Exploding operators for Majorana neutrino masses

HEFT 2022, Granada
Mainly based on JHEP 01, 074 (2021) (arXiv: 2009.13537) with Raymond Volkas

Dr John Gargalionis

https://github.com/johngarg/neutrinomass
arXiv https://arxiv.org/abs/2009.13537

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Outline

I. Motivation and introduction

II. Automated model building from EFT

III. Code and model database

IV. Closing thoughts and future directions

Motivation and introduction

UV

$E > \Lambda$

$E \sim \Lambda$

$E \sim v$

IR

$\mathscr{L}_{\mathrm{UV}}[\Phi_i, \phi, \psi]$

Integrate out Φ

Matchingtools
MatchMaker
SuperTracer
CoDeX
STrEAM
Matchete, …

$$\mathscr{L}_{\mathrm{eff}}[\phi_i, \psi_i] = \sum_i c_i(\Lambda)\mathcal{O}_i$$

Map onto basis of operators

ABC4EFT
DEFT
Rosetta
…

Run RGE

DsixTools
wilson
…

Calculate

flavio
SPheno
…

$$\mathscr{L}_{\mathrm{eff}}[\phi_i, \psi_i] = \sum_i c_i(v)\mathcal{O}_i$$

EFT Diagrammatica:
Bakshi et al. *JHEP* 06 (2021) 033
Naskar et al. arXiv:2205.00910

j-basis/UV correspondence ⇒ Talk by Li Hao-Lin this afternoon

Hao-Lin et al. arXiv: 2204.03660
Hao-Lin et al. *JHEP* 04 (2022) 140

Long tradition of approaches to building neutrino mass models!
neutrinomass

At $d = 6$ Granada dictionary can be inverted!

de Blas et al. *JHEP* 03 (2018) 109
Criado CPC 227 06 2018

$\mathscr{L}_{\mathrm{UV}}[\Phi_i, \phi, \psi]$

$E > \Lambda$

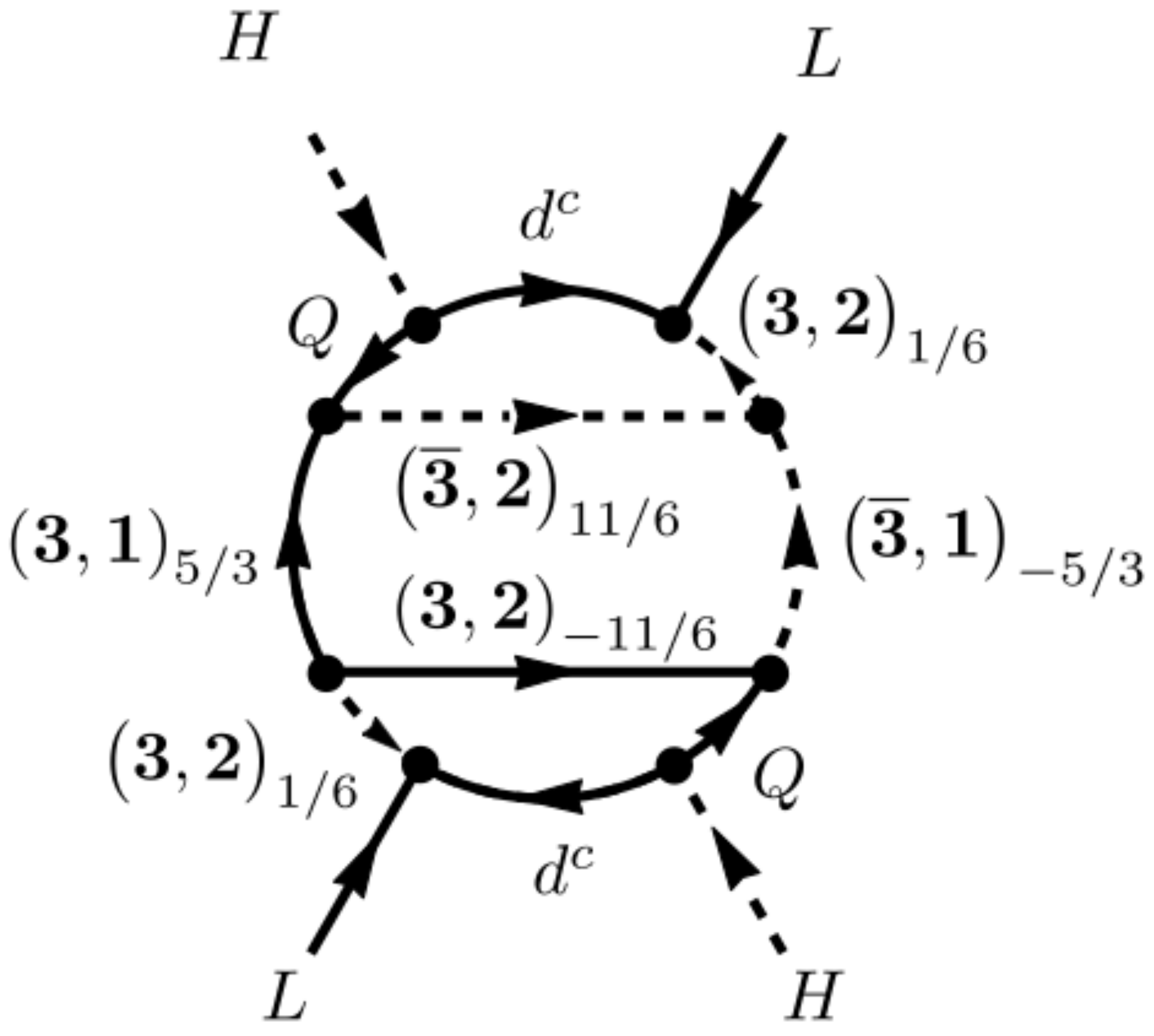
$E \sim v$

$\mathscr{L}_{\mathrm{eff}}[\phi_i, \psi_i]$

Tree- and loop-level completions of the Weinberg-like operators

$$\mathscr{L}_{\mathrm{W}} = \sum_n \frac{C_{5+2n}}{\Lambda^{2n+1}} \cdot LLHH(H^\dagger H)^n$$

Bonnet et al. JHEP 07, 153 (2012);
Cepedello, Hirsch, Helo JHEP 07, 079 (2017); JHEP 01, 009 (2018)
Cepedello, Fonseca, Hirsch JHEP 10, 197 (2018);
Anamiati et al. JHEP 12, 066 (2018)

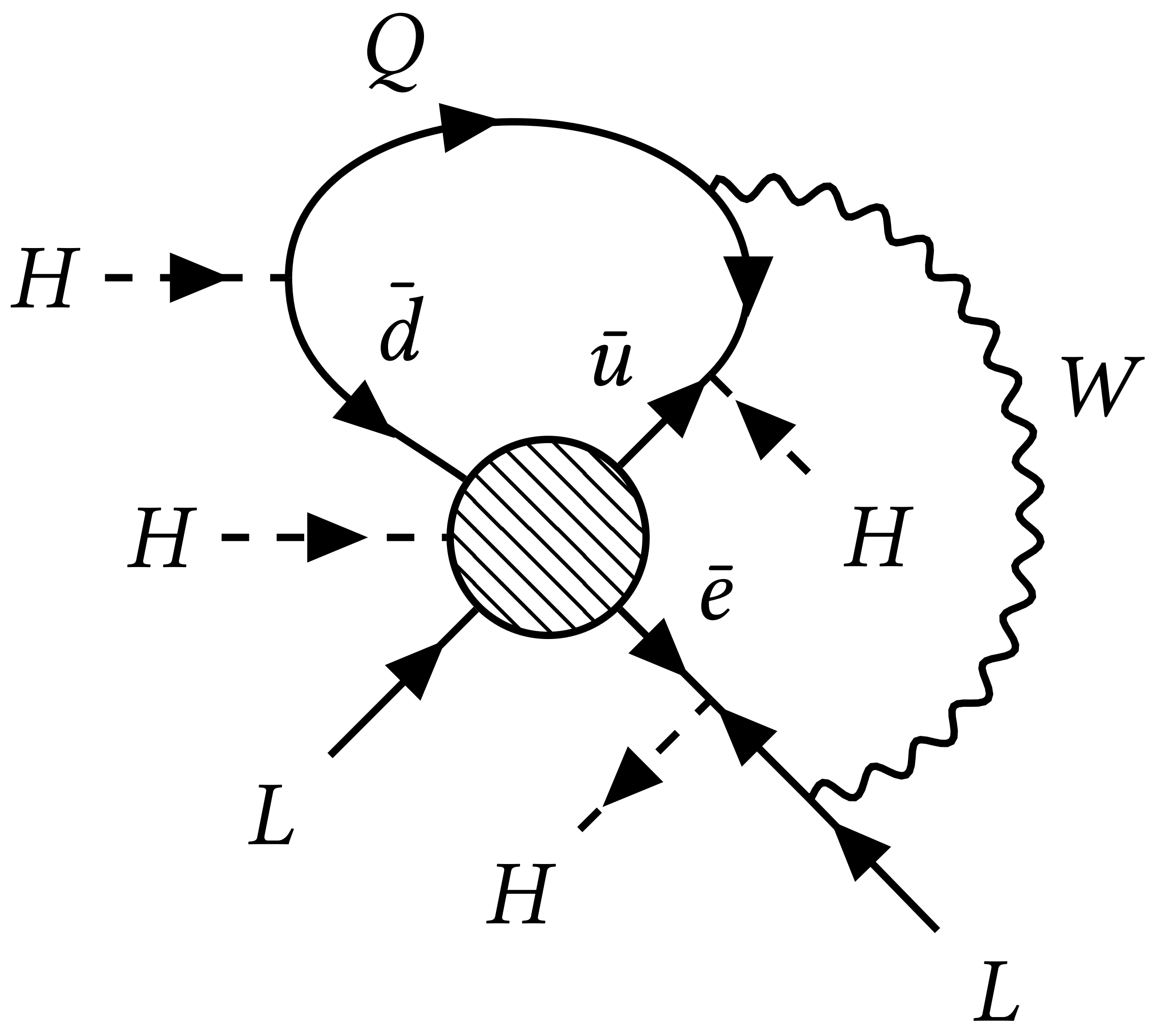


Review: Cai, et al. Front. in Phys. 5 (2017) 63

Tree-level completions of $\Delta L = 2$ operators in the SMEFT

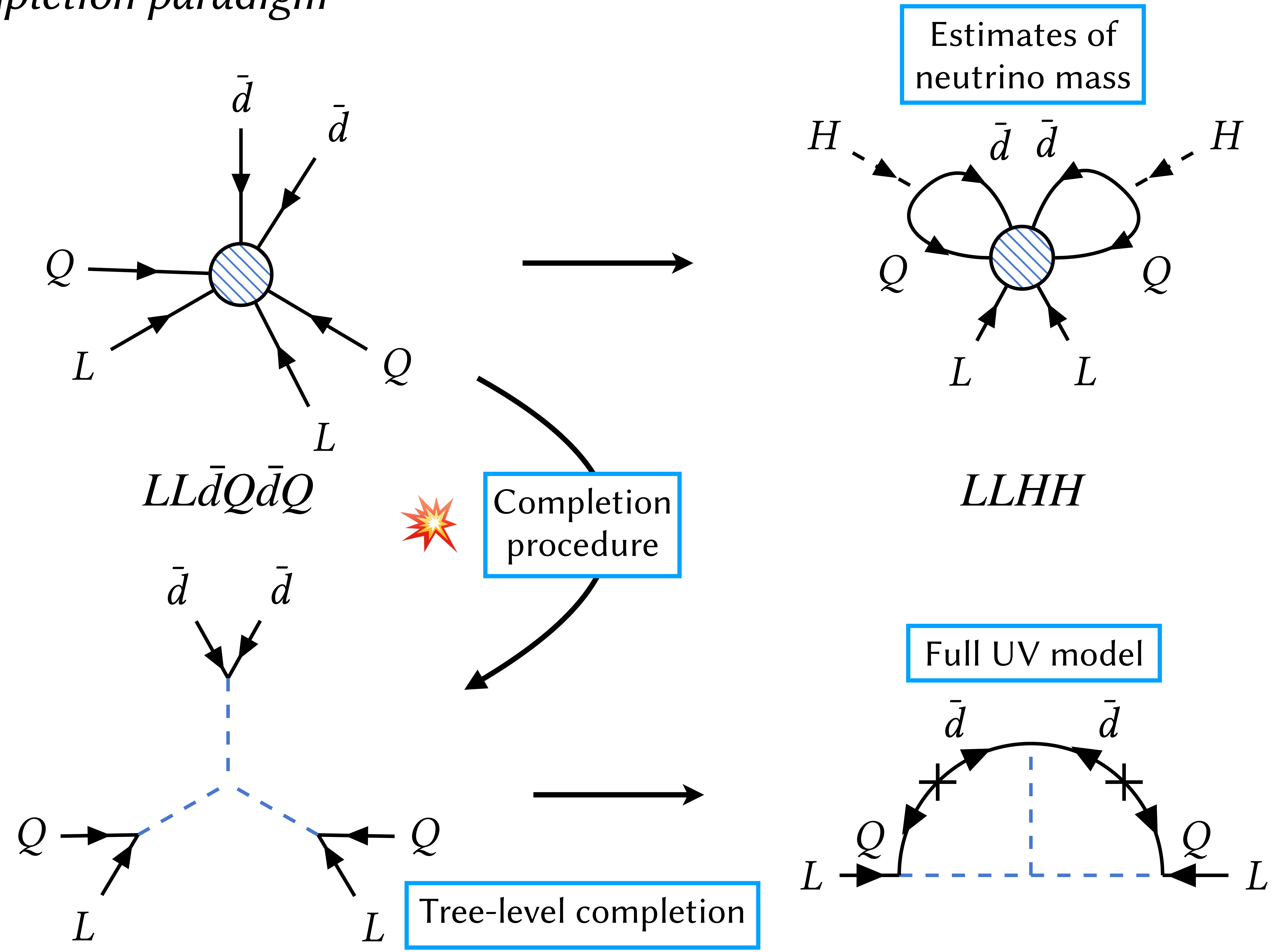
$$\mathscr{L}_{\Delta L=2} = \frac{C_5}{\Lambda} \cdot LLHH + \frac{C_7^{(1)}}{\Lambda^3} \cdot LLQ\bar{d}H + \frac{C_7^{(2)}}{\Lambda^3} \cdot L\bar{d}\bar{u}^\dagger\bar{e}^\dagger H + \cdots$$

Kobach *PLB* 758 (2016)
Lehman *PRD* 90, 125023 (2014)
Ma, Liao *JHEP* 11 (2020) 152, …



e.g.
Babu, Leung NPD 619, 667 (2001)
de Gouvêa, Jenkins PRD 77, 013008 (2008)
del Aguila et al. JHEP 06 146 (2012)
Herrero-García et al. JHEP 11 084 (2016)
Angel, Rodd, Volkas PRD 87, 073007 (2013)
Cai et al. JHEP 02 161 (2015)
Gargalionis, Volkas JHEP 01 074 (2021)

Tree-level completion paradigm



Automated model building from EFT

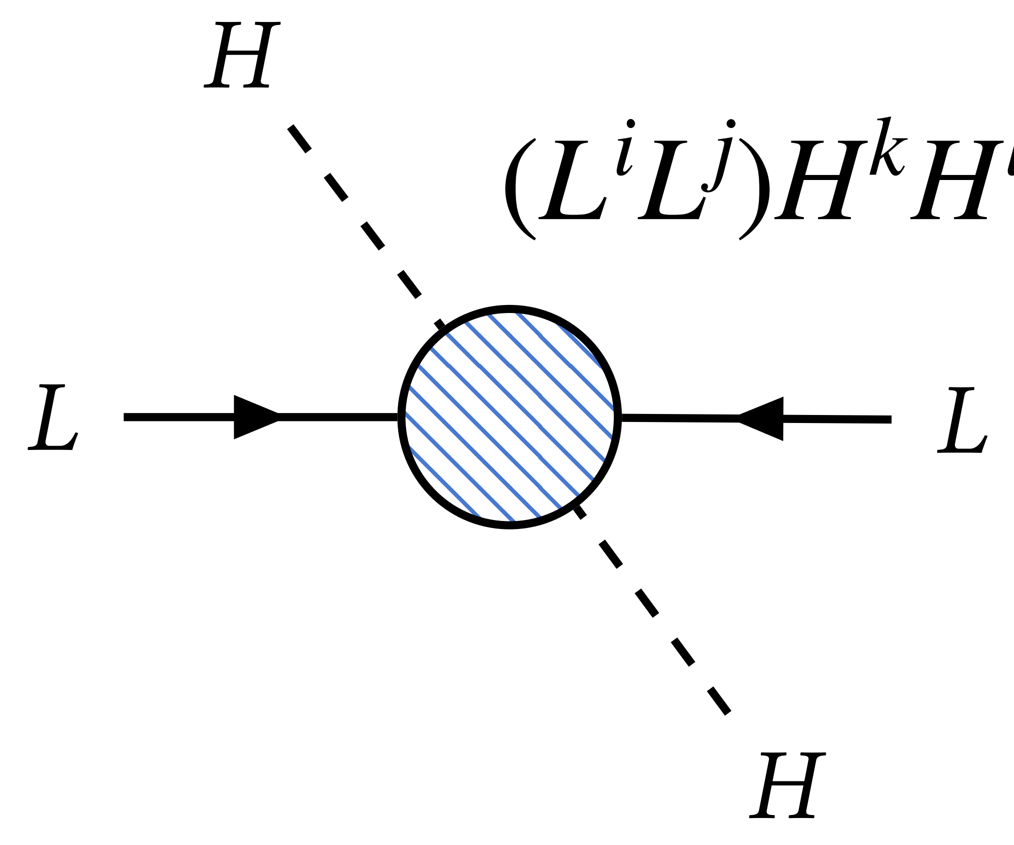
What does the UV physics look like?

Gauge | *Lorentz*

$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y + \mathrm{SU}(2)_+ \otimes \mathrm{SU}(2)_-$

$\{i, j, \dots\}$ $\{\alpha, \beta, \dots\}$ $\{\dot{\alpha}, \dot{\beta}, \dots\}$

$(\psi\chi) \equiv \psi^\alpha \chi^\beta \epsilon_{\alpha\beta}$

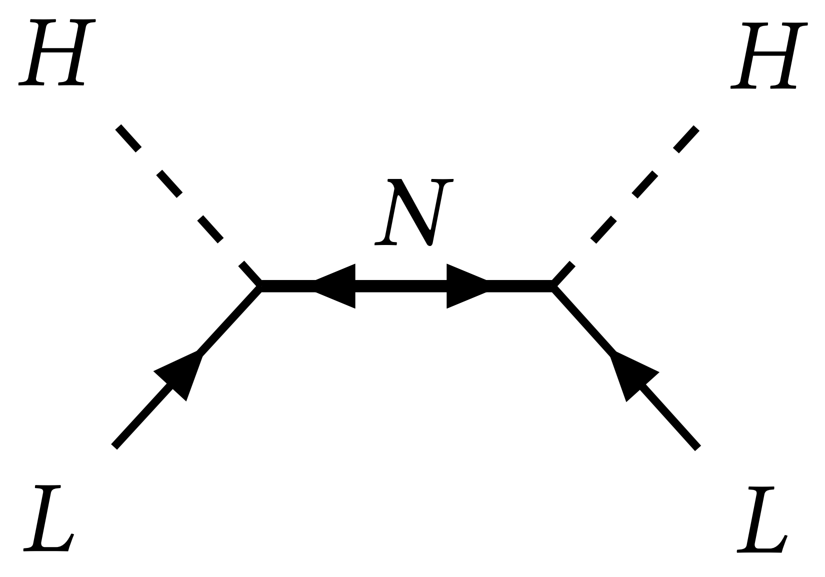


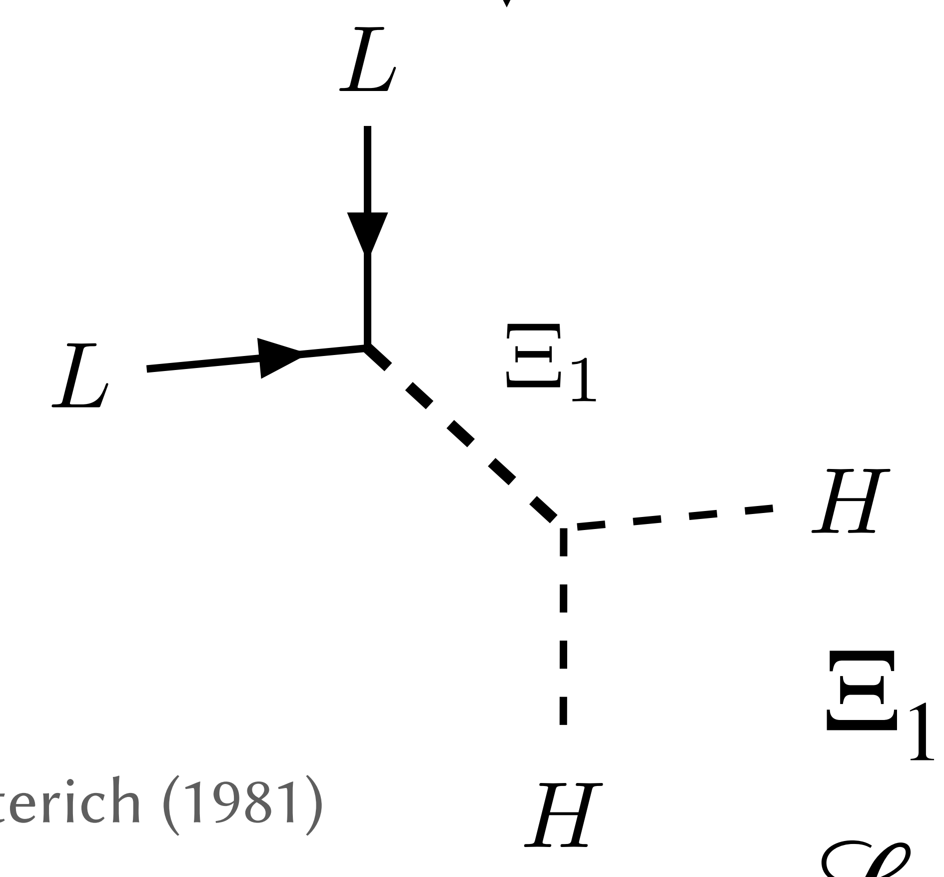
$(L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl}$

P. Minkowski (1977)
T. Yanagida (1979)
M. Gell-Mann, P. Ramond, R. Slansky (1979)
R. Mohapatra, G. Senjanović (1980)
S. Glashow (1980)

$N \sim (\mathbf{1}, \mathbf{1}, 0)_{(\mathbf{2},\mathbf{1})}$

$\mathscr{L}_N = y_N (L^i N) H^j \epsilon_{ij}$

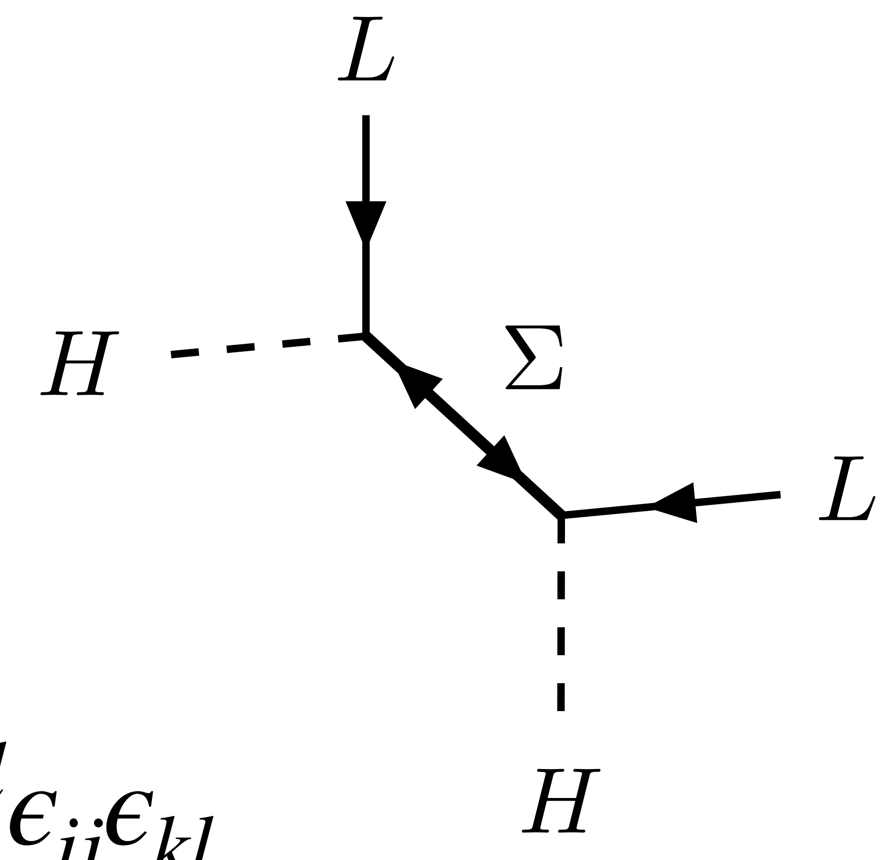




M. Magg, C. Wetterich (1980)
J. Schechter, J. Valle (1980)
T.-P. Cheng, L.-F. Li (1980)
G. Lazarides, Q. Shafi, C. Wetterich (1981)
C. Wetterich (1981)
R. Mohapatra, G. Senjanović (1981)

$\Xi_1 \sim (\mathbf{1}, \mathbf{3}, 1)_{(\mathbf{1},\mathbf{1})}$

$\mathscr{L}_{\Xi_1} = y_{\Xi_1} (L^i L^j) \Xi_1^{kl} \epsilon_{ik} \epsilon_{jl} + \kappa_{\Xi_1} H^i H^j \Xi^\dagger_{1ij}$



$\Sigma \sim (\mathbf{1}, \mathbf{3}, 0)_{(\mathbf{2},\mathbf{1})}$

$\mathscr{L}_\Sigma = y_\Sigma (L^i \Sigma^{jk}) H^l \epsilon_{ij} \epsilon_{kl}$

R. Foot, X.-G. He, H. Lew, G. Joshi (1989)

What does the UV physics look like?

Gauge *Lorentz*

$$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y + \mathrm{SU}(2)_+ \otimes \mathrm{SU}(2)_-$$

$\{i, j, \dots\}$ $\{\alpha, \beta, \dots\}$ $\{\dot\alpha, \dot\beta, \dots\}$

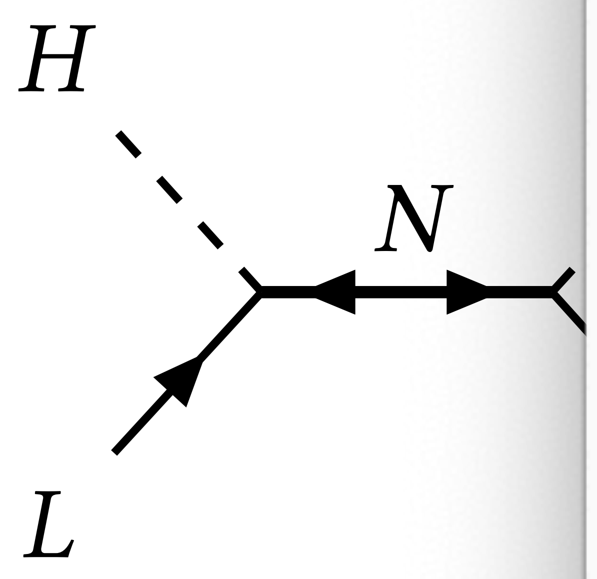
$$(L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl}$$

$$(\psi\chi) \equiv \psi^\alpha \chi^\beta \epsilon_{\alpha\beta}$$

P. Minkowski (1977)
T. Yanagida (1979)
M. Gell-Mann, P. Ramond, R. Slansky (1979)
R. Mohapatra, G. Senjanović
S. Glashow (1980)

$N \sim (\mathbf{1}, \mathbf{1}, 0)_{(2,}$

$\mathscr{L}_N = y_N (L^i N)$



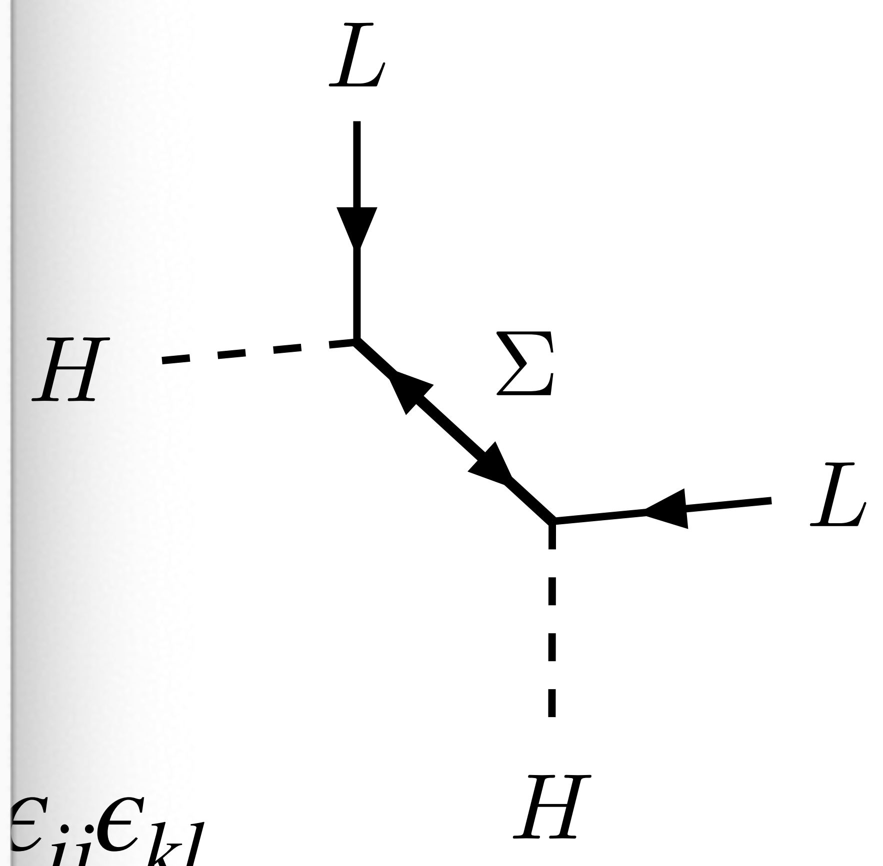

```
#!/usr/bin/env python

from neutrinomass.tensormethod import L, H, eps
from neutrinomass.completions import completions

op = L("u0 i0") * L("u1 i1") * H("i2") * H("i3") \
    * eps("-u0 -u1") * eps("-i0 -i2") * eps("-i1 -i3")

models = completions(op)
# => [Model(S(1, 3, 1)(0)), Model(F(1, 1, 0)(0)), Model(F(1, 3, 0)(0))]

# models[0].lagrangian
# models[0].effective_lagrangian
# models[0].symmetries
# models[0].diagram
```



$\epsilon_{ij} \epsilon_{kl}$

H. Lew, G. Joshi (1989)

R. Mohapatra, G. Senjanović (1981)

$+ \kappa_{\Xi_1} H^i H^j \Xi^\dagger_{1ij}$

$\Phi \rightarrow$ heavy field

$\phi, \psi \rightarrow$ light fields

Tree-level matching backwards

$$\mathscr{L}_{\rm HE}[\Phi, \phi, \psi]$$

$E > M$

$$\mathscr{L}_\Phi = -\Phi^\dagger(D^2 + M^2)\Phi + \Phi^\dagger \cdot \frac{\partial \mathscr{L}}{\partial \Phi^\dagger} + \mathscr{O}(\Phi^3)$$

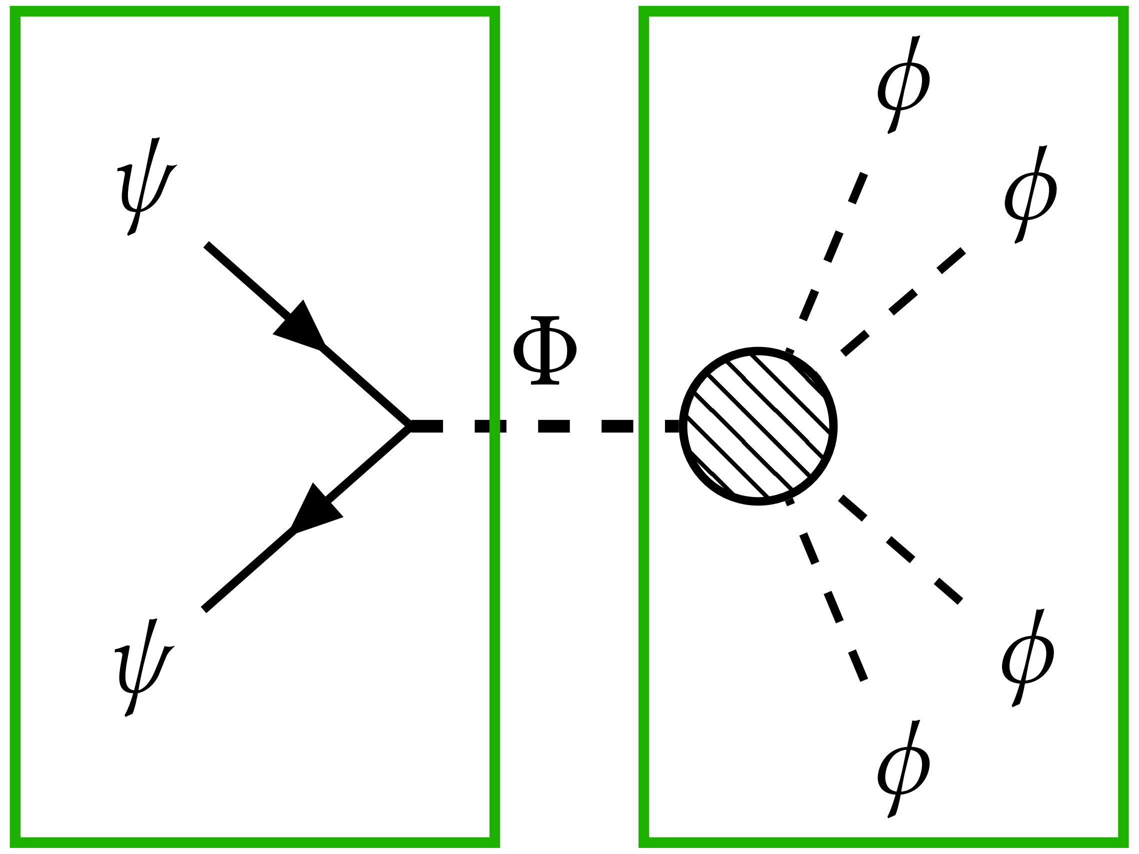
Replace by EOM

$E < M$

$$\mathscr{L}_{\rm eff} = \frac{\partial \mathscr{L}}{\partial \Phi} \cdot -\frac{1}{M^2}\left[1 + \frac{(iD)^2}{M^2} + \cdots\right] \cdot \frac{\partial \mathscr{L}}{\partial \Phi^\dagger}$$

Fierz
EOM
IBP

$$\sum_i c_i \mathscr{O}_i$$



One cannot talk about UV completions unambiguously **without defining some kind of a basis of operators**

Use a general spanning set of operators: Green's basis, implicit Lorentz structure…

Tree-level matching backwards

$\Phi \to$ heavy field

$\phi, \psi \to$ light fields

$$\mathcal{L}_{\rm HE}[\Phi, \phi, \psi]$$

$E > M$

$$\mathcal{L}_\Phi = -\Phi^\dagger(D^2 + M^2)\Phi + \Phi^\dagger \cdot \frac{\partial \mathcal{L}}{\partial \Phi^\dagger} + \mathcal{O}(\Phi^3)$$

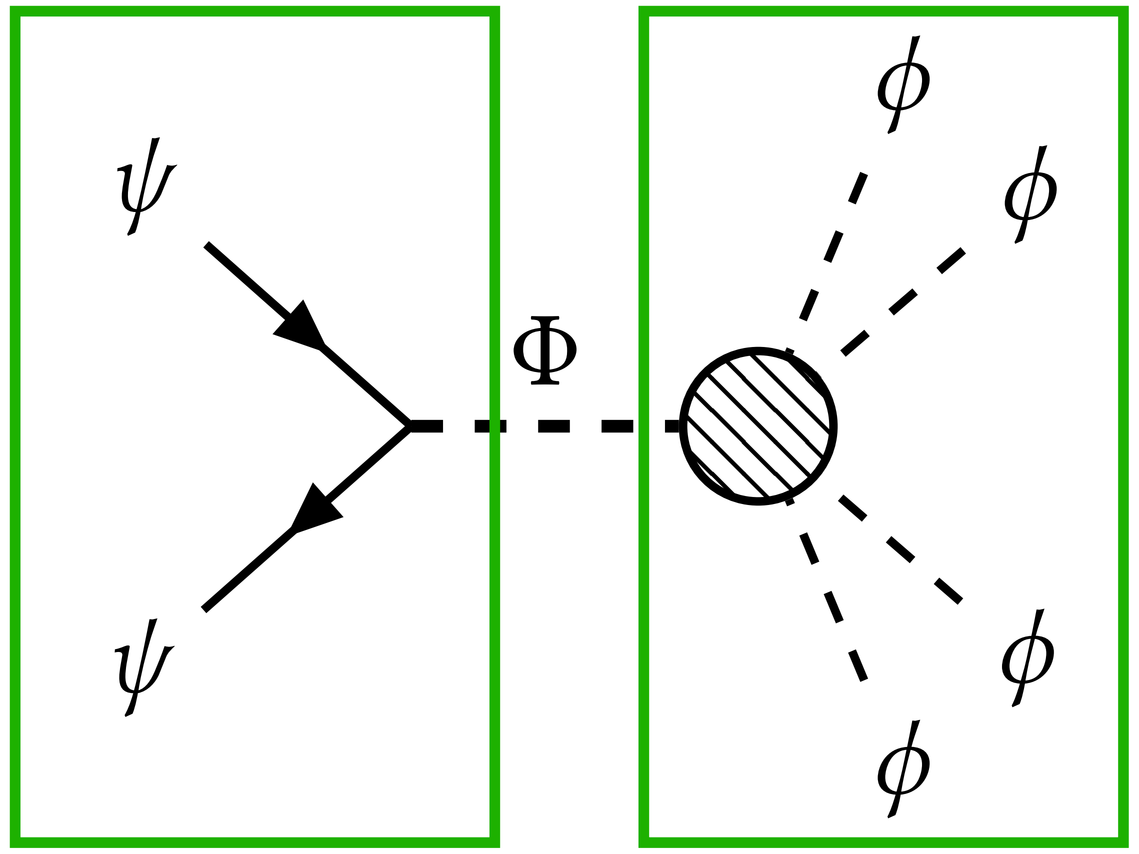
$E < M$

$$\mathcal{L}_{\rm eff} = \frac{\partial \mathcal{L}}{\partial \Phi} \cdot -\frac{1}{M^2}\left[1 + \frac{(iD)^2}{M^2} + \cdots\right] \cdot \frac{\partial \mathcal{L}}{\partial \Phi^\dagger}$$

Fill in all possible $\partial \mathcal{L}/\partial \Phi^\dagger$ $\to$ $+\mathcal{O}_2 + \cdots$

$$\sum_i c_i \mathcal{O}_i$$

$$\mathcal{O}_1$$

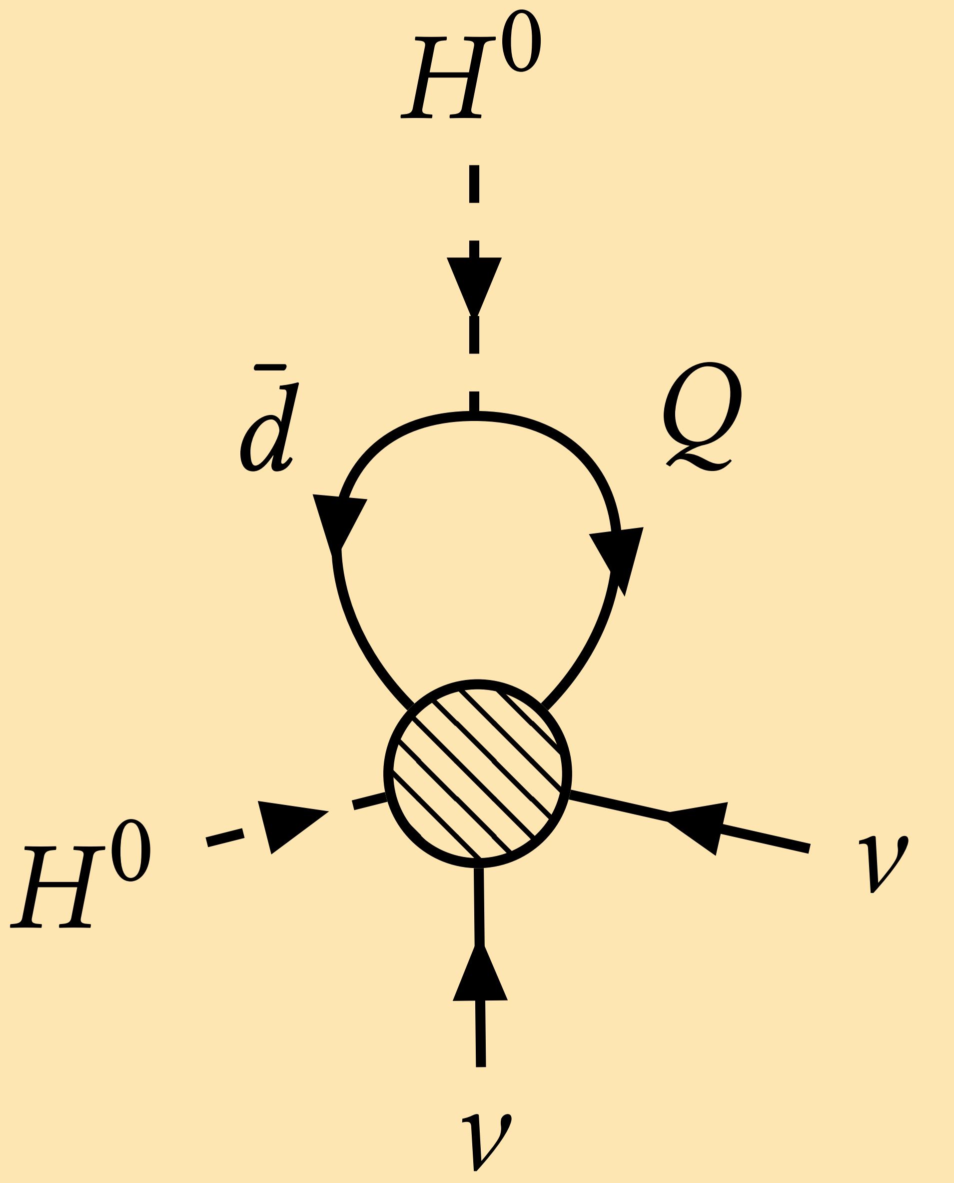


One cannot talk about UV completions unambiguously **without defining some kind of a basis of operators**

Use a general spanning set of operators:

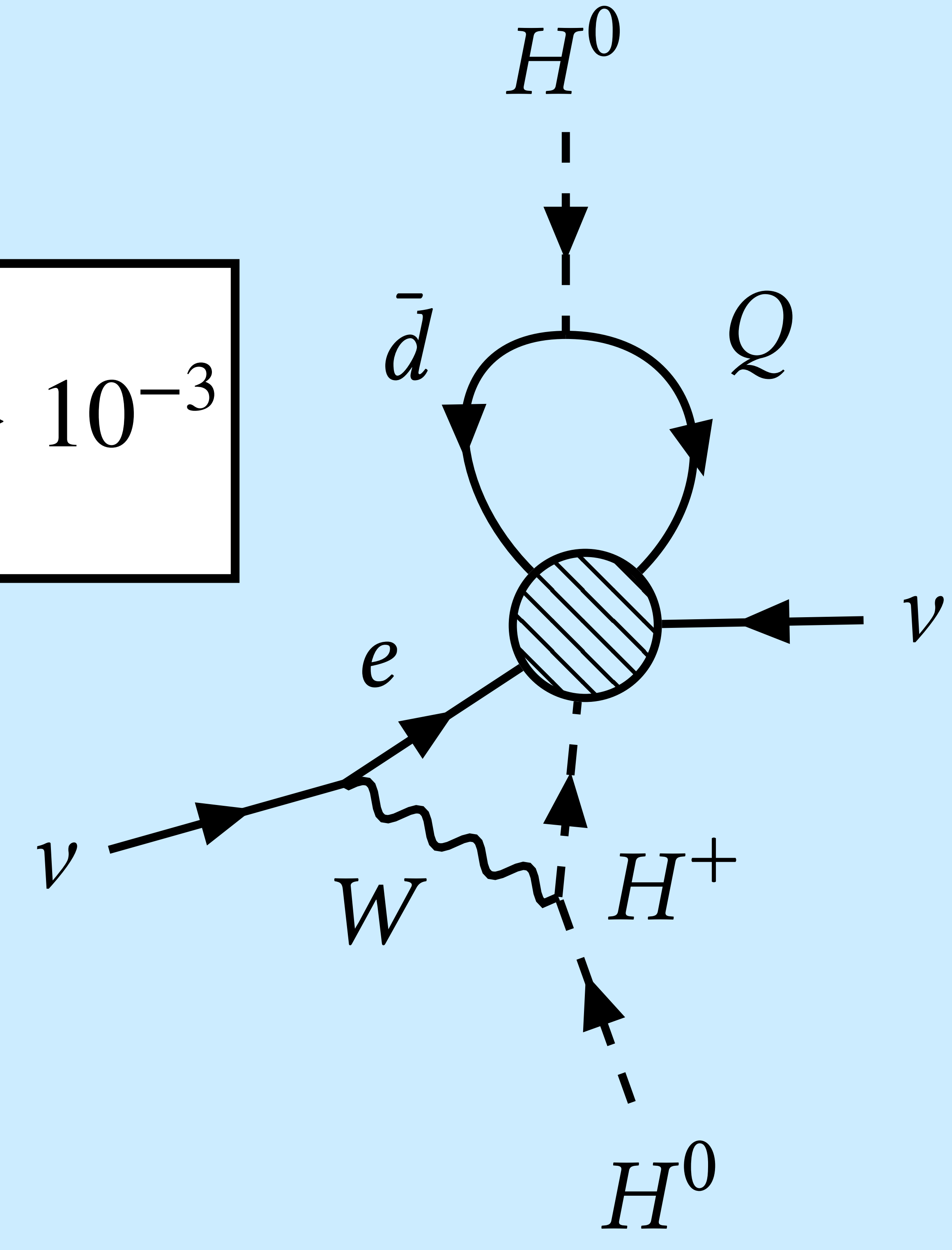
Green's basis, implicit Lorentz structure...

Want general spanning set of operators, for m_ν we care most about distinguishing $\mathrm{SU}(2)_L$ structures. *E.g.* $\mathcal{O}_3 = LLQ\bar{d}H$



$\mathcal{O}_{3b} = (L^i Q^k)(L^j \bar{d})H^l \cdot \epsilon_{ik}\epsilon_{jl}$

$$\frac{m_\nu^{(3a)}}{m_\nu^{(3b)}} \sim \frac{C_{3a}}{C_{3b}} \cdot g^2 \frac{1}{16\pi^2} \to 10^{-3}$$

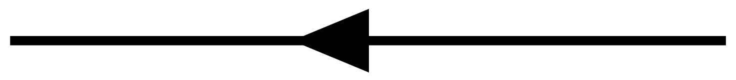


$\mathcal{O}_{3a} = (L^i Q^k)(L^j \bar{d})H^l \cdot \epsilon_{ij}\epsilon_{kl}$

Operators

Updated list of ~ 150 distinguished operators up to $d = 11$ including those with derivatives, kept when:

- Tree-level topology can accommodate as many *arrow-preserving* fermion propagators
- Structure like $H^i(DH)^j\epsilon_{ij}$ present



$$\sim \frac{\sigma \cdot p}{p^2 - m^2}$$

$$\sim \frac{m}{p^2 - m^2}$$

Labels	Operator	Models	Filtered	Loops	Λ [TeV]
1	$L^iL^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	3	3	0	$6 \cdot 10^{11}$
2	$L^iL^jL^k\bar{e}H^l \cdot \epsilon_{ik}\epsilon_{jl}$	8	2	1	$4 \cdot 10^{7}$
3a	$L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ij}\epsilon_{kl}$	9	2	2	$2 \cdot 10^{5}$
3b	$L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ik}\epsilon_{jl}$	14	5	1	$9 \cdot 10^{7}$
4a	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ik}\epsilon_{jl}$	5	0	1	$4 \cdot 10^{9}$
4b	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ij}\epsilon_{kl}$	4	2	2	$10 \cdot 10^{6}$
5a	$L^iL^jQ^k\bar{d}H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	790	36	2	$6 \cdot 10^{5}$
5b	$\mathcal{O}_1 \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$	492	14	1,2	$6 \cdot 10^{5}$
5c	$\mathcal{O}_{3a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	509	0	2,3	$1 \cdot 10^{3}$
5d	$\mathcal{O}_{3b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	799	16	1,2	$6 \cdot 10^{5}$
6a	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	289	14	2	$2 \cdot 10^{7}$
6b	$\mathcal{O}_1 \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$	177	0	1,2	$2 \cdot 10^{7}$
6c	$\mathcal{O}_{4a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	262	0	1,2	$2 \cdot 10^{7}$
6d	$\mathcal{O}_{4b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	208	0	2,3	$6 \cdot 10^{4}$
7	$L^i\bar{e}^\dagger Q^j\tilde{Q}^kH^lH^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	240	15	2	$2 \cdot 10^{5}$
8	$L^i\bar{e}^\dagger\bar{u}^\dagger\bar{d}H^j \cdot \epsilon_{ij}$	5	1	2,3	$2 \cdot 10^{1}$
D16a	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	58	8	2	$2 \cdot 10^{5}$
D16b	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$	58	8	2	$2 \cdot 10^{5}$
D16c	$L^i\bar{e}^\dagger\tilde{Q}^j\bar{u}^\dagger(DH)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	27	4	2	$2 \cdot 10^{5}$
D17	$\bar{e}^\dagger\bar{e}^\dagger\bar{u}^\dagger\bar{d}(DH)^iH^j \cdot \epsilon_{ij}$	16	7	3,4	$2 \cdot 10^{-1}$
D18a	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}$	53	1	0,1	$4 \cdot 10^{9}$
D18b	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ik}\epsilon_{jl}\epsilon_{mn}$	53	1	0,1	$4 \cdot 10^{9}$
D18c	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{im}\epsilon_{jl}\epsilon_{kn}$	53	1	0,1	$4 \cdot 10^{9}$
D18d	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	24	1	1,2	$10 \cdot 10^{6}$
D18e	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{in}\epsilon_{jl}\epsilon_{km}$	34	0	1	$4 \cdot 10^{9}$
D18f	$(DL)^iL^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	34	0	1	$4 \cdot 10^{9}$
D19a	$(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{ij}\epsilon_{kl}$	1	0	1	$2 \cdot 10^{9}$
D19b	$(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{il}\epsilon_{jk}$	3	3	0	$6 \cdot 10^{11}$
D19c	$(D^2L)^iL^j(D^2H)^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	3	3	0	$6 \cdot 10^{11}$
D20	$L^i\bar{e}^\dagger H^jH^kH^l(DH)^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	129	0	1,2	$2 \cdot 10^{5}$
D21	$(DL)^i(D\bar{e}^\dagger)H^jH^k(DH)^l \cdot \epsilon_{ik}\epsilon_{jl}$	2	0	1	$4 \cdot 10^{7}$
D22	$\bar{e}^\dagger\bar{e}^\dagger(DH)^i(DH)^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	9	0	2	$3 \cdot 10^{3}$

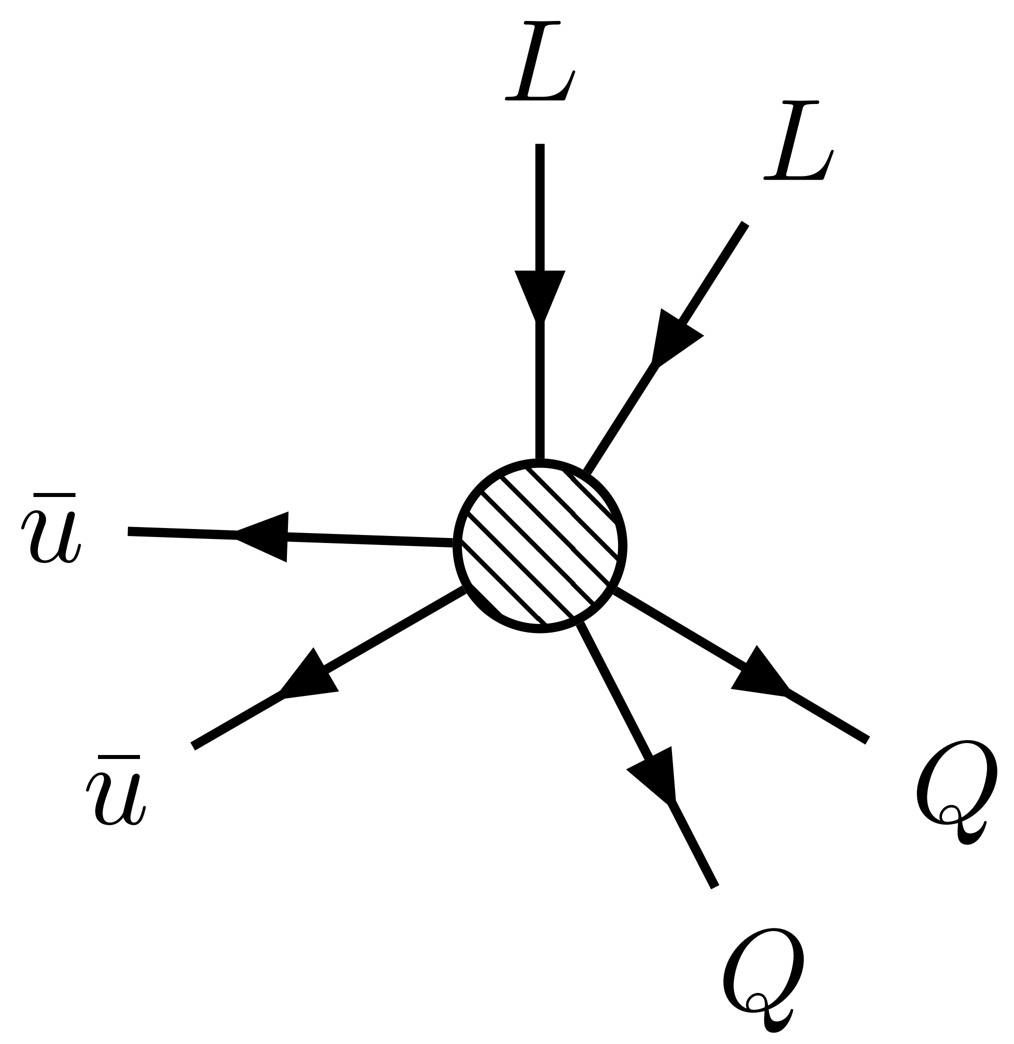
Example of completion algorithm

Gauge		*Lorentz*
$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	+	$\mathrm{SU}(2)_+ \otimes \mathrm{SU}(2)_-$
$\{a, b, \ldots\}$ $\{i, j, \ldots\}$		$\{\alpha, \beta, \ldots\}$ $\{\dot\alpha, \dot\beta, \ldots\}$

The procedure can be phrased as a kind of abstract term-rewriting system

$$\mathscr{L} = C \cdot L^i L^j Q^\dagger_{ia} Q^\dagger_{jb} \bar{u}^{\dagger a} \bar{u}^{\dagger b}$$

$$L^{\alpha i} L^{\beta j} Q^{\dagger\dot\alpha}_{ia} Q^{\dagger\dot\beta}_{jb} \bar{u}^{\dagger\dot\gamma a} \bar{u}^{\dagger\dot\delta b}$$



Example of completion algorithm

Gauge / *Lorentz*

$$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y + \mathrm{SU}(2)_+ \otimes \mathrm{SU}(2)_-$$

$\{i, j, \dots\}$ $\{\alpha, \beta, \dots\}$ $\{\dot\alpha, \dot\beta, \dots\}$

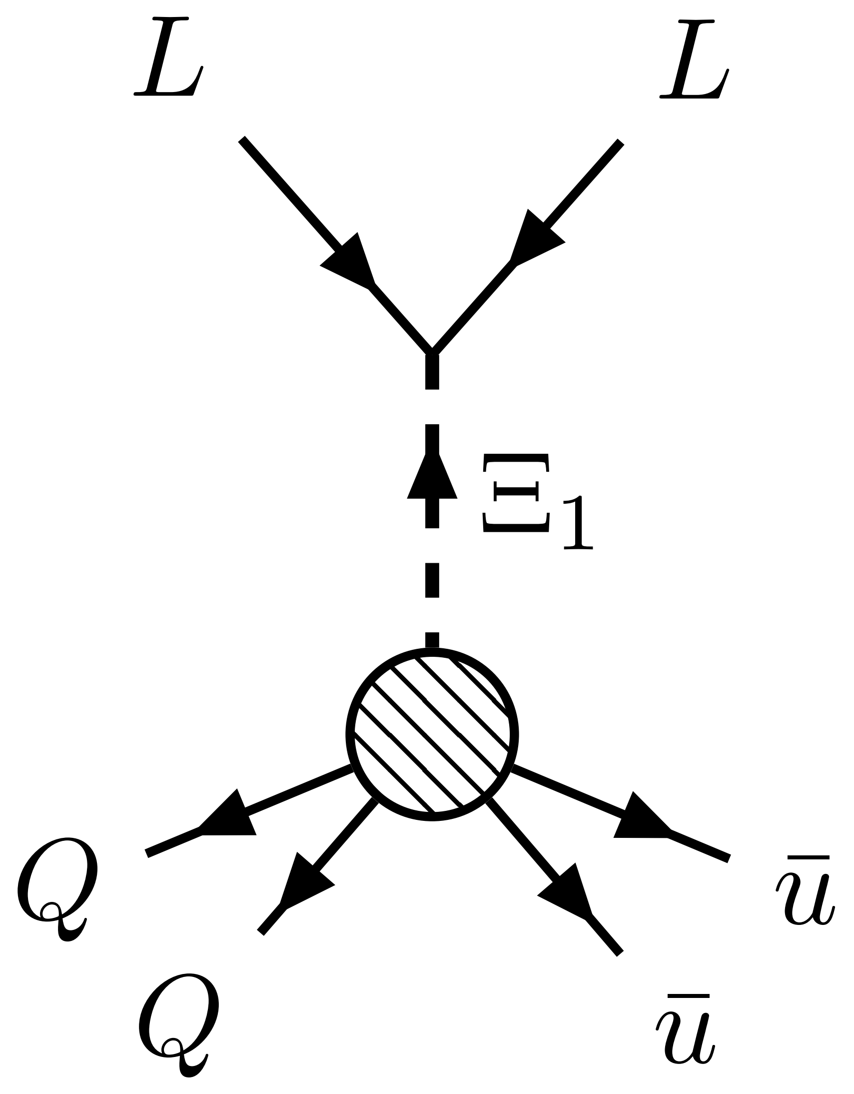
The procedure can be phrased as a kind of abstract term-rewriting system

$$\mathscr{L} = y_{LL}\Xi^{\dagger}_{1\{ij\}}(L^iL^j) + C' \cdot \Xi_1^{\{ij\}}Q^{\dagger}_{ia}Q^{\dagger}_{jb}\bar{u}^{\dagger a}\bar{u}^{\dagger b}$$

$$L^{\alpha i}L^{\beta j}Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}\bar{u}^{\dagger\dot\gamma a}\bar{u}^{\dagger\dot\delta b}$$

$$\to \underbrace{L^{\alpha i}L^{\beta j}}Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}\bar{u}^{\dagger\dot\gamma a}\bar{u}^{\dagger\dot\delta b} \quad +(i \leftrightarrow j) \quad \cdot\, \epsilon_{\alpha\beta}$$

$$\Xi_1 \sim (\mathbf{1}, \mathbf{3}, -1)_{(\mathbf{1},\mathbf{1})}$$



Example of completion algorithm

Gauge		*Lorentz*
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	+	$SU(2)_+ \otimes SU(2)_-$
$\{i, j, \ldots\}$		$\{\alpha, \beta, \ldots\}$ $\{\dot\alpha, \dot\beta, \ldots\}$

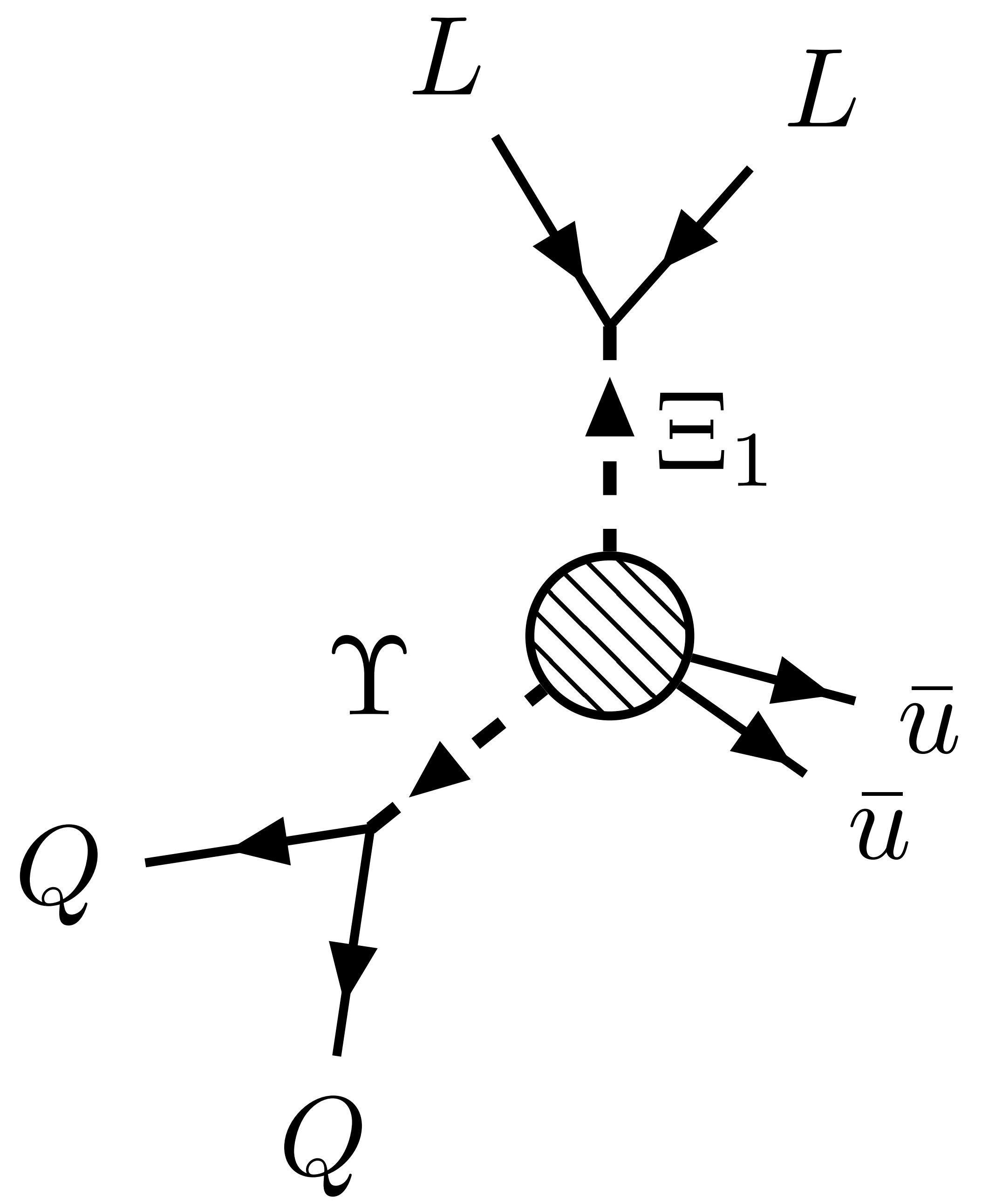
The procedure can be phrased as a kind of abstract term-rewriting system

$$\mathscr{L} = y_{QQ}\Upsilon^{\dagger\{ab\}\{ij\}}(Q_a^\dagger Q_b^\dagger) + y_{LL}\Xi^\dagger_{1\{ij\}}(L^i L^j) + C'' \cdot \Xi_1^{\{ij\}}\Upsilon_{ijab}\bar{u}^{\dagger a}\bar{u}^{\dagger b}$$

$$L^{\alpha i}L^{\beta j}Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}\bar{u}^{\dagger\dot\gamma a}\bar{u}^{\dagger\dot\delta b}$$

$$\to \underbrace{L^{\alpha i}L^{\beta j}}_{\Xi_1 \sim (\mathbf{1}, \mathbf{3}, -1)_{(\mathbf{1},\mathbf{1})}}Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}\bar{u}^{\dagger\dot\gamma a}\bar{u}^{\dagger\dot\delta b} \qquad +(i \leftrightarrow j) \quad \cdot\, \epsilon_{\alpha\beta}$$

$$\to \Xi^{ij}\underbrace{Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}}_{\Upsilon \sim (\bar{\mathbf{6}}, \bar{\mathbf{3}}, -\frac{1}{3})_{(\mathbf{1},\mathbf{1})}}\bar{u}^{\dagger\dot\gamma a}\bar{u}^{\dagger\dot\delta b} \qquad +(a \leftrightarrow b) \quad \cdot\, \epsilon_{\dot\alpha\dot\beta}$$



Example of completion algorithm

	Gauge		*Lorentz*
	$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	+	$\mathrm{SU}(2)_+ \otimes \mathrm{SU}(2)_-$
	$\{i, j, \dots\}$		$\{\alpha, \beta, \dots\}$ $\{\dot\alpha, \dot\beta, \dots\}$

The procedure can be phrased as a kind of abstract term-rewriting system

$$\mathscr{L} = y_{\bar u \bar u}\Omega^\dagger_{4\{ab\}}(\bar u^{\dagger a}\bar u^{\dagger b}) + y_{QQ}\Upsilon^{\dagger\{ab\}\{ij\}}(Q^\dagger_a Q^\dagger_b) + y_{LL}\Xi^\dagger_{1\{ij\}}(L^i L^j) + C''' \cdot \Xi_1^{\{ij\}}\Upsilon_{\{ab\}ij}\Omega_4^{ab}$$

$$L^{\alpha i}L^{\beta j}Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}\bar u^{\dagger\dot\gamma a}\bar u^{\dagger\dot\delta b}$$

$$\to \underbrace{L^{\alpha i}L^{\beta j}}Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}\bar u^{\dagger\dot\gamma a}\bar u^{\dagger\dot\delta b} \qquad +(i \leftrightarrow j) \cdot \epsilon_{\alpha\beta}$$

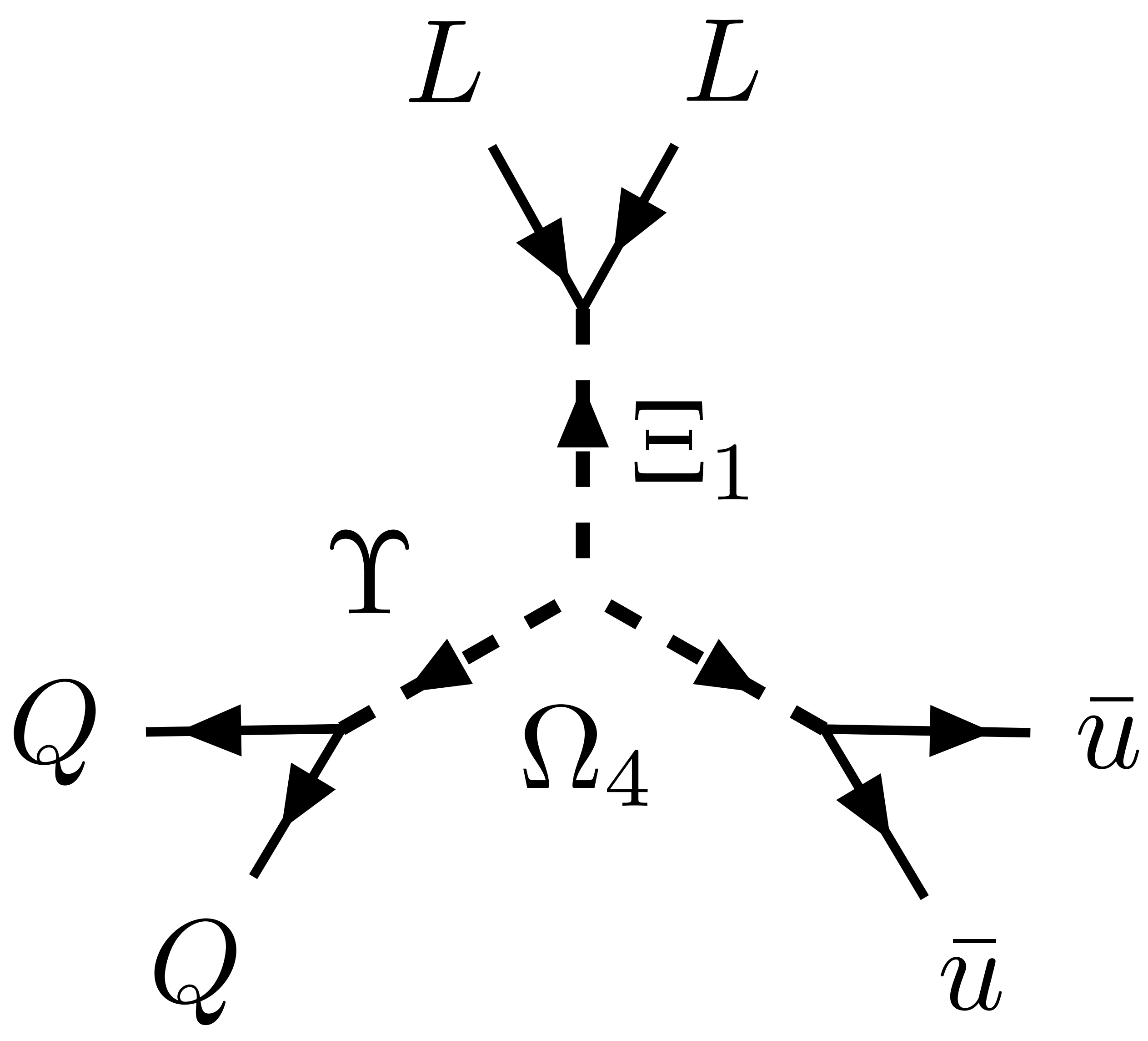
$\Xi_1 \sim (\mathbf{1}, \mathbf{3}, -1)_{(\mathbf{1},\mathbf{1})}$

$$\to \Xi_1^{ij}\underbrace{Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb}}\bar u^{\dagger\dot\gamma a}\bar u^{\dagger\dot\delta b} \qquad +(a \leftrightarrow b) \cdot \epsilon_{\dot\alpha\dot\beta}$$

$\Upsilon \sim (\bar{\mathbf{6}}, \bar{\mathbf{3}}, -\tfrac{1}{3})_{(\mathbf{1},\mathbf{1})}$

$$\to \Xi_1^{ij}\Upsilon_{abij}\underbrace{\bar u^{\dagger\dot\gamma a}\bar u^{\dagger\dot\delta b}} \qquad \cdot\, \epsilon_{\dot\gamma\dot\delta}$$

$\Omega_4 \sim (\mathbf{6}, \mathbf{1}, -\tfrac{4}{3})_{(\mathbf{1},\mathbf{1})}$



$$(L^{\alpha i}L^{\beta j} + i \leftrightarrow j)(Q^{\dagger\dot\alpha}_{ia}Q^{\dagger\dot\beta}_{jb} + a \leftrightarrow b)\bar u^{\dagger\dot\gamma a}\bar u^{\dagger\dot\delta b}$$

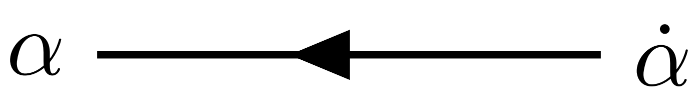
$$\cdot\, \epsilon_{\alpha\beta}\epsilon_{\dot\alpha\dot\beta}\epsilon_{\dot\gamma\dot\delta}$$

Example of completion algorithm

Many rules implemented, most important:

$$\psi^{\alpha}\phi \to \Psi^{\alpha}$$

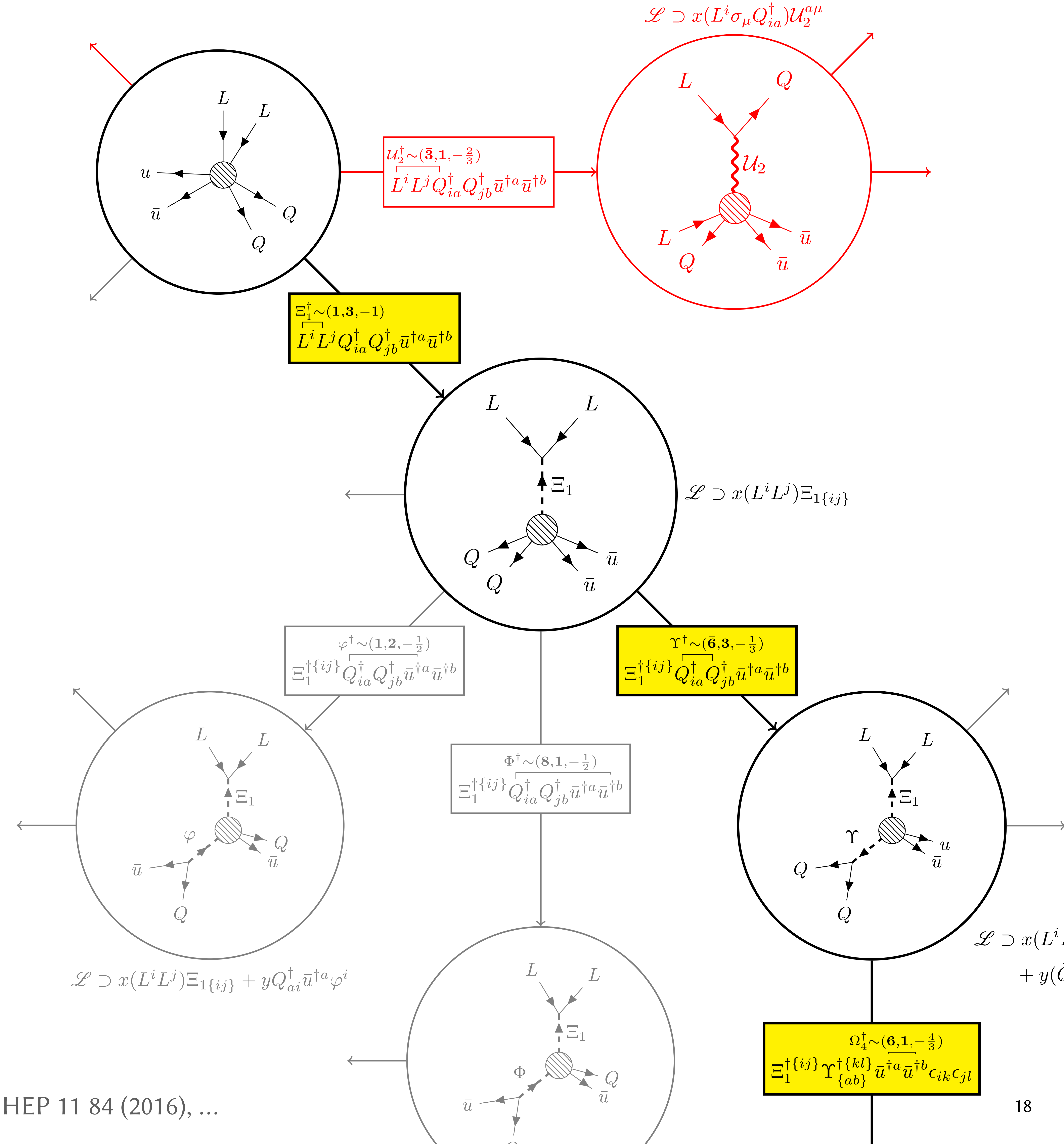
$$\partial^{\alpha\dot{\alpha}}\psi^{\dagger}_{\dot{\alpha}}\phi \to \Psi^{\alpha}$$



$$\phi_1\phi_2\phi_3 \to \Phi$$

All rules that match should be applied in all possible ways at each step of the procedure, leading to a *completion graph*

Validated against dimension-6 SMEFT and other neutrino-mass examples

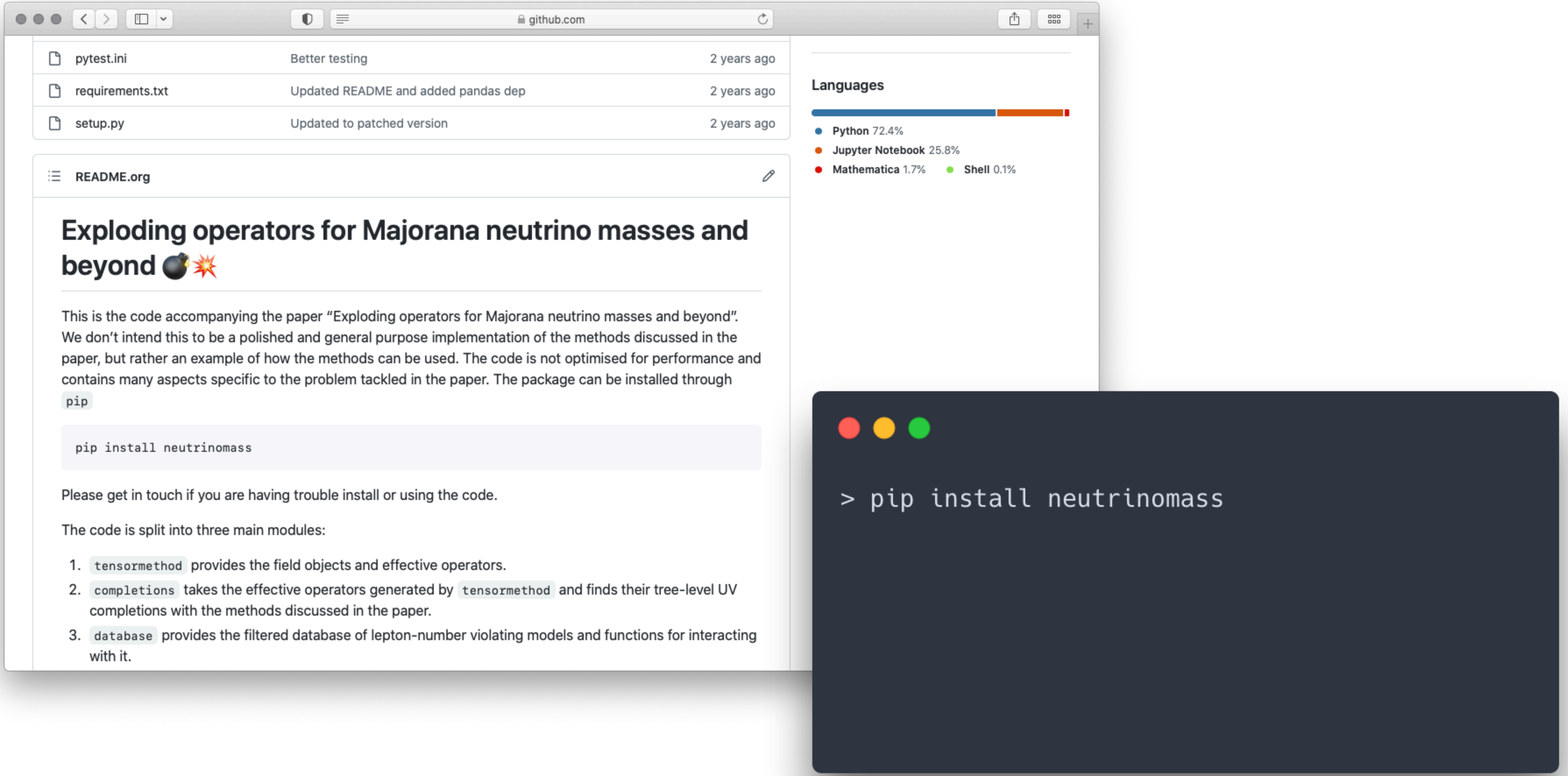


de Blas et al. JHEP 03 109 (2018) ; Criado CPC 227 06 2018; Herrero-García et al. JHEP 11 84 (2016), ...

Caveats

- Currently have only thought about $\mathrm{SU}(2)$ and $\mathrm{SU}(3)$, with colour structure not more complicated than $\mathbf{3} \otimes \bar{\mathbf{3}}$ and $(\mathbf{3} \otimes \bar{\mathbf{3}})^2$
- Code is not optimised, $d = 11$ operators currently need to be parallelised
- Exotic spin-1 and spin-3/2 fields are absent by design, can be included, but this needs thought

Program and model database


github.com
pytest.ini
Better testing
2 years ago
requirements.txt
Updated README and added pandas dep
2 years ago
setup.py
Updated to patched version
2 years ago
Languages
Python 72.4%
Jupyter Notebook 25.8%
Mathematica 1.7%
Shell 0.1%
README.org
Exploding operators for Majorana neutrino masses and beyond
This is the code accompanying the paper "Exploding operators for Majorana neutrino masses and beyond". We don't intend this to be a polished and general purpose implementation of the methods discussed in the paper, but rather an example of how the methods can be used. The code is not optimised for performance and contains many aspects specific to the problem tackled in the paper. The package can be installed through pip
pip install neutrinomass
Please get in touch if you are having trouble install or using the code.
The code is split into three main modules:
1. tensormethod provides the field objects and effective operators.
2. completions takes the effective operators generated by tensormethod and finds their tree-level UV completions with the methods discussed in the paper.
3. database provides the filtered database of lepton-number violating models and functions for interacting with it.
> pip install neutrinomass

```
In [13]: H = Field("H", "00001", charges={"y": Rational("1/2")})
         Q = Field("Q", "10101", charges={"y": Rational("1/6"), "3b": 1})

         print(H, Q)
         type(H)

         H(00001)(1/2) Q(10101)(1/6)

Out[13]: neutrinomass.tensormethod.core.Field
```

Tensor manipulations with large dependency on SymPy

```
In [4]: h = H("i0")
        q = Q("u0 c0 i1")

        type(q)

Out[4]: neutrinomass.tensormethod.core.IndexedField
```

```
In [14]: print(h * q * eps("-i0 -i1"))

         h * q * eps("-i0 -i1")

         H(I_0)*Q(u0, c0, I_1)*metric(-I_0, -I_1)
```

Out[14]: $Q^{\alpha a i} H^{j} \cdot \epsilon_{ij}$

Builds operators in our spanning set automatically

```
In [15]: weinberg = invariants(L, L, H, H)[0]
         weinberg
```

Out[15]: $L^{\alpha i} L^{\beta j} H^{k} H^{l} \cdot \epsilon_{ik} \epsilon_{jl}$

```
In [17]: model_1, model_2, model_3 = completions(weinberg)
         model_1.info()
```

Implements completion procedure, outputs *Completion* objects containing $\mathscr{L}_{\Delta L=2}$

```
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In [17]: model_1, model_2, model_3 = completions(weinberg)
         model_1.info()
```

Builds operators in our set automatically

Implements completio procedure, outputs Co objects containing $\mathscr{L}_{\Delta}$

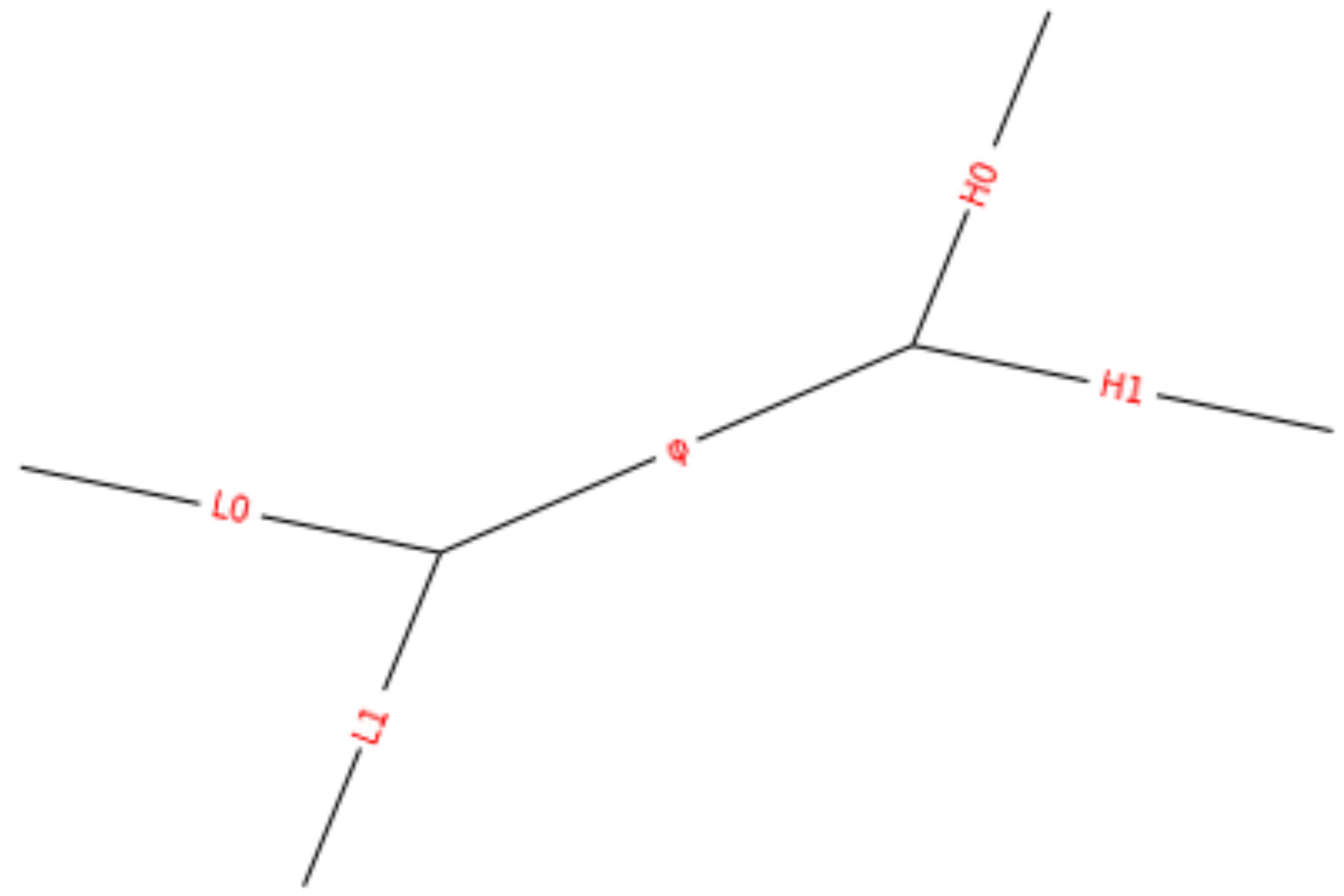
```
Fields:
φ    S(1, 3, 1)(0)

Lagrangian:
```

$L^{\alpha i} L^{\beta j} \tilde{\phi}^{kl} \cdot \epsilon_{\alpha\beta} \epsilon_{il} \epsilon_{jk}$

$H^{i} H^{j} \phi^{kl} \cdot \epsilon_{ik} \epsilon_{jl}$

```
Diagram:
```



Completion procedure produces 430,810 inequivalent $\Delta L = 2$ Lagrangians. About 70% contain seesaw fields! All published in database: https://doi.org/10.5281/zenodo.40546183

Only ~ 3% survive filtering (11,216 models). Published with Python package

github.com

12772	16179461	8614953467442367	63d	11	37.9148278684193	loop**2*loopv2*v**2*yd*ye/Λ	2s6f_4	4	3	1	2

There are many search results. Let's make a more specific query.

In [20]:

```
# Extend the query to look at the models with fewer than 5 fields that need to be at less than 7000 TeV
df[
    (df["democratic_num"] % df.exotics["S,01,0,1/3,-1"] == 0) &
    (df["democratic_num"] % df.exotics["S,00,0,1,0"] == 0) &
    (df["scale"] < 7000) &
    (df["n_fields"] < 5)
]
```

Out[20]:

	democratic_num	stringent_num	op	dim	scale	symbolic_scale	topology	n_fields	n_scalars	n_fermions	min_loops	max_loo
8387	3379507	30579275025083	10	9	5967.42299748072	loop**2*v**2*yd*ye/Λ	0s6f_1	3	3	0	2	
12771	12372529	1378968263787181	63d	11	37.9148278684193	loop**2*loopv2*v**2*yd*ye/Λ	2s6f_4	4	3	1	2	
12772	16179461	8614953467442367	63d	11	37.9148278684193	loop**2*loopv2*v**2*yd*ye/Λ	2s6f_4	4	3	1	2	

We find three models. Let's looks at one of them. Copy the index on the far left and ask for the completion.

In [21]:

```
comp = df.completion(8387)
comp.info()
```

Symbolic structures mapped to prime IDs, used to query the symbolic database *numerically* (and efficiently!) using *Pandas*

Labels	Operator	Models	Filtered	Loops	Λ [TeV]
1	$L^iL^jH^kH^l \cdot \epsilon_{ik}\epsilon_{jl}$	3	3	0	$6 \cdot 10^{11}$
2	$L^iL^jL^k\bar{e}H^l \cdot \epsilon_{ik}\epsilon_{jl}$	8	2	1	$4 \cdot 10^{7}$
3*a*	$L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ij}\epsilon_{kl}$	9	2	2	$2 \cdot 10^{5}$
3*b*	$L^iL^jQ^k\bar{d}H^l \cdot \epsilon_{ik}\epsilon_{jl}$	14	5	1	$9 \cdot 10^{7}$
4*a*	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ik}\epsilon_{jl}$	5	0	1	$4 \cdot 10^{9}$
4*b*	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^l \cdot \epsilon_{ij}\epsilon_{kl}$	4	2	2	$10 \cdot 10^{6}$
5*a*	$L^iL^jQ^k\bar{d}H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	790	36	2	$6 \cdot 10^{5}$
5*b*	$\mathcal{O}_1 \cdot Q^i\bar{d}\tilde{H}^j \cdot \epsilon_{ij}$	492	14	1,2	$6 \cdot 10^{5}$
5*c*	$\mathcal{O}_{3a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	509	0	2,3	$1 \cdot 10^{3}$
5*d*	$\mathcal{O}_{3b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	799	16	1,2	$6 \cdot 10^{5}$
6*a*	$L^iL^j\tilde{Q}^k\bar{u}^\dagger H^lH^m\tilde{H}^n \cdot \epsilon_{il}\epsilon_{jn}\epsilon_{km}$	289	14	2	$2 \cdot 10^{7}$
6*b*	$\mathcal{O}_1 \cdot \tilde{Q}^i\bar{u}^\dagger\tilde{H}^j \cdot \epsilon_{ij}$	177	0	1,2	$2 \cdot 10^{7}$
6*c*	$\mathcal{O}_{4a} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	262	0	1,2	$2 \cdot 10^{7}$
6*d*	$\mathcal{O}_{4b} \cdot H^i\tilde{H}^j \cdot \epsilon_{ij}$	208	0	2,3	$6 \cdot 10^{4}$
7	$L^i\bar{e}^\dagger Q^j\tilde{Q}^kH^lH^mH^n \cdot \epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	240	15	2	$2 \cdot 10^{5}$
8	$L^i\bar{e}^\dagger\bar{u}^\dagger\bar{d}H^j \cdot \epsilon_{ij}$	5	1	2,3	$2 \cdot 10^{1}$
9	$L^iL^jL^kL^l\bar{e}\bar{e} \cdot \epsilon_{ik}\epsilon_{jl}$	14	1	2	$3 \cdot 10^{3}$
10	$L^iL^jL^k\bar{e}Q^l\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$	50	1	2	$6 \cdot 10^{3}$
11*a*	$L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ij}\epsilon_{kl}$	48	0	3	$4 \cdot 10^{1}$
11*b*	$L^iL^jQ^kQ^l\bar{d}\bar{d} \cdot \epsilon_{ik}\epsilon_{jl}$	72	16	2	$1 \cdot 10^{4}$

Canonical seesaw models (row 1)

Not obvious! (row 4*a*)

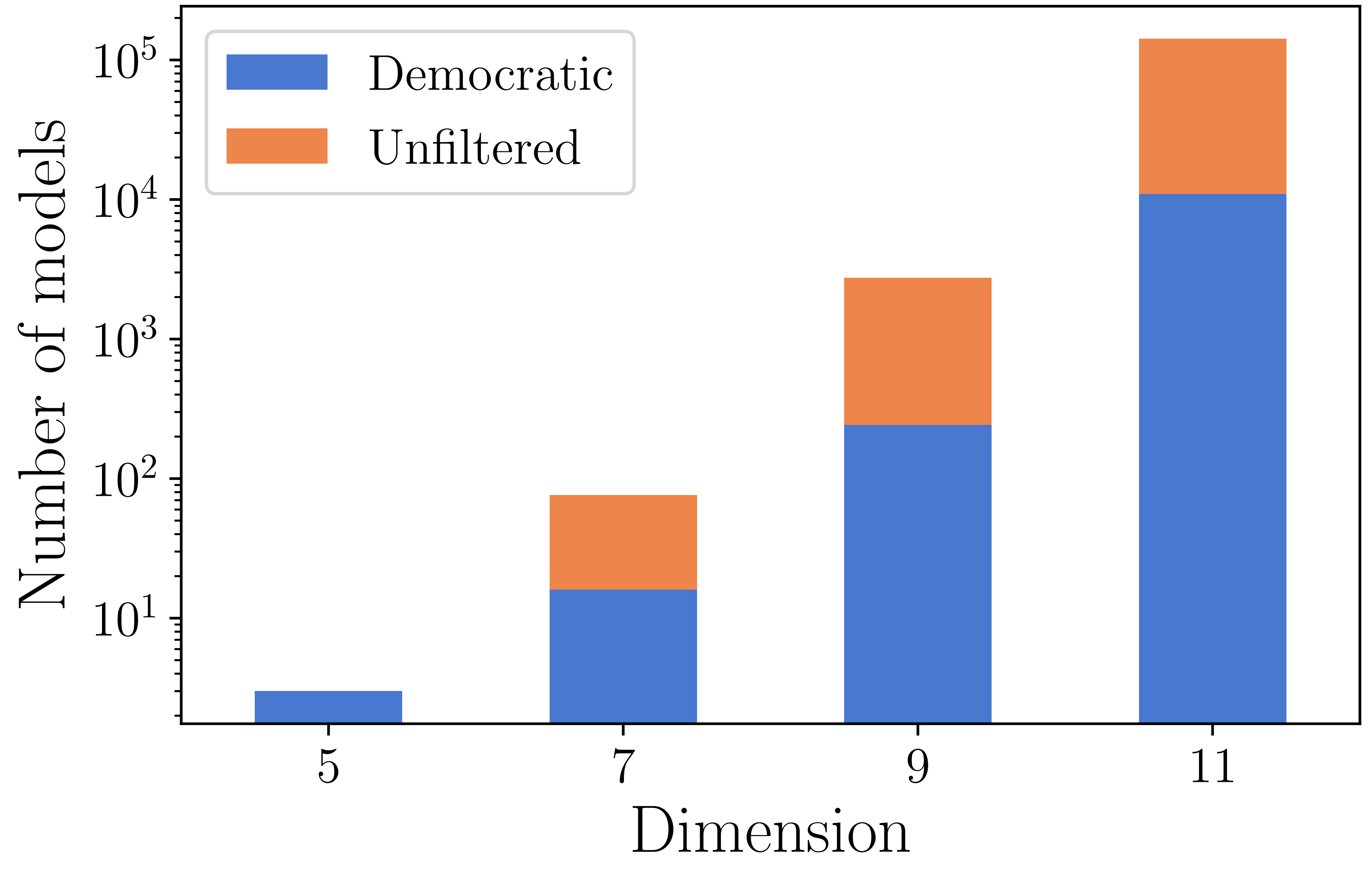
Some operators produce no filtered models (rows 4*a*, 5*c*, 6*b*–6*d*, 11*a*)

Zee-Babu model (row 9)

Babu *Phys. Lett.* B203 (1998) 132–136

Number of models

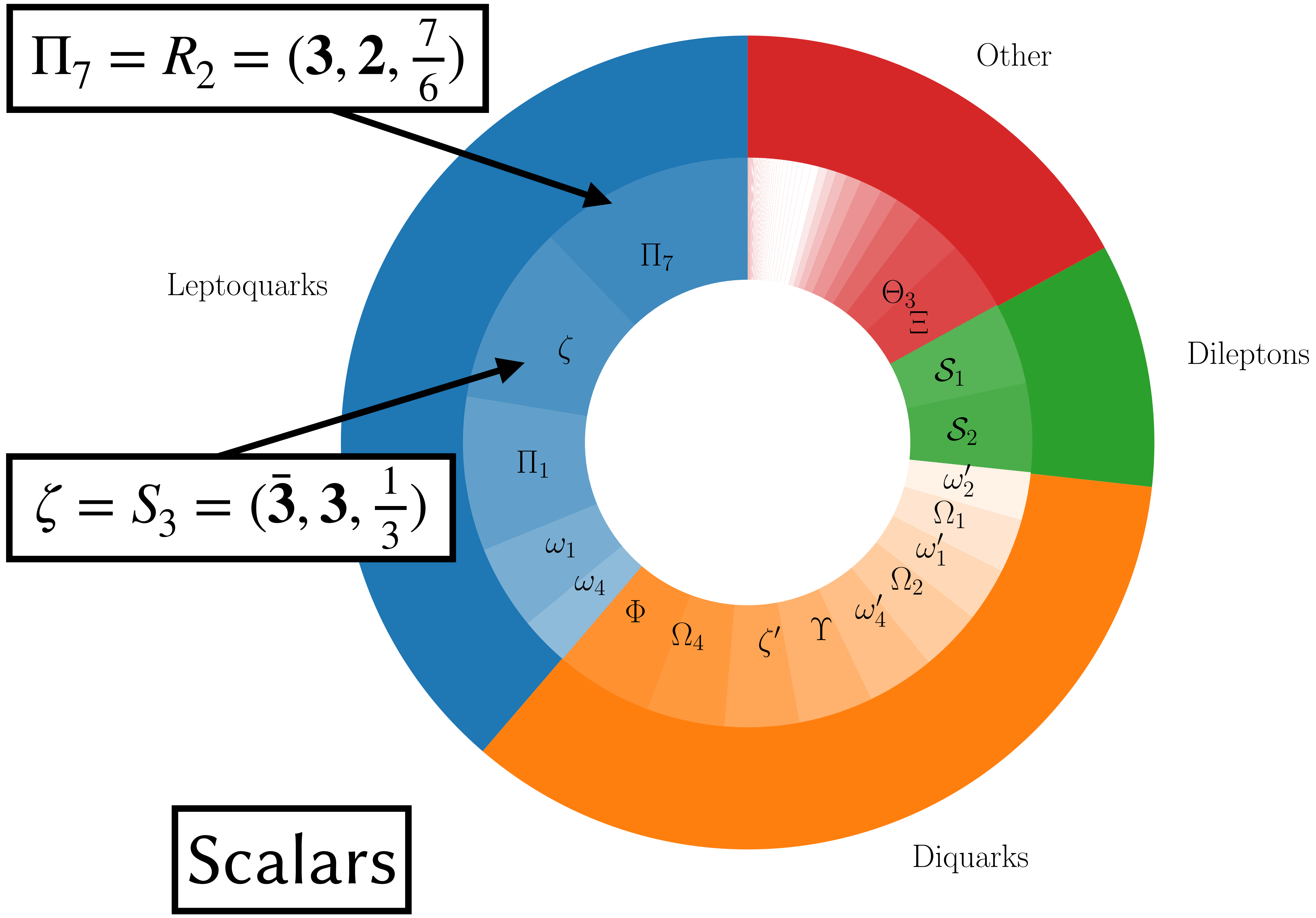
Field	Interactions	$\Delta L = 2$ Lagrangians	Models
$N \sim (\mathbf{1}, \mathbf{1}, 0)_F$	LHN	51,245 (11.9%)	17,139 (17.1%)
	Other	12,433 (2.9%)	
$\Sigma \sim (\mathbf{1}, \mathbf{3}, 0)_F$	$LH\Sigma$	87,535 (20.3%)	31,629 (31.5%)
	Other	28,157 (6.5%)	
$\Xi_1 \sim (\mathbf{1}, \mathbf{3}, 1)_S$	$LL\Xi_1$	59,791 (13.0%)	51,576 (51.4%)
	$HH\Xi_1^\dagger$	95,410 (22.1%)	
	Both	10,323 (2.4%)	
	Other	30,761 (7.1%)	

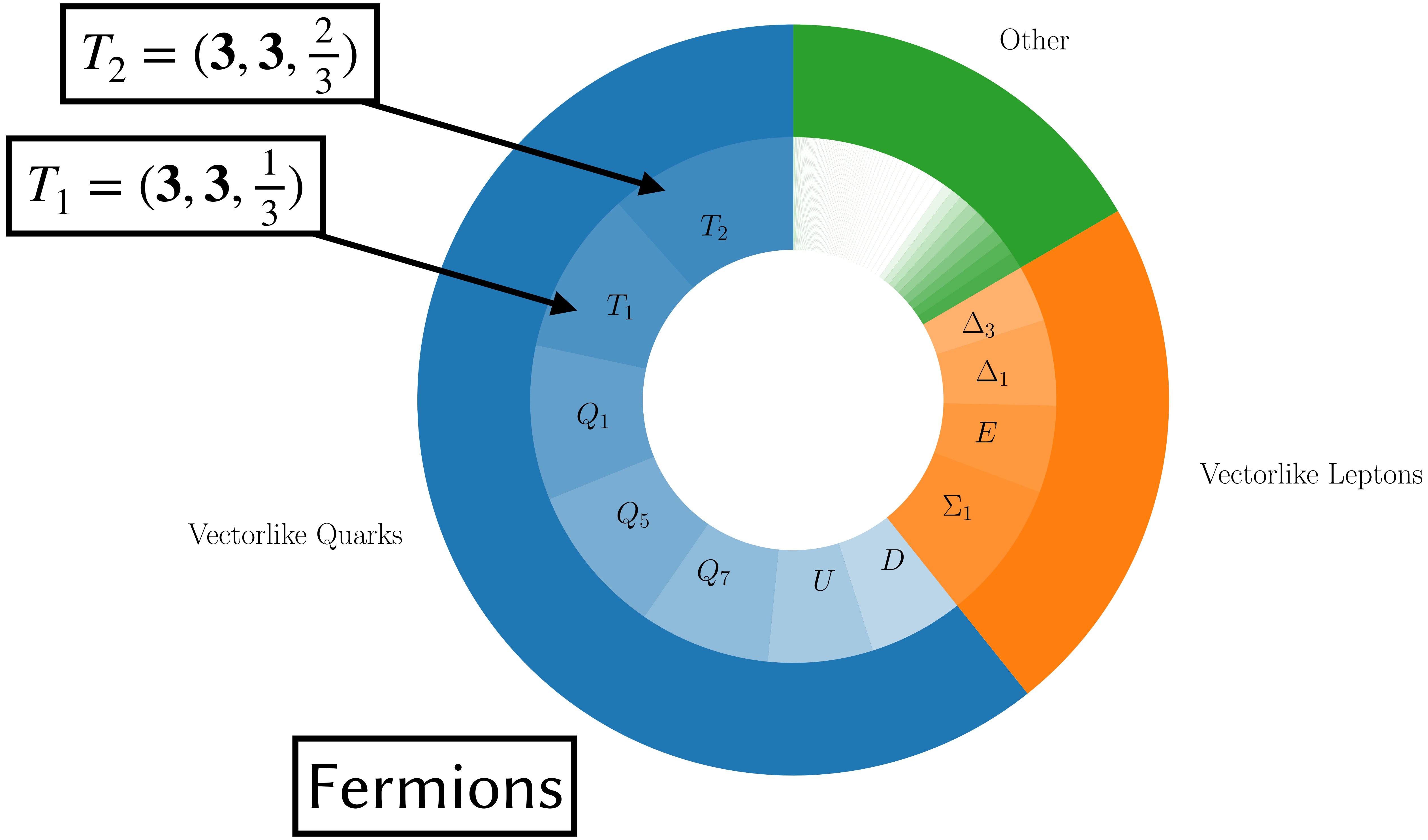


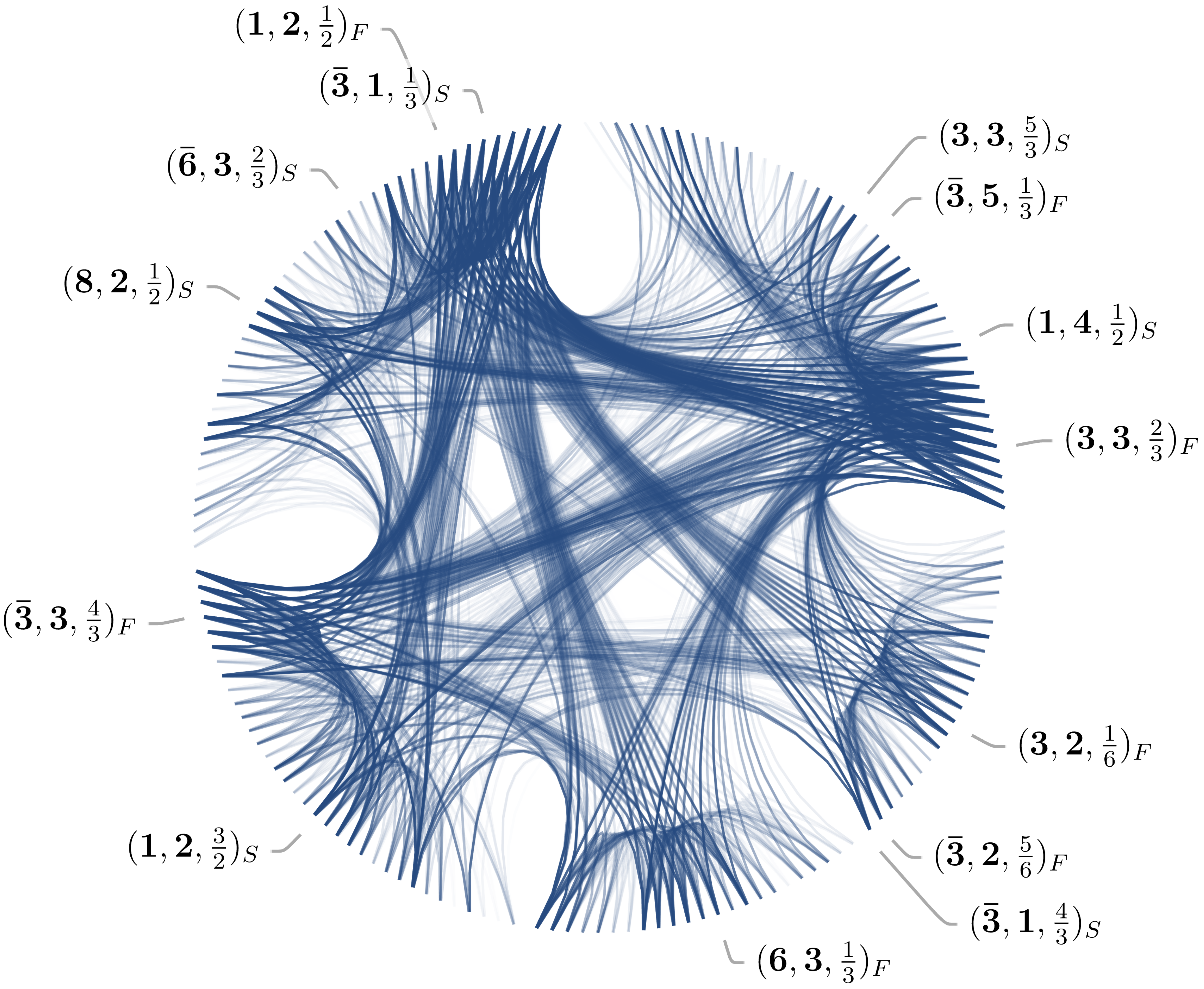
Exotic fields

In total, 84 different scalar species and 82 different fermions

Most represented class of fields are leptoquarks







$(\mathbf{1}, \mathbf{2}, \frac{1}{2})_F$
$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})_S$
$(\bar{\mathbf{6}}, \mathbf{3}, \frac{2}{3})_S$
$(\mathbf{8}, \mathbf{2}, \frac{1}{2})_S$
$(\bar{\mathbf{3}}, \mathbf{3}, \frac{4}{3})_F$
$(\mathbf{1}, \mathbf{2}, \frac{3}{2})_S$
$(\mathbf{6}, \mathbf{3}, \frac{1}{3})_F$
$(\bar{\mathbf{3}}, \mathbf{1}, \frac{4}{3})_S$
$(\bar{\mathbf{3}}, \mathbf{2}, \frac{5}{6})_F$
$(\mathbf{3}, \mathbf{2}, \frac{1}{6})_F$
$(\mathbf{3}, \mathbf{3}, \frac{2}{3})_F$
$(\mathbf{1}, \mathbf{4}, \frac{1}{2})_S$
$(\bar{\mathbf{3}}, \mathbf{5}, \frac{1}{3})_F$
$(\mathbf{3}, \mathbf{3}, \frac{5}{3})_S$

Closing thoughts and future directions

Our model database is perhaps a good laboratory for automated phenomenology

Can we automate the production of FeynRules files from the UV Lagrangians?

$\Rightarrow$ See talk by Renato Fonseca!

Can we rule out a large class of models just from their effects at dimension 6?

Symbolic Lagrangian $\Rightarrow$ MatchMaker/Matchete (talks to follow) $\Rightarrow$ Flavio?

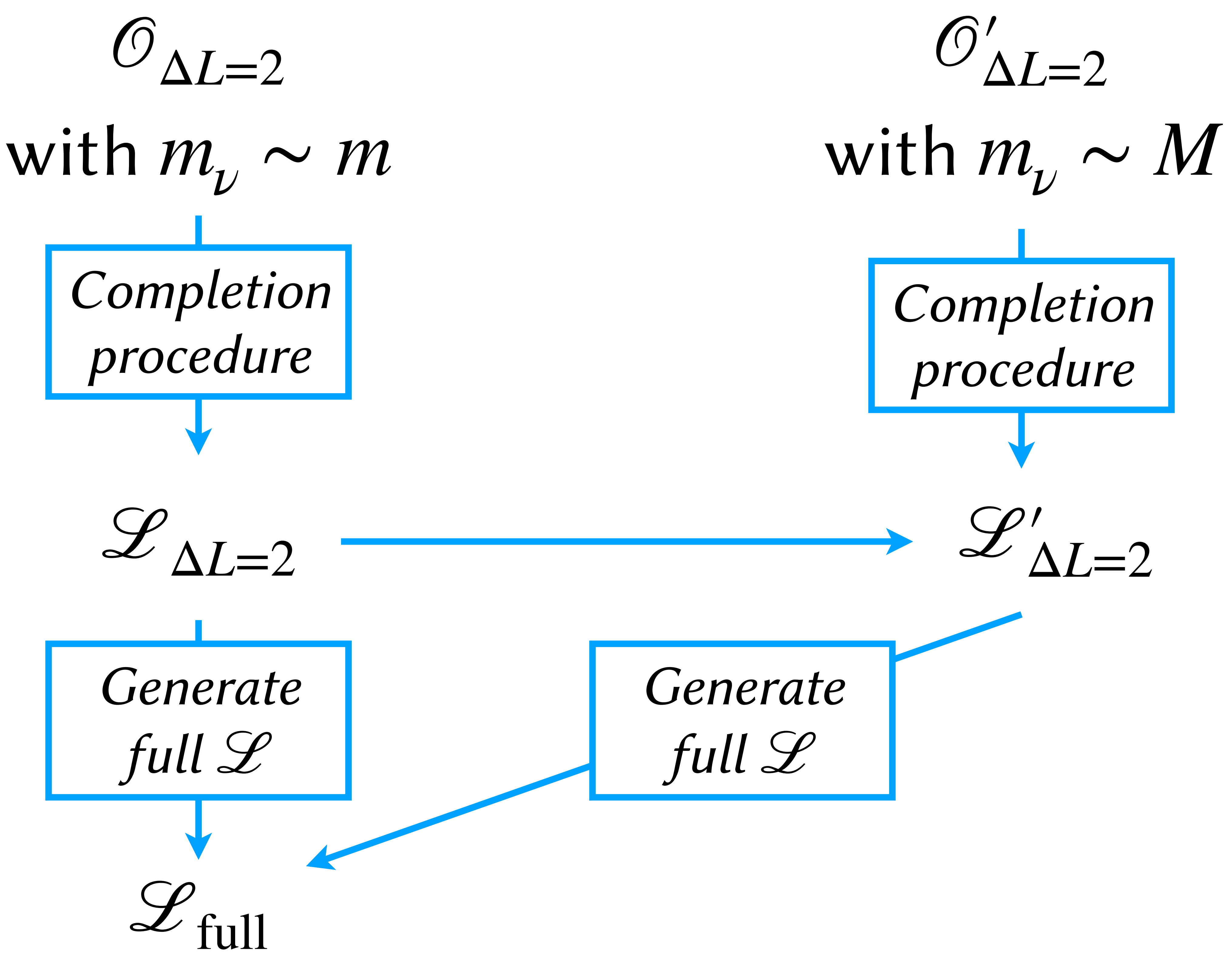
Techniques are more generally applicable!

Is it time to think about a standardised representation for *e.g.* models, Lagrangians, fields?

Backup

Model filtering

Want to ensure that each model gives a dominant contribution to the neutrino mass, and is not just a small correction to it



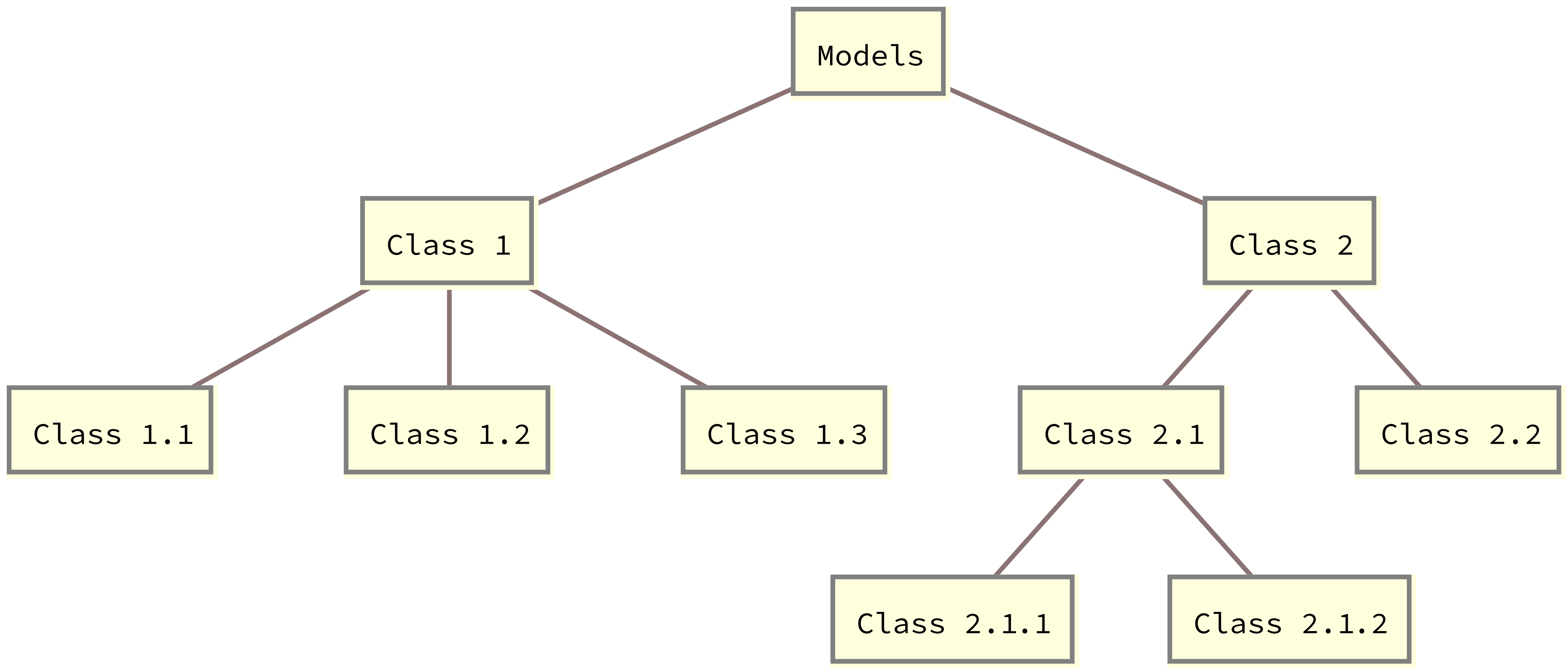
Suppose $M \gg m$, then $\mathcal{L}_{\Delta L=2}$ is only a small correction and should be removed

Take a *democratic* approach: assume no special hierarchy between couplings

Often because model already generates a lower-dimensional operator!

Neutrino oscillations and the implied non-zero neutrino masses cannot be accommodated without new physics. Nice to have:

1. A systematic method for deriving models
2. A(n) (preferably hierarchical) organising principle and classification
   - Can models be organised by testability, complexity, explanatory power?
   - Clustered by common features?



How can we understand the smallness of neutrino masses?

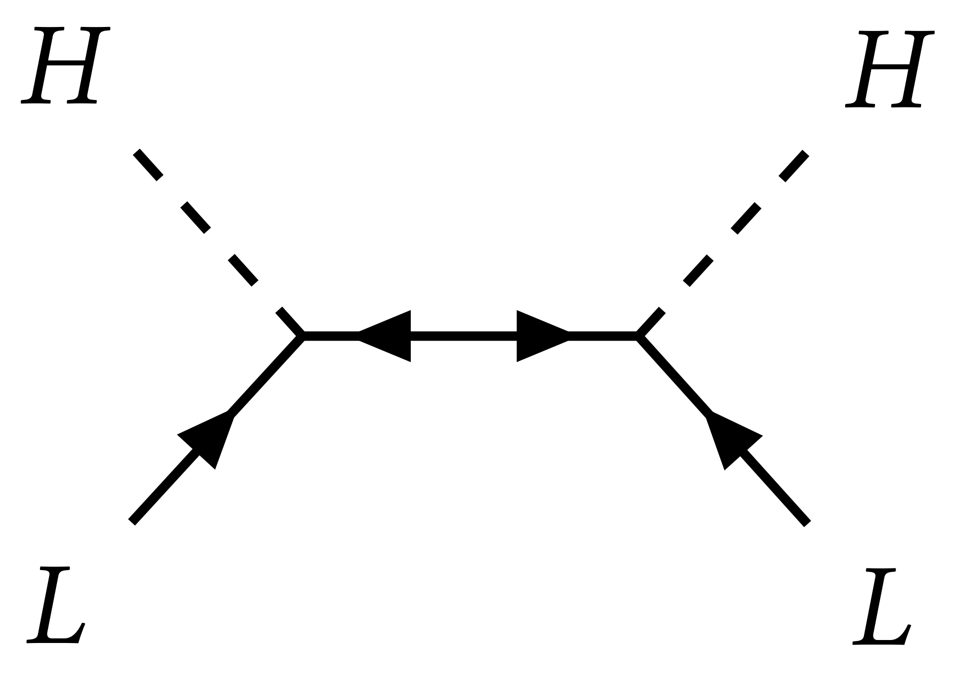
$$\mathcal{L}^{(5)} = \frac{C_5}{\Lambda} \cdot LLHH$$
$$\to C_5 \frac{v^2}{\Lambda} \cdot \nu\nu$$

Majorana

1. Large Λ with $C_5 \sim 1$

   Seesaw models

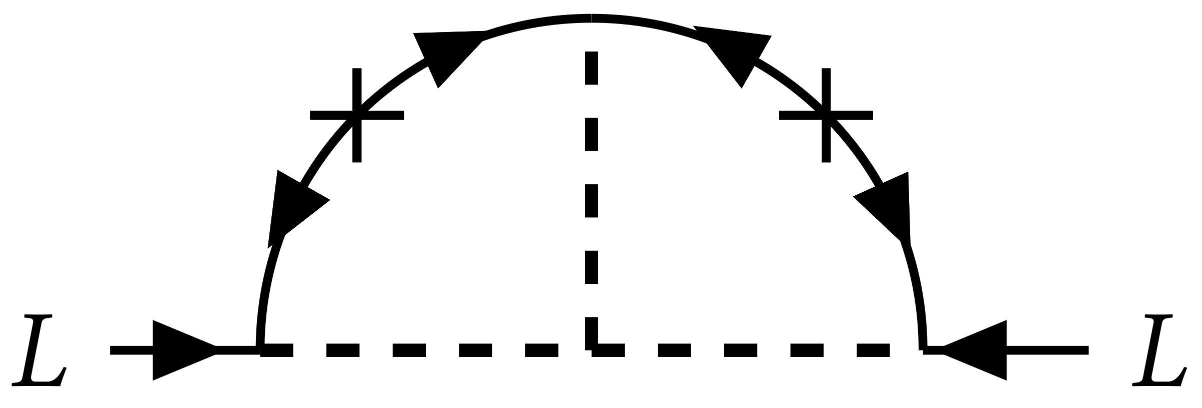
   $$\frac{v^2}{\Lambda} \sim 0.05 \text{ eV} \Rightarrow \Lambda \sim 10^{14} \text{ GeV}$$



2. Small C_5 with $\Lambda > v$

   Inverse seesaw, radiative models, ...

   $$C_5 \frac{v^2}{\Lambda} \sim \frac{v^2}{\Lambda} \left(\frac{1}{16\pi^2} \right)^n \prod_i y_i$$



Review: Cai et al. Front. Phys. 00063 (2017)

There are *very many* models...

$$G_{\mathrm{SM}} \sim \overbrace{\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y}^{\textit{Gauge}} + \overbrace{\mathrm{SU}(2)_+ \otimes \mathrm{SU}(2)_-}^{\textit{Lorentz}}$$

Quarks	Leptons	Higgs
$Q \sim (\mathbf{3}, \mathbf{2}, \frac{1}{6})_{(\mathbf{2},\mathbf{1})}$	$L \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2})_{(\mathbf{2},\mathbf{1})}$	$H \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2})_{(\mathbf{1},\mathbf{1})}$
$\bar{u} \sim (\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})_{(\mathbf{2},\mathbf{1})}$	$\bar{\nu} \sim (\mathbf{1}, \mathbf{1}, 0)_{(\mathbf{2},\mathbf{1})}$	
$\bar{d} \sim (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})_{(\mathbf{2},\mathbf{1})}$	$\bar{e} \sim (\mathbf{1}, \mathbf{1}, 1)_{(\mathbf{2},\mathbf{1})}$	

Gauge Bosons

$G \sim (\mathbf{8}, \mathbf{1}, 0)_{(\mathbf{3},\mathbf{1})}$	$W \sim (\mathbf{1}, \mathbf{3}, 0)_{(\mathbf{3},\mathbf{1})}$	$B \sim (\mathbf{1}, \mathbf{1}, 0)_{(\mathbf{3},\mathbf{1})}$

Integrating out a scalar at tree level

$\Phi \to$ heavy field
$\phi, \psi \to$ light fields

$$\mathscr{L}_{\text{HE}}[\Phi, \phi, \psi]$$

$E > M$

$$\mathscr{L}_\Phi = -\Phi^\dagger(D^2 + M^2)\Phi + \Phi^\dagger \cdot \frac{\partial \mathscr{L}}{\partial \Phi^\dagger} + \mathscr{O}(\Phi^3)$$

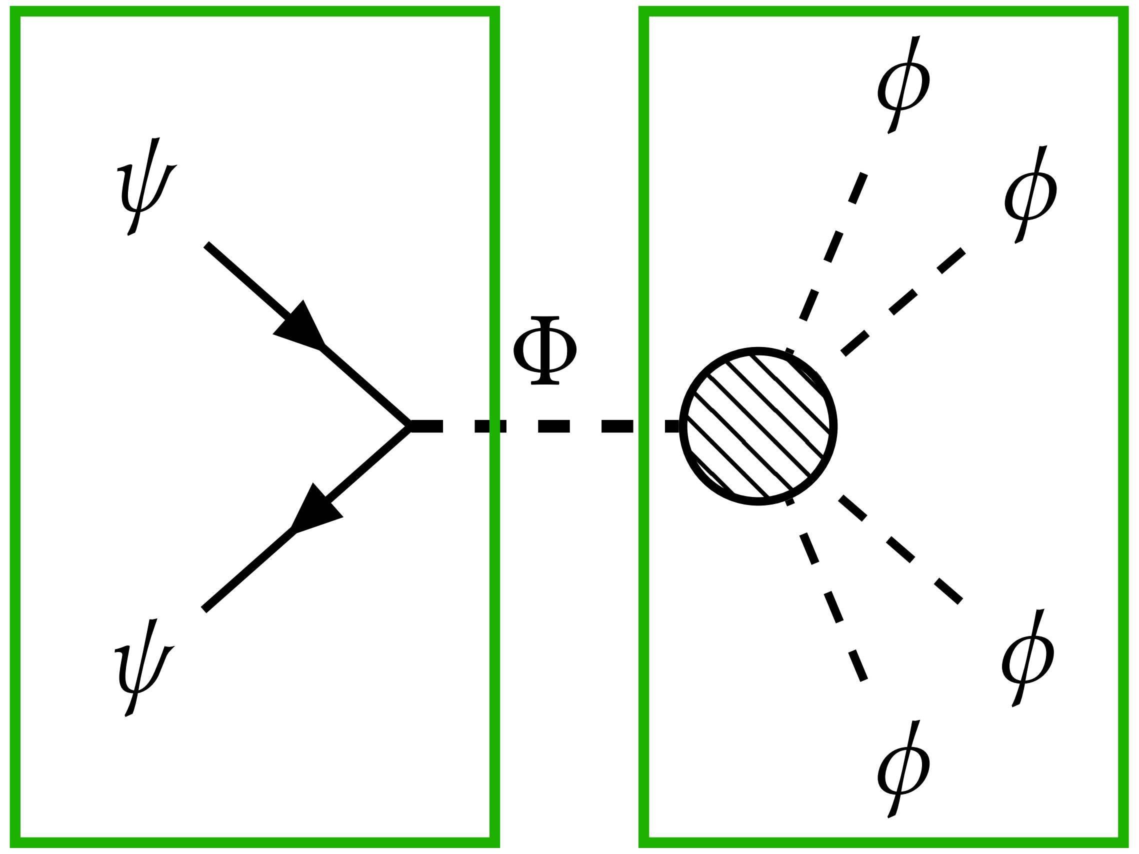
Replace by EOM

$E < M$

$$\mathscr{L}_{\text{eff}} = \frac{\partial \mathscr{L}}{\partial \Phi} \cdot -\frac{1}{M^2}\left[1 + \frac{(iD)^2}{M^2} + \cdots\right] \cdot \frac{\partial \mathscr{L}}{\partial \Phi^\dagger}$$

Fierz EOM IBP

$$\sum_i c_i \mathscr{O}_i$$



The fields inside $\partial\mathscr{L}/\partial\Phi^\dagger$ must transform *opposite* to $\Phi^\dagger$

$$\frac{\partial \mathscr{L}}{\partial \Phi^\dagger} \otimes \Phi^\dagger \sim (\mathbf{1}, \mathbf{1}, 0)_{(\mathbf{1},\mathbf{1})}$$

Derivatives can only arise past leading order

$\Psi, \bar{\Psi} \to$ heavy fields

$\phi, \psi \to$ light fields

Integrating out a VLF at tree level

$$\mathscr{L}_{\rm HE}[\Psi, \bar{\Psi}, \phi, \psi]$$

$E > M$

$\Psi \sim \Psi_L$

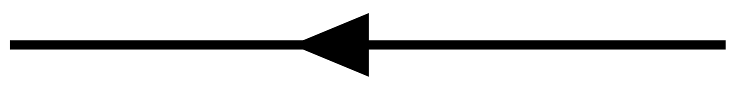
$\bar{\Psi} \sim \Psi_R^C$

$$\mathscr{L}_\Psi = i\Psi^\dagger \bar{\sigma}^\mu D_\mu \Psi + i\bar{\Psi}^\dagger \bar{\sigma}^\mu D_\mu \bar{\Psi} + \Psi^\dagger \cdot \frac{\partial \mathscr{L}}{\partial \Psi^\dagger} + \bar{\Psi}^\dagger \cdot \frac{\partial \mathscr{L}}{\partial \bar{\Psi}^\dagger} - M\bar{\Psi}\Psi$$

Replace by EOM

$E < M$

$$\mathscr{L}_{\rm eff} = \frac{\partial \mathscr{L}}{\partial \Psi_\beta}\frac{1}{M^2}\left(\epsilon_{\alpha\beta} + \frac{X_{\alpha\beta} - D^2\epsilon_{\alpha\beta}}{M^2} + \cdots\right) iD^{\alpha\dot{\alpha}} \frac{\partial \mathscr{L}}{\partial \Psi^\dagger_{\dot{\beta}}}\epsilon_{\dot{\alpha}\dot{\beta}}$$



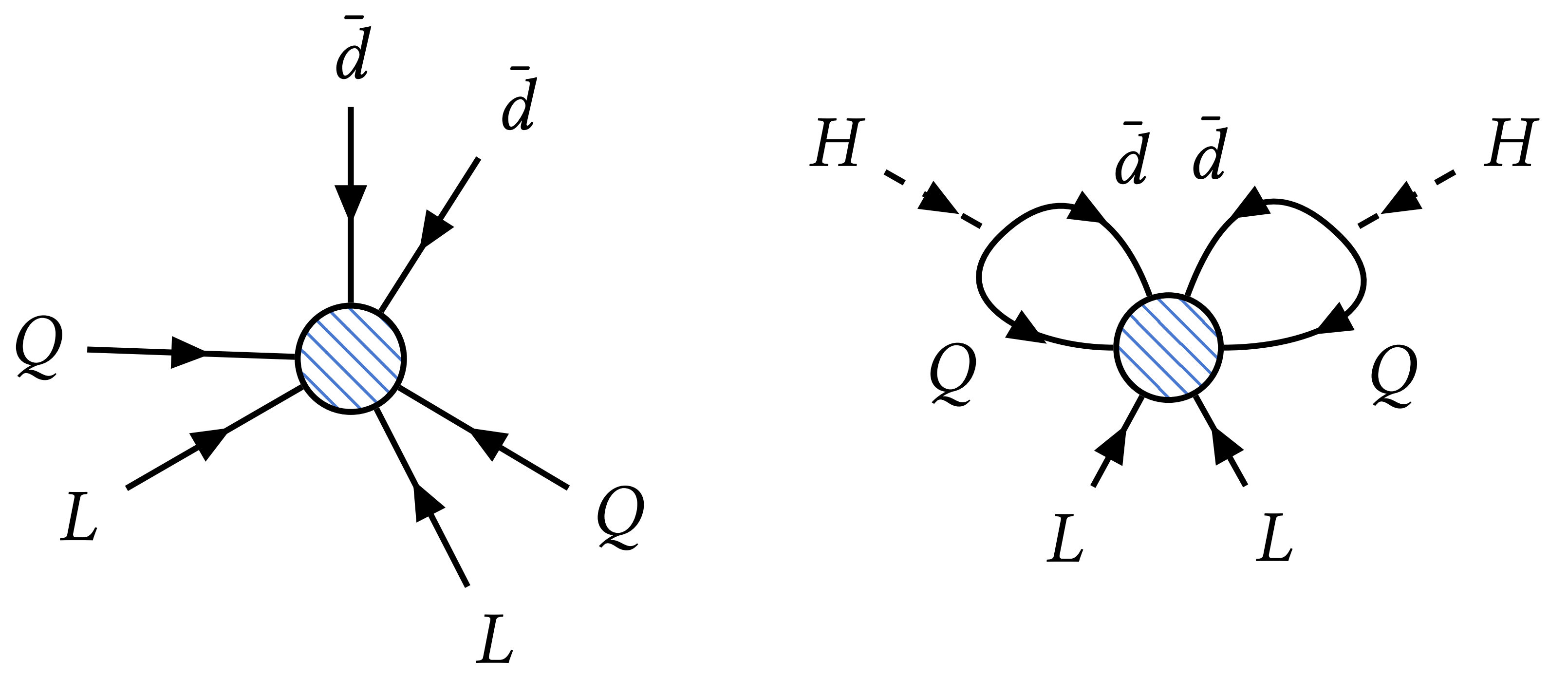
$$+\frac{\partial \mathscr{L}}{\partial \Psi_\beta}\frac{1}{M}\left(\epsilon_{\alpha\beta} + \frac{X_{\alpha\beta} - D^2\epsilon_{\alpha\beta}}{M^2} + \cdots\right)\frac{\partial \mathscr{L}}{\partial \bar{\Psi}_\alpha}$$

Fierz EOM IBP $\to \sum_i c_i \mathcal{O}_i$

Derivatives can arise from *arrow-preserving* fermion propagator already at leading order

But not field strengths!

Summary of approach to neutrino-mass model building



1. Loop off operator into Weinberg(-like) ones

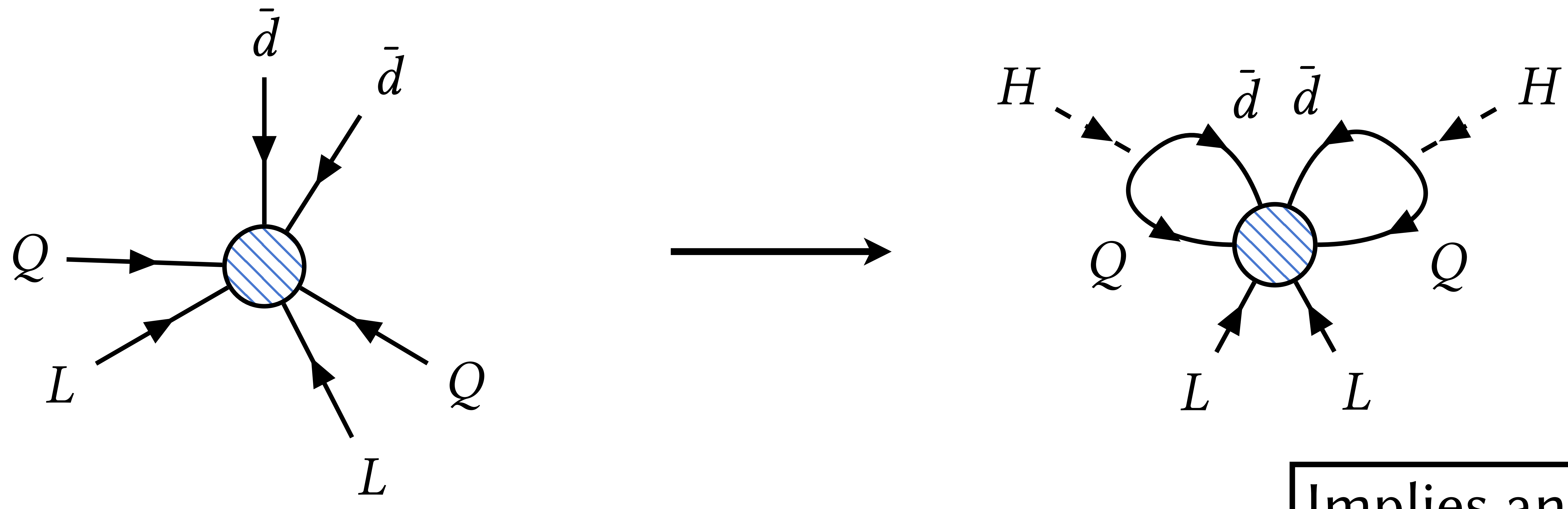
2. Derive bounded estimates of the new-physics scale from the atmospheric bound predicted by each operator in newly expanded catalogue up to dimension 11

3. Derive UV models for each operator using algorithm discussed previously

4. *Filter* these models, keeping only those that contribute dominantly to the neutrino mass

5. Package these into a convenient computation representation that is easy and efficient to query

IR considerations: loops and estimates of new-physics scale



$$\sim C \cdot \frac{y_d^2}{(16\pi^2)^2} \cdot \frac{v^2}{\Lambda} > 0.05 \text{ eV}$$

$$\mathcal{O}_{11b} = L^i L^j \bar{d} Q^k \bar{d} Q^l \cdot \epsilon_{il}\epsilon_{jl}$$

Implies an upper bound on Λ:

$$\Lambda \lesssim \frac{Cv^2}{0.05 \text{ eV}} \frac{y_d^2}{16\pi^2} \approx C \cdot 10^4 \text{ TeV}$$

Conservatively assume $C = 1$ in all estimates

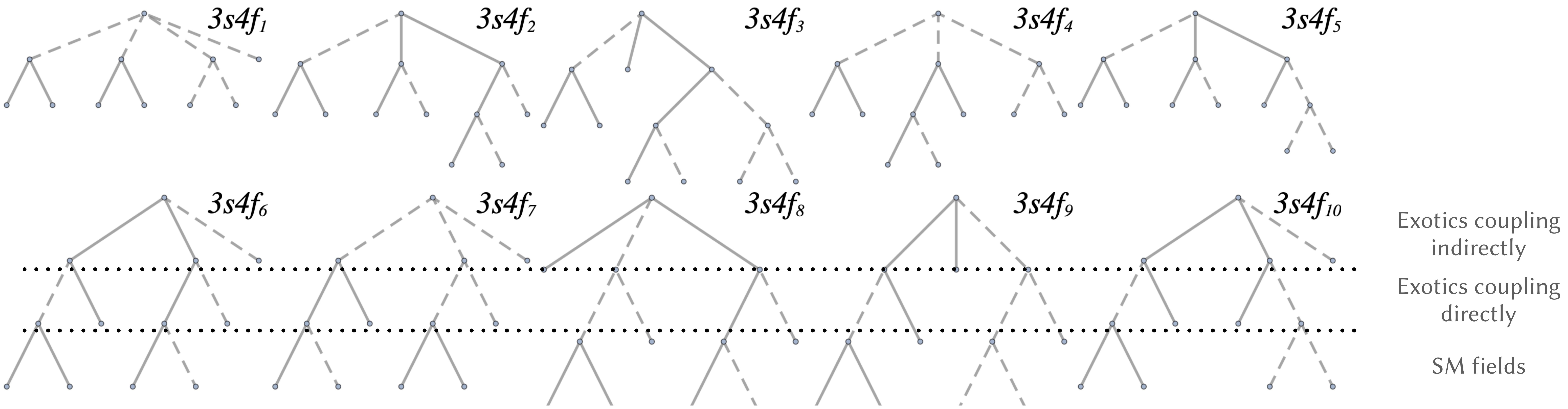
Automate closure procedure and validate against as many UV examples as possible

Suppression by SM Yukawa couplings a very common feature

Exotic fields

By far the most common fields are those that generate dimension-6 operators at tree-level, *i.e.* that couple directly to SM fields

de Blas et al. JHEP 03 109 (2018) ; Criado CPC 227 06 2018



Interesting example models

Database is easy to query on fields, interactions, NP scale, *etc.*

Example 1: Low-scale, *simple* models

```
700 GeV < Λ < 100 TeV && n_fields < 4
```

Field content	Operators	Λ [TeV]
$(\mathbf{3},\mathbf{2},\frac{1}{6})_S,\ (\mathbf{3},\mathbf{2},\frac{7}{6})_F$	$8,\ D15$	15
$(\bar{\mathbf{6}},\mathbf{2},\frac{7}{6})_F,\ (\mathbf{8},\mathbf{2},\frac{1}{2})_S,\ (\mathbf{3},\mathbf{2},\frac{1}{6})_S$	20	0.8
$(\mathbf{6},\mathbf{1},\frac{4}{3})_S,\ (\mathbf{6},\mathbf{1},\frac{1}{3})_F,\ (\mathbf{3},\mathbf{2},\frac{1}{6})_S$	20	0.8
$(\mathbf{6},\mathbf{2},\frac{5}{6})_S,\ (\mathbf{3},\mathbf{2},\frac{1}{6})_F,\ (\mathbf{3},\mathbf{2},\frac{1}{6})_S$	$50a,b$	10
$(\bar{\mathbf{6}},\mathbf{2},\frac{1}{6})_S,\ (\bar{\mathbf{3}},\mathbf{2},\frac{5}{6})_F,\ (\mathbf{3},\mathbf{2},\frac{1}{6})_S$	$50a,b$	10

Sextet fields can be replace by triplets with different baryon-number assignments

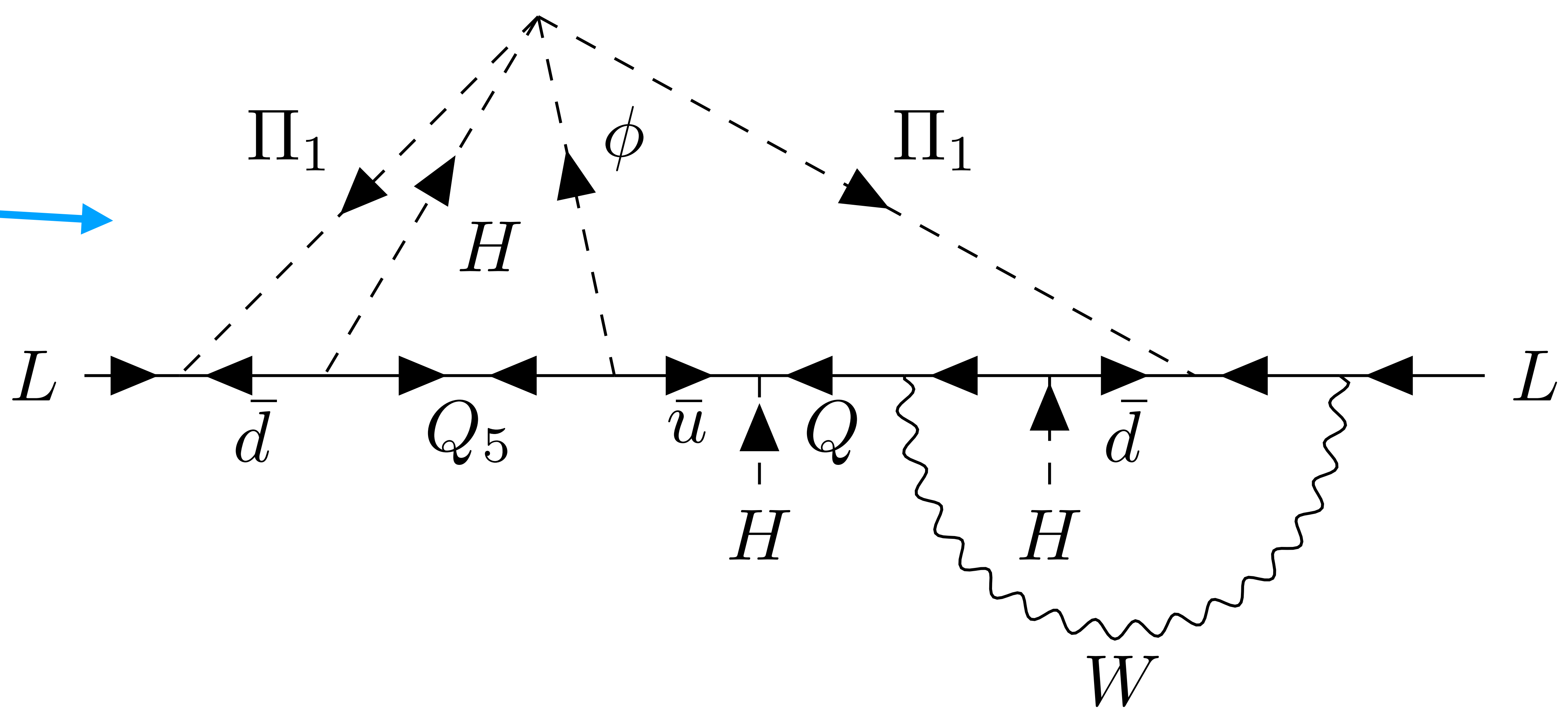
Cai et al. JHEP 02 161 (2016)
Klein et al. JHEP 03 018 (2019)

Only previously known model

$\Pi_1 \sim (\mathbf{3},\mathbf{2},\frac{1}{6})_S$

$Q_5 \sim (\mathbf{3},\mathbf{2},\frac{1}{6})_F$

$\phi \sim (\mathbf{6},\mathbf{2},\frac{5}{6})_S$

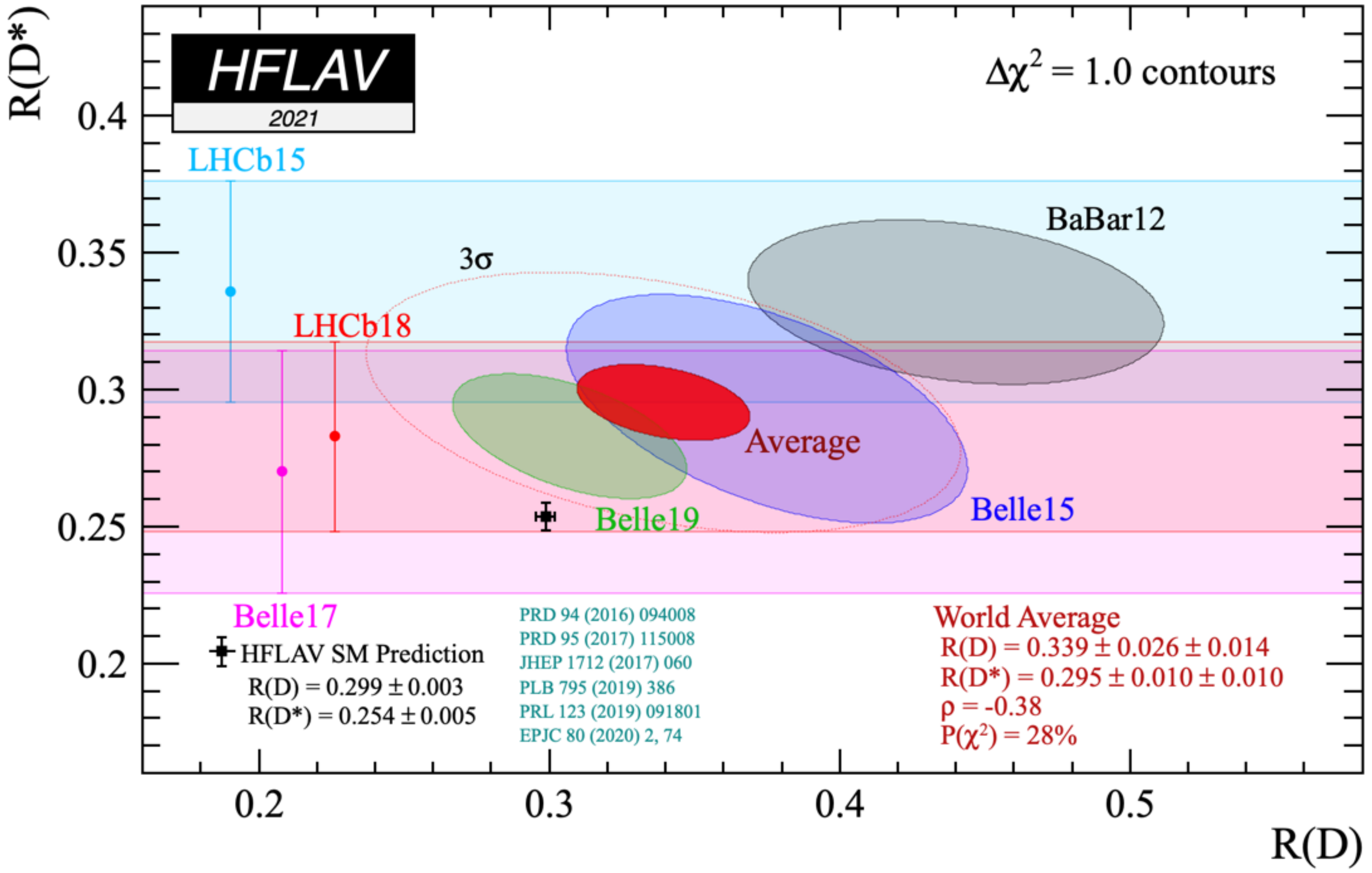


Interesting example models

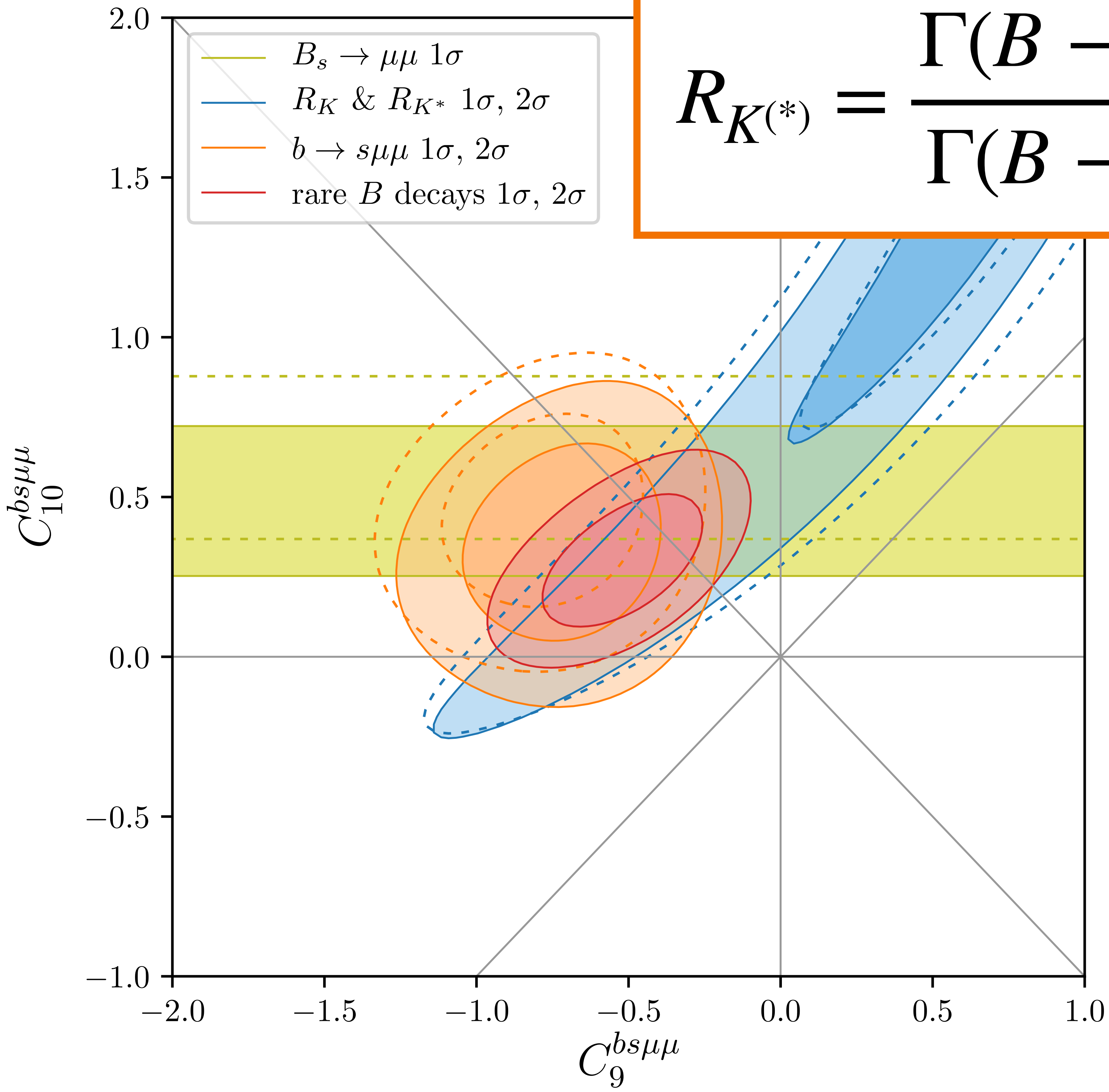
Database is easy to query on fields, interactions, NP scale, *etc.*

Example 2: Connection with flavour anomalies

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$



$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}$$



Example 2: Connection with flavour anomalies

Very many models contain the appropriate scalar leptoquarks

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}$$

$$\mathscr{L}_{S_1} = f_{rs} L_r Q_s S_1 + g_{rs} \bar{e}_r^\dagger \bar{u}_s^\dagger S_1 + \text{h.c.}$$

$$\mathscr{L}_{R_2} = x_{rs} L_r \bar{u}_s R_2 + y_{rs} \bar{e}_r^\dagger Q_s^\dagger R_2 + \text{h.c.}$$

← Most represented field in database!

$$\mathscr{L}_{S_3} = w_{rs} L_r Q_s S_3 + \text{h.c.}$$

← 2nd most represented field in database!

```
(LQS1 && euS1* in interactions)
|| (LuR2 && eQR2* in interactions)
```

↓

None!

```
S1 in model && S3 in model
R2 in model && S3 in model
```

88 models containing S_1 and S_3

178 models containing R_2 and S_3

IR considerations: loops and estimates of new-physics scale

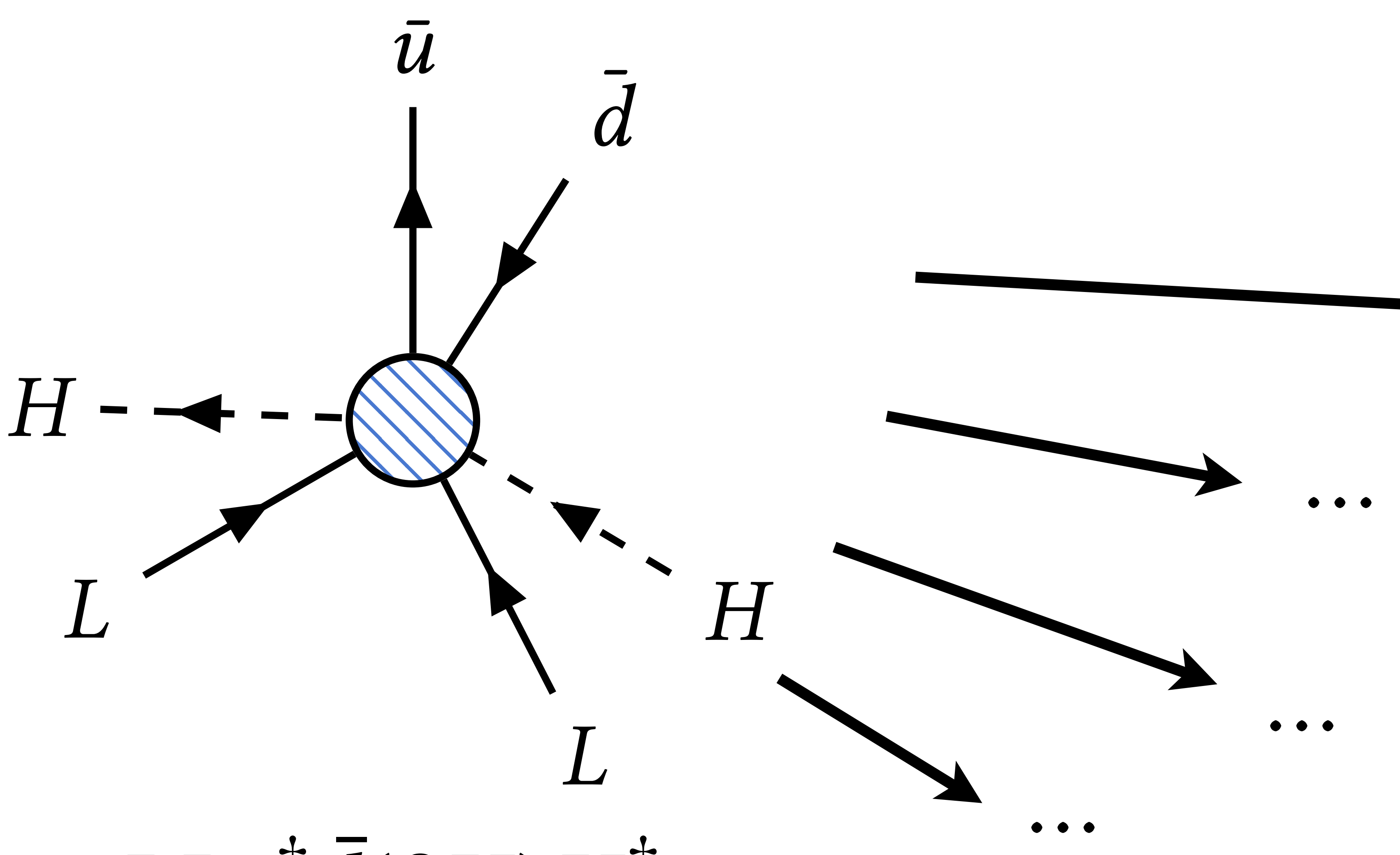
Least suppressed neutrino masses arise from operators like

$$LLHH \cdot \prod_{i=1}^{n} (\psi_i^\dagger \psi_i) \quad \Rightarrow \quad m_\nu \sim \frac{C}{(16\pi^2)^n} \cdot \frac{v^2}{\Lambda}$$

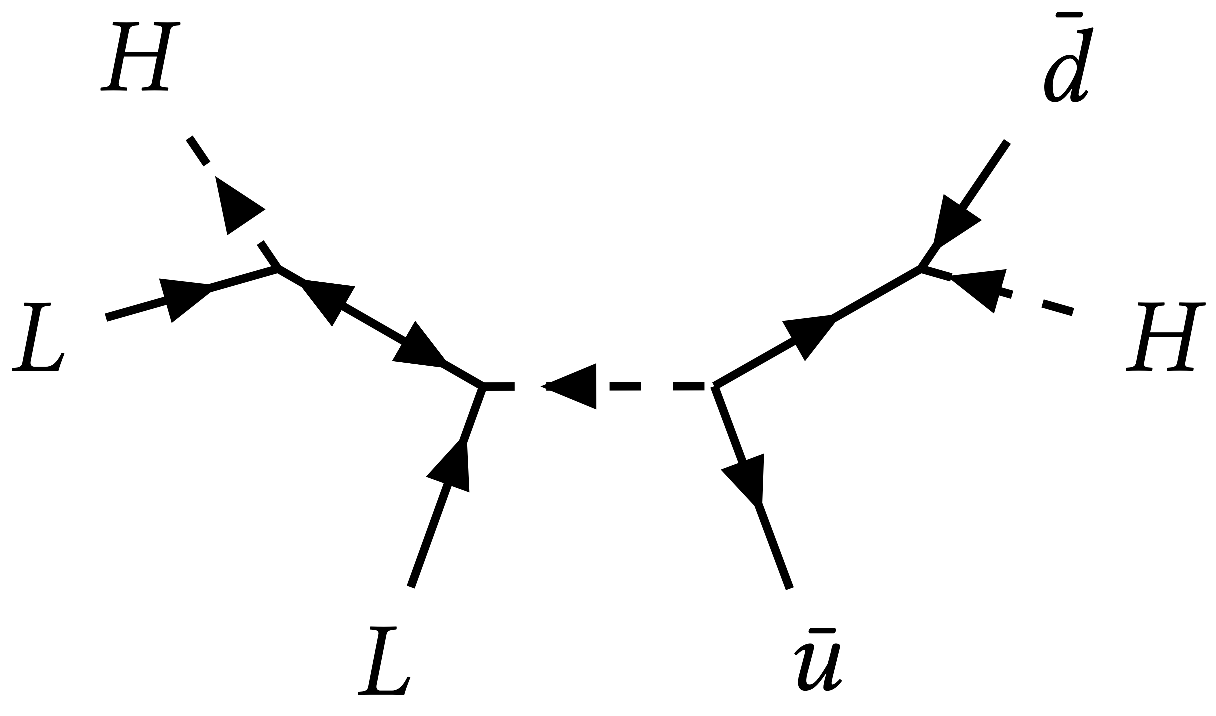
Applying atmospheric bound implies $n \leq 5.7$ for $C = 1$ and $\Lambda = v$, can come from dimension-21 operators of the form

$$LLH(\partial^\mu H)(\psi_0 \sigma_\mu \psi_0^\dagger) \prod_{i=1}^{4} \psi_i^\dagger \psi_i$$

What does the UV physics look like?



$LL\bar{u}^\dagger \bar{d}(\partial H)H^\dagger$



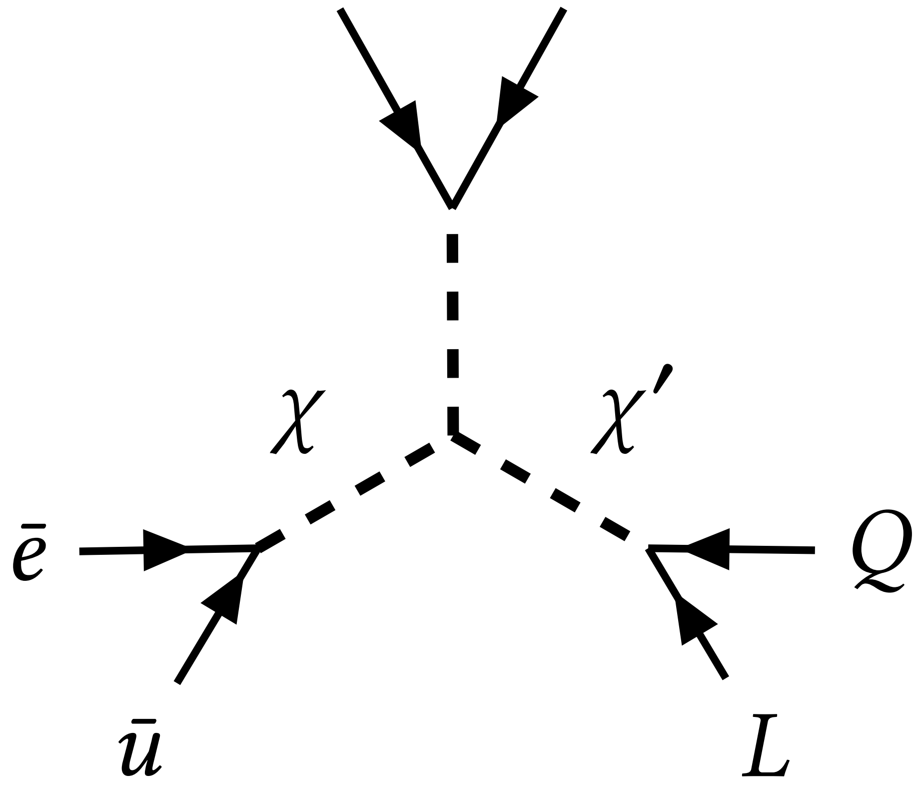
$\mathscr{L}_{\mathrm{UV}}, \mathscr{L}_{d=6}, \dots$

1. Exotic fields are vector-like or Majorana fermions, or scalars

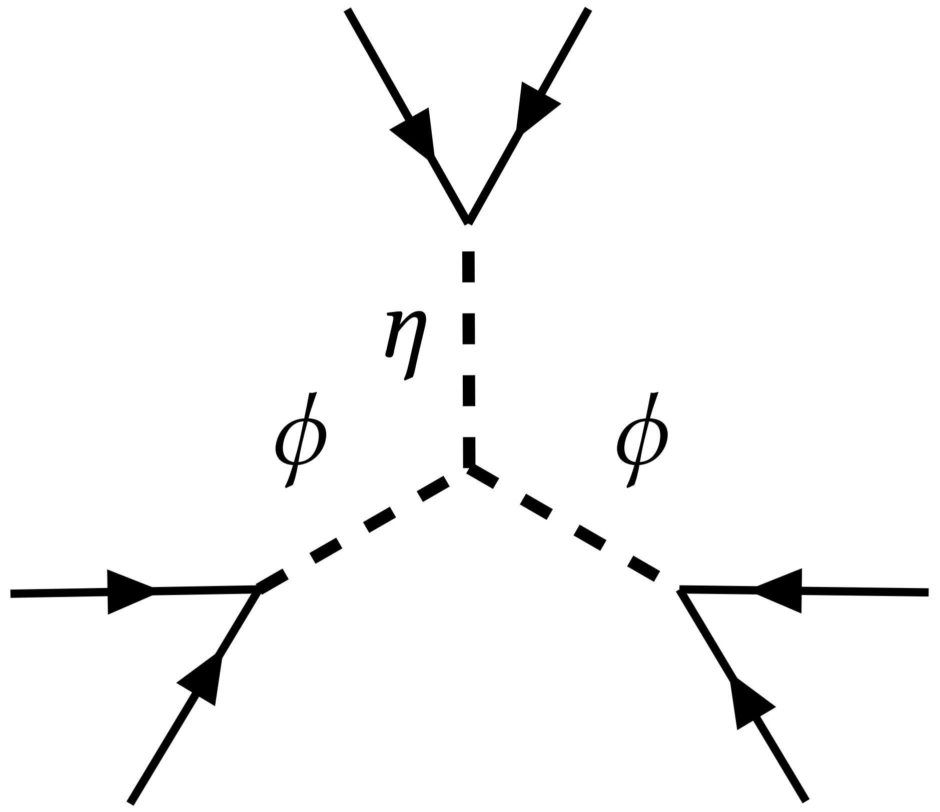
   A. Familial structure allowed if necessary

2. Assume SM gauge group

3. Assume B conservation



$B(\chi) \neq B(\chi')$



$\phi^I \phi^J \eta^K \epsilon_{IJK}$