Rare $B$ decays & new physics

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Outline

 introductions

 rare semileptonic mode $B \rightarrow K^* \ell^+ \ell^-$
  Model independent framework
  Evidence of new physics

 lepton flavor non-universality

 summary
Introduction

Loop and CKM suppressed SM amplitude

Sensitive to new particle in loop

Large no. of experimentally accessible observables

Valuable probe for indirect search of NP
Introduction

Angular analysis in well known helicity frame [Kruger, Sehgal, Sinha, Sinha ‘99]

The differential distribution

\[
\frac{d^4\Gamma(B \rightarrow K^*\ell^+\ell^-)}{dq^2 \, d\cos \theta_l \, d\cos \theta_K \, d\phi} = \frac{9}{32\pi} \left[ I_1^s \sin^2 \theta_K + I_2^c \cos^2 \theta_K + (I_2^s \sin^2 \theta_K + I_3^c \cos^2 \theta_K) \cos 2\theta_l + I_3^s \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ I_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + I_5 \sin 2\theta_K \sin \theta_l \cos \phi + I_6^s \sin^2 \theta_K \cos \theta_l \\
+ I_7 \sin 2\theta_K \sin \theta_l \sin \phi + I_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + I_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]
Motivation

\[ I_i = \text{short distance} + \text{long distance} \]
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Wilson coefficients: perturbatively calculable
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Wilson coefficients:
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Form-factors:
non-perturbative estimates
from LCSR, HQET, Lattice …

\textit{tremendous effort since past}
Motivation

\[ I_i = \text{short distance} + \text{long distance} \]

Wilson coefficients: 
perturbatively calculable

Form-factors: 
non-perturbative estimates
from LCSR, HQET, Lattice …

Non-factorizable contributions:

no quantitative computation

tremendous effort since past

Challenge: either estimate accurately or \textit{eliminate}
The amplitude \( \mathcal{A} \left( B(p) \rightarrow K^*(k) \ell^+ \ell^- \right) \) is given by

\[
\frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{ts}^* \left\{ C_9 \langle K^* | \bar{s} \gamma^\mu P_L b | \bar{B} \rangle - \frac{2 C_7}{q^2} \langle K^* | \bar{s} i \sigma^{\mu\nu} q_\nu (m_b P_R + m_s P_L) b | \bar{B} \rangle - \frac{16 \pi^2}{q^2} \sum_{i=\{1-6,8\}} C_i \mathcal{H}_i^{\mu} \right\} \bar{\ell} \gamma_\mu \ell + C_{10} \langle K^* | \bar{s} \gamma^\mu P_L b | \bar{B} \rangle \bar{\ell} \gamma_\mu \gamma_5 \ell \]

[RM, Sinha, Das '14]
Model Independent Framework

The amplitude \( \mathcal{A} (B(p) \to K^*(k)\ell^+\ell^-) \) \[ RM, Sinha, Das '14 \]

\[
\begin{align*}
&= \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left\{ C_9 \langle K^* | \bar{s}\gamma^\mu P_L b | \bar{B} \rangle - \frac{2C_7}{q^2} \langle K^* | \bar{s}i\sigma^{\mu\nu} q_\nu (m_b P_R + m_s P_L) b | \bar{B} \rangle \\
&\quad - \frac{16\pi^2}{q^2} \sum_{i=\{1-6,8\}} C_i \mathcal{H}_i^\mu \right\} \ell\gamma_\mu \ell + C_{10} \langle K^* | \bar{s}\gamma^\mu P_L b | \bar{B} \rangle \bar{\ell}\gamma_\mu \gamma_5 \ell
\end{align*}
\]

Wilson coefficients
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\end{align*}
\]

Wilson coefficients

lorentz & gauge invariance allow general parametrization with form-factors \( \mathcal{X}_j, \mathcal{Y}_j \)
Model Independent Framework

The amplitude $A(B(p) \rightarrow K^*(k)\ell^+\ell^-)$

$$= \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left\{ C_9 \left\langle K^* | \bar{s} \gamma^\mu P_L b | \bar{B} \right\rangle - \frac{2C_7}{q^2} \left\langle K^* | \bar{s} i \sigma^{\mu\nu} q_\nu (m_b P_R + m_s P_L) b | \bar{B} \right\rangle ight.$$ 

$$- \frac{16\pi^2}{q^2} \sum_{i=\{1-6,8\}} C_i H_{i}^\mu \left\{ \bar{\ell} \gamma_\mu \ell + C_{10} \left\langle K^* | \bar{s} \gamma^\mu P_L b | \bar{B} \right\rangle \bar{\ell} \gamma_\mu \gamma_5 \ell \right\}$$

Wilson coefficients

lorentz & gauge invariance allow general parametrization with form-factors $\chi_j$, $\psi_j$

non-local operator for non factorization contributions

$$H_i^\mu \sim \left\langle K^* | i \int d^4 x e^{iq \cdot x} T\{j_{em}^\mu(x), O_i(0)\} | \bar{B} \right\rangle$$

parametrize with ‘new’ form-factors $\chi_{ij}$

[Rm, Sinha, Das '14]

[Khodjamirian et. al’10]
Model Independent Framework

Absorbing factorizable & non-factorizable contributions into

\[ C_9 \rightarrow \tilde{C}_9^{(j)} = C_9 + \Delta C_9^{(\text{fac})}(q^2) + \Delta C_9^{(j),(\text{non-fac})}(q^2) \]

\[ \sim \sum_i C_i \frac{Z_j^i}{\lambda_j} \]

\[ \frac{2(m_b + m_s)}{q^2} C_7 \mathcal{V}_j \rightarrow \tilde{\mathcal{V}}_j = \frac{2(m_b + m_s)}{q^2} C_7 \mathcal{V}_j + \cdots \]
Model Independent Framework

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\[ C_9 \rightarrow \tilde{C}_9^{(j)} = C_9 + \Delta C_9^{(\text{fac})}(q^2) + \Delta C_9^{(j), (\text{non-fac})}(q^2) \]

\[ \sim \sum_i C_i \mathcal{Z}_j^i / \mathcal{X}_j \]

\[ \frac{2(m_b+m_s)}{q^2} C_7 \mathcal{Y}_j \rightarrow \tilde{\mathcal{Y}}_j = \frac{2(m_b+m_s)}{q^2} C_7 \mathcal{Y}_j + \cdots \]

Most general parametric form of amplitude in SM

\[ A_{\lambda}^{L,R} = (\tilde{C}_9^\lambda + C_{10}) \mathcal{F}_\lambda - \tilde{\mathcal{G}}_\lambda \quad A_t \big|_{m_\ell=0} = 0 \]

Form-factors: \( \mathcal{F}_\lambda \equiv \mathcal{F}_\lambda(\mathcal{X}_j) \) and \( \tilde{\mathcal{G}}_\lambda \equiv \tilde{\mathcal{G}}_\lambda(\tilde{\mathcal{Y}}_j) \)
Right-Handed Current

- Chirality flipped operators $\mathcal{O} \leftrightarrow \mathcal{O'}$
  
  $$\bar{s}\gamma_\mu P_L b \leftrightarrow \bar{s}\gamma_\mu P_R b$$
  $$\bar{s}i\sigma_{\mu\nu} P_R b \leftrightarrow \bar{s}i\sigma_{\mu\nu} P_L b$$

- In presence of right-handed gauge boson or other kind of new particles like leptoquarks etc..
RH Current

Amplitudes \( \mathcal{A}^{L,R}_\perp = ((\tilde{C}_9 \perp + C'_9) \mp (C_{10} + C'_{10})) \mathcal{F}_\perp - \tilde{\mathcal{G}}_\perp \)
\( \mathcal{A}^{L,R}_\parallel = ((\tilde{C}_9 \parallel,0 - C'_9) \mp (C_{10} - C'_{10})) \mathcal{F}_\parallel,0 - \tilde{\mathcal{G}}_\parallel,0 \)

Notation \( r_\lambda = \frac{\text{Re}(\tilde{\mathcal{G}}_\lambda)}{\mathcal{F}_\lambda} - \text{Re}(\tilde{C}_9^\lambda) \)
\( \xi = \frac{C'_{10}}{C_{10}} \quad \xi' = \frac{C'_9}{C_{10}} \)

Variables \( R_\perp = \frac{r_\perp}{1 + \xi} \), \( R_\parallel = \frac{r_\parallel}{1 - \xi} \), \( R_0 = \frac{r_0}{1 - \xi} \).

HQET limit \( \frac{\tilde{\mathcal{G}}_\parallel}{\mathcal{F}_\parallel} = \frac{\tilde{\mathcal{G}}_\perp}{\mathcal{F}_\perp} = \frac{\tilde{\mathcal{G}}_0}{\mathcal{F}_0} = -\kappa \frac{2m_bm_BC_7}{q^2}, \)
\[ \text{[Grinstein, Prijol '04]} \]
\[ \text{[Bobeth et. al'10]} \]

\( r_0 = r_\parallel = r_\perp \equiv r \) ignoring non-factorisable corrections

\( R_0 = R_\parallel \neq R_\perp \) in presence of RH currents
RH Current

At kinematic endpoint

- exact HQET limit
- polarization independent
- non-factorisable correction

**Observables**

\[ F_L(q^2_{\text{max}}) = \frac{1}{3}, \quad F_{\parallel}(q^2_{\text{max}}) = \frac{2}{3}, \quad A_4(q^2_{\text{max}}) = \frac{2}{3\pi}, \]

\[ F_\perp(q^2_{\text{max}}) = 0, \quad A_{FB}(q^2_{\text{max}}) = 0, \quad A_{5,7,8,9}(q^2_{\text{max}}) = 0. \]

[Hiller, Zwicky '14]

**Taylor series expansion around** \[ \delta \equiv q^2_{\text{max}} - q^2 \]

\[ F_L = \frac{1}{3} + F_L^{(1)} \delta + F_L^{(2)} \delta^2 + F_L^{(3)} \delta^3 \]

\[ F_\perp = F_\perp^{(1)} \delta + F_\perp^{(2)} \delta^2 + F_\perp^{(3)} \delta^3 \]

\[ A_{FB} = A_{FB}^{(1)} \delta^{\frac{1}{2}} + A_{FB}^{(2)} \delta^{\frac{3}{2}} + A_{FB}^{(3)} \delta^{\frac{5}{2}} \]

\[ A_5 = A_5^{(1)} \delta^{\frac{1}{2}} + A_5^{(2)} \delta^{\frac{3}{2}} + A_5^{(3)} \delta^{\frac{5}{2}}, \]
Fit to 14 bin LHCb data including correlation among observables
RH Current

Fit to 14 bin LHCb data including correlation among observables

<table>
<thead>
<tr>
<th></th>
<th>$O^{(1)}(10^{-2})$</th>
<th>$O^{(2)}(10^{-3})$</th>
<th>$O^{(3)}(10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_L$</td>
<td>$-2.85 \pm 1.26$</td>
<td>$12.13 \pm 1.90$</td>
<td>$-5.68 \pm 0.67$</td>
</tr>
<tr>
<td>$F_\perp$</td>
<td>$6.89 \pm 1.65$</td>
<td>$-9.79 \pm 2.47$</td>
<td>$3.83 \pm 0.86$</td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>$-30.58 \pm 1.95$</td>
<td>$26.96 \pm 3.58$</td>
<td>$-4.15 \pm 1.47$</td>
</tr>
<tr>
<td>$A_5$</td>
<td>$-15.85 \pm 1.87$</td>
<td>$5.38 \pm 3.33$</td>
<td>$2.46 \pm 1.29$</td>
</tr>
</tbody>
</table>
RH Current

Limiting analytic expressions

\[ R_\perp(q_{\text{max}}^2) = \frac{\omega_2 - \omega_1}{\omega_2 \sqrt{\omega_1 - 1}}, \quad R_\parallel(q_{\text{max}}^2) = \frac{\sqrt{\omega_1 - 1}}{\omega_2 - 1} = R_0(q_{\text{max}}^2) \]

\[ \omega_1 = \frac{3}{2} \frac{F_\perp^{(1)}}{A_{FB}^{(1)}} \quad \text{or} \quad \frac{3}{8} \frac{F_\perp^{(1)}}{A_5^{(1)}} \quad \text{and} \quad \omega_2 = \frac{4 \left( 2A_5^{(2)} - A_{FB}^{(2)} \right)}{3 A_{FB}^{(1)} \left( 3F_L^{(1)} + F_\perp^{(1)} \right)} \quad \text{or} \quad \frac{4 \left( 2A_5^{(2)} - A_{FB}^{(2)} \right)}{6 A_5^{(1)} \left( 3F_L^{(1)} + F_\perp^{(1)} \right)} \]

No RH current line

SM prediction

Large deviation between slopes
Results in $C'_{10}/C_{10} - C'_{9}/C_{10}$

SM input

More than $5\sigma$ deviation

$C'_{10}/C_{10} = -0.63 \pm 0.43$

$C'_{9}/C_{10} = -0.92 \pm 0.10$
Results in $\frac{C'_{10}}{C_{10}} - \frac{C'_{9}}{C_{10}}$

$\frac{r}{C_{10}} = 0.84$

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More than $5\sigma$ deviation

$\frac{C'_{10}}{C_{10}} = -0.63 \pm 0.43$

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Reduced significance of deviation for lowered $\frac{r}{C_{10}}$ value

Other kind of NP like $Z'$ as hinted in global fits

[Altmannshofer, Straub '14]
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Other kind of NP like $r/C_{10}$, as hinted in global fits [Altmannshofer, Straub '14]

Minimal significance for RH current

$[Altmannshofer, Straub '14]$
Fit to form factor observables

\[ q^2 \]

\[ F_L \]

\[ F_\perp \]

\[ A_{FB} \]

\[ A_5 \]
Fit to form factor observables

nicely explained by 3rd order polynomial
Convergence of coefficients

- $A^{(1)}_5$
- $A^{(2)}_5$
- $A^{(1)}_{FB}$
- $A^{(2)}_{FB}$

Bin no.

Order 3
Order 2
Order 4

Rusa Mandal, IMSc
Convergence of coefficients

Shows a good convergence with variation in polynomial order & no. of bins used for the data fit
Resonances

$c\bar{c}$ bound states added: $J/\psi$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$.

Observable $= \text{Form-factors} + \text{Kruger & Sehgal parametrization}$

Asymmetries decrease in high $q^2$ region makes observable $\omega_1$ unphysical

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Asymmetries decrease in high $q^2$ region

Random variation of each strong phases

makes observable $\omega_1$ unphysical
Lepton non-universality

Exciting discrepancies observed in charged current $B$ decays

\[
\mathcal{H}^{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left( 1 + C_{\text{NP}}^n \right) (\bar{c}_L \gamma_{\mu} b_L)(\bar{\tau}_L \gamma^\mu \nu_{\tau L})
\]

\[
R(D^{(*)}) \equiv \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)}, \quad \ell \in \{e, \mu\}
\]

\[
R(D) = (1.34 \pm 0.17) \times R(D)_{\text{SM}}, \quad R(D^*) = (1.23 \pm 0.07) \times R(D^*)_{\text{SM}}
\]

2.2$\sigma$ \hspace{.5cm} 3.3$\sigma$

combined deviation $\sim 4\sigma$
Lepton non-universality

Discrepancies in neutral current $B$ decays also

$$R_{K(*)} \equiv \frac{\text{BR}(B \to K(*)\mu\mu)}{\text{BR}(B \to K(*)ee)}$$

- $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad q^2 \in [1 : 6] \text{ GeV}^2 \quad \rightarrow \quad 2.6\sigma$
- $R_{K_*}^{\text{low}} = 0.660^{+0.110}_{-0.070} \pm 0.024 \quad q^2 \in [0.045 : 1.1] \text{ GeV}^2 \quad \rightarrow \quad 2.1\sigma$
- $R_{K_*}^{\text{cntr}} = 0.685^{+0.113}_{-0.069} \pm 0.047 \quad q^2 \in [1.1 : 6] \text{ GeV}^2 \quad \rightarrow \quad 2.4\sigma$

$$\Phi \equiv \left. d\text{BR}(B_s \to \phi\mu\mu)/dq^2 \right|_{q^2\in[1:6] \text{ GeV}^2}$$

$$= (2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8} \ \text{GeV}^{-2} \quad \text{(exp)}$$

$$= (4.81 \pm 0.56) \times 10^{-8} \ \text{GeV}^{-2} \quad \text{(SM)}$$

---

3σ
Lepton non-universality

Constraints from other modes

\[
\text{BR}(B_s \to \mu\mu) = \begin{cases} 
(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad \text{(exp.)} \\
(3.65 \pm 0.23) \times 10^{-9} \quad \text{(SM)}
\end{cases}
\]

well in agreement

\[
\text{BR}(B \to K^{(*)}\nu\bar{\nu}) < 1.6 (2.7) \times 10^{-5}
\]

\[
\text{BR}(B^+ \to K^+\mu^\pm\tau^\mp) < 4.5 (2.8) \times 10^{-5}
\]

\[
\text{BR}(B_s \to \tau\tau) < 6.8 \times 10^{-3}
\]

Quite challenging to explain all anomalies together by evading all the bounds.
Lepton non-universality

- NP operators with 2nd & 3rd generation fields

\[ \mathcal{H}^{NP} = A_1 (\bar{Q}_2 L^\gamma_\mu L_{3L}) (\bar{L}_{3L} \gamma^\mu Q_{3L}) + A_2 (\bar{Q}_2 L^\gamma_\mu Q_{3L}) (\bar{\tau}_R \gamma^\mu \tau_R) \]

- Directly contributes to \( R(D^{(*)}) \)

- Diagonalisation of Hamiltonian for lepton part through small mixing angle \( \theta \) : interaction basis \( \rightarrow \) mass basis

\[ \tau = \cos \theta \tau' + \sin \theta \mu' \]

Contribution to \( b \rightarrow s\mu\mu \) is generated
Lepton non-universality

\[ A_1(= A_2) = -2.92 \text{ TeV}^{-2} \]
\[ \sin \theta = \pm 0.022 \]

95% C.L.
99% C.L.

Allowed by \( B^+ \rightarrow K^+ \mu^- \tau^+ \)

\[ \chi^2_{\text{SM}} \approx 46 \]
\[ \chi^2_{\text{allowed region}} \approx 15 \]

\[ R_K \approx 0.86, \ R_{K^*}^{\text{cntr}} \approx 0.88, \ R_{K^*}^{\text{low}} \approx 0.90, \]
\[ R_{D(*)} \approx 1.25, \ \Phi \approx 4.1 \times 10^{-8} \text{ GeV}^{-2}. \]
Lepton non-universality

Allowing 20% breaking

\[ A_2 = \frac{4A_1}{5} \]

from quantum corrections or unknown dynamics of the UV completion of the model.

\[ \chi^2_{\text{SM}} \simeq 46 \]

\[ \chi^2_{\text{allowed region}} \simeq 10 \]

\[ R_K \simeq 0.80, \quad R_{K^*}^{\text{cntr}} \simeq 0.83, \quad R_{K^*}^{\text{low}} \simeq 0.88, \quad R_{D(*)} \simeq 1.24, \quad \Phi \simeq 3.8 \times 10^{-8} \text{GeV}^{-2}. \]
### Summary

<table>
<thead>
<tr>
<th>Popular approaches</th>
<th>Our approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Combine all $b \to s$ transitions</td>
<td>✓ Most general parametric form of SM amplitude</td>
</tr>
<tr>
<td>✓ Many decay modes i.e observables</td>
<td>✓ $B \to K^* \ell^+ \ell^-$ observables</td>
</tr>
<tr>
<td>✓ More hadronic uncertainties</td>
<td>✓ Eliminate hadronic uncertainties</td>
</tr>
<tr>
<td>✓ Conservative assumption of non-factorisable contributions</td>
<td>✓ No/minimal dependency on form-factors &amp; independent of non-factorisable contributions</td>
</tr>
<tr>
<td>✓ Focusing on low $q^2$ region</td>
<td>✓ Conclusion derived at endpoint</td>
</tr>
</tbody>
</table>
Summary

- Formalism developed to include all possible effects within SM
- Strong evidence of RH currents derived at endpoint limit —
  - systematics studied by varying polynomial order & bin no.
  - finite $K^*$ width effect is considered
  - resonance effects increase the deviation
Summary

☑ Several hints of lepton non universality are observed by various experimental groups

☑ In terms of effective operators we show a possible explanation to all the anomalies together

▶ The model has only two new parameters
▶ It predicts some interesting signatures both in the context of B decays as well as high-energy collisions

☑ Opens up way to construct UV complete theory

☑ Fluctuation? Wait for more data to be accumulated!
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