Horizontal gauge symmetries and flavour transfers

Luc Darmé

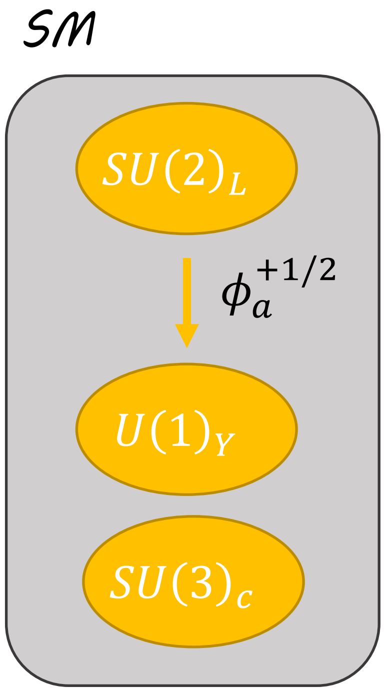
IP2I – UCBL

24/01/2024

Based on 2307.09595, 2211.05796, 2102.05055

This work has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101028626

Gauge groups and (accidental symmetries)



→ Tree-level baryon and lepton number conservation

→ No Majorana mass terms

→ Custodial symmetry

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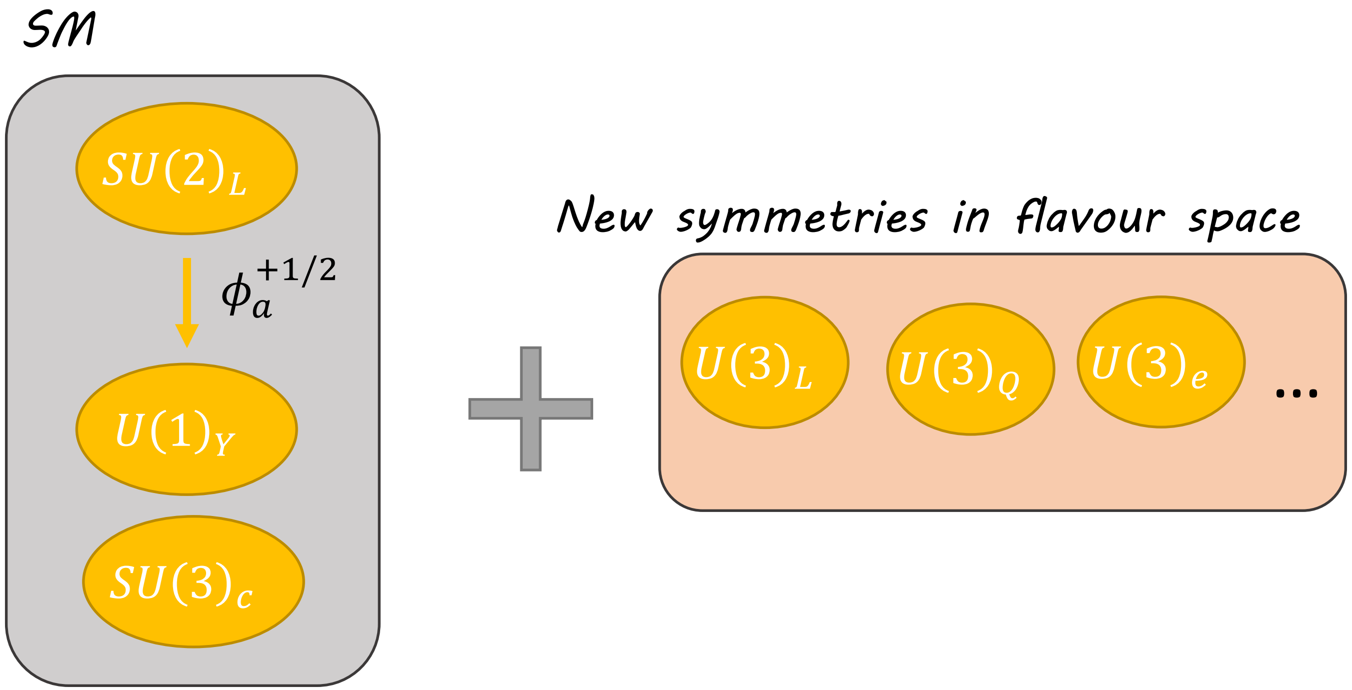

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- The SM has a large global $U(3)^5$ symmetry group
  - →broken by the Yukawa interactions
- New « horizontal gauge symmetries », acting mostly in flavour space
  - → Will likely adds new structures, both in the fermion and scalar sector of the UV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

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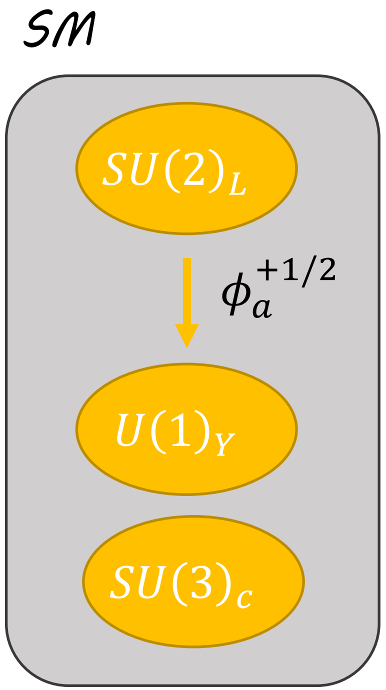

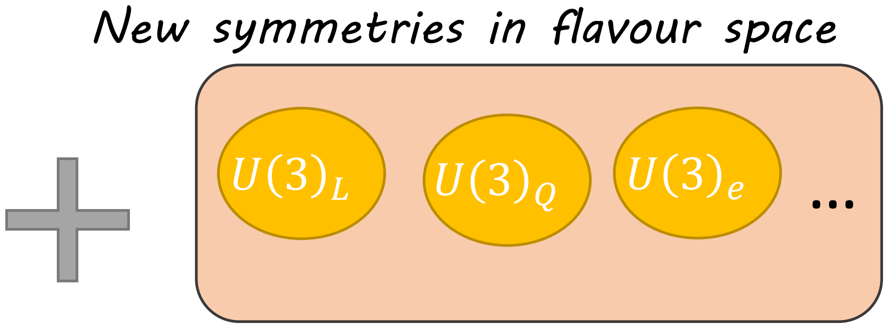

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Texture and flavour: the well-known example

Structure in the scalar sector and axion

Structure for NP processes (flavour transfers)

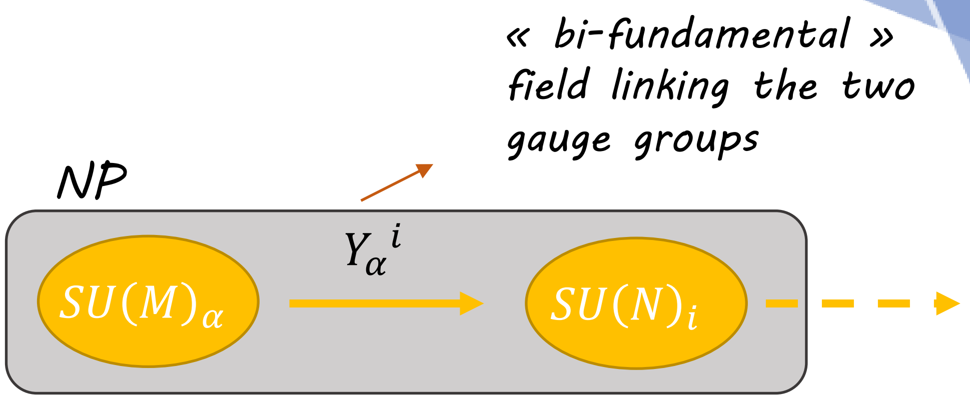
Musing around with rectangular symmetries

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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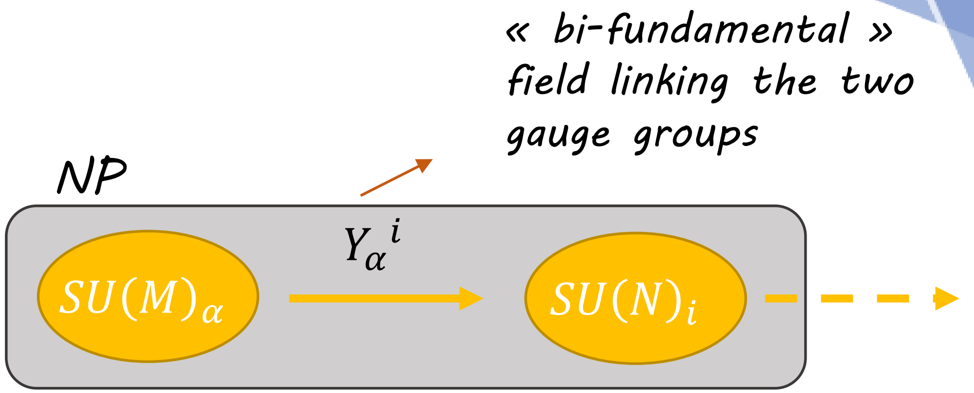

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- The scalar fields are rectangular matrices

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

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

$$V(Y) = \kappa \left(T - \mu_Y^2\right)^2 + \lambda\, A$$

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

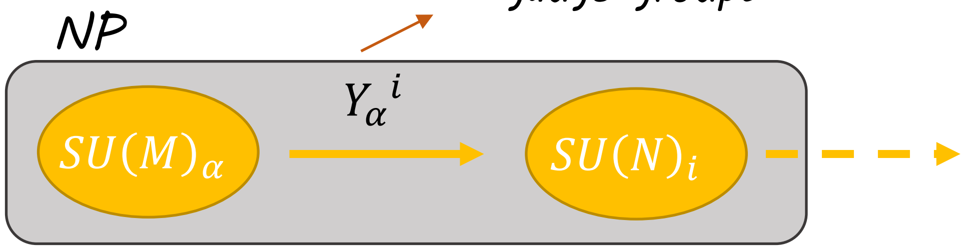
$$T_4 \equiv \mathrm{Tr}\left(Y^\dagger Y\right)^2$$

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

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

Rectangular gauge groups

« bi-fundamental » field linking the two gauge groups



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- Non-hermitian operators are also very constrained

  →Form « cycles » or/and are 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…)

A first use: flavour symmetries and axions

- The axion is only a solution to the strong CP problem insofar as its potential does not lead to a mass larger than the one generated by the QCD anomaly

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

→ 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

Based on 2211.05796

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

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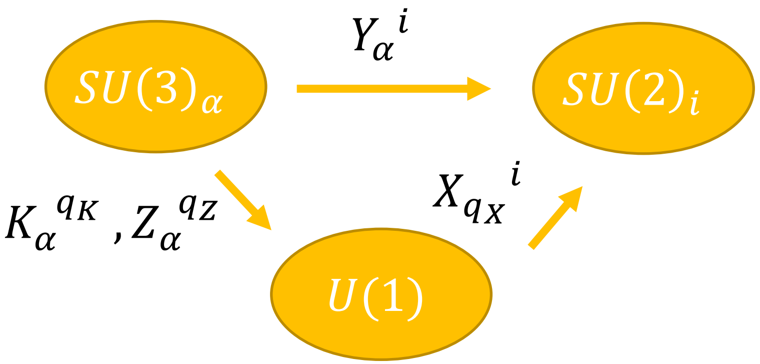

→ Need new VL pairs for the quark mass generations
→ Standard 2HDM Higgs structure to generate the axion

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

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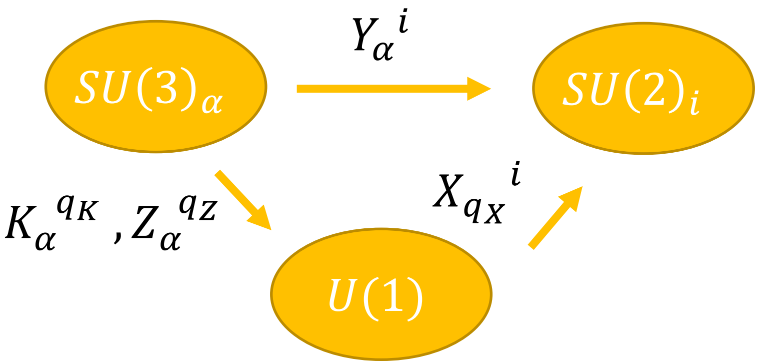

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✓ It works !

✓ VEVs hierarchies arise naturally from the structure of the potential

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

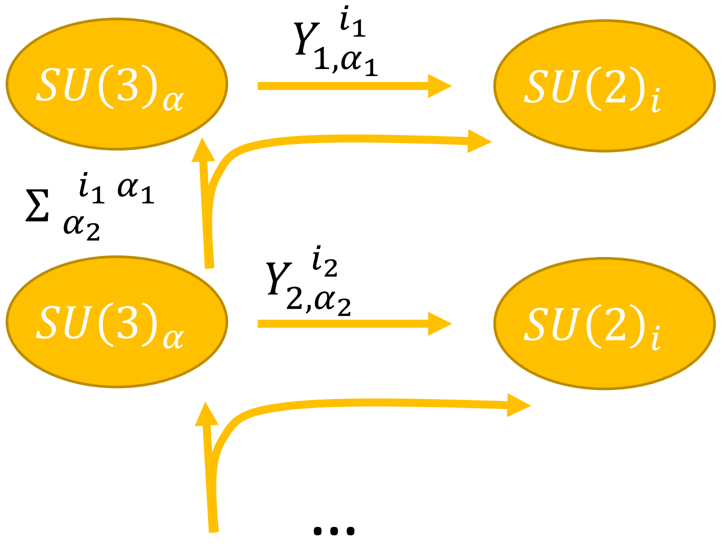
Another possibility: creating clockworks

- 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 :

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



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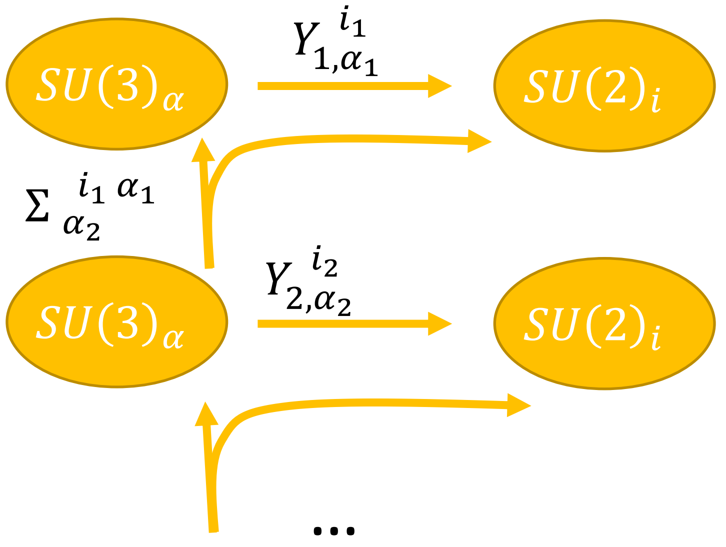

The VEVs of each fields can decrease as a power-law since each gear in Y_{p-1}^2 induces a linear term for Y_p

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

The residual PQ symmetry, present typical clockwork-like charges

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

Flavoured horizontal symmetries & flavour transfers

… the consequences of adding SU(2) of flavour

Based on 2307.09595 with A. Deandrea and N. Mahmoudi

SU(2) flavour gauge groups

- Starting point: add a new $SU(2)_f$ 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 !
LH, RH ; L, B ; and M1, M2

- Note that $SU(2)_f$ may be part of a larger (global) group for flavour texture

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- Gauge boson masses are free parameters!

  → Even with a large VEV, small gauge couplings required by flavour constraints imply light new states

$$M_{V_1}^2 = M_{V_2}^2 = M_{V_3}^2 = \frac{g_f}{2} \sum_i v_\phi^2$$

Flavour gauge groups are not part of big unification theories like SO(10) → no reason to believe they should be of the same interaction strength as the EW or strong interactions

Bottom-up approach

- Philosophy : we do not try to generate textures but focus rather on the possible phenomenological consequences (in particular on the presence of the new flavour gauge bosons)
  - → U(2) models of flavour a well charted path

Greljo et al. 2309.11547, 2311.09288 and before last year 2009.10437,1909.02519 etc…

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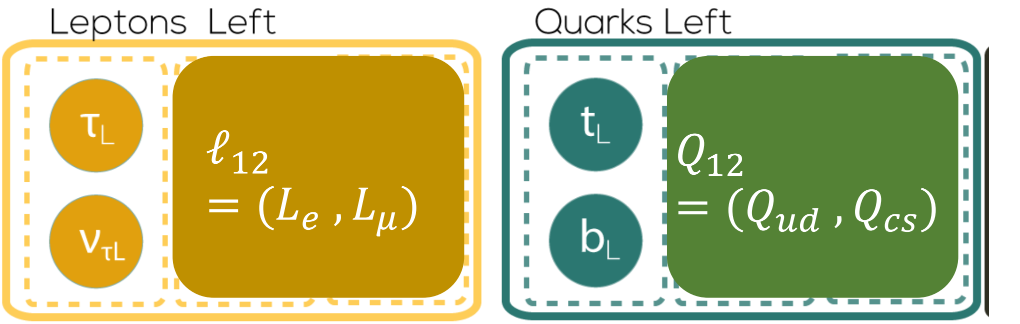
- In the following : left-handed scenario with interactions

  → Both LH leptons and LH quarks part of a flavour doublets



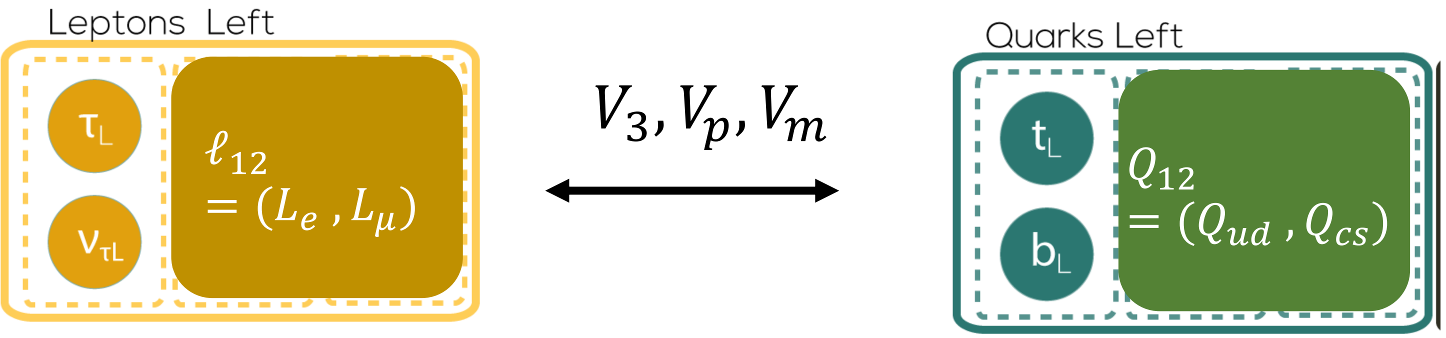
- Three new gauge bosons with mass M_V gauge coupling g_f

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

The corresponding generators in flavour space

Flavour transfer

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



For instance, the «W-like» flavour bosons 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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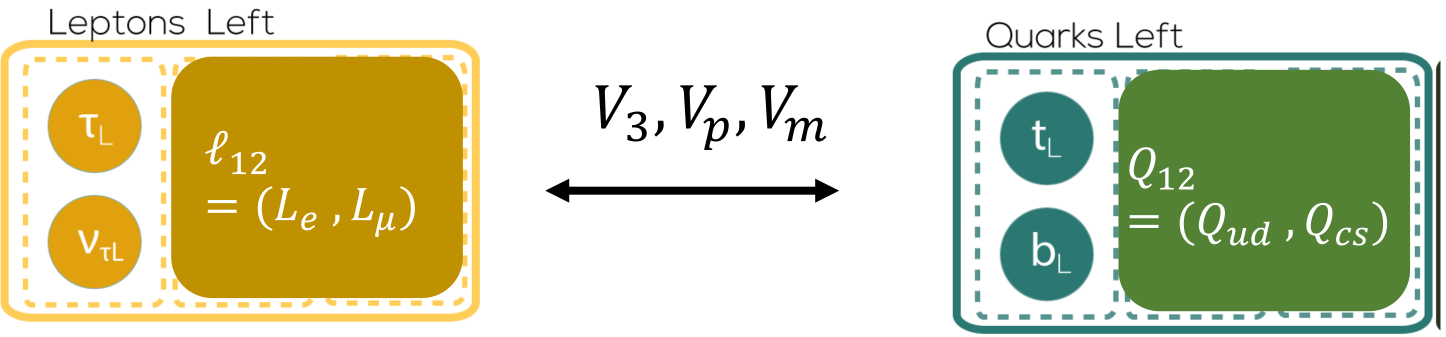

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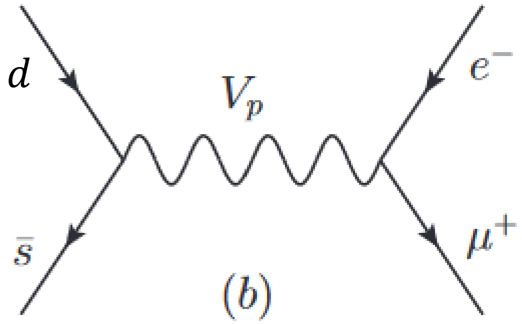
Different predictions than MFV like patterns

→ 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*



(b)

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

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

Greljo et al. 2309.11547

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

⇨

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

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

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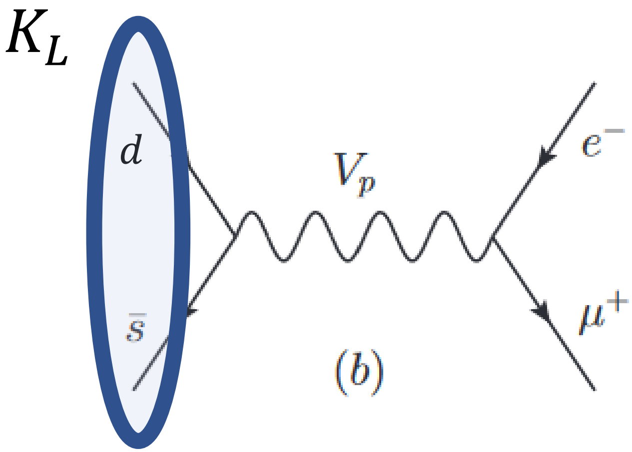
→ Numerically : scan full parameter space

→ Analytical result : use a small spurion approach, 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

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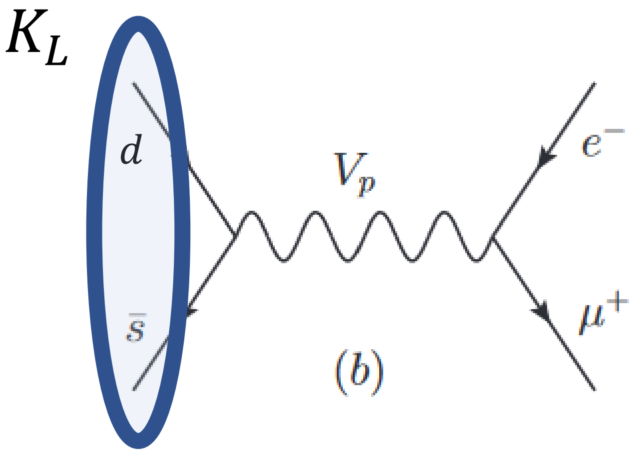

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In particular the process $K_L \to e\,\mu$, but $K_+ \to \pi_+\, e\,\mu$ is also similarly un-suppressed

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

- The corresponding limit is at the 250 TeV level

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

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	$+\theta_{\ell 13}$
$K \to \pi\mu\mu\ (C_9)$	/	$-\theta_{\ell 12}$	$+\theta_{Q12}$	$\theta_{\ell 12}\theta_{\ell 23}$
$\mathrm{BR}^{(\mathrm{E865})}_{K^+\to\pi^+\mu^+e^-} < 1.3\times10^{-11}$	[32, 82]	1	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(\mathrm{E865})}_{K^+\to\pi^+\mu^-e^+} < 6.6\times10^{-11}$	[32, 82]	0	0	0
$\mathrm{Br}^{(\mathrm{NA62})}_{K^+\to\pi^+\nu\bar{\nu}} = 1.06^{+0.41}_{-0.35}\times10^{-10}$	[22]	1	θ^2_{Q12}	1
$\mathrm{BR}^{(\mathrm{BNL})}_{K_L\to\mu^+e^-} < 4.7\times10^{-12}$	[20]	1	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(\mathrm{BaBar})}_{B^+\to K^+\nu\nu} < 1.6\times10^{-5}$	[95]	$2\theta^2_{Q13}+\theta^2_{Q23}$	1	$2\theta^2_{Q13}+\theta^2_{Q23}$
$\mathrm{BR}^{(\mathrm{LHCb})}_{B^+\to K^+e^-\mu^+} < 6.4\times10^{-9}$	[118]	θ^2_{Q13}	$\theta^2_{\ell 13}$	0
$\mathrm{BR}^{(\mathrm{BaBar})}_{B^+\to K^+\mu^-\tau^+} < 2.8\times10^{-5}$	[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}
$\mathrm{BR}^{(\mathrm{SINDRUM})}_{\mu\to e\bar{e}e} < 1.0\cdot10^{-12}$	[105]	0	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to3\mu} < 2.1\cdot10^{-8}$	[106]	$\theta^2_{\ell 23}$	0	0
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to3e} < 3.3\cdot10^{-8}$	[106]	$\theta^2_{\ell 13}$	0	0
$\mathrm{BR}^{(\mathrm{MEG})}_{\mu\to e\gamma} < 4.2\cdot10^{-13}$	[100, 101]	0	$\theta^2_{\ell 12}$	$\theta^2_{\ell 13}$
$\mathrm{BR}^{(\mathrm{Belle})}_{\tau\to e\bar{K}^*} < 3.2\cdot10^{-8}$	[110]	0	0	1
$\mathrm{BR}^{(\mathrm{Belle})}_{\tau\to\mu\bar{K}^*} < 7.0\cdot10^{-8}$	[110]	$\theta^2_{\ell 13}$	θ^2_{Q13}	$\theta^2_{\ell 12}$
$\mathrm{CR}^{(\mathrm{SINDRUM\text{-}II})}_{Au,\mu\to e} < 7\cdot10^{-13}$	[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, ($\sim$ 180 of B-physics, $\sim$ 15 of Kaons, $\sim$ 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 $(12)_Q(12)_\ell$	$(23)_Q(23)_\ell$	$(12)_Q(13)_\ell$
$B \to Kee\ (C_9)$		$-\theta_{Q23}$	$+\theta_{\ell 12}\theta_{\ell 13}$	$-\theta_{Q23}$
$B \to K\mu\mu\ (C_9)$		$+\theta_{Q23}$	$-\theta_{\ell 23}$	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	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(E865)}_{K^+\to\pi^+\mu^-e^+} < 6.6\times 10^{-11}$	[32, 82]	0	0	0
$\mathrm{Br}^{(NA62)}_{K^+\to\pi^+\nu\bar\nu} = 1.06^{+0.41}_{-0.35}\times 10^{-10}$	[22]	1	θ^2_{Q12}	1
$\mathrm{BR}^{(BNL)}_{K_L\to\mu^+e^-} < 4.7\times 10^{-12}$	[20]	1	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(BaBar)}_{B^+\to K^+\nu\nu} < 1.6\times 10^{-5}$	[95]	$2\theta^2_{Q13}+\theta^2_{Q23}$	1	$2\theta^2_{Q13}+\theta^2_{Q23}$
$\mathrm{BR}^{(LHCb)}_{B^+\to K^+e^-\mu^+} < 6.4\times 10^{-9}$	[118]	θ^2_{Q13}	$\theta^2_{\ell 13}$	0
$\mathrm{BR}^{(BaBar)}_{B^+\to K^+\mu^-\tau^+} < 2.8\times 10^{-5}$	[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}
$\mathrm{BR}^{(SINDRUM)}_{\mu\to e\bar e e} < 1.0\cdot 10^{-12}$	[105]	0	0	$\theta^2_{\ell 23}$
$\mathrm{BR}^{(BELLE)}_{\tau\to 3\mu} < 2.1\cdot 10^{-8}$	[106]	$\theta^2_{\ell 23}$	0	0
$\mathrm{BR}^{(BELLE)}_{\tau\to 3e} < 3.3\cdot 10^{-8}$	[106]	$\theta^2_{\ell 13}$	0	0
$\mathrm{BR}^{(MEG)}_{\mu\to e\gamma} < 4.2\cdot 10^{-13}$	[100, 101]	0	$\theta^2_{\ell 12}$	$\theta^2_{\ell 13}$
$\mathrm{BR}^{(Belle)}_{\tau\to e\bar K^*} < 3.2\cdot 10^{-8}$	[110]	0	0	1
$\mathrm{BR}^{(Belle)}_{\tau\to \mu\bar K^*} < 7.0\cdot 10^{-8}$	[110]	$\theta^2_{\ell 13}$	θ^2_{Q13}	$\theta^2_{\ell 12}$
$\mathrm{CR}^{(SINDRUM-II)}_{Au,\mu\to e} < 7\cdot 10^{-13}$	[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	$\theta^2_{\ell 12}$	$\theta^2_{\ell 12}$

Flavour universality violation

Flavour transfer observables

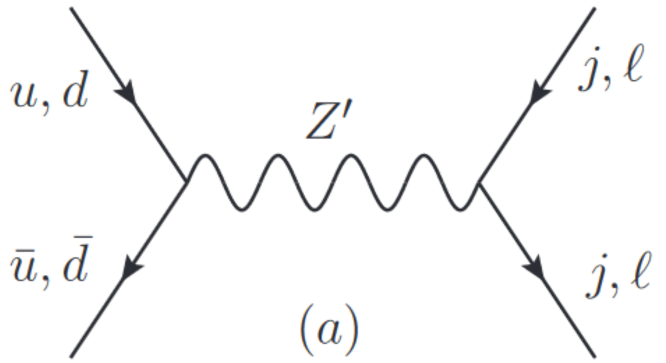
$\Delta F = 2$

LFV

On LHC constraints

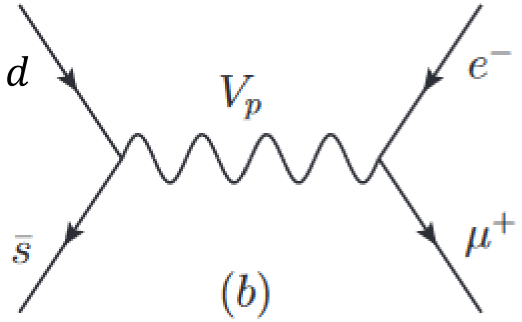
- When $M_V \lesssim$ few TeV, direct production at LHC becomes possible
- LHC is « perfect » for the flavour transfer processes since NP candidate can be produced from quark (or gluon) fusion, but decay leptonically to ensure detection.

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



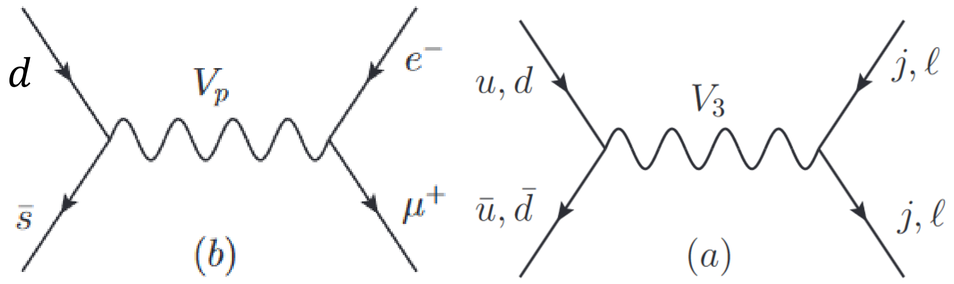
→ Standard searches for Z': di-leptons and di-jets

- 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

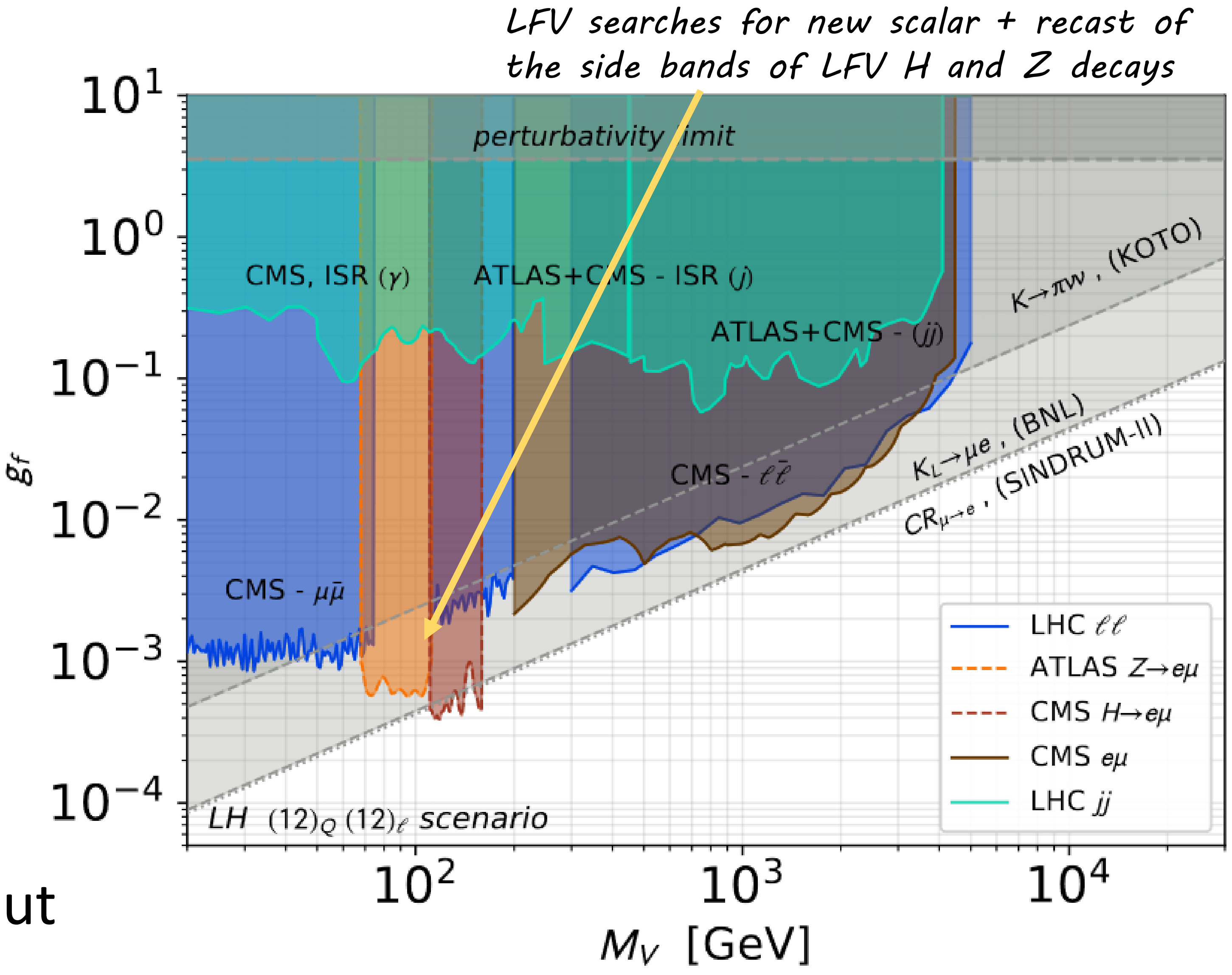


LHC limits and flavour: LH - $(12)_\ell(12)_Q$

- 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 !

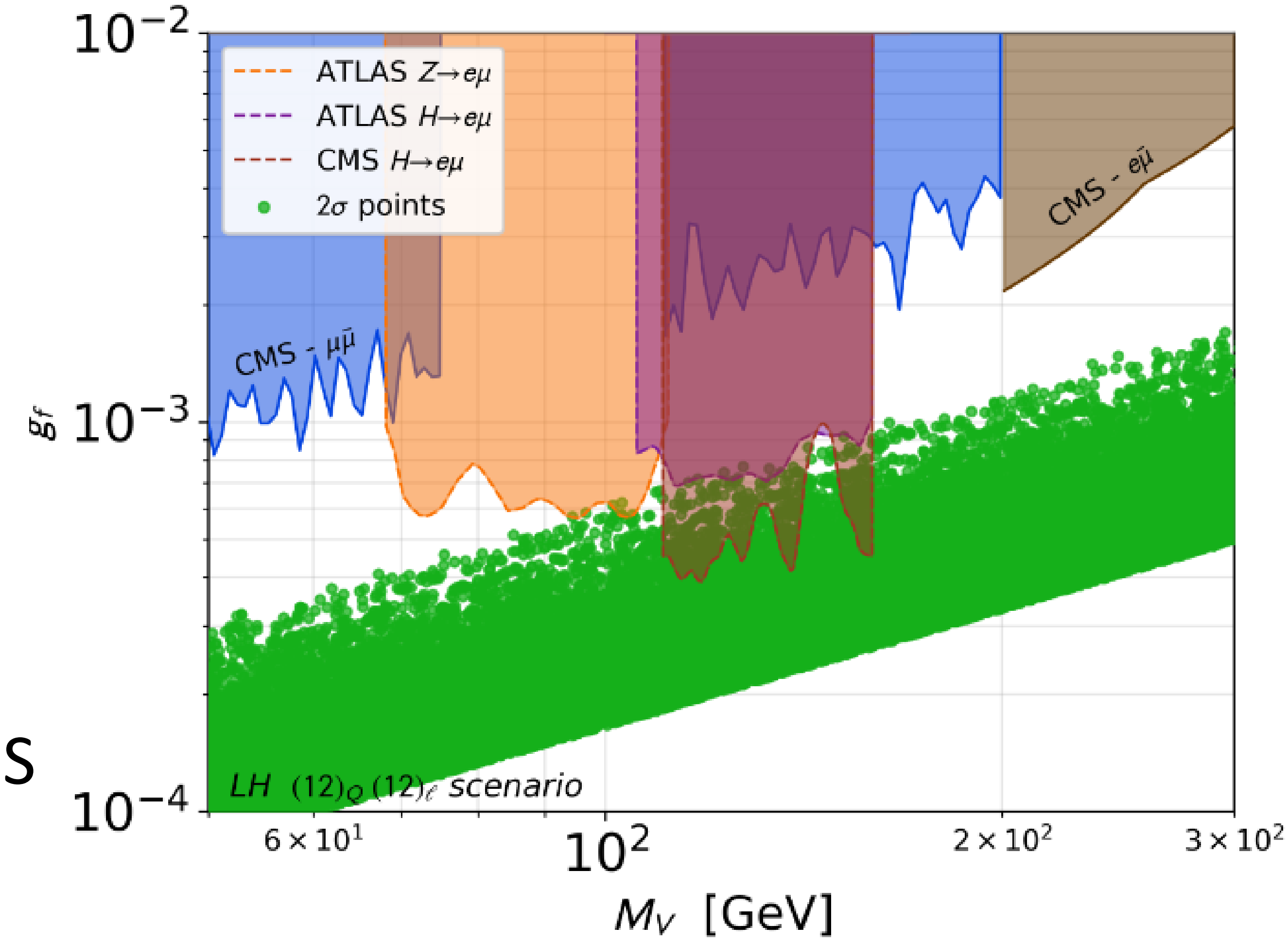


- Limits from Kaonic and muon conversion in nuclei dominate, but LHC constraints are close



LFV decays of H and Z

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

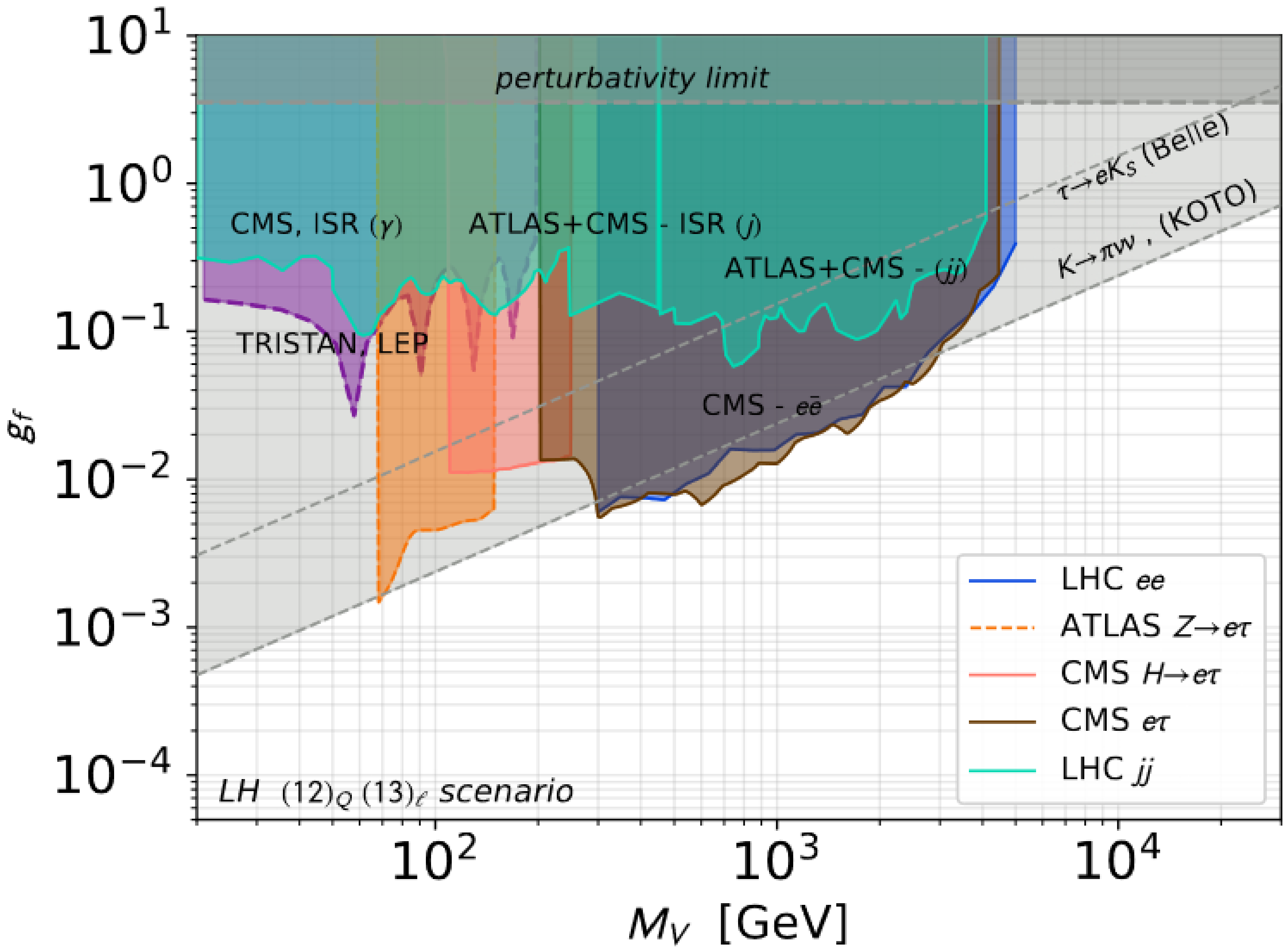


- There is a $\sim 3\sigma$ anomay in the CMS data set, ATLAS data not precise enough to call… for now

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

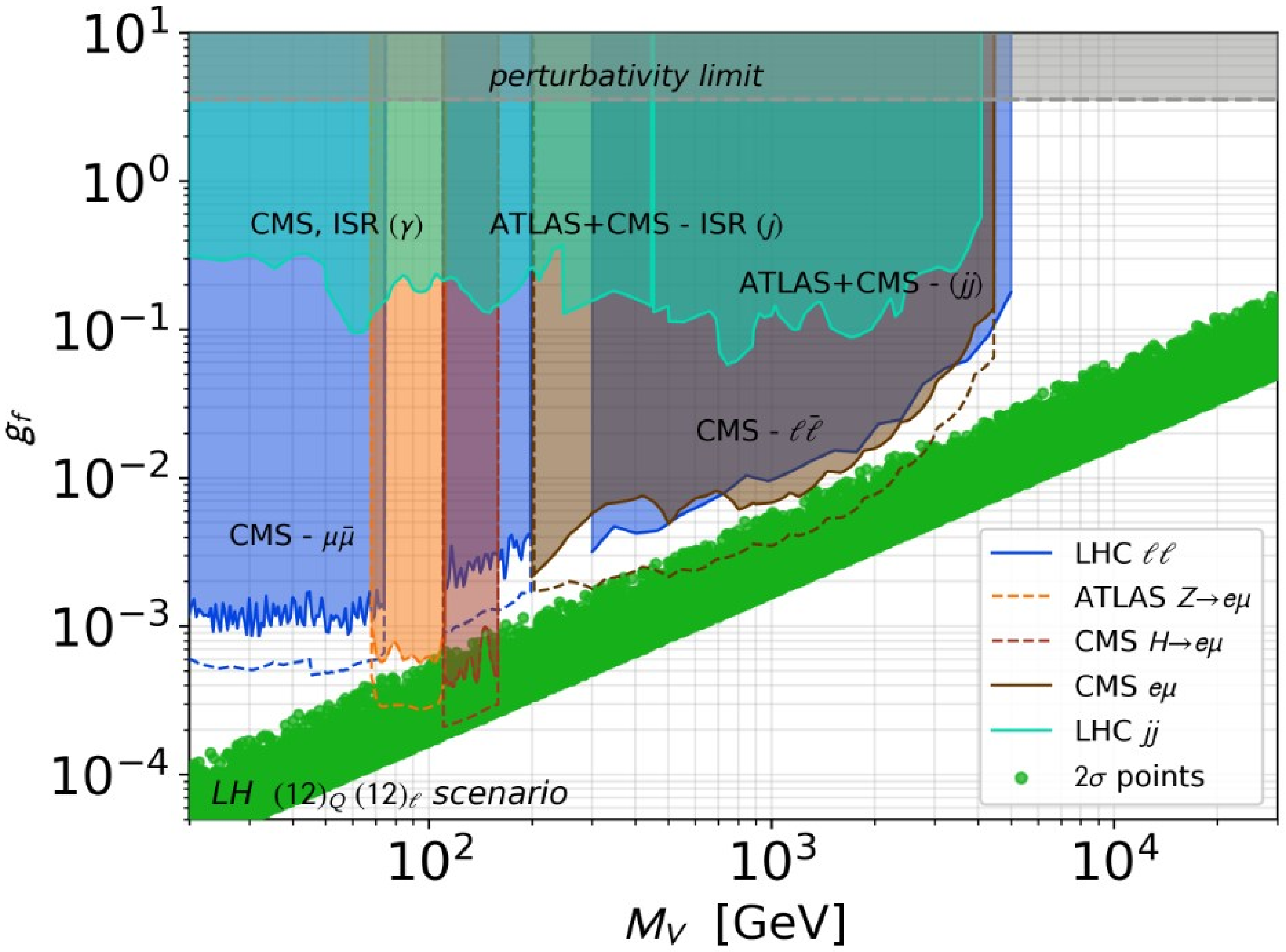
- Corresponds to a « muon as a third generation lepton » scenario

- 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 !
  → 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 can have significant phenomenological consequences
  → 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
- Flavour transfer processes lead to very specific signatures and form an interesting category of observables (nice classification tool!)

Backup

Non-zero mass quarks

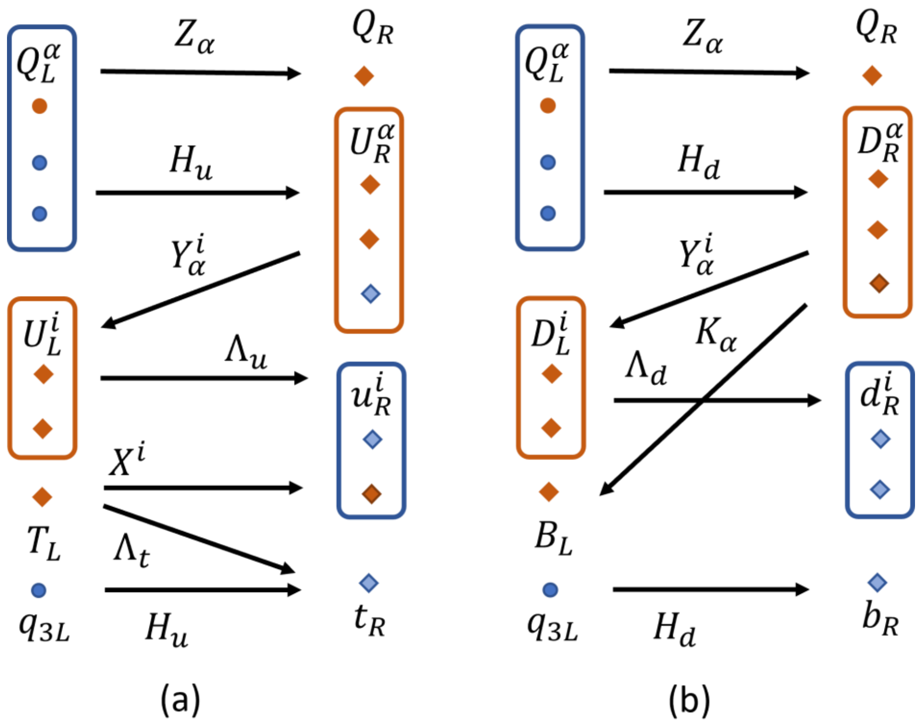
- Hard to protect the PQ symmetry while maintaining a mass for all quarks

$$\det \mathcal{M} = \epsilon_{i_1 i_2 \dots i_{n_Q}} \epsilon_{j_1 j_2 \dots j_{n_Q}} \mathcal{M}_{i_1 j_1} \mathcal{M}_{i_2 j_2} \dots \mathcal{M}_{i_{n_Q} j_{n_Q}} \neq 0$$

$$\sum_{Q_{L\ell}} m_\ell \mathcal{X}_{Q_{L\ell}} - \sum_{Q_{Rr}} n_r \mathcal{X}_{Q_{Rr}} = \mathcal{A} \neq 0$$

→The operator corresponding to the determinant of the quark masses breaks PQ

→We would need at least 10 pairs of chiral quarks with the same electric charge (as the final mass matrix is diagonal by block)

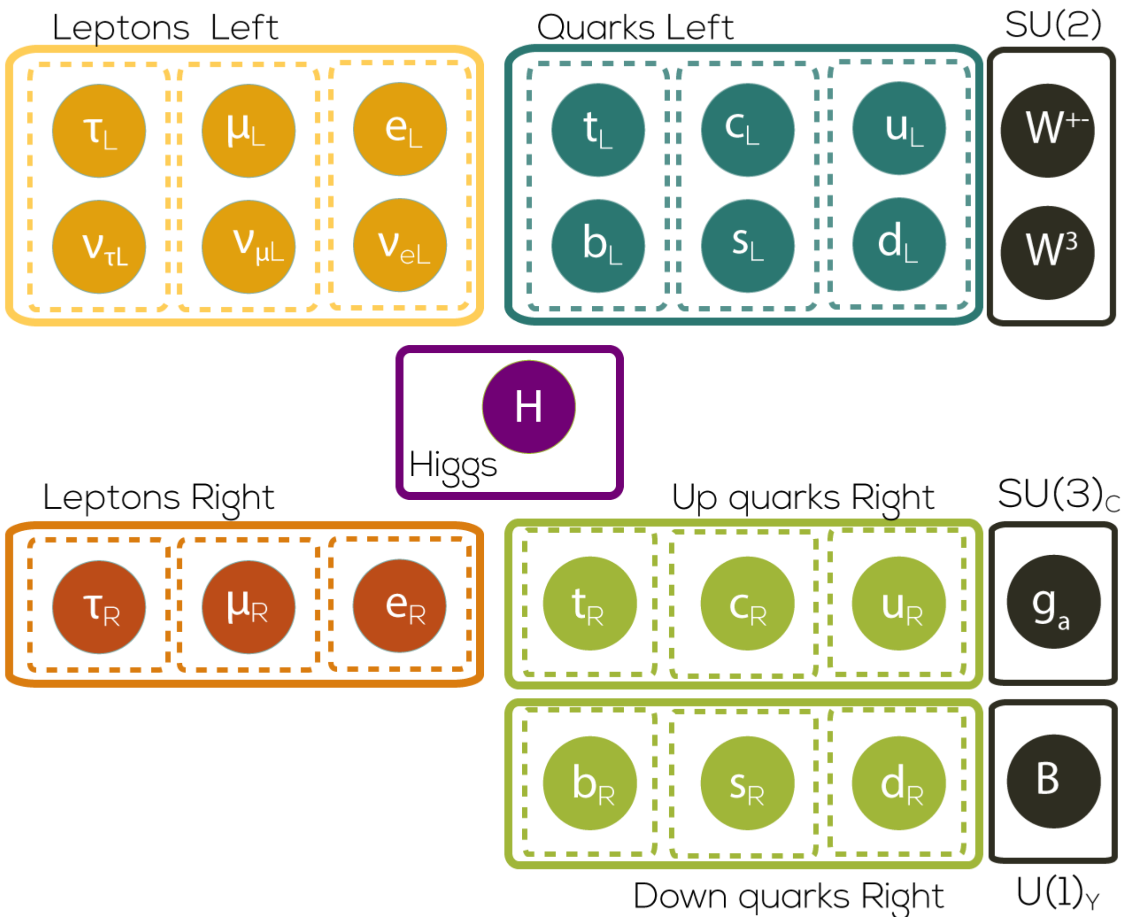


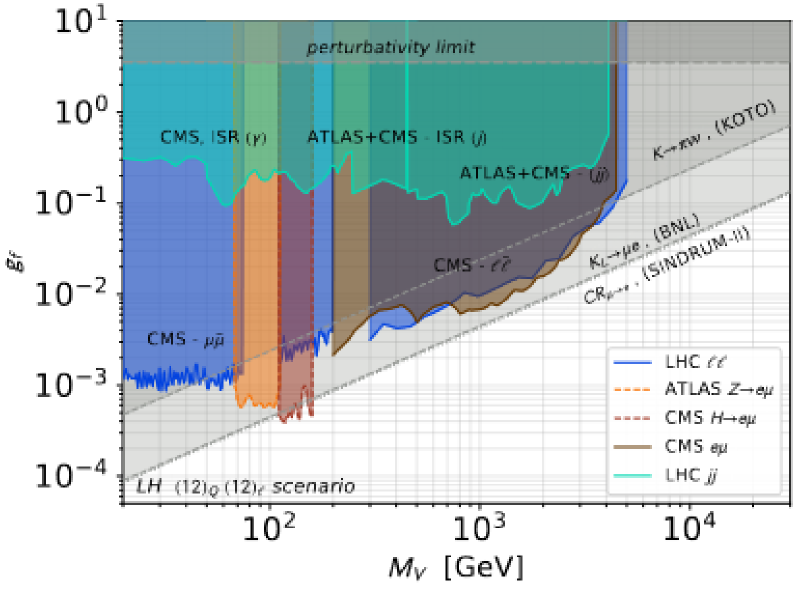
Horizontal flavour gauge groups

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

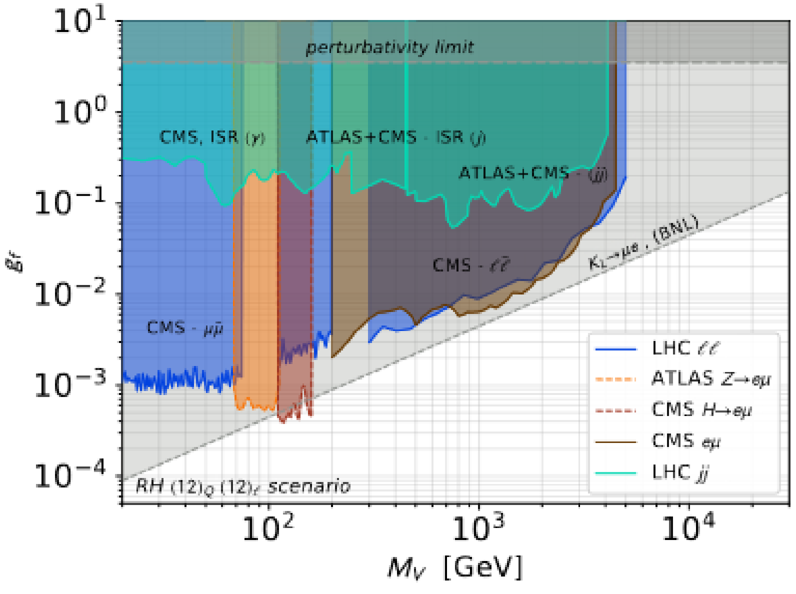
$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.},$$

- 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

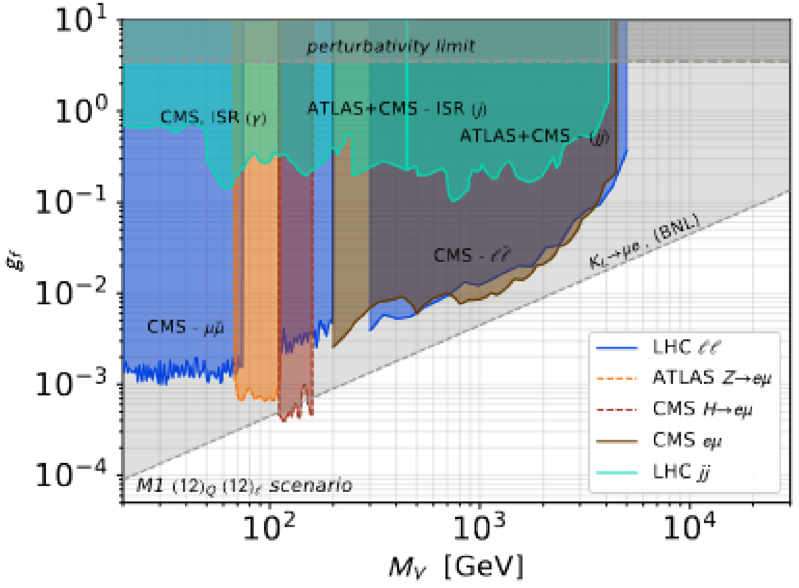


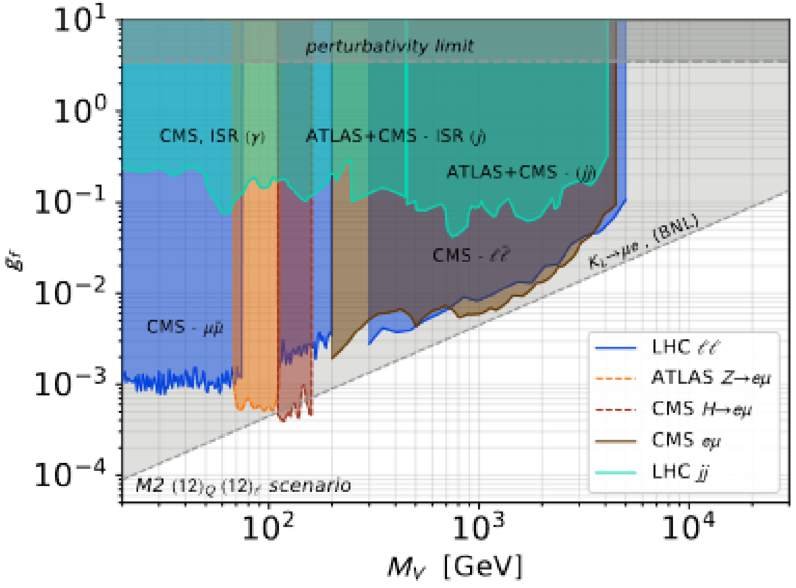

perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
K→πν , (KOTO)
K_L→μe , (BNL)
CR_μ→e , (SINDRUM-II)
CMS - ℓℓ̄
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
LH (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

(a)

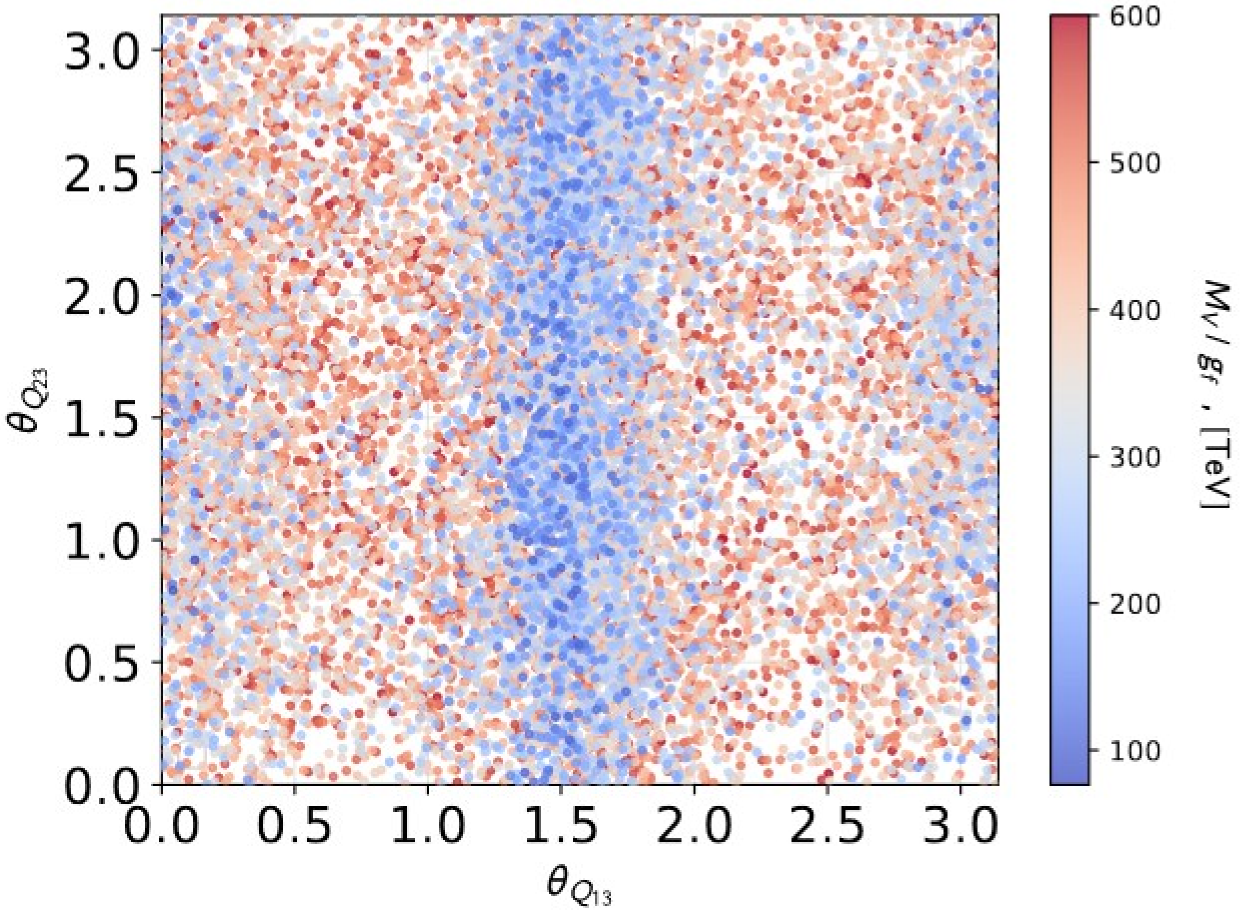

perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
K_L→μe , (BNL)
CMS - ℓℓ̄
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
RH (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

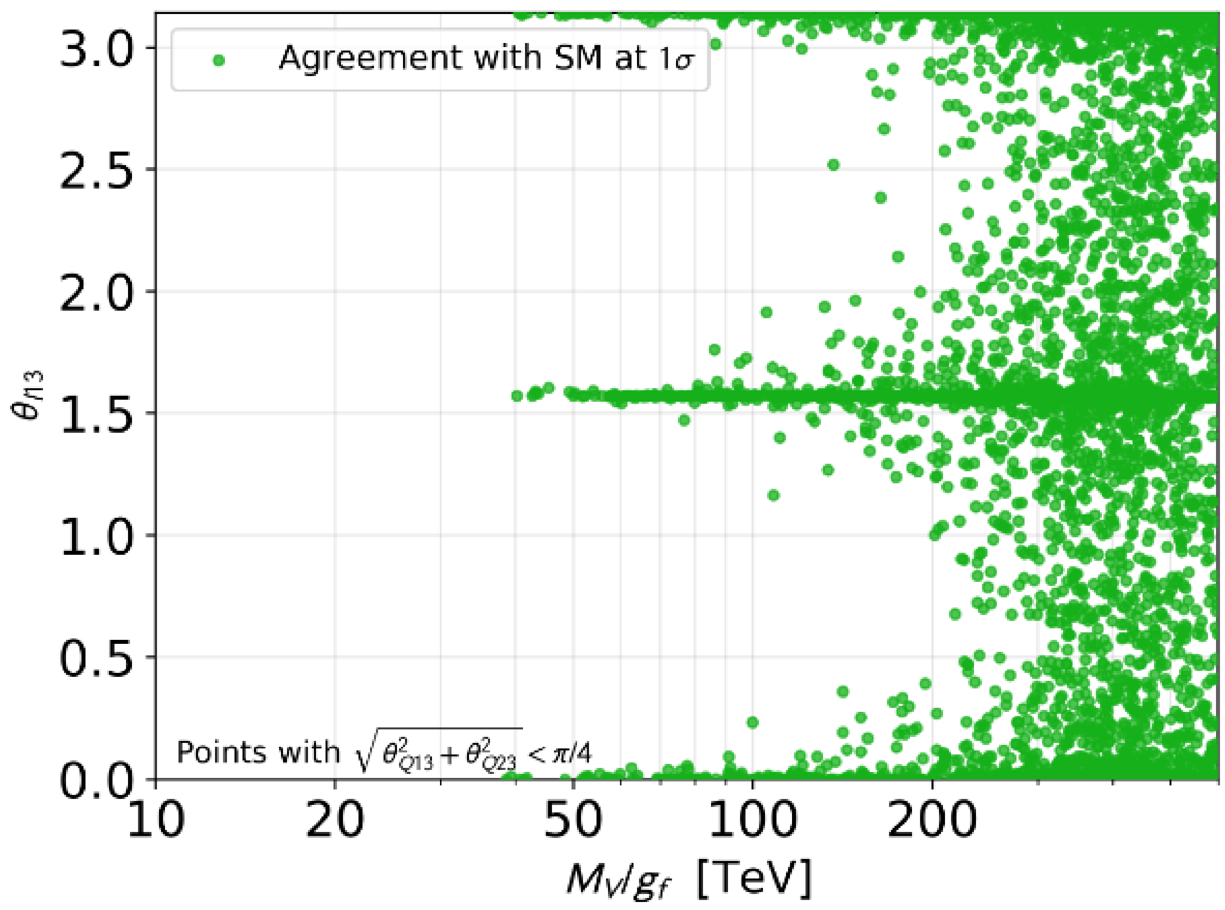
(b)


perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
K_L→μe , (BNL)
CMS - ℓℓ̄
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)
K_L→μe , (BNL)
CMS - ℓℓ̄
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]

Some scan results





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