Is the muon a third family lepton?

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based mainly on 2212.08691 in collaboration with G.Cacciapaglia (IP2I) and S.Vatani (CP3)

Why the muon?

The muon was a completely unexpected particle, first seen in cosmic rays

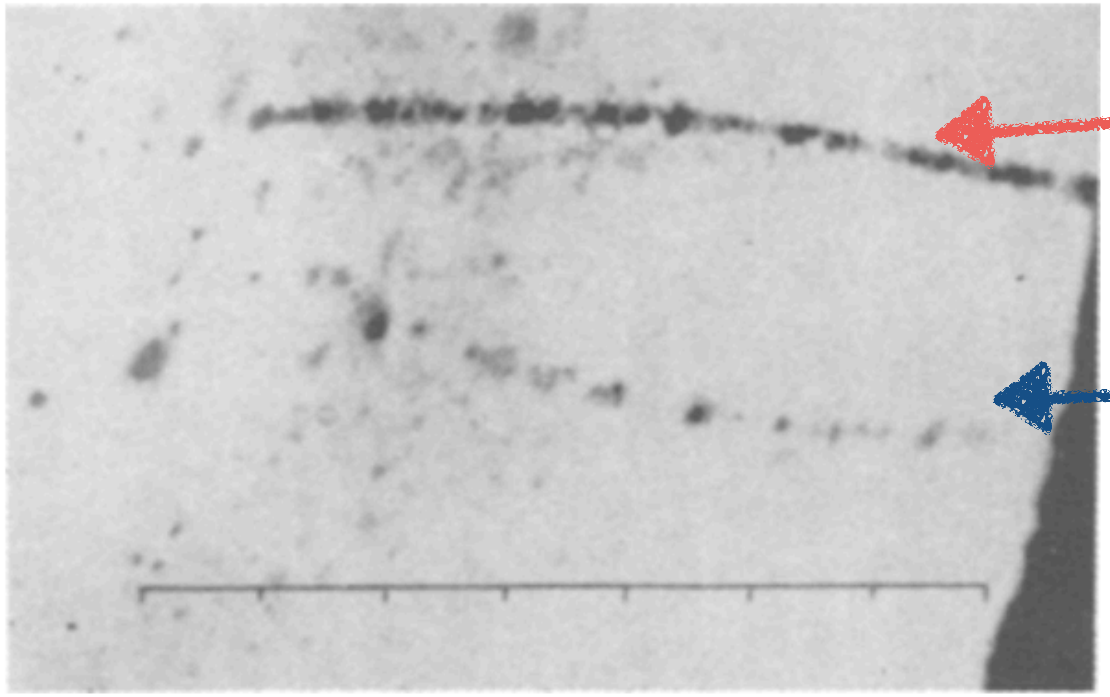


Fig. 5.

Doppelspur als Resultat einer vermutlichen Kernexplosion. 7-fache Vergrößerung. Untere Spur = Elektron von 37 000 000 V. Natur der oberen positiven Korpuskel nicht sicher bekannt.

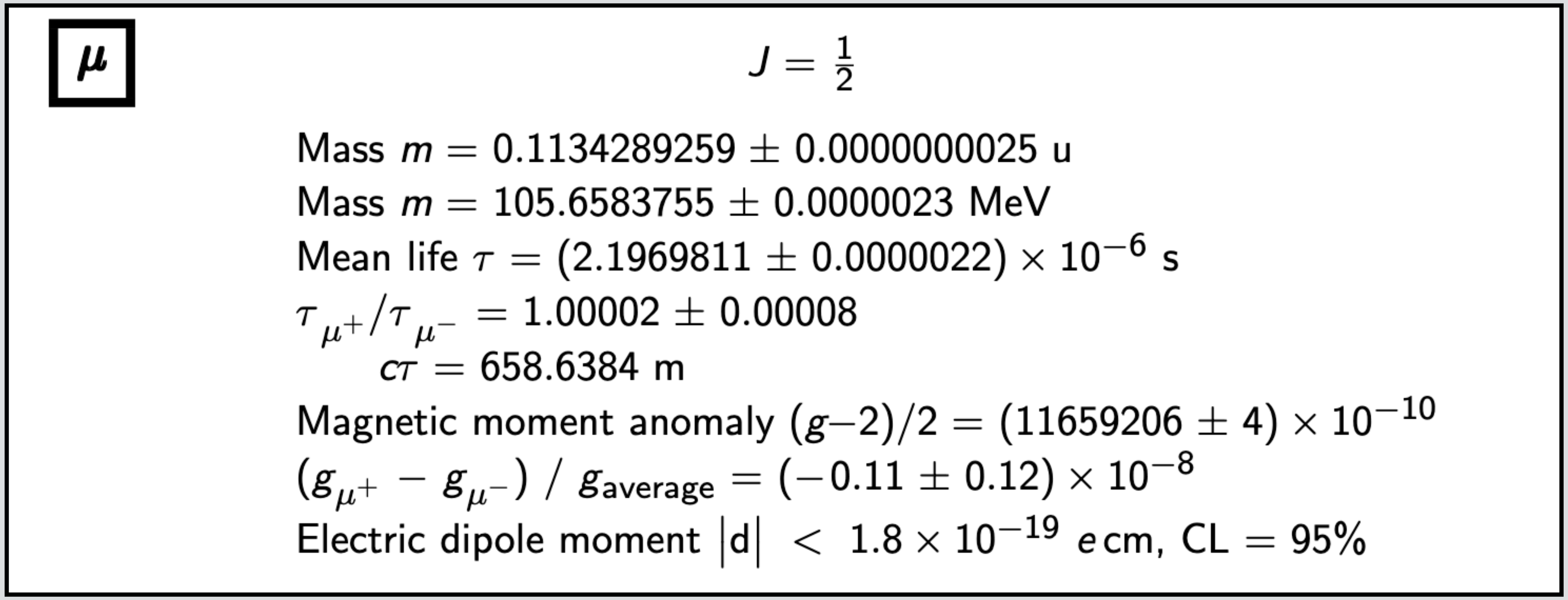
first muon picture,
the track allows to
estimate it is ~100 times
heavier than the electron

electron

famous quote:
“Who ordered that?”
(I.Rabi)

P.Kunze, Zeitschrift für Physik 83 (1933)

The muon today



μ

$J = \frac{1}{2}$

Mass $m = 0.1134289259 \pm 0.0000000025$ u
Mass $m = 105.6583755 \pm 0.0000023$ MeV
Mean life $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$
$c\tau = 658.6384$ m
Magnetic moment anomaly $(g-2)/2 = (11659206 \pm 4) \times 10^{-10}$
$(g_{\mu^+} - g_{\mu^-}) \;/\; g_{\text{average}} = (-0.11 \pm 0.12) \times 10^{-8}$
Electric dipole moment $\left|d\right| < 1.8 \times 10^{-19}$ e cm, CL = 95%

PDG, Prog. Theor. Exp. Phys. 2022, 083C01

Many open questions still there….
…and recent surprises

muon g-2

The SM value includes hadronic contributions calculated using a data-driven dispersive approach, and deviates from the experimental result

$$\Delta a_\mu = a_{\text{exp}\,\mu} - a_{\text{SM}\,\mu} = (25.1 \pm 5.9) \times 10^{-10}$$

by 4.2 σ but using the hadronic vacuum polarization contribution to g - 2, based on a lattice calculation, modifies it

$$\Delta a_\mu = (10.7 \pm 7.0) \times 10^{-10}$$

which is consistent with the measured value (however tension with e^+e^- data at 2.2 σ).

B flavour tests and anomalies

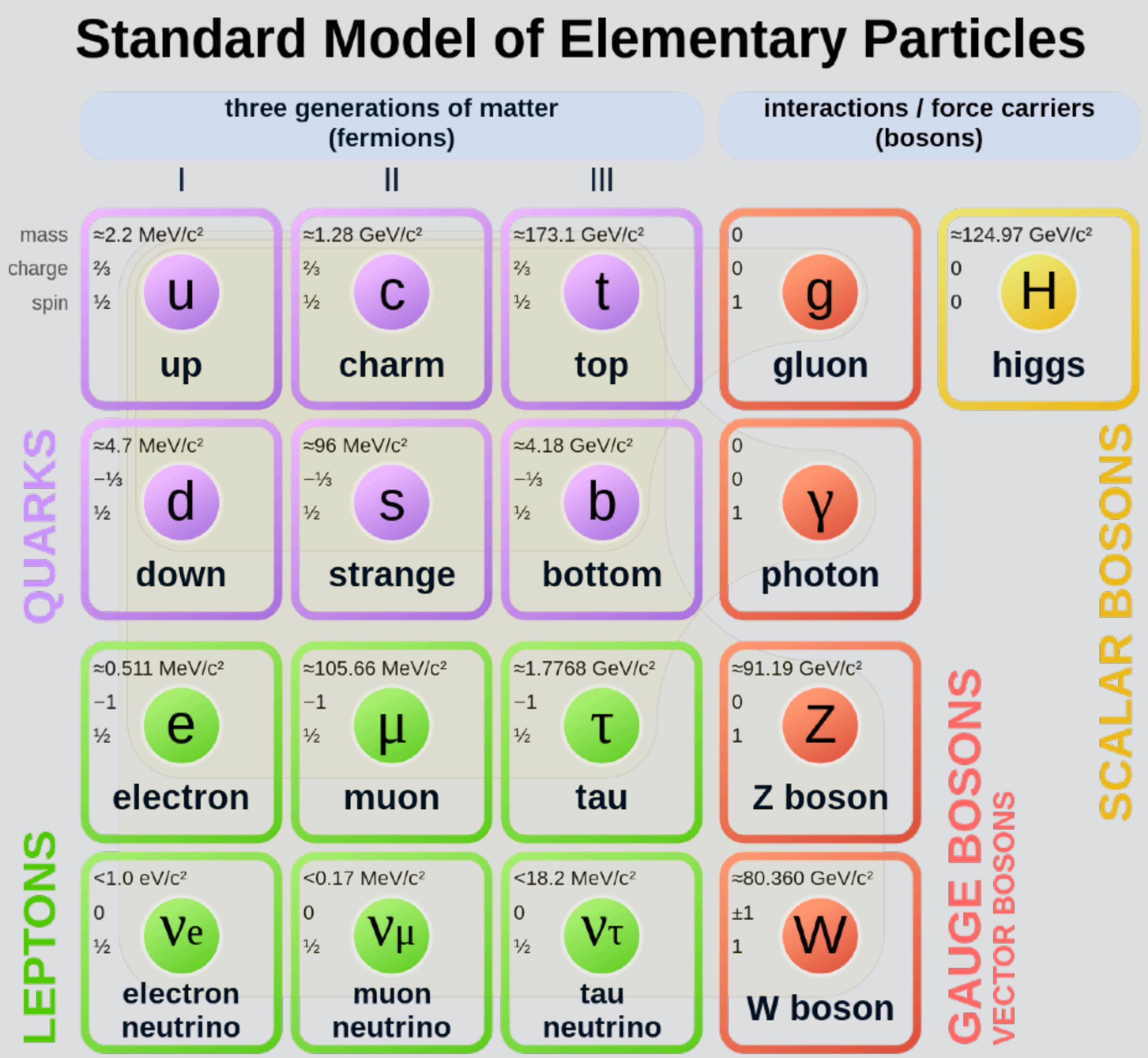
Measure B decays that only differ in final lepton content

$$B \to X\, l\, \nu_l \qquad\qquad B \to X\, ll$$

where X is meson under study

$$R_X = \frac{BR(B \to Xll\,/\,l\nu)}{BR(B \to Xl'l'\,/\,l'\nu')}$$

rare loop induced b decays $R_{K*}(b \to s)$
tree-level decays $R_{D*}(b \to c)$



Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III			
mass charge spin QUARKS	≈2.2 MeV/c^2 ⅔ ½ u up	≈1.28 GeV/c^2 ⅔ ½ c charm	≈173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon		≈124.97 GeV/c^2 0 0 H higgs
	≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	≈4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon		SCALAR BOSONS
LEPTONS	≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS	
	<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≈80.360 GeV/c^2 ±1 1 W W boson		

source: Wikipedia, Wikimedia Commons

Game of the day: how much can you mess with the generations moving matter particles around?

This is not a periodic table! And not even a good way of looking to this question, SM fermions are chiral!

Fermion families

The 3 copies of the fermion families/generations have the same quantum numbers under the SM gauge symmetry, so they can be freely rotated independently, there is a U(3)^5 global symmetry.

x 3

$$\underbrace{\begin{pmatrix}\nu\\ l\end{pmatrix}_L \qquad l_R \qquad \begin{pmatrix}q_u\\ q_d\end{pmatrix}_L \qquad (q_u)_R \qquad (q_d)_R}_{5}$$

The basic requirement of a “family” is anomaly cancellation:

[U(1), SU(2)^2] , [U(1), SU(3)^2] , [U(1)^3]

Fermion families

Yukawa couplings of the Higgs to the fermions

$$\phi\,\bar{\psi}_1\psi_2 = \phi\,\psi^{\dagger}_{1R}\psi_{2L} + \phi\,\psi^{\dagger}_{1L}\psi_{2R}$$

break explicitly this U(3)^5 symmetry and allow to define a physical basis (mass basis):

Diagonal Yukawas for the charged leptons: U(3)^2 → U(1)^3 (3 lepton numbers)

Diagonal Yukawas for the (down) quarks: U(3)^3 → U(1) (1 baryon number)

and leptons and quarks are still independent in the SM

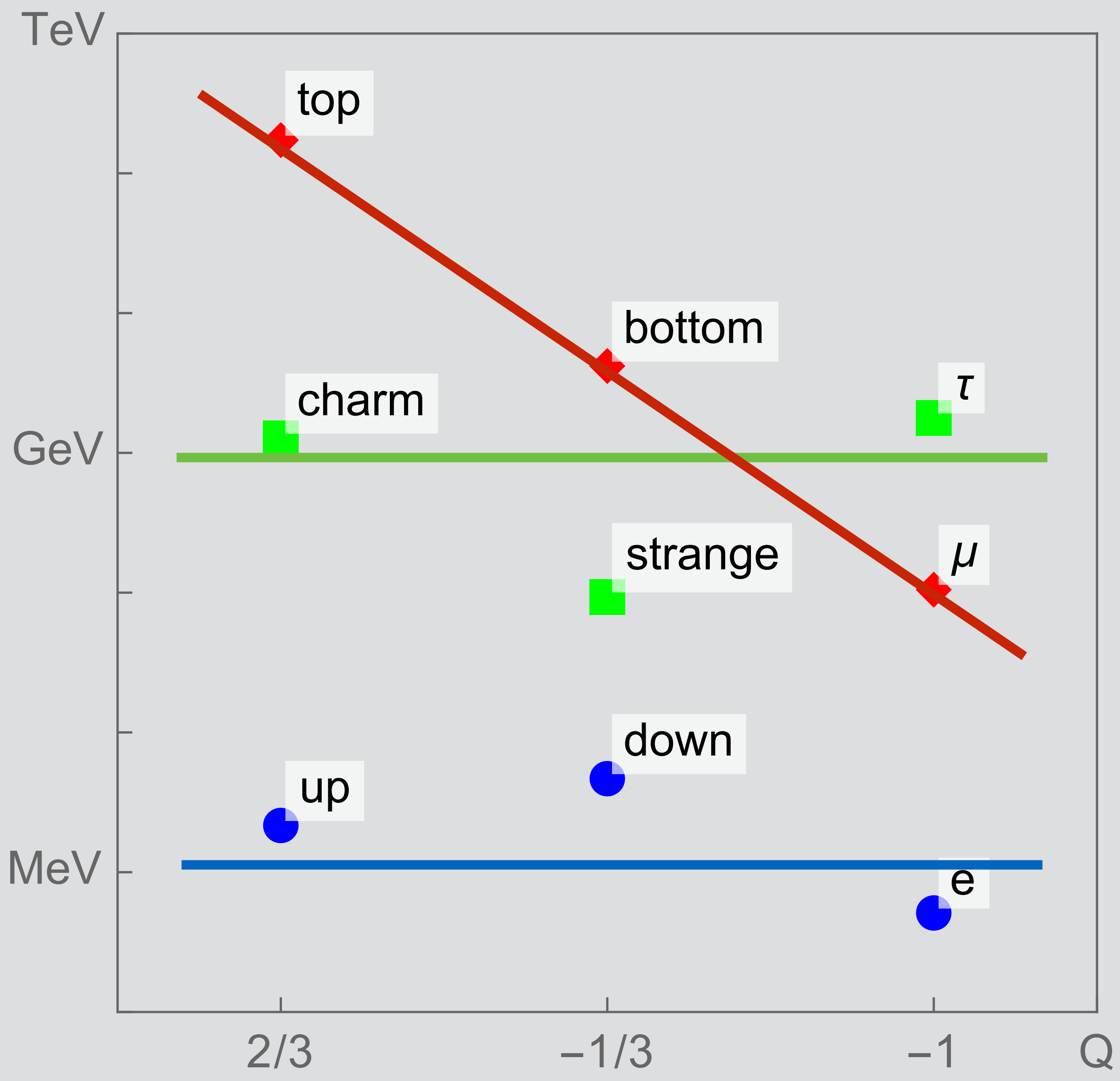
Is the muon a third family lepton?

We consider in the following what is the interest of associating a particular lepton mass eigenstate (the muon) into a “family” together with the quarks of the usual 3rd generation.

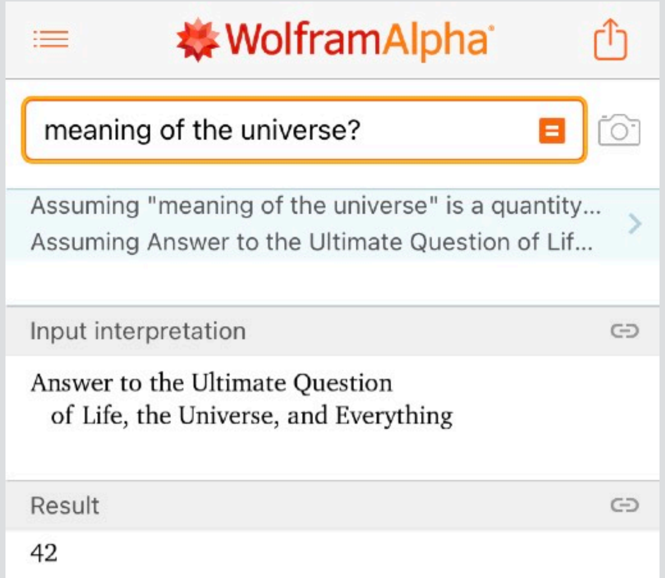
Not relevant in the Standard Model : quarks and leptons are not related so the residual symmetry still allows arbitrariness in the definition of the generations.

Relevant in BSM : quarks and leptons can be related not only generically (multiplets) but also in a specific way breaking the residual flavour symmetry (ex. a leptoquark coupling only to the 3rd family)

Patterns?



See what you like, but this seems to suggest that the origin of Yukawa couplings for the top and for the rest, may be different



meaning of the universe?

Assuming "meaning of the universe" is a quantity...
Assuming Answer to the Ultimate Question of Lif...

Input interpretation

Answer to the Ultimate Question
of Life, the Universe, and Everything

Result

42

$$X_{\mathrm{tb}} = \frac{m_{\mathrm{t}}}{m_{\mathrm{b}}} = 41.31^{+0.31}_{-0.21}\,, \qquad X_{\mathrm{b}\mu} = \frac{m_{\mathrm{b}}}{m_{\mu}} = 39.56^{+0.28}_{-0.19}$$

A possible scenario

A possible BSM motivated scenario has the following features:

- A family symmetry acting on the first two generations. This is broken by effective Yukawa couplings of the order $y_2 \approx 10^{-2}$ and $y_1 \approx 10^{-5}$.

- The third generation has tree-level Yukawa couplings $y_3 \approx 1$, which prevents a larger family symmetry SU(3).

- Only the Yukawa coupling of the top quark is allowed at leading order ($y_t \sim 1$), while some new interactions communicate the electroweak symmetry breaking to b and μ explaining their lighter mass (Froggatt-Nielsen, loops....)

Light families symmetries

A light family symmetry with the τ in the second generation is typically less constrained (from LFV). Many examples in the literature can be adapted:

- Effective: $U(2)^3$ is a good approximate symmetry of the SM quark sector, broken by $y_2 \approx 10^{-2}$ and $y_1 \approx 10^{-5}$ Yukawa couplings. Extendable to leptons with a $U(2)_l \times U(2)_e$
- Bounds on τ LFV are typically less stringent than on μ ($\mu \to e\gamma <\approx 10^{-13}$ vs $\tau \to e\gamma <\approx 10^{-8}$)
- Gauged: $SU(2)_X$ with new light flavour gauge boson
- Composite models/Susy
- Extra-dimensional models
- Unification: GUT, Pati-Salam: but family specific

- too many references, see some in the biblio of 2212.08691

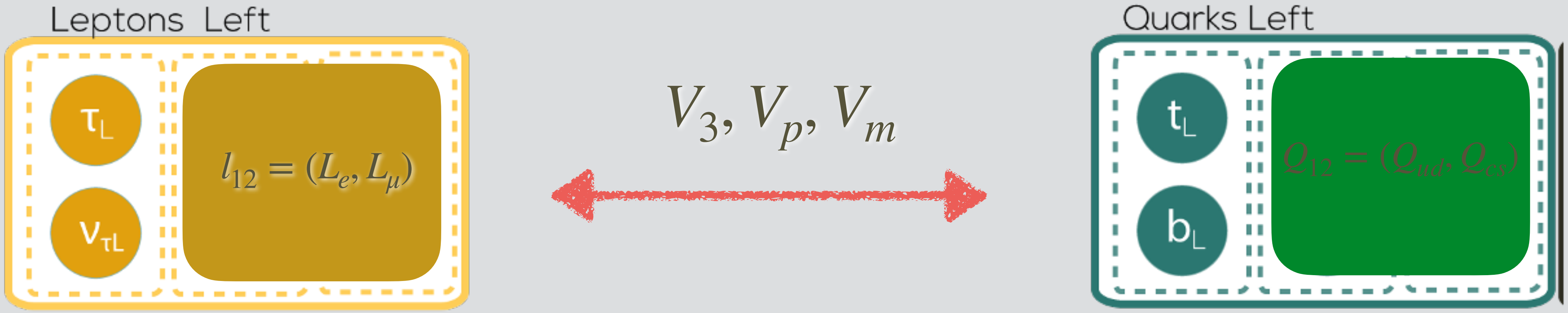
$SU(2)_f$ flavour gauge groups

Given the SM structure, $SU(2)_f$:

- « charged» SM fermion can be either doublets or triplets
- Only mixed $SU(2)^2_f \times U(1)_Y$ anomaly to be taken care of, leaving few possible combinations.

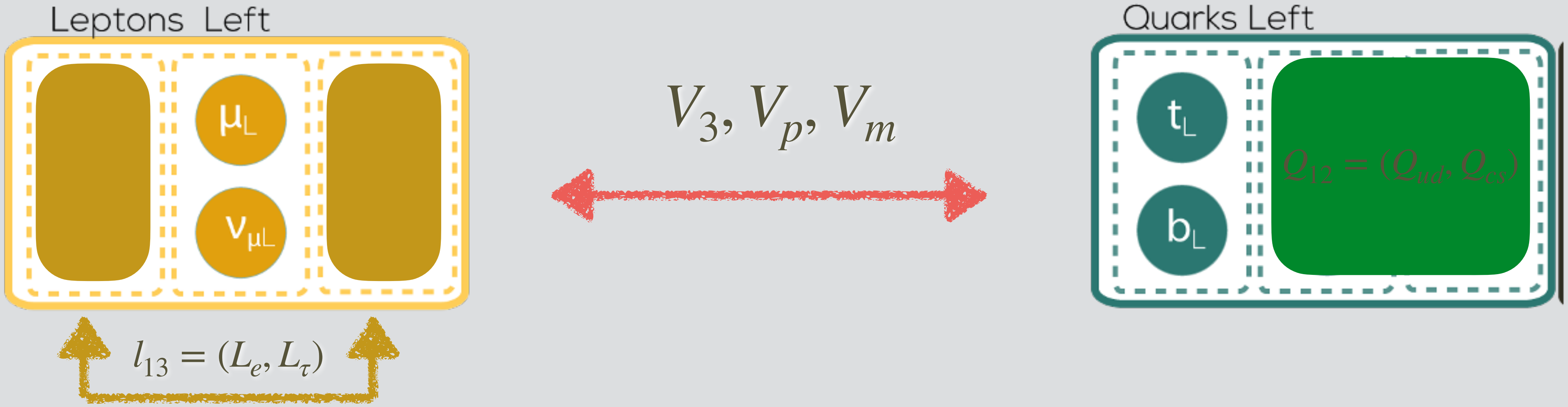
Example "LH" scenario

- Reduces the number of fundamental fermions
- Couples both to leptons and quarks



2307.09595 with L.Darme and N.Mahmoudi

$SU(2)_f$: muon as a 3rd generation



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

Example for down type quarks:

SU(2)$_f$ breaking terms

$$\mathscr{L}_Y = -\,Y^d_{ij}\,\overline{Q}^I_{Li}\,\phi\,d^I_{Rj} \longrightarrow M_d \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & \epsilon & \epsilon \\ 1 & 1 & 1 \end{pmatrix}$$

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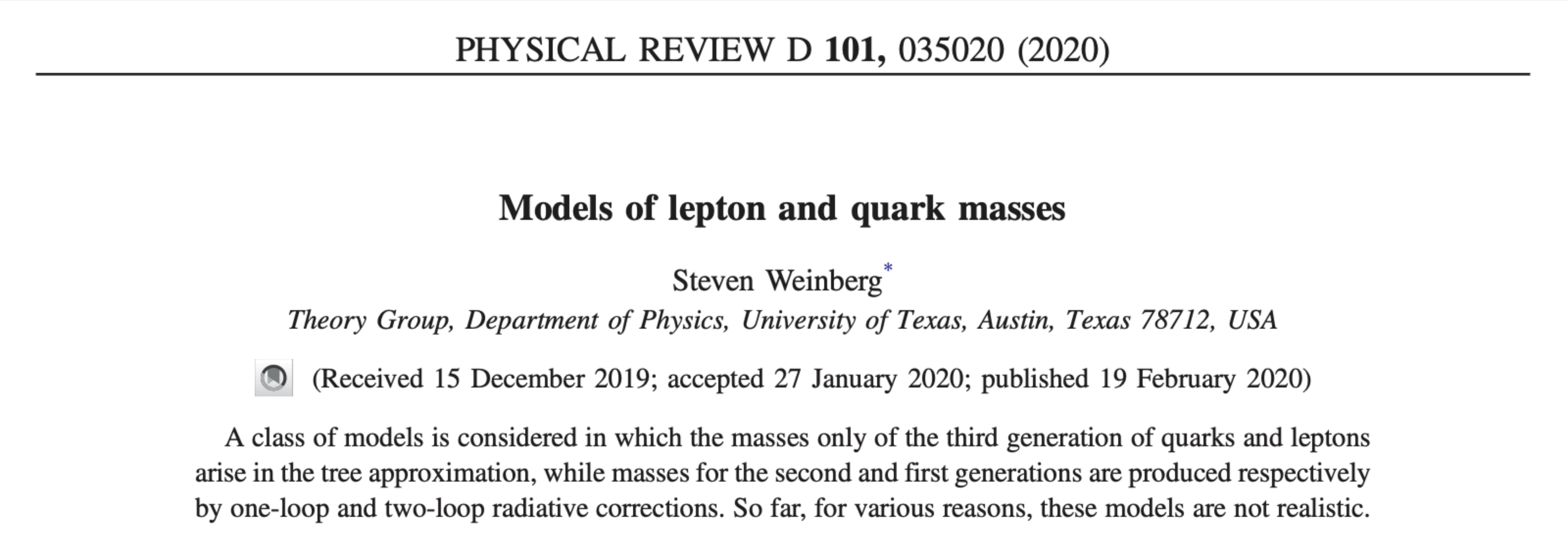
Masses: the wisdom of a Master



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Models of lepton and quark masses

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A class of models is considered in which the masses only of the third generation of quarks and leptons arise in the tree approximation, while masses for the second and first generations are produced respectively by one-loop and two-loop radiative corrections. So far, for various reasons, these models are not realistic.

“new scalar and vector particles in these models can (and must) be supposed to be heavy enough to have escaped observation, and where they are sufficiently heavy we can easily find the ratios of many quark and lepton masses.

…….

The best that can be hoped for the models discussed in this paper is that they may perhaps provoke new ideas for a realistic theory in which radiative corrections account for the masses of the first and second generations of quarks and leptons, together with guidance in dealing with the problems that will arise in such a theory. “

S.Weinberg

An effective model (masses)

Consider 2 LQ-scalars S: (3,1,-1/3) and ϕ: (3,2,1/6) with (SU3,SU2,U(1)$_Y$) quantum numbers

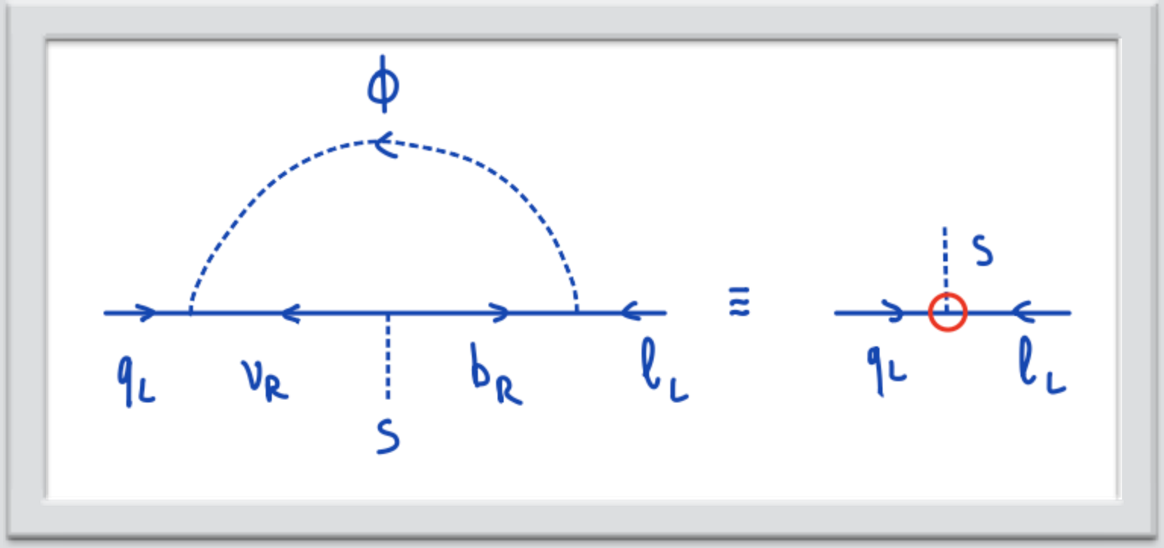
$$\mathcal{L}_{\rm Yuk} = y_t\ \bar{t}_R q_L\ H + \lambda_S\ S\ \Big(c_{qq}\ \bar{q}_L^c q_L + c_{tb}\ \bar{b}_R^c t_R \\ + c_{ql}\ \bar{q}_L l_L^c + c_{t\mu}\ \bar{t}_R \mu_R^c + c_{b\nu}\ \bar{b}_R \nu_R^c\Big) + \\ \lambda_\phi\ \phi\ \Big(c_{q\nu}\ \bar{q}_L \nu_R + c_{bl}\ \bar{b}_R l_L\Big) + \text{h.c.}$$

Yukawa-like couplings λ_S and λ_ϕ at a high scale Λ allow loop-generated masses for b and μ from the top.

ν_R^i are RH neutrinos with Majorana mass (for see-saw).

An effective model (masses)

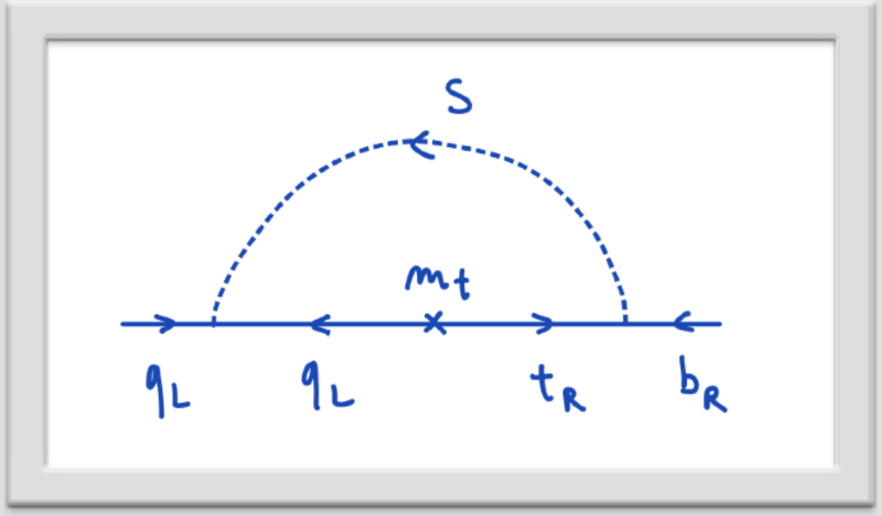
c_{qq} , c_{tb} , $c_{t\mu}$ =1, $c_{ql}(\Lambda)$ = 0 (loop induced)



$$c_{ql} \sim \lambda_\phi^2 \, n_R \, \epsilon_\phi$$

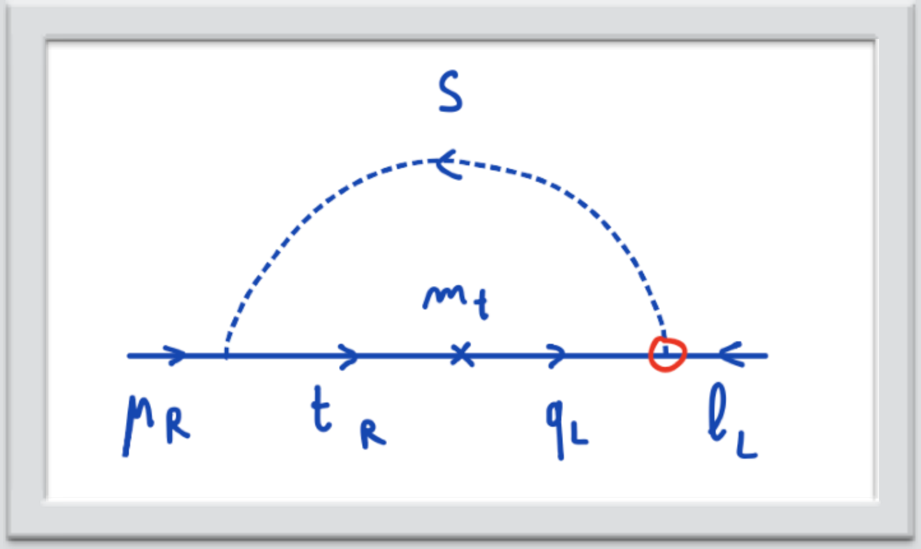
$$\epsilon_{S/\phi} = \frac{1}{8\pi^2} \ln \frac{\Lambda}{M_{S/\phi}}$$

Mass ratios are also loop induced

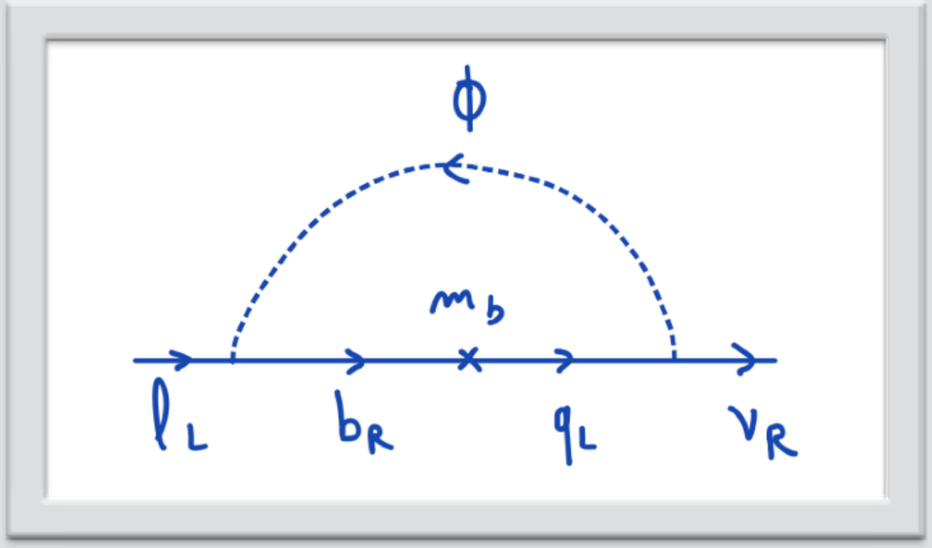


$$\frac{m_b}{m_t} \sim N_c \, \lambda^2 \, \epsilon_S$$

An effective model (masses)



$$\frac{m_\mu}{m_b} \sim n_R \, \lambda_\phi^2 \, \epsilon_\phi$$



$$\frac{m_D^\nu}{m_b} \sim N_c \, \lambda_\phi^2 \, \epsilon_\phi \quad \text{and seesaw} \quad m_\nu = \frac{(m_D^\nu)^2}{M_R}$$

$$m_\nu = 1eV, \quad n_R = 3, \quad \lambda_i = 0.3, \quad M_R = 1.3 \; 10^7 \text{ GeV}, \quad \frac{M_S}{M_\phi} = 1150, \quad \frac{\Lambda}{M_S} = 490$$

Flavour specific: a PS$_3$ example

As t-b-μ are in the same family, b and μ BSM effects are related without major LFV effects: interesting constraints "recasting" results obtained in the b and μ flavour hierarchies/anomalies game (see for example the PS model by Isidori et al 1712.01368).

$$PS_1 \times PS_2 \times PS_3 = [SU(4) \times SU(2)_L \times SU(2)R]^3$$

$$PS_1 \to SM_1 \text{ at } \Lambda_1 > 10^3 \mathrm{T}eV$$

$$SM_1 \times PS_2 \to SM_{1+2} \text{ at } \Lambda_2 \leq \Lambda_1$$

$$SM_{1+2} \times PS_3 \to SM_{1+2+3} \text{ at } \Lambda_3 \geq 1\mathrm{T}eV$$

SM_{1+2} × PS_3 gauge symmetry has a corresponding accidental $U(2)^5$ global flavour symmetry

A PS$_3$ example

At low energy this model has a spin-1 leptoquark (3,1,2/3): U1$_{2/3}$ (and also a coloron, Z' and VL fermions)

$$\mathcal{L}_U = U_1^\mu \; \bar{b}\,(\kappa_L P_L + \kappa_R P_R)\,\mu + \text{h.c.}$$

with a mass matrix induced by the PS breaking (ε terms)

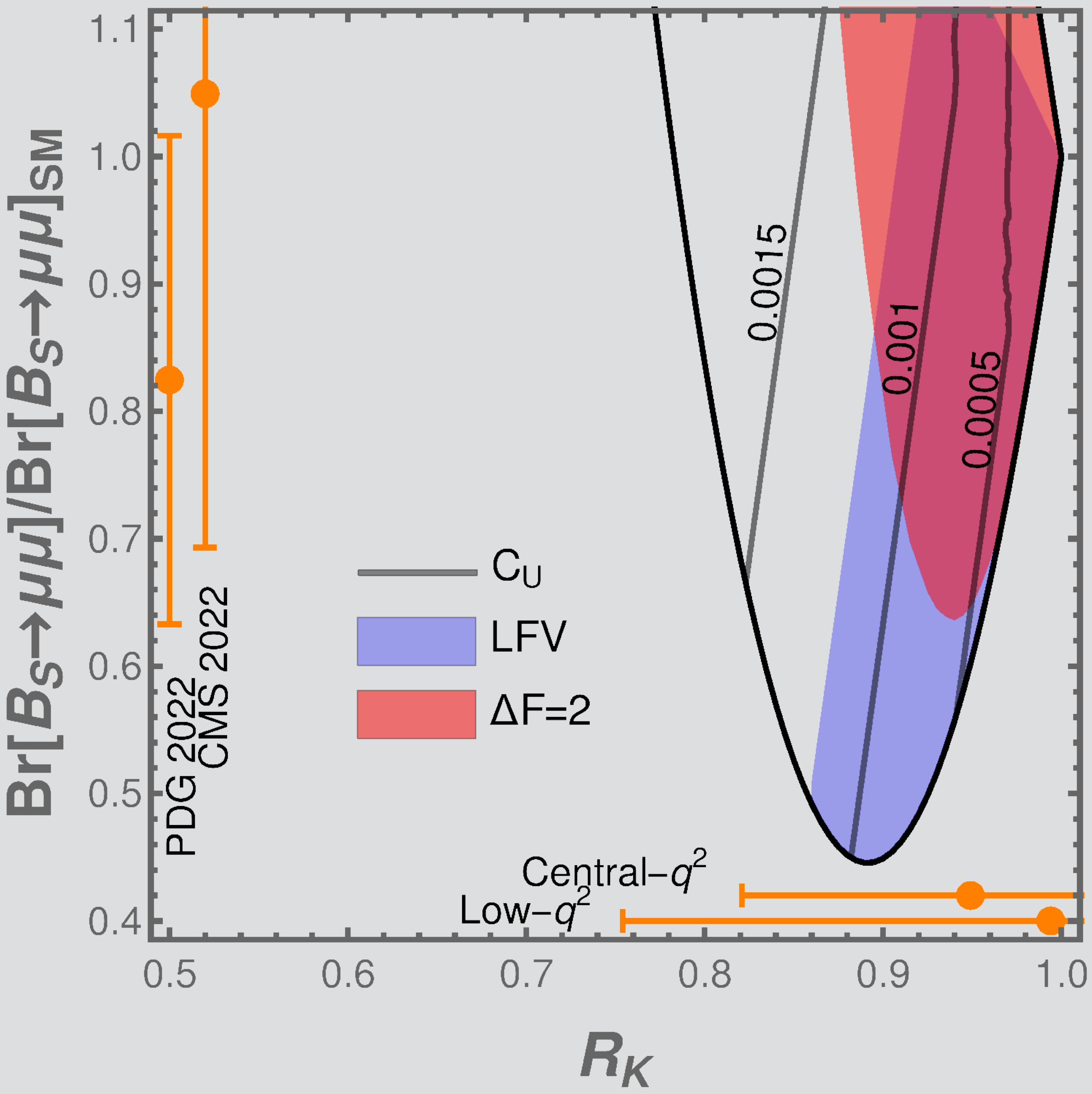
$$\mathcal{L}_{\rm mass} = -\bar{f}_R \begin{pmatrix} \epsilon_{LR} U_{11} & \epsilon_{LR} U_{12} & 0 \\ \epsilon_{LR} U_{21} & \epsilon_{LR} U_{22} & \epsilon_L \\ 0 & \epsilon_R & y_f v \end{pmatrix} f_L$$

and by the Higgs for the 3rd generation (y_f term). Here

$$\epsilon_R < \epsilon_{LR} < \epsilon_L < 1$$

$\epsilon_L \sim m_\tau$, $y_f\, v \sim m_\mu$ with the muon as a 3rd generation lepton

A PS_3 example



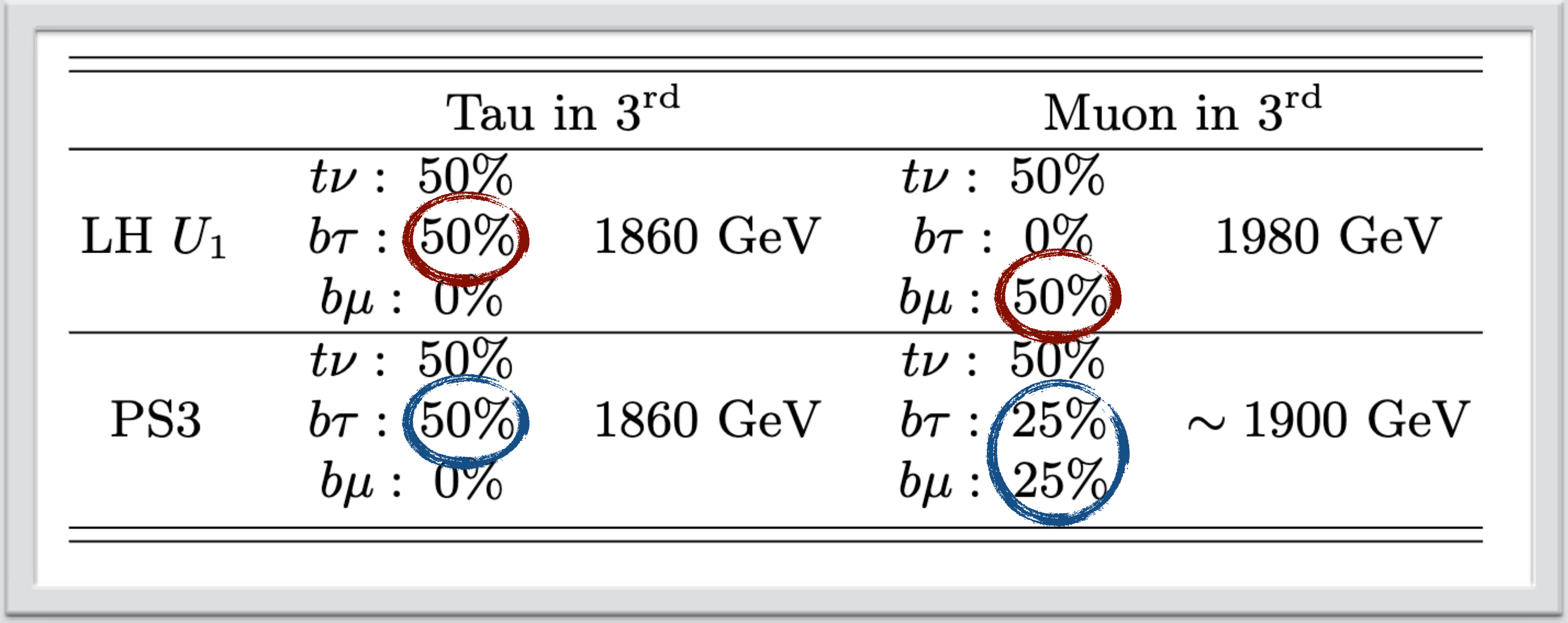
LFV ($\tau \to 3\mu$) in blue and $\Delta F = 2$ bounds in red (B_s-$\overline{B}_s$ mixing). Contours for the leptoquark coupling C_U in black. Orange points along the axes show the experimental measurements for RK and BS → $\mu+$ $\mu-$

$C_U \approx 10^{-3}$ as $C_U = g_U^2 v^2 / M_U^2$
$M_U \approx 10$ TeV

2212.08691 with G.Cacciapaglia and S.Vatani

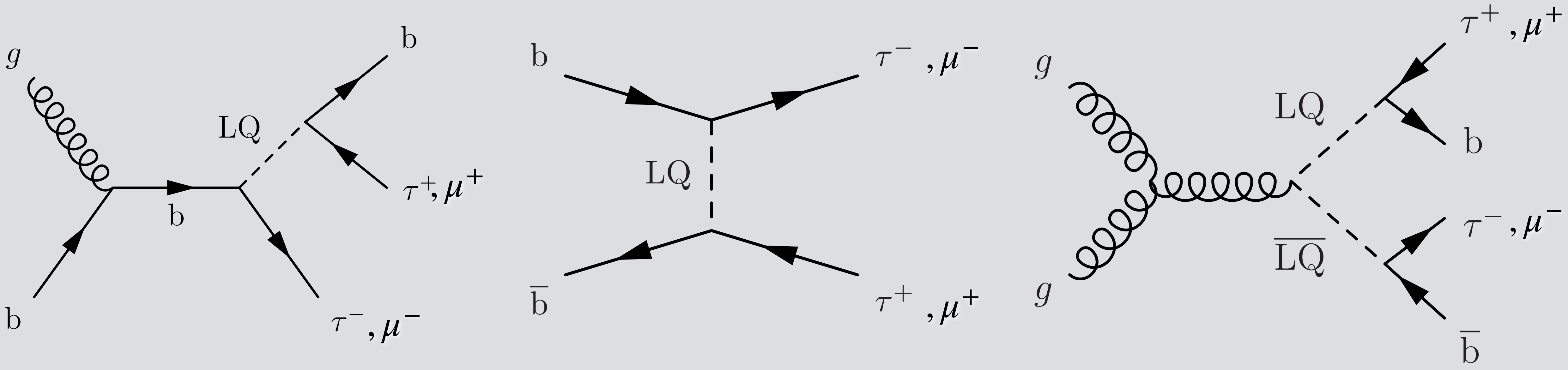
3rd family μ at colliders

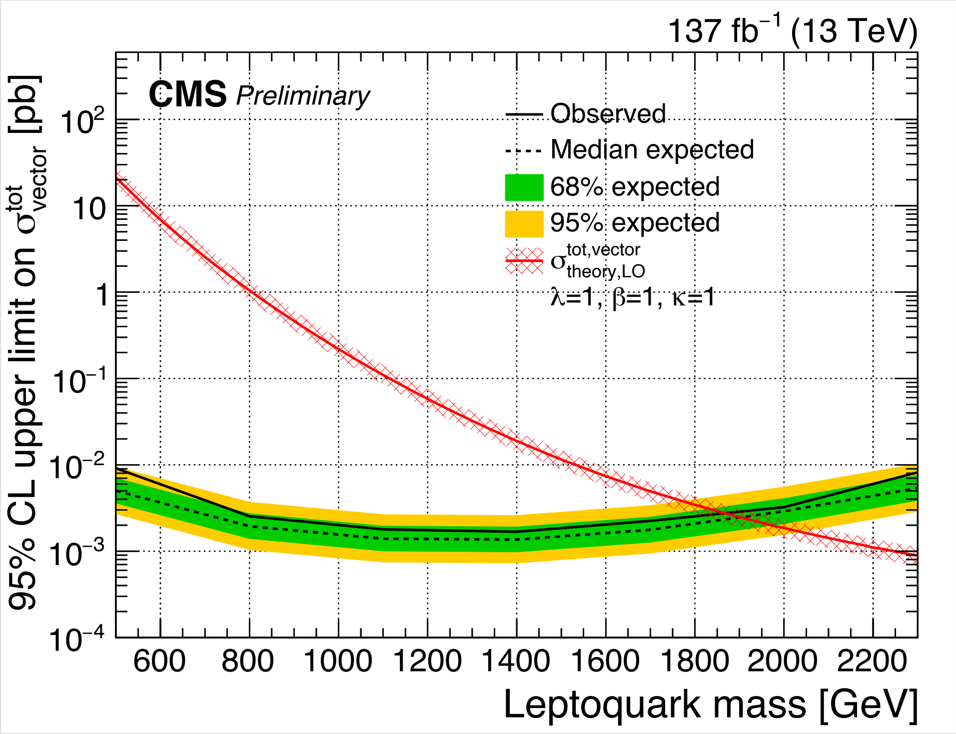
Assuming new physics couples dominantly to third generation fermions, we predict muon-rich final states at colliders.
The minimal model with left-handed couplings (LH U1) predicts 50% into tν and a 50% in b τ/μ. PS3 lepto-quark couple both to left- and right-handed fermions. In our alternative model, the left-handed coupling are muons instead of taus, hence leading to branching ratios of 50%–25%–25%

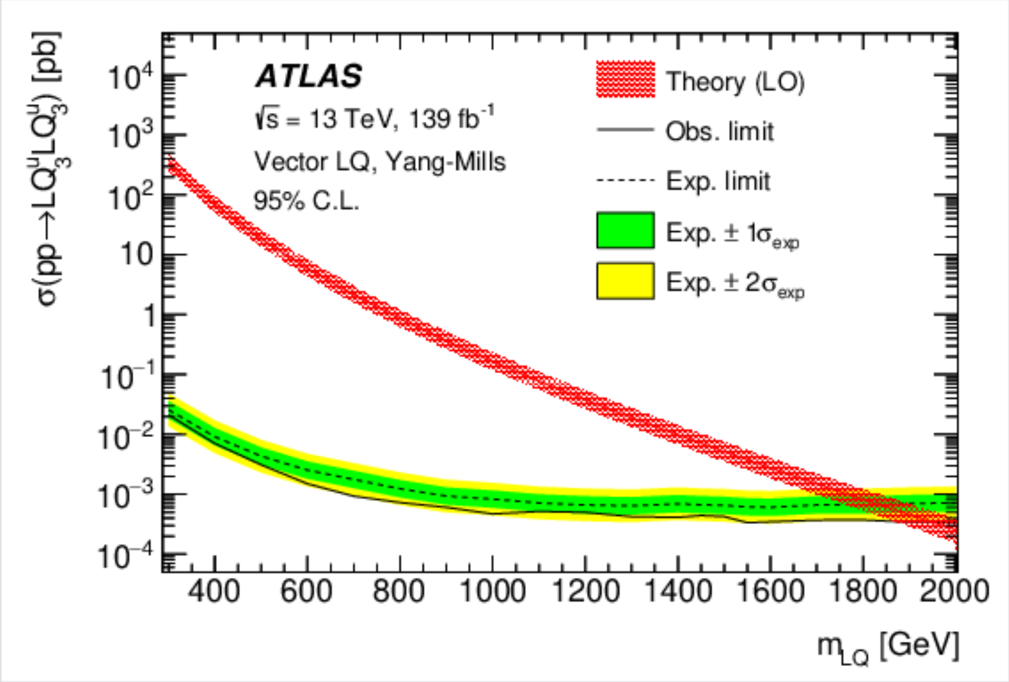


	Tau in 3^{rd}		Muon in 3^{rd}	
LH U_1	$t\nu$: 50% $b\tau$: 50% $b\mu$: 0%	1860 GeV	$t\nu$: 50% $b\tau$: 0% $b\mu$: 50%	1980 GeV
PS3	$t\nu$: 50% $b\tau$: 50% $b\mu$: 0%	1860 GeV	$t\nu$: 50% $b\tau$: 25% $b\mu$: 25%	$\sim$ 1900 GeV

3rd family μ at colliders







CMS-PAS-EXO-19-016

ATLAS arXiv:2303.01294
see also 2107.10094

3rd family μ at colliders from $SU(2)_f$

In the $SU(2)_f$ scenarios LH l_{12} vs l_{13} with Q_{12} a significant coupling to muons is expected to reproduce the experimental LHCb anomalies.

Non-abelian flavour gauge symmetries naturally lead to GeV to TeV new vectors for small couplings

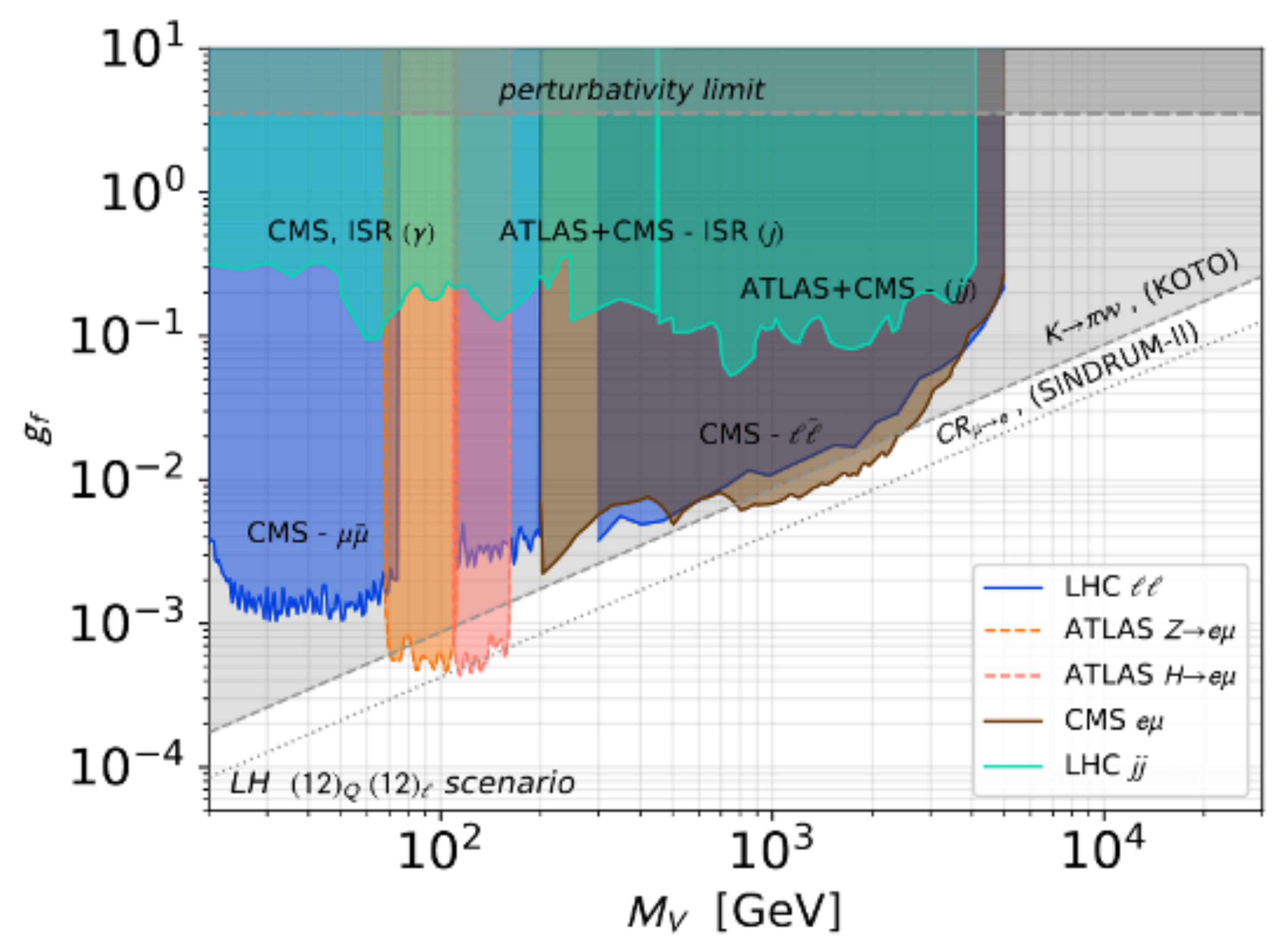
Collider constraints on both di-jets and di-leptons and search of lepton flavour-violating resonances are relevant.

LHC limits : LH l_{12} Q_{12}

1st and 2nd generation of left-handed fermions in a flavour doublet

Production at LHC is large: $u\bar{s} \to V_p \to e^-\mu^+$

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



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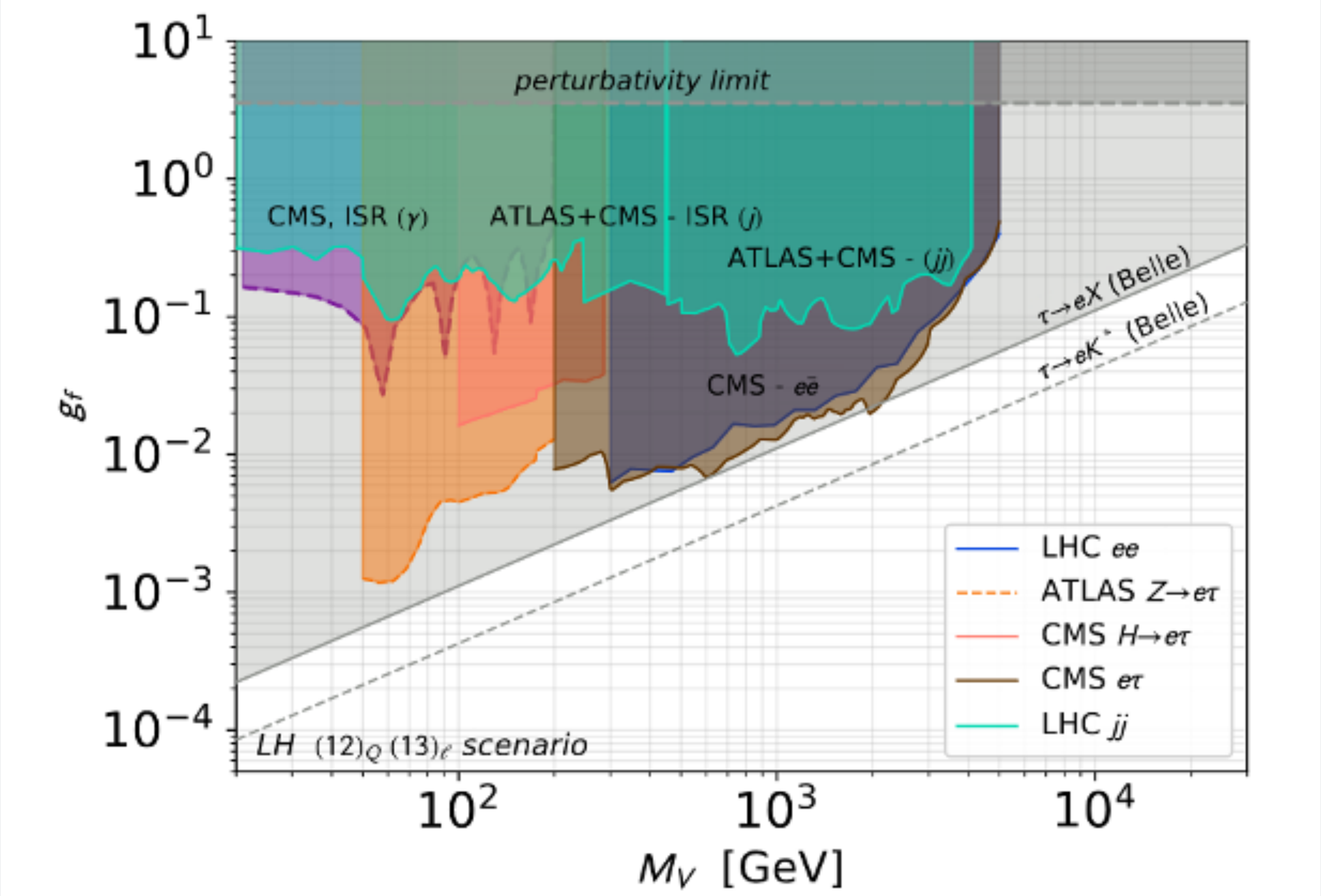
LHC limits : LH l_{13} Q_{12}

l_{13} is μ as a 3rd generation lepton

Strongest limits arise from hadronic τ decays

LHC constraints are weakened



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Conclusion

- Assignment of the muon to 2nd or 3rd generation is arbitrary in the SM but not necessarily in BSM
- Muon in 3rd generation leads to new mass patterns, predicts deviations in the couplings of muons and in the rare decays of mesons
- Collider bounds are partially different for muon in 3rd generation or 2nd (model and process dependent)
- New opportunity for model building with less LFV constraints
- Quite a few ideas can be revisited in this perspective
- Implications for the neutrino sector still to be investigated