An EFT approach to lepton and baryon number violation

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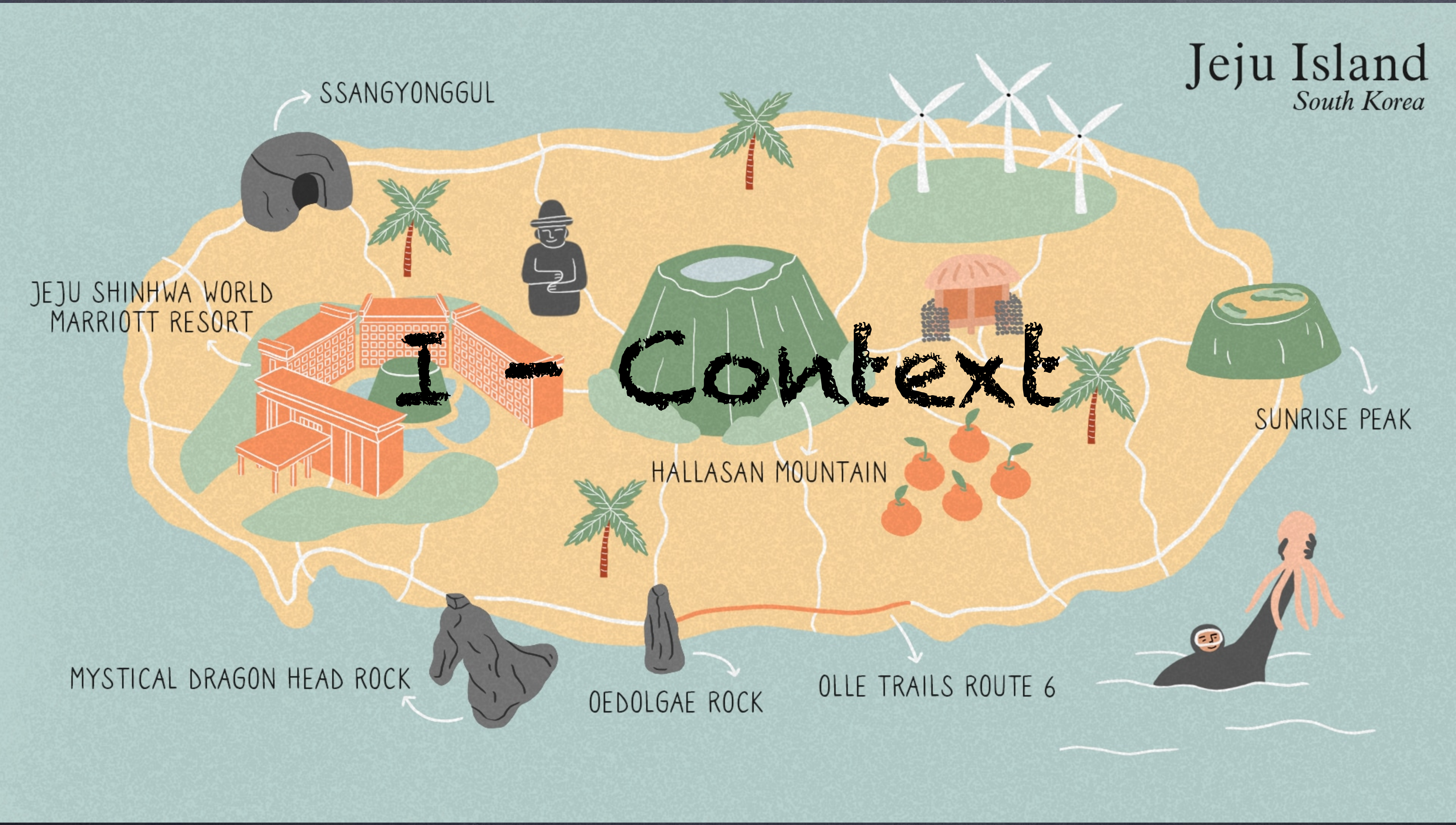
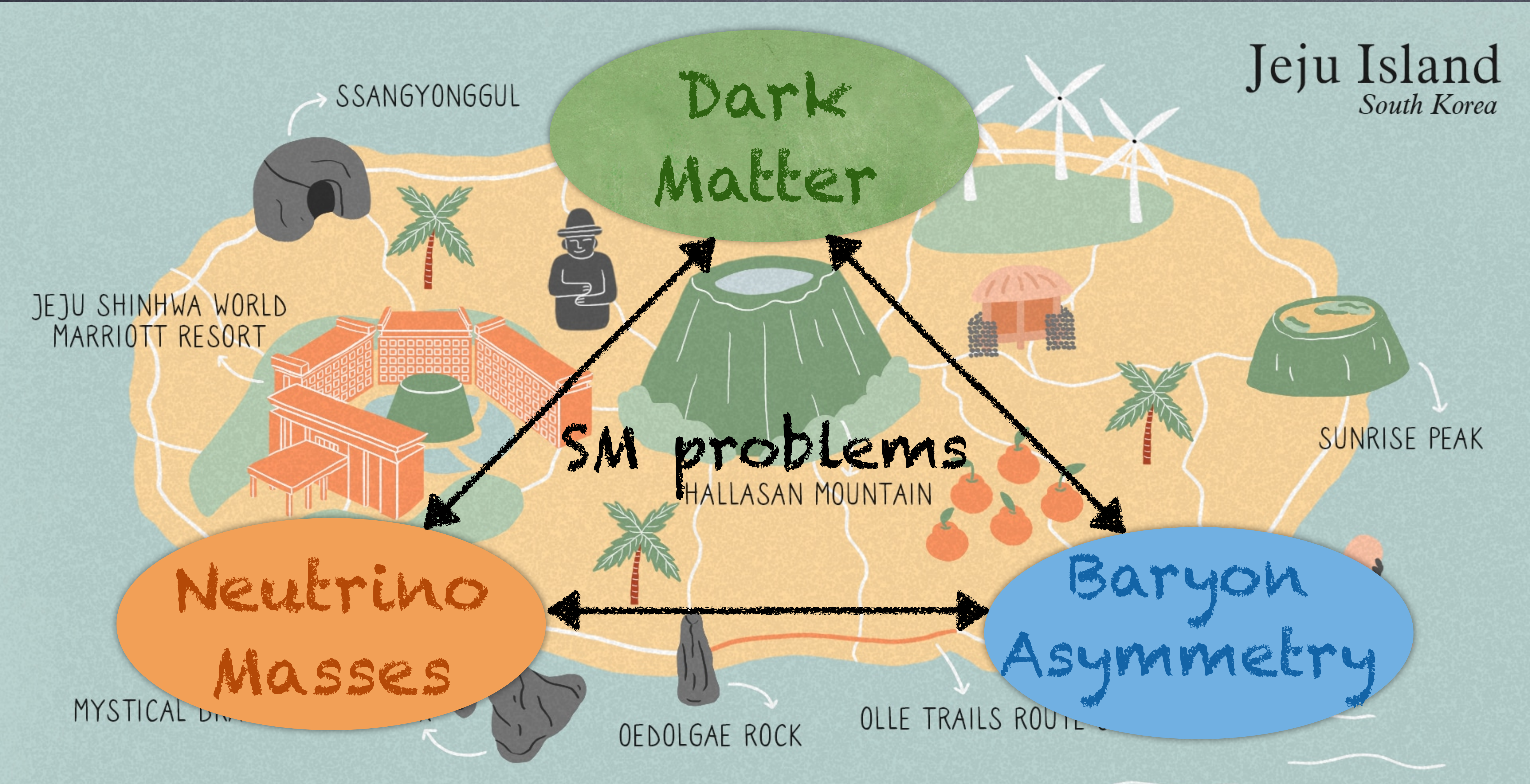


Jeju Island
South Korea
SSANGYONGGUL
JEJU SHINHWA WORLD
MARRIOTT RESORT
HALLASAN MOUNTAIN
SUNRISE PEAK
MYSTICAL DRAGON HEAD ROCK
OEDOLGAE ROCK
OLLE TRAILS ROUTE 6

SM problems with strongest experimental evidence



Many possible BSM paths... How to choose?

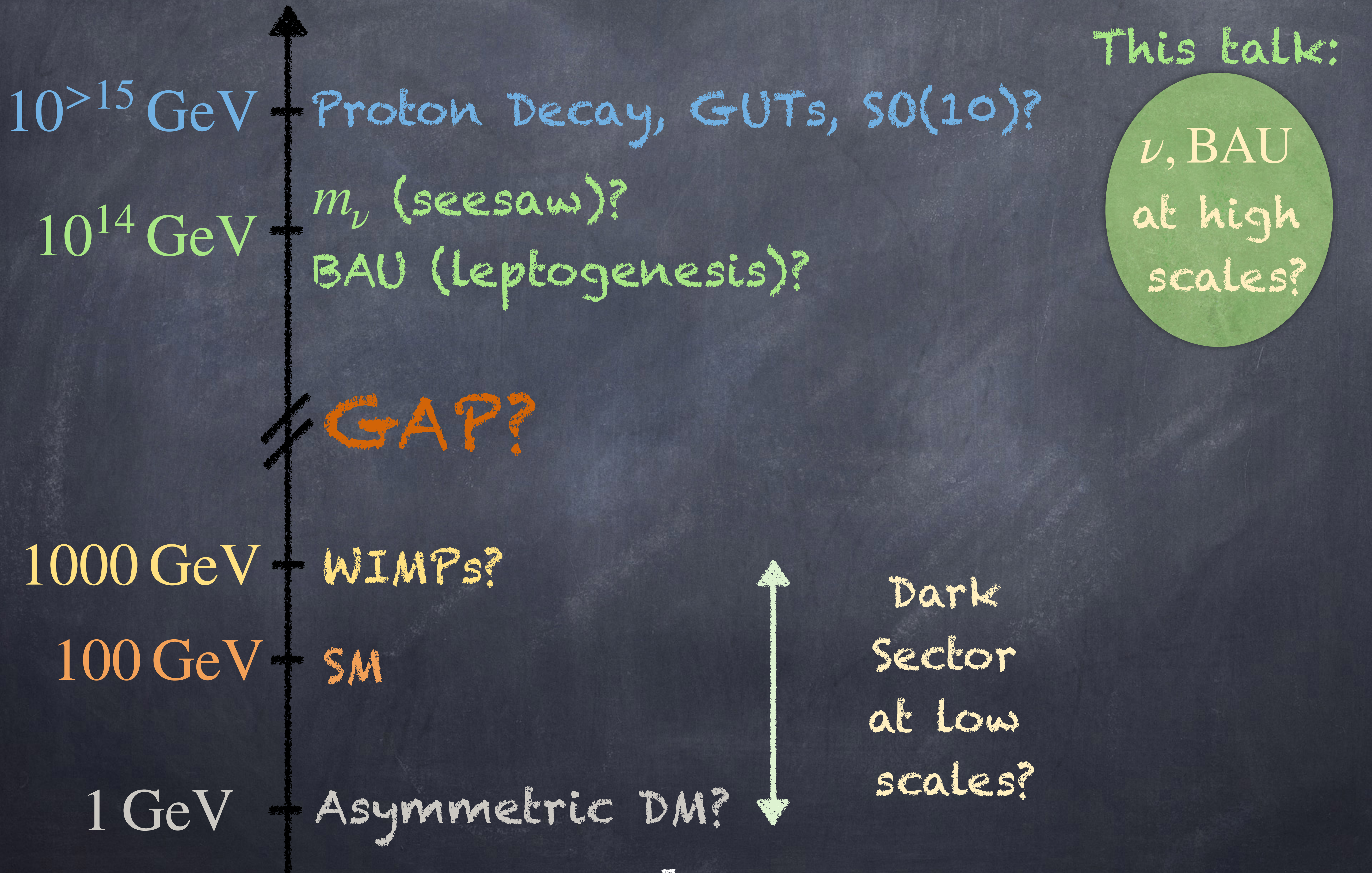
SM as an EFT: accidental symmetries

- At renormalisable (& perturbative) level, lepton (L) and baryon number (B) are accidental symmetries

- At $D = 5$, L is violated in 2 units by the Weinberg operator $LLHH$: Majorana neutrino masses, $m_\nu \simeq v^2/\Lambda$

- At $D = 6$, B is violated in 1 unit by $QQQL$ and other operators: nucleon decays, $\Gamma_p \simeq m_p^5/(8\pi\Lambda^4)$

Possible energy scales



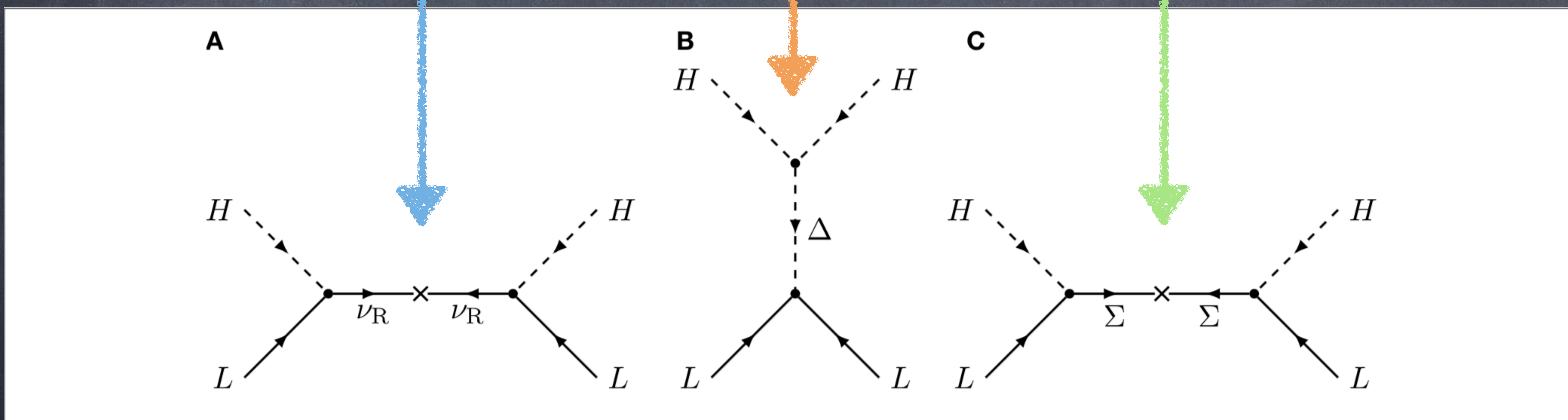
Neutrino masses at tree level: seesaws

[Minkowski, Yanagida, Gell-Mann, Mohapatra, Glashow…]

$yLHN, mNN$

$yL\Delta L, \mu H\Delta^\dagger H$

$yLH\Sigma, m\Sigma\Sigma$



SS I

SS II

SS III

Simple, GUTs, leptogenesis, but huge scales: very hard to test and hierarchy problem

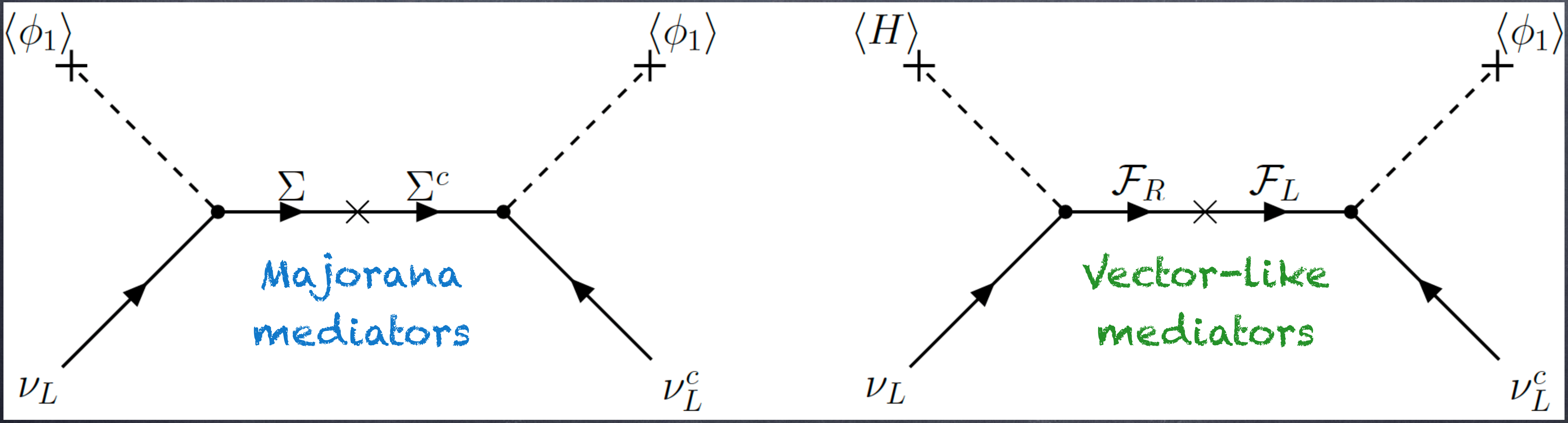
II - Neutrino masses from new Weinberg-like operators

[Alessio Giarnetti, JHG, Simone Marciano, Davide Meloni, Drona Vatsyayan, 23XX.XXXXX]

Homestake mine, 1970

Extra scalars ϕ_i at EW scale

$$\mathscr{L}_{\rm EFT} \supset \frac{c_5^{(0)}}{\Lambda} LLHH + \frac{c_5^{(1)}}{\Lambda} LLH\phi_i + \frac{c_5^{(2)}}{\Lambda} LL\phi_i\phi_i + \frac{c_5^{(3)}}{\Lambda} LL\phi_i\phi_j + \mathrm{H.c.}$$



- Standard seesaws from $c_5^{(0)}$: difficult to test
- New genuine models: no $c_5^{(0)}$ generated, smaller scales

List of genuine models

[See also McDonald *JHEP* 07 (2013) 020]

$\mathcal{O}_5^{(1)} = LLH\phi_i$ $\quad$ $\mathcal{O}_5^{(2)} = LL\phi_i\phi_i$ $\quad$ $\mathcal{O}_5^{(3)} = LL\phi_i\phi_j$

Model	New Scalar Multiplets	Fermion Mediator	Operator
$\mathbf{A_1}$	$\mathrm{SU(2)}_{\mathrm{Y}}^{\mathrm{S,F}}$ $\Phi_1 = 4^S_{-1/2}$	$\Sigma = 5^F_0$	$\mathcal{O}_5^{(2)}$
$\mathbf{A_2}$	$\Phi_1 = 4^S_{-3/2}$	$\mathcal{F} = 3^F_{-1}$	$\mathcal{O}_5^{(1)}$
$\mathbf{B_1}$	$\Phi_1 = 4^S_{1/2}, \quad \Phi_2 = 4^S_{-3/2}$	$\mathcal{F} = 5^F_{-1}$	$\mathcal{O}_5^{(3)}$
$\mathbf{B_2}$	$\Phi_1 = 3^S_0, \quad \Phi_2 = 5^S_{-1}$	$\mathcal{F} = 4^F_{-1/2}$	$\mathcal{O}_5^{(3)}$
$\mathbf{B_3}$	$\Phi_1 = 5^S_{-2}, \quad \Phi_2 = 5^S_1$	$\mathcal{F} = 4^F_{3/2}$	$\mathcal{O}_5^{(3)}$
$\mathbf{B_4}$	$\Phi_1 = 5^S_{-1}, \quad \Phi_2 = 5^S_0$	$\mathcal{F} = 4^F_{1/2}$	$\mathcal{O}_5^{(3)}$

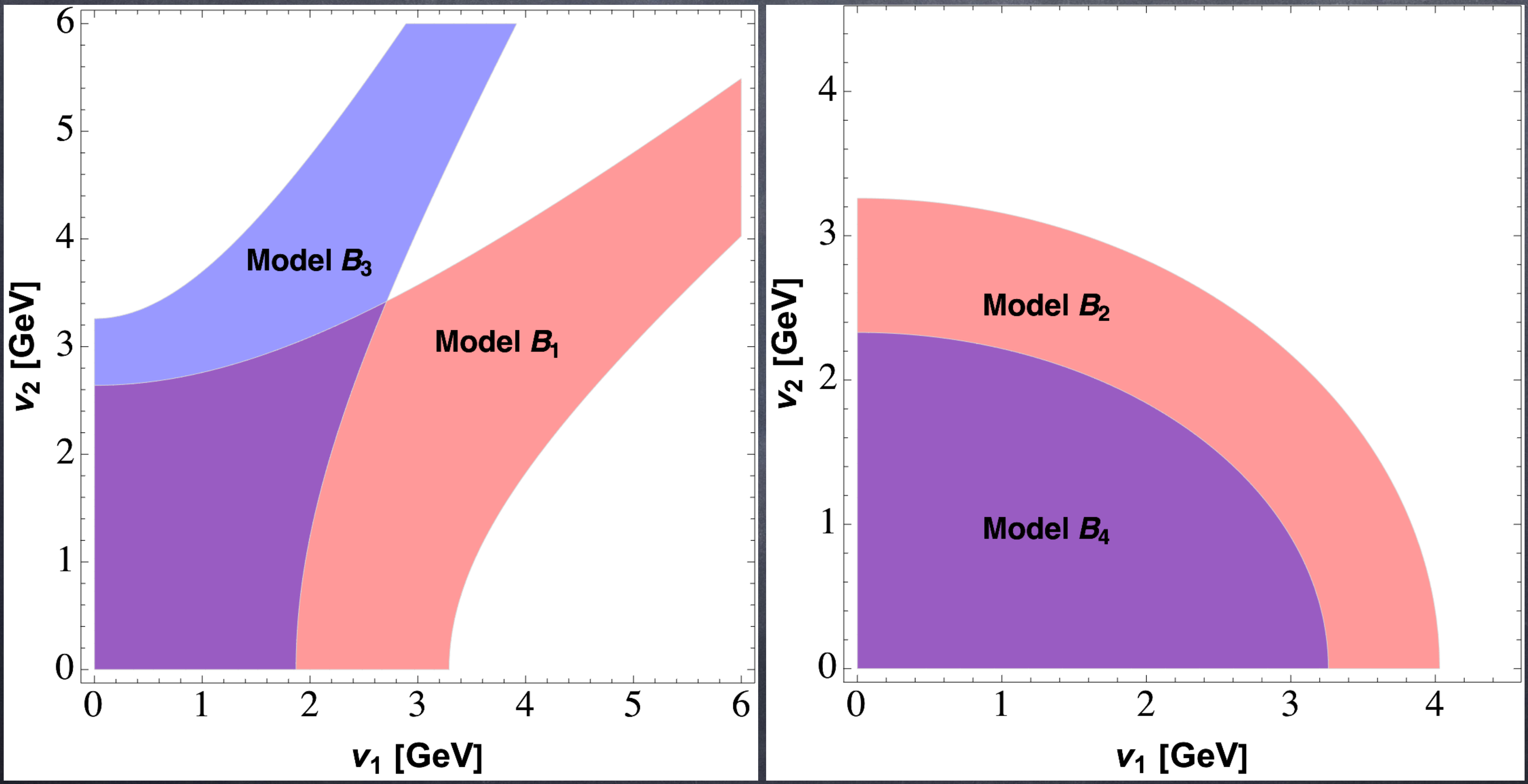
Tree-level neutrino masses:

$$(m_\nu)_{\alpha\beta} = \epsilon_2 v_1^2 \left(y_1 M_\Sigma^{-1} y_1^T\right)_{\alpha\beta} \quad \text{for } \mathbf{A1},$$

$$(m_\nu)_{\alpha\beta} = \epsilon_1 v_1 v \left(y_H M_{\mathcal{F}}^{-1} y_1^T + y_1 M_{\mathcal{F}}^{-1} y_H^T\right)_{\alpha\beta} \quad \text{for } \mathbf{A2},$$

$$(m_\nu)_{\alpha\beta} = \epsilon_3 v_1 v_2 \left(y_1 M_{\mathcal{F}}^{-1} y_2^T + y_2 M_{\mathcal{F}}^{-1} y_1^T\right)_{\alpha\beta} \quad \text{for } \mathbf{B_i},$$

The ρ parameter at tree level



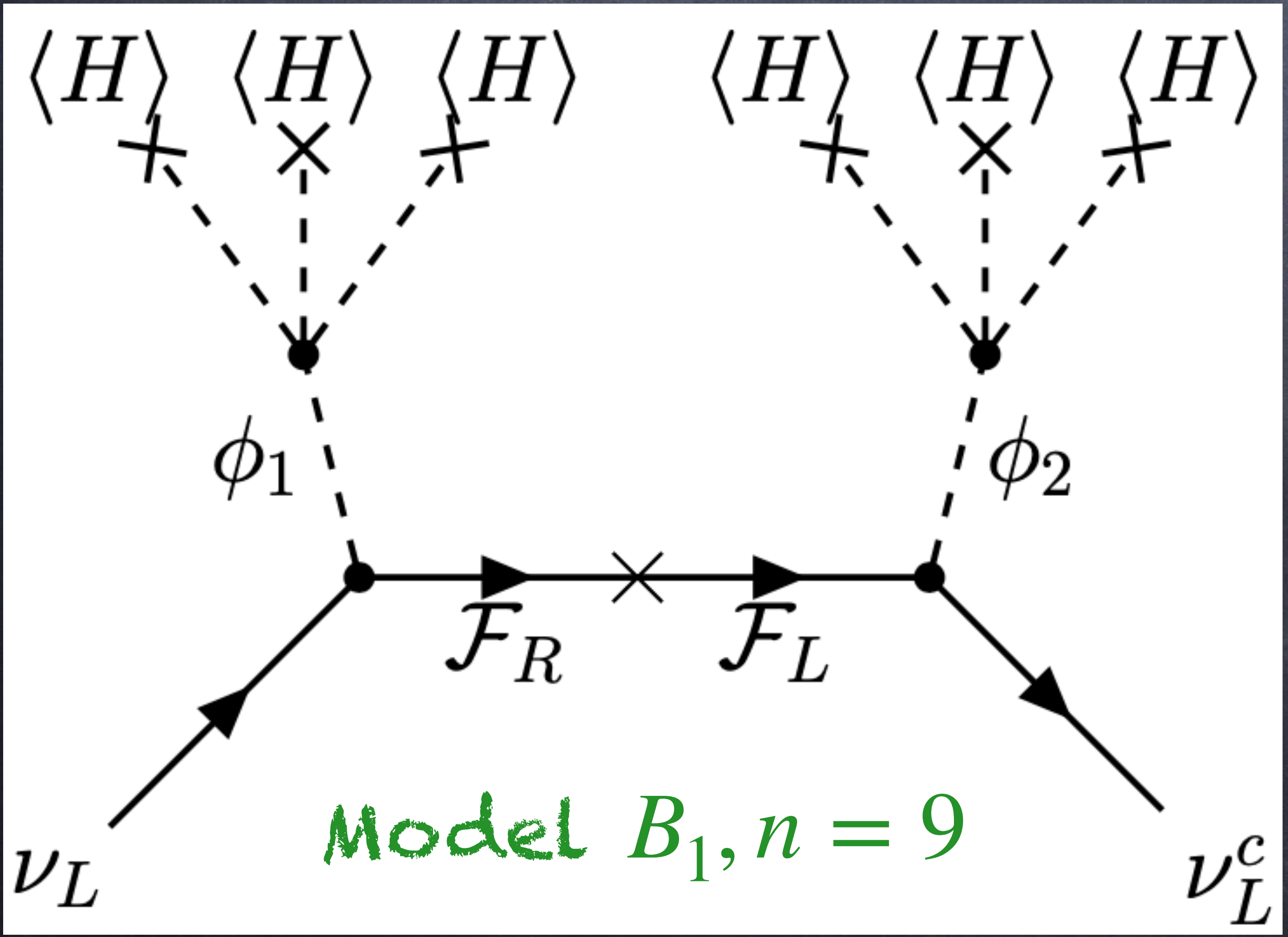
$\Longrightarrow$ New VEVs always small, $v_i < \mathcal{O}(\text{GeV}) \ll v$, so $\Lambda \Downarrow$

Naturally-small induced VEVs v_i

For example, for A_1, $\phi_1 = (4, -1/2)$:

$$V \supset \lambda_{\text{mix},1}\,(\phi_1 H)(H^\dagger H) + \text{H.c.} \Longrightarrow v_i \simeq \lambda_{\text{mix,i}}\,\frac{v^3}{m_{\phi_i}^2}$$

$\Longrightarrow v_i \ll v$ for $v \ll m_{\phi_i}$ and/or $\lambda_{\text{mix,i}} \ll 1$

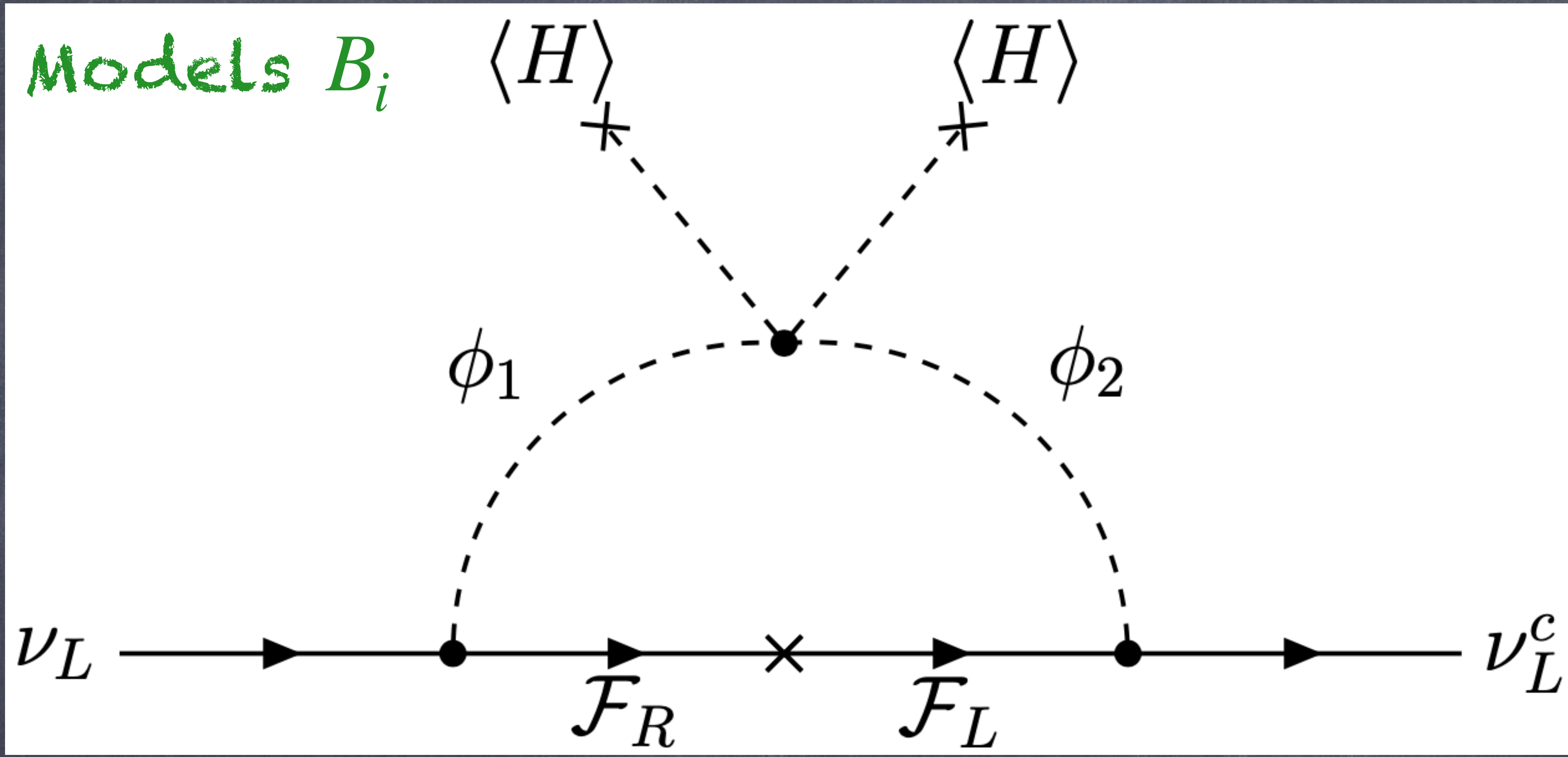


$D > 5$ Weinberg operators with the SM Higgs doublet:

$$\frac{c_n^{(0)}}{\Lambda^{n-4}}\,LLHH(H^\dagger H)^{\frac{n-5}{2}}$$

[Anamiati et al 2018]

Neutrino masses at one loop



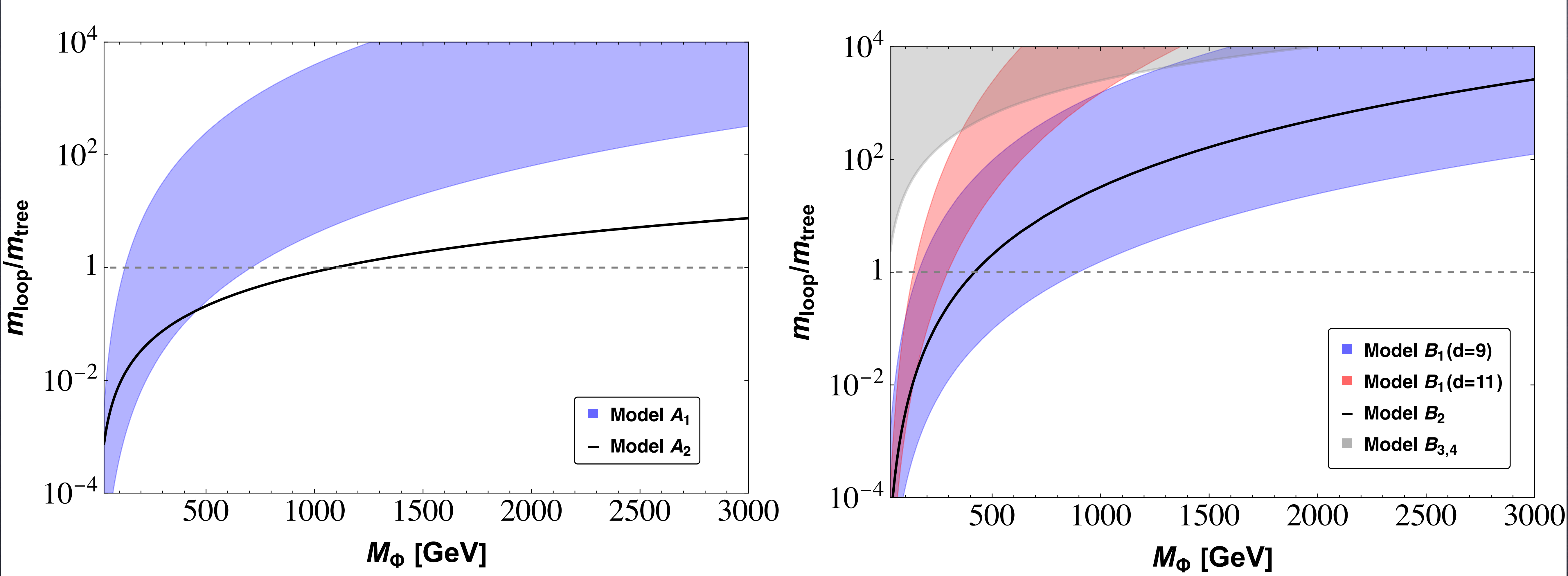
$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \delta_1\,\lambda_{\text{mix},1}\,\frac{v^2}{8\pi^2}\sum_{k=1}^{2} y_{1,\alpha k}\,y_{1,\beta k}\,m_k\;F_2(m_{(\phi_1)_0^R}, m_{(\phi_1)_0^I}, m_k) \quad \text{for } \mathbf{A_1}\,,$$

$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \delta_2\,\lambda_{\text{mix},1}\,\frac{v^2}{8\pi^2}\left(y_H y_1^T + y_1 y_H^T\right)_{\alpha\beta}\,M_{\mathcal{F}}\,F_2(m_{\phi_1}, m_H, M_{\mathcal{F}}) \quad \text{for } \mathbf{A_2}\,,$$

$$(m_\nu)^{\text{loop}}_{\alpha\beta} = \kappa_i\,\lambda_{\text{mix},12}\,\frac{v^2}{8\pi^2}\left(y_1 y_2^T + y_2 y_1^T\right)_{\alpha\beta}\,M_{\mathcal{F}}\,F_2(m_{\phi_1}, m_{\phi_2}, M_{\mathcal{F}}) \quad \text{for } \mathbf{B_i}\,,$$

Loop versus tree

$M_{\mathscr{F}} \gg M_{\phi_i} \quad \lambda_i \in [0.1, 1]$



In $A_{1,2}$ and $B_{1,2}$, for $M_{\phi_i} \lesssim 500$ GeV, tree level dominates. In $B_{3,4}$, loop level always dominate

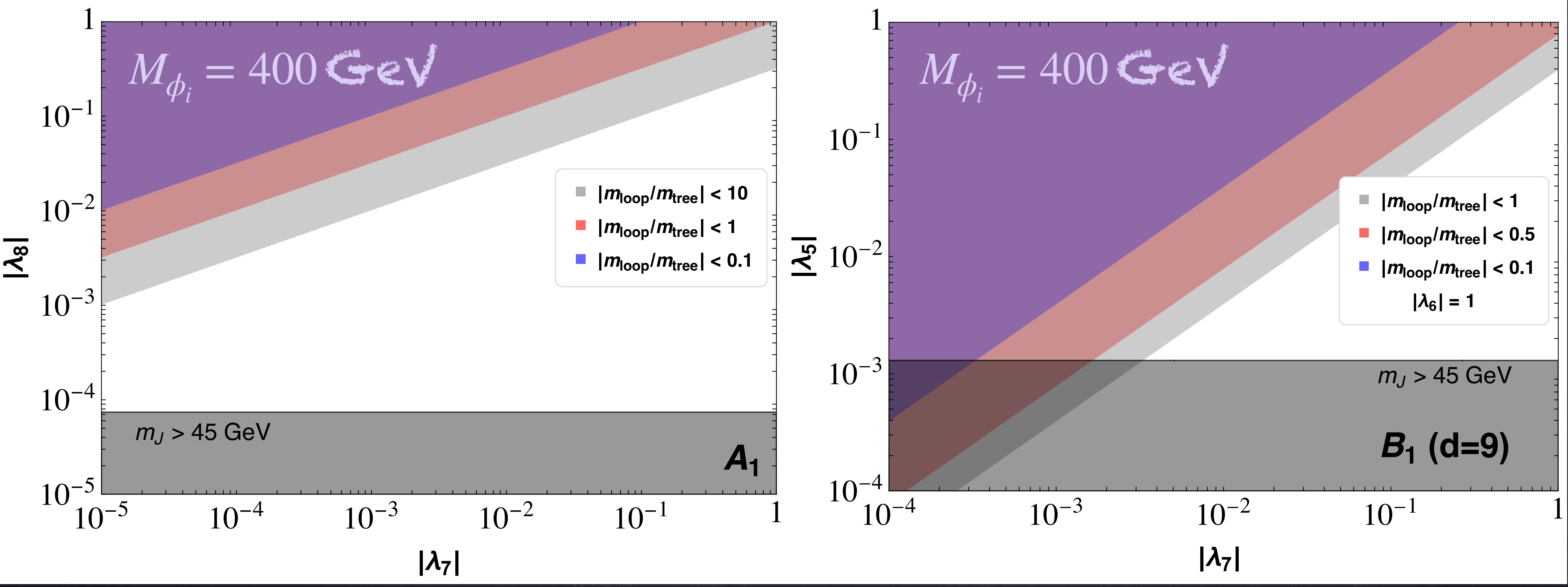
Pseudo-Majorons

loop → tree →

$V_{A_1} \supset \lambda_7 H\Phi H\Phi + \lambda_8 H^*\Phi HH$ + H.c.

loop → tree →

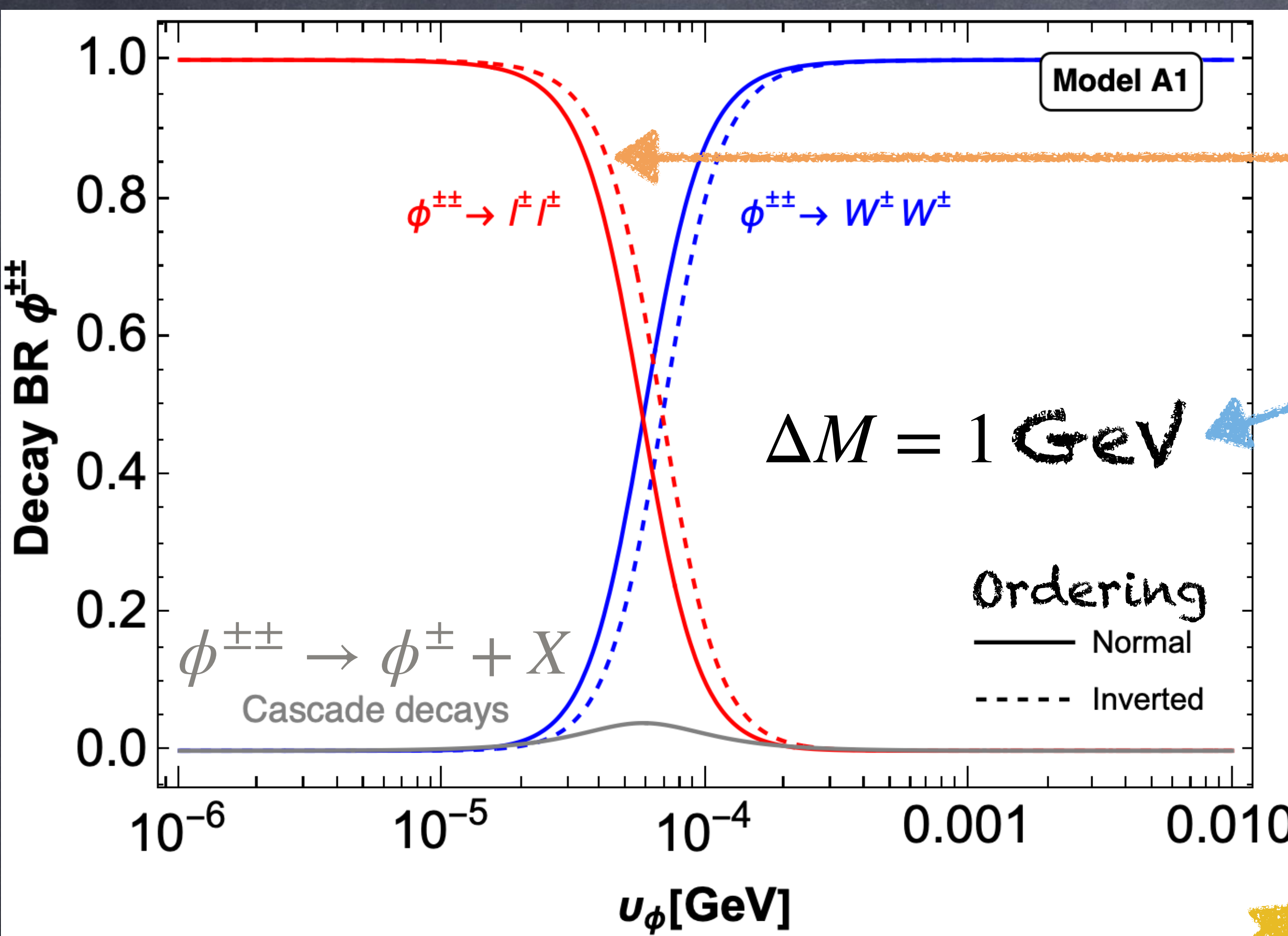
$V_{B_1} \supset \lambda_7 HH\Phi_1\Phi_2 + \lambda_5 \Phi_1^* H^* H H$ + H.c.



Doubly-charged scalars at colliders

tree ↓ $\frac{m_\nu^2}{v_i^2}$

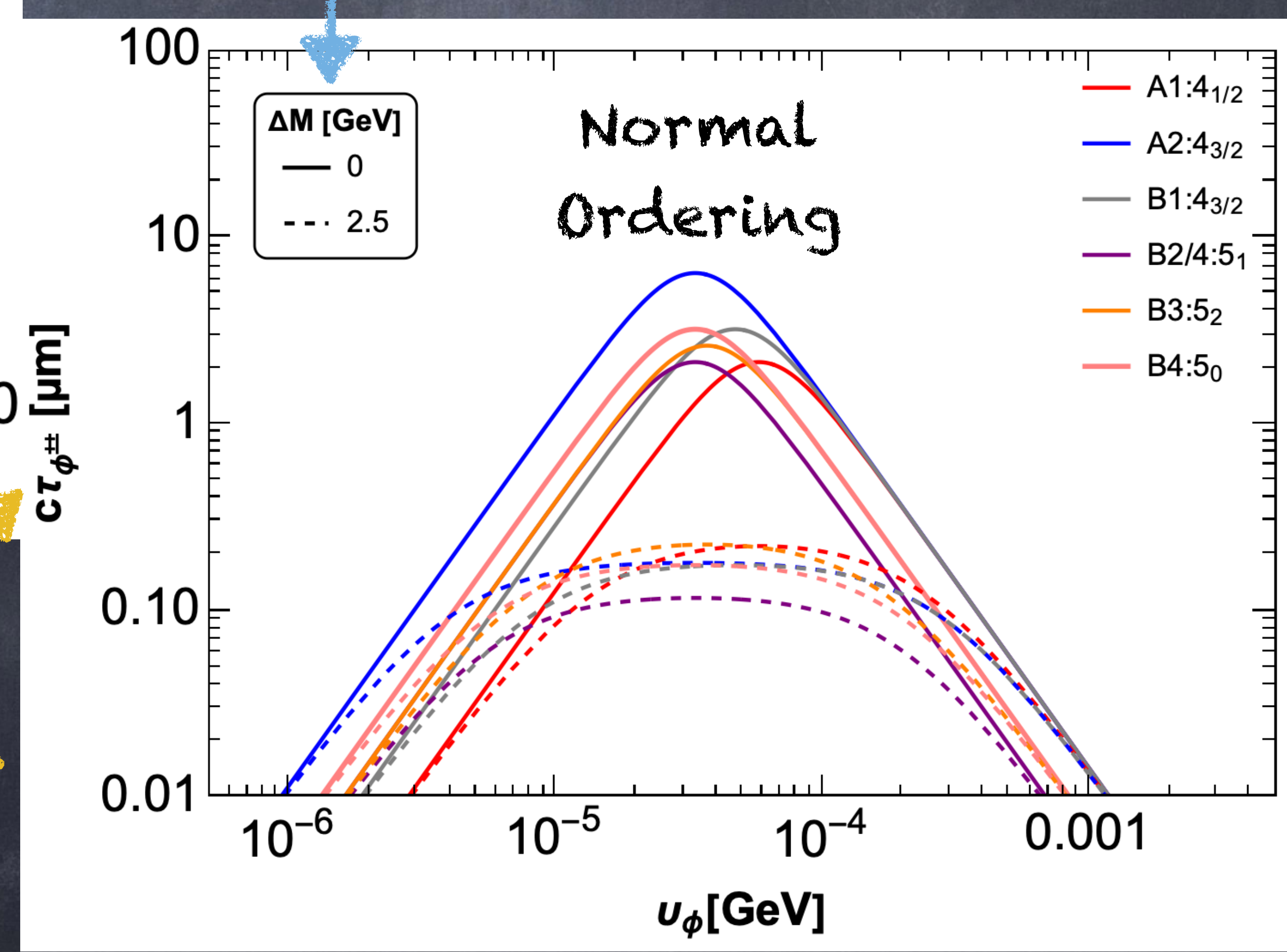
Same-sign leptons, $\propto \frac{m_\nu^2}{v_i^2}$



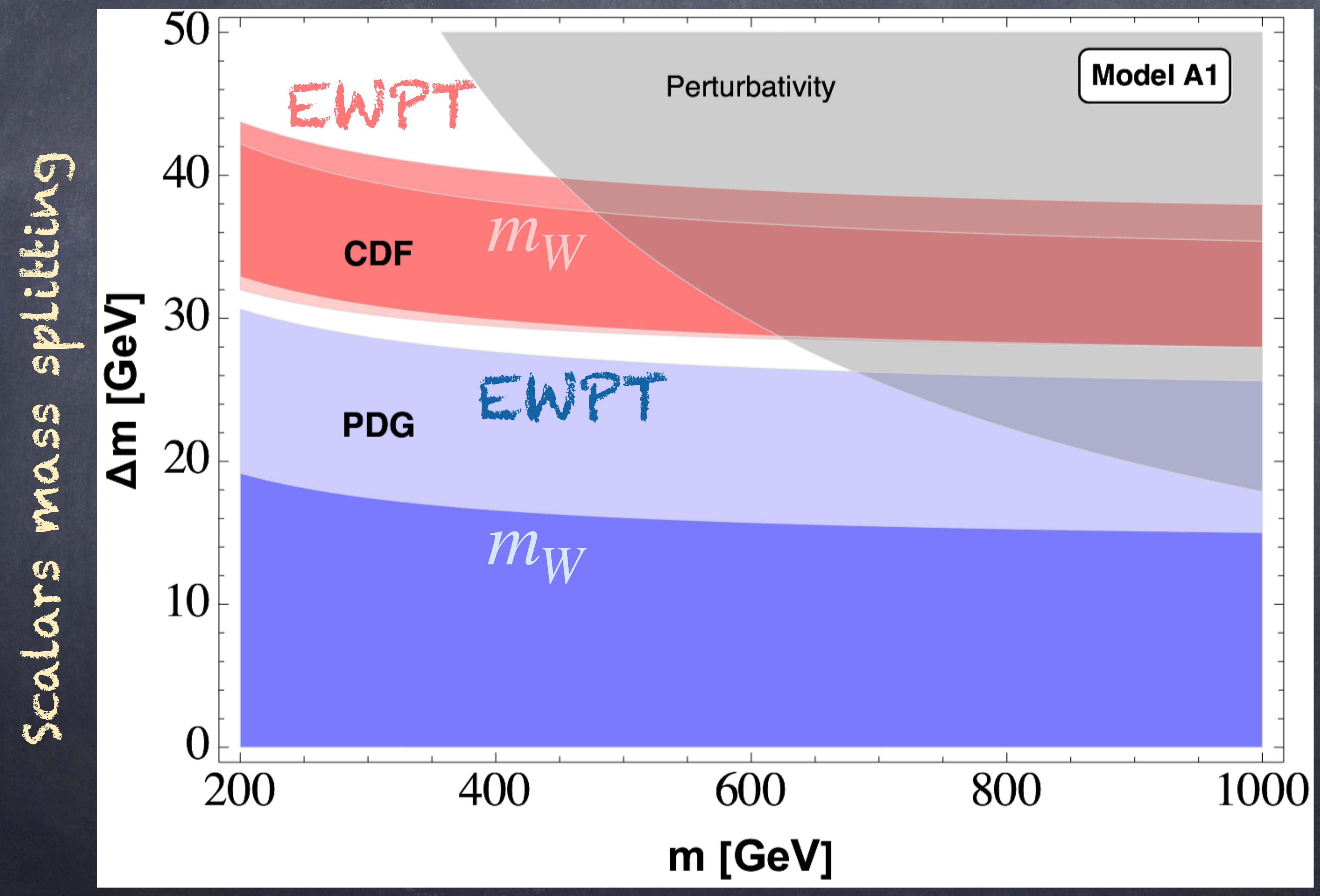
Scalars mass splitting

$M_{\phi_i} = 500$ GeV

Decay length



m_W and EWPT at 1 loop



Low-scale versions

Model A_1: Majorana mass $\Longrightarrow$ inverse seesaw

Model A_2: $y_1 v_1 \ll y_H v_H$ $\left(\frac{y_1}{10^{-10}}\right)\left(\frac{v_1}{\text{GeV}}\right) \simeq 1, M_{\mathscr{F}} \simeq \text{TeV}$

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

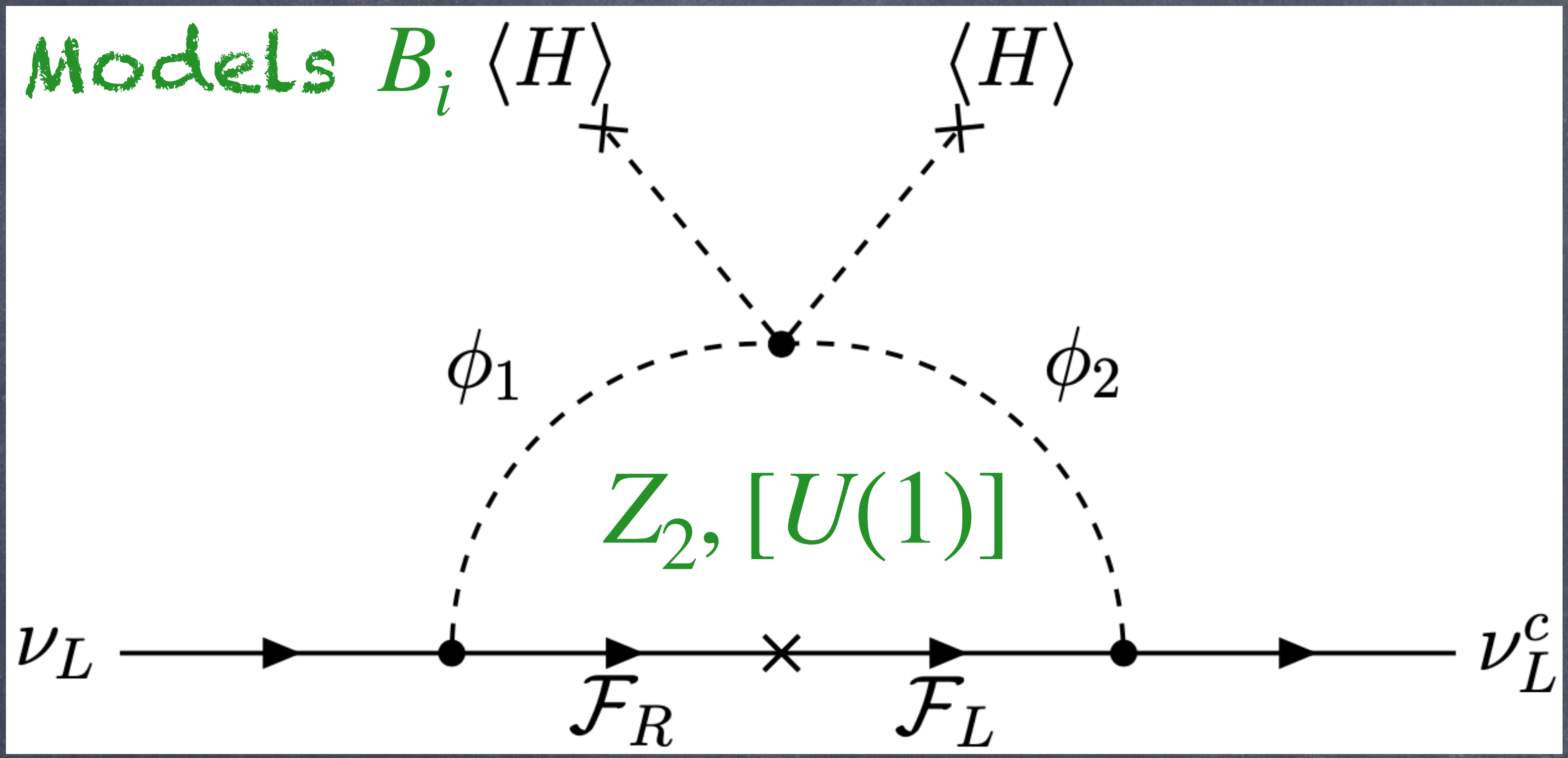
$= 1$ Richest pheno

LFV and modified Z, W couplings to leptons (FCNC, non-universal, non-unitary PMNS) from $D = 6$ ops. like

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

(Generalised) Scotogenic-like models

[Ma 06`,(Hagedorn, JHG, Molinaro, Schmidt 18')]



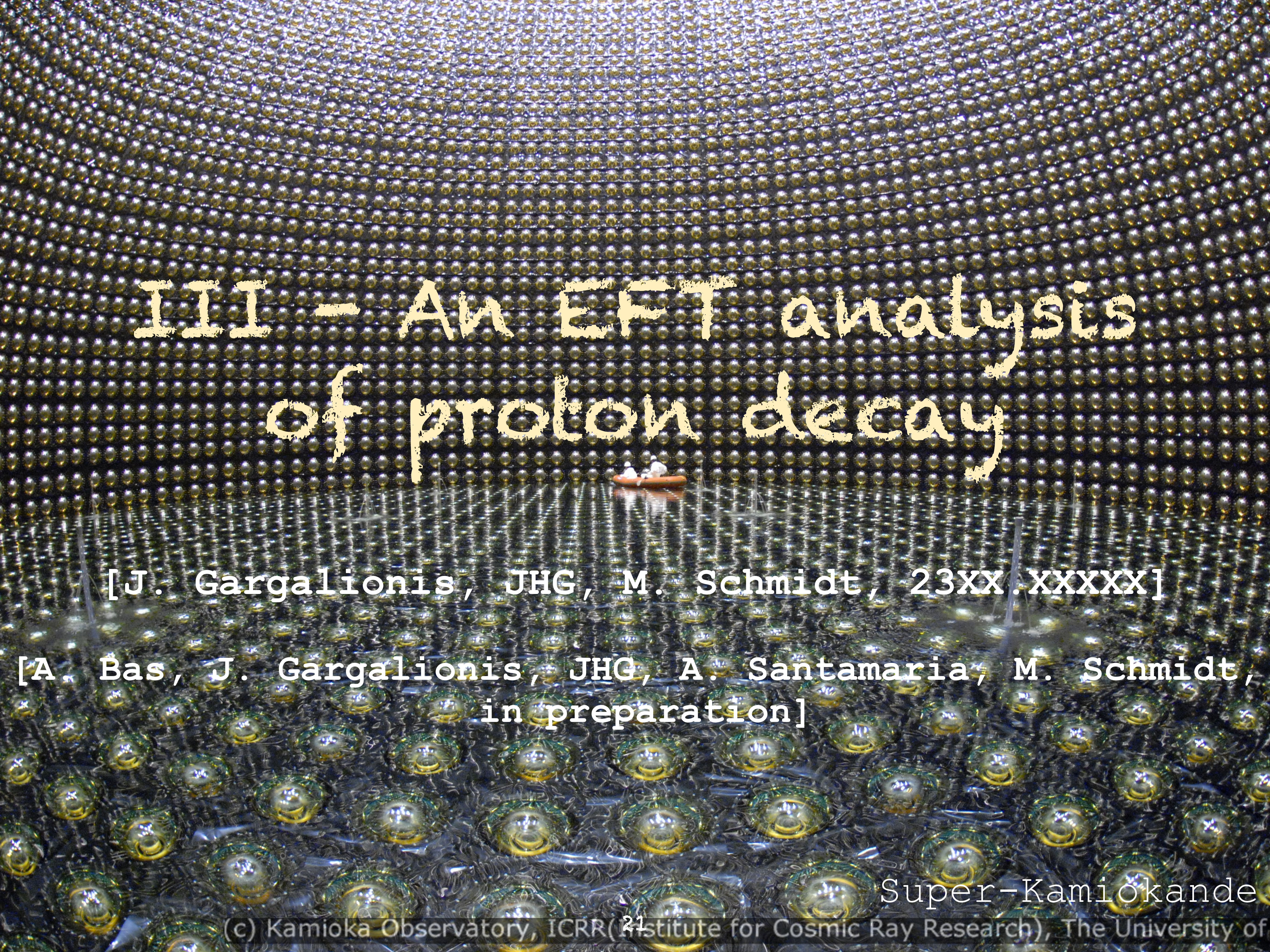
Non-pert. effects

Model	BSM Fields $SU(2)_Y^{S,F}$	Symmetry	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	$M_{\Phi_1} \approx 3.2, M_\Sigma \approx 10$
$\mathbf{A}'_2$	$\Phi_1 = 4^S_{-3/2}\,, \mathcal{F} = 3^F_{-1}$	–	–	–
$\mathbf{B}'_1$	$\Phi_1 = 4^S_{1/2}\,, \Phi_2 = 4^S_{-3/2}\,, \mathcal{F} = 5^F_{-1}$	$U(1)$	$4^S_{1/2}\,, 4^S_{-3/2}$	$M_{\Phi_1} \approx 3.2, M_{\Phi_2} \approx 3.5$
$\mathbf{B}'_2$	$\Phi_1 = 3^S_0\,, \Phi_2 = 5^S_{-1}\,, \mathcal{F} = 4^F_{-1/2}$	$U(1)$	$3^S_0\,, 5^S_{-1}$	$M_{\Phi_1} \approx 2.5, M_{\Phi_2} \approx 3.4$
$\mathbf{B}'_3$	$\Phi_1 = 5^S_{-2}\,, \Phi_2 = 5^S_1\,, \mathcal{F} = 4^F_{3/2}$	$U(1)$	$5^S_{-2}\,, 5^S_1$	$M_{\Phi_1} \approx 3.9, M_{\Phi_2} \approx 3.4$
$\mathbf{B}'_4$	$\Phi_1 = 5^S_{-1}\,, \Phi_2 = 5^S_0\,, \mathcal{F} = 4^F_{1/2}$	$U(1)$	$5^S_{-1}\,, 5^S_0$	$M_{\Phi_1} \approx 3.4, M_{\Phi_2} \approx 9.4$

III - An EFT analysis of proton decay

[J. Gargalionis, JHG, M. Schmidt, 23XX.XXXXX]

[A. Bas, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]



Super-Kamiokande

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of

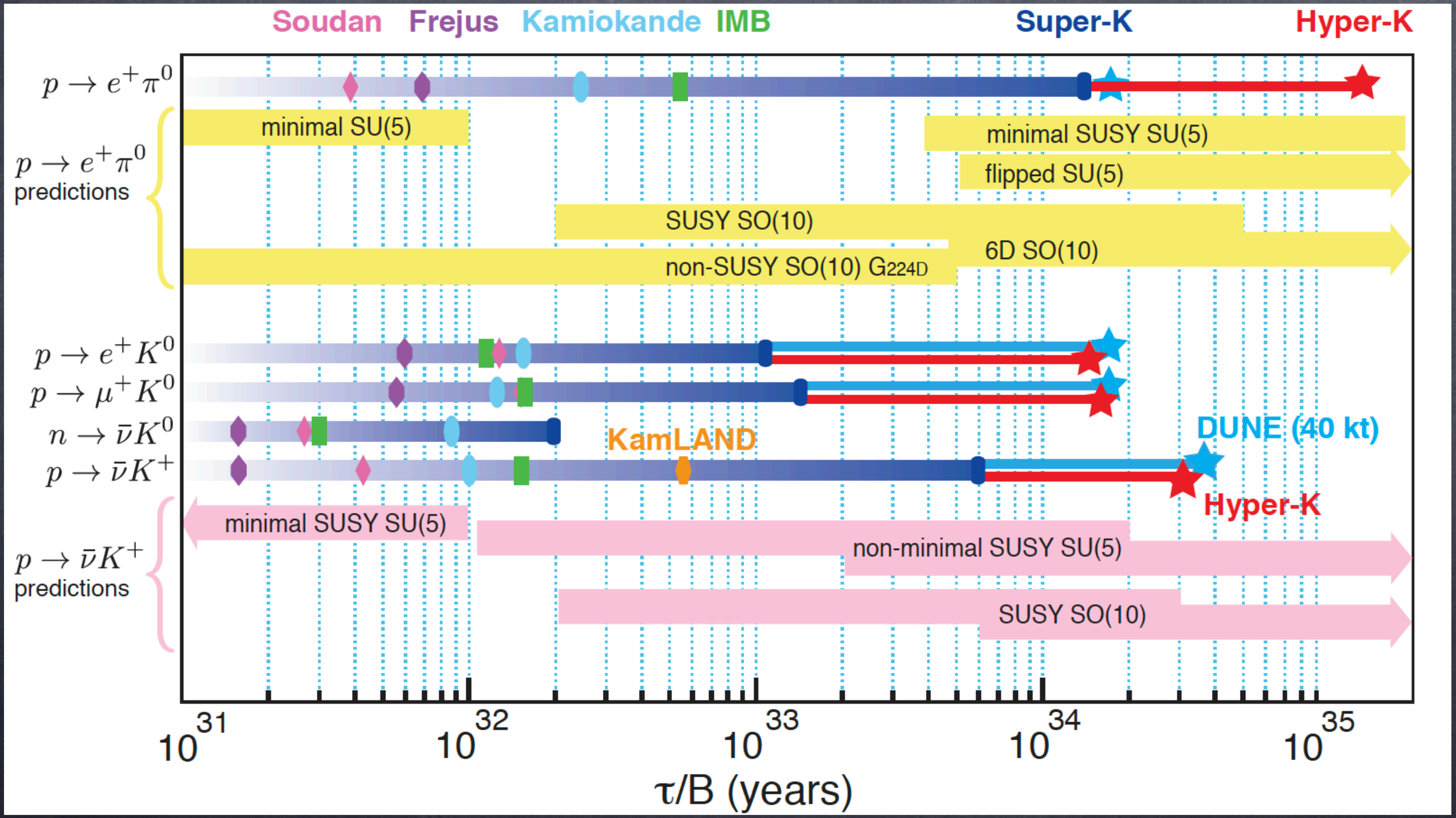
$\not{B}$: Proton Decay

- B expected to be violated at large energies ($\leq M_p$)
- BNV: necessary to generate the BAU [Shakarov 1967]
- Anomaly cancellation and GUTs: quarks - leptons unify
- At $D = 6$, $\Delta(B - L) = 0$ operators → QQ — QL | ue — ud
- Ej. $uued$, SK $\tau(p \to e^+\pi^0) > 2.4 \cdot 10^{34} y \implies \Lambda_{\rm BNV} > 10^{15}\,\mathrm{GeV}$

Proton decay probes highest energies

Experimental perspectives

[HK Design Report, 1805.04163]

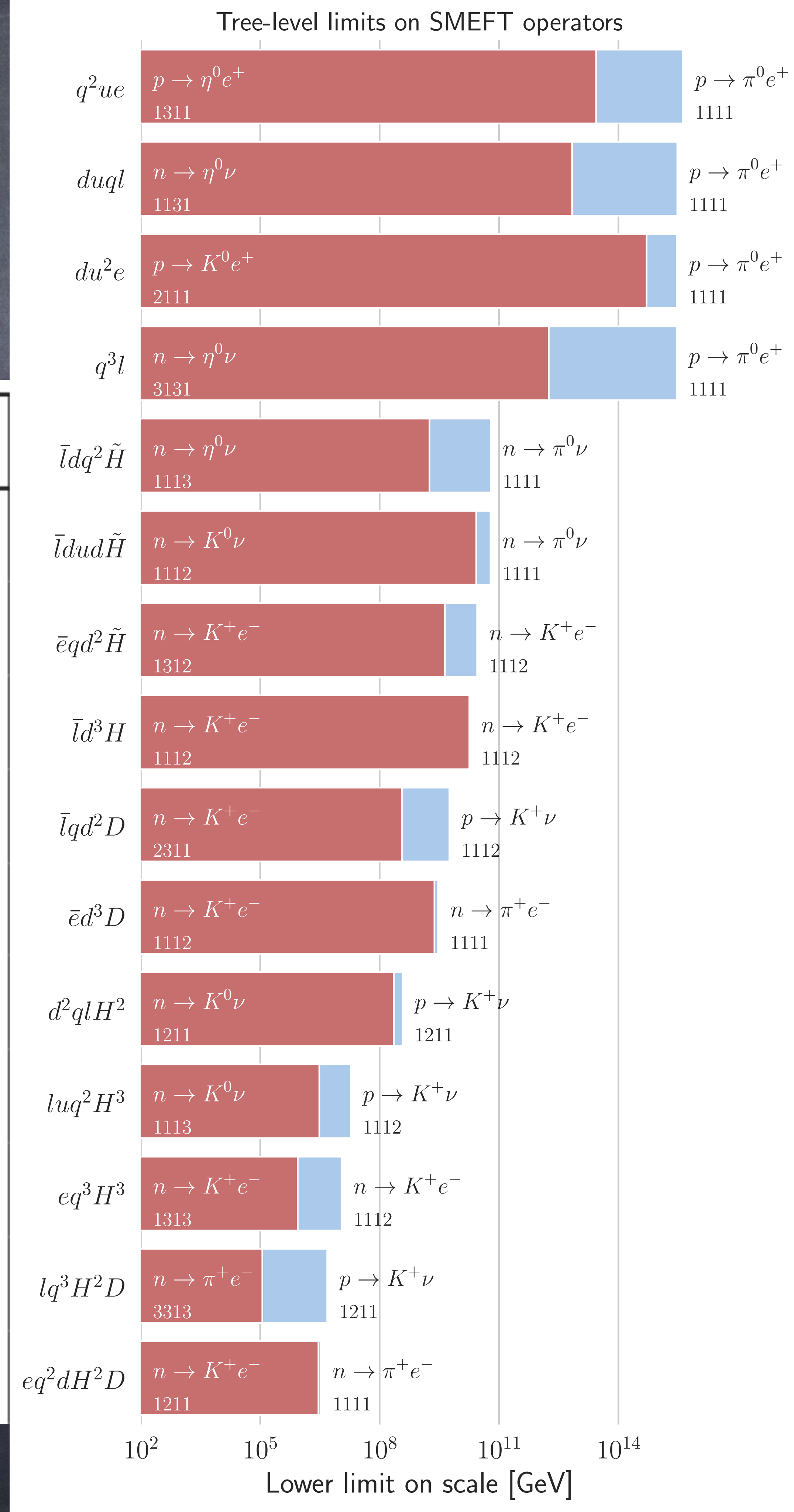


BNV could be the next big discovery

EFT for tree level proton decay $D \leq 9$

[**John Gargalionis**, JHG, M. Schmidt, 23XX.XXXXX]

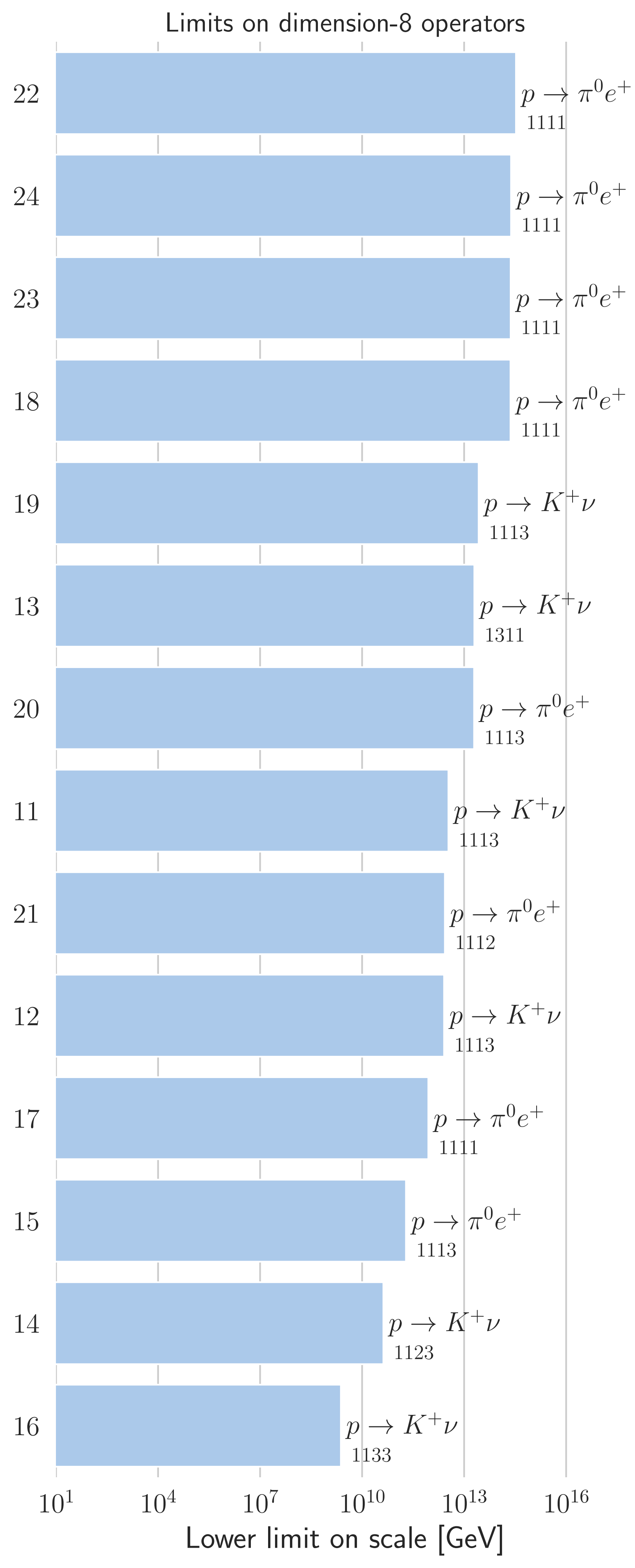
Label	Operator	D	B	L
1	$L_pQ_qQ_rQ_s$	6	1	1
2	$\bar{e}_p^\dagger Q_{\{q}Q_{r\}}\bar{u}_s^\dagger$	6	1	1
3	$\bar{e}_p^\dagger\bar{u}_q^\dagger\bar{u}_r^\dagger\bar{d}_s^\dagger$	6	1	1
4	$L_pQ_q\bar{u}_r^\dagger\bar{d}_s^\dagger$	6	1	1
5	$L_p\bar{d}_q\bar{d}_{[r}\bar{d}_{s]}H^\dagger$	7	-1	1
6	$DL_pQ_q^\dagger\bar{d}_{\{r}\bar{d}_{s\}}$	7	-1	1
7	$D\bar{e}_p^\dagger\bar{d}_{\{q}\bar{d}_r\bar{d}_{s\}}$	7	-1	1
8	$L_pQ_q^\dagger Q_r^\dagger\bar{d}_sH$	7	-1	1
9	$\bar{e}_p^\dagger Q_q^\dagger\bar{d}_{[r}\bar{d}_{s]}H$	7	-1	1
10	$L_p\bar{u}_q\bar{d}_r\bar{d}_sH$	7	-1	1



EFT for loop level proton decay, $D = 8$

[John Gargalionis, JHG, M. Schmidt, 23XX.XXXXX]

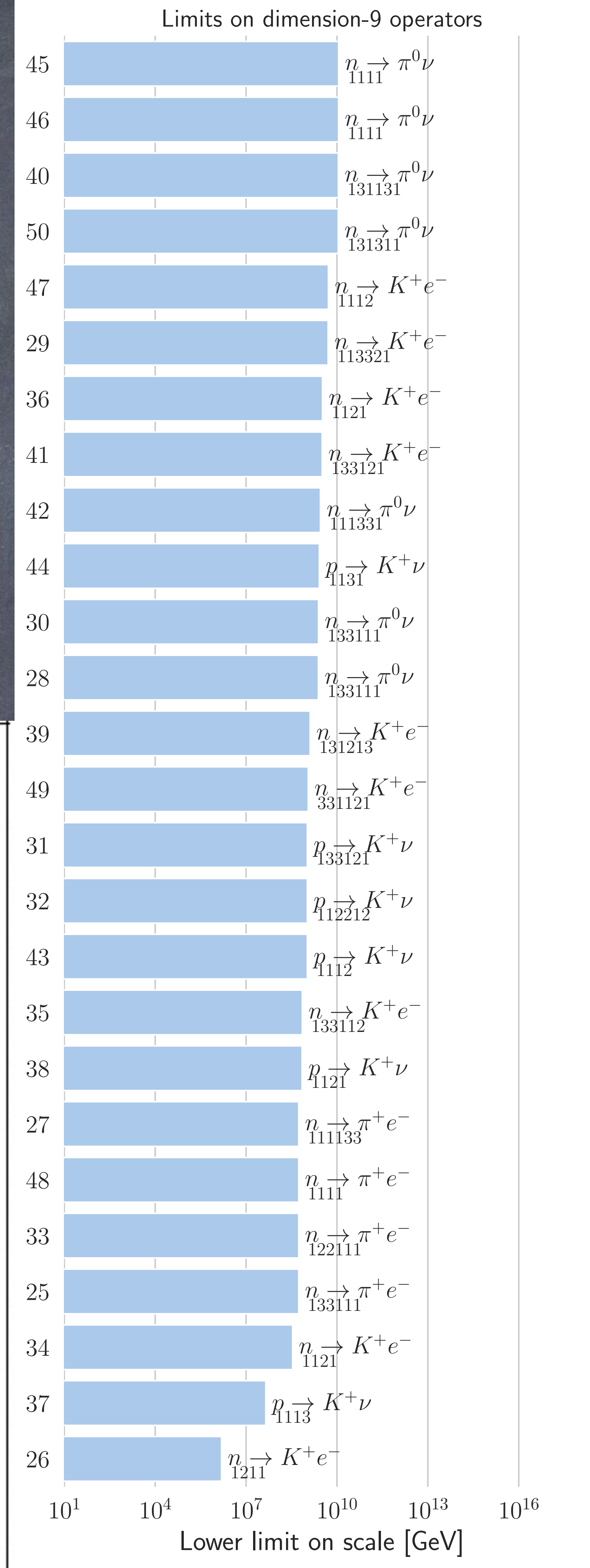
11	$DL_pQ_qQ_r\bar{d}_s^\dagger H$	8	1	1
12	$DL_p\bar{u}_q^\dagger\bar{d}_r^\dagger\bar{d}_s^\dagger H$	8	1	1
13	$DL_p\bar{u}_q^\dagger\bar{u}_r^\dagger\bar{d}_s^\dagger H^\dagger$	8	1	1
14	$L_pQ_q\bar{u}^\dagger_{[r}\bar{u}^\dagger_{s]}H^\dagger H^\dagger$	8	1	1
15	$\bar{e}_p^\dagger Q_{[q}Q_{r]}\bar{d}_s^\dagger HH$	8	1	1
16	$L_pQ_q\bar{d}^\dagger_{[r}\bar{d}^\dagger_{s]}HH$	8	1	1
17	$D\bar{e}_p^\dagger Q_q\bar{u}_r^\dagger\bar{u}_s^\dagger H^\dagger$	8	1	1
18	$L_pQ_qQ_rQ_sHH^\dagger$	8	1	1
19	$DL_pQ_qQ_r\bar{u}_s^\dagger H^\dagger$	8	1	1
20	$D\bar{e}_p^\dagger Q_qQ_rQ_sH$	8	1	1
21	$D\bar{e}_p^\dagger Q_q\bar{u}_r^\dagger\bar{d}_s^\dagger H$	8	1	1
22	$\bar{e}_p^\dagger Q_qQ_r\bar{u}_s^\dagger HH^\dagger$	8	1	1
23	$\bar{e}_p^\dagger\bar{u}_q^\dagger\bar{u}_r^\dagger\bar{d}_s^\dagger HH^\dagger$	8	1	1
24	$L_pQ_q\bar{u}_r^\dagger\bar{d}_s^\dagger HH^\dagger$	8	1	1



EFT for loop level proton decay, $D = 9$

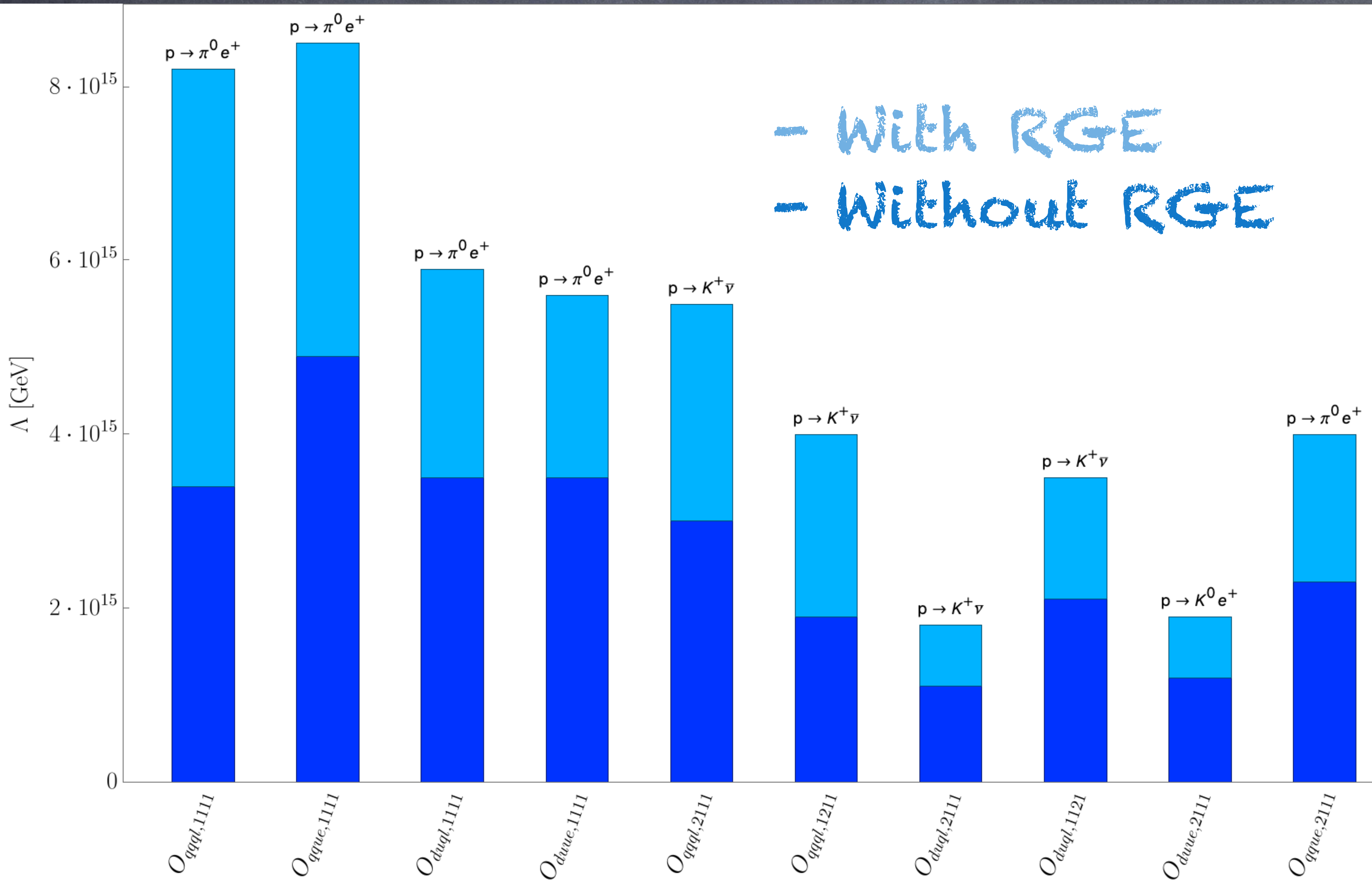
[**John Gargalionis**, JHG, M. Schmidt, 23XX.XXXXX]

25	$\bar{e}^\dagger_{\{p}\bar{e}^\dagger_{q\}}\bar{e}_r\bar{d}_s\bar{d}_{[t}\bar{d}_{u]}$	9	-1	1
26	$\bar{e}^\dagger_p Q^\dagger_q Q^\dagger_{[r} Q^\dagger_{s]} HHH$	9	-1	1
27	$\bar{e}^\dagger_p \bar{d}_{\{q}\bar{d}_{r\}}\bar{d}_{[s}\bar{d}_{t]}\bar{d}^\dagger_u$	9	-1	1
28	$L_pL_q\bar{e}_r\bar{u}_s\bar{d}_t\bar{d}_u$	9	-1	1
29	$\bar{e}^\dagger_p Q^\dagger_q Q^\dagger_r \bar{u}^\dagger_s \bar{d}_t\bar{d}_u$	9	-1	1
30	$L_pL_q\bar{e}_rQ^\dagger_sQ^\dagger_t\bar{d}_u$			
31	$L_pL_qL^\dagger_rQ^\dagger_s\bar{d}_t\bar{d}_u$			
32	$L_pQ^\dagger_q\bar{d}_r\bar{d}_s\bar{d}_t\bar{d}^\dagger_u$			
33	$\bar{e}^\dagger_p\bar{u}_q\bar{u}^\dagger_r\bar{d}_s\bar{d}_t\bar{d}_u$			
34	$D\bar{e}^\dagger_pQ^\dagger_qQ^\dagger_r\bar{d}_sHH$			
35	$L_pL^\dagger_q\bar{e}^\dagger_r\bar{d}_s\bar{d}_{[t}\bar{d}_{u]}$			
36	$L_p\bar{d}_q\bar{d}_{[r}\bar{d}_{s]}H^\dagger H^\dagger H$			
37	$L_pQ^\dagger_{[q}Q^\dagger_{r]}\bar{u}_sHHH$			
38	$DL_pQ^\dagger_qQ^\dagger_rQ^\dagger_sHH$	9	-1	1
39	$\bar{e}^\dagger_pQ_qQ^\dagger_r\bar{d}_s\bar{d}_t\bar{d}_u$	9	-1	1
40	$L_pQ^\dagger_qQ^\dagger_rQ^\dagger_s\bar{u}^\dagger_t\bar{d}_u$	9	-1	1
41	$L_pQ_q\bar{u}_r\bar{d}_s\bar{d}_t\bar{d}_u$	9	-1	1
42	$L_pQ^\dagger_qQ^\dagger_rQ_s\bar{d}_t\bar{d}_u$	9	-1	1
43	$DL_pQ^\dagger_q\bar{d}_r\bar{d}_sHH^\dagger$	9	-1	1
44	$DL_pQ^\dagger_q\bar{u}_r\bar{d}_sHH$	9	-1	1
45	$L_pQ^\dagger_qQ^\dagger_r\bar{d}_sHHH^\dagger$	9	-1	1
46	$L_p\bar{u}_q\bar{d}_r\bar{d}_sHHH^\dagger$	9	-1	1
47	$\bar{e}^\dagger_pQ^\dagger_q\bar{d}_{[r}\bar{d}_{s]}HHH^\dagger$	9	-1	1
48	$D\bar{e}^\dagger_p\bar{d}_q\bar{d}_{\{r}\bar{d}_{s\}}HH^\dagger$	9	-1	1
49	$L_p\bar{e}_q\bar{e}^\dagger_rQ^\dagger_s\bar{d}_t\bar{d}_u$	9	-1	1
50	$L_pQ^\dagger_q\bar{u}_r\bar{u}^\dagger_s\bar{d}_t\bar{d}_u$	9	-1	1



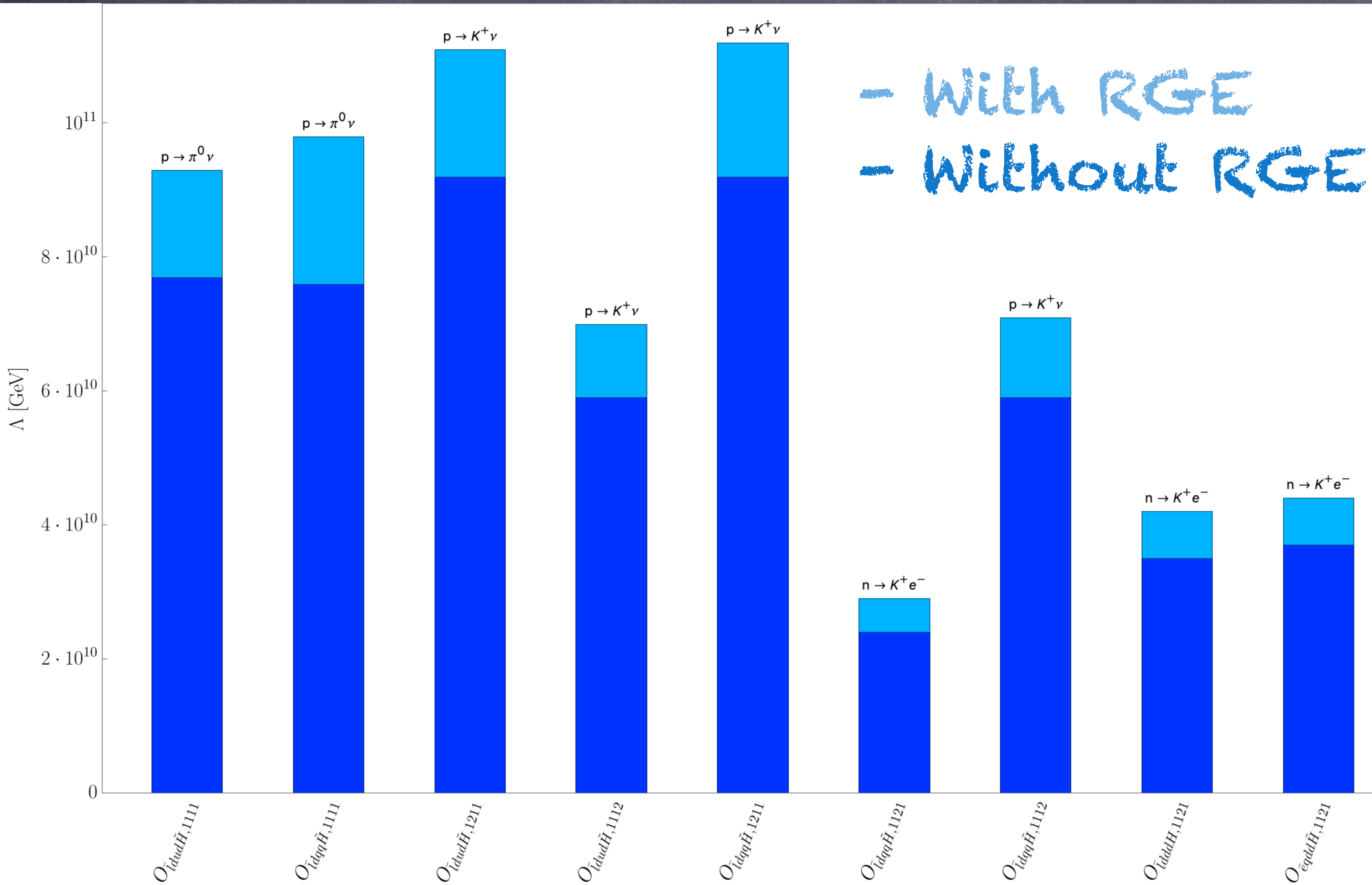
$D = 6$ lower limits, RGE effect

[**Arnau Bas**, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]



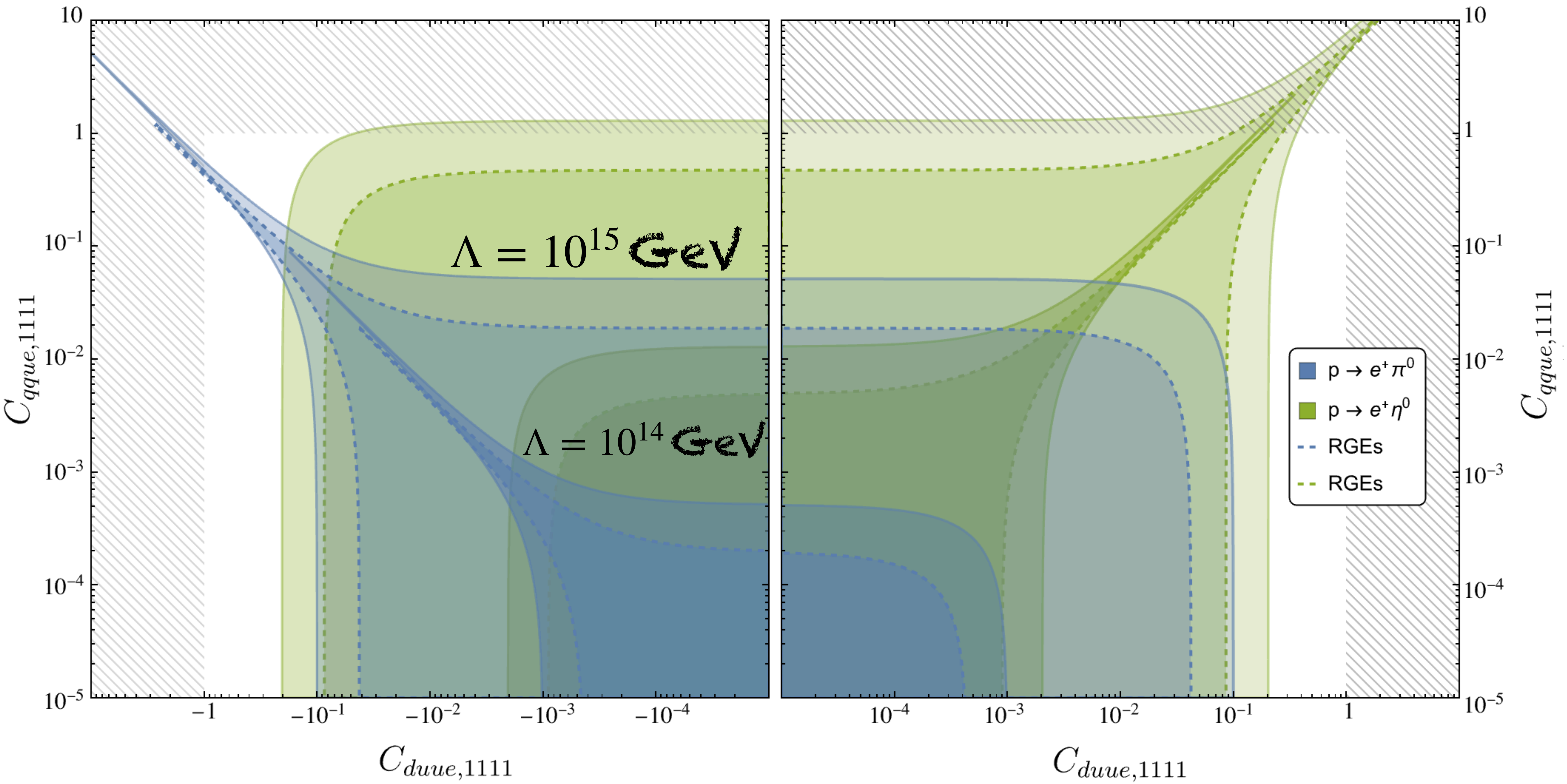
$D = 7$ lower limits, RGE effect

[**Arnau Bas**, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]



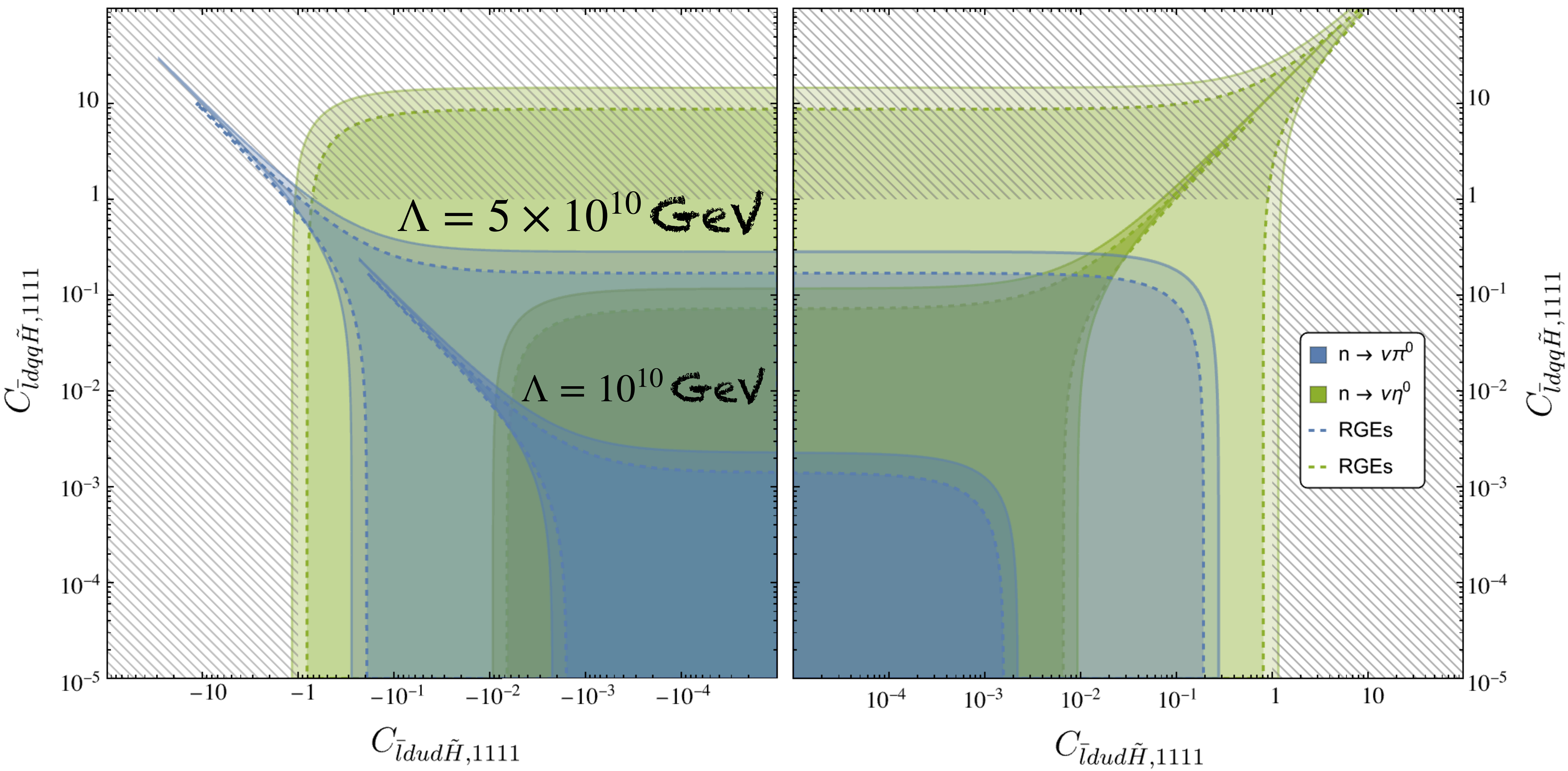
Wilson coefficients, $D = 6$

[**Arnau Bas**, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]

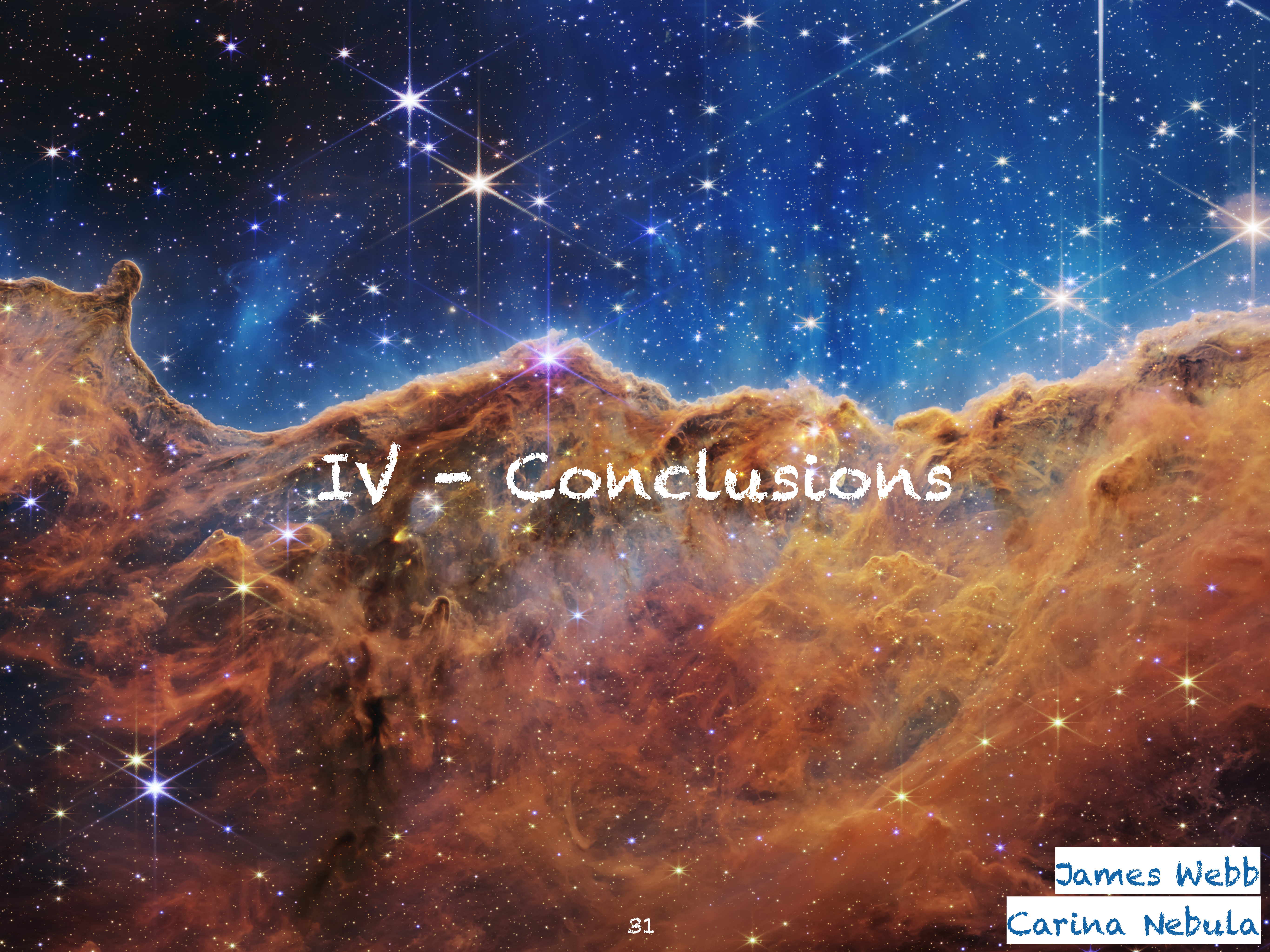


Wilson coefficients, $D = 7$

[**Arnau Bas**, J. Gargalionis, JHG, A. Santamaria, M. Schmidt, in preparation]



IV - Conclusions



James Webb
Carina Nebula

Conclusions

- The violation of the SM accidental symmetries points the way to new physics
- New Weinberg operators (and their seesaw UV completions) may be the origin of neutrino masses
- New scalars close to the EW scale with rich phenomenology: colliders, EWPT...
- Model-independent EFT analysis of nucleon decay in preparation for a positive signal in the near future

감사합니다!

James Webb
Pillars of creation


The 3rd International Joint Workshop & The 11th KIAS Workshop
on BSM and Cosmology
November 2023, Jeju Island
Back-up

How is m_ν generated?

- ν oscillations imply that ν are massive
- At least one ν has a mass ≥ 0.05 eV
- However, in the SM $m_\nu = 0$: need BSM physics
- Which is the UV completion of $LLHH$?

Neutrino mass mechanisms

- Tree level. Seesaws I, II, III. Simple, GUTs, leptogenesis, but huge scales: very hard to test and hierarchy problem

- Radiative. More testable, but $\mathcal{O}(100)$. Classified by:

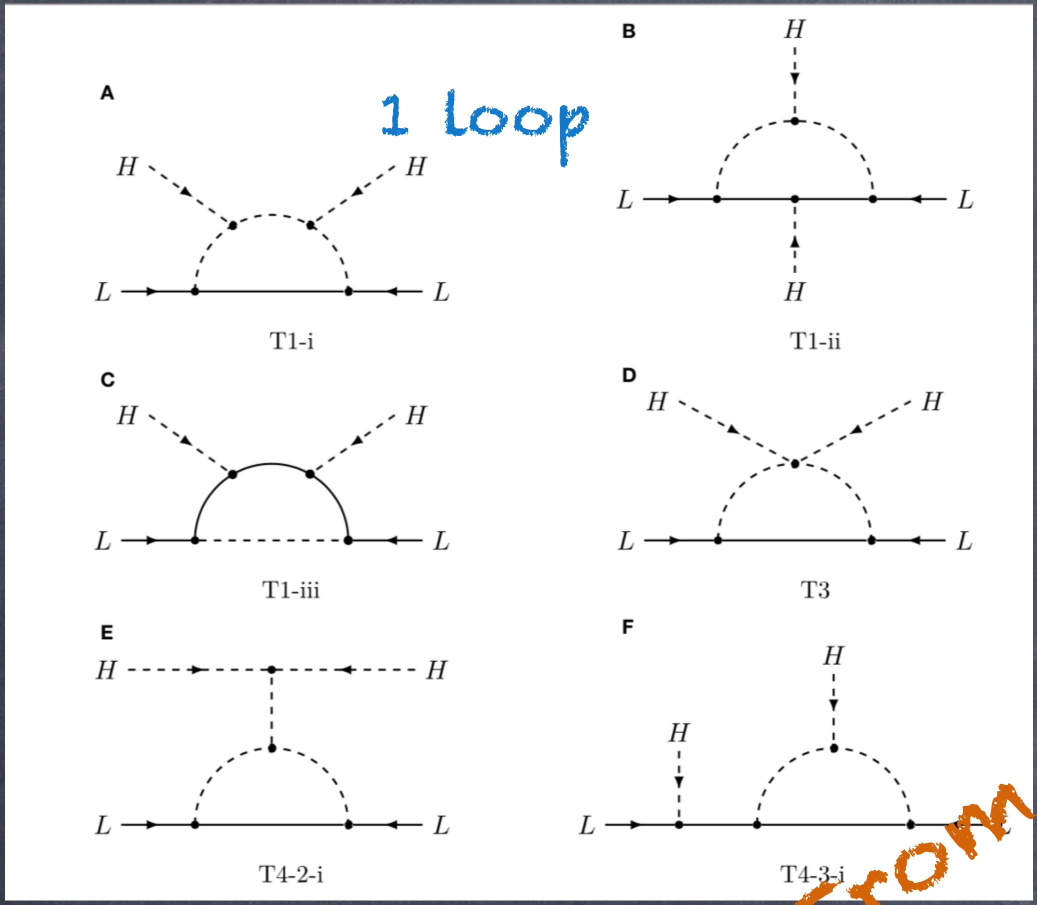
1. Topologies at a loop order (up to 3 loops)

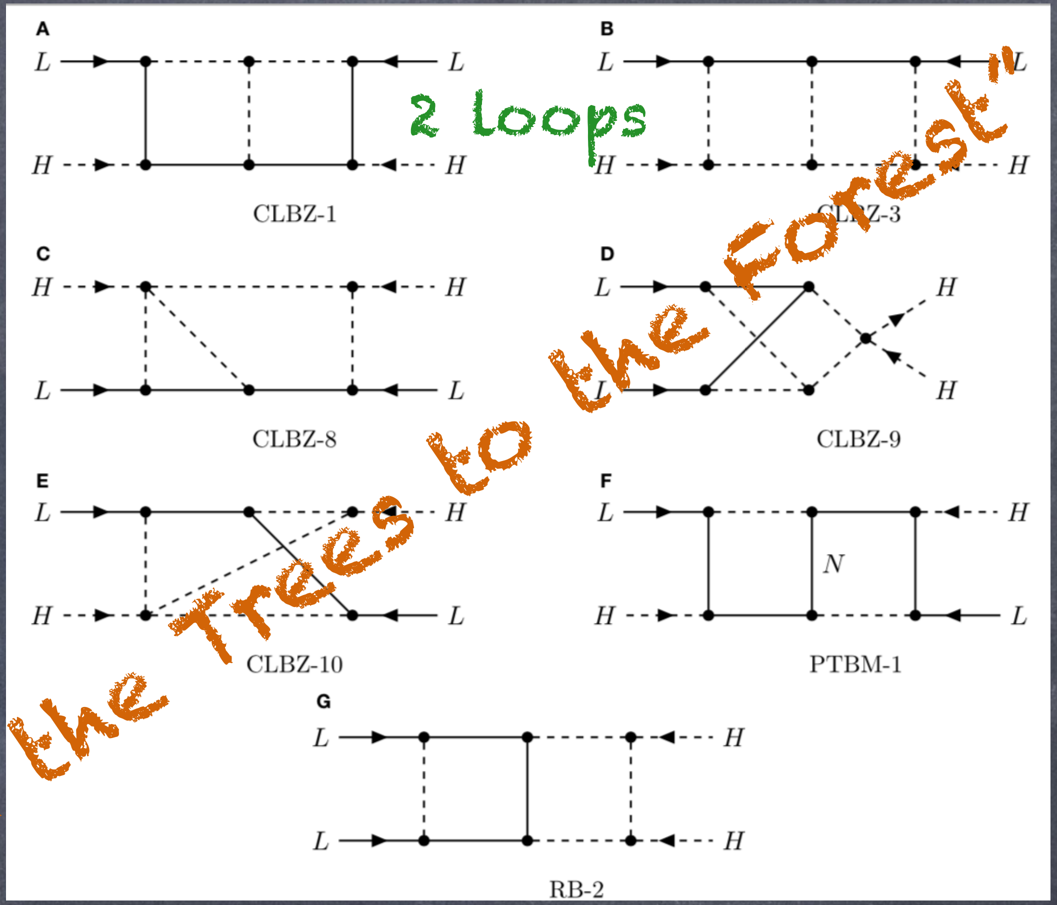
2. $\Delta L = 2$ EFT operators beyond the Weinberg operator

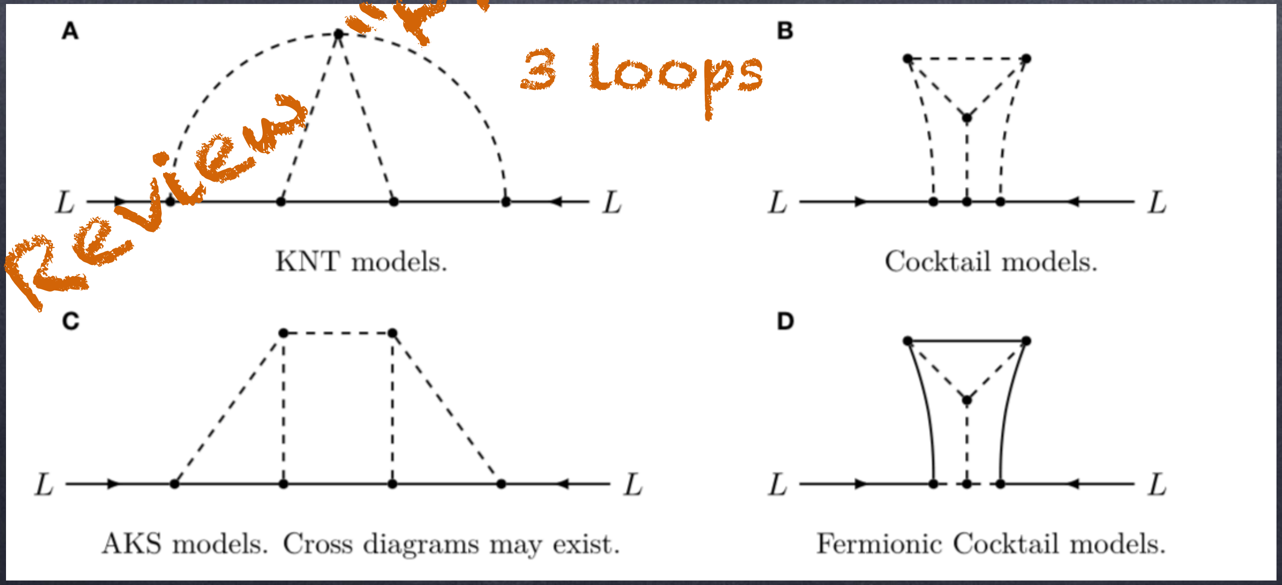
Review "From the Trees to the Forest"

Loop-level models

Zee, Cheng-Li, Babu, Ma, Bonnet, Cepedello, Aristizabal-Sierra, Krauss, Aoki...







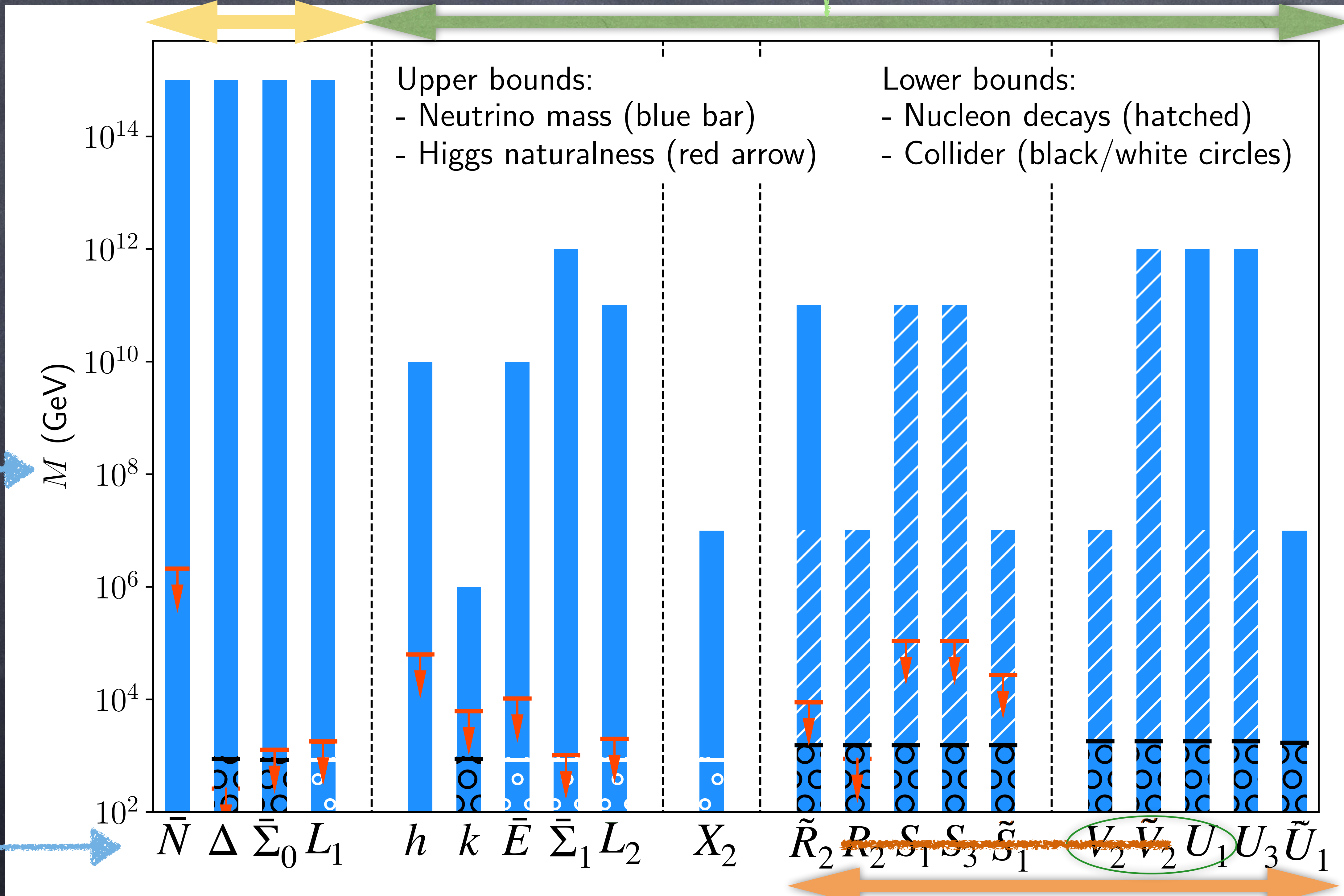
Review "From the Trees to the Forest"

Particles that generate Weinberg operator

[JHG, M. Schmidt, *EPJC* 79 (2019) 11938]

Tree level　　Loop level

Upper limits on X mass



GUTs
LQ

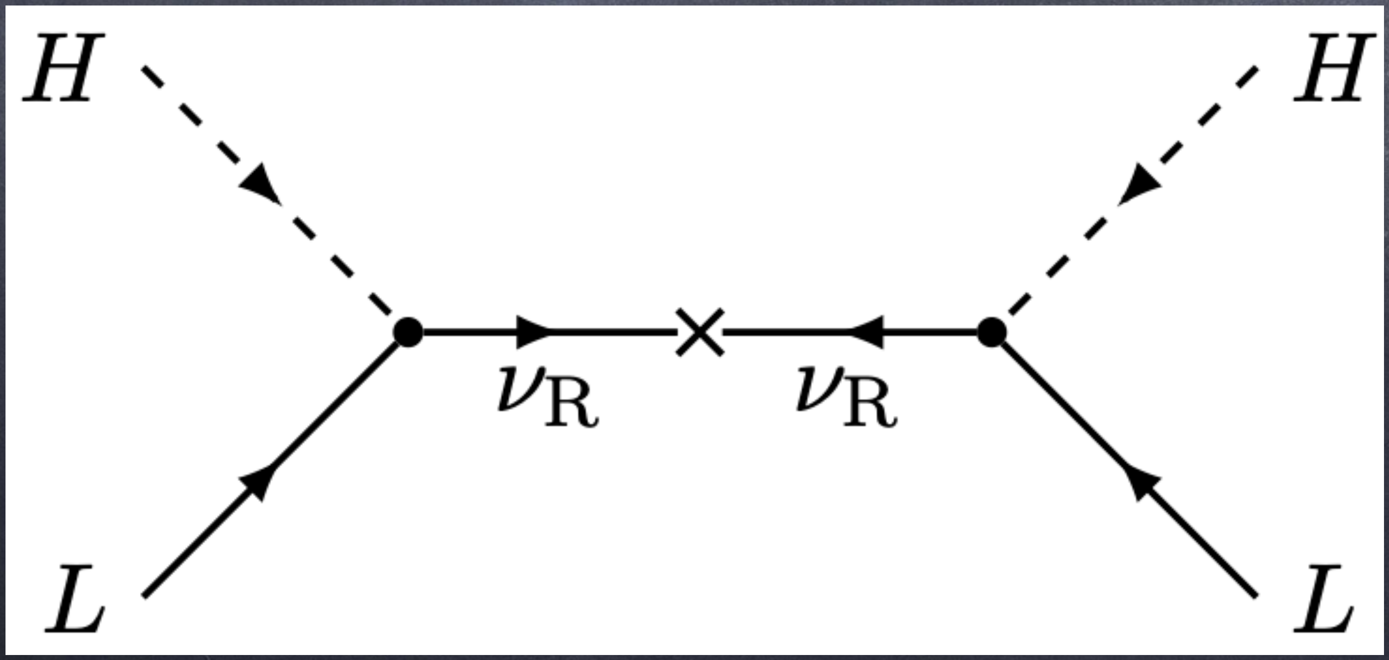
m_ν involve one of these 20 new heavy particles

Seesaw Type I

- At $D = 5$ $LLHH$ [Weinberg], $\Delta L = 2 \implies$

$$m_\nu \simeq c\,\frac{v^2}{\Lambda} \gtrsim 0.05\,\text{eV} \implies \Lambda \lesssim 10^{14}\,\text{GeV}$$

- UV model: heavy ν_R, seesaw Type I



Leptogenesis?

Scalar potentials

$$V_{A_1}(H,\Phi) \supset \lambda_6\,\Phi^*H\Phi\Phi + \lambda_7\,H\Phi H\Phi + \lambda_8\,H^*\Phi HH + \text{H.c.}$$

$$V_{A_2}(H,\Phi) \supset \lambda_6(\Phi HHH) + \text{H.c.}$$

$$V_{B_1}(H,\Phi,\Delta) \supset \lambda_1\Delta^*\Phi^*H\,\Delta + \lambda_2(\Delta^*\Phi^*H\,\Delta)' + \lambda_3\Phi^*\Phi^*H\,H + \lambda_4\Phi^*\Phi^*H\Phi + \lambda_5\Phi^*H^*H\,H + \text{H.c.}$$

$$V_{B_1}(H,\Phi,\Delta) \supset \lambda_6 H\,H\,H\Delta + \lambda_7 H\,H\Phi\Delta + \lambda_8 H\Phi\Phi\Delta + \lambda_9\Phi\Phi\Phi\Delta + \text{H.c.}$$

$$V_{B_2}(H,\Phi,\Delta) \supset \lambda_1\Delta^*\Phi HH + \lambda_2\Delta^*\Delta\Phi + \lambda_3\Delta^*\Delta\Phi\Phi + \lambda_4 H^*H\Phi\Phi + +\lambda_5 HH\Delta\Delta + \lambda_6\Phi\Phi\Phi\Phi + \text{H.c.}$$

$$V_{B_3}(H,\Phi,\Delta) \supset \lambda_1 HH\Phi\Delta + \lambda_2\Phi\Delta\Delta + \text{H.c.}$$

$$V_{B_4}(H,\Phi,\Delta) \supset \lambda_1\Delta^*\Phi HH + \lambda_2\Delta\Delta\Delta + \lambda_3\Phi^*\Phi\Delta + \lambda_4 H^*H\Delta\Delta + +\lambda_5 HH\Phi\Delta + \lambda_6\Delta\Delta\Delta\Delta + \text{H.c.}$$

LFV Limits

Model	Bounded Combination	Experimental Bound: $BR(l_\alpha \to l_\beta\gamma)$		
		$\alpha\beta = \mu e$ $< 4.2 \times 10^{-13}$	$\alpha\beta = \tau e$ $< 3.3 \times 10^{-8}$	$\alpha\beta = \tau\mu$ $< 4.4 \times 10^{-8}$
$\mathbf{A_1}$	$\lvert y_{\phi_1}^{\beta^*} y_{\phi_1}^{\alpha}\rvert (\mathrm{TeV}/M_\Sigma)^2$	< 0.0002	< 0.13	< 0.16
$\mathbf{A_2}$	$\lvert y_{\phi_1}^{\beta^*} y_{\phi_1}^{\alpha}\rvert (\mathrm{TeV}/M_\mathcal{F})^2$	< 0.0004	< 0.24	< 0.28
$\mathbf{B_1}$	$\lvert y_{\phi_1}^{\beta^*} y_{\phi_1}^{\alpha} - 0.5\, y_{\phi_2}^{\beta^*} y_{\phi_2}^{\alpha}\rvert (\mathrm{TeV}/M_\mathcal{F})^2$	< 0.0004	< 0.29	< 0.34
$\mathbf{B_2}$	$\lvert y_{\phi_1}^{\beta^*} y_{\phi_1}^{\alpha} - 50\, y_{\phi_2}^{\beta^*} y_{\phi_2}^{\alpha}\rvert (\mathrm{TeV}/M_\mathcal{F})^2$	< 0.0011	< 0.72	< 0.84
$\mathbf{B_3}$	$\lvert y_{\phi_1}^{\beta^*} y_{\phi_1}^{\alpha} - 2.12\, y_{\phi_2}^{\beta^*} y_{\phi_2}^{\alpha}\rvert (\mathrm{TeV}/M_\mathcal{F})^2$	< 0.0002	< 0.15	< 0.18
$\mathbf{B_4}$	$\lvert y_{\phi_1}^{\beta^*} y_{\phi_1}^{\alpha} + 6.6\, y_{\phi_2}^{\beta^*} y_{\phi_2}^{\alpha}\rvert (\mathrm{TeV}/M_\mathcal{F})^2$	< 0.0004	< 0.24	< 0.28

Proton decay modes

[JUNO, 1507.05613]