Toward explaining B Decay anomalies

Bhubanjyoti Bhattacharya
(bhujyo@wayne.edu)

Wayne State University

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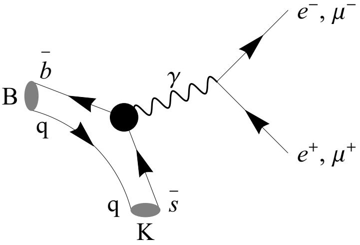
Argonne National Laboratory

B decay Anomalies

R_K anomaly :



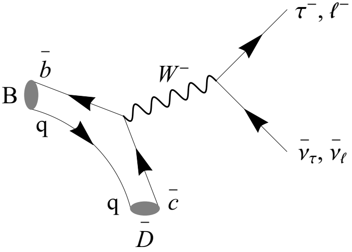
Expected: $R_K \;=\; 1.00 \pm 0.01$

(hep-ph\0310219, 0709.4174, 1605.07633,. . .)

LHCb measured (2.6 σ deviation):

$R_K \;=\; 0.745^{+0.097}_{-0.082}$ (PRL 2014)

R_D, D_{D*} anomalies :



Belle + BaBar :

$R_D^{\text{expt}}/R_D^{\text{SM}} = 1.29 \pm 0.17$ (1.7 σ)

$R_{D^*}^{\text{expt}}/R_{D^*}^{\text{SM}} = 1.28 \pm 0.09$ (3.1 σ)

(Watanabe et al. 1212.1878, 1310.1937, . . .)

Effective field theory

$b \to s\ell^+\ell^-$:

- $\mathcal{L} \ \sim \ G_F(V_{tb}^* V_{ts})(\overline{\psi}_d \Gamma \psi_d)(\overline{\psi}_\ell \Gamma \psi_\ell)$
- $\Gamma = 1, \gamma^\mu, \ldots$; Lorentz invariance
- Dimension 6 operator : $G_F \sim 1/m_W^2$
- Flavor-changing neutral-current : loop suppressed in SM

$b \to c\ell^+\nu_\ell$:

- $\mathcal{L} \ \sim \ G_F V_{cb}(\overline{\psi}_d \Gamma \psi_u)(\overline{\psi}_\ell \Gamma \psi_\ell)$
- $\Gamma = 1, \gamma^\mu, \ldots$; Lorentz invariance
- Dimension 6 operator : $G_F \sim 1/m_W^2$
- Charged-current : tree level, unsuppressed in SM

NP in $b \to c\ell^+\nu_\ell$

$b \to c\ell^+\nu_\ell$:

- $\mathcal{L}_{\mathrm{NP}} \;\sim\; G_{\mathrm{NP}}(\overline{\psi}_d\Gamma\psi_u)(\overline{\psi}_\ell\Gamma\psi_\ell)$
- $G_{\mathrm{NP}} \sim 1/\Lambda^2_{\mathrm{NP}}$; Scalar NP $\to$ 2HDMs
- R_D and R_{D^*} different $\Rightarrow$ different $\tan\beta/m_H$ for each
- Type III 2HDM : Crivellin et al. 1206.2634
  Also explains $B \to \tau\nu$
- More recent model-independent fits : Jung et al. 1612.07757
  Include measured differential distributions
  Need scalar couplings to both left and right-handed particles

NP in $b \to s\ell^+\ell^-$

$b \to s\ell^+\ell^-$:

- $\mathcal{L}_{\rm NP} \;\sim\; G_{\rm NP}(\overline{\psi}_d\gamma^\mu(1-\gamma^5)\psi_d)(\overline{\psi}_\ell\gamma_\mu(C_9+C_{10}\gamma^5)\psi_\ell)$
- $G_{\rm NP} \sim 1/\Lambda^2_{\rm NP}$; In SM : $C_9 \simeq -C_{10}$
- Fits indicate left-handed NP : $C_9^{\rm NP} \simeq -C_{10}^{\rm NP} < 0$
  Hiller et al. : 1408.1627, Matias et al. : 1510.04239
- Consistent with data from $B \to K^{(*)}\mu\mu$
- NP in μ favored : Renner et al. 1408.4097,

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- NP in μ favored : Renner et al. 1408.4097,
- $R_K < 1 \Rightarrow$ Lepton flavor non-universal new physics
  $\Rightarrow$ Lepton flavor violation Glashow et al. : 1411.0565
- Gauge basis : $\mathcal{L}_{\rm NP} \sim (1/\Lambda^2_{\rm NP})(\overline{b}_L\gamma^\mu b_L)(\overline{\tau}_L\gamma_\mu\tau_L)$

  Mass basis : $\mathcal{L}_{\rm NP} \sim (1/\Lambda^2_{\rm NP})U_d^{*3i}U_d^{3j}U_\ell^{*3k}U_\ell^{3l}(\overline{d}^i_L\gamma^\mu d^j_L)(\overline{\ell}^k_L\gamma_\mu\ell^l_L)$

  R_K appears due to $|U_\ell^{32}|^2$; LFV predictions such as $b \to s\mu\tau$

Simultaneous explanation of anomalies

- Grinstein et al. 1407.7044: (in context of B decays)
  $\Lambda_{\rm NP} >> v \Rightarrow$ restore electro-weak symmetry
- Proposal : with D.London, A.Datta, Shivasankara (1412.7164)
  $\rightarrow$ SU(2)$_W\times$ U(1)$_Y$ invariant third-generation operators
- Neutral current : $g_1(\overline{Q}_{3L}\gamma^\mu Q_{3L})(\overline{L}_{3L}\gamma_\mu L_{3L})$
  Charged current : $g_2(\overline{Q}_{3L}\gamma^\mu \sigma^I Q_{3L})(\overline{L}_{3L}\gamma_\mu \sigma^I L_{3L})$

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- R_K explanation similar to Glashow et al. : 1411.0565
- $b \rightarrow s\mu^+\mu^- \propto (g_1 + g_2)$
- In addition, constraints from $b \rightarrow s\nu\overline{\nu} \propto (g_1 - g_2)$
- Prediction: $R_D^{\rm expt}/R_D^{\rm SM} = R_{D^*}^{\rm expt}/R_{D^*}^{\rm SM}$
- Prediction: $BR(t \rightarrow c\tau^+\tau^-) \sim 5\times 10^{-8}$ (out of range of LHC?)
  See also Hiller et al. 1408.1627

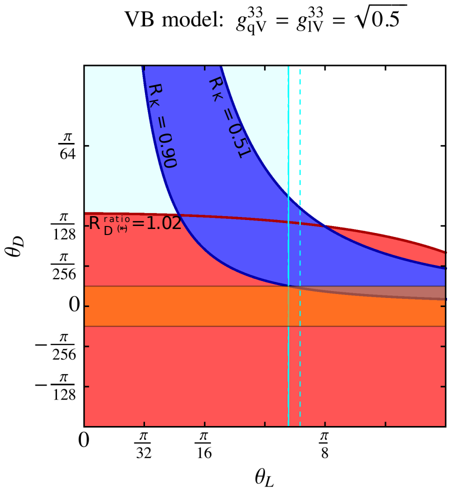
Tree-level new physics models : Choice 1

New triplet vector boson :

- Examples of models proposed :
  Crivellin et al. 1503.03477, Isidori et al. 1506.01705,
  Valencia at al. 1601.07328, ...
- $\mathcal{L} \ = \ \left[g_Q(\overline{Q}_{3L}\gamma_\mu\sigma^I Q_{L3}) + g_L(\overline{L}_{3L}\gamma_\mu\sigma^I L_{3L})\right] V^{\mu I}$
- Integrate out heavy vector : $g_1 = 0, \ \ g_2 = -g_Q g_L$
- Studied with A.Datta, D.London, J.-P.Guévin, R.Watanabe (1609.09078)
- Assume mixings between 2 - 3 generations Crivellin et al. 1506.02661
  Mixing parameters : θ_D (b and s); θ_L (μ and τ)
- Contributions to :

$b \to s\mu\mu$	NP contribution $\propto \cos\theta_D \sin\theta_D \sin^2\theta_L$
$B_s^0 - \bar{B}_s^0$ mixing	NP contribution $\propto \cos^2\theta_D \sin^2\theta_D$;
$\tau \to 3\mu$	BR $\propto \cos^2\theta_L \sin^6\theta_L$

New vector bosons



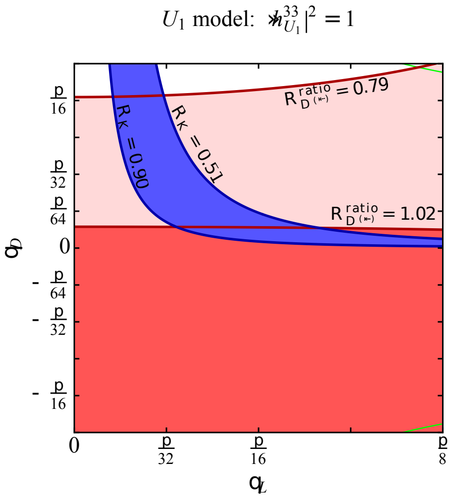
- $M_V \sim 1$ TeV
- Orange: $B^0_s - \bar{B}^0_s$ mixing (ΔM_s)
- Cyan: $\tau \to 3\mu \lesssim 10^{-8}$ (Belle measurement)
- Belle II update will perhaps rule out this simple scenario

Tree-level new physics models : Choice 2

Leptoquarks :

- Spin : Scalar, Vector; Isospin : Singlet, Doublet, Triplet;
  Watanabe et al. 1309.0301, ...
- Scalar Triplet : $g_{S_3}(\overline{Q}_{L3}\sigma^I i\sigma^2 L^c_{L3})S^I_3$ $\qquad g_1 = 3g_2$
- Vector Singlet : $g_{U_1}(\overline{Q}_{L3}\gamma_\mu L_{L3})U^\mu_1$ $\qquad g_1 = g_2$
- Vector Triplet : $g_{U_3}(\overline{Q}_{L3}\gamma_\mu\sigma^I L_{L3})U^{\mu I}_3$ $\qquad g_1 = -3g_2$
  Crivellin et al. 1506.02661
- Assume same mixing patterns as in VB :
  θ_D (b and s), θ_L (μ and τ)
- Vector singlet model is still allowed. Contributions:
  $b \to s\nu\bar{\nu}$: $g_1 = g_2 \Rightarrow$ No contribution;
  $b \to s\mu\mu$, $R_{D^{(*)}}$

Vector-singlet leptoquark



- $M_V \sim 1$ TeV
- Green: $\tau \to \mu\phi$ bound
- No B_s mixing or $\tau \to 3\mu$ at tree level
- Quite a bit of allowed parameter space
- Prediction : $\Upsilon(3S) \to \mu\tau \sim 8 \times 10^{-7}$ Should be seen at Belle II

Interesting channels

- Flavor-universality tests:
  $\rightarrow\ B \rightarrow K^{(*)}\tau^+\tau^-$
  $\rightarrow\ B_s \rightarrow \tau^+\tau^-$
  $\rightarrow\ \Upsilon(nS) \rightarrow \tau^+\tau^-$
  $\rightarrow\ R_K,\ R_{K^*},\ R_{X_s},\ R_D,\ R_{D^*}$
- Reconfirm using flavor-violation tests:
  $\rightarrow\ B \rightarrow K^{(*)}\tau\mu$
  $\rightarrow\ B_s \rightarrow \tau\mu$
  $\rightarrow\ \Upsilon(nS) \rightarrow \tau\mu$
- Future LHCb, Belle II precision measurements are important

Global fits

- Studied with Jacky Kumar, Dinesh Kumar and others (1703.09247)
- Observables :
  $\rightarrow$ Angular observables in $B \rightarrow K^* \mu^+ \mu^-$
  $\rightarrow$ Differential distribution in $B \rightarrow K \mu^+ \mu^-$
  $\rightarrow$ Angular observables in $B_s \rightarrow \phi \mu^+ \mu^-$ (partial)
  $\rightarrow B \rightarrow X_s \mu^+ \mu^-$, $B_s \rightarrow \mu^+ \mu^-$
- We use flavio by D. Straub
- Agreement with model-independent scenarios :
  $\rightarrow C_9(NP) < 0$ (Matias et al. 1510.04239)
  $\rightarrow C_9(NP) = -C_{10}(NP) < 0$
  $\rightarrow C_9(NP) = -C_9'(NP) < 0$
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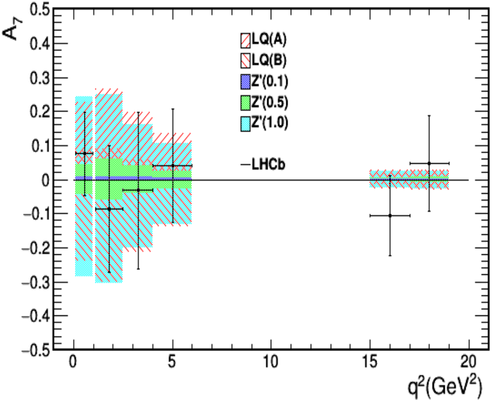
- Goal : distinguish models using future CPV measurements
- Studies including recent LHC data : Altmannshofer et al. 1703.09189

Example T-odd observable (1703.09247)



- Large T-odd asymmetries Hiller et al. 0805.2525
- CP asymmetry from CP-odd phase difference between SM and NP
- T-odd triple products: Large for small CP-even phase difference
- Z' : $g_{\mu\mu},\ g_{bs},\ g_{bs}^{*}$
- LQ : $g_{\ell q}^{\mu b} g_{\ell q}^{*\mu s}$

Conclusions

- Look for the flavor tail of new physics
- Precision measurements are important!
- Hopefully LHCb or Belle II data will give us the tail
- Combination of different channels/ anomalies are going to be important Example : Lepton non-universality + flavor violation

Thank You!

Back-up Slides

Wilson coefficients in $b \to s\mu\mu$

SM operators:

$$\mathcal{L}_{\text{eff}} \supset \frac{G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V_{tb} V_{ts}^* \left(C_9 \mathcal{O}_9 + C_{10} \mathcal{O}_{10} \right)$$

$$\mathcal{O}_9 = (\overline{s}_L \gamma^\mu b_L)(\overline{\mu} \gamma_\mu \mu) \qquad \mathcal{O}_{10} = (\overline{s}_L \gamma^\mu b_L)(\overline{\mu} \gamma_\mu \gamma^5 \mu)$$

New operators:

$$\mathcal{O}_9' = (\overline{s}_R \gamma^\mu b_R)(\overline{\mu} \gamma_\mu \mu) \qquad \mathcal{O}_{10}' = (\overline{s}_R \gamma^\mu b_R)(\overline{\mu} \gamma_\mu \gamma^5 \mu)$$

$B \to K^*\mu\mu$ angular distribution

$$\frac{1}{d(\Gamma+\overline{\Gamma})/dq^2}\frac{d^4(\Gamma+\overline{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_{K^*} \; + \; F_L\cos^2\theta_{K^*}$$

$$+ \; \frac{1}{4}(1-F_L)\sin^2\theta_{K^*}\cos 2\theta_\ell \; - \; F_L\cos^2\theta_{K^*}\cos 2\theta_\ell$$

$$+ \; S_3\sin^2\theta_{K^*}\sin^2\theta_\ell\cos 2\phi \; + \; S_4\sin 2\theta_{K^*}\sin 2\theta_\ell\cos\phi$$

$$+ \; S_5\sin 2\theta_{K^*}\sin\theta_\ell\cos\phi \; + \; \frac{4}{3}A_{FB}\sin^2\theta_{K^*}\cos\theta_\ell$$

$$+ \; S_7\sin 2\theta_{K^*}\sin\theta_\ell\sin\phi \; + \; S_8\sin 2\theta_{K^*}\sin 2\theta_\ell\sin\phi$$

$$+ \; S_9\sin^2\theta_{K^*}\sin^2\theta_\ell\sin 2\phi\Big]$$

$B \to K^*\mu\mu$ angles