Dark sector searches with tau-pair events at Belle and Belle II

5 December, 2023

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on behalf of the Belle and Belle II Collaboration
To Discuss:

• Search for a heavy neutral lepton that mixes predominantly with the $\tau$ neutrino (NEW RESULTS for this conference, to be submitted to PRL)

• Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair in $e^+e^-$ annihilation at center-of-mass energies near 10.58 GeV (Arxiv 2207.07476)

• Search for Lepton Flavor Violating $\tau$ Decays to a Lepton and an Invisible Boson at Belle II (PRL 130, 181803 (2023). Arxiv 2212.03634)

• Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment (PhysRevLett.131.121802)

Not covered in this talk
The Apparatus

Mt. Tsukuba

KEKB

Belle

Linac

3km

Analysis

Analysis
The Apparatus

- Description of Belle detector: 
  [talk](#) by Sourav Patra

- Description of Belle II detector: 
  [talk](#) by Radek, [talk](#) by Paul

\[
\sigma(e^+e^- \rightarrow b\bar{b}) = 1.05 \text{ nb}
\]
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\Upsilon(nS)e[n = 1,...,5], \text{ use of off resonance data : B factories are also } \tau \text{ factories}
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Heavy Neutral Lepton (N)

• Neutrino Oscillations: Neutrino has mass
• Neutrino masses can be incorporated to SM by introducing RH (Majorana) neutrinos
• Allows to solve some of the outstanding problems of the SM
  • Origin of the SM neutrino masses
  • Non-baryonic dark matter
  • Baryogenesis
• N are sterile: Interacts with $\nu_{SM}$ through mixing: $N \leftrightarrow \nu_{SM}$
• Long lifetime of N: due to small $m_N$ and small mixing
• Heavy Neutral Lepton also appears in SUSY, exotic Higgs, GUT…

Heavy Neutral Lepton: Direct searches

- Previous experiments explored $m_N$ from 100 MeV to ~ 1 TeV
  - $m_N > m_Z$: Direct searches @LHC: $pp \rightarrow Nl^\pm$
  - $m_N < m_{Z,W}$: DELPHI($Z^0 \rightarrow \nu N$), ATLAS/CMS($W^\pm \rightarrow Nl^\pm$)
  - $m_N < m_{B,D,K}$: Belle, LHCb, beam-dump, NA62

$|V_{eN}|^2$, $|V_{\mu N}|^2$, $|V_{\tau N}|^2$ = mixing coefficients of $\nu_e, \nu_\mu, \nu_\tau$ with N

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- All the experiments provide tight limits on $|V_{eN}|^2, |V_{\mu N}|^2$
- Limits on $|V_{\tau N}|^2$ are much weaker
- This motivates us to overcome the experimental challenges and explore $|V_{\tau N}|^2$
Analysis Method

- $N$ decays via the weak neutral current
- This analysis probes $|V_{\tau N}|^2$ directly
- This production mechanism implies $m_N < m_\tau - m_\pi$
- $N$ is long-lived for a range of $|V_{\tau N}|^2$ values that we are sensitive to

Full Belle data sample used
$(836 \pm 12) \times 10^6 \tau$ pairs
Analysis Method

- $e^+e^- \rightarrow \tau^+_{tag}\tau^-_{sig}$
  
  **Tag side:**
  - $\tau^+_{tag} \rightarrow \pi^+ \bar{\nu}_\tau$
  - $\pi^0 \nu_\tau$
  - $l^+ \nu_l \bar{\nu}_\tau$

  **Signal side:**
  - $\tau^-_{sig} \rightarrow \pi^- N(\rightarrow \mu^+ \mu^- \nu_\tau)$

- We look for a $\mu^+ \mu^-$ displaced vertex (DV)

- Radial position of DV > 15 cm from the beam axis
\( K^0 \rightarrow \pi^+ \pi^- \): displaced vertex similar to N: removed the mass region

- We divide the signal region into Low mass and High mass signal region:
  - SRH: \( m_{\pi\pi}^{DV} > 0.52 \text{ GeV}/c^2 \)
  - SRL: \( m_{\pi\pi}^{DV} < 0.42 \text{ GeV}/c^2 \)

- Light N distribution is different from heavy N distribution
- Full kinematics of the signal-decay chain reconstructed with a two-fold ambiguity ($m_+$ and $m_-$).
- In the signal regions targeting heavy and light $N$s we observe 1 and 0 events, respectively,
- in agreement with the background expectation.

![Graph showing relative density vs. $m_+$]
Results

- Uncertainties
  - N branching fraction
  - luminosity
  - uncertainty on the reconstruction of the two prompt tracks
  - the background yield expectations (largest)
- Handled with the nuisance parameters using $\text{CL}_s$ prescription
- Allows for direct measurement of the N mass if a signal is observed

In the mass range 1.3 - 1.4 $\text{GeV}/c^2$, our limits are the most stringent to date.

New for TAU2023
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Dark Leptophilic Scalar

- Scalars other than Higgs bosons appear in many BSM theories.

- The mixing between this dark scalar $\phi_L$ and the SM Higgs boson gives rise to couplings proportional to SM fermion masses, described by

\[ \mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi_L \ell \]

- Couples to both quarks and leptons, the existence of such particles is strongly constrained by the searches for rare flavor-changing neutral current decays of mesons, e.g. $B \rightarrow K\phi$ and $K \rightarrow \pi\phi$.

  - However, these bounds are evaded if the coupling of the scalar to quarks is suppressed and this scalar interacts preferentially with leptons.

- Can explain
  - $(g - 2)_{\mu}$ anomaly
  - Lepton flavor universality violation.

$\xi$ = coupling constant independent of lepton flavor,
$m_\ell$ = mass of lepton,
$v = 246$ GeV, is the vacuum expectation value of the Higgs field.
The scalar decays to a pair of leptons: search for narrow peak in lepton pair invariant mass distribution

\[ \phi_L \rightarrow e^+e^- \text{ for } m_{\phi_L} < 2m_\mu \]

\[ \phi_L \rightarrow \mu^+\mu^- \text{ for } m_{\phi_L} > 2m_\mu \]

High production cross-section times branching ratio in the region 40 MeV < \( m_{\phi_L} < 6.5 \) GeV.

Our search has sensitivity to place competitive limits on \( \xi \) till \( m_{\phi_L} < 6.5 \) GeV

Analysis Method

\[ e^+e^- \rightarrow \tau^+\tau^- \phi_L, \quad \phi_L \rightarrow e^+e^-/\mu^+\mu^- \]
Results: data vs. Monte Carlo in Control Region

- Extraction of the signal:
  - fitting $l^+l^-$ invariant mass distribution: simultaneous fit for both $e^+e^-$ and $\mu^+\mu^-$ channel
  - evaluation at each mass point of $\phi_L$
- Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5
Results: data vs. Monte Carlo in Signal Region

- Signal region: No obvious narrow peak structure is observed.
Results: upper limits on the signal cross-section

- 90% confidence level upper limits on the signal cross-section
- No significant excess in all masses
Results: level upper limits on the coupling constant

- 90% confidence level upper limits on the coupling constant
- No $\phi_L$ can explain observed excess in $(g - 2)_\mu$ for $m_{\phi_L} < 4$ GeV
• Search for a heavy neutral lepton that mixes predominantly with the $\tau$ neutrino (NEW RESULTS, to be submitted to PRL)

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Motivation

- Light, beyond-the-standard-model bosons ($\alpha$) that are not directly detectable (invisible) are predicted in models with, e.g., axion-like particles ([PhysRevLett.124.211803](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.211803))

- Direct search in $\tau^- \rightarrow \ell^- \alpha$ ($\ell = e/\mu$)

- Lepton Flavor Universality check

- This process was previously searched for by the MARK III and ARGUS collaborations ([Z. Phys. C 68, 25-28 (1995)](https://www.sciencedirect.com/science/article/pii/034057569500517X)).

- The current best upper limits on the $\tau^- \rightarrow \ell^- \alpha$ branching fractions (at 95% confidence level where the range indicates their dependence on the $\alpha$ mass in the (0–1.6) GeV/$c^2$ range)

\[
\frac{\mathcal{B}(\tau^- \rightarrow e^- \alpha)}{\mathcal{B}(\tau \rightarrow e^- \bar{\nu}_e \nu_\tau)} < (6 \ - \ 36) \times 10^{-3}
\]

\[
\frac{\mathcal{B}(\tau^- \rightarrow \mu^- \alpha)}{\mathcal{B}(\tau \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)} < (3 \ - \ 34) \times 10^{-3}
\]
• In center-of-mass frame: $\tau$ pairs: back to back
  • tag side: 3 charged particle from $\tau^− \to h^- h^+ h^- \nu_\tau (h = K, \pi)$
  • signal side: one charged particle

• $\tau \to \ell^− \bar{\nu}_\ell \nu_\tau$: irreducible background: however the magnitude of the lepton momentum depends only on the $\alpha$ mass: the difference thus exploited

• $\tau$ pseudo rest frame: $\hat{p}_\tau \approx -\frac{\vec{p}_{3h}}{|\vec{p}_{3h}|}$, $E_\tau \approx E_{CMS}/2$

• Search for a peak in normalized lepton energy $x_\ell \equiv \frac{E^*_\ell}{m_\ell c^2/2}$, $E^*_\ell$ = energy of the charged lepton in $\tau$ pseudo rest frame

Analysis Method

62.8 $fb^{-1}$ data from Belle II detector:
57.7 Million $\tau$ pairs

Measure
$$\frac{\mathcal{B}_{\ell\alpha}}{\mathcal{B}_{\ell\bar{\nu}\nu}} = \frac{\mathcal{B}(\tau^− \to \ell^- \alpha)}{\mathcal{B}(\tau^− \to \ell^- \bar{\nu}_\ell \nu_\tau)}$$
Results: Spectra of $x_\ell$

- Simulated spectra for standard-model processes: stacked, gray band: total uncertainty (dominated by the lepton-identification efficiency uncertainty)
- Remaining background processes combined together: collectively referred to as “other”
- The distributions for $\tau \rightarrow \ell^- \alpha$ are shown for three $\alpha$ masses assuming branching-fraction ratios of 5%
• Fit with SM and SM+NP expectations, compare likelihood of the two models
• No statistically significant signal observed
• Upper limits on 95% CL

most stringent limits on invisible spin-0 boson production from \( \tau \) lepton decays to date
Summary

- No significant excess observed
- Stringent limits in all three analyses
- **Search for a heavy neutral lepton that mixes predominantly with the $\tau$ neutrino**
  - For the first time, utilizes the displaced vertex originating from the long-lived Heavy Neutral Lepton decay
  - Ability to reconstruct the Heavy Neutral Lepton candidate mass and suppress background to the single-event level
- **Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair in $e^+e^-$annihilation at center-of-mass energies near 10.58 GeV**
  - No $\phi_L$ can explain observed excess in $(g - 2)_\mu$ for $m_{\phi_L} < 4$ GeV
- **Search for Lepton Flavor Violating $\tau$ Decays to a Lepton and an Invisible Boson at Belle II**
  - most stringent limits on invisible spin-0 boson production from $\tau$ lepton decays to date

Long shutdown now : for upgrades, will resume data taking in 2024 : improved detector, and more data, hope for more exciting results in the future
Backups
Search for a $\tau^+\tau^-$ Resonance in $e^+e^-\rightarrow \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment (PhysRevLett.131.121802)

- First search for $e^+e^-\rightarrow \mu^+\mu^-\tau^+\tau^-$ in 3.6 - 10 $GeV/c^2$ range
- 62.8 $fb^{-1}$ Belle II data
- Probes three different models
  - spin-1 particle coupling only to the heavier lepton families
  - a Higgs-like spin-0 particle that couples preferentially to charged leptons
  - an an axionlike particle
Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment (PhysRevLett.131.121802)

$\tau^+ + \tau^- + e^+ + e^- + \mu^+ + \mu^- + \tau^+ + \tau^-$

$30$

ALP mass coupling to leptons

$X = (Z', S, ALP)$
from Belle to The Belle II Detector

- **TOP** (barrel)
- **ARICH** (forward endcap)

Belle equipped ACC (Aerogel Cherenkov Counter) and TOF (Time Of Flight)

More space to VXD and CDC at Belle II
Luminosity

- Belle data taking period: 1999-2010 : 1040 fb⁻¹
- Belle II: Regular data-taking since April 2019
- Current integrated luminosity 424 fb⁻¹
- Long shutdown for accelerator and detector upgrades, will resume data taking in 2024
- Belle II Design integrated luminosity 50 ab⁻¹

- \( \sigma(e^+e^- \rightarrow b\bar{b}) = 1.05 \text{ nb} \)
- \( \sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb} \)
- \( \Upsilon(nS)e[n = 1,..,5] \), use of off resonance data : B factories are also \( \tau \) factories
from KEKB to SuperKEKB

• 40 times larger luminosity than previous generation KEKB
• using nano-beam scheme with a tiny beam spot:
  • 60 nm × 10 μm × few 100 μm in y, x, z
  • a few hundred atomic layers in y
Signal region: \( \tau^- \rightarrow DV( \rightarrow \mu^\mp \mu^\pm)\pi^- \)

Control region: \( \tau^- \rightarrow DV( \rightarrow \mu^\mp \pi^\pm)\pi^- \) (used in the fit for data-driven background estimate)

Validation region for Data-MC agreement:

- Reconstruct as \( \tau^- \rightarrow DV( \rightarrow \mu^- \mu^-)\pi^+ \)
- Reconstruct as \( \tau^- \rightarrow DV( \rightarrow \pi^+ \pi^-)\pi^- \) with \( m_{\pi\pi} < 0.42 \text{ GeV} \) and \( m_{\pi\pi} > 0.52 \text{ GeV} \)
- Reconstruct as \( \tau^- \rightarrow DV( \rightarrow \pi^+ \pi^-)\pi^- \) with \( 0.480 < m_{\pi\pi} < 0.515 \text{ GeV} \)

Control and validation regions are also divided as CRh, CRI and VRh, VRl (similar to signal region)
Despite the neutrino, we can reconstruct the decay chain kinematics completely, up to 2-fold ambiguity.

- 12 unknowns: $p_{\mu}^\tau$, $p_N^\tau$, $p_\tau^\mu$
- 12 constraints:
  - $p^\mu$ conservation in the $\tau$ and $N$ decays (8)
  - Known masses of $\tau$ and $\nu_\tau$ (2)
  - Unit vector from the production point of the $\pi$ system to that of the DV system, which is the direction of $\vec{p}_N$ (2)

Quadratic equation
(Using the square root argument $A_{sq} = b^2 - 4ac$ for cut)

Two HNL mass solutions: $m_+, m_-$

$A_{sq} < 0.4 \text{ GeV}^2$

If $A_{sq}$ is -ve then we set it to 0
- The accelerator collides electron and positrons

\[ \sqrt{s} = 10.58 \text{ GeV} : \text{mass of } \Upsilon(4S) \]

- \( B\bar{B}, \tau^+\tau^- \) pair production with a boost of the center-of-mass system: asymmetric collider

- Prospect for studying a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)
• $\sigma(e^+e^- \rightarrow b\bar{b}) = 1.05\ nb$
• $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92\ nb$
• $\Upsilon(nS)\epsilon[n = 1,..,5]$, use of off resonance data: B factories are also $\tau$ factories
- Design integrated luminosity 50 ab$^{-1}$
- Regular data-taking since April 2019
- Current integrated luminosity 424 fb$^{-1}$
- Peak luminosity recorded: $4.7 \times 10^{34} \text{cm}^{-1}\text{s}^{-1}$
- At present, we have a long shutdown for accelerator and detector upgrades, will resume data taking in 2024
• $N_{\text{signal}} = N_{\tau\tau} \times B(\tau \rightarrow \pi N) \times B(N \rightarrow \mu^+\mu^-\nu_\tau) \times \epsilon$, where $\epsilon$ is the efficiency
• Signal efficiencies in SRH and SRL as a function of $|V_{N\tau}|^2$ and $m_N$: efficiency map
• largest relative systematic uncertainty: the background yield expectations
• Other uncertainties
  • $N$ branching fraction
  • decay modeling
  • luminosity
  • cross section the uncertainty on the reconstruction of the two prompt tracks
• All systematic uncertainties are handled with the nuisance parameters using $CL_s$ prescription
• Requirement of 4 track events with net charge 0
• At least two tracks are identified as $e/\mu \rightarrow$ Same vertex
• Two known backgrounds
  • also $q\bar{q}, l^+l^-, l^+l^-l^+l^-, l^+l^-h^+h^-$ backgrounds
• backgrounds are suppressed using BDTs