

Recent results on dark sector searches at Belle II

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Workshop Italiano sulla Fisica ad Alta intensità, Bologna

12-15 November 2024

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Outline

- The Belle II experiment
 - Dark sector searches at Belle II
- Recent results on dark sector searches
 - The Z' searches: Z' decay into $\mu^+\mu^-$
 - Light (pseudo) scalars in B-meson decays
 - Inelastic dark matter and a dark higgs boson
- Summary

The Belle II experiment

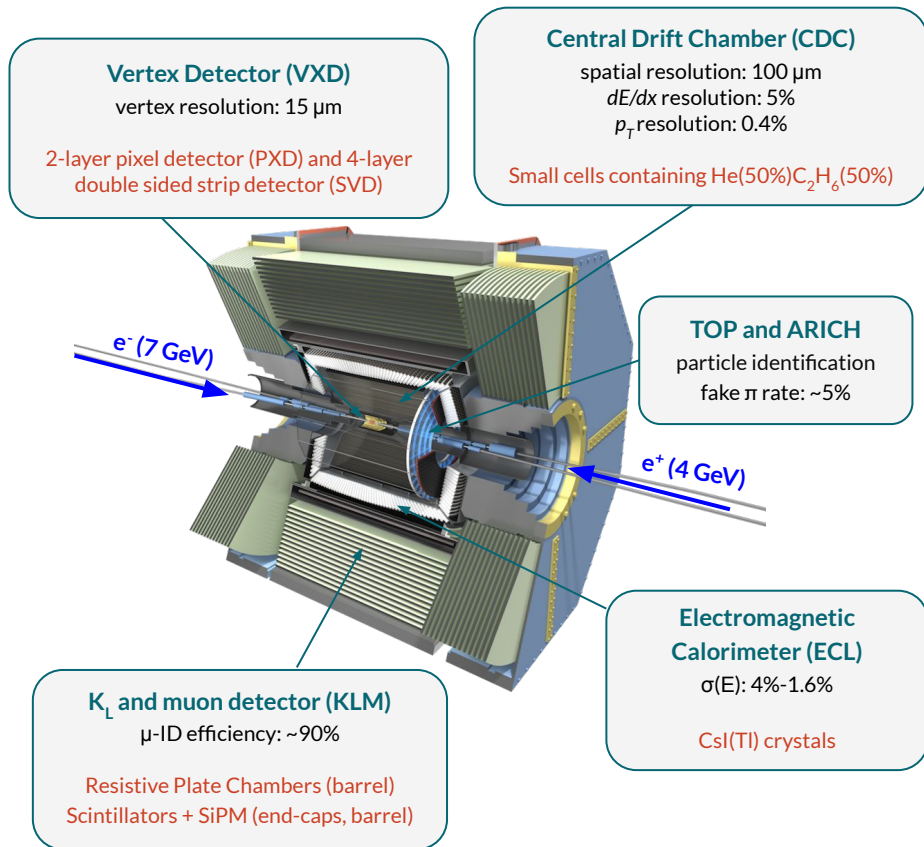
The Belle II experiment

Overview

- Second generation B-factory, optimized for the production of B meson pairs, but also D mesons and τ leptons.
- Operating at the SuperKEKB accelerator (Tsukuba, JP), an e^+e^- asymmetric energy collider
- Collisions occur mainly at $\sqrt{s} = 10.58$ GeV, corresponding to the $m_{\text{inv}} = Y(4S)$
- Detector is $\sim 4\pi$ general purpose magnetic spectrometer

Data taking status

- Run I (2019-2022) + Run II (February 2024-Now): Recorded a total luminosity of more than **530 fb^{-1}** .
- SuperKEKB reached world's highest instantaneous luminosity at $\mathcal{L} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.
- Target: $\int \mathcal{L} dt = 50 \text{ ab}^{-1}$ (**$50 \times$ Belle dataset!**)



See talks by [M.Mantovano](#), [A.Gaz](#), [L.Zani](#) and [D.Gosh](#) for more information

Dark sector searches at Belle II

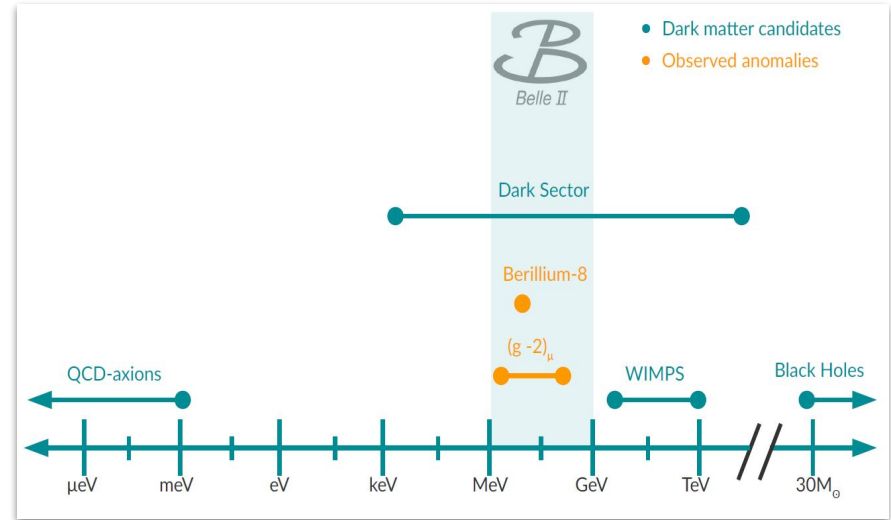
Belle II can access the mass range naturally favored by light dark sectors (DS) $M_{\text{Dark matter}} \sim \mathcal{O}(\text{MeV} - \text{GeV})$

■ Large potential for dark matter (DM) discoveries:

● Utilizing the advantages of B factories

- **High luminosity:** $\mathcal{L} > 10^{34} \text{ cm}^2 \text{ s}^{-1}$
- **Well defined initial state:** $E_{\text{CMS}} = 2 \times E_{\text{beam}}$
- **Clean environment** with low background
- **Hermiticity (4 π detectors)**

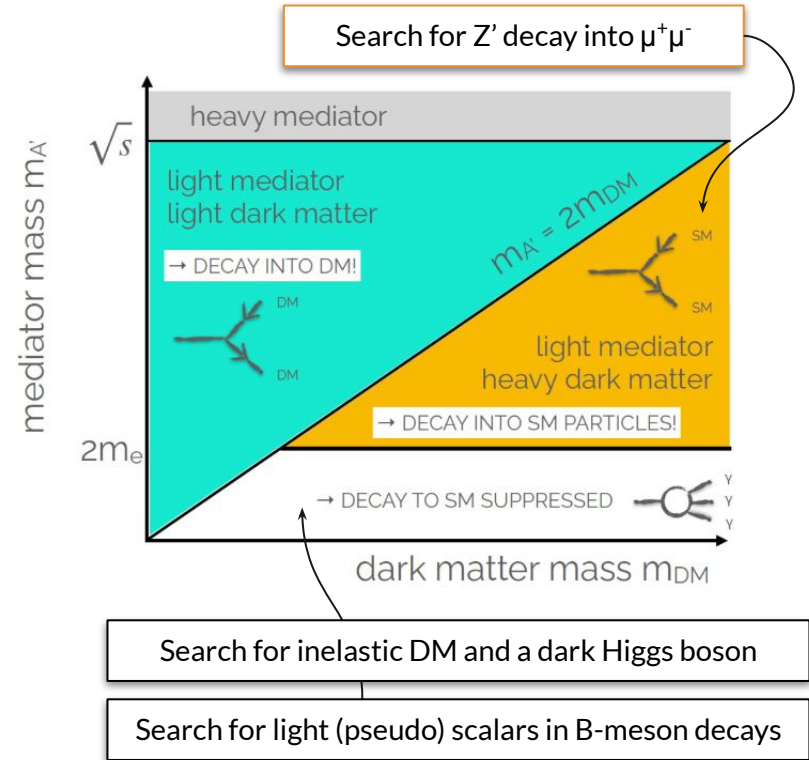
● Dedicated triggers for low multiplicity and missing energy final states, such as single photon, single track and single muon triggers → Make the Belle II dataset world-unique!



We can reconstruct missing energy events or search for invisible signatures which are crucial for the detection of DM and the DS searches.

Dark sector signatures

- **Searching for dark sector particles**
 - Directly produced in e^+e^- collisions
 - Emerging from the decay of mesons (such as B,D) or fermions (such as τ)
- Depending on the DS mediator and DM candidate mass hypothesis, different scenarios arise:
 - **Visible decay to SM:** Search for DS mediators
 - **Invisible decay to DM:**
Search for DM or DS mediators in final states with missing energy
 - **Suppressed decays to SM** lead to long-lived mediators



Recent results on dark sector searches

The Z' searches

■ $L_\mu - L_\tau$ model

Z' is a vector boson which couples at strength g' only to 2nd and 3rd generation leptons

→ Could provide insights to the $(g-2)_\mu$ anomaly and the DM phenomenology

■ Possible decays and signatures

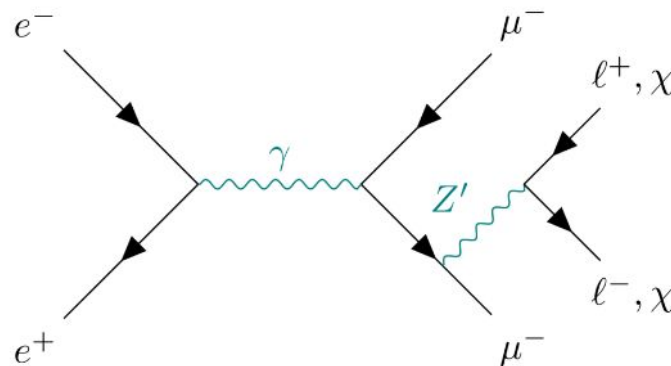
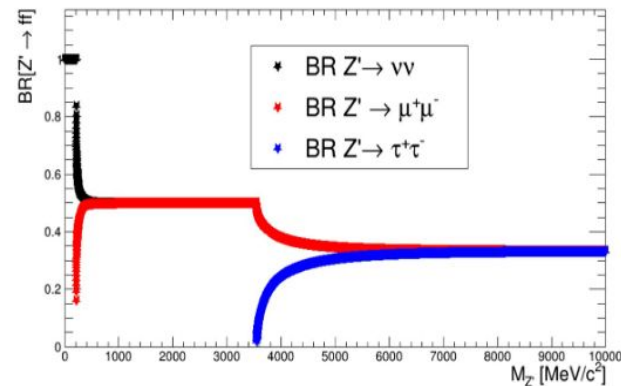
- **Visible decay:** $Z' \rightarrow \mu^+\mu^-$, $Z' \rightarrow \tau^+\tau^-$

Constraints from BaBar ([2016](#)), CMS ([2019](#)), Belle ([2022](#)) and neutrino-nucleus scattering experiments ([CCF.CHARM](#))

→ Reinterpretation of the results in different models:
 Z' , axion-like particle ALP, leptophilic/muonphilic dark-scalar

- **Invisible decay:** $Z' \rightarrow \nu\bar{\nu}$ or $\chi\bar{\chi}$

Constrained by Belle II ([2023](#)), BESII ([2024](#))



Search for Z' decay into $\mu^+\mu^-$

I. Adachi et al., Phys. Rev. D 109, 112015 (2024)

- **Strategy:** Search for a $\mu^+\mu^-$ resonance in four-muon events

Signal signature is a narrow peak in the opposite-charge **dimuon mass $M(\mu\mu)$**

→ Reinterpreted also as muonphilic dark scalar S

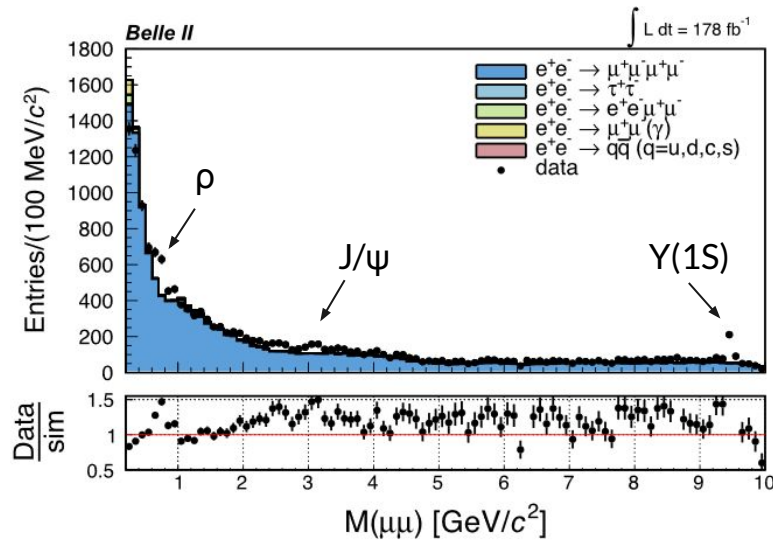
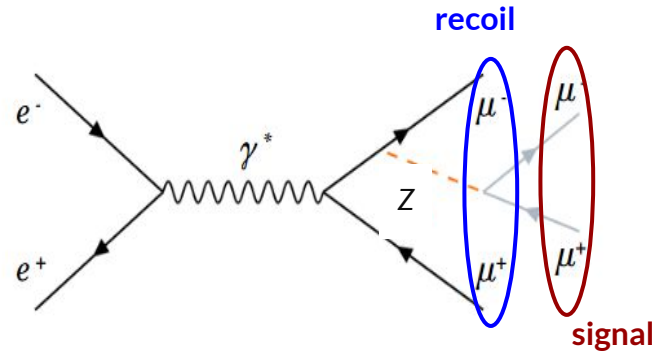
■ Selections

- Four-track final state with at least three identified as muons
- m_{inv} of the four-tracks compatible with the beam energy
- Zero total charge and no extra energy
- No ISR effects included in the MC simulation

- Main SM background contribution from $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ events

- **Signal extraction:** Fit scan on the di-muon reduced mass

spectrum defined as
$$M_{\mu\mu}^{reduced} = \sqrt{M_{\mu^+\mu^-}^2 - 4m_\mu^2}$$



Search for Z' decay into $\mu^+\mu^-$

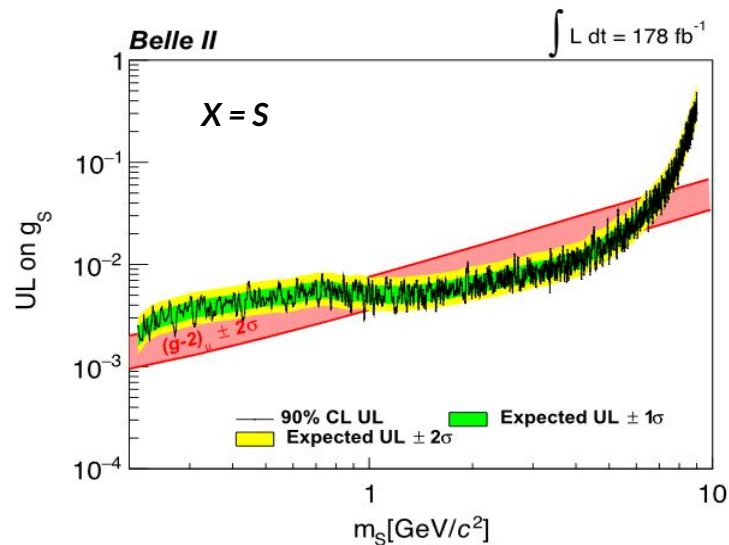
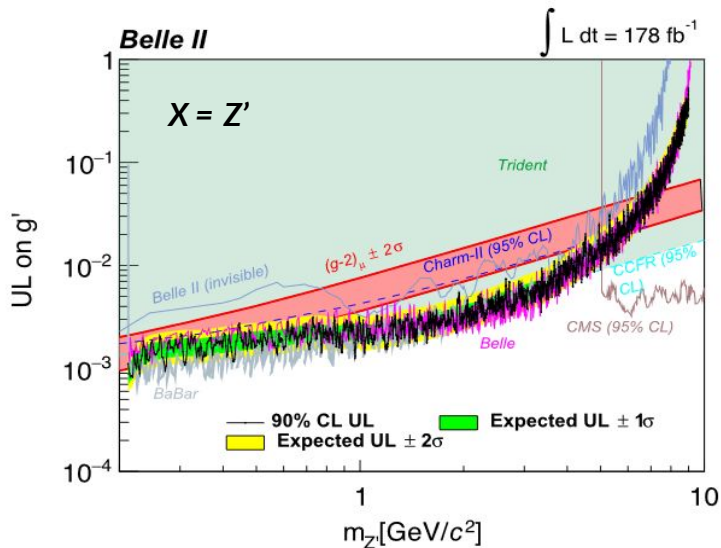
I. Adachi et al., Phys. Rev. D 109, 112015 (2024)

- No significant excess found with $178 \text{ fb}^{-1} \rightarrow$ **90% CL upper limits** set on the cross sections for the processes

$$e^+e^- \rightarrow \mu^+\mu^- X (\rightarrow \mu^+\mu^-) \text{ where } X = Z', S$$

Results translated into upper limits on the coupling constant:

- g' for the Z' ($L_\mu - L_\tau$ model) \rightarrow **Competitive results** with BaBar ($> 500 \text{ fb}^{-1}$) and Belle ($> 600 \text{ fb}^{-1}$)
- g_s for the muonphilic scalar model (S) \rightarrow **First limits** set on S from a dedicated search



Search for light (pseudo) scalars in B-meson decays

I. Adachi et al., Phys. Rev. D 108, L111104 (2023)

- A light scalar S mediator could be produced in b to s quark transitions:

$$B^+ \rightarrow K^+ S \text{ and } B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) S$$

S may interact with SM Higgs boson through a mixing angle θ (naturally long lived for small θ)

→ Reinterpreted also as an axion-like particle (ALP)

- **Strategy:** Search for a bump in the m_{inv} of tracks coming from a **displaced vertex** accompanied by a **charged K**

→ Look for S decays into **two oppositely charged tracks** $x^+ x^-$ where $x = e, \mu, \pi, K$

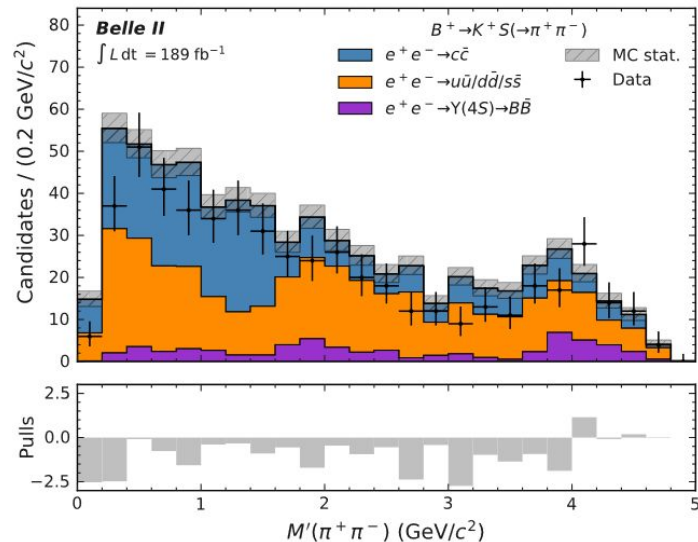
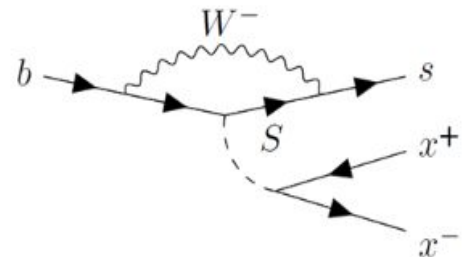
Selections

- Fully reconstructed B decay
- Probing lifetimes: $0.001 \text{ cm} < c\tau_S < 400 \text{ cm}$
- Long-lived K_S^0 mass region vetoed

- Main SM background contribution from combinatorial $e^+ e^- \rightarrow q\bar{q}$ events

- **Signal extraction:** Maximum likelihood fits to the reduced invariant

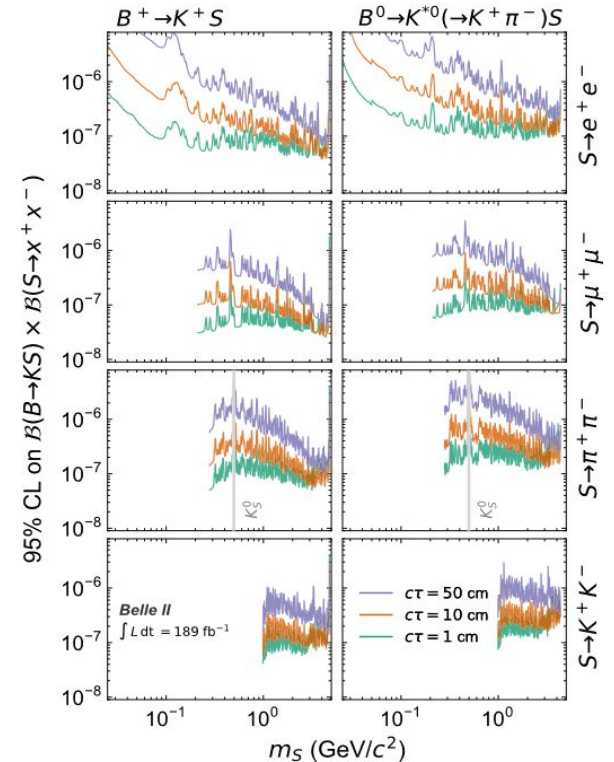
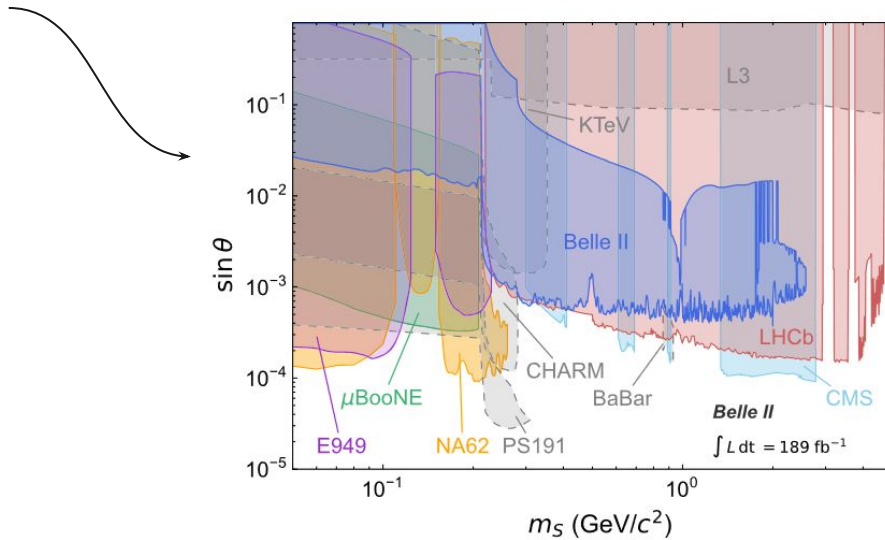
mass, defined as $M_{x^+ x^-}^{\text{reduced}} = \sqrt{M_{x^+ x^-}^2 - 4m_x^2}$



Search for light (pseudo) scalars in B-meson decays

I. Adachi et al., Phys. Rev. D 108, L111104 (2023)

- No significant excess found with $179 \text{ fb}^{-1} \rightarrow$ **95% CL upper limits** set on the cross section $B^+ \rightarrow K^+ S$ and $B^0 \rightarrow K^{*0}(\rightarrow K^+ \pi^-) S$
- **First limits** set on S on **exclusive hadronic final states** and for e^+e^- final states
- Results used to constrain the parameter space for the **sine of the mixing angle parameter θ** and the scalar mass m_s



Search for inelastic dark matter and a dark Higgs boson

Preliminary results

- Inelastic dark matter model with **4 dark sector** particles:
 - two dark matter states, χ_1 and χ_2 , with a small mass splitting Δm_χ
 χ_1 is stable (relic candidate) while χ_2 is long lived
 - a dark photon A'
 A' mixes with the SM photon at a strength ϵ and couples to DM with α_D
 - a dark higgs boson h'
 h' is long lived and mixes with the SM higgs at an angle θ

- **Strategy:** Search for a bump in the m_{inv} of the dark higgs in events with **up to two displaced vertices** and **missing energy**

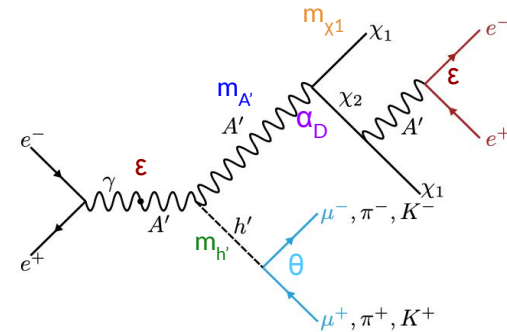
■ Selections

- Four tracks in the final state
 - 2 forming a displaced vertex **pointing back** to the IP (h')
 - 2 forming one **non-pointing** displaced vertex (χ_2)
- Probing lifetimes: $0.1 \text{ cm} < c\tau_{h'} < 10000 \text{ cm}$ and $0.01 \text{ cm} < c\tau_{\chi_2} < 1000 \text{ cm}$

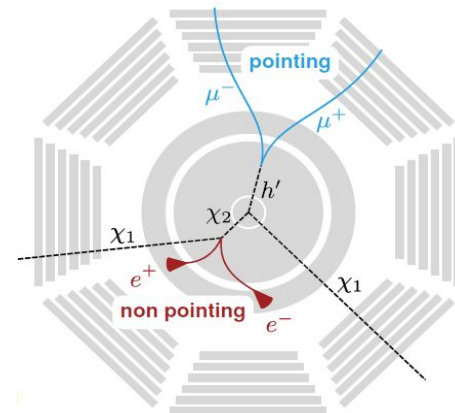
- Main SM background contribution from long-lived K_S^0 (mass region vetoed)

- **Signal extraction:** Cut-and-count technique due to low background levels

$$e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1e^+e^-)) \text{ where } x = \mu, \pi, K$$



7 parameters: $m_{A'}$, $m_{h'}$, m_{χ_1} , Δm_χ , θ , ϵ , α_D

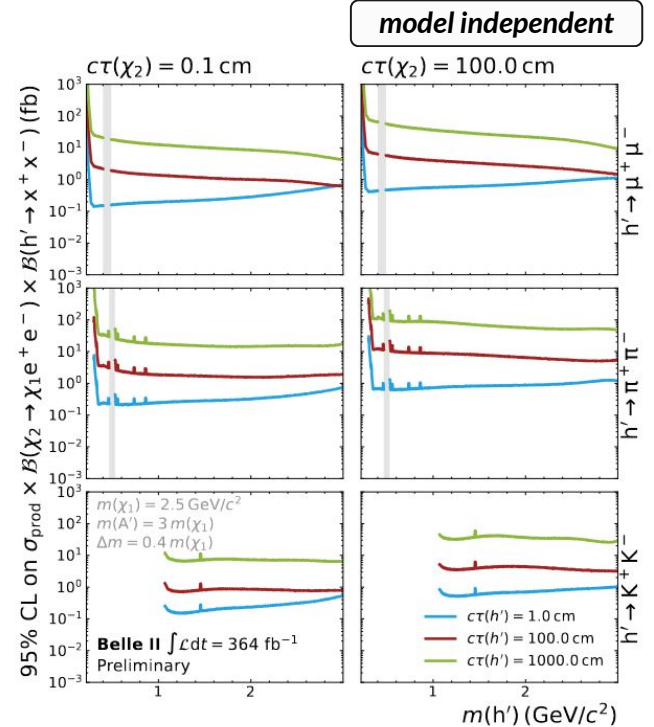
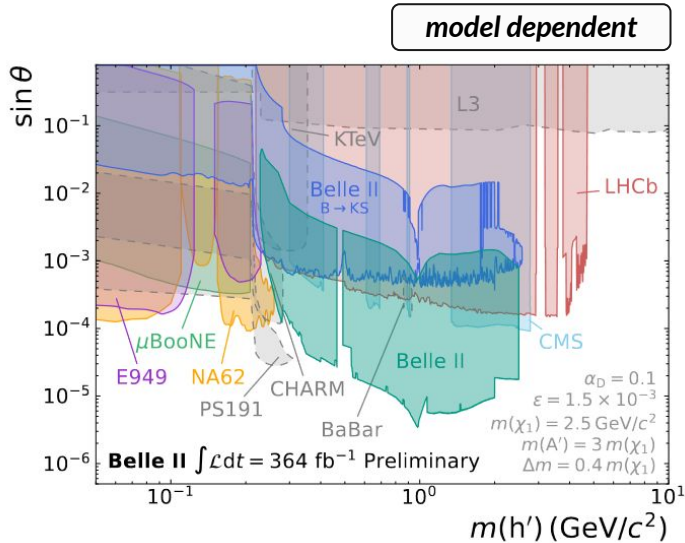


Search for inelastic dark matter and a dark Higgs boson

Preliminary results

- No significant excess found with $364 \text{ fb}^{-1} \rightarrow$ **95% CL upper limits** set on the cross section $\sigma(e^+e^- \rightarrow h' \chi_1 \chi_2)$ and the branching fractions $\mathcal{B}(\chi_2 \rightarrow \chi_1 e^+ e^-) \times \mathcal{B}(h' \rightarrow x^+ x^-)$ where $x = \mu, \pi, K$
- Results used to constrain the parameter space for the **sine of the mixing angle parameter θ** and the dark higgs mass $m(h')$

Probing **two orders of magnitude more in $\sin\theta$** than other experiments \rightarrow Excluding a region of parameters previously not-covered



Summary

- B-factories provide unique opportunities to explore the dark sector and study light dark matter/mediators
Excellent sensitivity, complementary to that of higher-energy experiments

- Belle II has a wide DS physics program (*presented today*) *+ many more ongoing analysis!*

Z' searches: $\mu^+\mu^-$, $\tau^+\tau^-$, invisible

Inelastic DM and a dark Higgs boson

Light (pseudo) scalars in B-meson decays

ALP-strahlung: $e^+e^- \rightarrow \alpha\gamma$ where $\alpha \rightarrow \gamma\gamma$

Invisible α boson produced in a LFV tau decay

Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$ where $A' \rightarrow \mu\mu$, $h' \rightarrow$ invisible

- Providing world-leading results and competitive limits on several models, with a subset of the available data

Large potential for future DS searches:

- Higher luminosity
- New analysis techniques implemented
- New triggers for low multiplicity events and displaced topologies

Thank you for your attention

Backup

Phases of the Experiment

- Belle II's data taking timeline is separated into three phases.
- ❖ **Phase (2016) + Phase II (April - July 2018)** :
Dedicated to commissioning both the machine and the detector.

Collected **0.5 fb⁻¹** of data with an incomplete vertex detector (VXD).
- ❖ **Phase III (March 25, 2019 - Now)** : Beginning of a full-scale data collection
 - **Run I (2019-2022)**: Recorded a total of **427 fb⁻¹**
 - **Run II (January 2024-Now)**

The total luminosity collected by the experiment for

Run I and Run II amounts to **538.8 fb⁻¹**

