

Recent results on dark sector searches at Belle II

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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

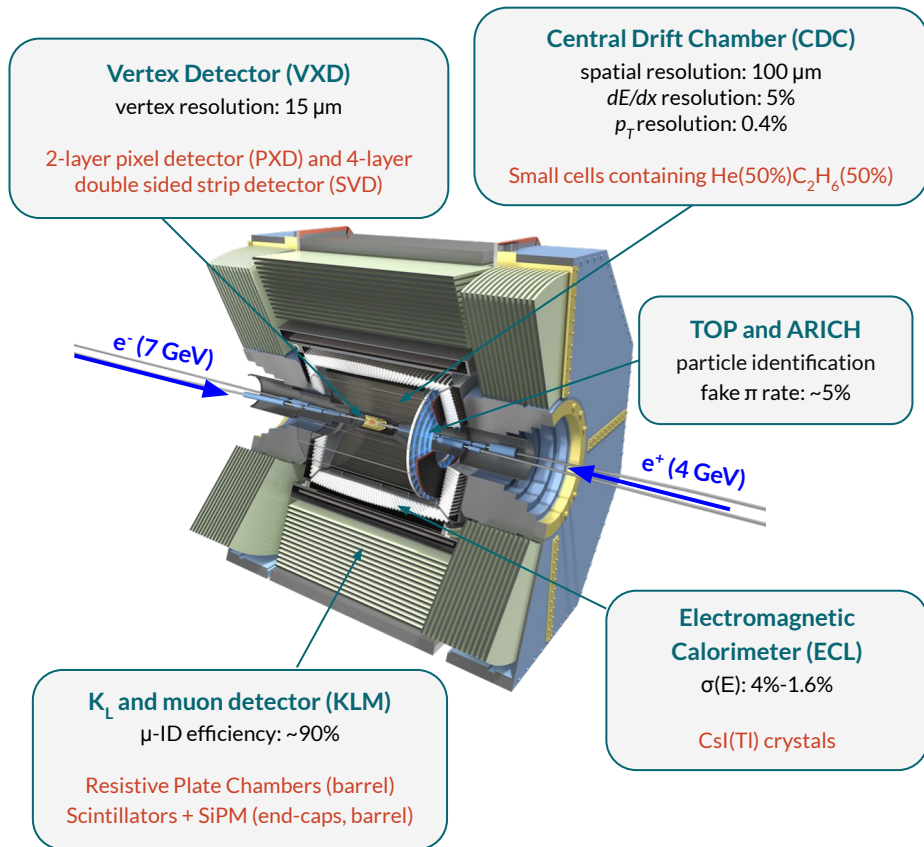
The Belle II experiment

Overview

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

Data taking status

- Run I (2019-2022) + Run II (February 2024-Now):
Recorded a total luminosity of more than 544 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 x Belle dataset!)

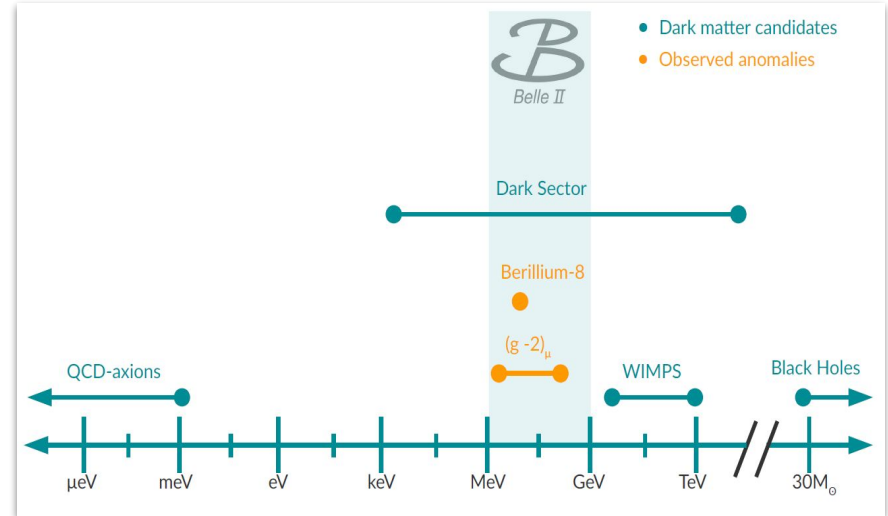


See talks by [M.Mantovano](#), [A.Gaz](#), [L.Zani](#) and [D.Gosh](#) for more information

Dark sector searches at Belle II

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

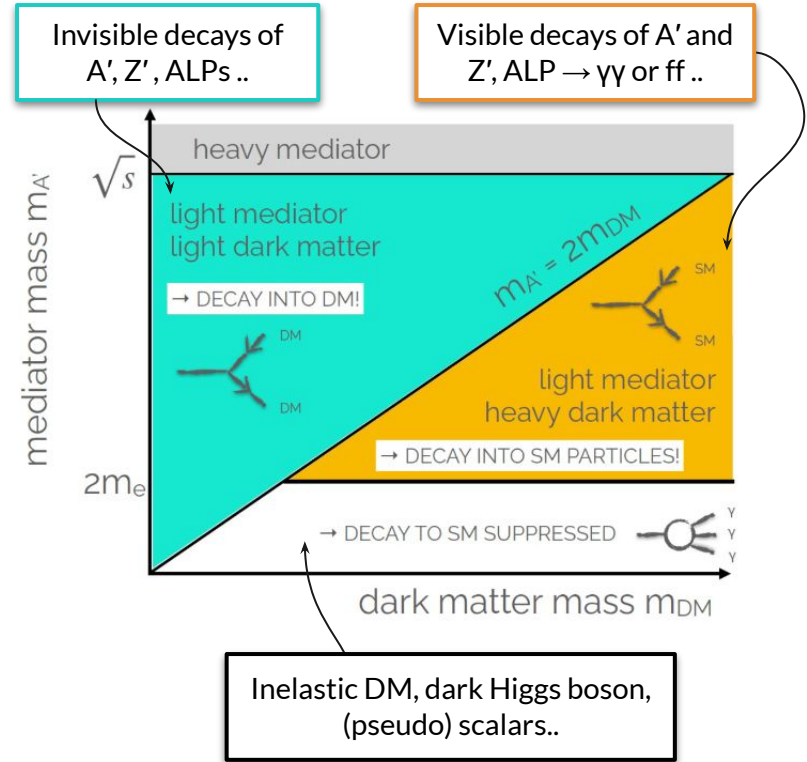
- Large potential for dark matter (DM) discoveries:
- Utilizing the advantages of B factories
 - **High luminosity:** $\mathcal{L} > 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - **Well defined initial state:** $E_{\text{CMS}} = 2 \times E_{\text{beam}}$
 - **Clean environment with low background**
 - **Hermiticity (4 π detectors):** excellent particle identification (PID) performance
- Dedicated **triggers for low multiplicity** final states: 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**, both crucial in DM detection and 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



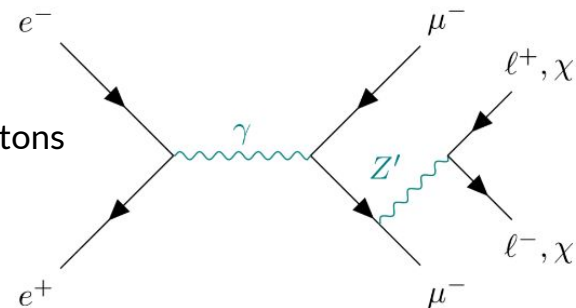
Recent results on dark sector searches

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



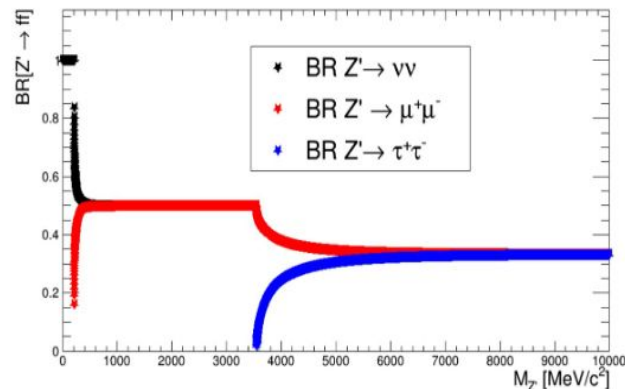
- Possible decays and signatures

- **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](#))

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

Constrained by Belle II ([2023](#)), BESII([2024](#)), NA64-e ([2022](#)) and NA64-mu ([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

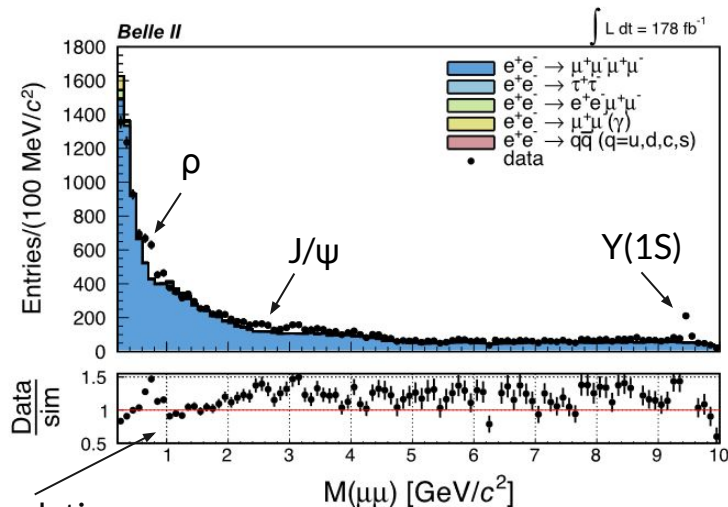
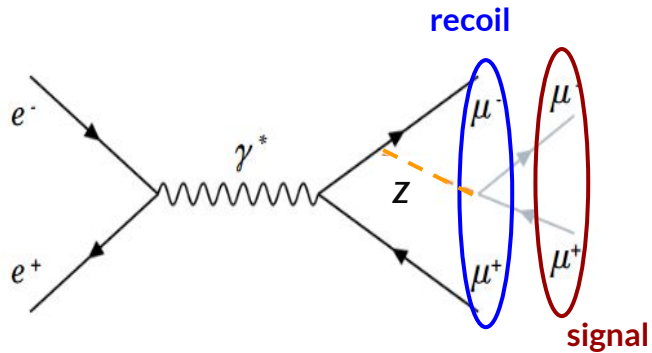
Signal signature is a narrow peak in the mass distribution of oppositely charged muons $M(\mu\mu)$

■ Selections

- Events with **4 tracks** in the final state:
 - At least three identified as muons
 - $m_{inv}(4 \text{ tracks}) \sim \sqrt{s}$
 - Zero net charge and no extra energy

- **Main SM background:** $e^+e^- \rightarrow \mu^+\mu^- \mu^+\mu^-$ events

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



No ISR effects included in the MC simulation

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

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

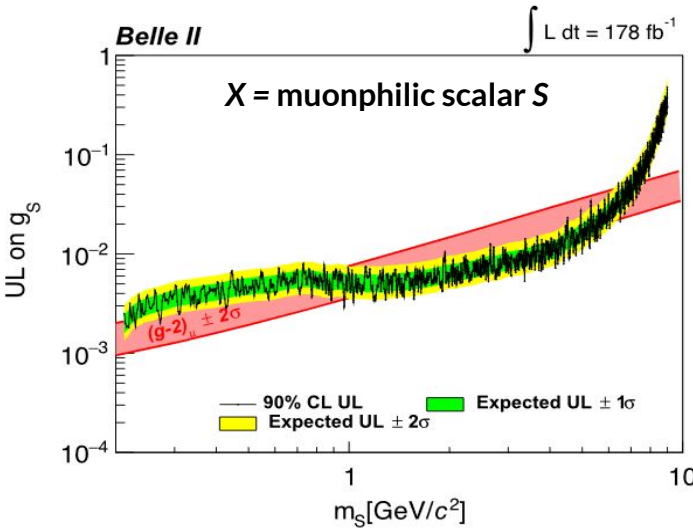
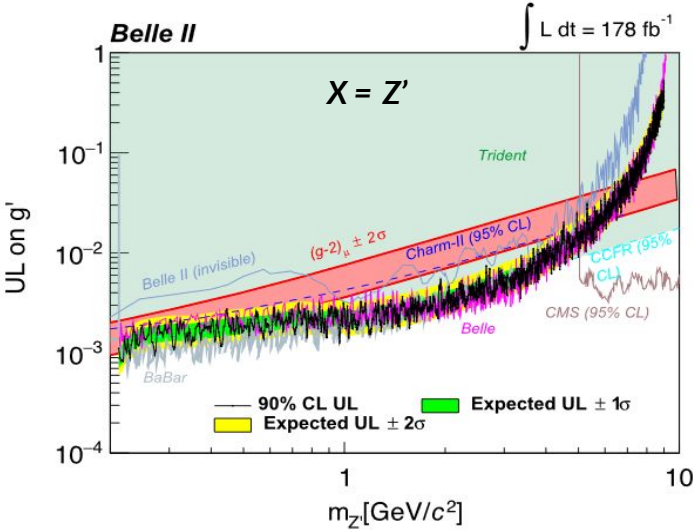
- No significant excess found with $178 \text{ fb}^{-1} \rightarrow$ **90% CL upper limits** set on the cross sections for the processes

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

Reinterpreted also as **muonphilic dark scalar S**.
Efficiency is *re-evaluated* for the new model

Results translated into upper limits on the coupling constant:

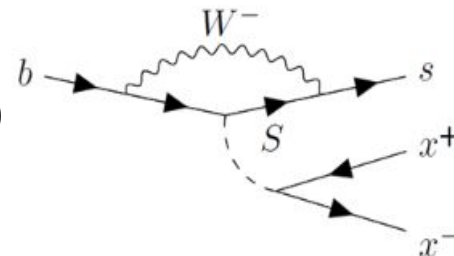
- g' for the Z' ($L_\mu - L_\tau$ model) \rightarrow **Competitive results** with BaBar ($> 500 \text{ fb}^{-1}$) and Belle ($> 600 \text{ fb}^{-1}$)
- g_s for the **muonphilic scalar model (S)** \rightarrow **First limits** set on S from a dedicated search



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

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

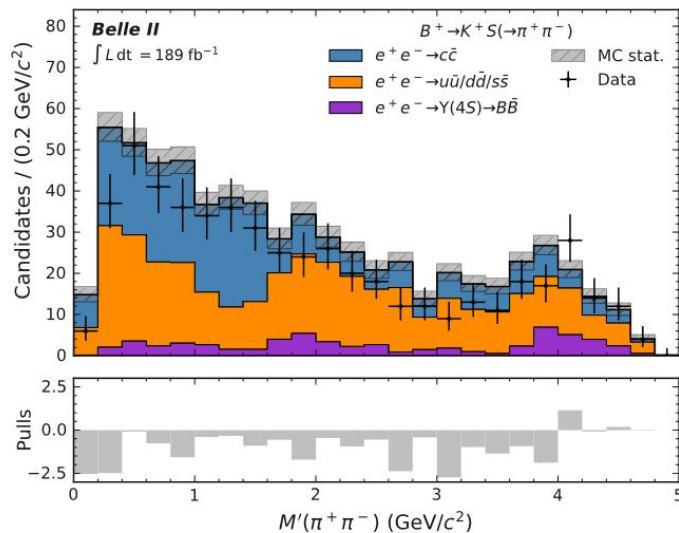
- A light scalar S mediator could be produced in $b \rightarrow s$ quark transitions:
 S may interact with SM Higgs boson through a mixing angle θ (naturally long lived for small θ)
- **Strategy:** Search for a bump in the m_{inv} of tracks coming from a **displaced vertex** accompanied by a **charged K**



→ Look for S decays into SM in **8 different channels:**

$$\left. \begin{array}{l} B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^+) S \\ B^+ \rightarrow K^+ S \end{array} \right\} S \rightarrow x^+ x^- \text{ where } x = e, \mu, \pi, K$$

- **Selections**
 - Fully reconstructed B decay
 - Long-lived K_S^0 mass region vetoed
 - Probing different lifetimes for S
- **Main SM background:** combinatorial $e^+e^- \rightarrow q\bar{q}$ events
- **Signal extraction:** Maximum likelihood fits to the reduced invariant mass



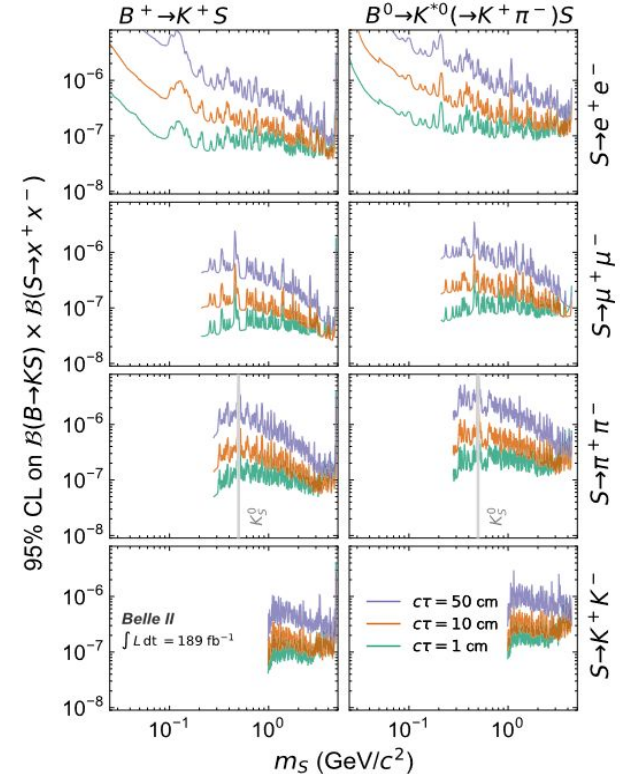
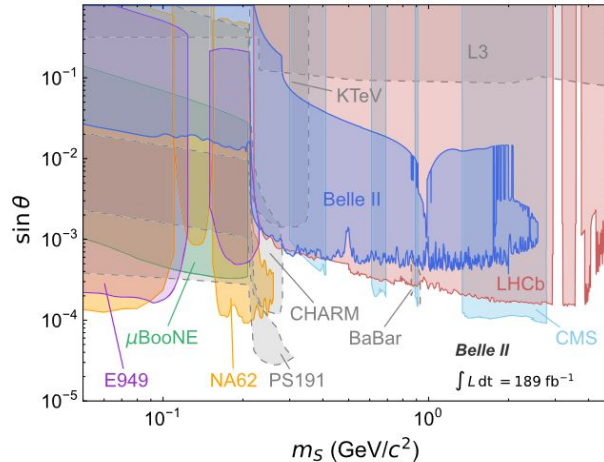
Search for light (pseudo) scalars in B-meson decays

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 sections

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

- **First limits** set on S on **exclusive hadronic final states** and for e^+e^- final states
- Reinterpreted also as an axion-like particle (ALP)
- 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

- 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)
 - χ_2 is long lived (mixing with the γ_{SM} at strength ϵ)
 - a dark photon A' and a dark higgs boson h'
 - h' is long lived (mixing with the h_{SM} 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

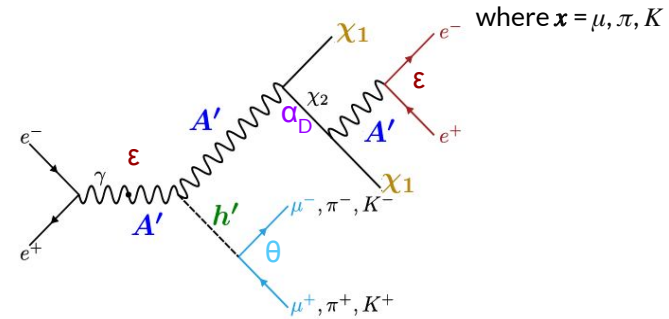
Selections

- 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 different lifetimes for h' and χ_2

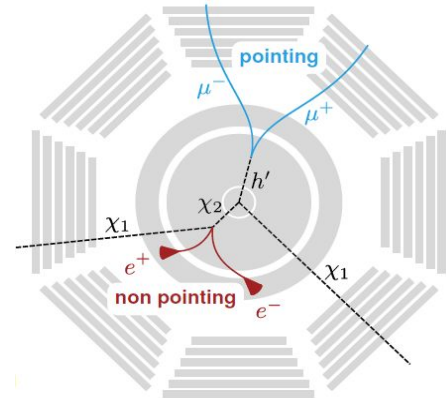
- Main SM background: long-lived K_S^0 (mass region vetoed)

- Signal extraction: Cut-and-count technique (low background levels)

$$e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1e^+e^-))$$



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



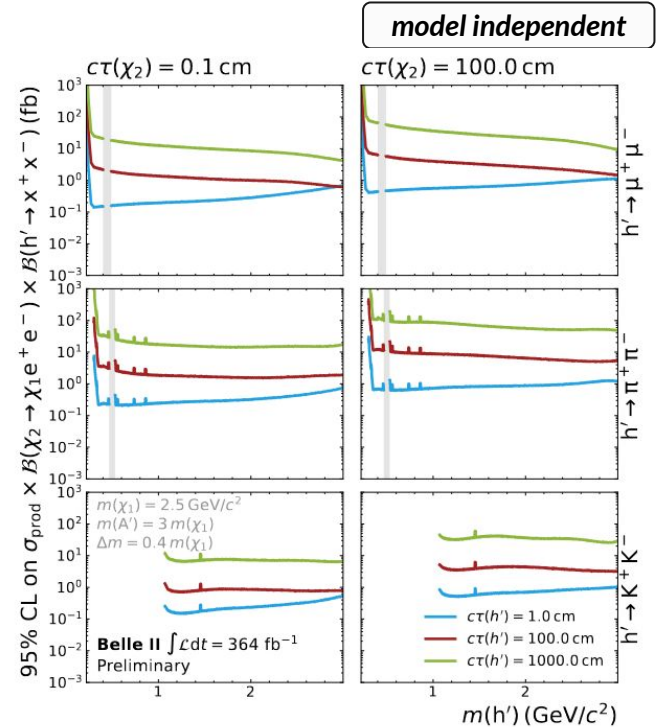
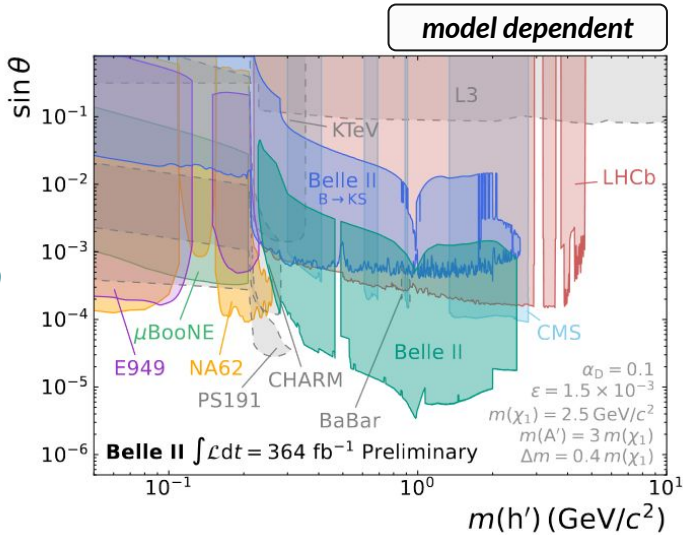
Search for inelastic dark matter and a dark Higgs boson



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 **2 orders of magnitude** more in $\sin\theta$ than other experiments



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' decay into $\mu^+\mu^-$

Light (pseudo) scalars in B-meson decays

Inelastic DM and a dark Higgs boson

Z' decay to $\tau^+\tau^-$ [[PRL](#)]

ALP-strahlung [[PRL](#)]

Z' decay to invisible [[PRL](#)]

Dark Higgs-strahlung [[PRL](#)]

Invisible ALP in LFV tau decays [[PRL](#)]

- 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

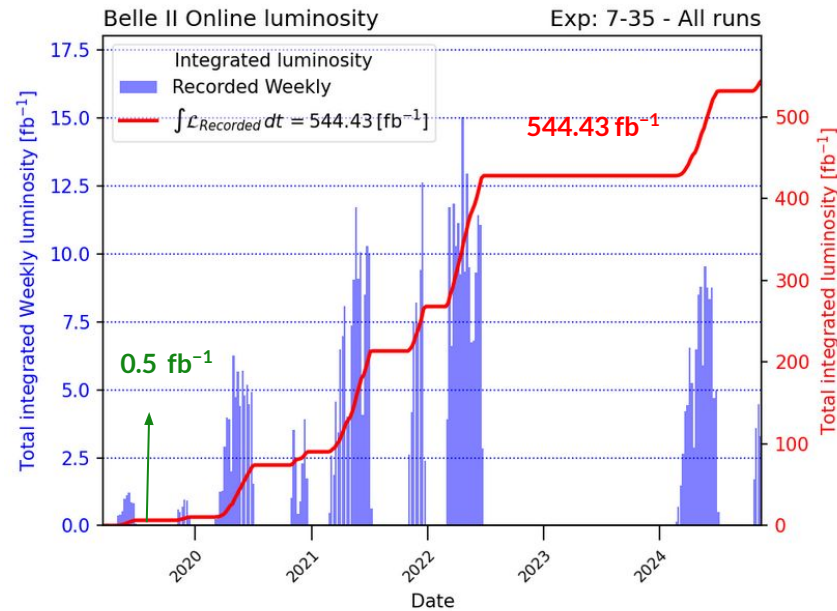
Phases of the Experiment

- 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)**

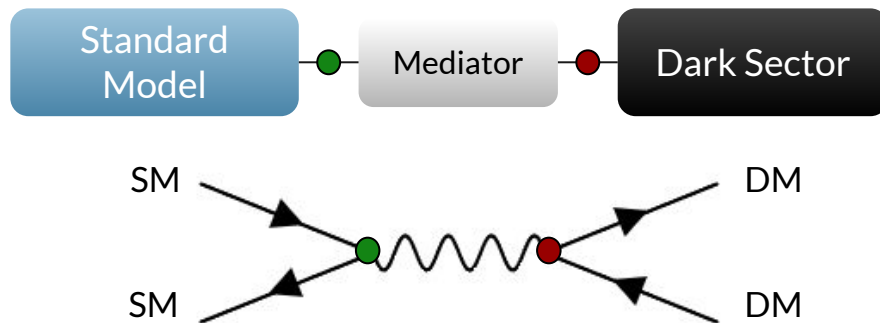
The total luminosity collected by the experiment for

Run I and Run II amounts to **544.43 fb⁻¹**



The Dark Sector

- Dark matter could be part of a larger hidden/dark sector, a collection of yet-unobserved quantum fields and their corresponding hypothetical particles.
- Dark sector and SM may interact **very weakly via subtle mixing** through **portals**, with particles mediating non gravitational interactions between them.
 - **Vector portal** → Dark photon A' , Z'
 - **Scalar portal** → Dark Higgs h' or new scalar particles S'
 - **Pseudo-scalar portal** → Axions & axion-like particles (ALPs)
 - **Neutrino portal** → Sterile neutrinos N



Strong motivation:

- Absence of light dark matter and light mediators discoveries in the electroweak scale ($M_{DM} \sim O(\text{MeV} - \text{GeV})$), despite extensive searches at the Large Hadron Collider (LHC) or non-collider searches.
- Could provide insights into certain anomalies in particle physics such as the muon's anomalous magnetic moment $(g-2)_\mu$