Tau physics program at Belle II

Alberto Martini
DESY (Deutsches Elektronen-Synchrotron)
On behalf of the Belle II collaboration

IPA2022: Interplay between Particle and Astroparticle physics 2022, 5-9 Sep 2022, Wien
Belle II: new generation of B-factory experiment
(talk given by Alan Schwarz on 6 Sep.)

Belle II will collect the world’s largest sample of $\tau$-pair events

**Advantages of studying $\tau$ physics at Belle II:**
- $\tau$ produced in pairs
- Well defined initial state energy
- Clean environment wrt hadronic collider-based experiments
- High hermeticity of the detector

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(4S)$</td>
<td>1.05</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.919</td>
</tr>
</tbody>
</table>

B-factories are also $\tau$-factories!
Introduction on \( \tau \) physics at Belle II

Belle II: new generation of B-factory experiment
(talk given by Alan Schwarz on 6 Sep.)

Belle II will collect the world’s largest sample of \( \tau \)-pair events

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Upsilon(4S) )</td>
<td>1.05</td>
</tr>
<tr>
<td>( \tau^+\tau^- )</td>
<td>0.919</td>
</tr>
</tbody>
</table>

Advantages of studying \( \tau \) physics at Belle II:
- \( \tau \) produced in pairs
- Well defined initial state energy
- Clean environment wrt hadronic collider-based experiments
- High hermeticity of the detector

B-factories are also \( \tau \)-factories!

Tau Physics program at Belle II is rich \( \rightarrow \) high precision measurements (★→ discussed in next slides)

Lifetime ★
Mass ★
\( \tau \rightarrow l\alpha \) ★
LFV channels ★
LFUV channels ★
Vus measurement ★
EDM measurement ★
CP channel: \( \tau \rightarrow K_{S}\pi\nu \)

Test of the SM

Direct New Physics (NP) searches

...
Main $\tau$ topologies @Belle II

BF of $\tau$ decays:

- 1-prong: 35.2% leptonic, 49.5% hadronic
- 3-prong: 15.2% hadronic
Main $\tau$ topologies @Belle II

BF of $\tau$ decays:
- 1-prong: 35.2% leptonic, 49.5% hadronic
- 3-prong: 15.2% hadronic

Each decay mode has its own experimental challenge:
- Large missing energy in leptonic modes
- Low multiplicity bkg for 1x1 topology
- $\pi^0/\gamma$ in the final state $\rightarrow$ large $q\bar{q}$ bkg
- Highly efficient trigger system against low multiplicity channels (for example ee $\rightarrow$ ee, $\gamma\gamma$, eell)
Triggers for $\tau$ @Belle II

2 trigger categories:
EM calorimeter (ECL) and drift chamber triggers

Belle II advantages wrt Belle and BaBar: several low multiplicity triggers based on number of calorimetric clusters
Triggers for $\tau$ @Belle II

2 trigger categories:
EM calorimeter (ECL) and drift chamber triggers

Belle II advantages wrt Belle and BaBar: several low multiplicity triggers based on number of calorimetric clusters

---

**Logical OR of all available lml triggers**

- High efficiency also for the 1x1 topology!
Lepton Flavor Violation (LFV) is allowed in various extensions of the SM but it has never been observed.
Lepton Flavour Violation (LFV) is allowed in various extensions of the SM but it has never been observed.

- $\tau \rightarrow \ell\ell\ell$
- $\tau \rightarrow \ell K_s, \Lambda h$
- $\tau \rightarrow \ell V_0 (\rightarrow hh')$
- $\tau \rightarrow \ell P^0 (\rightarrow \gamma\gamma)$
- $\tau \rightarrow \ell hh'$
- $\tau \rightarrow \ell \gamma$
- $\ldots$
- $\tau \rightarrow l + \text{invisible}$

Large irreducible bkgs $\rightarrow$ next slides
Search for LFV two-body decay $\tau \rightarrow l + \alpha$ ($l = e, \mu$)

$\alpha$ is an invisible gauge boson that can be predicted by several NP models $\rightarrow$ LFV $Z'$, **light ALP candidate**, more..
**τ → lα motivation**

Search for LFV two-body decay $\tau \rightarrow l + \alpha$ ($l = e, \mu$)

$\alpha$ is an invisible gauge boson that can be predicted by several NP models → LFV $Z'$, light ALP candidate, more..

Best upper limits on $B(\tau \rightarrow l\alpha)/B(\tau \rightarrow l\nu\bar{\nu})$

from ARGUS (1995, 476 pb$^{-1}$)

Can Belle II do better?

**Light ALP: JHEP 09 (2021) 173**

- MEGII-bin (F=100)
- MEGII-bin (F=1)
- Mu3e-online
- W.D.
- RG cooling
- SN1987A$_{en}$
- SN1987A$_{\mu\nu}$

Can Belle II do better?

\[ \tau \rightarrow l\alpha \] analysis status

ARGUS analysis approach is adopted \textarrow{\rightarrow} definition of pseudo-rest (ps) frame

- Tag side: \[ \tau \rightarrow 3\pi\nu_{\tau} \]
- Pseudo-rest frame implies:
  - \[ \vec{P}_{\tau} \sim -\vec{P}_{3\pi} \]
  - \[ E_{\tau} \sim \sqrt{s}/2 \]
- Veto neutrals: \[ \pi^0, \gamma \]
- Selection optimised on \[ \tau \rightarrow l\nu\bar{\nu}_{\tau} \] as irreducible background

Signal signature: bump in the lepton \[ p_{ps} \] distribution
**τ → lα results**

95% C.L. upper limits using the CLs method → no significant excess in 62.8 fb\(^{-1}\) of data (2019-20)

Ref: ICHEP talk

\[ R_{e\alpha} < (1.2 - 9.8) \times 10^{-3} \]

Best measurement today

\[ R_{\mu\alpha} < (0.8 - 12.6) \times 10^{-3} \]
Lepton Flavour Violation: golden channels

First golden channel: $\tau \rightarrow \mu \gamma$
as the Highest non-SM BF contribution

Decay scheme

e/\mu \quad \text{sig} \quad \tau \quad \tau \quad \text{tag} \quad 1\text{prong}

Experimentally tough: Irreducible physics backgrounds + large uncertainty in mass and energy determination

Lepton Flavour Violation: golden channels

First golden channel: $\tau \rightarrow \mu \gamma$

as the Highest non-SM BF contribution

nuSM

SUSY

Irreducible physics backgrounds + large uncertainty in mass and energy determination

Second golden channel: $\tau \rightarrow \mu \mu \mu$

experimentally the most accessible

Little Higgs mediated

Z’ mediated

Belle II can probe these NP models using 50 ab$^{-1}$

Decay scheme

<table>
<thead>
<tr>
<th>Physics models</th>
<th>$B(\tau \rightarrow \mu \gamma)$</th>
<th>$B(\tau \rightarrow \mu \mu \mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM + $\nu$ mixing</td>
<td>$10^{-49} \sim 10^{-52}$</td>
<td>$10^{-53} \sim 10^{-56}$ [1]</td>
</tr>
<tr>
<td>SM+heavy Majorana $\nu_R$</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-universal Z’</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>$10^{-8}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>mSUGRA + seesaw</td>
<td>$10^{-7}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
</table>

Ref: M. Blanke, et al., Charged Lepton Flavour Violation and $(g - 2)_{\mu}$ in the Littlest Higgs Model with T-Parity: a clear Distinction from Supersymmetry, JHEP 0705, 013 (2007).
τ→3µ Lepton Flavour Violation

Best upper limits on τ→3µ from Belle: $2.1 \times 10^{-8}$ @90% CL: $\int L dt = 782 fb^{-1}$

Closed signal side kinematics

- No physical backgrounds
- Tight signal region → large background reduction
  using $\Delta E_{3\mu} \equiv E_{\tau\text{sig}} - E_{\text{beam}}$ and $\tau_{3\mu}$ mass

Belle II 2020 (preliminary)

Simulation: $\tau \rightarrow 3\mu$ ($10^4$ events)
**τ→3µ Lepton Flavour Violation**

Best upper limits on $\tau\rightarrow 3\mu$ from Belle: $2.1 \times 10^{-8}$ @90% CL: \[ Ldt = 782 fb^{-1} \]

Closed signal side kinematics
- No physical backgrounds
- Tight signal region $\rightarrow$ large background reduction

using $\Delta E_{3\mu} \equiv E_{\tau} - E_{\mu}$ and $\tau_{3\mu}$ mass

**Proposed analysis improvement:**
3 muons in the event $\rightarrow$ muon identification (muonID) optimised as a function of the track momentum

Analysis first hints (based on MC only):
- 0 events surviving the selection
- x2 efficiency gain wrt Babar

The Belle II experiment will be already competitive with the current dataset of $\sim 400$ fb$^{-1}$ $\rightarrow$ analysis is ongoing!
Lepton Flavour Universality violation

Lepton Flavour Universality (LFU) requires that the coupling between the three charged leptons and W boson is the same

ref: https://indico.belle2.org/event/4615/contributions/22866/attachments/12010/18311/Mini-Workshop.pdf
Lepton Flavour Universality (LFU) requires that the coupling between the three charged leptons and W boson is the same.

Several NP models can explain the anomaly: W', Modified W/ν couplings, Z', Singly-Charged Scalar ...

\[
\begin{align*}
\frac{A_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{A_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} &= 1.0029 \pm 0.0014 \\
\frac{A_{\text{EXP}}(\tau \rightarrow \mu \nu \bar{\nu})}{A_{\text{SM}}(\tau \rightarrow e \nu \bar{\nu})} &= 1.0018 \pm 0.0014 \\
\frac{A_{\text{EXP}}(\tau \rightarrow e \nu \bar{\nu})}{A_{\text{SM}}(\mu \rightarrow e \nu \bar{\nu})} &= 1.0010 \pm 0.0014
\end{align*}
\]
The $\tau \rightarrow l\nu\nu$ LFU at Belle II

Best result from Babar (467 fb$^{-1}$):
$R_\mu = 0.9796 \pm 0.0016 \text{ (stat)} \pm 0.0036 \text{ (sys)}$

Cut based analysis @Belle II → efficiency ~4x larger than Babar with better purities!

$\tau \rightarrow e\nu\bar{\nu}$ channel

- BABAR
  PhysRevLett.105.051602
- Belle II
  - Likelihood LID
  - BDT LID
  - w/ BABAR tag
The $\tau \rightarrow l \nu \nu$ LFU at Belle II

Best result from Babar (467 fb$^{-1}$):
$R_\mu = 0.9796 \pm 0.0016$ (stat) $\pm 0.0036$ (sys)

Cut based analysis @Belle II $\rightarrow$ efficiency $\sim$4x larger than Babar with better purities!

Belle II simulation

Under development

Belle II relies on BDT and NN approaches $\rightarrow$ already shows compatible statistical precision wrt CLEO

Under development

Best result from Babar (467 fb$^{-1}$):
$R_\mu = 0.9796 \pm 0.0016$ (stat) $\pm 0.0036$ (sys)
Direct standard model probes

\( \tau \) mass and lifetime are crucial measurements for lepton flavour universality (LFU) tests of the SM:

\[
B_{\tau \ell}^{SM} = B_{\mu e} \left( \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5} \right) \left( \frac{f_{\tau \ell}}{f_{\mu e}} \right) \left( \frac{r_W^{\tau \gamma}}{r_W^{\mu \gamma}} \right)
\]

arXiv:1804.08436
**Direct standard model probes: $\tau$ lifetime**

$\tau$ mass and lifetime are crucial measurements for lepton flavour universality (LFU) tests of the SM:

$$B^\text{SM}_{\tau\ell} = B_{\mu\ell} \left\{ \frac{\tau}{\tau} \frac{m_\tau^5}{m_\ell^5} f_{\tau\ell} \frac{r^T_W r^T_\gamma}{r^T_W r^T_\gamma} \right\}$$

**arXiv:1804.08436**

**Tau lifetime analysis strategy at Belle II:**

- Reconstruct 3x1 topology
- $\tau$ vertex constrained to the IP
- $\tau$ travelled distance from IP $\rightarrow$ lifetime

Decay-time resolution is 2x better than Belle

Early stage analysis

$\sigma^\text{b} < 1 \mu m$
Measure $m_\tau$ using 3-prong decay → pseudo mass method developed by ARGUS

$$M_{\min} \equiv \sqrt{m_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - |p_{3\pi}|)} \leq m_\tau$$

Ref: https://doi.org/10.1016/0370-2693(92)90634-G

$m_\tau = 1777.28 \pm 0.75(\text{stat.}) \pm 0.33(\text{syst.})\text{MeV}/c^2$

Conclusions

• Various \( \tau \)-based searches are ongoing at Belle II

• Highly efficient trigger system allows to produce competitive analysis in an early stage

• Overview of some of the analyses is presented:
  
  • Search for \( \tau \rightarrow l\alpha \) offers world-best constraint!
    
    • Results no significant deviation/excess wrt the SM
    
    • Measurement of tau mass likely to be already competitive with current Belle II data set
  
  • LFUV, LFV and \( \tau \) lifetime analysis are underway with very promising perspectives

• With the current collected data sample Belle II is able to provide world leading results

Thank you
Emergency slides!!
Triggers for $\tau$ @Belle II

2 trigger categories:
EM calorimeter (ECL) and drift chamber triggers

Advantages at Belle II: several low multiplicity triggers based on number of calorimetric clusters

$e^+ e^- \rightarrow \tau^+ (\rightarrow \mu^+ \nu \bar{\nu}) \tau^- (\rightarrow \mu^- \nu \bar{\nu})$

Logical OR of all available lml triggers

High efficiency also for the 1x1 topology!
The $\tau \rightarrow l\nu\nu$ LFU at Belle II: 3x1 topology

Cut based analysis @Belle II → efficiency ~4x larger than Babar with better purities!

Improvements @Belle II:
- Trigger performances: data-MC model at few% level (preliminary studies)
- Better Lepton ID (LID) data-MC model: usage of likelihood and BDT based algorithms

Main systematics:

<table>
<thead>
<tr>
<th>Systematic uncertainties:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle ID</td>
<td>0.32</td>
</tr>
<tr>
<td>Detector response</td>
<td>0.08</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.08</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.10</td>
</tr>
<tr>
<td>$\pi^-\pi^-\pi^+$ modelling</td>
<td>0.01</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.04</td>
</tr>
<tr>
<td>$B(\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau)$</td>
<td>0.05</td>
</tr>
<tr>
<td>$\mathcal{L}e^+e^- \rightarrow \tau^+\tau^-$</td>
<td>0.02</td>
</tr>
<tr>
<td>Total [%]</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Best result from Babar (467 fb$^{-1}$):
$R_\mu = 0.9796 \pm 0.0016$ (stat) $\pm 0.0036$ (sys)

Under development
The $\tau \to l \nu \nu$ LFU at Belle II: 1x1 topology

Best results from CLEO using 3.56 fb-1
ref: inspirehep

Never studied by Belle/Babar due to trigger unavailability

Belle II relies on BDT and NN approaches → already shows compatible statistical precision wrt CLEO

Under development

@Belle II for the moment only $\mu$ are considered in the tag side of the events → $e/\mu$ or $\mu/\mu$ events
Expectations: $\tau \to lV^0(\phi \to h^+h^-)$

Experimental upper limits from Belle and BaBar for $\tau \to e/\mu\phi$:

- **Belle**: $3.1/8.4 \times 10^{-8}$ @90% confidence level using $\int L dt = 845 fb^{-1}$
  
  [Link](https://arxiv.org/pdf/1101.0755.pdf)

- **BaBar**: $3.1/19 \times 10^{-8}$ @90% confidence level using $\int L dt = 451 fb^{-1}$
  
  [Link](https://arxiv.org/pdf/0904.0339.pdf)

Leptoquark model

Experimental upper limits from Belle and BaBar for $\tau \to e/\mu \phi$:

- **Belle**: $3.1/8.4 \times 10^{-8}$ @90% confidence level using $\int L dt = 845 fb^{-1}$
  

- **BaBar**: $3.1/19 \times 10^{-8}$ @90% confidence level using $\int L dt = 451 fb^{-1}$
  

**Leptoquark model**


Leptoquark model $\tau^\pm \to l V^0 (\phi \to h + h^-)$


Angelescu, Becirevic, DAF, Sumensari [1808.08179]

**Nice interplay between B and $\tau$ physics!**
Cut based approach based on $\mu$ momentum ranges:

- $p_\mu < 0.7$ GeV/c: $\mu$ do not reach the $\mu$ detector (KLM)
- $0.7 < p_\mu < 1$ GeV/c: $\mu$ barely reach KLM
- $p_\mu > 1$ GeV/c: $\mu$ properly reach KLM

Proposed improvement:

3 muons in the event $\rightarrow$ muon identification (muonID) performance plays a crucial role

Best upper limits on $\tau \rightarrow 3\mu$:

- Belle: $2.1 \times 10^{-8}$ @90% CL: $\int Ldt = 782 fb^{-1}$
- BaBar: $3.3 \times 10^{-8}$ @90% CL: $\int Ldt = 468 fb^{-1}$

$0.82 \leq \theta < 1.16$ rad, muonID > 0.9
Belle II expected limits results on LFV channels

Belle II is expected to improve the results of previous B-factory by a factor $\sim$100 but…

With better analysis strategies results can be even better… and they are coming soon!

Expected limits with full statistics: 50 ab$^{-1}$