



Tau and dark sector measurements at Belle and Belle II

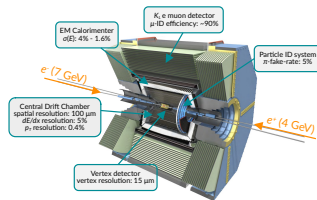
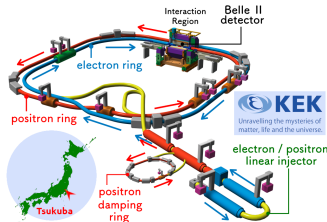
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58th Rencontres de Moriond 2025, QCD & High Energy Interactions
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Belle and Belle II experiments

B-factories with broad physics program

- » **Asymmetric e^+e^- colliders at KEK (Tsukuba, Japan)**
 - collision energy at 10.58 GeV ($\Upsilon(4S)$ mass)
 $\sigma(e^+e^- \rightarrow B\bar{B}) = 1.05 \text{ nb}$
 $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb}$
- **B-factories are also τ -factories!**
 - well-defined kinematics of initial state, hermetic detector
- **key features for good missing energy reconstruction**
 - good particle identification (leptonID, K/π separation)
- » **Belle @ KEKB accelerator (1998–2010)**
 - recorded luminosity $\approx 1 \text{ ab}^{-1}$
- » **Belle II @ SuperKEKB accelerator (2019–)**
 - major upgrade of both accelerator and detector
 - special triggers for low-multiplicity events
- **allows for the selection of signals that were not possible to trigger at Belle**
 - excellent tracking efficiency and improved vertex resolution
- **enables new measurement approaches**
 - recorded luminosity = 575 fb^{-1}
Run 1 = 428 fb^{-1} (365 @ $\Upsilon(4S)$ + 62 off-resonance)



world record inst. luminosity of

$$5.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ @ Belle II}$$

Light dark sector

B-factories can access mass range favored by light dark sectors

» **Existence of dark matter has been established in astrophysics**

- e.g. rotation curves of galaxies, gravitational lensing

» **No dark matter candidate in Standard Model**

- searches for dark matter is one of the main goals of particle physics [arXiv:2209.04671]

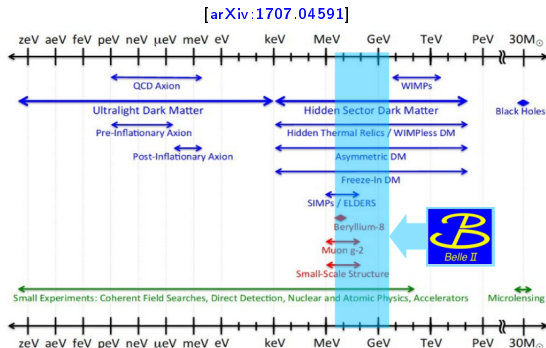


» **Searches at Belle & Belle II**

→ **Sub-GeV scale dark sector scenario**

- dark sector weakly coupled to Standard Model through a light mediator particle
- favoured by lack of results from direct searches

[J. Monroe, Granada ES, 2019]

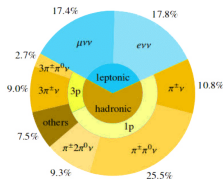


» **Mediator portals**

- scalar portal: Dark Higgs, Dark Scalar
- pseudo-scalar portal: Axion Like Particle (ALP)
- vector portal: Dark photon
- fermion portal: Sterile neutrinos

Tau physics

B-factories provide a great environment for tau lepton studies



3rd generation particle

- the heaviest known lepton
- can decay to lighter leptons but also hadrons

The τ properties are known with much worse precision compared to e and μ !

electron



muon



tau



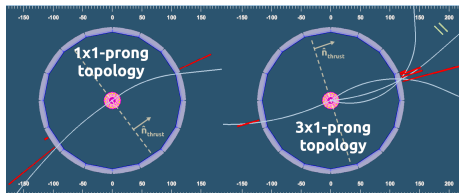
light ————— heavy
stable ————— unstable
well-known ————— not so much

Searches for forbidden τ decays

- lepton flavour/number violation

Possible τ physics probes

- lepton universality, CKM unitarity, new sources of CPV, ...
- some NP scenarios predict enhanced τ couplings to NP



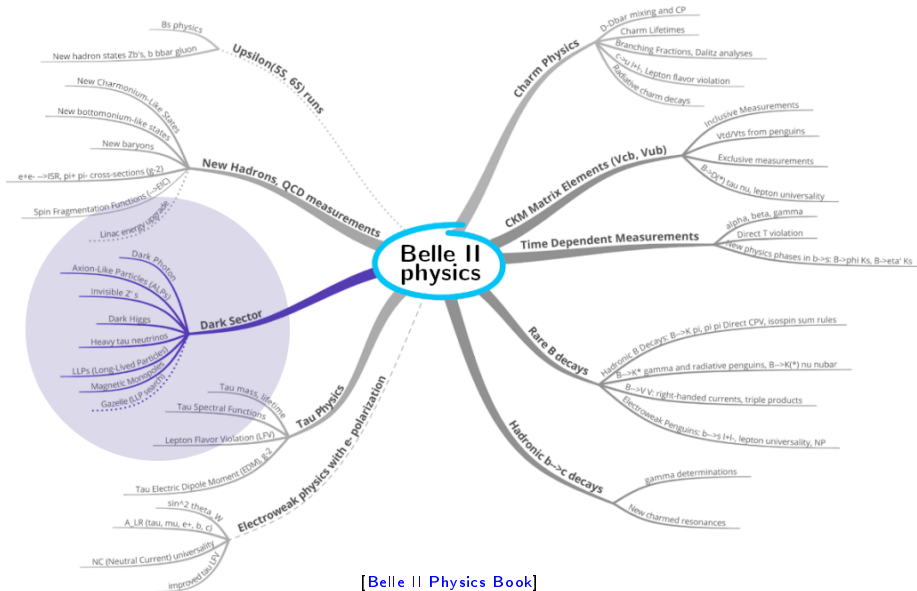
Taus at Belle & Belle II

- $\tau^+\tau^-$ produced back-to-back and boosted in the CM frame
- each τ is reconstructed via one (1-prong) or three (3-prong) charged tracks
- splitting the event into two hemispheres using thrust axis

$$T = \max_{\hat{n}_T} \left(\frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|} \right)$$

→ use one τ to tag the event and reconstruct signal in the other hemisphere

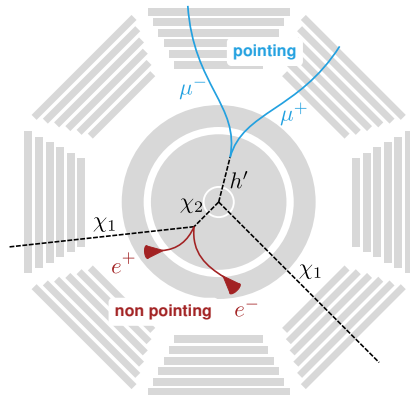
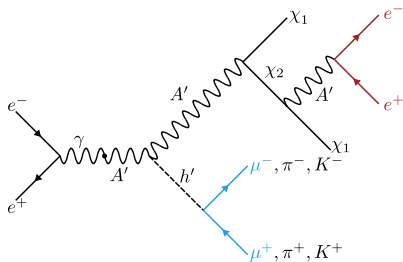
Dark sector at Belle II



[Belle II Physics Book]

» **Probing a non-minimal DS model predicting 4 new particles** [JHEP04(2021)146]

- dark photon A' , dark Higgs h' and two DM states χ_1, χ_2
- 7 free parameters:
3 masses, 2 mixings, 2 couplings



» **Looking for simultaneous production of A' and h'**

- 4 tracks in the final state:
- 2 forming a pointing displaced vertex
- other 2 forming a non-pointing displaced vertex
- missing energy

→ **challenging for tracking and trigger**

» **Exploring 3 final states:**

$$h' \rightarrow x^+ x^-, x = \mu, \pi, K$$

» Signal selection

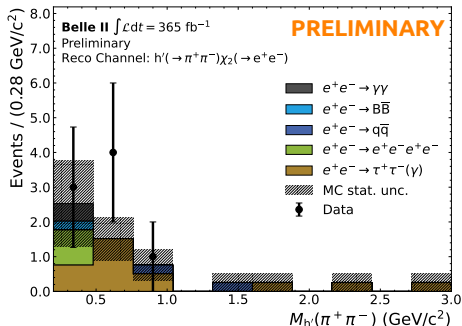
- using requirements on pointing angles and vertex distance from the interaction point

→ very low SM background

» Signal yield

- cut-and-count strategy in $M_{h'}(x^+x^-)$ distributions
- with background estimated from sidebands in data

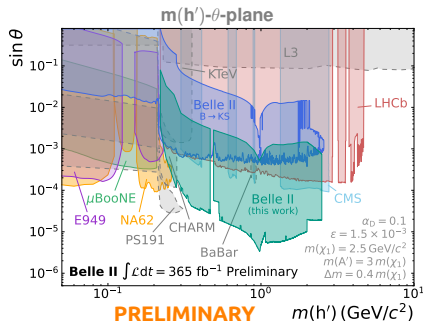
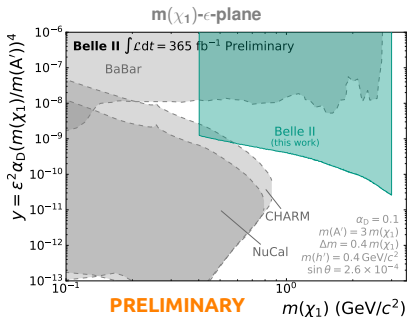
→ not relying on MC simulation



» No significant excess found in the individual final states or the combination

- 9 events observed (8 of 9 are $\pi^+\pi^-$) – consistent with expected background
- search performed using 365 fb^{-1} Belle II data – analysis statistically limited

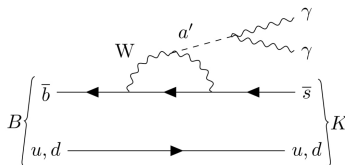
- » **95% CL upper limits on $\sigma(e^+e^- \rightarrow \chi_1 \chi_2 h') \times \mathcal{BR}(\chi_2 \rightarrow \chi_1 e^+e^-) [\times \mathcal{BR}(h' \rightarrow x^+x^-)]$**
- **strong limits on θ and $\varepsilon \propto \alpha_D$** (mixing angles of h' and A'), but depend on 5 other parameters
- provide interpretations for around 30 model parameter configurations



- » NP searches in flavour changing neutral current B decays
 - FCNC heavily suppressed in SM
 - NP can appear at the same order as SM processes
- production of an Axion-Like Particle (ALP) [[arXiv:1407.0546](#)]

» Search for an ALP emission by W boson in $B \rightarrow K^{(*)} a'$ decay

- $\mathcal{BR}(a' \rightarrow \gamma\gamma) \simeq 100\%$ for $m_{a'} \ll m_{W\pm}$
- probing $0.16 - 4.50 \text{ GeV}/c^2$ mass range
- including 4 kaon modes: $K_S^0, K^\pm, K^{*0}, K^{*\pm}$
- using full 711 fb^{-1} Belle dataset
- similar search done at BaBar [[PRL 128, 131802](#)]



» Signal reconstruction

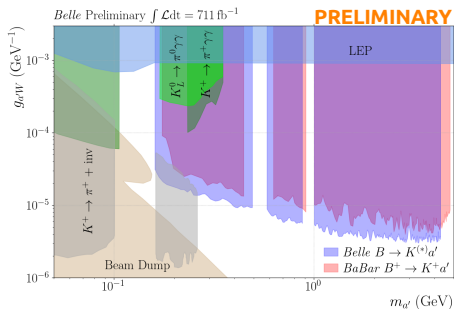
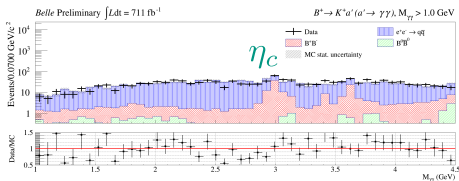
- B meson reconstructed from an ALP candidate (pair of photons) and a kaon candidate (charged or neutral)

» Background suppression

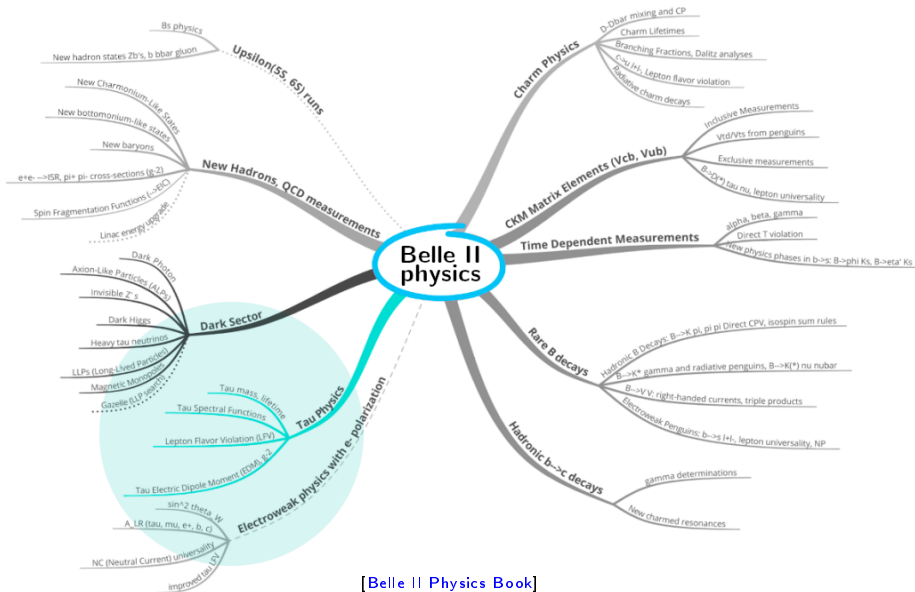
- main background from continuum $e^+e^- \rightarrow q\bar{q}$
- employ multiple BDTs exploiting event shape and kinematics variables, as well as energy cluster information to suppress π^0 backgrounds

New!

- **No significant excess observed**
 - simultaneous fit in all 4 kaon modes
- 90% CL upper limits on $g_{a'W}$
- **world-leading result**



Tau at Belle II



[Belle II Physics Book]

Lepton flavour in tau decays

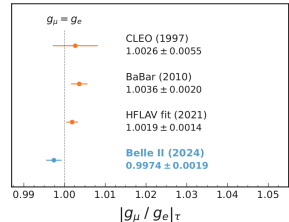
» Probing the SM

- lepton flavour universality (LFU): $g_e = g_\mu = g_\tau$

» R_μ measurement at Belle II:

- test of $e - \mu$ universality: $R_\mu = \frac{\mathcal{BR}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{BR}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} \stackrel{\text{SM}}{=} 0.9726$
- world's most precise measurement in τ decays from a single measurement

[JHEP08(2024)205]



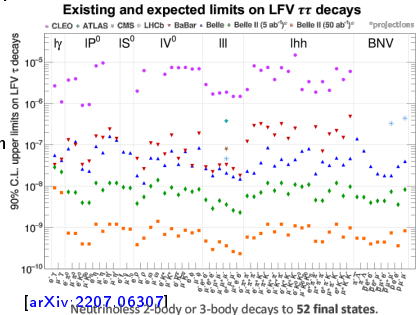
» Direct searches for NP

- lepton flavour violation (LFV) expected in SM due to neutrino masses and oscillations at rates 10^{-55} → beyond any current sensitivity
- several models (new Z' , charged Higgs boson) could enhance rates up to $10^{-10} - 10^{-8}$ → any observation would be unambiguous sign of NP

» Belle II already set world-leading limits:

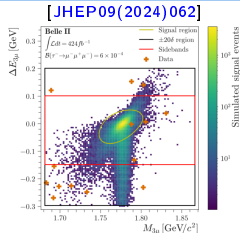
- $\tau \rightarrow 3\mu$: experimentally most accessible [JHEP09(2024)062]
- $\tau \rightarrow \Lambda(\bar{\Lambda})\pi$: baryon number violation → condition for matter/antimatter asymmetry [PRD 110, 112003]
- $\tau \rightarrow \ell\alpha$: new boson candidate for dark matter [PRD 107, 072002]

→ Belle II is expected to push forward the existing limits by at least 1 order of magnitude



» Extending the $\tau \rightarrow 3\mu$ study (reminder)

- clean channel, low SM background
- signal yield from 2D plane ($M_{3\mu} - \Delta E_{3\mu}$)
- 90% CL upper limit: $\mathcal{BR}(\tau \rightarrow 3\mu) < 1.9 \times 10^{-8}$
→ world-leading result set by Belle II
- the inclusive tag and BDT-based background rejection give $\sim 3\times$ the Belle signal efficiency at similar purity



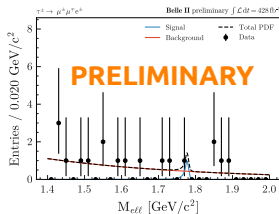
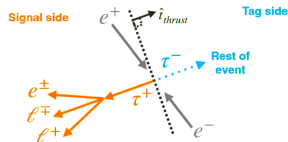
» Search for $\tau \rightarrow e2\ell$ (new)

- studying 5 more channels
 $e^-e^+e^-$, $e^-e^+\mu^-$, $e^-\mu^+e^-$, $\mu^-\mu^+e^-$, $\mu^-e^+\mu^-$
- higher background contamination
- untagged reconstruction, data-driven BDT classifier trained on sideband data
→ reject main 4ℓ background relying on ROE and kinematic variables
- signal from $M_{e\ell\ell}$ fit

» No significant excess was observed in 424 fb^{-1}

- 90% CL upper limit on \mathcal{BR} : $1.4 - 2.4 \times 10^{-8}$

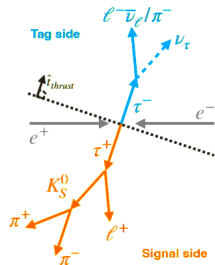
→ new world-leading results for all 5 modes



Search for $\tau \rightarrow \ell K_S^0$

New!

- » **Belle + Belle II search for $\tau \rightarrow \ell K_S^0$ ($\ell = e, \mu$)**
 - require 4 charged particles with 0 net charge in 3×1-prong topology
 - reconstruct K_S^0 from $\pi^+\pi^-$
 - $\tau \rightarrow \ell \bar{\nu}_\ell \nu_\tau / \pi \nu_\tau$ ($\ell = e, \mu$) on the tag side
- » **Cut-based preselection, BDT classifier trained using track kinematics, event shape and neutral variables**
 - resulting efficiency: 10%
 - signal yield from 2D plane ($M_\tau - \Delta E$) ($\Delta E = E_\tau - E_{\text{beam}}$)

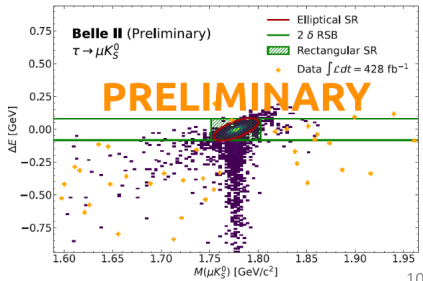


- » **No significant signal was observed in 424 fb^{-1} + 980 fb^{-1} (Belle + Belle II)**
 - combined 90% CL upper limit on \mathcal{BR} s:

$$\mathcal{BR}(\tau \rightarrow K_S^0 e) < 0.8 \times 10^{-8}$$

$$\mathcal{BR}(\tau \rightarrow K_S^0 \mu) < 1.2 \times 10^{-8}$$

→ new world-leading upper limits



Summary

- » Belle II has a unique sensitivity to new physics, setting world-leading limits in light dark sector and LFV searches in τ decays
- » New world-leading results presented today:
 - IDM with a dark Higgs
Belle II result presenting the first search for associated production of h' and IDM → To be submitted to PRL
 - $B \rightarrow K^{(*)} a' (\rightarrow \gamma\gamma)$
Belle search for ALP employing several BDTs → To be submitted to JHEP
 - $\tau \rightarrow e 2\ell$
Belle II measurement setting world's most stringent limits in 5 channels → To be submitted to JHEP
 - $\tau \rightarrow \ell K_S^0$
combined LFV search by Belle+Belle II → To be submitted to JHEP
- » Strive to improve further
 - increasing the statistics with larger data sample at Belle II
 - improving analysis techniques for reconstructing displaced vertices and reducing systematic uncertainties
 - develop even more robust trigger selecting low-multiplicity processes against higher background conditions coming with higher instantaneous luminosity



Stay tuned for more exciting results from Belle & Belle II!



Thank you!

Backup



Belle II luminosity

Belle II at SuperKEKB accelerator (2019–)

- Goals

- $50\times$ Belle data-sample size by increasing luminosity
- Renewed detector, trigger, analysis techniques, ...

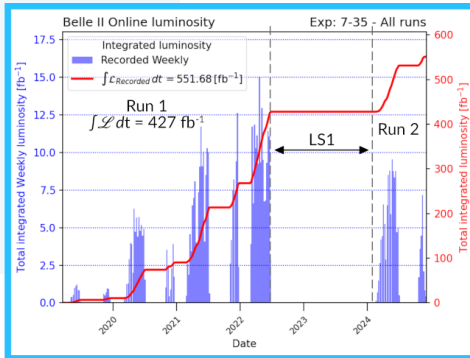
- Run 1 (2019–2022)

- Collected about

$1/2\times$ Belle data-sample size
 $1\times$ BaBar data-sample size

- Run2 started in spring 2024

- Upgraded detector
- World-record luminosity:
 $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



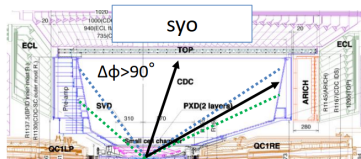
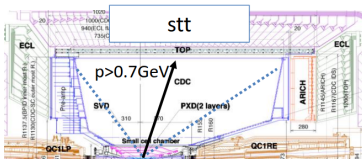
Special triggers – tau

List of output bits: τ

-CDC-KLM, ECL-KLM matching trigger

2021c

Physics target	bit name	condition	Raw rate (kHz)	Exclusive rate (kHz)
τ	stt	CDC #full track \geq 1, $ z < 15\text{cm}$, $p > 0.7\text{GeV}$	1.74	0.96
	syo	CDC #full track \geq 1, $ z < 15\text{cm}$, #short track \geq 1, $\Delta\phi > 90\text{deg}$.	0.74	0.38
	yioiecl1	CDC #full track \geq 1, $ z < 15\text{cm}$, #inner track \geq 1, $\Delta\phi > 90\text{deg}$.	0.37	0.08
	lml12	NCL ≥ 3 , at least 1 CL $\geq 500\text{ MeV(Lab)}$ (with $\theta_{ID} = 2 - 16$)	0.17	0.03
	ecltaub2b3	under commissioning	-	-



Process	Event rate
e^+e^- bunch collision	$\sim 200\text{MHz}$
$e^+e^- \rightarrow \tau^+\tau^-$	$\sim 0.6\text{kHz}$

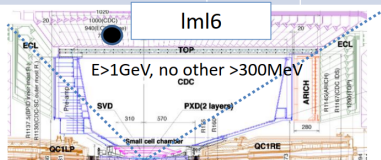
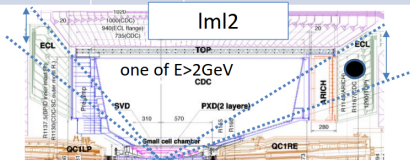
Special triggers – dark sector

List of output bits: lowmulti/dark

-Mainly ECL based photon trigger

2021c

Physics target	bit name	condition	Raw rate (kHz)	Exclusive rate (kHz)
Z'	fy30	$\text{CDC \#full track} \geq 2$, $\Delta\phi > 30\text{deg}$, $\# z < 20\text{cm} = 1$	1.59	0.14
ISR, π^0 FF	lml2	ECL one CL ≥ 2 GeV(CM) with $\theta_{\text{ID}} = 2, 3, 15$ or 16	0.18	0.01
single γ	lml6	ECL only one CL ≥ 1 GeV(CM) with $\theta_{\text{ID}} = 4 - 15$ and no other CL ≥ 300 MeV(Lab) anywhere	0.18	0.03
single γ	lml7	ECL only one CL ≥ 1 GeV(CM) with $\theta_{\text{ID}} = 2, 3$, or 16 and no other CL ≥ 300 MeV(Lab) anywhere	0.15	0.04
ALP	lml8	$170^\circ < \Delta\phi_{\text{CM}} < 190^\circ$, both CL > 250 MeV(Lab), no 2GeV(CM) CL in an event	0.08	0.05
ALP	lml9	$170^\circ < \Delta\phi_{\text{CM}} < 190^\circ$, one CL < 250 MeV(Lab), one CL > 250 MeV(Lab), no 2GeV(CM) CL in an event	0.34	0.28
dark photon	lml16	ECL only one CL ≥ 0.5 GeV(CM) with $\theta_{\text{ID}} = 6-11$ and no other CL ≥ 300 MeV(Lab) anywhere, $\#\text{CDC full track} = 0$	0.32	0.23



Parameters in the search for IDM with a dark Higgs

- Mass of the χ_1 m_{χ_1}
- Mass of the dark photon $m_{A'}$
- Mass of the dark Higgs boson $m_{h'}$
- Mixing angle of the dark photon ϵ
- Mixing angle of the dark Higgs θ
- Coupling between DM and dark photon $g_X = \sqrt{4\pi\alpha_D}$
- Coupling between DM and dark Higgs $f = \sqrt{4\pi\alpha_f}$

In addition, the mass of the χ_2 can be calculated via the mass splitting

$$\Delta m = m_{\chi_2} - m_{\chi_1}$$

LFU test in tau decays

» Testing $e - \mu$ universality

$$R_\mu = \frac{B(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} \stackrel{\text{SM}}{=} 0.9726 \quad \left(\frac{g_\mu}{g_e} \right)_\tau^2 \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \stackrel{\text{SM}}{=} 1$$

- R_μ measured in 1×1 prong topology with $\tau \rightarrow \pi \pi^0 \nu$ tag
- using 365 fb⁻¹ Belle II data

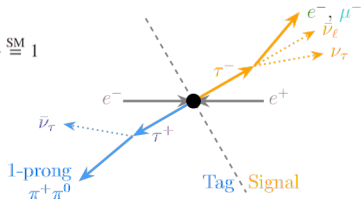
» Signal selection

- cut-based preselection followed by a neural network training
- 94% purity with 9.6% signal efficiency after NN selection
- main systematics are from PID (0.32%) and trigger (0.1%)

» World's most precise result

$$R_\mu = 0.9675 \pm 0.0007(\text{stat.}) \pm 0.0036(\text{sys.})$$

- in agreement with SM
- ## » Analysis continuation
- ongoing study using events with 3×1 topology with inclusive tag
 - improved trigger selection, reducing leading systematics



[JHEP08(2024)205]

