Dark sector searches at Belle II

International Conference on Neutrino and Dark Matter - NuDM2024

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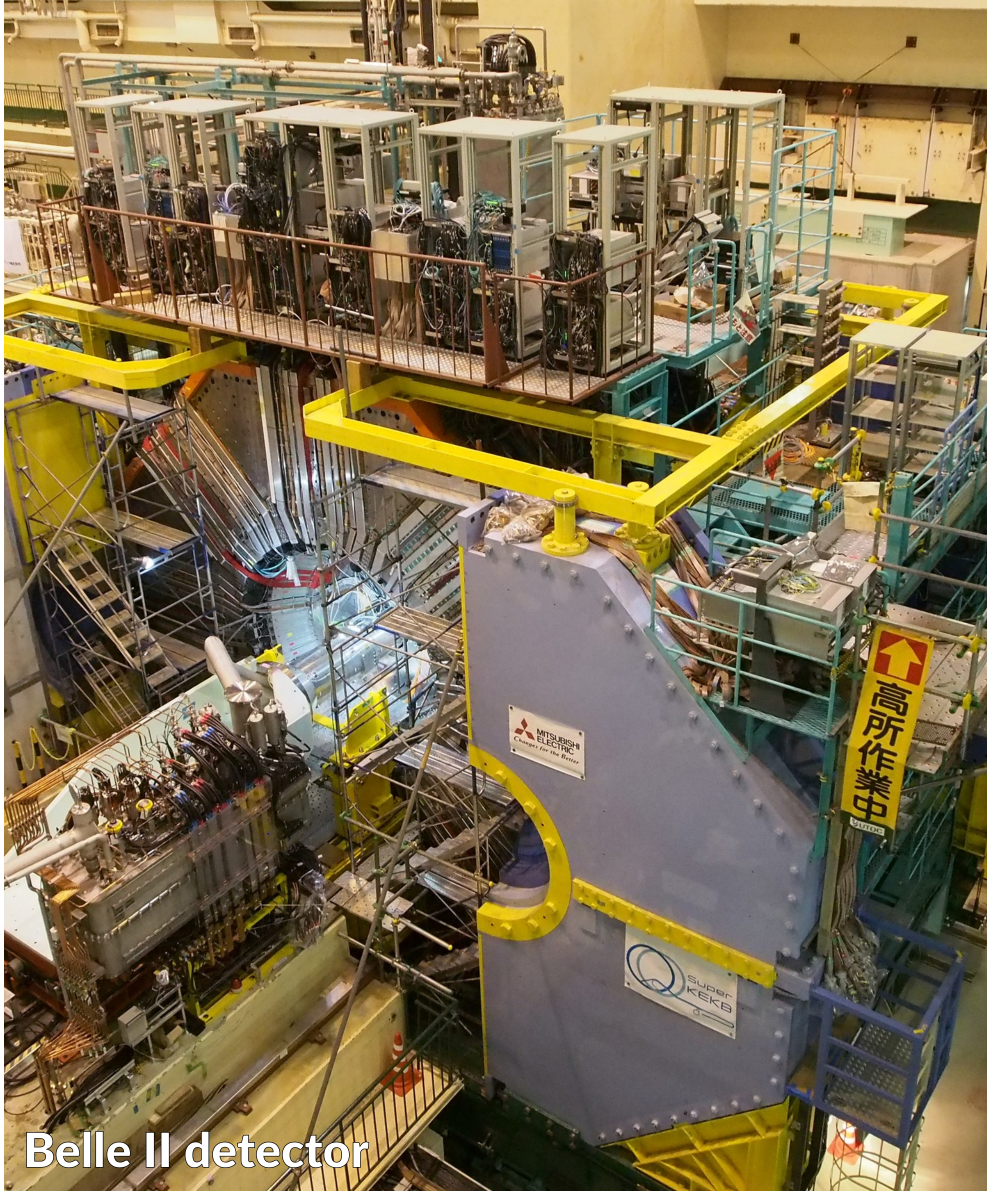
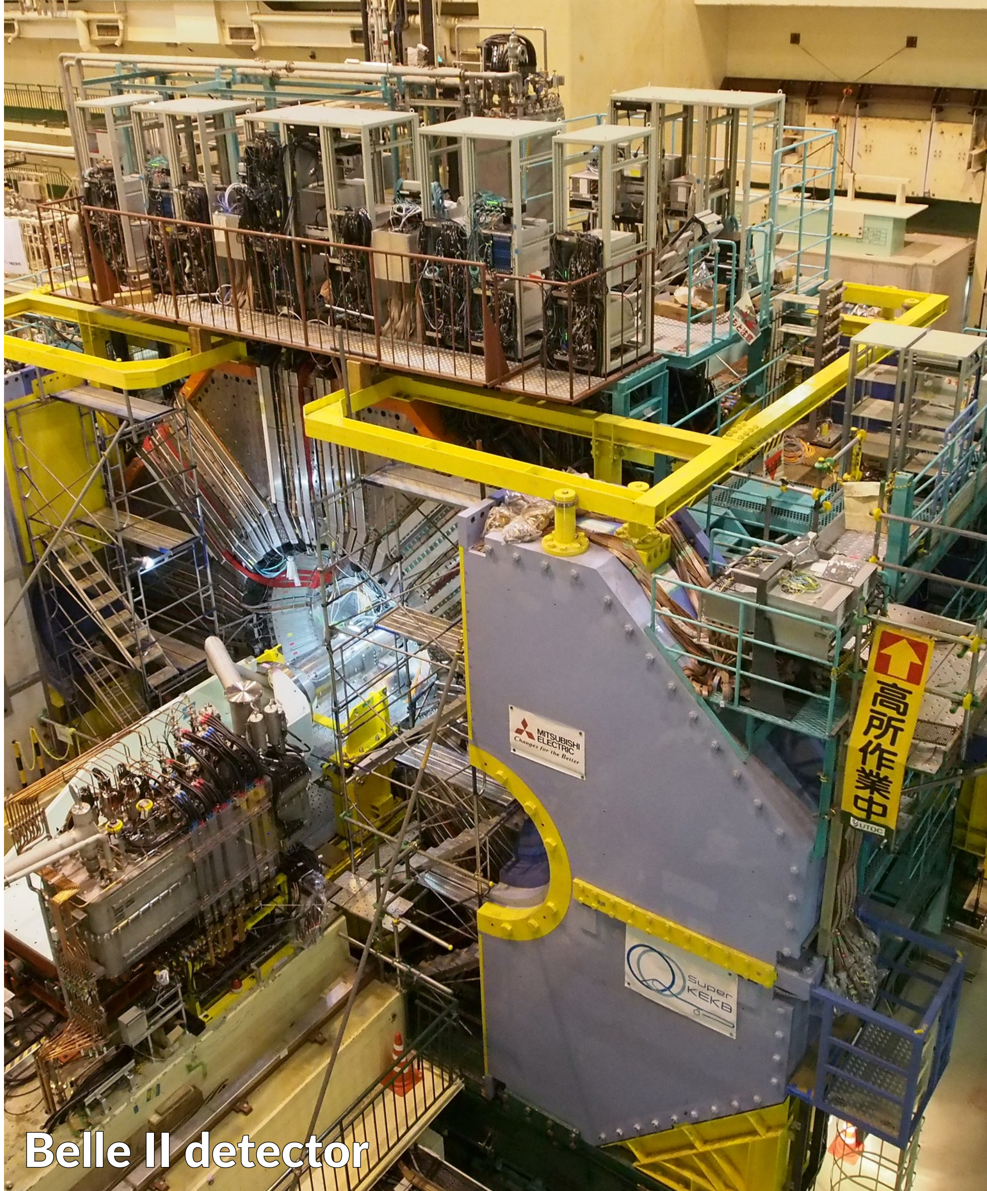
Outline

- Introduction to dark sectors
- Introduction to the Belle II experiment
- Overview of recent dark sector searches at Belle II
- Summary and Conclusions



Belle II detector

Introduction to dark sectors



Belle II detector

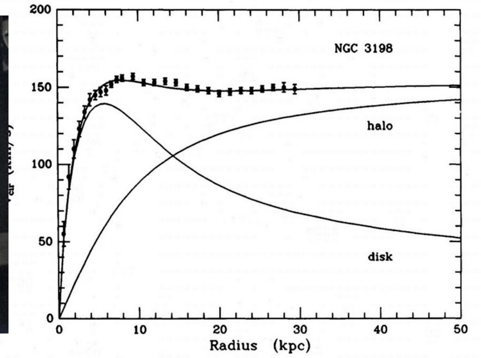
Evidences of dark matter

Many **astrophysics** and **cosmological observations** provide evidences for dark matter existence

- Flat rotational curves of galaxies
  - First **evidence of unseen mass**
- Gravitational lensing
- Cosmic Microwave Background anisotropy

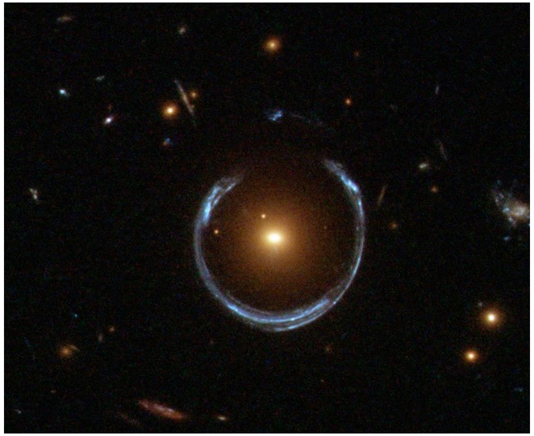
F. Zwicky in 1930s

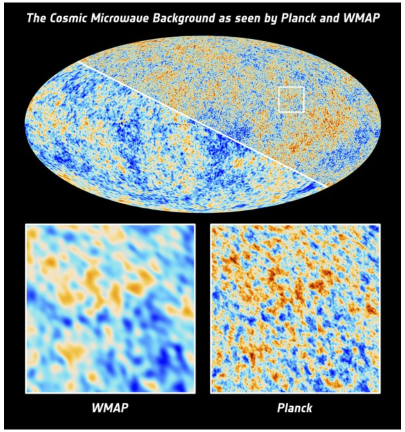
V. Rubin in 1970s



DM nature is unknown

- It is one of the most compelling phenomena in support for physics beyond the Standard Model
- Awaiting for discovery

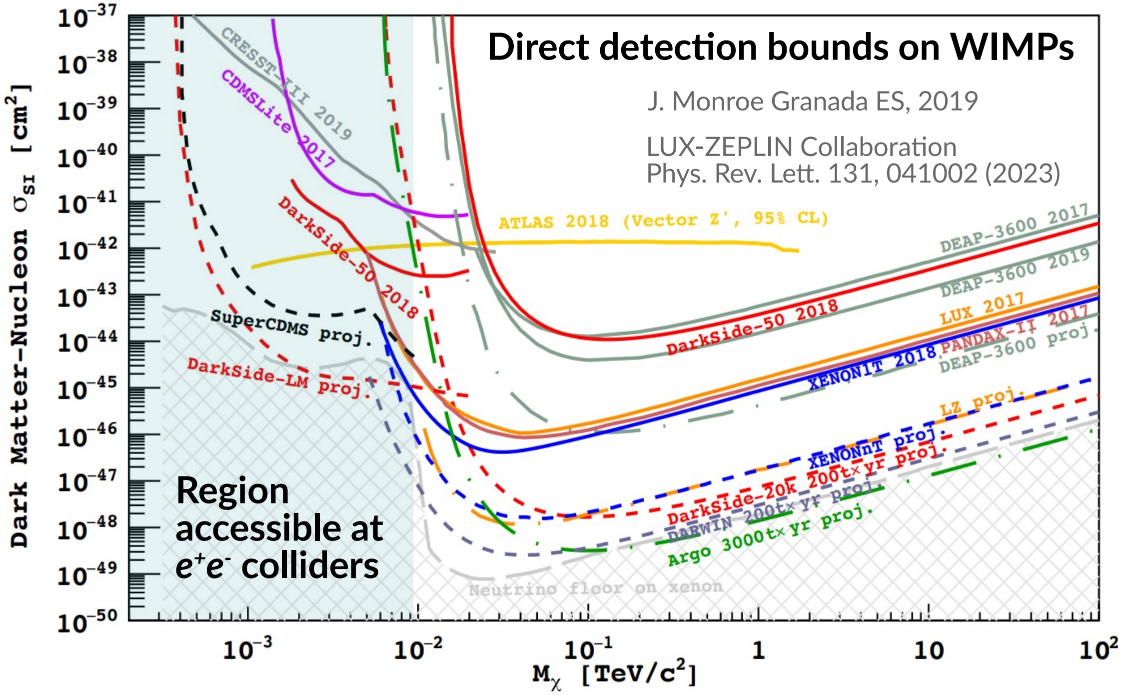




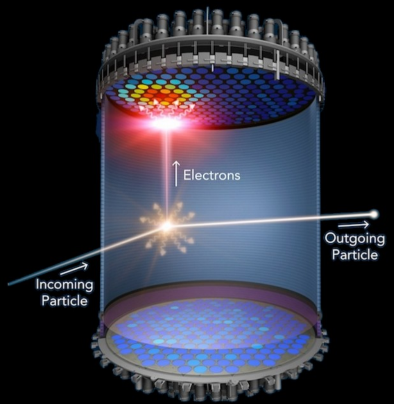
Dark matter searches

If DM weakly couples to SM particles, it can be produced in SM particles annihilation at accelerators

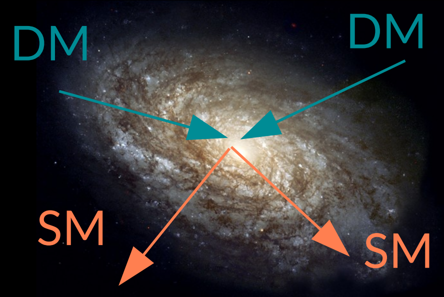
→ **Involve dark sector mediators**



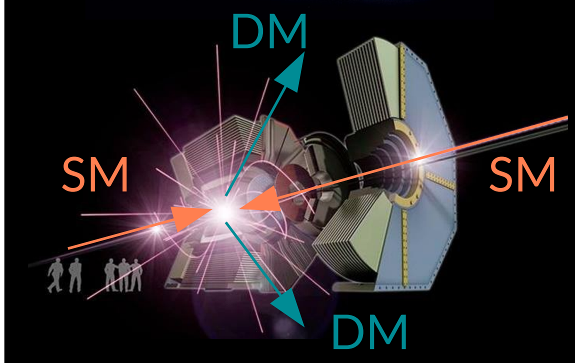
Direct detection



Indirect detection

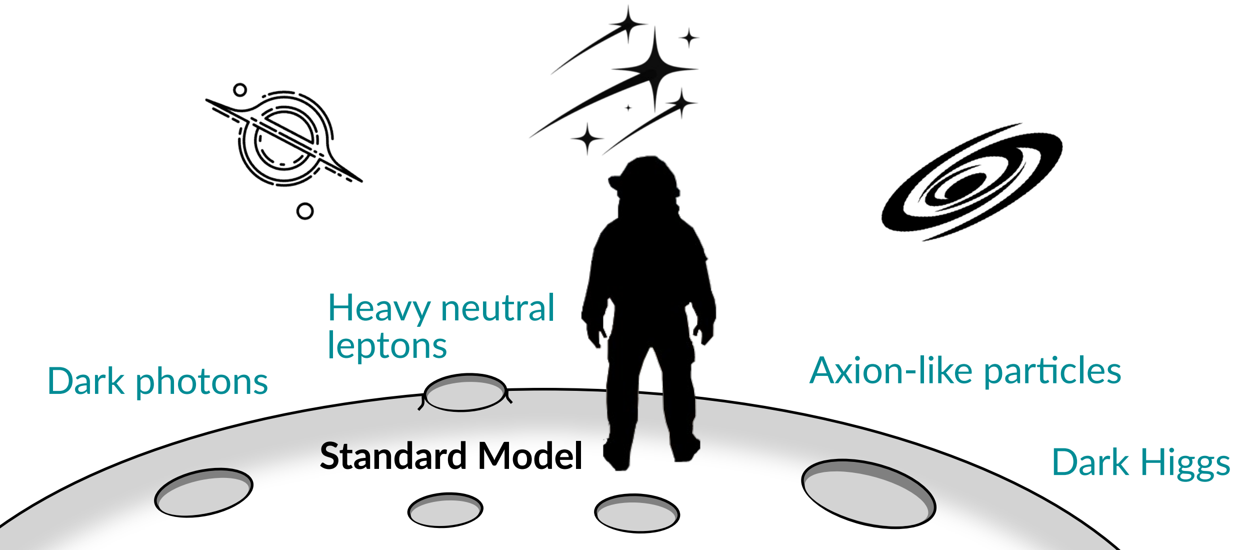


Colliders

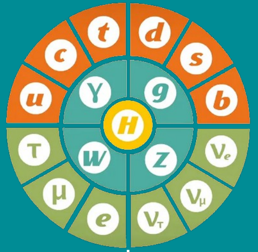


Dark sector landscape

- No evidence of DM at electro-weak scale in experiments
  - Light DM with **M ~ $\mathcal{O}$(MeV-GeV)** well motivated
    - They may **solve "DM puzzle"** and **explain observed anomalies** like the $(g-2)_\mu$
- **Light dark mediators** involved in the DM interaction with SM
  - "**portals**" of interaction



"Portals" of interaction



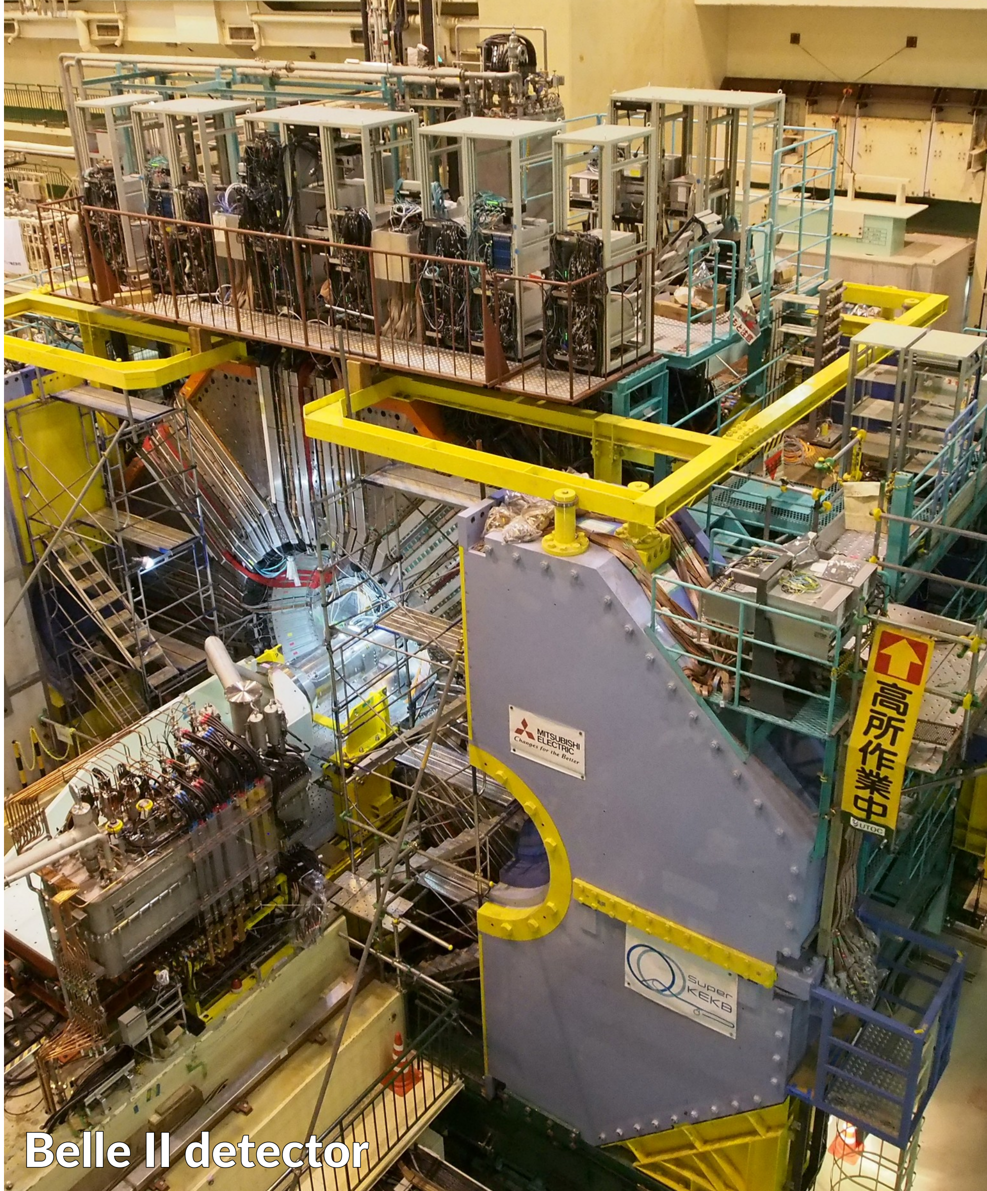
$$\mathcal{L}_{\text{vector}} \sim \varepsilon F^{\mu\nu} A'_{\mu\nu}$$

$$\mathcal{L}_{\text{scalar}} \sim |H|^2 \left(\kappa S + \lambda S^2\right)$$

$$\mathcal{L}_{\text{fermion}} \sim yHLN$$

$$\mathcal{L}_{\text{pseudo-scalar}} \sim \frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a + \ldots$$

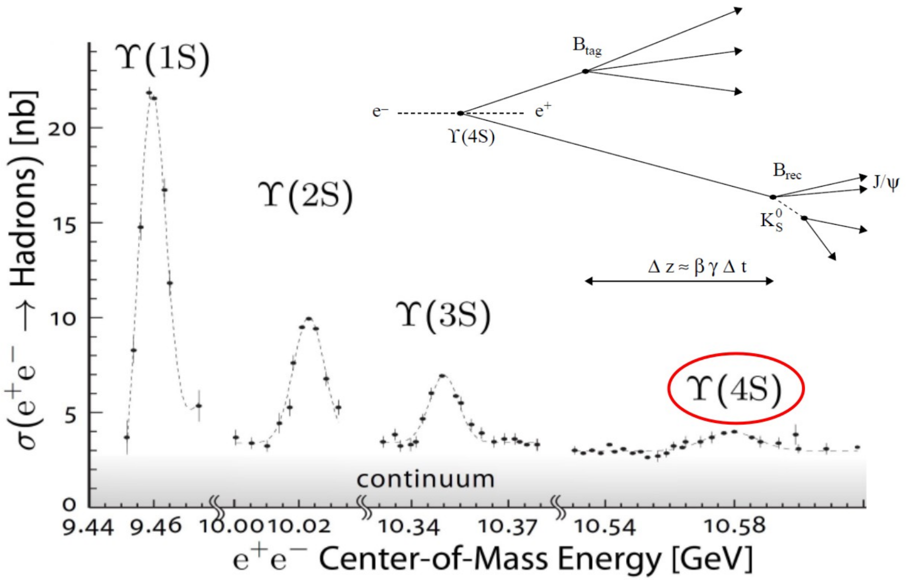
The Belle II experiment



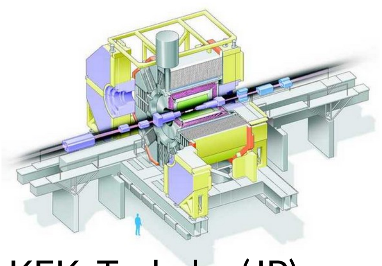
Belle II detector

B-factories

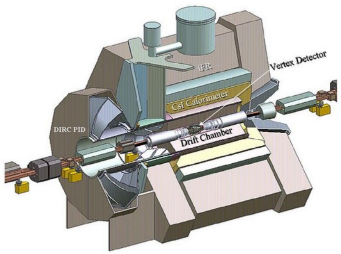
- **Asymmetric e^+e^- colliders** optimized for the production of *B* meson pairs, but also *D* mesons, *τ* leptons, …
- **Collisions occur at Υ(nS) resonances**
  - ➔ Mainly at Υ(4S): √s = 10.58 GeV
    just above the production threshold of $B\overline{B}$
    BR(Υ(4S) → $B\overline{B}$) > 96%
- **Asymmetric beam energies**: boosted $B\overline{B}$ pairs, for CP-violation time-dependent measurements
- **High peak luminosity** $L > 10^{34}$ cm^{-2}s^{-1}



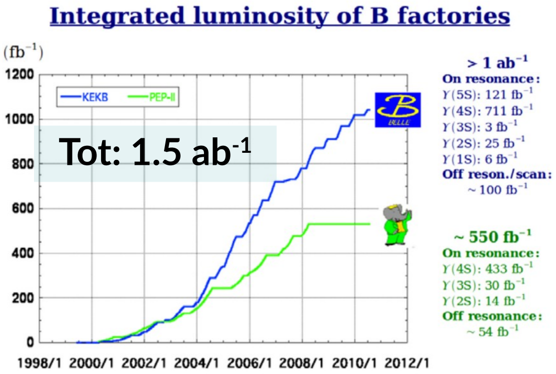
First generation of *B*-factories



Belle@KEKB, KEK, Tsukuba (JP)
1999–2010, $\int L\,dt$ = 1 ab^{-1}

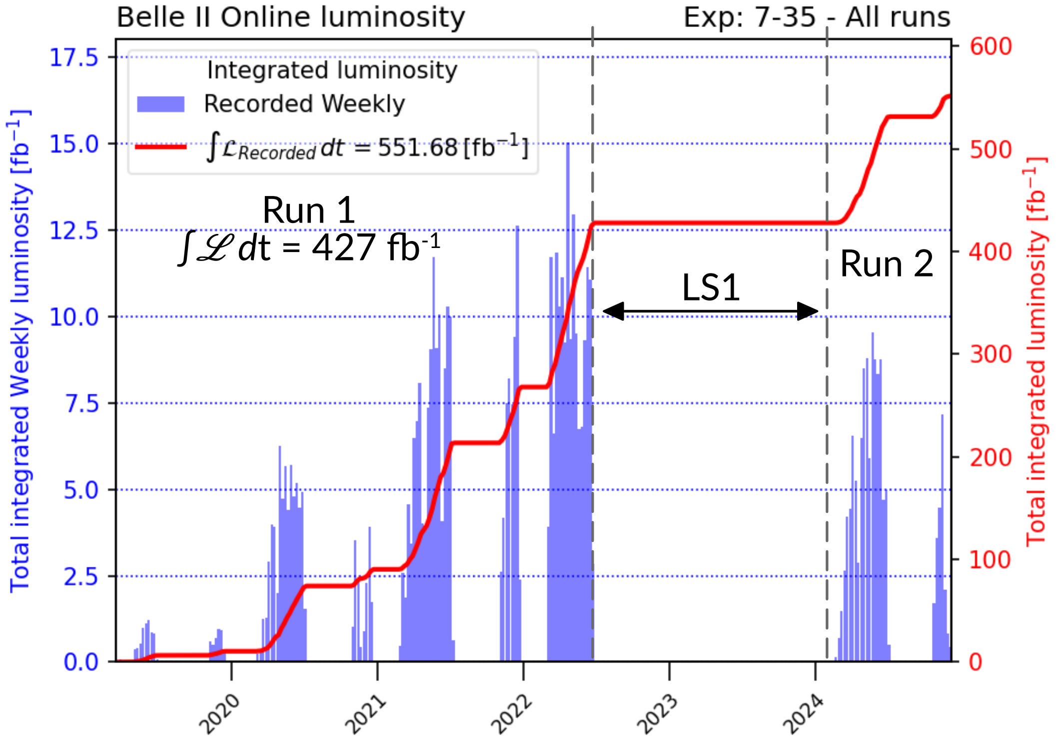


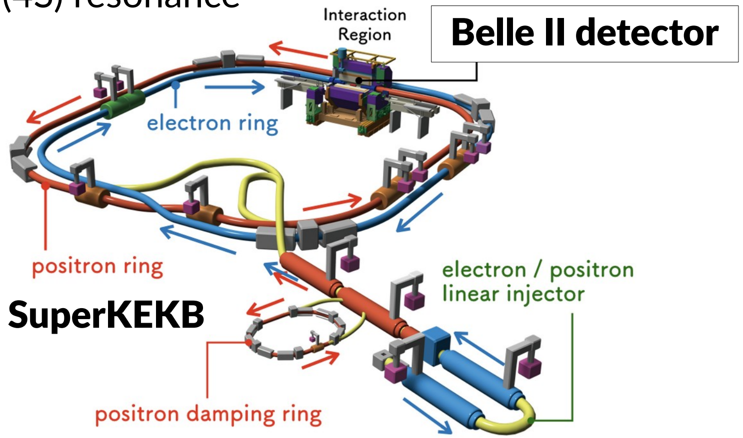
BaBar@PEP-II, SLAC (USA)
1999–2008, $\int L\,dt$ = 0.5 ab^{-1}



The Belle II experiment at SuperKEKB

- **Belle II** Luminosity-frontier experiment that **searches for physics beyond the Standard Model**
- **SuperKEKB** Asymmetric **e^+e^- collisions** mainly at **10.58 GeV**, i.e. at the Υ(4S) resonance





- **Long-shutdown (LS1)** Several accelerator and detector maintenance and improvements

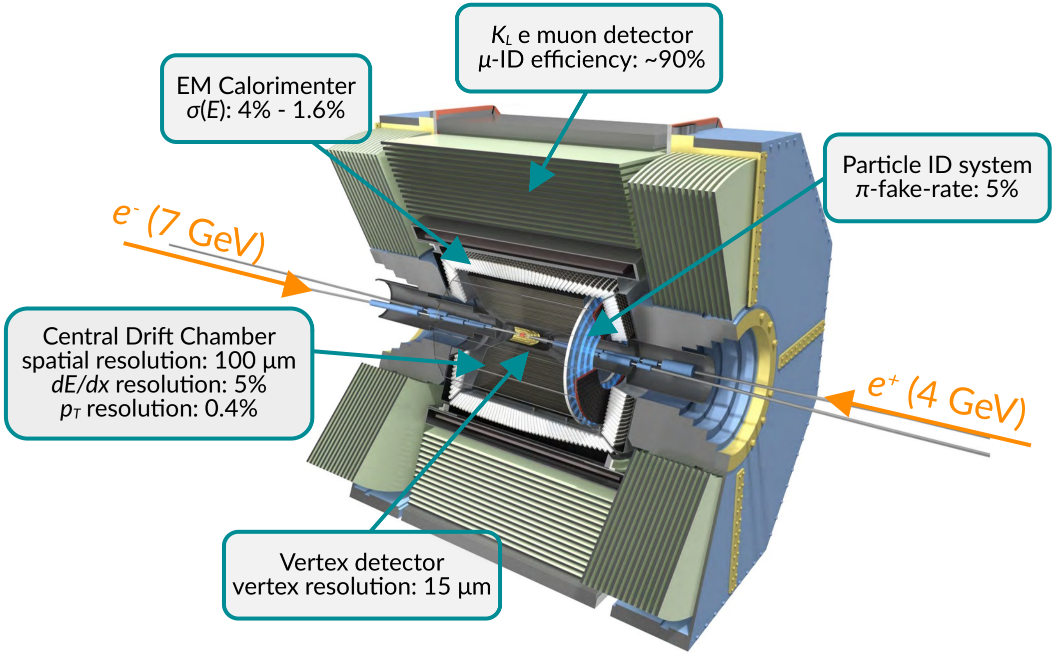
High luminosity

Target	Achieved
$\int \mathscr{L} dt$ = 50 ab^{-1}	$\int \mathscr{L} dt$ > 550 fb^{-1}
$\mathscr{L}_{peak}$ = 6 x 10^{35} cm^{-2}s^{-1}	$\mathscr{L}_{peak}$ = 4.7 x 10^{34} cm^{-2}s^{-1}

Belle II Physics Book, PTEP 2019 12 (2019)

The Belle II experiment at SuperKEKB

- **Belle II** Upgrade of Belle at KEKB → **Hermetic detector** with excellent particle identification (PID) performance
- **Well known initial-state condition** (e^+e^- collisions)
- **Clean environment** with low background
- **Dedicated low-multiplicity triggers**
  - Suppress high-cross-section QED processes **without "killing" the signal**
  - **Precise knowledge of acceptance and efficiencies of the detector required**
  - Example: single-photon trigger available in the full collected data set → makes Belle II dataset unique



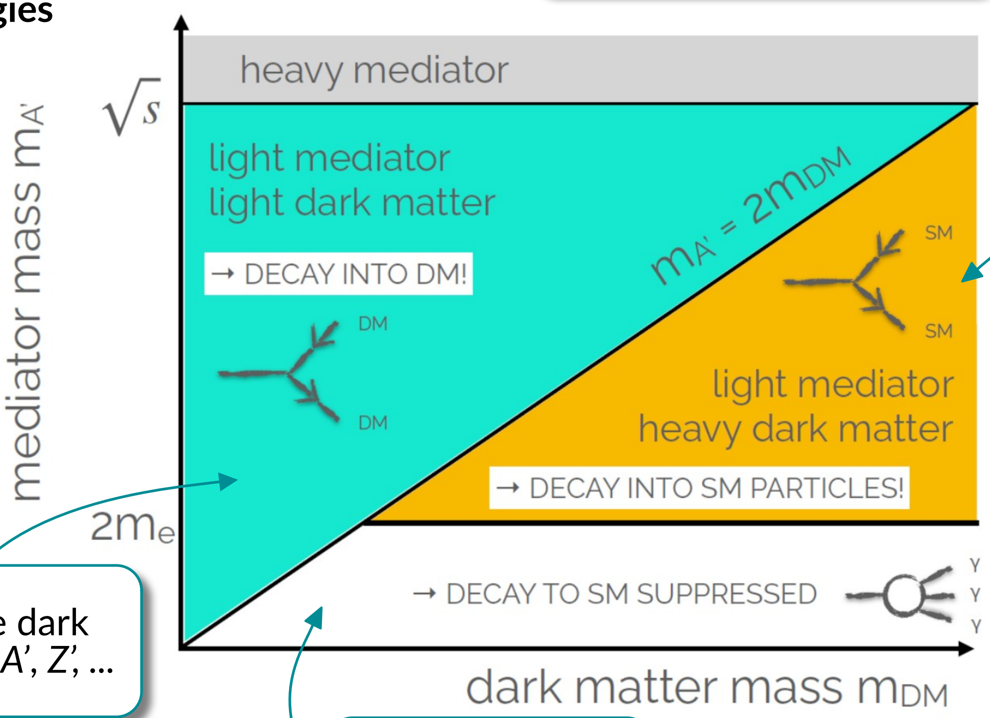
Excellent reconstruction capabilities for low multiplicities and missing energy signatures

Belle II Physics Book, PTEP 2019 12 (2019)

Dark sector experimental signatures

- The **relationship between mass of the mediators** and **mass of DM candidates** leads to **different topologies**
- **Negligible interaction probability of DM** with the detector
  - Search for final states with **missing mass**
  - Search for **mediators** (**visible** or **invisible**)
  - Search for both
- In models where decay to SM is suppressed
  - **Long-lived mediators**
- **Belle II** Sensitive in **M ~ $\mathcal{O}$(MeV-GeV)**
  - Search for **dark sector particles** produced **in e^+e^- annihilations** or **in rare meson decays**

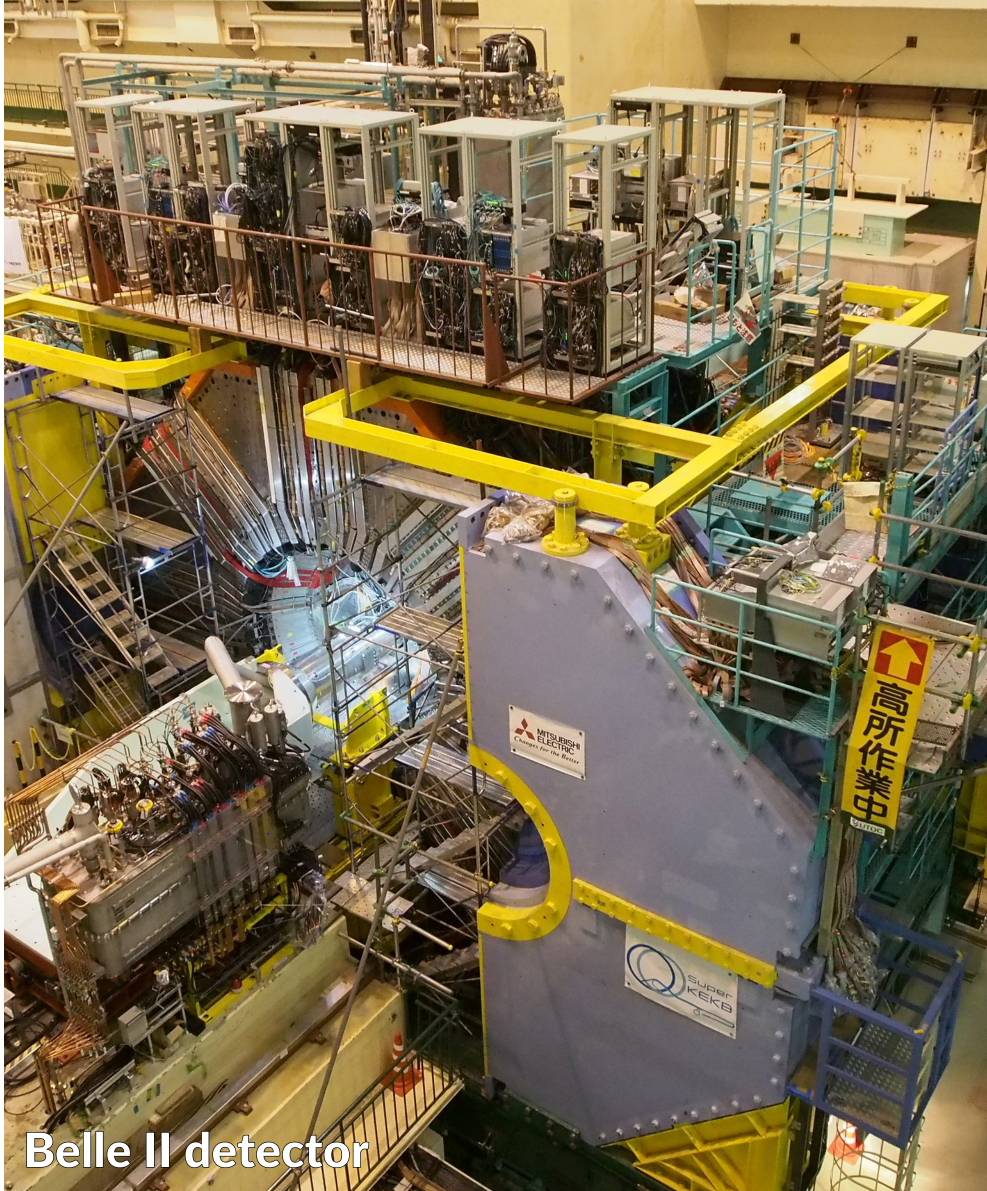
Visible dark photon *A’*, *Z’*, *ALP* → *γγ*, *ALP* → *ff*, ...



Invisible dark photon *A’*, *Z’*, ...

Inelastic DM, scalars, *h’*, ...

Exploring the dark sectors at Belle II

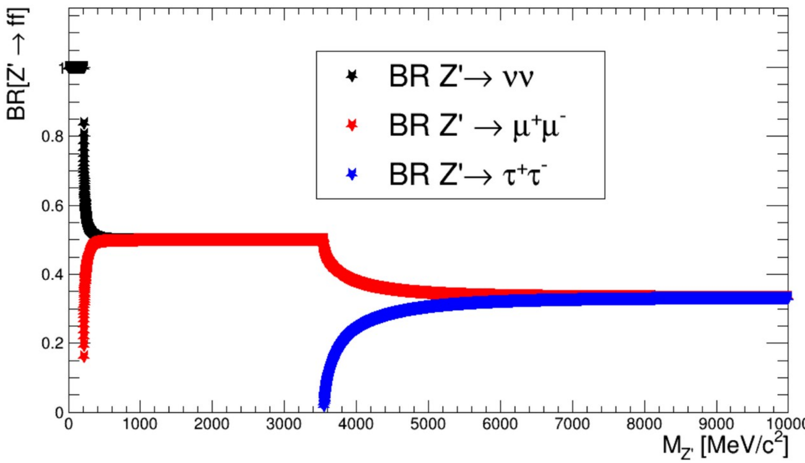


Search for Z' bosons

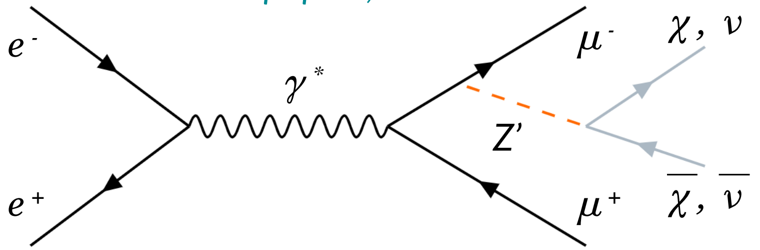
Shuve et al., Phys. Rev. D 89 , 113004 (2014)
D. Curtin et al., JHEP 02 (2015) 157
Altmannshofer et al., JHEP 106 (2016)

- **Massive Z' boson** with a **coupling g' only to leptons with μ- and τ-lepton numbers** → $L_\mu - L_\tau$ extension of the SM
  - It may explain $(g-2)_\mu$ anomaly and DM abundance
- Possible decays:
  - $Z' \to$ invisible ($\nu\bar{\nu}$ or $\chi\bar{\chi}$), $Z' \to \mu\mu$, $Z' \to \tau\tau$
- **$Z' \to$ invisible** ($Z' \to \nu\bar{\nu}/\chi\bar{\chi}$)
  - If light **DM χ kinematically accessible** exists, ***BR*($Z' \to$ invisible) = 100%**
  - Profit from the **excellent Belle II capabilities for missing energy signatures**
- Existing limits from BaBar (2016), CMS (2019), Belle II (2020), Belle (2022), BESIII (2024), NA64-e (2022), NA64-μ (2024), neutrino-nucleus scattering experiments (CCF, CHARM)

$L_\mu - L_\tau$ model Z' branching ratios in leptons



$e^+ e^- \to \mu^+ \mu^- Z', Z' \to$ inv.



Z' → invisible

I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

- Searched for through the process $e^+ e^- \to \mu^+ \mu^- Z', Z' \to$ **inv.**

- Signal signature is a **narrow peak in the recoil mass of the two final-state muons**

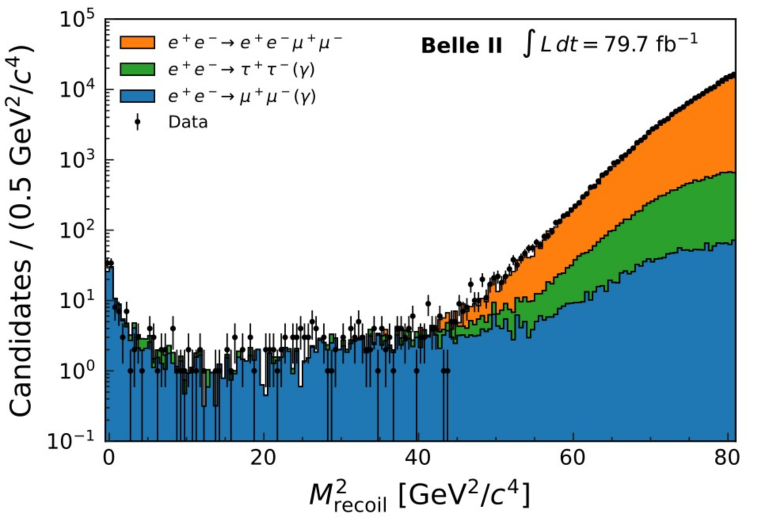
- Challenging $e^+e^- \to \tau^+\tau^- (\gamma)$ suppression tackled with **neural network** trained simultaneously on all Z' mass hypotheses

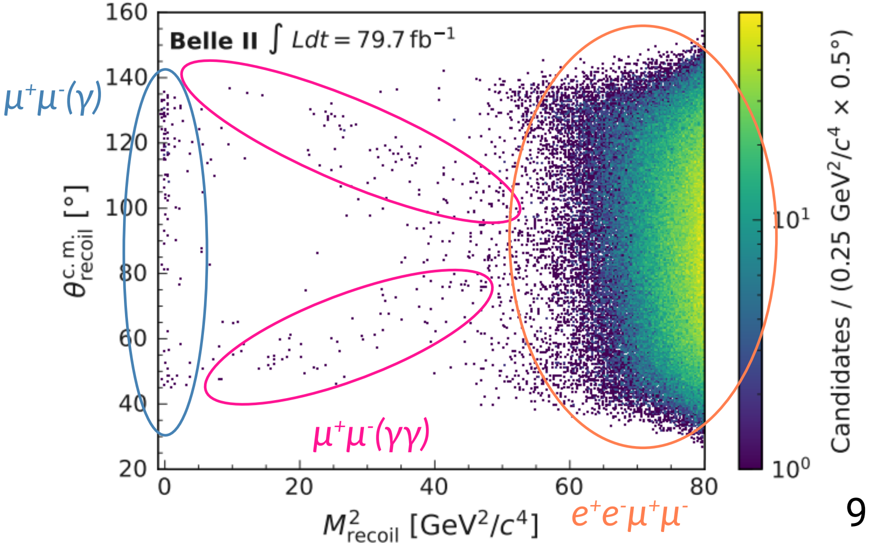
  F. Abudinén et al., Eur. Phys. J. C 82, 121 (2022)

  - Based on Z' property to be emitted as final state radiation (FSR) from one of the two muons in the final state
    - Different origin of missing energy with respect to main background components

- Signal extracted through **2D binned likelihood fit to** M^2_{recoil} **vs** θ^{CMS}_{recoil}

$$M^2_{recoil}(\mu\mu) = s + M(\mu\mu)^2 - 2\sqrt{s}(E^{CMS}_{\mu^+} + E^{CMS}_{\mu^-})$$



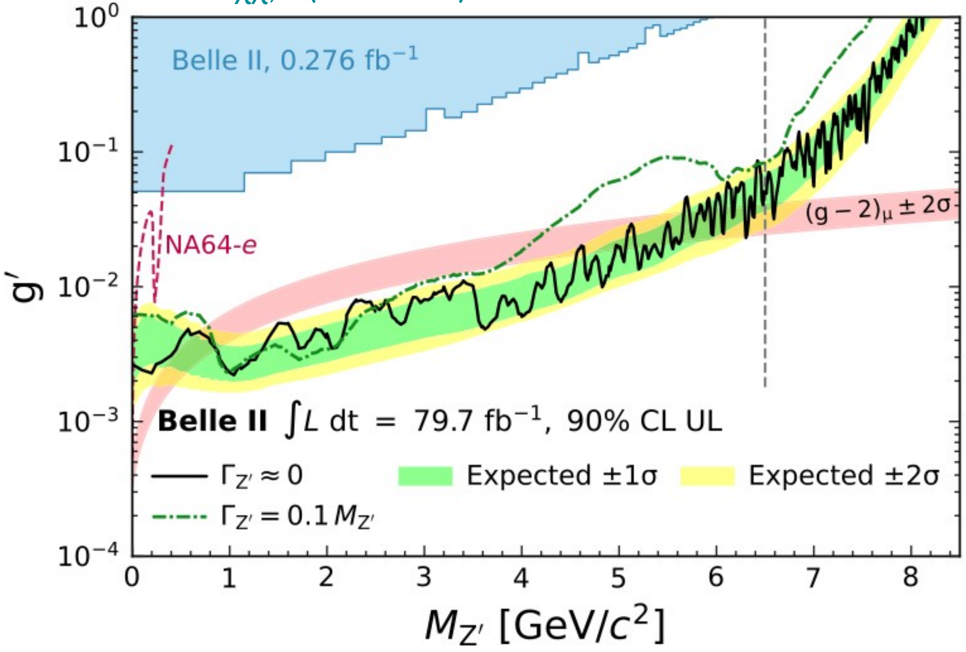


Z' → invisible

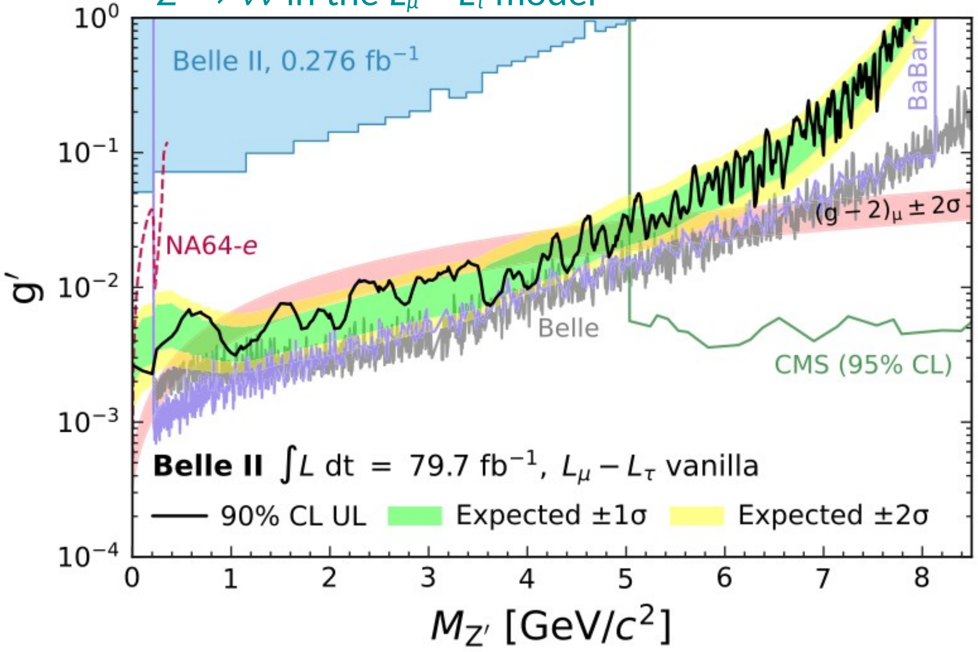
I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

- **No significant excess found in 79.7 fb^{-1}**
  - **$(g$ - $2)_\mu$ region escluded for $M_{Z'} \in (0.8, 5.0)$ GeV/c^2 for $\Gamma(Z' \to \text{inv.}) = 100\%$**

$Z' \to \chi\bar{\chi}$, $\Gamma(Z' \to \text{inv.}) = 100\%$



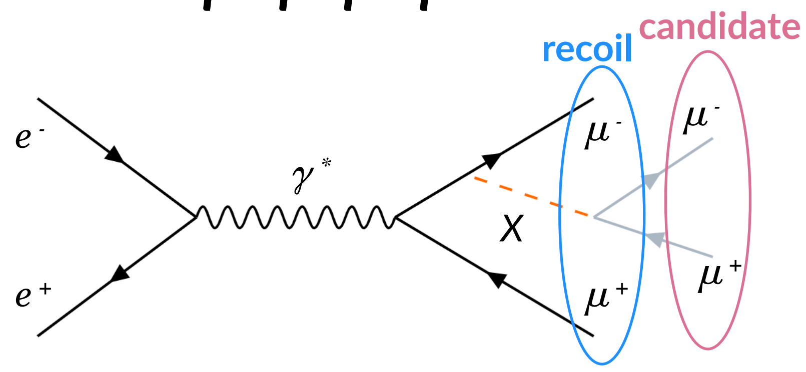
$Z' \to \nu\bar{\nu}$ in the $L_\mu - L_\tau$ model

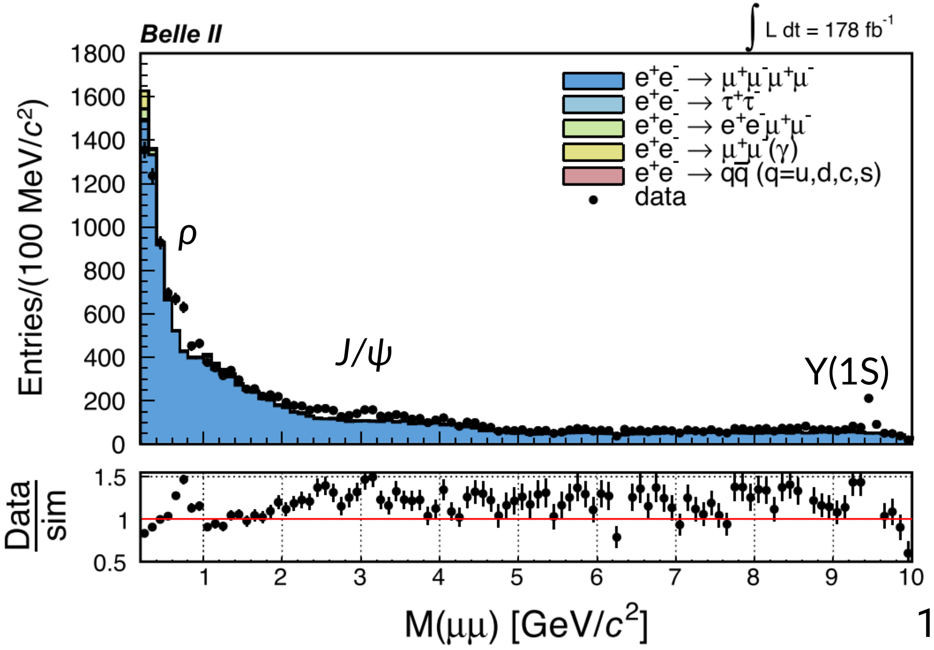


Search for a $\mu\mu$-resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

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

- Four-track final state with at least **three identified as muons**
  - Four-track invariant mass compatible with collision √s
  - No extra energy
- Signal signature is a **narrow peak in the opposite-charge di-muon mass $M(\mu\mu)$**
- Challenging aggressive suppression of main **SM background $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$**
  - Based on classifiers trained exploting the features of kinematic distributions in signal events
    - **Presence of a resonance in both candidate and recoil muon pairs**
- Signal extracted through **fits to $M(\mu\mu)$**





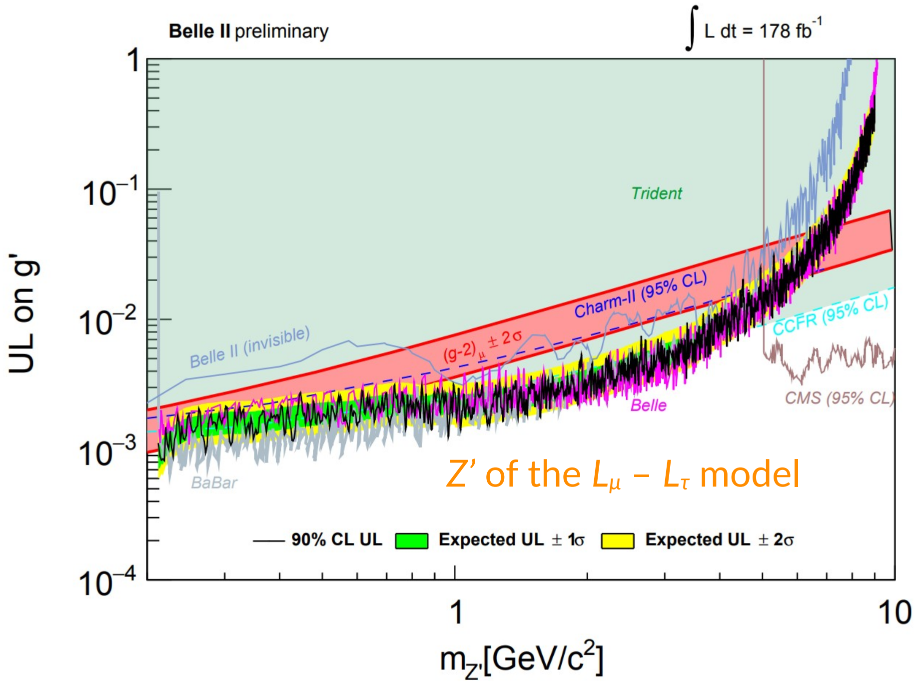
Search for a $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$: results

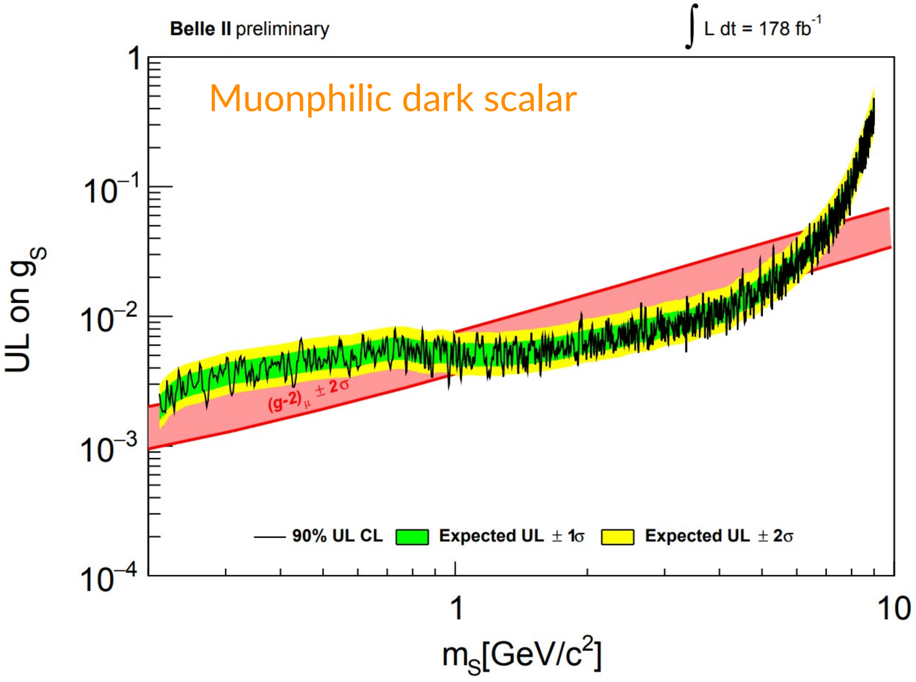
I. Adachi et al., Phys. Rev. D 109, 112015 (2024)

P. Harris et al., arxiv-2207.08990 (2022)
S. Gori et al., arxiv-2209.04671 (2022)

- **No significant excess found in 178 fb^{-1}**
  - **Competitive 90% CL upper limits on the *g'*** coupling of the $L_\mu - L_\tau$ model (Z') with BaBar (> 500 fb^{-1}) and Belle (> 600 fb^{-1}) results
  - **First 90% CL upper limits for the muonphilic scalar model** from a dedicated search

Efficiency is re-evaluated for the muonphilic scalar model

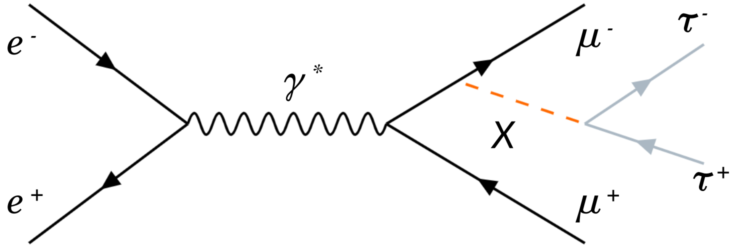


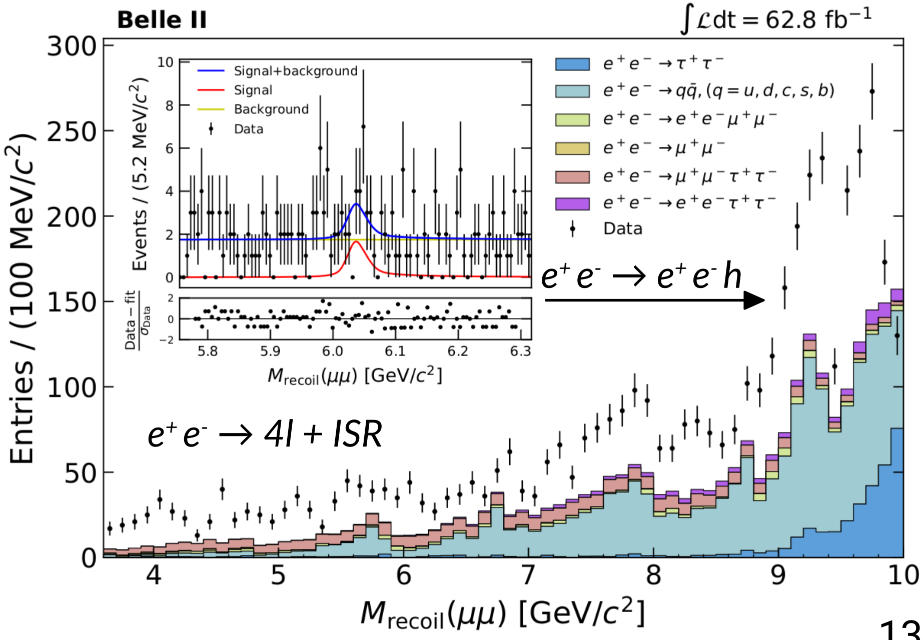


Search for a $\tau\tau$-resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$

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

- Four-track final state: τ decay in $\tau \rightarrow l\nu\bar{\nu}$, $\tau \rightarrow h\nu\bar{\nu}$
- Signal peaks in the **recoil mass of $\mu^+\mu^-$ $M_{recoil}(\mu\mu)$**
- Challenging **background rejection to reduce event contamination with missing energy not associated with signal signature**
  - Eight classifiers trained on different regions of recoil mass
    - Based on resonance X properties (FSR) and $\tau\tau$ system
- **Signal extracted through fit to $M_{recoil}(\mu\mu)$** distribution
  - **Background measured directly on data** to minimize impact of not correctly simulated backgrounds
  - **Smooth background** on the scale of signal resolution (~10 MeV)→ not problematic





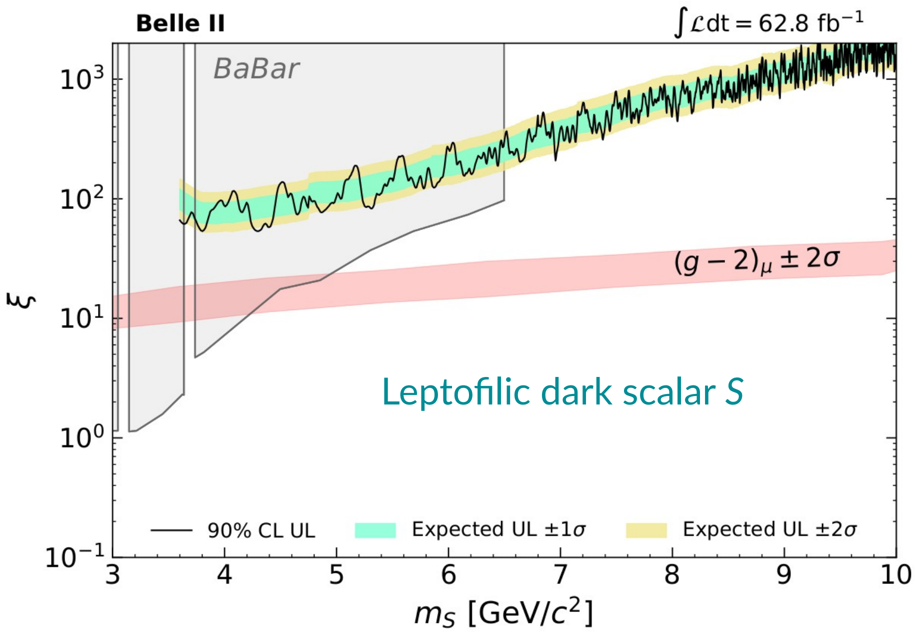
Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

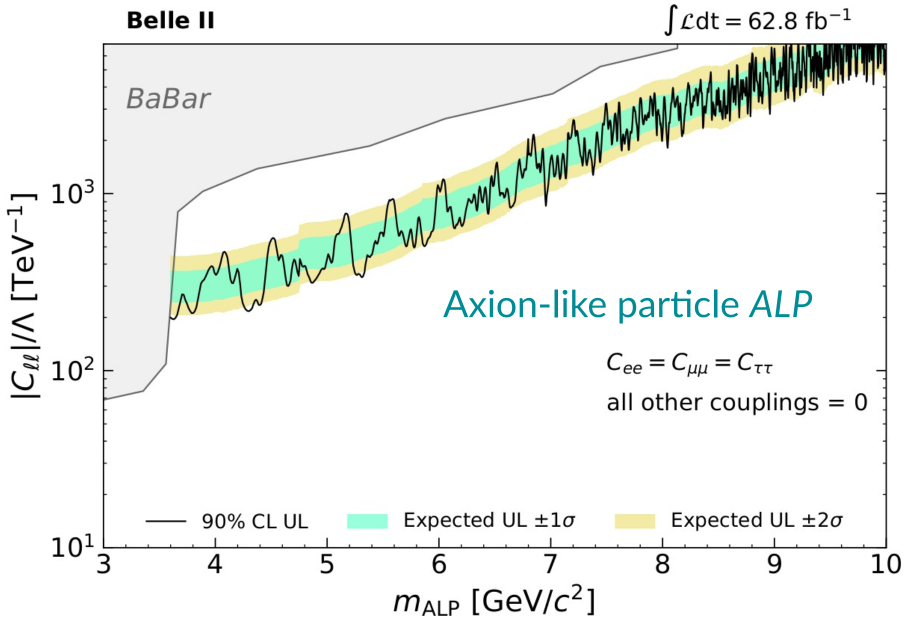
I. Adachi et al., Phys. Rev. Lett. 131, 121802 (2023)

J. P. Lees et al., PhysRevLett.125.181801 (2020)
M. Bauer et al., JHEP09-056 (2022)

- **No significant excess found in 62.8 fb^{-1}**
  - First **limits at 90% CL for a leptophilic dark scalar *S*** model with m_S > 6.5 GeV/c^2
  - First **direct limits at 90% CL for axion-like particle *ALP* → $\tau\tau$**

Efficiency is re-evaluated for the leptophilic scalar and *ALP* models





$\tau \to l\, \alpha$ (invisible) decay

I. Adachi et al., Phys. Rev. Lett. 130, 181803 (2023)

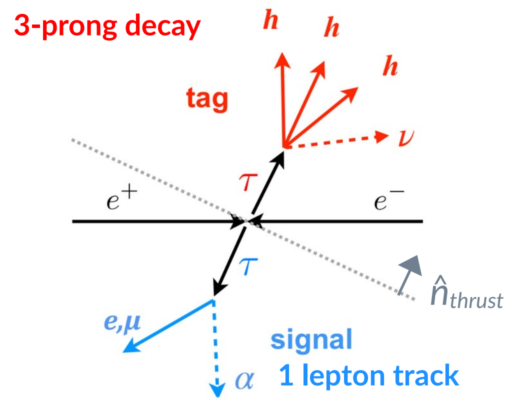
- Charged-Lepton Flavour Violation (**LFV**) is allowed in various SM extensions → it has never been observed
- τ-decays in new α bosons that **mediate LFV processes** are predicted in different theoretical models
- Search for $e^+ e^- \to \tau_{sig}\, \tau_{tag}$, $\tau_{tag} \to 3\pi\, \nu$
- The **presence of neutrinos** does not allow to define the reference frame in which τ_{sig} is at rest
  - → **Introduce the approximate τ_{sig} reference frame**
- **Search for a peak** in the normalized energy spectrum of the lepton x_l (in the approximate τ_{sig} reference frame) **over the irriducible SM $\tau \to l \bar{\nu} \nu$ background**

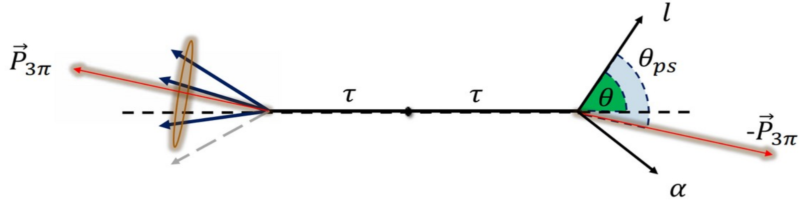
$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$$

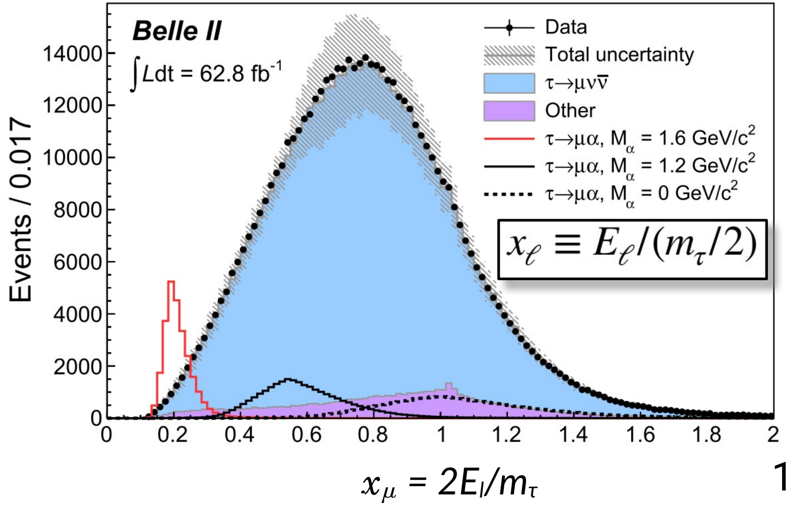
$$E_\tau \approx \sqrt{s}/2$$

Cross sections

$\sigma(e^+e^- \to b\bar{b}) \simeq 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb







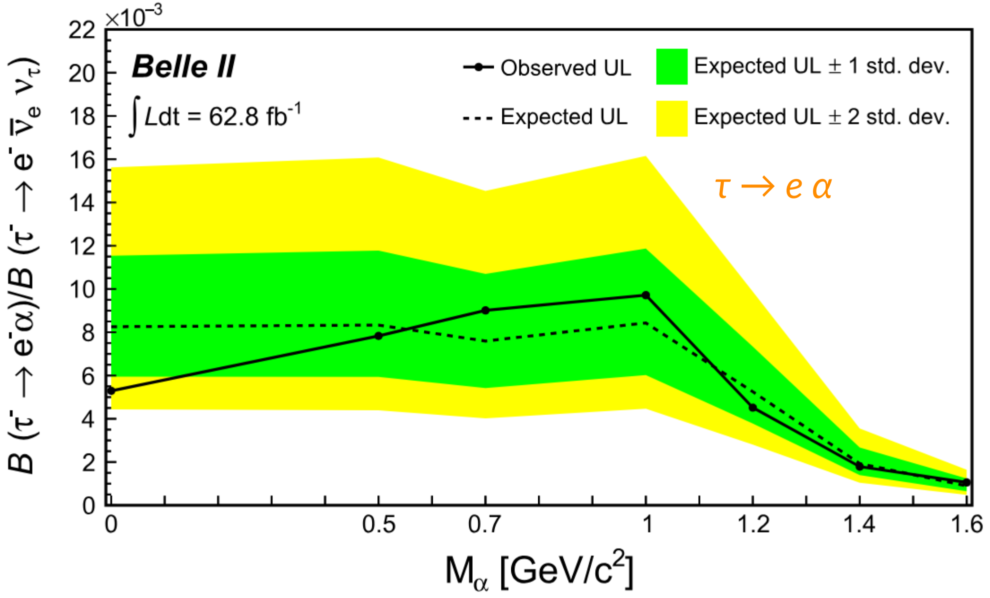
M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

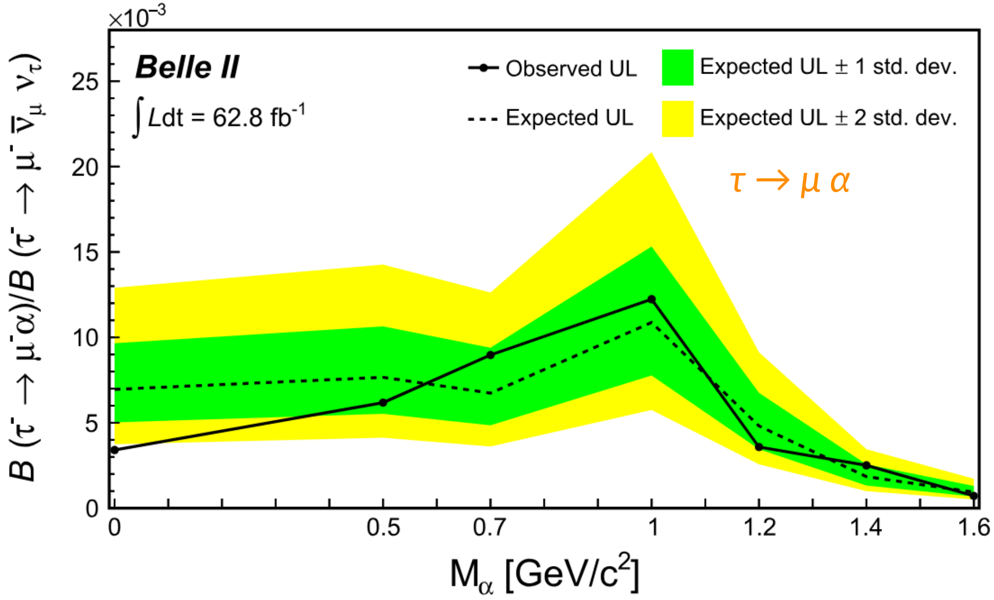
$\tau \to l\ \alpha$ (invisible) decay: results

I. Adachi et al., Phys. Rev. Lett. 130, 181803 (2023)

ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

- **No excess observed in 62.8 fb^{-1}**
  - **Limits from 2.2 to 14 times more stringent with respect to the previous existing limits** set by ARGUS





Long-lived spin-0 boson in $b \to s$ transitions

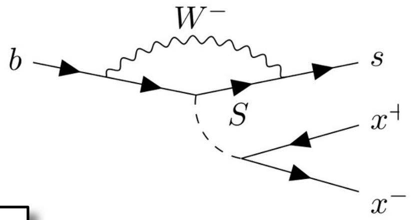
I. Adachi et al., Phys. Rev. D 108, L111104 (2023)

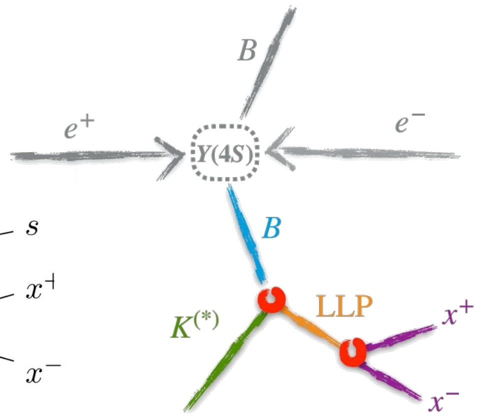
- Search for a **new scalar** S in B meson decays in $b \to s$ transitions
  - S can mix with SM Higgs boson with mixing angle θ_s → natural long-lived particle (*LLP*) for small θ_s
  - **High performance in *LLP* vertex reconstruction are necessary**
- B meson decays
  - Eight exclusive "visible" channels reconstructed
  - Prompt decay of K or K^* + opposite-charged tracks that make a **displaced vertex**
  - Backgrounds: combinatory $e^+e^- \to q\bar{q}$, K_S vetoed in $M_{\pi\pi}$ mass, additional peaking backgrounds suppressed with tighter selections on displaced vertices
- Signal extracted through **fit to the *LLP* reduced mass, separately for each channel and lifetime**

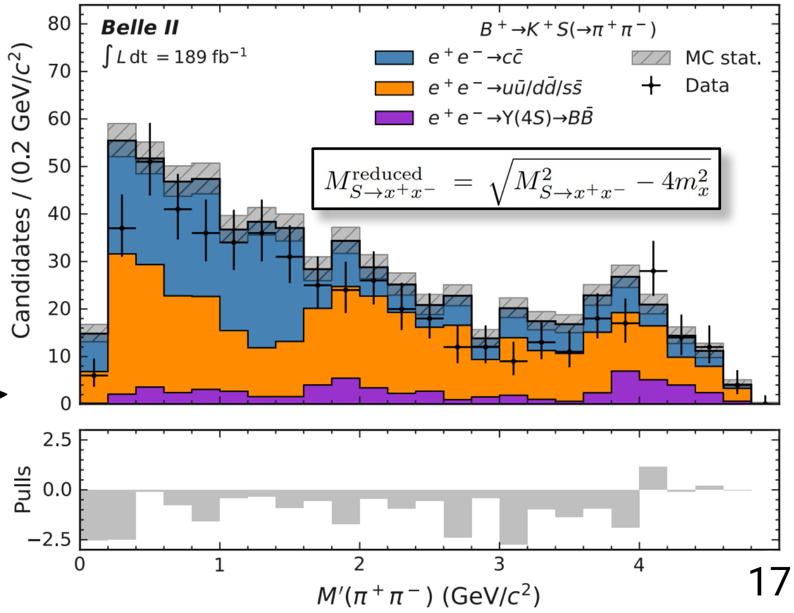
$B^+ \to K^+ S$

$B^0 \to [K^{*0} \to K^+\pi^-] S$

$S \to ee/\mu\mu/\pi\pi/KK$





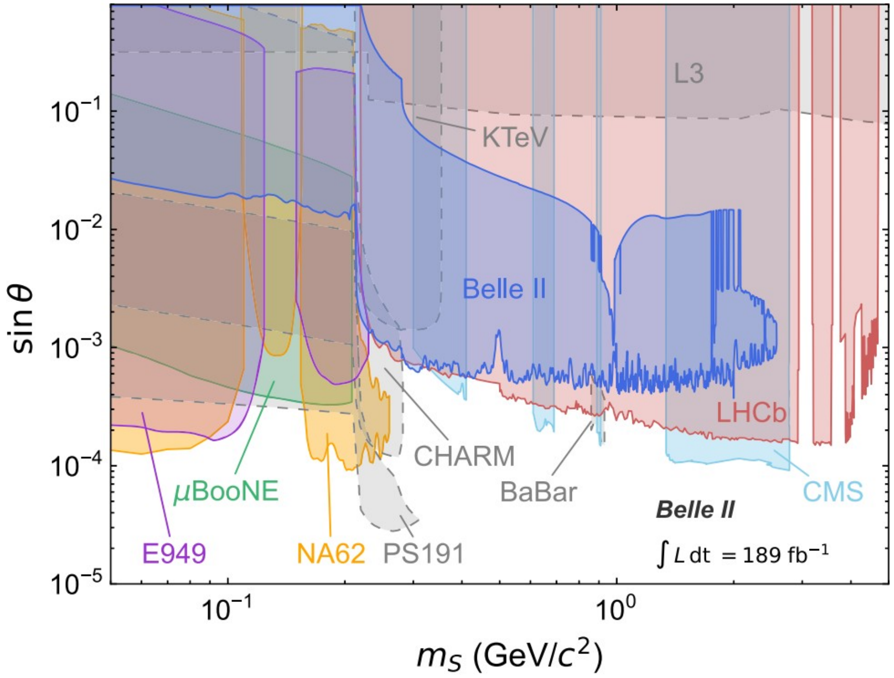


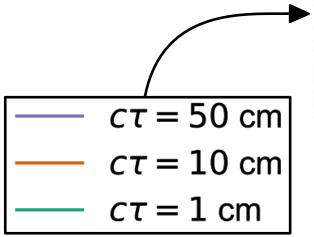
Long-lived spin-0 boson in $b \to s$ transitions: results

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

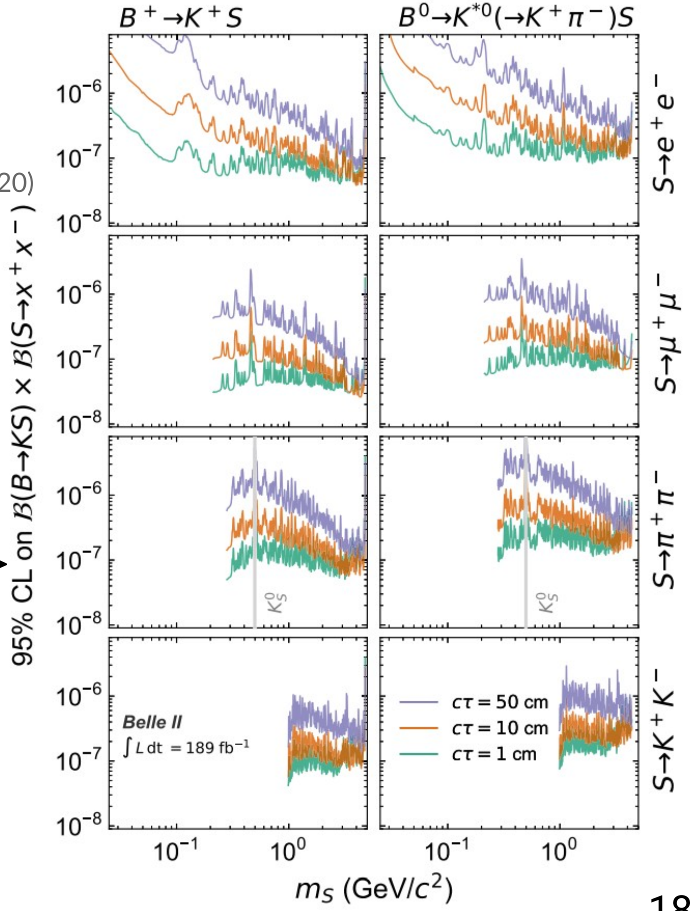
- **No significant excess observed in 189 fb^{-1}**
  - **First model-independent limits at 95% CL on $BR(B \to K_S) \cdot BR(S \to x^+x^-)$**
  - **First limits on decays to hadrons**
- Interpretation as dark scalar S

A. Filimonova et al. Phys. Rev. D 101, 095006 (2020)
J Beacham et al. J. Phys. G: Nucl. Part. Phys. 47 010501 (2020)





Limits for each channel and lifetime



Inelastic dark matter with a dark Higgs

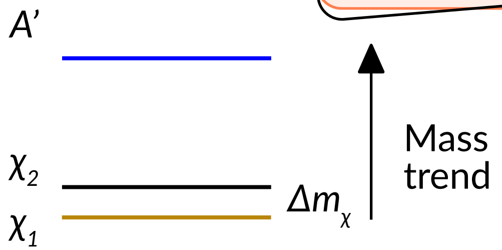
NEW

Inelastic dark matter ...

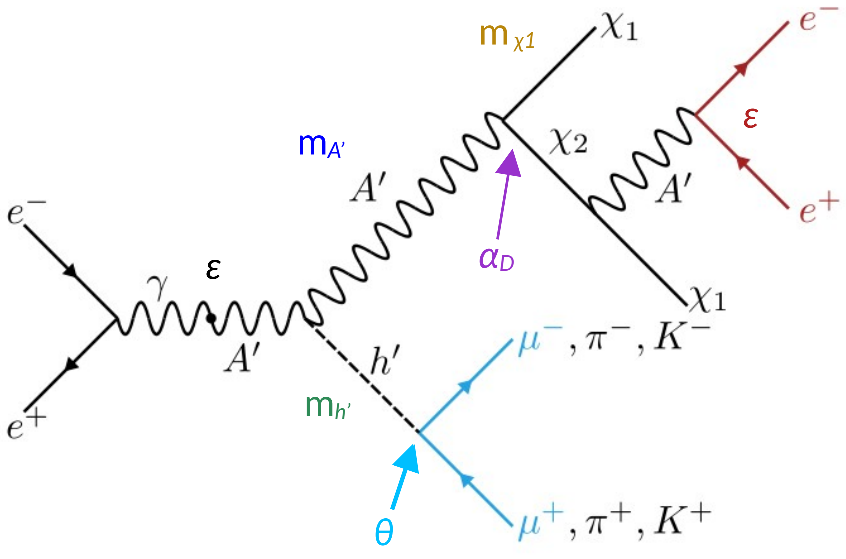
- Expanded dark sector with **two dark matter states** with a **small mass splitting** and a **dark photon**
  - χ_1 **is stable** (relic candidate), χ_2 **is long-lived**
- Focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$
  - the decay $A' \to \chi_1 \chi_2$ is favored

... with a dark higgs (provide mass to *A'*)

- ***h'* mixes with Standard Model Higgs** with **θ**
  - ***h'* is natural long-lived** (*LLP*) for small θ



$e^+e^- \to h'(\to x^+x^-)A'(\to \chi_1\chi_2(\to \chi_1 e^+e^-)$, $x = \mu, \pi, K$



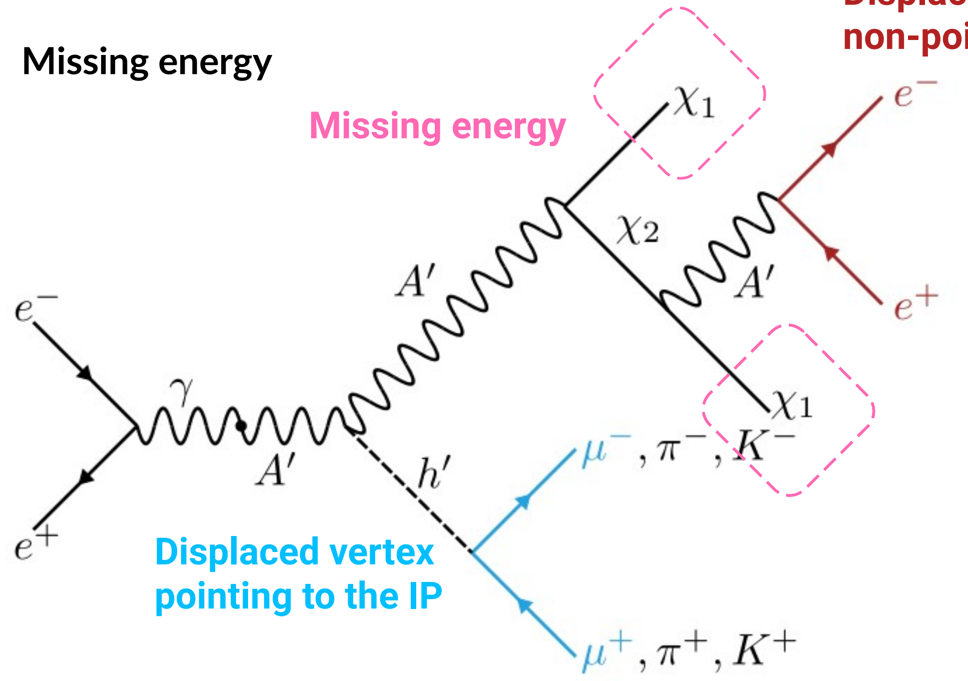
- We have 4 dark sector particles: A', h', χ_1 and χ_2
- We have 7 parameters: $m_{A'}$, $m_{h'}$, $m_{\chi 1}$, Δm_χ, θ, ε, α_D

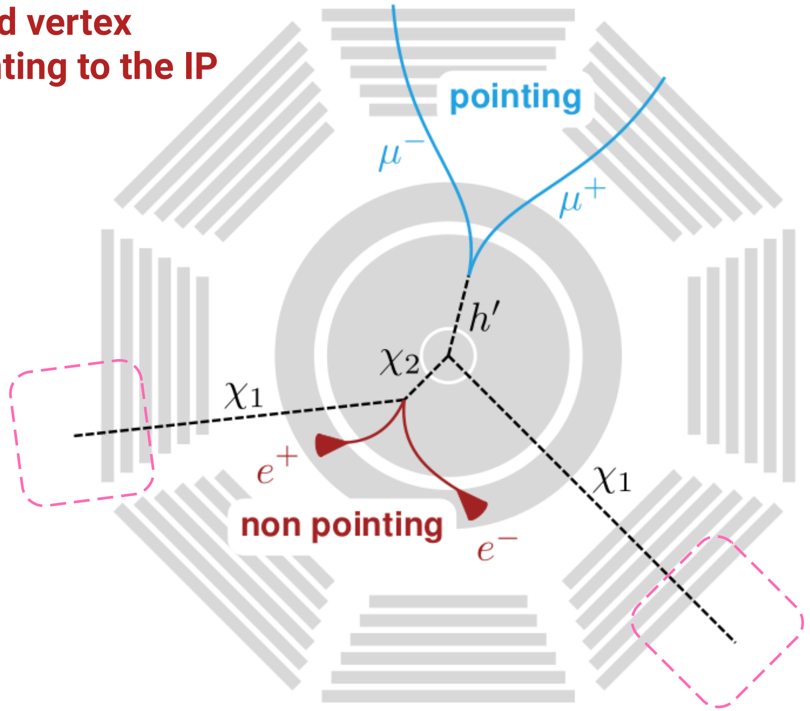
IDM with a dark Higgs: signature

NEW

- **Four tracks in the final state**
  - 2 forming a **pointing displaced vertex**
  - 2 forming a **non-pointing displaced vertex**
- **Missing energy**

- **Challenging for tracking and trigger**
- **Almost zero background analysis**

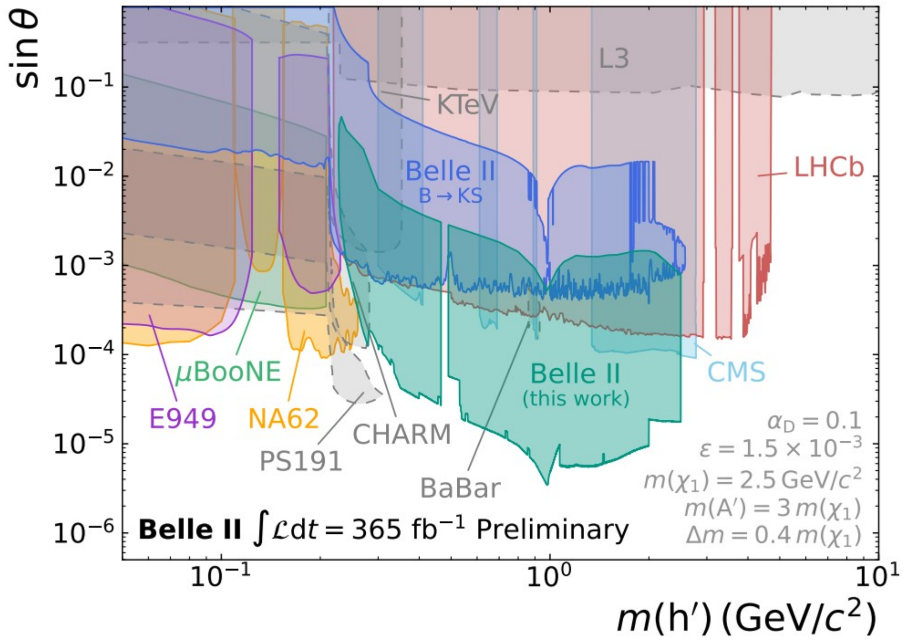


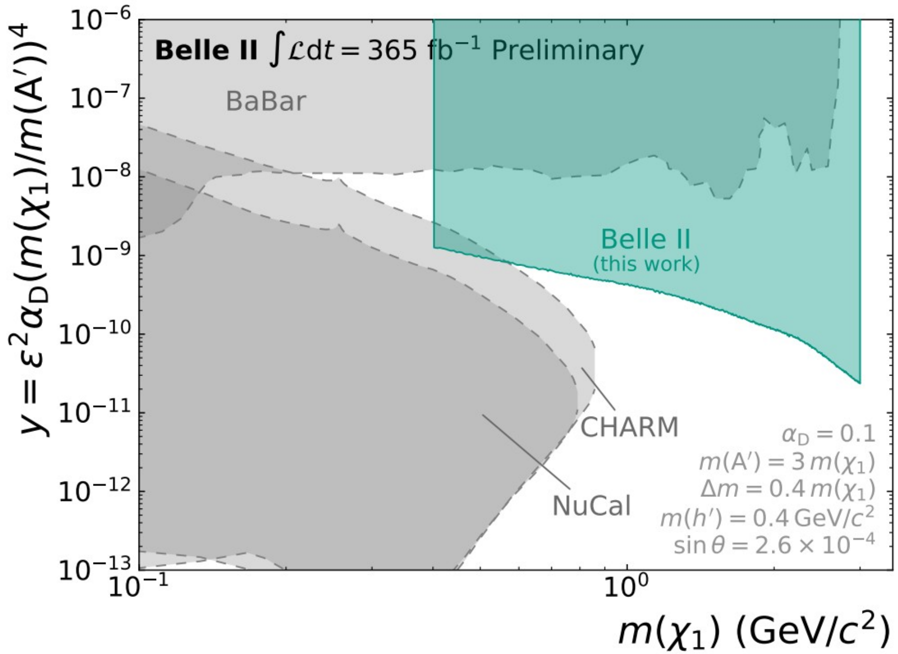


IDM with a dark Higgs: preliminary

NEW

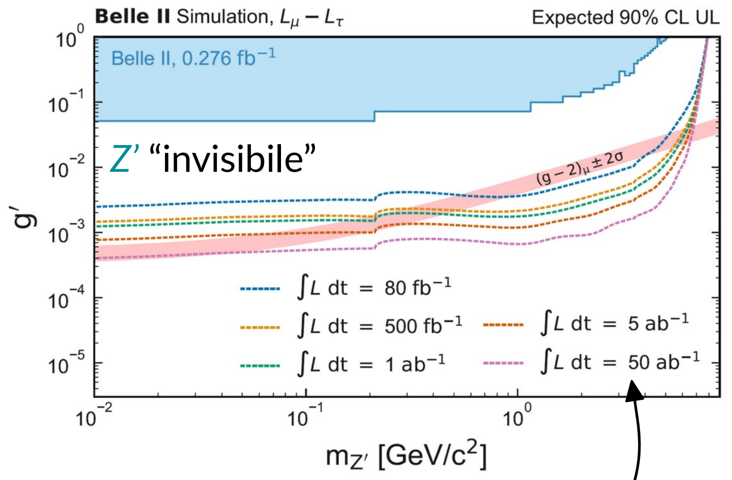
- **Cut-and-count strategy** for extracting signal yields
- **Expected background estimated in data** from sidebands to not rely on MC
- **No significant excess found** in the individual final states or the combination → **set 95% CL upper limits**





Summary and conclusions

Snowmass paper arxiv:2207.06307



Belle II target integrated luminosity is 50 ab^{-1} (almost x100 the dataset collected so far)

- Belle II has a **unique sensitivity** to light dark sector
  - Complementary to higher energy colliders and beam-dump experiments
  - World-leading results published with partial Run 1 datasets (< 427 fb^{-1})
- **Many frontiers of improvements**
  - **Increase data sample** size, **improved analysis techniques**, and **reduced systematic uncertainties**

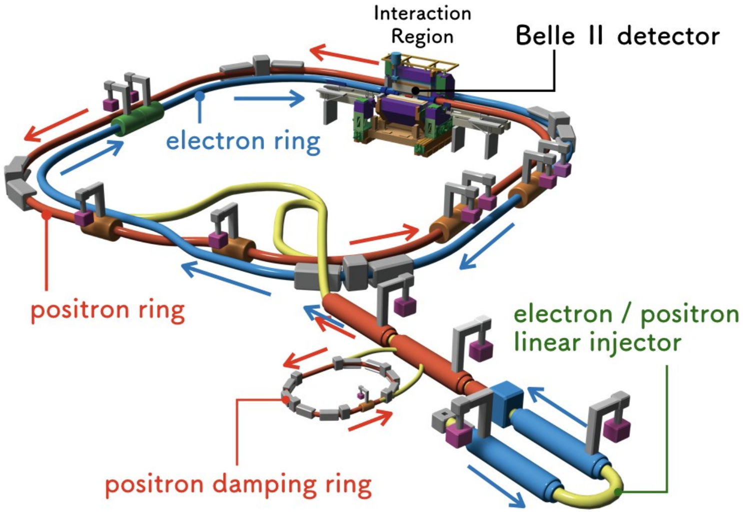
- Search for an invisible Z' in $ee \to \mu\mu Z'$ Phys. Rev. Lett. 130, 231801 (2023)
- Search for a resonance decaying to $\mu\mu$ in $ee \to \mu\mu\mu\mu$ events Phys. Rev. D 109, 112015 (2024)
- Search for a resonance decaying to $\tau\tau$ in $ee \to \mu\mu\tau\tau$ events Phys. Rev. Lett. 131, 121802 (2023)
- Search for the LFV $\tau \to l\,\alpha$ (invisible) decay Phys. Rev. Lett. 130, 181803 (2023)
- Search for a long-lived spin-0 boson in $b \to s$ transitions Phys. Rev. D 108, L111104 (2023)
- Search for inelastic dark matter with a dark Higgs **New**

Many more analyses published and ongoing at Belle and Belle II …

Thank you!

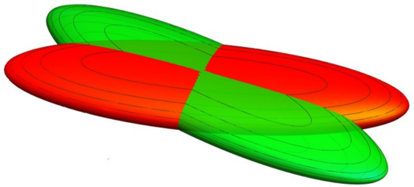
Backup slides

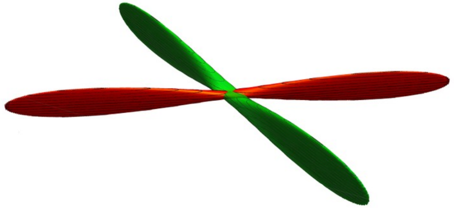
SuperKEKB



- New generation of B-factory that provides luminosity to the Belle II experiment
  - Asymmetric beam energies: e^- (7 GeV) / e^+ (4 GeV)
    Operating mainly at Y(4S), but foreseen runs from Y(2S) to Y(6S)
  - Designed to reach the world highest peak luminosity with the nano-beam scheme

Nano-beam scheme



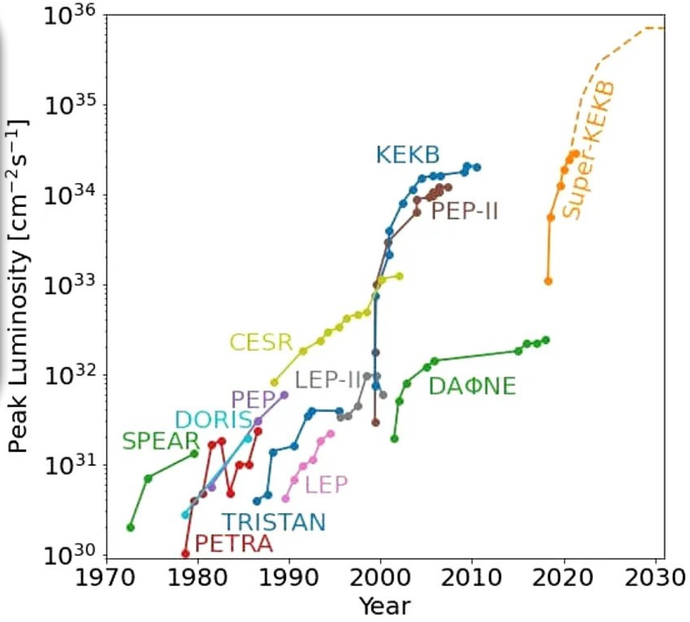


β_y^* ~ 1/20x
I ~ 1.5x

KEKB
- I(A) ~ 1.6/1.2
- β_y^*(mm) ~ 5.9/5.9

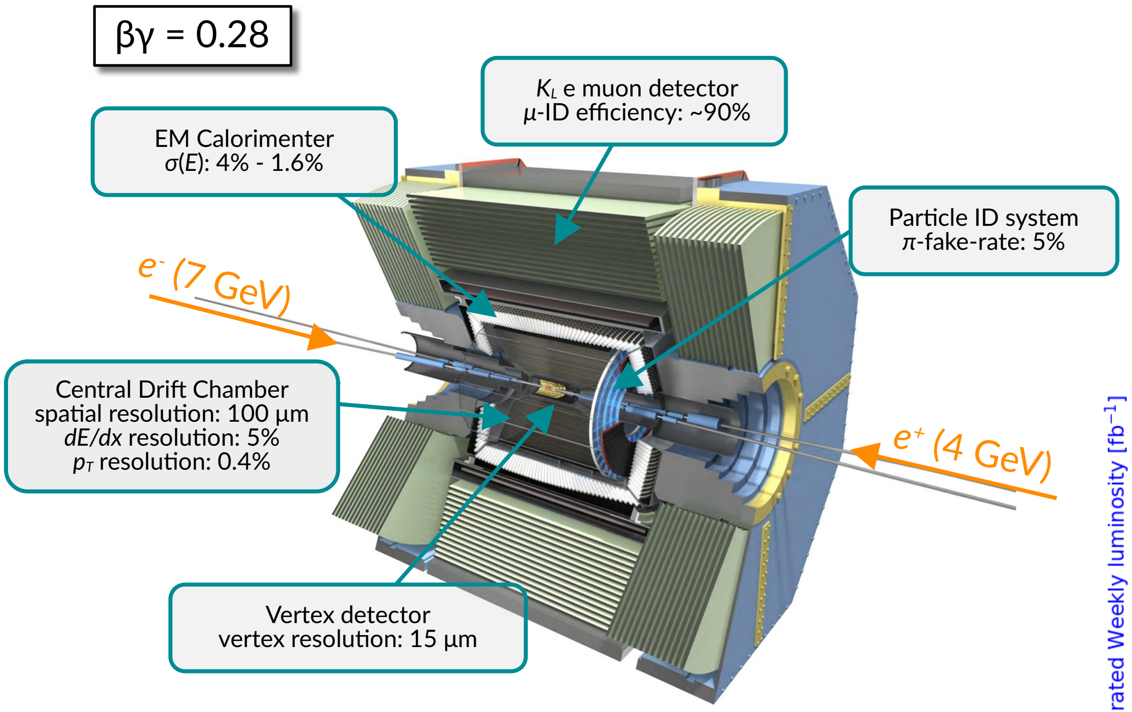
30x peak luminosity

SuperKEKB
- I(A) ~ 2.9/2.0
- β_y^*(mm) ~ 0.3/0.3



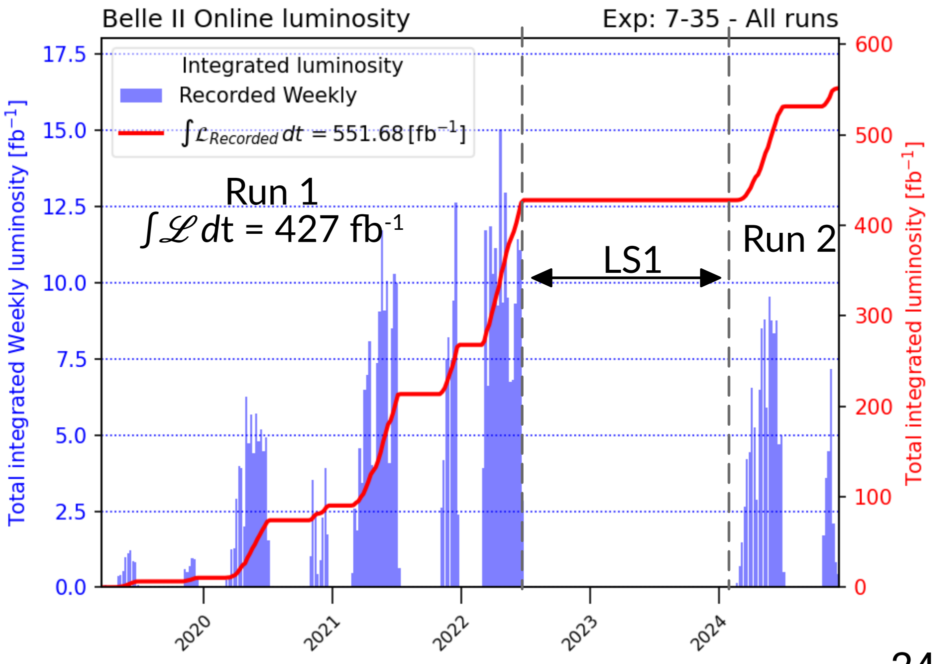
- World record luminosity: **4.7 x 10^{34}** $cm^{-2}s^{-1}$
- Target peak luminosity: **6 · 10^{35}** $cm^{-2}s^{-1}$

Belle II at SuperKEKB



- Major upgrade of Belle@KEKB → better resolution, particle identification (PID) and capability to cope with higher background
- Covers more than 90% of the total solid angle

- First collisions during commissioning run on April 26th 2018
  - ➔ 0.5 fb^{-1} collected in 2018
- First collisions with the full detector on March 2019
  - ➔ > 540 fb^{-1} collected in 4 years of data taking
- Target integrated luminosity of the Belle II experiment: **50 ab^{-1}** (x30 Belle + BaBar)

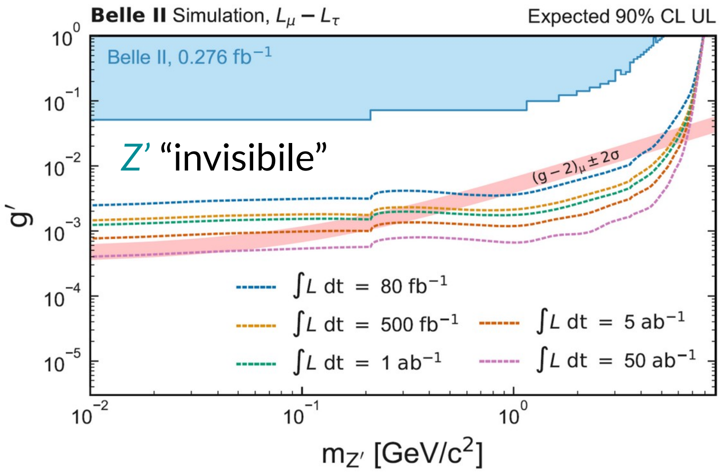


Belle II perspectives

- Target integrated luninosity: 50 ab^{-1}
- Target peak luminosity: $6x10^{35}$ cm^{-2} s^{-1}

Luminosity projection (plan for next years)

Snowmass paper arxiv:2207.06307

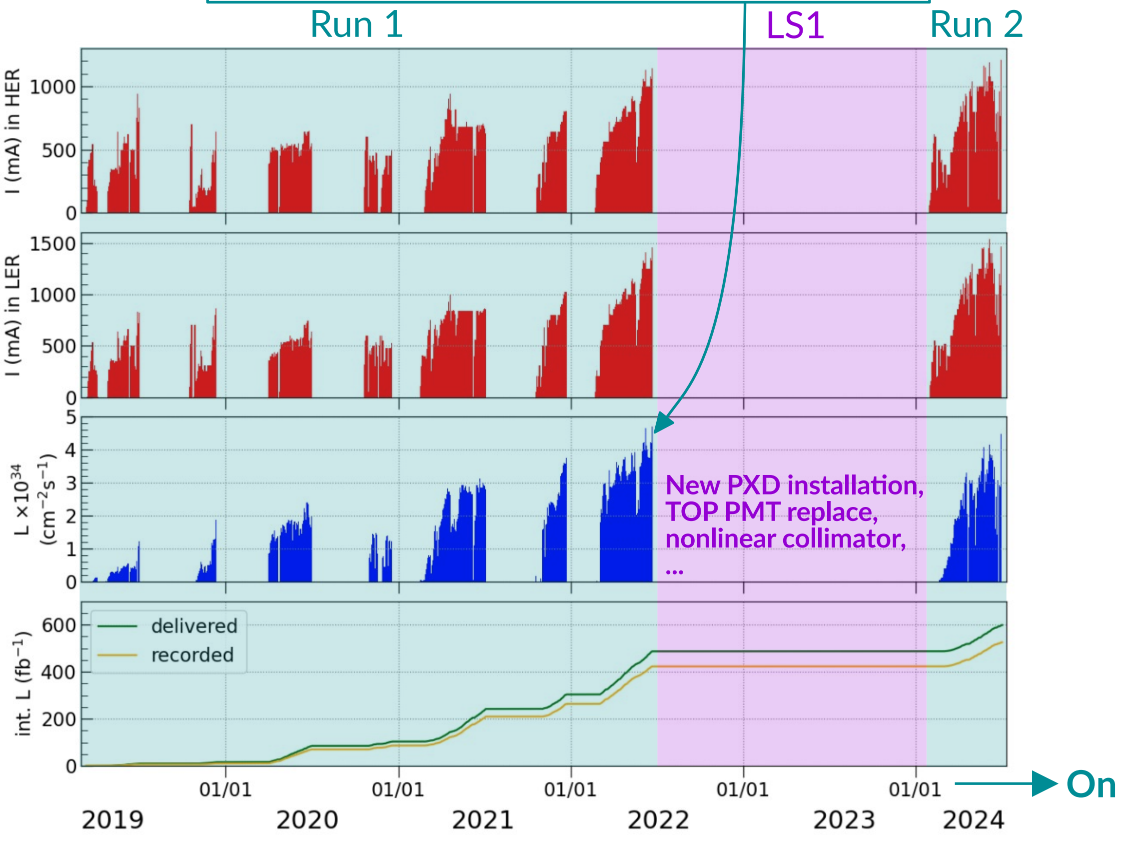


- 550 fb^{-1} collected (Run 1 (427 fb^{-1}) + Run 2)
- **Obtained results are strongly limited by statistics**
  World-leading results already published with early datasets (less than collected dataset of 427 fb^{-1})

- In next years, Belle II will collect 100-times the dataset collected up to now
  - ➔ **The best is yet to come!**

SuperKEKB/Belle II - Run 2 status

World record: $\mathscr{L}_{peak}$ = 4.7 x 10^{34} cm^{-2}s^{-1}

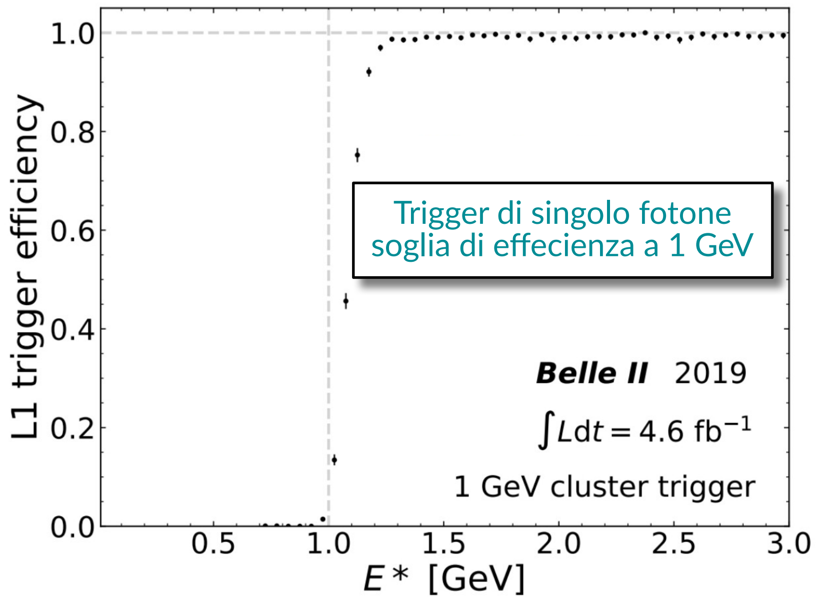


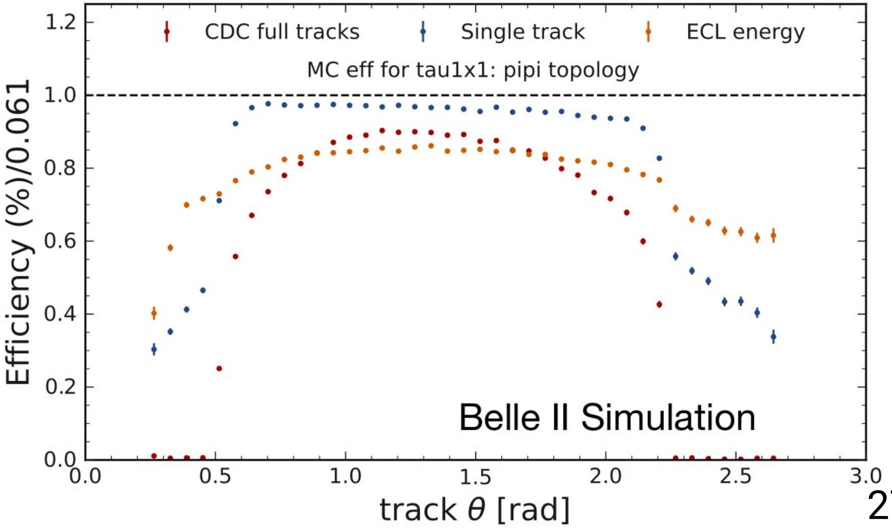
Run 2 (2024 – ongoing)

- **Back to operations at** 4 x 10^{34} cm^{-2}s^{-1}
- **Sudden beam losses** have happened frequently
  - Significant beam charge loss (> a few %) that occurs suddenly without any precursory phenomena
  - **Very large dose in the detector**
- **Two such losses led to damage of 2% of new PXD** (installed during LS1)
  - **Turned off PXD** as a precautionary measure until beam losses mitigated
- So far Run 2 has been largely dedicated to machine studies
  - Only ~130 fb^{-1} collected
- **Some understanding of how the losses start**
  - Remediation begun in summer shutdown

Low-multiplicity triggers

- Two-level trigger
  - Hardware-based Level 1 Trigger (L1): < 30 kHz
  - Software-based High Level Trigger (HLT): < 10 kHz
- Devised specific low-multiplicity trigger lines
  - Suppress high-cross-section QED processes **without "killing" the signal**
  - **Precise knowledge of acceptance and efficiencies of the detector required**
- Examples
  - Single-photon trigger
  - Single-muon trigger
  - Single-track trigger

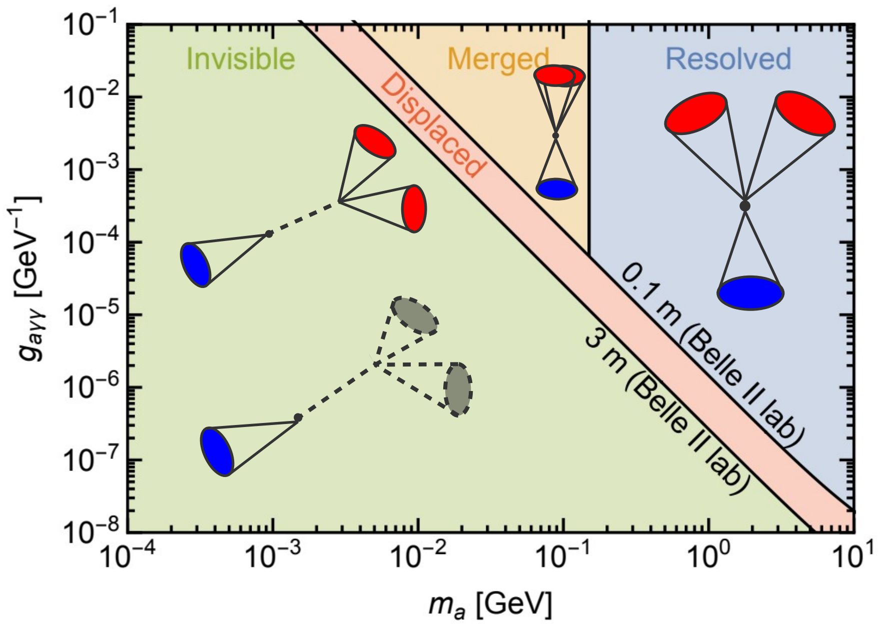


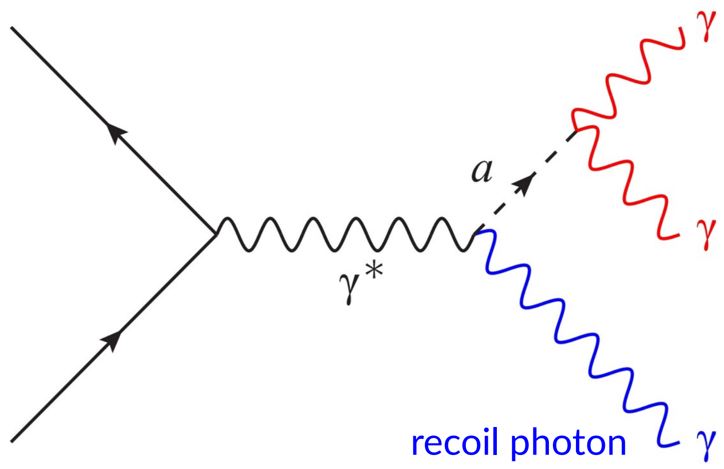


Axion-like particles (ALPs)

F. Abudinén et al., Phys. Rev. Lett. 125, 161806 (2020)

- GeV-scale ALPs: pseudo-scalar portal mediator between dark sector and Standard Model
- If ALP-photon coupling ($g_{a\gamma\gamma}$) dominates, than $BR(a \to \gamma\gamma)$ ~ 100%
- Focus on mass region where ALP decay is prompt and photons can be well resolved by Belle II



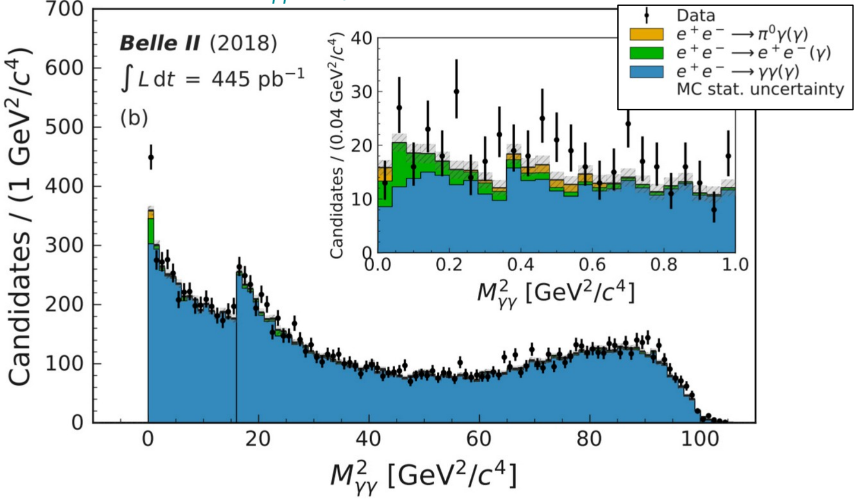


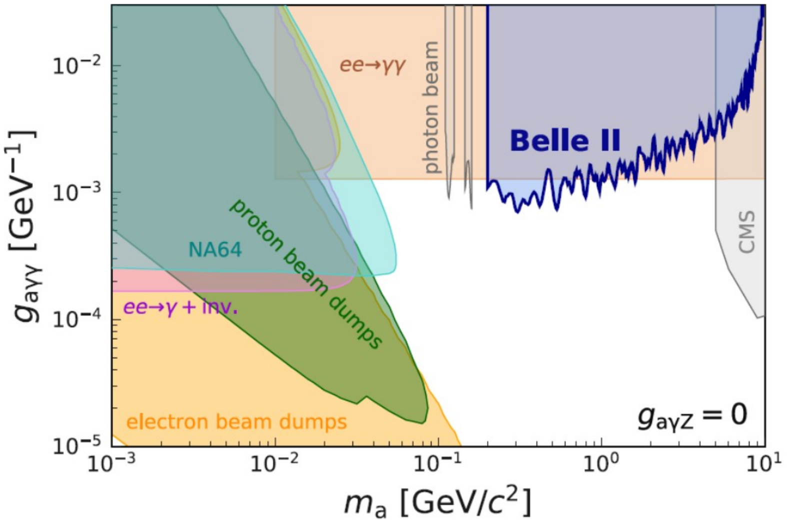
Search for an ALP at Belle II

F. Abudinén et al., Phys. Rev. Lett. 125, 161806 (2020)

- Event selection:
  - electromagnetic calorimeter trigger (efficiency ~100%)
  - three-γ invariant mass compatible with collision $\sqrt{s}$
- Signal signature is a **narrow peak in $M^2_{\gamma\gamma}$ or M^2_{recoil}** (depending on best resolution of signal peak)
- Largest background from $e^+e^- \to \gamma\gamma(\gamma)$
- Segnal extracted through fit
  - **No excess observed in 0.445 fb^{-1}**
  - Upper limits at 95% CL on $g_{a\gamma\gamma}$
  - **World-leading limits for m_a ~ 0.5 GeV/c^2**

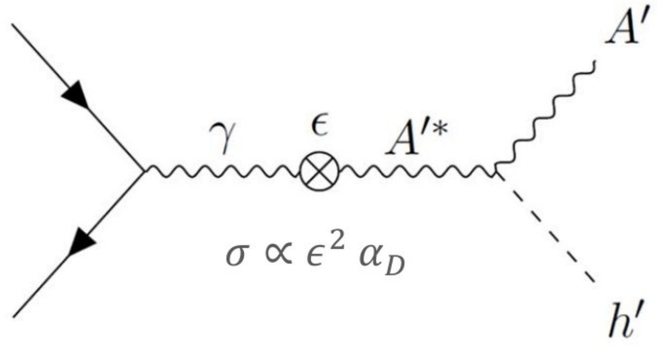
$M^2_{\gamma\gamma}$: m_a < 6.85 GeV/c^2



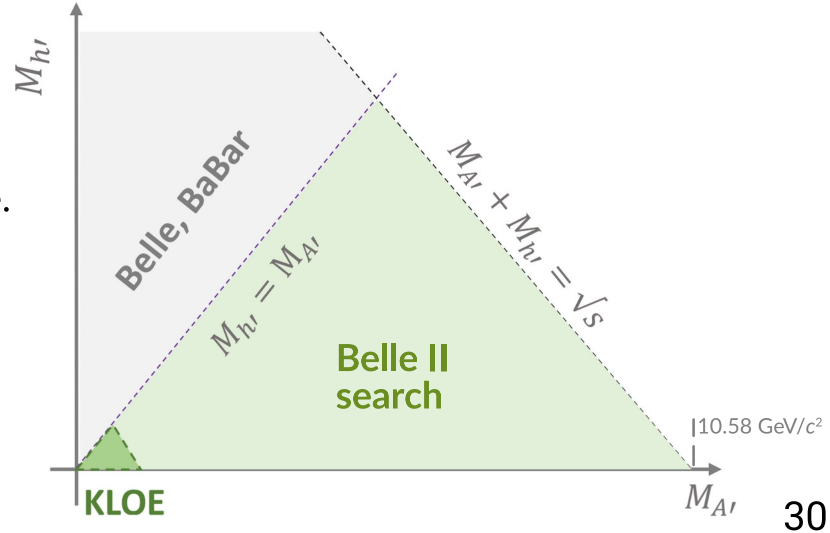


Search for a dark Higgs (and dark photon)

- Dark photon *A'*
  - kinetic mixing with SM photon with strength ε
  - mass produced by the Higgs mechanism involving a dark Higgs boson
- Dark higgs *h'*
  - couples to *A'* with α_D
  - does not mix with SM Higgs
- Both *A'* and *h'* can be produced at e^+e^- colliders through the dark higgsstrahlung process
  - → $\boldsymbol{e^+e^- \to A'^* \to A' h'}$
- Different signatures depending on *h'* mass
  - → $M_{h'} > M_{A'}$: prompt decay $h' \to A'A'$, up to 6 tracks in the final state. Investigated by BaBar (2012) and Belle (2015)
  - → $M_{h'} < M_{A'}$: *h'* is long-lived, thus invisible. Investigated by KLOE (2015)
- **Belle II focuses on the invisible *h'***

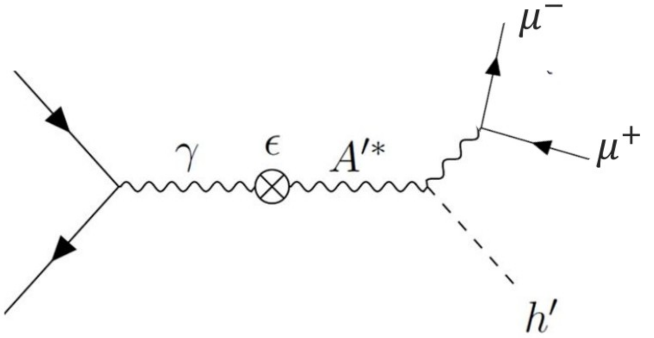


P. Fayet, Nucl. Phys. B 187, 184 (1981)
Batell et al., Phys. Rev. D 79, 115008 (2009)

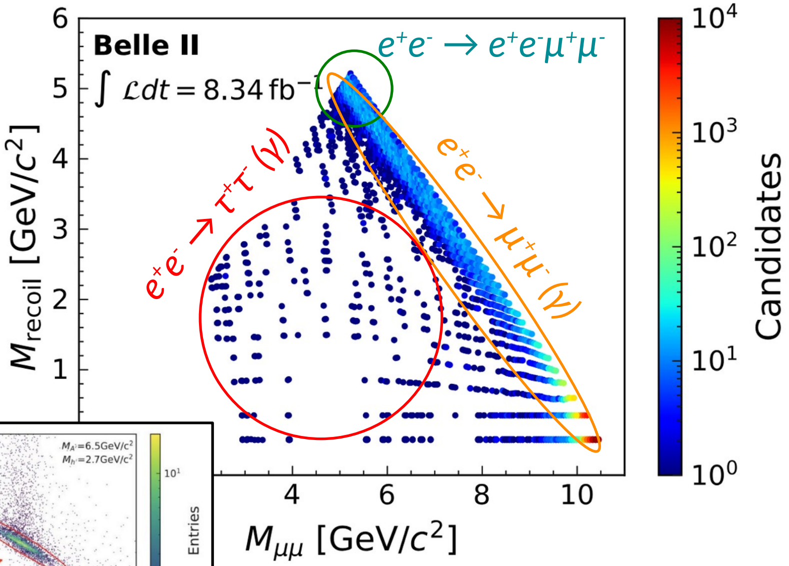


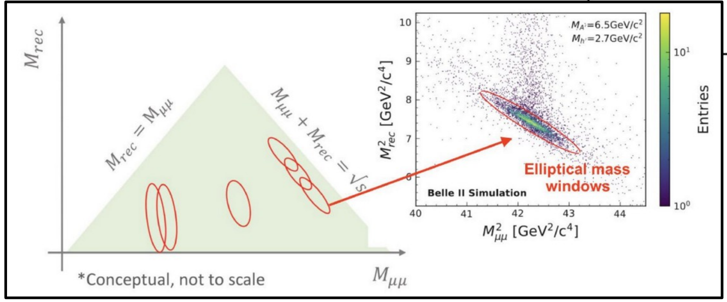
Dark higgsstrahlung at Belle II

F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)



- $e^+e^- \to A'h', A' \to \mu\mu, h' \to$ **invisible**
- Same final state as for the invisible Z', similar backgrounds: $e^+e^- \to \tau^+\tau^- (\gamma)$, $e^+e^- \to \mu^+\mu^- (\gamma)$, $e^+e^- \to e^+e^-\mu^+\mu^-$
- Signal signature is a 2D peak in the recoil mass vs the dimuon mass
- Event selection
  - Two reconstructed muons, $p_T^\mu > 0.1$ GeV/c
  - Recoil momentum in the ECL barrel, no nearby photon
  - Cut on dimuon helicity angle → efficiently suppress background
- Signal extraction through 2D fit in M_{recoil} vs $M_{\mu\mu}$ plane in elliptical windows

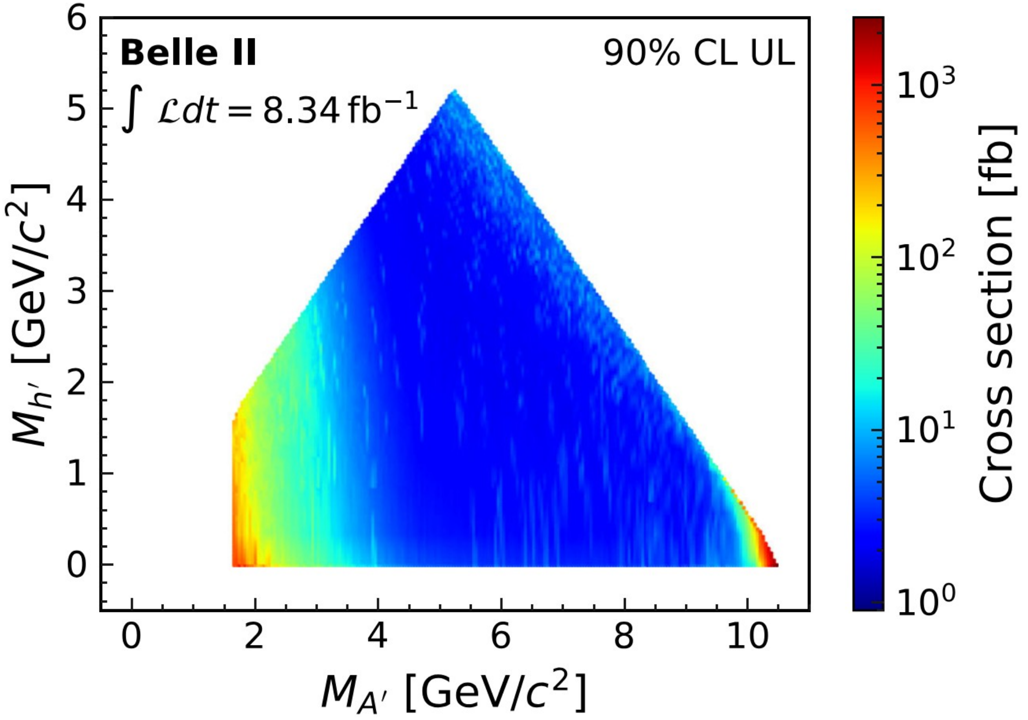


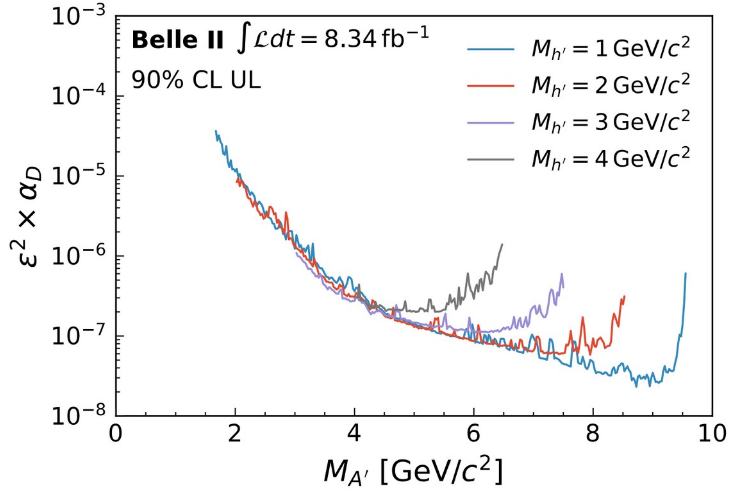


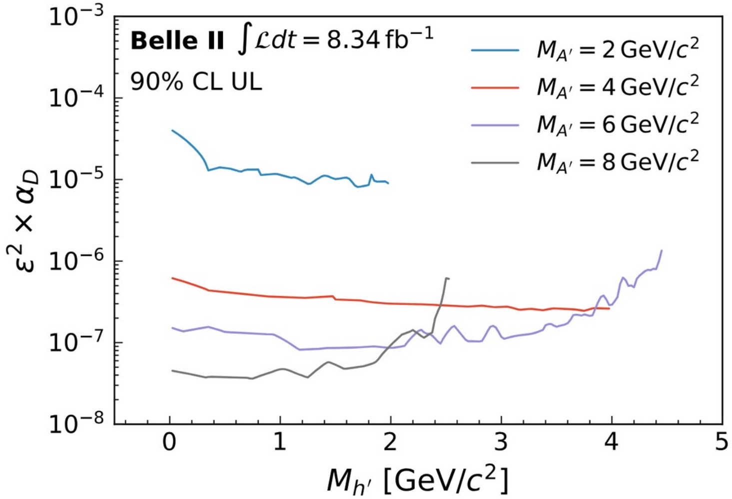
Dark higgsstrahlung at Belle II: results

F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)

- **No significant excess in 8.34 fb^{-1}**
  - 90% CL upper limits and **world leading limits for 1.65 < $M_{A'}$ < 10.51 GeV/c^2**







Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$: Z'

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

- **No significant excess found in 62.8 fb^{-1}**
  - 90% CL upper limits on the g' coupling of the $L_\mu - L_\tau$ model (Z')