STUDIES OF MISSING ENERGY DECAYS OF B-MESONS AT BELLE II

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on behalf of the Belle II collaboration

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Belle II and New physics searches

Search for new physics (NP)

- Energy frontier: direct production of new particles - limited by beam energy (LHC - ATLAS, CMS)

- Intensity frontier: new virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)

From Belle to Belle II: Factor $\times 40$ luminosity $\rightarrow$ higher data samples + higher rate and radiation damage to detectors from “machine background processes”

Upgrade of Belle detector and reconstruction algorithm in order to keep same or better performances wrt Belle in higher radiation environment
B meson decays with missing energy: how to

- Clean event environment and well defined initial state.
- Good and efficient reconstruction of decays with neutrons.
- Full solid angle detector, lower boost wrt Belle/BaBar ↔ higher detector hermeticity.
  → Ideal environment to search for decays with missing energy in the final state.

- **Full Event interpretation** reconstruction algorithm:
  - Multivariate technique to reconstruct the B-tag side through both semileptonic (SL) and hadronic (HAD).
  - Signal specific training technique.
  → \(x2\) in both HAD and SL reconstruction efficiency wrt Belle.
B→D(*)τν: theoretical and experimental status

- Observable:

\[ R(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)}\ell^+\nu_\ell)}{\Gamma(B \rightarrow D^{(*)}\ell^+\nu_\ell)} \quad \ell = e, \mu \]

- Very precise theoretical calculation in the SM framework: 3-4% level for \( R(D) \) \[sup]1\], 1% level for \( R(D^*) \) \[sup]2\]

- Experimental world average 4.08 \( \sigma \) away from SM expectations

- \( \tau \) polarisation measured by Belle \[sup]3\] :

\[ P(\tau) = -0.38 \pm 0.51^{+0.21}_{-0.16} \]
$B \rightarrow D(\ast)_{T\bar{U}}$ : perspectives @ Belle II

- Current measurements are statistically limited, dominant systematic uncertainties from
  - limited signal MC samples $\rightarrow$ larger at Belle II
  - limited knowledge of dominant bkg (involving soft pions) $\rightarrow$ dedicated measurement with large data samples feasible at Belle II

- With higher statistics, also study of $q^2$ distributions, essential to distinguish NP models, feasible

- Extrapolation from existing BaBar and Belle results:

  \[
  \frac{\sigma_{R_D}}{R_D}_{50\text{ab}^{-1}} = 2.0\% (\text{stat.}) \pm 2.5\% (\text{syst.}),
  \frac{\sigma_{R_{D^*}}}{R_{D^*}}_{50\text{ab}^{-1}} = 1.0\% (\text{stat.}) \pm 2.0\% (\text{syst.}),
  \sigma_{P_{(D^*)}}_{50\text{ab}^{-1}} = 0.06\% (\text{stat.}) \pm 0.04\% (\text{syst.}).
  \]
**$B\to\tau\nu$: theoretical and experimental status**

- **SM branching fraction:**

  $$B(B^+ \to \tau^+\nu) = \frac{G_F^2 m_B m_{\tau}^2}{8\pi} \left[1 - \frac{m_{\tau}^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_{B^+}$$

- Using $|V_{ub}|_{\text{excl}} = (3.55 \pm 0.12) \times 10^{-3}$, $f_B = (186 \pm 4)$ MeV [tn1]:

  $$\mathcal{B}(B \to \tau\nu) = (0.77 \pm 0.06) \times 10^{-4}$$

  World average of BaBar and Belle measurements using both semileptonic and hadronic tag [tn2]:

  $$\mathcal{B}(B \to \tau\nu) = (1.06 \pm 0.19) \times 10^{-4}$$

  - 5$\sigma$ significance exceeded combining the two experiments
  - consistent with SM expectation at 2 level

  **Statistically limited**, dominant **systematic** effects
  - data/MC disagreement and efficiency estimations
  - signal and bkg parameterisation in final fit

  (partly) **statistical in origin**

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Elisa Manoni - INFN PG

EPS-HEP 2017 - Flavour and Symmetries session
**B→τν : perspectives @ Belle II**

- Analysis on **Belle II Full simulation** using **hadronic** B reconstruction
  - signal and background yield extracted from ML fit to extra neutral energy

- Comparison with hadronic Belle analysis:

<table>
<thead>
<tr>
<th>$E_{ECL}$</th>
<th>&lt; 0.25 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Belle II</strong></td>
<td># background events 1348</td>
</tr>
<tr>
<td></td>
<td># signal events 136</td>
</tr>
<tr>
<td></td>
<td>signal efficiency (%) 1.6</td>
</tr>
<tr>
<td><strong>Belle</strong></td>
<td># background events 365</td>
</tr>
<tr>
<td></td>
<td># signal events 60</td>
</tr>
<tr>
<td></td>
<td>signal efficiency (%) 0.7</td>
</tr>
</tbody>
</table>

1 ab$^{-1}$ equivalent statistics

- Combination with Belle SL tag analysis \[^{[n1]}\] and extrapolation at full Belle II statistics:

<table>
<thead>
<tr>
<th>Tag</th>
<th>Integrated Luminosity (ab$^{-1}$)</th>
<th>Statistical Uncertainty (%)</th>
<th>Systematic Uncertainty (%)</th>
<th>Total Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>hadronic tag</strong></td>
<td>50</td>
<td>4.1</td>
<td>4.6</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>semileptonic tag</strong></td>
<td></td>
<td>2.7</td>
<td>4.5</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Extra energy in the calorimeter, nominal machine background included
Flavour changing neutral current, prohibited at tree level in the SM

NP contribution (from new mediators or sources of missing energy) may be comparable to SM ones

free of uncertain long-distant hadronic effects, theoretically clean

Experimental searches from BaBar and Belle on both HAD and SL recoil

no signal evidence, UL less than 1 order of magnitude away from SM predictions for $K^*$ channels
B→K^{(*)}ℓν: robustness against machine background

- Analysis on Belle II Full simulation using hadronic B reconstruction using $K^{*+} \rightarrow K\pi^0$ to establish machine background impact.

- Simple cut-and-count analysis, signal efficiency and bkg yield estimated in extra neutral energy signal region.

- Nominal machine bkg (BGx1) and machine bkg-free (BGx0) simulated samples analysed.

- Negligible impact of machine background both in terms of variables shape and signal significance.

<table>
<thead>
<tr>
<th>Lab⁻¹ equivalent statistics</th>
<th>“BGx0”</th>
<th>“BGx1”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{bkg}$</td>
<td>6415 ± 80</td>
<td>3678 ± 61</td>
</tr>
<tr>
<td>$\varepsilon \ (10^{-4})$</td>
<td>10.3 ± 0.3</td>
<td>5.38 ± 0.23</td>
</tr>
<tr>
<td>$N_{sig}/\sqrt{N_{bkg}}$</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>UL $\ (10^{-4})$</td>
<td>2.6</td>
<td>3.8</td>
</tr>
</tbody>
</table>

- Detector performances and reconstruction proves to be robust against machine background.
Extrapolation on full Belle II statistics on Belle HAD and SL analyses, assuming two times better $B_{\text{tag}}$ reconstruction efficiency:

- observation with about 18 ab$^{-1}$
- precision on the branching fraction at 50 ab$^{-1}$:

<table>
<thead>
<tr>
<th></th>
<th>stat only</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+\rightarrow K^+\nu \nu$</td>
<td>9.5%</td>
<td>10.7%</td>
</tr>
<tr>
<td>$B^+\rightarrow K^{*+}\nu \nu$</td>
<td>7.9%</td>
<td>9.3%</td>
</tr>
<tr>
<td>$B^+\rightarrow K^{*0}\nu \nu$</td>
<td>8.2%</td>
<td>9.6%</td>
</tr>
</tbody>
</table>

- Fraction of longitudinally polarized $K^*$ may be measured, $\sim 20\%$ precision with full statistics
- Robustness against machine background proved, predicted precision can be exceeded by improving analysis strategy
Summary

- Belle II unique or very competitive environment to study B decays with missing energy, sensitive to indirect NP effects
- x40 luminosity (and much higher machine background) wrt first generation B-factories
- Belle II full simulation studies proved the detector performances and the reconstruction algorithms to be robust against simulated machine background
  - measurements on machine background rates and spectra during phase I (2016) and phase II (starting Nov. 2018) operation phases
- Improvements in analysis strategy and larger data sample will allow to approach SM prediction (B \(\rightarrow\) K\((^0)\nu\nu\)) or further investigate deviation from/consistency with the SM predictions (B \(\rightarrow\) \(\tau\nu\) and B \(\rightarrow\) D\((^0)\tau\nu\))
- Phase III operation (Full detector) starting end 2018
Belle II unique or very competitive environment to study B decays with missing energy, sensitive to indirect NP effects

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Belle II full simulation studies proved the detector performances and the reconstruction algorithms to be robust against simulated machine background

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Improvements in analysis strategy and larger data sample will allow to approach SM predictions or further investigate deviation from/consistency with the SM predictions (B → K(*) and B → D(*)


Phase III operation (Full detector) starting end 2018
References

[rd1] HPQCD 2015, FNAL/MILC 2015


BACK-UP SLIDES
Phase I (2016)
- No Belle II
- Circulate both beams; no collisions
- Tune accelerator optics, etc.
- Vacuum scrub
- Beam studies

Phase II (2018)
- First collisions
- Develop beam abort
- Tune accelerator optics, etc. (nano-beam)
- Beam studies

Phase 1 (no collisions)

Touschek scattering:
- intra-bunch scattering process
- dominant with highly compressed beams
- 20 times higher

Beam-gas scattering:
- Bremsstrahlung (negligible) & Coulomb interactions (up to 100 times higher) with residual gas atoms & molecules

Synchrotron radiation:
- emission of photons by charged particles (e+e-) when deflected in B-field

Phase 2 (collisions)

Radiative Bhabha process:
- photon emission prior or after Bhabha scattering interaction with iron in the magnets leads to neutron background

Two photon process:
- very low momentum e+e- pairs via e+e-→e+e+e-e-
- increased hit occupancy in inner detectors

Injection Background:
- covered later in the talk
Belle II detector (I)

- Detector and reconstruction algorithm improvements result in:
  - Fast signal shaping and waveform fit of e.m. calorimeter signals to preserve excellent energy resolution in high-pileup environment
  - Increase Ks efficiency (by ~30%)
  - Improve IP and secondary vertex resolution (~factor 2)
  - Better K/π separation (π fake rate decreases by ~2.5)
  - Improve π^0 reconstruction
FEI performances

Table 5: Tag-side efficiency: Number of correctly reconstructed tag-side $B$ mesons divided by the total number of $\Upsilon(4S)$ events. The presented efficiencies depend on the used BASF2 release (7.2), MC campaign (MC 7) and FEI training configuration.

<table>
<thead>
<tr>
<th>Tag</th>
<th>FR$^2$ @ Belle</th>
<th>FEI @ Belle MC</th>
<th>FEI @ Belle II MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $B^+$</td>
<td>0.28 %</td>
<td>0.49 %</td>
<td>0.61 %</td>
</tr>
<tr>
<td>Semileptonic $B^+$</td>
<td>0.67 %</td>
<td>1.42 %</td>
<td>1.45 %</td>
</tr>
<tr>
<td>Hadronic $B^+0$</td>
<td>0.18 %</td>
<td>0.33 %</td>
<td>0.34 %</td>
</tr>
<tr>
<td>Semileptonic $B^0$</td>
<td>0.63 %</td>
<td>1.33 %</td>
<td>1.25 %</td>
</tr>
</tbody>
</table>
$\mathbf{B \to D(*) \tau\nu}$: theoretical and experimental status

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Tag method</th>
<th>$\tau^-$ decays</th>
<th>Observables</th>
<th>Fit variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [37]</td>
<td>Untagged</td>
<td>$e^-\nu_\tau\bar{\nu}<em>e, \pi\nu</em>\tau$</td>
<td>$\mathcal{B}(\bar{B}\to D^{(*)+}\tau^-\bar{\nu}_\tau)$</td>
<td>$M_{bc}^{\text{comp}}$</td>
</tr>
<tr>
<td>Belle [38]</td>
<td>Untagged</td>
<td>$\ell^-\nu_\tau\bar{\nu}<em>\ell, \pi\nu</em>\tau$</td>
<td>$\mathcal{B}(B^-\to D^{(*)0}\tau^-\bar{\nu}_\tau)$</td>
<td>$M_{bc}^{\text{comp}}$ and $p_{D^0}$</td>
</tr>
<tr>
<td>Belle [26]</td>
<td>Hadronic</td>
<td>$\ell^-\nu_\tau\bar{\nu}_\ell$</td>
<td>$R_D, R_{D^*}, q^2,</td>
<td>p^*_\ell</td>
</tr>
<tr>
<td>Belle [39]</td>
<td>Semileptonic</td>
<td>$\ell^-\nu_\tau\bar{\nu}_\ell$</td>
<td>$R_{D^*},</td>
<td>p^*_\ell</td>
</tr>
<tr>
<td>Belle [40]</td>
<td>Hadronic</td>
<td>$h^-\nu_\tau$</td>
<td>$R_{D^<em>}, P_\tau(D^</em>)$</td>
<td>$E_{\text{ECL}}$ and $\cos\theta_{\text{hel}}$</td>
</tr>
<tr>
<td>BaBar [25, 41]</td>
<td>Hadronic</td>
<td>$\ell^-\nu_\tau\bar{\nu}_\ell$</td>
<td>$R_D, R_{D^*}, q^2$</td>
<td>$M_{\text{miss}}^2$ and $p_\ell$</td>
</tr>
</tbody>
</table>

Table 7: Summary of experimental measurements of semitauonic $B$ decays. † Mainly based on $E_{\text{ECL}}$. ‡ Mainly based on $\cos\theta_{B-D^*\ell}$: further description in the text.

<table>
<thead>
<tr>
<th></th>
<th>$R_D$</th>
<th>$R_{D^*}$</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>0.440 ± 0.058 ± 0.042</td>
<td>0.332 ± 0.024 ± 0.018</td>
<td>-0.45/-0.07/-0.27</td>
</tr>
<tr>
<td>Belle (had. tag, $\tau^- \to \ell^-\nu_\tau\nu_\tau$)</td>
<td>0.375 ± 0.064 ± 0.026</td>
<td>0.293 ± 0.038 ± 0.015</td>
<td>-0.56/-0.11/-0.49</td>
</tr>
<tr>
<td>Belle (sl tag)</td>
<td>NA</td>
<td>0.302 ± 0.030 ± 0.011</td>
<td>NA</td>
</tr>
<tr>
<td>LHCb</td>
<td>NA</td>
<td>0.336 ± 0.027 ± 0.030</td>
<td>NA</td>
</tr>
<tr>
<td>Belle (had. tag, $\tau^- \to h^-\nu_\tau$)</td>
<td>NA</td>
<td>0.270 ± 0.035$^{+0.028}_{-0.025}$</td>
<td>NA</td>
</tr>
<tr>
<td>Average</td>
<td>0.397 ± 0.040 ± 0.028</td>
<td>0.310 ± 0.015 ± 0.008</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

Table 8: Measurements of $R_{D(*)}$ by Babar, Belle and LHCb. The averages presented are performed by HFflav [8]. The correlation column list the statistical, systematic and total correlations respectively.