Flavour Anomalies: A Review

JC110 Paper

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Introduction

1. **Flavour** is a property that distinguishes the various fermions of the **Standard Model**.
2. SM successful in describing physics up to the EW scale.
3. But **not complete**!
   - $\nu\ oscillations$
   - $darkmatter$
   - $matter - antimatterasymmetry$
4. Look for New Physics:
   - **directly**, with **high-**p_T searches
   - **directly**, with **intense** beams
   - **indirectly**, with **flavour physics**

Flavour Structure

1. In the SM, misalignment in between:
   - **Yukawa couplings**
   - **Weak Forces**
2. **The 3×3 CKM matrix** generates a flavour structure.
3. V_{CKM} **hierarchical** and nearly diagonal
   - 3^{rd} generation especially isolated
   - tree-level b decays $suppressed$, long b lifetime.
   - b-baryon decays sensitive to effects from **new virtual particles**
   - access to much **larger mass range** w.r.t. direct searches.

Lepton Flavour in the Standard Model

Lepton generations differ **only in mass.**

1. SM implies **universality** of **lepton flavour (LU)**: amplitude of processes with e , μ , τ **identical** (except phase space)
   - e.g. the decay $W \to l\nu$
2. LU will established in the decay of light mesons, e.g. $\pi \to l\nu$, $K \to \pi ll$, $J/\psi \to ll$
3. Lepton Flavour Number is conserved (for massless ν): no $l_1 \longleftrightarrow l_2$
4. stringent limits on LFV decays:
   - $\mu \to e\gamma$ X ($B \lesssim 10^{-13}$) [Eur. Phy. J.C76(2016)8, 434]
   - $K \to \pi e\mu$ X ($B \lesssim 10^{-11}$) [Phys.Rev. D72(2005)01 2005]
5. LUV or LFV $\to$ **unknown physics** not accounted for:
6. some SM extensions include particles that can cause LUV and/or LFV(e.g. LQ, Z')

Lepton Flaour in b decays

1. Semileptonic decays (**CC**): "β decays" of B hadrons.
2. tree level, large B few %
3. strong and weak part factorize $\rightarrow$ clean SM predictions
4. Rare Decays (**NC**:)great benchmarks for the SM
5. **FCNC** can only occur in loops: B 10^{-7} - 10^{-6}
6. new particles can enhance SM-suppressed amplitudes

Lepton Flaour in b decays

1. Semileptonic decays (**CC**): "β decays" of B hadrons.
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   - hints of LUV in $b \rightarrow c l \nu$
4. Rare Decays (**NC**:)great benchmarks for the SM
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6. new particles can enhance SM-suppressed amplitudes
   - anomalies in suppressed $b \rightarrow s l l$ transition

Lepton Universality in $b \to c l \nu$

Abundant $b \to c l \nu$ samples at LHC and B factories!

1. strong and weak part factorize $\to$ **clean** theory prediction
2. **hadronic** and **experimental** uncertainties cancel in **ratios** of B's
3. Standard Model: amplitude differ only because $m_\tau \gg m_{e,\mu}$
4. τ/μ: consistent **deviation** observed by 3 experiments

LHCb: R_{D^*} Muonic

1. With $\tau \to \mu\nu\nu$: **same** visible final state, with 1-3 neutrinos
2. 3D fit to **kinematic variables** to seperate μ from τ
3. $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$, 2.1σ above the SM
   - See Figure-2 (First two plots)

LHCb: R_{D^*} hadronic

1. $\tau \to \pi\pi\pi\nu$: normalize to $B \to D^*\pi\pi\pi$
2. use known ratio
   - $B\ (B \to D^*\pi\pi\pi)$ / $B\ (B \to D^*\mu\nu)$ to calculate R_{D^*}
3. additional source of uncertainty (external B's)
4. huge BG from prompt decays
5. $\to$ require displacement of τ
6. 3D fit of Kinematic variables
7. $R_{D^*} = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$, 1σ above the SM
   - See Figure-2 (plots (a) and (b))

LHCb: R_{D^*} combination

1. LHCb averages: 2.2σ above the SM prediction
2. many nice measurements from BaBar and Belle
3. R_{D^*} world average: 3.4σ above SM
4. combined with R_{D^*}: 4.1σ
5. new theory calculations seem to decrease tension
6. uncertainty dominated by lattice QCD [JHEP11(2017)061] [JHEP12(2017)060]
   - See Figure-1

1. $b \to sll$ is a FCNC transition, only possible at loop level in the SM
2. NP effects can be sizeable compared to the $b \to sll$ SM amplitude.
3. This transition is LFU in the SM
4. study $b \to sll$ search for new physics particles that distinguish between lepton flavours
5. many interesting deviations reported
6. none at the 5σ level

$b \to sll$ as a test for the SM

1. measure decay rates, angular distributions etc
2. to which new particles could contribute
3. how to parametrize all possibilities?
4. model-independent approach:
   - $L \propto \Sigma C_i O_i$, $C_i \equiv C_i^{SM} + C_i^{NP}$ "**Wilson Coefficients**"

1. many interesting anomalies in $b \to c l \nu$ and $b \to s l l$
2. some proposed decay channels currently working in BESIII too.

Xin's Question

Could you explain more about figure-6, and why "..has the potential of turning the anomalies into a groundbreaking discovery"?

Answer: we can discuss about this together.

Ryuta's Question

Could you explain what is the "optimized quantities Pi" mentioned in 3.2(and Fig.6)?

Answer: There are several observables with the combinations of spherical harmonics and the q^2 dependent angular observables. They all comprises with with CP-even (S_i) and CP-odd (A_i) observables, and with Wilson Coefficients. From these observables, optimised quantities $P_i^{(\prime)}$ can be constructed and are well explained in the reference paper [arXiv:1512.04442] (page-3).

Yuzhen's Question

In Figure-2, what is the term "combinatorial"?

Answer: This is the combined distribution of all the possible decay modes by leaving the background.

Meaning of this word: relating to the selection of a given number of elements from a larger number without regard to their arrangement.

Dengfeng's Question

Can we do something like this on BESIII?

Answer: Yes! Already proposed by professor Li Haibo arXiv: 1612.01775 and Professor Jusak Tandean in their papers arXiv: 1901.10447.

For more details look Kai's presentation :
https://indico.ihep.ac.cn/event/9325/contribution/29/material/slides/0.pdf

page-4 [experimental status]

The End