Tau and dark sector measurements at Belle and Belle II

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Belle and Belle II experiments

B-factories with broad physics program

» **B-factories at KEK (Tsukuba, Japan)**

- asymmetric e^+e^- colliders, running at the $\Upsilon(4S)$ energy (10.58 GeV)

» **Belle @ KEKB accelerator** (1998–2010)

- recorded limunosity $\approx 1\ \mathrm{ab}^{-1}$

» **Belle II @ SuperKEKB accelerator** (2019–)

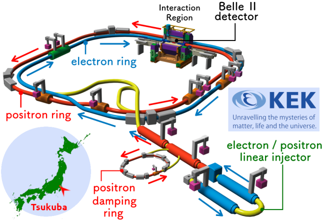
- major upgrade of both accelerator and detector, new analysis techniques
- special triggers for low-multiplicity events (single track/muon/photon triggers)

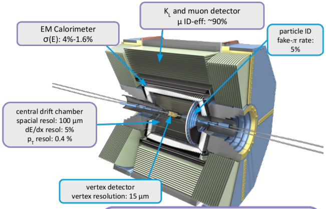
→ allows for the selection of signals that were not possible to trigger at Belle

- excellent tracking efficiency and improved vertex resolution

→ enables new measurement approaches

- recorded limunosity $= 575\ \mathrm{fb}^{-1}$
- world record inst. luminosity of $5.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$





trigger: hardware rate (L1) < 30 kHz
software rate (HLT) < 10 kHz

Light dark sector

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

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

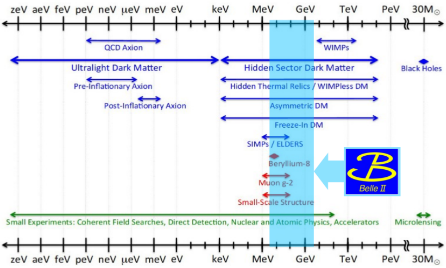
- rotation curves of galaxies

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

- searches for dark matter is one of the main goals of particle physics

» **Mediator portals**

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



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

- dark sector weakly coupled to Standard Model through a light mediator particle

» **Advantages of B-factories**

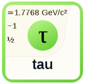
- well-defined kinematics of initial state
- hermetic detector

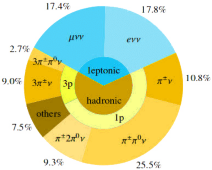
→ good missing energy reconstruction

→ searching for signatures with invisible particles

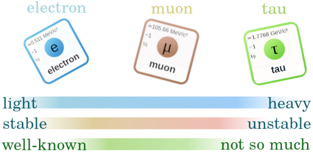
Tau physics

B-factories provide a great environment for precision measurements

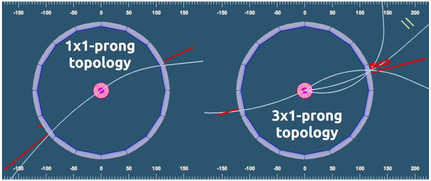




- **3rd generation particle**
  - the heaviest known lepton
  - can decay to lighter leptons but also hadrons
- **The τ properties are known with much worse precision compared to e and μ!**



- **Searches for forbidden τ decays**
  - lepton flavour/number violation
- **Possible τ physics probes**
  - lepton universality, CKM unitarity, new sources of CP violation, ...
  - some NP scenarios predict enhanced τ couplings to NP



- **Advantages of B-factories**
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

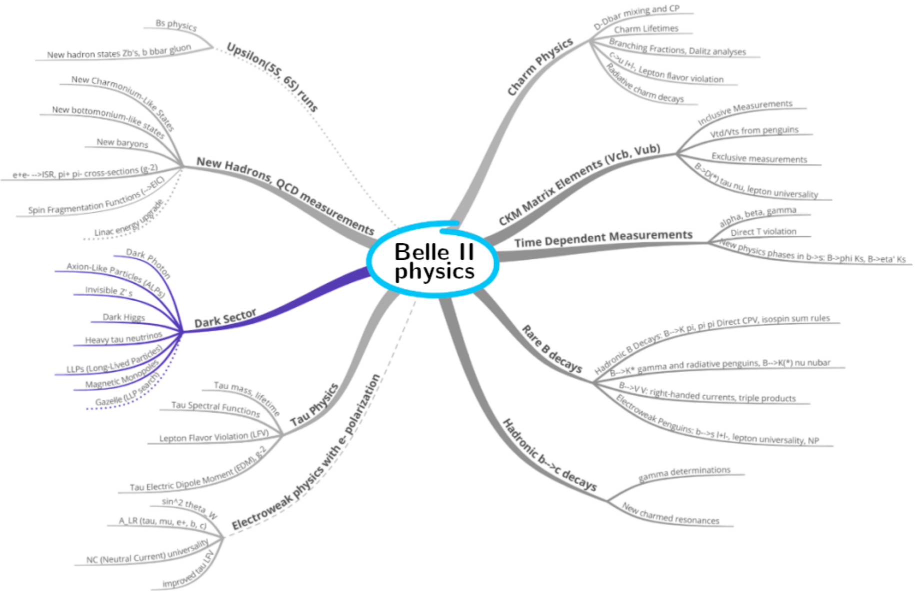
→ B-factories are also τ-factories!

  - excellent vertexing and tracking capabilities
  - sophisticated trigger system and particle ID

→ ability to trigger low-multiplicity event

  - taupair events are produced back-to-back and each tau is reconstructed via 1 or 3 charged tracks

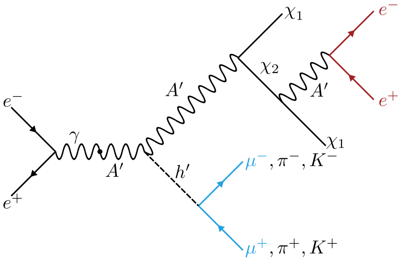
Dark sector at Belle II

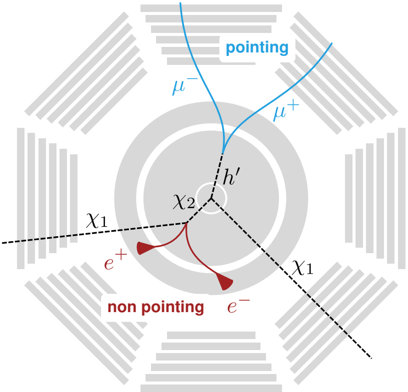


Inelastic dark matter with a dark Higgs

New!

- **Probing a non-minimal DS model predicting 4 new particles**
- 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 dispaced vertex
  - other 2 forming a non-pointing dispaced vertex
  - mising energy

→ challening for tracking and trigger

- **Exploring 3 final states:**
  $h' \to x^+x^-, x = \mu, \pi, K$

Inelastic dark matter with a dark Higgs

New!

» **Signal selection**

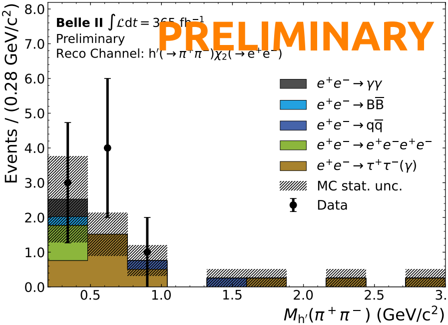
- using requirements on pointing angles and vertex distance from the interaction point

→ 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



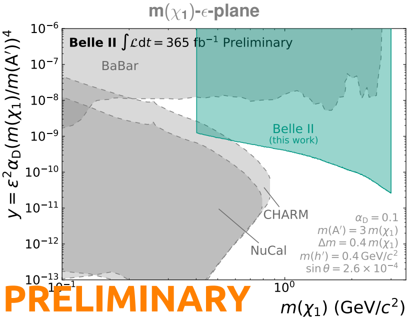
» **No significant excess found in the individual final states or the combination**

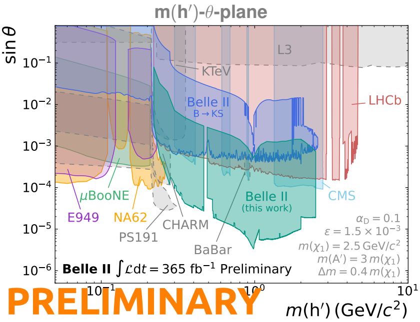
- 9 events observed (8 of 9 are $\pi^+\pi^-$) – consistent with expected background
- search performed using 365 fb^{-1} of Belle II data – analysis statistically limited

Inelastic dark matter with a dark Higgs

New!

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



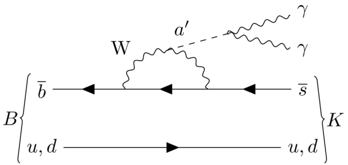


Search for $B \to K^{(*)} a'(\to \gamma\gamma)$

New!

» NP searches in flavour changing neutral current B decays
- FCNC heavily suppressed in SM
- NP can appear at the same order as SM processes

» **Search for an Axion-Like Particle (ALP) emission by W boson in $B \to K^{(*)} a'$ decay**
- $\mathcal{BR}(a' \to \gamma\gamma) \simeq 100\%$ for $m_{a'} << m_{W^\pm}$
- probing $0.16 - 4.50$ GeV/c^2 mass range
- including 4 kaon modes: $K_S^0, K^\pm, K^{*0}, K^{*\pm}$
- using full Belle dataset



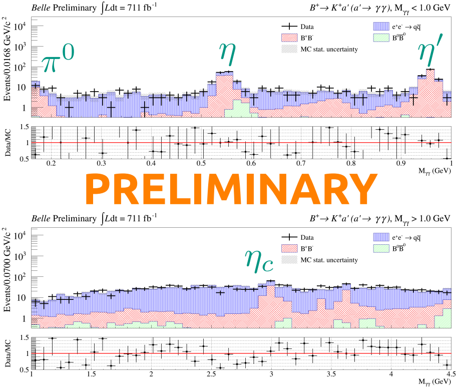
» **Signal reconstruction**
- B meson reconstructed from an ALP candidate (pair of photons) and a kaon candidate (charged or neutral)

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

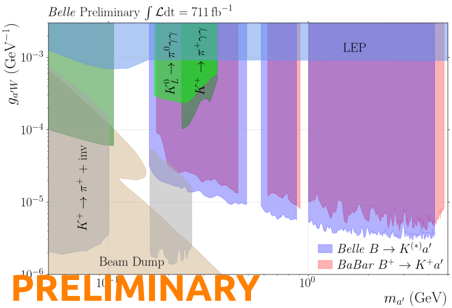
Search for $B \to K^{(*)} a'(\to \gamma\gamma)$

New!

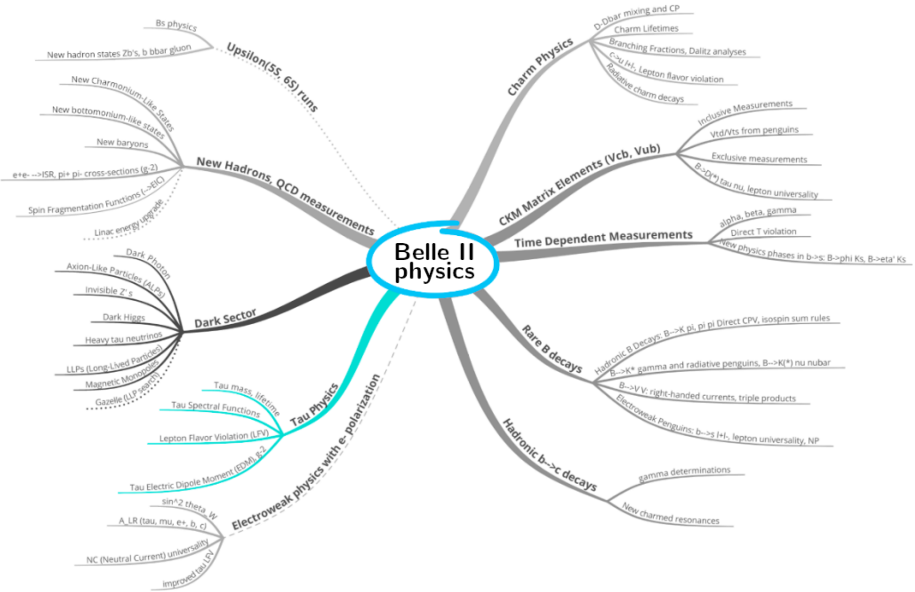
- **Signal extracted from a scan over $M_{\gamma\gamma}$**
  - veto regions with peaking background



- **No significant excess observed in 711 fb^{-1}**
  - simultaneous fit in all 4 kaon modes
  - → 90% CL upper limits on $g_{a'W}$
  - → **world-leading result**



Tau at Belle II



Lepton flavour in tau decays

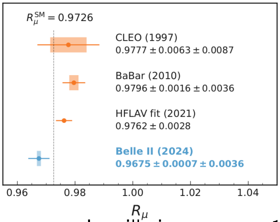
» **Probing the SM**

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

» **R_μ measurement at Belle II**:

- test of $e - \mu$ universality
- world's most precise measurement in τ decays from a single measurement

[JHEP08(2024)205]



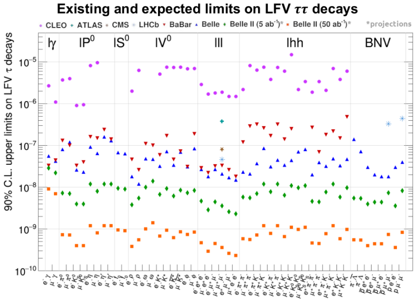
» **Searching for NP**

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

» **Belle II already set world-leading limits:**

- $\tau \rightarrow 3\mu$: most accessible
- $\tau \rightarrow \Lambda(\bar{\Lambda})\pi$: baryon number violation $\rightarrow$ condition for matter/antimatter asymmetry
- $\tau \rightarrow \ell\alpha$: new boson candidate for dark matter

$\rightarrow$ Belle II is expected to push forward the existing limits by at least 1 order of magniute



Neutrinoless 2-body or 3-body decays to **52 final states**.

Search for $\tau \to e2\ell$

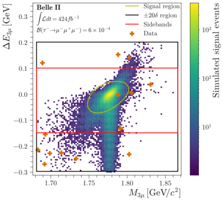
New!

» **Extending the $\tau \to 3\mu$ study**

- clean channel, low SM background
- untagged reconstruction, reject main $ee \to qq$ background using BDT classifier
- signal yield from 2D plane ($M_{3\mu} - \Delta E_{3\mu}$)
- 90% CL upper limit: $\mathcal{BR}(\tau \to 3\mu) < 1.9 \times 10^{-8}$
- the inclusive tag and BDT-based background rejection give 2.7× the Belle signal efficiency at similar purity

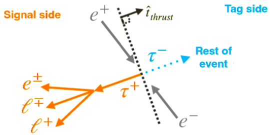
→ world-leading result set by Belle II

[JHEP09(2024)062]



» **Studying 5 more channels**

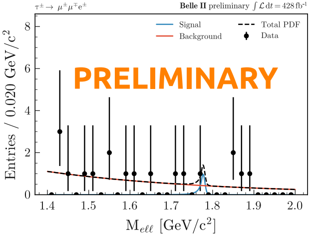
- $e^- e^+ e^-$, $e^- e^+ \mu^-$, $e^- \mu^+ e^-$, $\mu^- \mu^+ e^-$, $\mu^- e^+ \mu^-$
- higher background contamination
- untagged reconstruction, data-driven BDT classifier trained on sideband data
  → reject main 4ℓ background relying on ROE and kinematic variables
- signal from $M_{e\ell\ell}$ fit



» **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

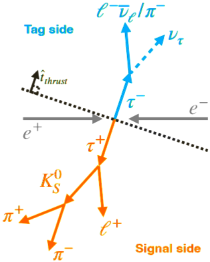


Search for $\tau \to \ell K_S^0$

New!

» **Belle + Belle II search for $\tau \to \ell K_S^0 (\ell = e, \mu)$**

- require 4 charged particles with 0 net charge in 3×1-prong topology
- reconstruct K_S^0 from $\pi^+\pi^-$
- $\tau \to \ell \bar{\nu}_\ell \nu_\tau / \pi \nu_\tau (\ell = e, \mu)$ 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 $(M_\tau - \Delta E)$ $(\Delta E = E_\tau - E_{\text{beam}})$

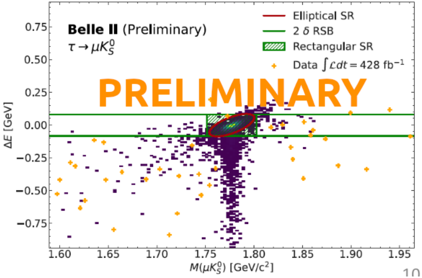
» **No significant signal was observed in 424 fb^{-1} + 980 fb^{-1} (Belle + Belle II)**

- combined 90% CL upper limit on $\mathcal{BR}$s:

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

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

→ 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**

» **Recent tau and dark sector searches:**

- IDM with a dark Higgs – first search for associated production of h' and IDM
- $B \to K^{(*)}a'(\to \gamma\gamma)$ – Belle analysis employing several BDTs
- $\tau \to e2\ell$ – setting world's most stringent limits in 5 channels
- $\tau \to \ell K^0_S$ – combined Belle+Belle II search

$\to$ New world-leading results!

$\to$ To be submitted to journals (JHEP, PRL)

» **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

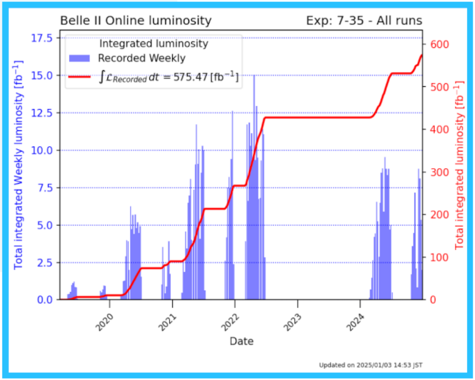
Belle II luminosity

Belle II at SuperKEKB accelerator (2019–)

- Goals
  - 50× Belle data-sample size by increasing luminosity
  - Renewed detector, trigger, analysis techniques, ...
- Run 1 (2019–2022)
  - Collected about

    1/2× Belle data-sample size
    1× BaBar data-sample size
- Run2 started in spring 2024
  - Upgraded detector
  - World-record luminosity:

    $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



Parameters in the search for IDM with a dark Higgs

- Mass of the χ_1 m_{χ_1}
- Mass of the dark photon $m_{\mathrm{A}'}$
- Mass of the dark Higgs boson $m_{\mathrm{h}'}$
- 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

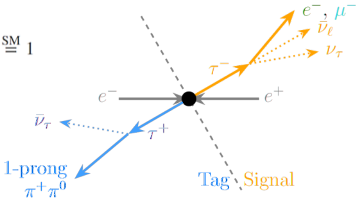
$$\Delta m = m_{\chi_2} - m_{\chi_1}$$

LFU test in tau decays

» **Testing $e-\mu$ universality**

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

- R_μ measured in 1×1 prong topology with $\tau \to \pi\pi^0\nu$ 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

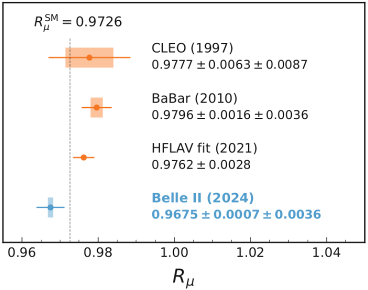
- main systematics are from PID (0.32%) and trigger (0.1%)

» **World's most precise result**

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

- in agreement with SM

[JHEP08(2024)205]



» **Analysis continuation**

- ongoing study using events with 3×1 topology with inclusive tag
- improved trigger selection, reducing leading systematics