Recent measurements of radiative and electroweak penguin decays at Belle

Lake Louise Winter Institute 2018

Presented by Simon Wehle
Radiative and Rare $b \rightarrow s$ Decays at Belle

Outline

- $B \rightarrow K^* \gamma$
- $B \rightarrow h(\ast) \nu \bar{\nu}$
- $B \rightarrow K^* \ell \bar{\ell}$
The Belle Experiment

- The Belle experiment is located at the KEKB accelerator in Tsukuba, Japan
- Data taking from 1999 to 2010
- It is designed as a “B factory”
- 772 million $B\bar{B}$ meson pairs

$$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

- World record for integrated luminosity

$$\int L \, dt = 1 \, \text{ab}^{-1}$$
Table of Contents

1. \( B \rightarrow K^* \gamma \)

2. \( B \rightarrow h(*) \nu \bar{\nu} \)

3. \( B \rightarrow K^* \ell^+ \ell^- \)
$B \rightarrow K^* \gamma$

- $B \rightarrow K^* \gamma$ mediated dominantly by one loop penguin diagrams
- Cleanest exclusive $b \rightarrow s \gamma$ decay
  - $B \sim 4 \times 10^{-5}$
  - Predictions to the branching fractions are limited by form-factor uncertainties

$K^* \rightarrow K^0_S \pi^0, K^+ \pi^-, K^+ \pi^0, K^0_S \pi^+$
Ratios with $B \rightarrow K^*\gamma$

- Ratios of branching fractions cancel important uncertainties
- Isospin asymmetry $\Delta_{0+}$

$$
\Delta_{0+} = \frac{\Gamma(B^0 \rightarrow K^{*0}\gamma) - \Gamma(B^+ \rightarrow K^{*+}\gamma)}{\Gamma(B^0 \rightarrow K^{*0}\gamma) + \Gamma(B^+ \rightarrow K^{*+}\gamma)}
$$

- CP violation $A_{CP}$

$$
A_{CP} = \frac{\Gamma(\bar{B} \rightarrow \bar{K}^{*}\gamma) - \Gamma(B \rightarrow K^{*}\gamma)}{\Gamma(\bar{B} \rightarrow \bar{K}^{*}\gamma) + \Gamma(B \rightarrow K^{*}\gamma)}
$$

- Difference $\Delta A_{CP}$ between isospins

$$
\Delta A_{CP} = A_{CP}(B^+ \rightarrow K^{*+}\gamma) - A_{CP}(B^0 \rightarrow K^{*0}\gamma)
$$

- Ratio of $\mathcal{B}(B^0 \rightarrow K^{*0}\gamma)/\mathcal{B}(B_s \rightarrow \phi\gamma)$
Extraction of BF, $A_{CP}$, $\Delta_{0+}$, $\Delta A_{CP}$

Unbinned maximum likelihood fit:

- $\text{BFs, } A_{CP}, \Delta_{0+}, \Delta A_{CP}$ extracted in simultaneous fit to 7 $M_{bc}$ distributions

\[
\mathcal{L}(M_{bc}|B^N, B^C, A_{CP}^N, A_{CP}^C) = \prod \mathcal{L}^{K_S^0 \pi^0}(M_{bc}|B^N) \\
\times \prod \mathcal{L}^{K^- \pi^+}(M_{bc}|B^N, A_{CP}^N) \times \prod \mathcal{L}^{K^+ \pi^-}(M_{bc}|B^N, A_{CP}^C) \\
\times \prod \mathcal{L}^{K^- \pi^0}(M_{bc}|B^C, A_{CP}^N) \times \prod \mathcal{L}^{K^+ \pi^0}(M_{bc}|B^C, A_{CP}^C) \\
\times \prod \mathcal{L}^{K_S^0 \pi^-}(M_{bc}|B^C, A_{CP}^C) \times \prod \mathcal{L}^{K_S^0 \pi^+}(M_{bc}|B^C, A_{CP}^C),
\]

- Signal (Signal with $\pi^0$) : Gauss (Crystal Ball)
- Cross-feed: Argus + Bifurcated Gaussian (the yield is proportional to signal yield)
- Continuum background : ARGUS
- $B\bar{B}$ background : ARGUS + Bifurcated Gaussian
Results

- First evidence of $\Delta_{0+}$ with $3.1\sigma$
- First measurement of $\Delta A_{CP}$

$$B(B^0 \to K^*\gamma) = (3.96 \pm 0.07 \pm 0.14) \times 10^{-5},$$
$$B(B^+ \to K^{++}\gamma) = (3.76 \pm 0.10 \pm 0.12) \times 10^{-5},$$
$$A_{CP}(B^0 \to K^*\gamma) = (-1.3 \pm 1.7 \pm 0.4)\%,$$
$$A_{CP}(B^+ \to K^{++}\gamma) = (+1.1 \pm 2.3 \pm 0.3)\%,$$
$$A_{CP}(B \to K^*\gamma) = (-0.4 \pm 1.4 \pm 0.3)\%,$$

$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%,$$
$$\Delta A_{CP} = (+2.4 \pm 2.8 \pm 0.5)\%,$$
$$\bar{A}_{CP} = (-0.1 \pm 1.4 \pm 0.3)\%,$$

- Published as PRL 119, 191802 (2017), arXiv:1707.00394
Table of Contents

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Search for $B \to h(\ast) \nu \bar{\nu}$

- $B \to h(\ast) \nu \bar{\nu}$ is sensitive to NP similar to $C_9$

  $$h(\ast) = K^{\ast}, K_0^{0}, K^{\ast}\pi^{0}, K^{0}\pi^{0}, K^{0}\pi^{\pm}, \rho^{\pm}, \rho^{0}$$

- Theoretically very clean channel (no charm loops)

- Experimentally challenging, tagging of companion $B$ meson needed
  
  - Hadronic tagging already measured at Belle
  - Semileptonic tagging in this analysis

  $$e^+e^- \to \Upsilon(4S) \to B_{tag}B_{sig}$$
Reconstruction of $B \rightarrow h(\ast)\nu\bar{\nu}$

- **Semileptonic tagging for companion $B$**
  - Neural network based particle selection
  - $\sim 2 - 3$ times more efficient compared to hardronic tag

- Requirement: No further tracks, $\pi^0$ or $K_L^0$

- Remove all associated energy from the calorimeter from $B_{tag}$ and $B_{sig}$

- Signal extracted in extra (additional) energy in the calorimeter ($E_{ECL}$)
Results

Signal Extraction

- Fit with template histograms
  - Signal, $b \rightarrow c$, continuum, light quark pairs
  - Signal consistent with zero

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed signal yield</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\nu\bar{\nu}$</td>
<td>$17.7 \pm 9.1 \pm 3.4$</td>
<td>$1.9\sigma$</td>
</tr>
<tr>
<td>$K_S^0\nu\bar{\nu}$</td>
<td>$0.6 \pm 4.2 \pm 1.4$</td>
<td>$0.0\sigma$</td>
</tr>
<tr>
<td>$K^{*+}\nu\bar{\nu}$</td>
<td>$16.2 \pm 7.4 \pm 1.8$</td>
<td>$2.3\sigma$</td>
</tr>
<tr>
<td>$K^{*0}\nu\bar{\nu}$</td>
<td>$-2.0 \pm 3.6 \pm 1.8$</td>
<td>$0.0\sigma$</td>
</tr>
<tr>
<td>$\pi^+\nu\bar{\nu}$</td>
<td>$5.6 \pm 15.1 \pm 5.9$</td>
<td>$0.0\sigma$</td>
</tr>
<tr>
<td>$\pi^0\nu\bar{\nu}$</td>
<td>$0.2 \pm 5.6 \pm 1.6$</td>
<td>$0.0\sigma$</td>
</tr>
<tr>
<td>$\rho^+\nu\bar{\nu}$</td>
<td>$6.2 \pm 12.3 \pm 2.4$</td>
<td>$0.3\sigma$</td>
</tr>
<tr>
<td>$\rho^0\nu\bar{\nu}$</td>
<td>$11.9 \pm 9.0 \pm 3.6$</td>
<td>$1.2\sigma$</td>
</tr>
</tbody>
</table>

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Upper Limits

- Worlds most stringent limits on
  \[ h(\ast) = K_S^0, K^{*0}, \pi^0, \pi^+, \rho^0, \rho^+ \]

- Upper limit on \( B(B^0 \rightarrow K^{*0}\nu\bar{\nu}) \) close to SM prediction

- BF measurable in Belle 2

Table of Contents

1. $B \to K^* \gamma$

2. $B \to h(\ast) \nu \bar{\nu}$

3. $B \to K^* \ell^+ \ell^-$
Analysis of $B \rightarrow K^* \ell \ell$

**SM example**

$B^0 \rightarrow K^* \ell \ell$

$B^0 \rightarrow \bar{s} \rightarrow \bar{u}, \bar{c}, \bar{t}$

$W^+ W^-$

$\nu_\ell$

$\ell^-$

$\ell^+$

**NP example**

$B^0 \rightarrow K^* \ell \ell$

$B^0 \rightarrow Z'$

$Z' \rightarrow \ell^+ \ell^-$
Lepton flavor dependence in $B \to K^* \ell \ell$

- Do we see first hints on lepton flavor non-universality?
- LHCb reports $2.6\sigma$ tension in
  \[ R_K \equiv \frac{\mathcal{B}(B \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B \to K^+ e^+ e^-)} \] (Phys. Rev. Lett. 113, 151601)
  \[ R_K^* \equiv \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)} \] (arXiv:1705.05802)

- Tensions in angular observables

- Check lepton flavor dependence in angular analysis!
Result $P'_5$ - Result for Combined Data

- Measurements are compatible with the SM
- Similar central values for the $P'_5$ anomaly with 2.5σ tension
The Largest deviation in the muon mode with $2.6\sigma$
Electron mode is deviating with $1.1\sigma$
Test on Lepton flavor universality
Result - Separate Lepton Flavor!

▶ Observables $Q_i = P_{i \mu} - P_{i e}$, JHEP 10, 075 (2016)

$B \to K^* \gamma \quad B \to h^{(*)} \nu \bar{\nu} \quad B \to K^* \ell^+ \ell^-$

Thank you!

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Table of Contents

4 Appendix
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The Belle Detector

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Theoretical Framework

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu), \]

\[ O_7 = \frac{e}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) b_\alpha F^{\mu\nu}, \]

\[ O_9 = \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_\mu \ell, \]

\[ O_{10} = \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_\mu \gamma_5 \ell, \]

- Effective theory
  - Wilson Coefficients \( C_{7,9,10} \)
  - Short distance couplings
  - \( C_7: b \rightarrow s \gamma, \ C_9, \ C_{10}: b \rightarrow s\ell\ell \)

In presence of NP:

- Deviations from SM
- New coefficients appear
- Lepton flavor dependence
Reconstruction of $B \rightarrow K^*\gamma$

- Four decay modes
  - $K^{*0} \rightarrow K_S^0\pi^0$, $K^+\pi^-$
  - $K^{*+} \rightarrow K_S^0\pi^+$, $K^+\pi^0$
  - Self-tagging

- Signal selection
  - Energy Difference: $-0.2 \text{ GeV} < \Delta E < 0.1 \text{ GeV}$
  - Beam constrained Mass: $5.20 \text{ GeV} < M_{bc} < 5.29 \text{ GeV}$
  - $|M_{K\pi} - M_{K^*}| < 0.075 \text{ GeV}$

- Background suppression
  - Continuum: Neural network with event shape variables
  - $\pi^0/\eta$ veto photon selection

- Best candidate selection
  - 1.16 candidates/event
  - Random candidate selection

$M_{bc}$ distribution summed four channels “with” $M(K\pi)$ selection after $\pi^0\eta$ veto
**Result** $\mathcal{B}(B \rightarrow K^*\gamma)$

- New result is consistent with previous measurements
- Consistent with theoretical predictions by Bharucha, Starub and Zwicky
- Most precise measurement
Appendix

Result $\Delta_{0+}$

- First evidence for isospin violation in $b \rightarrow s$ with $3.1\sigma$ significance
- Result consistent with theoretical predictions from Lyon and Zwicky and Kagan and Neubert and BaBar

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Result $A_{CP}$

- **New Belle results** are the most precise to date
- Consistent with zero, theoretical predictions from Paul and Straub and Matsumori et al and measurements by BaBar and LHCb
Full Angular Analysis

The differential decay rate for $B \to K^* \ell^+ \ell^-$ can be written as

$$\frac{1}{d\Gamma / dq^2} \frac{d^4\Gamma}{d\cos \theta_L \, d\cos \theta_K \, d\phi \, dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K 
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_L 
- F_L \cos^2 \theta_K \cos 2\theta_L + S_3 \sin^2 \theta_K \sin^2 \theta_L \cos 2\phi 
+ S_4 \sin 2\theta_K \sin 2\theta_L \cos \phi + S_8 \sin 2\theta_K \sin \theta_L \cos \phi 
+ S_5 \sin^2 \theta_K \cos \theta_L + S_7 \sin 2\theta_K \sin \theta_L \sin \phi 
+ S_6 \sin 2\theta_K \sin 2\theta_L \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_L \sin 2\phi \right],$$

The observables are depended on $q^2 = M_{\ell^+ \ell^-}^2$. 

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Folding Procedure

- With a transformation of the angles, the dimension is reduced to **three free parameters**
- Each transformation remains three observables \( S_j, F_L \) and \( S_3 \)
- The observables
  \[
  P'_{4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}},
  \]
  are considered to be largely free from form-factor uncertainties ([J. High Energy Phys. 05 (2013) 137]).
- Transverse polarization asymmetry
  \[
  A_T^{(2)} = \frac{2S_3}{(1 - F_L)}
  \]

Cut Optimization

- **Appendix**

- **Rare decays at Belle I**

- Most straightforward strategy:

  - Optimize a combined FOM for $e^+e^-$ and $\mu^+\mu^-$ channels

- FOM

  \[ \text{FOM} = \frac{N_s}{\sqrt{N_s + N_b}} \]

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Reconstruction of $B \rightarrow K^{*} \ell^{+} \ell^{-}$

- Reconstructing $B^{0}$ and $B^{+}$ modes
- Using muon and electron modes
- $K^{*}$ is reconstructed in $(K^{+}, \pi^{-})$, $(K_{S}^{0}, \pi^{+})$ and $(K^{+}, \pi^{0})$

**Electron Modes**

- $B^{0} \rightarrow K^{*}(892)^{0} e^{+} e^{-}$
- $B^{+} \rightarrow K^{*}(892)^{+} e^{+} e^{-}$

**Muon Modes**

- $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$
- $B^{+} \rightarrow K^{*}(892)^{+} \mu^{+} \mu^{-}$

Signal selection:
- Neural network (NN) classifier for all particles in the decay chain
- Final signal selection on four $B$ meson NN
- NN cut optimization on 2D figure of merit separate for the lepton flavor
Fit Procedure

1. The data is split into bins of $q^2$
2. $M_{bc}$ is fitted to determine the signal and background fractions
3. The data is split into a sideband and signal region
4. The shape of the background is determined and fixed in the sideband with smoothed histograms
5. The final fits are performed as 3D maximum likelihood fit in $\theta_L$, $\theta_K$ and $\phi$ for $P_4', P_5'$ each treated as an independent measurement

- **Signal:** Transformed differential decay rate
- **Background:** Kernel Density Estimation
- independent 3D unbinned maximum likelihood fit for:
  - $q^2$ bin: (1, 6), (0.1, 4), (4, 8), (10.09, 12.9), (14.18, 19)
  - $P_4'$ and $P_5'$