Two-loop snail diagrams: relating neutrino masses to dark matter

Yasaman Farzan
School of physics, IPM , Tehran

invisibles
neutrinos, dark matter & dark energy physics

- Neutrino mass<< Electron mass

- Neutrino mass<< Electron mass

Who cares?!

- Neutrino mass<< Electron mass

Who cares?!

Let’s try to explain

new mass scale

- Seesaw type I

$$\begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix}$$

$$m_D \ll m_M$$

new mass scale

- Seesaw type I

$$\begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix}$$

$$m_D \ll m_M$$

Not testable at the LHC ☹

Popularity can change in time

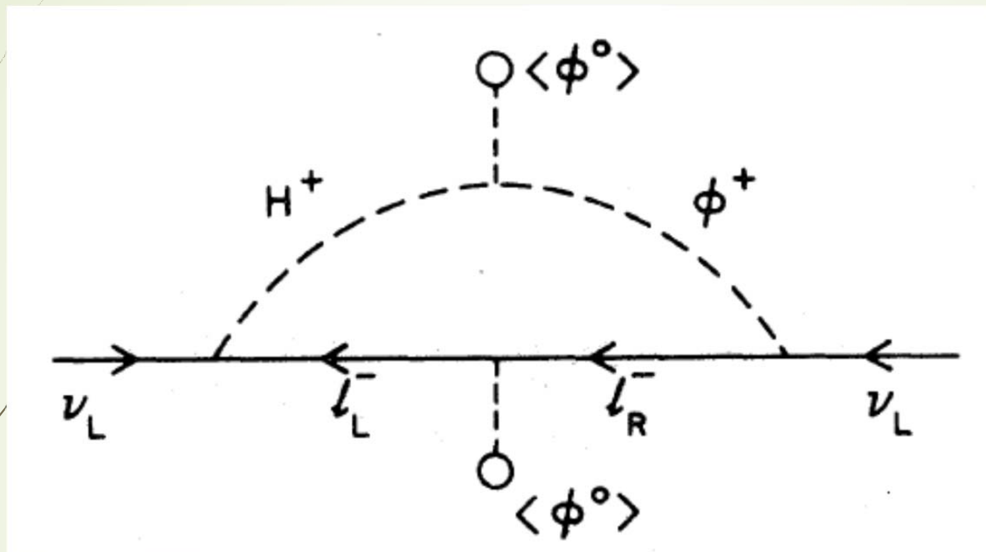
- LHC and other upcoming experiments

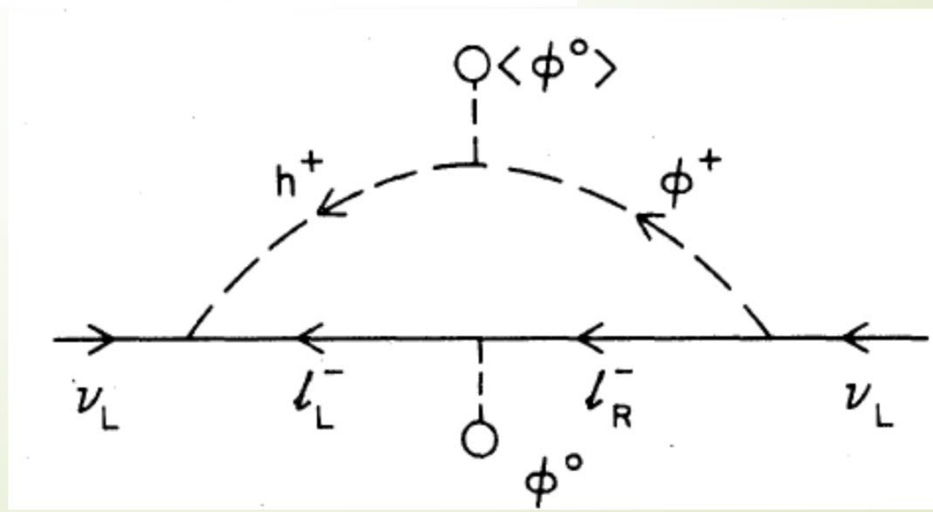
Testable models with
low scale mass

Loop suppression

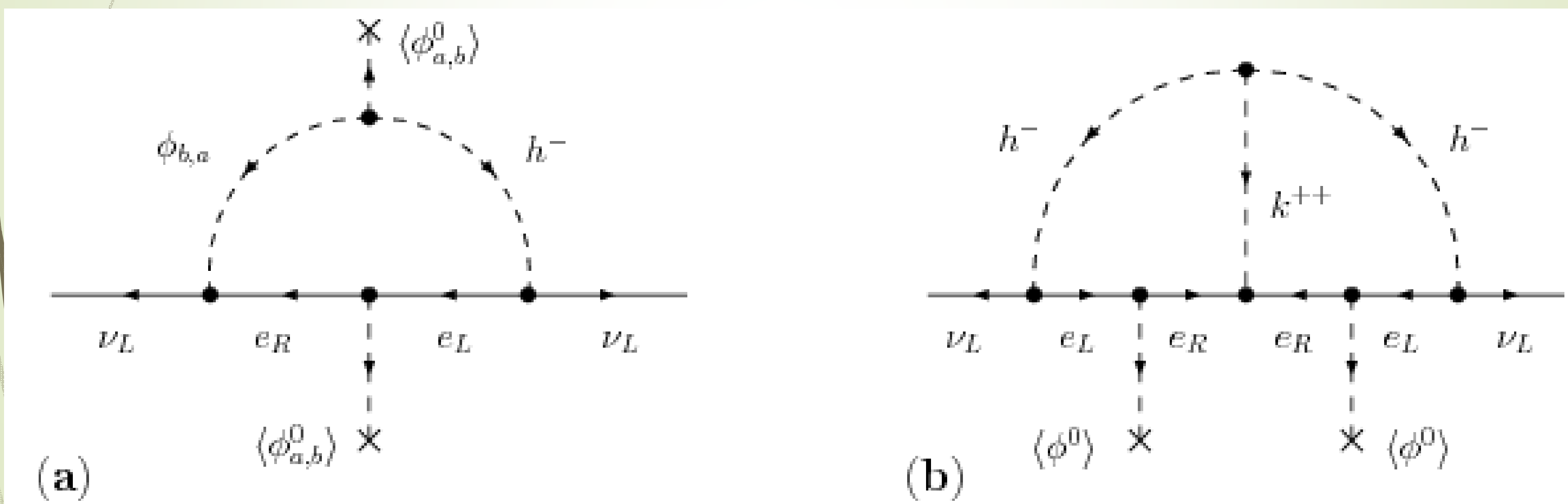
- Cheng-Li, PRD 1980
- Zee model, NPB 1986
- Babu model, PLB, 1988
- .....

Cheng-Li





Zee-Babu



$\langle\phi^0_{a,b}\rangle$
$\phi_{b,a}$
h^-
ν_L
e_R
e_L
ν_L
$\langle\phi^0_{a,b}\rangle$
(a)
h^-
h^-
k^{++}
ν_L
e_L
e_R
e_R
e_L
ν_L
$\langle\phi^0\rangle$
$\langle\phi^0\rangle$
(b)

Radiative neutrino mass production

- Symmetries to forbid lower order (and therefore dominant) loop contribution

- If SM fields are invariant under these symmetries, lightest new particle with non-trivial behavior under the symmetry can be stable.

- Dark matter

Ma's Scotogenic model and our SLIM scenario

E. Ma, Phys. Rev. **D73**, 077301 (2006), hep-ph/0601225.

C. Boehm, Y. Farzan, T. Hambye, S. Palomares-Ruiz, and S. Pascoli, Phys. Rev. **D77**, 043516 (2008), hep-ph/0612228.

Proliferation of radiative neutrino mass models in literature

- Recipes and Ingredients for Neutrino Mass at Loop Level

Y.F., S. Pascoli and T. Schmidt, JHEP 1303 (2013) 107

Weinberg operator

effective dimension 5 operator, $(HL)(HL)$

$$(H^\dagger H)^m (HL)(HL)$$

Weinberg operator

effective dimension 5 operator, $(HL)(HL)$

$$\mathcal{O}(5) \sim L^T c(i\tau_2)H \; H^T(i\tau_2)L$$

$$(H^\dagger H)^m (HL)(HL)$$

General n-loop contribution

$$m_\nu \sim \left(\frac{g^2}{16\pi^2}\right)^n \left(\frac{\langle H\rangle^2}{m_{\rm New}}\right)\left[1, \left(\log\frac{\Lambda}{m_{\rm New}}\right)^n\right]$$

Λ is the ultraviolet (UV) cut-off scale of the model satisfying $\Lambda \gg m_{\rm New}$.

$m_{\rm New} \sim 1$ TeV, $m_\nu \sim 0.1 - 1$ eV

$\Lambda/m_{\rm New} \sim 10$ and $n = 2$,

$$g \sim 10^{-3}.$$

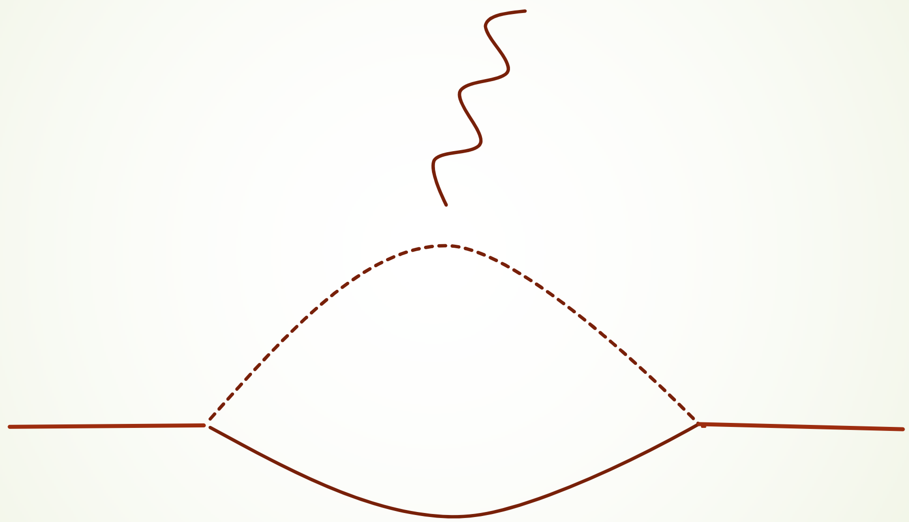
General n-loop contribution

$$m_\nu \sim \left(\frac{g^2}{16\pi^2}\right)^n \left(\frac{\langle H\rangle^2}{m_{\text{New}}}\right)\left[1, \left(\log\frac{\Lambda}{m_{\text{New}}}\right)^n\right]$$

n ↗ g ↗

$n = 3$ ⇒ $g \sim 0.01 - 0.1$

$$l_\alpha \to l_\beta \gamma$$



$$\Gamma(l_\alpha \to l_\beta \gamma) \sim \frac{g_\alpha^2 g_\beta^2}{16\pi(16\pi^2)^2} \frac{m_\alpha^5}{Max[m_S^4, m_F^4]}$$

$$Br(\mu \to e\gamma) < 5.7 \times 10^{-13} \ ,$$

$$Br(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

$$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

$$g_e g_\mu \lesssim 10^{-3} \frac{\text{Max}(m_S^2, m_{F_1^-}^2)}{\text{TeV}^2}$$

$$g_e g_\tau, g_\mu g_\tau \lesssim \frac{\text{Max}(m_S^2, m_{F_1^-}^2)}{\text{TeV}^2}.$$

$$Br(\mu \to e\gamma) < 5.7 \times 10^{-13} \; ,$$

$$Br(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

$$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

$$g_e g_\mu \lesssim 10^{-3} \frac{\mathrm{Max}(m_S^2, m_{F_1^-}^2)}{\mathrm{TeV}^2}$$

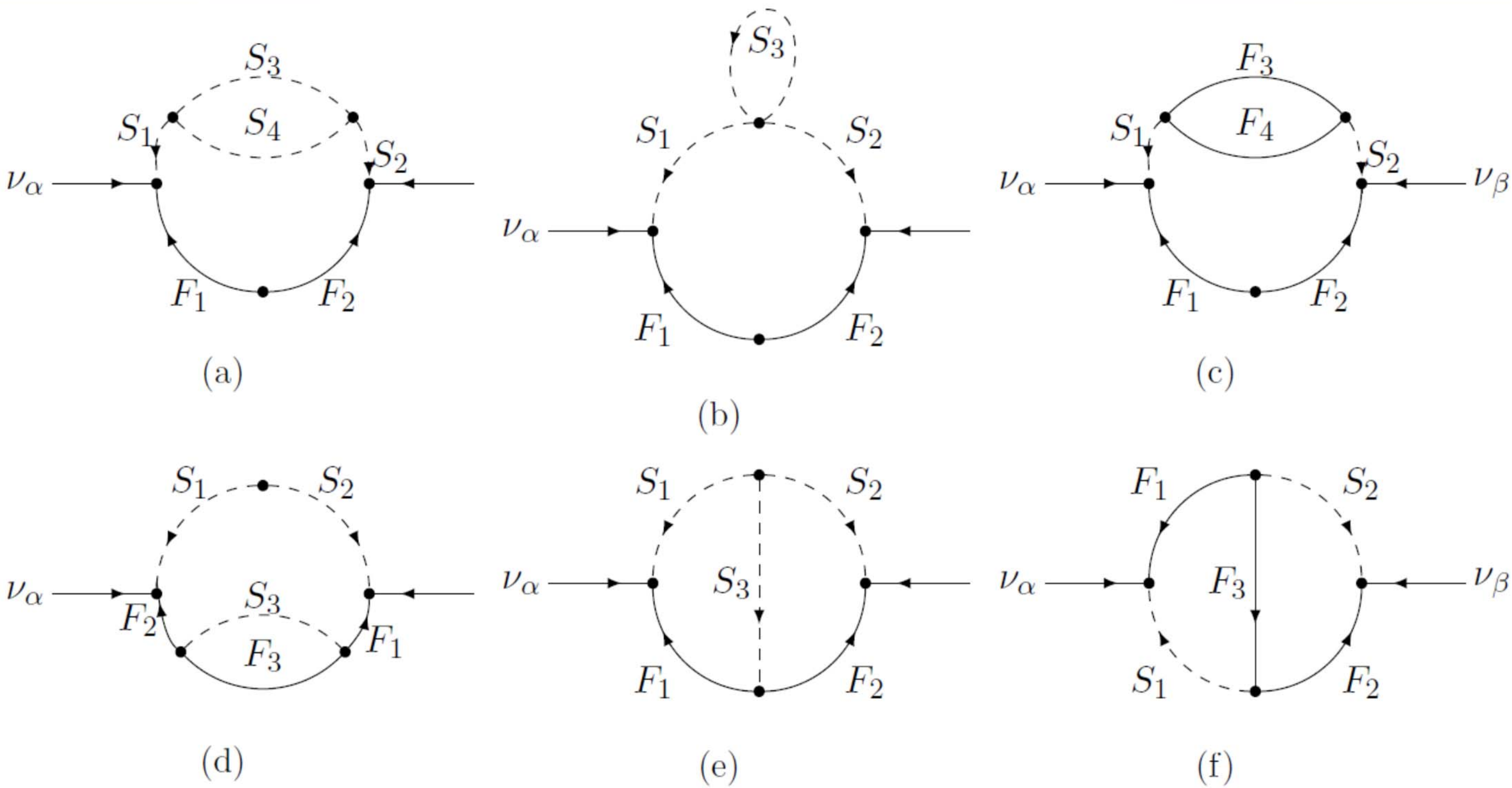
$$g_e g_\tau, g_\mu g_\tau \lesssim \frac{\mathrm{Max}(m_S^2, m_{F_1^-}^2)}{\mathrm{TeV}^2} .$$

If neutrino mass in obtained at two-loop level, these bounds are Readily satisfied.

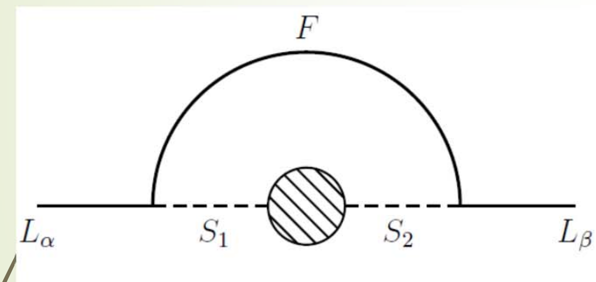
- Two-loop might be preferred.

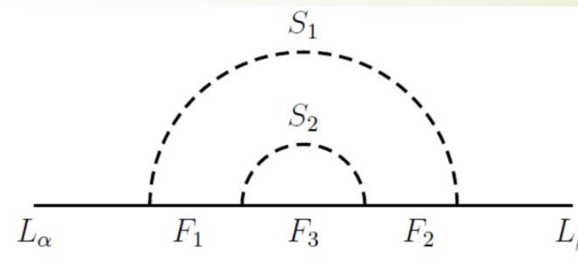
- See however, Ahriche, McDonald and Nasri, 1505.04320 which advocates three-loop.

Two loop diagrams



Two loop diagrams

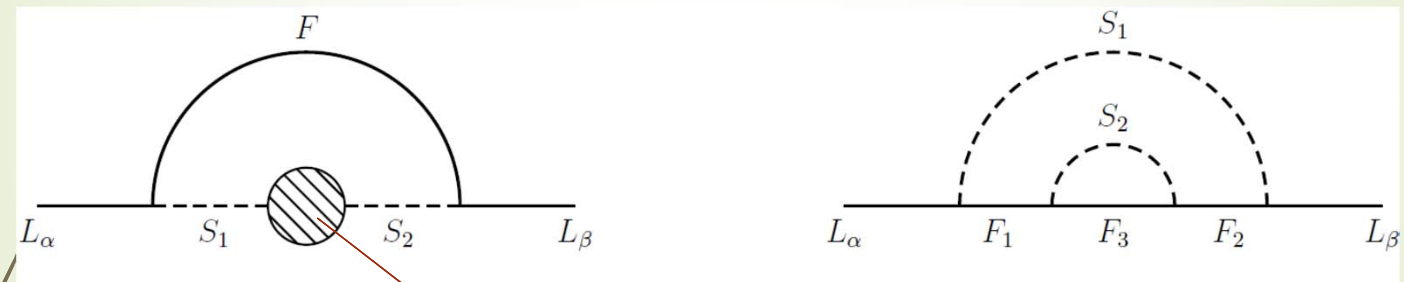




$SSHH$

$FFHH$

Two loop diagrams

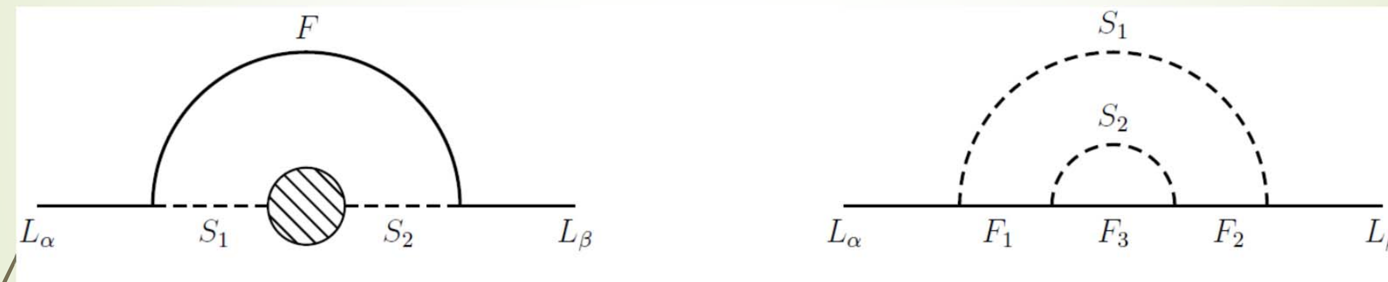


$SSHH$

$FFHH$

If there is no symmetry to forbid the bulb, the vertex can also exist.

Two loop diagrams

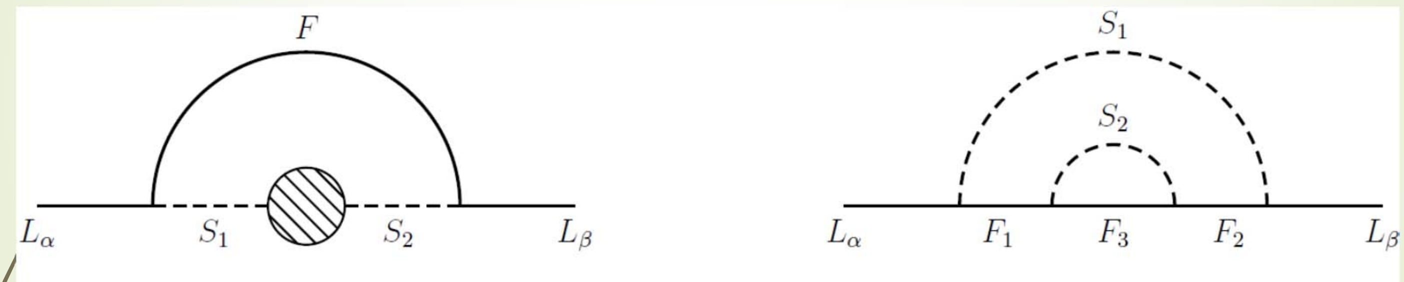


$SSHH$

$FFHH$

Accompanied by a one-loop dominant contribution

Two loop diagrams

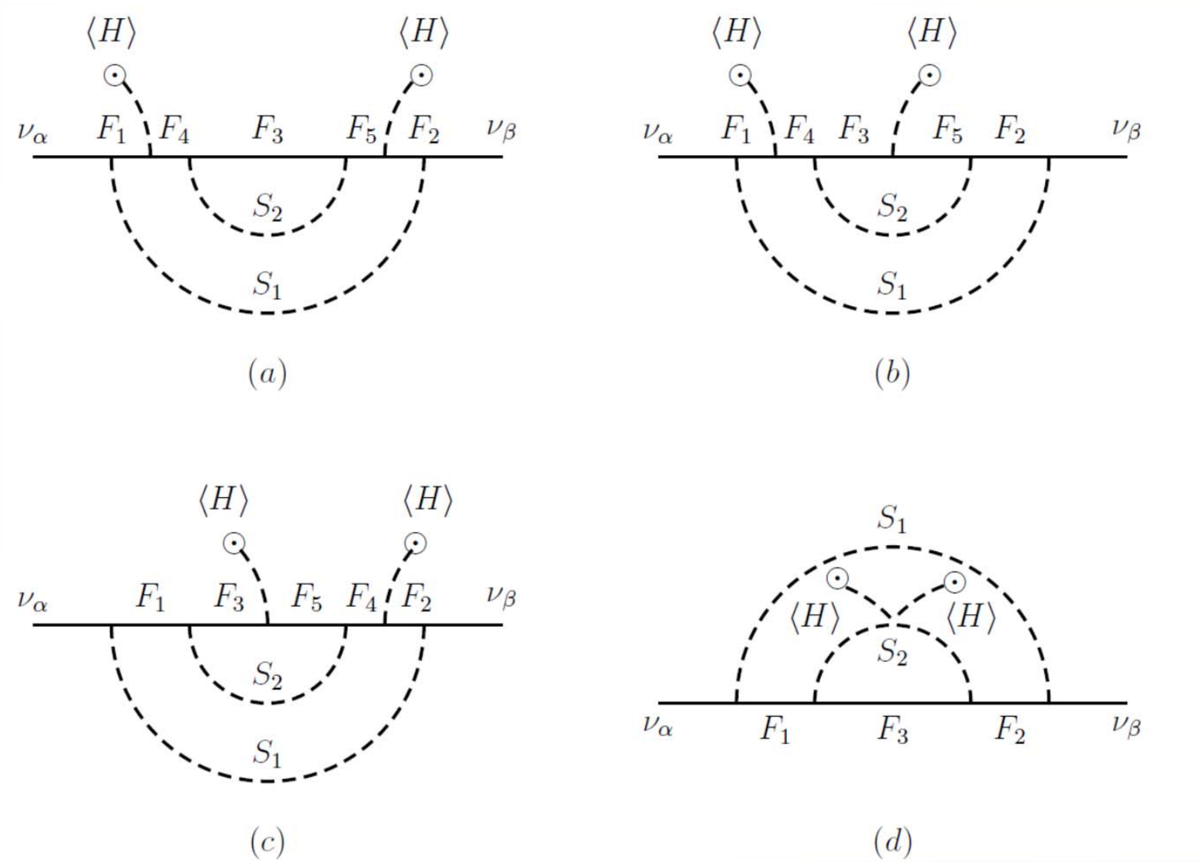


$SSHH$

$FFHH$

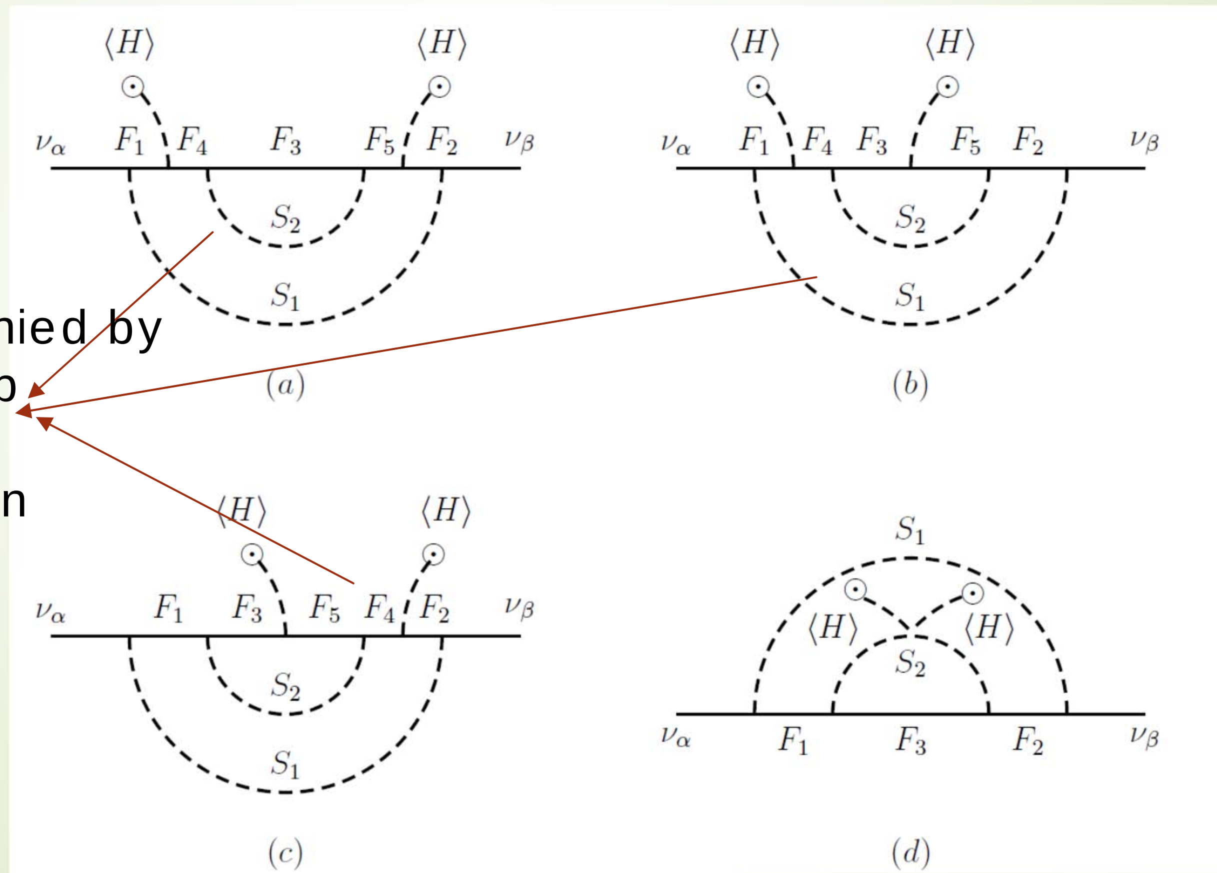
Leading loop contribution

Two-loop snail diagrams: relating neutrino masses to dark matter



$F_4\, F_5,\; F_4\, F_2\, H$ and $F_1\, F_4\, H$.

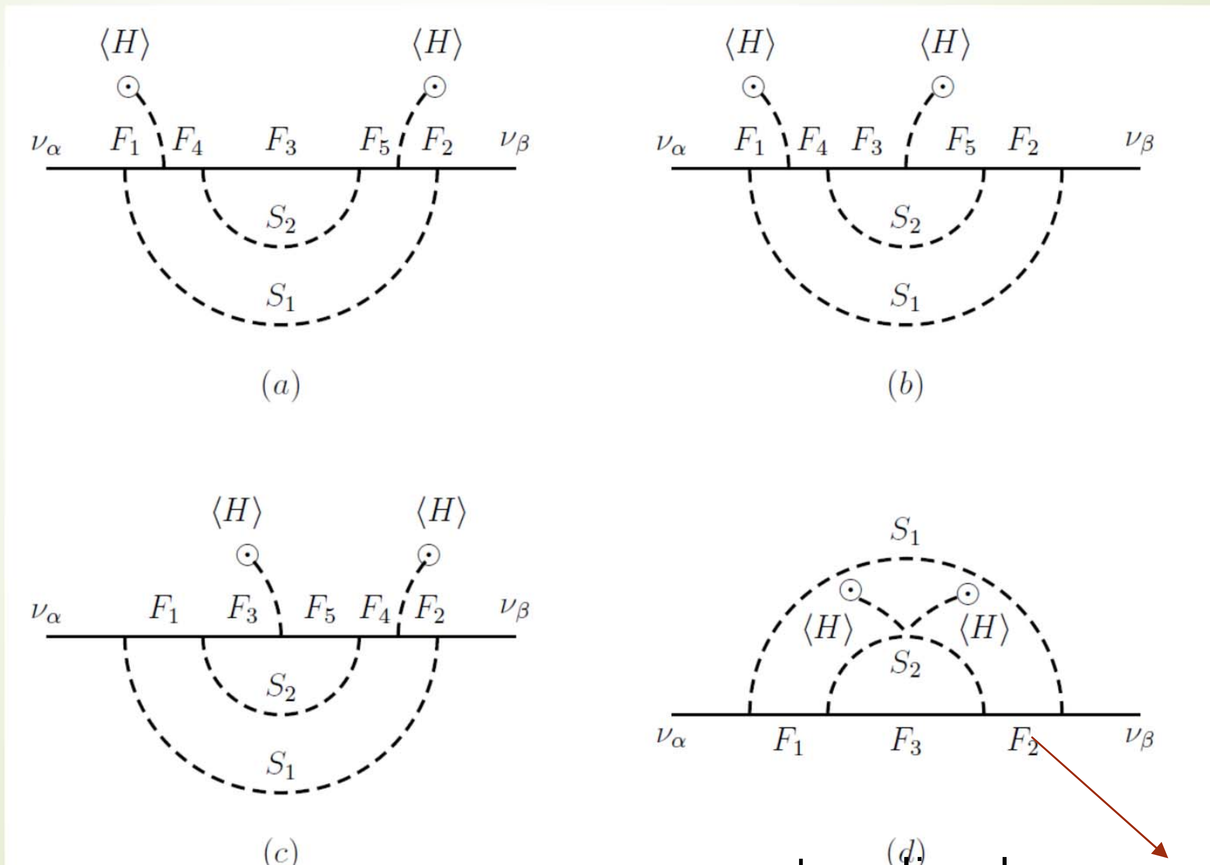
Two-loop snail diagrams: relating neutrino masses to dark matter



Accompanied by a one-loop dominant contribution

$F_4\,F_5,\;\; F_4\,F_2\,H$ and $F_1\,F_4\,H$.

Two-loop snail diagrams: relating neutrino masses to dark matter



Leading loop contribution

- Two-loop snail diagrams: relating neutrino masses to dark matter

JHEP 05 (2015) 029

	$SU(2)$	$U(1)_Y$	$U(1)_L$	$U(1)_{NEW}$	Z_2
F_1	d	-1	1	1	+
F_2	d	- 1	1	-1	+
F_3	d	1	1	1	+
ψ	s	0	1	1	-
S	s	0	0	-1	+
Φ	d	-1	0	0	-
Φ'	d	-1	0	-1	-

$$m_M (F_{2R}^a)^T c F_{3R}^b \epsilon_{ab} + m'_M (F_{2L}^a)^T c F_{3L}^b \epsilon_{ab} + \text{H.c.}$$

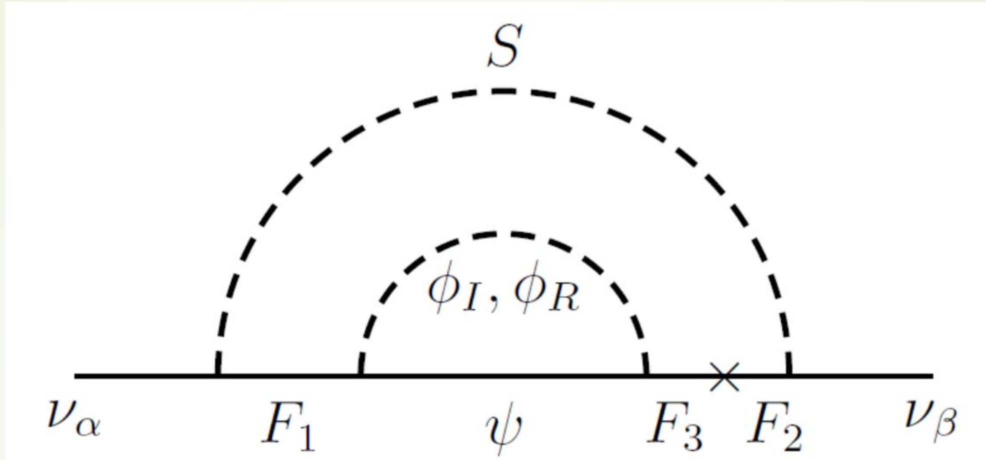
$$\mathcal{L}_{Yukawa} = g_\alpha S^\dagger F_{1R}^\dagger L_\alpha + h_\alpha S F_{2R}^\dagger L_\alpha + Y_{R\alpha} \Phi'^\dagger \psi_R^\dagger L_\alpha +$$

$$Y_1 \Phi^\dagger \psi_L^\dagger F_{1R} + Y_2 \epsilon_{ab} \Phi^a \psi_L^\dagger F_{3R}^b + Y_1' \Phi^\dagger \psi_R^\dagger F_{1L} + Y_2' \epsilon_{ab} \Phi^a \psi_R^\dagger F_{3L}^b + \text{H.c.}$$

$$(\lambda (H^a \Phi^b \epsilon_{ab})^2 + \text{H.c}) \quad \text{and} \quad \lambda' |H^\dagger \Phi|^2.$$

$$\Phi^0 \equiv (\phi_R + i\phi_I)/\sqrt{2}..$$

$$m_R^2 - m_I^2 = \lambda \langle H^0 \rangle^2.$$



$$m_\nu \sim (0.01 - 0.1\ \text{eV}) Y_1 Y_2 \frac{g \times h}{10^{-1} \times 10^{-2}} \frac{m_M}{5\ \text{GeV}} \frac{(m_R^2 - m_I^2)/m_{max}^2}{1/20}.$$

Dark matter candidate

$$U(1)_{NEW} \times Z_2$$

ϕ_I $\qquad\qquad$ ψ

Thermal freeze-out scenario

$$\Omega_{DM} = \frac{nm}{\rho_c} \propto \frac{m/T_f}{\langle \sigma v \rangle}$$

$$\langle \sigma_{tot} v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3 \mathrm{sec}^{-1}$$

Coannihilation

$$m_R^2 - m_I^2 = \lambda \langle H^0 \rangle^2$$

$(m_R - m_I)/m_R$ should be smaller than ~ 0.05

$$\phi_I \phi_R \to Z^* \to SM$$

$$\langle \sigma(\phi_I + \phi_R \to Z^* \to f + \bar{f}) v \rangle = \frac{16}{3\pi} N_C G_F^2 \frac{(a_L^2 + a_R^2)(m_I v)^2}{(1 - 4m_I^2/m_Z^2)^2}$$

Main dark matter component

$$\langle \sigma(\psi\bar{\psi} \to \ell_\alpha \bar{\ell}_\alpha) v \rangle = \frac{|Y_{R\alpha}|^4}{32\pi} \frac{m_\psi^2}{(m_\psi^2 + (m_{\phi'^-})^2)^2}.$$

$$\langle \sigma_{tot} v \rangle = 3 \times 10^{-26}\ \text{cm}^3 \text{sec}^{-1}$$

$$m_{\phi'^-},\ m_{\phi'^0} \leq 1.4 Y_{R\alpha}^2 \text{TeV}$$

LHC signals

- Mono-lepton plus missing energy signal through $u\bar{d} \to \phi'^{+}\phi'^{0} \to (l^{+}\psi)(\nu\bar{\psi})$ and the charge conjugate processes.
- Two-lepton plus missing energy signal through $u\bar{u}, d\bar{d} \to \phi'^{+}\phi'^{-} \to (l^{+}\psi)(l^{-}\bar{\psi})$.
- Missing energy through $u\bar{u}, d\bar{d} \to \phi'^{0}\bar{\phi}'^{0} \to (\bar{\nu}\psi)(\nu\bar{\psi})$.

G. Aad *et al.* [ATLAS Collaboration], JHEP **1405**, 071 (2014)

G. Aad *et al.* [ATLAS Collaboration], JHEP **1410**, 96 (2014)

Muon and electron: >325 GeV
Tau: >90 GeV

ILC signals

$g_\alpha S^\dagger \bar{F}_{1R} L_\alpha + h_\alpha S \bar{F}_{2R} L_\alpha$

$e^- e^+ \to S\bar{S}..$

$\Gamma(S \to l_\alpha^- F_1^+) \propto g_\alpha^2$ and $\Gamma(S \to l_\alpha^+ F_{2,3}^-) \propto h_\alpha^2$

F_i^+ can decay into $\phi^+ \psi$ and $\phi^+ \to (W^+)^* \phi_I \to \nu l^+ \phi_I, q\bar{q}\phi_I..$

$$\Gamma(S \to l_\alpha^- F_1^+) \propto g_\alpha^2 \text{ and } \Gamma(S \to l_\alpha^+ F_{2,3}^-) \propto h_\alpha^2.$$

$$\begin{aligned}
e^+e^- &\to l_\alpha^+ + l_\beta^- + l_\gamma^+ + l_\theta^- + \text{missing energy} ; \\
e^+e^- &\to l_\alpha^+ + l_\beta^- + l_\gamma^+ + 2 \text{ jets} + +\text{missing energy} ; \\
e^+e^- &\to l_\alpha^+ + l_\beta^- + l_\gamma^- + 2 \text{ jets} + \text{missing energy} ; \\
e^+e^- &\to l_\alpha^+ + l_\beta^- + 4 \text{ jets} + \text{missing energy} ,
\end{aligned}$$

$h_\alpha^2 h_\beta^2.$

$g_\alpha^2 g_\beta^2$

$$\Gamma(S \to l_\alpha^- F_1^+) \propto g_\alpha^2 \quad \Gamma(\bar{S} \to l_\beta^- F_{2,3}^+) \propto h_\beta^2$$

$$e^+e^- \to l_\alpha^- + l_\beta^- + 4 \text{ jets} + \text{missing energy}$$

Summary

- We presented a model that contribute to neutrino mass via “two-loop snail diagram.”

- Phenomenological consequences are rich.

Backup

$$\langle\sigma(\psi\bar{\psi}\to l\bar{l})v\rangle = 0.86\times 10^{-26}\ \mathrm{cm}^3\mathrm{sec}^{-1}\ \text{and}\ m_\psi \sim 10\,\mathrm{GeV},$$

$$Y_R = 0.5(m_{\phi'^-}/100\ \mathrm{GeV})(10\ \mathrm{GeV}/m_\psi)^{1/2}$$

Backup

taking $m_I < m_W$, we find that $\langle \sigma_{\rm tot} v \rangle \sim 40$ pb$(m_I/70\ \text{GeV})^2$

$$\mathcal{O}(1\ pb/\langle \sigma_{\rm tot} v \rangle) \sim 2.5\%(70\ \text{GeV}/m_I)^2$$

For $m_W < \phi_I < 200\,\text{GeV}$, new annihilation modes will open.

$$G_F^2 m_Z^2 / m_{\phi_I}^2$$

the λ' coupling

$\phi_I \phi_I$ and $\phi_R \phi_R$ pair annihilation.

$m_I \sim$ few TeV.

Backup

$Y_1, Y_2 \gg g, h$.

$$F_i^- \to \psi\phi^- \text{ and } F_i^0 \to \psi\phi^0_{I(R)}$$

Via tree-level Z^* exchange, $\phi_R \to \phi_I \nu\bar{\nu}$, $\phi_I ll$ and $\phi_I q\bar{q}$.

Backup

$$e^+e^- \to l_\alpha^- + l_\beta^- + 4\,\text{jets} + \text{missing energy}\ .$$

In general by studying these modes information on flavor structure of g_α and h_α can be extracted and cross checked against the information from neutrino mass matrix and LFV.

Notice that the signature of the present model at colliders is completely different from those of SLIM model or of Ma's Scotogenic model [5–13] which both lack doublet fermions. The present model is also distinguishable from models in which neutrino mass is produced via a one loop diagram in which a fermion doublet and scalar singlet propagate as in such a model fermion doublet will decay into leptons rather than $\psi\phi$.