Flavor

as a connection to the outside CMS world

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Overview

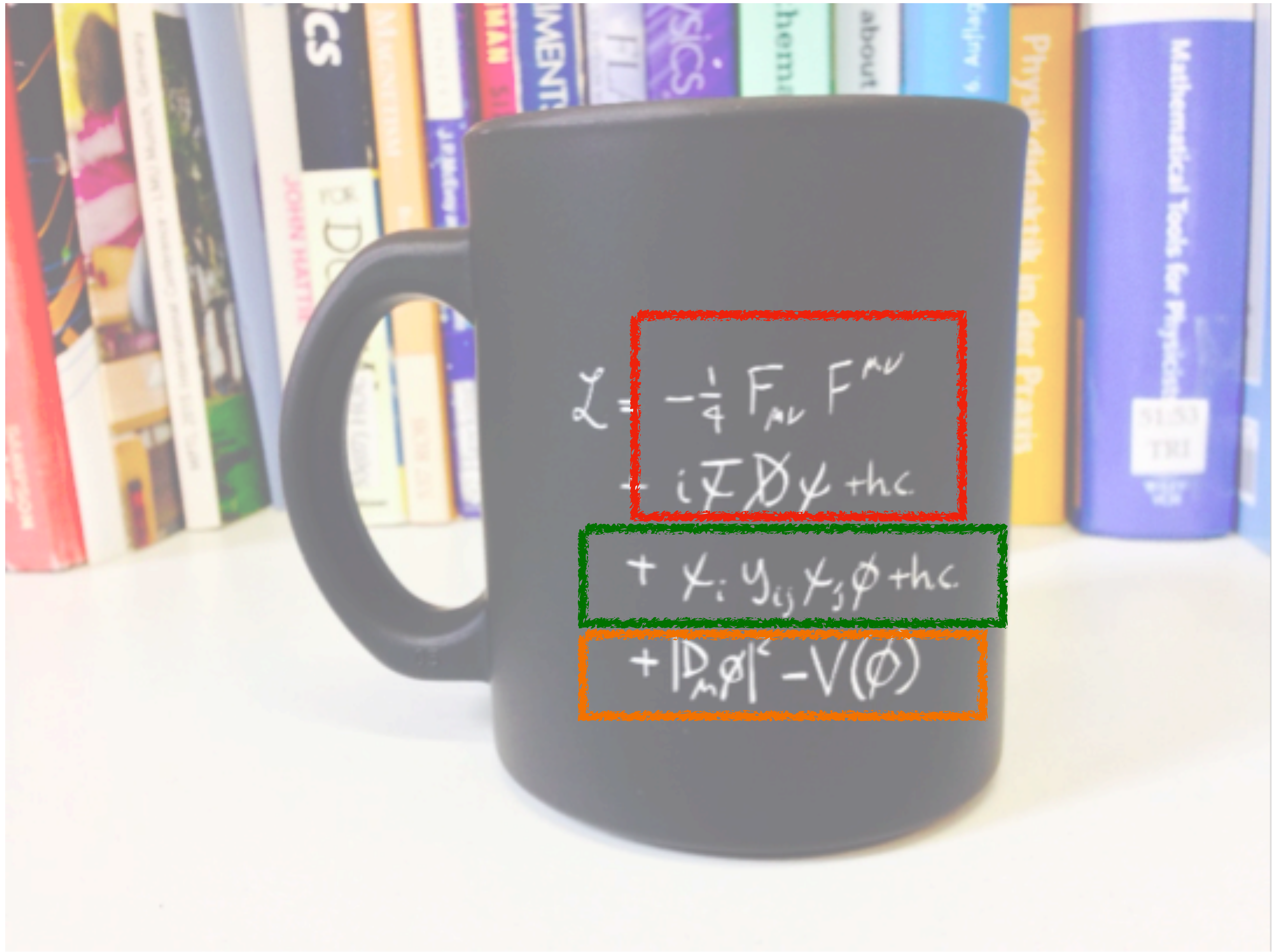
Part I: The Standard Model and flavour

Part II: BSM flavour probes

My aim:

to give you just an idea of some of the wide range of work done in the flavour theory community and how it complements and works together with what is being done by experimentalists.

Flavor in the SM

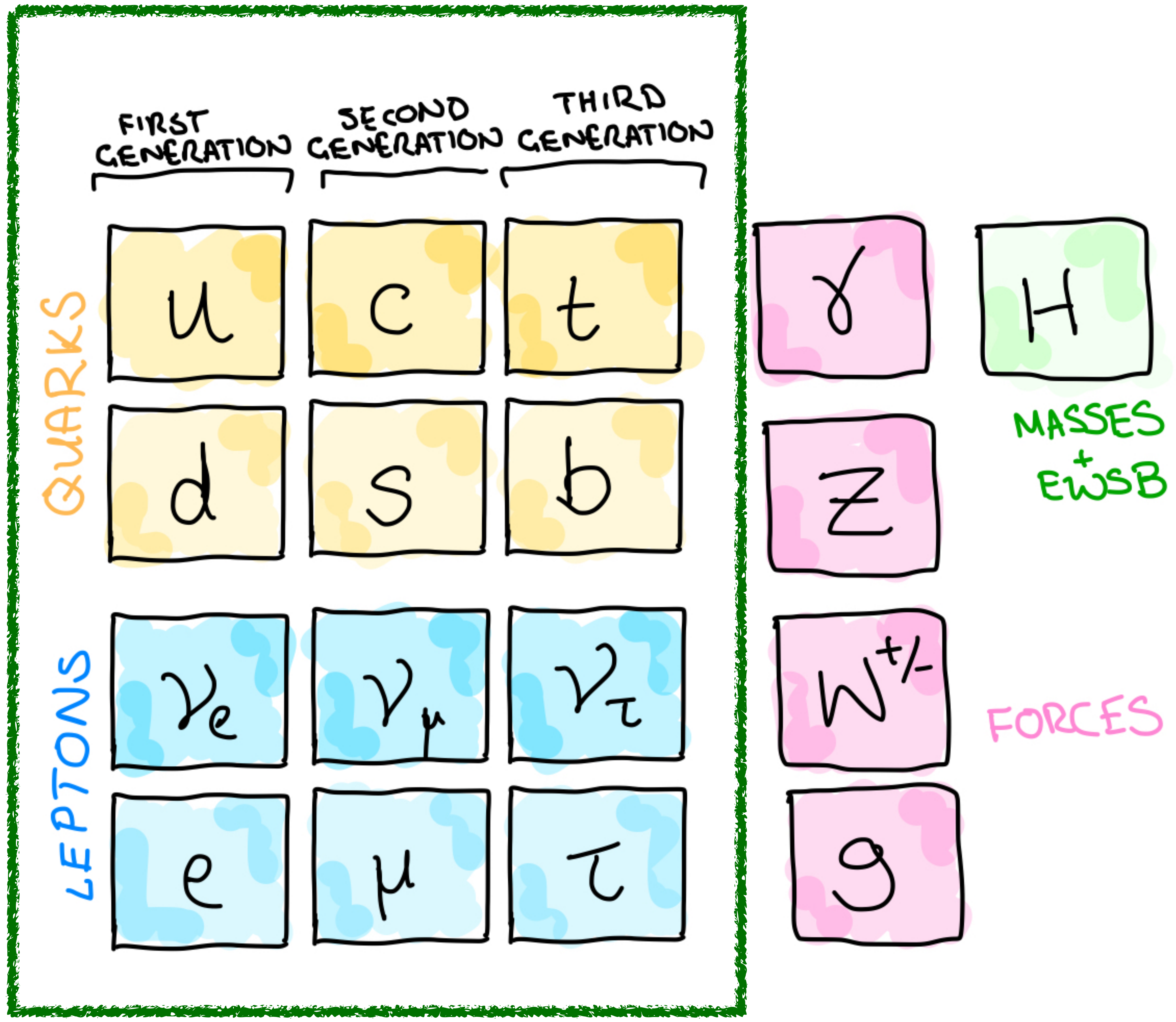


- The SM is a semi-empirical theory. Requires experimental input to fix ~ 27 free parameters to fully prescribe it

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

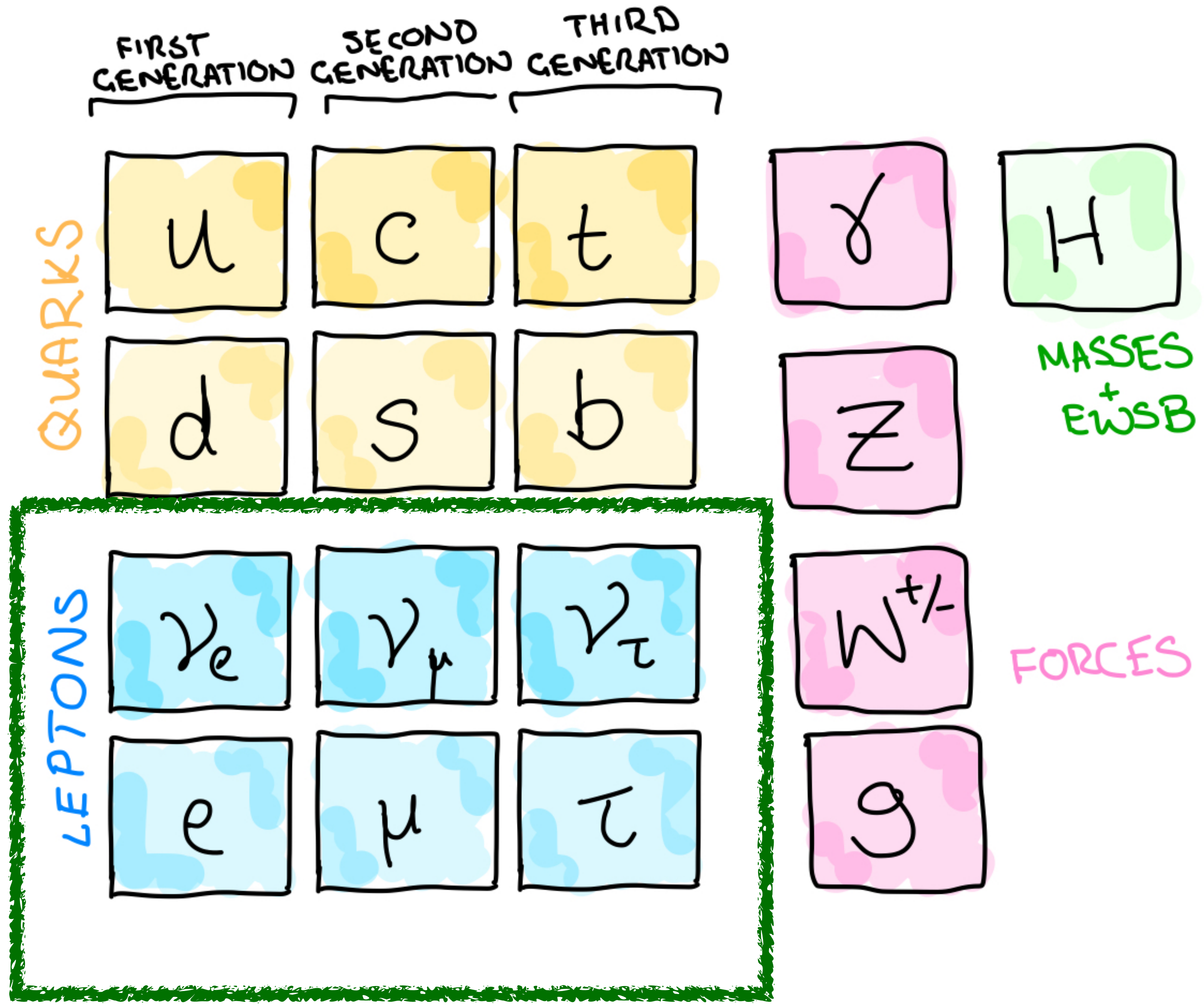
- We need experimentalists to measure these parameters!

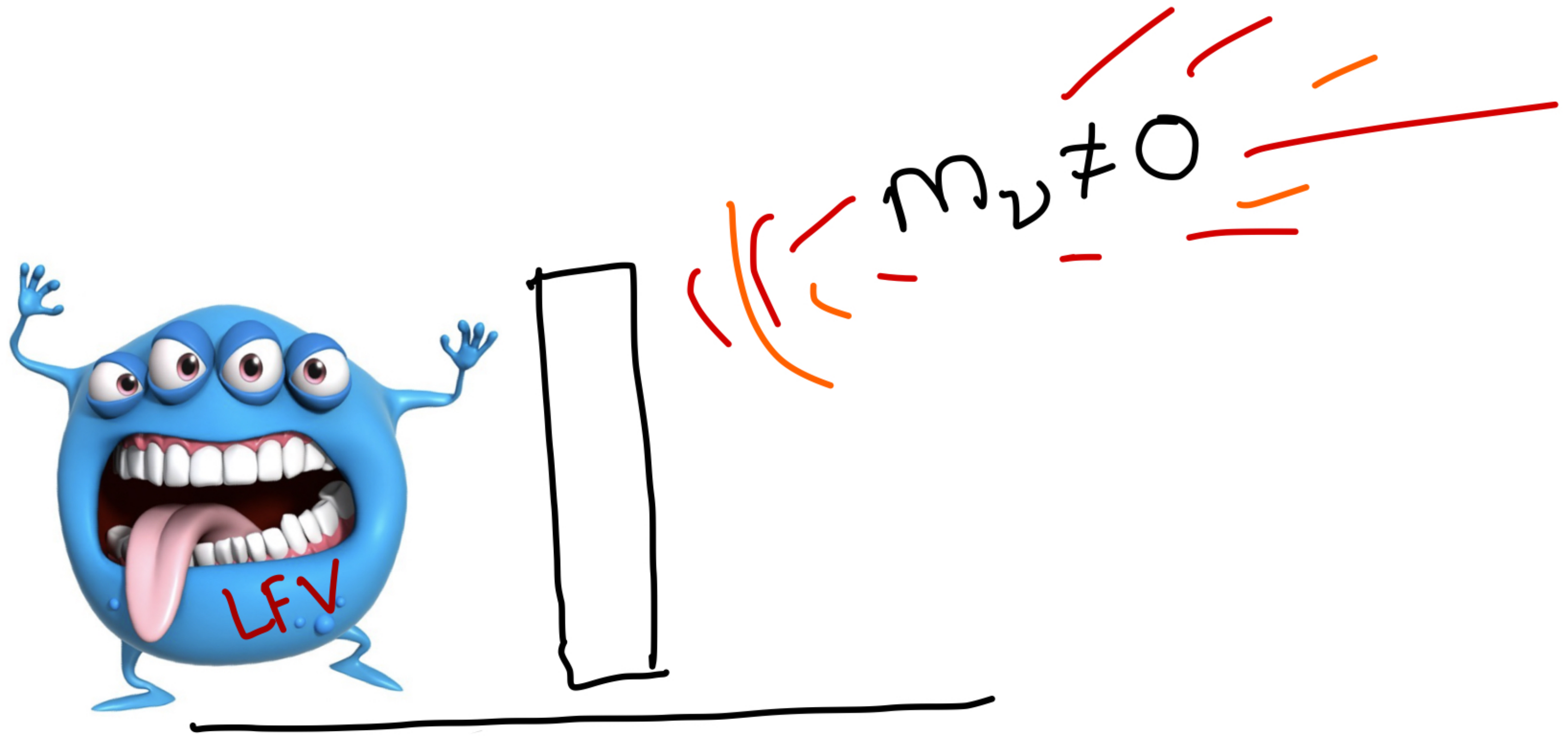
Flavor in the SM



- The flavor sector accounts for 22/27 of these parameters in the SM
  - 9 fermion masses
  - 3 rotation angles, 1 phase (CKM)
  - ~ [6 mixing parameters, 3 masses if we also have massive neutrinos]
- Studying the structure of the flavour sector may reveal something exciting about physics beyond the SM/ a more complete theory of nature

"Standard Model Flavor Puzzle"





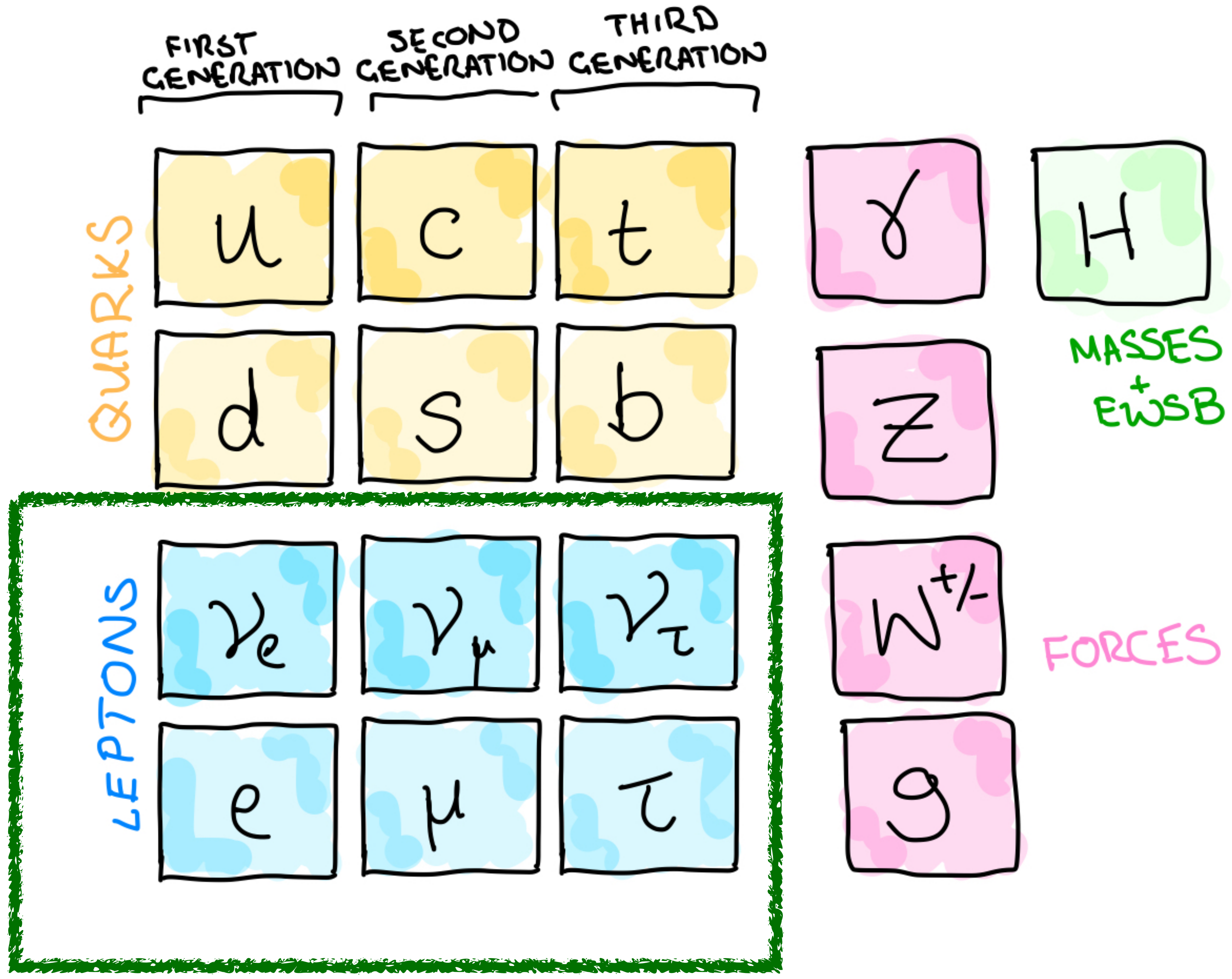
Lepton flavour in the SM

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

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

- Flavoured lepton number is conserved in [perturbative] SM interactions, thus also total (sum of flavours) lepton number (LN)
- Lepton flavour violation (LFV) is not possible in the SM. Neutrino masses break this symmetry, but smallness of neutrino masses suppress these effect. Observable signals of LFV are genuine new physics signals

Lepton flavour in the SM



- In the gauge sector, the EW bosons couple *flavour universally* to the SM leptons
- The only difference between observable rates of different interactions including different flavoured SM leptons can be explained via their masses
- This is the principle of lepton flavour universality (LFU)
- New physics doesn't necessarily need to couple flavour universally, so we can search for LFU violation to look for hints of new physics

Examples of testing LFU:

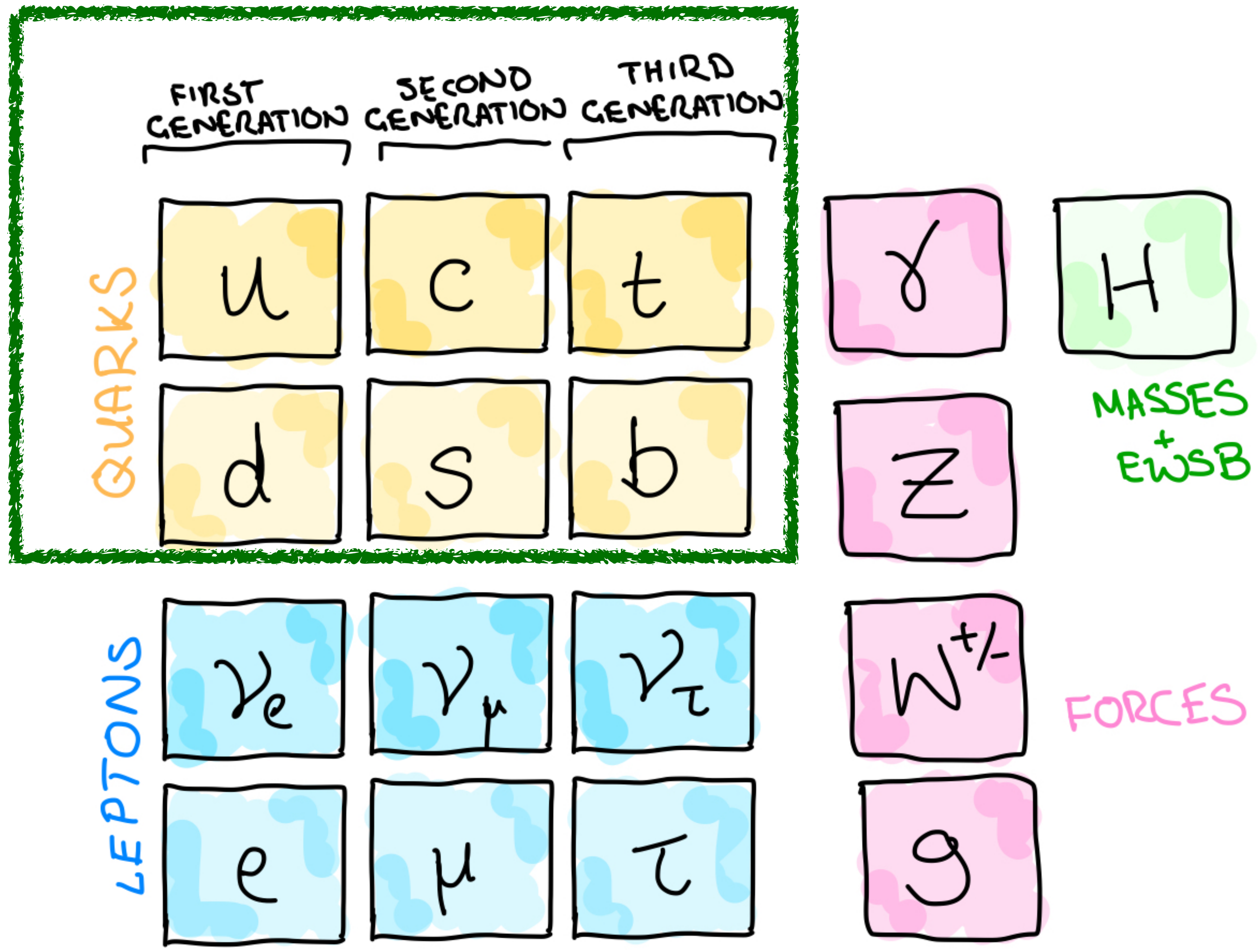
$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu_\tau)}{Br(B \to D^{(*)}\ell\nu_\ell)}$$

~ 3 sigma anomaly

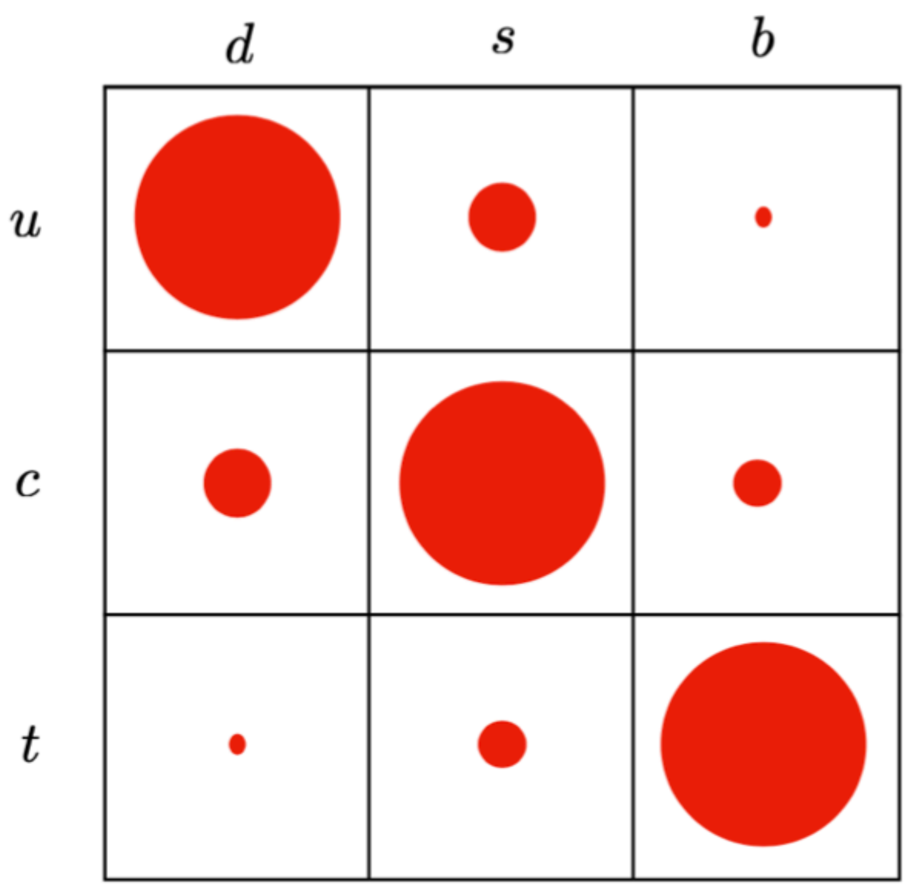
$$R_{K^{(*)}} = \frac{Br(B \to K^{(*)}\mu^+\mu^-)}{Br(B \to K^{(*)}e^+e^-)}$$

~ SM-like

Quark flavour in the SM



$V_{CKM} =$



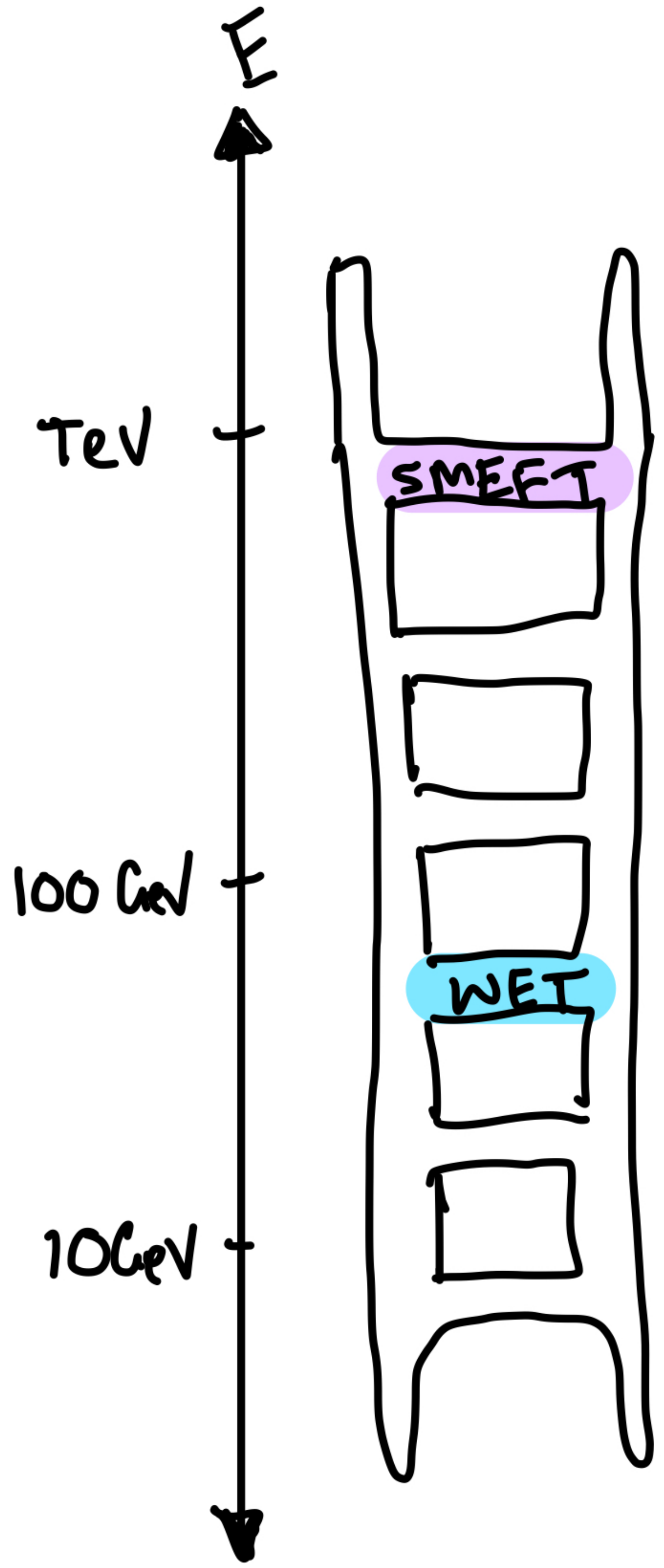
CKM matrix

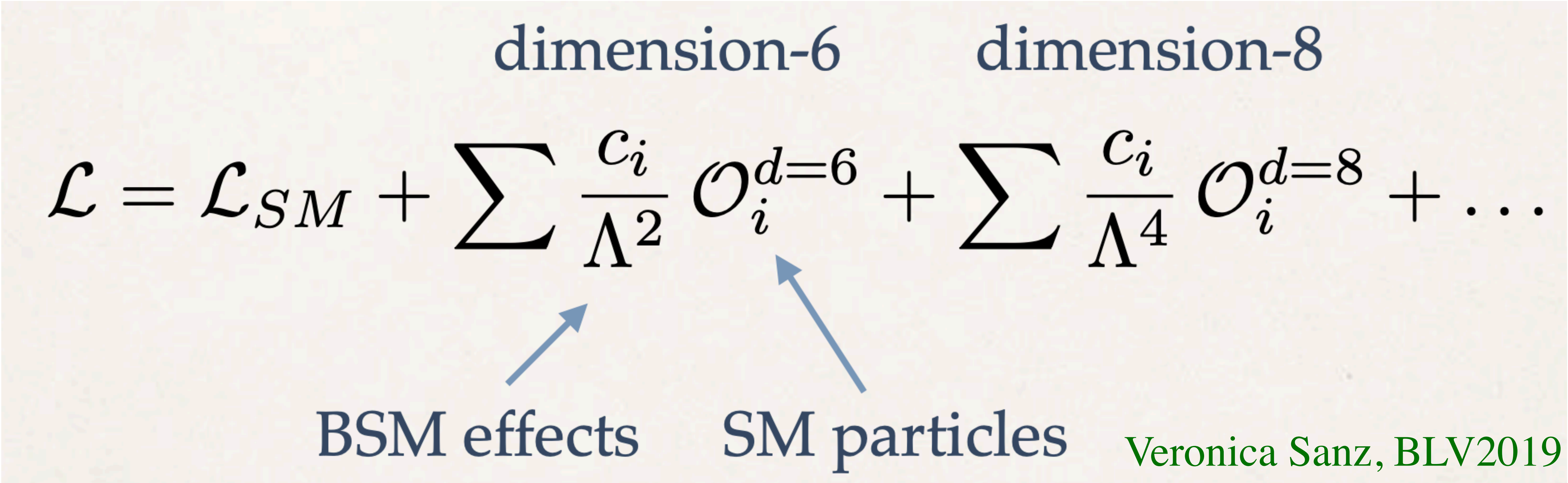
- Quark flavour can be violated in the SM. Quark mixing is parameterised by the CKM matrix
- Studying the structure: new symmetry of SM?
- The accidental symmetry in the quark sector is baryon number
- Beyond the SM, explaining the asymmetry in matter and antimatter requires a violation of baryon number in the early universe
- Tests of baryon number violation here on earth include, e.g. proton decay searches

Summary of Part I

- The SM has accidental lepton and quark flavour symmetries
- Lepton flavour violation (LFV): probes flavour-mixing due to BSM physics
- Lepton flavour universality (LFU): probes BSM physics coupling differently to different lepton flavours
- Studying the CKM may reveal information about new physics preferably enhancing different SM flavour transitions, and symmetry of the CKM may hint at new flavour structure of BSM physics

SMEFT and WE(F)T





$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\,\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\,\mathcal{O}_i^{d=8} + \dots$$

Veronica Sanz, BLV2019

- From top down: (a) Define UV complete theory with new states at high E, (b) Match onto the SMEFT, (c) Evolve to WET matching scale, match onto WET, (d) Evolve in WET to scale for low-energy constraints
- For bottom up: reverse the process.
- Each EFT only valid in regions where energies are not of scale of new/integrated-out resonances

WCxf

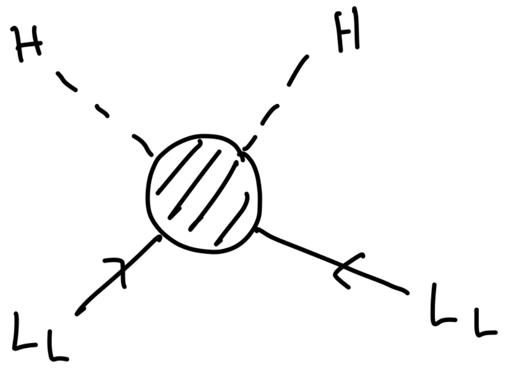
An exchange format for Wilson coefficients beyond the Standard Model

1712.05298

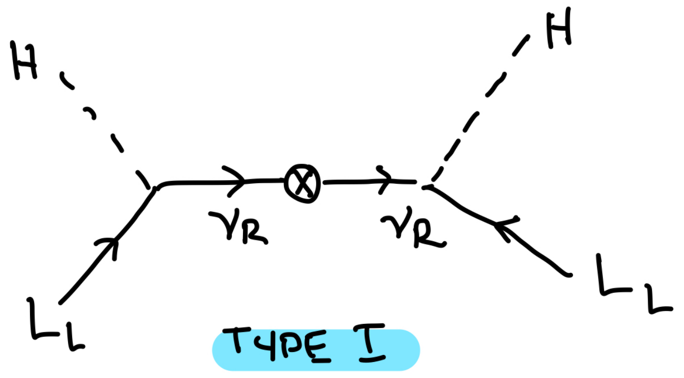
Why probe LFV? (a) Neutrinos

e.g. Weinberg operator (D=5)

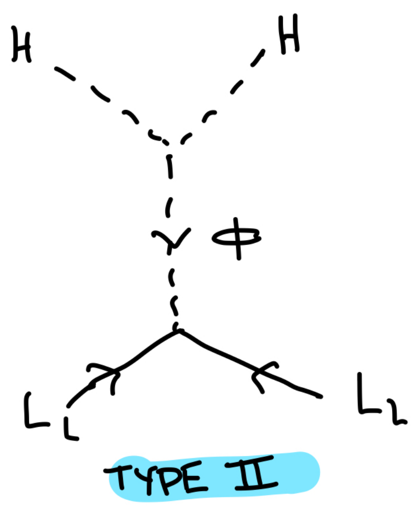
$$\mathcal{L}_{\text{effective}} \supset \frac{\lambda}{\Lambda} L_L L_L H H$$



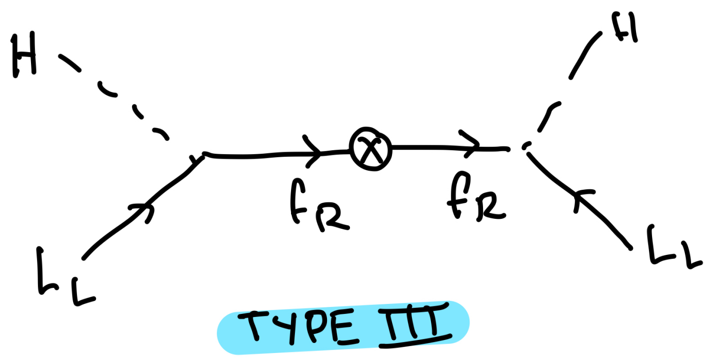
“Opening-up” the Weinberg operator: Seesaw Models



Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Mohapatra, Senjanovic 1980



Magg, Wetterich 1980
Schechter, Valle 1980
Cheng, Li 1980
Lazarides, Shafi, Wetterich 1981
Wetterich 1981
Mohapatra, Senjanovic 1981

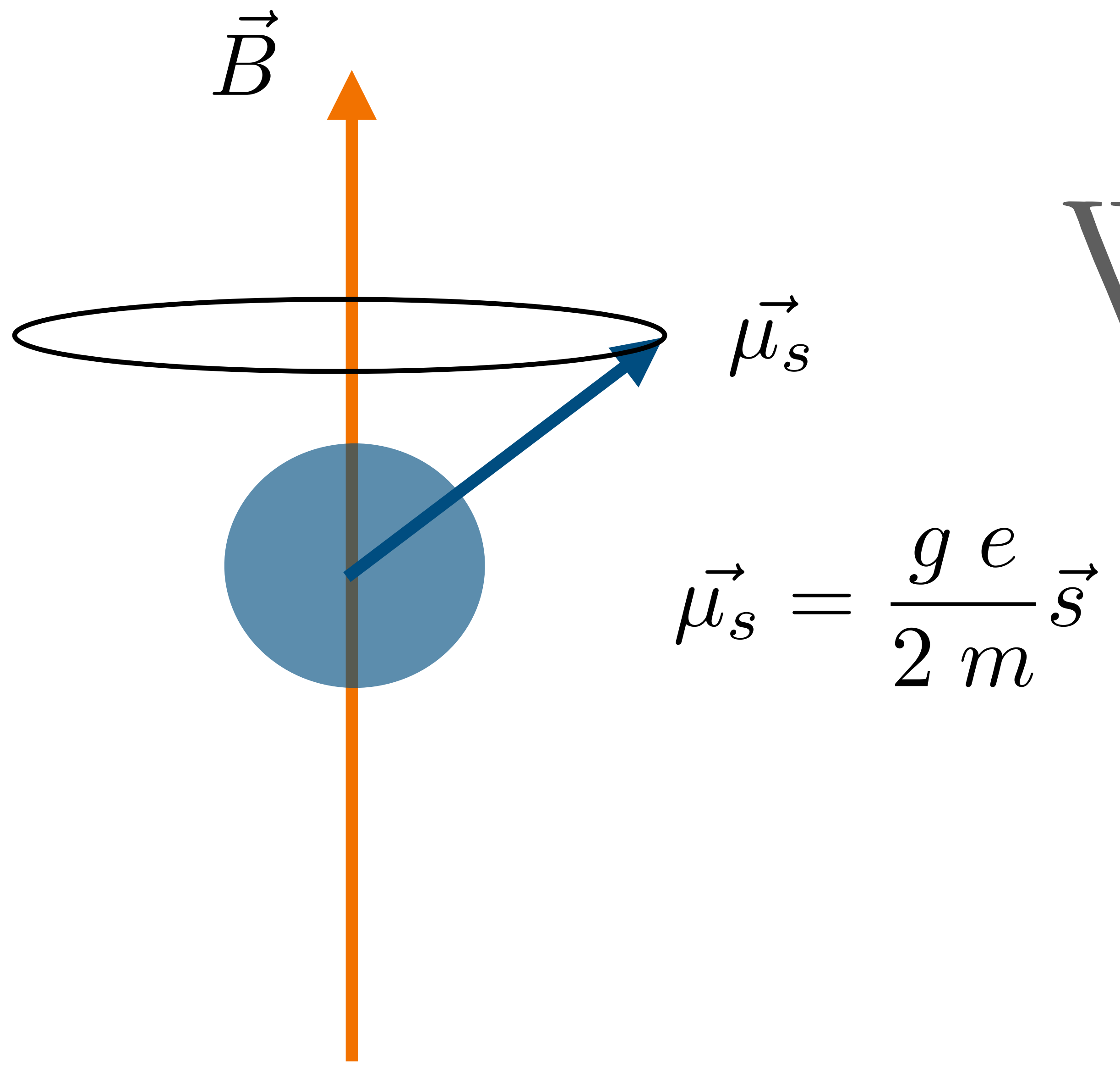


Foot, Lew, He, Joshi 1989

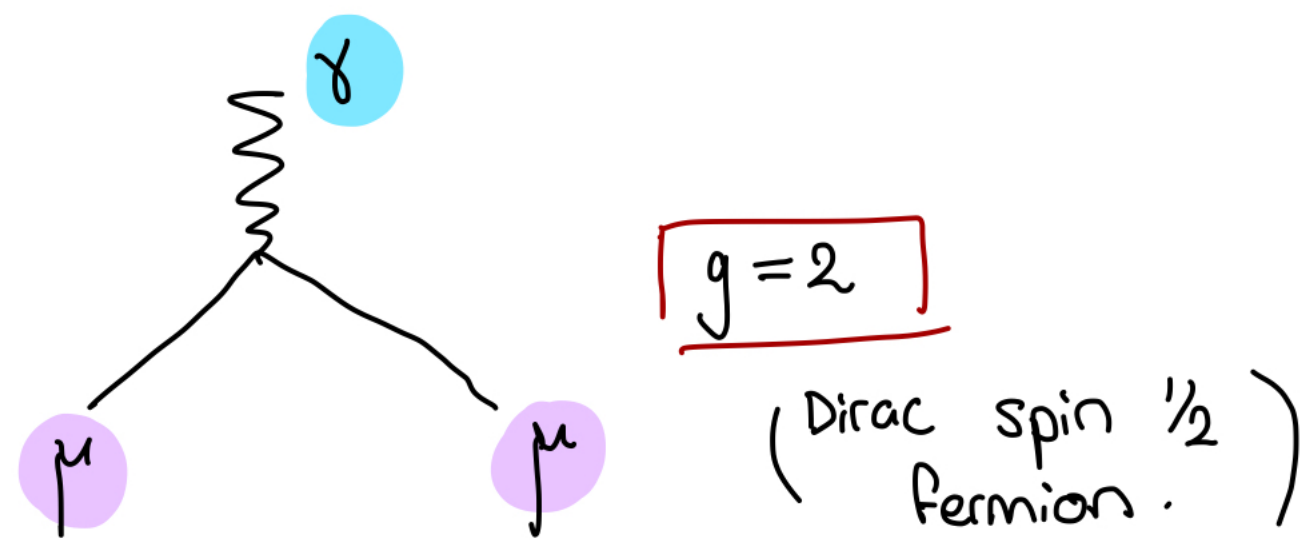
Higher dimensional operators: see, e.g. Babu and Leung ’01, de Gouvea and Jenkins ‘08

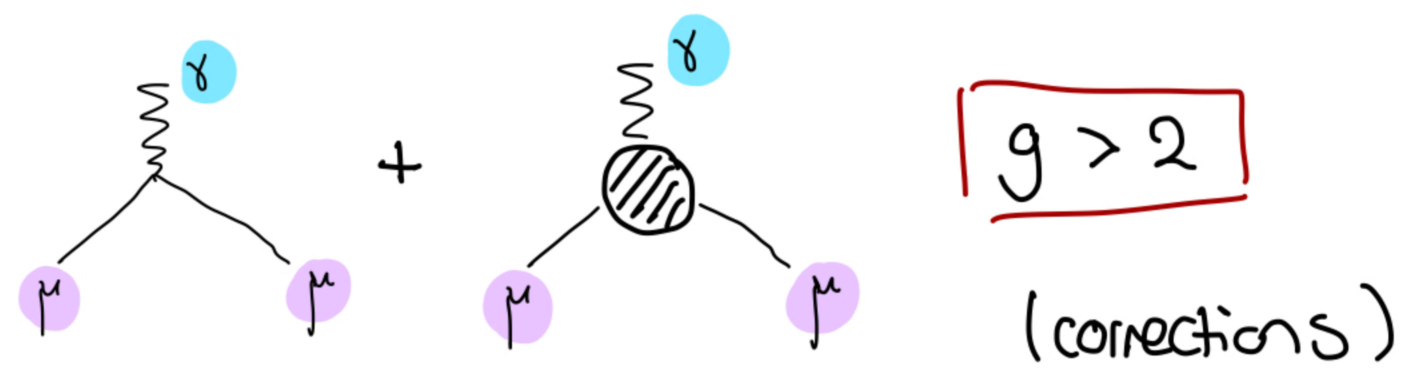
- Extending neutrino physics beyond the SM, write down effective operators of higher mass dimension which violate lepton flavour [inducing neutrino flavour mixing and masses]. Bottom up.
- “Opening up” EFT — write down UV-complete models that generate these interactions: new particles and fields
- This same BSM will generate other effective interactions, which can be probed at high and low energies. There may be (model-dependent) correlations in other EFT operators including charged leptons. Also can look at LNV effects.
- Complementarity EFT constraints at low and high energy, e.g. neutrino NSIs constrained via EFT, e.g. Falkowski et al 1910.02971

Why probe LFV? (b) Lepton properties



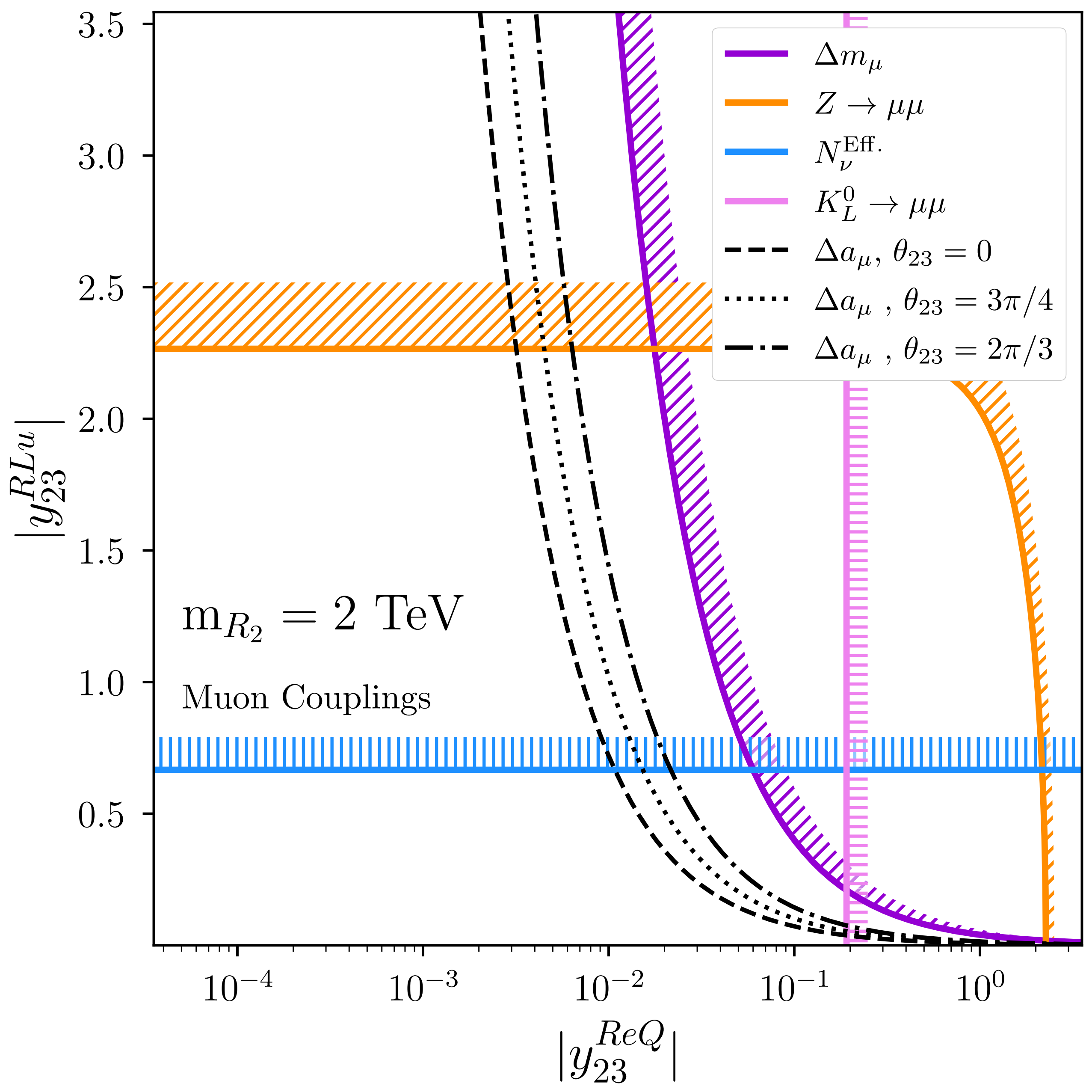
$$\vec{\mu_s} = \frac{g\ e}{2\ m}\vec{s}$$

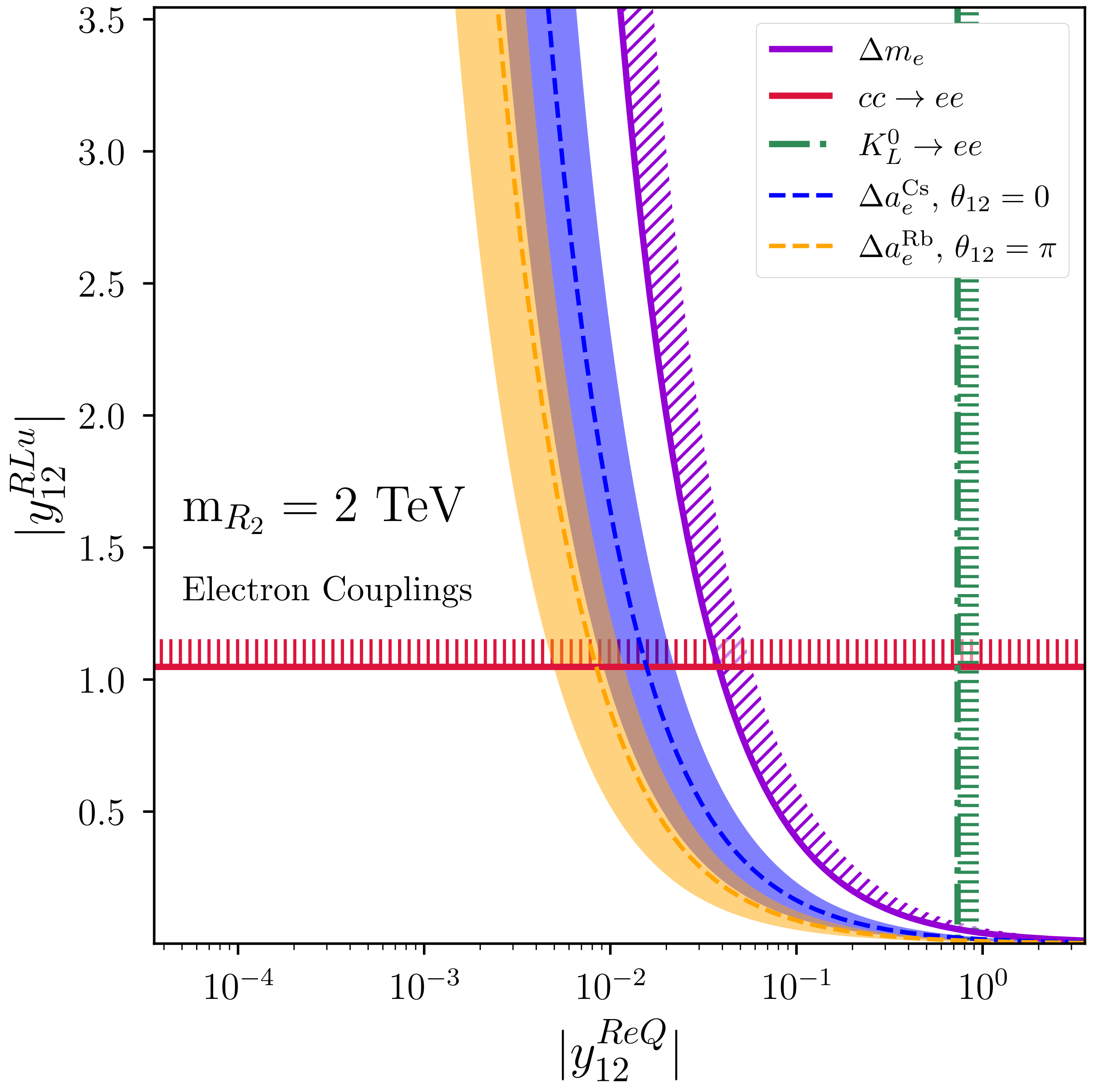




- Famously, there is an anomaly in the magnetic moment of the muon. Less famously, there's also one in the electron. Addressing both of these anomalies require flavour-specific new physics couplings e.g. IB, Volkas 2002.12544
- Strongest constraints on off-diagonal flavour effects (LFV) from low-energy constraints. For diagonal (flavour-conserving) effects via the EFT, e.g. Fuentes-Martin et al 2003.12421

Why probe LFV? (b) Lepton properties





IB, Volkas 2110.03707

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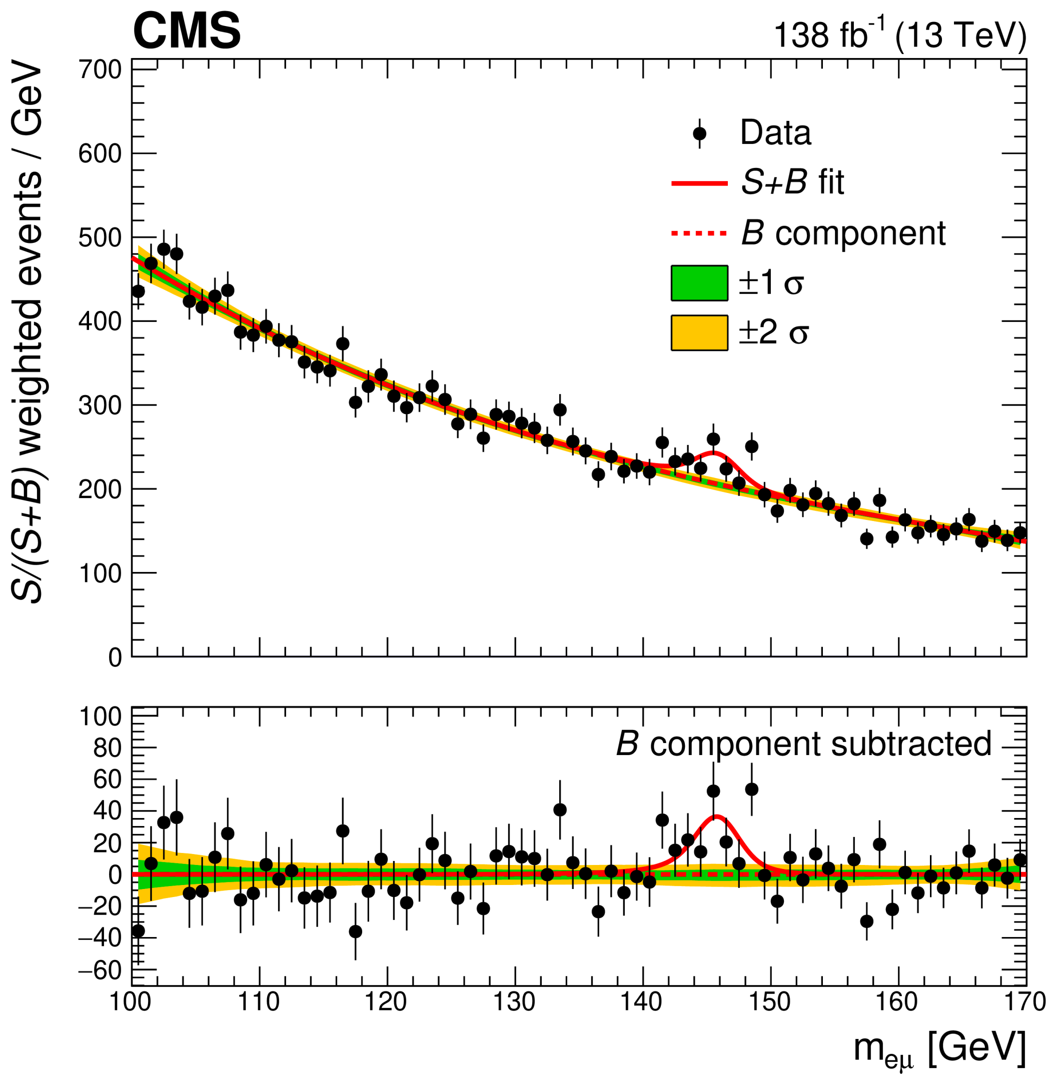
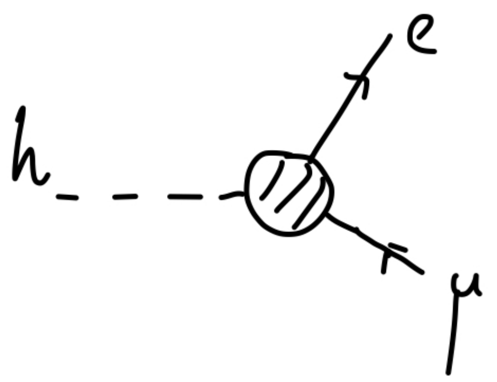
- People also study radiative (loop level) generation of charged lepton masses, also constrained by these processes e.g. Baker, et al 2103.13401

cLFV and Higgs physics

CMS, 2305.18106





by L_μ and L_e conservation, zero in the SM.

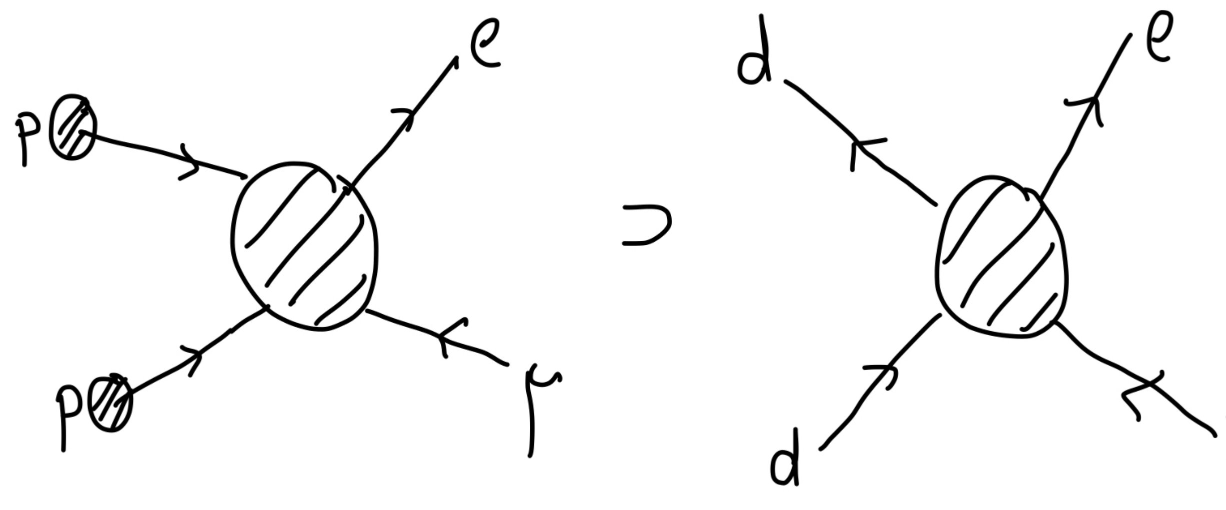
↓

measured 'bump' at 146 GeV

new physics?

new scalar?

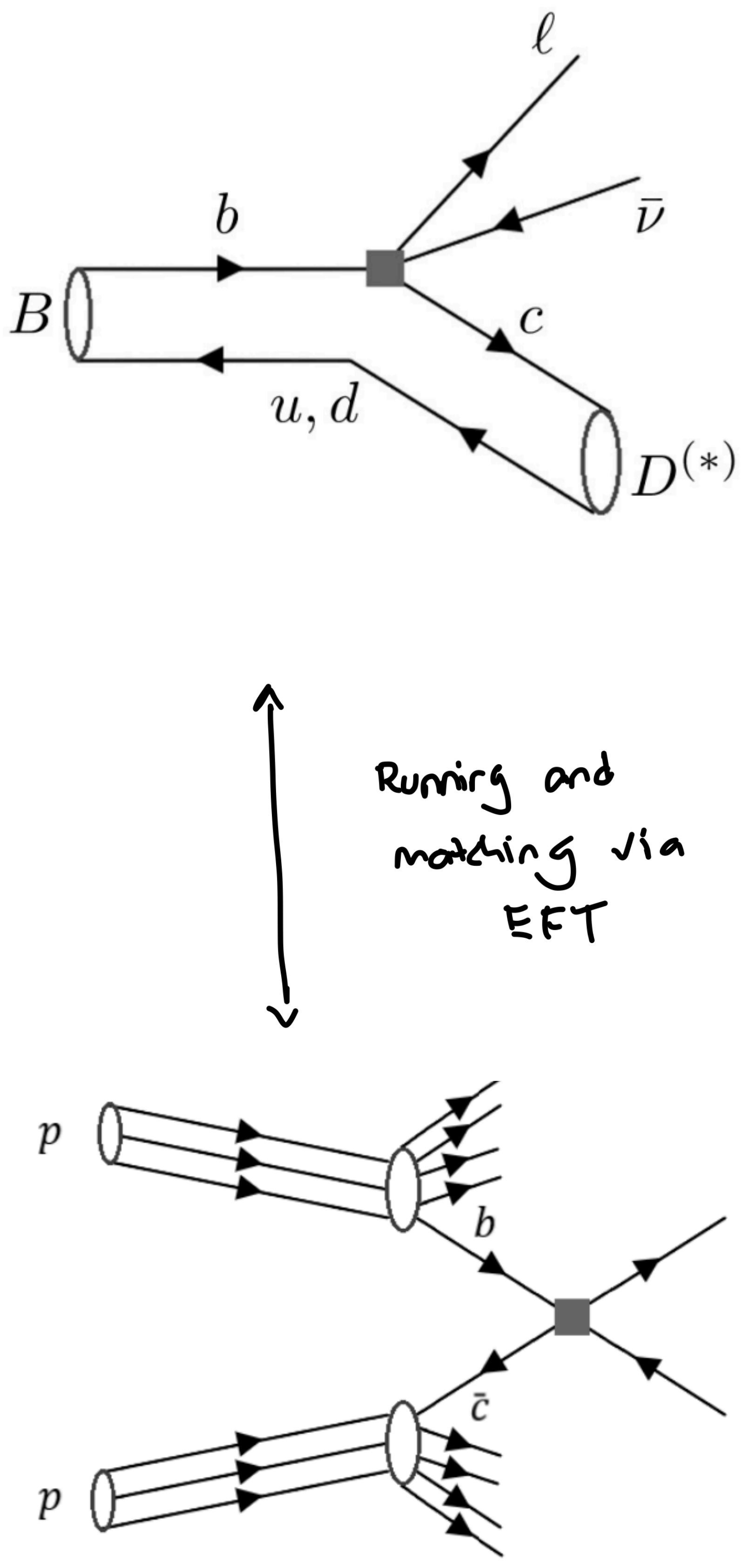
- e.g. the excess in $h \to e\mu$ at 146 GeV. I want to demonstrate to you that this is interesting to theorists even if it "goes away". Yes, people write papers to explain it but I will discuss what you can say from the EFT perspective.
- Usually, $\mu \to e$ constraints are stronger from low energy probes like $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion on nuclei. As we said earlier, these processes are zero in SM,
- Theoretically though, via EFT, we can link the interactions probed at the high energy (LHC Higgs study) with the low energy constraints, and apply constraints from low energy searches to tell you what excesses are immediately implausible*



⇒ $\mu \to e$ conversion on nuclei.

IB, Gao, Plestid, In prep.

Lepton Flavour and high pT Drell-Yann



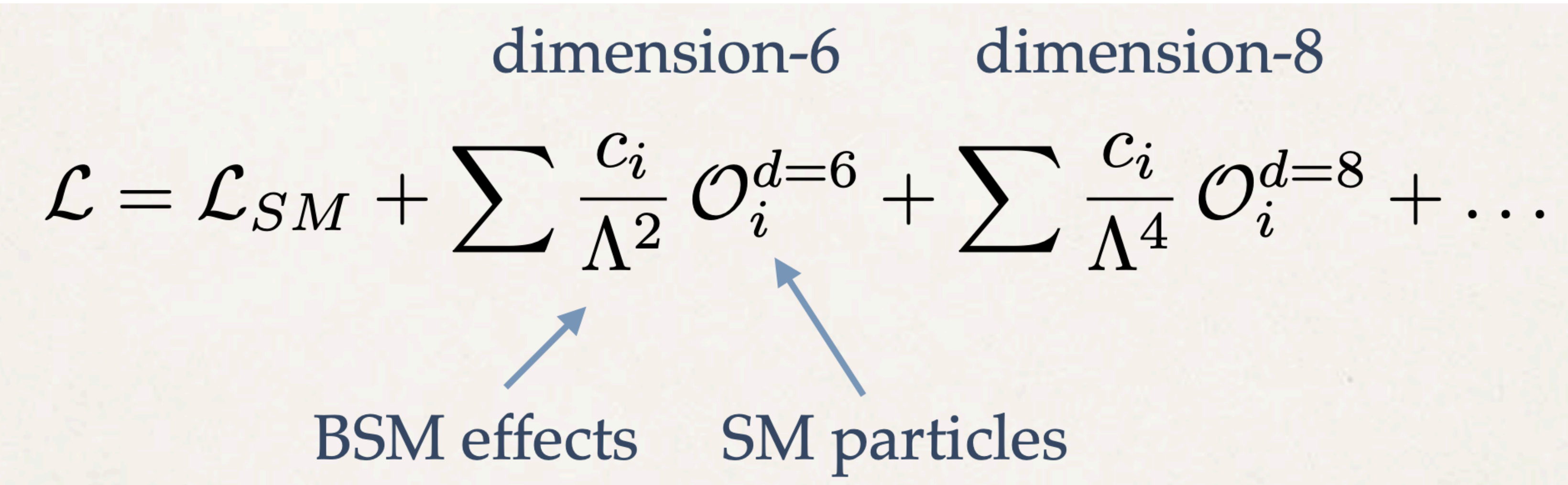
Effects scale as $\mathcal{O}(p^2/\Lambda^2)$

See for more information: Jaffredo, Portoroz 2023 talk, 2207.10714 and 2207.10756

- The semi-leptonic Drell-Yann processes $pp \to \ell\ell$ and $pp \to \ell\nu$ provide complementary probes of low energy flavour observables (e.g. $b \to c\tau\nu$, $b \to s\mu\mu$) e.g. Marzocca, Greljio 1704.09015
- Parameterising new physics contributions in terms of relevant form factors, high-energy (incl. CMS) searches for resonances in mono-, and di-lepton final states in high-pT tails can be recast into EFT bounds. 2→2 scattering scales as $\mathcal{O}(p^2/\Lambda^2)$
- This is not a simple exercise. Especially in generality with multiple EFT operators contributing at a time. The program HighPT (Allwicher et al 2207.10756) was developed to allow phenomenologists (and others!) to derive their own constraints from this procedure. Here you can use EFT, or also specific models — not confined by single-operator fits.

See above references for more information on this!

New physics in EW processes



dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \dots$$

BSM effects SM particles

$$\mathcal{M}_{process} = \mathcal{M}_{SM} + \mathcal{M}_{BSM}$$

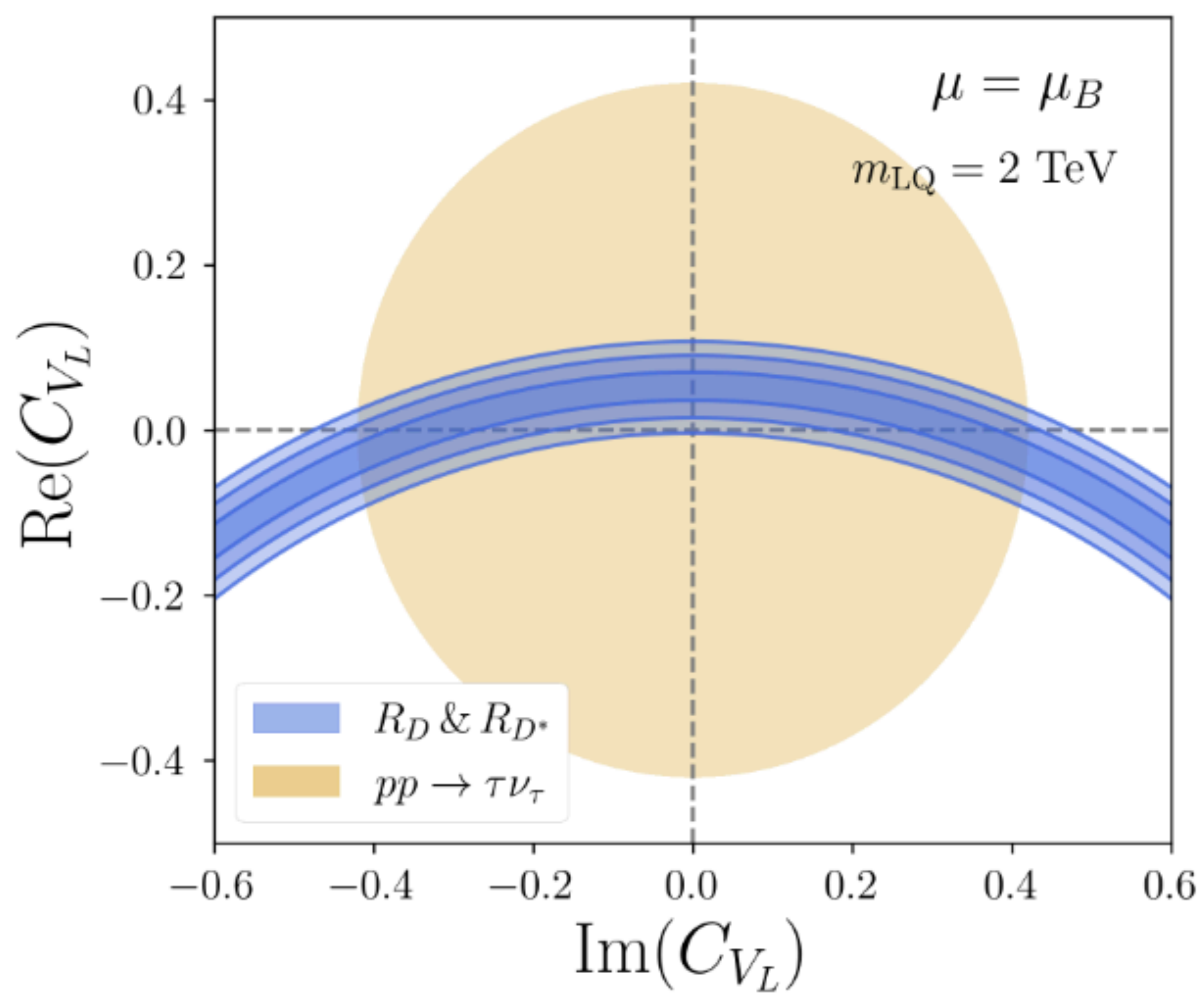
$$\sigma \propto |\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\mathrm{Re}\,(\mathcal{M}_{SM}\mathcal{M}_{BSM}^{\dagger}) + |\mathcal{M}_{BSM}|^2$$

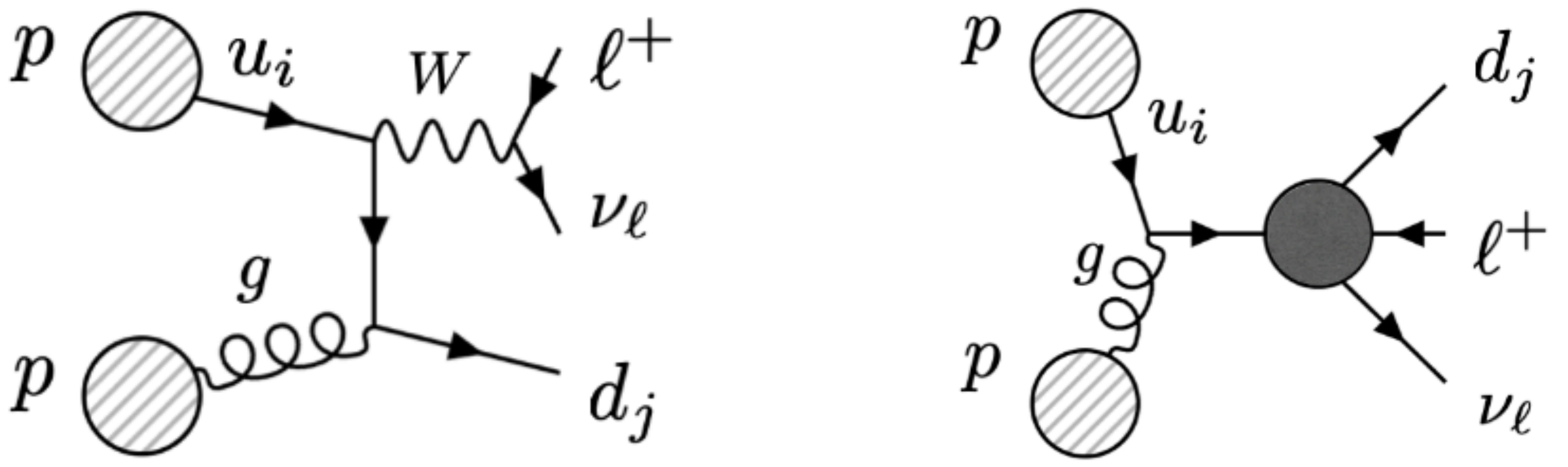
In general, $\mathcal{M}_{BSM} \propto c/\Lambda$ (wilson coefficient c, new physics scale Λ)

$\Rightarrow$ $\mathcal{M}_{SM}\mathcal{M}_{BSM}^{\dagger} \propto c/\Lambda$ while $|\mathcal{M}_{BSM}|^2 \propto c^2/\Lambda^2$

- In general the interference effects are expected to scale differently to the pure-new physics effects. Less suppressed by new physics scale.
- Difficult to simulate interference in a model-independent way, even at the the EFT level
- However, especially if we have any new physics with imaginary Wilson coefficients, this interference effect should be there and could be considerable depending on kinematics considered
- For example, let's look specifically at interference with SM charged-current processes…Here rather than 2→2 scattering, we focus on 1→3. The latter aids in background discrimination.

Interference in EW processes





- Modelling low-scale physics, e.g. B-meson decay anomalies, there is often a choice to reduce parameter space by fitting only to pure-real WCs. Helps to avoid other constraints, reduces model parameters.
- However, these same effects will influence high-energy processes, e.g. $pp \to b\ell\nu$, usually where is it assumed that the Im components of WCs are negligible

$$M_{SM} \propto \frac{V_{cb}\, g^2}{(p_\ell + p_\nu)^2 - m_W^2 + i m_W \Gamma_W} \xrightarrow{p_\ell + p_\nu \to m_W} \frac{-i V_{cb} g^2}{m_W \Gamma_W}.$$

$$M_{BSM} \propto \mathrm{Re}\, C + i\, \mathrm{Im}\, C$$

$$\Rightarrow |M_{SM} + M_{BSM}|^2 \sim |M_{SM}|^2 + |M_{BSM}|^2 + \frac{V_{cb} g^2}{m_W \Gamma_W} \mathrm{Im}\, C$$

the W pole "picks out" the Im C.

In preparation, IB, Capdevilla, Isaacson, Kim, Tame-Narvaez,

Complementary to CPV talk from Josh earlier!

Summary of Part II

- We look for LFV because a SM with neutrino masses mean that lepton flavour is no longer a symmetry BSM
- Models for neutrino masses generically lead to other LFV signals
- Higgs searches for lepton flavour violating final states provide complementary probes of low-energy LFV searches
- High energy semi and mono leptonic searches can be recast to extract constraints on EFT scenarios, allowing strong constraints (particularly on lepton flavour conserving) on BSM interactions
- Interference effects may not be negligible. We need to learn how to simulate it, and "picking out" these effects may help discriminate BSM models.

Conclusions

In light of the aims of this workshop

- Flavour physics is a rich area of developments, particularly with the use of EFT. Something to note is despite the brevity/death of some anomalies, we have learnt a lot about complementary probes of new physics effects at different scales
- Probing LFV via the EFT allows for probes of new physics that may also manifest in neutrino physics. This can be done at high and low E. Also lepton number violation?
- We need to understand how to motivate reduced parameter space fits for the EFT using UV complete models. Also by carefully considering the influence of reduced parameter space (i.e. truncating imaginary parts) on the observable effects at multiple scales.