Latest results on dark sector and tau physics at Belle II

∼ Lomonosov Conference ∼

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The SuperKEKB accelerator is pushing the collider luminosity frontier for Belle II to study lots of different kinds of physics. 

$B$-physics, matter-antimatter asymmetry, precision measurements, direct searches for new physics, ...
The SuperKEKB particle collider accelerates beams of electrons and positrons, stores them in a ring, and collides them.

- $e^-$ beam: 7 GeV
- $e^+$ beam: 4 GeV
- Centre of mass energy: $\sqrt{s} = 10.58$ GeV
- Continuous collision of beams in storage rings
- World record instantaneous luminosities

**June 21 2021:**

$$L_{\text{peak}}^{\text{inst.}} = 3.12 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} = 31.2 \text{ nb}^{-1} \text{ s}^{-1}$$
Recorded $213\, fb^{-1}$ of data but the target $= 50\, ab^{-1}$. Early days for experiment but enough data for initial or new studies.

https://confluence.desy.de/display/BI/Belle+II+Luminosity
Various sub-detectors measure the trajectories of charged particles, the energies of particles, and perform particle identification.

Belle II detector:
- Asymmetric particle beam energies + detector
- Cylindrical layout of layers of detectors
- Solenoid (1.5 T) bends trajectories of charged particles in $\phi$
- Particle identification detectors to distinguish $K^\pm$ from $\pi^\pm$ etc.

**Introduction**
- Frontiers
- Accelerator
- Luminosity
- Belle II Detector
  - B Factory
  - Physics goals++

**$\tau$ mass**
- BSM tau decays
- $Z'$
- Dark photons
- Axion-like particle
- Outro
- Backup

**Ewan Hill**
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SuperKEKB will produce a large number of $B^0$ and $B^\pm$ mesons to study $B$-physics.

- The collider centre of mass energy = 10.58 GeV $\sim m[\Upsilon (4S)]$ → large cross-section for producing $\Upsilon (4S)$

- $\Upsilon (4S) \rightarrow B\bar{B}$ : $> 96\%$ of decays

- SuperKEKB designed to be a “$B$ factory” .... $b$-quarks !!!

$\Upsilon (4S) = b\bar{b}$ meson
$B \equiv B^\pm, B^0, \bar{B}^0$
$B^+ = u\bar{b}$ meson
$B^0 = d\bar{b}$ meson

Main goal to study $B$-physics but ...
Other major goals include performing precision measurements, and searches for new physics

Other major Belle II physics goals:

- Search for new physics through precision measurements that are sensitive to the presence of heavy virtual particles (e.g. through studies of the $\tau$-lepton)
  - $\sigma [e^+e^- \rightarrow \Upsilon (4S)] = 1.05 \text{ nb}$
  - $\sigma [e^+e^- \rightarrow \tau^+\tau^-] = 0.92 \text{ nb}$
  - SuperKEKB makes lots of $\tau$’s too!

- Direct searches for physics beyond the standard model (e.g. Axion-like particles, $Z'$, dark photon)
TAU MASS MEASUREMENT
The tau mass is a SM quantity that needs measuring and will help test the SM.

- $m_\tau$ is a SM quantity that needs measuring.
- Deviations of relations involving the lepton masses in the SM could signal new physics: e.g. test lepton universality
  - $\mathcal{B}(\tau \rightarrow e$ or $\mu) \propto m_\tau^5 \tau_\tau$
  - SM branching ratio of $\tau \rightarrow e$ or $\mu$ is highly sensitive to the tau mass.
- Measure $m_\tau$ in: $e^+e^- \rightarrow \tau^+\tau^-$ events in 4-track final states
- Only one $\pi^0 \rightarrow \gamma\gamma$ allowed in final state (on the 1-prong side)
Measure $m_\tau$ in just the 3-prong decays by determining the endpoint of the distribution of $M_{\text{min}} \leq m_\tau$

- Measure $m_\tau$ (3-prong decay)
- Pseudomass, $M_{\text{min}}$, method developed by the ARGUS Collaboration
- Fit $M_{\text{min}}$ distribution to determine end-point
- Correct for endpoint bias, $0.72 \pm 0.12$ MeV/$c^2$ (from MC), to get $m_\tau$

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

Belle II (Preliminary)

![Graph showing distribution](image-url)

First Belle II tau mass measurement:

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

- Largest systematic uncertainty: momentum shift due to B field map = 0.29 MeV/c^2
- Second largest systematic: estimator bias for conversion from end-point to mass = 0.12 MeV/c^2
- Each remaining systematic < 0.1 MeV/c^2
- Comparatively small overall \( \sigma_{\text{syst.}} \); BES III better having done an energy scan.

Improving systematics (B-field re-mapped): will be systematics dominated after \( \sim 300 \text{ fb}^{-1} \)

LEPTON-FLAVOUR VIOLATING TAU DECAYS
Belle II will push the exclusion limits of many lepton flavour violating $\tau$-decays.

Add neutrino oscillations to SM:
Branching ratio $\sim \mathcal{O}(10^{-54})$

New physics:
Branching ratio $\sim \mathcal{O}(10^{-10}) - \mathcal{O}(10^{-7})$

▶ Search for lepton flavour violating $\tau$ decay
  ▶ Test lepton flavour conservation in SM
▶ Dozens of possible lepton flavour violating $\tau$ decay channels to be studied...
▶ Projection: extend the exclusion limits by 1-2 orders of magnitude with $50 \text{ ab}^{-1}$: see backup slides
Belle II starting search for $\tau \rightarrow e\alpha$, where $\alpha$ is invisible

Example lepton flavour violating $\tau$ decay that connects to dark matter studies:

- Search for $\tau \rightarrow e\alpha$, where $\alpha$ is invisible
- General search but $\alpha$ possibly a DM candidate in some models [1, 2, 3]
- Previous searches:
  - Mark III (1985, 9.4 pb$^{-1}$)
  - ARGUS (1995, 476 pb$^{-1}$)
- Since two-body decay, search for resonance in $e^\pm$ momentum measured in approximation of $\tau$ rest frame
- Require other $\tau$ to have 3-prong decay for better approximation of $\tau$ rest frame
- Current data set should give order of magnitude improvement in exclusion

![Diagram](image-url)
SEARCH FOR THE $Z'$
Search for invisibly decaying $Z'$ in $\mu^+\mu^-$ events.

$L_\mu - L_\tau$ model:
- $Z'$ does not interact with 1st generation leptons
- includes dark matter candidate
- potentially addresses $(g - 2)_\mu$ anomaly

$\tau$ mass

BSM tau decays

$Z'$

Dark sector

Dark photons

Axion-like particle

Outro

Backup

Simulations: can probe $(g - 2)_\mu$ band with $\sim 50$ fb$^{-1}$
SEARCH FOR DARK PHOTONS
Dark photon model could produce events with missing energy or displaced vertices

Inelastic DM model

If $\chi_2$ decays outside of detector:

- Single photon search
- Only directly detect initial state radiation: $\gamma$
- Single photon trigger with 0.5 GeV threshold
- Large background from $e^+e^- \rightarrow \gamma\gamma(\gamma)$
- Some cosmic muons background

If $\chi_2$ decay in the detector:

- search for displaced vertex

$\chi_1 = \text{DM candidate}$

Will have competitive results with the existing data set.
SEARCH FOR AXION-LIKE PARTICLES
Belle II sensitive to axion-like particles as portals to dark matter.

An Axion-like particle, $a$

- couples to bosons. Here focus on $a \rightarrow \gamma \gamma$
- could be a “portal” or “mediator” to connect SM to Dark Matter candidates if $m_a \sim \mathcal{O}(1 \text{ GeV}/c^2)$

![Feynman diagrams for ALP production in $e^+e^-$ collisions via ALP-strahlung (left) and photon fusion (right) and the subsequent decay of the ALP into two photons.](image)
After selecting clean events with self-consistent photons, no excess observed and exclusions set

- $445 \pm 3 \text{ pb}^{-1}$ of data taken in 2018
- Search for bump on large $e^+e^- \rightarrow \gamma\gamma\gamma$ background
- Require that the photon $t/\Delta t$ are all consistent with each other
- No tracks from the interaction point
- $0.88\sqrt{s} \leq m_{\gamma\gamma} \leq 1.03\sqrt{s}$
- No significant excesses observed
- Even with a small data set, results exclude previously unexplored parts of phase space.

FIG. 5. Upper limit (95% C.L.) on the ALP-photon coupling from this analysis and previous constraints from electron beam-dump experiments and $e^+e^- \rightarrow \gamma + \text{invisible}$ [6,9], proton beam-dump experiments [8], $e^+e^- \rightarrow \gamma\gamma$ [11], a photon-beam experiment [12], and heavy-ion collisions [13].
OUTRO
Early Belle II results show signs of promise for the future

Summary:

- Some early results already probing the unexplored
- Other early measurements show promise for the future
- The collider has set a new world record for instantaneous luminosity
- There is still a lot of work to be done to reach target of 50 ab$^{-1}$

To get to the future:

- Remove “draft” pixel detector and insert full one
- Upgrades to accelerator (shorter term)
- Upgrades to detector (longer term)
- Polarized beams?
- Me: job applications :D

For all the latest Belle II results see:
https://confluence.desy.de/display/BI/Journal+Publications
https://docs.belle2.org/
https://arxiv.org/archive/hep-ex
The higher luminosities are largely achieved by squeezing the beams to be even smaller at the collision point.

Instantaneous luminosity of SuperKEKB \( \times 30 \) that of KEKB (old collider):

- \( \times 1.5 \): more particles per beam (increased current, number of bunches, etc.)
- \( \times 20 \): squeezing the beams (“nano-beam” collision scheme)
SuperKEKB set a world record for instantaneous luminosity in June 2020 while on our way to target nominal specifications.


Look at di-tau events with one 1-prong tau decay and one tau decay to 3 charged pions

Measure tau mass in di-tau events: \( e^+ e^- \rightarrow \tau^+ \tau^- \)

Require four track final state: Require one 1-prong decay and one 3-prong decay of the two taus:

- **Selected 1-prong tau decays:**
  - \( \tau^- \rightarrow (1 \text{ or } 2 \nu) \left( \leq 1 \pi^0 \right) \) (1 charged particle)
    - \( \tau^- \rightarrow \nu_\tau h^- \), \( h^- \equiv \pi^- \) or \( K^- \)
    - \( \tau^- \rightarrow \nu_\tau \pi^- \pi^0 \)
    - \( \tau^- \rightarrow \nu_\tau \ell^- \bar{\nu}_\ell \), \( \ell^- \equiv e^- \) or \( \mu^- \)

- **Selected 3-prong tau decays:**
  - \( \tau^+ \rightarrow \bar{\nu}_\tau \pi^+ \pi^- \pi^+ \)

- Results in at most one \( \pi^0 \) in the final state.

Assume charge conjugates throughout
A simple selection to pick out clean events and good charged pions is used

8.8 fb$^{-1}$ of data taken in 2019

Some of the event selections:

- $E_{\text{ECL}}/p_{\text{lab}} < 0.8$ for charged pions
  - Enhances the selection of $\tau^+ \rightarrow \bar{\nu}_\tau \pi^+ \pi^- \pi^+$
- For $\pi^0 \rightarrow \gamma\gamma$:
  - Require $E_{\text{ECL}}(\gamma) > 100$ MeV
  - Require $0.115 < m_{\gamma\gamma} < 0.152$ GeV/$c^2$
- Reject events with a photon of $E > 200$ MeV that is not the daughter of a $\pi^0$
  - Reduces background contamination from $e^+e^- \rightarrow q\bar{q}$ processes.

After selections:

- Efficiency of reconstructing signal events = 16.6%
- Purity of sample = 84.5% (over non-zoomed $M_{\text{min}}$ window).
Measure $m_\tau$ in just the 3-prong decays by determining the endpoint of the distribution of $M_{\text{min}} \leq m_\tau$

Measure $m_\tau$ (3-prong decay)

Pseudomass, $M_{\text{min}}$, method developed by the ARGUS Collaboration.

Take $p_\tau = p_{3\pi} + p_\nu_\tau$

... Assume $\cos \alpha (p_{3\pi}, p_\nu_\tau) = 1$, $m_\nu = 0$ ...

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

- Fit the $M_{\text{min}}$ distribution for the end-point $\rightarrow m_\tau$.
- Apply corrections to compensate for the neutrino assumptions etc.

Apply somewhat simple event selection to 8.8 fb$^{-1}$ of data taken in 2019....
Correct end-point position by 0.72 MeV/c^2 to get tau mass measurement.

- Fit $M_{\text{min}}^{MC}$ distribution to determine end-point.
- Difference between measured MC end-point and $m_{\tau}^{MC}$ truth is $0.72 \pm 0.12$ MeV/c^2.
- Use this measured bias in MC to convert measured end-point in data to $m_{\tau}$ measurement.
Backgrounds small and flat in the end-point region

- Dominant background in these plots is from other 3-prong tau decays but does not contaminate the end-point region where fit is performed.
- Small and flat background in the fit region
### Tau mass measurement systematics

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>MeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum shift due to the B-field map</td>
<td>0.29</td>
</tr>
<tr>
<td>Estimator bias</td>
<td>0.12</td>
</tr>
<tr>
<td>Choice of p.d.f.</td>
<td>0.08</td>
</tr>
<tr>
<td>Fit window</td>
<td>0.04</td>
</tr>
<tr>
<td>Beam energy shifts</td>
<td>0.03</td>
</tr>
<tr>
<td>Mass dependence of bias</td>
<td>0.02</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Initial parameters</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Background processes</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>$\leq 0.01$</td>
</tr>
</tbody>
</table>
Future of the Belle II tau mass measurement

- Magnetic field has been remapped
- After improvements in the momentum scale factor systematic uncertainty, expect a future total systematic uncertainty of $\sim 0.15 \text{ MeV}/c^2$.
- After that, need $\sim 300 \text{ fb}^{-1}$ of data for the measurement to become systematically dominated.

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

\[ B_{\tau\ell}^{\text{SM}} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5} \]

\[ B_{\tau e}^{\text{SM}} \propto m_\tau^5 \tau_\tau \]

- Uncertainties on \( m_\mu \) are much smaller than uncertainties on \( m_\tau \)
- \( \tau_\tau \) is the lifetime of the \( \tau \)
- \( B_{\tau\ell} \) is the branching ratio of \( \tau \) decaying to \( \ell\nu\nu \)
- We can measure \( B_{\tau e}, m_\tau, \) and \( \tau_\tau \)
- The \( B_{\tau e}^{\text{SM}} \) equation is what the Standard Model says on how \( B_{\tau e} \) varies with \( \tau_\tau \) after inputting \( m_\tau \).
- The red point is \( (\tau_\tau^{\text{data measurement}}, B_{\tau e}^{\text{data measurement}}) = ((290.3 \pm 0.5) \text{ fs}, (17.85 \pm 0.04) \%) \).
- The yellow line is \( B_{\tau e}^{\text{SM}} \), based on the measured value of \( m_\tau \) with a width corresponding to the \( \tau \) lifetime uncertainty, which is dominated by the \( \tau \) mass uncertainty.

arXiv:1804.08436

Figure 1. Test of the SM prediction of the leptonic branching fractions to strange final states can be used in a similar way to obtain additional less precise information on hadronic form factors to provide the most precise determinations of hadronic partial widths to strange and to non-strange hadronic final states.

The measurements of the kaon branching fractions are used in conjunction with lattice QCD estimates accounting for all correlations.

Similar tests could be performed with decays to electrons, however they are less precise because the uncertainties on \( m_\mu \) are much smaller than the uncertainties on \( m_\tau \).
(projected) exclusion limits for lepton flavour violating $\tau$ decays

Fig. 177: Current 90% C.L. upper limits for the branching fraction of $\tau$ LFV decays obtained in the CLEO, BaBar, and Belle experiments. Purple boxes, blue inverted triangles, green triangles and yellow boxes show CLEO, BaBar, Belle and LHCb results, respectively, while red circles express the Belle II future prospects, where they are extrapolated from Belle results assuming the integrated luminosity of 50 ab$^{-1}$.

The Belle II physics book
Photons energy cuts:

1. $m_a > 4 \text{ GeV}$: $E_\gamma > 0.65 \text{ GeV}$
2. $m_a \leq 4 \text{ GeV}$: $E_\gamma > 1 \text{ GeV}$
3. Helps avoid shaping effects on the background mass distribution

Look at $m_{\gamma\gamma}$, and similar quantity calculated from recoil photon energy