Rare decays: a window on new physics

NIBEDITA DASH

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(On Behalf of the Belle II Collaboration)

Talk Outline:

- Introduction
- $b \rightarrow (s,d) \gamma$
- $b \rightarrow (s,d)l^+l^-$
- $b \rightarrow (s,d) \nu\nu$
- Summary
B-factories had a successful operational period (10 years) $1.5 \text{ ab}^{-1}$ ($1.25 \times 10^9$ Bpairs)

- Observation of CPV in B meson system and confirmation of CKM picture, first evidence for mixing in the D meson system, first evidence for exotic states X(3872) ....
- Still room for NP.

Belle II, as a next generation flavor factory, aims to search for NP in the flavour sector, and to further reveal the nature of QCD.

**Belle II Detector**

- All subdetectors are upgraded
- First Pixel layer closer to IP → Better vertex resolution
- Larger Vertex Detector → Better Ks efficiency
- TOP and ARICH → better K/$\pi$ separation.
- Better performance than Belle even under 20 times higher bkggs.

**Phase 2**: ongoing w/o VXD
Till mid-July

**Phase 3**: Full detector operation by end of 2018

**Already covered by Vishal Bhardwaj**
Detail will be covered by Thomas Browder on 18th in Review Talk
FCNC $b \rightarrow s$ and $b \rightarrow d$ processes continue to be of great importance to precision flavor physics.

Final states having color singlet leptons and photons are both theoretically and experimentally clean, radiative and electroweak (EW) penguin B decays are ideal place to search for NP.

Belle II physics program in this area will focus on process such as inclusive measurements of $B \rightarrow X_{(s,d)} \gamma$, $B \rightarrow X_{(s,d)} ll$ as well as decay $B \rightarrow K^{(*)} \nu \nu$.

Belle II will be very capable of B-meson decays into final states containing pairs of photons, neutrinos or taus (Fully-inclusive measurements).

Belle II will provide an independent test of anomalies recently uncovered by the LHCb and Belle experiments in the angular analysis of $B \rightarrow K^* \mu^+ \mu^-$ and in the determination of $R(K)$.

**Most of the Belle results are covered by S. Sandilya**
The inclusive $\bar{B} \to X_{(s,d)} \gamma$ decays provide important constraints on masses and interactions of many possible BSM scenarios and SUSY theories.

The inclusive $B \to X_{(s,d)} \gamma$ B.F. is sensitive to $|C_7|$ and in the new physics models such as 2HDM type II and SUSY. Precise prediction is available (for the CP- and IA branching ratios) for $E_\gamma > 1.6$ GeV:

$$\text{Br}_{s\gamma}^{\text{SM}} = (3.36 \pm 0.23) \cdot 10^{-4},$$
$$\text{Br}_{d\gamma}^{\text{SM}} = (1.73^{+0.12}_{-0.22}) \cdot 10^{-5}.$$  

**PRL 114, 221801 (2015)**

$$\text{Br}_{s\gamma}^{\text{exp}} = (3.27 \pm 0.14) \cdot 10^{-4},$$
$$\text{Br}_{d\gamma}^{\text{exp}} = (1.41 \pm 0.57) \cdot 10^{-5}.$$  

**JHEP, 04, 168 (2015)**

- Systematically dominated
- Exp. and theory are consistent – puts a strong limit on new physics.
- The newest Belle result with fully inclusive method has only 7.3% uncertainty: systematic dominated

Charged Higgs mass (2HDM type-II) > 580GeV in 95% C.L.
Mission at Belle II is to reduce the systematic uncertainty with more data.

3.9% total error will be reachable with 50 ab$^{-1}$ -which is comparable to uncertainty due to non-perturbative effect (which is hard to reduce) in theory. [Misiak et. al PRL 114, 221801 (2015)].

BF with $E_\gamma > 1.6$GeV can be measured w/o extrapolation

Lowering the photon energy threshold will however increase the size of the systematic uncertainty due to hadronic backgrounds.

(5-10 ab$^{-1}$ will be recorded in ~ 2-3 years)
In addition to BFs, asymmetry in decay rates (isospin asym. and CP asym.) are also sensitive to BSM contributions.

The direct CP asymmetry in the time-integral rates is defined as:

$$A_{\text{CP}} = \frac{\Gamma(\bar{B} \to X_{s} \gamma) - \Gamma(B \to X_{s} \gamma)}{\Gamma(\bar{B} \to X_{s} \gamma) + \Gamma(B \to X_{s} \gamma)}.$$ 

SM predicts: $B \to X_{s} \gamma$ and $B \to X_{d} \gamma$

- $A_{\text{CP}}^{\text{SM} (s\gamma)} = [-0.6, 2.8] \%$
- $A_{\text{CP}}^{\text{SM} (d\gamma)} = [-62, 14] \%$

$A_{\text{CP}}$ for the sum of $b \to s\gamma$ & $b \to d\gamma$ is predicted to be very small (close to zero, thanks to the unitarity of the CKM matrix)

$\Delta A_{\text{CP}}$ sensitive to phases in $C_{7}$ and $C_{8}$

In the SM, phases in $C_{7}$ and $C_{8}$ are zero $\rightarrow \Delta A_{\text{CP}} = 0$

If either is deviated from null, clear NP signal!

most of systematic cancels, statistically dominated @ Belle II (50 ab$^{-1}$)

Uncertainty in:
- $A_{\text{CP}} : \pm 0.6 \% \rightarrow 3.7\sigma$
- $\Delta A_{\text{CP}} : \pm 0.4 \%$

if the central value not change

BaBar’s measurement $\Delta A_{\text{CP}}(X_{s}\gamma) = +(5.0 \pm 3.9 \pm 1.5)\%$

[Belle II : +(5.0\pm0.37)\%]

Isospin asymmetry is defined as:

\[
\tilde{a}_I^0 = \frac{c_{\rho_0}^2 \Gamma(B^0 \to \bar{V}^0\gamma) - \Gamma(B^- \to V^-\gamma)}{c_{\rho_0}^2 \Gamma(B^0 \to \bar{V}^0\gamma) + \Gamma(B^- \to V^-\gamma)}
\]

\[
c_{\rho_0}^2 = 2 \quad \text{and} \quad c_{K^*}^2 = 1 \quad \text{are isospin-symmetry factors}
\]

To accumulate more statistics, CP-averaged IAs can be defined as:

\[
\bar{a}_I = (a_I^0 + a_I^{0+})/2.
\]

\[
\bar{a}_I^{SM}(K^{*}\gamma) = (4.9 \pm 2.6)\%
\]

\[
\bar{a}_I^{SM}(\rho\gamma) = (5.2 \pm 2.8)\%
\]

PRD 88 (2013), 094004

\[
\bar{a}_I^{exp}(K^{*}\gamma) = (5.2 \pm 2.6)\%
\]

\[
\bar{a}_I^{exp}(\rho\gamma) = (30^{+13}_{-16})\%
\]

HFLAV 2017

The observable with reduced uncertainty

\[
\delta_{aI}^{SM} = 0.10 \pm 0.11
\]

\[
\delta_{aI}^{exp} = -4.0 \pm 3.5
\]

Can be improved at Belle II with more statistics.
Mixing-induced CP asymmetry in an exclusive $b \rightarrow s \gamma$ mode such as $B \rightarrow K^*(K_s \pi^0)\gamma$ is an excellent probe for particular class of NP scenario.

In the SM, expected asymmetry $|S_{CP}|$

$$\approx \frac{2m_s}{m_B} \sin(2\phi_1) \sim \text{a few \%}.$$ 

At Belle II, significant improvement in the determination of $A_{CP}(t)$ in $K_s \pi^0 \gamma$ is expected:
- Larger VXD than Belle (6cm → 11.5cm).
- 30% more $K_s$
- Effective tagging efficiency

Expected errors for S measurements of $K_s \pi^0 \gamma$ and $\rho^0 \gamma$:

<table>
<thead>
<tr>
<th>Mode</th>
<th>5 ab$^{-1}$</th>
<th>50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s \pi^0 \gamma$</td>
<td>0.09</td>
<td>0.030</td>
</tr>
<tr>
<td>$\rho^0 \gamma$</td>
<td>0.19</td>
<td>0.064</td>
</tr>
</tbody>
</table>
B → K(*) ll proceeds via one loop diagram, and LU holds in SM

Current $R_{K^*}$, $R_K$ results

- However electron mode is challenging at LHCb, especially for high $q^2$
- Belle II:
  - electron and muon modes have similar efficiency
  - Both low and high $q^2$ regions are possible
  - All ratios $R(K)$, $R(K^*)$, $R(X_s)$ are possible

Ratio of $B → K^{(*)} μ μ$ and $B → K^{(*)} ee$
Belle II should be able to confirm the $R(K^{(*)})$ anomaly with a significance of 5\(\sigma\), if it is indeed due to new physics.

- The errors reach to 0.04 for all $K$, $K^{*}$ and $X_{s}$ modes in Belle II (with 50 ab\(^{-1}\))
- Errors are still statistically limited (systematic error \(~\) 0.4%)

Belle II should be able to confirm the $R(K^{(*)})$ anomaly with a significance of 5\(\sigma\), if it is indeed due to new physics.
Angular Analysis $B \rightarrow K^* l^+ l^-$

Full decomposition of angular distribution

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

Optimized observable

\[
P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L (1 - F_L)}},
\]

- Global fits including $P_5'Q_5'R(K^*)$,
  $B_s \rightarrow \mu \mu, B \rightarrow s\gamma$ suggests $C_{9\mu}^{\text{NP}} \approx -1.1$
- Belle II and LHCb will be comparable for this process.
- Electron mode more efficiently and can also explore $Q_{4,5}$
- Projection of uncertainties at Belle II for $P_5'$

<table>
<thead>
<tr>
<th>$q^2$ (GeV$^2c^{-4}$)</th>
<th>Belle</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 – 4</td>
<td>0.42</td>
<td>0.06</td>
</tr>
<tr>
<td>4 – 8</td>
<td>0.28</td>
<td>0.04</td>
</tr>
<tr>
<td>10.09 – 12</td>
<td>0.34</td>
<td>0.05</td>
</tr>
<tr>
<td>14.18 – 19</td>
<td>0.25</td>
<td>0.03</td>
</tr>
</tbody>
</table>

2.5σ (combined) tension

$\mu$ mode 2.6σ, $e$ mode 1.1σ

Low $q^2$ region

4% error with 50 ab$^{-1}$ comparable with LHCb 22fb$^{-1}$ result
Measurement of $BF$ and $A_{FB}$ in $B \to X_s l^+ l^-$ at Belle
- Sum-of-exclusive method is utilized
- Tension in low $q^2$ region
- Measurement can be improved at Belle II.

Decay rate $dBF/dq^2$, $A_{FB}$ Sensitive to $C_9$ and $C_{10}$
- Precise theory prediction available
Belle updated $b \to (s,d)\nu\nu$ measurement with semileptonic tag

**Well explained by S. Sandilya**

- Proceeds via penguin or box diagrams
- Theoretically very clean channel (no charm loops)

**[PRD96, 091101(R)]**

- Most stringent limits till date in most channels
- Close to SM prediction in $K^{(*)}$ mode Golden channel for Belle II

**[JHEP 02 184, 2015]**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B$ [10^{-6}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^+\nu\bar{\nu}$</td>
<td>3.98 ± 0.43 ± 0.19</td>
</tr>
<tr>
<td>$B^0 \to K^0_S\nu\bar{\nu}$</td>
<td>1.85 ± 0.20 ± 0.09</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}\nu\bar{\nu}$</td>
<td>9.91 ± 0.93 ± 0.54</td>
</tr>
<tr>
<td>$B^0 \to K^{*0}\nu\bar{\nu}$</td>
<td>9.19 ± 0.86 ± 0.50</td>
</tr>
</tbody>
</table>

**BaBar hadronic**

**Belle hadronic**

**Belle semileptonic**

**SM prediction**

**BaBar semileptonic**

*Figure showing limit on $B$ at 90% CL for various $B$ decay channels.*
Brighter prospects for Belle II to observe this decay.

**Expected uncertainty at Belle II**

<table>
<thead>
<tr>
<th></th>
<th>stat only</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \nu\nu$</td>
<td>10%</td>
<td>11%</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+} \nu\nu$</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*0} \nu\nu$</td>
<td>8%</td>
<td>10%</td>
</tr>
</tbody>
</table>

- Belle II extrapolation based on Belle hadronic and SL tag analyses, assuming 100% observation with about 18 ab$^{-1}$ precision on the branching fraction at 50 ab$^{-1}$
- BF($B \rightarrow K(*)\nu\nu$) is measurable at Belle II with about 10% uncertainty.
Many detector components and electronics replaced, software and analysis also improved

Belle II has a rich physics program, complementary to existing experiments and energy frontier programs

Belle II experiment will contribute strongly to apply further constraint on BSM and to understand the current anomalies, with abundant rare B decay data:
1. Radiative penguin B decays
2. Semileptonic penguin B decays

Moreover, Belle II has a sufficient ability to discover other interesting decay channels: $B \rightarrow K(*)\nu\nu$

THANK YOU !!
Extra
Belle II will be able to discover $B_d \rightarrow \gamma \gamma$ with the anticipated 50 ab$^{-1}$ at Y(4S)

large data at Y(5S) $B_s \rightarrow \gamma \gamma$ can be observed

Double-Radiative Decays

$B_q \rightarrow \gamma \gamma$

SM prediction

$Br(B_s \rightarrow \gamma \gamma)_{SM} \in [0.5,3.7] \cdot 10^{-6},$

$Br(B_d \rightarrow \gamma \gamma)_{SM} \in [1.0,9.8] \cdot 10^{-8},$

Exp. status

$Br(B_s \rightarrow \gamma \gamma)_{exp} < 3.1 \cdot 10^{-6},$

$Br(B_d \rightarrow \gamma \gamma)_{exp} <$

$\begin{cases} 
3.2 \cdot 10^{-7}, \\
6.2 \cdot 10^{-7} 
\end{cases},$

[JHEP 08 (2002) 054]

[Belle, PRD 91, 011101 (2015)]

[BaBar, PRD 83, 032006 (2011)]

[Belle, , PRD 73, 051107 (2006)]

$B \rightarrow X_s \gamma \gamma$

$B \rightarrow X_s \gamma \gamma$ decays are suppressed by $\alpha_s / 4\pi$ compared to $B \rightarrow X_s \gamma$

$Br(B \rightarrow X_s \gamma \gamma)_{SM}^{c=0.02} = (0.9 \pm 0.3) \cdot 10^{-7},$

[PRD 93, 014037 (2016)]

Measurements of the double-radiative decay mode would allow to put bounds on 1PI type corrections.

One can study more complicated distributions like, double differential rate $(d^2\Gamma/dE_1 dE_2)$ and forward backward asymmetry : sensitive to BSM physics

90% CL UL

17
Lepton Flavour dependent Angular Analysis $B\to K^*\ell\ell$
Lepton Flavour dependent Angular Analysis

4% error with 50 ab\(^{-1}\)
- comparable with LHCb 22fb\(^{-1}\) result
### Belle II Projected Sensitivity to (some of) Angular Observables

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab(^{-1})</th>
<th>Belle II 5 ab(^{-1})</th>
<th>Belle II 50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_L) ((1 &lt; q^2 &lt; 2.5 \text{ GeV}^2))</td>
<td>0.19</td>
<td>0.063</td>
<td>0.025</td>
</tr>
<tr>
<td>(F_L) ((2.5 &lt; q^2 &lt; 4 \text{ GeV}^2))</td>
<td>0.17</td>
<td>0.057</td>
<td>0.022</td>
</tr>
<tr>
<td>(F_L) ((4 &lt; q^2 &lt; 6 \text{ GeV}^2))</td>
<td>0.14</td>
<td>0.046</td>
<td>0.018</td>
</tr>
<tr>
<td>(F_L) ((q^2 &gt; 14.2 \text{ GeV}^2))</td>
<td>0.088</td>
<td>0.027</td>
<td>0.009</td>
</tr>
<tr>
<td>(P_5') ((1 &lt; q^2 &lt; 2.5 \text{ GeV}^2))</td>
<td>0.47</td>
<td>0.17</td>
<td>0.054</td>
</tr>
<tr>
<td>(P_5') ((2.5 &lt; q^2 &lt; 4 \text{ GeV}^2))</td>
<td>0.42</td>
<td>0.15</td>
<td>0.049</td>
</tr>
<tr>
<td>(P_5') ((4 &lt; q^2 &lt; 6 \text{ GeV}^2))</td>
<td>0.34</td>
<td>0.12</td>
<td>0.040</td>
</tr>
<tr>
<td>(P_5') ((q^2 &gt; 14.2 \text{ GeV}^2))</td>
<td>0.23</td>
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</tr>
</tbody>
</table>

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**Belle II Theory Interface Platform (B2TIP)**
(https://confluence.desy.de/display/BI/B2TIP+WebHome)

**6th Belle II Theory Interface Platform (B2TIP) Workshop, KEK**
https://kds.kek.jp/indico/event/27330/
Constraint (95% C.L.) on Charged Higgs (2HDM type-II)

THDM Type II - Flavour constraints

\[ \tan \beta, \quad 10 \]

\[ M_{H^+} \text{ (GeV)} \]

- allowed
- \( b \rightarrow s \gamma \)
- \( B \rightarrow \tau \nu \)
- \( D_s \rightarrow \tau \nu \)
- \( \Delta M_{b_s} \)
- \( B_s \rightarrow \mu \mu \)

\( b \rightarrow s \gamma \)

arXiv:1706.07414