Searches for Charged Lepton Flavor Violation in tau and hadron decays at Belle and Belle II

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on behalf of the Belle and Belle II Collaboration

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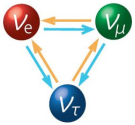
DESY

Belle

Belle II

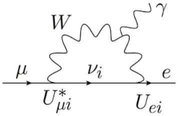
Introduction

Observation of neutrino oscillations provided clear evidence that neutrinos are massive and **lepton flavour conservation** is violated.



What about the charged leptons?

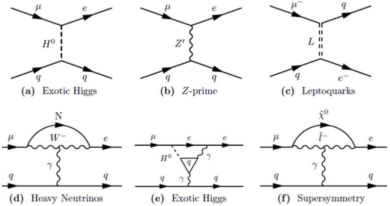
- Charged LFV can occur through oscillations in **loops**
- The predicted rates are **GIM suppressed** $\propto (\frac{m_\nu}{M_W})^4$ $(10^{-54} \sim 10^{-49})$ for all the LFV μ and τ decays.



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Observation of LFV will be a **signature of NP!**
Many scenarios of physics beyond the Standard Model (SM) introduce new sources of CLFV $(10^{-10} \sim 10^{-7})$.

Baryon Number Violation (BNV), crucial ingredient to explain matter-antimatter asymmetry, allowed in many models.

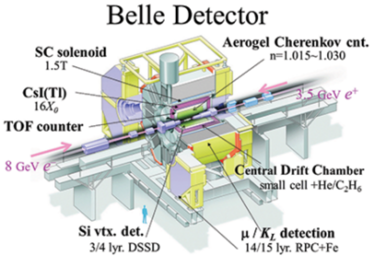


These models also holds for τ and hadron decays

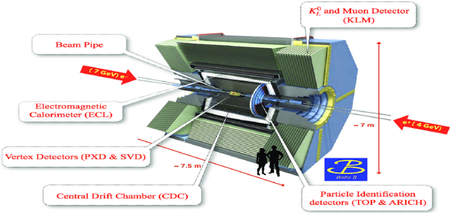
B(τ) factories: Belle & Belle II

- **Belle** (1999 - 2010) and **Belle II** (2018 -) operate at B-factories.
  - Asymmetric e^+e^- colliders optimized for the production of **B meson** pairs, but also **D mesons**, $\boldsymbol{\tau}$ **leptons**, . . . **dark sector**
  - Collisions mainly at $\boldsymbol{\Upsilon(4S)}$ **:** $\boldsymbol{\sqrt{s} = 10.58}$ **GeV** (60 MeV below $\Upsilon(4S)$, $\Upsilon(5S)$ and others)
- **Advantages** of experiments at **B-factories**
  - **Well known** initial-state condition and **clean environment** (low particle multiplicity)
  - Hermetic detectors with excellent **particle identification** (PID) and **tracking performance**

Belle **@KEKB**, recorded
$\int Ldt = 1$ **ab**$^{-1}$

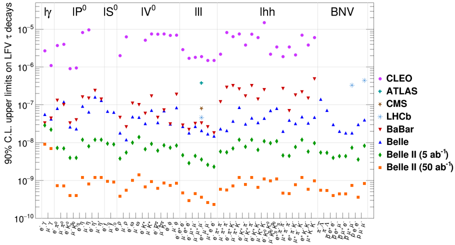


Belle II **@SuperKEKB**, recorded
$\int Ldt = 427$ **fb**$^{-1}$ (Run 1) [2018 - 2022]
$\int Ldt = 103$ **fb**$^{-1}$ (Run 2) [2024 -]



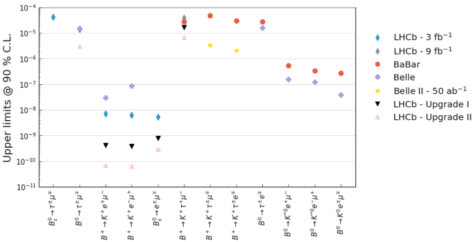
LFV at Belle and Belle II

Existing and expected limits on LFV τ decays [1]



- Neutrinoless 2-body or 3-body decays to **52 final states**.
- In some SM extensions, cLFV decays are expected at rates only one order of magnitude **below present bounds**.

Existing and expected limits on LFV B decays [2]



- Final state involving τ makes **harder the reconstruction** due to the presence of **missing energy**.
- **Hadronic B tag** used to infer the momentum of the signal side

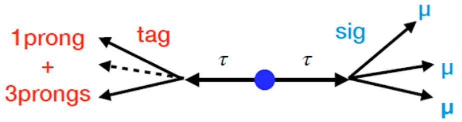
- Belle II will improve limits by **1-2 orders**.

[1] Snowmass 2021: cLFV in τ sector - arXiv:2203.14919

[2] G. De Marino, Anomalies and Precision in the Belle II era (2021)

τ LFV channels

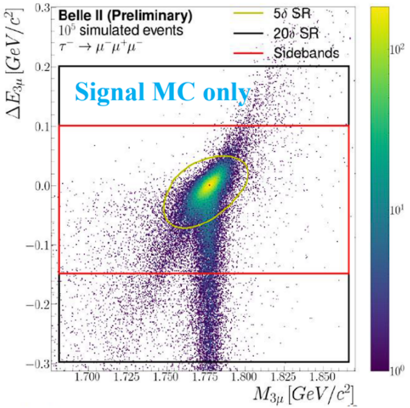
- Main analysis approach:
  - Inclusive of 3×1 and 3×3 topologies
  - Selection and background rejection using BDT



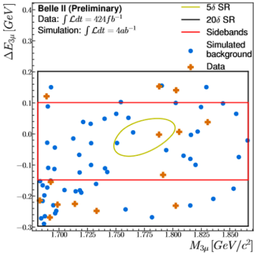
- **Belle II with 424 fb^{-1}**
  arXiv:2405.07386
  - Extract signal yield from 2D plane $(M_{3\mu}, \Delta E_{3\mu})$:

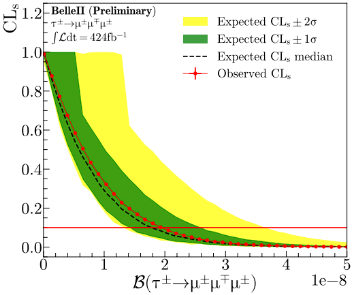
$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$$
$$\Delta E_{3\mu} = E_{3\mu}^{CM} - E_{\text{beam}}^{CM}$$

  - For signal:
    - $\Delta E_{3\mu}$ close to 0 and $M_{3\mu}$ close to τ mass
    - Tails due to initial and final state radiation



- Signal: efficiency: 20.4% (2.7 $\times$ Belle efficiency)
- Number of expected BG: 0.5
- 1 event observed inside the SR
- $\mathcal{B}(\tau \to 3\mu) < 1.9 \times 10^{-8}$ at 90% C.L.





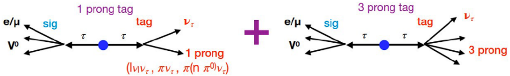
Most stringent limit to date

	UL at 90% C.L. on $\mathcal{B}(\tau \to 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L} = 20.3$ fb^{-1})
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0$ fb^{-1})
CMS	2.9×10^{-8} ($\mathcal{L} = 131$ fb^{-1})
Belle	2.1×10^{-8} ($\mathcal{L} = 782$ fb^{-1})
BaBar	3.3×10^{-8} ($\mathcal{L} = 486$ fb^{-1})
Belle II	1.9×10^{-8} ($\mathcal{L} = 424$ fb^{-1})

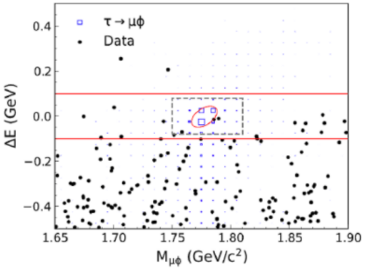
Previous search at Belle on 854 fb^{-1} exploiting 1-prong tag [1]

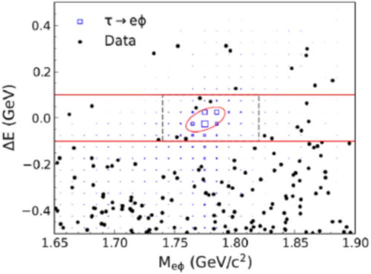
New results from Belle [2]:

- Increase the efficiency using
  - full data set of 980 fb^{-1} [2]
  - more decay modes in the tag side
  - background suppression with BDT



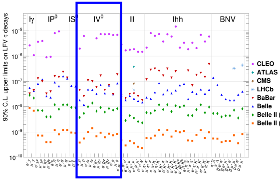
- Exploit topology and event/tag kinematics of the backgrounds
- Further suppress $\tau \to 3\pi\nu$ and $ee \to q\bar{q}$ with BDT
- Estimate expected background in SR from **sideband interpolation**





[1] Y. Miyazaki, *et. al.*, (Belle Collaboration) Phys. Lett. B 699, 251 (2011)

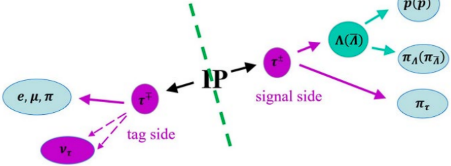
[2] N. Tsuzuki, *et. al.*, (Belle Collaboration) JHEP 2023, 118, (2023)

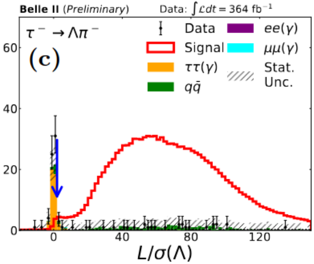


- **No significant excess in all modes → set ULs at 90% C.L.**
- **30% improvement over previous measurements:**
  - increased statistics (124 fb^{1})
  - higher signal efficiency (9%)

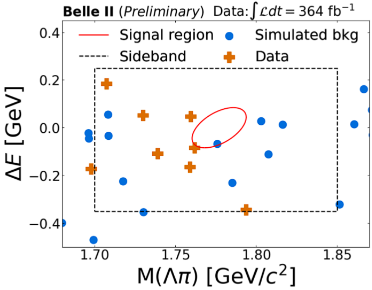
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{\text{obs}}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7

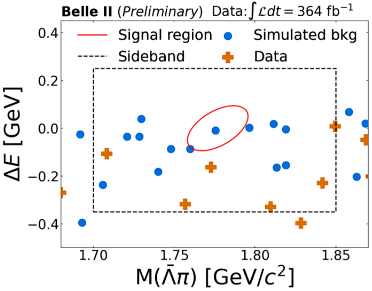
- **Belle II:** arXiv:2407.05117
  - Reconstruct exactly 4 charged tracks (total null charge) in one-prong tag approach
  - $\Lambda(\bar{\Lambda})$ is reconstructed from proton (anti-proton) and pion
  - Signal selection and background suppression using loose pre-selection, followed by Gradient-BDT
    - The flight significance (L/σ) of Λ and $\bar{\Lambda}$ candidates is one of the most discriminanting variables.





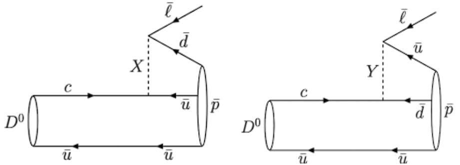
- Signal efficiencies are 9.5% and 9.9% for $\tau \to \Lambda\pi$ and $\tau \to \bar{\Lambda}\pi$ respectively
- Poisson counting experiment technique in signal region in the $M(\Lambda\pi) = \sqrt{E^2_{\Lambda\pi} - P^2_{\Lambda\pi}}$ and $\Delta E = E^{CM}_{\Lambda\pi} - \sqrt{s}/2$ plane
- Expected events are 1 and 0.5 for $\tau \to \Lambda\pi$ and $\tau \to \bar{\Lambda}\pi$ respectively
- No events observed
- **World's best upper limits** at 90% C.L. of $\mathbf{4.7 \times 10^{-8}}$ **for** $\boldsymbol{\mathcal{B}(\tau \to \Lambda\pi)}$ and $\mathbf{4.3 \times 10^{-8}}$ **for** $\boldsymbol{\mathcal{B}(\tau \to \bar{\Lambda}\pi)}$





Hadron LFV channels

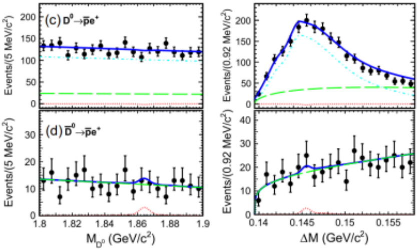
- **Motivation:** BNV is one of the crucial ingredients to explain matter-antimatter asymmetry
  - In many models, BNV and LNV but their difference $\Delta(B-L)=0$ is conserved
  - Valuable input to the search of leptoquarks



- **Belle** performed a search for $D^0 \to pl^-$, $\bar{D}^0 \to pl^-$, $D^0 \to \bar{p}l^+$ and $\bar{D}^0 \to \bar{p}l^+$ ($l = e$ or μ) PhysRevD.109.L031101
  - 921 fb^{-1} integrated data luminosity at and 60 MeV below the $\Upsilon(4S)$ and at the $\Upsilon(5S)$ resonance
  - The well-known $D^0 \to K^-\pi^+$ is used for normalization to measure the branching fractions of signal modes.

- Signal yields are extracted with extended maximum likelihood fits to the unbinned M_{D^0} and ΔM distributions of each decay mode

- Separate PDFs are used for signal, peaking and combinatorial background
  - **Signal**: sum of 4 gaussian for ΔM, 2 Gaussian + 1 asymmetric Gaussian for M_{D^0}
  - **peaking background**, **combinatorial background** and the **sum of the fits** are shown in the plots.



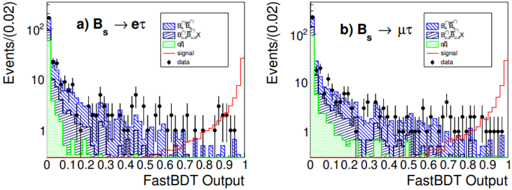
Decay mode	ϵ (%)	N_S	$\mathcal{S}$ (σ)	N_{pl}^{UL}	$\mathcal{B} \times 10^{-7}$
$D^0 \to pe^-$	10.2	-6.4 ± 8.5		17.5	< 5.5
$\bar{D}^0 \to pe^-$	10.2	-18.4 ± 23.0		22.0	< 6.9
$D^0 \to \bar{p}e^+$	09.7	-4.7 ± 23.0		22.0	< 7.2
$\bar{D}^0 \to \bar{p}e^+$	09.6	7.1 ± 9.0	0.6	23.0	< 7.6
$D^0 \to p\mu^-$	10.7	11.0 ± 23.0	0.9	17.1	< 5.1
$\bar{D}^0 \to p\mu^-$	10.7	-10.8 ± 27.0		21.8	< 6.5
$D^0 \to \bar{p}\mu^+$	10.5	-4.5 ± 14.0		21.1	< 6.3
$\bar{D}^0 \to \bar{p}\mu^+$	10.4	16.7 ± 8.8	1.6	21.4	< 6.5

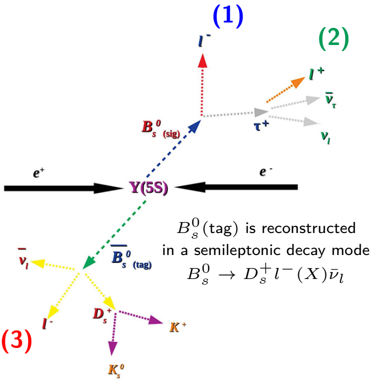
- Most stringent upper limits to date
- First results for $D \to p\mu$

Search for $B_s^0 \to \tau l$ @ Belle

Belle: using 121 fb^{-1} collected at the $\Upsilon(5S)$ resonance mass. JHEP08(2023)178

- To suppress $J/\psi \to l^+l^-$ background, $M_{l_1,l_2} \notin [3.01, 3.12]$ for electron and $M_{l_1,l_2} \notin [3.05, 3.12]$ for muon case
- To reduce **combinatorial background**, ensure l_1 and l_3 have the same charge
- FastBDT to remove $e^+e^- \to q\bar{q}$ and $e^+e^- \to B_s^{(*)0}\bar{B}_s^{(*)0}, B^{(*)}\bar{B}^{(*)}X$





B_s^0(tag) is reconstructed in a semileptonic decay mode $B_s^0 \to D_s^+ l^-(X)\bar{\nu}_l$

Search for $B_s^0 \to \tau l$ @ Belle

	ϵ (%)	$N_{\rm bkg}^{\rm exp}$	$N_{\rm obs}$	$\mathcal{B}$ ($\times 10^{-4}$)
$B_s \to e^- \tau^+$	0.031 ± 0.007	0.68 ± 0.69	3	< 14
$B_s \to \mu^- \tau^+$	0.030 ± 0.007	0.77 ± 0.78	1	< 7.3

- Most stringent limit on $\boldsymbol{\mathcal{B}(B_s^0 \to \mu\tau) < 3.4 \times 10^{-5}}$ **reported by LHCb** [1]
- **First such limit reported on the** $\boldsymbol{B_s^0 \to e\tau}$
- Belle II could improve in the future
  - **More data** collected at the $\Upsilon(5S)$ resonance.
  - Enhanced analysis techniques such as **full reconstruction of the tag** $\boldsymbol{B_s^0}$

[1] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. 123, 211801 (2019).

Search for LFV $B^0 \to K_S^0 \tau l$ @ Belle and Belle II

- **Motivation**: From the $\mathcal{B}(B^+ \to K^+ \nu\nu)$ excess [1] (2.7 σ larger than SM) the predicted $\mathcal{B}(B \to K\tau\mu)$ is quite close to the current experimental sensitivities ($[2,3] \times 10^{-6}$).

- **Belle and Belle II**: Search for LFV in $B^0 \to K_S^0 \tau l$ ($l = \mu, e$) from a combined analysis of **Belle (711 fb^{-1})** and **Belle II (364 fb $^{-1}$)** dataset.

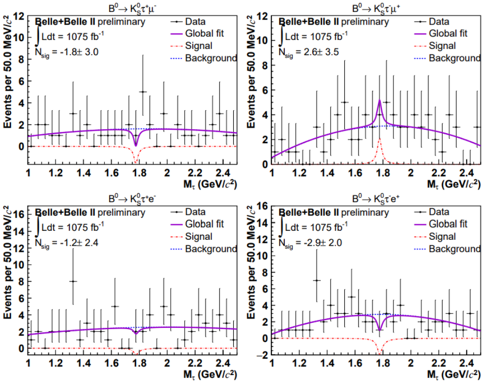
  - B_{tag} is fully reconstructed and kinematically constrained

$$M_{bc} \equiv \sqrt{E_{beam}^2/c^4 - |\vec{p}_{B_{tag}}|^2/c^2} > 5.27 \text{ GeV}/c^2$$
$$-0.15 < \Delta E < 0.1\text{GeV}$$

  - **Full Event Interpretation (FEI) algorithm** score is used to select the best candidate
  - τ lepton kinematics is obtained from kinematic constraints and the signal yields are extracted from τ mass (M_τ) as signal event peaks

[1] I. Adachi *et al.* (Belle II Collaboration), Phys. Rev. D 109, 112006 (2024).

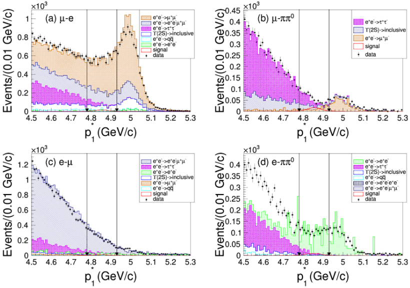
- **BDT** is used to remove **charm meson** semileptonic decays background.
- PDFs (Johnson's S_U function) are used to model M_τ

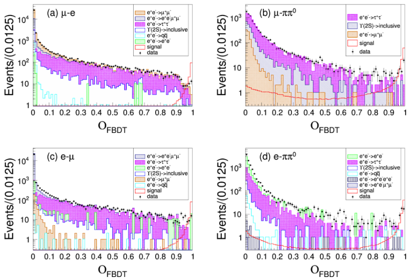


Channels	$\epsilon(10^{-4})$	N_{sig}	$\mathcal{B}(10^{-5})$ Central value	$\mathcal{B}(10^{-5})$ UL
$B^0 \to K_S^0 \tau^+ \mu^-$	1.7	-1.8 ± 3.0	$-1.0 \pm 1.6 \pm 0.2$	1.1
$B^0 \to K_S^0 \tau^- \mu^+$	2.1	2.6 ± 3.5	$1.1 \pm 1.6 \pm 0.3$	3.6
$B^0 \to K_S^0 \tau^+ e^-$	2.0	-1.2 ± 2.4	$-0.5 \pm 1.1 \pm 0.1$	1.5
$B^0 \to K_S^0 \tau^- e^+$	2.1	-2.9 ± 2.0	$-1.2 \pm 0.9 \pm 0.3$	0.8

These results are among the most stringent limits achieved of $b \to s\tau l$ transition to date.

- **Motivation:** Experimental limit on the two-body CLFV quarkonium decay provides complementary constraints on the Wilson coefficients of the effective Lagrangian of new physics models
- **Belle with 25 fb^{-1}:** JHEP02(2024)187
  - **Signal signature:** high-momentum lepton l_1
  - The τ lepton decays to $l_2 \nu_2 \nu_\tau$ or $\pi^+ \pi^0 \nu_\tau$
  - The l_2 is required to have different flavour respect to the non-τ lepton (l_1) coming from the Υ decay (to remove copious Bhabha background).
  - MVA (FastBDT) performed to further suppress the background (BhaBha)





Search for cLFV in $\Upsilon(2S) \to l\tau$ decays @ Belle

- Signal efficiencies are **12.3% (8.1%) for $\boldsymbol{\Upsilon(2S) \to \mu\tau}$ ($\boldsymbol{\Upsilon(2S) \to e\tau}$)**
- Expected events are 3.9 ± 1.8 (5.9 ± 2.6) for $\Upsilon(2S) \to \mu\tau$ ($\Upsilon(2S) \to e\tau$)
- Observed events are 3 (12) for $\Upsilon(2S) \to \mu\tau$ ($\Upsilon(2S) \to e\tau$)
- Upper limits at 90% C.L. of

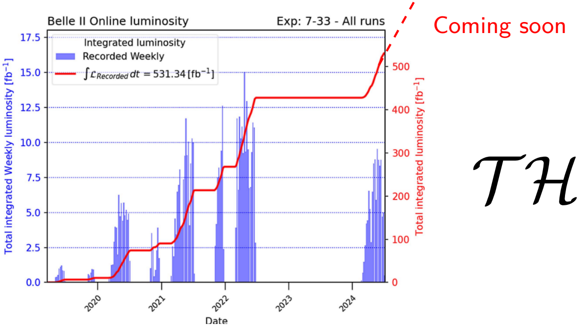
$$\mathcal{B}(\Upsilon(2S) \to \mu\tau) < 0.23 \times 10^{-6}$$
$$\mathcal{B}(\Upsilon(2S) \to e\tau) < 1.12 \times 10^{-6}$$

- Belle obtained 14 (3) times better upper limits for $\Upsilon(2S) \to \mu\tau$ ($\Upsilon(2S) \to e\tau$) as compared to previous results from BaBar [1].

[1] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. 104, 151802 (2010).

- **Belle** is still providing **new LFV results in τ and hadron decays** and **Belle II** will contribute more in the future.
  - Some of them are **world leading results**: $\tau \to \mu\mu\mu$, $\tau \to lV^0$, $\tau \to \Lambda\pi$, $D \to pl$, $B^0 \to \tau e$, $\Upsilon(2S) \to l\tau$, and others...

- Within the next years of data taking Belle II will collect more data with expectations of significant improvements in current limits, spanning from a few parts in $\mathbf{10^{-10}}$ **to** $\mathbf{10^{-9}}$



THANK YOU!

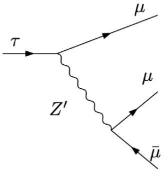
BACKUP SLIDES

- **Search for various decay models:**
  - $\tau \to lll$
  - $\tau \to lK_S^0, \Lambda\pi$
  - $\tau \to lV^0(\to hh')$
  - $\tau \to lP^0(\to \gamma\gamma)$
  - $\tau \to lhh'$
  - $\tau \to l\gamma$

Simple:good determination of m_τ and E_τ
few SM background sources

Golden Channel: $\tau \to \mu\mu\mu$
Experimentally the most accessible

higher background

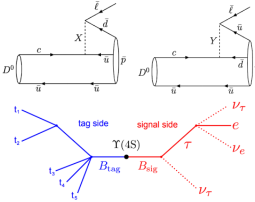


- **Motivation:** the decay channels forbidden in the SM but allowed in several new physics scenarios
  - LFV decay $\tau \to lV^0$
    - The $\tau \to \mu\phi$ mode is a sensitive probe for leptoquark models
  - BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$
    - BNV is one of the necessary conditions to explain the asymmetry of matter
    - Beyond SM scenarios allow for BNV and LNV
  - LFV decay $\tau \to \mu\mu\mu$ (**Golden Channel**)

Physics Models	$\mathcal{B}(\tau \to \mu\mu\mu)$
SM	10^{-53}~10^{-55}
SM + seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

B and other LFV channels

- **We present results for these other decay models:**
  - $D \to pl$
  - $B_s^0 \to \tau l$
  - $B^0 \to K_S^0 \tau l$
  - $\Upsilon(2S) \to l\tau$

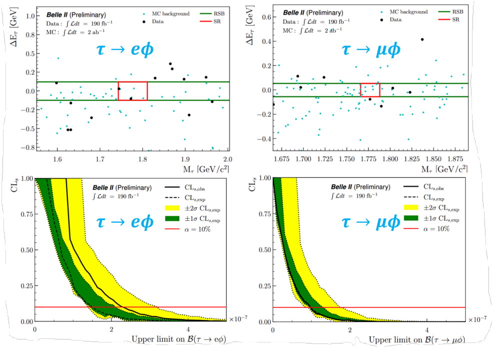


- The decay channels are fobidden in the SM but allowed in **many BSM theories**.
- Some of them are searching also for **BNV**, and are optimal for **leptoquarks** searches.
- Final states involving τ generally require special techniques due to the presence of missing energy (neutrinos) and lack of a distinctive signature
  - Belle II offers **improved software/tools** (B-tagging with FEI)

Search for LFV decay $\tau \to l\phi$ @ Belle II

- **Untagged inclusive reconstruction, reconstruct signal side as phi meson + lepton candidate, assign everything else (neutral clusters, tracks) to the rest of event (ROE):**
  - higher signal efficiency ($\sim 16\%$ improvement), more background
  - backgrounds reduced with pre selections and a BDT trained against $q\bar{q}$ events

arXiv:2305.04759



Experiment	Lum (fb^{-1})	$\mathcal{B}^{90}_{UL}(e\phi)$ ($\times 10^{-8}$) exp. / obs.	$\mathcal{B}^{90}_{UL}(\mu\phi)$ ($\times 10^{-8}$) exp. / obs.
BaBar [1]	451	5.0 / 3.1	8.2 / 19
Belle	854	4.3 / 3.1	4.9 / 8.4
Belle II	190	15 / 23	9.9 / 9.7

- Results not competitive yet (Small data set)
- First, successfully untagged strategy approach for tau physics at Belle II
- exploited for other measurements

[1] B. Aubert, *et. al.*, (BaBar Collaboration) Phys. Rev. Lett. 103, 021801 (2009)