Isospin Asymmetry in $B \rightarrow K^*\gamma$
and Hint for $B \rightarrow \mu\nu$

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On behalf of the Belle Collaboration
Prelude

- Flavor seems to be the toast of the town

➢ Imperative to look for other places as well...
Enter $B \to K^*\gamma$ Decays

- Dominantly mediated by one-loop electromagnetic penguin diagram
- Cleanest exclusive $b \to s\gamma$ decay with expected BF $\sim 4\times 10^{-5}$
- Calculations suffer from large uncertainties due to form factors

➤ Need theoretically clean observables...

Look for Ratios

- **Isospin asymmetry:**
  \[ \Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)} \]

- **CP violation asymmetry:**
  \[ A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)} \]

- **CP asymmetry difference between isospin channels:**
  \[ A_{CP}(B^+ \to K^{*+}\gamma) - A_{CP}(B^0 \to K^{*0}\gamma) \]

- **Ratio of branching fractions:**
  \[ \frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} \]

- Theory uncertainties largely cancel out

Matsumori, Sanda and Keum, PRD72 (2005) 014013
**Fit Strategy**

- Unbinned maximum likelihood to $M_{bc}$ distributions in seven modes:

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

- signal (with $\pi^0$): Gaussian (Crystal Ball)
- cross-feed: ARGUS + asymmetric Gaussian with its yield proportional to that of signal
- continuum $q\bar{q}$: ARGUS
- $B\bar{B}$ bkg: ARGUS + asymmetric Gaussian
Branching Fraction

- Most precise one to date
- Consistent with theory
- Agree with earlier measurements

Bharucha, Straub and Zwicky, JHEP 08 (2016) 098

PRL119 (2017) 191802
Ratio of Branching Fractions

- Belle measurement of \( BF(B_s \to \phi \gamma) \) based on 121 fb\(^{-1} \) used in the calculation

- Only \( K^* \to K^+ \pi^- \) used in order to cancel common systematics

- Result:

\[
\frac{\mathcal{B}(B^0 \to K^{*0} \gamma)}{\mathcal{B}(B_s^0 \to \phi \gamma)} = 1.10 \pm 0.16 \pm 0.09 \pm 0.18
\]

is consistent with theory as well as LHCb
Isospin Asymmetry

- First evidence for isospin violation in $b \to s$ transition exceeding 3$\sigma$ significance

- Agree with theory predictions of Lyon and Zwicky PRD88 (2013) 094004

- Consistent with and more precise than BaBar result

- To observe isospin violation with 5$\sigma$ significance at Belle II, reduction of dominant systematic uncertainty due to $f_{+-}/f_{00}$ is also essential
**CP Asymmetry**

- Most precise results to date
  - PRL119 (2017) 191802

- Consistent with theory predictions
  - Paul and Straub JHEP04 (2017) 027
  - Matsumori, Sanda and Keum, PRD72 (2005) 014013

- Agree with BaBar and LHCb (in the neutral mode)

- As the measurements are dominated by statistical errors, we expect substantial improvement at Belle II
Average and Difference in $A_{CP}$

- First measurements of:
  \[
  \Delta A_{CP} = (+2.4 \pm 2.8 \pm 0.5)\%
  \]
  \[
  \bar{A}_{CP} = (-0.1 \pm 1.4 \pm 0.3)\%
  \]

- Results consistent with zero and dominated by statistical errors

➢ Substantial improvement expected at Belle II
Now to $B \to \mu \nu$ Decay

- Tree level diagram and strongly helicity suppressed:

\[
\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B \cancel{m}_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B
\]

- Decay rate could be modified due to possible NP contribution, such as charged Higgs boson or leptoquark

Hou, PRD48 (1993) 2342
Georgi and Glashow, PRL32 (1974) 438
Our Expectation

- Using these inputs, with the full Belle dataset we expect

- $B \rightarrow \tau \nu$ is already measured by B-factories, while $B \rightarrow \mu \nu$ is potentially measurable with the full Belle dataset

- $B \rightarrow e \nu$ won’t be possible even with Belle II
Improved Muon Identification

- Highest momentum muon in an event is signal candidate muon
- Although well detected by the dedicate $K_L$/muon system, find considerable amount of kaon contamination

<table>
<thead>
<tr>
<th>$B \rightarrow \mu \nu \times 500$</th>
<th>$2.45 &lt; p_{\mu}^* &lt; 2.85$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \pi \nu$</td>
<td></td>
</tr>
<tr>
<td>$B \rightarrow \rho \nu$</td>
<td></td>
</tr>
<tr>
<td>$B \rightarrow u \nu$</td>
<td></td>
</tr>
<tr>
<td>$e^+e^- \rightarrow BB$</td>
<td></td>
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<tr>
<td>$e^+e^- \rightarrow c\bar{c}$</td>
<td></td>
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<tr>
<td>$e^+e^- \rightarrow \mu\mu$</td>
<td></td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tau^+\tau^-$</td>
<td></td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \mu^+\mu^-$</td>
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<tr>
<td>$e^+e^- \rightarrow e^+e^-e^+e^-$</td>
<td></td>
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<tr>
<td>$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$</td>
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<td></td>
</tr>
<tr>
<td>$e^+e^- \rightarrow e^+e^-\tau^+\tau^-$</td>
<td></td>
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</tbody>
</table>

- Dedicated neural network is designed employing information from the other detectors, such as drift chamber and electromagnetic calorimeter

➤ For a signal-muon detection efficiency of 97%, a background suppression of 33% is achieved
Background Fighting is the Key!

- An artificial neural network is formed out of 14 kinematic variables $\Rightarrow$ largely uncorrelated to the muon momentum

- Major background peaking in the $O_{\text{nn}}$ signal region: $B \rightarrow \pi\ell\nu$

- Determine the signal yield with a binned maximum likelihood fit in $p_\mu^* \sim O_{\text{nn}}$ plane using the method in:
  

\[ B^- \rightarrow \mu^-\bar{\nu}_\mu \]

\[ \bar{B} \rightarrow \pi\ell^-\bar{\nu}_\ell \]

\[ e^+e^- \rightarrow \tau^+\tau^- \]

Consult the arXiv:1712.04123 document for further details.
Results

- Fit the ratio
  \[ R = \frac{N_{B \rightarrow \mu \bar{\nu}}}{N_{B \rightarrow \pi \mu \bar{\nu}}} \]
- We get \( R = (1.66 \pm 0.57) \times 10^{-2} \), which is equivalent to:
  \[ N_{B \rightarrow \mu \bar{\nu}} = 195 \pm 67 \]

Branching fraction

\[ B(B \rightarrow \mu \bar{\nu}) = (6.46 \pm 2.22) \times 10^{-7} = (6.46 \pm 2.22_{\text{stat}} \pm 1.6_{\text{syst}}) \times 10^{-7} \]

- 3.4\( \sigma \) statistical significance
  \[ \Rightarrow 2.4\sigma \] including systematic uncertainties
- 90% confidence interval for \( BF \in (2.9,10.7) \times 10^{-7} \)
- Belle II will make definitive measurement
What the Future Holds?

- Seems to be bright...

  - Belle II would be soon up and running $\Rightarrow$ phase 2 (without the vertex detector) starts in this summer and phase 3 (with full detector) by early 2019

Belle II Detector

- First pixel layer closer to the IP $\Rightarrow$ better vertex resolution
- Larger vertex detector $\Rightarrow$ $\sim$30% better $K_S$ coverage
- TOP and ARICH ensure at least similar or better PID performance under harsher (20$\times$ higher) background condition

- These features make Belle II an ideal device to probe rare decays

- Along with LHCb and taking related information from CMS+ATLAS, flavor enthusiasts would likely have sunnier days ahead...
Supplementary Information
Why Rare Decays?

• Typical examples:

![Diagram](image1)

![Diagram](image2)

\[ \mathcal{O}_7 \]

\[ \mathcal{O}_9 \text{ and } \mathcal{O}_{10} \]

• Decay dynamics can be expressed by an effective Hamiltonian

\[
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)
\]

• Wilson coefficients \( C_{7,9,10} \) → short distance couplings

➢ In presence of new physics (NP), possible new coefficients can give rise to deviations from the standard model
Systematic Uncertainties for $B \to \mu \nu$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B} \to \pi^\ell^- \bar{\nu}_\ell$ form-factor</td>
<td>0.9</td>
</tr>
<tr>
<td>$\bar{B} \to \rho^\ell^- \bar{\nu}_\ell$ form-factor</td>
<td>12</td>
</tr>
<tr>
<td>$B^- \to K_L^0 \pi^-$</td>
<td>5.5</td>
</tr>
<tr>
<td>$B^- \to \mu^- \bar{\nu}_\mu \gamma$</td>
<td>6</td>
</tr>
<tr>
<td>Continuum shape</td>
<td>15</td>
</tr>
<tr>
<td>Signal peak shape</td>
<td>11</td>
</tr>
<tr>
<td>Trigger</td>
<td>8</td>
</tr>
<tr>
<td>$\mathcal{B}(\bar{B} \to \pi^\ell^- \bar{\nu}_\ell)$</td>
<td>3.4</td>
</tr>
<tr>
<td>Total</td>
<td>24.6</td>
</tr>
</tbody>
</table>

- $B \to \rho \ell \nu$ form-factor: several FF calculations are employed in the fit $\Rightarrow$ the resultant maximal deviation is attributed as the systematic error.
- $B \to \mu \nu \gamma$: uncertainty due to this background is estimated from a fit where the former contribution is fixed to half of the best upper limit from Belle.