Measurements of $R_K$ and $R_{K^*}$ at LHCb

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On behalf of the LHCb Collaboration
The R ratios family

In the SM:

- $\ell = e, \mu$ or $\tau$

\[ R_H = \frac{\int \frac{d\Gamma(B \to H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to He^+ e^-)}{dq^2} dq^2} \quad q = M(\ell \ell) \]

- $R_H = 1$ (at $10^{-3}$) in the SM (neglecting lepton masses)

QED effects $\sim %$ arXiv:1605.07633

$R_K, R_{K^*}, R_{\phi}, \ldots$
Electrons emit a large amount of bremsstrahlung → degraded momentum and mass resolutions → recovery procedure is in place but incomplete (calorimeter acceptance, $E_T$ of the photon $> 75$ MeV ....)

⇒ the reconstructed B mass shifts towards lower values and events migrate in and out of the q2 bins
LHC : 15 MHz of visible crossing

⇒ hardware trigger :

L0 Muon $p_T > 1.5 - 1.8$ GeV
L0 Electron $E_T > 2.5 – 3.0$ GeV
L0 Hadron $E_T > 3.5$ GeV

Electron channels :
three exclusive trigger categories

Muon channels :
one single muon trigger category

LHCb : readout of the detector : 1 MHz

K* $\ell\ell$ Generator level, $1.1<q^2<6$ GeV$^2$/c$^4$

Max of lepton $p_T$ (GeV)

LHCb Internal
For illustration only

Electron (L0E)
Hadron (L0H)
Other (L0I)
\[ R_{K^{(*)0}} = \frac{\mathcal{B}(B \rightarrow K^{(*)0}\mu^+\mu^-)}{\mathcal{B}(B \rightarrow K^{(*)0}J/\psi (\rightarrow \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B \rightarrow K^{(*)0}e^+e^-)}{\mathcal{B}(B \rightarrow K^{(*)0}J/\psi (\rightarrow e^+e^-))} \]

- Selection as similar as possible between $\mu\mu$ and $ee$ for physics-related variables

Mitigating electron/muon differences

- The $ee$ channels are treated separately for the various trigger categories (different mass shapes, different background levels, different efficiencies ...)

- The efficiencies are determined using simulation, but tuned using data

- Blind analyses
in 2014 : $R(K)$

$$R_K = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} d\Gamma[B \to K^+ \mu^+ \mu^-]}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} d\Gamma[B \to K^+ e^+ e^-]} \frac{dq^2}{dq^2}$$

$1 < q^2 < 6 \text{ GeV}^2/c^4$  \quad J/ψ

<table>
<thead>
<tr>
<th>Trigger</th>
<th>$\mu\mu$</th>
<th>ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$</td>
<td>$1226 \pm 41$</td>
<td>$667k$</td>
</tr>
<tr>
<td>ee</td>
<td>$254 \pm 28$</td>
<td>$62k$</td>
</tr>
</tbody>
</table>

Run1 : 3 fb$^{-1}$
$R_K = 0.745^{+0.090}_{-0.074}\text{(stat)} \pm 0.036\text{(syst)}$

1<$q^2<$ 6 GeV$^2$/c$^4$

PRL 113 (2014) 151601

2.6 standard deviations from the SM prediction
Replace the K by a $K^{*0}$

$$R_{K^{*0}} = \frac{\int \frac{d\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{dq^2} \, dq^2}{\int \frac{d\Gamma(B^0 \rightarrow K^{*0} e^+ e^-)}{dq^2} \, dq^2}$$

$K^{*0}$: $M(K^+ \pi^-) = M(K(892)^0) \pm 100$ MeV

Two hadrons instead of one:
lower $p_T$, higher combinatorial background

Low-$q^2$: [0.045-1.1] GeV$^2$/c$^4$
$M(\ell\ell) : [212 - 1049]$ MeV/c$^2$

Central-$q^2$: [1.1-6.0] GeV$^2$/c$^4$
$M(\ell\ell) : [1049-2449]$ MeV/c$^2$

The $\phi$ resonance is fully included in the low-$q^2$ region

The $J/\psi$ leakage is limited in the central-$q^2$ region
Analysis roadmap:

- Selection using MVA & kinematics properties of the event (ee)
- Data/simulation differences in $K\pi$ ee mass reconstruction obtained from $J/\psi(\text{ee}) K\pi$
- Partially reconstructed background: simulation checked against data

Details in the backup slides

To compute the absolute scale of the efficiency in the ee and $\mu\mu$ channels:

- Large set of corrections to the simulation, based on tag and probe technique

  - Particle Identification
  - Generator (event multiplicity, $B^0$ kinematics)
  - Trigger
  - Residual discrepancies in variables entering the MVA tool used to separate the signal from background.
Yields:

<table>
<thead>
<tr>
<th></th>
<th>Low-$q^2$</th>
<th>Central-$q^2$</th>
<th>J/$\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$</td>
<td>285 ± 18</td>
<td>353 ± 21</td>
<td>274k</td>
</tr>
<tr>
<td>$ee$</td>
<td>89 ± 11</td>
<td>111 ± 14</td>
<td>58k</td>
</tr>
</tbody>
</table>

arXiv:1705.05802
Crosschecks:

- \( r_{J/\psi} = \frac{B(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))}{B(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))} = 1.043 \pm 0.006 \pm 0.045 \)

~ independent of the decay kinematics and event multiplicity (non flatness in the systematics of \( R_{K^*0} \))

Extremely stringent test, systematics due to corrections larger than those for \( R_{K^*0} \)

- \( BR(B^0 \rightarrow K^{*0} \mu \mu) \) in good agreement with \( \text{arxiv:1606.04731} \)

- \( \mathcal{R}_{\psi(2S)} = \frac{B(B^0 \rightarrow K^{*0} \psi(2S) (\rightarrow \mu^+ \mu^-))}{B(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{B(B^0 \rightarrow K^{*0} \psi(2S) (\rightarrow e^+ e^-))}{B(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))} \) compatible with expectations

- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus \( R_{K^*0} \)) changes by less than 5%
Other checks:
distributions obtained from background-subtracted data (sPlot NIM A555,356-369 (2005)) and compared to simulation

Good agreement between electrons and muons and data and simulation

Distributions normalized to the same area

arXiv:1705.05802
Distributions normalized to the same area

e/\mu\mu\text{ difference expected (threshold)}

arXiv:1705.05802
Systematics uncertainties on $R_{K^*0}$:

- Use of a double ratio: many experimental systematic effects cancel
- Statistically dominated (~15%)

<table>
<thead>
<tr>
<th>Trigger category</th>
<th>low-$q^2$</th>
<th>central-$q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L0E</td>
<td>L0H</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Kinematic selection</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Residual background</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Mass fits</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Bin migration</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$r_{J/\psi}$ flatness</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>4.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Brem tail description

Residual background contamination due to $B \rightarrow K^0J/\psi(\text{ee})$ events with a $K \leftrightarrow e$ or $\pi \leftrightarrow e$ swap

(table in %)

arXiv:1705.05802
Good agreement between trigger categories

<table>
<thead>
<tr>
<th>$R_{K^{*0}}$</th>
<th>low-$q^2$</th>
<th>central-$q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$95.4%$ CL</td>
<td>$0.66 \pm 0.11 \pm 0.03$</td>
<td>$0.69 \pm 0.11 \pm 0.05$</td>
</tr>
<tr>
<td>$99.7%$ CL</td>
<td>$[0.52, 0.89]$</td>
<td>$[0.53, 0.94]$</td>
</tr>
</tbody>
</table>

$0.045 < q^2 < 1.1$ [GeV$^2$/c$^4$]

$1.1 < q^2 < 6.0$ [GeV$^2$/c$^4$]

arXiv:1705.05802
Compatibility with the SM expectation(s):

- Low-$q^2$: 2.1 – 2.3 standard deviations
- Central-$q^2$: 2.4 – 2.5 standard deviations

**arXiv:1705.05802**
Summary

$R_K$

$R_{K^0}$

$\phi$

LHCb

BaBar

Belle

1

2

0.5

1

[ LHCb - PRL 113, 151601]
[BaBar - PRD 86 (2012) 032012]
[Belle - PRL 103 (2009) 171801]

PRL 113 (2014) 151601

arXiv:1705.05802

Mitesh talk!
Backup slides
• Fit MC to extract initial parameters
• Fit the data allowing (some) parameters to vary

**Signal**
• Ipatia
• Free parameters mass shift and width scale

**Backgrounds**
• Combinatorial exponential
• $\Lambda_b$ simulation & data
• $B_s$ same as signal but shifted by $m_{B_s} - m_{B_0}$
• Fit MC in different trigger and bremsstrahlung categories to extract initial parameters (separately for all modes)

• Combine bremsstrahlung PDFs into one signal model per each trigger category (bremsstrahlung fractions fixed from MC)

• Fit the data in trigger categories allowing (some) parameters to vary

**Signal**

- $0\gamma$ (1$\gamma$ and 2$\gamma$) Crystal-Ball (Crystal-Ball and Gaussian)
- Free parameters mass shift and width scale

**Backgrounds**

- Combinatorial exponential
- $\Lambda_b$ simulation & data, yield constrained using muons
- $B_s$ same as signal but shifted by $m_{B_s} - m_{B_0}$, yield constrained using muons
- Leakage simulation, yield constrained using data
- Part-Reco simulation & data

* Create a $K_1+K_2$ cocktail from simulation but using data to determine the relative fraction

* Use sPlotted data from LHCb-PAPER-2014-030 to re-weight $B \rightarrow K\pi\pi\ell\ell$ simulated events
• **Selection steps**
  
  • Pre-selection requirements on trigger and quality of the candidates
  
  • Cuts to remove the peaking backgrounds
  
  • Particle identification to further reduce the background
  
  • Multivariate classifier to reject the combinatorial background
  
  • Kinematic requirements to reduce the partially-reconstructed backgrounds
  
  • Multiple candidates randomly rejected
On the low $q^2$ region and the hadronic resonances:

In the SM $R_{K^*} \sim 0.90$, we are in a regime where electrons and muons are very similar.

<table>
<thead>
<tr>
<th>V</th>
<th>BR($V \rightarrow ee$)</th>
<th>BR($V \rightarrow \mu\mu$)</th>
<th>BR($B^0 \rightarrow K^*V$)</th>
<th>BR($B^0 \rightarrow K^*V(ee)$)</th>
<th>BR($B^0 \rightarrow K^*V(\mu\mu)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ</td>
<td>$(2.95 \pm .03) \times 10^{-4}$</td>
<td>$(2.87 \pm .19) \times 10^{-4}$</td>
<td>$(1.00 \pm .05) \times 10^{-5}$</td>
<td>$(29.5 \pm 1.5) \times 10^{-10}$</td>
<td>$(28.7 \pm 2.4) \times 10^{-10}$</td>
</tr>
<tr>
<td>ρ</td>
<td>$(4.72 \pm .05) \times 10^{-5}$</td>
<td>$(4.55 \pm .28) \times 10^{-5}$</td>
<td>$(3.9 \pm 1.3) \times 10^{-6}$</td>
<td>$(1.84 \pm 0.61) \times 10^{-10}$</td>
<td>$(1.77 \pm 0.60) \times 10^{-10}$</td>
</tr>
<tr>
<td>ω</td>
<td>$(7.28 \pm .14) \times 10^{-5}$</td>
<td>$(9.0 \pm 3.1) \times 10^{-5}$</td>
<td>$(2.0 \pm .5) \times 10^{-6}$</td>
<td>$(1.46 \pm 0.37) \times 10^{-10}$</td>
<td>$(1.8 \pm 0.77) \times 10^{-10}$</td>
</tr>
</tbody>
</table>

φ : larger product of BR, no lepton mass effect

ρ : product of BR significantly smaller than the φ.
   wide resonance : interference? But should be the same for electrons and muons

ω : significantly smaller than the φ

We are not subtracting these backgrounds; if anything they should increase the measured value of $R_{K^*}$
\begin{align*}
\text{BR}(\eta \to \text{ee}) &= (6.9 \pm 0.4) \times 10^{-3} \\
\text{BR}(\eta \to \mu\mu) &= (0.31 \pm 0.04) \times 10^{-3} \\
\text{One missing photon} \rightarrow \text{in the partially reconstructed background}
\end{align*}

\textbf{Table:}

<table>
<thead>
<tr>
<th>V</th>
<th>BR(V\to\text{ee})</th>
<th>BR(V\to\mu\mu)</th>
<th>BR(B^0\to K^*V)</th>
<th>BR(B^0\to K^*V(\text{ee}))</th>
<th>BR(B^0\to K^*V(\mu\mu))</th>
</tr>
</thead>
<tbody>
<tr>
<td>\eta</td>
<td>&lt; 2.3 \times 10^{-6}</td>
<td>(5.8 \pm 0.8) \times 10^{-6}</td>
<td>(1.59 \pm 0.10) \times 10^{-5}</td>
<td>&lt; 0.4 \times 10^{-10}</td>
<td>(9.2 \pm 10^{-10})</td>
</tr>
</tbody>
</table>

\textbf{arXiv:1212.2263}