Musings on horizontal gauge symetries

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IP2I – UCBL

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Based on 2307.09595, 2211.05796, 2102.05055 and ongoing works

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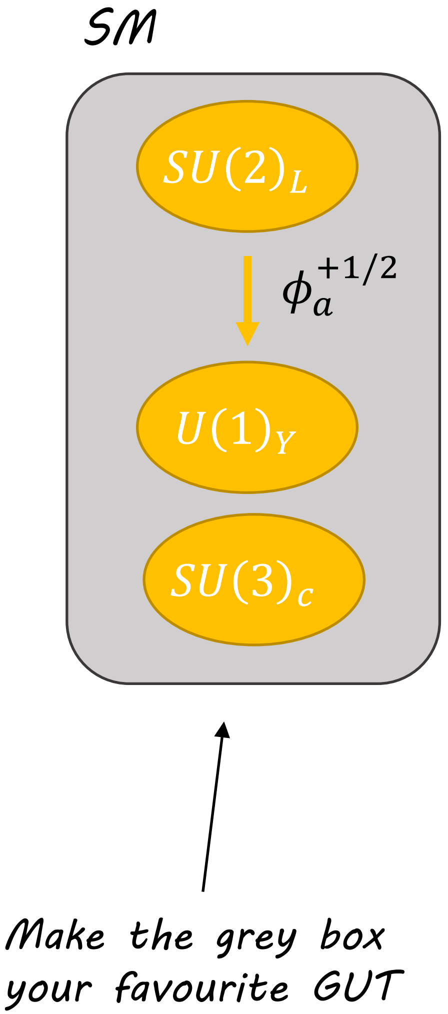
The SM gauge groups and beyond

- The Standard Model gauge content is remarkably anomaly-free and somehow « maximal »
  - →It is surprisingly hard to add more gauge structure without adding fermionic matter in the theory



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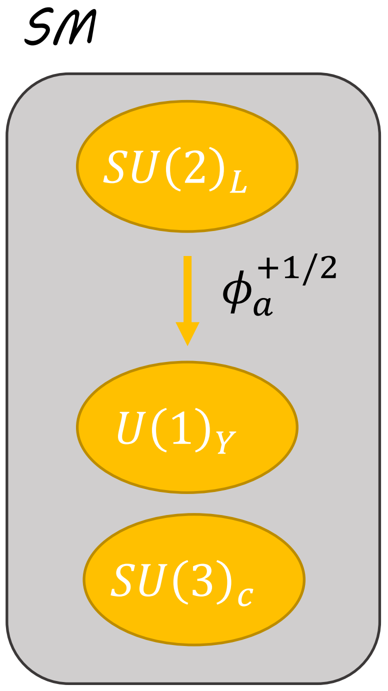
  - →It is surprisingly hard to add more gauge structure without adding fermionic matter in the theory

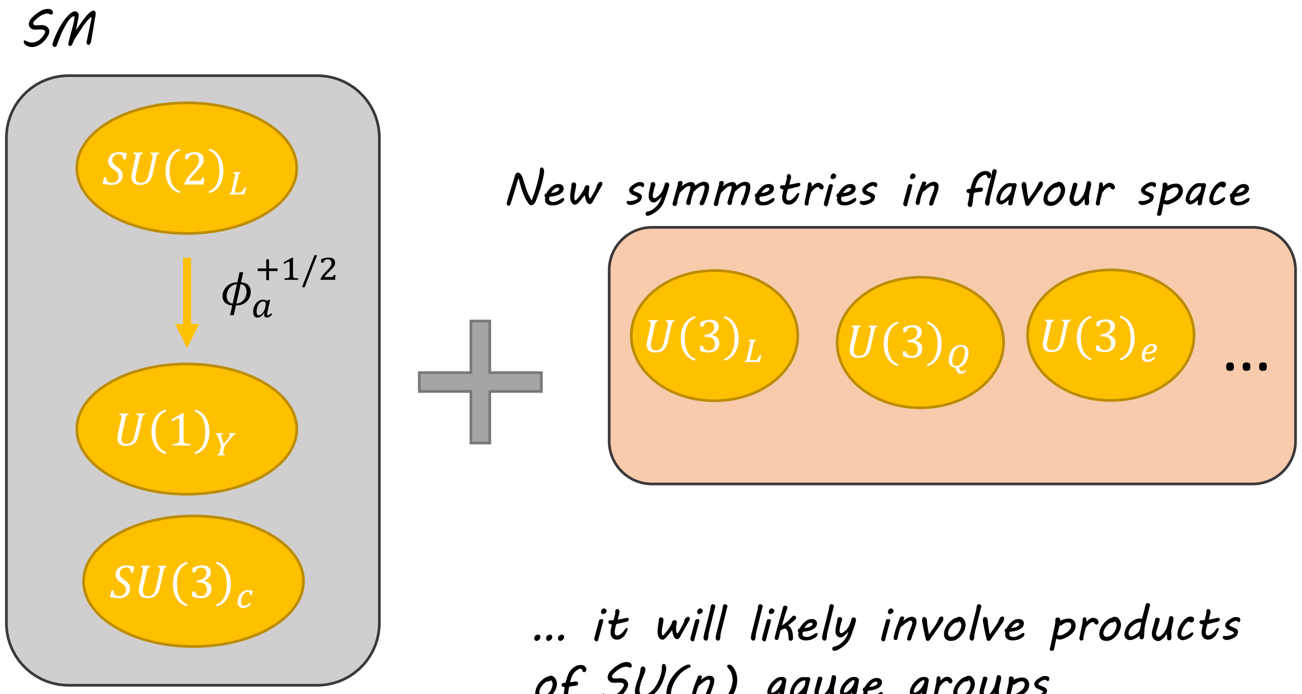
- The gauge structure is constraining enough to lead to several "accidental" symmetries into the final theory
  - →Custodial symmetry
  - → Tree-level baryon and lepton number conservation
  - →No Majorana mass terms

→How can I add gauge structures without increasing the fermionic content ?



Horizontal gauge symetries

- The SM has a large global $U(3)^5$ symmetry group
  - →broken by the Yukawa interactions
- New « horizontal gauge symmetries », acting mostly in flavour space
  - → Will likely adds new structures, both in the fermion and scalar sector of the UV theory



… it will likely involve products of $SU(n)$ gauge groups

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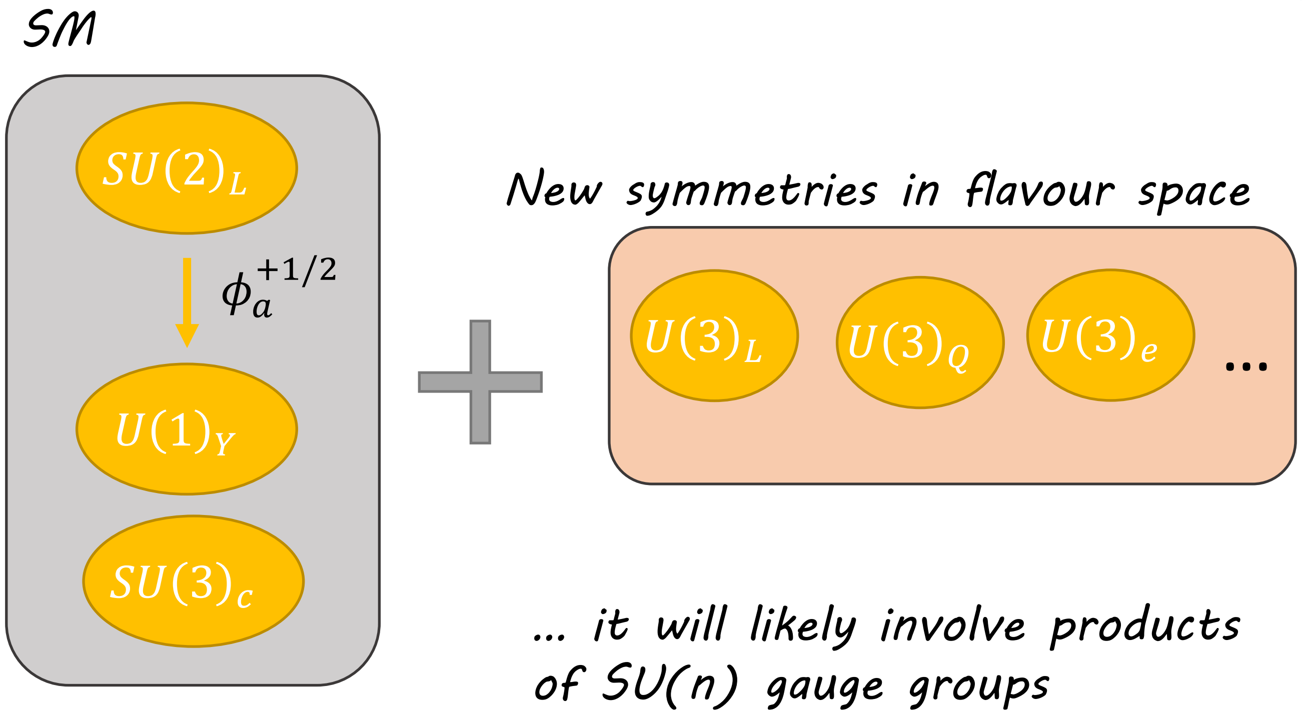

Generate new accidental symetries

Structure in the Yukawa interaction (flavour)

Structure for NP processes (flavour transfers)

Horizontal gauge symmetries

- The gauge coupling itself is completely free and we have little guidance on its value
  - → Small gauge couplings possible, and thus light new bosons $M_V \propto g_f \, v_S$
  - → Alternative approaches to set this coupling interesting to explore (AS, etc…)

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  - → Small gauge couplings possible, and thus light new bosons $M_V \propto g_f\, v_S$
  - → Alternative approaches to set this coupling interesting to explore (AS, etc…)
- Anomaly cancellation a stringent requirement (may lead to extra required fermions)

$$\sum_{i=1}^{3}(6F_{Q_i}+2F_{L_i}-3F_{u_i}-3F_{d_i}-F_{e_i}-F_{\nu_i})=0. \quad \sum_{i=1}^{3}(F_{Q_i}+3F_{L_i}-8F_{u_i}-2F_{d_i}-6F_{e_i})=0, \quad \sum_{i=1}^{3}(3F_{Q_i}+F_{L_i})=0,$$

$$\sum_{i=1}^{3}(F_{Q_i}^2-F_{L_i}^2-2F_{u_i}^2+F_{d_i}^2+F_{e_i}^2)=0, \quad \sum_{i=1}^{3}(2F_{Q_i}-F_{u_i}-F_{d_i})=0 \quad \sum_{i=1}^{3}(6F_{Q_i}^3+2F_{L_i}^3-3F_{u_i}^3-3F_{d_i}^3-F_{e_i}^3-F_{\nu_i}^3)=0,$$

… for adding a single U(1)

- Of course, gauging the flavour space leads to strong constraint from flavour …

Semi-simple gauge groupes and rectangular symmetries

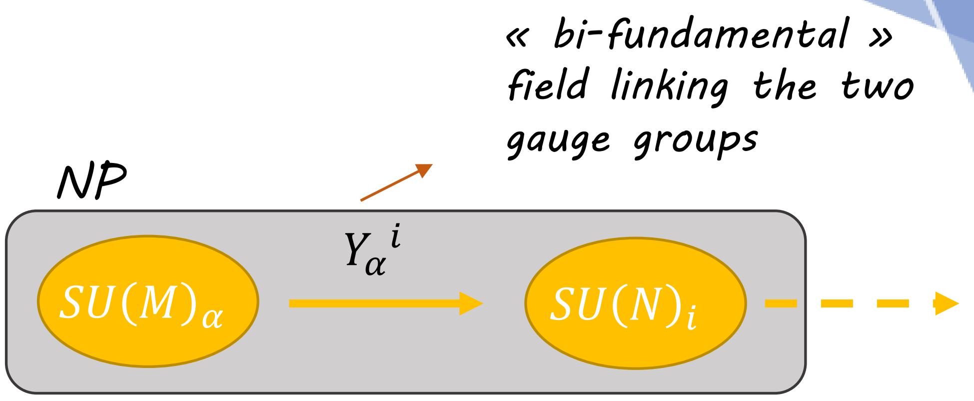
… or what happens when you gauge a big semi-simple gauge group

Based on 2211.05796, 2102.05055 with E. Nardi and C. Smarra

Rectangular gauge groups

- Semi-simple gauge groups of the form $SU(M) \times SU(N)$, with $M > N$

  → Invariance under such gauge groups is very constraining on effective operators in the scalar sector



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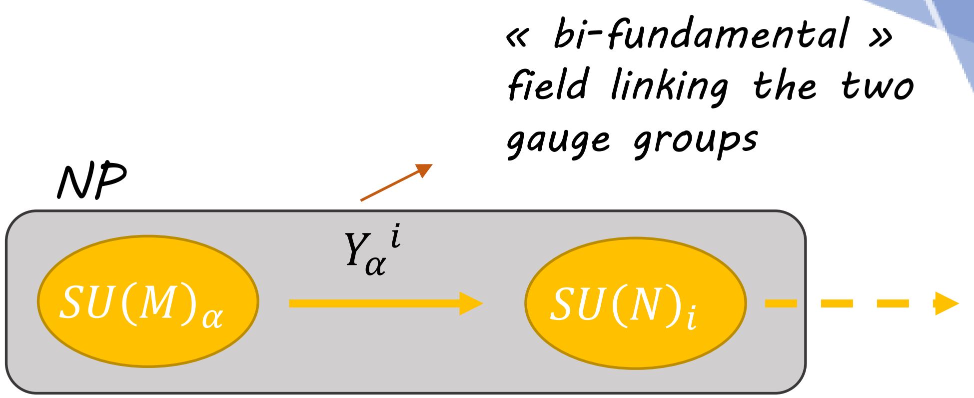

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- The scalar fields are rectangular matrices

  → The hermitian terms are quite simple with a structure close to the SM Higgs one

  → Automatically invariants global re-phasing $U(1)$ symmetries

  → Such $U(1)$ are only broken by operators which are non-hermitians

$$Y = \begin{pmatrix} Y_1^1 & \cdots & Y_1^N \\ \vdots & \ddots & \vdots \\ Y_{M-1}^1 & \cdots & Y_{M-1}^N \\ Y_M^1 & & Y_M^N \end{pmatrix}$$

$$T \equiv \mathrm{Tr}\,(Y^\dagger Y)$$

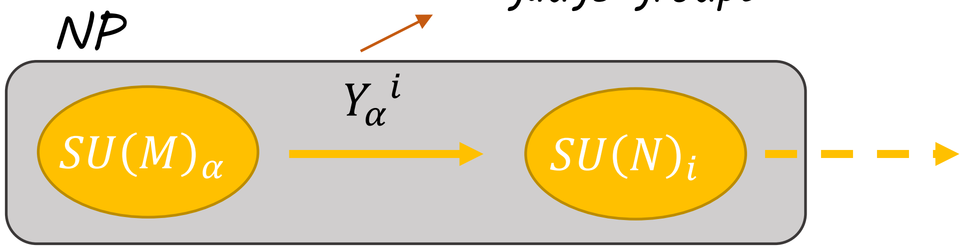
$$\boxed{V(Y) = \kappa\,(T - \mu_Y^2)^2 + \lambda\,A}$$

$$A = \tfrac{1}{2}(T^2 - T_4)$$

$$T_4 \equiv \mathrm{Tr}\,(Y^\dagger Y)^2$$

Rectangular gauge groups

« bi-fundamental » field linking the two gauge groups



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In eigenvalues …

$$T(\hat{Y}) = \sum_{i=1}^{N} y_i^2, \qquad A(\hat{Y}) = \sum_{i<j} y_i^2 y_j^2 .$$

Like a « radius »

Vanishes if a single non-zero y_i

Rectangular gauge groups (2)

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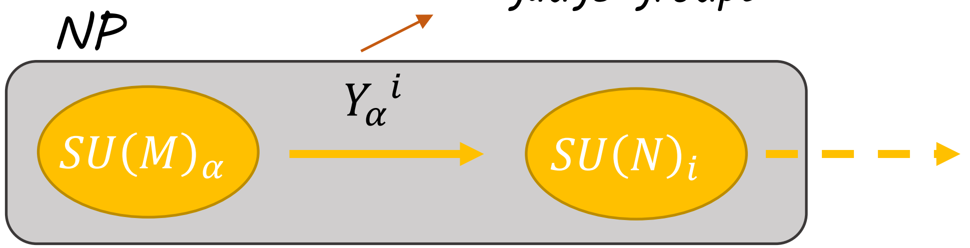


- Non-hermitians operators are very constrained

  → Either form « cycles » of the diagrams or constructed from ϵ-tensors, which have a strong tendency to vanish

$$\epsilon^{\alpha_1\ldots\alpha_M} Y_{\alpha_1,i_1}\ldots Y_{\alpha_M,i_M} \equiv (\epsilon_M Y^M)_{i_1\ldots i_M}$$

Always vanishes when M>N since it must have two redundant i indices (there are only N possibilities, but we must have M>N indices…)

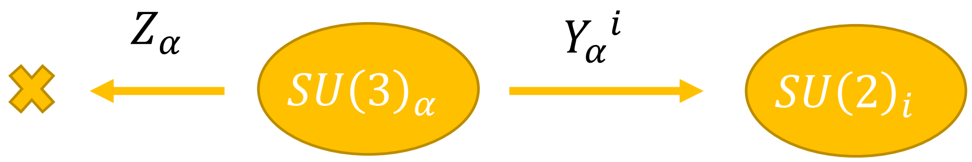
Simliar to $\epsilon^{ab}H_aH_b = 0$ in SM

- Accidental global U(1) symetries (from rephasing of the scalar fields) can easily occur

  → And the non-hermitian U(1) breaking operators can be made naturally small

A first use: shaping the scalar potential

- Rectangular symetries are powerful tools to « shape » the scalar potential of the theory:
  - → A simple $SU(3) \times SU(2)$ example



$$V(Y,Z) = \left(\kappa_Y \left(T_Y - \mu_Y^2\right)^2 + \lambda_Y A_Y\right) + V(Z) + V(Y,Z) + A_3\, \epsilon^{\alpha_1\alpha_2\alpha_3} \epsilon_{i_1 i_2} Y_{\alpha_1}^{i_1} Y_{\alpha_1}^{i_2} Z_{\alpha_3} + \cdots$$

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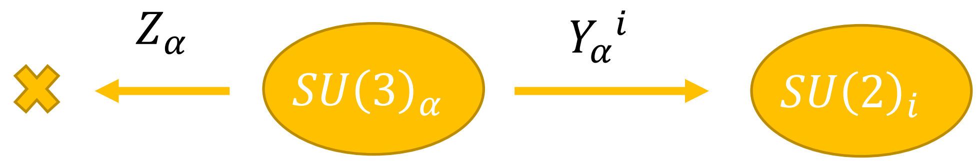

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Negative squared term, Y will pick up a VEV v_Y

Choosing $\lambda_Y < 0$ align the VEVs of Y

$$Y \propto \begin{pmatrix} v_Y & 0 \\ 0 & v_Y \\ 0 & 0 \end{pmatrix}$$

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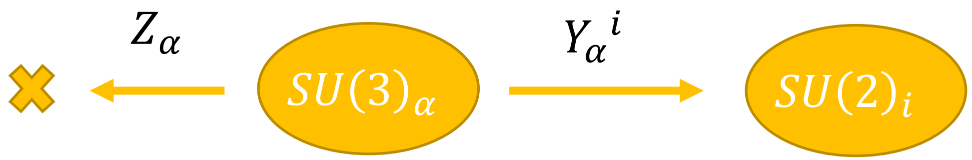

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$\mu_Z^2 > 0$ implies that Z does not pick up a VEV

Choosing $\lambda_Y < 0$ align the VEVs of Y

$$Y \propto \begin{pmatrix} v_Y & 0 \\ 0 & v_Y \\ 0 & 0 \end{pmatrix}$$

Non-hermitian contribution $\propto A_3 \cos(\phi_{A_3})\, v_Y^2\, Z_3$ must always be maximised → triggers a VEV for Z :

(Known setup to generate tiny VEVs)

$$v_{Z_3} \propto \frac{A_3\, v_Y^2}{\mu_Z^2}$$

A second use: flavour symmetries and axions

- Very well protected global U(1) symmetries have a range of applications, and can be useful to generate axion

$$V(a,\pi^a) = -m_\pi^2 f_\pi^2 \cos\left(\frac{\pi}{f_\pi}\right) \cdot \; +(PQ\ breaking\ terms)$$
$$+\frac{1}{2}\frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2} a^2 \cos\left(\frac{\pi}{f_\pi}\right) + \mathcal{O}\left(\frac{a^3}{f_a^3}\right)$$

→ Stringent criterium on the Peccei-Quinn symmetry (PQ): it must be endow with a $U(1)_{PQ} \times SU(3)_c^2$ anomaly, while being protected in effective operators up to dimension ∼10

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- The PQ « quality problem » thus requires an very-well protected global symmetry

→We can use a rectangular gauge group to do the job !

→That means charging quarks under the rectangular gauge groups, leading to two main problems

Avoid anomalies (we must be careful with the quarks representations)

Fully break the horizontal gauge group → must include more scalar fields, thus leading to more possible non-hermitian terms

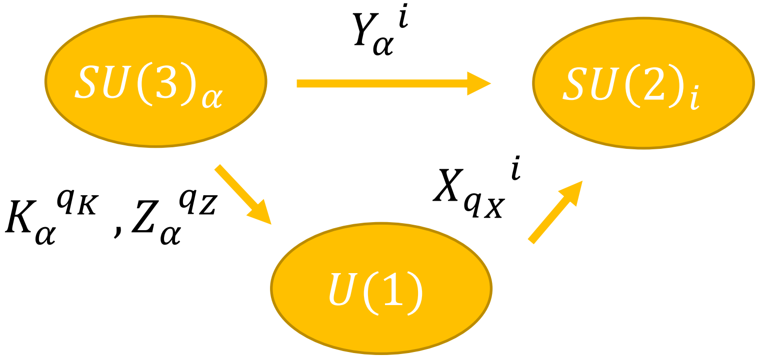
An explicit example

- Goal : Build an horizontal gauge group model reproducing the SM fermion mass hierarchies AND preserving a high-quality accidental PQ global symmetry solving the strong CP problem

→ Extra $U(1)$ needed to ensure simultaneously a QCD anomaly and non-zero quark masses

→ Need new VL pairs for the quark mass generations

→ Standard 2HDM Higgs structure to generate the axion



$$\mathcal{M}_u = \begin{array}{c} \begin{array}{ccccccc} u_R & u_R & t_R & U_R & U_R & U_R & Q_R \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & v & 0 & 0 & z_1 \\ 0 & 0 & 0 & 0 & v & 0 & z_2 \\ 0 & 0 & 0 & 0 & 0 & v & z_3 \\ 0 & 0 & v & 0 & 0 & 0 & M \\ \Lambda_u & 0 & x_1^* & y_1^* & 0 & 0 & 0 \\ 0 & \Lambda_u & x_2^* & 0 & y_2^* & 0 & 0 \\ x_1 & x_2 & \Lambda_t & z_1^* & z_2^* & z_3^* & v \end{pmatrix} \end{array} \begin{array}{c} \\ q_L \\ q_L \\ q_L \\ Q_L \\ U_L \\ U_L \\ T_L \, , \end{array}$$

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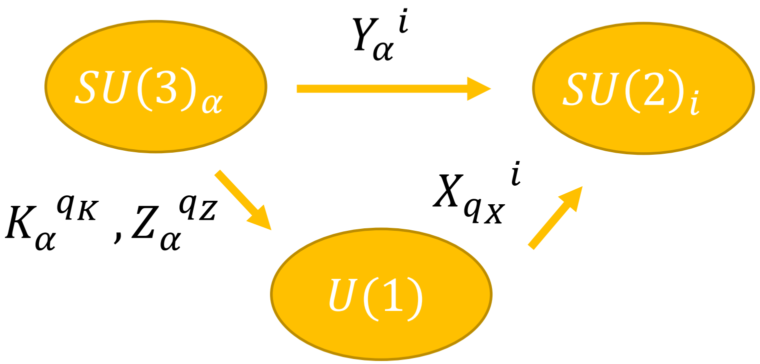

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✓ It works !

✓ VEVs hierarchies arise naturally from the structure of the potential

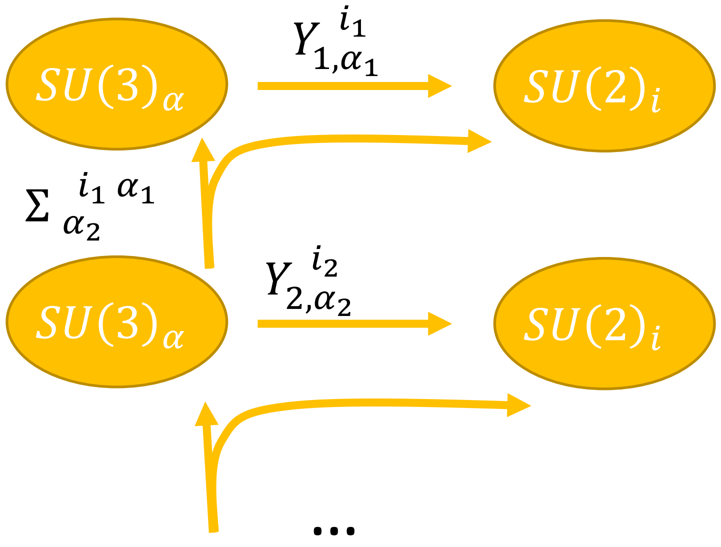
✗ Several new fields required, including « redundant » scalar fields

An other funny possibility, creating clockworks

- Start from a theory with long « quiver-like » chains of gauge groups

  →The scalar sector link each gauge groups together

  → The renormalisable non-hermitian part of scalar potential is extremely constrained with only terms of the form :



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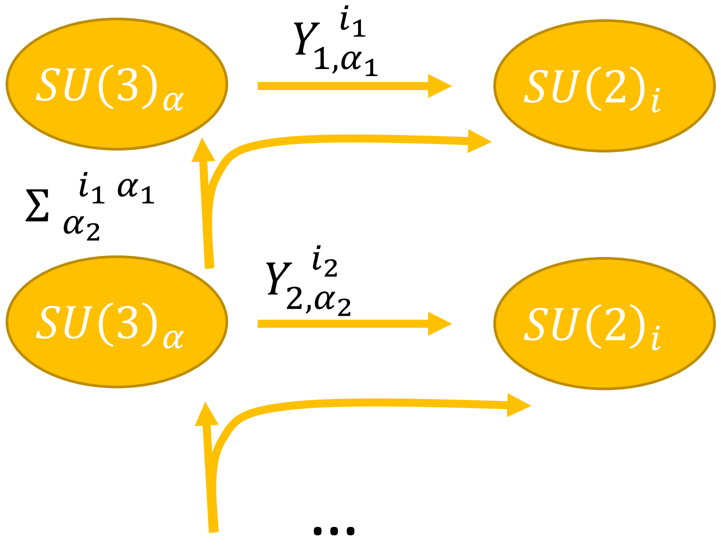
These are the only allowed non-hermitian terms !

$$V \supset \sum_{p=2}^{n} (\epsilon_3 \epsilon_2 Y_{p-1}^2 \Sigma_p)^{\alpha_p i_p} Y_{p_{\alpha_p i_p}}$$



The residual PQ symmetry, presents typical clockwork-like charges

$$\tilde{\mathcal{X}}_{Y_p} = (-2)^p \qquad \tilde{\mathcal{X}}_{\Sigma} = 0$$

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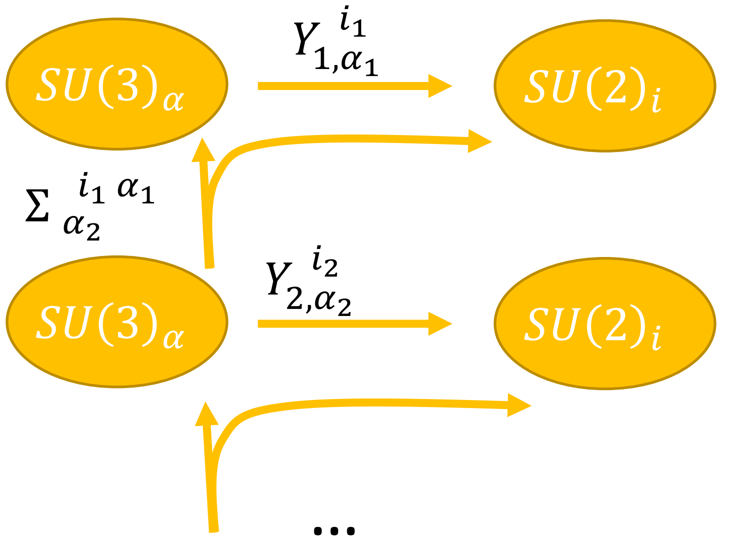

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$$V \supset \sum_{p=2}^{n} (\epsilon_3\epsilon_2 Y^2_{p-1}\Sigma_p)^{\alpha_p i_p} Y_{p_{\alpha_p i_p}}$$

The VEVs of each fields can decrease as a power-law since each gear in Y^2_{p-1} induces a linear term for Y_p

$$(\epsilon_3\epsilon_2 Y^2_{p-1}\Sigma_p)^{\alpha_p i_p} Y_{p_{\alpha_p i_p}}$$

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Flavoured horizontal symmetries and the flavour problem

SU(2) flavour gauge groups

- Starting point: add a new SU(2) gauge group in the SM, acting on flavour space
  - → The « charged» SM fermion can be either part of a doublets or a triplet
  - → Only the mixed $SU(2)_f^2 \times U(1)_Y$ anomaly is non-zero

$$\mathcal{A} = ([C(Q_i) - C(L_i)] - [2C(u_{R,i}) - C(d_{R,i}) - C(e_{Ri})])$$

- In absence of new low-energy fermions, there is a finite (and quite small) number of possible combination !
  - →Left-handed (or right-handed) : Q_i, L_i (or $d_{R,i}, u_{R,i}$, $e_{R,i}$)
  - →Lepton (or baryon) : $Q_i, d_{R,i}, u_{R,i}$ (or $L_i, e_{R,i}$)
  - →SU(5)-motivated $Q_i, u_{R,i}$, $e_{R,i}$ (or $L_i, d_{R,i}$)

Masses and textures (1)

- The presence of $SU(2)_f$ implies that the fermion mass matrices have a structure: let us focus on a left-handed model with Q_i, L_i
  - →We introduce δY_i , a $SU(2)_f$ spurion
  - →In the most generic case, this does not distinguish first and second generation

$$L \supset y_d^\alpha \delta Y_i \bar{Q}^i \cdot H\, d_{\boxed{R,\alpha}} + \tilde{y}_d^\alpha \delta Y^{\dagger,i} \epsilon_{\boxed{ij}} \bar{Q}^j \cdot H\, d_{R,\alpha} + Y_{3,d} \bar{Q}_3 \cdot H\, b_{\boxed{R}}$$

α are generation indices but NOT gauge indices

i,j are $SU(2)_f$ gauge indices

We use the $U(3)_f$ global reparametrisation for $d_{R,\alpha}$

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$$\delta Y_i = (\delta Y, 0)$$

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$$\begin{aligned} L \supset\ & \delta Y(\bar{Q}^1 \cdot H\, (y_d^\alpha d_{R,\alpha}) \\ & -\delta Y\, (\bar{Q}^2 \cdot H\, (\tilde{y}_d^\alpha d_{R,\alpha}) \\ & +Y_{3,d} \bar{Q}_3 \cdot H\, b_R \end{aligned}$$

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We use the $U(3)_f$ global reparametrisation for $d_{R,\alpha}$

Arranging $\delta Y \ll Y_3$ still leads to the same mass scale for first and second generation

Masses and textures (2)

- How can we generate a hierarchy between 1st and 2nd generation ?
  - → Standard approach: add another U(1) factor distinguishing 1st and 2nd
  - → We take a step back and realise that y_d^α and $\tilde{y}_d^\alpha$ are not necessarily independent parameters
  - → Let's consider a simple model with a $SU(2)_f$ breaking scalar S_i and a VL quark

and therefore a new spurion…

$$y_d^\alpha \delta Y_i \, \bar{Q}^i \cdot H \, d_{R,\alpha} \; + \tilde{y}_d^\alpha \delta Y^{\dagger,i} \epsilon_{ij} \bar{Q}^j \cdot H \, d_{R,\alpha}$$

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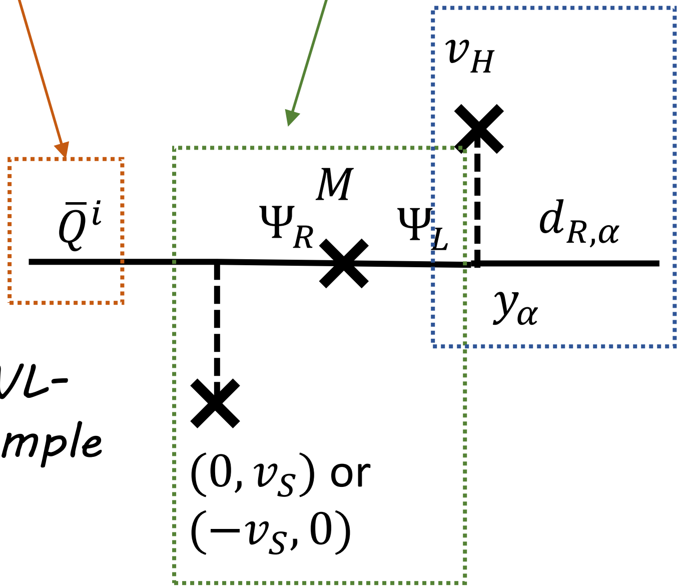
A simple VL-driven example



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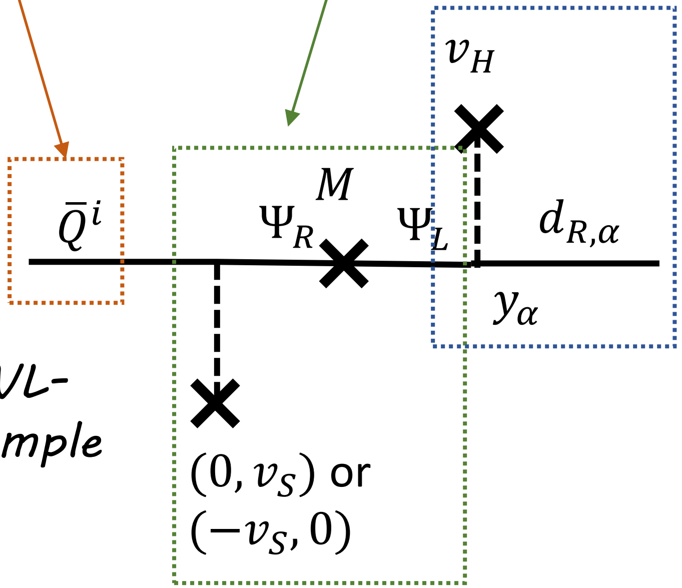

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$$L \supset \delta Y(\,\bar{Q}^1 \cdot H\,(y_d^\alpha d_{R,\alpha})$$
$$-\delta Y\,(\bar{Q}^2 \cdot H\,(\tilde{y}_d^\alpha d_{R,\alpha})$$
$$+Y_{3,d}\bar{Q}_3 \cdot H\, b_R$$

Leads to $y_d^\alpha \propto \tilde{y}_d^\alpha$

→ The down-quark mass matrix is only rank 2

$$L \supset \delta Y(\,\bar{\tilde{Q}}^2 \cdot H\,(y_d^\alpha d_{R,\alpha})$$
$$+Y_{3,d}\bar{Q}_3 \cdot H\, b_R$$

→ Repeat for the third generation

Rising through the ranks

Coined by Greljo et al. 2309.11547

- Main idea : generate the spurions « by steps », with two scales to ensure a hierarchy
  - →Use the reparametrisation on right-handed particle to put the spectrum in triangular form
  - →Generate both spurions using different mechanisms

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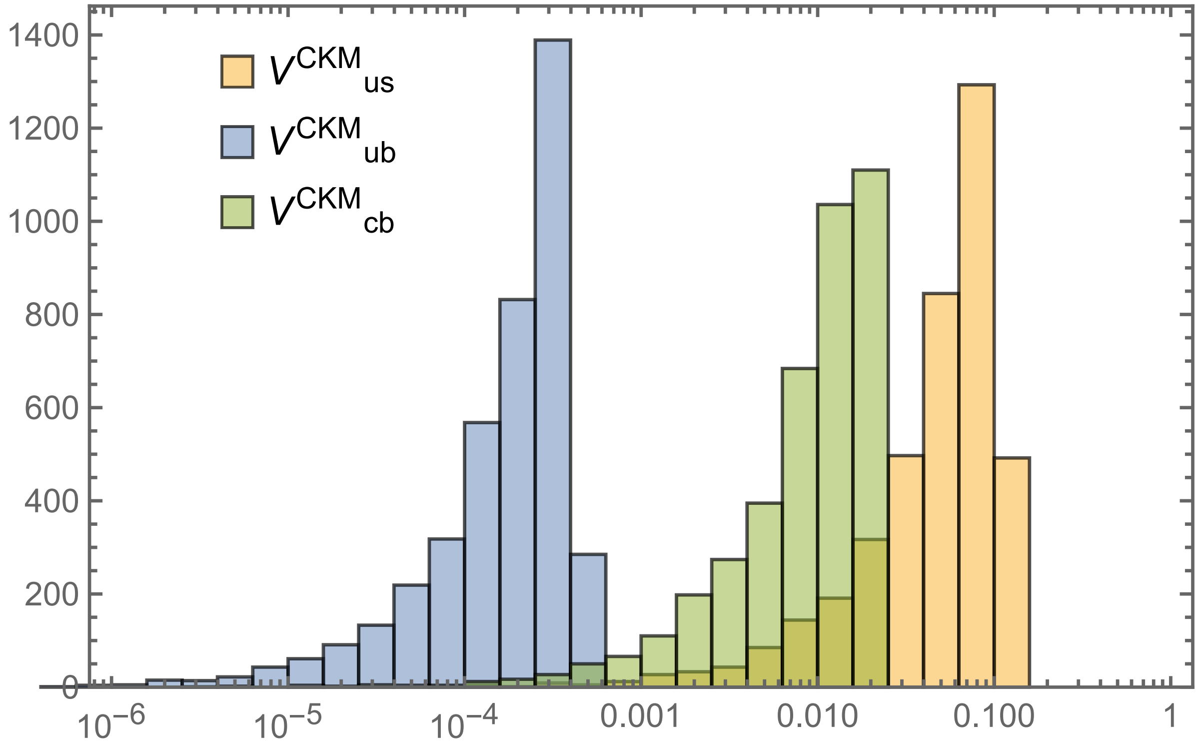
  - →Use the reparametrisation on right-handed particle to put the spectrum in triangular form
  - →Generate both spurions using different mechanisms



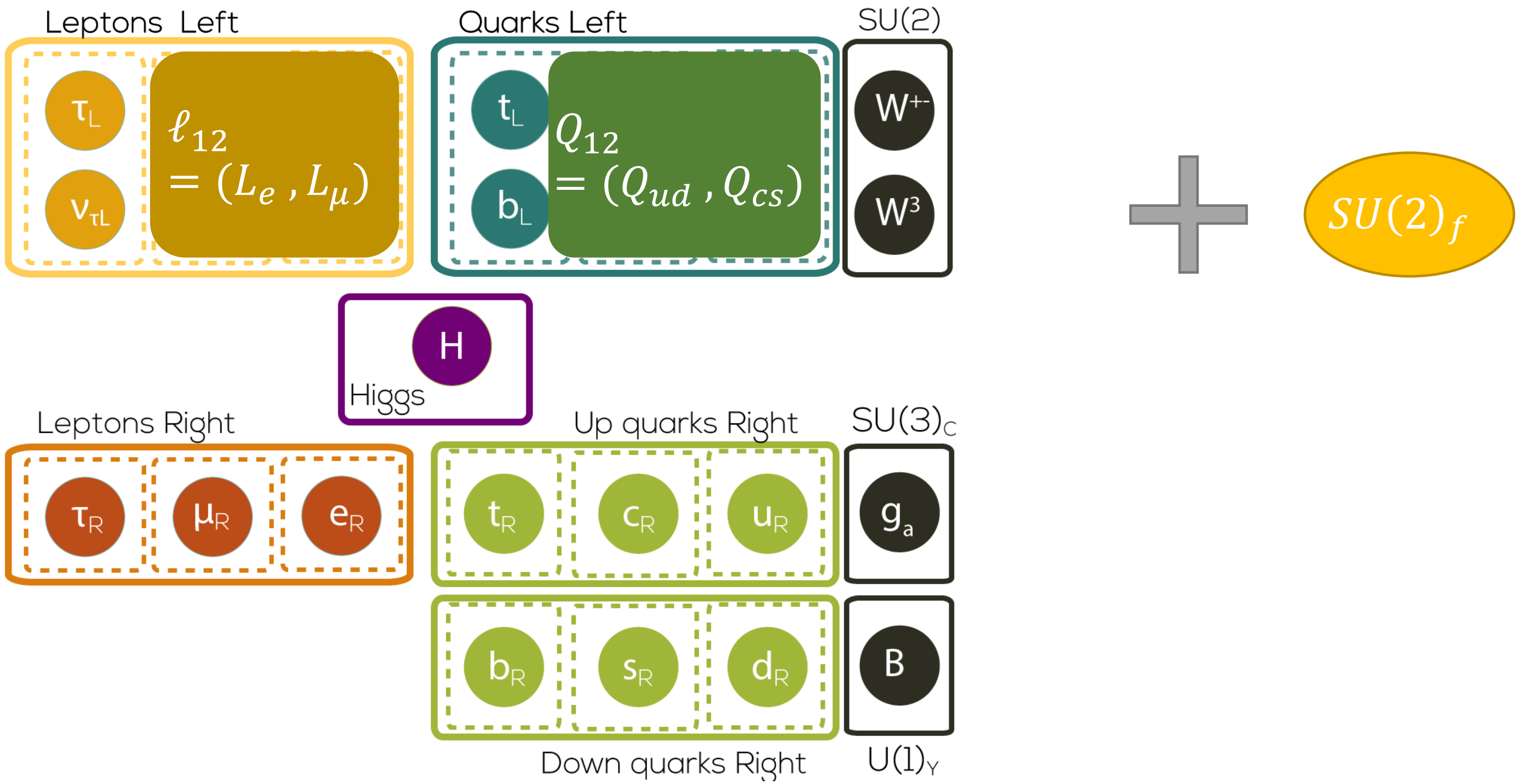
2309.11547 used a VL for 2nd generation, and loop-induced LQ-driven contribution for the 1st generation, but all standard techniques can be used here

$$Y_d = V_Z \begin{pmatrix} z_{d1}b & z_{d2}b & z_{d3}b \\ & y_{d2}a & y_{d3}a \\ & & x_{d3} \end{pmatrix}, \ Y_e = V_Z \begin{pmatrix} z_{\ell 1}b & & \\ z_{\ell 2}b & y_{\ell 2}a & \\ z_{\ell 3}b & y_{\ell 3}a & x_{\ell 3} \end{pmatrix}$$

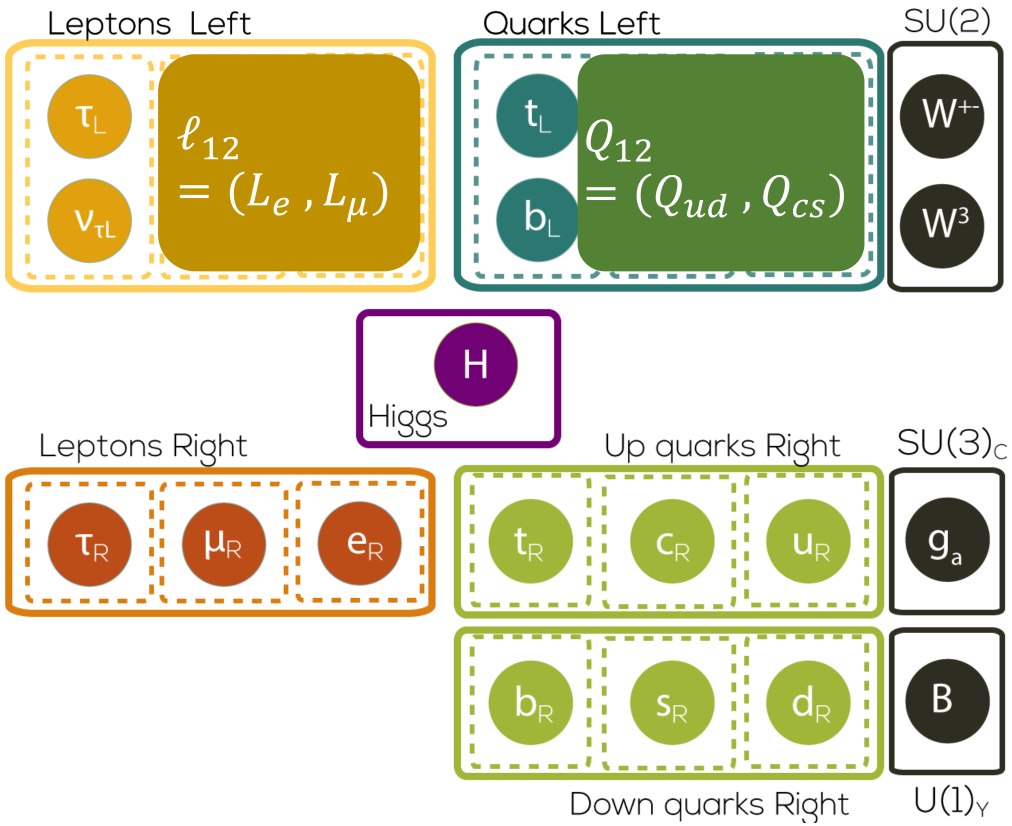
Flavour transfers

Based on 2307.09595 with A. Deandrea and N. Mahmoudi

Beyond textures : low-energy SU(2)f ?



Beyond textures : low-energy SU(2)f ?



+ $SU(2)_f$

+ The rotation matrices to the mass basis: $V_{uL}, V_{dL}, \ldots$

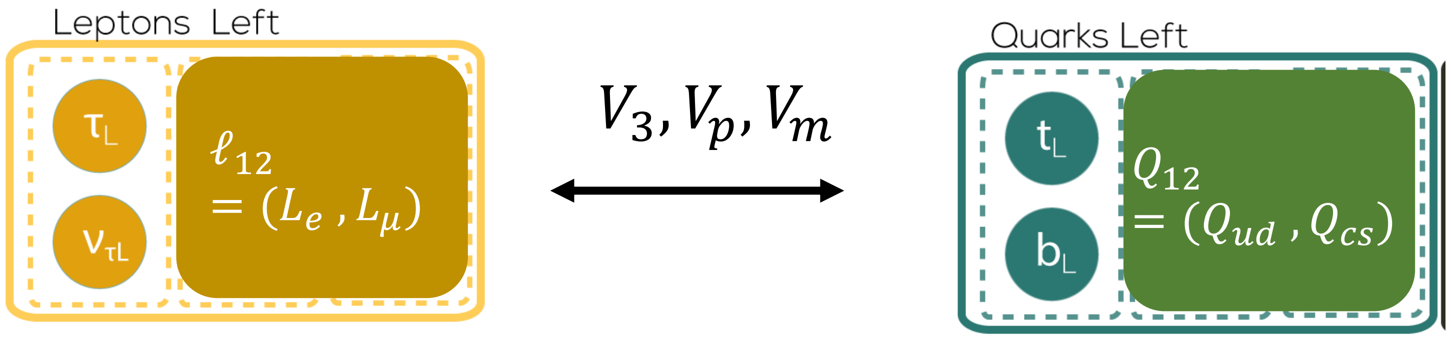
- Three new gauge bosons with mass M_V gauge coupling g_f

$$V_3\,, V_p, V_m \quad \longleftrightarrow \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The corresponding generators in flavour space

Flavour transfer

- The key point: new flavour gauge boson do not « break » flavour, they only transfer it from one fermionic sector to another



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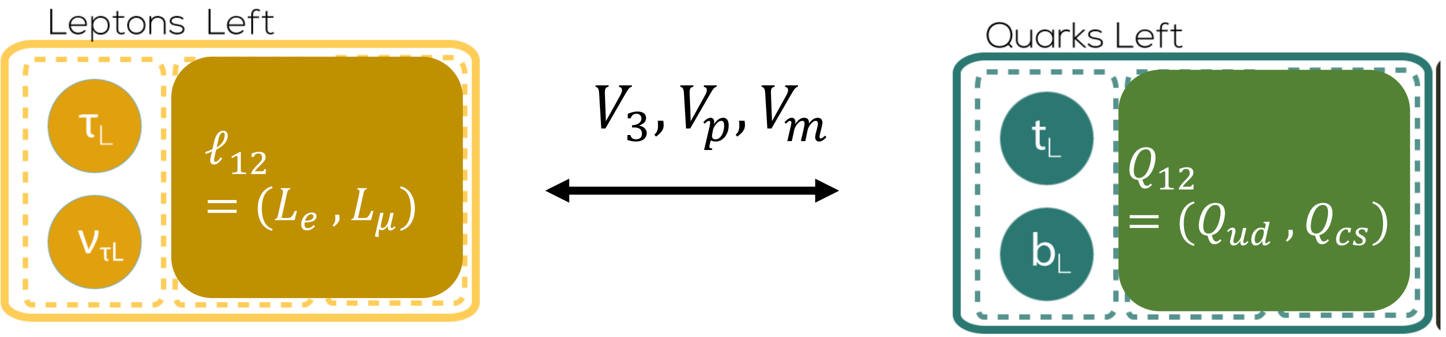
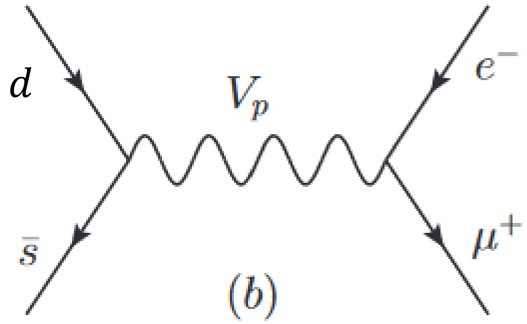


- The «W-like» flavour bosons thus carry a « flavour-charge »

$$V_p^\nu\,(\bar{\mu}\;\gamma_\nu e + \bar{s}\gamma_\nu d)$$
$$+\,V_m^\nu(\bar{e}\;\gamma_\nu\,\mu\;+\bar{d}\;\;\gamma_\nu\,s)$$



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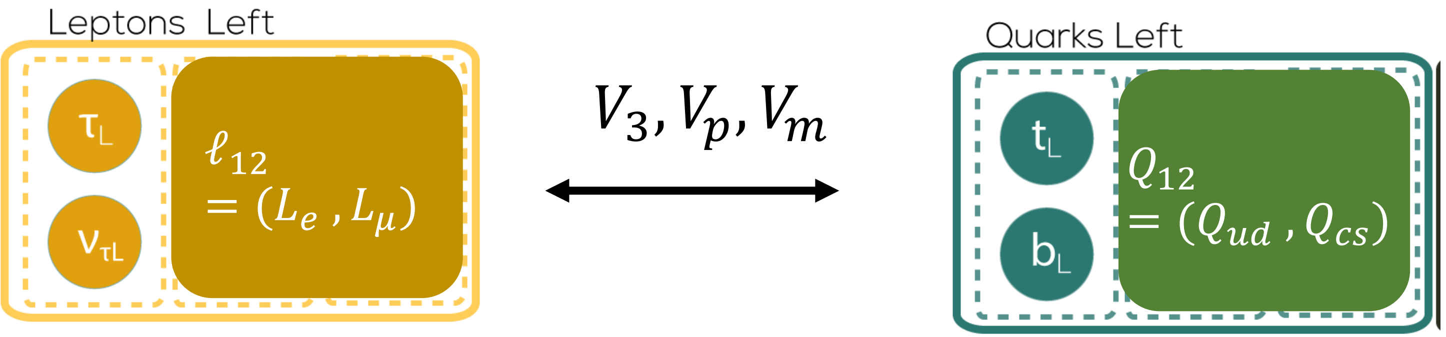
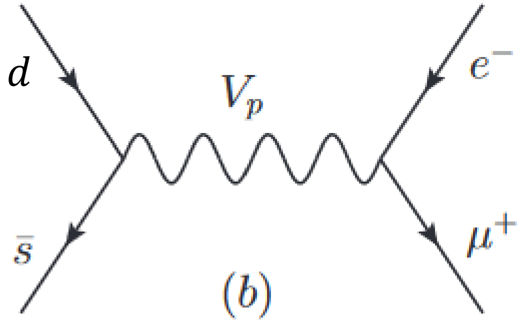


Different predictions than MFV like patterns

→ Particularly for $M_{V_1} = M_{V_2} = M_{V_3}$, in the gauge basis we have

$$\mathcal{L}_{\rm eff} \supset -\sum_{a,f,f'} \frac{g_f^2}{8M_V^2}\left(2\delta^{il}\delta^{jk} - \delta^{ij}\delta^{kl}\right)\left(\bar{f}_i\gamma^\mu f_j\right)\left(\bar{f}'_k\gamma_\mu f'_l\right)$$

Symmetry factor *Flavour transfer !* *Flavour diagonal*



Moving to the mass basis

- Since we did not focused on a particular flavour texture mechanism, the rotation matrices are « a priori » free

  → Of course in most actual models, the rotation matrices will be hierarchical as a by-product of the hierarchy in the fermion masses

Moving to the mass basis

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Greljo et al. 2309.11547

$$L_d \simeq \begin{pmatrix} 1 & \frac{m_d}{m_s}\frac{z_{d2}}{z_{d1}} & \frac{m_d}{m_b}\frac{z_{d3}}{z_{d1}} \\ -\frac{m_d}{m_s}\frac{z^*_{d2}}{z_{d1}} & 1 & \frac{m_s}{m_b}\frac{y_{d3}}{y_{d2}} \\ \frac{m_d}{m_b}\left(\frac{y^*_{d3}z^*_{d2}}{y_{d2}z_{d1}} - \frac{z^*_{d3}}{z_{d1}}\right) & -\frac{m_s}{m_b}\frac{y^*_{d3}}{y_{d2}} & 1 \end{pmatrix}$$

⇨

$$V_f = \Phi^z V_x V_z V_y$$

$$V_{dLx} = \mathbb{1} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\epsilon_{23} \\ 0 & \epsilon_{23} & 0 \end{pmatrix}$$

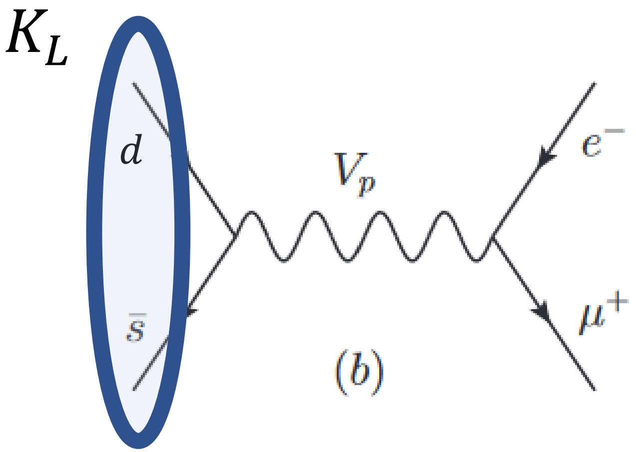
…

→ Numerically : scan full parameter space

→ Analytical result : use a small spurion approach, but allowing for different flavour alignment for the $SU(2)$ doublets (e.g $(12)_\ell(12)_{Q_L}$)

An example: kaonic decays

- With the above choice of flavour doublets, V_p, V_m bosons trigger the decays of kaons



$\mathrm{BR}(K_L \to \mu^{\pm} e^{\mp}) < 4.7 \times 10^{-12}$

In particular the process

$K_L \to e\,\mu$, but $K_+ \to \pi_+\, e\, \mu$ is also similarly un-suppressed

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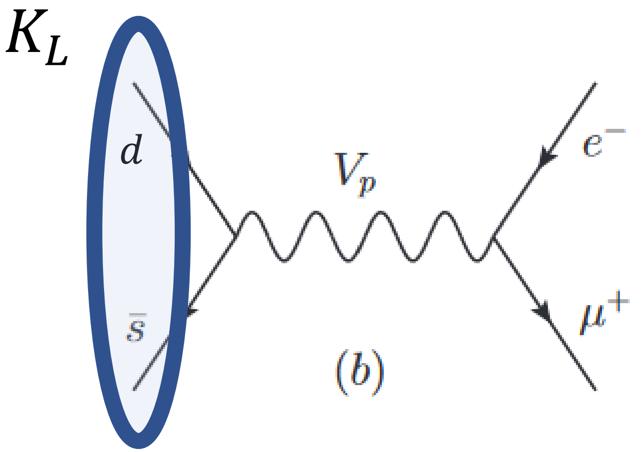

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In particular the process

$K_L \to e\,\mu$, but $K_+ \to \pi_+\, e\, \mu$ is also similarly un-suppressed

$$\mathrm{BR}(K_L \to \mu^+ e^-) = \frac{1}{\Gamma_{K_L}} \frac{M_K f_K^2}{128\pi^3} \alpha_{\rm em}^2 G_F^2 |V_{td}^* V_{ts}|^2 \left(1 - \frac{m_\mu^2}{M_K^2}\right)^{3/2} \times \left(|C_9^{sd\mu e} + C_9^{sde\mu\,*}|^2 + |C_{10}^{sd\mu e} + C_{10}^{sde\mu\,*}|^2\right)$$

- The corresponding limit is at the 250 TeV level

$$\mathrm{BR}(K_L \to \mu^\pm e^\pm) = 1.2 \cdot 10^{-10} \left(\frac{100\ \mathrm{TeV}}{M_V/g_f}\right)^4 \times \begin{cases} 1 & \text{for } (12)_\ell \\ \theta_{\ell 23}^2 & \text{for } (13)_\ell \end{cases}$$

SuperIso implementation

- Interface between the χ^2 routines of SuperIso and BSMArt (using MultiNest)
  -> 212 observables included, ($\sim$ 180 of B-physics, $\sim$ 15 of Kaons, $\sim$ 15 of leptons

Constraints	Refs.	$SU(2)_f$ flavour alignment $(12)_Q(12)_\ell$	$(23)_Q(23)_\ell$	$(12)_Q(13)_\ell$
$B \to Kee\ (C_9)$	/	$-\theta_{Q23}$	$+\theta_{\ell 12}\theta_{\ell 13}$	$-\theta_{Q23}$
$B \to K\mu\mu\ (C_9)$	/	$+\theta_{Q23}$	$-\theta_{\ell 23}$	0
$K \to \pi ee\ (C_9)$	/	$+\theta_{\ell 12}$	0	$+\theta_{\ell 13}$
$K \to \pi\mu\mu\ (C_9)$	/	$-\theta_{\ell 12}$	$+\theta_{Q12}$	$\theta_{\ell 12}\theta_{\ell 23}$
$\mathrm{BR}^{(\mathrm{E865})}_{K^+\to\pi^+\mu^+e^-} < 1.3\times 10^{-11}$	[32, 82]	1	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(\mathrm{E865})}_{K^+\to\pi^+\mu^-e^+} < 6.6\times 10^{-11}$	[32, 82]	0	0	0
$\mathrm{Br}^{(\mathrm{NA62})}_{K^+\to\pi^+\nu\bar\nu} = 1.06^{+0.41}_{-0.35}\times 10^{-10}$	[22]	1	θ^2_{Q12}	1
$\mathrm{BR}^{(\mathrm{BNL})}_{K_L\to\mu^+e^-} < 4.7\times 10^{-12}$	[20]	1	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(\mathrm{BaBar})}_{B^+\to K^+\nu\nu} < 1.6\times 10^{-5}$	[95]	$2\theta^2_{Q13}+\theta^2_{Q23}$	1	$2\theta^2_{Q13}+\theta^2_{Q23}$
$\mathrm{BR}^{(\mathrm{LHCb})}_{B^+\to K^+e^-\mu^+} < 6.4\times 10^{-9}$	[118]	θ^2_{Q13}	$\theta^2_{\ell 13}$	0
$\mathrm{BR}^{(\mathrm{BaBar})}_{B^+\to K^+\mu^-\tau^+} < 2.8\times 10^{-5}$	[119]	0	1	0
K oscillations (C_1)	[120]	0	θ^2_{Q12}	0
D oscillations (C_1)	[120]	θ^2_{Q13}	$1-8\theta_{Q12}$	θ^2_{Q13}
B_d oscillations (C_1)	[120]	θ^2_{Q13}	θ^2_{Q13}	θ^2_{Q13}
B_s oscillations (C_1)	[120]	θ^2_{Q23}	0	θ^2_{Q23}
$\mathrm{BR}^{(\mathrm{SINDRUM})}_{\mu\to e\bar e e} < 1.0\cdot 10^{-12}$	[105]	0	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to 3\mu} < 2.1\cdot 10^{-8}$	[106]	$\theta^2_{\ell 23}$	0	0
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to 3e} < 3.3\cdot 10^{-8}$	[106]	$\theta^2_{\ell 13}$	0	0
$\mathrm{BR}^{(\mathrm{MEG})}_{\mu\to e\gamma} < 4.2\cdot 10^{-13}$	[100, 101]	0	$\theta^2_{\ell 12}$	$\theta^2_{\ell 13}$
$\mathrm{BR}^{(\mathrm{Belle})}_{\tau\to e\bar K^*} < 3.2\cdot 10^{-8}$	[110]	0	0	1
$\mathrm{BR}^{(\mathrm{Belle})}_{\tau\to\mu\bar K^*} < 7.0\cdot 10^{-8}$	[110]	$\theta^2_{\ell 13}$	θ^2_{Q13}	$\theta^2_{\ell 12}$
$\mathrm{CR}^{(\mathrm{SINDRUM\text{-}II})}_{Au,\mu\to e} < 7\cdot 10^{-13}$	[21, 103, 112]	$1+20\theta_{\ell 12}$	$\theta^2_{\ell 12}$	$\theta_{\ell 12}(2.3\theta_{\ell 12}-\theta_{\ell 23})$
$\mu\bar e \to e\bar\mu$ oscillations (C_1)	[117]	0	$\theta^2_{\ell 12}$	$\theta^2_{\ell 12}$

SuperIso implementation

- Interface between the χ^2 routines of SuperIso and BSMArt (using MultiNest)
  -> 212 observables included, (~ 180 of B-physics, ~ 15 of Kaons, ~ 15 of leptons
- Flavour transfer observables lead to strong bounds even for small mixing angles.

$$\Delta F_f + \Delta F_{f'} = 0$$

→ Typical limits on $M_V\ /g_f$ at the 100 TeV scale

Constraints	Refs.	$SU(2)_f$ flavour alignment $(12)_Q(12)_\ell$	$(23)_Q(23)_\ell$	$(12)_Q(13)_\ell$
$B \to Kee\ (C_9)$	Flavour universality violation	$-\theta_{Q23}$	$+\theta_{\ell 12}\theta_{\ell 13}$	$-\theta_{Q23}$
$B \to K\mu\mu\ (C_9)$		$+\theta_{Q23}$	$-\theta_{\ell 23}$	0
$K \to \pi ee\ (C_9)$		$+\theta_{\ell 12}$	0	$+\theta_{\ell 13}$
$K \to \pi\mu\mu\ (C_9)$		$-\theta_{\ell 12}$	$+\theta_{Q12}$	$\theta_{\ell 12}\theta_{\ell 23}$
$\mathrm{BR}^{(E865)}_{K^+\to\pi^+\mu^+e^-} < 1.3\times 10^{-11}$	[32, 82]	1	0	$\theta^2_{\ell 23}$
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$\mathrm{BR}^{(LHCb)}_{B^+\to K^+e^-\mu^+} < 6.4\times 10^{-9}$	[118]	θ^2_{Q13}	$\theta^2_{\ell 13}$	0
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B_d oscillations (C_1)	[120] $\mathbf{\Delta F = 2}$	θ^2_{Q13}	θ^2_{Q13}	θ^2_{Q13}
B_s oscillations (C_1)	[120]	θ^2_{Q23}	0	θ^2_{Q23}
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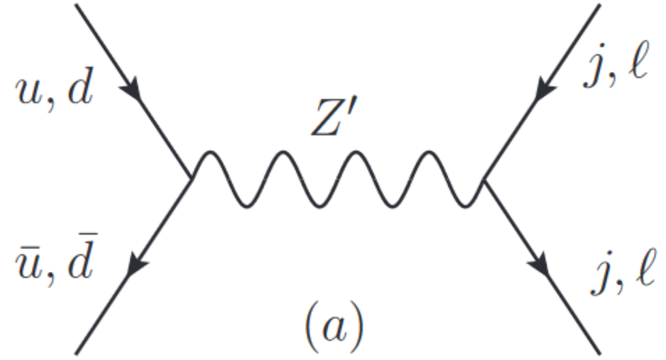
$\mu\bar e\to e\bar\mu$ oscillations (C_1)	[117]	0	$\theta^2_{\ell 12}$	$\theta^2_{\ell 12}$

On LHC constraints

- When $M_V \lesssim$ few TeV, direct production at LHC becomes possible $M_V \propto g_f\, v_S$
- LHC is « perfect » for the flavour transfer processes since NP candidate can be produced from quark (or gluon) fusion, but decay leptonically to ensure detection.

$$pp \to V + X, V \to \ell\ell$$

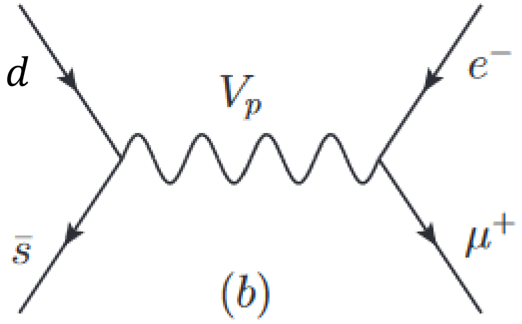


→ Standard searches for Z': di-leptons and di-jets

- Searches using LFV final states are extremely attractive

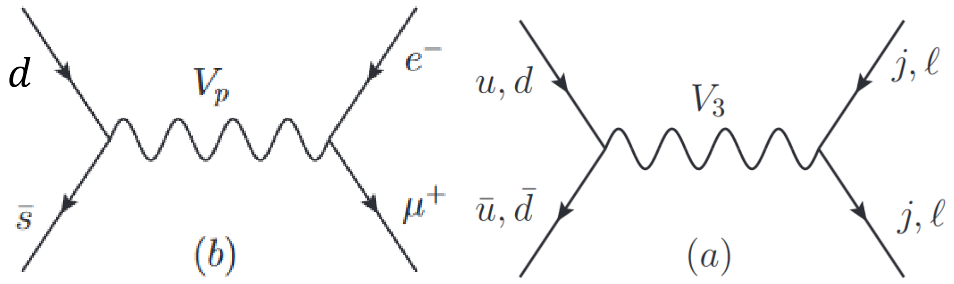
  → The proton contains enough sea-quarks to produce the off-diagonal flavour boson

  → Lepton flavour violation in the final states limit the QED background

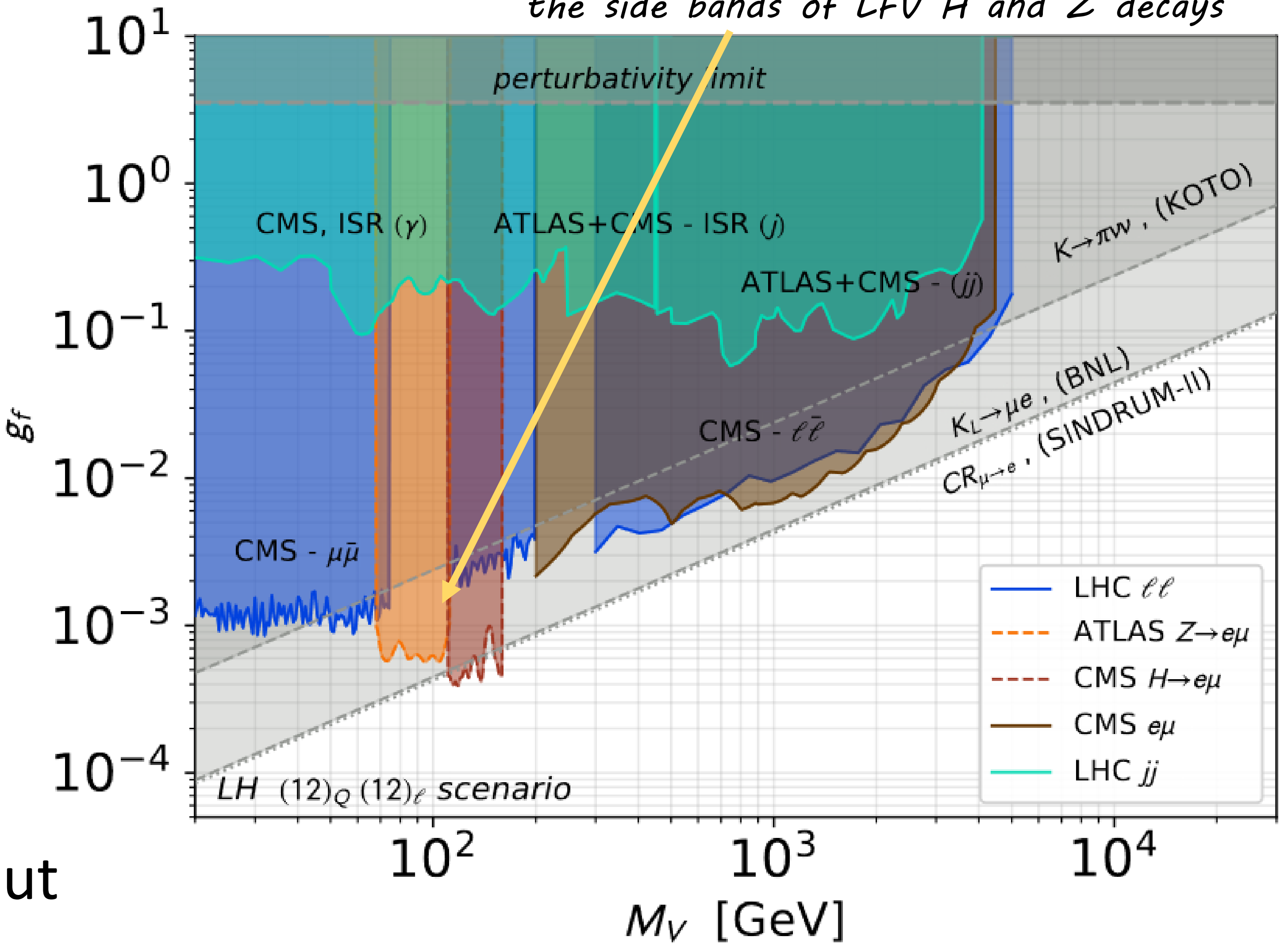


LHC limits and flavour: LH - $(12)_\ell(12)_Q$

- Use the (LH) scenario
  - → Assume that 1st and 2d generations of left-handed fermions are part of a flavour doublets
  - → Production at LHC is huge !



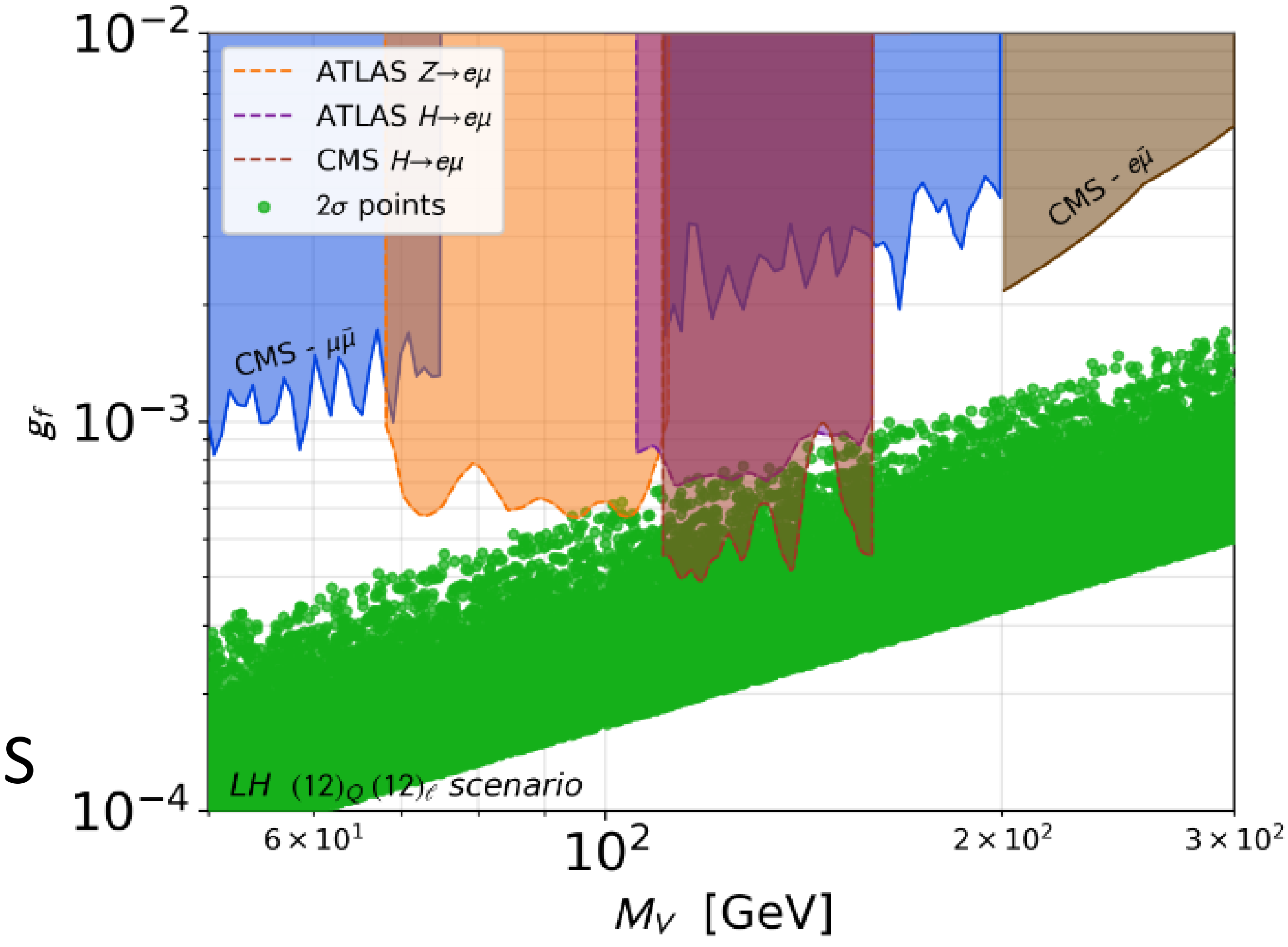
LFV searches for new scalar + recast of the side bands of LFV H and Z decays



- Limits from Kaonic and muon conversion in nuclei dominate, but LHC constraints are close

LFV decays of H and Z

- The best constraints arise from the recasting of LFV H and Z decays
  - → $Z \to e\mu, e\tau, \mu\tau$ and $h \to \ e\mu, e\tau, \mu\tau$
  - →We calibrate the signal on the Z and H one for the efficiency, then uses the side-band data to put a limit

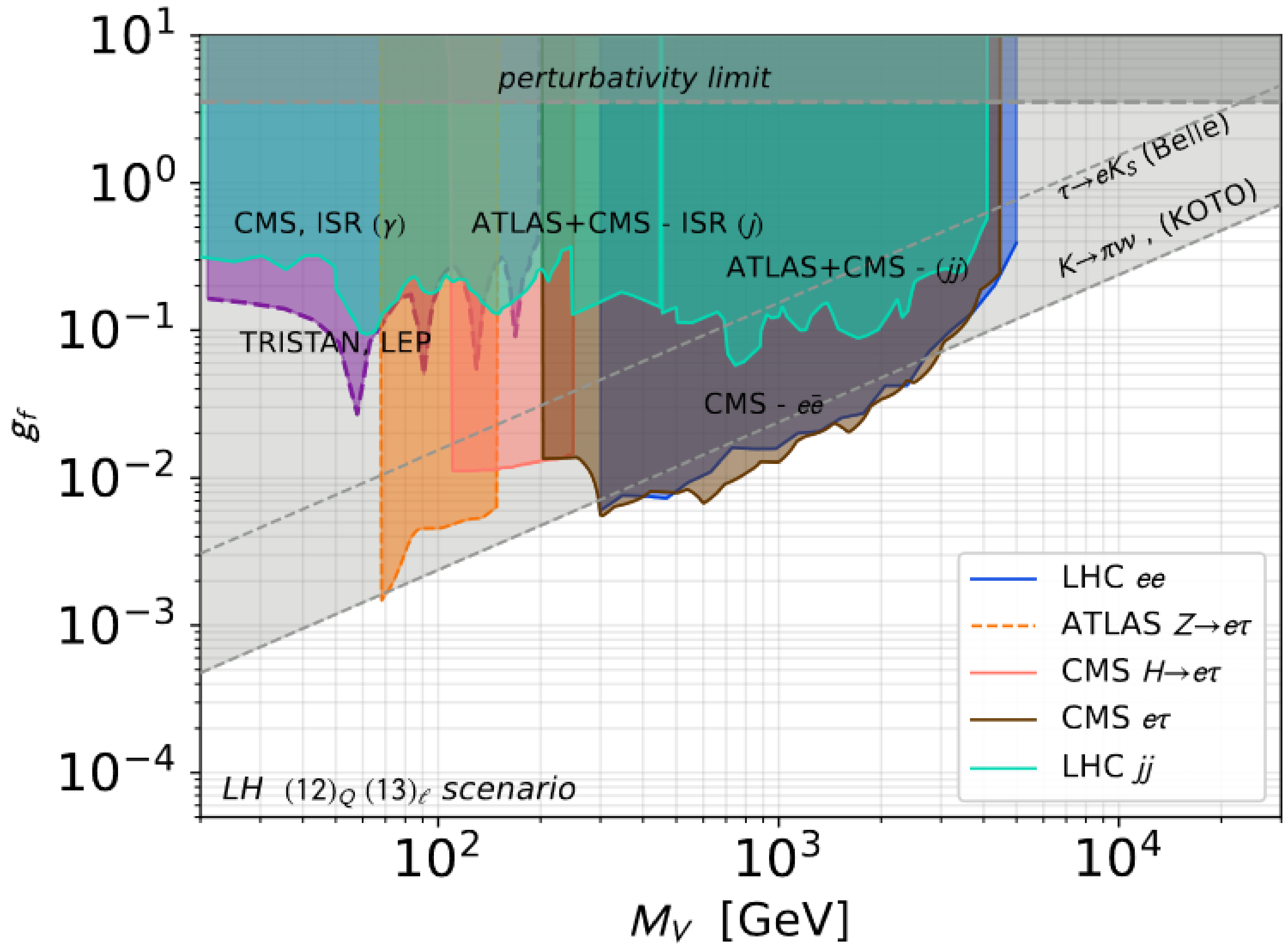


- There is a $\sim 3\sigma$ anomay in the CMS data set, ATLAS data not precise enough to call… for now

Another flavour alignement LH - $(13)_\ell(12)_Q$

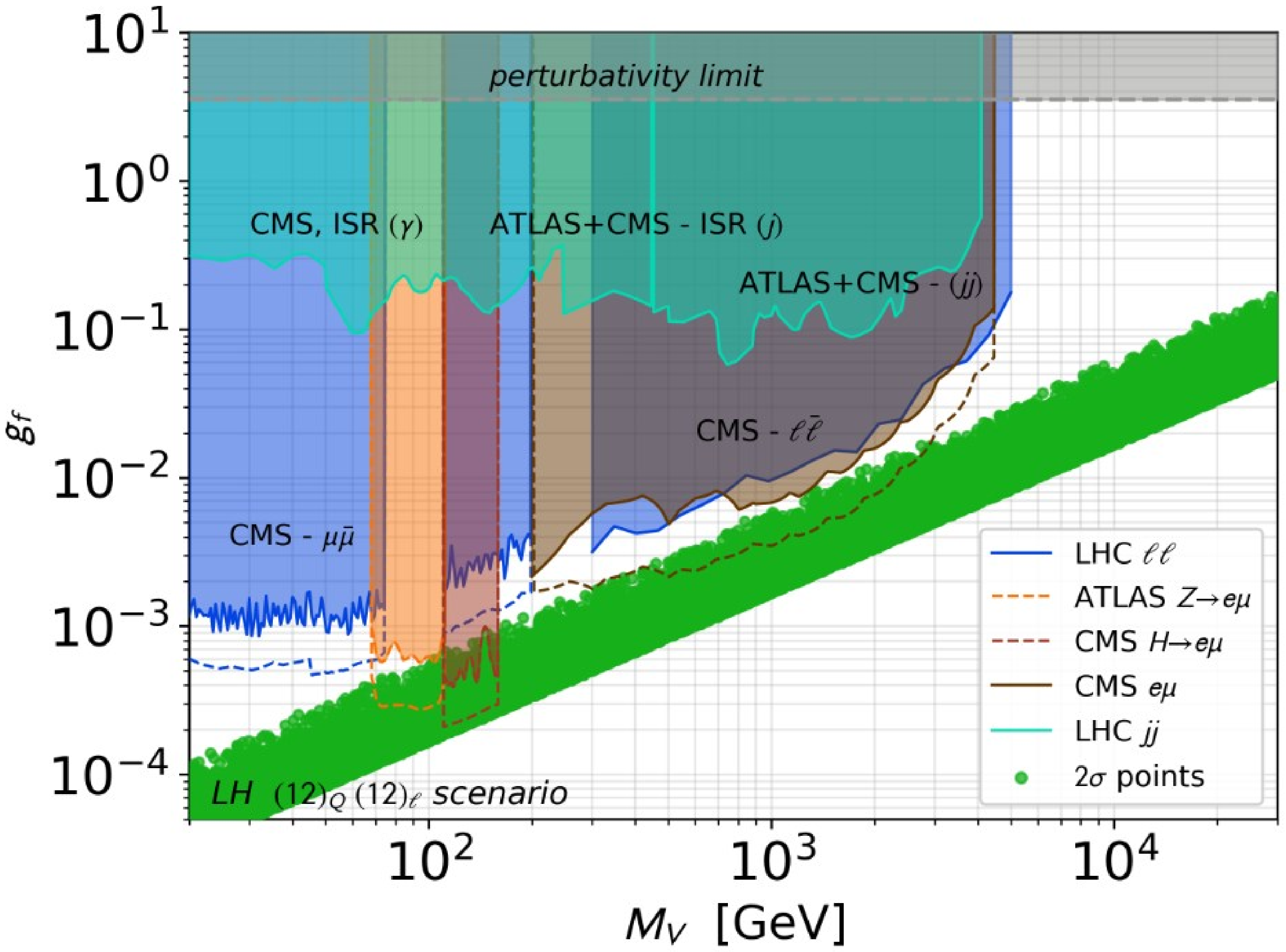
- Corresponds to a « muon as a third generation lepton » scenario

- Now the strongest limits arise from Kaonic neutrino decays (since do not depend on the neutrino flavour)
- LHC constraints are also weakened



Future prospects

- LHC contraints (and most importantly the recasting of $H \to e\,\mu$ and $Z \to e\,\mu$ limits) are close or overlapping with the flavour constraints
- HL-LHC could probe even deeper, as would dedicated resonance searches around and below the 100 GeV range



Conclusion

Conclusion

- New horizontal gauge symmetries are a great model building tool ! Which do not necessarily increase the SM complexity
  - → Create and protect new accidental symmetries
  - → Generate textures
  - → Shape the scalar potential (clockwork structures …) and the vacuum structure of the theory (create hierarchical VEVs)
- They have significant consequences for pheno
  - →Non-abelian flavour gauge symmetries can naturally lead to GeV to TeV new vectors for small couplings
  - →LHC has an important role to play for new vectors at and below the TeV
- Creating links with GUT / AS approach an interesting issue as it could help it constraining the actual values of the new gauge couplings

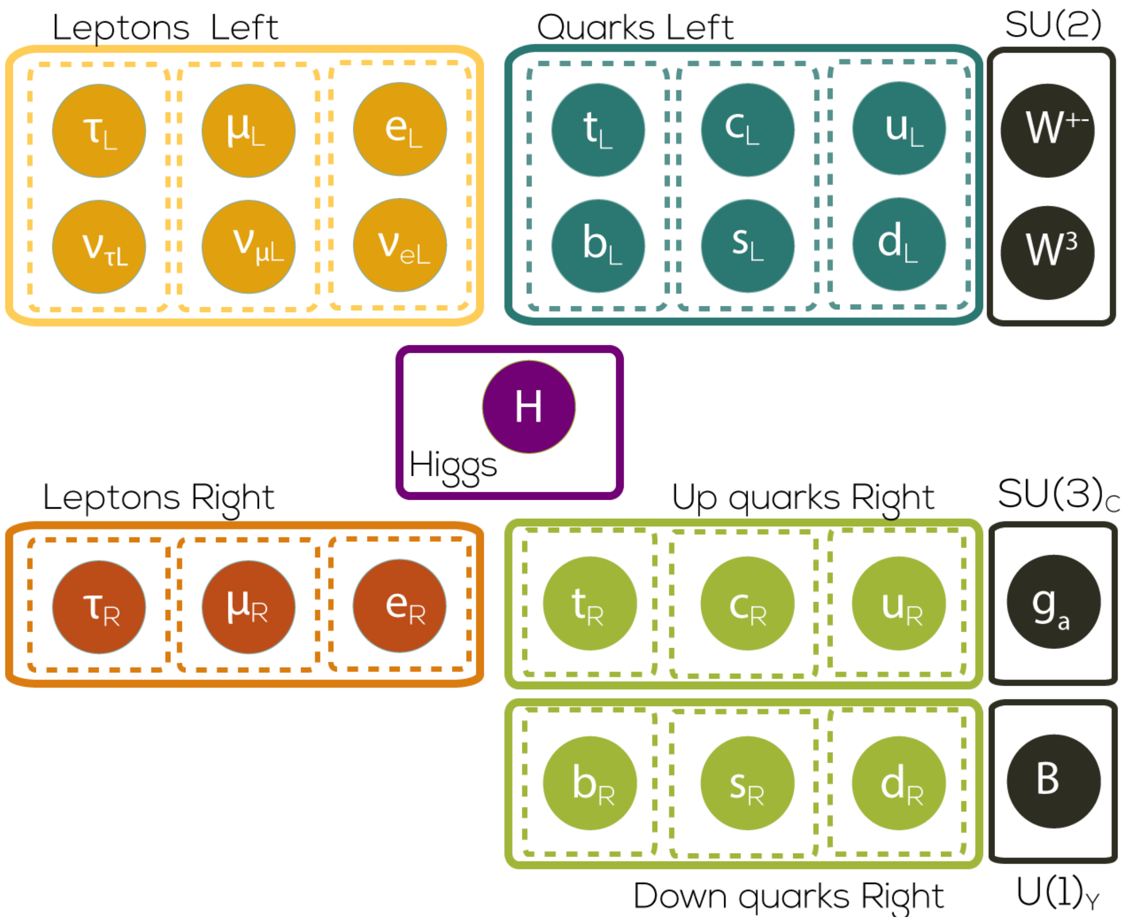
Backup

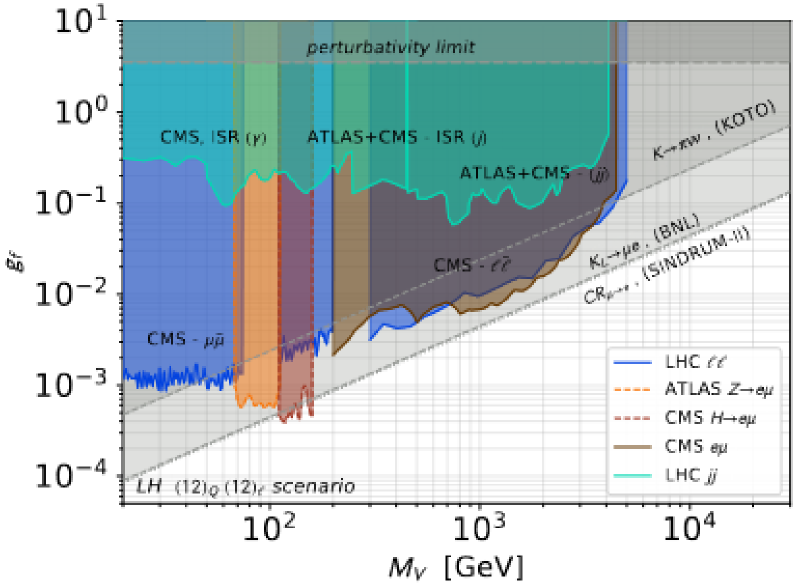
Horizontal flavour gauge groups

- The SM has a large global $U(3)^5$ symmetry group
  - →broken by the Yukawa interactions

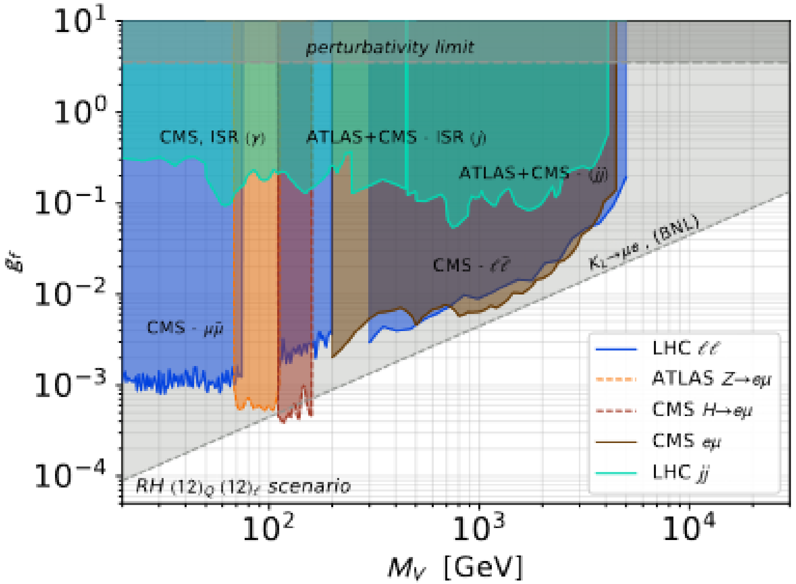
$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \mathrm{h.c.},$$

- We can gauge a subset of this group ?
  - →U(1) case: Frogatt-Nielsen constructions, $L_\mu - L_\tau$, flavons, etc…
  - → The non-abelian case has been sparsely studied.
- We can also consider larger gauge groups by adding fermions




perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
K→πνν , (KOTO)
CMS - ℓℓ̄
K_L→μe , (BNL)
CR_{μ→e} , (SINDRUM-II)
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
LH (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

(a)


perturbativity limit
CMS, ISR (γ)
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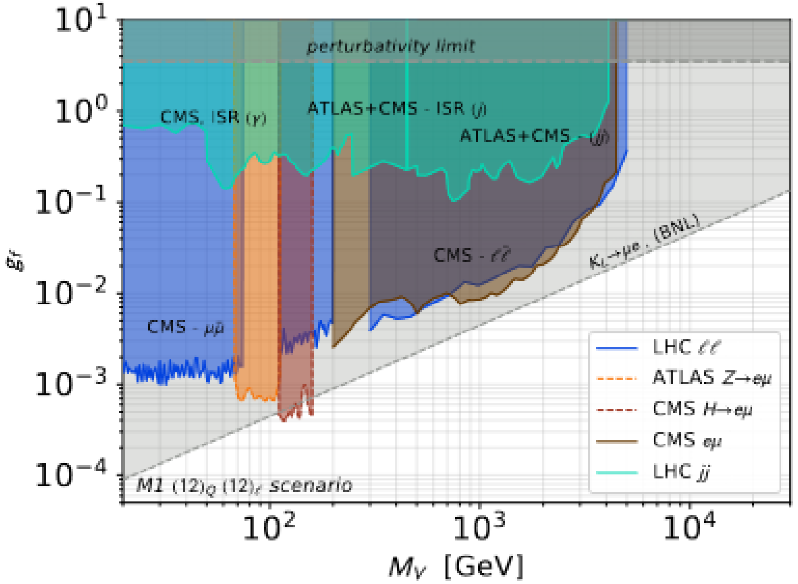
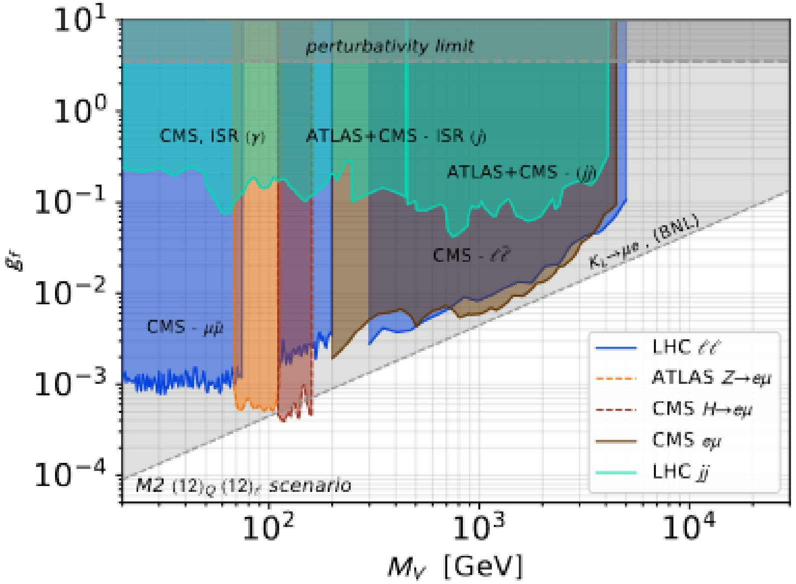
K_L→μe , (BNL)
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
RH (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

(b)


perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
CMS - ℓℓ̄
K_L→μe , (BNL)
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
M1 (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]


perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
CMS - ℓℓ̄
K_L→μe , (BNL)
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
M2 (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

Accidental symmetries vs accidentally light scalars

- Comparison with Michele's works
  - →Operators will vanish on the vacuum
  - →Test larger mixed representations

Two accidental phenomena

(I) Familiar : **accidental symmetries → light scalars**

- A given gauge theory → accidental global symmetries

Spontaneous symmetry breaking (SSB)	$G \to H$
Nambu Goldstone bosons (NGBs) $\in$	G/H

- NGB masses controlled by explicit-symmetry-breaking sources

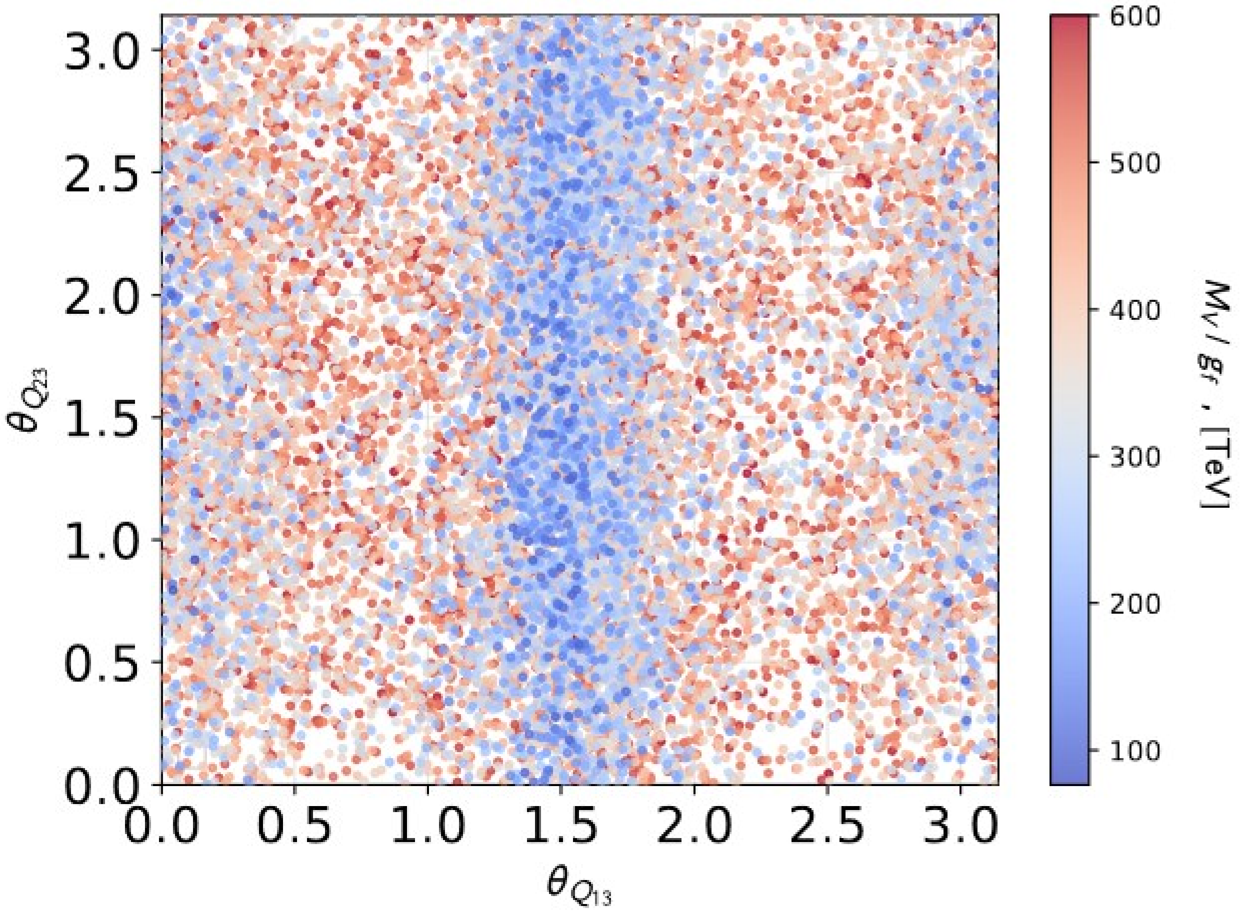
(II) Unfamiliar: **accidentally light scalars, without a symmetry**

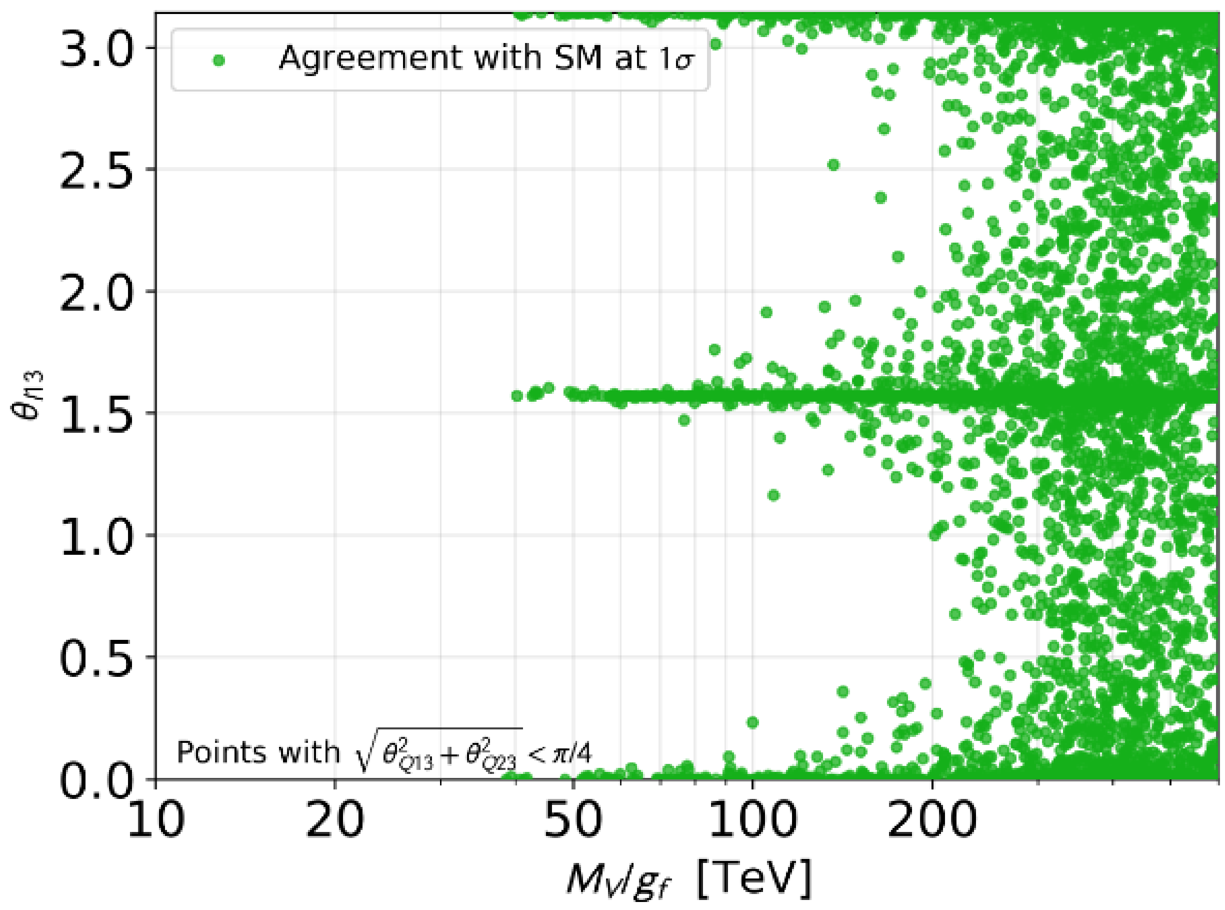
- For some special choices of scalar representations

$$\langle \phi \rangle : \; G \to H \quad \text{but vacuum manifold larger than} \quad G/H$$

- Unexpected, still natural hierarchy among scalar masses

Some results





- First generations couplings are avoided as much as possible of course …