

Searches for Dark Sector Particles at Belle and Belle II

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Dark Sector Searches at Belle and Belle II

- High luminosity e^+e^- colliders operating at or near $\Upsilon(4S)$ ($\sqrt{s} \sim 10.6$ GeV)
- Sensitive to MeV to GeV scale dark mediators via direct production and production in decays

$$e^+e^- \rightarrow B\bar{B} \sim 1.1 \text{ nb}$$

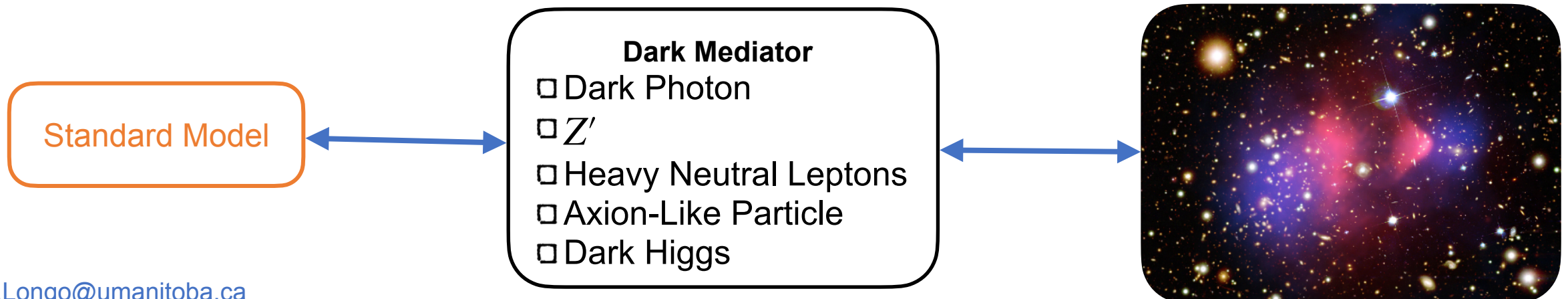
$$e^+e^- \rightarrow c\bar{c} \sim 1.3 \text{ nb}$$

$$e^+e^- \rightarrow \tau^+\tau^- \sim 0.9 \text{ nb}$$

$$e^+e^- \rightarrow X_{\text{Dark}}X_{\text{SM}}$$

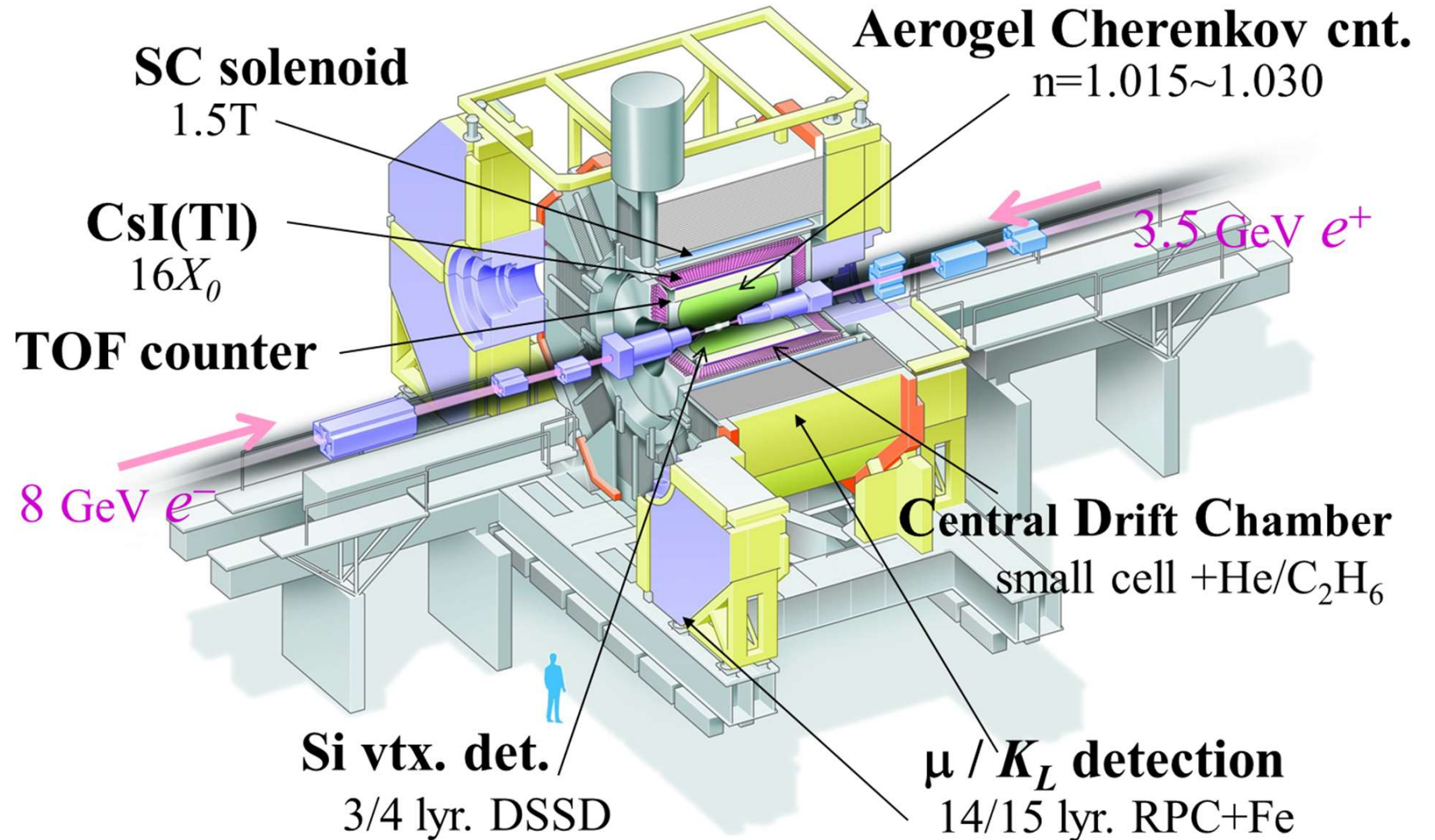
$$B/D/\tau/\dots \rightarrow X_{\text{Dark}}X_{\text{SM}}$$

- Precise determination of missing energy/momentum:
 - ✓ Minimal collision pile-up
 - ✓ Well-known initial collision energy and momentum
 - ✓ Hermetic detectors with high detection efficiency for charged and neutral particles



Belle Experiment

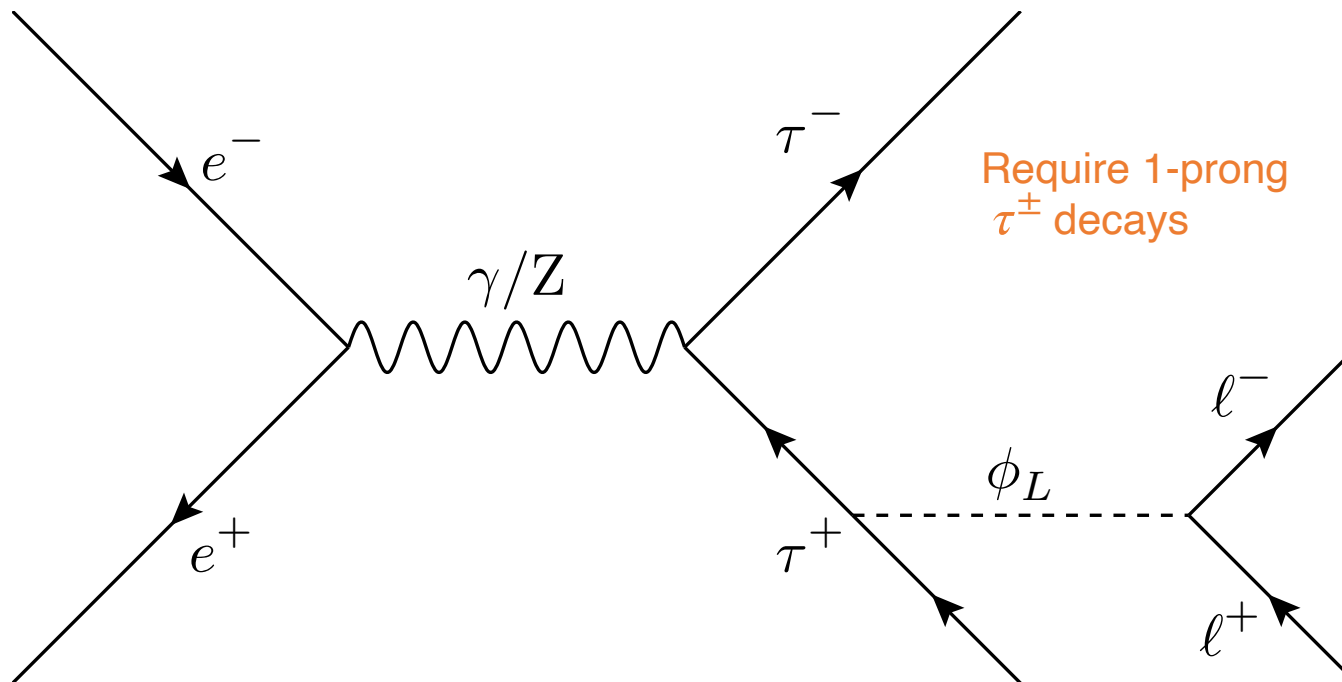
- Operated at KEKB collider from from 1999 - 2010
- Total dataset of 1040 fb^{-1}



Belle: Search for Dark Leptophilic Scalar

- Dark scalars that couple to leptons and not quarks (Leptophilic) ϕ_L evade constraints from FCNC searches
- Can impact $(g - 2)_\mu$ anomaly
- ϕ_L mixes with Higgs boson leading to coupling proportional to fermion mass
- Production via $e^+e^- \rightarrow \tau^+\tau^-\phi_L$ with $\phi_L \rightarrow \ell^+\ell^- (\ell = e, \mu)$

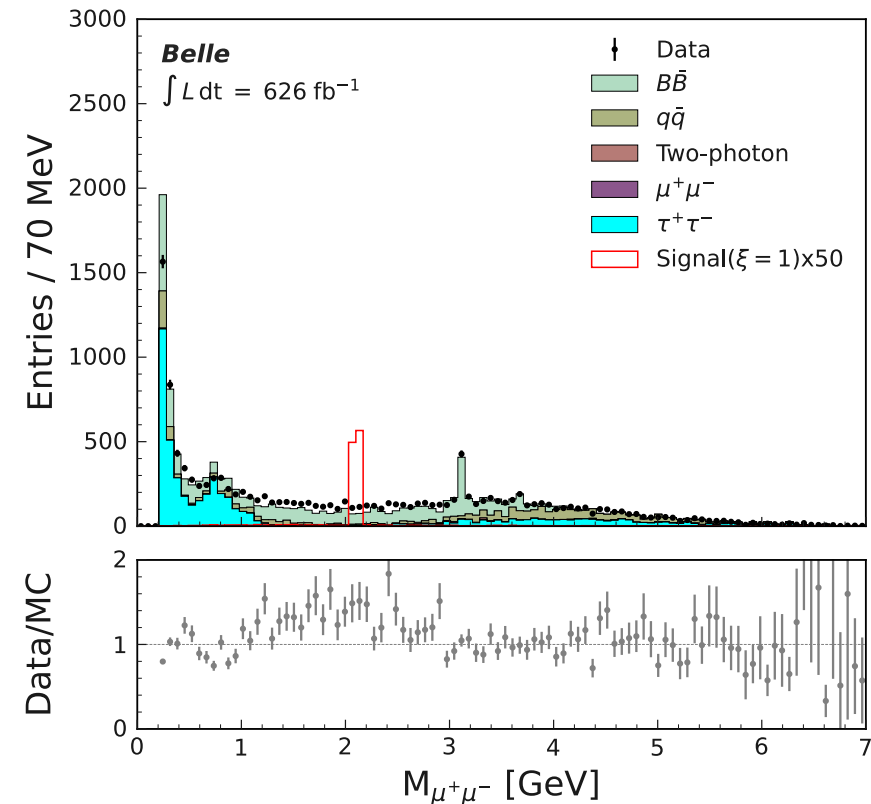
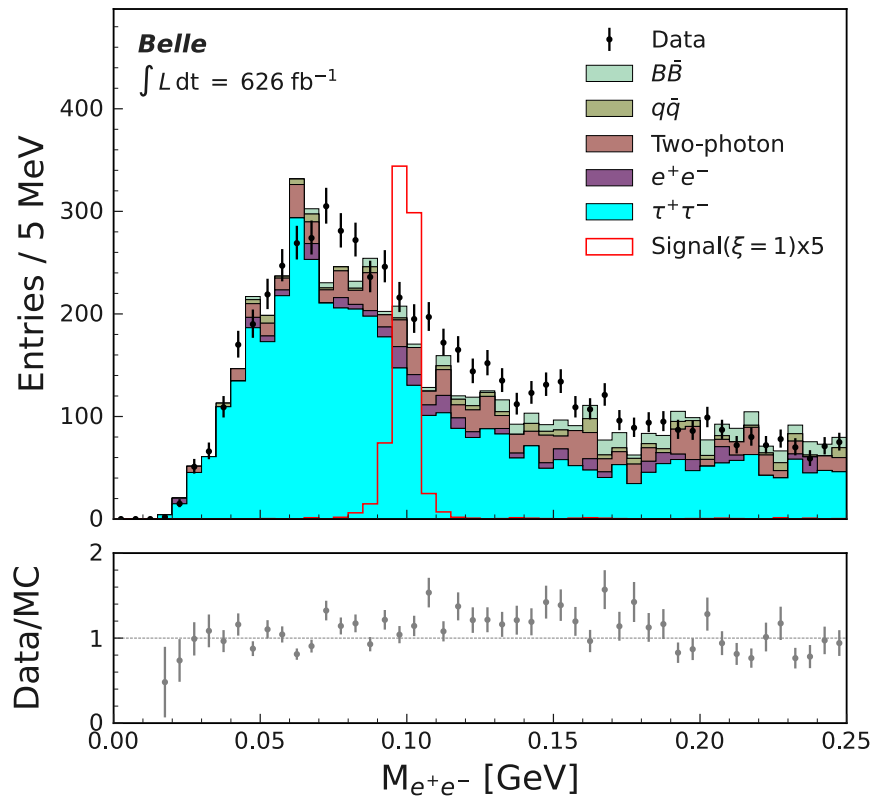
P. Agrawal, Z. Chacko, and C. B. Verhaaren, J. High Energy Phys. 08 (2014) 147.
 B. Batell et al., Phys. Rev. D 95, 075003 (2017).
 J. Liu et al., J. High Energy Phys. 04 (2020) 197.



- Event signature is 4 tracks and missing energy
- $m_{\ell\ell}$ distribution peaks at ϕ_L mass
- ϕ_L can decay prompt or long-lived

Belle: Dark Leptophilic Scalar Search

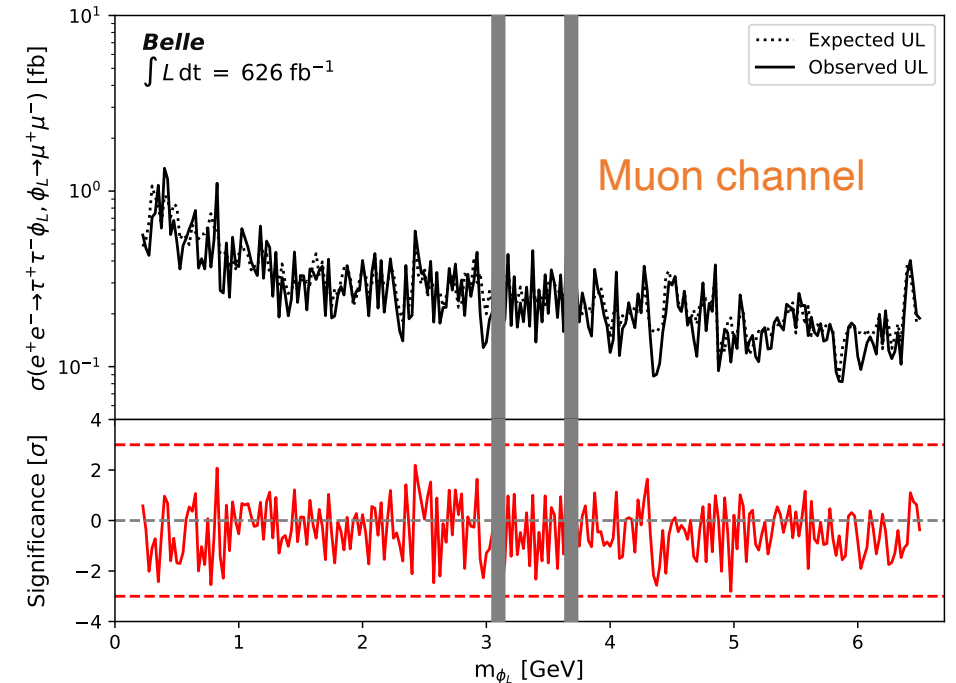
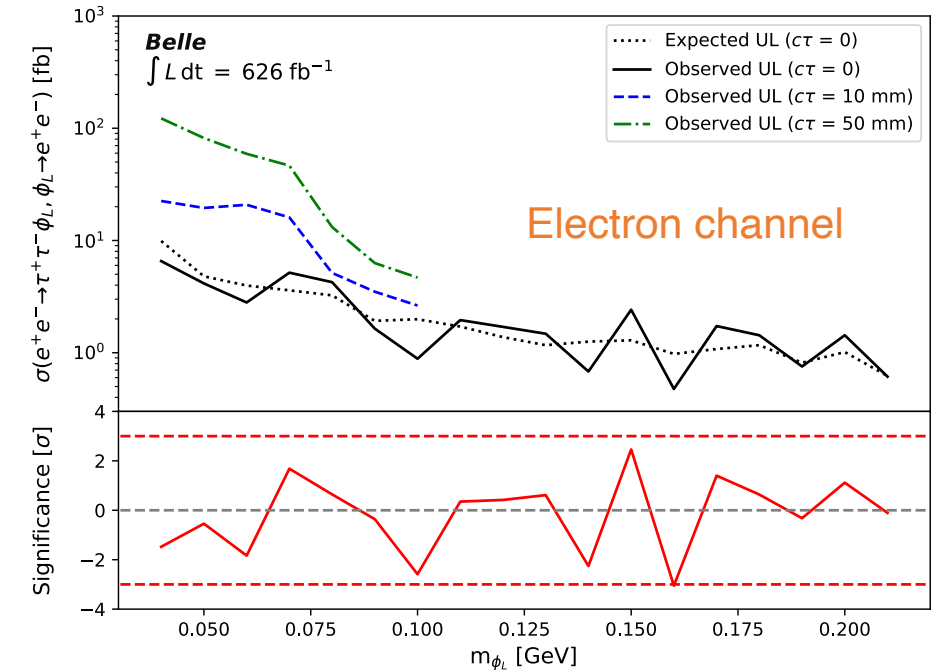
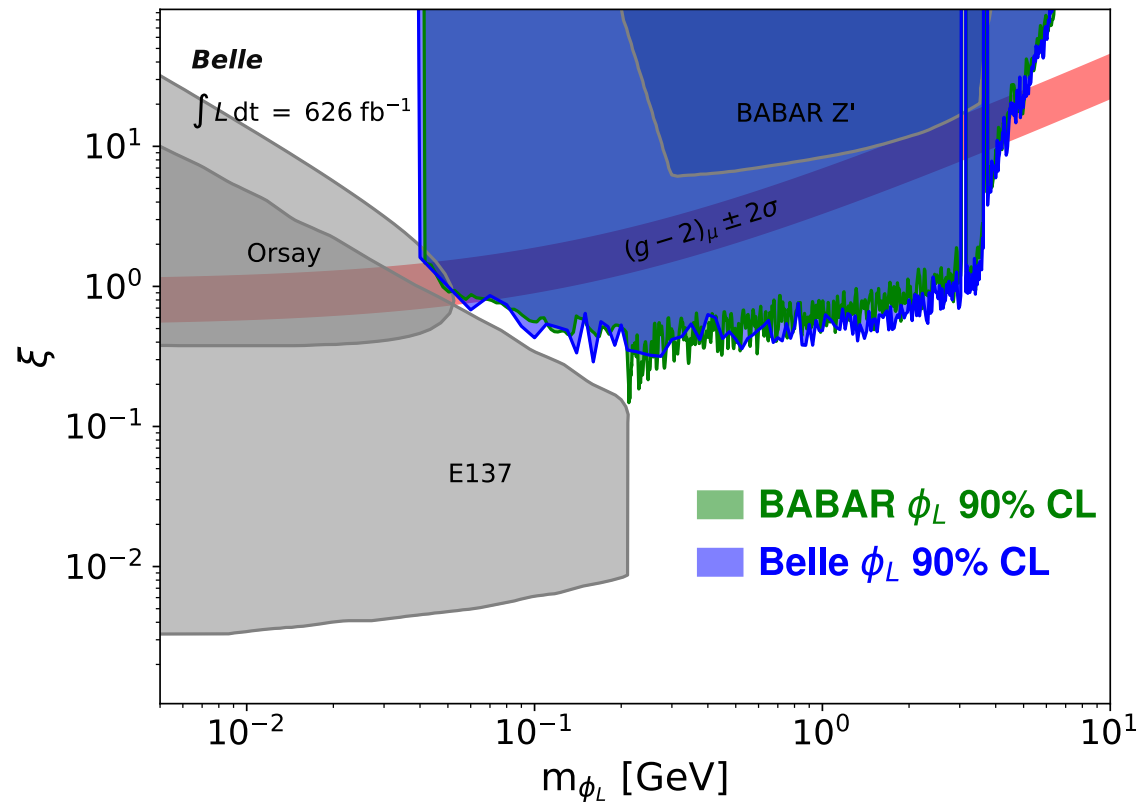
- Search for localized excess in $m_{\ell\ell}$ distribution
- Background suppression with Boosted Decision Tree (BDT)
- Remaining backgrounds:
 - Electron channel: $\pi^0 \rightarrow e^+e^-\gamma$ from ρ^\pm produced in τ^\pm decay
 - Muon channel: $\tau \rightarrow 3\pi\nu$ with π mis-id as μ and semi-leptonic heavy quark decays



Belle: Dark Leptophilic Scalar Search

- No significant excess observed in 626 fb^{-1}
- Limits set as a function of ϕ_L mass and lifetime
- Parameter space below 4 GeV that could explain $(g - 2)_\mu$ excluded

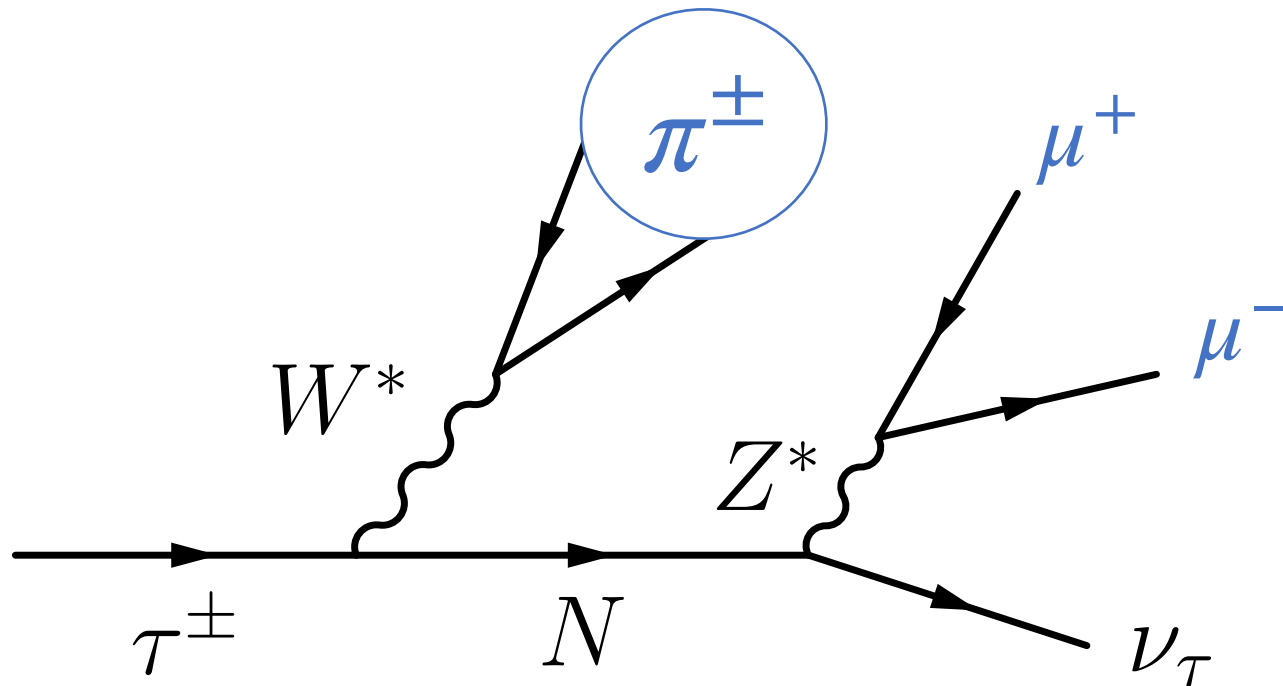
D. Biswas et al. (Belle Collaboration) Phys. Rev. D 109, 032002 (2024)



Belle: Heavy Neutral Lepton (HNL) Search

- GeV-scale HNL (N) could explain baryon asymmetry of universe; keV-scale HNL could be a dark matter candidate
- HNL with predominant ν_τ coupling challenging to probe experimentally
- Search considers decay $\tau^- \rightarrow N\pi^-$ with $N \rightarrow \nu_\tau\mu^+\mu^-$

T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B 631, 151-156 (2005)
C. O. Dib *et al.* Phys. Rev. D 101, 093003 (2020)

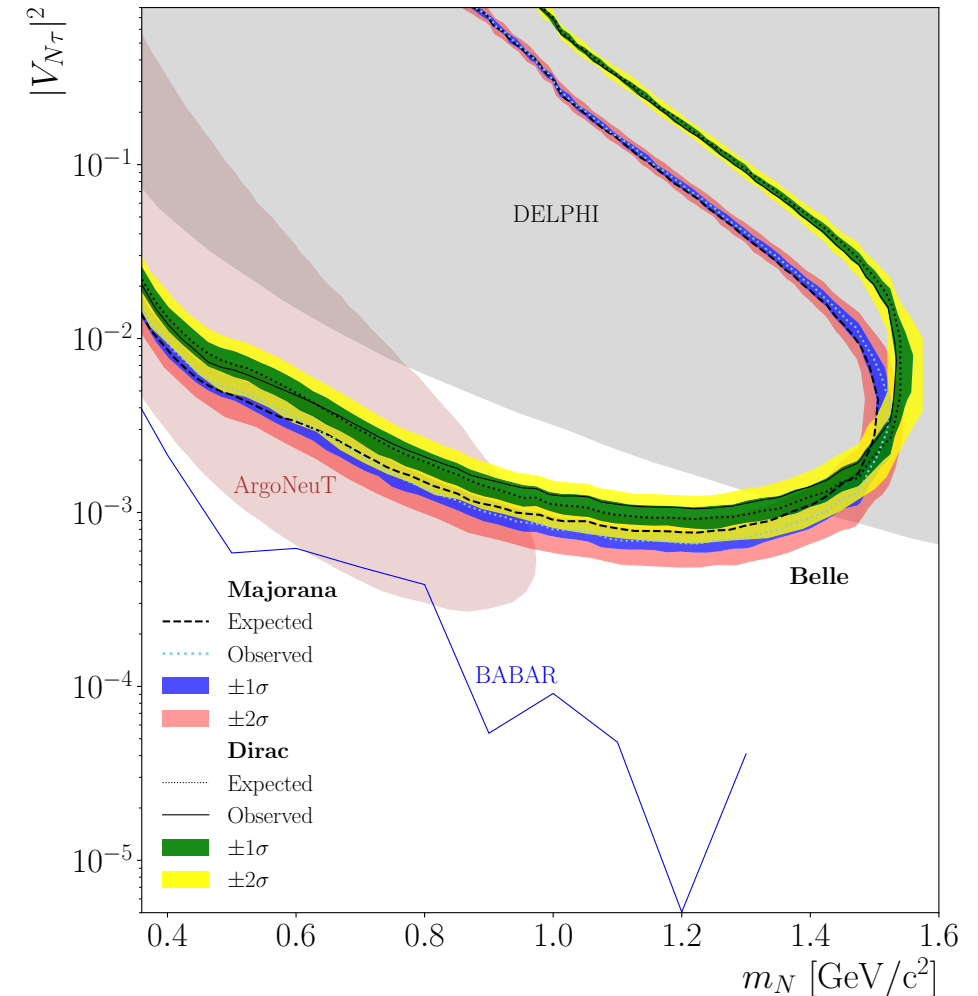
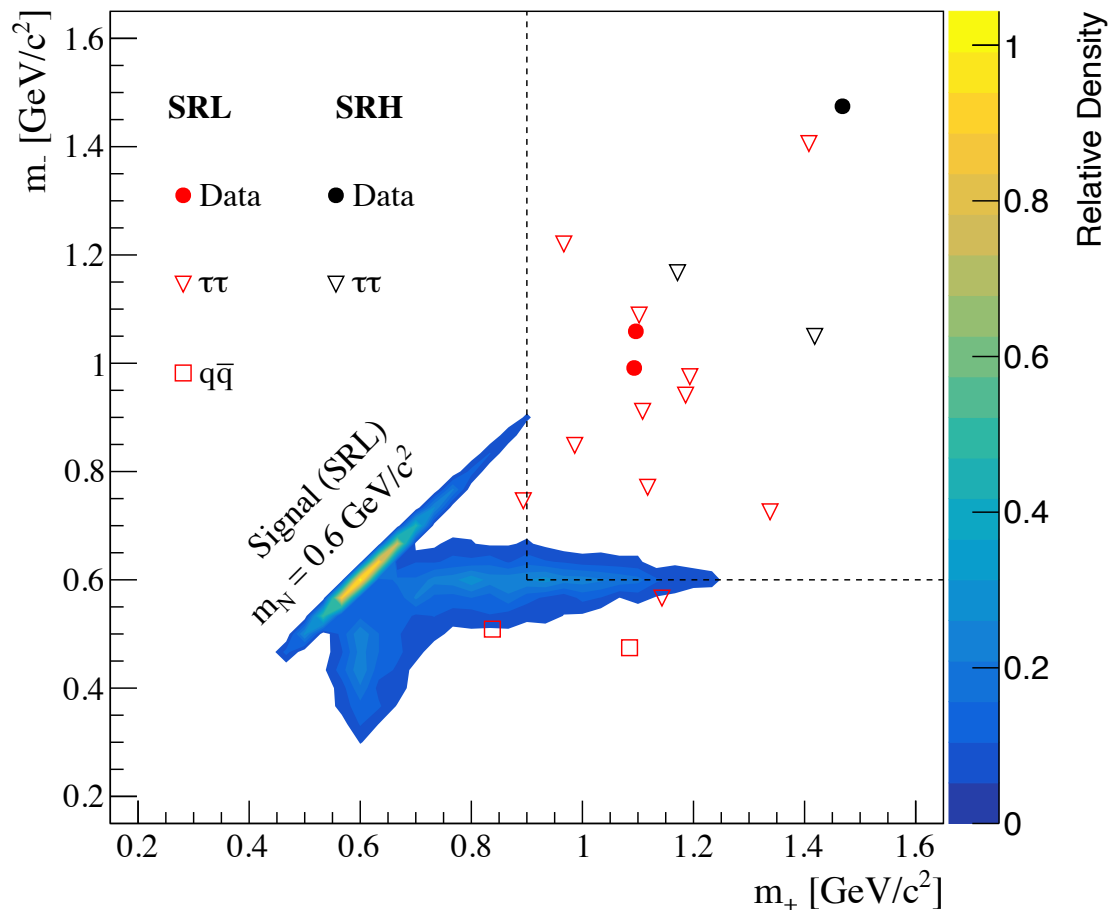


Analysis explores m_N and $|V_{N\tau}|^2$ parameter space where N is long lived

Belle: Heavy Neutral Lepton Search

- Displaced vertex from $N \rightarrow \mu^+ \mu^- \nu_\tau$ decay provides significant background rejection
- Kinematics of the signal- τ decay allow two solutions for m_N (m_+ , m_-)
- No significant excess observed in 915 fb⁻¹

M. Nayak et al. (Belle Collaboration), to appear in PRD(L)
arXiv:2402.02580

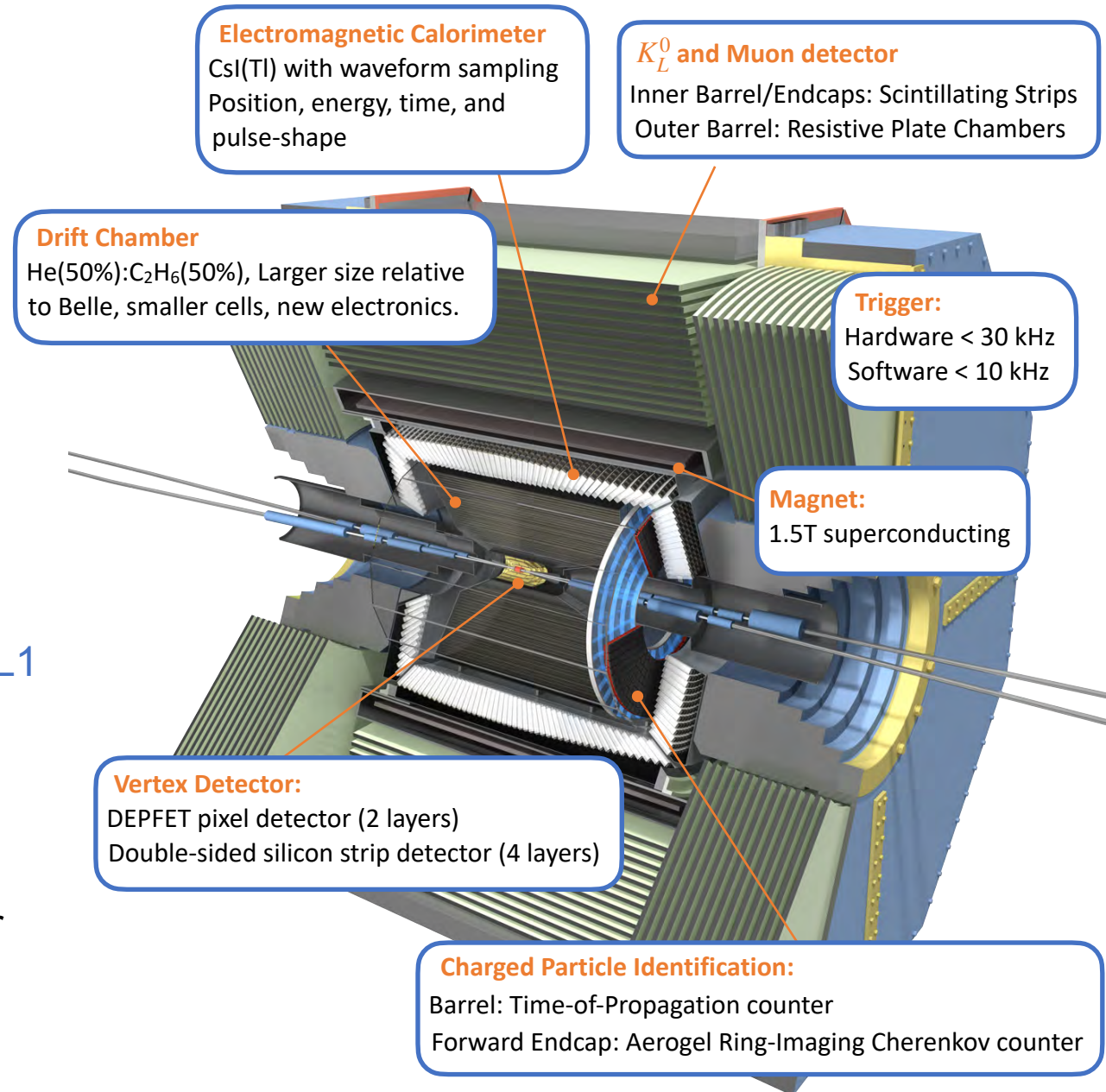


Belle II Experiment

- Major detector and accelerator upgrade from Belle
- Operations at SuperKEKB from 2019 - present
- Total dataset to-date is 498 fb^{-1}
- Target dataset is 50 ab^{-1}

New low multiplicity triggers allow new dark sector analysis opportunities at Belle II

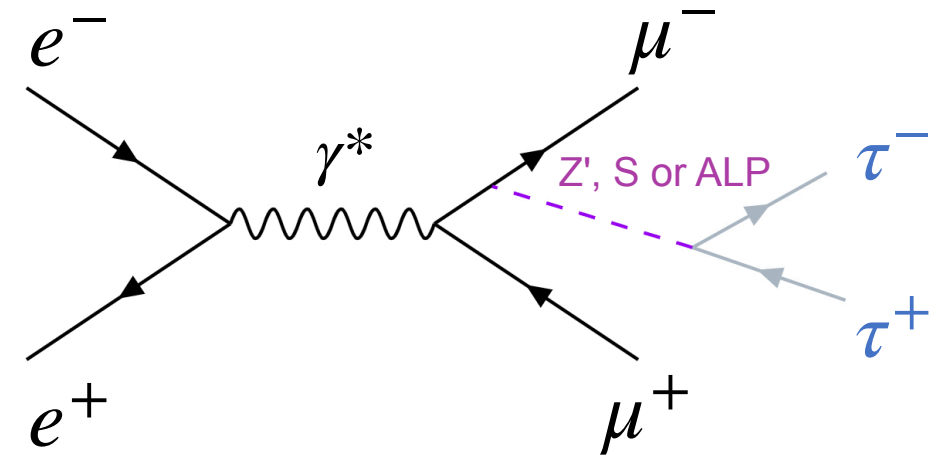
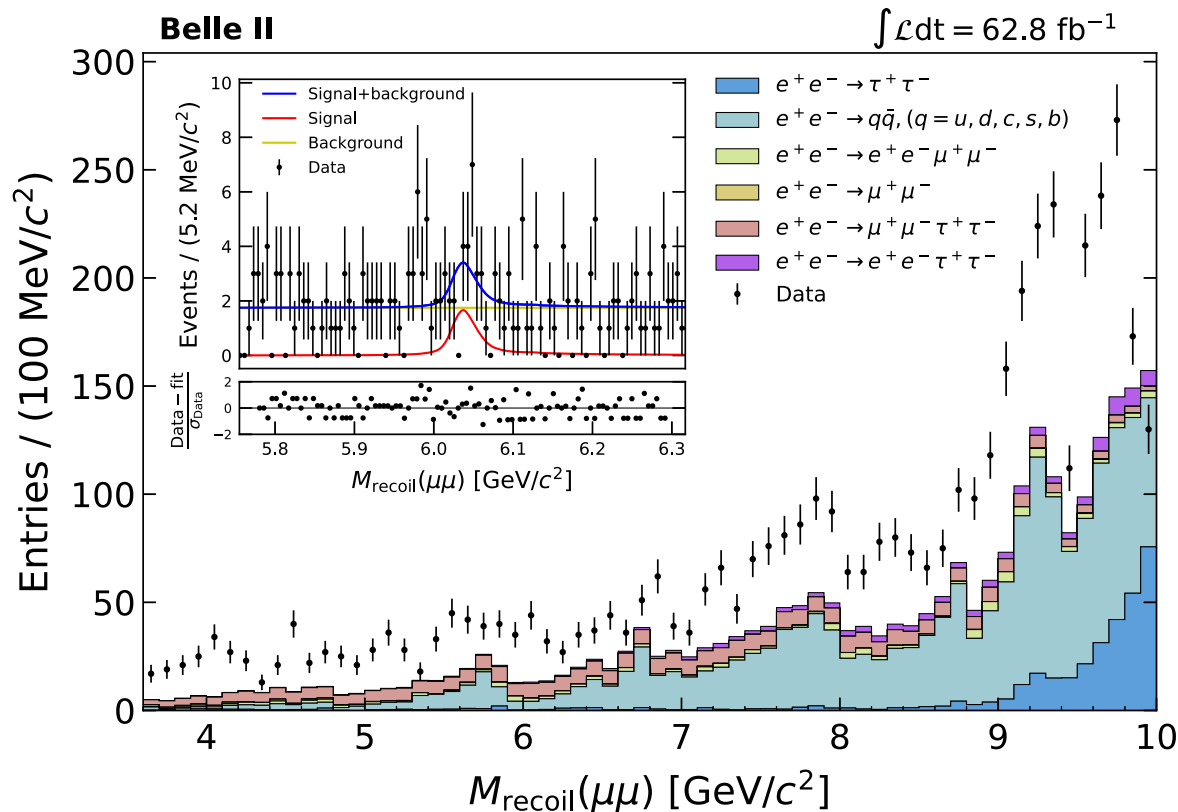
- ➔ Single muon trigger
- ➔ Single Track Trigger with 3D track reconstruction at L1 using neural networks
- ➔ Single photon trigger operational for entire dataset
 - Not present at Belle
 - 53 fb^{-1} recorded by BaBar with single photon trigger
- ➔ Displaced vertex trigger in development



Belle II: Search for $\tau\tau$ resonance

B. Shuve and I. Yavin, PRD 89, 113004 (2014)
 W. Altmannshofer et al, JHEP 12, 106 (2016)
 B. Batell et al, PRD 95, 075003 (2017)
 M. Bauer et al, JHEP. 2022, 1 (2022)

- $\tau\tau$ resonance in $e^+e^- \rightarrow \mu\mu\tau\tau$ arise in many dark sector models:
 - Spin-1 particle coupling only to the heavier lepton families
 - Higgs-like spin-0 particle that couples preferentially to charged leptons (leptophilic scalar)
 - Axion-like particles



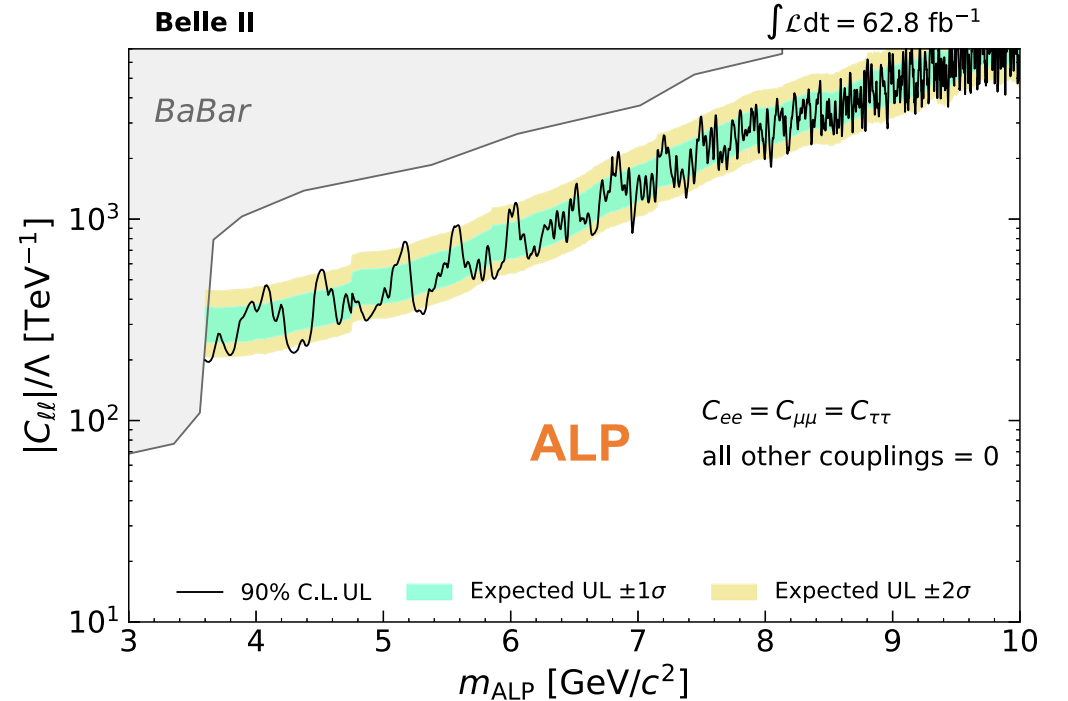
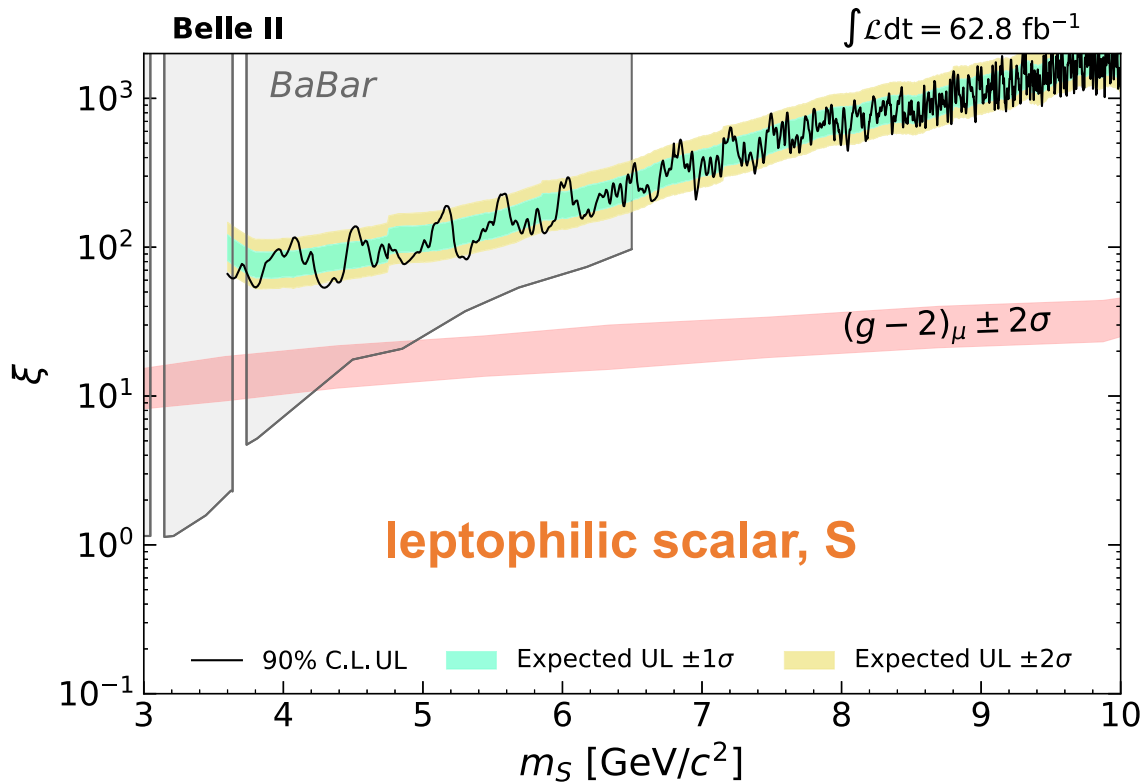
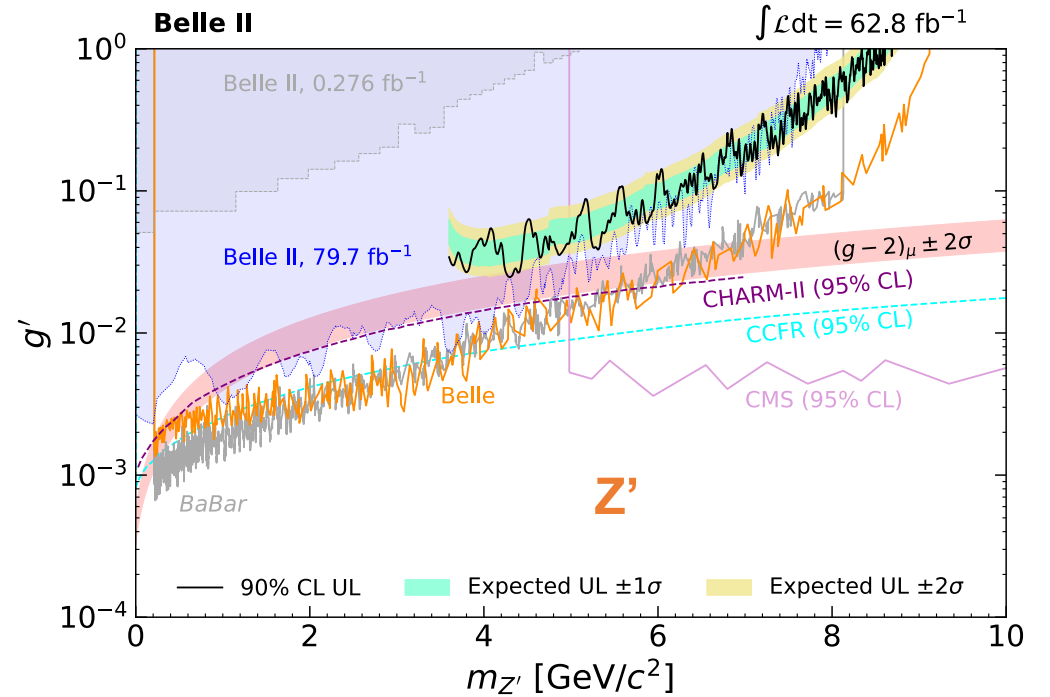
Require τ^\pm decay as
 $\tau^- \rightarrow \ell^- \nu \nu$ or $\tau^- \rightarrow \pi^- \nu n \pi^0$

- Event signature is four tracks with missing energy
- Muons used to compute $M_{\text{recoil}}(\mu\mu)$, which peaks for signal
- Background suppression via neural network
- $e^+e^+ \rightarrow e^+e^- X_{\text{had}}$ and $e^+e^+ \rightarrow 4\ell(\gamma)$ backgrounds not included in simulation

Belle II: Search for $\tau\tau$ resonance

- No significant excess observed in 62.8 fb⁻¹
- Limits on $e^+e^- \rightarrow X(\rightarrow \tau^+\tau^-)\mu^+\mu^-$ cross section translated to limits on leptophilic scalar, Z', and ALP mediator interpretations

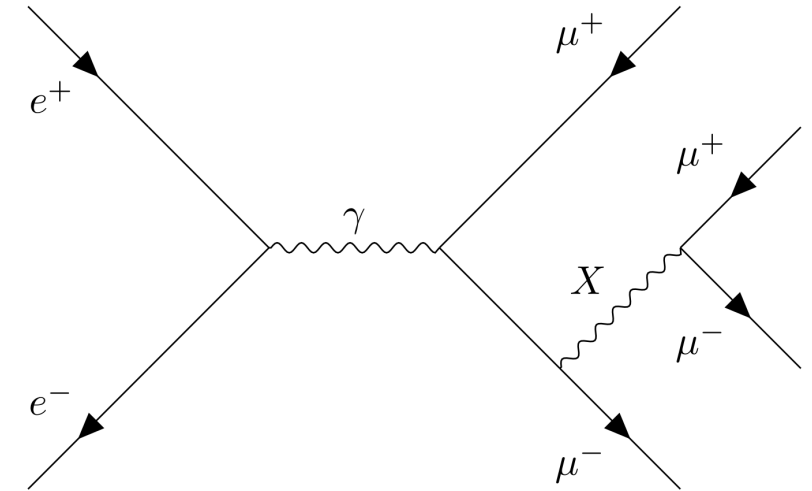
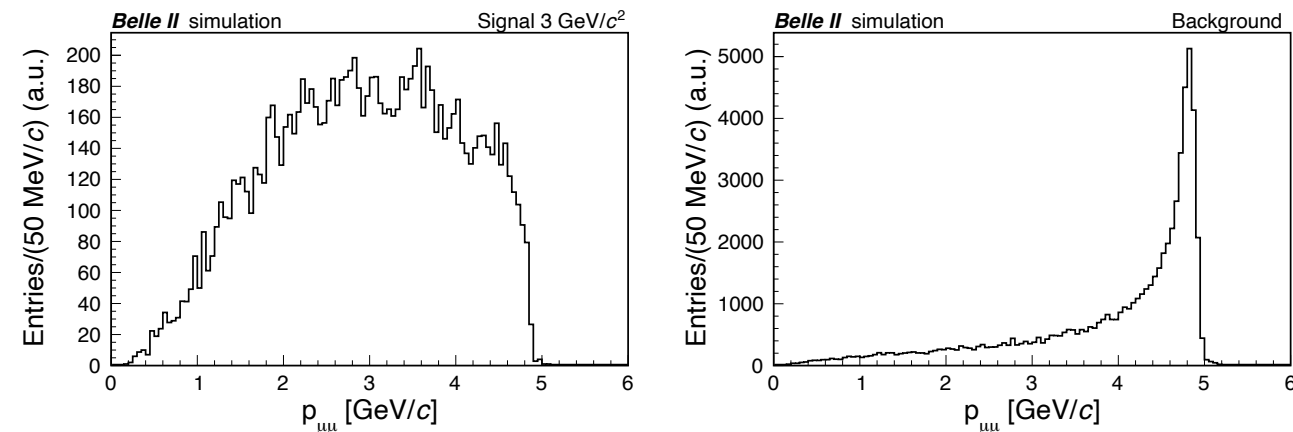
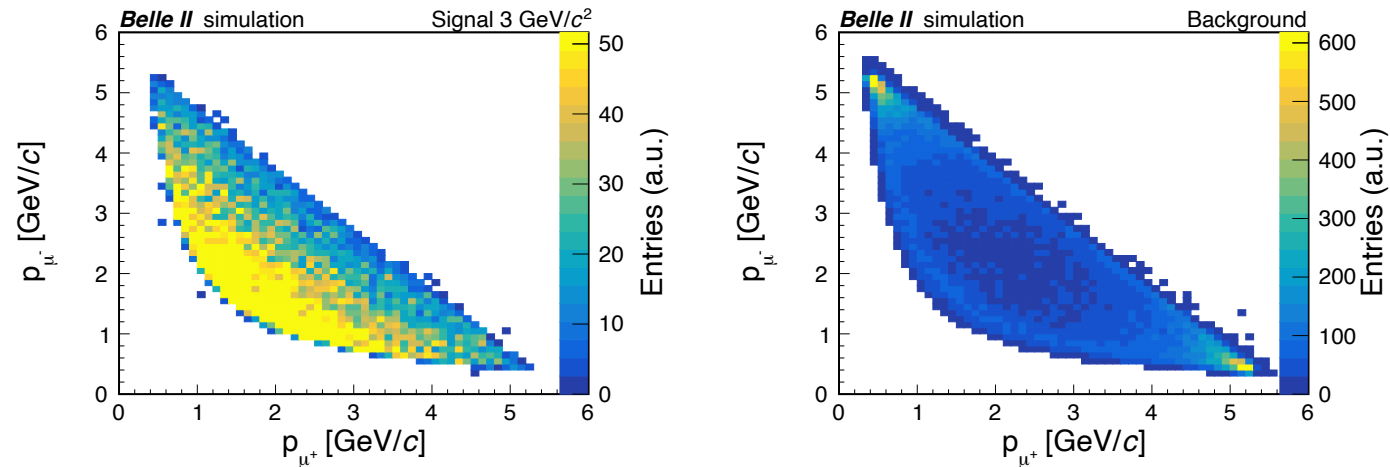
I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 131, 121802 (2023)



Belle II: Search for a $\mu^+\mu^-$ resonance

P. Harris, P. Schuster, and J. Zupan (2022), arXiv:2207.08990
N. Tran, and A. Whitbeck, PRD 107, 116026 2023)

- Variety of dark sector models predict new particles decaying to $\mu^+\mu^-$
 - $Z' \rightarrow \mu^+\mu^-$ from $L_\mu - L_\tau$ extensions of SM
 - Muonphilic scalar $S \rightarrow \mu^+\mu^-$ proposed to resolve $(g - 2)_\mu$ anomaly

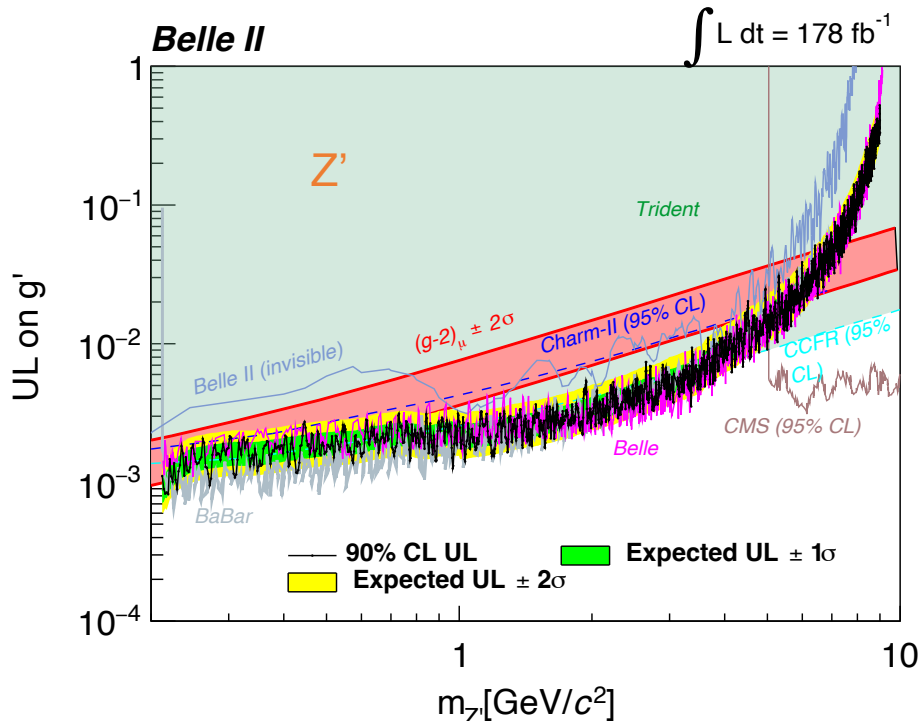
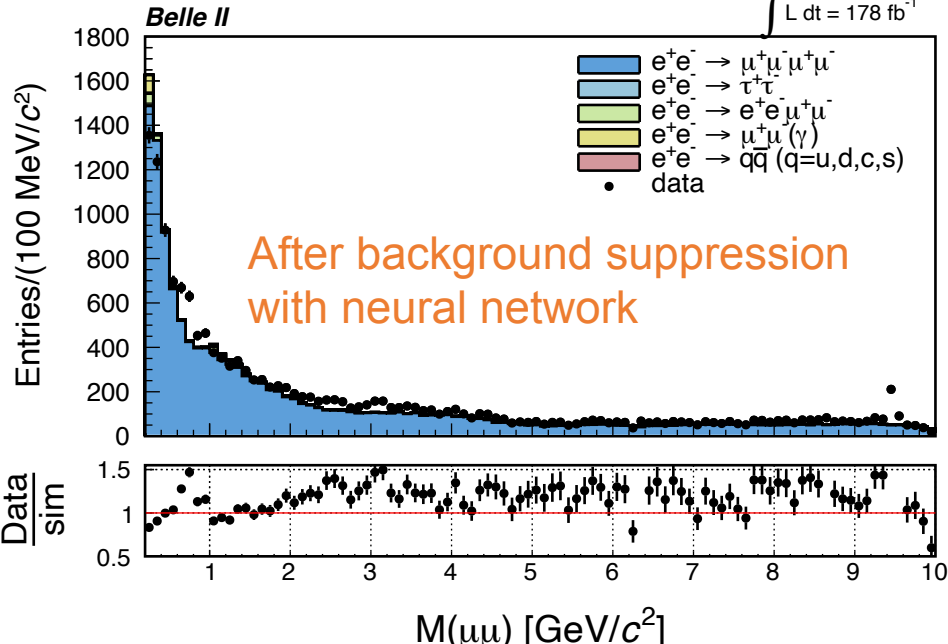
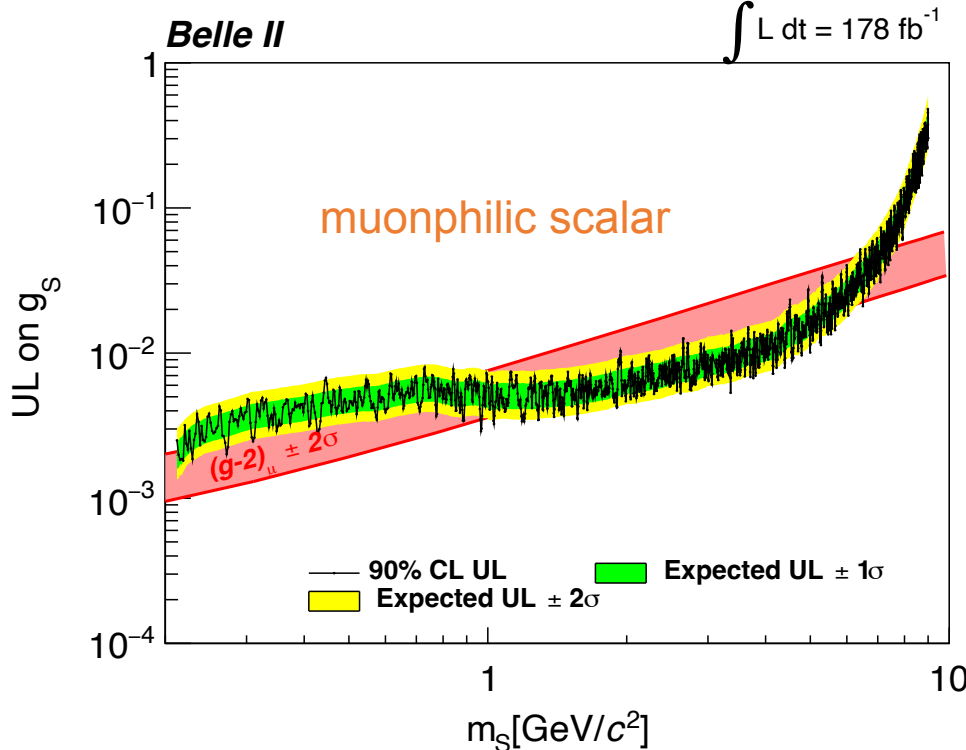


- Search in channel $e^+e^- \rightarrow \mu^+\mu^-X$, $X \rightarrow \mu^+\mu^-$
- Select events with four muons with total centre-of-mass energy consistent with \sqrt{s}
- Main background $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ has distinct kinematics from signal
- Neural network for background suppression

Belle II: Search for a $\mu^+\mu^-$ resonance

- Search for localized excess in $M(\mu\mu)$
- No significant excess observed in 178 fb⁻¹
- Sets first limits on muonphilic scalar, which constrain explanation for muon g-2 anomaly
- Limits also set on Z' interpretation

Accepted to PRD arXiv:2403.02841



Conclusions

- e^+e^- collision environment at Belle and Belle II presents unique capabilities for dark sector searches
- New triggers at Belle II targeting low multiplicity final states open new dark sector search opportunities
- Recent dark sector searches by Belle and Belle II were reported

D. Biswas et al. (Belle Collaboration) *Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair* Phys. Rev. D 109, 032002 (2024) — [626 fb⁻¹](#)

M. Nayak, S. Dey, A. Soffer, et al. (Belle Collaboration), *Search for a heavy neutral lepton that mixes predominantly with the tau neutrino* to appear in PRD(L) arXiv:402.02580 — [915 fb⁻¹](#)

I. Adachi et al. (Belle II Collaboration) *Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment* Phys. Rev. Lett. 131, 121802 (2023) — [62.8 fb⁻¹](#)

I. Adachi et al. (Belle II Collaboration) *Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II*, Accepted to PRD arXiv:2403.02841 — [178 fb⁻¹](#)

- Belle II Run 2 now ongoing — Additional dark sector searches in progress and future results will benefit from full Belle II dataset of [>498 fb⁻¹](#)