What if cLFV was only manifest in tau decays?

Dr. Innes Bigaran

Based on IB, XG He, M.A. Schmidt, G. Valencia, R.Volkas
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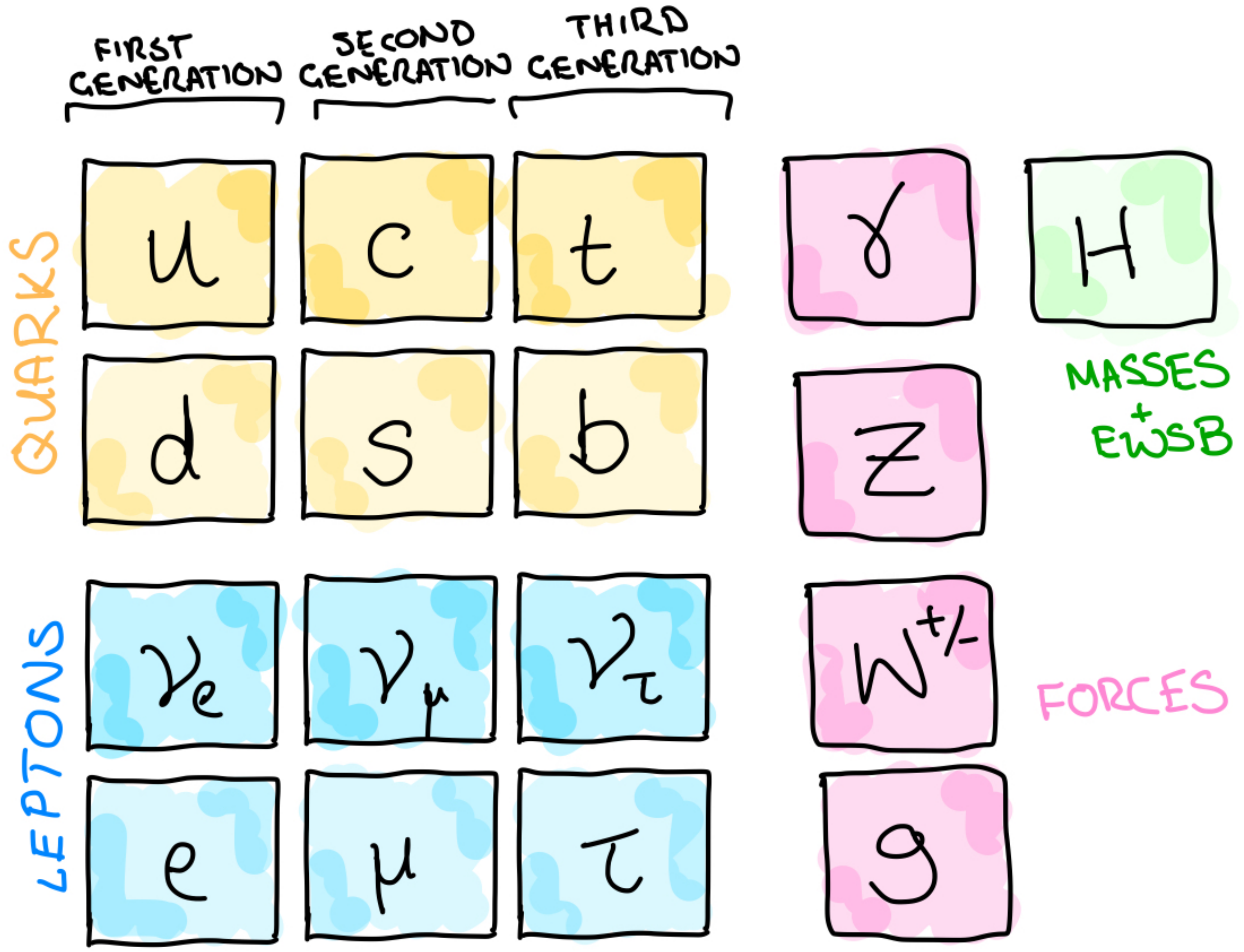
Flavour in the Standard Model



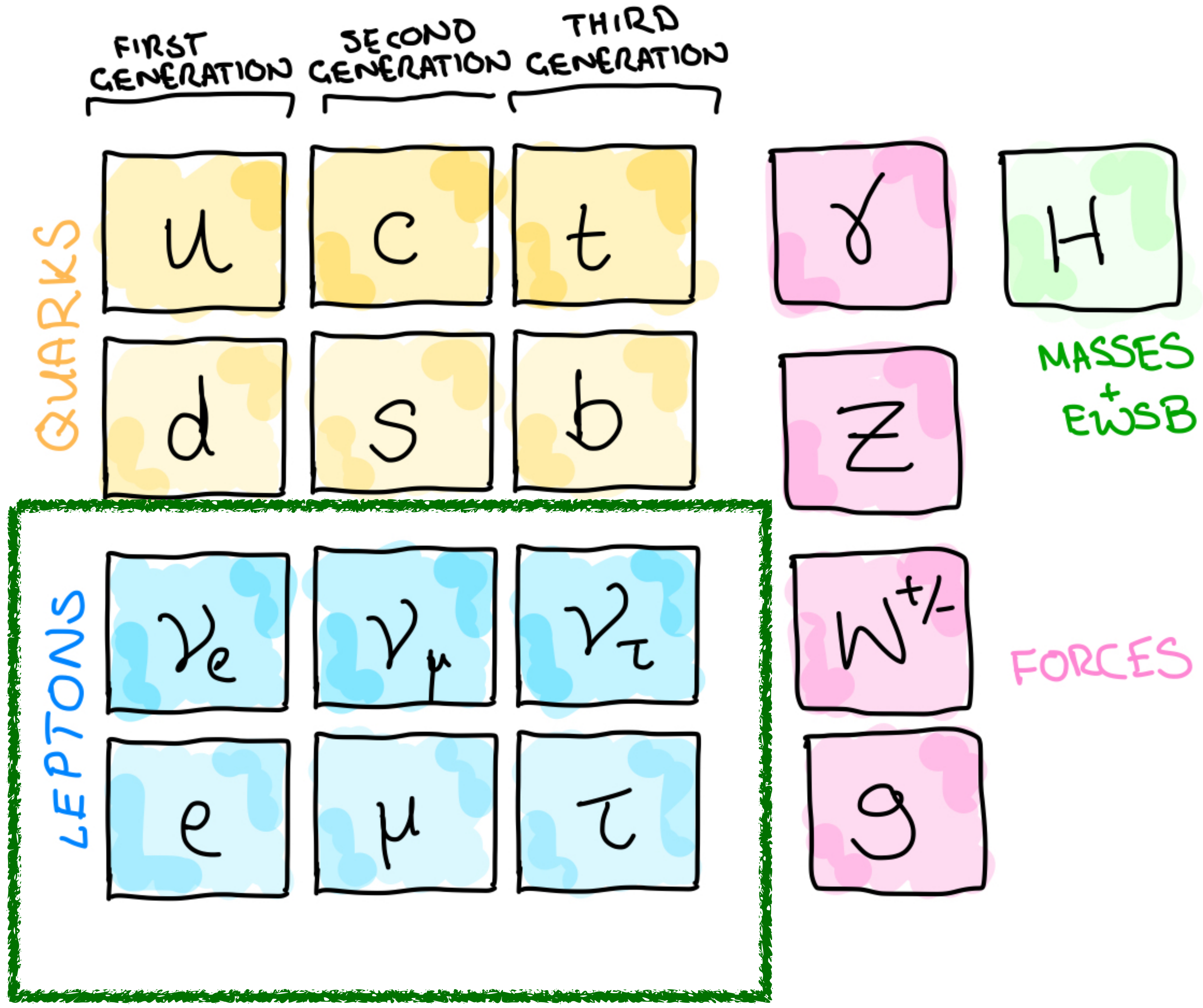
- The SM is a semi-empirical theory. Requires experimental input to fix ~ 27 free parameters to fully prescribe it

Gauge	Force interactions	3 gauge couplings
Higgs	EWSB and W/Z masses	2 Higgs-potential couplings
Flavour	Quark and lepton masses and	~ 22 free parameters

- We need experimentalists to measure these parameters. Can we understand the underlying symmetries that guide them?

"Standard Model Flavour Puzzle"

Lepton flavour in the Standard Model



- In the SM lepton sector [with no neutrino masses], there is an accidental symmetry "lepton flavour"

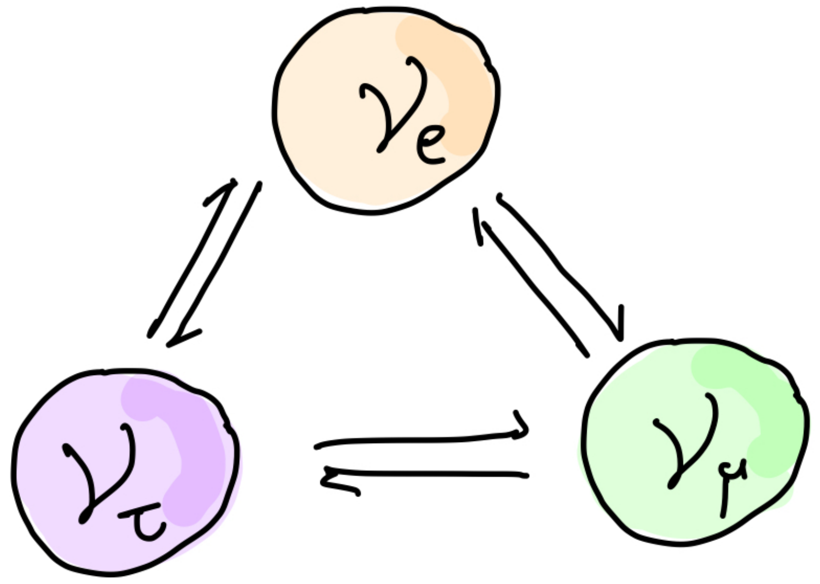
$$\mathcal{G}_{\mathrm{L}} = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$

- Flavoured lepton number is conserved in [perturbative] SM interactions, thus also total (sum of flavours) lepton number

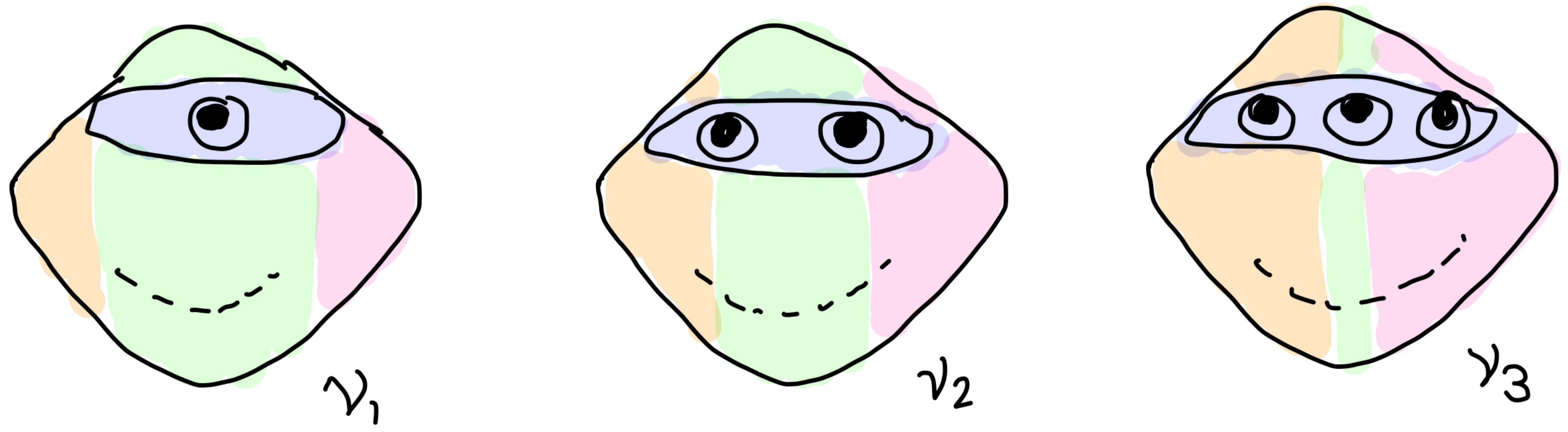
$$L = L_\mu + L_e + L_\tau$$

- Lepton flavour violation (LFV) is not possible in the SM.

Leptons in the SM + neutrino masses



Mass eigenstates are linear combinations of flavour eigenstates

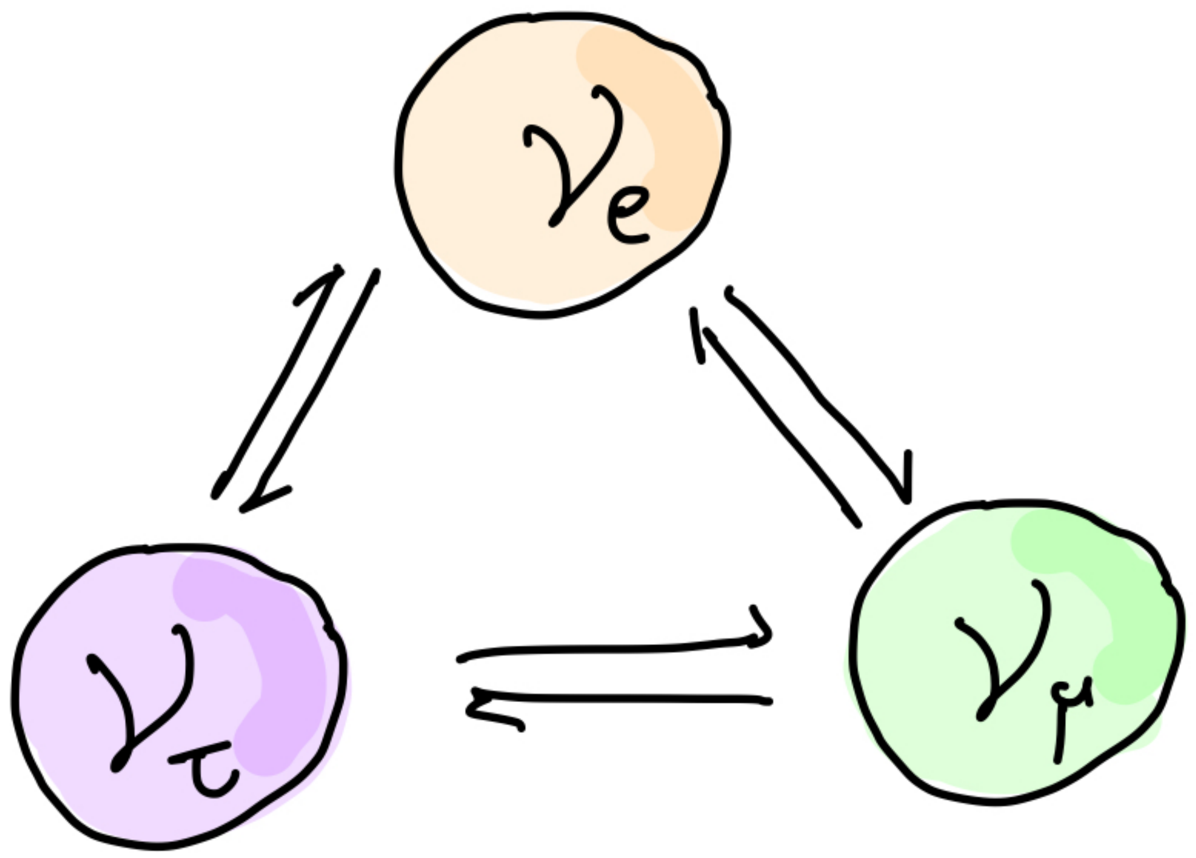


- In the *vanilla* SM, neutrinos are massless.
- Neutrino and neutrino physics provide a probe of lepton flavour symmetries
- Neutrino flavour oscillations tell us that beyond the SM lepton flavour *is* violated.

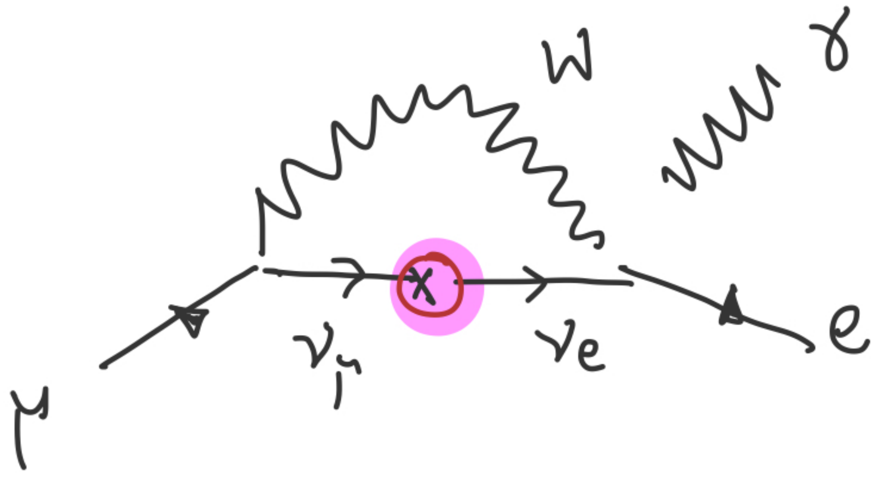
Neutrino masses/oscillation mean

1. *We need BSM physics (an extended theory)*
2. *This new physics violates lepton flavour symmetry*

So why is a symmetry useful if it's broken?



$$\mathcal{G}_{\mathrm{L}} = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$



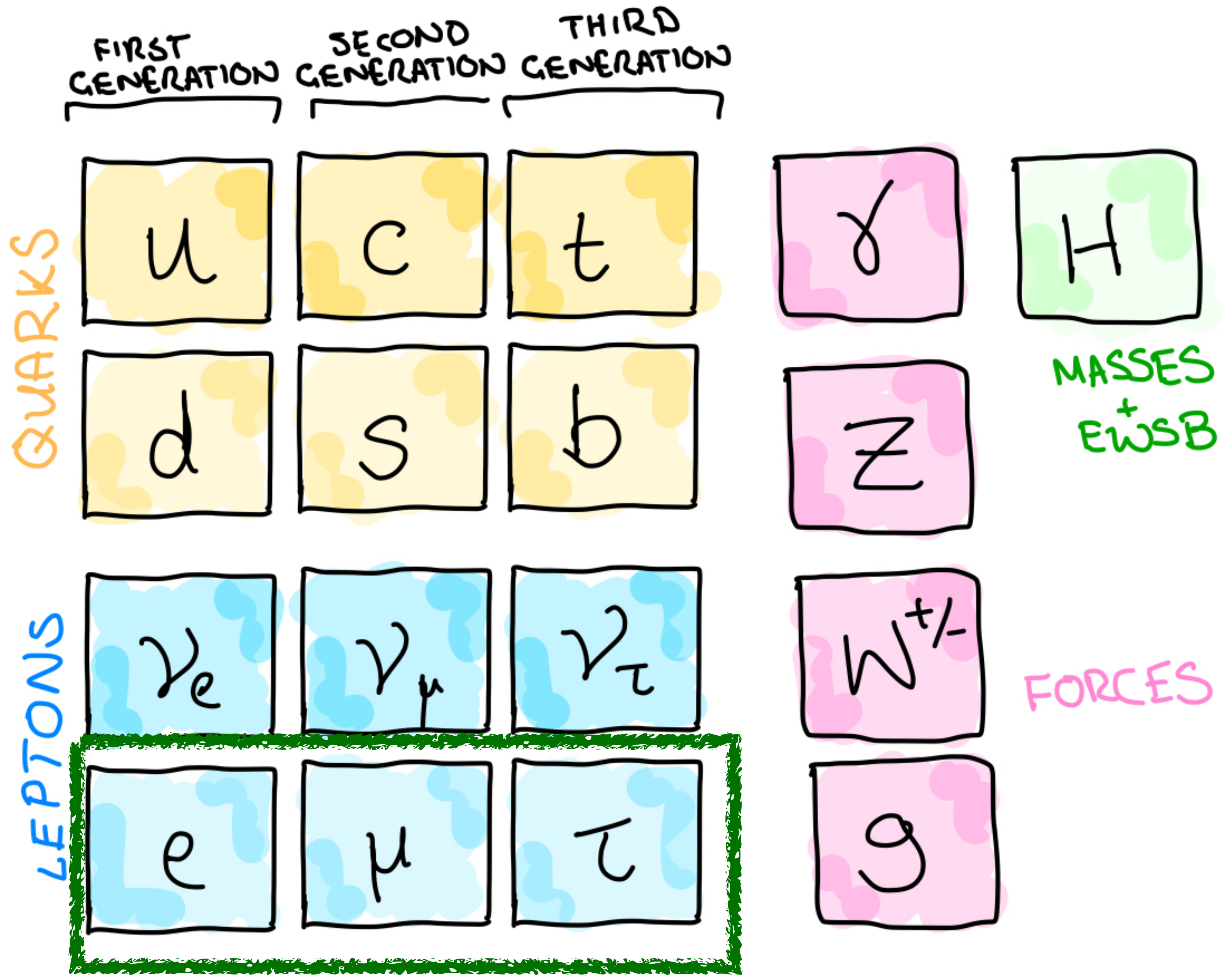
< O(1e-54)

Petcov, 1977

- Thus far, our only signal of lepton flavour violation is generated via neutrino masses
- These neutrino masses are *small*.
- It is natural for these effects to be small if they are signals that result from an explicitly broken symmetry of the flavour sector
- We can say the symmetry "protects" the size of the observable effects of its breaking
- It remains to be seen if lepton flavour is *only* observably broken in the neutrino sector, though…cLFV?

$$\mathcal{G}_{\rm L} = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$

How is it broken?

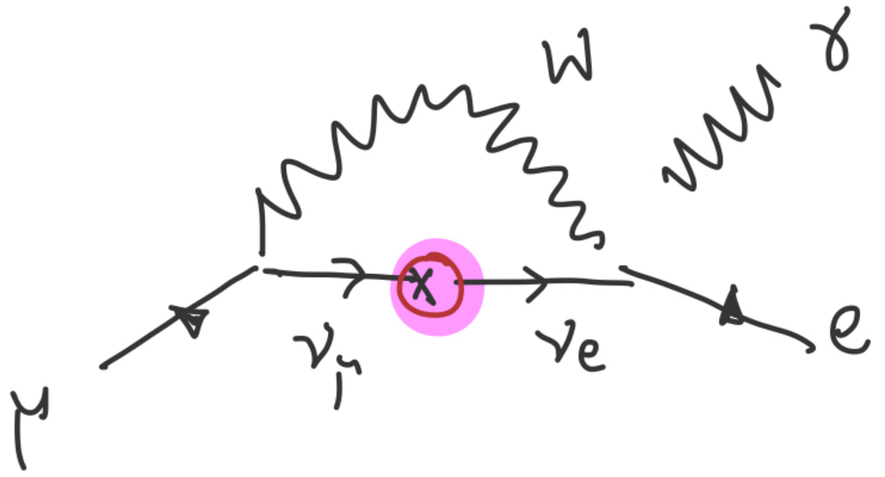


Charged LFV (cLFV)

Why am I telling you about cLFV if I am also saying it's all totally self consistent for LFV effects to be small?

- We still haven't explained how neutrinos get their mass. Some new physics needs to generate neutrino masses. We don't know exactly how SM+ that will behave under this narrative.
- Maybe symmetry breaking in the lepton and neutrino sectors is different? Depending how flavour symmetry breaking manifests, e.g. we have right-handed charged leptons.
- In the context of the whole SM flavour puzzle, there is more to unpack here…

Charged LFV (cLFV)



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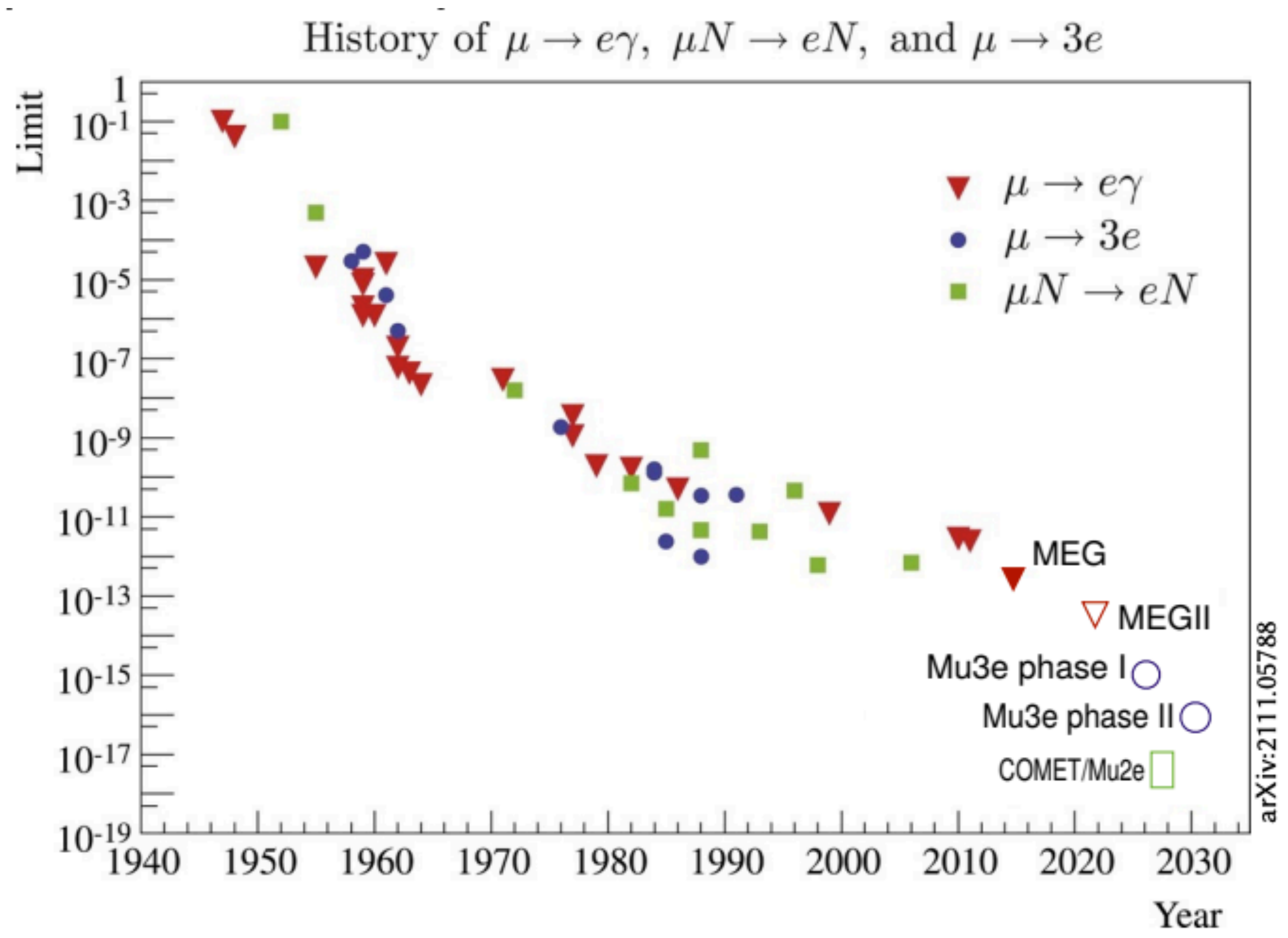
Petcov, 1977

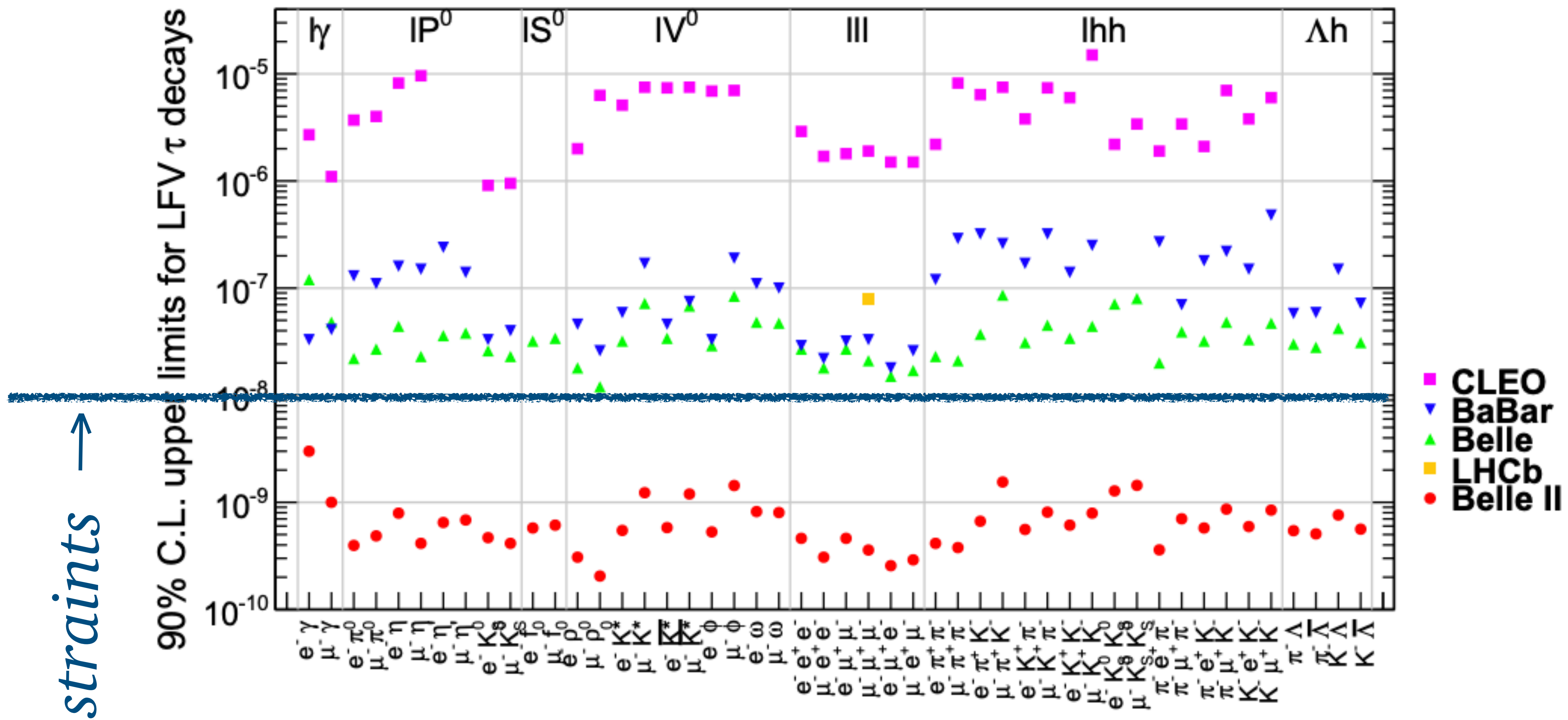


- SU(2) symmetry of the SM links neutrinos and (left handed) charged leptons : can we see LFV in the charged-lepton sector?
- Many searches for cLFV have focussed on muon decays:
  - Muon mass ~ 105 MeV and lifetime ~ 2.2 μs

    'Goldilocks mass': no hadronic decays, but does decay!
- Of course, if we only extended the SM by neutrino masses and don't allow for other LFV, we expect only small cLFV effects (symmetry!). Other LFV BSM models yield larger signals.

So an observable detection of cLFV is genuine sign of new physics!

New prospects for tau physics



Present constraints →

Bell II Physics Book, 1808.10567

- The tau is more challenging than the muon: smaller lifetime, decays also into mesons…
- But: it can decay into both electrons and muons, so probe all types of lepton flavour transitions
- Belle II plans to improve many of the tau decay sensitivities by up to two orders of magnitude in the BRs.
- Even current bounds from tau decays are very strong constraints on many new physics models coupling to third generation leptons.

Today’s focus

Muon physics is still very exciting. But what if there was a well-motivated physics reason for why we haven’t seen $\mu \to e$ cLFV? Could cLFV with τ’s be right around the corner?

Lepton flavour *triality*

The idea: each charged lepton is *charged* under this Z_3 (flavour triality)

$$\psi_T \to \left(e^{2\pi i/3}\right)^T \psi .$$

T is a triality charge.

electron : T = 1
muon : T = 2
tau : T = 3

} In line with generation.

- Ernest Ma, 2010 “Quark and lepton flavour triality” 1006.3524
- Motivated by the success of non-Abelian discrete flavour symmetry A_4 to explain neutrino tribimaximal mixing.
  (Altarelli + Feriglio 0512103, He, Kuem +Volkas 0601001)
- In the charged lepton sector, A_4 breaks to an approximate Z_3 “lepton triality”: a discrete subgroup of lepton flavour.
- Each charged lepton is assigned a triality charge.
- This same residual symmetry can be a feature of many other (discrete) flavour models for the lepton sector.

What does this say about cLFV?

Charge assignments:

L_i has triality $T=i$

$e_{R,i}$ has triality $T=i$

& Triality sums modulo 3

Implications:

$\mu \to e\gamma$

$T=2$ $T=1$

$\Delta T \neq 0$

$\tau^- \to \mu^+ e^- e^-$

$T=3$ $T=-2+1+1=0$

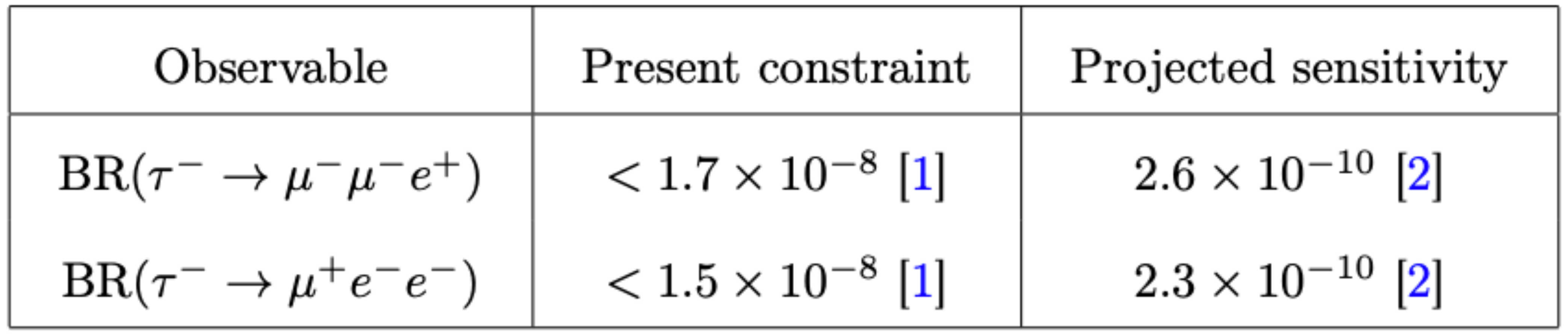
$0 \bmod 3 = 3$

$\Rightarrow \Delta T = 0$!

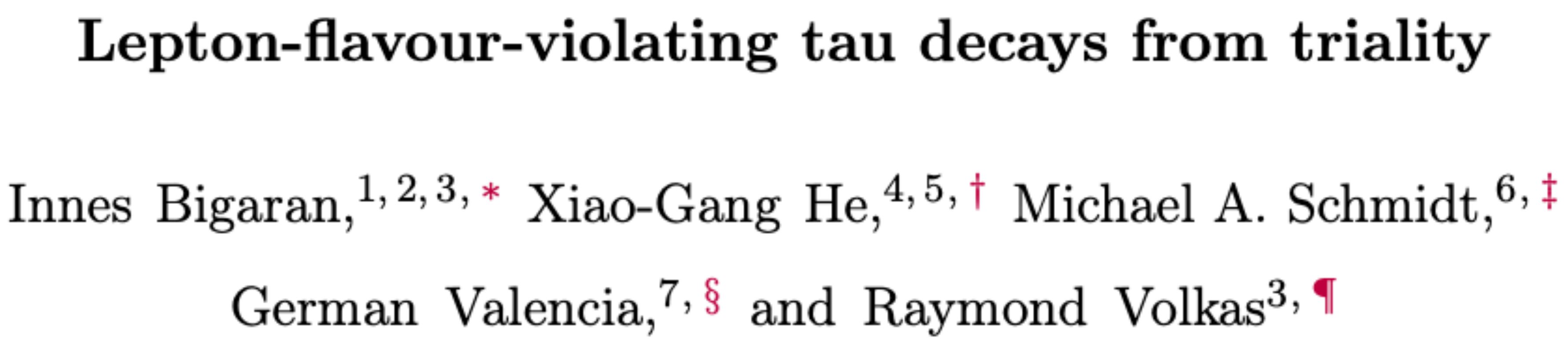
- If triality is a good symmetry, then it should be conserved.
- This permits certain cLFV processes, and forbids others. If triality is ultimately broken by some small parameter, then this approximate symmetry suppresses the size of any triality breaking processes [ν mass requirement]
- So if the lepton flavour symmetry has triality as a feature, then we are MUCH more likely to see cLFV in tau decays.

Where should we look for cLFV?

Triality-preserving charged-lepton decays:



Observable	Present constraint	Projected sensitivity
$\mathrm{BR}(\tau^- \to \mu^- \mu^- e^+)$	$< 1.7 \times 10^{-8}$ [1]	2.6×10^{-10} [2]
$\mathrm{BR}(\tau^- \to \mu^+ e^- e^-)$	$< 1.5 \times 10^{-8}$ [1]	2.3×10^{-10} [2]



Lepton-flavour-violating tau decays from triality

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German Valencia,[7, §] and Raymond Volkas[3, ¶]

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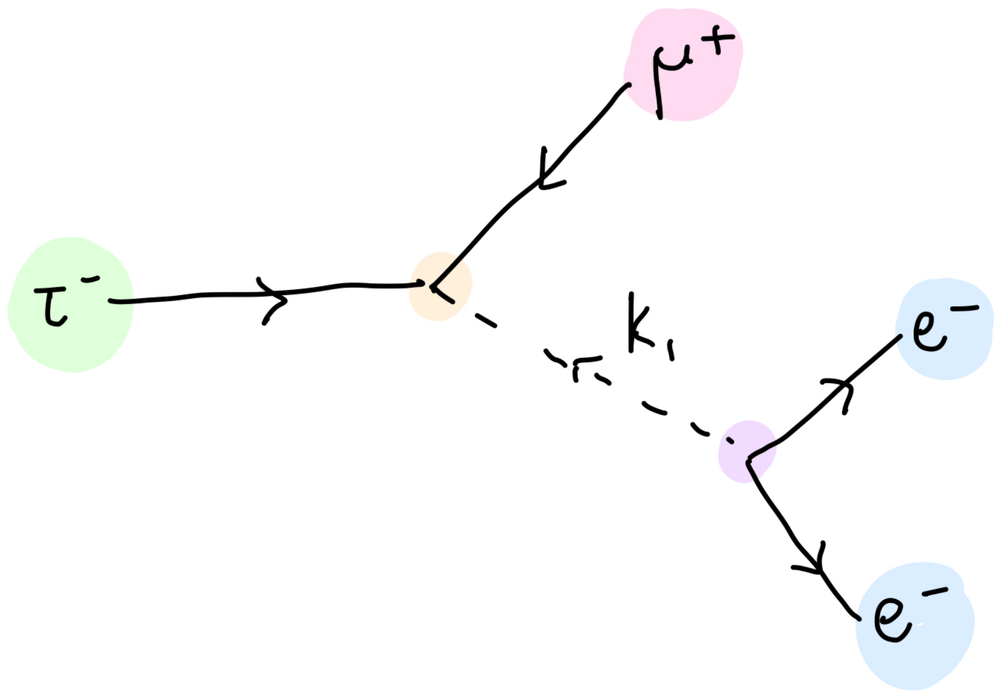
- There are two triality-preserving cLFV decays
- The sensitivity to these decays at experiment is expected to be improved significantly at Belle II
- If triality is a good lepton flavour symmetry, these are our best bet for finding signs of the underlying new physics violating lepton flavour beyond the SM
- What we did in 2212.09760: with triality as a starting point, established simple extensions featuring doubly charged scalar bileptons and studied the phenomenology of these models and decays

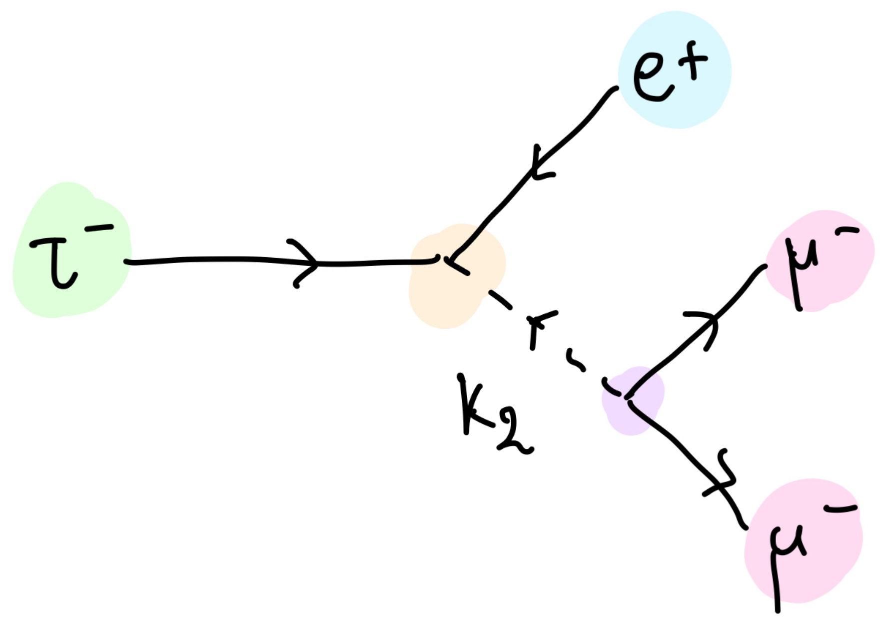
Electroweak Singlet Scalars

Observable
$\mathrm{BR}(\tau^- \to \mu^-\mu^-e^+)$
$\mathrm{BR}(\tau^- \to \mu^+e^-e^-)$

T=1 scalar



T=2 scalar



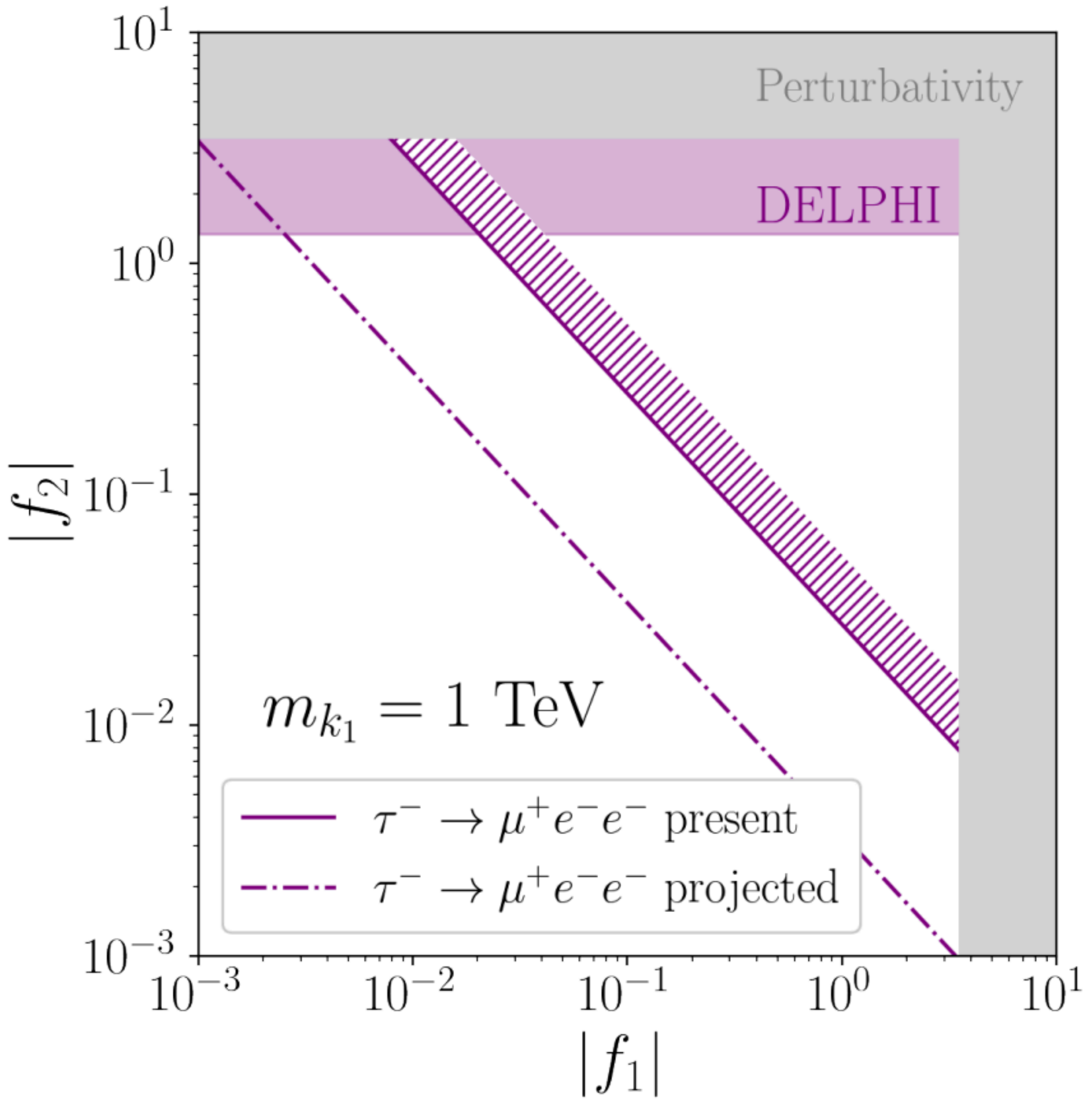
- Most simple extensions are electroweak singlet scalar *bileptons* : they couple directly to two leptons. Triality forbids other SM interactions, making their phenomenology straightforward.
- Mediating this interaction at tree-level, we can either assign the scalar a triality of T=2 or T=1
- The T=1 scalar $k_1$mediates $\tau^- \to \mu^+e^-e^-$

$$\mathcal{L}_{k_1} = \frac{1}{2}\left(2f_1\, \overline{\tau_R^c}\, \mu_R + f_2\, \overline{e_R^c}\, e_R\right)k_1 + h.c.$$

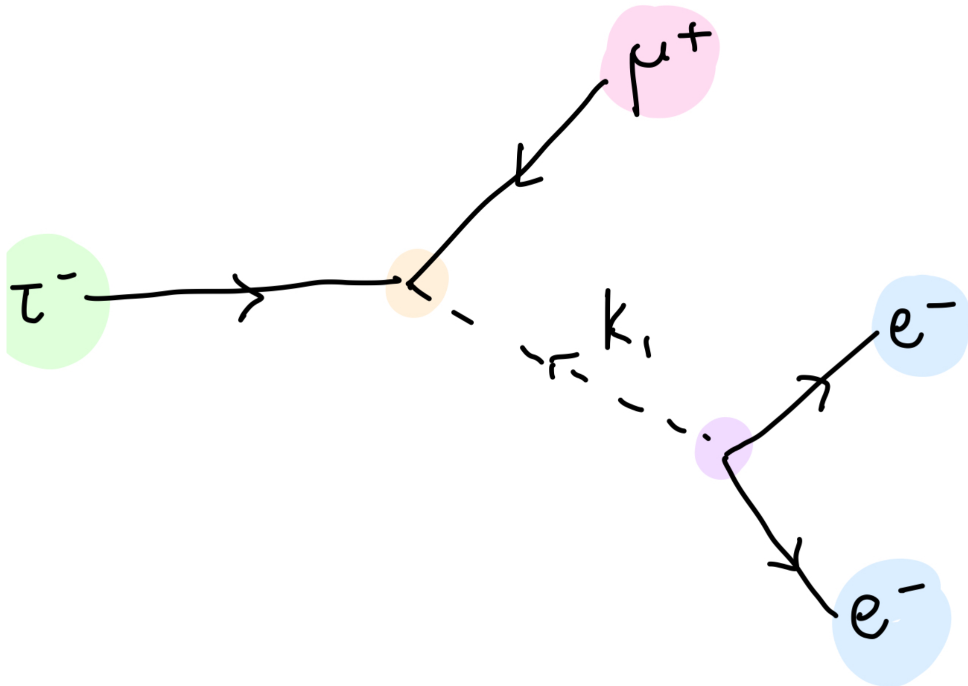
- The T=2 scalar k_2 mediates $\tau^- \to e^+\mu^-\mu^-$

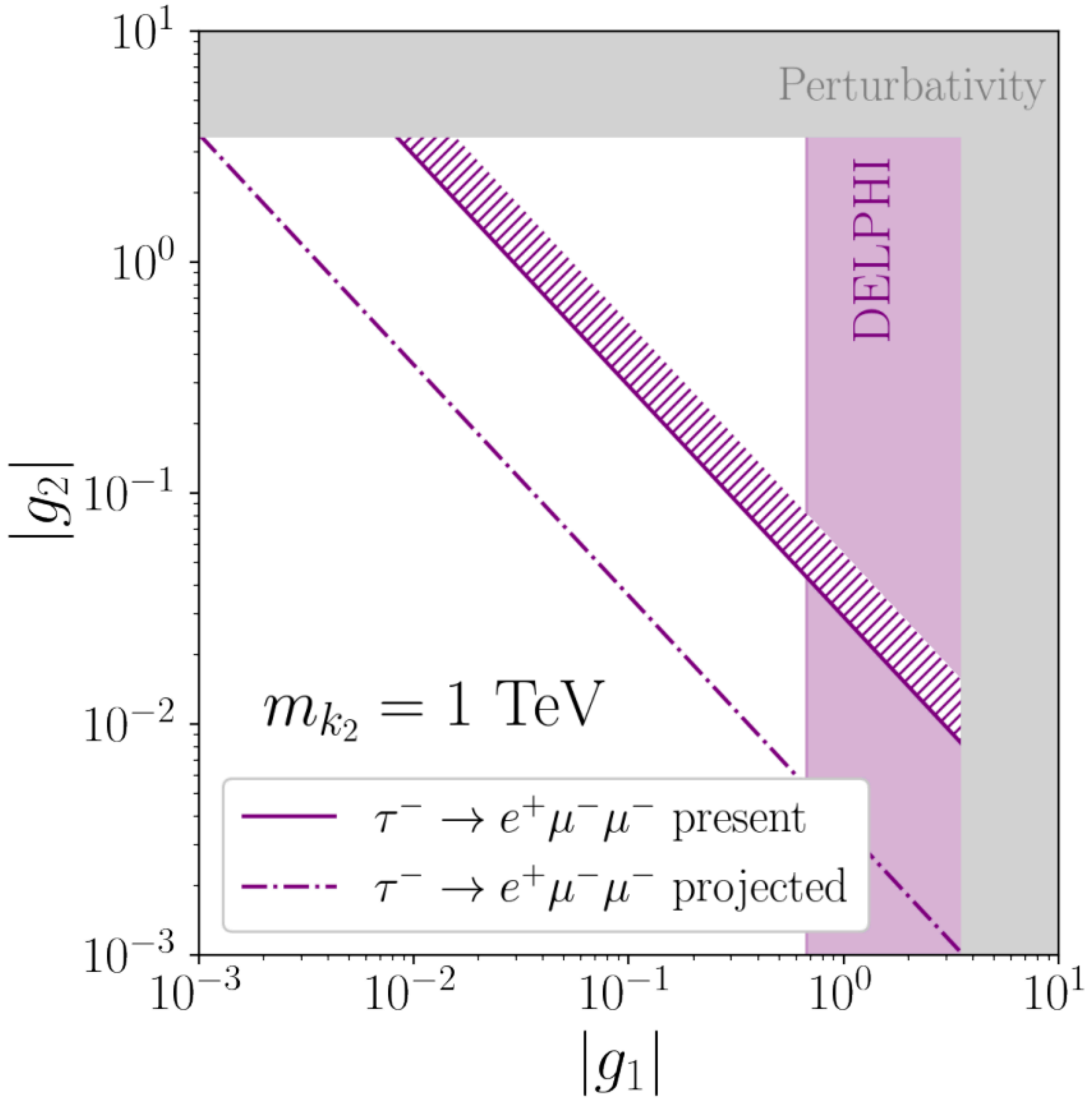
$$\mathcal{L}_{k_2} = \frac{1}{2}\left(2g_1\, \overline{\tau_R^c}\, e_R + g_2\, \overline{\mu_R^c}\, \mu_R\right)k_2 + h.c.$$

Electroweak Singlet Scalars

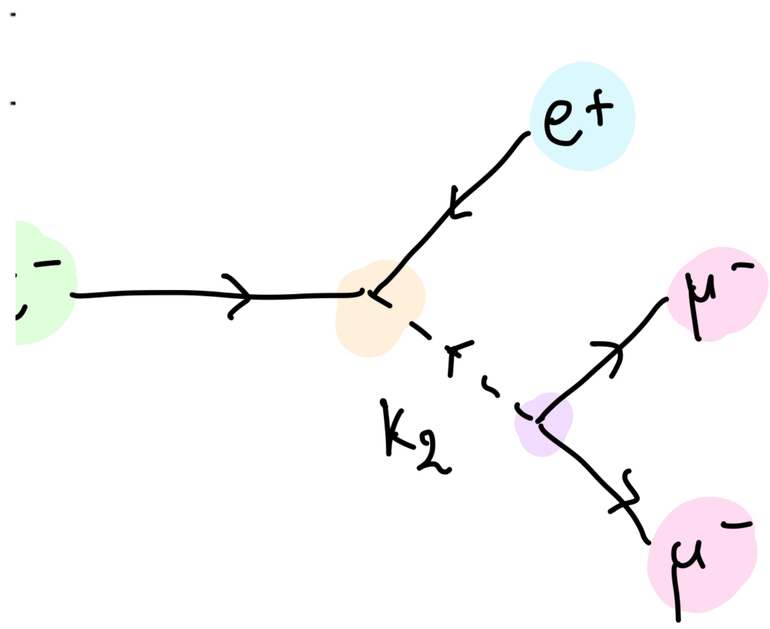


T=1 scalar





T=2 scalar

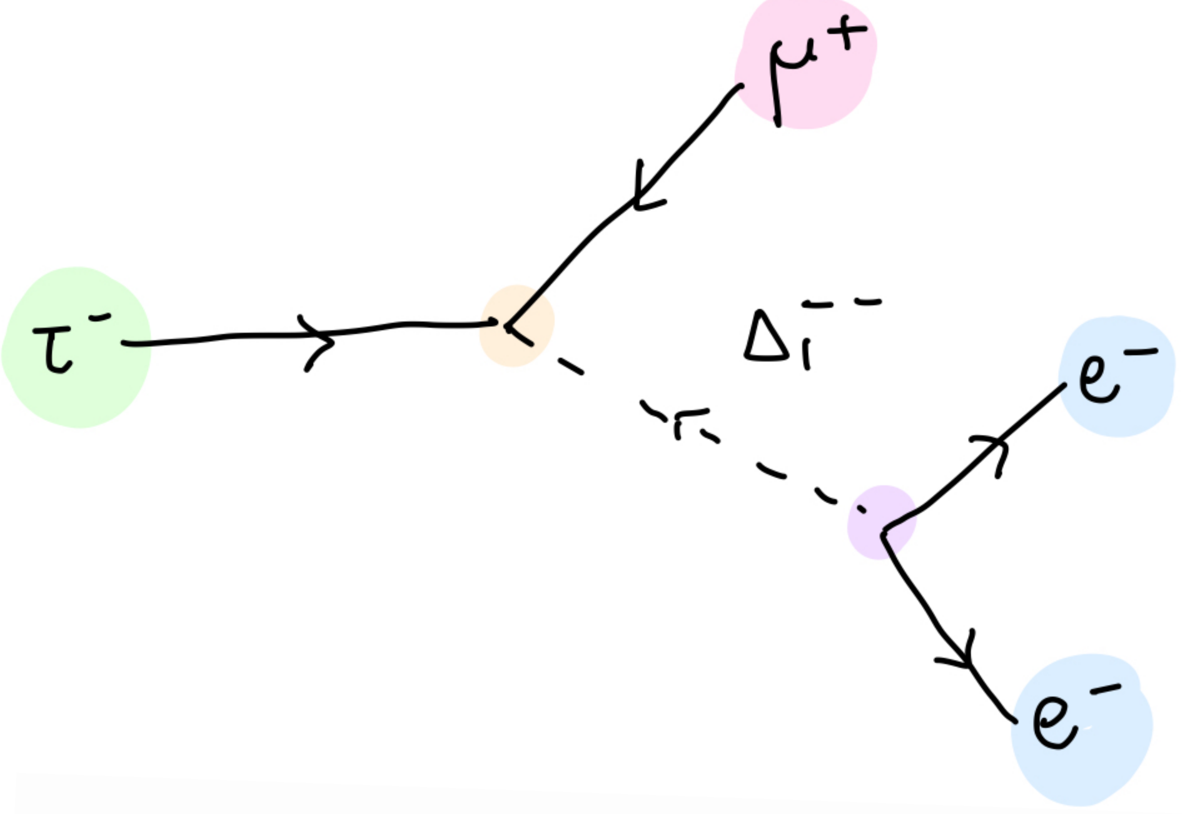


$$\mathcal{L}_{K_1} = \frac{1}{2}\left(2 f_1 \overline{\tau_R^c} \mu_R + f_2 \overline{e_R^c} e_R\right) K_1 + h.c.$$

$$\mathcal{L}_{K_2} = \frac{1}{2}\left(2 g_1 \overline{\tau_R^c} e_R + g_2 \overline{\mu_R^c} \mu_R\right) K_2 + h.c.$$

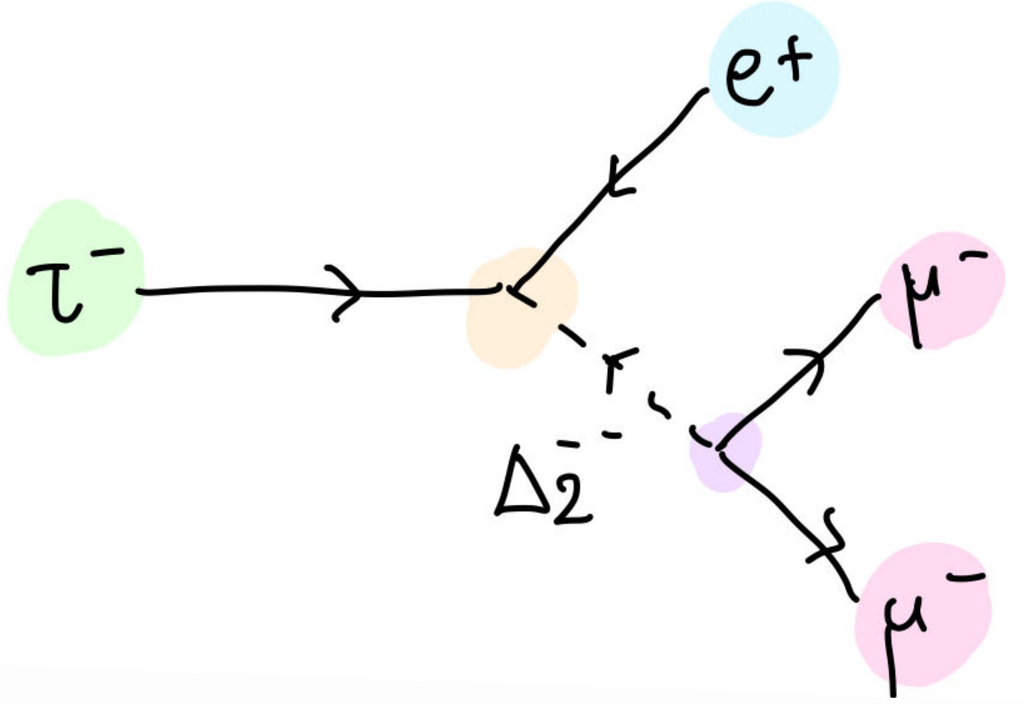
- Doubly-charged scalar bilepton is constrained to be TeV scale by direct searches
- Contribution from (T=1) [T=2] to e+ e- → (e+ e-) [τ+ τ-] constrained by DELPHI

Electroweak Triplet Scalars



T=1

$$\mathcal{L}_{\Delta_1} = \frac{1}{2}\left(2f_1 \overline{L_3^c}\,\Delta_1 L_2 + f_2 \overline{L_1^c}\,\Delta_1 L_1\right) + h.c.$$



T=2

$$\mathcal{L}_{\Delta_2} = \frac{1}{2}\left(2g_1 \overline{L_3^c}\,\Delta_2 L_1 + g_2 \overline{L_2^c}\,\Delta_2 L_2\right) + h.c.$$

- Much richer phenomenology. Can be thought of as an extension of the singlet scalar study.
- Electroweak triplet scalar bileptons

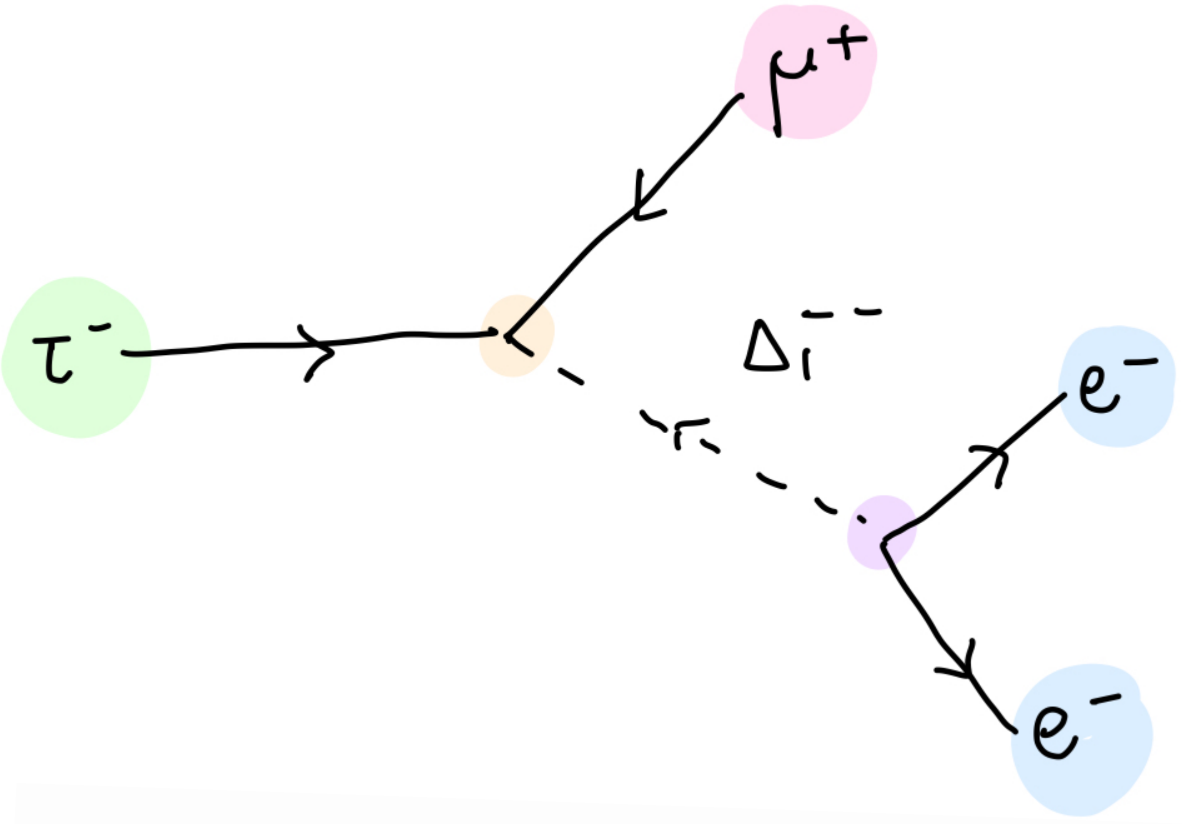
$$\Delta_T \sim \begin{pmatrix} \Delta_T^{+} & \Delta_T^{++} \\ \Delta_T^{0} & -\Delta_T^{+} \end{pmatrix}$$

doubly charged scalar.

isospin partners

- Similarly constrained to be TeV scale by bilepton searches
- Couple to lepton doublet: constraints also from neutrino interactions

Electroweak Triplet Scalars



T=1

$$\mathcal{L}_{\Delta_1} = \frac{1}{2}\left(2f_1 \overline{L_3^c}\, \Delta_1 L_2 + f_2 \overline{L_1^c}\, \Delta_1 L_1\right) + h.c.$$

Example of expanded interaction terms:

$$\overline{L_3^c}\, i\sigma_2 \mathbf{\Delta}_1 L_2 = -\overline{(\tau_L)^c}\,\mu_L\,\Delta_1^{++} \boxed{-\frac{1}{\sqrt{2}}\left[\overline{(\tau_L)^c}\,\nu_{\mu L} + \overline{(\nu_{\tau L})^c}\,\mu_L\right]\Delta_1^{+}} + \overline{(\nu_{\tau L})^c}\,\nu_{\mu L}\,\Delta_1^0,$$

$$\overline{L_1^c}\, i\sigma_2 \mathbf{\Delta}_1 L_1 = -\overline{(e_L)^c}\, e_L\,\Delta_1^{++} - \sqrt{2}\,\overline{(e_L)^c}\,\nu_{eL}\,\Delta_1^{+} + \overline{(\nu_{eL})^c}\,\nu_{eL}\,\Delta_1^0.$$

$$\Delta_T \sim \begin{pmatrix} \Delta_T^{+} & \Delta_T^{++} \\ \Delta_T^{0} & -\Delta_T^{+} \end{pmatrix}$$

doubly charged scalar.

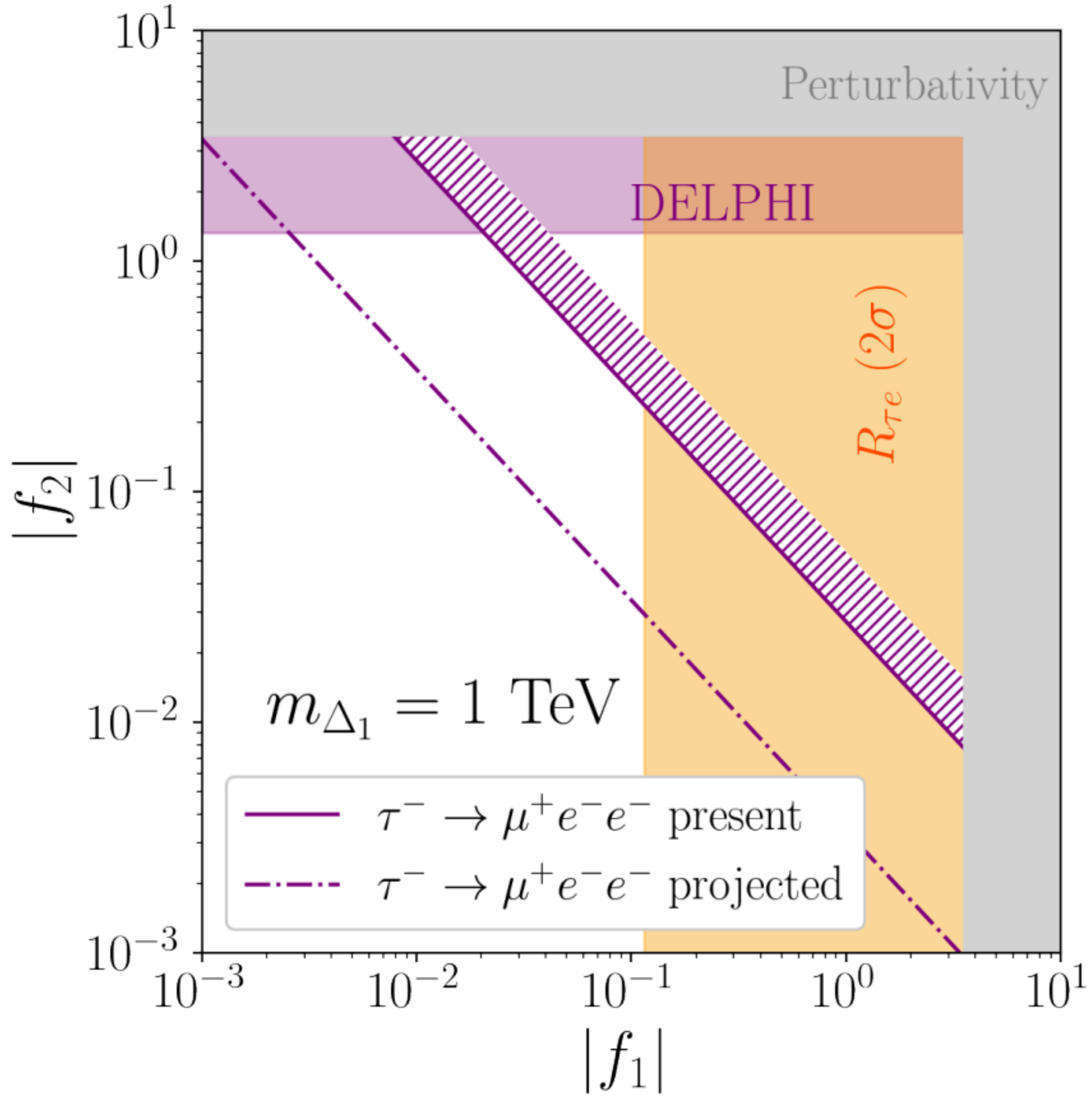
isospin partners

- Isospin partners: single and doubly charged components
- LFU ratios of tau decays also constrain parameter space, e.g.

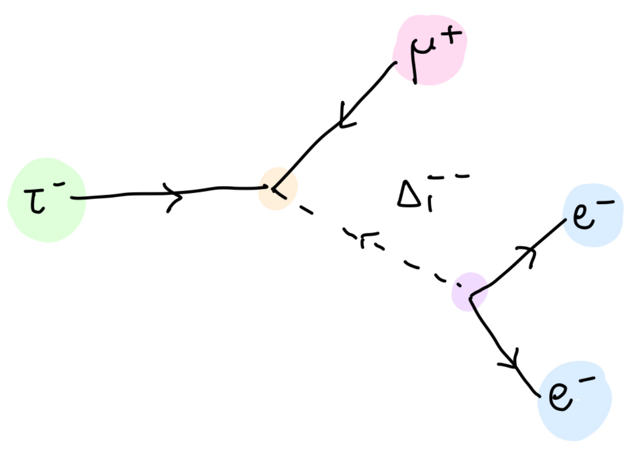
$$R_{\tau e} = \frac{\Gamma(\tau \to \mu + \text{inv})}{\Gamma_{SM}(\tau \to \mu + \text{inv})} \times \frac{\Gamma_{SM}(\mu \to e + \text{inv})}{\Gamma(\mu \to e + \text{inv})}$$

- Majorana-mass type interaction induced by neutral component. Constrained in structure by triality…[we will return to this later]

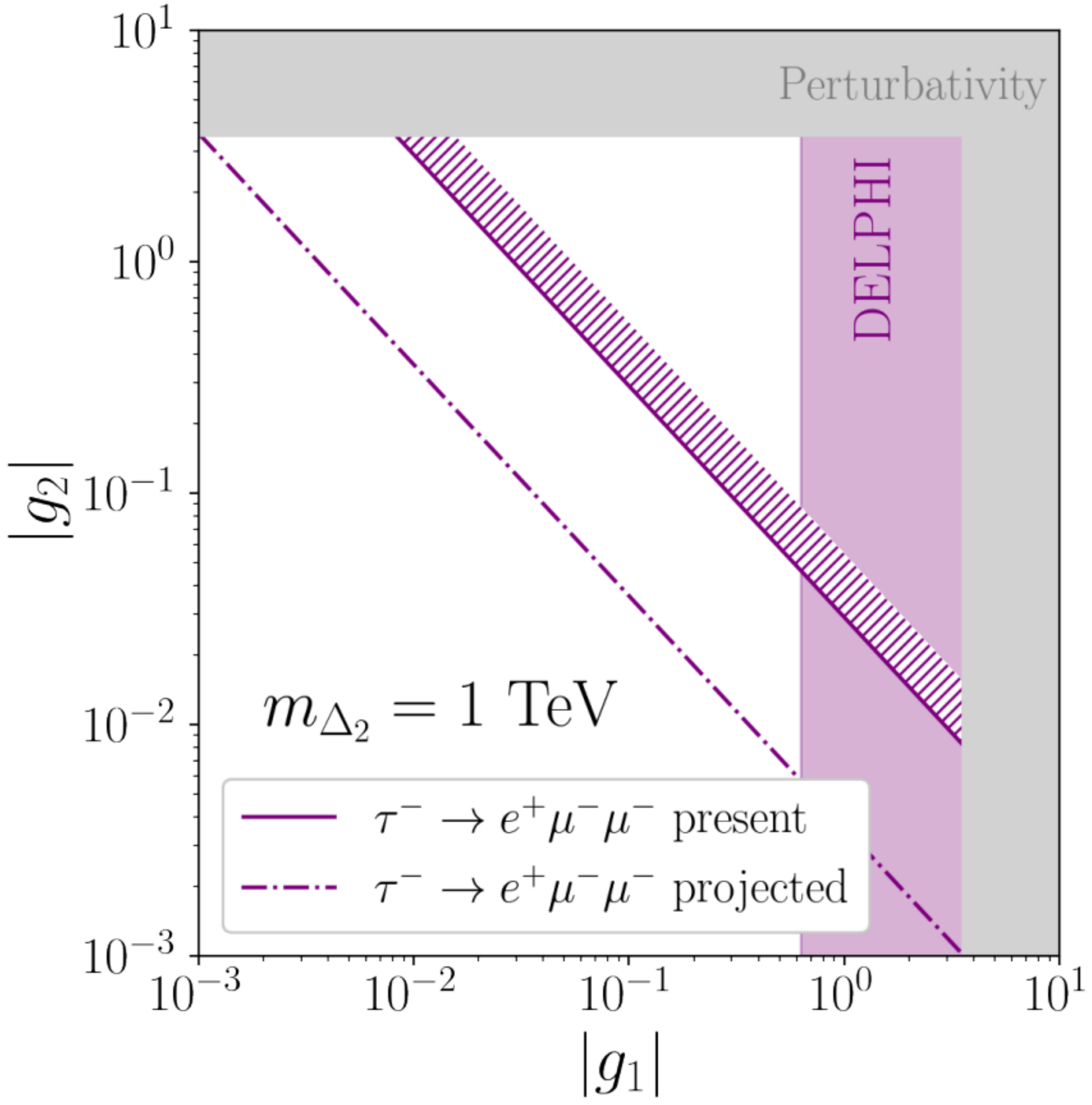
Electroweak Triplet Scalars



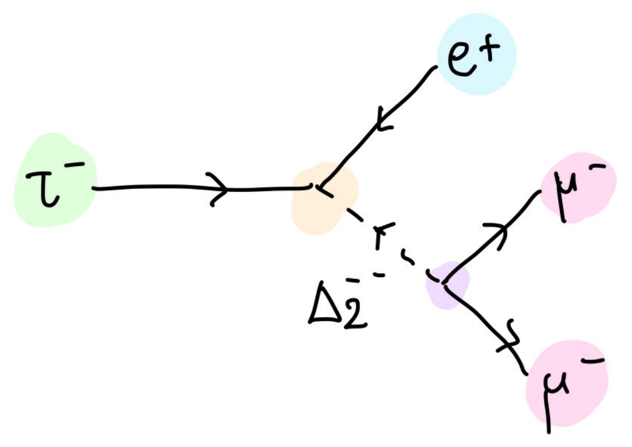
T=1 scalar



$$\mathcal{L}_{\Delta_1} = \frac{1}{2}(2f_1 \overline{L^c_3} \Delta_1 L_2 + f_2 \overline{L^c_1} \Delta_1 L_1) + h.c.$$



T=2 scalar



$$\mathcal{L}_{\Delta_2} = \frac{1}{2}(2g_1 \overline{L^c_3} \Delta_2 L_1 + g_2 \overline{L^c_2} \Delta_2 L_2) + h.c.$$

Brief recap of the story so far.

- Lepton flavour triality could be a residual symmetry in the flavour sector which constrains observable cLFV decays
- Moreover, motivated by flavour triality we could expect cLFV tau decays as outlined to be the first signal of LFV new physics
- Simple UV completions: triality-preserving extensions to the SM contain scalar bileptons EW triplet and singlet phenomenology study shows there's regions of parameter space that would predict a signal within reach of Belle II.

Tau decay kinematic study in light of triality

Observable	Present constraint	Projected sensitivity
$\mathrm{BR}(\tau^- \to \mu^-\mu^-e^+)$	$< 1.7 \times 10^{-8}$ [1]	2.6×10^{-10} [2]
$\mathrm{BR}(\tau^- \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$ [1]	2.3×10^{-10} [2]

Expt. limits assume ~ 1

$$\frac{d^2\Gamma(\tau^- \to \ell_i^- \ell_i^- \ell_j^+)}{dm_{--}^2\, dm_{+-}^2} = \frac{1}{256\pi^3 m_\tau^3}\boxed{|\overline{\mathcal{M}}|^2}$$

$$= \frac{|C_{i3ij}|^2}{64\pi^3 m_\tau^3}(m_{--}^2 - 2m_{\ell_i}^2)(m_\tau^2 + m_{\ell_j}^2 - m_{--}^2)$$

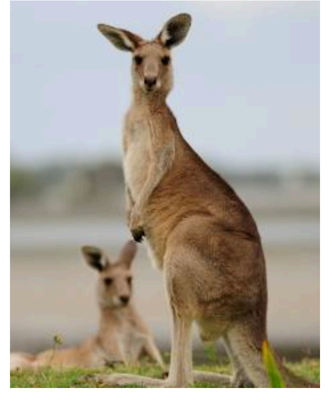
invariant mass of $\ell_i^- \ell_i^-$

invariant mass of $\ell_i^- \ell_j^+$

wilson coefficient ~ couplings.

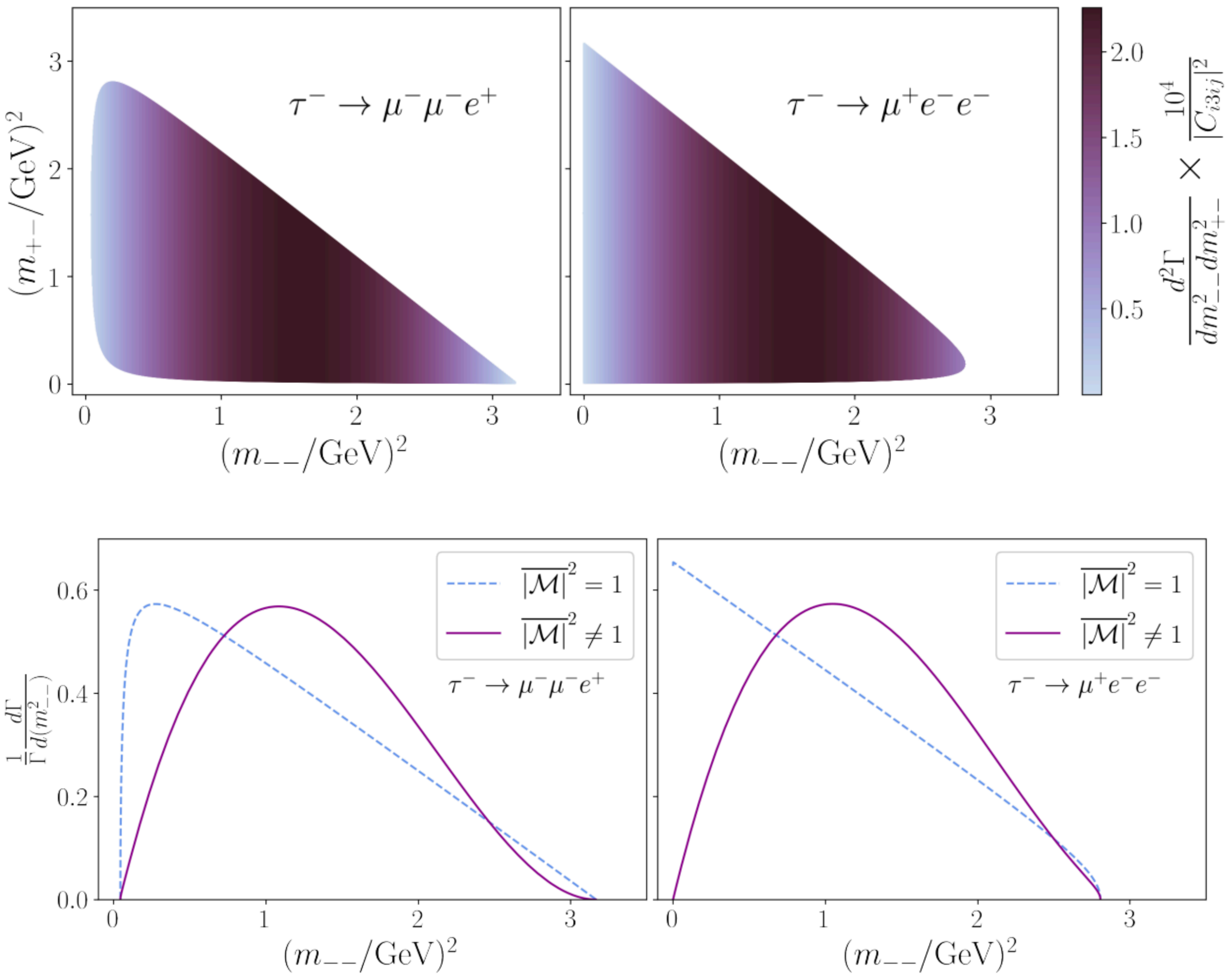
(BSM here is too heavy to go on-shell)

- Bounds on these decays have phase-space dependence that isn't taken into account
- In particular, phase space of three body decays depends on the nature of the effective interaction and mediators present (R. H. Dalitz (1953)



- Limits assume that there's no kinematic dependence in the matrix element, which is not necessarily true
- Discriminating power of three-body phase space of taus studied in e.g. Dassinger et al 0707.0988, Celis et al 1403.5781 ++, though not in these decay channels above.

Phase space distributions



- Both scalar triplet/singlet models contribute to both processes via a RH or LH vector interaction. Differential decay rates are of the same form
- Different structure of the Dalitz plots arise from different decay kinematics. These differential decay rates are *not* the same as those from the “phase space” approximation (M~1).
- A bound is derived from looking at what we *expect* to see, and thus constraining the size of the effect. We need internal experimental information to be able to recast constraints, though…(e.g. detection efficiency as a function of invariant masses)

Neutrino masses in the triality-based models

Dirac masses

$$\mathcal{L} \supset -y_{ij} \bar{L}_i \nu_{R_i} \tilde{H} + h.c.$$

$$y = \begin{pmatrix} y_{11} & 0 & 0 \\ 0 & y_{22} & 0 \\ 0 & 0 & y_{33} \end{pmatrix}$$

majorana masses

$$\mathcal{L} \supset \kappa_{ij} (L_i H)(L_j H)$$

$$\kappa = \begin{pmatrix} 0 & \kappa_{12} & 0 \\ \kappa_{12} & 0 & 0 \\ 0 & 0 & \kappa_{33} \end{pmatrix}$$

- In my abstract, I promised a connection to neutrino masses.
  - If we add RH neutrinos with three flavours, generationally-assigned triality, we can also obtain a triality-preserving neutrino mass matrix, but with a restricted texture.

- Lepton triality needs to be broken to achieve observed neutrino mass texture.

Neutrino masses in the triality-based models

$$\Delta_T \sim \begin{pmatrix} \Delta_T^{+} & \Delta_T^{++} \\ \Delta_T^{0} & -\Delta_T^{+} \end{pmatrix}$$

doubly charged scalar.

isospin partners

$$\mathcal{L}_{\Delta_1} = \frac{1}{2}\left(2f_1\, \overline{L_3^c}\, \Delta_1 L_2 + f_2\, \overline{L_1^c}\, \Delta_1 L_1\right) + h.c.$$

$$\overline{L_3^c}\, i\sigma_2 \mathbf{\Delta}_1\, L_2 = -\overline{(\tau_L)^c}\, \mu_L\, \Delta_1^{++} - \frac{1}{\sqrt{2}}\left[\overline{(\tau_L)^c}\, \nu_{\mu L} + \overline{(\nu_{\tau L})^c}\, \mu_L\right] \Delta_1^{+} + \boxed{\overline{(\nu_{\tau L})^c}\, \nu_{\mu L}\, \Delta_1^{0}}$$

$$\overline{L_1^c}\, i\sigma_2 \mathbf{\Delta}_1\, L_1 = -\overline{(e_L)^c}\, e_L\, \Delta_1^{++} - \sqrt{2}\, \overline{(e_L)^c}\, \nu_{eL}\, \Delta_1^{+} + \boxed{\overline{(\nu_{eL})^c}\, \nu_{eL}\, \Delta_1^{0}}$$

- Lepton triality needs to be broken to achieve observed neutrino mass texture.

Breaking triality to generate neutrino masses isn't bad, neutrino masses are small so triality protection helps to keep triality breaking effect small.

- e.*g*. in the T=1 triplet model, we can see from the Lagrangian that if the neutral component gets a vev then we obtain a nonzero Majorana neutrino mass, though with a restricted flavour structure (Type II seesaw). Naturally small *vev* due to soft breaking by a cubic Higgs coupling.

Summary

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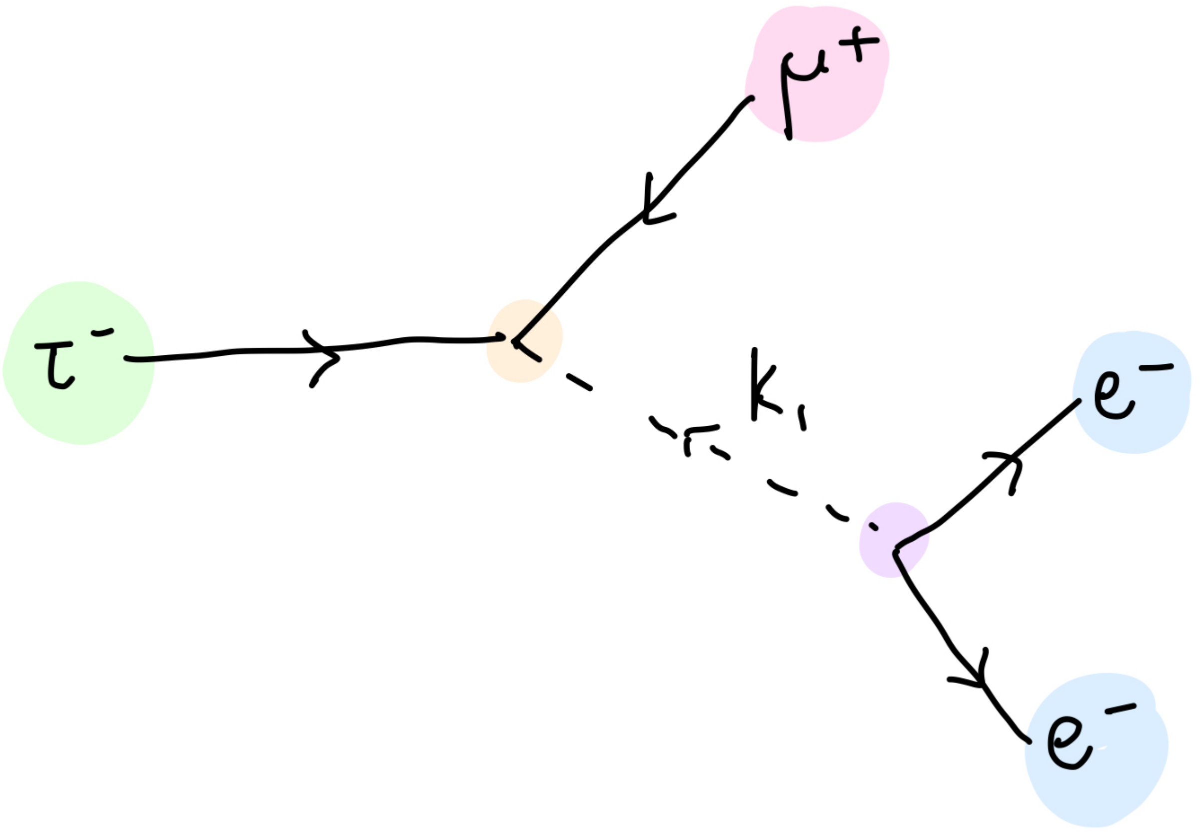
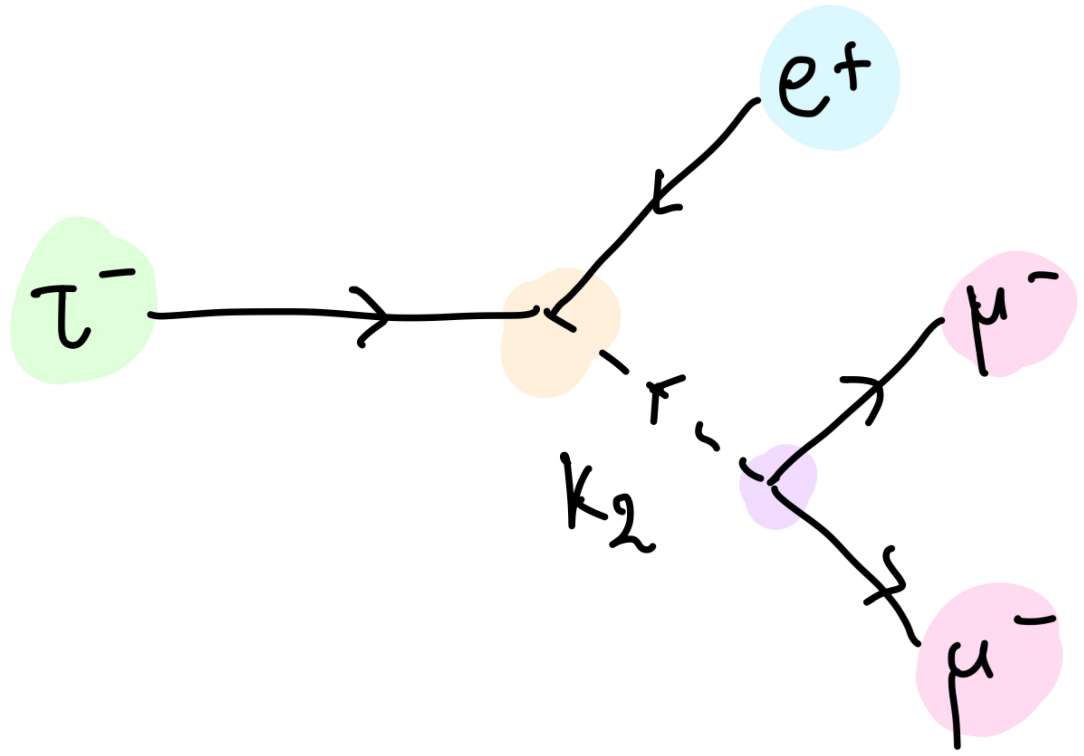


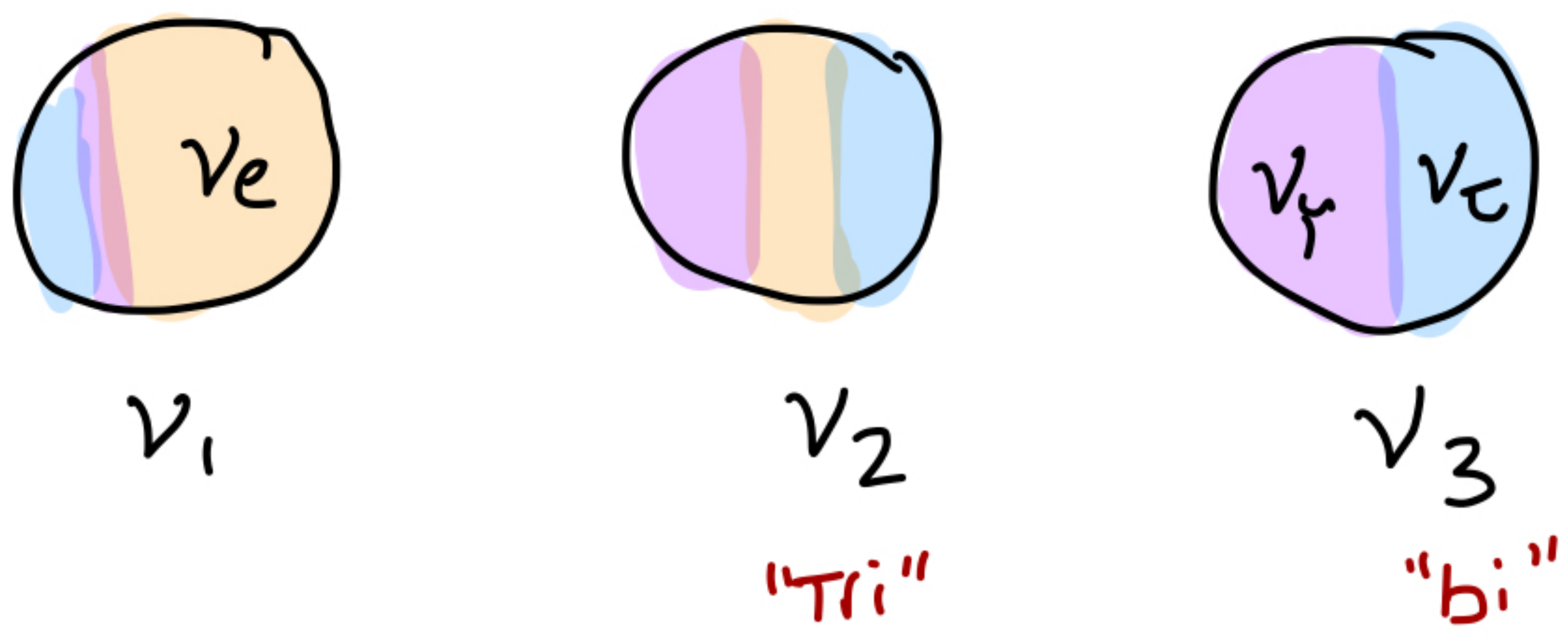


- Lepton triality: assign lepton flavours different “charges” under a Z_3 Motivates the search for cLFV signals in tau decays, and explains non-observation of cLFV in μ to e transitions
- Motivated by a residual Z_3 flavour symmetry in the lepton sector: can guide flavour model-building
- Minimal models furnished by EW singlet and triplet bileptons
- Dominant signals of cLFV in models with lepton flavour triality are in tau three-lepton decays. Discovery could be around the corner…

Thank you!

Backup

Tribimaximal mixing



$\theta_{12} \sim 35.3^\circ \longrightarrow 33.4^\circ$

$\theta_{23} \sim 45^\circ \longrightarrow 49.1^\circ$

$\theta_{13} = 0 \longrightarrow 8.54^\circ$

δ undefined. $\longrightarrow 197^\circ$

- In 2011, Daya Bay and Reno measured a nonzero θ_{13}, inconsistent with tribimaximal mixing
- Green data shows the results from 2022 NuFit collaboration fit to neutrino oscillation data.

Breaking triality to generate neutrino masses

$$\mathcal{L}_S = -\frac{\kappa_{ij}}{4}(L_i H)^T C (L_j H) + h.c.$$

triality → $\kappa = \begin{pmatrix} 0 & \kappa_{12} & 0 \\ \kappa_{12} & 0 & 0 \\ 0 & 0 & \kappa_{33} \end{pmatrix}$

Singlet complex scalar S, $T = 1$

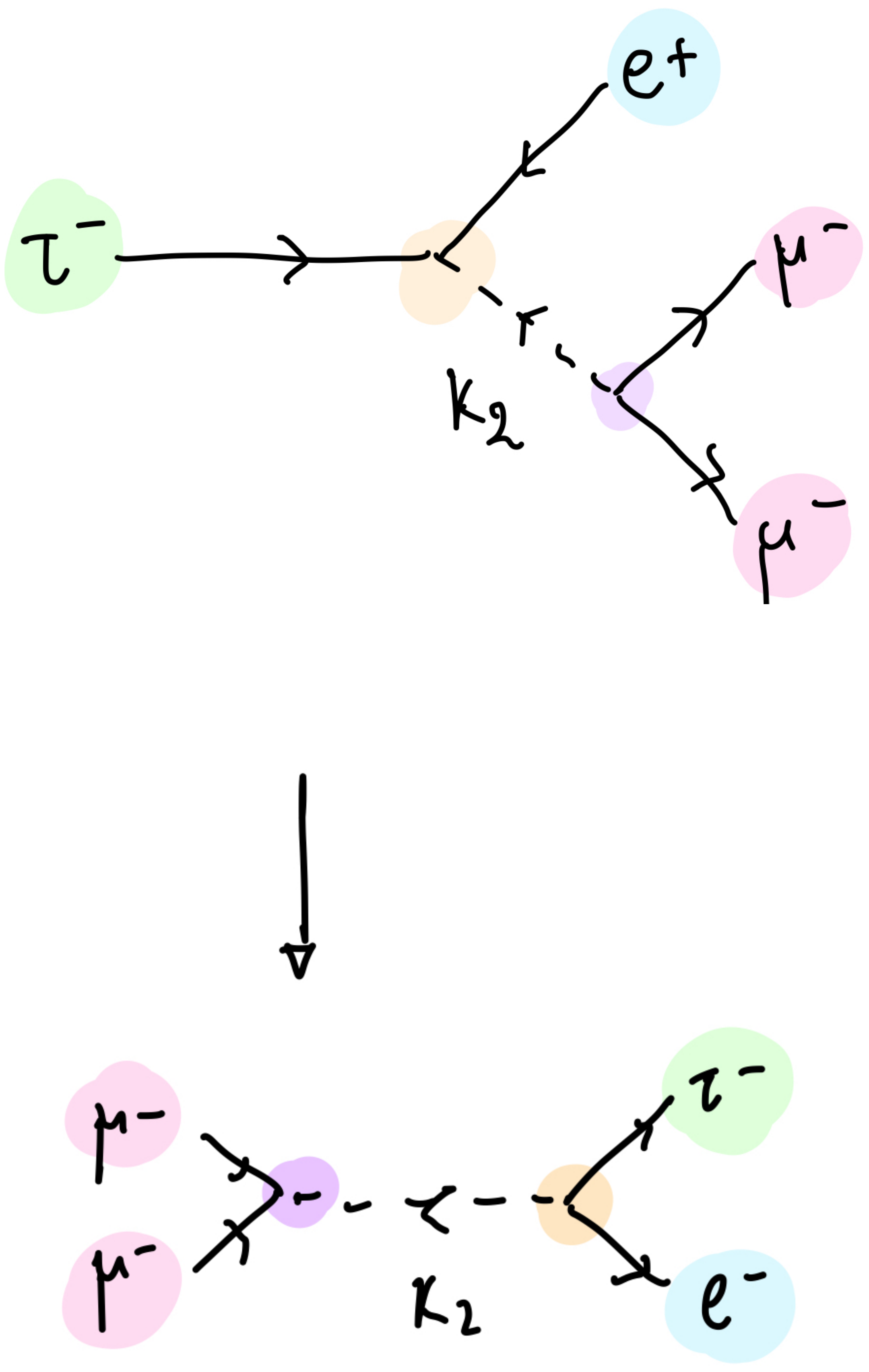
$S^{(*)}(L_i H)^T C (L_j H)$ operator $(D=6)$

⇒ leads to additional triality preserving couplings and if S gets a vev breaking triality we can have all zero entries populated.

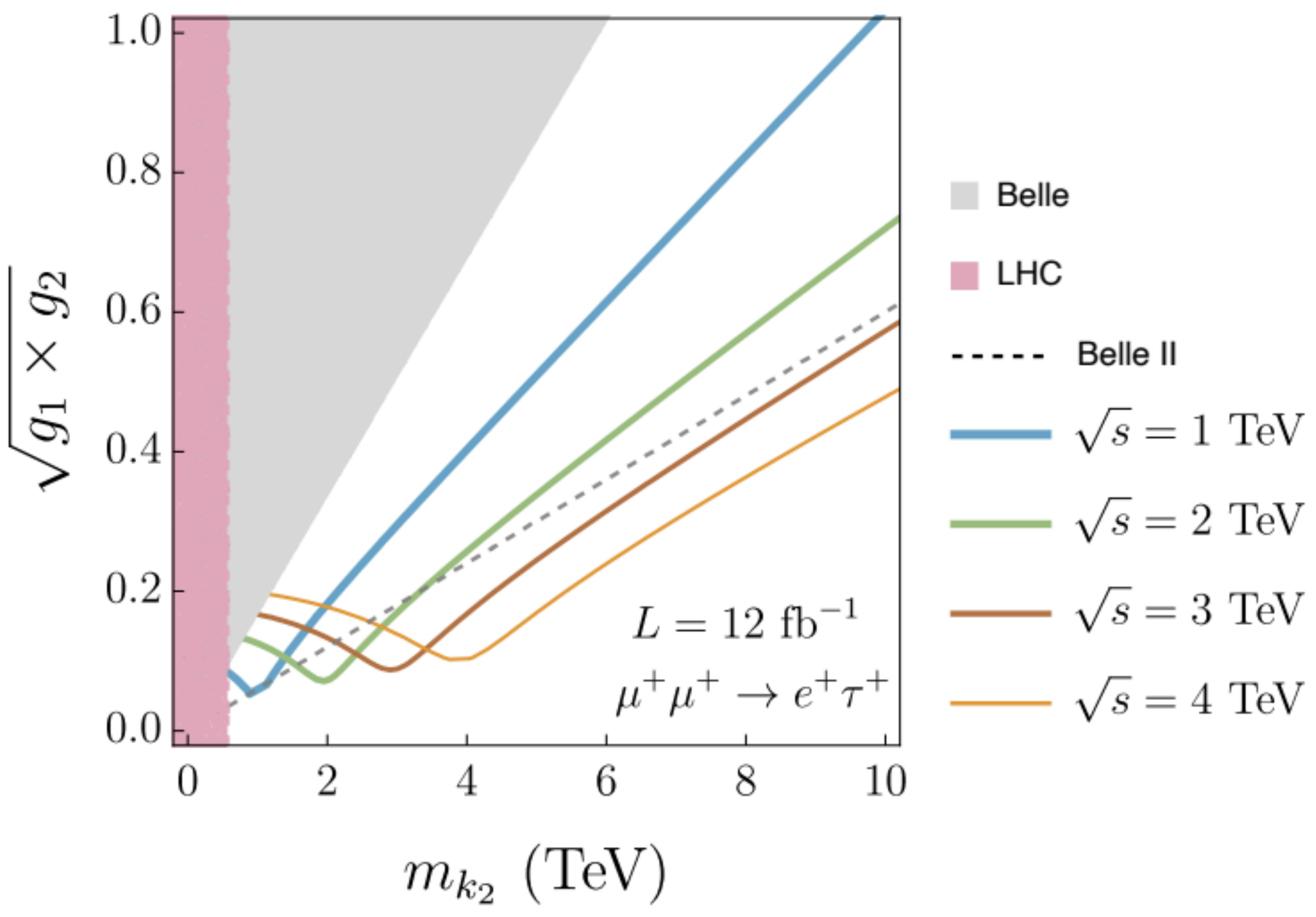
- A diagonal Dirac neutrino matrix together with a general RH neutrino Majorana mass matrix can generate the required neutrino mass and mixing parameters.

Same-sign muon collider signals

G. Lichtenstein M.A. Schmidt, G. Valencia, R.Volkas , 2307.11369



- Related by crossing-symmetry to processes that could be probed at a same-sign muon collider (μTRISTAN, 2201.06664)



- Demonstrated reach of this experiment after a year of data taking for these models