Study of $B^0 \rightarrow p\bar{\Lambda}\pi^-\gamma$ decay at Belle

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Yun-Tsung, Lai
National Taiwan University
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for the Belle Collaboration

• The Belle experiment
• $B^0 \rightarrow p\bar{\Lambda}\pi^-\gamma$ study
**KEK B-factory**

- An asymmetric energy $e^+e^-$ collider at KEK.
- LER($e^+$): 3.5 GeV
  HER($e^-$): 8 GeV
  Crossing angle: $\pm 11$ mrad

- Target: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B^0}(B^+B^-)$
- Main background: $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) with 3 times larger cross section.

- The CM energy of $e^+e^-$ are set to be $\Upsilon(4S)$ resonance to produce $B$ meson pairs.

![Diagram of KEK B-factory](http://www.lns.cornell.edu/public/lab-info/upsilon.html)

**Integrated luminosity of B factories**

- $> 1$ ab$^{-1}$
  - On resonance:
    - $\Upsilon(5S)$: 121 fb$^{-1}$
    - $\Upsilon(4S)$: 711 fb$^{-1}$
    - $\Upsilon(3S)$: 3 fb$^{-1}$
    - $\Upsilon(2S)$: 25 fb$^{-1}$
    - $\Upsilon(1S)$: 6 fb$^{-1}$
  - Off resonance/scan:
    - $\sim 100$ fb$^{-1}$

- $\sim 550$ fb$^{-1}$
  - On resonance:
    - $\Upsilon(4S)$: 433 fb$^{-1}$
    - $\Upsilon(3S)$: 30 fb$^{-1}$
    - $\Upsilon(2S)$: 14 fb$^{-1}$
  - Off resonance:
    - $\sim 54$ fb$^{-1}$
Belle Detector

Electromagnetic Calorimeter
- $\gamma, \pi^0$ reconstruction
- $e$ identification

Time Of Flight
- Particle identification

Aerogel Čerenkov Counter
- Particle identification

3.5 GeV $e^+$

8 GeV $e^-$

$K_L / \mu$ identification

Central Drift Chamber
- Charged track momentum
- Particle identification

Silicon Vertex Detector
- $B$ vertex determination

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**Particle Identification**

**Particle Identification:**
- **Aerogel Cerenkov Counter:** Silica aerogel
- **Time of Flight:** Plastic scintillator
- **Central Drift Chamber (dE/dx):** Small cell + He/C$_2$H$_6$

$e, \mu, \pi, K, p$ can be reconstructed.

**Momentum Measurement (CDC)**
1. $P_{x,y}$: Curvatures in the transverse plane
2. $P_z$: Helical track information

$dE/dx$ Information

Cerenkov light detected by FM-PMT
Timing resolution $\sim$100ps

**Likelihood:** $\mathcal{L}_i = \mathcal{L}_{i}^{CDC} \times \mathcal{L}_{i}^{TOF} \times \mathcal{L}_{i}^{ACC}$
Motivation

- $B \to X_s \gamma$ with $b \to s \gamma$ penguin loop diagram, is very sensitive to physics beyond SM because new heavy particles can contribute in the loop at the leading order.
  - NNLO SM calculation: $\mathcal{B}(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$ for $E_\gamma > 1.6$ GeV. [PRL 98(2007) 022002] M. Misiak
  - World average of experimental result: $\mathcal{B}(B \to X_s \gamma) = (3.40 \pm 0.21) \times 10^{-4}$ [PDG]
  - Recent measurement using sum of exclusive final states: $\mathcal{B}(B \to X_s \gamma) = (3.29 \pm 0.19 \pm 0.48) \times 10^{-4}$ [PRD 86(2012) 052012] BABAR

- Only one baryonic $B$ decay observation with $b \to s \gamma$: $\mathcal{B}(B^+ \to p \bar{\Lambda} \gamma) = (2.45^{+0.44}_{-0.38} \pm 0.22) \times 10^{-6}$. [PRD 76(2007) 052004] Belle
• In the MC simulation of $s \to X_s$ fragmentation and hadronization by JETSET, $X_s$ with a $\Lambda$ is only $\sim 1\%$, which is consistent with $B(B^+ \to p\Lambda\gamma)$.

• In multi-body hadronic baryonic $B$ decay, hierarchy in the branching fraction is observed: $\mathcal{B}(\text{4-body}) > \mathcal{B}(\text{3-body}) > \mathcal{B}(\text{2-body})$

\begin{align*}
  &b \to c: &b \to s: \\
  \mathcal{B}(B^0 \to p\Lambda_c\pi^+\pi^-) = (1.12\pm0.32) \times 10^{-3} & \mathcal{B}(B^0 \to p\Lambda\pi^+\pi^-) = (5.9\pm1.1) \times 10^{-6} \\
  \mathcal{B}(B^+ \to p\Lambda_c\pi^+) = (2.8\pm0.8) \times 10^{-4} & \mathcal{B}(B^+ \to p\Lambda\pi^-) = (3.14\pm0.29) \times 10^{-6} \\
  \mathcal{B}(B^0 \to p\Lambda_c) = (2.0\pm0.4) \times 10^{-5} & \mathcal{B}(B^0 \to p\Lambda) < 3.2 \times 10^{-7}
\end{align*}
To check the hierarchy in $b \to s\gamma$, $\mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-\gamma)$ is searched.

The measurement of $\mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-\gamma)$ can be helpful to understand the fragmentation and hadronization involved in $B \to X_s\gamma$, and to tune the parameters in JETSET. The uncertainty on the measurement of $\mathcal{B}(B \to X_s\gamma)$ would be reduced using a sum of exclusive final states.
Signal decay model

- \( B^+ \rightarrow p\Lambda\gamma \) [PRD 76(2007), 052004] Belle
  - Higher energy \( \gamma \) occupies the majority
  - Low mass threshold enhancement
  - Two body decay from \( B \).

- Signal MC model:
  \( B^0 \rightarrow (Xs)\gamma, \ (Xs) \rightarrow p\Lambda\pi^- \),
  \( Xs: 2.5 \pm 0.3 \text{ GeV/c}^2 \)
### MC samples & Selection criteria

- **Signal $B$ event** is reconstructed with the 4 final state particles.

- **Besides the signal decay MC**, other kinds of MC samples are also considered for background study:
  - Continuum BG:
    $$ e^+ e^- \rightarrow q\bar{q} \ (q = u, d, s, c) $$
  - Generic $B$ decay:
    $B$ decay with $b \rightarrow c$
  - Rare $B$ decay:
    $B$ decay with $b \rightarrow u, d, s$

<table>
<thead>
<tr>
<th>Selection criterion</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged pion</td>
<td>$\mathcal{L}_k/\pi &lt; 0.4$</td>
</tr>
<tr>
<td>Proton</td>
<td>$\mathcal{L}<em>{p/K} &gt; 0.6$, $\mathcal{L}</em>{p/\pi} &gt; 0.6$</td>
</tr>
<tr>
<td>Lambda</td>
<td>$1.111 &lt; M_\Lambda &lt; 1.121 \text{ GeV}/c^2$</td>
</tr>
<tr>
<td>Impact parameters</td>
<td>$</td>
</tr>
<tr>
<td>Photon</td>
<td>$E_\gamma &gt; 1.7 \text{ GeV}$ in CM frame</td>
</tr>
<tr>
<td>Continuum suppression</td>
<td>$\mathcal{R} &gt; 0.85$</td>
</tr>
<tr>
<td>Multiple counting</td>
<td>Smaller $\chi_B^2 + \chi_\Lambda^2$ (vertex fit)</td>
</tr>
</tbody>
</table>
Continuum suppression

- In our analysis, $e^+e^- \rightarrow q\bar{q}$ process is the dominant background.
- We combine several event topology variables using Fisher discriminant ($F = \sum_i \alpha_i x_i$, look for a best set of $\alpha_i$ to separate) and do training with spherical shape signal MC and jet-like continuum background, then a variable Likelihood ratio ($\mathcal{R}$) is constructed.

$$\mathcal{R} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B}$$

$$\mathcal{L}_{S(B)} = P(\mathcal{F})_{S(B)}, \mathcal{F}: \text{event topology variables}$$
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic Uncertainties</th>
<th>(%)</th>
<th>Control sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track reconstruction (2 protons, 2 pions)</td>
<td>1.4 (4 tracks)</td>
<td>$D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow \pi^+ \pi^- K_S^0$</td>
</tr>
<tr>
<td>Charged particles identification</td>
<td>0.6 (2 protons), 1.1(pion)</td>
<td>$\Lambda \rightarrow p \pi^-$, $D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^- \pi^+$</td>
</tr>
<tr>
<td>$N_{B\bar{B}}$</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\Lambda \rightarrow p \pi^-)$</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Lambda selection</td>
<td>3.3</td>
<td>$\Lambda \rightarrow p \pi^-$</td>
</tr>
<tr>
<td>Photon selection</td>
<td>2.2</td>
<td>Radiative Bhabha</td>
</tr>
<tr>
<td>$\mathcal{R}$ selection</td>
<td>1.9</td>
<td>$B^+ \rightarrow K^{*+}\gamma$</td>
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<tr>
<td>Reconstruction eff. (MC statistics)</td>
<td>2.2</td>
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<tr>
<td>PDF shape</td>
<td>4.1</td>
<td>$B^+ \rightarrow K^{*+}\gamma$</td>
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<tr>
<td>Signal decay model</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Rare $B$ decay</td>
<td>8.2</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.8</strong></td>
<td></td>
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Result

- Signal yield $= 9.5^{+11.5}_{-10.7}$
- Statistical significance $= 0.9$
- $\text{90\% confidence level upper limit: } 6.5 \times 10^{-7}$
- $\langle \mathcal{B}(B^+ \rightarrow p\bar{\Lambda}\gamma) \rangle = (2.45^{+0.44}_{-0.38} \pm 0.22) \times 10^{-6}$
  - In $b \rightarrow s\gamma$, the expected hierarchy is not observed.
Summary

• In conclusion, we have performed a search for the $B^0 \to p\bar{\Lambda}\pi^-\gamma$ decay, which proceeds via the $b \to s\gamma$ radiative penguin process, by using the full data sample of 772 million $B\bar{B}$ pairs at Belle. There is no significance observed, and we set the upper limit of branching fraction to be $6.5 \times 10^{-7}$ at the 90% confidence level for the $B^0 \to p\bar{\Lambda}\pi^-\gamma$ decay.

• We also conclude that the decay under study does not follow the expected hierarchy; instead, we find $\mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-\gamma) < \mathcal{B}(B^+ \to p\bar{\Lambda}\gamma)$. 
Backup
Control sample study \((B^+ \rightarrow K^{*-+} \gamma)\)

2D smooth function with 6 shape parameters

- For each dimension, look for its mean point (maximum) of the smooth function. Set a mean shift parameter, and 2 width expansion parameters for the two direction relative to the mean.
- 2D will have 6 shape parameters.
Thanks for your listening