SUSY-related Lepton and Hadron Flavor Results from Belle

Yutaro Sato
For the Belle Collaboration (Nagoya Univ., KMI)
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New physics search at Belle

- New particles (e.g. SUSY particles) could enter in the tree, loop, and box diagrams.
  - Observables (such as branching fraction or asymmetry) are modified.

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**Topics covered in this talk:**

1. $B \rightarrow D^{(*)}\tau\nu$ with hadronic tag (arXiv:1507.03233, submitted to PRD)
2. $B \rightarrow \pi\pi\tau\nu$ with hadronic tag
3. $B_s \rightarrow \phi\gamma, \gamma\gamma$ (PRD 91, 011101(R)(2015))
4. $A_{CP}(B \rightarrow X_{s+d}\gamma)$ (PRL 114, 151601 (2015))
• KEKB accelerator and Belle detector at Tsukuba, Japan.
  – Asymmetric $e^+e^-$ energy to boost B mesons
  – Data taking for 1999-2010
  – Good particle ID capability
    • $(p, \pi^\pm, K^\pm, \gamma, e, \mu, K_L^0)$
  – Good momentum resolution
    • $\frac{\sigma_{P_t}}{P_t} = 0.19P_t \oplus \frac{0.30}{\beta} \%$

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Integrate luminosity [fb$^{-1}$]

\[ \mathcal{L}_{\text{int.}} > 1 \text{ ab}^{-1} \]
\[ \mathcal{L}_{\text{peak}} = 2.11 \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \]

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**KEKB accelerator**

\( e^- \) \( e^+ \)

~3 km circumference

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**Aerogel Cherenkov cnt.**
(n=1.015~1.030)

**Central Drift Chamber**
small cell +He/C$_2$H$_6$

**Si vtx. det.**
(3/4 lyr. DSSD)

**m / K$_L$ detection**
14/15 lyr. RPC+Fe

**SC solenoid** (1.5T)
\( 16X_0 \)

**TOF counter**
Hadronic tagging with Neural Network

- Event selection by using NeuroBayes (neural network).
  - 1104 exclusive decays are used.
- Especially, useful for final states with neutrinos.
  (e.g.) $B \rightarrow D(\ast)\tau\nu, \pi\tau\nu, \ldots$

$B_{\text{tag}}$ is completely reconstructed from hadronic decay ($B \rightarrow D(\ast)X, J/\psi X, \ldots$).

NIMA 654, 432 (2011)
**B → D(∗)τν with Hadronic Tag**

- Sensitive to charged Higgs.

**Observables**

- \[ R(D^{(*)}) = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to Dl\nu)} \quad (l = e, \mu) \]

- Several systematic uncertainties mostly cancel out in the ratio.
  - \( V_{cb} \) (part of) form factors, experimental efficiencies.

- All measurements indicate \( R(D^{(*)}) \) higher than SM.

**Selection**

- \( B_{\text{tag}} \) is reconstructed by hadronic tagging based on Neural network.

- Leptonic \( \tau \) decays are used.
  - Same final state as \( B \to D^{(*)}l\nu \)

- 4 \( D^{(*)}l \) final states \( (D^{*+}l, D^{*0}l, D^{+}l, D^{0}l) \)

- No further tracks or \( \pi^0 \)

- \( q^2 > 4 \text{ GeV}^2 \)

- \(-0.2 \text{ GeV}^2 < M_{\text{miss}}^2 < 8.0 \text{ GeV}^2 \)

- Virtual boson mass-squared
  \[ q^2 = (p_B - p_{D^{(*)}})^2 \]

- Missing mass-squared
  \[ M_{\text{miss}}^2 = (p_{\text{Beam}} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_l)^2 \]
Fit Strategy

- Split sample at $M_{\text{miss}}^2 = 0.85 \text{ GeV}^2/c^4$

Fit in $M_{\text{miss}}^2$ to determine $D^{(*)}l\nu$

Fit in Neural Network output to separate sig. from bkg. (mainly $D^{**}l\nu$)

$B \rightarrow D^{(*)}\tau\nu$ with hadronic tag
• 4 $D^{(*)}l$ channels are simultaneously fitted.

- **Total 12 free parameters**
  - 4 parameters for $B \rightarrow D^{(*)}l\nu$
  - 2 parameters for $R(D^{(*)})$ assuming isospin symmetry
  - 2 parameters for cross-feed from $D^*l$ to $Dl$
  - 4 parameters for $B \rightarrow D^{**}l\nu$

- **$D^{(*)}l\nu$ enhanced**
- **$D^{(*)}\tau\nu$ enhanced**

Small backgrounds are fixed, relying MC expectation.

Events with falsely reconstructed $D^{(*)}$ is determined by sideband of $\Delta m (m_D)$. 
Fit for $D^* l$ Samples

$B \to D^* l\nu$ (normalization)

$B \to D^* \tau\nu$ (signal)
Fit for $Dl$ Samples

$Dl\nu$-enhanced region
$(M_{\text{miss}}^2 < 0.85 \text{ GeV}^2/c^4)$

$D\tau\nu$-enhanced region
$(M_{\text{miss}}^2 > 0.85 \text{ GeV}^2/c^4)$

$B \to D^* l\nu$ (normalization, CF)
$B \to D l\nu$ (normalization)

$D^+ l$

$D^0 l$

$B \to D^{(*)} \tau\nu$ (signal, CF)
$B \to D \tau\nu$ (signal)
Belle result is consistent with SM and BaBar result within $2\sigma$.

Analysis is repeated for type-II 2HDM with $\tan\beta/m_{H^+} = 0.5$ GeV$^{-1}$.

$$R(D) = 0.375_{-0.063}^{+0.064} \text{ (stat.)} \pm 0.026 \text{ (syst.)}$$

$$R(D^*) = 0.293_{-0.037}^{+0.039} \text{ (stat.)} \pm 0.015 \text{ (syst.)}$$
Motivation

- Deviation from SM in $B \to D^{(*)} \tau \nu$ decay.
- $B \to \pi \tau \nu$ can be also used for SM test.
  - Decay amplitude

Vector FF

$$
\langle \pi^+(p) | \bar{u} \gamma_{\mu} b | \bar{B}^0(p + q) \rangle = f_{B\pi}^+(q^2) \left[ 2p_{\mu} + \left( \frac{1 - m_B^2 - m_{\pi}^2}{q^2} \right) q_{\mu} \right] + f_{B\pi}^0(q^2) \frac{m_B^2 - m_{\pi}^2}{q^2} q_{\mu}
$$

Scalar FF

$$
\frac{B(B \to \pi \tau \nu)/dq^2}{B(B \to \pi l \nu)/dq^2} \text{ only depends on the ratio of form factors: } f^0(q^2)/f^+(q^2).
$$

→ Search for first evidence of $B \to \pi \tau \nu$
**Analysis**

- $B_{\text{tag}}$ is reconstructed by hadronic tag based on Neural network.
- Four one-prong $\tau$ decays are used
  - $\tau \rightarrow e\nu\nu, \mu\nu\nu, \pi\nu, \rho\nu$
  - ($\tau \rightarrow \mu\nu\nu$ is only used as veto due to less significance)
- Signal signature
  - exactly 2 oppositely charged tracks in signal side
  - large missing momentum by (two or three) neutrinos

**Backgrounds**

- No remaining tracks and $K_L^0$ veto.
- $B \rightarrow \pi l\nu$ is removed by selection on $M_{\text{miss}}^2$.
- Backgrounds are suppressed using Boosted Decision Trees.
  - Main backgrounds in signal region: $B \rightarrow D l\nu, B \rightarrow D\pi$ with $D \rightarrow K_L^0\pi$
- Signal is extracted from extra energy on ECL ($E_{\text{ECL}}$)
• Fit is simultaneously performed in all three modes.
  – 4 fit parameters: 1 parameter for Sig. and 3 parameters for $b \rightarrow c$ Bkg.
  – Other background is fixed and systematic uncertainty is estimated.

• Signal yields: $52 \pm 24$ events
• $\mathcal{B}(B^0 \rightarrow \pi\tau\nu) = (1.52 \pm 0.74) \times 10^{-4}$ (stat. only)
  $\rightarrow$ Close to SM prediction: $(9.35 \pm 0.38) \times 10^{-5}$
  $\rightarrow$ 2.4 $\sigma$ significance including systematic uncertainties.

Upper Limits
$\mathcal{B}(B^0 \rightarrow \pi\tau\nu) < 2.5 \times 10^{-4}$ @ 90% C.L.
$\mathcal{B}(B^0 \rightarrow \pi\tau\nu) < 2.8 \times 10^{-4}$ @ 95% C.L.

Dominant syst. sources:
• Tag side efficiency
• $K_L^0$ veto efficiency
**$B_s \rightarrow \phi \gamma, \gamma \gamma$**

### $B_s \rightarrow \phi \gamma$
- First observation by Belle \( \text{PRL 100, 121801 (2008) (23.6 fb}^{-1}) \)
- Update with full Belle data (121.4 fb\(^{-1}\))
- Theoretical prediction is \(4 \times 10^{-5}\) with 30% uncertainty
- Most precise measurement by LHCb: \((35.1 \pm 3.5 \pm 1.2) \times 10^{-6}\)

### $B_s \rightarrow \gamma \gamma$
- Current best upper limits: \(8.7 \times 10^{-6}\) @ 90% C.L. by Belle.
- Theoretical predictions
  - \((2 - 8) \times 10^{-7}\) \(\text{PRD 56, 5805 (1997)}\)
  - \((1.8 \pm 0.4) \times 10^{-7}\) \(\text{PRD 85, 014008 (2012)}\)
  - \(1.23 \times 10^{-6}\) \(\text{JHEP 08, 054 (2002)}\)
- In R-parity violating model, it may be enhanced.
  - Search for first evidence with full Belle data (121.4 fb\(^{-1}\))
Result of $B_s \rightarrow \phi \gamma$

- 4-dimensional fit
  - $M_{bc} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{B_s}|^2}$
  - $\Delta E = E_{B_s} - E_{\text{beam}}$
  - $C'_{NB}$ (Neural network output for continuum suppression)
  - $\cos \theta_{\text{hel}}$ ($\phi$ helicity angle)

- $N_{\text{sig}} = 91^{+14}_{-13}$

Three signal peaks ($B_s B_s, B_s^* B_s, B_s^* B_s^*$)

$B_s \rightarrow \phi \gamma = (36 \pm 5(\text{stat.}) \pm 3(\text{syst.}) \pm 6(f_s)) \times 10^{-6}$

(10.7$\sigma$ significance including systematics)

Consistent with theoretical prediction and LHCb result.

$f_s = (17.2 \pm 3.0)\%$

$f_{B_s^* B_s^*} = (87.0 \pm 1.7)\%$

$f_{B_s^* B_s} = (7.3 \pm 1.4)\%$
Result of $B_s \rightarrow \gamma\gamma$

- 2-dimensional fit ($M_{bc}, \Delta E$)
- Dominant backgrounds of continuum ($ee \rightarrow qq$ ($q = u, d, s, c$)) are suppressed by neural network output
  - Modified Fox-Wolfram moments and thrust angle are used.

Upper Limits

$\mathcal{B}(B_s \rightarrow \gamma\gamma) < 3.1 \times 10^{-6}$ @ 90% C.L.
\[ A_{CP}(B \rightarrow X_{s+d}\gamma) = \frac{\Gamma(\bar{B} \rightarrow X_{s+d}\gamma) - \Gamma(B \rightarrow X_{s+d}\gamma)}{\Gamma(\bar{B} \rightarrow X_{s+d}\gamma) + \Gamma(B \rightarrow X_{s+d}\gamma)} \]

- Cancellation due to CKM unitarity,
- Negligible theory error

### Inclusive analysis

- Only reconstruct photon and charged lepton for tagging.
  - \( 1.7 < E_{\gamma}^* < 2.8 \) GeV
  - \( 1.10 < p_{l}^* < 2.25 \) GeV/c

\[ A_{CP} = \frac{N^+ - N^-}{N^+ + N^-} \] (using tag-lepton)

<table>
<thead>
<tr>
<th>channel</th>
<th>( A_{CP}(SM) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B \rightarrow X_{s}\gamma )</td>
<td>[−0.6%, +2.8%]</td>
</tr>
<tr>
<td>( B \rightarrow X_{d}\gamma )</td>
<td>[−62%, +14%]</td>
</tr>
<tr>
<td>( B \rightarrow X_{s+d}\gamma )</td>
<td>0</td>
</tr>
</tbody>
</table>

@ PRL 106, 141801 (2011)
Wrong Tag Fraction and Corrections

- Measured $A_{CP}^{\text{meas}}$ is corrected for various effects.

$$A_{CP}^{\text{true}} = \frac{1}{1 - 2w} (A_{CP}^{\text{meas}} - A_{\text{bkg}} - A_{\text{det}})$$

1. **Wrong tag factor**: $w = 0.1332 \pm 0.0052$
   - $B\bar{B}$ mixing
   - lepton from $D$ decays
   - $K/\pi$ miss-identified as lepton

2. **Asymmetry from detector**: $A_{\text{det}} = (0.10 \pm 0.22)\%$
   - Lepton ID, tracking

3. **Asymmetry from $BB$ bkg**: $A_{\text{bkg}} = (-0.14 \pm 0.78)\%$
   - Low $E_\gamma$ region ($E_\gamma < 1.7$ GeV) in data
• Measure as function of $E_\gamma$ threshold.

\[ A_{CP}(B \to X_{s+d}\gamma) = (2.23 \pm 4.02 \pm 0.78)\% \text{ with } E_\gamma^* > 2.1 \text{ GeV} \]

- Consistent with SM.
- Most precise measurement of $A_{CP}(B \to X_{s+d}\gamma)$.
-Statistically dominated
- Leading systematic comes from BB bkg asymmetry
Summary

- Various $B$ decays are sensitive to new physics.
  - New particles such as SUSY particles might enter in the loop diagrams.
  - Charged Higgs might contribute in addition to the W boson.

1. $B \to D^{(*)}\tau\nu$ with hadronic tag (arXiv:1507.03233, submitted to PRD)
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3. $B_s \to \phi\gamma, \gamma\gamma$ (PRD 91, 011101(R)(2015))
4. $A_{CP}(B \to X_{s+d}\gamma)$ (PRL 114, 151601 (2015))

- There are many SUSY-related results not covered in this talk an a lot of ongoing analysis.
Backup
$B \rightarrow D^{(*)}\tau\nu$ with Hadronic Tag

- Neurobayes input
  - $M_{\text{miss}}^2$
  - $E_{\text{ECL}}$
  - $q^2, p^C_M$
  - # of unused $\pi^0$ with $|S_{\gamma\gamma}| < 5$
  - Angle between $D^{(*)}$ momentum and vertex direction
  - $B/D^{(*)}$ decay channel identifiers
$B \rightarrow D^{(*)}\tau\nu$ with Hadronic Tag

$q^2$ distributions in SM and in 2HDM type-II

$B \rightarrow D^{(*)}\tau\nu$ Hadronic tagging

SM $B \rightarrow D\tau\nu$: $p=64\%$

NP $B \rightarrow D\tau\nu$: $p=53\%$

SM $B \rightarrow D^*\tau\nu$: $p=11\%$

NP $B \rightarrow D^*\tau\nu$: $p=49\%$
$B \to D^{(*)}\tau\nu$ with Hadronic Tag

<table>
<thead>
<tr>
<th></th>
<th>$R[%]$</th>
<th>$R^*[%]$</th>
<th>correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{(*)}\tau\nu$ shapes</td>
<td>4.2</td>
<td>1.5</td>
<td>0.04</td>
</tr>
<tr>
<td>$D^{**}$ composition</td>
<td>1.3</td>
<td>3.0</td>
<td>-0.63</td>
</tr>
<tr>
<td>wrong charge factor</td>
<td>0.0</td>
<td>0.0</td>
<td>0.84</td>
</tr>
<tr>
<td>$Y_{D+\ell^-D}$</td>
<td>0.1</td>
<td>0.0</td>
<td>-0.95</td>
</tr>
<tr>
<td>$Y_{D^+\ell^-\text{rest}}$</td>
<td>0.1</td>
<td>0.0</td>
<td>-0.92</td>
</tr>
<tr>
<td>$Y_{D+\ell^-\text{wrong}D}$</td>
<td>0.4</td>
<td>0.1</td>
<td>-0.99</td>
</tr>
<tr>
<td>$Y_{D^+\ell^-\text{wrong}D}$</td>
<td>0.3</td>
<td>0.1</td>
<td>-0.99</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-D}$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.81</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{rest}}$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.60</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{wrong}D}$</td>
<td>0.3</td>
<td>0.2</td>
<td>0.96</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{wrong}D}$</td>
<td>0.2</td>
<td>0.1</td>
<td>0.98</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{wrong}D}$</td>
<td>0.1</td>
<td>0.1</td>
<td>-1.00</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{rest}}$</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.99</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{wrong}D}$</td>
<td>0.3</td>
<td>0.2</td>
<td>0.96</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{wrong}D}$</td>
<td>0.1</td>
<td>0.2</td>
<td>-1.00</td>
</tr>
<tr>
<td>$Y_{D^0\ell^-\text{wrong}D}$</td>
<td>0.1</td>
<td>0.1</td>
<td>-0.83</td>
</tr>
<tr>
<td>$Y_{D^{0}\ell^-\text{wrong}D}$</td>
<td>0.1</td>
<td>0.2</td>
<td>-1.00</td>
</tr>
<tr>
<td>$B^0$</td>
<td>2.2</td>
<td>2.0</td>
<td>-1.00</td>
</tr>
<tr>
<td>$g_{B^0}$</td>
<td>1.7</td>
<td>1.0</td>
<td>-1.00</td>
</tr>
<tr>
<td>$f_{R,B^0}$</td>
<td>2.5</td>
<td>0.7</td>
<td>-0.98</td>
</tr>
<tr>
<td>$f_{R,B^+}$</td>
<td>1.8</td>
<td>0.4</td>
<td>0.86</td>
</tr>
<tr>
<td>$f_{R,B^0}$</td>
<td>1.3</td>
<td>2.5</td>
<td>-0.99</td>
</tr>
<tr>
<td>$f_{R,B^0}$</td>
<td>0.7</td>
<td>1.1</td>
<td>0.94</td>
</tr>
<tr>
<td>$M_{miss \text{ shape}}$</td>
<td>0.6</td>
<td>1.0</td>
<td>0.00</td>
</tr>
<tr>
<td>$\sigma_{\text{NB,trafo shape}}$</td>
<td>3.2</td>
<td>0.8</td>
<td>0.00</td>
</tr>
<tr>
<td>lepton PID efficiency</td>
<td>0.5</td>
<td>0.5</td>
<td>1.00</td>
</tr>
</tbody>
</table>

$\Sigma$ | 7.1     | 5.2       | -0.32       |

state | uncertainty in % |
----------|------------------|
$D_2^*$ | 42.3             |
$D_0^*$ | 34.6             |
$D_1$  | 14.9             |
$D_1'$ | 36.2             |
$D(2S)$ | 100.0            |
$D^*(2S)$ | 100.0            |
$B \rightarrow D^{(*)}\tau\nu$
$B \rightarrow D^{(*)}\tau\nu$

$\Delta \chi^2 = 1.0$

$P(\chi^2) = 55\%$

SM prediction
$B \rightarrow \pi \tau \nu$ with Hadronic Tag

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$13.2 \pm 6.2$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>$30.6 \pm 14.3$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$8.1 \pm 3.8$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$51.9 \pm 24.3$</strong></td>
</tr>
</tbody>
</table>

| systematic | $\sigma$ | $\Delta \sigma = \sigma_{\text{none}} - \sigma_{\text{syst}}$ | $|\Delta \sigma| [\%]$ |
|------------|---------|--------------------------------|----------------|
| none       | 2.74    |                                    |                |
| eID        | 2.69    | $-0.05$                          | 1.81           |
| $\pi$ ID   | 2.55    | $-0.19$                          | 6.87           |
| $\pi^0$ ID | 2.67    | $-0.07$                          | 2.47           |
| slow $\pi^0$ | 2.77   | $+0.03$                          | 1.22           |
| $K_L$ veto | 2.68    | $-0.06$                          | 2.15           |
| track efficiency | 2.60 | $-0.14$                          | 5.11           |
| slow tracks | 2.48 | $-0.25$                          | 9.25           |
| finite MC   | 2.43    | $-0.31$                          | 11.31          |
| background fit | 2.46 | $-0.28$                          | 10.22          |
| BG $B$      | 2.43    | $-0.30$                          | 11.13          |
| $V_{ub}$    | 2.51    | $-0.22$                          | 8.22           |
| signal model | 2.54  | $-0.20$                          | 7.33           |
| $D^{(*)}\ell\nu$ model | 2.60 | $-0.14$                          | 5.11           |
| tagside    | 2.57    | $-0.17$                          | 6.14           |
| $B \rightarrow X_u \tau \nu$ | 2.60 | $-0.13$                          | 4.84           |

$\sqrt{\sum (\Delta \sigma)^2} = 0.74$ 27.18