What if R_π is SM-like?

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Beyond the Flavour Anomalies III

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Theory Thoughts

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Want to identify the new physics flavor structure and, along the way, maybe also make progress in understanding the SM flavor structure

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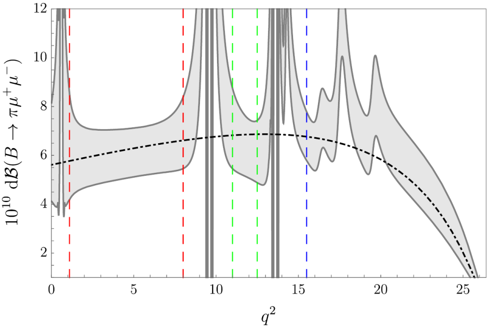
- already existing measurements of $b \to d$ processes can be used to probe new physics (Rusov 1911.12819)
- $b \to d$ will become the new $b \to s$ (after high-lumi phase, will have $\sim$ comparable statistics for $b \to d$ as there is now for $b \to s$)

SM Prediction for R_π



Bordone et al.
2101.11626

- SM predictions of the individual branching ratios require modeling of non local effects
- in addition to the famous "charm loops" in $b \to s\ell\ell$, there are also light resonances: ρ, ω, ϕ (Hambrock et al. 1506.07760, Khodjamirian, Rusov 1703.04765, ...)
- resonance contributions are to a very good approximation lepton universal

$$R_\pi = 1.00 \pm 0.01 \quad \text{(inclusive of photon radiation)}$$

Generic New Physics Sensitivity

$$\mathcal{H}_{\text{eff}}^{b\to q\ell\ell} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \frac{\alpha}{4\pi}\Big(C_9^{bq\ell\ell}\mathcal{O}_9^{bq\ell\ell} + C_{10}^{bq\ell\ell}\mathcal{O}_{10}^{bq\ell\ell} + ...\Big)$$

$$\frac{4G_F}{\sqrt{2}}|V_{tq}^* V_{tb}|\frac{\alpha}{4\pi} = \frac{1}{\Lambda_{bq\ell\ell}^2} \simeq \begin{cases} 1/(35\text{ TeV})^2 & \text{for } q = s \\ 1/(78\text{ TeV})^2 & \text{for } q = d \end{cases}$$

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- Actual new physics sensitivity depends on the experimental precision

$$\Lambda_{\text{NP}} \sim 70\text{ TeV} \times \left(\frac{5\%}{\delta R_K / R_K} \right)^{\frac{1}{2}} , \quad \Lambda_{\text{NP}} \sim 70\text{ TeV} \times \left(\frac{25\%}{\delta R_\pi / R_\pi} \right)^{\frac{1}{2}}$$

- The generic new physics sensitivity of a R_π measurement with 25% precision is comparable to a R_K measurement with 5% precision (assuming that the new flavor changing couplings are all $\mathcal{O}(1)$)

Minimal Flavor Violation and $U(2)^5$

- New physics models with new flavor changing couplings that are all $\mathcal{O}(1)$ should have been discoverd long time ago (remember: ϵ_K is sensitive to new physics at 10^5 TeV)
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- If B anomalies are due to new physics, its flavor structure cannot be completely generic.
- Want some form of flavor protection, e.g. Minimal Flavor Violation, or minimally broken $U(2)^5$
- Such scenarios predict a tight link between $b \to s$ and $b \to d$ transitions

$$C_{9,10}^{bd\ell\ell} \simeq C_{9,10}^{bs\ell\ell}$$

- Based on global $b \to s\ell\ell$ fits (e.g. WA Stangl 2103.13370), one expects

$$R_\pi \simeq R_K = 0.85 \pm 0.03$$

Froggatt-Nielsen Type Models

- small fermion masses are forbidden by flavor symmetries
  and arise only after spontaneous breaking of some symmetry
  (Froggatt, Nielsen ’79; ...)
- mass and mixing hierarchies given by powers of a spurion $\epsilon = \langle\varphi\rangle/M$
- simplest $U(1)$ flavor model (Leurer, Nir, Seiberg ’93)

$$Q(q_1) = 3,\ Q(q_2) = 2,\ Q(q_3) = 0,$$
$$Q(d_1) = -3,\ Q(d_2) = -2,\ Q(d_3) = -2,$$
$$Q(u_1) = -3,\ Q(u_2) = -1,\ Q(u_3) = 0$$

$$Y_u \sim \begin{pmatrix} \epsilon^6 & \epsilon^4 & \epsilon^3 \\ \epsilon^5 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^1 & \epsilon^0 \end{pmatrix} , \quad Y_d \sim \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \end{pmatrix}$$

Froggatt-Nielsen Type Models

Froggatt-Nielsen predictions for $b \to d\ell\ell$ transitions

$$C_{9,10}^{bd\ell\ell} \sim \epsilon^{|Q(q_1)-Q(q_2)|} \frac{V_{ts}^* V_{tb}}{V_{td}^* V_{tb}} \times C_{9,10}^{bs\ell\ell} = \mathcal{O}(1) \times C_{9,10}^{bs\ell\ell}$$

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- Expect the same order of magnitude effect in R_π and R_K. However, the new physics effect in R_π could have any sign/phase
- Such scenarios are typically subject to strong constraints from Kaon physics (ϵ_K)
- $\Delta R_\pi \gg \Delta R_K$ or $\Delta R_\pi \ll \Delta R_K$ (or R_π completely SM-like) can in principle be accommodated (by tuning the unknown $\mathcal{O}(1)$ factors) but would be somewhat a surprise.
- A SM-like R_π would suggest a non-trivial flavor model

An Even Cleaner Ratio?

"A ratio of ratios of branching ratios"

$$\frac{R_\pi}{R_K} = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \text{BR}(B \to \pi\mu^+\mu^-)}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \text{BR}(B \to \pi e^+ e^-)} \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \text{BR}(B \to K e^+ e^-)}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \text{BR}(B \to K\mu^+\mu^-)}$$

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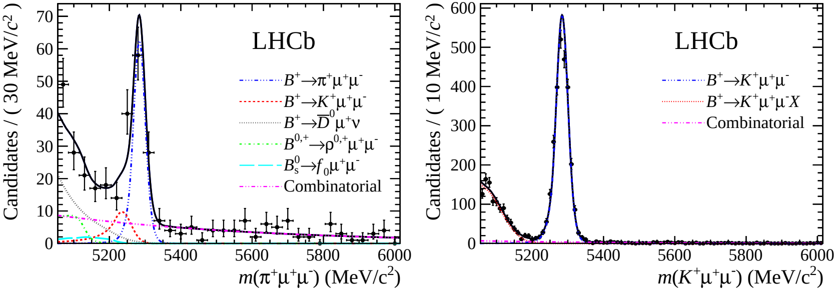
- hadronic effects cancel in the ratio of muons to electrons
- QED corrections cancel (?) in the ratio of π to K
- measurement of R_π/R_K is a test of the quark flavor structure of lepton universality violation
- departure of R_π/R_K from 1 implies new sources of quark flavor violation beyond MFV or $U(2)^5$ models

Experimental Prospects on $B \to \pi\ell\ell$

Current state

$B^\pm \to \pi^\pm \mu^+ \mu^-$ **measured with 3 fb^{-1} LHCb (JHEP 10 (2015) 034)**

- Selected $\mathcal{O}(100)$*events*



- Total BF and $\mathcal{A}_{CP}$

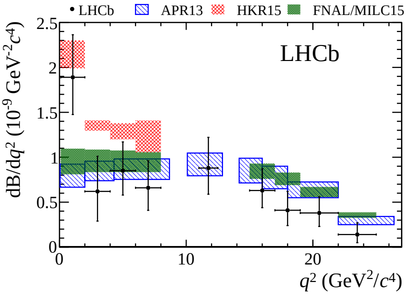
$$\mathcal{B}(B^\pm \to \pi^\pm \mu^+ \mu^-) = (1.83 \pm 0.24(\mathrm{stat}) \pm 0.05(\mathrm{syst})) \times 10^{-8}$$
$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm \mu^+ \mu^-) = -0.11 \pm 0.12(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

$B^\pm \to \pi^\pm\mu^+\mu^-$ **measured with 3 fb^{-1} LHCb (JHEP 10 (2015) 034)**

- BF relative to $B^\pm \to K^\pm\mu^+\mu^-$

$$0.038 \pm 0.009(\mathrm{stat}) \pm 0.001(\mathrm{syst}) \qquad (1 \leq q^2 < 6\,\mathrm{GeV}^2)$$
$$0.037 \pm 0.008(\mathrm{stat}) \pm 0.001(\mathrm{syst}) \qquad (15 \leq q^2 < 22\,\mathrm{GeV}^2)$$
$$\to \left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04}$$

- Differential branching fraction



Immediate future

$B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ **with 9 fb^{-1} at LHCb**

- Expect $\mathcal{O}(400)$ events
- Measure BF, $\mathcal{A}_{CP}$, & rel BF simulataneously in 2 GeV^2 bins
  - Naive lumi scaling 10-15% resolution (bin dependent)
  - Better method to extract $\left|\frac{V_{td}}{V_{ts}}\right|$ (as suggested in JHEP08(2017)112)
- Measure A_{FB} and F_H in wide bins
- Analysis well advanced

$B^{\pm} \to \pi^{\pm}e^{+}e^{-}$ **with 9 fb^{-1} at LHCb**

- Expect $\mathcal{O}(20)$ events (assuming $R_{\pi} \approx 1$)
- Analysis underway
- Maybe get first observation of $B^{\pm} \to \pi^{\pm}e^{+}e^{-}$ and limit on R_{π}
- Becomes more interesting with more data

With LHCb Run 3 data

$B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ at LHCb with Run 3 data

- Expect $\mathcal{O}(2000)$ events
- Can look at narrow bins
- Can start to think of unbinned analyses
- Fitting for Wilson coeffs

$B^{\pm} \to \pi^{\pm}e^{+}e^{-}$ at LHCb with Run 3 data

- Expect $\mathcal{O}(100)$ events
- Now in interesting territory

$B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ at LHCb with 300 fb^{-1}

- Expect $\mathcal{O}(17k)$ events
- Can repeat all the current $B \to K\mu\mu$ analyses with the pion mode

$B^{\pm} \to \pi^{\pm}e^{+}e^{-}$ at LHCb with 300 fb^{-1}

- Expect $\mathcal{O}(600)$ events
- $\sim 4\%$ resolution of R_{π}

The other experiments

Belle II

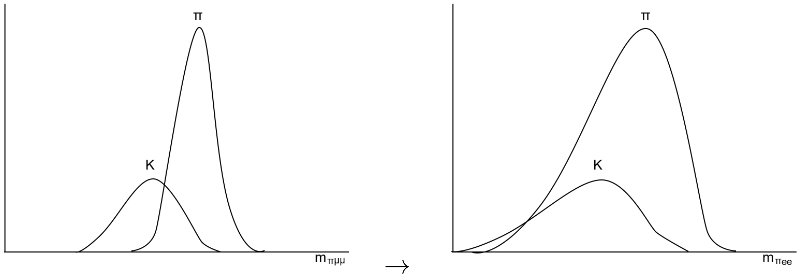
- Unofficial numbers for 50 ab^{-1}
- Expect $\mathcal{O}(150)$ $B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ events
- Expect $\mathcal{O}(150)$ $B^{\pm} \to \pi^{\pm}e^{+}e^{-}$ events
- Short term competitive with LHCb for R_{π} esp with electron resolution

ATLAS & CMS

- Seemingly will be swamped by the kaon modes
- Without improvements hard to see contributions soon

What to do with the data

$B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ **vs** $B^{\pm} \to \pi^{\pm}e^{+}e^{-}$



- Need to control shape and size of $B \to K\mu\mu$ leakage
- Size is R_K
- Can constrain from dedicated R_K measurement
- Or simultaneous measurement of R_π and R_K
- Conceivable to perform in bins of PID with different purities

Questions

- Which q^2 bins should one use for R_π ?
- Is there value in a q^2 integrated R_π (vetoing the resonances)?
- Are there advantages measuring R_π/R_K ?