Tau physics and dark sector searches at Belle and Belle II

Vietnam Flavour Physics Conference 2025

Jing-Ge Shiu

on behalf of the Belle and Belle II collaborations

Outline

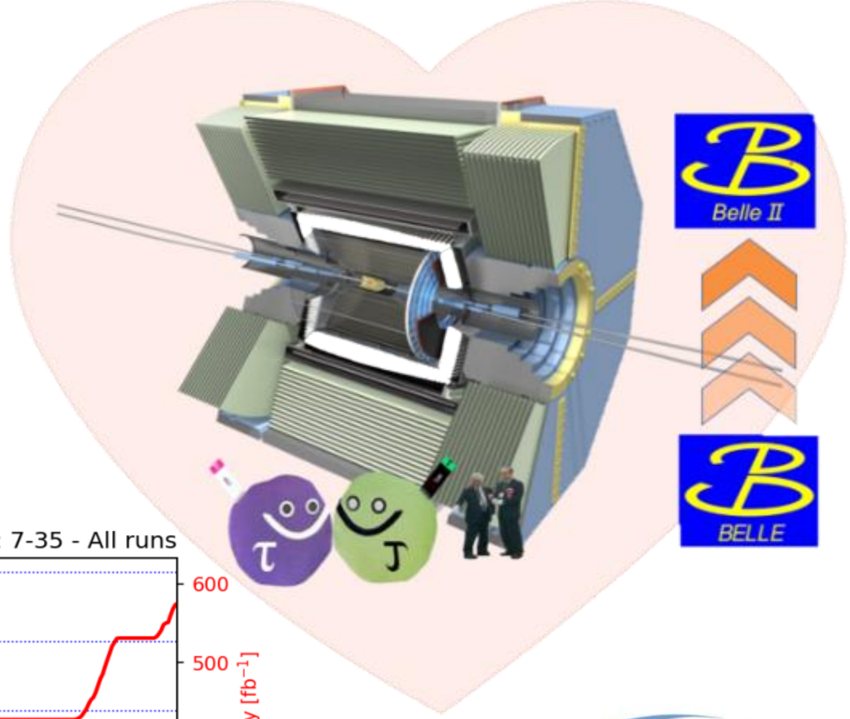
- SuperKEKB and Belle II
- τ physics at Belle and Belle II
  - ✓ Lepton Flavour Violation
- Dark sector search at Belle and Belle II
- Summary

SuperKEKB and Belle II

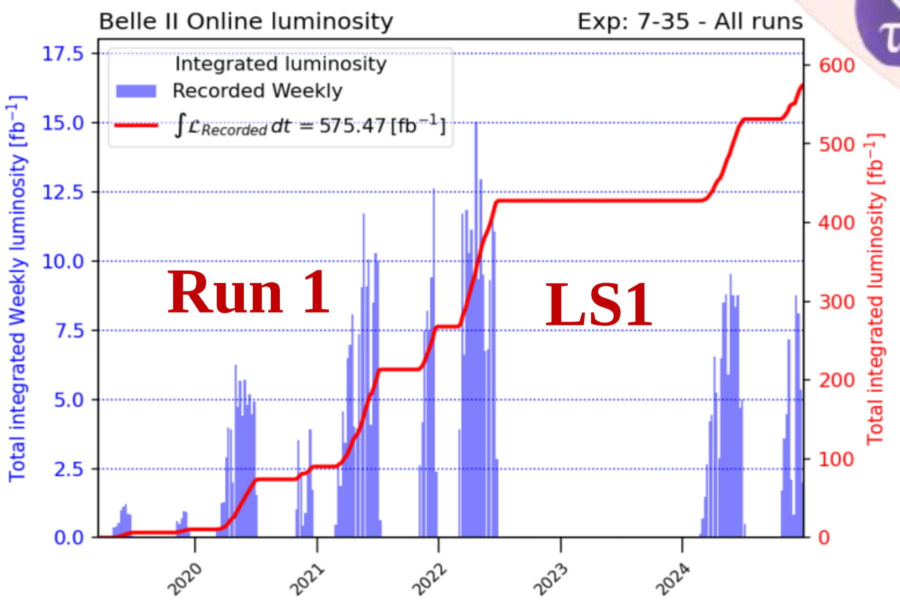
- Succeeding Belle/KEKB, designed to explore the luminosity frontier
  - ✓ Targeting at $6\times10^{35}/cm^2/s$ and 50 ab^{-1} data
    - ➢ precision measurements and searching for physics beyond the Standard Model (SM).
  - ✓ Center-of-mass (c.m.) energy 10.58GeV
    - ➢ besides B and charm, also good for τ physics and dark sector searches.

      $\sigma(e^+e^- \to \Upsilon(4S)) = 1.05\,nb$

      $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\,nb$ and no need to be on $\Upsilon(4S)$



- Physics commissioning started in 2019, up to the end of 2024,
  - ✓ peak luminosity $5.1\times10^{34}/cm^2/s$
  - ✓ integrated luminosity 575 fb^{-1}



- Data used in this report:

  Belle: 900M τ pairs (1 ab^{-1})

  Belle II: 400M τ pairs (0.4 ab^{-1}) (run 1, till 2022)

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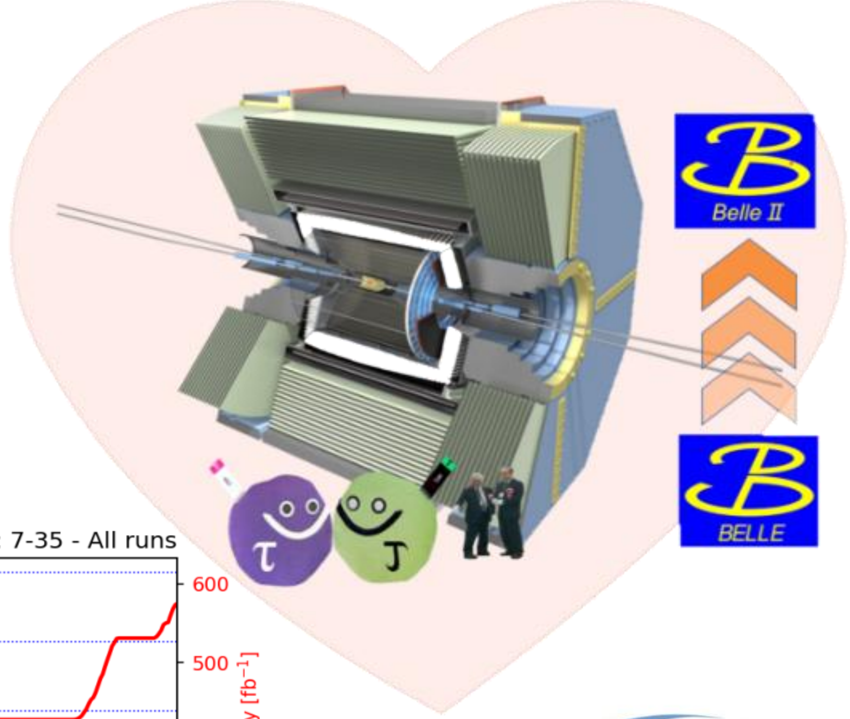

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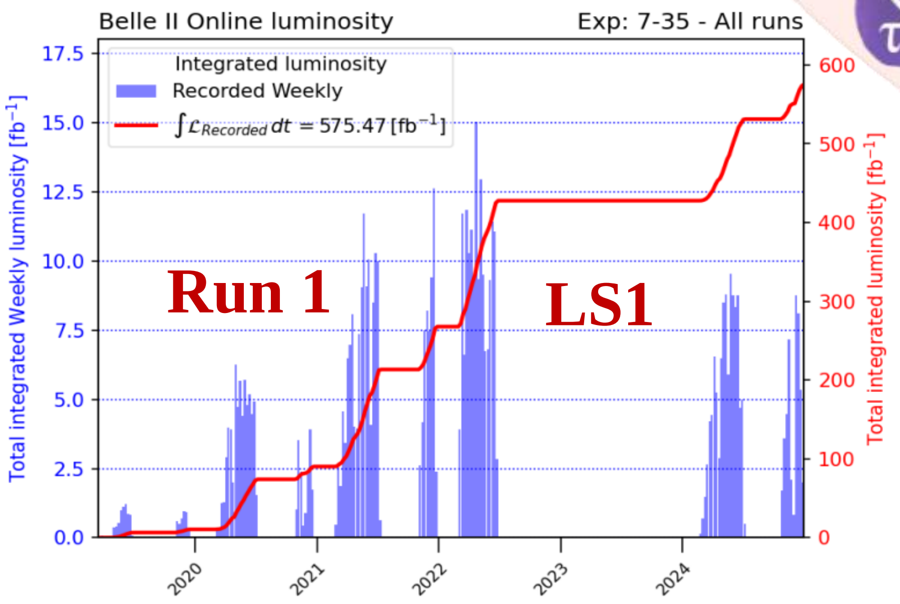

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τ physics
at Belle and Belle II

Lepton Flavour Violation (LFV)

τ Physics at Belle and Belle II

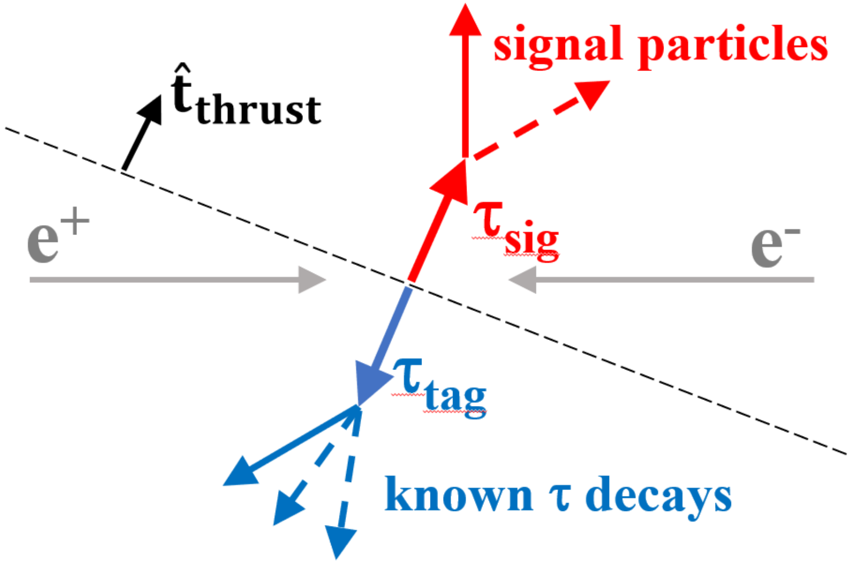
- In the c.m. frame, $\tau^+\tau^-$ fly back to back from the interaction point (IP), with 5 GeV/c for each, with low multiplicity.
  - ✓ Background from $q\bar{q}$ and low multiplicity events.
  - ✓ Machine learning classifiers, Boosted Decision Tree (BDT), are widely used for signal and background separation.
- A thrust vector, $\hat{t}$, is determined to separate the signal and tag hemispheres. [Phys.Lett. 12 (1964) 57-61]

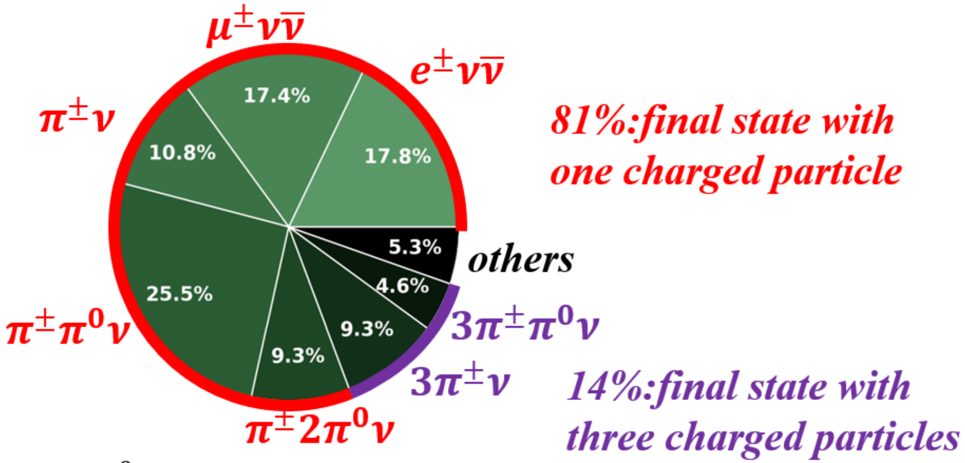
$$\text{Thrust } T = \max_i \left\{ \frac{\Sigma_i |p_i^{cm} \cdot \hat{t}|}{\Sigma_i |p_i^{cm}|} \right\}$$

> $\hat{t}$, the best approximation of the τ direction of flight

- On the tag side, well known τ decays are used as a “tagger”.
  - ✓ 1(3)- prong tag with 1(3) charged tracks
  - ✓ leptonic τ decays: 2 neutrinos
    hadronic τ decays: 1 neutrino
  - ✓ inclusive tagger using rest of event information (new approach)
- Signal region usually defined on $(\Delta E_\tau, m_\tau)$ plane

$$\Delta E_\tau = E_\tau^{c.m.} - \sqrt{S}/2$$

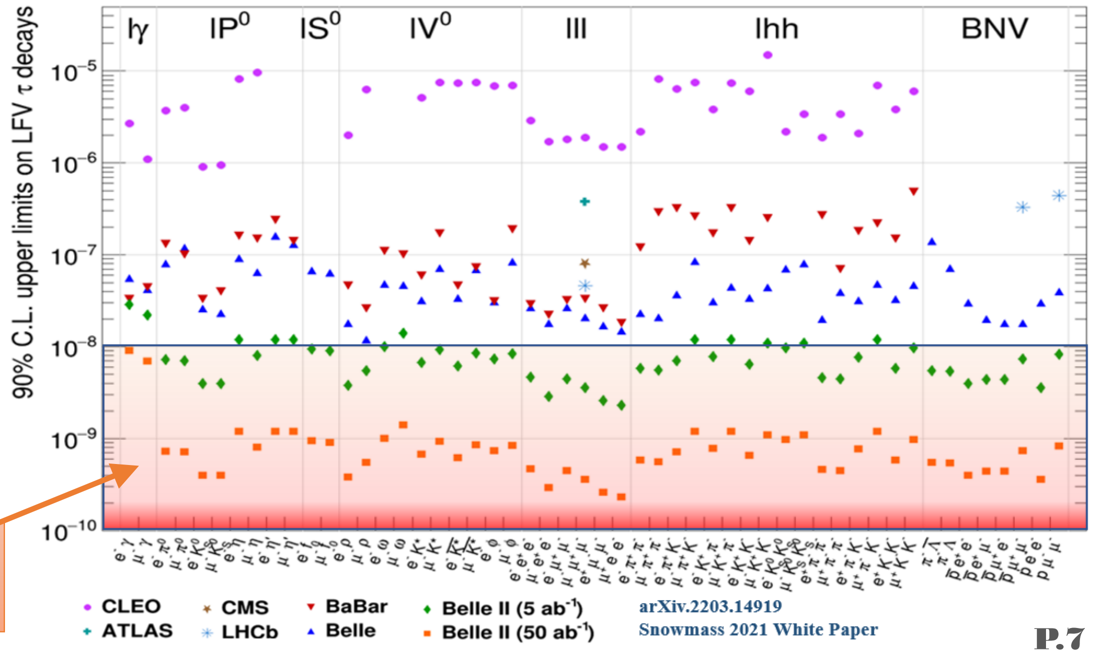




($\pi\pi^0$ peaking at the ρ mass)

τ Physics at Belle and Belle II
Lepton Flavour Violation

- Belle and Belle II have collected ~1.3B τ pairs, and pursued many precision measurements.
  - ✓ $m_\tau = 1777.09 \pm 0.08 \pm 0.11$ GeV/c^2, most precise up to date. [PRD 108, 032006 (2023)]
  - ✓ Novel technics for Michel parameter ξ' measurement. [PRL 131, 021801; PRD 108, 012003 (2023)]
  - ✓ Test of light Lepton Flavour Universality. [JHEP 08, 205 (2024)]
- Recently, charged LFV gets attention in searching for new physics. In SM, the charged LFV is allowed with finite neutrino mass. The rate is ~ 10^{-50}, far below the current experiments reach.
- Various new models could enhance them to 10^{-8}~10^{-10}, reachable by Belle II. [PRD 77, 073010 (2008)]
- Many studies in the LFV search have been done at Belle and Belle II, e.g. the recent results at
  - ✓ $\tau \to K_S^0 \ell$ (lepton and pseudo-scalar)
  - ✓ $\tau \to \ell\ell\ell$ (3 leptons)
  - ✓ $\tau \to \ell a$ (lepton and invisible spin-0 boson)
  - ✓ Many other modes, e.g. LNV, ℓV_0, …



hot zone
in the next decade

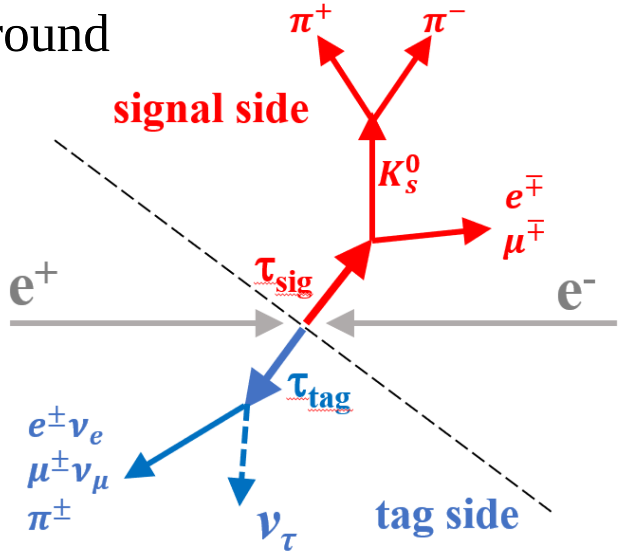
$\tau \to K_S^0 \ell, (\ell = e, \mu)$

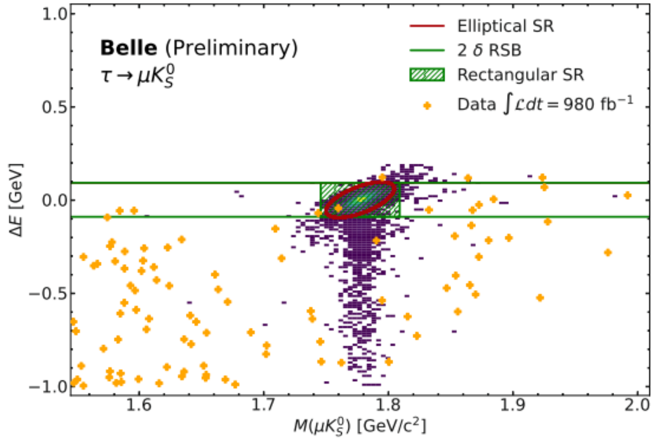
[JHEP 08,092](2025)
published last week
1.3B τ pairs

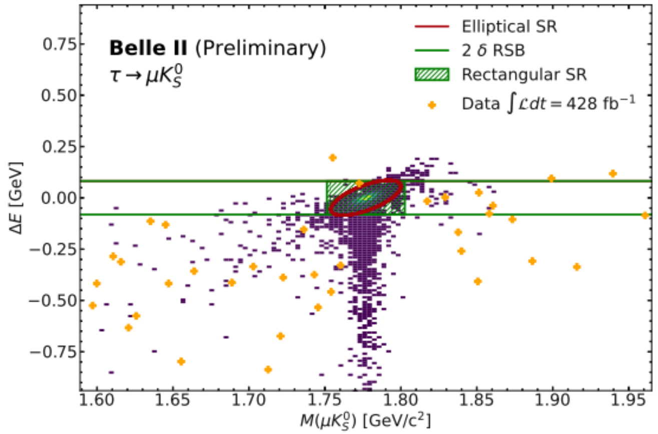
- The decay rate could be enhanced by leptoquark mediators ($\tau\mu ds$). [EPJC 70, 1071]
- First LFV study to combine the Belle and the Belle II data
- Total 4 charged tracks with 0 net charge
  signal side: 3 charged tracks ($K_S^0 \to \pi^+\pi^-$)
  tag side: single-prong $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi^{\pm}\nu$
  major background from $q\bar{q}$ (and low multiplicity process for $\ell = \mu$)
  ε = ~ 10.2%
- No significant excess above expected background in the elliptical signal regions

$\mathcal{B}(\tau \to eK_S^0) < 0.8 \times 10^{-8}$ @90% CL
$\mathcal{B}(\tau \to \mu K_S^0) < 1.2 \times 10^{-8}$ @90% CL

World most stringent upper limits







$\tau \to \ell\ell\ell$

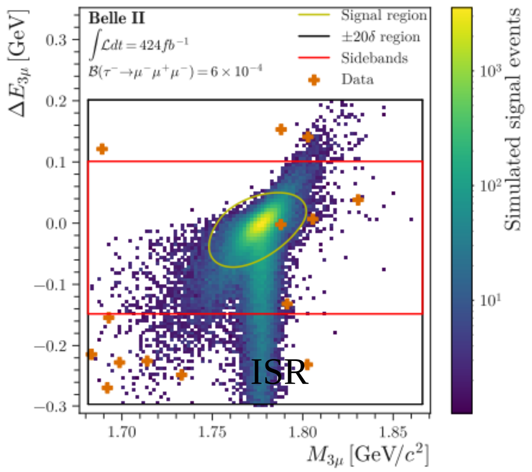
$\tau \to \mu\mu\mu$

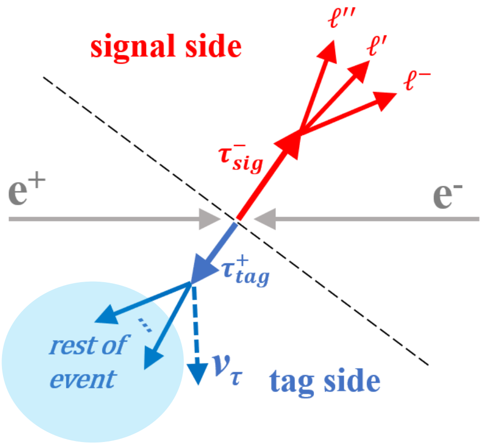
JHEP 09 2024, 062 (2024)
389M τ pairs, 424 fb^{-1}

- Almost free from SM background, new model can enhance the rate to 10^{-8}
- Signal side: 3μ
  tag side: all kinematic information of rest of the event
  (inclusive tagging)
  ε = 20.4%

New approach!!

- 1 event observed with 0.7 expected background
  $\mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$ @90% CL ★





$\tau \to e^{\pm}\ell^{\pm}\ell'$

arXiv 2507.18236 submitted to JHEP
393M τ pairs, 428 fb^{-1}

- Similar approach applied to other 5 modes
- Signal side: $\ell, \ell' = e, \mu$ selected by lepton ID
  background, $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ dominate,
  rejected by data-driven BDT
  ε = 15~24%
- No significant signal observed
  $\mathcal{B} < 1.3\text{~}2.5 \times 10^{-8}$ @90% CL

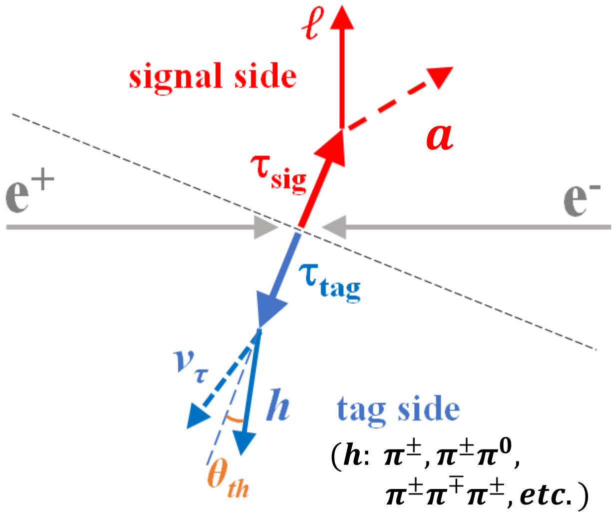
	ϵ_{sig}	N_{exp}	N_{obs}	$\mathcal{B}^{UL}_{obs}$ (10^{-8})
$e^-e^+e^-$	$(15.0 \pm 0.1)\%$	$6.1^{+4.3}_{-2.9}$	5	2.5 ★
$e^-e^+\mu^-$	$(20.4 \pm 0.1)\%$	$12.1^{+5.7}_{-4.3}$	12	1.6 ★
$e^-\mu^+e^-$	$(23.5 \pm 0.1)\%$	$10.5^{+5.3}_{-4.3}$	17	1.6
$\mu^-\mu^+e^-$	$(20.1 \pm 0.1)\%$	$20.7^{+6.6}_{-5.5}$	18	2.4 ★
$\mu^-e^+\mu^-$	$(24.1 \pm 0.1)\%$	$7.5^{+4.5}_{-3.2}$	9	1.3 ★

★ most stringent one to date

$\tau \to \ell a$

[arXiv 2503.22195](#)
JHEP accepted
736M τ pairs, 800 fb^{-1}
PRL 130 (2023) 181803 Belle II

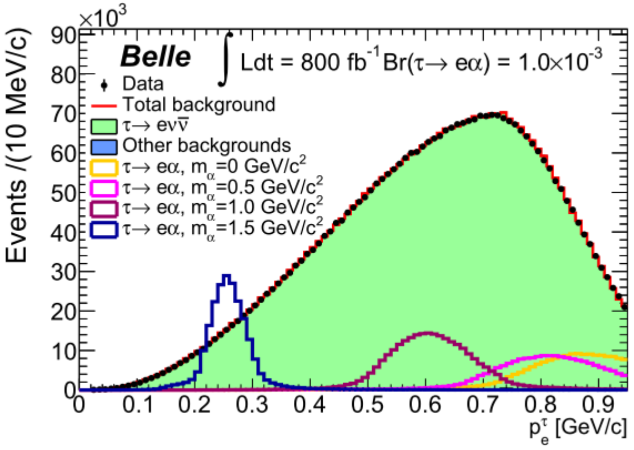
- a a neutral boson invisible to the detector (e.g. ALPs), not allowed in SM, but predicted in many new models. [PRL 124, 211803 (2020)]
- Signal side: two body decay with only single lepton (e or μ) detected
  tag side: hadronic 1-prong and 3-prong τ decays (with single neutrino)
  ε = 0.9~1.4% (0.3~1.5%) for $\ell = e(\mu)$
- Search for excess of P_ℓ^τ distribution over irreducible $\tau \to \ell\nu\bar{\nu}$ (3 body decays) in the pseudo-rest frame of τ_{sig}, whose τ direction is determined by the tag side hadrons and a selection on θ_{th}

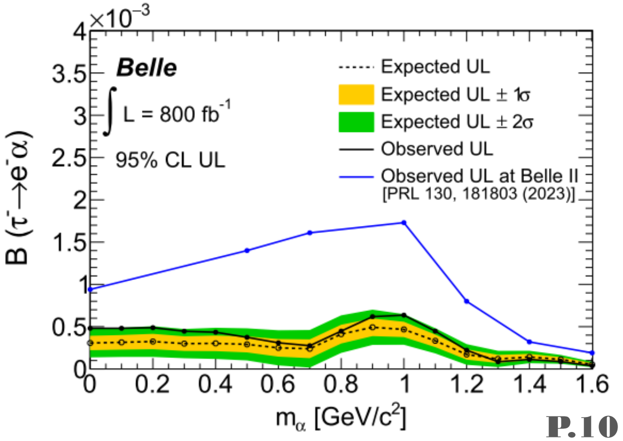


$$\theta_{\tau h} = \arccos\left(\frac{|\vec{p}^{\,\mathrm{c.m.}}_{\tau_{\mathrm{tag}}}|^2 + |\vec{p}^{\,\mathrm{c.m.}}_{h_{\mathrm{tag}}}|^2 - (\sqrt{s}/2 - E^{\mathrm{c.m.}}_{h_{\mathrm{tag}}})^2}{2|\vec{p}^{\,\mathrm{c.m.}}_{\tau_{\mathrm{tag}}}||\vec{p}^{\,\mathrm{c.m.}}_{h_{\mathrm{tag}}}|}\right)$$

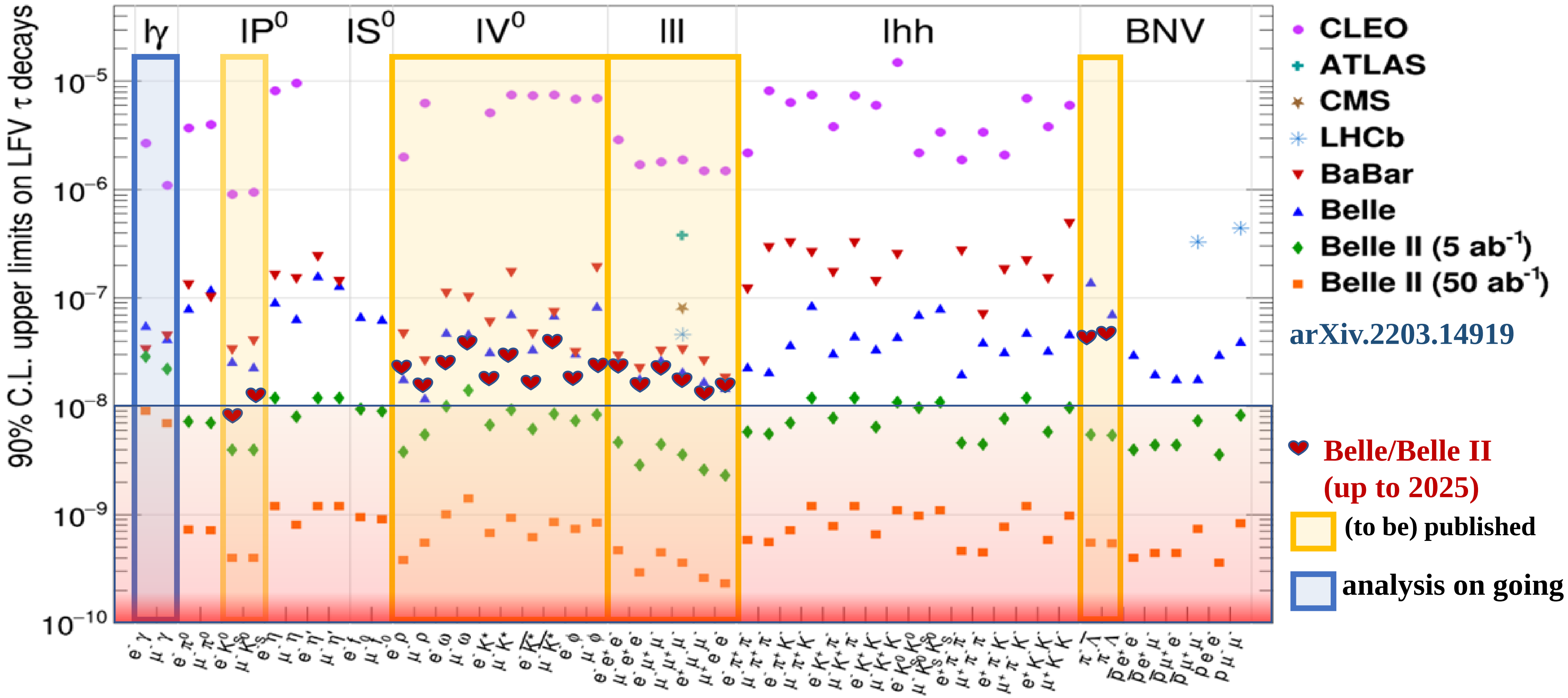
- Scanning a mass hypothesis from 0 to 1.6GeV/c^2 no excess observed and 95%CL set on the rate

$$\mathcal{B}(\tau \to ea) < (0.4 - 6.4) \times 10^{-4}$$
$$\mathcal{B}(\tau \to \mu a) < (0.2 - 3.5) \times 10^{-4}$$





Status of LFV search in τ sector at Belle/Belle II



We are approaching the hot zone!!!

LFV related publications in recent years

Belle

- $\tau \to \ell a$ .... [arXiv 2503.22195; JHEP] (2025)
- $B \to K^{(*)} a(\to \gamma\gamma)$ .... [arXiv 2507.01249 (JHEP)] (2025)
- $\Upsilon(2S) \to \ell\tau, (\ell = e, \mu)$ .... [JHEP 02 2024, 187] (2024)
- $B^+ \to K^+\tau^\pm\ell^\mp, (\ell = e, \mu)$ ...... [PRL 136, 261802] (2023)
- $B_s^0 \to \tau^\pm\ell^\mp, (\ell = e, \mu)$ .... [JHEP 08 2023, 178] (2023)
- $\tau \to \ell V^0, (V^0 = \rho^0, \phi, \omega, K^{*0})$ ... [JHEP 06 2023, 118] (2023)
- $B^0 \to \tau^\pm\ell^\mp, (\ell = e, \mu)$ ....[PRD 104, L091105] (2021)
- $\tau \to \ell\gamma, (\ell = e, \mu)$ ....[JHEP 10 2021, 019] (2021)

Belle + Belle II

- $\tau \to \ell K_s^0$ [arXiv 2504.15745; JHEP] (2025)
- $B^0 \to K^{*0}\tau^\pm\ell^\mp(\ell = e, \mu)$ [arXiv 2505.08418; JHEP] (2025)
- $B^0 \to K_s^0\tau^\pm\ell^\mp(\ell = e, \mu)$ [arXiv 2412.16470; PRL] (2024)

Belle II

- $\tau \to e\ell\ell$ .... [arXiv 2507.18236 (JHEP)] (2025)
- R(D*) in semileptonic B decays [arXiv 2504.1220; PRD] (2025)
- $\tau \to \mu\mu\mu$ .... [JHEP 09 2024, 062] (2024)
- $\tau^- \to \Lambda\pi^- / \bar{\Lambda}\pi^-$ .... [PRD 110, 112003] (2024)
- light LFU in τ decays ....[JHEP 08 2024, 205] (2024)
- R(D*) in hadronic B decays ......[PRD 110, 072020] (2024)
- $\tau \to \ell a$ .... [PRL 130.181803] (2023)
- light LFU in B decays .... [PRL 131, 051804] (2023)
- LFU in $B^0 \to D^{*-}\ell\nu$ .... [PRL 131, 181801] (2023)

https://www.belle2.org/research/physics/publications

LFV in τ

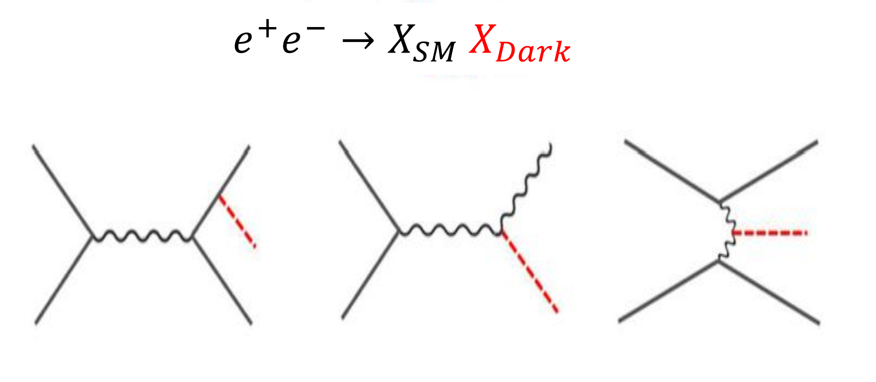
- EPJC 8:513 (1999)
- PRD 66, 115013 (2002)
- PRD 66, 034008 (2002)
- PRL 89, 24 (2002)
- PLB 547, 252 (2002)
- PRD 68, 033012 (2003)
- PLB 566, 217 (2003)
- PRD 77, 073010 (2008)
- PRD 97, 095009 (2018)
- EPJC 80:506 (2020)
- EPJC 85:805 (2025)
- ……

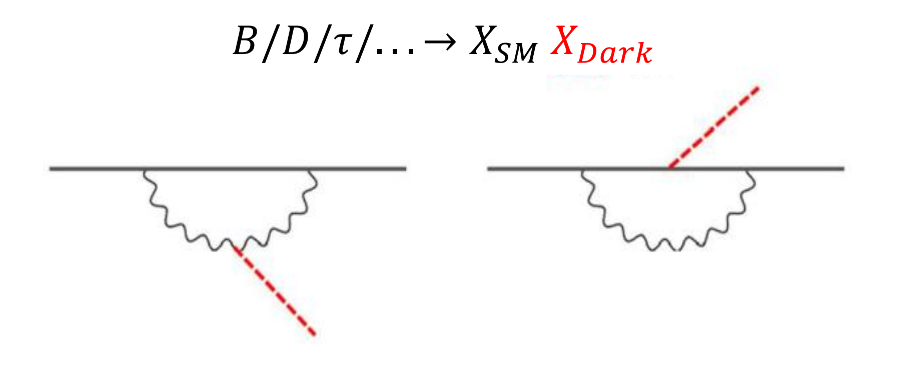
$\tau \to \ell a$, is not only for LFV search in τ sector
as ALP could also be for dark matter candidate

dark sector search at Belle and Belle II

Dark sector search at Belle and Belle II

- The e^+e^- B factory, Belle/Belle II, is good to access the mass range favored by light dark sector, with on-shell mediators in MeV/c^2 – 10GeV/c^2 range.
- Typical production mechanisms to search for dark sector
  - ✓ $e^+e^- \rightarrow$ SM particles + mediator (direct production from collision)
  - ✓ SM particle → SM particles + mediator (production in decay)





- Different event topologies
  - ✓ visible decays: final states with all SM particles → dark sector mediator search
  - ✓ invisible decays: final states with dark matter or dark sector mediators candidates → missing energy
  - ✓ displaced vertices: weak couplings lead to long lifetime, could decay outside the detector (invisible)

Dark Higgs with inelastic dark matter

[arXiv 2505.09705]
PRL accepted
365 fb^{-1}

- Non-minimal model with inelastic coupling between DM and SM [PRD 64, 043502 (2001)]

  $e^+e^- \to h'A'$

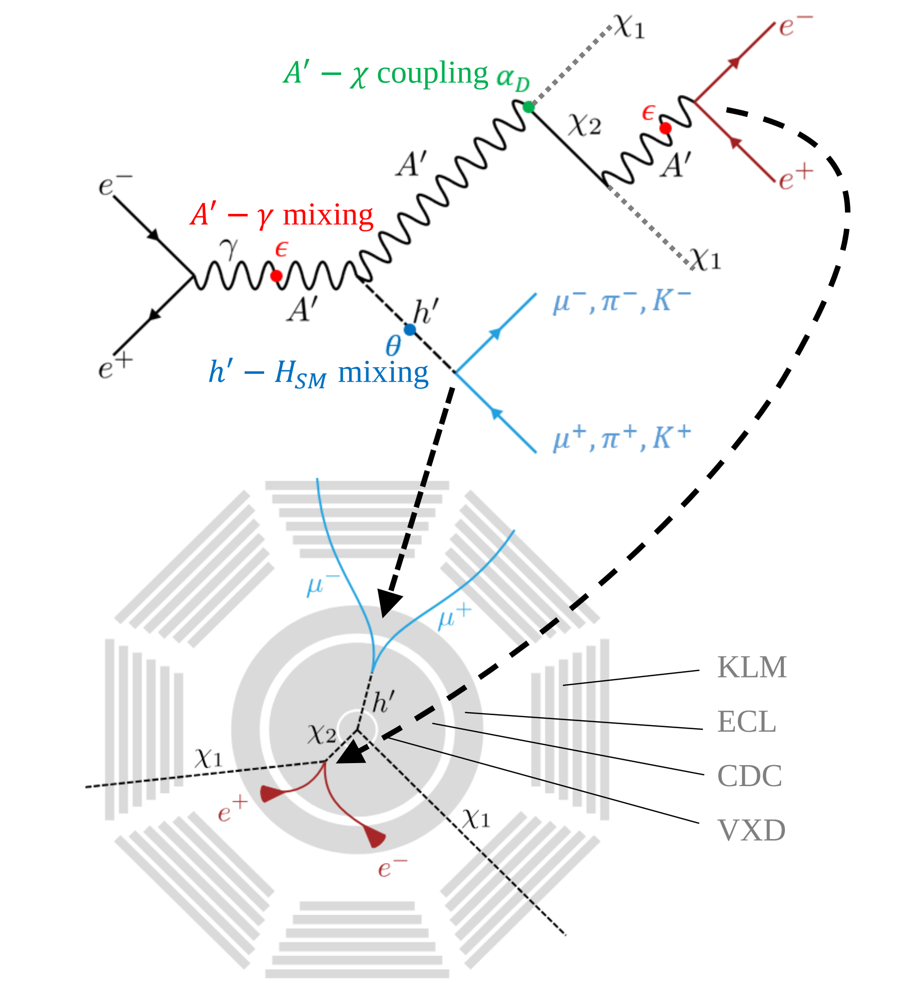
  $h' \to x^+x^-$ and $A' \to \chi_1\,\chi_2$

  $\chi_2 \to \chi_1 e^+e^-$ $(\mu^+\mu^-, \pi^+\pi^-, K^+K^-)$

  where $x = \mu, \pi, K$

  - ✓ h' dark Higgs (long lived)
    mixing with SM Higgs, mixing parameter θ
  - ✓ A' massive dark photon,
    mixing with SM γ, missing parameter ϵ
    coupling to dark matter $\sim \sqrt{\alpha_D}$
  - ✓ two dark matter χ_1, χ_2 with mass splitting
    χ_2 long lived and could decay into DM
    χ_1 invisible (relic DM candidate)

- 4 charged particles with up to two displaced vertices
  - ✓ $h' \to \mu^+\mu^-,\ \pi^+\pi^-,\ K^+K^-$ pointing back to IP
  - ✓ $\chi_2 \to \chi_1 e^+e^-$ non-pointing to IP
  - ✓ missing energy due to two χ_1
  - ✓ 7 free parameters:
    $m_{h'}, m_{A'}, m_{\chi_1}, \Delta m = m_2 - m_1$, and
    $\theta, \epsilon, g_D = \sqrt{4\pi\alpha_D}$

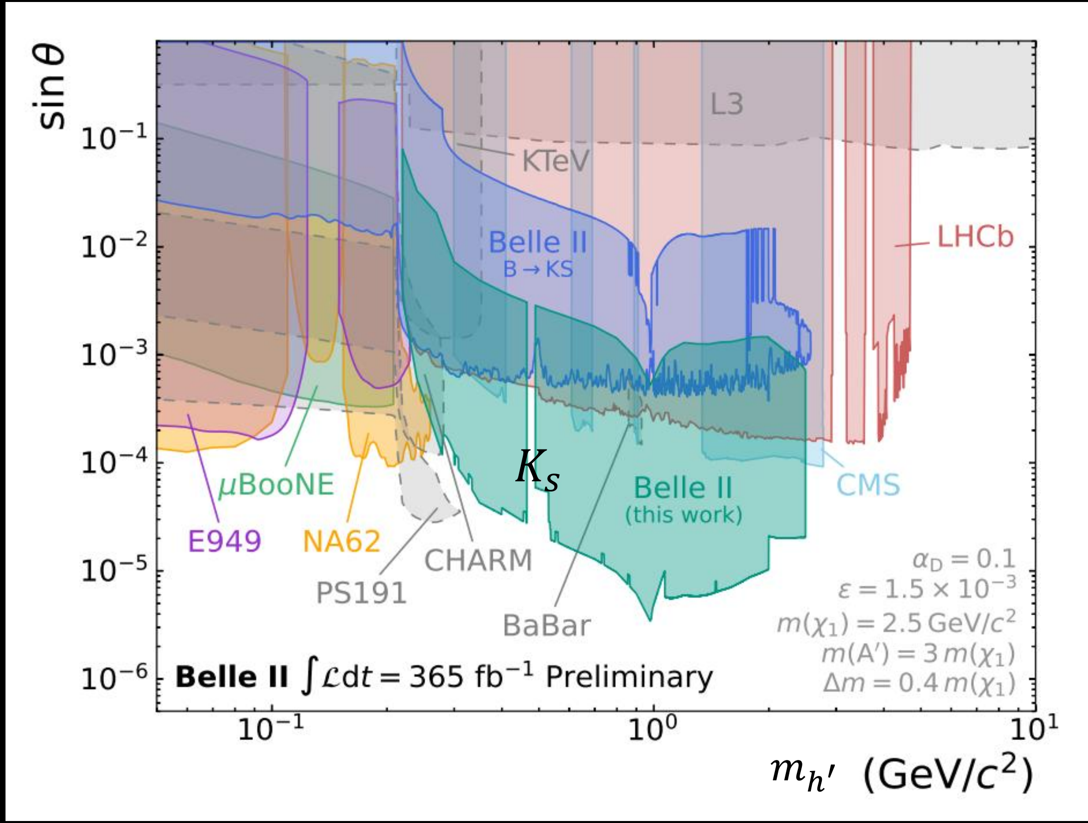


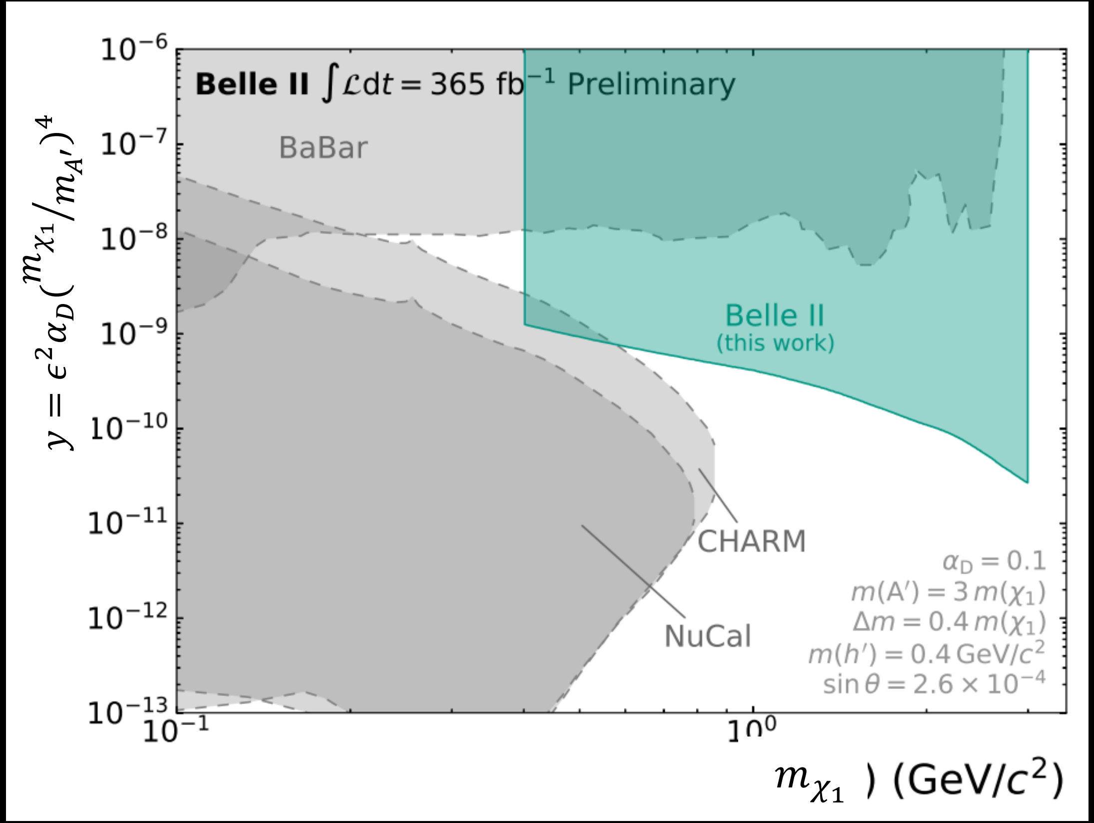
first search for long-lived DM at Belle II

Dark Higgs with inelastic dark matter

[arXiv 2505.09705]
PRL accepted
365 fb^{-1}

- search for enhancement peak in $m_{h'} = m_{(\chi^+\chi^-)}$ spectrum
- 95% CL upper limits, under different parameters' hypotheses, set to
  - ✓ $\sigma(e^+e^- \to h'\,\chi_1\,\chi_2)\cdot\mathcal{B}(h' \to \chi_1\,\chi_2)\cdot\mathcal{B}(\chi_2 \to \chi_1 e^+e^-)$: 10^{-1}~10^{3} fb
  - ✓ $\sin(\theta)$ and $\epsilon^2\alpha_D(\frac{m_{\chi_1}}{m_{A'}})^4$

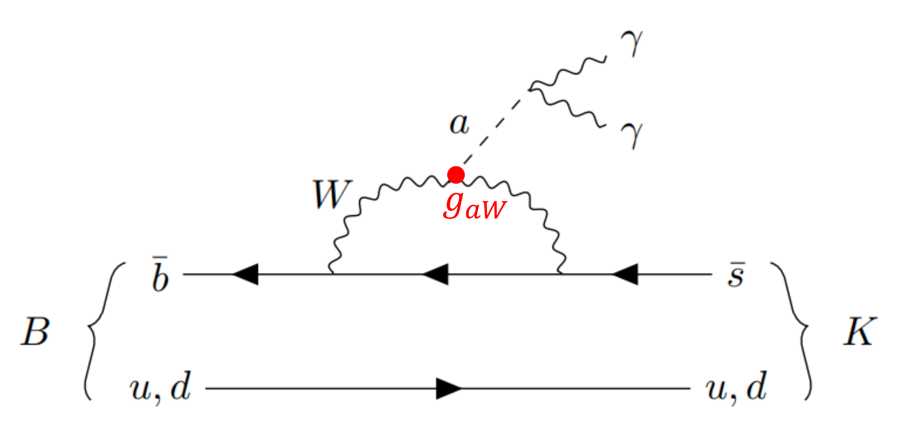


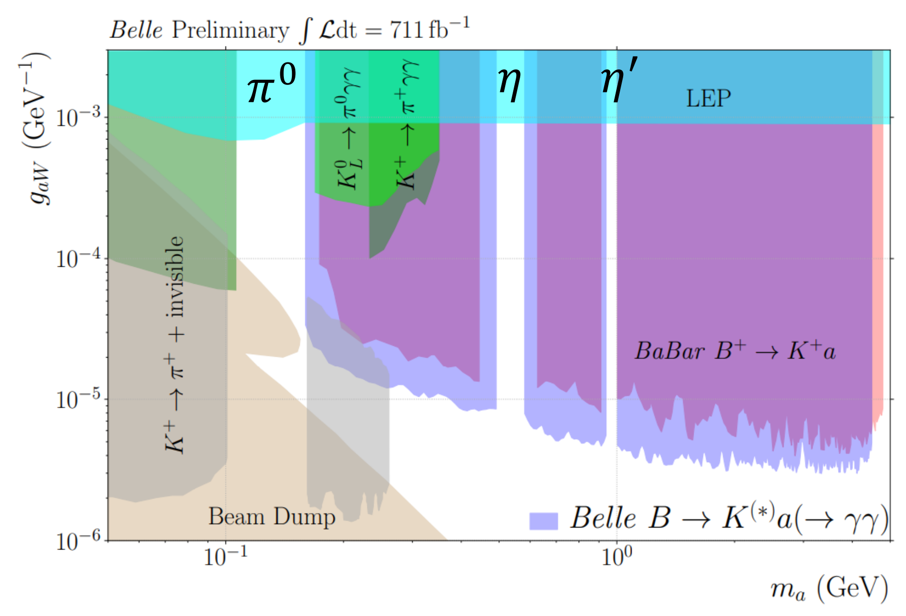


$B \to K^{(*)} a(\to \gamma\gamma)$

[arXiv 2507.01249]
submitted to JHEP
711 fb^{-1}

- Search for an ALP in FCNC B decays, which has the similar rate of the SM process in new physics
- $B \to K^{(*)} a(\to \gamma\gamma)$:
  - ✓ 4 modes: $B^0 \to (K_S^0/K^{*0})a$; $B^+ \to (K^+/K^{*+})a$
    $K_S^0 \to \pi^+\pi^-$, $K^{*0} \to K^+\pi^-$, K^+, $K^{*+} \to K_S^0\pi^+$
  - ✓ Signal: one identified/reconstructed kaon with one di-photon to form a B candidate
  - ✓ a emission from W boson, coupling $\propto g_{aW}$, $\mathcal{B}(a \to \gamma\gamma) \cong 100\%$ when $m_a \ll m_W$
- Scan for signal in $0.16 < m_{\gamma\gamma} < 4.5(4.2)$ GeV/c^2 for $K^{(*)}$ modes peaking background due to π^0, η, η' excluded ($B^+ \to K^+\eta^{(\prime)}$ approach validation)
- No significant excess from simultaneous fit on all 4 kaon modes 90% CL upper limits on g_{aW} are set (most stringent) improved by a factor of 2 from previous result [PRL 128,131802,BaBar]





DM search related publications in recent years

Belle

$B \to K^{(*)} a(\to \gamma\gamma)$	[arXiv 2507.01249 (JHEP)]	(2025)
$\tau \to \ell a$	[arXiv 2503.22195; JHEP]	(2025)
$\tau^- \to \pi^- N(\to \mu^+\mu^-\tau_\nu)$, N = heavy neutral lepton	[PRD 109.L111102]	(2024)
$e^+e^- \to \tau^+\tau^-\phi_L(\to \ell^+\ell^-)$, ϕ_L = leptophilic scalar	[PRD 109,032002]	(2024)
Heavy neutrino in τ decays	[PRL 131, 211802]	(2023)
$e^+e^- \to Z'(\to \mu^+\mu^-)\mu^+\mu^-$	[PRD 106.012003]	(2022)

Belle II

Inelastic dark matter with a dark Higgs	[arXiv 2505.09705; PRL]	(2025)
$e^+e^- \to \mu^+\mu^-(\mu^+\mu^-)$, with non SM resonance state	[PRD 109.112015]	(2024)
long-lived spin-0 mediator in $b \to s$ transitions	[PRD 108.L111104]	(2023)
$e^+e^- \to \mu^+\mu^- X(\tau^+\tau^-)$, X = Z‘, S, or ALP	[PRL 131.121802]	(2023)
$e^+e^- \to \mu^+\mu^- Z'$	[PRL 130.231801]	(2023)
$e^+e^- \to A'(\to \tau^+\tau^-)h'$	[PRL 130.071804]	(2023)
$\tau \to \ell a$	[PRL 130.181803]	(2023)
$e^+e^- \to \gamma a(\to \gamma\gamma)$	[PRL 125.161806]	(2020)
$e^+e^- \to \ell^\pm\mu^\mp Z', \ell = e, \mu$	[PRL 124.141801]	(2020)

https://www.belle2.org/research/physics/publications

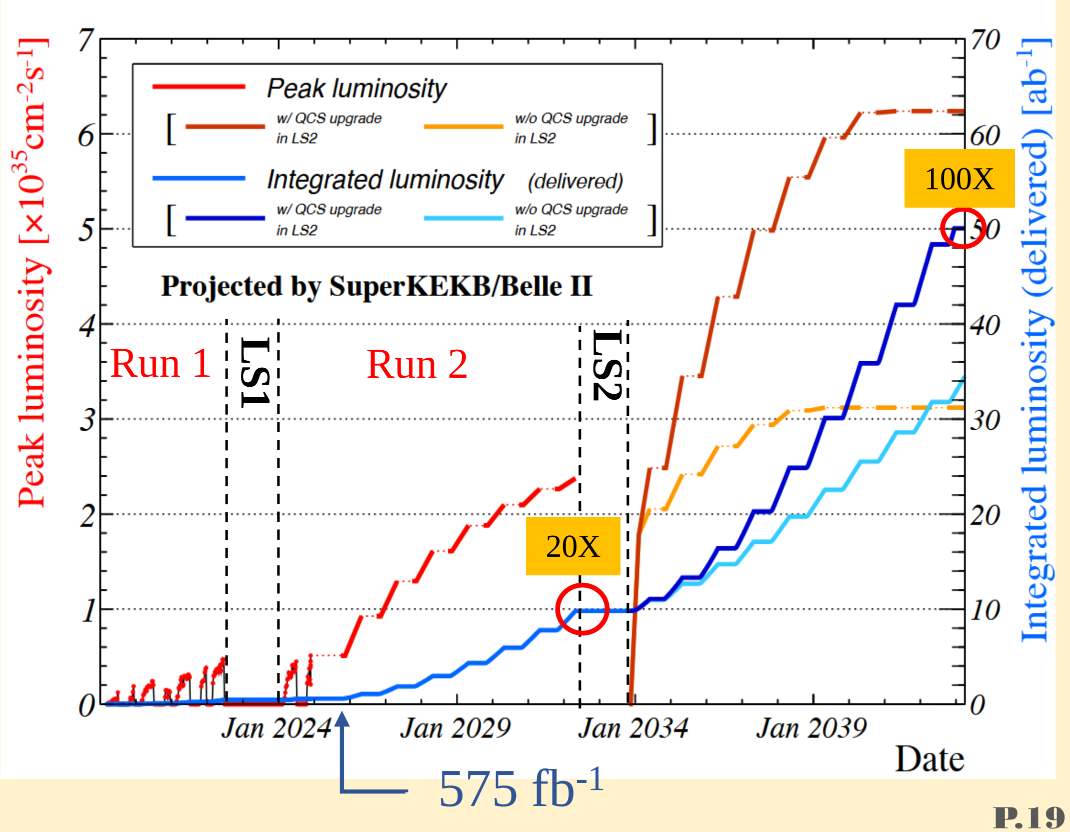
Summary

- Besides B and charm physics, Belle and Belle II are also unique experiments for τ physics study and low mass dark matter search.

- Belle II is taking data since 2019 and has already completed many exciting results in τ decays, especially in testing LFV, and in dark sector search.
  - ✓ $\tau \to \ell\ell\ell$
  - ✓ $\tau \to K_s^0 \ell$
  - ✓ $\tau \to \ell a$
  - ✓ Dark Higgs with inelastic dark matter
  - ✓ ALP search in $B \to K^{(*)} a(\to \gamma\gamma)$

- Belle II will eventually collect 50 ab^{-1} data, which is about 100 times of the current recorded dataset. Certainly more exciting physics outputs will come in the near future.

Exciting era of Belle II is coming. Please stay tuned!



BACKUP

$\tau^- \to (\Lambda/\bar{\Lambda})\pi^-$

[PRD 110 (2024) 112003]
364 fb^{-1}

Belle II

- LFV and Baryon number not conserved, but $|\Delta(B-L)| = 2, 0$, allowed in some models

$$\mathcal{B}(\tau^- \to \Lambda\pi^-) < 4.7 \times 10^{-8} \text{ @90\% CL}$$
$$\mathcal{B}(\tau^- \to \bar{\Lambda}\pi^-) < 4.3 \times 10^{-8} \text{ @90\% CL}$$

$\tau \to \ell V^0$

[JHEP 06 2023, 118]
980 fb^{-1}

BELLE

- $\ell = e, \mu$ and $V^0 = \rho^0, \phi, \omega, K^{*0}$, and $\bar{K}^{*0}$
- 10 modes are measured (8 of them the world‘s most stringent limits)

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm\rho^0$	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