Missing Energy B Decays at the Belle II Experiment

Mario Merola (Università di Napoli Federico II and INFN)
On behalf of the Belle II Collaboration

Beauty 2018, 10 May, Isola d’Elba
• **Electron-positron collider** situated at KEK (Tsukuba, Japan), upgrade of KEKB

• $e^+e^- (4 \text{ GeV} + 7 \text{ GeV}) \rightarrow B\overline{B}$ mainly at $\sqrt{s_{\text{cm}}} = 10.58 \text{ GeV}$ (peak of $\Upsilon(4S)$ resonance)

• **First collisions recorded on 26 April** (see more in the talk tomorrow “Phase II running of SuperKEKB and Belle II” – Carlos Marinas)

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**Cross sections at $\Upsilon(4S)$**

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Cross section (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(4S) \rightarrow BB$</td>
<td>1.2</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow$ continuum</td>
<td>2.8</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>0.8</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.8</td>
</tr>
<tr>
<td>Bhabha ($\theta_{\text{lab}} \geq 17^\circ$)</td>
<td>44</td>
</tr>
<tr>
<td>$\gamma\gamma$ ($\theta_{\text{lab}} \geq 17^\circ$)</td>
<td>2.4</td>
</tr>
<tr>
<td>$2\gamma$ processes $^b$</td>
<td>$\sim 80$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\sim 130$</td>
</tr>
</tbody>
</table>

$^a$ The rate is pre-scaled by a factor of $1/100$.

$^b\theta_{\text{lab}} \geq 17^\circ$, $p_t \geq 0.1\text{GeV}/c$
From KEKB to SuperKEKB

Nano-beam scheme firstly proposed by P. Raimondi for SuperB

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GeV)</td>
<td>3.5/8.0</td>
<td>4.0/7.0</td>
</tr>
<tr>
<td>(\beta^*_y) (mm) LER/HER</td>
<td>5.9/5.9</td>
<td>0.27/0.30</td>
</tr>
<tr>
<td>(\beta^*_y) (cm) LER/HER</td>
<td>120/120</td>
<td>3.2/2.5</td>
</tr>
<tr>
<td>(\varphi) (mrad)</td>
<td>11</td>
<td>41.5</td>
</tr>
<tr>
<td>I (A) LER/HER</td>
<td>1.6/1.2</td>
<td>3.6/2.6</td>
</tr>
<tr>
<td>L (cm(^2)s(^{-1}))</td>
<td>2.1 \times 10^{34}</td>
<td>80 \times 10^{34}</td>
</tr>
</tbody>
</table>

Factor \(~ 40-50\) in the luminosity

Flavour MILESTONE 5-10 ab\(^{-1}\)

Higher backgrounds

- Radiation damage
- Occupancy in inner detectors
- Fake hits and pile-up

Radiative Bhabha

\[ e^+e^- : \sigma \sim O(10^7 \text{nb}) \]
From Belle to Belle II

Belle Upgrade:

- **Extended VXD region** (added pixel detector)

- **Extended Drift Chamber region**

- **New ECL electronics** (waveform sampling and fitting)

- **Better hermeticity: new PID detector** in the forward region

- **High efficiency KLM detector** (some RPCs layers substituted with scintillators to resist neutron background)

  - improved IP and secondary vertex resolution
  - better $K/\pi$ separation and flavor tagging
  - robust against machine background
  - higher $K_S$, $\pi^0$ and slow pions reconstruction efficiency
**Unique capabilities of e⁺e⁻ B factories - Belle II**

- **Beam energy constraint** and adjusted for different resonances \( \Upsilon(nS) \)

- **Clean experimental environment**: high B, D, K, \( \tau \) lepton reconstruction efficiency

- **Excellent EM calorimetry performance**: high reconstruction efficiency of neutral final states too

The **full reconstruction of one B** (\( B_{tag} \)) constraints the 4-momentum of the other (\( B_{sig} \))

Reconstruction of **channels with missing energy**

\[
p_{\nu} = p_{e^+e^-} - p_{B_{tag}} - p_{B_{sig}}
\]
B tag reconstruction strategy

- **Hadronic tagging**
  - Low efficiency
  + B tag completely reconstructed

- **Semileptonic tagging**
  - More backgrounds, B momentum unmeasured
  + Higher efficiency

- **Inclusive tagging (no tagging)**
  - B-tag not explicitly reconstructed
  - Reconstruct the signal and then use the Rest of Event (ROE) to constrain the neutrino momentum

\[
\varepsilon = \mathcal{O}(0.5\%) \quad \varepsilon = \mathcal{O}(1\%) \quad \varepsilon = \mathcal{O}(100\%)
\]
Tag side reconstruction: Full Event Interpretation (FEI)

- It is an extension of the Full Reconstruction (FR) used in Belle, and uses a multivariate technique to reconstruct the B-tag side through $O(10^3)$ decay modes in a $Y(4S)$ decay.

- Hierarchical approach: train multivariate classifiers (MVC) on FSP, then reconstruct intermediate particles and build new dedicated MVC. For each candidate a signal probability is defined, which represents the “goodness” of its reconstruction. It uses:
  - PID, tracks momenta, impact parameters;
  - Cluster info, energy and direction;
  - Invariant masses, daughter momenta, vertex quality;
  - Classifier output of the daughters

Belle FR: NIM A 654, 432-440 (2011)
Improvement in Belle II algorithms: background rejection

FEI performance with hadronic B-tag reconstruction

<table>
<thead>
<tr>
<th>Tag algorithm date</th>
<th>MVA</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle (2007)</td>
<td>Cut-based</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>Belle FR (2011)</td>
<td>Neurobayes</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Belle II FEI (2017)</td>
<td>Boosted Decision Trees</td>
<td>0.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Rejection of the continuum $e^+ e^- \rightarrow q\bar{q}$ background

Beam background rejection
MVA using ECL clusters info

Residual energy in the calorimeter after $\Upsilon(4S)$ reconstruction

Deep Neural Network based

Belle II Full Simulation study

Belle II Full Simulation study
Missing energy B meson decays

- Inclusive semileptonic decays ($B \rightarrow X \ell \nu$)
  
  BR $\sim 22\%$

- Semileptonic decays with tau ($B \rightarrow D^{(*)} \tau \nu$)

- Leptonic decay to tau leptons ($B \rightarrow \tau \nu$)

- Penguin electroweak decays ($B \rightarrow K^{(*)} \nu \nu$)

- Leptonic decays to muon, electron, neutrinos and radiative ($B \rightarrow \mu \nu, \epsilon \nu, \nu \nu, l\nu\gamma$)

BR $\sim 10^{-7} \div 10^{-20}$

Belle II Physics Book to be published in 2018
Missing energy B meson decays

- Inclusive semileptonic decays \((B \rightarrow Xl\nu)\)  
  \(\text{BR} \sim 22\%\)

- Semileptonic decays with tau \((B \rightarrow D(\ast)\tau\nu)\)

- Leptonic decay to tau leptons \((B \rightarrow \tau\nu)\)

- Penguin electroweak decays \((B \rightarrow K(\ast)\nu\nu)\)

- Leptonic decays to muon, electron, neutrinos and radiative \((B \rightarrow \mu\nu, e\nu, \nu\nu, l\nu\gamma)\)  
  \(\text{BR} \sim 10^{-7} \div 10^{-20}\)

Updates expected by the next Beauty Conference!
Semileptonic decays: $B \rightarrow X_u \ell \nu$

**Measurement of $|V_{ub}|$ from inclusive and exclusive $B$ decays**

- **Inclusive decays measurement**
  - Hadronic tag
  - Exploit kinematic endpoints to reduce $B \rightarrow X_c \ell \nu$ bkg

**Graphical Representation**

- $|V_{ub}|^2 = \Delta B_{ul\nu} / (\tau_B \Delta R)$
- Measured BR in fiducial phase space region
- B meson lifetime
- Predicted partial decay rate
Semileptonic decays: $B \rightarrow X_u \ell \nu$

- $B^0 \rightarrow \pi \ell \nu$ decay
  - Untagged or tagged (with FEI)
  - Exploit missing mass and extra energy in the calorimeter
  - $\mathcal{B} \sim f_i |V_{ub}|^2$; form factors $f_i$ computed with LQCD (PRD 91, 074510 (2015))

Belle II Full Simulation study

Belle II MC

signal

background

$B \rightarrow \pi \ell \nu$ projections

Belle II @ 50 ab$^{-1}$: $\sim 3\%$ (inclusive) / $\sim 2\%$ (exclusive $\pi \ell \nu$) uncertainty
Semileptonic decays: $B \rightarrow D^{(*)}\tau\nu$

Clear test of the SM LFU: NP (as charged Higgs in 2HDM models or Leptoquarks) can affect the BR and the tau polarization $P_\tau$

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

Important background due to $D^{**}$; not well known, poor modeling $\rightarrow$ big uncertainty (1.4% over a total systematic uncertainty of 3.4%)

Extract the fractions with positive and negative tau helicity
Semileptonic decays: $B \rightarrow D^{(*)}\tau\nu$

Belle II projections

Current combination:
4.1$\sigma$ from the SM

- Projections based on Belle SL measurement
- Belle II full simulation studies in progress

<table>
<thead>
<tr>
<th></th>
<th>$\Delta R(D)$ [%]</th>
<th>$\Delta R(D^*)$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stat</td>
<td>Sys</td>
</tr>
<tr>
<td>Belle 0.7 ab$^{-1}$</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>Belle II 5 ab$^{-1}$</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Belle II 50 ab$^{-1}$</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

50 ab$^{-1}$ projection of subtracted $q^2$ spectrum in $B \rightarrow D^{(*)}\tau\nu$
Leptonic B decays

- **Helicity suppressed** decays

\[ BR_{SM} (B \rightarrow \ell \nu) = \frac{G_F^2 m_B \tau_B}{8\pi} f_B^2 |V_{ub}|^2 \left( 1 - \frac{m_\ell^2}{m_B^2} \right)^2 \]

- **Sensitive to NP contributions**, e.g. type III Higgs doublet model [PhysRevD.86.054014]

- Clean theoretically, hard experimentally: only \( B \rightarrow \tau \nu \) has been measured

Belle combination

\[ B = [0.91 \pm 0.19\text{ (stat.)} \pm 0.11\text{ (syst.)}] \times 10^{-4} \]

(evidence at \( \sim 4.6 \sigma \) level)

Belle PRD 92, 051102 (2015), SL tag
Leptonic B decays: $B \rightarrow \tau \nu$

Belle II full simulation study

- Hadronic tag with FEI
- 1-prong $\tau$ decays ($\mu\nu\nu$, $e\nu\nu$, $\pi\nu$, $\rho\nu$)
- Dedicated study on machine background impact
- ML fit to extra energy $E_{ECL}$

Extra energy in the calorimeter

$E_{ECL}$ resolution robust against beam background

Main systematic uncertainties:
background $E_{Extra}$ PDF, branching fractions of the peaking backgrounds, tagging efficiency, and $K^0_L$ veto efficiency

<table>
<thead>
<tr>
<th></th>
<th>Integrated Luminosity (ab$^{-1}$)</th>
<th>1</th>
<th>5</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronic tag</td>
<td>statistical uncertainty (%)</td>
<td>29.2</td>
<td>13.0</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>systematic uncertainty (%)</td>
<td>12.6</td>
<td>6.8</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>total uncertainty (%)</td>
<td>31.6</td>
<td><strong>14.7</strong></td>
<td>6.2</td>
</tr>
<tr>
<td>semileptonic tag</td>
<td>statistical uncertainty (%)</td>
<td>19.0</td>
<td>8.5</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>systematic uncertainty (%)</td>
<td>17.9</td>
<td>8.7</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>total uncertainty (%)</td>
<td>26.1</td>
<td><strong>12.2</strong></td>
<td>5.3</td>
</tr>
</tbody>
</table>

Observation at $\sim 3$ ab$^{-1}$
Leptonic B decays: 
\( B \rightarrow \mu \nu \) and radiative \( B \rightarrow l\nu\gamma \)

**B \rightarrow \mu \nu**
- Two body decay: \( p_\mu^* = m_B / 2 \) in B rest frame
- Tagging \( \rightarrow \) better \( p_\mu^* \) resolution but small statistics
- \( \sim 2.4\sigma \) measurement

**B \rightarrow l\nu\gamma**
- Radiative decay lifts the helicity suppression
- Allows a measurement of \( \lambda_B \rightarrow \) crucial input to QCD factorization predictions of charmless hadronic B decays
Flavour changing neutral current

$B \rightarrow K^{(*)}\nu\bar{\nu}$

- Prohibited in the SM at tree level: penguin + box diagrams
- $\text{BR} \sim 10^{-5} \div 10^{-6}$; NP contribution can increase the BR by factor 50
  - non standard Z-couplings (SUSY)
  - New missing energy sources (DM, extra dim.)
**Flavour changing neutral current**

\[ B \rightarrow K^{(*)}\nu\bar{\nu} \]

**Belle II full simulation study**

- Hadronic tag with FEI
- \( K^* \rightarrow K\pi^0 \)
- Cut and count in extra energy signal window

**Constraints on new physics contributions to Wilson coefficients** \( C_L, C_R \)

- 90% CL excluded by Belle and Babar
- 68% CL allowed by Belle II at 50 ab\(^{-1}\)

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle II 5 ab(^{-1})</th>
<th>Belle II 50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Br(B^+ \rightarrow K^+\nu\bar{\nu}) )</td>
<td>30%</td>
<td>11%</td>
</tr>
<tr>
<td>( Br(B^0 \rightarrow K^{*0}\nu\bar{\nu}) )</td>
<td>26%</td>
<td>9.6%</td>
</tr>
<tr>
<td>( Br(B^+ \rightarrow K^{*+}\nu\bar{\nu}) )</td>
<td>25%</td>
<td>9.3%</td>
</tr>
</tbody>
</table>

Observation at \( \sim 18 \) ab\(^{-1}\)
Conclusions

• Unique capabilities of Belle II to study **B decays with missing energy in the final state**

• Within the first **two years of data taking** Belle II will collect **5 to 10 ab\(^{-1}\)** and will be able to
  
  ➢ address the Lepton Flavour Universality Violation by precisely measuring \(R(D) / R(D^*)\)
  
  ➢ address the \(|V_{ub}|\) **puzzle** from inclusive and exclusive semileptonic decays

• Discovery potential also in rare processes suppressed in the SM (\(B \rightarrow \tau \nu, B \rightarrow l\nu\gamma, B \rightarrow K(*)\nu\nu, B \rightarrow \mu\nu, B \rightarrow \nu\nu\))
Thanks!
Backup
### Belle II Detector

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Configuration</th>
<th>Readout</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>Beryllium double-wall</td>
<td>Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PXD</td>
<td>Silicon pixel (DEPFET)</td>
<td>Sensor size: 15×100 (120) mm$^2$ pixel size: 50×50 (75) μm$^2$ 2 layers: 8 (12) sensors</td>
<td>10 M</td>
<td>impact parameter resolution $\sigma_{z0} \sim 20 \mu$m (PXD and SVD)</td>
</tr>
<tr>
<td>SVD</td>
<td>Double sided Silicon strip</td>
<td>Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors</td>
<td>245 k</td>
<td></td>
</tr>
<tr>
<td>CDC</td>
<td>Small cell drift chamber</td>
<td>56 layers, 32 axial, 24 stereo $r = 16 - 112$ cm $- 83 \leq z \leq 159$ cm</td>
<td>14 k</td>
<td>$\sigma_{r\phi} = 100 \mu$m, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2 % p_t)^2 + (0.3 % /\beta)^2}$ (with SVD)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Background</th>
<th>Generic</th>
<th>$BB$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PXD</td>
<td>10000 (580)*</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>SVD</td>
<td>284 (134)</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>CDC</td>
<td>654</td>
<td>810</td>
<td></td>
</tr>
<tr>
<td>TOP</td>
<td>150</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>ARICH</td>
<td>191</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>ECL</td>
<td>3470</td>
<td>510</td>
<td></td>
</tr>
<tr>
<td>BKLM</td>
<td>484</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>EKLM</td>
<td>142</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

Total number of hits per event in each subdetector

* in parentheses numbers without $\bar{\nu}$ OED
Phase II

What can we do with phase II data?
• Background studies
• Detector and trigger performance studies
• Simulation validation
• Exercising of calibration and alignment procedures
• Reconstruction algorithm tuning
• Physics measurements
Belle II Physics Book

- B2TiP Report (600p)
  - [https://confluence.desy.de/display/BII/B2TiP+ReportStatus](https://confluence.desy.de/display/BII/B2TiP+ReportStatus)
- To be published in PTEP / Oxford University Press & printed.
  - Belle II Detector, Simulation, Reconstruction, Analysis tools
  - Physics working groups
  - New physics prospects and global fit code
Roadmap

Goal of Belle II/SuperKEKB

- B\to\eta' Ks New CP
- \Phi_2, \Phi_3 < 2\degree
- W_R in B\to\gamma
- \tau LFV Discovery
- Confirm B\to D^* \tau \nu
  New physics
- Resolve |V_{ub}| puzzle
- B\to K \nu \nu SM Discovery
- B\to K\nu e LFUV
  New Physics
- ee\to A' (X \chi) \gamma
- ee\to \pi\pi(\gamma) precision
- B \to \mu \nu Discovery

Integrated luminosity (ab^{-1})

Peak luminosity (cm^{-2} s^{-1})

Calendar Year

10/05/18
FEI validated on Belle real data

Figure 4.18.: The overall efficiency correction calculated by measuring the known branching fractions of 10 control channels on converted Belle data [76].

Thomas Keck's master thesis
Physics prospects: Belle II vs LHCb

<table>
<thead>
<tr>
<th>Observables</th>
<th>Expected th. accuracy</th>
<th>Expected uncertainty</th>
<th>Facility (2025)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT angles &amp; sides</td>
<td>**</td>
<td>0.4</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\phi$</td>
<td>**</td>
<td>1.0</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\phi_s$</td>
<td>**</td>
<td>1.0</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ incl.</td>
<td>***</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ excl.</td>
<td>***</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ incl.</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ excl.</td>
<td>**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle or LHCb* (2014)</th>
<th>Belle II</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charm Rare</td>
<td>$B(D_s \to \mu\nu)$</td>
<td>5.31 - 10^{-3}(1 ± 5.3% ± 3.8%)</td>
<td>2.9%</td>
</tr>
<tr>
<td></td>
<td>$B(D_s \to \tau\nu)$</td>
<td>5.70 - 10^{-3}(1 ± 3.7% ± 5.4%)</td>
<td>3.5%</td>
</tr>
<tr>
<td></td>
<td>$B(D^0 \to \gamma\gamma)$ [10^{-6}]</td>
<td>&lt; 1.5</td>
<td>30%</td>
</tr>
<tr>
<td>Charm CP</td>
<td>$A_{CP}(D^0 \to K^+K^-)$ [10^{-4}]</td>
<td>-32 ± 21 ± 9</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>$\Delta A_{CP}(D^0 \to K^+K^-)$ [10^{-3}]</td>
<td>3.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$A_{T}$ [10^{-2}]</td>
<td>0.22</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>$A_{CP}(D^0 \to \pi^0\pi^0)$ [10^{-2}]</td>
<td>-0.03 ± 0.04 ± 0.10</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>$A_{CP}(D^0 \to K^0\bar{K}^0)$ [10^{-2}]</td>
<td>-0.21 ± 0.16 ± 0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>Charm Mixing</td>
<td>$\varepsilon(D^0 \to K_S^0\pi^+\pi^-)$ [10^{-2}]</td>
<td>0.56 ± 0.19 ± 0.07</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon(D^0 \to K_S^0\pi^+\pi^-)$ [10^{-2}]</td>
<td>0.30 ± 0.15 ± 0.08</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>q/p</td>
<td>(D^0 \to K^0\pi^+\pi^-)$</td>
</tr>
<tr>
<td></td>
<td>$\phi(D^0 \to K^0\pi^+\pi^-)$ [°]</td>
<td>-6 ± 11 ± 4</td>
<td>6</td>
</tr>
<tr>
<td>Tau</td>
<td>$\tau \to \mu\gamma$ [10^{-9}]</td>
<td>&lt; 45</td>
<td>&lt; 14.7</td>
</tr>
<tr>
<td></td>
<td>$\tau \to e\nu\nu$ [10^{-9}]</td>
<td>&lt; 120</td>
<td>&lt; 39</td>
</tr>
<tr>
<td></td>
<td>$\tau \to \mu\mu\mu$ [10^{-9}]</td>
<td>&lt; 21.0</td>
<td>&lt; 3.0</td>
</tr>
</tbody>
</table>

[Image]: ![Image](image_url)
Semileptonic decay: $B^0 \rightarrow \pi \ell \nu$

Table 54: Summary of systematic uncertainties on the branching fractions of $B^0 \rightarrow \pi^- \ell^+ \nu_\ell$ decays in hadronic tagged and untagged Belle analyses with 711 fb$^{-1}$ [271] and 605 fb$^{-1}$ [269] data samples, respectively. The estimated precision limit for some sources of systematic uncertainties is given in brackets.

<table>
<thead>
<tr>
<th>Source</th>
<th>Error (Limit) [%]</th>
<th>Tagged</th>
<th>Untagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>0.4</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Pion identification</td>
<td>–</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Lepton identification</td>
<td>1.0</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Kaon veto</td>
<td>0.9</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Continuum description</td>
<td>1.0</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Tag calibration and $N_{BB}$</td>
<td>4.5 (2.0)</td>
<td>2.0 (1.0)</td>
<td></td>
</tr>
<tr>
<td>$X_u\ell\nu$ cross-feed</td>
<td>0.9</td>
<td>0.5 (0.5)</td>
<td></td>
</tr>
<tr>
<td>$X_c\ell\nu$ background</td>
<td>–</td>
<td>0.2 (0.2)</td>
<td></td>
</tr>
<tr>
<td>Form factor shapes</td>
<td>1.1</td>
<td>1.0 (1.0)</td>
<td></td>
</tr>
<tr>
<td>Form factor background</td>
<td>–</td>
<td>0.4 (0.4)</td>
<td></td>
</tr>
<tr>
<td>Total (reducible, irreducible)</td>
<td>5.0 (4.6, 2.0)</td>
<td>4.5 (4.2, 1.6)</td>
<td></td>
</tr>
</tbody>
</table>

LQCD: current is the world average by FLAG group

- 5 yr w/o EM$^w$: We assume a factor of 2 reduction of the lattice QCD uncertainty in the next five years and that the uncertainty of the EM correction is negligible (e.g. for processes insensitive to the EM correction).
- 5 yr w/ EM$^w$: The lattice QCD uncertainty is reduced by a factor of 2, but we add in quadrature 1% uncertainty from the EM correction.
- 10 yr w/o EM$^w$: We assume a factor of 5 reduction of the lattice QCD uncertainty in the next ten years. It is also assumed that the EM correction will be under control and its uncertainty is negligible.
- 10 yr w/ EM$^w$: We assume lattice QCD uncertainties reduced by a factor of 5, but add in quadrature 1% uncertainty from the EM correction.
## $R(D^*)$ Belle measurement

Belle PRD 94, 072007(2016) SL tag

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\ell^{\text{sig}} = e, \mu$</th>
<th>$\ell^{\text{sig}} = e$</th>
<th>$\ell^{\text{sig}} = \mu$</th>
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</thead>
<tbody>
<tr>
<td>MC size for each PDF shape</td>
<td>2.2</td>
<td>2.5</td>
<td>3.9</td>
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<tr>
<td>PDF shape of the normalization in $\cos \theta_{B-D^*\ell}$</td>
<td>$^+1.1_{-0.0}$</td>
<td>$^+2.1_{-0.0}$</td>
<td>$^+2.8_{-0.0}$</td>
</tr>
<tr>
<td>PDF shape of $B \to D^{**}\ell\nu_\ell$</td>
<td>$^+1.0_{-1.7}$</td>
<td>$^+0.7_{-1.3}$</td>
<td>$^+2.2_{-3.3}$</td>
</tr>
<tr>
<td>PDF shape and yields of fake $D^{(*)}$</td>
<td>1.4</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>PDF shape and yields of $B \to X_cD^*$</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Reconstruction efficiency ratio $\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$</td>
<td>1.2</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Modeling of semileptonic decay</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>$B(\tau^- \to \ell^- \bar{\nu}<em>\ell \nu</em>\tau)$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$^+3.4_{-3.5}$</td>
<td>$^+4.1_{-3.7}$</td>
<td>$^+5.9_{-5.8}$</td>
</tr>
</tbody>
</table>
Leptonic radiative $B \rightarrow l\nu\gamma$

$$
\Gamma = \frac{d\Gamma}{dE_\gamma} = \alpha_{em} \frac{G_F^2 m_B^4 |V_{ub}|^2}{48\pi^2} x_\gamma^3 (1 - x_\gamma) [F_A^2 + F_V^2].
$$

$$
F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[ \xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2} \right],
$$

$$
F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[ \xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma} \right],
$$

Flavour changing neutral current

\[ B \rightarrow K^{(*)}\nu\bar{\nu} \]

In BSM right handed operator for neutrinos

\[ Q_R^\ell = (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_{\ell L} \gamma^\mu \nu_{\ell L}) \]

\[
\frac{\text{Br}(B \rightarrow K\nu\bar{\nu})}{\text{Br}(B \rightarrow K\nu\bar{\nu})_{\text{SM}}} = \frac{1}{3} \sum_\ell (1 - 2 \eta_\ell) \epsilon_\ell^2 ,
\]

\[
\frac{\text{Br}(B \rightarrow K^{*}\nu\bar{\nu})}{\text{Br}(B \rightarrow K^{*}\nu\bar{\nu})_{\text{SM}}} = \frac{1}{3} \sum_\ell (1 + \kappa_\eta \eta_\ell) \epsilon_\ell^2 ,
\]

\[
\epsilon_\ell = \frac{\sqrt{|C_L^\ell|^2 + |C_R^\ell|^2}}{|C^\text{SM}_L|} ,
\]

\[
\eta_\ell = -\text{Re} \left( C_L^\ell C_R^{\ast \ell} \right) \frac{1}{|C_L^\ell|^2 + |C_R^\ell|^2} .
\]