Flavour physics with electroweak-penguin and semileptonic decays at Belle and Belle II

Elisa Manoni (Istituto Nazionale di Fisica Nucleare, Sezione di Perugia) for the Belle and Belle II collaborations

5-10 September 2021
Belle and Belle II experiments

- **Belle @ KEKB:**
  - one of the first generation B factories, $771 \times 10^6 \text{ BB}$ pairs collected in $\sim 10$ years of data taking
  - experiment goal: measurement of CP violation in B meson system but they did much more

- **Belle II @ SUPERKEKB:**
  - from KEKB to SuperKEKB: aim to collect $50 \text{ ab}^{-1}$ ($\sim 50x$ Belle) by 2031 reaching $\sim 60 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($\sim 30x$ KEKB)
  - Upgrade of Belle detector: similar or better performances wrt Belle in much higher machine background/event rate environments
  - Total integrated luminosity as of today: $213 \text{ fb}^{-1}$, $>120 \text{ fb}^{-1}$ in February-June 2021
  - Current world record instantaneous luminosity = $3.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (KEKB world record: $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
Semileptonic and electroweak penguin decays at Belle II

- Large Belle II dataset will allow to continuing investigating the flavour sector, in a complementary way wrt other experiments

- Electroweak and semileptonic B decays are among the golden channels of Belle II physics program.

New Physics searches in tree and penguin+box -mediated processes

Indirect New Physics (NP) searches: non standard particles as decay mediators

Direct NP searches: new sources of missing energy ($b \rightarrow s \nu \bar{\nu}$)

[ will mainly focus on this ]
B meson pair reconstruction: Tagged analysis

- Reconstruct one B in the event ($B_{\text{tag}}$) and constraint the kinematic of the other B ($B_{\text{sig}}$)

- $B_{\text{tag}}$ reconstruction with **Full Event Interpretation** (FEI): multivariate algorithm with hierarchical approach to reconstruct $O(200)$ **hadronic** and **semileptonic** decay channels

- $B_{\text{sig}}$ reconstruction: once the $B_{\text{tag}}$ has been reconstructed, search for the signal signature in the rest of the event

- Knowing the initial energy, the missing energy associated to the **neutrinos** can be computed

---

**BELLE2-NOTE-PL-2020-002**

**Belle II preliminary**

$x 10^4$

Events / (0.0010 GeV/c²)

$N_{B_{\text{tag}}} = 84907 \pm 734$

$P_{\text{tag}} > 0.1$

$M_{bc} = \sqrt{s/4 - (p_B^*)^2}$

**Hadronic FEI**

B meson pair reconstruction: Untagged analysis

- Search for the final state particles consistent with the signature (and eventually constraint the kinematics of the rest of the event)
  - **exclusive** $B_{\text{sig}}$ reconstruction: all final state particles are reconstructed (e.g. $B^+ \rightarrow K^+ \ell^+ \ell^-$), can apply kinematic constraint to ROE that should be compatible with a $B$ meson
  - **inclusive** $B_{\text{sig}}$ reconstruction: one/few final state particle(s) are reconstructed (e.g. $B \rightarrow X_s \gamma$), the ROE is the other $B$ in the event + what is left from signal reconstruction
Semileptonic decays
**b→clv: latest Belle R(D(*)) measurement**

- Sensitive probes for New Physics (leptoquarks, two Higgs doublets etc.) which could impact **lepton flavour universality ratios**:

\[
R(D(\ast)) = \frac{B(\bar{B} \to D(\ast)\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to D(\ast)\ell^-\bar{\nu}_\ell)}
\]

(where \(\ell = e, \mu\))

- **Belle analysis** (711 fb\(^{-1}\))
  - Tag side reconstructed with Semileptonic FEI, \(\tau\) in purely leptonic modes
  - Signal extracted from 2D fit to BDT output and \(E_{\text{ECL}}\):
    - \(E_{\text{ECL}}\) = neutral energy deposited in the calorimeter not associated to signal nor to tag side, key ingredient in analysis with missing energy
  - **Most precise measurements** reported to date

\[
R(D) = 0.307 \pm 0.037 \pm 0.016
\]

\[
R(D^*) = 0.283 \pm 0.018 \pm 0.014
\]

**b → clv: toward R(D(∗)) Belle II measurement (II)**

- Measurement of **normalisation channel** with 34.6 fb⁻¹ using hadronic FEI

Dedicated Belle II studies to **improve E_{ECL} reconstruction**

\[ \mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \nu_{\ell}) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_S}) \% \]

In agreement with world average

Main systematic from soft π reconstruction, will improved in the future with auxiliary measurements
Plethora of $\tau/\ell$ ratio measurements from LHCb and Belle

On $R(D^{(*)})$, (sub)-% level precision can be reached

@ Belle, one of the dominant systematics from $D^{**}$ background, can be studied in more detail with Belle II data
b→ulν: new Belle measurements

- Challenging due to B→Xcℓν contamination: clear separation through kinematic variables, e.g. lepton momentum endpoint or low Mₓ

- Full Reconstruction of hadronic Btag (NIM A 654, 432-440 (2011))

- Inclusive measurement: measure the 6 kinematic variables in the phase space of E_B > 1 GeV

\[ q^2, E^B, M_X, M_X^2, P_+ , P_- \] (light-cone momenta: \( p_\perp = E_X \gamma X p_X \))

Necessary input for future model-independent determinations of \(|V_{ub}|\)
Radiative and Electroweak penguin decays
$b \rightarrow s \gamma$ state of the art

- $b \rightarrow s \gamma$ transitions excellent probe for physics beyond the Standard Model
- $BF \sim 10^{-5}$, large uncertainty in the exclusive measurements due to form factors, which cancels in CP and isospin asymmetries (ratios of rates)

- State of the art, best measurements from Belle:

<table>
<thead>
<tr>
<th>BF precision</th>
<th>$B \rightarrow K^* \gamma$</th>
<th>$B \rightarrow X s \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{CP}$</td>
<td>consistent with zero and SM predictions [1], [4]</td>
<td>10-12% [2], [3]</td>
</tr>
<tr>
<td>$\Delta a$</td>
<td>3% [4]</td>
<td>10-12% [2], [3]</td>
</tr>
<tr>
<td></td>
<td>consistent with zero [1]</td>
<td>consistent with zero [1]</td>
</tr>
</tbody>
</table>

- Can be improved with the larger data set by Belle II in future

[3] PRL 103, 241801 (2009), 605 fb$^{-1}$,
b→sγ: first results at Belle II (I)

- $B \to K^* \gamma$ branching fraction measurement, with 63 fb$^{-1}$
  - full reconstruction of the decay chain: charged and neutral $K^* +$ high energy photon

- Measured BR consistent with world average values at 1-2 $\sigma$

- CP and isospin asymmetry measurement foreseen in the next iterations of the analysis

<table>
<thead>
<tr>
<th>Mode</th>
<th>Br (fit) x10$^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^*[K^+\pi^-]\gamma$</td>
<td>$4.5 \pm 0.3$ (stat) $\pm 0.2$ (syst)</td>
</tr>
<tr>
<td>$B^0 \to K^*[K^0_\pi^0]\gamma$</td>
<td>$4.4 \pm 0.9$ (stat) $\pm 0.6$ (syst)</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}[K^+\pi^0]\gamma$</td>
<td>$5.0 \pm 0.5$ (stat) $\pm 0.4$ (syst)</td>
</tr>
<tr>
<td>$B^+ \to K^{*+}[K^0_\pi^+]\gamma$</td>
<td>$5.4 \pm 0.6$ (stat) $\pm 0.4$ (syst)</td>
</tr>
</tbody>
</table>
$b \rightarrow s\gamma$: first results at Belle II (II)

- $B \rightarrow X_s \gamma$ with untagged method, $63 \text{ fb}^{-1}$
- Reconstruct only high energy $\gamma$ from signal side, monochromatic particle is expected
- Extract signal from photon energy spectrum
- **Excess** visible in the expected signal region
**B→K(*)ll: R(K(*)) status of the art**

- Evidence of lepton universality violation on $B^+ \rightarrow K^+ \ell^+ \ell^-$ from LHCb (arXiv:2103.11769) at 3.1σ level

- **Belle** measurements on full dataset (711 fb$^{-1}$):
  - $R(K)$ measured in $q^2$ bins, in agreement with SM expectations
  - $R(K^*)$ measurement, charged ratio never measured before
  - Statistically limited

\[ R_{K(*)} = \frac{B(B \rightarrow K(*) \mu^+ \mu^-)}{B(B \rightarrow K(*) e^+ e^-)} \]
**B→K(*)l⁺l⁻: status and perspectives at Belle II**

- Search for $B^+ \rightarrow K^+ \ell^+\ell^-$ with 63 fb⁻¹ of Belle Data

- Rehearsing analysis using $B^+ \rightarrow J/\psi(\ell^+\ell^-)K^+$ control sample (same final state but large BR)

- Signal yield extracted from 2D fit to $M_{bc}$ and $\Delta E$, 2.7σ significance
  - $N_{\text{sig}} = 8.6^{+4.3}_{-3.9}\text{(stat)} \pm 0.4\text{(syst)}$

- Long term perspectives for $R(K^*)$:
  - LHCb with full luminosity (∼2035, 300 fb⁻¹) is expected to have better precision in the low $q^2$ wrt to full Belle II data sample
  - In the high $q^2$ Belle II precision will reach few % level
**b → sνν**: state of the art prior to Moriond2021

- **SM predictions:**
  
  \[
  \begin{align*}
  \text{BR}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} &= (4.6 \pm 0.5) \times 10^{-6}, \\
  \text{BR}(B^+ \rightarrow K^{*+} \nu \bar{\nu})_{\text{SM}} &= (8.4 \pm 1.5) \times 10^{-6},
  \end{align*}
  \]

  T. Blake et al, Prog. Part.Nucl. Phys.92, 50 (2017)

- **Possible enhancement in NP scenarios, e.g. Leptoquark models explaining flavour anomalies**

- **BaBar and Belle key ingredient:** hadronic and semileptonic tag side reconstruction

<table>
<thead>
<tr>
<th>Reaction</th>
<th>UL @ 90% CL (10^{-5})</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>

Cornella et al, arXiv:2103.16558

parameter regions preferred for different type of NP interaction consistent with flavour anomalies measurements

\(\sigma_2 \sigma\)
**B⁺ → K⁺νν measurement @ Belle II (I)**

**NOVEL INCLUSIVE APPROACH** on 63 fb⁻¹ of Belle II data:

- Signal kaon = highest p_T track
- Associate all other tracks and clusters to other B in the event
- Use multivariate approach (2 BDTs in cascade) based on kinematics, event shape and vertexing variables to suppress background

- **Signal efficiency ~ 4.3 %** (SM signal)
$B^+ \rightarrow K^+ \nu \bar{\nu}$ measurement @ Belle II (II)

- Check data-simulation agreement in BDTs output using $B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+$ control sample
- **Data/MC ratio in fit region**: $1.06 \pm 0.10$
- Extract signal from simultaneous maximum likelihood fit to on-resonance + off-resonance data (taken 60 MeV below $\Upsilon(4S)$ resonance) in bins of $p_T(K^+)$ and second BDT ($BDT_2$):
  - **Signal strength**: $\mu = 4.2^{+2.9}_{-2.8}(\text{stat})^{+1.8}_{-1.6}(\text{syst})$
    - consistent with SM exp ($\mu=1$) at 1 $\sigma$
    - consistent with background-only hypothesis at 1.3 $\sigma$
- Leading systematics: **background normalisation** uncertainty can be also reduced with increasing statistics
B$^+ \rightarrow K^+ \nu\bar{\nu}$ measurement @ Belle II (III)

- No evidence for signal, upper limit on BR using CLs method (assuming SM signal)

$$\mathcal{B}(B^{\pm} \rightarrow K^{\pm} \nu\bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5} @ 90 \% \text{ CL}$$

- Comparing theory and experiments:

  $$\mathcal{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$

  - When converted to the same luminosity, our measurement is better$^{*}$ than semi-leptonic tagging by 10-20%
  - … and than hadronic tagging by a factor 3.5!

* assuming the total uncertainty on the branching-fraction scales with $1/\sqrt{L}$

- Room for improvement in $K^+$ channel, application of inclusive method to other channels in progress
Conclusions

• **Belle** is still producing interesting results, moreover the accumulated knowledge on MC modelling, analysis techniques, etc. will be beneficial for future measurements by e.g. Belle II or LHCb

• SuperKEKB has set a new world record in instantaneous luminosity of $3.1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ and is entering the regime of a "Super B factory"
  
  • plan to record $50 \text{ ab}^{-1}$, 30x Belle dataset, by **2031**

• As proven by performed measurements in agreement with world averages, **Belle II** detector is performing very well

• In the SL and EWP sector:
  
  • *complementarity* with LHCb
  
  • preliminary results on channels of interest and competitive measurements based on **new analysis technique**
    
    • $B^+ \rightarrow K^+ \nu \bar{\nu}$ inclusive measurement in the same ballpark wrt Belle and BaBar ones with $\sim 1/10$ Belle statistics

• Belle II is starting playing a role in understanding the **flavour physics puzzle**.
Extra slides
• LHCb with full luminosity (~2035, 300fb⁻¹) is expected to have better precision in the low q² wrt to full Belle II data sample,

• In the high q² Belle II precision at few % level
## Belle II - LHCb Comparison

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current Belle/ Babar</th>
<th>2019 LHCb</th>
<th>Belle II (5 ab⁻¹)</th>
<th>Belle II (50 ab⁻¹)</th>
<th>LHCb (23 fb⁻¹)</th>
<th>Belle II Upgrade (250 ab⁻¹)</th>
<th>LHCb upgrade II (300 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CKM precision, new physics in CP Violation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\sin 2\beta/\phi_1 (B\to J/\psi K_s))</td>
<td>0.03</td>
<td>0.04</td>
<td>0.012</td>
<td>0.005</td>
<td>0.011</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>(\gamma/\phi_3)</td>
<td>13°</td>
<td>5.4°</td>
<td>4.7°</td>
<td>1.5°</td>
<td>1.5°</td>
<td>0.4°</td>
<td>0.4°</td>
</tr>
<tr>
<td>(\alpha/\phi_2)</td>
<td>4°</td>
<td>2</td>
<td>0.6°</td>
<td>–</td>
<td>–</td>
<td>0.3°</td>
<td>–</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>(Belle) or</td>
<td>(</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>(LHCb))</td>
</tr>
<tr>
<td>(\phi_b)</td>
<td>–</td>
<td>49 mrad</td>
<td>–</td>
<td>–</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
</tr>
<tr>
<td>(S_{CP}(B\to \eta' K_s, gluonic penguin))</td>
<td>0.08</td>
<td>–</td>
<td>0.03</td>
<td>0.015</td>
<td>–</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>(A_{CP}(B\to K\pi^0))</td>
<td>0.15</td>
<td>–</td>
<td>0.07</td>
<td>0.04</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td>New physics in radiative &amp; EW Penguins, LFUV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(S_{CP}(B_s\to K^+ \gamma))</td>
<td>0.32</td>
<td>–</td>
<td>0.11</td>
<td>0.035</td>
<td>–</td>
<td>0.015</td>
<td>–</td>
</tr>
<tr>
<td>(R(B\to K^+ l^+ l^-) (1&lt;q^2&lt;6 GeV^2/c^2))</td>
<td>0.24</td>
<td>0.1</td>
<td>0.09</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>(R(B\to D^+\tau\nu))</td>
<td>6%</td>
<td>10%</td>
<td>3%</td>
<td>1.5%</td>
<td>3%</td>
<td>&lt;1%</td>
<td>1%</td>
</tr>
<tr>
<td>(Br(B\to \tau\nu), Br(B\to K^{*}\nu\nu))</td>
<td>24%, –</td>
<td>–</td>
<td>9%, 25%</td>
<td>4%, 9%</td>
<td>–</td>
<td>1.7%, 4%</td>
<td>–</td>
</tr>
<tr>
<td>(Br(B_d\to \mu\nu))</td>
<td>–</td>
<td>90%</td>
<td>–</td>
<td>–</td>
<td>34%</td>
<td>–</td>
<td>10%</td>
</tr>
<tr>
<td>Charm and (\tau)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta A_{CP}(KK-\pi\pi))</td>
<td>–</td>
<td>8.5×10⁻⁴</td>
<td>–</td>
<td>5.4×10⁻⁴</td>
<td>1.7×10⁻⁴</td>
<td>2×10⁻⁴</td>
<td>0.3×10⁻⁴</td>
</tr>
<tr>
<td>(A_{CP}(D\to \pi^+\pi^0))</td>
<td>1.2%</td>
<td>–</td>
<td>0.5%</td>
<td>0.2%</td>
<td>–</td>
<td>0.1%</td>
<td>–</td>
</tr>
<tr>
<td>(Br(\tau\to e \gamma))</td>
<td>&lt;12×10⁻⁹</td>
<td>–</td>
<td>&lt;4×10⁻⁹</td>
<td>&lt;12×10⁻⁹</td>
<td>–</td>
<td>&lt;5×10⁻⁹</td>
<td>–</td>
</tr>
<tr>
<td>(Br(\tau\to \mu\mu))</td>
<td>&lt;2×10⁻⁹</td>
<td>&lt;46×10⁻⁹</td>
<td>&lt;3×10⁻⁹</td>
<td>&lt;3×10⁻⁹</td>
<td>&lt;16×10⁻⁹</td>
<td>&lt;0.3×10⁻⁹</td>
<td>&lt;5×10⁻⁹</td>
</tr>
</tbody>
</table>

- Possible in similar channels, lower precision
- Not competitive.

---

Overlapping in various key areas to verify discoveries.

**Upgrades**

Most key channels will be stats. limited (not theory or syst.).

LHCb scheduled major upgrades during LS3 and LS4. Belle II formulating a 250 ab⁻¹ upgrade program post 2028.

---

*arXiv:1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)*

---

Beauty 2020

Phillip URQUIJO 57
Indirect searches: ATLAS

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary

1. Only a selection of the available mass limits on new states or phenomena is shown.
2. Small radius (large radius) jets are denoted by the letter L (C).

Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models. C.f. refs. for the assumptions made.
FIG. 3. Two versions of $E_{\text{ECL}}$ are shown: (left) is the version applying detector region dependent energy selection criteria, (right) shows the impact of using a BDT to identify neutral energy depositions from beam background processes. It is based on shower shape variables and the detector region of the reconstructed neutral cluster.