Displaced vertex and disappearing track signature in type III Seesaw

Sudip Jana

Max-Planck-Institut für Kernphysik
Heidelberg, Germany

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Based on *arXiv: 1911.09037*

in collaboration with
N. Okada and D. Raut

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❖ BSM Motivations

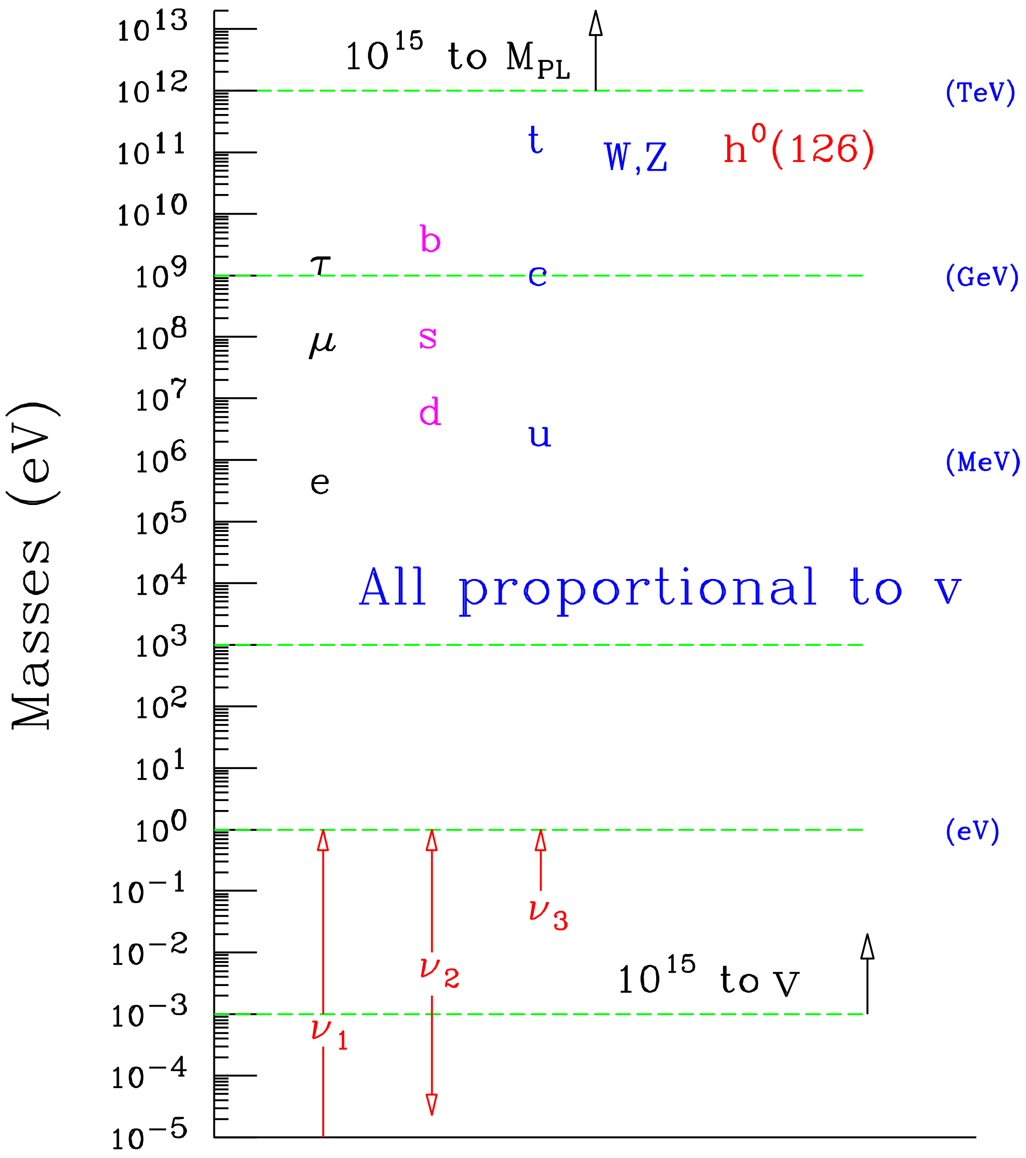
Experimental Evidences

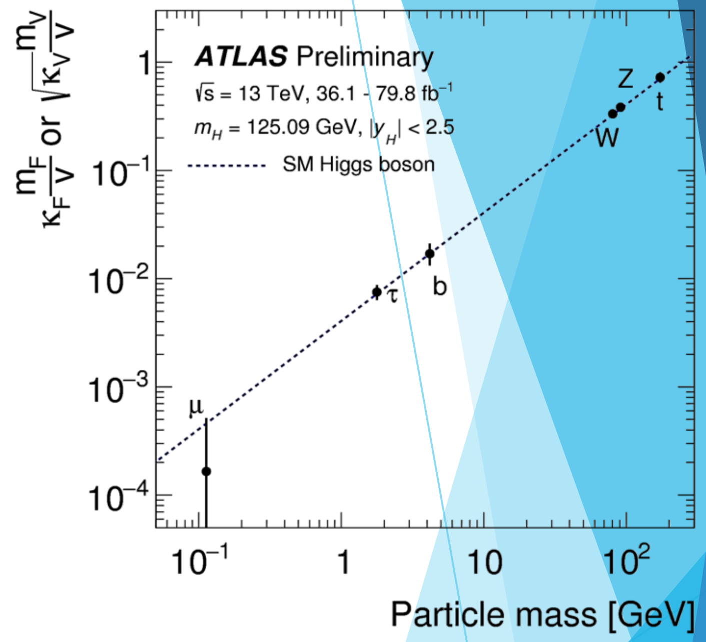
- Neutrino Masses and Mixing
- Dark Matter and Dark Energy
- Matter-antimatter Asymmetry
- Anomalies

Theoretical Motivations

- Naturalness Problem
- Strong CP Problem
- Grand Unification
- Flavor Puzzle

Neutrino Masses and Mixings > New physics beyond SM





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

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

❖ Small Neutrino Masses

❖ "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.

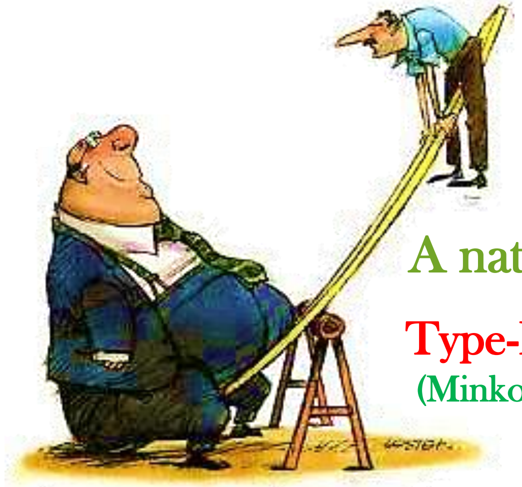
❖ Suppression by loop radiative generation: the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.

❖ Neutrino Mass Models

- 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)

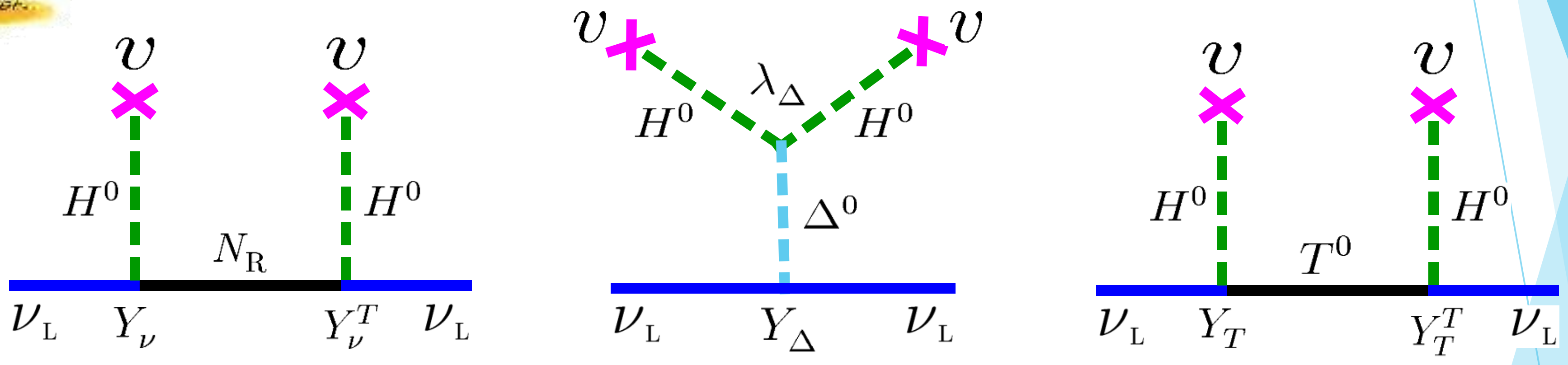


❖ Seesaw Models

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)



$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

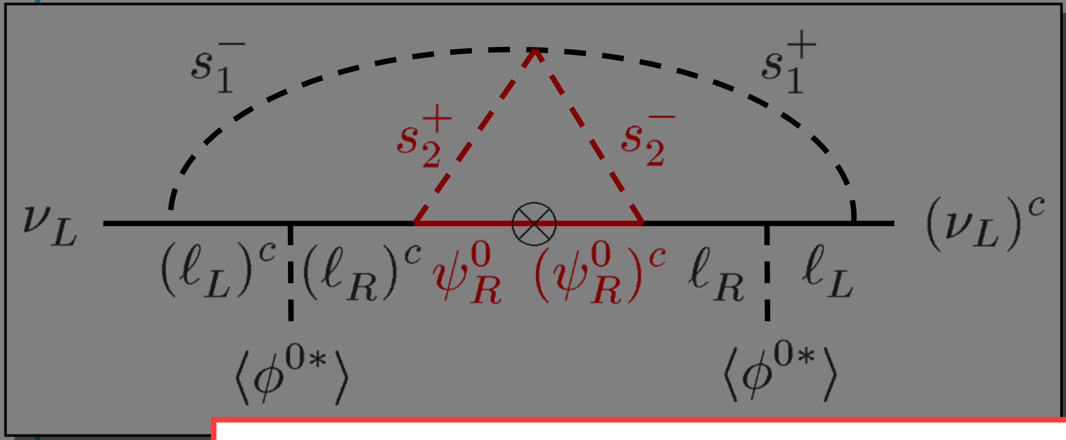
Type-II: SM + 1 Higgs triplet

(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)

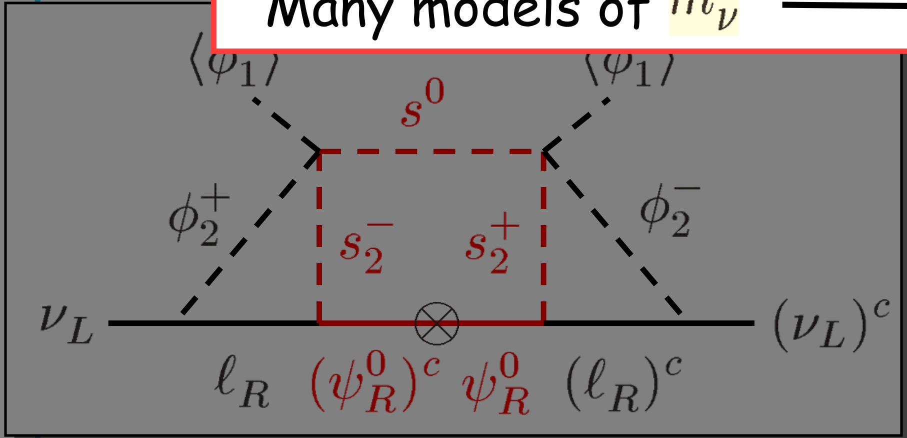
Higher-loop models with DM



Krauss-Nasri-

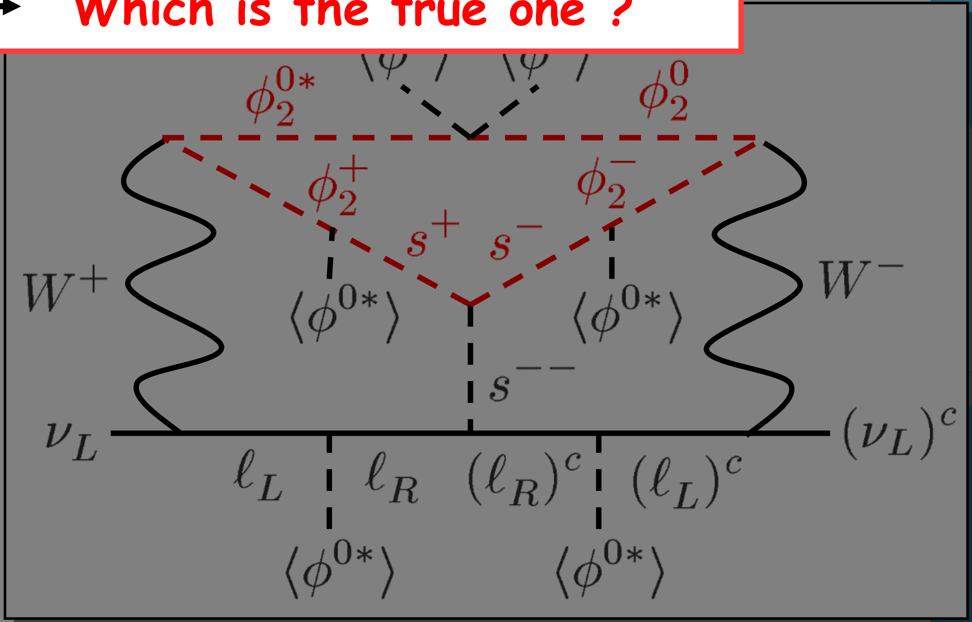
M.L. Krauss, S. N

Many models of m_ν → **Which is the true one ?**



Aoki-Kanemura-Seto model

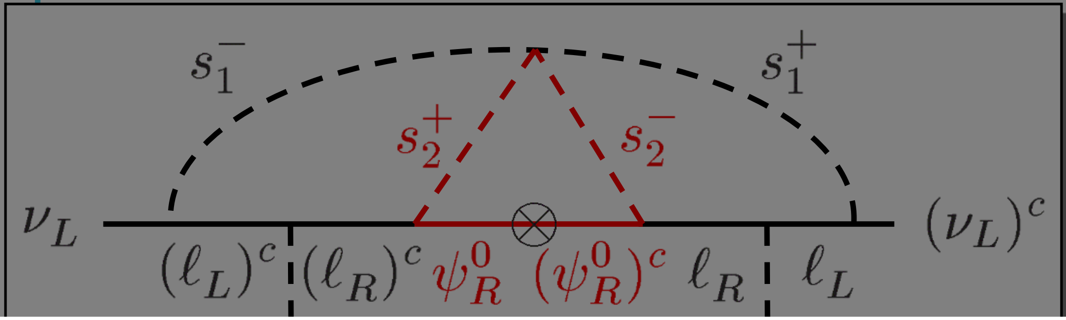
M. Aoki, S. Kanemura and O. Seto,
PRL**102**, 051805 (2009)



Gustafsson-No-Rivera model

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

Higher-loop models with DM



Krauss-Nasri-

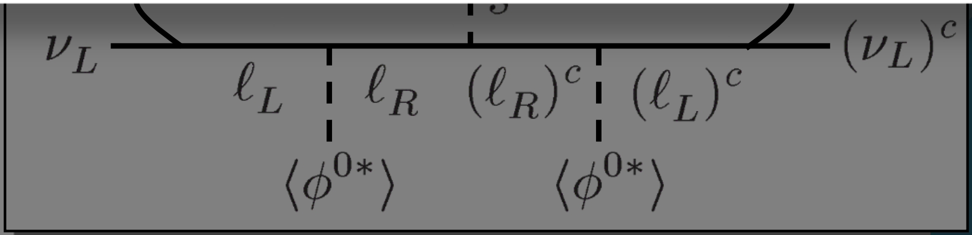
M.L. Krauss, S. N

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

2. Can we explore the new Physics Scale M ?

Aoki-Kanemura-Seto model

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



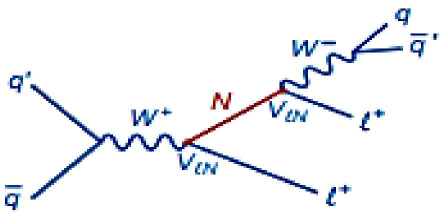
Gustafsson-No-Rivera model

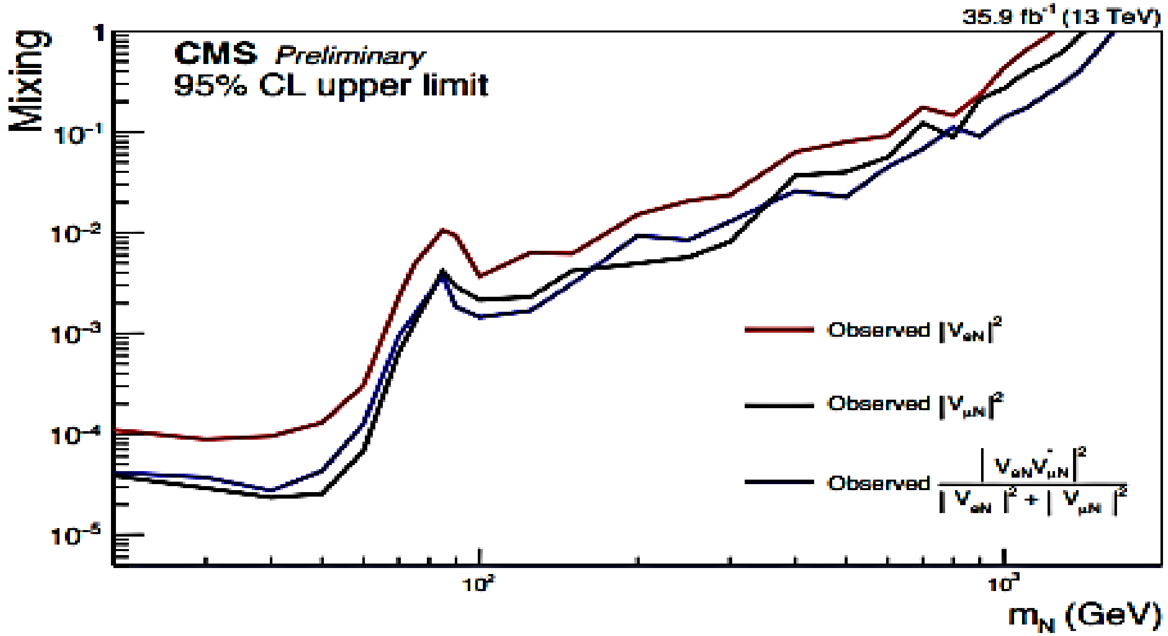
M. Gustafsson, J.M. No, and M.A. Rivera, PRL**110**, 21802 (2013)

❖ Testing Type-I Seesaw Experimentally

[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 $\not{E}_T$)





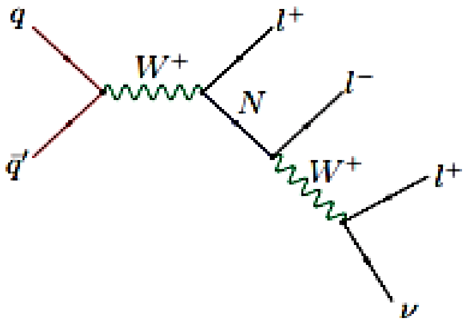
[CMS PAS EXO-17-028]

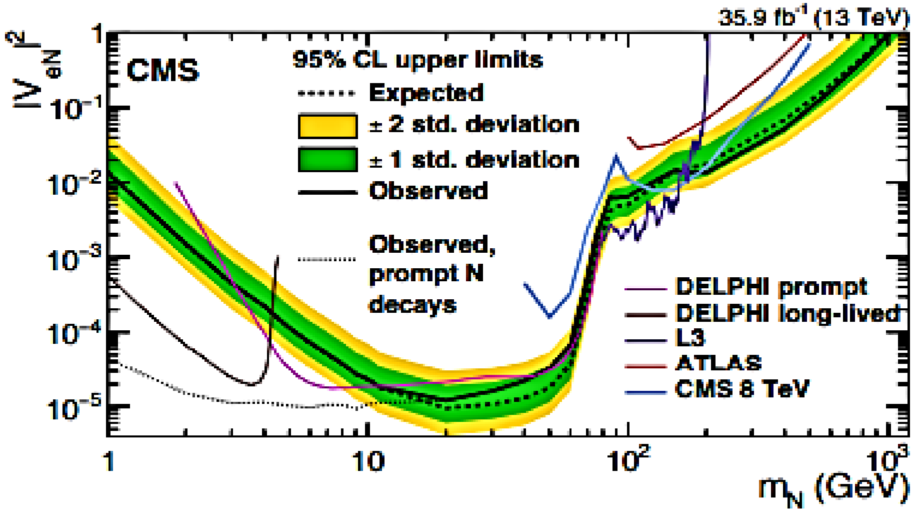
❑ Need (sub)-TeV scale heavy neutrinos with 'large' mixing with active neutrinos.

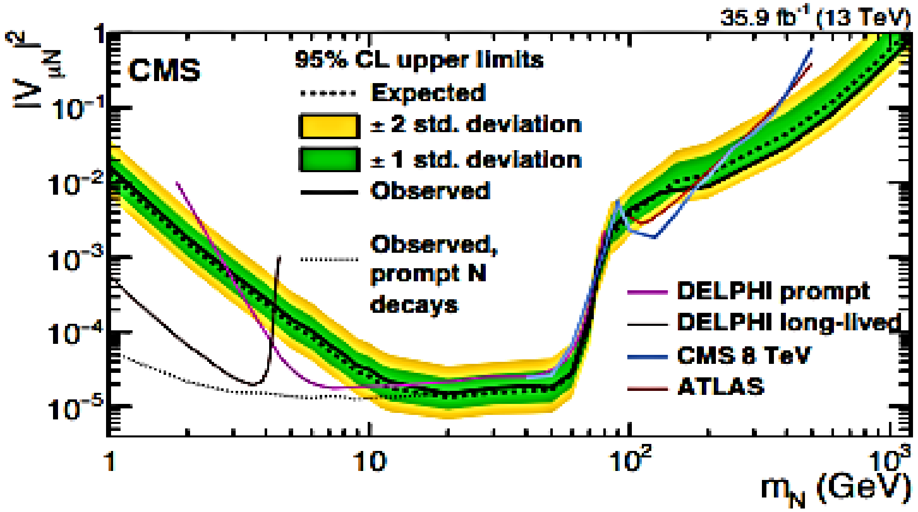
Testing Inverse Seesaw Experimentally

[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 $\not{E}_T$

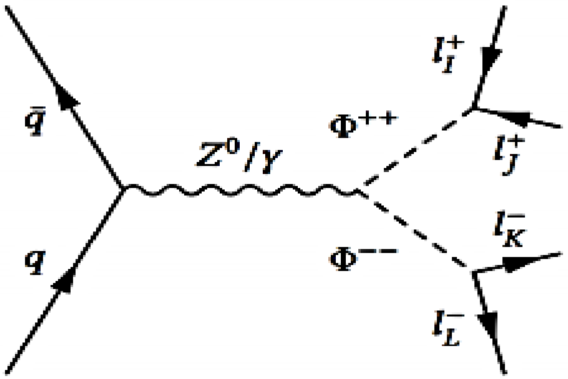




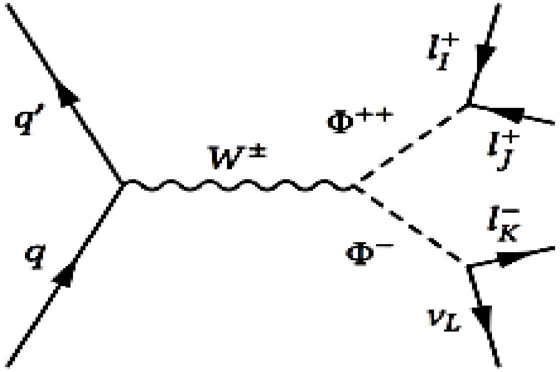


[CMS Collaboration, Phys. Rev. Lett. **120**, 221801 (2018)]

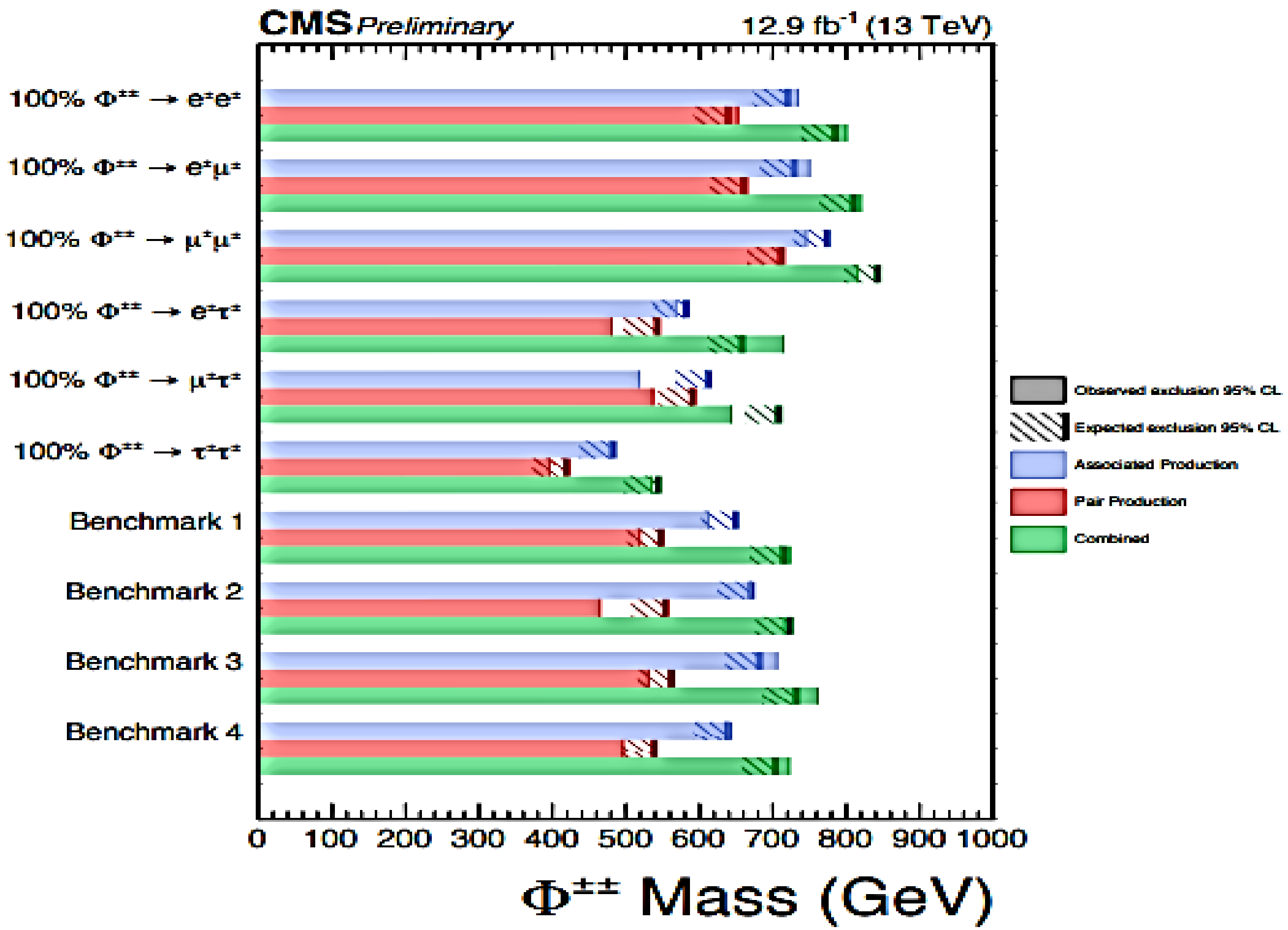
❖ Testing Type-II Seesaw at the LHC



(a) 4ℓ



(b) 3ℓ

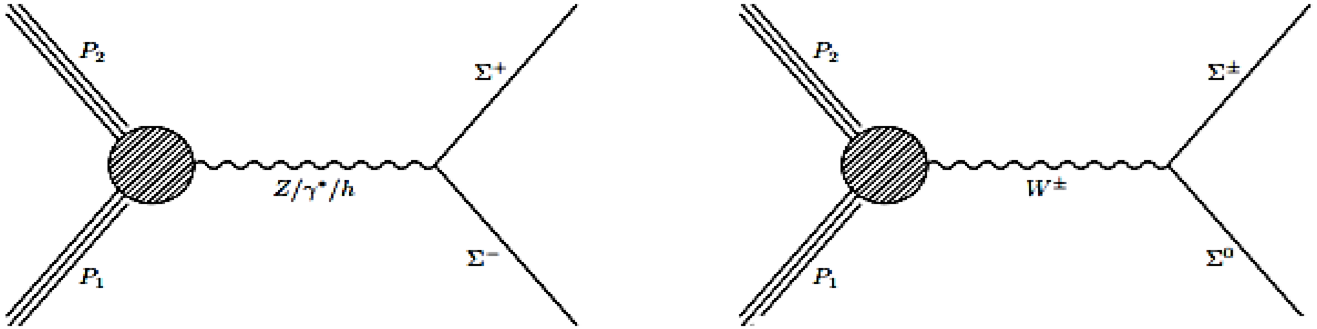


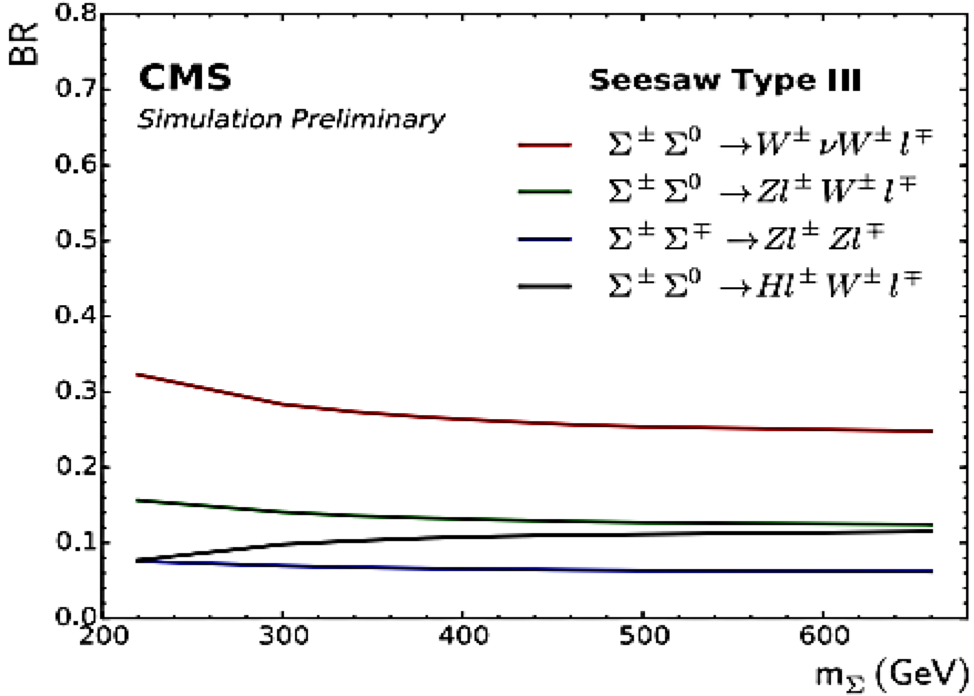
[CMS-PAS-HIG-16-036]

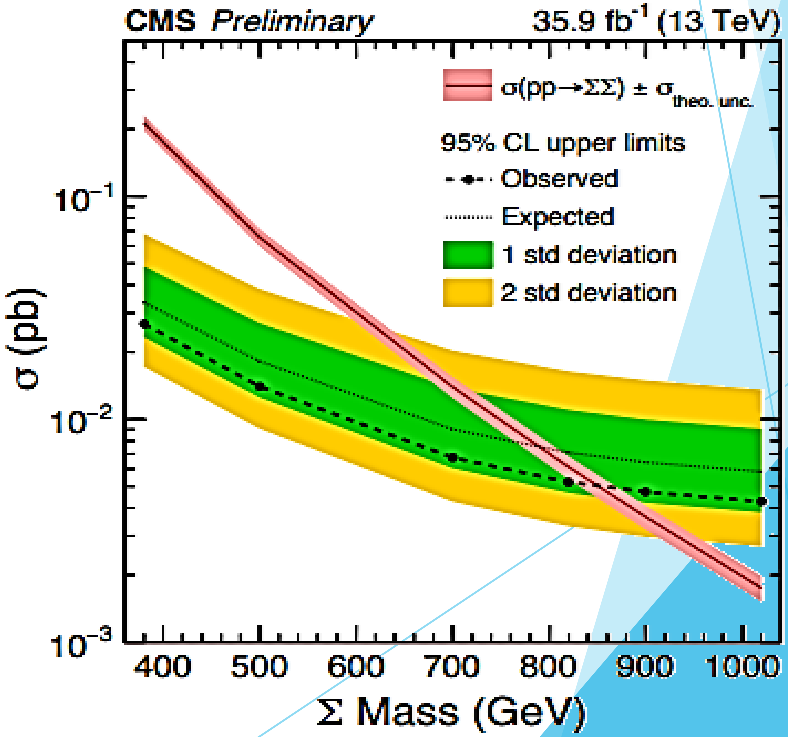
Rizzo (1982); Huitu, Maalampi, Pietila, Raidal (1997); Gunion, Loomis, Pitts (1996); Akeryod, Aoki (2005); Han, Mukhopadhyaya, Ci, Wang (2005), N. Sahu, Uma Sankar (2005); Sarma, Devi, Singh (2007); Chao, Luo, Xing, Zhao (2007); Perez, Han, Huang, Li, Wang (2008); McDonald, Sahu, Sarkar (2008); Chiang,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

❖ Testing Type-III Seesaw at the LHC

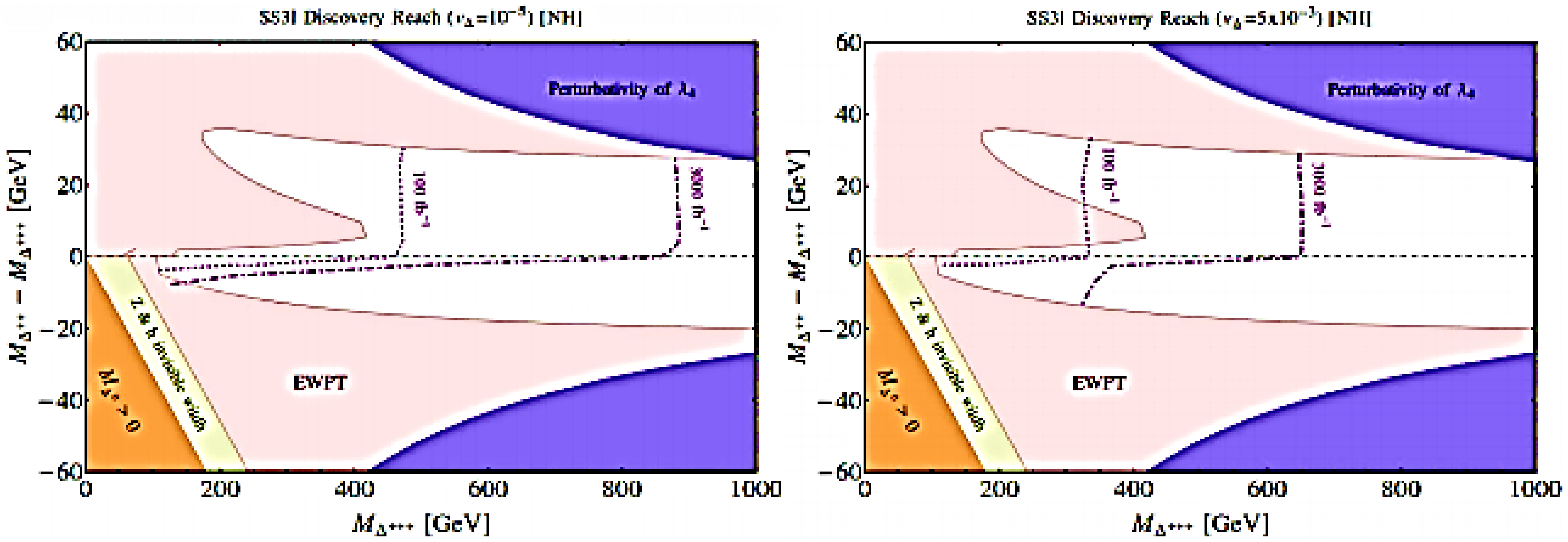
- Multi-lepton signatures. [Franceschini, Hambye, Strumia (PRD '08); Li, He (PRD '09); Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović (PRD '10); Ruiz (JHEP '15)]







❖ 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)

Probe 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.

- 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.

- It may show up at experiments at near future.

❖ Type III Seesaw

- *Lagrangian*

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

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

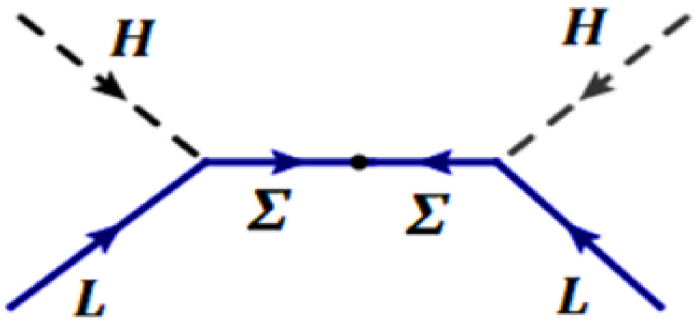
$$\mathcal{L} = \mathcal{L}_{SM} + Tr[\overline{\Sigma} i \not{D} \Sigma] - \frac{1}{2} Tr[\overline{\Sigma} M_\Sigma \Sigma^c + \overline{\Sigma^c} M_\Sigma^* \Sigma] - \tilde{\phi}^\dagger \overline{\Sigma} \sqrt{2} Y_\Sigma L + h.c.$$

Majorana mass term

kinetic term: interactions with W and Z bosons

Yukawa interactions

- *Neutrino Mass Generation:*



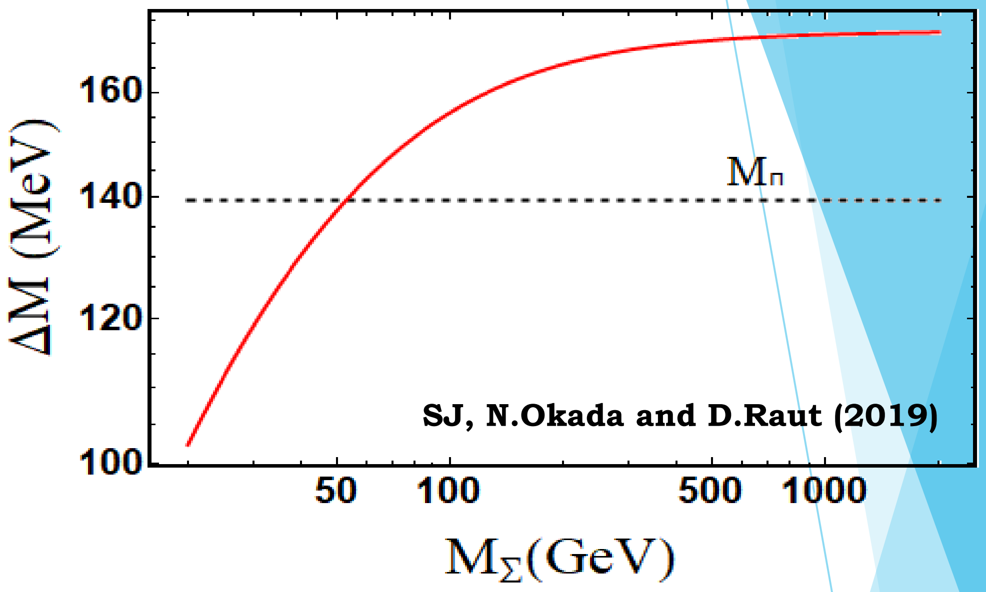
$$\longrightarrow \quad m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

❖ Type III Seesaw

- *Mass splitting:*

Although their masses are degenerate at the tree-level, radiative corrections induced by the electroweak gauge boson loops removes the degeneracy and generate mass-splitting between the consecutive members of the fermion triplet.

$$\Delta M = \frac{\alpha_2 m_\Sigma}{4\pi}\left[f\left(\frac{M_W}{m_\Sigma}\right) - \cos^2\theta_W f\left(\frac{M_Z}{m_\Sigma}\right)\right].$$



- *Main differences between type I and type III Seesaw:*

↪ triplets unlike N singlets:

- have gauge interactions:

$$\bar\Sigma^-\Sigma^- Z\,,\ \bar\Sigma^+\Sigma^+ Z\,,\ \bar\Sigma^0\Sigma^+ W^-\,,\ \bar\Sigma^0\Sigma^- W^+ \quad (+h.c.)$$

- induce mixing of the charged leptons with new physics states: $\Sigma^{+c} - l^-$ mixing (much easier to see than mixing of neutral neutrino states)

$$\mathcal{L} \ni vY_\Sigma \Sigma^+ l^-$$

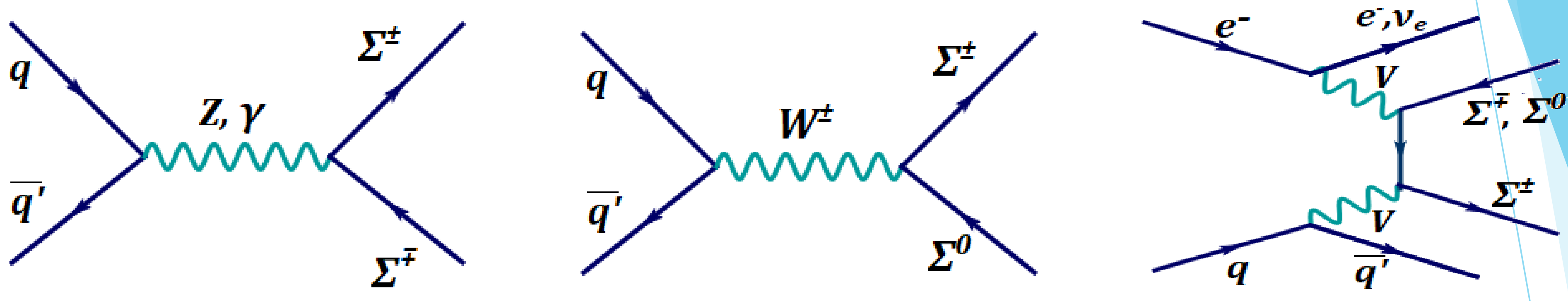
production at colliders and rare decays

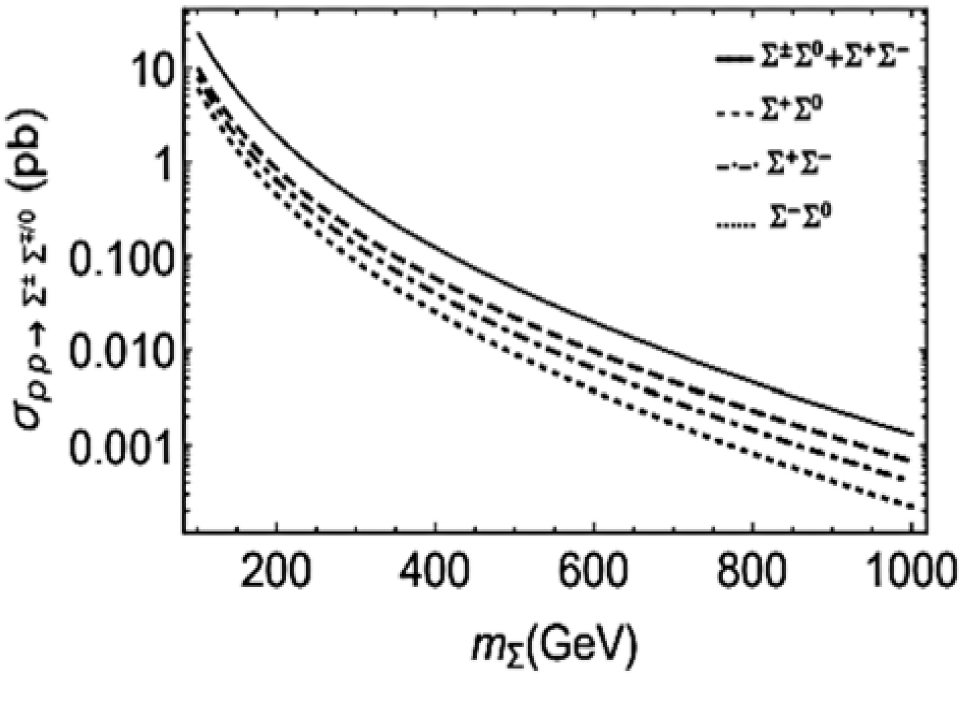
For type I seesaw, see Oliver's Talk

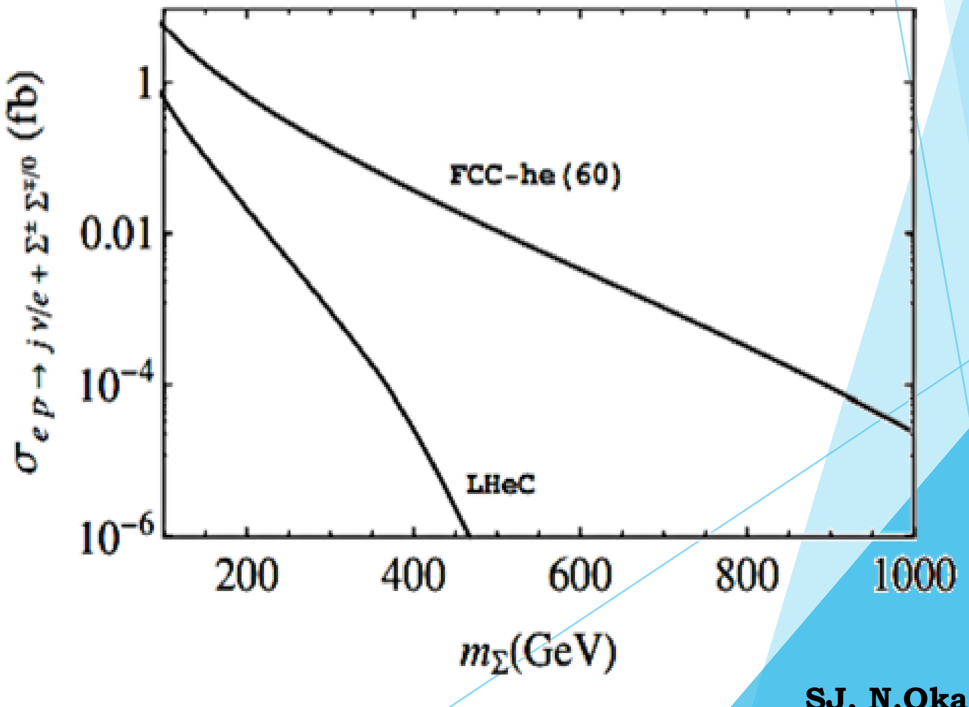
Roberto Franceschini et al. (2008)

❖ Production and decay modes of the fermion triplet

- Production:



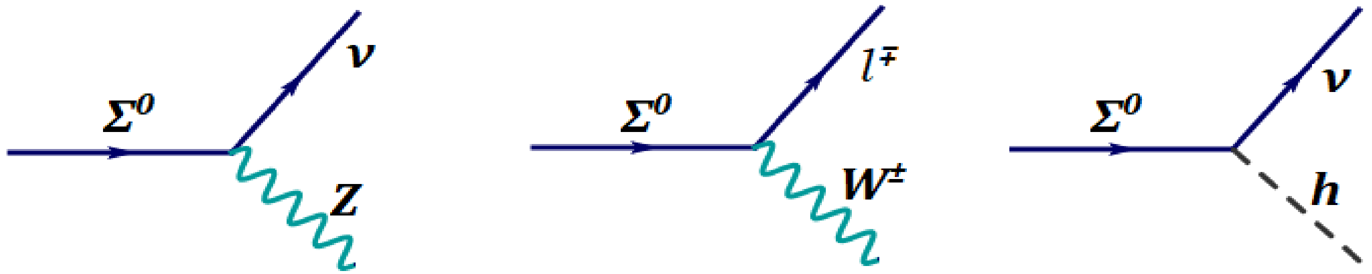




SJ, N.Okada and D.Raut (2019)

❖ Production and decay modes of the fermion triplet

- *Decay modes of neutral fermion :*



$$\Gamma(\Sigma_i^0 \to h\nu_\alpha) = \Gamma(\Sigma_i^0 \to h\bar{\nu}_\alpha) = \frac{1}{8}\frac{M_\Sigma}{8\pi}\left(\frac{|R_{\alpha i}|^2}{2v^2}\right)\left(1-\frac{m_h^2}{M_\Sigma^2}\right)^2,$$

$$\Gamma(\Sigma_i^0 \to Z\nu_\alpha) = \Gamma(\Sigma_i^0 \to Z\bar{\nu}_\alpha) = \frac{1}{8}\frac{M_\Sigma}{8\pi}\left(\frac{|R_{\alpha i}|^2}{2v^2}\right)\left(1-\frac{2M_Z^2}{M_\Sigma^2}\right)^2\left(1+\frac{2M_Z^2}{M_\Sigma^2}\right)$$

$$\Gamma(\Sigma_i^0 \to W^+\ell_\alpha^-) = \Gamma(\Sigma_i^0 \to W^-\ell_\alpha^+) = \frac{1}{4}\frac{M_\Sigma}{8\pi}\left(\frac{|R_{\alpha i}|^2}{2v^2}\right)\left(1-\frac{M_W^2}{M_\Sigma^2}\right)^2\left(1+\frac{2M_W^2}{M_\Sigma^2}\right)$$

where $\alpha = e, \mu, \tau$ denotes different lepton flavors and

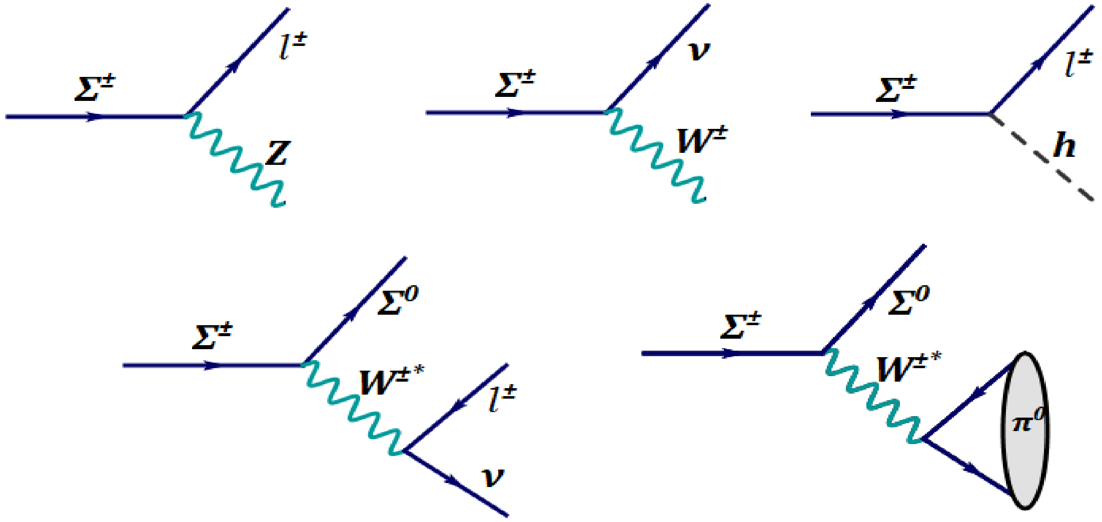
$$R_{\alpha i} = (m_D)_{\alpha i}(M_\Sigma)^{-1} = \frac{1}{\sqrt{m_\Sigma}} U_{\rm MNS}^* \sqrt{D_\nu}\, O.$$

If O is a unit 3×3 matrix, $|R_{\alpha i}|^2 = m_i/m_\Sigma$

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

❖ Production and decay modes of the fermion triplet

- *Decay modes of charged fermion :*



$$\Gamma(\Sigma_i^\pm \to h\ell_\alpha^\pm) = \frac{1}{4}\frac{M_\Sigma}{8\pi}\left(\frac{|R_{\alpha i}|^2}{2v^2}\right)\left(1-\frac{m_h^2}{M_\Sigma^2}\right)^2,$$

$$\Gamma(\Sigma_i^\pm \to Z\ell_\alpha^\pm) = \frac{1}{4}\frac{M_\Sigma}{8\pi}\left(\frac{|R_{\alpha i}|^2}{2v^2}\right)\left(1-\frac{M_Z^2}{M_\Sigma^2}\right)^2\left(1+\frac{2M_Z^2}{M_\Sigma^2}\right),$$

$$\Gamma(\Sigma_i^\pm \to W^\pm \overset{(-)}{\nu}_\alpha) = \frac{1}{2}\frac{M_\Sigma}{8\pi}\left(\frac{|R_{\alpha i}|^2}{2v^2}\right)\left(1-\frac{2M_W^2}{M_\Sigma^2}\right)^2\left(1+\frac{2M_W^2}{M_\Sigma^2}\right).$$

$$\Gamma(\Sigma_i^\pm \to \Sigma_i^0 \pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi}\sqrt{1-\frac{m_\pi^2}{\Delta M^2}},$$

$$\Gamma(\Sigma_i^\pm \to \Sigma_i^0 e^\pm \overset{(-)}{\nu}_e) = \frac{2G_F^2 \Delta M^5}{15\pi^3},$$

$$\Gamma(\Sigma_i^\pm \to \Sigma_i^0 \mu^\pm \overset{(-)}{\nu}_\mu) = 0.12\,\Gamma(\Sigma^\pm \to \Sigma^0 e^\pm \overset{(-)}{\nu}_e).$$

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

❖ 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:*

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

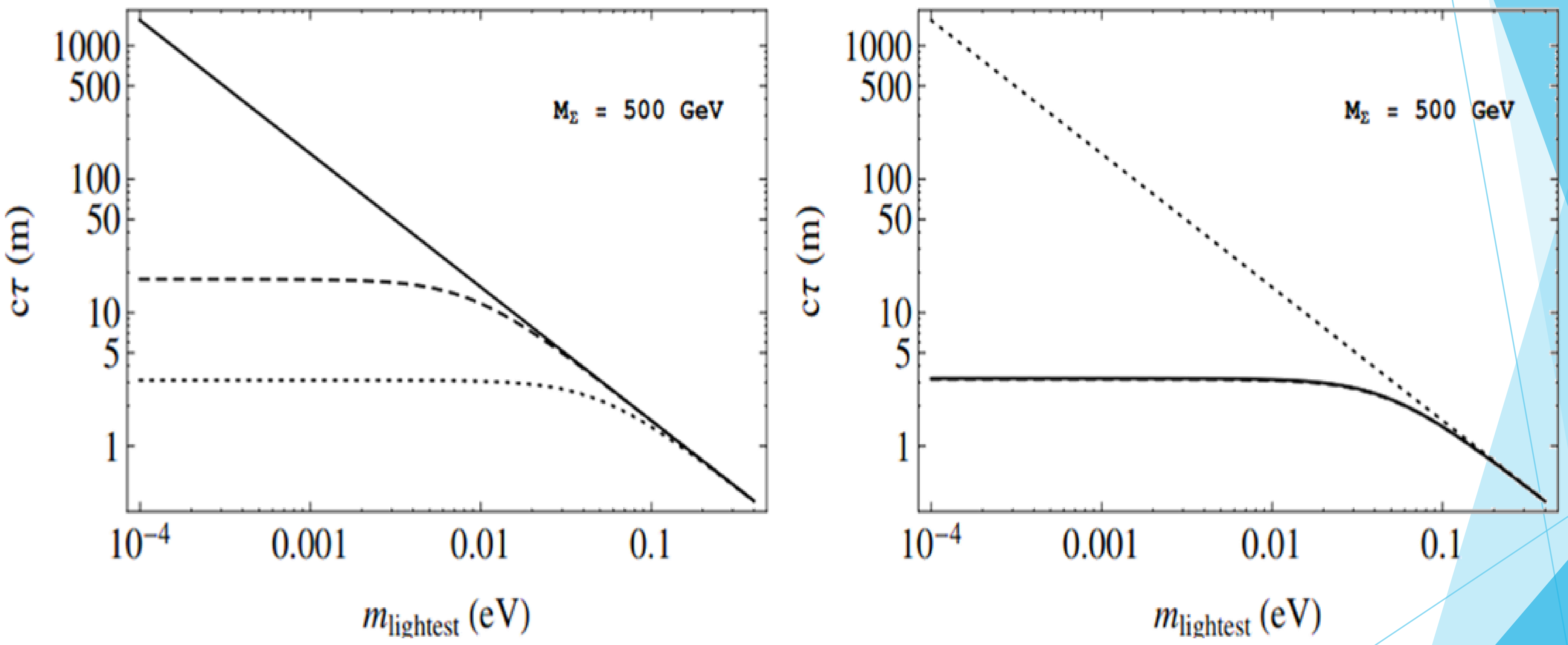
$$\sqrt{D_\nu} = {\rm diag}\left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}\right)$$

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

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

❖ Production and decay modes of the fermion triplet

- Decay length:

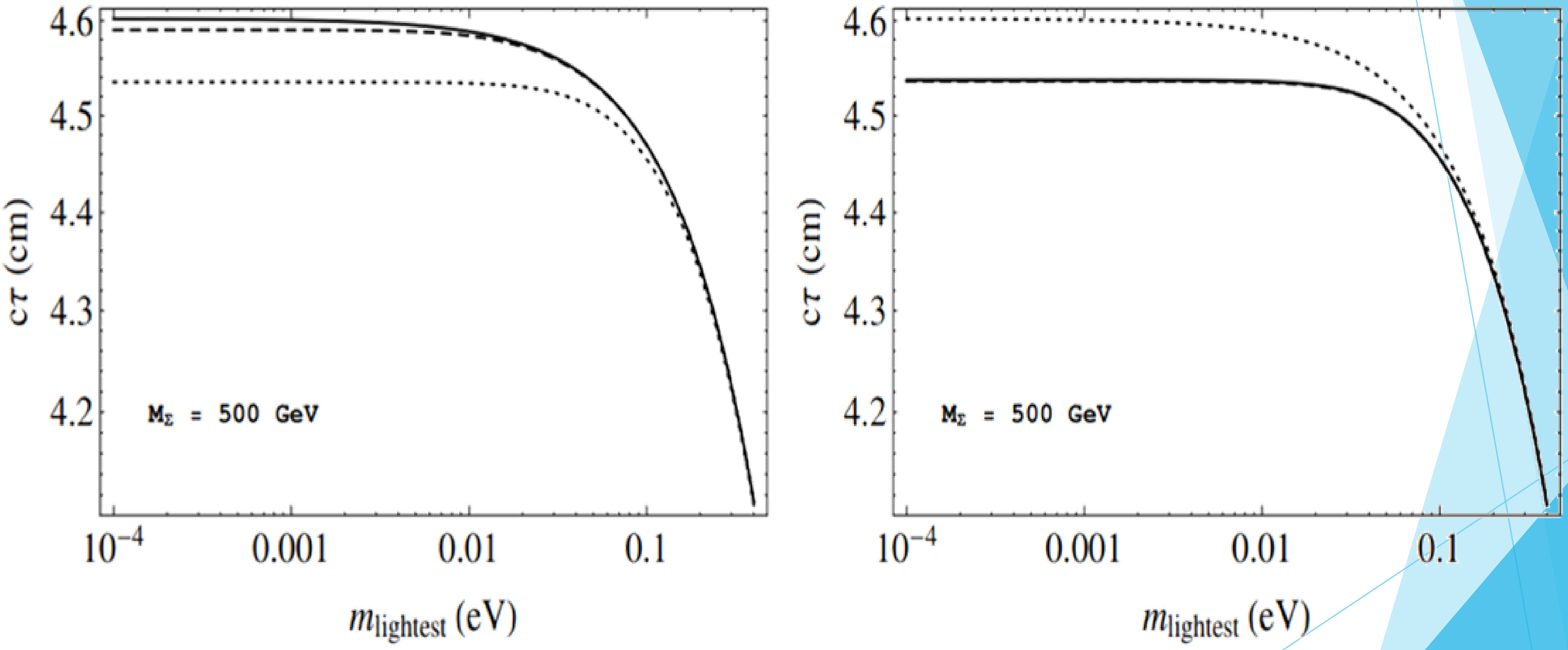


$$|R_{\alpha i}|^2 = m_i/m_\Sigma$$

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

❖ Production and decay modes of the fermion triplet

- *Decay length:*



$$|R_{\alpha i}|^2 = m_i/m_\Sigma$$

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

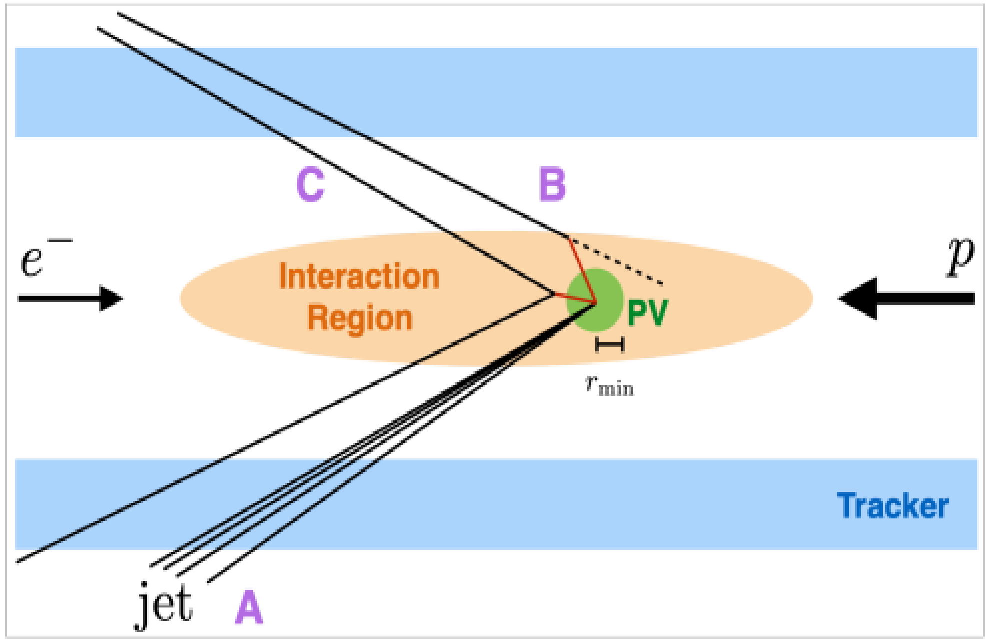
❖ Charged Fermion disappearing track

- One or two charged fermions are produced at the PV, which is identified by the triggering jet (A).

- If the impact parameter with respect to the PV is greater than a given r_{min} we can tag this track as originating from an LLP decay

- Heavily relies on backgrounds due to pile-up being either absent or controllable. p_T threshold for reconstruction of a single charged particle is chosen as 100 MeV and r_{min} = 40μm assuming 100% efficiency

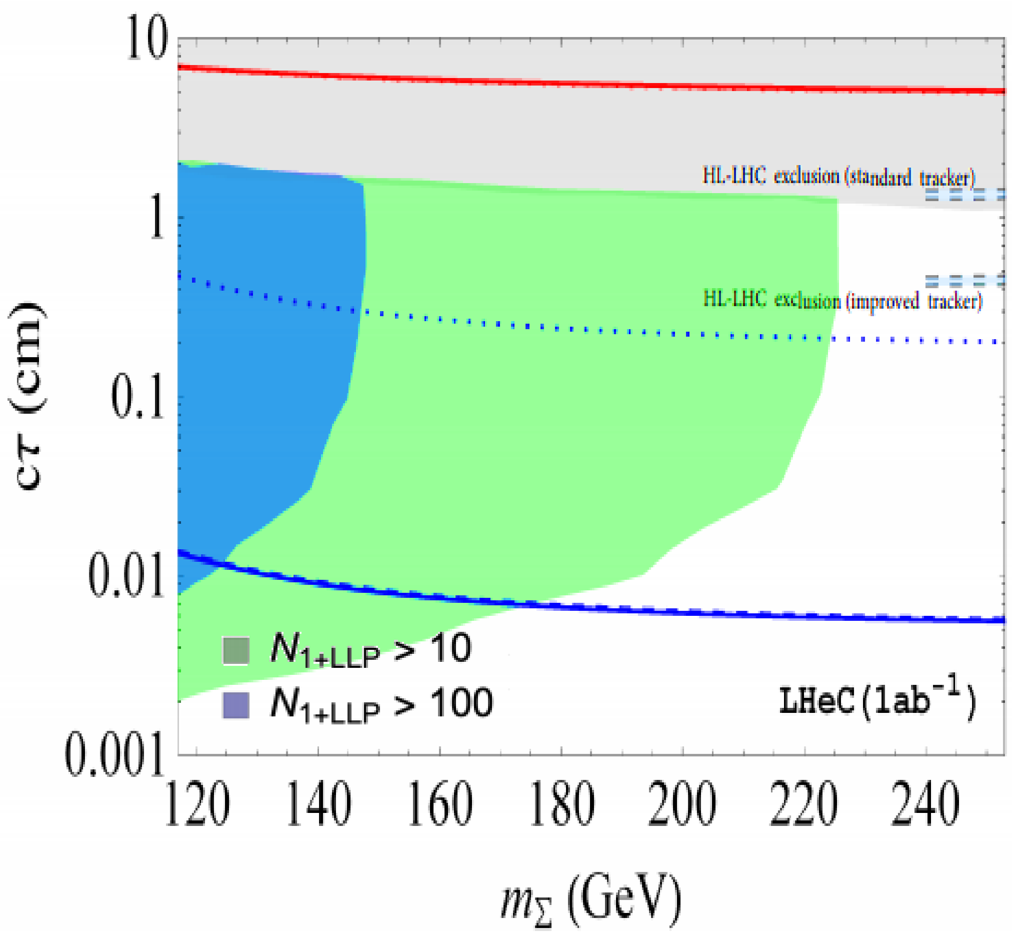
- We estimate the probability of detecting 1 or 2 LLP

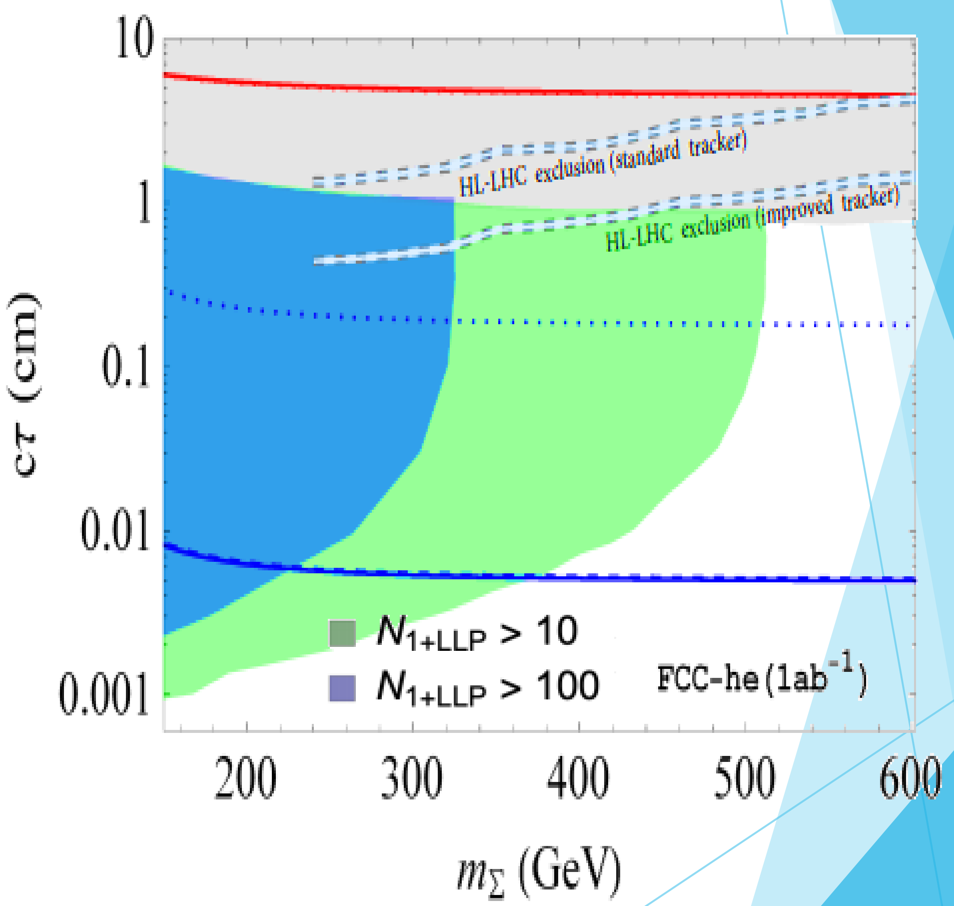


Credit: Monica D'Onofrio's slide

For chargino/neutralino case: O. Fischer et al. (1712.07135)
See talk by Monica D'Onofrio

❖ Results of disappearing track analysis

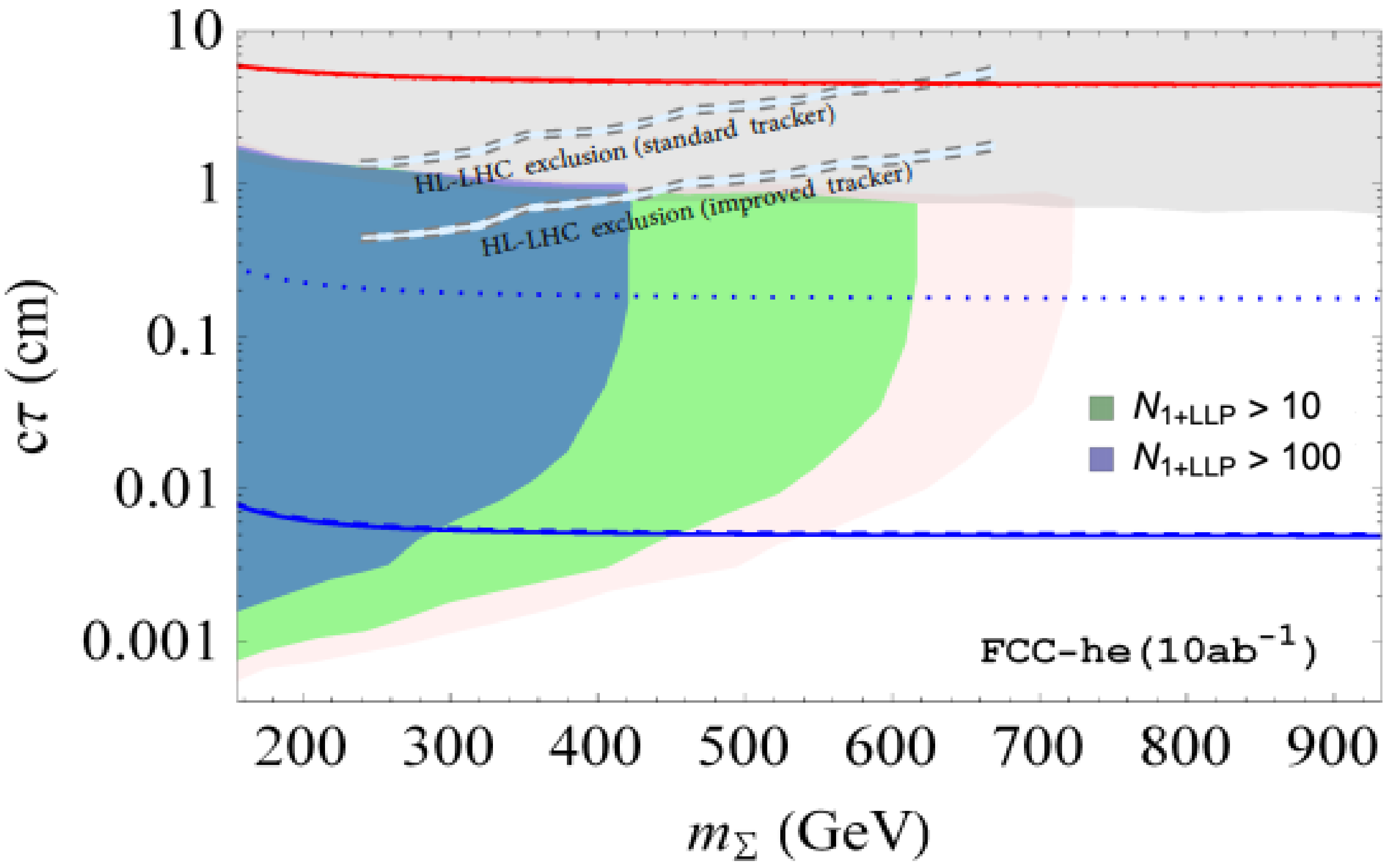




SJ, N.Okada and D.Raut (2019)

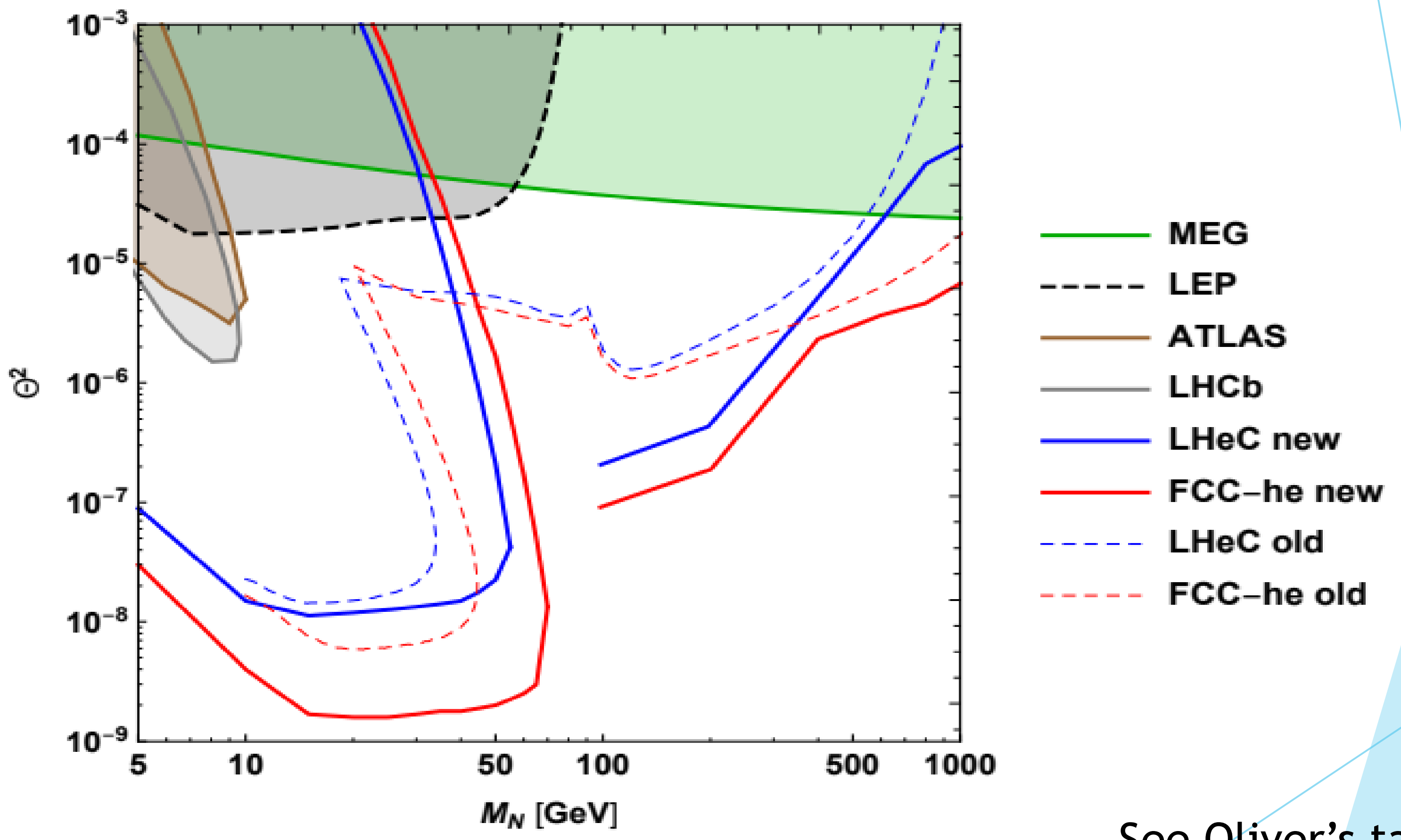
For chargino/neutralino case: O. Fischer et al. (1712.07135)
See talk by Monica D'Onofrio

❖ Results of disappearing track analysis



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

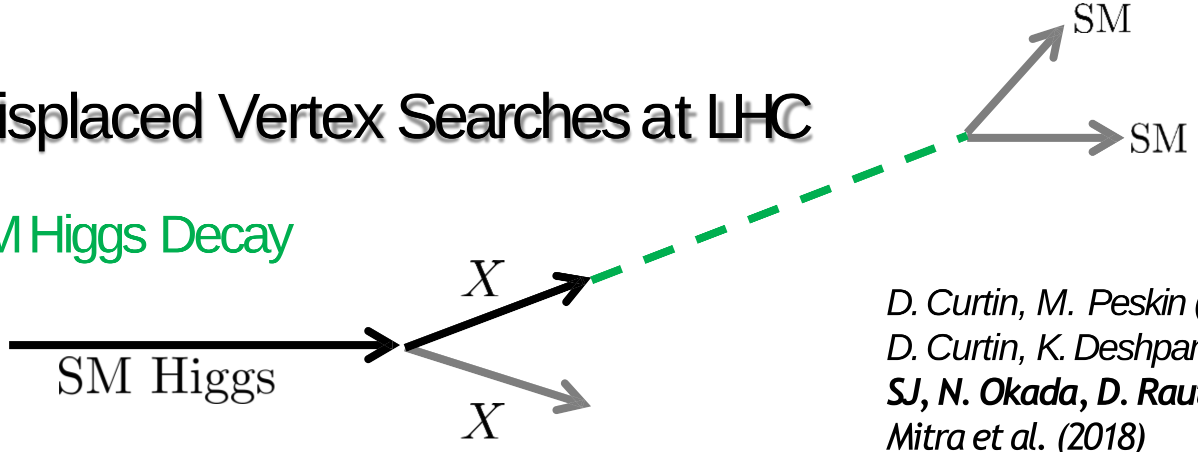
❖ *In comparison with type I seesaw*



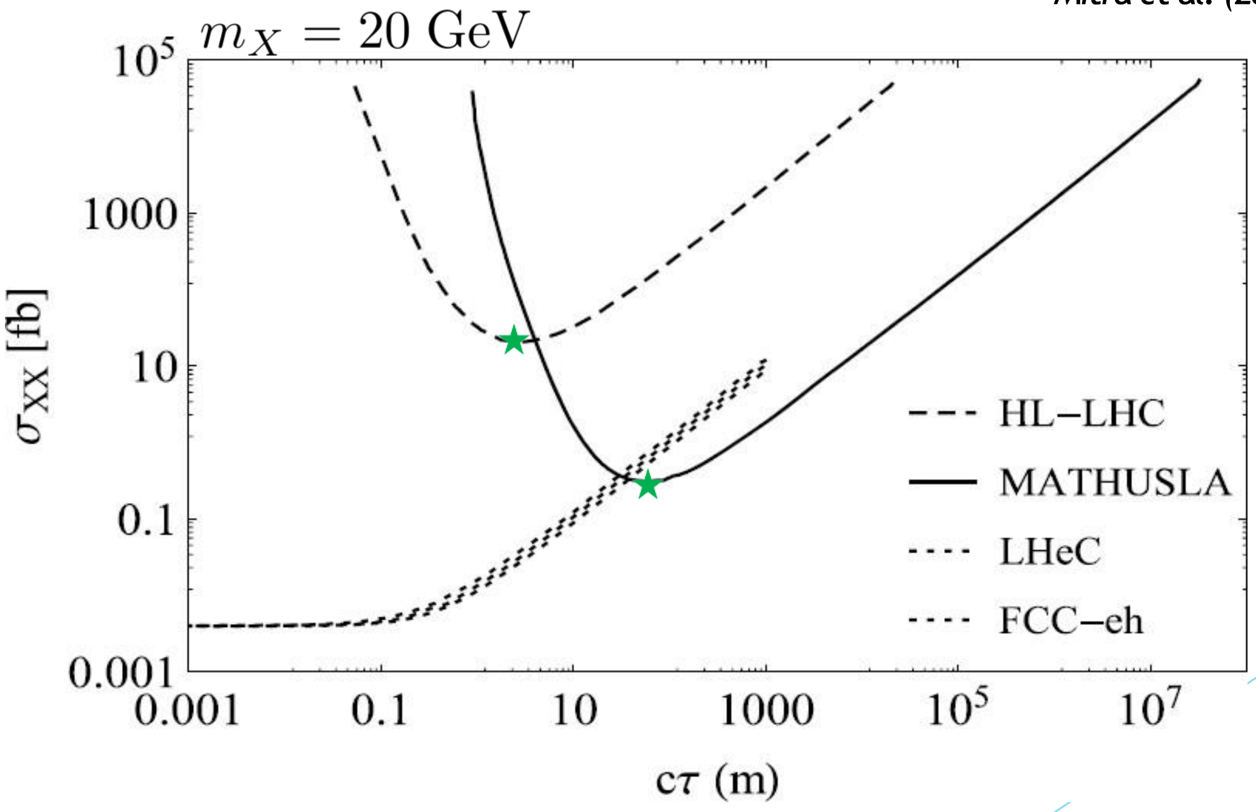
See Oliver's talk

❖ In comparison with type I seesaw

- Future Displaced Vertex Searches at LHC
  - ➢ Rare SM Higgs Decay



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



Conclusions :

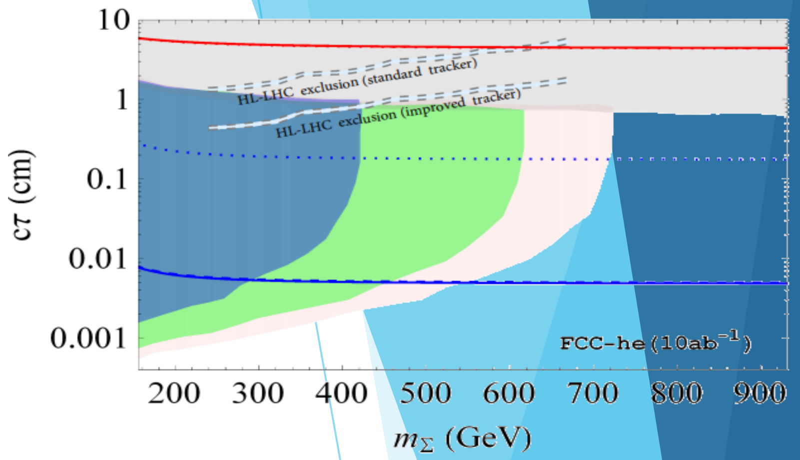
- FCC has unique potential to test <u>neutrino mass generation mechanism</u>

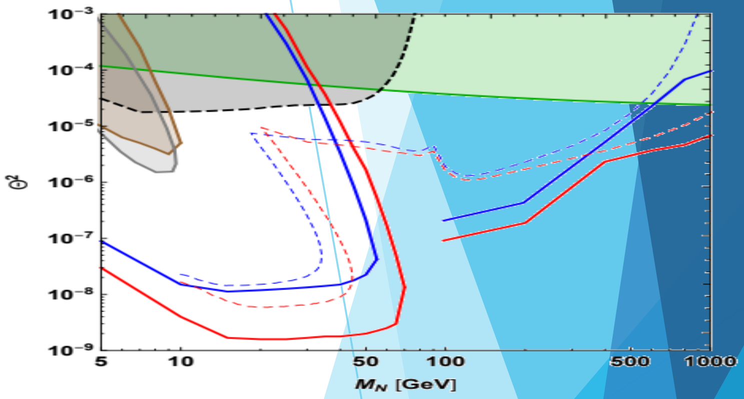
- Displaced vertex and disappearing track signatures: deep connection to neutrino oscillation parameters

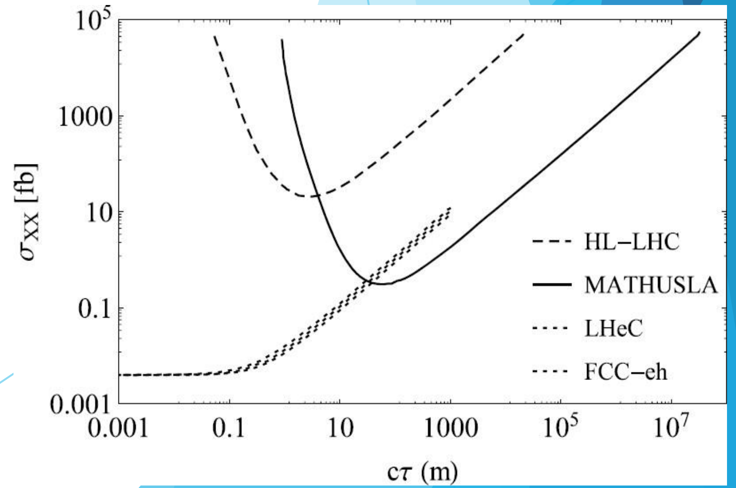
- Novel, simple frameworks

- Rich phenomenology

- As expected, due to low production rate coverage is reduced with respect to hh colliders in case of prompt signature. However, low background conditions allow sensitivity to short decay lengths making disappearing track searches at ep complementary to those at hh collider








Thank you!