Probing Charged Lepton Flavor Violation with Axion-like Particles at Belle II

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arXiv:2108.11094

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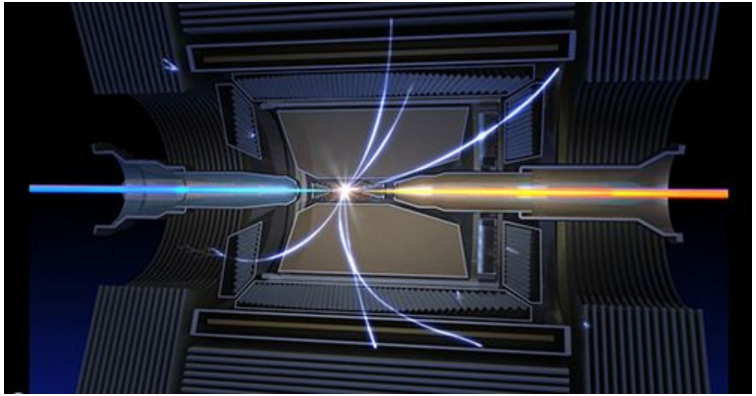
Motivation

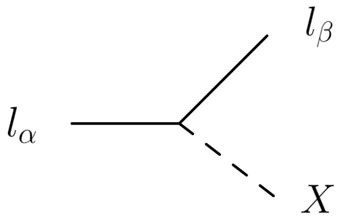
- Belle II: e^- of energy 7 GeV and e^+ of energy 4 GeV
- A large number of τ pair events → study rare τ decays
- Sensitive to new physics beyond the SM
- Leptophilic axion-like particles

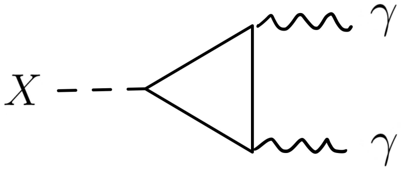


Model

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

- $\tau \to e/\mu\ X$
- Signature: $X \to e^- e^+ / \mu^- \mu^+$
- $X \to \gamma\gamma$ induced from a triangular loop





Decay widths

- LFV decays

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

- ALP decays (loop function B1)

$$\Gamma(X \to l_\beta^- l_\beta^+) = \frac{m_X\, m_\beta^2}{2\pi} g_{\beta\beta}^2 \sqrt{1-\frac{4m_\beta^2}{m_X^2}}$$

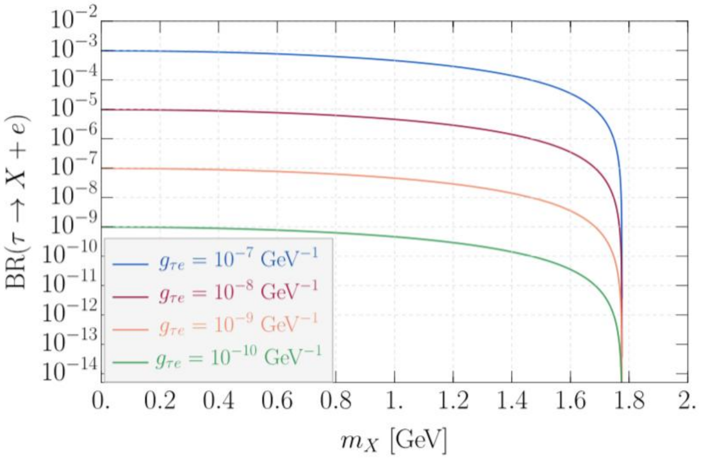
$$\Gamma(X \to \gamma\gamma) = 4\pi\alpha^2 m_X^3 |g_{\gamma\gamma}^{\text{eff}}|^2 \qquad g_{\gamma\gamma}^{\text{eff}} = \frac{1}{8\pi^2}\sum_{\alpha=e,\mu,\tau} g_{\alpha\alpha}\, B_1(4m_\alpha^2/m_X^2)$$

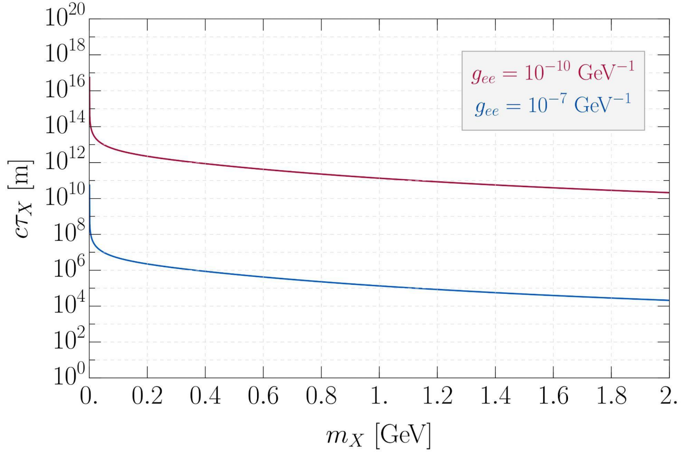
Benchmark scenarios

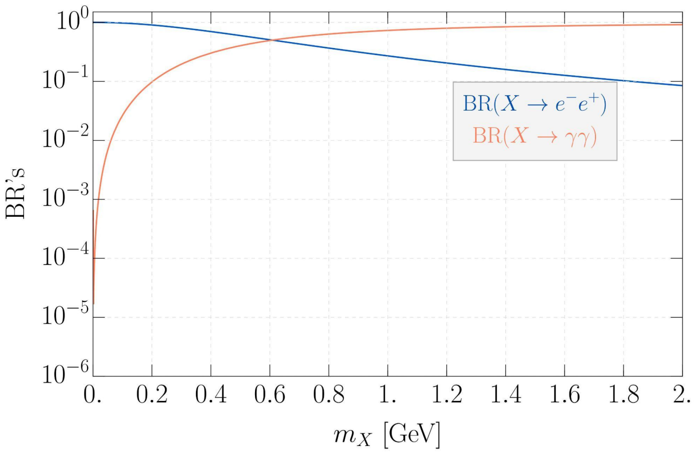
	Scenario 1	Scenario 2
$g_{\tau\alpha}$ τ decays	$g_{\tau e}$ $\tau \to Xe$	$g_{\tau\mu}$ $\tau \to X\mu$
$g_{\beta\beta}$ X decays	g_{ee} $X \to e^- e^+ (\text{sig.})/\gamma\gamma$	$g_{\mu\mu}$ $X \to \mu^- \mu^+ (\text{sig.})/\gamma\gamma$

Scenario 1

- $\tau \rightarrow Xe$, $X \rightarrow e^- e^+$
- $BR(X \rightarrow \gamma\gamma) > BR(X \rightarrow e^- e^+)$ if $m_X \gtrsim 0.6$ GeV

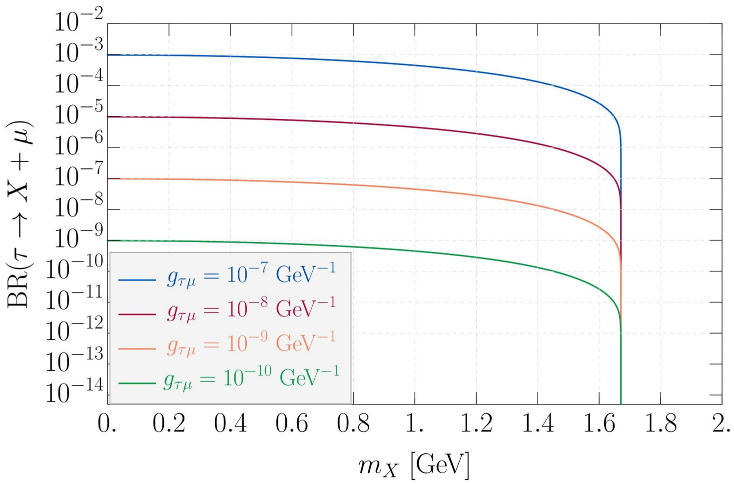


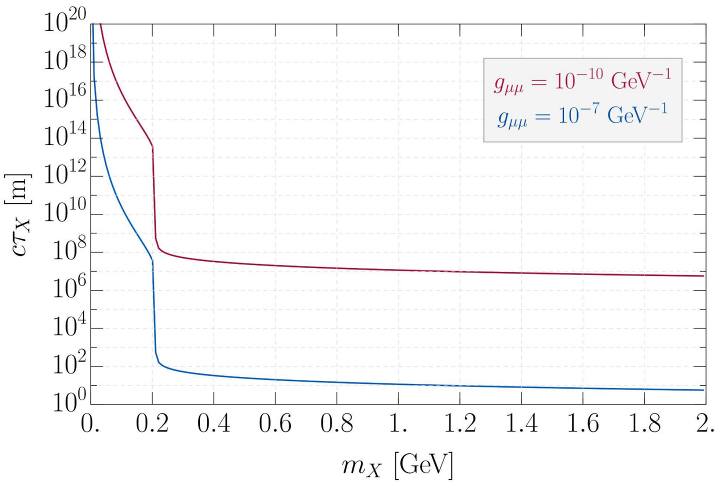


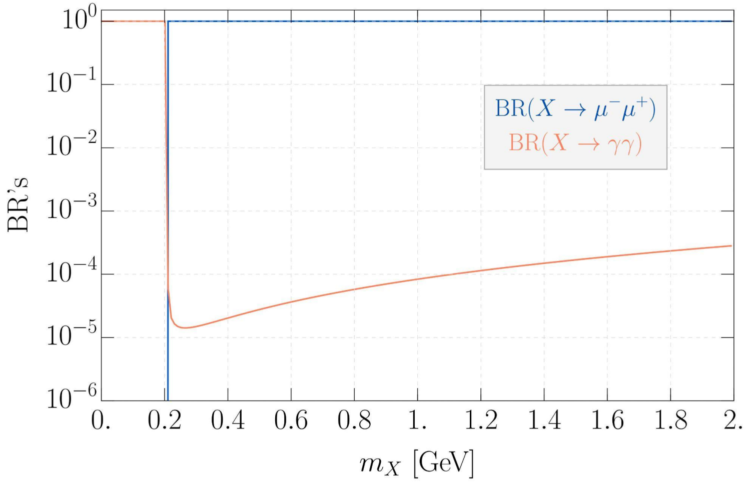


Scenario 2

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

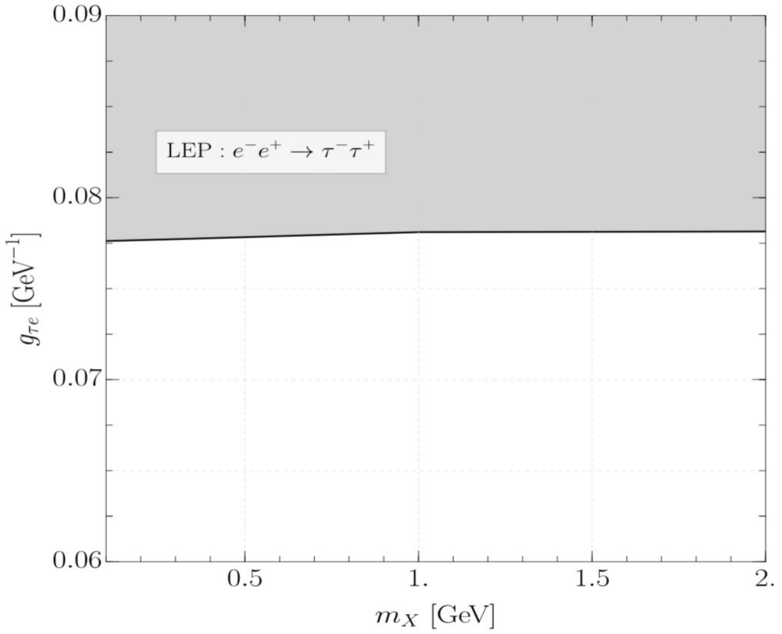






Constraints - LEP

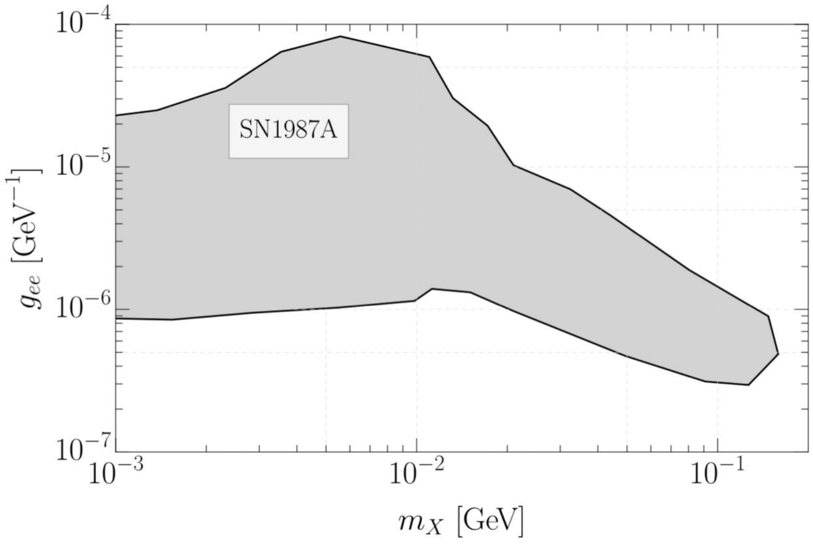
- ALEPH: measured inclusive σ of $e^-e^+ \to \tau^-\tau^+$ at $\sqrt{s}$ = 209 GeV
- σ = 6.02 ± 0.39 (stat) ± 0.09 (syst) pb
- Theory prediction modified
- A weak bound on our model



Constraints - Supernova

- Cooling rate of the core
- $g_{\mu\mu}$ at 10^{-8} GeV^{-1} for m_X < 1 MeV
- g_{ee} limits with SN1987A bound

arXiv:2005.07141 arXiv:2107.12393



Constraints - Lepton-flavor-violating tau decays

- 782 fb^{-1} data from Belle detector
- 90% C.L. upper limits on the branching fraction

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

Constraints - Lepton flavor universality

- The ratio of rates

$$R_{\mu e} = \frac{\Gamma_{\tau\to\mu\nu\bar{\nu}}}{\Gamma_{\tau\to e\nu\bar{\nu}}} \qquad R_{\mu e}^{\mathrm{SM}} = 0.972559 \pm 0.000005$$
$$R_{\mu e}^{\mathrm{BaBar}} = 0.9796 \pm 0.0039$$

- The discrepancy

$$\Delta R_{\mu e} \equiv R_{\mu e}^{\mathrm{BaBar}}/R_{\mu e}^{\mathrm{SM}} - 1 = 0.0072 \pm 0.0040$$

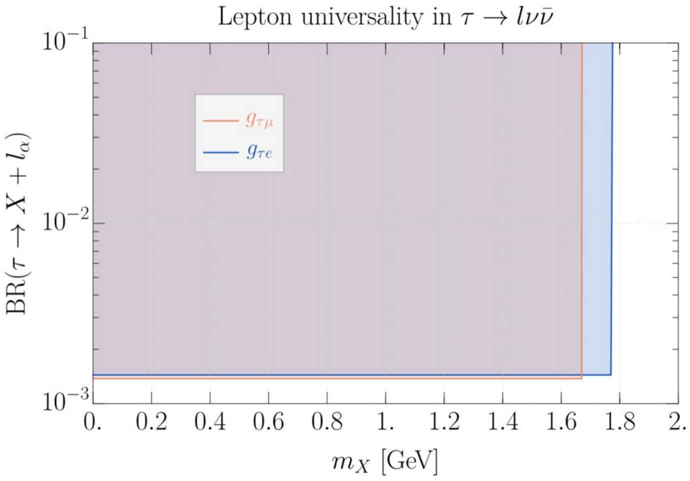
- In the presence of the ALP   arXiv:0912.0242

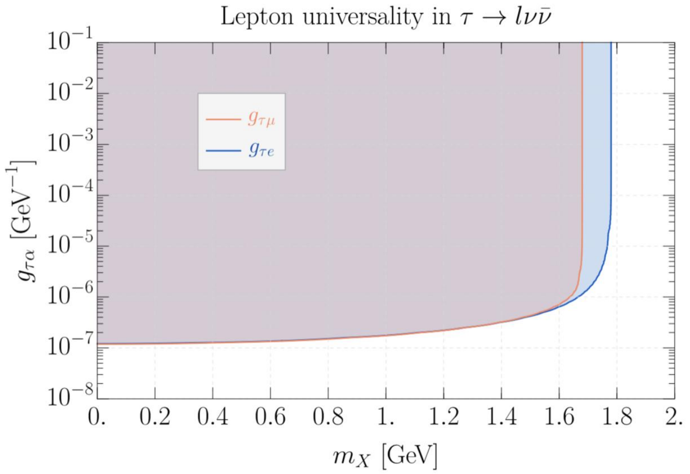
$$R^{\mathrm{SM}+X} = R_{\mu e}^{\mathrm{SM}} + \Gamma(\tau \to X\mu)/\Gamma_{\tau\to e\nu\bar{\nu}}^{\mathrm{SM}}$$

$$\Gamma_{\tau\to e\nu\bar{\nu}}^{\mathrm{exp}} = 4.04\times 10^{-13}\ \mathrm{GeV}$$

$$|R_{\mu e}^{\mathrm{BaBar}}/R_{\mu e}^{\mathrm{SM}+X} - 1 - \Delta R_{\mu e}| < 2\times 0.0040$$

See also arXiv:2106.02451





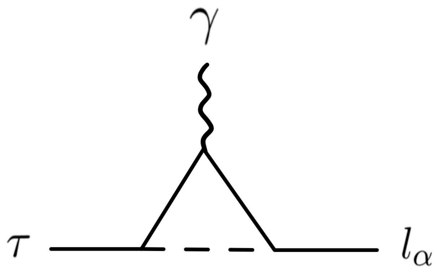
Constraints - lγ final states

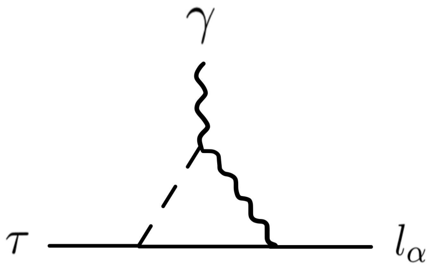
- Experimental upper bounds on coupling products

$$\mathrm{BR}(\tau \to e\gamma) < 3.3\times 10^{-8} \qquad \mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

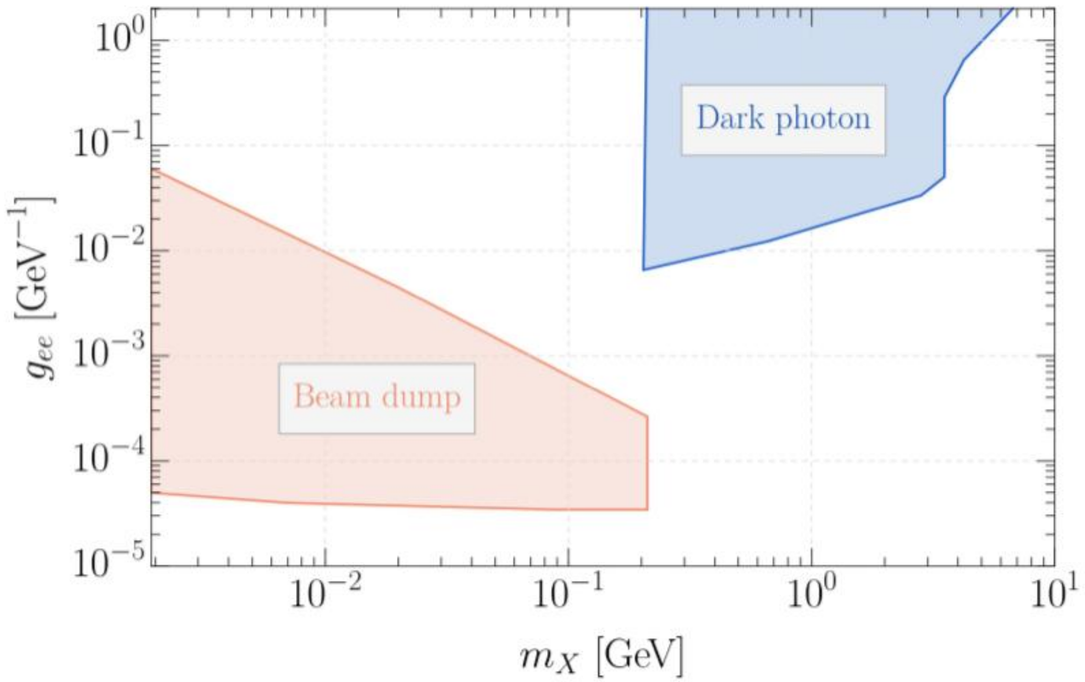
arXiv:0908.2381 arXiv:1911.06279

- $g_{\tau e} g_{ee}$ and $g_{\tau\mu} g_{\mu\mu}$ ~ 10^{-6} GeV^{-2} for m_X between 0 and 2 GeV





Constraints-Beam-dump experiments and dark-photo searches



arXiv:1708.00443 arXiv:1008.0636 arXiv:1005.3978 arXiv:1606.03501

Selections - Belle and Belle II

- Belle and Belle II: E_{e^-}= 7 GeV, E_{e^+} = 4 GeV (CM energy 10.58 GeV)
- Belle samples are 1 ab^{-1}
- 50 ab^{-1} at Belle II
- 4.6 * 10^{10} $\tau^-\tau^+$ pair production at Belle II

Prompt search selections

- Baseline efficiency

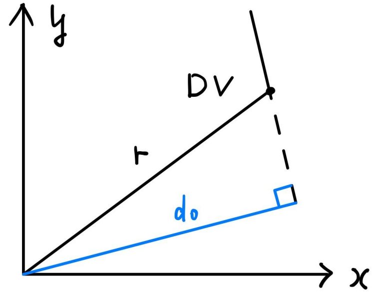
Decay modes	Baseline efficiency
$\tau \to Xe, X \to e^- e^+$	$6.0\,\%$
$\tau \to X\mu, X \to \mu^- \mu^+$	$7.6\,\%$

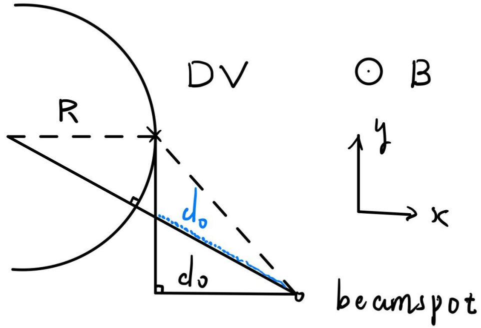
arXiv:1001.3221

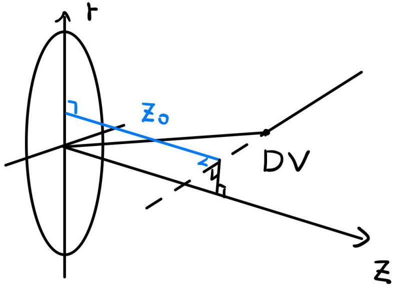
- Impact parameters:

  $d_0 < 5$ mm, $z_0 < 30$ mm

- Small r : r < 10 cm







DV search selections

- 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 %

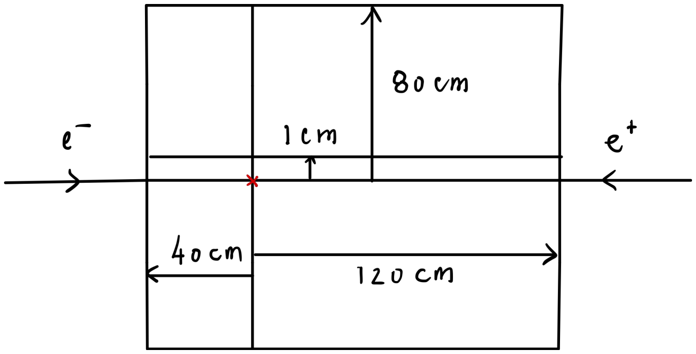
arXiv:1001.3221

- Fiducial volume: arXiv:1810.12602

  1 cm < r < 80 cm, -40 cm < z < 120 cm

- Linear displaced-tracking efficiency :

  100% for r = 1 cm, 0% for r = 80 cm



Final sensitivity computation

- The number of signal events

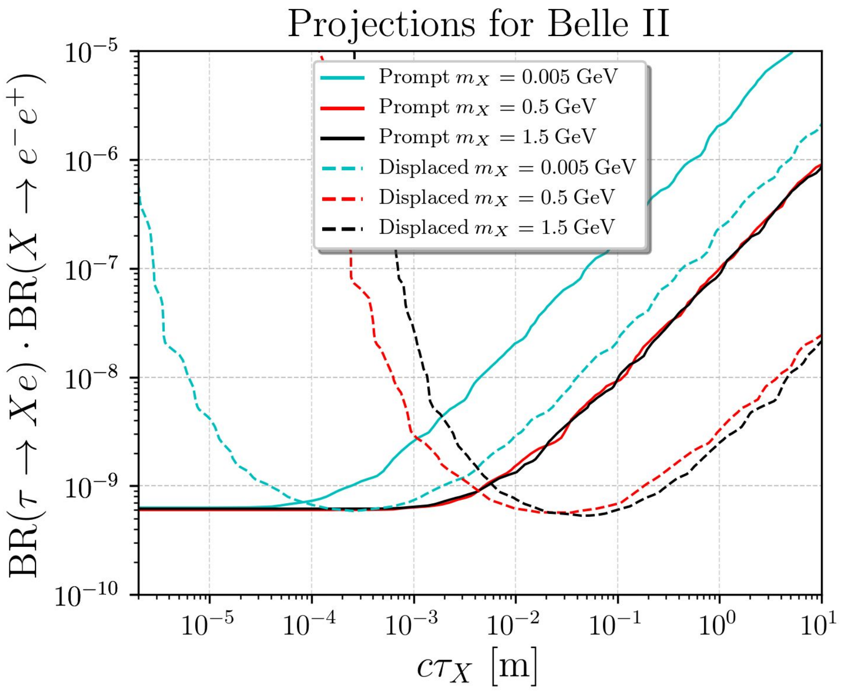
$$N_S^{\text{Belle II}} = 2 \cdot N_{\tau^-\tau^+} \cdot \text{BR}(\tau \to 1 \text{ prong}) \cdot \text{BR}(\tau \to X l_\alpha) \cdot \epsilon \cdot \text{BR}(X \to l_\alpha^- l_\alpha^+)$$

- Kinematics simulated with Pythia8 (decay position, boost factor, direction)

- Expected vanishing background → 3 signal events for 95% C.L. exclusions

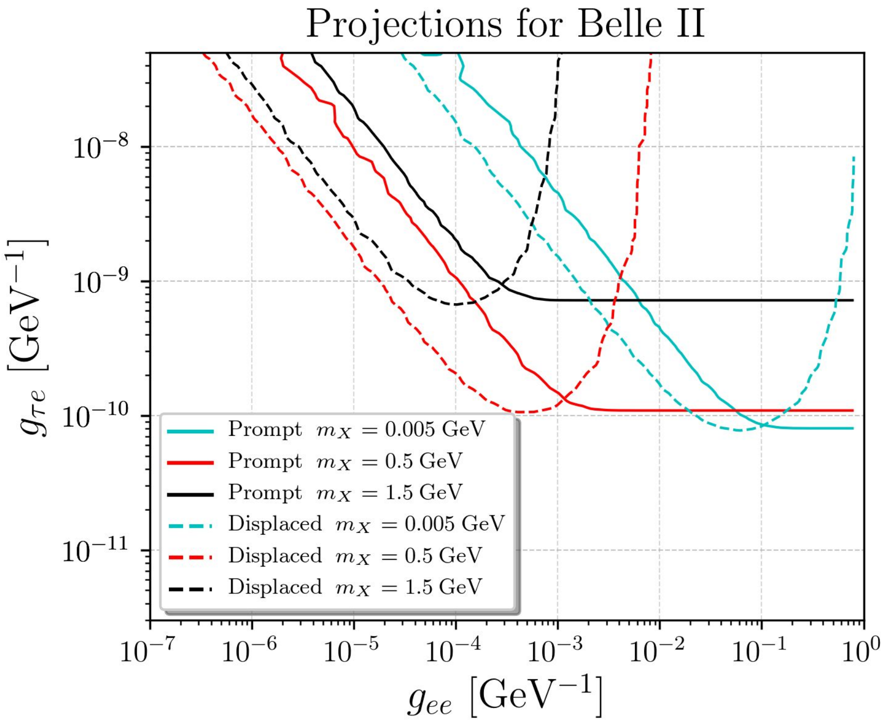
Scenario 1 - Model-independent results

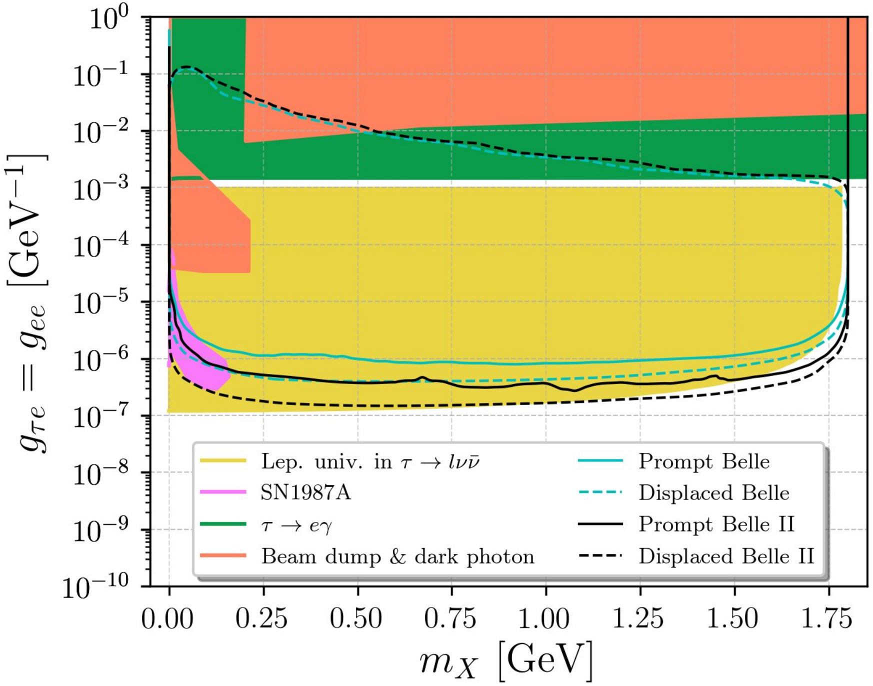
- Similar the strongest reach in BR in both strategies, at diff. cτ
- 40 times stronger in DV. search at large cτ region



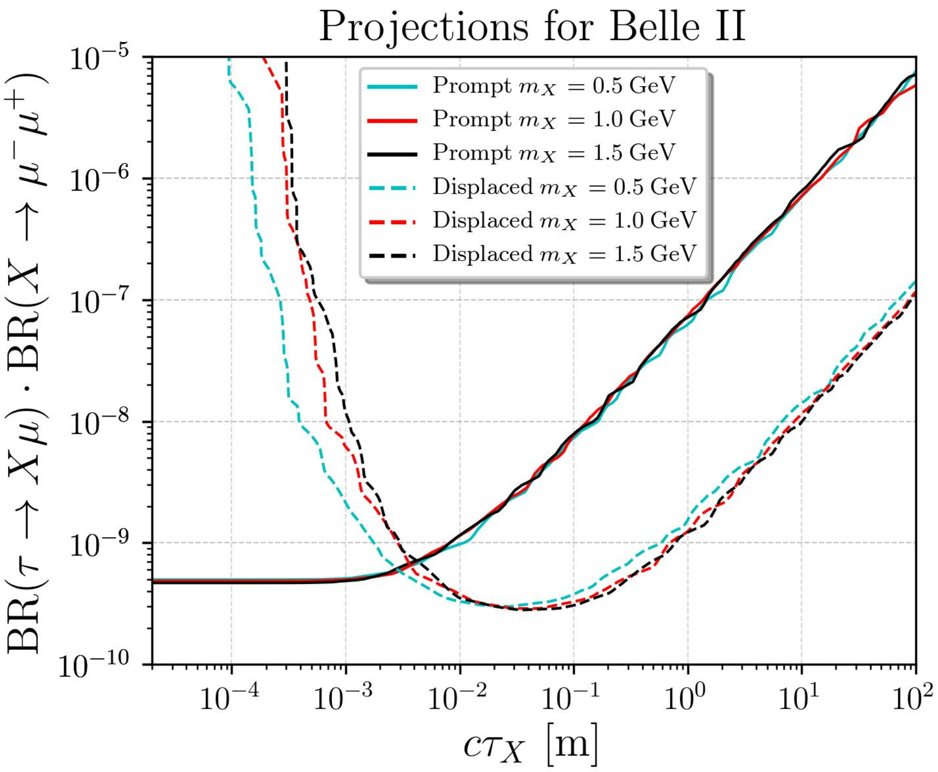
Scenario 1 - Model-dependent results

- At small g_{ee}, DV reach in $g_{\tau e}$ stronger by ~ 6
- Beyond current constraints (left)



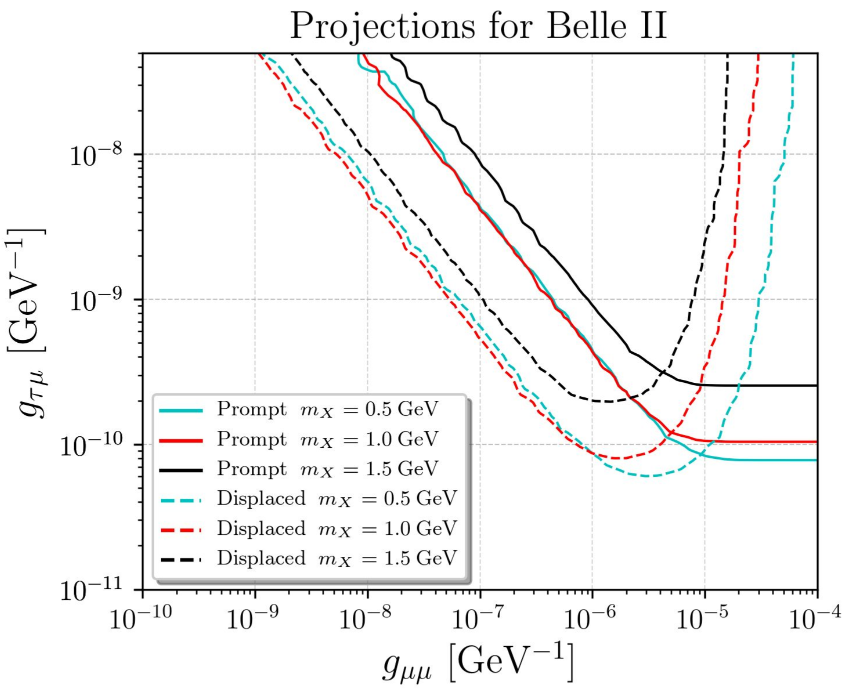


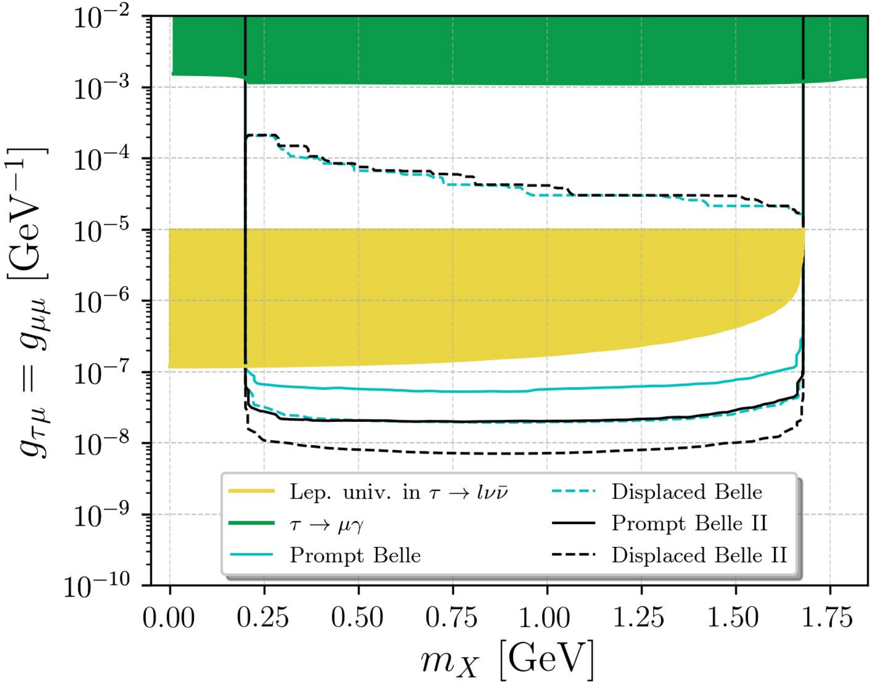
Scenario 2 - Model-independent results



Scenario 2 - Model-dependent results

- Diagonal coupling sensitivity enhanced





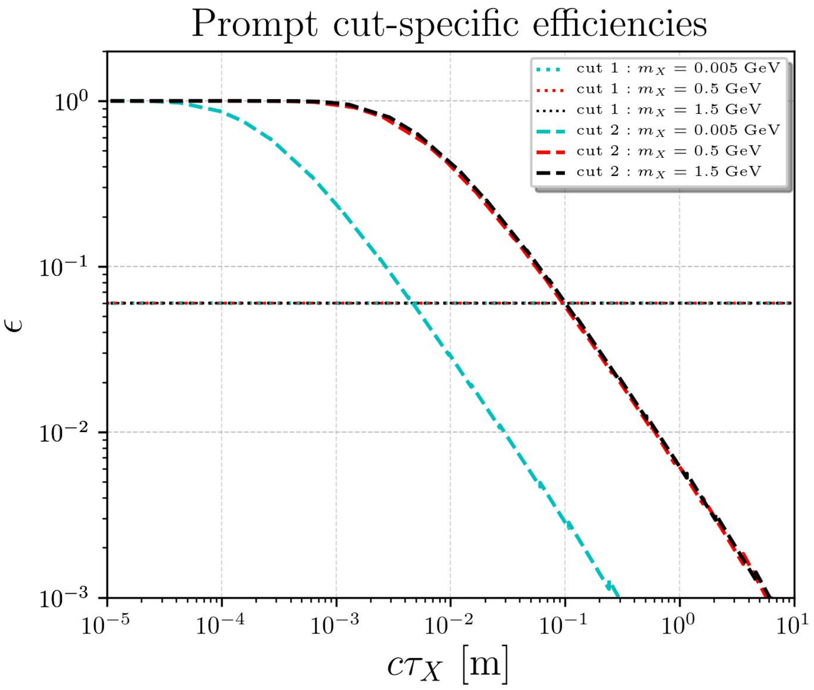
Conclusions

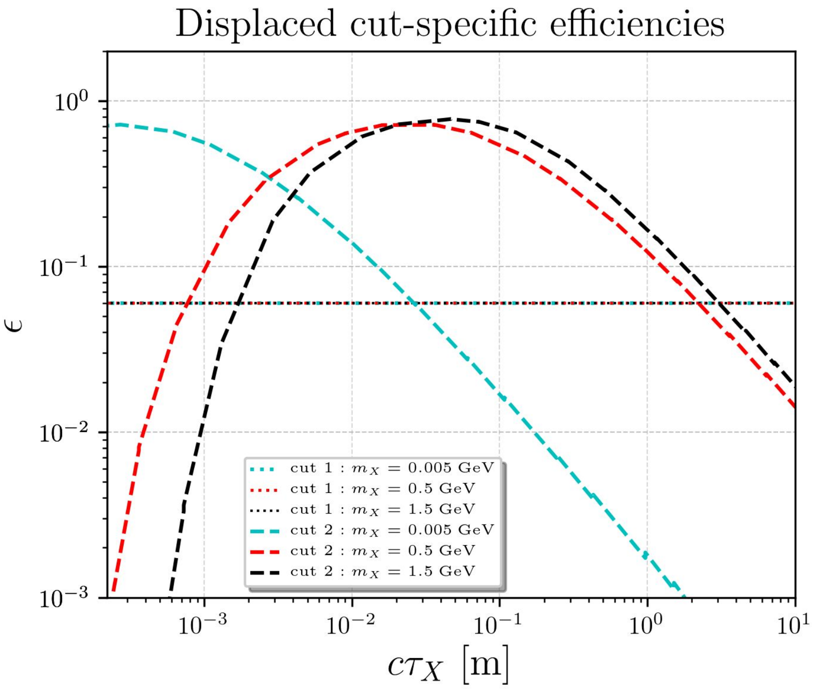
- Recast a Belle prompt search and proposed a DV search for studying LFV with ALP at Belle II
- Performed Monte-Carlo simulation to determine sensitivity limits
- DV/prompt search shows better sensitivity at long/short decay length regime
- For long decay lengths, DV search extends the prompt search's sensitivity to the branching-fraction product by a factor of 40

THANK YOU!

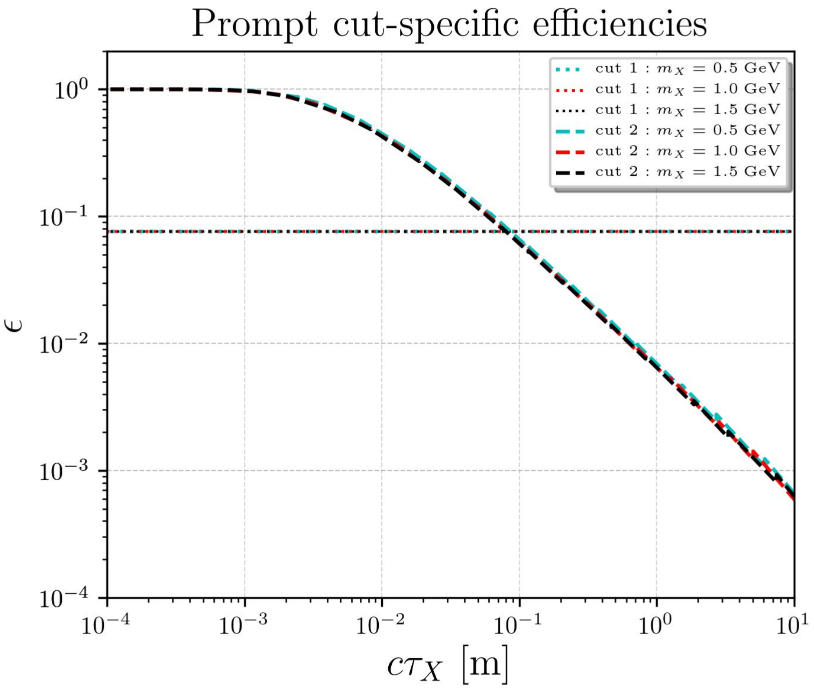
Backup Slides

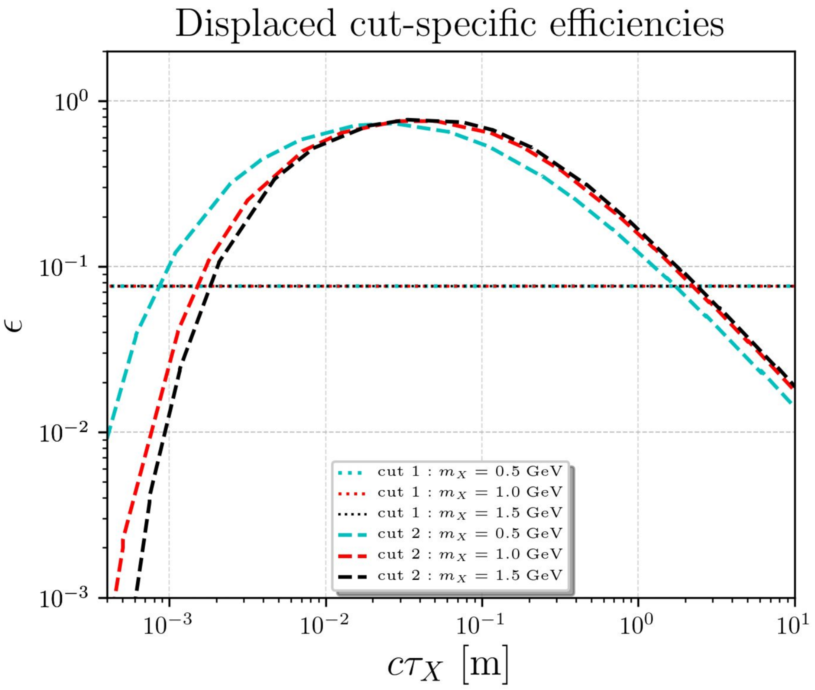
Scenario 1 - Efficiencies





Scenario 2 - Efficiencies





Constraints - lγ final states

- Experimental upper bounds on coupling products

arXiv:0908.2381 arXiv:1911.06279

$$\mathrm{BR}(\tau \to e\gamma) < 3.3\times 10^{-8} \qquad \mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

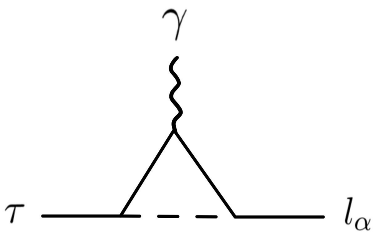
- Analytic expressions

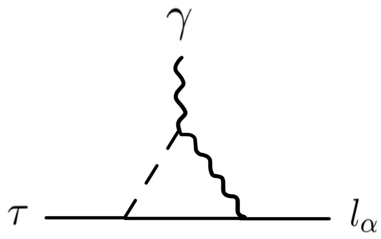
$$\Gamma(\tau \to l_\alpha \gamma) = \frac{m_\tau e^2}{8\pi}\left(|\mathcal{F}_2^\alpha(0)|^2 + |\mathcal{G}_2^\alpha(0)|^2\right), \text{ for } m_\tau \gg m_e, m_\mu$$

$$\begin{aligned}
\mathcal{F}_2^\alpha(0)_{\text{lin.}} &= -\frac{e^2 m_\tau^2}{8\pi^2} g_{\tau\alpha} g_{\gamma\gamma}^{\text{eff}} g_\gamma(x_\tau), \\
\mathcal{G}_2^\alpha(0)_{\text{lin.}} &= -\frac{e^2 m_\tau^2}{8\pi^2} g_{\tau\alpha} g_{\gamma\gamma}^{\text{eff}} g_\gamma(x_\tau), \\
\mathcal{F}_2^\alpha(0)_{\text{quad.}} &= -\frac{m_\tau}{16\pi^2}\, g_{\tau\alpha}\, g_{\alpha\alpha}\, m_\alpha\, g_2(x_\tau), \\
\mathcal{G}_2^\alpha(0)_{\text{quad.}} &= +\frac{m_\tau}{16\pi^2}\, g_{\tau\alpha}\, g_{\alpha\alpha}\, m_\alpha\, g_2(x_\tau),
\end{aligned}$$

$$\begin{aligned}
\mathcal{F}_2^\alpha(0) &= \mathcal{F}_2^\alpha(0)_{\text{lin.}} + \mathcal{F}_2^\alpha(0)_{\text{quad.}} \\
\mathcal{G}_2^\alpha(0) &= \mathcal{G}_2^\alpha(0)_{\text{lin.}} + \mathcal{G}_2^\alpha(0)_{\text{quad.}},
\end{aligned}$$

$$\text{where } x_\tau = m_X^2/m_\tau^2 - i\epsilon \text{ with } \epsilon \to 0^+$$





- $g_{\tau e}g_{ee}$ and $g_{\tau\mu}g_{\mu\mu}$ ~ 10^{-6} GeV^{-2} for m_X between 0 and 2 GeV

Leptonic decays of the muon

- BR($\mu \to e\gamma$) limits place very strong bounds on coupling products
- $\mu \to 3e$, $\mu \to e\gamma\gamma$ and $\mu \to e$+missing are not studied here

Leptonic g - 2 anomalies

- 1.6 and 4.2 uncertainty of a = (g-2)/2

$$\Delta a_e = a_e^{\exp} - a_e^{\rm SM} = (4.8 \pm 3.0) \times 10^{-13}.$$

$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{\rm SM} = (25.1 \pm 5.9) \times 10^{-10}.$$

$$(\Delta a_{l_\alpha})_{\rm diag.} = -\frac{m_\alpha^2}{4\pi^2}\left[16\pi\,\alpha_{\rm em}\, g_{\gamma\gamma}^{\rm eff}\, g_{\alpha\alpha}\left(\log\frac{\Lambda^2}{m_\alpha^2} - h_2(x_\alpha)\right) + |g_{\alpha\alpha}|^2 h_1(x_\alpha)\right],$$

where $x_\alpha = m_X^2/m_\alpha^2$, $g_{\gamma\gamma}^{\rm eff}$ can be computed by Eq. (2.7), and

$$h_1(x) = 1 + 2x - (x-1)x\log x + 2x(x-3)\sqrt{\frac{x}{x-4}}\log\left(\frac{\sqrt{x}+\sqrt{x-4}}{2}\right),$$

$$h_2(x) = 1 + \frac{x^2}{6}\log x - \frac{x}{3} - \frac{x+2}{3}\sqrt{(x-4)x}\log\left(\frac{\sqrt{x}+\sqrt{x-4}}{2}\right).$$

Muonium-antimuonium oscillations

- Muonium M = (e-μ+)
- Conversion probability < 8.3 * 10^{-11} at 90% C.L.
- μ -> e NOT included