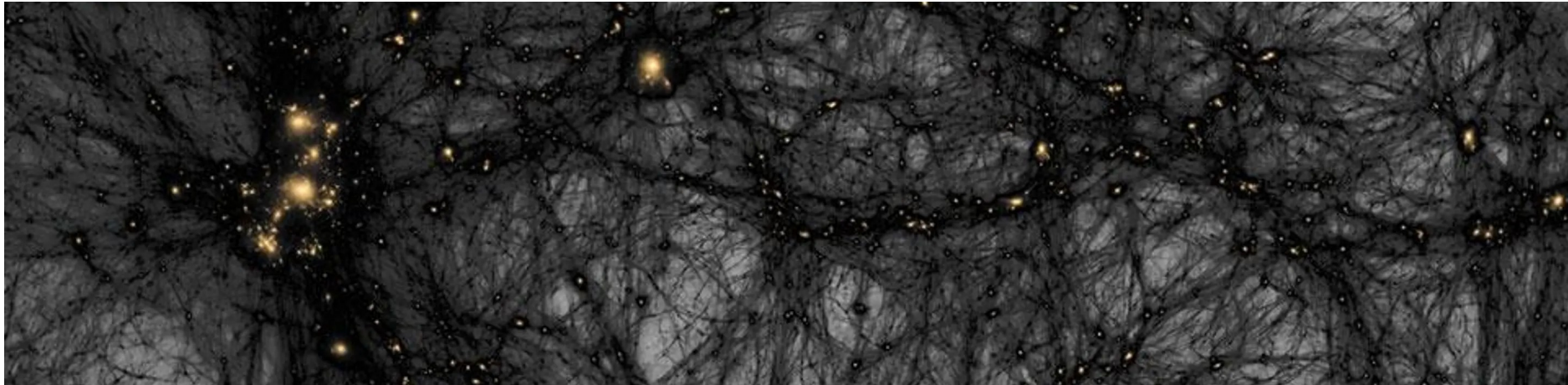


Searches for dark sector particles at Belle and Belle II

Giacomo De Pietro (giacomo.pietro@kit.edu)

Institute of Experimental Particle Physics, Karlsruhe Institute of Technology

42nd International Conference on High Energy Physics @ Prague, Czech Republic



Belle and Belle II experiments

■ Belle (1999 – 2010) and Belle II (2018 -): previous and current generation of B-factories

- Asymmetric e^+e^- colliders running mainly at the $\Upsilon(4S)$ resonance, $\sqrt{s} = 10.58$ GeV

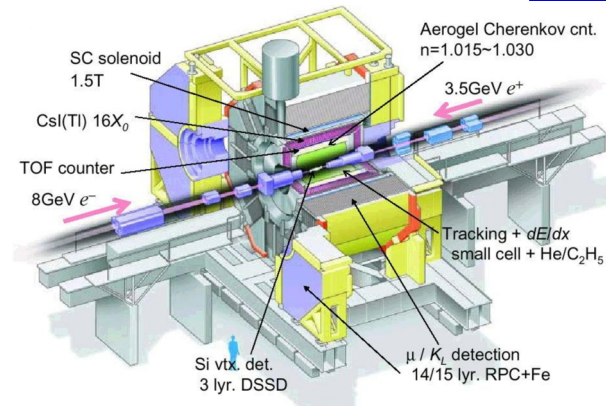
■ Key features:

- Well known initial conditions
- Hermetic detectors
- Little/no pile-up and clean environment

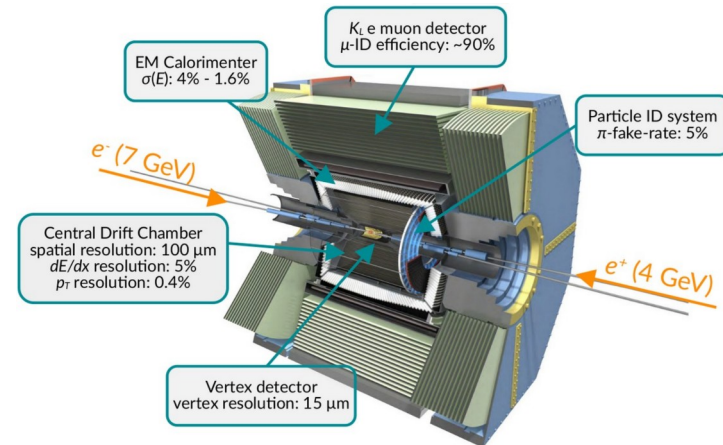
■ Special triggers for low multiplicity @ Belle II

- Single photon trigger
- Single muon trigger
- Single track trigger using neural networks

Belle @ KEKB, recorded ~ 1 ab^{-1}



Belle @ SuperKEKB, recorded:
427 fb^{-1} in Run1 (2018 - 2022)
103 fb^{-1} in Run2 (2024 -)



Outline

- Belle and Belle II have excellent sensitivity for dark sector searches in the MeV – GeV range
 - Also possible to probe all the possible dark sector portals
- Analyses shown today
 - $\mu^+\mu^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ @ Belle II
[Belle II, Phys. Rev. D 109, 112015 \(2024\)](#)
 - Long-lived scalar in B decays @ Belle II
[Belle II, Phys. Rev. D 108, L111104 \(2023\)](#)
 - Leptophilic scalar in $e^+e^- \rightarrow \tau^+\tau^-\ell^+\ell^-$ @ Belle
[Belle, Phys. Rev. D 109, 032002 \(2024\)](#)
 - Heavy neutral leptons in τ decays @ Belle
[Belle, Phys. Rev. D 109, L111102 \(2024\)](#)

$\mu^+\mu^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ @ Belle II

Belle II, Phys. Rev. D 109, 112015 (2024)

Search for the process $e^+e^- \rightarrow \mu^+\mu^-X$ with $X \rightarrow \mu^+\mu^-$

- Look for a narrow peak in the $\mu^+\mu^-$ mass distribution

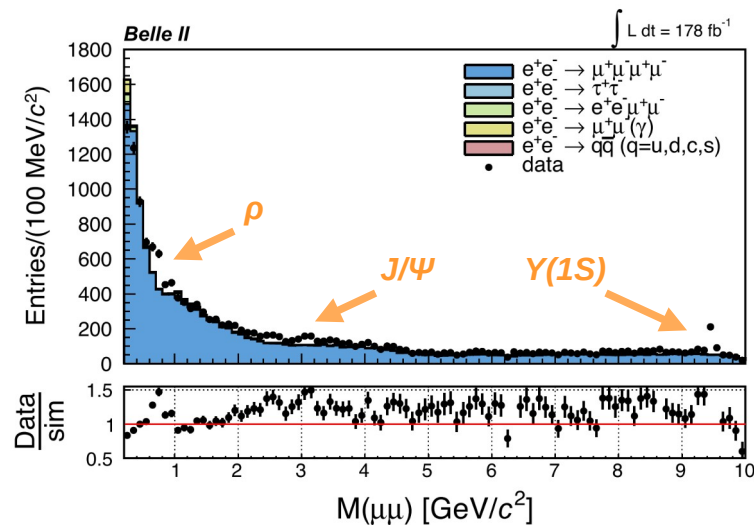
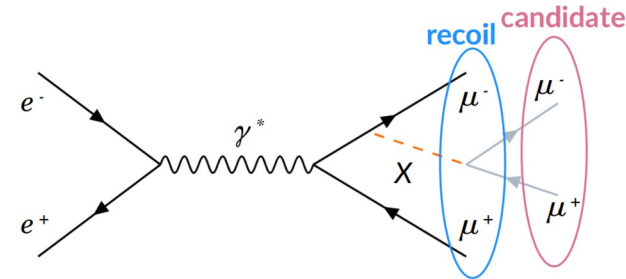
Probing two different models:

- $L_\mu - L_\tau$ vector mediator (Z') [1]
- Muonphilic dark scalar (S) [2]

Event selection

- 4 charged particles
 - At least 3 identified as muons
- $M(4 \text{ tracks}) \sim \sqrt{s}$
- No extra energy

Aggressive background suppression based on training of NNs



[1] W. Altmanshofer et al., J. High Energy. Phys. 2016, 106 (2016)

[2] R. Capdevilla et al., J. High Energy. Phys. 2022, 129 (2022)

$\mu^+\mu^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ @ Belle II

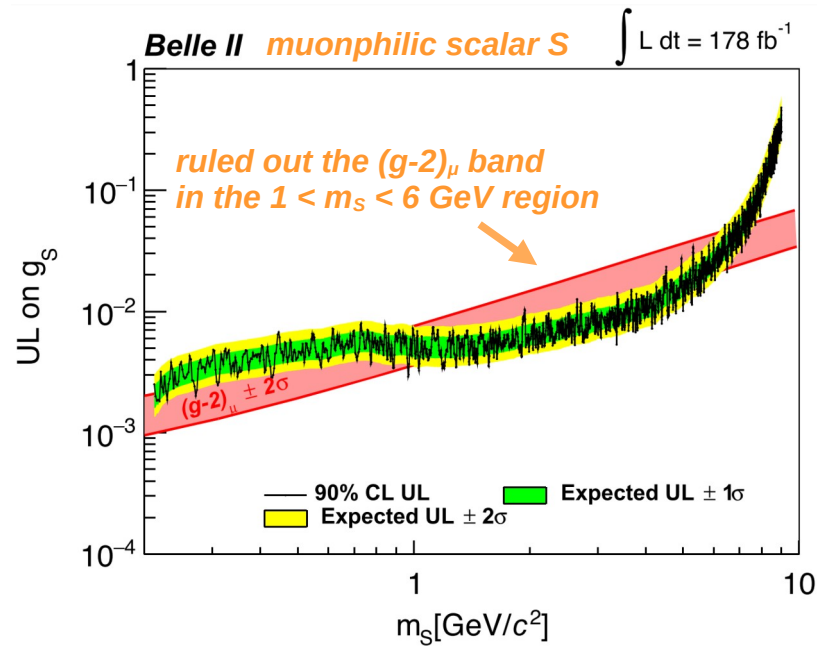
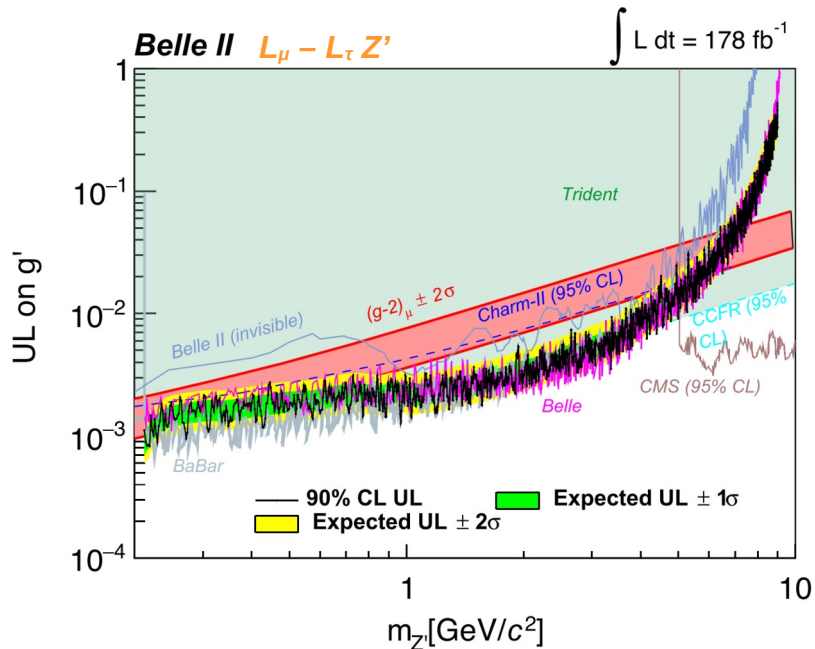
Belle II, Phys. Rev. D 109, 112015 (2024)



■ No significant excess found in 178 fb⁻¹

■ Competitive 90% CL upper limits for g' coupling of the $L_\mu - L_\tau Z'$ model (Z') with BaBar (> 500 fb⁻¹) and Belle (> 600 fb⁻¹) results

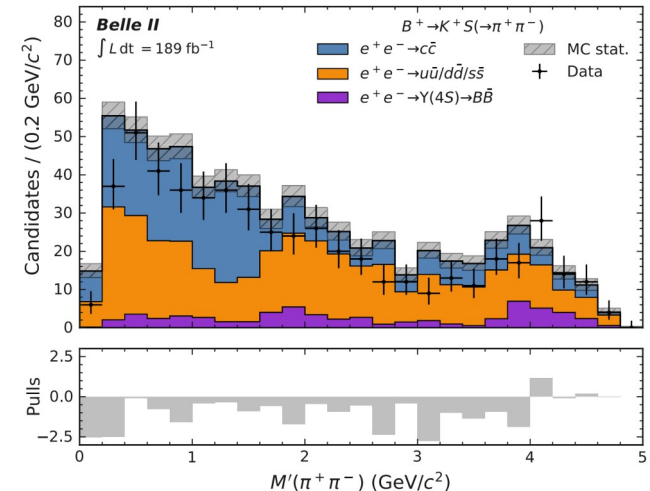
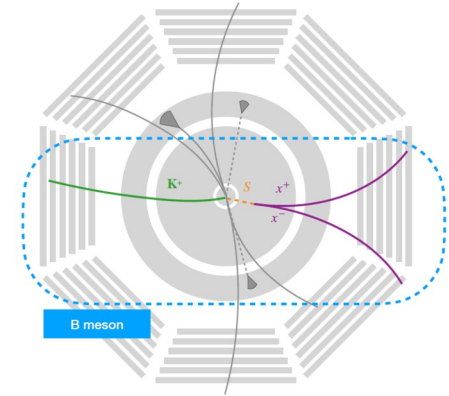
■ First 90% CL upper limits for the muonphilic dark scalar (S) model from a dedicated search



Long-lived scalar in B decays @ Belle II

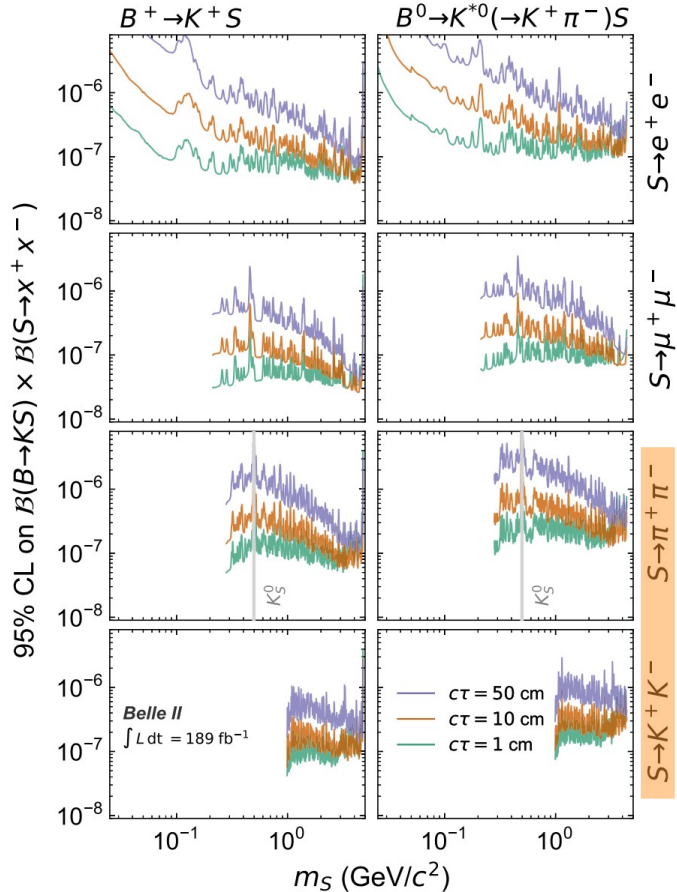
Belle II, Phys. Rev. D 108, L111104 (2023)

- First Belle II long-lived particle search
- Search for scalar S in eight visible B channels:
 $B^+ \rightarrow K^+ S$ and $B^0 \rightarrow K^{*0} (\rightarrow K\pi) S$
 - $S \rightarrow e^+e^- / \mu^+\mu^- / \pi^+\pi^- / K^+K^-$
- Signal B-meson fully reconstructed
 - Other B non reconstructed
- Combinatorial $ee \rightarrow q\bar{q}$ reduced by requiring kinematics similar to B-meson expectations
- Bump hunt in dark scalar mass distribution using unbinned maximum likelihood fits
 - Background determined directly in data



Long-lived scalar in B decays @ Belle II

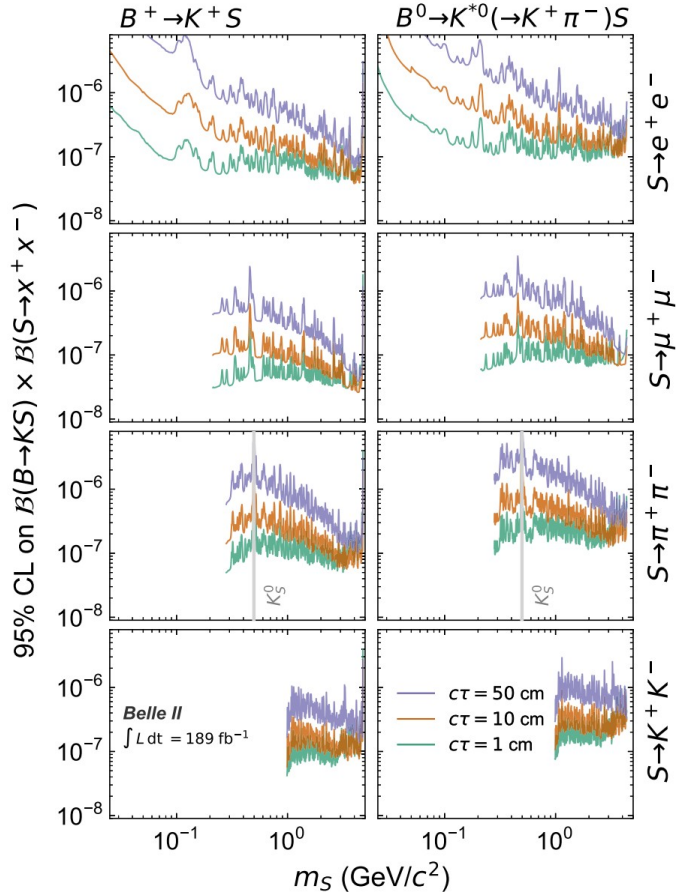
Belle II, Phys. Rev. D 108, L111104 (2023)



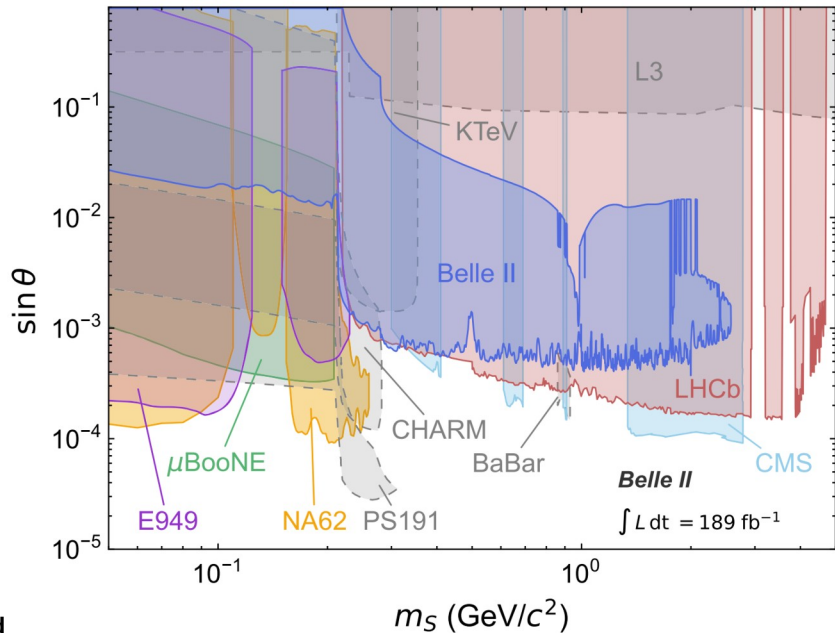
- First model-independent limits for exclusive $B^0 \rightarrow K^{(*)} S$; $S \rightarrow$ hadrons

Long-lived scalar in B decays @ Belle II

Belle II, Phys. Rev. D 108, L111104 (2023)



- First model-independent limits for exclusive $B^0 \rightarrow K^{(*)} S$; $S \rightarrow$ hadrons
- Interpretation as dark scalar with mixing angle θ with SM Higgs



Leptophilic scalar in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle

Belle, Phys. Rev. D 109, 032002 (2024)

■ Bounds on dark scalars from $B \rightarrow KS$ are evaded if S couples predominantly to leptons:
Leptophilic dark scalar Φ_L with flavor-independent ξ coupling to leptons [1]

■ Search for a narrow l^+l^- resonance in $e^+e^- \rightarrow \tau^+\tau^-\Phi_L$; $\Phi_L \rightarrow l^+l^-$ events

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \Phi_L \ell,$$

■ $\Phi_L \rightarrow e^+e^-$ for $m_\phi < 2m_\mu$

■ $10 < c\tau_\phi < 50$ mm for $m_\phi < 0.1$ GeV

■ $\Phi_L \rightarrow \mu^+\mu^-$ for $m_\phi > 2m_\mu$

■ Competitive search for $m_\phi < 6.5$ GeV

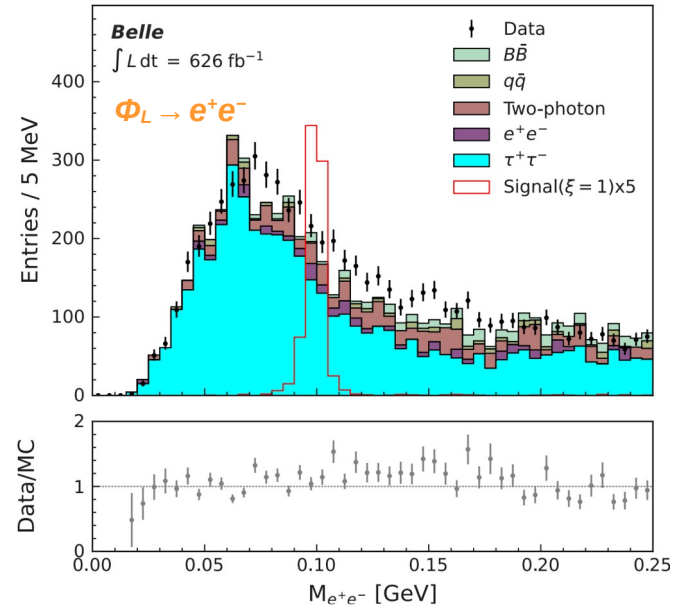
■ Event selection

■ 4 charged particles

■ Large missing mass

■ Background suppressed with a dedicated BDT for both channels

■ Signal extracted performing binned maximum likelihood fits



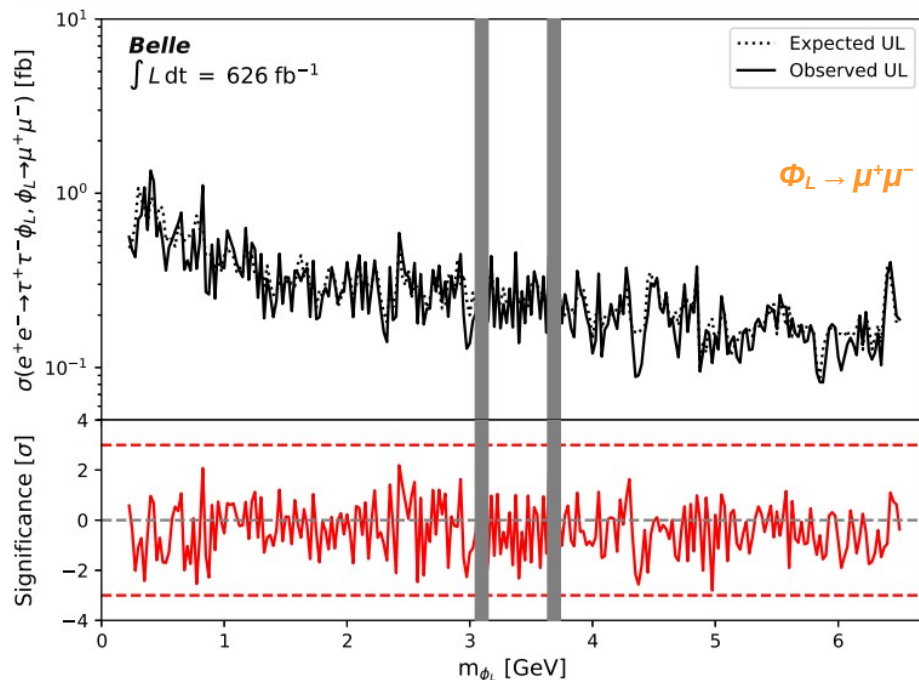
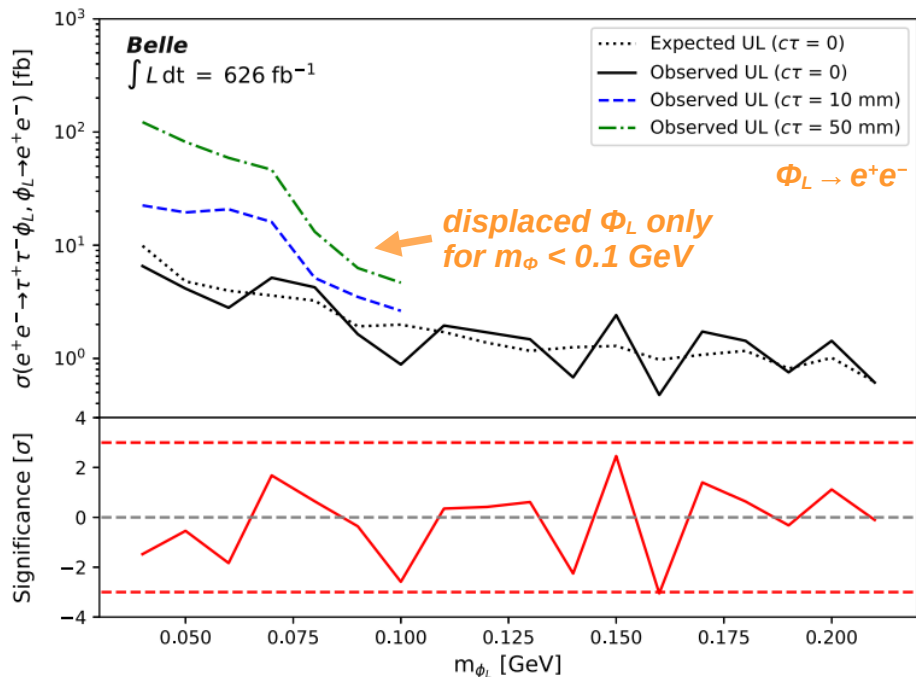
Leptophilic scalar in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle

Belle, Phys. Rev. D 109, 032002 (2024)



■ No significant excess found in 626 fb⁻¹

■ 90% CL upper limits $\sigma(e^+e^- \rightarrow \tau^+\tau^-\Phi_L ; \Phi_L \rightarrow l^+l^-)$

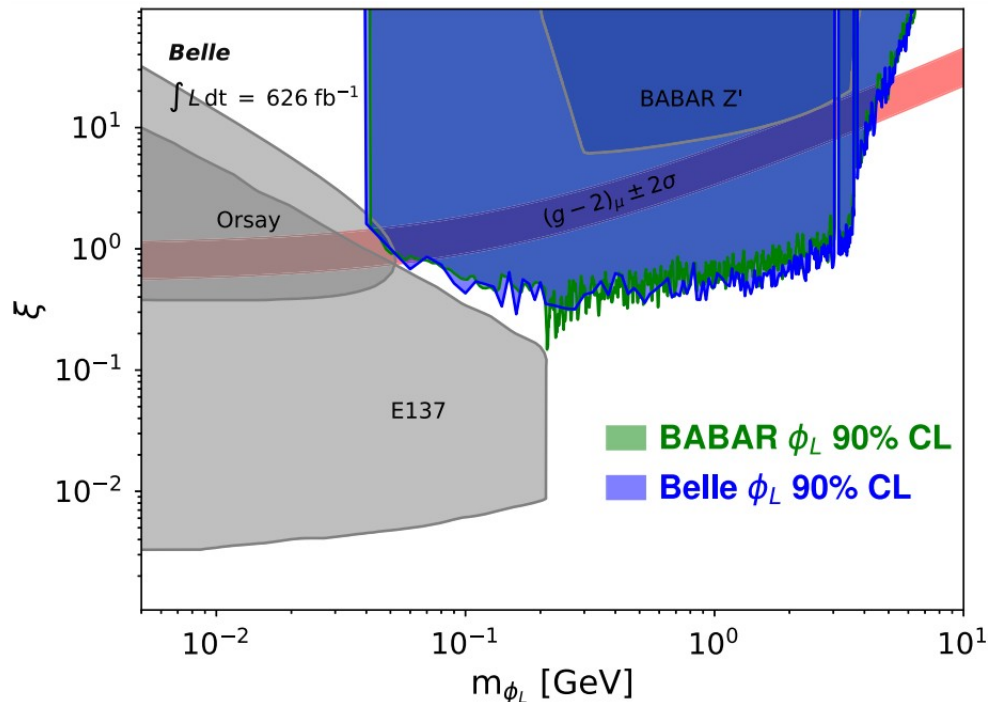


Leptophilic scalar in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle

Belle, Phys. Rev. D 109, 032002 (2024)



- No significant excess found in 626 fb^{-1}
 - 90% CL upper limits $\sigma(e^+e^- \rightarrow \tau^+\tau^-\Phi_L ; \Phi_L \rightarrow l^+l^-)$
 - Obtained model dependent limits for coupling constant ξ
 - On average, our limits are more constraining by 19% w.r.t. BaBar



Heavy neutral leptons in τ decays @ Belle

Belle, Phys. Rev. D 109, L111102 (2024)



■ Heavy sterile neutrinos N appears in many extensions of the SM [1]

- N mixes with ν_{SM}
- N long-lived for small values of N - ν_{SM} coupling

■ Limits on $|V_{N\tau}|^2$ are much weaker than limits on $|V_{Ne}|^2$, $|V_{N\mu}|^2$ [2]

■ Process: $e^+e^- \rightarrow \tau^+\tau^-$

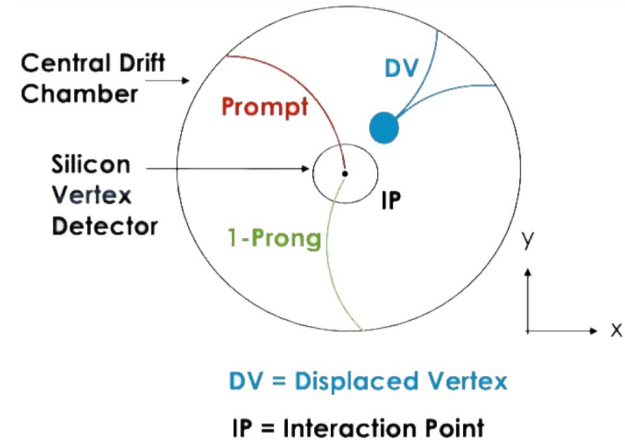
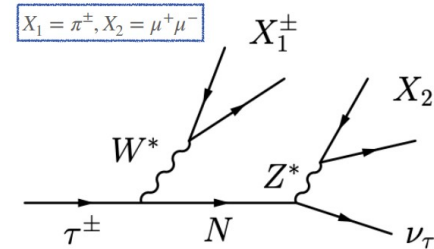
- Signal side: $\tau^- \rightarrow \pi^- N$; $N \rightarrow \mu^+ \mu^- \nu_\tau$
 - $N \rightarrow \mu^+ \mu^- \nu_\tau$ forms a displaced vertex (DV) > 15 cm from the beam axis

■ Tag side: $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$ / $\pi^+ \pi^0 \bar{\nu}_\tau$ / $l^+ \nu_l \bar{\nu}_\tau$

■ Main background from $K^0 \rightarrow \pi^+ \pi^-$ vetoed

■ Signal region divided in

- Low-mass region: $m_{DV} < 0.42$ GeV
- High-mass region: $m_{DV} > 0.52$ GeV



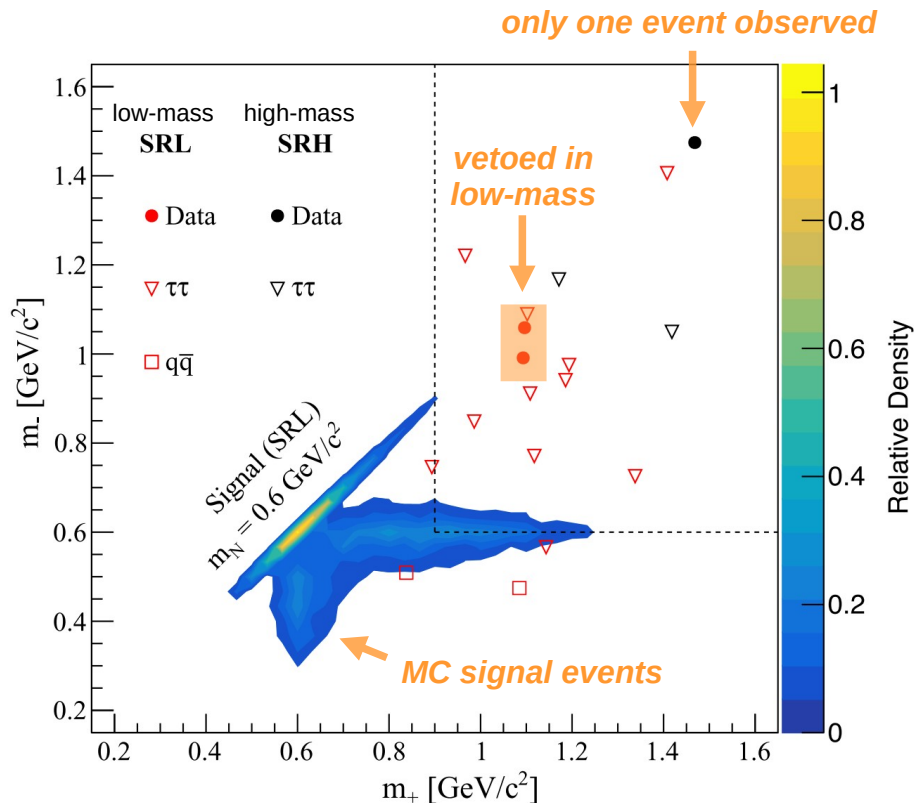
Heavy neutral leptons in τ decays @ Belle

Belle, Phys. Rev. D 109, L111102 (2024)



■ Full kinematics of the signal-decay chain reconstructed with a two-fold ambiguity on m_N (m_+ and m_-)

■ In low-mass and high-mass regions observed respectively 0 and 1 events in 915 fb^{-1}

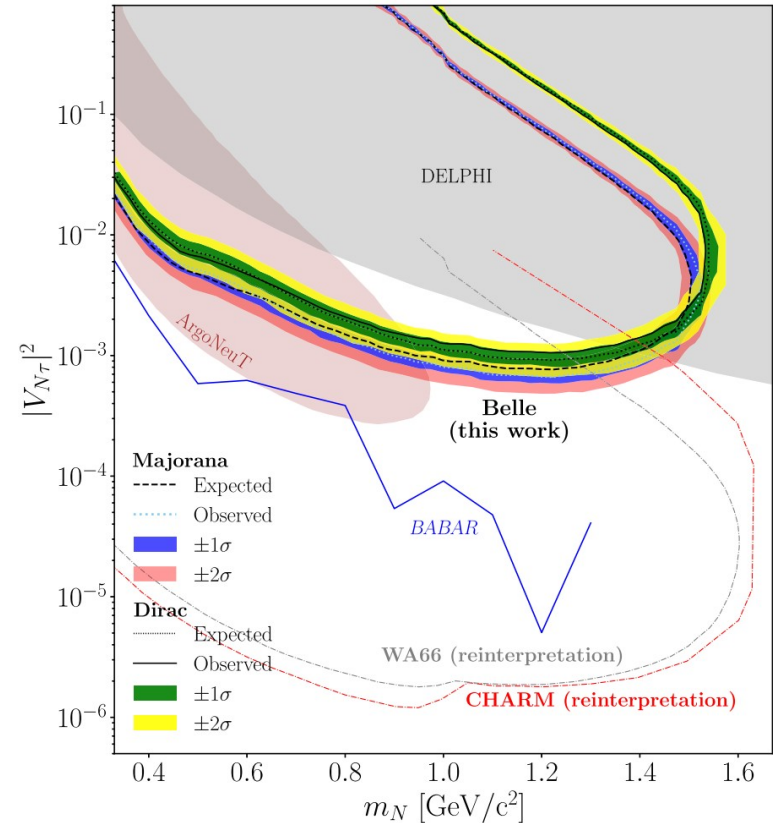


Heavy neutral leptons in τ decays @ Belle

Belle, Phys. Rev. D 109, L111102 (2024)

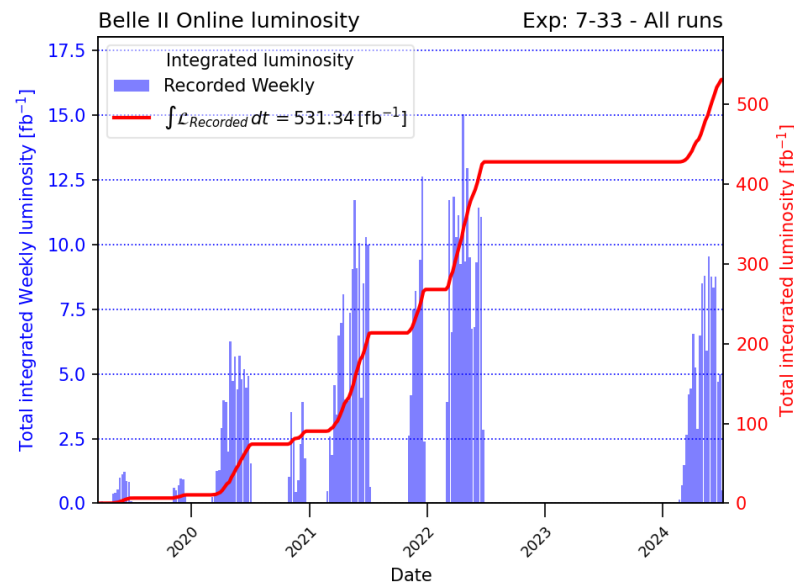


- Full kinematics of the signal-decay chain reconstructed with a two-fold ambiguity on m_N (m_+ and m_-)
 - In low-mass and high-mass regions observed respectively 0 and 1 events in 915 fb^{-1}
 - Since no significant excess is observed, 95% CL upper limits on $|V_{N\tau}|^2$ are set
 - Most stringent limits in the mass range $1.3 < m_N < 1.4 \text{ GeV}$
 - Innovative analysis technique exploited!
 - First Belle dark sector search with a displaced vertex!



Summary

- Belle and Belle II provide a unique environment to search for light dark matter or mediators
- Excellent sensitivity for dark sector searches in the MeV – GeV range
 - At Belle II: world leading or competitive results even with a subset of the available data
- So far Belle II recorded $\sim 531 \text{ fb}^{-1}$, more results with higher statistics and improved analyses are in the pipeline

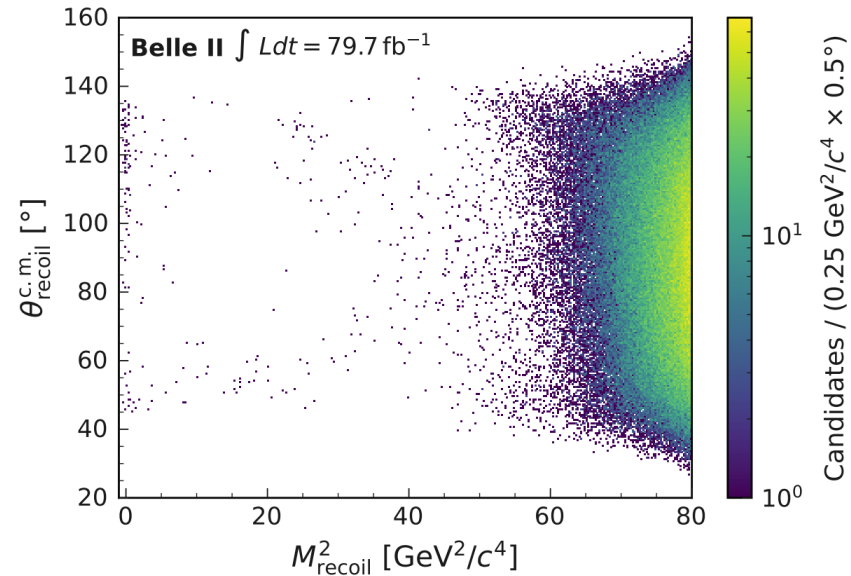


Backup

Invisible Z' decay

Belle II, Phys. Rev. Lett. 130, 231801 (2023)

- Additional massive gauge vector boson Z' with model $L_\mu - L_\tau$
- Could explain discrepancies in $(g - 2)_\mu$ [1]
- Study (invisible) system recoiling against $\mu^+\mu^-$
 - 2D fit in M_{recoil}^2 and $\theta_{\text{recoil}}^{\text{CM}}$ plane



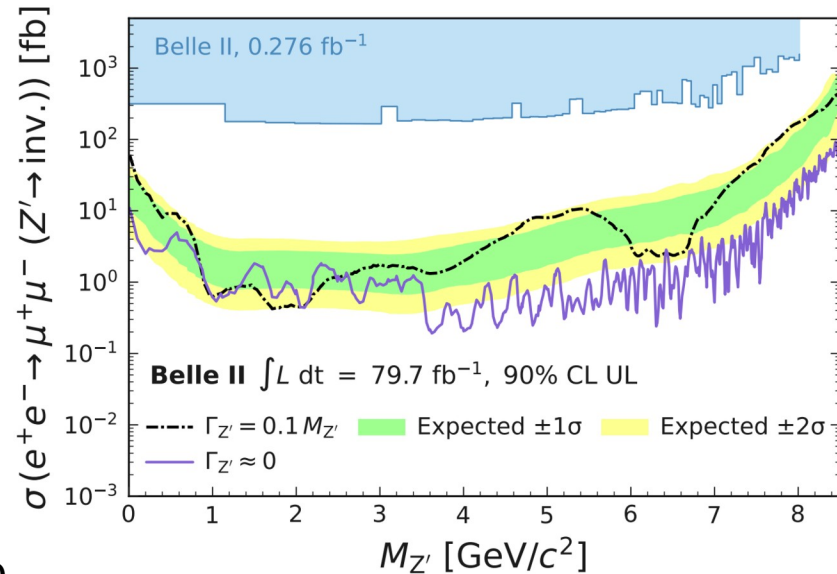
[1] B. Shuve and I. Yavin., Phys. Rev. D 89, 113004 (2014)

Invisible Z' decay

Belle II, Phys. Rev. Lett. 130, 231801 (2023)



- Additional massive gauge vector boson Z' with model $L_\mu - L_\tau$
- Could explain discrepancies in $(g - 2)_\mu$ [1]
- Study (invisible) system recoiling against $\mu^+\mu^-$
 - 2D fit in M_{recoil}^2 and $\theta_{\text{recoil}}^{\text{CM}}$ plane
- Challenging background tackled with neural network simultaneously trained for all masses [2]
- Systematics and corrections from $e\mu$ and ee control samples
- Update of first Belle II analysis [3] with 300x dataset

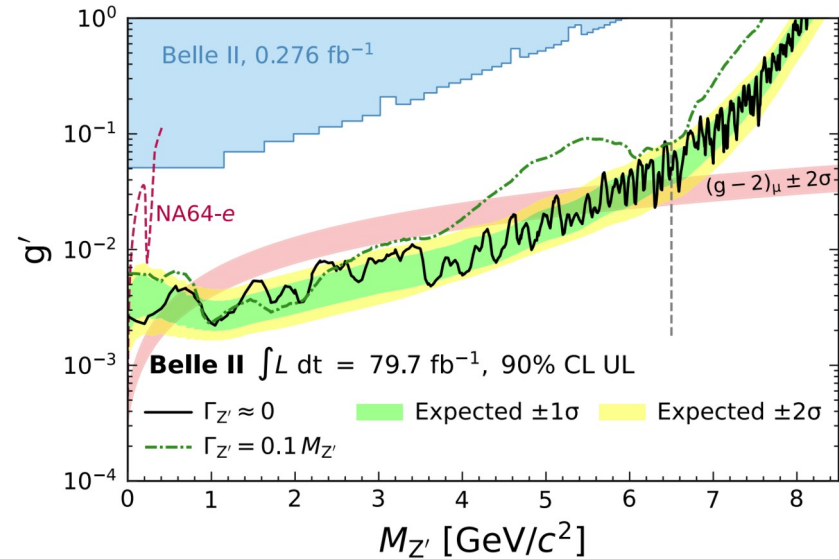


[1] B. Shuve and I. Yavin., Phys. Rev. D 89, 113004 (2014)
[2] F. Abudinén et al., Eur. Phys. J. C 82, 121 (2022)
[3] Belle II, Phys. Rev. Lett. 124, 141801 (2020)

Invisible Z' decay

Belle II, Phys. Rev. Lett. 130, 231801 (2023)

- Additional massive gauge vector boson Z' with model $L_\mu - L_\tau$
- Could explain discrepancies in $(g - 2)_\mu$ [1]
- Study (invisible) system recoiling against $\mu^+\mu^-$
 - 2D fit in M_{recoil}^2 and $\theta_{\text{recoil}}^{\text{CM}}$ plane
- Challenging background tackled with neural network simultaneously trained for all masses [2]
- Systematics and corrections from $e\mu$ and ee control samples
- Update of first Belle II analysis [3] with 300x dataset
- Preferred region excluded for $0.8 < m_{Z'} < 2.0$ GeV



[1] B. Shuve and I. Yavin., Phys. Rev. D 89, 113004 (2014)

[2] F. Abudinén et al., Eur. Phys. J. C 82, 121 (2022)

[3] Belle II, Phys. Rev. Lett. 124, 141801 (2020)