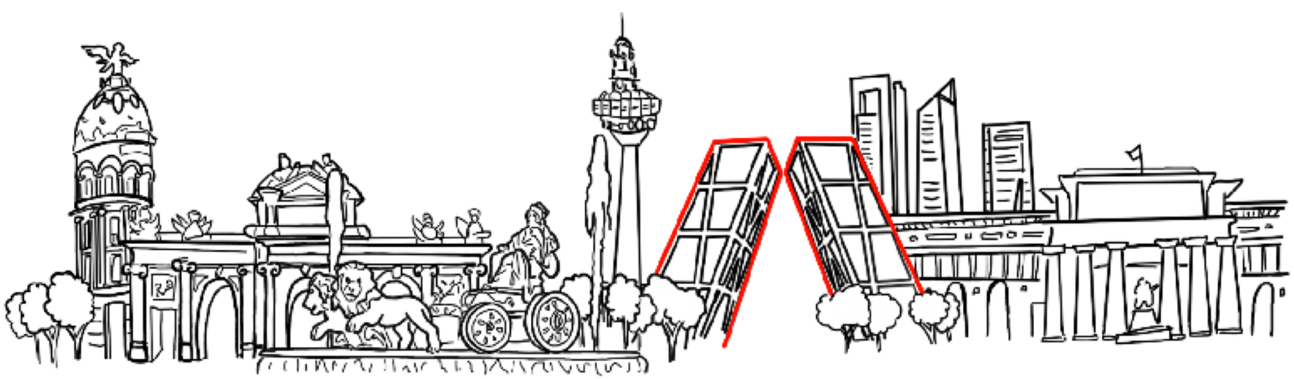
Madrid reflections on the SM & Beyond



P. Hernández
IFIC, U. Valencia-CSIC

The Standard Model

a baroque quantum world

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

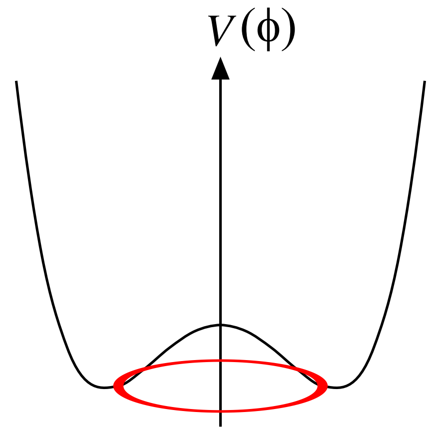
Lepton<-> quark: anomaly cancellation

$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$
$\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i \\ d^i\end{pmatrix}_L$	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

(Toy model) SSB



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

The Standard Model

Accidental symmetries:

- Baryon, Lepton Number

- Loop and GIM suppressed FCNC

- Subtle breaking of CP: matter-antimatter

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

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

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

The Standard Model

+ A non-accidental "symmetry": strong CP

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

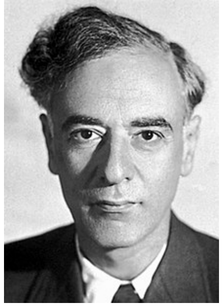
$$\bar{\theta} \leq 10^{-10}$$

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

The Weirdness of the Standard Model

- Three families

"who ordered that ?" I. Rabi



- Fundamental breaking of Parity

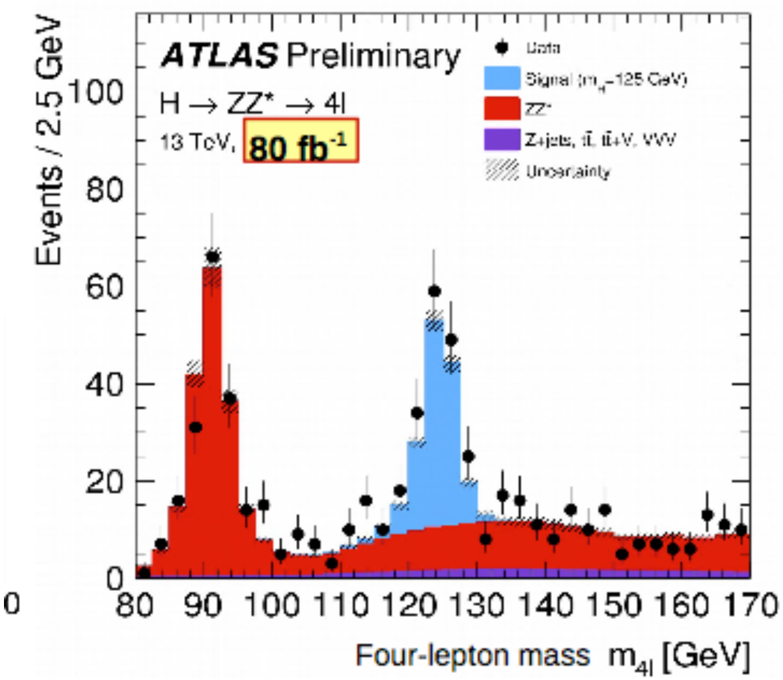
"space cannot be asymmetric!" L. Landau

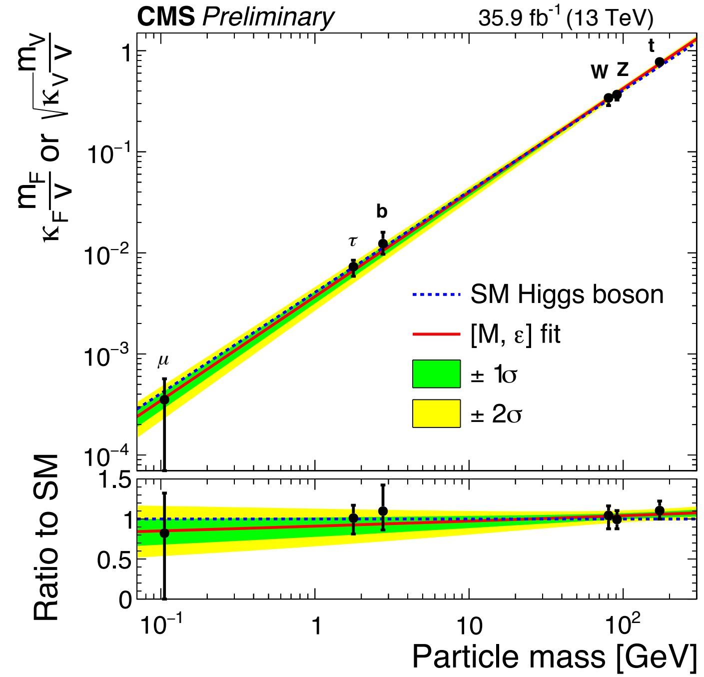
- Predictivity: 3 gauge couplings+ 16 higgs couplings (+ 7 higgs-neutrino) !

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

The Standard Model under scrutiny: “the” Higgs

L=80 fb^{-1} at 13 TeV

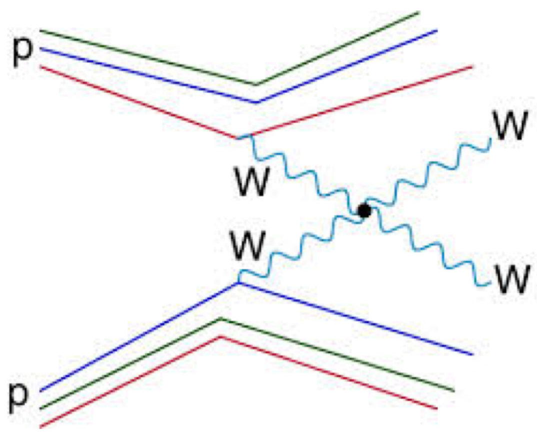




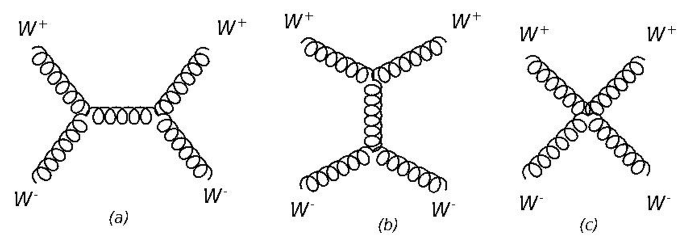
$J^{CP} = 0^+$

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

LHC "No Lose Theorem"



Without the Higgs:



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

Unitarity violated

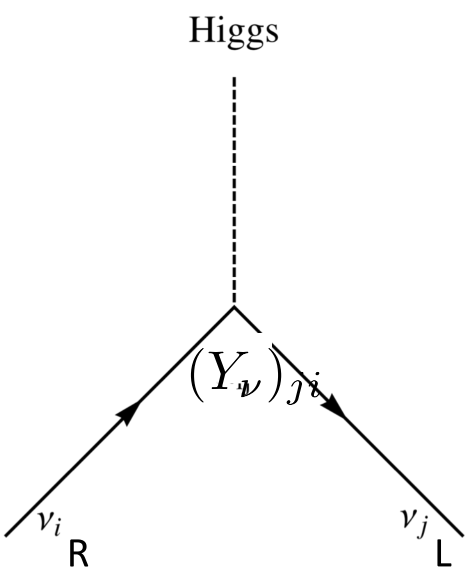
$$s \geq (1.7 \text{ TeV})^2$$

The Standard Model under scrutiny: lepton flavour

Massive neutrinos require an extension of the baroque table: eg. ν_R

(+ arbitrary choice: global L)

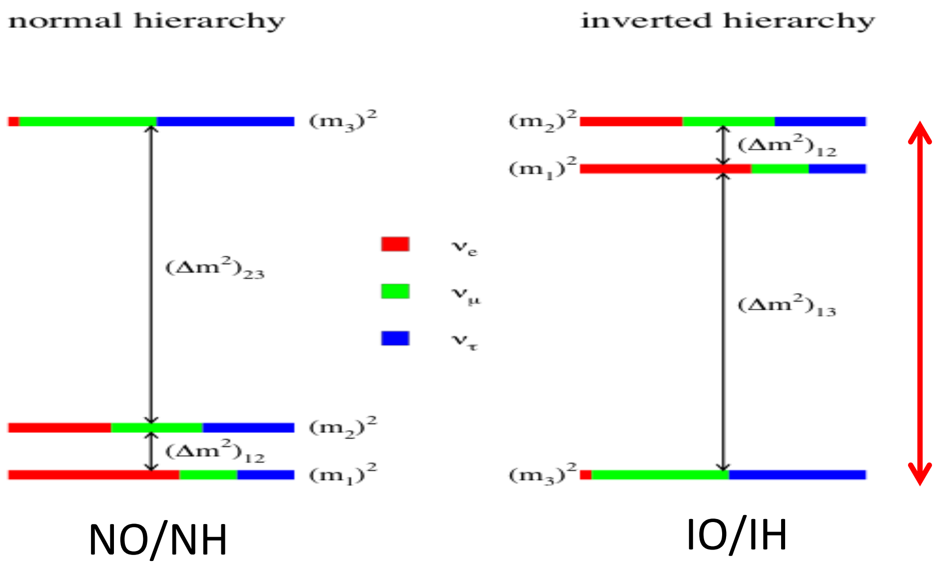
$$-\mathcal{L}_{\rm SM} \supset Y_{\nu ij}\bar{L}_i\tilde{\phi}\;\nu_{Rj}$$



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

A lepton flavour sector analogous to the quark one

The Standard Model under scrutiny: massive ν



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

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

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

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

$\theta_{23} \sim 42^\circ$ o 48°

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

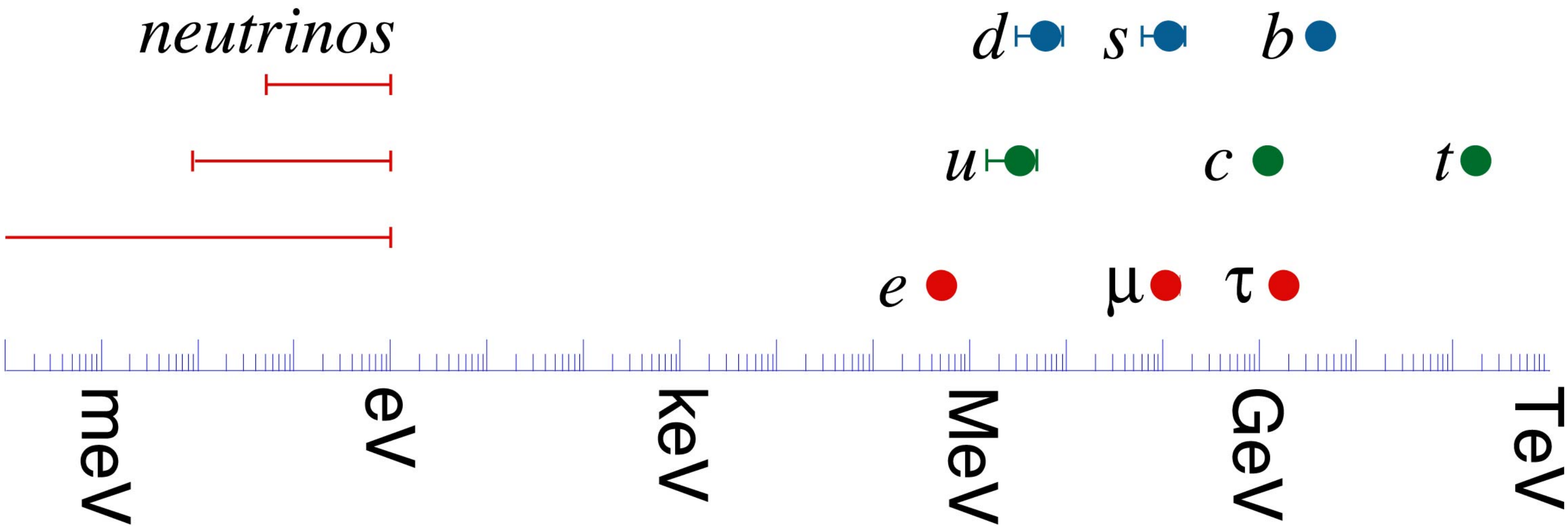
$\delta \sim \ ?$

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

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

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

PMNS

3σ

NuFIT 3.2 (2018)

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

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

The Standard Model under scrutiny: predicting its own destruction ?

(Perturbatively) Renormalizable Theory =

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

$\nexists$ Future-Collider "no lose" theorem

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

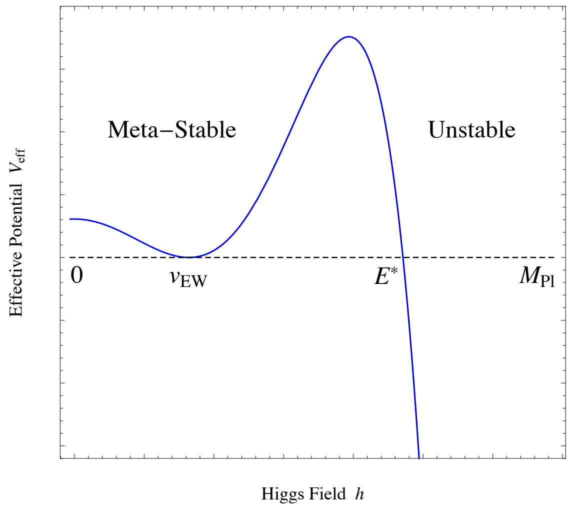
SM predicting its own destruction ?

1. Landau poles (perturbative) <-> triviality (non-perturbative)

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

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

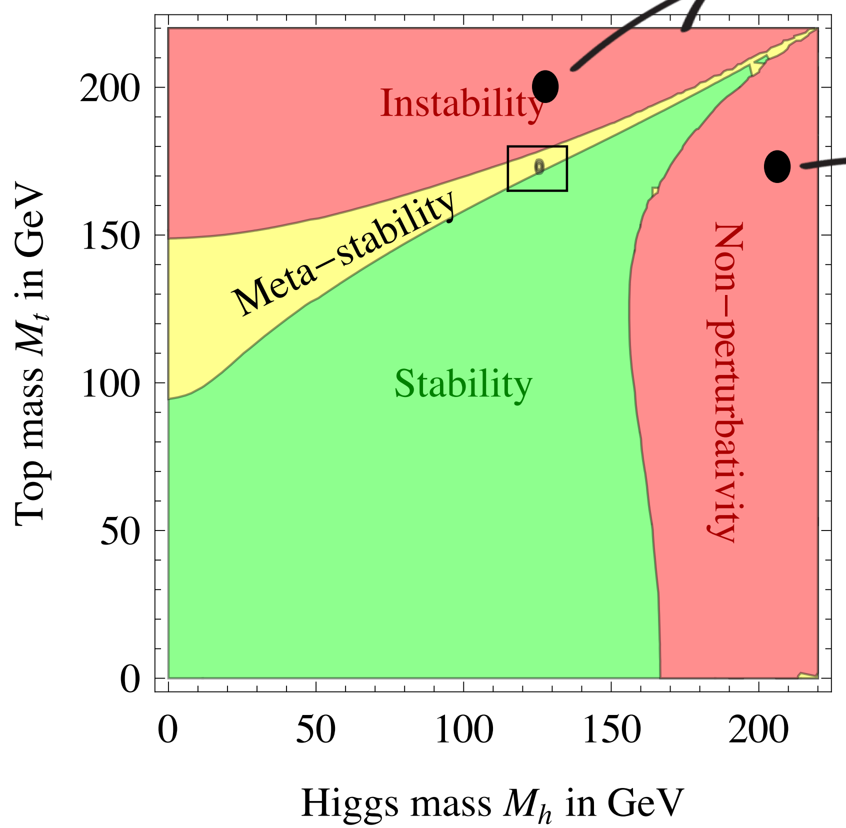
2. Stability of the higgs potential <-> $\lambda_R(\mu) > 0$



SM predicting its own destruction ?

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

Inconsistent theory



$\Lambda_{\rm SM} < M_P$

Degrassi et al '12

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

Outstanding Questions or Why we need BSM ?

Underlying Principles:

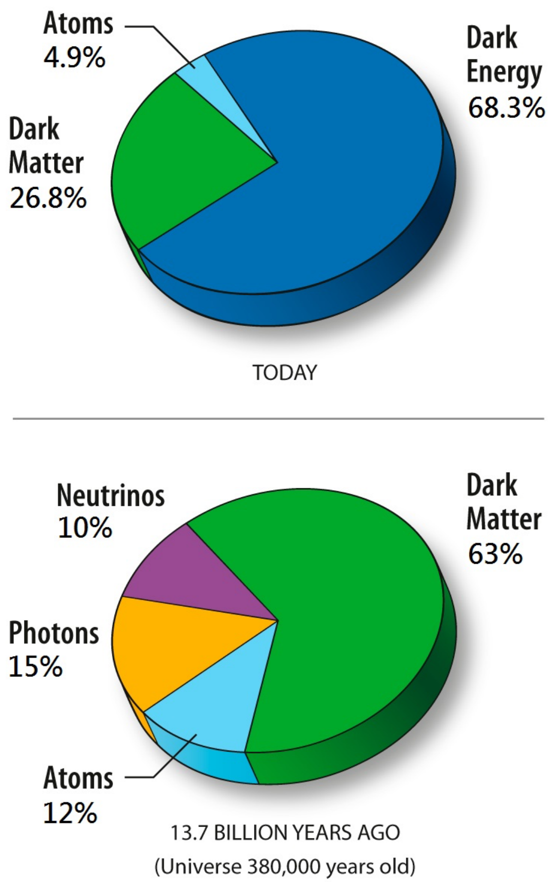
Deeper understanding of the SM

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

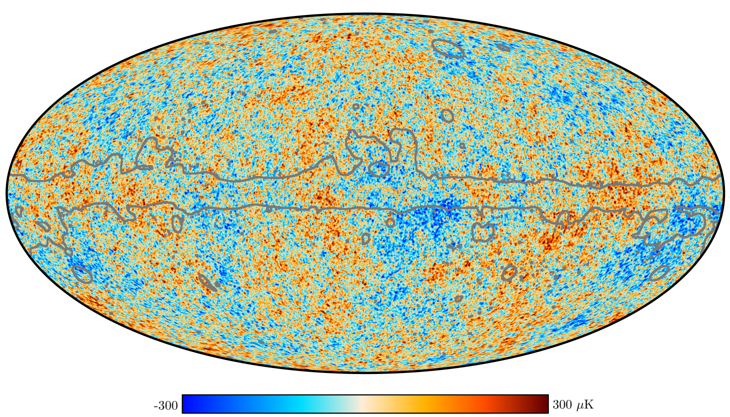
Quantum gravity

Outstanding Questions or Why we need BSM ?

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



SM + gravity ≠ 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 Λ >> v)?

E

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

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

Λ

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

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

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

Hierarchy problem !

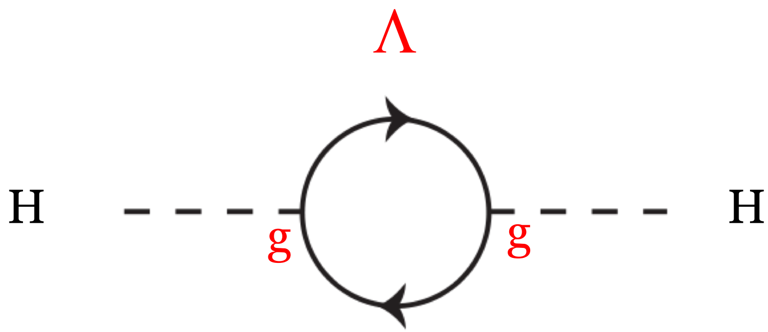
Violation of unitarity !

SMEFT and hierarchy problem

Fine-tunning ?

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

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

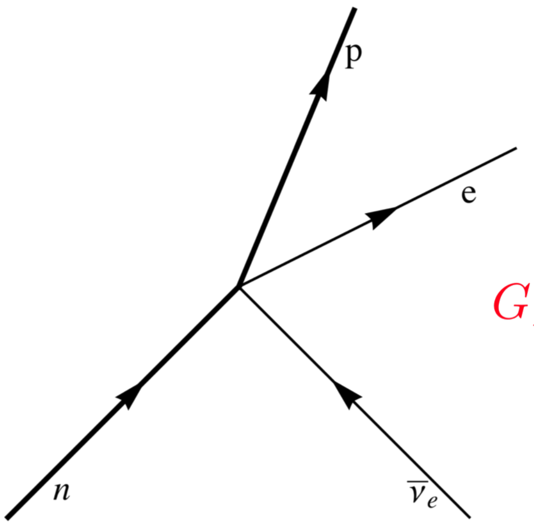


$$\mu'^2 = \mu^2 + \frac{g^2}{16\pi^2}\Lambda^2$$

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

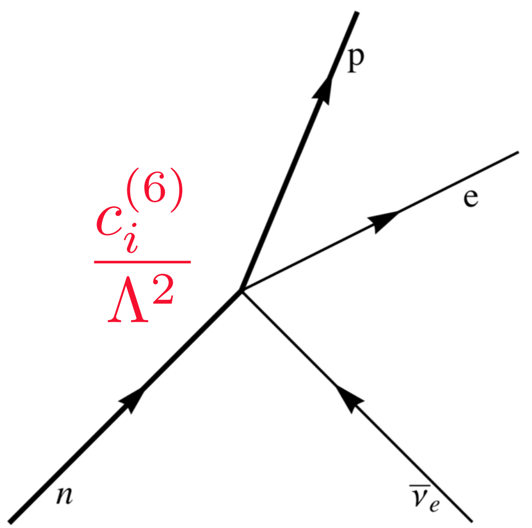


$$G_F \sim \frac{1}{M_W^2}$$

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

SMEFT would predict its own destruction

NP can induce similar non-renormalizable interactions



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

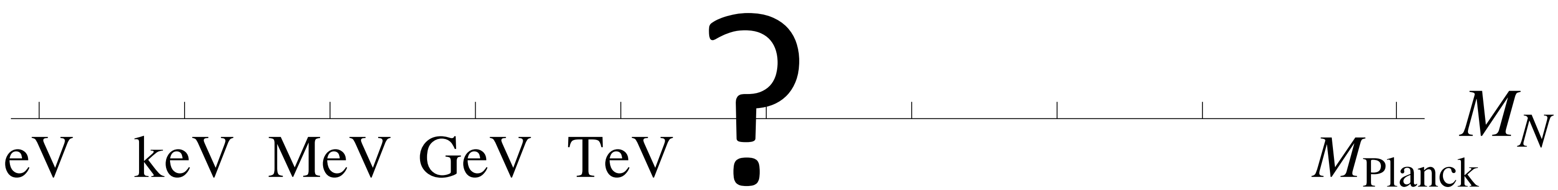
New physics must show up before unitarity is violated

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

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 $\dfrac{c_i^{(d)}}{\Lambda^{d-4}}$ -> degeneracy between c and Λ

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

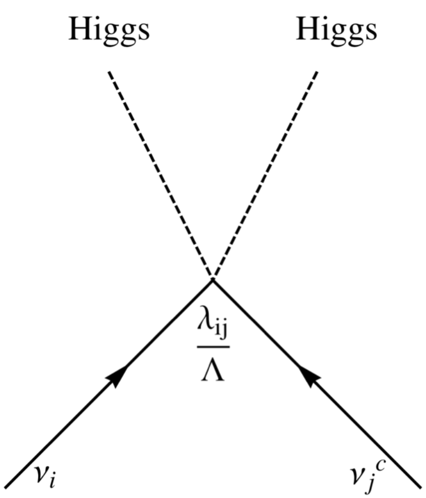


$c_i^{(d)} \leq 1$ upper bound on Λ

SMEFT @ d=5

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

$\Delta L = 2$



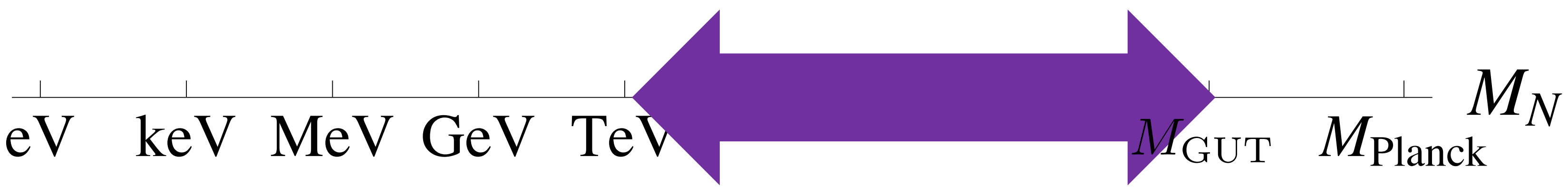
$$\mathcal{O}^{(5)} = \frac{c_{ij}^{(5)}}{\Lambda}\bar{L}_i H (H L_j)^c + h.c. \rightarrow \overline{\nu}_L \frac{m_\nu}{2}\nu_L^c + h.c.$$

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

Neutrino mediator mass scale ?

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

$$c^{(5)} \in [Y_e^2, 1]$$



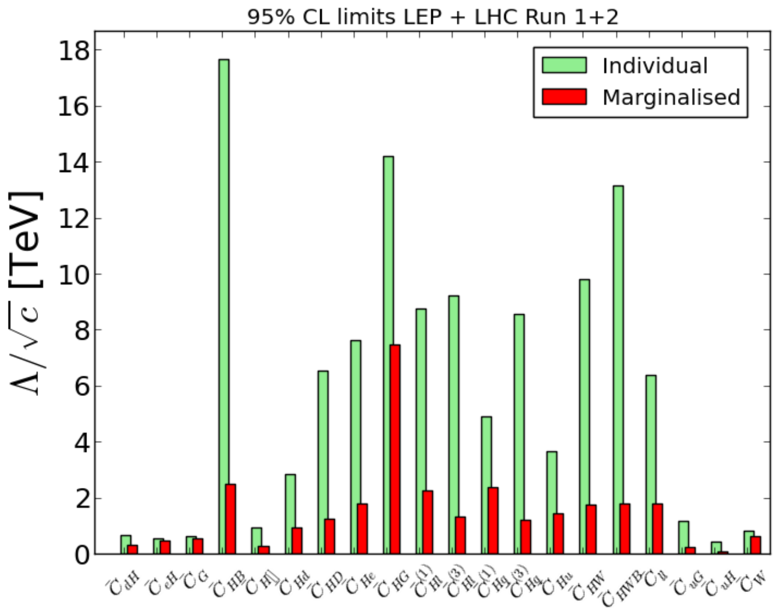
There is a model independent prediction of this new scale: ββ0ν!

SMEFT @ d=6

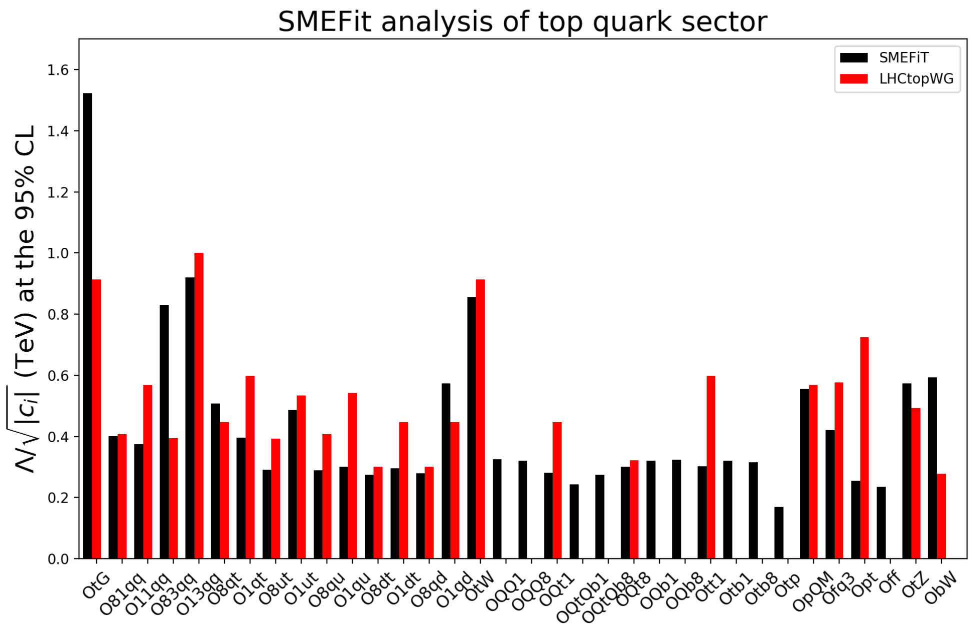
$$\mathcal{L}_{\text{SMEFT}} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)}}_{\text{1 operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda} \mathcal{O}_i^{(6)}}_{\text{63 operators}}$$

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

SMEFT = SM ?



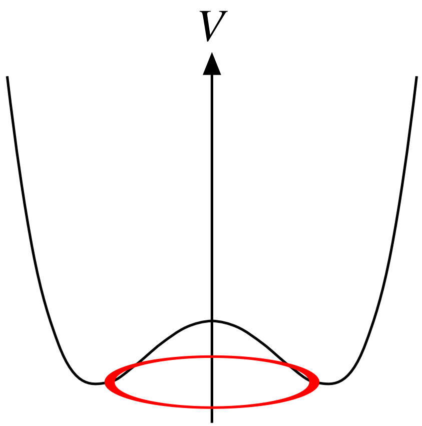
Ellis, Murphy, Sanz, You '18



Hartland et al '19

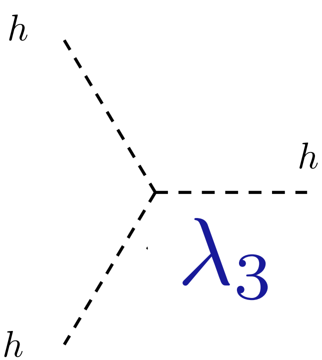
SMEFT and unitarity

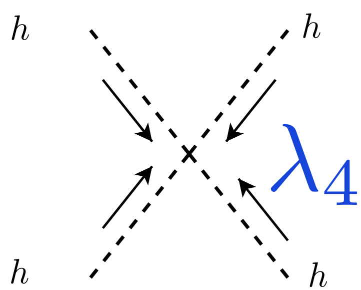
Modifications to higgs self-couplings (higgs potential) still unconstrained



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

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





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

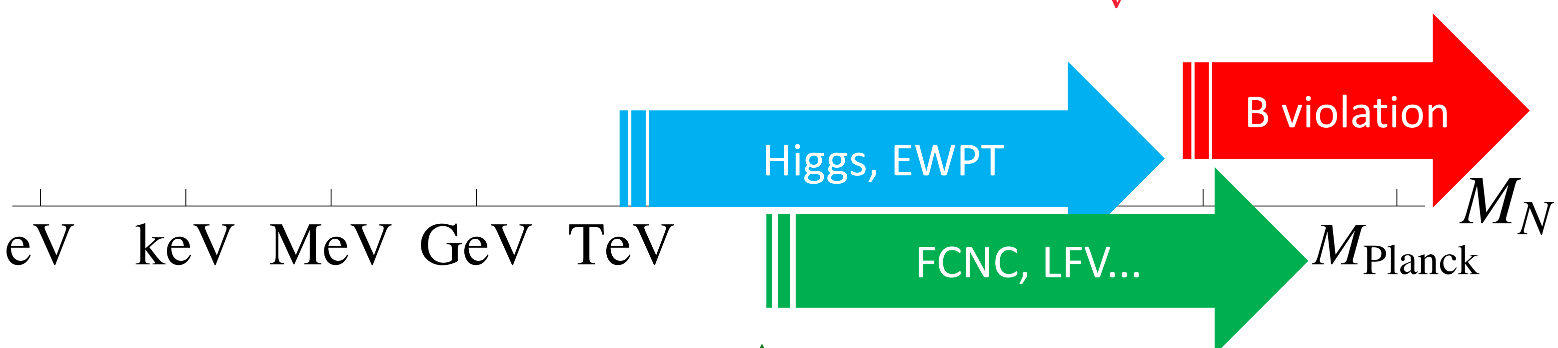
Chang, Luty '19

SMEFT vs Flavour

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

$$\mathcal{L}_{\rm SMEFT} \supset \underbrace{\frac{c^q_{ij}}{\Lambda^2}(\bar{Q}_i\gamma_\mu P_L Q_j)^2}_{\Delta m_K,\Delta m_D,\Delta m_B,\ldots} + \ldots + \underbrace{\frac{c^l_{ij}}{\Lambda^2}\bar{L}_i\sigma_{\mu\nu}\Phi l_j F^{\mu\nu}}_{\mu\to e\gamma,\mathrm{EDMs}\ldots} + \ldots + \underbrace{\frac{c^b_{ijkl}}{\Lambda_B^2}\epsilon_{\alpha\beta\gamma}Q_i^\alpha Q_j^\beta Q_k^\gamma L_l}_{\mathrm{p-decay}}$$

$$\frac{\Lambda_B}{\sqrt{c}} \geq [10^{12} - 10^{13}]\ \mathrm{TeV}$$



$$\frac{\Lambda}{\sqrt{c}} \geq [10^2 - 10^5]\ \mathrm{TeV}$$

SMEFT vs Flavour

BSM flavour puzzle: why SM accidental symmetries?

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

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

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

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

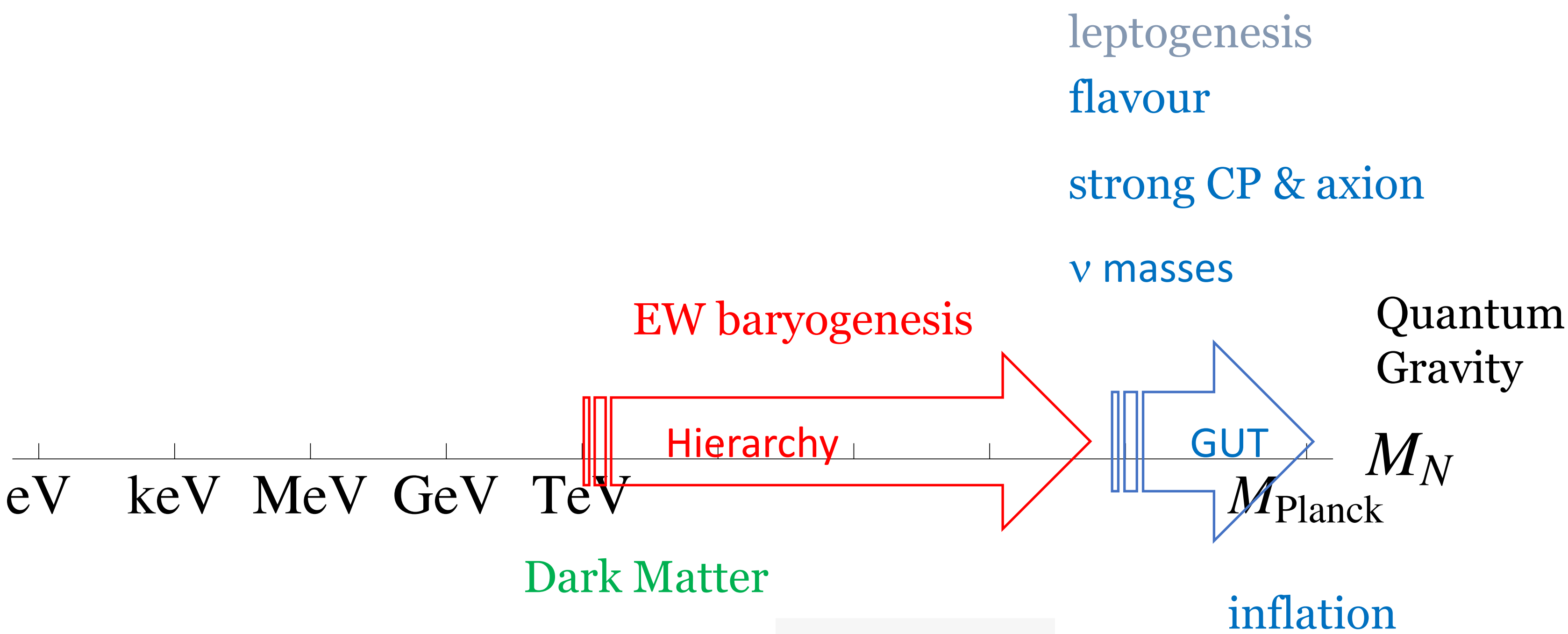
+ Discrete/Global/Gauge symmetries (B, L , ...)

BSM searches should pay important attention to flavour!

The concrete BSM way…

The grand scheme

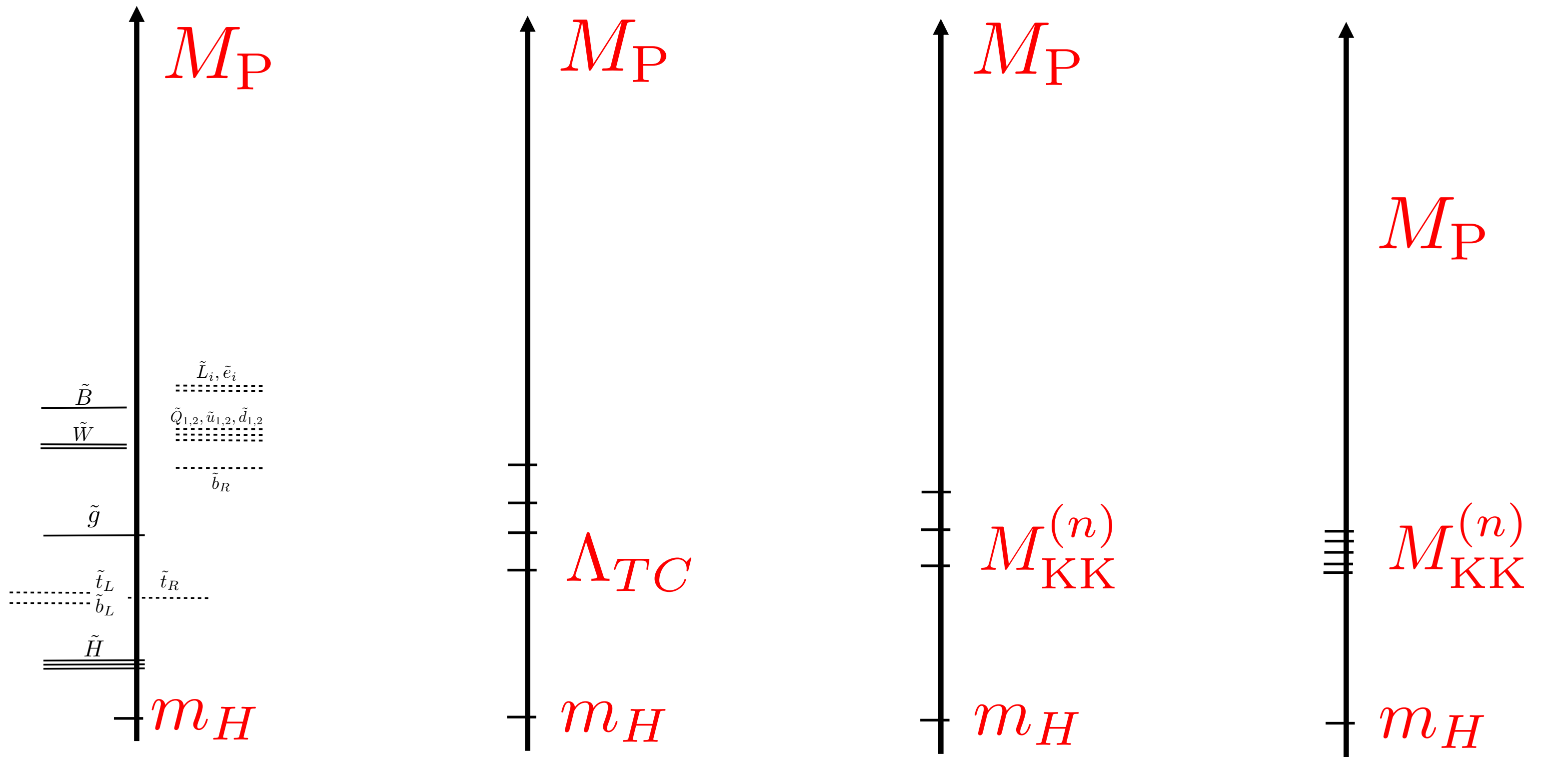
In the “good old days”, we had a grand scheme:



Hierarchy problem and dark matter

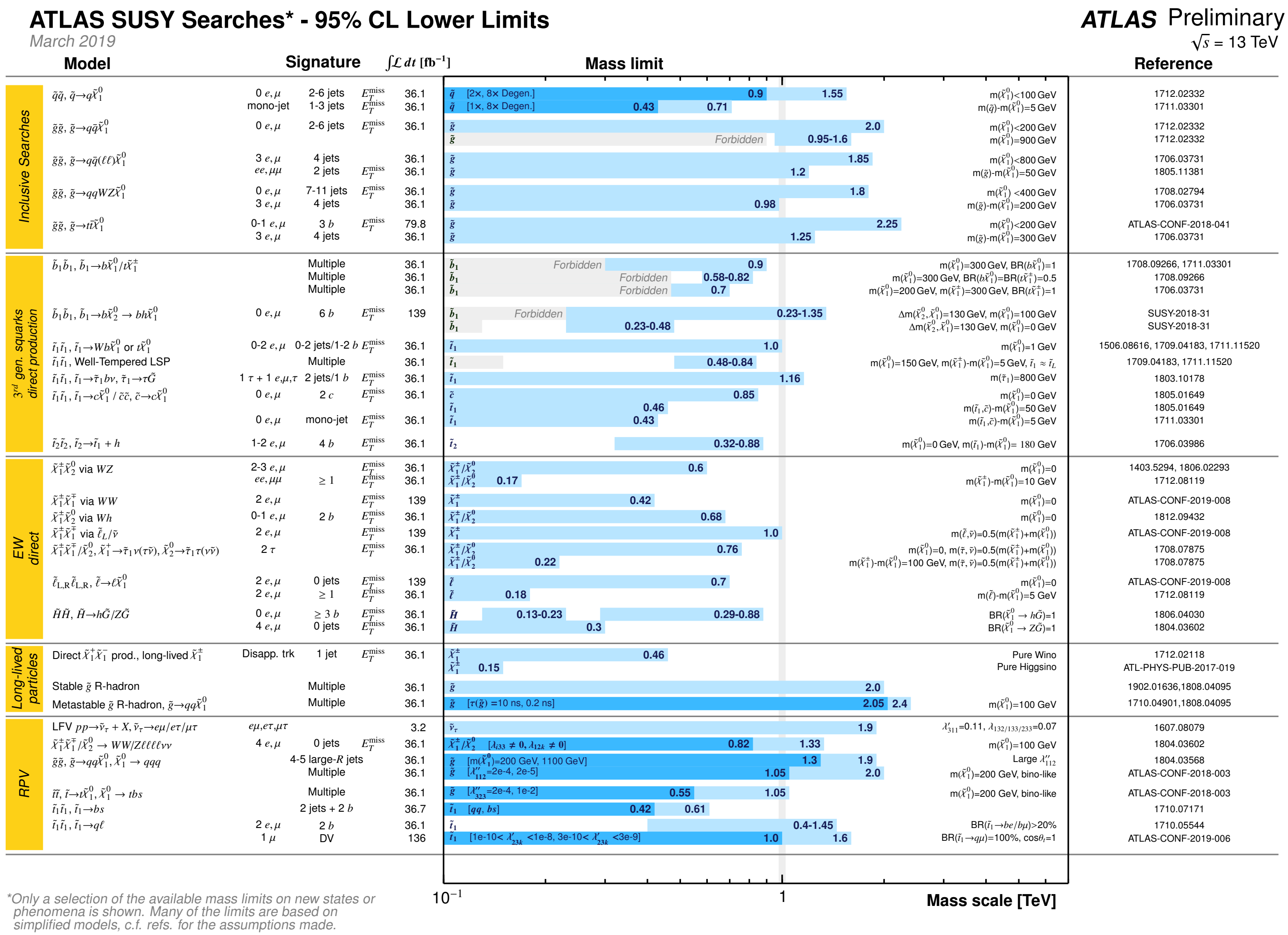
EW Hierarchy problem ?

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

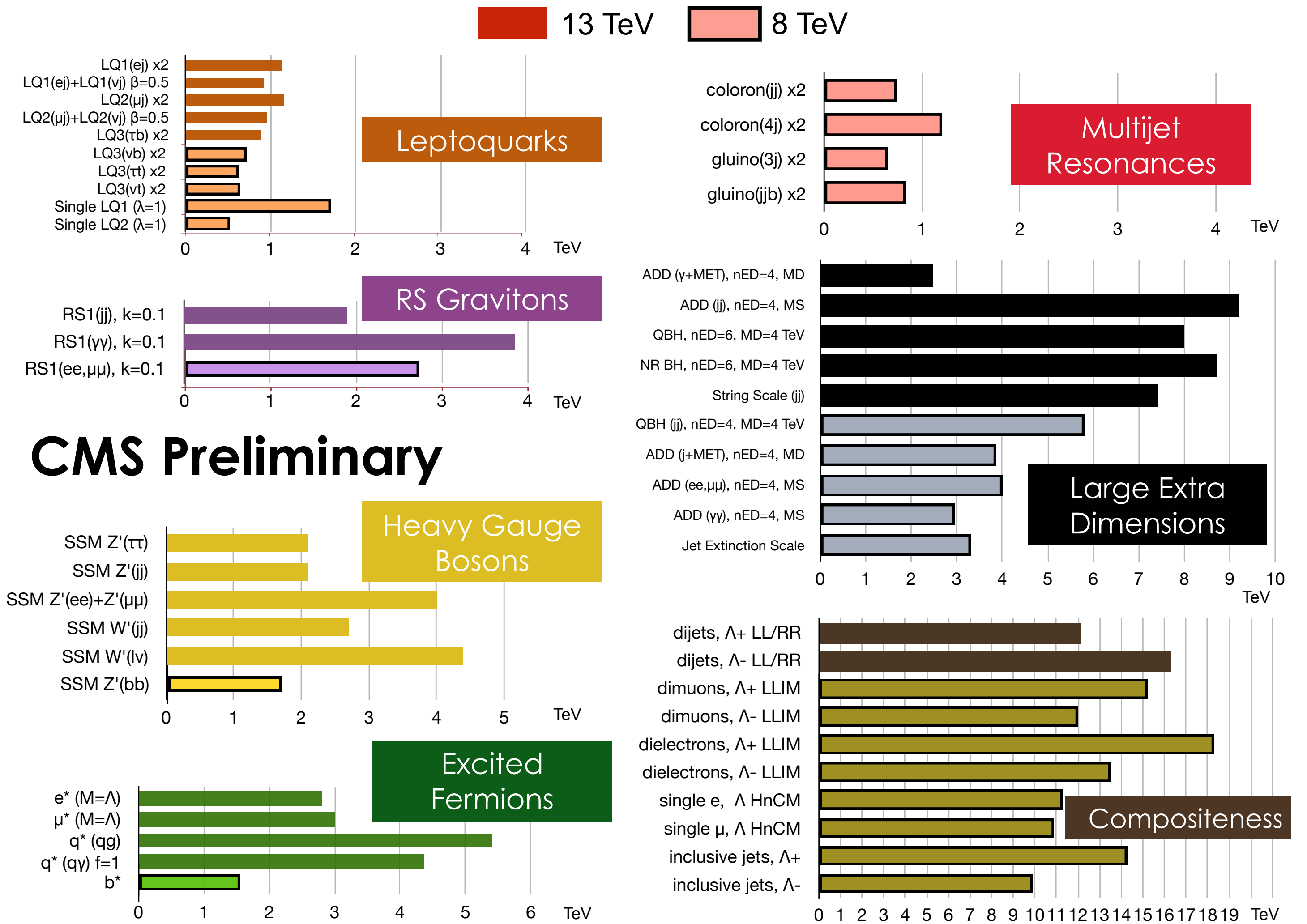


New states at TeV, fine-tune the Little hierarchy, top quark special

LHC EW hierarchy razor



LHC EW hierarchy razor



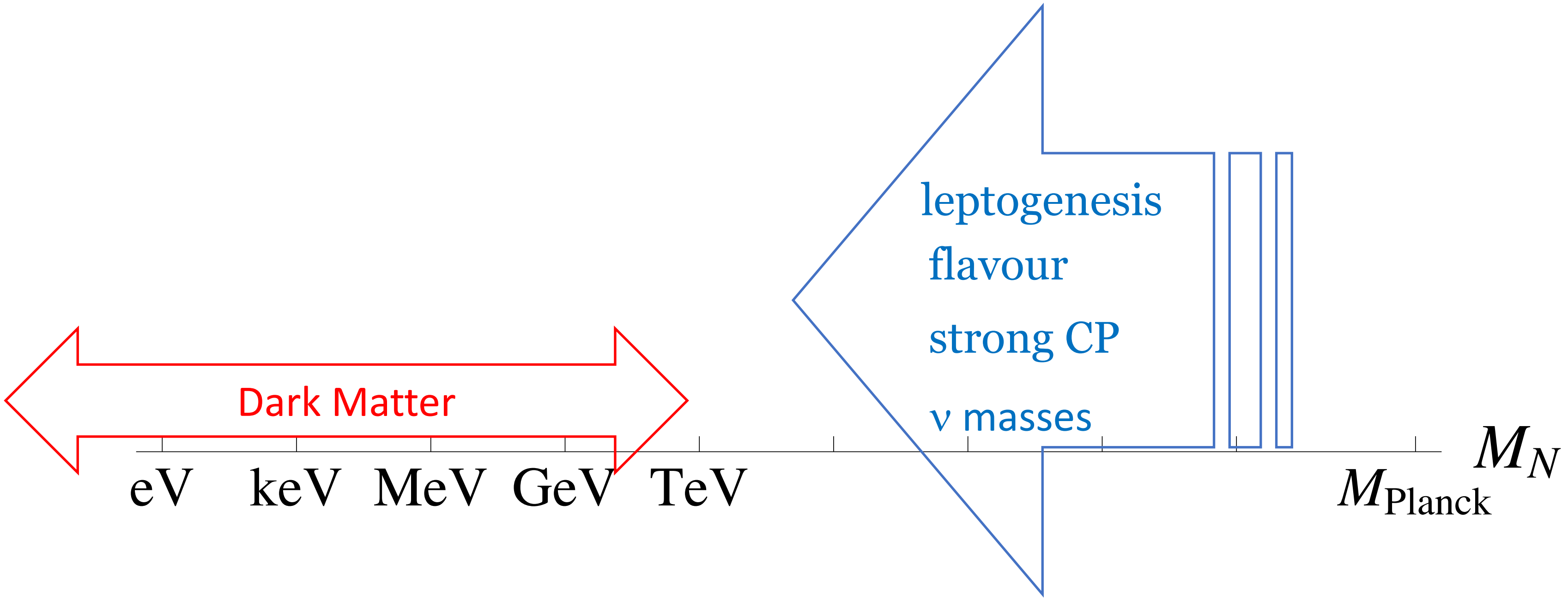
EW Hierarchy Problem ?

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

But O(10-100)TeV still an interesting scale to explore!

Motivational Toolkit beyond EW hierarchy

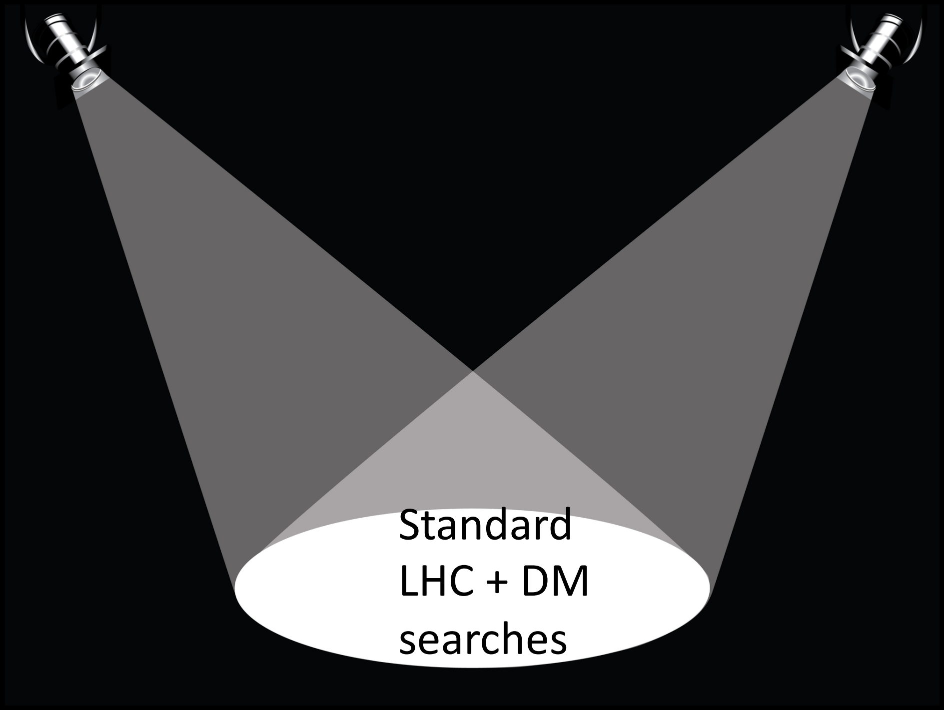
I. Avoid hierarchy problem & testability



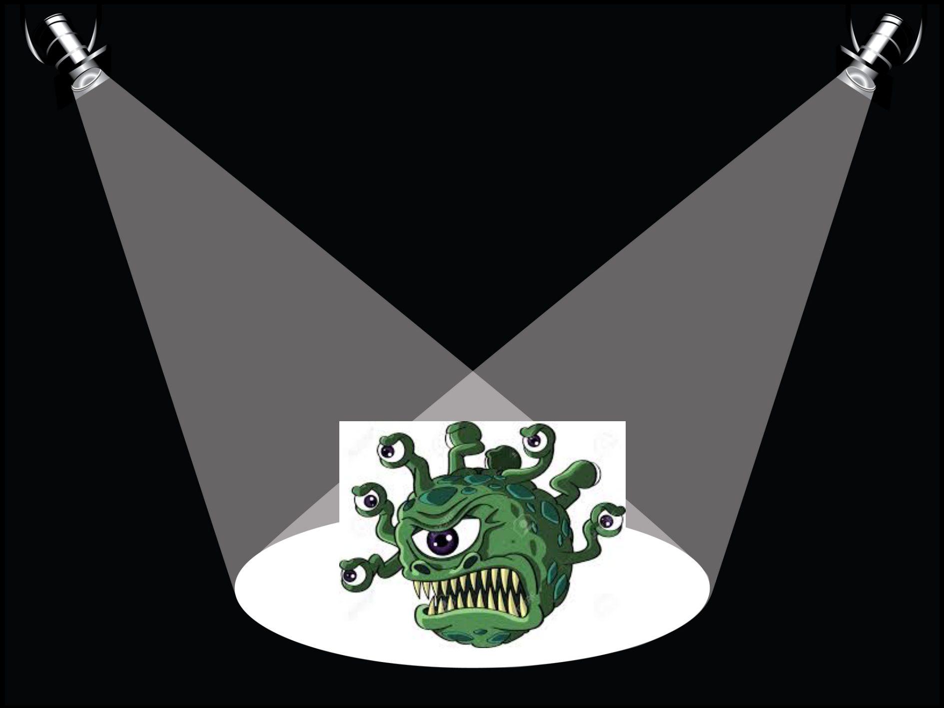
new DM production mechanism (FIMPs, asymmetric Dark Matter…)

changing paradigms: lighter and more feably coupled,

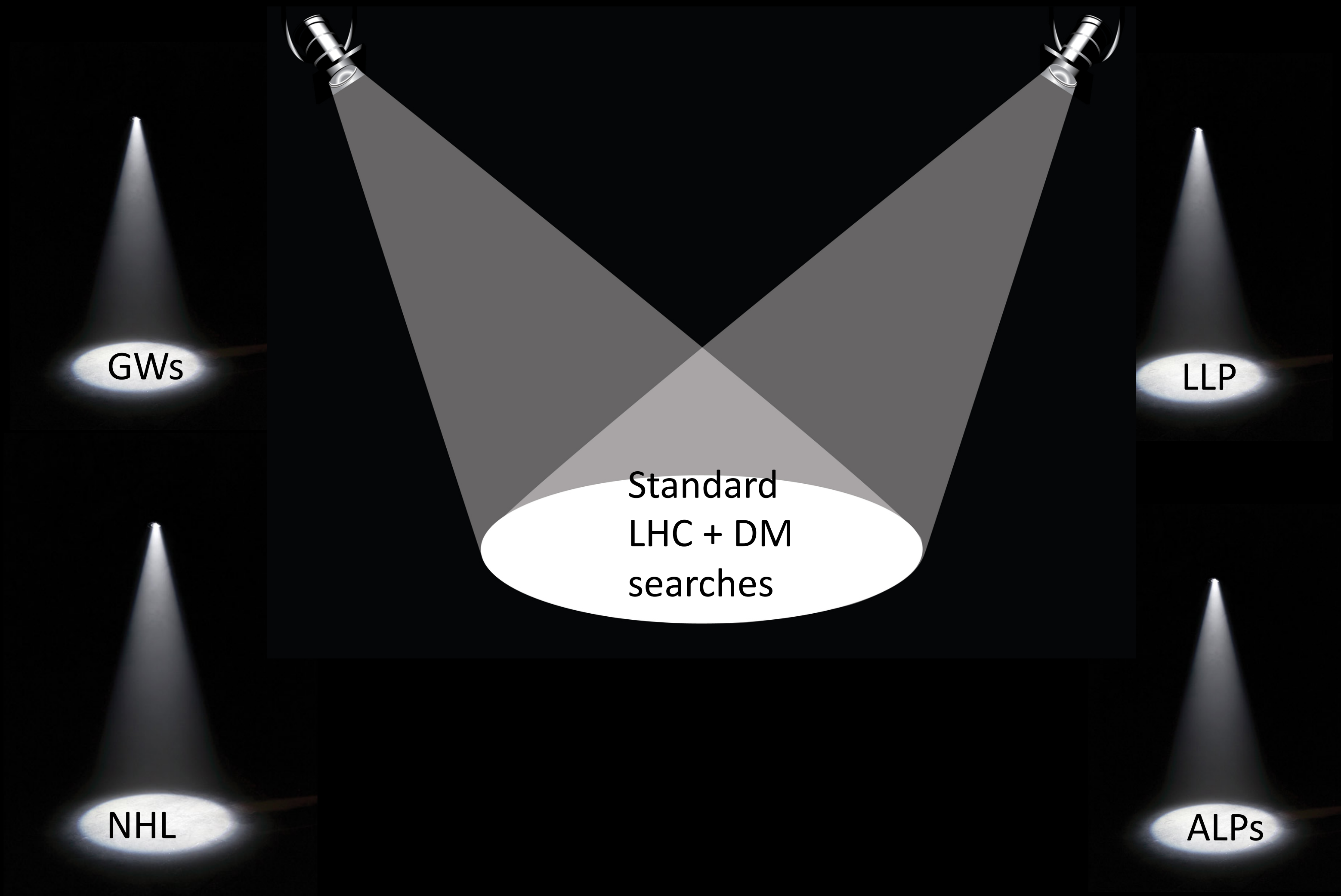
Models for the spotlight ?



Models for the spotlight ?

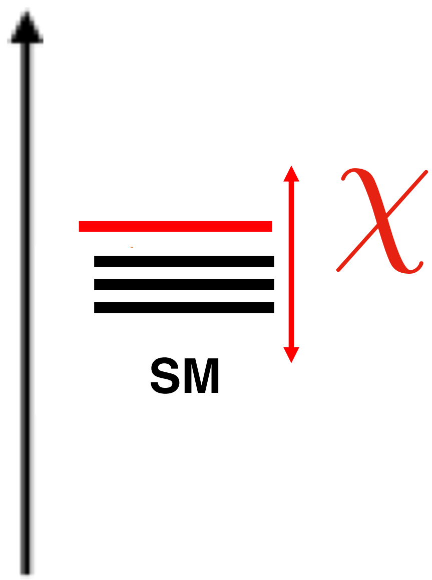


New spotlights for well motivated models



Motivational Toolkit beyond EW hierarchy

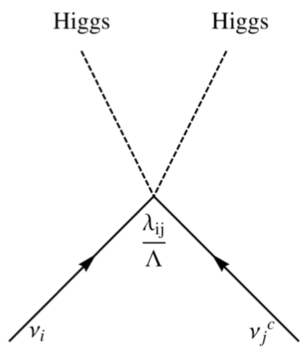
II. Occam's Razor

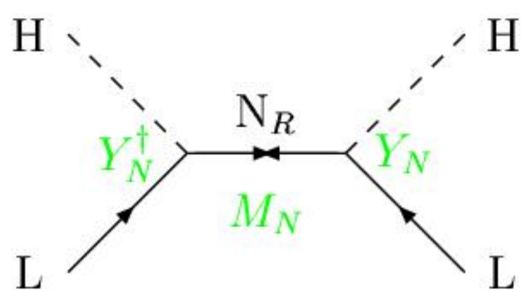


Example I: heavy majorana neutrino<-> type I seesaw

$$\chi = N$$

Origin of neutrino mass:



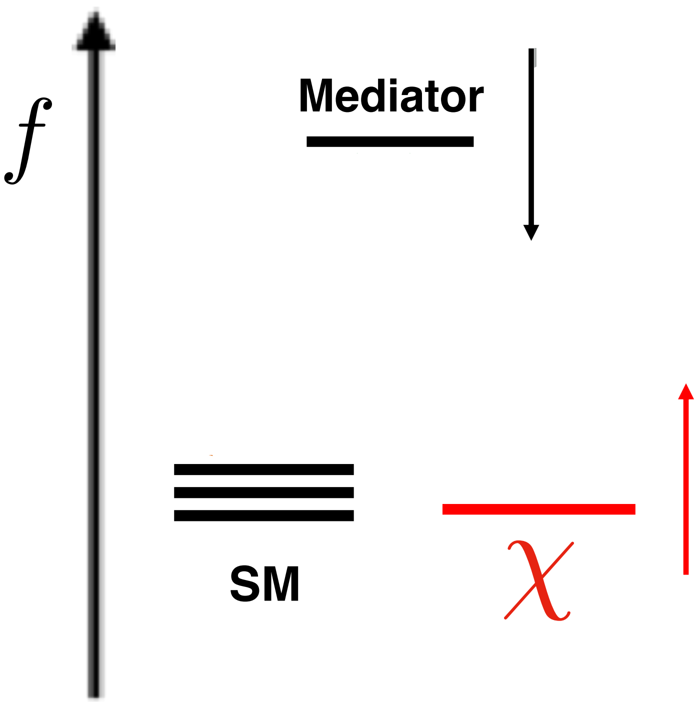


+ Origin of matter-antimatter asymmetry for M_N > O(100)MeV

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

Motivational Toolkit beyond EW hierarchy

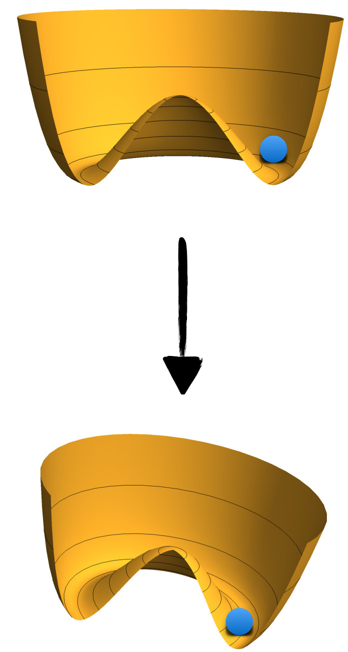
II. Occam's Razor



Axion, ALPs and more generally pNGB: strong CP, dark matter, flavour…

$$\chi = a$$

$$\phi = (f + s)e^{ia/f}$$



Alternatives to QCD anomalous breaking: $m_a^2 f^2 \gg m_\pi^2 f_\pi^2$

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

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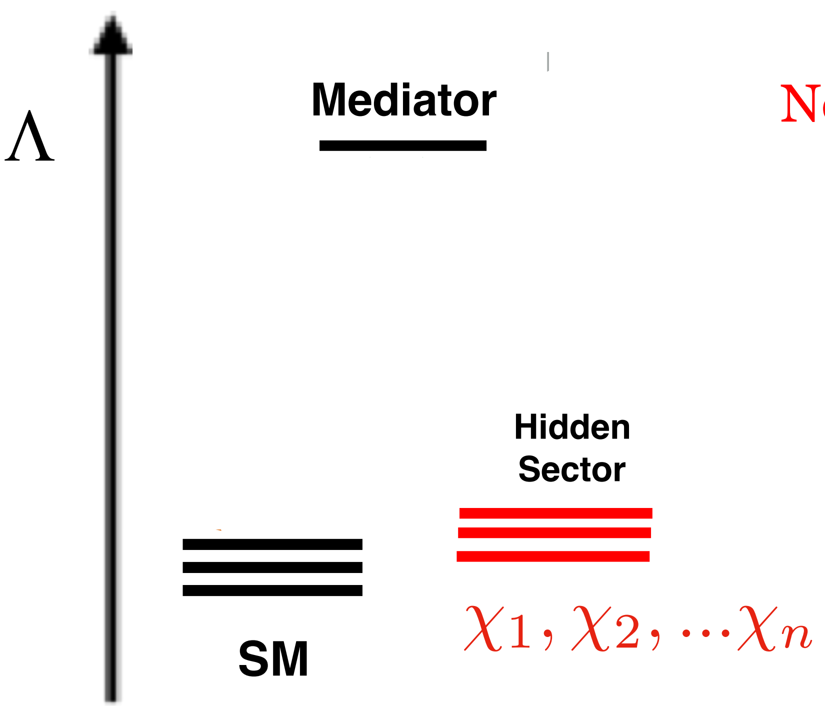
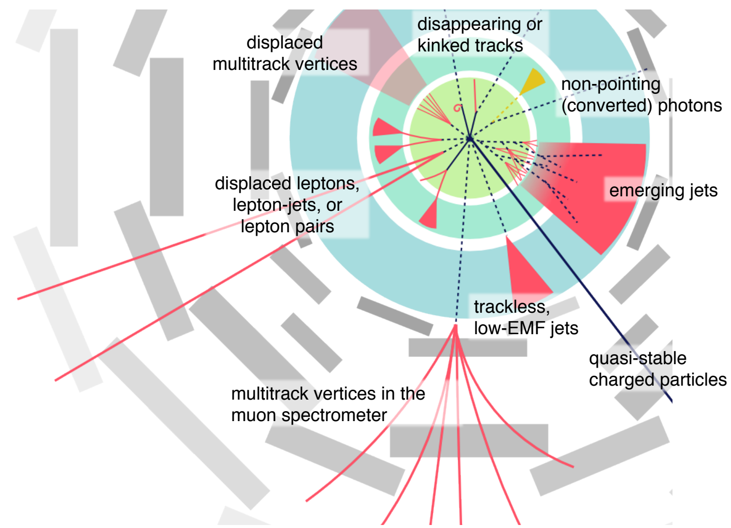
II. Occam's Razor



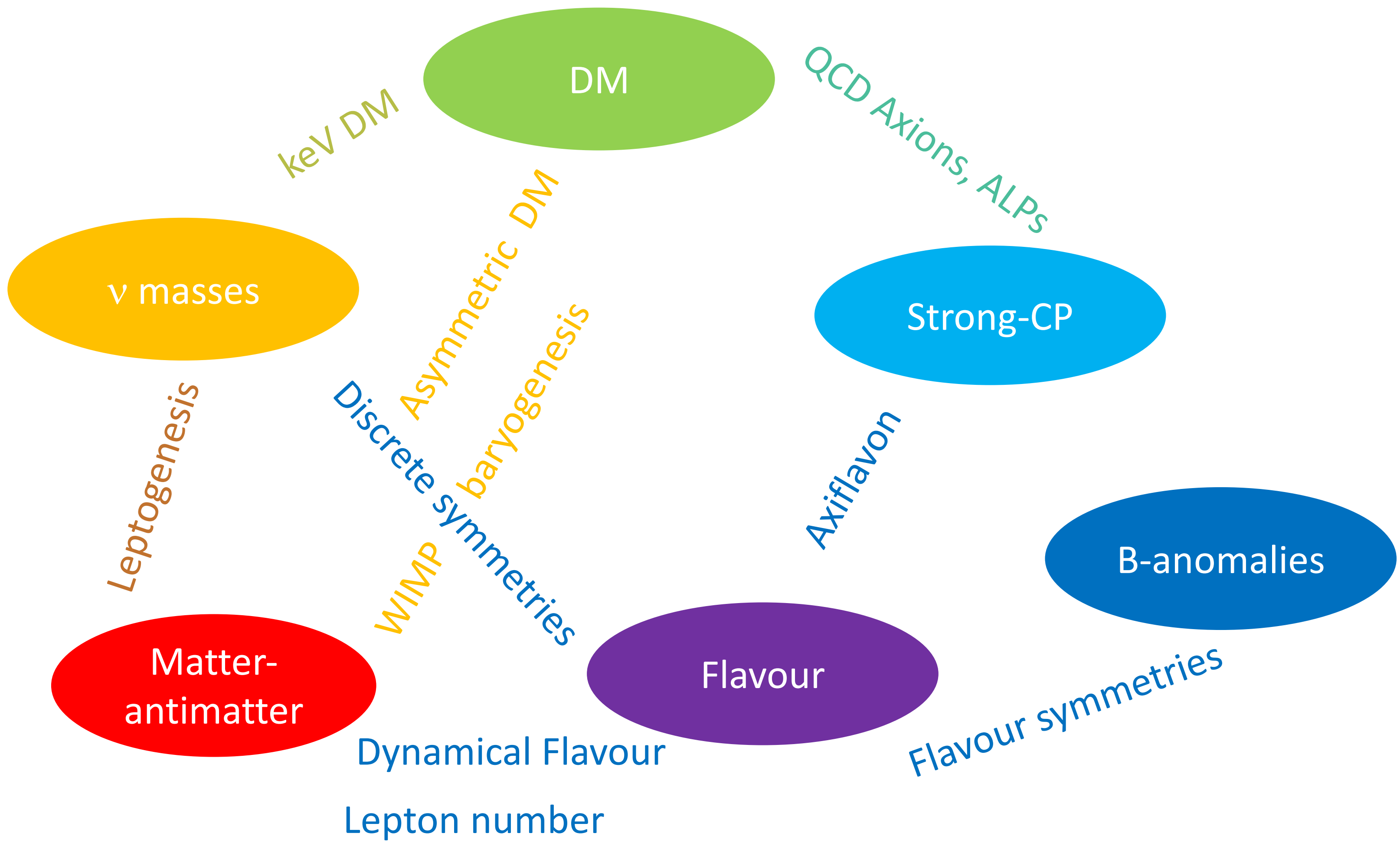
New spotlight: Long-Lived Particles



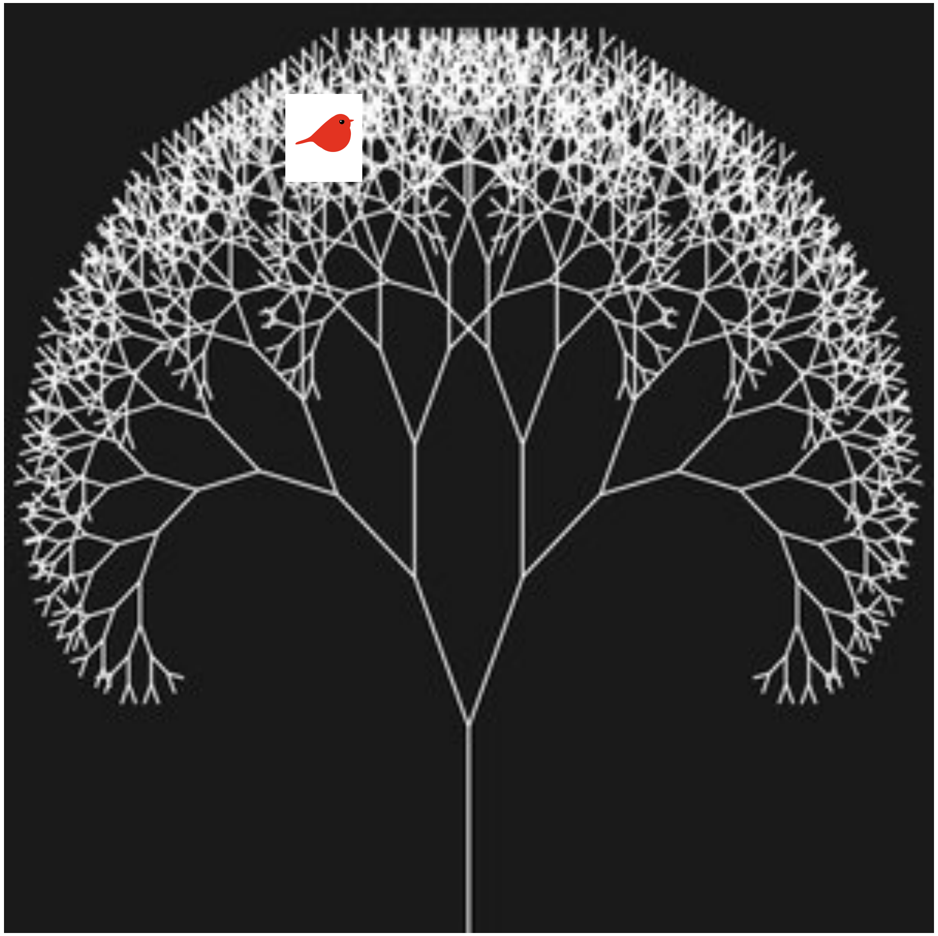
Many models of this type to explain Dark Matter: FIMPs, SIMPs, Mirror worlds…

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