Gauge SU(2) flavour transfers

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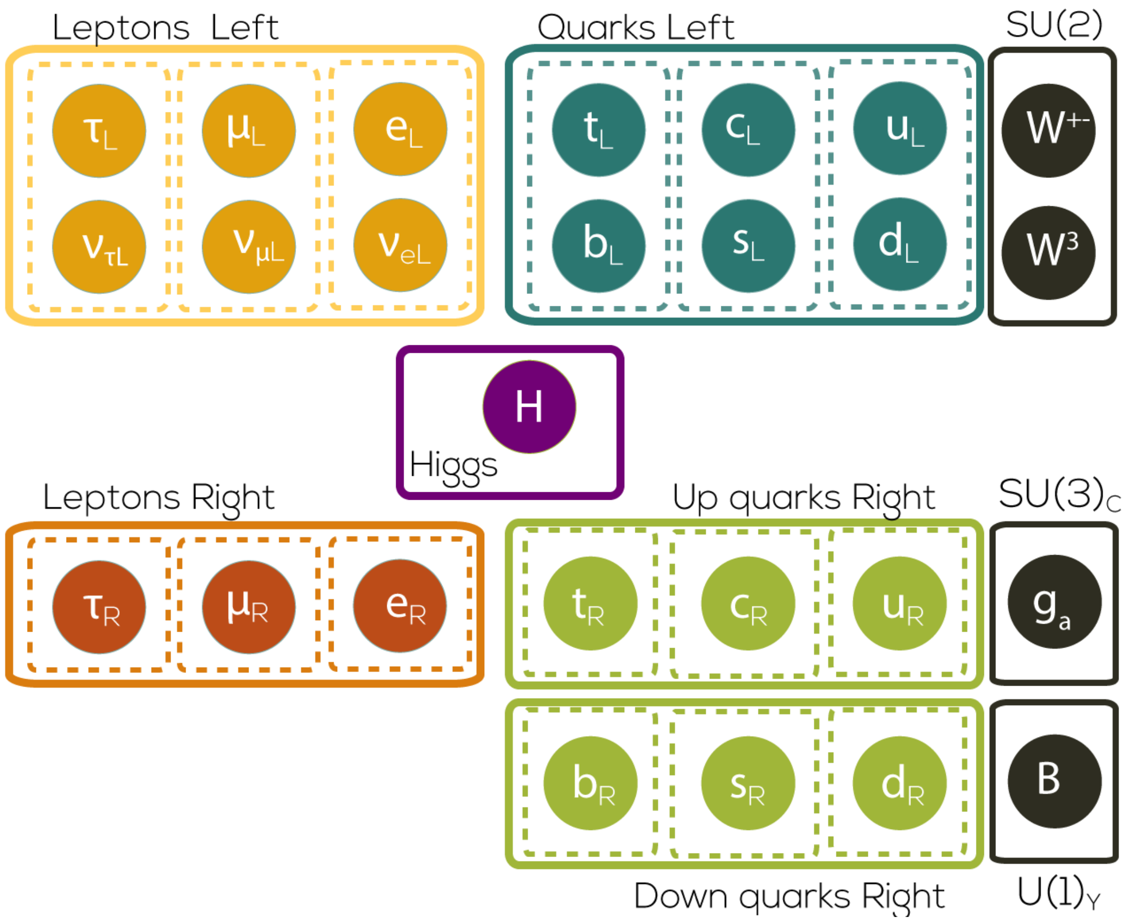
Horizontal flavour gauge groups

- 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.
  - →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

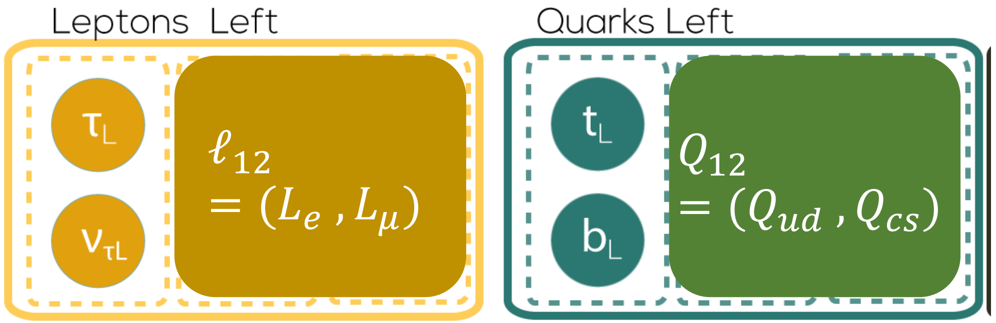
$$\mathcal{A} = ([C(Q_i) - C(L_i)] - [2C(u_{R,i}) - C(d_{R,i}) - C(e_{Ri})])$$

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 (required by flavour constraints imply light new states

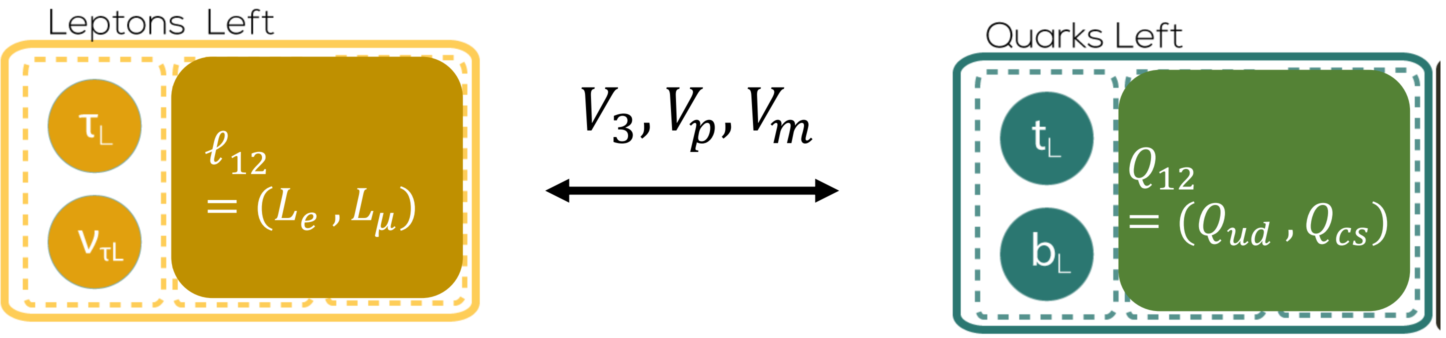
$$M_{V_1}^2 = M_{V_2}^2 = M_{V_3}^2 = \frac{g_f}{2}\sum_i v_\phi^2$$

- For instance: left-handed scenario with $(12)_\ell(12)_{Q_L}$ interactions
  - → Reduce the number of fundamental fermions
  - →Couples both to LH leptons and LH 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 »

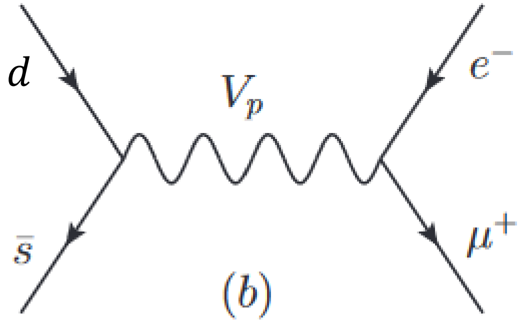
$$V_p^\nu\,(\bar{\mu}\;\gamma_\nu e + \bar{s}\gamma_\nu d) + V_m^\nu(\bar{e}\;\gamma_\nu\,\mu\; + \bar{d}\;\;\gamma_\nu\,s)$$

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

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

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

Symmetry factor *Flavour transfer !* *Flavour diagonal*



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.

$K \to \pi e \mu$, $K \to \pi \nu \nu$

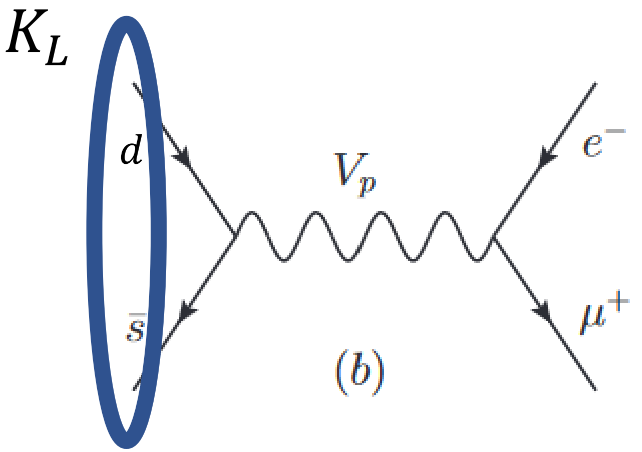
$B \to K e \mu$, $\tau \to \mu K$

$B \to \pi e \mu$

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

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

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

- 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

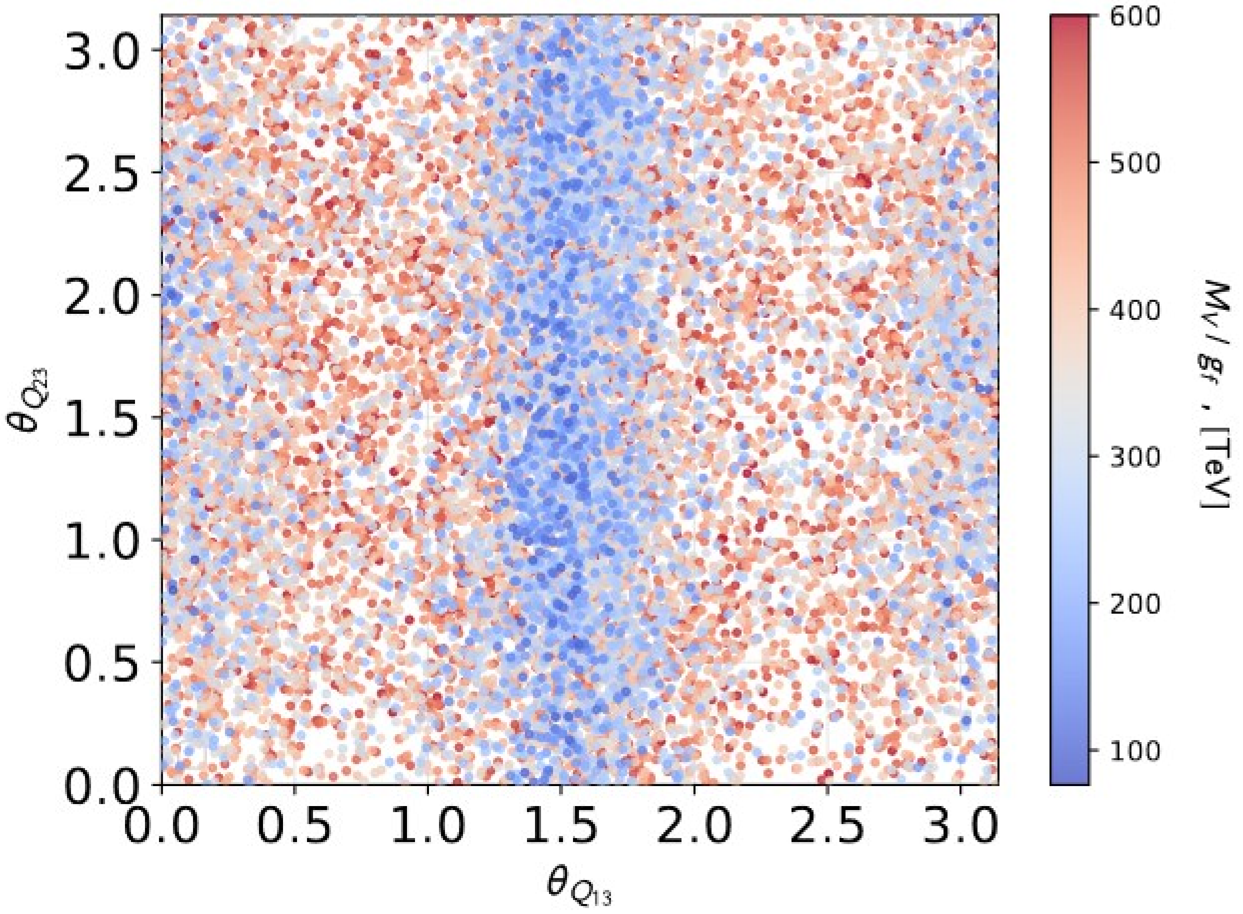
- Thanks to Nazila and Siavash, Kaonic observables have been included (+ some additions for LFV final states)
- Added several leptonic observables

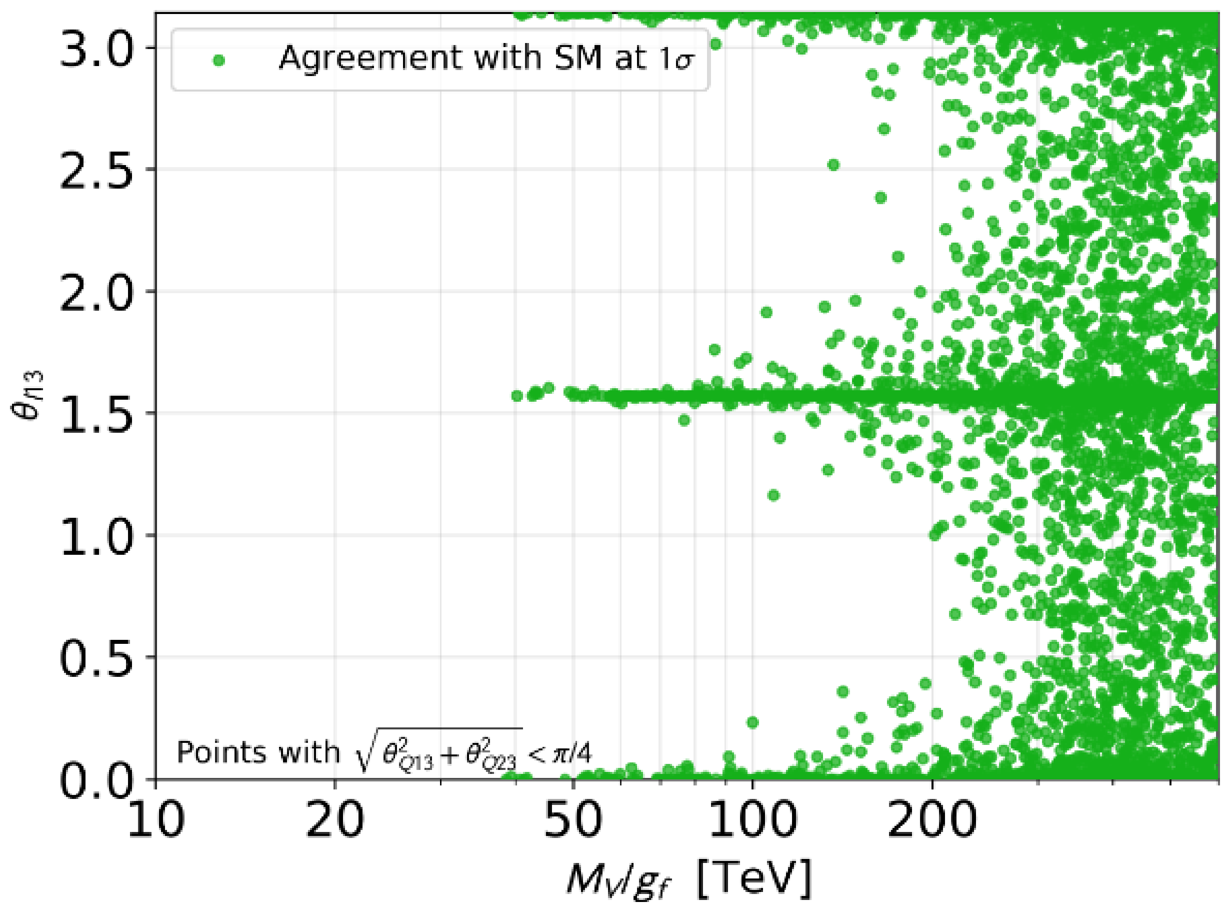
  → Not always generic at this stage, more work needed to have fully generic routines.
- Interface between the χ^2 routines of SuperIso and BSMArt (using MultiNest)

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

Some results



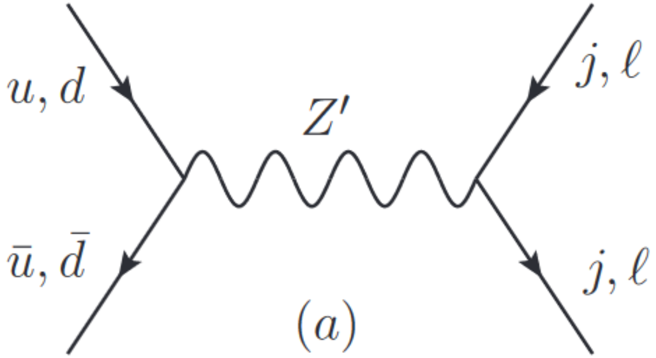


- First generations couplings are avoided as much as possible of course …

On LHC constraints

- LHC is « perfect » for the flavour transfer models since NP candidate can be produced from quark (or gluon) fusion, but decay leptonically to ensure detection.

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

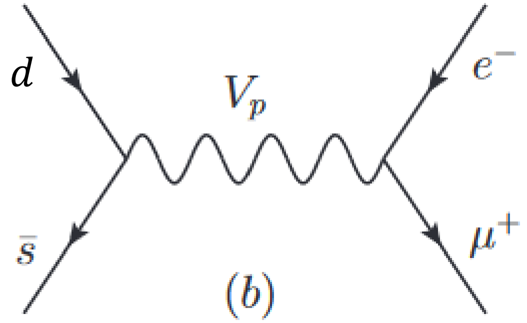


→ Standard searches : di-leptons and di-jets

- More exotic searches are additional viable:

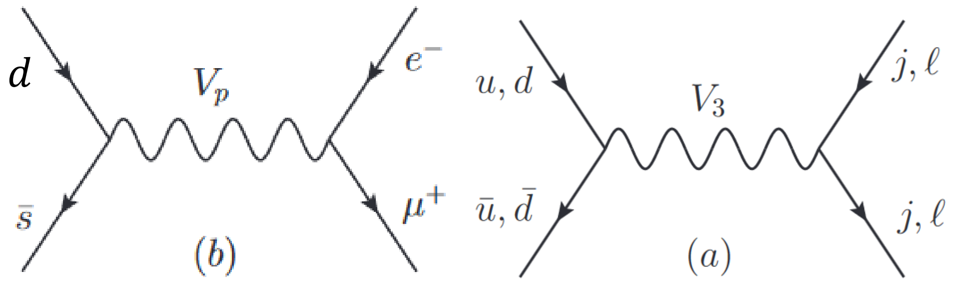
  → The proton contains enough sea-quarks to produce the off-diagonal flavour boson

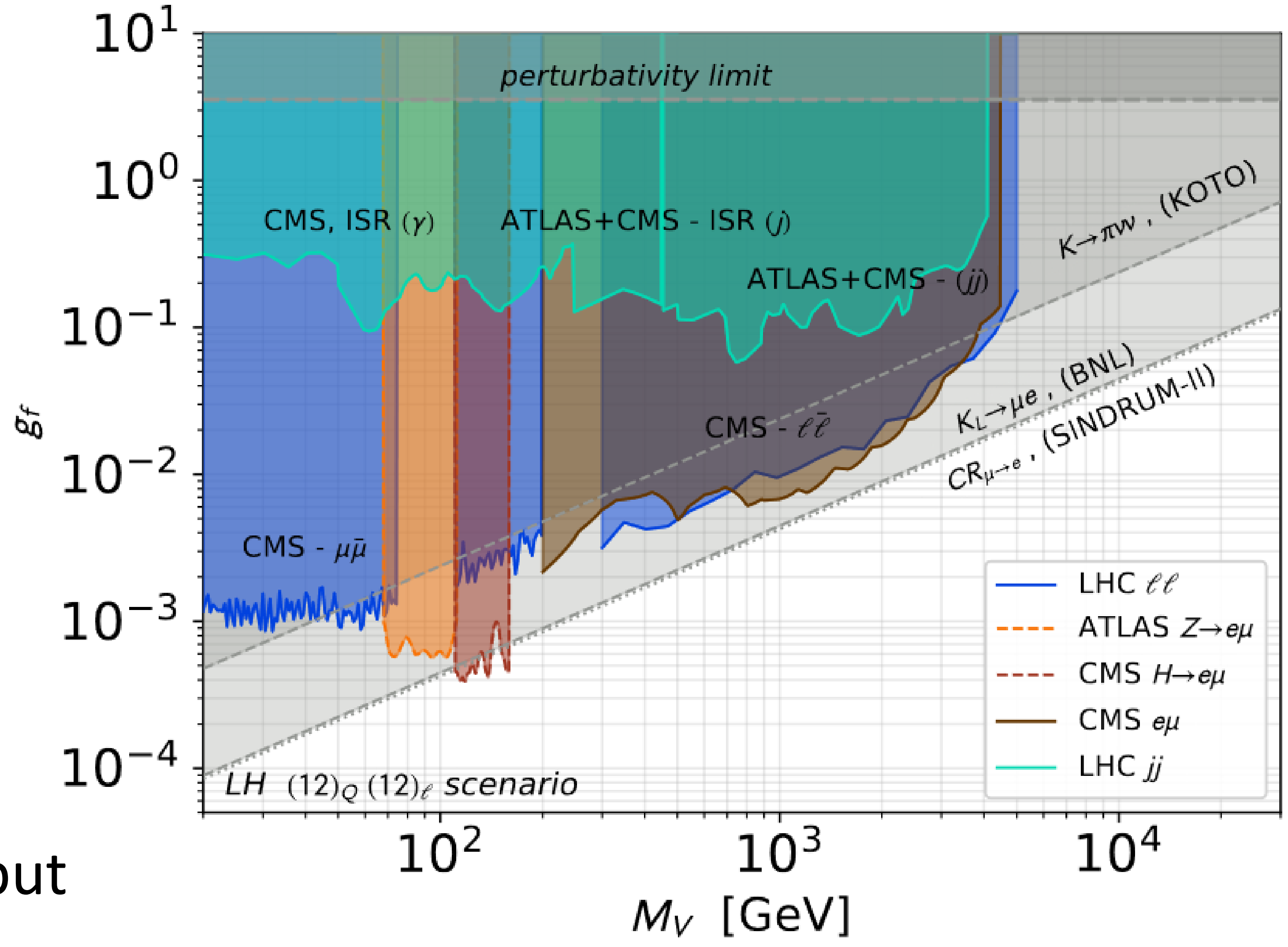
  → Lepton flavour violation in the final states limit the QED background



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 !

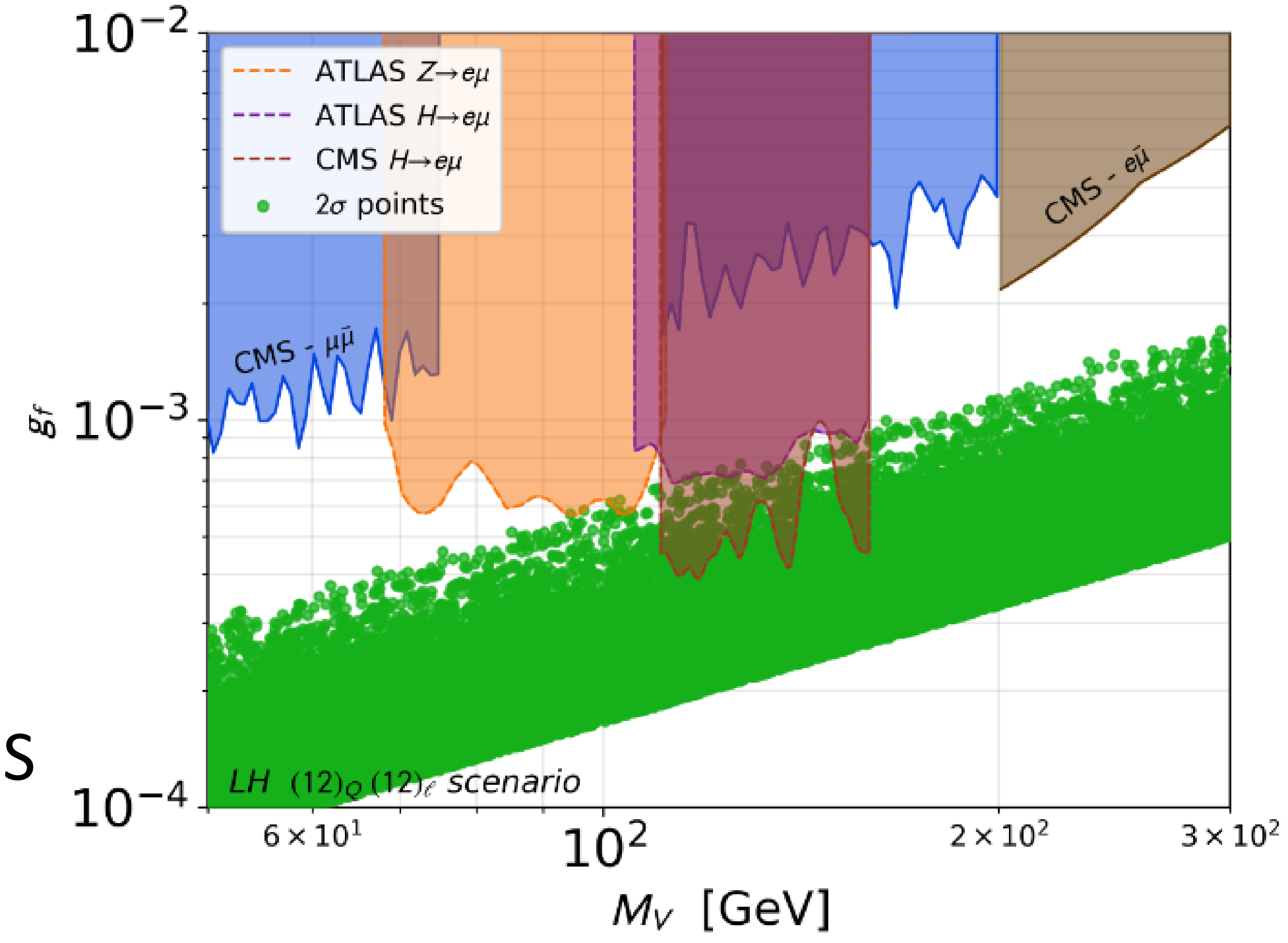




- Limits from Kaonic and muon conversion in nuclei dominate, but LHC constraints are close

LFV decays of H and Z

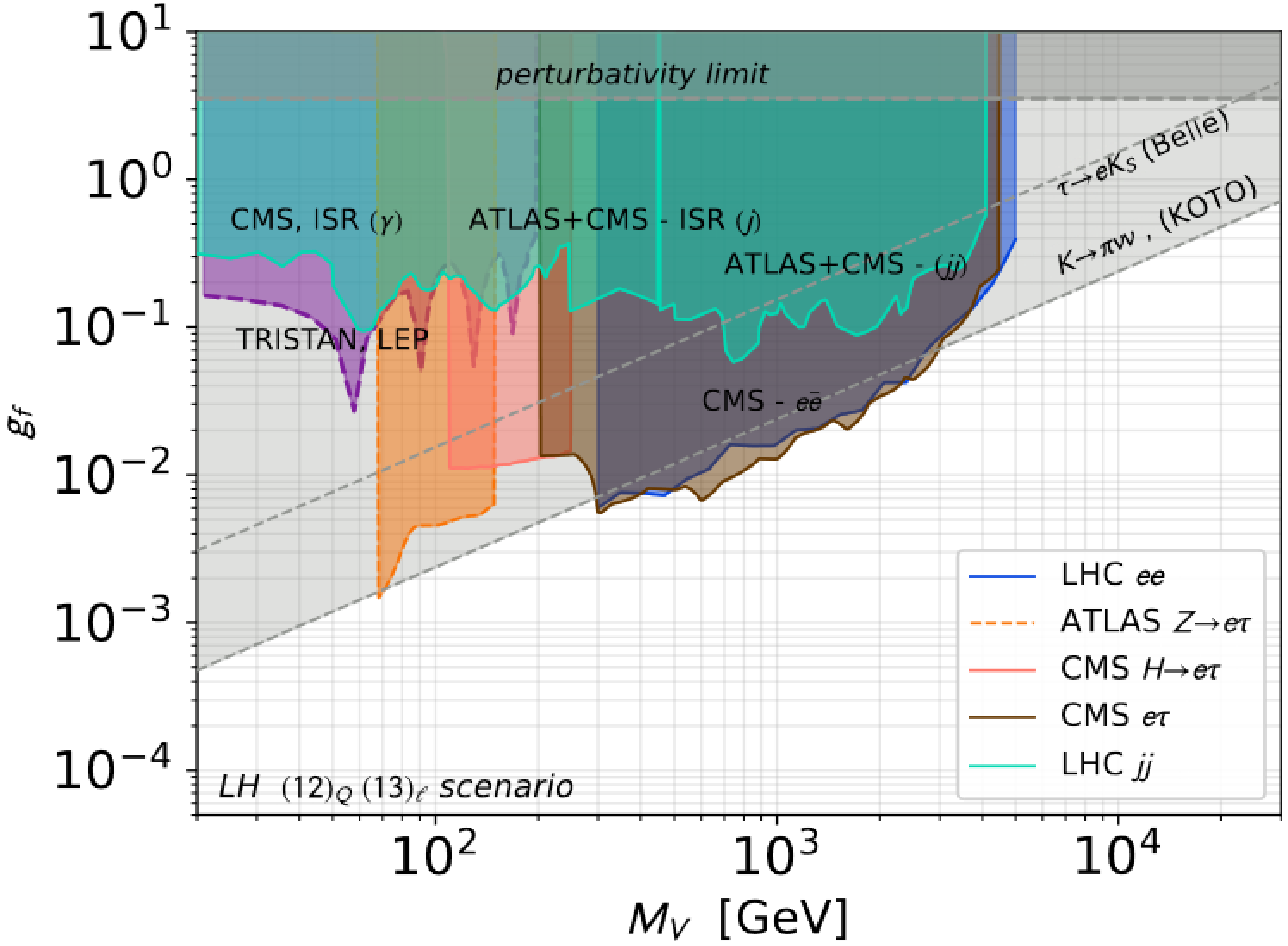
- The best constraints arise from the recasting of LFV H and Z decays
  - → $Z \rightarrow e\mu, e\tau, \mu\tau$ and $h \rightarrow \ e\mu, e\tau, \mu\tau$
  - →We calibrate the signal on the Z and H one for the efficiency, then uses the side-band data to put a limit
- There is a $\sim 3\sigma$ anomay in the CMS data set, ATLAS data not precise enough to call



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

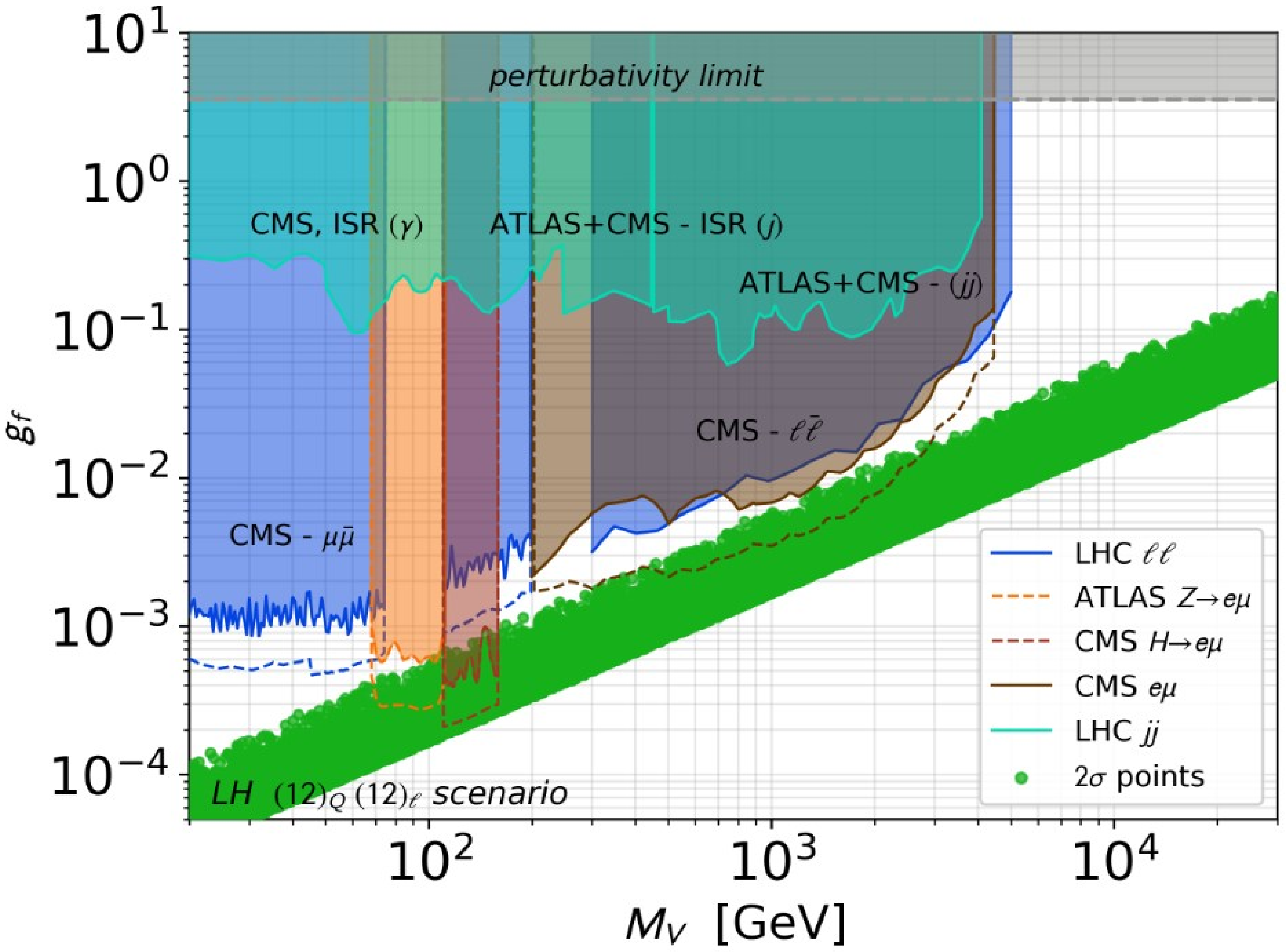
- Corresponds to a « muon as a third generation lepton » scenario.

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



Putting everything together

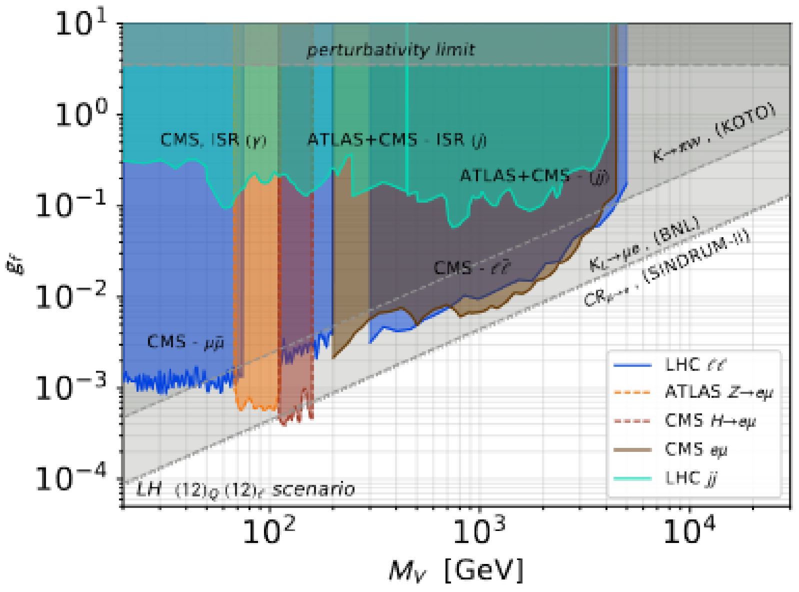
- LHC contraints (and most importantly the recasting of $H \to e\,\mu$ and $Z \to e\,\mu$ limits) are close or overlapping with the flavour constraints
- HL-LHC could probe even deeper, as would dedicated resonance searches around and below the 100 GeV range



Conclusion

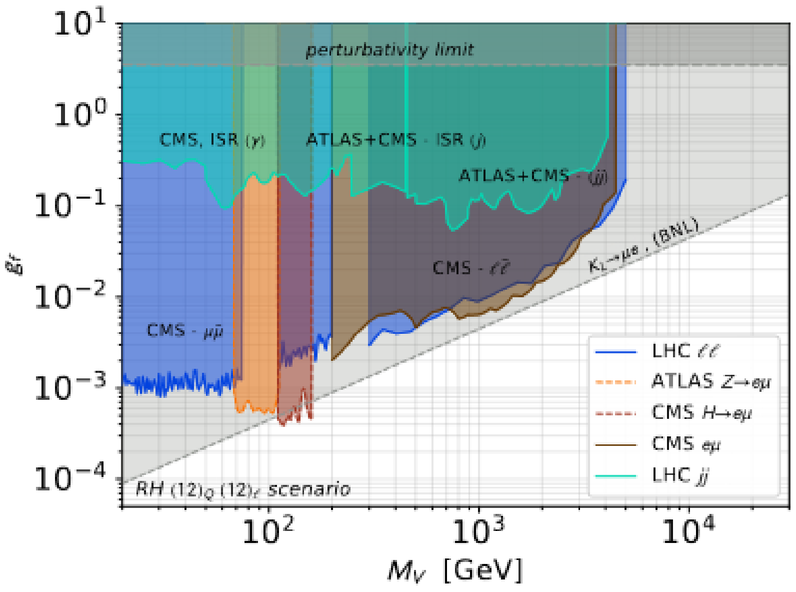
- FIPs have an extremely rich phenomenology in link with flavour and have been long used to fit various "precision anomalies"
  - →In a sense, flavour physics lives naturally at the scale of these NP particles
- Non-abelian flavour gauge symmetries naturally lead to GeV to TeV new vectors for small couplings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

Backup



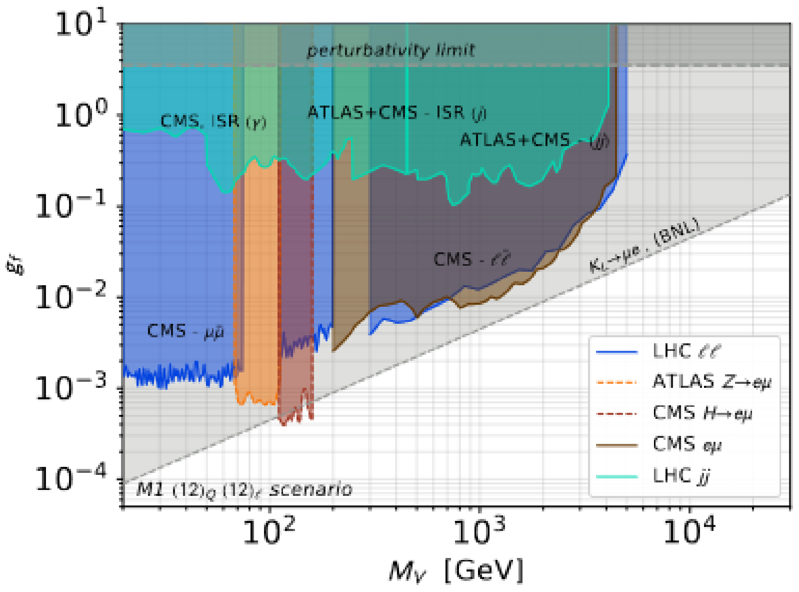
perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
K→πν , (KOTO)
K_L→μe , (BNL)
CR_μ→e , (SINDRUM-II)
CMS - ℓℓ̄
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
LH (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

(a)

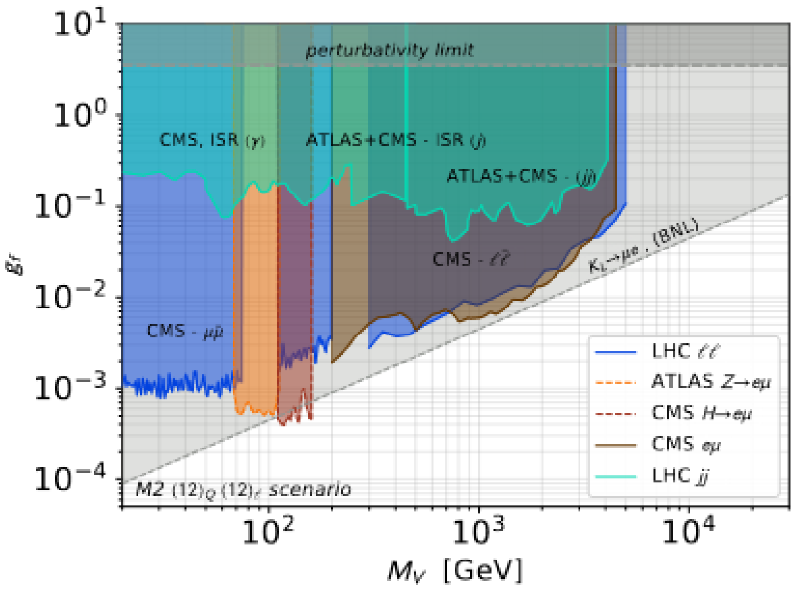


perturbativity limit
CMS, ISR (γ)
ATLAS+CMS - ISR (j)
ATLAS+CMS - (jj)
K_L→μe , (BNL)
CMS - ℓℓ̄
CMS - μμ̄
LHC ℓℓ
ATLAS Z→eμ
CMS H→eμ
CMS eμ
LHC jj
RH (12)_Q (12)_ℓ scenario
g_f
M_V [GeV]

(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]