Closing Theory Talk

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Beyond the Flavour Anomalies 2025

11.04.2025

Outline:

1. The problem of flavour

2. Open problems in hadronic physics

3. A glance into BSM physics

Motivation

Despite the SM successes,
there are open problems:

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Hierarchy problem

dark matter/dark energy

flavour hierarchies

neutrino masses

gravity

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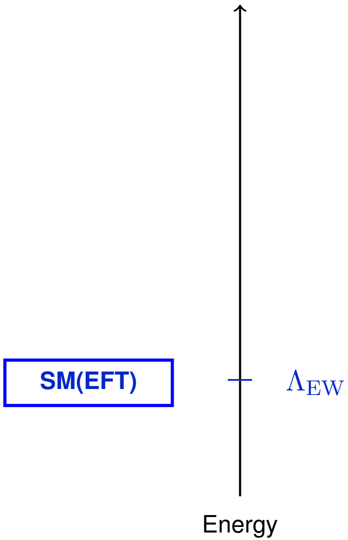

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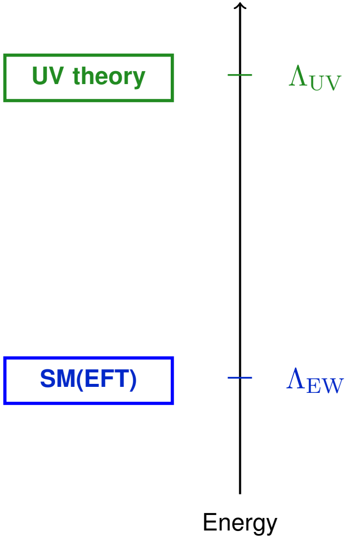

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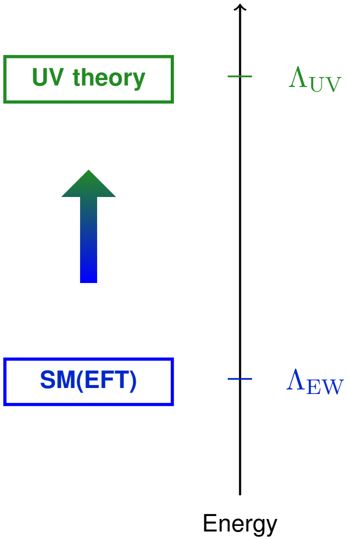


The (two) flavour problems

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 Λ, 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

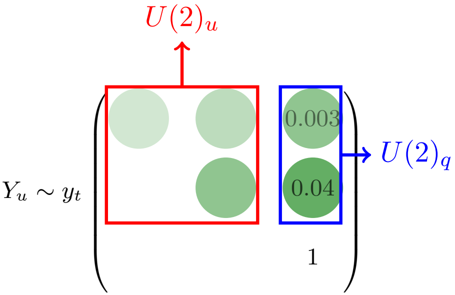
$$\mathcal{L}_{\text{Yukawa}} \supset Y_u^{ij} \bar{Q}_L^i H u_R^j$$

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

Exact $U(2)^n$ limit

The SM flavour problem

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



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

The NP flavour problem

$$\mathcal{L} = \boxed{\mathcal{L}_{\rm gauge}} + \boxed{\mathcal{L}_{\rm Higgs}}$$

Large Flavour symmetry

Three replica of the same fermion fields

$\Downarrow$

$U(3)^5$ symmetry

Flavour degeneracy is broken

The breaking is peculiar

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

The NP flavour problem

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

Large Flavour symmetry

Flavour degeneracy is broken

Three replica of the same fermion fields

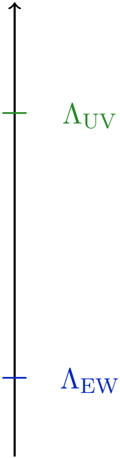
The breaking is peculiar

$U(3)^5$ symmetry

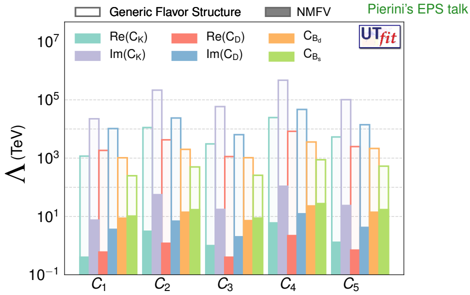
- In the SM: accidental $U(3)^5 \rightarrow$ approx $U(2)^n$
- **What happens when we switch on NP?**

The NP flavour problem

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

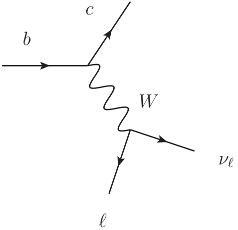


- What is the energy scale of NP?
- Why haven't observed any violation of accidental symmetries yet?

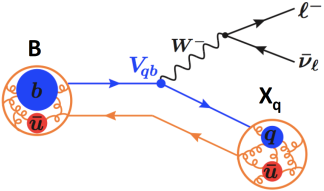


no breaking of the $U(2)^n$ flavour symmetry at low energies

Partonic vs Hadronic



$$\mu_{\text{partonic}} = m_b$$



$$\mu_{\text{hadronic}} = \Lambda_{\text{QCD}}$$

Fundamental challenge to match partonic and hadronic descriptions

What's the problem for BSM?

B-physics

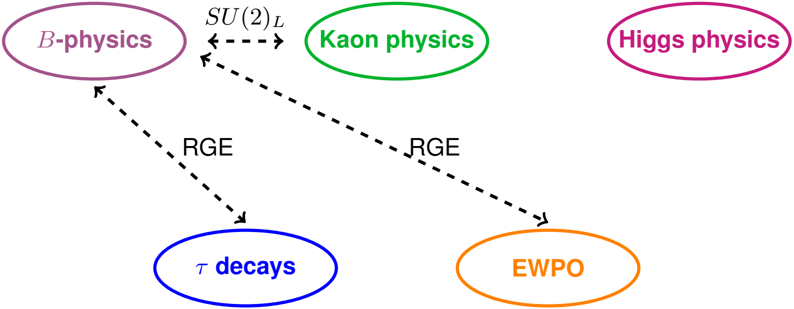
Kaon physics

Higgs physics

τ decays

EWPO

What's the problem for BSM?



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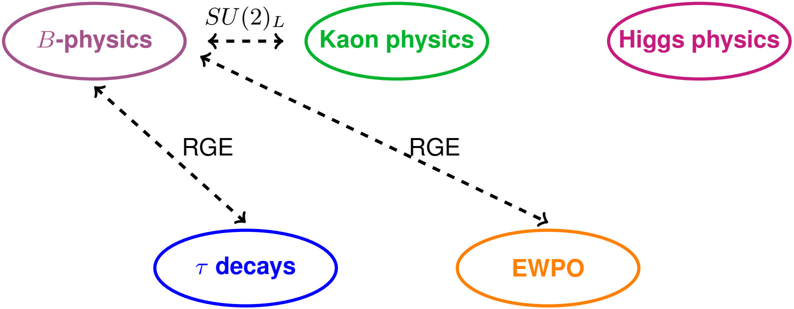


How to satisfy all the constraints at the same time?

Open problems in hadronic physics

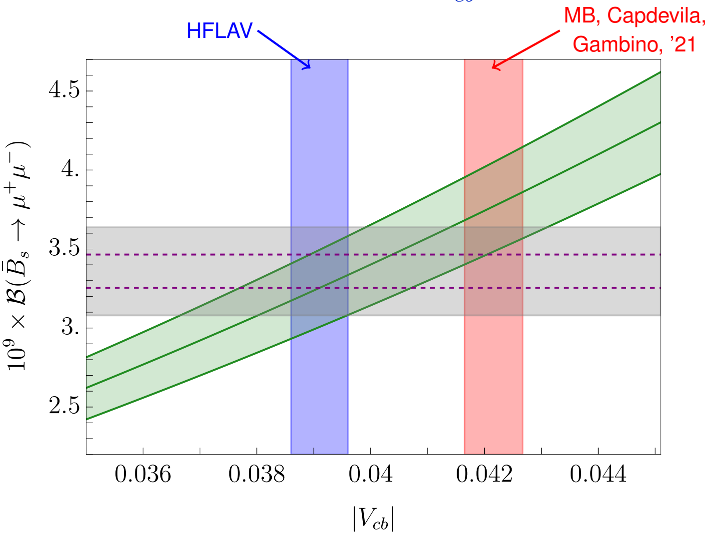
What are the open themes in hadronic physics?

1. Calculation of local form factors for semileptonic and rare decays
   - Extraction of CKM elements — Andreas and Ludovico, Paolo, Silvano, Marcello, Carolina and Camille
   - Search for LFUV — Mark and Quim, Alex and Marco

2. Non-local effects in $b \to s\ell\ell$ — Nico and Simon, Arianna, Chris and Giuseppe

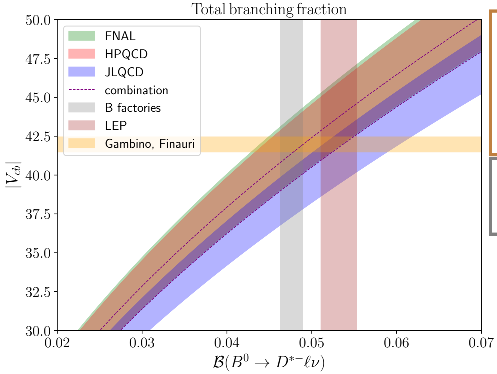
3. Non-leptonic decays
   - b decays — Matthew and Stefan, Marta
   - CP violation, D mixing — Stefan and Tommaso, Roberto
   - Extracting e.g. f_s/f_d

The crucial role of V_{cb}



Crucial to understand the V_{cb} puzzle to exploit current and future datasets

Exclusive V_{cb} from $B \to D^*$

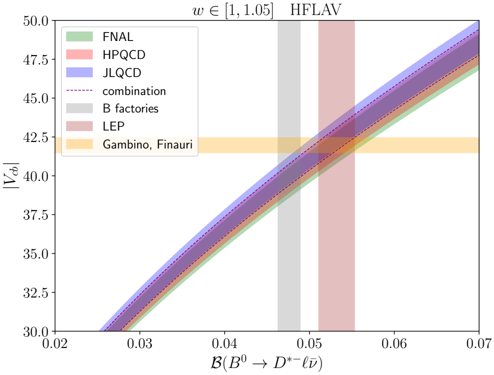


Experiment	BF (rescaled) [%]	Parameters	
ALEPH	5.56 +/- 0.27 +/- 0.33	input	parameters
OPAL incl	6.13 +/- 0.28 +/- 0.57	input	parameters
OPAL excl	5.17 +/- 0.20 +/- 0.36	input	parameters
DELPHI incl	4.96 +/- 0.14 +/- 0.35	input	parameters
DELPHI excl	5.23 +/- 0.20 +/- 0.42	input	parameters
CLEO	6.17 +/- 0.19 +/- 0.37	input	parameters
BELLE untagged	4.90 +/- 0.02 +/- 0.16	input	parameters
BELLE tagged	4.95 +/- 0.11 +/- 0.22	input	parameters
BABAR untagged	4.52 +/- 0.04 +/- 0.33	input	parameters
BABAR tagged	5.26 +/- 0.16 +/- 0.31	input	parameters
Average	**5.06 +/- 0.02 +/- 0.12**	**chi2/dof = 16.0/9 (CL = 0.0661)**	

- Shape information shifts the total branching fraction prediction

Thanks to C. Schwanda
for the averages!

Exclusive V_{cb} close to zero-recoil

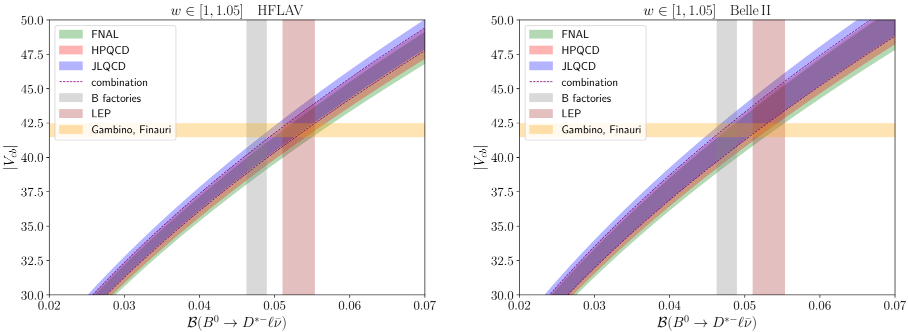


- Combination of Belle and Belle II angular distribution data
  - Only the zero-recoil bin
  - In that region, one form factor dominates
- Which branching ratio should we use?

B factories: $|V_{cb}| = 40.07 \pm 0.86$

LEP: $|V_{cb}| = 42.37 \pm 1.09$

Exclusive V_{cb} close to zero-recoil



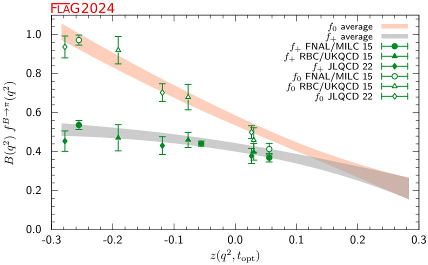
B factories: $|V_{cb}| = 40.07 \pm 0.86$

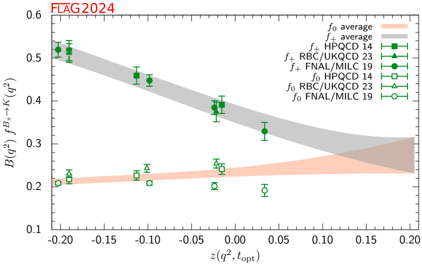
LEP: $|V_{cb}| = 42.37 \pm 1.09$

B factories: $|V_{cb}| = 41.24 \pm 1.15$

LEP: $|V_{cb}| = 43.60 \pm 1.35$

A few words on exclusive V_{ub}





- There are tensions in the lattice determinations of f_0
- f_+ and f_0 are correlated through the kinematic constraint

$$f_+(q^2 = 0) = f_0(q^2 = 0)$$

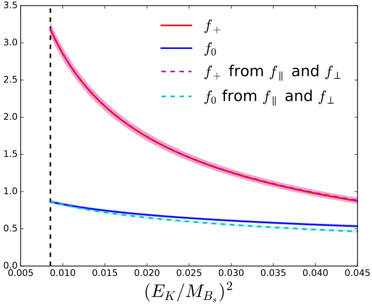
- Even for light leptons, this has an impact on phenomenology and potentially for V_{ub} extraction

Consistency checks in $B_s \to K$ RBC/UKQCD '23

- On the lattice, we don't access directly f_+ and f_0 but $f_\parallel$ and $f_\perp$
- The form factor will look like

$$f_X = \frac{\Lambda}{E_K + \Delta_X}[\chi(M_\pi^2) + k(E_K) + d((a\Lambda)^2)]$$

- The pole positions Δ_X are well defined for f_+ and f_0 Does it make a difference to perform the chiral continuum extrapolation in $f_{+,0}$ or $f_{\perp,\parallel}$?



- All fine for f_+
- Sizeable deviations for f_0
- WIP to check this for $B \to \pi$ as well

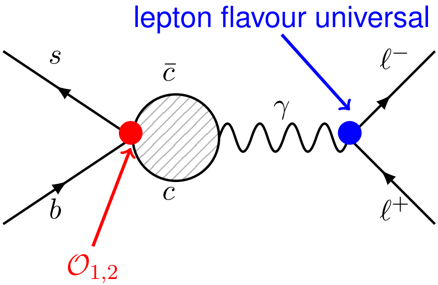
Charm-loop effects in $b \to s\ell^+\ell^-$

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[-\mathcal{C}_1\mathcal{O}_1 - \mathcal{C}_2\mathcal{O}_2 + \mathcal{C}_7\mathcal{O}_7 + \mathcal{C}_9\mathcal{O}_9 + \mathcal{C}_{10}\mathcal{O}_{10}\right]$$

$$\mathcal{O}_1 = (\bar{s}\gamma^\mu P_L b)\,(\bar{c}\gamma_\mu c) \qquad \mathcal{O}_2 = (\bar{s}\gamma^\mu T^a P_L b)\,(\bar{c}\gamma_\mu T^a c)$$

$$\mathcal{O}_9 = (\bar{s}\gamma^\mu P_L b)\,(\bar{\ell}\gamma_\mu \ell) \qquad \mathcal{O}_{10} = (\bar{s}\gamma^\mu P_L b)\,(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_7 = (\bar{s}\sigma^{\mu\nu} P_R b)\,F_{\mu\nu}$$

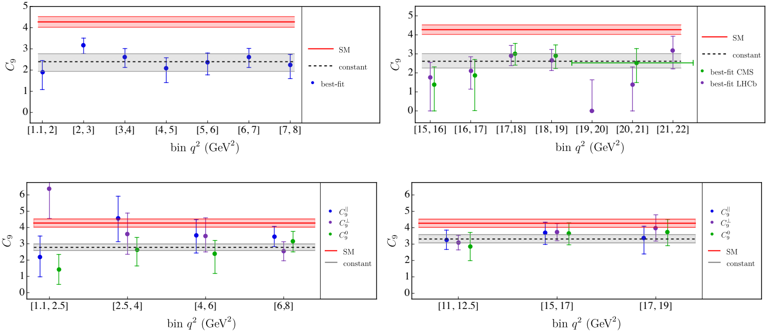


$$C_9 \to C_9^{\text{eff}}(q^2) = C_9 + C_9^{\text{LD}}(q^2)$$

How do we parametrise these long-distance effects?

$B \to K$ vs $B \to K^*$ at low and high q^2

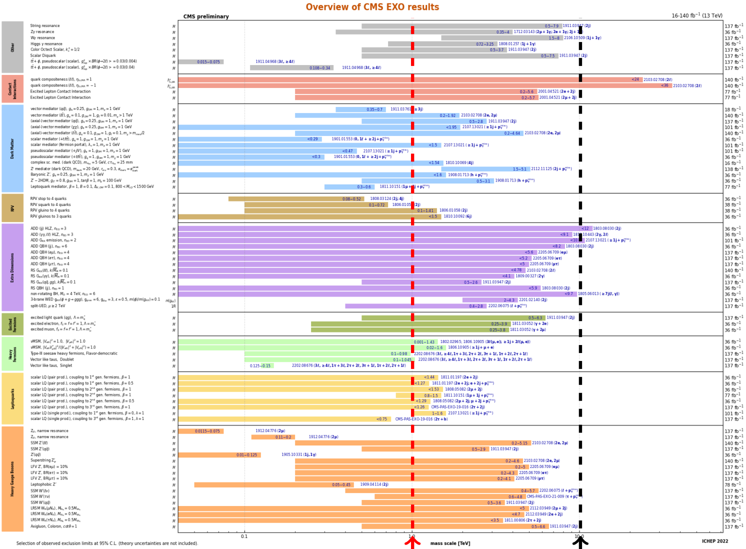
[MB, G. Isidori, S. Mächler, A. Tinari, '24]



- The complementarity of low and high q^2 data is essential to test estimations of charm re-scattering
- In the long run, a statistically compelling comparison with the electron mode is needed

A glance into BSM physics

Status of high energy bounds

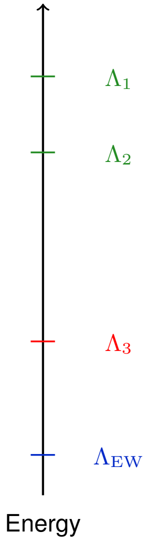


3rd generation

universal new physics

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

Flavour Non-Universal New Physics

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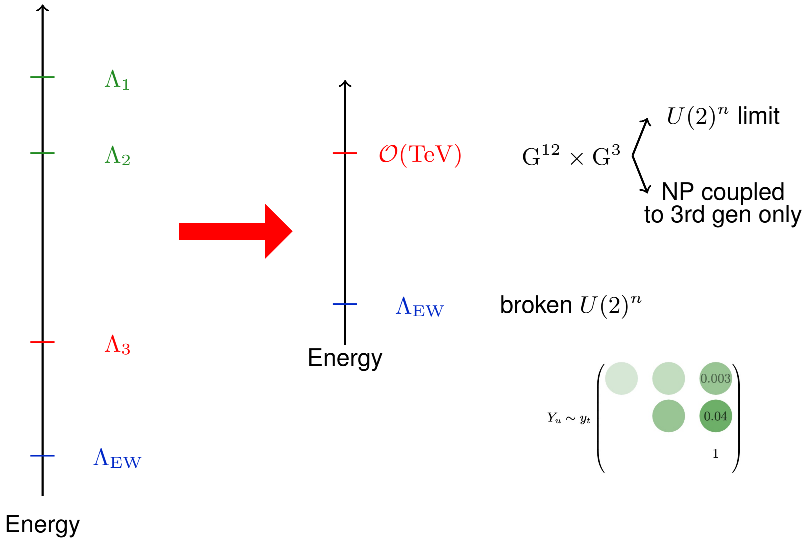
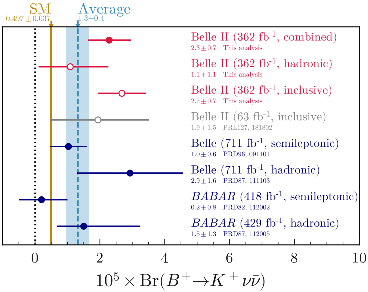
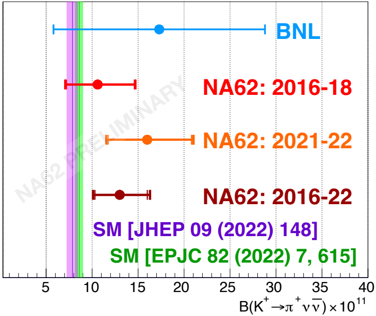
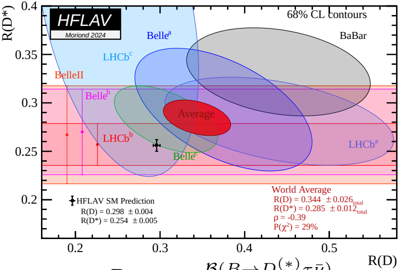


What about BSM?

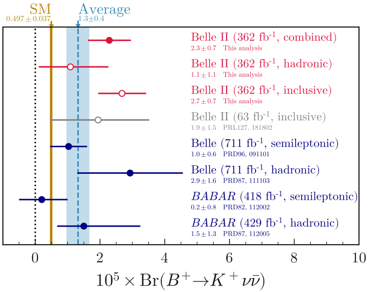


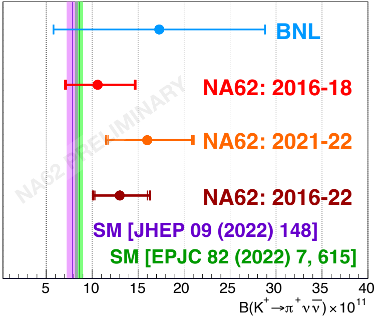


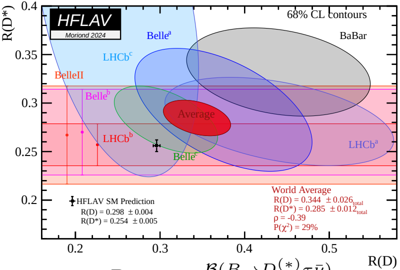


$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)} \tau \bar{\nu})}{\mathcal{B}(B \to D^{(*)} \ell \bar{\nu})}$$

What about BSM?







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

Can we accommodate all these data together?

See also Wolfgang, Martin, Lukas and Sally, Alfredo e Laura

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

CKM or $\hat{V}$

$\hat{V}$

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

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

two insertion of $\hat{V}$

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

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

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two insertion of $\hat{V}$

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

Correlations among all these modes is essential to prove NP scenarios

What do we expect in the SMEFT?

$$\mathcal{L}_{\rm EFT} \supset \boxed{\frac{C_{bc\tau\tau}}{\Lambda^2}}(\bar{b}_L\gamma_\nu c_L)(\bar{\nu}_\tau\gamma^\mu\tau_L)$$

From $U(2)^n \Rightarrow C_{bc\tau\tau} \sim V_{cb}\mathcal{O}(1)$

From $R_{D^{(*)}} \Rightarrow \Lambda \sim \mathcal{O}(\mathrm{TeV})$

Using $SU(2)_L$ invariance, we have

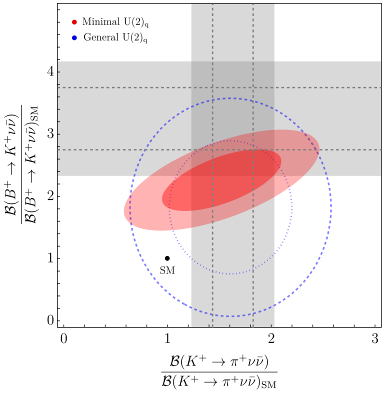
$$\mathcal{L}_{\rm EFT} \supset \frac{C_{ij\tau\tau}}{\Lambda^2}(\bar{d}^i_L\gamma_\nu d^j_L)(\bar{\nu}_\tau\gamma^\mu\nu_\tau)$$

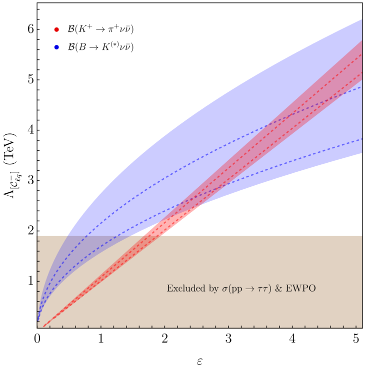
$B^+ \to K^+\nu\bar{\nu}$

From $U(2)^n \Rightarrow C_{bs\tau\tau} \sim V_{cb}\mathcal{O}(1)$

$K^+ \to \pi^+\nu\bar{\nu}$

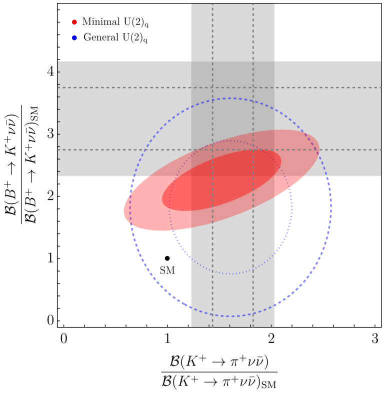
From $U(2)^n \Rightarrow C_{sd\tau\tau} \sim 10^{-1}V_{cb}\mathcal{O}(1)$

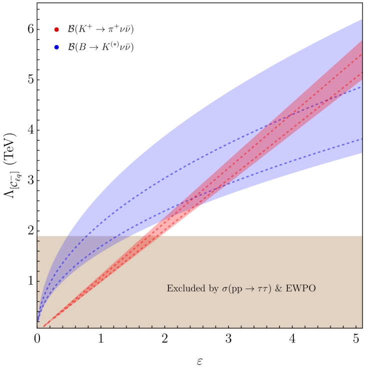




- The $U(2)^n$ symmetry creates a natural link between all this observables
- The complementarity between low- and high-energy data is useful to probe the parameter space

[L. Allwicher, MB, G. Isidori, G. Piazza, A. Stanzione, '24]

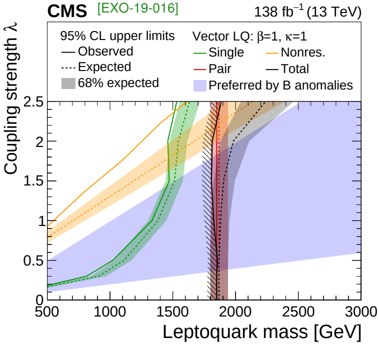


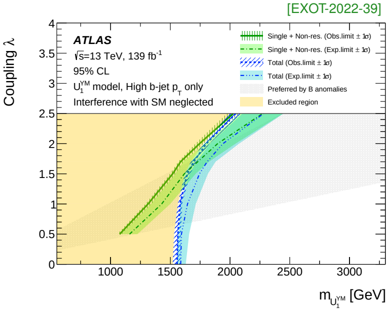


- The $U(2)^n$ symmetry creates a natural link between all this observables
- The complementarity between low- and high-energy data is useful to probe the parameter space

Further data is essential!

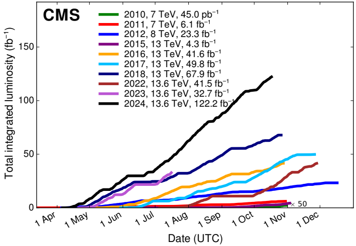
Things are moving also at high-energy

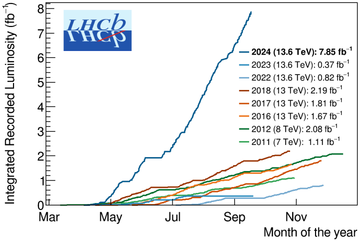




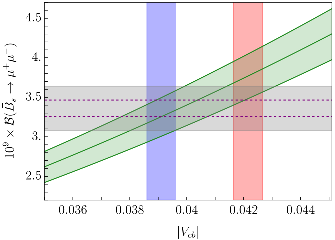
Still a long way to go, but prospects are promising

Experimental prospects





- Experimental facilities are delivering unprecedented datasets
- The experimental reach supported by new analysis techniques already superseded the expectations
- The theoretical developments are essential to keep understanding with higher precision flavour processes and assessing possible hints of new physics signals



Conclusions

- Flavour physics is a powerful test for new physics living at different energy scales
- We have a lot of puzzles to solve, but this is just a sign of the advancements in both theory and experiments
- A compelling option connecting flavour hierarchies and BSM is flavour deconstruction
- There are a few hints pointing to a strong link between new physics and the third generations, with possible new physics reach close to the current searches
- The excellent experimental prospects, combined with theory advancements, will shed light on the current picture

Appendix

On the V_{cb} puzzle (again)

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |\lambda_{ts}|^2 \quad \lambda_{ts} \equiv \lambda |V_{cb}| \left[(\bar{\rho} - 1) \left(1 - \frac{\lambda^2}{2} \right) + i\bar{\eta} \left(1 + \frac{\lambda^2}{2} \right) \right] + \mathcal{O}(\lambda^4)$$

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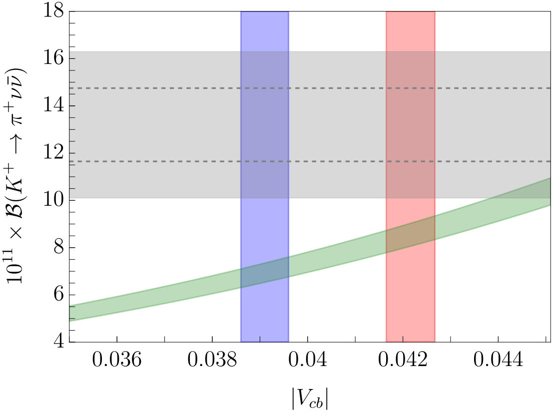
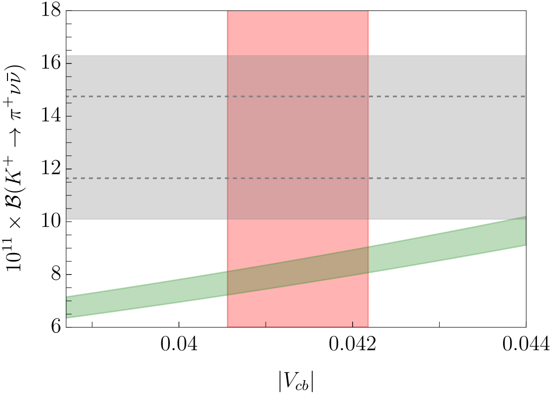


On the V_{cb} puzzle (again)

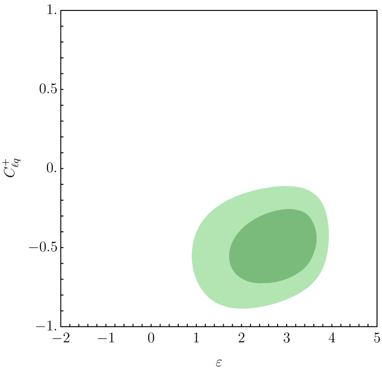
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |\lambda_{ts}|^2 \quad \lambda_{ts} \equiv \lambda |V_{cb}| \left[(\bar{\rho} - 1)\left(1 - \frac{\lambda^2}{2}\right) + i\bar{\eta}\left(1 + \frac{\lambda^2}{2}\right)\right] + \mathcal{O}(\lambda^4)$$

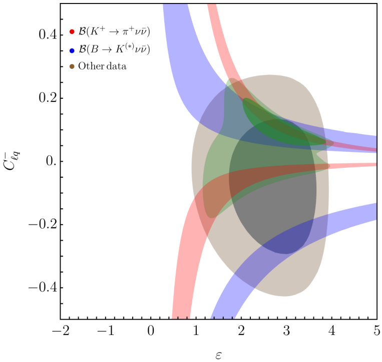


$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})^{\text{SM}} = (8.09 \pm 0.63) \times 10^{-11}$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})^{\text{SM}} = (2.58 \pm 0.30) \times 10^{-11}$$

[L. Allwicher, MB, G. Isidori, G. Piazza, A. Stanzione, '24]

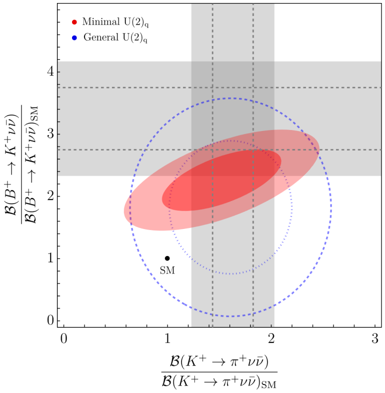


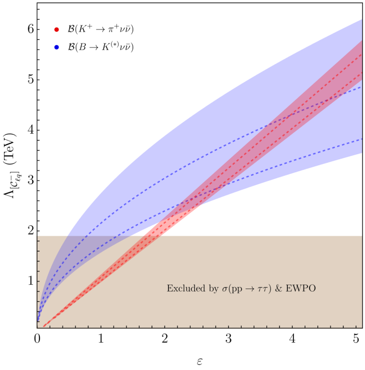


- EWPO and direct searches
- $R_{D^{(*)}}$
- $B \to K^{(*)} \mu^+ \mu^-$

- $B \to K^{(*)} \nu\bar{\nu}$
- $K^+ \to \pi^+ \nu\bar{\nu}$

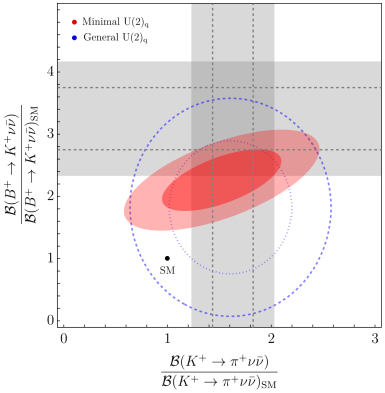
[L. Allwicher, MB, G. Isidori, G. Piazza, A. Stanzione, '24]

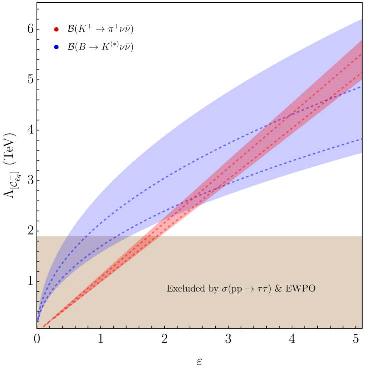




- The $U(2)^n$ symmetry creates a natural link between all this observables
- The complementarity between low- and high-energy data is useful to probe the parameter space

[L. Allwicher, MB, G. Isidori, G. Piazza, A. Stanzione, '24]





- The $U(2)^n$ symmetry creates a natural link between all this observables
- The complementarity between low- and high-energy data is useful to probe the parameter space

Further data is essential!

Which operators?

$$Q_{\ell q}^{\pm} = (\bar{q}_L^3 \gamma^\mu q_L^3)(\bar{\ell}_L^3 \gamma_\mu \ell_L^3) \pm (\bar{q}_L^3 \gamma^\mu \sigma^a q_L^3)(\bar{\ell}_L^3 \gamma_\mu \sigma^a \ell_L^3) \quad Q_S = (\bar{\ell}_L^3 \tau_R)(\bar{b}_R q_L^3)$$

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$SU(2)$ singlet

$SU(2)$ triplet

scalar

Which operators?

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$SU(2)$ singlet — $SU(2)$ triplet — scalar

- Only left-handed neutrinos
- $q_{3L} \equiv q^b_L + \hat{V} \cdot Q_L$

$$q^b_L = \begin{pmatrix} V^*_{j3} u^j_L \\ b_L \end{pmatrix} \qquad Q^i_L = \begin{pmatrix} V^*_{ji} u^j_L \\ d^i_L \end{pmatrix} \qquad \hat{V}_q \equiv -\epsilon V_{ts} \begin{pmatrix} \kappa V_{td}/V_{ts} \\ 1 \end{pmatrix}$$