RECENT RESULTS ON SEMILEPTONIC, RADIATIVE, AND ELECTROWEAK PENGUIN DECAYS AT BELLE II

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Lake Louise Winter Institute - February 24, 2023
OVERVIEW

SEMILEPTONIC DECAYS

- SM precision measurements
- Lepton flavor universality (LFU) tests

ELECTROWEAK + RADIATIVE PENGUINS

- LFU tests
- Non-SM physics probes

$$R(K^{(*)}) = \frac{B(B \to K^{(*)} \mu^+ \mu^-)}{B(B \to K^{(*)} e^+ e^-)}$$

arXiv: 2205.05222v1
$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{sig}} B_{\text{tag}}$
RECONSTRUCTION STRATEGIES

\[ e^+ e^- \rightarrow \gamma(4S) \rightarrow B_{\text{sig}} B_{\text{tag}} \]

**Tagged:**
- \( B_{\text{sig}} \) and \( B_{\text{tag}} \) reconstructed
- \( B_{\text{tag}} \) reconstructed using Full Event Interpretation

**Untagged (inclusive tag):**
- Only \( B_{\text{sig}} \) reconstructed

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*Source: Comput Softw Big Sci 3, 6 (2019)*
$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{sig}} B_{\text{tag}}$

**Tagged:**
- $B_{\text{sig}}$ and $B_{\text{tag}}$ reconstructed
- $B_{\text{tag}}$ reconstructed using Full Event Interpretation

**Untagged (inclusive tag):**
- Only $B_{\text{sig}}$ reconstructed

**Efficiency**
- Low
- High

**Purity**
- Low
- High

*Comput Softw Big Sci 3, 6 (2019)*
$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{sig}} B_{\text{tag}}$
MOTIVATION: CKM MATRIX ELEMENTS

- Test SM by over-constraining unitarity triangle
- Important inputs to SM rates of ultra rare decays
- Tension between exclusive and inclusive $|V_{xb}|$ measurements
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- Test SM by over-constraining unitarity triangle
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- Tension between exclusive and inclusive $|V_{xb}|$ measurements

Measure decay rates:

\[
\frac{d\Gamma}{dq^2} \propto |V_{ub}|^2 \times |FF(q^2)|^2
\]

\[
\frac{d\Gamma}{dw} \propto |V_{cb}|^2 \times |FF(w)|^2
\]

Momentum transfer squared:

\[ q^2 = (p_B - p_X)^2 \]

Hadronic recoil:

\[ w = \frac{p_B \cdot p_X}{m_B m_X} \]
UNTAGGED $B^0 \rightarrow \pi^- \ell \nu$

- Large backgrounds suppressed using BDTs

\[ \Delta E = E_B - E_{\text{beam}} \]
\[ M_{bc} = \sqrt{E_{\text{beam}}^2 - |p_B|^2} \]

- Binned fit of $\Delta E$ and $M_{bc}$ in six $q^2$ bins
UNTAGGED $B^0 \rightarrow \pi^- l\nu$  

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- Binned fit of $\Delta E$ and $M_{bc}$ in six $q^2$ bins

TAGGED $B \rightarrow \pi l\nu$  

\[ M_{\text{miss}}^2 = p_{e^+} - p_{B\text{tag}} - p_{\pi} - p_e \]

- Binned fit of $M_{\text{miss}}^2$ in three $q^2$ bins
UNTAGGED $B^0 \to \pi^- l \nu$  

- Large backgrounds suppressed using BDTs

$$\Delta E = E_B - E_{\text{beam}} \quad M_{bc} = \sqrt{E_{\text{beam}}^2 - |p_B|^2}$$

- Binned fit of $\Delta E$ and $M_{bc}$ in six $q^2$ bins

TAGGED $B \to \pi e\nu$  

$$M_{\text{miss}}^2 = p_{e^+ e^-} - p_{\text{Btag}} - p_\pi - p_e$$

- Binned fit of $M_{\text{miss}}^2$ in three $q^2$ bins

- Combined fit to BCL expansion and form-factor LQCD constraints

$$|V_{ub}| = (3.55 \pm 0.12_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.17_{\text{theo}}) \times 10^{-3}$$

$$|V_{ub}| = (3.88 \pm 0.45_{\text{tot}}) \times 10^{-3}$$
UNTAGGED $B \rightarrow Dl\nu$  arxiv: 2210.13143

- Large backgrounds from $B \rightarrow D^*l\nu$

  \[
  \cos\theta_{BY} = \frac{2E_BE_Y - m_B^2 - m_Y^2}{2p_Bp_Y} \quad Y = Dl
  \]

- Binned fit of $\cos\theta_{BY}$ in ten $w$ bins
UNTAGGED $B \to Dl\nu$  
- Large backgrounds from $B \to D^*l\nu$

$$\cos\theta_{BY} = \frac{2E_BE_Y - m_B^2 - m_Y^2}{2p_Bp_Y} \quad Y = Dl$$

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TAGGED $B^0 \to D^{*-}l\nu$  
- Binned fit of $M_{\text{miss}}^2$ in ten w bins
UNTAGGED $B \to Dl\nu$

- Large backgrounds from $B \to D^* l\nu$

\[
\cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2p_B p_Y} \quad Y = Dl
\]

- Binned fit of $\cos\theta_{BY}$ in ten $w$ bins

- Combined fit to BGL expansion and form-factor LQCD constraints

Phys. Rev. D 56, 6895
Phys. Rev. D 92, 034506
Phys. Rev. D 92, 054510

TAGGED $B^0 \to D^{*-} l\nu$

- Binned fit of $M_{\text{miss}}^2$ in ten $w$ bins

- Fit CLN parametrized form factor to differential decay rates

NPB530, 153 (1998)

\[
|V_{cb}| = (38.3 \pm 1.2\text{,_{tot}}) \times 10^{-3}
\]

\[
|V_{cb}| = (37.9 \pm 2.7\text{,_{tot}}) \times 10^{-3}
\]
MOTIVATION: LFU TESTS AND EW PENGUINS

- Test LFU in semileptonic decays and electroweak penguins

\[ R(D^*) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)} \]

Tension with SM at \( \approx 3\sigma \)

\[ \Delta \chi^2 = 1.0 \text{ contours} \]

arXiv:2206.07501
MOTIVATION: LFU TESTS AND EW PENGUINS

- Test LFU in semileptonic decays and electroweak penguins

\[ R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)} \]

Tension with SM at \( \approx 3\sigma \)

\[ R(D) = 0.298 \pm 0.005 \]

\[ R(D^*) = 0.285 \pm 0.010 \pm 0.008 \]

\[ \rho = -0.29 \]

\[ \Gamma(K^{(*)}) = 32\% \]

- Flavor changing neutral current suppressed at tree level

- But allowed in SM through loops

- Sensitive to non-SM contributions
- Inclusive test in tagged semileptonic decays

\[ R(X_e/\mu) = \frac{B(B \to Xe\nu)}{B(B \to X\mu\nu)} \]

- Fit lepton momentum \( (p_l^* > 1.3 \text{ GeV/c}) \) in B frame
- Inclusive test in tagged semileptonic decays

\[ R(X_{e/\mu}) = \frac{B(B \to Xe\nu)}{B(B \to X\mu\nu)} \]

- Fit lepton momentum \( (p_l^* > 1.3 \text{ GeV/c}) \) in B frame

\[ R(X_{e/\mu}) = 1.033 \pm 0.010_{\text{stat}} \pm 0.019_{\text{syst}} \]

- Compatible with SM prediction \( \text{arxiv:2207.03432} \)

- Most precise BF-based LFU test with semileptonic decays

- Next: measurement of \( R(X_{\tau/\ell}) \)
$B \to K^* l^+ l^-$  

- Suppress background using dilepton mass and BDT
- Unbinned fit of $\Delta E$ and $M_{bc}$

\[
B(B \to K^* l^+ l^-) = (1.25 \pm 0.30_{\text{stat}}^{+0.08}_{-0.07\text{syst}}) \times 10^{-6}
\]
**Preparation for $R(K^*)$**

- $B \rightarrow K^* l^+ l^-$ \text{ arxiv:2206.05946}
  - Suppress background using dilepton mass and BDT
  - Unbinned fit of $\Delta E$ and $M_{bc}$

\[
B(B \rightarrow K^* l^+ l^-) = (1.25 \pm 0.30_{\text{stat}}^{+0.08}_{-0.07\text{syst}}) \times 10^{-6}
\]

- $B \rightarrow J/\psi K$ \text{ arxiv: 2207.11275}
  - No $b \rightarrow s$ transition
  - Important control channel $\rightarrow$ very pure

\[
R_K(J/\psi) = \frac{B(B \rightarrow J/\psi[\mu^+ \mu^-]K)}{B(B \rightarrow J/\psi[e^+ e^-]K)}
\]

- Unbinned fit of $\Delta E$ and $M_{bc}$

\[
R_{K^+}(J/\psi) = 1.009 \pm 0.022_{\text{stat}} \pm 0.008_{\text{syst}}
\]

\[
R_{K^0}(J/\psi) = 1.042 \pm 0.042_{\text{stat}} \pm 0.008_{\text{syst}}
\]
Complementary to $B \rightarrow K^{(*)} l^+ l^-$

- Best upper limit: $1.6 \times 10^{-5}$ at 90% CL by BaBar

- First attempt using inclusive reconstruction of $B_{tag}$

- Reduce backgrounds using nested BDTs

- Signal strength from simultaneous fit of $p_T$ in different classifier regions

Phys. Rev. Lett. 127, 181802

Phys. Rev. D 87, 112005

Belle II

\[ \int \mathcal{L} dt = (63 + 9) \text{fb}^{-1} \]
Complementary to $B \rightarrow K^{(*)} l^+ l^-$

- Best upper limit: $1.6 \times 10^{-5}$ at 90% CL by BaBar

- First attempt using inclusive reconstruction of $B_{\text{tag}}$

- Reduce backgrounds using nested BDTs

- Signal strength from simultaneous fit of $p_T$ in different classifier regions

**Limit of $4.1 \times 10^{-5}$ at 90% CL**

- Soon: Update with data set 6 times as large
$B \rightarrow X_s \gamma$

- Higher rates and sensitive to non-SM physics in different ways
- Can extract shape function parameters describing motion of $b$-quark inside $B$ meson
$B \rightarrow X_s \gamma$

- Higher rates and sensitive to non-SM physics in different ways
- Can extract shape function parameters describing motion of b-quark inside B meson

**Inclusive $B \rightarrow X_s \gamma$:**

- Tagged measurement: direct access to $E^B_\gamma$
- Extract good $B_{\text{tag}}$ events by fitting $M_{bc}$ in 11 bins of $E^B_\gamma$
 Higher rates and sensitive to non-SM physics in different ways
- Can extract shape function parameters describing motion of b-quark inside B meson

Inclusive $B \to X_s \gamma$:
- Tagged measurement: direct access to $E_Y^B$
- Extract good $B_{\text{tag}}$ events by fitting $M_{bc}$ in 11 bins of $E_Y^B$
- Subtract background using simulation

*arxiv: 2210.10220*
**$B \rightarrow X_S \gamma$**

- Higher rates and sensitive to non-SM physics in different ways
- Can extract shape function parameters describing motion of b-quark inside B meson

**Inclusive $B \rightarrow X_S \gamma$:**

- Tagged measurement: direct access to $E^B_Y$
- Extract good $B_{tag}$ events by fitting $M_{bc}$ in 11 bins of $E^B_Y$
- Subtract background using simulation

$arxiv: 2210.10220$

\[
B(B \rightarrow X_S \gamma) = (3.54 \pm 0.78_{\text{stat}} \pm 0.83_{\text{syst}}) \times 10^{-4}
\]
SUMMARY

- First results with data set smaller than data set of BaBar and Belle
- Only presented a subset of results
- Already produce highly competitive results:
  \[ R(X_e/\mu), B(B^+ \rightarrow K^+\nu\bar{\nu}), \ldots \]
- Soon results with data set 2 (to 6) times larger!

Thank you for your attention!
Backup
SUPERKEKB, BELLE II DETECTOR

- Now in Long Shutdown 1 (15 months)
- Detector upgrades and beam-pipe improvement

EM Calorimeter:
- CsI(Tl), waveform sampling (barrel)
- Pure CsI + waveform sampling (end-caps)

KL and muon detector:
- Resistive Plate Counter (barrel)
- Scintillator + WLSF + MPPC (end-caps)

Vertex Detector
- 2 layers DEPFET + 4 layers DSSD

Beryllium beam pipe
- 2cm diameter

Central Drift Chamber
- He(50%):C2H6(50%), Small cells, long lever arm, fast electronics

Particle Identification
- Time-of-Propagation counter (barrel)
- Front focusing Aerogel RICH (fwd)

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Particle Identification
- Time-of-Propagation counter (barrel)
- Front focusing Aerogel RICH (fwd)

Belle II detector
- Tsukuba
- Oho
- Nikko
- Fuji
- electron-positron injector linac

Target
- 510fb^-1
- 480fb^-1

arXiv:1809.01958
FULL EVENT INTERPRETATION (FEI)

- FEI algorithm used to reconstruct $B_{tag}$

- Uses $\approx 200$ BDTs to reconstruct $O(10000)$ different $B$ decay chains

- Assigns signal probability of being correct $B_{tag}$
Tension:

- Most indications point to inconsistent experimental/theoretical inputs
- Cannot exclude non-SM physics

Improvements:

- Theoretical understanding
- $B \to Xl\nu$ background modeling
- Calibration of $B_{\text{tag}}$ efficiency

arXiv:2207.11275
\( R(D^{(*)}) \): 

- Understand \( B \to D^{**} \ell \nu \) downfeed

\( R(X_{\tau/\ell}) \)

- Control inclusive background composition
– Reduced theoretical uncertainties compared to $B \to K^* l^+ l^-$

– No virtual photon contribution

<table>
<thead>
<tr>
<th>Decay</th>
<th>1 ab$^{-1}$</th>
<th>5 ab$^{-1}$</th>
<th>10 ab$^{-1}$</th>
<th>50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^+ \nu \bar{\nu}$</td>
<td>0.55 (0.37)</td>
<td>0.28 (0.19)</td>
<td>0.21 (0.14)</td>
<td>0.11 (0.08)</td>
</tr>
<tr>
<td>$B^0 \to K_S^0 \nu \bar{\nu}$</td>
<td>2.06 (1.37)</td>
<td>1.31 (0.87)</td>
<td>1.05 (0.70)</td>
<td>0.59 (0.40)</td>
</tr>
<tr>
<td>$B^+ \to K^{*+} \nu \bar{\nu}$</td>
<td>2.04 (1.45)</td>
<td>1.06 (0.75)</td>
<td>0.83 (0.59)</td>
<td>0.53 (0.38)</td>
</tr>
<tr>
<td>$B^0 \to K^{*0} \nu \bar{\nu}$</td>
<td>1.08 (0.72)</td>
<td>0.60 (0.40)</td>
<td>0.49 (0.33)</td>
<td>0.34 (0.23)</td>
</tr>
</tbody>
</table>

Baseline: no further improvements
Improved: efficiency increases by 50% at same background level

For the $B^+ \to K^{*+} \nu \bar{\nu}$ decay:
Baseline: 20% efficiency increase
Improved: 70% efficiency increase

arXiv:2207.11275
$B \rightarrow X_S \gamma$

**Inclusive:**
- $E^B_\gamma$ threshold
  - Lower: higher BB background
  - Higher: larger theoretical uncertainties
- Background from events with energetic $\pi^0 \rightarrow \gamma\gamma$ photon
- Systematic limit from $\pi^0 \rightarrow \gamma\gamma$ veto modeling

**Exclusive: $B \rightarrow K^*\gamma$**
- Untagged measurement
- Unbinned fit to $\Delta E = E_B - E_{\text{beam}}$
  - Experimentally more straightforward but larger theoretical uncertainties
  - Ratios best $\rightarrow$ uncertainties related to FF suppressed

<table>
<thead>
<tr>
<th>Lower $E^B_\gamma$ threshold</th>
<th>Statistical uncertainty</th>
<th>Baseline (improved)</th>
<th>system uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 GeV</td>
<td>10.7%</td>
<td>2.2%</td>
<td>10.3% (5.2%)</td>
</tr>
<tr>
<td>1.6 GeV</td>
<td>9.9%</td>
<td>2.1%</td>
<td>8.5% (4.2%)</td>
</tr>
<tr>
<td>1.8 GeV</td>
<td>9.3%</td>
<td>2.0%</td>
<td>6.5% (3.2%)</td>
</tr>
<tr>
<td>2.0 GeV</td>
<td>8.3%</td>
<td>1.7%</td>
<td>3.7% (1.8%)</td>
</tr>
</tbody>
</table>

Baseline: Background at 10% level
Improved: Background at 5% level

<table>
<thead>
<tr>
<th>Observable</th>
<th>$1 \text{ ab}^{-1}$</th>
<th>$5 \text{ ab}^{-1}$</th>
<th>$10 \text{ ab}^{-1}$</th>
<th>$50 \text{ ab}^{-1}$</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_0(B \rightarrow K^*\gamma)$</td>
<td>1.3%</td>
<td>0.6%</td>
<td>0.4%</td>
<td>0.2%</td>
<td>1.2%</td>
</tr>
<tr>
<td>$A_{CP}(B^0 \rightarrow K^*0\gamma)$</td>
<td>1.4%</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$A_{CP}(B^+ \rightarrow K^{*+}\gamma)$</td>
<td>1.9%</td>
<td>0.9%</td>
<td>0.6%</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\Delta A_{CP}(B \rightarrow K^*\gamma)$</td>
<td>2.4%</td>
<td>1.1%</td>
<td>0.7%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

**arXiv:2207.11275**

**Belle II**

(Preliminary)

Ldt = 62.8 fb$^{-1}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B_{\text{meas}} [10^{-5}]$</th>
<th>$B_{\text{PDG}} [10^{-5}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0}\gamma$</td>
<td>4.5 ± 0.3 ± 0.2</td>
<td>4.18 ± 0.25</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}\gamma$</td>
<td>5.2 ± 0.4 ± 0.3</td>
<td>3.92 ± 0.22</td>
</tr>
</tbody>
</table>

**arXiv:2110.08219**

**Prog. Theor. Exp. Phys. 2020, 083C01**