Electroweak penguin measurements and prospects at Belle II

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Outline

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● Belle II status
● Electroweak $B$ decays
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Motivation

- FCNC transition $b \rightarrow s (d)$ is forbidden at tree level in the Standard Model and proceeds via electroweak loop diagrams.
- New physics effects can contribute in the loop or mediate the process at tree level.
Belle II and SuperKEKB
Belle II status

- Reached a record peak luminosity of $2.9 \times 10^{34}\text{ cm}^{-2}\text{ s}^{-1}$
- Luminosity goal: $6.5 \times 10^{35}\text{ cm}^{-2}\text{ s}^{-1}$
- Collected $\approx 170 \text{ fb}^{-1}$ data since 2018, ultimate goal to collect 50 ab$^{-1}$
Electroweak $B$ decays (semi-leptonic)

**Observables**

\[
R_H[q_0^2, q_1^2] = \frac{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}} \quad (q^2 = M_{\ell\ell}^2) \\
(\ell \Rightarrow e \text{ or } \mu)
\]

\[Q_i = P_i^\mu - P_i^e \quad \text{(def of } P_i : \text{JHEP 05 (2013) 137)}
\]

**Belle II vs hadron machines**

- Equal sensitivity to electron and muon modes
- Access to high and low $q^2$ regions
- $B \to X\gamma, B \to X\ell\ell$ inclusive measurements

**Overview**

- SM gauge bosons don’t discriminate between different leptons, similar couplings
- $R_H$ is a clean observable
- Belle $R_K$ measurement: JHEP 03, 105 (2021)
- $B \to K^*\ell\ell$ angular analysis: PRL 118, 111801
Electroweak $B$ decays (semi-leptonic)

- First $b \to s\ell\ell$ decay observed at Belle II
- Reject $B^+ \to K^+ \psi(nS)$ [where $n=1,2$] background with di-lepton invariant mass veto
- Employed BDT (event shape, vertex related and missing energy variables) to suppress background from light quark and inclusive $B$ decays.

First observation with just $63 \times 10^{-1}$ fb$^{-1}$ of collision data

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^*}$$

$$\Delta E = E_{beam}^* - E_B^*$$

- $8.6^{+4.3}_{-3.9} \pm 0.4$ signal events ($2.7\sigma$ significance) [errors are stat. and syst. resp.]
Electroweak $B$ decays (missing energy)

**Observables**

Branching fraction: $\mathcal{B}(B \rightarrow K^{(*)} \nu \bar{\nu})$

Longitudinal polarisation fraction ($F_L$) of $K^*$

$F_L^{SM} = 0.47 \pm 0.03$

<table>
<thead>
<tr>
<th>$B \rightarrow K^{(*)} \nu \bar{\nu}$</th>
<th>UL @ 90% CL (10^-3)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^{+} \rightarrow K^{+} \nu \bar{\nu}$</td>
<td>1.6</td>
<td>BaBar, HAD+SL TAG, 429 fb⁻¹</td>
</tr>
<tr>
<td>$B^{+} \rightarrow K^{*+} \nu \bar{\nu}$</td>
<td>4.0</td>
<td>Belle, HAD TAG, 711 fb⁻¹</td>
</tr>
<tr>
<td>$B^{0} \rightarrow K^{0} \nu \bar{\nu}$</td>
<td>2.6</td>
<td>Belle, SL TAG, 711 fb⁻¹</td>
</tr>
<tr>
<td>$B^{0} \rightarrow K^{*0} \nu \bar{\nu}$</td>
<td>1.8</td>
<td>Belle, SL TAG, 711 fb⁻¹</td>
</tr>
</tbody>
</table>

**Overview**

- Belle ([PRD 87, 111103](http://link.aps.org/doi/10.1103/PhysRevD.87.111103)) and BaBar ([PRD 82, 112002](http://link.aps.org/doi/10.1103/PhysRevD.82.112002)) measurements provided UL on the BF
Electroweak $B$ decays (missing energy)

Tagging approach

- Previous searches for $\mathcal{B}(B \to K\nu\bar{\nu})$ adopted a tagging technique where the tag-side $B$ meson was explicitly reconstructed.
- Hadronic tag: $\epsilon(\text{tag}) \times \epsilon(\text{sig}) \approx 0.04\%$
- Semi-leptonic tag: $\epsilon(\text{tag}) \times \epsilon(\text{sig}) \approx 0.2\%$
Electroweak $B$ decays (missing energy)

- Reconstruct the track with highest $p_T$ and at least one hit in the PXD as the signal candidate.
- Inclusive reconstruction of remaining tracks as cluster as rest of event (ROE)
- Identification of signal using topological features of decay

$B\bar{B}$  
$B(\to K\nu\bar{\nu})\bar{B}$  
$q\bar{q}$
Electroweak $B$ decays (missing energy)

- First results for $B(B \rightarrow K \nu \bar{\nu})$ at Belle II employing inclusive tag approach
- Use of nested statistical-learning discriminators exploiting the event topology
- Sizeable signal selection efficiency (4%) while controlling large backgrounds.

![Graph showing Belle II preliminary results]

- Validation using $B \rightarrow K J/\psi[\rightarrow \mu^+ \mu^-]$
- Ignore $\mu^+ \mu^-$ and modify $K^+$
- 4-momentum using generator level info of $K^+$ from $B \rightarrow K^+ \nu \bar{\nu}$
- Validation channel now mimics signal!
- Excellent Data/MC agreement between the BDTs of signal and control channel
Electroweak $B$ decays (missing energy)

- Signal strength: $\mu = 4.2^{+2.9+1.8}_{-2.9-1.6}$ [errors are stat. and syst. resp.]
- Consistent with the bkg-only (SM) hypothesis at CL $1.3\sigma$ ($1\sigma$)
- Observed (expected) UL @90% CL: $4.1 \times 10^{-5}$ ($2.6 \times 10^{-5}$)

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Sensitivity with just 63 fb$^{-1}$ data is already close to previous searches with significantly larger data-set.

$$B(B \to K^+ \nu\bar{\nu}) = 1.9^{+1.3+0.8}_{-1.3-0.7} \times 10^{-5}$$
Electroweak $B$ decays (missing energy)

Prospects for Belle II

- Expected to observe $B \rightarrow K^* \nu \bar{\nu}$ with 5 $ab^{-1}$ collision data
- Sensitivity on branching fraction will be about 10% with 50 $ab^{-1}$ data
- Possible to determine $F_L$ with a sensitivity of 0.08 with 50 $ab^{-1}$ data
- Work in progress to improve the inclusive tag method and employ the same strategy for other modes like $B \rightarrow K^* \nu \bar{\nu}$
Radiative electroweak $B$ decays

**Observables**

Branching fraction: $\mathcal{B}(B \to X_s \gamma)$, $\mathcal{B}(B \to X_{s+d} \gamma)$

$$A_{CP}^{X_{s+d} \gamma} = \frac{\Gamma(\bar{B} \to X_{s+d} \gamma) - \Gamma(B \to X_{s+d} \gamma)}{\Gamma(\bar{B} \to X_{s+d} \gamma) + \Gamma(B \to \bar{X}_{s+d} \gamma)}, \quad \Delta A_{CP} = A_{CP}(B^+ \to X_s^+ \gamma) - A_{CP}(B^0 \to X_0 \gamma)$$

**Overview**

- Belle measurement of $A_{CP}$ and $\Delta A_{CP}$ for $B \to X_s \gamma$: [PRD 99, 032012](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.032012)
- $A_{CP}$ measurement for $B \to X_{s+d} \gamma$ with lepton tag: [PRL 114, 151601](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.151601)
Radiative electroweak $B$ decays

- Presence of monochromatic (smeared) photon from $b \rightarrow s \gamma$ two-body decay.
- Select high energy photon $E_{\gamma}^* > 1.4$ GeV
- Photon should not be arising from $\pi^0$ decay
- BDT based continuum suppression with event shape variables
- Data driven scaling of MC (off-resonance and side-bands)

Spectrum of selected candidates overlaid with various background contributions.
Radiative electroweak $B$ decays

Prospects for Belle II

- Fully inclusive measurements: reduce systematics by better modeling of neutral hadrons faking photons
- Sum-of-exclusive measurements: increase the number of modes to reduce systematic from $X_s$ hadronization
- Hadronic tagging method to increase purity and reduce $E_\gamma$ threshold
Summary

- Clean environment at Belle II grants access to unique observables $(R_{X_s}, Q_5)$ in rare B decays
- Improved detector and analysis methods, better sensitivity.
- Opportunity to probe neutral as well as charged final states.
- Belle II is collecting data despite the Covid-19 pandemic thanks to our collaboration, inching towards the ultimate goal to record 50 ab collision data.