Neutrino Masses from new Weinberg-like Operators

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Based on:
JHEP 05 (2024) 055 [Alessio Giarnetti, Juan Herrero-Garcia, Simone Marciano, Davide Meloni, **DV**]
arXiv: 2312.13356, 2312.14119

Neutrino masses

Usual Seesaws

$$\mathscr{L}_5 = \frac{c_5}{\Lambda_{\mathrm{NP}}} LLHH \xrightarrow[\langle H \rangle = v]{\text{EWSSB}} m_\nu \sim \frac{c_5}{\Lambda_{\mathrm{NP}}} v^2 \gtrsim 0.05 \times 10^{-9}\ \mathrm{GeV}$$

v: 174 GeV

$\Lambda_{\mathrm{NP}} \lesssim 10^{14}$ GeV

Unique operator at $d = 5$

Weinberg: PRL 43 (1979)

UV completions at the tree level → Usual Seesaws (SSI/II/III)

Difficult to probe this NP scale for neutrino masses and lepton number violation

Beyond the usual Seesaws

New Weinberg-like Operators

Augment SM by new SU(2) scalar multiplets→ New operators

$\mathcal{O}_5^{(1)} = (LH)_{\mathbf{N}}(L\Phi_i)_{\mathbf{N}}$

$\mathcal{O}_5^{(2)} = (L\Phi_i)_{\mathbf{N}}(L\Phi_i)_{\mathbf{N}}$

$\mathcal{O}_5^{(3)} = (L\Phi_i)_{\mathbf{N}}(L\Phi_j)_{\mathbf{N}}$

New scalars take a VEV $\rightarrow \langle \Phi_i \rangle = v_i,\ \langle \Phi_j \rangle = v_j \rightarrow$ Can't be far from the EW scale

$m_\nu \sim v v_i / \Lambda$

$m_\nu \sim v_i^2 / \Lambda$

$m_\nu \sim v_i v_j / \Lambda$

ρ parameter: $\langle \Phi_{i,j} \rangle \ll \langle H \rangle \rightarrow \Lambda$ is parametrically suppressed ✓

Extra suppression possible from the WCs

Collider searches + EWPTs → More testable than the usual seesaws

Genuine Models

UV Completions

Do not generate the Weinberg operators with just the SM Higgs

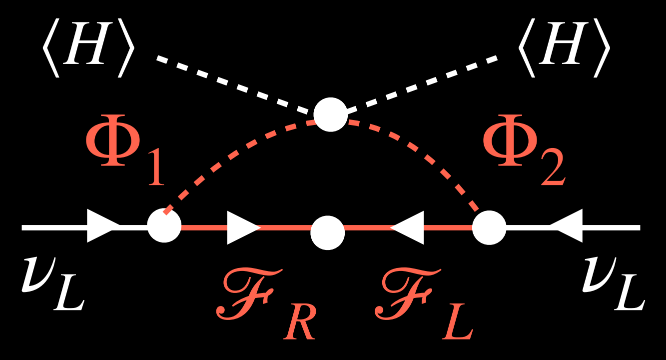
Model	Scalar Multiplets	Mediators	Op.	Wilson Coefficients
$\mathbf{A_1}$	$\Phi_1 = \mathbf{4}^S_{-1/2}$	$\Sigma = \mathbf{5}^F_0$	$\mathcal{O}_5^{(2)}$	$C_5^{(2)} = y_1 M_\Sigma^{-1} y_1^T$
$\mathbf{A_2}$	$\Phi_1 = \mathbf{4}^S_{-3/2}$	$\mathcal{F} = \mathbf{3}^F_{-1}$	$\mathcal{O}_5^{(1)}$	$C_5^{(1)} = y_1 M_\mathcal{F}^{-1} y_H^T + y_H M_\mathcal{F}^{-1} y_1^T$
$\mathbf{B_1}$	$\Phi_1 = \mathbf{4}^S_{1/2},\quad \Phi_2 = \mathbf{4}^S_{-3/2}$	$\mathcal{F} = \mathbf{5}^F_{-1}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$
$\mathbf{B_2}$	$\Phi_1 = \mathbf{3}^S_0,\quad \Phi_2 = \mathbf{5}^S_{-1}$	$\mathcal{F} = \mathbf{4}^F_{-1/2}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$
$\mathbf{B_3}$	$\Phi_1 = \mathbf{5}^S_{-2},\quad \Phi_2 = \mathbf{5}^S_1$	$\mathcal{F} = \mathbf{4}^F_{3/2}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$
$\mathbf{B_4}$	$\Phi_1 = \mathbf{5}^S_{-1},\quad \Phi_2 = \mathbf{5}^S_0$	$\mathcal{F} = \mathbf{4}^F_{1/2}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$

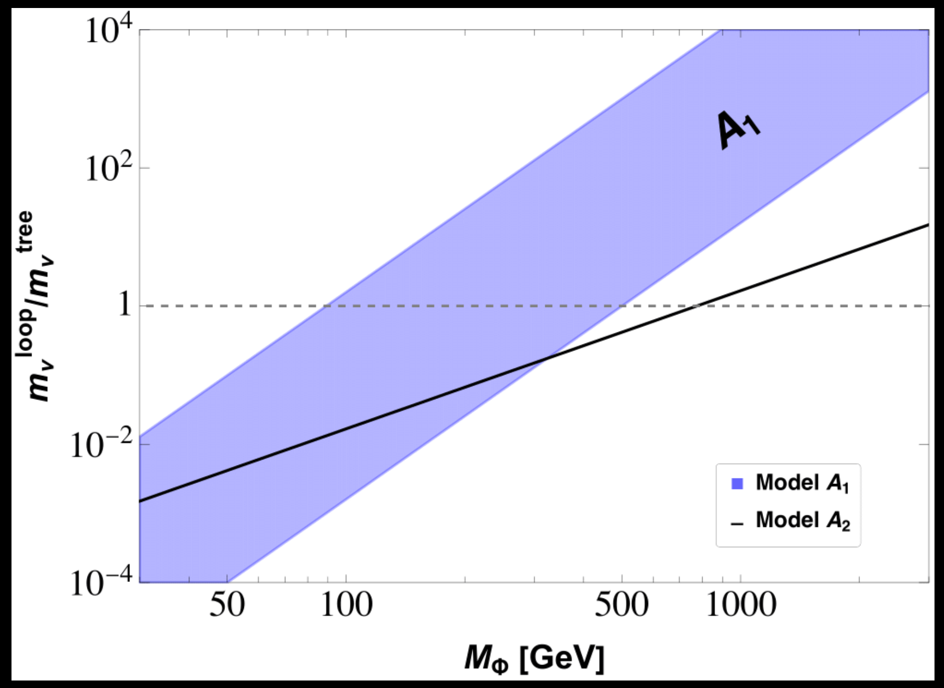
Kumericki, Picek, Radovic (2012); Babu, Nandi, Tavartkiladze (2009); McDonald (2013);
Bonnet, Hernandez, Ota, Winter (2009); Cepedello, Hirsch, Helo (2018)

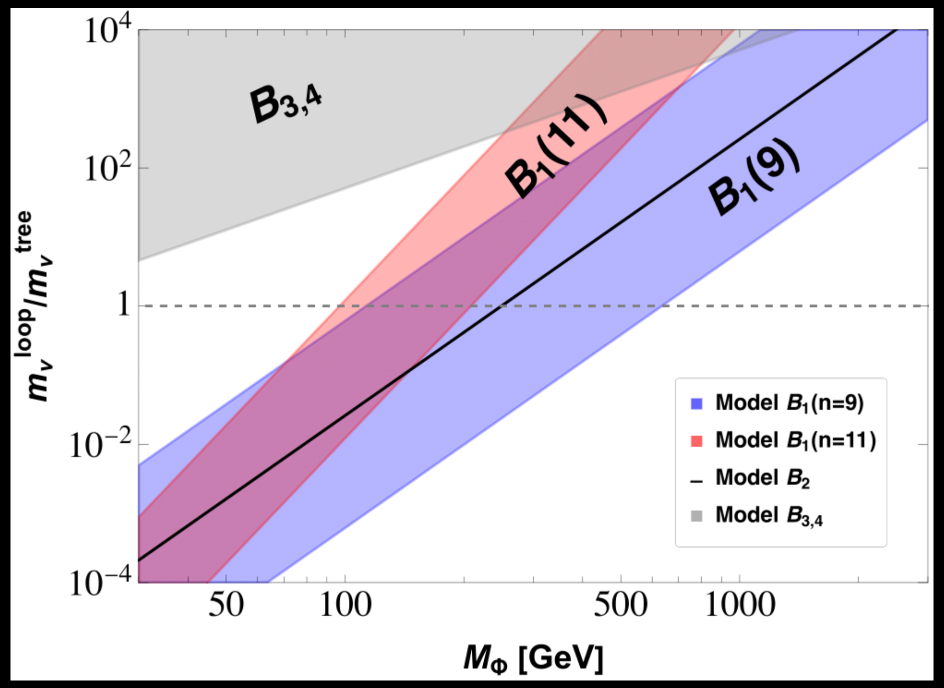
Genuine Models

Loop Contribution

$$(m_\nu)^{\text{loop}}_{\alpha\beta} \propto \lambda'' \frac{v^2}{8\pi^2 M_{\mathcal{F}}} \left(y_1 y_2^T + y_2 y_1^T\right)_{\alpha\beta}$$







$\mathbb{Z}_2/U(1) \rightarrow m_\nu$ at one loop only,
no tree contribution

(Generalised) Scotogenic models → Minimal DM Candidates $\mathcal{O}(1-10)$ TeV

Low-scale variants

A1: Majorana mass → Inverse seesaw $\quad M_{\mathcal{F}} \simeq \mathcal{O}(1)$ TeV

A2: Hierarchy among Yukawas/VEVs: $y_1 v_1 \ll y_H v$

$$y_H \simeq 1 \rightarrow \left(\frac{y_1}{10^{-10}}\right)\left(\frac{v_1}{\text{GeV}}\right) \simeq 1$$

Bi: $y_1 v_1 \ll y_2 v_2 \rightarrow$ Rich phenomenology from Φ_2

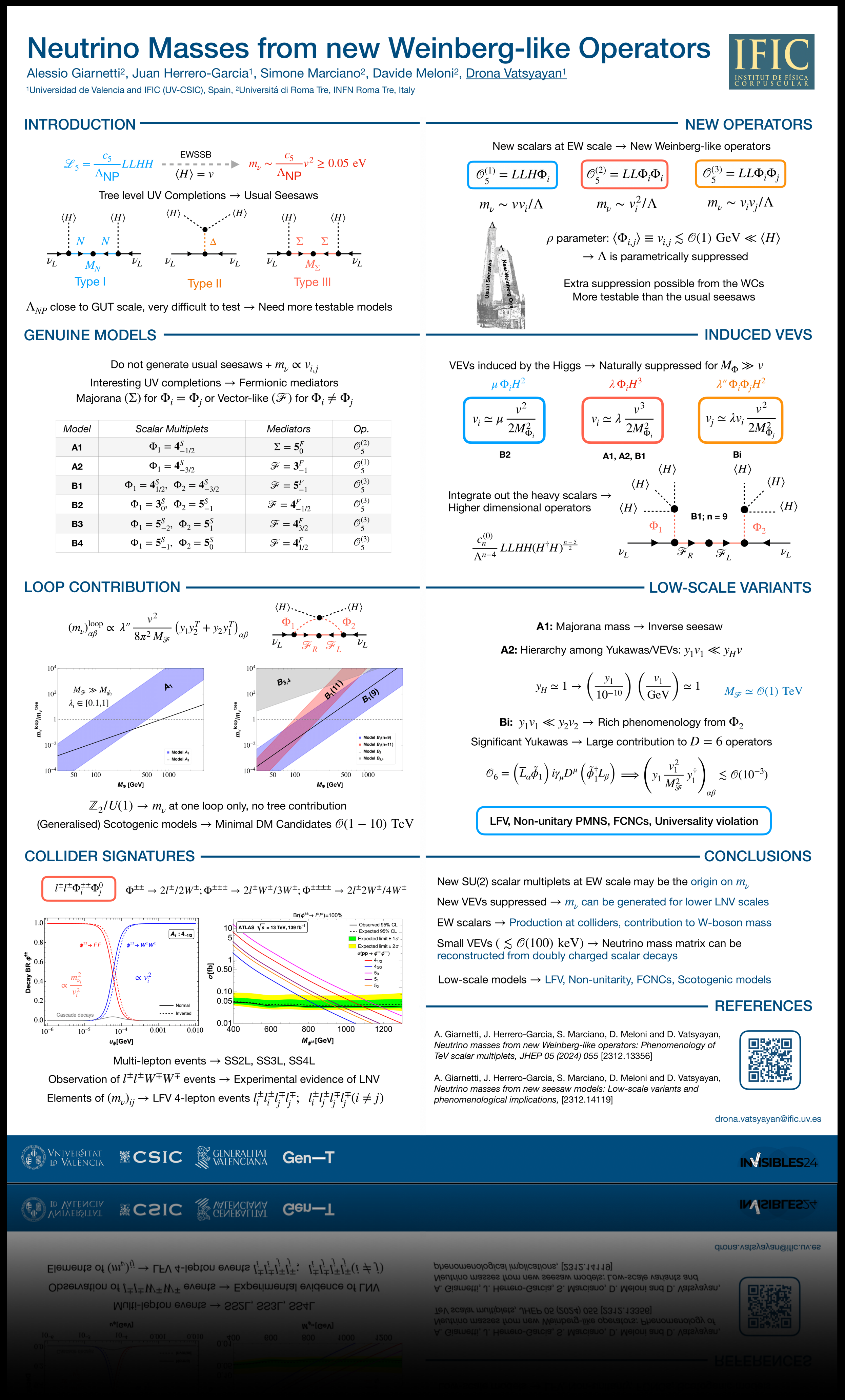
Significant Yukawas → Large contribution to $D = 6$

$$\mathcal{O}_6 = \left(\bar{L}_\alpha \tilde{\phi}_1\right) i\gamma_\mu D^\mu \left(\tilde{\phi}_1^\dagger L_\beta\right) \Longrightarrow \left(y_1 \frac{v_1^2}{M_{\mathcal{F}}^2} y_1^\dagger\right)_{\alpha\beta} \lesssim \mathcal{O}(10^{-3})$$

LFV, Non-unitary PMNS, FCNCs, Universality violation

Conclusions

More details and phenomenological implications



New scalar multiplets at EW scale → New Weinberg-like operators

New scalar VEVs suppressed → Neutrino masses can be generated for lower LNV scales

EW scalars → Production at colliders, contribution to W-boson mass

Collider signatures → SS2L, SS3L, SS4L, LNV + LFV events

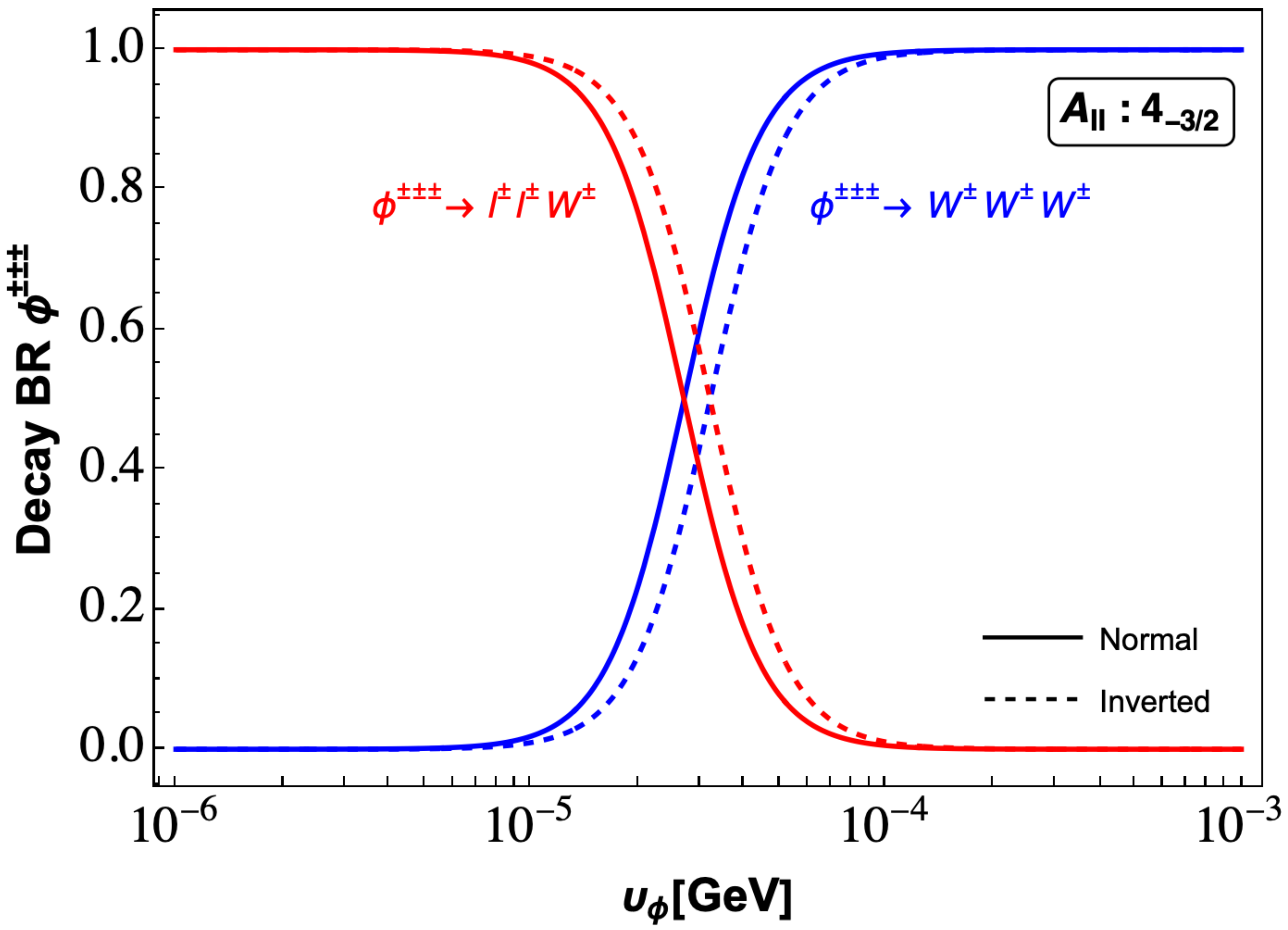
Small VEVs ($\lesssim \mathcal{O}(100)\ \mathrm{keV}$) → Neutrino mass matrix can be reconstructed from doubly charged-scalars decays

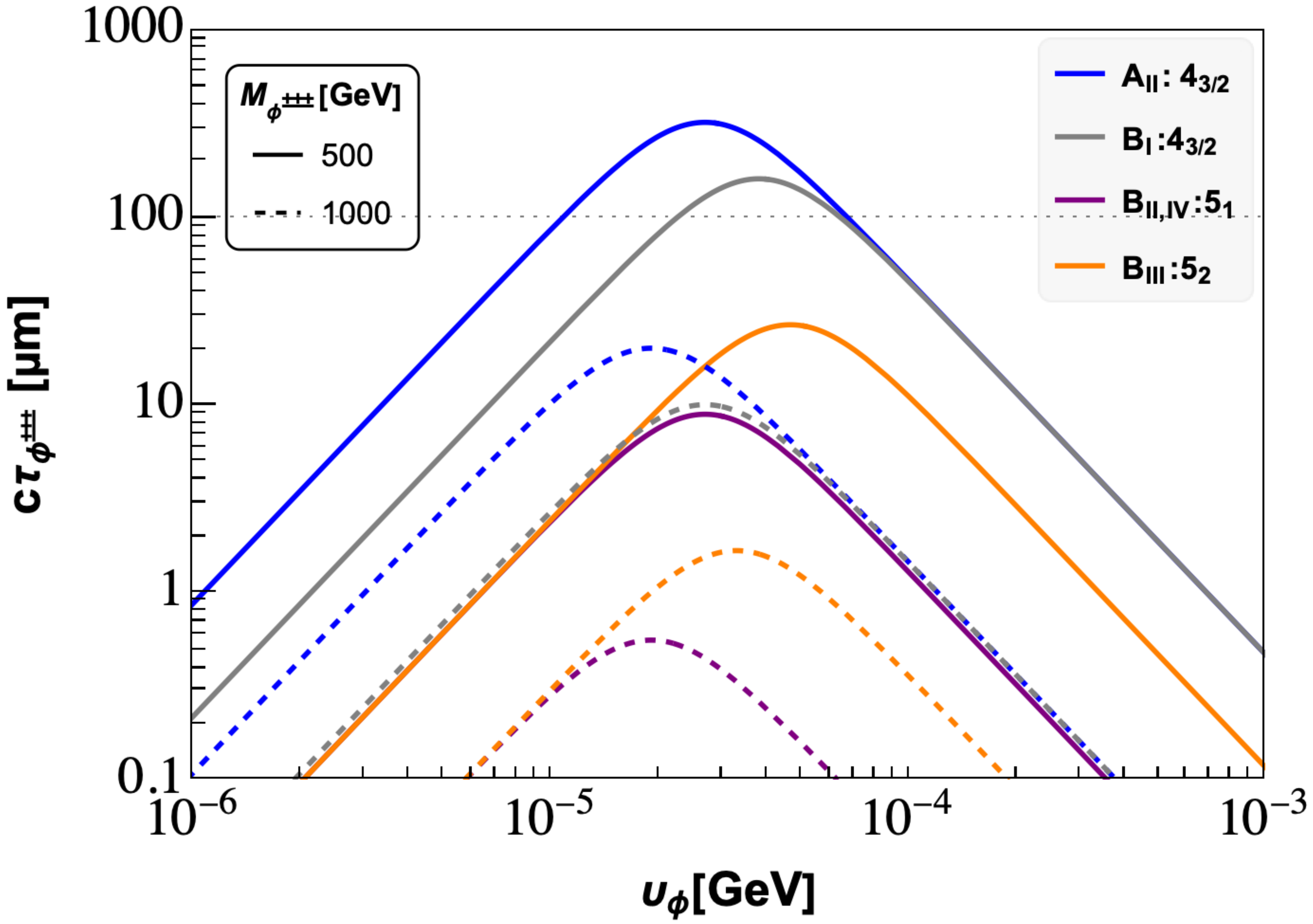
Backup

Collider Phenomenology

Triply-charged scalar decays

$$\Phi^{\pm\pm\pm} \to \Phi^{\pm\pm} W^{\pm} \to \begin{cases} W^{\pm}W^{\pm}W^{\pm} \\ W^{\pm}l^{\pm}l^{\pm} \end{cases}$$



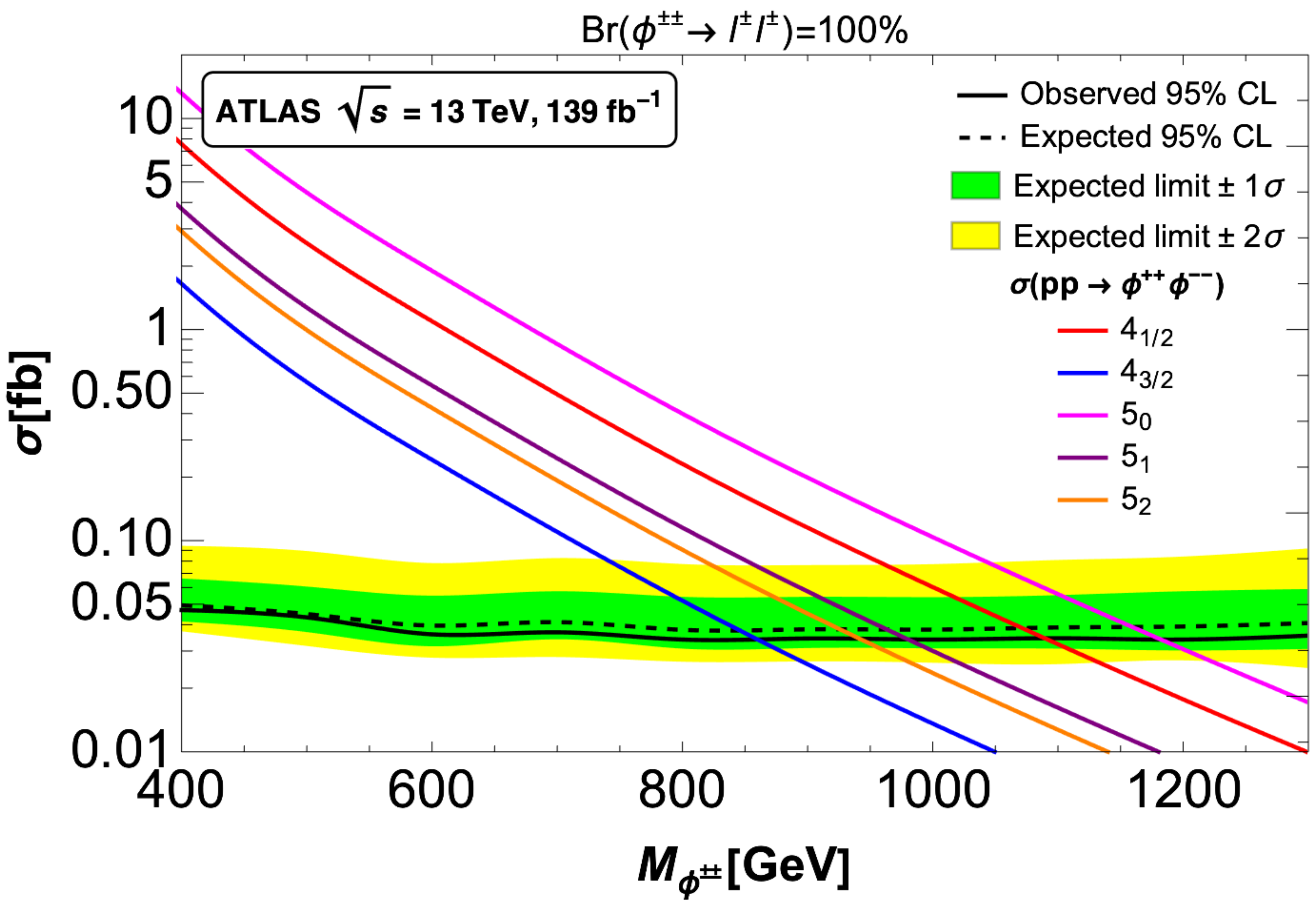


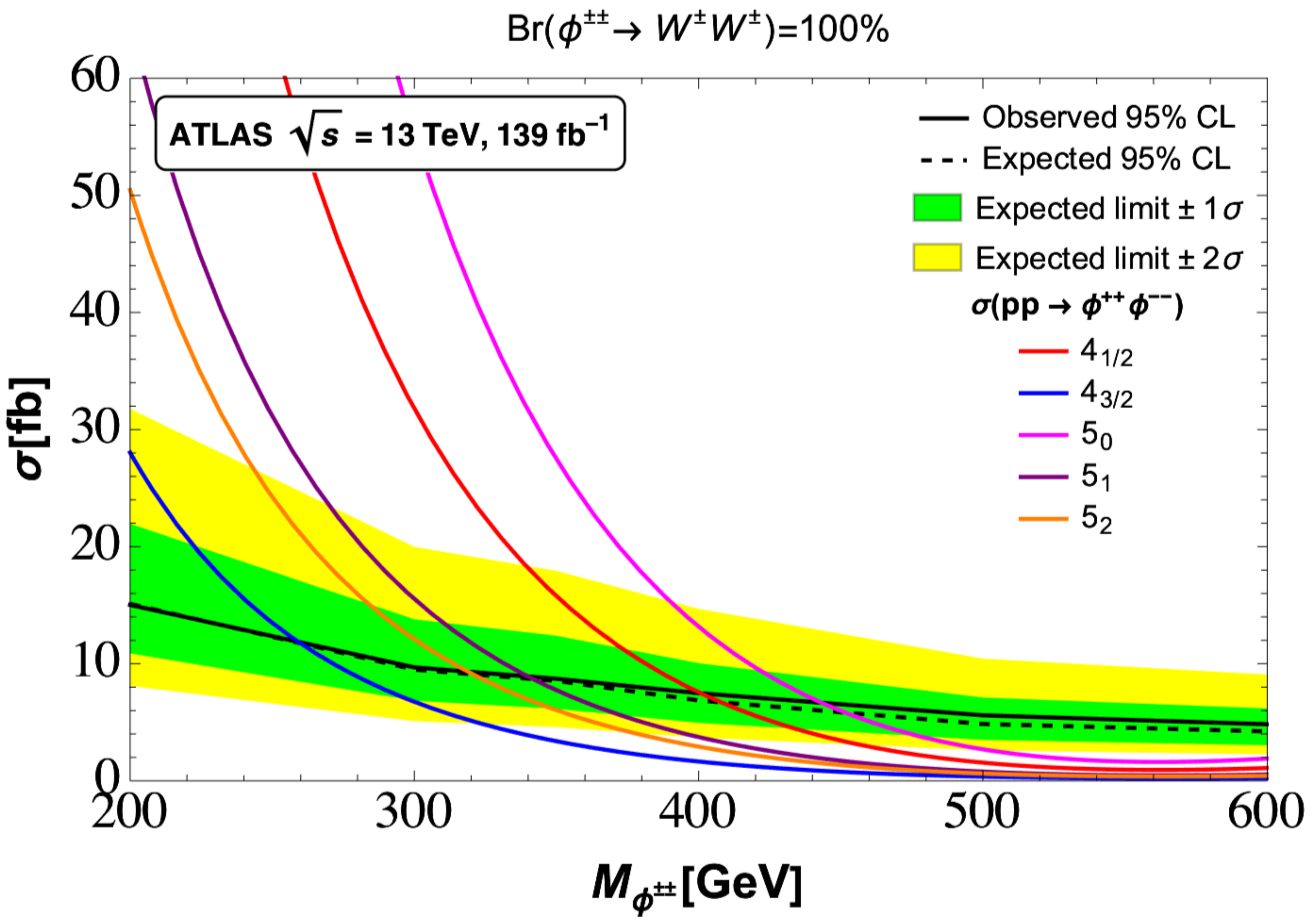
May lead to
Displaced vertices

Ghosh, Jana, Nandi (2018)

Collider Phenomenology

Searches





Phenomenology

LFV Constraints

		Upper limits		
Model	**Yukawa combination**	$\alpha\beta = \mu e$	$\alpha\beta = \tau e$	$\alpha\beta = \tau\mu$
$\mathbf{A_1}$	$\lvert y_1^{\beta^*} y_1^{\alpha}\rvert(\mathrm{TeV}/M_{\Sigma})^2$	< 0.0002	< 0.13	< 0.16
$\mathbf{A_2}$	$\lvert y_1^{\beta^*} y_1^{\alpha}\rvert(\mathrm{TeV}/M_{\mathcal{F}})^2$	< 0.0004	< 0.24	< 0.28
$\mathbf{B_1}$	$\lvert y_1^{\beta^*} y_1^{\alpha} - 0.5\, y_2^{\beta^*} y_2^{\alpha}\rvert(\mathrm{TeV}/M_{\mathcal{F}})^2$	< 0.0004	< 0.29	< 0.34
$\mathbf{B_2}$	$\lvert y_1^{\beta^*} y_1^{\alpha} - 50\, y_2^{\beta^*} y_2^{\alpha}\rvert(\mathrm{TeV}/M_{\mathcal{F}})^2$	< 0.0011	< 0.72	< 0.84
$\mathbf{B_3}$	$\lvert y_1^{\beta^*} y_1^{\alpha} - 2.12\, y_2^{\beta^*} y_2^{\alpha}\rvert(\mathrm{TeV}/M_{\mathcal{F}})^2$	< 0.0002	< 0.15	< 0.18
$\mathbf{B_4}$	$\lvert y_1^{\beta^*} y_1^{\alpha} + 6.6\, y_2^{\beta^*} y_2^{\alpha}\rvert(\mathrm{TeV}/M_{\mathcal{F}})^2$	< 0.0004	< 0.24	< 0.28

Scotogenic/Generalised Scotogenic Models
DM Candidates

Model	New fields	Sym.	DM candidates	DM Mass (TeV)
$\mathbf{A_1'}$	$\Phi_1 = 4^S_{-1/2}\,, \Sigma = 5^F_0$	Z_2	$4^S_{-1/2},\, 5^F_0$	$M_{\Phi_1} \approx 3.2, M_\Sigma \approx 10$
$\mathbf{A_2'}$	$\Phi_1 = 4^S_{-3/2}\,, \mathcal{F} = 3^F_{-1}$	–	–	–
$\mathbf{B_1'}$	$\Phi_1 = 4^S_{1/2}\,, \Phi_2 = 4^S_{-3/2}\,, \mathcal{F} = 5^F_{-1}$	$U(1)$	$4^S_{1/2}\,, 4^S_{-3/2}$	$M_{\Phi_1} \approx 3.2, M_{\Phi_2} \approx 3.5$
$\mathbf{B_2'}$	$\Phi_1 = 3^S_0\,, \Phi_2 = 5^S_{-1}\,, \mathcal{F} = 4^F_{-1/2}$	$U(1)$	$3^S_0\,, 5^S_{-1}$	$M_{\Phi_1} \approx 2.5, M_{\Phi_2} \approx 3.4$
$\mathbf{B_3'}$	$\Phi_1 = 5^S_{-2}\,, \Phi_2 = 5^S_1\,, \mathcal{F} = 4^F_{3/2}$	$U(1)$	$5^S_{-2}\,, 5^S_1$	$M_{\Phi_1} \approx 3.9, M_{\Phi_2} \approx 3.4$
$\mathbf{B_4'}$	$\Phi_1 = 5^S_{-1}\,, \Phi_2 = 5^S_0\,, \mathcal{F} = 4^F_{1/2}$	$U(1)$	$5^S_{-1}\,, 5^S_0$	$M_{\Phi_1} \approx 3.4, M_{\Phi_2} \approx 9.4$

List of *(Generalised) Scotogenic*-like models which generate neutrino masses at one loop. We give the stabilising symmetry in the third column and the possible DM candidates in the fourth column. The mass for the DM candidate that reproduces the observed relic abundance is listed in the last column, including non-perturbative effects for the $Y = 0$ candidates