Outline

● New Measurements
● Anomalies in Flavor
● Combined Explanations- Heavy Physics
● Combined Explanations-Light and Heavy physics.
Complimentary approach: Test the Standard Model (SM) at low energies by making very precise experiments with high data sample.

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_n c_n \left( \frac{O_n}{\Lambda^n} \right). \]

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.
In spite 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: $B \rightarrow \pi K$ puzzle.
- In $K$ Decays: $Re\left[\frac{\epsilon'}{\epsilon}\right]$.
- $(g - 2)_\mu$ of the muon, $(g - 2)_e$ of the electron(?).
- CPV in $\tau^- \rightarrow K^- \pi^0 \nu_\tau$.
- LSND, MiniBoone, Reactor... Anomalies.
Results

\[ \Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2 \text{ (stat.)} \pm 0.9 \text{ (syst.)}] \times 10^{-4} \]
\[ \Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.)}] \times 10^{-4} \]

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

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

\[ CP \text{ violation observed at } 5.3 \sigma \]!!
What is measured is

\[ A_{CP}(D^0/\bar{D}^0 \rightarrow K^+K^-) - A_{CP}(D^0/\bar{D}^0 \rightarrow \pi^+\pi^-) \]

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

\[ A_{CP} \sim \frac{2P}{T} \sin \Delta \phi_w \sin \Delta \phi_s \sim 10^{-4}. \]
Is it NP?

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

Rescattering or penguin contractions can enhance the penguin amplitude.
Many estimates of $\frac{P}{T}$:

Eg. \textcolor{red}{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 (\textcolor{blue}{1903.10952}) and not $C = \frac{\alpha_s}{\pi}$ (perturbative).

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

Not clear if NP is involved here.
$R_{D^{(*)}}$ puzzle

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

\[
R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)} \quad R(D^{*}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+} \ell^- \bar{\nu}_\ell)}. \]
$R_D$, $R_{D^*}$, HFAG

Average of SM predictions

\[
\begin{align*}
R(D) &= 0.299 \pm 0.003 \\
R(D^*) &= 0.258 \pm 0.005
\end{align*}
\]

$P(\chi^2) = 27\%$
The average of $R(D)$ and $R(D^*)$ measurements evaluated by the Heavy-Flavor Averaging Group are

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

According to 1904.09311

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

There are also measurements of $q^2$ distribution, $F_L^{D^*}$, $\tau$ polarization.
Model independent NP analysis

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

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

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

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...
$b \rightarrow s\mu^+\mu^-$ Anomaly

\[ H_{\text{eff}}(b \rightarrow s\ell\bar{\ell}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[ C_9 (\bar{s}_L \gamma^\mu b_L) (\bar{\ell}_\gamma \gamma^\mu \ell) \right. \]
\[ \left. + C_{10} (\bar{s}_L \gamma^\mu b_L) (\bar{\ell}_\gamma \gamma^5 \ell) \right] , \]

\[ H_{\text{eff}}(b \rightarrow s\nu\bar{\nu}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* C_L (\bar{s}_L \gamma^\mu b_L) (\bar{\nu}_\gamma \gamma^\mu (1 - \gamma^5)\nu) , \]

\[ H_{\text{eff}}(b \rightarrow s\gamma^*) = C_7 \frac{e}{16\pi^2} [\bar{s}_\sigma_{\mu\nu}(m_s P_L + m_b P_R) b] F^{\mu\nu} \]
$b \to s \mu^+ \mu^-$ 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 $m_{\text{heavy}}$. But sub-leading corrections are not known.

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

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

$H(q^2) \sim q^2$ and you reproduce $\Delta C_9$ from pure SM hadronic effect.
$R_K$, puzzle, Ratios of $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$.

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

The SM prediction of $R_{K}^{\text{SM}} = 1 \pm 0.01$

These effects can fake a $\Delta C_9$ 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 $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$. 

\[ R_K^{\text{expt}} = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} \]

$1 \leq q^2 \leq 6.0 \text{ GeV}^2$
Recently, LHCb announced new $R_K$.

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

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

Second, the Run 2 data was analyzed:

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

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

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

This is closer to the SM prediction, though the discrepancy is still $\sim 2.5\sigma$ due to the smaller errors.
Figure: Comparison of the measurements of $R_K$ from LHCb (black dots), BaBar (red squares) and Belle (blue triangles) with the SM expectation (purple line).

[Th.Humair,talkatMoriond2019]
Figure: Comparison of the measurements of $R_{K^*}$ from LHCb with (left) SM predictions and (right) BaBar and Belle.

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

$R_K$ and $R_{K^*}$ in the SM very close to 1 in the central bin and $R_{K^*} \sim 0.92$ in the low bin.
The $b \to s\mu^+\mu^-$ transitions are defined via an effective Hamiltonian with vector and axial vector operators:

$$H_{\text{eff}} = -\frac{\alpha G_F}{\sqrt{2\pi}} V_{tb} V_{ts}^* \sum_{a=9,10} (C_a O_a + C'_a O'_a),$$

$$O_{9(10)} = [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu(\gamma_5)\mu],$$

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:

$$C_a^{(i)} = C_{a,\text{SM}} + C_{a,\text{NP}}$$
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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>WC</th>
<th>$R_K$</th>
<th>$R_{K^*}^{cen}$</th>
<th>$R_{K^*}^{low}$</th>
<th>$P_5^I$</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) $C_{9,\text{NP}}^{\mu\mu}$</td>
<td>$-1.10 \pm 0.16$</td>
<td>0.78</td>
<td>0.84</td>
<td>0.89</td>
<td>$-0.50$</td>
<td>5.6</td>
</tr>
<tr>
<td>(II) $C_{9,\text{NP}}^{\mu\mu} = -C_{10,\text{NP}}^{\mu\mu}$</td>
<td>$-0.53 \pm 0.08$</td>
<td>0.76</td>
<td>0.76</td>
<td>0.86</td>
<td>$-0.70$</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table: Best-fit values of the WCs (taken to be real), the predictions for $R_K$, $R_{K^*}^{cen}$, $R_{K^*}^{low}$ and $P_5^I$, evaluated at these best-fit values, and the pull $= \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{SM+NP}}}$ 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.
### Table: Best-fit values of the WCs (taken to be real) for separate fits including the $b \to s \mu^+ \mu^-$ or $R_K(\ast)$ observables.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Data Set</th>
<th>WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) $C_{9,\text{NP}}^{\mu\mu}$</td>
<td>$R_K(\ast)$, $b \to s \mu^+ \mu^-$</td>
<td>$-0.82 \pm 0.28$ $-1.17 \pm 0.18$</td>
</tr>
<tr>
<td>(II) $C_{9,\text{NP}}^{\mu\mu} = -C_{10,\text{NP}}^{\mu\mu}$</td>
<td>$R_K(\ast)$, $b \to s \mu^+ \mu^-$</td>
<td>$-0.38 \pm 0.11$ $-0.62 \pm 0.14$</td>
</tr>
</tbody>
</table>

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

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


❖ \(R_D\) 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
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:

\[
O_{NP}^{1} = \frac{G_1}{\Lambda_{NP}^2} (\bar{Q}'_L \gamma_\mu Q'_L)(\bar{L}'_L \gamma^\mu L'_L), \\
O_{NP}^{2} = \frac{G_2}{\Lambda_{NP}^2} (\bar{Q}'_L \gamma_\mu \sigma^I Q'_L)(\bar{L}'_L \gamma^\mu \sigma^I L'_L) \\
= \frac{G_2}{\Lambda_{NP}^2} \left[ 2(\bar{Q}'_L^i \gamma_\mu Q'_L^j)(\bar{L}'_L^j \gamma^\mu L'_L^i) - (\bar{Q}'_L \gamma_\mu Q'_L)(\bar{L}'_L \gamma^\mu L'_L) \right].
\]

Here $Q' \equiv (t', b')^T$ and $L' \equiv (\nu^\tau', \tau')^T$. The key point is that $O_{NP}^{2}$ 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 $R_D(\ast)$ 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 $\mathcal{O}^{NP}_{1,2}$.

- (i) a vector boson ($VB$) that transforms as $(1, 3, 0)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as in the SM.

- (ii) an $SU(2)_L$-triplet scalar leptoquark ($S_3$) $[(3, 3, -2/3)$.

- (iii) an $SU(2)_L$-singlet vector leptoquark ($U_1$) $[(3, 1, 4/3)$.

- $SU(2)_L$-triplet vector leptoquark ($U_3$) $[(3, 3, 4/3)$.

- The vector boson generates only $\mathcal{O}^{NP}_2$, but the leptoquarks generate particular combinations of $\mathcal{O}^{NP}_1$ and $\mathcal{O}^{NP}_2$. 
Models: allowed parameter space: 1609.09078, 1806.07403

$V_B$ model: $g_{qV}^{33} = g_{iV}^{33} = \sqrt{0.5}$

$U_1$ model: $|h_{U_1}^{33}|^2 = 1$

$Z'$ models highly constrained. $U_1$ LQ is the favored model.
Predictions (Leptoquarks)

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

  \[
  VB \quad B(\Upsilon(3S) \rightarrow \mu \tau) \approx 3.0 \times 10^{-9},
  \]

  \[
  U_1 \quad B(\Upsilon(3S) \rightarrow \mu \tau)|_{\text{max}} = 8.0 \times 10^{-7}.
  \]

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

- Large observable effects in $b \rightarrow s \tau^+ \tau^- \left( B \rightarrow K(\ast) \tau^+ \tau^-, B_s \rightarrow \tau^+ \tau^- \right)$ or $b \rightarrow s \tau \mu$ and possibly LFUV in $B \rightarrow \pi \ell \bar{\nu}_\ell$ Decays.
Collider Search: 1706.07808

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

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

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

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

\[
\Delta \mathcal{L}_{t\bar{t}\tau\mu} = -\frac{1}{\Lambda_0^2} \left( \bar{t}_L \gamma_\mu t_L \right) \left( \bar{\tau}_L \gamma_\mu \mu_L \right) \tag{2}
\]
Collider Search: 1706.07808

$Z'$ $(1, 3, 0)$ is strongly constrained (ruled out) unless width is large. $Z'$ $(1, 1, 0)$ explaining only $R_K$ is fine: $M_{Z'} \sim 30$ TeV.
$\Delta(g - 2)_\mu = -\frac{N_c(h^{U}_{i\mu})^2}{16\pi^2} \left( \frac{4m^2_\mu}{3m^2_U} Q_b - \frac{5m^2_\mu}{3m^2_U} Q_U \right)$, \hspace{1cm} (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,

$\Delta(g - 2)_\mu = -1.4 \times 10^{-10} (h^{U}_{i\mu})^2 \left( \frac{\text{TeV}}{m_U} \right)^2$, \hspace{1cm} (4)
\((g - 2)_\mu\) and \(B\) anomalies: Dark Higgs

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

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

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

\[
\mathcal{L}_U = - \frac{1}{4} F_{\mu\nu}^U F^{U\mu\nu} - m_U^2 U_\mu U^\mu - \left[ h_{ij}^U \left( \bar{Q}_i L^\mu L_j L \right) U_\mu + \text{H.c.} \right] - g m_U S U_\mu U^\mu.
\]
Also contribution to $B \rightarrow K^(*)S(S \rightarrow e^+ e^-)$ and affect $R_{K^(*)}$ in the low $q^2$ bin. (1702.01099, 1705.08423, 1705.01822, 1711.07494, 1808.02611)
$S_{\gamma\gamma}$ coupling

\[ \mathcal{L}_{V_i} = -\frac{1}{4} F_{\mu\nu} V_i F^{\mu\nu} - m_{V_i}^2 V_{i\mu} V_i^{\mu} - \left[ h_{jk}^V (\bar{Q}_{jR} \gamma^{\mu} L_{kR}) V_{i\mu} + \text{H.c.} \right] \\
- g V_i m_{V_i} S V_{i\mu} V_i^{\mu}, \]

where for simplicity we add only leptoquarks with SM quantum numbers $(3, 1, \frac{5}{3})$. 
In the SM the amplitudes for the four decays can be related by isospin. The four decays can be represented by the following amplitudes:

\[
\frac{|T|}{|P|} = \frac{V_{ub} V_{us}^* c_1}{V_{cb} V_{cs}^* c_t} \sim 0.2 \quad \frac{|C|}{|P|} \sim \frac{1}{N_c} \frac{|T|}{|P|} \sim 0.04 \quad \frac{|P_{EW}|}{|P|} \sim 0.14
\]
We begin by reviewing the $B \to \pi K$ puzzle. Including only the leading diagrams the $B \to \pi K$ amplitudes become

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

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

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>$BR[10^{-6}]$</th>
<th>$A_{CP}$</th>
<th>$S_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \pi^+ K^0$</td>
<td>$23.79 \pm 0.75$</td>
<td>$-0.017 \pm 0.016$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^0 K^+$</td>
<td>$12.94 \pm 0.52$</td>
<td>$0.040 \pm 0.021$</td>
<td></td>
</tr>
<tr>
<td>$B_d^0 \rightarrow \pi^- K^+$</td>
<td>$19.57 \pm 0.53$</td>
<td>$-0.082 \pm 0.006$</td>
<td></td>
</tr>
<tr>
<td>$B_d^0 \rightarrow \pi^0 K^0$</td>
<td>$9.93 \pm 0.49$</td>
<td>$-0.01 \pm 0.10$</td>
<td>$0.57 \pm 0.17$</td>
</tr>
</tbody>
</table>

**Table:** Branching ratios, direct CP asymmetries $A_{CP}$, and mixing-induced CP asymmetry $S_{CP}$ (if applicable) for the four $B \rightarrow \pi K$ 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).

\[ b \rightarrow sZ' \rightarrow b \rightarrow s\bar{q}q \quad b \rightarrow \bar{q}D(D \rightarrow sq). \]

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

\[
\mathcal{L}_{\text{int}} = -\bar{Y}^{ij}_{i} \bar{L}^{c}_{i} i \sigma_{2} Q_{j}^{\alpha} S^{\alpha*}_{3L} - Y^{ij}_{d} \bar{d}_{i}^{\alpha c} d_{j}^{\beta} S^{\alpha \beta*}_{D} + \mu S^{\alpha*}_{3L} S^{\beta*}_{3L} S^{\alpha \beta}_{D} + (h.c.),
\]
Colored Zee Babu Model

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

\[
M_{\nu}^{i,j} = 24 \mu Y_{i}^{ik} m_{d}^{k} Y_{d}^{kl} I^{kl} m_{d}^{l} Y_{l}^{lj}.
\] (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 $\Upsilon(3S) \rightarrow \mu\tau$ and highly enhanced $b \rightarrow s\tau^+\tau^-$.  

- If true then new states like new gauge bosons, leptoquarks could be discovered.

- Light NP is highly constrained but might play a role in some of the anomalies and produce interesting signals.