B decays with missing energy, Belle II perspective

A. Bożek, IFJ PAN Kraków

for the Belle II Collaboration
SuperKEKB and Belle II

SuperKEKB

Mt. Tsukuba (877m)

Belle II

LINAC

main ring: 3km
e− (HER): 7GeV
e+ (LER): 4GeV
SuperKEKB: the nano beam scheme

Lower emittance beam
DR for LER and RF gun

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LER</td>
<td>HER</td>
<td>LER</td>
</tr>
<tr>
<td>Beam energy</td>
<td>$E_b$</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>Beam crossing angle</td>
<td>$\varphi$</td>
<td>22</td>
<td>83</td>
</tr>
<tr>
<td>$\beta$ function @ IP</td>
<td>$\beta_x / \beta_y$</td>
<td>1200/5.9</td>
<td>32/0.27</td>
</tr>
<tr>
<td>Beam current</td>
<td>$I_b$</td>
<td>1.64</td>
<td>1.19</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$2.1 \times 10^{34}$</td>
<td>$8 \times 10^{35}$</td>
</tr>
</tbody>
</table>
SuperKEKB: the nano beam scheme

"Detuned optics"

The smallest $\beta_y^*$ in the world!

$\beta_y^* = 3\,\text{mm}$

$\beta_y^* = 3\,\text{mm}$

First collision

Beam current

Luminosity

<table>
<thead>
<tr>
<th>L</th>
<th>2.1 x 10^{34}</th>
<th>8 x 10^{35}</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm^{-2}s^{-1}</td>
<td>X 40</td>
<td></td>
</tr>
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</table>
SuperKEKB: the nano beam scheme

<table>
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<tr>
<th>β function @ IP</th>
<th>$\beta_x/\beta_y$</th>
<th>$1200/5.9$</th>
<th>$32/0.27$</th>
<th>$25/0.30$</th>
<th>mm</th>
</tr>
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<tr>
<td>Beam current</td>
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<td>1.64</td>
<td>1.19</td>
<td>3.6</td>
<td>2.6</td>
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<td>cm$^{-2}$s$^{-1}$</td>
<td>40</td>
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Max. $I_{HER} = 800$ mA

Max. $I_{LER} = 860$ mA

$L_{peak} = 5.55 \times 10^{33}$ cm$^{-2}$s$^{-1}$
SuperKEKB: commissioning

- Phase 1: Beam operation without final focus magnets and Belle II
  - Commissioning of beam transportation and vacuum scrubbing
  - Only single beam studies
- Phase 2 (ended on July 2018):
  - No final vertex detector but one ladder/layer with background sensors
  - Achieved Luminosity of $5.5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
  - Recorded integrated luminosity of 500 pb$^{-1}$
- Phase 3: 2019 - detector with silicon vertex detector, $\approx$ 8 months of operation
Belle II first event(s)

most likely $e^+ e^- \rightarrow \gamma(4s) \rightarrow B\bar{B}$
Belle II first event(s)

\[ \int L \, dt = 472 \text{ pb}^{-1} \]
Belle II first event(s)
B decays with missing energy

Tagging techniques

- **Inclusive**
  \[ B \rightarrow \text{hadrons} \] (inclusive modes)
  \[ \epsilon \approx O(1\%) \]

- **Semileptonic**
  \[ B \rightarrow D(\ast)\ell\nu_\ell \]
  \[ \epsilon \approx O(0.3\%) \]
  (Y. Sato: PRD 94, 072007, (2016).)

- **Hadronic**
  \[ B \rightarrow \text{hadrons} \] (exclusive modes)
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B decays with missing energy

Tagging techniques

efficiency

- Inclusive
  \[ B \rightarrow \text{hadrons} \text{ (inclusive modes)} \]
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First measurement:

B decays with missing energy

Tagging techniques

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Semileptonic tagging:

\[ E_{ECL} \text{ remaining energy in the calorimeter} \]

B decays with missing energy

Tagging techniques

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  \[ \epsilon \approx O(1\%) \]
  A. Bozek: PRD 82, 072005, (2010).)

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  S. Hirose: PRL 118, 211801, (2017).)

Rest Of the Event (ROI)
$B \rightarrow \bar{D}(\ast)\tau^+\nu_\tau$ current situation

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow \bar{D}(\ast)\tau^+\nu_\tau)}{\mathcal{B}(B \rightarrow \bar{D}(\ast)\ell^+\nu_\ell)}$$

$\ell = e, \mu$ : normalization

SM predictions

$$R(D^{(*)})_{SM} = \frac{\mathcal{B}(B \rightarrow \bar{D}^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \rightarrow \bar{D}^{(*)}\ell^+\nu_\ell)} = 0.258 \pm 0.005$$

$$R(D)_{SM} = \frac{\mathcal{B}(B \rightarrow \bar{D}\tau^+\nu_\tau)}{\mathcal{B}(B \rightarrow \bar{D}\ell^+\nu_\ell)} = 0.299 \pm 0.003$$

HFLAV

$$R_D = 0.407 \pm 0.039_{stat} \pm 0.024_{syst}$$

$$R_{D^*} = 0.306 \pm 0.013_{stat} \pm 0.007_{syst}$$

deviation from SM:

$\sim 2.3\sigma$ for $R(D)$

$\sim 3.0\sigma$ for $R(D^*)$

$\sim 3.7\sigma$ tension between SM and combined $R(D^{(*)})$ experimental results

BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, PRL120,171802(2018)

Average of SM predictions

$\Delta \chi^2 = 1.0$ contours

Average

HFLAV: $P(\chi^2) = 74\%$
Belle II will improve the statistical uncertainty on $R(D)$ and $R(D^*)$ with $\sim 5ab^{-1}$ accumulate data we can achieve

- $\sim 6\%$ uncertainty on $R(D)$
- $\sim 3\%$ uncertainty on $R(D^*)$

the excess can be confirmed with early data

The ultimate precision (with $50ab^{-1}$) of $3\%$ and $2\%$ will be limited by systematic

The major contribution to systematic is the uncertainty on $D^{**}$ component.

In Belle II:

- we will study in details $B \to \bar{D}^{(**)}X$ decays,
- especially $B \to \bar{D}^{(**)}\ell^+\nu_\tau$ decays,
- a simultaneous determination of $R(D)$, $R(D^*)$ and may be $R(D^{**})$ components is possible.
Kinematic variables describing $B \rightarrow \bar{D}^{(*)} \tau^- \nu_\tau$

$q^2 \equiv M_W^2$ - effective mass squared of the $\tau\nu$ system

$\theta_{\tau}$ - angle between $\tau$&$B$ in $W^*$ rest frame

$\chi$ - angle between the $\tau\nu$ and $D^*$ decay planes

$\theta_{\text{hel}}(D^*)$ - angle between $D$&$B$ in $D^*$ rest frame

$\theta_{\text{hel}}(\tau)$ - angle between $\pi$& direction opposite to $W^*$ in $\tau$ rest frame

$$\frac{d\Gamma}{d \cos \theta_{\text{hel}}(\tau)} = \frac{1}{2} \left( 1 + \alpha P_{\tau} \cos \theta_{\text{hel}}(\tau) \right)$$

$$\alpha = 1.0 \text{ for } \tau \rightarrow \pi\nu; \quad \alpha = 0.45 \text{ for } \tau \rightarrow \rho\nu$$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{\text{hel}}(D^*)} = \frac{3}{4} \left[ 2F_L^{D^*} \cos^2(\theta_{\text{hel}}(D^*)) + (1 - F_L^{D^*}) \sin^2(\theta_{\text{hel}}(D^*)) \right]$$

$q^2, \cos \theta_{\text{hel}}(\tau)$ and $\cos \theta_{\text{hel}}(D^*)$ can be reconstructed at B-factories with hadronic decays of $B_{\text{tag}}$.
$B \rightarrow \bar{D}^* \tau^- \nu_\tau$ differential distribution: $q^2$

M. Tanaka, R. Watanabe - arXiv:1212.1878v1

Differential distribution can be measured to constrain NP contributions

Detailed measurement of $q^2$ and other kinematic distributions including polarization of the $\tau$ and $D^*$

Belle II MC are generated in the SM hypothesis
Block histograms is a 2HDM-type II benchmark
$B \rightarrow \bar{D}^* \tau^- \nu_\tau$ differential distribution : $\tau$ polarisation


Measured from the two body semileptonic $\tau (\rightarrow \pi \nu , \rightarrow \rho \nu )$ decays -experimentally challenging

Belle II perspectives : 

\[
P_{\tau}(D^*) = \frac{5 \text{ ab}^{-1}}{0.18 \pm 0.08} \quad \frac{50 \text{ ab}^{-1}}{0.06 \pm 0.04}
\]
$B \rightarrow \bar{D}^* \tau^- \nu_\tau$ differential distribution : $D^*$ polarisation

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{\text{hel}}(D^*)} = \frac{3}{4} \left[ 2 F_{L^*}^D \cos^2(\theta_{\text{hel}}(D^*)) + (1 - F_{L^*}^D) \sin^2(\theta_{\text{hel}}(D^*)) \right]$$

All $\tau$ decays are usable.

Belle result presented on CKM2018:

$$F_{L^*}^D = 0.60 \pm 0.08 (\text{stat.}) \pm 0.035 (\text{syst.})$$

SM: $F_{L^*}^D = 0.46 \pm 0.03$ (Phys. Rev. D 95, 115038 (2017), A.K. Alok, et al) (1.5 $\sigma$)

SM: $F_{L^*}^D = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) (1.8 $\sigma$)

$\Rightarrow$ consistent with the SM within 2$\sigma$

Expected number of events for $F_{L^*}^D$ in full data set is $\sim 15000$. 

Andrzej Bożek  IFJ PAN, Kraków  
The Workshop on High-energy implications of flavor anomalies October 24
Testing lepton flavor universality in $b \to u$ semileptonic decays

$$R(\pi) = \frac{\mathcal{B}(B \to \pi \tau^+ \nu_\tau)}{\mathcal{B}(B \to \pi \ell^+ \nu_\tau)}$$

Feasibility already demonstrated with Belle. No statistically significant signal was observed $\mathcal{B}(B \to \pi \tau^+ \nu_\tau) < 2.5 \times 10^{-4}$


Central value:

$\mathcal{B}(B \to \pi \tau^+ \nu_\tau) = (1.52 \pm 0.72 \pm 0.13) \times 10^{-4}$

Belle II extrapolation of uncertainty

$R^{5ab^{-1}}_{\pi} \pm 0.23$ or $R^{50ab^{-1}}_{\pi} \pm 0.09$
Testing lepton flavor universality with leptonic $B$ decays

Very clean theoretically, hard experimentally SM is helicity suppressed
Sensitive to NP contribution (charged Higgs)

\[
R^{\mu\mu} = \frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}
\]

\[
R^{e\nu} = \frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}
\]

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

\[
B(B \to l\nu) = \frac{G_F m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B
\]

<table>
<thead>
<tr>
<th>Mode</th>
<th>SM BR</th>
<th>Current meas.</th>
<th>Belle II 5 ab-1</th>
<th>Belle II 50 ab-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau\nu$</td>
<td>$10^{-4}$</td>
<td>20% uncertainty</td>
<td>15%</td>
<td>6%</td>
</tr>
<tr>
<td>$\mu\nu$</td>
<td>$10^{-6}$</td>
<td>40% uncertainty*</td>
<td>20%</td>
<td>7%</td>
</tr>
<tr>
<td>$e\nu$</td>
<td>$10^{-11}$</td>
<td>Beyond reach</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* arxiv:1712.04123 2.4$\sigma$ excess [2.9,10.7]x10$^{-7}$ at 90% C.L.

Belle II Full simulation with expected background conditions (hadronic tags only)
S.L. tag expected to have similar sensitivity

Extrapolation of Belle Analysis
$B \rightarrow K\nu\nu$ decays

Suppressed in the SM: BRs $10^{-5} - 10^{-6}$ may be enhanced by NP

90% CL excluded by Belle and Babar

Current limits

Constraints on new physics contributions to Wilson coefficients $C_L$, $C_R$

68% CL allowed by Belle II at 50 ab$^{-1}$

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

• Belle II started to run on collision this year,
• from next year we are going to collect data meaningful for $B$ physics,
• $B$ decays with missing energy are one of the focus of Belle II,
• in 2020 we should surpass current luminosity accumulated by B-factories
Challenges for $D^*$ polarisation measurement

Main experimental problem:
strong acceptance effects for $\cos \theta_{\text{hel}}(D^*) \geq 0.0$

efficiency
distribution of slow $\pi^{\pm}$ from $D^*$

Effectively only $\cos \theta_{\text{hel}}(D^*) < 0$ is useful for $F_L^{D^*}$ measurement
Measurement of $\tau$ polarization in $B$ decays

- **both $B^0$ and $B^-$ decays are used; only 2 body $\tau$ decays:** $\tau \to \pi \nu, \rho \nu$
- **sample divided into two bins of $\cos \theta_{hel}$:**
  1. $-1 < \cos \theta_{hel} < 0$
  2. $0 < \cos \theta_{hel} < 0.8$ (for $\tau \to \pi \nu$)

Experimental challenges

- **Distribution of $\cos \theta_{hel}(\tau)$ is modified by:**
  - cross-feeds from other $\tau$ decays (contribute mainly in the region of $\cos \theta_{hel}(\tau) < 0$)
  - peaking background (concentrated around $\cos \theta_{hel}(\tau) \approx 1$)
- **corrections for detector effects:** acceptance, asymmetric $\cos \theta_{hel}$ bins, crosstalks between different $\tau$ decays
- **for $\tau \to \pi(\rho)\nu$ modes combinatorial background from poorly known hadronic $B$ decays**

$$P_{\tau} = \frac{2}{\alpha} \frac{\Gamma_{\cos \theta_{hel} > 0} - \Gamma_{\cos \theta_{hel} < 0}}{\Gamma_{\cos \theta_{hel} > 0} + \Gamma_{\cos \theta_{hel} < 0}}$$