# Connecting theories of flavour to Kaon physics

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## Outline:

1. General Introduction to the Flavour Problem
2. Effective Field Theories for BSM
3. Explicit BSM examples

# Motivation

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**dark matter/dark energy**

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**neutrino masses**

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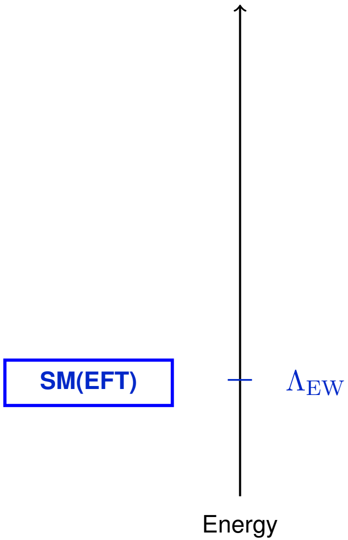

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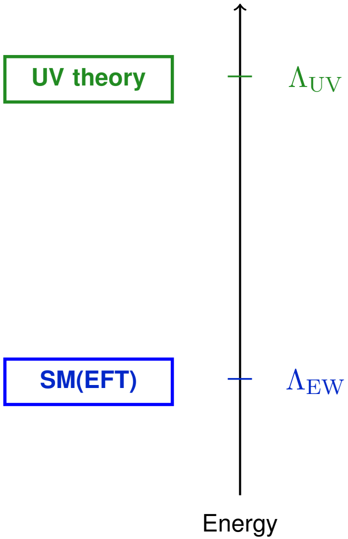

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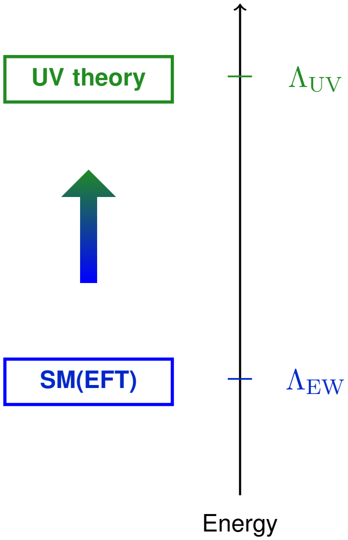

# The (two) flavour problems

1. **The SM flavour problem**: The measured Yukawa pattern doesn't seem accidental

   $\Rightarrow$ Is there any deeper reason for that?

2. **The NP flavour problem**: If we regard the SM as an EFT valid below a certain energy cutoff $\Lambda$, why don't we see any deviations in flavour changing processes?

   $\Rightarrow$ Which is the flavour structure of BSM physics?

# The SM flavour problem

$$\mathcal{L}_{\text{Yukawa}} \supset Y_u^{ij} \bar{Q}_L^i H u_R^j$$

$$Y_u \sim y_t \begin{pmatrix} & & 0.003 \\ & & 0.04 \\ & & 1 \end{pmatrix}$$

# The SM flavour problem

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$$Y_u \sim y_t \begin{pmatrix} & & \\ & & \\ & & 1 \end{pmatrix}$$

Exact $U(2)^n$ limit

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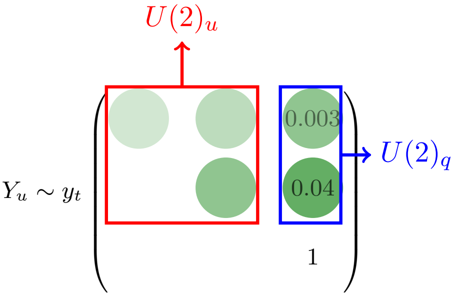


An approximate $U(2)^n$ is acting on the light families!

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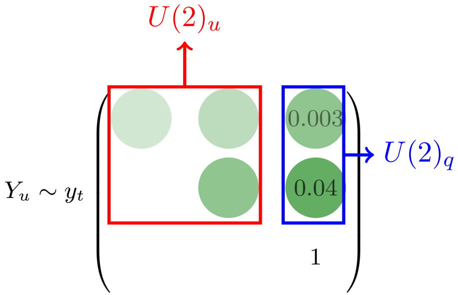


An approximate $U(2)^n$ is acting
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# The NP flavour problem

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$$

Large Flavour symmetry

Three replica of the same fermion fields

$U(3)^5$ symmetry

Flavour degeneracy is broken

The breaking is peculiar

- In the SM: accidental $U(3)^5 \to$ approx $U(2)^n$

# The NP flavour problem

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^d$$

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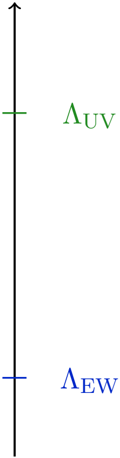
The breaking is peculiar

- In the SM: accidental $U(3)^5 \to$ approx $U(2)^n$
- **What happens when we switch on NP?**

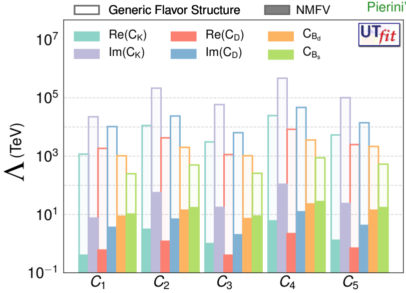
# The NP flavour problem

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- What is the energy scale of NP?
- Why haven't observed any violation of accidental symmetries yet?




Pierini's EPS talk




**no breaking of the $U(2)^n$ flavour symmetry at low energies**

# What’s the problem for BSM?

$B$-physics

Kaon physics

Higgs physics

$\tau$ decays

EWPO

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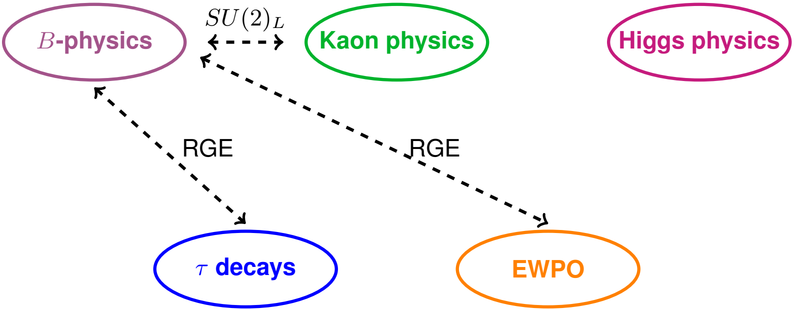

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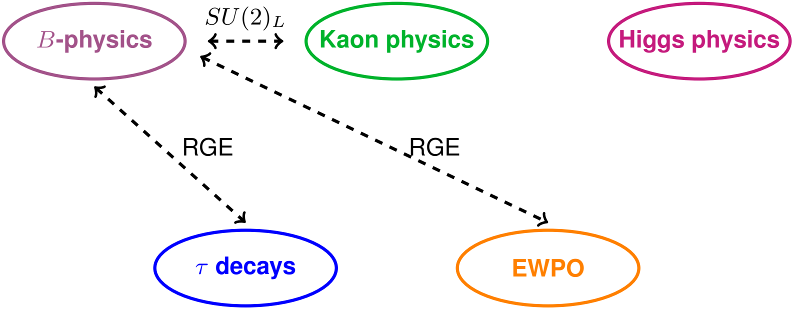


**How to satisfy all the constraints at the same time?**

# Effective Field Theories for BSM

# The EFT approach

- Since we haven't observed any clear sign of NP yet at low energies, we can work in an EFT context

  $\Rightarrow$ Agnostic of the nature of new physics, describe more than one UV model with the same operators

  $\Rightarrow$ Try to derive model-independent bounds

- We use the SMEFT

  $\Rightarrow$ Build all possible operators with SM fields and respecting SM symmetries

- The remnant of high-energy new physics is contained in the Wilson Coefficients

  $\Rightarrow$ With flavour, we have a lot of free degrees of freedom

  $\Rightarrow$ We need a criterium to infer their magnitude

# The $U(2)^n$ symmetry for BSM

$$q_{3L} \sim (\mathbf{1}, \mathbf{1}) \qquad \ell_{3L} \sim (\mathbf{1}, \mathbf{1})$$

$$Q_L = (Q_L^1, Q_L^2) \sim (\bar{\mathbf{2}}, \mathbf{1}) \qquad L_L = (\ell_L^1, \ell_L^2) \sim (\mathbf{1}, \bar{\mathbf{2}})$$

Unbroken $U(2)^5$

$$Y_u = y_t \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \Longrightarrow$$

$\bar{q}_{3L} \Gamma q_{3L}$ ✓

$\bar{q}_{3L} \Gamma Q$ ✗

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$$V_q \sim (\mathbf{2},\mathbf{1}) \qquad V_\ell \sim (\mathbf{1},\mathbf{2})$$

Unbroken $U(2)^5$

$$Y_u = y_t \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad \Rightarrow \quad \bar{q}_{3L}\Gamma q_{3L} \; ✓ \qquad \bar{q}_{3L}\Gamma Q \; ✗$$

Soft symmetry breaking

$$Y_u = y_t \begin{pmatrix} \Delta & V_q \\ 0 & 1 \end{pmatrix} \quad \Rightarrow \quad \bar{q}_{3L}\Gamma q_{3L} \; ✓ \qquad \bar{q}_{3L}\Gamma (V_q Q) \; ✓$$

# Which operators?

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu\sigma^a q_{3L})(\bar{\ell}_{3L}\gamma^\mu\sigma^a\ell_{3L}) - \frac{c_{13}}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu q_{3L})(\bar{\ell}_{3L}\gamma^\mu\ell_{3L})$$

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$SU(2)$ triplet

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$SU(2)$ triplet $\qquad$ $SU(2)$ singlet

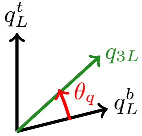
- Left-handed fields only

  $\Rightarrow$ Only ones contributing to di-neutrino modes without considering right-handed $\nu$

- $q_{3L} \equiv q_L^b + \theta_q e^{i\phi_q}\,\hat{V}_q^\dagger \cdot Q_L$

$$q_L^b = \begin{pmatrix} V_{j3}^* u_L^j \\ b_L \end{pmatrix} \qquad Q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix} \qquad \hat{V}_q \equiv (V_{td}^*, V_{ts}^*)$$

  $\Rightarrow$ $\theta_q$ and $\phi_q$ are small mixing angles



$$(\bar{q}_{3L}\gamma_\mu q_{3L})(\bar{\ell}_{3L}\gamma^\mu \ell_{3L})$$

CKM or $\theta_q$

$\theta_q$

$$(\bar{c}_L\gamma_\mu b_L)(\bar{\nu}_\tau\gamma^\mu \tau_L)$$

$$(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_\tau\gamma^\mu \nu_\tau)$$

two insertion of $\theta_q$

$$(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_\tau\gamma^\mu \nu_\tau)$$

$$(\bar{q}_{3L}\gamma_\mu q_{3L})(\bar{\ell}_{3L}\gamma^\mu \ell_{3L})$$

CKM or $\theta_q$ → $$(\bar{c}_L\gamma_\mu b_L)(\bar{\nu}_\tau\gamma^\mu \tau_L)$$

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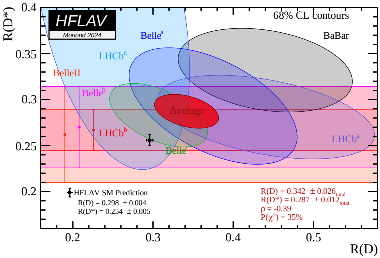
two insertion of $\theta_q$ → $$(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_\tau\gamma^\mu \nu_\tau)$$

**Correlations among all these modes is essential to prove NP scenarios**

# Observables: $R_{D^{(*)}}$




$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

- Test of Lepton Flavour Universality between the 3rd and light lepton families
- Ratios allow cancelling hadronic uncertainties and experimental uncertainties

$$\Delta R_{D^{(*)}} = \left[\frac{R_{D^{(*)}}}{R^{\text{SM}}_{D^{(*)}}} - 1\right] \approx 2R_0(1 - \theta_q \cos\phi_q) \qquad R_0 = \frac{1}{\Lambda^2}\frac{1}{\sqrt{2}G_F}$$

# Observables: $B^+ \to K^+ \nu\bar{\nu}$

[2311.14647]

Hadronic Tagging

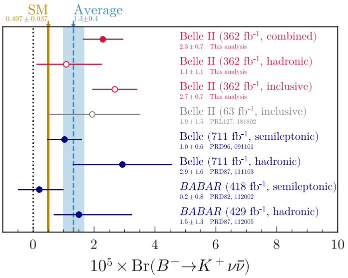
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$$

Inclusive Tagging

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

Combined

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (2.7 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$$




$3.5\,\sigma$ evidence wrt background only

$2.7\,\sigma$ tension wrt SM

# Observables: $B^+ \to K^+ \nu\bar{\nu}$

- From the theory point of view, the $B^+ \to K^+ \nu\bar{\nu}$ mode is very clean
  - No charm pollution
  - Pollution from $B \to \tau(\to K\nu)\bar{\nu}$, but removable experimentally
  - Very precise, already hitting the wall with precision

$$\frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})_{\rm SM}} = \left[\frac{2}{3} + \frac{1}{3}\left|1 - \frac{\pi s_w^2 \Delta R_{D^{(*)}}}{2\alpha X_t (1-\theta_q \cos\phi_q)}\theta_q e^{i\phi_q}(1-c_{13})\right|^2\right]$$

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Direct connection with $b \to c\tau\bar{\nu}$

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distinguishes among UV models

# Kaon decays

$$\frac{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM}} = \frac{2}{3} + \left| \frac{1}{3} + \frac{\Delta R_{D^{(*)}}\, \theta_q^2 (1 - c_{13})}{2(\alpha/\pi) C_{sd,\tau}^{\rm SM,eff} (1 - \theta_q \cos\phi_q)} \right|^2$$

$$\frac{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})}{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM}} = \frac{2}{3} + \left| \frac{1}{3} - \frac{\Delta R_{D^{(*)}}\, \theta_q^2 (1 - c_{13})}{2(\alpha/\pi)(X_t/s_w^2)(1 - \theta_q \cos\phi_q)} \right|^2$$

- Same proportionality to $\Delta R_{D^{(*)}}$ as in $B \to K\nu\bar{\nu}$
- Same CKM structure as in the SM
- We have a large interference also for the $K_L \to \pi^0\nu\bar{\nu}$ decay

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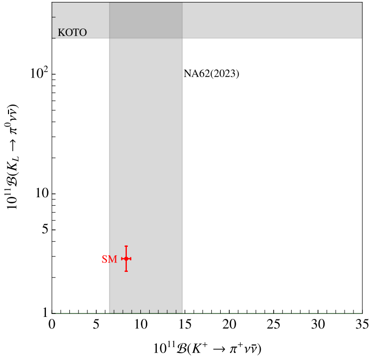
# The BSM reach of Kaon decays




- Currently, the NA62 limits are not enough to ping down a specific parametric window
- KOTO-II sensitivity at 25% of the measured branching fraction
  - Hypothesis: $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} = 1.3\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM}$
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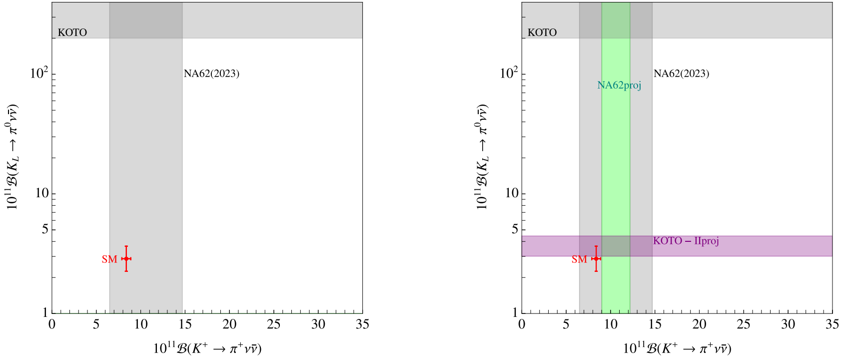


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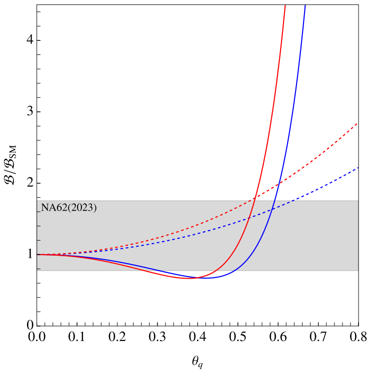


- Blue lines: $K^+ \to \pi^+ \nu\bar{\nu}$, red lines: $K_L \to \pi^0 \nu\bar{\nu}$
- $\Delta R_{D^{(*)}}$ fixed to its central value
- filled: $c_{13} = 0\, \phi_q = 0$, dashed $c_{13} = 2\, \phi_q = \pi$
- “Model” allows for large modifications, NA62 and KOTO-II updates are **essential** to constrain the parameter space

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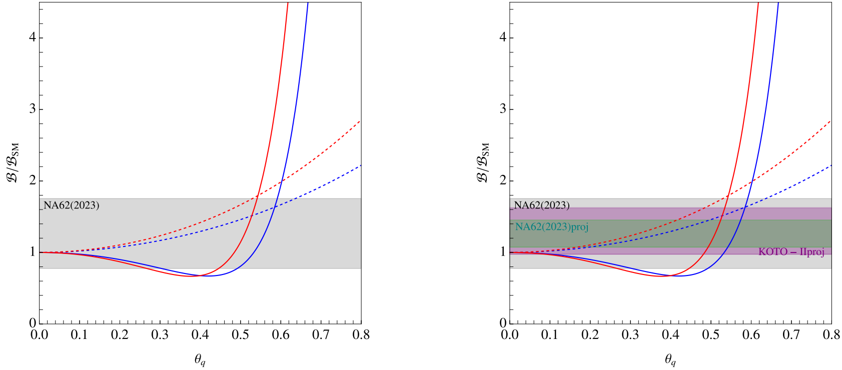


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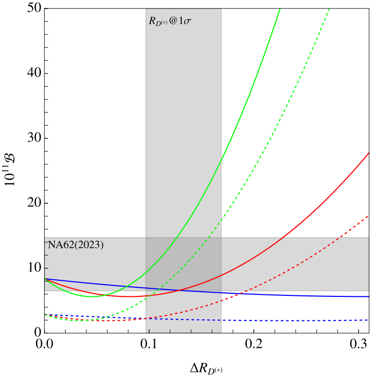
# Correlation with $B$-physics

If In this setup, the relative shift to fit $R_D$ and $R_{D^*}$ is the same

$$\Delta R_{D^{(*)}} = \left[\frac{R_{D^{(*)}}}{R^{\rm SM}_{D^{(*)}}} - 1\right] = 0.133 \pm 0.036$$

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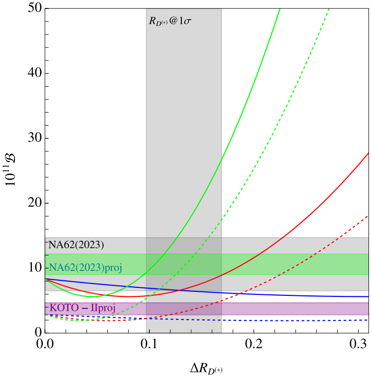


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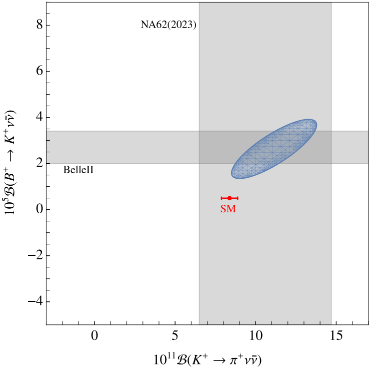
**KOTO-II is essential to select the parameter space**

# Fit to di-neutrino modes




- Fit assuming the current central value for $\Delta R_{D^{(*)}}$ and $c_{13} = 0.5$

  $\Rightarrow$ Excellent fit quality

- We predict

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (6.7 \pm 1.8) \times 10^{-11}$$

testable at $2\sigma$ at KOTO-II

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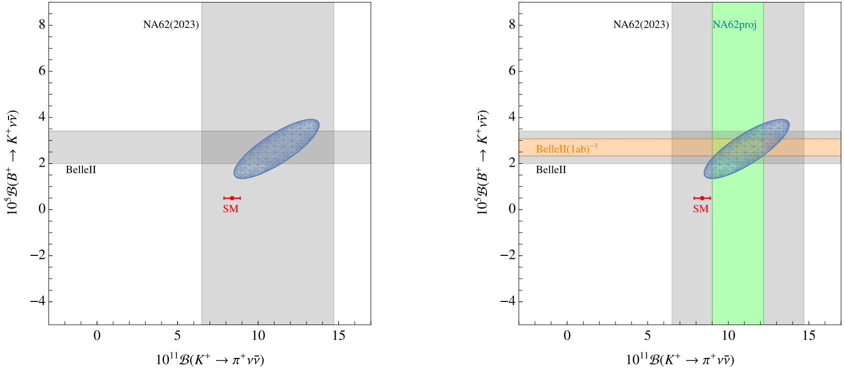


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# Explicit BSM examples

# Which NP particle?

## 1) Colourless Mediators

- $W' + Z'$: tension with high-$p_T$ searches with $\tau_L \tau_L$ or $b_L b_L$ final states

[Greljo,Isidori,Marzocca,'15]

- Solutions with right-handed neutrino are motivated and help to ease the tension with $b \to c\tau\nu$ data but they are most likely to be excluded from high-$p_T$

[Greljo, Camalich,Ruiz-Álvarez,'18]

## 2) Leptoquark Mediators

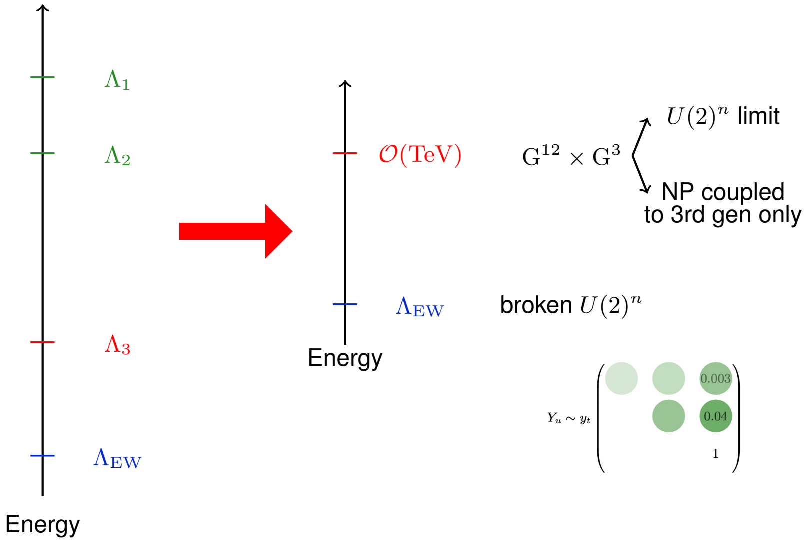
| Model | $R_{K^{(*)}}$ | $R_{D^{(*)}}$ | $R_{K^{(*)}}$ & $R_{D^{(*)}}$ |
|---|---|---|---|
| $S_1$ | ✗* | ✓ | ✗* |
| $R_2$ | ✗* | ✓ | ✗ |
| $\widetilde{R}_2$ | ✗ | ✗ | ✗ |
| $S_3$ | ✓ | ✗ | ✗ |
| $U_1$ | ✓ | ✓ | ✓ |
| $U_3$ | ✓ | ✗ | ✗ |

[Angelescu, Bečirević, Faroughy , Sumensari, '18]

$$S_1 \sim (\bar{\mathbf{3}}, 1, 1/3)$$
$$S_3 \sim (\bar{\mathbf{3}}, 3, 1/3)$$
$$U_1 \sim (\mathbf{3}, 1, 2/3)$$

# Flavour Non-Universal New Physics

Dvali, Shifman, '00
Panico, Pomarol, '16
MB, Cornella, Fuentes-Martin, Isidori '17
Allwicher, Isidori, Thomsen '20
Barbieri, Cornella, Isidori, '21
Davighi, Isidori '21



# The Pati-Salam Leptoquark

$$\mathrm{G}_i = \mathrm{SU}(4)^i \times \mathrm{SU}(2)_L^i \times \mathrm{SU}(2)_R^i$$

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$$\mathrm{G}_i = \mathrm{SU}(4)^i \times \mathrm{SU}(2)_L^i \times \mathrm{SU}(2)_R^i$$

$$\mathrm{G}_{12} \times \mathrm{G}_3 \Rightarrow \mathrm{SM} + U_1 + Z'$$

# The Pati-Salam Leptoquark

$$\mathrm{G}_i = \mathrm{SU}(4)^i \times \mathrm{SU}(2)_L^i \times \mathrm{SU}(2)_R^i$$

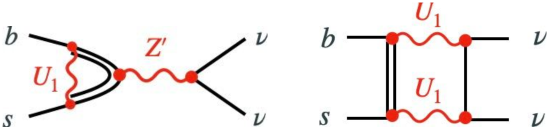
$$\mathrm{G}_{12} \times \mathrm{G}_3 \Rightarrow \mathrm{SM} + U_1 + Z'$$

**Large couplings to third generation**

+other (heavy) states that depend on the details of the model in the UV

# Phenomenology

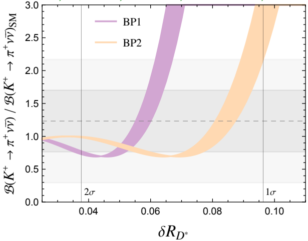
- The $Z'$ mediates neutral meson mixing at tree-level
  - $\Rightarrow$ Suppressed parametrically
- The $U_1$ LQ has tree level matching $c_{13} = 1$, no tree-level contribution to $s \to d\nu\bar{\nu}$
- However, there are loop contributions




$$\Delta C_\tau \approx V_{us}^* V_{ud}$$

- The loop doesn't preserve the $U(2)$ CKM structure
- The contribution to $K_L \to \pi\nu\bar{\nu}$ is negligible

[O. Crosas, G. Isidori, J. Lizana, N. Selimović, B. Stefanek, '22]

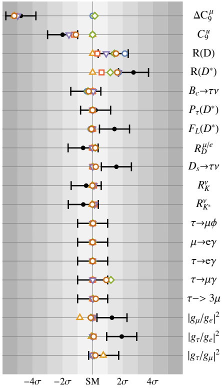


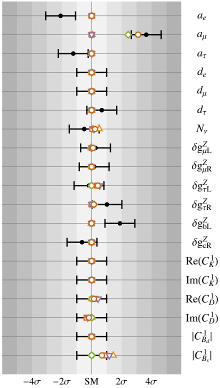
# The scalar leptoquarks $S_1 + S_3$

- Scalar leptoquarks don't require a UV completion
- They both contribute at tree-level to $s \to d\nu\bar{\nu}$ transitions such as

$$c_{13}|_{S_1} = \frac{1}{2} \qquad c_{13}|_{S_3} = \frac{1}{2}$$

- Sweet spot to connect to $B^+ \to K^+\nu\bar{\nu}$




[V. Gherardi, D. Marzocca, E. Venturini, '20]

# Conclusions

- Flavour physics has exciting prospects in the search for New Physics
- Understanding the origin of the Flavour Puzzle might hint at what structure new physics couplings have
- Correlations among different observables are crucial to studying the viability of classes of models

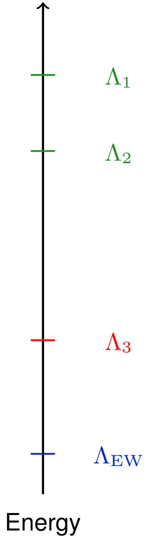
  ⇒ Di-neutrino modes are one of the golden modes where to look for new physics signals

  ⇒ The complementarity between measurements $B^+ \to K^+ \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ are essential to ping down specific scenarios

# Appendix

# Flavour Non-Universal New Physics

Dvali, Shifman, '00
Panico, Pomarol, '16
MB, Cornella, Fuentes-Martin, Isidori '17
Allwicher, Isidori, Thomsen '20
Barbieri, Cornella, Isidori, '21
Davighi, Isidori '21




**Basic idea:**

- 1st and 2nd have small masses and small couplings to NP because they are generated by dynamics at a heavier scale
- 3rd generation is linked to dynamics at lower scales and has stronger couplings

**Flavour deconstruction**:
fermion families interact with different gauge groups and flavour hierarchies emerge as accidental symmetries