Neutrino Masses from new Weinberg-like Operators

Drona Vatsyayan

14th June 2024, SUSY24 - Madrid

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

CSIC · Universitat de València · IFIC Institut de Física Corpuscular · Generalitat Valenciana · Gen-T

Outline

PART I: Neutrino Masses & EFT

SM Effective Field Theory

New Weinberg-like operators

UV completions

Scalar sector

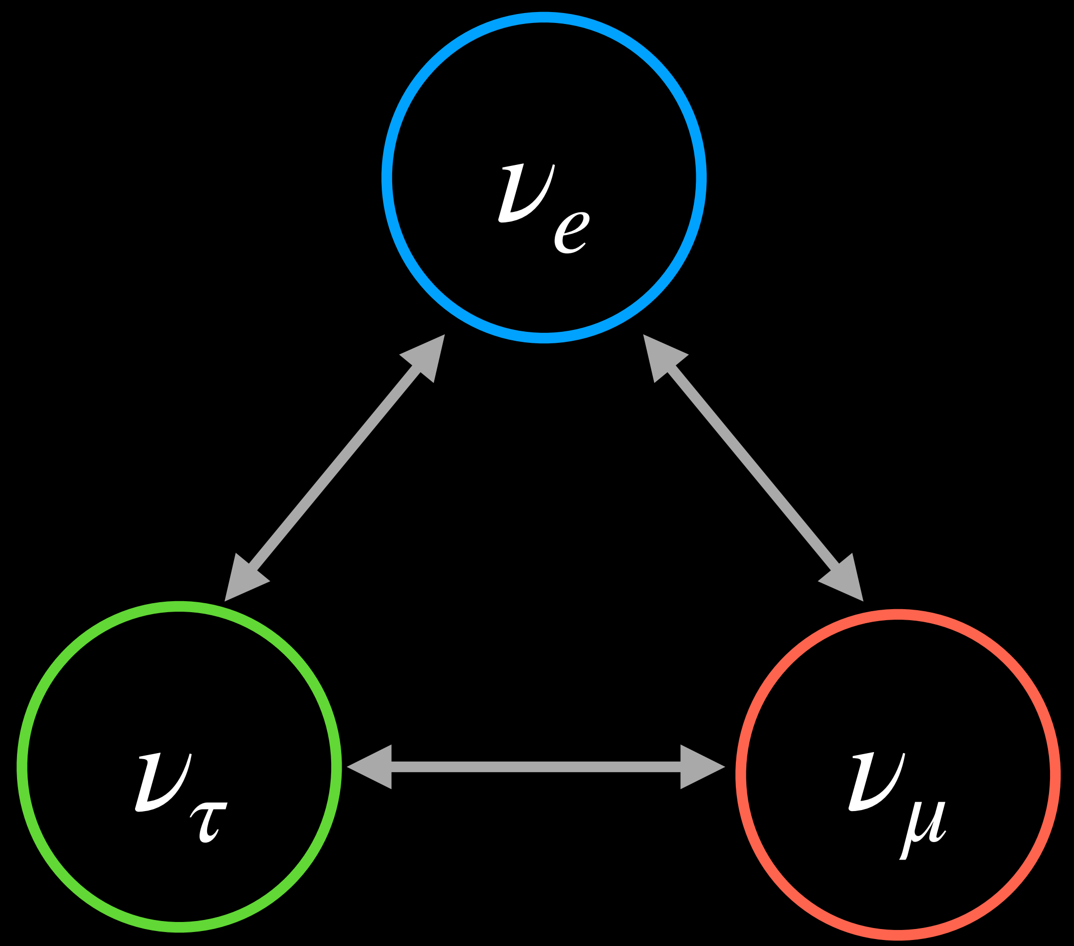
PART II: Phenomenology

Collider searches for multi-charged scalars

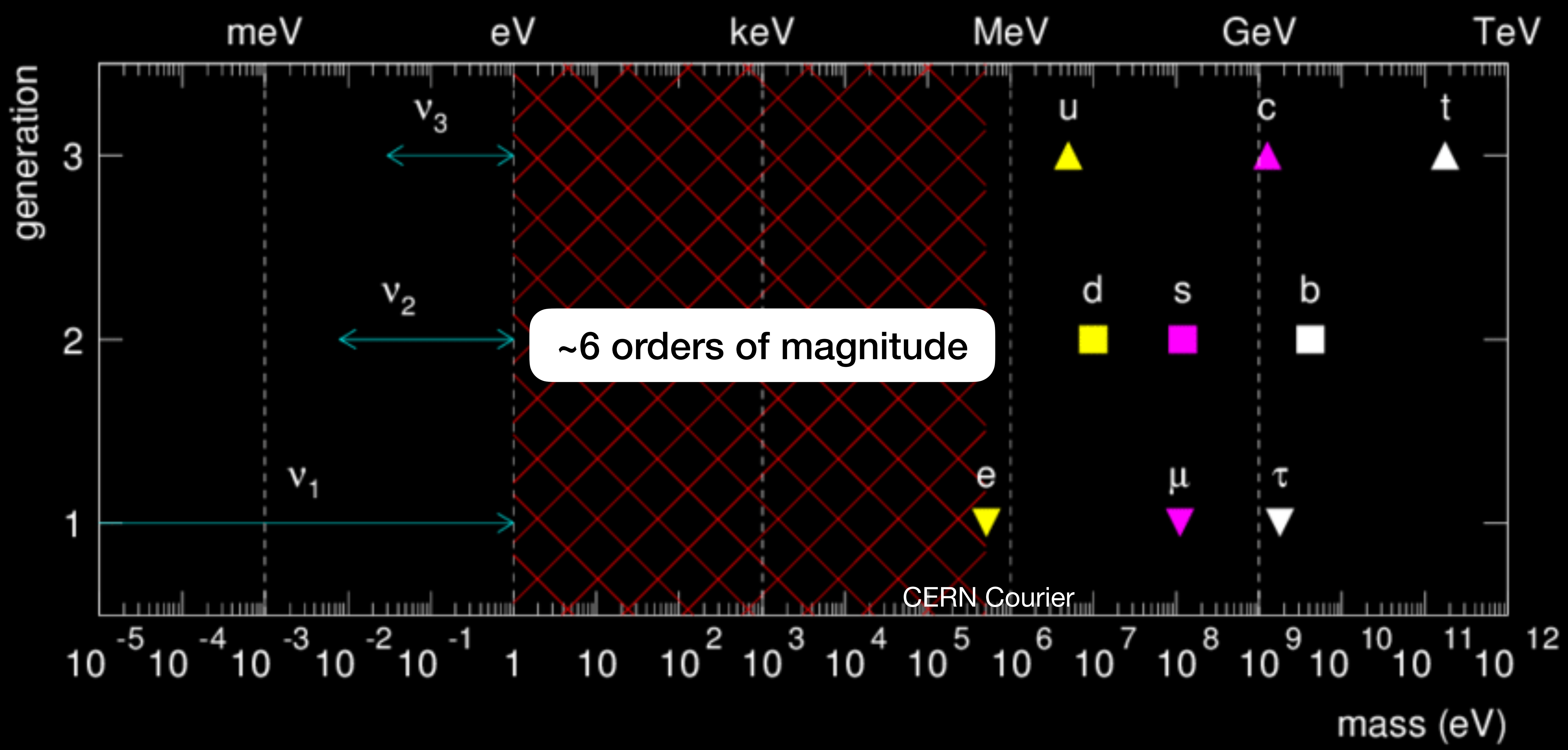
Electroweak precision tests

Neutrinos

Mass spectrum



Neutrino Oscillations →
Neutrinos have a tiny mass



Absolute mass unknown!

Origin of mass unknown!

Neutrino masses

SM Effective Field Theory

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

Neutrino masses

SM Effective Field Theory

Unique operator at $d = 5$

Weinberg: PRL 43 (1979)

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EWSSB

$\langle H \rangle = v$

$$m_\nu \sim \frac{c_5}{\Lambda_{\mathrm{N}P}} v^2$$

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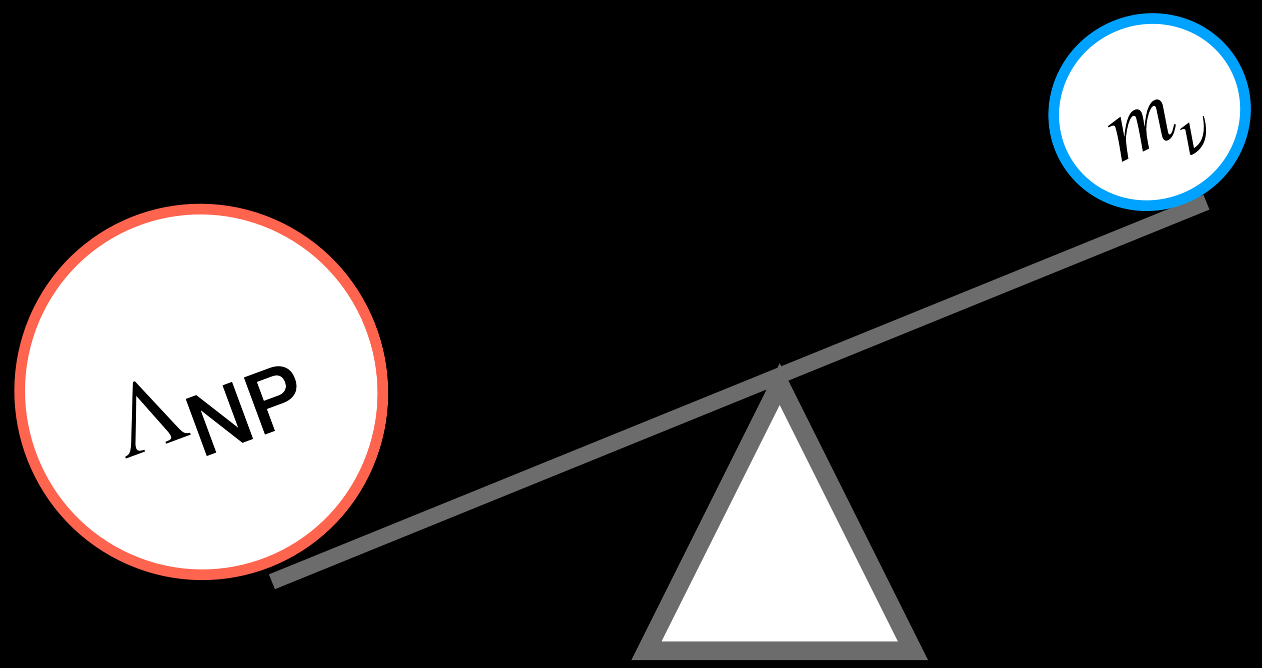

The Seesaw Mechanism

Yanagida, Tokyo (1981)

Neutrino masses

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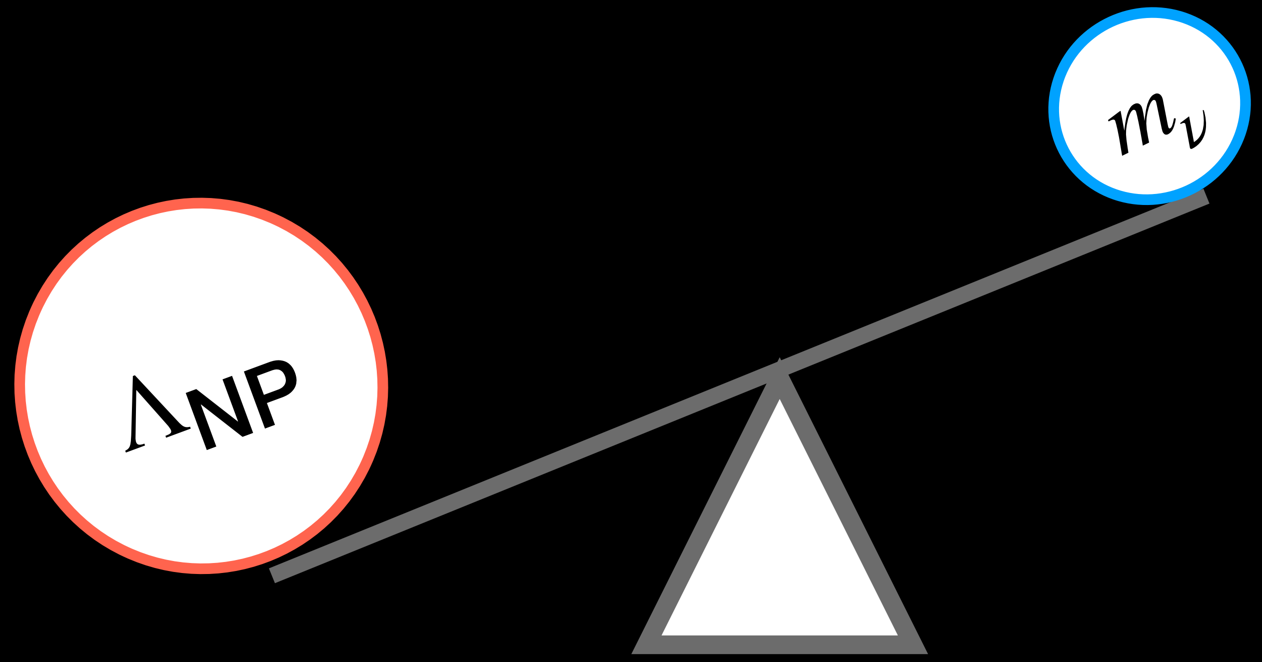
$\langle H \rangle = v$

$$m_\nu \sim \frac{c_5}{\Lambda_{\mathrm{NP}}} v^2 \gtrsim 0.05 \times 10^{-9}\ \mathrm{GeV}$$

174 GeV

$\lesssim 10^{14}$ GeV



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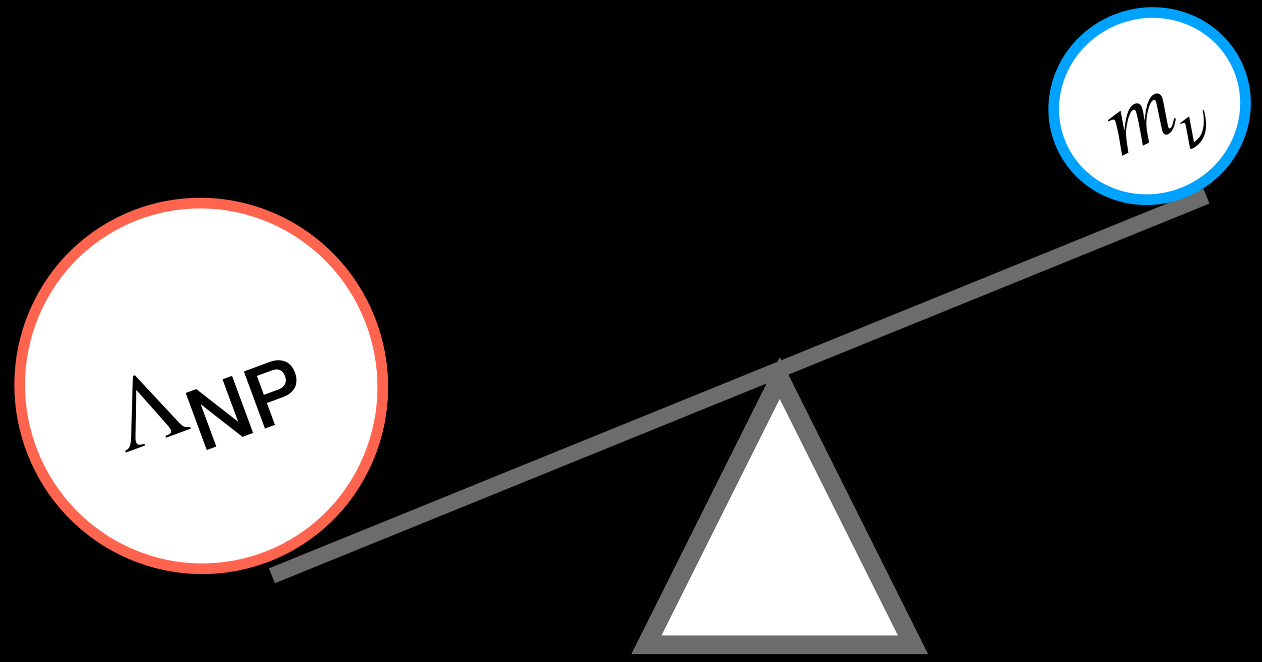

The Seesaw Mechanism

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

Neutrino masses

The Weinberg Operator: *LLHH*

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

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

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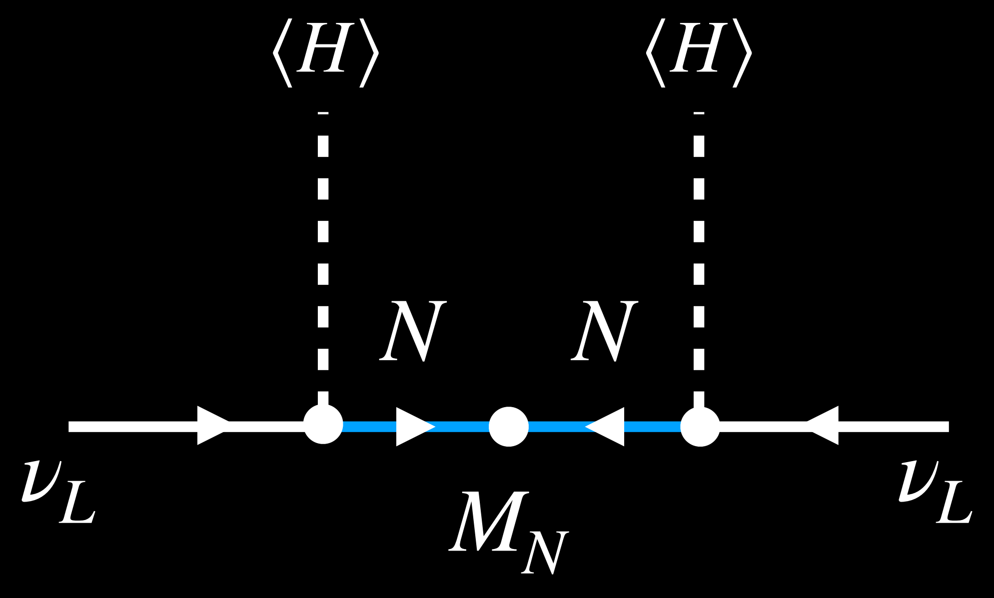
UV completions at the tree level → Usual Seesaws

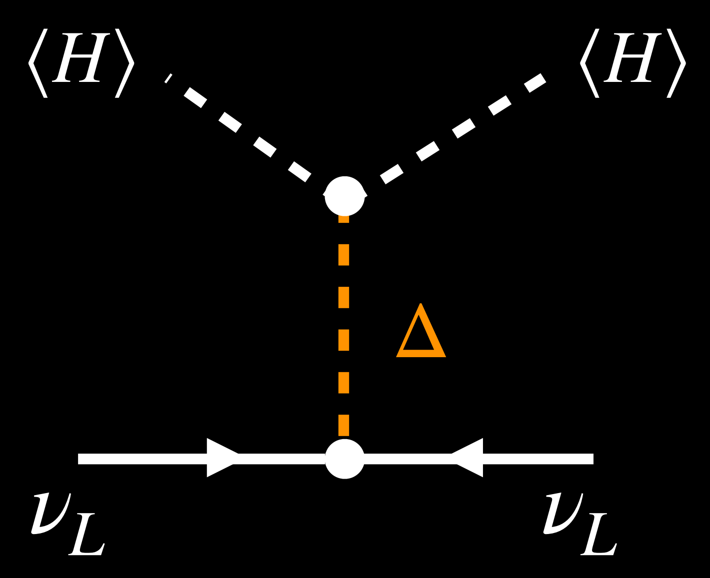
Fermion singlet: N



I

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

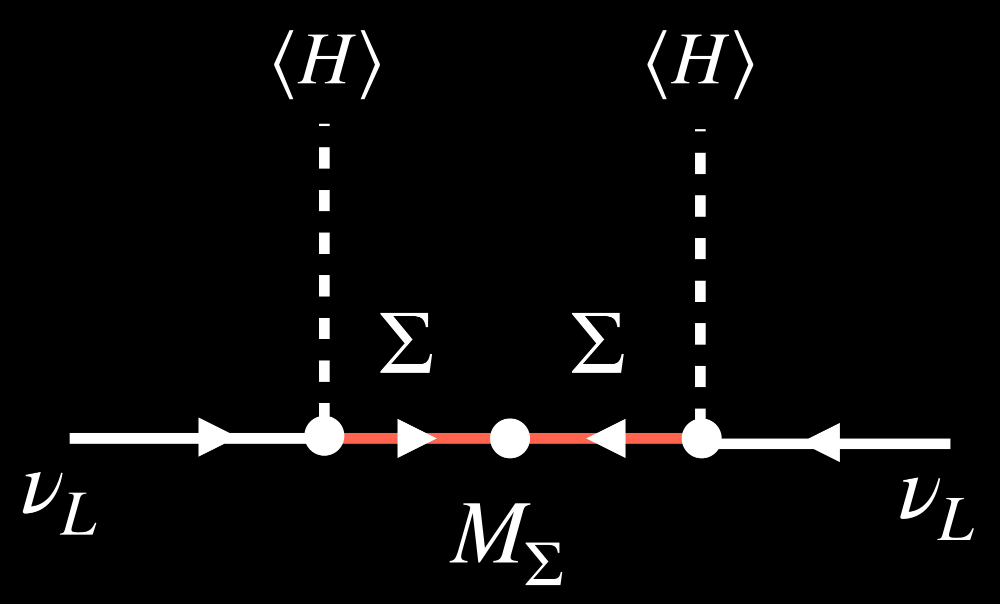
Scalar triplet: Δ



II

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

Fermion triplet: Σ



III

Foot, Lew, He, Joshi (1989)

Beyond the usual Seesaws

New Scalar Multiplets

Augment SM by new low-energy $\mathcal{O}(\mathrm{TeV})$ degrees of freedom

Masses bounded by perturbativity and unitarity

Should not be far from the EW scale

Φ_i

$\mathbf{N}_{\mathbf{i}Y_i}$

Dimension , Hypercharge

VEVs are bounded to be small from custodial symmetry $\lesssim \mathcal{O}(1)$ GeV

Can be naturally suppressed if induced by Higgs VEV

Collider searches + EWPTs

→ More testable than the usual seesaws

Beyond the usual Seesaws

New Weinberg-like Operators

$$-\mathscr{L}_5 = \frac{1}{2}\sum_i C_5^{(i)}\mathcal{O}_5^{(i)} + \mathrm{H.c.}$$

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Possible new operators with up to 2 new scalar multiplets after integrating out a heavy mediator at the tree level

Fermion-like contraction

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

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New scalars take a VEV $\rightarrow \langle\Phi_i\rangle = v_i,\ \langle\Phi_j\rangle = v_j$

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

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

$\langle\Phi_{i,j}\rangle \ll \langle H\rangle \rightarrow \Lambda$ is parametrically suppressed ✔

Extra suppression possible from the WCs

New Weinberg-like Operators

Scenarios

Natural scenarios → Suppressed induced VEVs $v_i \sim v^3/M_\Phi^2$

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)

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

Do not generate the usual seesaws contributions

$\langle \Phi_{i,j} \rangle \ll \langle H \rangle$ → SM Higgs contribution will always dominate unless strong hierarchies/ad-hoc symmetries are imposed

New Weinberg-like Operators

Extensions with 1 Scalar multiplet

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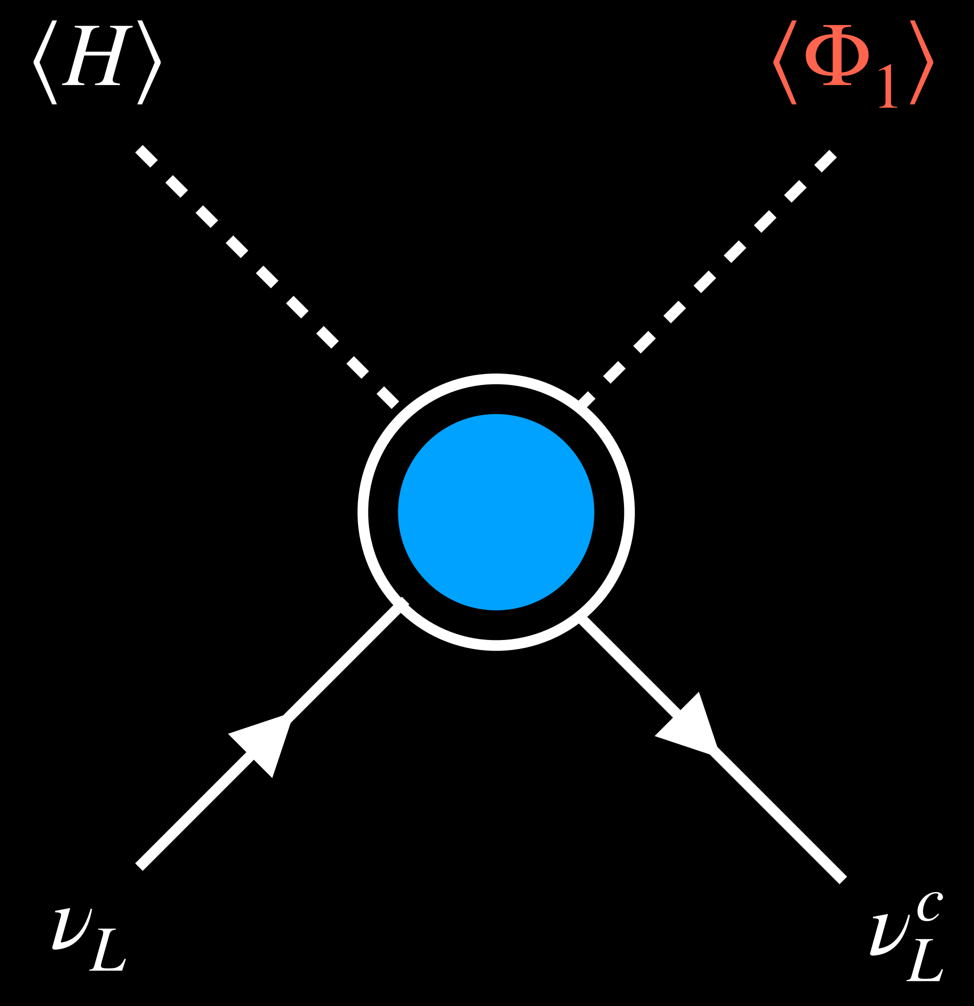

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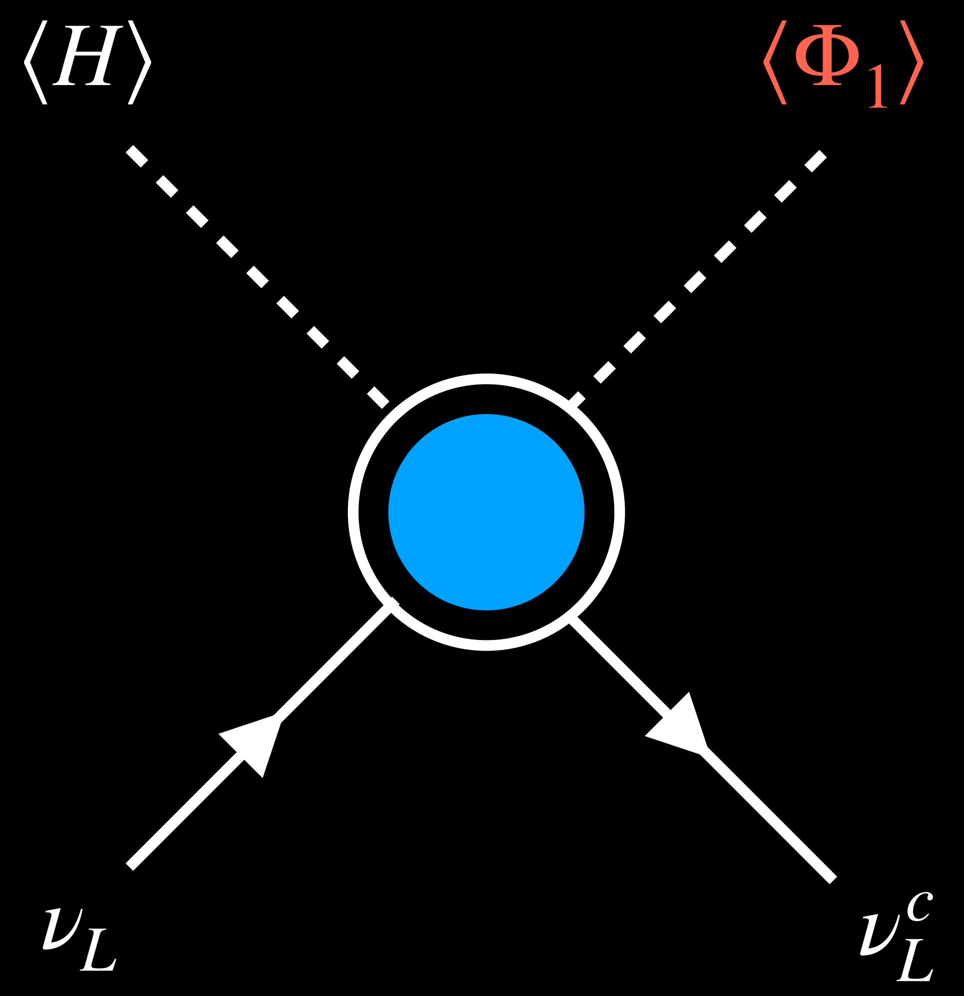

Possible SU(2) representations for Φ_1

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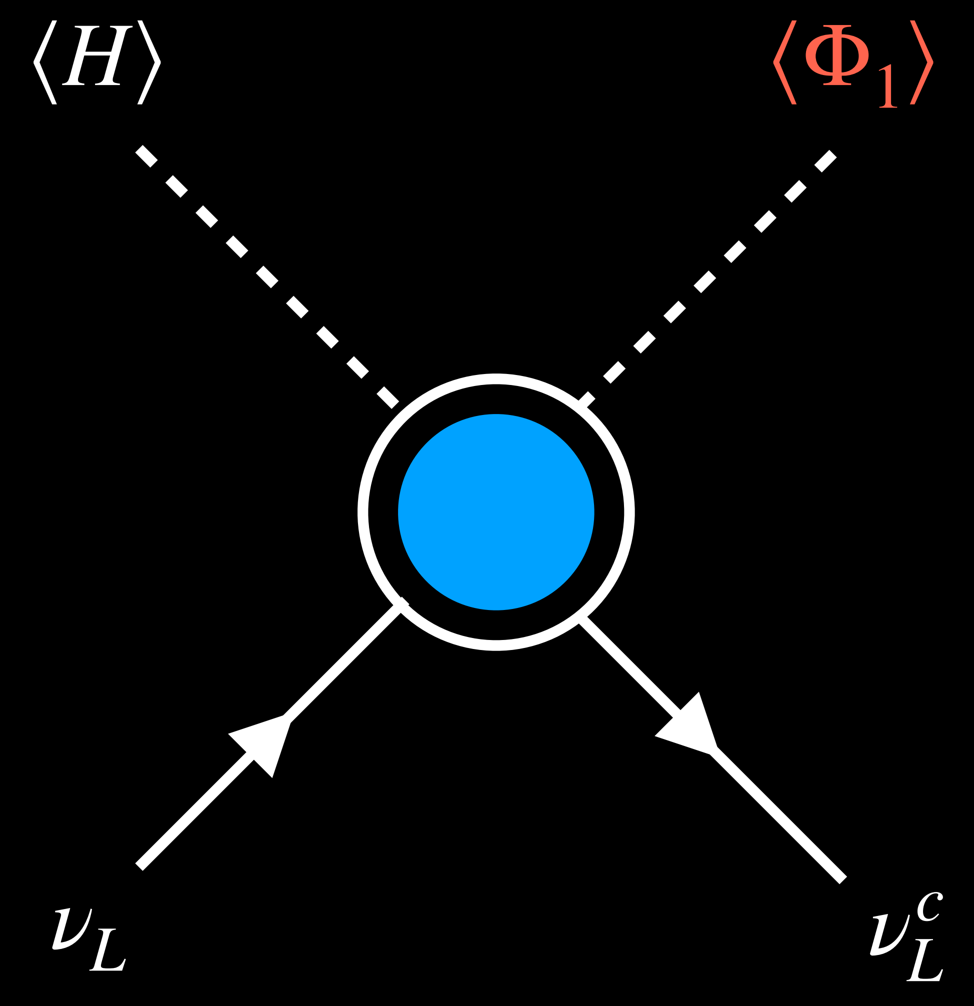

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Doublet $\mathbf{2}^S_{\pm 1/2}$

Recovers 2HDM

UV completions:
Usual seesaws

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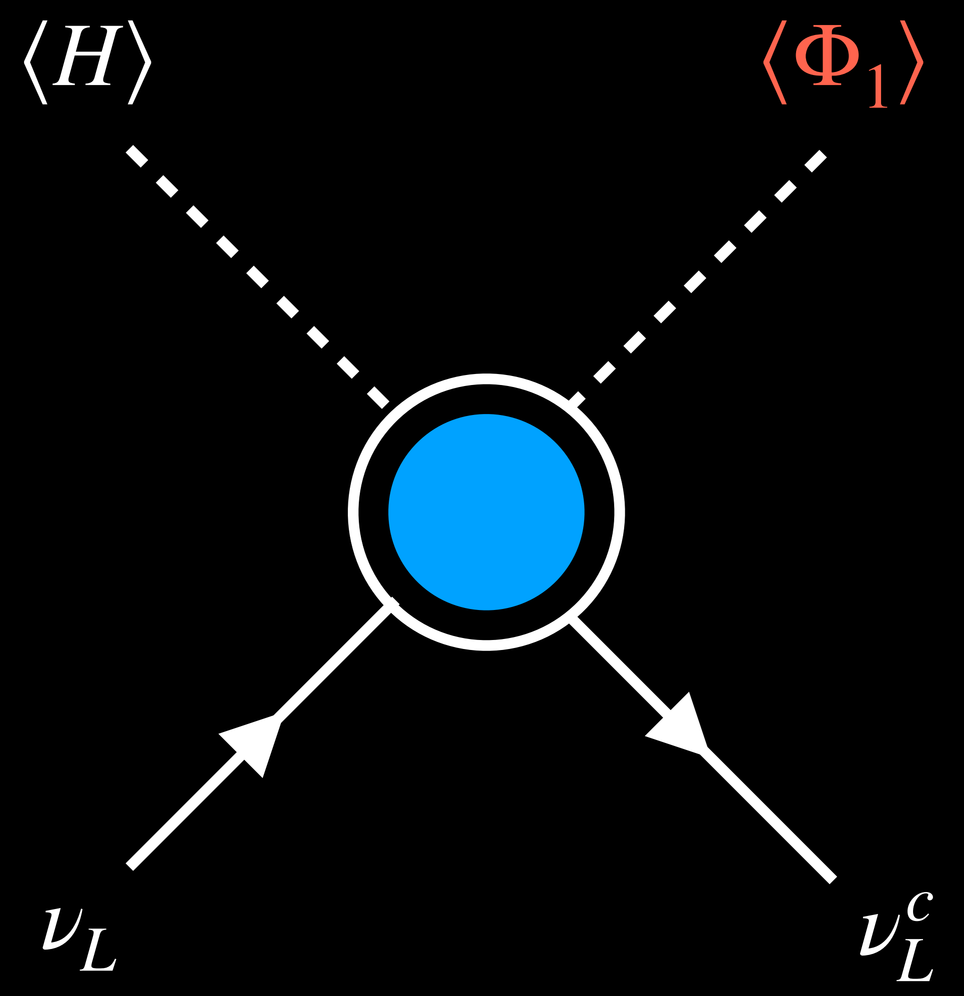

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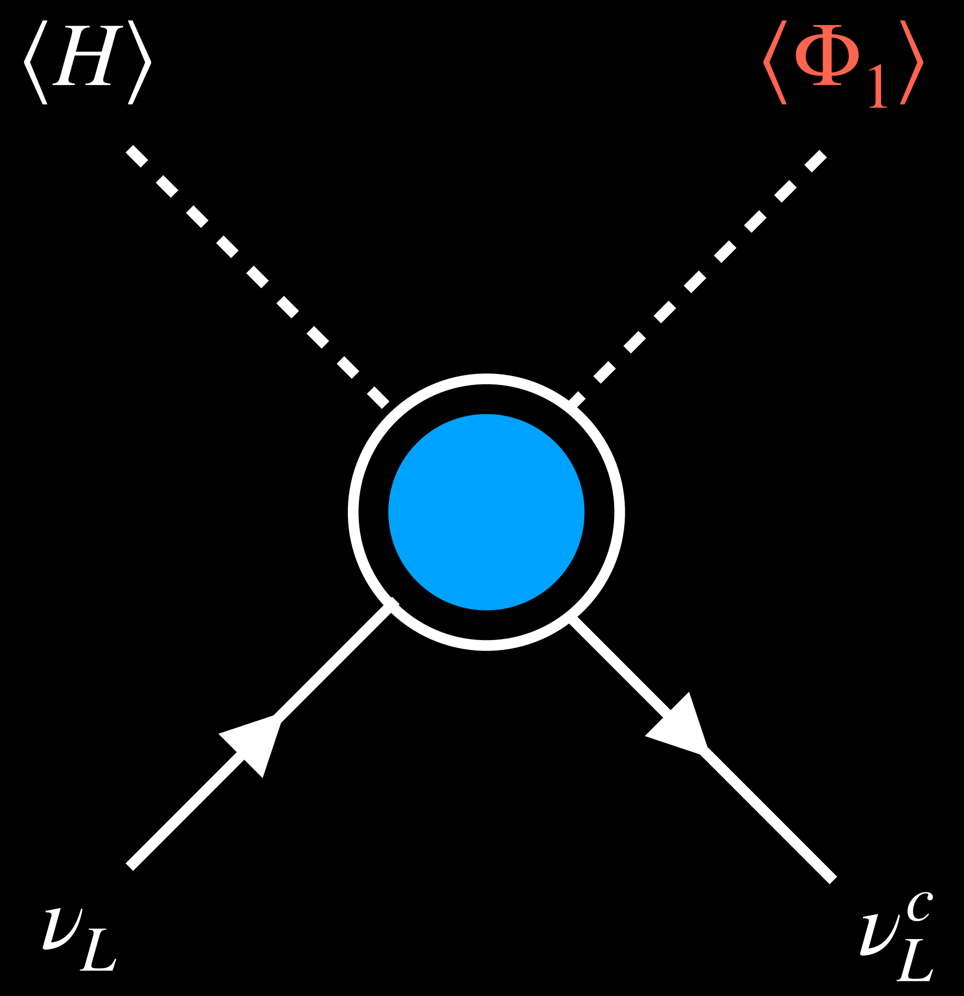

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UV Completions

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

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

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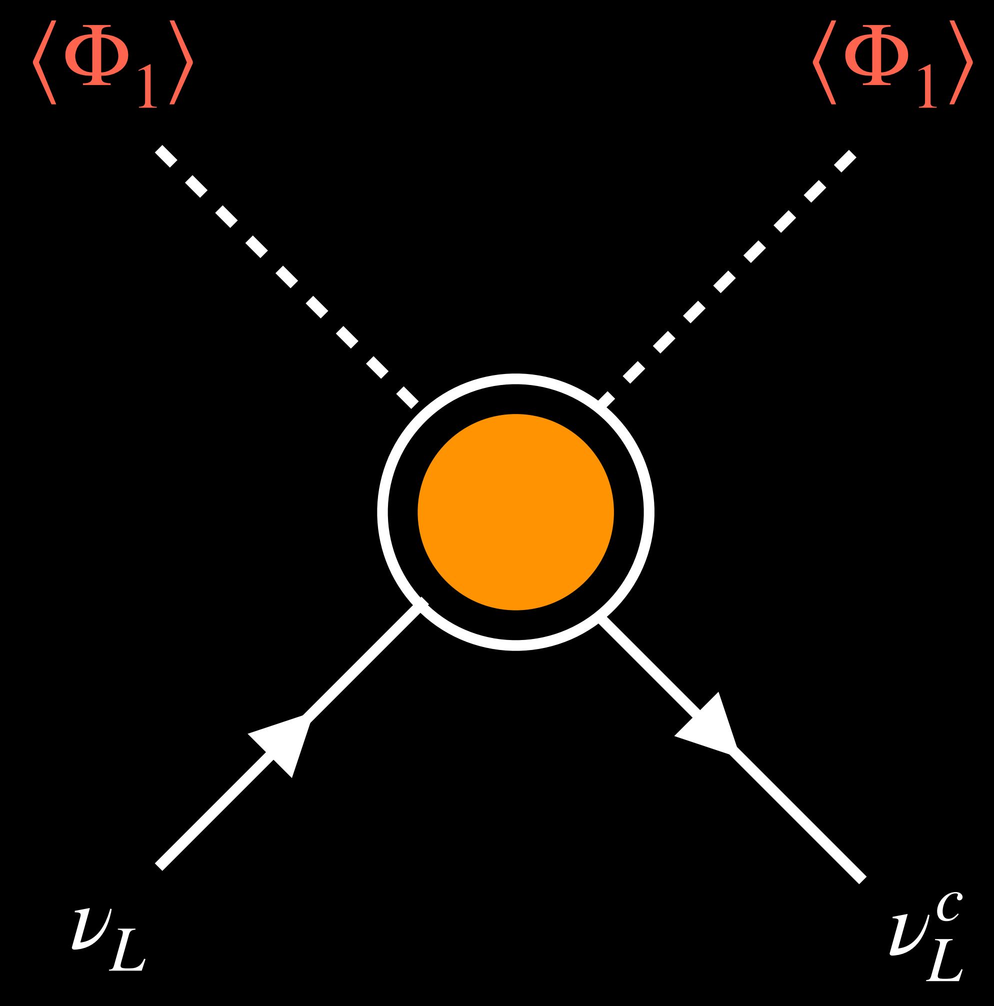

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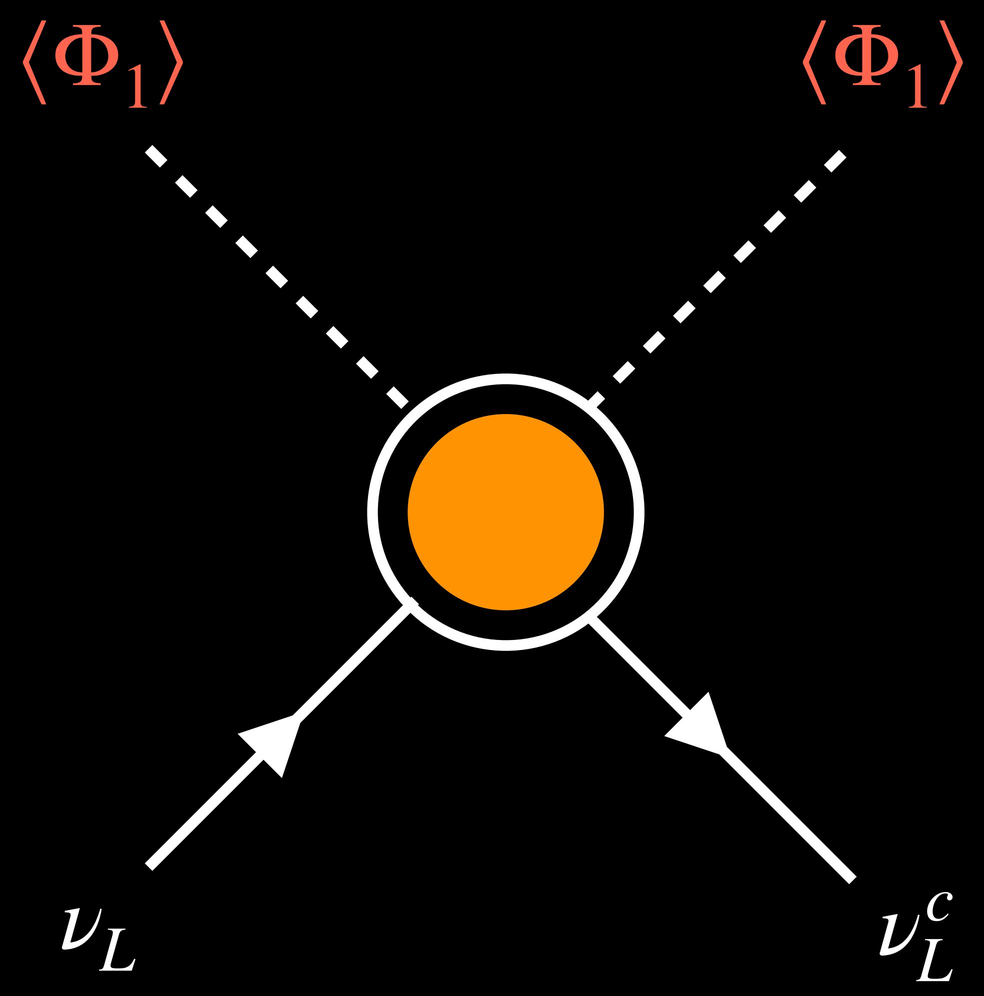

Possible SU(2) representations for Φ_1

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

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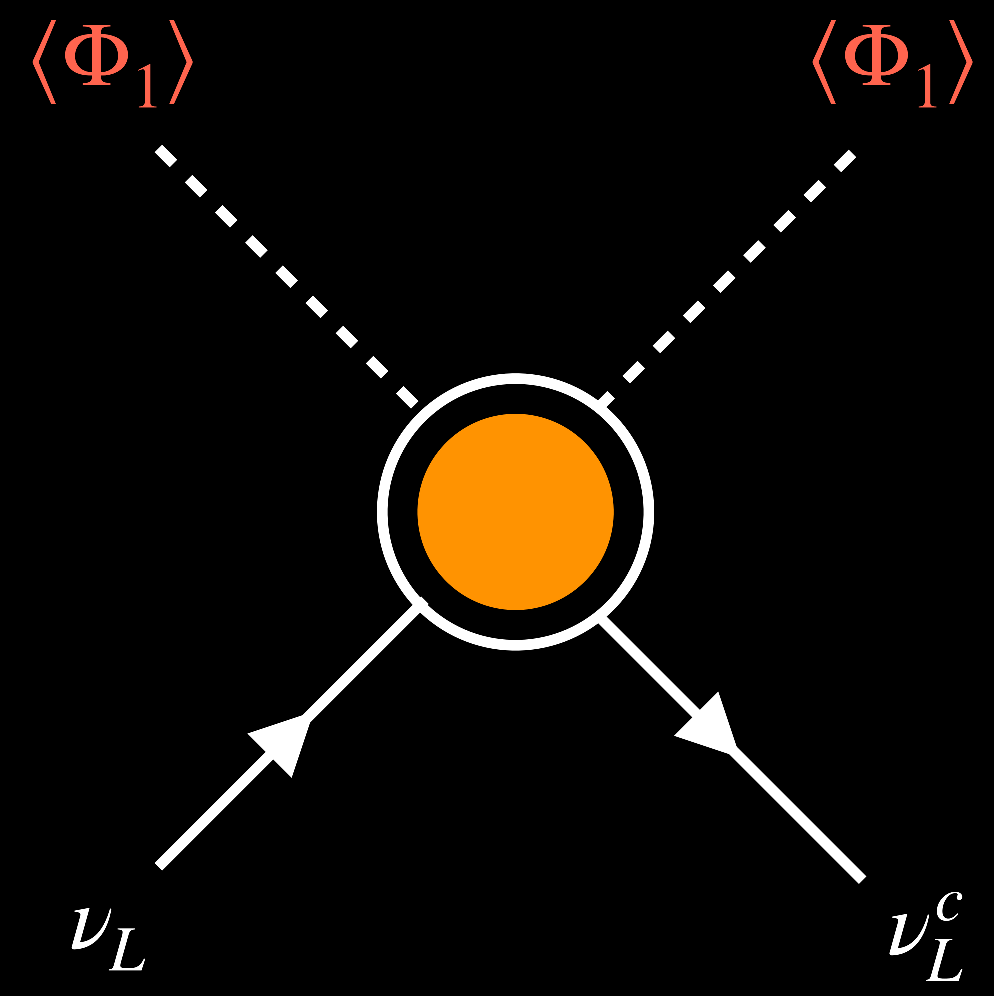

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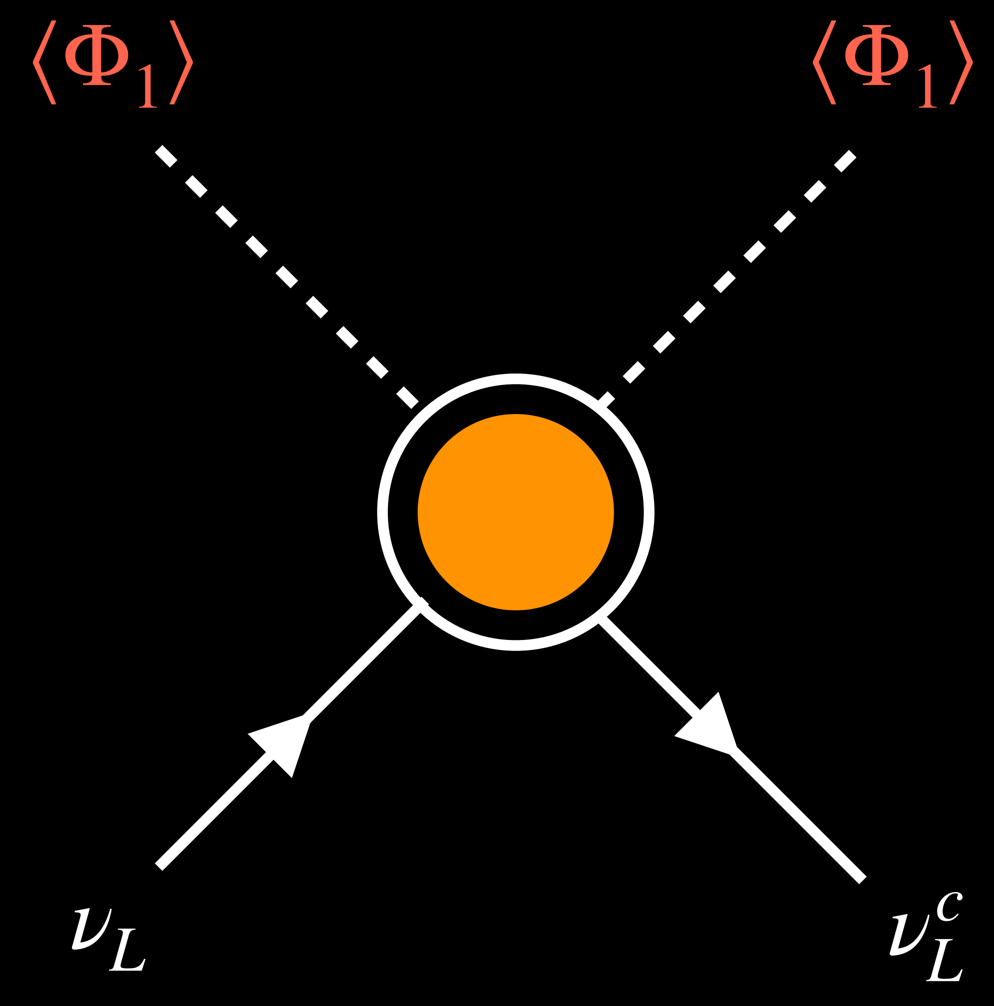

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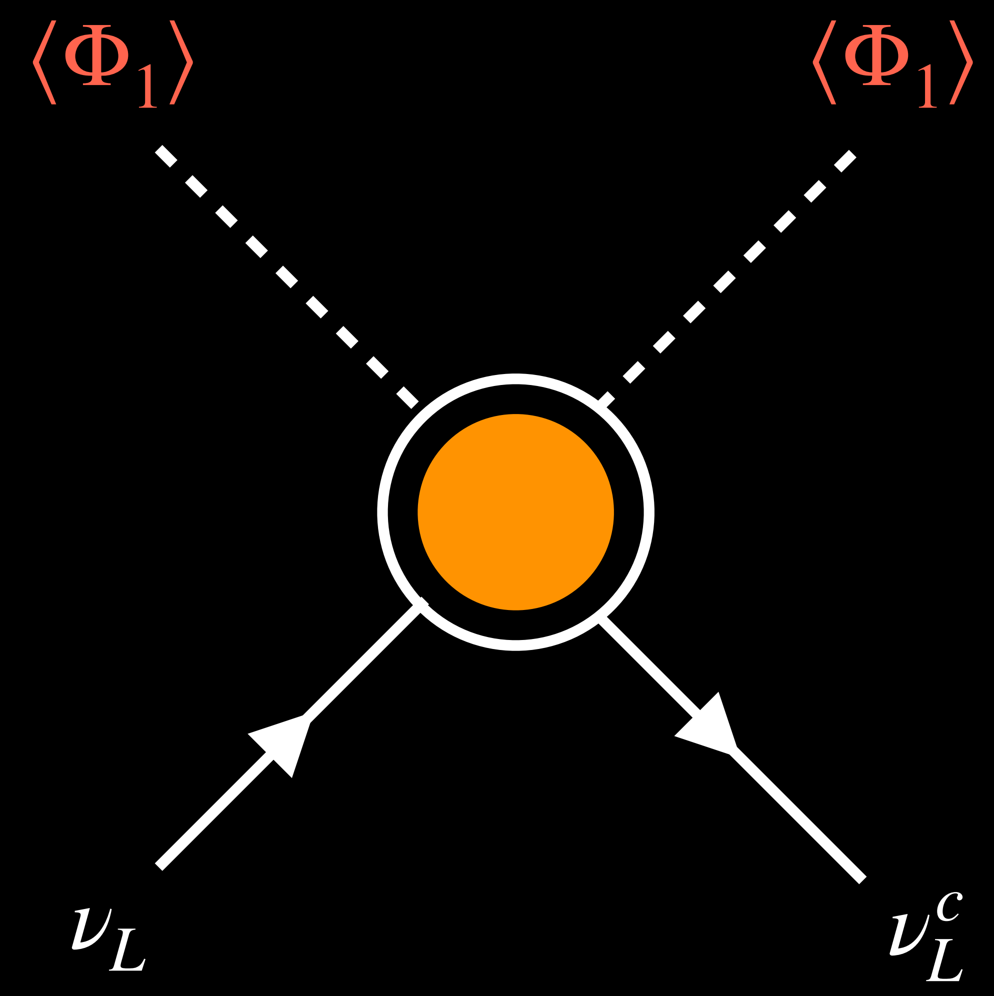

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Fermion triplet

Fermion quintuplets

$(LL)_{\mathbf{1,3}}(\Phi_i\Phi_i)_{\mathbf{1,3,5,7}}$

Scalar triplet,

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New Weinberg-like Operators

Extensions with 2 Scalar multiplets

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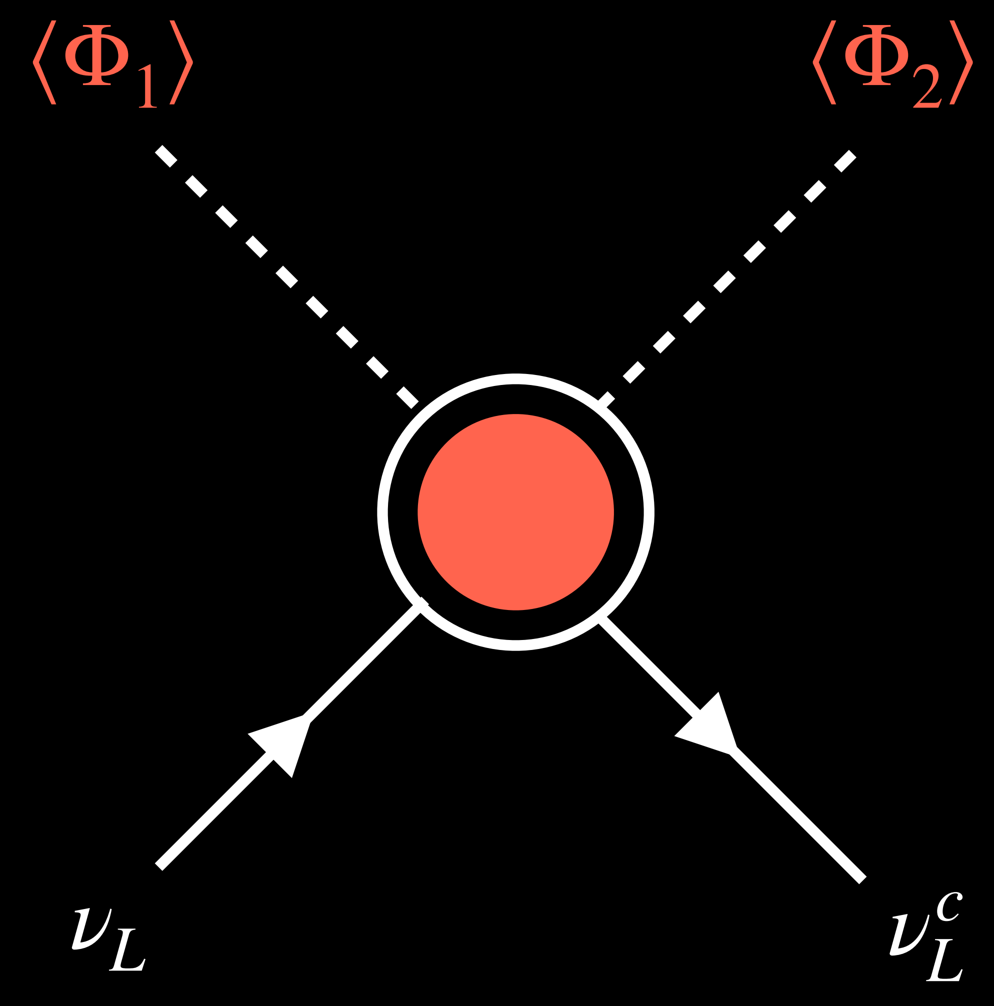

Possible SU(2) representations for Φ_1 and Φ_2: $(\mathbf{N_1}, Y_1)$, $(\mathbf{N_2}, Y_2)$

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

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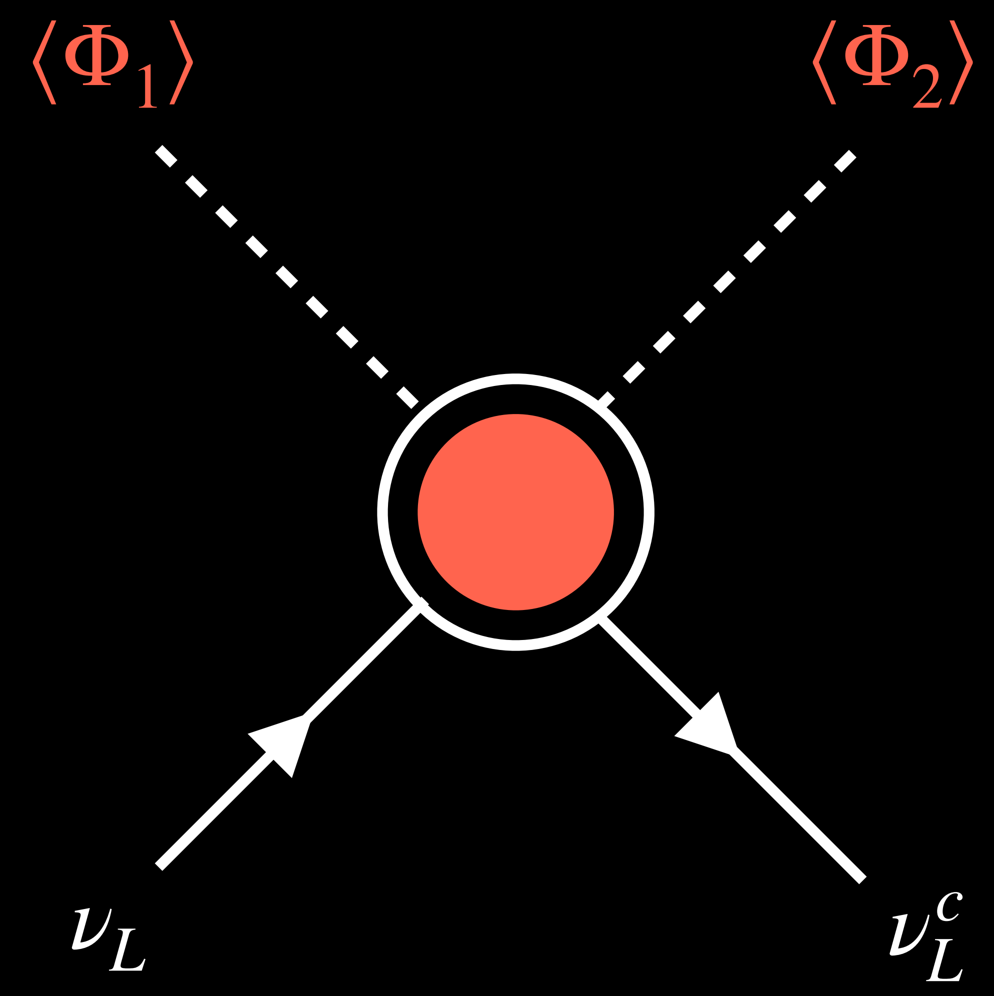

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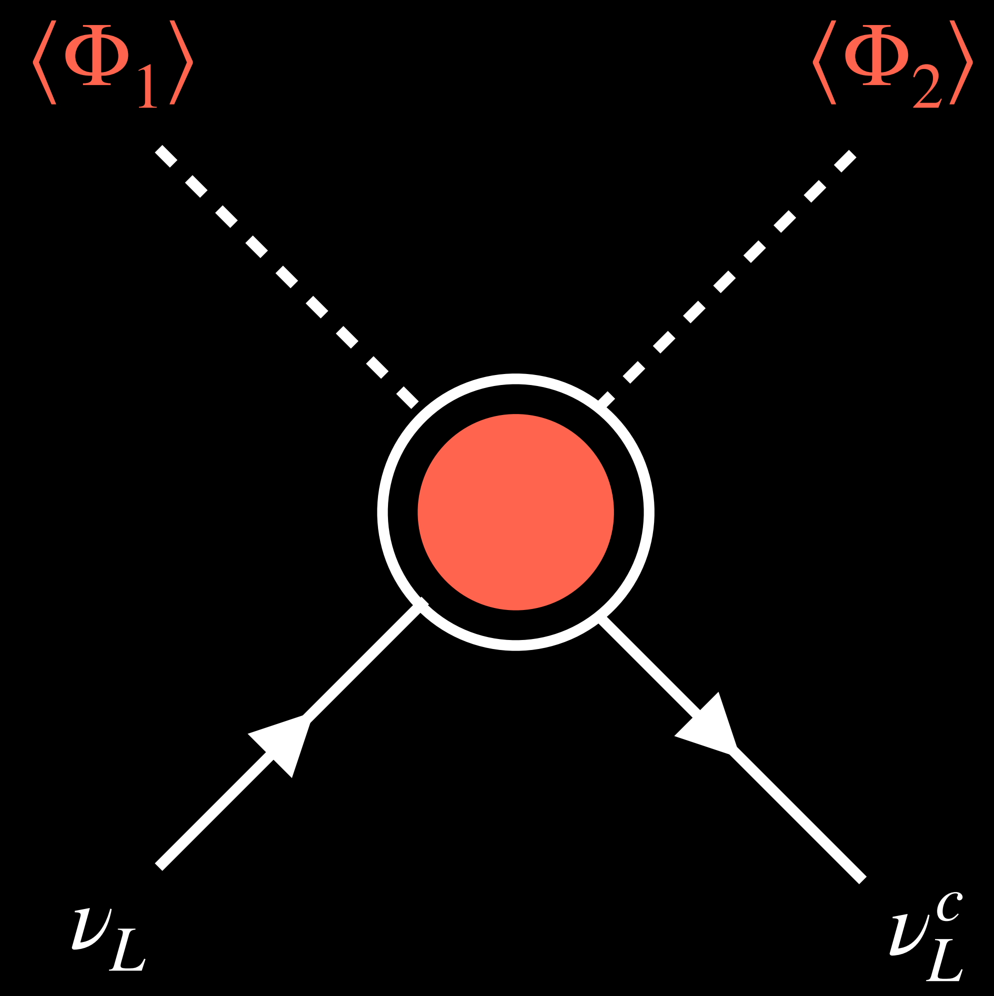

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$\mathbf{N_1} \otimes \mathbf{3} = (\mathbf{N_1} - \mathbf{2}) \oplus \mathbf{N_1} \oplus (\mathbf{N_1} + \mathbf{2})$

Two consecutive even/odd representations

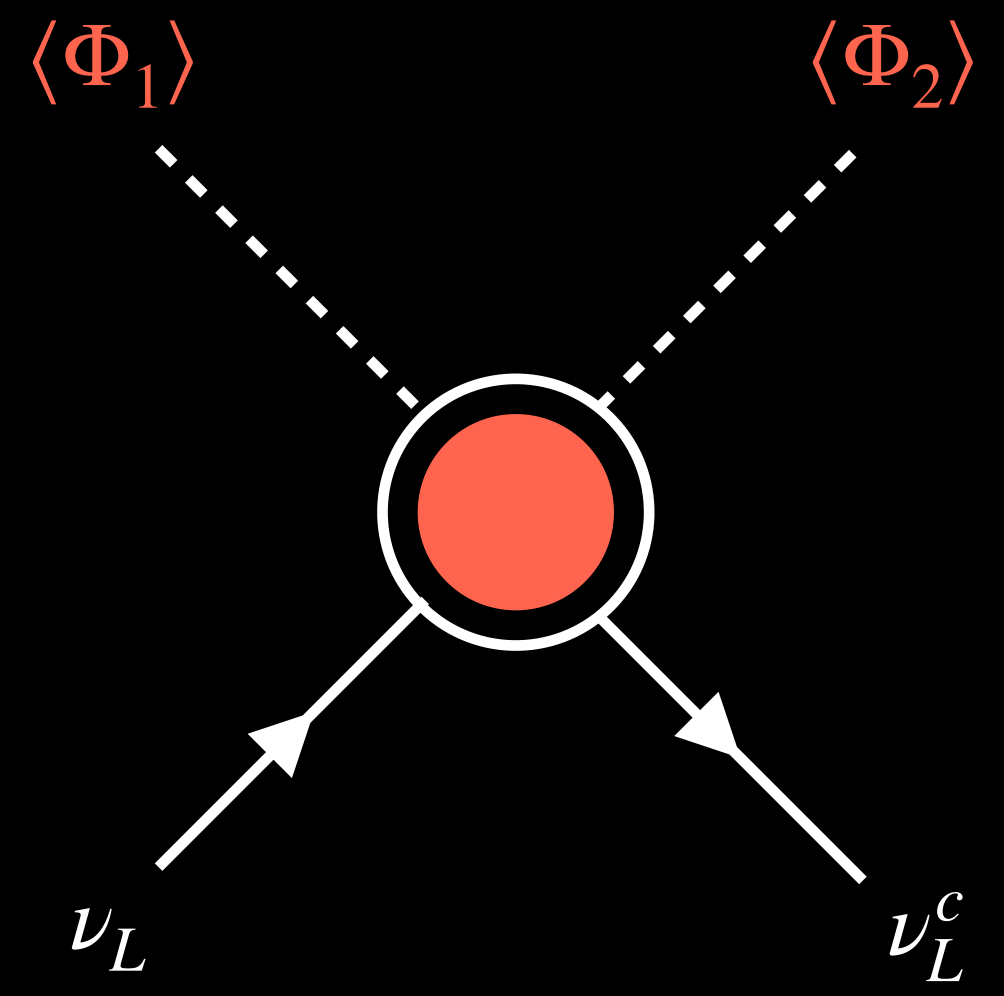
$\mathbf{1}^S_0, \mathbf{3}^S_{\pm 1}$ $\quad \mathbf{3}^S_0, \mathbf{3}^S_{\pm 1}$ $\quad \mathbf{2}^S_{\pm 1/2}, \mathbf{4}^S_{\pm 1/2}$

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

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

Genuine Models

Do not generate the Weinberg operators with just the SM Higgs

	Model	Scalar Multiplets	Mediators	Op.	Wilson Coefficients	Tree level m_ν
One multiplet	$\mathbf{A_1}$	$\Phi_1 = \mathbf{4}^S_{-1/2}$	$\Sigma = \mathbf{5}^F_0$	$\mathcal{O}_5^{(2)}$	$C_5^{(2)} = y_1 M_\Sigma^{-1} y_1^T$	$1/2\ v_1^2$
	$\mathbf{A_2}$	$\Phi_1 = \mathbf{4}^S_{-3/2}$	$\mathcal{F} = \mathbf{3}^F_{-1}$	$\mathcal{O}_5^{(1)}$	$C_5^{(1)} = y_1 M_\mathcal{F}^{-1} y_H^T + y_H M_\mathcal{F}^{-1} y_1^T$	$-1\ v_1\, v$
Two multiplets	$\mathbf{B_1}$	$\Phi_1 = \mathbf{4}^S_{1/2},\quad \Phi_2 = \mathbf{4}^S_{-3/2}$	$\mathcal{F} = \mathbf{5}^F_{-1}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$	$-\sqrt{3/4}v_1\, v_2$
	$\mathbf{B_2}$	$\Phi_1 = \mathbf{3}^S_0,\quad \Phi_2 = \mathbf{5}^S_{-1}$	$\mathcal{F} = \mathbf{4}^F_{-1/2}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$	$-\sqrt{1/2}v_1\, v_2$
	$\mathbf{B_3}$	$\Phi_1 = \mathbf{5}^S_{-2},\quad \Phi_2 = \mathbf{5}^S_1$	$\mathcal{F} = \mathbf{4}^F_{3/2}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$	$2v_1\, v_2$
	$\mathbf{B_4}$	$\Phi_1 = \mathbf{5}^S_{-1},\quad \Phi_2 = \mathbf{5}^S_0$	$\mathcal{F} = \mathbf{4}^F_{1/2}$	$\mathcal{O}_5^{(3)}$	$C_5^{(3)} = y_1 M_\mathcal{F}^{-1} y_2^T + y_2 M_\mathcal{F}^{-1} y_1^T$	$-\sqrt{6}v_1\, v_2$

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

Scalar Sector

Bounds on VEVs

$$\rho = m_W^2/(c_W^2 m_Z^2)$$

$\rho = 1$ Theoretical value (in SM) → Custodial symmetry

$\rho = 1.00017 \pm 0.00025$ Experimental value
PDG 2022

Veltman (1977); Skive, Susskind, Voloshin, Zakharov (1980)

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

$$\rho = \frac{\sum_j [(I_j(I_j+1) - Y_j^2]v_j^2}{2\sum_j Y_j^2 v_j^2}$$

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

Extraction of Fermi's constant → $2\sum_j [I_j(I_j+1) - Y_j^2]v_j^2 = (2\sqrt{2}G_F)^{-1} = (174\text{ GeV})^2$

$$v \gg v_i$$

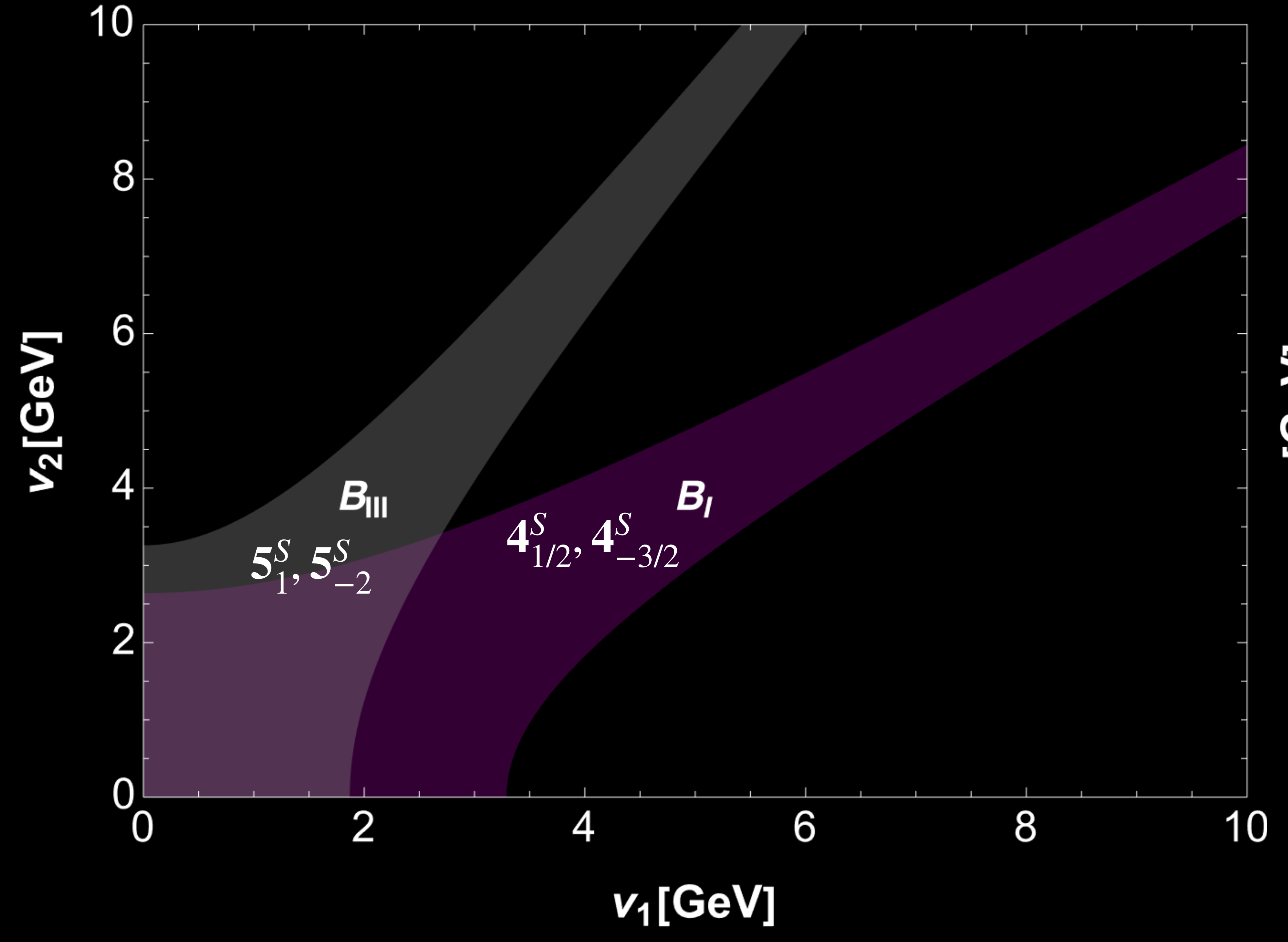
Scalar Sector

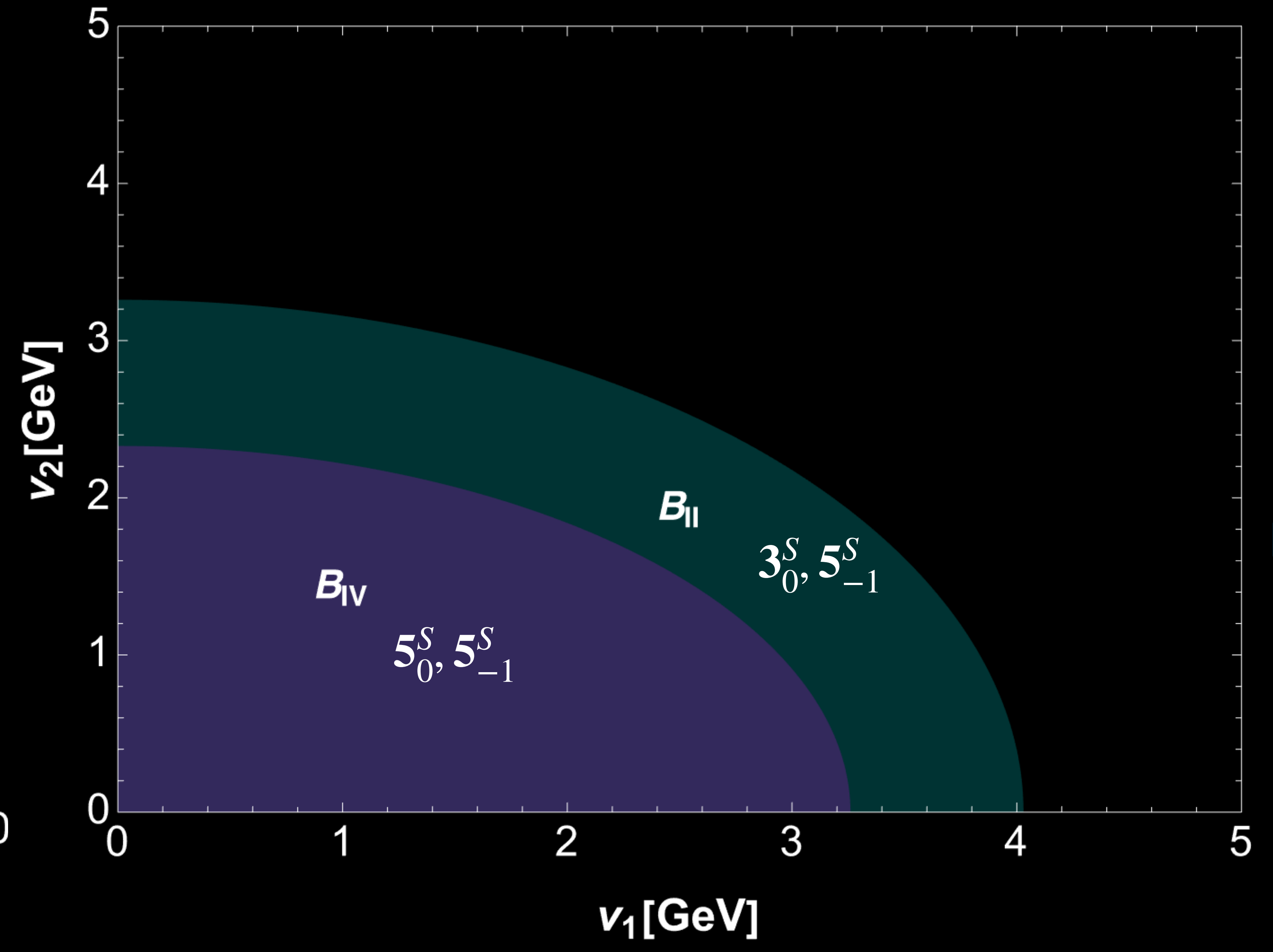
Bounds on VEVs

Class A models: $v_1 \leq 3.3\ \mathrm{GeV}$ for $\mathbf{4}^S_{-1/2}$ and $v_1 \leq 2.6\ \mathrm{GeV}$ for $\mathbf{4}^S_{-3/2}$

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

Holds for only 1 scalar





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

Holds for both scalars

Scalar Sector
Potential

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

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

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

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

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

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

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

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

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

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

Scalar Sector
Potential

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$$V^{\mathbf{B}}_{\not{X}}(H,\Phi_1,\Phi_2) = \lambda_1 H\,H\,\Phi_1\,\Phi_2 \qquad X_1 = -X_2$$

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

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

Scalar Sector

Induced VEVs

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

Scalar Sector
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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

Scalar Sector
Induced VEVs

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

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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 $(n > 5)$

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

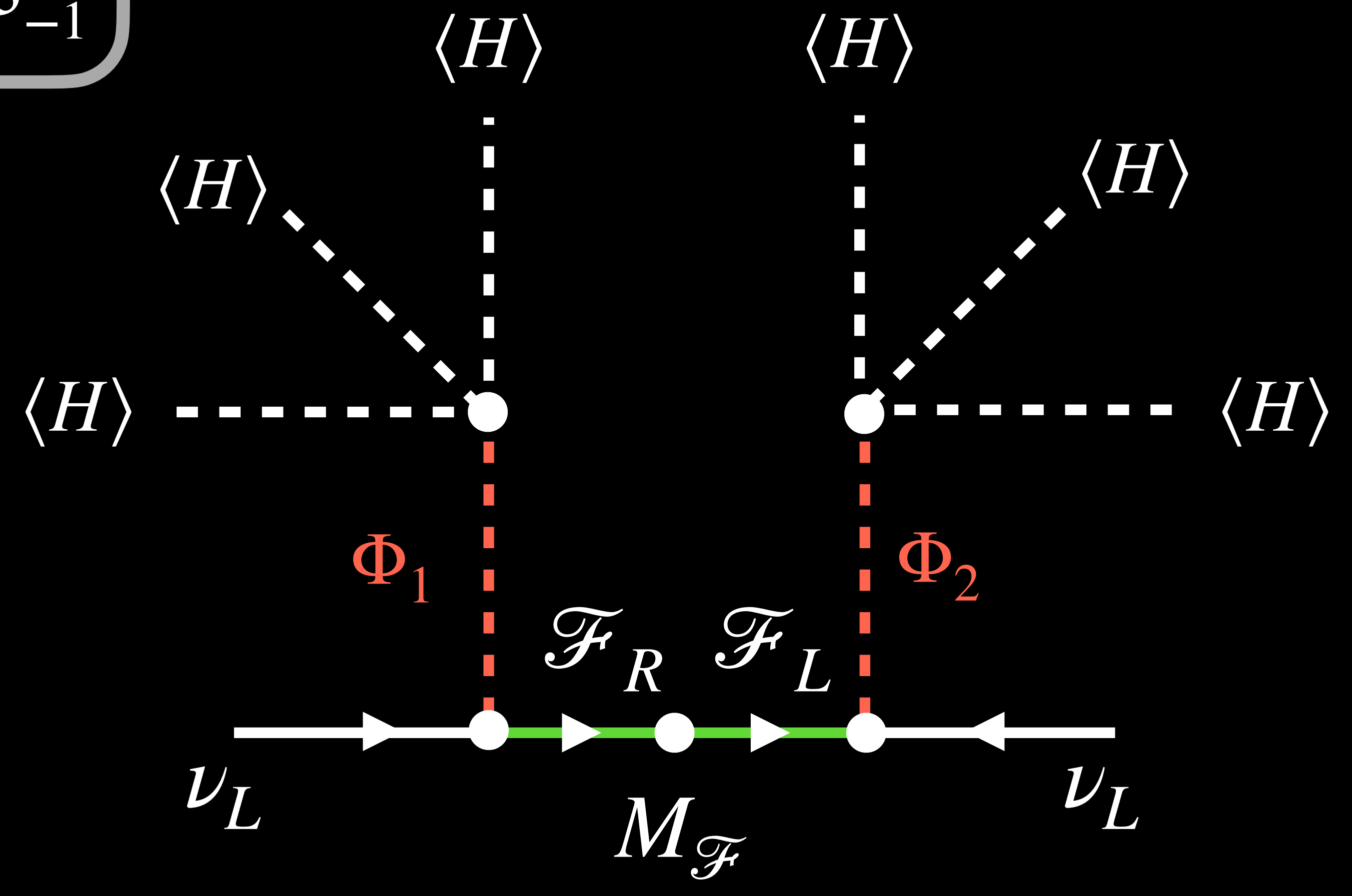
Scalar Sector
Induced VEVs

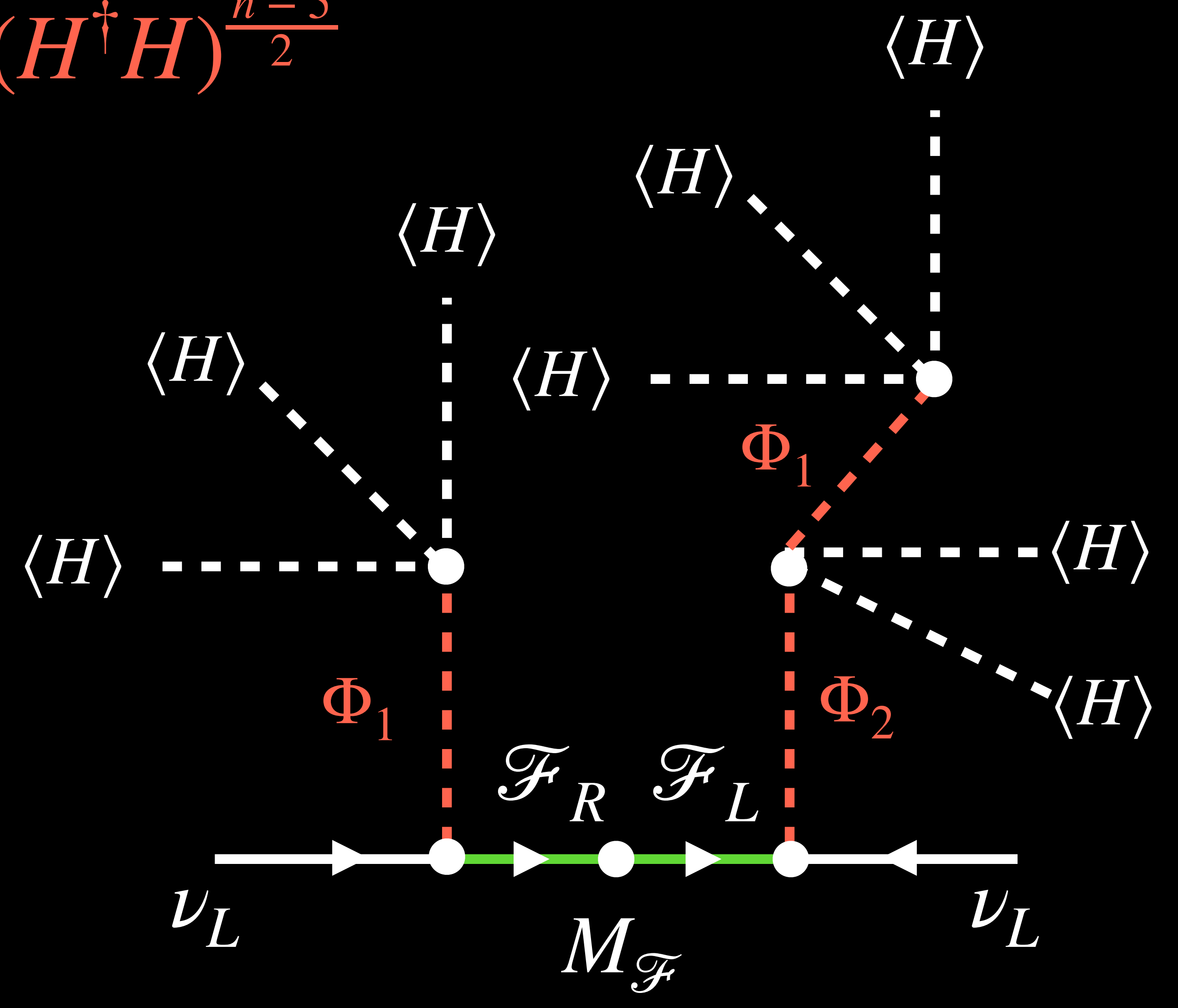
New scalars get induced VEVs → Integrate out the heavy scalars → Higher dimensional operators ($n > 5$)

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

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

$n = 9$





$n = 11$

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

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

Phenomenology

Multi-charged Scalars

Doubly-charged

$\mathbf{4}^S_{1/2}$ $\mathbf{4}^S_{-3/2}$

$\mathbf{5}^S_0$ $\mathbf{5}^S_1$ $\mathbf{5}^S_2$

Triply-charged

$\mathbf{4}^S_{-3/2}$

$\mathbf{5}^S_1$ $\mathbf{5}^S_2$

Quadruply-charged

$\mathbf{5}^S_2$

Production + Decays $\rightarrow$ Interesting phenomenological signatures at colliders

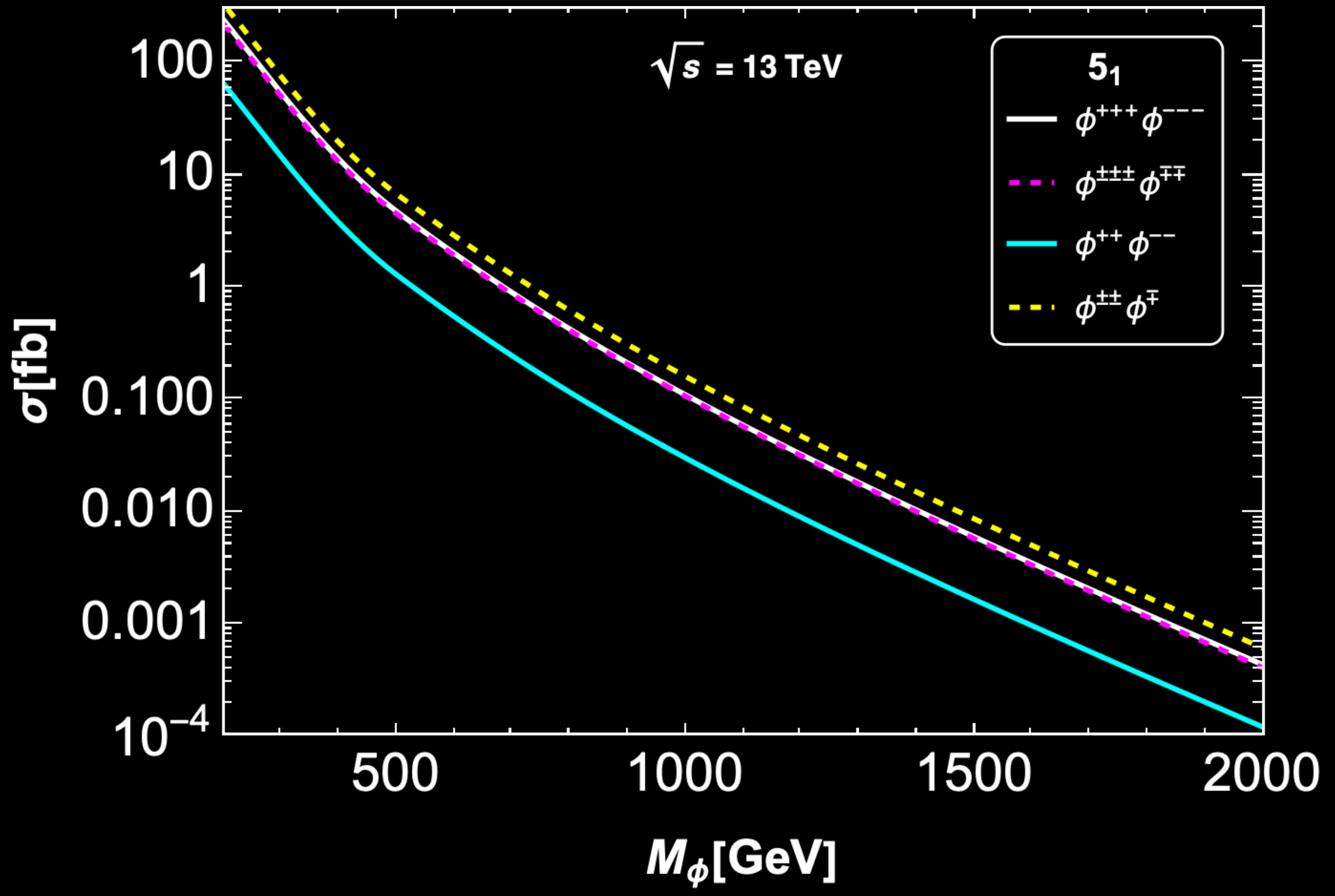
Collider Phenomenology

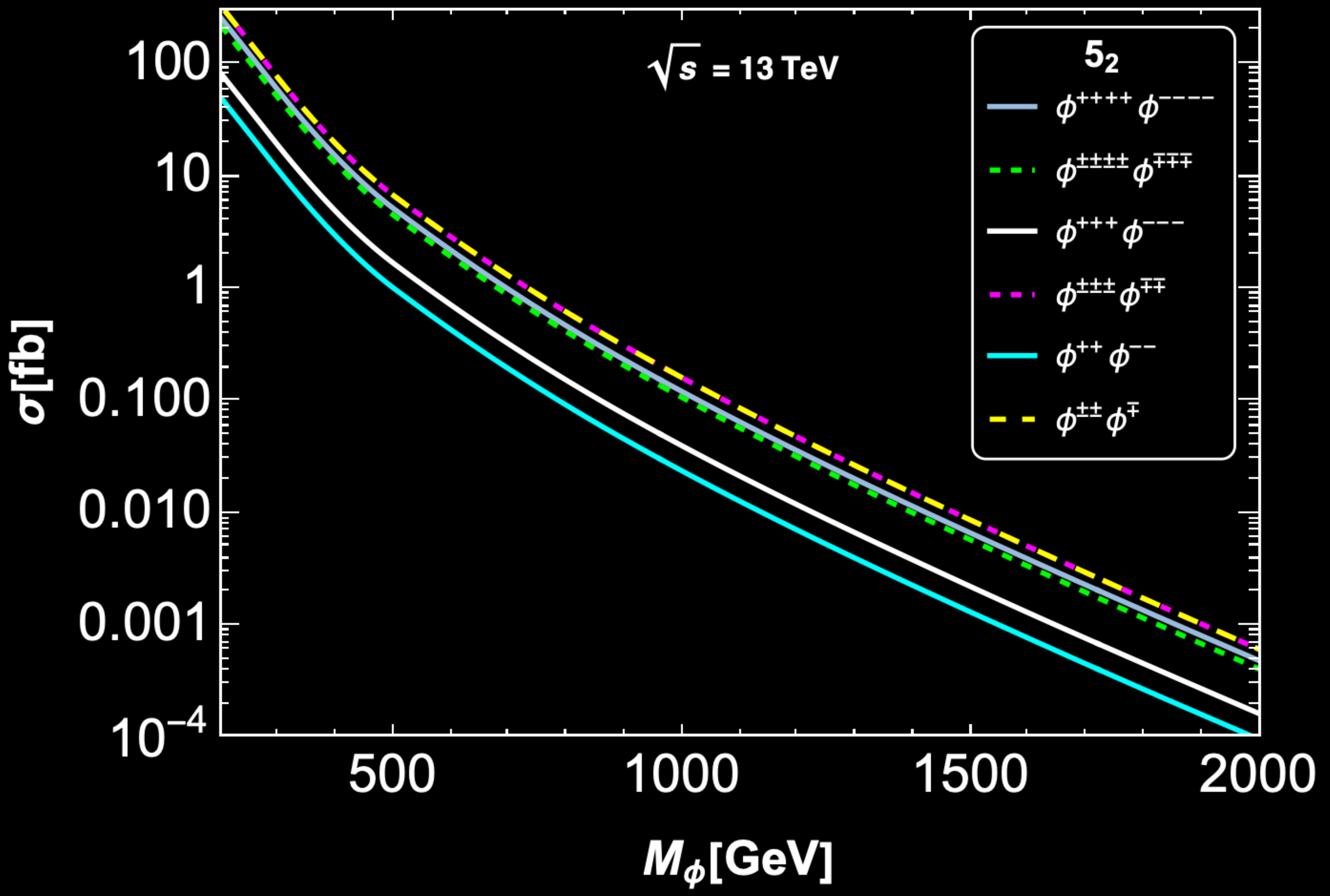
Production of multi-charged scalars

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

$$LL\Phi_i\Phi_j$$

Collider Phenomenology

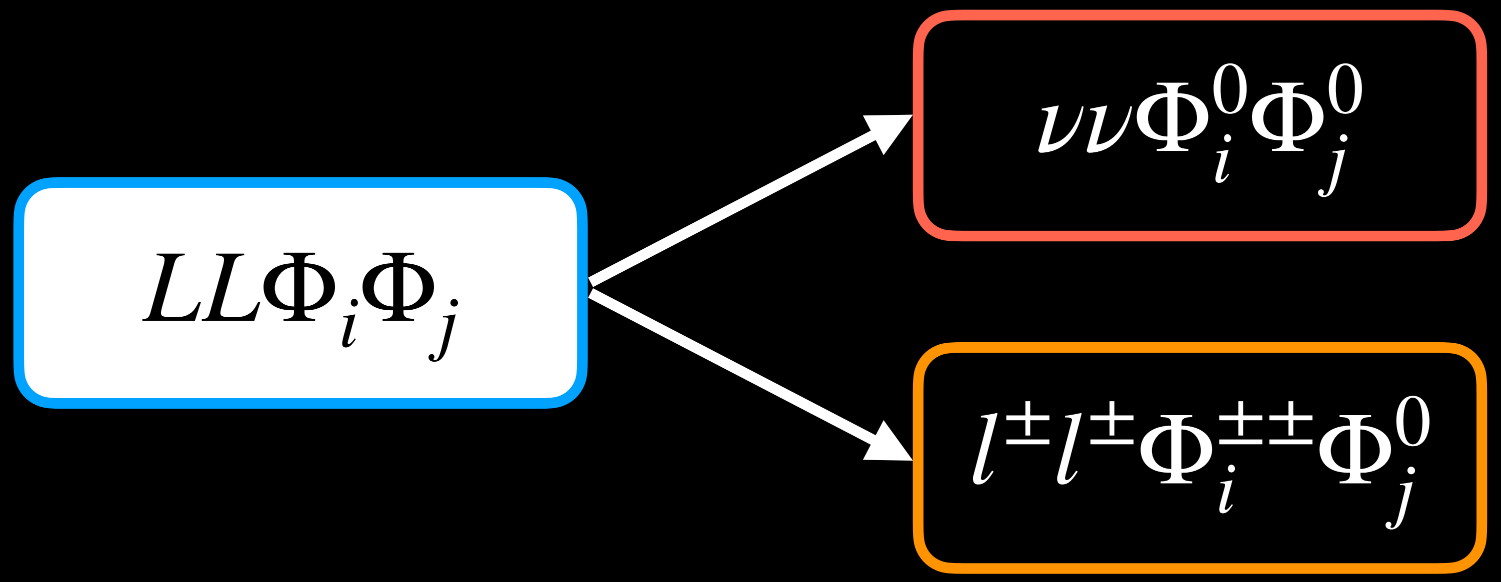
Doubly-charged scalar decays

$LL\Phi_i\Phi_j$ → $\nu\nu\Phi_i^0\Phi_j^0$

Leads to m_ν

Collider Phenomenology

Doubly-charged scalar decays



Leads to m_ν

Effective interaction between doubly charged scalars and a pair of leptons

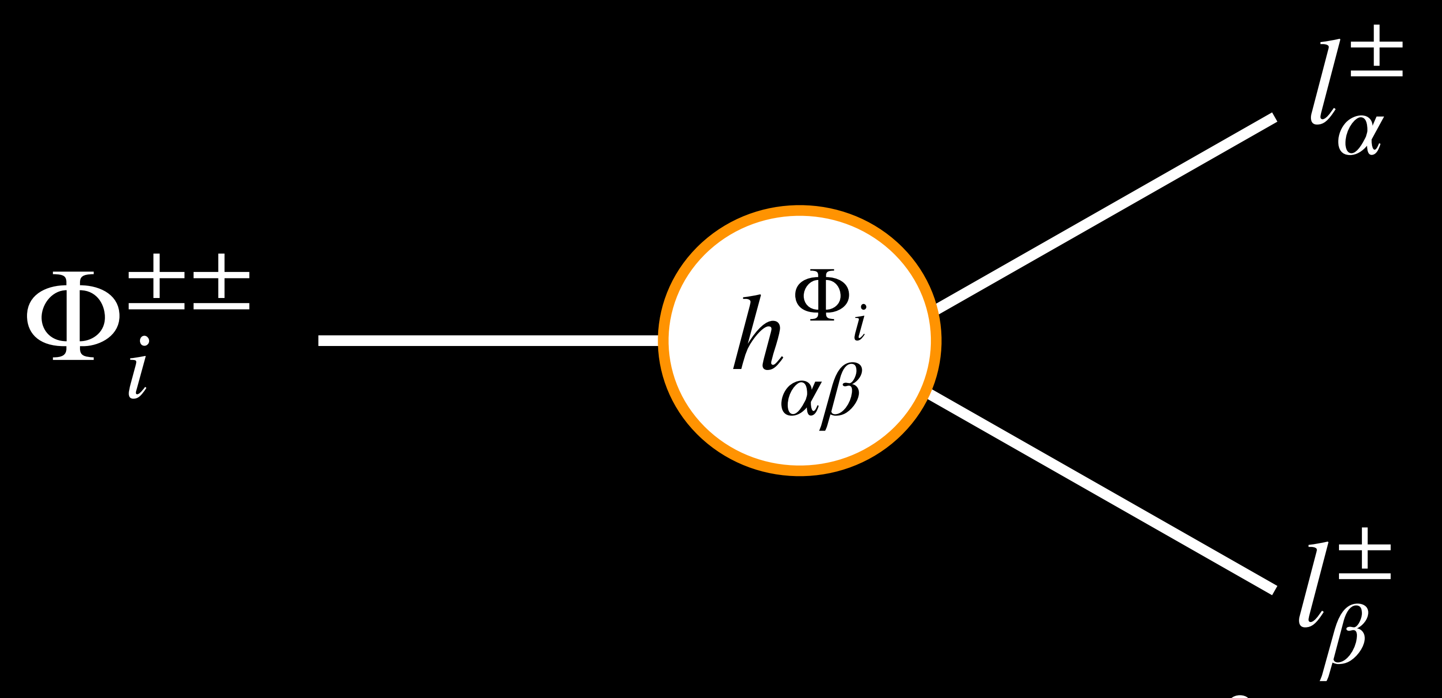
Collider Phenomenology

Doubly-charged scalar decays

I

$LL\Phi_i\Phi_j$ → $\nu\nu\Phi_i^0\Phi_j^0$ — 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



$$\Gamma(\Phi^{\pm\pm} \to l_\alpha^\pm l_\beta^\pm) = \kappa^2 \frac{M_{\Phi^{\pm\pm}}}{8\pi\, v_\Phi^2} \sum_{k=1}^{3} m_k^2$$

← Sum of ν masses

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

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

v_i ← Decays suppressed for large v_i

κ_i ← Model-dependent numerical factor

Collider Phenomenology

Doubly-charged scalar decays

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

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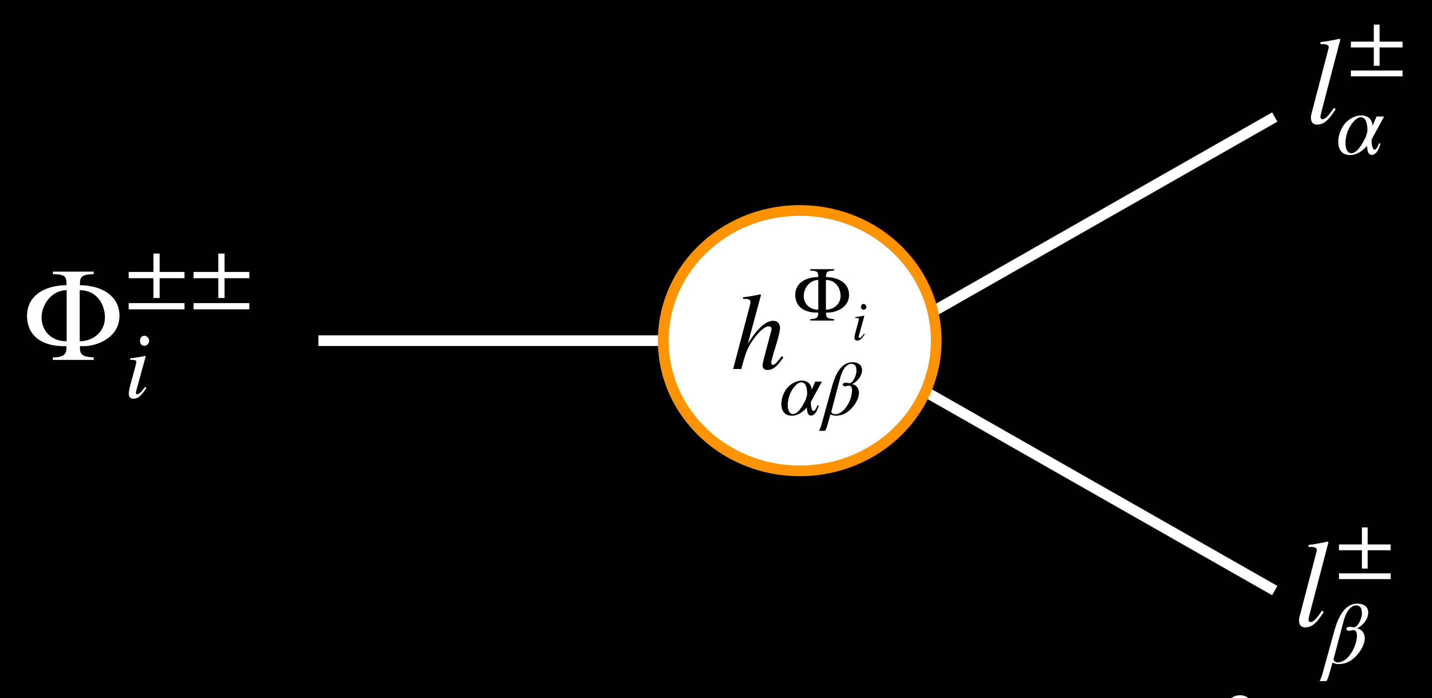

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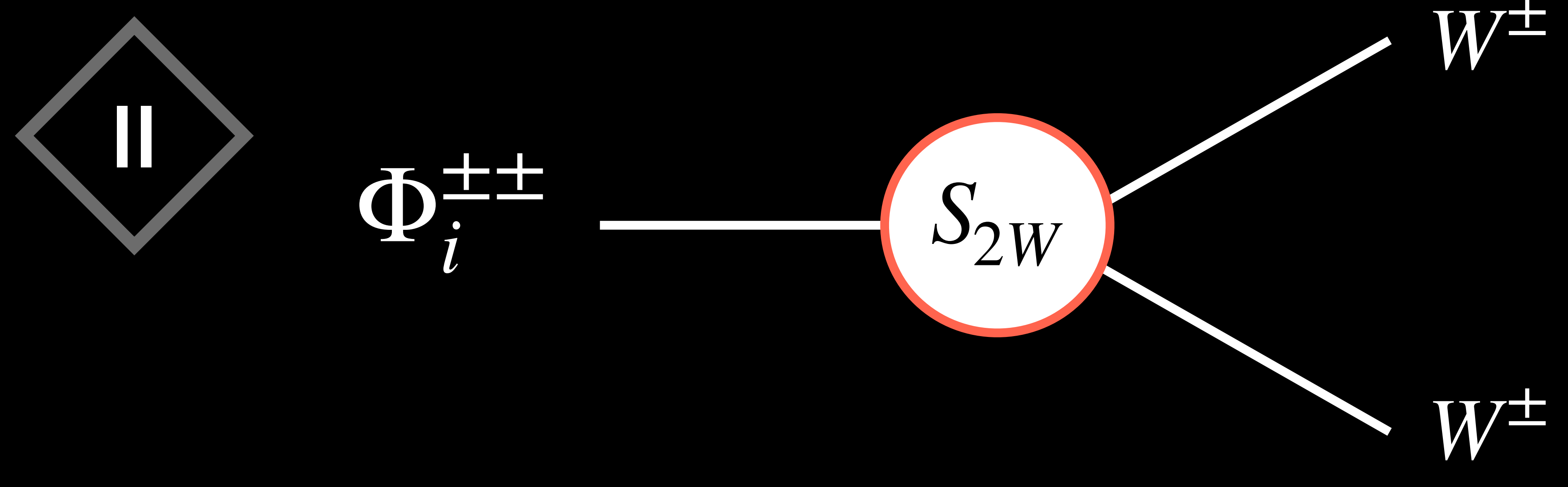
← Sum of ν masses

Decays of doubly charged scalars → Same-sign Dilepton signatures

Free of SM background

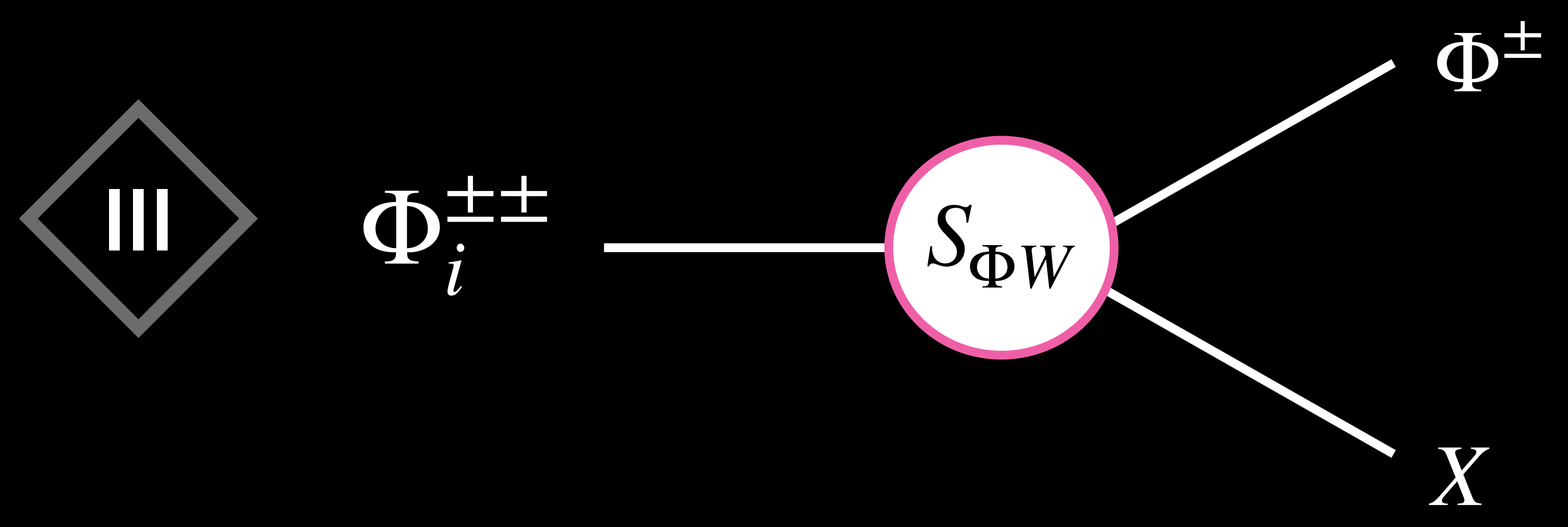
Collider Phenomenology

Doubly-charged scalar decays



$$\Gamma(\Phi^{\pm\pm} \to W^{\pm}W^{\pm}) = S_{2W^{\pm}}^2 \frac{g^4 v_\Phi^2 M_{\Phi^{\pm\pm}}^3}{64\pi M_W^4}$$

Proportional to v_i
Dominant channel for large VEVs



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

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

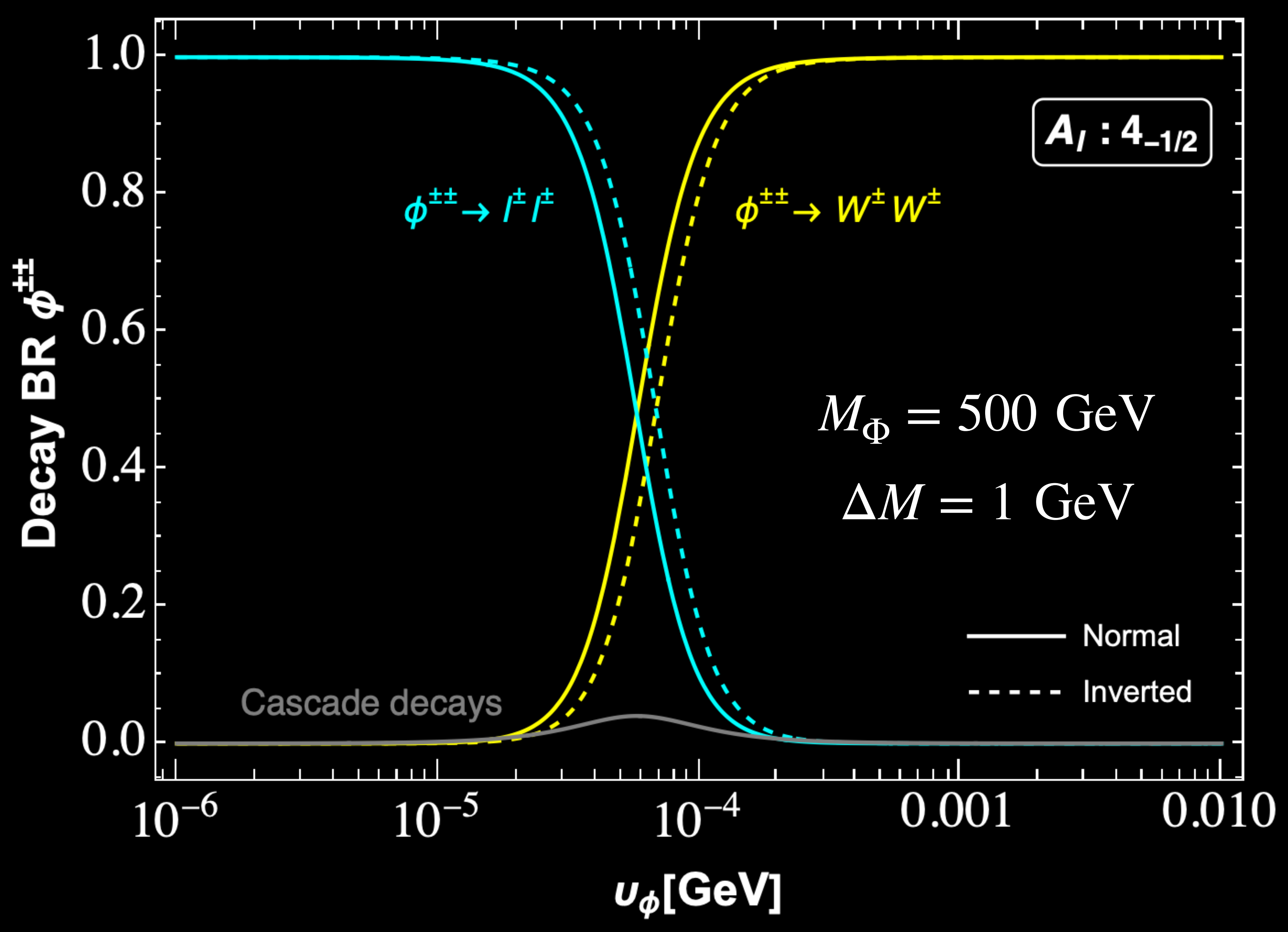
$$\Phi^{\pm\pm} \to \Phi^{\pm}q\bar{q}'$$

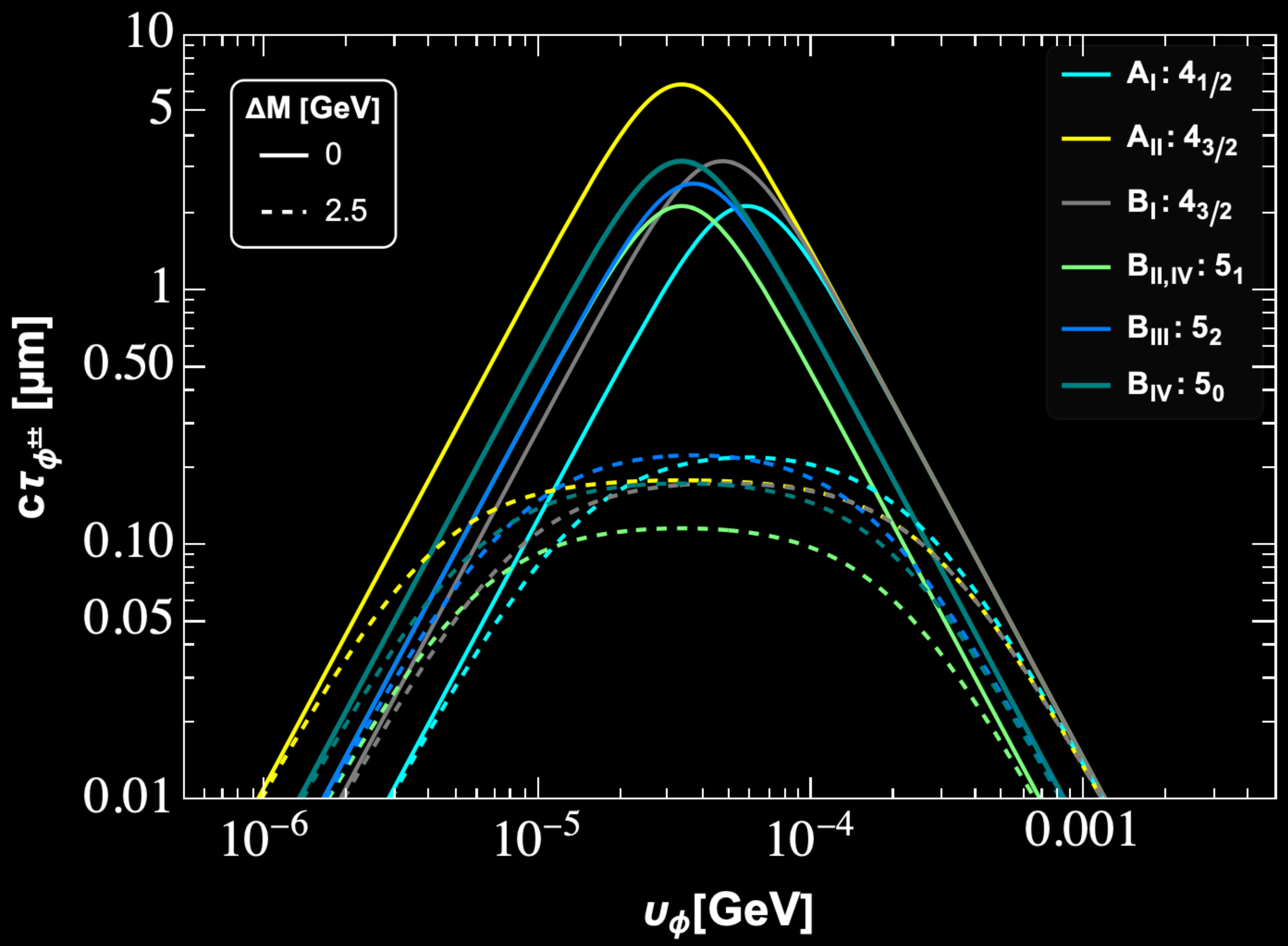
Cascade decays

Proportional to ΔM, the scalar mass splitting

Collider Phenomenology

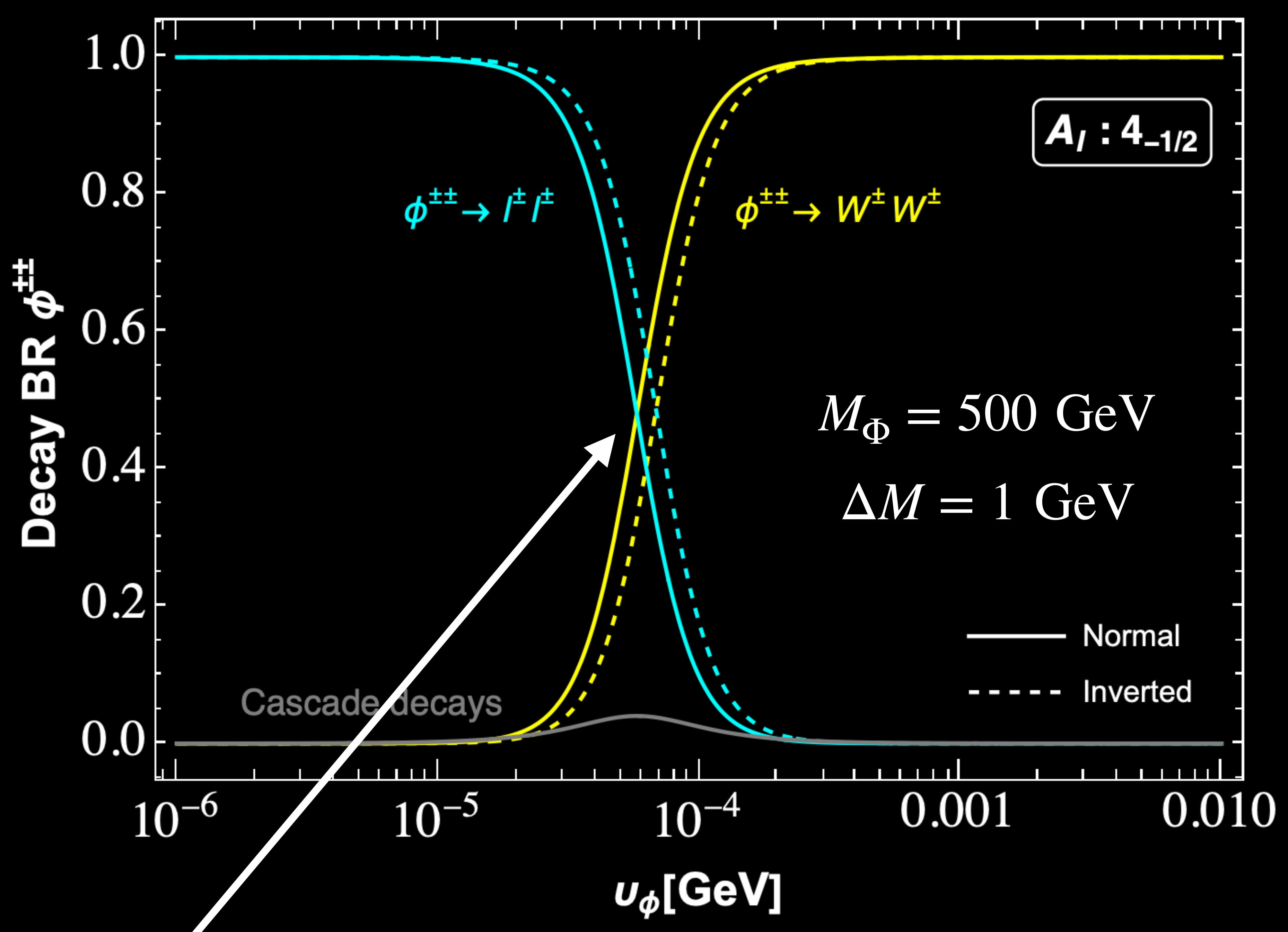
Doubly-charged scalar decays

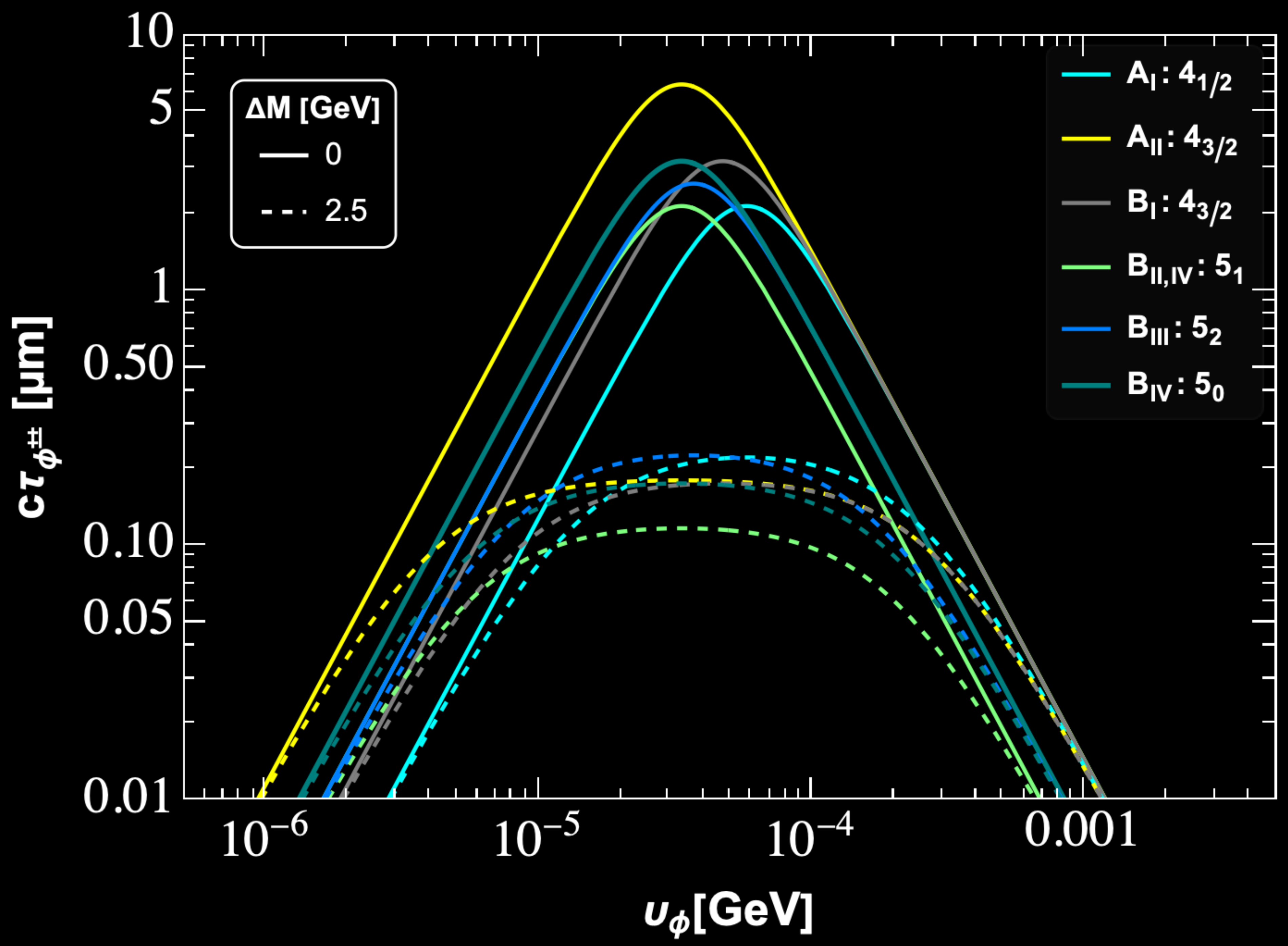




Collider Phenomenology

Doubly-charged scalar decays

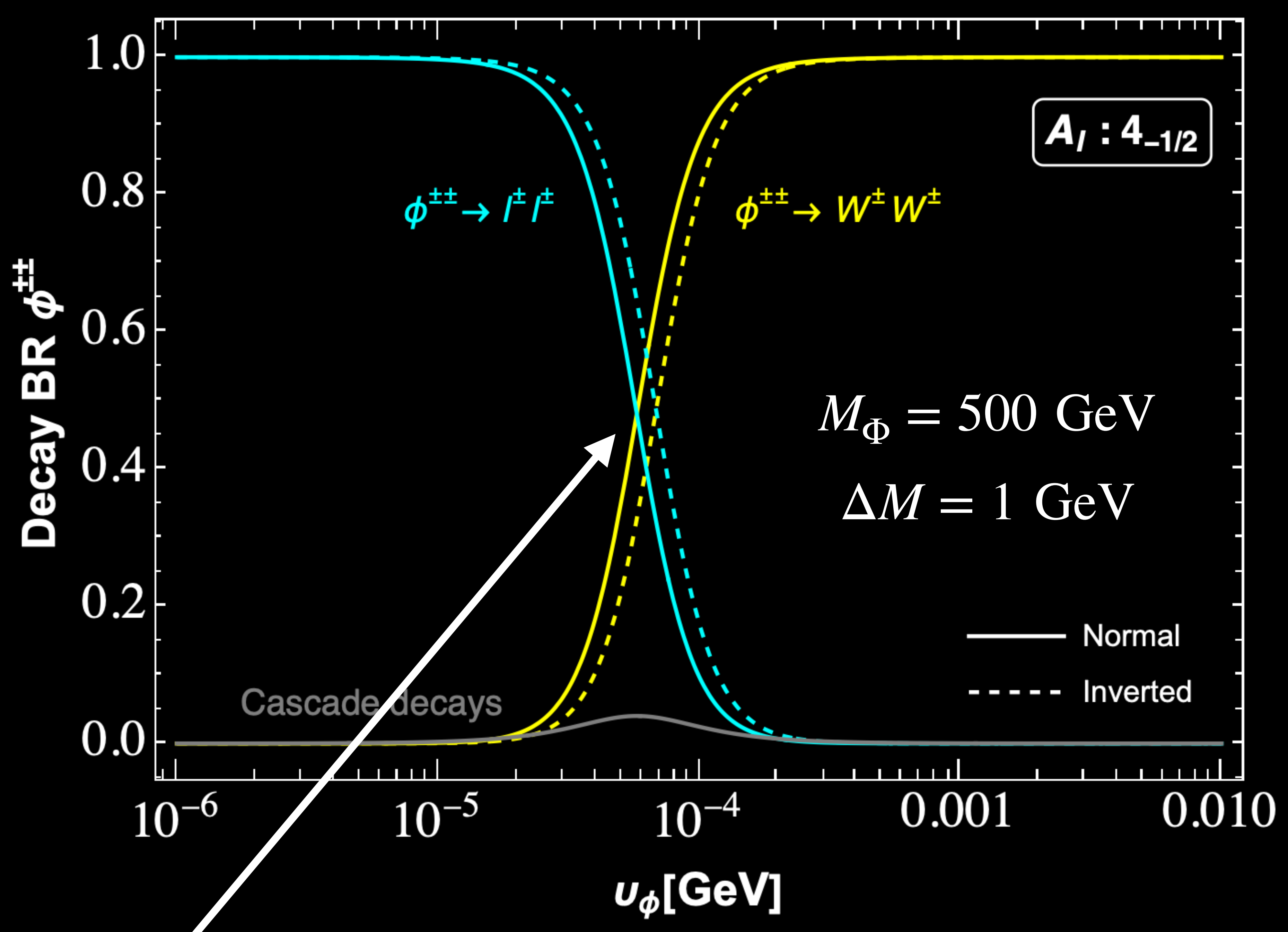


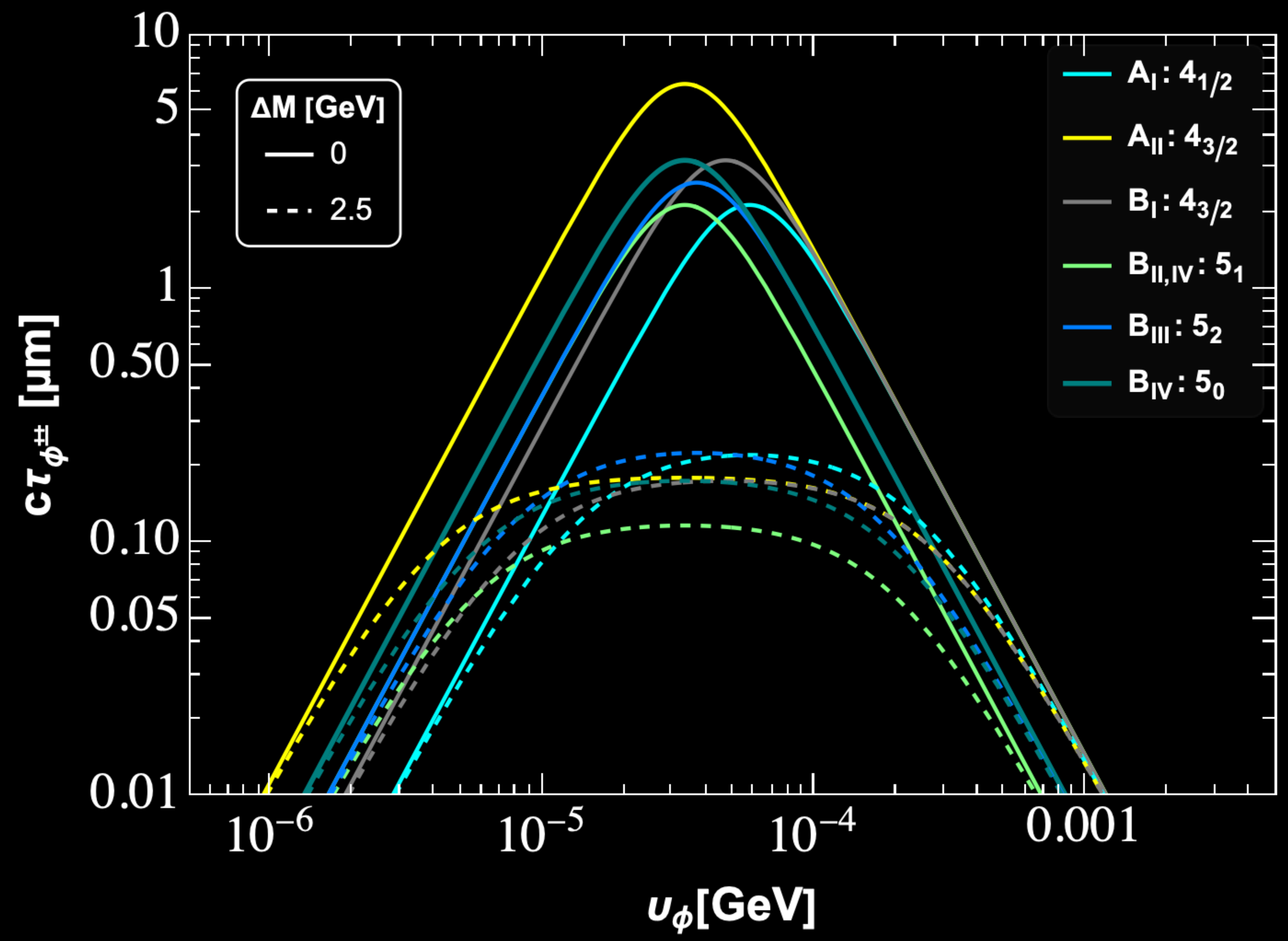


Crossover VEV

Collider Phenomenology

Doubly-charged scalar decays





Crossover VEV

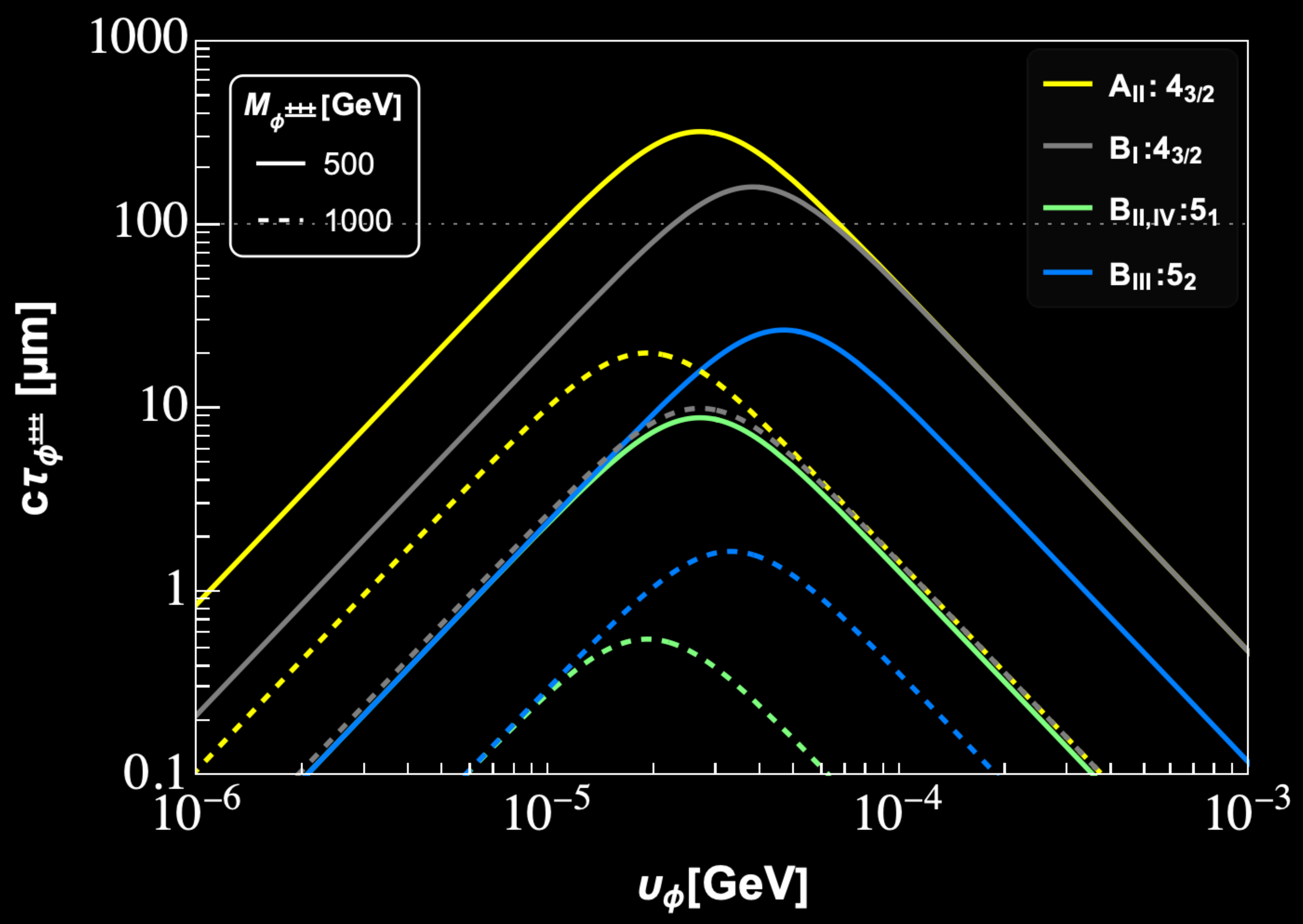
$$v^c_{\Phi^{\pm\pm}} \simeq 65 \text{ KeV} \left(\frac{\kappa}{S_{2W^\pm}}\right)^{1/2} \left(\frac{\sum_i m_i^2}{0.05^2 \text{ eV}^2}\right)^{1/4} \left(\frac{500 \text{ GeV}}{M_{\Phi^{\pm\pm}}}\right)^{1/2}$$

→ Decay length maximised → $< \mathcal{O}(100\mu\text{m})$ No signal for displaced vertices

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

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

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

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)

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)

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)

Collider Phenomenology

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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)

Collider Phenomenology

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

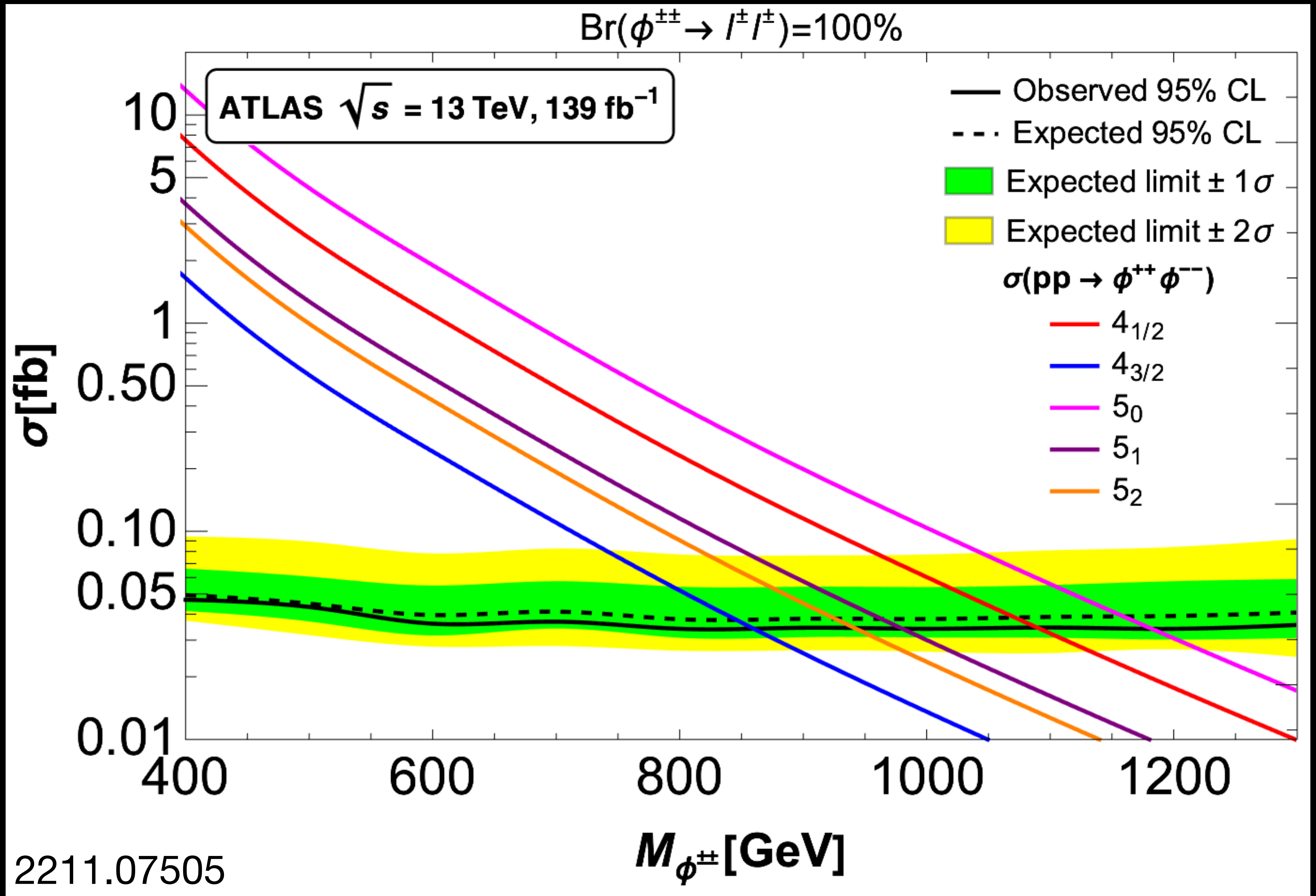
Decays	$\Phi^{2-} \to 2l^-$	$\Phi^{2-} \to 2W^-$	$\Phi^{3-} \to 2l^- W^-$	$\Phi^{3-} \to 3W^-$	$\Phi^{4-} \to 2l^- 2W^-$	$\Phi^{4-} \to 4W^-$
$\Phi^{2+} \to 2l^+$	$2l^+ 2l^-$	$2l^+ 2W^-$	$2l^+ 2l^- W^-$	$2l^+ 3W^-$	✘	✘
$\Phi^{2+} \to 2W^+$	$2W^+ 2l^-$	$2W^+ 2W^-$	$2W^+ W^- 2l^-$	$2W^+ 3W^-$	✘	✘
$\Phi^{3+}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

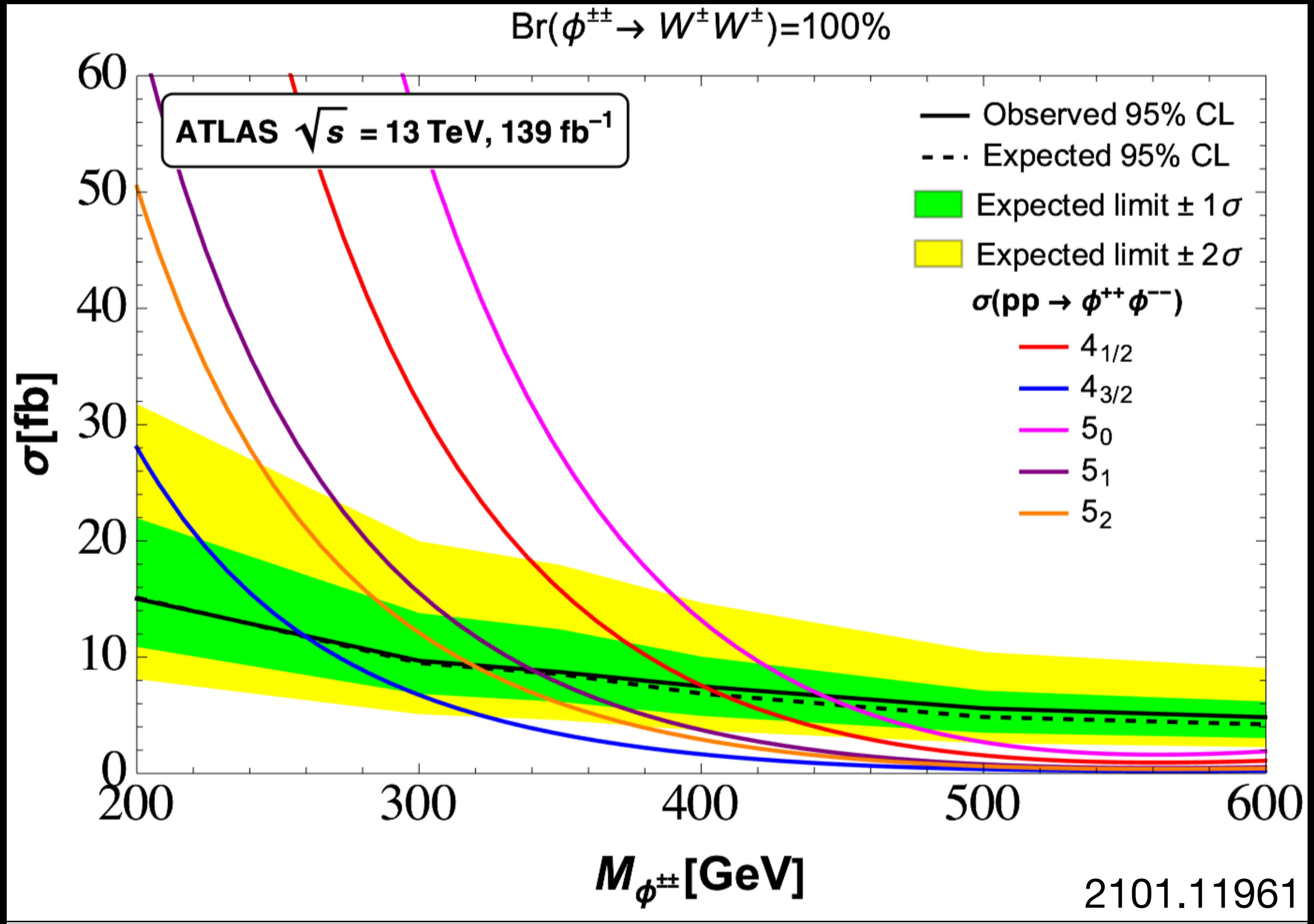
Bambhaniya, Chakrabortty, Goswami Konar (2013); Ghosh, Jana, Nandi (2018)

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





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

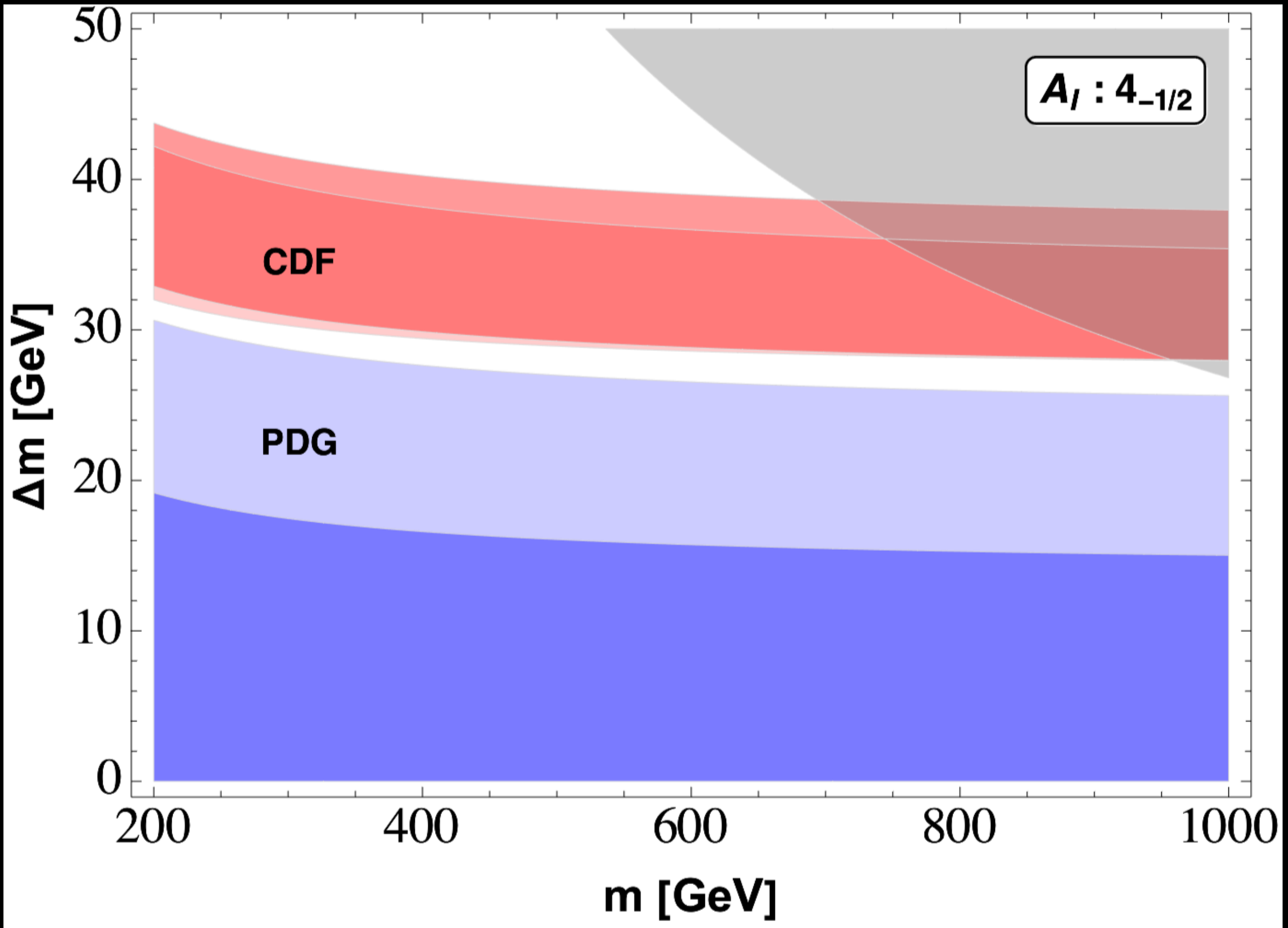
Take U = 0 → Improves the precision on S and T

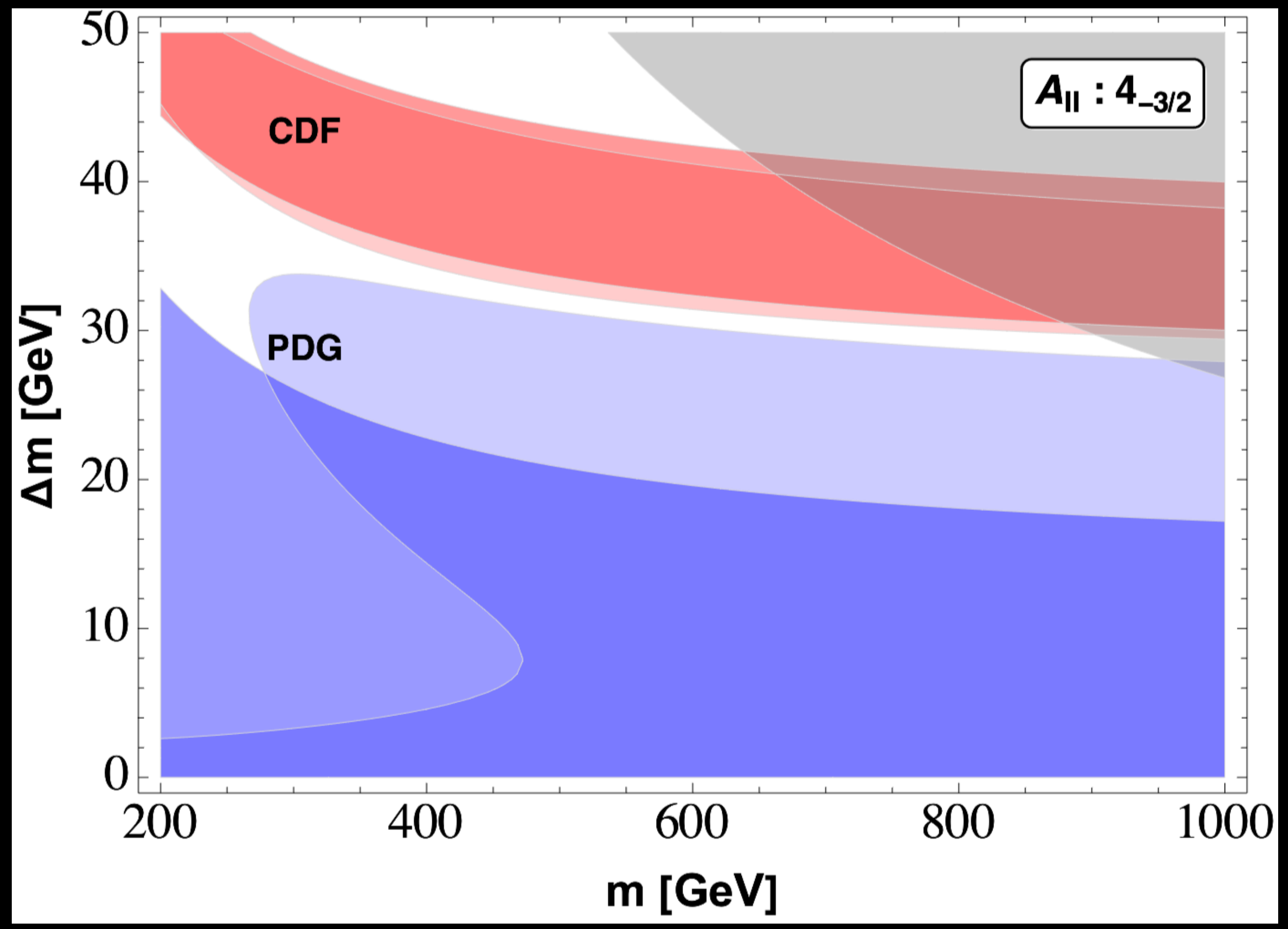
$$\Phi = (\Phi_I, \Phi_{I-1}, \ldots, \Phi_{-I})^T \quad M_{\Phi_{-I}} = m, M_{\Phi_{-I+1}} = m + \Delta m, \ldots, M_{\Phi_I} = m + 2I\,\Delta m$$

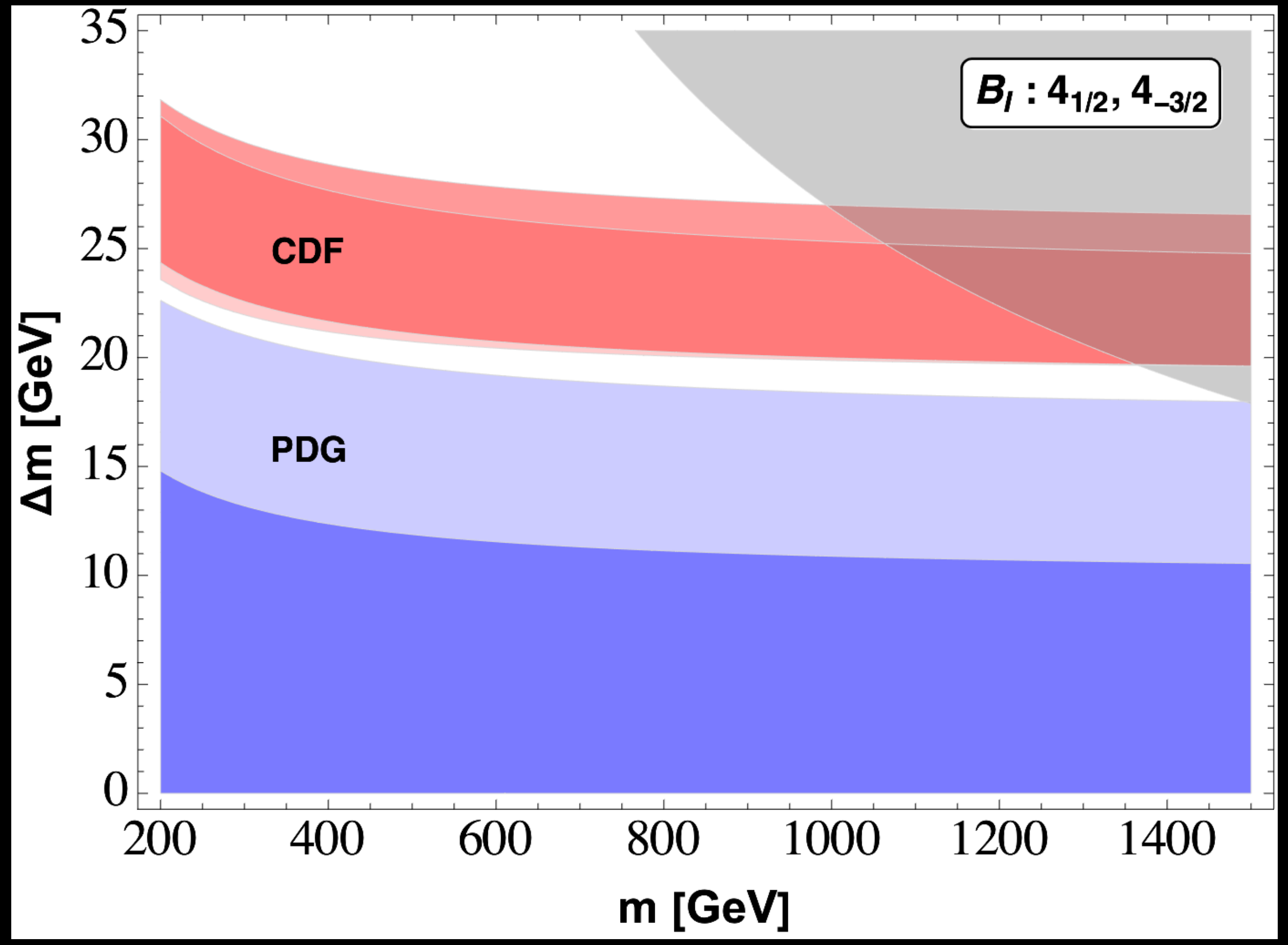
Electroweak Precision Tests

At Loop-level

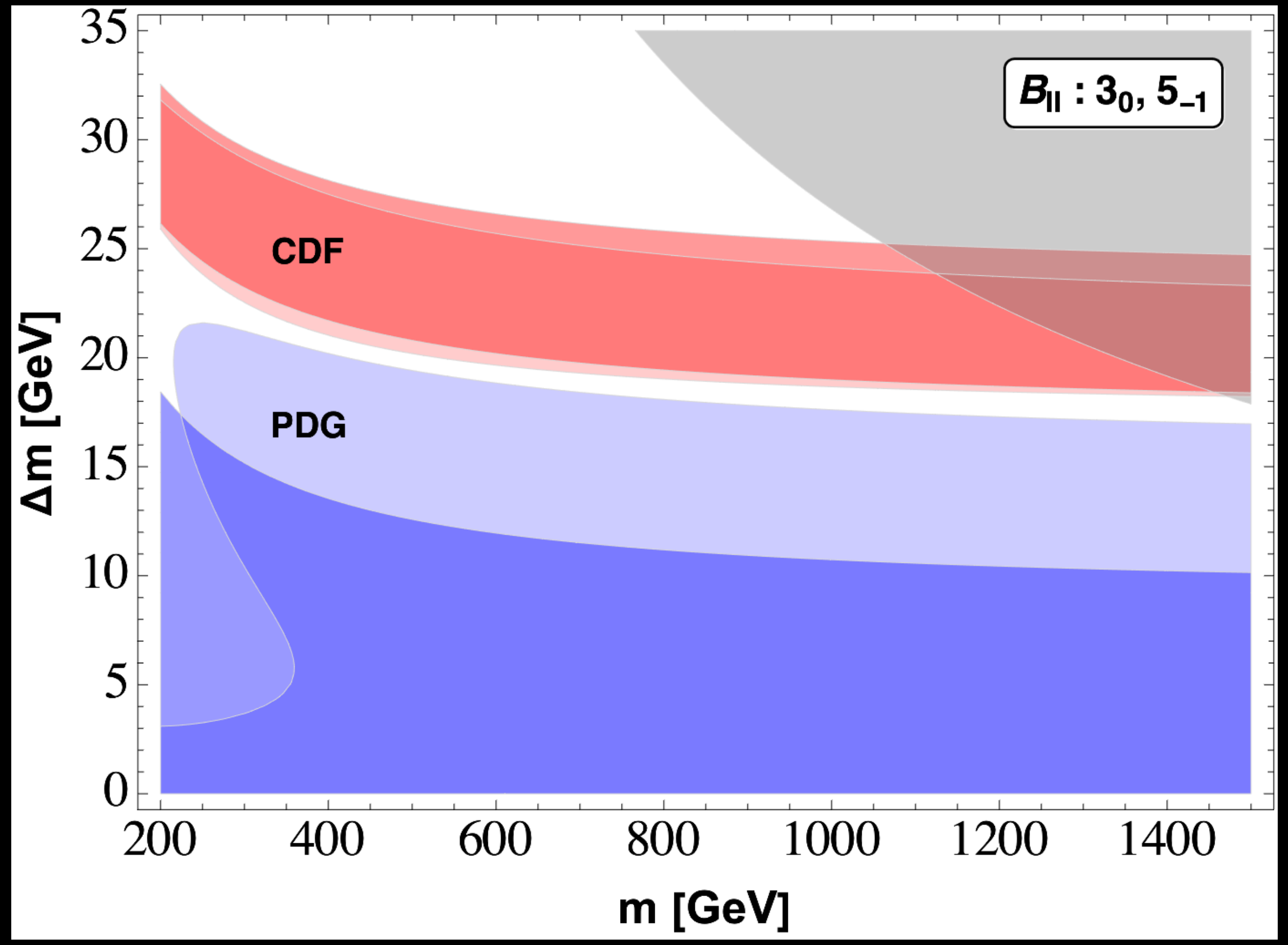
2 parameter χ^2 analysis

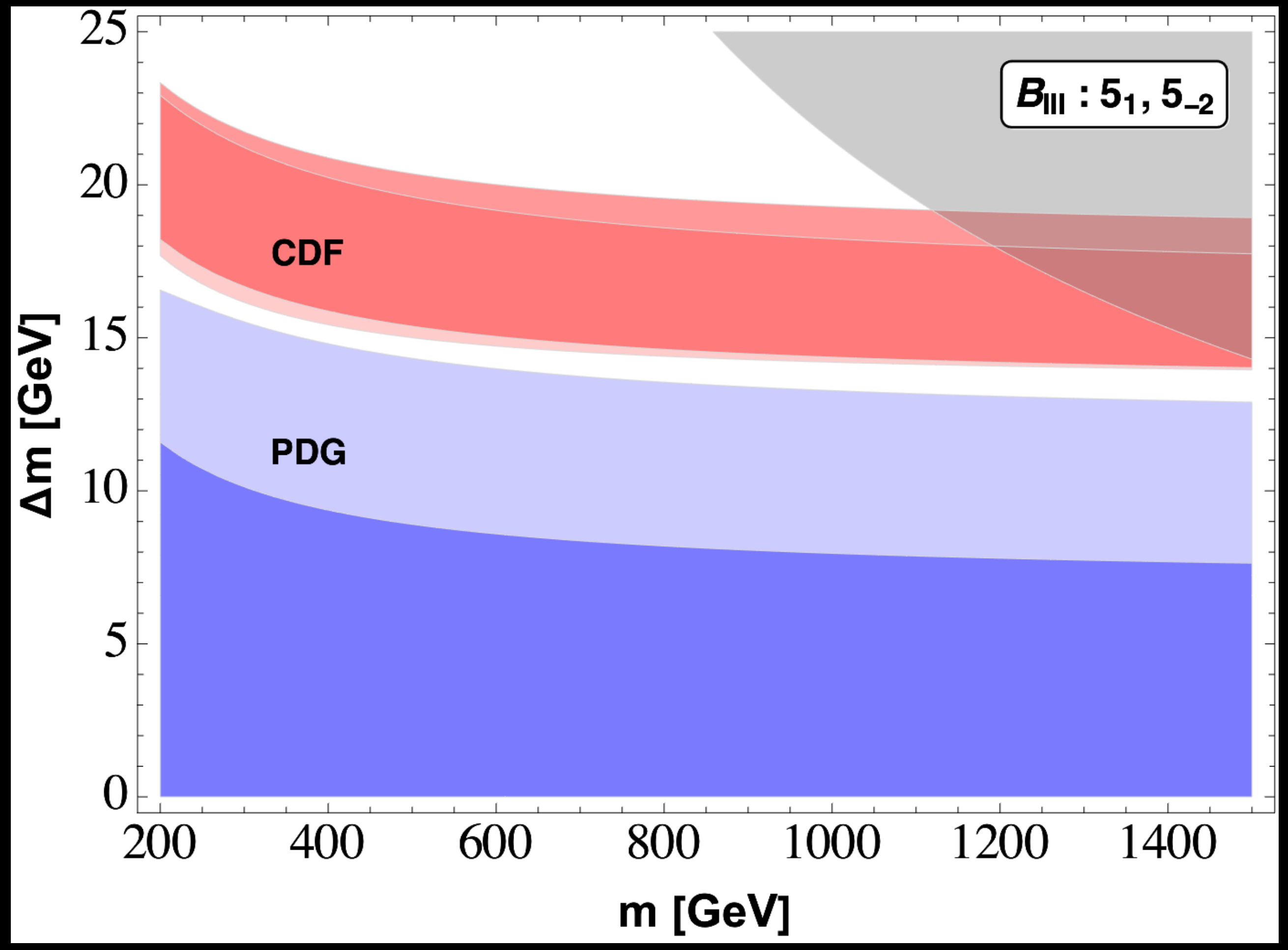


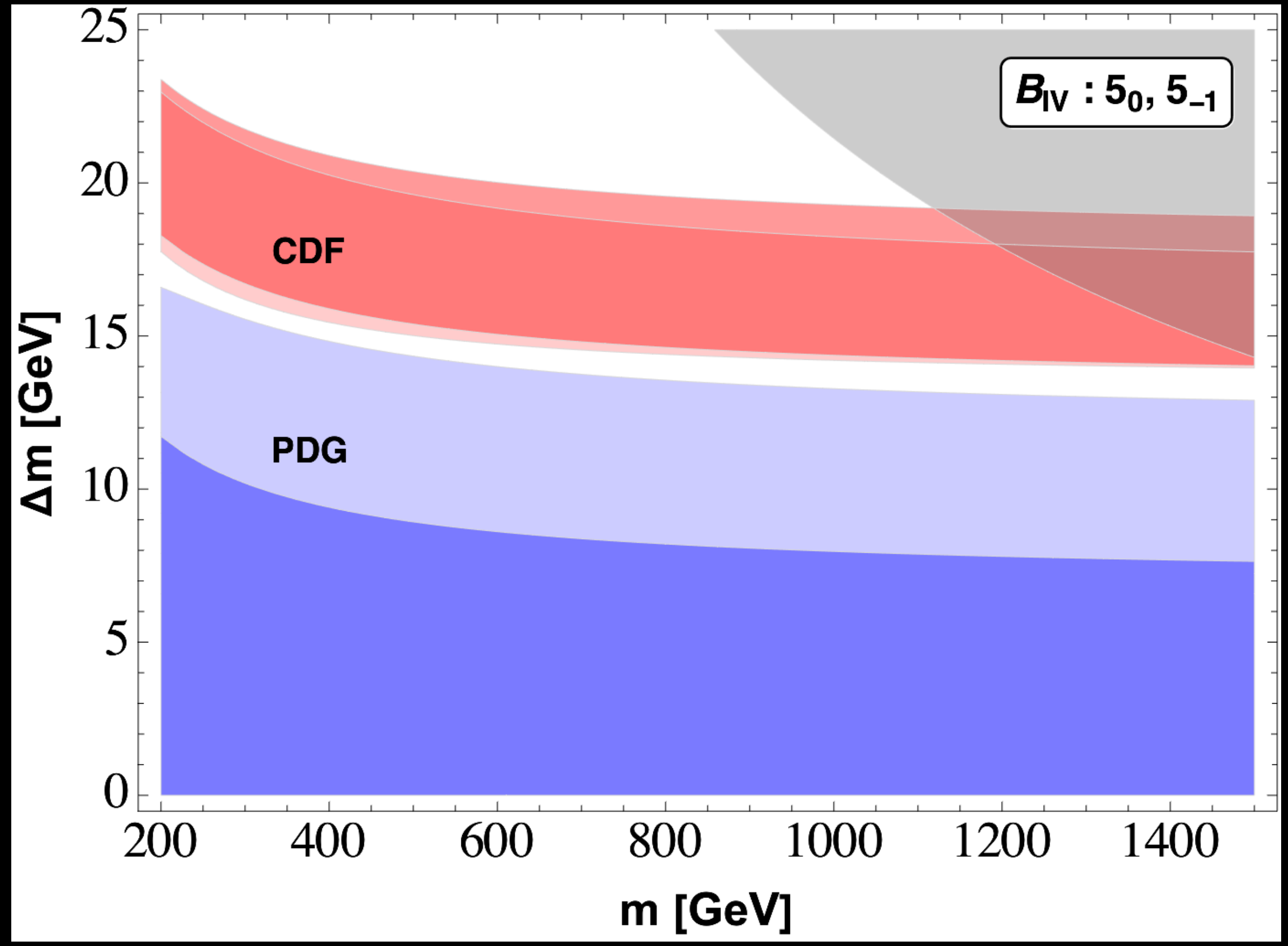




$$\Delta m \sim \mathcal{O}(0.1)\,\lambda\,\frac{v^2}{m}$$







Conclusions

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

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

Quintuplet cut-off → 6 Genuine models (2 with 1 new scalar, 4 with 2 new scalars)

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

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

Other phenomenological implications → Non-unitarity of PMNS matrix, LFV decays, Universality violation

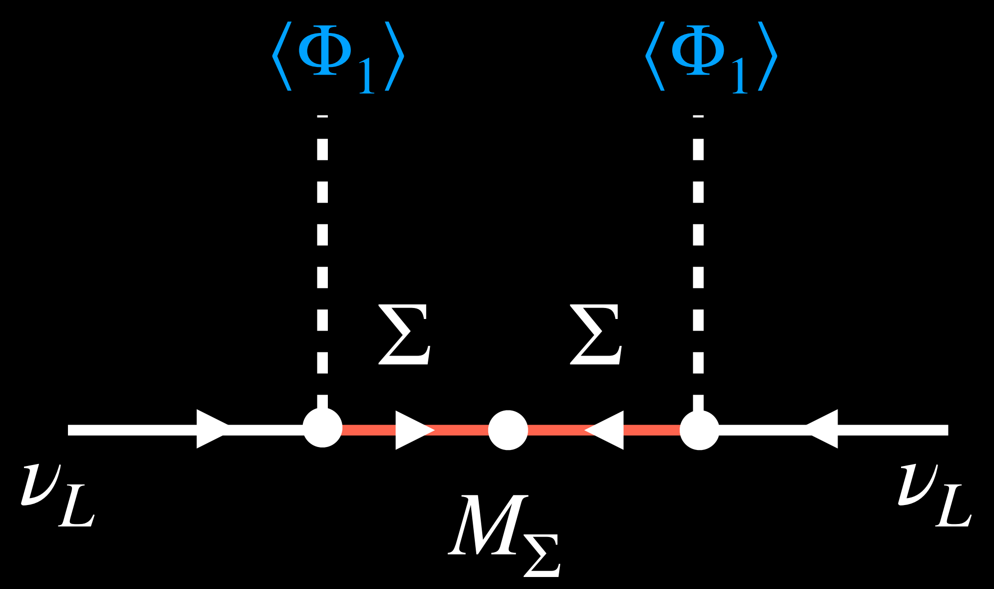
Backup

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

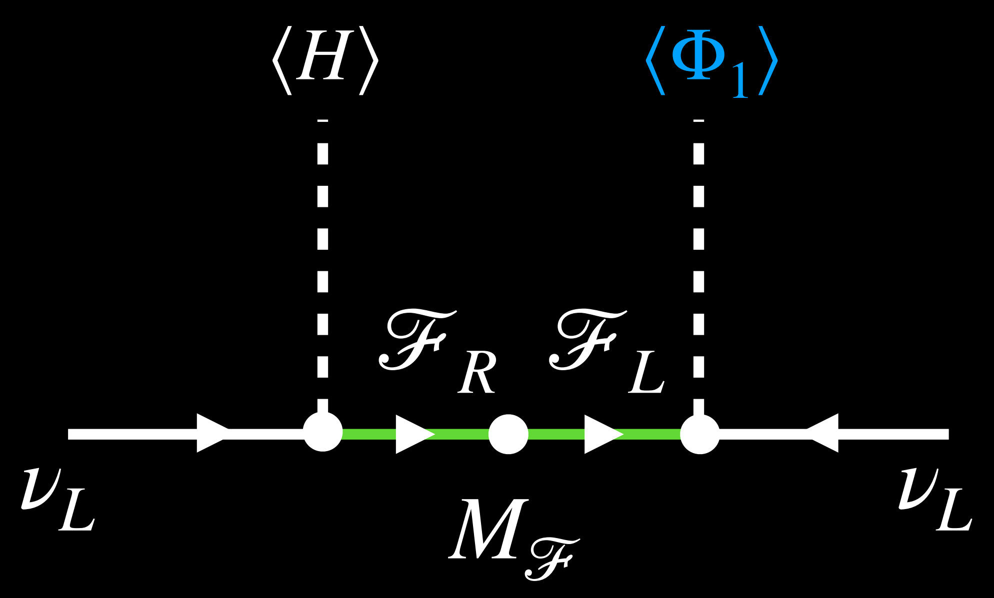
5^F_0

$4^S_{-1/2}$

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

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

$\mathcal{O}_5^{(2)} = (L\Phi_i)_{\mathbf{N}}(L\Phi_j)_{\mathbf{N}}$ ⟶ $\mathbf{N_2} = \mathbf{N_1} + 2$ 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

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

$\mathbf{N_2} = \mathbf{N_1} + 2$ $\quad (\mathbf{2N_1 + 1})_0^F$

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

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

Vector-like (Y ≠ 0)

$|Y_1 + Y_2| = 1$

Both even/odd reps. allowed

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

$\mathbf{N_1} = \mathbf{N_2}$ $\quad (\mathbf{N_1 \pm 1})^F_{-1/2-Y_1}$

$\mathbf{N_1} < \mathbf{N_2}$ $\quad (\mathbf{N_1 + 1})^F_{-1/2-Y_1}$

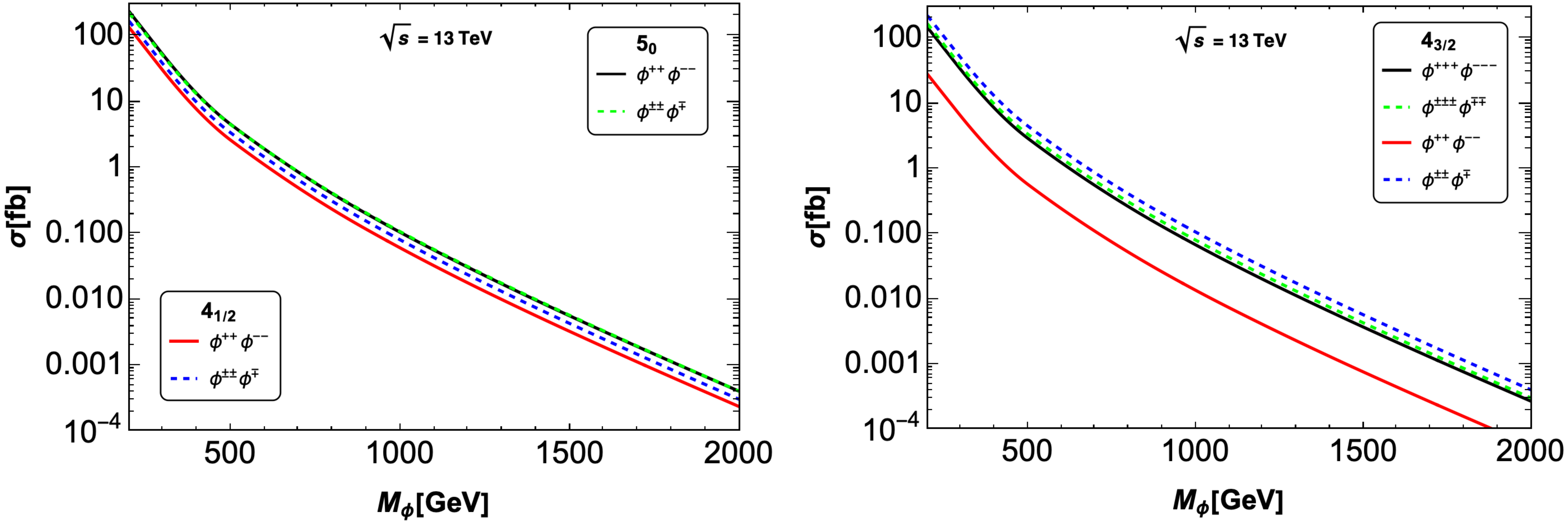
Collider Phenomenology

Production of multi-charged scalars

Pair production   Associated production

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

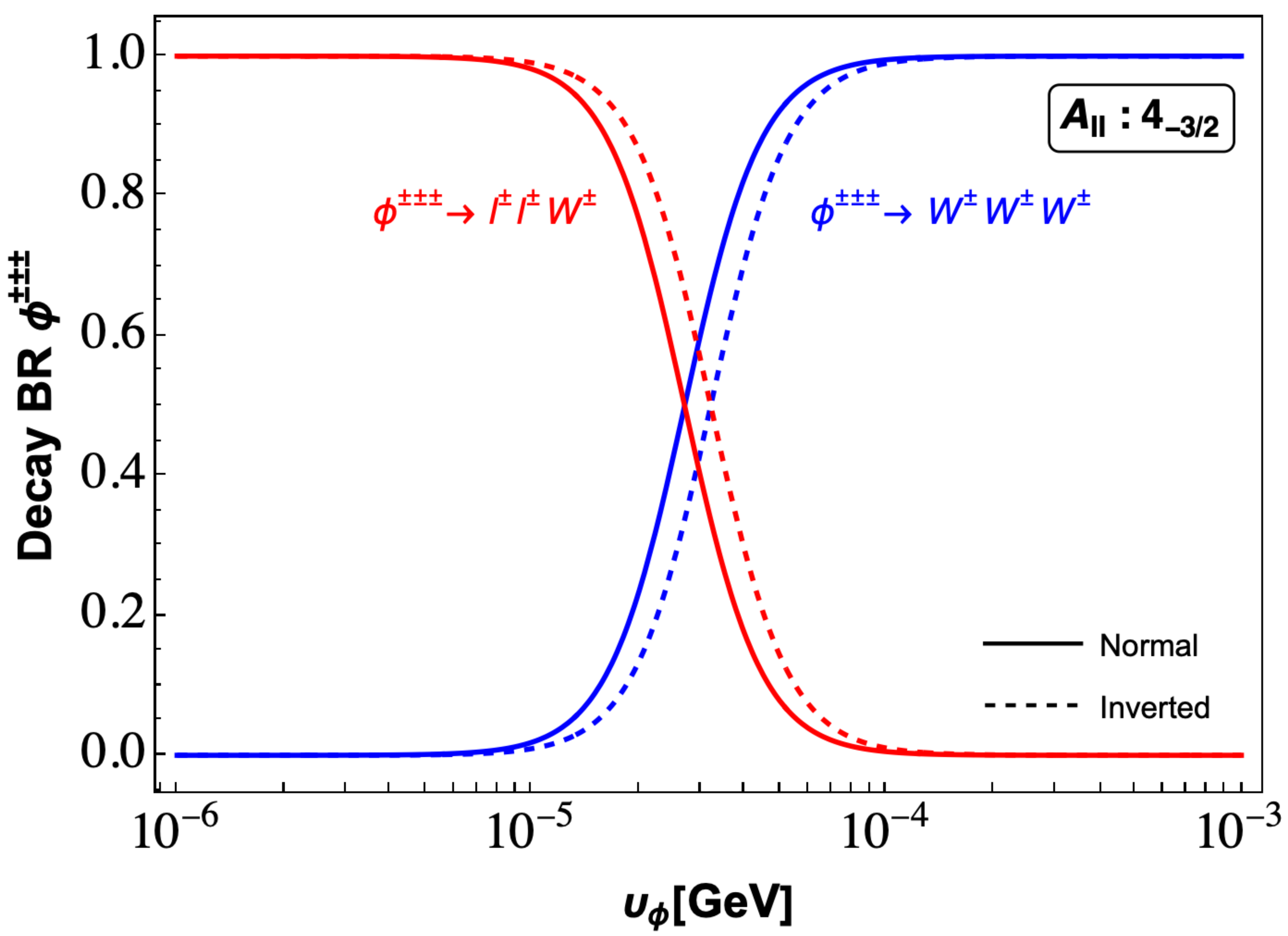
$$q\bar{q}' \to W^{\pm} \to \Phi^{\pm\pm\pm\pm}\Phi^{\mp\mp\mp}, \Phi^{\pm\pm\pm}\Phi^{\mp\mp}, \Phi^{\pm\pm}\Phi^{\mp}$$

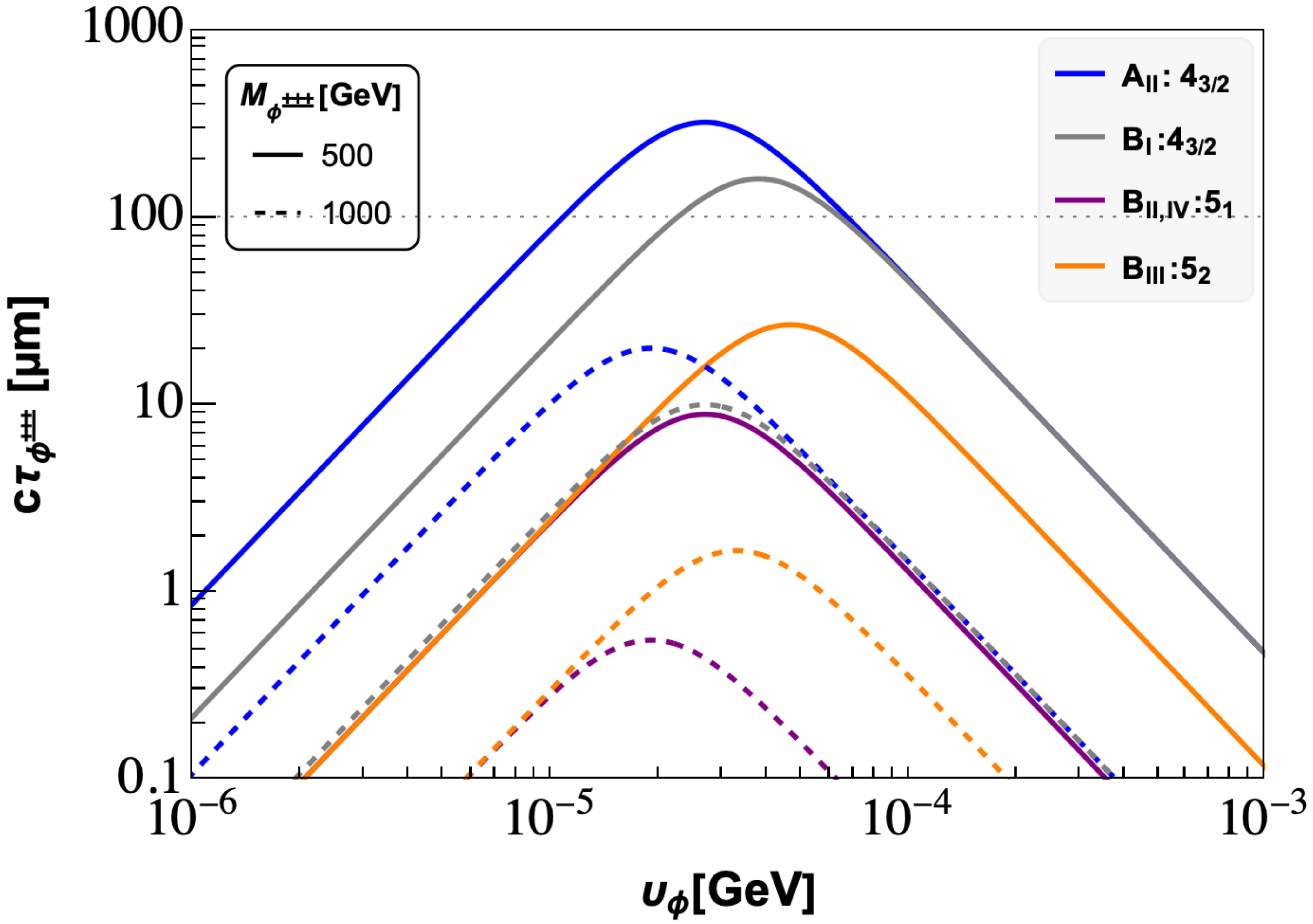


Collider Phenomenology

Triply-charged scalar decays

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



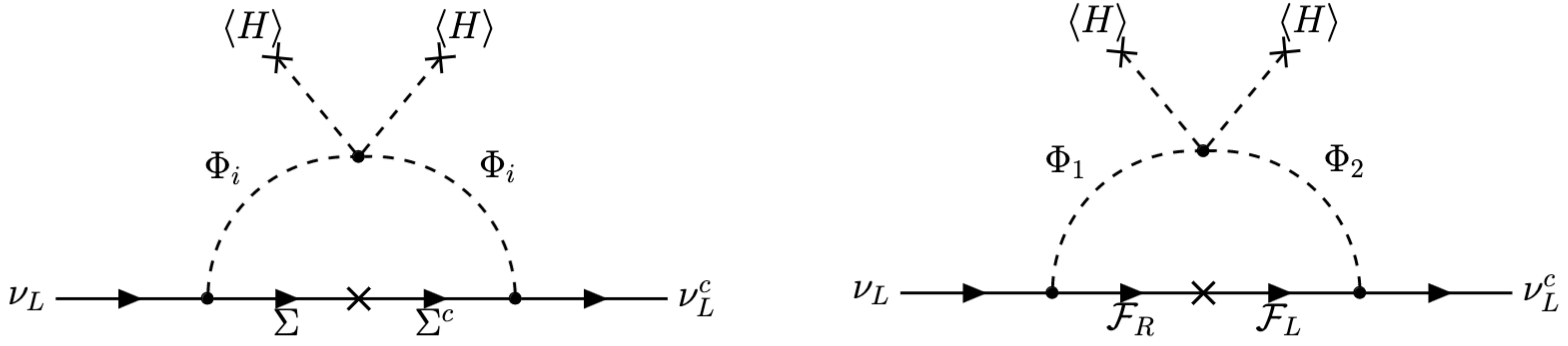


May lead to Displaced vertices

Ghosh, Jana, Nandi (2018)

Neutrino Masses

One-loop contribution



$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \eta\,\bar{\lambda}\,\frac{v^2}{8\pi^2}\sum_k y_{1,\alpha k}\,y_{1,\beta k}\,M_\Sigma\;F_2(M_{(\Phi_1)^R_0}, M_{(\Phi_1)^I_0}, M_\Sigma) \quad \text{for } \mathbf{A_1}$$

$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \eta\,\lambda_1\,\frac{v^2}{8\pi^2}\left(y_H y_1^T + y_1 y_H^T\right)_{\alpha\beta}\,M_{\mathcal{F}}\,F_2(M_{\Phi_1}, M_H, M_{\mathcal{F}}) \quad \text{for } \mathbf{A_2}$$

$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \eta\,\lambda_{12}\,\frac{v^2}{8\pi^2}\left(y_1 y_2^T + y_2 y_1^T\right)_{\alpha\beta}\,M_{\mathcal{F}}\,F_2(M_{\Phi_1}, M_{\Phi_2}, M_{\mathcal{F}}) \quad \text{for } \mathbf{B_i}$$

$$F_2(x,y,z) = \frac{x^2}{x^2 - z^2}\ln\frac{x^2}{z^2} - \frac{y^2}{y^2 - z^2}\ln\frac{y^2}{z^2}$$

Neutrino Masses

One-loop contribution

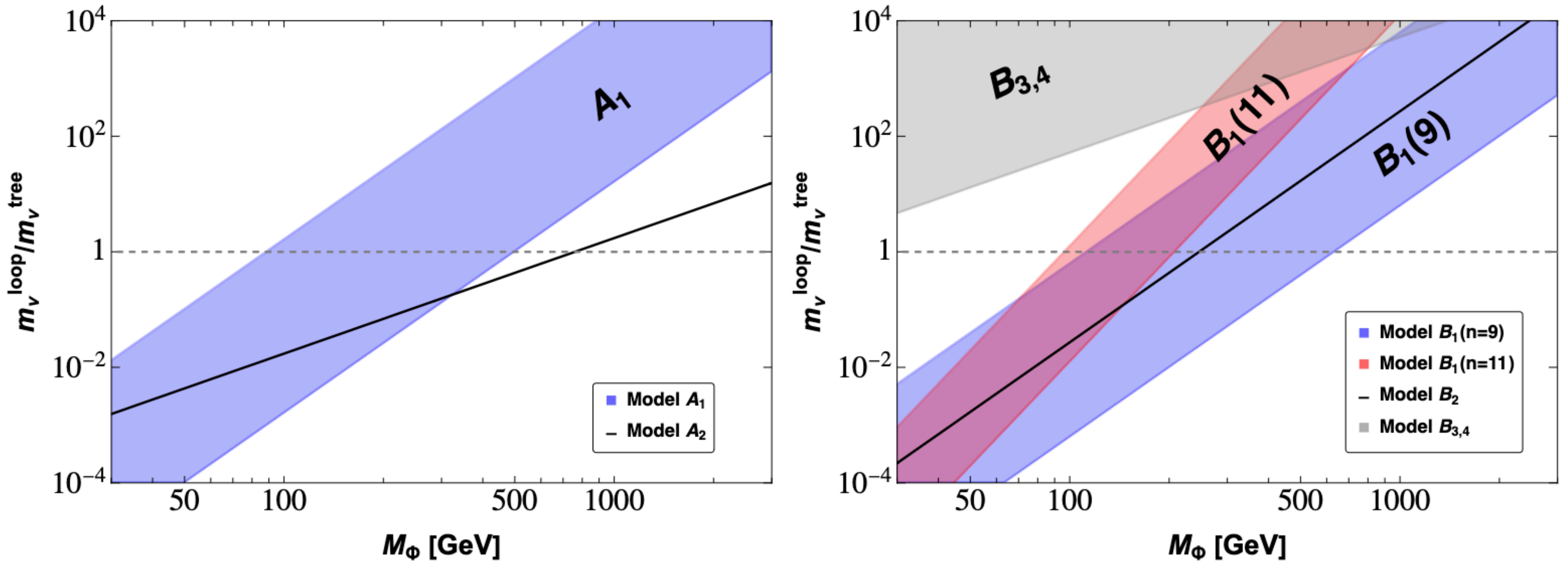


Figure 4. Ratio of the contribution to neutrino masses at one loop and at tree level versus the scalars mass in the limit $M_\Psi \gg M_\Phi$ for class-**A** (*left*) and class-**B** (*right*) models. The colored bands are obtained taking the couplings $\lambda_i \in [0.1; 1]$. Notice that the dependence on λ_i drops in models $\mathbf{A_1}$ and $\mathbf{B_2}$. For $\mathbf{B_3}$ and $\mathbf{B_4}$, the behaviour is very similar, therefore we report only $\mathbf{B_3}$.

Neutrino Masses

Numerical coefficients

	Tree level	Tree level with induced VEVs		Loop level
Model	ω	ξ	n	η
$\mathbf{A_1}$	$1/2$	$1/2\sqrt{3}$	9	$-5/6$
$\mathbf{A_2}$	-1	1	7	2
$\mathbf{B_1}$	$-\sqrt{3}/4$	$1/4$	9	$5/6$
		$-1/12$ ($-1/4$)	11	
$\mathbf{B_2}$	$-1/\sqrt{2}$	$1/4$	9	$5/3$
$\mathbf{B_3}$	2	-1	7^*	-5
$\mathbf{B_4}$	$-\sqrt{6}$	$-3/2$	7^*	-5

Phenomenology

LFV Constraints

		Upper limits		
Model	**Yukawa combination**	$\alpha\beta = \mu e$	$\alpha\beta = \tau e$	$\alpha\beta = \tau\mu$
$\mathbf{A_1}$	$\lvert y_1^{\beta^*} y_1^\alpha \rvert (\text{TeV}/M_\Sigma)^2$	< 0.0002	< 0.13	< 0.16
$\mathbf{A_2}$	$\lvert y_1^{\beta^*} y_1^\alpha \rvert (\text{TeV}/M_\mathcal{F})^2$	< 0.0004	< 0.24	< 0.28
$\mathbf{B_1}$	$\lvert y_1^{\beta^*} y_1^\alpha - 0.5\, y_2^{\beta^*} y_2^\alpha \rvert (\text{TeV}/M_\mathcal{F})^2$	< 0.0004	< 0.29	< 0.34
$\mathbf{B_2}$	$\lvert y_1^{\beta^*} y_1^\alpha - 50\, y_2^{\beta^*} y_2^\alpha \rvert (\text{TeV}/M_\mathcal{F})^2$	< 0.0011	< 0.72	< 0.84
$\mathbf{B_3}$	$\lvert y_1^{\beta^*} y_1^\alpha - 2.12\, y_2^{\beta^*} y_2^\alpha \rvert (\text{TeV}/M_\mathcal{F})^2$	< 0.0002	< 0.15	< 0.18
$\mathbf{B_4}$	$\lvert y_1^{\beta^*} y_1^\alpha + 6.6\, y_2^{\beta^*} y_2^\alpha \rvert (\text{TeV}/M_\mathcal{F})^2$	< 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	$4^S_{-1/2},\, 5^F_0$	$M_{\Phi_1} \approx 3.2, M_\Sigma \approx 10$
$\mathbf{A'_2}$	$\Phi_1 = 4^S_{-3/2}\,, \mathcal{F} = 3^F_{-1}$	$-$	$-$	$-$
$\mathbf{B'_1}$	$\Phi_1 = 4^S_{1/2}\,, \Phi_2 = 4^S_{-3/2}\,, \mathcal{F} = 5^F_{-1}$	$U(1)$	$4^S_{1/2}\,, 4^S_{-3/2}$	$M_{\Phi_1} \approx 3.2, M_{\Phi_2} \approx 3.5$
$\mathbf{B'_2}$	$\Phi_1 = 3^S_0\,, \Phi_2 = 5^S_{-1}\,, \mathcal{F} = 4^F_{-1/2}$	$U(1)$	$3^S_0\,, 5^S_{-1}$	$M_{\Phi_1} \approx 2.5, M_{\Phi_2} \approx 3.4$
$\mathbf{B'_3}$	$\Phi_1 = 5^S_{-2}\,, \Phi_2 = 5^S_1\,, \mathcal{F} = 4^F_{3/2}$	$U(1)$	$5^S_{-2}\,, 5^S_1$	$M_{\Phi_1} \approx 3.9, M_{\Phi_2} \approx 3.4$
$\mathbf{B'_4}$	$\Phi_1 = 5^S_{-1}\,, \Phi_2 = 5^S_0\,, \mathcal{F} = 4^F_{1/2}$	$U(1)$	$5^S_{-1}\,, 5^S_0$	$M_{\Phi_1} \approx 3.4, M_{\Phi_2} \approx 9.4$

Table 8. 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