Hot topic at Belle and Belle II: \( \tau \) physics

Jim Libby on behalf of Belle and Belle II

Indian Institute of Technology Madras
Outline

1. Not the only hot topic
   • a trailer for other Belle and Belle II talks
2. Why τ physics? Why Belle and Belle II?
3. Recent results
   1. Beyond-the-standard-model physics: lepton-flavour violation
   2. Precision measurement: τ mass
4. More to come: a further trailer

28/11/2023
1) Belle (II)@HQL

Seven other talks with physics results – hot topics for all!

1. Wed. 12:10: **LFU tests and searches for new physics in charged current decays at Belle II** – Henrik Junkerkalefeld
2. Wed, 15:00: **Recent spectroscopy results from Belle II** – Renu Garg
3. Wed. 17:20: **New LFV results from e^+e^- colliders** – Devendar Kumar
4. Fri. 10:10: **Rare decays from Belle and Belle II** - Seema Choudhuri
5. Fri. 12:00: **Time-dependent CP violation in B^0 decay** - Seema Bahinipati
6. Sat. 09:30: **Search for B→K_{inv} decay** – Roberta Volpe
7. Sat. 10.35: **CP violation in charmless B decays** – Luka Santlej
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But all heavy quarks.....what about the heavy leptons?
2) Why $\tau$? Why Belle (II)?
Tau physics motivation I

- 185 standard model decay modes studied
  - principally hadronic final states
- Unique laboratory to study weak interaction

Any observation of lepton flavour violation in $\tau \rightarrow 3\mu$, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow l\phi$ etc.

SM highly suppressed

Connections to $g-2$ and lepton universality violation in $b$ decay
Tau physics motivation I

• 185 standard model decay modes studied
  • principally hadronic final states
• Unique laboratory to study weak interaction
• Third-generation therefore beyond-SM-sensitivity anticipated
  • Any observation of lepton-flavour violation in $\tau \rightarrow 3\mu$, $\tau \rightarrow \mu \gamma$, $\tau \rightarrow l\phi$ etc new physics
  • SM highly suppressed
• Connections to $g-2$ and lepton universality violation in $b$ decay
Tau physics motivation II

• **Precision measurements** of the $\tau$ lepton can have significant impact
Tau physics motivation II

- **Precision measurements** of the $\tau$ lepton can have significant impact

- **Example:**
  - first row unitarity of CKM matrix – ‘Cabibbo angle anomaly’
  - $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint
Tau physics motivation II

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  - first row unitarity of CKM matrix – ‘Cabibbo angle anomaly’
  - $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint
- Additionally, lepton-flavour universality and dipole moments
- **Mass** and lifetime important inputs to these calculations
Why $\tau$ physics at the $\Upsilon(4S)$?

- The centre-of-mass energy of the B factories process $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ has comparable cross section to $e^+e^- \rightarrow q\bar{q}$, $q = u, d, s, c$ a.k.a. continuum.

- Similar cross section for $e^+e^- \rightarrow \tau^+\tau^-$

- $920$ million tau pairs per $ab^{-1}$ of integrated luminosity

- A HQL-factory!
Why $\tau$ physics at the Y(4S)?

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- Similar cross section for $e^+e^- \rightarrow \tau^+\tau^-$
- 920 million tau pairs per ab$^{-1}$ of integrated luminosity
- A HQL-factory!

Non Bhabha cross section in nb

- $e^+e^- \rightarrow \tau^+\tau^-$
- $e^+e^- \rightarrow u\bar{u}$
- $e^+e^- \rightarrow d\bar{d}$
- $e^+e^- \rightarrow s\bar{s}$
- $e^+e^- \rightarrow c\bar{c}$
- $e^+e^- \rightarrow B\bar{B}$

$e^+e^- \rightarrow \gamma\gamma$
Detectors and data samples

- Belle: \( \sim 1 \text{ ab}^{-1} \)
  - Many achievements:
    - Confirmation of KM mechanism,
    - \( b \rightarrow c \tau v \), direct CPV in B decay

- SuperKEKB + Belle II
  - Nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-\( \text{ab}^{-1} \) sample
  - World record: \( 4.7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)
  - Target: \( 6 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1} \)
  - So far: \( 424 \text{ fb}^{-2} \)
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How to reconstruct a $\tau$ lepton at Belle (II)

- Missing energy from neutrinos does not allow full reconstruction
  - Identify using the thrust axis $\vec{n}_{th}$
    - maximizes the momentum projection
  - Divide event into two hemispheres
- Signal side
  - e.g. $\tau \rightarrow \nu +$ hadrons
- Tag side: a standard model decay
  - single prong: $\tau \rightarrow l\nu \nu$ or $\tau \rightarrow \pi \nu + n\pi^0$
  - three prong decay: $\tau \rightarrow 3\pi \nu + n\pi^0$
Performance for $\tau$ lepton physics

Electron ID: efficiency and mis-ID
Performance for $\tau$ lepton physics

Electron ID: efficiency and mis-ID

L1: trigger for 1x1 tau pairs (min $p_T$)
3.1) Lepton-flavour violating searches
**LFV: \( \tau \rightarrow lV^0 \) \((V^0=\rho, \omega, \phi, K)\)**

- Forbidden in SM but enhanced many leptoquark models, c.f., R(D(*))

- \( V^0=\rho, \omega, \phi, K \)
- Full data set of 980 fb\(^{-1}\)
- 3 and 1 prong tag: \(3\pi\nu, l\nu\nu, \pi\nu+u\)p to \(2\pi^0\)
- Background suppression with BDT
- **JHEP 06 (2023) 118**

High efficiency key for best sensitivity: multivariate selection and inclusive tagging

- \( V^0=\phi \)
- Data set of 190 fb\(^{-1}\)
- **Inclusive tag**
- Background suppression with BDT
- **arXiv:2305.04759**
LFV: Belle $\tau \rightarrow lV^0$ ($V^0=\rho, \omega, \phi, K^*$) approach

- Tagged with 1-prong or 3-prong decay
- Background from $\tau \rightarrow 3\pi\nu$ and $ee \rightarrow qq$ suppressed with a boosted decision tree (BDT)
- Prepared separate BDT classifier for each $lV^0$ mode

$$\Delta E = (E_{lV^0}^{CM} - \sqrt{s}/2)$$

- $\tau \rightarrow e\rho^0$
- $\tau \rightarrow \mu\rho^0$

Signal region (SR)
LFV: Belle $\tau \rightarrow lV^0$ ($V^0=\rho$, $\omega$, $\phi$, $K^*$) results

No significant excess in all $\ell V^0$ modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}$</th>
<th>$\sigma_{syst}$ (%)</th>
<th>$N_{obs}$</th>
<th>$B_{obs} \times 10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm \rho^0$</td>
<td>7.78</td>
<td>0.95±0.20(stat.) ±0.15(syst.)</td>
<td>4.6</td>
<td>0</td>
<td>&lt; 1.7</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow e^\pm \rho^0$</td>
<td>8.49</td>
<td>0.80±0.27(stat.) ±0.04(syst.)</td>
<td>4.4</td>
<td>1</td>
<td>&lt; 2.2</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm \phi$</td>
<td>5.59</td>
<td>0.47±0.15(stat.) ±0.05(syst.)</td>
<td>4.8</td>
<td>0</td>
<td>&lt; 2.3 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow e^\pm \phi$</td>
<td>6.45</td>
<td>0.38±0.21(stat.) ±0.00(syst.)</td>
<td>4.5</td>
<td>0</td>
<td>&lt; 2.0 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm \omega$</td>
<td>3.27</td>
<td>0.32±0.23(stat.) ±0.19(syst.)</td>
<td>4.8</td>
<td>0</td>
<td>&lt; 3.9 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow e^\pm \omega$</td>
<td>5.14</td>
<td>0.74±0.43(stat.) ±0.06(syst.)</td>
<td>4.5</td>
<td>0</td>
<td>&lt; 2.4 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm K^{*0}$</td>
<td>4.52</td>
<td>0.84±0.25(stat.) ±0.31(syst.)</td>
<td>4.3</td>
<td>0</td>
<td>&lt; 2.9 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow e^\pm K^{*0}$</td>
<td>6.94</td>
<td>0.54±0.21(stat.) ±0.16(syst.)</td>
<td>4.1</td>
<td>0</td>
<td>&lt; 1.9 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow \mu^\pm K^{*0}$</td>
<td>4.58</td>
<td>0.58±0.17(stat.) ±0.12(syst.)</td>
<td>4.3</td>
<td>1</td>
<td>&lt; 4.3 $*$</td>
</tr>
<tr>
<td>$\tau^\pm \rightarrow e^\pm K^{*0}$</td>
<td>7.45</td>
<td>0.25±0.11(stat.) ±0.02(syst.)</td>
<td>4.1</td>
<td>0</td>
<td>&lt; 1.7 $*$</td>
</tr>
</tbody>
</table>

World leading results

Counting method 90% confidence levels

30% improvement over previous measurements

28/11/2023
LFV: Belle II $\tau \rightarrow l\phi$ approach

- Untagged: train BDT inclusively to discriminate from background
  - event shape variables, signal kinematics, $\phi$ mass and rest-of-the-event, i.e., tracks and clusters not used to reconstruct signal
  - 6% efficiency – twice Belle
LFV: Belle II $\tau \rightarrow l\phi$ results

Not competitive with the Belle results
But first application of the inclusive tag

Obs. $B_{UL}(\tau \rightarrow e\phi) = 23 \times 10^{-8}$
Exp. $B_{UL}(\tau \rightarrow e\phi) = 15 \times 10^{-8}$

Obs. $B_{UL}(\tau \rightarrow \mu\phi) = 9.7 \times 10^{-8}$
Exp. $B_{UL}(\tau \rightarrow \mu\phi) = 9.9 \times 10^{-8}$
LFV: Belle II $\tau \rightarrow l\alpha$ motivation

- $\alpha$ is a non-detected (invisible) particle
  - e.g., an axion-like particle (ALP)
- Interesting mass range from 100 MeV-1.6 GeV not covered by other searches
- Previous limits from ARGUS (1995) – $10^{-2}$ to $10^{-3}$ with masses from zero to 1.6 GeV
  - Only 0.5 fb$^{-1}$ of data
LFV: Belle II $\tau \to l\alpha$ approach

• Using 63 fb$^{-1}$ of data
• Tag with $\tau \to 3\pi\nu$ with $\pi^0$ veto
• Background from $\tau \to l\nu\nu$
  • Use difference in two-body (signal) and three-body kinematics (background) to isolate signal
• Workout lepton momentum in **pseudo tau rest frame**
  • Assume signal direction opposite $3\pi$ direction and tau energy is $\sqrt{s}/2$
LFV: Belle II $\tau \rightarrow l\alpha$ signal extraction

- Use $x_l = \frac{2E_l^*/m_\tau}{\tau}$ where lepton energy is in pseudo rest frame
  - signal would be monochromatic in rest frame – broaden by the approximations

- Simulation derived templates fit for different $\alpha$ mass hypotheses

\[ \tau \rightarrow ea \text{ search} \quad \tau \rightarrow \mu\alpha \text{ search} \]
LFV: Belle II $\tau \rightarrow l\alpha$ signal results

- 95% C.L. branching fraction limits for $M_\alpha$ from 0 to 1.6 GeV
- 2 to 14 times more stringent than ARGUS

$\tau \rightarrow \alpha e$ search

$\tau \rightarrow \alpha \mu$ search

$\int L \ dt = 62.8 \text{ fb}^{-1}$
“Ali’s weight was announced as 206 pounds. He had not been so low in years: 216 pounds came through as the correction. A miscalculation of the kilos. A whistle from the press. He was four to eight pounds heavier than he said he would be, a poor prospect for his ability to dance and run”, *The Fight*, Norman Mailer

3.2) Heavyweight weigh-in: $\tau$ mass measurement:
τ mass measurement

- Fundamental parameter of the standard model
- Important input to lepton-flavour-universality tests

\[ R_e = \frac{B[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}{B[\mu^- \to e^- \bar{\nu}_e \nu_\mu]} \left( \frac{g_\tau}{g_\mu} \right)_e = \sqrt{R_e \frac{\tau_\mu m_\mu^3}{\tau_\tau m_\tau^3} (1 + \delta_W)(1 + \delta_\gamma)} \]

(δs are radiative corrections)
**τ mass measurement**

- Fundamental parameter of the standard model
  - Important input to lepton-flavour-universality tests

\[
R_e = \frac{B[\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau]}{B[\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu]} \left( \frac{g_\tau}{g_\mu} \right)_e = \sqrt{R_e \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^3}{m_\tau^3} (1 + \delta_W)(1 + \delta_\gamma)}
\]

(δs are radiative corrections)

- We use the pseudomass variable to determine mass

\[
M_{\text{min}} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau
\]
\( \tau \) mass measurement

\[
M_{\text{min}} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau
\]

- Fit to distribution with analytic form that accounts for ISR and resolution
## Tau Mass Measurement

The mass of the tau particle, $\tau$, can be measured through the following equation:

$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_{\tau}$$

- **Fit to distribution with analytic form that accounts for ISR/FSR and resolution**
- **Knowing the scale key:**
  - beam energy (from $E_B^*$) and
  - momentum (from D mass)
τ mass measurement

World’s most precise measurement to date
- dominant systematics from beam energy and momentum scale
5) Prospects and conclusion
Belle II: after current shutdown

• We have not collected the sample size planned to date
  • Beam conditions

• Since summer 2022 shutdown for accelerator upgrades to mitigate background and increase luminosity

• Detector upgrades too
  • two-layer pixel detector installed

• Restart of SuperKEKB in January

• Path to $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ but new final focus to go beyond

• Proposed upgrade from 2027
  • Wed 18:00: Belle II upgrade programme – Peter Lewis
More results coming v. soon
Conclusion

• Belle and Belle II will be leading the way in investigating properties of the tau lepton
  • Searches for beyond-the-SM physics
  • Precision measurements of tau properties and SM parameters
• A lot more to come once we enter the “10^{35} era”
• Upgrade plans for reaching the 10s of ab$^{-1}$