



Madrid reflections on the SM & Beyond



P. Hernández
IFIC, U. Valencia-CSIC

The Standard Model

a baroque quantum world

Gauge principle: $SU(3) \times SU(2) \times U(1)_Y$

Lepton \leftrightarrow quark: **anomaly cancellation**

(Toy model) SSB

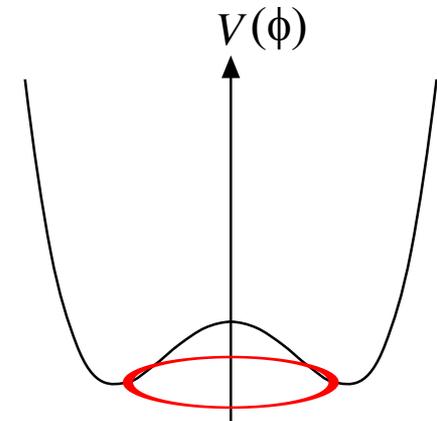
| $(\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$ | $(\mathbf{3}, \mathbf{2})_{-\frac{1}{6}}$ | $(\mathbf{1}, \mathbf{1})_{-1}$ | $(\mathbf{3}, \mathbf{1})_{-\frac{2}{3}}$ | $(\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$ |
|--|--|---------------------------------|---|---|
| $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ | $\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$ | e_R | u^i_R | d^i_R |
| $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ | $\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$ | μ_R | c^i_R | s^i_R |
| $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ | $\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$ | τ_R | t^i_R | b^i_R |



Family



Parity Violation



$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

The Standard Model

Accidental symmetries:

- Baryon, Lepton Number
- Loop and GIM suppressed FCNC
- Subtle breaking of CP: **matter-antimatter**

$$\text{Im}[\det([Y_u Y_u^\dagger, Y_d Y_d^\dagger])] \propto J \sum_{i < j} (m_{d_i}^2 - m_{d_j}^2) \sum_{i < j} (m_{u_i}^2 - m_{u_j}^2)$$

$$J = \text{Im}[V_{ij}^* V_{ii} V_{ji}^* V_{jj}] = c_{23} s_{23} c_{12} s_{12} c_{13}^2 s_{13} \sin \delta$$

Unflavoured CP violating effects in the quark sector tiny: unable to explain the apparent difference between **matter** & **antimatter** in the early Universe

The **S**tandard **M**odel

+ A non-accidental “symmetry”: **strong CP**

$$\mathcal{L}_{\text{SM}} \supset \bar{\theta} \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\bar{\theta} \leq 10^{-10}$$

Strong CP invariant: $\arg \det(Y_u Y_d)$

The Weirddness of the Standard Model

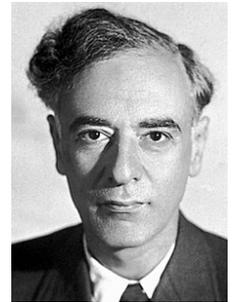


- Three families

“who ordered that ?” I. Rabi

- Fundamental breaking of Parity

“space cannot be asymmetric!” L. Landau

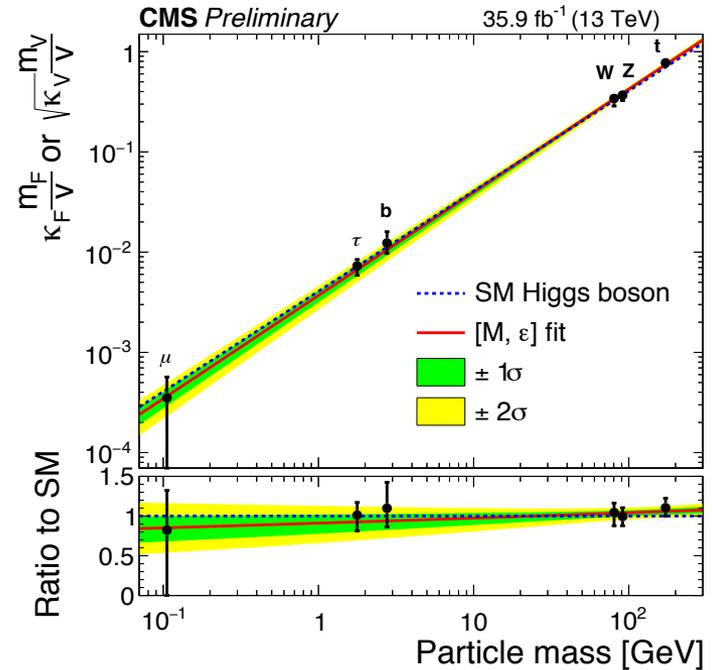
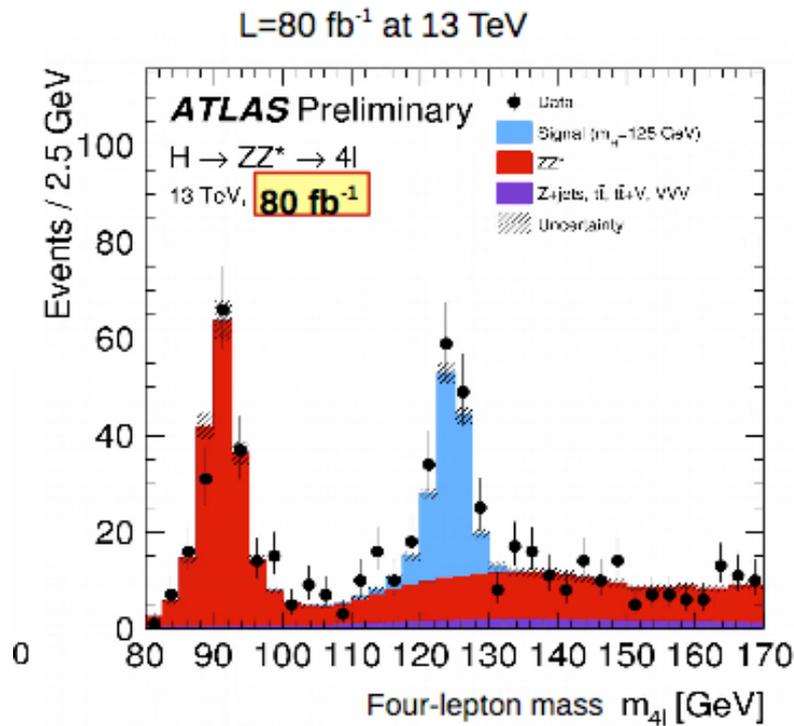


- Predictivity: 3 gauge couplings+ 16 higgs couplings (+ 7 higgs-neutrino) !

“has too many arbitrary features for [its] predictions
to be taken very seriously” S. Weinberg '67



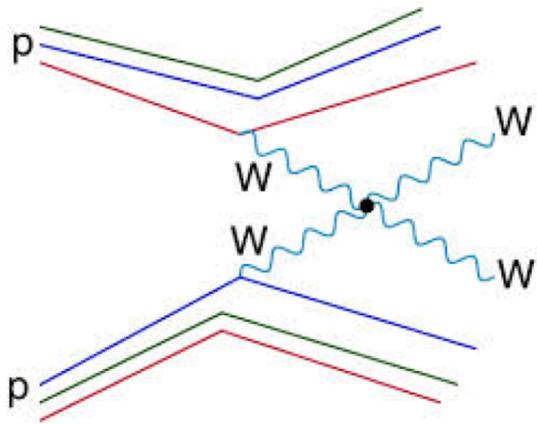
The Standard Model under scrutiny: “the” Higgs



$$J^{CP} = 0^+$$

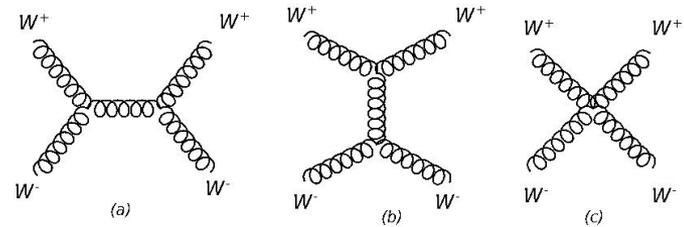
$$m_{\text{Higgs}} = 125.09(24) \text{ GeV}$$

LHC “No Lose Theorem”



Unitarity violated

Without the Higgs:



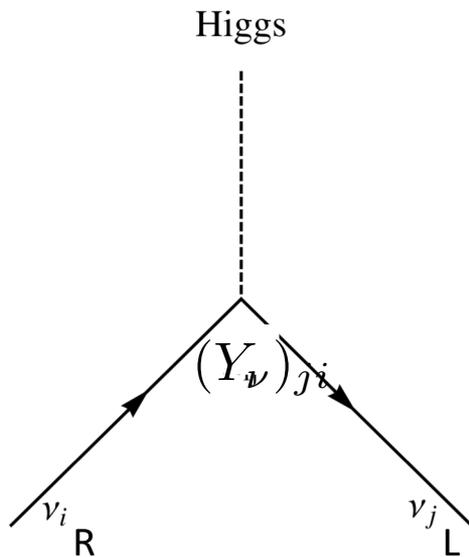
$$a_0^0 \simeq -\frac{s}{32\pi v^2}$$

$$s \geq (1.7 \text{ TeV})^2$$

The Standard Model under scrutiny: lepton flavour

Massive neutrinos require an extension of the baroque table: eg. ν_R
(+ arbitrary choice: global L)

$$-\mathcal{L}_{\text{SM}} \supset Y_{\nu ij} \bar{L}_i \tilde{\phi} \nu_{Rj}$$

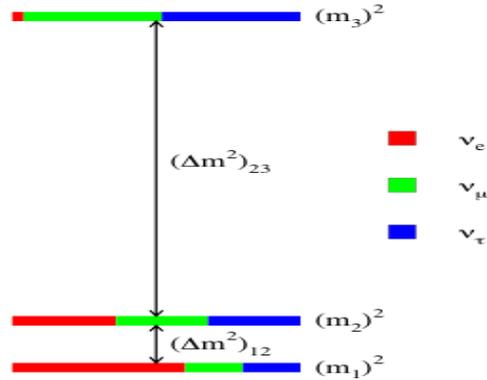


$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

A lepton flavour sector analogous to the quark one

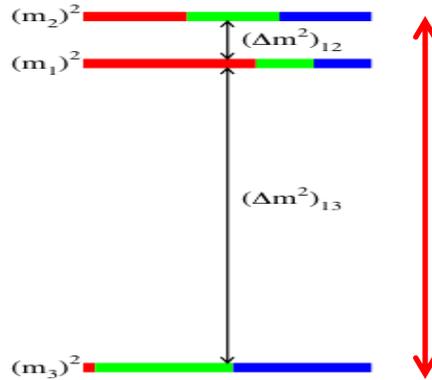
The Standard Model under scrutiny: massive ν

normal hierarchy



NO/NH

inverted hierarchy



IO/IH

$$\updownarrow 7.5 \cdot 10^{-5} \text{eV}^2$$

$$2.5 \cdot 10^{-3} \text{eV}^2$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \dots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\theta_{12} \sim 34^\circ$$

$$\theta_{23} \sim 42^\circ \text{ o } 48^\circ$$

$$\theta_{13} \sim 8.5^\circ$$

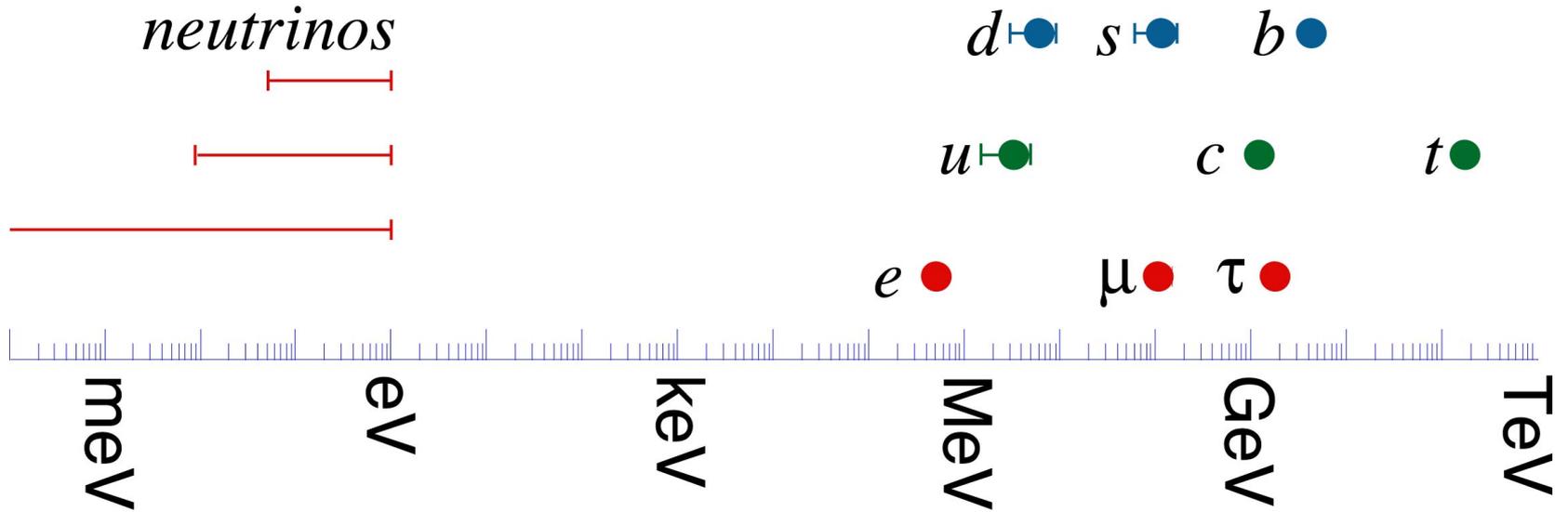
$$\delta \sim ?$$

Leptonic CP violation new source of matter-antimatter asymmetry!

Caveat: O(eV) neutrinos...reactor/short baseline anomalies still unresolved

Massive neutrinos: a new flavour perspective

Why are neutrinos so much lighter ?



Massive neutrinos: a new flavour perspective

Why do they mix so differently ?

CKM

$$V_{\text{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$$J = (3.18 \pm 0.15) \times 10^{-5}$$

PMNS

3σ

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.516 \rightarrow 0.582 & 0.141 \rightarrow 0.156 \\ 0.242 \rightarrow 0.494 & 0.467 \rightarrow 0.678 & 0.639 \rightarrow 0.774 \\ 0.284 \rightarrow 0.521 & 0.490 \rightarrow 0.695 & 0.615 \rightarrow 0.754 \end{pmatrix}$$

NuFIT 3.2 (2018)

$$J \simeq 0.033 \sin \delta$$

The **S**tandard **M**odel under scrutiny: predicting its own destruction ?

(Perturbatively) Renormalizable Theory =

Effective QFT insensitive to the cutoff (e.g. new physics scale)



Future-Collider “no lose” theorem

BUT: does the Standard Model without a cutoff describe Nature ?

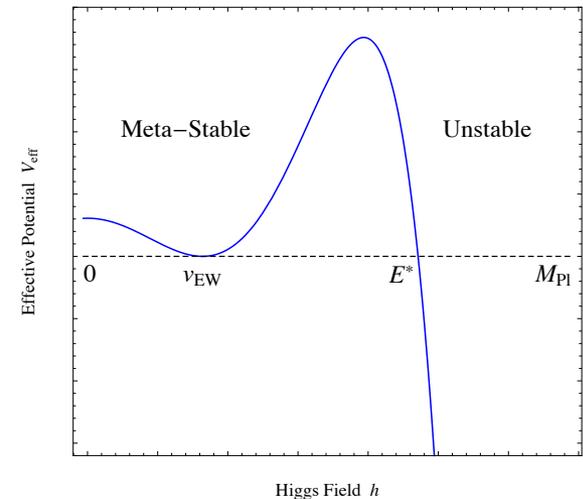
SM predicting its own destruction ?

1. **Landau poles** (perturbative) \leftrightarrow **triviality** (non-perturbative)

$$\Lambda \rightarrow \infty : \lambda_R(\mu) = 0, g_{1R}(\mu) = 0$$

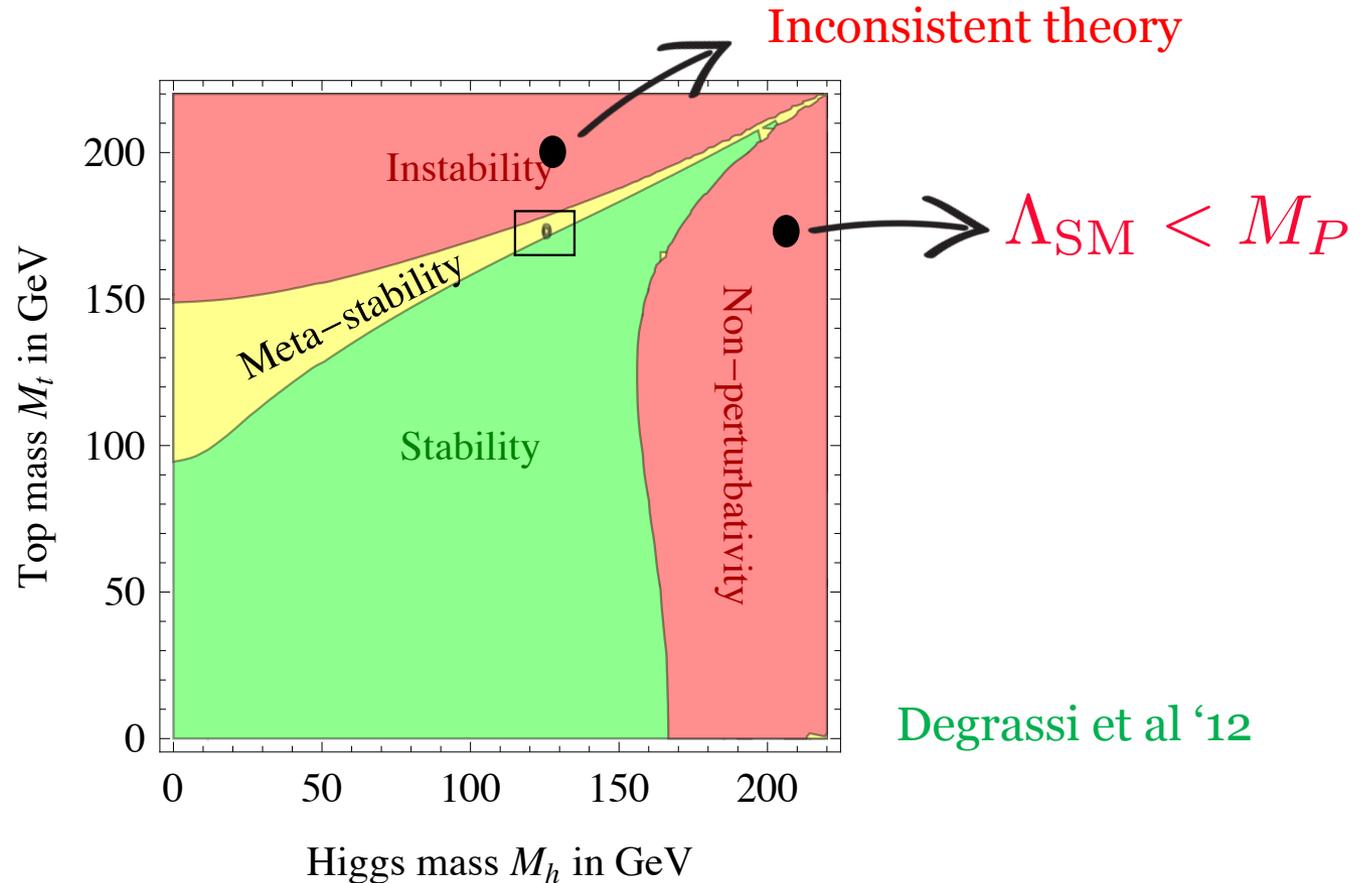
The physics we observe does not comply with a SM without a cutoff !
Where is that cutoff ?

2. **Stability** of the higgs potential $\leftrightarrow \lambda_R(\mu) > 0$



SM predicting its own destruction ?

Intriguing correlation between SM parameters: m_t , m_h , α_s !



SM : Landau poles beyond the Planck scale, stability at the edge!

Outstanding Questions or Why we need BSM ?

Underlying Principles:

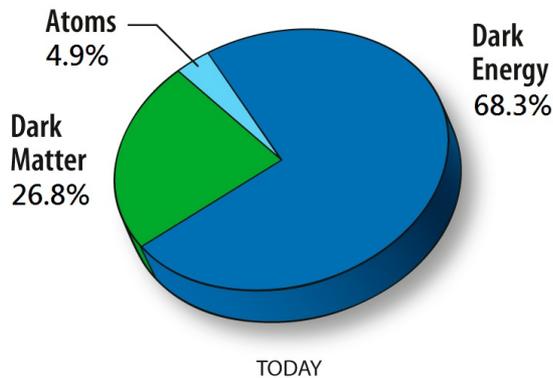
Deeper understanding of the SM

Flavour puzzle & neutrino masses,
Strong CP,
SM needs a cutoff
correlations between parameters ?
higgs potential

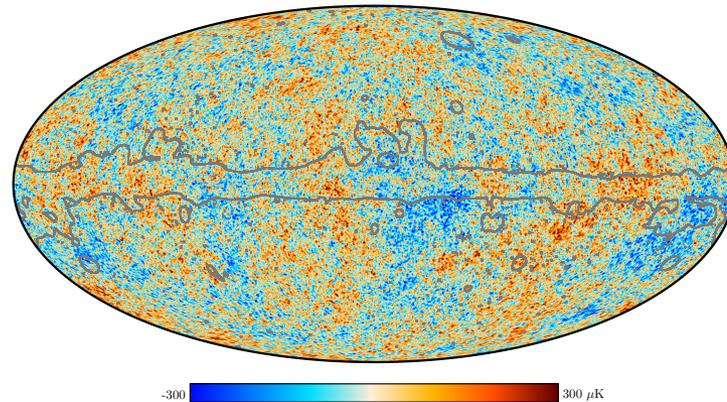
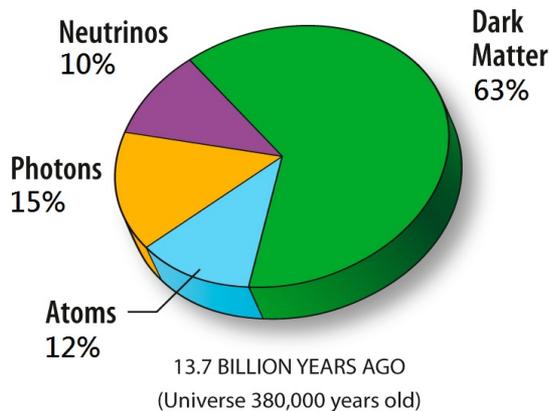
Quantum gravity

Outstanding Questions or Why we need BSM ?

Data we definitely cannot explain! matter-antimatter asymmetry,
dark matter
dark energy
inflation



SM + gravity \neq cosmos



Can we understand this with BSM particle physics ?

The generic BSM way...

SM + high scale BSM = SMEFT

What if there is new physics (ie. new fields with mass $\Lambda \gg v$)?

E ↑

$$\mathcal{L}_{\text{SM}}[\phi] + \mathcal{L}_{\text{BSM}}[\phi, \Phi]$$

$$(g_3, g_2, g_1, y_q, y_l, \lambda, \mu^2, \dots)$$

Λ —

$$\mathcal{L}'_{\text{SM}}[\phi] + \mathcal{L}_{\text{SMEFT}}[\phi]$$

$$(g'_3, g'_2, g'_1, y'_q, y'_l, \lambda', \mu'^2, \dots)$$

Hierarchy problem !

$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

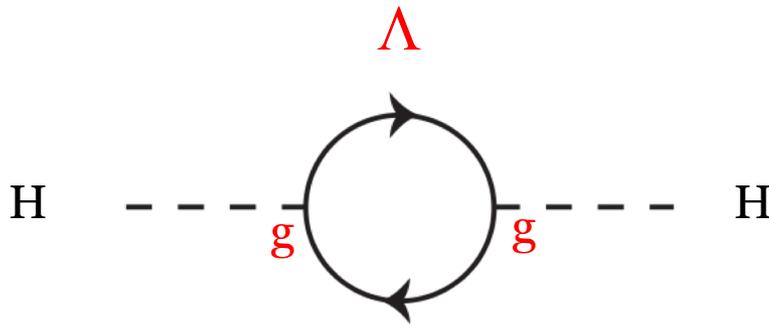
Violation of unitarity !

SMEFT and hierarchy problem

Fine-tuning ?

$$g' = g + \mathcal{O}(\log(\Lambda))$$

$$\mu'^2 = \mu^2 + \mathcal{O}(\Lambda^2)$$

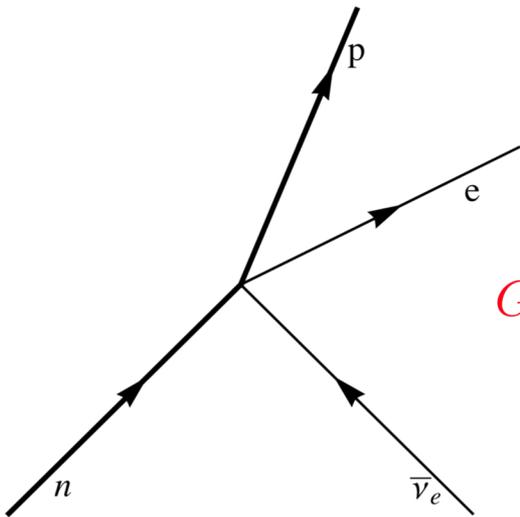


$$\mu'^2 = \mu^2 + \frac{g^2}{16\pi^2} \Lambda^2$$

If there are heavy new particles, the Higgs mass should know about them...

SMEFT predicting its own destruction ?

Non-renormalizable terms imply violation of unitarity at high energies:
analogous situation of the Fermi theory before the SM

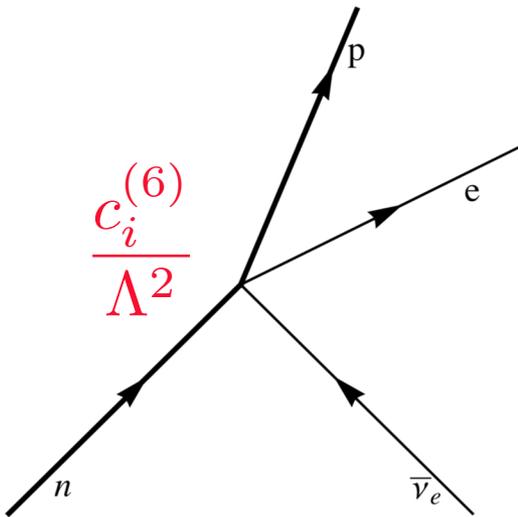


$$G_F \sim \frac{1}{M_W^2}$$

$$\sigma \propto G_F^2 s$$

SMEFT would predict its own destruction

NP can induce similar non-renormalizable interactions



$$\sigma \propto \left(\frac{c_i^{(6)}}{\Lambda^2} \right)^2 s$$

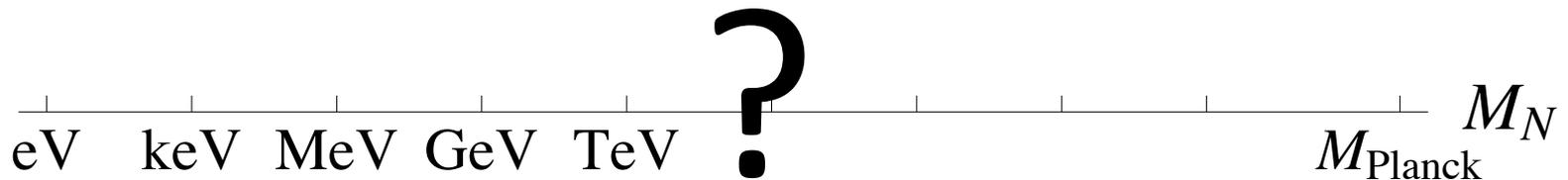
New physics must show up before unitarity is violated

$$E_{\max} \sim \frac{\Lambda}{\sqrt{c_i^{(6)}}}$$

SMEFT “No Lose Theorem” ? modification to SM couplings or a new type of interaction implies NP must show up before E_{\max}

Observation: we can only measure $\frac{c_i^{(d)}}{\Lambda^{d-4}}$ -> degeneracy between c and Λ

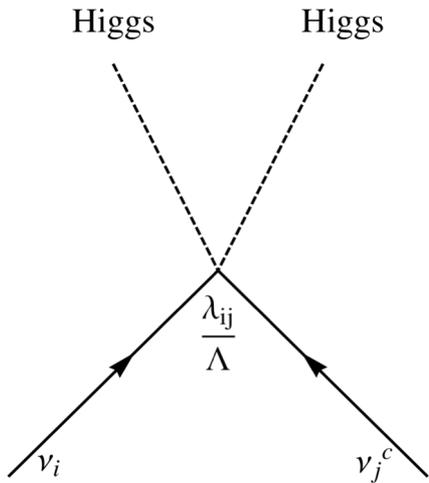
$$c_i^{(d)} \propto (\text{couplings})^\#$$



$$c_i^{(d)} \leq 1 \text{ upper bound on } \Lambda$$

SMEFT @ d=5

$$\mathcal{L}_{\text{SMEFT}} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)}}_{\substack{1 \text{ operator} \\ \Delta L = 2}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda} \mathcal{O}_i^{(6)}}_{63 \text{ operators}}$$

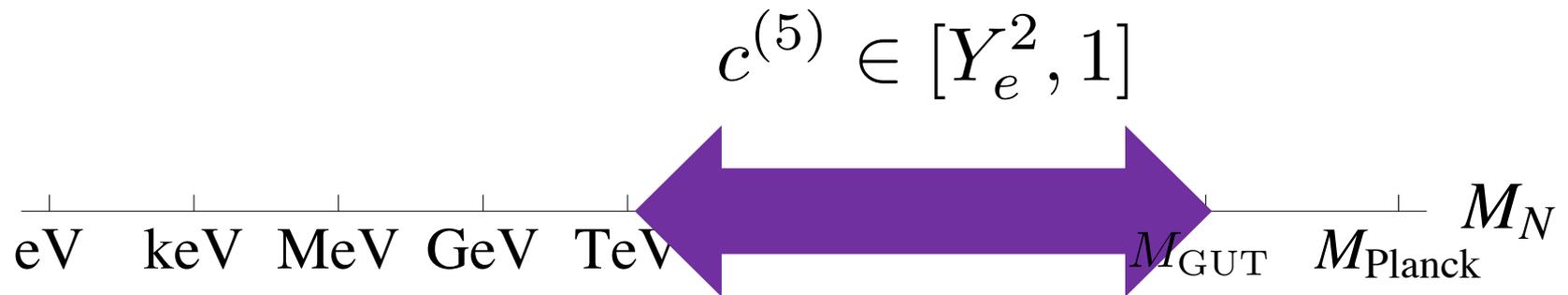


$$\mathcal{O}^{(5)} = \frac{c_{ij}^{(5)}}{\Lambda} \bar{L}_i H (H L_j)^c + h.c. \rightarrow \bar{\nu}_L \frac{m_\nu}{2} \nu_L^c + h.c.$$

$$\frac{c^{(5)}}{\Lambda} = \frac{m_\nu}{v^2} \sim \mathcal{O}\left(\frac{1}{10^{15} \text{ GeV}}\right)$$

Neutrino mediator mass scale ?

12 order of magnitude of possibilities that can explain why neutrinos are special



There is a model independent prediction of this new scale: $\beta\beta 0\nu$!

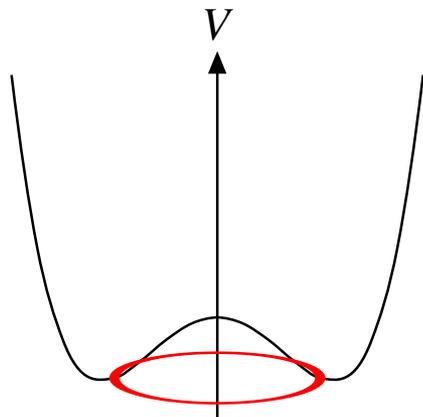
SMEFT @ d=6

$$\mathcal{L}_{\text{SMEFT}} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)}}_{1 \text{ operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda} \mathcal{O}_i^{(6)}}_{63 \text{ operators}}$$

$c_i^{(6)}$ can modify the SM gauge boson, higgs, top couplings and generate new ones...

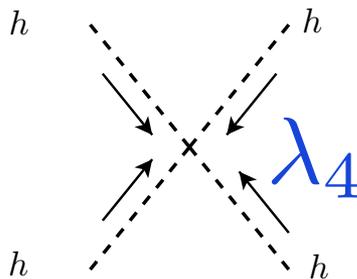
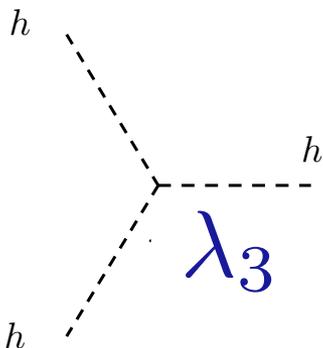
SMEFT and unitarity

Modifications to higgs self-couplings (**higgs potential**) still unconstrained



The shape of this potential is essential to understand EW phase transition and fate of this theory in the cosmological context

$$\delta_i = \frac{\lambda_i - \lambda_i^{\text{SM}}}{\lambda_i^{\text{SM}}}$$

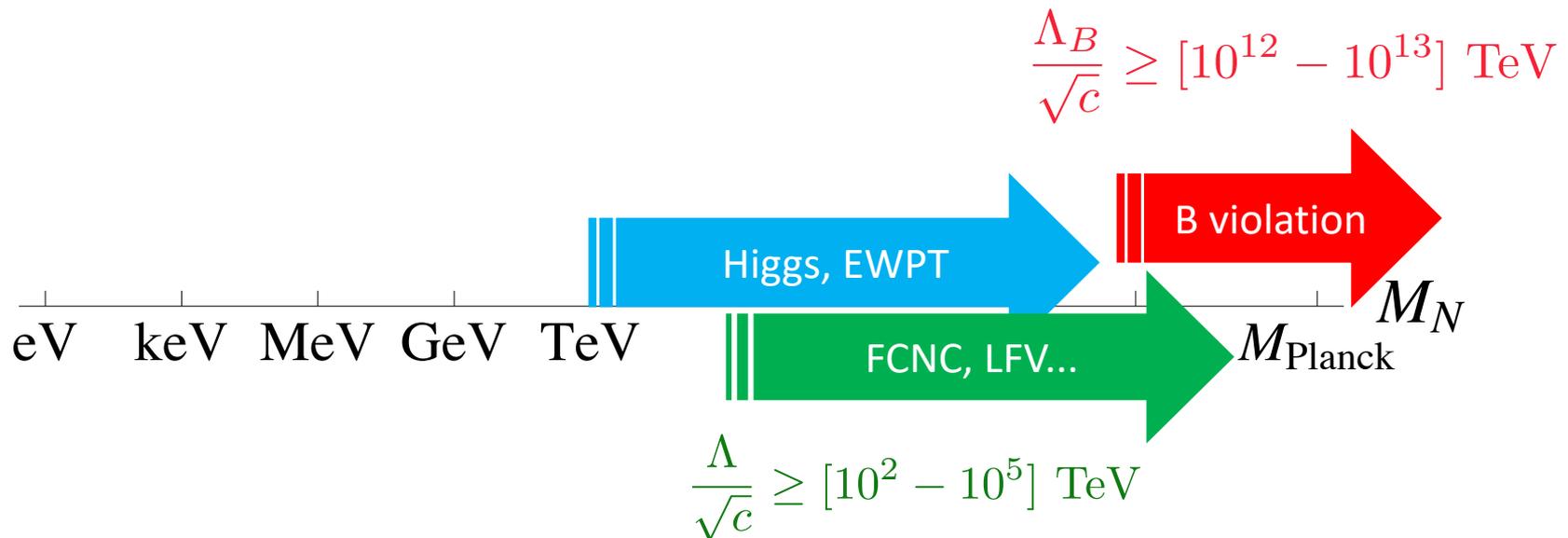


| Process | Unitarity Violating Scale |
|---|--|
| $h^2 Z_L \leftrightarrow h Z_L$ | $66.7 \text{ TeV}/ \delta_3 - \frac{1}{3}\delta_4 $ |
| $h Z_L^2 \leftrightarrow Z_L^2$ | $94.2 \text{ TeV}/ \delta_3 $ |
| $h W_L Z_L \leftrightarrow W_L Z_L$ | $141 \text{ TeV}/ \delta_3 $ |
| $h Z_L^2 \leftrightarrow h Z_L^2$ | $9.1 \text{ TeV}/\sqrt{ \delta_3 - \frac{1}{5}\delta_4 }$ |
| $h W_L Z_L \leftrightarrow h W_L Z_L$ | $11.1 \text{ TeV}/\sqrt{ \delta_3 - \frac{1}{5}\delta_4 }$ |
| $Z_L^3 \leftrightarrow Z_L^3$ | $15.7 \text{ TeV}/\sqrt{ \delta_3 }$ |
| $Z_L^2 W_L \leftrightarrow Z_L^2 W_L$ | $20.4 \text{ TeV}/\sqrt{ \delta_3 }$ |
| $h Z_L^3 \leftrightarrow Z_L^3$ | $6.8 \text{ TeV}/ \delta_3 - \frac{1}{6}\delta_4 ^{\frac{1}{3}}$ |
| $h Z_L^2 W_L \leftrightarrow Z_L^2 W_L$ | $8.0 \text{ TeV}/ \delta_3 - \frac{1}{6}\delta_4 ^{\frac{1}{3}}$ |
| $Z_L^4 \leftrightarrow Z_L^4$ | $6.1 \text{ TeV}/ \delta_3 - \frac{1}{6}\delta_4 ^{\frac{1}{4}}$ |

SMEFT vs Flavour

BSM flavour puzzle: SM accidental symmetries must be there up to higher scales

$$\mathcal{L}_{\text{SMEFT}} \supset \underbrace{\frac{c_{ij}^q}{\Lambda^2} (\bar{Q}_i \gamma_\mu P_L Q_j)^2}_{\Delta m_K, \Delta m_D, \Delta m_B, \dots} + \dots + \underbrace{\frac{c_{ij}^l}{\Lambda^2} \bar{L}_i \sigma_{\mu\nu} \Phi l_j F^{\mu\nu}}_{\mu \rightarrow e\gamma, \text{EDMs} \dots} + \dots + \underbrace{\frac{c_{ijkl}^b}{\Lambda_B^2} \epsilon_{\alpha\beta\gamma} Q_i^\alpha Q_j^\beta Q_k^\gamma L_l}_{p\text{-decay}}$$



SMEFT vs Flavour

BSM flavour puzzle: why SM accidental symmetries?

$$Y = 0 \quad SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{L_L} \times SU(3)_{l_R}$$

Minimal Flavour Violation $c_{ij} = f(YY^\dagger, \dots)_{ij}$

Where is this principle coming from ? Dynamical flavour ? Froggatt-Nielsen ?

$$Y_{ij} = \frac{\langle \phi_{ij} \rangle}{\Lambda} \quad Y_{ij} = \left(\frac{\Phi}{\Lambda} \right)^{q(Q_L)_i - q(q_R)_j}$$

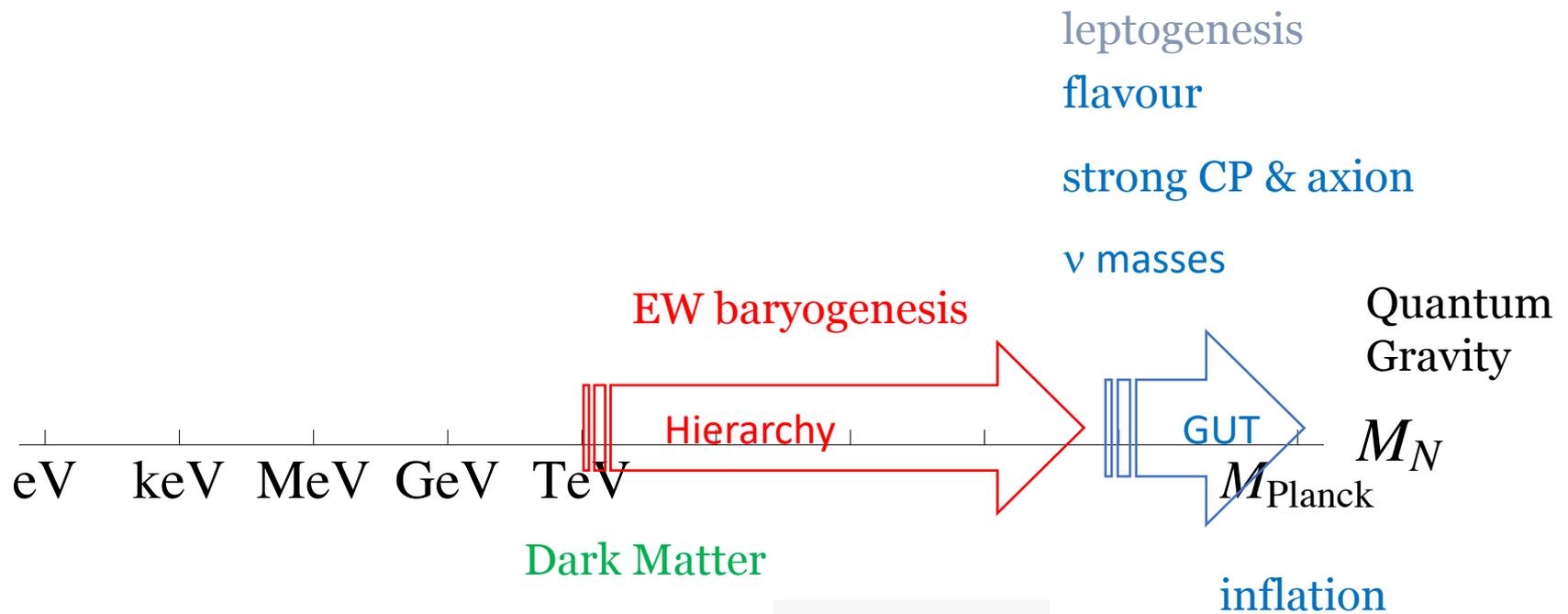
+ Discrete/Global/Gauge symmetries (B, L , ...)

BSM searches should pay important attention to flavour!

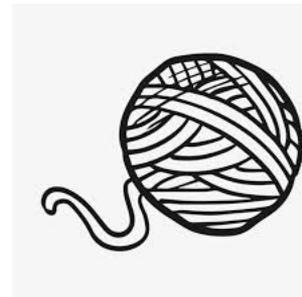
The concrete BSM way...

The grand scheme

In the “good old days”, we had a grand scheme:

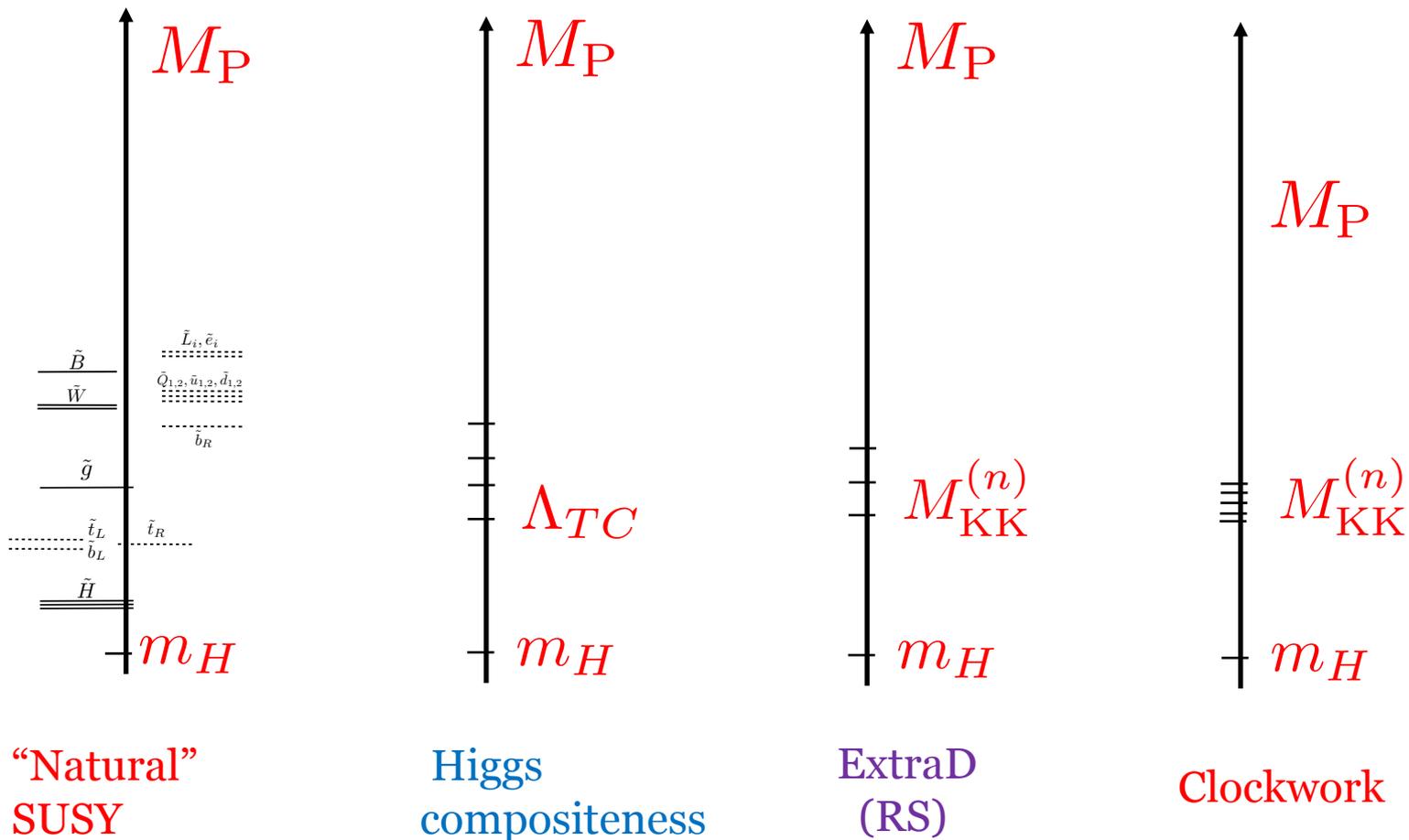


Hierarchy problem and dark matter



EW Hierarchy problem ?

An enormous brain effort has been devoted to solving this problem, ie. understanding the separation between M_{Higgs} and M_{Planck}



New states at TeV, fine-tune the Little hierarchy, top quark special

LHC EW hierarchy razor

ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019

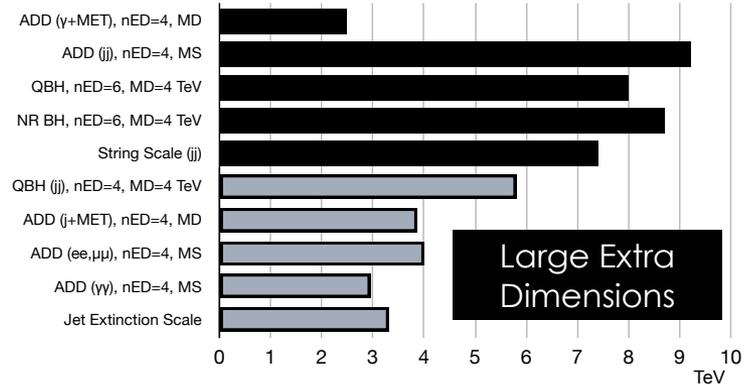
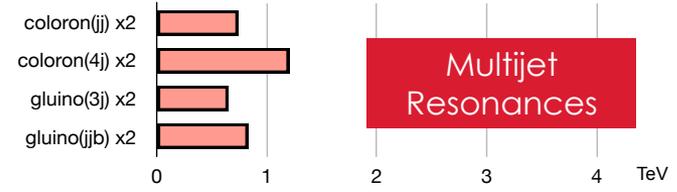
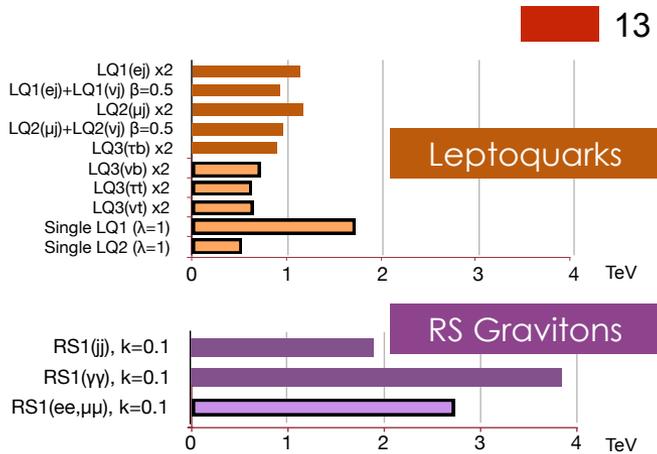
ATLAS Preliminary
 $\sqrt{s} = 13$ TeV

| Model | Signature | $\int \mathcal{L} dt$ [fb ⁻¹] | Mass limit | Reference | | | | | |
|---|--|---|--|--|--|--|---|--|---|
| Inclusive Searches | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ | 0 e, μ mono-jet | 2-6 jets 1-3 jets | E_T^{miss} E_T^{miss} | 36.1 36.1 | \tilde{q} [2x, 8x Degen] \tilde{q} [1x, 8x Degen] | 0.9 1.55 | $m(\tilde{\chi}_1^0) < 100$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV | 1712.02332 1711.03301 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 0 e, μ | 2-6 jets | E_T^{miss} | 36.1 | \tilde{g} \tilde{g} | 2.0 0.95-1.6 | $m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) = 900$ GeV | 1712.02332 1712.02332 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\ell\ell\tilde{\chi}_1^0$ | 3 e, μ $ee, \mu\mu$ | 4 jets 2 jets | E_T^{miss} E_T^{miss} | 36.1 36.1 | \tilde{g} \tilde{g} | 1.85 1.2 | $m(\tilde{\chi}_1^0) < 800$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV | 1706.03731 1805.11381 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$ | 0 e, μ 3 e, μ | 7-11 jets 4 jets | E_T^{miss} E_T^{miss} | 36.1 36.1 | \tilde{g} \tilde{g} | 1.8 0.98 | $m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV | 1708.02794 1706.03731 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ | 0-1 e, μ 3 e, μ | 3 b 4 jets | E_T^{miss} E_T^{miss} | 79.8 36.1 | \tilde{g} \tilde{g} | 2.25 1.25 | $m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV | ATLAS-CONF-2018-041 1706.03731 |
| | 3 rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 / t\tilde{\chi}_1^+$ | Multiple Multiple | Multiple Multiple | E_T^{miss} E_T^{miss} | 36.1 36.1 36.1 | \tilde{b}_1 \tilde{b}_1 \tilde{b}_1 | 0.9 0.58-0.82 0.7 | $m(\tilde{\chi}_1^0) = 300$ GeV, $\text{BR}(\tilde{\chi}_1^+) = 1$ $m(\tilde{\chi}_1^+) = 300$ GeV, $\text{BR}(\tilde{\chi}_1^+) = \text{BR}(\tilde{\chi}_1^+) = 0.5$ $m(\tilde{\chi}_1^+) = 200$ GeV, $m(\tilde{\chi}_1^+) = 300$ GeV, $\text{BR}(\tilde{\chi}_1^+) = 1$ |
| $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$ | | 0 e, μ | 6 b | E_T^{miss} | 139 | \tilde{b}_1 \tilde{b}_1 | 0.23-0.48 0.23-1.35 | $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV | SUSY2018-31 SUSY2018-31 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W b\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | | 0-2 e, μ | 0-2 jets/1-2 b | E_T^{miss} | 36.1 | \tilde{t}_1 | 1.0 | $m(\tilde{\chi}_1^0) = 1$ GeV | 1506.08616, 1709.04183, 1711.11520 |
| $\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP | | Multiple | Multiple | E_T^{miss} | 36.1 | \tilde{t}_1 | 0.48-0.84 | $m(\tilde{\chi}_1^0) = 150$ GeV, $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = 5$ GeV, $\tilde{t}_1 \approx \tilde{t}_2$ | 1709.04183, 1711.11520 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau} b \nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$ | | 1 $\tau + 1 e, \mu, \tau$ | 2 jets/1 b | E_T^{miss} | 36.1 | \tilde{t}_1 | 1.16 | $m(\tilde{\tau}_1) = 800$ GeV | 1803.10178 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$ | | 0 e, μ | 2 c | E_T^{miss} | 36.1 | \tilde{t}_1 \tilde{t}_1 | 0.85 0.46 0.43 | $m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV | 1805.01649 1805.01649 1711.03301 |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ | | 0 e, μ | mono-jet | E_T^{miss} | 36.1 | \tilde{t}_2 | 0.32-0.88 | $m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180$ GeV | 1706.03986 |
| EW direct | $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ | 2-3 e, μ $ee, \mu\mu$ | ≥ 1 | E_T^{miss} E_T^{miss} | 36.1 36.1 | $\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ $\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ | 0.6 0.17 | $m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 10$ GeV | 1403.5294, 1806.02293 1712.08119 |
| | $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via WW | 2 e, μ | | E_T^{miss} | 139 | $\tilde{\chi}_1^+$ | 0.42 | $m(\tilde{\chi}_1^0) = 0$ | ATLAS-CONF-2019-008 |
| | $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via Wh | 0-1 e, μ | 2 b | E_T^{miss} | 36.1 | $\tilde{\chi}_1^+$ | 0.68 | $m(\tilde{\chi}_1^0) = 0$ | 1812.09432 |
| | $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via $\tilde{\chi}_1 / \tilde{\nu}$ | 2 e, μ | | E_T^{miss} | 139 | $\tilde{\chi}_1^+$ | 1.0 | $m(\tilde{\chi}_1^0) = 0$ | ATLAS-CONF-2019-008 |
| | $\tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_2^0, \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\tau}_1 \nu(\tilde{\tau}\tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau(\tilde{\nu}\tilde{\tau})$ | 2 τ | | E_T^{miss} | 36.1 | $\tilde{\chi}_1^+$ $\tilde{\chi}_1^+$ | 0.76 0.22 | $m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}_1, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$ $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 100$ GeV, $m(\tilde{\tau}_1, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$ | 1708.07875 1708.07875 |
| | $\tilde{t}_{1R} \tilde{t}_{1R}, \tilde{t} \rightarrow t\tilde{\chi}_1^0$ | 2 e, μ ≥ 1 | 0 jets ≥ 1 | E_T^{miss} E_T^{miss} | 139 36.1 | \tilde{t} \tilde{t} | 0.7 0.18 | $m(\tilde{\chi}_1^0) = 0$ $m(\tilde{t}) - m(\tilde{\chi}_1^0) = 5$ GeV | ATLAS-CONF-2019-008 1712.08119 |
| $\tilde{H} \tilde{H}, \tilde{H} \rightarrow h\tilde{G} / Z\tilde{G}$ | 0 e, μ 4 e, μ | ≥ 3 b 0 jets | E_T^{miss} E_T^{miss} | 36.1 36.1 | \tilde{H} \tilde{H} | 0.29-0.88 0.13-0.23 0.3 | $\text{BR}(\tilde{H}^+ \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{H}^+ \rightarrow Z\tilde{G}) = 1$ | 1806.04030 1804.03602 | |
| Long-lived particles | Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$ | Disapp. trk | 1 jet | E_T^{miss} | 36.1 | $\tilde{\chi}_1^+$ $\tilde{\chi}_1^+$ | 0.46 0.15 | Pure Wino Pure Higgsino | 1712.02118 ATL-PHYS-PUB-2017-019 |
| | Stable \tilde{g} R-hadron | Multiple | Multiple | | 36.1 | \tilde{g} | 2.0 | $m(\tilde{\chi}_1^0) = 100$ GeV | 1902.01636, 1808.04095 |
| RPV | Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | Multiple | Multiple | | 36.1 | \tilde{g} | 2.05, 2.4 | $m(\tilde{\chi}_1^0) = 100$ GeV | 1710.04901, 1808.04095 |
| | LFV $p\tilde{p} \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e\mu/\ell\tau/\mu\tau$ | $e\mu, e\tau, \mu\tau$ | | | 3.2 | $\tilde{\nu}_e$ | 1.9 | $\lambda'_{111} = 0.11, \lambda'_{132}/\lambda'_{233}/\lambda'_{233} = 0.07$ | 1607.08079 |
| | $\tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_2^0 \rightarrow WWll\ell\ell\nu\nu$ | 4 e, μ | 0 jets | E_T^{miss} | 36.1 | $\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ | 0.82, 1.33 | $m(\tilde{\chi}_1^0) = 100$ GeV | 1804.03602 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$ | Multiple | 4-5 large- R jets | | 36.1 | \tilde{g} \tilde{g} | 1.3, 1.9 1.05, 2.0 | Large λ'_{112} | 1804.03568 |
| | $\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{b}s$ | Multiple | Multiple | | 36.1 | \tilde{g} | 1.05 | $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$ | 2 e, μ | 2 jets + 2 b | | 36.7 | \tilde{t}_1 | 0.55, 0.61 | $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like | ATLAS-CONF-2018-003 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$ | 2 e, μ 1 μ | 2 b DV | | 36.1 136 | \tilde{t}_1 \tilde{t}_1 | 0.4, 1.45 1.0, 1.6 | $\text{BR}(\tilde{t}_1 \rightarrow b\ell/h\mu) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_{\tilde{t}} = 1$ | 1710.07171 1710.05544 ATLAS-CONF-2019-006 | |

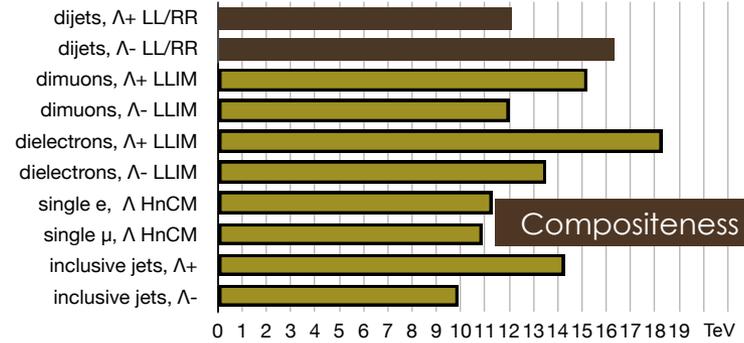
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

LHC EW hierarchy razor



CMS Preliminary



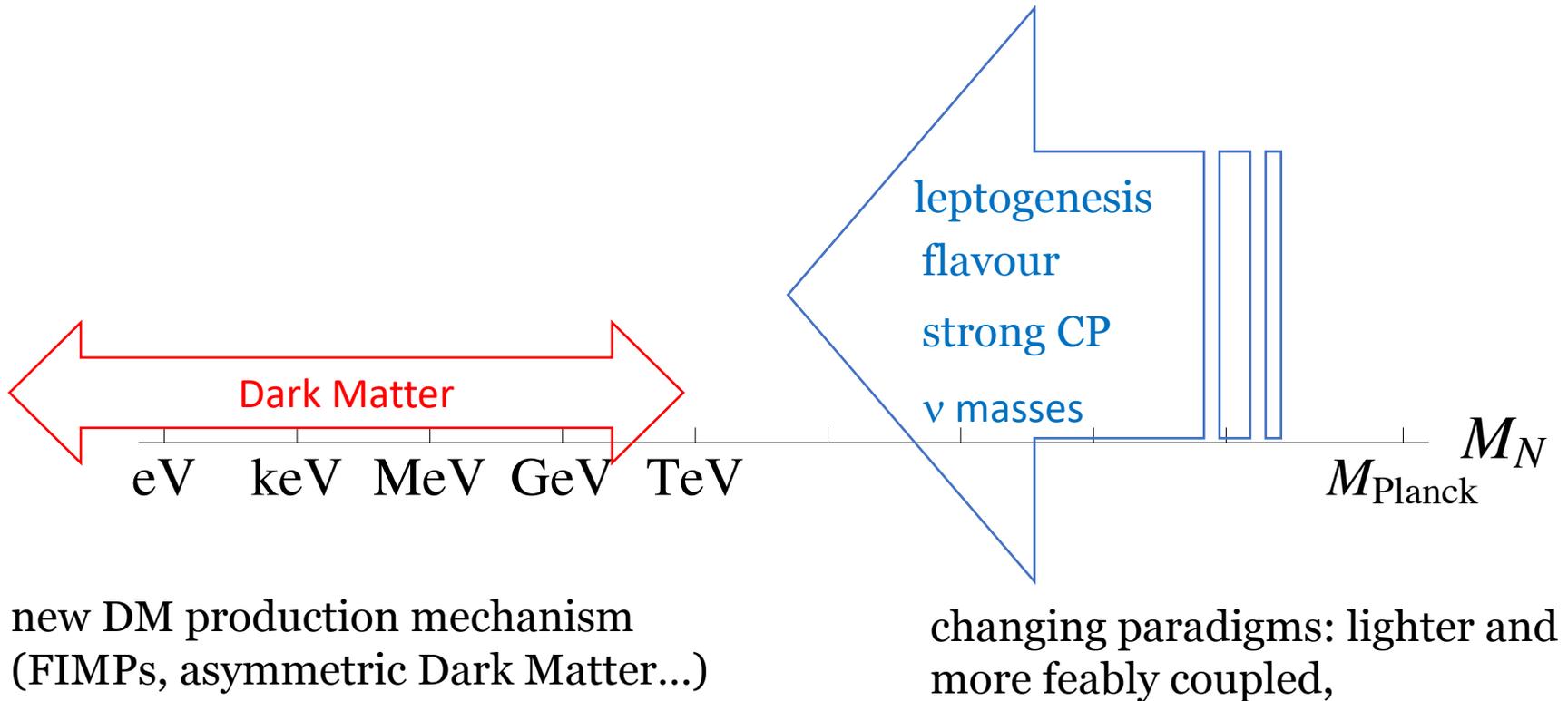
EW Hierarchy Problem ?

LHC has found no smoking gun for a solution to the big hierarchy problem and enhanced the “**Little hierarchy problem**”:

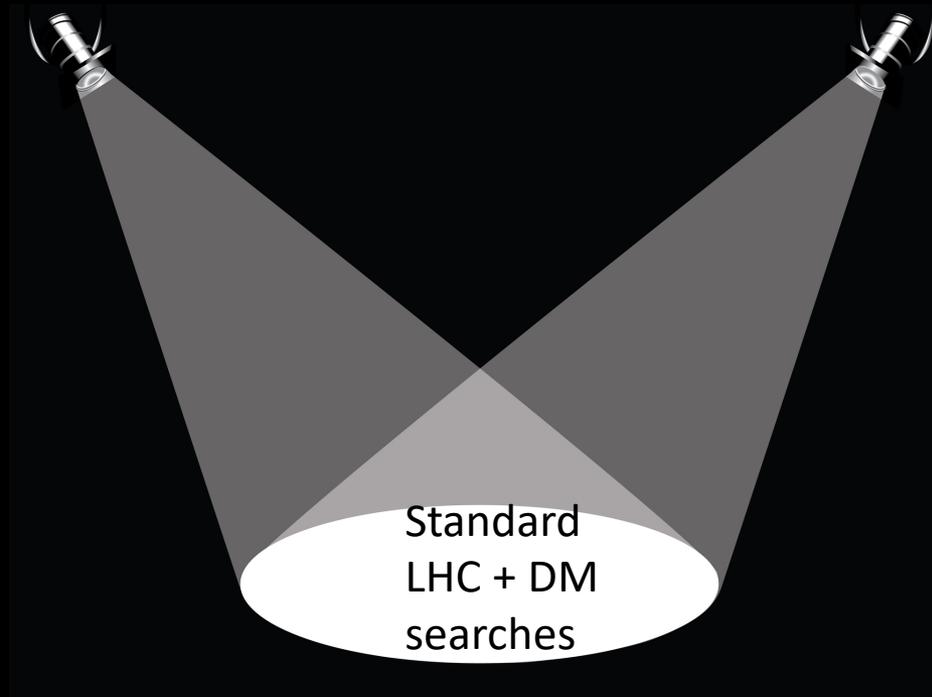
But $O(10-100)\text{TeV}$ still an interesting scale to explore!

Motivational Toolkit beyond EW hierarchy

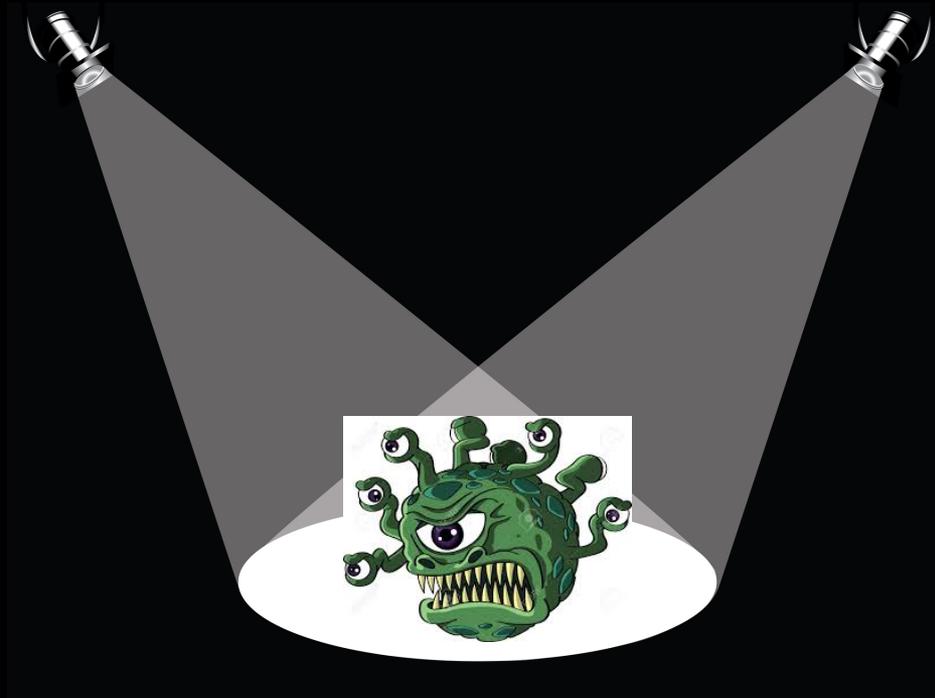
I. Avoid hierarchy problem & testability



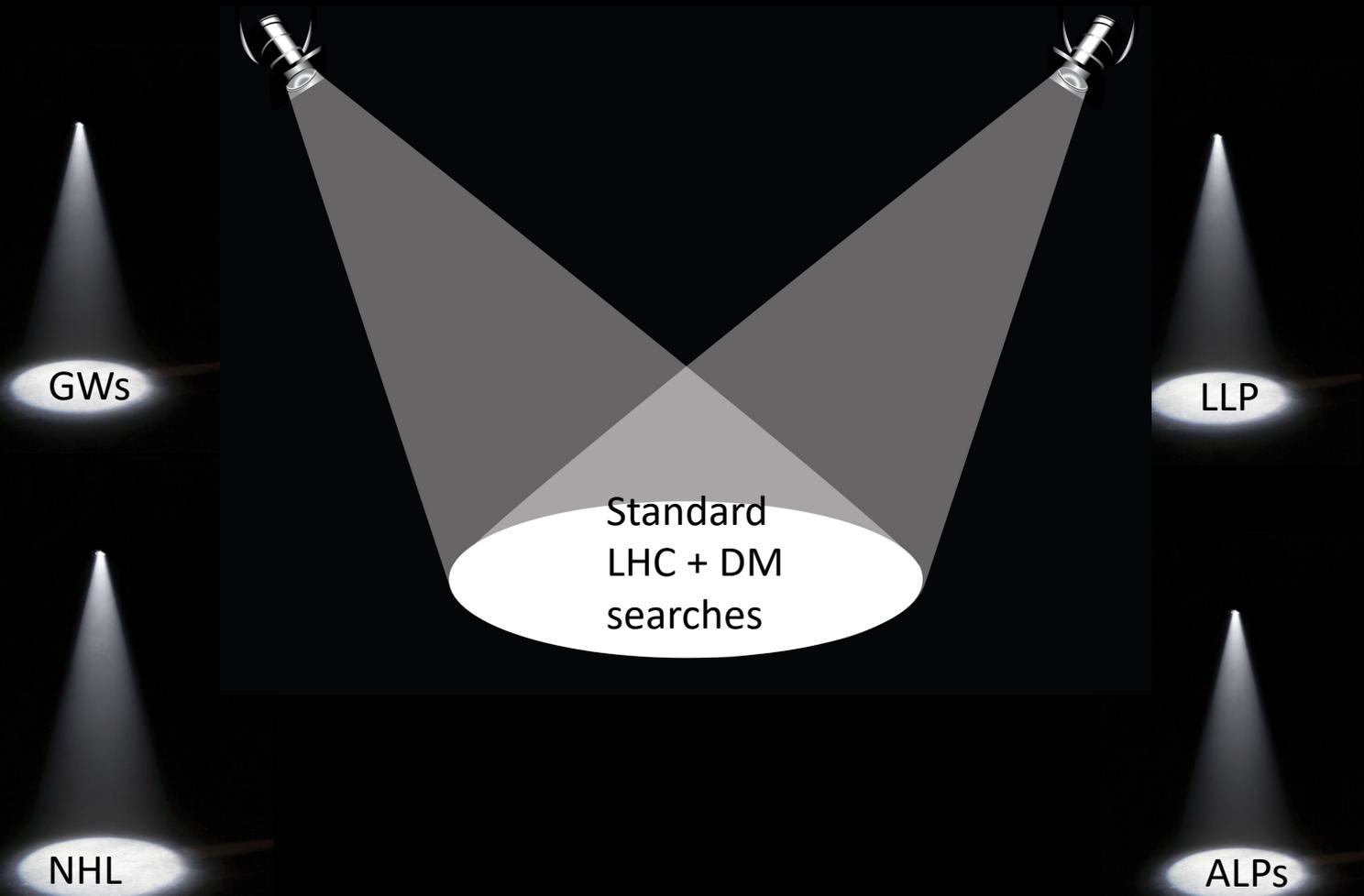
Models for the spotlight ?



Models for the spotlight ?



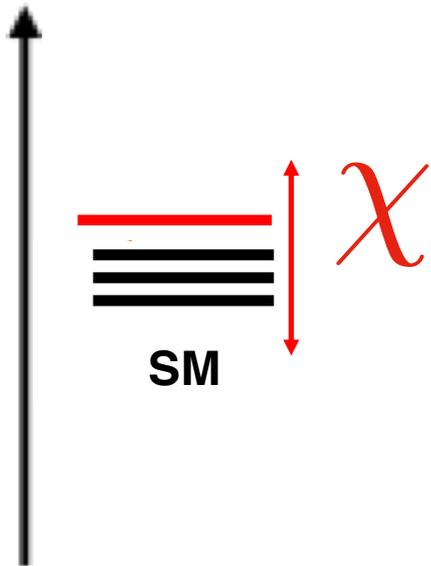
New spotlights for well motivated models



Motivational Toolkit beyond EW hierarchy

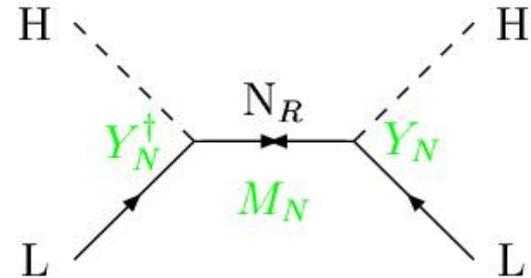
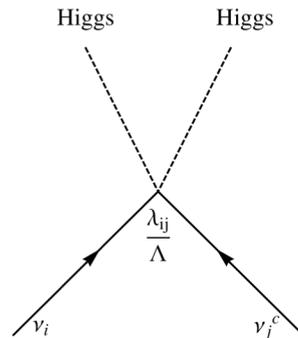
II. Occam's Razor

Example I: heavy majorana neutrino \leftrightarrow type I seesaw



$$\chi = N$$

Origin of neutrino mass:

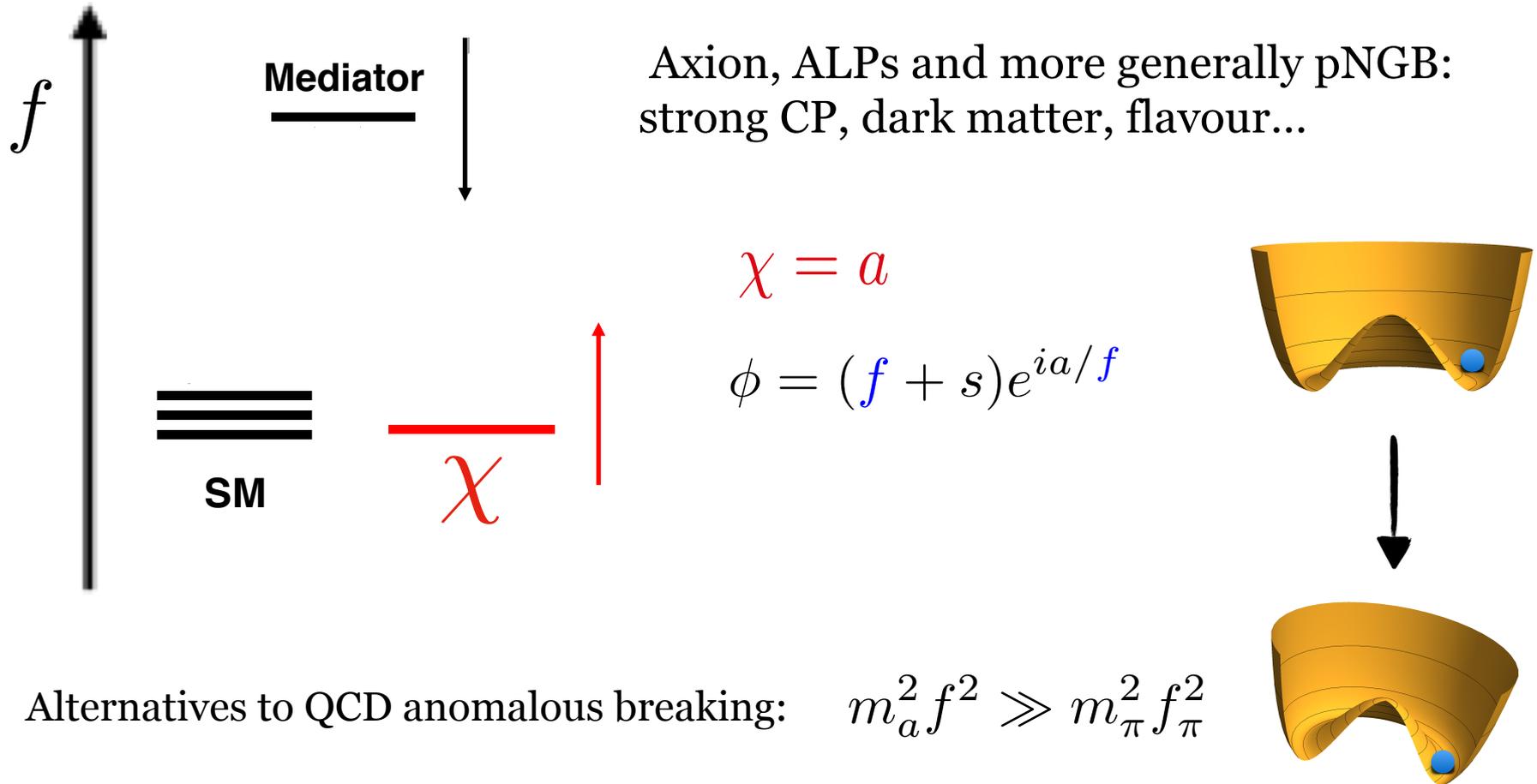


+ Origin of matter-antimatter asymmetry for $M_N > O(100)\text{MeV}$

New spotlights: beam dump and collider searches of neutral heavy leptons

Motivational Toolkit beyond EW hierarchy

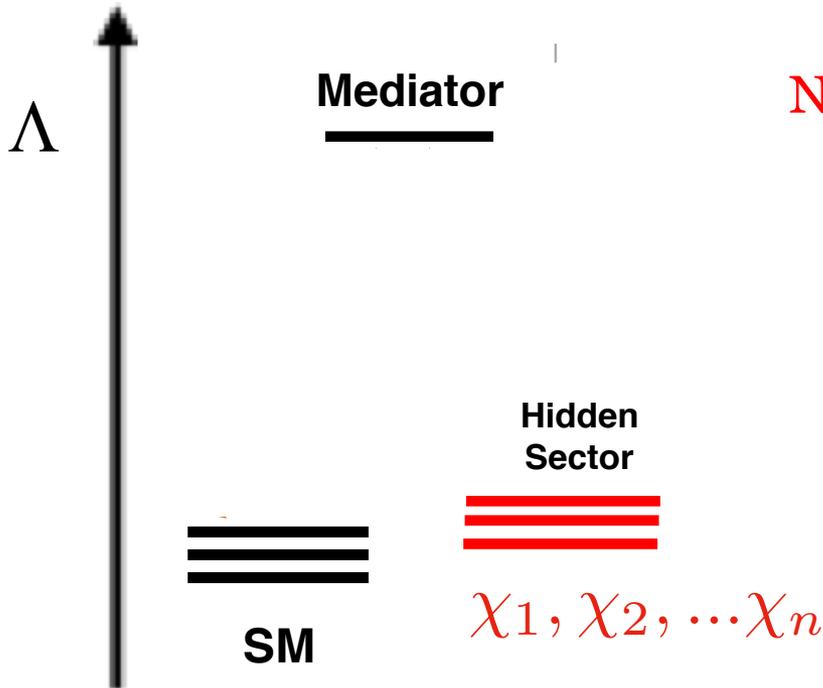
II. Occam's Razor



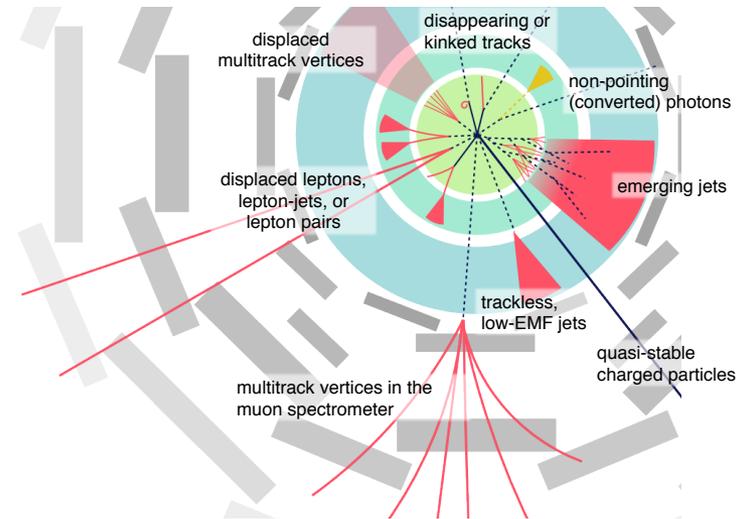
New spotlights: ALP searches @ colliders and beam dump experiments, GWs

Motivational Toolkit beyond EW hierarchy

II. Occam's Razor



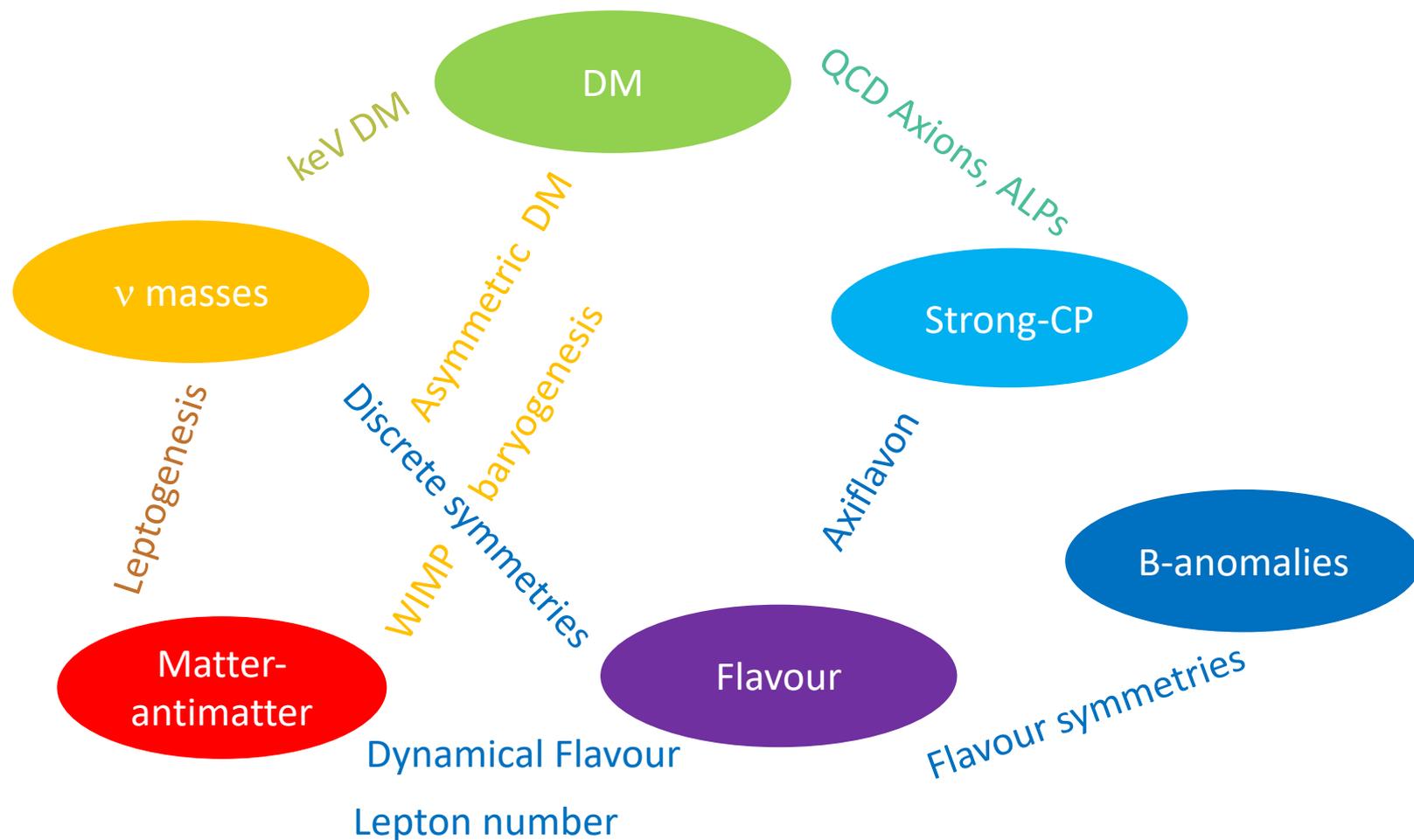
New spotlight: Long-Lived Particles



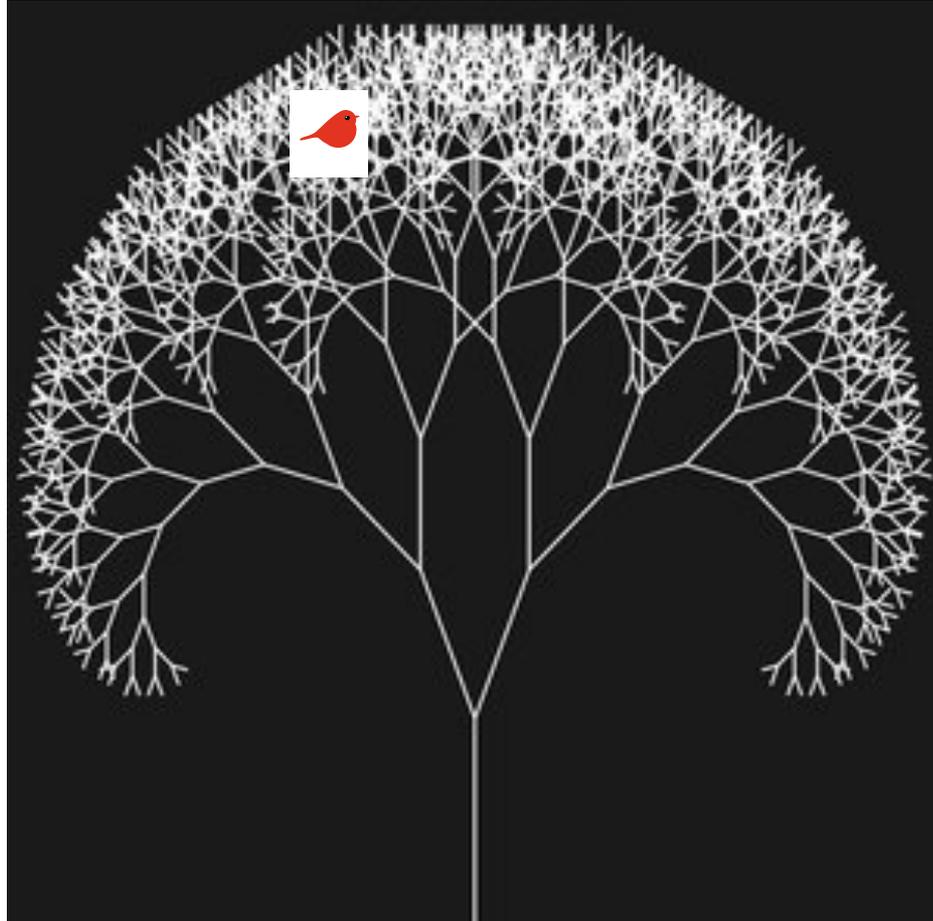
Many models of this type to explain Dark Matter: FIMPs, SIMPs, Mirror worlds...

Motivational Toolkit beyond EW hierarchy

III. Searching for connections: towards a new grand scheme



The BSM Landscape



“Truth is ever to be found in simplicity, and not in the multiplicity and confusion of things”

I. Newton