BSM Flavor Physics

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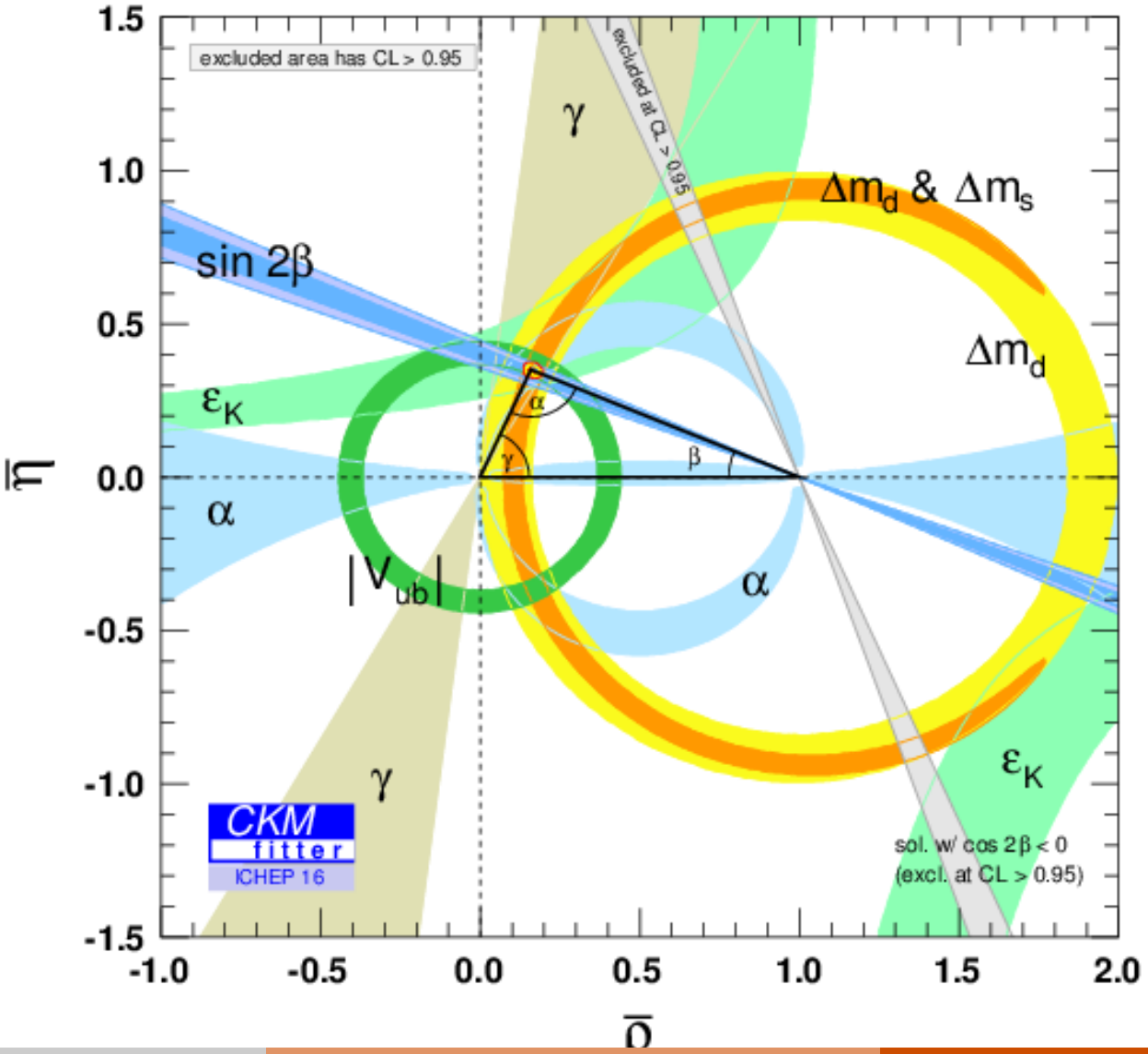
Outline

- New Measurements
- Anomalies in Flavor
- Combined Explanations- Heavy Physics
- Combined Explanations-Light and Heavy physics.

Flavor Physics

- Complimentary approach: Test the Standard Model (SM) at low energies by making very precise experiments with high data sample.
- $$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \Sigma_n c_n(\frac{O_n}{\Lambda^n}).$$
- Measurements at the many Flavor Experiments offer clues to BSM physics.
- Explanation of Flavor anomalies gives information about new states that might be discovered at colliders.

Inspite of impressive agreement with SM....



Several New Measurements- Many anomalies.

- Measurement of CP violation in the up-sector (NP ?).
- Semileptonic B anomalies- $R_{D^{(*)}}$ and R_K puzzles.
- Nonleptonic B decay anomaly: $B \to \pi K$ puzzle.
- In K Decays: $Re[\frac{\epsilon'}{\epsilon}]$.
- $(g-2)_\mu$ of the muon, $(g-2)_e$ of the electron(?).
- CPV in $\tau^- \to K^- \pi^0 \nu_\tau$.
- LSND, MiniBoone, Reactor... Anomalies.

Results

NEW

LHCb-PAPER-2019-006

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Compatible with **previous** LHCb results and the **WA**
- **Combination** with LHCb Run 1 gives:

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$$

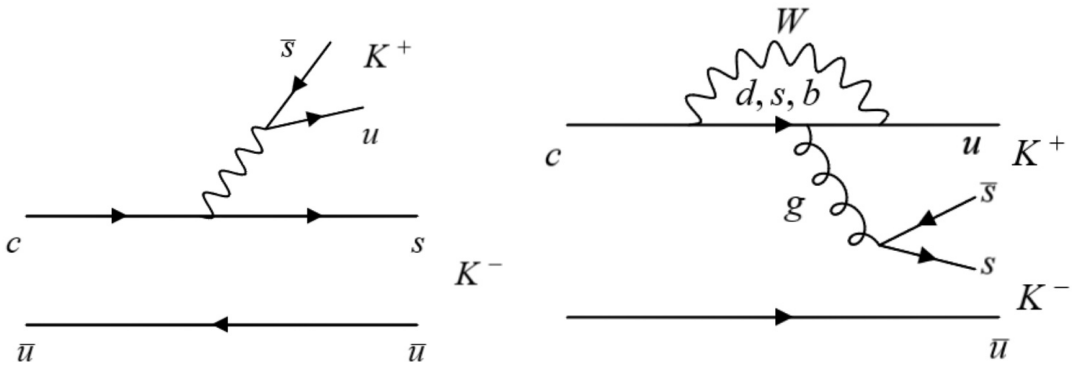
CP violation observed at $\boldsymbol{5.3\sigma}$!!

F. Betti - INFN Bologna, University of Bologna Moriond EW 2019 - 21/03/2019 24

D CP Violation

What is measured is

$$A_{CP}(D^0/\overline{D}^0 \to K^+K^-) - A_{CP}(D^0/\overline{D}^0 \to \pi^+\pi^-)$$



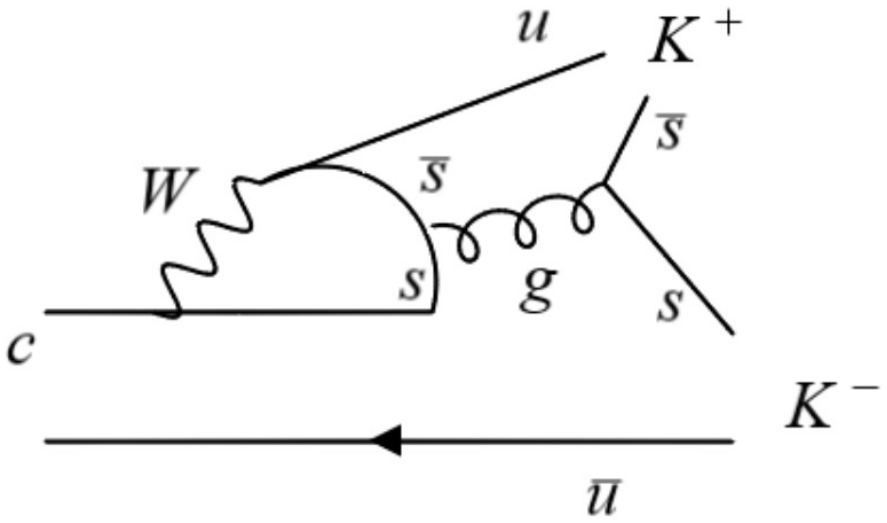
$$\frac{P}{T} = \frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\frac{\alpha_s}{\pi} \sim 10^{-4}$$

$$A_{CP} \sim \frac{2P}{T}\sin\Delta\phi_w \sin\Delta\phi_s \sim 10^{-4}.$$

Is it NP?

Nonleptonic decays, specially D decays are very difficult to calculate-systematic expansion in $\frac{\Lambda_{QCD}}{m_c}$ questionable.

Rescattering or penguin contractions can enhance the penguin amplitude.



Is it NP?

Many estimates of $\frac{P}{T}$:

Eg. 1203.6659 finds a consistent framework within SM to explain all the data- branching ratios and CP asymmetries.

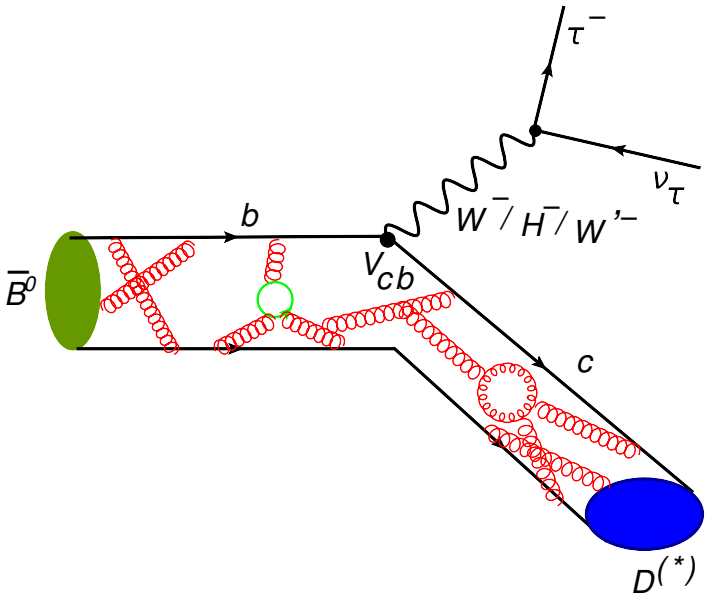
$$\frac{P}{T} = \frac{V_{cb}V_{ub}}{V_{cs}V_{us}}C$$

Data can be explained by $C \sim 1$ non perturbative effects (1903.10952) and not $C = \frac{\alpha_s}{\pi}$ (perturbative).

1706.07780; Estimates much smaller $\frac{P}{T}$ and predicts $|\Delta A_{CP}| < (0.020 \pm 0.003)$ % (Expt: ~ 0.15 %).

Not clear if NP is involved here.

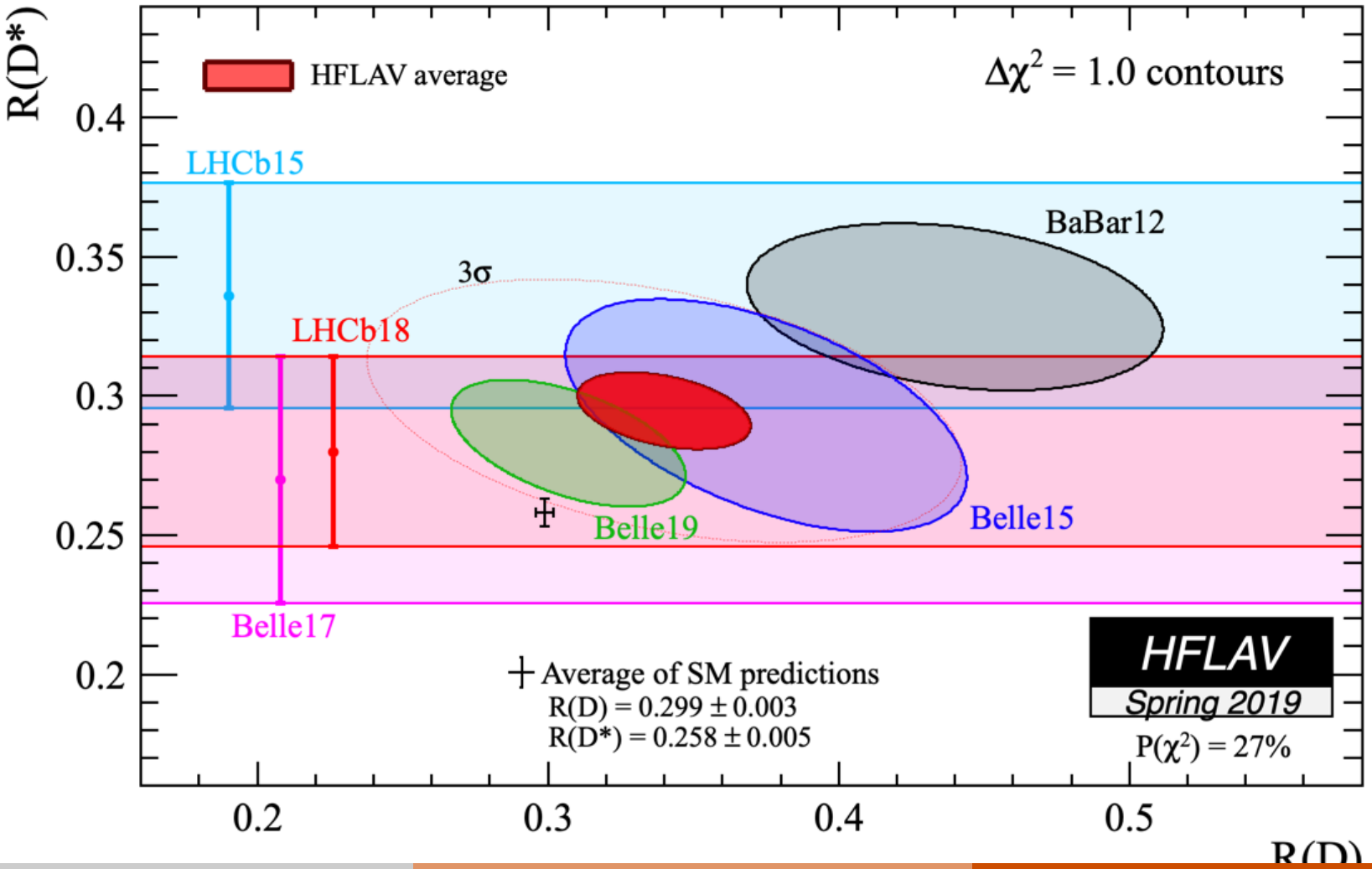
$R_{D^{(*)}}$ puzzle



$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\langle D^{(*)}(p') | \bar{c}\gamma^\mu (1-\gamma_5) b | \bar{B}(p) \rangle \right] \bar{\tau}\gamma_\mu (1-\gamma_5)\nu_\tau$$

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)} \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+} \ell^- \bar{\nu}_\ell)}.$$

R_D, R_{D^*}, HFAG


R(D*)
HFLAV average
Δχ² = 1.0 contours
LHCb15
BaBar12
3σ
LHCb18
Belle19
Belle15
Belle17
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
HFLAV
Spring 2019
P(χ²) = 27%
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
R(D)

The average of $R(D)$ and $R(D^*)$ measurements evaluated by the Heavy-Flavor Averaging Group are

$$\begin{aligned} R(D)_{exp} &= 0.340 \pm 0.027 \pm 0.013, \\ R(D^*)_{exp} &= 0.295 \pm 0.011 \pm 0.008. \end{aligned}$$

According to 1904.09311

$$\begin{aligned} R(D)_{SM} &= 0.300^{+0.005}_{-0.004} \\ R(D^*)_{SM} &= 0.251^{+0.004}_{-0.003} \end{aligned}$$

There are also measurements of q^2 distribution, $F_L^{D^*}$, τ polarization.

Model independent NP analysis

At the m_b scale: $SU(3)_c \times U(1)_{em}$.

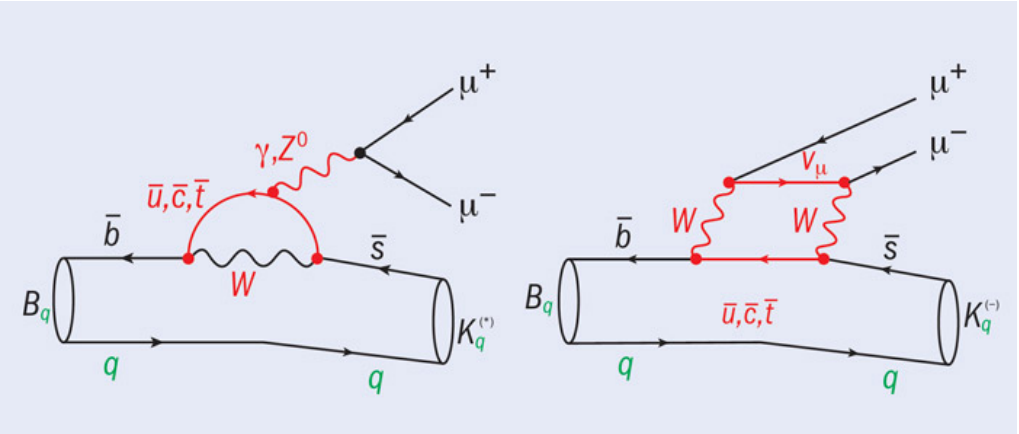
- Effective Hamiltonian for $b \to c l^- \bar{\nu}_l$ with Non-SM couplings. The NP has to be LUV.

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+V_L)\,[\bar{c}\gamma_\mu P_L b]\,[\bar{l}\gamma^\mu P_L \nu_l] + V_R\,[\bar{c}\gamma^\mu P_R b]\,[\bar{l}\gamma_\mu P_L \nu_l]$$
$$+ S_L\,[\bar{c}P_L b]\,[\bar{l}P_L\nu_l] + S_R\,[\bar{c}P_R b]\,[\bar{l}P_L\nu_l] + T_L\,[\bar{c}\sigma^{\mu\nu}P_L b]\,[\bar{l}\sigma_{\mu\nu}P_L\nu_l]\Big]$$

The NP can be probed via distributions and other related decays. Recent fit 1904.09311 find a good fit with LH interactions.

Other options viable: 1211.0348, 1704.06659,1711.09525, 1804.04135,1804.04642, 1804.04753, 1810.06597, 1811.04496...

$b \to s\mu^+\mu^-$ Anomaly



$$
\begin{aligned}
H_{\rm eff}(b \to s\ell\bar{\ell}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[C_9 \, (\bar{s}_L \gamma^\mu b_L) \, (\bar{\ell}\gamma_\mu \ell) \right. \\
&\qquad \left. + \, C_{10} \, (\bar{s}_L \gamma^\mu b_L) \, (\bar{\ell}\gamma_\mu \gamma^5 \ell) \right] \, , \\
H_{\rm eff}(b \to s\nu\bar{\nu}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \, C_L \, (\bar{s}_L \gamma^\mu b_L) \, (\bar{\nu}\gamma_\mu (1-\gamma^5)\nu) \, , \\
H_{\rm eff}(b \to s\gamma^*) &= C_7 \, \frac{e}{16\pi^2} \, [\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b] \, F^{\mu\nu}
\end{aligned}
$$

Hadronic Uncertainties: Charm Loop effects: Ciuchini et.al. 1512.07157

$b \to s\mu^+\mu^-$ can also receive corrections from non-leptonic operators

$$M = \langle K^*\mu^+\mu^- | \bar{s}b\bar{q}q | B \rangle$$

$\bar{q}q \to \gamma^* \to \mu^+\mu^-$. There can also be resonant contributions $\bar{q}q \to J/\psi \to \mu^+\mu^-$.

This long distance dominated contribution cannot be calculated from first principle. There are factorization theorem for small q^2 in leading order in m_{heavy}. But sub-leading corrections are not known.

$$M = \bar{s}\gamma_\mu P_L b \left[\frac{H(q^2)}{q^2}\right] \bar{\mu}\gamma^\mu\mu$$

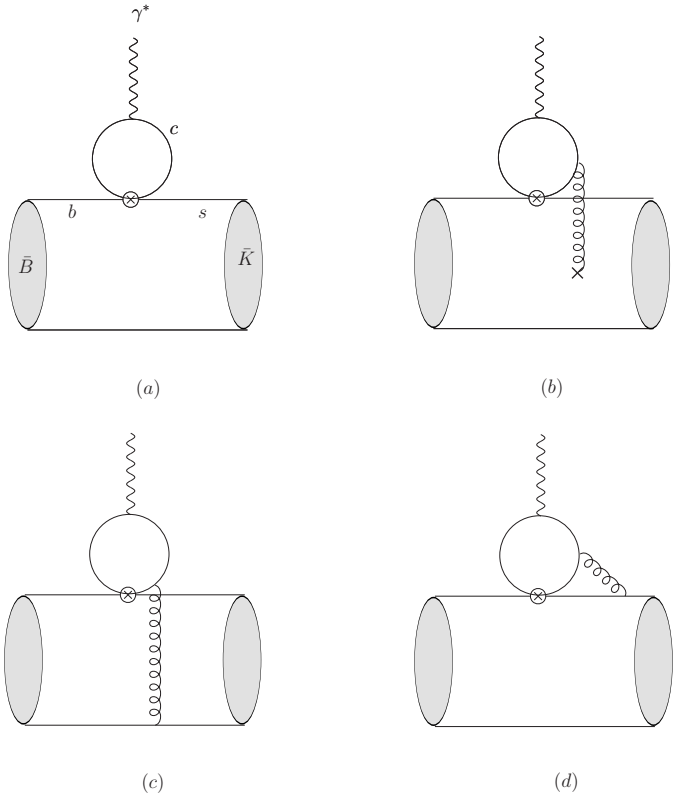
$$H(q^2) = a + b\frac{q^2}{m_B^2} .....$$

$H(q^2) \sim q^2$ and you reproduce ΔC_9 from pure SM hadronic effect.

R_K puzzle, Ratios of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$.

$$R_K \equiv \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$$

The SM prediction of $R_K^{\rm SM} = 1 \pm 0.01$

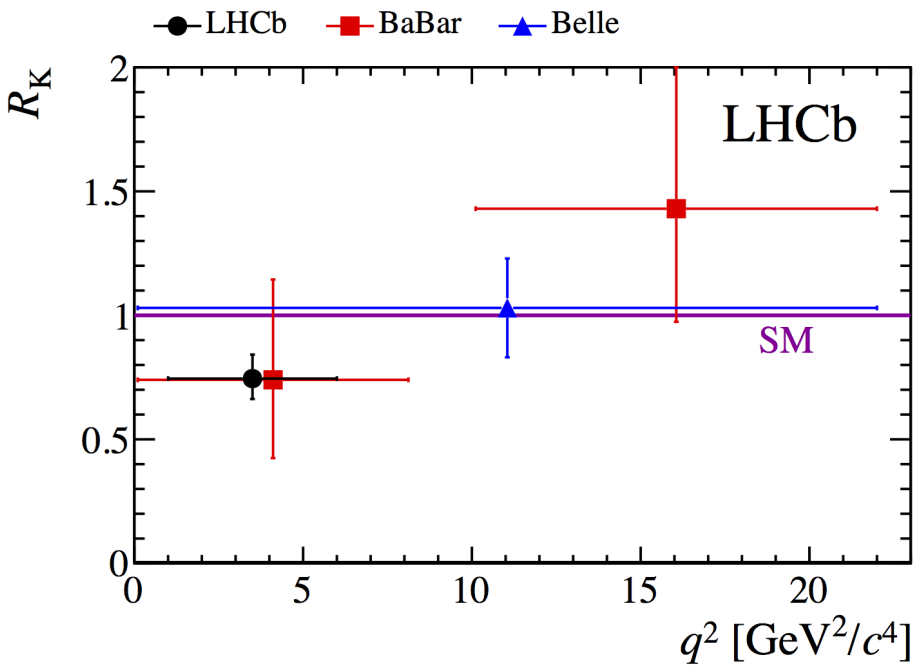


These effects can fake a ΔC_9 but this is lepton universal and so cannot explain R_K and R_{K^*} if $q^2 > 4m_\mu^2$.

R_K puzzle, Ratios of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$.

$R_K^{expt} = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$

$1 \leq q^2 \leq 6.0\,\mathrm{GeV}^2$



Recently, LHCb announced new R_K.

First, the Run I data was reanalyzed using a new reconstruction selection method. The new result is

$$R_{K,\mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083}_{-0.071}\ (\mathrm{stat})^{+0.017}_{-0.016}\ (\mathrm{syst})\ .$$

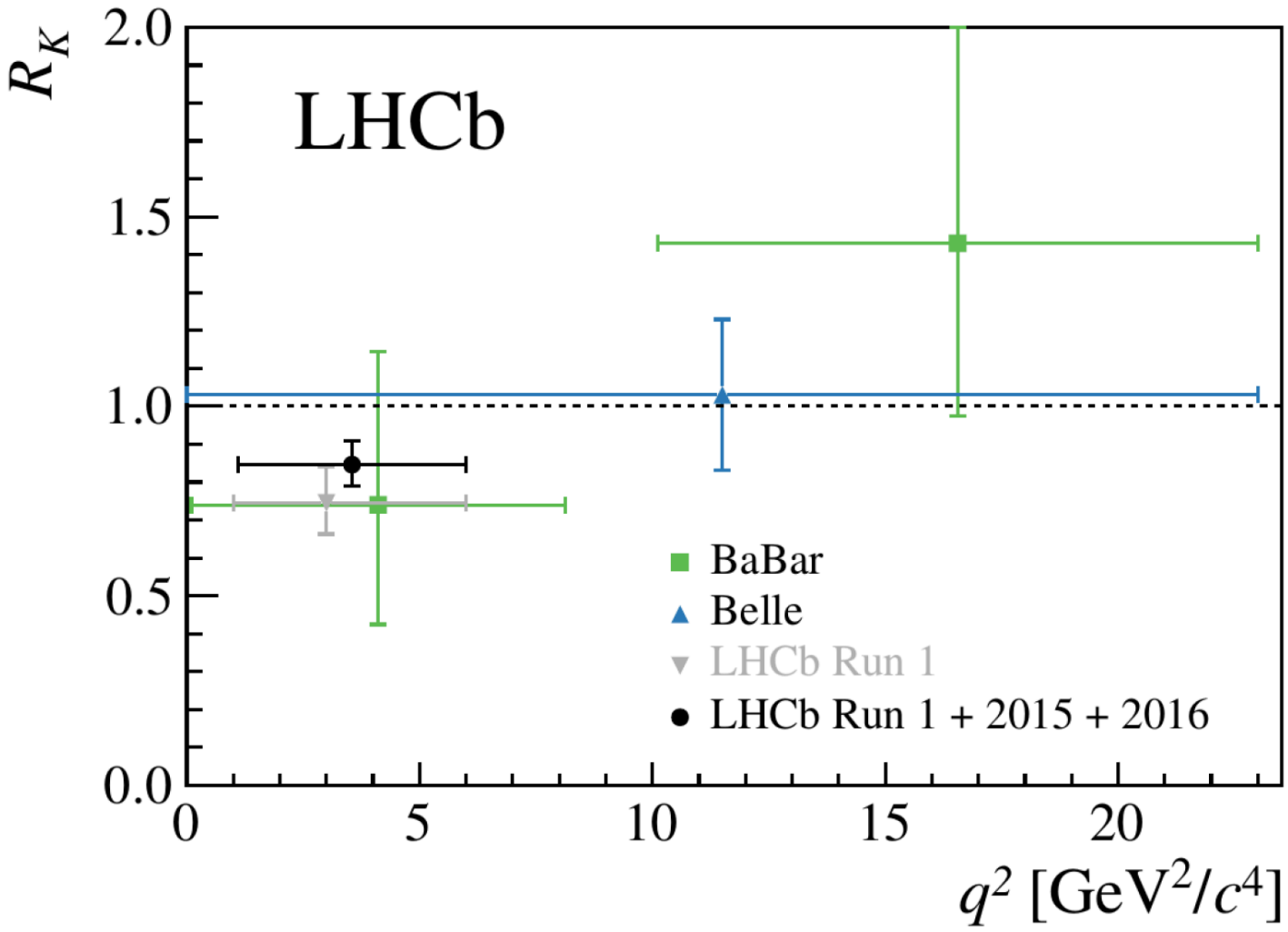
Second, the Run 2 data was analyzed:

$$R_{K,\mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}\ (\mathrm{stat}) \pm^{+0.020}_{-0.017}\ (\mathrm{syst})\ .$$

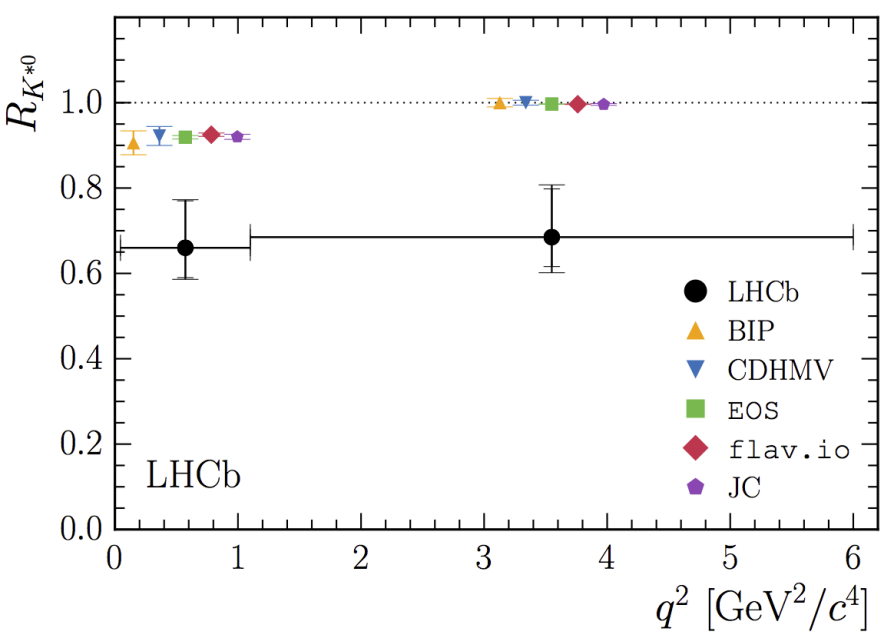
Combining the Run 1 and Run 2 results, the LHCb measurement of R_K is

$$R_K = 0.846^{+0.060}_{-0.054}\ (\mathrm{stat})^{+0.016}_{-0.014}\ (\mathrm{syst})\ .$$

This is closer to the SM prediction, though the discrepancy is still $\sim 2.5\sigma$ due to the smaller errors.



[Th.Humair,talkatMoriond2019]



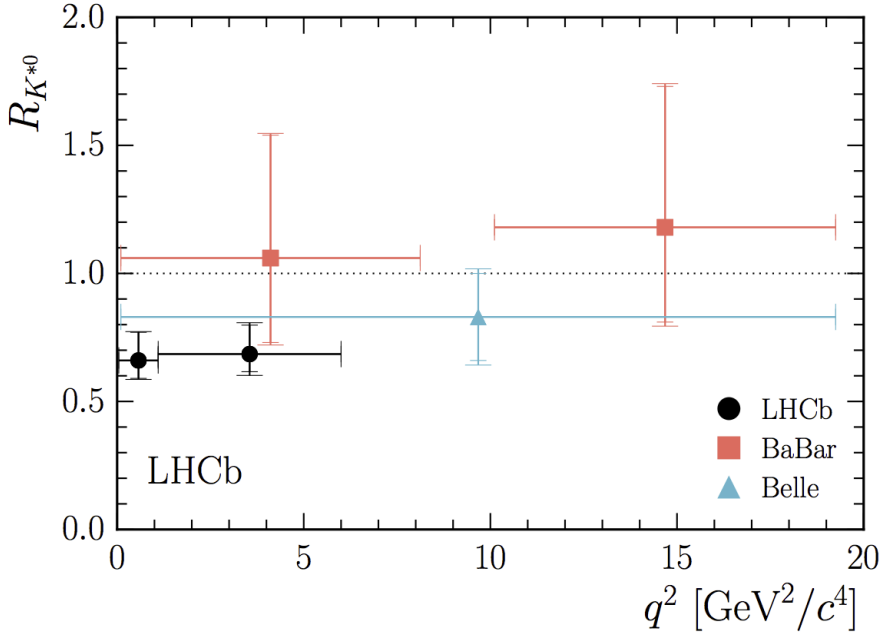


Figure: Comparison of the measurements of R_{K^*} from LHCb with (left) SM predictions and (right) BaBar and Belle.

$$R_{K^*}^{\rm expt} = \begin{cases} 0.660^{+0.110}_{-0.070}\ (\text{stat}) \pm 0.024\ (\text{syst}) & 0.045 \le q^2 \le 1.1\ \text{GeV}^2\ , \\ 0.685^{+0.113}_{-0.069}\ (\text{stat}) \pm 0.047\ (\text{syst}) & 1.1 \le q^2 \le 6.0\ \text{GeV}^2\ . \end{cases}$$

R_K and R_{K^*} in the SM very close to 1 in the central bin and $R_{K^*} \sim 0.92$ in the low bin.

Model Independent

The $b \to s\mu^+\mu^-$ transitions are defined via an effective Hamiltonian with vector and axial vector operators:

$$\begin{aligned} H_{\rm eff} &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_{a=9,10} \left(C_a O_a + C_a' O_a' \right) , \\ O_{9(10)} &= [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu(\gamma_5)\mu] , \end{aligned}$$

where the V_{ij} are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and the primed operators are obtained by replacing L with R.

The Wilson coefficients (WCs) include both the SM and NP contributions:

$C_a^{(\prime)} = C_{a,\rm SM} + C_{a,\rm NP}^{(\prime)}$

Recent Fits after $R_{K^{(*)}}$

Fits by many authors- recent (1902.04900, 1903.09617, 1903.10086, 1903.10434....) to all $b \to s\ell\ell$ observables: arXiv:1903.10086

Scenario	WC	R_K	$R_{K^*}^{cen}$	$R_{K^*}^{low}$	P_5'	pull
(I) $C_{9,\mathrm{NP}}^{\mu\mu}$	-1.10 ± 0.16	0.78	0.84	0.89	-0.50	5.6
(II) $C_{9,\mathrm{NP}}^{\mu\mu} = -C_{10,\mathrm{NP}}^{\mu\mu}$	-0.53 ± 0.08	0.76	0.76	0.86	-0.70	5.3

Table: Best-fit values of the WCs (taken to be real), the predictions for R_K, $R_{K^*}^{cen}$, $R_{K^*}^{low}$ and P_5', evaluated at these best-fit values, and the pull $= \sqrt{\chi^2_{\mathrm{SM}} - \chi^2_{\mathrm{SM+NP}}}$ for the global fit including all $b \to s\mu^+\mu^-$ and $R_{K^{(*)}}$ observables. For each case there are 115 degrees of freedom.

Here NP effects only the muons.

Remember in the $R_{D^{(*)}}$ puzzle also indicated LH NP interactions. This gives a hint to connect the two anomalies.

Interesting trend

Scenario	Data Set	WC
(I) $C_{9,\mathrm{NP}}^{\mu\mu}$	$R_{K^{(*)}}$	-0.82 ± 0.28
	$b \to s\mu^+\mu^-$	-1.17 ± 0.18
(II) $C_{9,\mathrm{NP}}^{\mu\mu} = -C_{10,\mathrm{NP}}^{\mu\mu}$	$R_{K^{(*)}}$	-0.38 ± 0.11
	$b \to s\mu^+\mu^-$	-0.62 ± 0.14

Table: Best-fit values of the WCs (taken to be real) for separate fits including the $b \to s\mu^+\mu^-$ or $R_{K^{(*)}}$ observables.

- Before new results there was overlap of NP in $R_{K^{(*)}}$ and $b \to s\mu^+\mu^-$.
- Internal tension in $R_{K^{(*)}}$ and $b \to s\mu^+\mu^-$ NP could indicate NP in $b \to se^+e^-$.
- NP in $b \to se^+e^-$ also indicated in low q^2 R_{K^*} measurement.

Model building

- Several (but not all) models aim at explaining all anomalies, sometimes along with $(g\text{-}2)_\mu$ (optimistic 😊)

  [Bhattacharya, Datta, London, Shivashankara 2014; Alonso, Grinstein, Martin Camalich 2015; Greljo, Isidori, Marzocca 2015; Calibbi, Crivellin, Ota 2015; Bauer, MN 2015; Fajfer, Kosnik 2915; Barbieri, Isidori 2015; Das, Hati, Kumar, Mahajan 2016; Boucenna, Celis, Fuentes-Martin, Vicente, Virto 2016; Becirevic, Kosnik, Sumensari, Zukanovich Funchal 2016; Becirevic, Fajfer, Kosnic, Sumensari 2016; Hiller, Loose, Schoenwald 2016; Bhattacharya, Datta, Guevin, London, Watanabe 2016; Buttazzo, Greljo, Isidori, Marzocca 2016; Barbieri, Murphy, Senia 2016; Bordone, Isidori, Trifinopoulos 2017; Crivellin, Müller, Ota 2017; Megias, Quiros, Salas 2017; Cai, Gargalionis, Schmidt, Volkas 2017; …]

- R_D and R_{D^*} require tree-level NP near TeV scale
- Rare decays $b \to s\ell^+\ell^-$ (R_K, R_{K^*}, P_5', …) require suppressed NP contributions
- If common origin: suppression either dynamically or by means of a symmetry

R_K and $R_{D^{(*)}}$

Assuming the scale of NP is much larger than the weak scale, the semileptonic operators should be made invariant under the full $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group. (Bhattacharya, Datta, London, Shivshankara, 1412.7164) considered two possibilities for LH interactions:

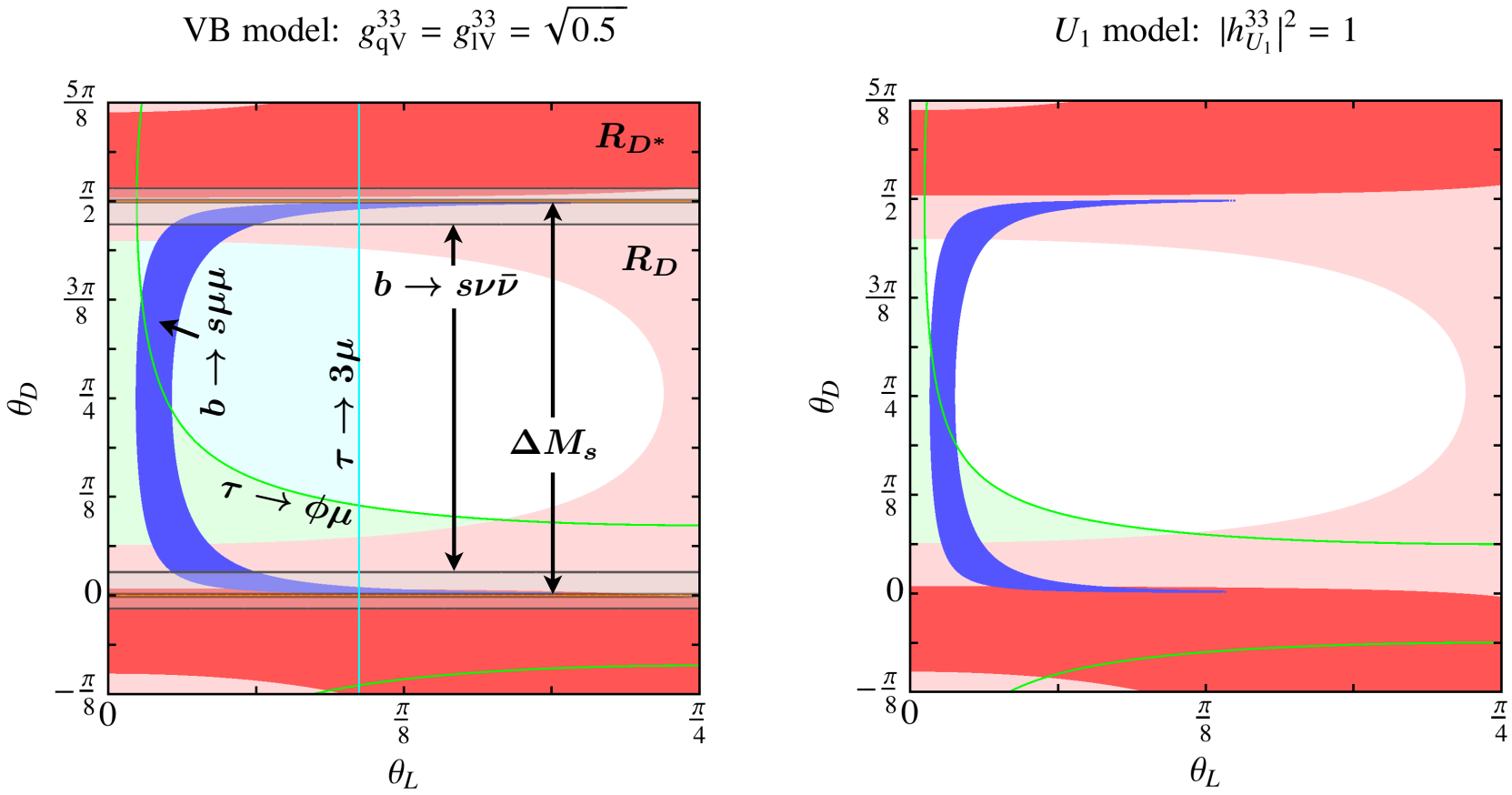
$$\begin{aligned}
\mathcal{O}_1^{NP} &= \frac{G_1}{\Lambda_{NP}^2}(\bar{Q}'_L\gamma_\mu Q'_L)(\bar{L}'_L\gamma^\mu L'_L) \ , \\
\mathcal{O}_2^{NP} &= \frac{G_2}{\Lambda_{NP}^2}(\bar{Q}'_L\gamma_\mu\sigma^I Q'_L)(\bar{L}'_L\gamma^\mu\sigma^I L'_L) \\
&= \frac{G_2}{\Lambda_{NP}^2}\left[2(\bar{Q}'^i_L\gamma_\mu Q'^j_L)(\bar{L}'^j_L\gamma^\mu L'^i_L) - (\bar{Q}'_L\gamma_\mu Q'_L)(\bar{L}'_L\gamma^\mu L'_L)\right] \ .
\end{aligned}$$

Here $Q' \equiv (t', b')^T$ and $L' \equiv (\nu'_\tau, \tau')^T$. The key point is that $\mathcal{O}_2^{NP}$ contains both neutral-current (NC) and charged-current (CC) interactions. The NC and CC pieces can be used to respectively explain the R_K and $R_{D^{(*)}}$ puzzles.

UV completion

- UV completions considered by many authors e.g. L. Calibbi, A. Crivellin and T. Ota, 1506.02661 considered possible UV completions that can give rise to $\mathcal{O}_{1,2}^{NP}$.
- (i) a vector boson (VB) that transforms as $(\mathbf{1}, \mathbf{3}, 0)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as in the SM.
- (ii) an $SU(2)_L$-triplet scalar leptoquark (S_3) $[(\mathbf{3}, \mathbf{3}, -2/3)$.
- (iii) an $SU(2)_L$-singlet vector leptoquark (U_1) $[(\mathbf{3}, \mathbf{1}, 4/3)$.
- $SU(2)_L$-triplet vector leptoquark (U_3) $[(\mathbf{3}, \mathbf{3}, 4/3)]$.
- The vector boson generates only $\mathcal{O}_2^{NP}$, but the leptoquarks generate particular combinations of $\mathcal{O}_1^{NP}$ and $\mathcal{O}_2^{NP}$.

Models: allowed parameter space: 1609.09078, 1806.07403



Z' models highly constrained. U_1 LQ is the favored model.

Predictions(Leptoquarks)

- May observe $\Upsilon(3S) \to \mu\tau$:

$$\begin{aligned} VB \qquad & \mathcal{B}(\Upsilon(3S) \to \mu\tau) \simeq 3.0 \times 10^{-9} \ , \\ U_1 \quad : \quad & \mathcal{B}(\Upsilon(3S) \to \mu\tau)|_{\max} = 8.0 \times 10^{-7} \ . \end{aligned}$$

  Belle II should be able to measure $\mathcal{B}(\Upsilon(3S) \to \mu\tau)$ down to $\sim 10^{-7}$.

- Large observable effects in $b \to s\tau^+\tau^-$ ($B \to K^{(*)}\tau^+\tau^-$, $B_s \to \tau^+\tau^-$) or $b \to s\tau\mu$ and possibly LFUV in $B \to \pi\ell\bar{\nu}_\ell$ Decays.

Collider Search: 1706.07808

High-p_T searches are concerned, particularly stringent bounds are set by $pp \to \tau\bar{\tau} + X$

$$\Delta\mathcal{L}_{bb\tau\tau} = -\frac{1}{\Lambda_0^2}\ \left(\bar{b}_L\gamma_\mu b_L\right)\left(\bar{\tau}_L\gamma_\mu\tau_L\right)\ , \qquad \Lambda_0^2 = \frac{v^2}{G_1 + G_2}\ . \tag{1}$$

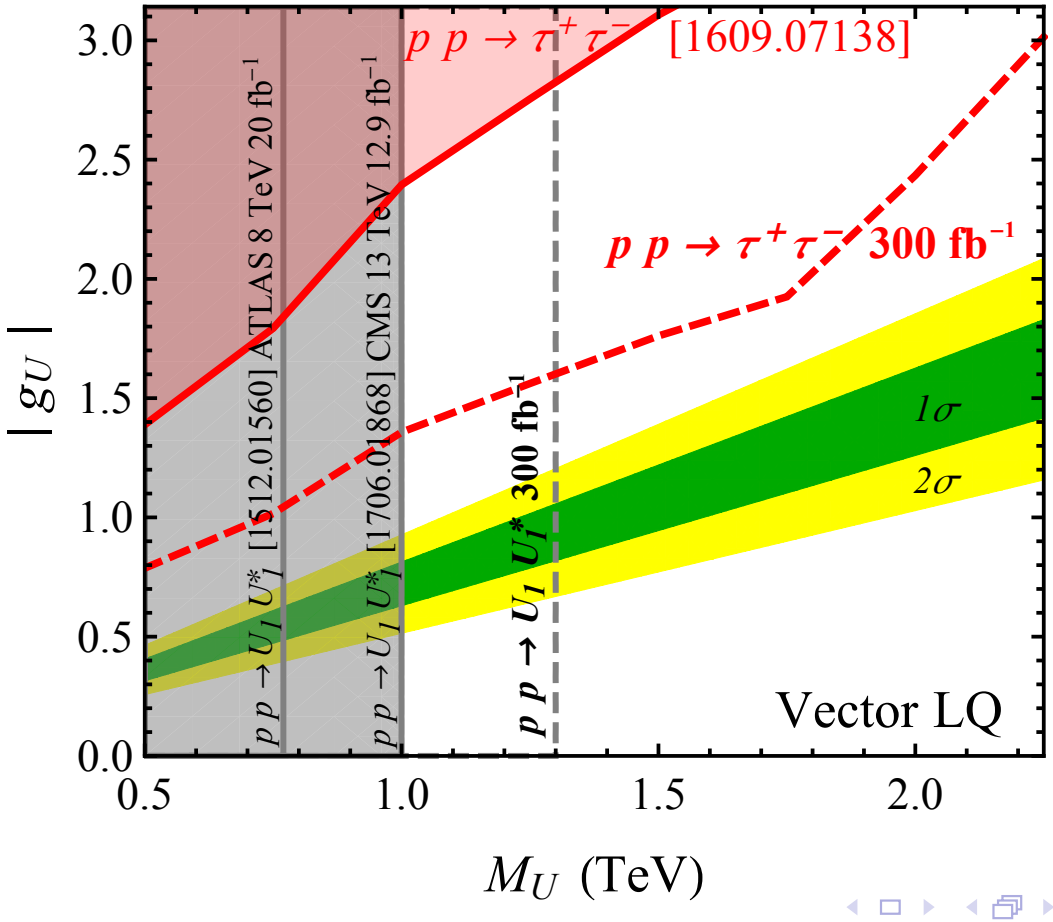
The present bounds on the EFT scale Λ_0 were derived recasting different ATLAS searches for $\tau\bar{\tau}$ resonances, and read $\Lambda_0 > 0.62\,\mathrm{TeV}$. Newer fits: $\Lambda_0 \approx 1.2$ TeV, which is well within the experimental limit.

Lepton flavor violating decays: $gg \to \tau\mu$ (1802.06082, 1802.09822) or $gg \to \bar{t}t\tau\mu$ (1412.7164).

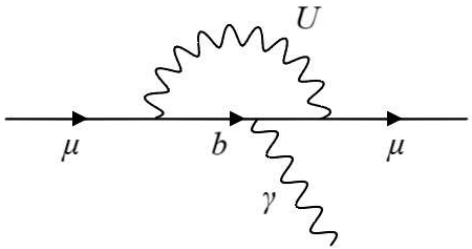
$$\Delta\mathcal{L}_{tt\tau\mu} = -\frac{1}{\Lambda_0^2}\ \left(\bar{t}_L\gamma_\mu t_L\right)\left(\bar{\tau}_L\gamma_\mu\mu_L\right) \tag{2}$$

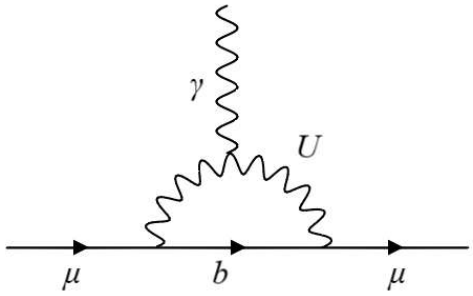
Collider Search: 1706.07808

Z' $(\mathbf{1}, \mathbf{3}, 0)$ is strongly constrained(ruled out) unless width is large. Z' $(\mathbf{1}, \mathbf{1}, 0)$ explaining only R_K is fine: $M_{Z'} \sim 30$ TeV.



$(g-2)_\mu$ and B anomalies





$$\Delta(g-2)_\mu^U = -\frac{N^c (h_{i\mu}^U)^2}{16\pi^2}\left(\frac{4m_\mu^2}{3m_U^2}Q_b - \frac{5m_\mu^2}{3m_U^2}Q_U\right), \tag{3}$$

where $N^c = 3$ is the number of colors, $i = d, s, b$ and $Q_b = -\frac{1}{3}$ and $Q_U = -\frac{2}{3}$ are the electric charges of the bottom quark and the U leptoquark. Putting in the numbers for the muon mass, we find,

$$\Delta(g-2)_\mu^U = -1.4 \times 10^{-10} (h_{i\mu}^U)^2 \left(\frac{\text{TeV}}{m_U}\right)^2, \tag{4}$$

$(g-2)_\mu$ and B anomalies: Dark Higgs

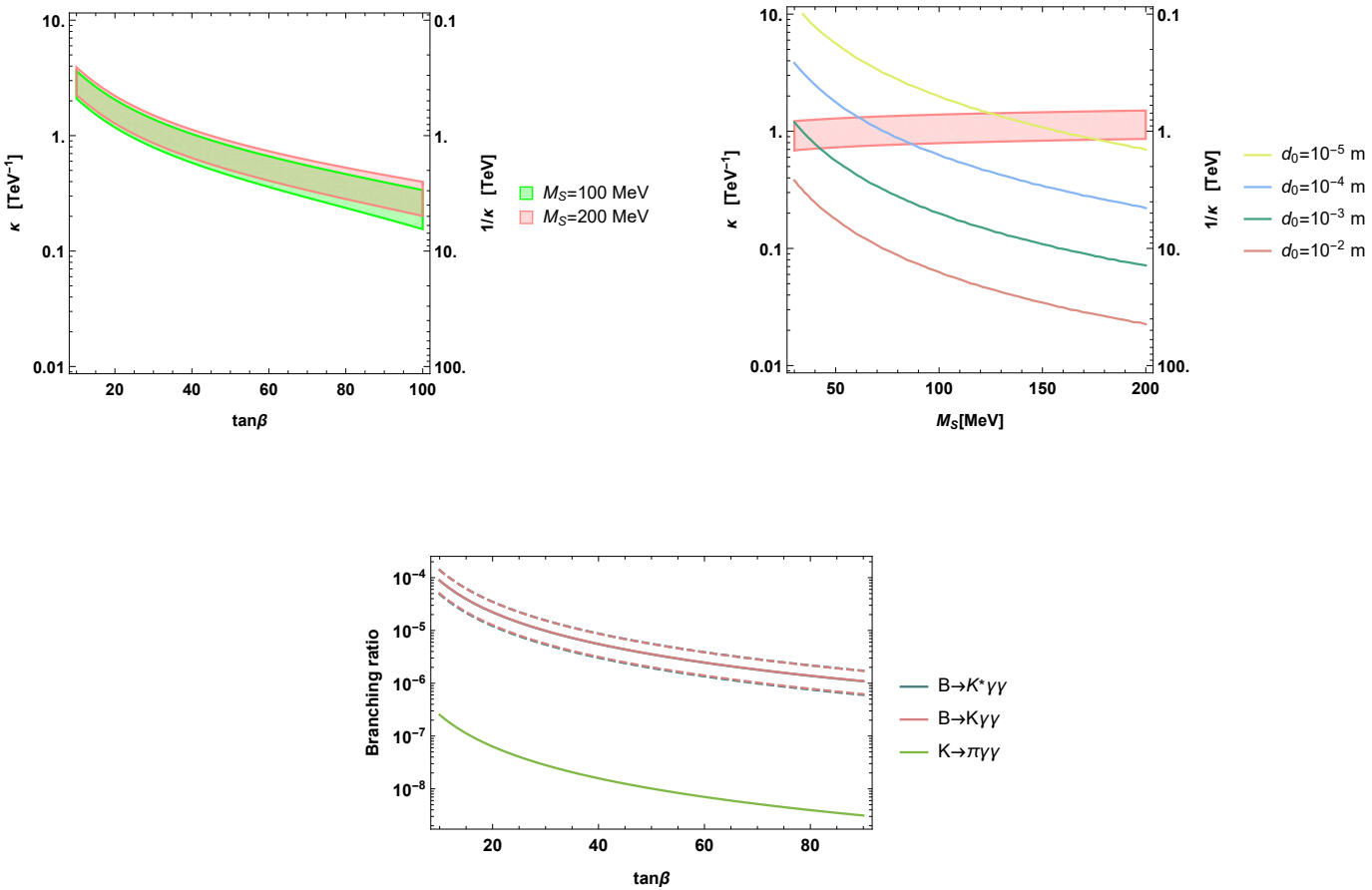
$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \sin\theta\tan\beta\sum_{f=d,l}\frac{m_f}{v}\bar{f}fS - \sin\theta'\cot\beta\sum_{f=u}\frac{m_f}{v}\bar{f}fS - \frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu},$$

$$\sin\theta \simeq -\frac{vA}{m_H^2}\,, \quad \sin\theta' \simeq -\frac{2vA}{m_h^2}\left(1-\frac{m_h^2}{2m_H^2}\right).$$

The last term of is an $S\gamma\gamma$ coupling parametrized by the mass scale m_κ. This coupling is generically induced by heavy states, such as leptoquarks, as will be discussed next

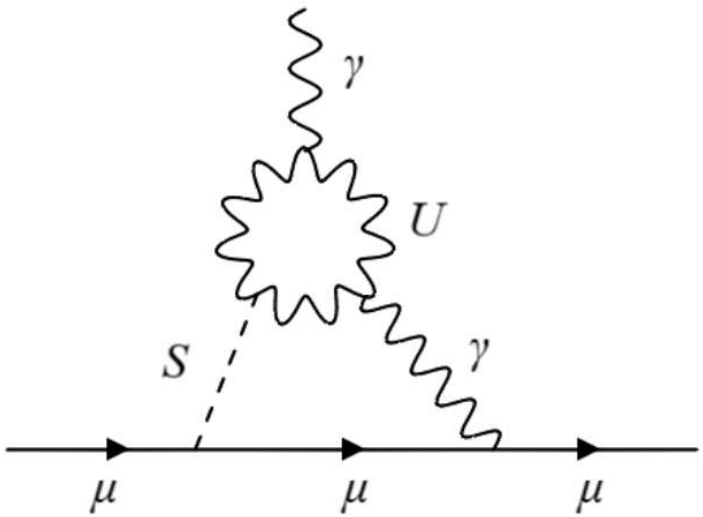
$$\mathcal{L}_U = -\frac{1}{4}F^U_{\mu\nu}F^{U\mu\nu} - m_U^2 U_\mu U^\mu - \left[h^U_{ij}\left(\bar{Q}_{iL}\gamma^\mu L_{jL}\right)U_\mu + \text{H.c.}\right] - g m_U S U_\mu U^\mu\,. \tag{5}$$

$(g-2)_\mu$ and B anomalies



Also contribution to $B \to K^{(*)} S(S \to e^+ e^-)$ and affect $R_{K^{(*)}}$ in the low q^2 bin. (1702.01099, 1705.08423, 1705.01822, 1711.07494, 1808.02611)

$S\gamma\gamma$ coupling



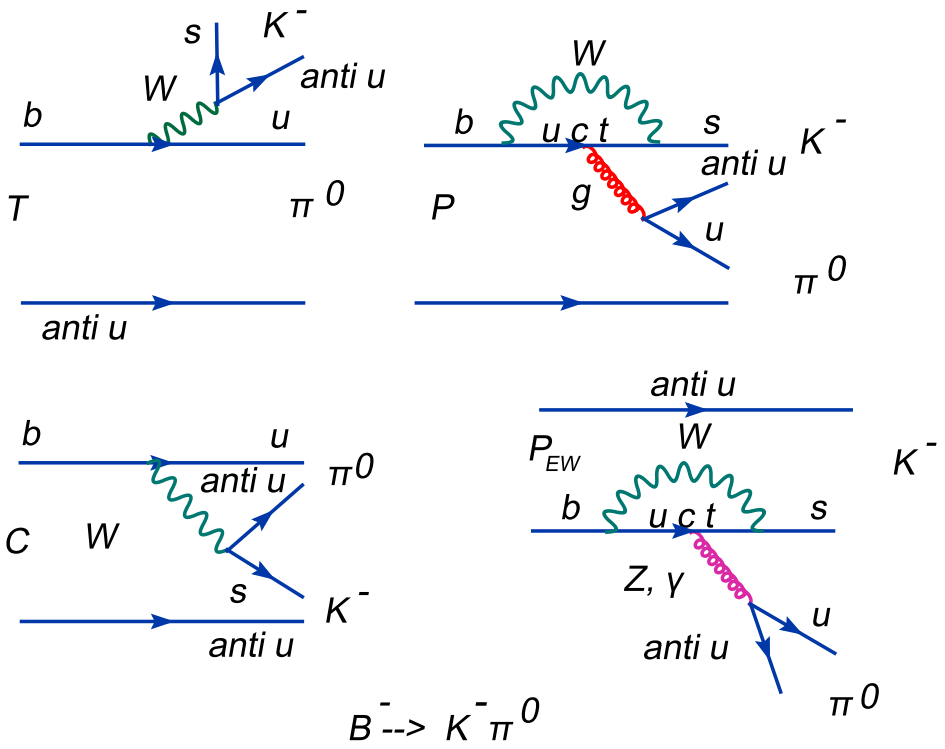
$$\begin{aligned}\mathcal{L}_{V_i} &= -\frac{1}{4}F^{V_i}_{\mu\nu}F^{V_i\mu\nu} - m^2_{V_i}V_{i\mu}V_i^{\mu} - \left[h^V_{jk}\left(\bar{Q}_{jR}\gamma^{\mu}L_{kR}\right)V_{i\mu} + \text{H.c.}\right] \\ &- g_{V_i}m_{V_i}SV_{i\mu}V_i^{\mu}\ ,\end{aligned}$$

where for simplicity we add only leptoquarks with SM quantum numbers $(3, 1, \frac{5}{3})$.

$B \to K\pi$- SM

In the SM the amplitudes for the four decays can be related by isospin.

The four decays can be represented by the following amplitudes:



$$\frac{|T|}{|P|} = \frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\frac{c_1}{c_t} \sim 0.2 \quad \frac{|C|}{|P|} \sim \frac{1}{N_c}\frac{|T|}{|P|} \sim 0.04 \quad \frac{|P_{EW}|}{|P|} \sim 0.14$$

$B \to \pi K$ puzzle

We begin by reviewing the $B \to \pi K$ puzzle. amplitudes. Including only the leading diagrams the $B \to \pi K$ amplitudes become

$$\begin{aligned} A^{+0} &= -P'_{tc} \ , \\ \sqrt{2}A^{0+} &= -T' e^{i\gamma} + P'_{tc} - P'_{EW} \ , \\ A^{-+} &= -T' e^{i\gamma} + P'_{tc} \ , \\ \sqrt{2}A^{00} &= -P'_{tc} - P'_{EW} \ . \end{aligned}$$

In A^{0+}, P'_{EW} and T' have the same strong phase ($P'_{EW} \propto T'$, while P'_{EW} and P'_{tc} have the same weak phase ($= 0$), so that P'_{EW} does not contribute to the direct CP asymmetry. This means that we expect $A_{CP}(B^+ \to \pi^0 K^+) = A_{CP}(B_d^0 \to \pi^- K^+)$.

Not only are $A_{CP}(B^+ \to \pi^0 K^+)$ and $A_{CP}(B_d^0 \to \pi^- K^+)$ not equal, they are of opposite sign! Experimentally, we have $(\Delta A_{CP})_{\rm exp} = (12.2 \pm 2.2)\%$. This differs from 0 by 5.5σ. This is the naive $B \to \pi K$ puzzle.

Mode	$BR[10^{-6}]$	A_{CP}	S_{CP}
$B^+ \to \pi^+ K^0$	23.79 ± 0.75	-0.017 ± 0.016	
$B^+ \to \pi^0 K^+$	12.94 ± 0.52	0.040 ± 0.021	
$B_d^0 \to \pi^- K^+$	19.57 ± 0.53	-0.082 ± 0.006	
$B_d^0 \to \pi^0 K^0$	9.93 ± 0.49	-0.01 ± 0.10	0.57 ± 0.17

Table: Branching ratios, direct CP asymmetries A_{CP}, and mixing-induced CP asymmetry S_{CP} (if applicable) for the four $B \to \pi K$ decay modes. The data are taken from HFAG.

Semileptonic and NonLeptonic

LQ solve the SL anomalies.

For the nonleptonic two kinds of NP are possible: Z' and Diquarks (1709.07142).

$$b \to sZ' \to b \to s\bar{q}q \quad b \to \bar{q}D(D \to sq).$$

Consider a model with with triplet LQ $(3, 3, -1/3)$ and a color sextet $(6, 1, -2/3)$ Diquark.

With the particle content discussed above, the most general interaction lagrangian is given as

$$\mathcal{L}_{int} = -Y_l^{ij}\,\overline{L_i^c}\,i\,\sigma_2\,Q_j^{\alpha}\,S_{3L}^{\alpha *} - Y_d^{ij}\,\overline{d_{iR}^{\alpha c}}\,d_{jR}^{\beta}\,S_D^{\alpha\beta *} + \mu\,S_{3L}^{\alpha *}\,S_{3L}^{\beta *}\,S_D^{\alpha\beta} + (h.c.),$$

Colored Zee Babu Model

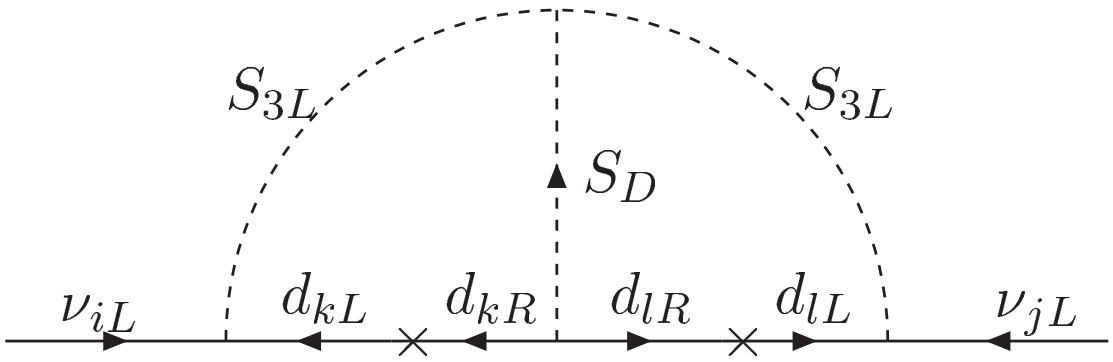


Figure: The two loop neutrino mass generated by $(3, 3, -1/3)$ leptoquark and $(6, 1, -2/3)$ diquark.

$$M_\nu^{ij} = 24\,\mu\, Y_l^{ik}\, m_d^k\, Y_d^{kl}\, I^{kl}\, m_d^l\, Y_l^{lj}. \tag{6}$$

A consistent framework to address the SL, NL B anomalies and neutrino masses is possible: 1905.04046

Conclusions

- SM working well but several anomalies which hint at New Physics.
- Measurements B decays indicating lepton non-universal interactions.
- Combined explanations:These anomalies may arise from the same New Physics.
- If true striking signals are expected $\Upsilon(3S) \to \mu\tau$ and highly enhanced $b \to s\tau^+\tau^-$.
- If true then new states like new gauge bosons, leptoquarks could be discoved.
- Light NP is highly constrained but might play a role in some of the anomalies and produce interesting signals.