Neutrino mass models
in the era of precision neutrino physics

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14 August 2026

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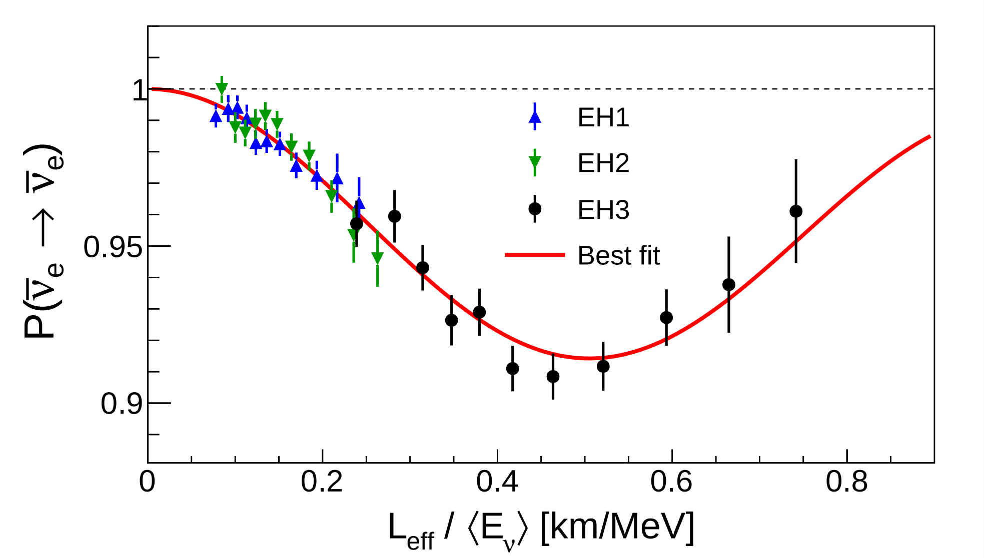
Oscillating neutrinos

- Neutrinos oscillate among flavours $$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$
- Oscillatory pattern in L/E dependence clearly observed in Daya Bay $\overline{\nu}_e$ among others



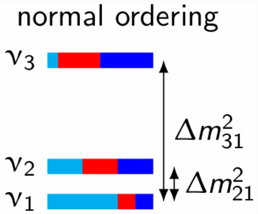
Daya Bay [1505.03456]

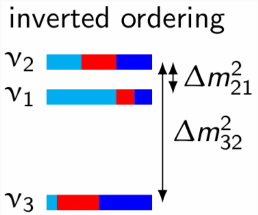
- Flavour oscillations require at least two neutrinos to have non-zero masses

Current knowledge of three-neutrino oscillations

	best fit $\pm 1\sigma$		3σ rel prec
	IC23 w/o SK-ATM	w IC24 & SK-ATM	
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.537^{+0.094}_{-0.10}$	**7.8%**
$\sin^2\theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.3088^{+0.0067}_{-0.0066}$	**13 %**
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$ (NO)	$+2.521^{+0.026}_{-0.018}$	$+2.511^{+0.021}_{-0.010}$	**5.5–5%**
(IO)	$-2.500^{+0.024}_{-0.023}$	$-2.483^{+0.020}_{-0.020}$	**5.6–5%**
$\sin^2\theta_{23}$ (NO)	$0.470^{+0.017}_{-0.014}$	$0.470^{+0.017}_{-0.014}$	30–29%
(IO)	$0.555^{+0.013}_{-0.016}$	$0.550^{+0.013}_{-0.016}$	29–28%
$\sin^2\theta_{13}$ (NO)	$0.02249^{+0.00057}_{-0.00057}$	$0.02248^{+0.00055}_{-0.00059}$	**15%**
(IO)	$0.02261^{+0.00056}_{-0.00056}$	$0.02262^{+0.00057}_{-0.00056}$	
$\delta_{\mathrm{CP}}/^\circ$ (NO)	207^{+23}_{-20}	212^{+26}_{-36}	100–98%
(IO)	283^{+24}_{-28}	274^{+22}_{-25}	54–55%
$\chi^2_{\mathrm{IO}} - \chi^2_{\mathrm{NO}}$	1.5	5.9	

Concha Gonzalez-Garcia (Neutrino 2026) Esteban, Gonzalez-Garcia, Maltoni, Marinez-Soler, Pinheiro, Schwetz [2410.05380]





Leptonic (PMNS) mixing matrix

$$U_{\mathrm{PMNS}} = R_{23}(\theta_{23})\, U_{13}(\theta_{13}, \delta)\, R_{12}(\theta_{12})$$

$$U_{13}(\theta_{13}, \delta) = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

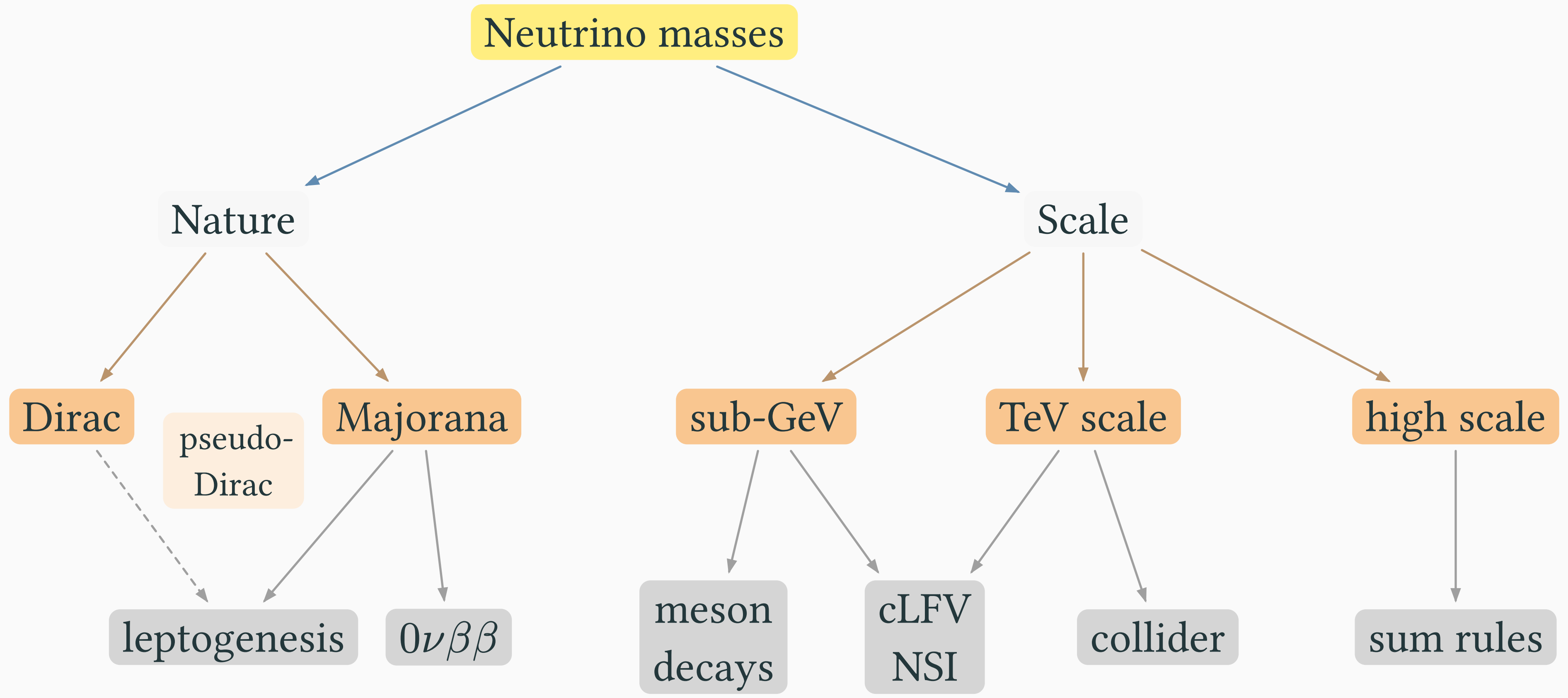
JUNO Yi-Fang Wang @ Neutrino 2026

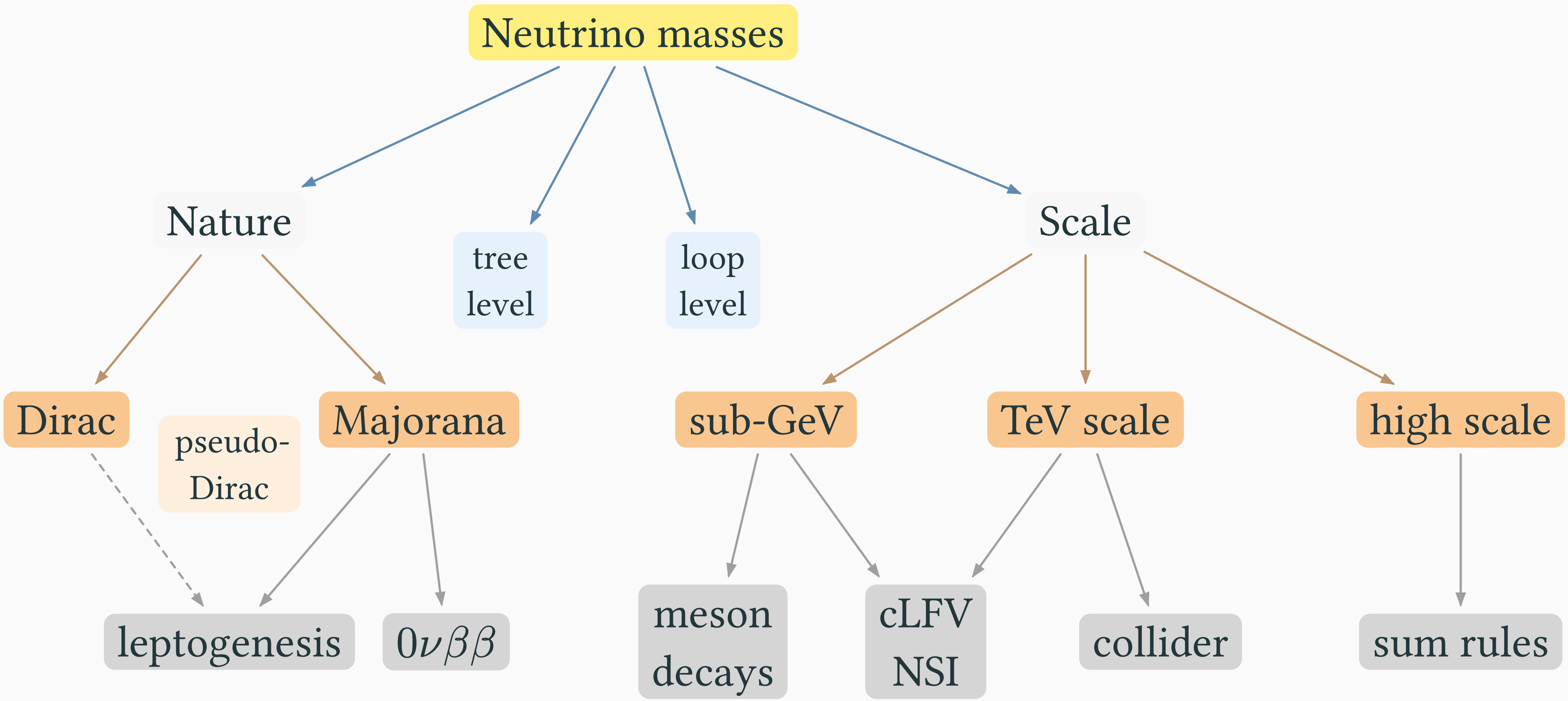
$$\sin^2\theta_{12} = 0.3036 \pm 0.0064$$

$$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2} = 7.388 \pm 0.078$$

$$\frac{\Delta m^2_{31}}{10^{-3}\mathrm{eV}^2} = \begin{cases} 2.509^{+0.027}_{-0.025}[\mathrm{NO}] \\ 2.482^{+0.026}_{-0.025}[\mathrm{IO}] \end{cases} \quad \text{(incl Daya Bay)}$$

Roadmap to neutrino masses





review on neutrino mass models Cai+ [1706.08524]

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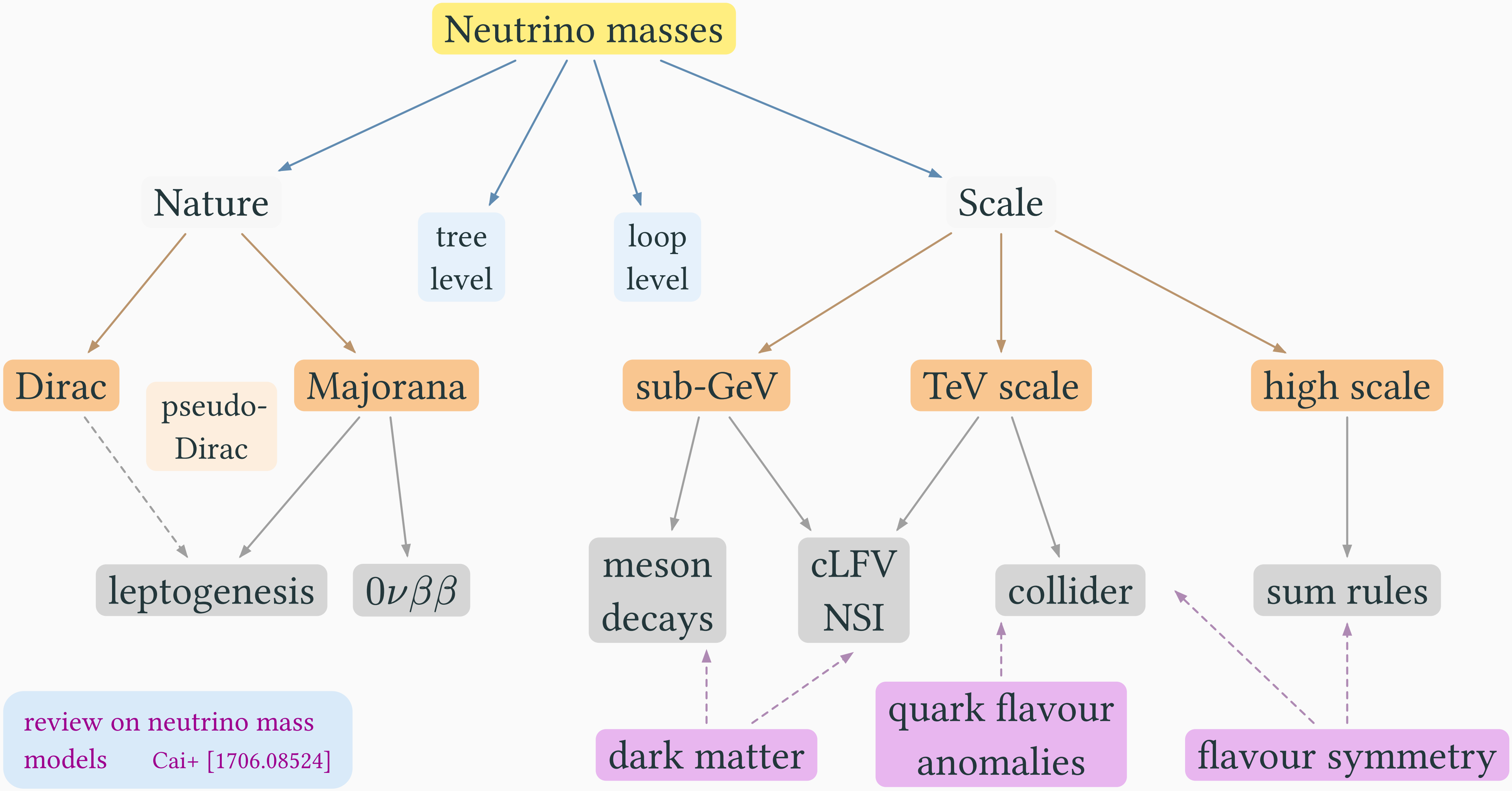

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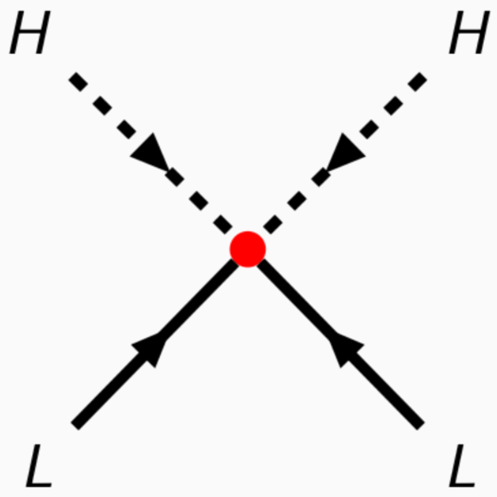
Vanishing neutrino masses in SM. Explanation of oscillations requires **new physics**



- unique dimension-5 operator in SMEFT with $\Delta L = 2$ Weinberg (1979)
  Weinberg operator $\mathcal{O}_1$

$$\mathcal{L} = -\frac{1}{2}\kappa_{fg}[\mathcal{O}_1]_{fg} \qquad [\mathcal{O}_1]_{fg} = L^i_f L^j_g H^k H^l \varepsilon_{ik}\varepsilon_{jl}$$

- generates neutrino masses $\qquad [m_\nu]_{fg} = \kappa_{fg}\langle H\rangle^2$

  the observed oscillation data requires $\kappa^{-1} \sim 10^{15}$ GeV

Effective theory of Majorana neutrino masses

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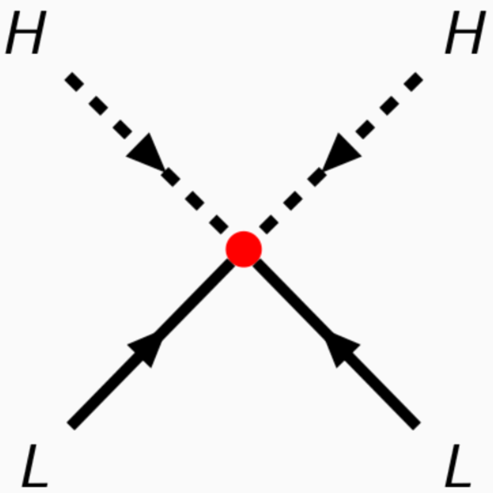

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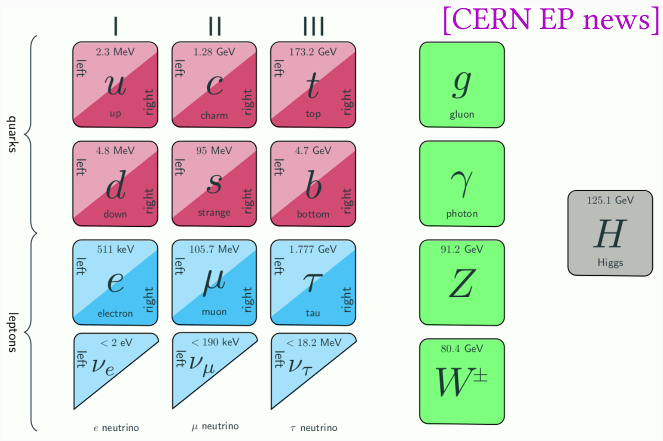
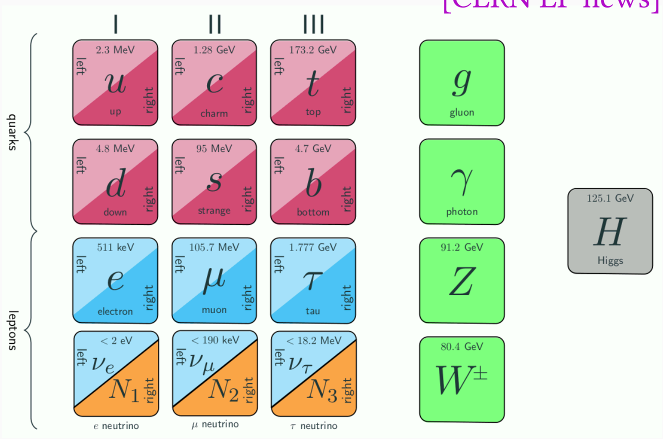
- Effective field theory requires UV completion. Weinberg op. cannot be the ultimate theory.
- It cannot describe Dirac neutrinos. Experimental input needed to decide the nature of ν's.

Seesaw mechanism



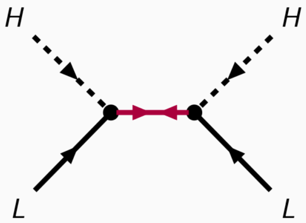
[CERN EP news]



- ν_L has a RH partner N
- in addition to the Dirac mass m_D, there is a large Majorana mass M_R for N

Minkowski (1977)
Yanagida (1979)
Glashow (1979)
Gell-Mann, Ramond, Slansky (1980)
Mohapatra, Senjanovic (1980)

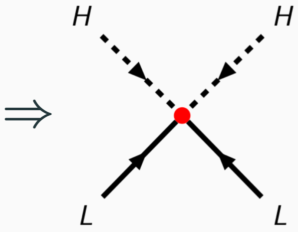
$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$



- M_R is not protected by symmetry and can be very large which results in tiny neutrino masses

$$m_\nu^{\text{light}} = -m_D M_R^{-1} m_D^T$$

for $m_D \sim 100$ GeV, $M_R \sim 10^{15}$ GeV, $m_\nu^{\text{light}} \sim 10^{-2}$ eV



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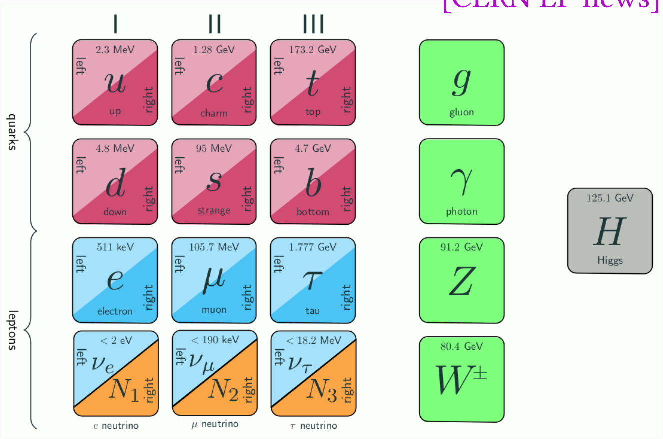

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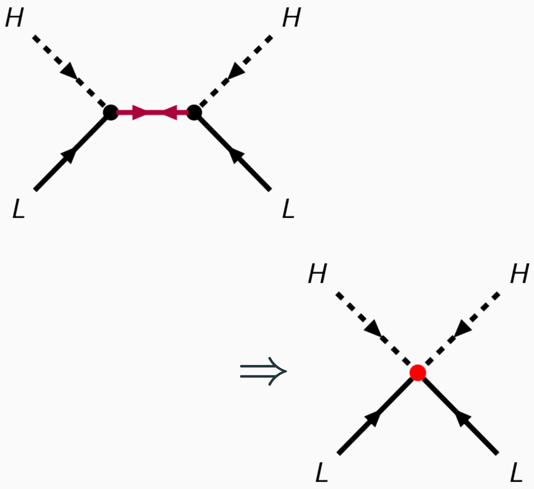

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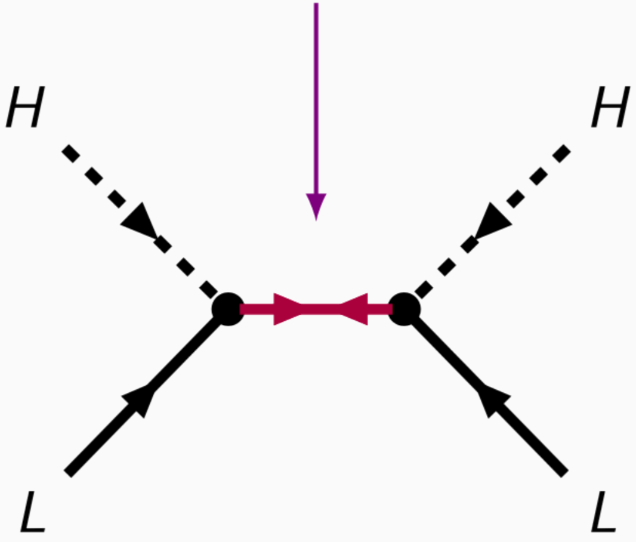
for $m_D \sim 100$ GeV, $M_R \sim 10^{15}$ GeV, $m_\nu^{\text{light}} \sim 10^{-2}$ eV

Dirac neutrino mass models
require additional symmetry to forbid Majorana mass

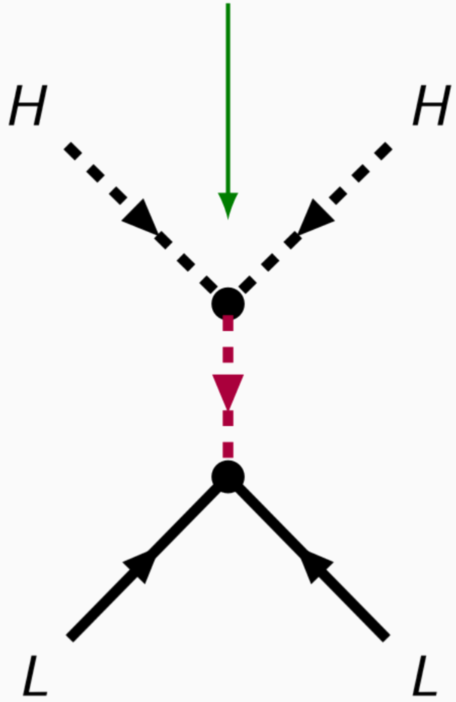
Alternative realizations of seesaw model

SS I: $\bar{N} \sim (1,1,0)$
$yLH\bar{N} + m\bar{N}\bar{N}$



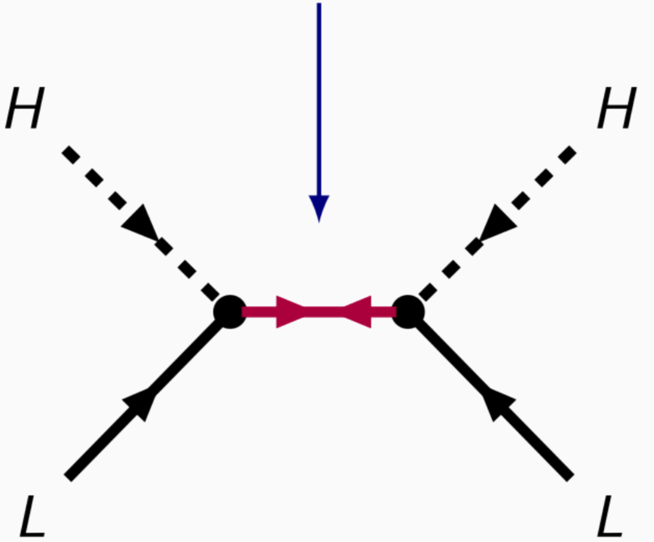
Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

SS II: $\Delta \sim (1,2,1)$
$yL\Delta L + \mu H\Delta^\dagger H$



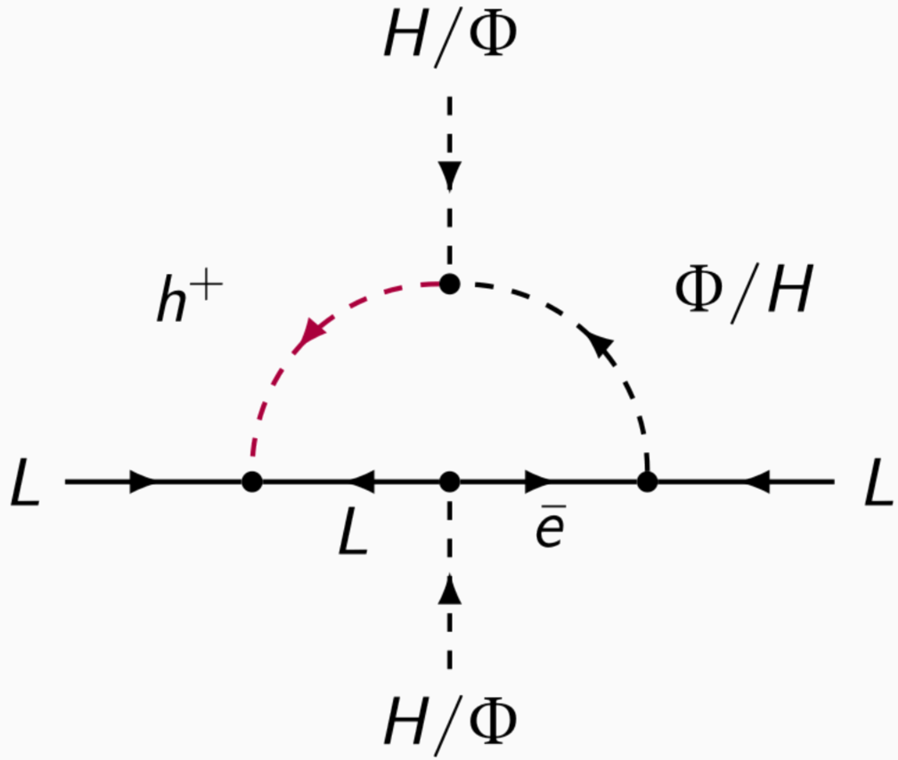
Mohapatra, Senjanovic; Magg, Wetterich; Lazarides, Shafi, Wetterich; Schechter, Valle

SS III: $\bar{\Sigma} \sim (1,3,0)$
$yLH\bar{\Sigma} + m\bar{\Sigma}\bar{\Sigma}$



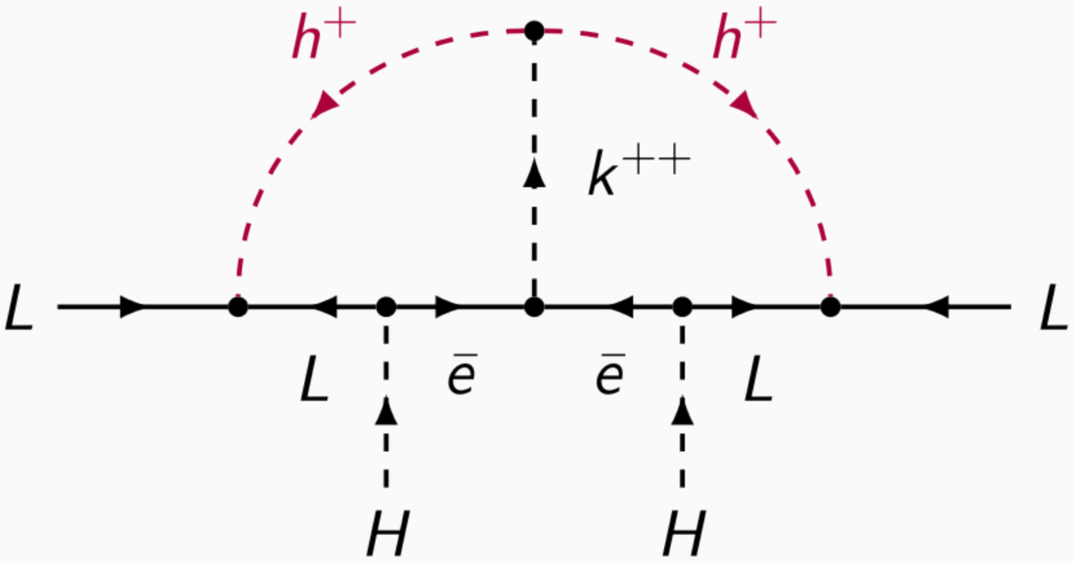
Foot, Lew, He, Joshi

Zee model Zee (1980)



$h^+ \sim (1,1,1) \qquad \Phi \sim (1,2,\frac{1}{2})$

Zee-Babu model Zee (1986) Babu (1988)



$h^+ \sim (1,1,1) \qquad k^{++} \sim (1,1,2)$

Many possible ways to generate neutrino masses

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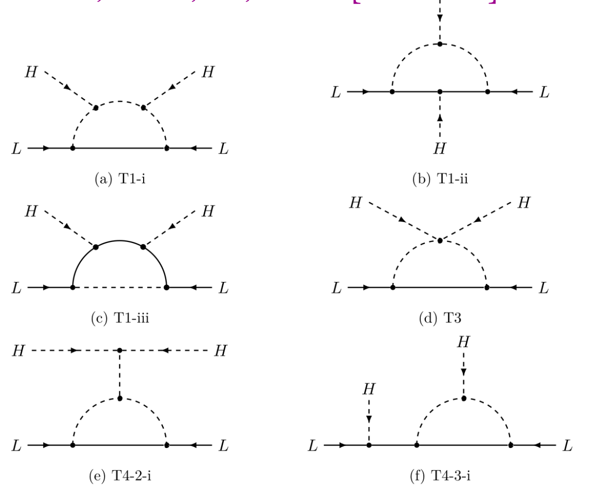
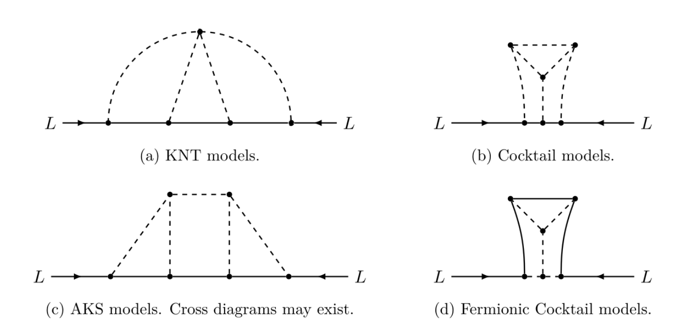
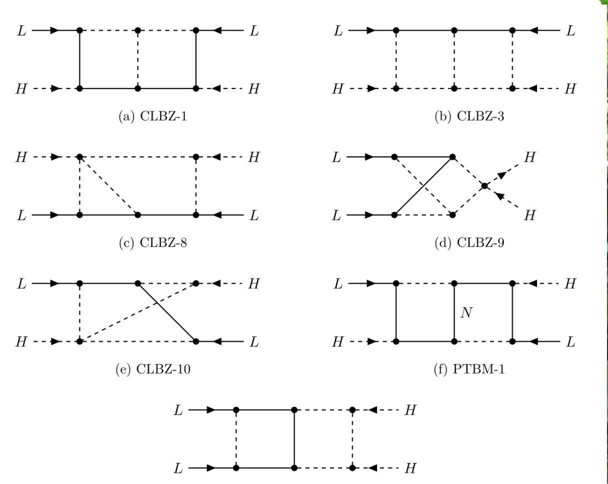
Bonnet,Hirsch,Ota,Winter [1204.5862]







Aristizabal,Degee,Dorame,Hirsch [1411.7038]

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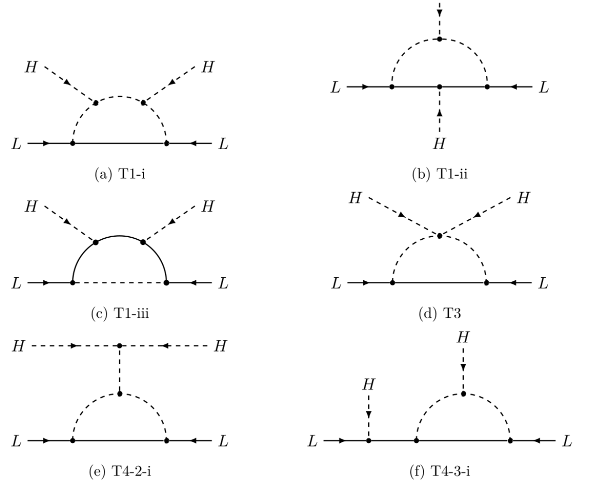

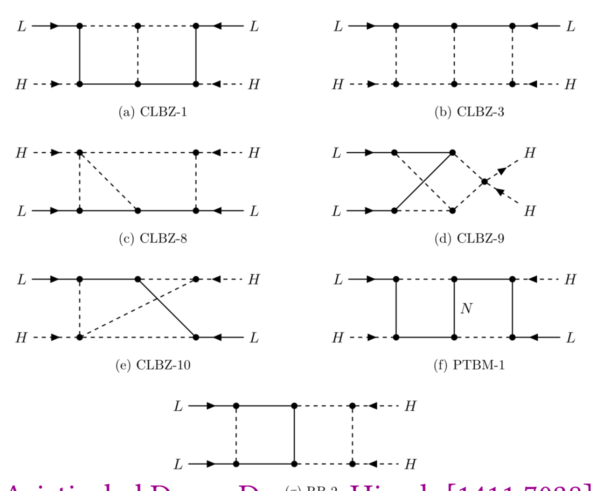

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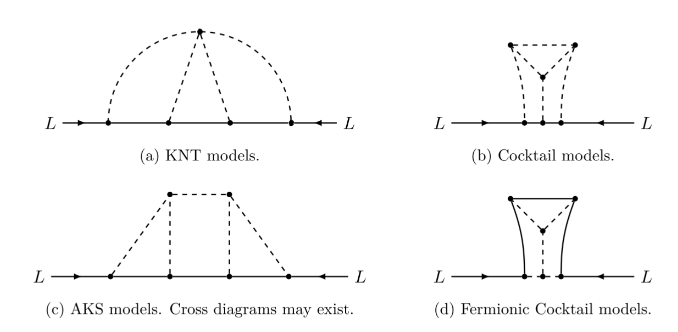

Organising principles

- topology
- $\Delta L = 2$ operators
- simplified models
- ...

D7 $\Delta L = 2$ operators Babu, Leung [hep-ph/0106054]

$$\mathcal{O}_2 = L^i L^j L^k \bar{e} H^l \varepsilon_{ij}\varepsilon_{kl} \qquad \mathcal{O}_8 = L^i \bar{d} \bar{e}^\dagger \bar{u}^\dagger H^j \varepsilon_{ij}$$

$$\mathcal{O}_{3a} = L^i L^j Q^k \bar{d} H^l \varepsilon_{ij}\varepsilon_{kl} \qquad \mathcal{O}_{3b} = L^i L^j Q^k \bar{d} H^l \varepsilon_{ik}\varepsilon_{jl}$$

$$\mathcal{O}_{4a} = L^i L^j Q_i^\dagger \bar{u}^\dagger H^k \varepsilon_{jk} \qquad \mathcal{O}_{4b} = L^i L^j Q_k^\dagger \bar{u}^\dagger H^k \varepsilon_{ij} \qquad \ldots$$

construct models for each $\Delta L = 2$ operator Angel, Rodd, Volkas [1212.5862] Cai, Clarke, MS, Volkas [1308.0463] Gargalionis,Volkas [2009.13537]

review on neutrino mass models
Cai, Herrero-Garcia, MS, Vicente, Volkas [1706.08524]

Simplified model approach

1. m_ν requires at least one new particle X (mass M) coupled to SM lepton(s)
2. QFT: L is violated through operators at scale Λ which encode UV physics
3. Majorana neutrino masses, $m_\nu \propto 1/\Lambda$ are generated
4. $m_\nu > 0.05$ eV and $M < \Lambda$
   $\Rightarrow$ conservative upper bound on M
5. $\Delta L = 0$ phenomenology governed by renormalizable interactions of lightest particle

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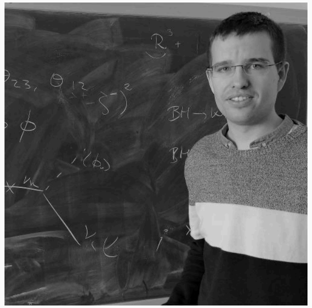

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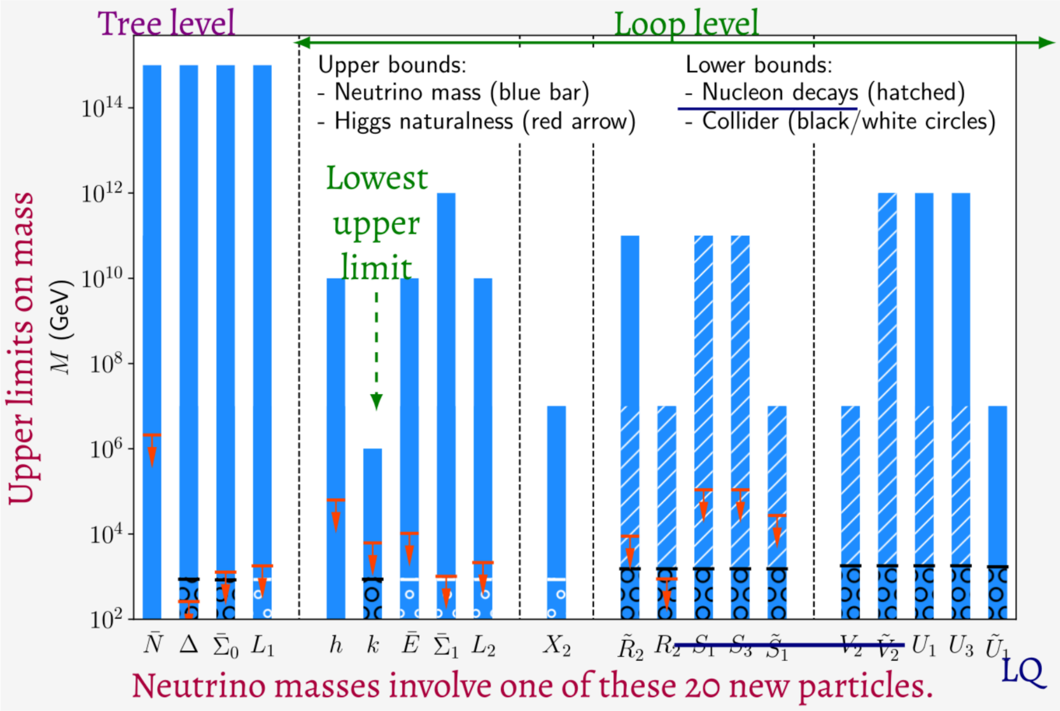


Bounds apply to models where X is the lightest new particle

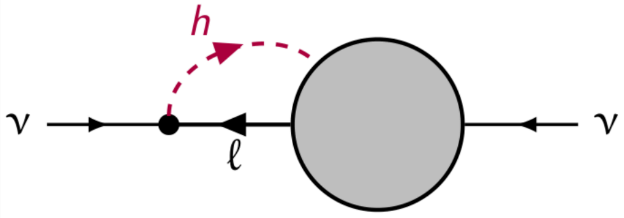
see similar analysis for $\Delta B = 1$: Bas I Beneito,Gargalionis,Herrero-Garcia,MS [2503.20928]

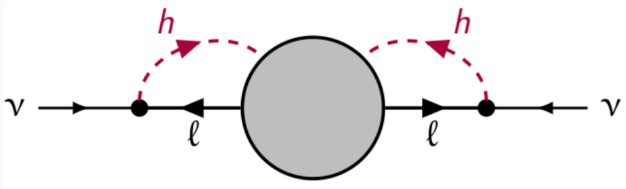
Singly-charged scalar

Felkl,Herrero-Garcia,MS [2102.09898]

- relevant Yuakaw interaction $y_h^{\alpha\beta} L_\alpha L_\beta h$
- y_h is antisymmetric $y_h = -y_h^T$
  $\to$ non-trivial eigenvector v_h with zero eigenvalue $y_h v_h = 0$

related work:
symmetry of couplings also used in
Kanemura,Sugiyama [1510.08726]





$$M_\nu = X y_h - y_h X^T$$

$\Rightarrow$ 1 complex condition

$$0 = v_h^T M_\nu v_h$$

e.g. Zee model

$$M_\nu = y_h S y_h, \quad S = S^T$$

$\Rightarrow$ 2 complex conditions

$$0 = m_{\rm diag} U^\dagger v_h$$

e.g. Zee-Babu, KNT, … discussed in
Zee-Babu model [0711.0483] see also
Irie, Seta, Shindou [2104.09628]

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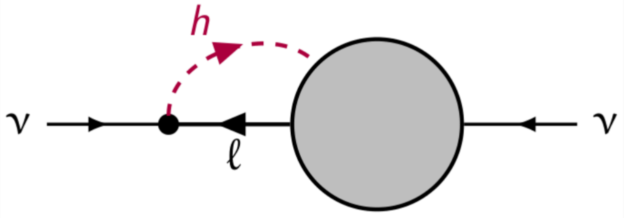

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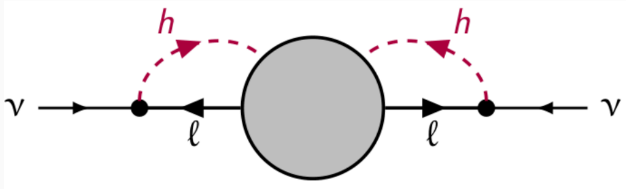

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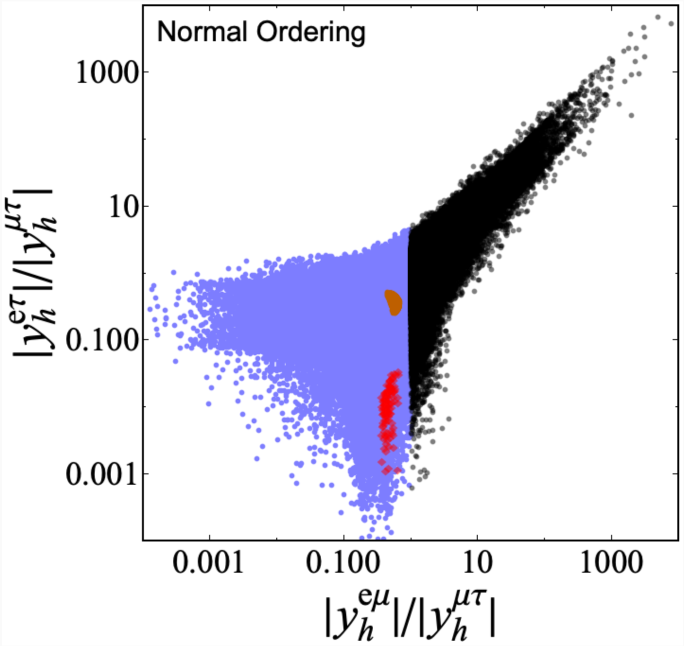

quadratic, linear 2σ (3σ)
Cabibbo angle anomaly

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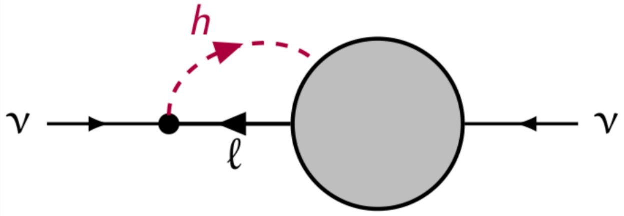

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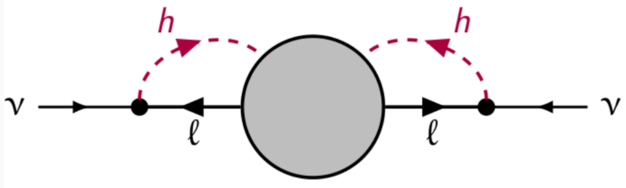

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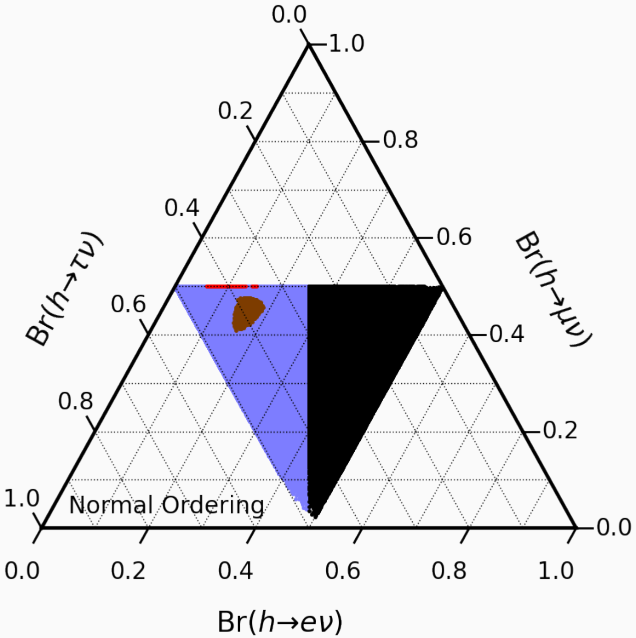
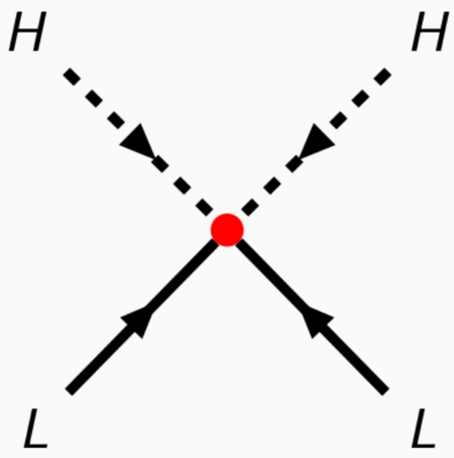
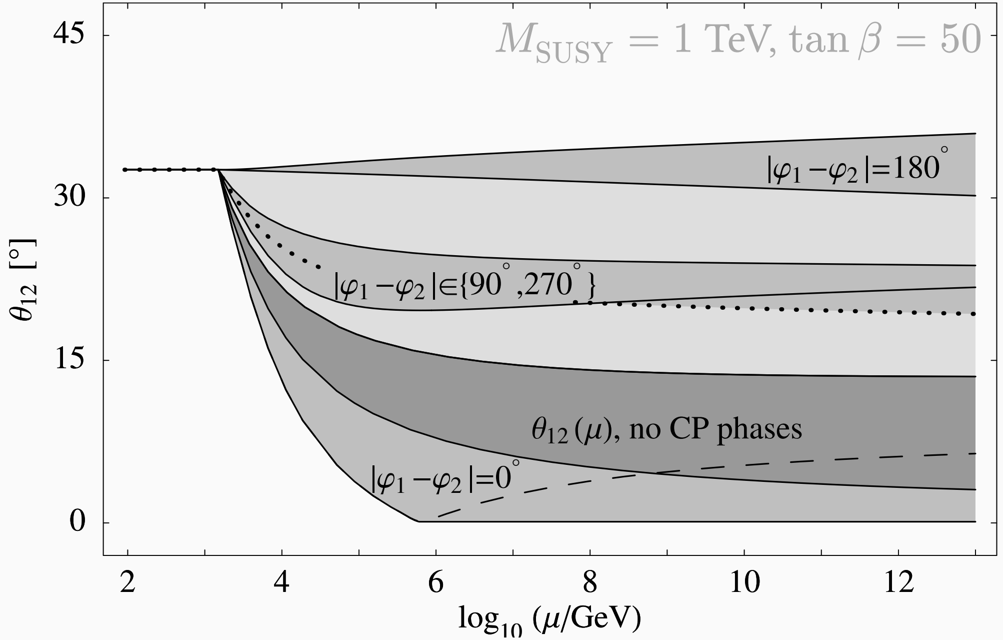


quadratic, linear 2σ (3σ)
Cabibbo angle anomaly

Precision neutrino physics – effective theory



$$\frac{\mathrm{d}\theta_{12}}{\mathrm{d}\ln\mu} = -\frac{C y_\tau^2 (1+\tan^2\beta)}{32\pi^2} \sin 2\theta_{12} s_{23}^2 \frac{|m_1 e^{i\varphi_1} + m_2 e^{i\varphi_2}|^2}{\Delta m^2_{\mathrm{sol}}} + \mathcal{O}(\theta_{13})$$



Antusch,Kersten,Lindner,Ratz [hep-ph/0305273]

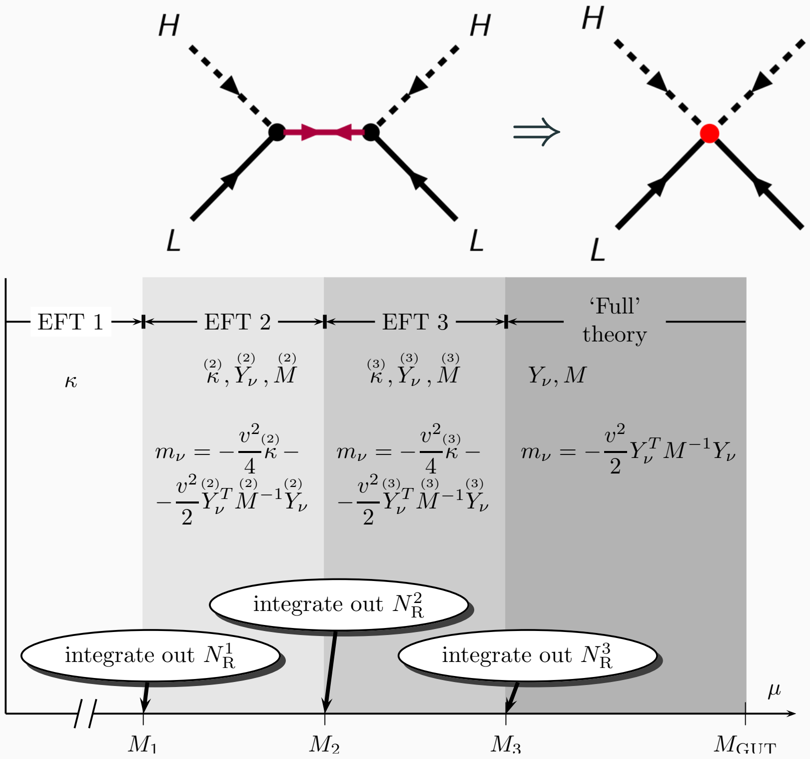
general form of RGE

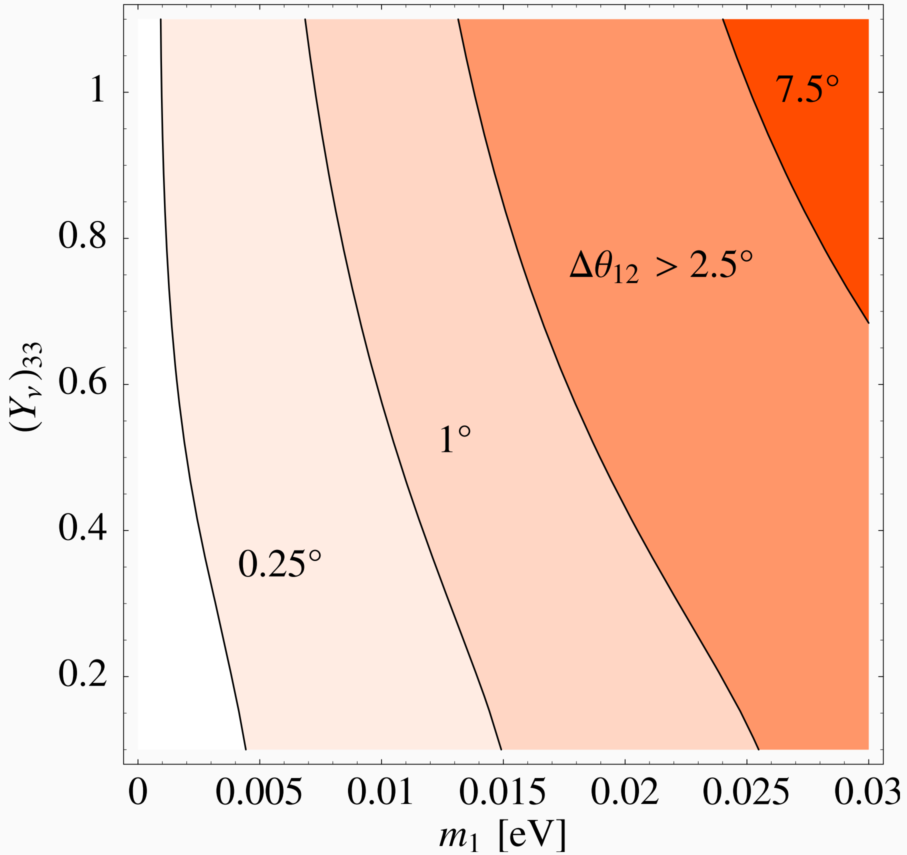
RGEs take simple form for small θ_{13}

$$\frac{\mathrm{d}\theta_{ij}}{\mathrm{d}\ln\mu} \sim \frac{f(m_i, \delta, \varphi_1, \varphi_2)}{m_j^2 - m_i^2} F(Y_e, \theta_{12}, \theta_{13}, \theta_{23})$$

largest corrections to θ_{12} and phases

- RG effects enhanced by $\tan^2\beta$
- more modest effects in SM





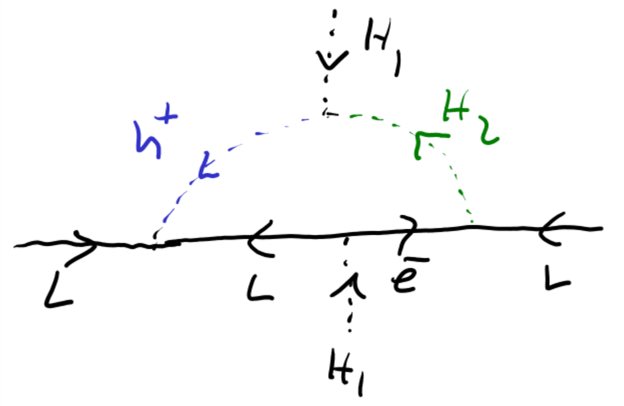
Antusch,Kersten,Lindner,Ratz,MS [hep-ph/0501272]

$M_{SUSY} = 1$ TeV, $\tan\beta = 20$, $\mu = 10^{14}$ GeV,
$\theta_{13} = 0$, $\theta_{23} = 45^o$, $\theta_{12} + \theta_c = 45^o$

see also recent work

- 1-loop matching Zhang+ [2107.12133]Wang+ [2302.08140]
- 2-loop RGEs Ibarra+ [2411.08011] Zhang [2504.00792]
- threshold effects increase rank at 1-loop [2405.18017]

Quantum corrections in a radiative neutrino mass model – Zee model

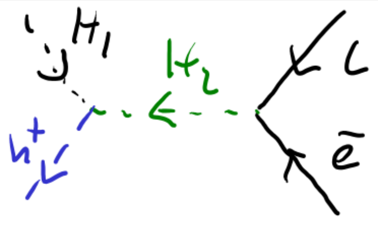


Two additional scalar fields Zee [PLB 93(1980)389]

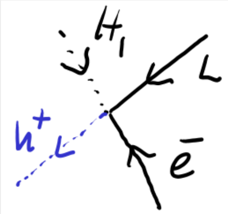
- charged scalar $h^+ \sim (1,1,1)$
- second isodoublet scalar $H_2 \sim \left(1,2,\frac{1}{2}\right)$

$$m_\nu = \frac{f m_E Y_e^2}{8\pi^2}\frac{\mu\langle H_1\rangle \ln\left(\frac{m_\varphi^2}{m_h^2}\right)}{m_h^2 - m_{H_2}^2} + (\ldots)^T$$

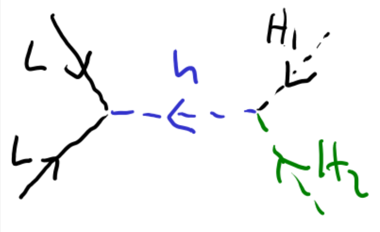
Tree-level matching – $m_{H_2} \gg m_h$



$E^2 \overset{=}{\ll} m_{H_2}^2$



Tree-level matching – $m_h \gg m_{H_2}$



$E^2 \overset{=}{\ll} m_h^2$

$\Delta L = 2$ dim-5 operator at tree level

MS, Vandeleur [2512.17235]

Neutrino mass in Zee model with $m_h \gg m_{H_2}$

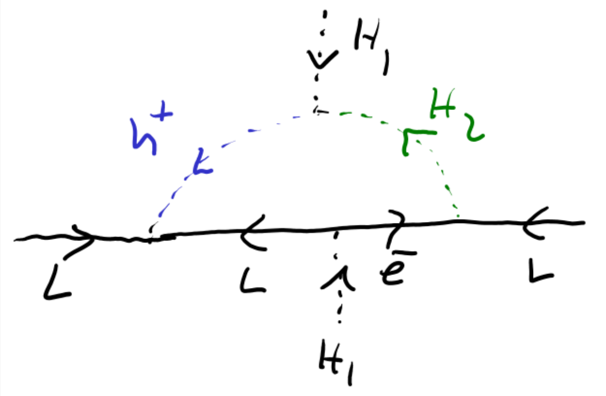
MS,Vandeleur [2512.17235]

- Neutrino mass in the full theory

$$m_\nu = \frac{f m_E Y_e^2}{8\pi^2} \frac{\mu \langle H \rangle \ln\left(\frac{m_{H_2}^2}{m_h^2}\right)}{m_h^2 - m_{H_2}^2} + (\ldots)^T$$

$$\kappa^{12(0)} = -\frac{f\mu}{m_h^2}$$

- In EFT m_ν dominantly generated through RG corrections sourced by $\kappa^{12(0)}$ $\rightarrow$ consistent with $\ln\left(\frac{m_{H_2}^2}{m_h^2}\right)$ term



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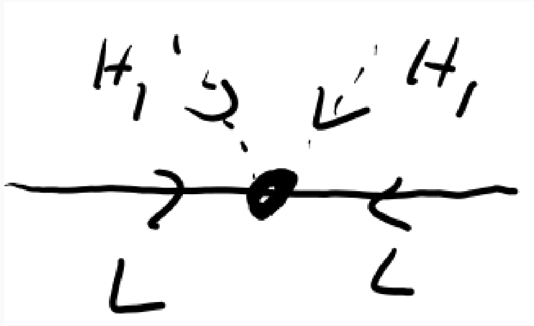

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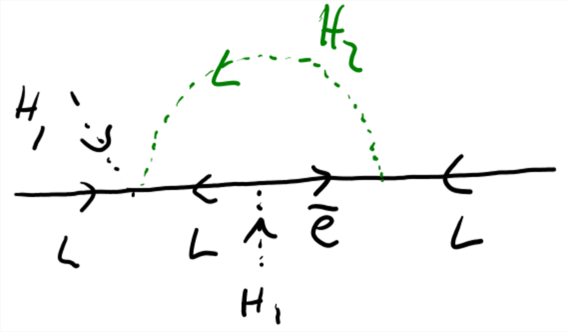
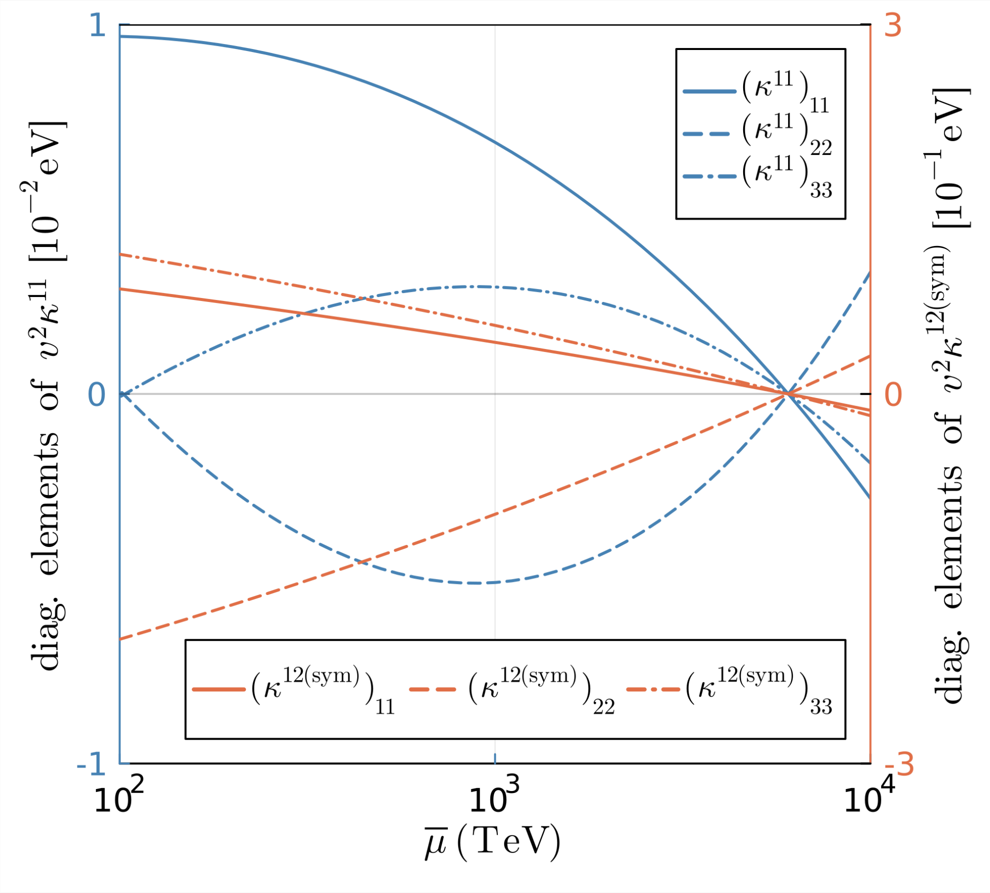


How large are quantum corrections?



$m_h = 10^4$ TeV, $Y_e^2 \gg Y_e^1$, $Y_q^2 = Y_q^1$

- tree-level matching at m_h $\kappa^{12(0)} = -\frac{f\mu}{m_h^2}$
- 1-loop matching at $\mu = m_{H_2}$

$$C^{\mathrm{Weinberg}} = \kappa^{11} + \frac{1}{16\pi^2}\left[\kappa^{12(0)} Y_e^{1\dagger} Y_e^2 + Y_2^{2T} Y_e^{1*} \kappa^{21(0)}\right]$$

$$= \frac{1}{16\pi^2} \ln\left(\frac{m_{H_2}^2}{m_h^2}\right) \frac{\mu}{m_h^2} f Y_e^{1\dagger} Y_e^2 + (\dots)^T$$

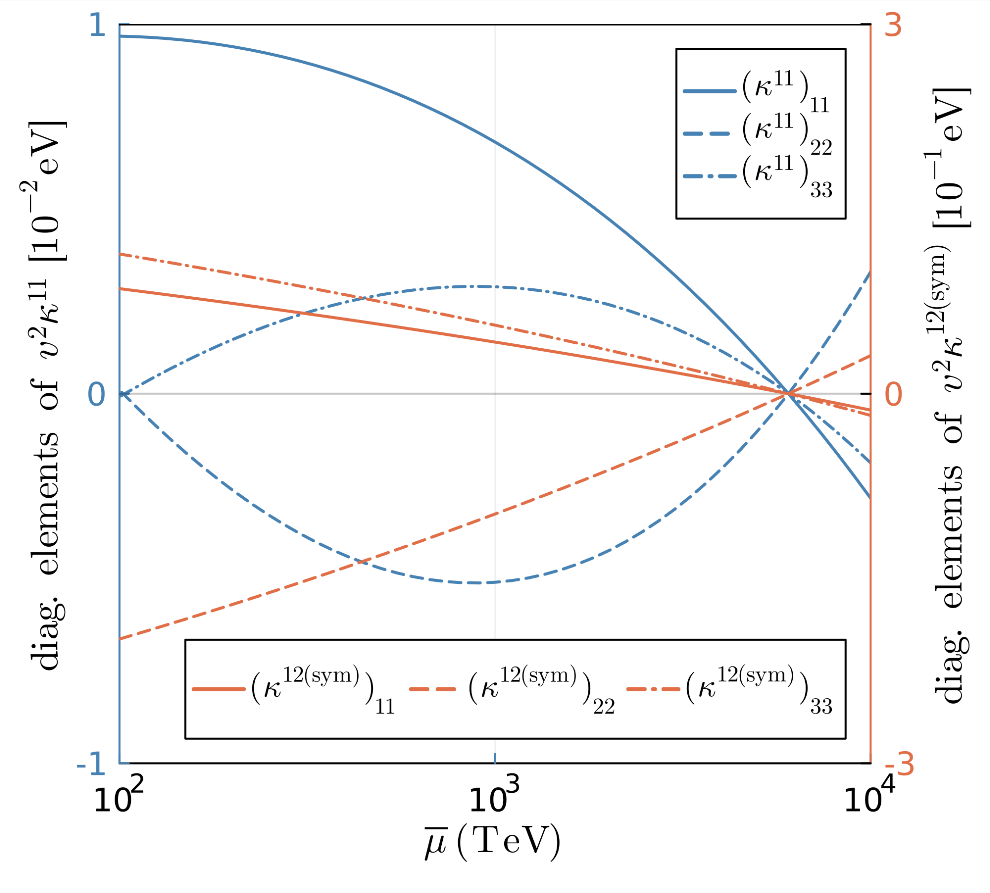
- cancellation between κ^{11} and $\kappa^{12(0)}$
- RG running of κ^{12} and κ^{11} differ

$$\frac{\mathrm{d}\kappa^{12}}{\mathrm{d}t} = B\kappa^{12} + \dots$$

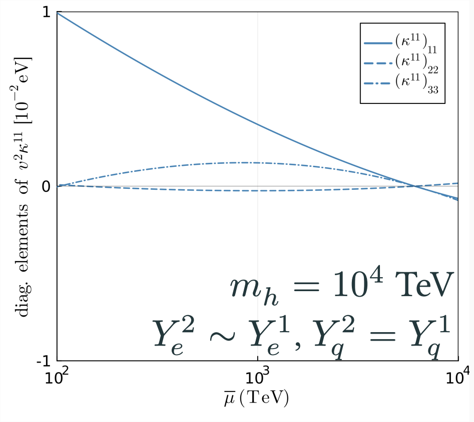
$$\frac{\mathrm{d}\kappa^{11}}{\mathrm{d}t} = 2\kappa^{12} Y_e^{1\dagger} Y_e^2 + (\dots)^T + \dots$$

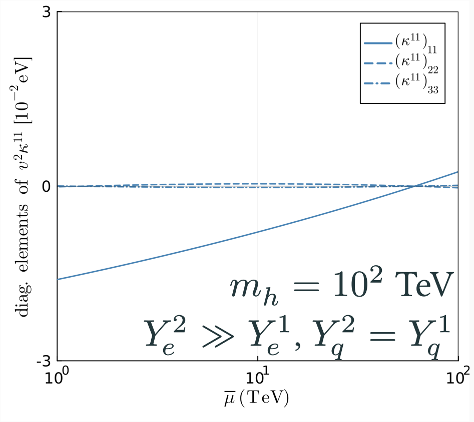
Running in the Zee model (cont.)

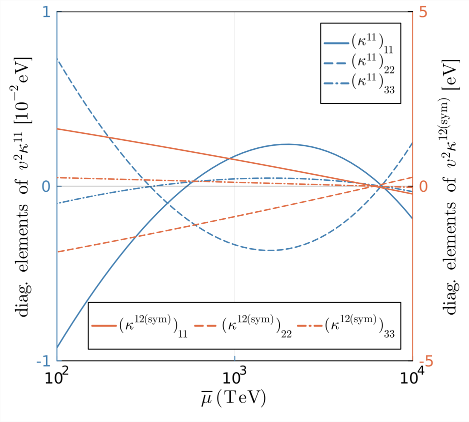
MS,Vandeleur [2512.17235]



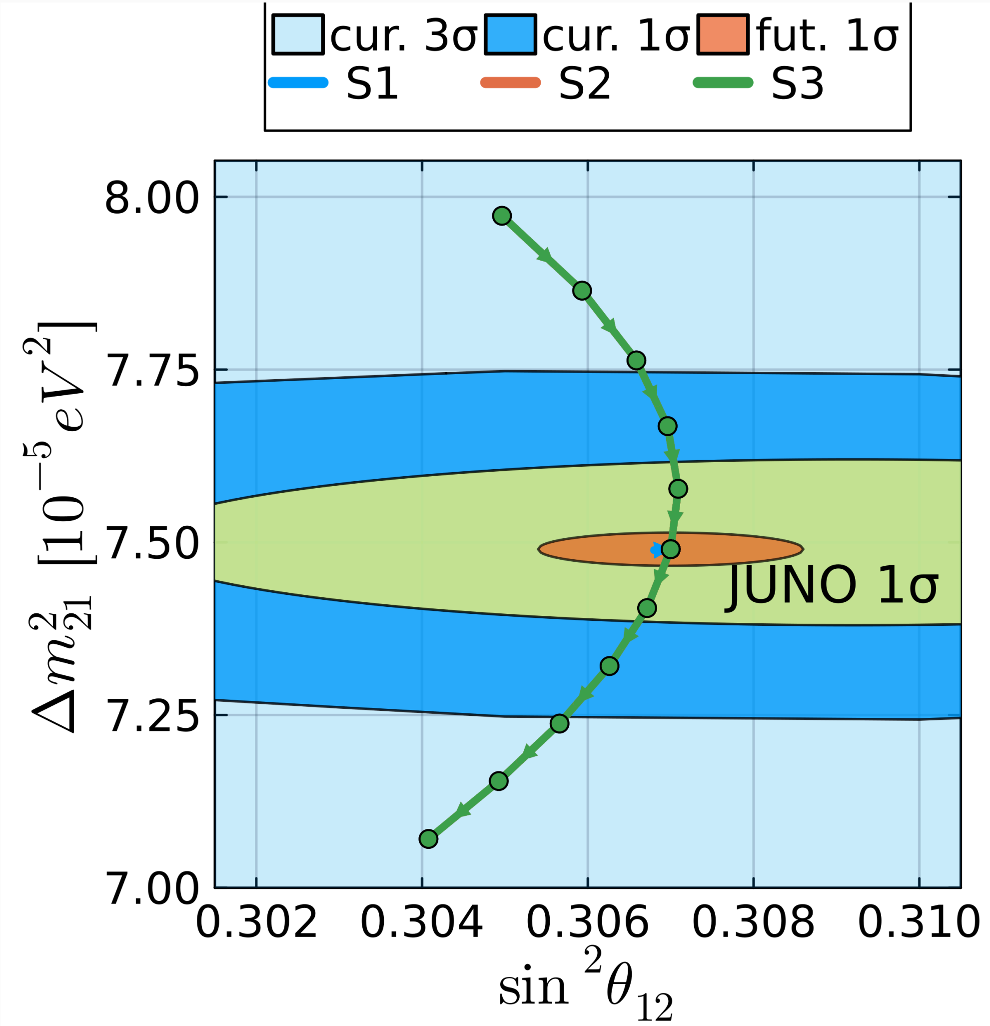
$m_h = 10^4$ TeV, $Y_e^2 \gg Y_e^1, Y_q^2 = Y_q^1$







$m_h = 10^4$ TeV, $Y_e^2 \gg Y_e^1, Y_q^2 = 0$



Neutrino mass in the full theory

$$m_\nu = \frac{f m_E Y_2}{8\pi^2} \frac{\mu \langle H \rangle \ln\left(\frac{m^2_{H_2}}{m^2_h}\right)}{m^2_h - m^2_{H_2}} + (\dots)^T$$

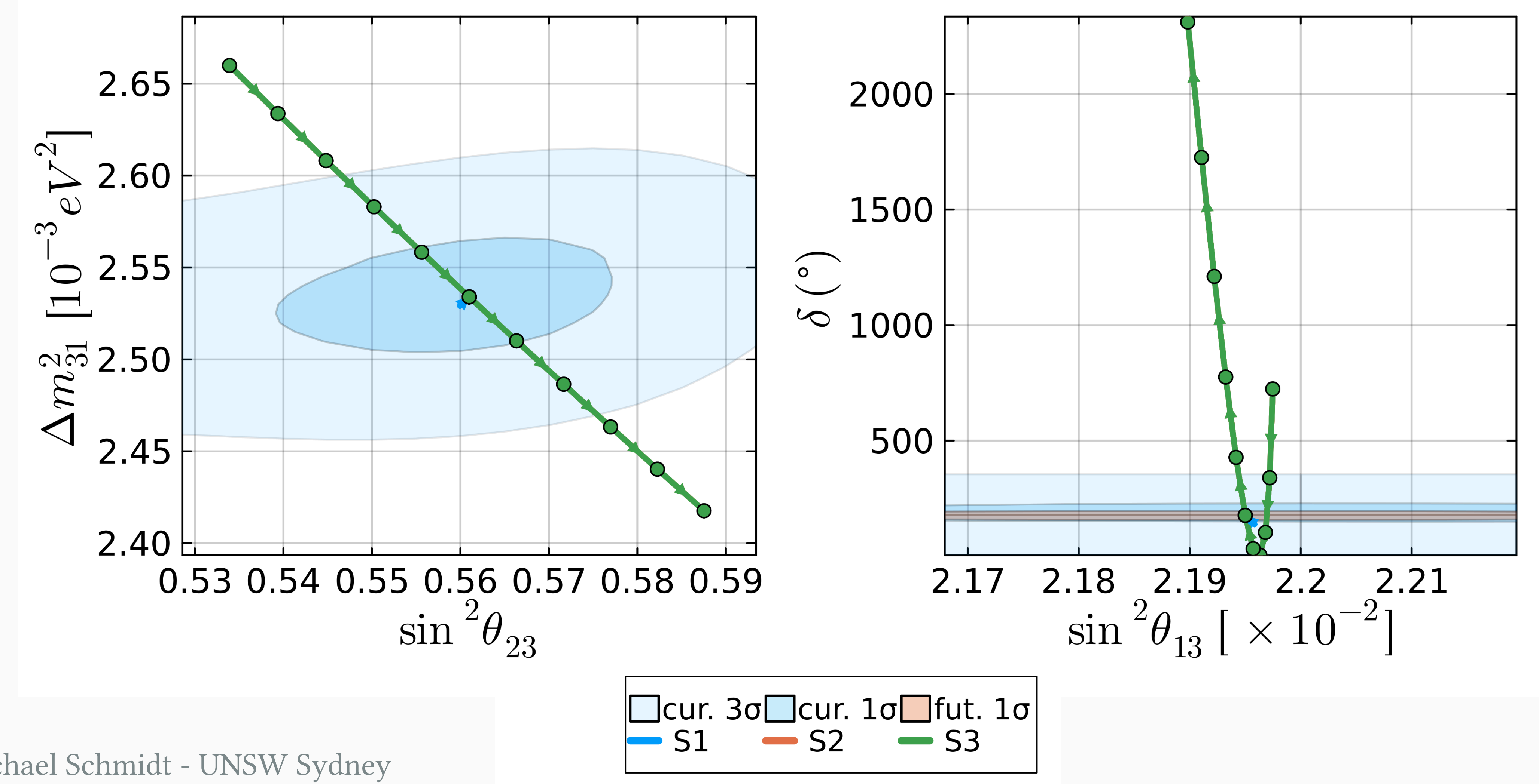
Example: $m_h = 100$ TeV, $m_{H_2} = 1$ TeV, $m_E \frac{\sqrt{2}}{v} \ll Y_e^2 \sim \mathcal{O}(0.1 - 0.5)$, $Y_q^2 = Y_q^1$

Rescaling $f \to \gamma f$ with $\gamma \in [0.95, 1.05]$

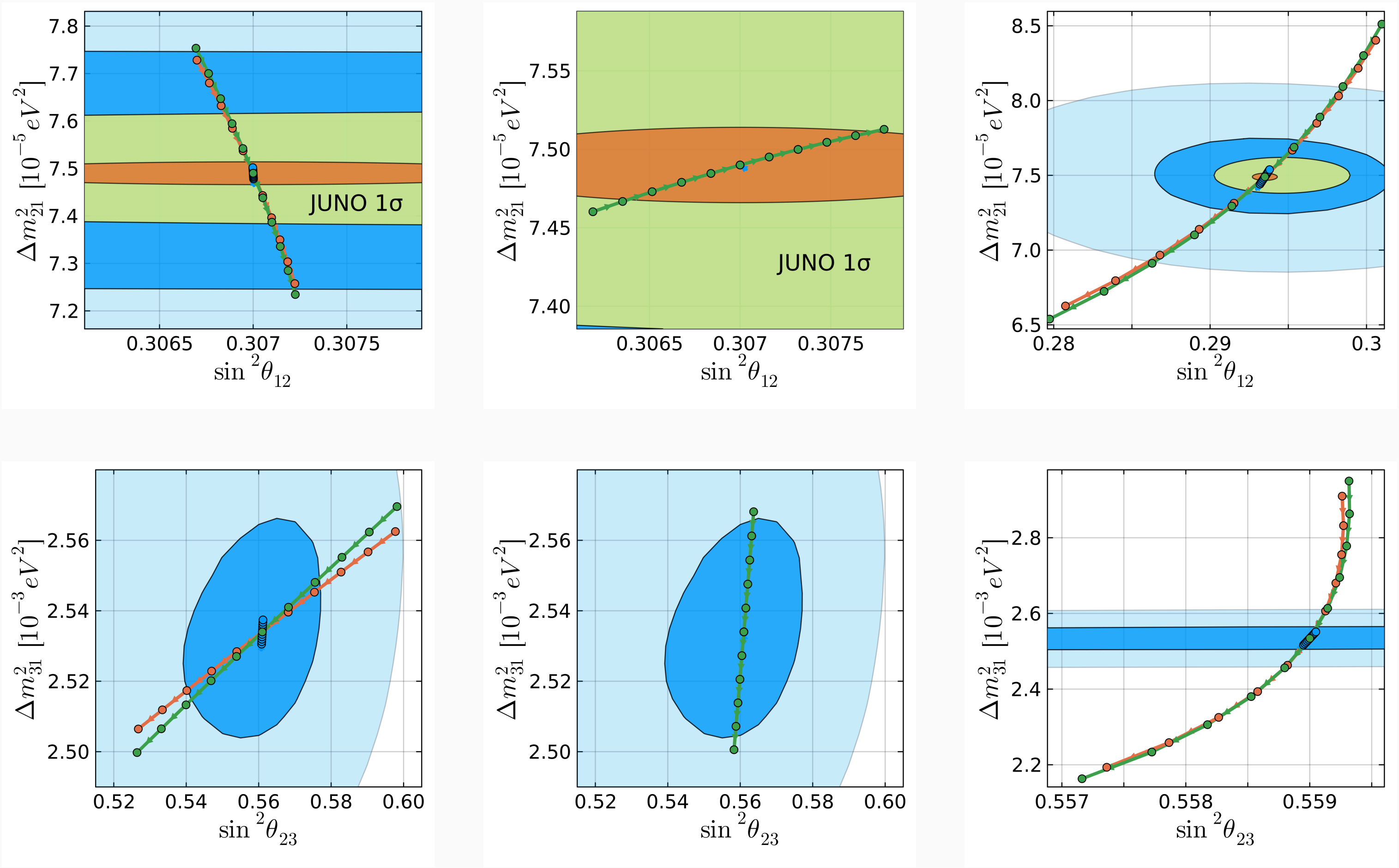
- S1: $Y_{e1,2} \to \gamma^{-\frac{1}{2}} Y_{e1,2}$
- S2: $Y_{e2} \to \gamma^{-1} Y_{e2}$
- S3: $Y_{e1} \to \gamma^{-1} Y_{e1}$

leaving *full theory* m_ν^{FT} *invariant*, but different predictions in EFT

MS,Vandeleur [2512.17235]



Other benchmarks



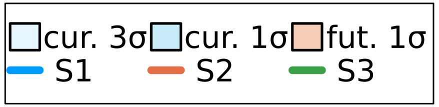
$Y_e^2 \gg Y_e^1, \quad Y_q^2 = Y_q^1$ $\qquad$ $Y_e^2 \sim Y_e^1, \quad Y_q^2 = 0$ $\qquad$ $Y_e^2 \gg Y_e^1, \quad Y_q^2 = Y_q^1$

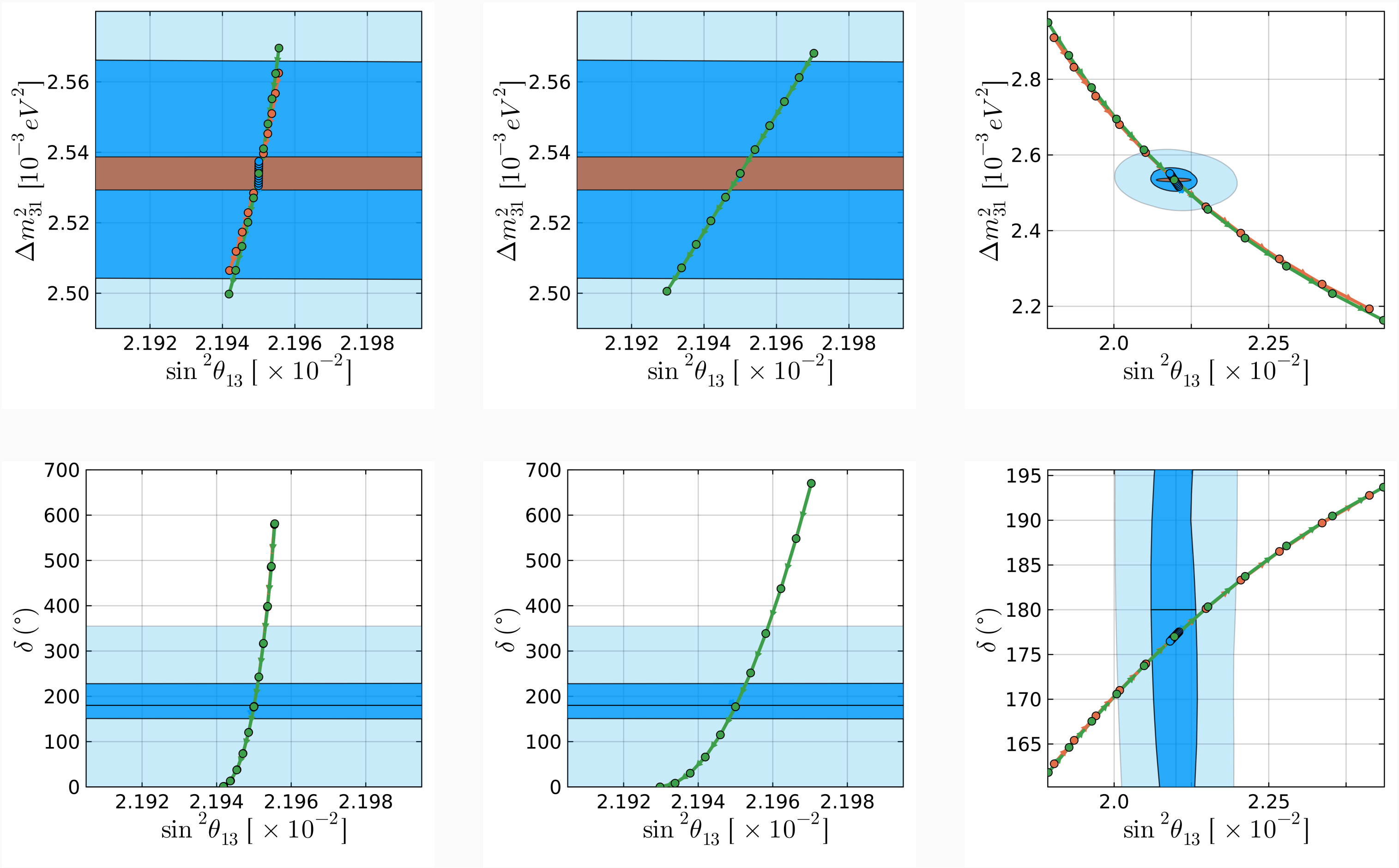
masses

- $m_h = 10^4$ TeV,
- $m_{H_2} = 100$ TeV

Rescaling $f \to \gamma f$

with $\gamma \in [0.99, 1.01]$



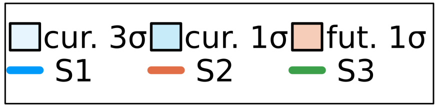


masses

- $m_h = 10^4$ TeV,
- $m_{H_2} = 100$ TeV

Rescaling $f \to \gamma f$

with $\gamma \in [0.99, 1.01]$



$Y_e^2 \gg Y_e^1, \quad Y_q^2 = Y_q^1$

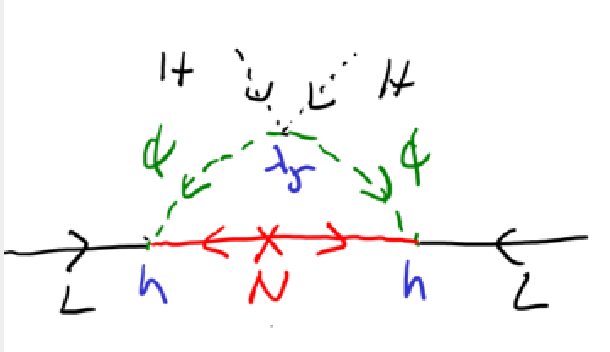
$Y_e^2 \sim Y_e^1, \quad Y_q^2 = 0$

$Y_e^2 \gg Y_e^1, \quad Y_q^2 = Y_q^1$

Comments on quantum corrections in the radiative seesaw model

Model

Tao [hep-ph/9603309] Ma [hep-ph/0601225]



- $\mathbb{Z}_2$ parity
- SM singlet fermions $N \sim (1,1,0)_-$
- isodoublet scalar $\phi \sim (1,2,\frac{1}{2})_-$

$$m^{\nu}_{ij} \simeq \frac{\lambda_5 \langle H\rangle^2}{16\pi^2} \frac{h_{ik} M_k h_{jk}}{m_\phi^2} f\left(\frac{M_k^2}{m_\phi^2}\right)$$

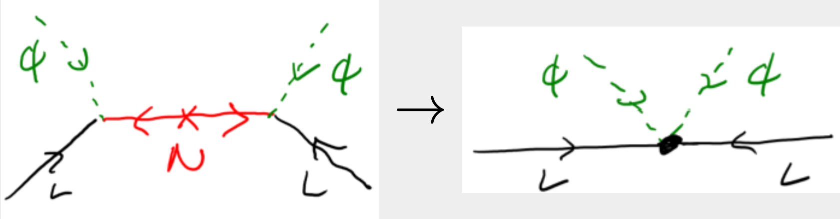
for $\lambda_5 \langle H\rangle^2 \ll M_k^2, m_\phi^2$

$M_k \gg m_\phi$

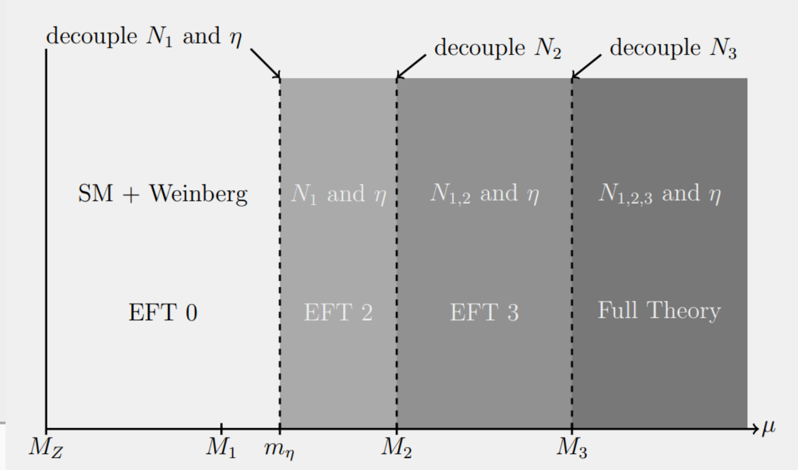
Bouchand,Merle [1205.0008] Merle,Platscher [1507.06314]

D5 operators generated at $\mu = M_k$:

- $LL\phi\phi$ via at tree level

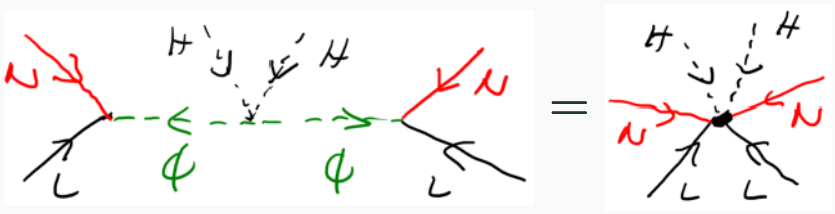


- $LLHH$ at one-loop level

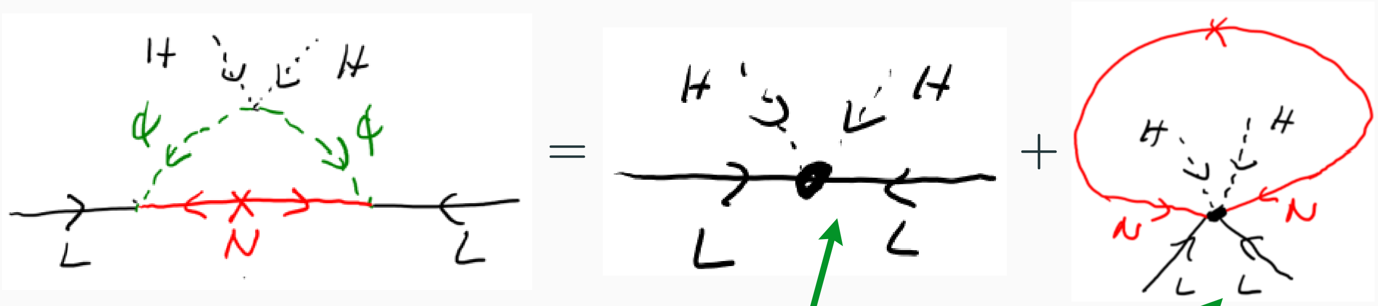


Dimension-8 operator $LNHLNH$ generated at tree level

tree level



loop level



Neutrino mass

$$m^\nu_{ij} \simeq \frac{\lambda_5 \langle H \rangle^2}{16\pi^2} \frac{h_{ik} M_k h_{jk}}{m_\phi^2} \left[1 + \frac{M_k^2}{m_\phi^2} \left(1 + \ln\left(\frac{M_k^2}{m_\phi^2} \right) \right) \right]$$

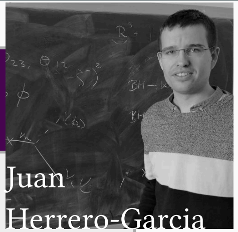
EFT power counting identifies relevant contributions

for $\lambda_5 \langle H \rangle^2 \ll M_k^2 \ll m_\phi^2$

Take-home messages

neutrino mass models

- Seesaw is simple and elegant explanation of neutrino masses but not the only one
- simplified models provide organizing principle using a small number of categories
- robust limits on all possible new particles generating m_ν
- useful framework to study phenomenology



precise predictions require effective field theory treatment

- quantum corrections important for comparison of theory predictions to upcoming precision data
- **EFT power counting** identifies relevant contributions

Take-home messages

neutrino mass models

- Seesaw is simple and elegant explanation of neutrino masses but not the only one
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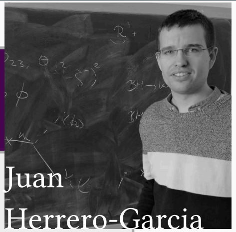

Juan Herrero-Garcia


Tobias Felkl

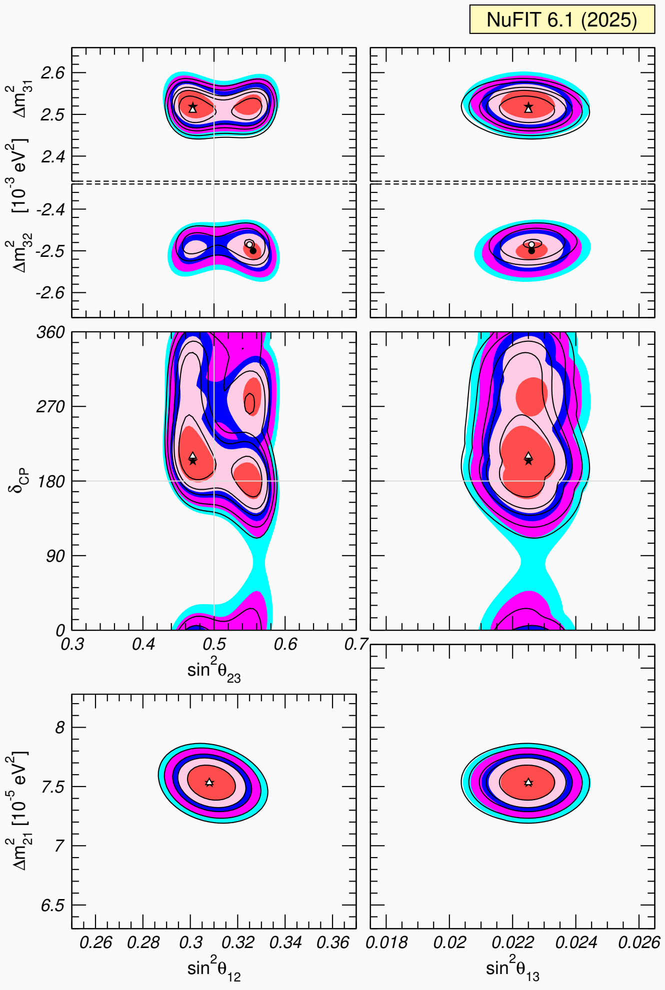
precise predictions require effective field theory treatment

- quantum corrections important for comparison of theory predictions to upcoming precision data
- **EFT power counting** identifies relevant contributions


James Vandeleur

谢谢！ Thank you!

Backup slides



Leptonic (PMNS) mixing matrix

$$U_{\mathrm{PMNS}} = R_{23}(\theta_{23})\, U_{13}(\theta_{13}, \delta)\, R_{12}(\theta_{12})$$

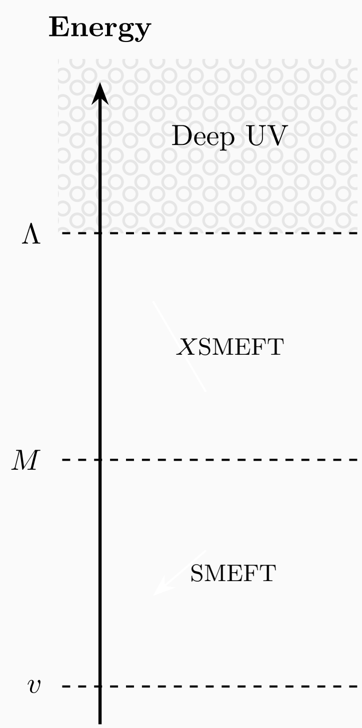
with $\quad U_{13}(\theta_{13}, \delta) = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \qquad R_{12}(\theta_{12}) = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$

$\sin^2\theta_{12}$	$0.2893 - 0.3295$	$\approx \frac{1}{3}$	0.3036 ± 0.0064 [JUNO @ Neutrino 2026]
$\sin^2\theta_{23}$	$0.432 - 0.590$	$\approx \frac{1}{2}$	
$\sin^2\theta_{13}$	$0.02070 - 0.02420$	≈ 0	
$\delta[^\circ]$	$114 - 405$		

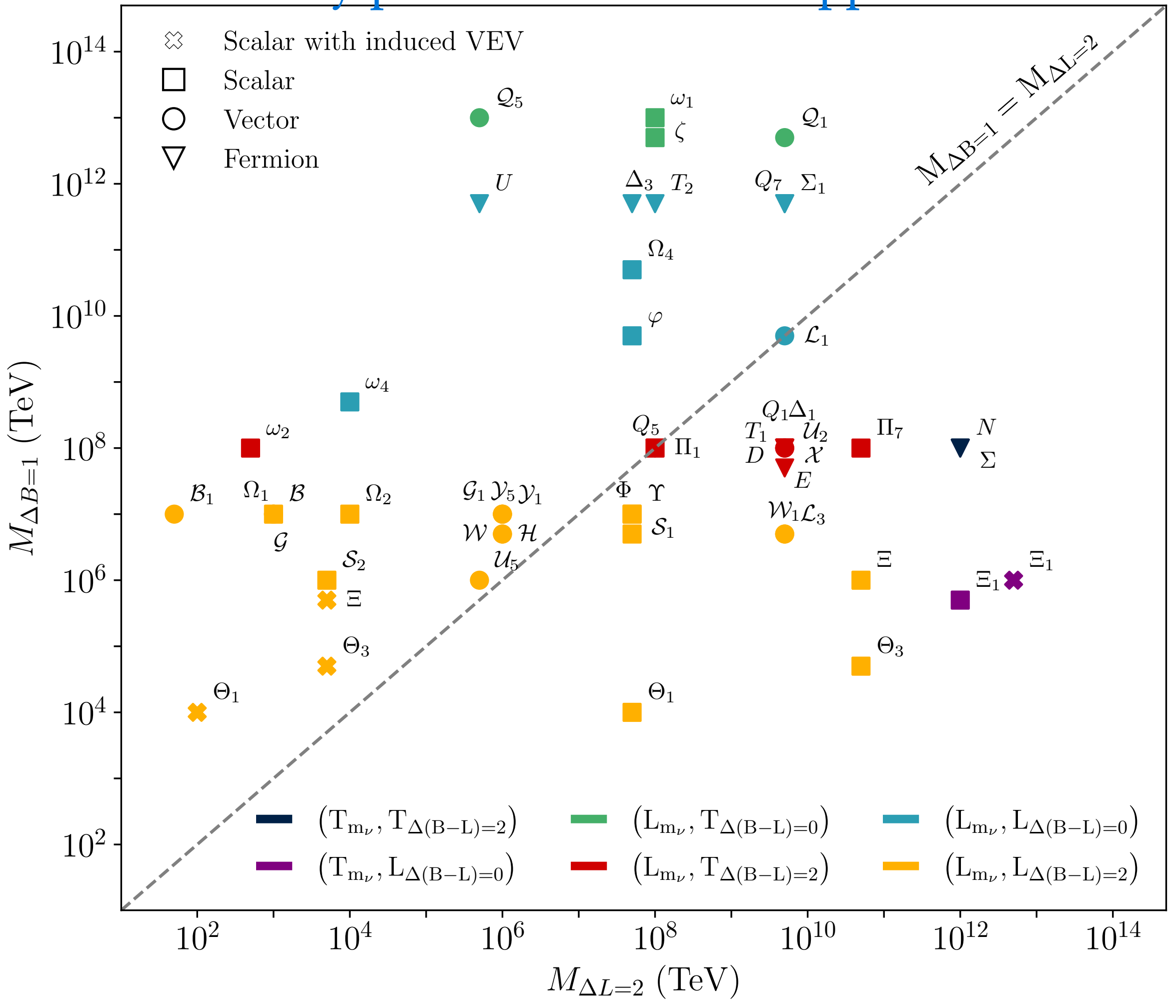
Symmetries work well for gauge interactions.

Is there a symmetry in the lepton sector?

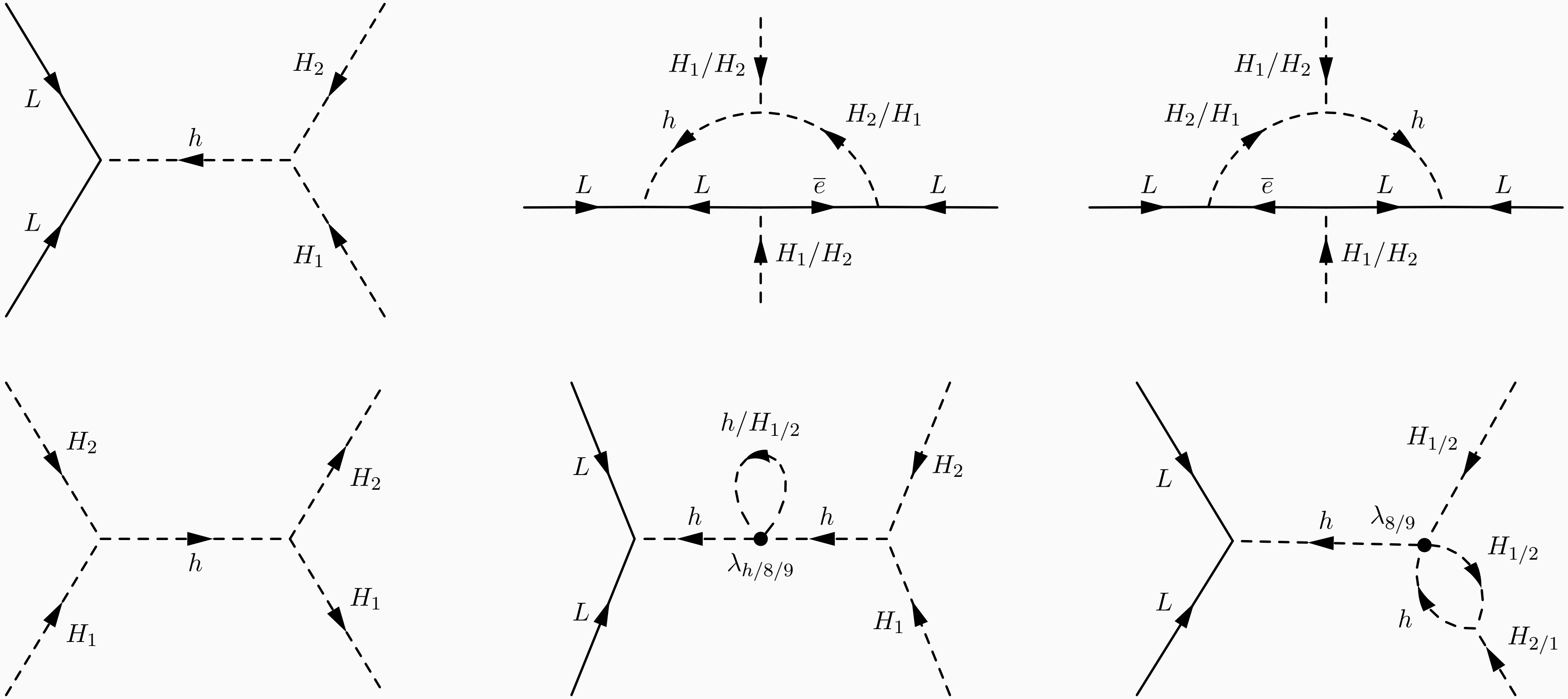
- SM extended by one particle
- with mass gap to heavier ones



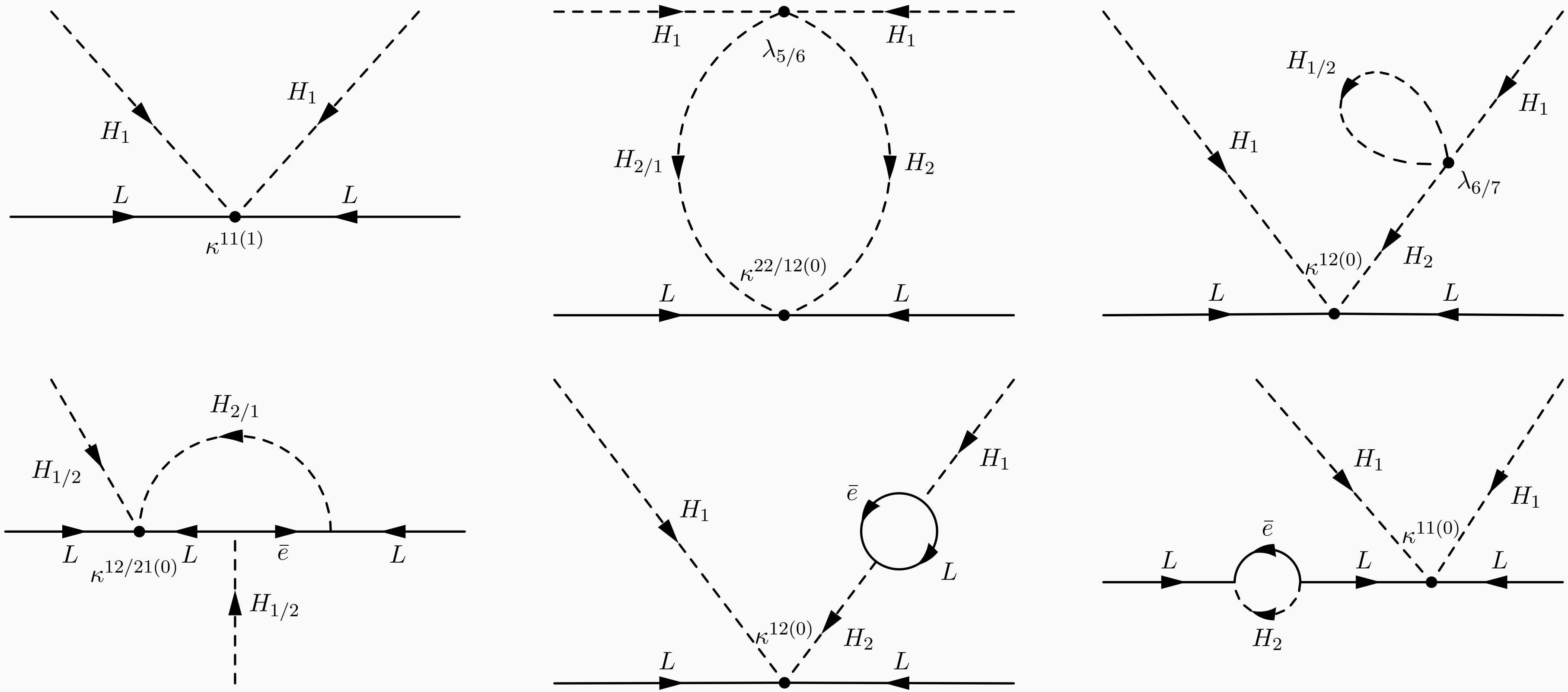
Sensitivity plot - conservative upper bounds on M

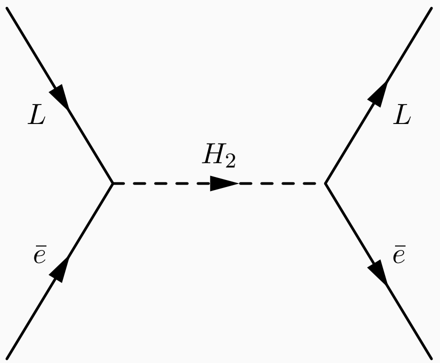


Zee model matching singly-charged scalar @ one-loop order



Zee model matching second Higgs doublet @ one-loop order

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L
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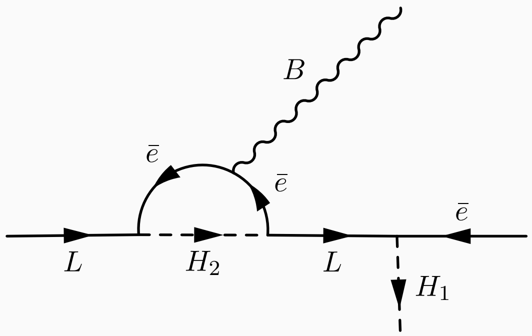
$\bar{e}$
$\bar{e}$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$\bar{e}$
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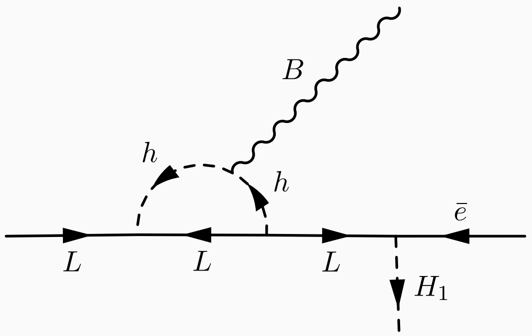
L
H_2
L
H_1


B
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L
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H_1