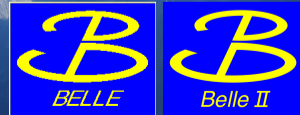


Recent results from Belle and Belle II on dark sector searches

Sungjin Cho (sjcho93@yonsei.ac.kr)

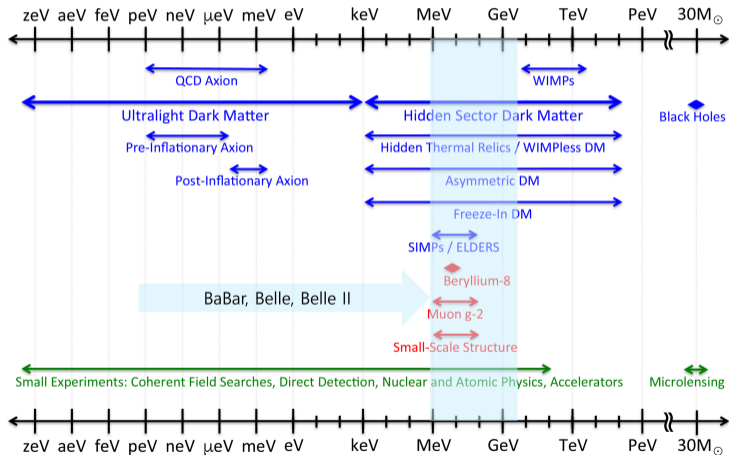
On behalf of Belle and Belle II collaboration

Dec 10th, 2024
BCVSPIN Conference
Kathmandu, Nepal



Dark Sector Covered by e^+e^- B-Factories

Dark Sector Candidates, Anomalies, and Search Techniques



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

Dark matter mediators

- Vector portal
 - ▶ Dark photon, Z'
- Pseudoscalar portal
 - ▶ Axions, Axion-like particles
- Scalar portal
 - ▶ Dark Higgs, scalars
- Neutrino portal
 - ▶ Sterile neutrino

Dark Sector searches in Belle and Belle II

Vector portal: Dark Photons, Z' bosons

- $e^+e^- \rightarrow \mu^+\mu^-Z', Z' \rightarrow \text{invisible}$
Belle II : PRL 130, 231801 (2023)
- $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$
Belle II : PRL 131, 121802 (2023)
- $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$
Belle II : PRD 109, 112015 (2024)

Pseudo-scalar portal: Axion Like Particles (ALPs)

- $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$
Belle II : PRL 125, 161806 (2020)
- $\tau \rightarrow l\alpha, \alpha \rightarrow \text{invisible}$
Belle II : PRL 130, 181803 (2023)
- $B^{+0} \rightarrow K^{+0}S, S \rightarrow x^+x^-, x = e, \mu, \pi, K$
Belle II : PRD 108, L111104 (2023)

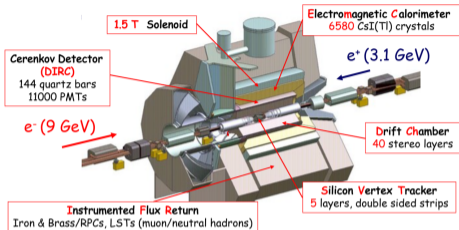
Scalar portal: Dark Higgs / Scalars

- $e^+e^- \rightarrow \mu^+\mu^- + \text{invisible } h'$
Belle II : PRL 130, 071804 (2023)
- $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$
Belle : PRD 109, 032002 (2024)

Neutrino portal: Sterile neutrinos

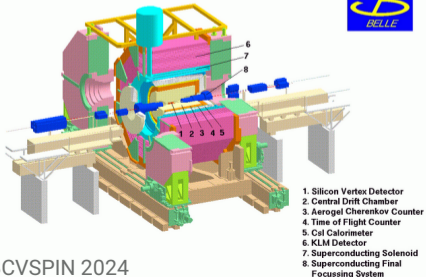
- $\tau \rightarrow \pi N (\rightarrow \mu^+\mu^-\nu\tau)$
Belle : PRD 109, L111102 (2024)

Asymmetric e^+e^- B Factories: Concept



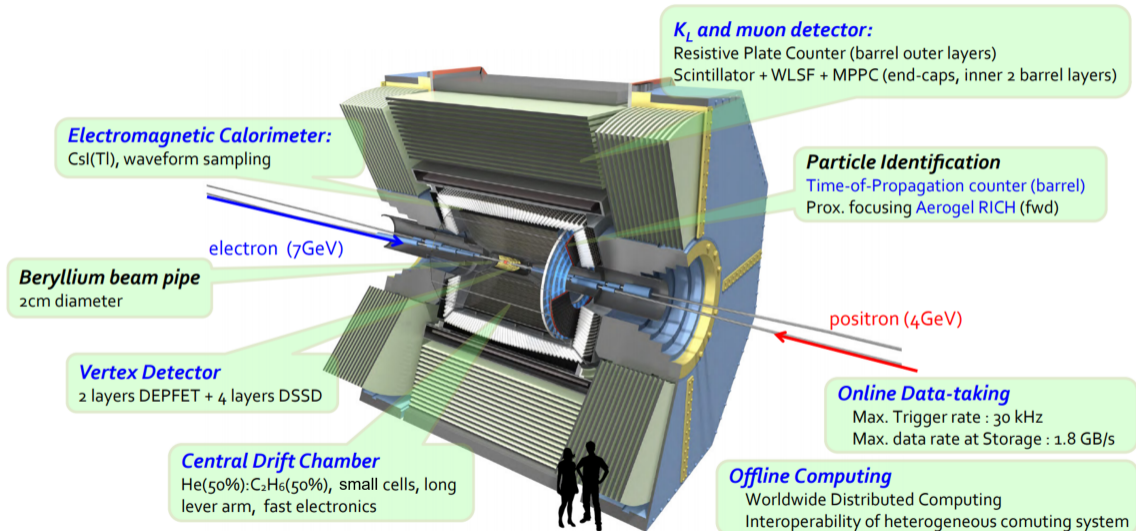
BaBar / PEP II

BELLE Detector



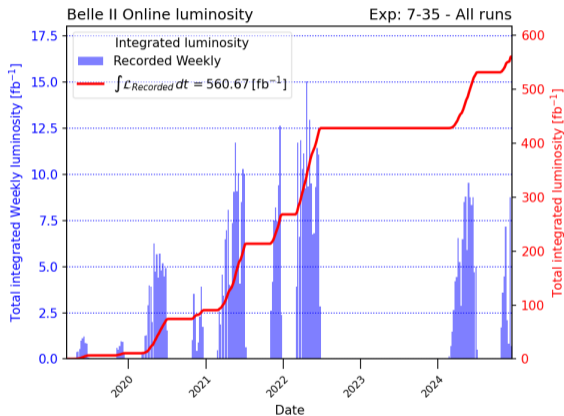
- B pairs can be generated plentifully using 10.58 GeV $\Upsilon(4S)$ colliders ($M_B = 5.28$ GeV)
- Relatively lower energy \rightarrow intensity up easily \rightarrow intensity frontier
- Asymmetric B factory: one side flavor tag, the other side signal
 - ▶ BaBar/PEP-II at SLAC 1999 - 2008
 - ▶ Belle/KEKB at KEK 1999 - 2010
- 2nd generation asymmetric B factory:
 - ▶ Belle II/SuperKEKB at KEK 2019 - Present
- Detectors at B-Factories have versatile particle identification and reconstruction abilities.
 - ▶ Dark sector search is one of core projects at B-Factories.

The Belle II Detector



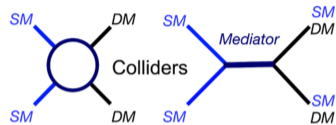
SuperKEKB Luminosity: Current Status

- After SuperKEKB commissioning phases, physics runs started spring 2019.
- Run 1 ended June 2022.
 - ▶ Peak luminosity at $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record set on June 22nd, 2022.
 - ▶ Run 1 integrated luminosity at $\int L_{recorded} dt = 424 fb^{-1}$. (~ BaBar, ~ 1/2 Belle sample size)
- Long shutdown 1 (LS1) 2022 – 2023.
- Run 2 started February 2024.
- Integrated luminosity at $560 fb^{-1}$ at last week.



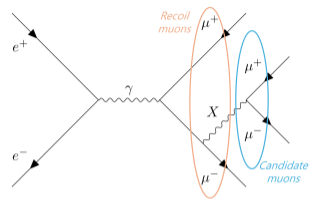
Merits of Dark Sector Search at e^+e^- B-Factories

- B-Factories are competitive in the light dark matter search from 1 MeV to ~ 10 GeV.
- Background is lower compared to hadron colliders (LHCb).
- Closed detectors means the coverage is almost 4π .
 - ▶ Missing momentum and energy can indicate the presence of invisible particle(s).
 - ▶ Full event interpretation is possible.
- Have better efficiencies on finding the neutral particles than Belle
- Dedicated trigger for low-multiplicity is introduced for Belle II.
 - ▶ Low multiplicity signature observation is possible.
 - ▶ Dark particle signatures in B and τ decays are available ($\sigma(b\bar{b}), \sigma(c\bar{c}), \sigma(\tau\bar{\tau}) \sim 1\text{nb}$).
 - ▶ Clean environment can compensate for lower production cross-section than LHCb.



$\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II (178 fb^{-1})

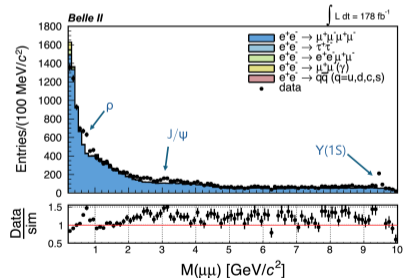
- Search for process $e^+ e^- \rightarrow \mu^+ \mu^- X, X \rightarrow \mu^+ \mu^-$.
- Probing two different models :
 - ▶ $L_\mu - L_\tau$ vector mediator (Z') [$\mathcal{L} = \Sigma_l \theta g' \bar{l} \gamma^\mu Z'_\mu$] [1]
 - ▶ Muonphilic scalar (S) [$\mathcal{L} \subset g_s S \bar{\mu} \mu$] (first time search) [2]
- Used luminosity is 178 fb^{-1} , which is $\sim 2\text{-}3$ times less data used by BaBar[3] and Belle[4] experiments for the Z' search.
- The difference in kinematics:
heavy resonance produced in final-state radiation.



Event Selections :

- At least three muons are identified.
- Total charge is zero and mass of 4 tracks close to CM energy.
No extra energy is allowed.
- Multi-layer Perceptron is applied to suppress background peaks.

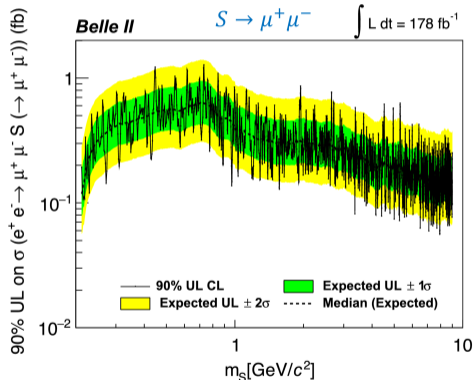
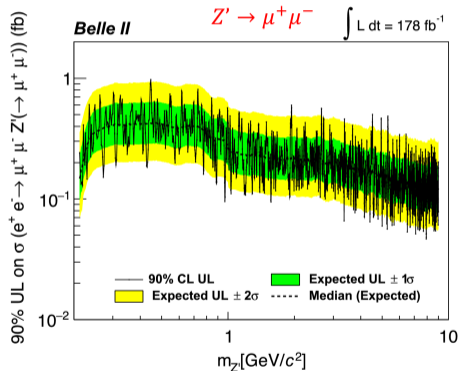
- [1] J. High Energ. Phys. 2016, 106 (2016) [2] J. High Energ. Phys. 2022, 129 (2022)
[3] Phys. Rev. D 94, 011102(R) (2016) [4] Phys. Rev. D 106, 012003 (2022)



Data MC disagreement mainly due to missing ISR of the used generator

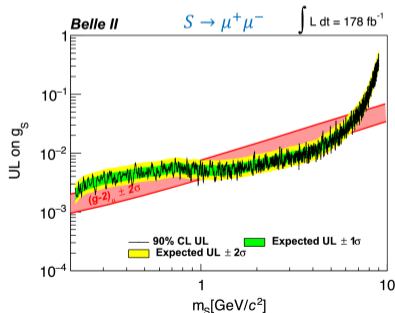
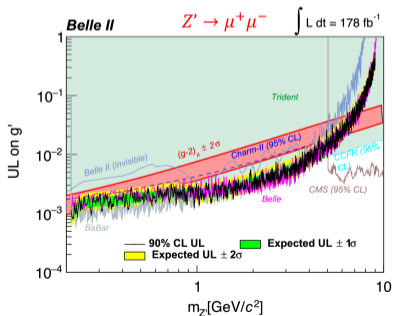
$\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II (178 fb^{-1})

- No significant excess are found in 178 fb^{-1}
- 90% CL upper limits on the process cross-section are obtained.



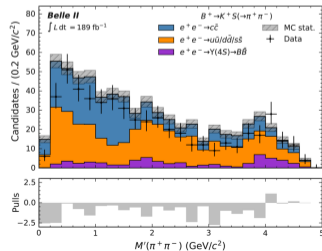
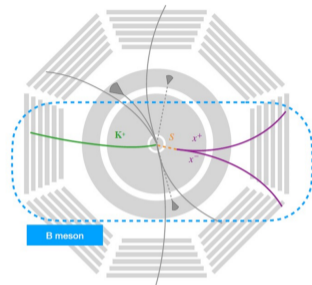
$\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II (178 fb^{-1})

- Cross-section limits are translated into upper limits on the coupling constant for respective hypotheses,
 - ▶ g' for the $L_\mu - L_\tau$ model and g_s for the muon-philic dark scalar S model
- Almost similar result of BaBar ($\sim 500 \text{ fb}^{-1}$) and Belle ($\sim 600 \text{ fb}^{-1}$) with 178 fb^{-1} for the $L_\mu - L_\tau$ model.
- First 90% CL upper limits for the muonphilic dark scalar (S) model
- Muonphilic scalar results exclude part of the muon $g-2$ region of parameter space.

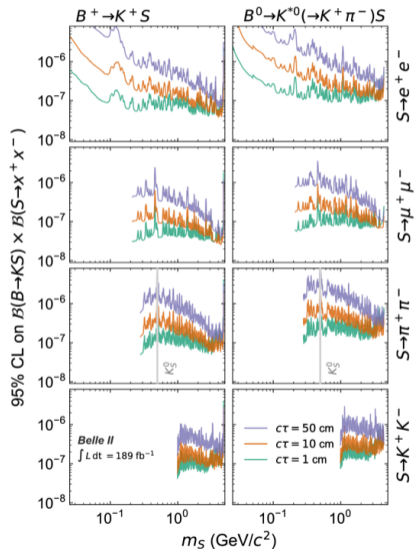


Long-lived Scalar (S) in B decays @ Belle II (189 fb^{-1})

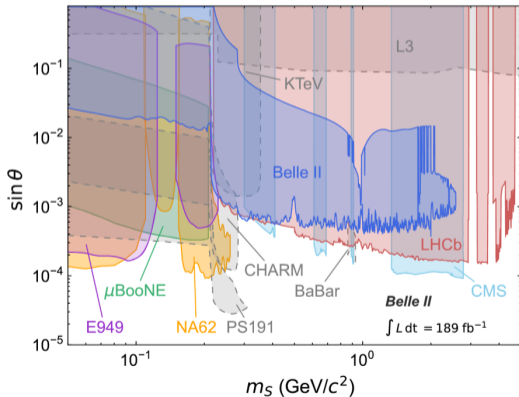
- Search parameters are mass of dark scalar S and mixing angle θ between the SM Higgs and S .
- Search for long lived spin-0 mediator S in B decays
 - ▶ $(e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B})$.
 - ▶ **First Belle II long-lived spin-0 (S) particle search**
- Channels studied : $B^+ \rightarrow K^+ S, B^0 \rightarrow K^{*0} S$
- S is assumed to decay to a pair of charged tracks
 - ▶ $S \rightarrow x^+ x^-, x = e, \mu, \pi, K$.
- S is assumed to live long: S decay vertex is far from the beam interaction point.



Long-lived Scalar (S) in B decays @ Belle II (189 fb^{-1})

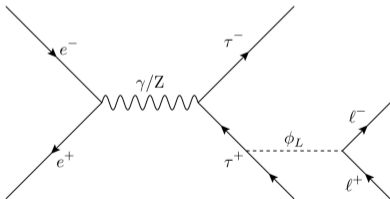


- No observed excess for scanning result of the m_S (mass of Scalar S).
- 95% CL exclusion region is obtained.
- Limits on branching fractions and mixing angle $\sin\theta$.
- First measurements for exclusive hadronic states.

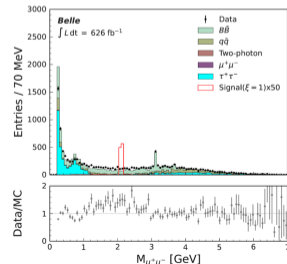
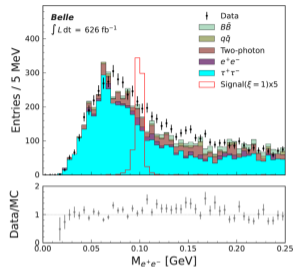


Leptophilic scalar (ϕ_L) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle (626 fb^{-1})

- Belle on 626 fb^{-1} : search for leptophilic dark scalar (ϕ_L) in 2τ (1-prong decay) + $2 l$ (e or μ) events.
- 1-prong: one charged track + neutrals
- This mode can affect $(g-2)_\mu$ results. [1]
- Major background is $e^+e^- \rightarrow \tau^+\tau^-$.
- Radiative Bhabha (photon decaying to two muons) are removed by cuts on missing energy and its angle.
- Boosted Decision Tree is used to suppress backgrounds.

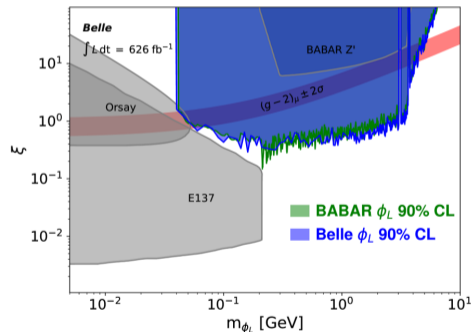
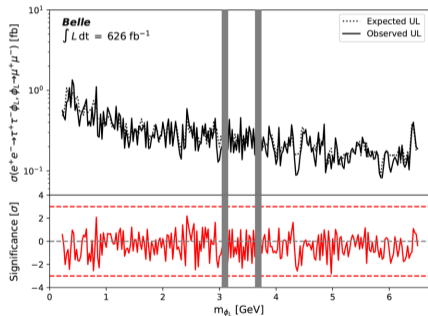


[1] J. High Energy. Phys. 2014, 147 (2014)



Leptophilic scalar (ϕ_L) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle (626 fb^{-1})

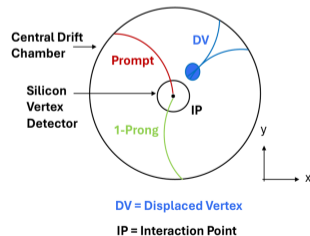
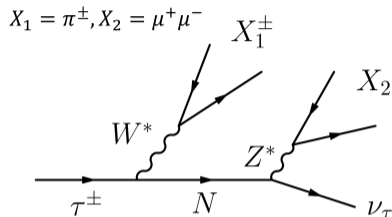
- No significant excess found in 626 fb^{-1} .
- 90% CL upper limits on $\sigma(e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow l^+l^-))$ and ξ (flavor-independent coupling to leptons).
- Limits are on average 19% more constraining than BaBar.[1]
- More searches on the full Belle sample is continuing.



[1] Phys. Rev. Lett. 125, 181801 (2020)

Heavy Neutral Leptons (HNL) in τ decays @ Belle (915 fb^{-1})

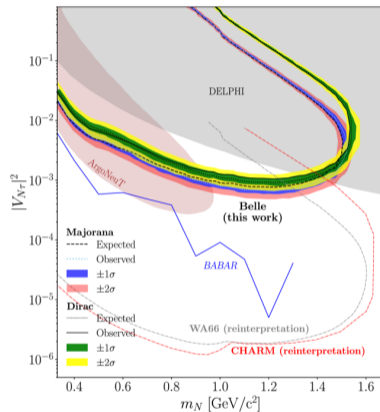
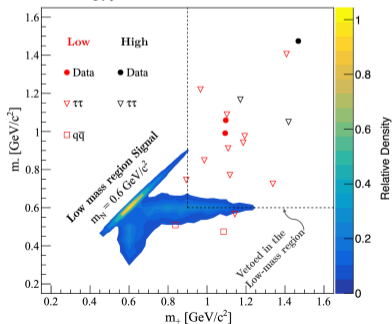
- Heavy neutrinos N appear in several extensions of the SM
 - ▶ N long-lived for small values of N - ν_{SM} coupling
- The search model probes $|V_{N\tau}|^2$ and coupling with other leptons considered negligible[1].
- Process: $e^+e^- \rightarrow \tau^+\tau^-$
 - ▶ Signal side: $\tau^- \rightarrow \pi^- N$; $N \rightarrow \mu^+\mu^-\nu_\tau$
 - ▶ $N \rightarrow \mu^+\mu^-\nu_\tau$ forms a displaced vertex (DV) $> 15 \text{ cm}$ 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:** $m_{DV} < 0.42 \text{ GeV}$
 - ▶ **High-mass region:** $m_{DV} > 0.52 \text{ GeV}$



[1] J.Phys.G47,010501(2020)

Heavy Neutral Leptons (HNL) in τ decays @ Belle (915 fb^{-1})

- Despite the neutrino in the final state, the constraints of the signal decay allows reconstruction of full kinematics with a two-fold ambiguity on m_N (m_+ and m_- /Two solutions for m_N).
- **Low** and **High** mass region have only 0 and 1 events respectively.
- Since no significant excess is observed for 915 fb^{-1} , 95% CL upper limits on $|V_{N\tau}|^2$ are set.



Summary

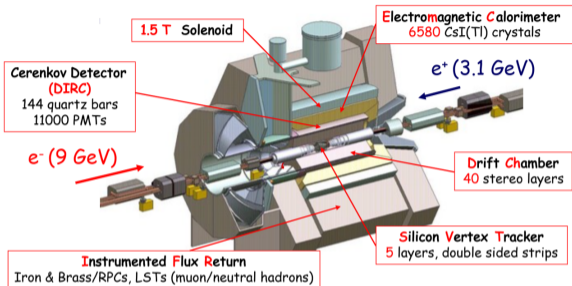
Today I showed some recent results from Belle and Belle II on dark sector searches :

- $\mu^+\mu^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ @ Belle II
- Long-lived Scalar (S) in B decays @ Belle II
- Leptophilic scalar (ϕ_L) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle
- Heavy Neutral Leptons (HNL) in τ decays @ Belle

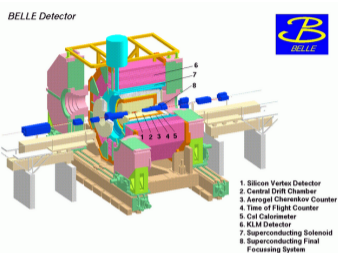
No significant signal observed
and we set stringent exclusion region.

- e^+e^- B factories provide unique opportunities to study dark sector.
- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, **the world record**.
- Belle II started Run 2 this year (2024).
- The SuperKEKB and Belle II are now full physics data taking mode.
- **There will be new search results beyond the Standard Model with the upcoming data, especially in the Dark Sector.**

Asymmetric e^+e^- B Factories: History



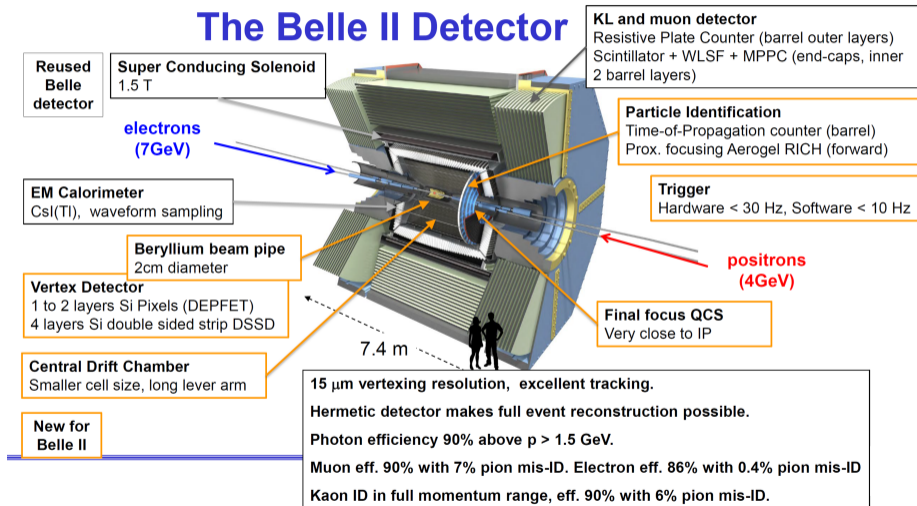
BaBar / PEP II



Belle / KEKB

- First generation B factory
 - ▶ ARGUS/DORIS II at DESY 1982 - 1992
 - ▶ CLEO/CESR at Cornell 1979 - 2008 (including Cleo-c)
- Next, asymmetric B factory: one side flavor tag, the other side signal
 - ▶ BaBar/PEP-II at SLAC 1999 - 2008
 - ▶ Belle/KEKB at KEK 1999 - 2010
- 2nd generation asymmetric B factory:
 - ▶ Belle II/SuperKEKB at KEK 2019 - Present

The Belle II Detector



$\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II (178 fb^{-1})

Signal Search Results

- Maximum local significance: 3.4σ at $M(\mu\mu) = 5.307 \text{ GeV}/c^2$
 - ▶ Global significance: 1.6σ
- Three additional mass points with local significance $> 3\sigma$:
 - ▶ $1.939 \text{ GeV}/c^2$ (global: 0.6σ)
 - ▶ $4.518 \text{ GeV}/c^2$ (global: 1.2σ)
 - ▶ $4.947 \text{ GeV}/c^2$ (global: 1.1σ)

Upper Limits

- 90% CL upper limits on cross sections:
 - ▶ $L_\mu - L_\tau$ model: 0.046 fb to 0.97 fb
 - ▶ Muonphilic scalar model: 0.055 fb to 1.3 fb

Coupling Constants Constraints

- For masses below $6 \text{ GeV}/c^2$:
 - ▶ $L_\mu - L_\tau$ model: $g^I = 0.0008 - 0.039$
 - ▶ Muonphilic scalar: $g_S = 0.0018 - 0.040$
- Excluded regions for $(g-2)_\mu$ anomaly:
 - ▶ $L_\mu - L_\tau$: $0.8 < m_{Z'} < 4.9 \text{ GeV}/c^2$
 - ▶ Muonphilic scalar: $2.9 < m_S < 3.5 \text{ GeV}/c^2$

Systematic Uncertainties

Main contributions:

- MLP selection: $1.1-8.1\%$
- Tracking efficiency: 3.6%
- Mass resolution: 7%
- Total uncertainty: $9.5-12.9\%$

Long-lived scalar (S) in $B^+ \rightarrow K^+ \chi(\mu^+ \mu^-)$ decays @ LHCb

Analysis Summary:

- Search for long-lived scalar particle χ in $B^+ \rightarrow K^+ \chi, \chi \rightarrow \mu^+ \mu^-$ decays
- Dataset: 3 fb^{-1} of pp collisions at $\sqrt{s} = 7,8 \text{ TeV}$
- Mass range: $250 < m(\chi) < 4700 \text{ MeV}/c^2$
- Lifetime range: $0.1 < \tau(\chi) < 1000 \text{ ps}$

Key Analysis Features:

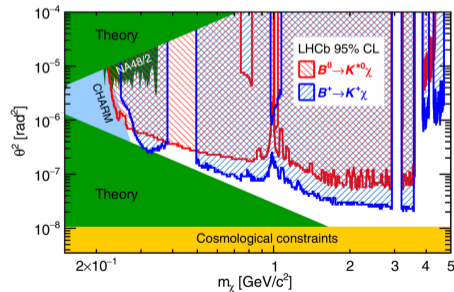
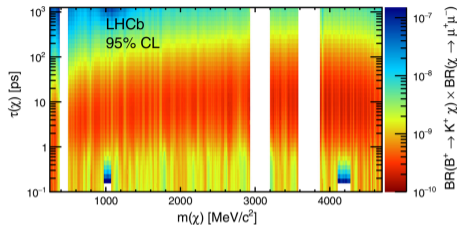
- Signal: 2 muons forming displaced vertex + kaon
- Background suppression:
 - ▶ Vertex quality & displacement requirements
 - ▶ Boosted Decision Tree classification
 - ▶ Removes $K_S^0, J/\psi, \psi(2S)$ vetoes

Results:

- No significant excess observed
- Set upper limits on $\mathcal{B}(B^+ \rightarrow K^+ \chi) \times \mathcal{B}(\chi \rightarrow \mu^+ \mu^-)$
 - ▶ Limits between 2×10^{-10} and 10^{-7}
 - ▶ Most stringent constraints to date
 - ▶ Significantly improves previous limits by up to factor 20

Interpretation:

- Results interpreted in Higgs portal inflaton model
- Excludes significant portion of theoretically allowed parameter space
- Constrains mixing angle θ^2 between inflaton and SM Higgs



Long-lived Particles Decaying to Muon Pairs @ CMS

Data & Method

- $\sqrt{s} = 13$ TeV pp collisions, $\mathcal{L} = 101 \text{ fb}^{-1}$ (2017-2018)
- Special "scouting" triggers: low p_T thresholds, high rate
- Search for displaced vertices: $0 < l_{XY} < 11$ cm

Signal Models Tested

- **Dark Photon (Z_D):** $H \rightarrow Z_D Z_D \rightarrow 4\mu$
 - ▶ Via Higgs or hypercharge portal, coupling ϵ
 - ▶ m_{Z_D} up to 50 GeV
- **Light Scalar (ϕ):** $h_b \rightarrow \phi X \rightarrow \mu^+ \mu^- X$
 - ▶ Via Higgs mixing, angle θ
 - ▶ $m_\phi \lesssim 5$ GeV

Results

- No significant excess observed
- Most stringent limits to date in several regions

Key Feature

- Novel trigger strategy enables exploration of previously inaccessible phase space in low mass and non-zero displacement region

