ANOMALIES (b – FLAVOUR)

TWO SETS OF ANOMALIES

b quark decays, potentially related?

$b \to c \ell \nu$ | $b \to s \ell \ell$

Tree process (charged)

Loop process (neutral)

Different hadronic processes

$$\left(\begin{array}{l} B_{(s)} \to D_{(s)} \ell \nu \\ B_{(s)} \to D^*_{(s)} \ell \nu \\ \Lambda_b \to \Lambda_c \ell \nu \end{array} \right.$$

$B \to K \ell\ell$, $(B_s \to f_0 \ell\ell)$

$B \to K^* \ell\ell$, $B_s \to \phi \ell\ell$

$\Lambda_b \to \Lambda \ell\ell$

$R_D (B \to D^{(*)} \tau \nu)$, $R_K (B \to K^{(*)} \mu\mu)$

Deviations Probes of LFU

Lepton Flavour Universality

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

$l = e, \mu$

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

+

Other observables

Br $b \to s \mu\mu$ processes

Angular Observables

$b \to s \mu\mu$ processes

$(B \to K^{*} \mu\mu)$

$b \to c l \nu$

- $B \to D^{*} \tau \nu$ from the angular analysis

longitudinal polarisation D^{*}

$[\to D\pi]$

polarisation τ

$[\to \rho\nu, \pi\nu]$

compatible with SM (angular observables)

- $B_c \to J/\psi \, l\nu$ $\quad R_{J/\psi} = \frac{Br(B_c \to J/\psi \, \tau\nu)}{Br(B_c \to J/\psi \, l\nu)}$

→ form factors are not so well known

→ central value is very low

(hard to accommodate with the current form factors)

→ Branching ratios measured are all larger than SM

⇝ How to interpret these deviations?

→ Effective Hamiltonian
add NP as additional operators
to $\mathcal{H}_{eff}$

→ Model-independent approach
* considering all dim-6 operators $\mathcal{H}_{eff}$
* determining the values of the Wilson coefficients from data
* build models that will exhibit the required deviations from the SM in the Wilson coefficients

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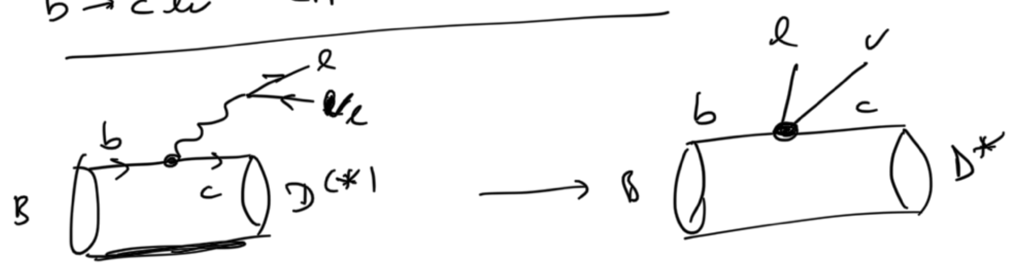
$b \to c\ell\nu$ EFF HAMILTONIAN



— $C^{(\ell)}$ $C^{(\ell)}$

$\mathcal{H}_{eff} \propto G_F V_{cb} \sum_i \mathcal{C}_i O_i$

* in the SM $\quad O_{VL}^{(l)} = (\bar{c}\gamma_\mu P_L b)(\bar{l}\gamma_\mu P_L \nu_l)$

$\mathcal{C}_{VL}^{(l)} = 1$ (same for all 3 leptons)

* in the presence of NP
  * modifications of the SD Wilson coefficients $\mathcal{C}_{VL}^{(l)}$ (potentially LFUV)
  * additional operators

→ chirally flipped operators

$$O_{VR} = (\bar{c}\gamma_\mu P_R b)(\bar{l}\gamma_\mu P_L \nu_l)$$

→ scalar or pseudoscalar operators

$$O_{SL} = (\bar{c} P_L b)(\bar{l} P_L \nu_l) \quad , O_{SR}$$

→ tensor operators

$$O_{TL} = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{l}\sigma_{\mu\nu} P_L \nu_l) , \; O_{TR}$$

→ compute all the observables as functions of decay amplitudes $A = \sum_i \mathcal{C}_i T_i$

T_i ↓ obtained from $\langle D^* | \bar{c}\Gamma b | B \rangle$

FORM FACTORS & <u>OBSERVABLES</u>

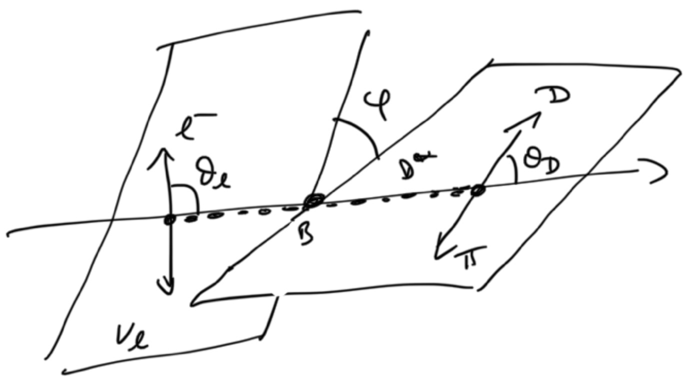
- More form factors than in the SM since you take into account all the operator structures
  - $B \to D l \nu$ $\quad f_+, f_0$ + tensor f_T
  - $B \to D^* l \nu$ $\quad V, A_1, A_2, A_3$ + tensor $T_{1,2,3}$

$\to$ form factors to compute from lattice QCD

$\oplus$ HQET $\oplus$ extrapolate in q^2 data assuming that NP is negligible in $[e\, \mu]$

ANGULAR ANALYSIS

$B \to D^* l \nu$
$\quad \hookrightarrow D\pi$ (strong interaction)



q^2 invariant mass of the lepton pair

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_e\, d\cos\theta_D\, d\varphi} = \,?$$

$$A = \langle D\pi\, l\nu \,|\, \mathcal{H}_{eff} \,|\, B\rangle$$

$$A_i = C_i \langle l\nu | \bar{e}\, \Gamma_i^L \nu | 0\rangle \langle D^* | \bar{c}\, \Gamma_i^H b | B\rangle$$
$$\times \text{ propagation of } D^* \langle D\pi | D^* \rangle$$

$$\frac{d^4\Gamma}{d\ldots} \propto \left|\sum A_i\right|^2 \to \text{interferences between the different}$$

amplitudes

- For instance, if I consider an axial/vector operator
$$\Gamma^L_{i\mu} \qquad \Gamma^H_{i\mu}$$

$\to B \to D^* V$ (virtual) polarizations $\varepsilon \leftrightarrow V$, $\eta \leftrightarrow D^*$

$D^* \to D\pi$, $V \to l\nu$

introduce complete set of polarization vectors
$$\omega^\mu(\lambda) \qquad \lambda = t, \pm, 0$$

completeness
$$g_{\mu\nu} = \sum_{\lambda\lambda' \in \{t,0,\pm\}} \omega_\mu(\lambda)\,\omega^*_\nu(\lambda')\, G_{\lambda\lambda'}$$

$$\begin{array}{c} G_{\lambda\lambda'} = \begin{bmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{bmatrix} \\ \quad\;\; t \quad\;\; 0 \quad\;\; + \quad\;\; - \end{array}$$

$$L_{i\mu} = \langle l\nu | \bar{l}\,\Gamma^L_{i\mu}\, \nu_l | 0 \rangle$$
$$= \sum_\lambda \varepsilon_\mu(\lambda)\, L_i^{(\lambda)}$$
$$L_i^{(\lambda)} \to \varepsilon^*_\nu(\lambda)\, G_{\lambda\lambda} \langle l\nu | \bar{l}\,\Gamma^\nu_{iL} \nu | 0 \rangle$$

$$H_{i\mu} = \sum_{\lambda'} \eta_\mu(\lambda')\, \underbrace{\eta^*_\nu(\lambda')\, G_{\lambda\lambda'} \langle D^* | \bar{c}\,\Gamma_i^{H\nu}\, b | B \rangle}_{H_i^{(\lambda)}}$$

$$\Big|\sum_i A_i\Big|^2 \propto \Big| \sum_{i\lambda\lambda'} c_i\, \underbrace{\varepsilon_\mu(\lambda)\, \eta^\mu(\lambda')}\, L_i^{(\lambda)}\, H_i^{(\lambda\lambda')} \Big|^2$$

[propagation D^α]

In the respectif

sum over pol. for leptonic & hadronic

$\varepsilon_\mu(\lambda)\,\eta^\mu(\lambda') \neq 0$

L U

allowed for V

D^* is real (only $0,+,-$)

$(t,0)$

$(+,+)$

$(-,-)$

$(0,0)$

$d^4\Gamma$ = Interference of amplitudes with definite polarisations of D^* & V

* each involves only very specific combination of form factors

* each involves specific combinations of Wilson coefficients

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_D\, d\cos\theta_\ell\, d\varphi} = \frac{9}{32\pi}\Big[I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + \left[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D\right] \times \cos 2\theta_\ell + \ldots + \left[I_5\cos\varphi + I_7\sin\varphi\right] \times \sin\theta_\ell \sin 2\theta_D$$

$\rightarrow$ 12 observables interference of helicity amplitudes

$H^{(\lambda)} = C_i \times F_i$

$\rightsquigarrow F_L [D^*]$, P_τ ...

in term of Wilson coefficients

EXTRACTING NP CONTRIB INTO C_i?

- Set of data $= f[C_i]$

  $\to$ fit to the data to extract C_i

- However for the moment, not so many data

  $$\underbrace{R_D, \; R_{D^*}}, \quad \underbrace{F_L(D^*), \; P_\tau}.$$

  Ex: $\dfrac{R_{D\,exp}}{R_{D\,SM}} = \dfrac{R_{D^*\,exp}}{R_{D^*\,SM}}$ Angular Obs SM?

- One simple solution: NP in $C_{V_L}^{(\tau)}$ [in other word $G_F^{(b \to c\tau\nu)} \neq G_F^{(b \to c\ell\nu)}$]

- What other operators?

  * tensor contributions disfavoured by $F_L(D^*)$

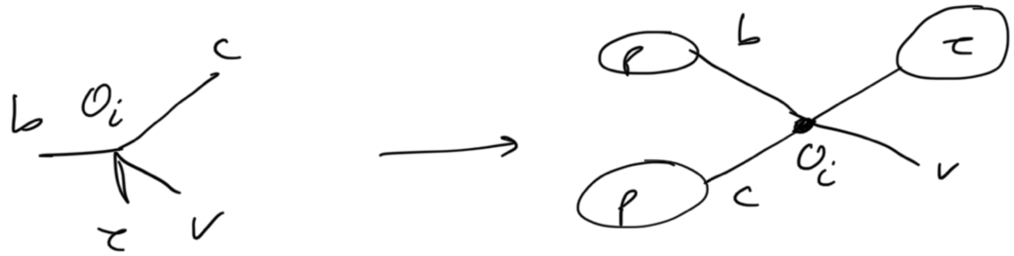
  * right handed vector and (pseudo) scalar

  ... $B_c (B_c \to \tau\nu)$

couplings lw bounds in (...)

[not measured but cannot exceed the total width of B_c measured]

* further contraints LHC



$pp \to \tau\nu X$

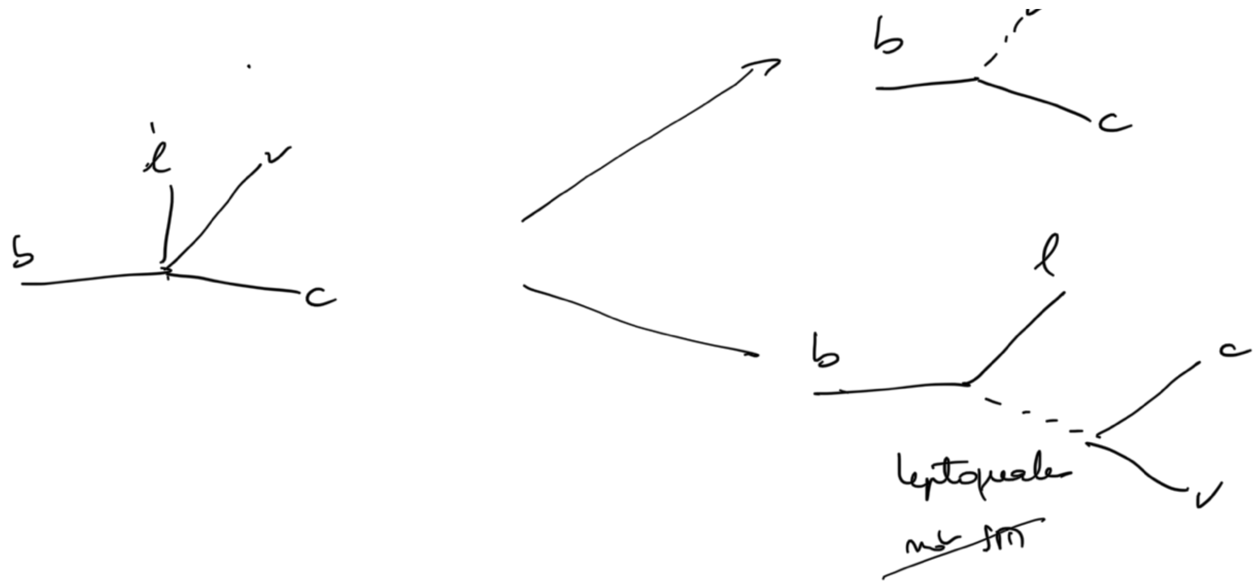
SINGLE MEDIATOR EXPLANATIONS

- Explain the shifts of the EFT with the presence of a single new dof of "intermediate" mass $\Lambda_{EW} < m_{new} < \Lambda_{NP}$

- Charged Higgs → scalar couplings ×

  Excited W' → Z' involved ×
  → affect neutral meson mixing

→ be careful that we need a shift of O(10%) compared to a SM tree-level process



leptoquarks decay into 1 q and 1 ℓ

→ 6 spin 0
possibilities
→ 6 spin 1

⇝ from these 12 possibilities, 2 are good explanations for $b \to c\tau\nu$

scalar LQ S_1 $(\bar{3}, 1)_{1/3}$

vector LQ U_1 $(3, 1)_{1/3}$

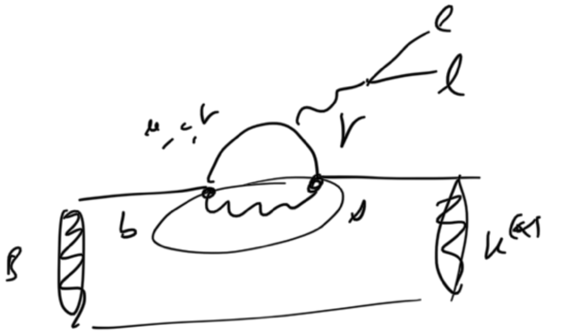
with a mass of a few TeV

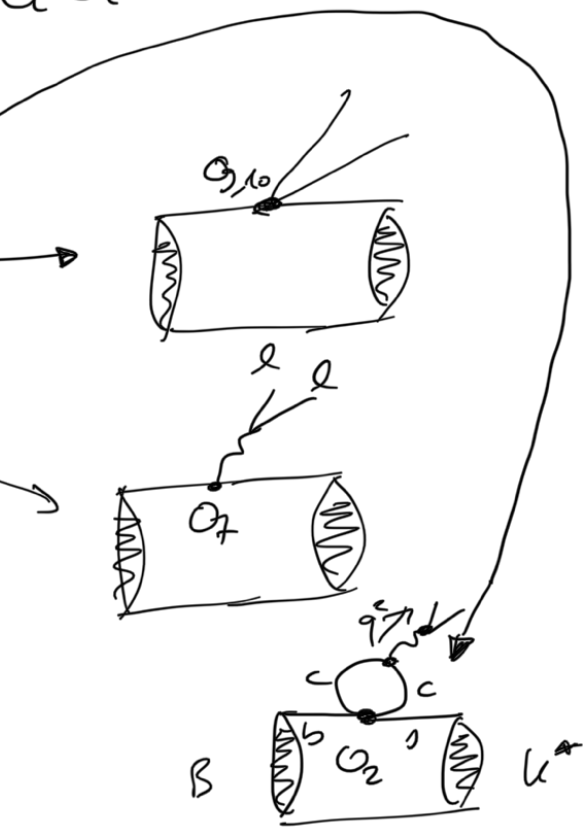
→ simple mediator explanations,

as you have to embed them in a UV complete theory

EFFECTIVE HAMILTONIAN FOR $b \to s \ell\ell$

$$\mathcal{H}_{eff} \propto G_F V_{tb} V_{ts}^* \sum C_i O_i$$





$$O_9 \propto \bar{s} \gamma_\mu (1-\gamma_5) b \; \bar{\ell} \gamma^\mu \ell$$

$$O_{10} \propto \bar{s} \gamma_\mu (1-\gamma_5) b \; \bar{\ell} \gamma^\mu \gamma^5 \ell$$

$$O_7 \propto m_b \; \bar{s} \sigma_{\mu\nu} (1+\gamma_5) b F^{\mu\nu}$$

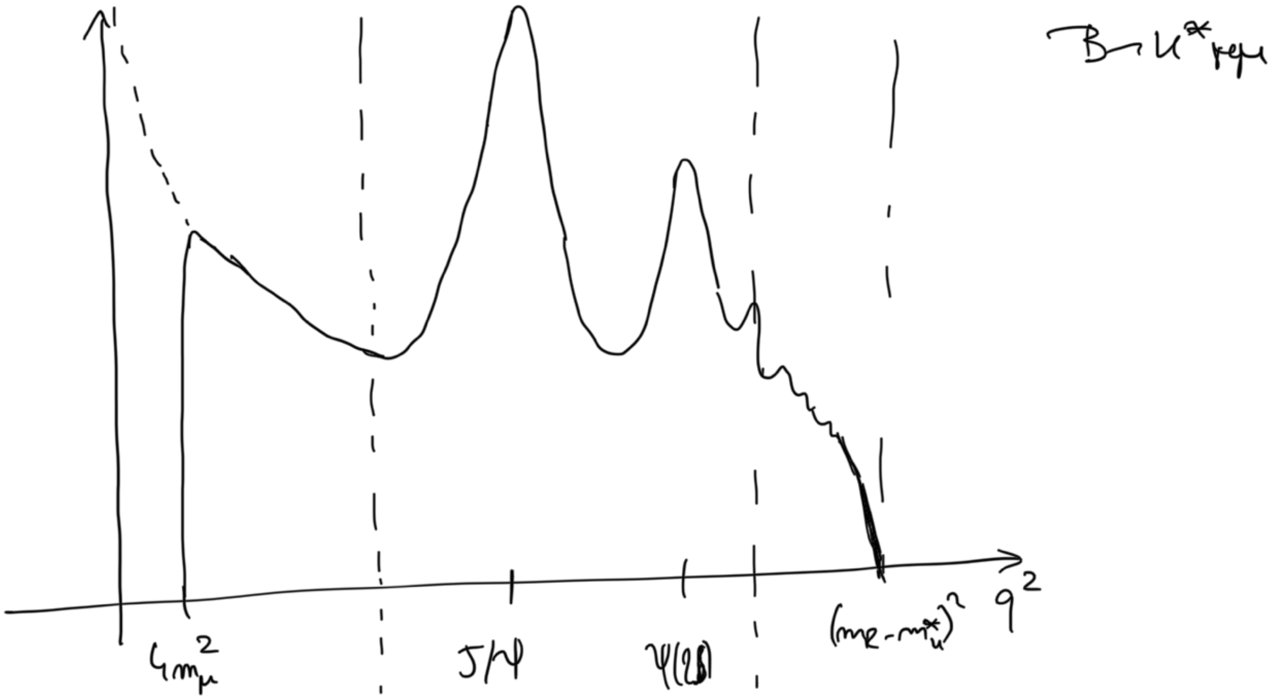
$$\left.\begin{aligned} C_7^{SM} &= -0.29 \\ C_9^{SM} &= 4.1 \qquad \mu = m_b \\ C_{10}^{SM} &= -4.3 \end{aligned}\right\}$$

main operators for the discussion

- NP in deviation of $C_{7,9,10}$
- NP in additional operators
  - * chirality flipped operators $O_{7'}, O_{9'}, O_{10'}$ — $1-\gamma_5 \longleftrightarrow 1+\gamma_5$ in the peak bilinear
  - * scalar / pseudoscalar $O_{S,S',P,P'}$

$$O_S = \bar{s}(1+\gamma_5)b \quad \bar{\ell}\ell$$

* tensor operators $O_T, \; O_{T5}$



γ pole — large K* recoil — charmonia — low K* recoil

light cone sum rules — lattice QCD

SCET
Soft Collinear Effective Theory

HQET
Heavy Quark Effective Theory

TWO EFFECTIVE THEORIES OF INTEREST

• <u>HQET</u> $E_{K^*} \ll m_B$ } at these / peaks + beyond peaks

- SCET $\quad E_{K^*} = O(m_B)$ $\Big\{$ soft degrees of freedom, low also; collinear d.o.f.

K^* flies almost light like direction

$\simeq$ collinear partons

→ both cases $\Big\{$ integrate out the other degrees of freedom

→ perturbative corrections (hard gluons)

$\mathcal{L}_{eff}$ with some decoupling between the QCD degrees of freedom

→ In particular, in both limits,

fewer degrees of freedom

→ relations between the form factors

$$\begin{pmatrix} 3 \text{ form factors } B \to K \\ 7 \text{ form factors } B \to K^* \end{pmatrix}$$

HQET $\downarrow$ $\qquad$ SCET $\downarrow$

2   1

3   2

$$F(q^2) = \xi(q^2) + O(\alpha_s) \text{ corrections}$$

$$+ O\left(\frac{1}{m_b}\right) \text{ corrections}$$

full form factor

soft form factor of the EFT

→ one way of reducing the impact of hadronic uncertainties (FF)

TWO SOURCES OF HADRONIC UNCERTAINTIES

$$A(B\to\pi\ell\ell) \propto G_F V_{tb} V_{ts}^* \left[(A_\mu + T_\mu)\, \underline{\underline{\bar{u}_\ell \gamma^\mu v_\ell}} + B_\mu\, \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell\right]$$

local $\boxed{C_7, C_9}$ × form factor

$\boxed{\text{SD Wilson coefficients}}$

Non local

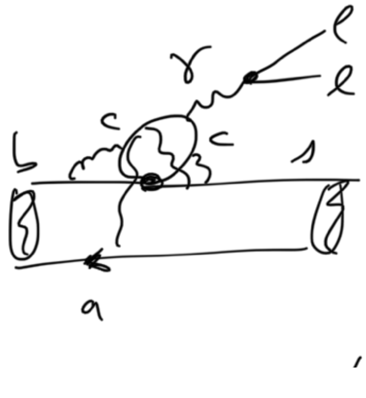
$c\bar{c}$ contribution

C_{10} × form factor

LD hadronic physics

q^2 dependent

final/initial state dependent



→ different estimates / competition

TAMING HADRONIC UNCERTAINTIES

- Focus on reducing the uncertainties coming from the form factors

  $* \quad R_K = \dfrac{Br(B \to K\mu\mu)}{Br(B \to Kee)}$ expressing everything in terms of ratios of form factors

  $R_{K^*} = \dfrac{Br(B \to K^*\mu\mu)}{Br(B \to K^* ee)}$

  → very precise values in the SM

  → cancellation of form factors is not as efficient (drastic increase of the uncertainties in the presence of NP)

  $*$ angular observables $\dfrac{d^4\Gamma(B \to K^* \ell\ell)}{dq^2 \, d\cos\theta_{K^*} \, d\theta_\ell \, d\varphi}$

  → I_i angular obs (interferences of helicity amplitudes)

  → HQET / SCET to identify combinations of I_i depending on a single ξ

(reduced form factor)

$\longrightarrow$ Take ratios of these angular observables so that the same ξ gets cancelled out

$\rightsquigarrow P_5'$ [less affected by uncertainties from form factors]

FIT TO CONSTRAIN NP IN C_i

- Large nr of observables [~ 250 observables] [CP averaged]

$b \to s\mu\mu$

- $C_{9\mu}$
- $(C_{9\mu}, C_{10\mu})$
- $(C_{9\mu}, C'_{9\mu})$

SINGLE MEDIATOR EXPL ?

- Z' appropriate couplings
- 1 or 2 LQs

In particular $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$

explained by $U_1\ (3,1)_{2/3}$ vector leptoquark

→ combined explanation for $b \to s\ell\ell$

$b \to c\tau\nu$

⇝ Also possible combining 2 scalar leptoquarks

[no successful explanation with H^+, W', Z']

AND NOW ?

- LHC
- Belle II
- Hadronic effects

→ much more to come