Probing charged lepton flavor violation with axion-like particles at Belle II

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Motivation

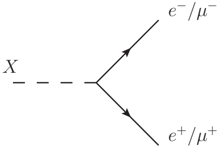
- Belle II: e^- and e^+ beams at $\Upsilon(4S)$
- A large number of $\tau^+\tau^-$ events $\Rightarrow$ study rare τ decays
- Sensitive to LFV related to the third-generation leptons
- Leptophilic axion-like particles

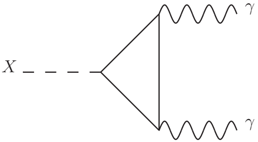
Model

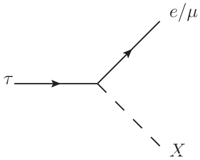
- X: axion-like particle

$$
\begin{aligned}
\mathcal{L}_X &= \frac{\partial_\mu X}{\Lambda} \bar{l}_\alpha G_{\alpha\beta} \gamma^\mu (1+\gamma^5) l_\beta \\
&= -i \frac{X}{\Lambda} \bar{l}_\alpha G_{\alpha\beta} ((m_\alpha - m_\beta) + (m_\alpha + m_\beta)\gamma^5) l_\beta \\
g_{\alpha\beta} &\equiv G_{\alpha\beta}/\Lambda
\end{aligned}
$$

- *Sign. production*: $\tau \to Xe/\mu$
- *Sign. decay*: $X \to e^- e^+ / \mu^- \mu^+$
- $X \to \gamma\gamma$ induced via a triangular loop







Decay widths of τ and X

- $\tau \to Xe/\mu$:

$$\Gamma(l_\alpha \to l_\beta X) = \frac{m_\alpha^3}{8\pi}\sqrt{\left(1-\left(\frac{m_\beta+m_X}{m_\alpha}\right)^2\right)\left(1-\left(\frac{m_\beta-m_X}{m_\alpha}\right)^2\right)}$$
$$\times \; g_{\alpha\beta}^2\left[\left(1-\frac{m_\beta^2}{m_\alpha^2}\right)^2-\frac{m_X^2}{m_\alpha^2}\left(1+\frac{m_\beta^2}{m_\alpha^2}\right)\right]$$

- ALP decays:

$$\Gamma(X \to l_\beta^- l_\beta^+) = \frac{m_X\, m_\beta^2}{2\pi} g_{\beta\beta}^2\sqrt{1-\frac{4m_\beta^2}{m_X^2}}$$
$$\Gamma(X \to \gamma\gamma) = 4\pi\alpha^2 m_X^3 |g_{\gamma\gamma}^{\text{eff}}|^2,\; g_{\gamma\gamma}^{\text{eff}} = \frac{1}{8\pi^2}\sum_{\alpha=e,\mu,\tau} g_{\alpha\alpha}\, B_1(4m_\alpha^2/m_X^2)$$

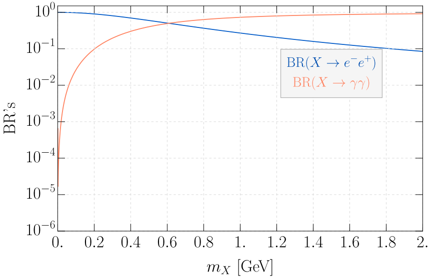
Benchmark scenarios

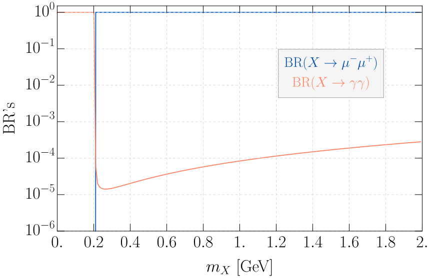
	Scenario 1	Scenario 2
$g_{\tau\alpha}$ tau decays	$g_{\tau e}$ $\tau \to Xe$	$g_{\tau\mu}$ $\tau \to X\mu$
$g_{\beta\beta}$ X decays	g_{ee} $X \to e^- e^+(\text{sig.})/\gamma\gamma$	$g_{\mu\mu}$ $X \to \mu^-\mu^+(\text{sig.})/\gamma\gamma$

- $g_{\tau\alpha}$ and $m_X \Rightarrow$ prod. rates
- $g_{\beta\beta}$ and $m_X \Rightarrow c\tau_X$

X decays

- $\Gamma(X \to l_\beta^- l_\beta^+) \sim m_X\, m_\beta^2, \Gamma(X \to \gamma\gamma) \sim m_X^3$





Tightest current constraint

- Belle results on tau LFV decays which we recast:

Decay modes	Upper bounds on BR $[10^{-8}]$
$\tau^- \to e^- e^+ e^-$	2.7
$\tau^- \to \mu^- \mu^+ \mu^-$	2.1
$\tau^- \to e^- \mu^+ \mu^-$	2.7
$\tau^- \to \mu^- e^+ e^-$	1.8
$\tau^- \to e^+ \mu^- \mu^-$	1.7
$\tau^- \to \mu^+ e^- e^-$	1.5

arXiv:1001.3221

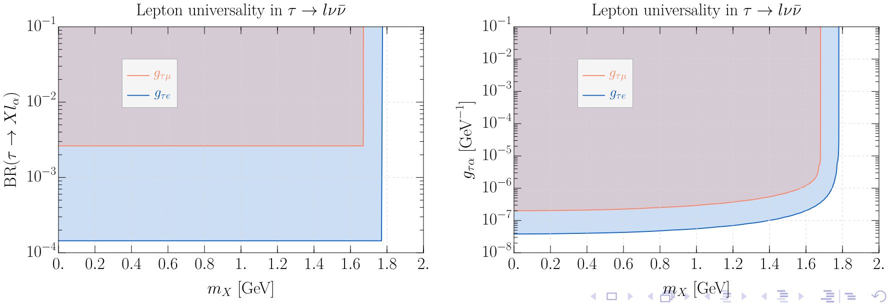
Second-tightest current constraint

Lepton flavor universality from BaBar, for long-lived X ($c\tau_X \gtrsim 1$ m)

- $$R_{\mu e} = \frac{\Gamma_{\tau\to\mu\nu\bar{\nu}}}{\Gamma_{\tau\to e\nu\bar{\nu}}}, R_{\mu e}^{\rm SM} = 0.972559 \pm 0.000005, R_{\mu e}^{\rm BaBar} = 0.9796 \pm 0.0039$$
$$\Delta R_{\mu e} \equiv R_{\mu e}^{\rm BaBar}/R_{\mu e}^{\rm SM} - 1 = 0.0072 \pm 0.0040$$
$$R_{\mu e}^{\rm SM+X} = R_{\mu e}^{\rm SM} + \Gamma(\tau\to X\mu)/\Gamma^{\rm SM}_{\tau\to e\nu\bar{\nu}}$$
$$R_{\mu e}^{\rm SM+X}/R_{\mu e}^{\rm SM} - 1 < 0.0072 + 2\times 0.0040$$

$\Rightarrow$ bounds on $g_{\tau\mu}$ and BR($\tau\to X\mu$)

- Similarly for the e scenario, where $\Delta R_{e\mu} < 0 \Rightarrow$ particularly stringent bounds



Event selections

- $E_{e^-} = 7$ GeV, $E_{e^+} = 4$ GeV $\Rightarrow \sqrt{s} = 10.58$ GeV
- $\mathcal{L}^{\text{int}}_{\text{Belle}} = 1\ \text{ab}^{-1}$, $\mathcal{L}^{\text{int}}_{\text{Belle II}} = 50\ \text{ab}^{-1}$
- 4.6×10^{10} tau pair production events at Belle II

- Prompt search, recast arXiv:1001.3221:

1. Baseline efficiency:

Decay modes	Baseline efficiency
$\tau \to Xe, X \to e^- e^+$	6.0 %
$\tau \to X\mu, X \to \mu^- \mu^+$	7.6 %

2. $d_0 < 5$ mm (includ. track curvature in the B field) and $z_0 < 30$ mm
3. Small transverse distance: $r < 10$ cm

- Propose a displaced-vertex search:

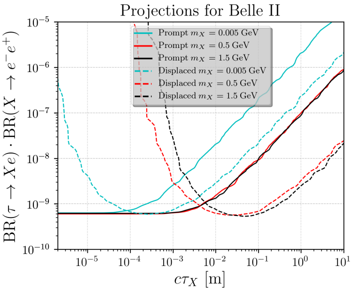
1. Baseline efficiency, same as above
2. Fiducial volume: 1 cm $< r <$ 80 cm, -40 cm $< z <$ 120 cm
3. Linear displaced-tracking efficiency: $\epsilon^{\text{track}}(r = 1\ \text{cm}) = 100\%$, $\epsilon^{\text{track}}(r = 80\ \text{cm}) = 0\%$

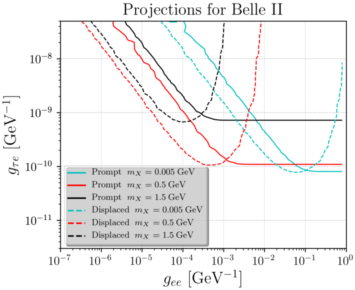
Sensitivity computation

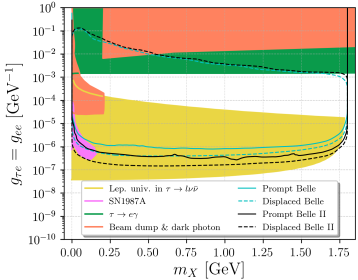
$$N_S^{\text{Belle II}} = 2 \cdot N_{\tau^-\tau^+} \cdot \text{BR}(\tau \to 1 \text{ prong}) \cdot \text{BR}(\tau \to X l_\alpha) \cdot \epsilon \cdot \text{BR}(X \to l_\alpha^- l_\alpha^+)$$

- $\text{BR}(\tau \to 1 \text{ prong}) \sim 85\%$
- Simulate kinematics with Pythia8
- Expected zero background $\to$ 3 signal-event isocurves as 95% C.L. exclusion limits

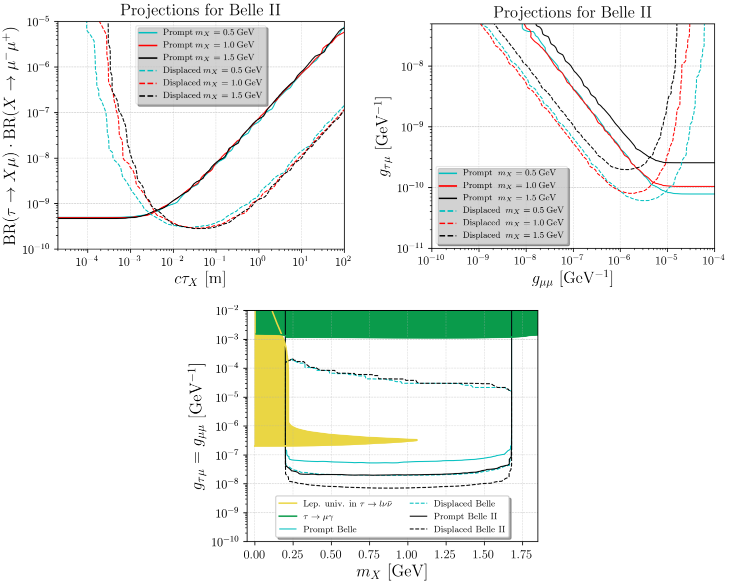
Results: Scenario 1







Results: Scenario 2



Summary

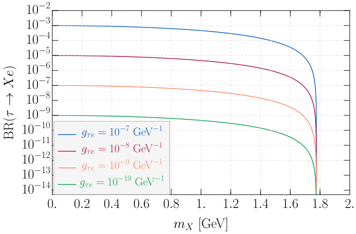
- Recast a Belle prompt search and proposed a DV search, for studying LFV with leptophilic ALPs at Belle II
- Estimated the search efficiencies with Monte-Carlo simulation
- DV/prompt searches better sensitivity at long/short decay lengths
- For long decay lengths, the DV search extends the prompt search's sensitivity to the branching-fraction product by a factor of 40

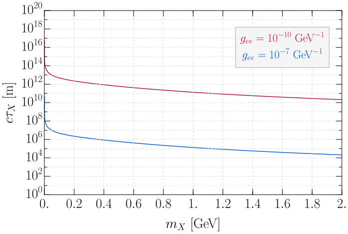
Thank You!

Back-up slides

Scenario 1

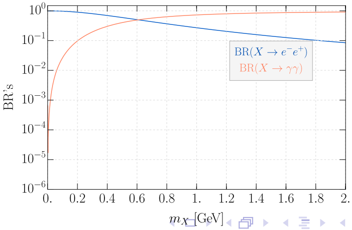
- Signature: $\tau \to Xe$, $X \to e^- e^+$





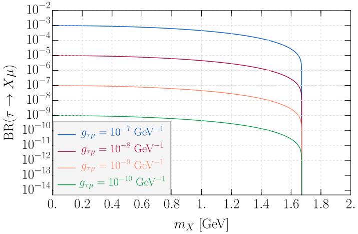
- $\mathrm{BR}(X \to \gamma\gamma) > \mathrm{BR}(X \to e^- e^+)$ for $m_X \gtrsim 0.6$ GeV

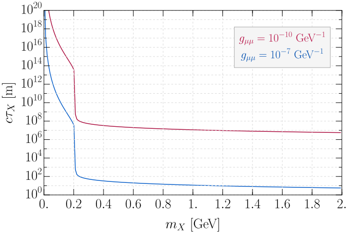
- $\Gamma(X \to l_\beta^- l_\beta^+) \sim m_X\, m_\beta^2$
- $\Gamma(X \to \gamma\gamma) \quad \sim m_X^3$

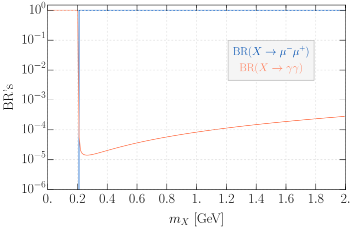


Scenario 2

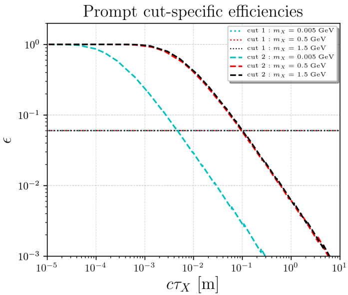
- Signature: $\tau \to X\mu$, $X \to \mu^-\mu^+$

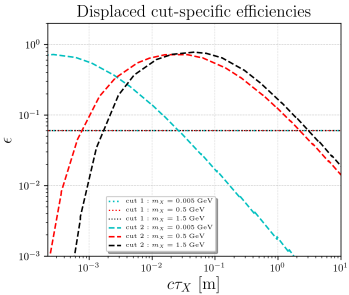


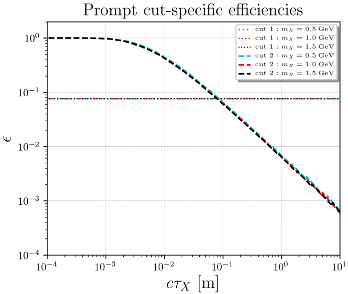


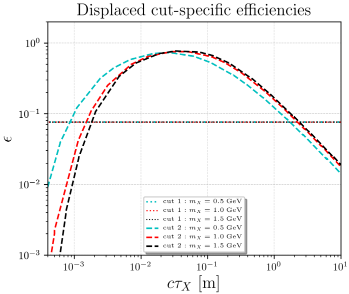


Efficiencies







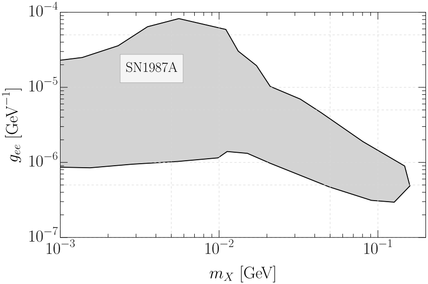


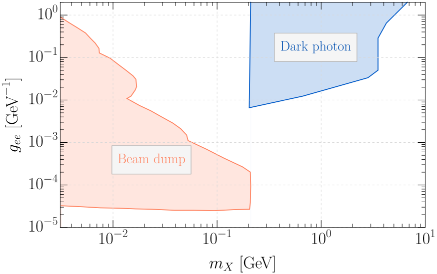
Less important constraints – I

- LEP ALEPH: $\sigma(e^- e^+ \to \tau^- \tau^+) = 6.02 \pm 0.39(\text{stat} \pm 0.09(\text{syst}))$ pb at

$\sqrt{s} = 209$ GeV$\Rightarrow g_{\tau e} < 0.078$ GeV^{-1}

- X coupled to leptons enhances cooling rate of supernova (arXiv:2107.12393):





- Beam-dump experiments (arXiv:1008.0636, arXiv:1005.3978)
- BaBar dark photon search (arXiv:1708.00443)
- BR($\tau \to e\gamma$)$< 3.3 \times 10^{-8}$ and BR($\tau \to \mu\gamma$)$< 4.4 \times 10^{-8}$ (arXiv:0908.2381)

$\Rightarrow g_{\tau e} g_{ee}$ and $g_{\tau\mu} g_{\mu\mu} \lesssim 10^{-6}$ GeV^{-2} for $m_X \lesssim m_\tau$

Less important constraints – II

- Leptonic decays of μ: $\mu \to e\gamma, \mu \to 3e, \mu \to e\gamma\gamma, \mu \to e +$ missing, strong bounds on coupling combinations or couplings, irrelevant to Scenarios 1 or 2
- Muonium-antimuonium oscillations with $g_{\mu e}$: not considered
- $\mu^- \to e^-$ conversion in nuclei with $g_{\mu e}$: not considered
- Leptonic $g-2$'s:

$$\begin{aligned} \Delta a_e &= a_e^{\rm exp} - a_e^{\rm SM} = (4.8 \pm 3.0) \times 10^{-13} \\ \Delta a_\mu &\equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (25.1 \pm 5.9) \times 10^{-10} \end{aligned}$$

$(g-2)_e$: the leptophilic X considered in Scenario 1 can bring the theoretical prediction to reach the 95% lower limit of Δa_e but not up to the central value
$(g-2)_\mu$: the ALPs in Scenario 2 cannot even bring the theoretical prediction to the edge of the 95% lower limit of the experimental value