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Protecting Lepton Flavour Universality
The role of gauged flavour symmetry

Master's Thesis at SAPIENZA UNIVERSITÀ DI ROMA

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Women in Theoretical Physics
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Giulia Muco - 08.10.24

Why this thesis?

- The Standard Model of particle physics is a very successful model: many experimental confirmations, good description of phenomena at energies currently accessible in accelerators.
- Clues we need to go beyond:

1. Experimental data not explained within the SM (ν masses, Dark Matter, baryon asymmetry...)
2. Experimental anomalies in indirect searches.

Anomalies in B-meson decays - observables of interest

– $b \to s\mu^+\mu^-$ branching ratios and angular observables (e.g. $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$)

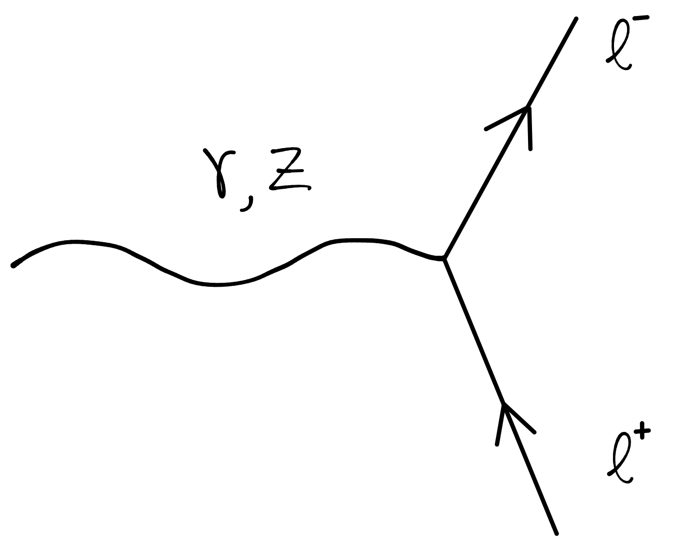
– The Lepton Flavour Universality ratios

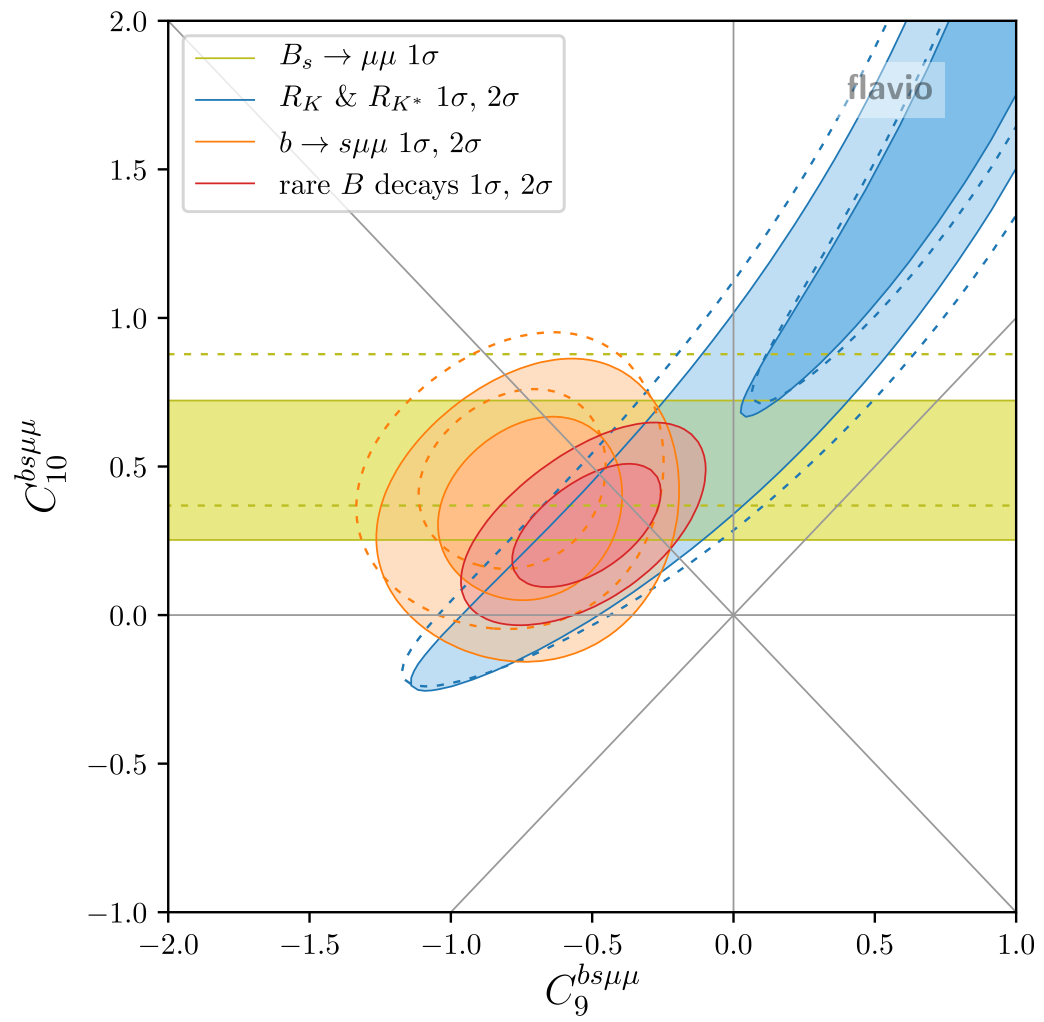
$$R_{K^{(*)}} = \frac{BR[B \to K^{(*)}\mu^+\mu^-]}{BR[B \to K^{(*)}e^+e^-]}$$

1. Clean observables.
2. SM prediction: $R^{SM}_{K^{(*)}} \approx 1$.

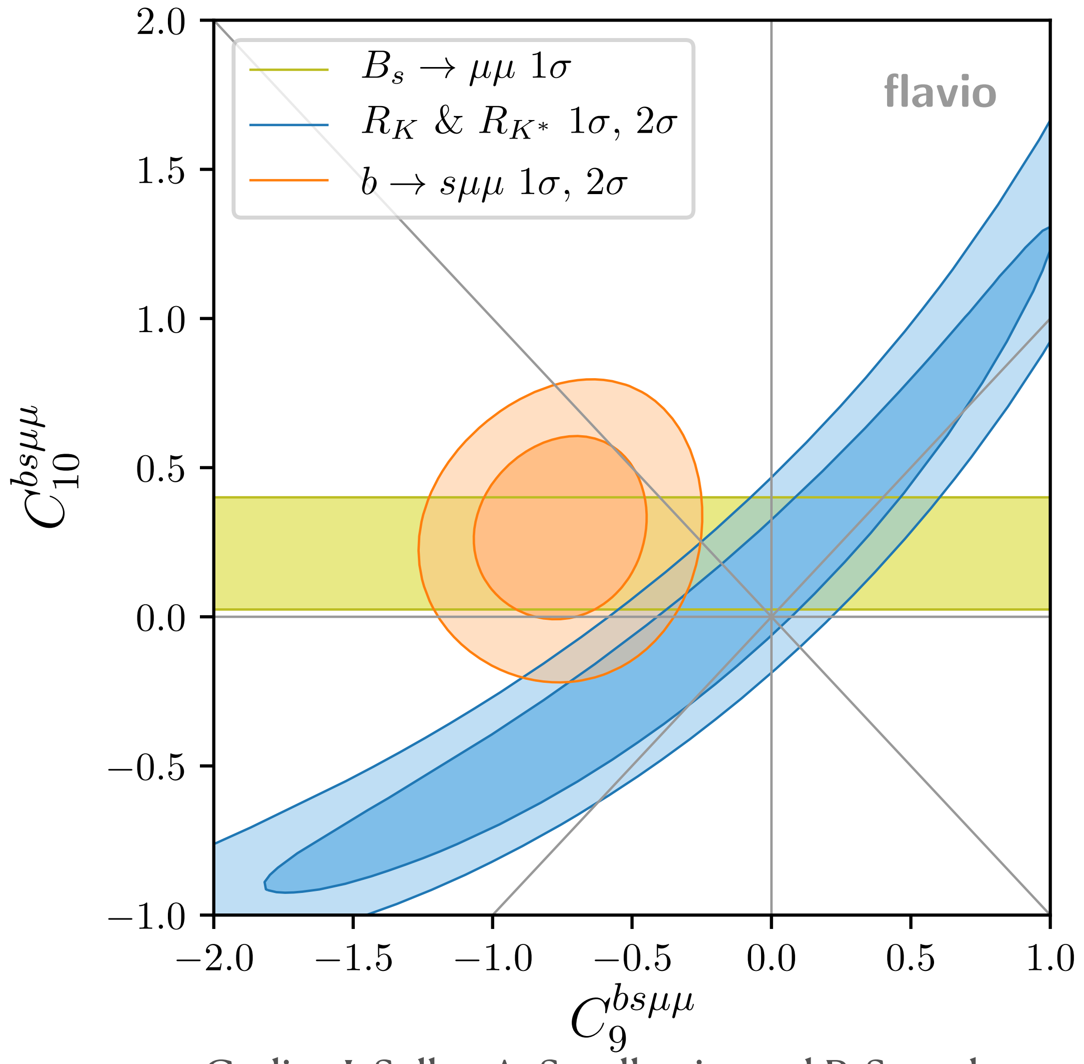
– $B_s \to \mu^+\mu^-$

1. Another clean observable.
2. Can distinguish between different NP scenarios.



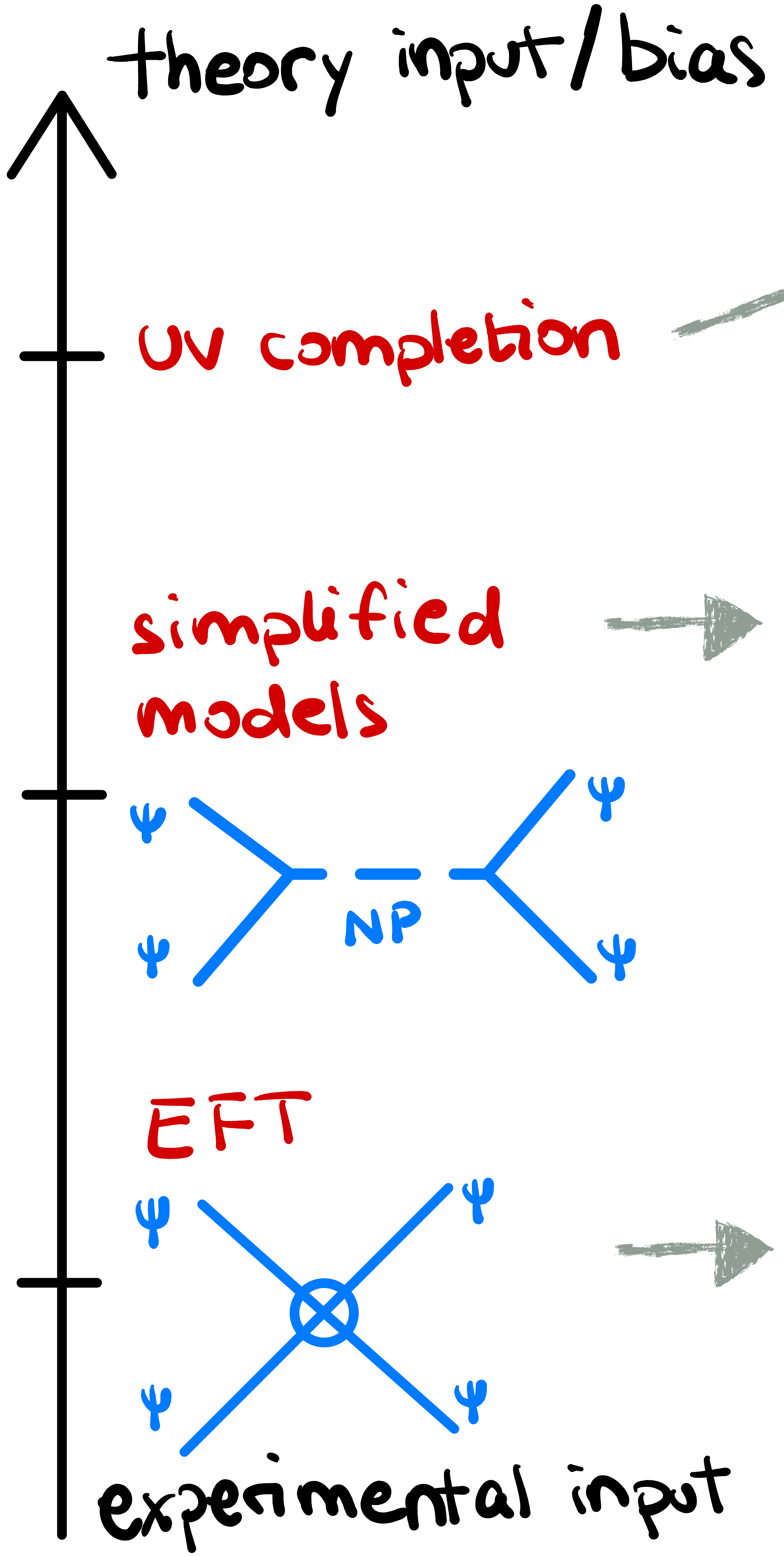


W. Altmannshofer, P. Stangl,
New Physics in Rare B Decays after Moriond 2021, arXiv: 2103.13370



Greljo, J. Salko, A. Smolkovic, and P. Stangl,
Rare b decays meet high-mass Drell-Yan, JHEP, arXiv: 2212.10497

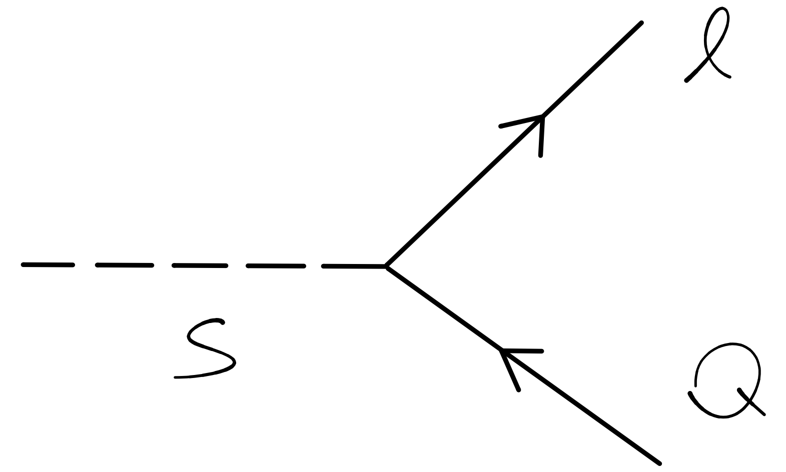
Methodology:



Our model: SM extension with a gauged flavour symmetry.

Leptoquark models with $\mathscr{L}_{\text{int}} = \alpha Q \ell S$

Perform better: suppression of $|\Delta F| = 2$ and four-lepton processes.



B-meson decays are described by the Weak Effective Theory (WET) Hamiltonian

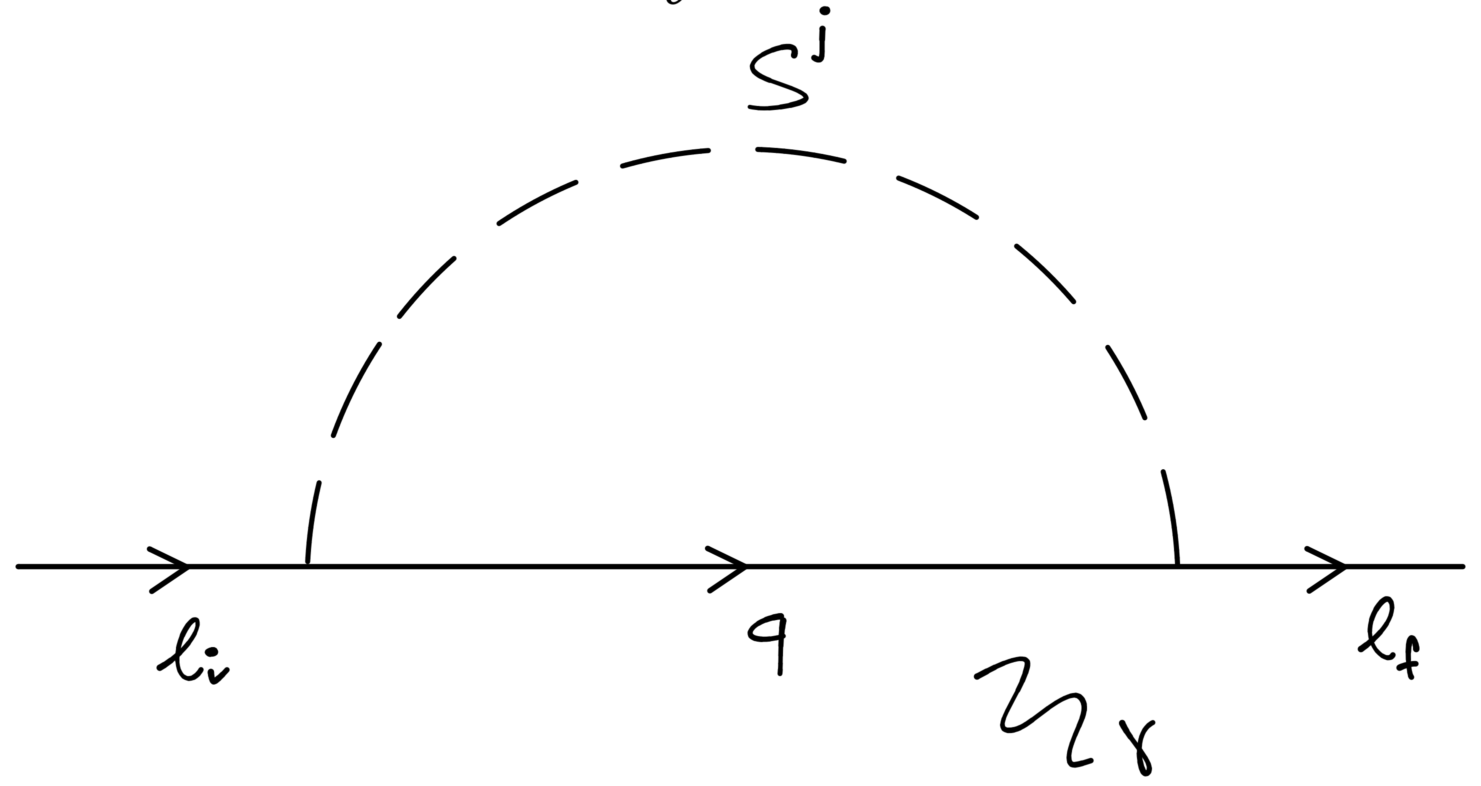
$$\mathscr{H}_{\text{eff}} = \mathscr{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} \frac{e^2}{16\pi^2} \sum_{q=s,d} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} V_{tb} V_{tq}^{*} (C_i^{bq\ell\ell} O_i^{bq\ell\ell} + C_i^{\prime bq\ell\ell} O_i^{\prime bq\ell\ell}) + h.c.$$

$$O_9^{bs\ell\ell} = (\bar{b}\gamma_\mu P_L s)(\bar{\ell}\gamma^\mu \ell), \quad O_{10}^{bs\ell\ell} = (\bar{b}\gamma_\mu P_L s)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

The $SU(2)_\ell$ flavour symmetry

- Goal: build a UV completion of the SM.
- Main idea: if LFU must be preserved, it may be protected in the UV. How? A $SU(2)_\ell$ gauged flavour symmetry, acting on light lepton generations.
- NP scenario: $C_9^{bs\ell\ell} = -C_{10}^{bs\ell\ell}$, i.e. NP only coupled to left-handed leptons. Hence, we charge under the new symmetry $L = (l_1,\ l_2)^T \sim \mathbf{2}$.
- We add scalar LQs: we work with $S \sim (\bar{\mathbf{3}}, \mathbf{3})_{1/3}$ of G_{SM}.
- Symmetry not observed $\Rightarrow$ SSB mechanism at work. We postulate a scalar $\phi \sim \mathbf{2}$ of $SU(2)_\ell$ (SM-singlet) s.t. $<\phi> = (0,\ v_\phi)^T$, hence $SU(2)_\ell \xrightarrow{<\phi>} 1$.
- Other reasons to gauge this symmetry: we assign charge $S = (S_1,\ S_2)^T \sim \mathbf{2}$ of $SU(2)_\ell$. This prevents:

1. LFV processes such as $\ell_i \to \ell_f \gamma$.
2. Baryon number-violating interactions such as $\mathscr{L} = QQS$.



- Starting requirements:

1. Anomaly-free gauge theory → this requirement may predict a new light fermionic sector (not in our model).

2. $m_e \ll m_\mu \ll m_\tau$.

- Identify mass eigenstates of the theory: fundamental to explore the phenomenological implications of the model.

- At the renormalisable level the Yukawa sector is

$$-\mathscr{L}_{\text{Yuk}}^{D=4} = C_{12} L H E^c + C_3 l_3 H e_3^c + h.c. \quad \Rightarrow \quad M_l = v \begin{pmatrix} C_{12} \cdot 1_{2\times 2} & 0 \\ 0 & C_3 \end{pmatrix}$$

- We must take into account radiative corrections, described by effective operators:

$$\mathscr{L}_{\text{Yuk}} = \mathscr{L}_{\text{Yuk}}^{D=4} + \mathscr{L}_{\text{Yuk}}^{D=5} \;\Rightarrow\; M_l = v \begin{pmatrix} C_{12} & 0 & \epsilon \tilde{C}_L \\ 0 & C_{12} & \epsilon C_L \\ \epsilon \tilde{C}_R & \epsilon C_R & C_3 \end{pmatrix}, \quad \epsilon = \frac{v_\phi}{\Lambda}$$

- If we admit $C_{12} \sim \epsilon_e \ll 1$, we find: $m_e \sim v\epsilon_e \ll m_\mu \sim \epsilon v \ll m_\tau \sim v$.

- The diagonalisation of M_l implies that the states corresponding to $e,\ \mu,\ \tau$ are a mixing of the interaction eigenstates:

$$L = \begin{pmatrix} l_1 \\ l_2 \end{pmatrix} = \begin{pmatrix} (U_L)_{1\alpha} l_\alpha \\ (U_L)_{2\alpha} l_\alpha \end{pmatrix} \quad \Rightarrow \quad \mathscr{L}_{\text{int}} = \sum_{j=1,2} \sum_{\beta=e,\mu,\tau} (U_L)_{j\beta} \alpha_i \bar{Q}_i^{ca} \epsilon^{ab} (\sigma^k S_j^k)^{bd} l_\beta^d + h.c$$

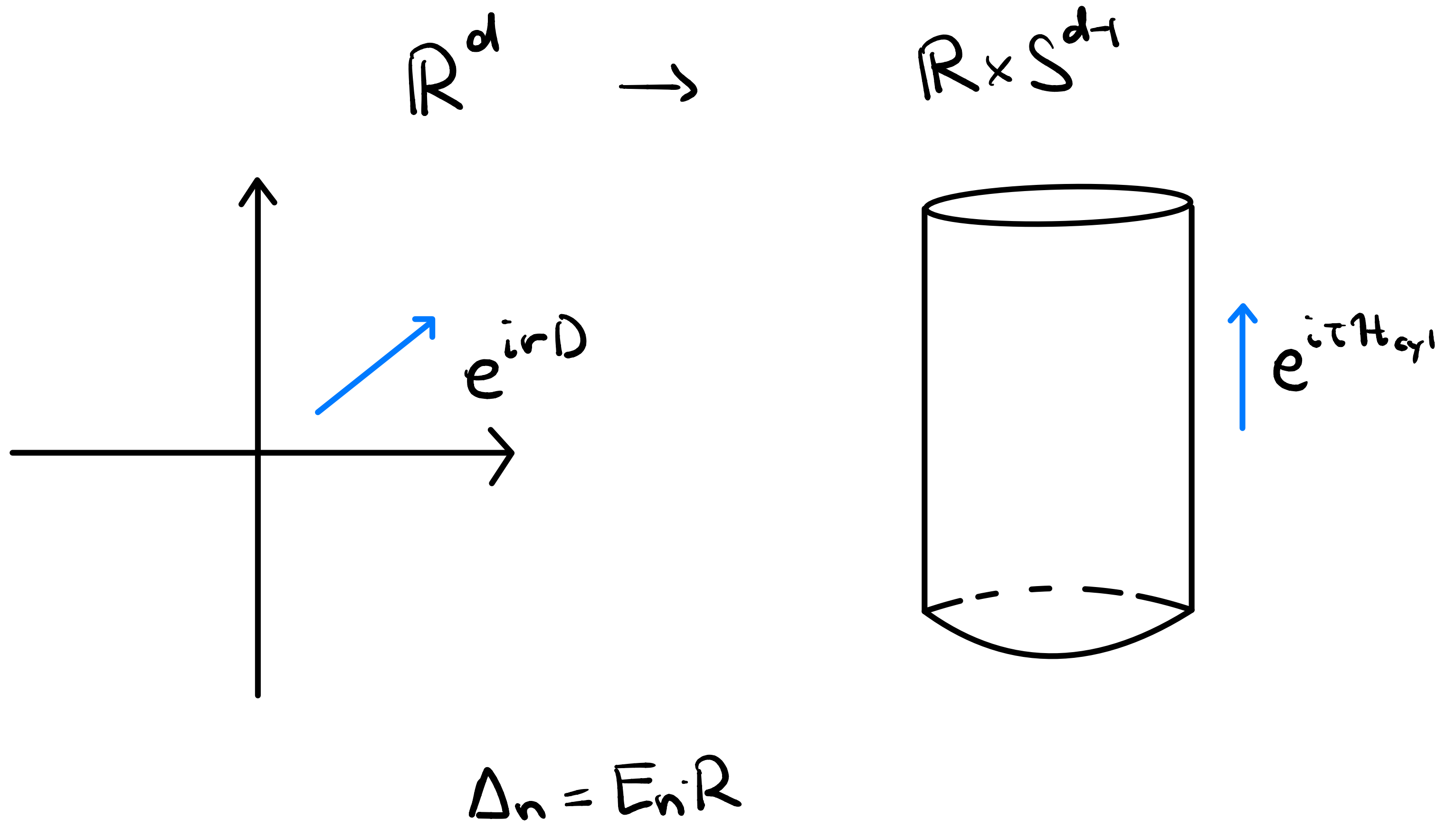
- This introduces correlations between different observables that may be used in the future to test/falsify the model!

Conclusions

- In absence of signals in direct searches, flavour physics plays a key role, as it offers an insight into new physics through indirect searches.
- We identified possible new mediators of NP, i.e. Leptoquarks.
- We identified a possible process which might help to test our model.
- Many possible routes for future studies: a more thorough study of the scalar sector, the Landau pole of $G_{SM} \times SU(2)_\ell$, ν masses and oscillations, phenomenological comparison with a gauged $U(1)_{L_e - L_\mu}$ model.

My current focus: CFTs, defects and semiclassics

- CFTs characterised by the absence of running in the theory.
- Add impurity in space ⇒ is it possible to define a Defect Conformal Field Theory (DCFT) in such a setting?
- Study of the phases Wilson Lines can have [O. Aharony, G. Cuomo, Z. Komargodski, M. Mezei, and A. Raviv-Moshe. *Phases of Wilson lines: conformality and screening.* JHEP, 12:183, 2023]
- Extension of the study to fermion-boson interacting theories.



- Employment of semiclassical methods for computation of CFT data to any loop order.
- E.g.: scaling dimension Δ_n of composite operators ϕ^n. [O. Antipin, J. Bersini, and F. Sannino. *Exact Results for Scaling Dimensions of Composite Operators in the ϕ^4 Theory*. 8 2024.]
- Next to come: NLO computations.

Thank you for your attention!