From Feebly Interacting Particles to flavour transfer models

Luc Darmé
IP2I – CNRS
04/05/2023

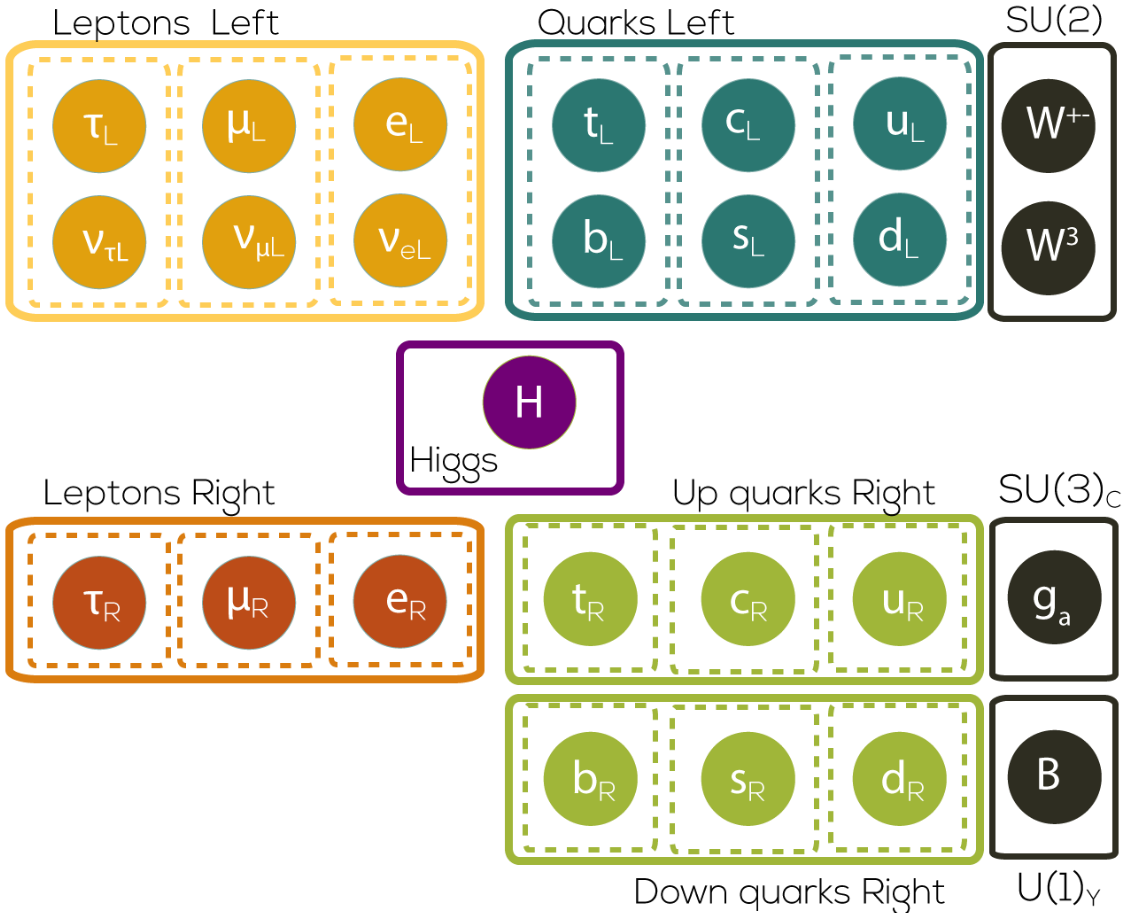
This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101028626

Horizontal flavour gauge groups

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

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

- What if a subset of this group is actually gauged ?
  - →U(1) case: Frogatt-Nielsen constructions, $L_\mu - L_\tau$, flavons, etc…
  - → The non-abelian case has been sparsely studied.
  - →In any case the new gauge coupling is a free parameter



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

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

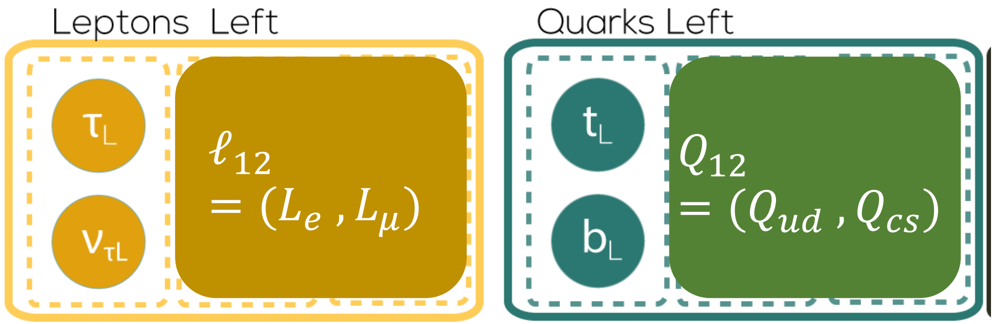
$$\mathcal{A} = ([C(Q_i) - C(L_i)] - [2C(u_{R,i}) - C(d_{R,i}) - C(e_{Ri})])$$

In absence of new low-energy fermions, there is a finite (and quite small) number of possible combination !
LH, RH ; L, B ; and M1, M2

- Gauge boson masses are free parameters!
  - → Even with a large VEV, small gauge couplings imply light new states

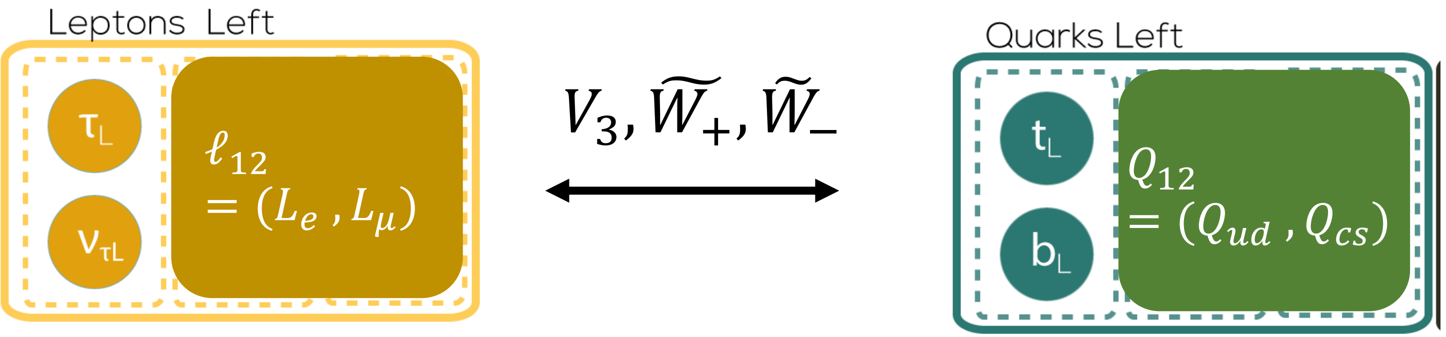
$$M_{V_1}^2 = M_{V_2}^2 = M_{V_3}^2 = \frac{g_f}{2} \sum_i v_\phi^2$$

- For instance: (LH) scenario
  - → Reduce the number of fundamental fermions
  - → Couples both to leptons and quarks



Flavour transfer - 1

- The key point: new flavour gauge boson 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 »

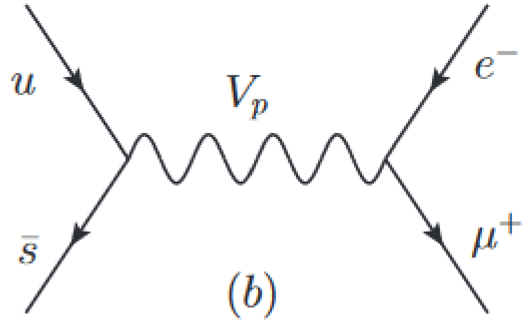
$$L \supset \widetilde{W}_+^{\nu}\ (\bar{\mu}\ \gamma_\nu e + \bar{s}\gamma_\nu d) + \widetilde{W}_-^{\nu}\ (\bar{e}\ \gamma_\rho\, \mu\ + \bar{d}\ \gamma_\nu\, s)$$

Grant an extremely strong protection against "pure" four-fermions FV processes

→ Particularly for $M_{V_1} = M_{V_2} = M_{V_3}$

$$\mathcal{L}_{eff} \supset -\sum_{a,f,f'} \frac{g_f^2}{2S_{ijkl} M_V^2} (2\delta^{il}\delta^{jk} - \delta^{ij}\delta^{kl}) (\overline{F}_i \gamma^\mu F_j) (\overline{F}'_k \gamma_\mu F'_l) \ ,$$

Symmetry factor *Flavour transfer !* *Flavour diagonal*



Flavour transfer - 2

- The presence of $SU(2)_f$ implies that the fermion mass matrices have a structure

For instance, in the case of down-type quarks

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\,d^I_{Rj} \quad \Rightarrow \quad \mathcal{M}_d \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & \epsilon & \epsilon \\ 1 & 1 & 1 \end{pmatrix}$$

This should be exactly zero if the SU(2) flavour gauge in the (LH) scenarios is not broken

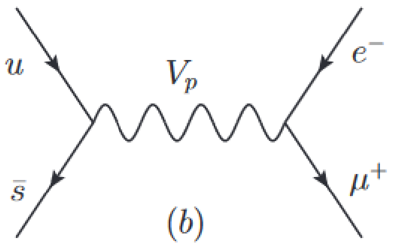
- We can parametrise SU(2) breaking by small spurions → corresponds to angles in the quarks/lepton rotations matrices
- But even in absence of spurions, flavour-transfer processes will play an important role by generating many exotic flavourful processes.

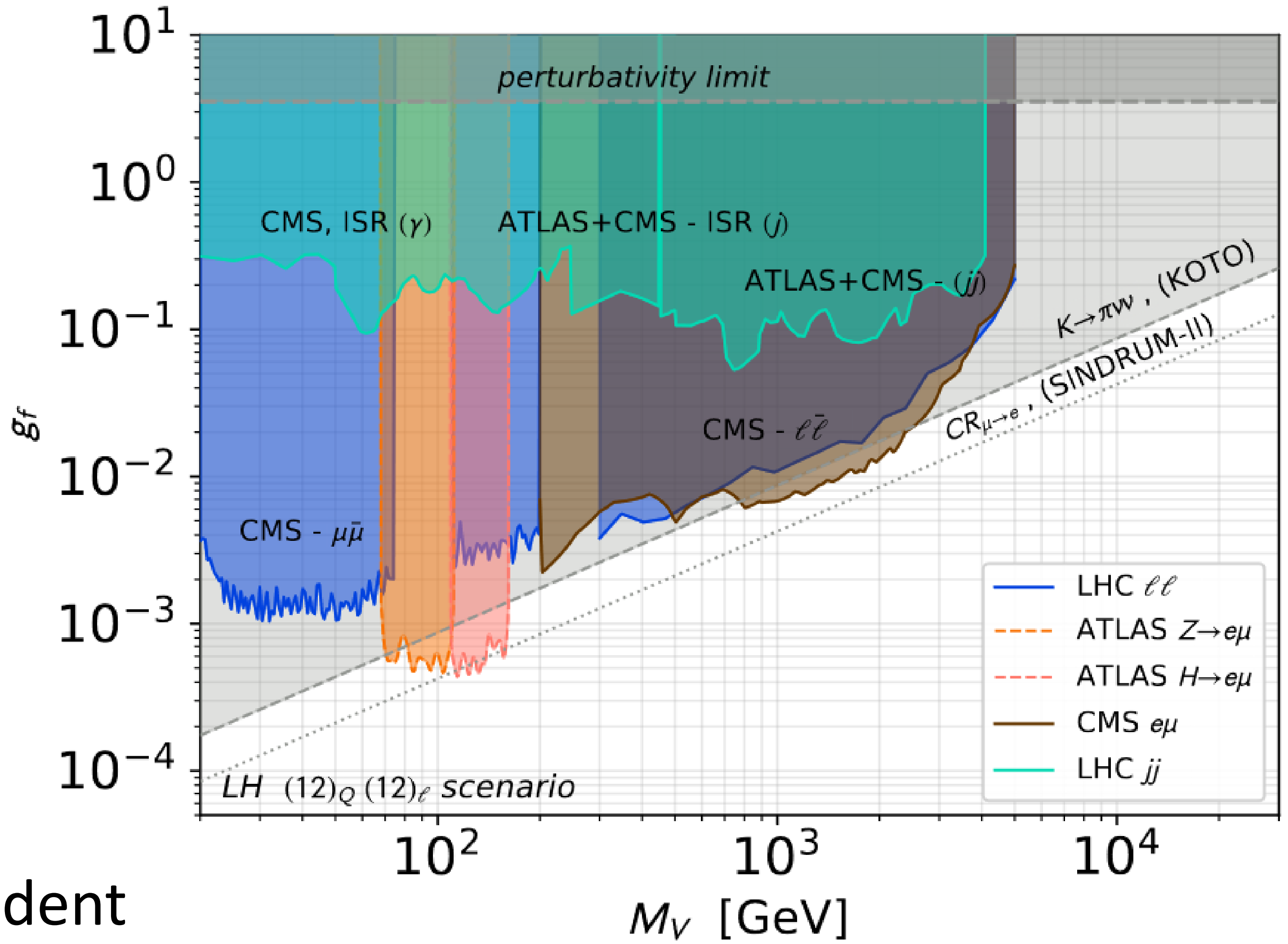
$$K \to \pi e \mu\,, \quad K \to \pi \nu \nu$$
$$B \to K e \mu \quad \tau \to \mu K$$
$$B \to \pi e \mu$$

Etc … this depends on which generation is included in the SU(2)f doublet, and which type of fermions participate in the interaction

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



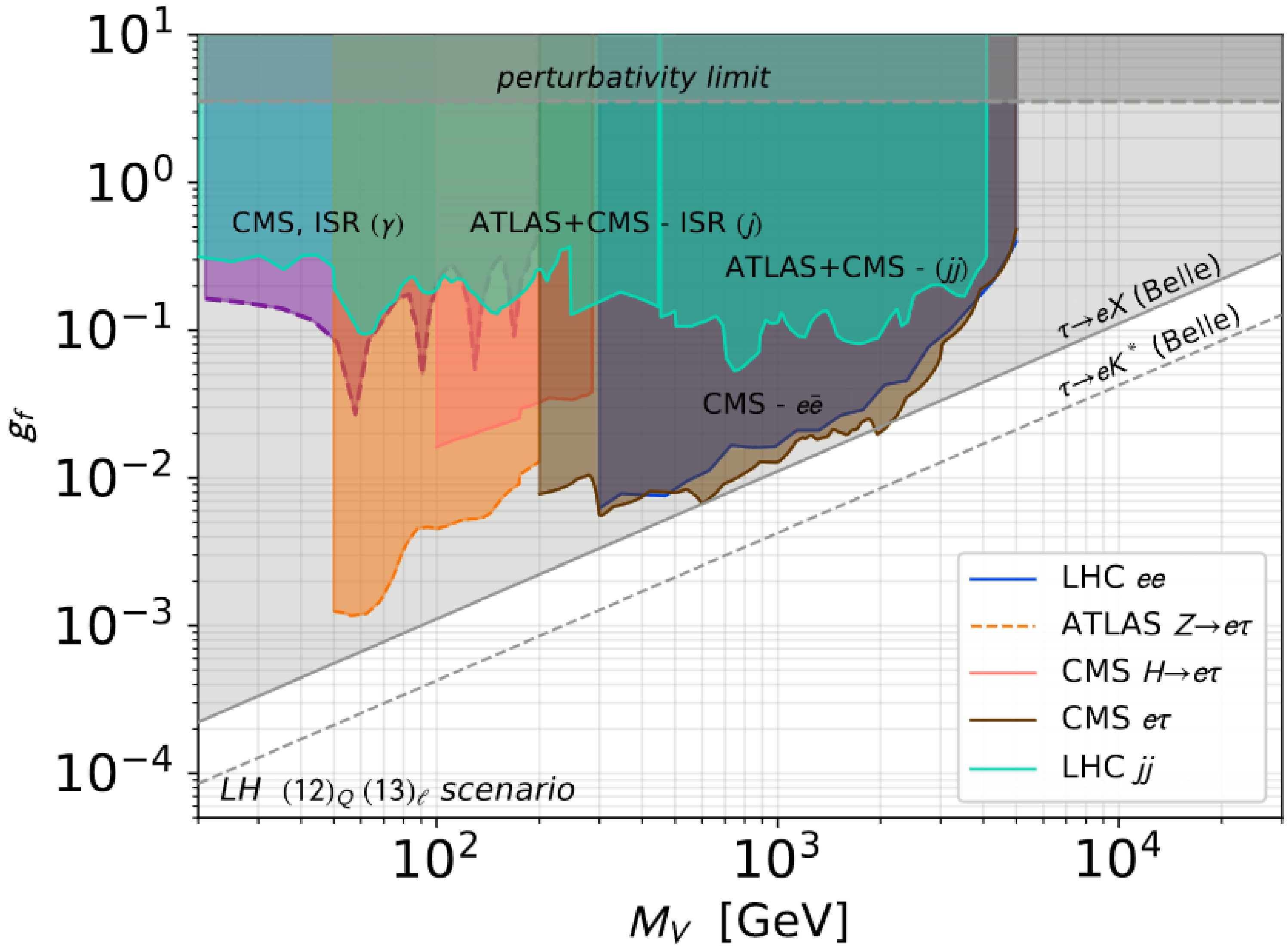


- The strongest model-independent flavour limit comes from $K \to \pi\,\bar{\nu}_e\nu_\mu$

LHC limits and flavour: LH - $(13)_\ell(12)_Q$

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

- Now the strongest limits arise from hadronic τ decays
- LHC constraints are also weakened



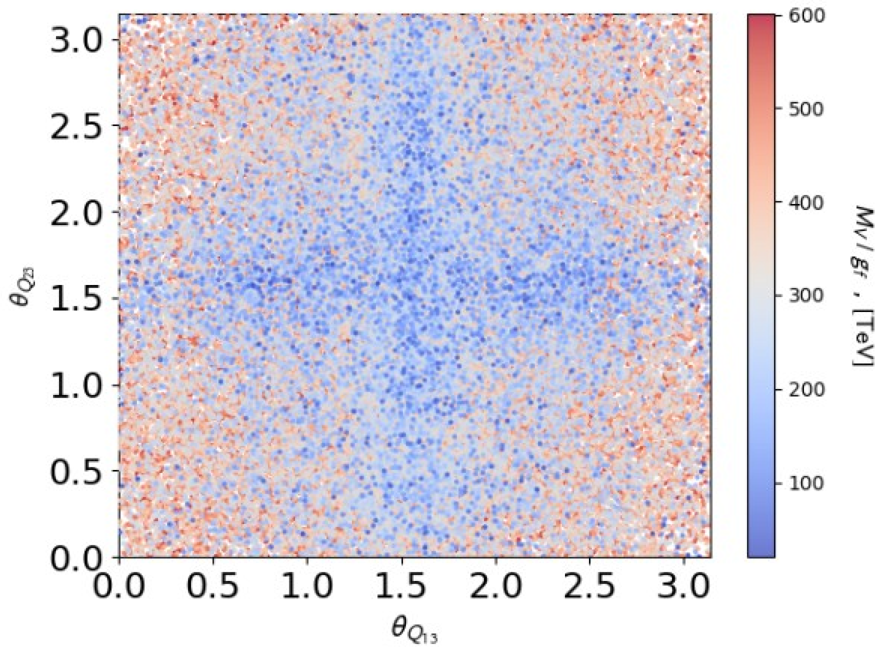
Conclusion

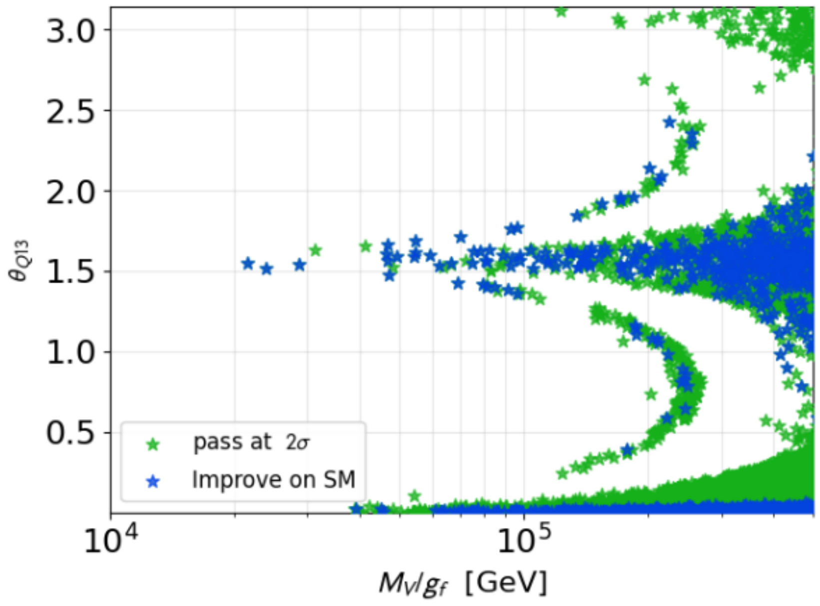
- FIPs have an extremely rich phenomenology in link with flavour and have been long used to fit various "precision anomalies"
  - →In a sense, flavour physics lives naturally at the scale of these NP particles
- Non-abelian flavour gauge symmetries naturally lead to GeV to TeV new vectors for small couplings
- Flavour transfer paradigm leads to very specific (and not often experimentally considered) signatures
  - → SuperIso implementation under way
- LHC has an important role to play for new vectors below the TeV

Backup

SuperIso implementation

- @Nazila: added the mesons oscillations observables
- Added several leptonic observables
  - → Not always generic at this stage, more work needed to have fully generic routines.
- Scan created via BSMArt (work in progress)
  - → Interface with SuperIso done by requiring a χ^2 output + launching minimisation



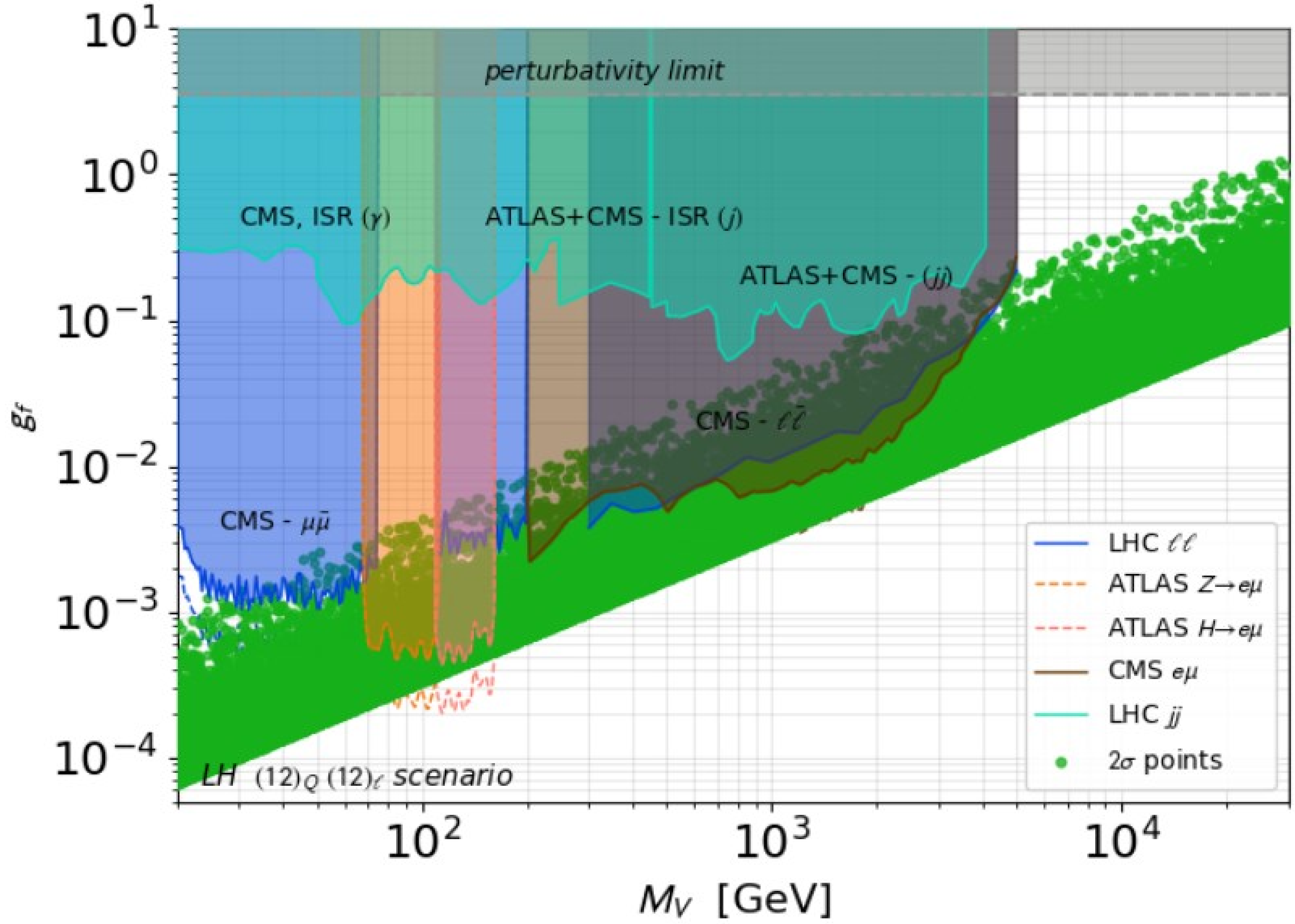


A great many observables to include ...

- Once spurions are introduced, basically every possible FV observables may contribute
- We

Constraints	Used Refs.	$SU(2)_f$ flavour orientation $(12)_Q(12)_L$	$(12)_Q(\tilde{12})_L$	$(12)_Q(13)_L$
$B \to Kee\ (C_9)$		$-\theta_{Q13}$	$+\theta_{Q13}$	$\theta_Q\theta_L^2$
$B \to K\mu\mu\ (C_9)$		$+\theta_{Q13}$	$-\theta_{Q13}$	$+\theta_{Q13}$
$R_K,\ R_K^*$		$+\theta_{Q13}$	$-\theta_{Q13}$	$+\theta_{Q13}$
$K \to \pi ee\ (C_9)$		$-\theta_{\ell 12}$	$+\theta_{\ell 12}$	$\theta_{\ell 23}\theta_{\ell 13}$
$K \to \pi\mu\mu\ (C_9)$		$+\theta_{Q13}$	$-\theta_{Q13}$	$\theta_{\ell 12}$
$\mathrm{BR}^{(\mathrm{E865})}_{K^+\to\pi^+\mu^+e^-} < 1.3\times 10^{-11}$	[17, 40, 42]	1	$\theta_{\ell 12}^4$	0
$\mathrm{BR}^{(\mathrm{E865})}_{K^+\to\pi^+\mu^-e^+} < 6.6\times 10^{-11}$	[17, 40, 42]	$\theta_{\ell 12}^4$	1	$\theta_{\ell 23}^2$
$\mathrm{Br}^{(\mathrm{NA62})}_{K^+\to\pi^+\nu\bar{\nu}} = 1.06^{+0.41}_{-0.35}\times 10^{-10}$	[43–47]	1	1	1
$\mathrm{BR}^{(\mathrm{BNL})}_{K_L\to\mu^+e^-} < 4.7\times 10^{-12}$	[48?]	1	$\theta_{\ell 12}^4$	$\theta_{\ell 23}^2$
$\mathrm{BR}^{()}_{K_L\to\mu\mu} <$	[82]			
$\mathrm{BR}^{()}_{K_S\to\mu\mu} <$	[82]			
K oscillations				
D oscillations	[83–85]	θ_{Q23}^2	"	"
B_d oscillations		θ_{Q13}^2	"	"
B_s oscillations		θ_{Q23}^2	"	"
$\mathrm{BR}^{(\mathrm{SINDRUM})}_{\mu\to e\bar{e}e} < 1.0\cdot 10^{-12}$	[57]	$\theta_{\ell 13}^2\theta_{\ell 23}^2$	"	0
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to 3\mu} < 2.1\cdot 10^{-8}$	[58]	$\theta_{\ell 13}^2$	"	$\theta_{\ell 13}^2\theta_{\ell 23}^2$
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to 3e} < 3.3\cdot 10^{-8}$	[58]	$\theta_{\ell 23}^2$	"	0
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau^-\to\mu^-e^+e^-} < 1.8\cdot 10^{-8}$	[58]	$\theta_{\ell 13}^2$	"	$\theta_{\ell 13}^2\theta_{\ell 23}^2$
$\mathrm{BR}^{(\mathrm{BELLE})}_{\tau\to e^-\mu^+\mu^-} < 2.7\cdot 10^{-8}$	[58]	$\theta_{\ell 23}^2$	"	"
$\mathrm{BR}^{(\mathrm{MEG})}_{\mu\to e\gamma} < 4.2\cdot 10^{-13}$	[53, 54]	$\theta_{\ell 13}^2\theta_{\ell 23}^2$	"	$\theta_{\ell 13}^2$
$\mathrm{BR}^{(\mathrm{BaBar})}_{\tau\to e\gamma} < 3.3\cdot 10^{-8}$	[55]	$\theta_{\ell 23}^2$	"	"
$\mathrm{BR}^{(\mathrm{BaBar})}_{\tau\to\mu\gamma} < 3.3\cdot 10^{-8}$	[55]	$\theta_{\ell 13}^2$	"	$\theta_{\ell 13}^2\theta_{\ell 23}^2$
$\mathrm{CR}^{(\mathrm{SINDRUM\text{-}II})}_{Au,\mu\to e} < 7\cdot 10^{-13}$	[56, 78, 79]	$1-20\theta_{\ell 12}$	"	$\theta_{\ell 23}^2 - 20\theta_{\ell 13}\theta_{\ell 23} + 46\theta_{\ell 13}^2$
$\mu\bar{e}\to e\bar{\mu}$ oscillations				
$\frac{\sigma^{\mathrm{CCFR}}_{\mathrm{trid.}}}{\sigma^{\mathrm{SM}}_{\mathrm{trid.}}} = 0.82\pm 0.28$	[74–77]			

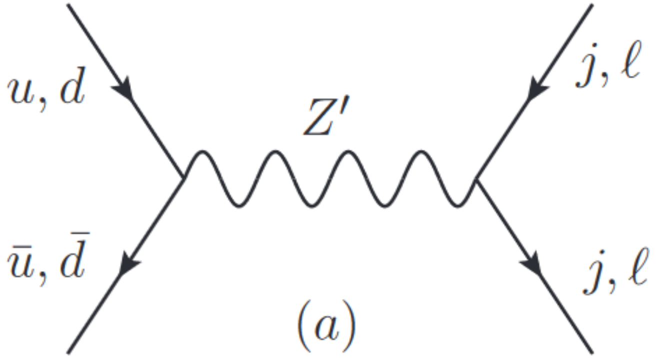
Putting everything together



On LHC constraints

- LHC « perfect » 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 : di-leptons and di-jets

- More exotic searches: flavour violation to kill the QED background