Flavor physics

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Preface

Though all phenomena seems to be well described by **the Standard Model**, it should be regarded as an effective theory of a more fundamental theory

Flavor puzzle, Neutrino, Hierarchy problem, DM, BAU,,

Indirect searches are complementary to direct searches at the LHC and probe NP at high energy scale which is not accessible at collider

Energy frontier

LHC at high-pT

Intensity frontier

Flavor physics

Flavor physics play a role of

probing NP

identify origin of flavor puzzle

Recent low-energy data ("flavor anomalies")

Outline

Introduction to flavor physics

Flavor symmetry

Lepton Flavor Universality & Future prospects

Summary

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Introduction to flavor physics

Flavor symmetry

Lepton Flavor Universality & Future prospects

Summary

Flavor structure in the SM

$$\mathscr{L}_{SM} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}}$$

fermion sector $\displaystyle\sum_{i=1}^{3} \sum_{\psi_i} \bar{\psi}_i i \not{D} \psi_i$

- in gauge sector, there is 3 identical replicas of the basic fermion family $[\psi = Q_L, u_R, d_R, L_L, e_R]$

$$\psi_i \to U_{ij} \psi_j$$

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$\psi_i \to U_{ij}\psi_j \quad \Rightarrow$ large flavor symmetry $U(3)^5$ is found in gauge sector

$U(1)$ flavor-independent phase
+ $SU(3)$ flavor-dependent mixing matrix

$$\boxed{\begin{aligned} U(3)^5 &= U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{L_L} \times U(3)_{e_R} \\ &= SU(3)^5 \times U(1)^5 \end{aligned}}$$

controll flavor dynamics

can be identified with B, L, $U(1)_Y$, PQ and $U(1)_E$

Flavor structure in the SM

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fermion sector $\displaystyle\sum_{i=1}^{3}\sum_{\psi_i}\bar{\psi}_i i\not{D}\psi_i$ $\quad$ $\mathscr{L}_Y = \bar{Q}^i_L Y^{ij}_D d^j_R H + \bar{Q}^i_L Y^{ij}_U u^j_R \tilde{H} + \bar{L}^i_L Y^{ij}_E e^j_R H + (h.c.)$

- $U(3)^5$ flavor symmetry is broken only by the Yukawa interaction

quark sector

$$\bar{Q}^i_L Y^{ij}_D d^j_R H \rightarrow \bar{d}^i_L M^{ij}_D d^j_R$$
$$\bar{Q}^i_L Y^{ij}_U u^j_R \tilde{H} \rightarrow \bar{u}^i_L M^{ij}_U u^j_R$$

The Y are not hermitian → diagonalized by bi-unitary transformations:

$$V_D^\dagger Y_D U_D = \text{diag}(y_d, y_s, y_b)$$
$$V_U^\dagger Y_U U_U = \text{diag}(y_u, y_c, y_t)$$

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$$Y_D = V_D \, \text{diag}(y_d, y_s, y_b) \, U_D^\dagger$$
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quark sector

$$\bar{Q}_L^i Y_D^{ij} d_R^j H \rightarrow \bar{d}_L^i M_D^{ij} d_R^j$$

$$\bar{Q}_L^i Y_U^{ij} u_R^j \tilde{H} \rightarrow \bar{u}_L^i M_U^{ij} u_R^j$$

The residual flavor symmetry let us to choose flavor basis where only one of Y_D or Y_U is diagonal:

	<u>down-quark diagonal basis</u>		<u>up-quark diagonal basis</u>
$Y_D = V_D \, \text{diag}(y_d, y_s, y_b) \, U_D^\dagger$	$\rightarrow \text{diag}(y_d, y_s, y_b)$	or	$\rightarrow V_U^\dagger V_D \, \text{diag}(y_d, y_s, y_b)$
$Y_U = V_U \, \text{diag}(y_u, y_c, y_t) \, U_U^\dagger$	$\rightarrow V_D^\dagger V_U \, \text{diag}(y_u, y_c, y_t)$		$\rightarrow \text{diag}(y_u, y_c, y_t)$

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$Y_U = V_U \,\text{diag}(y_u, y_c, y_t)\, U_U^\dagger$	$\to V_D^\dagger V_U \,\text{diag}(y_u, y_c, y_t)$		$\to \text{diag}(y_u, y_c, y_t)$

$V_U^\dagger V_D \equiv V$: non-trivial unitary matrix

Flavor structure in the SM

Take down-quark diagonal basis

$$Y_D = \mathrm{diag}(y_d, y_s, y_b), \qquad Y_U = V^\dagger \times \mathrm{diag}(y_u, y_c, y_t)$$

To diagonalize both mass matrix, we need to rotate separately u_L and d_L (non gauge-invariant basis)

$$\mathscr{L}_{\text{gauge}} \supset \frac{g}{\sqrt{2}}(\bar{u}_L^i \gamma^\mu d_L^i) W_\mu$$

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(non gauge-invariant basis) $\Rightarrow$ V appears in charged-current gauge interactions:

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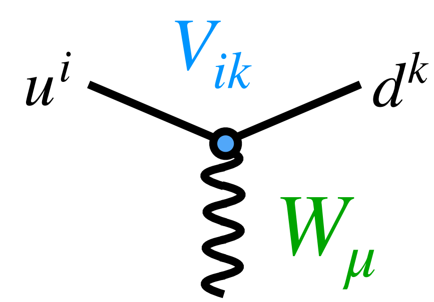

V : **Cabibbo-Kobayashi-Maskawa (CKM) matrix**

This non-trivial mixing matrix V originates only from the Higgs sector

Neutral-current remains flavor diagonal

Flavor structure in the SM

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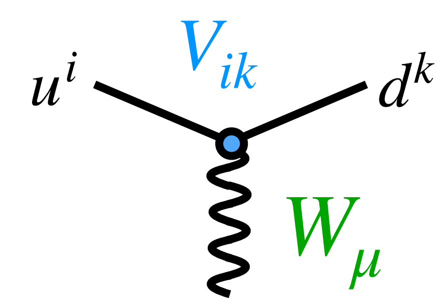

V : **Cabibbo-Kobayashi-Maskawa (CKM) matrix**

In the SM quark sector
10 observables parameters

6 quark masses
3+1 CKM parameters

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

3 real parameters (angles)
+
1 complex phase (CP violation)

Flavor structure in the SM

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In the lepton sector, we can diagonalize Y_E in a gauge invariant way
(we ignore neutrino mass at this level)

$$Y_E = \mathrm{diag}(y_e, y_\mu, y_\tau)$$

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In the SM lepton sector
3 observables parameters

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- **6** quark masses
- **3+1** CKM parameters

In the SM lepton sector
3 observables parameters

- **3** lepton masses

13 flavor parameters in the SM

Majority of the SM parameters (19)

Hierarchical structure :

Mass : 3rd > 2nd > 1st   Is there deeper explanation ?

$M_{u,d,e} \sim$ 

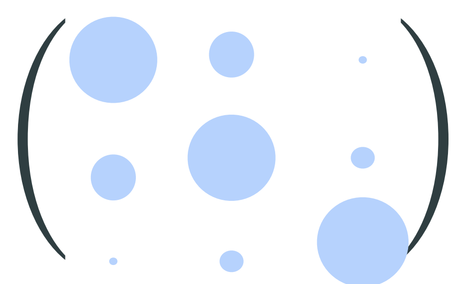
The SM flavor problem

CKM fit

Wolfenstein parametrization $(\lambda_c, \rho, \eta, A)$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 - \frac{\lambda_c^2}{2} & \lambda_c & A\lambda_c^3 (\rho - i\eta) \\ -\lambda_c & 1 - \frac{\lambda_c^2}{2} & A\lambda_c^2 \\ A\lambda_c^3 (1 - \rho - i\eta) & -A\lambda_c^2 & 1 \end{pmatrix}$$

$\lambda_c = 0.22$: Cabibbo angle

$V_{CKM} \sim$ 

Strongly hierarchical structure

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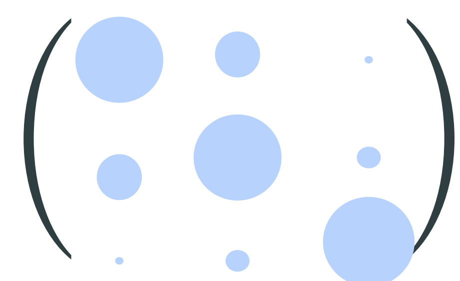
Unitarity

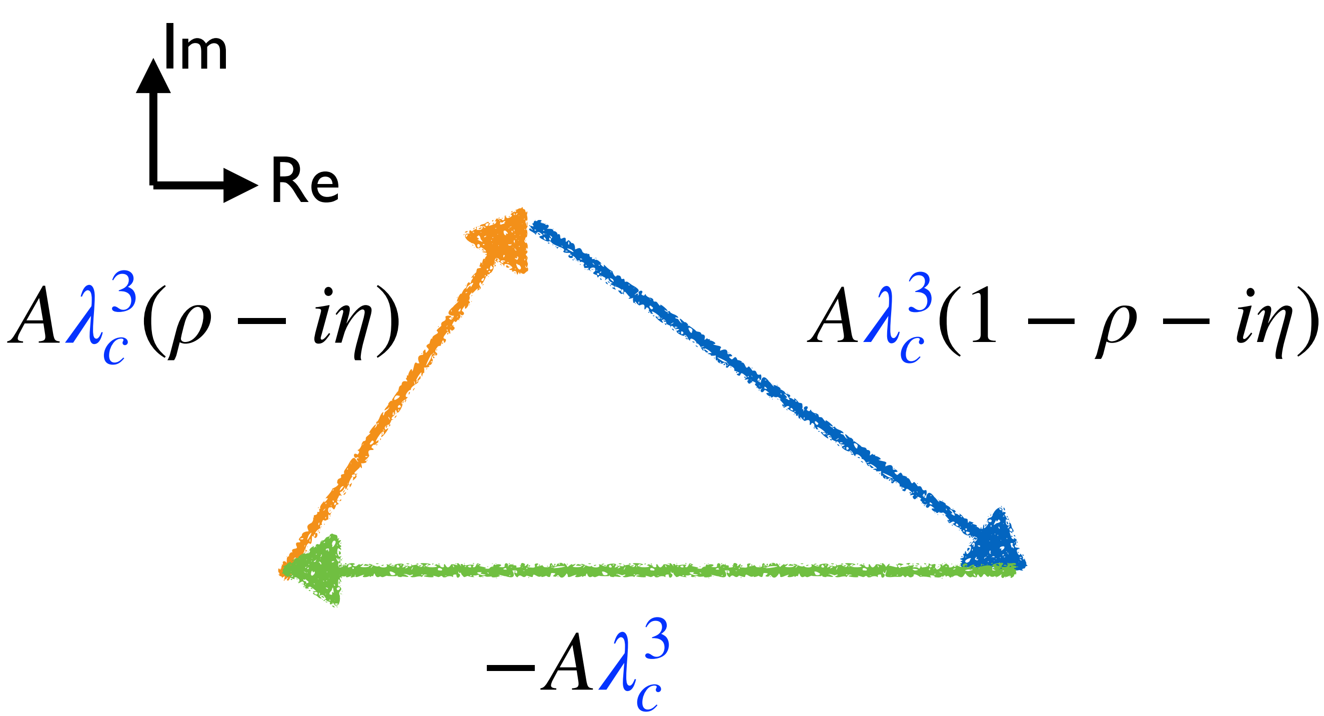
$$V_{CKM} V_{CKM}^\dagger = 1$$

$V_{CKM} \sim$ 

Strongly hierarchical structure

$b \to d$ Unitarity triangle

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



Only $b \to d$ UT (3-1 transition) have three sides with same order in λ_c

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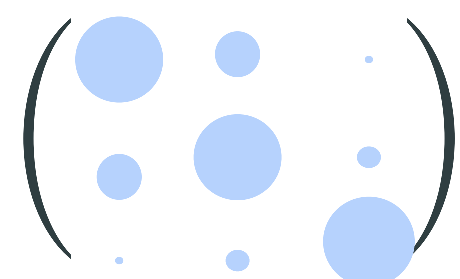
$V_{CKM} \sim$ 

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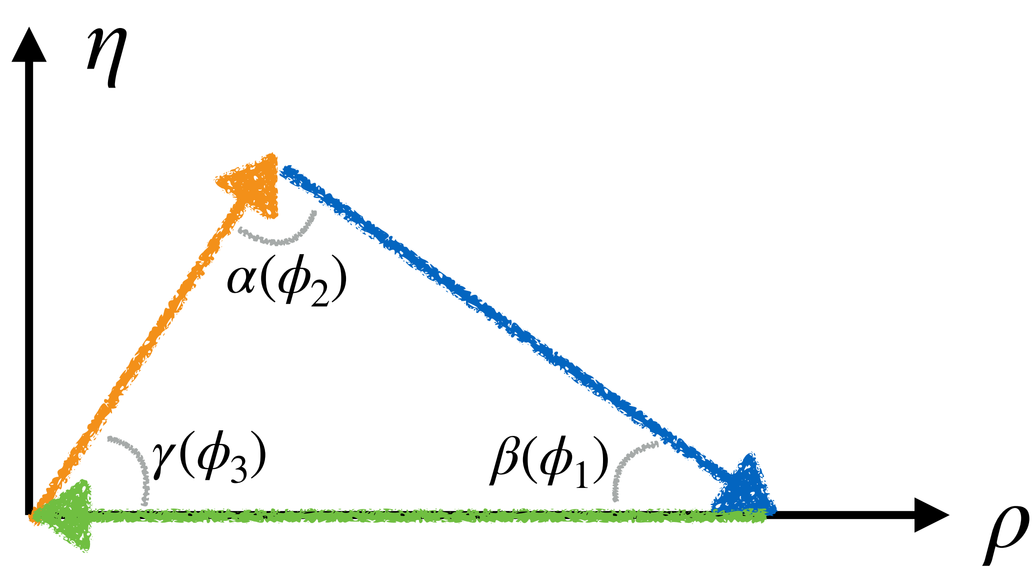

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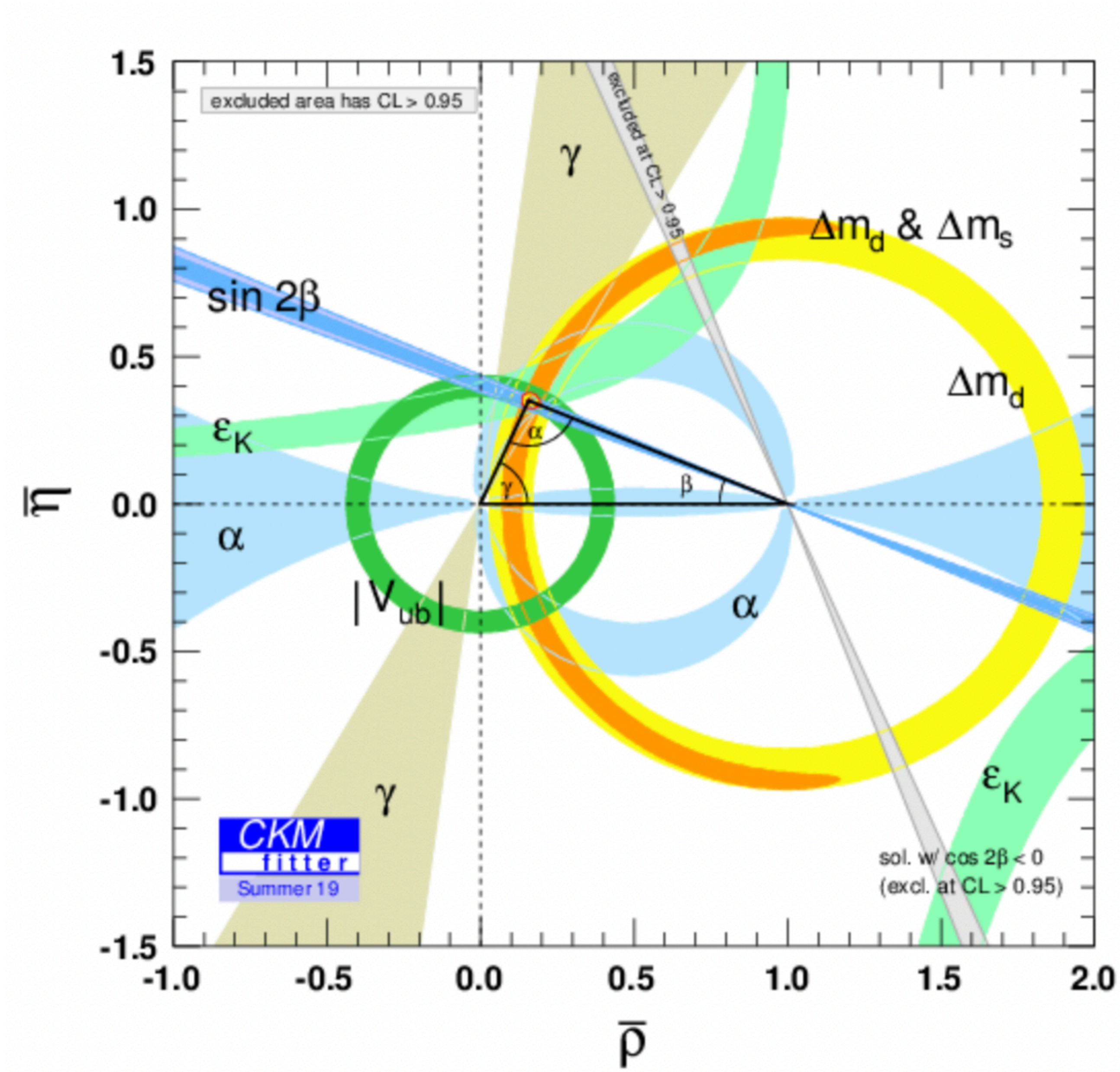
These angles and sides of UT are determined by various B decays experimentally

CKM fit

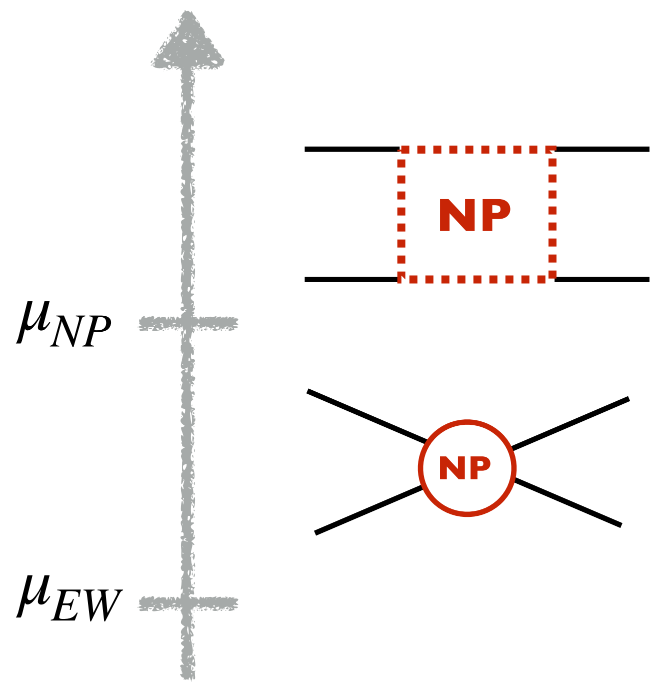


At present, measurements of sides and angles of CKM UT show a remarkable success of the SM

Serious bounds for NP

The NP flavor problem

The NP flavor problem



full theory

↓ Integrate heavy particle

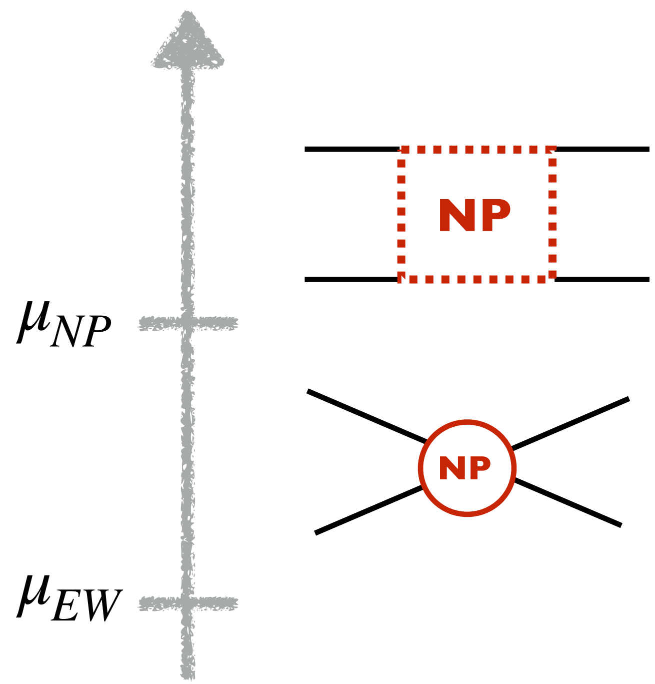
$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathscr{O}_i^{d=6} \quad \text{NP}$$

Bs-system $V_{tb}^* V_{ts} \sim \lambda^2$ $\gg$ Bd-system $V_{tb}^* V_{td} \sim \lambda^3$ $\gg$ K-system $V_{ts}^* V_{td} \sim \lambda^5$

$$|C_{NP}| \sim 1 \longrightarrow \Lambda_{NP} \sim \begin{cases} 500 \text{ TeV} & : \quad B_s \\ 2000 \text{ TeV} & : \quad B_d \\ 10^4 - 10^5 \text{ TeV} & : \quad K^0 \end{cases}$$

Serious conflict with the expectation of NP around the TeV scale, to stabilize the electroweak sector of the SM (***The NP flavor problem)***

The NP flavor problem



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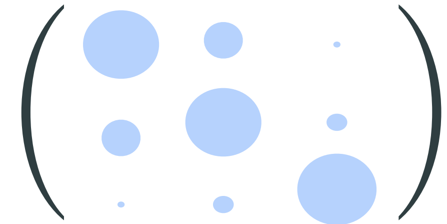
$$|C_{NP}| \ll 1 \quad \longleftarrow \quad \Lambda_{NP} \sim \text{TeV}$$

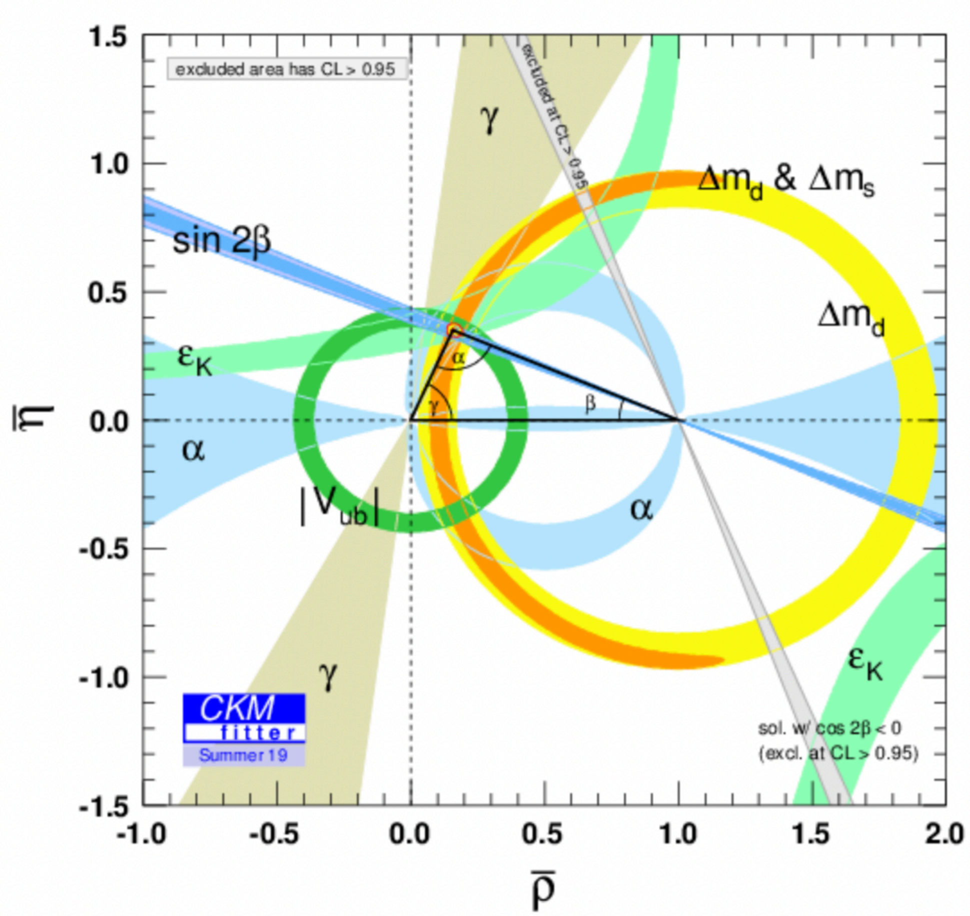
If we insist with the theoretical prejudice that NP has to emerge in the TeV region, we have to conclude that NP have **highly non-generic flavor structure**

The SM flavor problem : the hierarchical structure of the SM Yukawa couplings

$M_{u,d,e} \sim$  $V_{CKM} \sim$ 

Is there deep reason?

The NP flavor problem : current data show no significant deviations from the SM in many quark flavor observables



NP is very heavy..

or

NP has a highly non-trivial flavor structure

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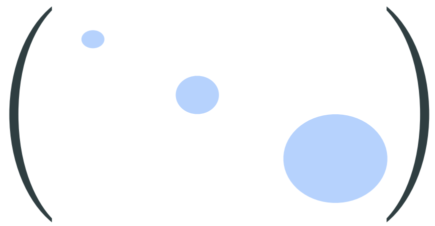
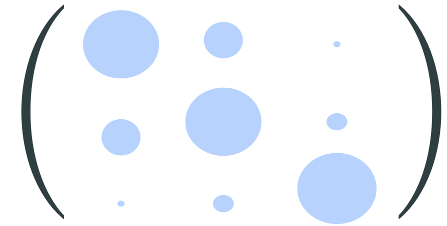
$M_{u,d,e} \sim$ 

$V_{CKM} \sim$ 

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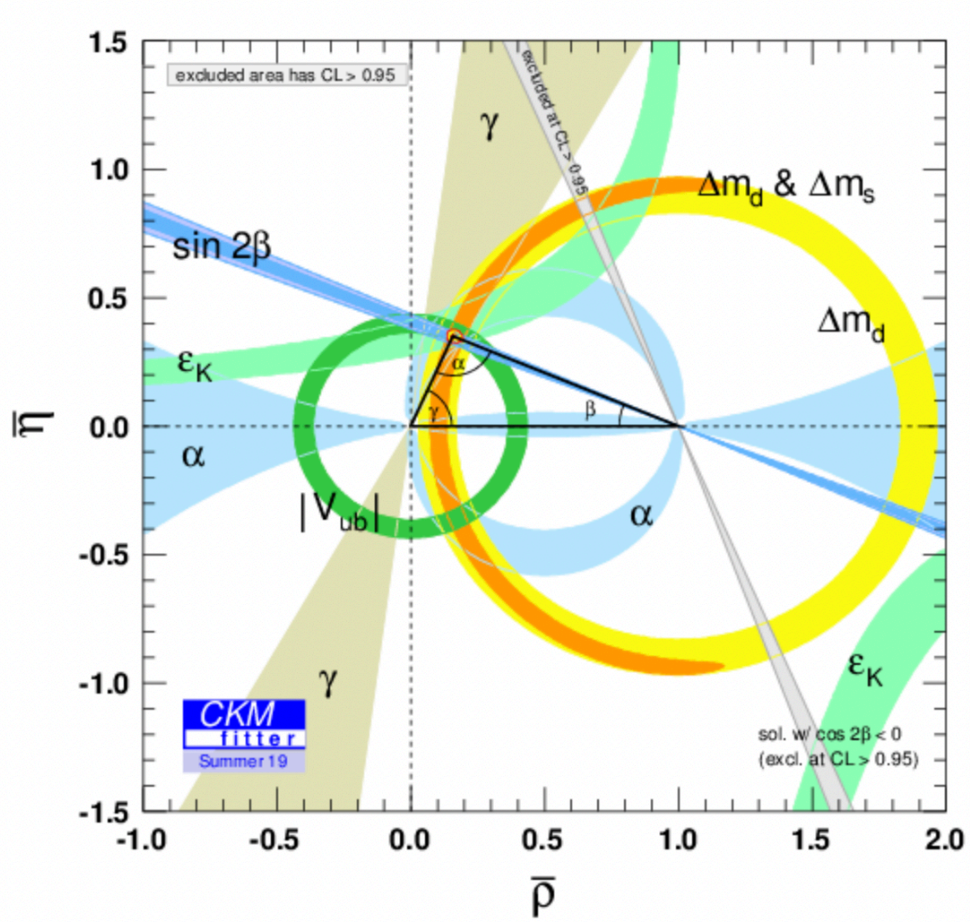

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Flavor symmetry?

(→more detail next)

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Flavor symmetry

Lepton Flavor Universality & Future prospects

Summary

In the SM

flavor symmetry $U(3)^5$ of the gauge sector

SM Yukawa coupling → unique breaking terms of the flavor symmetry

GIM & CKM suppression

Assumption that flavor structure in NP is also **controlled by Yukawa** is the most reasonable solution to the NP flavor problem

Automatic GIM & CKM suppression as in the SM

⇒ Minimal Flavor Violation paradigm

Minimal Flavor Violation (MFV)

D'Ambrosio, Giudice, Isidori, Strumia [hep-ph/0207036]

$$\mathscr{L}_Y = \bar{Q}_L^i Y_D^{ij} d_R^j H + \bar{Q}_L^i Y_U^{ij} u_R^j \tilde{H} + \bar{L}_L^i Y_E^{ij} e_R^j H + (h.c.)$$

- assume that $G_F \equiv SU(3)^5$ is a good symmetry, and consider $Y_{U,D,E}$ as a spurion with non-trivial transformation properties under G_F :

under $G_F = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{L_L} \times SU(3)_{e_R}$

$$Y_U \sim (3,\bar{3},1,1,1),\ Y_D \sim (3,1,\bar{3},1,1),\ Y_E \sim (1,1,1,3,\bar{3})$$

$$Q_L \sim (3,1,1,1,1), u_R \sim (1,3,1,1,1), d_R \sim (1,1,3,1,1),$$
$$L_L \sim (1,1,1,3,1),\ e_R \sim (1,1,1,1,3)$$

Minimal Flavor Violation (MFV)

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$\bar{3}_{Q_L}$ $\quad 3_{Q_L} \times \bar{3}_{d_R}$ $\quad 3_{d_R}$

$\longrightarrow$ G_F invariant

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Minimal Flavor Violation (MFV)

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$\bar{3}_{Q_L}$ $\quad 3_{Q_L} \times \bar{3}_{d_R}$ $\quad 3_{d_R}$

$\rightarrow$ G_F invariant

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$$Y_U \sim (3,\bar{3},1,1,1),\ Y_D \sim (3,1,\bar{3},1,1),\ Y_E \sim (1,1,1,3,\bar{3})$$

$$Q_L \sim (3,1,1,1,1), u_R \sim (1,3,1,1,1), d_R \sim (1,1,3,1,1),$$
$$L_L \sim (1,1,1,3,1),\ e_R \sim (1,1,1,1,3)$$

We then define that an effective theory satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and $Y_{U,D,E}$ (spurion) fields

$$\mathscr{L}_{NPinMFV} = \sum_i \frac{C_i}{\Lambda^2} \mathscr{O}_i^{d=6}(\text{SM fields} + Y_{U,D,E})$$

Minimal Flavor Violation (MFV)

- By introducing $Y_{U,D,E}$ fields, we can write higher-dimensional operators in G_F invariant way

$$G_F = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$$

$$Y_U \sim (3,\bar{3},1)$$

$$(\bar{Q}_L^i \qquad \gamma_\mu Q_L^j)$$

Minimal Flavor Violation (MFV)

- By introducing $Y_{U,D,E}$ fields, we can write higher-dimensional operators in G_F invariant way

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e.g.) $b_i \to b_j$ FCNC transition

int basis $(\bar{b}_L^i Y_U Y_U^\dagger \gamma_\mu b_L^j)$

$$Y_D = \lambda_d \qquad Y_U = V_{CKM}^\dagger \lambda_u \qquad Y_E = \lambda_e$$

where

$$\lambda_d = \mathrm{diag}(m_d, m_s, m_b)/v$$
$$\lambda_u = \mathrm{diag}(m_u, m_c, m_t)/v \sim \mathrm{diag}(0,0,1)$$
$$\lambda_e = \mathrm{diag}(m_e, m_\mu, m_\tau)/v$$

$$\boxed{(Y_U Y_U^\dagger)^{ij} = (V^\dagger \lambda_u^2 V)^{ij} \simeq \lambda_t^2 V_{ti}^* V_{tj}}$$

mass basis $\lambda_t^2 V_{ti}^* V_{tj} (\bar{b}_L^i \gamma_\mu b_L^j)$ $\propto \left(\frac{m_t}{v}\right)^2$ largest effect

Minimal Flavor Violation (MFV)

$$A(d_i \to d_j) = A_{SM} + A_{NP}$$

$$\frac{C_{SM}}{16\pi^2 v^2}\lambda_t^2 V_{ti}^* V_{tj} \qquad \frac{C_{NP}}{\Lambda^2}\lambda_t^2 V_{ti}^* V_{tj}$$

$$\propto (\text{ CKM factor }) \left[\frac{C_{SM}}{16\pi^2 v^2} + \frac{C_{NP}}{\Lambda^2}\right]$$

In MFV, flavor violation is completely determined by Yukawa couplings and all CP violation originates from the CKM phase

Different flavor transitions are correlated, differences are only CKM

$$A(b \to s) = (V_{tb} V_{ts}^*) \left[\frac{C_{SM}}{16\pi^2 v^2} + \frac{C_{NP}}{\Lambda^2}\right]$$

$$A(s \to d) = (V_{ts} V_{td}^*) \left[\qquad \text{〃} \qquad \right]$$

exactly same structure

very predictive

From MFV to $U(2)^5$

$U(3)^5 = U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{L_L} \times U(3)_{e_R}$ flavor symmetry

- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of $U(3)^5$ by SM Yukawa couplings

MFV virtue

Naturally small effects in FCNC observables assuming TeV-scale NP

MFV main problem

No explanation for Yukawa hierarchies (masses and mixing angles)

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$U(2)^5$ flavor symmetry

Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

- $U(2)^5$ symmetry gives "natural" explanation of why 3rd Yukawa couplings are large

  acting on 1st & 2nd generations only

  3rd Yukawa coupling is allowed by the symmetry

  $$\psi = (\underbrace{\psi_1, \psi_2}_{\text{U(2) doublet}}, \underbrace{\psi_3}_{\text{singlet}})$$

- The symmetry is good approximation in the SM Yukawa

  exact symmetry for $m_u, m_d, m_c, m_s = 0$ & $V_{CKM} = 1$

  $\Rightarrow$ we only need small breaking terms

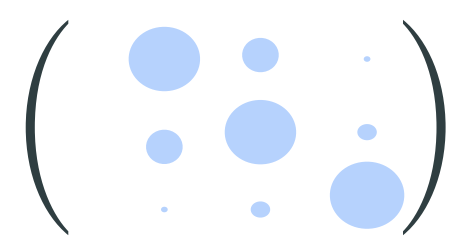
The SM flavor puzzle

Striking hierarchy

Mass : 3rd > 2nd > 1st

$M_{u,d} \sim$ 

Almost diagonal CKM matrix

$V_{CKM} \sim$ 

$U(2)^5$ flavor symmetry

Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

Under $U(2)^3 = U(2)^q \times U(2)^u \times U(2)^d$ symmetry

quark

$$
\begin{aligned}
Q^{(2)} &= (Q^1, Q^2) \sim (2,1,1) & Q^3 &\sim (1,1,1) \\
u^{(2)} &= (u^1, u^2) \sim (1,2,1) & t &\sim (1,1,1) \\
d^{(2)} &= (d^1, d^2) \sim (1,1,2) & b &\sim (1,1,1)
\end{aligned}
$$

Spurion

(U(2) breaking term)

$$V_q \sim (2,1,1),\ \Delta_u \sim (2,\bar{2},1),\ \Delta_d \sim (2,1,\bar{2})$$

Unbroken symmetry

$$Y_u = y_t \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}^{U(2)_q}_{U(2)_u}$$

After breaking

$$\left(\begin{array}{cc|c} \multicolumn{2}{c|}{\Delta_u} & V_q \\ \hline 0 & 0 & 1 \end{array}\right)$$

U(2) breaking (Spurion)

$$|V_q| \sim |V_{ts}| \sim \mathcal{O}(10^{-1})$$

$$|\Delta_u| \sim y_c \sim \mathcal{O}(10^{-2})$$

$U(2)$ flavor symmetry provides natural link to the Yukawa couplings

$U(2)^5$ flavor symmetry

Yukawa after removing unphysical parameters

$$Y_u = |y_t| \begin{pmatrix} U_q^\dagger O_u^\intercal \hat{\Delta}_u & |V_q|\,|x_t|\, e^{i\phi_q}\, \vec{n} \\ 0 & 1 \end{pmatrix}$$

$$Y_d = |y_b| \begin{pmatrix} U_q^\dagger \hat{\Delta}_d & |V_q|\,|x_b|\, e^{i\phi_q}\, \vec{n} \\ 0 & 1 \end{pmatrix}$$

$\hat{\Delta}_{u,d,e}$: 2×2 diagonal positive matrix

$O_{u,e}$: 2×2 orthogonal matrix

$$U_q = \begin{pmatrix} c_d & s_d\, e^{i\alpha_d} \\ -s_d\, e^{-i\alpha_d} & c_d \end{pmatrix}, \quad \vec{n} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Structure of Yukawa is fixed under $U(2)$ symmetry

→ elements in diagonal matrixes are described by CKM elements & fermions masses

$$Y_f \xrightarrow{\;Q_L \to L_d^\dagger Q_L \quad d_R \to R_d{}^\dagger d_R\;} \mathrm{diag}(Y_f) = L_f^\dagger Y_f R_f \quad (f = u, d)$$

where

$$L_d \approx \begin{pmatrix} c_d & -s_d\, e^{i\alpha_d} & 0 \\ s_d\, e^{-i\alpha_d} & c_d & s_b \\ -s_d\, s_b\, e^{-i(\alpha_d+\phi_q)} & -c_d\, s_b\, e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix} \qquad R_d \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \frac{m_s}{m_b}\, s_b \\ 0 & -\frac{m_s}{m_b}\, s_b\, e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix}$$

constrained

$s_d/c_d = |V_{td}/V_{ts}|$, $\alpha_d = -\,\mathrm{Arg}(V_{td}/V_{ts})$, $s_t = s_b - V_{cb}$, s_u $\quad s_b/c_b = |x_b|\,|V_q|$, ϕ_q

$U(2)^5$ flavor symmetry

U(2) relations

- NP strength in $b \to c(s)$ = NP strength in $b \to u(d)$

$$\frac{b \to c\ell\nu}{b \to u\ell\nu} = \frac{b \to c\ell\nu}{b \to u\ell\nu}\bigg|_{\mathrm{SM}} \qquad \frac{b \to s\ell\ell}{b \to d\ell\ell} = \frac{b \to s\ell\ell}{b \to d\ell\ell}\bigg|_{\mathrm{SM}}$$

- process with right-handed light fermions suppressed by $\dfrac{m_s}{m_b}, \dfrac{m_\mu}{m_\tau}$

$$Y_f \xrightarrow{Q_L \to L_d^\dagger Q_L \quad d_R \to R_d^\dagger d_R} \mathrm{diag}(Y_f) = L_f^\dagger Y_f R_f \quad (f = u, d)$$

where

$$L_d \approx \begin{pmatrix} c_d & -s_d\, e^{i\alpha_d} & 0 \\ s_d\, e^{-i\alpha_d} & c_d & s_b \\ -s_d\, s_b\, e^{-i(\alpha_d+\phi_q)} & -c_d\, s_b\, e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix} \qquad R_d \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \frac{m_s}{m_b}\, s_b \\ 0 & -\frac{m_s}{m_b}\, s_b\, e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix}$$

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$s_d/c_d = |V_{td}/V_{ts}|$, $\alpha_d = -\,\mathrm{Arg}(V_{td}/V_{ts})$, $s_t = s_b - V_{cb}$, s_u $\quad s_b/c_b = |x_b||V_q|$, ϕ_q

From MFV to $U(2)^5$

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$$U(2)^5 = U(2)_{Q_L} \times U(2)_{u_R} \times U(2)_{d_R} \times U(2)_{L_L} \times U(2)_{e_R} \text{ flavor symmetry}$$

- acting on 1st & 2nd generations only
- The exact symmetry limit is good starting point for the SM quark spectrum ($m_u, m_d, m_c, m_s = 0$ & $V_{CKM} = 1$) $\Rightarrow$ we only need small breaking terms
- **B-anomalies are compatible with U(2) flavor symmetry** (→ more later)

Comments

These flavor symmetries are not necessarily fundamental symmetries of UV theory

This effective approach is useful way for systematic NP analysis

SMEFT with flavor symmetry

Classification SMEFT operators under U(3) and U(2)

A. Faroughy, Isidori, Wilsch, KY [2005.05366]

2499 in SMEFT $\xrightarrow{\text{flavor symmetry}}$ drastic reduction for number of independent parameters

Correlations between low-energy phenomena and high-pT

Froggatt-Nielsen in SMEFT

Bordone, Cata, Feldmann [1910.02641]

Outline

Introduction to flavor physics

Flavor symmetry

Lepton Flavor Universality & Future prospects

Summary

Lepton Flavor Universality test

Lepton Flavour Universality is a consequence of the accidental flavor symmetry of the SM Lagrangian in the limit neglecting Yukawa couplings :

$$\mathscr{L}_{SM} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}}$$

There lepton families are **identical** in gauge sector
→ $U(3)^5$ flavor symmetry

No reason to assume it holds beyond the SM

However, it has been extremely well satisfied in several systems:

$Z \to \ell\ell$ decays : $\sim 0.1\,\%$
$\tau \to \ell\nu\bar{\nu}$ decays : $\sim 0.1\,\%$
$K \to (\pi)\ell\nu$ decays : $\sim 0.1\,\%$
$\pi \to \ell\nu$ decays : $\sim 0.01\,\%$

What about Semileptonic processes involving 3rd gen. quarks ? → Next

B anomalies

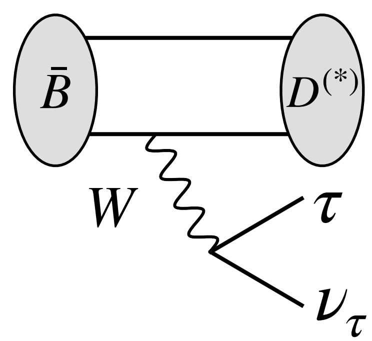
In the last few years, LHCb, Belle and BaBar reported some deviations from the SM in LFU of semileptonic B decays $b \to c\tau\bar{\nu}$ and $b \to s\mu\bar{\mu}$ ("**B anomalies**")

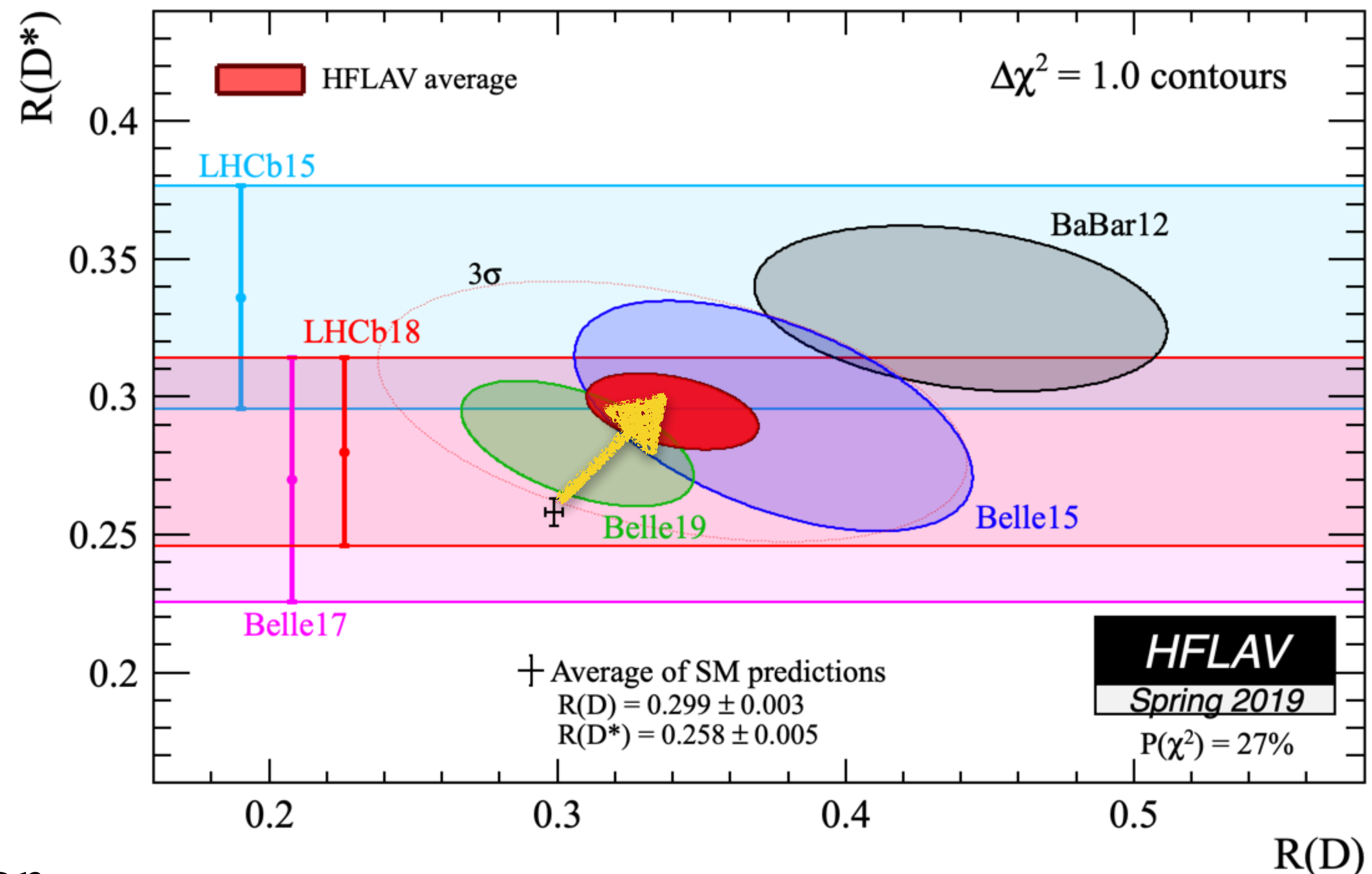
$$b \to c\tau\nu$$

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

Tree-level in SM

LFUV in τ vs μ/e





$$D^{(*)} \begin{cases} D : \text{pseudo scalar meson} \\ D^* : \text{vector meson} \end{cases}$$

$$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$$

Hadronic uncertainties cancel (to a large extent) in the ratio

R_D & R_{D^*} are consistent with universal enhancement of the SM like $b_L \to c_L\tau_L\bar{\nu}_L$ contribution

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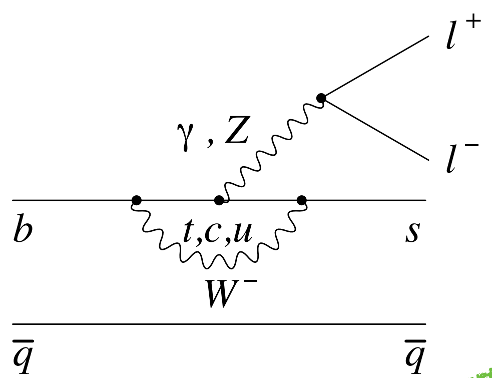
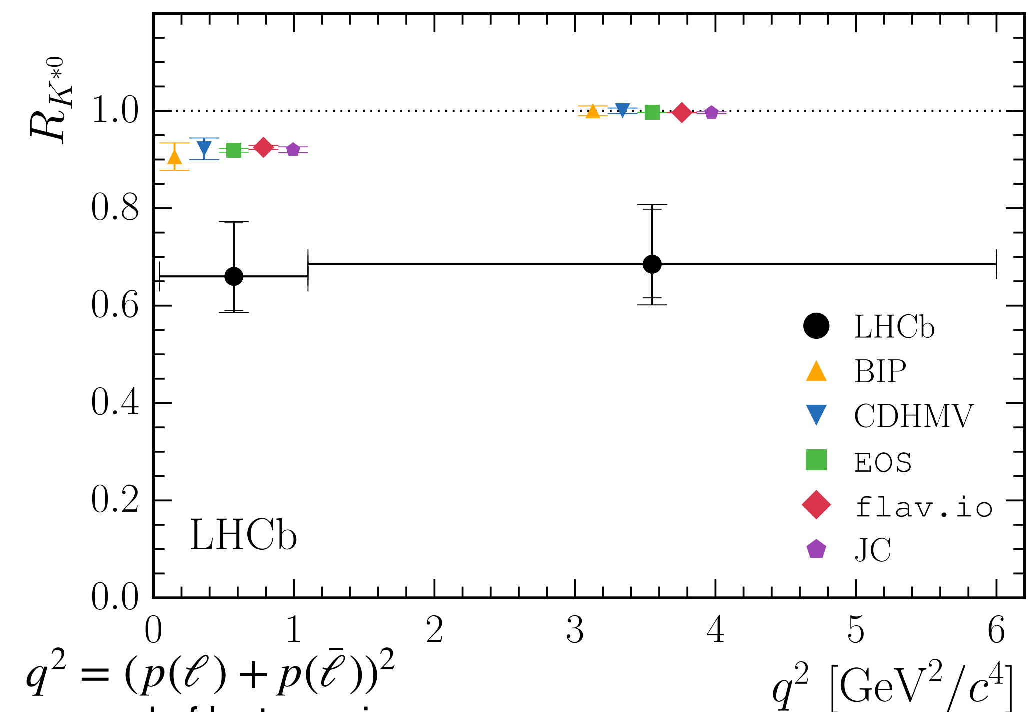
$$b \to s\ell\ell$$

$$R_{K^{(*)}} = \frac{\int d\Gamma(B \to K^{(*)}\mu\mu)}{\int d\Gamma(B \to K^{(*)}ee)}$$

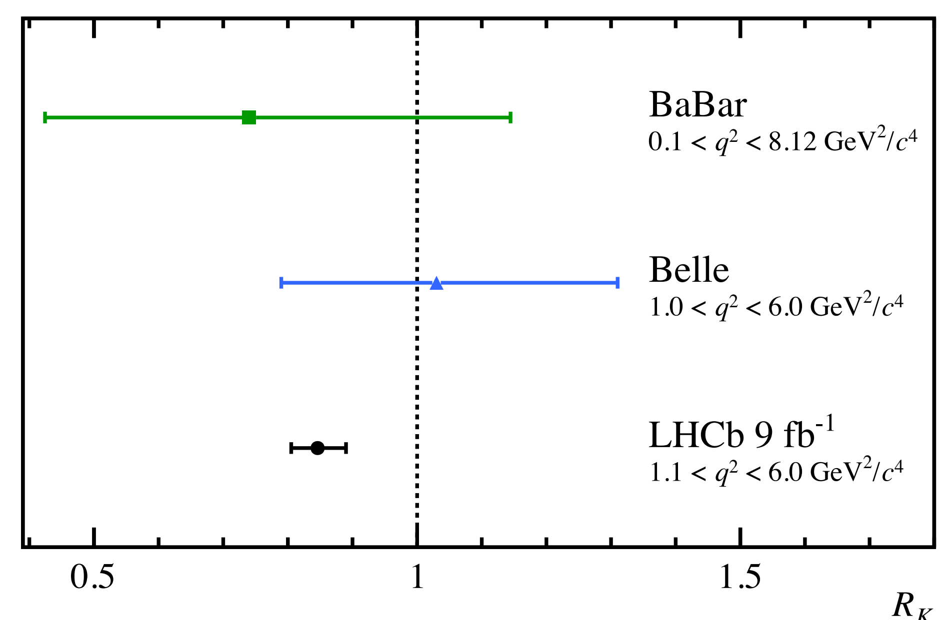
loop-level in SM

LFUV in μ vs e





q^2 : $q^2 = (p(\ell) + p(\bar{\ell}))^2$
mass squared of lepton pair



2012

2021

2021

In the SM $\qquad R_{K^{(*)}} \simeq 1$

R_K & R_{K*} data show discrepancy from the SM in same direction → Left-handed NP

$b_L \to s_L\mu_L\bar{\mu}_L$

$$R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}}$$

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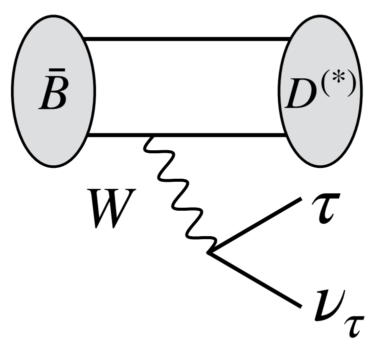
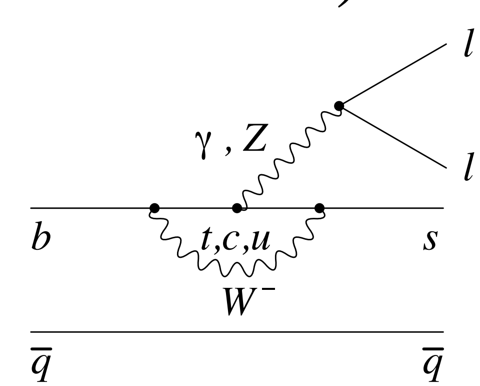


$$b \to s\ell\ell$$

$$R_{K^{(*)}} = \frac{\int d\Gamma(B \to K^{(*)}\mu\mu)}{\int d\Gamma(B \to K^{(*)}ee)}$$

loop-level in SM

LFUV in μ vs e



$$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$$

~15% of SM **tree-level** effect

$$R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}}$$

~20% of SM **loop** effect

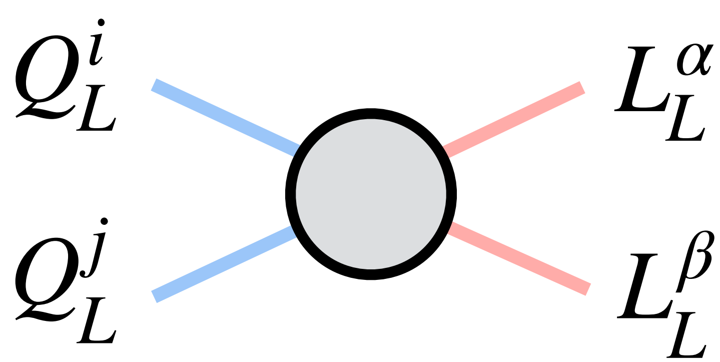
NP in $b \to c\tau\nu_\tau$ (**33**) $\gg$ NP in $b \to s\mu\mu$ (**22**)

NP which strongly couples to **3rd** gen. is favored

B anomalies

Combined EFT solution

- Anomalies are seen in only **semi-leptonic** (quark × lepton) operators
- **left-handed** current current operators are favored
- **Hierarchical NP** is needed



$$\frac{C_{ij\alpha\beta}}{\Lambda^2}(\bar{Q}_L^i \Gamma Q_L^j)(\bar{L}_L^\alpha \Gamma L_L^\beta)$$

3rd

2nd (&1st)

$C_{ij\alpha\beta} = \delta_{i3}\delta_{j3}\delta_{i3}\delta_{j3}$ + [small terms for 2nd (& 1st) generations]

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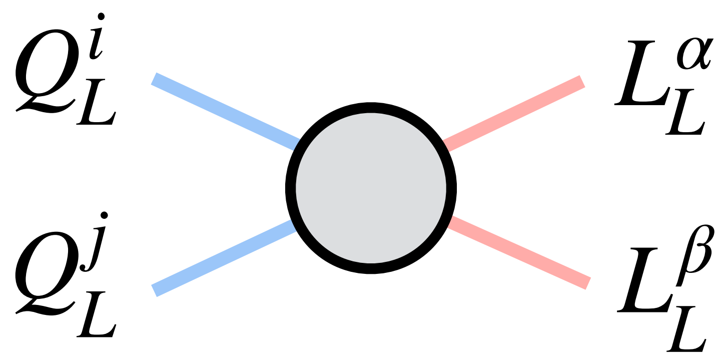


$$\frac{C_{ij\alpha\beta}}{\Lambda^2}(\bar{Q}_L^i \Gamma Q_L^j)(\bar{L}_L^\alpha \Gamma L_L^\beta)$$

3rd **2nd (& 1st)**

$C_{ij\alpha\beta} = \delta_{i3}\delta_{j3}\delta_{i3}\delta_{j3}$ + [small terms for 2nd (& 1st) generations]

Similar hierarchy in Yukawa couplings!

Nicely match with U(2) flavor symmetry

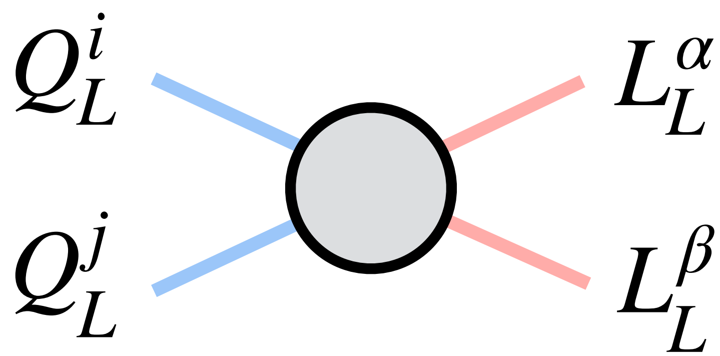
Yukawa (SM flavor hierarchies) $\xleftrightarrow{U(2)^5}$ B-anomaly hint NP coupled dominantly to 3rd generation

B anomalies in U(2) EFT

Flavor structure is controlled by minimally broken $U(2)_Q \times U(2)_\ell$

Relevant spurions : $V_q \sim (2,1)$, $V_\ell \sim (1,2)$

Realize hierarchical NP favored by B anomalies :



$$\frac{C_{ij\alpha\beta}}{\Lambda^2}(\bar{Q}_L^i \Gamma Q_L^j)(\bar{L}_L^\alpha \Gamma L_L^\beta)$$

3rd **2nd (&1st)**

$$C_{ij\alpha\beta} = \delta_{i3}\delta_{j3}\delta_{i3}\delta_{j3} + \underline{\text{[small terms for 2nd (\& 1st) generations]}}$$

$\hookrightarrow \delta_{i3} V_q \delta_{i3}\delta_{j3} + \delta_{i3} V_q V_\ell V_\ell + \ldots$

b→cτν b→sμμ

$\mathcal{O}(V) \gg \mathcal{O}(V^3)$ $V \sim \mathcal{O}(10^{-1})$

Yukawa (SM flavor hierarchies) $\overset{U(2)^5}{\longleftrightarrow}$ B-anomaly hint NP coupled dominantly to 3rd generation

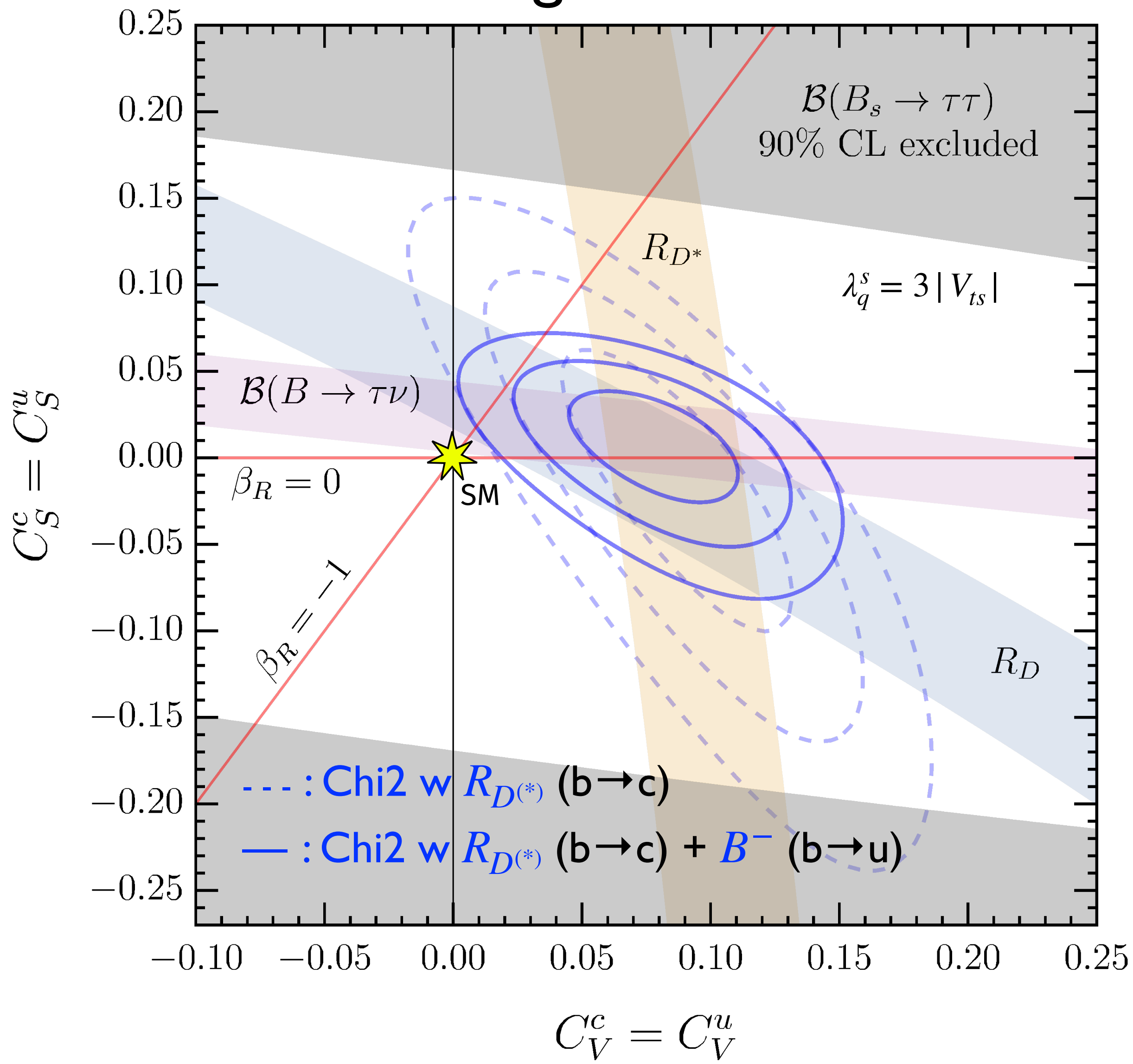
B anomalies in U(2) EFT

Fuentes-Martin, Isidori, Pages, KY [1909.02519]

$$\mathscr{L}_{\rm EFT} \supset \mathscr{L}_{\rm SM} - \frac{1}{v^2}\Big[C_V \Lambda_V^{[ij\alpha\beta]}\left(\mathcal{O}^{(1)}_{\ell q}+\mathcal{O}^{(3)}_{\ell q}\right) + \left(2\, C_S \Lambda_S^{[ij\alpha\beta]}\, \mathcal{O}_{\ell edq} + \mathrm{h.c.}\right)\Big]$$

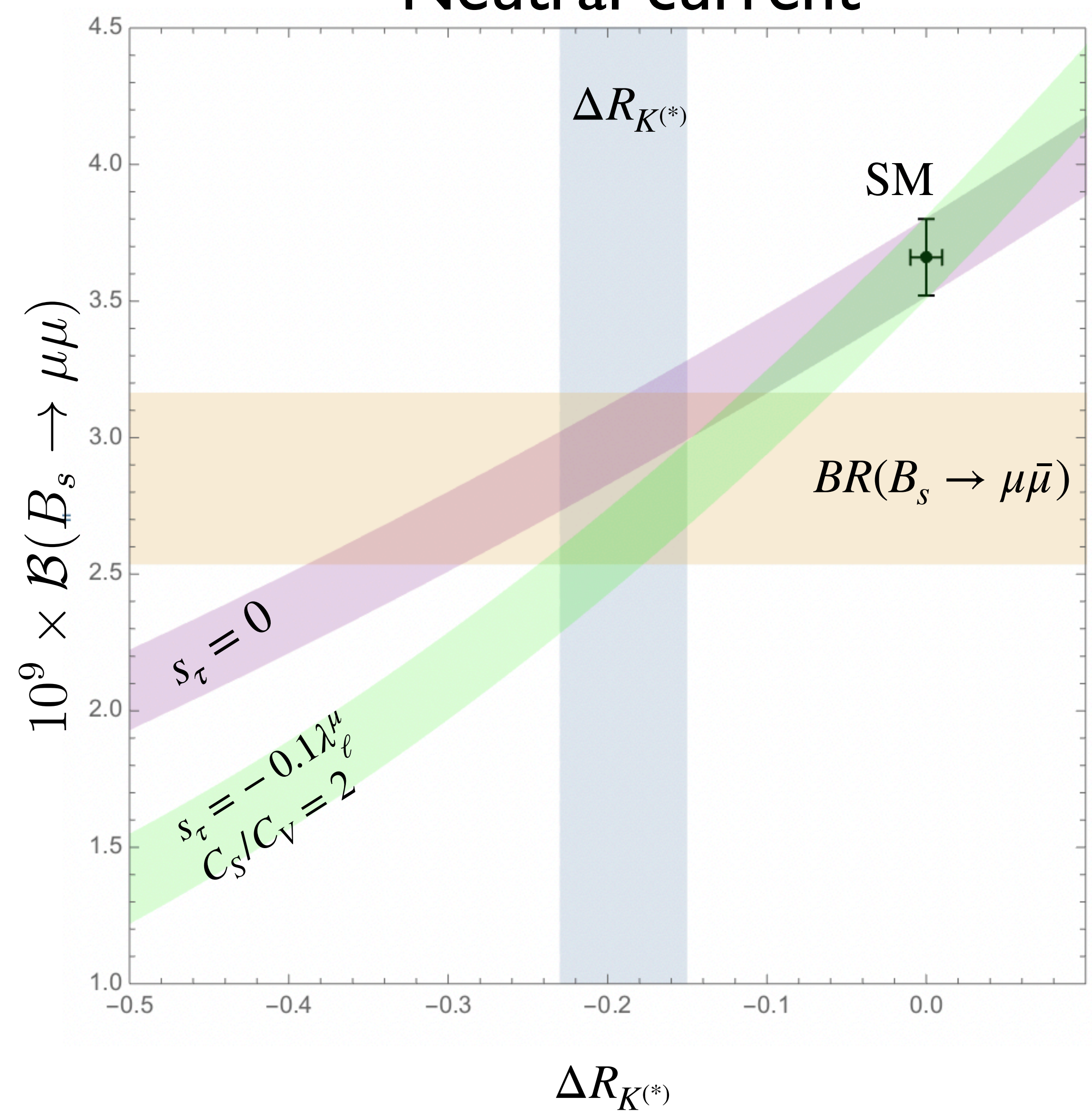
C_V, C_S : NP strength, Λ_V, Λ_S : Flavor structure

Charged-current



U(2) Predictions : b→c($C^c_{V(S)}$)= b→u($C^u_{V(S)}$)

Neutral-current



Two bench mark point

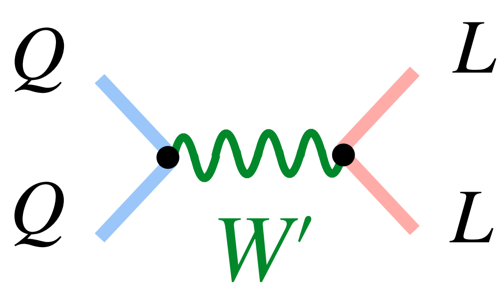
Current data is consistent with U(2) prediction

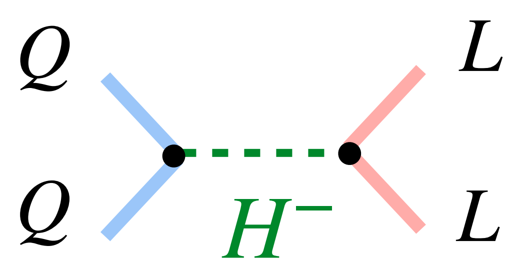
From EFT to simplified model and UV

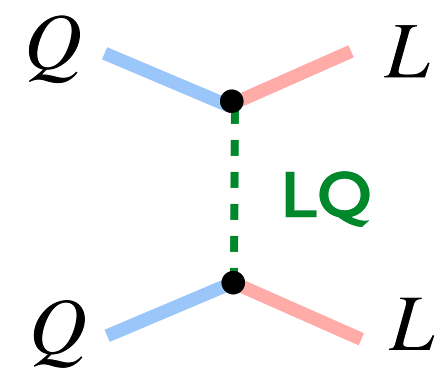
What is the scale of NP? Di Luzio, Nardecchia [1706.01868]

$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}} \rightarrow \Lambda_{NP} \lesssim 9$ TeV $R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}} \rightarrow \Lambda_{NP} \lesssim 84$ TeV

Which mediator?







Challenges for NP : $\Delta F = 2$ & $\tau \to \ell \nu \bar{\nu}$ constraints / Direct search

Status :

☹ W' : tension with high-pT di-tau constraints Faroughy et al.2016

H^- : tension with τ_{B_c} constraints Alonso et al. 2016

☺ **LQ** : Leptoquark (LQ) is the best solution for B anomaly so far

U_1 vector LQ S_1 & S_3 , R_2 & S_3 scalar LQ

UV completion needed → Pati-Salam unification Di Luzio, Greljo, Nardecchia, '17, Bordone, Cornella, Fuentes-Mart ́ın,Isidori,'17 etc.

Nicely match with U(2)

Implications for future measurements

If B anomalies is due to NP, it is expected that NP effects appear in several other low-energy observables

LHCb, Belle II, CLFV, Kaon

Implications for future measurements

Charged-current

Universality in other b→c transitions

Left-handed NP → universality of all **R$_{\tau/\mu}$(b→c)** ratios

$$\frac{R_D}{R_D^{\rm SM}} = \frac{R_{D^*}}{R_{D^*}^{\rm SM}} = \frac{\Gamma(B_c \to J/\psi \tau\nu)}{\Gamma(B_c \to J/\psi \mu\nu)} \Big/ {\rm SM} = \frac{\Gamma(\Lambda_b \to \Lambda_c \tau\nu)}{\Gamma(\Lambda_b \to \Lambda_c \mu\nu)} \Big/ {\rm SM}$$ → LHCb

Polarizations → NP model discrimination

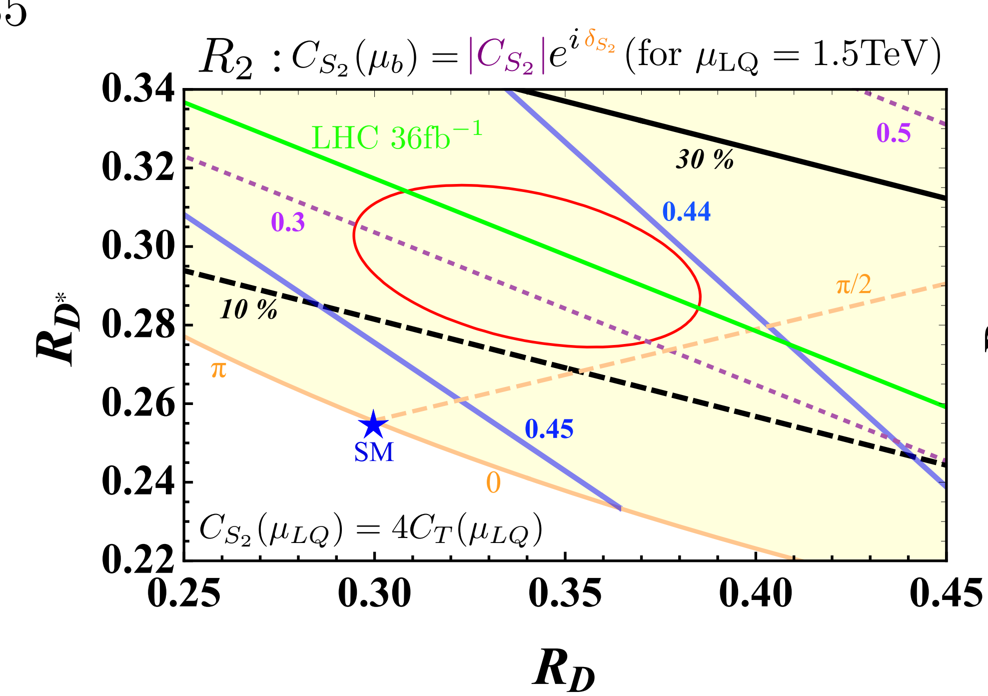
$F_L^{D^*}$: Longitudinal D^* polarization , $P_\tau^{D^{(*)}}$: τ polarisation asymmetries

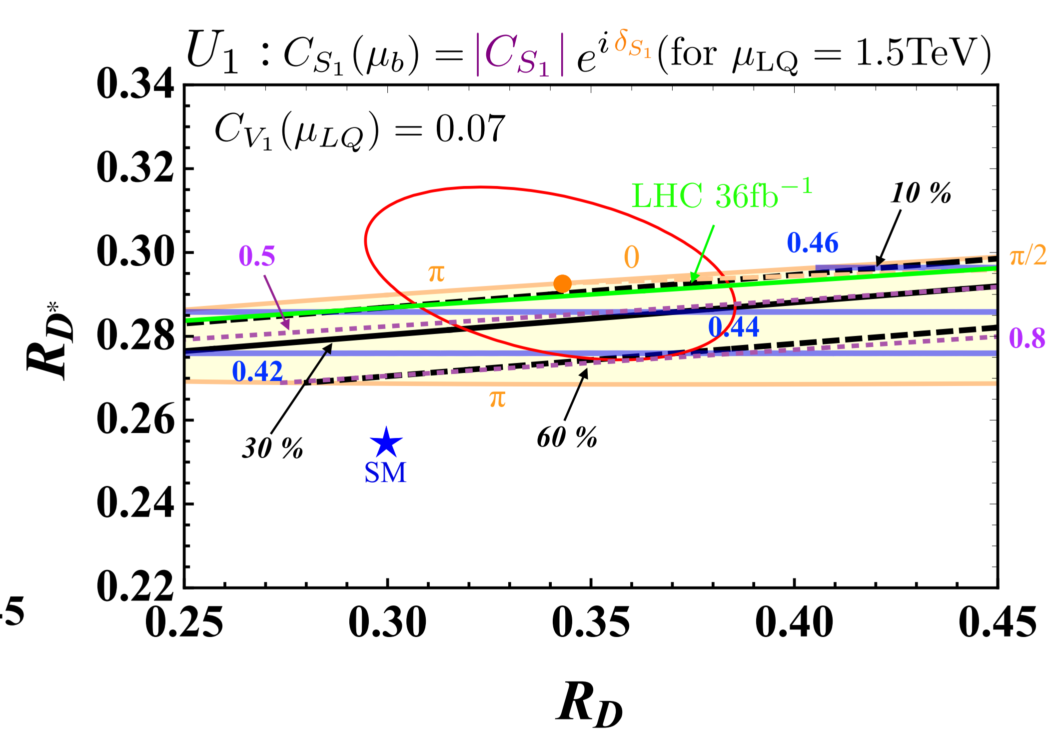
Iguro, Kitahara, Omura Watanabe and KY [1811.08899]

Belle : $0.60 \pm 0.08 \pm 0.035$
SM : 0.46 ± 0.04

— : $F_L^{D^*}$
— : $\mathscr{B}(B_c \to \tau\nu)$
— : collider bound

→ Belle II





Implications for future measurements

Neutral-current

Fuentes-Martin, Isidori, Pages, KY [1909.02519]

Universality in other b→s transitions

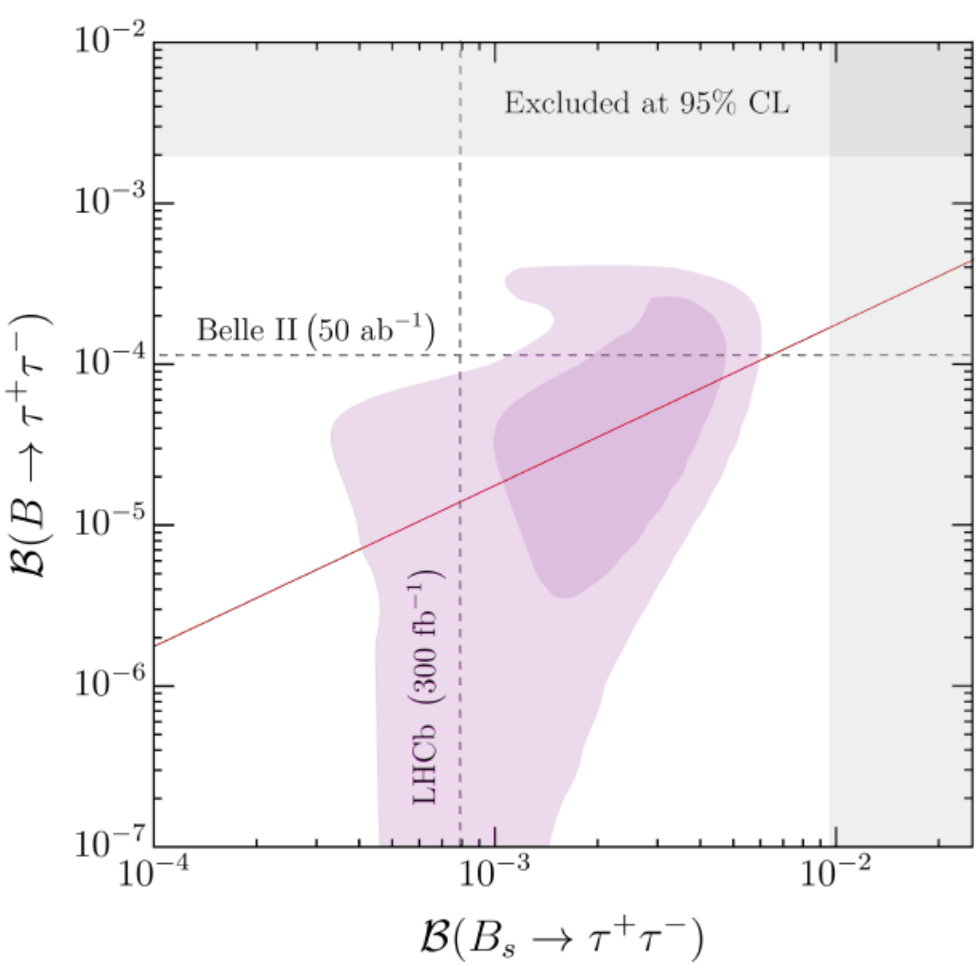
Left-handed NP → universality of all $\mathbf{R}_{\mu/e}(\mathbf{b \to s})$ ratios

$$R(Y_b)_{X_s} = \frac{\Gamma(Y_b \to X_s \mu \bar{\mu})}{\Gamma(Y_b \to X_s e \bar{e})}$$

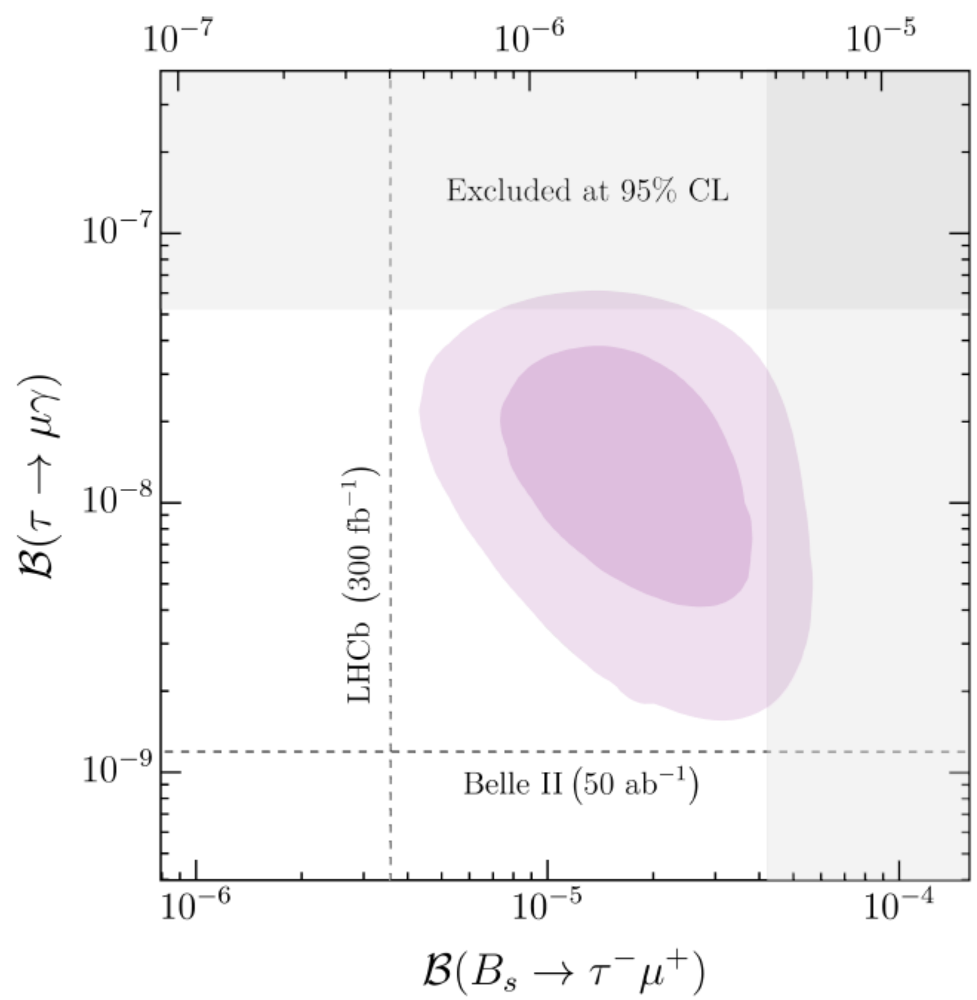
$$R_\phi(B_s) \approx R_{\pi K}(B) \approx R(\Lambda_b)_\Lambda \approx R(\Lambda_b)_{pK} \approx \ldots \approx R_K$$

→ LHCb

The $b \to s\tau\tau$ process



LFV in B & τ decay



PS³ model

Cornella, A. Faroughy, Fuentes-Martín, Isidori and Neubert [2103.16558]

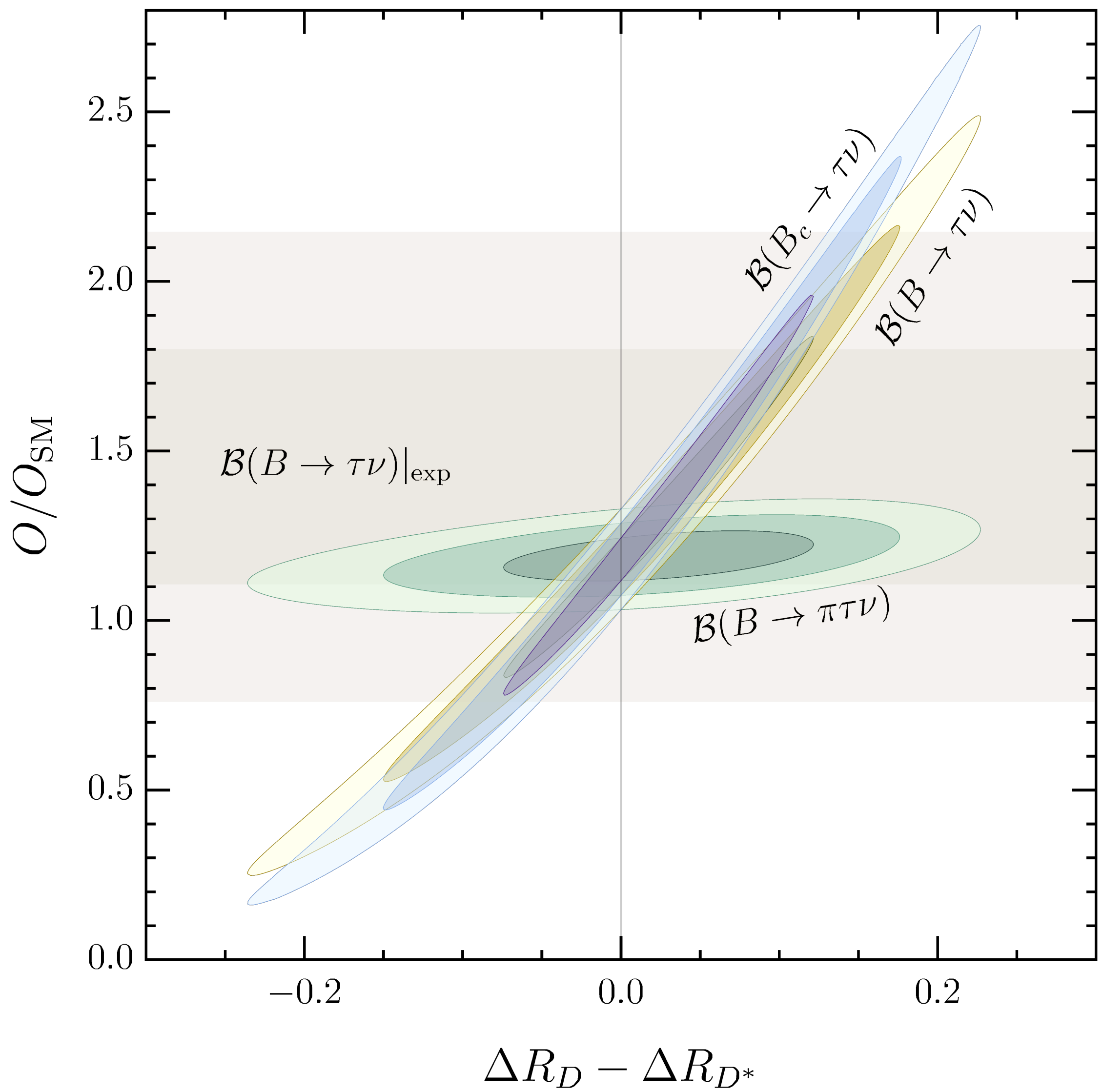
→ LHCb, Belle II

Implications for future measurements

Charged-current

Fuentes-Martin, Isidori, Pages, KY [1909.02519]

In U(2) model, **NP(b→c)= NP(b→u)**



$\propto C_S^c$

U(2) Predictions: b→c= b→u

$$\frac{\mathscr{B}(\bar B_u \to \tau\bar\nu)}{\mathscr{B}(\bar B_u \to \tau\bar\nu)_{\rm SM}} \approx \frac{\mathscr{B}(\bar B_c \to \tau\bar\nu)}{\mathscr{B}(\bar B_c \to \tau\bar\nu)_{\rm SM}}$$

$$\frac{R_\pi}{R_\pi^{\rm SM}} \approx 0.75\,\frac{R_D}{R_D^{\rm SM}} + 0.25\,\frac{R_{D^*}}{R_{D^*}^{\rm SM}}$$

— : Chi2 w $R_{D^{(*)}}, B^+$

$$R_\pi = \frac{B \to \pi\tau\nu_\tau}{B \to \pi\ell\nu_\ell}$$

$R_\pi/R_\pi^{\rm SM} \lesssim 1.3$

$R_\pi^{\rm SM} = 0.641 \pm 0.016$ F. U. Bernlochner [1509.06938] D. Du et al [1510.02349]

$R_\pi^{\rm exp} \simeq 1.05 \pm 0.51$

→ Belle II

Implications for future measurements

Neutral-current

Fuentes-Martin, Isidori, Pages, KY [1909.02519]

In U(2) model, **NP(b→s)= NP(b→d)**

U(2) Predictions : b→d=b→s

$$R_K \approx R_{K^*} \approx \frac{\mathscr{B}(B \to \pi\mu\bar{\mu})_{[\Delta q^2_{\rm pert}]}}{\mathscr{B}(B \to \pi e\bar{e})_{[\Delta q^2_{\rm pert}]}}$$

$$\frac{\mathscr{B}(B_s \to \mu\mu)}{\mathscr{B}(B_s \to \mu\mu)_{\rm SM}} \approx \frac{\mathscr{B}(B_d \to \mu\mu)}{\mathscr{B}(B_d \to \mu\mu)_{\rm SM}}$$

deviation ~ 2σ

$$\mathscr{B}(B \to \pi\mu\bar{\mu})_{[1,6]} = 0.91(21) \times 10^{-9}$$

$$\mathscr{B}(B \to \pi\mu\bar{\mu})^{\rm SM}_{[15,22]} = 0.72(7) \times 10^{-9} \quad \longleftrightarrow \quad \mathscr{B}(B \to \pi\mu\bar{\mu})_{[15,22]} = 0.46(11) \times 10^{-9}$$

well consistent with U(2)

→ LHCb

$$\mathscr{B}(B_d \to \mu\bar{\mu})_{\rm SM} = 1.06(9) \times 10^{-10} \qquad \mathscr{B}(B_d \to \mu\bar{\mu})_{\rm exp} = 1.6(1.1) \times 10^{-10}$$

Implications for future measurements

What about the effect on Kaon observables?

Natural link between B anomalies and $K \to \pi\nu\bar{\nu}$ is expected, thanks to the presence of 3rd generation leptons in the final state

$$BR(K \to \pi\nu\bar{\nu}) = BR(K \to \pi\nu_e\bar{\nu}_e) + BR(K \to \pi\nu_\mu\bar{\nu}_\mu) + BR(K \to \pi\nu_\tau\bar{\nu}_\tau)$$

SM like

few % deviation as $b \to s\mu\mu$ 22 $\ll$ Possible large deviation as $b \to c\tau\nu_\tau$ 33

Implications for future measurements

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$K \to \pi\nu\bar{\nu}$ is extremely rare and precise process in the SM → Golden modes

- Very rare decays **BR~10^{-11}** (Loop, GIM and CKM)
- Theoretically clean (Absence of virtual photon contribution, Hadronic matrix elements obtained from $BR(K_{\ell 3})$ with isospin symmetry)

On-going experiments

BR(K$_L$) KOTO @J-PARC

$< 3 \times 10^{-9} (90\,\%\,CL)$ (KOTO '15)

BR(K$^+$) NA62 @CERN

$(10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11} (68\,\%\,CL)$ (NA62 '16-18)

Implications for future measurements

What about the effect on Kaon observables?

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e.g.) EFT approach with flavor symmetry

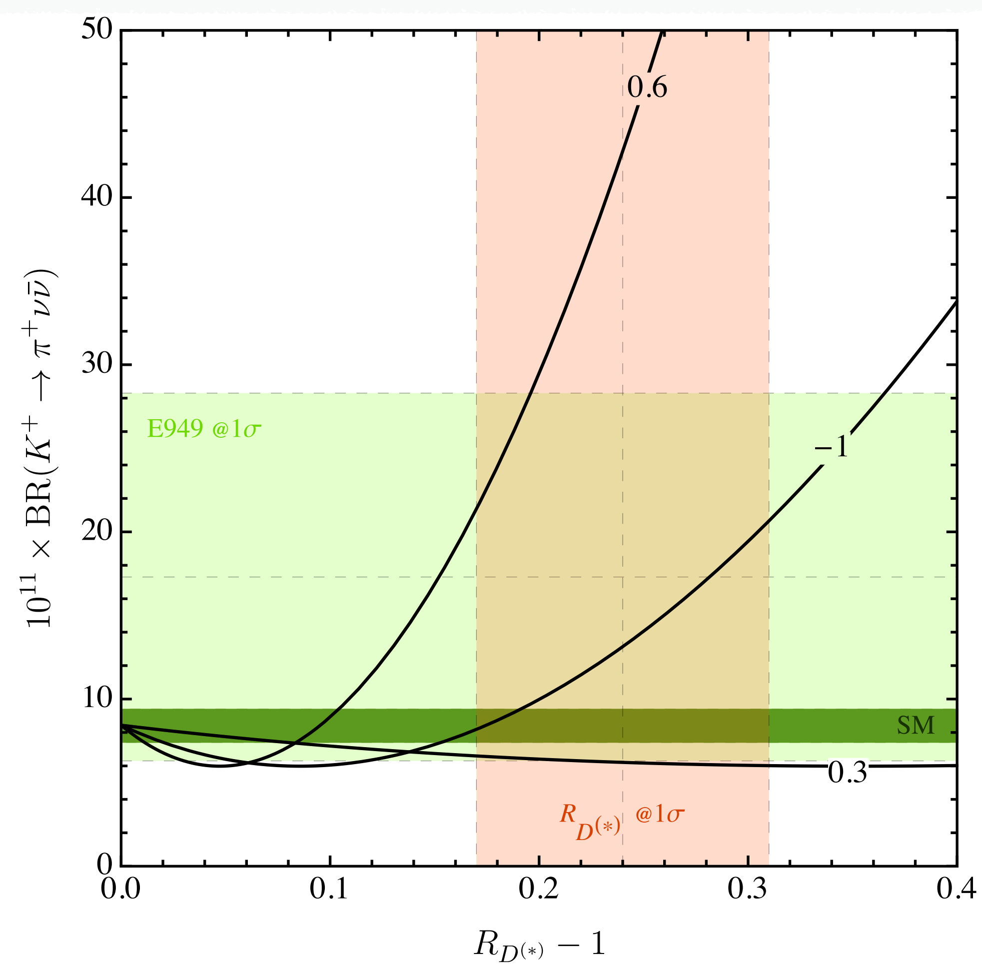
$U(2)$ flavor symmetry

B meson ⟷ Kaon

Correlation

There is strong constraint from $BR(B \to K^{(*)}\nu\bar{\nu})$, but does not exclude O(1) enhancements for $K^+ \to \pi^+\nu\bar{\nu}$

[Bordone, Buttazzo, Isidori, Monnard 1705.10729]



Outline

Introduction to flavor physics

Flavor symmetry

Lepton Flavor Universality & Future prospects

Summary

Summary

Flavor physics remains a mystery (**Two SM & NP flavor puzzles**)

We learned that NP has a highly non-trivial flavor structure → **Flavor symmetry?**

The statistical significance of the **LFU B anomalies** is growing
If it is combined, it points to non-trivial flavor dynamics around the TeV scale, involving mainly the **3rd** family → connection to the origin of flavor (**U(2)**)

A lot of fun ahead of us!
both on exp. & pheno.