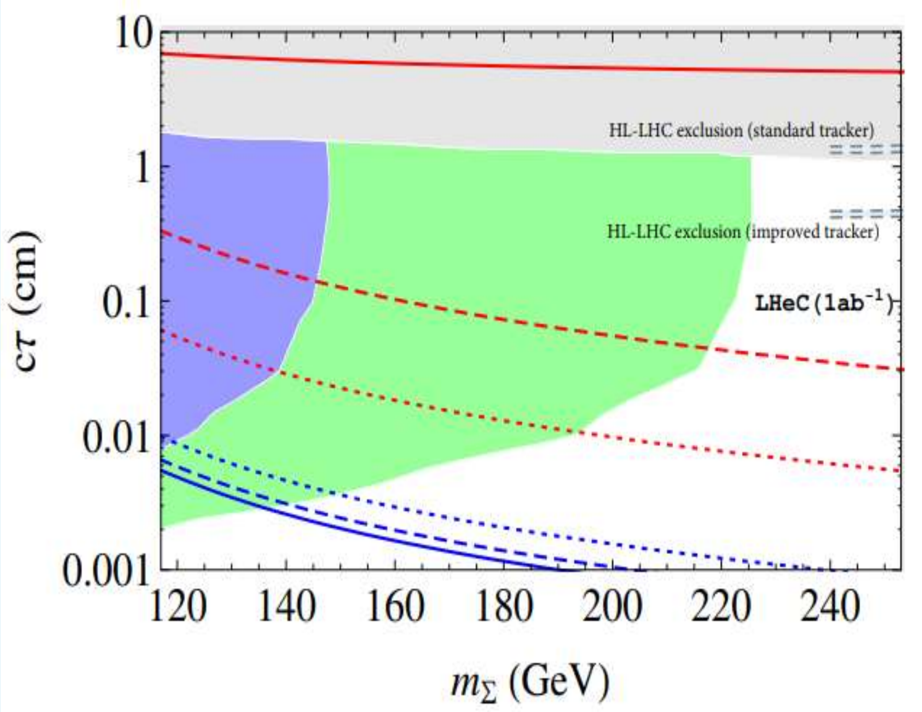
- *Dirac mass matrix:* $m_D = U_{\rm MNS}^* \sqrt{D_\nu}\, O \sqrt{M_\Sigma} = \frac{1}{m_\Sigma} U_{\rm MNS}^* \sqrt{D_\nu}\, O$

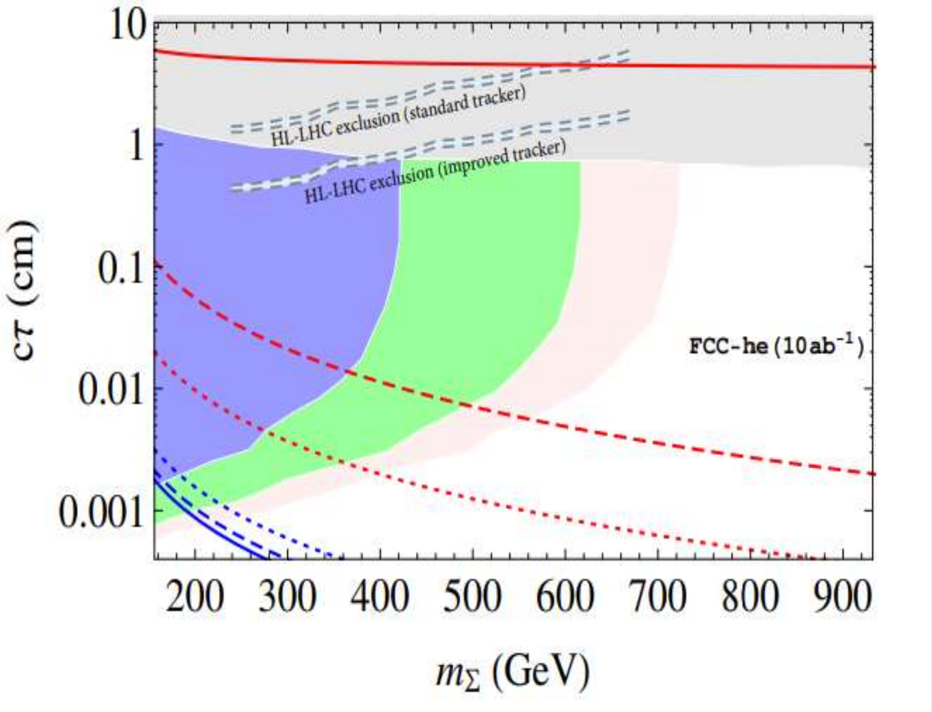
$$\sqrt{D_\nu} = {\rm diag}\left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}\right)$$

$$O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_1 & \sin\theta_1 \\ 0 & -\sin\theta_1 & \cos\theta_1 \end{pmatrix} \begin{pmatrix} \cos\theta_2 & 0 & \sin\theta_2 \\ 0 & 1 & 0 \\ -\sin\theta_2 & 0 & \cos\theta_2 \end{pmatrix} \begin{pmatrix} \cos\theta_3 & \sin\theta_3 & 0 \\ -\sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

SJ, N.Okada and D.Raut (2019)

Displaced vertex and disappearing signature in type-III Seesaw





SJ, N.Okada and D.Raut (2019)

For chargino/neutralino case: O. Fischer et al. (2017)

ν

$\updownarrow$

Intensity frontier

Scale of Seesaw Mechanism

- Despite numerous searches for neutrino mass models (at TeV scale) at high-energy colliders, no compelling evidence has been found so far.

- The new physics scale behind neutrino mass generation mechanism might be at low scale and which is less sensitive to high energy collider experiments

- It may show up at low energy neutrino experiments at near future.

Scale of Seesaw Mechanism

- Despite numerous searches for neutrino mass models (at TeV scale) at high-energy colliders, no com… evidence has been found so fa…

- Is it really sufficient to searc… …de behind neutrino mass … …at LHC

- The ne… …d neutrino mass generation … at low scale and which is less … high energy collider experiments

- …ay show up at low energy neutrino experiments at near future.

Can neutrino masses come from light physics ?

Neutrino masses from light physics

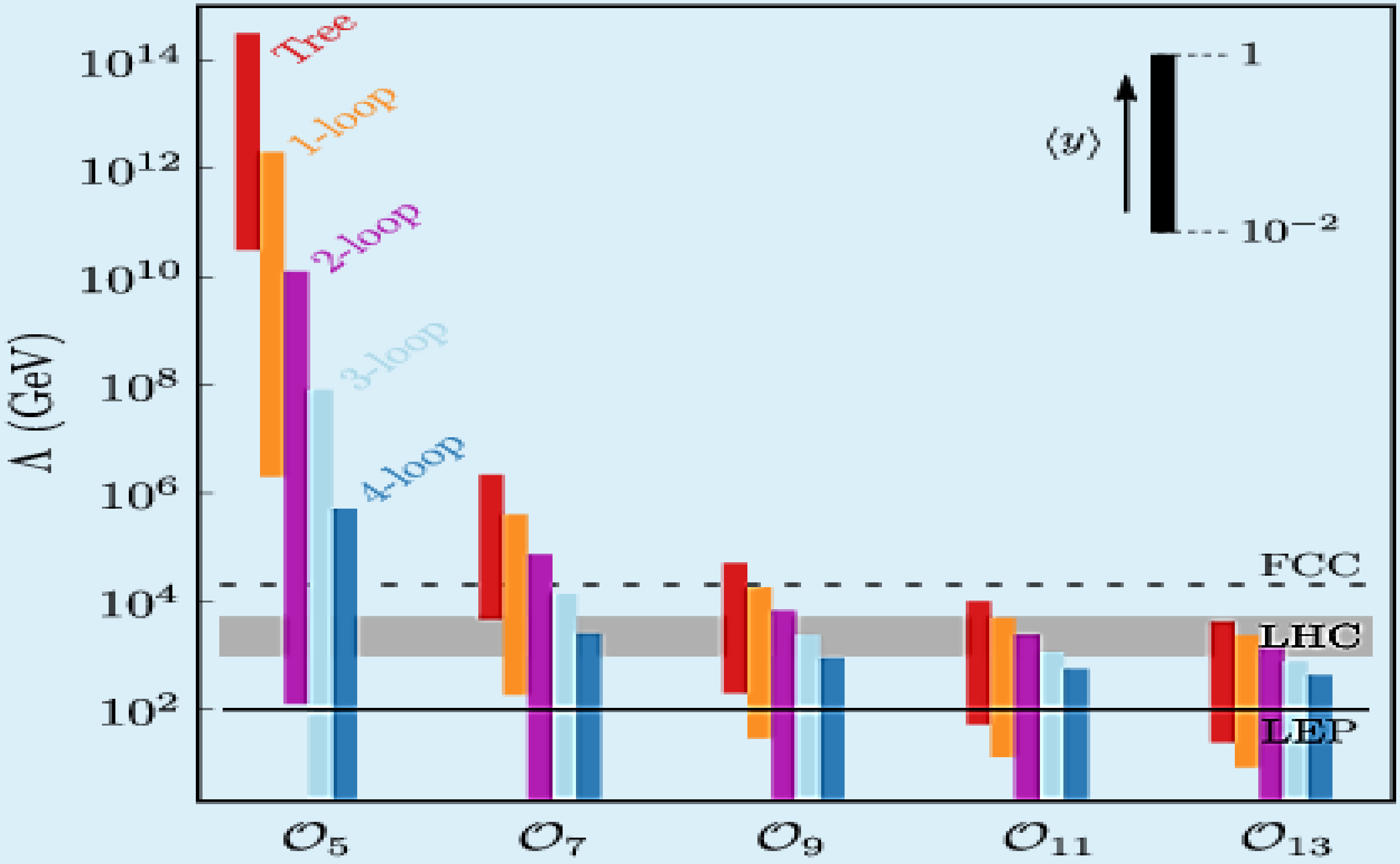
In an effective theory, the Lagrangian should be described as

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\mathrm{NP}}^3}\mathcal{O}^{d=7} + \cdots$$

Neutrino masses from a n-loop-induced dim-d operator

$$m_\nu = v \times \left(\frac{1}{16\pi^2}\right)^n \times \left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^{d-4}$$

Scale of Seesaw Mechanism

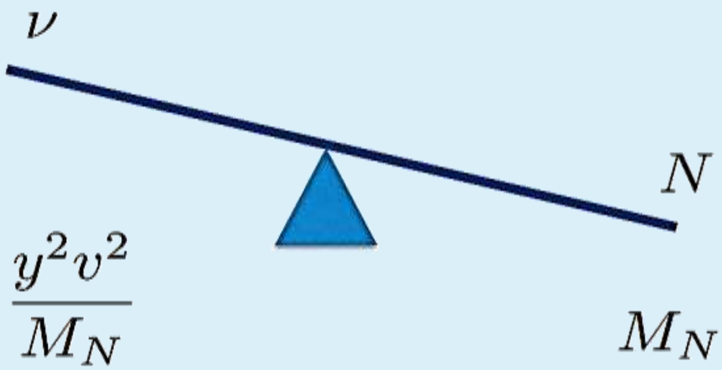


Standard/ type I Seesaw mechanism

$$yNH\ell + M_N NN$$

$$\frac{y^2 \ell H \ell H}{M_N}$$

$$m_\nu \sim \frac{y^2 v^2}{M_N}$$



$$\boxed{m_\nu \sim 0.1\text{eV} \qquad y \sim 0.1 \qquad M_N \sim 10^{12}\text{GeV}}$$

Lepton number is broken at very high scale M_N

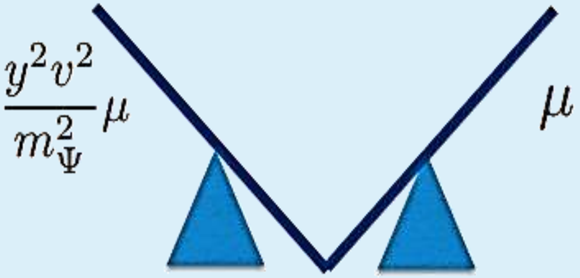
Inverse Seesaw

[Mohapatra, 86]
[Mohapatra,Valle, 86]

$$y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$

Ψ, Ψ^c **Pseudo-Dirac**

$$m_\nu \sim \frac{y^2 v^2}{m_\Psi^2}\mu$$



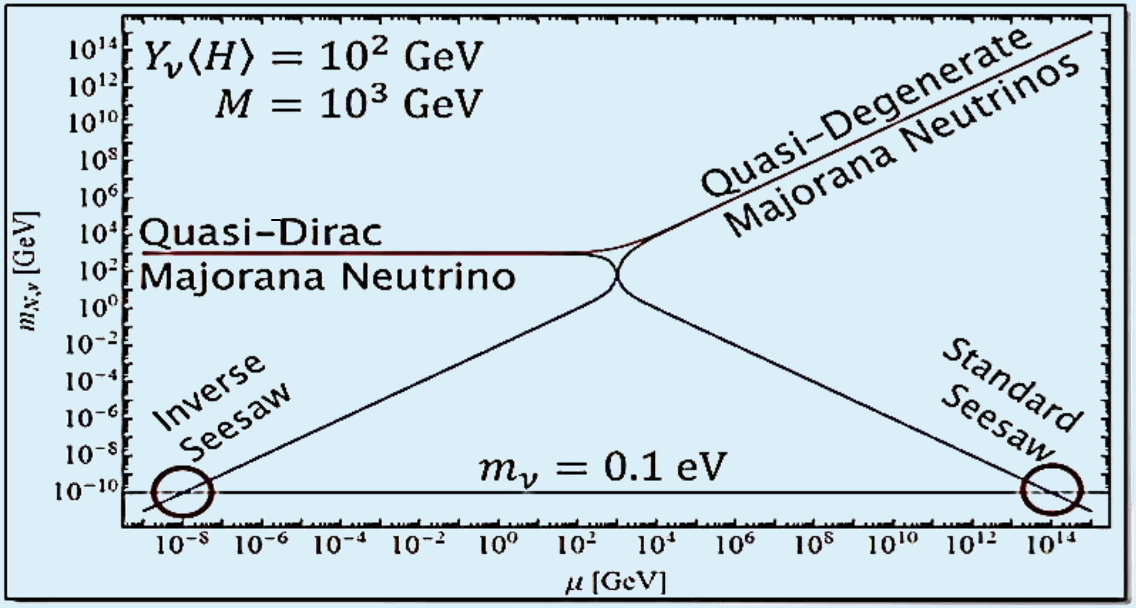
$$y \sim 0.1 \quad m_\Psi \sim 1\text{TeV} \quad \mu \sim 1\text{keV}$$

- Why μ is much smaller than TeV scale?

Scale of Seesaw Mechanism

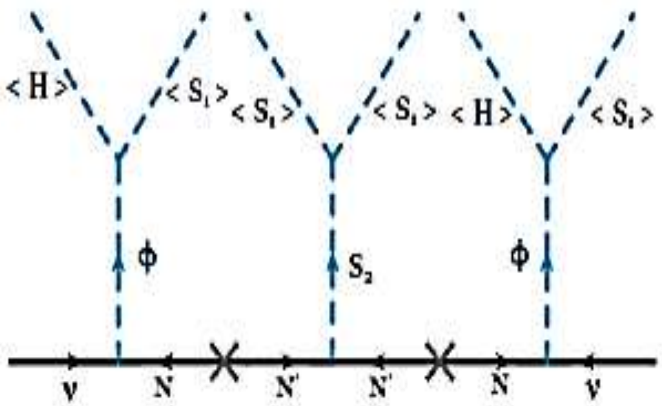
- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $\boxed{Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}}$
  - “Bent” Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$\boxed{\begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}}$$



    - Large Yukawa couplings $\approx 10^{-2}$
    - Quasi-Dirac heavy neutrino

Neutrino masses from light physics



$$\mathcal{L}_{\nu}^{d=9} \sim y_{\nu}^2 \, y_N \, \frac{\mu^2}{M_{H_D}^2} \frac{\mu'}{M_{S'_D}^4} \frac{(\overline{L^c} H)(H^T L)}{m^2} (S_1^* S_1)^2$$

Neutrino masses from D=9 operator

Bertuzzo, SJ, Machado, Z. Funchal (2018)

All scales involved may be below electroweak

Light Z_D, ν-N mixing, Z_D-ν-N coupling, kinetic mixing unavoidable

Neutrino masses from light physics

Gauge $U(1)_D$: SM has no charge, RH neutrinos N have charge +1

Anomaly cancellation: N' with opposite charge should be included

anomaly cancellation is a requirement to have a consistent QFT

Walks and quacks like inverse seesaw

$$\mathcal{M}_\nu = \begin{array}{cc} \begin{pmatrix} 0 & m & 0 \\ m & 0 & M \\ 0 & M & \mu \end{pmatrix} & \begin{array}{cc} \nu & 0 \\ N & + \\ N' & - \end{array} \end{array} \Longrightarrow \quad m_\nu = \mu \frac{m^2}{M^2}$$

m and μ are forbidden by dark symmetry, they need to be generated dynamically

Bertuzzo, SJ, Machado, Z. Funchal (2018)

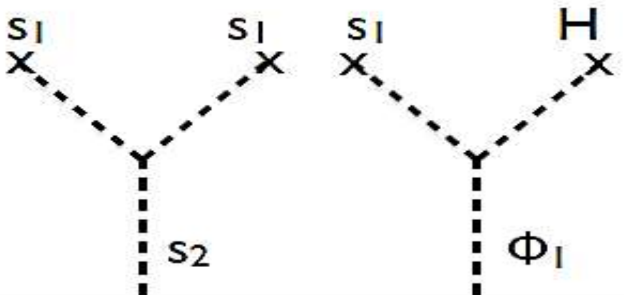
Neutrino masses from light physics

Minimum scalar content

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & y' s_2 \end{pmatrix}$$

Φ_1 = doublet with dark charge +1
s_2 = singlet with dark charge +2

Add s_1 with charge +1 and something special happens:
Φ_1 and s_2 start with no vevs, s_1 develops a vev like the Higgs



Φ_1 and s_2 vevs are **induced**, like in type II seesaw, and thus can be naturally very small!

Bertuzzo, SJ, Machado, Z. Funchal (2018)

Neutrino masses from light physics

Vacuum Expectation Values

v (GeV)	ω_1 (MeV)	v_ϕ (MeV)	ω_2 (MeV)
246	136	0.176	0.65

Coupling Constants

λ_H	$\lambda_{H\phi} = \lambda'_{H\phi}$	λ_{HS_1}	λ_{HS_2}
0.129	10^{-3}	10^{-3}	-10^{-3}
$\lambda_{\phi S_1}$	$\lambda_{\phi S_2}$	λ_{S_1}	$\lambda_{S_1 S_2}$
10^{-2}	10^{-2}	2	0.01
μ (GeV)	μ' (GeV)	α	$g_{\mathcal{D}}$
0.15	0.01	10^{-3}	0.22

Bare Masses

m_ϕ (GeV)	m_2 (GeV)
100	5.51

$$
\begin{aligned}
V = & -m_H^2 (H^\dagger H) + m_\phi^2 (\phi^\dagger \phi) - m_1^2 S_1^* S_1 + m_2^2 S_2^* S_2 \\
& - \left[\frac{\mu}{2} S_1 (\phi^\dagger H) + \frac{\mu'}{2} S_1^2 S_2^* + \frac{\alpha}{2} (H^\dagger \phi) S_1 S_2^* + \text{h.c.} \right] \\
& + \lambda'_{H\phi} \phi^\dagger H H^\dagger \phi + \sum_{\varphi}^{\{H,\phi,S_1,S_2\}} \lambda_\varphi (\varphi^\dagger \varphi)^2 \\
& + \sum_{\varphi < \varphi'}^{\{H,\phi,S_1,S_2\}} \lambda_{\varphi\varphi'} (\varphi^\dagger \varphi)(\varphi'^\dagger \varphi') \, .
\end{aligned}
$$

$$
v_\phi \simeq \frac{1}{8\sqrt{2}} \left(\frac{\alpha \mu' v \omega_1^3}{M_{S'_{\mathcal{D}}}^2 M_{H_{\mathcal{D}}}^2} + 4 \frac{\mu \omega_1 v}{M_{H_{\mathcal{D}}}^2} \right) \quad \omega_2 \simeq \frac{1}{8\sqrt{2}} \left(\frac{\alpha \mu v^2 \omega_1^2}{M_{S'_{\mathcal{D}}}^2 M_{H_{\mathcal{D}}}^2} + 4 \frac{\mu' \omega_1^2}{M_{S'_{\mathcal{D}}}^2} \right)
$$

Masses of the Physical Fields

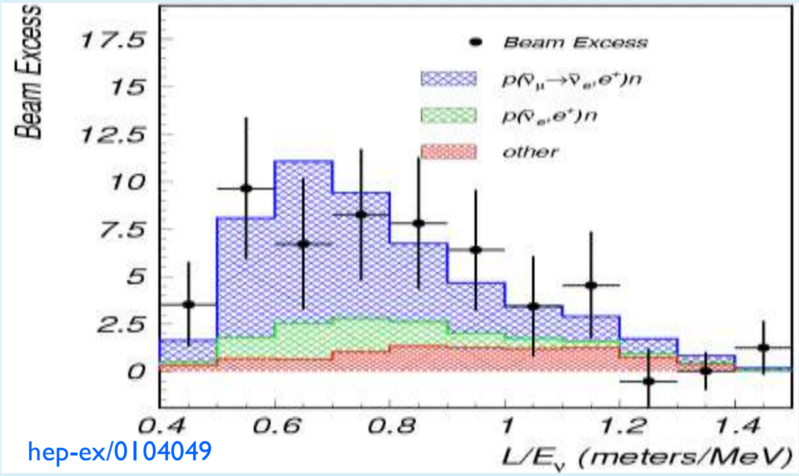
$m_{h_{\rm SM}}$ (GeV)	$m_{H_{\mathcal{D}}}$ (GeV)	$m_{S_{\mathcal{D}}}$ (MeV)	$m_{S'_{\mathcal{D}}}$ (MeV)	$m_{H^\pm_{\mathcal{D}}}$ (GeV)	$m_{A_{\mathcal{D}}}$ (GeV)	$m_{a_{\mathcal{D}}}$ (MeV)	$m_{Z_{\mathcal{D}}}$ (MeV)	$m_{N_{\mathcal{D}}}$ (MeV)
125	100	272	320	100	100	272	30	150

Mixing between the Fields

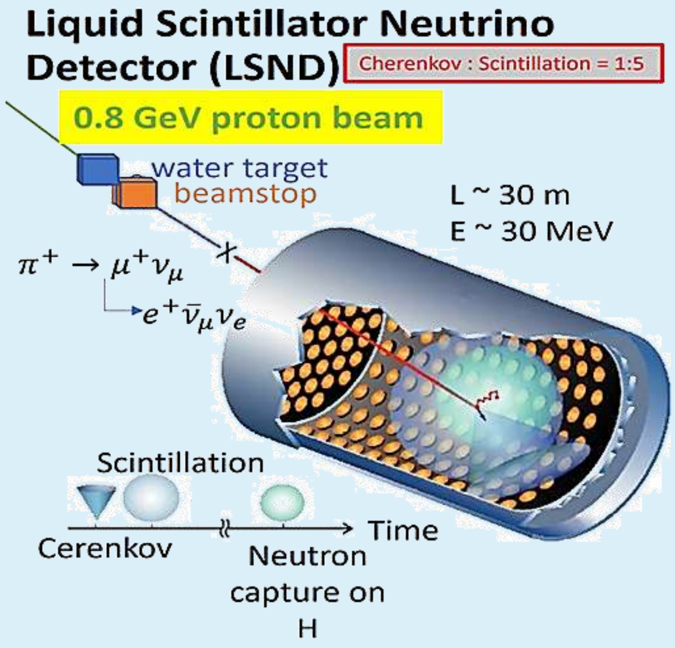
$\theta_{H\phi}$	θ_{HS_1}	θ_{HS_2}	$\theta_{\phi S_1}$	$\theta_{\phi S_2}$	$\theta_{S_1 S_2}$	$e\epsilon$	ϵ'	$\lvert U_{\alpha N}\rvert^2$
1.3×10^{-6}	2.1×10^{-6}	10^{-8}	1.2×10^{-3}	8.3×10^{-7}	3.4×10^{-2}	2×10^{-4}	3.6×10^{-14}	$\mathcal{O}(10^{-6})$

Bertuzzo, SJ, Machado, Z. Funchal (2018)

LSND anomaly



hep-ex/0104049

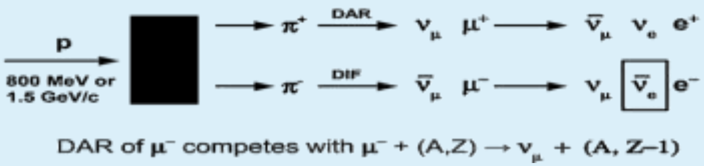


LSND detected more $\bar{\nu}_e$ than expected :

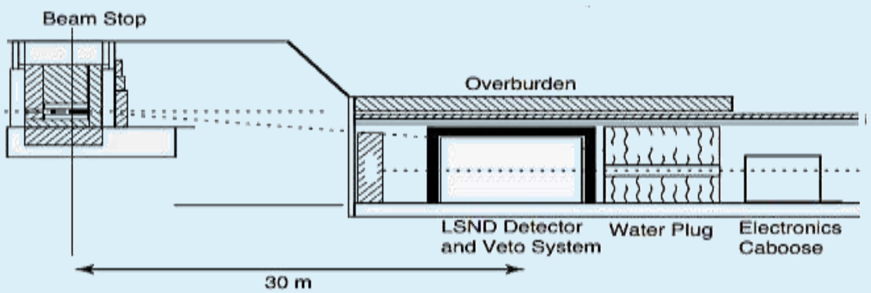
87.9 ± 22.4 ± 6.0 events

3.8 σ excess

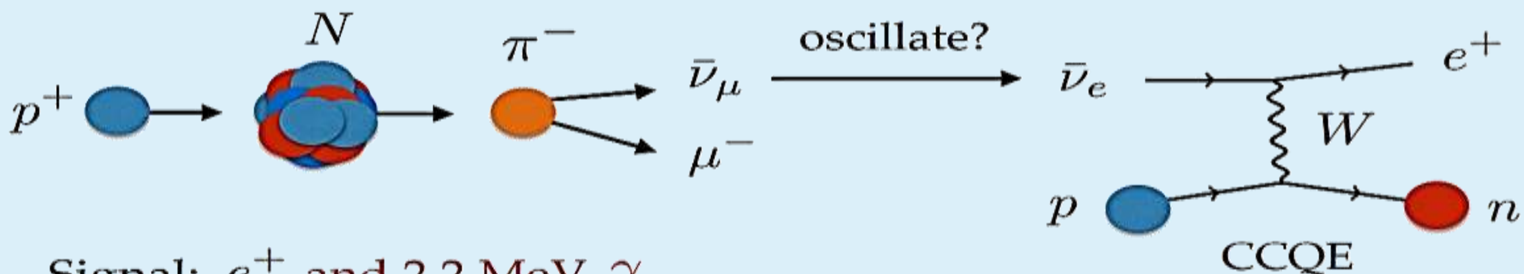
LSND neutrino source



LSND anomaly



10^{22} POT, $E_p = 800$ MeV



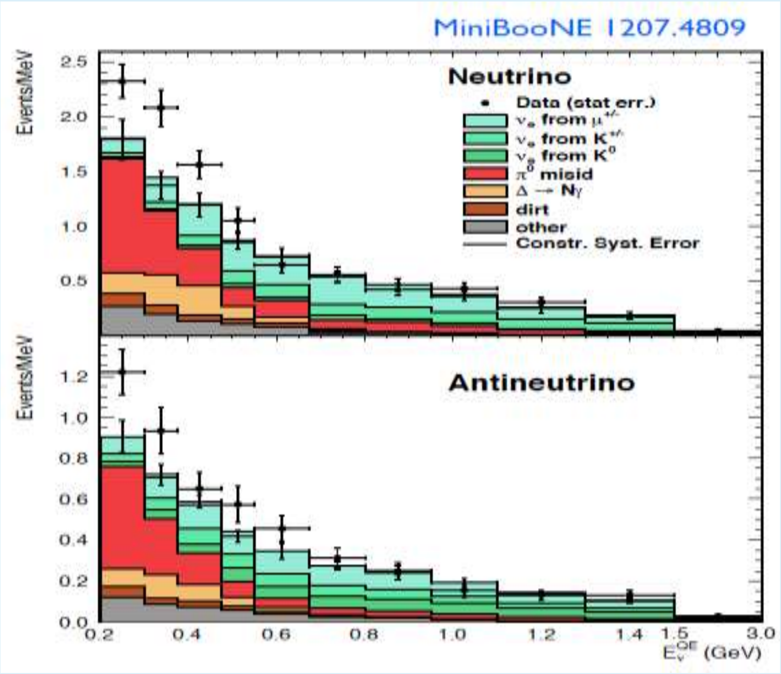
Signal: e^+ and 2.2 MeV γ
Scatter + neutron absorption

Observed 90 events
Expectation of 0 events
3.8σ significance

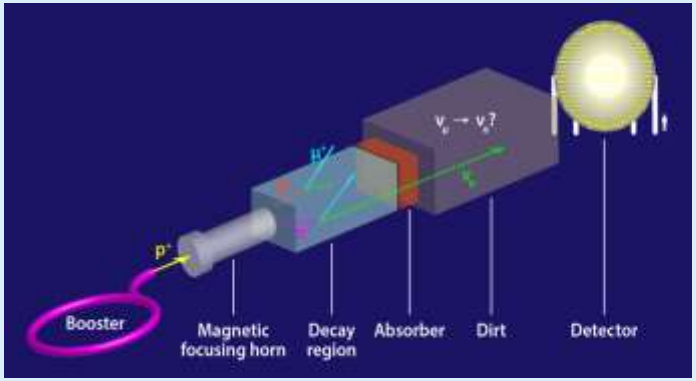
$$P_{\rm osc} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

LSND Collaboration hep-ex/0104049

MiniBooNE anomaly

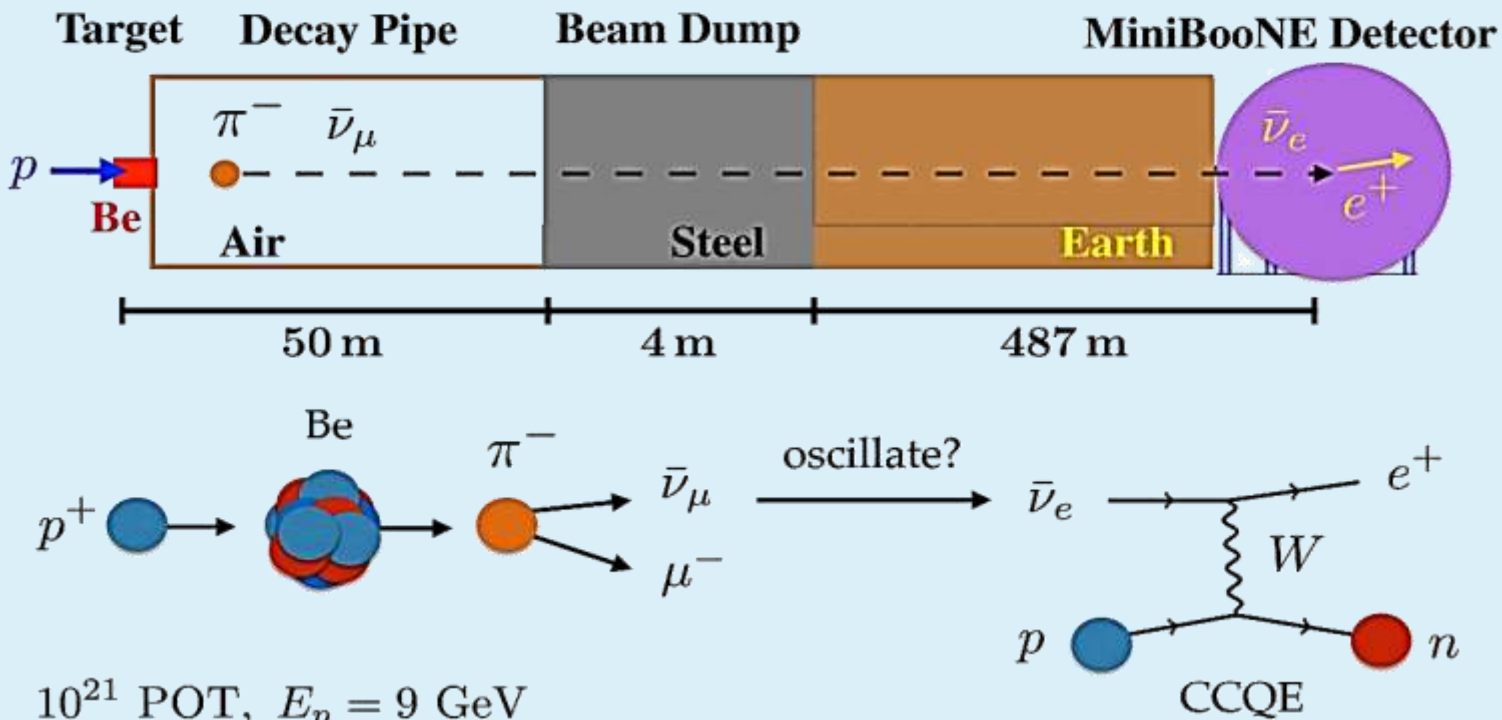


•Neutrino and anti neutrino modes see excesses of ν_e and $\overline{\nu}_e$ (Combined is also 3.8 σ excess)



- To test the LSND indication of anti-electron neutrino oscillations
- Keep L/E same, change beam, energy, and systematic errors
- Baseline: L = 540 meters, ~ x 15 LSND
- Neutrino Beam Energy: E ~ x (10-20) LSND
- Different systematics: event signatures and backgrounds different from LSND High statistics: ~ x 6 LSND
- Perform experiment in both neutrino and anti-neutrino modes.

MiniBooNE anomaly



10^{21} POT, $E_p = 9$ GeV

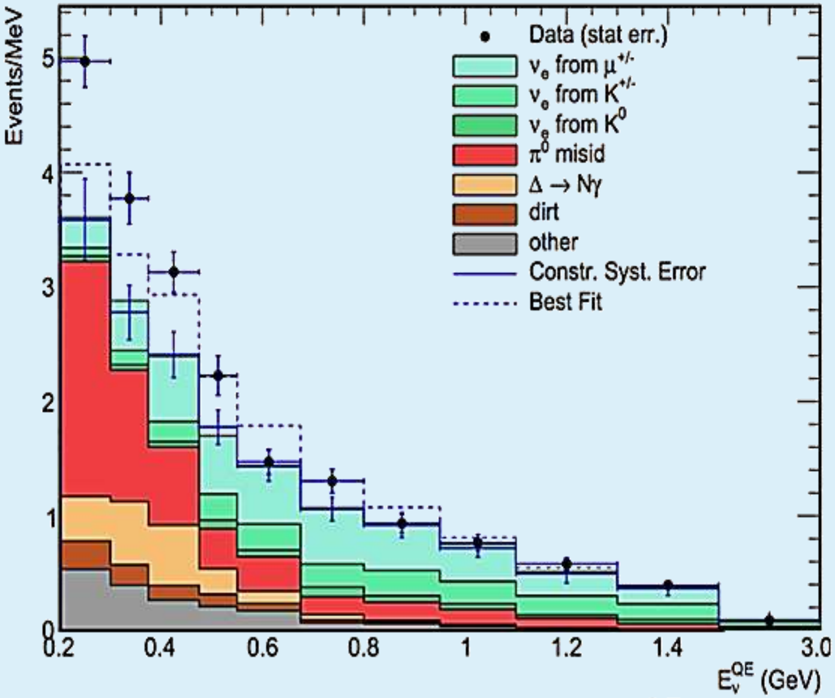
Energy and baseline chosen to test LSND

Comparable oscillation probabilities

MiniBooNE Collaboration 1805.12028

MiniBooNE anomaly

MiniBooNE Collaboration hep-ex/1805.12028



- ❖Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short Baseline Neutrino Experiment
- ❖Double neutrino-mode data in 2016-2017 ($6.46\times10^{20} + 6.38\times10^{20}$ POT)
- ❖Event excess: 381.2 ± 85.2 (4.5σ)

What is going on?

- What is the nature of the excess?
- Possible detector anomalies or reconstruction problems?
- Incorrect estimation of the background?
- New sources of background?
- New physics including/excluding exotic oscillation scenarios?

The origin of such excess is unclear – it could be the presence of new physics, or a large background mismodeling.

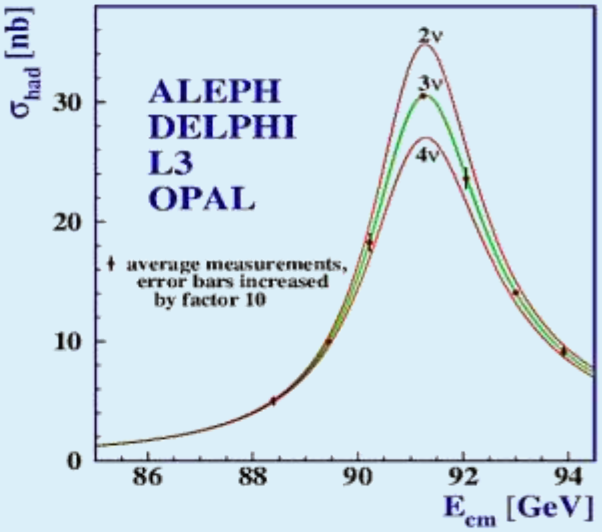
What sort of new physics can explain these anomalies?

What about eV Sterile Neutrino Interpretation ???

Beyond three-neutrino oscillations

- We can add a forth neutrino
- This neutrino must be sterile, which means it is a singlet under all standard model gauge groups
- A forth active neutrino is excluded by observations of invisible Z-decays

$$e^+e^- \to Z \to \sum_{j=e,\mu,\tau} \nu_j$$



Phys. Rept. 427 (2006) 257, LEP

What about eV Sterile Neutrino Interpretation ???

Effective 3+1 oscillations

We extend the mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

APPearance

$$P^{\mathrm{SBL}}_{\alpha\beta} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\nu_\mu \to \nu_e : \sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

@LSND, Karmen, MiniBoone, Opera

DISappearance

$$P^{\mathrm{SBL}}_{\alpha\alpha} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$\nu_e \to \nu_e : |U_{e4}|^2 = \sin^2\theta_{14}$$

@Reactors and **Gallium**

$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

@atmospherics and **accelerators**

What about eV Sterile Neutrino Interpretation ???

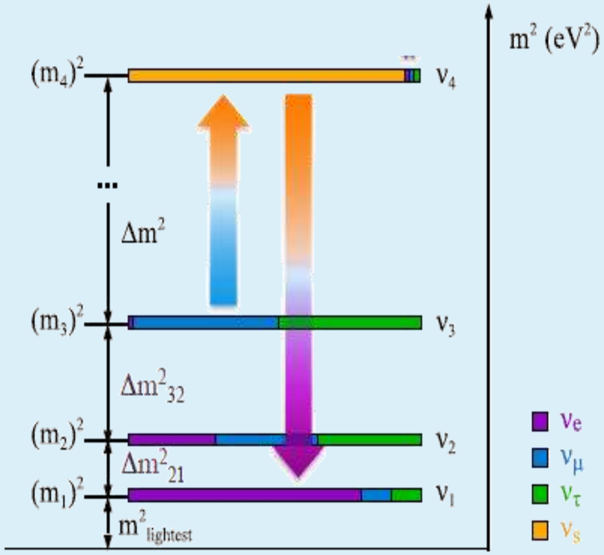
$$P^{\rm SBL}_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\,\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P^{\rm SBL}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\,\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right).$$

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\,U_{\mu 4}|^2$$

Leads to ν_e disappearance

Leads to ν_μ disappearance

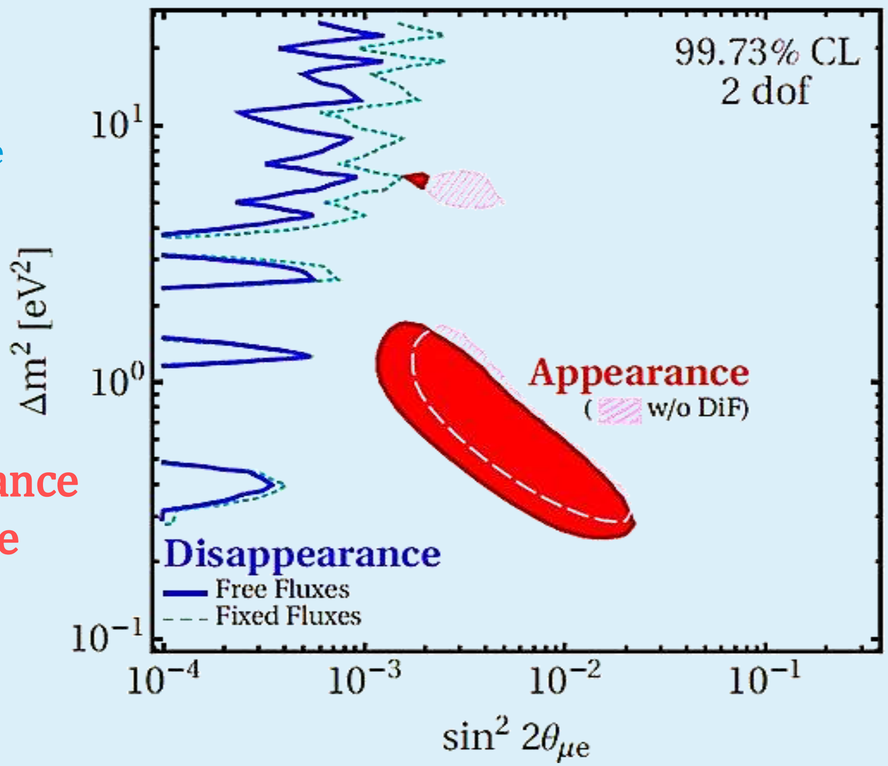


What about eV Sterile Neutrino Interpretation ???

$$\sin^2 2\theta_{\mu e} = 4\,|\underbrace{U_{e4}\ U_{\mu 4}}_{\text{Leads to } \nu_\mu \text{ to } \nu_e \text{ disappearance}}|^2$$

- <u>2 variables</u>: U_{e4}, $U_{\mu 4}$
- <u>3 data sets</u>: ν_e- Disappearance
  ν_μ- Disappearance
  ν_e- Appearance

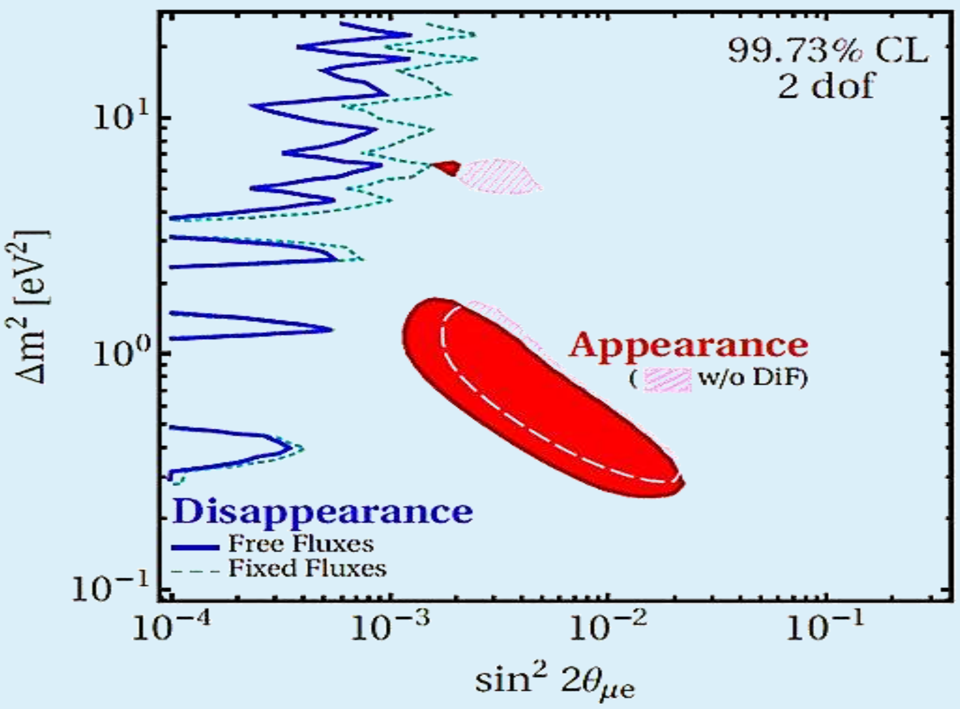
Mona Dentler et al. JHEP 1808 (2018) 010



What about eV Sterile Neutrino Interpretation ???

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}\ U_{\mu 4}|^2$$

4.7 σ tension between Appearance and Disappearance data sets under eV sterile interpretation

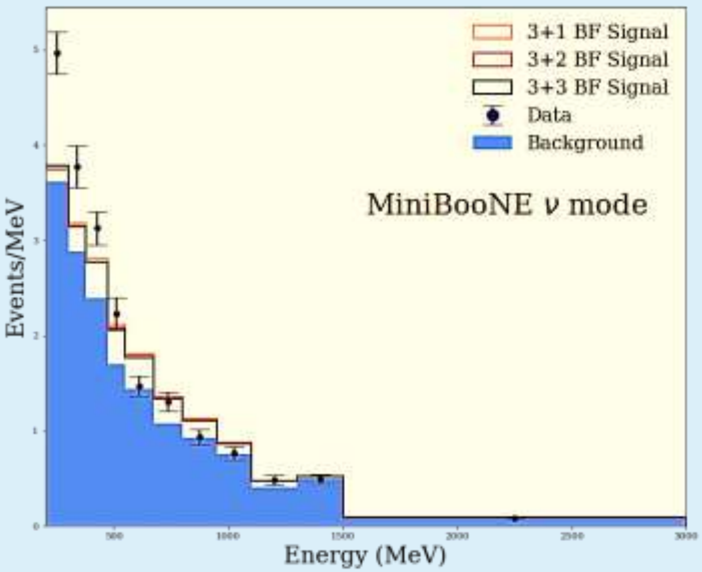


Mona Dentler et al. JHEP 1808 (2018) 010
Collin et al. 1602.00671
Gariazzo et al 1703.00860

What about 3 + N Sterile Neutrino Interpretation ???

Shortcoming:
Failure to accommodate MiniBooNE low-energy excess.

"3+N STANDARD STERILE NEUTRINOS": INSUFFICIENT

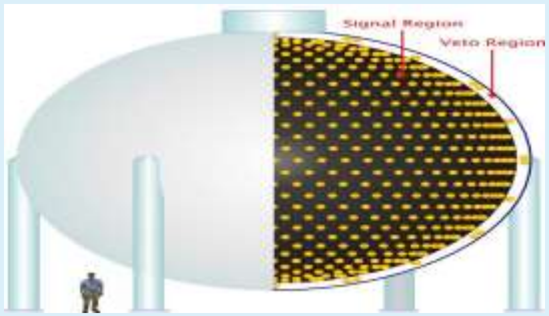


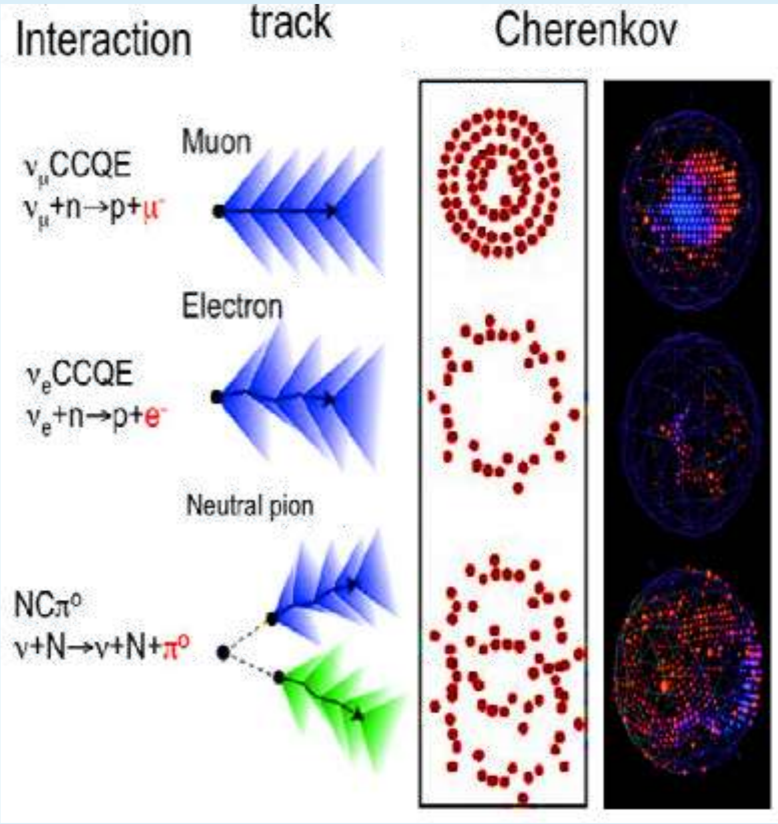
D. Cianci, et al. (Talk presented at Applied Antineutrino Physics Workshop 2018)

❑ *Explanation of MiniBooNE's low energy excess*

- ❖ Sterile ν at the eV scale present strong tension between data sets
- ❖ Cosmological bounds further threat the eV sterile ν hypothesis
- ❖ Is there an explanation that is not ruled out?
- ❖ Is there a "real model" for these explanations?
- ❖ Can this relate to any of the theoretical problems of the SM?

Explanation of MiniBooNE's low energy excess

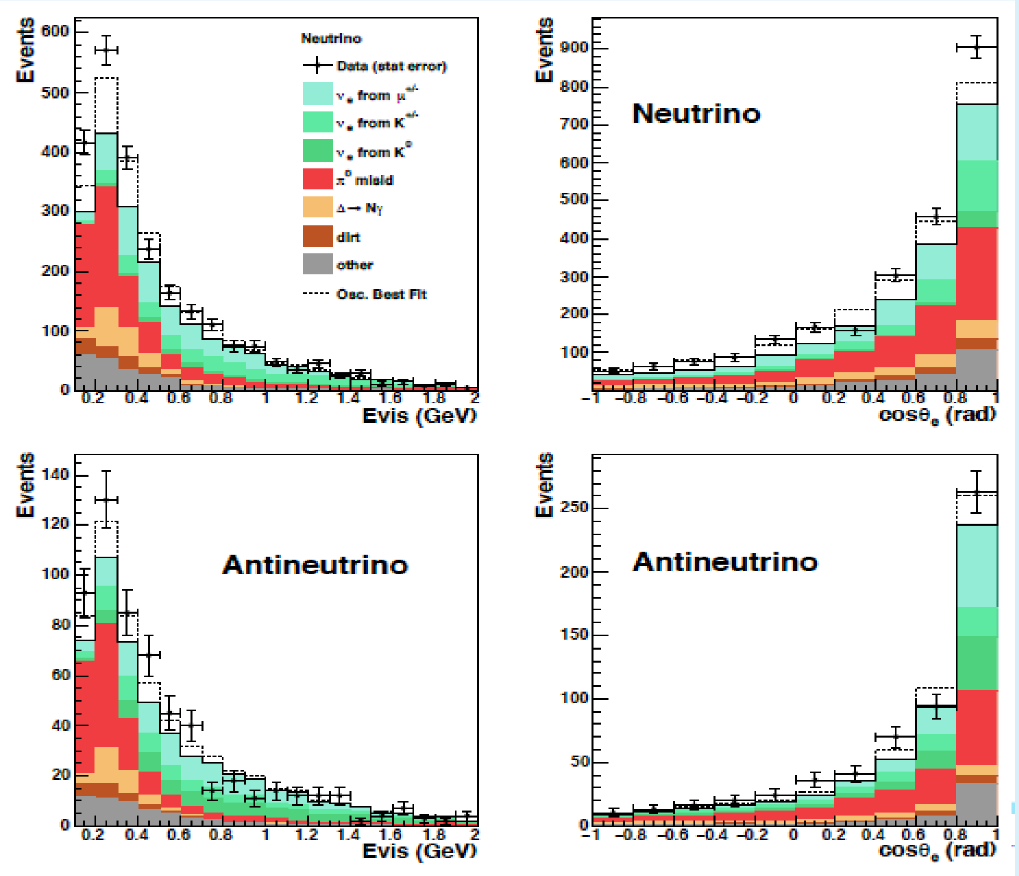




- MiniBooNE is a mineral oil (CH_2) detector that can observe Cherenkov radiation of charged particles.
- Crucially, it could not distinguish electron induced Cherenkov cones from photon induced Cherenkov cones.
- Excess is correlated with beam in power, angle and timing. It is present in positive and negative horn polarities. It is not present in beam dump configuration

Explanation of MiniBooNE's low energy excess

- Angular spectrum is forward, but not that much
- Scattering on electrons would typically lead to $\cos\theta > 0.99$
- Decays of invisible light (<10 MeV) particles produced in the beam would also lead to forward spectrum
- The Cherenkov and scintillation light emitted by charged particles traversing the detector are used for particle identification and neutrino energy reconstruction, assuming the kinematics of CCQE scattering.

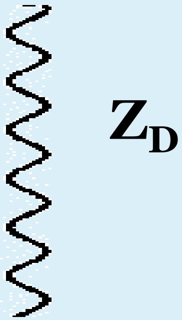


arxiv : 1805.12028 [hep-Ex]

Explanation of MiniBooNE's low energy excess

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction

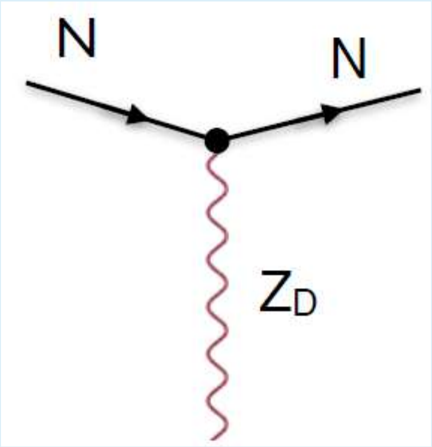


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction

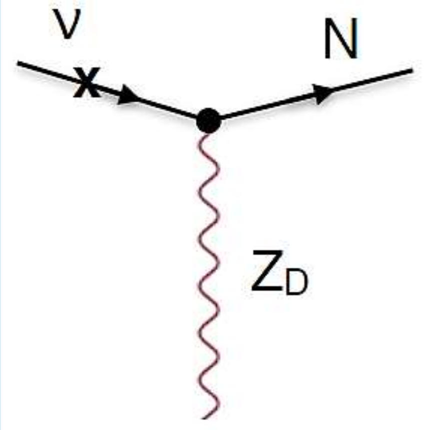


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector

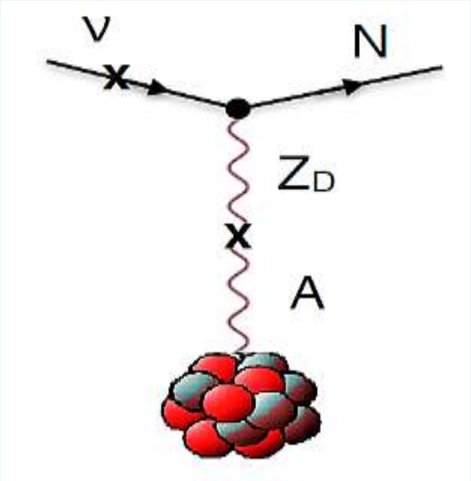


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between Z_D and photon leads to interaction with protons

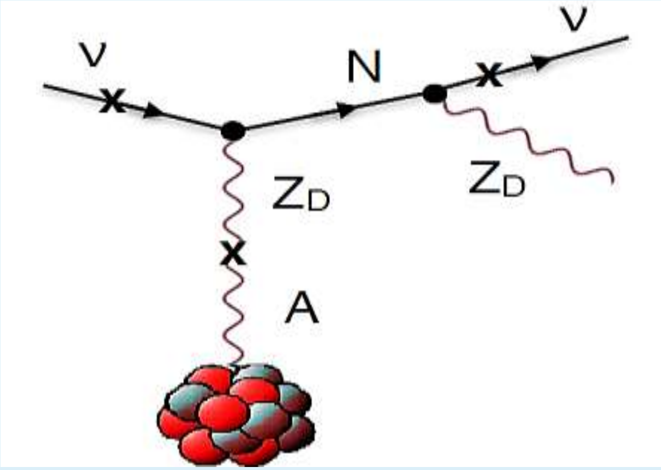


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ Explanation of MiniBooNE's low energy excess

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between Z_D and photon leads to interaction with protons

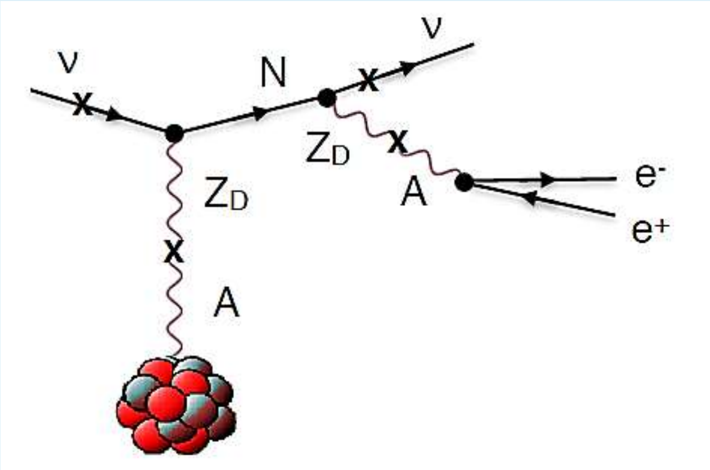


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between Z_D and photon leads to interaction with protons

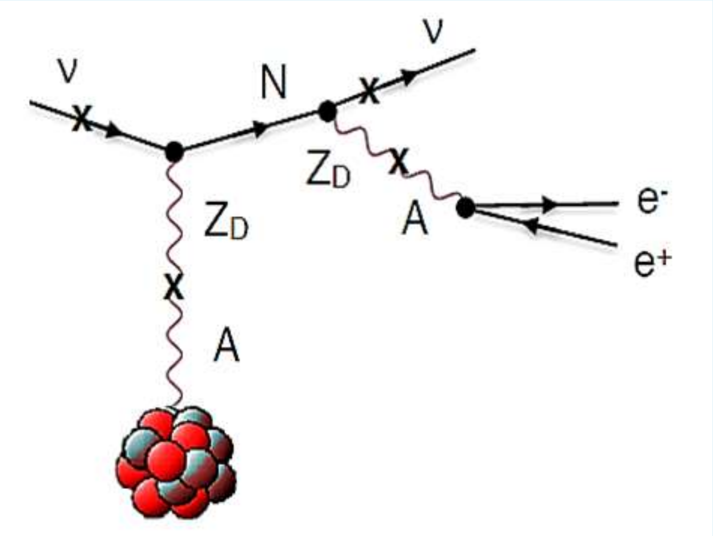


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between Z_D and photon leads to interaction with protons
- Relevant part of the Lagrangian :

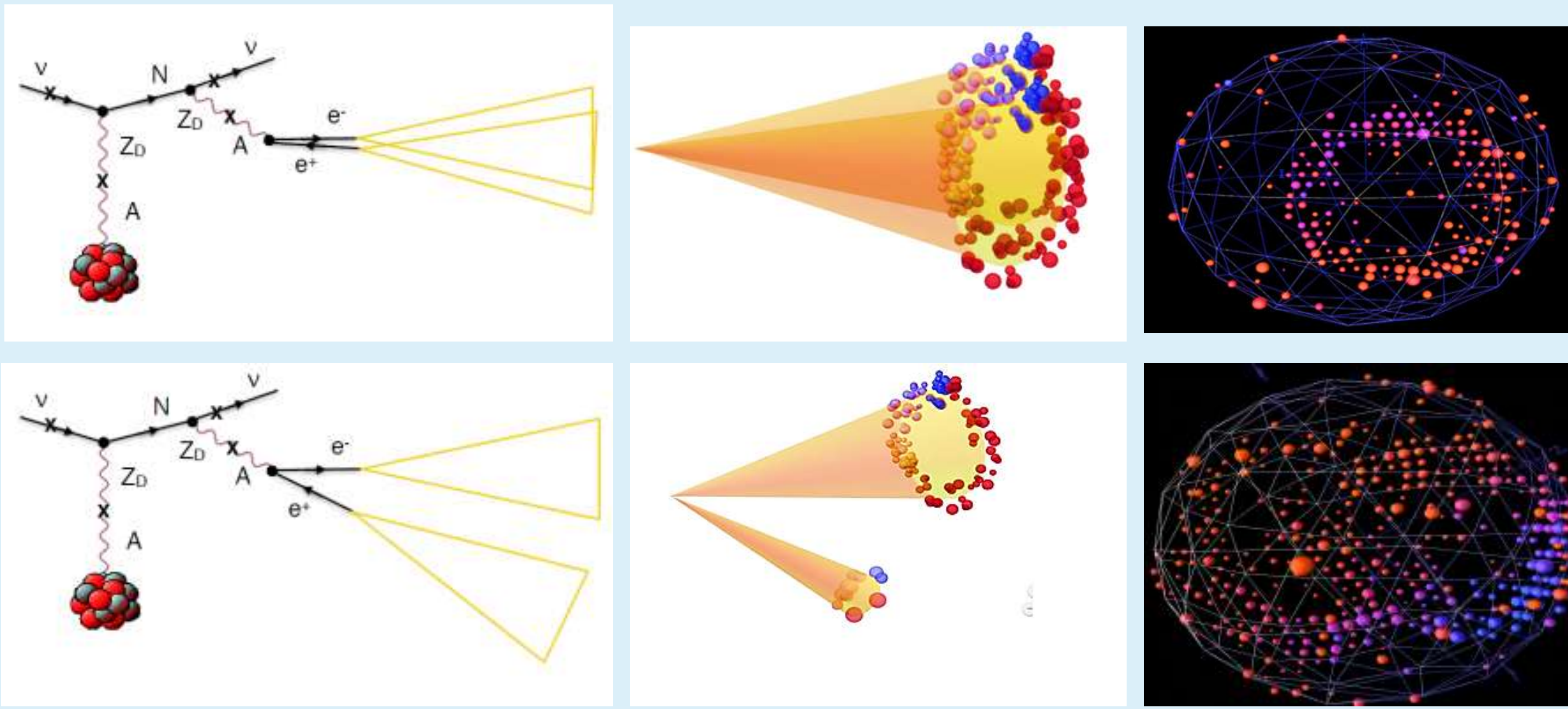


Bertuzzo, SJ, Machado, Z. Funchal (2018)

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} J_{\mathcal{D}\mu} + e\epsilon\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{\text{em}} + \frac{g}{c_W} \epsilon'\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{Z}$$

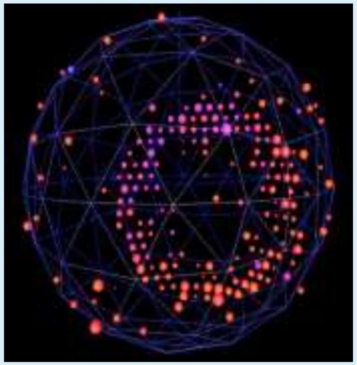
❖ *Explanation of MiniBooNE's low energy excess*

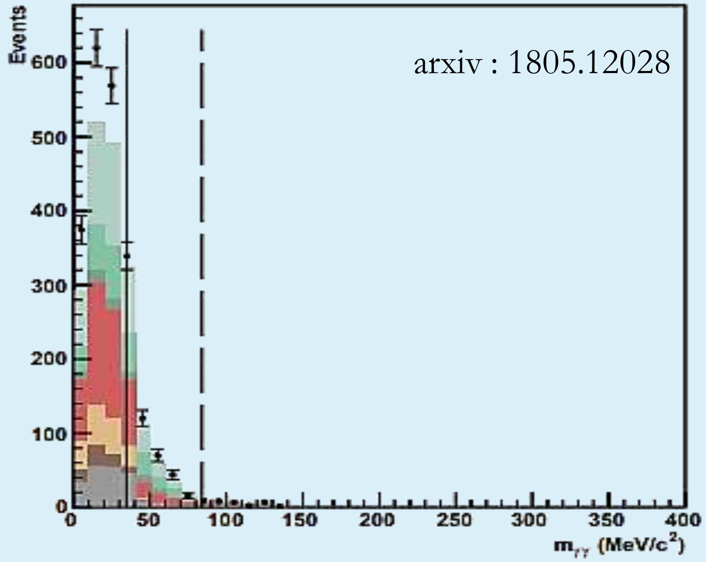
A LIGHT DARK SECTOR – THE IDEA

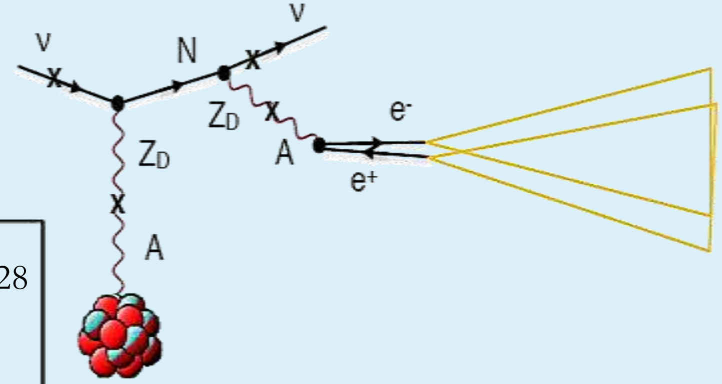


❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



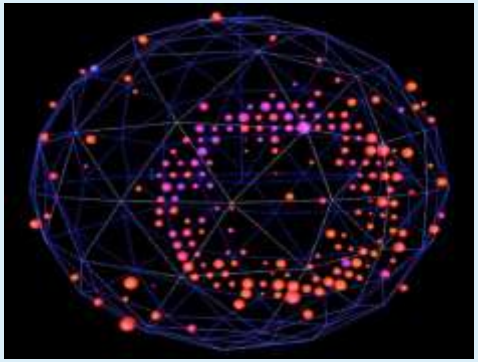


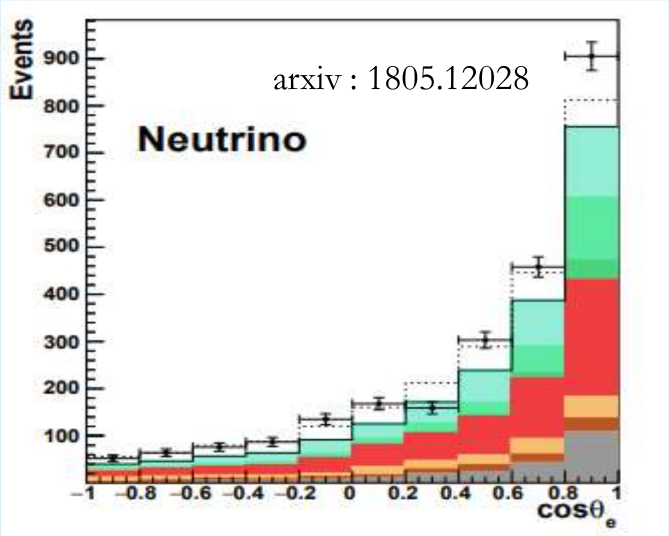


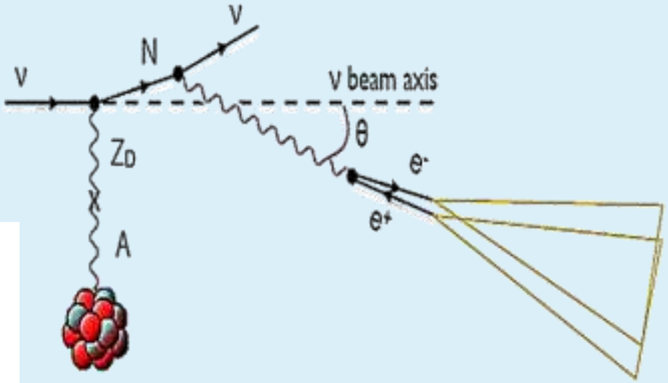
If e^+e^- pair is collimated ($\cos\theta_{ee}$ > 0.99-ish), it will be classified as e-like

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA



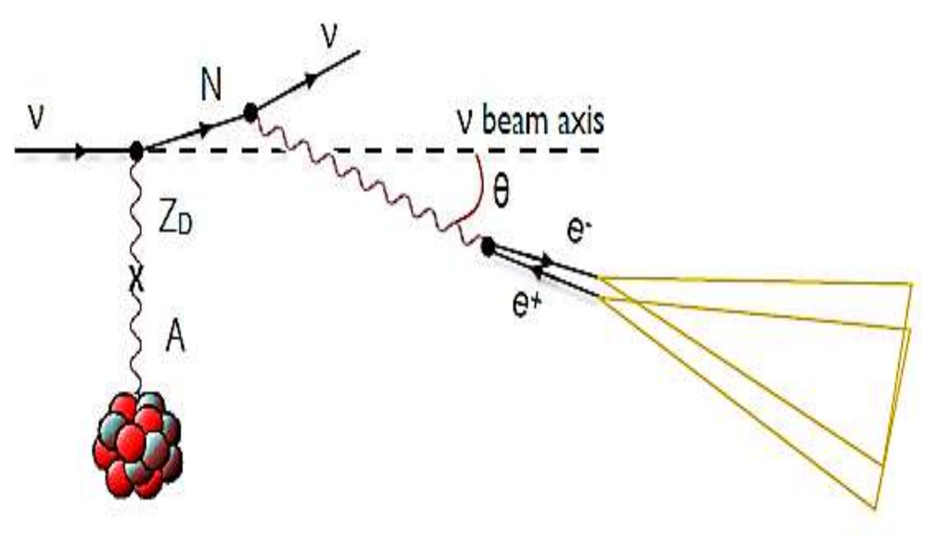


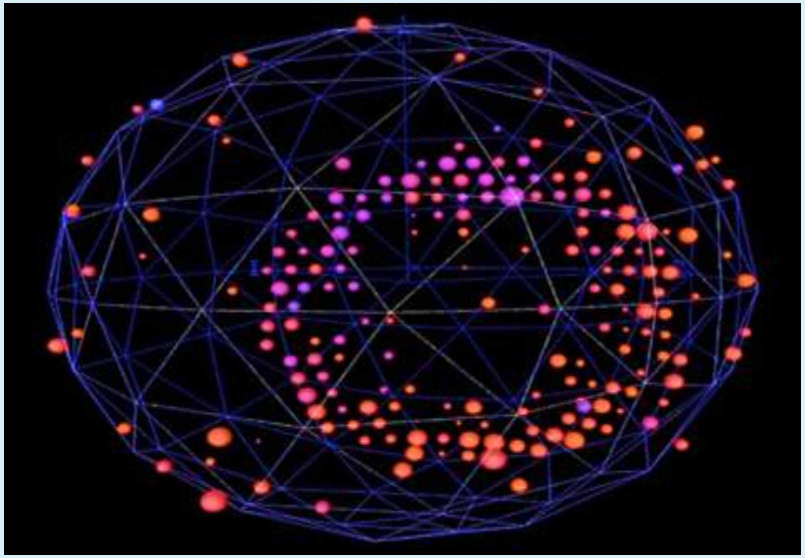


We have to get this angular spectrum

❖ *Explanation of MiniBooNE's low energy excess*

A LIGHT DARK SECTOR – THE IDEA





(1) N_D should be heavy (> 100 MeV) so its decay products are not so boosted

(2) Z_D should be light (< 60 MeV) so that the e^+e^- pair is collimated

Explanation of MiniBooNE's low energy excess

Fit to energy spectrum only

(Official MB data release)

Benchmark Points :

$m_N = 420$ MeV

$m_{ZD} = 30$ MeV

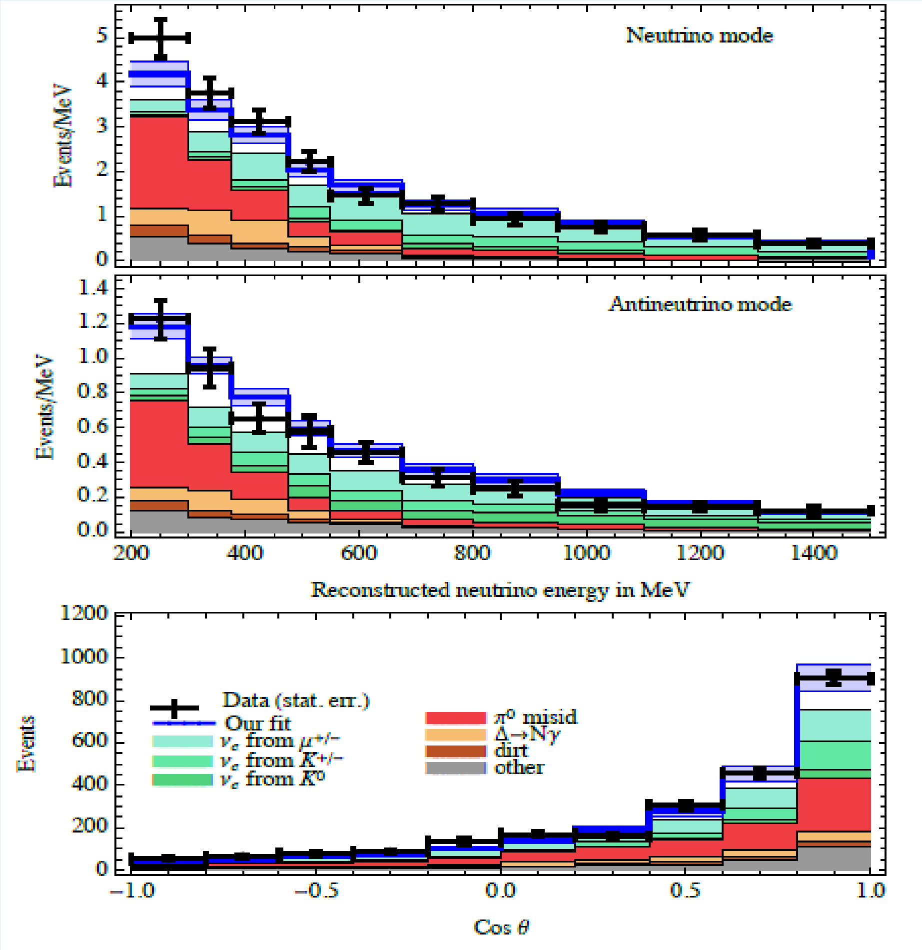
$|U_{\mu 4}|^2 = 9\times10^{-7}$

$\alpha_D = 0.25$

$\alpha\varepsilon^2 = 2 \times 10^{-10}$

$\chi^2/\mathrm{dof} = 33.2/36$

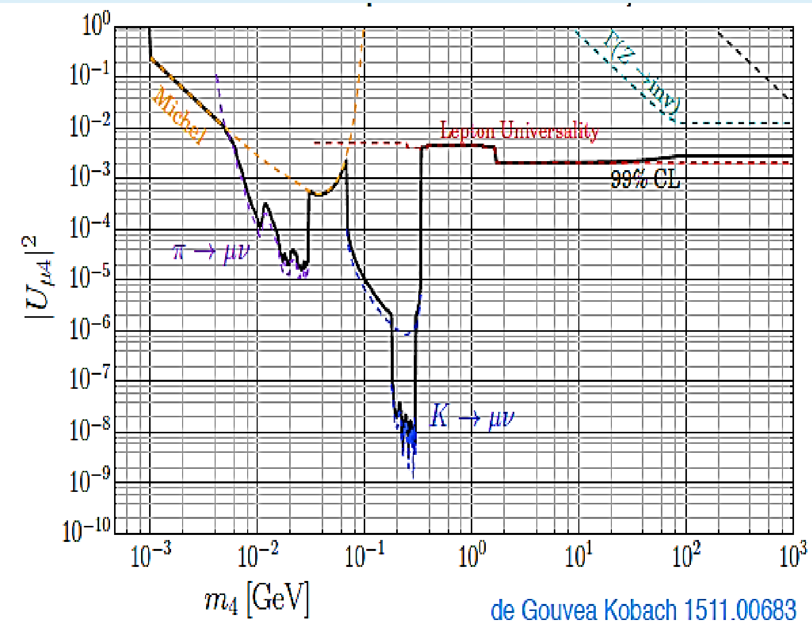
See also Ballett et al 1808.02915
for different realization of the mechanism

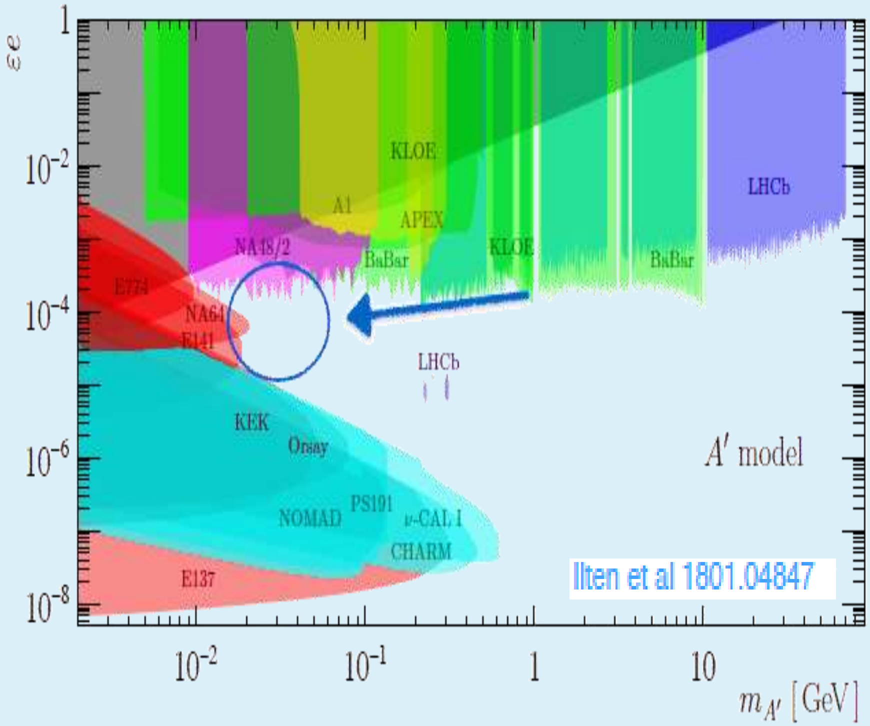


Bertuzzo, SJ, Machado, Z. Funchal (2018)

❖ Constraint on Light Dark Sector

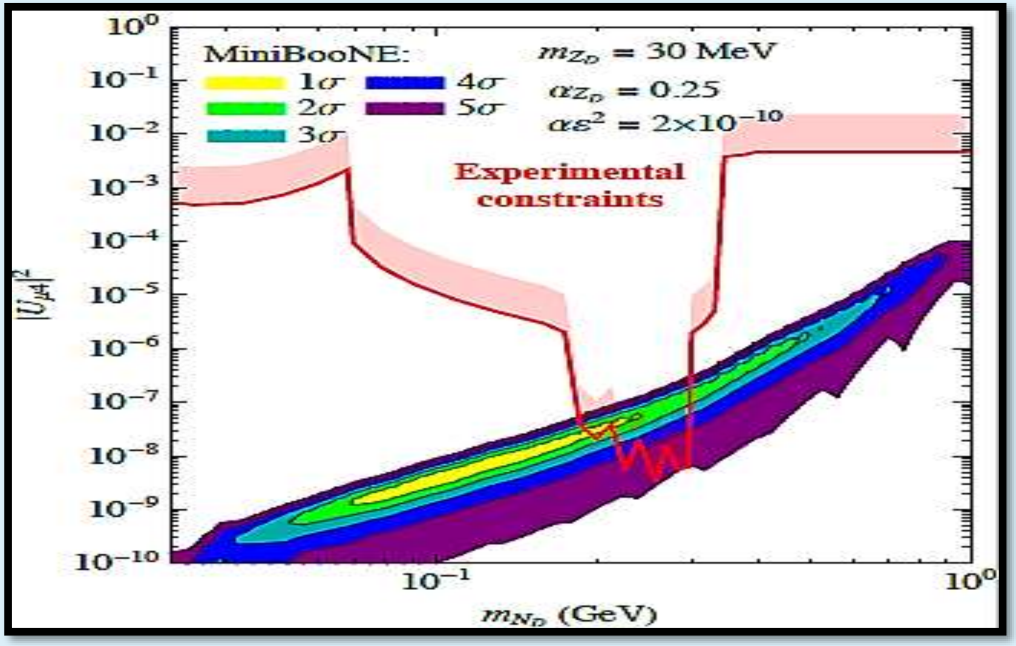
Model Independent Constraint
on Heavy Sterile Neutrino





- ➢ Z_D phenomenology is similar to dark photon case
- ➢ LHC constraints are not expected to be stringent below 1 GeV

❖ *Explanation of MiniBooNE's low energy excess*



Region of our model in the $|U_{\mu 4}|^2$ versus $m_{N_{\mathcal{D}}}$ plane satisfying MiniBooNE data at 1σ to 5σ CL, for the hypothesis $m_{Z_{\mathcal{D}}} = 30$ MeV, $\alpha_{Z_{\mathcal{D}}} = 0.25$ and $\alpha\epsilon^2 = 2 \times 10^{-10}$. The region above the red curve is excluded at 99% CL by meson decays, the muon decay Michel spectrum and lepton universality

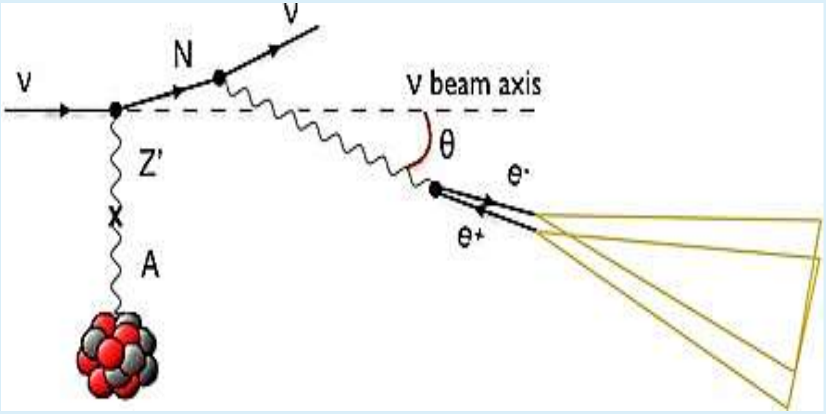
Bertuzzo, SJ, Machado, Z. Funchal (2018)

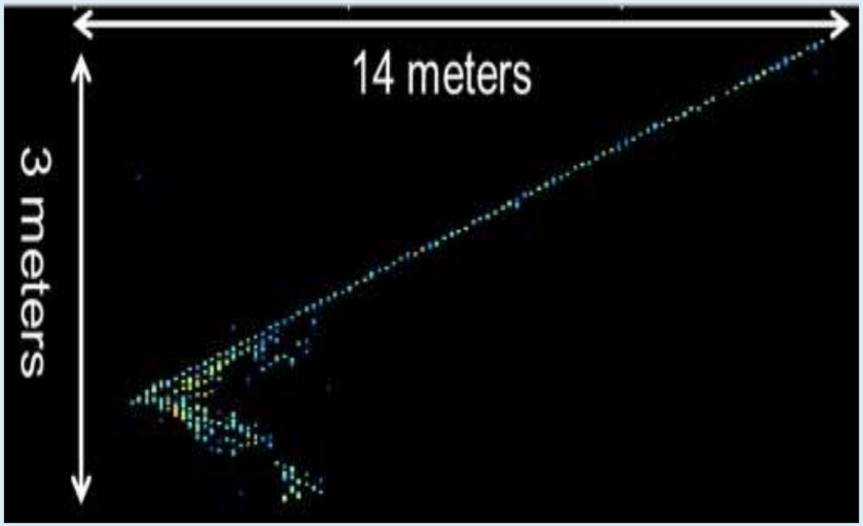
❖ Phenomenology on other neutrino experiment

MiniBooNE's signature: Collimated e^+e^- pair in MINOS+, NOvA, or T2K is likely be tagged as ν_e event

General signature:
Heavy enough Z_D can decay to $\mu^+\mu^-$ or $\pi^+\pi^-$ pair, much easier signature (MINOS+ is magnetized…)

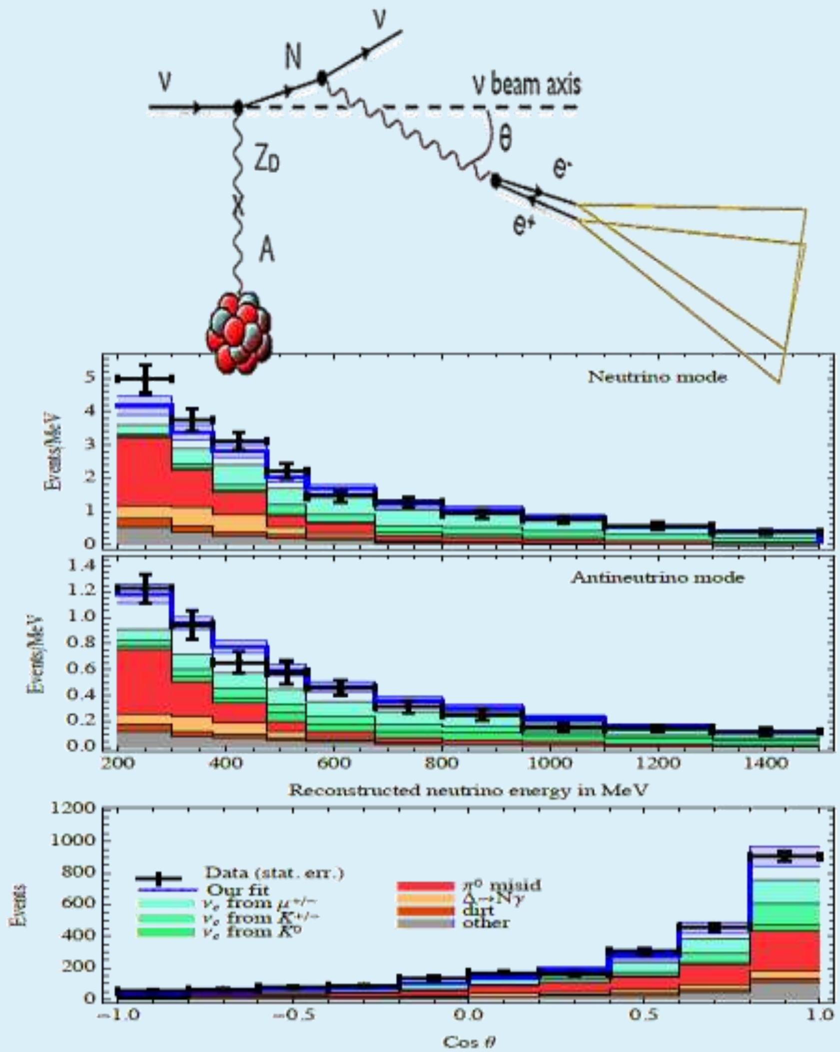
Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N





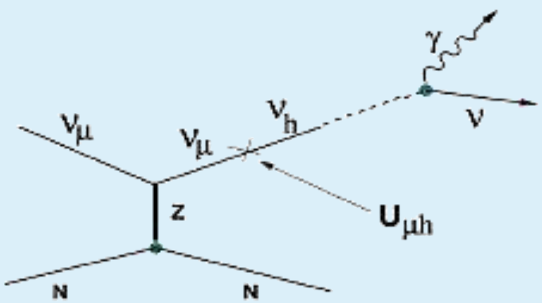
Summary of MiniBooNE's low energy excess

- Novel explanation of MiniBooNE
- Agreement with all EXP data
- Novel, simple frameworks
- Deep connection to neutrino mass generation mechanism
- A realistic "complete" model below EW scale to explain neutrino mass generation
- Solves the hierarchy of Inverse Seesaw
- Rich phenomenology



Beyond standard physics in neutrino experiments

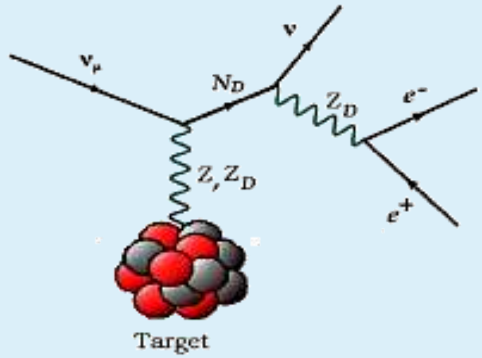
ν magnetic moment



Explains MiniBooNE

Gninenko 0902.3802
Fischer et al. (2019)
so many people...

Dark neutrinos

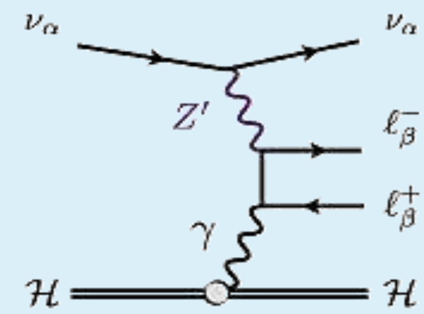


Explains MiniBooNE

Explains m_ν

Bertuzzo et al 1807.09877, 1807.02500
Ballett et al 1808.02915, Arguelles et al 1812.08768

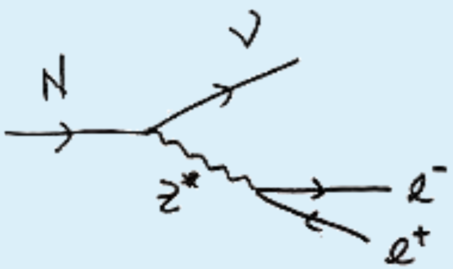
New gauge bosons (e.g. L_μ-L_τ)



Explains $(g-2)_\mu$

Altmannshofer et al 1406.2332
Ballet et al 1902.08579

Heavy neutrinos

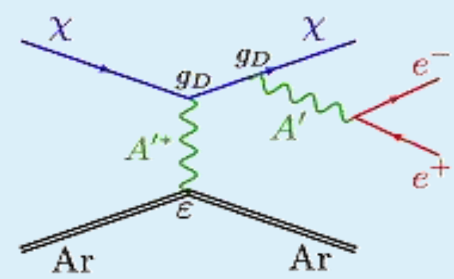


Explains m_ν

Neutrino decay
Decoherence
Non-unitarity
Non-standard interactions
Ultra-light scalars
Dark matter
Extra dimensions
New forces/mediators
Millicharged particles
Neutrino self interactions
...

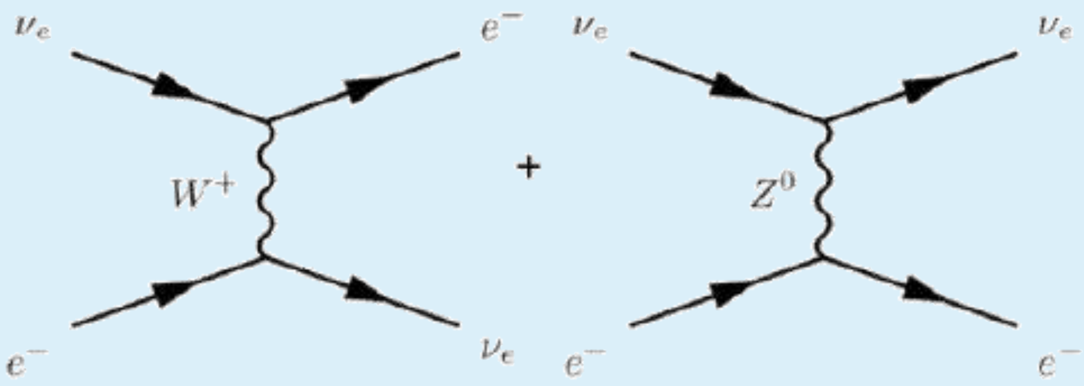
de Gouvêa et al 1809.06388

Dark tridents



Explains DM

Neutrino Standard Interaction



Charged current and Neutral current

- Coherent forward scattering of ν_e off electron in matter generates a matter potential:

  $V = \sqrt{2} G_F N_e \approx 8.2 \times 10^{-12}$ eV in solar core (Wolfenstein)

- Modifies refractive index of ν_e (Mikheyev-Smirnov)
- Neutral current interaction is universal

Neutrino Non-Standard Interaction

- How does this picture change if there are non-standard interactions affecting neutrinos?
- This questions can be formulated in an effective theory of neutrino interactions:

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{f,X,\alpha,\beta} \varepsilon_{\alpha\beta}^{fX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_X f\right) ,$$

$$\mathcal{L}_{\rm NSI}^{\rm CC} = -2\sqrt{2}G_F \sum_{f,f',X,\alpha,\beta} \varepsilon_{\alpha\beta}^{ff'X} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta\right)\left(\bar{f}'\gamma_\mu P_X f\right)$$

Wolfenstein (1978)

- Effective Hamiltonian for neutrino propagation in matter is now:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^\star & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^\star & \varepsilon_{\mu\tau}^\star & \varepsilon_{\tau\tau} \end{pmatrix}$$

- $\epsilon_{\alpha\beta}$ measure of NSI normalized to weak interaction strength

Neutrino Non-Standard Interaction

- These NSI are of great phenomenological interest, as their presence would modify the standard three neutrino oscillation picture.
- The NSI will modify scattering experiments, as the production and detection vertices are corrected; they would also modify neutrino oscillations, primarily through new contributions to matter effects.
- Presence of ε_{ij} affect mass ordering and CP violation

  Esteban, Gonzalez-Garcia, Maltoni (2019)
- There have been a variety of phenomenological studies of NSI in the context of oscillations, but relatively lesser effort has gone into the ultraviolet (UV) completion of models that yield such NSI.
- A major challenge in generating observable NSI in any UV-complete model is that there are severe constraints arising from charged-lepton flavor violation (cLFV).

NSI from non-unitarity of U_{PMNS}

- In seesaw mechanism for neutrino mass generation, (ν, ν^c) mix:

$$\mathcal{M}^{\nu} = \begin{pmatrix} 0 & M_\nu^D \\ M_\nu^{DT} & M_R \end{pmatrix} \qquad \Rightarrow M_\nu^\ell = -M_\nu^D M_R^{-1} M_\nu^{DT}$$

- Such $\nu - \nu^c$ mixing can cause violation of unitarity in 3×3 matrix $U_{\rm PMNS}$. This will show up as NSI
- This light-heavy mixing is not proportional to light neutrino mass. For e.g:

$$M_\nu^D = m_D^0 U \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} U^\dagger, \; M_R = U^* \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & 0 & M_{23} \\ 0 & M_{23} & 0 \end{pmatrix} U^\dagger$$

$$M_\nu^\ell = -M_\nu^D M_R^{-1} M_\nu^{DT} = 0$$

- There is an unbroken lepton number symmetry under which (N_1, N_2, N_3) have charges $(0, 1, -1)$. Kersten, Smirnov (2007)
- Mass matrices stable under radiative corrections.

NSI from non-unitarity of U_{PMNS}

- NSI parameters can be expressed in terms of ν_α mixing with a heavy neutrino ν_4:

$$\varepsilon_{ee} = \left(\frac{Y_n}{2} - 1\right)|U_{e4}|^2, \qquad \varepsilon_{\mu\mu} = \frac{Y_n}{2}|U_{\mu 4}|^2, \qquad \varepsilon_{\tau\tau} = \frac{Y_n}{2}|U_{\tau 4}|^2,$$

$$\varepsilon_{e\mu} = \frac{1}{2}(Y_n - 1)\, U_{e4} U^\star_{\mu 4}, \qquad \varepsilon_{e\tau} = \frac{1}{2}(Y_n - 1)\, U_{e4} U^\star_{\tau 4}, \qquad \varepsilon_{\mu\tau} = \frac{Y_n}{2} U_{\mu 4} U^\star_{\tau 4}$$

- The values of $|U_{\alpha 4}|^2$ are constrained by lepton universality, $\ell_i^- \to \ell_j^- + \gamma$ decay, etc, leading to:

$$|\varepsilon_{ee}^{\max}| = 1.3 \times 10^{-3}, \qquad \varepsilon_{\mu\mu}^{\max} = 2.2 \times 10^{-4}, \qquad \varepsilon_{\tau\tau}^{\max} = 2.8 \times 10^{-3},$$

$$\varepsilon_{e\mu}^{\max} = 3.5 \times 10^{-5}, \qquad \varepsilon_{e\tau}^{\max} = 1.4 \times 10^{-4}, \qquad \varepsilon_{\mu\tau}^{\max} = 1.2 \times 10^{-3}$$

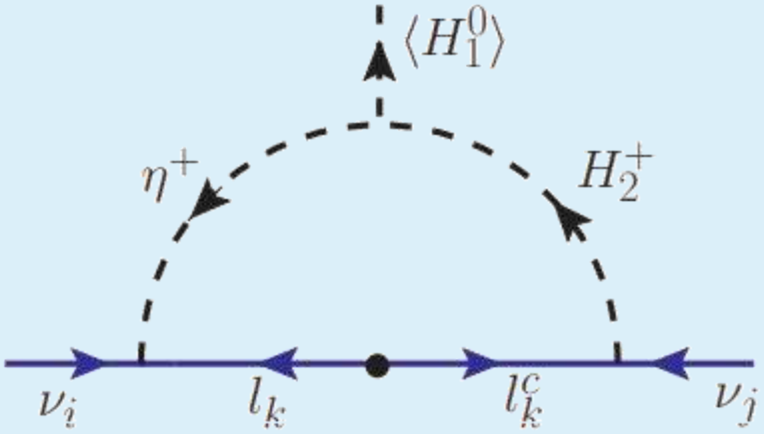
- Appears to be difficult to probe these values at DUNE, IceCube, etc.

NSI in Radiative Neutrino Mass Models

- An alternative to high scale seesaw for neutrino mass generation is "radiative mechanism"
- A large number of models of this type exist in the literature
- The new physics scale is typically near the TeV scale
- Neutrino NSI in these models could be relatively large
- We have systematically analyzed these models for their predicted NSI Babu, Dev, Jana, Thapa (2019)

Radiative Neutrino Mass Generation

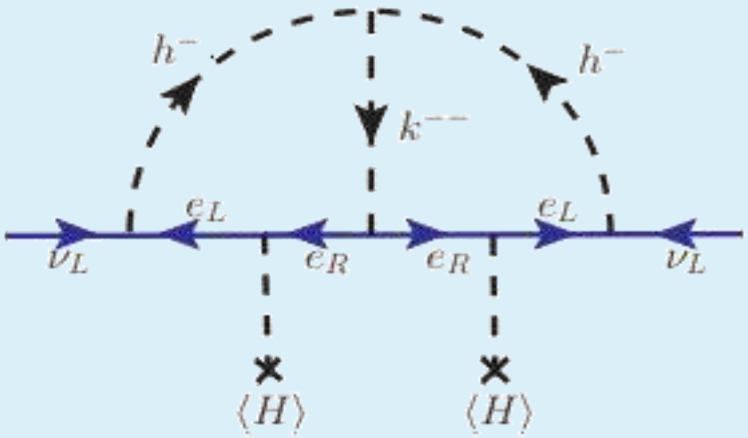
- Neutrino masses are zero at tree level as SM: ν_R may be absent.
- Small, finite Majorana masses are generated at the quantum level.
- Typically new heavy scalar fields introduced violates lepton number, gives rise to neutrino flavor transitions, and lepton flavor violation.
- Simple realization is the Zee Model, which has a second Higgs doublet and a charged singlet.



- Smallness of neutrino mass is explained via loop and chiral suppression.
- New physics in this framework may lie at the TeV scale.

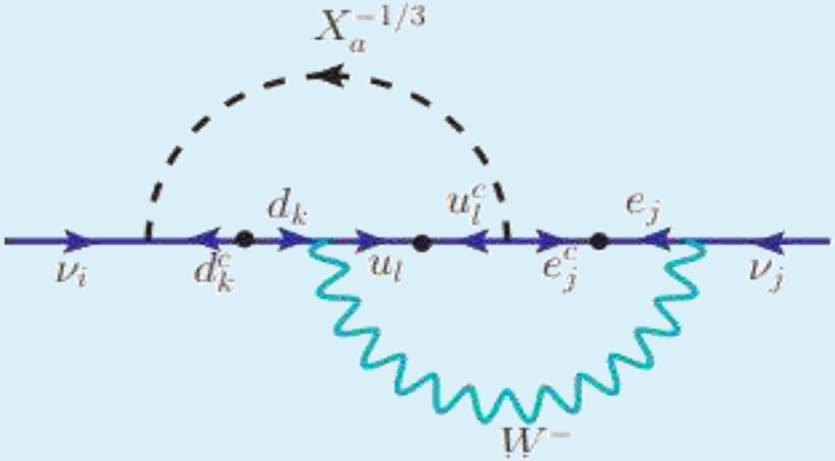
Type-I Radiative Mechanism

- Obtained from effective d = 7, 9, 11... operators with $\Delta L = 2$ selection rule
- If the loop diagram has at least one Standard Model particle, this can be cut to generate such effective operators



$\mathcal{O}_9 = L_i L_j L_k e^c L_l e^c \epsilon^{ij} \epsilon^{kl}$

Zee, Babu



$\mathcal{O}_8 = L_i \bar{e^c} \bar{u^c} d^c H_j \epsilon^{ij}$

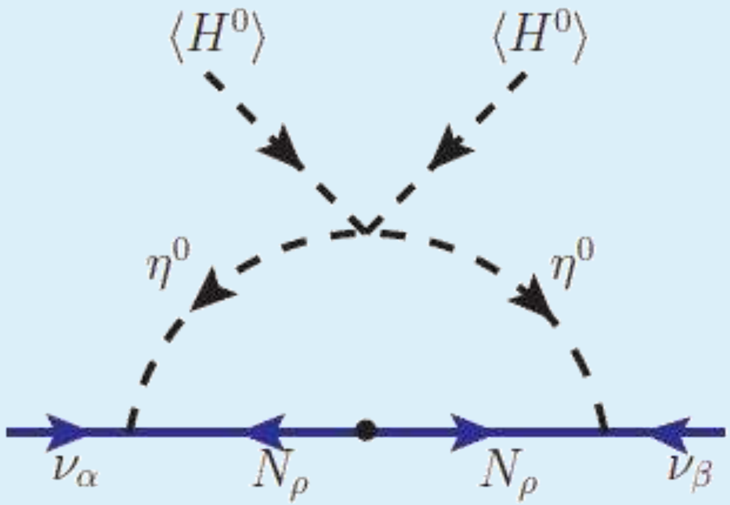
Babu, Julio (2010)

Classification: Babu, Leung (2001)

Cai, Herrero-Gracia, Schmidt, Vicente, Volkas (2017)

Type-II Radiative Mechanism

- No Standard Model particles inside loop
- Cannot be cut to generate $d = 7, 9, \ldots$ operators
- Scotogenic model is an example



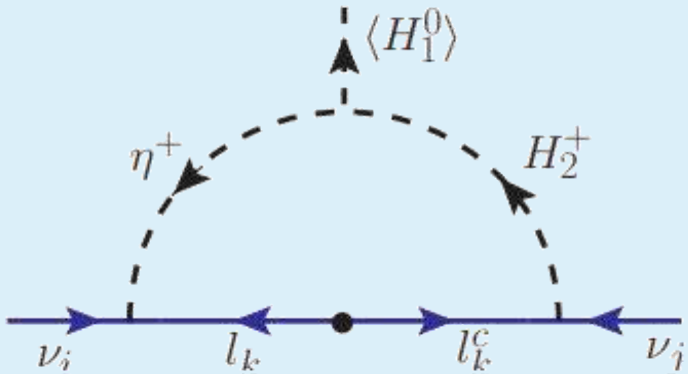
- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new physics Ma (2006)
- These models predict negligible NSI

NSI in Zee model

- Yukawa coupling matrices:

$$f = \begin{pmatrix} 0 & f_{e\mu} & f_{e\tau} \\ -f_{e\mu} & 0 & f_{\mu\tau} \\ -f_{e\tau} & -f_{\mu\tau} & 0 \end{pmatrix}, \qquad Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

- Neutrino mass



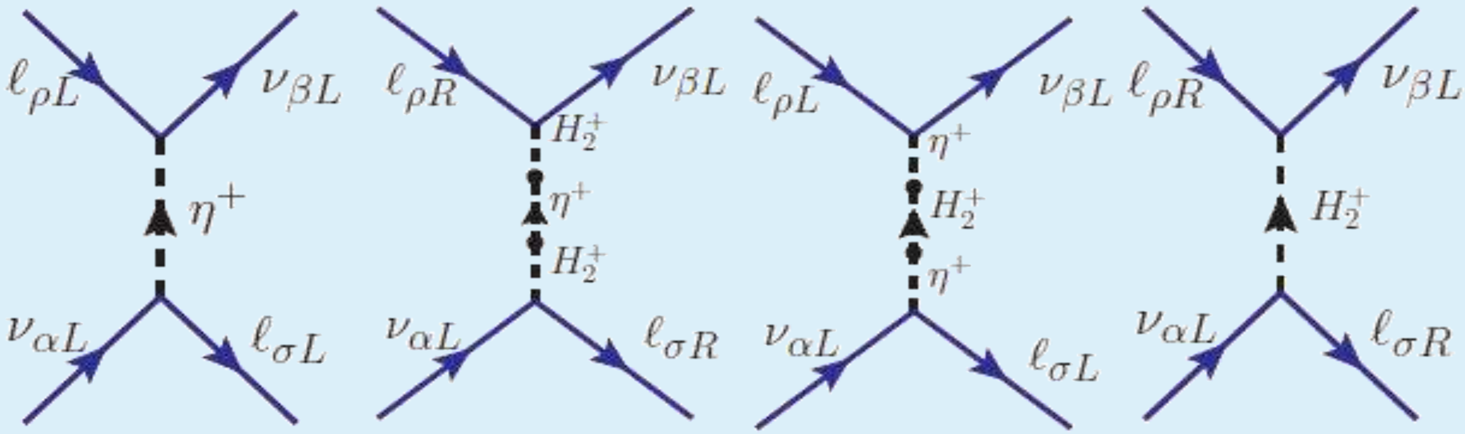
$$M_\nu = \kappa \left(f M_l Y^T + Y M_l f^T \right)$$
$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$

- If $Y \propto M_l$, which happens with a Z_2, then model is ruled out

  Wolfenstein (1980)

- In general, Y is not proportional to M_l, and the model gives reasonable fit to oscillation data
- NSI arises via the exchange of $h^\pm$ and $H^\pm$

NSI in Zee model



- The singly-charged scalars η^+ and H^+ induce NSI at tree level:

$$\boxed{\varepsilon_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^{(h^+)} + \varepsilon_{\alpha\beta}^{(H^+)} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y_{\beta e}^{\star} \left(\frac{\sin^2\varphi}{m_{h^+}^2} + \frac{\cos^2\varphi}{m_{H^+}^2} \right)}$$

- For a benchmark value of 100 GeV masses, we have:

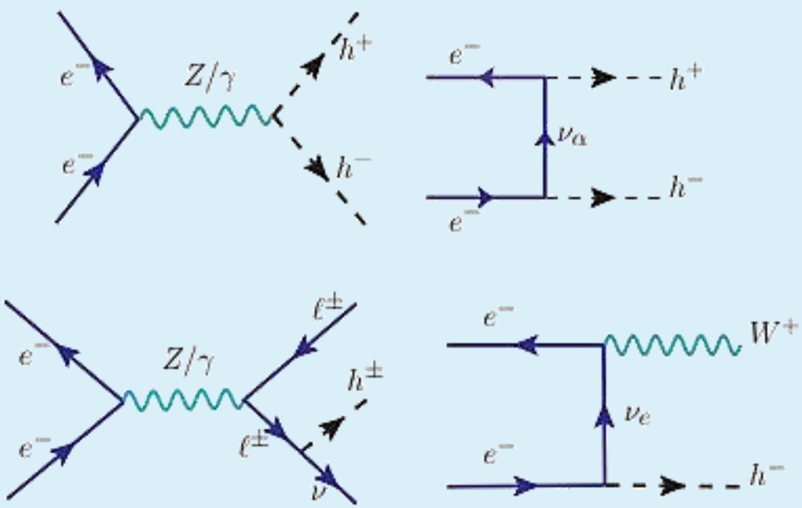
$$\varepsilon_{ee}^{\max} \approx 3.5\%, \quad \varepsilon_{\mu\mu}^{\max} \approx 5.6\%, \quad \varepsilon_{\tau\tau}^{\max} \approx 71.6\%$$

NSI in Zee model

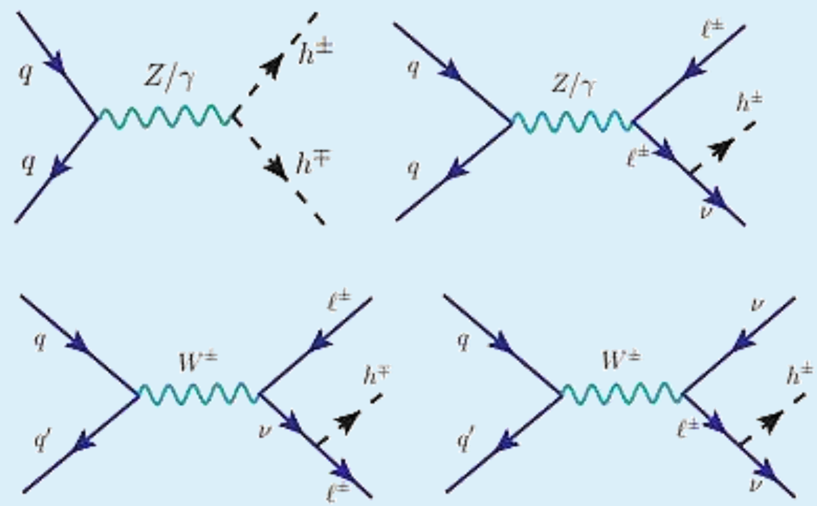
- Electroweak T parameter sets limits on mixing $\sin\varphi$
- $\mu \to e + \gamma$ type processes limit products of couplings
- $\mu \to 3e$ type processes lead to further constraints
- τ lifetime and universality constraints
- Lepton universality in $W^{\pm}$ decays
- Theoretical constraint from avoiding charge breaking minima
- LEP direct search limits on charged scalars
- Constraints from LHC searches
- Higgs precision physics limits

NSI in Zee model

- New Physics at sub-TeV scale is highly constrained from direct searches as well as indirect searches.
- Direct searches: we can put bound on h^+ mass by looking at the final state (leptons + missing energy)
  - Some supersymmetirc searches (Stau, Selectron) exactly mimics the charged higgs searches.



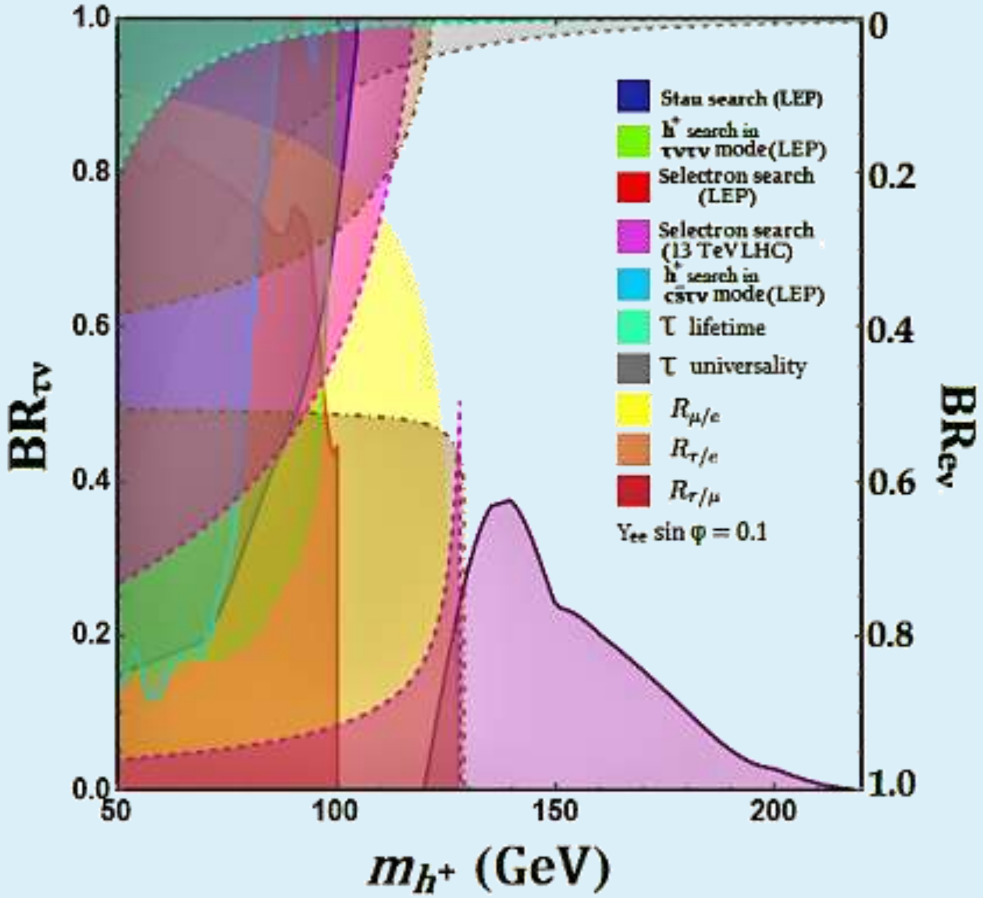
Dominant production in LEP



Dominant production in LHC

Collider Constraints

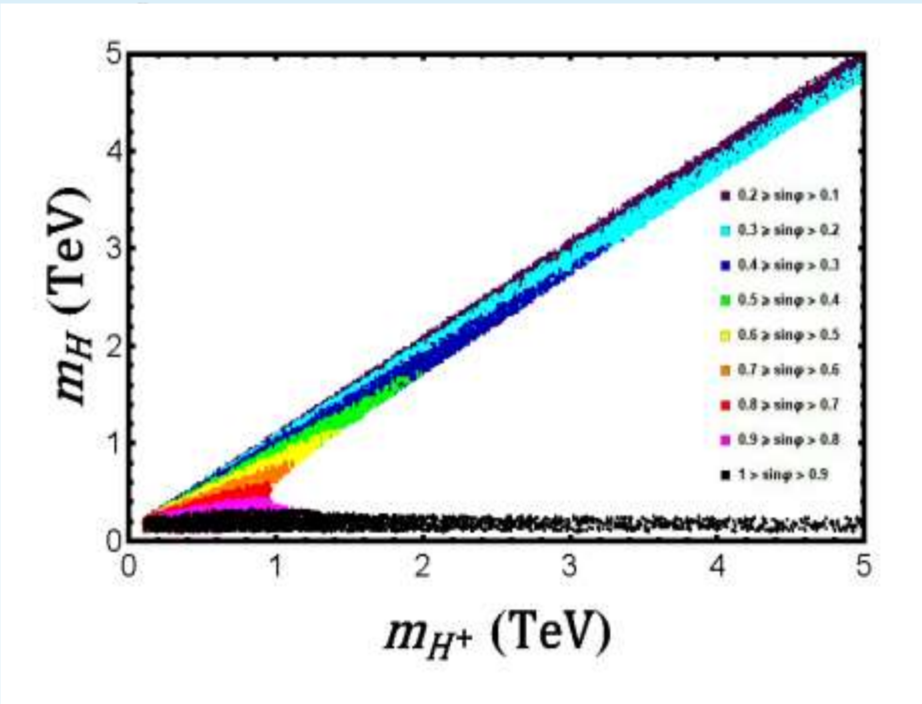
- $\mathrm{BR}_{\tau\nu} + \mathrm{BR}_{e\nu} = 1$ ($\mathrm{BR}_{\mu\nu} \approx 0$) to avoid stringent limit from muon decay.



Babu, DeV, SJ, Thapa (2019)

T parameter constraint

- T parameter imposes the most stringent constraint
- No mixing between the neutral $\mathcal{CP}$-even scalars h and H

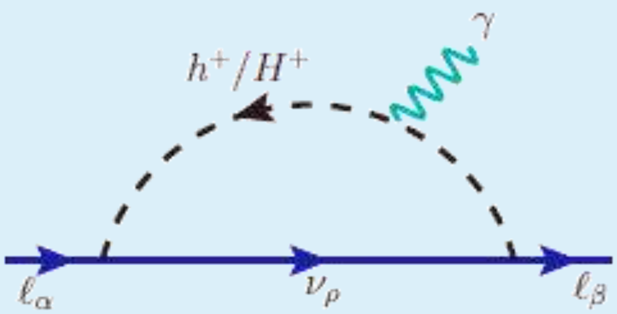


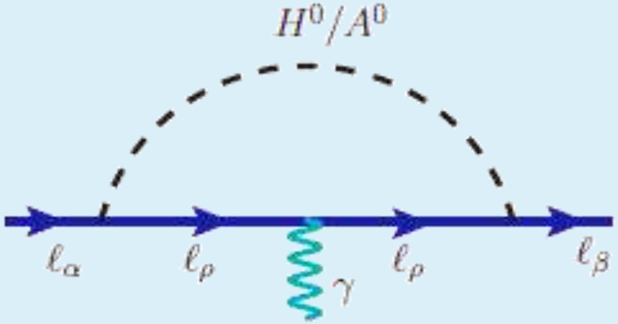
- For $m_H = 0.7\,\text{TeV}$ and $m_h^+ = 100\ \text{GeV}$, the maximum mixing is 0.63.

Babu, DeV, SJ, Thapa (2019)

$\ell_\alpha \to \ell_\beta + \gamma$ constraints

- Both charged and neutral Higgs mediate $\mu \to e + \gamma$ type processes

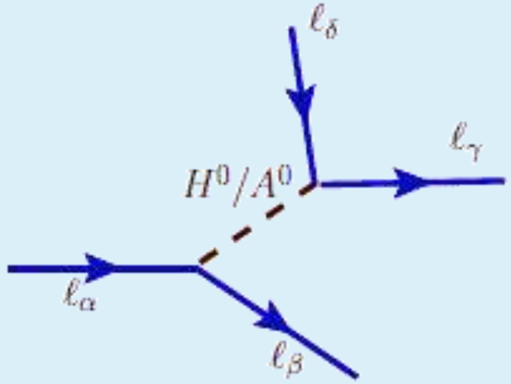




Process	Exp. bound	Constraint
$\mu \to e\gamma$	BR $< 4.2 \times 10^{-13}$	$\lvert Y^\star_{\mu e} Y_{ee}\rvert < 1.05 \times 10^{-3} \left(\frac{m_H}{700\ \text{GeV}}\right)^2$
$\tau \to e\gamma$	BR $< 3.3 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{ee}\rvert < 0.69 \left(\frac{m_H}{700\ \text{GeV}}\right)^2$
$\tau \to \mu\gamma$	BR $< 4.4 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{\mu e}\rvert < 0.79 \left(\frac{m_H}{700\ \text{GeV}}\right)^2$

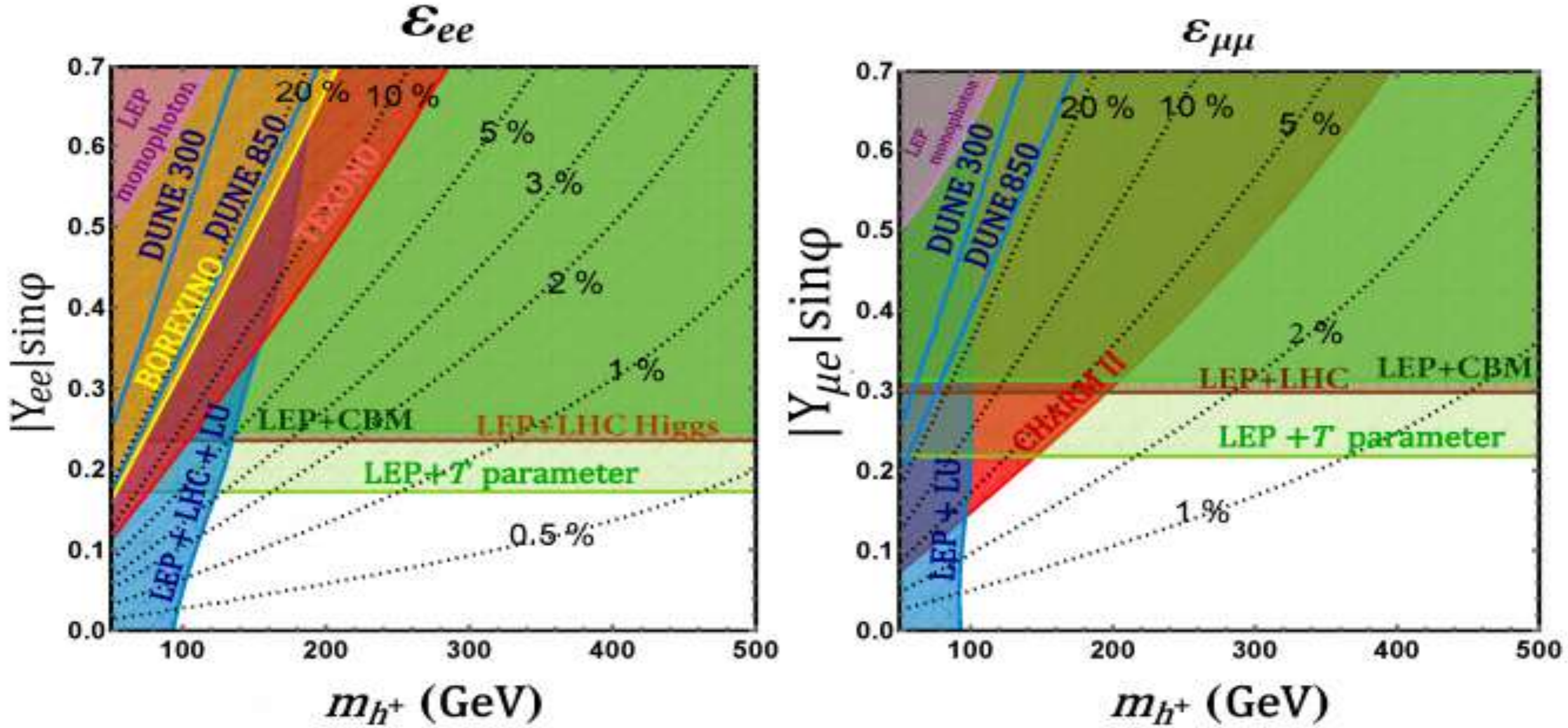
$\mu \to 3e$ type constraints

- Neutral scalars of the model mediate $\ell_i \to \ell_j \ell_k \ell_m$ type decays at tree level



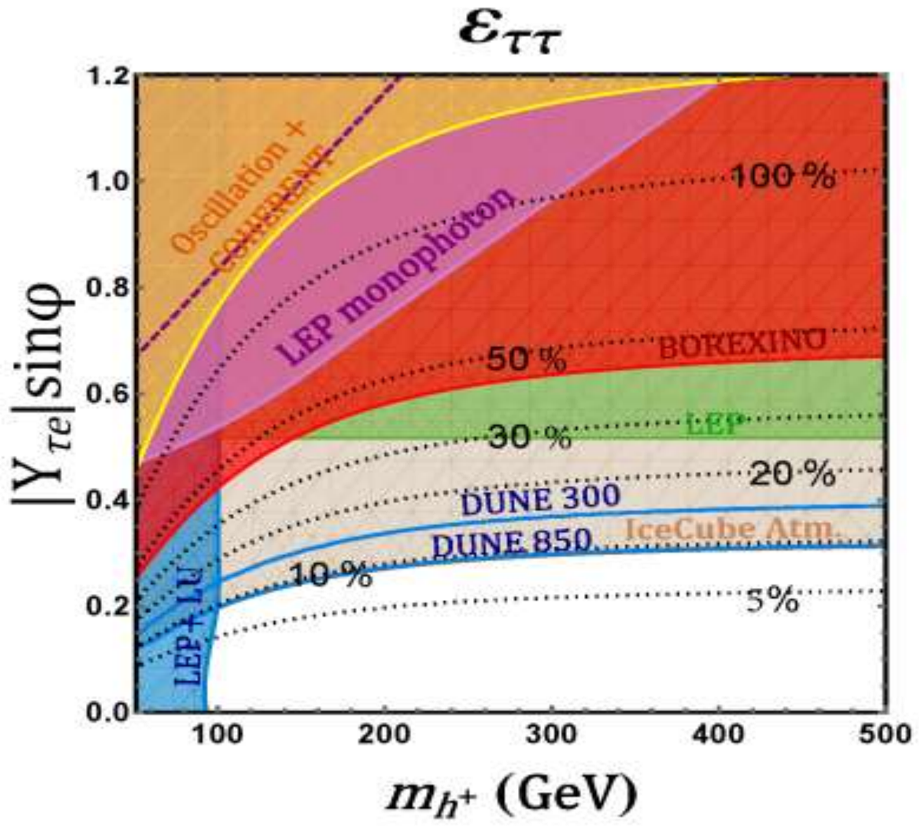
Process	Exp. bound	Constraint
$\mu^- \to e^+ e^- e^-$	BR $< 1.0 \times 10^{-12}$	$\lvert Y^\star_{\mu e} Y_{ee} \rvert < 3.28 \times 10^{-5} \left(\frac{m_H}{700 \text{ GeV}} \right)^2$
$\tau^- \to e^+ e^- e^-$	BR $< 1.4 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{ee} \rvert < 9.05 \times 10^{-3} \left(\frac{m_H}{700 \text{ GeV}} \right)^2$
$\tau^- \to e^+ e^- \mu^-$	BR $< 1.1 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{\mu e} \rvert < 5.68 \times 10^{-3} \left(\frac{m_H}{700 \text{ GeV}} \right)^2$

Numerical results for NSI



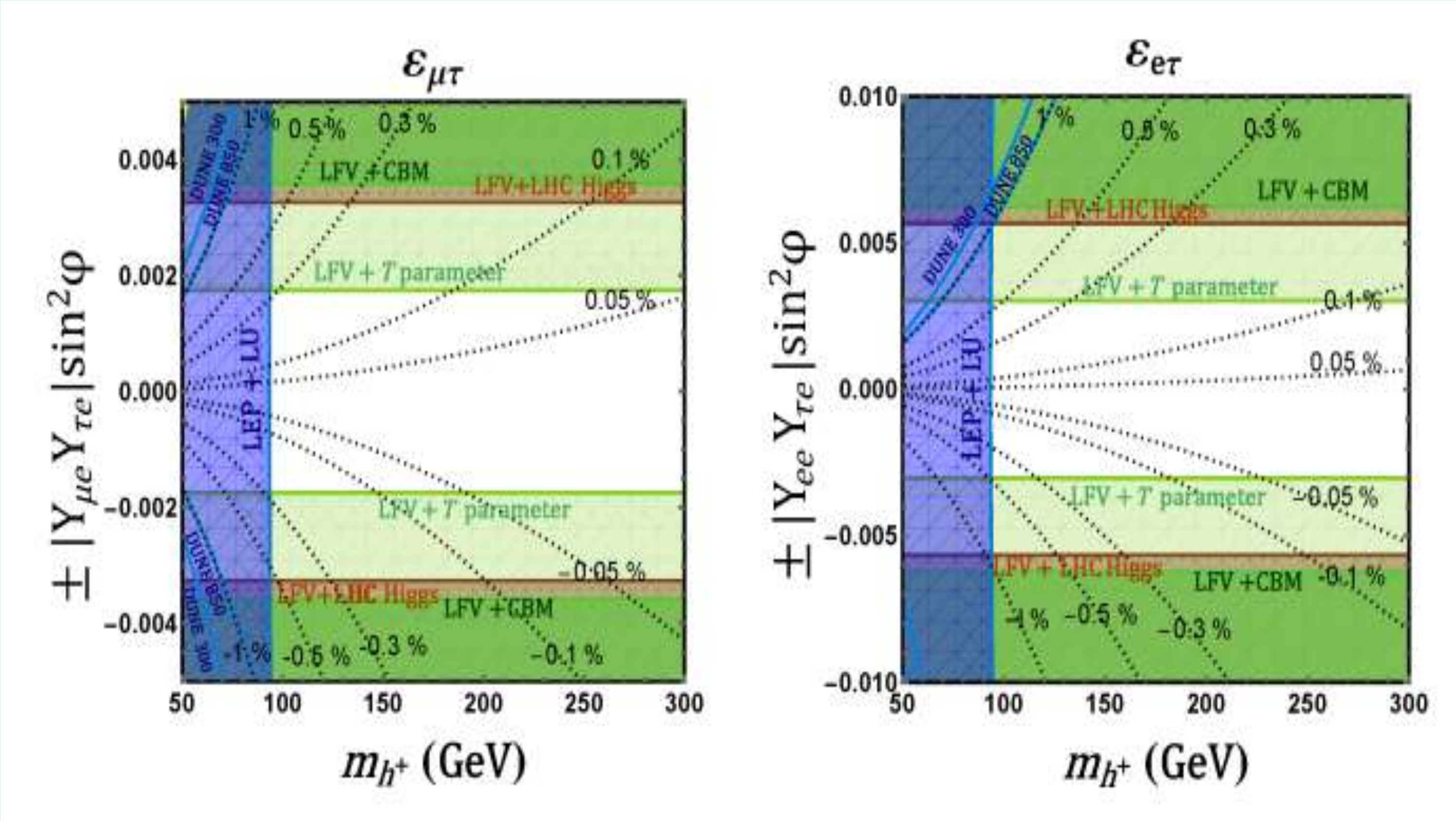
$\varepsilon_{ee}^{\max} \approx 3\%$ $\varepsilon_{\mu\mu}^{\max} \approx 3.8\%$

Numerical results for NSI

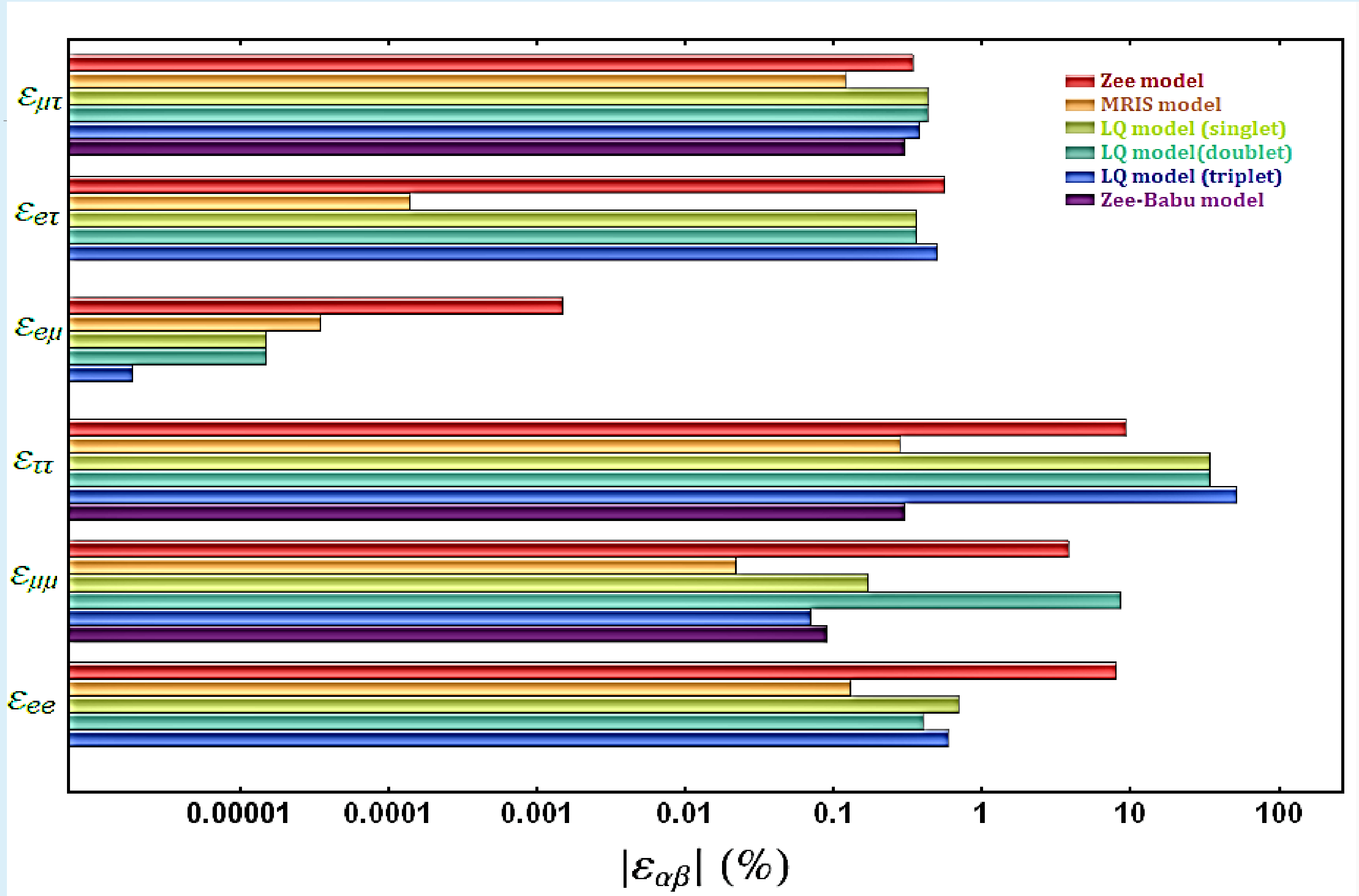


$\varepsilon_{\tau\tau}^{\max} \approx 9.3\%$

Numerical results for NSI



Summary of NSI in various neutrino mass models



Babu, DeV, SJ , Thapa (2019)

Zee-Burst: A new test of NSI at IceCube

- Ultra High Energy neutrinos at IceCube can probe NSI in the Zee model

- $\overline{\nu_e} + e^- \to W^- \to$ anything has a resonant enhancement at

$$E_\nu = \frac{m_W^2}{2m_e} = 6.3\,\mathrm{PeV} \qquad \text{Glashow resonance}$$

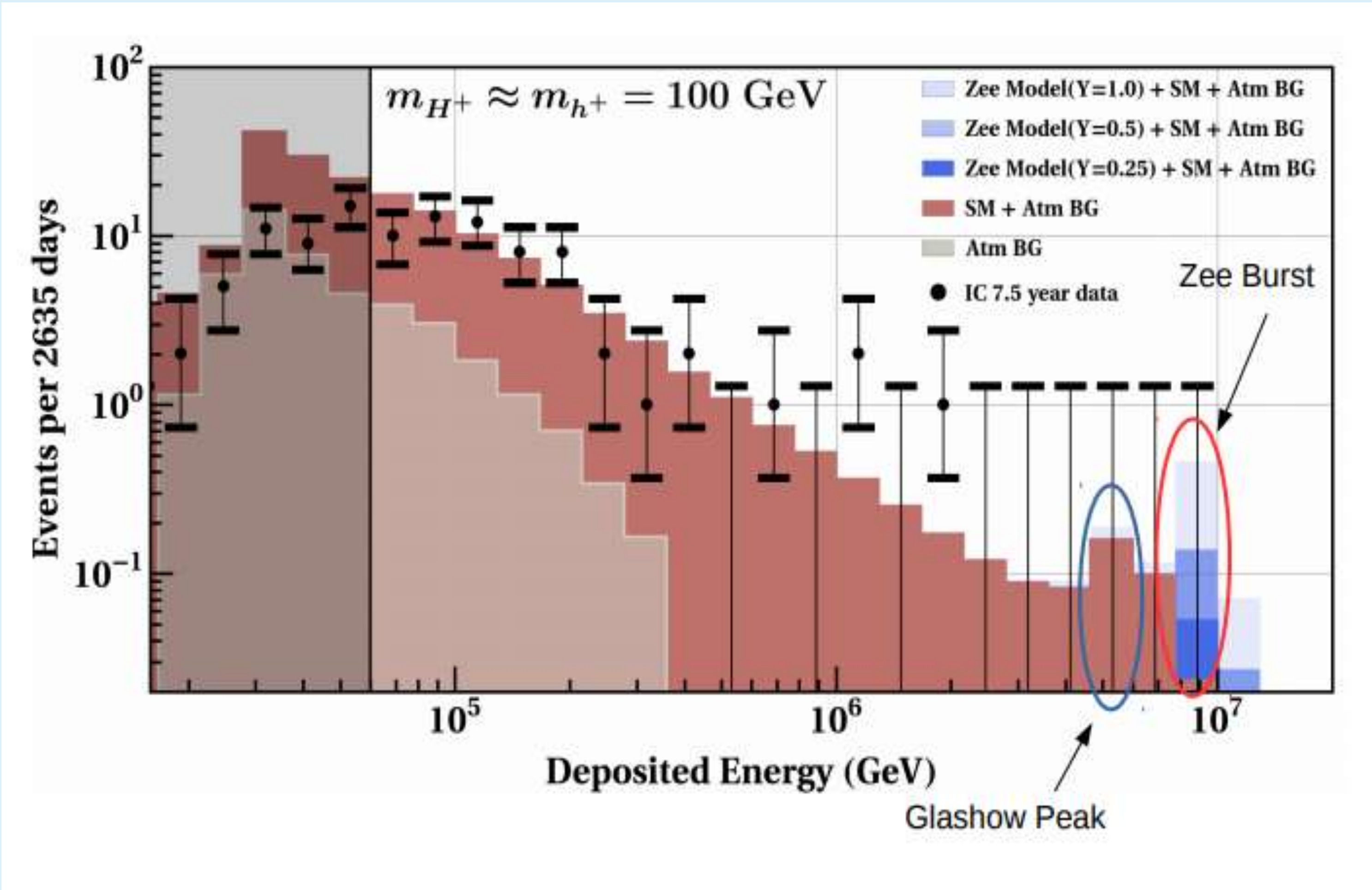
- Since $h^\pm$ and $H^\pm$ in Zee model are allowed to be as light as 100 GeV, $\overline{\nu}_\alpha + e^- \to h^- \to$ anything is resonantly enhanced

$$E_\nu = \frac{m_h^2}{2m_e} \simeq 9.3\,\mathrm{PeV} \qquad \text{“Zee burst”}$$

- We have analyzed this possibility of “Zee burst”

Babu, DeV, SJ , Sui (2019)

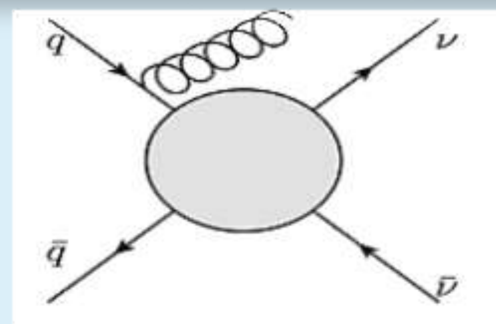
Zee-Burst: A new test of NSI at IceCube

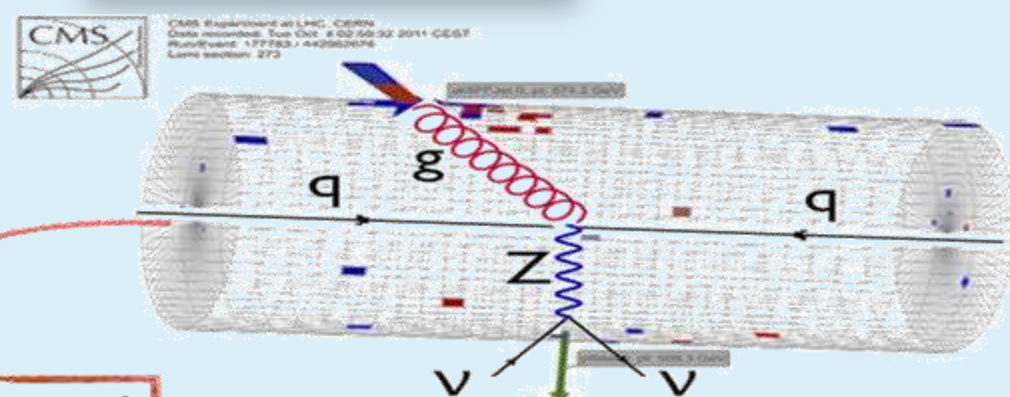


Babu, DeV, SJ, Sui (2019)

Neutrino NSI at LHC

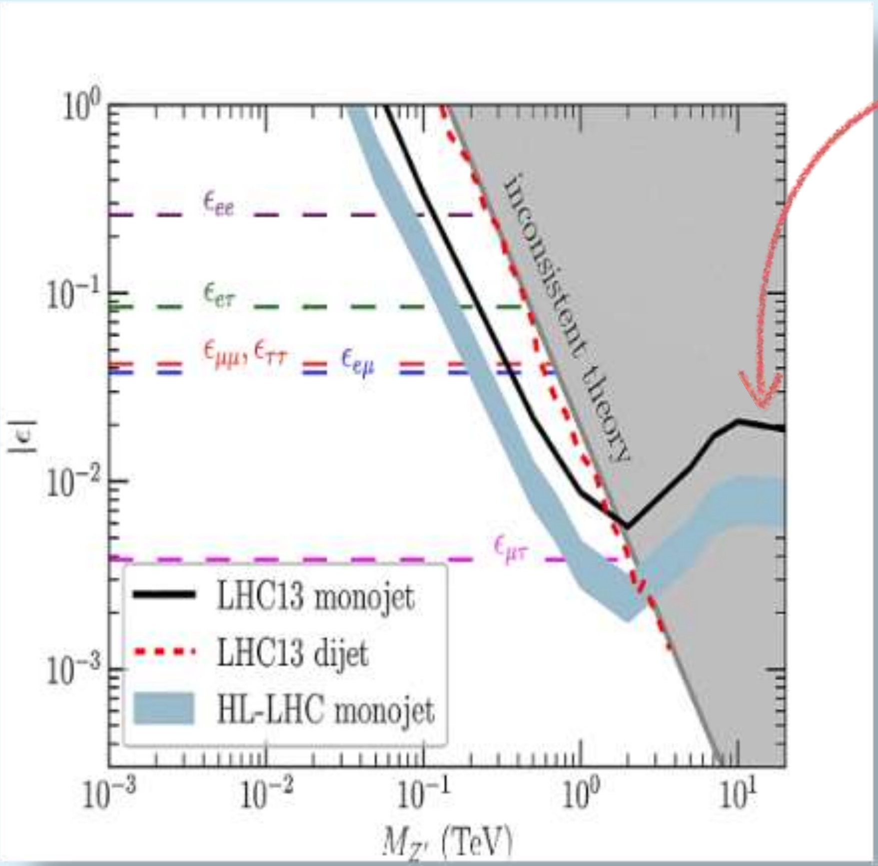
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\, G_F \varepsilon_{\alpha\beta}^{fP} \left(\bar{\nu}_\alpha \gamma_\rho \nu_\beta\right) \left(\bar{f} \gamma^\rho P f\right)$$





Irreducible SM background

Complementarity between LHC and neutrino experiments



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

We can identify the EFT regime for the LHC when the mass of the mediator is much above the scale of the process involved.

For any fixed ratio $\Gamma_{Z'}/M_{Z'}$, we can write the following inequality

$$|\epsilon| \leq \frac{\sqrt{3}\pi}{\sqrt{N} G_F M_{Z'}^2} \frac{\Gamma_{Z'}}{M_{Z'}}$$

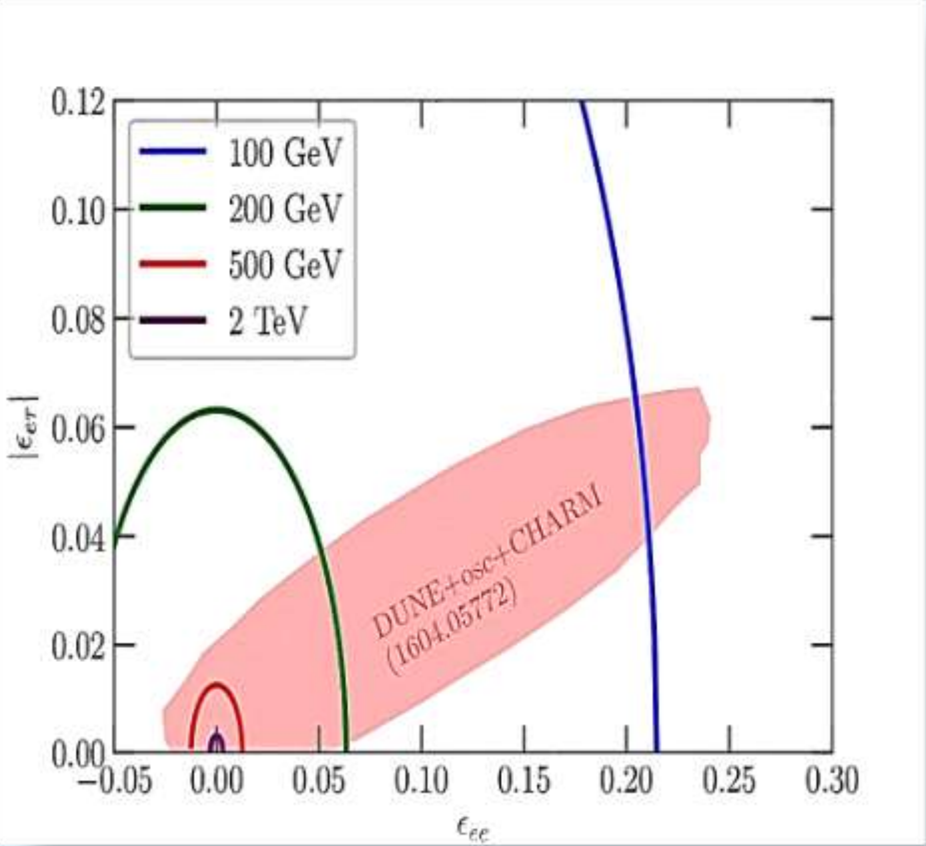
This constraint originates from the fact that the total width of the Z' should be larger than the partial widths to $q_i q_i$ and νν:

$$\Gamma_{Z'} \geq M_{Z'}/(24\pi)\left(g_\nu^2 + 3N\left\{\left(g_u^V\right)^2 + \left(g_d^V\right)^2\right\}\right)$$

Considering narrower Z' makes the constraint stronger, while broader Z' implies non-perturbativity

Traditional EFT analyses at the LHC using four-fermion operators will typically not be valid, at least having simple/minimal UV completions in mind.

Complementarity between LHC and neutrino experiments



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
P. Coloma et al. (2016) , J. Liao et al. (2016)

Differently from the LHC, the effects of NSIs in neutrino oscillations strongly depend on the flavor structure of the NSI and the oscillation channel being studied.

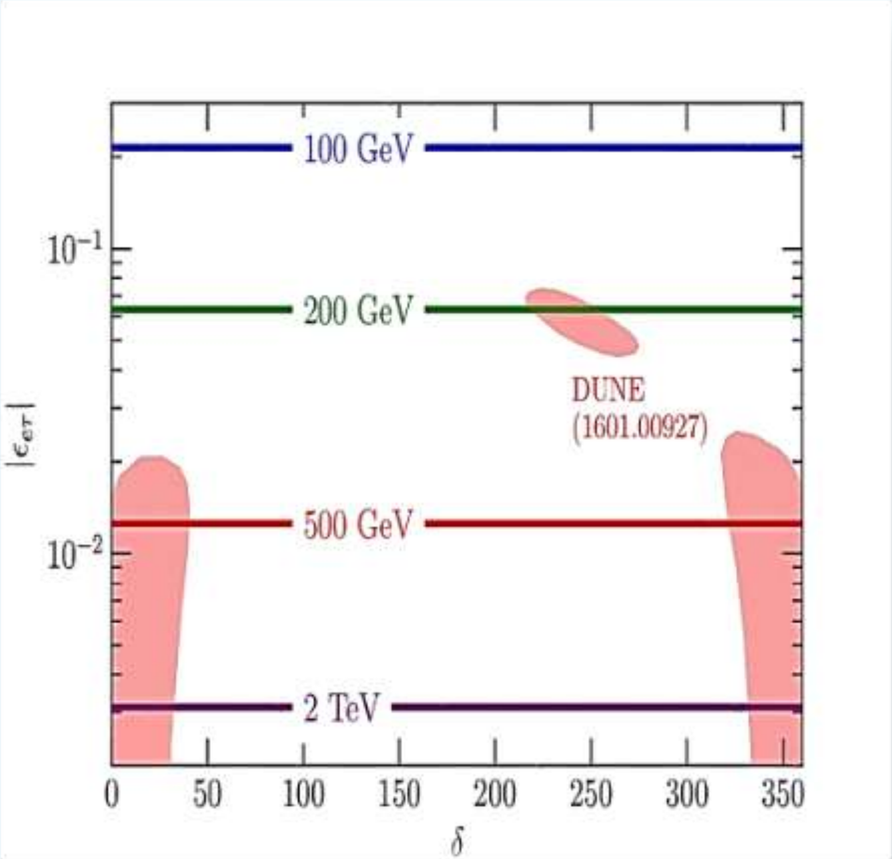
The effects of different NSIs and/or variations of the standard oscillation parameters can, in some cases, compensate each other and lead to well known degeneracies.

Disentangling those is a difficult task at neutrino facilities.

In contrast, the mono-jet signal at the LHC, does not distinguish between different choices of flavors i.e., they all lead to the same observables.

Besides constraining the currently allowed NSI parameter space, this feature can be further exploited to break relevant degeneracies.

Complementarity between LHC and neutrino experiments



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
P. Coloma et al. (2016) , J. Liao et al. (2016)

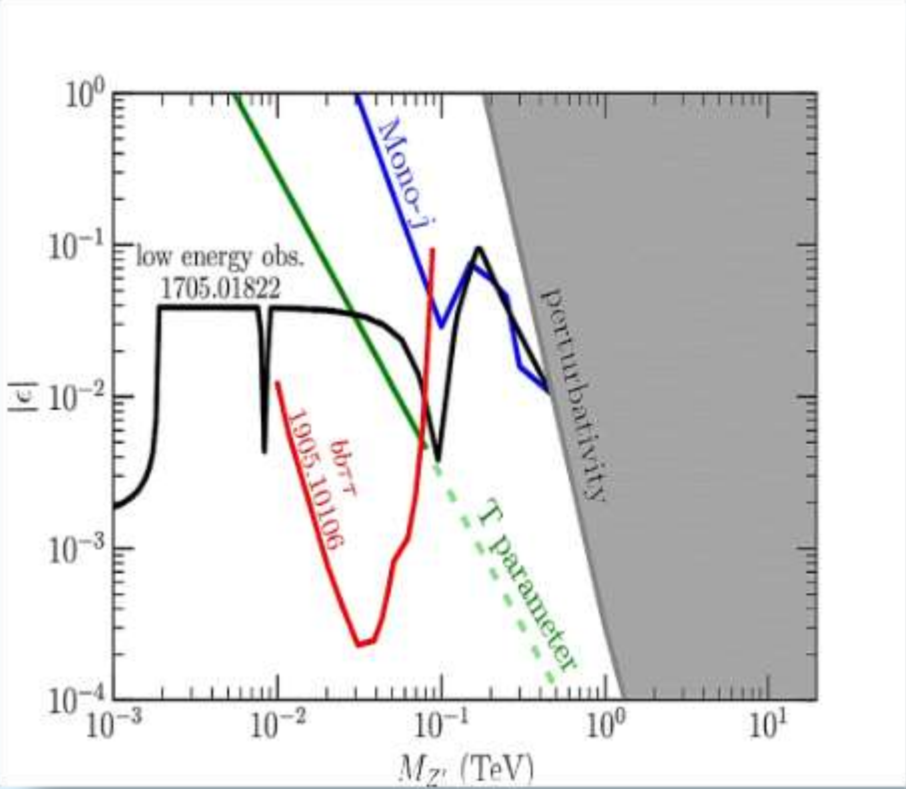
The LHC sensitivity displays a strong dependence on the mediator mass, but it is free of parameter degeneracies. Neutrino oscillation measurements, on the other hand, exhibit the opposite behavior: significant degeneracies and no mediator mass dependence.

The matter potential induced when neutrinos travel through a medium is not affected by a diagonal, universal contribution (as this just induces an overall phase shift on the neutrino state). On the other hand, LHC data is sensitive to each and all NSI parameters independently.

Neutrino oscillations are not sensitive to axial interactions, while LHC data is sensitive to both vector and axial new physics contributions.

All these features show the synergies between oscillation measurements and collider data on probing new physics in the neutrino sector.

Towards a UV complete scenario



K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)
K.S. Babu, A. Friedland, P.A.N. Machado, I. Mocioiu (2017)
F. Elahi and A. Martin (2019)

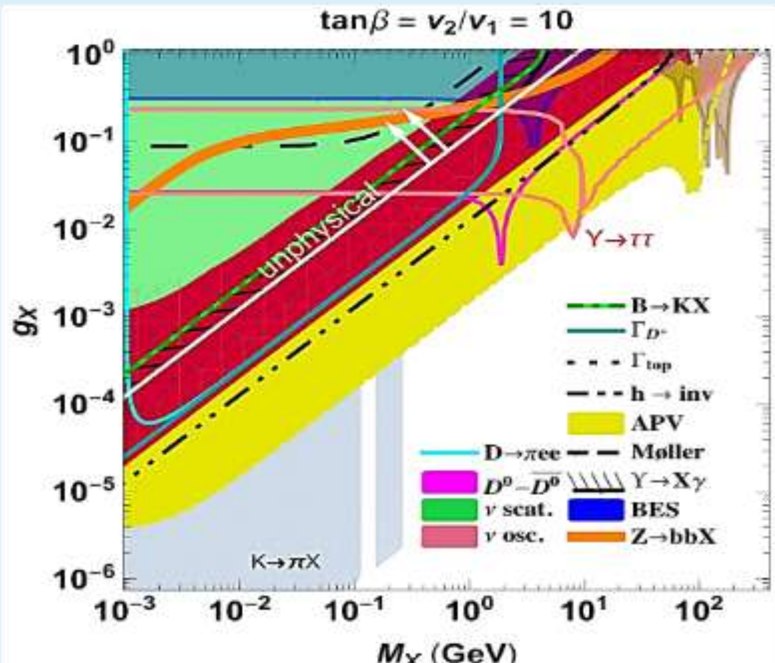
Any UV complete model of neutrino NSI is expected to provide a more extensive phenomenology, especially since neutrinos are in the same $SU(2)_L$ doublet as charged leptons.

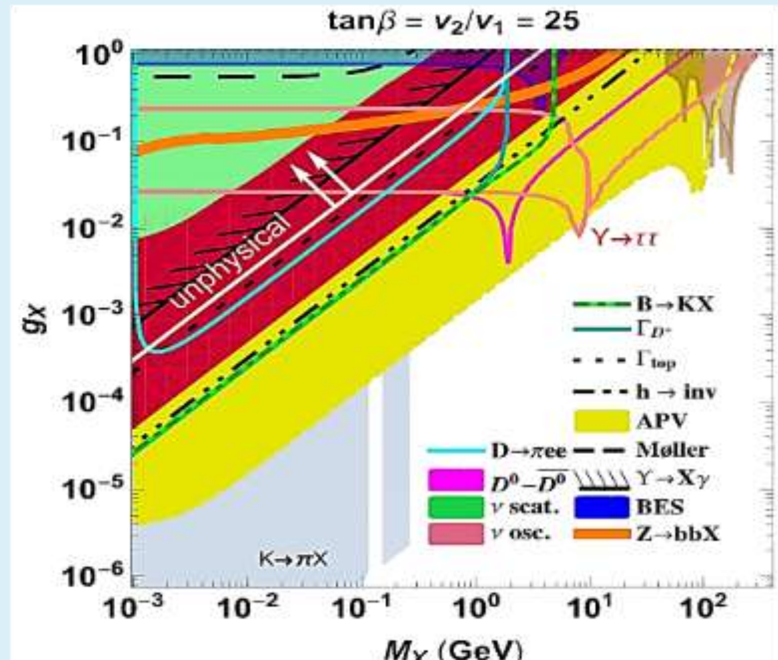
In this UV completion the B − L number is gauged, but only for the third family.

Heavy mediators are strongly constrained by LHC data.

Low mediators constrained by low-energy experiments.

Towards a UV complete scenario





K.S. Babu, D. Gonçalves, **SJ**, P.A.N. Machado (2020)

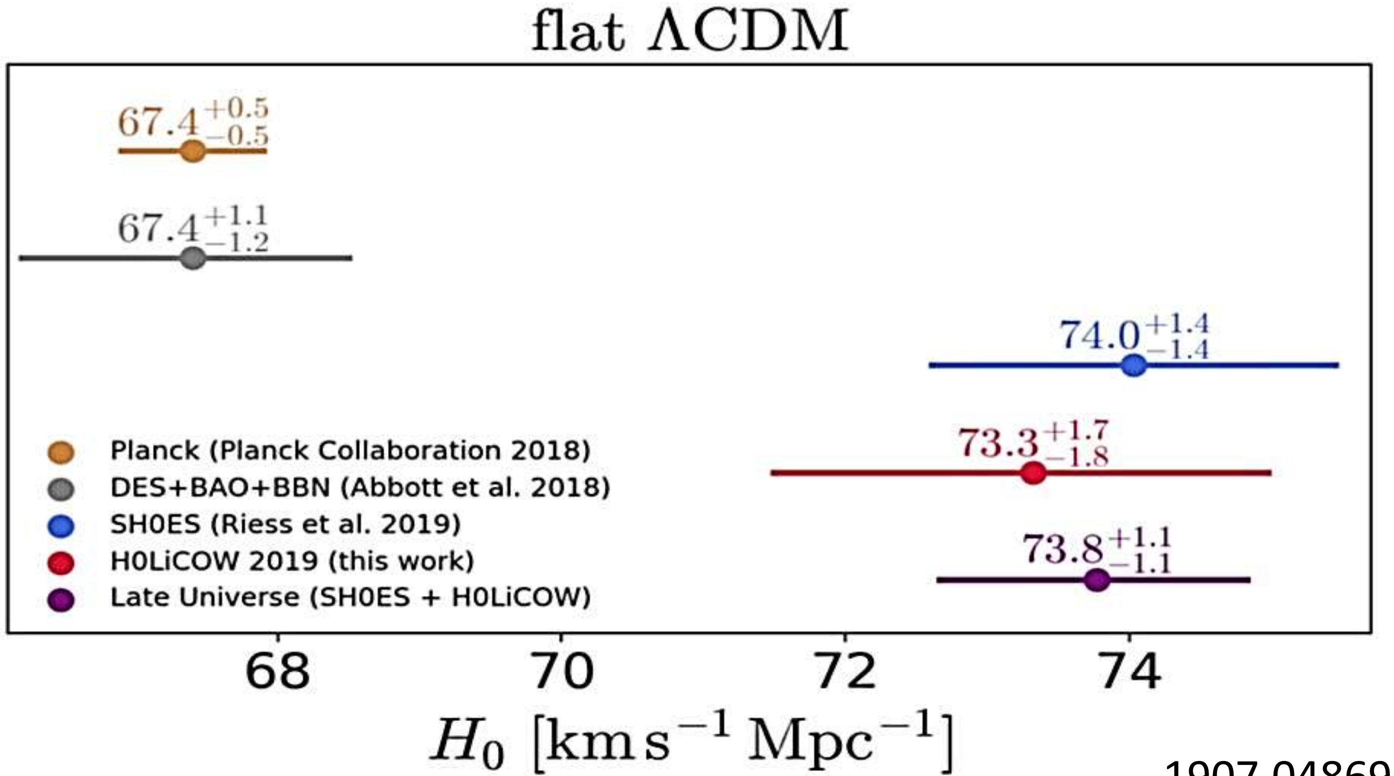
For collider/other studies on NSI: See A. Friedland, M. L. Graesser, I. M. Shoemaker, and L. Vecchi (2011), D. Choudhury, K. Ghosh, and S. Niyogi (2018), T. Han, J. Liao, H. Liu, and D. Marfatia (2019), Julian Heeck, Manfred Lindner, Werner Rodejohann, Stefan Vogl (2018) etc.

ν

Cosmic frontier

The Hubble Tension

Long standing disagreement between direct ("local") measurements of H_0
and early-time inferences



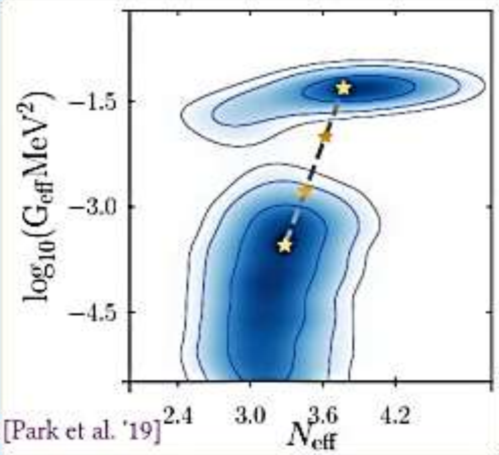
1907.04869

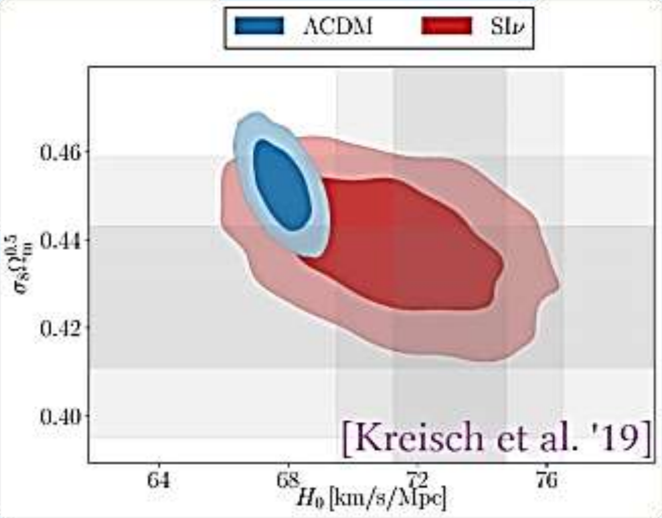
Self-interacting neutrino solution

$$G_{\rm eff} \equiv \frac{g_{\rm eff}^2}{m_{Z'}^2} \approx \begin{cases} (5\ \mathrm{MeV})^{-2} & \text{“SI}\nu\text{”} \\ \lesssim (100\ \mathrm{MeV})^{-2} & \text{“WI}\nu\text{”}\ . \end{cases}$$

[Kreisch et al. 19]

Parameter	Strongly Interacting Neutrino Mode
$\Omega_b h^2$	$0.02245^{+0.00029}_{-0.00033}$
$\Omega_c h^2$	$0.1348^{+0.0056}_{-0.0049}$
$100\theta_{MC}$	1.04637 ± 0.00056
τ	0.080 ± 0.031
$\sum m_\nu$ [eV]	$0.42^{+0.17}_{-0.20}$
$N_{\rm eff}$	4.02 ± 0.29
$\log_{10}(G_{\rm eff}\mathrm{MeV}^2)$	$-1.35^{+0.12}_{-0.066}$
$\ln(10^{10}A_s)$	3.035 ± 0.060
n_s	0.9499 ± 0.0098
H_0 [km/s/Mpc]	72.3 ± 1.4
Ω_m	0.3094 ± 0.0083
σ_8	0.786 ± 0.020
$10^9 A_s$	$2.08^{+0.11}_{-0.13}$
$10^9 A_s e^{-2\tau}$	1.771 ± 0.016
r_* [Mpc]	136.3 ± 2.4
$100\theta_*$	1.04604 ± 0.00056
D_A [Gpc]	13.03 ± 0.23
$r_{\rm drag}$ [Mpc]	138.8 ± 2.5





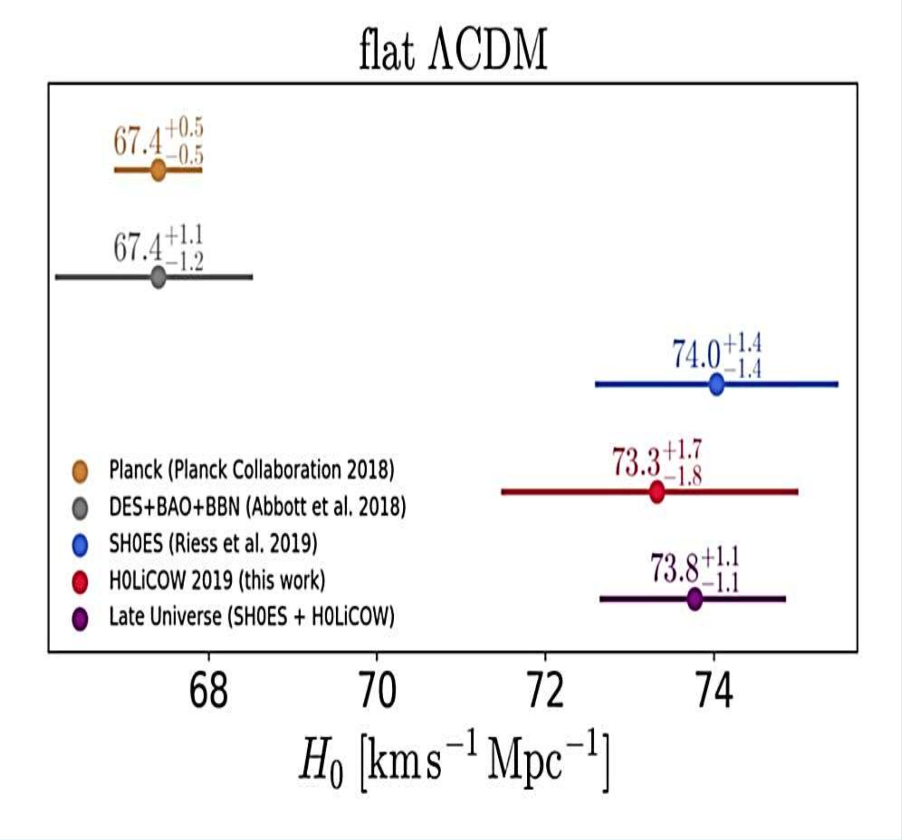
[Cyr-Racine, Sigurdson'13; Archidiacono, Hannestad'14] [Lancaster, Cyr-Racine, Knox, Pan '17; Oldengott, Tram, Rampf, Wong '17] [Kreisch, Cyr-Racine, Dore '19; Park, Kreisch, Dunkley, Hadzhiyska, Cyr-Racine'19]

The Hubble Tension

Long standing disagreement between direct (“local”) measurements of H_0
and early-time inferences

- The positive correlation of H_0 and N_{eff} with the amplitude of the matter power spectrum σ_8, as observed in CMB data, prohibits a resolution of the H_0 tension simply by increasing N_{eff} alone (LSS prefers low σ_8).

- However, a delay in the onset of neutrino free streaming during recombination could achieve both: breaking the positive correlation of H_0 and σ_8, while solving the Hubble tension at the cost of increasing ΔN_{eff} during recombination.

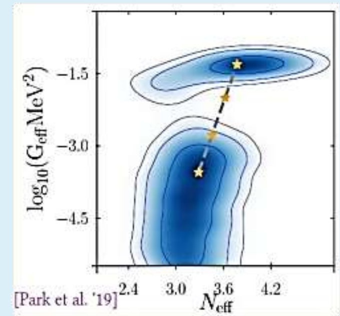


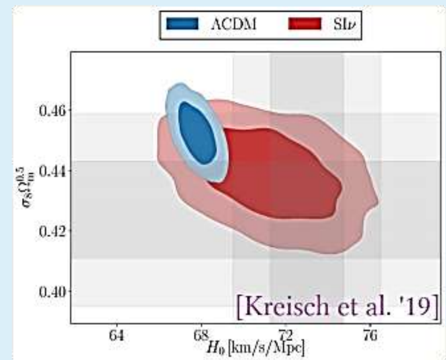
Self-interacting neutrino solution

$$G_{\rm eff} \equiv \frac{g_{\rm eff}^2}{m_{Z'}^2} \approx \begin{cases} (5\ \text{MeV})^{-2} & \text{“SI}\nu\text{”} \\ \lesssim (100\ \text{MeV})^{-2} & \text{“WI}\nu\text{”}. \end{cases}$$

[Kreisch et al. 19]

Parameter	Strongly Interacting Neutrino Mode
$\Omega_b h^2$	$0.02245^{+0.00029}_{-0.00033}$
$\Omega_c h^2$	$0.1348^{+0.0056}_{-0.0049}$
$100\theta_{\rm MC}$	1.04637 ± 0.00056
τ	0.080 ± 0.031
$\sum m_\nu$ [eV]	$0.42^{+0.17}_{-0.20}$
$N_{\rm eff}$	4.02 ± 0.29
$\log_{10}(\rm G_{eff} MeV^2)$	$-1.35^{+0.12}_{-0.066}$
$\ln(10^{10} A_s)$	3.035 ± 0.060
n_s	0.9499 ± 0.0098
H_0 [km/s/Mpc]	72.3 ± 1.4
Ω_m	0.3094 ± 0.0083
σ_8	0.786 ± 0.020
$10^9 A_s$	$2.08^{+0.11}_{-0.13}$
$10^9 A_s e^{-2\tau}$	1.771 ± 0.016
r_* [Mpc]	136.3 ± 2.4
$100\theta_*$	1.04604 ± 0.00056
D_A [Gpc]	13.03 ± 0.23
$r_{\rm drag}$ [Mpc]	138.8 ± 2.5





Can one have such an enormous neutrino self-interaction in realistic models?

$$G_{\rm eff}(\text{SI}\nu) \sim 10^9 G_F$$

Self-interacting neutrino solution

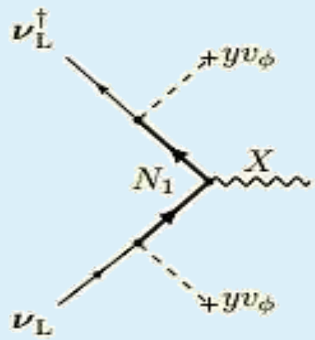
The model

$$\mathcal{L}_{\text{new}} = -y\,\overline{L}\,\tilde{\Phi}\,N_1 - M\,N_1\,N_2 + \text{h.c.},$$

Field	Φ	N_1	N_2	S	X_μ
$\mathrm{SU(2)_L \times U(1)_Y}$	$(\mathbf{2}, -\frac{1}{2})$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
$\mathrm{U(1)_X}$	$+1$	$+1$	-1	$+1$	0
$\mathrm{U(1)_L}$	0	$+1$	-1	0	0

Berbig, SJ, Trautner (2020)

$$\overbrace{v_h \quad v_\phi}^{\mathrm{SU(2)_L \otimes U(1)_Y}} \quad v_s \qquad v_h \quad \underbrace{v_\phi \quad v_s}_{\mathrm{U(1)_X}}$$



$$\Longrightarrow \quad G_{\text{eff}}^{4\nu} = \frac{g_X^2\,\varepsilon_m^4}{m_{Z'}^2}\,,$$

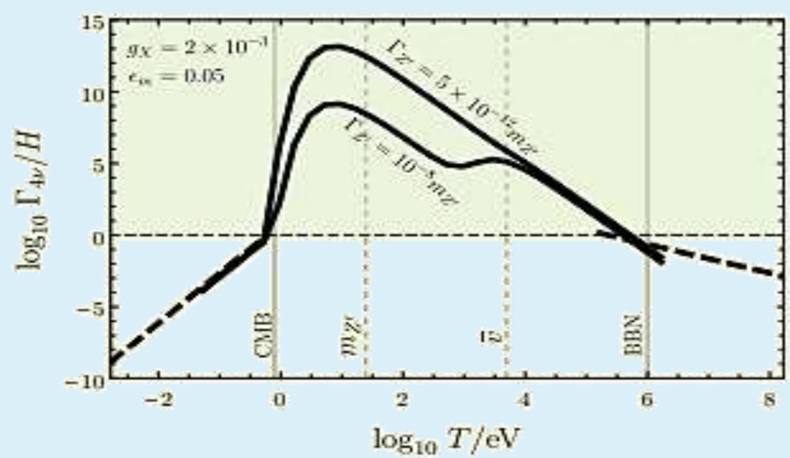
with $\tan\varepsilon_m := (yv_\phi)/(\sqrt{2}M)$.
(neutrino mass mixing)

Re- and *de*-coupling behavior:

$$\Longrightarrow 2\times10^{-7} \lesssim g_X\,\varepsilon_m^2 \lesssim 5\times10^{-6}\,,$$
$$1\,\text{eV} \lesssim m_{Z'} \lesssim 25\,\text{eV}.$$

$$\Longrightarrow \quad \xi := \frac{\sqrt{v_\phi^2+v_s^2}}{v_h} \approx \varepsilon_m^2\times2\times10^{-5}$$

One more useful ratio: $\tan\gamma := \dfrac{v_\phi}{v_s}$;

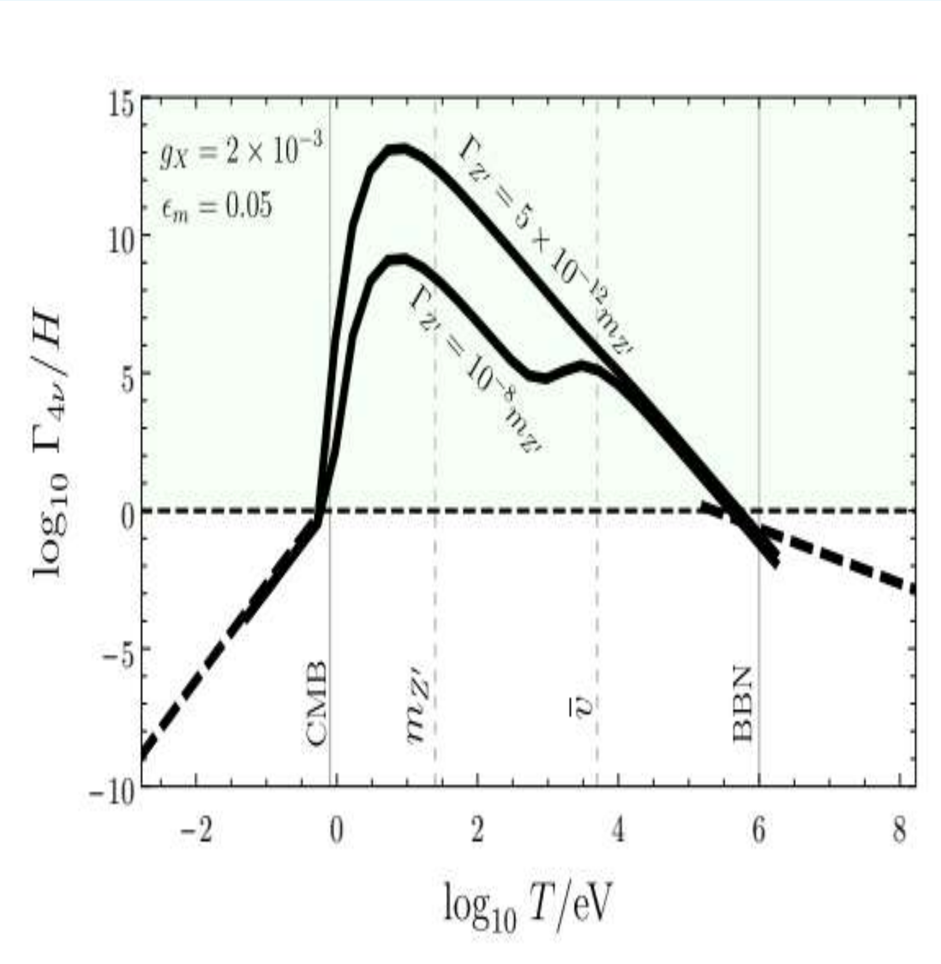


Parameters to have in mind: $2\times10^{-5} \lesssim y \lesssim 6\times10^{-3}$, $5\times10^{-4} \lesssim \varepsilon_m \lesssim 0.05$, $s_\gamma \lesssim 0.2$

Slide courtesy: Andreas Trautner

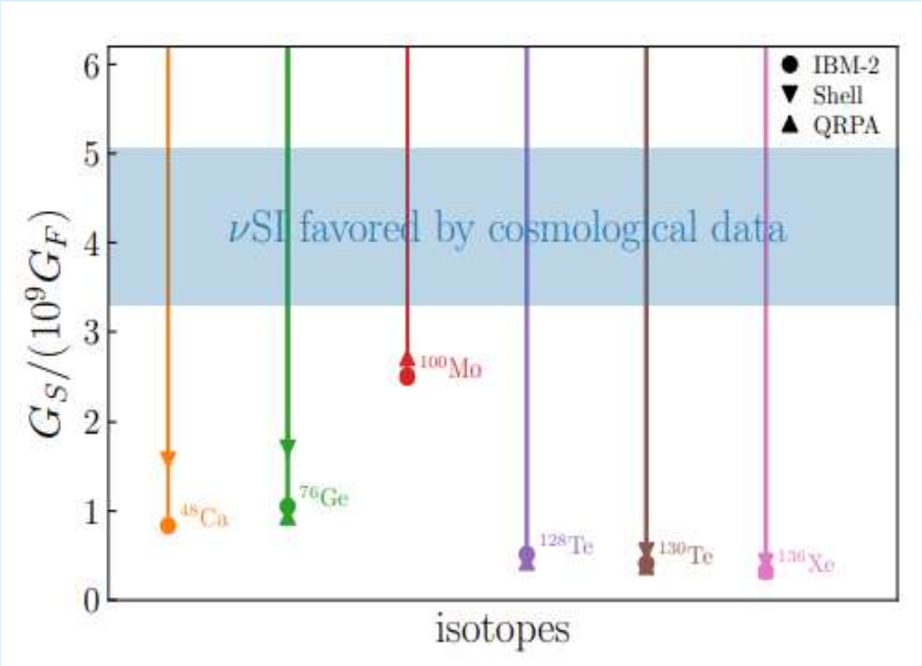
Self-interacting neutrino solution

- Light mediators strongly interacting with neutrinos are highly constrained by the bound on ΔNeff during BBN.
- However, while one may feel that it is just a relatively short time between BBN and recombination, we recall that it is still six orders of magnitude in temperature.
- This certainly is enough to establish a mass scale, say after a phase transition, and subsequently integrate it out to obtain a decoupling behavior of neutrinos during CMB closely resembling.
- In this way, neutrinos recouple by the new interactions only after BBN, and fall out of equilibrium shortly before or during recombination.

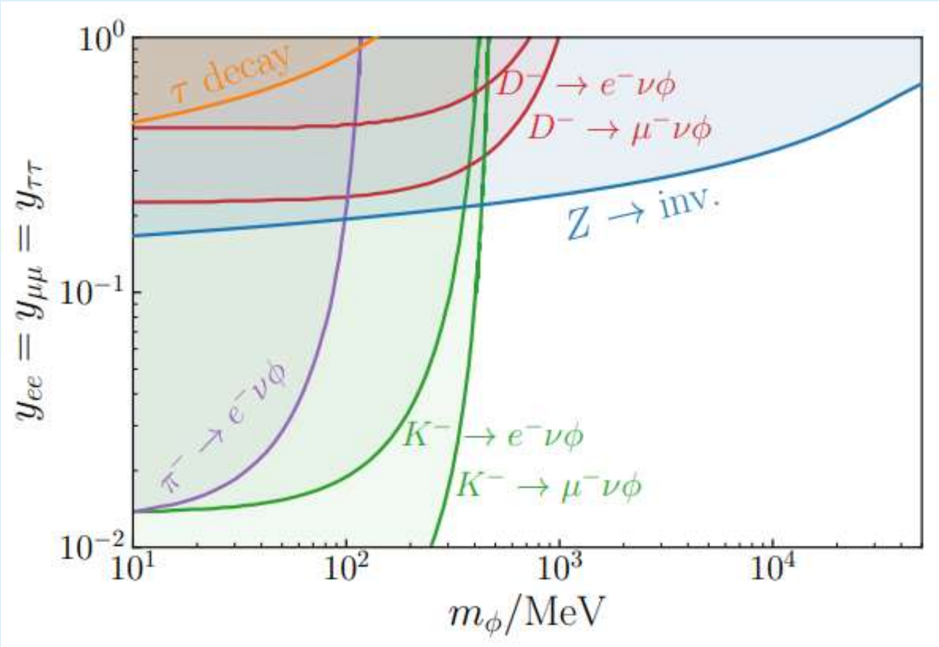


Berbig, SJ, Trautner (2020)

Self-interacting neutrino solution



Deppisch, Graf, Rodejohann, Xu (2020)



Brdar, Lindner, Vogl, and Xu (2020)
Blinov, Kelly, Krnjaic, McDermott (2019)
Lyu, Stamou, Wang (2020)

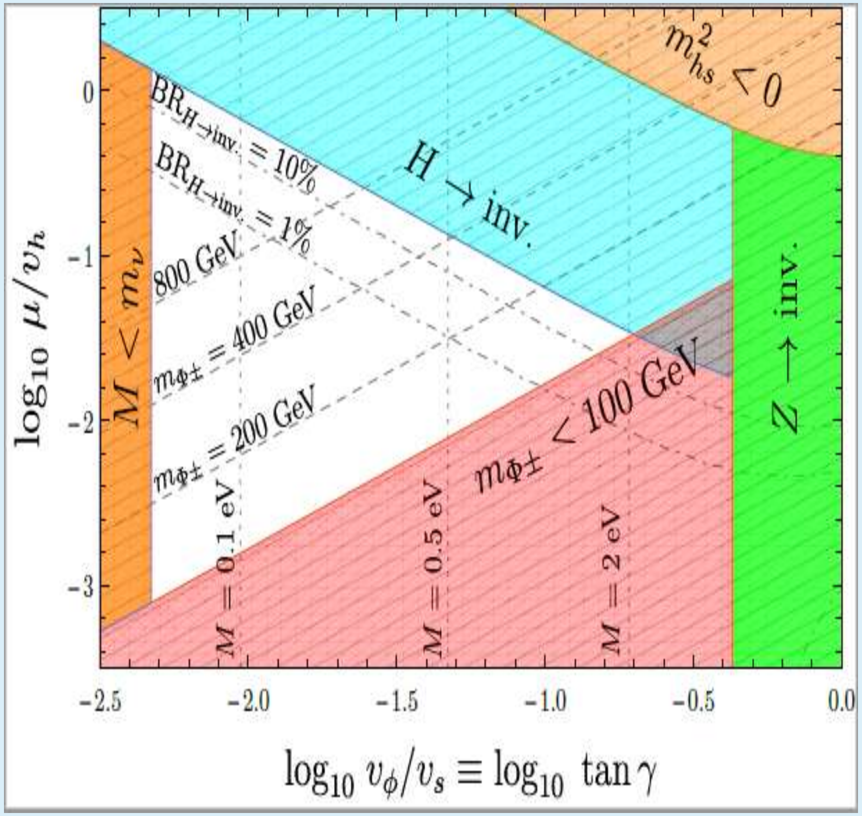
The bounds are slightly below the interaction strength required to explain H_0. In the case of momentum transfer $p_\nu \ll m_\phi$ this holds. One can revive this by departing from the EFT approximation and go to lighter mediator particles. However, here naively we have $p_\nu \sim Q > \sim$MeV . For light $m_\phi \ll Q$, the correct scaling behavior should be g^2/Q^2 and the bound does not apply.

Self-interacting neutrino solution

- Despite strong constraints, this model shows that it is, in principle, possible to have consistent self-interacting neutrino models (not only) for Hubble tension.

- Preferred parameter region:
- Charged Higgses at a few 100 GeV,
- Sizable BR(Higgs → inv.),
- Hidden neutrino(s) with mass(es) $M_N \sim 1 \div 300$ eV and active-hidden mixing with angle $\varepsilon_m > 5 \times 10^{-4}$,

- This is also the correct range to potentially resolve SBL ν anomalies. Either with eV-scale hidden neutrinos, or with O(100 eV) "decaying hidden neutrino solution". [Dentler,Esteban,Kopp,Machado'19],[De Gouvea,Peres,Prakash'19]



Berbig, SJ, Trautner (2020)

Summary

Neutrinos are one of the most abundant of all known particles in the universe, but yet the least understood ones.

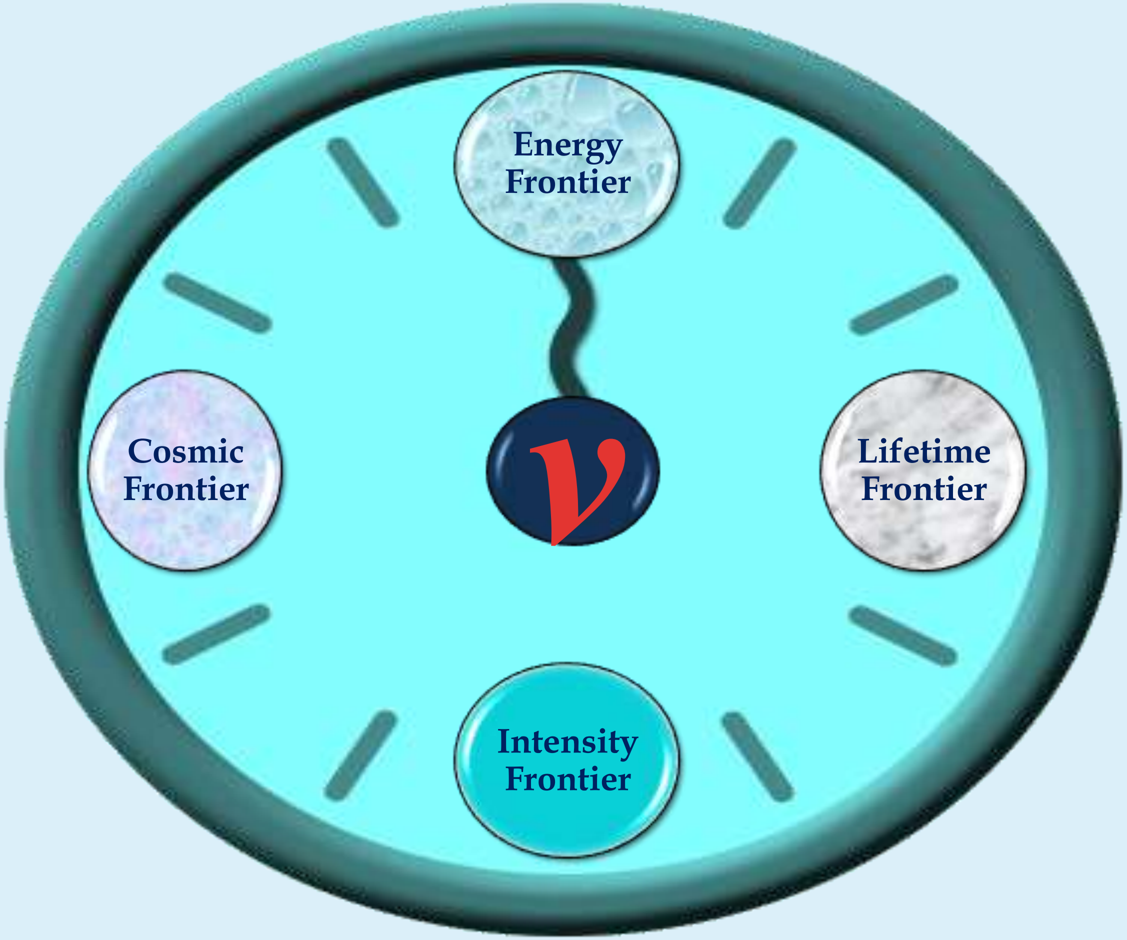
Here I give a try to revisit what sort of physics we expect to learn from neutrinos and highlight the big questions in neutrino physics and the impact of future experiments in answering these, including the complementarities among the experiments at the energy, lifetime, intensity, and cosmic frontiers.

Seesaw models are attractive, but where is the new physics scale? $\Lambda \sim 10^{13}$ GeV > 100 GeV > keV ?

Only if we determined this, could we make fundamental progress in underlying theory!

Can we observe the new physics associated with the neutrino mass at colliders or at other experiments ? YES!	Must we see the new physics effects ? NO.

Neutrino clock




thank you!