SUSY-related lepton and hadron flavour results from Belle

OUTLINE

- Belle & SUSY
- selected results
  - prospects for BelleII
- summary

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Belle experiment

KEKB B-factory at KEK (Japan): asymmetric energy e⁺e⁻ collider

\[ e^+e^- \rightarrow \gamma(4S) \rightarrow \bar{B}B \]

**Belle detector:**
multi-purpose, large-solid-angle magnetic spectrometer

Data taking: 1999-2010

- \( L_{\text{int.}} > 1 \text{ab}^{-1} \)
- \( L_{\text{peak}} = 2.11 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \)

771 million \( \bar{B}B \) events
>6 million \( \bar{B}_sB_s \) events

\[ \frac{2}{16} \text{ few ten times more expected from Bellell} \]
SUSY in flavour physics

Many places and ways to look for new physics effects in $B_{(s)}$ and lepton decays

Examples of SUSY contributions to tree, penguin and box diagrams

GOALS:
- get a hint of new physics,
- distinguish between different models based on pattern of deviations from the SM,
- determine the flavor structure of squark mass matrixes (new sources of flavor mixing and CP phases)...

...or constrain parameter space of various SM extensions

Need observables that are:
- sensitive to NP
- clean theoretically
- accessible experimentally

E.g.
- Branching ratios and distributions in $B \rightarrow D^{(*)} \tau \nu$;
- Branching ratios and angular distributions of $b \rightarrow s l l$;
- Branching ratio and CP asymmetries in $B \rightarrow X \gamma$
- Mixing-induced and direct CP asymmetries in hadronic $B_{(s)}$ decays
- Lepton flavor violation in tau decays.
Semileptonic, tree-dominated decay

\[ b \rightarrow c W^- \tau \bar{\nu}_\tau \]

New Physics at the tree level

\[ b \rightarrow c H^- \tau \bar{\nu}_\tau \]

Sensitive to NP and theoretically clean observables:

\[
R(D)^*_{SM} = 0.299 \pm 0.003
\]

D. Bigi, P. Gambino, arXiv:1606.08030

\[
R(D)_{SM} = 0.297 \pm 0.017
\]

S. Fajfer et al., PRD 85, 094025 (2012)

\[
R(D^*)_{SM} = 0.252 \pm 0.003
\]

Common uncertainties (partly) cancel out

- Theoretical uncertainty of some form factors
- Uncertainty of \(|V_{cb}|\)
- Experimental uncertainty of efficiencies, partial \(BF\) etc…

Challenging experimentally

At B-factories B decays to multiple \(\nu\)'s final states can be observed in recoil of fully reconstructed \(B_{tag}\).

Till recently all B-factory results based on hadronic decays of \(B_{tag}\)

\[ R(D^*) \text{ 3}\sigma \text{ away from the SM} \]

\[ R(D) \text{ 1.9}\sigma \text{ away from the SM} \]

\[ R(D^*) & R(D) \text{ 3.9}\sigma \text{ away from the SM} \]
Use the cleanest mode: $B^0 \rightarrow D^* \rightarrow \tau^+ \nu_\tau$, $\tau \rightarrow l \nu_l \nu_\tau$

$$R(D^{(*)}) = \frac{BF(B \rightarrow D^{(*)} \tau \nu_\tau)}{BF(B \rightarrow D^{(*)} l \nu_l)}$$

$$\cos \theta_{B-D^* l} = \frac{2E_{\text{beam}} E_{D^* l} - m_B^2 - M_{D^* l}^2}{2 | \vec{p}_B \parallel \vec{p}_{D^* l} |}$$

**Table:**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Signal</th>
<th>Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\cos \theta_{B-D^* l}$</td>
<td>&lt;0</td>
<td>[-1,1]</td>
</tr>
<tr>
<td>$M_{\text{mis}}^2$ - missing mass squared</td>
<td>large</td>
<td>$\approx 0$</td>
</tr>
<tr>
<td>$E_{\text{vis}}$ - sum of energies of secondary particles</td>
<td>small</td>
<td>large</td>
</tr>
</tbody>
</table>

Use the full Belle data sample of $772 \times 10^6$ $\bar{B}B$-pairs

Signal events can be separated from normalization events based on the kinematics - two more $\nu$'s in the signal

A. Abdessalam, et al., (Belle Collaboration), arXiv:1603.006711
**Signal extraction:**

- Two-dimensional fit to neural network classifier output NN, and \( E_{ECL} \), residual energy in the electromagnetic calorimeter; \( E_{ECL} \approx \) for signal, tends to be higher for background.
- Signal, \( B \rightarrow D^* \nu \) (normalization) and \( B \rightarrow D^{**} \nu \) yields are floated in the fit, other components are fixed to MC expectation.

**231\(\pm\)13 signal events with the significance of 13.8\(\sigma\)**
$B^0 \to D^{*-}\tau^+\nu_\tau$ with semileptonic tagging

Result: $R(D^*) = 0.302 \pm 0.030\text{(stat)} \pm 0.011\text{(syst)}$ 1.6σ larger than the SM prediction

Consistent with earlier measurements; precision better than for other Belle and LHCb measurements

(BaBar result $R(D^*) = 0.332 \pm 0.024\text{(stat)} \pm 0.018\text{(syst)}$ combines $B^0$ and $B^+$ decays)
Tantalizing but inconclusive hints of a deviation from the Standard Model in $b\to c\tau\nu_\tau$ transitions:

- $R(D^{(*)})$ systematically above the SM expectations, surprisingly large effect for $R(D^*)$;
- More observables with more data needed to clarify the situation;

Angular observables not yet explored experimentally.

\[ \cos\theta_V \text{ and } \cos\theta_{hel} \text{ can be reconstructed} \]

at B-factories with hadronic decays of $B_{tag}$ 

$\Rightarrow$ polarization of $D^*$ ($F_{L(T)}^{D^*}$) and $\tau$ ($P_\tau$)

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_V} = \frac{3}{4} [2F_L^{D^*} \cos^2 \theta_V + F_T^{D^*} \sin^2 \theta_V], \quad F_L^{D^*} + F_T^{D^*} = 1
\]

all $\tau$ decays

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1}{2} [1 + \alpha P_\tau \cos \theta_{hel}]
\]

only $\tau \to M\nu_\tau$ decays, $\alpha=1$ for $M=\pi$

Important topics for Belle II

some constraints on $F_{L(T)}^{D^*}$ and $P_\tau$ feasible with the Belle data

(N.B. the $\tau \to \pi\nu_\tau$ mode was used in two Belle analyses of $B\to D^{(*)}\tau^+\nu_\tau$ [PRL 99, 191807 (2007), PRD 82, 072005 (2010)])
Flavor-changing neutral current (FCNC) decays that are forbidden in the SM at tree level, and proceed at higher orders via penguin loops & box diagrams.

Main contributions from: semi-leptonic operators $O_9$ ($V$ current), $O_{10}$ ($A$ current) and EM dipol operator $O_7$

New physics adds new loops with new particles

NP modifies SM values of the Wilson coefficients $C_{i}^{\text{eff}}$ and may introduce new terms, e.g. scalar & pseudoscalar couplings $C_{S}$ & $C_{P}^{\text{eff}}$,

**angular observables bear high sensitivity to NP.**

$\Rightarrow$ probes of new physics at a scale of few TeV.
Angular variables

The $B \to K^* l^+ l^-$ decay is described by 4 variables:

- $q^2$ - effective mass squared of the $l^+ l^-$ system,
- $\theta_l$ - angle between $l^+ (l^-)$ & $B (\bar{B})$ in $l^+ l^-$ rest frame
- $\theta_K$ - angle between $K$ & $B$ in $K^*$ rest frame
- $\phi$ - angle between the di-lepton and $K \pi$ decay planes

$$
\frac{1}{d\Gamma dq^2 d\cos \theta_l d\cos \theta_K d\phi d^2 q} = \frac{9}{32 \pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right] \\
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l \\
+ S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ S_6 \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi
$$

$$F_L \to K^* \text{ longitudinal polarization}$$

$$F_L, S_i \text{ - functions of } q^2$$

**folding method:**

*for $S_5$:*

$$
\begin{cases} 
\phi \to -\phi & \text{for } \phi < 0 \\
\theta_l \to \pi - \theta_l & \text{for } \theta_l > \pi / 2
\end{cases}
$$

All $S_i$ terms except for $S_3$ and $S_5$ vanish

Number of free parameters reduced from 8 to 3: $F_L, S_3$ and $S_{5(4,7,8)}$

**Notation consistent with the LHCb paper.**

**LHCb reported 3.4σ deviation from the SM prediction in $P_5'$ for $4 < q^2 < 8$ GeV$^2$ from full angular analysis of $B^0 \to K^{*0} \mu^+ \mu^-$**

**LHCb Collab., JHEP 02, 104 (2016)**

**form factor independent observables, $P_i'$:**

$$P_i' = \frac{S_{i=4,5,7,8}}{\sqrt{F_L (1 - F_L)}}$$
Challenges:
- $BF(B^0 \rightarrow K^*(892)\ell^+\ell^-) \approx 10^{-7}$
- irreducible background from $B \rightarrow K^*J/\psi$ and $B \rightarrow K^*\psi(2S)$
- expect $\mathcal{O}(100)$ candidates in the Belle data-sample

Experimental approach:
- use both, di-electron and di-muon modes
- Neural Network based selections adopted to improve the sensitivity;
- Robust fitting technique, suitable for low statistics;
- Signal and background yields from fits to $M_{bc}$ distribution;
  \[
  M_{bc} = \sqrt{(E_{\text{beam}})^2 - |\vec{p}_B|^2}
  \]
- 3-dim UML fits to angular distributions in the region of $M_{bc} > 5.27$ GeV to extract $F_L, P'_3$ and $P'_i$ ($i=4,5,6,8$)
- The fits are performed in bins of $q^2$

Use the full Belle data sample of $772 \times 10^6 \bar{B}B$-pairs

The measurements are compatible with the SM predictions and the LHCb measurements.

The result for $4 < q^2 < 8$ GeV$^2$ is $2.1\sigma$ away from the theoretical prediction in the same direction as observed by LHCb.

Global analyses of the deviations in EW $b\rightarrow s$ transitions point towards a large additional contribution to the Wilson coefficient $C_9^{\mu}$ of the semi-leptonic operator in the effective Hamiltonian for $b\rightarrow s\mu^+\mu^-$ (significance over $4\sigma$).

On the other hand, $B\rightarrow K^*(e^+e^-)$ observables suggest that $b\rightarrow s e^+e^-$ transitions agree well with the SM.

**A full angular analysis of $B\rightarrow K^* e^+e^-$ and its comparison with $B\rightarrow K^* \mu^+\mu^-$ could improve our understanding of these anomalies and help confirming their interpretation in terms of short-distance New Physics.**

There is a significant difference in the theoretical accuracy of the inclusive and exclusive $b\rightarrow s l^+l^-$ decays in the low-$q^2$ region (theoretical description of power corrections exists only in the inclusive case). This issue makes it rather difficult or even impossible to separate new physics effects from such potentially large hadronic power corrections within these exclusive angular observables. **These tensions might stay unexplained until Belle-II will clarify the situation by measuring the corresponding inclusive $b\rightarrow s l^+l^-$ observables.**

The deviations in EW $b\rightarrow s$ transitions can be explained either by new particles or by unexpectedly large hadronic effects (charm loops).

Tasks for Belle II (~2000 events of $B^0\rightarrow K^* e^+e^-$ and ~5000 events of $B^0\rightarrow K^* \mu^+\mu^-$): **measurements of angular observables in $B\rightarrow K^* e^+e^-$ and in inclusive $B\rightarrow s l^+l^-$ decays.**
The two-body decays $B_s \rightarrow h^+_1 h^-_2$, where $h^+_1(2) = K^\pm$, or $\pi^\pm$ have now all been observed, in contrast to the neutral-daughter decays $B_s \rightarrow h^+_0 h^+_2$.

The decay $B_s \rightarrow K^0 \bar{K}^0$ is of particular interest:

- Predicted branching fraction $BF(B_s \rightarrow K^0 \bar{K}^0)$ is in the range $(1.6-2.7) \times 10^{-5}$
- The presence of non-standard particles or couplings such as model with $Z'$ coupling may enhance the branching fraction up to $3.0 \times 10^{-5}$
  

- The direct CP asymmetry $A_{CP}$ is not more than 1% in SM, can be 10% larger in the presence of SUSY without changing the branching ratio.

  [A. Hayakawa et al., PTEP 2014, no. 2, 023B04 (2014); S. Baek et al., JHEP 0612, 019 (2006)]

Previous searches by Belle with 23.6 fb$^{-1}$ gave an upper limit of $BF(B_s \rightarrow K^0 \bar{K}^0) < 6.6 \times 10^{-5}$ at 90% CL.

The new analysis uses 121.4 fb$^{-1}$ of Belle data collected at $\Upsilon(5S)$ resonance;

The data set corresponds to $(6.53 \pm 0.66) \times 10^6$ $B_s \bar{B}_s$ pairs produced in three $\Upsilon(5S)$

decay channels: $B_s \bar{B}_s$, $B_s^* \bar{B}_s$ or $\bar{B}_s B_s$ and $B_s \bar{B}_s$

The latter two channels dominate, with production fractions: $f_{B_s^* \bar{B}_s} = (7.3 \pm 1.4)\%$ $f_{B_s \bar{B}_s} = (87.0 \pm 1.7)\%$

$B_S \rightarrow K^0 \bar{K}^0$

- $K^0$ mesons are reconstructed only via the decay $K_S \rightarrow \pi^+\pi^-$;
- 3D fit is performed to extract the signal yield;

$$M_{bc} = \sqrt{(E_{\text{beam}})^2 - |\vec{p}_B|^2}$$

$$\Delta E = E_R - E_{\text{beam}}$$

$$C'_{NN} = \ln \frac{C_{NN} - C_{\text{min}}}{C_{\text{max}} - C_{NN}}$$

- The three peaks in $M_{bc}$ arise from $\Upsilon(5S) \rightarrow B_s \bar{B}_s$, $(B_s \bar{B}_s^* + B_s^* \bar{B}_s)$, $B_s^* \bar{B}_s^*$

$$29.0^{+8.5}_{-7.6} \text{ signal events} \quad \text{significance } 5.1 \sigma \text{ (syst. included)}$$

**first observation**

$$BF(B_s^0 \rightarrow K^0 \bar{K}^0) = [19.6^{+5.8}_{-5.1} \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 2.0(N_{B_s \bar{B}_s})] \times 10^{-6}$$

in good agreement with the Standard Model expectations

- in Belle II (~5 ab$^{-1}$ of data) ~1200 events expected
  ⇒ much higher sensitivity search for new physics, including CP violation study.
Summary and prospects

- New measurements at Belle confirm the existing tensions:
  - The result for $R(D^*)$ obtained with semileptonic tagging $R(D^*) = 0.302 \pm 0.030\text{(stat)} \pm 0.011\text{(syst)}$ confirms the excess seen by other measurements and brings to tension with the SM to $4.0\sigma$; we need more data and more observables on $b \to c(u)\tau\nu_\tau$ transitions, e.g. inclusive $BF(B \to X_c\tau\nu_\tau)$, polarizations of $\tau$ and $D^*$...
  - The $P_5$ value for $4 < q^2 < 8 \text{ GeV}^2$ from angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ is $2.1\sigma$ away from the theoretical prediction and supports the anomaly seen by LHCb; The deviations in EW $b \to s$ transitions can be explained either by new particles or by unexpectedly large hadronic effects (charm loops). Measurements of angular observables in inclusive $b \to sl^+l^-$ and $B \to K^*e^+e^-$ decays are needed to clarify the situation.

- First observation of of a charmless two-body $B_s$ decay involving only neutral hadrons in the channel $B_s^0 \to K^0\bar{K}^0$ - good place to look for NP in gluonic penguins

Interesting program for Belle II
$B^0 \rightarrow D^*-\tau^+\nu_\tau$ with semileptonic tagging

compatibility tests with $D^*$ and lepton momenta

$q^2 = (p_B - p_{D^*})^2$ cannot be calculated with semileptonic tags

**Standard Model**

Background-subtracted $D^*$ and lepton spectra in the $\Upsilon (4S)$ rest frame, in the signal enhanced region: $NN>0.8$, $E_{ECL}<0.5$ GeV.

**New Physics compatibility tests**

$$-\mathcal{L}_{\text{eff}} = 2\sqrt{2} G_F V_{cb} [O_{V1} + \sum_{X=S1,S2,V1,V2,T} C_X O_X]$$

added one by one:

- $O_{S1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_L)$
- $O_{S2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_L)$
- $O_{V1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L)$
- $O_{V2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma^\mu \nu_L)$
- $O_T = (\bar{c}_R \sigma^{\mu\nu} b_R)(\bar{\tau}_L \sigma_{\mu\nu} \nu_L)$

efficiency corrections applied as a function of $C_X$

**Type-II 2 Higgs Doublet Model**

$C_{S1} = -m_\mu m_\tau \tan^2 \beta / m_{H^+}^2$

$\tan \beta$ - ratio of the vacuum expectation values of the 2 Higgs doublets

- excluded by BaBar at 99.8% C.L.

based on combined $R(D)$ & $R(D^*)$

**Models with scalar leptoquarks**

$R_2$-type - compatible with data in some regions of parameter space

$m_{LQ} = 1$ TeV  $C_{S1} = +7.8 C_T$

\(B^0 \to D^*-\tau^+\nu_\tau\) with semileptonic tagging

compatibility tests with \(D^*\) and lepton momenta

2HDM-II

Efficiency corrected
\(R(D^*)_{\text{meas}}\) matches the \(R(D^*)_{\text{th}}\) at \(\tan\beta/m_{H^+} \approx 0.7\) GeV\(^{-1}\); \(p\)-values of \(p_{D^*}\) and \(p_l\) similar to the SM case

\(R_2\)-type scalar LQ

\(C_T = 0.36\)

\(R(D^*)_{\text{meas}}\) matches the \(R(D^*)_{\text{th}}\) at \(C_T \approx -0.03\) and \(C_T \approx +0.36\); \(p_{D^*}\) distribution disfavors the \(C_T = 0.36\) case
Input variables to neural network
The $P'_5$ asymmetry suggested by Ref. [99] is based on the angles $\theta_K$ and $\phi$. It is defined as the relative difference between the number of decays in the regions in red and blue in Fig. 12 (right), divided by $\sqrt{F_L(1 - F_L)}$. Quantities based on several angles are more difficult to measure than single-angle ones as they require a better understanding of the reconstruction efficiencies depending on the kinematics of the outgoing particles.
$B^0 \rightarrow K^{*0} l^+ l^-$

FIG. 4. Projections for the fit result of $P^l_2$ in bin 2. Fit to the $M_{bc}$ sideband for the determination of the background shape (top) and signal region (bottom) are displayed. Combinatorial (dashed blue), signal (red filled) and total (solid) fit distributions are superimposed on the data points.