Neutrino Masses from new Weinberg-like Operators

Drona Vatsyayan

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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

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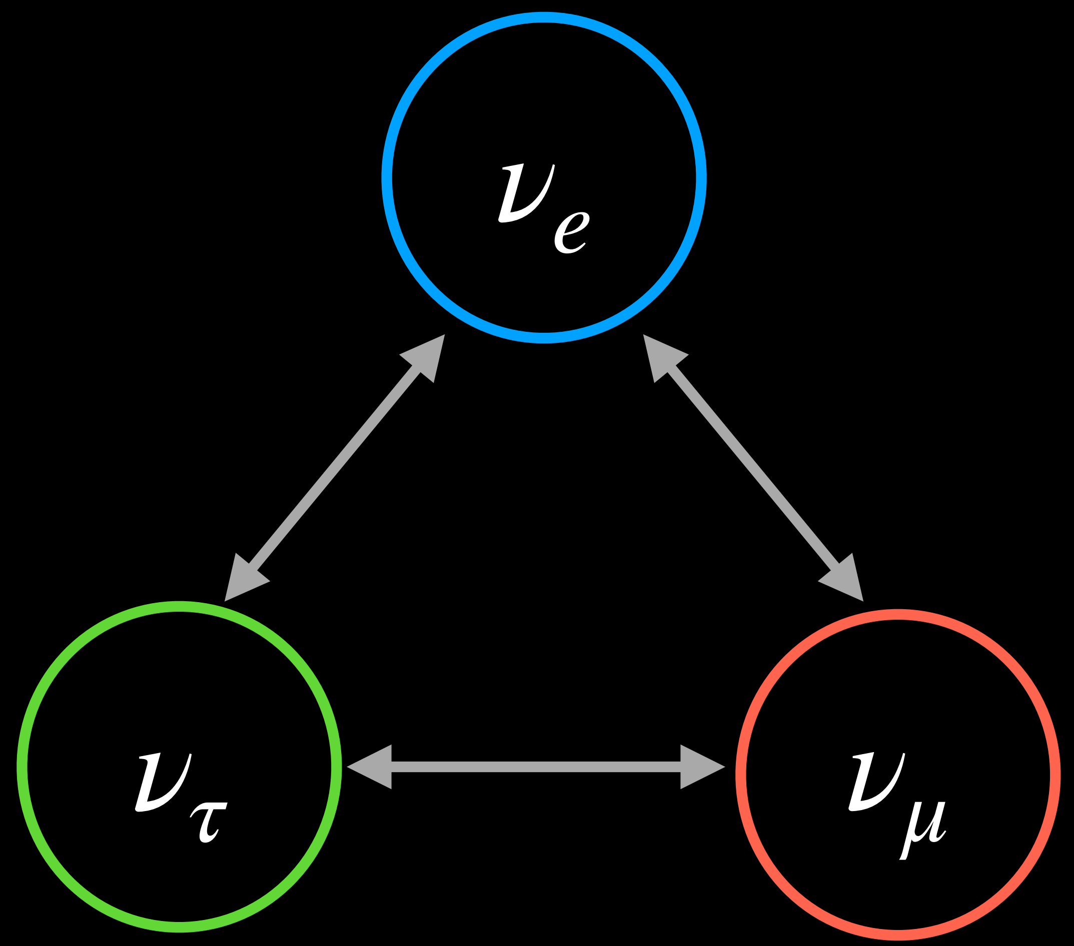
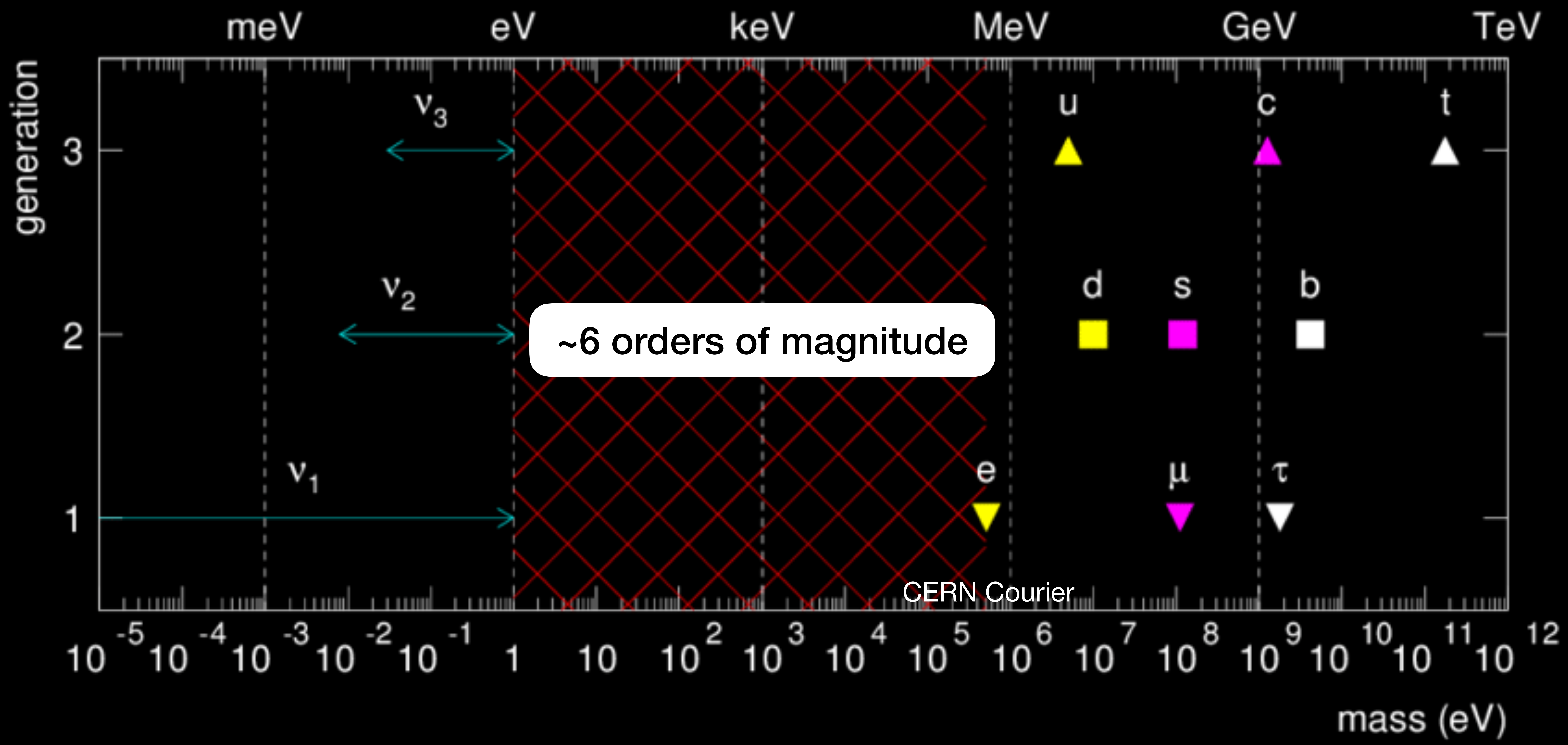
Neutrinos

Mass spectrum



Neutrino Oscillations →
Neutrinos have a tiny mass



Absolute mass unknown!

Origin of mass unknown!

Neutrino masses

Usual Seesaws

Unique operator at $d = 5$

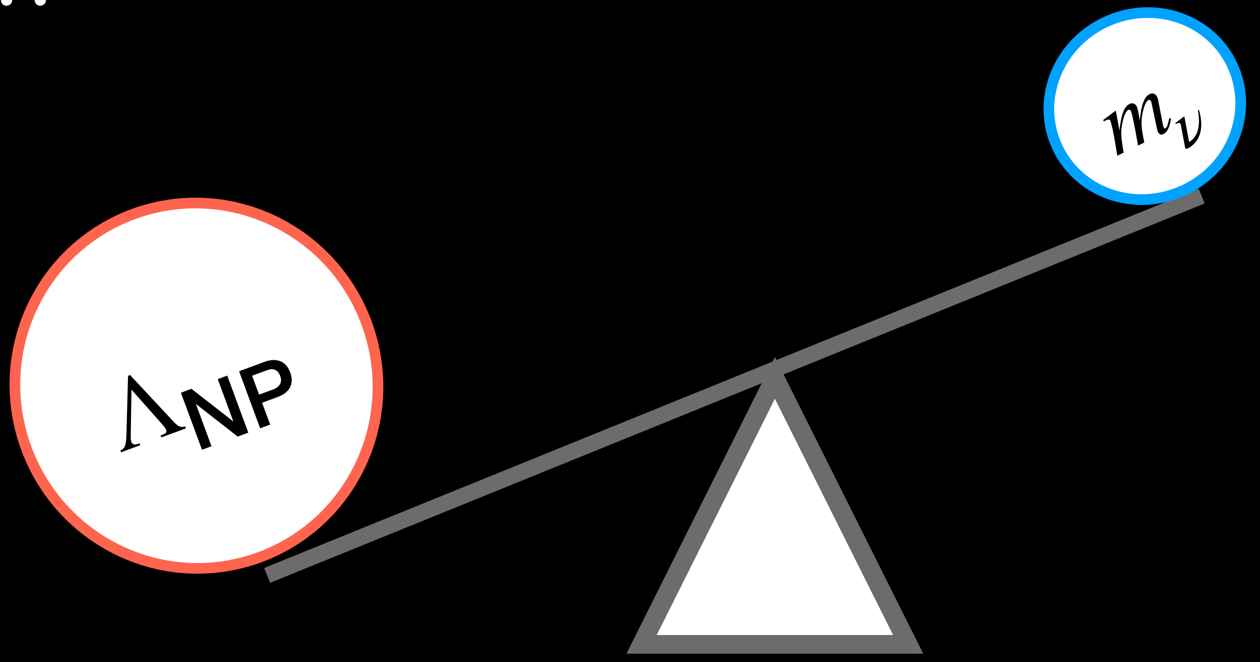
Weinberg: PRL 43 (1979)

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \boxed{\frac{c}{\Lambda_{\text{NP}}}\mathcal{O}^{d=5}} + \frac{c'}{\Lambda_{\text{NP}}^2}\mathcal{O}^{d=6} + \frac{c''}{\Lambda_{\text{NP}}^3}\mathcal{O}^{d=7} + \ldots$$

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

Λ_{NP}: $\lesssim 10^{14}$ GeV

v: 174 GeV



The Seesaw Mechanism

Yanagida, Tokyo (1981)

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

$\mathcal{O}_5^{(1)} = LLH\Phi_i$

$\mathcal{O}_5^{(2)} = LL\Phi_i\Phi_i$

$\mathcal{O}_5^{(3)} = LL\Phi_i\Phi_j$

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

UV completions of scenarios → *Genuine* models → $m_\nu \propto v_i$

Do not generate the Weinberg operators with just the SM Higgs

$\mathbf{N}_Y^{S,F}$

Dimension , Hypercharge, Scalar/Fermion

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

Scalar multiplets upto the quintuplet representation i.e. $\mathbf{N_i} \leq \mathbf{5}$

Avoid problems with unitarity, non-perturbativity close to the EW scale due to RGE running

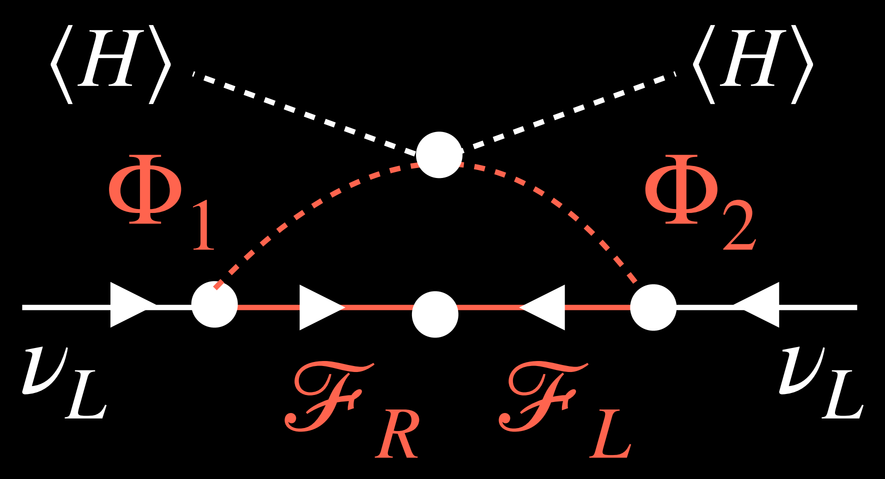
Hally, Logan, Pilkington (2012)

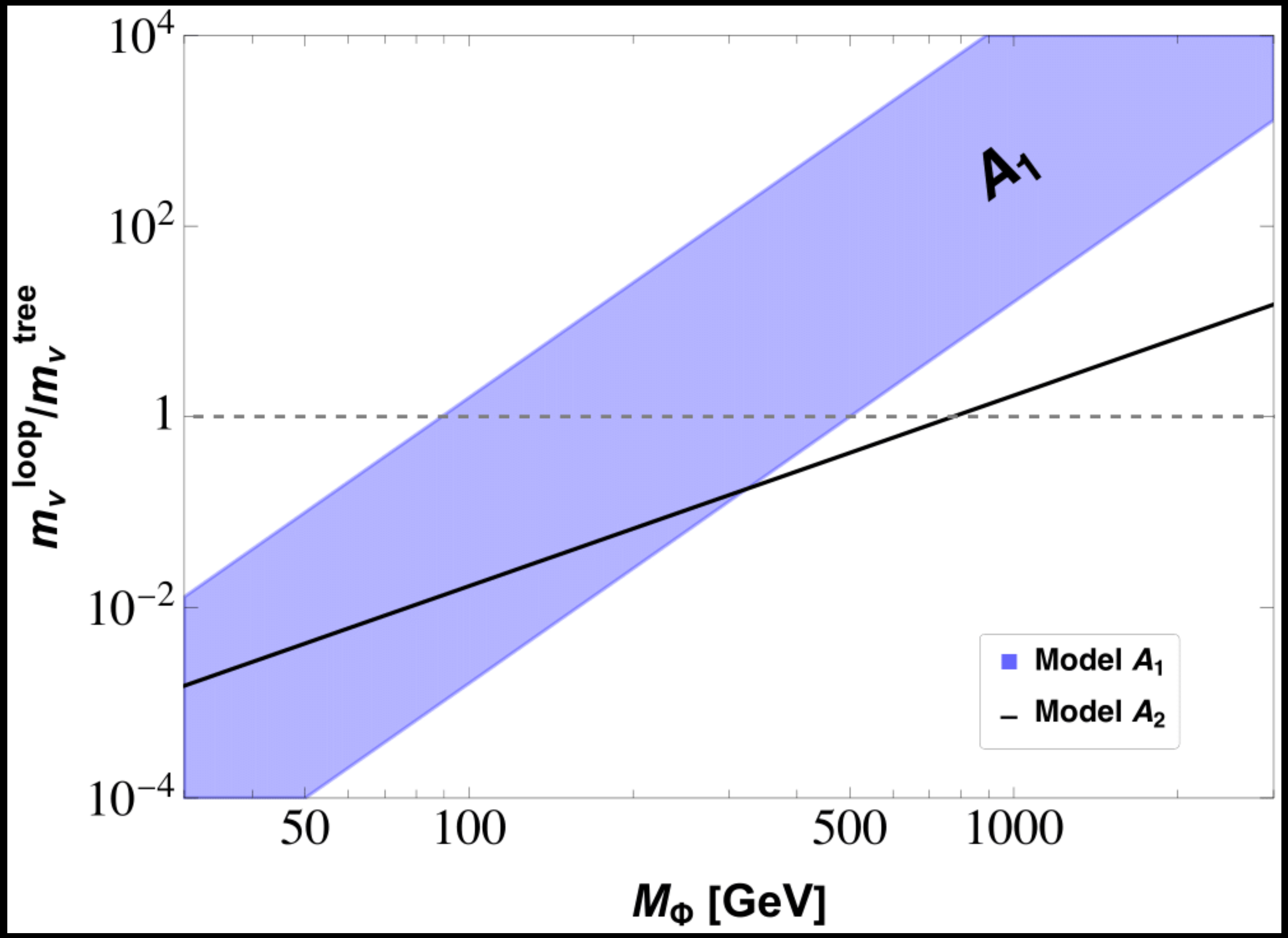
Kumericki, Picek, Radovic (2012); Babu, Nandi, Tavartkiladze (2009); McDonald (2013); Bonnet, Hernandez, Ota, Winter (2009); Cepedello, Hirsch, Helo (2018)

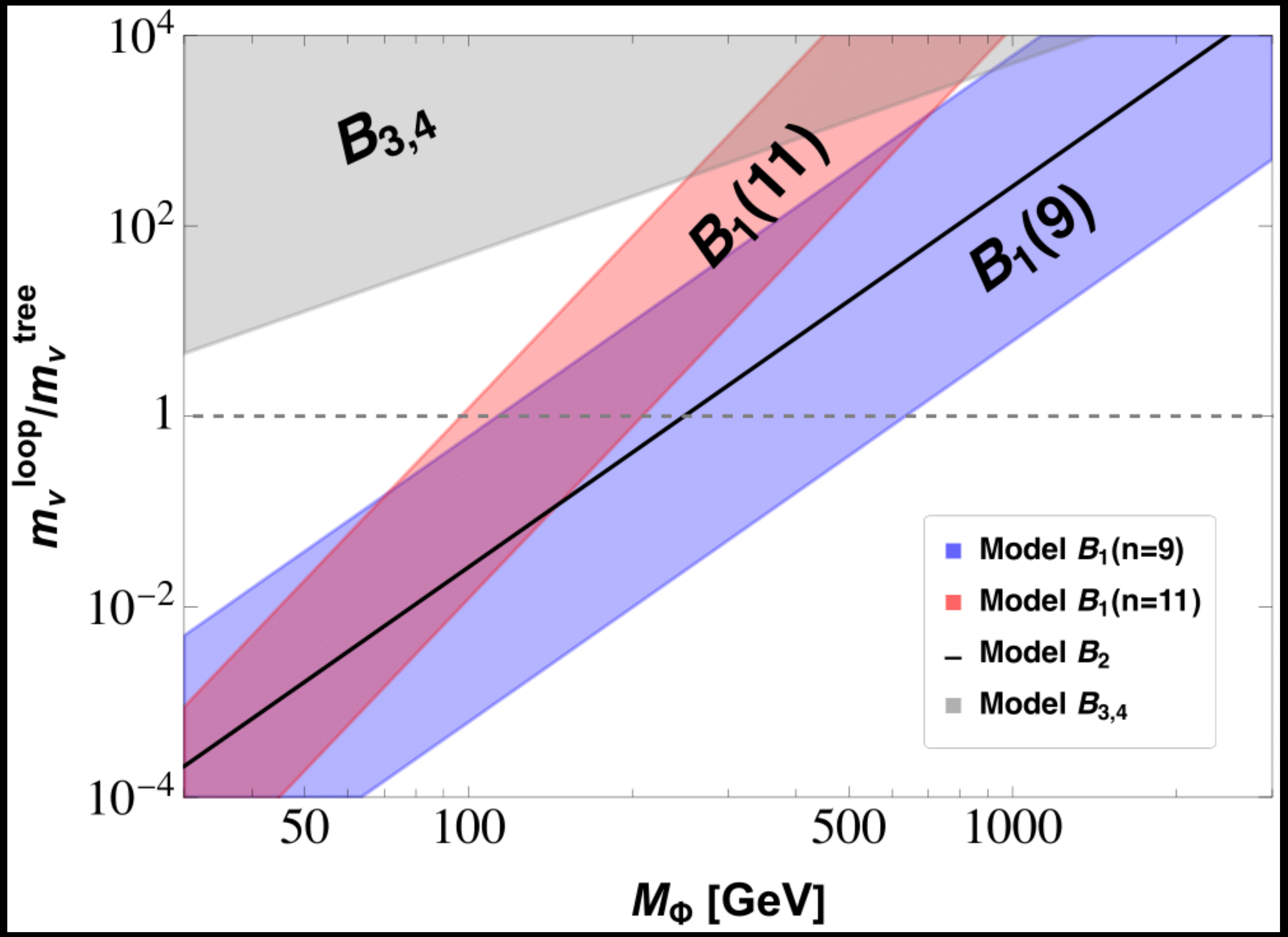
Genuine Models

Loop Contribution

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







Genuine Models

Scotogenic/Generalised Scotogenic Models

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

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

Model	New Fields	Sym.	DM candidates	DM Mass (TeV)
$\mathbf{A}'_1$	$\Phi_1 = 4^S_{-1/2}\,, \Sigma = 5^F_0$	Z_2	$4^S_{-1/2},\ 5^F_0$	$M_{\Phi_1} \approx 3.2, M_\Sigma \approx 10$
$\mathbf{A}'_2$	$\Phi_1 = 4^S_{-3/2}\,, \mathcal{F} = 3^F_{-1}$	$-$	$-$	$-$
$\mathbf{B}'_1$	$\Phi_1 = 4^S_{1/2}\,, \Phi_2 = 4^S_{-3/2}\,, \mathcal{F} = 5^F_{-1}$	$U(1)$	$4^S_{1/2}\,, 4^S_{-3/2}$	$M_{\Phi_1} \approx 3.2, M_{\Phi_2} \approx 3.5$
$\mathbf{B}'_2$	$\Phi_1 = 3^S_0\,, \Phi_2 = 5^S_{-1}\,, \mathcal{F} = 4^F_{-1/2}$	$U(1)$	$3^S_0\,, 5^S_{-1}$	$M_{\Phi_1} \approx 2.5, M_{\Phi_2} \approx 3.4$
$\mathbf{B}'_3$	$\Phi_1 = 5^S_{-2}\,, \Phi_2 = 5^S_1\,, \mathcal{F} = 4^F_{3/2}$	$U(1)$	$5^S_{-2}\,, 5^S_1$	$M_{\Phi_1} \approx 3.9, M_{\Phi_2} \approx 3.4$
$\mathbf{B}'_4$	$\Phi_1 = 5^S_{-1}\,, \Phi_2 = 5^S_0\,, \mathcal{F} = 4^F_{1/2}$	$U(1)$	$5^S_{-1}\,, 5^S_0$	$M_{\Phi_1} \approx 3.4, M_{\Phi_2} \approx 9.4$

Cirelli, Forego, Strumia (2006);
Cirelli, Strumia, Tamburini (2007)

Non-perturbative effects

Genuine Models

Low-scale variants

$M_{\mathcal{F}} \simeq \mathcal{O}(1)$ TeV

A1: Majorana mass → Inverse seesaw

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

$$\left(\frac{y_1 v_1}{10^{-8}\ \text{GeV}}\right)\left(\frac{y_2 v_2}{\text{GeV}}\right) \simeq 1, M_{\mathcal{F}} \simeq \text{TeV}$$

Significant Yukawas → Large contribution to $D = 6$ operators

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

LFV, Modified couplings of Z/W to leptons, Non-unitary PMNS, FCNCs, Universality violation

Scalar Sector

Bounds on VEVs

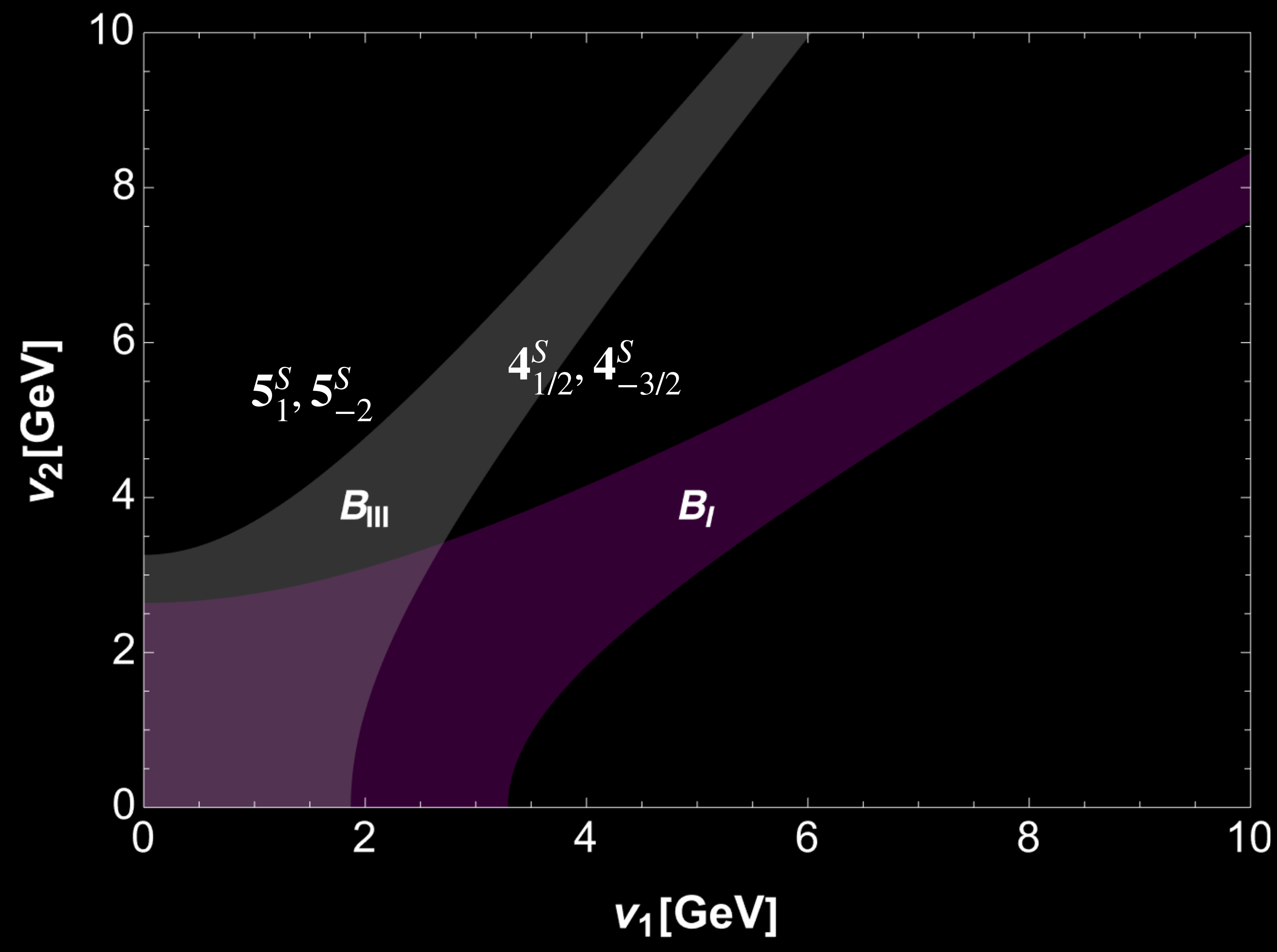
New SU(2) scalar multiplets → Violate Custodial symmetry → Contribute to $\rho \to \rho \neq 1$

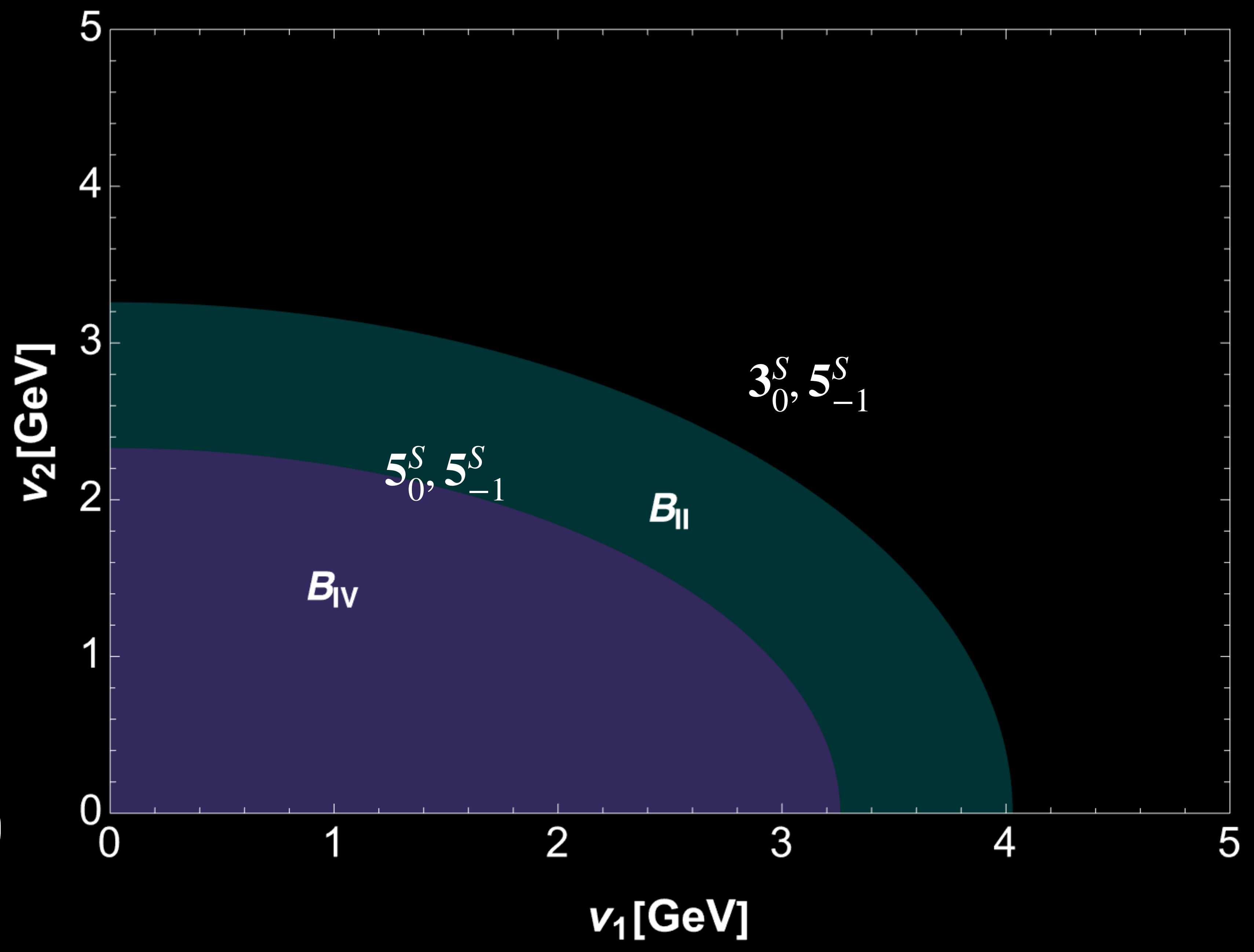
Electroweak precision measurements → $\Delta\rho = \rho - 1 \ll 1$

Class A models: $v_i < \mathcal{O}(\mathrm{GeV}) \ll v$

$$\sqrt{\frac{\mathbf{N_i}^2 - 1}{12}} > |Y_i|$$

Holds for only 1 scalar





$$\sqrt{\frac{\mathbf{N_i}^2 - 1}{12}} > |Y_i|$$

Holds for both scalars

Scalar Sector

Induced VEVs

New VEVs induced by the Higgs doublet → Naturally suppressed for $M_\Phi \gg v$

$\mu\, \Phi_i H^2$

$$v_i \simeq \mu \frac{v^2}{2m_{\Phi_i}^2}$$

Present for triplets: Model B2

$\lambda\, \Phi_i H^3$

$$v_i \simeq \lambda \frac{v^3}{2m_{\Phi_i}^2}$$

Present for quadruplets: Models A1 & A2, B1

$\lambda''\, \Phi_i \Phi_j H^2$

$$v_j \simeq \lambda v_i \frac{v^2}{2m_{\Phi_j}^2}$$

Present for all B type models

Models with just quintuplets → Both VEVs cannot be naturally suppressed

New scalars get induced VEVs → Integrate out the heavy scalars → Higher dimensional operators

Scalar Sector

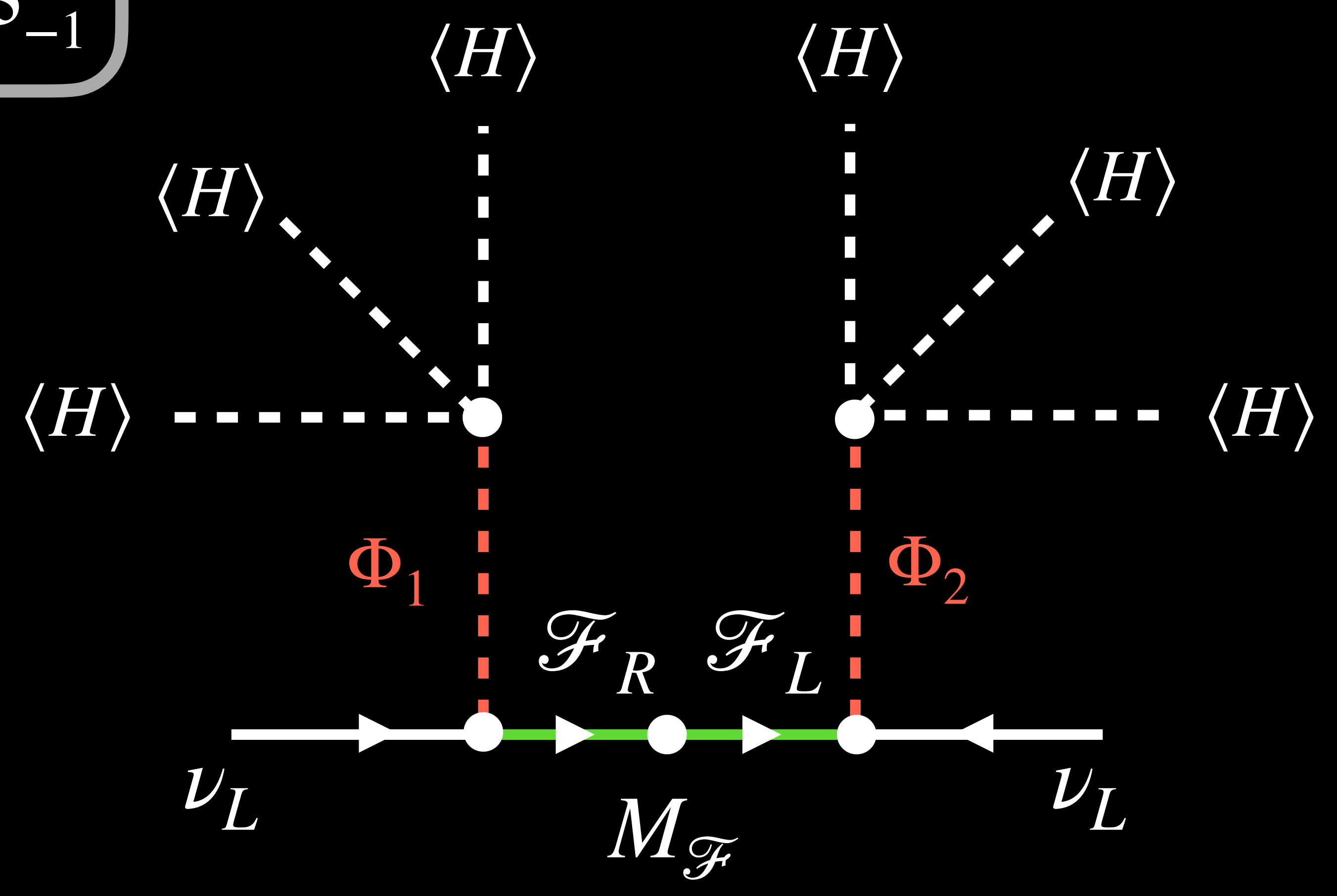
Induced VEVs

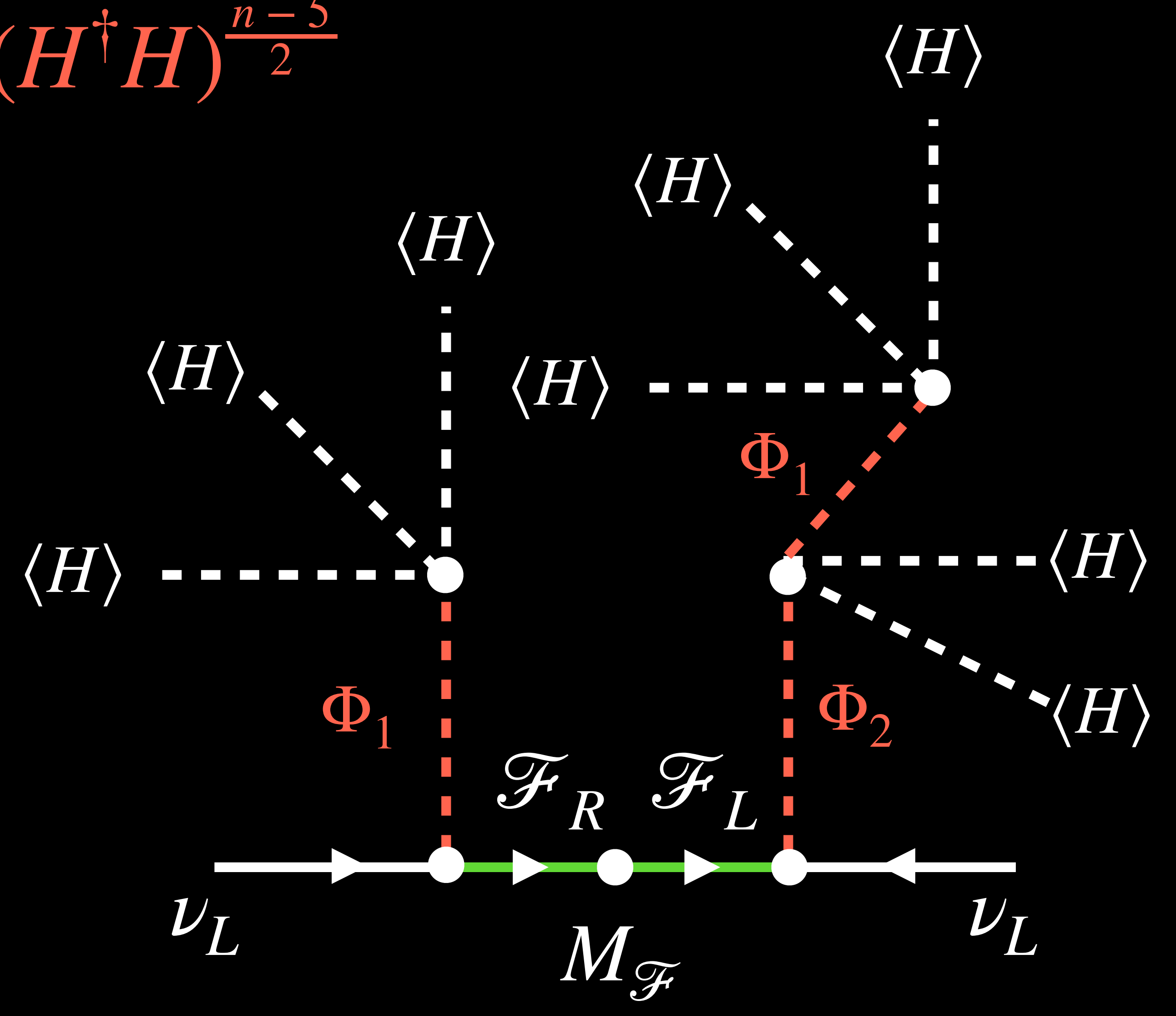
New scalars get induced VEVs → Integrate out the heavy scalars → Higher dimensional operators ($n > 5$)

$$\mathcal{O}_n^{(0)} = (LH)_{\mathbf{1}}(LH)_{\mathbf{1}}(H^\dagger H)^{\frac{n-5}{2}}$$

$\mathbf{B_I}: \mathbf{4}^S_{1/2}, \mathbf{4}^S_{-3/2}, \mathbf{5}^F_{-1}$

$n = 9$





$n = 11$

$$(m_\nu)_{\alpha\beta} \sim \lambda^2 \frac{v^6}{4m^2_{\Phi_1} m^2_{\Phi_2}} \left(y_1 M^{-1}_{\mathcal{F}} y_2^T + y_2 M^{-1}_{\mathcal{F}} y_1^T\right)_{\alpha\beta}$$

$$(m_\nu)_{\alpha\beta} \sim \lambda^2 \lambda'' \frac{v^8}{8m^4_{\Phi_1} m^2_{\Phi_2}} \left(y_1 M^{-1}_{\mathcal{F}} y_2^T + y_2 M^{-1}_{\mathcal{F}} y_1^T\right)_{\alpha\beta}$$

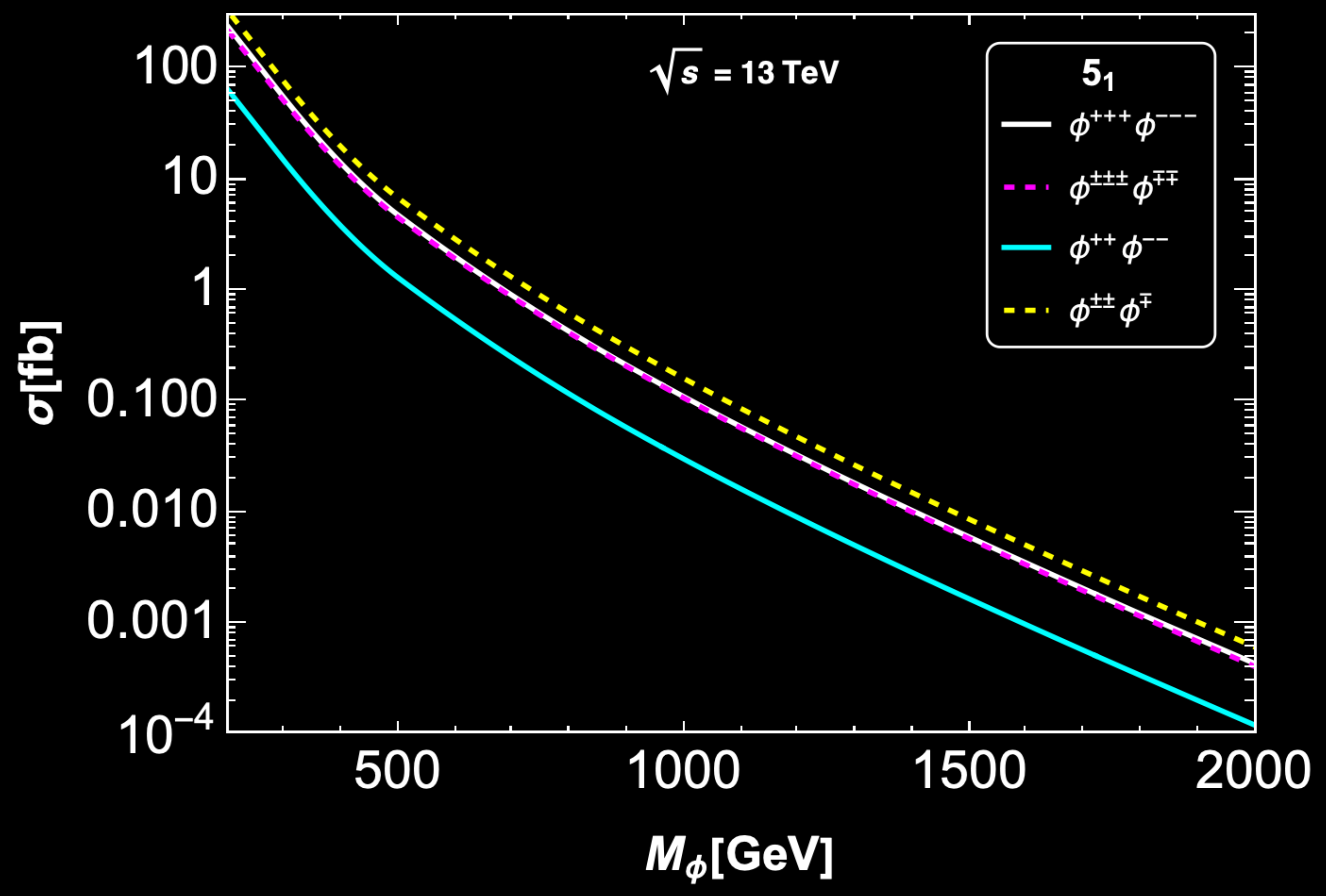
Collider Phenomenology

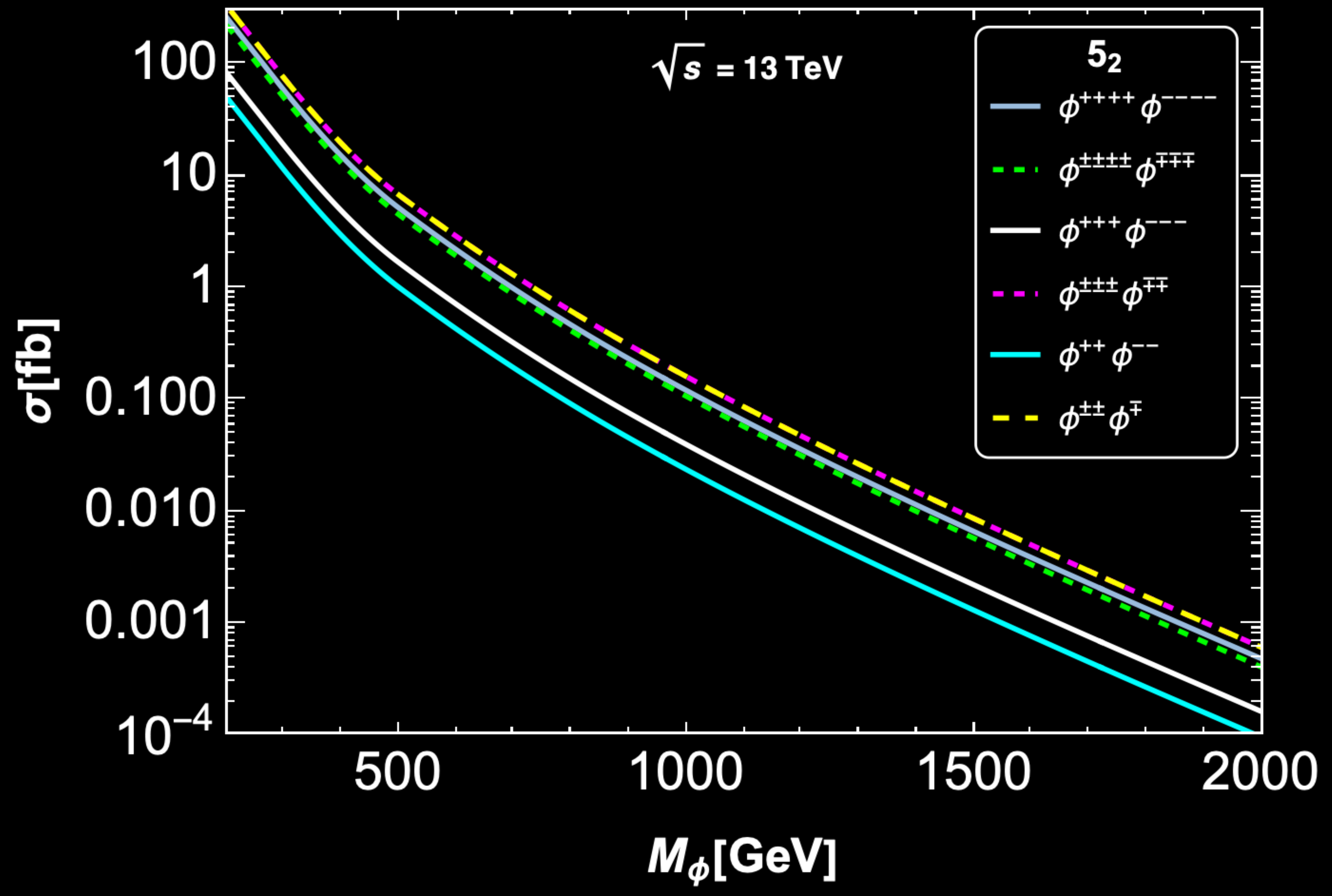
Production of multi-charged scalars

Pair production and Associated production at the LHC

$$q\bar{q} \to \gamma, Z \to \Phi^{\pm\pm\pm\pm}\Phi^{\mp\mp\mp\mp}, \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp}, \Phi^{\pm\pm}\Phi^{\mp\mp}, \Phi^{\pm}\Phi^{\mp}$$

$$q\bar{q}' \to W^{\pm} \to \Phi^{\pm\pm\pm\pm}\Phi^{\mp\mp\mp}, \Phi^{\pm\pm\pm}\Phi^{\mp\mp}, \Phi^{\pm\pm}\Phi^{\mp}$$



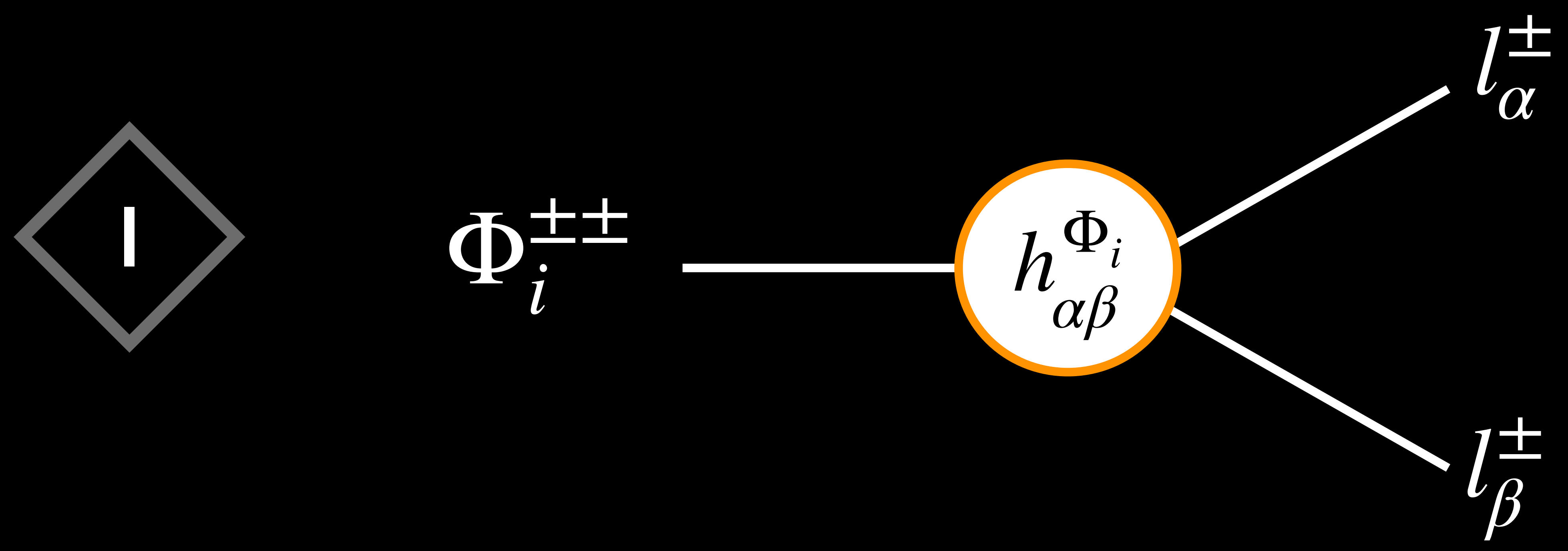


Collider Phenomenology

Doubly-charged scalar decays

$LL\Phi_i\Phi_j$ → $\nu\nu\Phi_i^0\Phi_j^0$ — Leads to m_ν

$LL\Phi_i\Phi_j$ → $l^\pm l^\pm \Phi_i^{\pm\pm}\Phi_j^0$ — Effective interaction between doubly charged scalars and a pair of leptons



$$h_{\alpha\beta}^{\Phi_i} = \kappa_i \frac{(m_\nu)_{\alpha\beta}}{v_i}$$

$(m_\nu)_{\alpha\beta}$ → $c_5 v_i v_j / \Lambda$

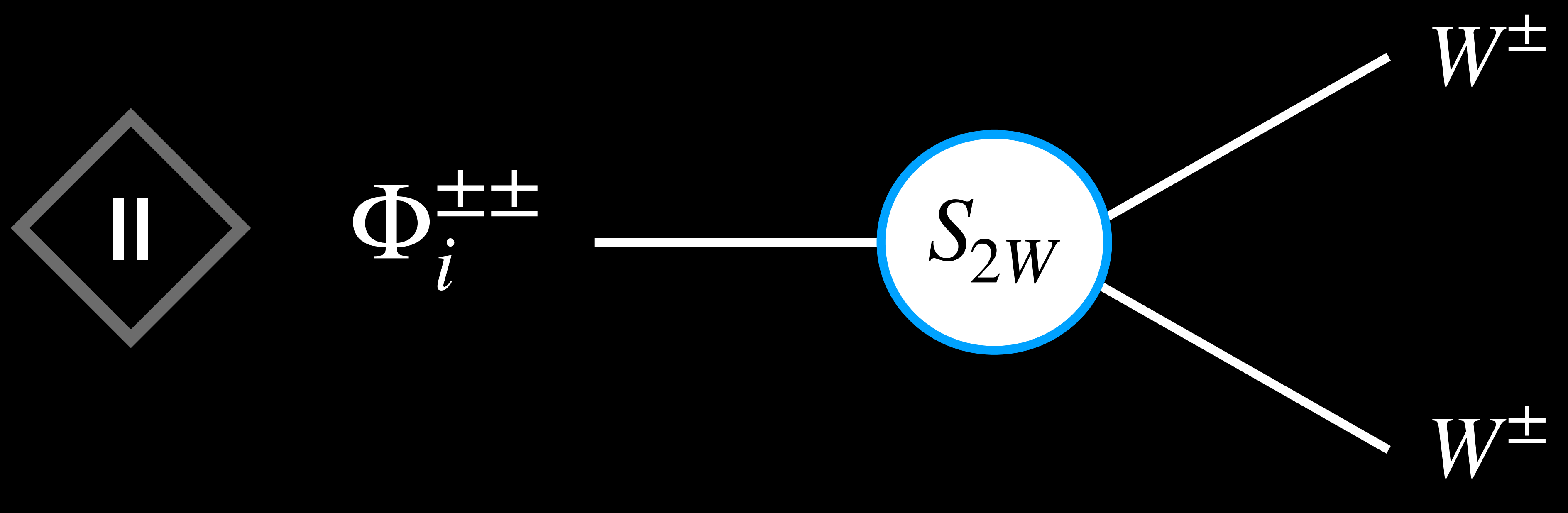
Decays suppressed for large v_i

Decays of doubly charged scalars → Same-sign Dilepton signatures

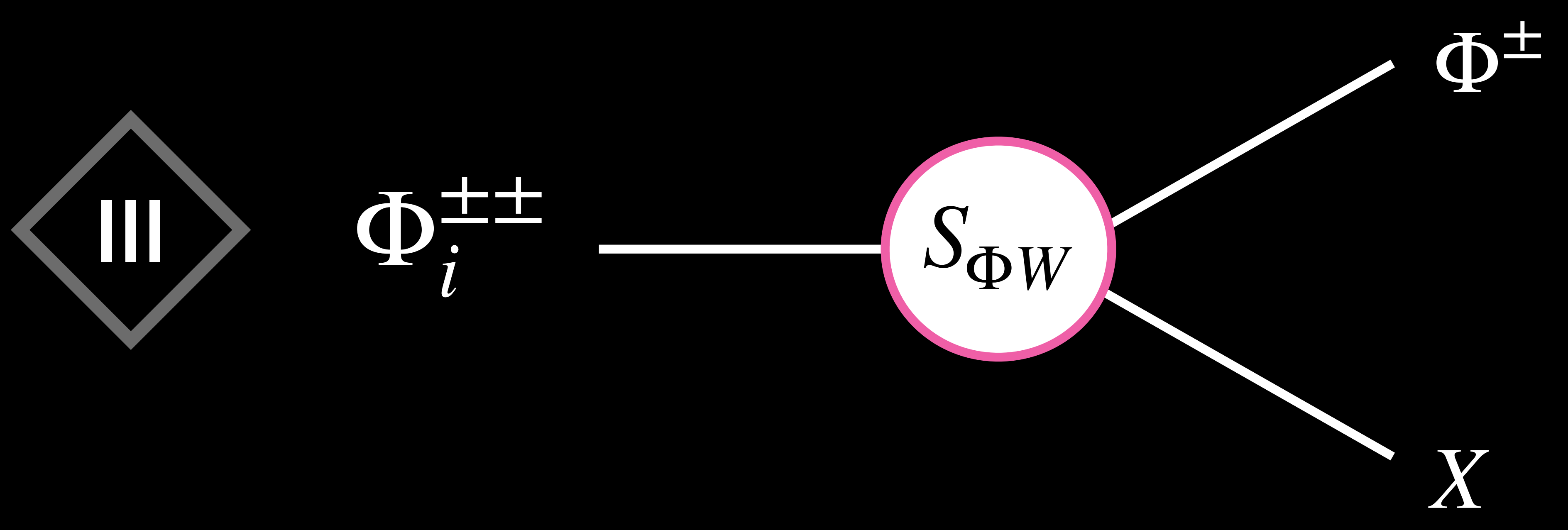
Free of SM background

Collider Phenomenology

Doubly-charged scalar decays



Proportional to v_i^2
Dominant channel for large VEVs



$\Phi^{\pm\pm} \rightarrow \Phi^\pm \pi^\pm$

$\Phi^{\pm\pm} \rightarrow \Phi^\pm l^\pm \nu_l$

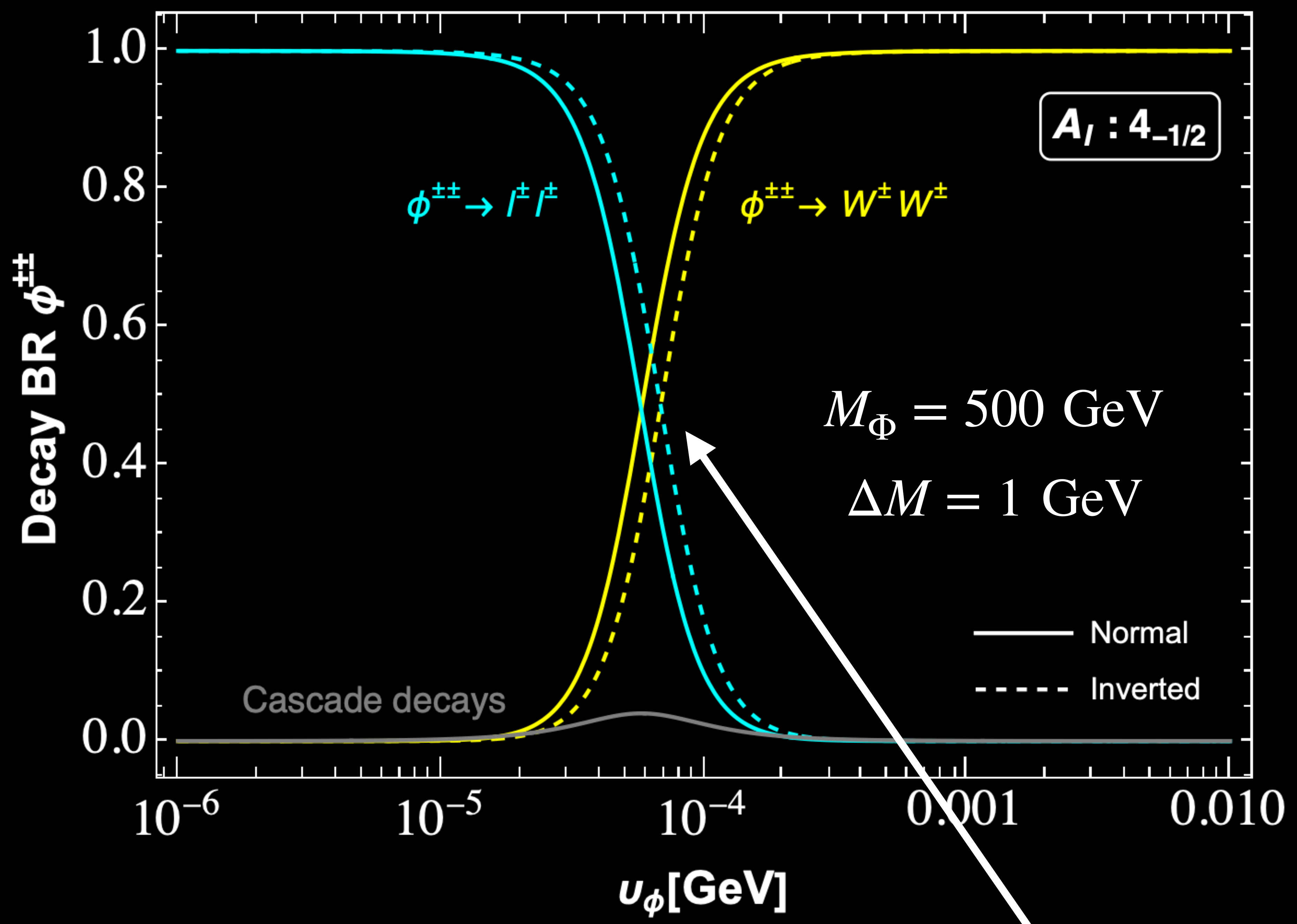
$\Phi^{\pm\pm} \rightarrow \Phi^\pm q\bar{q}'$

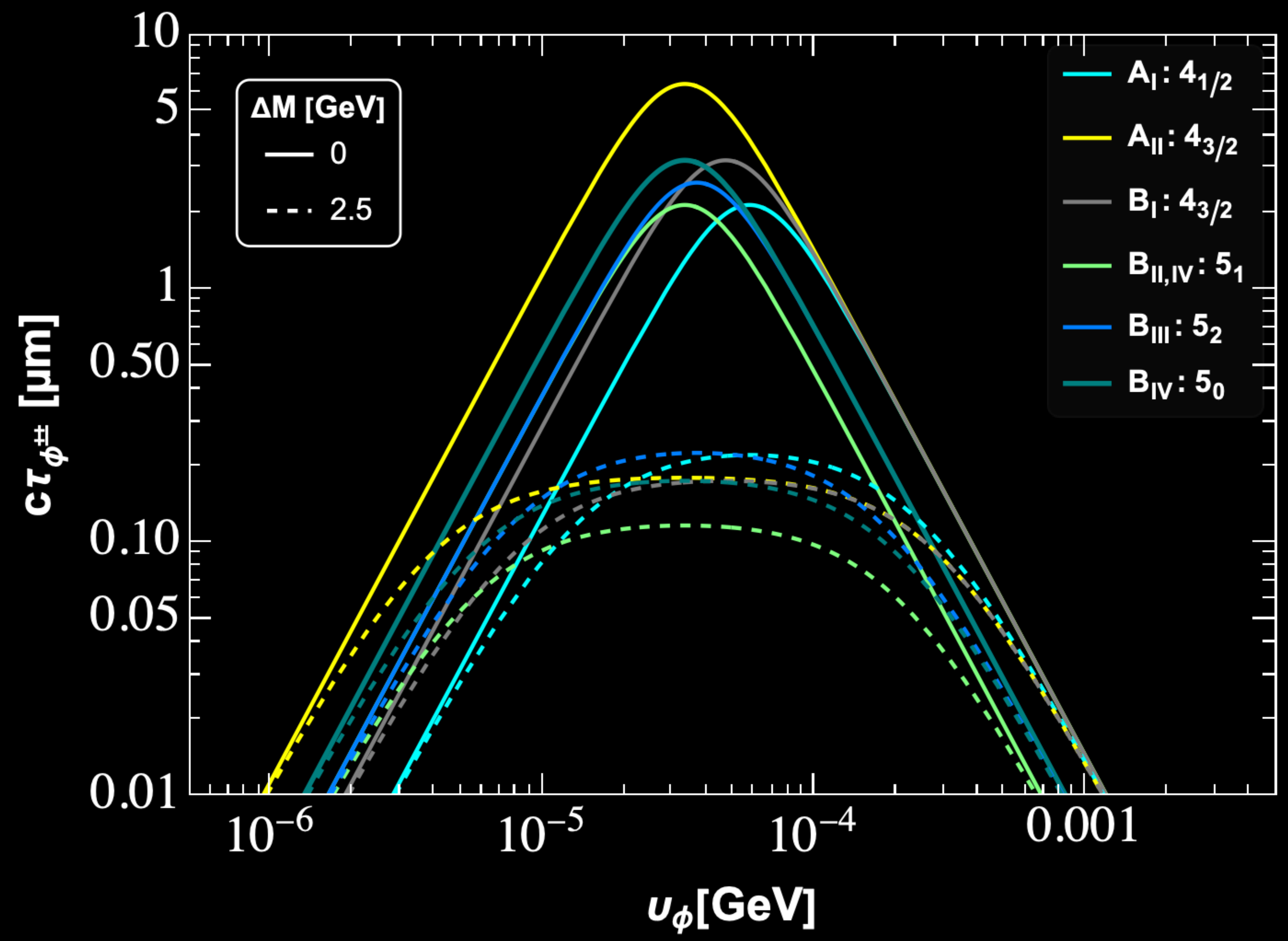
Cascade decays

Proportional to ΔM, the scalar mass splitting

Collider Phenomenology

Doubly-charged scalar decays





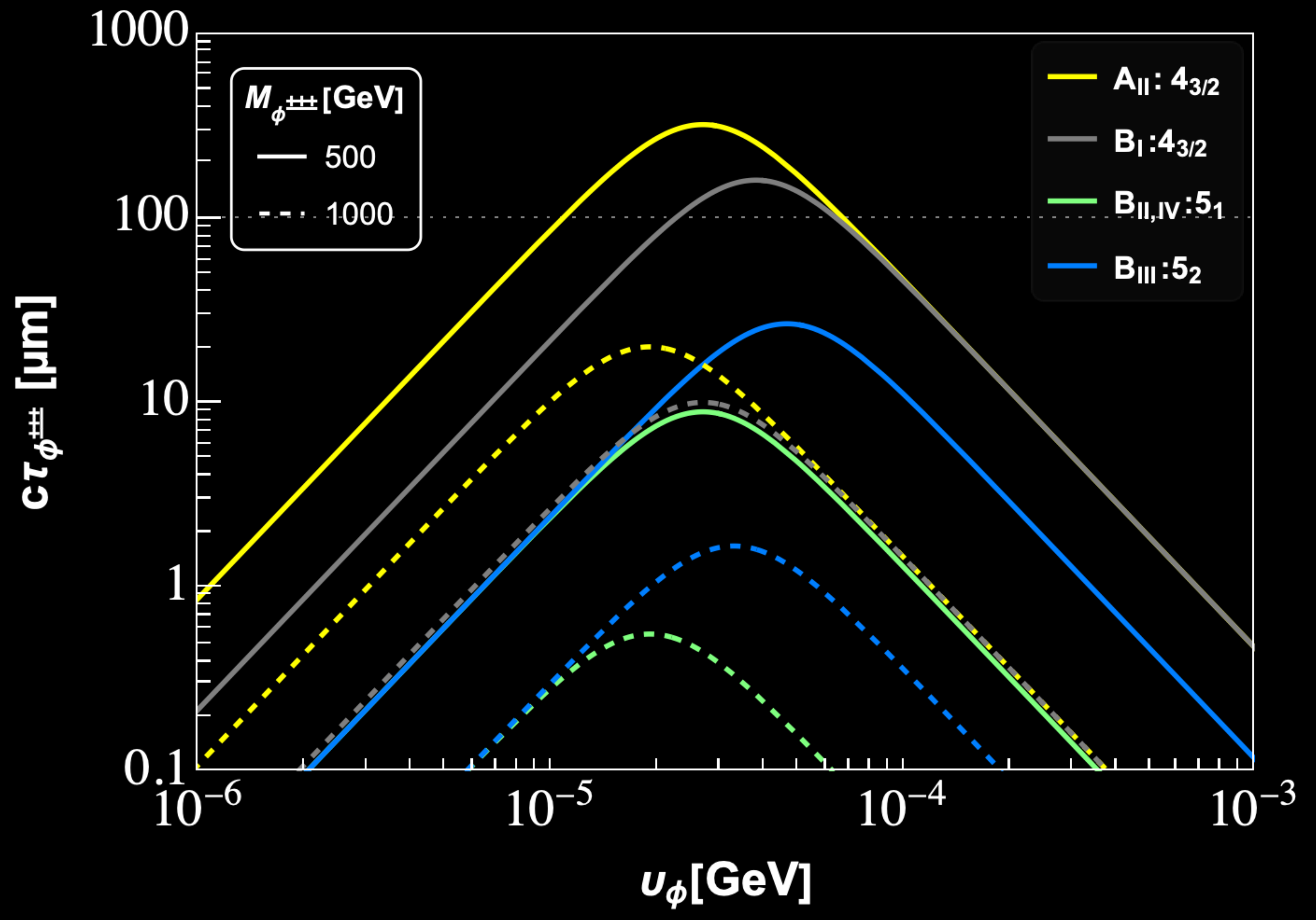
Crossover VEV → Decay length maximised → No signal for displaced vertices

$< \mathcal{O}(100\mu\text{m})$

Collider Phenomenology

Triply/Quadruply-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)

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

4 body decays → Phase space suppression → Smaller decay widths

$$\Gamma_{\rm tot}(\Phi^{\pm\pm\pm\pm}) \sim \Gamma_{\rm tot}(\Phi^{\pm\pm\pm})\frac{f(3)}{f(4)}\frac{g^2M^2_{\Phi^{\pm\pm\pm\pm}}}{M_W^2} \simeq 0.017\left(\frac{M_{\Phi^{\pm\pm\pm\pm}}}{500\ \mathrm{GeV}}\right)^2\Gamma_{\rm tot}(\Phi^{\pm\pm\pm})$$

Phase space suppression: $f(n) = 4\,(4\pi)^{2n-3}\,(n-1)!(n-2)!$

Displaced vertices at the LHC for $M_{\Phi} < \mathcal{O}(1)$ TeV

Arbeláez, Helo, Hirsch (2019)

Collider Phenomenology

Signatures

Production + Decays of multi-charged scalars and $W^{\pm}$ → Signatures of new physics at the LHC

Observation of $l^{\pm}l^{\pm}W^{\mp}W^{\mp}$ events → Experimental evidence of LNV

Aguila, Chala, Santamaria, Wudka (2013)

Diagonal/Off-diagonal elements of $(m_{\nu})_{ij}$ → LFV 4-lepton events $l_i^{\pm}l_i^{\pm}l_j^{\mp}l_j^{\mp}$; $l_i^{\pm}l_j^{\pm}l_j^{\mp}l_j^{\mp}(i \neq j)$

Decays	$\Phi^{2-} \to 2l^-$	$\Phi^{2-} \to 2W^-$	$\Phi^{3-} \to 2l^-W^-$	$\Phi^{3-} \to 3W^-$	$\Phi^{4-} \to 2l^-2W^-$	$\Phi^{4-} \to 4W^-$
$\Phi^{2+} \to 2l^+$	$2l^+2l^-$	$2l^+2W^-$	$2l^+2l^-W^-$	$2l^+3W^-$	✘	✘
$\Phi^{2+} \to 2W^+$	$2W^+2l^-$	$2W^+2W^-$	$2W^+W^-2l^-$	$2W^+3W^-$	✘	✘
$\Phi^{3+} \to 2l^+W^+$	$2l^+2l^-W^+$	$2l^+2W^-W^+$	$2l^+2l^-W^+W^-$	$2l^+3W^-W^+$	$2l^+2l^-2W^-$	$2l^+4W^-W^+$
$\Phi^{3+} \to 3W^+$	$3W^+2l^-$	$3W^+2W^-$	$2l^-3W^+W^-$	$3W^+3W^-$	$2l^-3W^+2W^-$	$3W^+4W^-$
$\Phi^{4+} \to 2l^+2W^+$	✘	✘	$2l^+2l^-2W^+W^-$	$2l^+2W^+3W^-$	$2l^+2l^-2W^+2W^-$	$2l^+2W^+4W^-$
$\Phi^{4+} \to 4W^+$	✘	✘	$2l^-4W^+W^-$	$4W^+3W^-$	$2l^-4W^+2W^-$	$4W^+4W^-$

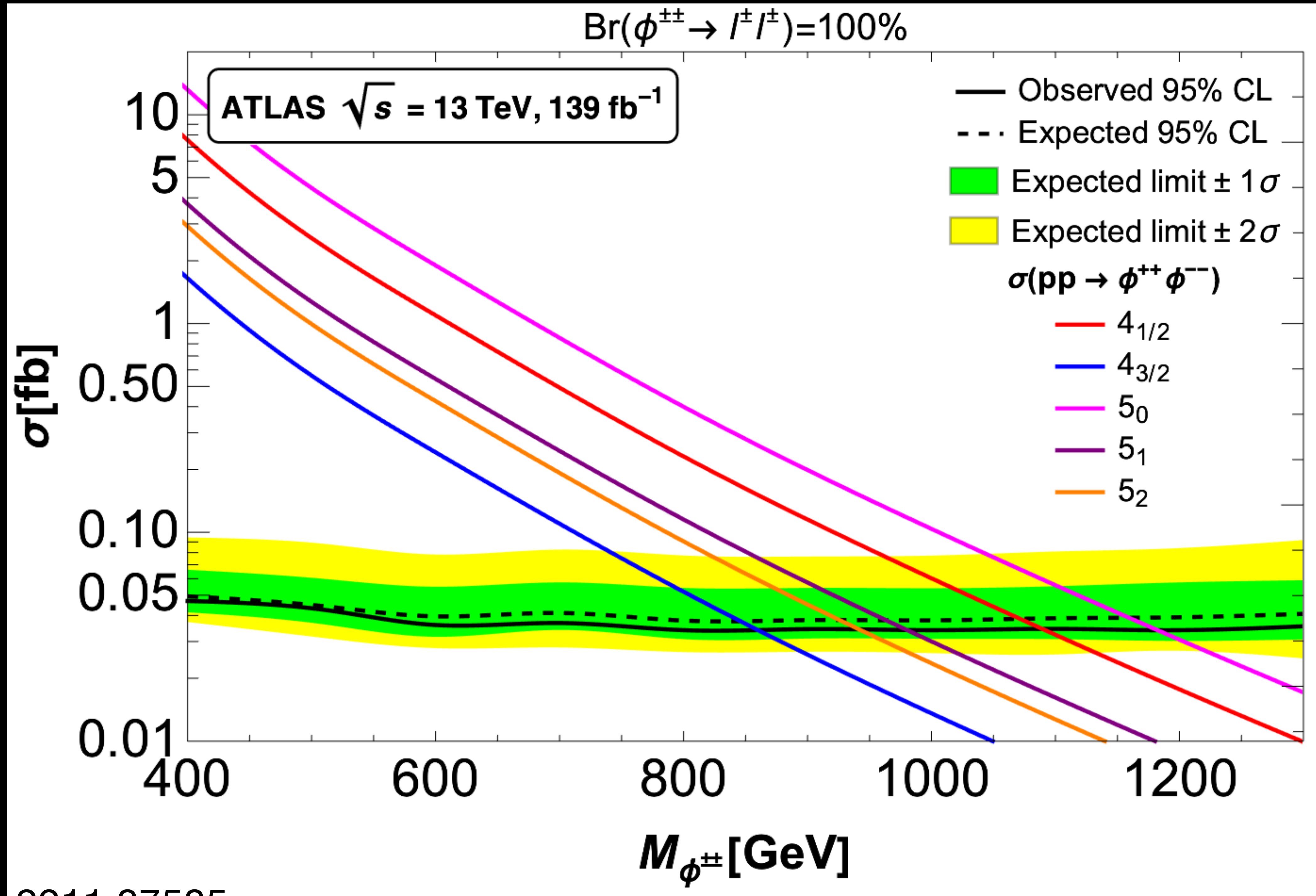
Bambhaniya, Chakrabortty, Goswami Konar (2013); Ghosh, Jana, Nandi (2018)

0-8 lepton events: SS2L, SS3L and SS4L

Collider Phenomenology

Searches for Doubly-charged scalars

ATLAS & CMS search for doubly-charged scalars in multi-lepton final states



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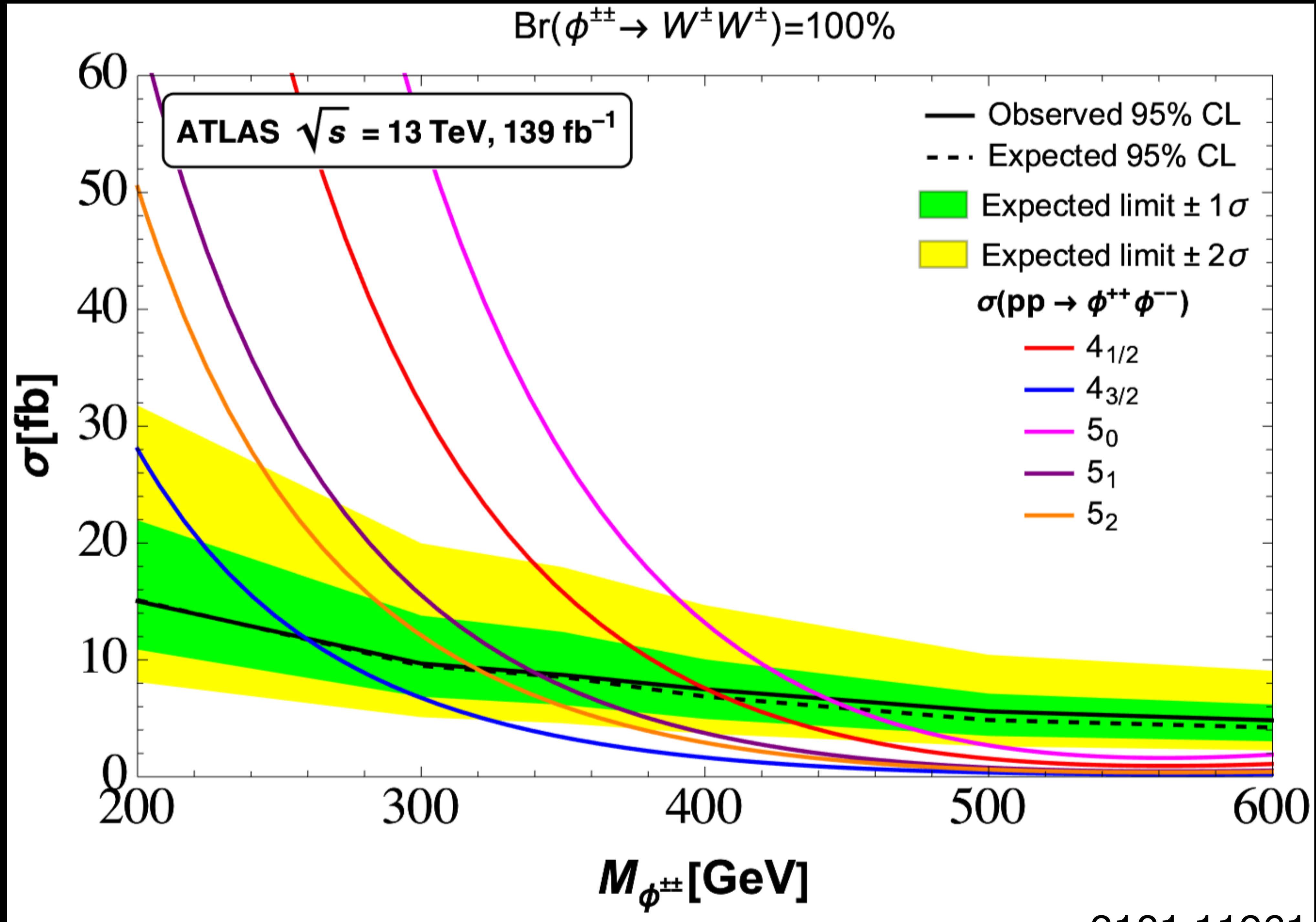

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Electroweak Precision Tests

At Loop-level

New SU(2) multiplets → Modify the oblique parameters S, T, U

Peskin, Takeuchi (1992); Lavoura, Li (1994)

Custodial symmetry broken → Complications with computation of S,T,U at one-loop level

Jegerlehner (1991); Gunion, Vega, Wudka (1991); Albergaria, Lavoura (2022)

Corrections to W-boson mass $m_W \simeq m_W^{\rm SM}\left[1 - \frac{\alpha}{4(1-2s_W^2)}(S - 2(1-s_W^2)T)\right]$

Maksymyk, Burgess, London (1994)

	PDG 2022	CDF 2022
S	-0.01 ± 0.07	0.14 ± 0.08
T	0.04 ± 0.06	0.26 ± 0.06
ρ_{ST}	0.92	0.93

Assumptions

New scalar VEVs $v_i \ll v$ → Taken to be negligible

Scalars do not mix among themselves or with other scalars

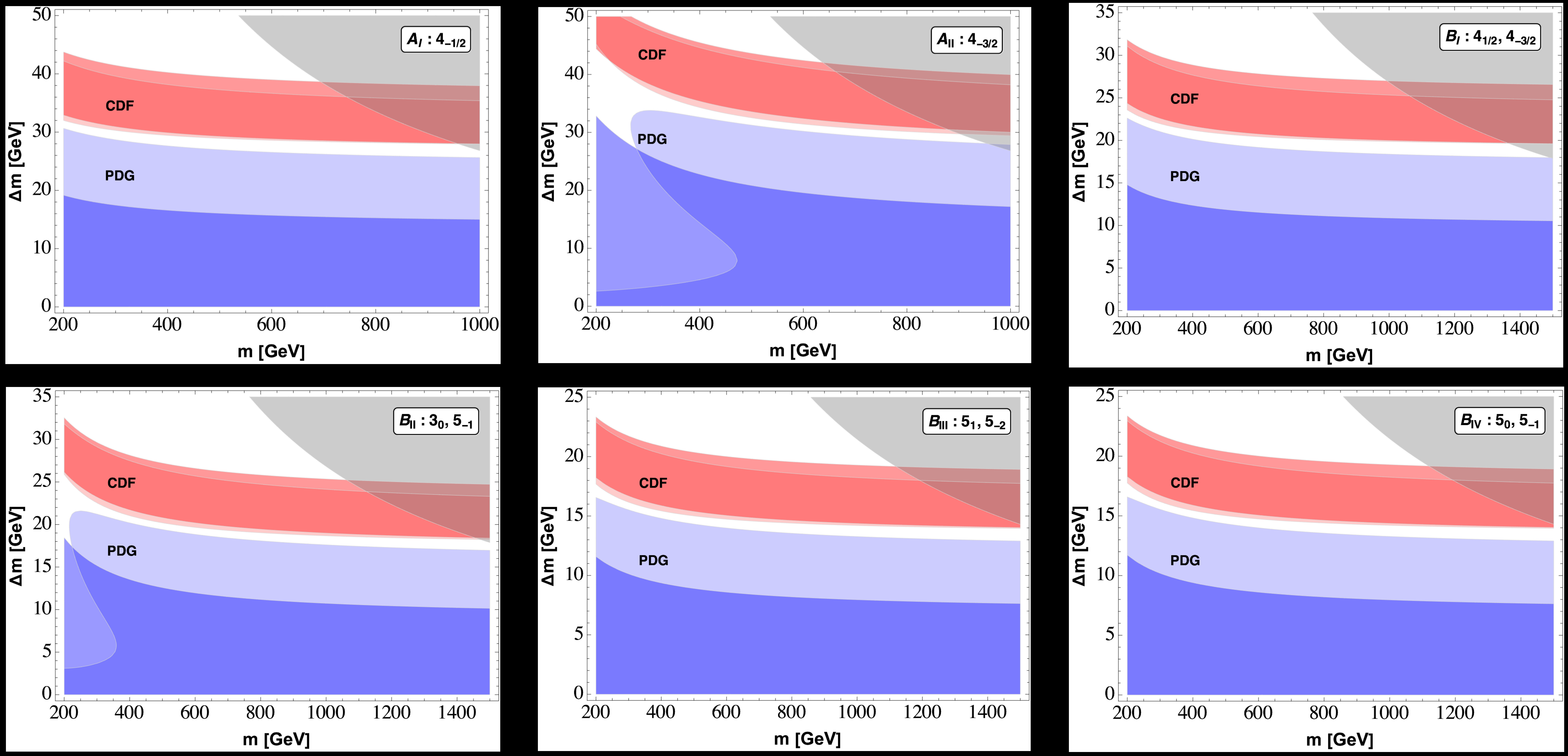
Take U = 0 → Improves the precision on S and T

$$\Phi = (\Phi_I, \Phi_{I-1}, \ldots, \Phi_{-I})^T \quad M_{\Phi_{-I}} = m, M_{\Phi_{-I+1}} = m + \Delta m, \ldots, M_{\Phi_I} = m + 2I\,\Delta m$$

Electroweak Precision Tests

At Loop-level

2 parameter χ^2 analysis



$$\Delta m \sim \mathcal{O}(0.1)\,\lambda\,\frac{v^2}{m}$$

Conclusions

New scalar multiplets at EW scale $\rightarrow$ New Weinberg-like operators

New scalar VEVs suppressed $\rightarrow$ Neutrino masses can be generated for lower LNV scales

EW scalars $\rightarrow$ Production at colliders, contribution to W-boson mass

Collider signatures $\rightarrow$ SS2L, SS3L, SS4L, LNV + LFV events

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

Backup

Neutrino masses

The Weinberg Operator: *LLHH*

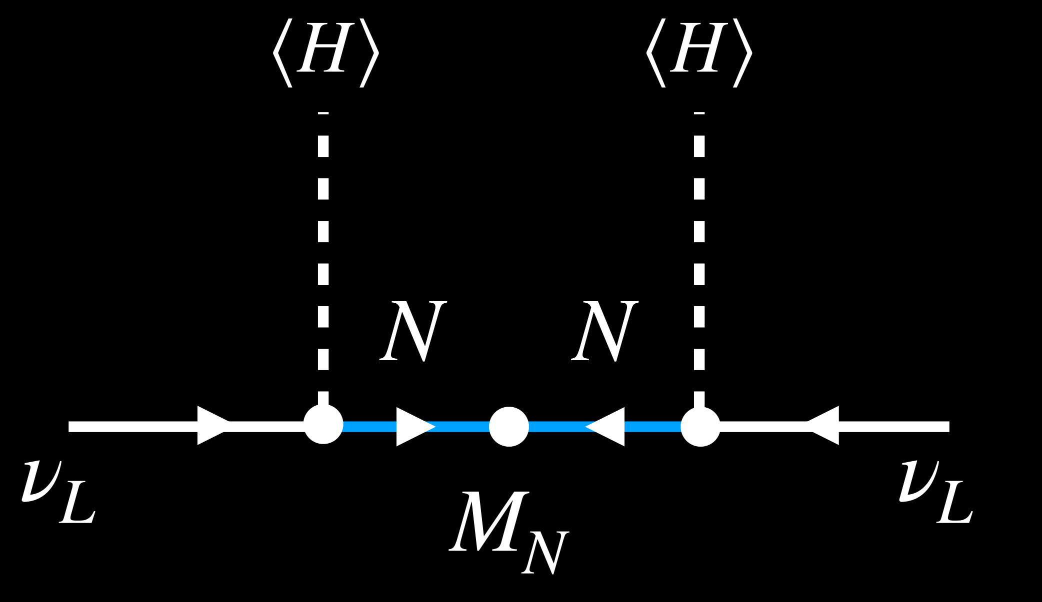
$\mathcal{O}^{(0)}_{5,a} = (HL)_{\mathbf{1}}(HL)_{\mathbf{1}}$

$\mathcal{O}^{(0)}_{5,c} = (HH)_{\mathbf{3}}(LL)_{\mathbf{3}}$

$\mathcal{O}^{(0)}_{5,b} = (HL)_{\mathbf{3}}(HL)_{\mathbf{3}}$

UV completions at the tree level → Usual Seesaws

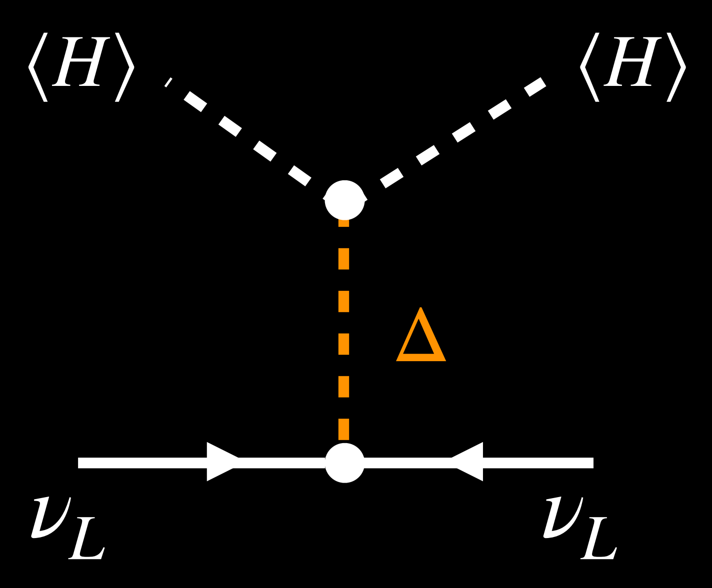
Fermion singlet: N



I

Minkowski (1977); Yanagida (1980); Gell-Mann, Raymond, Slansky (1979), Mohapatra, Senjanovic (1980)

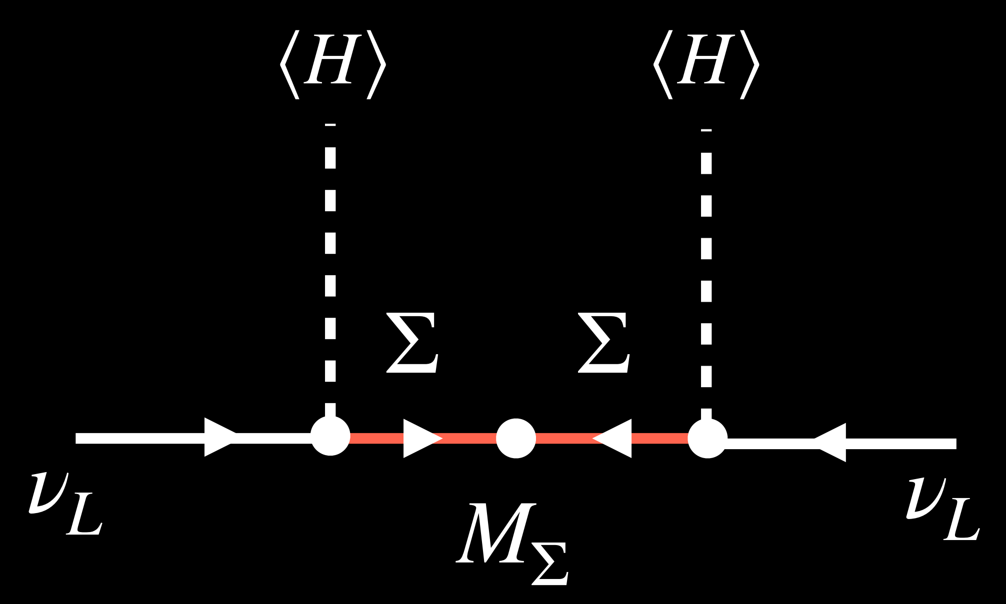
Scalar triplet: Δ



II

Schechter, Valle (1980); Lazarides, Shafi, Wetterich (1981); Mohapatra, Senjanovic (1981)

Fermion triplet: Σ



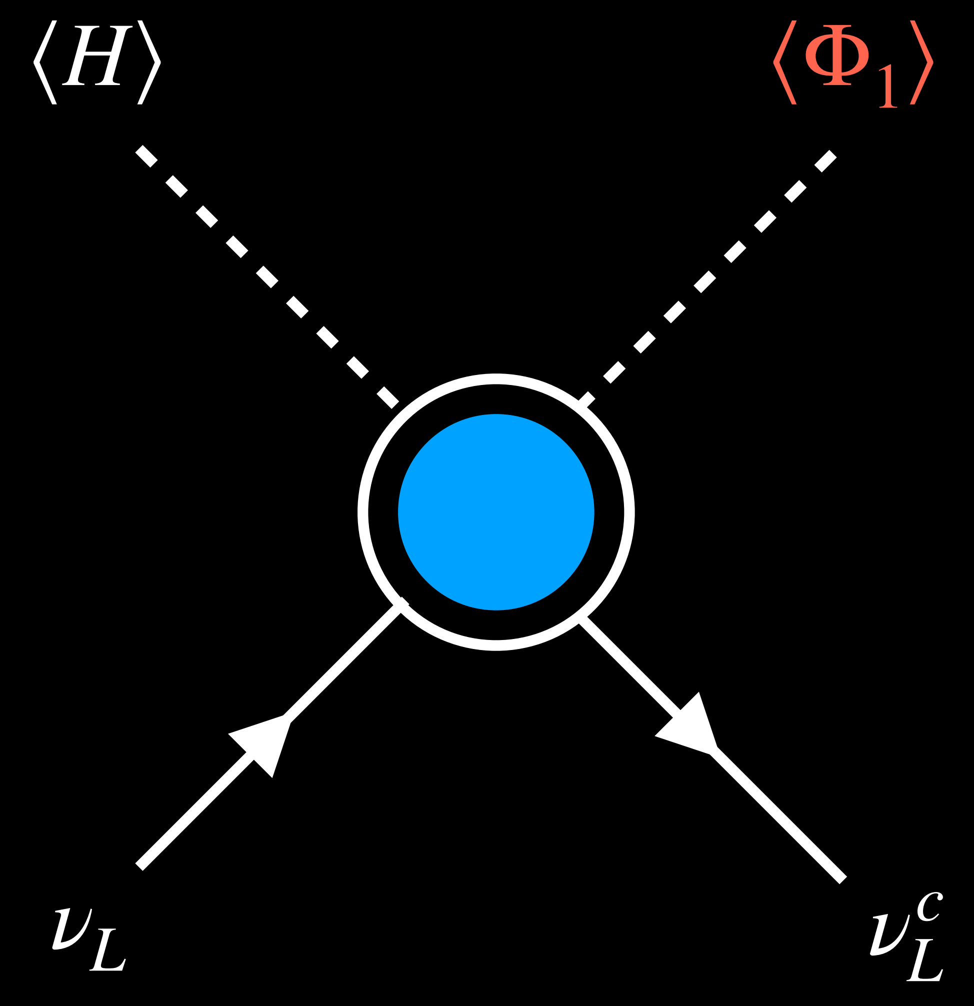
III

Foot, Lew, He, Joshi (1989)

New Weinberg-like Operators

Extensions with 1 Scalar multiplet

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



Possible SU(2) representations for Φ_1

$$H L_\alpha L_\beta \sim \mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2} = \mathbf{4} \oplus \mathbf{2} \oplus \mathbf{2}'$$

$\mathbf{4}^S_{\pm 1/2}$ **Quadruplet** $\mathbf{4}^S_{\pm 3/2}$

Doublet $\mathbf{2}^S_{\pm 1/2}$

Recovers 2HDM

UV completions:
Usual seesaws

UV Completions

$(LH)_{\mathbf{1,3}}(L\Phi_i)_{\mathbf{3,5}}$

Fermion triplet

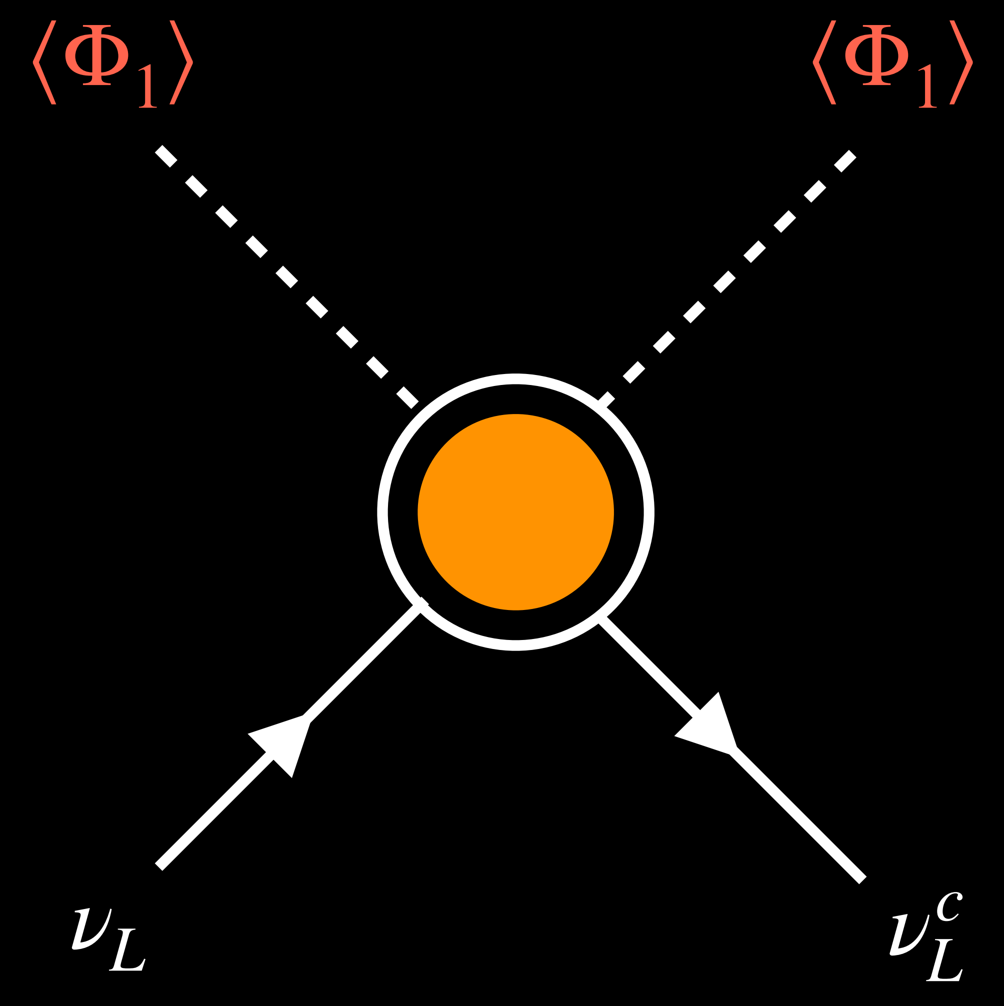
$(LL)_{\mathbf{1,3}}(H\Phi_i)_{\mathbf{1,3,5}}$

Scalar triplet,
~~Scalar Singlet~~

New Weinberg-like Operators

Extensions with 1 Scalar multiplet

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



Possible SU(2) representations for Φ_1

$(2\mathbf{N}, \pm 1/2),\ 1 < \mathbf{N} \leq 2$

Doublet $\mathbf{2}^S_{\pm 1/2}$

Recovers 2HDM

UV completions:
Usual seesaws

Quadruplet $\mathbf{4}^S_{\pm 1/2}$

UV Completions

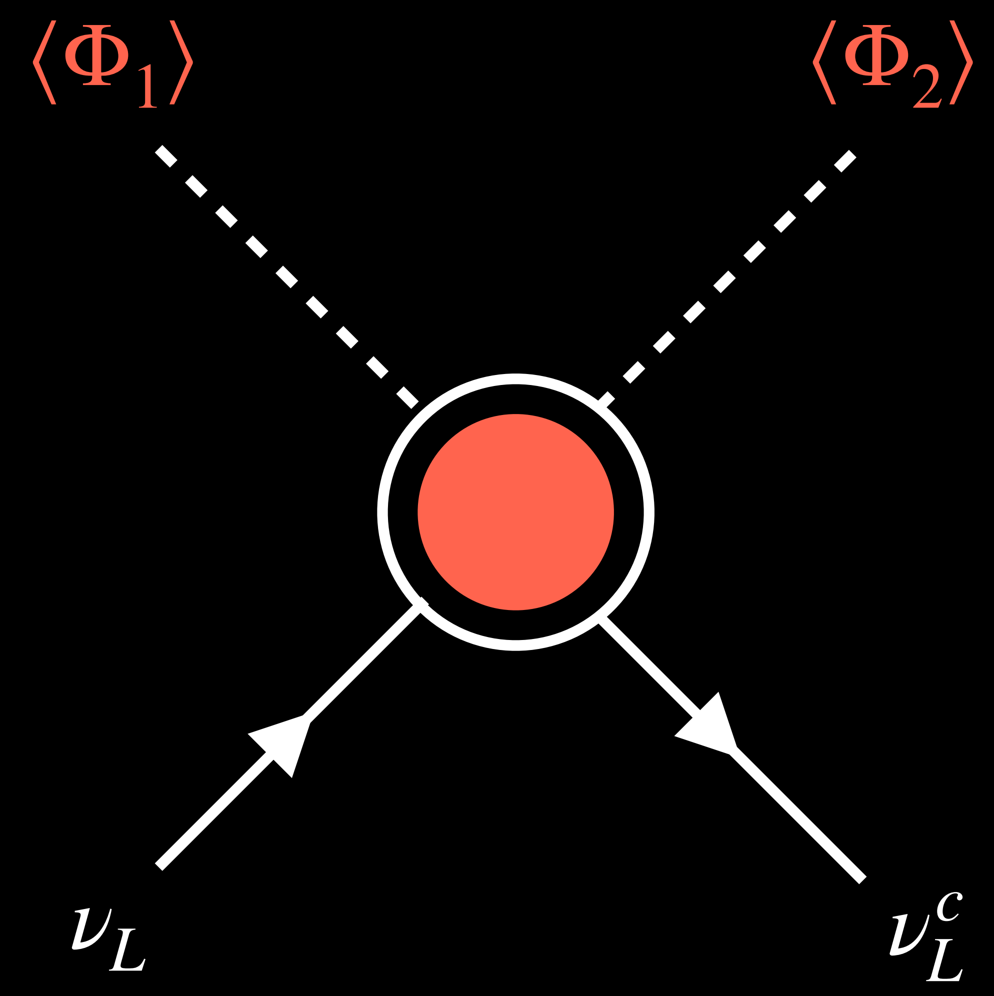
$(L\Phi_i)_{\mathbf{3,5}}(L\Phi_i)_{\mathbf{3,5}}$
Fermion triplet
Fermion quintuplets

$(LL)_{\mathbf{1,3}}(\Phi_i\Phi_i)_{\mathbf{1,3,5,7}}$
Scalar triplet,
~~Scalar Singlet~~

New Weinberg-like Operators

Extensions with 2 Scalar multiplets

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



Possible SU(2) representations for Φ_1 and Φ_2: $(\mathbf{N_1}, Y_1)$, $(\mathbf{N_2}, Y_2)$

$\mathbf{N_1} \otimes \mathbf{N_2} \subset \mathbf{1}$ or $\mathbf{N_1} \otimes \mathbf{N_2} \subset \mathbf{3}$ $\quad |Y_1 + Y_2| = 1$

$\mathbf{N_1} = \mathbf{N_2}$

$\mathbf{2}^S_{\pm 1/2}, \mathbf{2}^S_{\pm 1/2}$ $\quad \mathbf{3}^S_0, \mathbf{3}^S_{\pm 1}$ $\quad \mathbf{4}^S_{\pm 1/2}, \mathbf{4}^S_{\pm 1/2}$

$\mathbf{5}^S_0, \mathbf{5}^S_{\pm 1}$ $\quad \mathbf{5}^S_{\pm 1}, \mathbf{5}^S_{\pm 2}$ $\quad \mathbf{4}^S_{\pm 1/2}, \mathbf{4}^S_{\pm 3/2}$

$\mathbf{N_1} \otimes \mathbf{3} = (\mathbf{N_1} - \mathbf{2}) \oplus \mathbf{N_1} \oplus (\mathbf{N_1} + \mathbf{2})$

Two consecutive even/odd representations

$\mathbf{1}^S_0, \mathbf{3}^S_{\pm 1}$ $\quad \mathbf{3}^S_0, \mathbf{3}^S_{\pm 1}$ $\quad \mathbf{2}^S_{\pm 1/2}, \mathbf{4}^S_{\pm 1/2}$

$\mathbf{3}^S_{\pm 1}, \mathbf{5}^S_0$ $\quad \mathbf{3}^S_0, \mathbf{5}^S_{\pm 1}$ $\quad \mathbf{2}^S_{\pm 1/2}, \mathbf{4}^S_{\pm 3/2}$

UV Completions

$(L\Phi_i)_{\mathbf{N_1}\otimes\mathbf{2}}(L\Phi_i)_{\mathbf{N_2}\otimes\mathbf{2}}$

$(LL)_{\mathbf{1},\mathbf{3}}(\Phi_i\Phi_i)_{\mathbf{N_1}\otimes N_2}$

Scalar triplet,

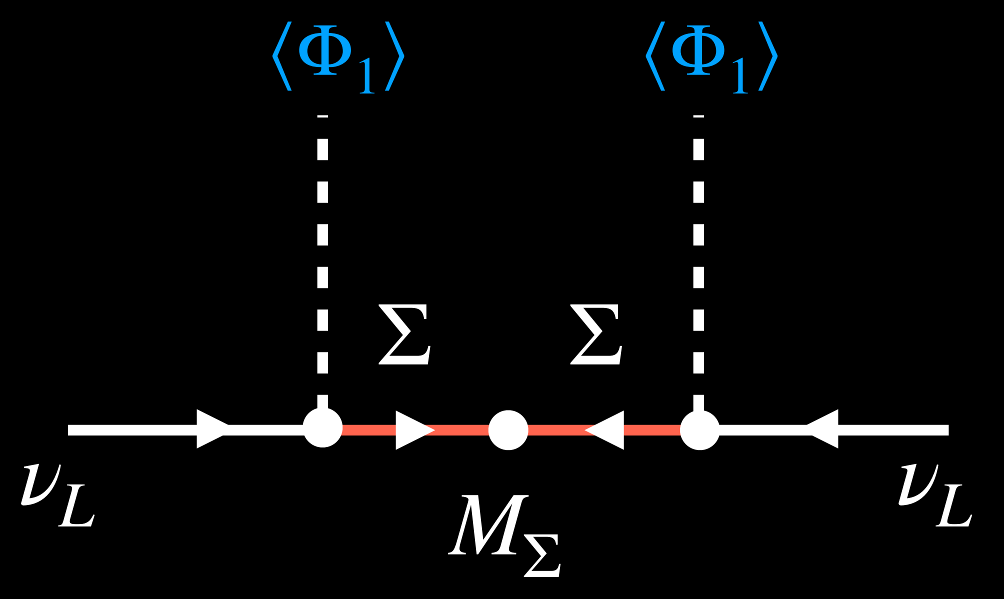
~~Scalar Singlet~~

UV Completions

Extensions with 1 Scalar multiplet

Possible scalar multiplet: Quadruplet

Majorana (Y = 0)



$$\mathscr{L} \supset -\overline{L} y_H \widetilde{H} \Sigma - \overline{L} y_1 \Phi_1 \Sigma - \frac{1}{2} \overline{\Sigma^c} M_\Sigma \Sigma + \mathrm{H.c.}$$

Singlet/Triplet

Triplet/Quintuplet

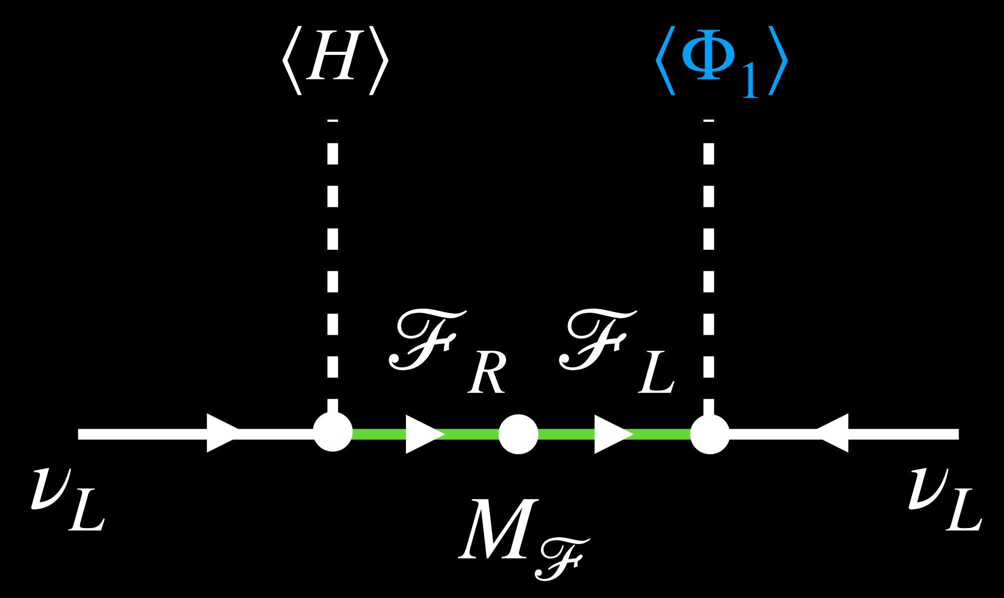
5^F_0

$4^S_{-1/2}$

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

Interesting UV models → Fermion mediator

Vector-like (Y ≠ 0)



$$\mathscr{L} \supset -\overline{L} y_H H \mathscr{F}_R - \overline{L} y_1 \Phi_1 \mathscr{F}^c_L - \overline{\mathscr{F}} M_{\mathscr{F}} \mathscr{F} + \mathrm{H.c.}$$

3^F_{-1}

$4^S_{-3/2}$

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

UV Completions

Extensions with 2 Scalar multiplets

$\mathcal{O}_5^{(2)} = (L\Phi_i)_{\mathbf{N}}(L\Phi_j)_{\mathbf{N}}$ $\longrightarrow$ $\mathbf{N}_2 = \mathbf{N}_1 + 2$ Or $\mathbf{N}_1 = \mathbf{N}_2$

Interesting UV models → Fermion mediator

Majorana (Y = 0)

$Y_1 = Y_2 = -1/2$

Only even reps. allowed

$$\mathcal{L} \supset -\bar{L}y_1\Phi_1\Sigma - \bar{L}y_2\Phi_2\Sigma - \frac{1}{2}\bar{\Sigma}M_\Sigma\Sigma^c + \mathrm{H.c.}$$

$\mathbf{N}_2 = \mathbf{N}_1 + 2$ $\quad (2\mathbf{N}_1 + 1)_0^F$

$\mathbf{2}^S_{-1/2}, \mathbf{4}^S_{-1/2}$

$\mathbf{4}^S_{-1/2}, \mathbf{6}^S_{-1/2}$

Vector-like (Y ≠ 0)

$|Y_1 + Y_2| = 1$

Both even/odd reps. allowed

$$\mathcal{L} \supset -\bar{L}y_1\Phi_1\mathcal{F}_R - \bar{L}y_2\Phi_2\mathcal{F}_L^c - \bar{\mathcal{F}}M_{\mathcal{F}}\mathcal{F} + \mathrm{H.c.}$$

$\mathbf{N}_1 = \mathbf{N}_2$ $\quad (\mathbf{N}_1 \pm 1)^F_{-1/2-Y_1}$

$\mathbf{N}_1 < \mathbf{N}_2$ $\quad (\mathbf{N}_1 + 1)^F_{-1/2-Y_1}$

Scalar Sector

Potential

New scalars carry lepton number L → Scalar potential terms may violate $U(1)_L$ symmetry

$$V^{\mathbf{A}}(H,\Phi_1) = V^{\mathbf{A}}_{L}(H,\Phi_1) + V^{\mathbf{A}}_{\not{L}}(H,\Phi_1)$$

$$V^{\mathbf{A}_{\mathrm{I}}}_{\not{L}}(H,\Phi_1) = \lambda_6\,\Phi_1^* H\Phi_1\Phi_1 + \lambda_7\,H\Phi_1 H\Phi_1 + \boxed{\lambda_8\,H^*\Phi_1 HH} + \mathrm{H.c.}$$

$$V^{\mathbf{A}_{\mathrm{II}}}_{\not{L}}(H,\Phi_1) = \boxed{\lambda_6\Phi_1 HHH} + \mathrm{H.c.}$$

$$M_{\Phi_i} \simeq \sqrt{\lambda'}\cdot v\left(1+\sqrt{\frac{\lambda''}{\lambda'}\frac{v}{v_i}}\right)$$

$$\lambda^{'('')} < \sqrt{4\pi} \to M_\Phi < 10^3\,\mathrm{TeV}$$

Two new scalar multiplets → Scalar potential can have an accidental $U(1)_X$ symmetry

$$V^{\mathbf{B}}_{\not{L}}(H,\Phi_1,\Phi_2) \supset V^{\mathbf{B}}_{X}(H,\Phi_1,\Phi_2) + V^{\mathbf{B}}_{\not{X}}(H,\Phi_1,\Phi_2)$$

$$V^{\mathbf{B}}_{X}(H,\Phi_1,\Phi_2) = \lambda_1 H\,H\,\Phi_1\,\Phi_2 \qquad X_1 = -X_2$$

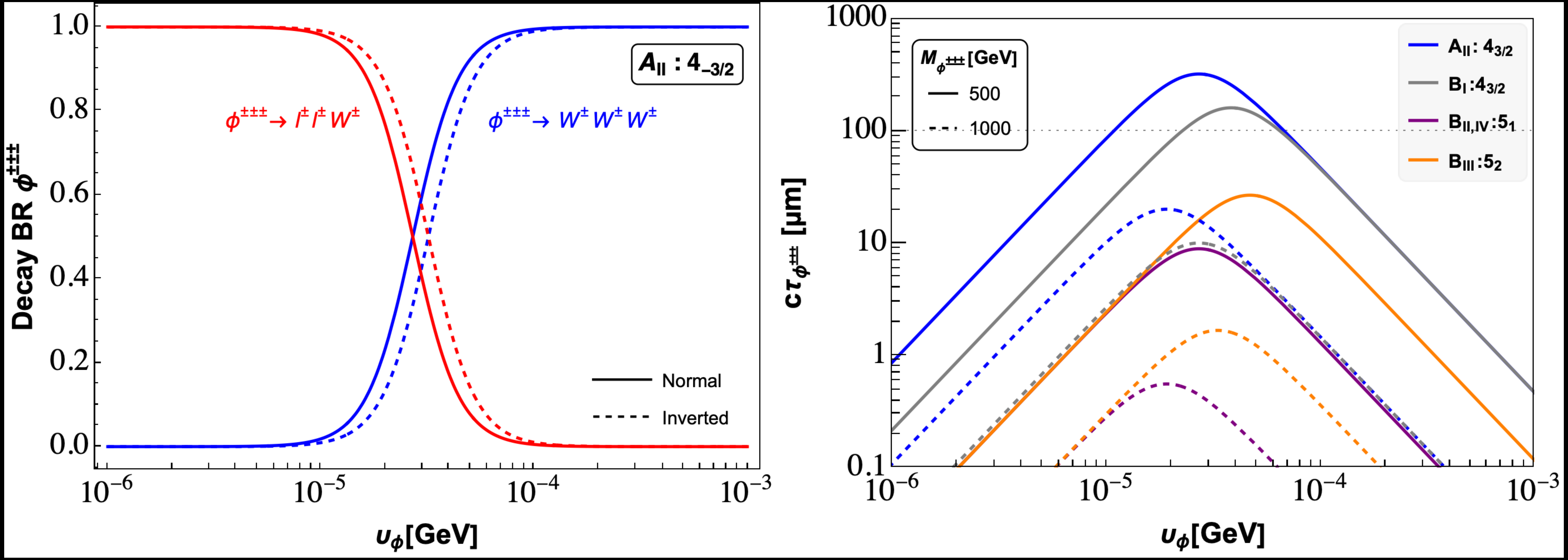
Symmetry breaking → Implications for two different pseudo-Nambu-Goldstones

Massive pseudoscalars ($M < 45$ GeV) → Constraints on the LNV couplings

Collider Phenomenology

Triply-charged scalar decays

$$\Phi^{\pm\pm\pm} \rightarrow \Phi^{\pm\pm} W^{\pm} \rightarrow W^{\pm}W^{\pm}W^{\pm}$$
$$\Phi^{\pm\pm\pm} \rightarrow \Phi^{\pm\pm} W^{\pm} \rightarrow W^{\pm}l^{\pm}l^{\pm}$$



May lead to Displaced vertices

Ghosh, Jana, Nandi (2018)

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