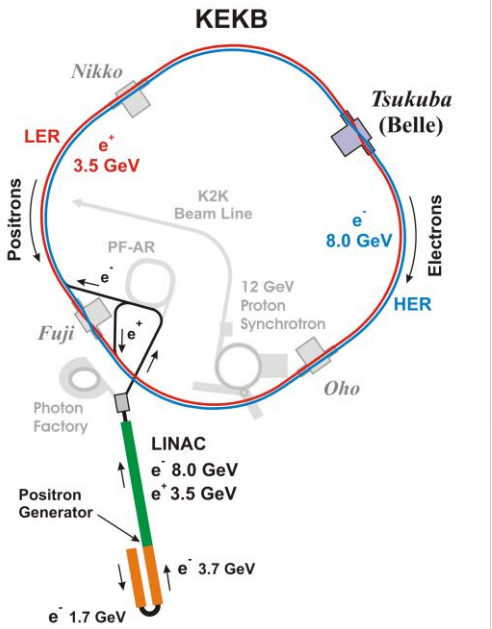
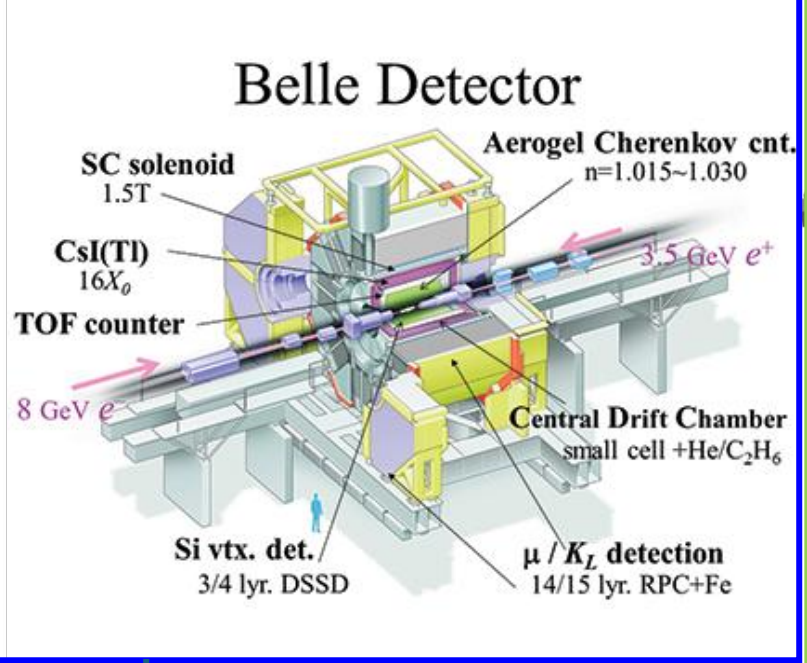
Dark sector and tau physics at Belle and Belle II

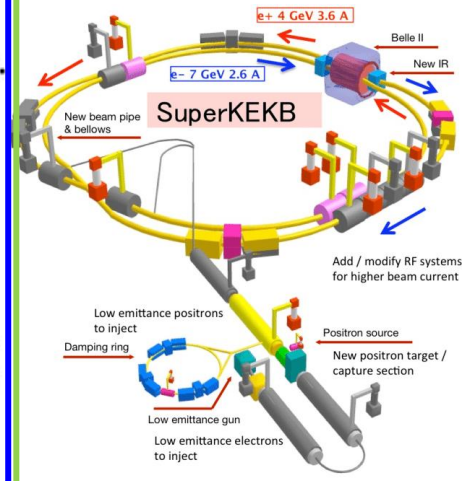
Lake Louise Winter Institute, March 2026

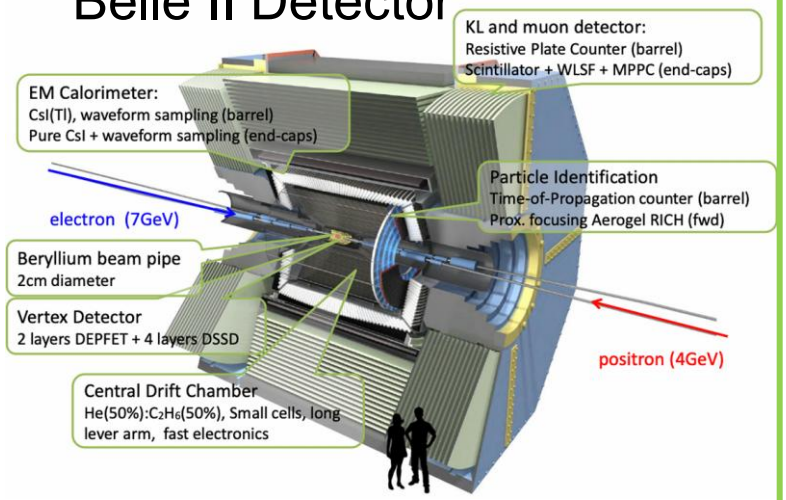
H. Lee (on behalf of the Belle II Collaboration)

Belle and Belle II



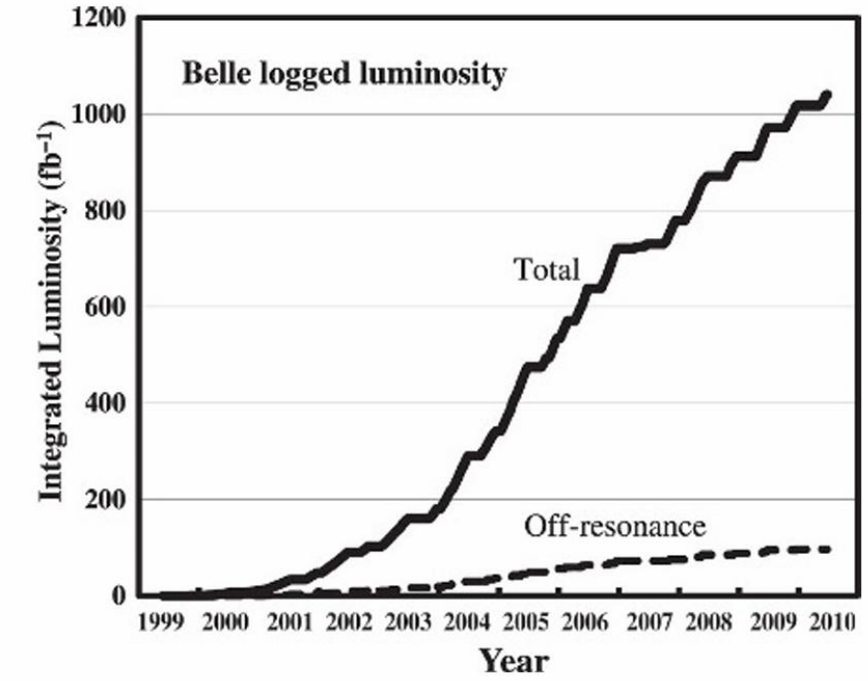


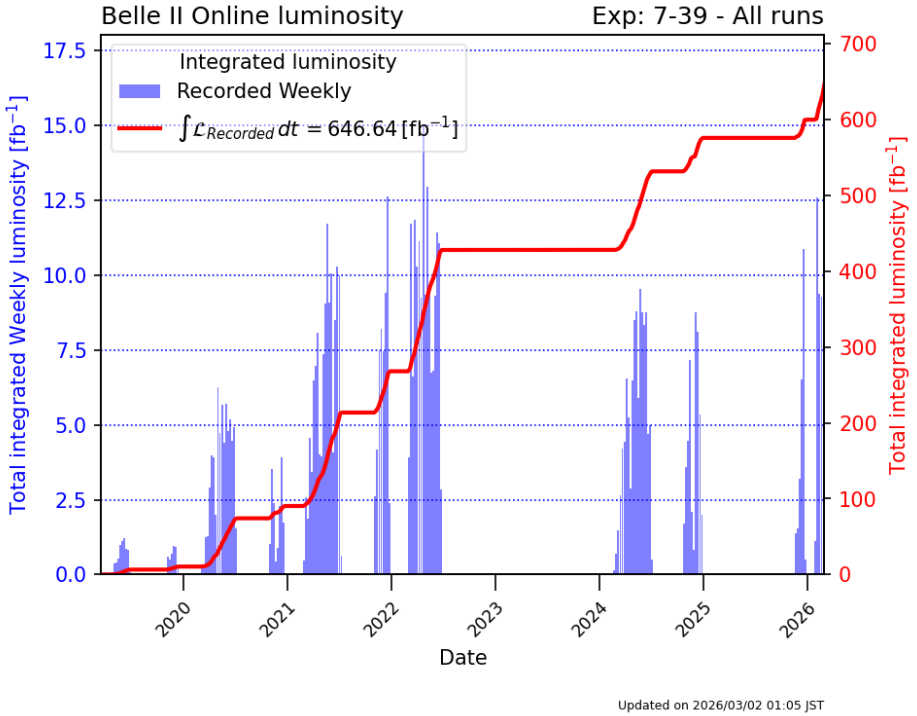




- $\sqrt{s} = 10.58$ GeV : $\Upsilon(4S)$ resonance
- Asymmetric energy
- Various physics programs : B, Charm, tau, CPV, low-multiplicity, exotic hadron
- Belle → Belle II : 30 times higher instantaneous luminosity
  - 2024/12/27 World best peak luminosity $5.1 \times 10^{34} cm^{-2} s^{-1}$

Data





- Belle : 1/ab
- Belle II : 0.6/ab (from 2019)
- $\sigma\left(e^+e^- \to b\bar{b}\right) = 1.05$ nb
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb
- **B factory is also tau factory!**

Experiment	$N(\tau^+\tau^-)$
BABAR (424/fb)	390×10^6
Belle (988/fb)	910×10^6
Belle II obtained (647/fb)	600×10^6
Belle II expected (50/ab)	$\mathbf{46.0 \times 10^9}$

Tau & Dark sector at Belle and Belle II

- Clean electron–positron collisions, excellent vertexing, and nearly full 4π coverage
  - Ideal environment for precise new physics searches
  - In this talk : **Recent LFV and Dark sector searches results**

- Tau physics
  - Huge tau pair production
  - Precision measurements: tau properties, lepton flavor universality, CP violation
  - Sensitive searches for lepton flavor violation $(10^{-9} - 10^{-10})$
  - $\boldsymbol{\tau^- \to \mu^- \gamma,\ \tau^- \to \ell^- \eta}$

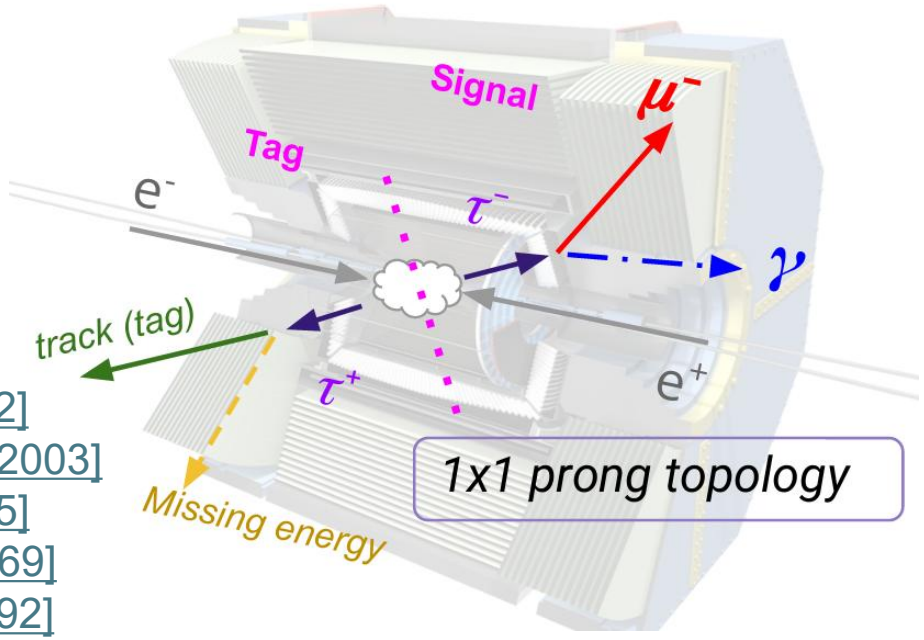
- Dark sector searches
  - Probe a wide mass range (sub-GeV to few-GeV)
  - Sensitive to missing energy and displaced vertex signatures
  - $\boldsymbol{\tau^- \to \ell^- \alpha,\ B \to K^{(*)} \alpha,}$ and $\boldsymbol{e^+ e^- \to \gamma a (\to \gamma\gamma)}$

- At the intensity frontier, Belle II can directly discover light new particles and indirectly probe heavy mediators through rare decays.

Tau LFV Searches

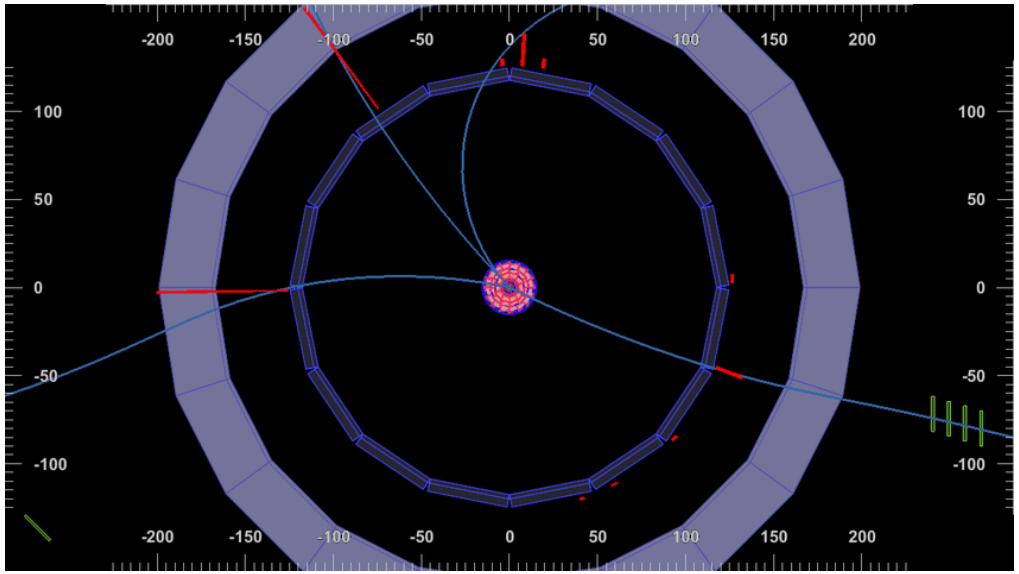
- Tau event and tau LFV searches
  - $e^+e^- \to \tau^+\tau^-$: Back-to-back topology in the CM system
  - Thrust axis ($\hat{\mathbf{n}}_{\text{thrust}}$) : maximize the V_{thrust}
    - Clear separation of two hemispheres → help the recon & bkg. Supp.
  - Tracks are called prongs, usually.
  - Statistically limited; high signal efficiency and strong background suppression are essential.

$$V_{\text{thrust}} = \frac{\sum |\mathbf{p}_i^{\text{CM}} \cdot \hat{\mathbf{n}}_{\text{thrust}}|}{\sum |\mathbf{p}_i^{\text{CM}}|}$$



- Recent Pubs.

$\tau \to 3\mu$ [JHEP09(2024)062]
$\tau \to \Lambda\pi$ [PRD110(2024)112003]
$\tau \to \ell\alpha$ [JHEP08(2025)155]
$\tau \to e\ell\ell'$ [JHEP12(2025)169]
$\tau \to \ell K_S^0$ [JHEP08(2025)092]

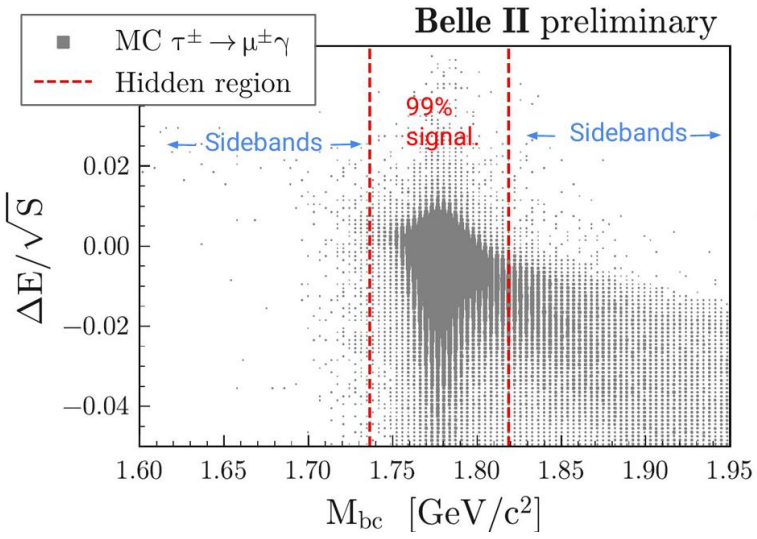


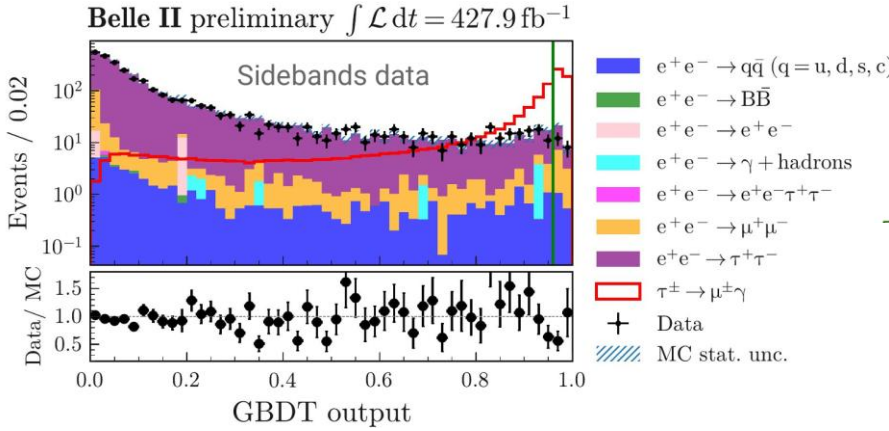
Tau decay topology : 3x1 prong

$\tau^- \to \mu^-\gamma$: Motivation, and Event Selection

- Immeasurably small within the SM: Any observation of LFV will be an indication of physics beyond SM
  - Sensitive to dipole-type new physics
- Search performed on 428/fb of Belle II data
  - Corresponds to about 390×10^6 taupair events.
- Previous most stringent upper limit set by Belle (90% C.L.)
  - $B(\tau \to \mu\gamma) < 4.2 \times 10^{-8}$ with 988/fb [JHEP10(2021)019]
- Reconstruction
  - 1x1 prong topology divided by thrust axis
  - Search in the 2D plane
- Background Suppression $M_{\rm bc} = \sqrt{(E^{\rm c.m.}_{\rm beam})^2 - (|\vec{p}^{\,\rm c.m.}_{\mu\gamma}|)^2}$, $\Delta E/\sqrt{s} = (E^{\rm c.m.}_{\mu\gamma} - E^{\rm c.m.}_{\rm beam})/\sqrt{s}$
  - Gradient Boosted Decision Tree (GBDT) trained with 11 input variables
  - Better Muon ID compared to Belle
  - 50% increase in signal efficiency
  - 80% decrease in background yield (when compared in same area)
- Sideband fits to data are utilized to extrapolate

  number of expected background inside the signal region





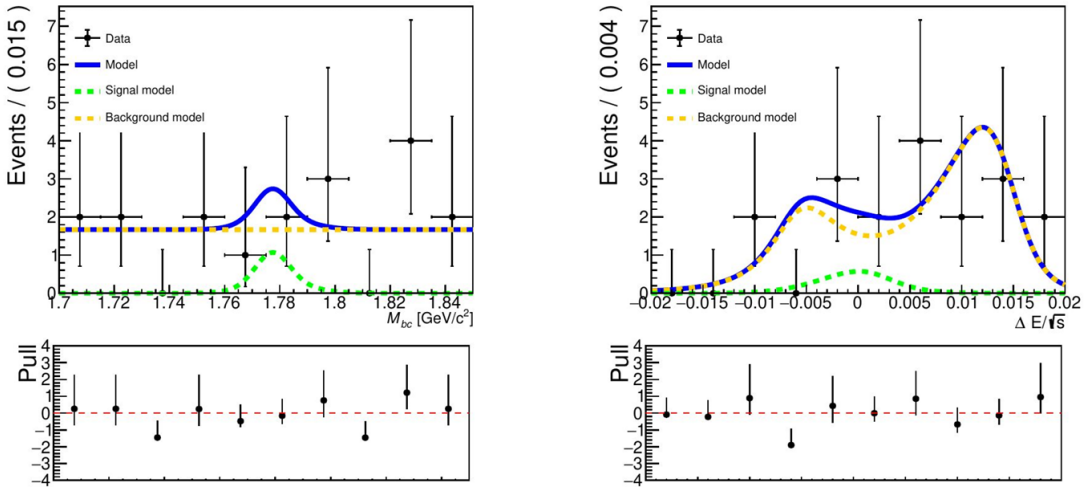
$\tau^- \to \mu^-\gamma$: Results

- Statistical uncertainty dominates.
- Among the larger systematic sources
  - GBDT selection : 5.7%
- Signal extraction
  - Unbinned likelihood fit is performed in $(M_{bc}, \Delta E/\sqrt{s})$ plane
    - Including nuisance parameter as constraint term.
  - Expected events : 15.7 ± 3.4
  - Observed events : 18
  - The fit result for signal is consistent with zero.
- Upper limit (UL at 90% C.L.)
  - CLs method is utilized.
  - The observed UL is consistent with Belle result.

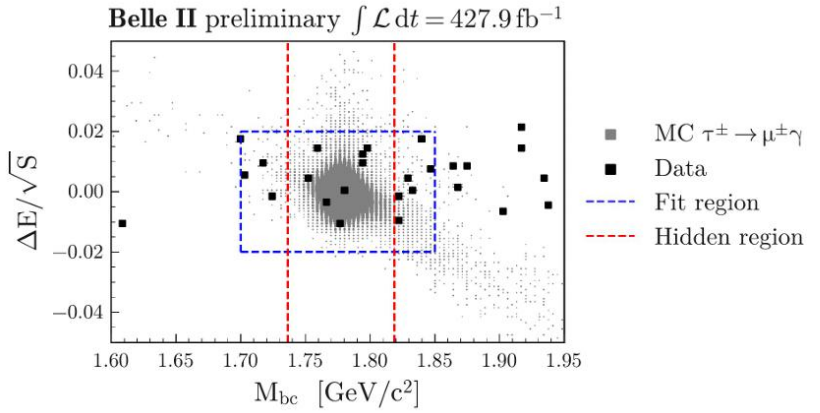
$$\mathcal{B}(\tau^- \to \mu^-\gamma)^{\mathrm{exp}} < 5.8 \times 10^{-8}$$
$$\mathcal{B}(\tau^- \to \mu^-\gamma)^{\mathrm{obs}} < 9.5 \times 10^{-8}$$

  - Belle II sensitivity with 1/ab is expected to be better than Belle
    - Higher efficiency and lower backgrounds
- Preparing JHEP submission

$$L = \frac{e^{-(s+b)}}{N!} \prod_{i=1}^{N} (sS_i + bB_i) \prod_k \mathcal{G}(\alpha_k; \mu_k, \sigma_k)$$



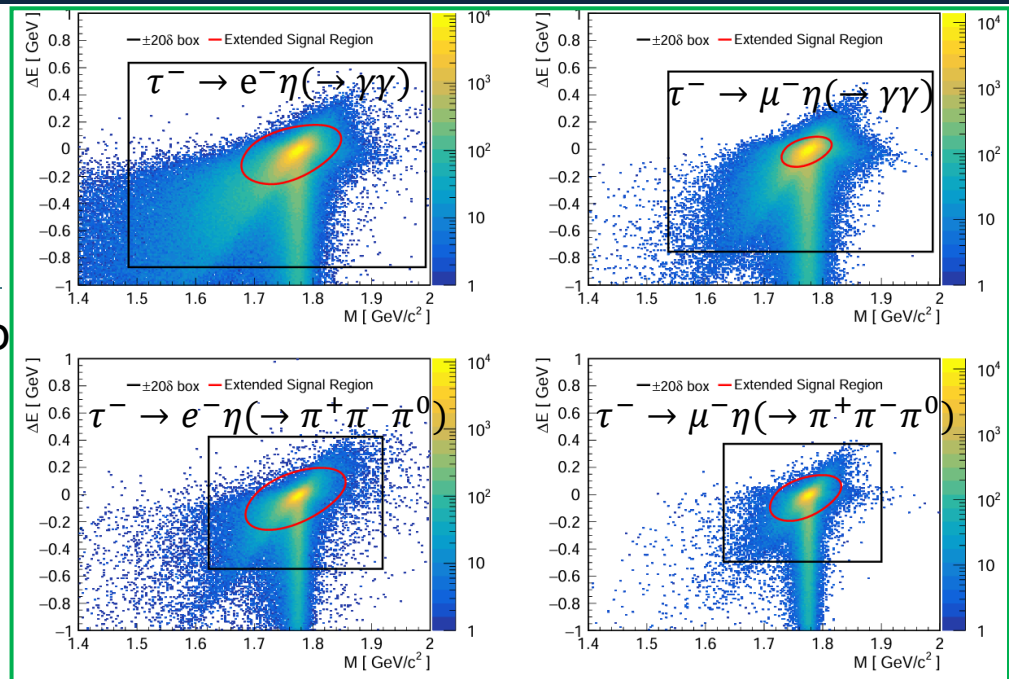
1D projection



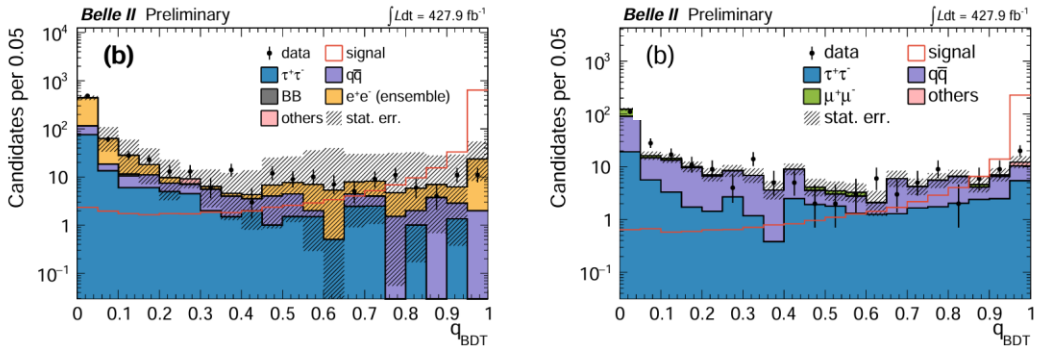
$\tau^- \to \ell^- \eta$: Motivation, and Event Selection

New preliminary result!

- Complementary LFV new physics
  - Many kinds of effective operator can interact with.
- Search performed on 428/fb of Belle II data
- Previous stringent upper limit set by Belle (90% C.L.) [PLB648 (2007) 341]
  - $B(\tau \to e\eta) < 9.2 \times 10^{-8}$ and $B(\tau \to \mu\eta) < 6.5 \times 10^{-8}$ with 401/fb
- Reconstruction
  - 4 orthogonal searches : $(e,\ \mu) \times\ \eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
  - 1x1 (3x1) prong topology divided by thrust axis
  - Search in the 2D plane : $(M_\tau\ , \Delta E)$
- Background Suppression
  - Selections to reject obvious background from e^+e^- or $\mu^+\mu^-$
  - GBDT is also used for further suppression in $\eta \to \gamma\gamma$
    - Residual backgrounds: $\tau^+\tau^-$, $q\bar{q}$, radiative e^+e^-
  - Signal region size are optimized to maximize the sensitivity.
- Sideband data is used for background estimation



Belle II simulations: signal distributions in $(M_\tau\ , \Delta E)$



BDT output distributions

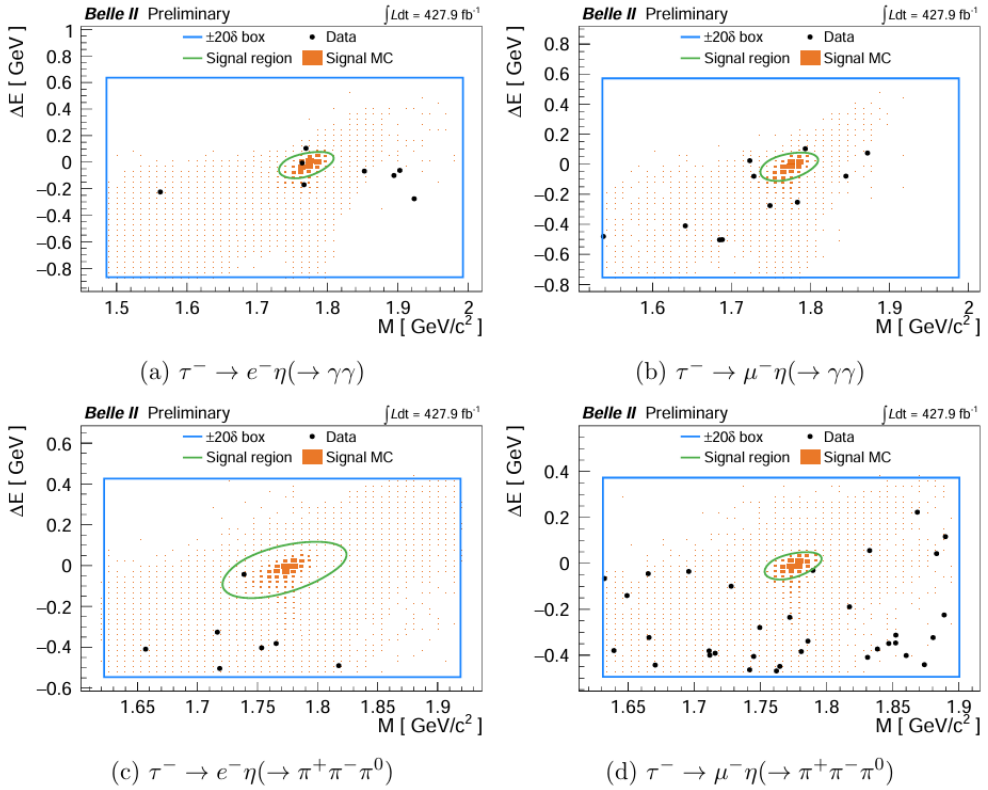
$\tau^- \to \ell^- \eta$: Results

New preliminary result!

- Signal extraction
  - Likelihoods are built with Poisson counting models
    - Two bin counting ($\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$)
    - Including nuisance parameter as constraint term.

$$\mathcal{L}(\mu, \boldsymbol{\theta} \mid N_{obs}^{\eta\to\gamma\gamma}, N_{obs}^{\eta\to3\pi}) = \prod_i (\mu s_i + b_i)^{N_i} \times \frac{e^{-(\mu s_i + b_i)}}{N_i!} \times f(\boldsymbol{\theta})$$

Channel	Observed	Expected
$e^-\eta(\to \gamma\gamma)$	1	$0.22^{+0.54}_{-0.18}$
$\mu^-\eta(\to \gamma\gamma)$	0	$0.36^{+0.83}_{-0.28}$
$e^-\eta(\to \pi^+\pi^-\pi^0)$	1	$0.06^{+0.09}_{-0.04}$
$\mu^-\eta(\to \pi^+\pi^-\pi^0)$	0	$0.28^{+0.09}_{-0.08}$



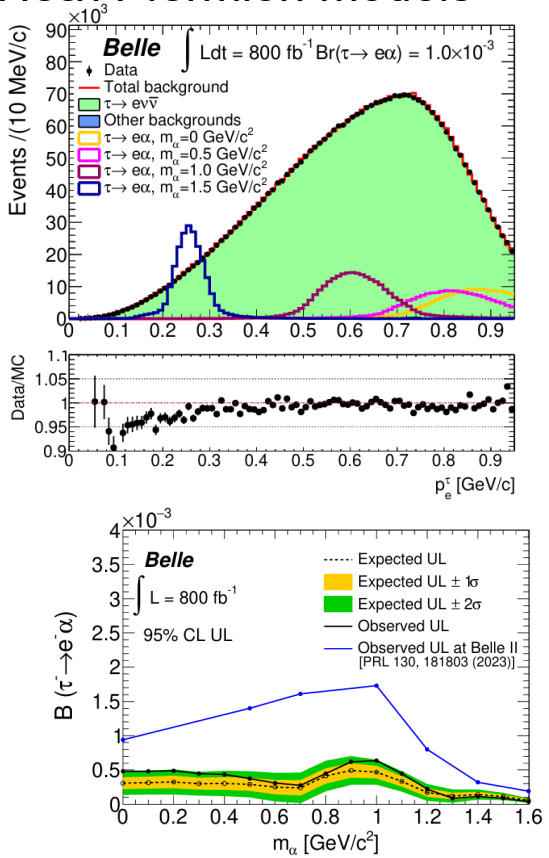
(a) $\tau^- \to e^-\eta(\to \gamma\gamma)$ (b) $\tau^- \to \mu^-\eta(\to \gamma\gamma)$

(c) $\tau^- \to e^-\eta(\to \pi^+\pi^-\pi^0)$ (d) $\tau^- \to \mu^-\eta(\to \pi^+\pi^-\pi^0)$

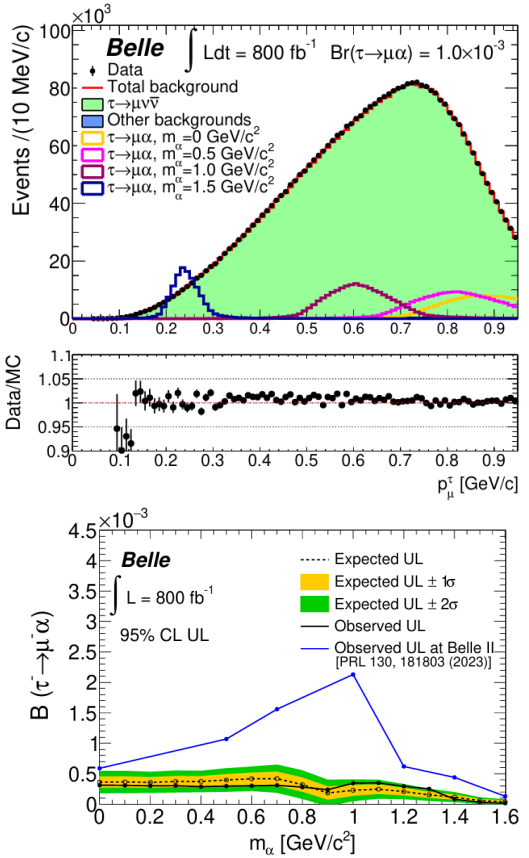
- Statistical uncertainty is dominant.
- Upper limit (UL at 90% C.L.)
  - CLs method is utilized.
  - $B(\tau \to e\eta) < 9.2 \times 10^{-8}$ and $B(\tau \to \mu\eta) < 4.2 \times 10^{-8}$
  - Observed UL is **world-leading** in the muon channel, and similar to Belle in the electron channel.
- Preparing PRD submission

$\tau^- \to \ell^- \alpha$: Motivation, and Event Selection

- Lepton-flavor violation with an invisible boson
  - Predicted in many BSM scenarios with axion-like particles (ALPs)
    - Dark sector portal models, Extended Higgs sector, Heavy fermion models
- Dataset
  - Belle data: 800/fb, corresponds to 740×10^6 taupairs
- Reconstruction
  - Required tag-side decays like $\tau \to 3\pi\nu, \pi\nu, or\ \pi\pi^0\nu$
  - Signal signature
    - $\tau \to \ell\alpha$ single lepton + missing energy
- Background suppression
  - Key discriminating variable
    - lepton momentum in tau rest frame p_ℓ^τ
    - $\theta_{\tau h}$: angle between hadronic system and tag-side tau
  - dominant background : $\tau \to \ell\nu\nu$ (~99%)



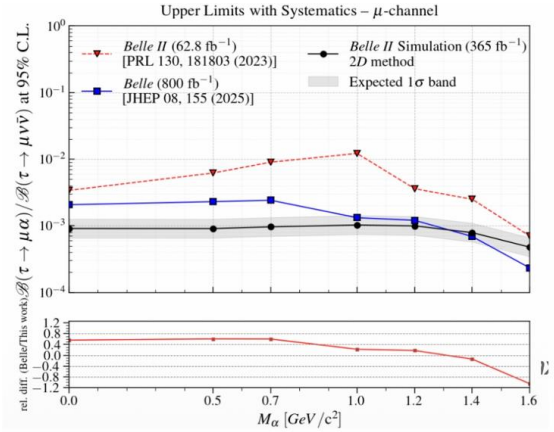
(a) $\tau^- \to e^-\alpha$.

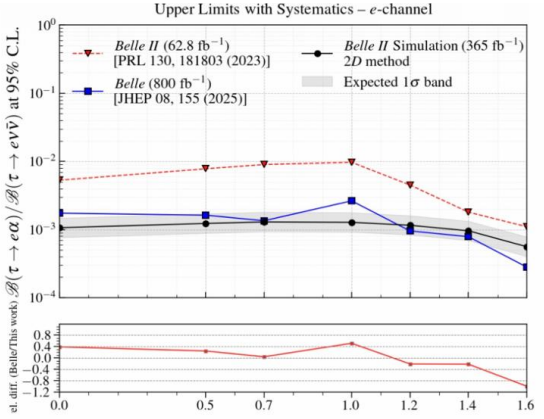


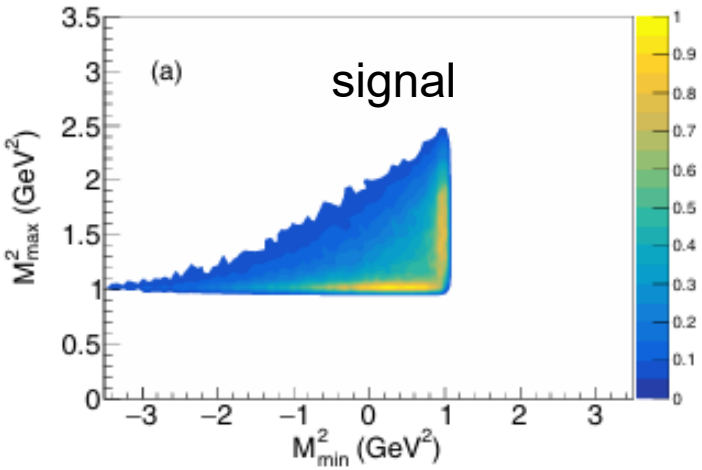
(b) $\tau^- \to \mu^-\alpha$.

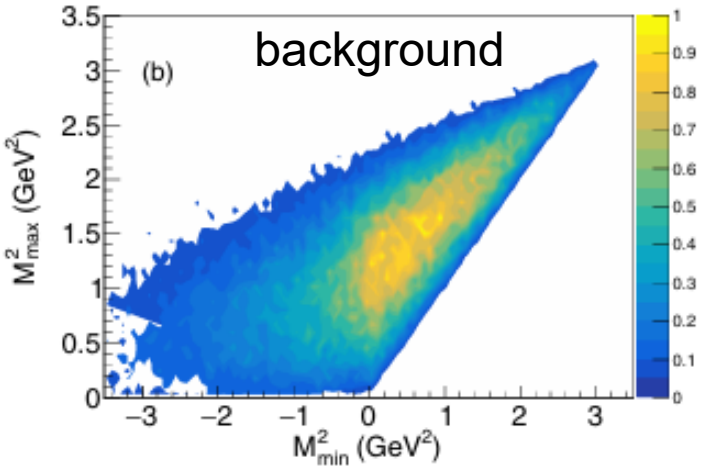
$\tau^- \to \ell^- \alpha$: Results

- Signal extraction
  - Extended maximum likelihood fit is performed to the lepton momentum spectrum.
  - No significant excess is observed.
- Upper limit (UL at 95% C.L.)
  - Frequentist method is utilized.
  - Results are the **most stringent limits** to date. [JHEP08(2025)155]
- More sensitive approach in Belle II is ongoing. [PRD102 (2020) 115001]
  - Signal and background occupy different regions in (M^2_{min}, M^2_{max}).
  - Belle II MC uses only the 1×1 topology and ~50% of the Belle dataset, yet are expected to achieve world-leading ULs below 1.2 GeV



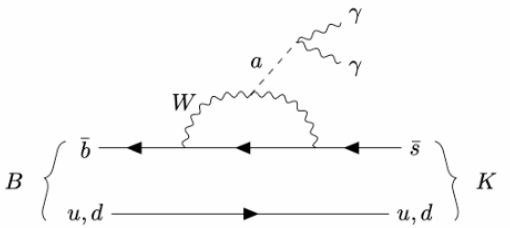


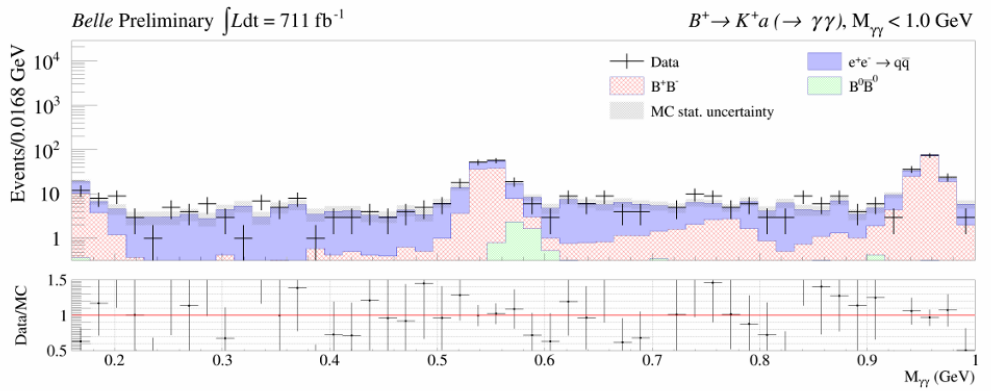


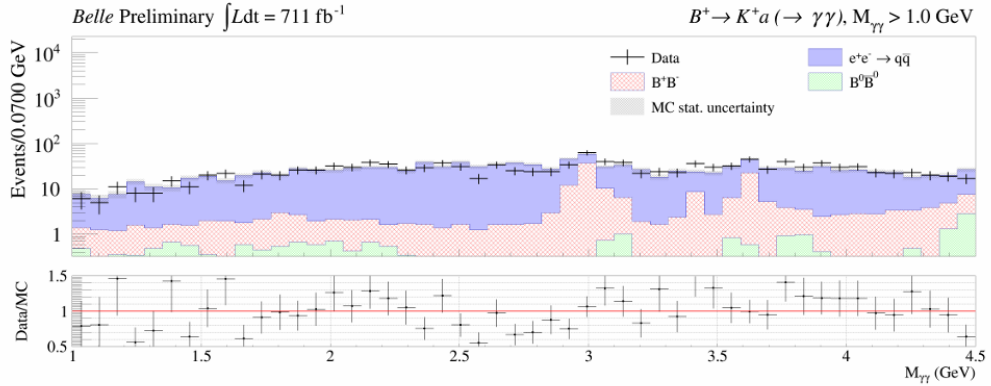


$B \to K^{(*)}\mathrm{a}(\to \gamma\gamma)$: Motivation and Event Selection

- Motivation
  - ALP can also be produced in rare B decays
- Dataset
  - Belle dataset 711/fb collected at the $\Upsilon(4S)$
- Reconstruction
  - Assume ALP decays dominantly into two photons: $a \to \gamma\gamma$
  - Four kaon modes reconstructed simultaneously.
    - K^+, K_S^0, K^{*+}, and K^{*0}
- Signal extraction
  - Scan ALP mass range: 0.16 - 4.50 GeV/c^2
  - Signal identified as narrow peak in $m_{\gamma\gamma}$.
- Background suppression
  - BDT
    - Dominant continuum background ($e^+e^- \to q\bar{q}$)
    - Separate training for low and high mass regions
  - SM resonance veto applied : π^0, η, and η'



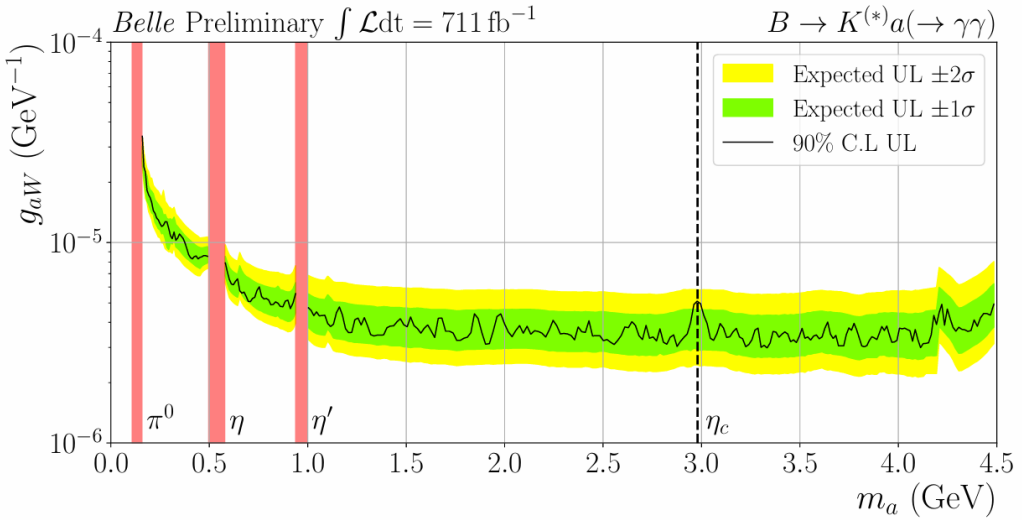


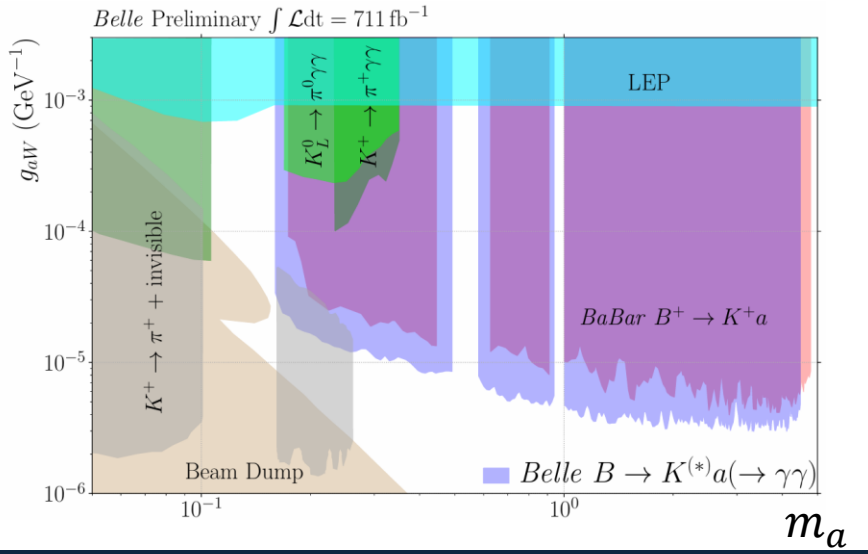


$M_{\gamma\gamma}$ (GeV)

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

- Systematic uncertainty
  - Total systematic uncertainty for signal extraction: 22.3%
- Signal extraction
  - No significant signal excess observed in any kaon decay modes.
  - The largest local significance observed 2.74σ (global : 1.89σ)
- Upper limits (90% C.L.)
  - Set on coupling strength $\boldsymbol{g_{aW}}$ as a function of m_a through a simultaneous fit to all four channels
  - Improve the limits on by a factor of two, provide **stringent constraints** on dark sector models. [JHEP12(2025)109]

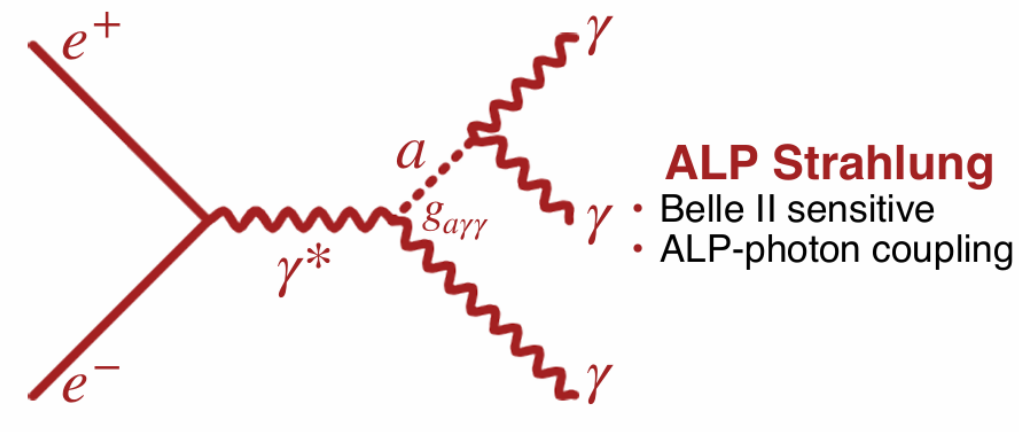




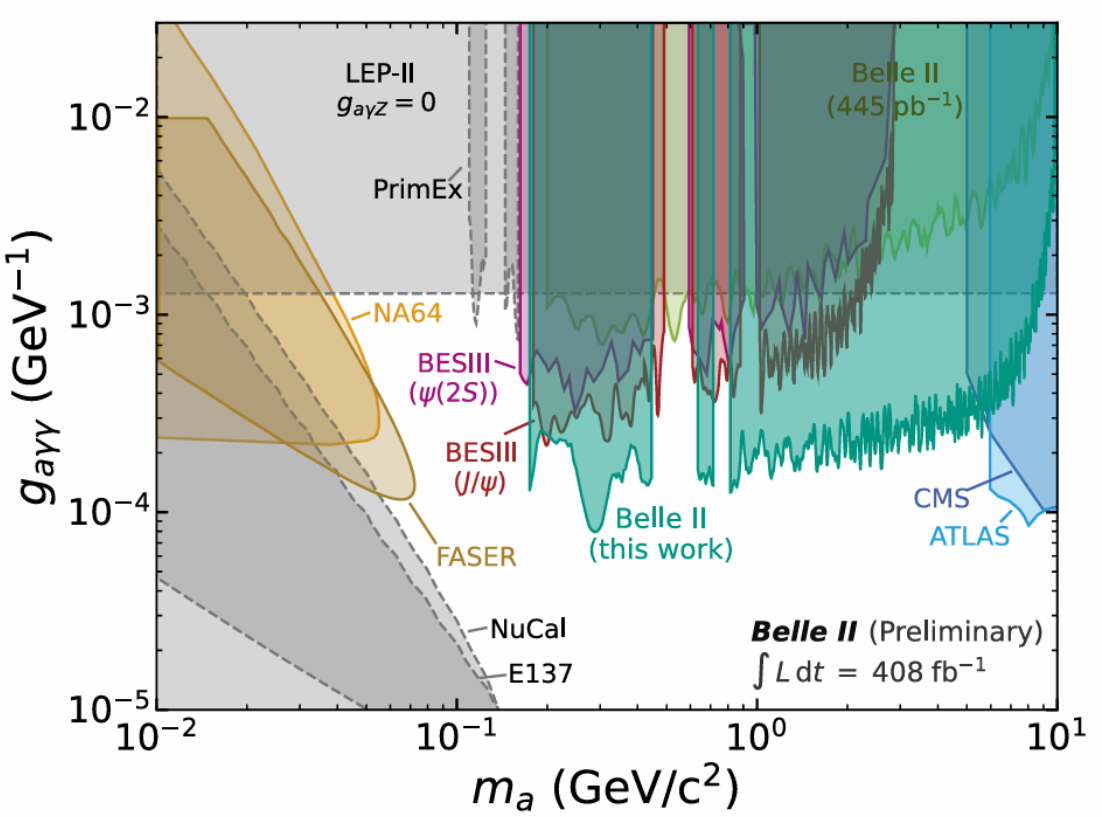
$e^+e^- \to \gamma a(\to \gamma\gamma)$: Recent Results

New preliminary result!

- In addition to ALP searches in tau and B decays, Belle II has recently performed a new search for ALPs produced directly in e^+e^- collisions.
- Search for ALPs in $e^+e^- \to a\gamma, a \to \gamma\gamma$
- Identify signal as a peak in the di-photon invariant mass spectrum.
- Belle II Run1 dataset (408/fb)
- Approved for public presentation the last week
  - Local (global) significance 3.3σ (1.4σ)
  - **World-leading sensitivity** for $g_{a\gamma\gamma}$

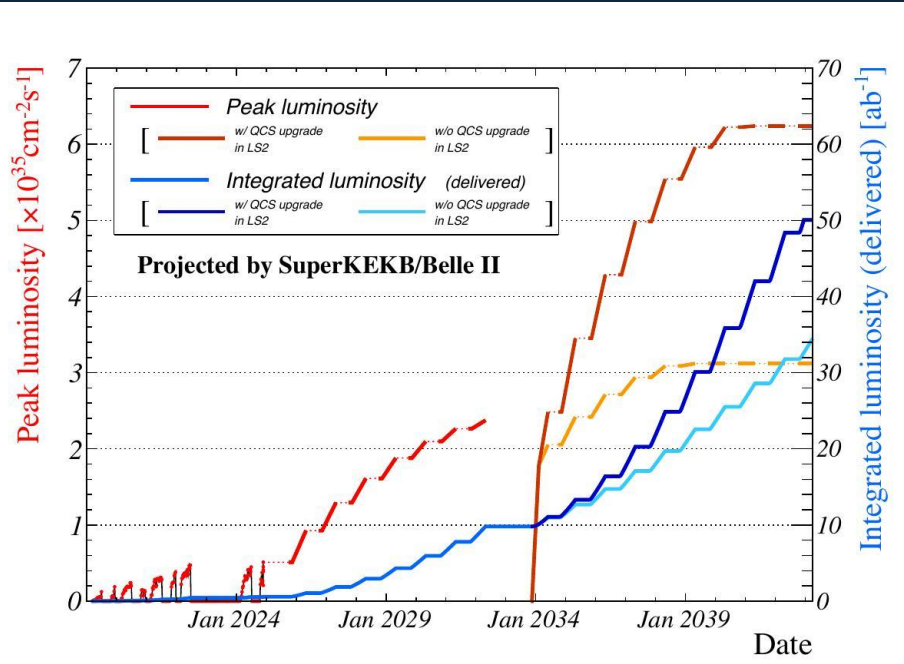


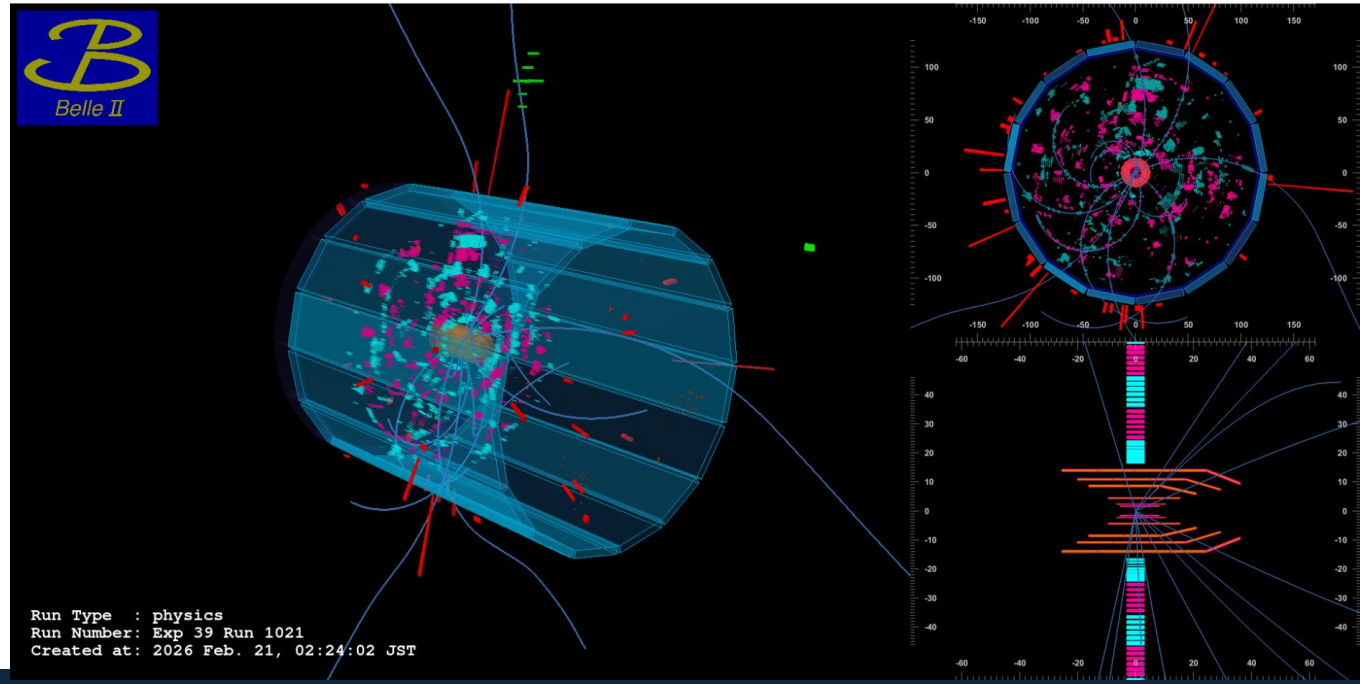
- Preparing PRL submission



Summary

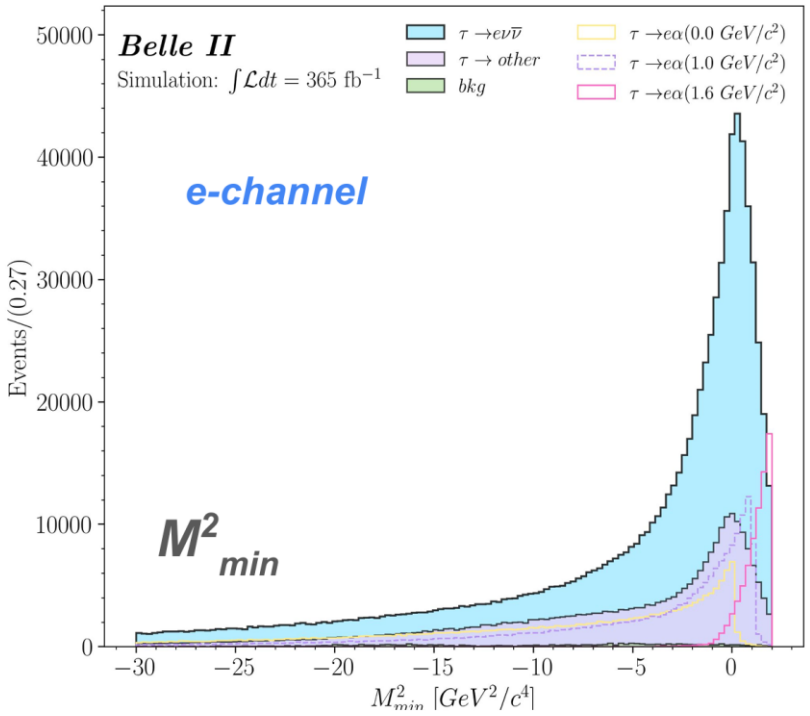
- No significant excess observed in Tau LFV and dark sector searches.
- Most analyses achieve world-leading sensitivity.
- Belle II is continuing physics data taking.
  - Efforts toward higher luminosity.
  - Ongoing detector improvements.
  - Advanced analysis techniques.
- **Strong discovery potential remains at Belle II!**

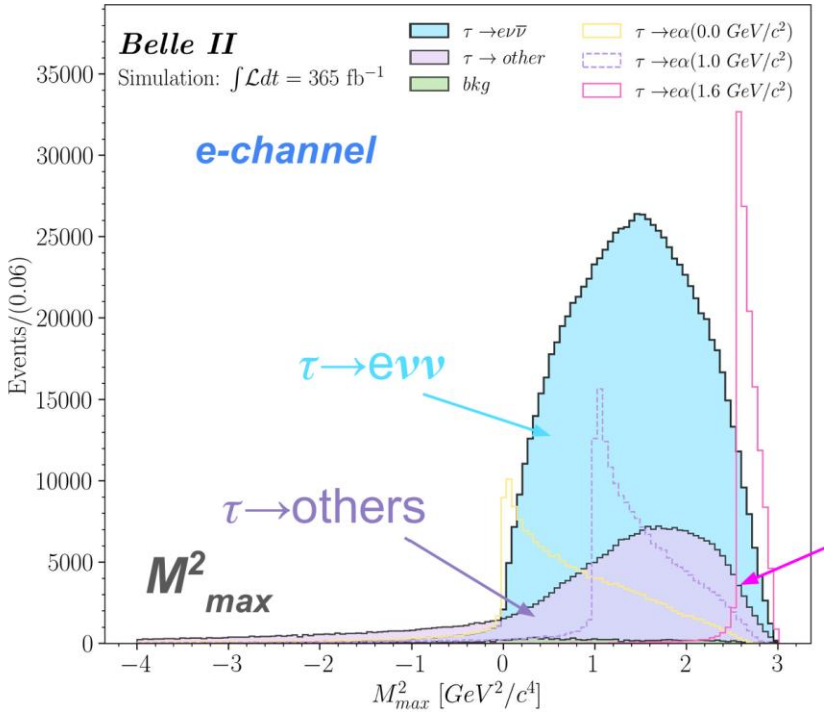




Thank you for listening!

backup


Belle II
Simulation: $\int \mathcal{L}dt = 365$ fb^{-1}
$\tau \to e\nu\bar{\nu}$
$\tau \to other$
bkg
$\tau \to e\alpha(0.0\ GeV/c^2)$
$\tau \to e\alpha(1.0\ GeV/c^2)$
$\tau \to e\alpha(1.6\ GeV/c^2)$
e-channel
M^2_{min}
Events/(0.27)
M^2_{min} [GeV^2/c^4]


Belle II
Simulation: $\int \mathcal{L}dt = 365$ fb^{-1}
$\tau \to e\nu\bar{\nu}$
$\tau \to other$
bkg
$\tau \to e\alpha(0.0\ GeV/c^2)$
$\tau \to e\alpha(1.0\ GeV/c^2)$
$\tau \to e\alpha(1.6\ GeV/c^2)$
e-channel
$\tau \to e\nu\nu$
$\tau \to others$
M^2_{max}
Events/(0.06)
M^2_{max} [GeV^2/c^4]